Long- and Short-Baseline Neutrino Oscillation Experiments

Andrzej M. Szelc
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The Plan

- The Standard Model of Particle Physics
  - *And what we know and don't know about neutrinos in it.*
- Detecting (accelerator-energy) Neutrinos
  - The special role of electron neutrinos.
- Searching for Short-Baseline oscillations
  - And why we think argon is a good idea?
- Searching for Long-Baseline oscillations with DUNE
  - Or, why put 40kT of cryogenic liquids underground.

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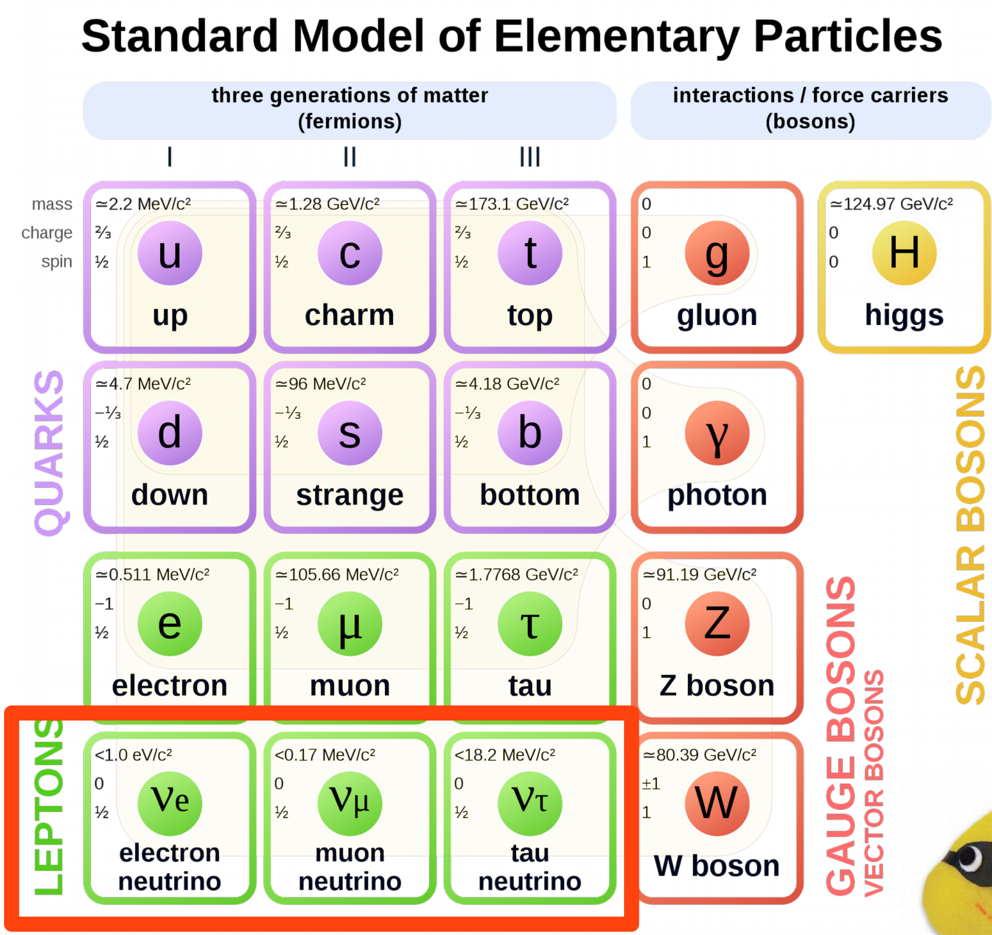
Neutrinos in the Standard Model of Particle Physics



- Neutrinos are the second most abundant particle in the Universe.
- In the original definition of the Standard Model the neutrinos were massless.
- They may hold the answer to some key questions in particle physics and cosmology. To answer them, we need to measure how they oscillate.

How the Neutrino Came to be

- W. Pauli proposes the neutrino (then called neutron) to solve the problem on non-conservation of energy in beta-decays:
- ***"I have done a terrible thing, I have postulated a particle that cannot be detected."***

$$n \to p + e^- + \bar{\nu}_e$$

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

"Dear Radioactive Ladies and Gentlemen"

Pauli feared that the neutrino would never be detected because of how weakly it should interact!

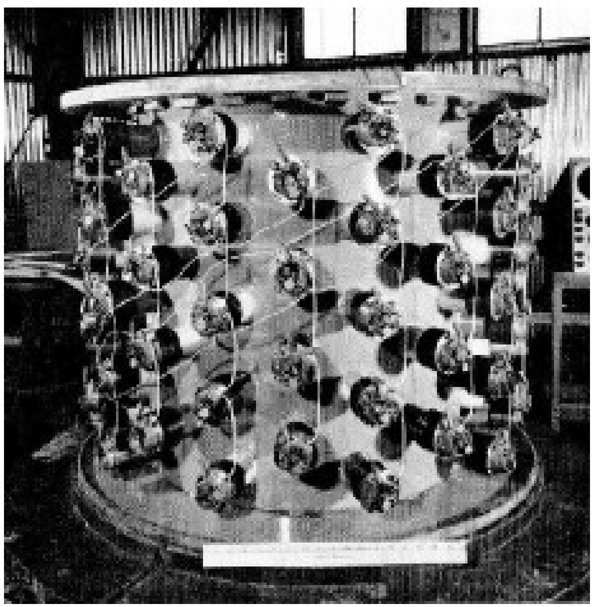
First Detection

- Fortunately, he was proven right (per theory prediction) and wrong (per experimental prediction) by Reines and Cowan in 1956.
- A clever signature: Inverse Beta Decay (IBD):

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Prompt annihilation 2x 511keV γ → Unique signature of neutrino

Delayed (5×10^{-6} s) γ capture on Cd → Unique signature of neutrino



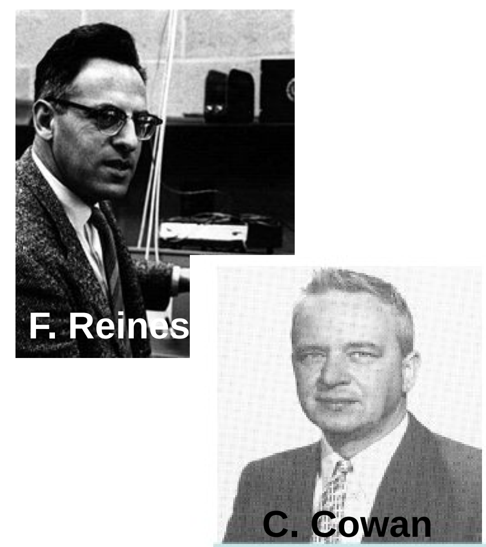
W E S T E R N   U N I O N

June 14, 1956

Dear Professor Pauli,

We are happy to inform you that we have definitely detected neutrinos. . .

Fred Reines
Clyde Cowan



Neutrino Puzzles

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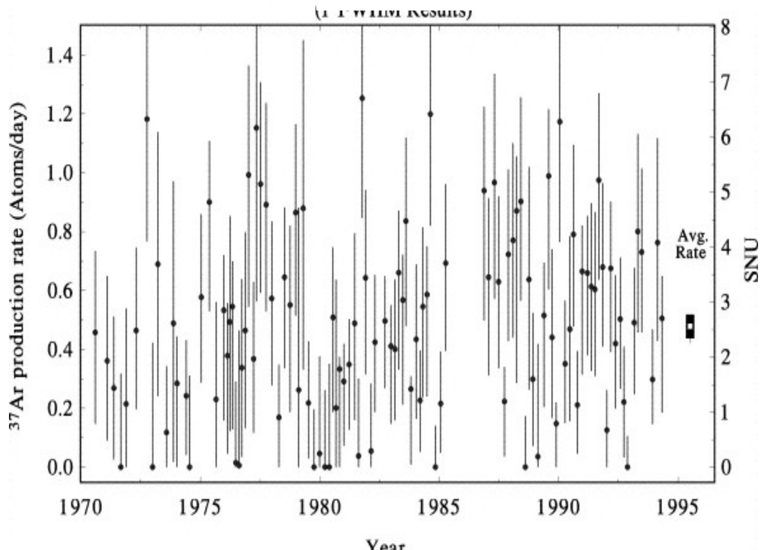
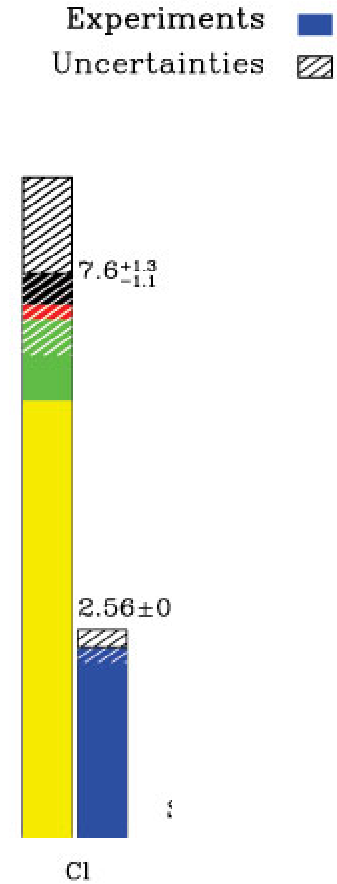
- Used neutrino capture on ^{37}Cl, which results in ^{37}Ar which is radioactive (~0.5 atoms produced/day – in 100000 gallons of cleaner fluid)
- The number of neutrinos observed was way below expectation.
- Despite many attempts nor theory nor experiment could be proven wrong.



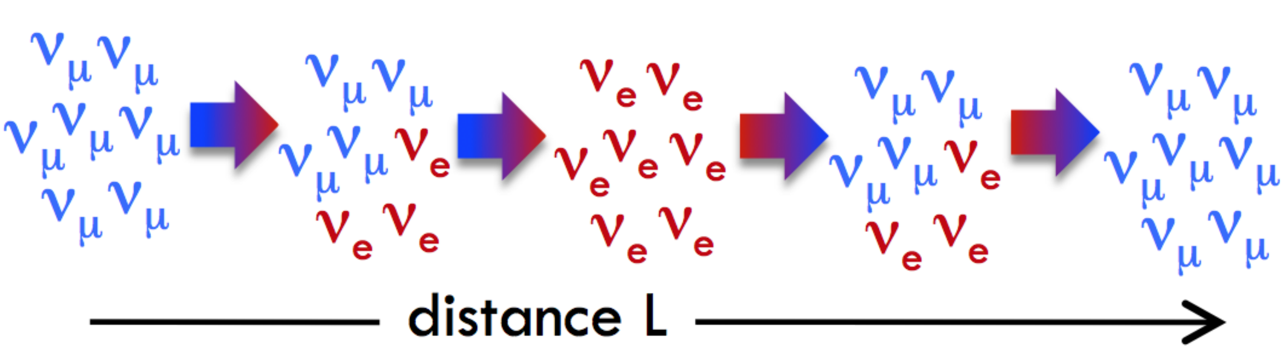
R. Davis Jr constructing his experiment in the Homestake mine



Turns out the deficit was due neutrino oscillations.

Electron-neutrinos, which the experiment detected turned into different ones.

Neutrino Oscillations

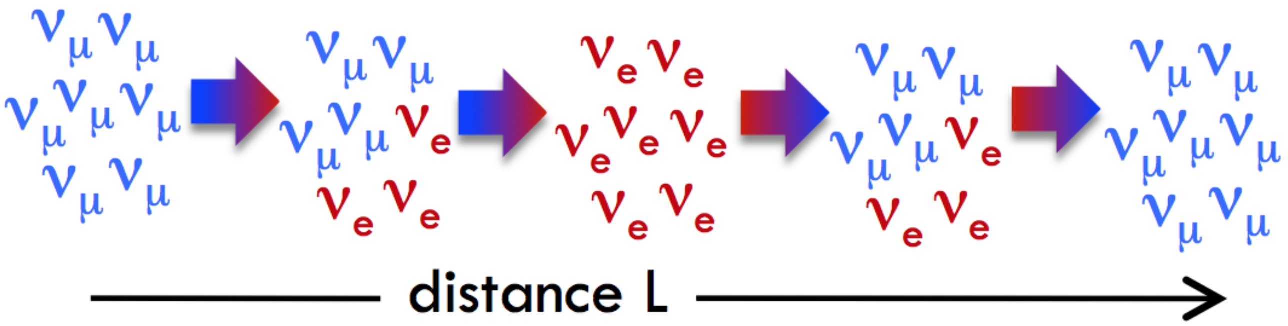


B. Pontecorvo

- We know three neutrino flavors: ν_e, ν_μ **and** ν_τ
- We know that neutrinos change into one another. They oscillate.
- That means that even if you start with only one type of neutrino, if you wait you may have all three!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Oscillations



- We usually start with one type of neutrino and measure how it changes into another.

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4[(U_{\alpha 1}U_{\beta 1}U_{\alpha 2}U_{\alpha 2})sin^2(1.27\Delta m^2_{12}\frac{L}{E}) + (U_{\alpha 1}U_{\beta 1}U_{\alpha 3}U_{\alpha 3})sin^2(1.27\Delta m^2_{13}\frac{L}{E}) + (U_{\alpha 2}U_{\beta 2}U_{\alpha 3}U_{\alpha 3})sin^2(1.27\Delta m^2_{23}\frac{L}{E})]$$

Oscillations are only possible if neutrinos have mass!

"amplitude" "frequency"

$$P(\nu_x \rightarrow \nu_y) = sin^2(2\theta)sin^2(1.27\Delta m^2 \frac{L(km)}{E(GeV)})$$

- We can do this by detecting the new neutrinos (appearance) or registering the loss of original (disappearance).
- Need to know how many neutrinos there were originally (flux or near detector).

Two flavour approximation is good enough in most cases.

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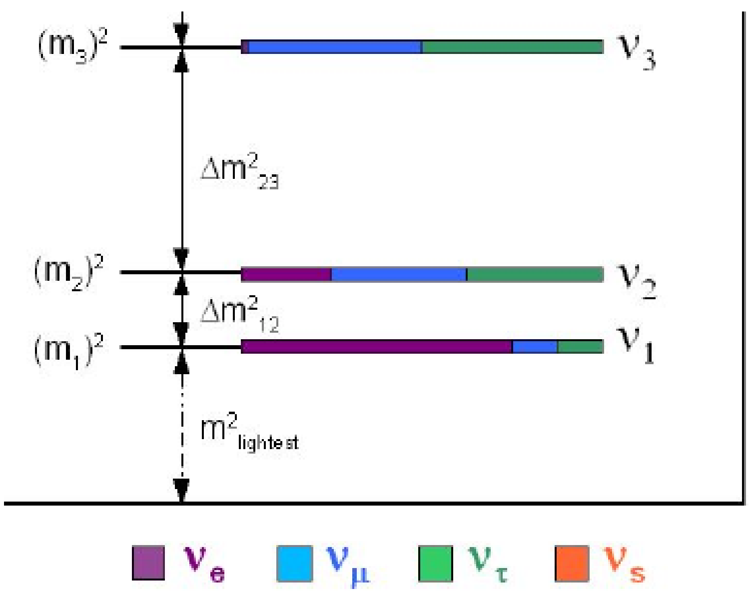
The Current State of Neutrino Knowledge

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{23: Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{13: Reactor/Interference}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{12: Solar}}$$

$\mu \Rightarrow \tau$ — $\mu \Leftrightarrow e$ — $e \Leftrightarrow \mu$

θ_{13} was first measured fairly recently.

Unknown: δ_{CP} phase and the mass ordering,



"Known" neutrino physics

Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.56 ± 0.19
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.55 ± 0.04
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	2.49 ± 0.04
$\theta_{12}/^\circ$	$34.5^{+1.1}_{-1.0}$
$\theta_{13}/^\circ$	$8.44^{+0.18}_{-0.15}$
$\delta/^\circ$	252^{+56}_{-36}
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$
$\theta_{23}/^\circ$	41.0 ± 1.1
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$
$\theta_{23}/^\circ$	50.5 ± 1.0

Salas, Forero, Ternes, Tortola, Valle: 2017

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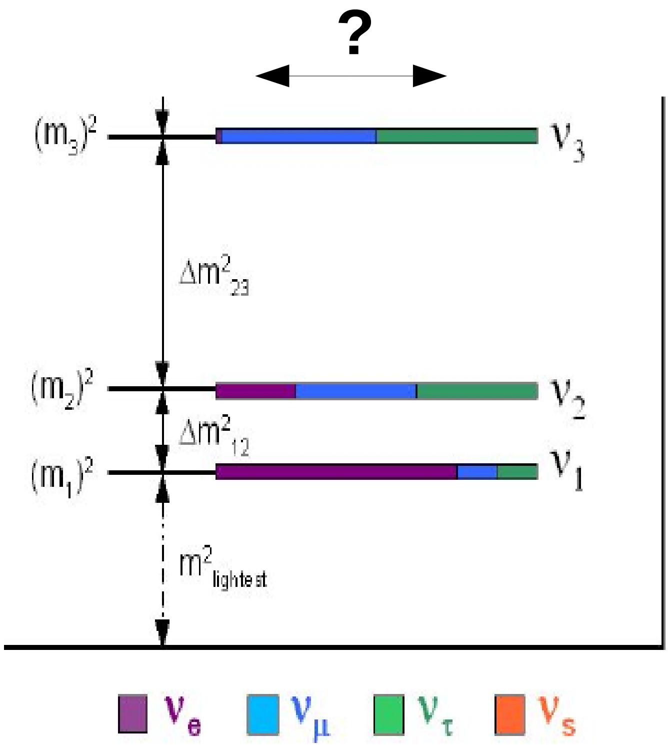
Big Questions in Neutrino Physics

- The questions below, are what is currently driving the field of experimental neutrino physics

- ***how much do neutrinos weigh?*** - ***what is the nature of the ν?***	β decay and 0νββ decay
- ***which neutrino is the heaviest and which is the lightest (MH)?*** - ***do neutrinos violate CP?***	long-baseline neutrinos
- ***is our picture correct?*** - ***are there more than 3 kinds of neutrinos?***	short-baseline neutrinos

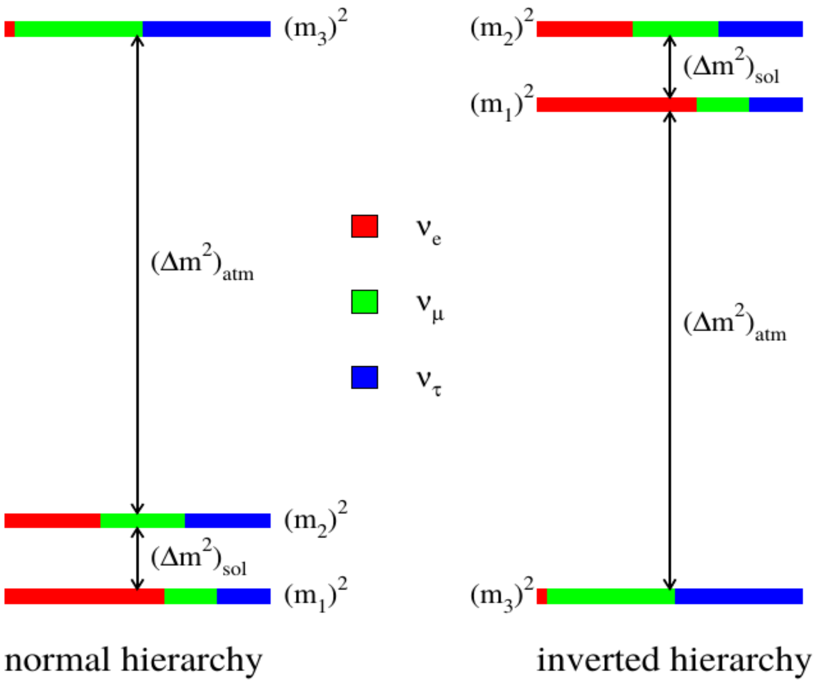
Is θ_{23} maximal?

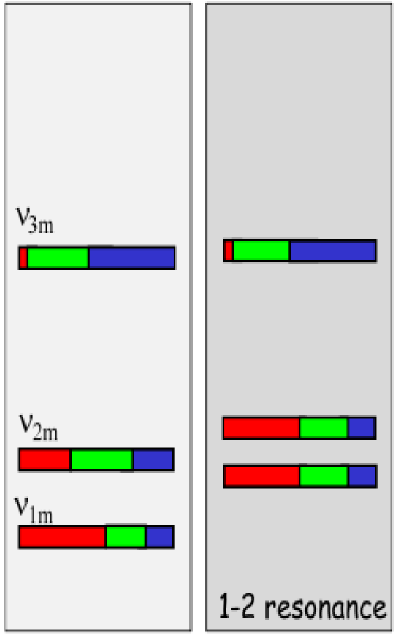
- Is mixing in the atmospheric sector maximal or a bit less?
- If so, is ν_3 more ν_μ or ν_τ? (in which octant?)
- If not maximal, this will affect our measurements of δ_{CP} and mass ordering.
- Measure e.g. through ν_μ disappearance.



Neutrino Mass Ordering

- We know the sign of Δm^2_{12} from matter effects in the Sun.
- Not in the case of Δm^2_{23} yet. Can be “normal” or “inverted”.
- Measurement through $\nu_\mu \rightarrow \nu_e$ using matter effects.

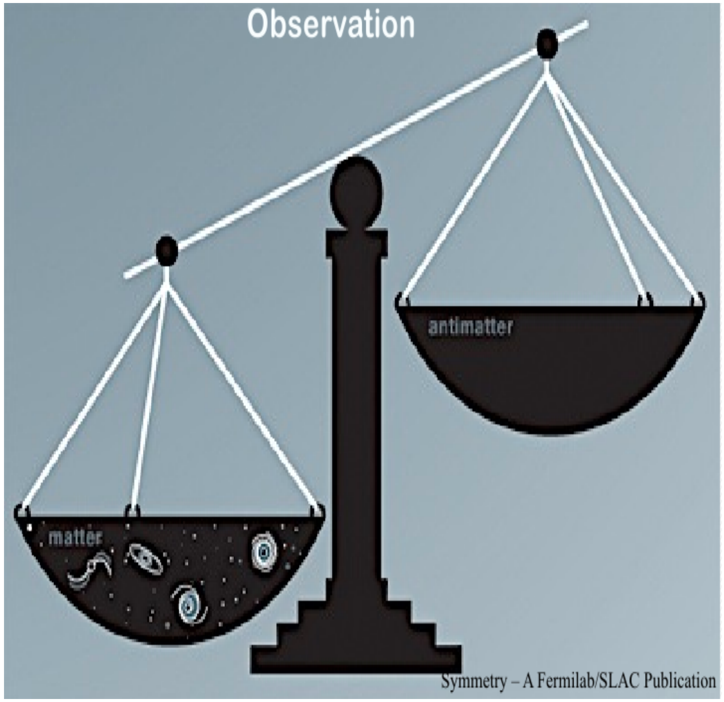




A. Smirnov

Matter Dominance in the Universe

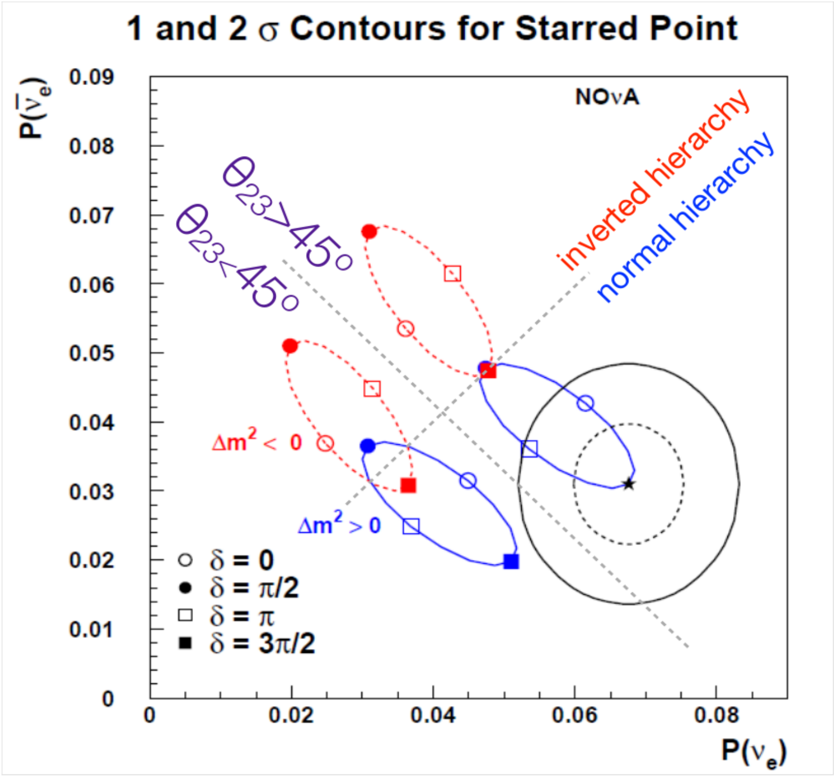
- The Universe is surprisingly asymmetric – we see “matter” and almost no “anti-matter”.
- Need an asymmetry of 1 in 10^{10} to generate in Cosmology.
- Naively, particles need to behave differently than anti-particles (we call this Charge-Parity violation (CPV)).
- CPV observed in the quark sector, but nowhere near enough.
- Lepton sector one of the few places left, where it could be hiding.



- Measurement through difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

CP-violation vs MH vs θ_{23}

- Interplay (degeneracy) between these three measurements.
- There are different strategies to avoid it.
  - Set up experiment to not be sensitive to one or more effects
  - Control all of them
  - Wait for someone else to measure one of them.



M. Messier

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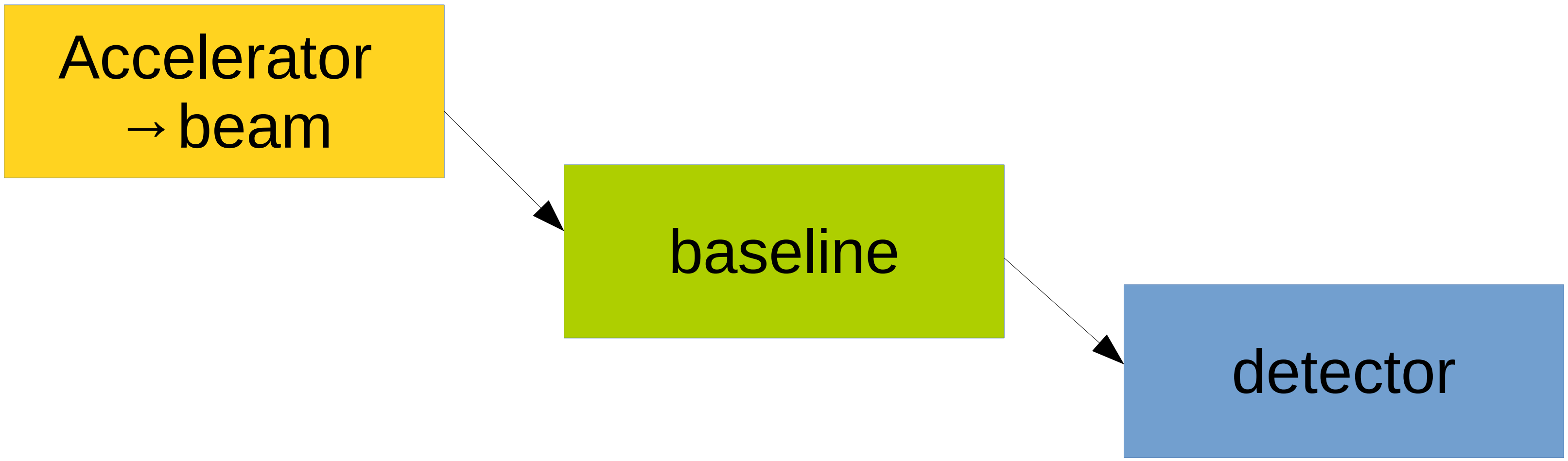
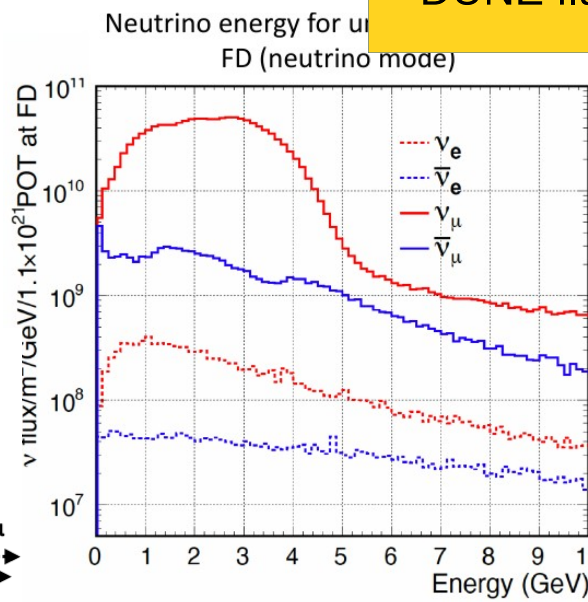
What makes up an accelerator oscillation experiment?



