E4: Fourth-generation European infrastructure for studying the birth, evolution, and contents of the Universe using the Cosmic Microwave Background Radiation

List of participants

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Abstract

We propose to design the European observatory infrastructure necessary to use the Cosmic Microwave Background Radiation (CMB) to study the birth and the “Dark Side” of the Universe.

The CMB is the light left over from the birth of the Universe – the remnants of the Big Bang. Since its discovery, it has become one of our most important tools for understanding the Universe, confirming that the Universe did actually start with the Big Bang and helping us to infer how the Universe evolved from a dense, featureless place in the beginning to what we have today, with various large structures such as galaxies and clusters of galaxies. But we can learn still more about from the CMB.

- The growth of these cosmological structures is influenced by the expansion of the Universe, and in particular by the recently discovered acceleration of this expansion. By studying structures with the CMB we can study the "Dark Energy" thought to drive this acceleration.

- The CMB passes by the bulk of the matter in the Universe as it travels to us – passing both normal and Dark Matter, which we cannot see directly. But we can study it by observing its gravitational effects on the CMB.

- Perhaps most excitingly, the CMB was created shortly after the Big Bang and could therefore contain hints to what fuelled the Big Bang itself. Cosmic Inflation, our leading theory for the pre-Big Bang indicates that there should be specific primordial patterns in the CMB which we do not know how to create in any other way. Detecting these would be the next big step in understanding the creation of the Universe itself.

We will design the microwave observatory needed to address these and other goals in the context of the world-wide CMB effort spanning ground-based, balloon-based and space-based experiments. While the basic science is of interest to all cosmologists, this study will focus on aspects of particular interest to the European community and will ensure European access and that European standards are upheld in its construction and operation.

1. Excellence

1.1 Objectives

The CMB is sometimes called a "baby picture" of the Universe. It is the light which was emitted when the Universe was around 1/35,000 of its age today and which has traveled, largely untouched, to our observatories. Studying it us valuable insights into what the Universe looked like in its infancy, and by comparing it with the Universe today, it also informs us about what is in the Universe as a whole and how the Universe evolved.

The discovery of the CMB in 1965 helped cement the Big Bang as the leading theory for the birth of the Universe. The discovery and characterization of so-called "anisotropies", or small variations on top of what is otherwise a very uniform glow, has helped us characterize the geometry of the Universe, estimate its age with new precision, and usher in the "Lambda Cold Dark Matter" model of the Universe, in which less than 5% of what is in the Universe is what we consider "normal" material – protons, neutrons, etc. The other 95% is a combination of what is called Dark Matter and what is called Dark Energy. Rather than, or possibly in addition to, being mysterious, these names are intended to capture the difficulty cosmologists have had in measuring and even characterizing these constituents, which dominate the evolution of the Universe.

While we have already learned an enormous amount from the CMB, it still harbours a wealth of untapped information about our Universe. So we propose here to do a design study of possible CMB observatories which will allow the European community continue to use it to study the birth and contents of the Universe. This so-called "Stage-4" observatory will be based on existing technology, but on a scale larger than anything attempted before. This project will build upon the experience won by the European and international CMB communities over recent decades while developing previous generations of less ambitious experiments.

In particular, the work of the proposal will address:

• The choice of science focus – will we fix on the very first instances of the Universe, the constituents of the Universe, or a combination of these?

• The choice of where to put the experiment or experiments. Like other observatories, CMB telescopes must be located in high, remote areas in order to avoid contamination from the atmosphere and man-made contaminants.

• The choice of telescope type to put on the chosen sites. As noted above and below, there is a wealth of science to be done with the CMB, but the detailed design of the telescopes to be made will depend on the exact mix of science to be emphasized.

• The choice of detection technology to integrate into the telescopes. The CMB field is blessed with multiple technologies which may fulfill Stage-IV requirements, but work is necessary to find the optimal choice in terms of ease of fabrication, use and testing vis-a-vis resource costs.

• The presentation of community preferences as a function of cost. There are a number of different possibilities for a CMB observatory. The final step in the design study is to distill the multiple possibilities into the communities preferred scenarios in terms of impact versus cost.

• The establishment of a governance structure for the future infrastructure facility.

1.2 Relation to the work program

This Design Study proposal is a response to the Horizons 2020 European Research Infrastructures 2016-2017 Work Program Call for Development and long-term sustainability of new pan-European research infrastructures, INFRADEV-01-2017.

Europe has been at the forefront of many aspects of cosmological research using measurements of the CMB from the Planck Satellite, which was a mission from the European Space Agency. With the successful end to Planck's mission, however, the international community has begun to plan an ambitious set of ground-based observatories, with much larger numbers of detectors. This will ultimately supersede the Planck work. This new effort is called the CMB Stage-4, or S4 for short. The name of this proposal, E4, highlights the concurrent goals.

The decades-long work on Planck created a community of hundreds of European scientists with unique skills and knowledge. If no coordinated European effort is made to either contribute significantly to this international effort or to build an independent effort of comparable scope, the hard-won European know-how gained from the Planck Satellite will diffuse elsewhere or even disappear completely. The work proposed here would be to design a ground-based cosmology experiment of scale sufficiently ambitious to allow European researchers to do CMB cosmology on a par with that being designed elsewhere (mostly in North America) or to contribute to the international effort on a significant-enough scale to engage the large European CMB community.

Based on previous CMB experience, we know that this type of work can only be done by facilities in remote locations such as islands, mountain ranges, or Antarctica. The cost of the entire, final project will probably be in the range of hundreds of millions of euros. To remain at the forefront of CMB cosmology, Europe must find and motivate significant resources for its large community to participate in this effort.

1.3 Concept and methodology

(a) Concept

The CMB: The Universe is expanding. Thus, when it was much younger, it was also smaller. But with the same basic material in it then as today, it was necessarily denser and hotter. In fact, early enough in the life of the Universe, the material we are familiar with today, everything made up of protons and electrons, was, in fact, so hot that it was ionized. The Universe was a soup of simple elementary particles, including photons. The photons, being electromagnetic, were tightly coupled to the charged protons and electrons. As the Universe expanded from this point, however, it cooled.

About 400,000 years after the Big Bang, the Universe had cooled enough that the protons and electrons combined to form lasting, neutral hydrogen for the first time. From this point on, the photons which were previously tightly mixed with the charged particles are liberated and essentially travel unimpeded from then on. This is the CMB. Because the Universe is today about 14 billion years old, we often refer to the CMB as a "baby picture" of the Universe. If the Universe were the age of a human – say 50 years old – the CMB would by analogy be a picture of the person when he or she was a half-day old.

CMB Anisotropies: While to first order the CMB is very smooth (representing the 'soup' mentioned above), if we look for non-uniformities in our maps of the CMB, we begin to see small variations, or "anisotropies" from place-to-place. Our best measurement to date of these anisotropies over the entire sky come from the Planck satellite, and are at the level of one part in 100,000, and are shown in Illustration 1.

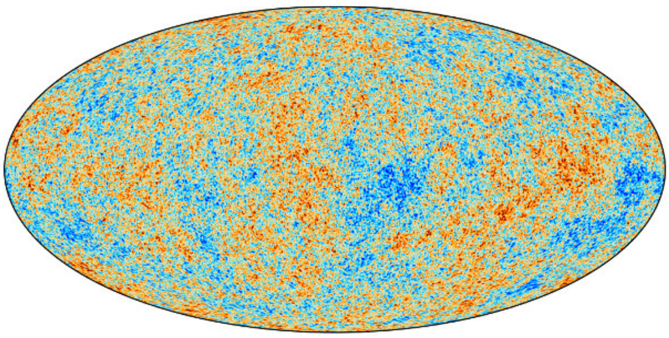

Illustration 1: The CMB as measured by the Planck Satellite. From ESA and the Planck Collaboration.

These anisotropies represent regions in the early Universe with different densities and temperatures, and are the "seeds" of the large scale structure we see in the Universe today. Over the 14 billion years between today and when the CMB was liberated, gravity has worked to form Large Scale Structures (LSS) such as the filaments and clusters of galaxies we see with large telescopes today.

Over the last couple of decades, cosmologists have converged towards a fairly simple "concordance cosmology". This scenario, dubbed "Lambda Cold Dark Matter" (LCDM), has now been verified with exquisite precision by the WMAP and Planck satellites. The combination of these observations and models has allowed the cosmological community to pin down such "universal" parameters as the age of the Universe, the rate at which it is expanding today, and the constituent densities in the Universe.

But we can learn still more from the CMB.

Gravitational Lensing and Neutrinos: Neutrinos are elementary particles postulated and discovered in the 20th century, which were initially thought to be massless. Recent measurements, however, have shown that different flavours of neutrinos (electron, muon, and tau) can change or "oscillate", implying also that at least some combination of these states have mass. While we have some indication of the difference in masses of some neutrino "eigenstates", we do not have a handle on the total mass of any of the neutrinos. Because this mass difference, about 60 meV, or ten million times lighter than the electron, sets a lower limit on the mass of one neutrino, we have a quantitive target for the mass of neutrinos we want to measure.

The CMB can help with this. The Large-Scale Structure we measure in cosmology in general and with the gravitational lensing of the CMB in particular is sensitive to the mass of a neutrino. If it were completely massless, the neutrino would not "cluster". With some mass, it still moves quite fast early in the Universe and thus does not cluster on "small" scales, but will slow down with time and hence show some clustering on the largest scales. The CMB and its measure of structure is thus sensitive to the sum of the masses of the three states of neutrinos. This proposal will thus target an absolute value measurement of the sum of the masses of the neutrino states, something that has eluded us since their discovery.

The CMB anisotropies, which were imprinted when the universe was about a thousandth its present size, constitutes the farthest observable source for gravitational lensing. While similar studies can be done with other probes of large-scale structure, the lensing of the CMB is sensitive to more distant structure than other probes. Its interpretation is also more 'linear' and, arguably, easier to interpret. Moreover, CMB lensing is immune to systematics such as 'intrinsic alignments' of galaxies that introduce systematic errors into other, non-CMB, gravitational lensing studies. CMB lensing can thus be used to measure total neutrino masses and also can be used for cross-correlation studies that normalize other probes of large scale-structure, and characterize and remove systematic errors of non-CMB lensing studies. Formulating precise science requirements and instrument optimization for CMB lensing constitutes another work package.

Mapping Dark Energy with Galaxy Clusters

Another key science objective of E4 is to probe Dark Energy through mapping galaxy clusters over a broad range of redshifts. Spectral distortions of the CMB frequency spectrum through from the so-called Sunyaev-Zeldovich effect by the hot intra-cluster gas allows one to map the density of galaxy clusters as a function of redshift and thus establish powerful constraints on the evolution of the Universe during precisely the epoch when Dark Energy starts to dominate. This basic technique has been demonstrated with Planck and ground-based experiments such as ACT and SPT, but with the improvement in sensitivity attainable by passing to Stage 4 CMB experiments, even more powerful constraints will result. The constraints on the nature of the Dark Energy have great discovery potential because the Dark Energy model involving just a simple cosmological constant could be ruled out. Establishing precise science requirements and instrument optimization for this key science objective constitutes one of the work packages of this proposal.

Cosmic Inflation and Primordial Gravitational Waves

Cosmic Inflation was proposed in the 1980s to explain why the primordial Universe was so smooth on large scales, so close to spatially flat, and not dominated by magnetic monopoles, which in most models of Grand Unification would to have been copiously produced under the prior, standard Hot Big Bang cosmological scenarios. At that time, Inflation was regarded as a very interesting but speculative theoretical paradigm, which linked physics near the Planck scale (where the four fundamental forces are believed to be unified, perhaps through Superstring theory) and the large-scale structure of the Universe. With the detection and precise mapping of CMB temperature anisotropies by the COBE satellite and subsequent experiments more recently, however, the case for Inflation strengthened significantly.

Another key objective of the E4 Observatory is to probe Cosmic Inflation through precise mapping the *polarization* of the CMB anisotropies. Inflation makes a very specific prediction that has not yet been tested. Inflation stipulates that the large-scale structure we see in the Universe today arose from quantum fluctuations, roughly speaking as a result of the Heisenberg uncertainty principle, actings as "seeds" in the very early Universe, augmented over time by gravity. But quantum field theory predicts that the graviton field in the early Universe should also fluctuate in the same way during Cosmic Inflation. These gravitational perturbations would still exist when the CMB was formed, and would leave their imprint on the CMB, observable through ultra-precise observations of what is known as the B mode of the CMB polarization. At present there exists a plethora of Inflationary models, although WMAP and Planck, as well as observations from ground-based experiments, have significantly reduced the volume of parameter space of allowed models. The amplitude of these primordial gravitational waves is typically parametrized by the tensor-to-scalar ratio r. E4 will either measure r, through a first detection of primordial B modes, or alternatively establish better upper limits on it.

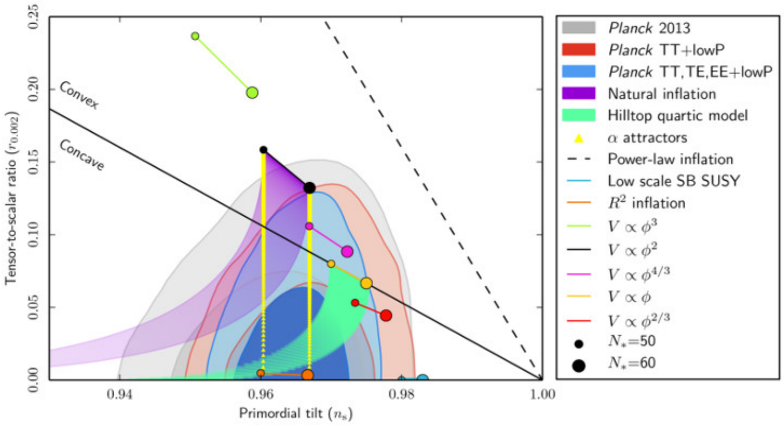

Illustration 2: Marginalized joint 68 % and 95 % CL regions for n_s and r=0.002 from Planck in combination with other data sets, compared to the theoretical predictions of selected inflationary models. Taken from Planck 2015 results. XX. Constraints on inflation.

The scientific importance of detecting *r*, as well as the obstacles to making this measurement, were highlighted by the excitement sparked by the BICEP2 claim in 2014 to have detected r~0.2, a value previously believed too high to be plausible. A more careful subsequent analysis combining with the ESA Planck dust polarization maps revealed that most of the signal could be explained by polarized thermal dust emission from our own galaxy. The BICEP2 experience emphasized the need to map the polarized sky over many frequency bands in order to remove such Galactic contamination.

One of the scientific objectives of the E4 observatory will be to map the polarized microwave sky over a broad range of frequencies over at least most of the sky in order to detect at high statistical significance a value of r of 10^{-3}. This is a natural target because there exist a number of well-motivated inflationary models, such as the Starobinsky model (located at the 'R2 inflation' points in Illustration 2), that would yield a statistically significant detection with this sensitivity.

An important part of this proposal will be to define precise science requirements for E4 and optimize the design of E4 to meet these requirements. Important questions include optimizing the frequency bands and the sensitivity in each band in order to yield the "cleanest" map of the primordial polarization, free of parasitic galactic and extragalactic contaminants. This is a formidable challenge given that with present upper limits on *r*, the microwave sky is dominated by these contaminants at all frequencies and everywhere in sky.

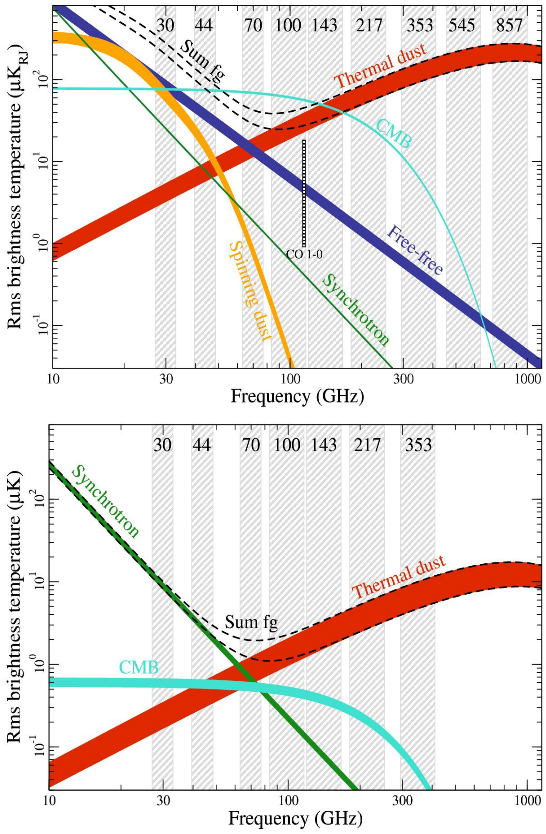

*Illustration 3: Brightness temperature rms as a function of frequency and astrophysical component for temperature (top) and polarization (bottom). Taken from Planck 2015 results X. A&A, **Volume** 594, 63, October 2016.*

<u>Foregrounds</u>

Foregrounds, or astrophysical emission from anything between our instrument and the emission of the CMB, are a major issue. Current measurements of the Galactic foreground emission (Planck Collaboration Int. XXXVIII, A&A, 586, A141, 2016; Krachmalnicoff et al., A&A 588, A65, 2016; Choi, Steve K. & Page, Lyman A., JCAP 12, 020, 2015) imply that primordial B-modes will be sub-dominant on all angular scales and over all observational frequencies in the microwave regime. Here we provide a review of the current level of understanding about the nature of such foregrounds.

Emission from our own Galaxy is a primary example of this. As emission from our Galaxy is not "primordial", it must be removed or "separated" from the CMB data in order to do cosmological analyses. As shown in Illustration 3, the total intensity sky maps are consistent with an overall picture of the Galactic foreground that comprises four components: synchrotron emission from relativistic cosmic ray electrons, free-free (thermal *bremmstrahlung*) emission in the diffuse ionized medium, thermal (vibrational) emission from dust heated by the interstellar radiation field, and finally an anomalous microwave emission (AME) component strongly correlated spatially with the thermal dust emission but that exhibits a rising spectrum towards lower frequencies. The latter has been associated with rotational modes of excitation of small dust grains (so-called 'spinning dust'). A time-variable contribution on large angular scales from interplanetary dust (zodiacal light emission) has also been detected by Planck (Planck Collaboration XIV, A&A, 571, A14, 2014), which may lead to a systematic leakage from temperature to polarization.

In contrast to the situation for intensity, where the foreground emission dominates over only 20% of the sky, the polarized flux at 20 GHz exceeds the level of CMB polarization over the full sky, and reveals the presence of large, coherent emission features. Analysis of the WMAP and Planck data has demonstrated that the polarized Galactic emission is well described, at first order, by a simple two-component model of the interstellar medium comprising synchrotron radiation and thermal dust emission. However, the polarization contribution of other physical mechanisms, such as AME, is currently neglected.

Synchrotron emission is produced by cosmic-ray electrons spiraling in the Galactic magnetic field. The use of microwave maps at frequencies below 20 GHz, as those provided by C-BASS at 5 GHz (Irfan, M. O. et al., MNRAS 448, 3572, 2015) and QUIJOTE at 10-20 GHz (Génova-Santos et al. 2015), will help to separate the synchrotron component from free-free and AME, as demonstrated in several Galactic compact regions (e.g. Génova-Santos et al. 2017) within the RADIOFOREGROUNDS H2020 project (http://www.radioforegrounds.eu).

Polarized dust emission results from non-spherical grains that adopt a preferential orientation with the Galactic magnetic field and then emit thermal radiation along their longest axis.

Although the synchrotron and thermal dust emission are clearly the dominant contributors to the diffuse polarized Galactic foreground emission, uncertainties in the current data may still allow other components, more evident in intensity measurements, to contribute at fainter levels.

Other emission mechanisms. The best upper limits to date on the AME polarization fraction have been obtained by the QUIJOTE experiment in the W43 molecular complex, at the level of $< 0.39\%$ at 17 GHz, and 0.22% at 40 GHz (Génova-Santos et al. 2017). Other recent measurements place upper limits on the AME polarization at the few per cent level (López-Caraballo et al. 2011; Dickinson et al. 2011; Macellari et al. 2011; Rubiño-Martin et al. 2012; Planck Collaboration XXV 2016). Nevertheless, while the level at which the AME is polarized appears to be low, a failure to account for it could bias the measurement of r in B-mode searches (Remazeilles et al. 2016).

Extragalactic foregrounds

The presence of polarized extragalactic sources constitutes an additional source of contamination.

The two significant contributors for CMB experiments are radio sources and dusty star-forming galaxies. The average frequency spectra of the two populations are widely different: the radio emission declines with increasing frequency while the dust emission steeply increases. A detailed study of the polarization properties of extragalactic radio sources was carried out by Massardi et al. (2013). However, the polarization properties of dusty galaxies as a whole at (sub-)mm wavelengths are almost completely unexplored. The impact of point source contamination on B-mode analyses is an issue that requires careful appraisal for both current and future CMB experiments that aim to detect the tensor-to-scalar ratio.

Positioning of the Project in the spectrum from ‘idea to application’

Above we have discussed the scientific (as opposed to experimental and technical) concept. We will discuss experimental and technical concepts below, but it is perhaps useful to note here that the study of the CMB has been done continuous essentially since its discovery in 1965. Experiments from satellites, balloons, airplanes, and from ground-based observatories have been developed over the past few decades. In addition, much of the technology to be used for E4 is operating now at CMB observatories. For the most part, E4 should be considered a large expansion of existing technologies. In this sense, most of the technology is in the TRL range of 7-8. As noted in section 1.4, however, there are issues which this expansion raises. These mostly relate to the fact that to multiply the number of detectors which we use for our experiments, we run into some optical limits – while we want to “expand” some parts of the experiment, we are still using the same wavelengths of light, and this sets some fundamental limits to the optics. We have designs to overcome this particular challenge, so this one aspect would be considered TRL 2. We hasten to note that this is an active area of work being addressed by a number of international groups. This proposal will help in this effort.

(b) Methodology

Requirements:

As with all purely scientific experiments, there will always be trade-offs to be made between science and cost. For E4, one of the biggest questions concerns telescope size. Generally, the larger the telescope, the more science which can be done. Unfortunately, the larger the telescope, the larger the cost as well. Thus, one of the more important tasks for work-package 2 will be to understand the science we get for a given sized telescope (and thus, the science we get for a given cost).

