JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Symmetry Breaking

PRISMA

Neutrino Physics

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Summary on “solar” oscillations

- **“Disappearance”**
  - Borexino and Super-K confirm electron neutrino disappearance as predicted by the MSW effect
  - This was earlier observed by Ray Davis and the Gallium experiments
  - KamLAND has observed consistent electron anti-neutrino disappearance
- **“Appearance”**
  - SNO has observed that the total number of neutrinos from the Sun is fixed, and indirectly observed ν_μ and ν_τ appearance
  - Why not “direct” observation?

the picture looks consistent with neutrino mixing and oscillations!

Confirming atmospheric oscillations

- We need an experiment sensitive to

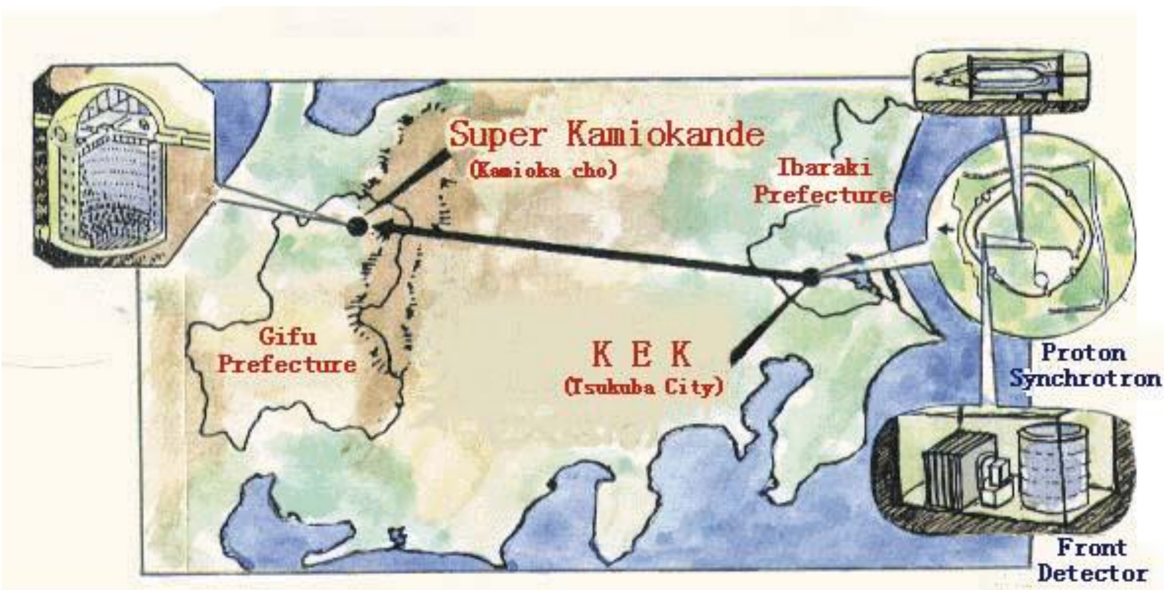
$$\boxed{\Delta m^2_{23}(eV^2)\frac{L(km)}{E(GeV)} \sim 2.5\cdot 10^{-3}\frac{1.3\cdot 10^4}{10} \sim 3}$$

$$\cancel{\Delta m^2_{12}(eV^2)\frac{L(km)}{E(GeV)} \sim 7\cdot 10^{-5}\frac{1.3\cdot 10^4}{10} \sim 0.1}$$

not yet developed…

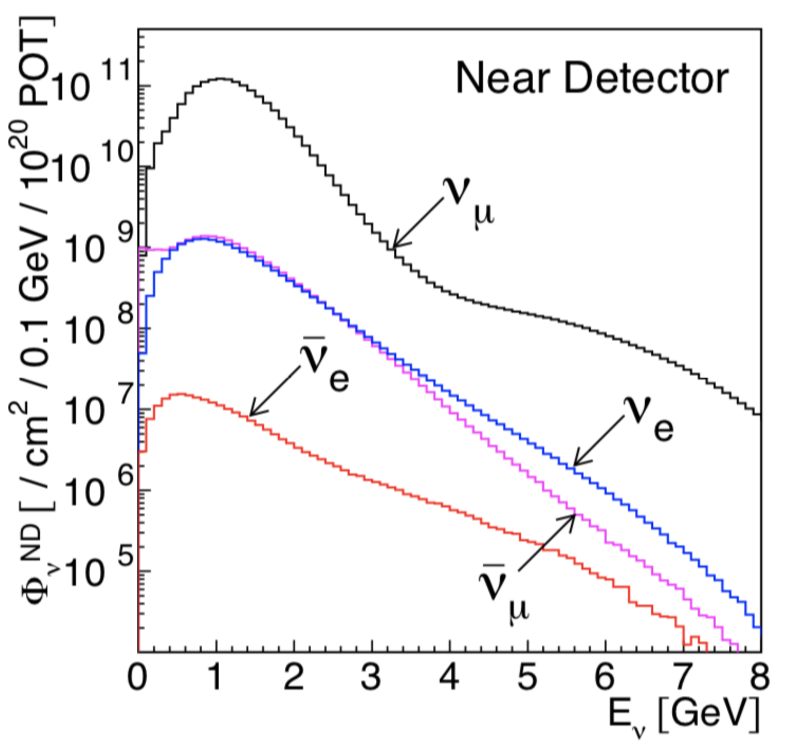
- Basically confirming ν_μ disappearance into ν_τ as observed by Super-K:
    - **using accelerator based neutrino beams for the first time!**
    - K2K and MINOS experiments
- Confirming ν_μ **disappearance is NOT enough! One needs to also see ν_τ appearance**
    - OPERA experiment

