Cross-correlations of CMB and LSS cosmological probes

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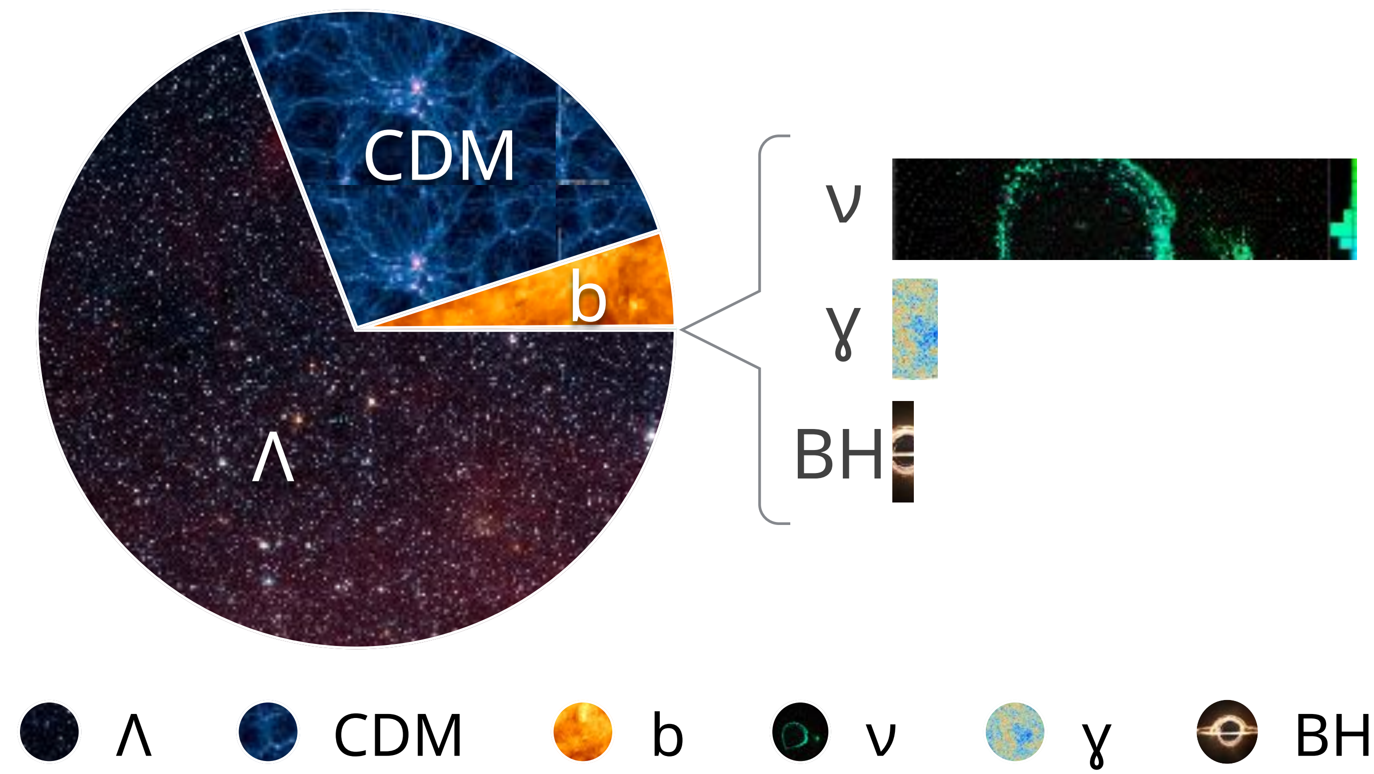
Our universe's standard model : ΛCDM

- Our Universe's ingredient list :

CDM = non-relativistic non-interacting matter

Λ = uniform energy w/ negative pressure 



- Scale factor evolution $$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$
- Primordial fluctuations $\mathcal{P}_\zeta = A_\mathrm{s}\left(\frac{k}{k_0}\right)^{n_\mathrm{s}-1}$ after inflation or bounce or whatnot

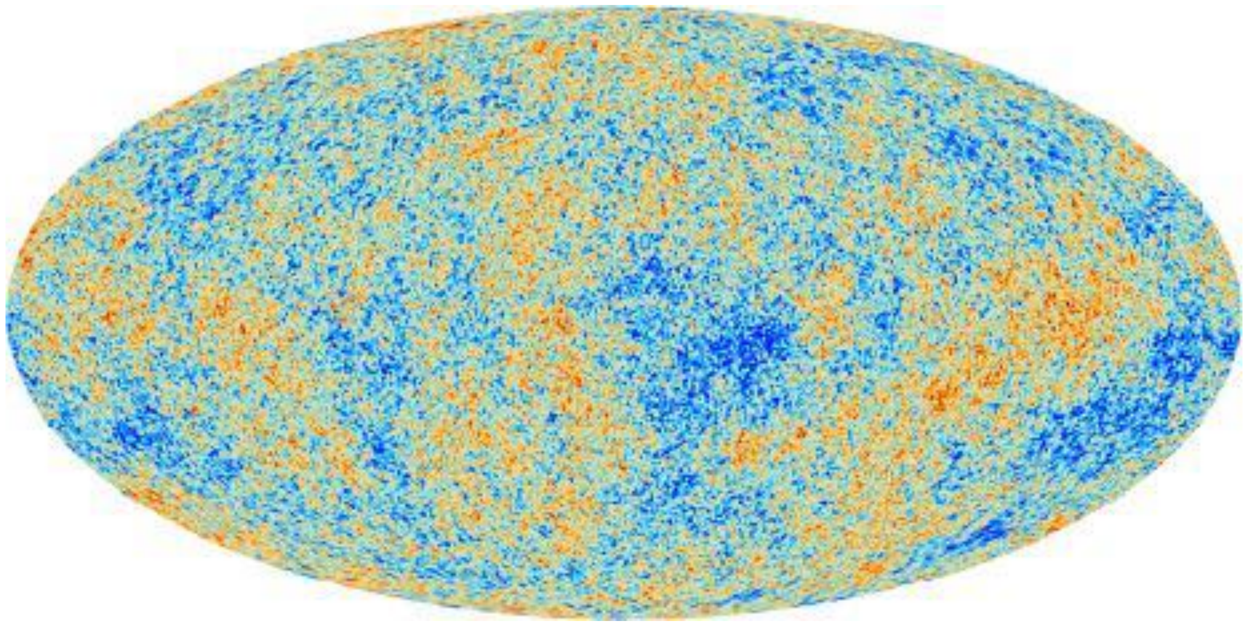
*To test DM and DE models, we want the **strongest contraints** achievable on the cosmological parameters !*

What is observable ?