- To perform precision measurements, ideally you'd like to:
  - control L/E, energy,
  - backgrounds,
  - flux,
  - have lots of events in both appearance and disappearance modes,
  - a wide energy range to see a couple of maxima.

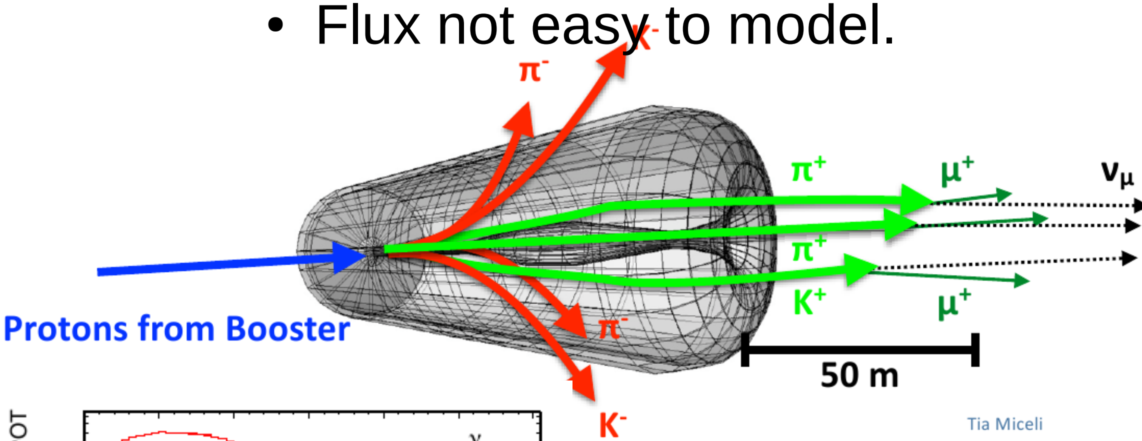
Neutrino Beams

DUNE flux

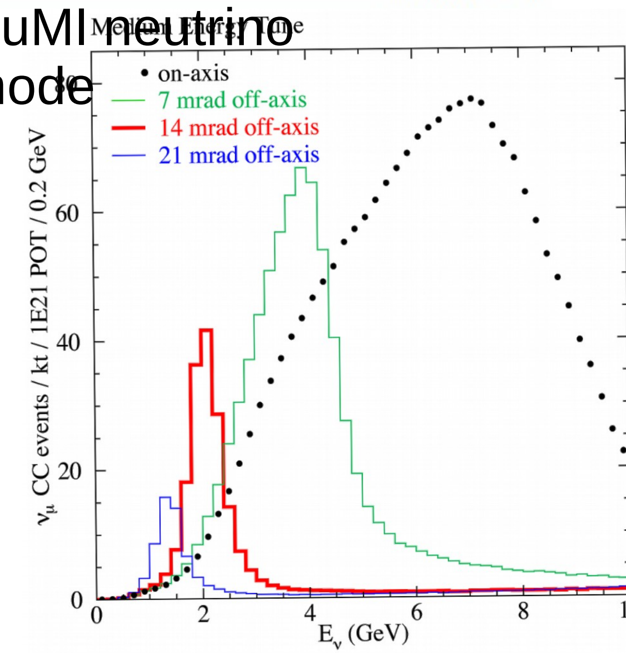


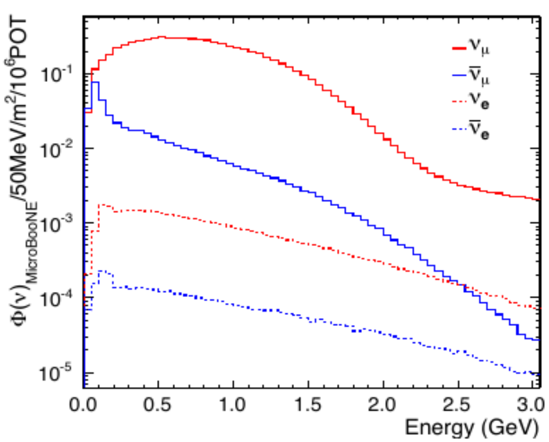
- Beam of protons
- Target
- Focusing horn (magnetic field)
- Decay pipe

• Flux not easy to model.



NuMI neutrino mode





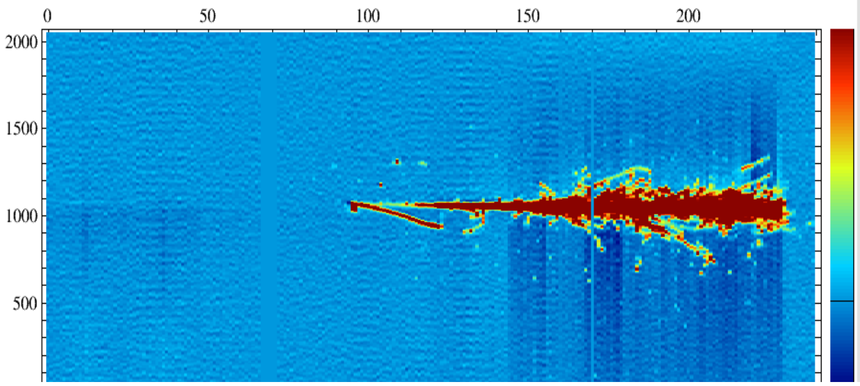
at MicroBooNE

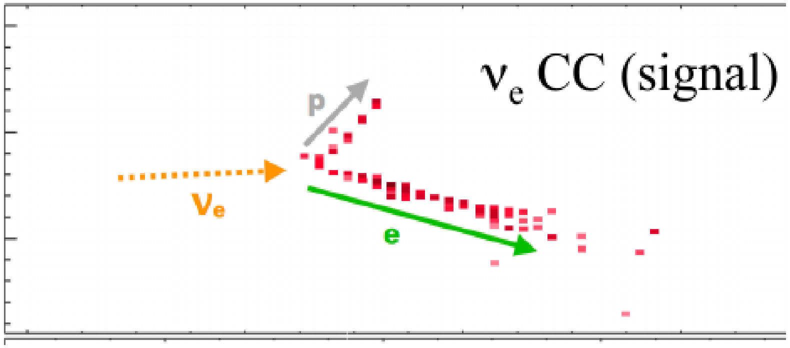
Accelerator beams are mostly composed of ν_μ (or anti-)

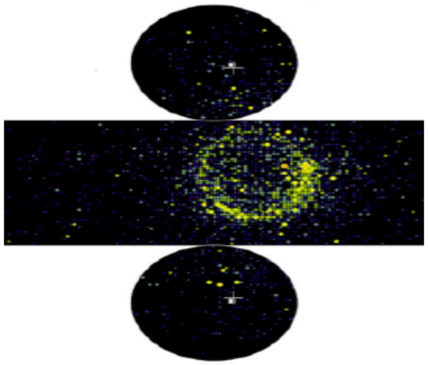
A near-dector is desirable

Electron Neutrino Appearance

- Electron neutrino appearance amplitude happens to depend on $\theta_{13}, \theta_{23}, \delta_{CP}$ and matter effects.
- Selecting these events efficiently and removing EM backgrounds, e.g. from π^0 decays is key.
- Again, different strategies.

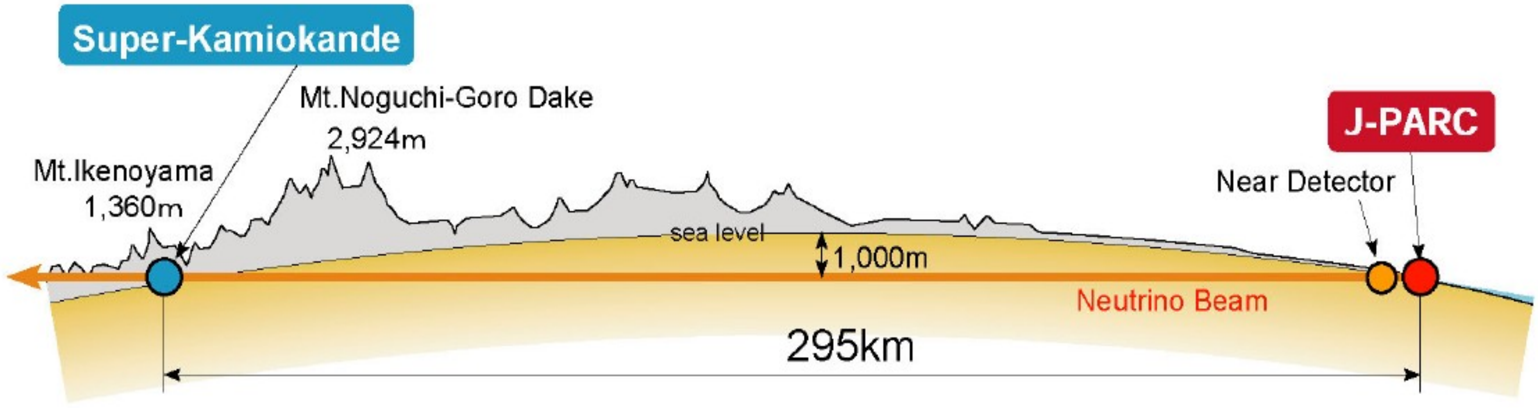




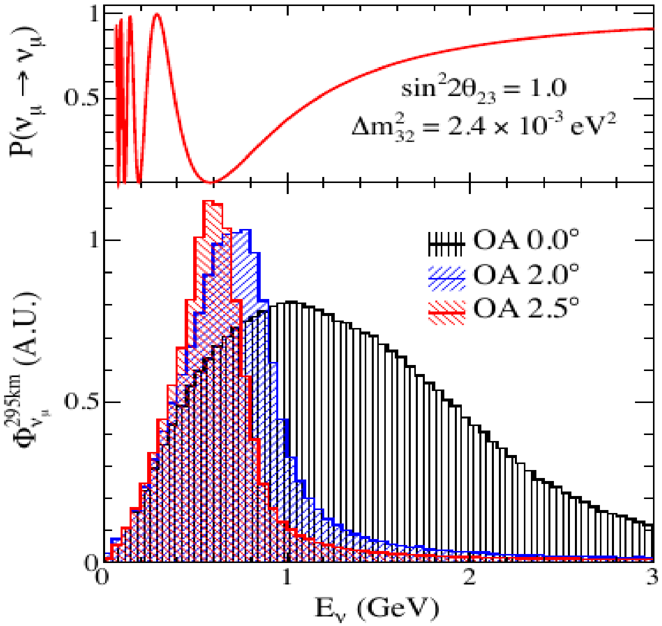


ν_e CCQE

T2K



- Off-axis beam energy centered around 600 MeV.



T2K ν_μ + $\bar{\nu}_\mu$ disappearance

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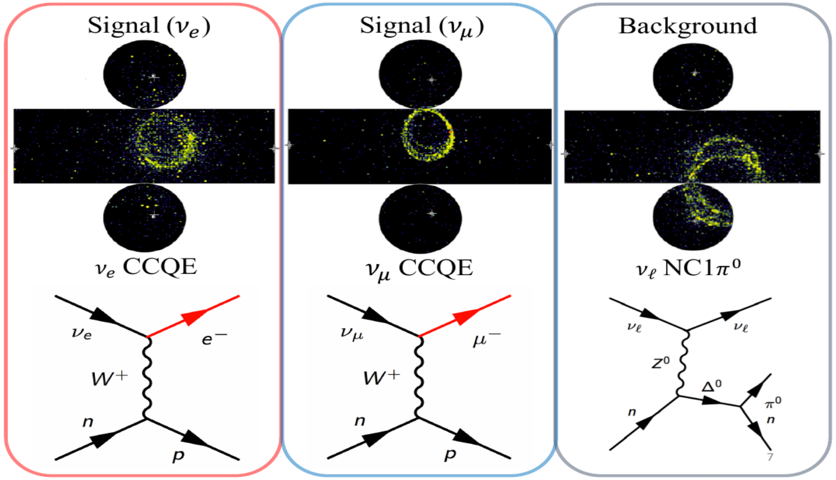
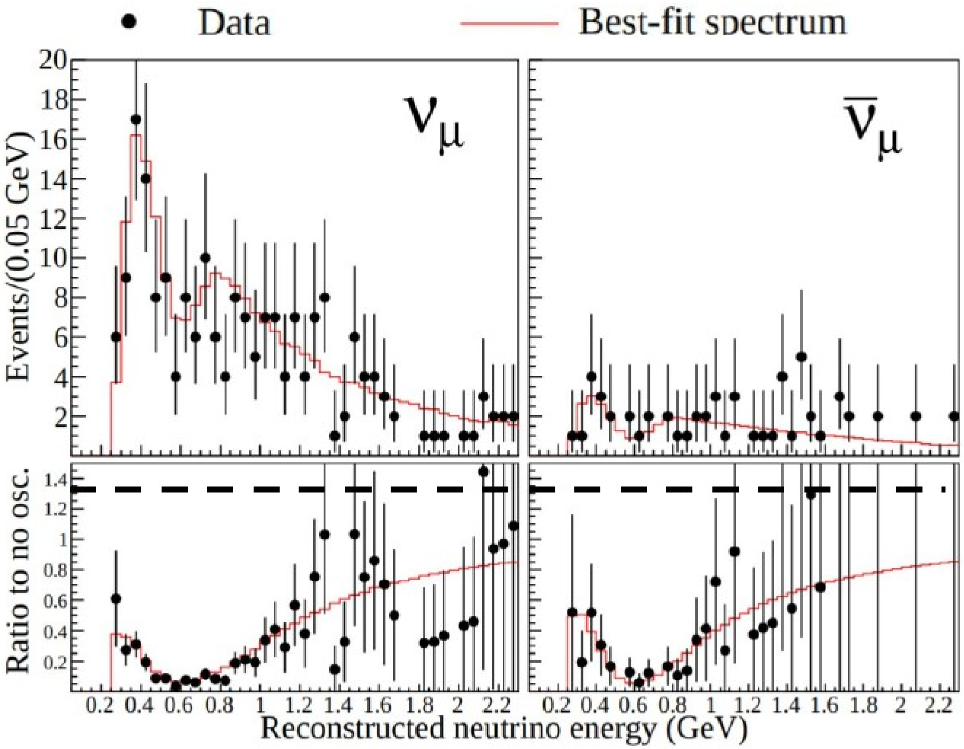
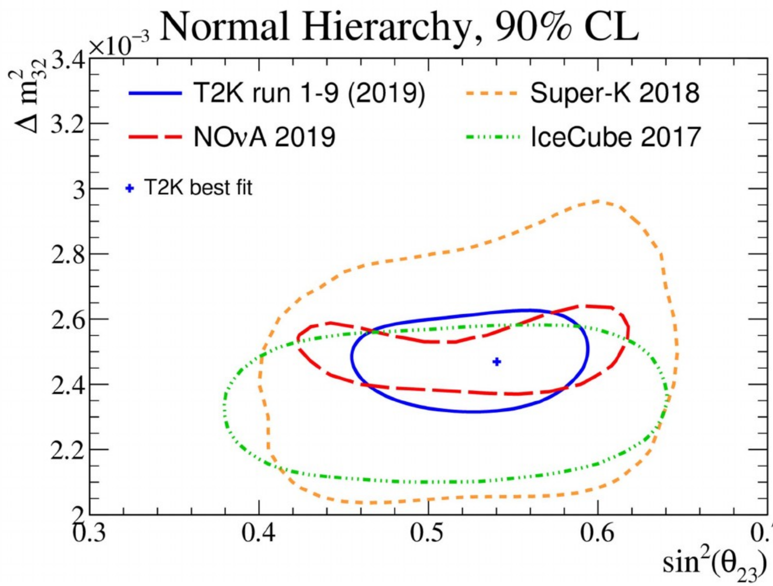
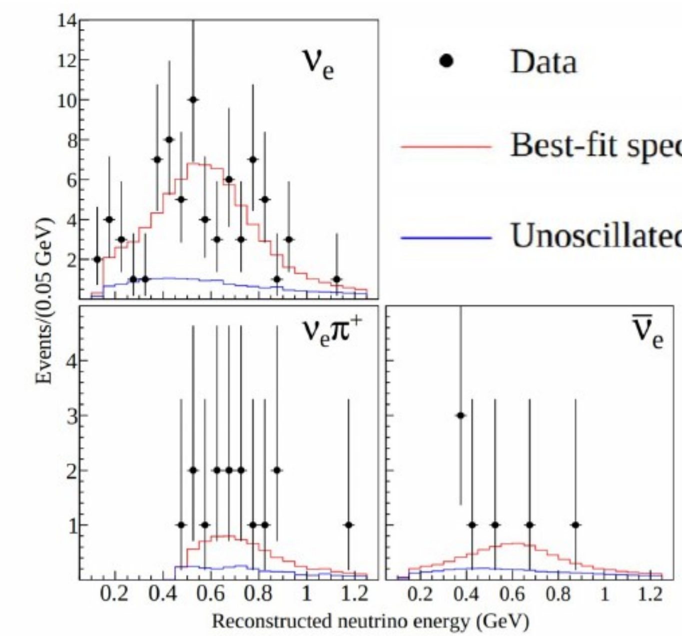


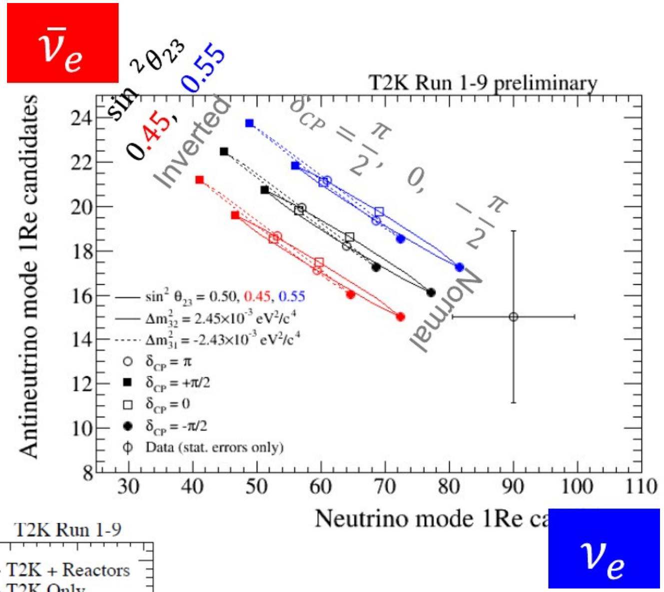


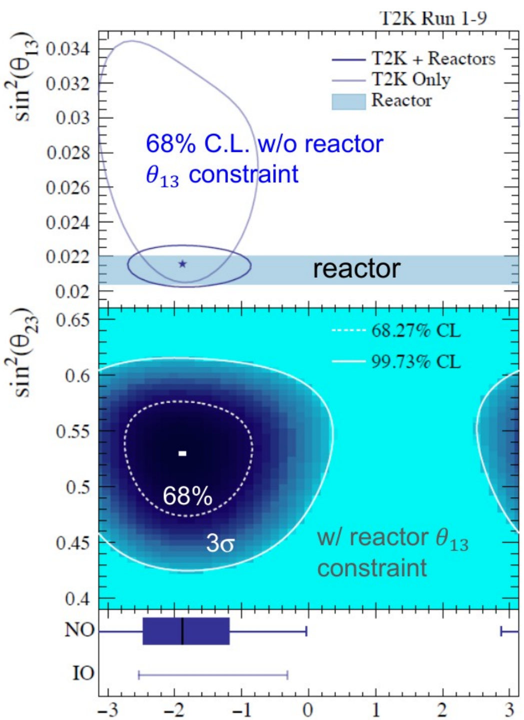


L. Pickering@NNN

T2K $\nu_e + \bar{\nu}_e$ appearance



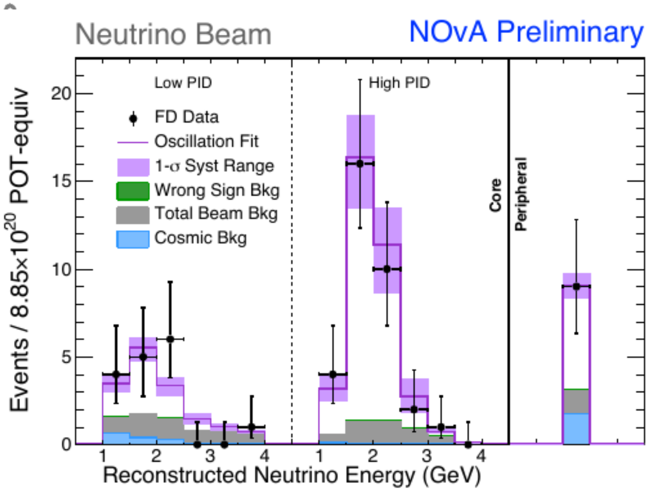




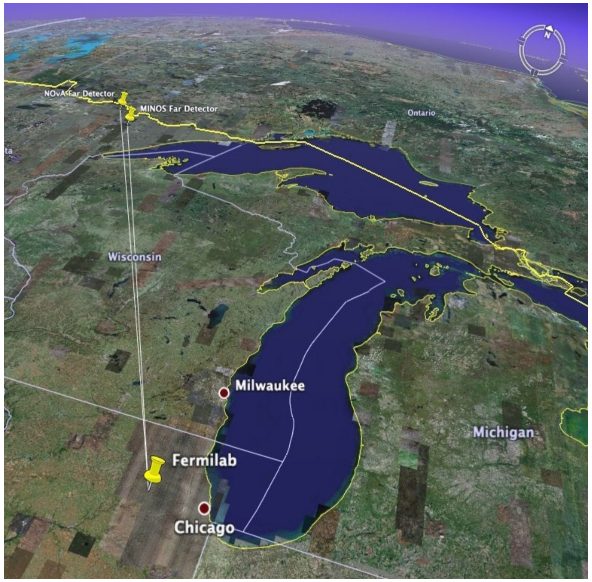
- More neutrinos than expected and less anti-neutrinos.
- Beginning to exclude regions of of CP violation (particularly in IO).

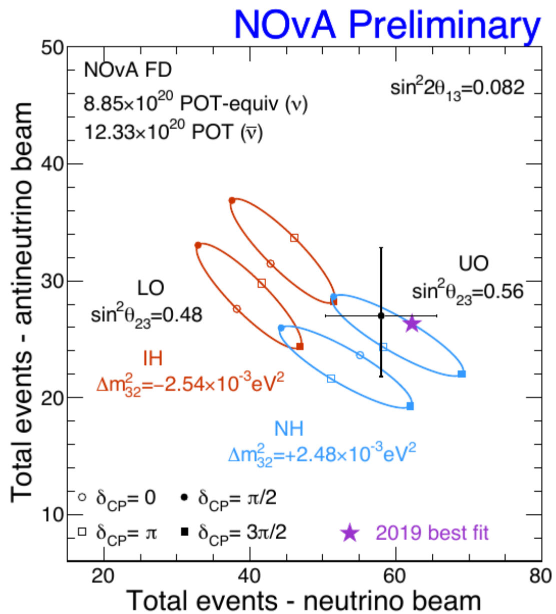
NOvA experiment at Fermilab working on similar measurements

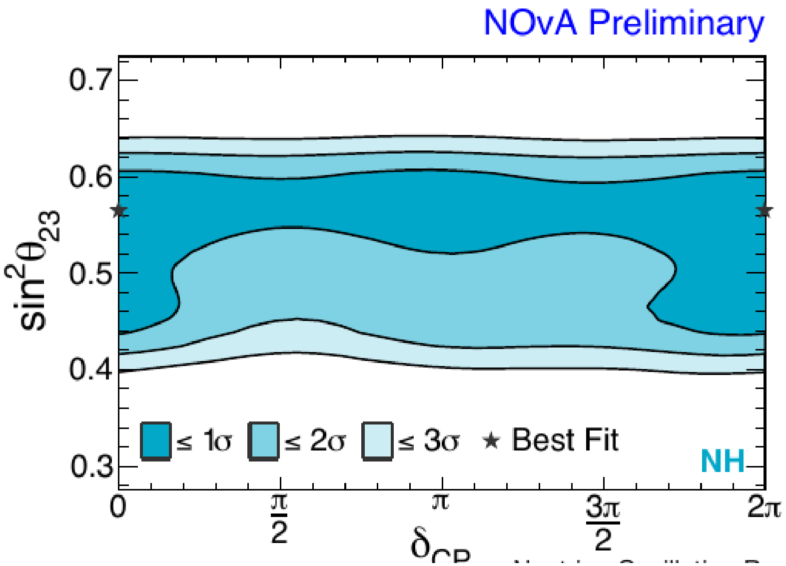
NOvA



- 810 km baseline.
- Functionally identical near and far detectors.
- Off-axis beam with energy centered aro 2GeV.