Another important requirement to define, before other technology decisions can be taken, is the wavelength range the observations will cover. This is essentially limited by our atmosphere. Illustration 4 shows the expected signal-to-noise for CMB measurements (assuming $\Delta T/T=10^{-6}$) from the ground, assuming noise from 0.5 and 2 mm precipitable water vapour. This indicates that observation bands near 100 and 150 GHz. As noted above, however, we must also consider observations of foregrounds in general, and Galactic dust and synchrotron emission in particular, to be able to extract the faint CMB signals we search. Thus, Illustration 5 shows a similar plot with the signal-to-noise on Galactic dust, and Illustration 6 does the same for Galactic synchrotron emission. Taken together, these Illustrations show that higher- and lower-frequency channels may not be as useful per-se as those at 100 and 150 GHz for measuring the CMB, but that they may still be important for characterizing and removing the foregrounds. The primary question to be answered is the definition the highest and lowest frequency bands to be used in the E4 instruments, taking into account not only the atmosphere, but also the instrumental noise, angular resolutions and our ability to disentangle the primordial CMB component from the foregrounds.

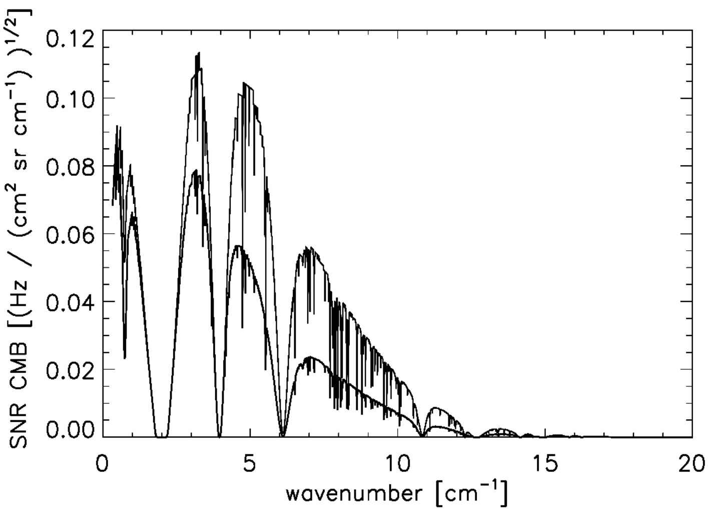

Illustration 4: Signal-to-Noise on the CMB. Note that to convert from inverse-cm to Hz, multiply by the speed of light in cm/s. That is, 5/cm is 150 GHz.

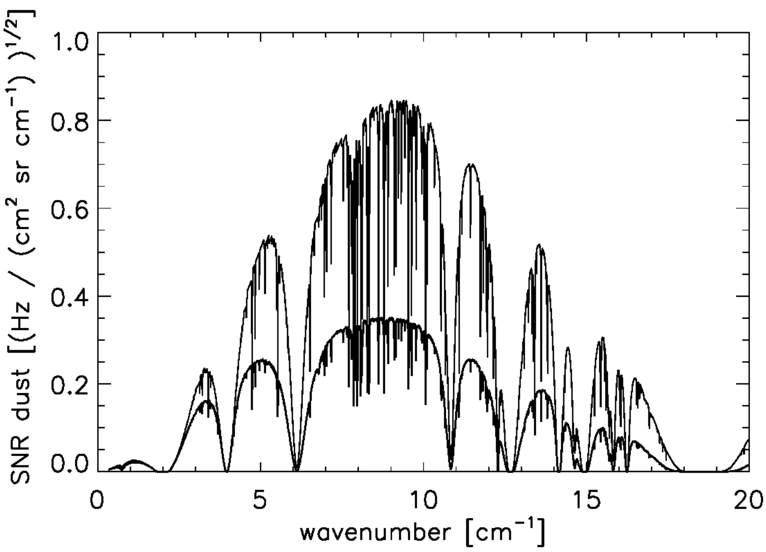

Illustration 5: Signal-to-Noise on Galactic dust. Note that to convert from inverse cm to Hz, multiply by the speed of light in cm/s. That is, 10/cm is 300 GHz.

On the low frequency side, we will have to decide which is the minimum frequency channel required to be able to remove the contamination from foreground synchrotron, free-free and spinning dust at the required accuracy level.

Existing results in the literature (e.g. Errard et al. 2015; Remazeilles et al. 2016; Genova-Santos et al. 2017) show that frequency bands as low as 10 GHz will be needed to properly separate the synchrotron from the other radio-foreground components, and to provide a highly accurate template for the amplitude of this emission (Illustration 6).

Within E4 we will study if we can rely on existing (or planned) low frequency surveys as C-BASS or QUIJOTE (see also the data products of the RADIOFOREGROUNDS H2020 project), or if a specifically dedicated and more sensitive instrument is needed at these frequencies.

On the high-frequency side, we will need to determine the number of bands (and the required sensitivities for each of them) to mitigate the thermal dust contamination. In particular, we will have to define the highest frequency band to be explored from the ground (this channel would be a bit below the 10/cm mark in Illustrations 4, 5, and 6). An essential aspect of this study is to fully take into account the complexity of the physics describing the thermal dust emission, with spatial variations of multiple dust components, with different temperatures and opacities.

Finally, an additional key aspect of our study will be to define the required sky coverage and the beam specifications, as well as the scanning strategy. We note that the maps that we plan to obtain with the instrumentation designed in E4, and specially the low frequency maps, will provide a unique complement to any future CMB space missions (PIXIE, LITEBIRD, or something like CORE).

Foreground Removal: While one can, in principle, attain more raw sensitivity by adding more detectors, "contaminating" emissions from, for example, our Galaxy will set more fundamental limits on our observations of the primordial Universe. After Planck, we know that the primordial B-mode polarization of the CMB cannot be measured without subtracting the Galactic foreground emission, even in the faintest dust-emitting regions at high Galactic latitude (Planck Collaboration Int. XXX 2016; BICEP2/Keck and Planck Collaborations et al. 2015). This, for example, is why the foregrounds and frequency coverage figure so prominently in the definition of requirements above.

Given this, it is important to develop a suite of tools to remove any foregrounds from the CMB as well as possible. The best way to remove this emission is to use the fact that, for the most part, their spectra (or the frequency dependence of their brightnesses) are not the same as that of the CMB. Thus, by making measurements at multiple frequencies we can distinguish between the CMB and other, less fundamental, sources of radiation. This is termed "Component Separation". A wide range of approaches has been developed in the past two decades, and are briefly summarized here. This will be one of the on-going work-package 2 tasks.

Template removal: This uses fits to external templates of the foreground emission, based on observations at higher or lower frequencies where the emission from single foreground components are expected to dominate. With suitable, multi-frequency observations of the microwave sky, the necessary information can be extracted from the observed sky maps (and is why the highest and lowest frequencies of observation are such crucial requirements to have).

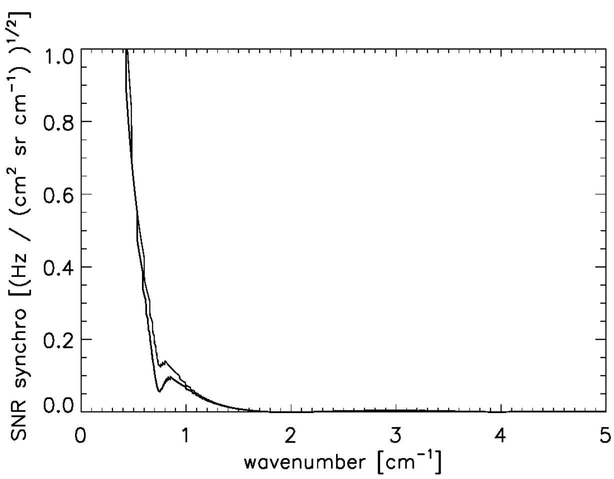

Illustration 6: Signal-to-Noise on Galactic synchrotron. Note that to convert from inverse-cm to Hz, multiply by the speed of light in cm/s. That is, 1/cm is about 30 GHz.

Blind algorithms: Other approaches are based on concepts from image processing. These so-called blind or semi-blind algorithms make minimal assumptions about the number or statistical nature/morphology of the foreground components. The advantage of blind methods is their ability to treat unknown or complex foreground contamination. Examples include the Internal Linear Combination (ILC) approach of Bennett, C. L., et al. (ApJS, 148, 97, 2003), the Independent Component Analysis (ICA) method as implemented by Maino, D., et al. (MNRAS, 334, 53, 2002), the Spectral Matching Independent Component Analysis (SMICA) described by Delabrouille, J., Cardoso, J.-F., & Patanchon, G. (MNRAS, 346, 1089, 2003), and the Correlated Component Analysis (CCA) due to Bonaldi, A., *et al.* (MNRAS, 382, 1791, 2007)

Parametric approaches: The parametric approach makes the maximum use of prior knowledge of foreground emission and fits foreground unknowns along with the CMB. In general, a parametric spectral model is assumed for each signal component, and the parameters fitted on a pixel-by-pixel basis. The advantages of this approach are that the fitted model may be chosen freely, and the method is therefore completely general, all assumptions are transparent, no restrictions on spatial variations of foreground properties are imposed and the results may be rigorously monitored by goodness-of-fit tests. Most importantly, the methodology allows a joint CMB estimation and component separation and therefore reliable error estimates are obtained on all estimated quantities with foreground uncertainties rigorously propagated through to CMB power spectrum and cosmological parameter inference. A specific implementation of a Bayesian parametric method, Commander (Eriksen *et al.* 2006, Eriksen *et al.* 2008), was adopted for Planck temperature and polarization analysis, leading not only to estimates of the

CMB but also the foreground emission (Planck Collaboration X 2016).

Two sources of foreground emission are also key tools to address the science program of this proposal: clusters of galaxies, observed through the so-called Sunyaev-Zel'dovich effects, which provide complementary constraints of the cosmological scenario, and are also useful for the understanding of the formation of structures; fluctuations of the brightness of the cosmic infrared background (CIB), integrated emission from extragalactic dusty galaxies, which is an alternate tracer of mass at redshifts similar to those generating the CMB lensing, and can be used either to help separate primordial B-modes from lensing B-modes, or as a complementary tool to investigate the distribution of structures in the Hubble volume. The study will answer the following question: what combination of ground-based and space-borne observations can best exploit these two emissions in synergy with CMB observations to address the scientific objectives considered in this proposal?

Finally, the connection between foreground emission and systematic error contributions to observations of the sky should be considered. A particular example arises when measurements from multiple detectors are required in order to reconstruct the polarization signal adequately. Bandpass mismatch between the detectors can lead to spurious signals arising from the leakage of temperature signal into polarization. Modelling such a contribution can be problematic, particularly at lower frequencies, where the temperature foreground emission certainly has additional significant emission components that still remain difficult to disentangle (Planck Collaboration X 2016; Planck Collaboration XXV 2016). Even when single detectors are used to measure polarization (by rotating them around each sky direction), large band-passes raise the issue of the accuracy of per-pixel colour-corrections, which require high-precision bandpass determination for each detector.

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Large-Scale Structure

An important aspect of the CMB S4 campaign will be how it can be combined with other large-scale structure surveys. The specific surveys that will come online over the time scale of the CMB S4 are: DESI (2018) – a spectroscopic redshift survey covering ~14,000 square degrees on the sky; Euclid (2020) – an ESA/NASA-funded satellite mission that will carry out a spectroscopic redshift survey and an imaging (weak lensing) survey covering ~15,000 square degrees on the sky; SKA (2021) – a wide area radioastronomy facility leading to an HI galaxy spectroscopic redshift survey, a continuum survey with a flux limit of 5 µJy and an HI intensity mapping survey; LSST (2022) – a photometric redshift survey and imaging (weak lensing) survey covering ~20,000 square degrees on the sky with a magnitude limit r~27; WFIRST (2025) – a NASA-funded satellite mission that will carry out a spectroscopic redshift survey and an imaging (weak lensing) survey with observational strategy still to be determined.

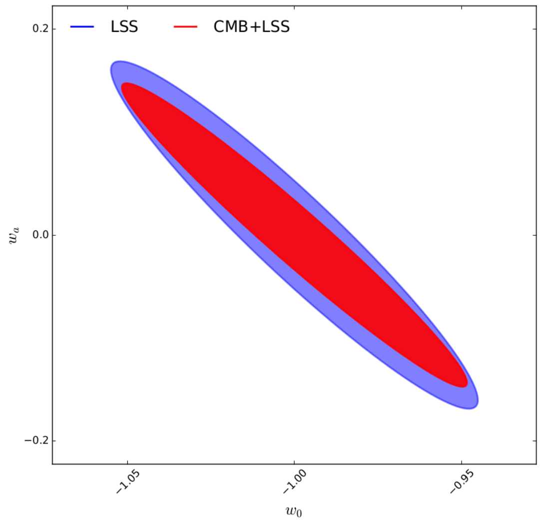

Illustration 7: Forecast constraints on the Dark Energy Equation of State from an LSST-like experiment alone (blue) and in combination with a CMB-S4-like experiment.

Large scale structure (LSS) measurements will considerably sharpen cosmological parameter constraints from CMB S4 data. The main observables in LSS can constrain cosmology through measurements of the geometry and growth of the matter distribution. In the case of geometry, this is usually done by measuring the so-called baryon acoustic oscillation (BAO) scale, a characteristic scale of the matter distribution that can be used to recover the distance-redshift relation in a robust model. The growth of structure, on the other hand, can be constrained through measurements of the weak lensing (i.e. the correlated bending of light rays caused by the intervening structure) or through the detection of redshift-space distortions (RSDs), the correlated shift in the redshift of sources caused by the interplay between the cosmic density and velocity fields. Two notable parameters which will greatly benefit from the combination of CMB and LSS S4 measurements are the equation of state parameters, (w_0, w_a), and the neutrino mass, m_ν. A preliminary analysis shows that in the case of the equation of state, the figure of merit (FOM) of CMB S4 is ~4 while that of the LSST surveys (for example) is ~793. But, as can be seen in Illustration 7, the combination will improve the constraints to a FOM ~1130; combined with a cosmic variance limited measurement of the optical depth, τ, the FOM goes up to 1320, achieving the S4 goal of 1250. With neutrinos, a preliminary analysis shows a similar trend: CMB S4 will detect a 1-σ lower bound of m_ν =68 meV while the LSST surveys will constrain m_ν =25 meV. In combination (and supplemented by cosmic variance limited measurement of τ) this uncertainty would reduce to mν =12 meV, which would easily allow a >3-σ constraint of the most conservative estimate of the neutrino mass from oscillation measurements (see Illustration 8).

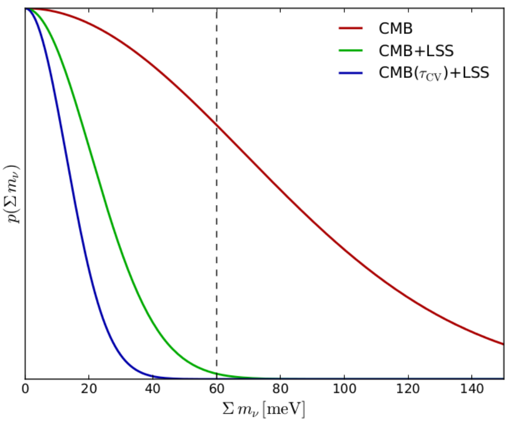

Illustration 8: Forecast Gaussian posterior on the sum of the neutrino masses for CMB-S4 alone (red), in combination with an LSST-like survey (green), and after adding a cosmic variance-limited prior on the optical depth (blue).

Analysis Infrastructure

The goal of this task, which is encapsulated in work package 2, is to provide the E4 project with a global simulation and data analysis framework. Previous experience acquired in the European community on the Planck satellite data processing has shown the need for such infrastructure. At the scale of Stage-4 ground based CMB experiments, with focal planes comprising of order 100,000 detectors, data analysis (which requires significant simulation capabilities) is a daunting task and must be planed ahead, well before the start of the survey, along with the definition of the instrument itself. Note that this is a familiar trend, already seen in the particle physics/cosmology community, and more recently in astrophysics as well (see for example SKA or LSST). The objective for the second work-package will be to provide both a relatively easy, deployable set of tools within which the simulation and analysis/optimization of future, ground based CMB experiments can be performed, and to provide the E4 project with a few reference computing centres where the tools are readily available. In addition to providing the environment for the development of future simulation and analysis software, the task will be responsible of integrating the existing codes in order to participate to the optimization of ground based infrastructure, testing different site and instrumental configurations and propagating the consequences of the instrumental choices (in an approximate way) toward figures of merits on the different science goals sets by he other subtasks of WP2.

A first version of such tools was created in the context of the Planck mission. A sky simulator tool (Planck sky model, http://www.apc.univ-paris7.fr/%7Edelabrou/PSM/psm.html) was built to allow the creation of realistic sky simulations (i.e., including foregrounds) in many different frequency bands. The Planck Level-S simulation package (https://sourceforge.net/projects/planck-ls/) was developed to allow the construction of simulated observation of sky simulation by the Planck satellite. This was further improved internally to describe the instruments and fine details of the detectors behaviors. In the context of the preparation of the CORE mission, the TOAST framework (https://hpc4cmb.github.io/toast/) was developed in order to allow the study and optimization of the mission concept. This task will build upon the already available body of work and experience within the European community to produce a similar set of tools that will scale to the demanding requirements of future CMB observations. Similar to the work performed by the particle physics community with the GEANT simulation package, it will propose a modular infrastructure that will allow for the inclusion of current state of the art sky and detector simulation and standardize the future development to those packages. The framework will provide software infrastructure for the development of analysis pipelines (including in particular simplified "shortcuts" for the optimization of experimental concepts) in a fashion similar to what the TOAST framework currently provides, aiming again at the standardization of the interface to allow future interoperability.

Among its responsibilities within E4, this task will also be to host reference physical parameters for the sky simulations (i.e., foreground models and some sky realizations) and to distribute them to the different work package tasks. It will also be responsible for the instrument model databases for each reference instrumental concept and its synchronization and distribution to other tasks and work-packages. It will help the other work-packages to implement, within the common infrastructure, the computing tools needed to simulate and analyze synthetic data in order to investigate different experimental concepts. This task will be in charge of running the infrastructure to compute figures of merits on the different physical goals of the project for each instrumental concept explored by other work-packages in order to optimize instrumental design and site selection.

Computer infrastructure for this task will be provided by the Max Planck Institute for Astronomy in Germany, with additional resources being available in France from the IN2P3’s Centre de Calcul in Lyon and the computing centre at the Institut d’Astrophysique de Paris. In keeping with the “Open” philosophy of most recent CMB collaborations, he tools will be available to deploy on other sites as well. To this end, the task will need 3 postdoc/engineer-years to build a first version of this infrastructure (again using the current best available tools), deploy it on shared computing resources, assist participants of the project in deployment on their small scale computing resources in order to develop new modules, and prepare further evolution and standardization of the framework interface.

<u>Site</u>:

Two main criteria for selecting a site are (1) atmospheric conditions at CMB frequencies and (2) logistics. Both must be excellent for high-quality CMB polarization measurements to be made. Atmospheric transmission must be very high and emission must be very low and very stable in the traditional mm-wave atmospheric windows. Moreover, site logistics must be able to accommodate complex demanding experiments such as modern CMB telescopes. In addition, a third aspect to be considered in detail is sky coverage. In this proposal, we are considering five different locations: Dome Concordia (Antartica), South Pole station (Antartica), Atacama desert (Chile), the Teide Observatory (Tenerife, Canary Islands), and Argentina.

The atmospheric quality will be tested in all these places with a specific site-testing instrument measuring both intensity and polarization properties at mm-waves in at least one-year timescale. In this context, Harvard, Chicago and other American institutes have begun a coordinated program to compare sites for CMB suitability (see Illustration 9), using scanning 183 GHz water vapour radiometers (WVRs). For E4, we anticipate working closely with these, and other international groups.

THE UNIVERSITY OF CHICAGO
KICP
HARVARD UNIVERSITY
HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

To the E4 Proposal Team
Attn: Ken Ganga; Laboratoire APC 10 rue Alice Domon et Léonie Duquet
75013 Paris, France

March 17, 2017

To Whom it May Concern:

We have started a campaign to perform coordinated characterization of current and potential future CMB sites using scanning 183 GHz water vapor radiometers (WVRs). The goal is to obtain measurements of atmospheric fluctuations at a variety of sites (South Pole, Chile, Greenland, and possibly Tibet) on timescales and angular scales relevant for CMB polarization observations, and use co-located CMB telescopes where applicable to translate the measured atmospheric fluctuation levels to noise contributions in CMB maps. Our instrument design is based on ALMA WVRs and includes: a base WVR unit, an environmental enclosure, temperature control, and azimuth/elevation scanning optics. We have so far deployed two units: one to South Pole (January 2016), co-located with BICEP and the Keck Array, and a second at Summit Station in Greenland (June 2016). An important feature of this effort is that the hardware, observing strategy, data analysis are identical and interchangeable between all units. This is critical for ensuring one-to-one comparison between sites, so that we can inform design decisions for CMB experiments. We would welcome collaboration with the E4 team and are happy to share our instrument design and to further develop a common analysis pipeline. Maintaining this common instrumental and analysis framework is essential to the usefulness of this project. To expand our efforts to characterizing more sites, it would be very beneficial to purchase and construct further units. Our current collaboration consists of Harvard: Denis Barkats, John Kovac, Scott Paine. University of Chicago: Abby Vieregg, Nicole Larsen. Brookhaven: Chris Sheehy. ALMA (retired): Richard Hills.

Sincerely,

Denis Barkats	John Kovac	Abby Vieregg
Harvard University	Harvard University	University of Chicago
dbarkats@cfa.harvard.edu	jmkovac@cfa.harvard.edu	avieregg@kicp.uchicago.edu

Illustration 9: Collaboration letter from Denis Barkats, John Kovac, and Abby Vieregg.