Cosmic Microwave Background

380 000 years after Big Bang

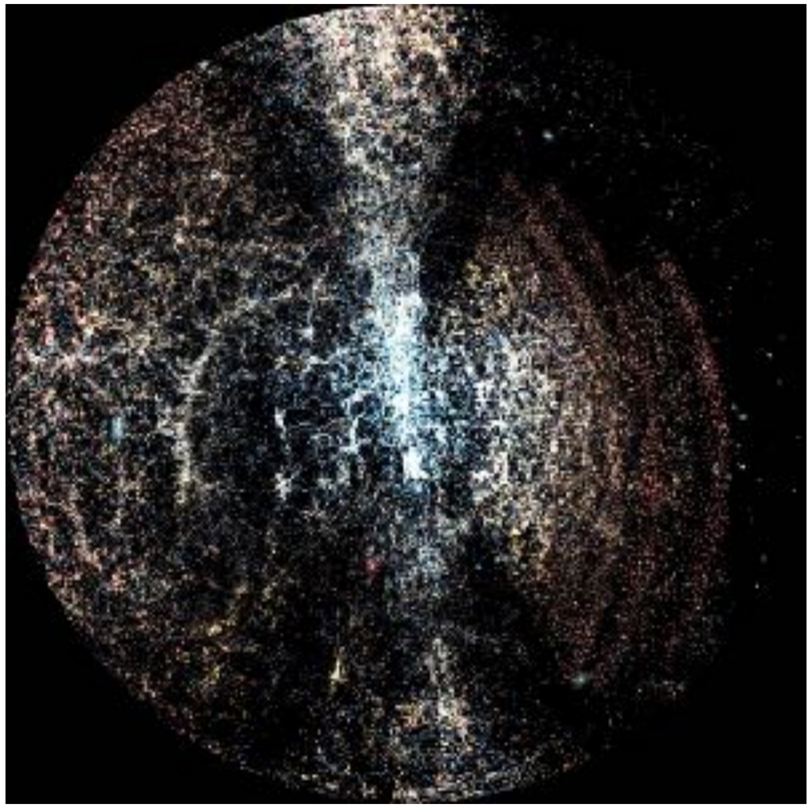
z = 1100



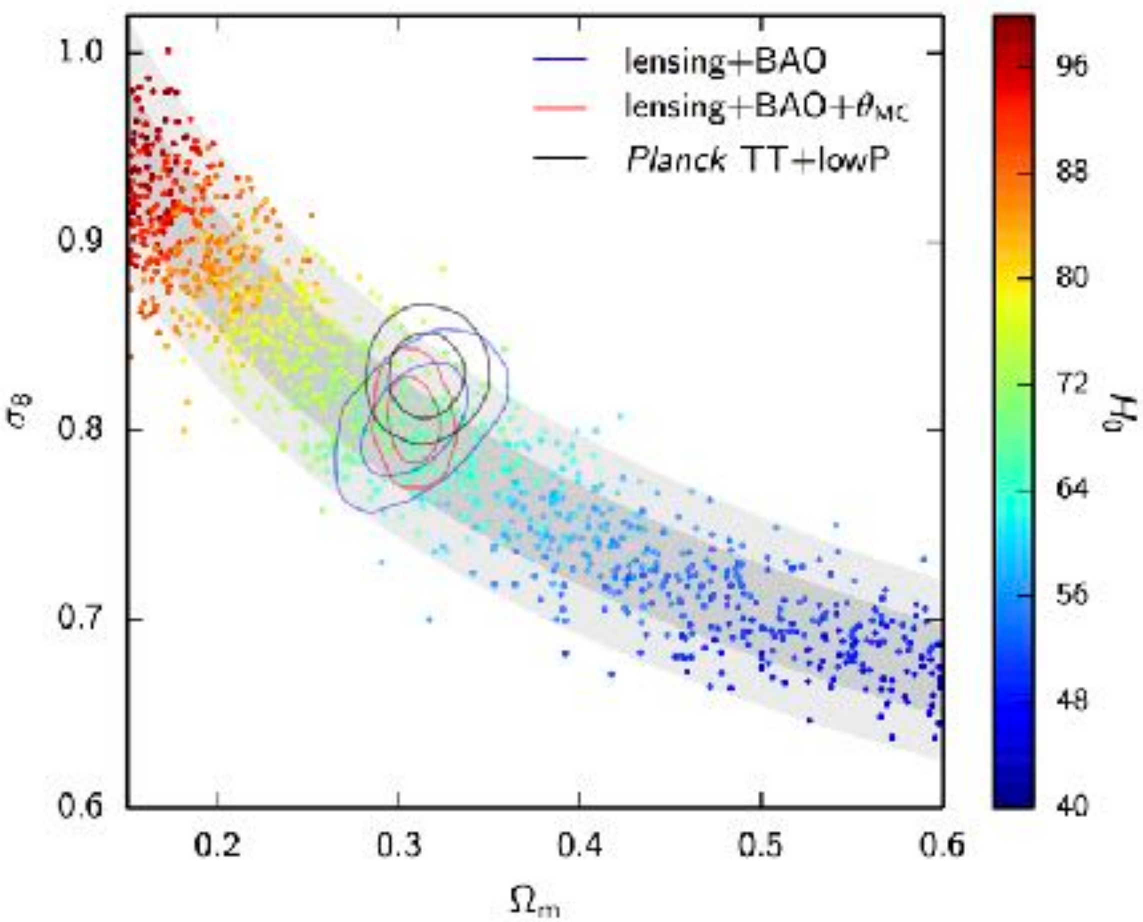
Large-scale structure

3D map of local Universe

z=0 to 5

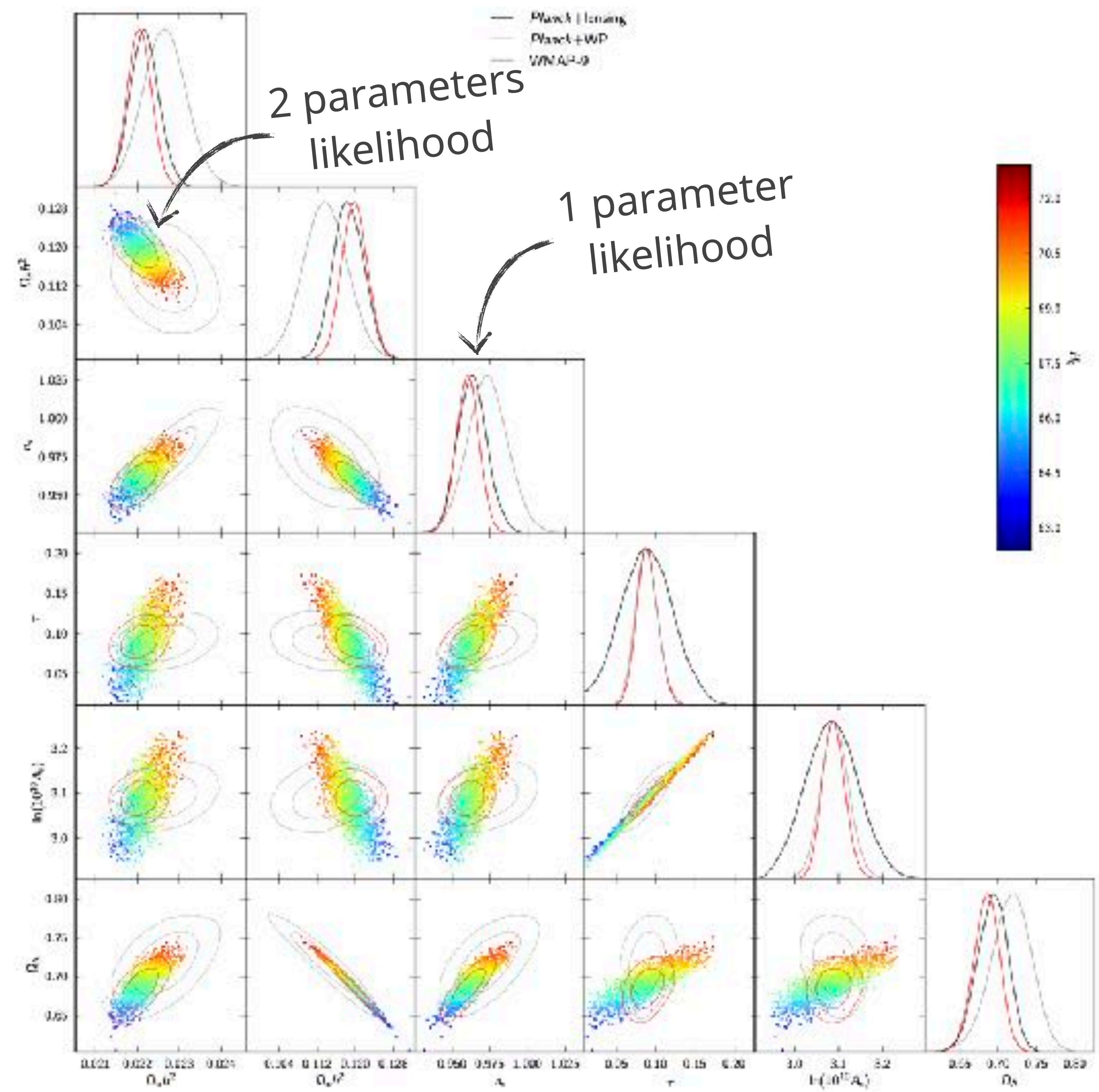


Both give contraints on *combinations* of cosmological parameters, but not the same !



Degeneracy between parameters : one experiment can only *constraints combinations of parameters*…

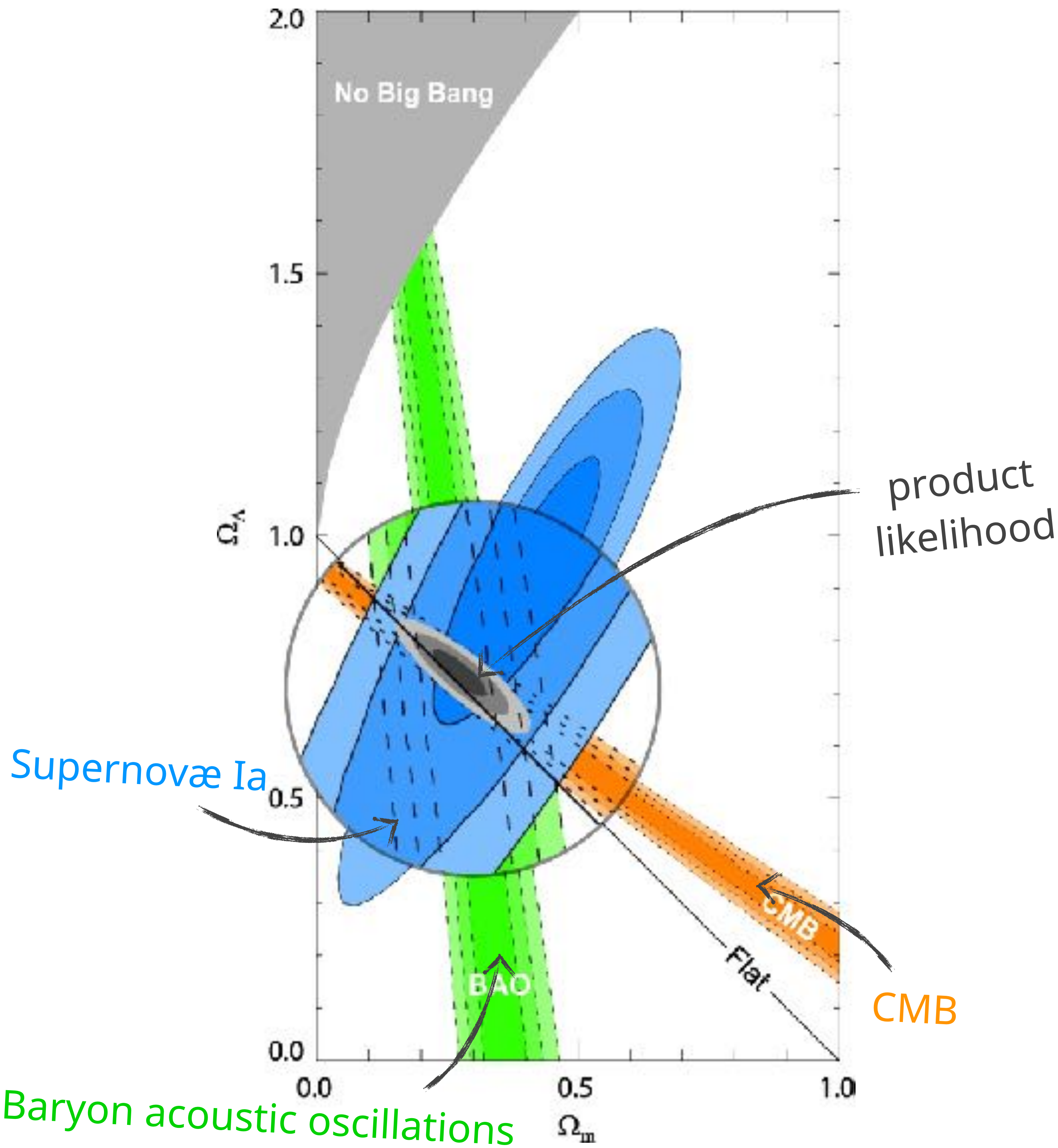
Here, $\Omega_m H_0^3$ and $\Omega_m^{0.26}\sigma_8$.