The K2K (KEK to Kamioka) experiment



- Operated 1999-2004, first long baseline neutrino oscillation experiment
- Baseline ~250km
- Neutrino energy ~ 1GeV
- We will discuss more extensively neutrino production at accelerators tomorrow
- Near-Far detector concept

$$\Delta m^2_{23}(eV^2)\frac{L(km)}{E(GeV)} \sim 2.5 \cdot 10^{-3}\frac{250}{1} \sim 0.6$$



Near Detector

Far Detector

ν_μ

Neutrino productio
n

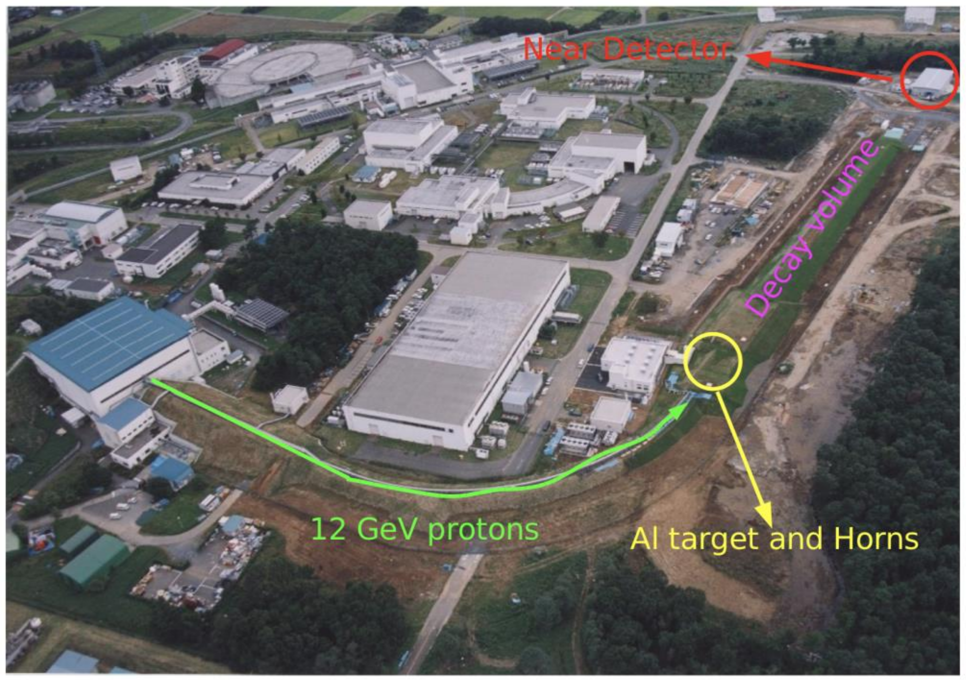
oscillation develops…

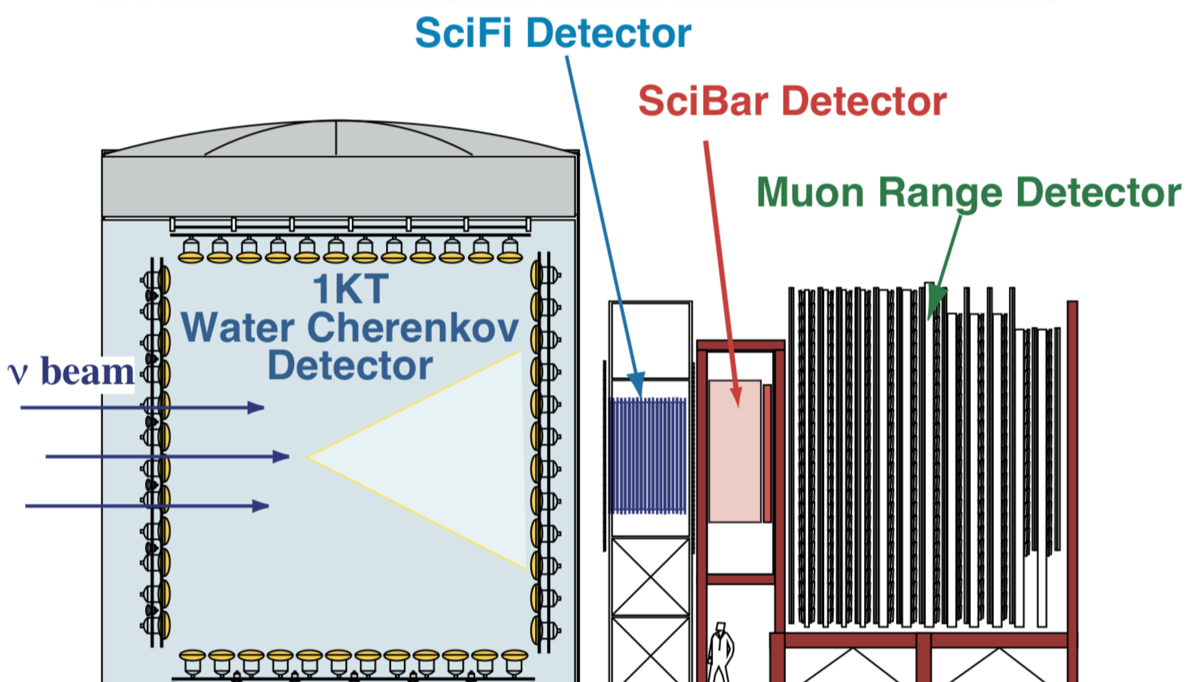
Measure original spectrum and neutrino interaction rate