Dome Concordia, Antarctica

As a matter of fact, a continuous coverage of atmospheric properties relevant here is still missing for Dome-C. Noticeable recent contributions have been:

- HAMSTRAD (**H2O Antarctica Microwave Stratospheric and Tropospheric Radiometers**), (see http://www.umr-cnrm.fr/spip.php?article961&lang=en and references therein) monitoring precipitable water vapor from the 183 GHz line from 2009 to 2016
- CASPER, a Fourier Transform spectrometer measuring absolute spectra of atmospheric emission from 90 to 450 GHz during one Antarctic summer campaign (M. De Petris et al., to be published)
- BRAIN-Pathfinder, measuring *absolute and polarized* atmospheric emission in the 150 GHz band during one Antarctic summer campaign (E. Battistelli et al. MNRASm 423, 1293, 2012). The BRAIN/pathfinder experiment tested the atmospheric brightness and polarization at 150 GHz with several hundreds of elevation scans, and an upper limit on the air-mass correlated polarized signal has been set for the first time at these frequencies from Dome- C. The BRAIN pathfinder has also been the first instrument to be successfully operated from Dome-C with helium 3 fridge and pulse tube cryocooler: this is a key technology for continuous operations in Dome C.
- The radio sounding program carried out daily by PNRA, used together with atmospheric models to estimate mm-wave properties of the Dome-C stratosphere (S. De Gregori et al. *MNRAS*, 425, 222, 2012)
- The sub-mm site testing carried out using a 200 μm tipper (P. Tremblin et al. A&A, 535, A112, 2011)

In general, the results of these measurements point to excellent characteristics for mm-wave atmospheric emission at Dome-C, especially during the winter season (see Illustration 10).

Peculiar characteristics of the Dome-C site are the presence of diamond-dust ice very close to the ground (P. Ricaud et al., Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-815), and the hypothetical presence of ice crystal clouds in the high troposphere (L. Pietranera et al. MNRAS 376, 645, 2007), potentially affecting CMB polarization measurements.

Issues particularly relevant for site-testing at Dome-C site are:

- Special mechanical/electronics requirements for the instrument to be operated in Dome-C
- Automatic operation of the instruments
- Proper infrastructure for the site testing equipment
- Cryogenic system for continuous operation

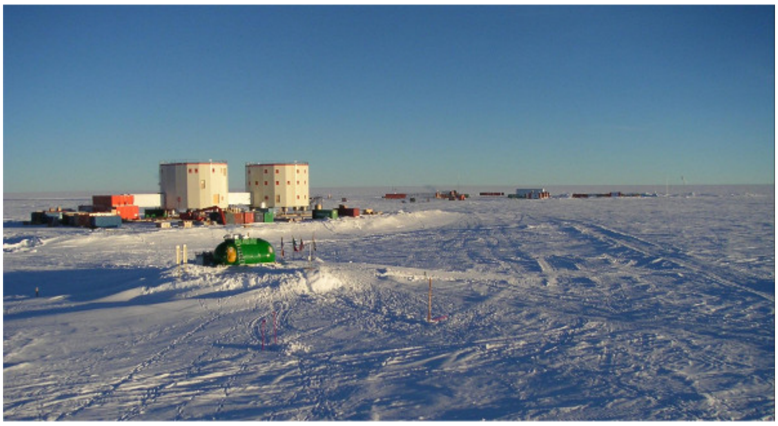

Illustration 10: Concordia Station, Antarctica. Image taken from the ISAC CNR web site.

Logistics in Dome-C is well developed, but certainly more difficult than in other candidate sites. Reaching Dome-C requires a long travel with special airplanes, and can be done only coordinating with the Italian and French Antarctic Programs. Moreover, a large infrastructure like a S4 CMB polarization telescope would challenge the capabilities of the Concordia station, in terms of power, transportation, communications, and manpower required. However, large-size projects have already been carried out very successfully in Dome-C. The EPICA drilling is certainly the most important example. An important activity of this proposal is an accurate costing of the infrastructure construction, commissioning, and operation. Important issues to be analysed will be:

- Special mechanical/electronics requirements for the instrument to be operated in Dome-C
- Transportation method and cost (traverse vs. plane)
- Construction issues (cranes, operators, etc)
- Commissioning personnel
- Power required and available / dedicated generators / cost of fuel /alternative solutions
- Environmental control of the instrument (shelter/dome/open, heaters, snow removal, etc.)
- Availability of communications: (remote control, data transmission)
- Dedicated personnel, and in general winter-overs for emergency maintenance

South Pole Station, Antarctica

The South Pole Station (see Illustration 11), like Dome C above, has a number of features which make it one of the best places on the planet from which to observe the CMB:

- it is at an altitude of almost 3000 meters, putting it above a large part of the Earth’s atmosphere, which interferes with CMB measurements;
- it is cold, causing a good part of the water in the atmosphere, which is particularly detrimental to CMB observations, to freeze out;
- it is dark for months at a time, allowing continuous observations without the passage of the Sun to interrupt observations;
- it has a well-developed scientific infrastructure sponsored by the American National Science Foundation;
- it already hosts the South Pole Telescope and the BICEP/Keck projects, two of the handful of American projects upon which the CMB-S4 program will probably be based.

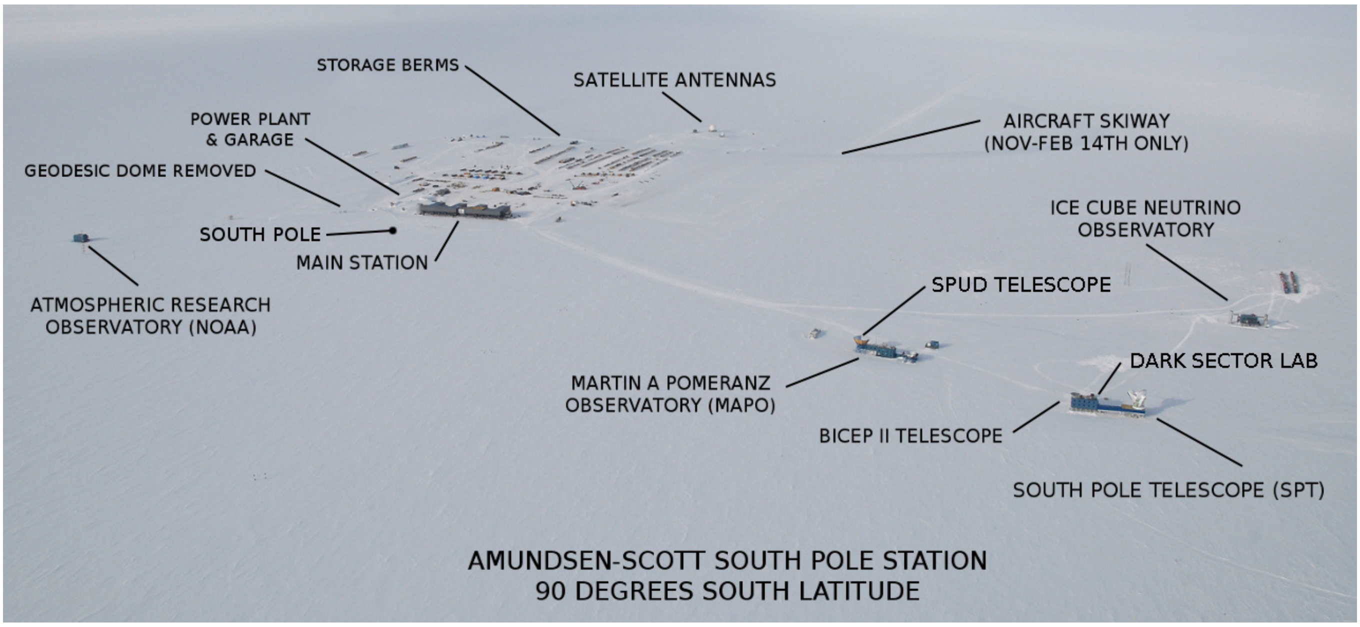

Illustration 11: South Pole Station in 2013, including the South Pole Telescope and BICEP experiments towards the lower right of the photo. Image from http://www.polarwinter.com/2013/southpole-2013.html.

A video explaining a number of aspects of studying the CMB from the South Pole can be seen at the following link:

https://www.khanacademy.org/partner-content/science-engineering-partners/amnh/the-universe/universe/v/cmb-new-view-south-pole.

Illustration 12: Simons Observatory, in the Atacama Desert, from above. The scale can be inferred from the size of the red and blue cars, next to each other about ¾ of the way from the left of the image, roughly ½-way down from the top. Taken from the Simons Foundation-sponsored film "The Eternal Sky" (https://www.simonsfoundation.org/features/foundation-news/the-eternal-sky/) by Debora Kellner.

The South Pole Station is not, however, European infrastructure. If we were to use the South Pole Station, European work would obviously be done as part of international agreements. This work package task, therefore, will investigate the organizational and other hurdles which would need to be overcome to permit a collaboration in which European infrastructure can be installed at the South Pole. These will include:

- agreement among the participants on the perimeter of European work;
- agreement needed from the US NSF;
- agreement to funding needed from European Polar agencies;
- agreement among parties on governance, access and data rights.

Atacama Desert, Chile

The Atacama Desert has seen at least a half-dozen CMB experiments deployed for the last two decades, including those producing some of the most successful CMB measurements. The site is at an altitude of over 5,000 meters above sea level, so the column density of the atmospheric vapor contributing to signals measured in the sub-millimetre band is greatly reduced. It is also very dry. Both these factors make it one of the best observational sites for these kinds of observations. Indeed, on the best days, the site is at least comparable to, if not better than, the Antarctic stations. On average, however, this is not the case. This is, in part, due to significant weather variability and seasonal changes. For example, the rainy, so-called Bolivian winter. Moreover, the observations need to contend with the presence of the Sun; scanning strategies must be designed accordingly, employing expensive Sun-shields or avoiding observing during the day-time altogether.

The site has, however, a number of advantages. These include year-around access to the site and well-developed infrastructure – roads, both at the desert itself as well as in the nearest town of San Pedro as well as research facilities and accommodations. Thanks to its two-decade-long history, there is abundant information concerning the weather conditions, atmosphere emissions as well as atmospheric instabilities, directly relevant to the measurements in the sub-mm range. There are also active weather monitoring stations.

The presence of active CMB observatories such as CLASS, ACT, POLARBEAR and non-CMB installations, such as the ESO-led ALMA, provides opportunities to capitalize on synergies and develop fruitful and resource-saving collaborations, as well as potential for sharing know-how.

The Atacama Desert is government land under direct control of the president of Chile. The operating observatories benefit from a long-term land lease, which has to be granted by the president's office directly. Alternately, new facilities could be set up on a land leased by other experiments, on the basis of agreements between the relevant teams. The observational teams are encouraged to set up collaborations with Chile-based researchers and develop outreach programs in Chile.

Teide Observatory (Tenerife, Canary Islands, Spain).

The Instituto de Astrofísica de Canarias (IAC) administers the "Observatorios de Canarias" (OOCC), a single Singular Scientific and Technical Infrastructure (ICTS) formed by the Observatorio del Roque de los Muchachos (ORM) and the Observatorio del Teide (OT). These two astronomical reserves, protected by Law, have been open to the international scientific community since 1979, in accordance with the Agreements for Cooperation in Astrophysics. Currently, the OOCC contain telescopes and instruments belonging to 60 institutions from 18 countries. The OOCC is the most important assembly of observational facilities for optical and infrared astrophysics within the territories of the European Union. Other experiments for high-energy astrophysics (Magic, CTA-N) and the study of the CMB complete the battery of facilities available.

The OT is located in the island of Tenerife, at 28º18´00" N, 16º30´35" W, and an altitude of 2.400m above the sea level. The OT has a long tradition (more than 30 years) in the study of CMB anisotropies. Starting with the Tenerife radiometers operating at 10, 15, and 33 GHz (1984-2000), multiple CMB experiments have operated at this observatory, including the IAC-Bartol (1994-1997) at 3.3, 2.1, 1.3 and 1.1 mm; the JBO-IAC two-element interferometer at 30 GHz (1997-2002), the COSMOSOMAS experiment (1998-2007) at 10, 13, 15 and 17 GHz; and the Very Small Array interferometer (2000-2008) at 30 GHz.

At the moment, the only active CMB experiment at the OT is QUIJOTE, a scientific collaboration between the IAC, IFCA, DICOM and IDOM in Spain and the Universities of Manchester and Cambridge in the UK, with the aim of characterizing the polarization of the CMB and other Galactic and extragalactic physical processes with six frequency bands in the range 10-40 GHz at angular scales larger than a degree (Génova-Santos *et al.*, 2015). The project has two telescopes, already installed, and three instruments: the Multi-Frequency Instrument (MFI) , the Thirty GHz Instrument (TGI) and the Forty GHz Instrument (FGI). The project has been operating for four years with the MFI, and it is now starting operations with the TGI and FGI instruments.

In the near future, there will be other CMB experiments in the site:

Illustration 13: Observatory in Tenerife. Image taken from the IAC website.

- STRIP. This experiment is part of LSPE (Large Scale Polarization Experiment), a combined programme of ground-based and balloon-borne (SWIPE) B-mode polarization observations. STRIP consists of a rotating 1.5-metre telescope coupled with a polarimeter array based on HEMT amplifiers cooled to 20 K and operated in the Q and W bands (centred at 42 and 90 GHz, respectively), covering 20% of the sky at an angular resolution of 20 arcminutes in Q band. It will be installed at the Teide Observatory on the time-scale of one-year.

- GroundBIRD. This is an MKIDS array to study CMB polarization in two frequency bands, centred at 145 and 220 GHz, and on large angular scales. This is a scientific collaboration formed by the RIKEN Centre for Advanced Photonics, the High Energy Accelerator Research Organization (KEK), the National Astronomical Observatory of Japan (NAOJ), the Saitama University, the Tohoku University (Japan), the Korea University and the IAC. The Teide Observatory was selected in 2016 as the location of this experiment, whose first light is expected towards the end of 2017 and whose operation will extend for three years.

- KISS. This is a spectrometer using a Martin-Pupplet interferometer coupled to a KID-based camera operating in a 100 mK dilution fridge. The camera will consist of 500 hundred detectors in the frequency range from 80 to 280 GHz. The Martin-Puplett spectrometer is a Fourier transform interferometer. The project involves the Institut Néel and the Laboratoire de Physique Subatomique et Cosmologie (LPSC), both in Grenoble, and the IAC. The instrument will be mounted on one of the QUIJOTE telescopes.

- A CMB spectrometer at 10-20GHz. It is based on a Front-End Module cooled down to 4-10K, with an internal reference load at 4K, and uses a switched stabilized filter-bank. It will have 40 spectral bands between 10-20 GHz, with a ~2 degree beam. The project, led by the IAC, is fully funded, and has a development time scale of two years.

Sky quality. The IAC created the Sky Quality Team and the Technical Office for Sky Protection (OTPC) to ensure that the sky quality for astronomy is maintained, and to provide support and supervision of the implementation of laws protecting the darkness of the night sky. Since 1990, site characterization studies have been carried out in both observatories, funded by the IAC and co-funded by several programmes over the years. These studies, together with the past and current experience with CMB experiments, mainly at frequencies below 40 GHz, demonstrate the high quality of the atmospheric properties for CMB research: low precipitable water vapor content (PWV) and high stability of the atmosphere in long periods of time. These studies will be complemented with a detailed characterization of the atmospheric quality at mm-wavelengths, based on the same site-testing instrument that will be used for other observatories.

Logistics. Due to its geographical location in the Northern hemisphere (much less explored by other current or planned CMB efforts), the OT is an excellent location for CMB experiments aiming to survey the northern sky. The OT is a well-developed European infrastructure, in a relatively easy access location. Finally, an important point is that the operational costs for an experiment at the OT are very low compared to other places.

Argentinean site

The site is located in the North/West of Argentina, close to the Chilean border, in the province of Salta. It has Latitude: 24°11'12.6"S and Longitude: 66°28'41.16"W and extends on the top of a large flat area at 4.870 m above sea level. It has been chosen by the LLAMA (http://www.iar.unlp.edu.ar/llama-web/english.html) and QUBIC (http://qubic.in2p3.fr) collaborations. The former is a 12-m dish radio-telescope, while the latter is a bolometric interferometer dedicated to the search of B-mode polarization of the Cosmic Microwave Background.

Illustration 14: The LLAMA site. Adapted from https://upload.wikimedia.org/wikipedia/commons/1/1a/LLAMA_Gorund_Zero.jpg

Sky quality. The site has been surveyed by the LLAMA collaboration with a 210 GHz tipper continuously since 2010, providing detailed opacity data that can be found on the LLAMA website (http://www.iar.unlp.edu.ar/llama-web/site.htm). The data exhibits a median 210 GHz opacity ranging from 0.7 to 1.2 over 8 months while November to February are affected by the Bolivian Summer with higher opacity. Further characterization with a dedicated instrument for specific polarized site testing could be installed next to QUBIC and benefit from its logistics and maintenance. QUBIC itself will operate starting from late 2018 and will offer direct polarization measurements, and therefore atmospheric polarization monitoring at 150 and 220 GHz.

Logistics. The site is easily accessible all year long by car (~30 min) from the nearby town of San Antonio de los Cobres (population 6000, 3775m above sea level) that offers extensive facilities: hotels, restaurants, hospital, internet connection, shops with food, tools, clothes materials, bank with ATM, post and train station to Salta. The city's activity is currently increasing due to touristic activities. A road connecting the National Road 51 to the LLAMA site (8 km) is currently being finalized while the remaining 800 m to the QUBIC site will be finalized by 2018. A gas line and an optical fibre link pass just down the site (2km in direct line). The high-rate internet connection to the instruments will be provided by a microwave link. The gas line could be used to build a dedicated electrical plant as was initially planned by LLAMA to offer 300 kW power. San Antonio de los Cobres is at 3 hours' drive (200 km) from the capital of the province, Salta (population 500000) that hosts an international airport, Universities, a large CNEA facility that will be used by QUBIC for integration with a clean room to be built in 2018. Salta also provides local qualified manpower.

Synergy with QUBIC and LLAMA. LLAMA will be constructing headquarters in San Antonio de los Cobres with rooms, workshop and a clean room that will be shared with QUBIC and could be used for a future instrument. Both QUBIC and LLAMA will be relying on local technicians for maintenance that will therefore be largely qualified by the time any E4 instrument would be installed on the site. Energy, cold water and internet connections will be available for these two instruments and could be shared with a future experiment or upgraded to match its requirements. The access road to the site is being finalized and was constructed for these two projects and will be fully available for such a project as E4.

Local support (political and scientific). The logistics for QUBIC and LLAMA are funded by Argentina through the MINCYT (Ministry of Science and Technology), CONICET (National Council for Research on Science and Technology), CNEA (National Atomic Commission) and the government of Salta Province. These four parties are highly interested in developing astrophysics and benefiting from the dry and clear skies of the Salta Province. They would actively participate in any large international project such as E4.

Argentina already hosts a major scientific infrastructure, the Pierre Auger Observatory, which has been running successfully for the last 15 years with significant local scientific and political support. Argentina was also a very serious candidate site for hosting the Cerenkov Telescope Array (CTA) with similar scientific and political involvement. There is a large community of astrophysicists in Argentina ranging from Radioastronomy (Instituto Argentino de Radioastronomía, La Plata) to high-energy astrophysics (ITEDA, Buenos Aires and Mendoza; IAFE, Buenos Aires; Instituto Balseiro, Bariloche) with significant activities in the Pierre Auger Observatory. The enthusiasm for Cosmic Microwave Background cosmology is clear from the large community that has rapidly formed around QUBIC in less than a year. There has been a historical involvement in theoretical CMB Physics (D. Harari, S. Mollerach and M. Zaldarriaga at Instituto Balseiro in Bariloche) which is now continuing with QUBIC.

Telescope & Optics:

The choice of telescope design(s) will depend not only on the main science goals but also on practical considerations such as cost-benefit, number of telescopes, site logistics and local concerns. Since the design must consider the required field-of-view, resolution, frequency bands, focal plane/detector array size and modulation scheme, this task will be carried out in close collaboration with work-packages 2, 3 and 5. We will consider instruments to be integrated in the framework of the ongoing S4 study and/or to work in a complementary way depending on the feasibility of their realization and implementation.

The telescope design task will take as its initial input the science requirements that are identified for this project in work-package 2. In addition, there already exists a wealth of literature from telescope design studies, in particular from the recent US CMB-S4 and European COrE work, from which we can draw. Our science goals may narrow the range of designs to consider and our site choices could also impose additional constraints (with regard to single vs multiple telescopes, for example). New developments in technology must also be taken into consideration. An example of this is in the telescope mirror fabrication: will it be made from a single piece of material or will it be composite – a mirror made from multiple pieces.

Once general layouts have been selected they will be studied using a range of both commercial and in-house software, depending on the frequency bands considered. Possible software packages include Zemax (ray-tracing for initial design optimisation and high-frequency, large aperture studies) GRASP (physical optics for detailed analysis) MODAL (in-house mode-matching and physical optics software) and CST (finite-element analysis for detector coupling). The optical performance of the telescope can be quantified by, for example, its Strehl ratio and beam ellipticity across the focal plane, the level of cross-polarisation produced, its spillover, susceptibility to stray light, throughput and tolerance of manufacturing errors.

It is likely that the two main science goals (B-mode and cluster observations) would best be met by different telescope designs. If this is indeed the case, then we will study complementary optical configurations that can be used as test cases in other work package tasks.

QUIJOTE telescopes:

The two QUIJOTE telescopes are based on an offset crossed-Dragone design (a scaled version of the former Clover design – Grimes *et al.*, 2009, *Proceedings of the 20th International Symposium on Space Terahertz Technology*), with projected apertures of 2.25 m and 1.89 m for the primary and secondary mirrors, respectively. The mirrors are monolithic elements made of aluminium. The use of industrial-like fabrication techniques, such as sand-mould casting, CNC machining, and laser tracker measuring for alignment, provided the required performances for microwave observation.

Illustration 15: The two QUIJOTE telescopes at the Teide Observatory, in Tenerife.

The first QUIJOTE telescope (QT1) has been operating since November 2012, and the second unit (QT2) was installed in July 2014. The data from the MFI instrument (10-20GHz) installed on the QT1 shows highly symmetric beams (ellipticity > 0.98) with very low side-lobes (<-40 dB) and polarization leakage (<-25 dB). A surface roughness of 2 microns and 1.6 microns was achieved for the mirrors of the QT1 and QT2, respectively, and the final overall shape of those mirrors was below 200 microns *rms* error with respect to the theoretical optical surface, so in principle both units could operate at higher frequencies (e.g. up to 200 GHz). The pointing and tracking accuracies for the azimuth and elevation axes in both telescopes are better than 4 and 2 arc-seconds, respectively.

The telescopes were fabricated by IDOM, in Spain (see http://www.idom.com/projects/ada/science/). A detailed description of the two units, as well as the fabrication procedures, assembly and factory tests can be found in Gomez et al. (2010) for QT1 and Sanquirce et al. (2014) for QT2.