Planck collaboration, 2013

Post-analysis combination

Example in the Ω_Λ-Ω_m plane



Kowalski et al, 2008

Multiplying likelihoods from the 3 probes CMB, BAO, SNe gives posterior product likelihood

BUT

this does not take into account the fact that *it is the same observed sky !*

THE OBSERVABLES ARE CORRELATED

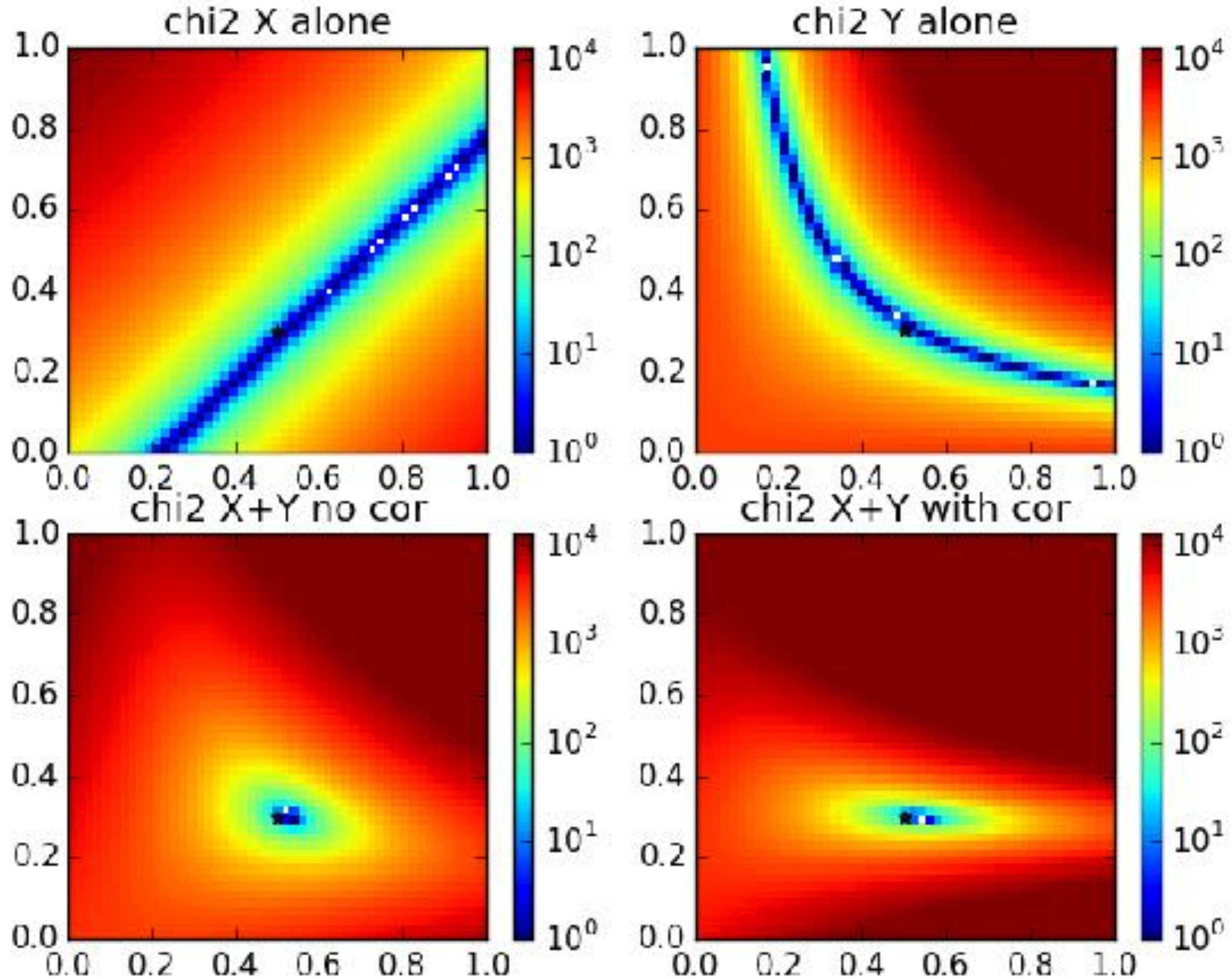
A toy model

Take two *correlated* random variables $X(t)$ and $Y(t)$ depending on two parameters a and b :

$$\begin{pmatrix}X(t)\\ Y(t)\end{pmatrix} = \mathcal{N}\left(\begin{pmatrix}(a-b)\times t\\ 4abt^2\end{pmatrix}, \begin{pmatrix}\sigma_X & \rho\\ \rho & \sigma_Y\end{pmatrix}\right) + \text{uncorrelated noise}$$

X constraints
a-b

Y constraints
ab



Product of likelihoods
$\mathcal{L}_X \times \mathcal{L}_Y$

Joint X-Y likelihood
$\mathcal{L}_{X,Y}$

A toy model

Why is it better ?

Because :

- $\mathcal{L}_{X,Y}$ uses *more information* than $\mathcal{L}_X \times \mathcal{L}_Y$

$$\mathcal{L}_{X,Y} \propto \exp\left[-\frac{1}{2}\sum_i (X_i, Y_i)\,\mathbf{C}_{X,Y}^{-1}\,(X_i, Y_i)^T\right]$$

- difference of Shannon entropy $\Delta S = \ln\sqrt{1 - \frac{\rho^2}{\sigma_X \sigma_Y}} < 0$

- observations are *noisy*, but if experimental noises are uncorrelated

$$\langle (X + N_X)(Y + N_Y)\rangle = \langle XY\rangle + \underbrace{\cancel{\langle XN_Y\rangle}}_{=0} + \underbrace{\cancel{\langle N_X Y\rangle}}_{=0} + \underbrace{\cancel{\langle N_X N_Y\rangle}}_{=0}$$

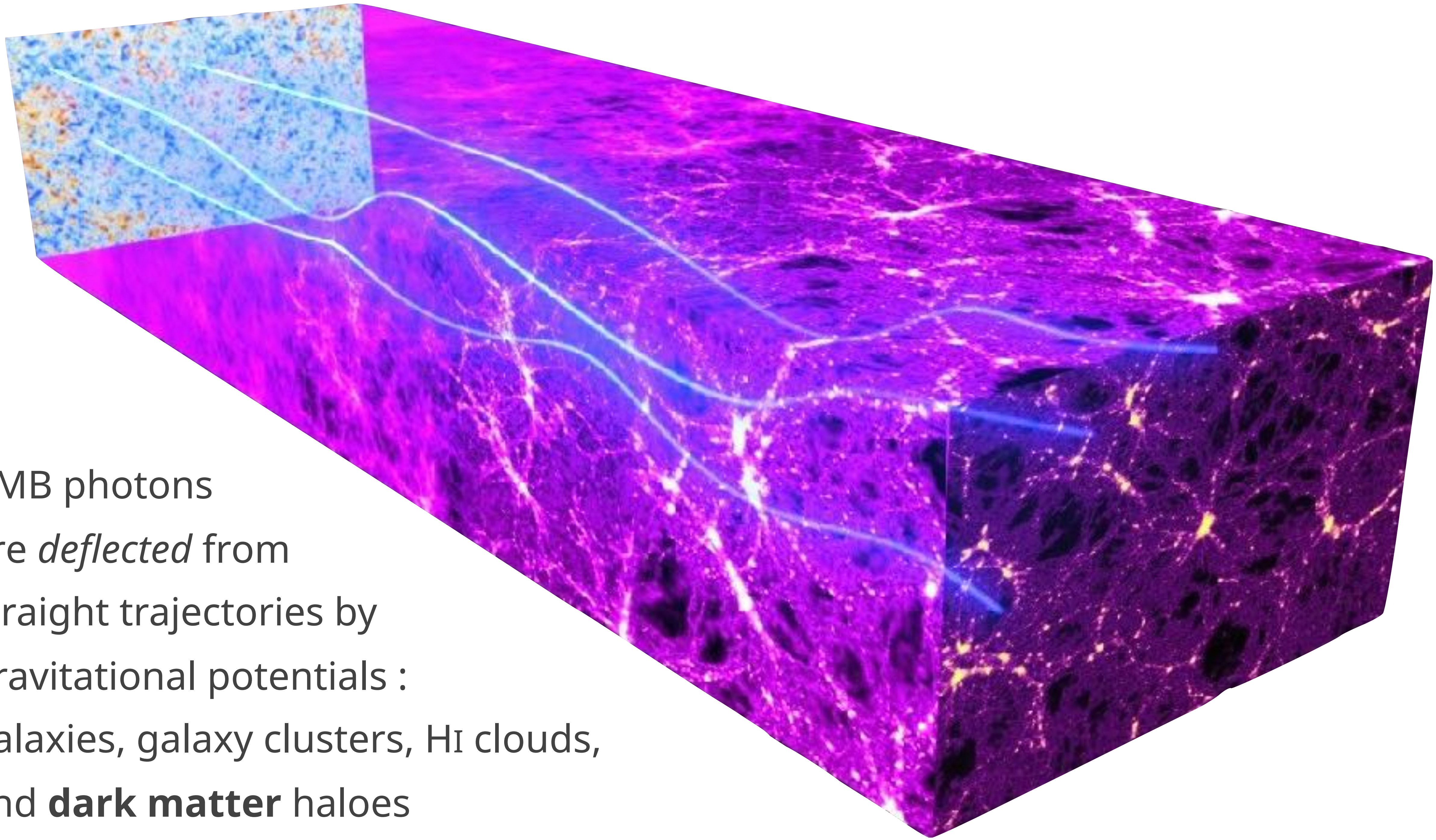
- so ***experimental noise*** and ***part of the systematics*** just ***go away !***

- it's free additional unbiased information !