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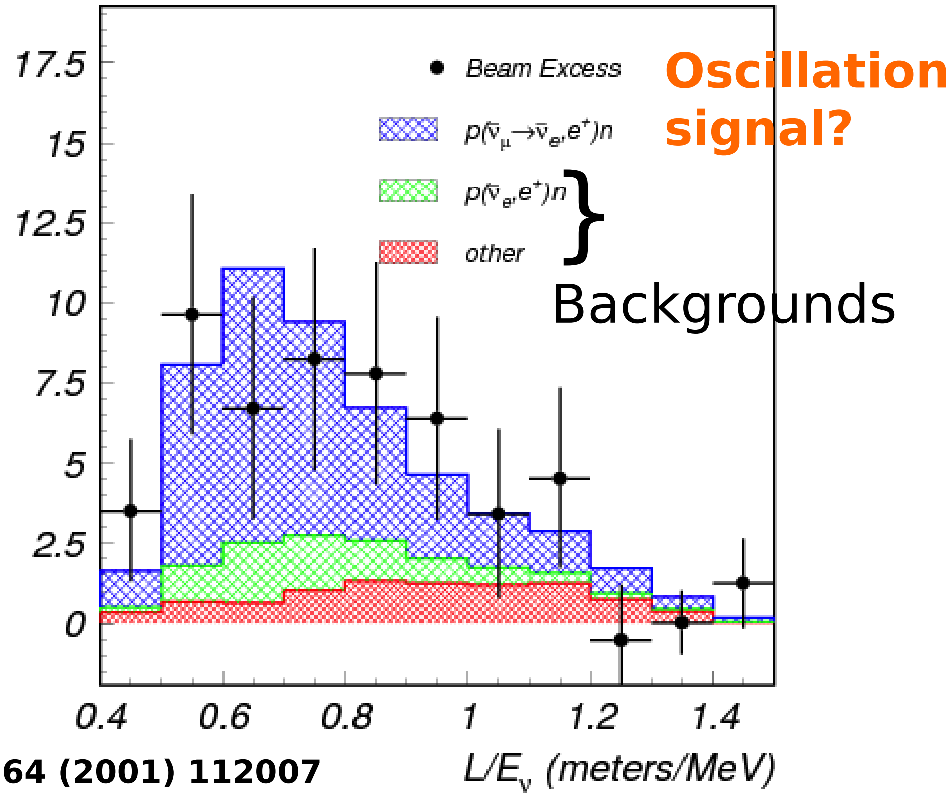
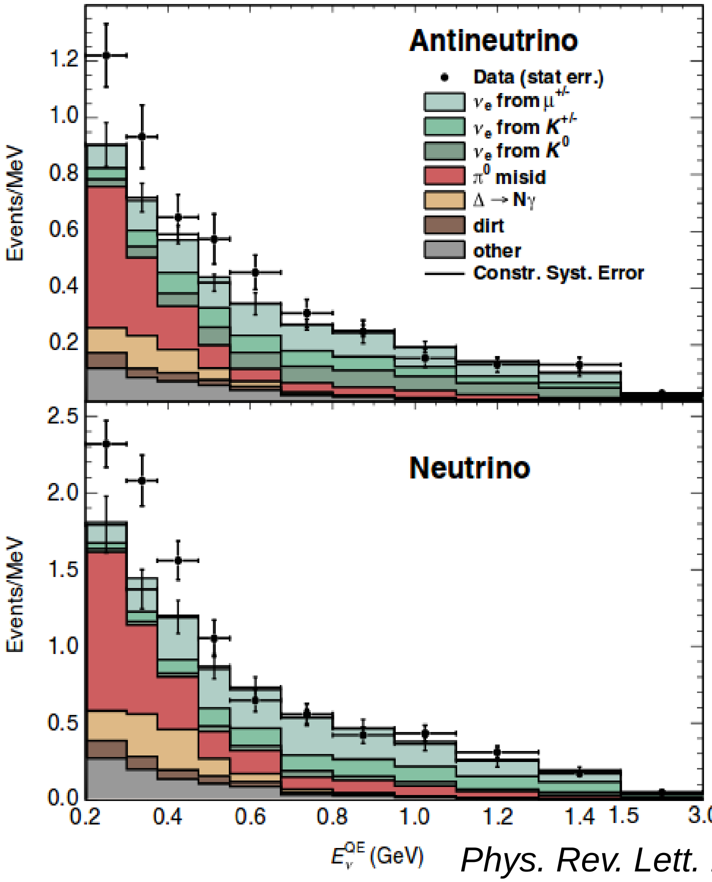
Accelerator Anomalies



PRD 64 (2001) 112007



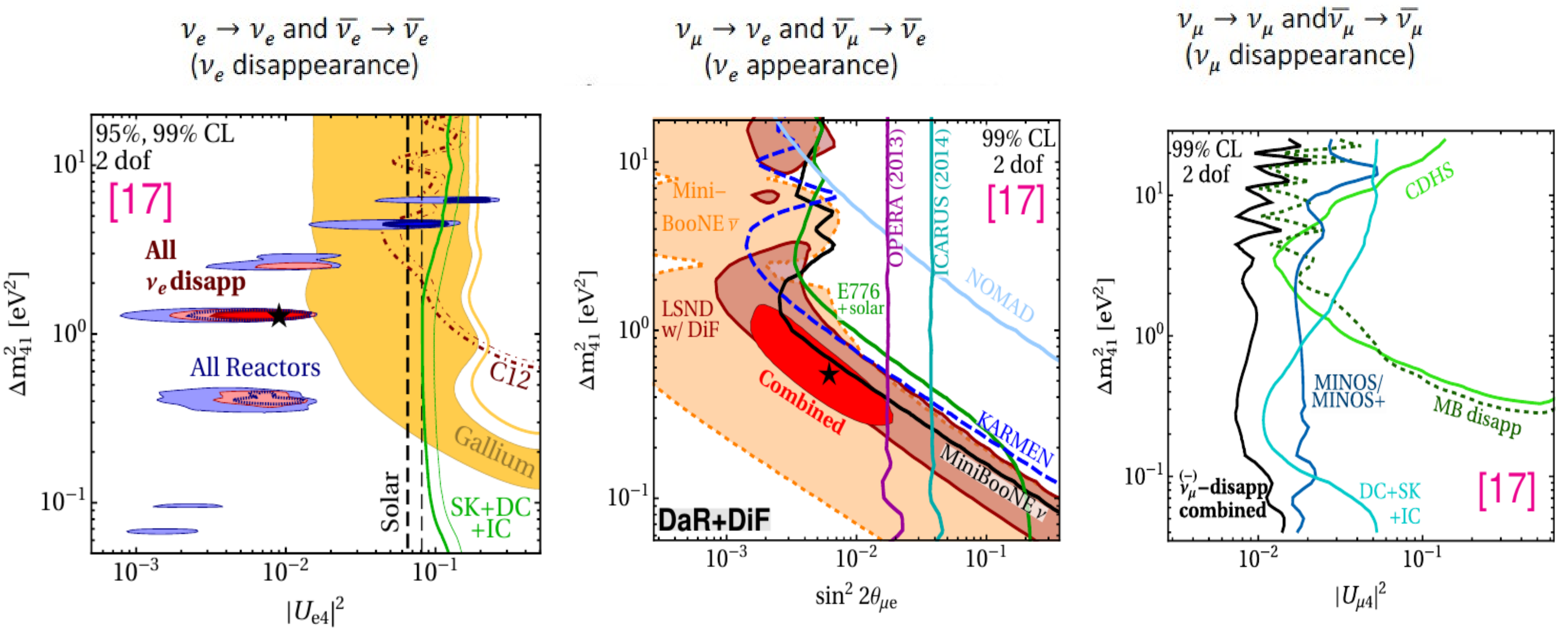
Phys. Rev. Lett. 110, 161801 (2013)

Two neutrino experiments: LSND and MiniBooNE observed signals compatible with oscillations with $\Delta m^2 \simeq 1$ eV^2

~Compatible hints from reactor experiments, and radioactive source measurements.

Global Fits

Dentler, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661.



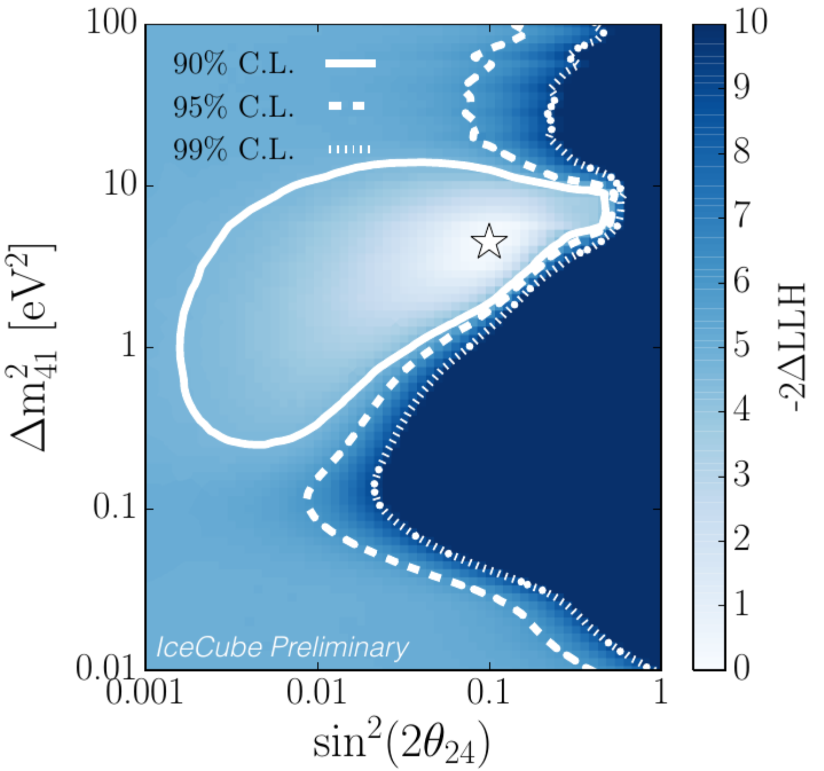
Tension with experiments that observe no signal, especially recent measurements by **IceCube and MINOS+** leads to significant constraints on possible sterile neutrino parameters. But…

Recent IceCube result

Best fit location (☆) found at:

$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08}\,\mathrm{eV}^2$
$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$

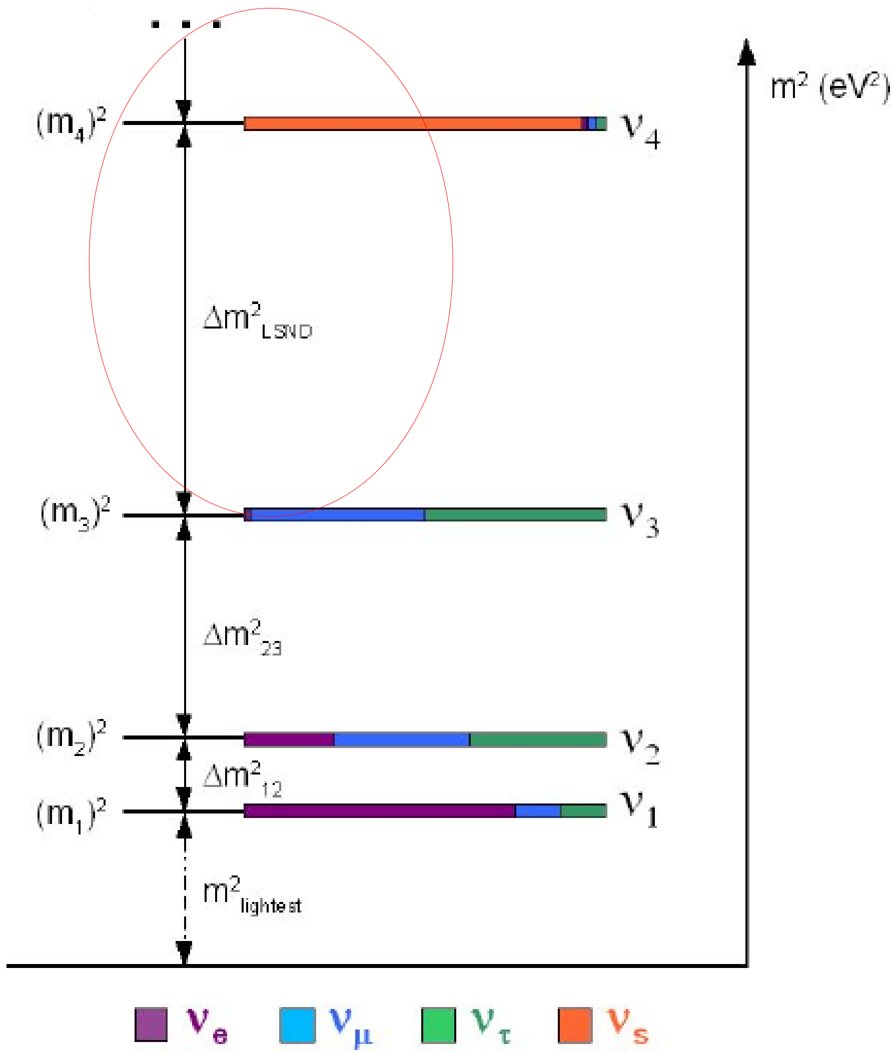
Consistent with Null hypothesis with a **p-value of 8%**



Closed 90% CL contour, shown relative to the best fit location.

- Shown by S. Axani in December at TeVPA.
- First non-exclusion in muon-disappearance!

Why is this a problem/opportunity?



If we are indeed seeing oscillations with $\Delta m^2 \sim 1eV^2$

Then this cannot fit in with the previous oscillation measurements - need a new neutrino state.

The new neutrino state must be sterile.

Clear Sign of New Physics Beyond the Standard Model if found.

Need precision detectors for the definitive search.

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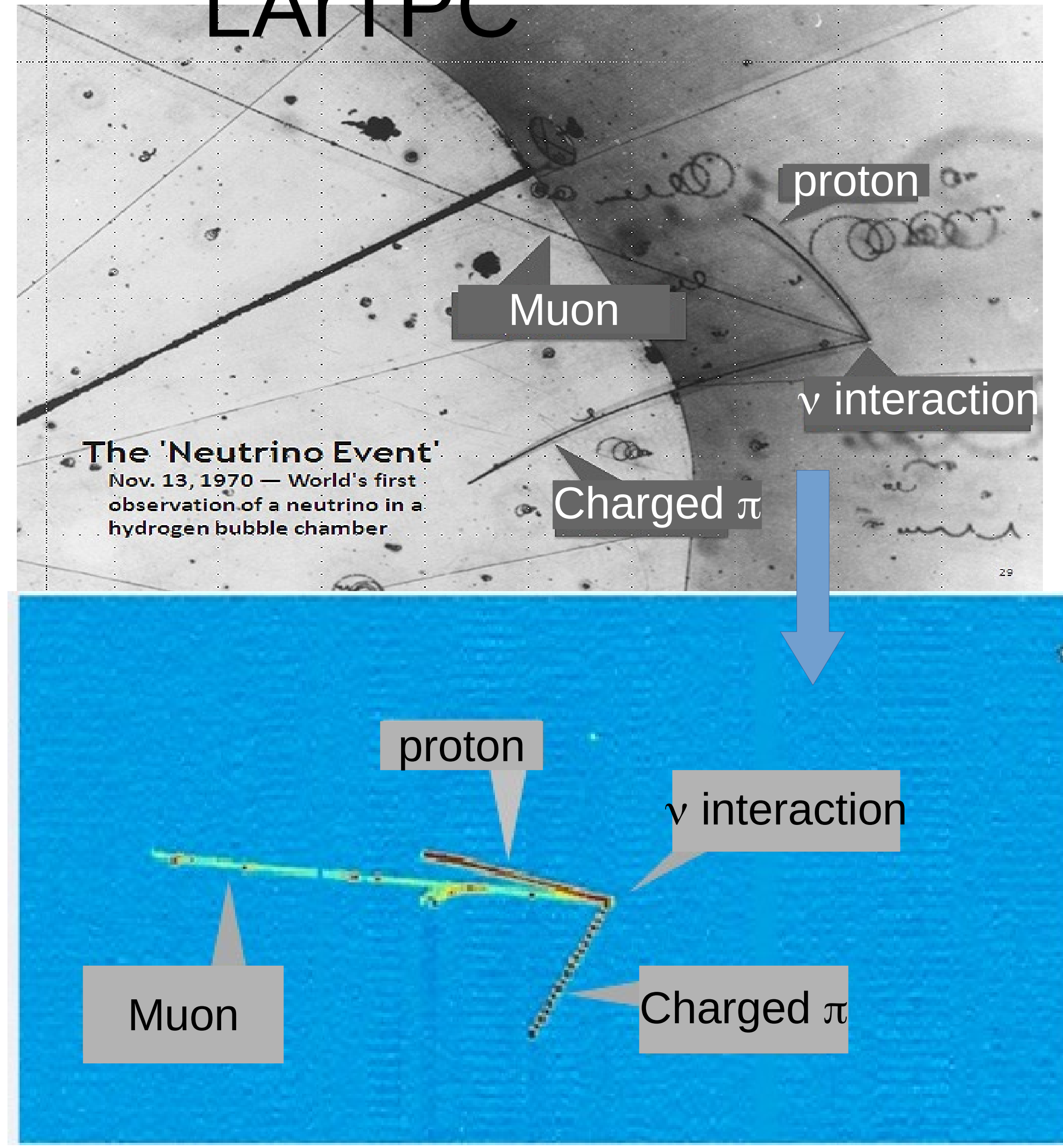
Liquid Argon

- Noble liquids are dense, so they make a good target for neutrinos.
- Chemically inert, can make detectors large.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).
- LArTPC are the way to use it.

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation λ [nm]	80	78	128	150	175	

Detecting neutrinos in a LArTPC

- The LArTPC and its bubble chamber-like data gives us excellent tools for precision neutrino measurements.



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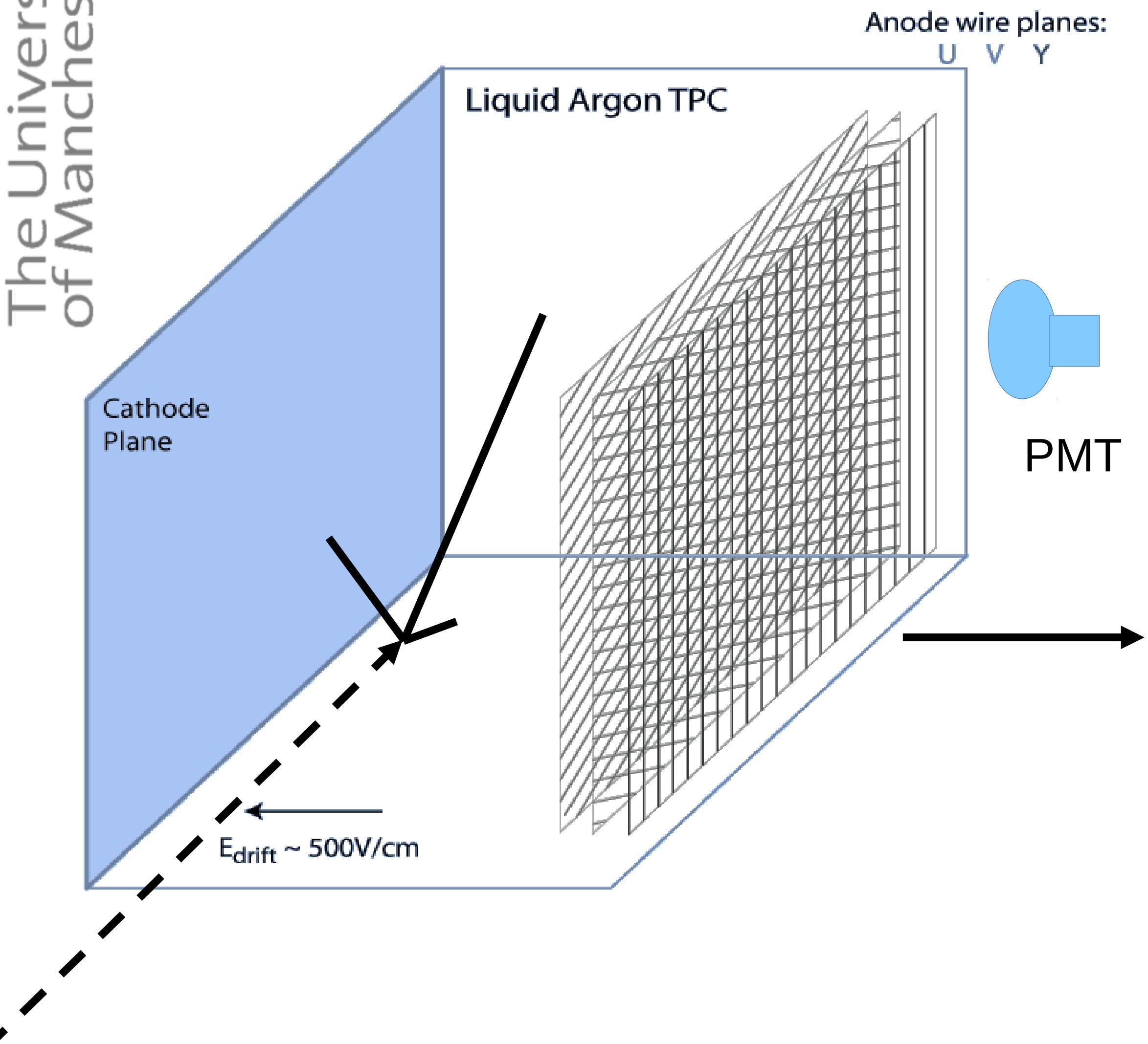
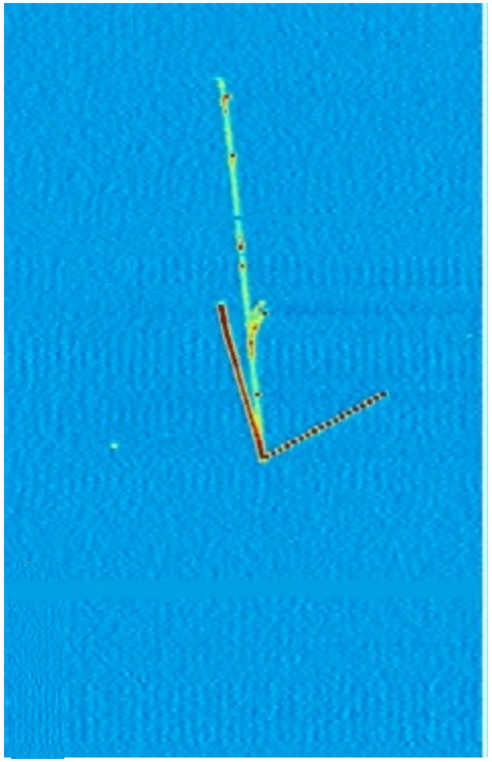
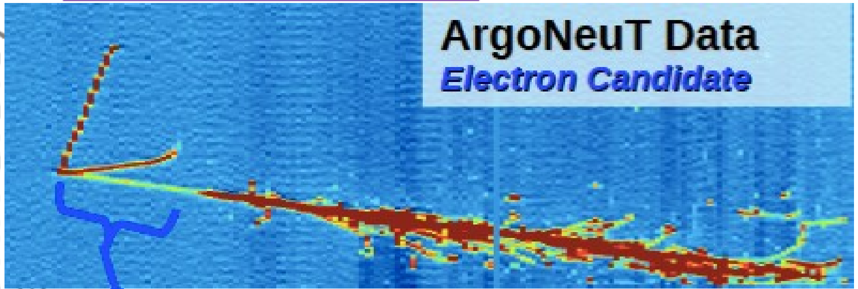
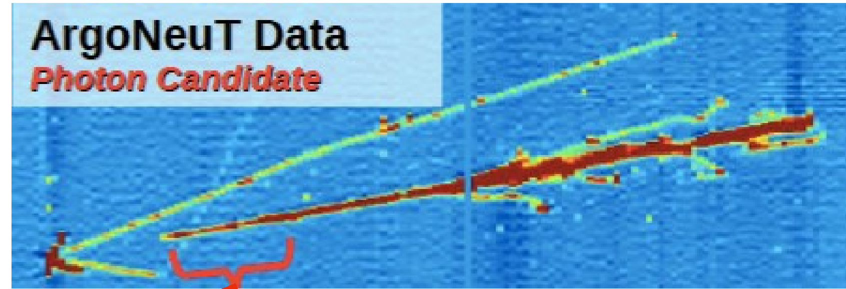
LArTPC Operation

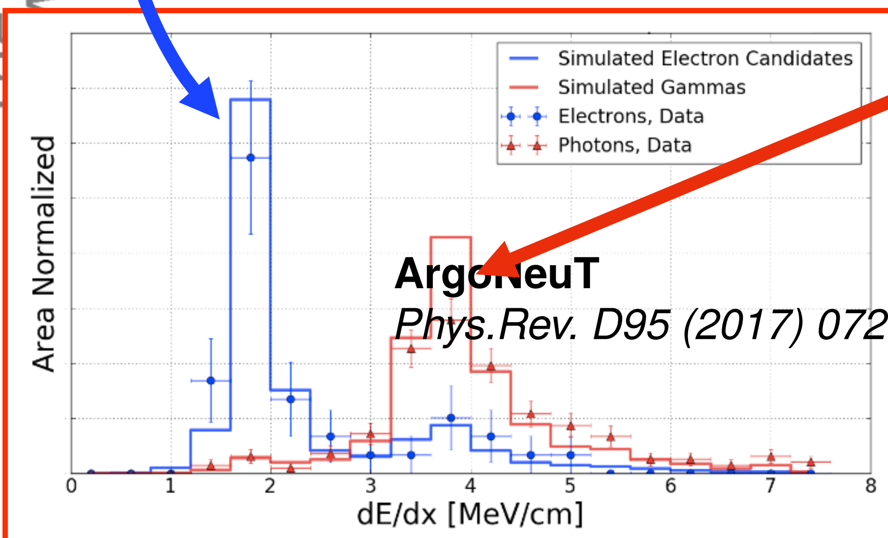




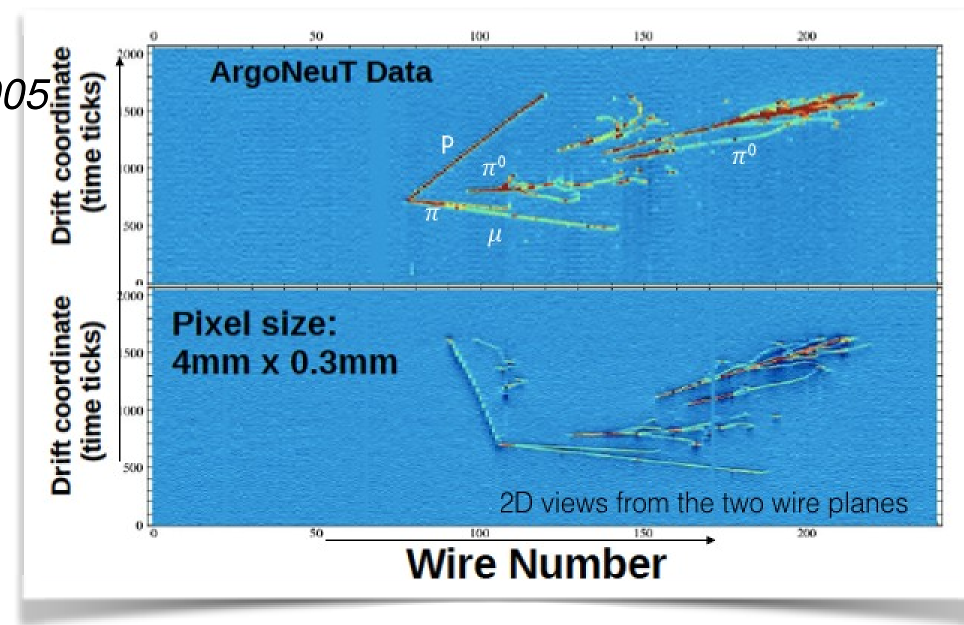
Electron-γ separation in LAr





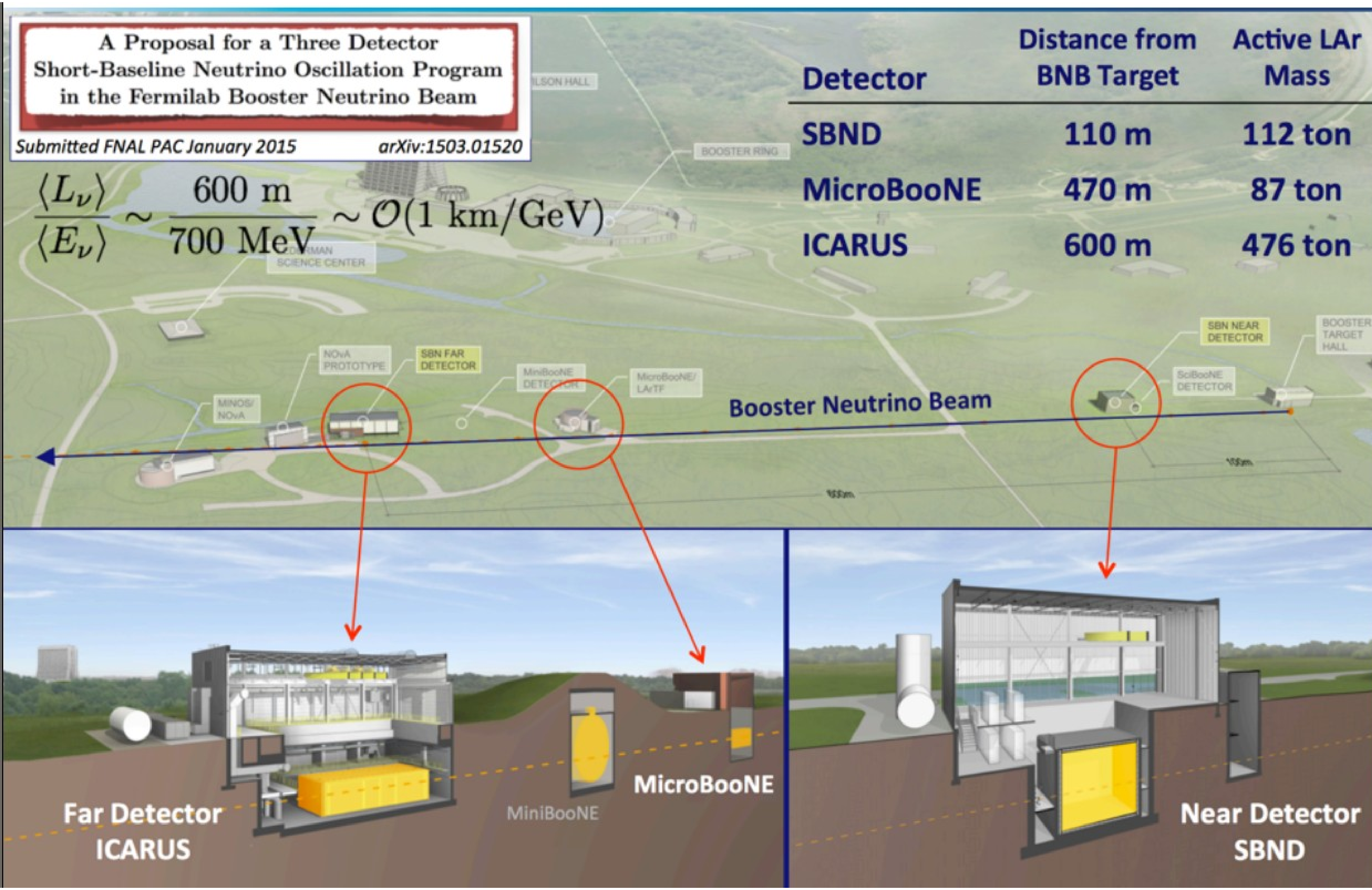


Double handle: topology and dE/dx



The LArTPC is an excellent tool for electron/photon separation

SBN Programme



$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600 \text{ m}}{700 \text{ MeV}} \sim \mathcal{O}(1 \text{ km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