References:

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Simons-Style Telescopes

The Simons Array has already deployed telescopes in the Chilean Atacama (they are visible in Illustration 12 at the top, middle and bottom of the cluster of material on the right-hand side of the figure). As part of work-package 3, we will study the possibility of using the present designs, and adding to this effort. This would require explicit agreement and tight collaboration with the existing Simons team. Technically, much of the work has already been done in this case. The bulk of the task would be to understand the feasibility of replicating and financing this new work, and making the necessary agreements to have access to the necessary designs and expertise to do the replication.

An important aspect of this study is represented by the complementarity, in terms of frequency coverage and scan area, with the existing probes within the design phase (ACTpol, Class, PolarBear and the Simons Array) and those which will be operating in combination with the E4 observatory. In this phase, an MoU concerning mutual science goals and exploitation of data will be defined with the existing experiments. We stress that European scientists participate at the management level to the analysis of data for PolarBear, Simons Array and Observatory.

Existing knowledge of foreground emissions and technology will be exploited, in conjunction with work-package 2, for defining a design which could complement scientifically the existing and planned probes in a strategic manner. Progressing observations from operating probes will allow a first optimization of the instrumental design configurations, with adjustment in the Cost and Risk assessment, Infrastructure Construction Plan.

Filters, Anti-reflection coatings, Mesh retarders and Mesh lenses.

Several optical elements are considered to be key components along the optical chain, after the telescope and before the detectors, to condition and spectrally select sky radiation to allow pure detection.

The Cardiff group has pioneered the employment of microwave and Terahertz filters manufactured as multiple-layered metal-meshes embedded in polymeric dielectrics to define FIR photometric bandwidths, reject unwanted optical/NIR radiation and control the thermal environment in cryogenic instruments. These devices are currently manufactured with excellent uniformity and reproducibility in sizes of (optically-active) diameter up to 300mm; however, it is underway the process of scaling up the capabilities up to 530mm devices to meet the needs of future CMB experiments. By using multiple layers of well well-known inductive, capacitive or resonant metal mesh patterns and their combinations it is possible to achieve high-pass, low-pass and band-pass optical filtering, respectively (Ade et al., 2006). The effective fabrication of a composite dielectric slab leads to a stable and robust device; these have been space- and cryogenically-qualified over many years and missions. Finally, high-pass filters can be installed just above the detectors at the focal plane to mitigate radio-frequency interference originating outside of the receiver. IR blocking filters (i.e. thermal filters) are designed as a combination of very thin scattering and single-layer metal-mesh devices, deployed at various temperature stages to sequentially reject short to mid-range radiation.

Anti-reflection coatings are produced by porous dielectric material (see porous polypropylene or porous Teflon) or metamaterials realized by loading dielectric materials with stacked metal mesh grids miming an “equivalent" refractive index dependent on the number of grids, their geometry and their spacing (Zhang et al., 2009).

To manipulate the polarization state of the light, phase retarders are realised by stacking capacitive and inductive grids in orthogonal directions, the phase-shift of the relative polarization vectors change in opposite directions. Quarter-Wave Plates (or circular polarisers), with bandwidths ranging from 30% to 90% (Pisano et al., 2012), can be used to convert linear polarization into circular and vice-versa.

Instead Rotating Half-Wave Plates are used to rotate the polarization direction of incoming light for further modulation. The challenge of the large bandwidths, potentially required by the E4 program, is to maintain high in-band transmission while keeping the differential phase-shift close to 180°. Alternatively, Reflective Half-Wave Plates can be built by locating a polariser at a quarter-wavelength distance from a plane mirror (“variable-delay polarization modulators").

Mesh technology has been also recently used to realize flat devices with focusing properties by manipulating the effective refractive index of the medium (see, e.g. Savini et al., 2012) or the phase across the surface of the lens (Pisano et al., 2013). Those devices did not require anti-reflection coatings and the overall modelled transmission is above 97%. The diameter of these lenses (currently 10-50mm) can be in principle increased by adopting a Fresnel-lens like approach or assembling arrays of small diameter mesh lenses (Pisano et al., 2016).

References

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<u>Polarisation modulation</u> is being considered for the E4 program.

The choice of the strategy of polarization measurement is a critical task in this study and it must be taken into account together with optical considerations. For example, in order to strongly reduce the error on Stokes parameters and minimize the systematics errors, it is preferable that the three Stokes parameters are derived quasi-simultaneously for each pixel. This can be achieved with a fast rotating half wave plate followed by a polariser or by polarized sensitive KID depending on the detectors design.

In this context, transmissive and reflective Achromatic Half-Wave-Plates (AHWP) developed at Cardiff University have advanced significantly in recent years due to European-funded projects and also have been used in several ground-based and ballon-borne experiments like NIKA2, BLAST-Pol, PILOT, and others. In this case, the polarised signal is modulated at four times the mechanical speed such that it can be easily placed above 1-2 Hz. This permits natural rejection of 1/f noise from turbulent atmospheric emission and detector noise components from electronics, thermal variations and vibrations. If the modulation speed is also fast compared to the experiment's scanning speed and the angular resolution of the telescope, the three Stokes parameters can be derived quasi-simultaneously, rejecting further residual low-frequency drifts. However, as shown, for example, in Ritacco *et al*. (2016), the fast modulation of the background and of internal reflections induces an additional spurious signal, modulated at harmonics of the HWP rotation frequency. While this effect can be suppressed to the required precision for current measurements, it has to be further characterised to be sure it can be removed at E4 sensitivity levels.

The rotation mechanism that would be used for the AHWP, depends on the design strategy: the ground-based, NIKA2 camera, for example, measures the polarised signal in a band centred at 240 GHz from the IRAM 30-meter telescope. It uses a 300 K, hot-pressed, metal-mesh AHWP designed and fabricated at Cardiff University. The NIKA2 collaboration showed that this contributes only few per-cent of the total optical load on the detectors. Nevertheless, since the total optical load on the detectors strongly depends on the telescope site, we will consider the option of using a stepped, cryogenic AHWP rotator such as that developed by the Roma1 group for the ballon-borne PILOT experiment (Salatino et al. A&A 528 A138, 2011), or rotators based on superconducting rings inserted in a friction-less mechanism based on superconducting magnetic levitation. A dedicated study will be carried out in order to optimise the design considering mechanical constraints, detector optical load, and AHWP performance among other things.

Focal Plane:

Detectors are used to transduce sky signals into electrical signals and are at the end of a pipeline composed of telescope, receivers (filters, lenses), antennas/absorbers (or couplings in general) and the detector themselves. The main object of this part of the study is to review the most promising, scalable technologies towards the development of focal planes with more than 100,000 CMB-Stage-4-like detectors/sensors.

Kinetic Induction Devices (KID):

Requirements for 100k pixels array: Considering the sensitivity of recent CMB-dedicated ground-based experiments such as ACT, BICEP2/Keck, the Simons Array, SPT and expectations for upcoming CMB Stage III experiments, characterized by of order 10,000 detectors, it is obvious that access to a survey experiment with of order 100,000 or more detectors will be needed for Europe to remain at the forefront of CMB science. While not the case in the US, in Europe, for the 50 to 300 GHz frequency range, Kinetic Inductance Detectors (KID) are currently the most advanced solution in terms of technology readiness. It has been shown with the NIKA2, 3,000-pixel camera that KIDs can have Background Limited Instrument Performance (BLIP) for ground-based applications in the range of frequencies between 120 and 300 GHz. Also, they have several advantages with respect other technologies: fabrication robustness, fast time response (between 10-100 μs for typical ground-based optical loads), very good linearity, not limited by thermal constraints and intrinsic Frequency Division Multiplexing (FDM).

The specific detailed requirements on individual detector arrays will heavily depend on the final characteristics of the focal plane instruments such as total frequency range, number of bands, coverage of the focal plane (filled arrays, or horned-coupled detectors) and strategy of polarization measurement. This will allow us to identify the main challenges in the detector technology.

Requirements for polarization pixels: During the last few years, Grenoble, INTA-CSIC, APC and Cardiff

University have been working in collaboration on polarized sensitive KID development along three different axes:

- KID arrays with polarization-sensitive detectors each oriented with the same angle;
- KID arrays with polarization-sensitive detectors each oriented individually;
- Back-to-back mesh lenses to optically couple with detectors.

High frequency aspects (100-300 GHz): Aluminium Lumped Elements KIDs (LEKID) represents the state-of-the-art for the frequencies in the range between 120 GHz and 300 GHz. Several laboratories in Europe are developing this technology (Cardiff, Grenoble, Rome, Madrid); it is currently used in the 3,000-pixel NIKA2 camera and it is planned to be used in the ballon-borne OLIMPO experiment. In the coming years, each of these groups will actively maintain the design, production, and testing processing of such technology in order to ensure the best performance and upgrades for the instruments.

Low-frequency aspects (50-100 GHz): The frequency range below 120 GHz is not accessible using pure Aluminium KIDs due to the superconducting gap cut-off. Therefore, in order to have access to lower frequencies several materials with lower superconducting cut-offs have been investigated, such as Titanium-Nitride (TiN), Niobium-Silicium (Nb(x)Si(1-x)) and Titanium-Aluminium bi-layers. The latter has shown the best performance in the range of frequencies between 60 and 120 GHz, approaching a Noise Equivalent Power close to that of photon noise limited detectors for a typical ground-based optical load. This development has been lead by Grenoble group in collaboration INTA-CSIC (Madrid) and Sapienza (Roma I).

Readout electronics: Two options have already been demonstrated for ground-based applications in Europe. Current options available are:

1. Ring buffer integration systems similar to those developed by the Bonn Max-Planck Institute for AMKID or by SRON for the SPACEKIDS electronics;

2. The NIKEL Advanced Mezzanine Card system developed for the NIKA2 camera and the high-speed readout electronics (NIXA) for the SPACEKIDS project, both developed in Grenoble;

A MUX factor of 1000 has already been achieved with a power consumption of about 20 W per module. The particular KID technology adopted (absorber or antenna coupled) will not influence the readout electronics scheme.

Acquisition Software, Photometry and Calibration: One of the most difficult challenges in operating with KIDs, is to convert the observed in-phase (I(t)) and in-quadrature (Q(t)) signals to absorbed optical power. This is a very different task compared to thermal detectors (high impedance bolometer, TES, etc...). One possible solution is to perform a frequency sweep before starting each scan on the sky and to determine the centre of the resonance circle (I, Q) and calibrate the change of phase as a function of frequency. The validity of this method depends directly on the stability of the atmosphere. Indeed, if the sky emission fluctuates during a scan, the resonance circle changes and therefore the responsively of the detector changes. Therefore, other solutions must be developed in order to improve the photometric reproducibility.

Transition Edge Sensors (TES):

Among the most promising scalable technologies towards the development of focal planes with more than 100,000 detectors/sensors (CMB Stage-4 like), Transition Edge Sensors (TESs) present a viable solution because they exhibit a long record of optimum performance, with a host of CMB science results. They are, in fact, well characterized over a broad frequency range (40 GHz to more than 300 GHz), encompassing the frequency bands accessible from ground (See, for example, Illustration 3).

Transition-Edge Sensors present hitherto unsurpassed sensitivity – $O(10\,aW/\sqrt{Hz})$ – using architectures that rely on cold-stage signal amplification from SQUIDs.

TESs are high-sensitivity thermometers which are fabricated by photo-lithographic techniques consisting of depositing several layers of superconducting, normal conducting or insulating material on silicon wafers in a multi-layer process. This reproducible planar technology makes it possible to envisage the realization of several thousand detectors, with great homogeneity over large arrays. Their principle of operation is based on electro-thermal feedback that stabilizes and accelerates their natural time constant when voltage biased. With a time constants of the order of 1 ms (governed by their heat capacity, conductivity and voltage bias), they are well matched with scanning speeds of CMB telescopes.

Due to their peculiar fabrication process, which often includes a final step – silicon etching – to suspend the sensitive portion from a 1 μm silicon nitride membrane, R&D is needed to scale the production of large TES arrays. Particular attention to high production yields and quality assurance are necessary. A relative new approach is to develop nanoscale sensitive films (few nm side instead of few μm side) for which the thermal conductance is already sufficiently small that the etching process is no more needed. In any case dedicated equipment and manpower in clean room environments to produce quasi-industrial array quantities are required.

A companion technology to be scaled up is that of the cold and warm readouts. In this respect, a fundamental concept is that of multiplexing; *i.e.* reading out multiple sensors with a single pair of wires in order to minimize heat load, reduce the complexity of the system and to simplify its integration. Two main types of multiplexing are presently being used: Time Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM). In the former, a single SQUID is used as a switch to cycle through different detectors, while in the latter superconducting LC resonators are put in series with each sensor. For TDM a large number of SQUIDs (equal to the number of TESes) is required, making the manufacturing of SQUIDs and their hybridization on the focal plane a critical issue. For FDM the same consideration applies to the LC filters.

Multiplexing and sensor biasing are driven by warm electronics that work in the $<$10MHz frequency range and are based on established technology (LNA, FPGAs, ADCs and DACs) and appear to be scalable with modest R&D. However, to fit with a CMB-S4-like instrument, a larger multiplexing factor leads to an increase in the readout frequency band up to a few hundred MHz, requiring dedicated R&D.

At the European level, TESes are being developed as sensors in various energy regimes for many physics experiments (Athena, HOLMES, CRESST, COSINUS). In the CMB field, there are presently projects that are planning to deploy hundreds of them in the focal planes of ground-based (QUBIC) and balloon-borne (LSPE/SWIPE) experiments, being developed respectively in France and in Italy.

In the visible/UV/Xray range they have shown optimum performance and their foreseen development in the microwave region will allow them to reach, within the next few months, a NEP of few $\times 10^{-17}$ W/√Hz.

In the SWIPE instrument onboard the balloon-borne LSPE experiment (http://planck.roma1.infn.it/lspe/) the microwave radiation will be collected by 330 detectors at frequencies of 140, 220 and 240 GHz. The detectors are spiderweb bolometers built by INFN Genova around a thin Ti/Au film [see ref. INFN/1 and INFN/2] whose transition temperature can be tuned in the range 380 to 500 mK. Demonstration of the performance of 380mK bolometers has been demonstrated in laboratory and it is presently being extended to those with a tuned transition at 500mK. The bolometers, located on two different focal planes at a base temperature of 260 mK, will be readout by means of a 16-channel frequency domain multiplexing readout developed by INFN Pisa [see ref. INFN/3].

The QUBIC instrument hosts detectors for the 150 and 220 GHz frequencies, which are composed of four 256-pixel arrays assembled together to obtain a 1024-pixel detector at the focal planeThe detectors are Transition Edge Sensors (TES) with a critical normal-to-superconducting temperature close to 500 mK. The TES are made with a Nb_xSi_{1-x} amorphous thin film ($x\approx 0.15$ in our case), a compound that has been extensively studied and whose production is well mastered. The total Noise Equivalent Power (NEP) is of the order of 5×10^{-17} W/√Hz at 150 GHz, with a time constant in the 10-100 ms range. The detectors will be readout by means of a Time Domain Multiplexing based on 4 columns of 32 SQUID in series associated to a cryogenic ASIC developed at APC Paris.

TESes can now be fabricated reproducibly, transition curves are narrow, and transition temperatures can be adjusted, while maintaining excellent performance in both sensitivity and noise.

In Italy, there is the capacity to prototype and develop detectors based on TES sensors whose initial development dates back to the 1990s at the laboratories of INFN Genova for applications to nuclear spectroscopy at very low energy. Another facility which is active in the production of thin superconducting films that will be involved in this project is TIFPA/Trento [see ref. INFN/4].

The fabrication of the TES arrays for the QUBIC experiment is done in France and is based on commercially available silicon-on-insulator (SOI) wafers. The detector is realized using lithography process at the IEF-Renatech nano-fabrication facility and electron-beam film deposition technology at the Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM) Orsay.

Background-limited operation in the 140-240 GHz regime is demonstrated or will be demonstrated in the near future with European technology. Extension to lower frequencies may require the study of different transition temperatures of super-conducting/normal metal bilayers (e.g., Mo/Au) with particular care devoted to the transition temperature of such devices: this is very important since it fixes the cooling chain that is needed for the devices. Specialized cryostats are required that can reach the necessary operating temperatures, that can range from 500 mK down to 50 mK. Pre-cooling to a temperature anywhere near 4 K is needed, regardless of the scheme for reaching base temperature. The emergence of low-vibration pulse tube coolers that reach 4 K using a sealed charge of He gas has eliminated the need for liquid cryogens and thereby played an important role in enabling instruments that can be operated outside of a cryogenics laboratory. To reach the milliKelvin regime, two-stage adiabatic demagnetization refrigerators (ADRs) have proven attractive because they do not require a large external gas circulation system and because the modest heat load from arrays of cryogenic sensors is well matched to the capacity of this cooling technique. The use of more powerful but also larger dilution refrigerators may increase as array sizes grow and as the reliability of this cooling technique improves. Hybrid cooling architectures such as ADRs backed by sorption-pumped helium may also play a larger role in the future.

The next goal is to reach a NEP down to $10^{-18} W/\sqrt{Hz}$ which can be attained thanks to careful design and choice of geometry and film material. Extension to lower frequencies will require a design of the coupling with the radiation through lithographed antennas, possibly coupling the sensitive TES with polarization-sensitive and/or broadband antennas. With the former, the information on the polarization of the impinging radiation can be read out at the pixel level, while with the latter an on-chip filter can split the signal into multiple frequency bands, enabling one to use a smaller number of detectors compared to a single-frequency readout.

HEMTs:

Detector technologies based on cryogenic very Low Noise Amplifiers (LNAs) made with High Electron Mobility Transistors (HEMT) represent an interesting option for CMB observations, especially for frequencies lower than 50 GHz, just below the 60 GHz atmospheric forbidden band. They show very good performance, being commonly used in current European CMB experiments such as C-BASS (Irfan et al., 2015), QUIJOTE (Génova-Santos et al. 2015) and Planck LFI (Planck Collaboration I 2016). They are also being considered for future European ground-based experiments such as the STRIP instrument of the LSPE project (http://planck.roma1.infn.it/lspe/strip.html).

Relevant characteristics of the LNAs that will be studied are the noise figure and bandwidth that can be achieved at the state of the art.

The main objective of the observations at these low frequency bands is the characterization of the synchrotron emission whose amplitude strongly increases when the frequency decreases. Due to this behaviour the number of detectors needed would be in between several tens and several hundreds depending on the frequency band.

Two different concepts have been successfully developed based on HEMT devices, direct image and interferometry. In direct image observations, the number of pixels is limited by the size of the focal plane. This is especially relevant for the low frequency range since the physical size of each pixel is constrained by the wavelength. For instance, considering the range 10-50 GHz, the number of pixels that can be accommodated in a single focal plane of a 3m class telescope can vary from one to several tens, depending on the specific frequency band of observation. This limitation implies that considering 3m class telescopes, between two and ten units would be needed in order to have a hundred pixels at those frequencies. This limitation can be somewhat reduced if we consider 10-m class radio-telescopes. The viability of large arrays of receivers allocated in the focal plane in terms of physical size and performance of front-end module (FEM) wave-guide components will be studied. Technical solutions for the fabrication, assembly, integration and verification (AIV) will be also considered.

An alternative to avoid the use of large aperture telescopes is to develop large-format interferometers. The main limitation of microwave interferometers to correlate a large number of wide band signals is the complexity due to aspects as the signal routing and phase correction and also the cost of the correlator. This explains why the interferometers built for CMB observations have incorporated a reduced number of pixels (~15). A way to overcome this problem, allowing hundreds or thousands of detectors in a single interferometer, is to use electro-optical correlators based on Mach-Zender modulators to up-convert the microwave signals' frequency to the IR domain. In this case, the correlation and detection processes can be performed in the IR band by means of lenses, one optical filter and a NIR camera, implying a significant simplification and cost reduction. The viability of the optical correlator and the optimization of the interferometer concept will be studied.

A comparative study of these options and also in relation to the other technologies (TESs, KIDs), in terms of performance, sensitivity, cost, operation, etc. will be carried out within this project.

Cryogenics: autonomously operated cryogenic systems for CMB experiments at remote sites

Ground-based observations of the CMB are carried-out from high-altitude, cold, dry sites, such as those described above in work-package 3. CMB instruments require complex cryogenic systems to cool down the optical chain and the detectors, so custom-developed rugged cryogenics must be used, able to operate for long periods without any maintenance, and under automated/remote control.

The system cools a large volume (order 1 m^3) inside the cryostat, at two main stages, one at about 40 K and the other at about 3 K. A typical value for the heat lift needed at 3 K is between 1 and 1.5 Watts. Pulse tubes are optimal to this purpose, due to their low vibration level and continuous operation. A lower temperature operating stage is then achieved by using 3He evaporation refrigerators (0.3 K) or dilution/ADR fridges (0.1 K) with a heat lift of the order of 1-10 mW for cooling the focal plane.

The activity will take advantage of the significant experience present in Europe (and among the proposers) in cryogenic systems for CMB experiments. The cryogenic systems developed in recent years for operations at telescopes in remote sites, are mostly based on the dry cryostats based on pulse tube cryocoolers, with compressor and cooling system of the compressor either with air or, most of the times, and depending on the heat load on the pulse tube, with glycole or water. This kind of 3 K stage has been developed for the BRAIN CMB experiment at Dome-C (Polenta *et al.*, New Astronomy Reviews, 51, 256–259, 2007), and for the NIKA2 instrument at IRAM-Pico Veleta (Calvo, M. *et al.*, JLTP, 184, 816, 2016), just to mention two European experiments. ^{3}He fridges (0.3 K) have been developed, for example, for the BOOMERanG (S. Masi et al. "A self contained 3He refrigerator suitable for long duration balloon experiments", Cryogenics, 38, 319-324, 1998 and S. Masi et al., "A long duration cryostat suitable for balloon borne photometry", Cryogenics, 39, 217-224, 1999.), Pronaos (Beaudin G et al Proc. SPIE Vol. 1874, p. 246-255) and PILOT (Bernard, JP., Ade, P., André, Y. et al. Exp Astron 2016 42) experiments. An innovative dilution fridge (0.1K) has been developed for Planck (S. Triqueneaux, L. Sentis, P. Camus, A. Benoit, and G. Guyot. Design and performance of the dilution cooler system for the Planck mission. *Cryogenics*, 46(4):288–297, 2006.). The research groups achieving these results are collaborators of this proposal, so the development of a cryogenic system for the European E4 is based on solid grounds.