Why are there correlations between CMB and LSS ?

IDEA

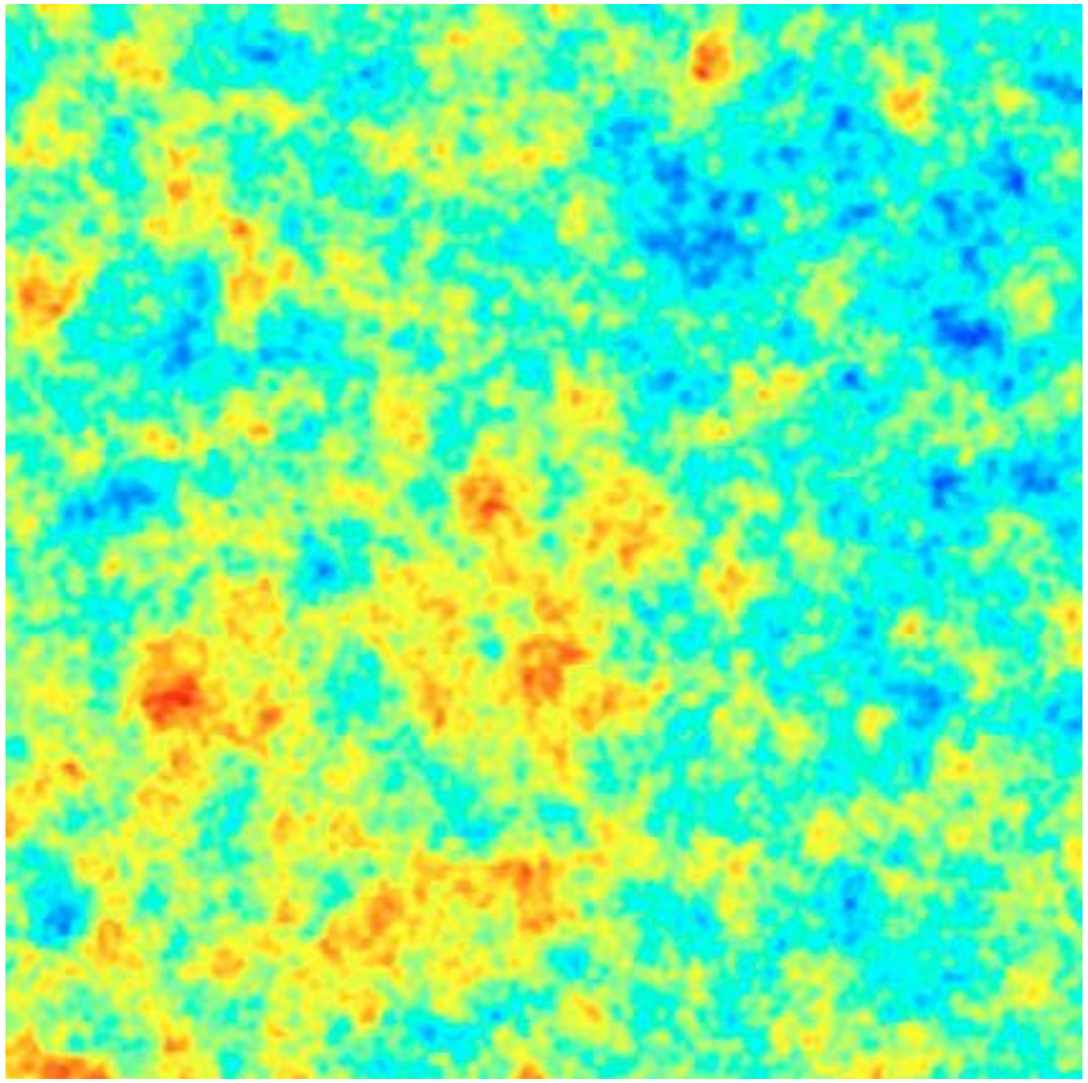
Looking for physical effects of large-scale structures on the CMB…



CMB photons
are *deflected* from
straight trajectories by
gravitational potentials :
galaxies, galaxy clusters, HI clouds,
and **dark matter** haloes