Searching for Oscillations

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

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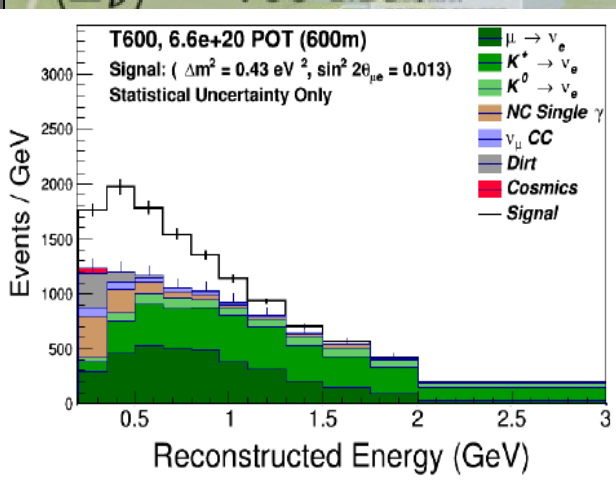

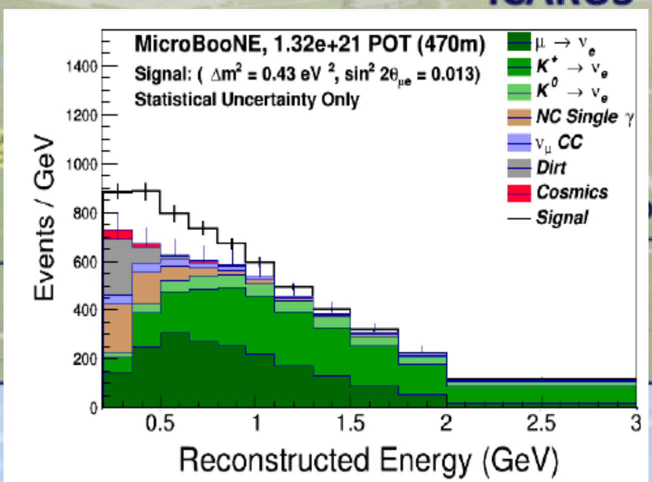

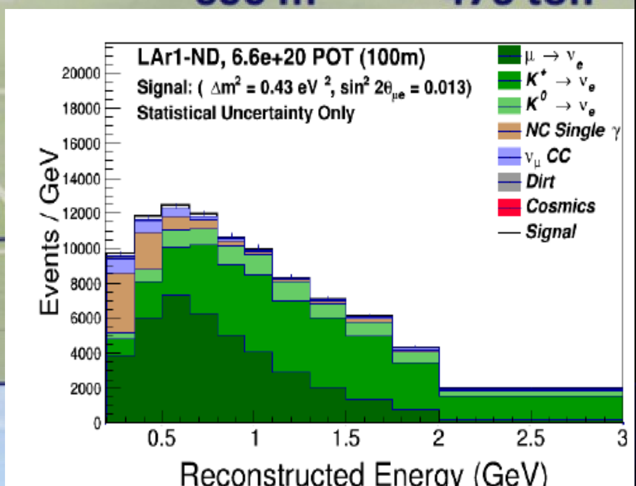

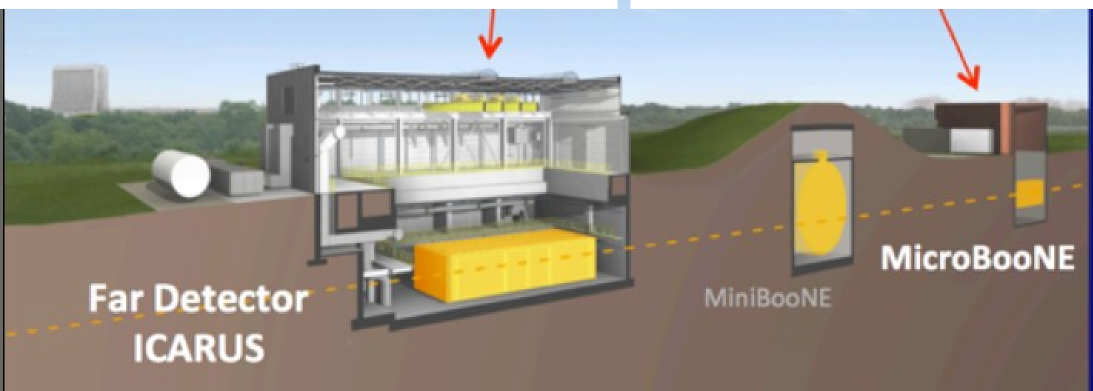

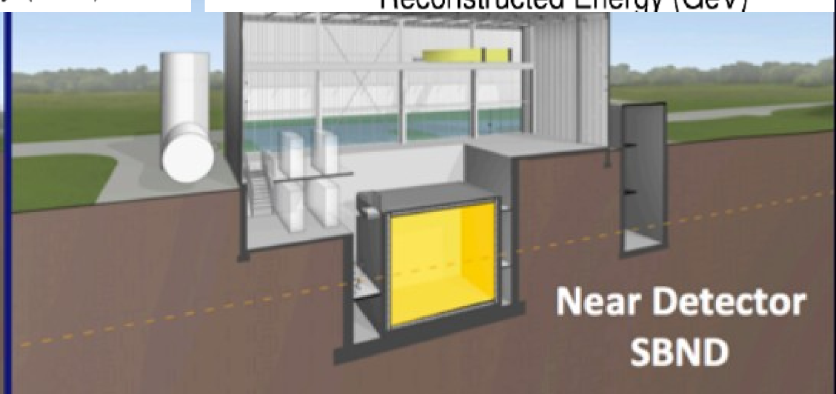

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MicroBooNE

The University of Manchester

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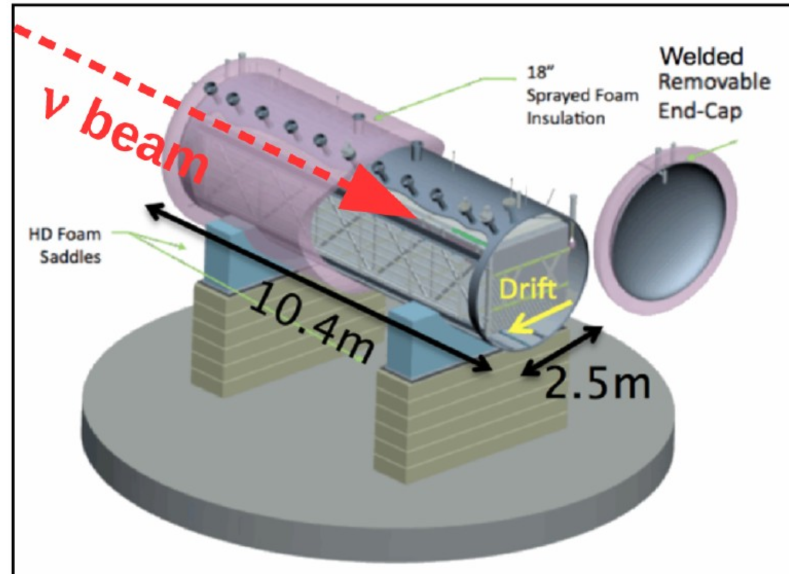
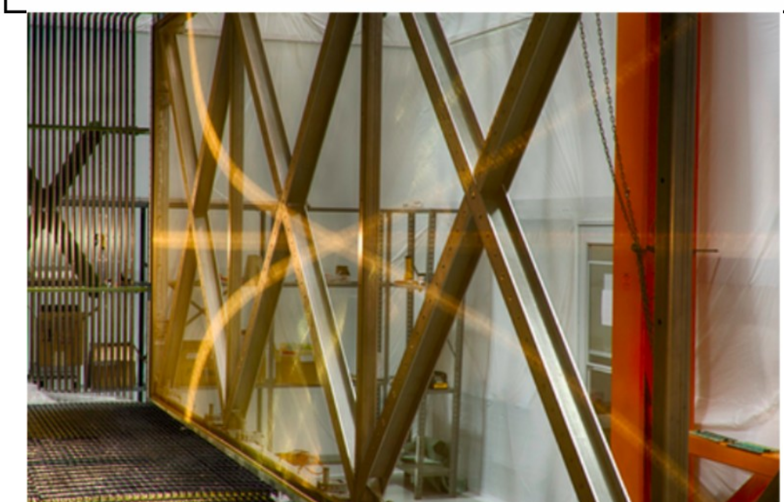
MicroBooNE at a glance

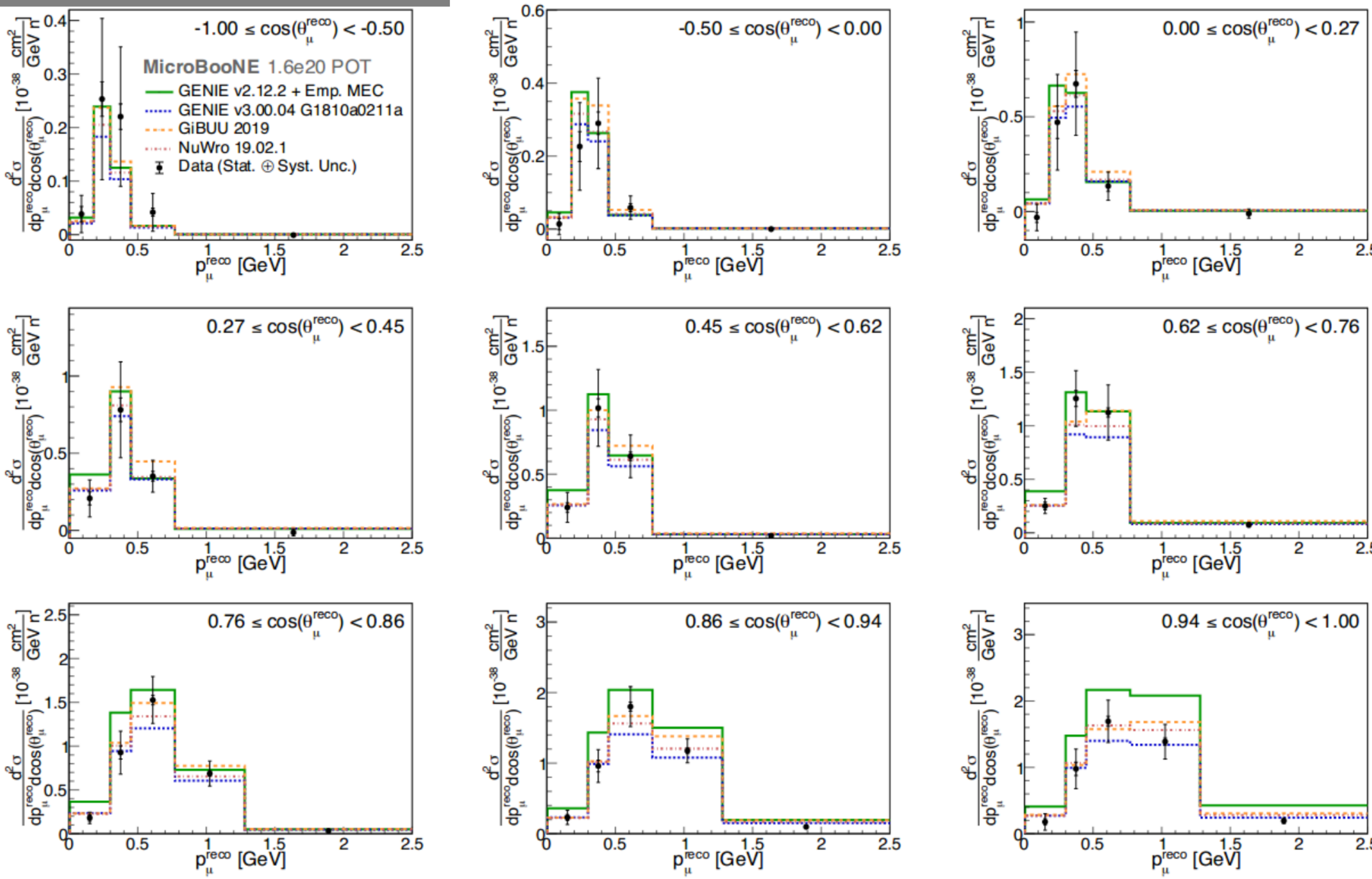
- 170 tons of LAr (90 tons active).
- Longest running LArTPC in a neutrino beam.
- Over 8000 wires (3mm pitch).
- 32 8'' PMTs serve as light collection system.
- A large number of crucial R&D in LArTPC operation as well as important physics results coming out.





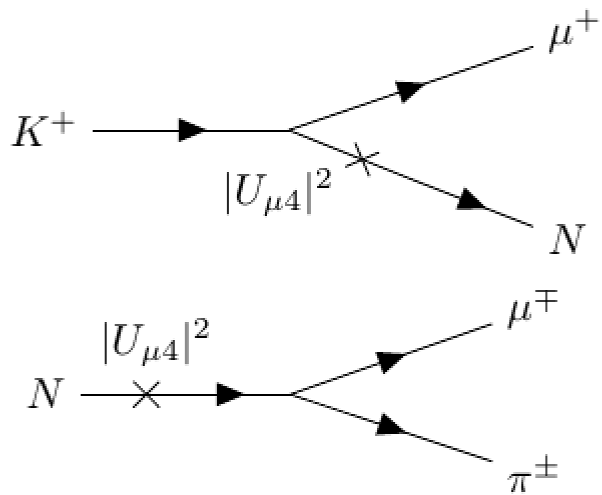
MicroBooNE Recent Highlight: CC ν_μ inclusive

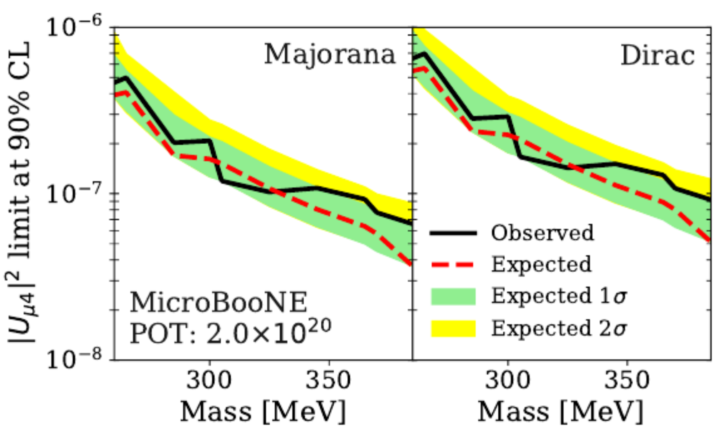
Phys. Rev. Lett. 123, 131801



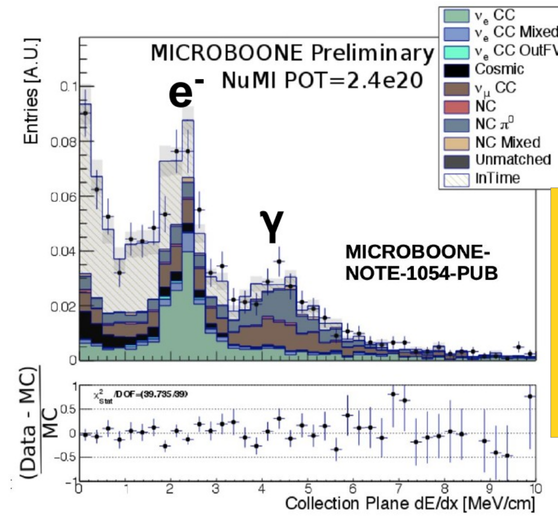
More MicroBooNE results

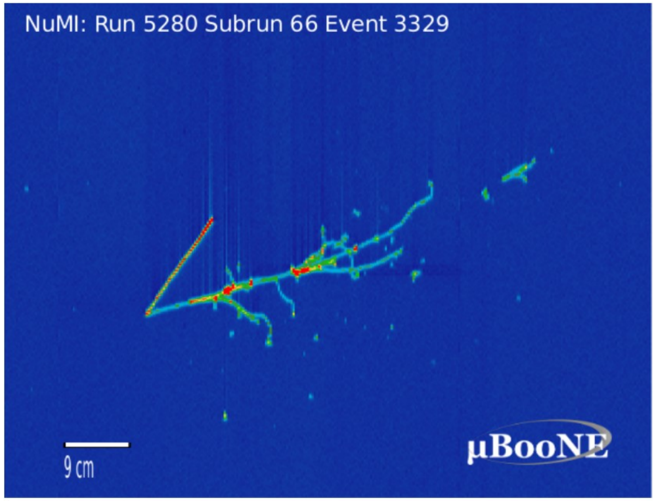
- Heavy Neutral Leptons





- CC ν_e from NUMI

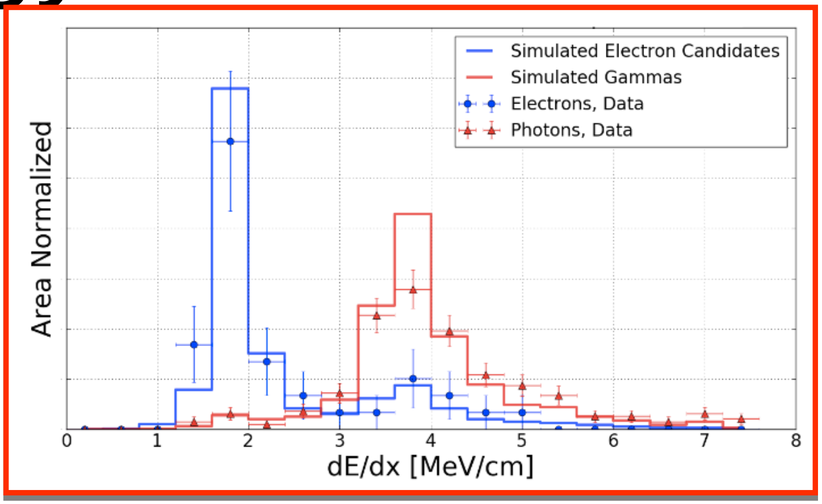


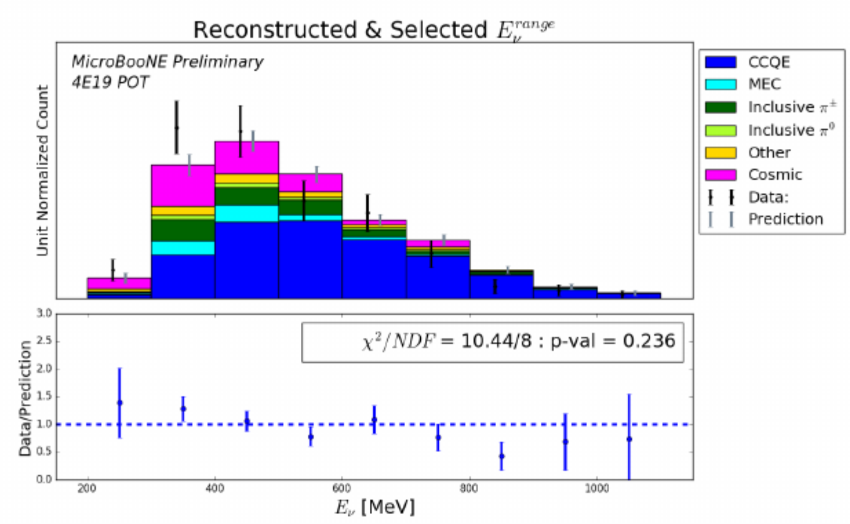


Crucial cross -check for understanding ν_e in LAr

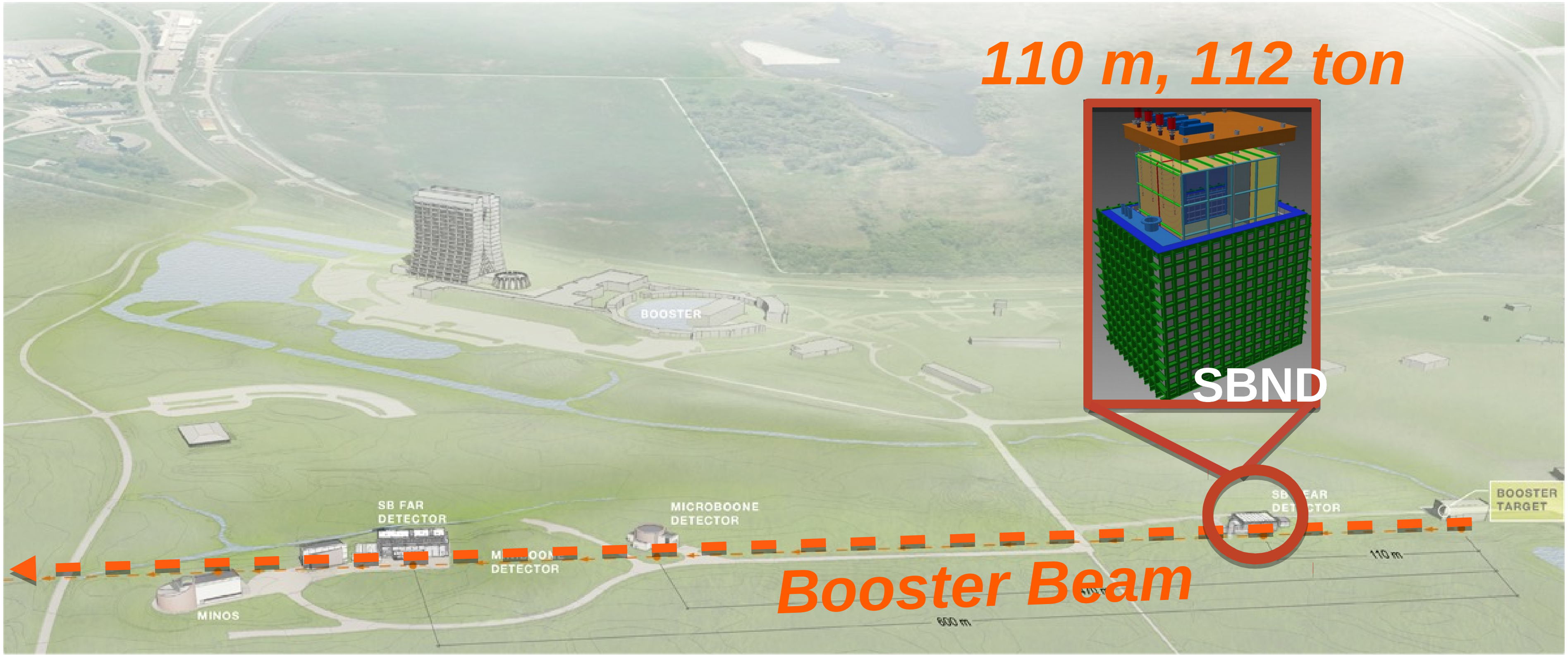
Understanding the Low Energy Excess

- Main goal of MicroBooNE is to understand the nature of LEE observed by MiniBooNE.
- LArTPCs can tell us whether the excess is electrons (supporting oscillation hypothesis) or photons.
- 12e20 POT already acquired. Analyses (x3) are being finalized.
- First results expected by the summer.





SBND – the near detector



The Short-Baseline Near Detector (SBND), will be located closest to the source of neutrinos.

It will characterize the beam before oscillations occur and address one of the dominant systematic uncertainties.

Planned start of operation 2020/2021.

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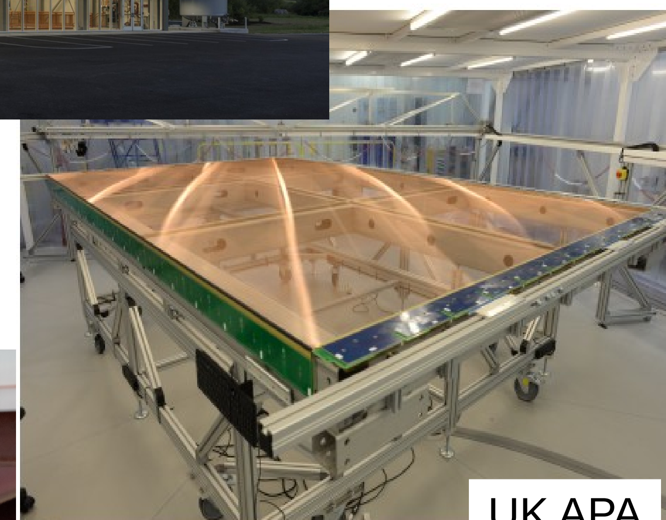
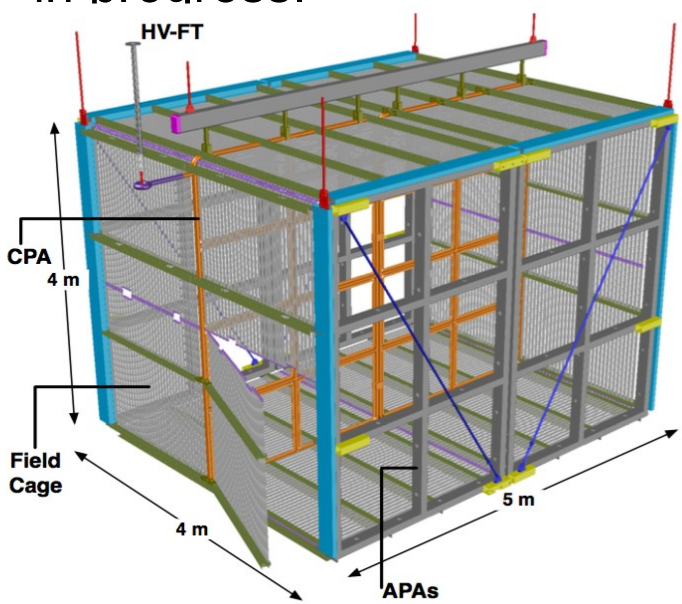
SBND at a glance

112-ton (active volume) in two Liquid Argon Time Projection Chambers.