Calibration & System Engineering:

Robust system engineering and calibration is crucial for the success of a complex facility like E4. We will build on the experience of previous successful microwave and millimetre-wave systems, such as the two instruments of the PLANCK space mission (the Low Frequency Instrument operating in the range 30-70 GHz, and the High Frequency Instrument operating in the range 100-850 GHz), balloon borne instruments (e.g., Boomerang, Archeops, and others), and ground based experiments (e.g., QUIJOTE, C-Bass, and others), which were led by key people in our E4 team.

The development of the E4 facility will require careful assessment of all the system and subsystem requirements, control of interfaces, a well-defined plan for assembly, integration and verification (AIV), and a complete calibration plan. These activities will be an integral part of this 3-year design study, to be developed in parallel with the definition of the infrastructure configuration. In this section we outline the main guidelines of our approach to system engineering and calibration.

1. System and subsystem requirements

A first step in our system design study will be to translate requirements from work-package 2 into a design concept, and to propagate the above first-level requirements into a set of second-level requirements, including:

- Number of telescopes
- Observing site(s)
- Size of (each) telescope
- Detector technology
- Detector number
- Scanning strategy

Then, for each telescope a cascade set of detailed instrumental parameter will be defined, and on each of them a specific requirement will be placed, such as to ensure meeting the performance required at system level. An experienced system engineer will coordinate the overall activity (put in work package). The instrument requirements will be organized in five classes: mechanical, thermal, electrical, optical, and RF. Key people in our

E4 team, coordinated by the system engineer, will be identified to manage these classes of requirements. Depending on the chosen observing site, environmental constraints (weather conditions, wind load, etc.) will also be taken into account.

The definition of each instrumental parameter crucial for the achievement of the science goal will be associated with the accuracy required for its measurement during test and calibration. Each parameter will be measured as part of the test and calibration plan, as outlined below.

The system engineer and their team will be responsible for maintaining the mass and power budget of the E4 system and of each subassembly. All interfaces will be defined with a detailed set of requirements and tolerances. A margin philosophy will be implemented to optimise the efficiency of the development process while minimising the risk. Margins on interface parameters and uncertainties will be managed with clear rules in an open and shared fashion among the partners involved.

2. Control of interfaces

The very large number of detectors in the cryogenically cooled E4 focal plane represents the main challenge in the management of interfaces. In particular, thermal aspects are among the main drivers of the design of the E4 instrument, since the focal plane must be cooled to cryogenic temperatures (down to 20K for HEMTs and to 0.1K for KIDs or TESes) with extreme thermal stability (typically, variations of order less than one part in a million). These requirements impose strict limits on all thermal, mechanical and electrical interfaces within the Focal Plane Unit (FPU), and between the FPU and the overall system. Strategies for efficient thermal decoupling and stabilisation will benefit from the vast experience gained by the E4 team in previous projects.

Optical interfaces are likely a second-rank challenge. The optical quality of the system is affected not only by the mirror manufacturing errors and the off-axis location of the detectors in the focal plane, but also by other sources of degradation such as alignment errors and thermal distortions. The impact of these sources on the wave-front error (WFE) and on the de-pointing of the nominal line-of-sight will be evaluated numerically, in conjunction with work package 4, using software tools which incorporate the thermo-elastic properties of the reflectors and the system structure elements.

3. Assembly, Test and Verification

Adequate facilities must be planned in advance for assembly, integration and verification (AIV) of the E4 infrastructure. Testing of the full system under operating conditions will be very difficult to achieve prior to deployment to the observing site. The philosophy will be to test and measure the performance of individual units separately as fully as possible at different integration stages; subsequently, after deployment at the site, system functionality and performance will be evaluated through a pre-defined calibration plan.

Most of the AIV activities are expected to be carried out in normal clean rooms and assembly halls. Alignment of the telescope mirrors will require particular care, and will be carried out using light at optical or NIR wavelengths (e.g., with the Shack-Hartman technique). The alignment of the focal plane instruments will subsequently be carried out using mechanical and/or optical means (i.e. utilizing pre-planned mechanical references and/or reflective patterns). Because of their cryogenic nature, TES of KID detectors cannot be operated after integration into the system until full cool-down is achieved. Therefore end-to-end thermal-vacuum tests are be foreseen with the FPU operated at temperatures close to nominal operating conditions while viewing a blackbody target cooled to 4 K. At this time, polarisation angle and polarisation purity will also be measured in dedicated tests.

The stringent nature of the stray-light rejection requirements implies that special attention must be given to verify that the radiation patterns meet the side-lobe level design goals. The *Planck* experience has shown that side-lobe measurements down to -90 dB can be achieved in the E4 frequency range in specialized anechoic chambers. The measured patterns will be verified, again in conjunction with work-package 4, by mathematical models capable of predicting the optical properties of the system. After deployment, the beams will be measured to the required dynamic range using celestial sources. If necessary, artificial calibrators will be employed.

4. Calibration

The extreme sensitivity of the E4 detectors is such that the ultimate performance will be likely limited not by white noise, but by residual systematic effects. These, in turn, reflect the level of accuracy achieved in the calibration of the instrument. The experience of previous CMB experiments, including *Planck*, shows that non-idealities in the instrument response can be corrected for in the data processing as long as they are known with sufficient precision. Thus, a complete calibration plan will be a vital element in the system-level control of the E4 design study.

By calibration we mean the measurement of all instrument characteristics which impact the data analysis and hence the science products of the project (Pajot *et al*., 2010, Mennella *et al*., 2010). A broad requirement for calibration accuracy is that uncertainties in the measurements of all the instrument parameters give rise to a level of systematics which is significantly less than the statistical noise. By statistical noise we mean the white noise in the final product maps arising from detector sensitivity averaged over the entire range of angular scales of interest. However, the way in which systematic effects impact the science products of CMB observations is far from trivial. In general it is necessary to simulate systematic effects and propagate them through the data analysis pipeline up to the cosmological results, with an accuracy and a level of detail that depends on the significance of the specific effect being evaluated (Planck Collaboration III 2016; Planck Collaboration XLVI 2016).

Defining correct requirements on all calibration parameters is essential and must be done in close interaction with instrument and system design. This will be an important part of the E4 design study. The main classes of instrumental parameters to be characterized are:

1. Photometric (or absolute) calibration: conversion of the timelines and product maps from generic telemetry units to physical units (μK_{CMB}). Conversion (gain) factors for each channel will be measured at several stages during AIV. The final calibration will be performed on the full system at the observing site.

2. Relative calibration: stability of the gain and zero-level. Depending on the details of the scanning strategy, the redundancy provided by multiple measurements of the same sky pixels (or rings, depending on the scanning strategy) will facilitate the assessment of this parameter.

3. Thermal effects: systematics induced by thermal fluctuations in the various thermal interfaces (typically at 0.1K, 1.7K, 4K, 20K and 300K) must be controlled. A set of temperature sensors will monitor the thermal configuration of the instrument and stability. The necessary accuracy and resolution of thermal calibration will be based on simulations requiring a detailed thermal model of the E4 focal plane. Cooler-induced microphonics will also be controlled.

4. Detector chain non-ideal behaviour: these include a variety of potential features, such as detector time-response; non-linearity of the detector response; non-linearity of ADC converters; sensitivity to microphonics. These effects will be parametrised, adequate requirements will be placed, and their values measured.

5. Spectral calibration: detailed bandpass measurements will be carried out during the AIV phase. System-level verification of the bandpass shapes will be possible through observation of diffuse and point sources with steep spectra and/or with artificial calibration sources.

6. Optical calibration: main beam determination, near sidelobes, far sidelobes (both total intensity and polarization). Direct measurements of the main beams and near lobes down to -35 = -40 dB will be possible exploiting signals from planets and strong polarized sources. Detailed models of the far sidelobes will be constructed with state-of-the-art physical optics codes (GRASP) and convolved to models of the full sky emission to evaluate stray-light effects. The optical model will be validated by comparing simulation with direct measurements of main beams and near lobes.

7. Polarization-specific calibration: polarization efficiency and polarization angle of each detector; spurious systematics induced by the reflectors and other optical elements will be controlled.

8. Intrinsic noise characterization: detailed measurements of the noise properties (noise power spectrum, 1/f noise, possible non-gaussianities) and their time evolution are needed. These will be standard measurements in ground testing and during operation.

For each calibration parameter, the E4 calibration plan will specify a combination of tests to be carried out during the AIV phase and at the observing site. The calibration plan will be based on three main stages: 1) pre-deployment characterization; 2) on-site system calibration; 3) calibration during routine observations.

Pre-deployment characterization – Compared to CMB instruments of the previous generation, E4 will incorporate a much larger number of channels in the focal plane (several thousands, compared to a few ten's). It would be costly and time consuming to characterize all the pixels individually with extremely high accuracy, as it was done, for example, for the PLANCK instruments. The E4 strategy will include general tests conducted on all components and pixels to check for anomalies, failures, and performance in homogeneity, complemented with thorough testing on a subset of pixels across the frequency bands. The E4 optical testing will include an intermediate, representative focal plane system, with a limited number of detectors, and multiple in-band pattern measurements. Full-beam polarization calibrators will be designed, as needed to fulfil the scientific requirements. Simulations will be run in conjunction with work package 2 to estimate the level of mitigation of non-ideal behaviour of single channels when combined in large numbers. The results will be taken into account when placing requirements on single channels.

On-site system calibration – Once established at the observing site, each E4 telescope will need to undergo a pre-defined procedure of end-to-end calibration tests (commissioning phase, typically lasting a few months). For each of the five classes of requirements (mechanical, thermal, electrical, optical, and RF), we will develop a detailed program of system tests to evaluate system functionality and performance. System level results will be compared to tests carried out at lower level of integration. Optical tests at system level (beams, polarization angles, cross-polarisation) are crucial measurements, as they can be only approximately measured during AIV. A possible solution, to be studied, includes the use of noise sources on board a drone or balloon-borne systems. A selection of astronomical sources suitable for system-level calibration (from Ka to D frequency bands) will be identified, with requirements on observing time and scan angles. These will be exploited also during the routine phase, depending on the scanning strategy.

Calibration during routine observations – A number of calibration measurements will naturally extend into the routine observing phase. Depending on the size and location of the sky region observed by E4, the CMB dipole (measured to a precision of $\sim 10^{-4}$ by Planck) and/or the diffuse emission from the Galactic plane can be used for photometric calibrator. Detector noise characteristics, assessed at various stages during AIV, will be regularly measured during routine observations in terms of power spectrum, 1/f and other non-Gaussian components to track the time evolution and amplitude of these noise components. Detector time response (particularly for TES detectors) and main beam characterization will be performed on planets as they fall into the field of view and, if needed in dedicated repointing routines. These observations will require multiple crossing (scanning directions and angles) of celestial calibration sources to achieve a high signal-to-noise. These observations will be also used to measure instrumental polarization and scanning strategy-induced systematic effects (in-scan and cross-scan differences). Polarization efficiency and polarization angles can be verified on well-known polarized astronomical sources, such as the Crab Nebula. Direct monitoring of the instruments (subsystem temperatures, electrical bias parameters, thermal stability, cooler performance) and regular processing of the time-ordered data will be implemented. The cross-correlation between monitored parameters and data processing will facilitate systematic effect removal algorithms.

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Planck Collaboration XLVI, 2016; *Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth*; Astronomy and Astrophysics, 2016, 596, A107.

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Governance:

Governing a project as large as the anticipated CMB Stage-IV work is complicated. In addition, the international aspects, including both pan-European and pan-Atlantic cooperation, all require specific attention and agreement. We are thus defining a specific work package dedicated to these issues for E4.

Working through existing European institutions and funding agency consortia, such as APPEC (http://www.appec.org/) and AstroNet (http://www.astronet-eu.org/), which have already dealt with these types of multi-national endeavors, we will:

1. Define a common European scientific policy on ground-based CMB;
2. Compare and evaluate common models (e.g., from other large projects) for the lifecycle of infrastructures and assess how they would work given the outputs from the other work-packages here;
3. Prepare negotiations between the European funding agencies and the site "owners", who may not be European;
4. Define procurement rules that respect the equal information of the partner countries and encourage fair distribution of industrial returns;

1.4 Ambition

CMB-Stage-IV, and by association E4, will be a significant advance over present-day, ground-based CMB experiments. However, it should be noted that this advance will be one of scale for the most part. That is, most of the technology necessary (but certainly not all) for E4 exists already and will simply be used in industrial quantities for the project.

An example may help illustrate. The detectors used in the CMB field are already "Background Limited", meaning that noise from outside our detectors already dominate our error budget – that is, making more sensitive individual detectors will not improve the overall sensitivity of the experiment. To get more sensitivity, we must use more of these background limited pixels. In 2010, the BICEP2 experiment had hundreds of detectors in their focal plane (as seen in the lower-left of Illustration 16). In order to gain in sensitivity, it was necessary for them to use multiple focal planes. Thus, they essentially replicated their earlier focal plane 5 times in 2012. This is the Keck Array, shown in the second column of Illustration 16. To gain still more sensitivity, they have more recently been able to design focal planes with still more detectors, and thereby continue to increase sensitivity. This is BICEP3, shown in the third column of Illustration 16.

This illustrates the over-arching ambition of E4 (and all CMB Stage-IV experiments) – increase sensitivity by increasing detector counts. The most obvious way to do this, and the method upon which much of E4 will depend, will be simply to replicate the instruments. That is, for every BICEP2/Keck-like CMB telescope that exists today, the CMB community may endeavour to make of order 10, very similar to the original. This will, quite simply, increase the number of detectors observing the sky in order to get more sensitivity.

There is a caveat to the proposition above – it can be done with simpler, cheaper telescopes such as those used for BICEP2/Keck. There is, however, some science which requires much larger telescopes, like the South Pole Telescope (SPT). It would be far too expensive, even for a large, international consortium, to replicate something like the SPT a number of times. In this case, we must find some way to put an order of magnitude more detectors in a single (or a couple) telescope. The community believes that such a telescope can be made – the proposed design is sometimes call the "Niemack Design" ("Designs for a large-aperture telescope to make the CMB 10x faster", Niemack, M.D., Ap. Opt., 55, 7, p. 1686, 2016). This design is also being considered by the community preparing the CCAT-Prime telescope for other science goals (http://www.ccatobservatory.org/index.cfm). E4 will contribute to the verification of the suitability of this design for CMB science goals.

An alternative to multiplying the number of pixels in an experiment would be to increase the number of modes each detector sees. A careful analysis of the data taken by the European Planck mission has led to an increased understanding of the operation of multi-mode optics (see also PIXIE and LSPE), and these should now be considered when discussing telescope designs. As far as sensitivity is concerned, this would effectively be like increasing the number of detectors. The optical modelling of such systems is notoriously difficult, however. We will thus be studying these, and a breakthrough would be another significant contribution to the field.

We will also be considering more novel optical techniques that are based on bolometric interferometry (e.g. MPI and the on-going QUBIC project) and that are also modified to perform multi-frequency observations of polarised sky emission and thereby minimising the systematics. If these were found to be more suitable for CMB observations, this would be a major innovation in the CMB field.

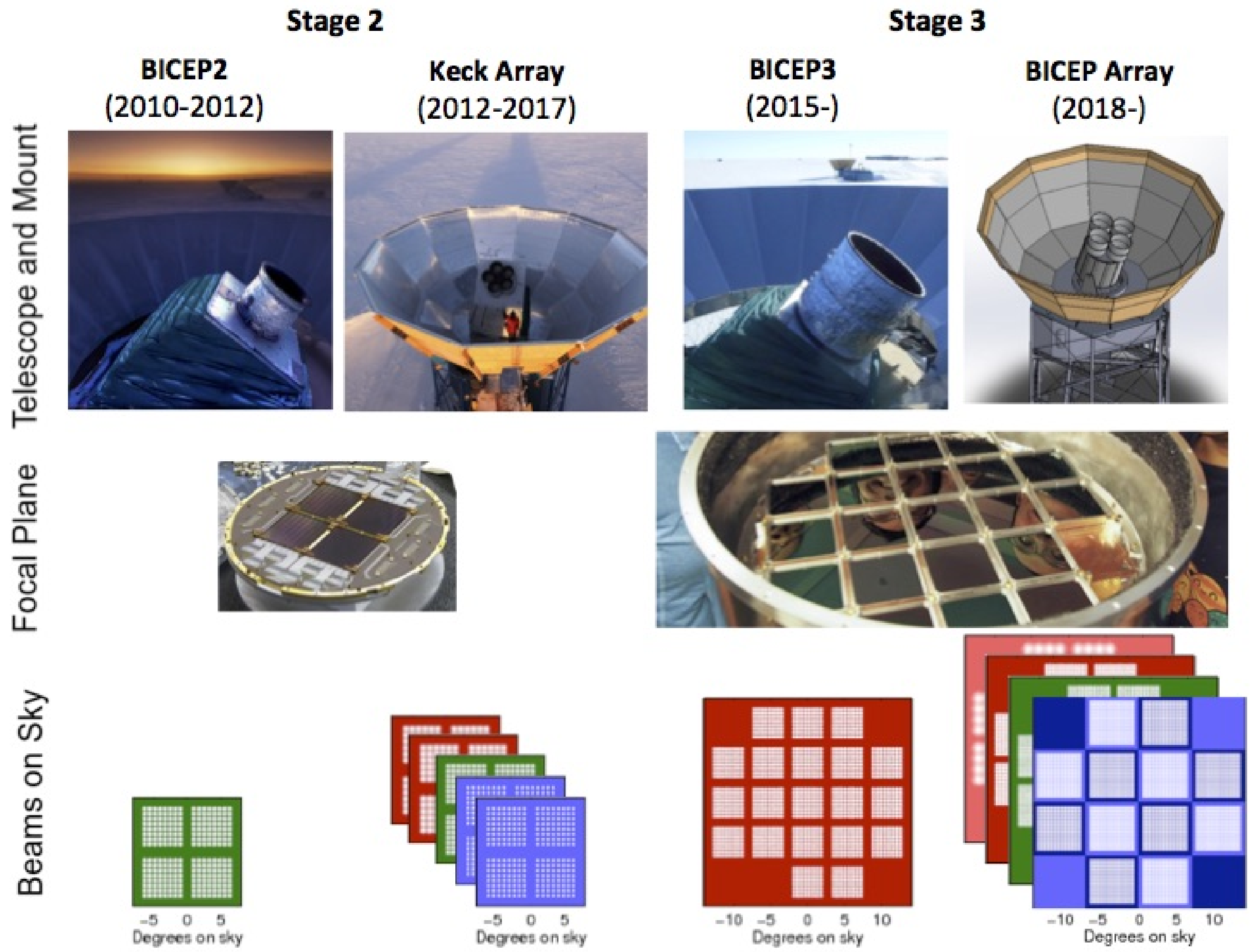

Illustration 16: The evolution of the BICEP2/Keck project in terms of numbers of detectors. Taken from the presentation "The CMB S-3 Landscape" by Clement Pryke from the BICEP2/Keck Collaborations, given at the CERN workshop "Towards a Next Space Probe for CMB Observations and Cosmic Origins Exploration", May 17, 2016.

2. Impact

2.1 Expected impacts

This proposal is one of the first steps in Europe towards a next-generation (Stage-IV), ground-based CMB experiment. The deliverables of this project will lay the ground-work necessary for the European CMB community to move to the next Stage of ground-based CMB research.

The goal is ambitious and will be costly, so this proposal is only a beginning. However, with this project we hope to:

- Allow European access to next-generation CMB studies.

  This is the overarching impact this project will have. With the end of the European Space Agency's Planck Satellite mission to study the CMB, there is no systematic plan for continued, Europe-wide study of the Cosmic Microwave Background. At the moment, the most concrete plans for a Stage-IV (i.e., next-generation) CMB experiment are being developed in the United States (see, for example, https://cmb-s4.org/). While there are some European groups with access to the American effort, significantly more European collaboration with the international effort, or creating a separate but comparable European effort, requires a proportionally larger commitment of resources. This study will present a design to do this.

- Understand the scientific requirements.

  The CMB is such a rich field, there are actually many different kinds of cutting-edge science that can be done with it. From exploring the very first instants of the Big Bang itself, to understanding the "Dark Side" of the Universe and studying almost the entire history and makeup of the Universe from start to finish, the scientific possibilities are almost endless. To create an effective experiment and make the most of the resources used, however, we must focus the work on attainable, consistent goals. This proposal will allow us to understand the scientific priorities of the European cosmology community – for example, are they (as a whole) more interested in understanding the mass of the neutrino, or in understanding how clusters of galaxies form? Or both? While all the different infrastructure possibilities we will study share much in common, these different emphases will dictate some differences in the experiment that must be designed.

- Create a community

  This program will create the "seed" that allows us to bring the CMB community together. With the end of the Planck Satellite mission, much of the community "infrastructure" is disappearing. Not only does the community gather far less often, but even such mundane things as mailing lists and wiki pages are disappearing. This project will help provide cohesion for the community that exists, and will help provide a focus towards which new CMB scientists will be able to gravitate. We should note that this has already begun as part of the preparation of this proposal. See http://wiki.e-cmb.org/index.php?n=Main.E4Contributors.

- Understand the analysis needs

  E4 will be a significant enhancement in the CMB infrastructure available to European cosmologists. This necessarily implies a significant increase in the amount of data which will need to be analyzed. It will also represent a significant advance in terms of sensitivity – the data will ultimately be less "noisy" than that from previous, similar experiment. This means that we will have to come up with new techniques for finding and removing even subtler problems which might appear in the data. Work-Package 2 of this project will address these issues.

- Choose a site or sites

  The Earth's atmosphere can add significant noise to CMB observations. This noise can be minimized by observing from high, dry sites like those found in Antarctica and the mountains and deserts of South America. However, not all sites are created equal. Some have less atmospheric noise than others. Some have already been used, and some have not – so the infrastructure costs to use different sites varies. And most of the best CMB sites are outside of Europe, political considerations must be taken into account. Work-Package 3 of this project will address these issues.

- Choose a telescope

  There are, of course, small telescopes and large telescopes. It turns out that small telescopes are in many ways sufficient for certain studies of the CMB. Others require much larger telescopes. Depending, therefore, on the European CMB community's scientific priorities, the mix of large versus small CMB telescopes will vary. This implies design choices which need to be made. Work-Package 4 of this project will address these issues.

- At the heart of any CMB experiment is a set of detectors. There are three different technologies which have been used recently on European CMB experiments – Kinetic Inductance Devices (KIDs), Transition-Edge Sensors (TESes), and those that use HEMTs (High-Electron Mobility Transistors). KIDs and TESes perform well at higher frequencies, but at the lowest frequencies which might be of interest to E4 work, HEMTs would have to be used. Work-Packages 5, 6, and 7 will clarify the resources, in money, time, and otherwise, which would be needed to field the unprecedented numbers of the appropriate detectors to do E4 work.