CMB weak lensing

$$T_{\text{obs}}(\hat{n}) = T(\hat{n} + \nabla\phi(\hat{n}))$$

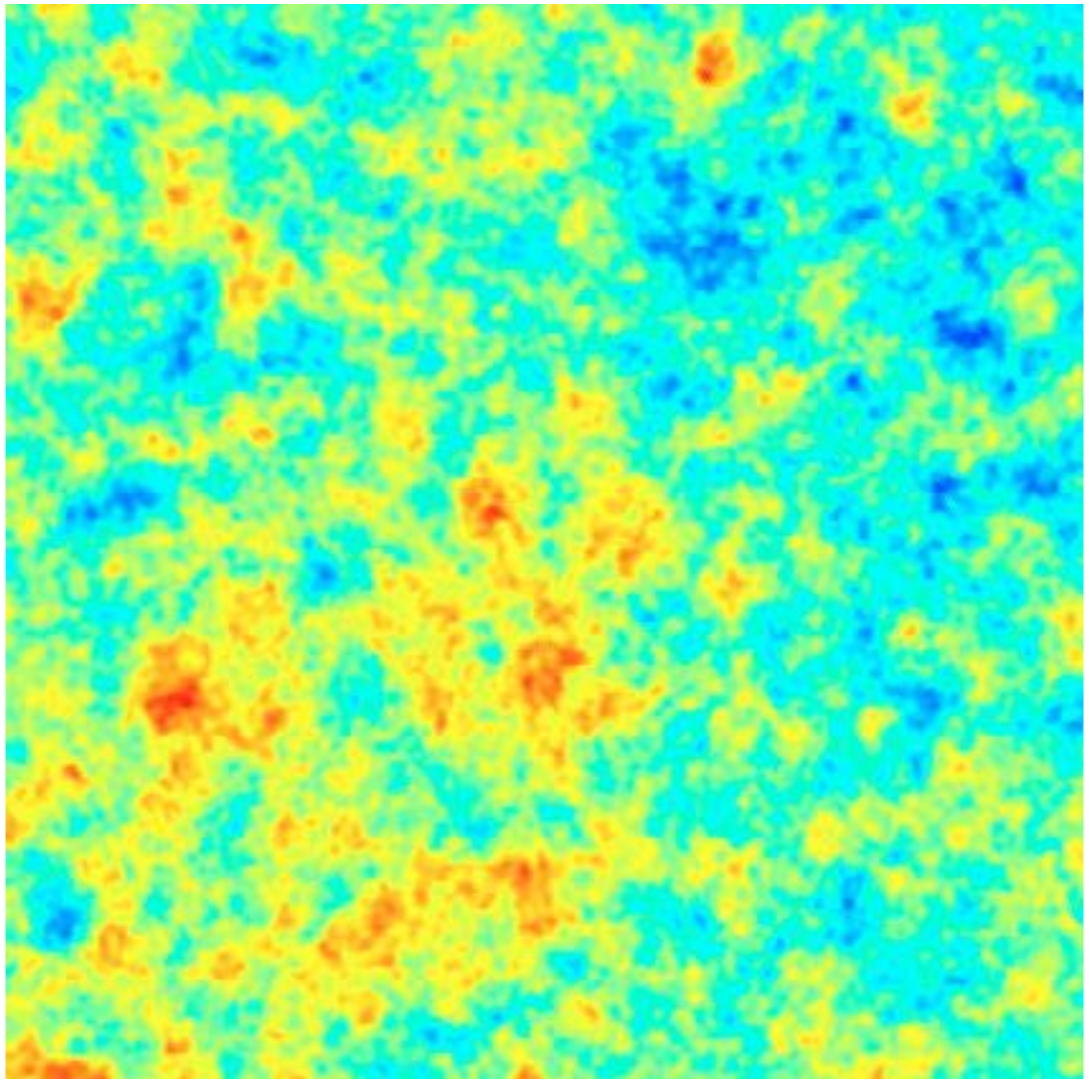


UNLENSED CMB

Basak et al, 2009

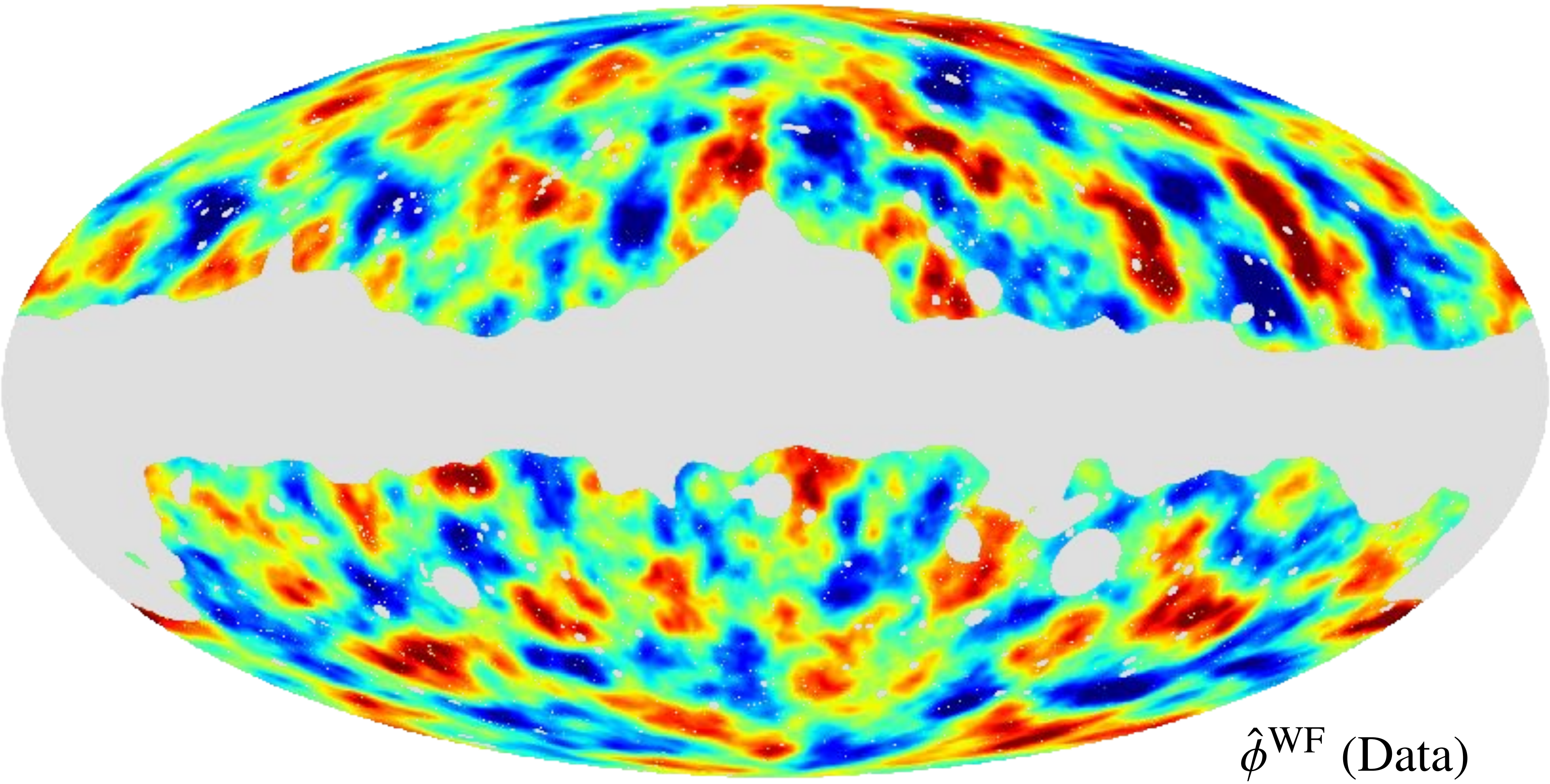
CMB weak lensing

$$T_{\text{obs}}(\hat{n}) = T(\hat{n} + \nabla\phi(\hat{n}))$$



LENSED CMB

Basak et al, 2009