4x4x5m Active Volume.

- All TPC components are ready for installation.
- cryostat assembly in progress.

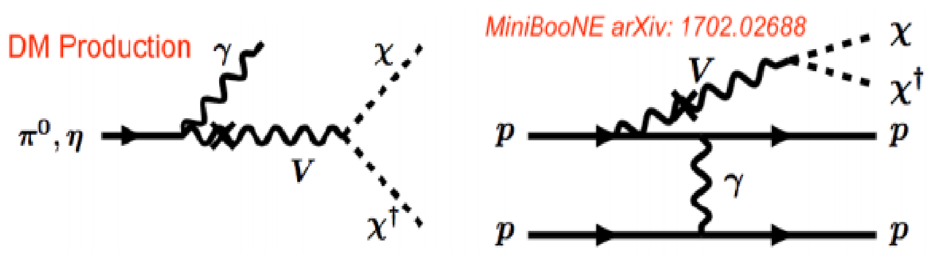


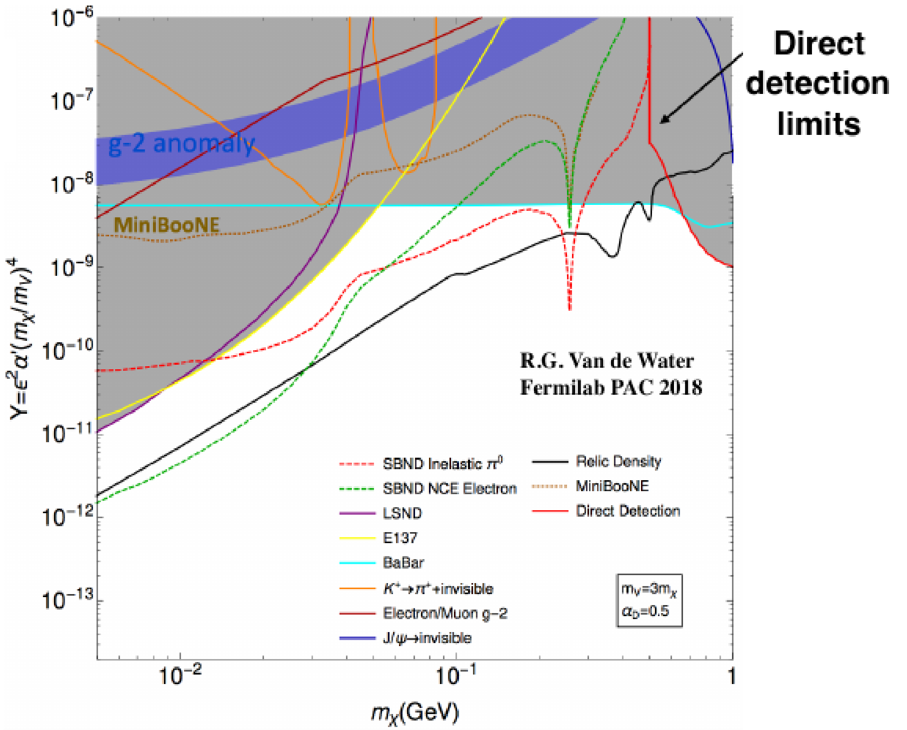


Beyond SM Searches

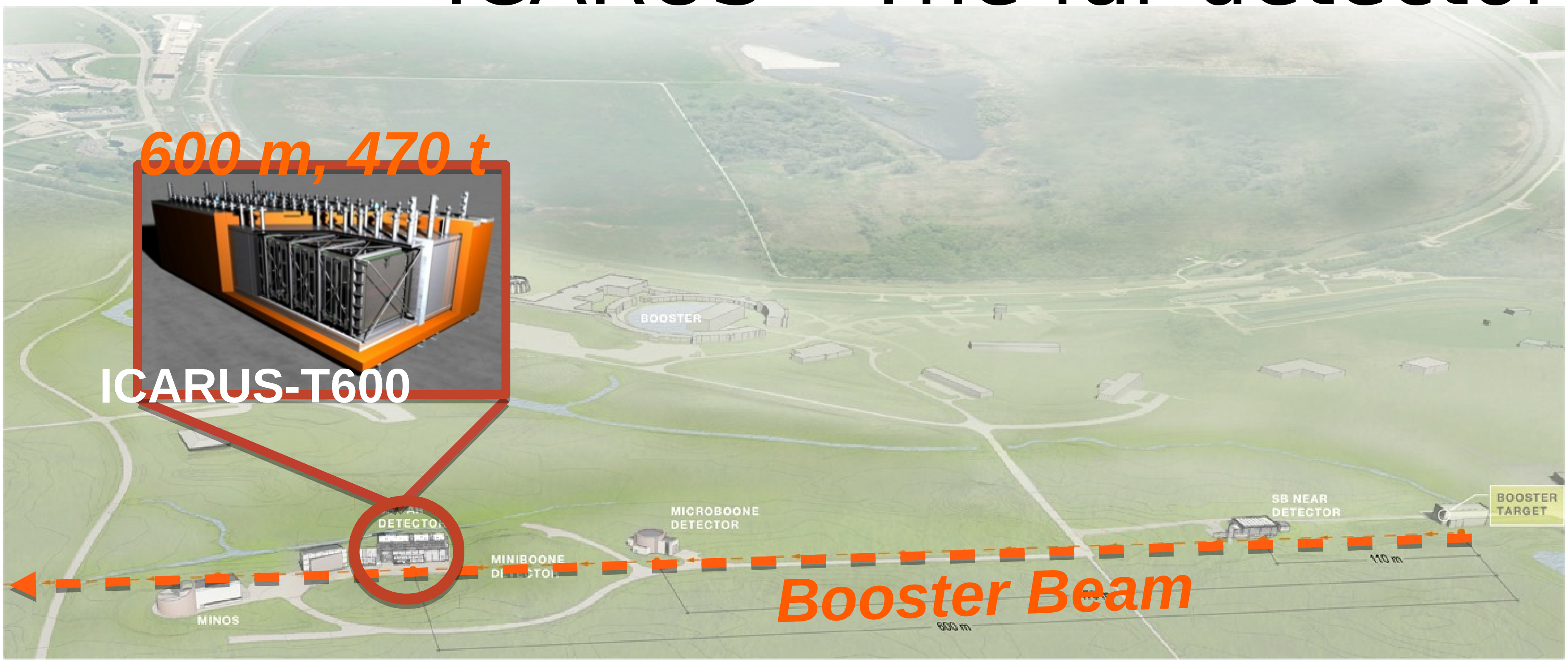
- There is a rising interest in potential detection of unconventional neutrino-sector and dark-sector physics signals in large-volume neutrino experiments
- The proximity to the beam target, large detector mass and relative detection isotropy makes the LAr TPC SBN detectors well suited for beyond the standard model searches.
  - Sub-GeV dark matter (with proton beam dump)
  - Hidden-sector particles
  - Exotic signatures

Dark Matter Production





ICARUS – The far detector



Given its large mass and relatively large distance from the source the ICARUS-T600 will have high sensitivity to neutrino oscillation effects.

- Planned start of operation 2019.

ICARUS

The University of Manchester

The ICARUS T600, after a succesful Run at Gran Sasso on the CNGS beam was transported to CERN for refurbishment.

It then travelled to Fermilab (#IcarusTrip).

- Two cryostats: 760t total LAr mass / 476t active.
- Two TPCs per cryostat, with a common central cathode.
- Cool down has begun.

SBN Physics reach

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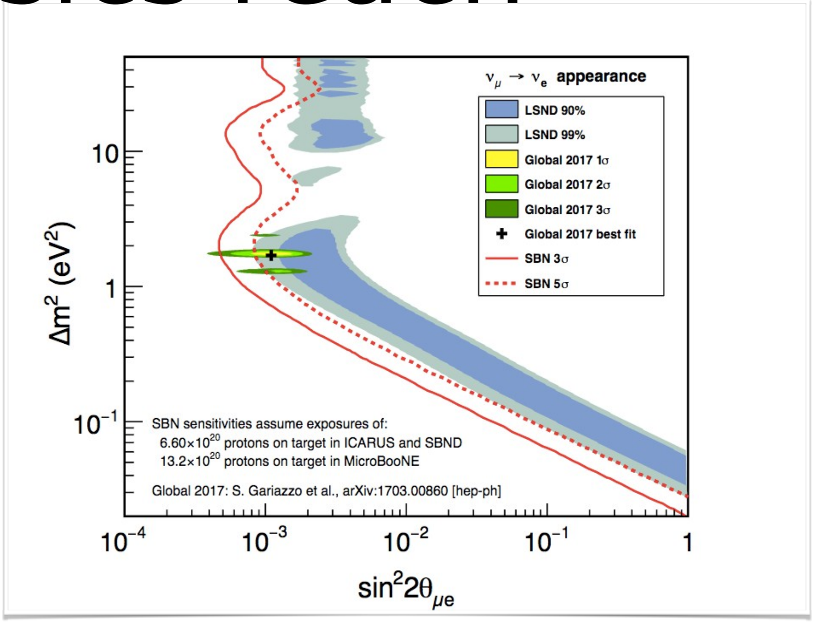
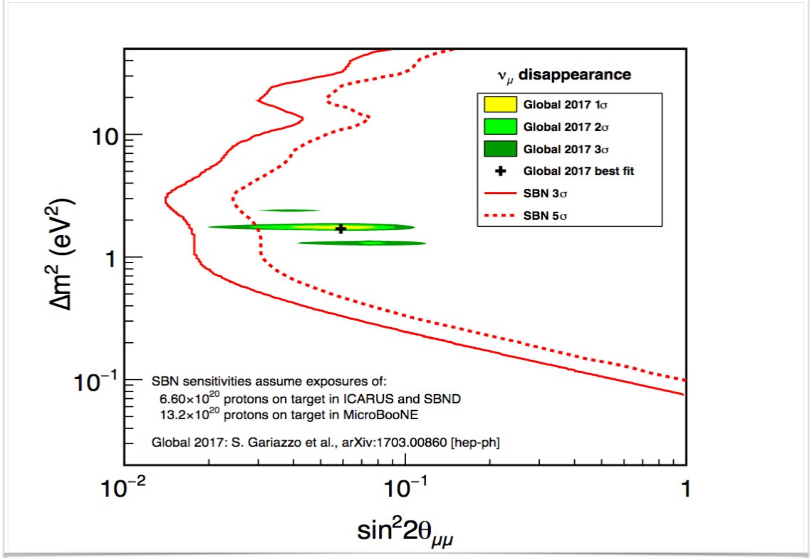
Constraints on the flux and cross-sections from the near detector lead to a powerful combined exclusion region.

LSND parameter space excluded at 5σ.

In addition, SBN can also perform ν_μ disappearance searches. Would confirm an oscillation interpretation of any observed ν_e appearance signal.



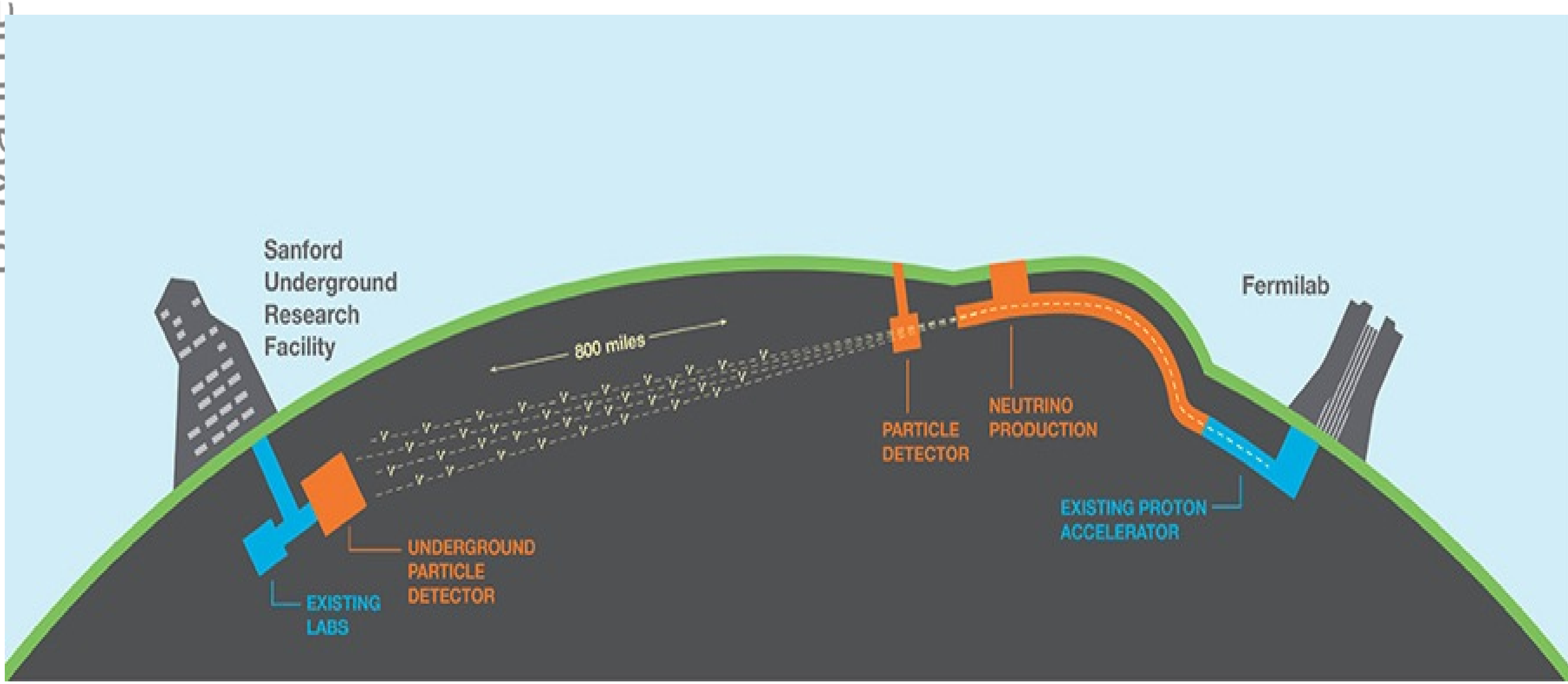


Fit from S. Gariazzo et al., arXiv:1703.00860

The Plan

- The Standard Model of Particle Physics
  - *And what we know and don't know about neutrinos in it.*
- Detecting (accelerator-energy) Neutrinos
  - The special role of electron neutrinos.
- Searching for Short-Baseline oscillations
  - And why we think argon is a good idea?
- Searching for Long-Baseline oscillations with DUNE
  - Or, why put 40kT of cryogenic liquids underground.

The DUNE experiment



- DUNE stands for Deep Underground Neutrino Experiment
- It will look for differences between neutrinos and anti-neutrinos traveling from Fermilab near Chicago and the HomeStake Mine in South Dakota (800 miles/1300 km away!)

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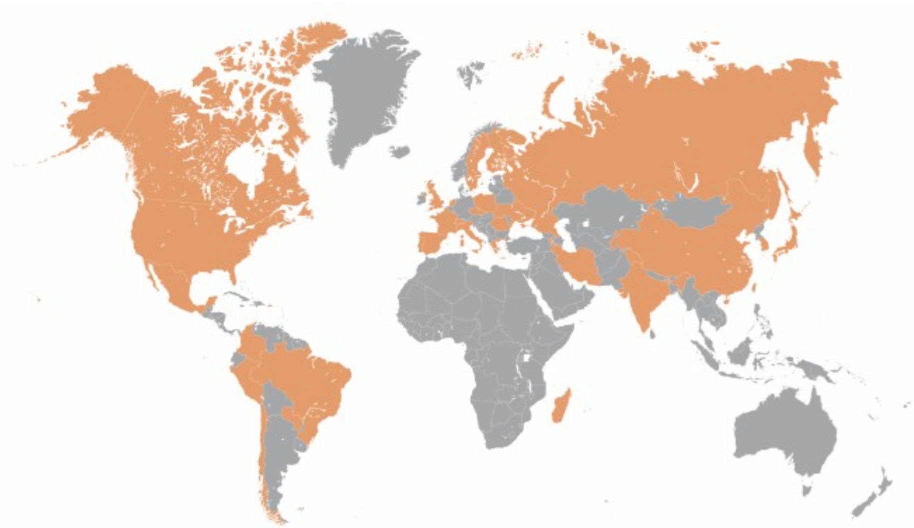
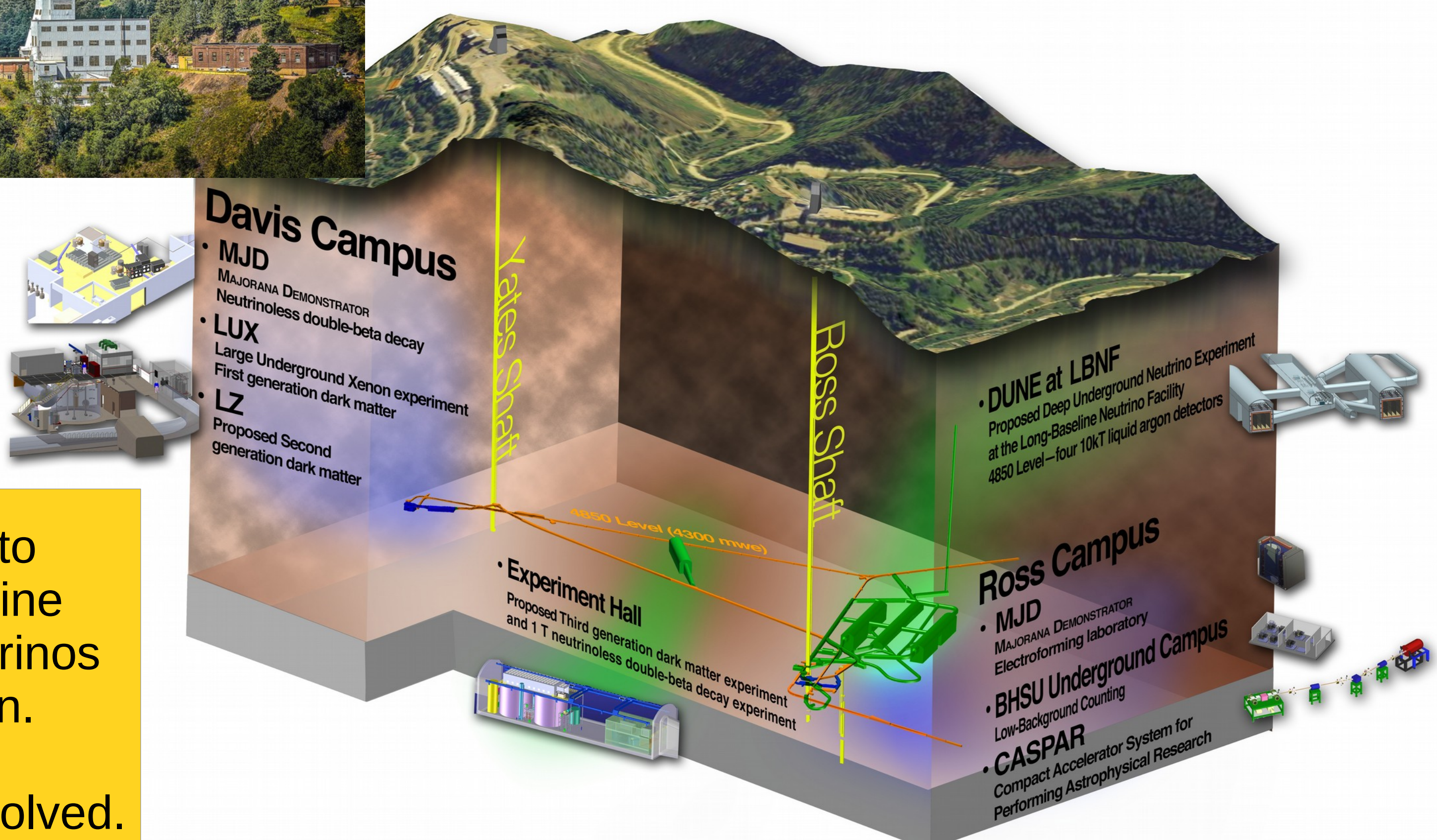
DUNE – a global Collaboration



~1100 collaborators from
188 institutions in 32 countries

The Homestake Mine

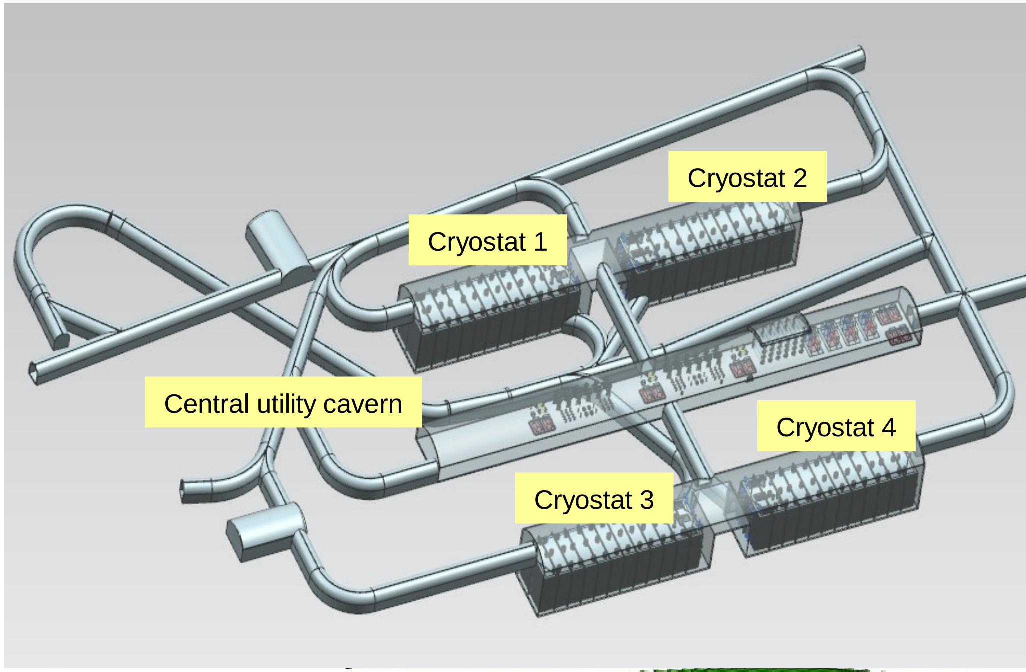


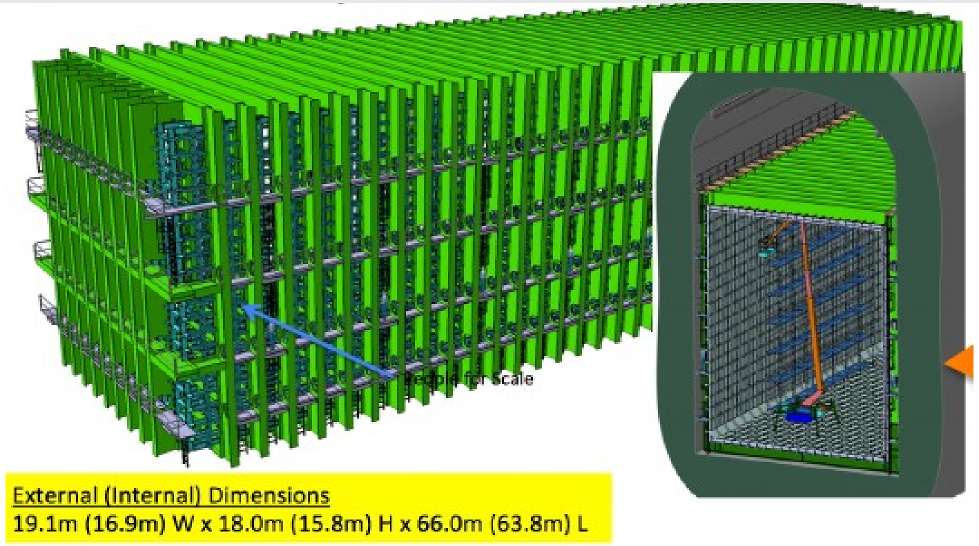
This happens to be the same mine where solar neutrinos were first seen.

Argon is again involved.