Measure oscillated spectrum

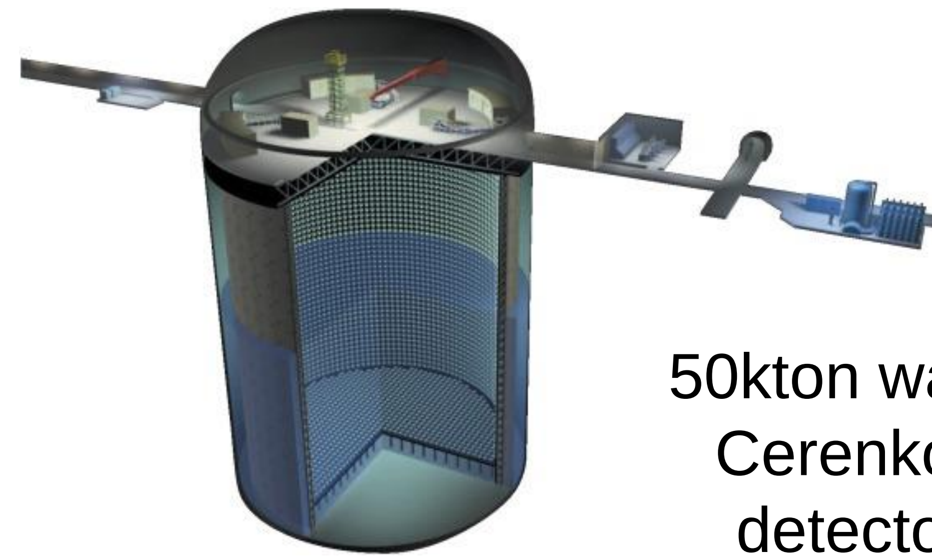
K2K Near and Far detectors

Near Detector @ KEK