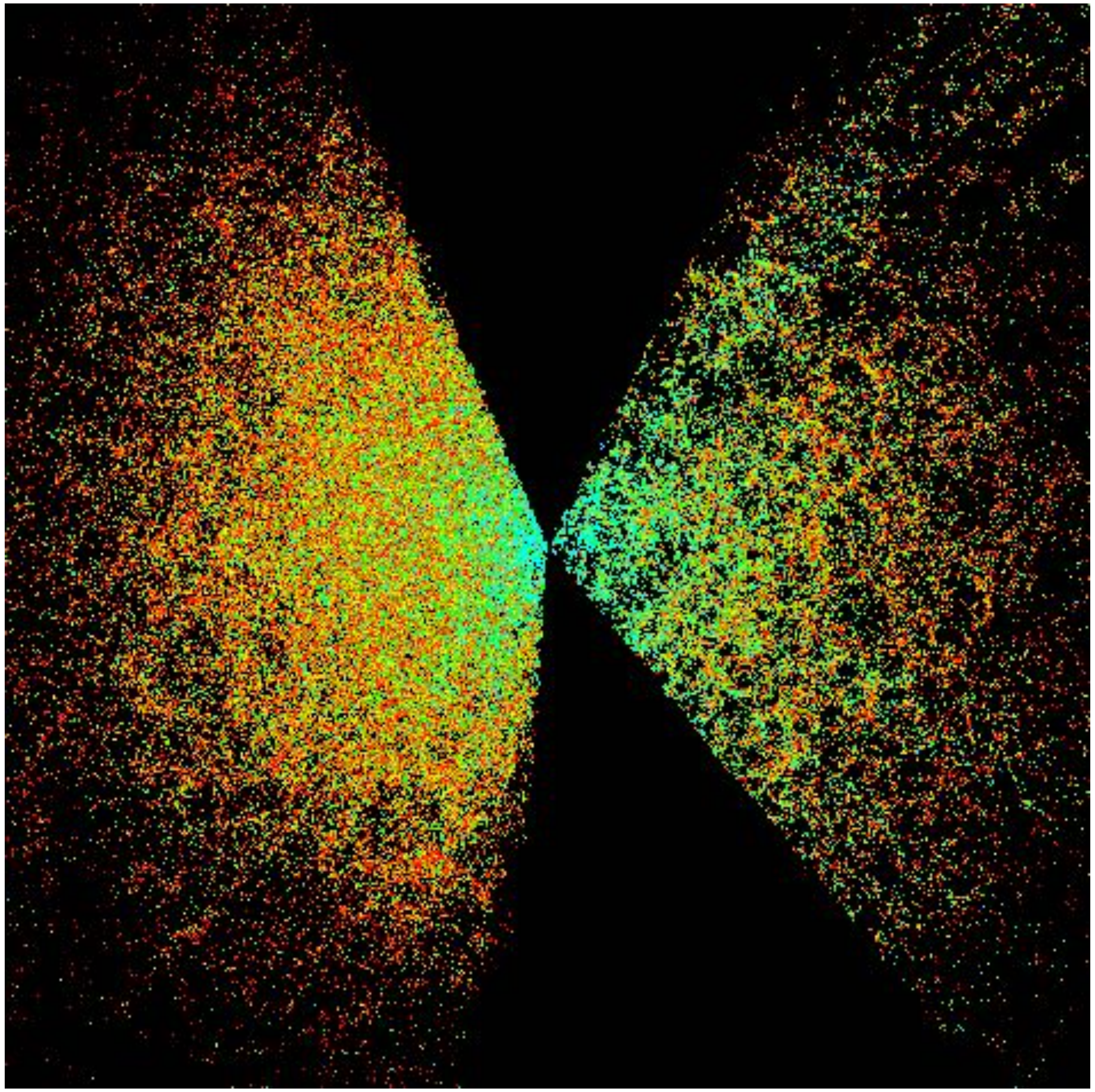
LENSING POTENTIAL

Planck collaboration

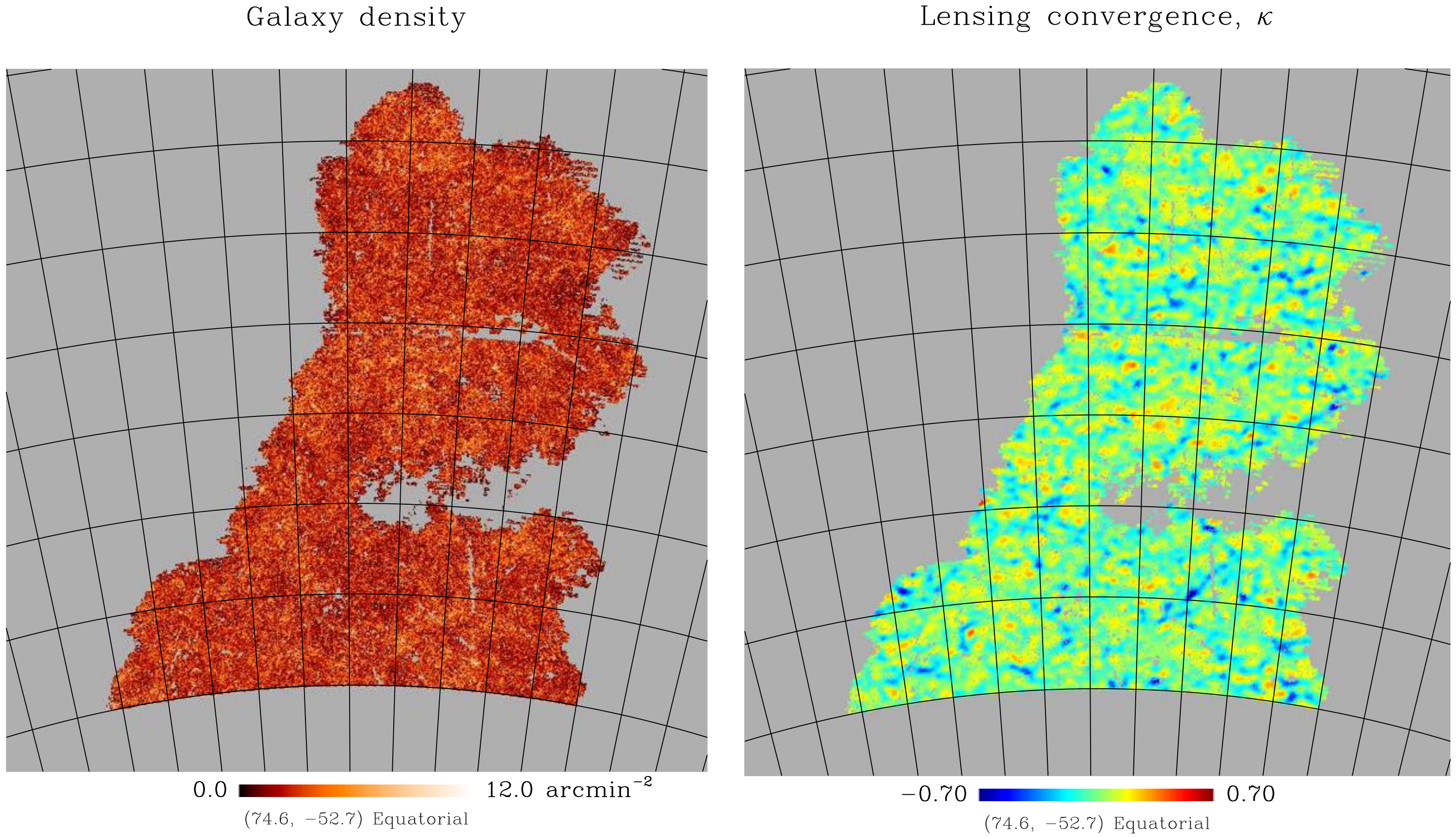
SDSS-III/BOSS galaxy survey

BOSS/eBOSS at Apache Point Observatory, NM

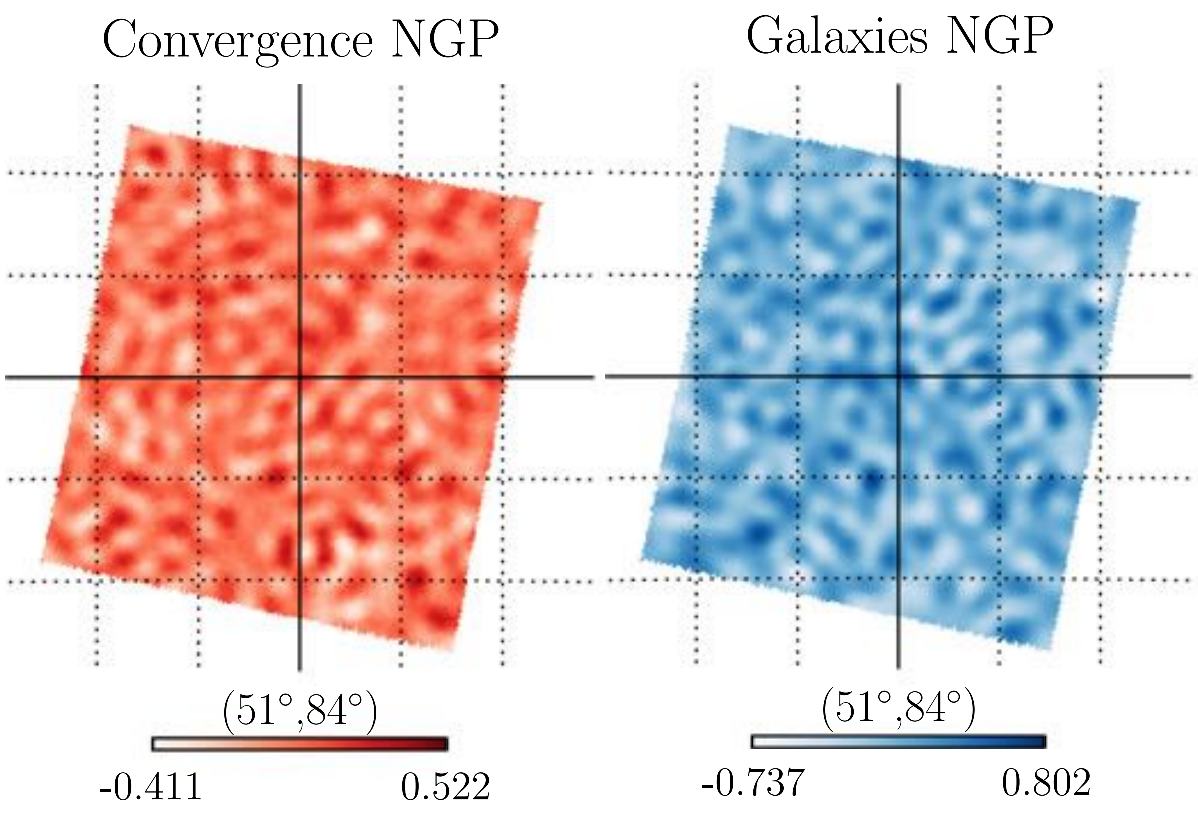
- 1,000-fiber spectrograph, resolution R~2000, λ=360-1100 nm
- 10^6 galaxies, 200000 quasars