Far Detector

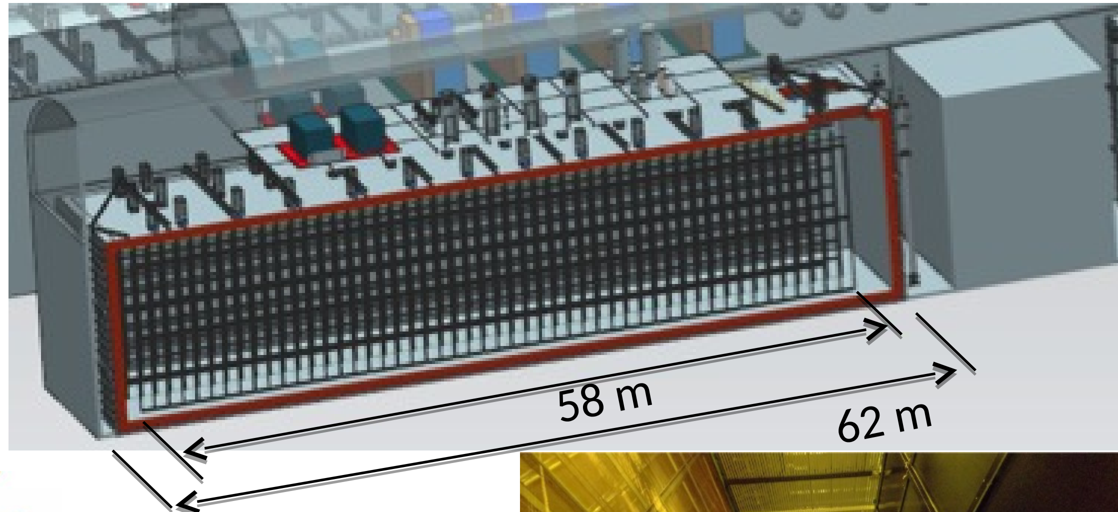
- Four ~10 ktonne liquid argon modules
  - 2 “single-phase”
  - 1 “double-phase”
  - 1 “module of opportunity”
- Full detector built in stages
- ~40 ktonne total fiducial volume
- Steel-supported membrane cryostat technology
- Three caverns: two to support the modules and a central utility space

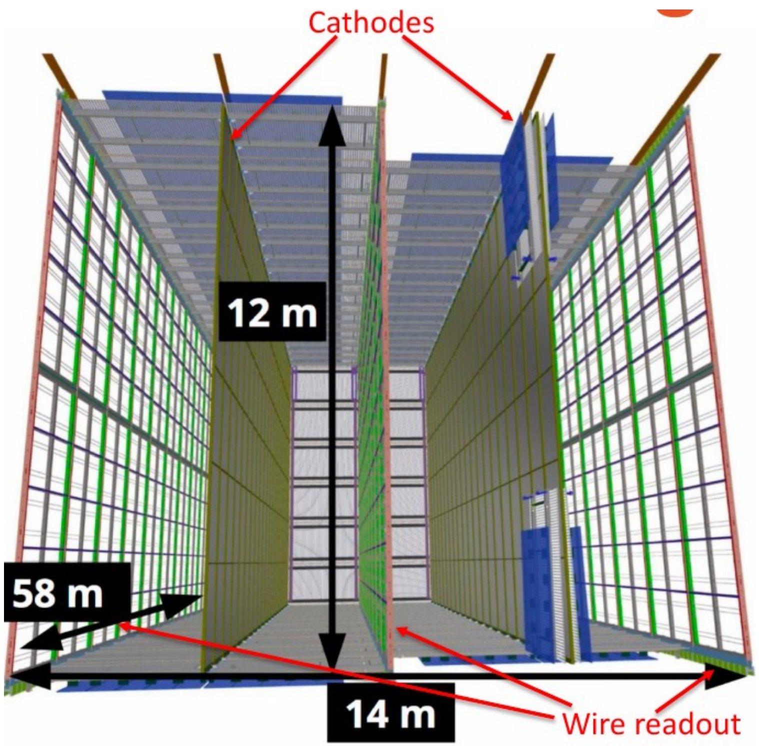




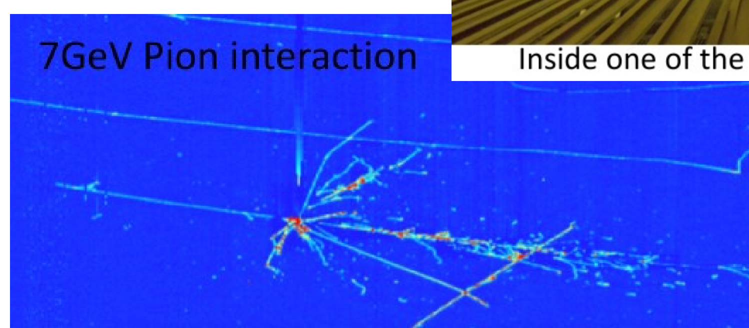
Single Phase DUNE Detector

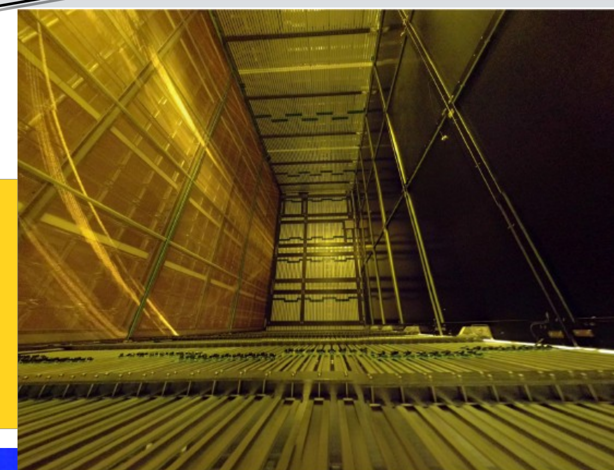
- Active volume:
  12m x 14m x 58 m
- 17.1 kton Total mass





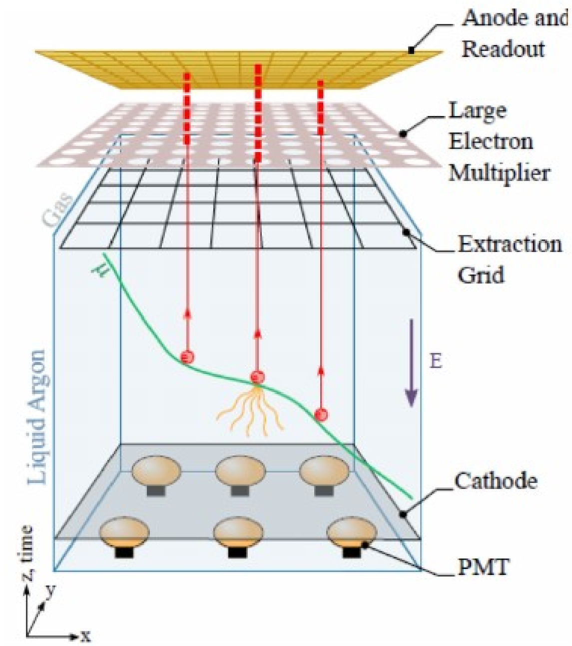
ProtoDUNE SP prototype running at CERN

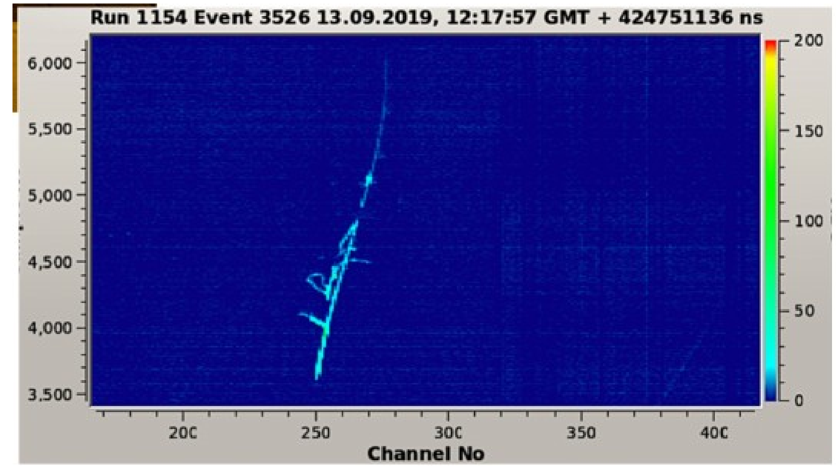


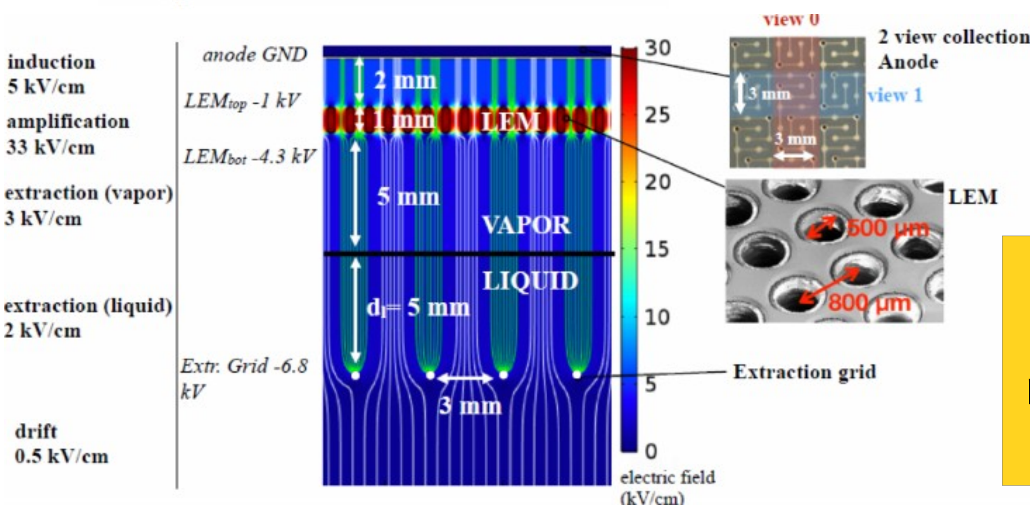


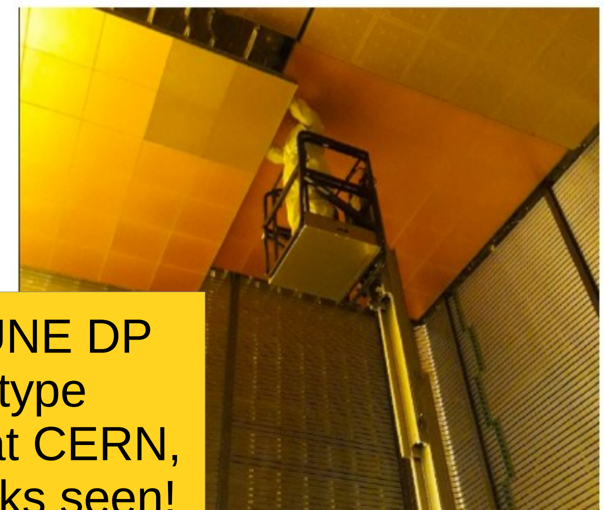
Inside one of the TPC drift volumes

Dual Phase DUNE Detector



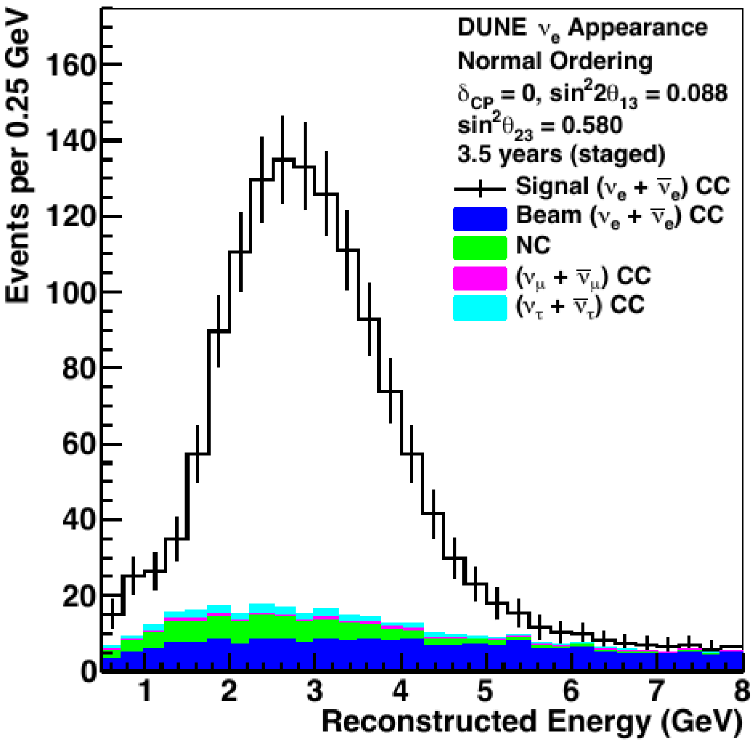


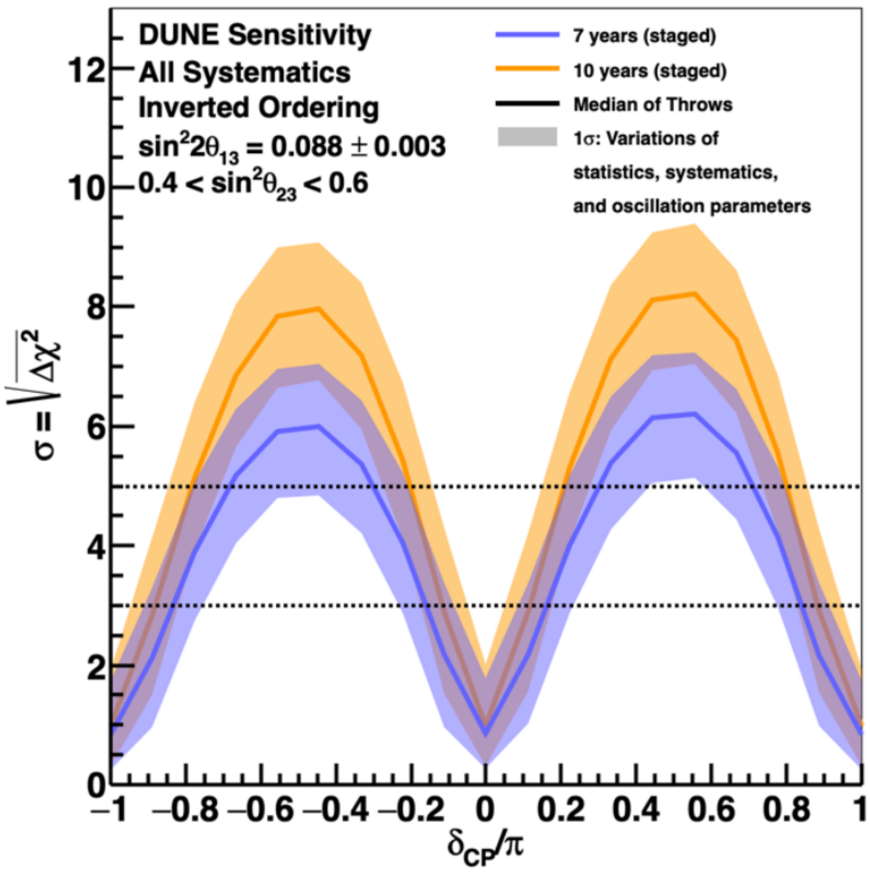




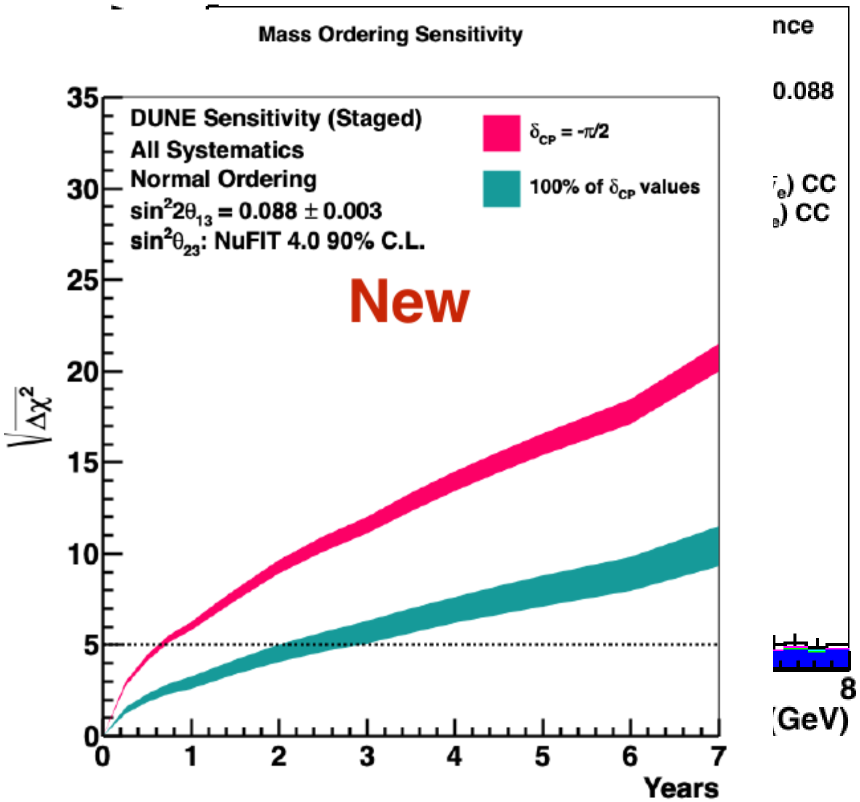
ProtoDUNE DP prototype running at CERN, First tracks seen!

Searching for CP Violation

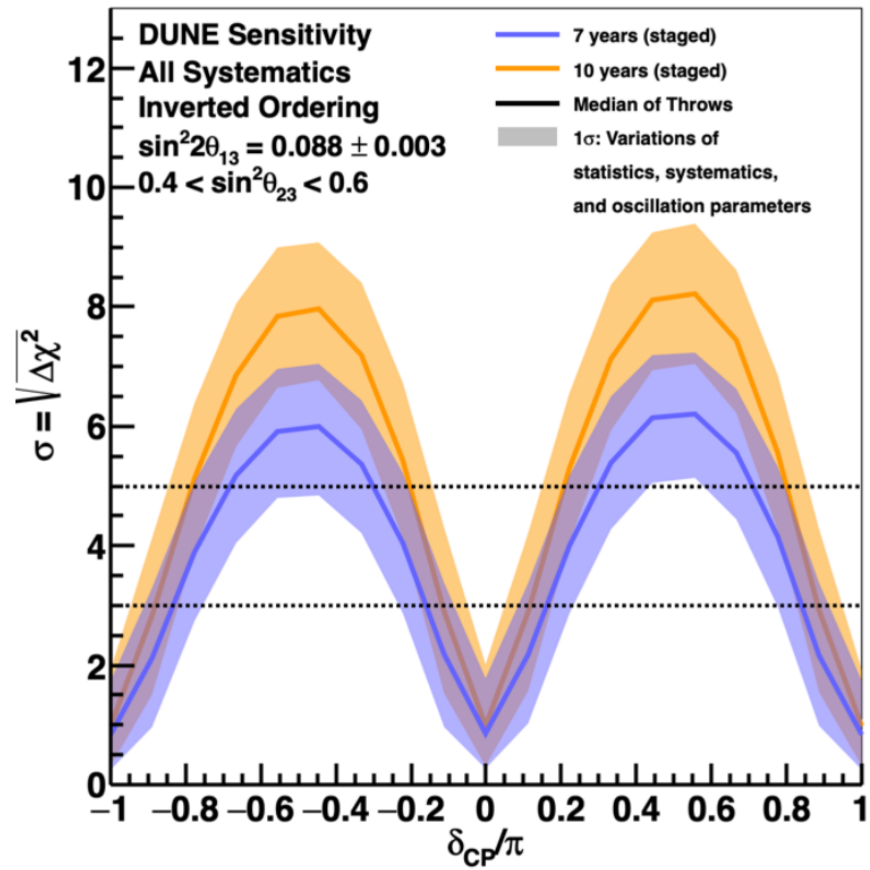




Searching for Mass Ordering



Mass ordering at 5σ
2 years after beam starts



Supernova Neutrinos

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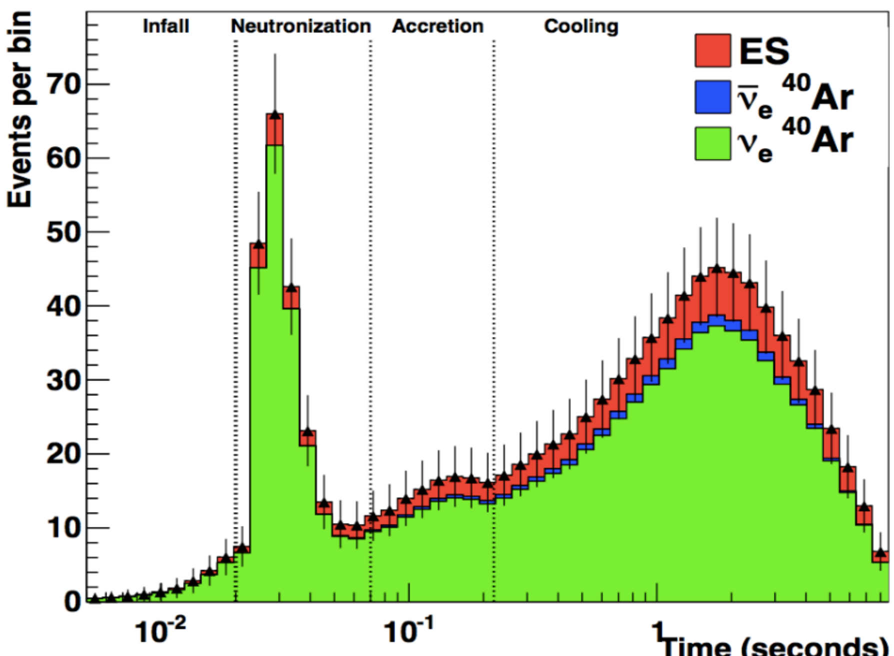
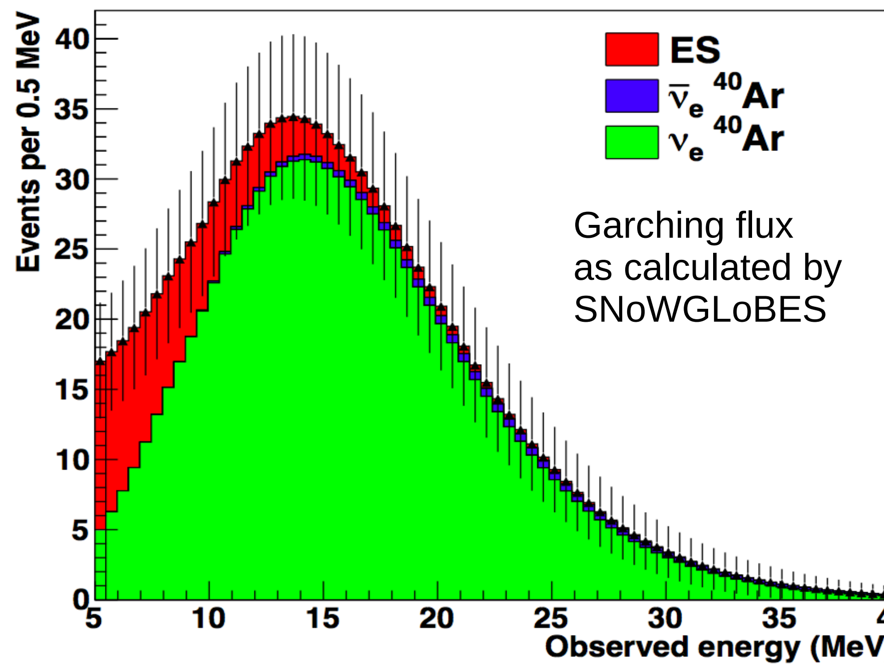
- Supernova explosions emit an enormous number of neutrinos!
- LAr detectors are mainly sensitive to ν_e via: $\boldsymbol{\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*}$
- Sensitivity to neutronization burst

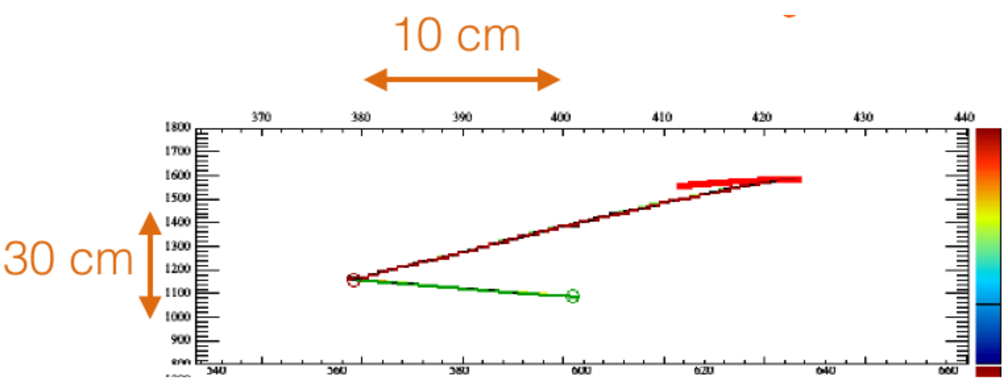




A Multitude of Other Physics Topics

- Large mass of FD enables Proton decay searches
  - Golden channel in LArTPCs: $p \rightarrow K^{+}\bar{\nu}$

- Large flux in ND enables precision
- cross-section measurements
- Combination of large mass and flux enables searches in the ND for
  - Non-standard interactions
  - Sterile neutrinos
  - Neutrino Tridents
  - Dark Matter
  - Extra dimensions



DUNE Timeline

- 2024: Start installing first module (SP)
- 2025: Start installing second module
  - DUNE physics data starts with atmospheric neutrinos!
- 2026: Beam operational at 1.2 MW
  - DUNE physics data taking with beam starts!
  - Total fiducial mass of 20 kt
- 2027: Add third FD module
  - Total fiducial mass of 30 kt
- 2029: Add fourth FD module
  - Total fiducial mass of 40 kt
- 2032: Upgrade to 2.4 MW beam

Conclusions

- We have learned a lot about neutrinos and their role in particle physics, but important questions remain!
- Liquid argon time projection chambers will be used in the framework of the Fermilab International Neutrino Programme to try to answer these questions.
- Observing electron-neutrino appearance will be a crucial part of these measurements, both at short and long baselines.
- In the next four years, expect new results from the SBN programme and the start of DUNE construction.
- Exciting times ahead!

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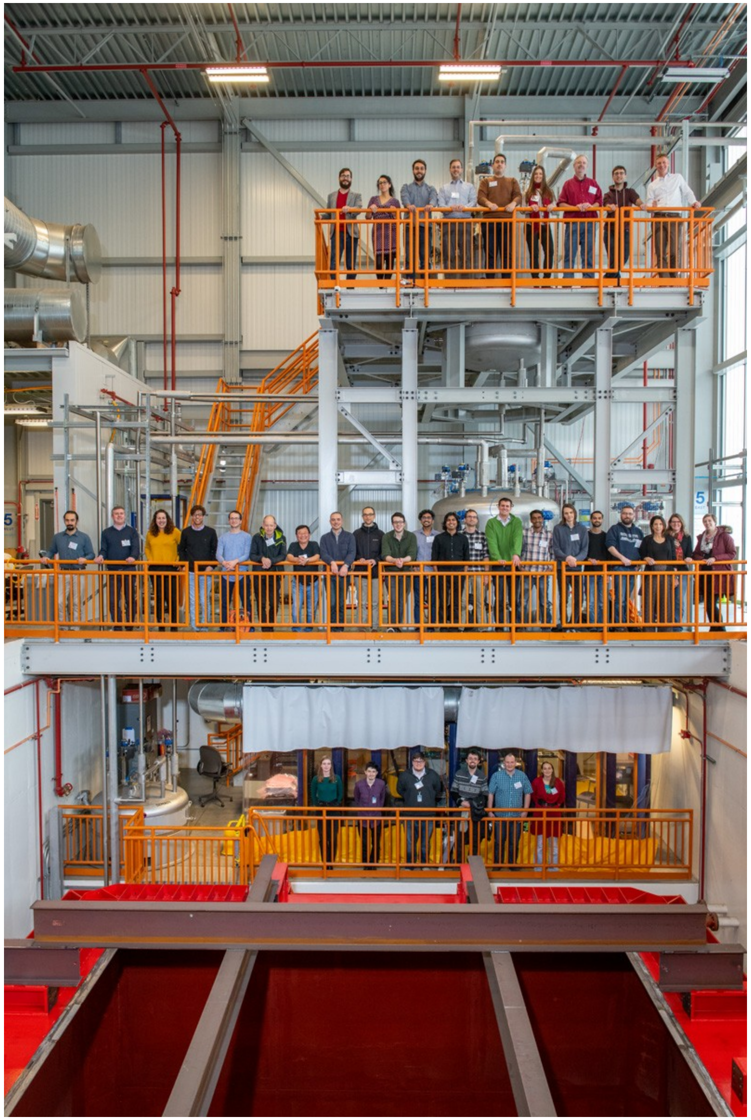


Thank you for your attention!