- Ensure the system works as a whole

  As noted above, some of the most important investigations this project will do is to define the cost and other requirements on certain parts of an E4 observatory. However, we must ensure that the observatory as a whole works as well. Work package 8 will address this issue.

- Understand the costs

  There are a number of different aspects to designing a CMB observatory as ambitious as the CMB-Stage-IV – computing and analysis, building and operating telescope at a remote site, designing the most sensitive detectors and putting them all together. While Europeans have done this exercise a number of times for CMB satellite missions, and have done this exercise for less ambitious ground-based CMB observatories, it has never been done on this scale by the European CMB community. This would be the first time we would have a good estimate of what the next-generation CMB experiment should cost in euros and other resources.

- Understand the international community

  As mentioned elsewhere, there is a vibrant international CMB community, many of whom are contributing to the American CMB Stage-IV effort. This includes a number of Europeans. The goal of this proposal is to allow Europeans to continue to do cutting edge cosmology with the Cosmic Microwave Background. If this is done most effectively by creating a European-only observatory, then this is what will be designed. However, given the size and ambition of the science, this next-generation experiment might require a world-wide effort, much like we have seen in some particle physics experiments, at CERN, for example. Part of the work of this project will be to interact and share with our international colleagues to come up with the best solution in terms of science for Europeans.

- Help funding agencies to understand the needs

  Unfortunately, the experiment we are talking about will be expensive. There have been estimates that the microwave detectors alone will cost of order a hundred million euros. One of the major points of this work will be to make sure the national physics and astronomy funding agencies across Europe understand the importance of what we are doing, but also have dependable cost estimates not only for the project as a whole, but also for those parts of the ultimate observatory which are of particular interest to different constituencies.

- Help the general public to understand the need

  The European public has become accustomed to learning about cutting edge cosmology from European cosmologists, in their own languages (see, for example,http://www.lemonde.fr/planete/article/2013/03/21/l-enfance-de-l-univers-devoilee_1851505_3244.html). This project will allow the European community to continue to do this on the scale the public has come to expect.

2.2 Measures to maximize impact

a) Dissemination and exploitation of results

Plan for the dissemination and exploitation of the project's results

The plan for dissemination of general knowledge to students and the general public are outlined in section (b), below. Here we address the plan for dissemination of the results to scientists and their funding agencies.

European Scientists

One of the primary goals of this project is to help inform and support the large community of European cosmologists. It is therefore imperative that we effectively communicate with the community. As research scientists, the primary form of dissemination of these results is via publication in scholarly journals. It is usual in our community, and this will be continued in the E4 project, to upload papers to the *arXiv* (https://arxiv.org/) preprint server, specifically to allow access to the largest cross-section of readers as possible. But as "preparatory" work, some of the results from E4 will not be appropriate for journal publication.

Letter of support for the E4 proposal in response of Horizon 2020 Call INFRADEV-01-2017

Dear Dr Ganga,

In our capacity as chairs of the Boards of the ASTRONET and APPEC[1] Consortia in which the main European agencies funding Astrophysics, Astroparticle Physics and Cosmology are represented, we are writing to you to express our support for the E4 proposal as a response to the EC's Horizon 2020 Call INFRADEV-1-2017.

As is well known, the study of the CMB B-modes of polarisation requires combined observations from the space and the ground. In recent years, with the Planck satellite mission, Europe has clearly secured leadership in space-based CMB studies; the recent rejection for programmatic reasons of the COrE mission proposal to the ESA-M5 call certainly puts that part of the strategy in difficulty. Alternative solutions are currently sought.

On ground, APPEC and ASTRONET have encouraged in the past detectors R&D towards a next-generation observatory complementary to initiatives in the US. Our two Consortia [2] initiated the effort of an European coordination of this field through the yearly editions of the Florence CMB Workshops that started in 2015. The E4 proposal represents the continuation and intensification of those efforts to achieve a coordinated path towards a large European CMB telescope infrastructure of the 4th generation. Such RI should clearly be embedded in a global CMB RI network holding a relevant and visible place in it. As such the E4 proposal undoubtedly deserves our full support.

The E4 design study will be the blueprint of such a RI, including ways to deal with issues such as coordinated funding, institutional matters, optimal operation, data access and relations to industry. Remarkably enough, CMB detectors, i.e. large arrays of TES (Transition Edge Sensors) and KIDS (Kinetic Inductance Detectors) operating in a cryogenic environment, are considered to be the CDDs of the future and, hence, they are the focus of an intense R&D program by many regional agencies around the world.

For the above reasons, on behalf of the two Consortia we're chairing, we intend to express our full endorsement to the submission of the E4 proposal.

Sincerely,

Antonio Masiero chair of APPEC | Ronald Stark chair of ASTRONET

[1] Astroparticle Physics European Consortium

[2] It is interesting to note here that both APPEC and ASTRONET are sustainable continuations of EU funded ERANETs of FP6/FP7

Illustration 17: Letter of support from APPEC and ASTRONET.

For the important task of informing the community of preparations and designs in particular, which may not be appropriate for journal publication, we have other outlets. A major alternative will be a set of "Technical Notes", which will be publicly available. An example of how this might be used is demonstrated by our ALMA colleagues. See https://almascience.eso.org/documents-and-tools/alma-technical-notes-a-subset-of-documents-from-the-eoc-memo-series.

Some of the roots of this proposal are in the so-called "Florence Process". This is as follows: in 2015 and 2016, in conjunction with APPEC and AstroNet, two community meetings were organized with European CMB experts and representatives of physics funding agencies, in order to discuss the science possibilities of the CMB and how such might be funded (see https://indico.cern.ch/event/376392/contributions/1799155/ and https://indico.in2p3.fr/event/13232/). In order to directly report the E4 results to the CMB community, these meetings will continue each year, transitioning from the current "community structuring" focus towards dissemination of E4 results in future years.

In addition, the extended E4 team actually includes a significant portion of the European CMB community. See http://wiki.e-cmb.org/index.php?n=Main.E4Contributors for names. Our collaborators organize a significant number of professional meetings, to which we are invited. Even before submission, this proposal generated two invitations to scientific meetings to explain the goals and approaches of the project. We expect and will encourage this to continue.

After the 2016 Florence meeting, a group of 10 CMB scientists – two each from France, Germany, Italy, Spain, and the UK – as a first step towards coordinating at the European level. This group is called the European CMB coordinators, or ECMB. The ECMB group has had two face-to-face meetings thus far. The second was where the decision to make this E4 proposal was taken. Another way we communicate with European CMB scientists will be through this group. There are regular ECMB meetings, at which E4 results will be reported. The members of the ECMB group take it as their responsibility to report this progress (and everything else reported at the ECMB meeting) to their local, country-wide CMB colleagues.

International Scientists & Funding Agencies

While E4 is a European project, it should not, and cannot, live in a void. The analogous project, called CMB-S4, is being undertaken in the US. A number of E4 team members actively participate in the "S4" effort as well, ensuring that not only does the US team understand what their European counterparts are doing, but also that we in Europe understand their priorities and capabilities, and how we might find synergies. In fact, the E4 coordinator presented the E4 concept at the last US CMB-S4 meeting, and would continue to do so were the project financed (see https://cmb-s4.org/CMB-S4workshops/index.php/SLAC-2017:_Cosmology_with_CMB-S4).

European Funding Agencies

While funding for this design study is important, the E4 team is acutely aware that the final E4 Observatory will require significant funding from a number of funding agencies. To ensure that they are aware of E4 work, we plan the following:

- Working with the Astro-Particle Physics European Consortium (APPEC – see http://www.appec.org/), which is a consortium of 17 funding agencies, national government institutions, and institutes from 14 European countries, responsible for coordinating and funding national research efforts in astro-particle physics. APPEC has sponsored the "Florence Process" described above. By continuing with this Florence process we will immediately have access to a number of the most important funding agencies which would be interested in this work. In particular, the yearly meetings will serve to update the most crucial possible E4 sponsors regularly.

- ASTRONET. Similar to APPEC, ASTRONET was created by a group of European funding agencies in order to establish a strategic planning mechanism for all of European astronomy. Again, they have sponsored the precursor meetings to the E4 proposal and we will nurture this relationship in order to disseminate our results to a wide swath of European astronomy agencies.

- ECMB member recognition by national funding agencies. As part of their community coordination activities, some of the 10 ECMB coordination group members are helping organize groups local to a given country. These, we are (or will be we believe) recognized by national-level agencies as CMB representatives, and which can feed information to these agencies. To this point, this process has been begun and reached varying states in France, Italy and the UK. E4 will be directly disseminated to these funding agencies through this route.

Through these mechanisms we will be able to both directly and indirectly inform national agencies of E4 opportunities their countries may be interested in, either for large, long-term opportunities, but also shorter-term, smaller possibilities.

Proprietary Data

The CMB field, led by publicly funded satellites such as *COBE*, *WMAP* and *Planck*, have a heritage of making their data public. At a certain level, having become accustomed to it in the past, our community now demands it. In general, there is no reason to change this openness for E4.

There are times, however, when certain elements of our work cannot be shared. Obvious example are cases where collaborators are willing to share important information with us, but which they demand that they be kept confidential. This is more typically a problem for space satellite projects, where large swaths of the work are systematically categorized secret, but may arise occasionally for E4.

In fact, for certain past projects, the lack of the ability to fabricate certain detectors in Europe, has meant that European projects have often found themselves required to use American detectors, with confidentiality clauses attached to them. It should be noted that this is one of the primary reasons that the E4 project should be funded – if Europe does not develop its own, cutting edge capabilities, this sort of situation will continue to repeat itself.

b) Communication activities

The Objectives of the public outreach (PO) work-package are:

- to inform the funding agencies and the private sector of the exciting discoveries in the area of the Cosmic Microwave Background (CMB) Physics and Cosmology and of the opportunities of investment in specialized related high technology
- to inspire young people to follow careers in astrophysics and the related technology.
- To inform the general public, students and educators on the exciting area of CMB Physics & Cosmology.

Description of work

The above objectives will be achieved in a manifold of ways:

a) a CMB portal with news, videos, images, educational material as well as press related material.

b) co-ordination of press releases across Europe and liaison with the press

c) organization of exhibitions in observatory and university visitor centres as well as in science & technology museums

d) production of videos and planetarium movies about the early Universe and the CMB as well as the experiments or missions that explore it.

This work is encapsulated as part of work-package 1 and described further in section 3.2, below.

3. Implementation

3.1 Work plan — Work packages, deliverables

The basic work plan described below and is shown graphically in Illustration 18.

3.2 Management structure, milestones and procedures

The E4 project will be implemented using 10 different work packages (WP), which are subdivided into specific tasks. The work package tasks are described in Section 3.1. The design study will be carried out using an organizational structure designed to ensure effective project management, visible reporting, and strategic oversight. In addition to the "Partners" participating in the project, the key organizational units are the following:

Consortium Board: this is the body for decision- and policy-making. It provides the direct point of contact with

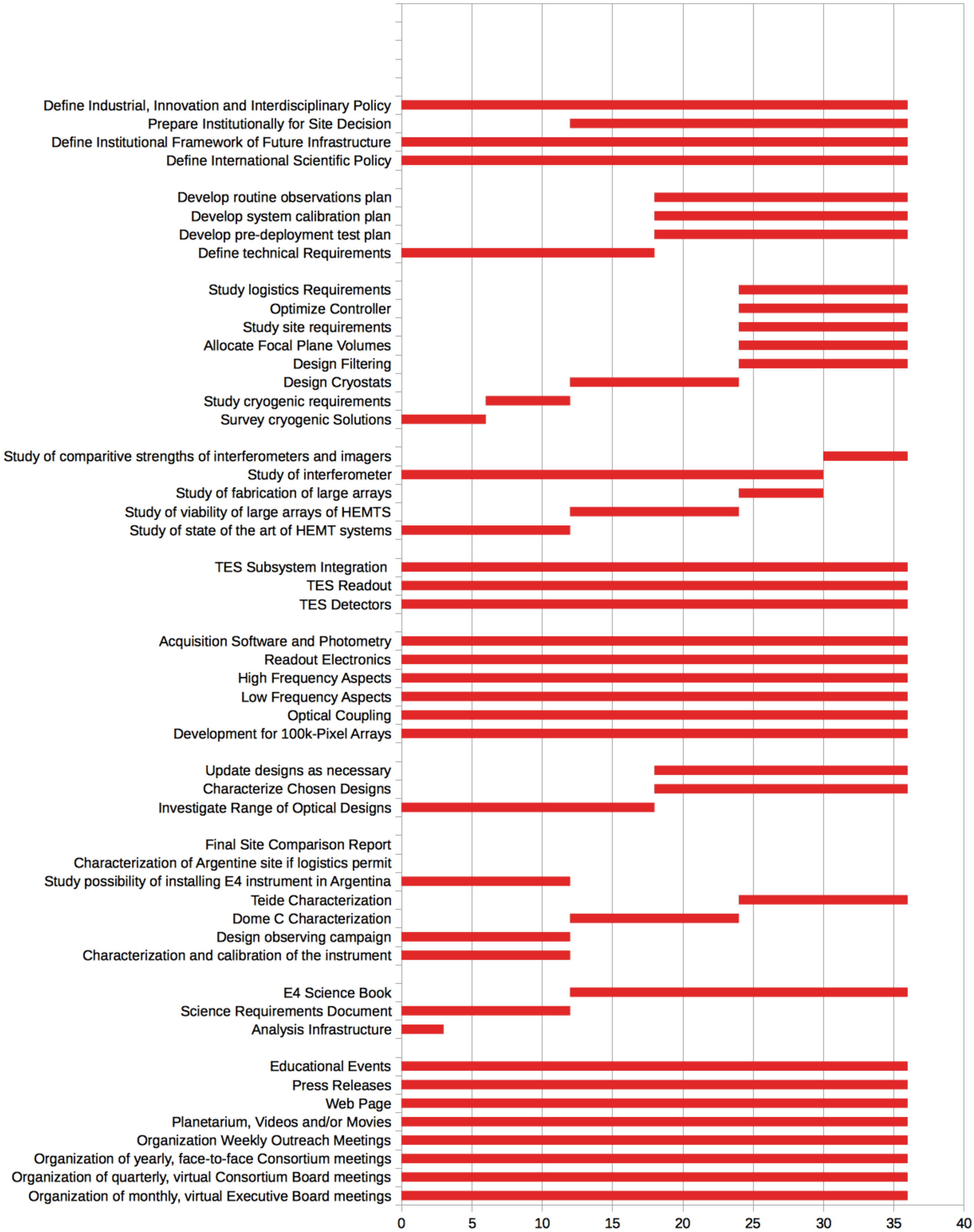

Illustration 18: Schedule of E4 Tasks. The x-axis is months from project start.

EU Horizon2020, with the national funding agencies and with APPEC and AstroNet, where in general the communication occurs via the project coordinator, who is responsible for all management decisions of the consortium, for the approval of all documents and for the dissemination of information. The Consortium Board is composed of the project coordinator and one representative of each Partner in the consortium. Upon request, the consortium board can allow the participation of extra members in the board meetings and discussions, however, every node only has a single vote. The consortium board will elect a chair which leads its meetings.

Executive board: primary body for directing the execution and coordination of the E4 design study, and for the direct coordination between the work packages. The Executive Board supplies all the deliverables. It is composed of the Project Coordinator and the work package leaders.

Project coordinator: responsible for the administrative management of the consortium, for the coordination of all the activities and of knowledge management. He or she is responsible for the submission of the required reports and for the supervision of the implementation of the decisions of the Consortium Board and the Executive board.

Work Package: led by work-package coordinators; they conduct specific tasks within the E4 design study.

Advisory Board: composed of up to six external experts who can assist in guiding the project and in reviews in preparation of decision milestones. Upon funding of the design study, the consortium board will approach renowned scientists and funding agencies, as well as entities such as AstroNet and APPEC, with invitations to join the board.

We will organize monthly virtual meetings of the Executive Board in order to continuously follow progress in the various tasks of the design study, and to provide guidance and facilitate information exchange. At least once per year, we will organize a plenary meeting open to all consortium members. The Consortium Board will meet in person at the plenary meetings, and will organize additional virtual meetings as required (at least four per year). The continuous work within the WPs will be organized by the respective WP leader, who will set up frequent virtual meetings and webinars in order to promote communication between the different nodes. Face-to-face meetings and visits to other nodes will be organized if necessary. Highlights and the achievements of important milestones will be communicated to the entire consortium via the mailing list, and supplemented by extra webinars and/or written documentation, as organized by the Executive Board.

Outreach

E4 public outreach is coordinated by the National Observatory of Athens. There will be a scientific committee that takes the final decisions on the content of the public outreach material. This will consist of the representatives of the 11 Partner institutes. For each outreach task, a responsible scientist will be appointed as the leader.

A scientist will be employed who will be responsible for the update and maintenance of the web-page. This scientist should have a specialty in either science communication or astrophysics. He/she will be responsible for the prompt publication of the news items, the distribution of the press releases in all participating countries, the coordination of the necessary translations and the delivery of the exhibition items. The setting up and continuous updating of a public outreach portal is the main vehicle of this work-package as it will host the links to most of the other proposed outreach activities. The main topic of the portal will be CMB, Cosmology and related Astrophysics news. Although there are many popular pages with astronomical news (e.g. http://media.inaf.it, http://hubblesite.org), our proposed portal will be specialised portal in CMB physics, Early Universe Cosmology and related Astrophysics themes around the world. The portal will contain some ‘static’ pages, which will include brief introductory papers on the CMB physics, related Astrophysics topics (e.g. acoustic oscillations, ISW effect, S-Z effect, etc). Although we plan to write these pages involving CMB physicists and cosmologists, there will be links to already existing articles that appear in other reputable science portals (e.g. NASA, ESA). We expect that these short papers will have a long-standing impact even after the end of the project.

The portal’s menu will appear in English in German, Italian, French and Spanish. The press releases, videos and educational material only, will be translated from English in these languages.

A variety of educational booklets will be produced by RCAAM and will be posted on the relevant web-pages. The education section of our portal will also contain links to other educational material concerning Cosmology and related astrophysics themes on the web.

Risks

Atmospheric Testing

An atmospheric testing campaign should last an entire year, since changes in atmospheric conditions tend to repeat on yearly time scales. Given that we would like to test three sites and this is a three-year projects, any delays at all will result in not being able to do all tests desired. To mitigate this, we will first test those sites with the more developed infrastructure, in order to not be delayed by externalities. The newest, most least developed sites will be tested last, allowing us to use them when they are more developed.

Schedule Risk

This project has a number of people working all over Europe. It is also relatively short for such an ambitious study. In order to stay on schedule, we will hold monthly executive board meetings, quarterly consortium board meeting, and yearly consortium wide meeting, in order to track progress.

3.3 Consortium as a whole

The E4 consortium is being formed as part of a community building process which started with open meetings in 2015 and 2016, sponsored by APPEC and ASTRONET, and hereafter called the "Florence Meetings". These meetings were attended by European and North American CMB experts, as well as members of funding agencies and other parties. This led to, after the second meeting, the creation of the "ECMB" group of European ground-based CMB coordinators – two each from France, Germany, Italy, Spain and the United Kingdom, who took as their charge to try to help to constitute and define the basis for a pan-European, sub-orbital CMB collaboration or consortium.

There are of order 140 people associated with E4 (see http://wiki.e-cmb.org/index.php?n=Main.E4Contributors), though a number are external experts. Many of the larger consortium were also members of the Planck Satellite consortia. They are quite familiar with each other, having worked together since the inception of the Planck project in 1995 (or earlier, in some cases).

E4 also includes essentially all of the members of current European suborbital CMB experiments, as well as a significant portion of most previous European CMB experiments. There are also significant a number of people who are members of North American, Stage-3 CMB experiments, as well as members of the proposed LiteBird and PIXIE CMB satellite projects. It is not unfair to say that the E4 community does represent a majority of the European CMB community.

In addition to the Co-Principle Investigator of the HFI instrument on the Planck satellite and the Instrument Scientist for the Planck/LFI instrument, the E4 consortium also includes members of the Archeops (https://en.wikipedia.org/wiki/Archeops), ARGO (http://iopscience.iop.org/article/10.1086/310069/fulltext/5792.text.html), BOOMERANG (https://en.wikipedia.org/wiki/BOOMERanG_experiment), COSMOSOMAS (https://en.wikipedia.org/wiki/COSMOSOMAS), LSPE (http://planck.roma1.infn.it/lspe), MAXIMA (https://en.wikipedia.org/wiki/Millimeter_Anisotropy_eXperiment_Imaging_Array), OLIMPO (http://planck.roma1.infn.it/olimpo), Polarbear (https://en.wikipedia.org/wiki/POLARBEAR), QUAD (https://en.wikipedia.org/wiki/QUaD), QUBIC (https://en.wikipedia.org/wiki/Qubic_experiment), QUIJOTE (https://en.wikipedia.org/wiki/QUIJOTE_CMB_Experiment), and a number of others.

Each of the work-packages has coordinators and contributors with ample experience in CMB studies in general and with the associated tasks in particular. Work-Package 2, however, deserves a special explanation.

Work-Package 2 consists of much of the computing and analysis necessary for the project, especially for determining the scientific requirements on the instrument to be designed. While the necessary infrastructure for this computing will be sponsored through this project, the bulk of the actual calculations will be done by a number of external experts not formally included in this proposal, but who are members of the larger CMB community and who count on the success of E4. That is, their time is not funded by this project.

This is a model which has worked well in the past for definition of earlier CMB experiments. Recently, for example, the unselected CORE proposal for a next-generation CMB satellite had some seed money from space agencies, but the bulk of the analysis and calculations done to set requirements and confirm capabilities was provided by the CMB community (see, for example, https://arxiv.org/abs/1612.00021 and https://arxiv.org/abs/1612.08270). In fact, a similar exercise is happening now in the US, with members of the

US CMB community helping to define the US CMB-Stage-IV effort (see http://xxx.lanl.gov/abs/1610.02743). While a bit unorthodox from a project-management point of view, this has been proven to be one of the best ways to motivate the CMB community and arrive at a community-wide consensus on how to best do cutting-edge science.

The management of the outreach aspects of work-package 1 will be led by National Observatory of Athens, an established research centre with a wealth of experience in PO activities (in conjunctions with the Research Centre for Astronomy and Applied Maths of the Academy of Athens for selected tasks).