CMB lensing × LSS



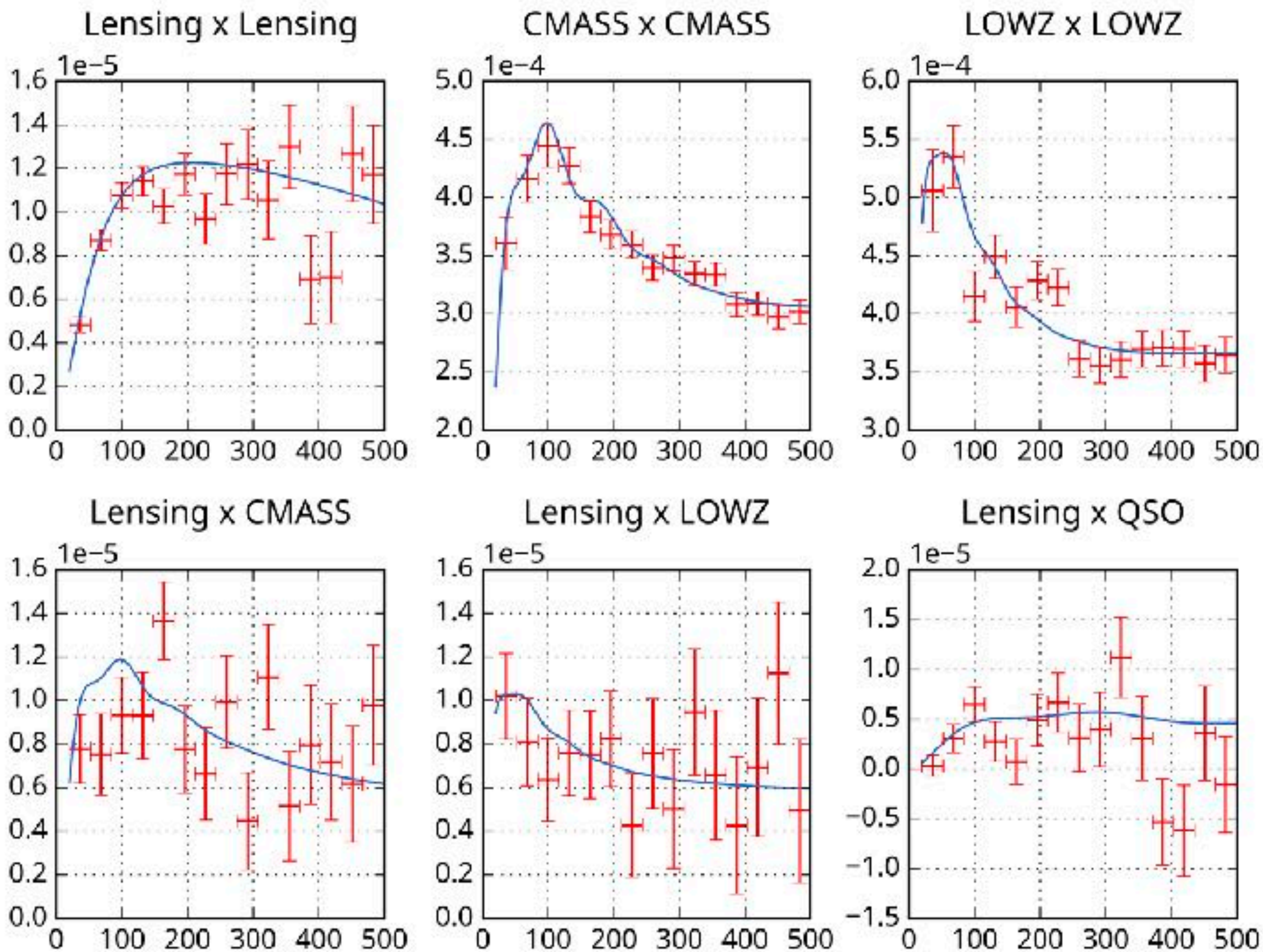
Baxter+16 : DES SV x SPT

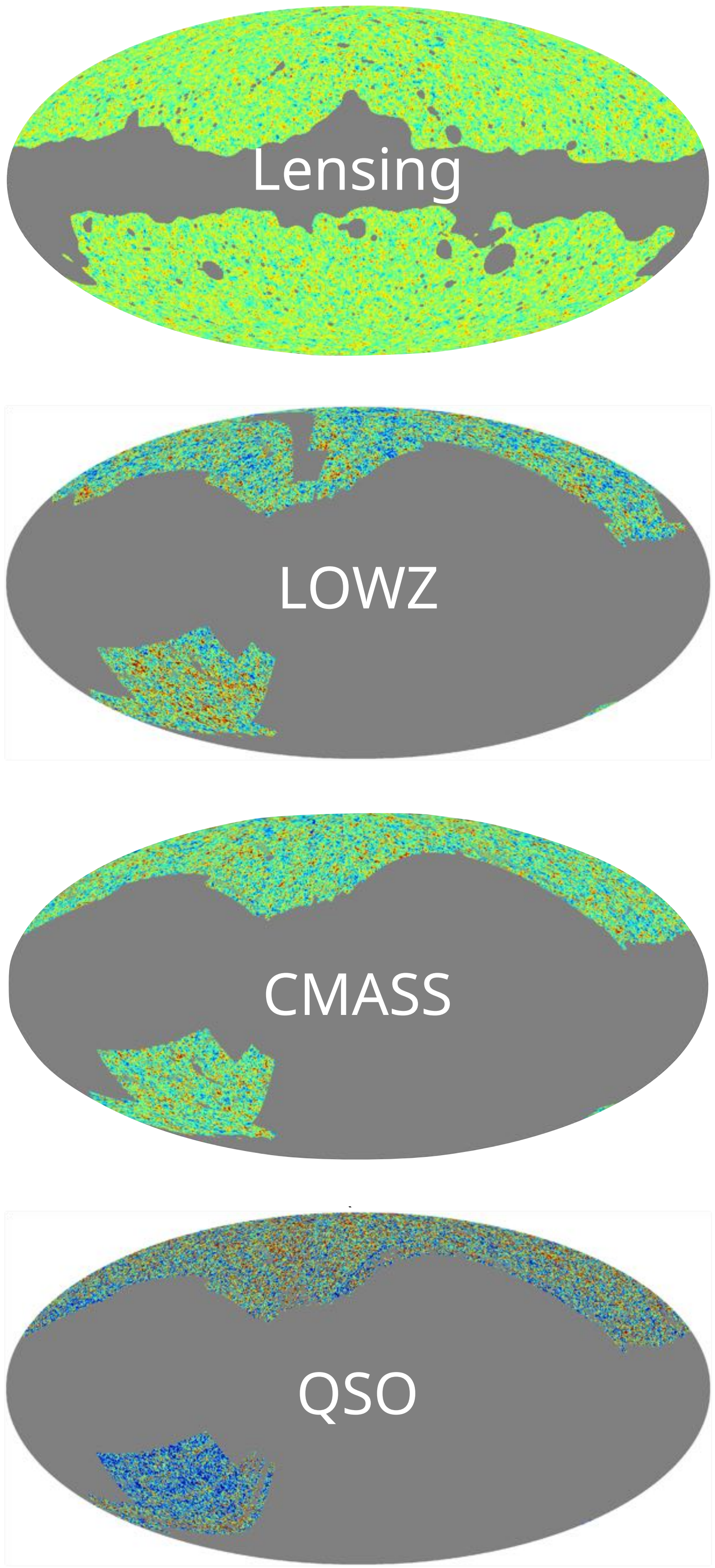


Bianchini+15 : high-z
Herschel galaxies x Planck lensing

CMB lensing × LSS

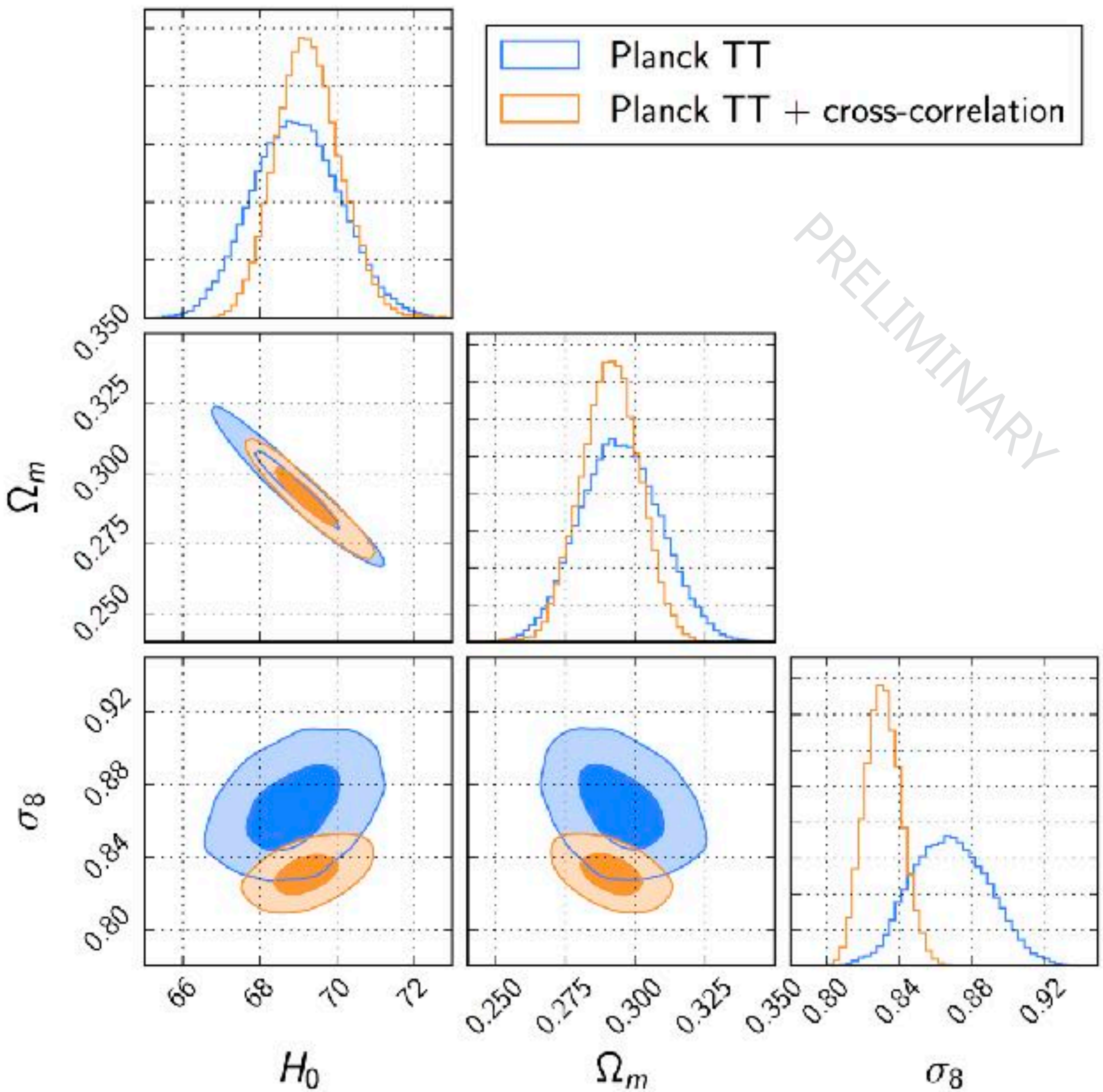
Measurement : angular power spectra C_ℓ (cross + auto)