Things to note

- Oscillations are only possible if neutrinos have mass
- But we don't know what it is, only the squared difference (a parameter).
- Mixing angles are another parameter.
- Adjusting L/E allows us to measure different mixings.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

$$\Delta m_{12}^2 = m_1^2 - m_2^2$$

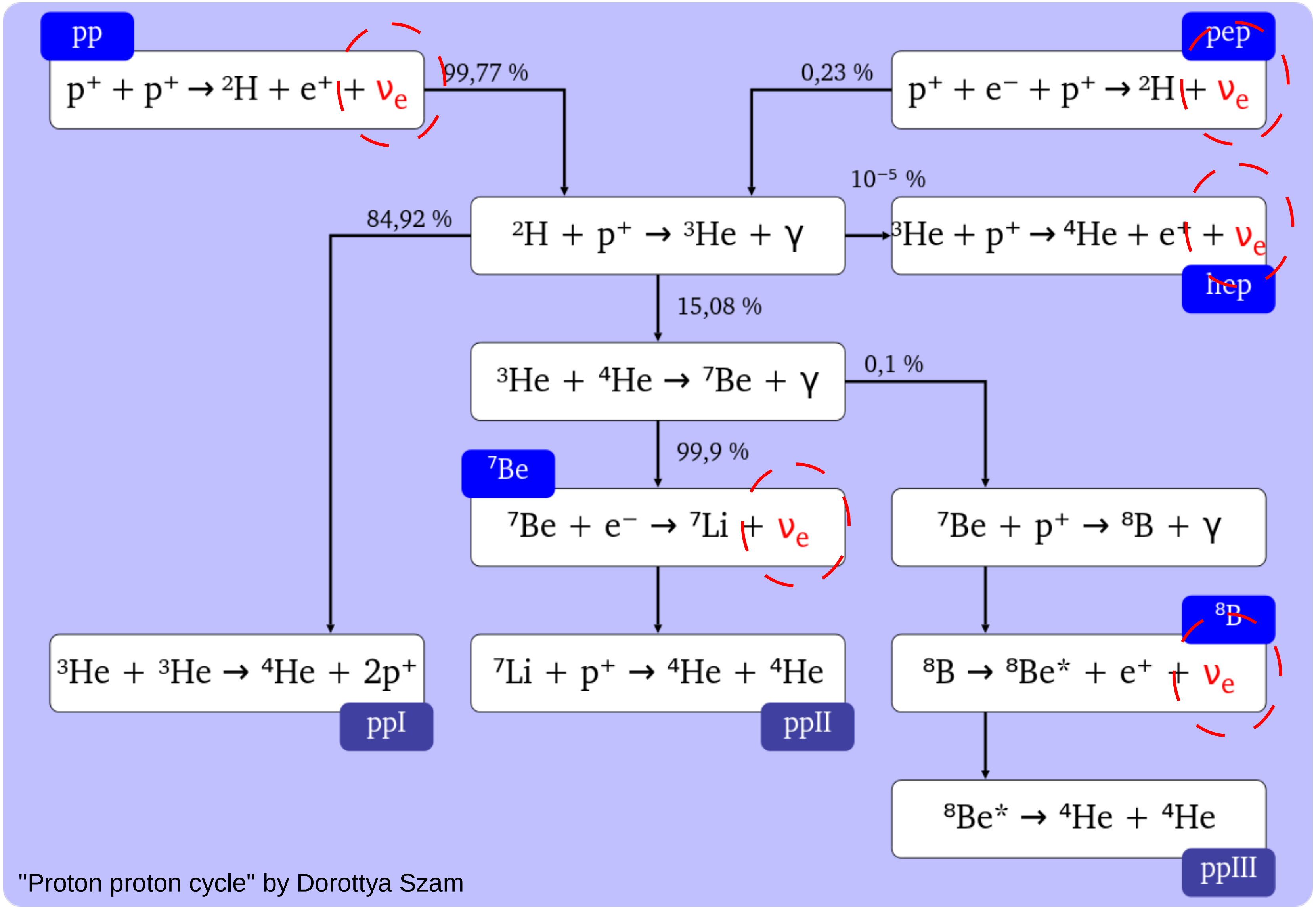
$$\frac{\Delta m^2 L}{4E} \ll 1$$

Oscillations did not have a chance to happen

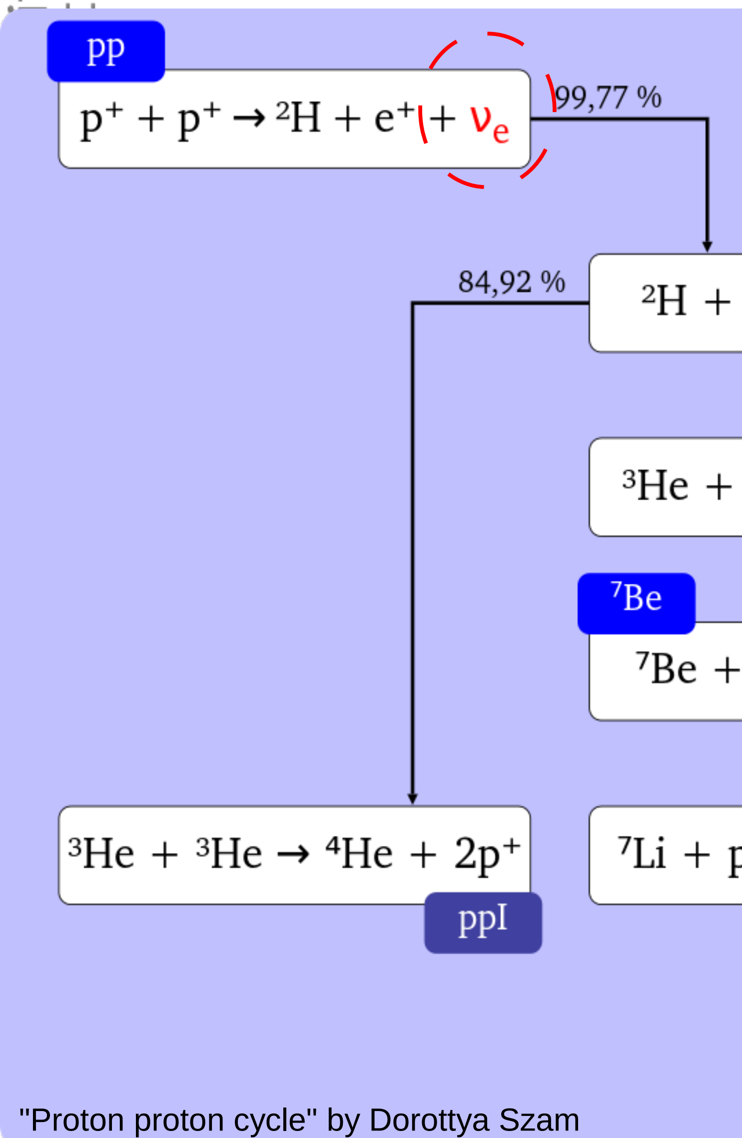
$$\frac{\Delta m^2 L}{4E} \gg 1$$

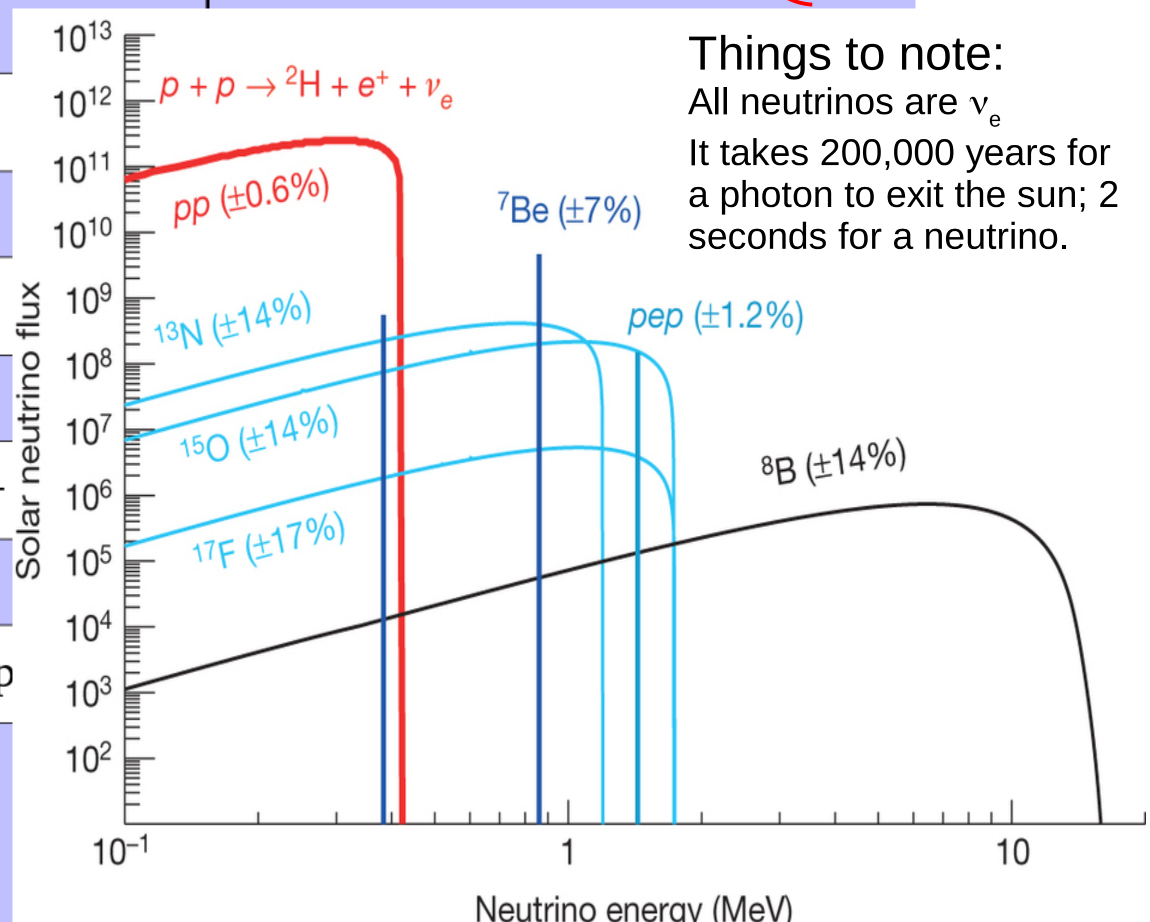
Oscillations averaged out – only sensitive to mixing angle

Solar Neutrinos



Solar Neutrinos





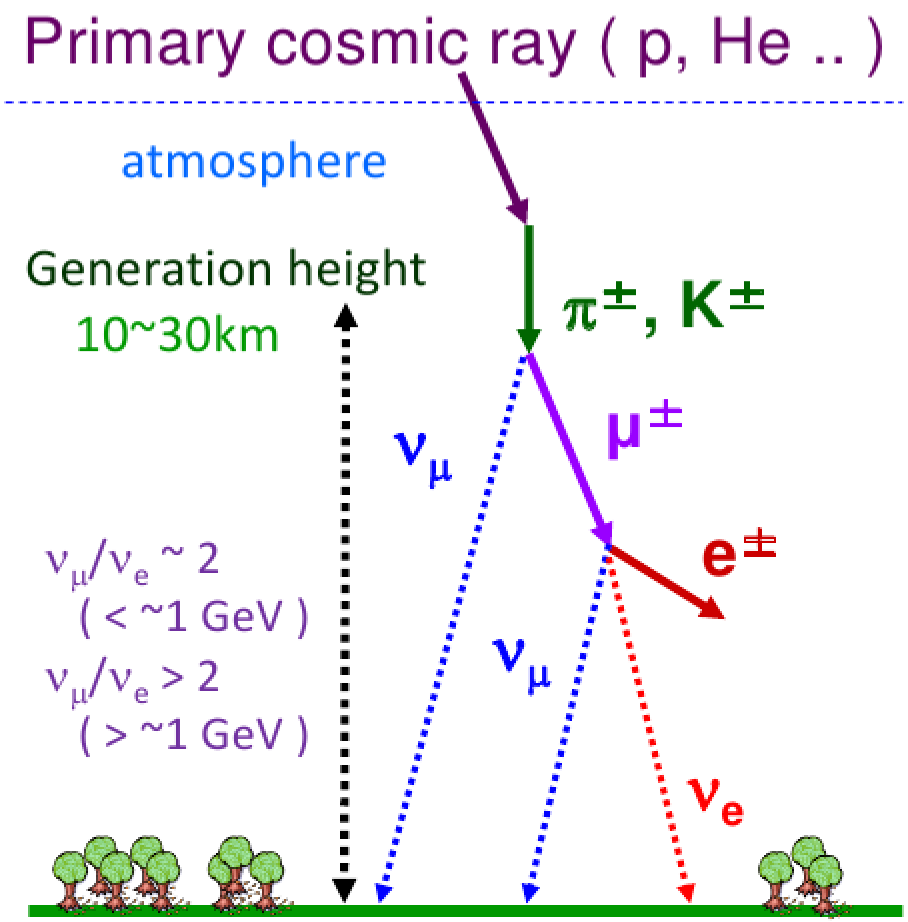
Things to note:

All neutrinos are ν_e

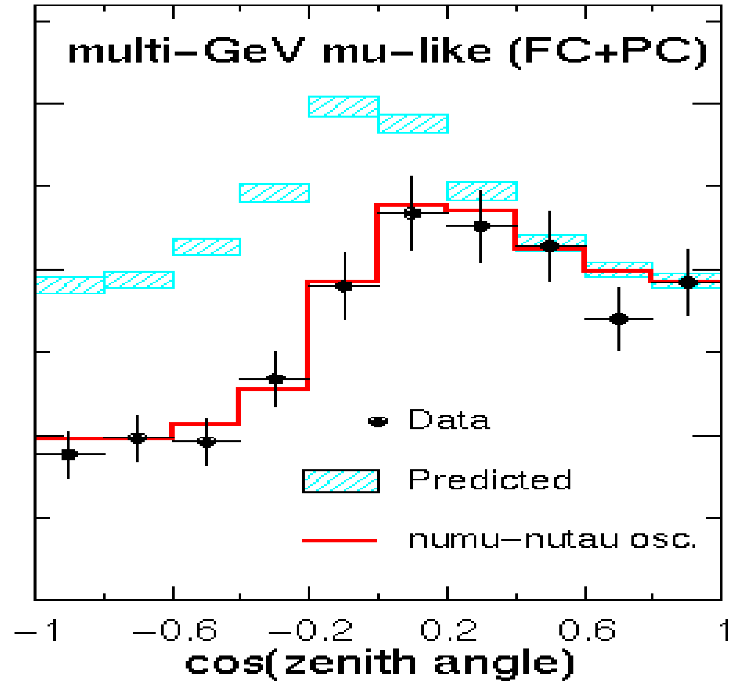
It takes 200,000 years for a photon to exit the sun; 2 seconds for a neutrino.

"Proton proton cycle" by Dorottya Szam

Discovery of atmospheric neutrinos and their asymmetry



Super Kamiokande detector misses muon neutrinos from the bottom (but not from the top).



Super-Kamiokande Collaboration Phys. Rev. Lett. 81, 1562–1567 (1998)

Neutrinos are disappearing.
What is happening to them?

Sudbury Neutrino Observatory (SNO)

The University of Manchester

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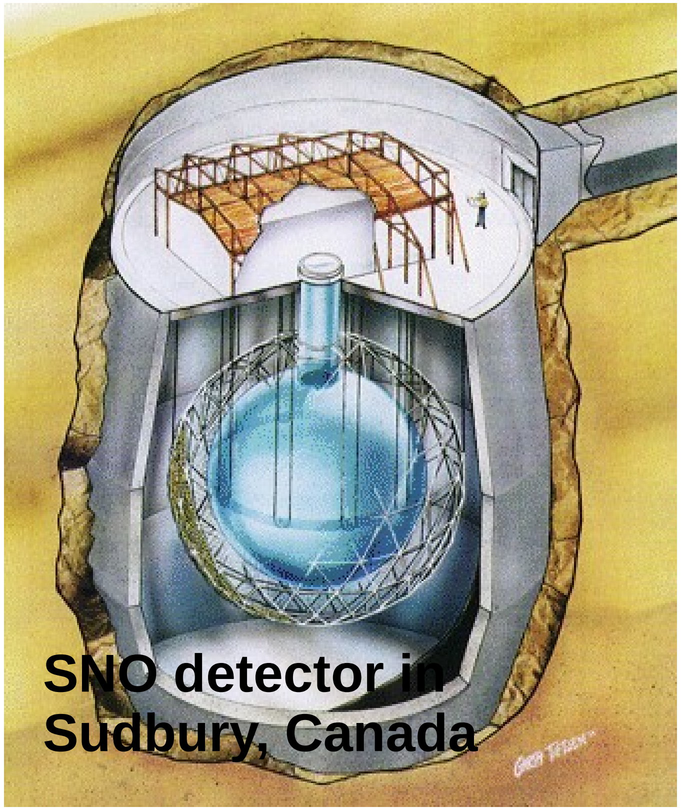
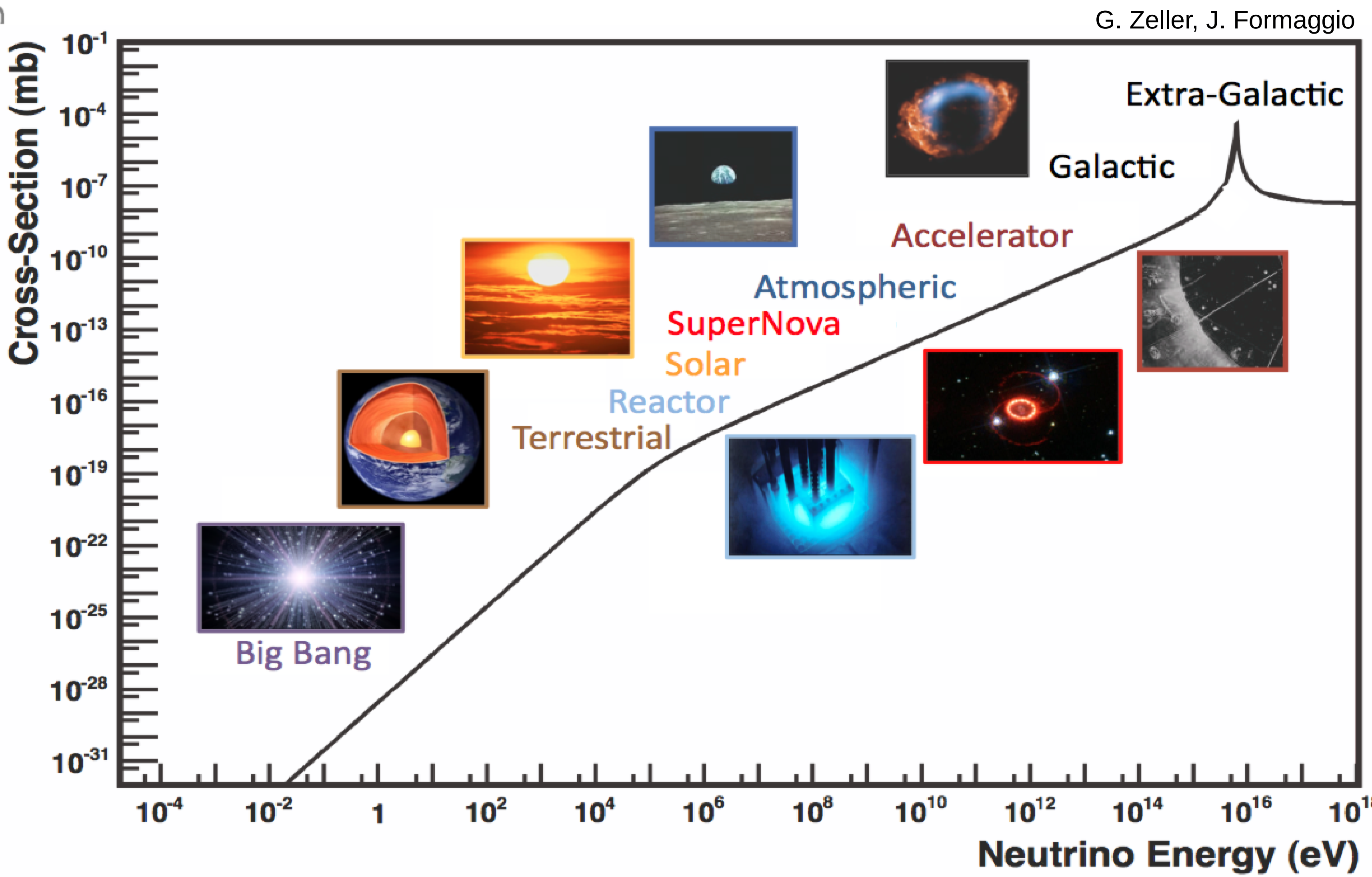
Extremely clever idea: try to observe electron and other neutrinos separately using properties of Heavy Water.



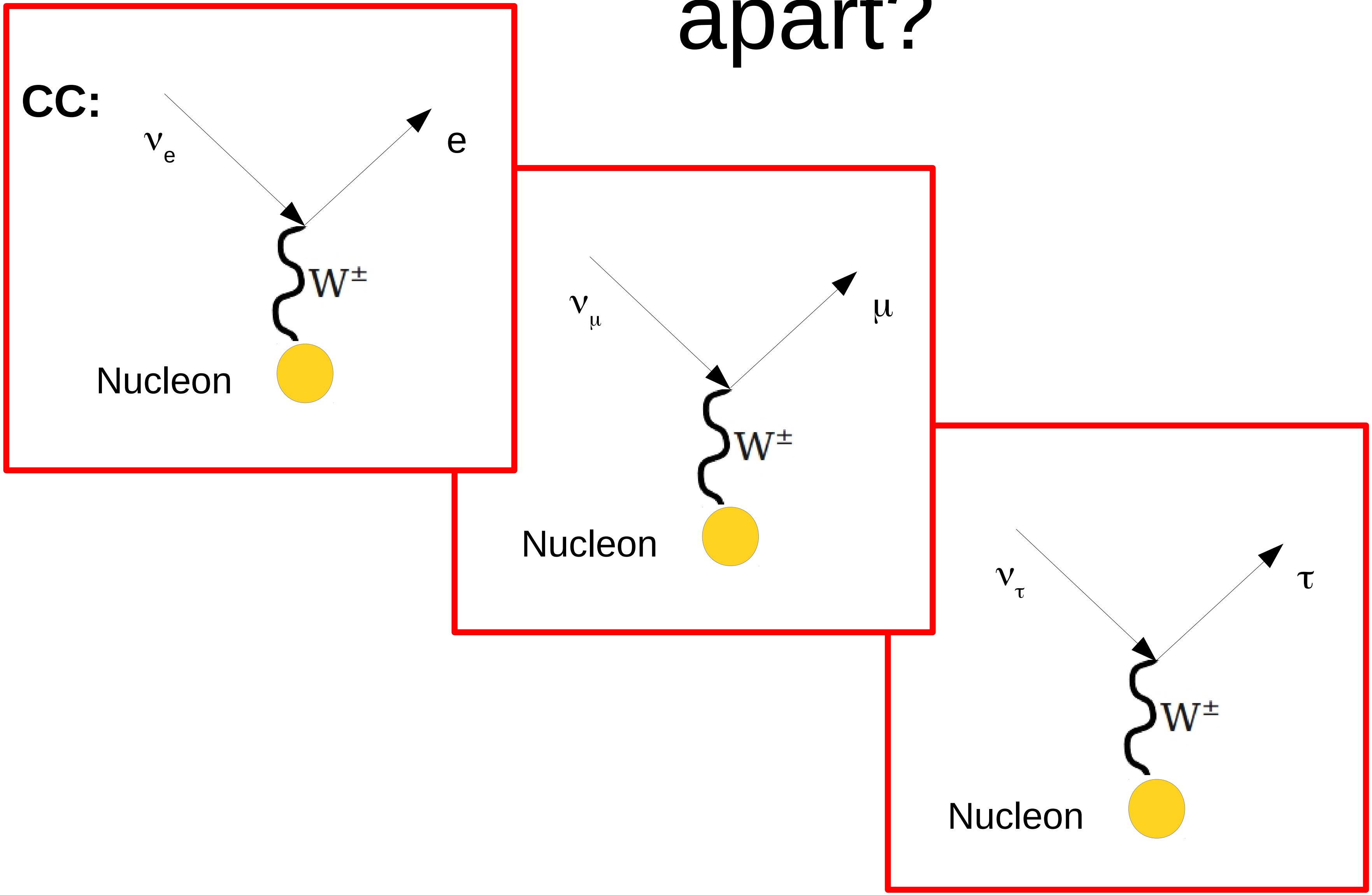
Look at three different reactions have different signatures:
CC – isotropic Cherenkov Rings
NC – delayed neutron capture (~6.25 MeV)
ES – Cherenkov Rings pointing back to the sun
They allow us to see what kind of neutrinos interact!

Charged Current	$\nu_e + d \rightarrow p + p + e^-$	Only ν_e
Neutral Current	$\nu_x + d \rightarrow \nu_x + p + n$	All neutrinos equally
Elastic Scattering	$\nu_x + e^- \rightarrow \nu_x + e^-$	All neutrino types, but the ν_e the most

Sources of Neutrinos



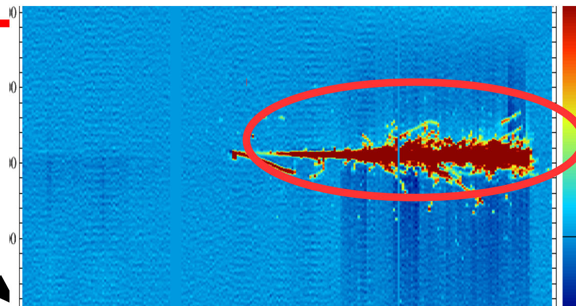
How do we tell neutrinos apart?



How do we tell neutrinos apart?

CC:

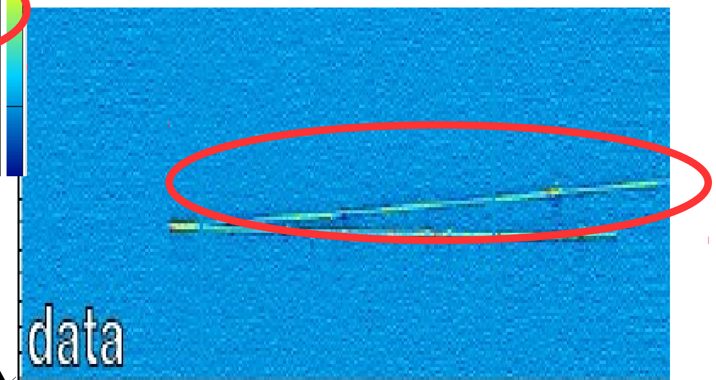
ν_e



$W^\pm$

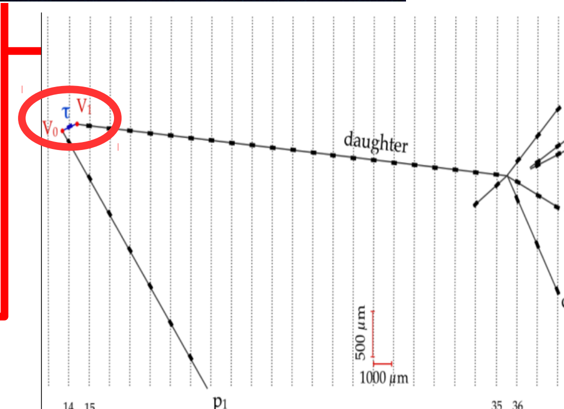
Nucleon

ν_μ



$W^\pm$

Nucleon



$W^\pm$

Nucleon

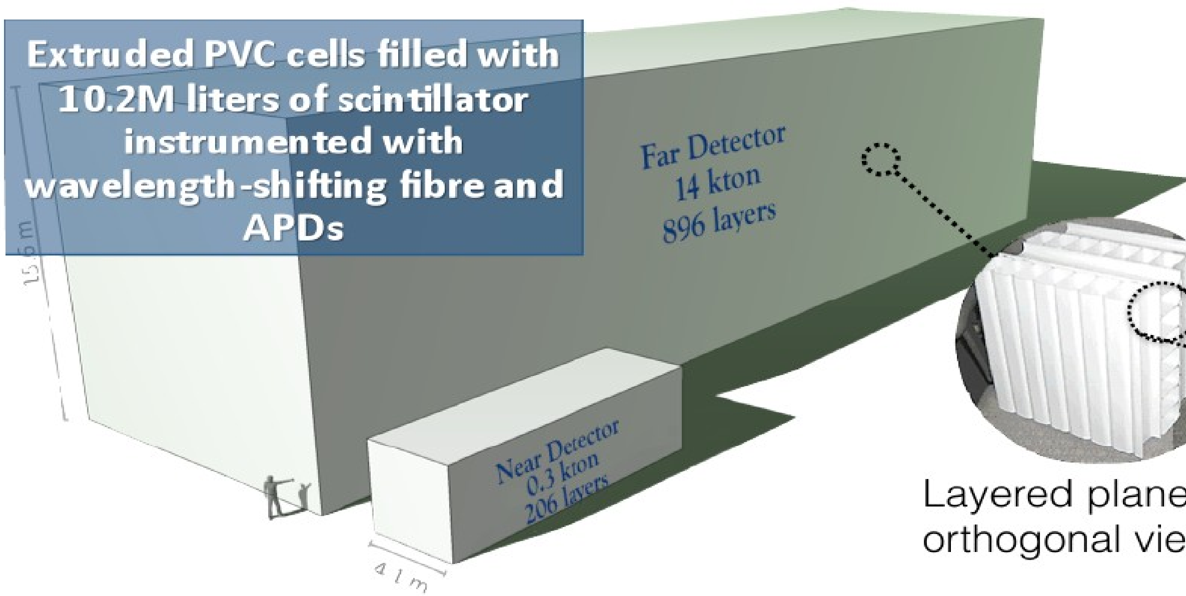
Neutrinos can also interact via Neutral Current (NC) or Elastic Scattering (ES) – but then we cannot tell which neutrino it was!