3.4 Resources to be committed

Tables for section 3.1

Table 3.1a: Work package 1 description

Work package number	1	**Lead beneficiary**	CNRS				
Work package title	Design Study Management						
Participant number	1	11					
Short name of participant	CNRS	NOA					
Person months per participant:	47	12					
Start month	0	**End month**	36				

Objectives: This work-package organizes management and outreach activities.

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

This is the work-package which implements the structure defined in section 3.2. In particular, it outlines the project coordinators tasks, and those associated with the management of the project.

Project management:

Task 1.1: Organization of monthly, virtual Executive Board meetings, as described in section 3.2 (CNRS).

Task 1.2: Organization of quarterly, virtual Consortium Board meetings, as described in section 3.2 (CNRS).

Task 1.3: Organization of yearly, face-to-face Consortium meetings, as described in section 3.2 (CNRS).

Task 1.4: Outreach Meetings (NOA): weekly meeting between the WP coordinator and task leaders; weekly meeting between task leaders and the Institution representatives involved; monthly meetings between the WP coordinator and the project scientist and PI of the project. The communications will take place via phone/electronic mailing/skype/video conference. There will also be extraordinary Skype meetings before major events such as press-releases, exhibition setting up or the video/movie production. Especially for the video production, we consider that a physical kick-off meeting will be necessary. A yearly physical meeting of the participating institutes in the WP is also foreseen.

The material for the exhibitions (e.g. stands) will be either transferred by surface mail or it will be produced electronically and then it will be printed locally in each country. The video production will be paid on an item basis (including narration or subtitles) and can be outsourced.

TASK 1.5. Planetarium Movie and Videos (NOA). Possibilities include a 30’ Planetarium movie regarding the Early Universe, the CMB and the evolution of the Universe. Such a movie will have a very large publicity impact since it can be distributed freely in planetaria world-wide targeting a very wide audience or short (~10 min) educational videos using the podcast method to keep the cost low:

- video to be used in visitors centres as the main introductory theme before the scientific talks or the telescope observations.
- educational video aimed primarily at high school students (12-15yr)
- video that will describe the institutes involved, containing interviews from important figures in CMB, Cosmology and the related astrophysics.

TASK 1.6. Project Web-page. (NOA)

TASK 1.7. Press Releases (NOA) issued by NOA in collaboration with the E4 coordinator. The dissemination to the media in each country will be done through the main E4 nodes in each country. We anticipate a press releases 3-4 times a year. The press releases will be issued in English and then translated to other key European languages. The translations will be carried out either directly from the public outreach nodes or from the public outreach offices of each country’s Astronomical Societies. Some Institutes (e.g., MPG) have dedicated press release officers who can be responsible for the dissemination of the press releases in their countries. As such offices are not available in all countries the translation could be carried out by a postdoctoral researcher in the main E4 node in each country. It is expected that a postdoctoral researcher will devote 5% of his time on public outreach activities.

TASK 1.8. Education (Research Centre for Astronomy and Applied Maths- Academy of Athens- RCAAM; coordinated by S. Basilakos).

This task concentrates in the production of relevant educational material. Most of the participating institutes devote significant manpower to education. These efforts concentrate on school visits at the visitor centres (e.g. NOA hosts two classes per day), as well as nighttime public observations. One of the aims of this task is to introduce the students to the basic elements of the CMB physics and Cosmology. The major means will be the videos produced (Task 1.5) that will be played during the visits.

The accompanying teacher’s booklet will explain in detail the physical phenomena displayed in the video and the basic physics principles behind these phenomena. The booklet will also contain a few relevant exercises that address 13-15 year-old students. These manuals will be written in English and translated to other languages. Both the videos and the booklet will be available for download from the E4 public outreach portal.

Deliverables (brief description and month of delivery)

1.1: Outreach video (approximately one per year).

1.2: Press Releases (when appropriate)

1.3: Educational Material (yearly)

Milestones

1.1: Web Page (t0+3 month)

Table 3.1a (2): Work package 2 description

Work package number	2	**Lead beneficiary**	MPA				
Work package title	Requirements & Analysis						
Participant number	1	3	4	5	6	8	9
Short name of participant	CNRS	Roma-I	INFN	IAC	CSIC	Cardiff	MPA
Person months per participant:	33.75	14.4	33	3	3	4	33
Start month	0	**End month**	36				

Objectives: This work-package coordinates all the proposal's analysis work, from defining the requirements to using specifications to calculate performances and finally calculate expected scientific return. In particular,

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

The lead partner is MPA who will provide the computing infrastructure, but the large amount of analysis work will be done by a wide cross-section of the European CMB community using this infrastructure, or their own.

Task 2.1: Build the science and computing infrastructure with the necessary tools and support needed to produce reliable performance studies for different instrumental designs and for future data analysis (MPA).

Task 2.2: Use these science cases to derive instrumental requirements guiding the design of CMB S4.

- Canvas the European CMB community for their science goals.
- Define the angular resolution needed to achieve the science goals.
- Define the frequency range necessary for the component separation needed to reach the science goals.
- Define the sky coverage necessary to achieve the science goals.
- Define the noise sensitivity needed to achieve the science goals.

Task 2.3: Identify the key novel science cases that can be achieved by a Stage-4 CMB (CMB S4) experiment in combination with existing large-scale structure surveys.

Deliverables (brief description and month of delivery)

2.1 E4 Science Book defining requirements (t0+12 months)

2.2 Papers describing synergies with other experiments and how to exploit them (t0+36 months)

Milestones (brief description and month of delivery)

2.1 Science platform for use by the E4 community (t0+3 months)

Table 3.1a: Work package 3 description

Work package number	3	**Lead beneficiary**	IAC				
Work package title	Site evaluation, construction and operations						
Participant number	1	3	5				
Short name of participant	CNRS	RomaI	IAC				
Person months per participant:	3	2.4	32				
Start month	0	**End month**	36				

Objectives: This WP focuses on the evaluation of several locations for a European CMB facility using uniform and easily comparable methodologies and parameters. The main aspects to be explored for each location are:

- Sky quality. Atmospheric transmission must be very high and emission must be very low and very stable in the required atmospheric windows.
- Logistics. The site logistics must be able to accommodate complex demanding experiments such as modern CMB telescopes.
- Operational costs. This parameter is relevant in order to plan for a future CMB facility.
- Geographic location. Sky fraction that is accessible from the site.

In this proposal we consider five possible locations: Dome Concordia (Antartica), South Pole station (Antartica), Atacama desert (Chile), the Teide Observatory (Tenerife, Canary Islands), and Argentina. Two of them (South Pole and Atacama) are being monitored by the Harvard group led by Dr. Barkats. We plan to share data with this team, and to carry out the characterization of at least two of the three remaining sites.

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

The atmospheric quality for the potential installation of a new CMB infrastructure will be tested in all these five places (Dome Concordia, South Pole station, Atacama desert, Teide Observatory and Argentina) with a specific site-testing instrument measuring both intensity and polarization properties at mm-waves in at least one-year timescale. In this context, Harvard, Chicago and other American institutes have begun a coordinated program to compare sites for CMB suitability, using scanning 183 GHz water vapour radiometers (WVRs). Their goal is to obtain measurements of atmospheric fluctuations at a variety of sites (South Pole, Chile, Greenland, and possibly Tibet) on timescales and angular scales relevant for CMB polarization observations, and use co-located CMB telescopes where applicable to translate the measured atmospheric fluctuation levels to noise contributions in CMB maps. Their **instrument design is based on ALMA WVRs and includes: a base WVR unit, an environmental enclosure, temperature control, and azimuth/elevation scanning optics**. They have so far deployed two units: one to South Pole (January 2016), co-located with BICEP and the Keck Array, and a second at Summit Station in Greenland (June 2016).

An important feature of this effort is that the hardware, observing strategy, data analysis are identical and interchangeable between all units. This is critical for ensuring one-to-one comparison between sites, so that we can inform design decisions for CMB experiments. They welcome additional collaborators to work with they and will share their instrument design and will develop a common analysis pipeline. Maintaining this common instrumental and analysis framework is essential to the usefulness of this project.

To expand our efforts to characterizing more sites, it would be very beneficial to purchase and construct further units. The current H2020 proposal will use results from this project for comparisons between European-associated sites and those from their studies. Their current collaboration consists of Harvard: Denis Barkats, John Kovac, Scott Paine. UChicago: Abby Vieregg, Nicole Larsen. Brookhaven: Chris Sheehy. ALMA (retired): Richard Hills. Here, we plan to purchase one additional unit of a WVR, and use it to characterize the three sites that are not considered by the Harvard team: Dome C, Tenerife and Argentina.

Sub-WP3.1. Calibration and characterization of the WVR. Design of the testing campaigns. Lead: IAC

We plan to purchase one WVR, and use it to characterize the Tenerife and Dome C sites during the duration of the project. If additional time is available, and if the lifetime of the WVR extends beyond 2 years of operations, we will try to extend the measurements to the Argentina site.

The Harvard group will be providing the instrument. They worked with *Omnisys Instruments* (the vendor for the 54 fielded ALMA WVRs) to develop the core radiometer, and designed the AZ/EL optical scanning platform, data recording, and environmental enclosure subsystems appropriate for this application. The proposed WVR is a warm, double-sideband, Dicke-switching 183GHz radiometer with 4 spectral channels straddling the 183.31GHz water vapour emission line. The Dicke-switching between the hot and ambient internal loads provide long-term stability and real time calibration into sky brightness temperature units. We then use standalone atmospheric radiative transfer model (am) to infer the PWV from the four observed sky brightness temperatures. The sensitivity of these units is an excellent match to what we need for CMB site characterization. Specifically, the sensitivity of the ALMA WVR is 1um PWV rms in 1 sec in the driest conditions (PWV<1mm). From the previous experience at the South Pole, 1um PWV is equivalent to a 5mK temperature fluctuation at 150 GHz.

A complete campaign for each site should have, ideally, a minimum duration of 1 year. In this way, we can identify which are the best seasons for the observing runs, and the atmospheric conditions throughout the year. We identify the following tasks:

- Task 1. Characterization and calibration of the instrument. Once the WVR is purchased, it will be characterized and calibrated against the existing instruments in South Pole. We should guarantee that the data obtained with this instrument could be easily compared with other units. The instrument is expected to be available for M8. Calibration should be finished by M12.
- Task 2. Design of the observing campaigns. A dedicated postdoc will carry out the calibration of the instrument, and will design the logistics of the observing campaigns. This should be concluded by M12, so the observations can start on M13 the latest.

Sub-WP3.2. Characterization of Dome Concordia. Lead: RomaI.

- Task 3. Characterization of Dome C. With the support from the RomaI group, we will carry out the monitoring campaign in Dome C. Duration: 1 year.

Sub-WP3.3. Characterization of Teide Observatory. Lead: IAC.

- Task 4. Characterization of the Teide Observatory. With the support of the IAC group and the personnel at the Teide Observatory, we will carry out the monitoring campaign in a location next to the CMB installations. This data will overlap in time with the observations of the QUIJOTE telescopes, the STRIP-LSPE instrument and the GroundBird experiment. The data will be complemented with this information, as well as the measurements of the meteorological stations located at the Teide observatory, including GPS measurements of PWV. Duration: 1 year.

Sub-WP3.4. Characterization of Argentinean site. Lead: CNRS.

- Task 5. Study of the possibility of installing the E4 instrument on the already available surface or to obtain more from the Salta Province. Topological measurements can be done by CNEA Regional Salta and if more surface is needed, the land session should be done before starting installation. [M1-M12].
- Task 6. Full characterization of the site in polarization using a dedicated radiometer and the QUBIC data. If the installation is feasible, and we can organize the logistics for the installation, we could design a

campaign in Argentina, by the end of the project.

Sub-WP3.5 Comparison of sites. Lead: IAC.

- Task 7. Final report including the comparison of sites. The IAC node will collect the information of all the campaigns, and will share the data with the Harvard node. A final report will be prepared for M36 of the project. This report will include information about: atmospheric conditions in each site; logistics and operational costs (cost estimation of the provision of energy, Internet, cold water and further needed infrastructures); and information about location and impact on sky coverage.
- Task 8. Possible prospection of other sites. During the lifetime of the project, we will also explore other potential sites for installation of European CMB infrastructures.

Deliverables (brief description and month of delivery)

D3.1. Technical report with the WVR measurements at Dome C [M34].

D3.2. Technical report with the WVR measurements at Teide Observatory [M34].

D3.3. Public report with the comparison of the five different sites [M36].

Table 3.1a: Work package 4 description

Work package number	4	**Lead beneficiary**	Roma I				
Work package title	Telescope & Optics						
Participant number	3	10	2	5	1		
Short name of participant	Roma I	NUIM	Milan	IAC	CNRS		
Person months per participant:	32.4	31.5	8.4	1	2		
Start month	0	**End month**	36				

Objectives

The Optical Design task will study possible telescope designs for an E4 facility. Designs produced can be used as examples for tasks investigating e.g. mirror technologies, site logistics etc.

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

Task 4.1: In this task we will investigate a range of possible telescope designs bearing in mind the available literature, recent advances in technology, our science goals and the specific requirements of sites chosen. t0-t36.

Task 4.2: We will use optical design and analysis software to characterise the performance of the designs we study. (t0-t36)

Task 4.3: The designs will we updated on an on-going basis as required by the results of other tasks (e.g. frequency bands/detector numbers required, limits on specific component sizes). t0-t36

Deliverables (brief description and month of delivery)

4.1: A report detailing a trade-off study of the telescope designs considered and any requirements particular to the E4 infrastructure project. (t0+36)

4.2: An example telescope design will be produced for each of the main science goals (i.e. a large FOV and low angular resolution for B-mode observations and a limited FOV with high resolution for clusters and small scale observations). The designs will include the number and layout of reflecting/refracting components, size and position of focal plane, stops, operating frequency bands and baffling. (t0+36)

4.3 The optical performance of each design will be characterised (e.g. Strehl ratio, cross-polarisation performance across the focal plane, beam-pattern for a given pixel type). (t0+36)

Table 3.1a: Work package 5 description

Work package number	5	Lead Beneficiary	CNRS		
Work package title	KIDs Focal plane and detector R&D and design				
Participant number	1	3	6	7	5
Short name of participant	CNRS [LPSC, Institute Néel, IPAG (Grenoble), & APC (Paris)]	Roma I [“Sapienza” & CNR]	CSIC [CAB (Madrid) & IFCA (Santander)]	DICOM-UC (Santander)	IAC
Person months per participant:	25 [8, 8, 1, 8]	88.8 [74.4, 14.4]	6 [4, 2]	2	2
Start month	0	End month	36		

Objectives: Investigate the cost and feasibility of using Kinetic Inductance Devices for the E4 observatory (corresponding to the KIDs text in section 1.3)

Description of work: Investigate the cost and feasibility of using Kinetic Inductance Devices, including the possibility of integrating detectors & readouts and making multi-chroic pixels. The lead partner is the CNRS.

Task 5.1) Development for 100k pixel arrays (Néel Institute/CNRS)
Task 5.2) Optical coupling (horns/filled arrays, polarization, multi-color) (APC/CNRS)
Task 5.3) Low frequency aspects – 50/100 GHz (CAB/CSIC)
Task 5.4) High frequency aspects – 100/300GHz (Roma I)
Task 5.5) Readout electronics (LPSC/CNRS)
Task 5.6) Acquisition software and photometry (Roma I)

Deliverables: 5.1 Large-Array KIDs Feasibility Report (t0+36)

Milestones

5.1. Demonstrate single-pixel BLIP performance over the E4 instruments frequency bands (50-300 GHz) (t0 + 18 months)

5.2 Adapt single-pixel design to large-scale arrays with similar performance. (t0 + 36 months)

5.3 Perform critical environmental characterization on large-scale arrays (micro-phonics, thermal stability, magnetic field interference). (t0+36 months)

Table 3.1a: Work package 6 description

Work package number	6	**Lead beneficiary**	INFN	
Work package title	TES Focal plane and detector R&D and design			
Participant number	4	1		
Short name of participant	INFN (PI/GE /TIFPA)	CNRS (APC)		
Person months per participant:	60 (18, 30, 12)	12		
Start month	0	**End month**	36	

Objectives
This work package will investigate the cost and feasibility at European level of a focal plane for a CMB measuring instrument based on Transition Edge Sensors (TESs). At the end of the study we will have a broad knowledge of the requirements for such a development and, detail, of:

1. Technology for detectors in the frequency band 50 to 300 GHz;
2. Survey of fabrication possibility of 100,000-detectors arrays within the European context (existing infrastructures, possible industrial partners, cost of establishing an infrastructure;
3. Technology for readout electronics for the 100,000-detectors focal plane;
4. Survey of possible industrial partnership to build the necessary readout electronics and cost estimate;
5. Prototypical detector-readout chain for the proposed technology in the full frequency range.

Description of work: The work flows naturally along two lines: detector development and electronics development but it is understood that in many aspect there will be interexchange of people/information.

Detectors (Task 6.1) [INFN/GE + INFN/TIFPA]

- Survey of the present technologies for detector in the various frequency bands (40 GHz – 300 GHz);
- Survey of possible techniques to extend the present technology towards multi-chroic and polarization sensitive pixels;
- Design of a production chain able to deliver 100,000 detectors with the required characteristics;
- Survey of possible industrial partners to accomplish the production of detectors;
- Cost estimate of a production facility for such an instrument within a European context.
- Measurements of characteristics of prototypical detectors of different conception. Possible characterization in a real-experimental environment (note that both QUBIC and LSPE should be operational during this project’s timeline)

Readout (Task 6.2) [INFN/PI + APC]

- Survey of the present technologies for readout in the various frequency bands (40 GHz – 300 GHz);
- Survey of possible techniques to extend the present technology towards e.g. in pixel multiplexing or full-digital readout.
- Evaluation of the needs for a future experiment in term of multiplexing multiplicity, electronics noise, power needs;
- Survey, implementation and tests of software and firmware algorithms to accomplish the desired readout;
- Survey of expertise and technologies present in Italian industries to establish possible partnerships in view of the deployment of the technology studied;
- Design, evaluation of performance, power consumption and costing of the optimal readout for a 100,000 detector instruments.
- Measurement and characterization of prototypical electronics readout chains. Possible characterization in a real-experimental environment (note that both QUBIC and LSPE should be operational during this project's timeline)

System level (Task 6.3) [INFN + APC]

- Estimate of feasibility of a complete detector+readout chain;
- Measurement and characterization of a complete prototypical detector+electronics chain

To accomplish this tasks two 1-year equivalent post-doc positions will be required (meant as a co-financing of existing or future projects) as well as a small amount of consumables/construction for the three sub WPs.

Deliverables

6.1 Report summarizing the status of the TES production in different frequency bands (T0+12 mos.)

6.2 Report summarizing the possibility to extend the present detectors towards multichroic-non-etched-polarization sensitive pixels (T0+18 mos.)

6.3 Report summarizing a full scale production study with possible implementation of the production chain in partnership with possible industrial partners (T0+30 mos.)

6.4 Report summarizing the status of electronics readout and future prospects (T0+12 mos.)

6.5 Report summarizing a possible electronics implementation with intensive study on the firmware/software development (T0+24 mos.)

6.6 Report summarizing a full scale electronics production study with investigation of possible industrial partners (T0+30 mos.)

6.7 Report with Design and Cost estimates of a European production facility for a detector + Electronics focal plane with 100,000 detectors (T0+36 months).

6.8 Report on construction of a prototype demonstrator in a critical environment of a detector+readout chain (T0+36m)

Table 3.1a: Work package 7 description

Work package number	7	**Lead beneficiary**	CSIC				
Work package title	HEMT Focal plane and detector R&D and design						
Participant number	6	7	5	2	1		
Short name of participant	CSIC	UC	IAC	Milan	CNRS		
Person months per participant:	11	18	6	4	4		
Start month	0	**End month**	36				

Objectives: In this WP it will be analysed the possibilities that radiometers based on cryogenic very low noise amplifiers made with High Electron Mobility Transistors (HEMT) offer to characterize foreground emissions in the CMB lower frequency bands. Since it is expected that for frequencies around 100 GHz and higher KIDs and TES would be more competitive in terms of sensitivity and number of pixels, this WP will be more focused on frequencies < 50 GHz just below the 60 GHz atmospheric forbidden band. In that range three frequency bands of interest can be identified for ground-based observations, 15, 30 and 40 GHz (e.g. QUIJOTE). Two different instrumental concepts implementing HEMT-based large arrays of detectors will be studied and compared: direct image instruments mounted on telescopes and large format interferometers. In relation to the instrument receivers, Front-End components (horns, orthomode transducers, polarisers) and Back-End components (phase switching, microwave correlation modules) will be studied. Several aspects as number of detectors (sensitivity), operational characteristics optical beams, angular scales coverage and cryogenics will be analysed and compared between the two reported options. In particular, for direct image instruments a critical point is the number of detectors that can be accommodated on the focal plane as a function of the allowed systematic level. On the other hand, the use of electro-optical correlators based on Mach-Zender modulators to up-convert the microwave frequency to the IR domain has shown to be a promising solution to correlate hundreds of signals for synthesized image interferometry. These studies will be carried out considering the different instrumental aspects related to the three frequency bands.

Description of work

The work will be organized in 6 tasks:

7.1 Study of the state of the art of HEMT technologies. (UC)

The sensitivity, in terms of noise and band width, of radiometers based on HEMT low noise amplifiers will be studied as a function of frequency.

7.2 Viability of large arrays of receivers allocated in the focal plane for direct image instruments. (UC)

Design and optimization of large arrays in the focal plane, considering number and characteristics of the receivers. In particular, the size of the FEM wave-guide components (horns, ortho-modes, polarisers) will be confronted with its performance in terms of bandwidth and systematics (e.g. polarization purity).

7.3 Viability and technical solutions for large focal plane radiometer arrays based on HEMTs (IAC).

Solutions for the fabrication, assembly, integration and verification (AIV), optimization of the data acquisition electronics (DAE) and maintenance of the arrays.

7.4 Viability and test of the electro-optical correlator of a large format interferometer. (IFCA)

Viability of the up-conversion stage of the electro-optical correlator for the different frequency bands.

Viability of the implementation in the IR domain of polarimeter receiver operations (90 and 180 degrees hybrids for signal combination and optical polarization modulators).

Tests of critical subsystems in the laboratory.

7.5 Modelling and optimisation of the interferometer concept. (IFCA)

Interferometer modelling and simulation. In particular, analysis of the field of view, synthesized beam requirements and coverage of angular scales.