C_ℓ observed ⟶ $\mathcal{L}(\theta_{\rm cosmo} \,|\, C_\ell\text{'s})$

Constraints on cosmological parameters

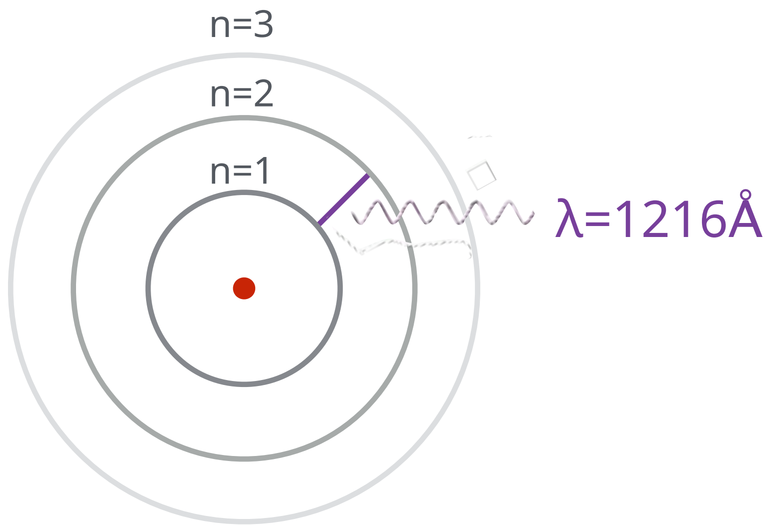


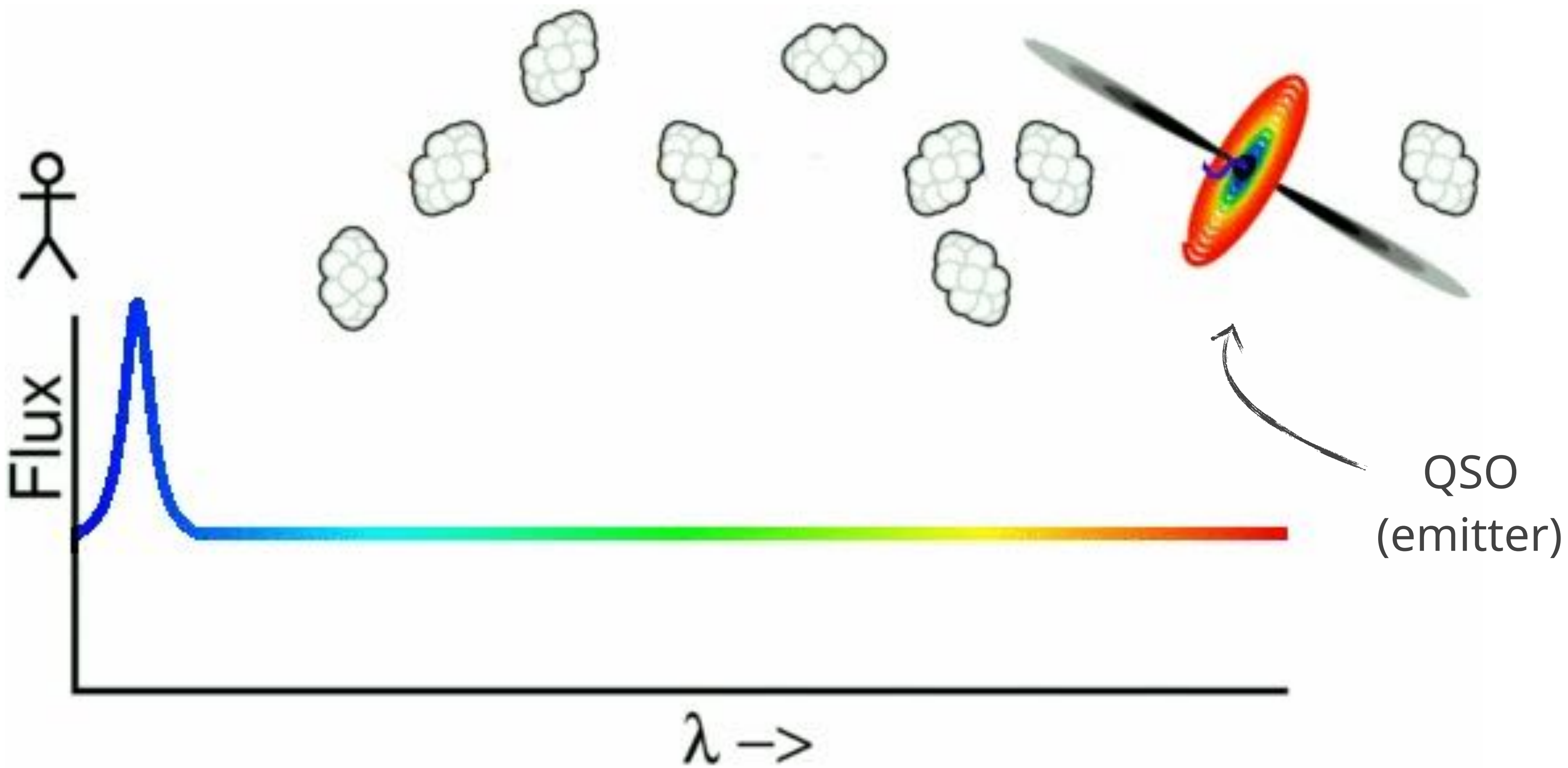
New cross-correlation : Ly-α forest × CMB lensing

Cross-correlation can show new physics too !

What's the **Lyman-α forest** ?

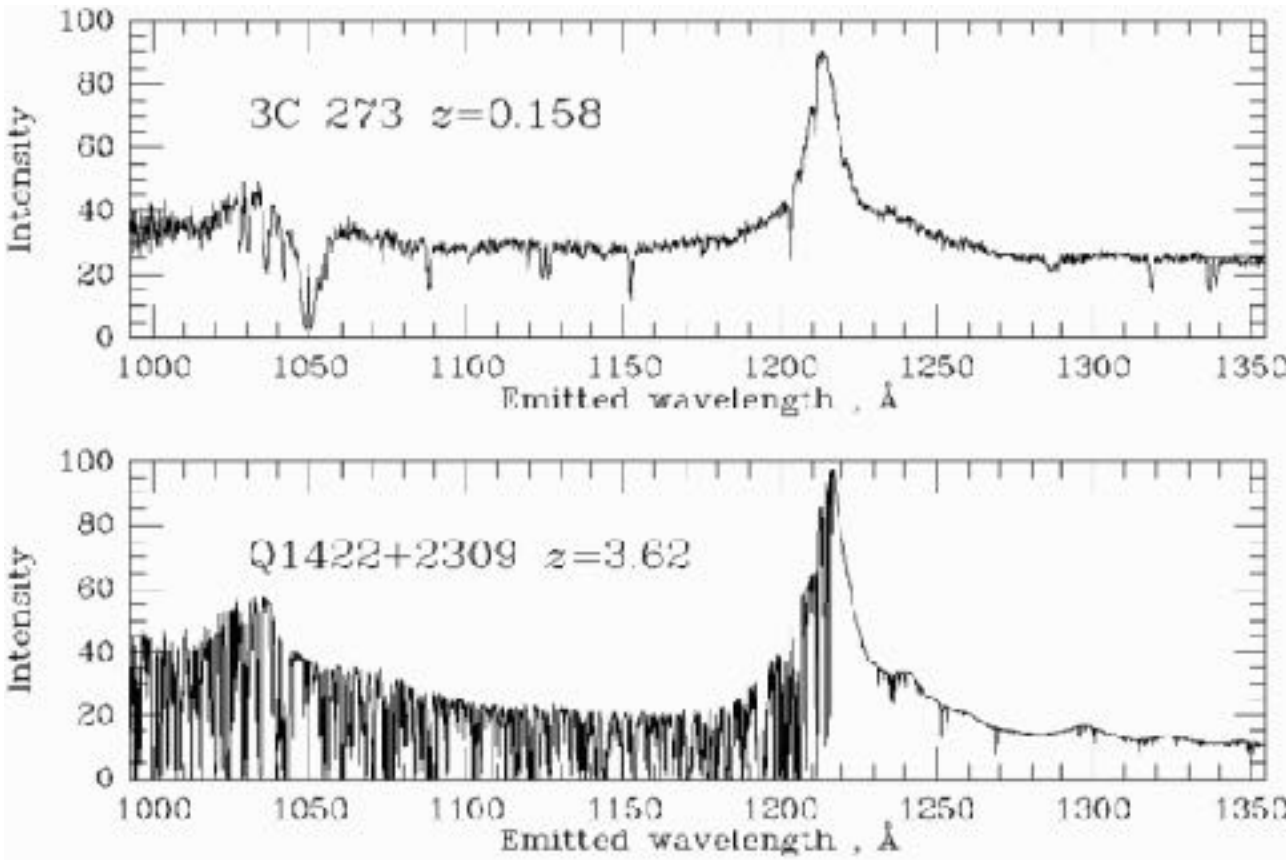
- absorption lines in quasar spectra
- Ly-α transition in neutral hydrogen n=1 to n=2
- reveals **intergalactic HI** clouds like a *core sample*

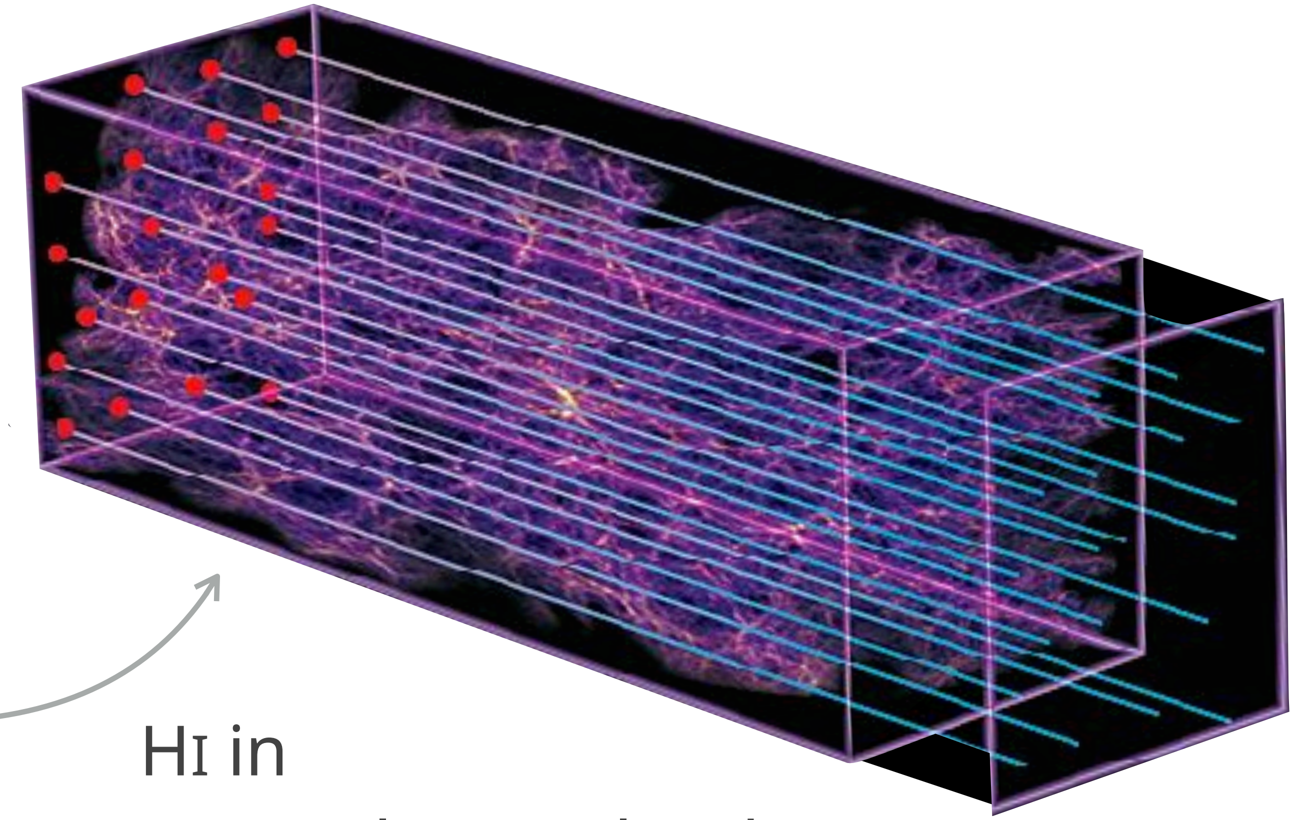




Ly-α forest × CMB lensing

Ly-α forest in quasar spectra





HI in
intergalactic "clouds"

- cross-correlation of **fluctuations in Ly-α** and **CMB lensing** *CD, Schaan+16, PRD*
- **denser regions** ($\kappa_{\mathrm{CMB}} > 0$) $\Longrightarrow$ **more fluctuations** in $P_{\text{Ly-}\alpha}(k)$
- tests our understanding of intergalactic baryonic physics

Thanks !