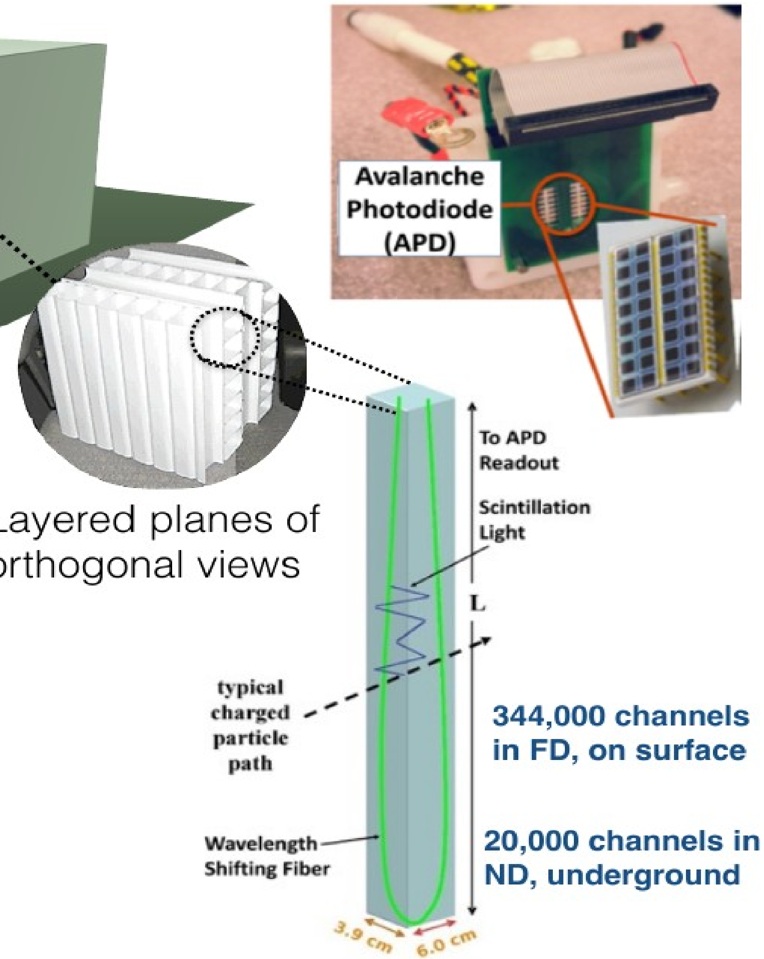
NOvA Principle of operation

The University of Manchester

Functionally-identical PVC-cell Near and Far Detectors filled with 10.2M liters of scintillator

Extruded PVC cells filled with 10.2M liters of scintillator instrumented with wavelength-shifting fibre and APDs





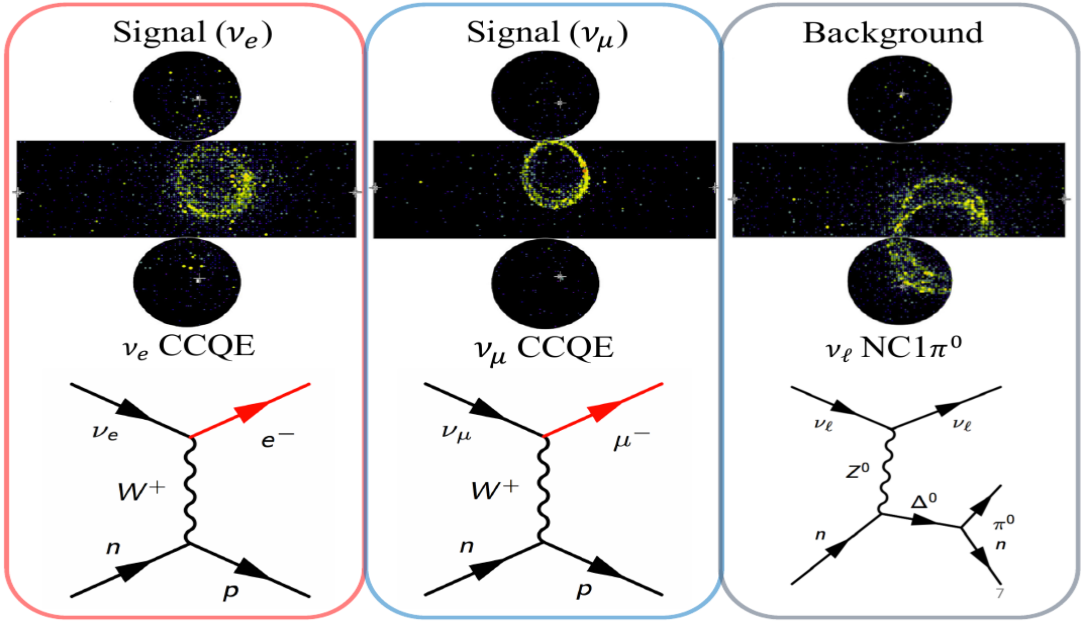
Low-Z materials, 65% active

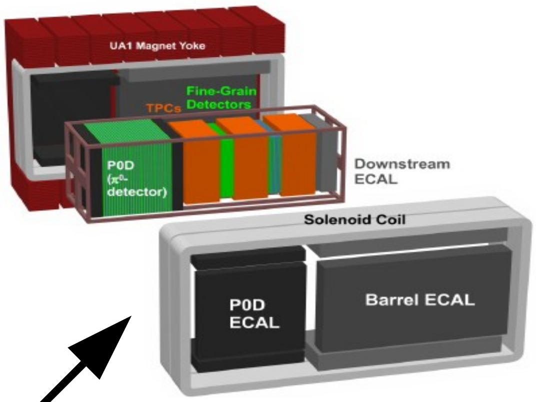
DAQ runs with zero deadtime

Triggers on beam, SNEWS, exotics, cosmic ray calibration samples

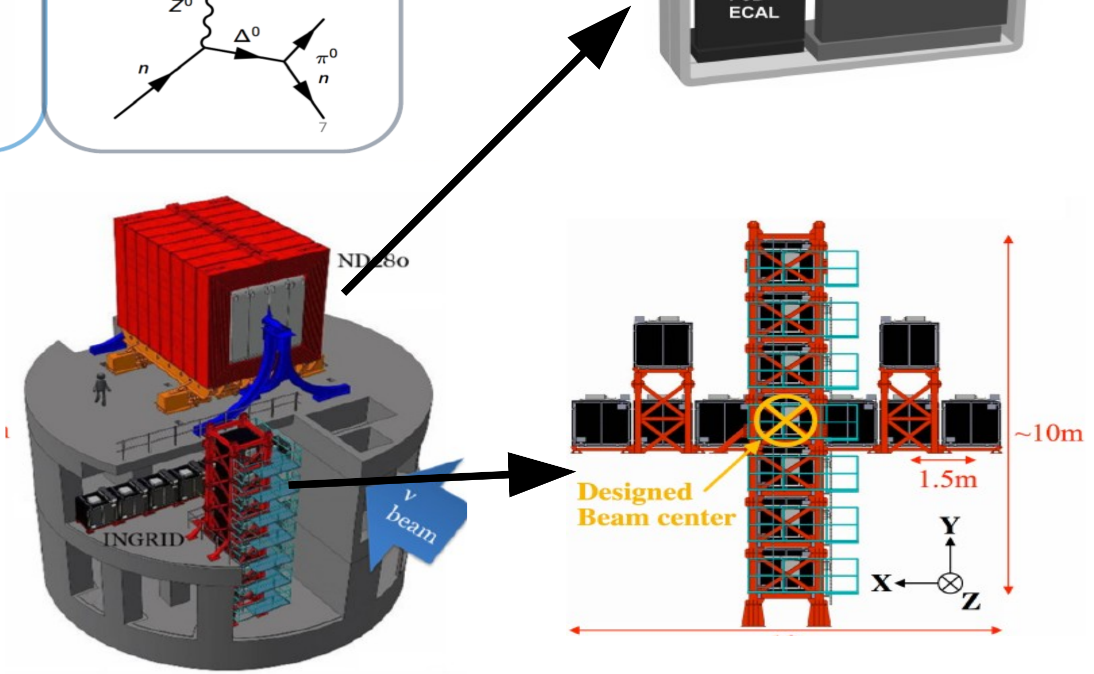
K. Matera

T2K detectors





- Complex of on-axis and off-axis near detectors to understand the flux.



SBND cross-section physics

Charged Current

ν_μ Inclusive	5,389,168
$\rightarrow 0\pi$	3,814,198
$\longrightarrow 0p$	27,269
$\longrightarrow 1p$	1,261,730
$\longrightarrow 2p$	1,075,803
$\longrightarrow \geq 3p$	1,449,394
$\rightarrow 1\pi^+ + X$	942,555
$\rightarrow 1\pi^- + X$	38,012
$\rightarrow 1\pi^0 + X$	406,555
$\rightarrow 2\pi + X$	145,336
$\rightarrow \geq 3\pi + X$	42,510
$\rightarrow K^+K^- + X$	521
$\rightarrow K^0\bar{K}^0 + X$	582
$\rightarrow \Sigma_c^{++} + X$	294
$\rightarrow \Sigma_c^{+} + X$	98
$\rightarrow \Lambda_c^{+} + X$	672
ν_e Inclusive	**$\approx$ 12,000**

Neutral Current

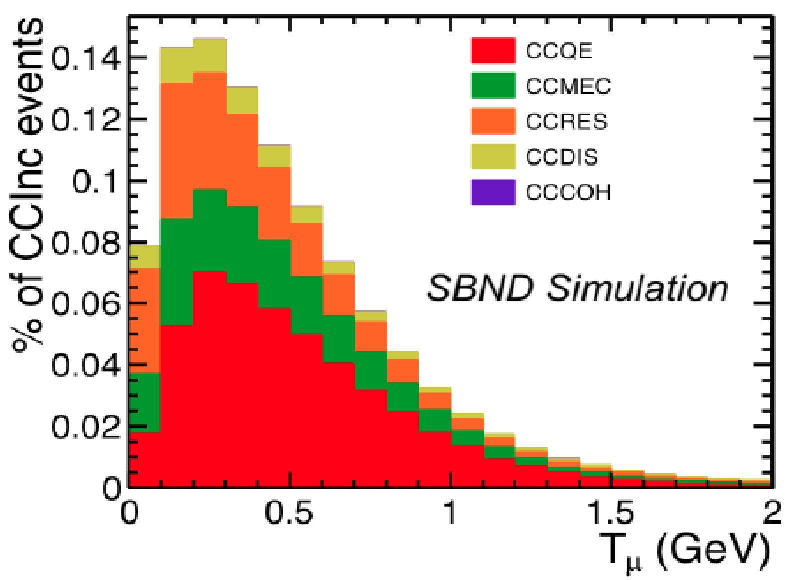
Inclusive	2,170,990
$\rightarrow 0\pi$	1,595,488
$\rightarrow 1\pi^\pm + X$	231,741
$\rightarrow \geqslant 2\pi^\pm + X$	343,760
$\rightarrow e(^-)$	374

SBND will see a huge event rate.

Enables precision measurements of neutrino cross-sections and nuclear effects.

Crucial for energy reconstruction in oscillation measurements.

A multitude of exclusive channels



SBND event rates for rare event searches

Charged Current	
ν_μ Inclusive	5,389,168
$\rightarrow 0\pi$	3,814,198
$\longrightarrow 0p$	27,269
$\longrightarrow 1p$	1,261,730
$\longrightarrow 2p$	1,075,803
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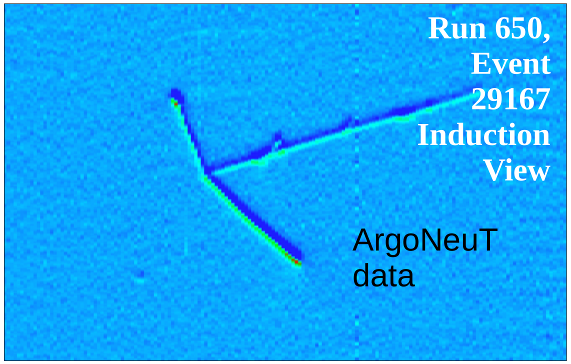
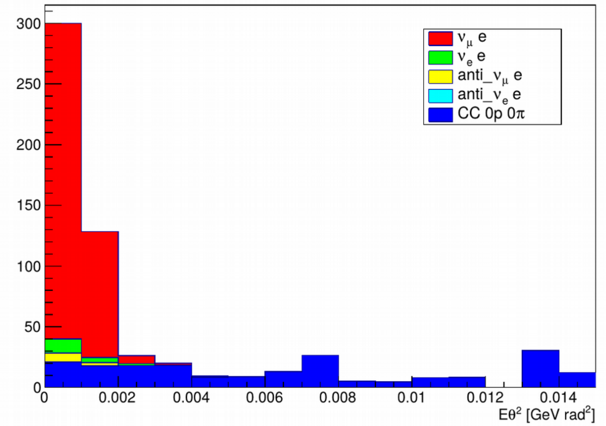
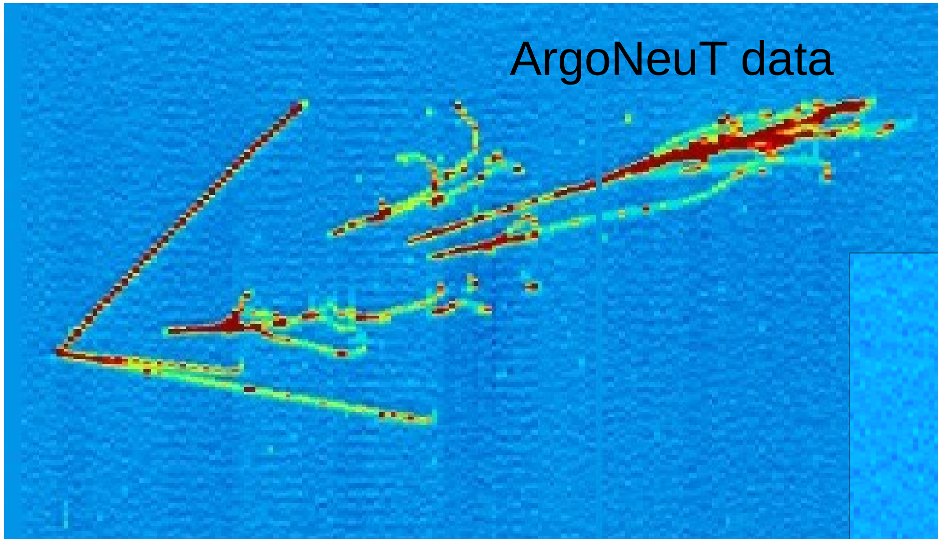
Inclusive	2,170,990
$\rightarrow 0\pi$	1,595,488
$\rightarrow 1\pi^\pm + X$	231,741
$\rightarrow \geqslant 2\pi^\pm + X$	343,760
$\rightarrow e(^-)$	374

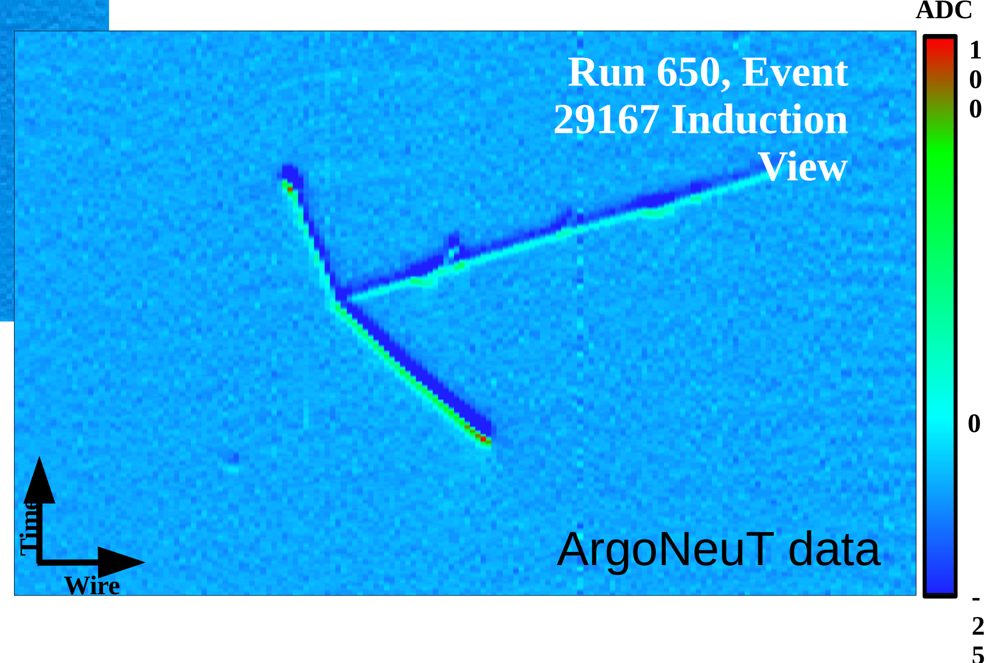
- Two proton events will no longer be “rare”
- v. large sample of electron neutrinos.
- significant number of hyperons produced.
- Electron scattering measurements also possible.

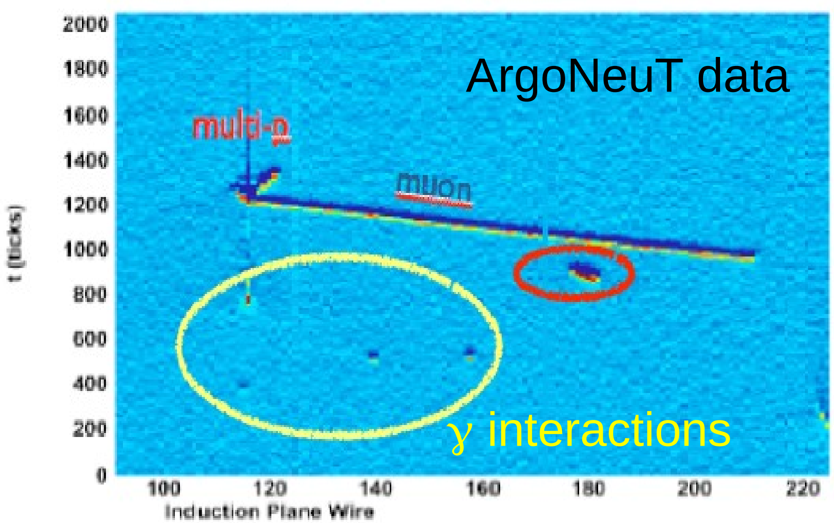




Neutrino interactions in LArTPCs

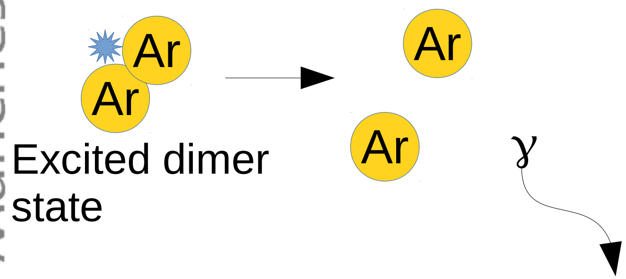




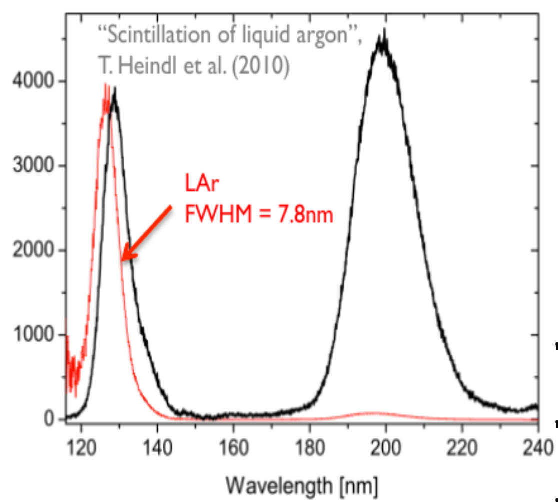


Scintillation Light in Argon

Emission:



Photons are all ~128 nm – VUV

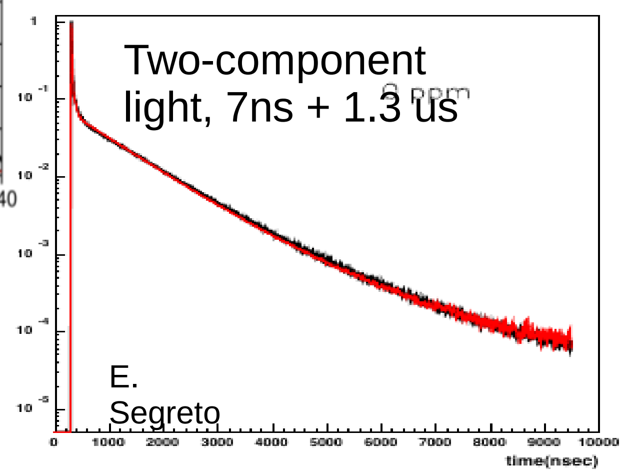


Transport:

Liquid argon is mostly transparent to its scintillation.

At longer distances Rayleigh scattering ~55cm f(λ) and absorption, e.g. on nitrogen ~30 m @2ppm N_2 begins to play a role.

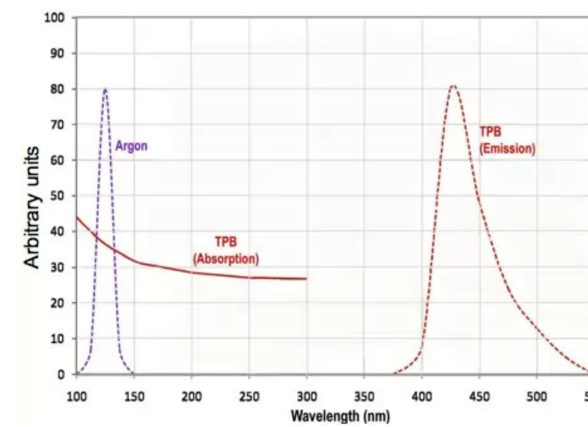
Note high refractive index ~1.5 for VUV.



Detection:

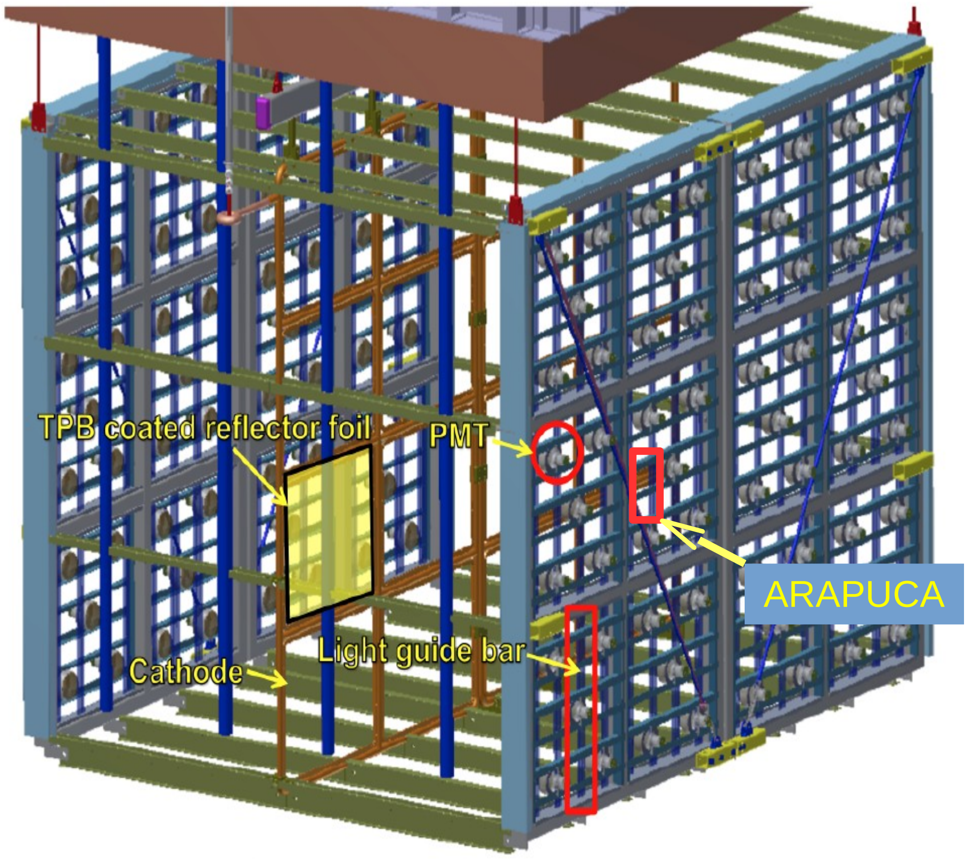
Liquid argon is almost the only thing transparent to its scintillation.

Detection is challenging – most often need to use Wavelength shifting compounds, like TPB.



Scintillation Light Detection in SBND

- Important R&D aspect
- Scintillation light applications:
  - trigger, t_0
  - background rejection
  - calorimetry, particle ID
- **Mounted on anode planes:**
  - PhotoMultiplier Tubes
  - ARAPUCA/X-ARAPUCA light traps
- **Mounted on cathode planes:**
  - WLS covered reflector foils



Boosting Light Collection

- Adding wavelength-shifting surface at the cathode recovers a large fraction of light that would normally be lost.
- The SBND LDS enables new applications of argon scintillation light – calorimetry, timing, drift position reconstruction.
- Enhancement expected especially at low energies.
- Largest WLS coated area (38m2) in a detector to date.