7.6 Comparison of direct image versus interferometer concepts. (IFCA)

Comparative analysis in terms of sensitivity, coverage of angular scales, systematics, cost, instrument operation and calibration, among others.

Deliverables (brief description and month of delivery)

7.1 Report on the state of the art of HEMT technologies. t0+12

7.2 Report on the viability of large arrays of receivers allocated in the focal plane. t0+24

7.3 Report on solutions for the fabrication, AIV, optimization of the DAE and maintenance of large focal plane radiometer arrays. t0+30

7.4 Report on modelling and viability of the interferometer concept. t0+30

7.5 Report on Comparison of direct image versus interferometer concepts. t0+36

Table 3.1a: Work package 8 description

Work package number	8	**Lead beneficiary**	Roma-I				
Work package title	Cryogenics						
Participant number	3	1	5				
Short name of participant	Roma I	CNRS	IAC				
Person months per participant:	63.6	1	1				
Start month		**End month**					

Objectives: Define cryogenic requirements for the infrastructure.

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

Task 8.1: Study the requirements on the cryogenic system from the different instruments (HEMT-based, or KIDs/TES-based): cooling power at different temperatures, cooling time, temperature stability, vibrations, size, weight, power available, operating temperatures etc.)

Task 8.2: Design dry cryostats, using pulse-tube coolers or alternative solutions, to reach a base temperature of 3 K, based on existing literature, experience of the proposers, and tests of key components/devices in existing facilities

Task 8.3: Design sub-Kelvin, closed-cycle coolers using dilution technology and/or the ADR technology, to reach a base temperature of 0.1 K for TES/KID, based on existing literature, experience of the proposers, and tests of key components/devices in existing facilities

Task 8.4: Design the filtering scheme to allow a huge radiation throughput in the cryostat all the way to the 0.1K focal plane, while rejecting efficiently warm radiation from the outer parts of the instrument and the operation environment (in conjunction with work-package 4).

Task 8.5: Allocate volumes for the focal plane, the re-imaging optics system, the cold polarization modulator (if applicable; in conjunction with work-package 4).

Task 8.6: Study the customization of the related equipment (compressors, cables, pipes, pumps, temperature sensors and controllers) for operation at remote sites. This is particularly critical for the most extreme sites, like Dome Concordia, with external temperatures ranging from -75 C to -55 C, challenging the seals and the mechanisms of the cryogenic systems, and human-operated maintenance.

Task 8.7: Optimize the software and hardware of the cryogenic operation controller/programmer used to operate heat switches, cryo-pump heaters, thermometer readout, pumps, etc.

Task 8.8: Define the logistic requirements (size, weight, power, vibrations, control) for reliable operation of these systems in the observatory (in conjunction with work-package 3)

Deliverables (brief description and month of delivery)

8.1 Report on CMB cryogenics survey or census of what is available and needed (Roma-I; t0+6)

8.2 Cryogenics requirements definition document (t0+12)

8.3 Report Preliminary Design of cryogenics system(s) (t0+24)

8.4 Final cryogenics design document (t0+36)

Table 3.1c: Work package 9 description

Work package number	9	**Lead beneficiary**	Milan				
Work package title	System Engineering & Overall Calibration						
Participant number	2	3					
Short name of participant	Milan	Roma I					
Person months per participant:	30	3.6					
Start month	0	**End month**	36				

Objectives Define the system engineering, test and calibration plan.

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

The development of the E4 facility will require careful assessment of all the system and subsystem requirements, control of interfaces, a well-defined plan for assembly, integration and verification, and a complete calibration plan. These activities will be an integral part of this 3-year design study, to be developed in parallel with the definition of the infrastructure configuration.

Task 1: Define the primary instrumental parameters that characterise the functionality and performance of the E-CMB system. Specify the requirements on each parameter needed to ensure compliance with the science objectives.
Task 2: Identify the critical interfaces (mechanical, thermal, electrical, optical, RF). Define the management philosophy for detailed interface definition. Define margin management.
Task 3: Identify potential systematic effects impacting the E-CMB observations (thermal, optical, electrical, RF, polarisation specific). Develop simulations of the main potential systematic effects, in combination with E-CMB scanning strategy. Define a suitable plan for photometric calibration and relative calibration during routine observations.
Task 4: Develop an end-to-end calibration plan to ensure control of systematic effects. Define the required accuracy in the measurement of each key parameter. Define tests to be performed (possibly repeated) at different levels of integration (AIV): individual unit, sub-assembly, system level. Define the methodology and required test facilities to carry out the test sequence. Specify the calibration plan at different phases: 1) pre-deployment characterization; 2) on-site system calibration; 3) calibration during routine observations.

Deliverables (brief description and month of delivery)

9.1 Technical requirements document, in which the scientific requirements are translated to hardware tolerances.

(t+18)
9.1 Pre-deployment test plan Document (t0+36).
9.2 System calibration plan Document (t0+36).
9.3 Routine Observation Plan Document (t0+36).

Table 3.1a: Work package 10 description

Work package number	10	**Lead beneficiary**	CNRS				
Work package title	Governance						
Participant number	1						
Short name of participant	CNRS						
Person months per participant:	14						
Start month	0	**End month**	36				

Objectives:

1. Examine the options for the institutional framework of a pan-European collaboration on a 4th Generation CMB Infrastructure and its inclusion in a global framework, including the options for the common funding of the infrastructure
2. Examine the optimality and sustainability of the construction and operational scenarios from an institutional point of view, based on the evaluations of the other work packages. As well as the options of use of the infrastructure, including observation policies and data access.
3. Examine the site options from the institutional point of view in complementarity and coordination with global partners.
4. Define a common interdisciplinary, industrial and innovation policy

Description of work (where appropriate, broken down into tasks), lead partner and role of participants

Task 1: Definition of a common European and International scientific policy on CMB-S4 *(duration t0 to t0+36m)*

Objectives. Define a common policy on CMB research through the formation of a program committee consisting of key European agency executives. Prepare and propose a sustainable coordination scheme on the subject beyond the lifetime of the design study. Engage the coordination with key non-European agencies: DOE and NSF proposing a similar program in the US, Japan and China, as well as countries with potential sites Argentina and Chile, South Pole agencies. Thus define a glob strategy on the CMB along the lines of the global coordination of gravitational wave antennas and large neutrino infrastructures or the convergence to a single large global infrastructure on CTA and SKA observatories. It is also important to note that on all of the above convergence schemes, the European Consortium of Astrophysics (Astronet) and the Astroparticle Physics European Consortium (APPEC), both having started as EU supported ERANET's and key stakeholders supporting this proposal was a determinant factor.

Methodology: The members of the program committee will be named by the European Consortium of Astrophysics (Astronet) and Astroparticle Physics European Consortium (APPEC), ensuring the close interaction with national funding agencies with participation of representatives from established national and international organisations (ESO, ESA, CERN). Key agency executives of other regional agencies (DOE, NSF, Japan, China, Argentina, Chile, …) will be invited to participate. Two agency meetings per year will be organised in the context of this work package. One at a European level and a second one at a global level. There will also be the continuation of the so-called "Florence meetings" (https://indico.cern.ch/event/376392/ and https://indico.in2p3.fr/event/13232/) assembling scientific PI's and agency representatives to gauge the progress towards the design of a common infrastructure. These meetings were the seeds of the current proposal and they follow e.g. the successful example of similar workshops on neutrino physics that were at the origin of the definition of a global infrastructure on neutrino physics (DUNE at Fermilab and eventually HyperKamioka in Japan) with key contributions from other regions (including Europe and CERN).

Participants: Top agency executives + node and work-package leaders + scientific secretary

Milestones: Two program committee meetings per year: one exclusively European and one with the Global partners (six in total). One workshop between agencies and key scientific representatives of the scientific community (50-60 attendants)/year (3 in total)

Resources*:* Travel funds for six(6) 20-person meetings, organisation costs of 3 medium scale workshops and 3 PM of scientific secretary

Task 2: Definition of the institutional framework of the future infrastructure *(t0 to t0+36m)*

Objectives. Compare and evaluate common models for the full lifecycle of the future CMB infrastructure from planning and construction, to operation and decommissioning, based on findings of the other work packages. Compare and choose among the financial arrangements for the construction, operation and decommission of the facility, using notably the complementarities between national and EU instruments. Define the legal status of the facility and its position in the ecosystem of other European and global infrastructures. Define its relationships to ESA and CERN. Supervise the coordination the relations with national centres of excellence be there on research and development of sensors and their valorisation or computing and data access centres. Prepare the public accessibility of data.

Methodology: Form a working group of experienced project scientists, and experts responsible for maintenance and operation and administration from previous large infrastructures (e.g. of large telescopes, high energy photon, cosmic rays or neutrino observatories, gravitational antenna's etc) to compare and propose solutions for the common institutional issues mentioned in the objectives. The working group will meet twice a year. The findings of the group will form a final report to be submitted to the program committee.

Participants: Working group + task leaders of WP8 + scientific secretary (1 month/year)

Milestones: Two working group meetings every year. A workshop of the working group, open to the scientific community during the last year (attendance 50-60 persons).

Resources*:* Travel funds for six (6) 10-person meetings, organisation costs of one medium scale workshop and 3 PM of scientific secretary.

Task 3: Prepare the decision on the site from the institutional point of view *(t0+12 to t0+36m)*

Objectives. Examine and compare the different site options, based on the findings on site characterisation by WP3 and propose to the funding agencies a scheme for negotiations with the site "owners" as well as the global partners.

Methodology: Form an international Site Evaluation Committee to judge the WP3 propositions, Have the committee visit the different sites and make a final proposal.

Participants: International experts (7) + task leaders of work-package 3 + scientific secretary

Milestones: Three to four site visits (in conjunction with work-package 3) and a final meeting.

Resources: Travel funds for four (4) 7-person visits and a final working group meeting. 2 PM of scientific secretary.

Task 4: Definition of a common industrial, interdisciplinary and innovation policy *(duration t0 to t0+36m)*

Objectives. Define procurement rules that respect the equal information of the partner countries and encourage the just distribution of industrial returns. Negotiate procurement of large quantities of certain materials and instruments. Negotiate access to computing and data storage resources both to public and private centres (eg clouds). Define measures to increase the potential for innovation, of the infrastructures, such as networking with industries (including SMEs), dissemination of research outcome and technology transfer. Liaise with other relevant WPs. Define common models of intellectual property rights. Also exploit the eventual interdisciplinary synergies (e.g. climate or detector us in medical, homeland security and other applications). Prepare a large workshop on applications of CMB detectors (TES and KIDS).

Methodology: Form a 10 person working group of agency and RI industrial experts, technical managers to study, compare and propose solutions for industrial and innovation issues, meeting twice a year.

Participants: Working group + task leaders of WP8 + scientific secretary

Milestones: Two working group meetings every year. A large workshop with industrial partners to promote CMB detector applications during the 3rd year.

Resources: Travel funds for three (3) 10-person meetings. Funds for a large workshop on industrial matters. 3 PM of scientific secretariat.

Deliverables (brief description and month of delivery)
10.1 Short annual report on common CMB policy (t0+12)
10.2 Short annual report on common CMB policy (t0+24)
10.3 Final report on common CMB policy matters (t0+36)

10.4 Short annual report on institutional implementation of the infrastructure (t0+12)
10.5 Short annual report on institutional implementation of the infrastructure (t0+24)
10.6 Final report on the institutional implementation of the infrastructure (t0+36)

10.7 Final report by the International Site Evaluation Committee (t0+36)
10.8 A document with a proposal on best practices concerning procurement rules (t0+24)
10.9 A final report on the 3 year progress on industrial and innovation matters (t0+36)

Milestones

10.1 4th Workshop Scientific Community-Agencies on CMB (t0+ 9)
10.2 5th Workshop Scientific Community-Agencies on CMB (t0+21)
10.3 6th Workshop Scientific Community-Agencies on CMB (t0+33)

10.4 Workshop on the institutional implementation of the infrastructure (t0+30)

10.5 Workshop research-industry on the industrial/innovation relations (t0+20)

Table 3.1b: List of work packages

Work-Package Number	Work Package Title	Lead Participant No	Lead Participant Short Name	Person-Months	Start Month	End month
1	Management & Outreach	1	CNRS	59	1	36
2	Requirements & Analysis	9	MPA	124.15	1	36
3	Site Evaluation, Construction & Operation	5	IAC	37.4	1	36
4	Telescope & Optics	3	Roma-I	75.3	1	36
5	Kinetic Inductance Devices	1	CNRS	123.8	1	36
6	Transition-Edge Sensors	4	INFN	72	1	36
7	High-Electron Mobility Transistors	6	CSIC	43	1	36
8	Cryogenics	3	Roma-I	65.6	1	36
9	System Engineering & Calibration	2	Milan	33.6	1	36
10	Infrastructure Governance	1	CNRS	14	1	36
				643.85		

Table 3.1c: List of Deliverables

Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (in months)
1.1	Outreach Video	1	NOA	DEC	PU	18, 36
1.2	Press Releases	1	NOA	DEC	PU	12, 24, 36
1.3	Educational Material	1	NOA	DEC	PU	12, 24, 36
2.1	E4 Science Book	2	Cardiff	R	PU	12
2.2	E4 Science Papers	2	Cardiff	R	PU	36
3.1	Technical report with the WVR measurements at Dome C.	3	IAC	R	PU	34
3.2	Technical report with the WVR measurements at Teide Observatory.	3	IAC	R	PU	34
3.3	Public report with the comparison of the five different sites.	3	IAC, Roma-I, CNRS	R	PU	36
4.1	Telescope Design Trade-Off Report	4	Roma-I/NUIM	R	PU	36
4.2	Example Telescope Designs	4	Roma-I/NUIM	DEM	PU	36
4.3	Telescope Optical Performance Reports	4	Roma-I/NUIM	R	PU	36
5.1	Large-Array KIDs Feasibility Report	5	CNRS	R	PU	36
6.1	TES Bands Report	6	INFN	R	PU	12
6.2	Multi-chroic Report	6	INFN	R	PU	18
6.3	Production Report	6	INFN	R	PU	30
6.4	Readout Report	6	CNRS	R	PU	12
6.5	Firmware Report	6	INFN	R	PU	24
6.6	Industrial Report	6	INFN	R	PU	30
6.7	Cost Estimate Report	6	INFN	R	PU	36
6.8	Prototype Report	6	INFN	R	PU	36
7.1	HEMT Status Report	7	UC	R	PU	12
7.2	HEMT Array Report	7	UC	R	PU	24

7.3	HEMT Fabrication Report	7	IAC	R	PU	30
7.4	Interferometer Viability Report	7	CSIC	R	PU	30
7.5	Interferometer/Imager Comparison Report	7	CSIC	R	PU	36
8.1	Cryogenics survey Report	8	Roma-1	R	PU	6
8.2	Cryogenic requirements Document	8	Roma-1	R	PU	12
8.3	Preliminary Cryogenics Design Report	8	Roma-1	R	PU	24
8.4	E4 final cryogenic design Document	8	Roma-1	R	PU	36
9.1	Technical Reqs. Document	9	Milan	R	PU	18
9.2	Pre-deployment Test Plan Document	9	Milan	R	PU	36
9.3	System Calibration Plan Document	9	Milan	R	PU	36
9.4	Routine Observation Plan Document	9	Milan	R	PU	36
10.02, 10.04, 10.06	CMB Policy Reports	10	CNRS	R	PU	12, 24, 36
10.07, 10.08, 10.10	Institutional Infrastructure Implementation Report	10	CNRS	R	PU	12, 24, 36
10.11	International Site Committee Report	10	CNRS	R	PU	36

KEY

Deliverable numbers in order of delivery dates. Please use the numbering convention <WP number>.<number of deliverable within that WP>.

For example, deliverable 4.2 would be the second deliverable from work package 4.

Type: *Use one of the following codes:*

R: Document, report (excluding the periodic and final reports)
DEM: Demonstrator, pilot, prototype, plan designs
DEC: Websites, patents filing, press & media actions, videos, etc.
OTHER: Software, technical diagram, etc.

Dissemination level:
Use one of the following codes:

PU = Public, fully open, e.g. web
CO = Confidential, restricted under conditions set out in Model Grant Agreement
CI = Classified, information as referred to in Commission Decision 2001/844/EC.

Delivery date
Measured in months from the project start date (month 1)

Tables for section 3.2

Table 3.2a: List of milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
1.1	Web Page Installation	1	3	Up and running
2.1	Computing Platform	2	3	Up and running
5.1	Single-Pixel KID BLIP demonstrated	5	18	Data quality validated
5.2	Design Arrays	5	36	Design validated by user group.
5.3	KID Characterization	5	36	Data quality validated
10.1	Workshop	10	9	Presentations online
10.3	Workshop	10	21	Presentations online
10.5	Workshop	10	33	Presentations online
10.9	Institutional Infrastructure Implementation Workshop	10	30	Presentations online

KEY

Due date
Measured in months from the project start date (month 1)

Means of verification
Show how you will confirm that the milestone has been attained. Refer to indicators if appropriate. For example: a laboratory prototype that is 'up and running'; software released and validated by a user group; field survey complete and data quality validated.

Table 3.2b: Critical risks for implementation

Description of risk (indicate level of likelihood: Low/Medium/High)	Work package(s) involved	Proposed risk-mitigation measures
Delay in atmospheric testing activities. Probability: Medium. Gravity: Low	3	Staged deployment to most developed sites first, allowing less developed sites to develop, and thus not delay our work once we get there.
Schedule Risk. Probability: High. Gravity: Low.	All	Weekly, quarterly and yearly progress tracking.

Definition critical risk:
A critical risk is a plausible event or issue that could have a high adverse impact on the ability of the project to achieve its objectives.

Level of likelihood *to occur:* **Low/medium/high**
The likelihood is the estimated probability that the risk will materialise even after taking account of the mitigating measures put in place.

Tables for section 3.4

Table 3.4a: Summary of staff effort

Please indicate the number of person/months over the whole duration of the planned work, for each work package, for each participant. Identify the work-package leader for each WP by showing the relevant person-month figure in bold.

	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	WP9	WP10	Total Person-Months per Participant
1 / CNRS	**47**	33.75	3	2	**25**	12	4	1	0	**14**	141.75
2 / Milan	0	0	0	8.4	0	0	4	0	**30**	0	42.4
3 / Roma I	0	14.4	2.4	**32.4**	88.8	0	0	**63.6**	3.6	0	205.2
4 / INFN	0	33	0	0	0	**60**	0	0	0	0	93
5 / IAC	0	3	**32**	1	2	0	6	1	0	0	45
6 / CSIC	0	3	0	0	6	0	**11**	0	0	0	20
7 / UC	0	0	0	0	2	0	18	0	0	0	20
8 / Cardiff	0	4	0	0	0	0	0	0	0	0	4
9 / MPA	0	**33**	0	0	0	0	0	0	0	0	33
10 / NUIM	0	0	0	31.5	0	0	0	0	0	0	31.5
11 / NOA	12	0	0	0	0	0	0	0	0	0	12
Total Person Months	59	124.15	37.4	75.3	123.8	72	43	65.6	33.6	14	647.85

Table 3.4b: 'Other direct cost' items (travel, equipment, other goods and services)

1/CNRS	Cost (€)	Justification
Travel	348k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. The CNRS will be providing travel funds for CNRS and CEA researchers to go to meetings to understand the needs and present the results. In addition, as a participant in the "Site Testing" work package, they will need a bit more travel money to visit the remote sites to be used for these telescopes. The CNRS will be hosting a number of meetings with external agencies and experts for oversight and negotiation with external bodies.
Equipment		
Other goods and services	83k€	- Silicon wafers - Clean room utilisation - Cryogenic liquids - Electronics components - Material for thermal testing
Total	431k€	

2/UMIL	Cost (€)	Justification
Travel	54k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. The University of Milan will be providing travel funds for Milan, Milan-Bicocca & SISSA researchers to go to meetings to understand the needs and present the results.
Equipment		
Other goods and services		
Total	54k€	

3/Roma-I	Cost (€)	Justification
Travel	53k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. Roma-I will be providing travel funds for Roma-I and Roma-IFN researchers to go to meetings to understand the needs and present the results. In addition, as a participant in the "Site Testing" work package, they will need a bit more travel money to visit the remote sites to be used for these telescopes.
Equipment		
Other goods and services	50k€	- Optical Modelling software: 10k€ - Thermal simulation software: 30k€ - Electronics: 10k€
Total	103k€	

4/INFN	Cost (€)	Justification
Travel	35k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. The INFN will be providing travel funds for INFN researchers to go to meetings to understand the needs and present the results.
Equipment		
Other goods and services	32k€	- Consumables for device fabrication (resist/primer: 3k€, Developers 5k€, pure metals 7k€) - Consumables for electronics (PCB fabrication: 5k€, Components: 5k€, FPGA evaluation boards: 5k€) - Consumables for integration/testing (testbed modifications 3 k€, sensors 3k€, cryogenic liquids 4€)
Total	67k€	

5/IAC	Cost (€)	Justification
Travel	66k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. IAC will be providing travel funds for IAC, UGR, CEFCA, and USAL researchers to go to meetings to understand the needs and present the results. In addition, as the coordinator in the “Site Testing” work package, they will need travel money to visit the remote sites to be used for these telescopes.
Equipment	120k€	Omnisys PWV radiometer
Other goods and services	30k€	Material for the radiometer mount
Total	216k€	

6/CSIC	Cost (€)	Justification
Travel	51k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. The CSIC will be providing travel funds for CSIC, Oviedo, UPV/EHU, and Barcelona researchers to go to meetings to understand the needs and present the results.
Equipment		
Other goods and services	20k€	Microwave components
Total	71k€	

8/Cardiff	Cost (€)	Justification

Travel	78k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. Cardiff will be providing travel funds for Cardiff, Manchester, Cambridge and Oxford researchers to go to meetings to understand the needs and present the results.
Equipment		
Other goods and services		
Total	78k€	

10/NUIM	**Cost (€)**	**Justification**
Travel	14k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. The NUIM will be providing travel funds for NUIM researchers to go to meetings to understand the needs and present the results.
Equipment		
Other goods and services	10k€	Optical Modelling Software
Total	24k€	

11/NOA	**Cost (€)**	**Justification**
Travel	9k€	As noted in sections 3.3, 3.4 and table 3.1a for work-package 2, external experts have agreed to provide calculations for work package 2. The NOA will be providing travel funds for NOA and RCAAM researchers to go to meetings to understand the needs and present the results.
Equipment		
Other goods and services	84k€	- Video narration, translation, and planetarium conversion for web - Production of educational materials and translation.
Total	93k€	