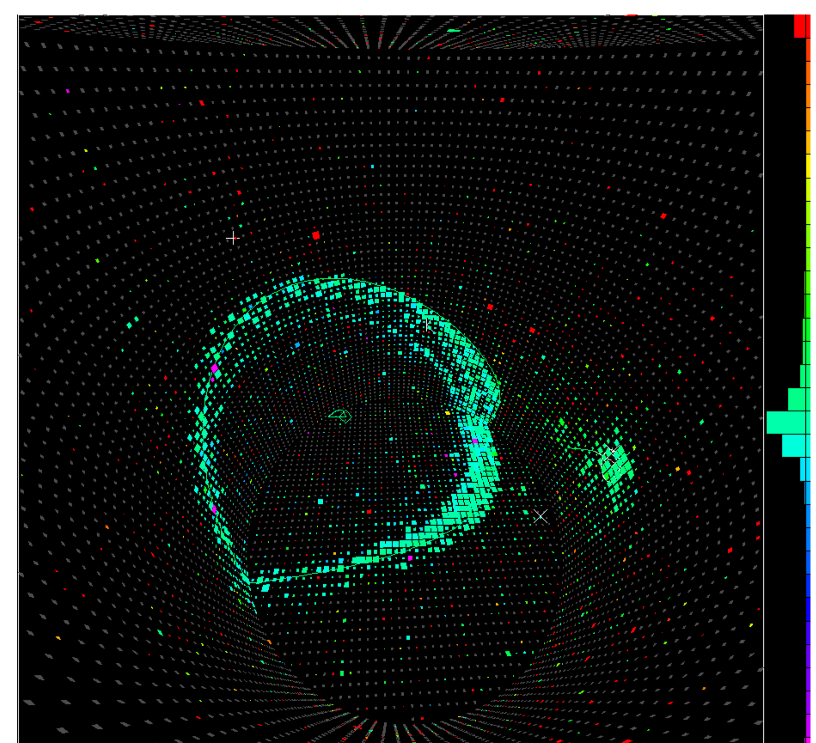




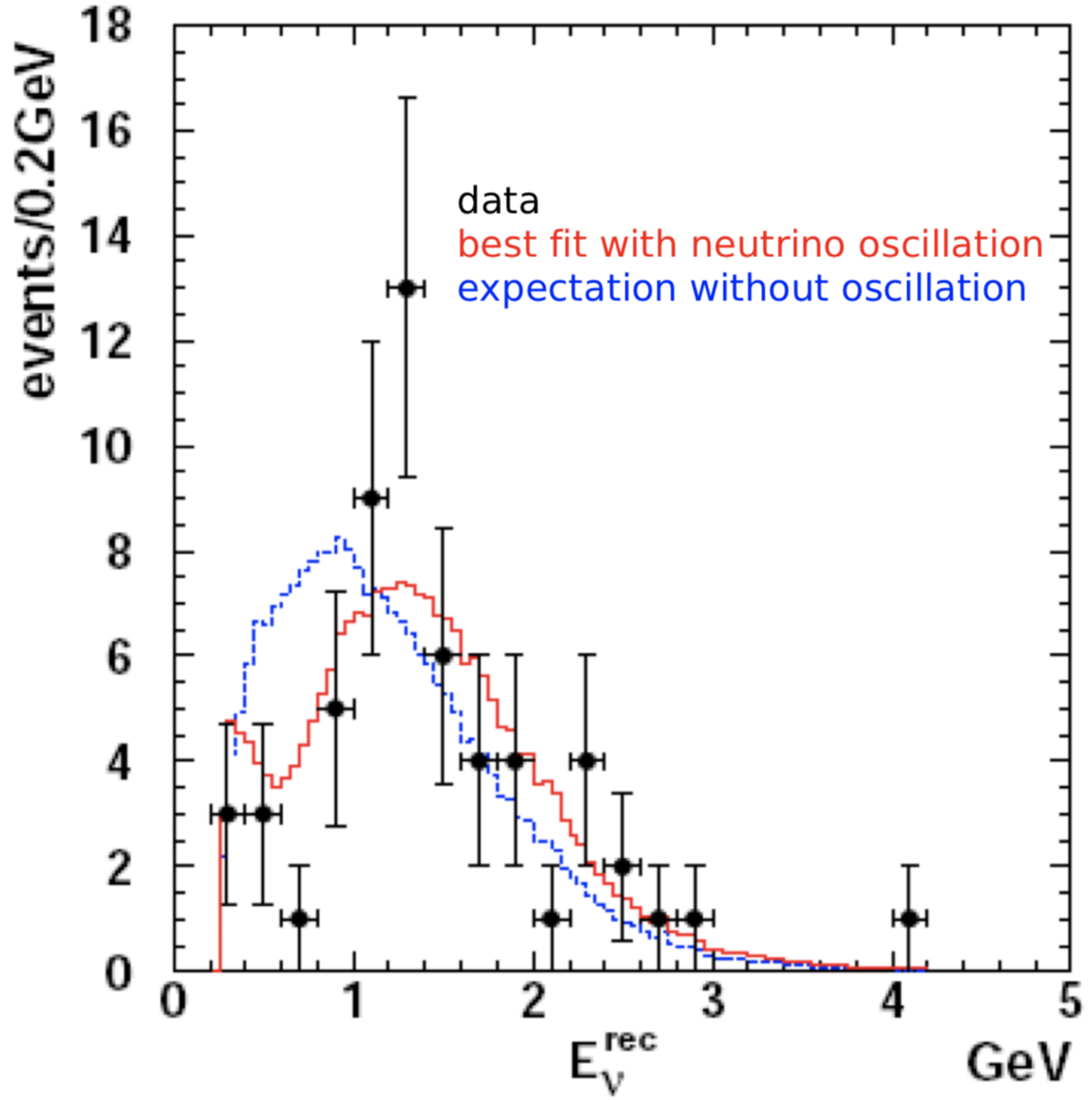
Far Detector is Super-K at Kamioka mine

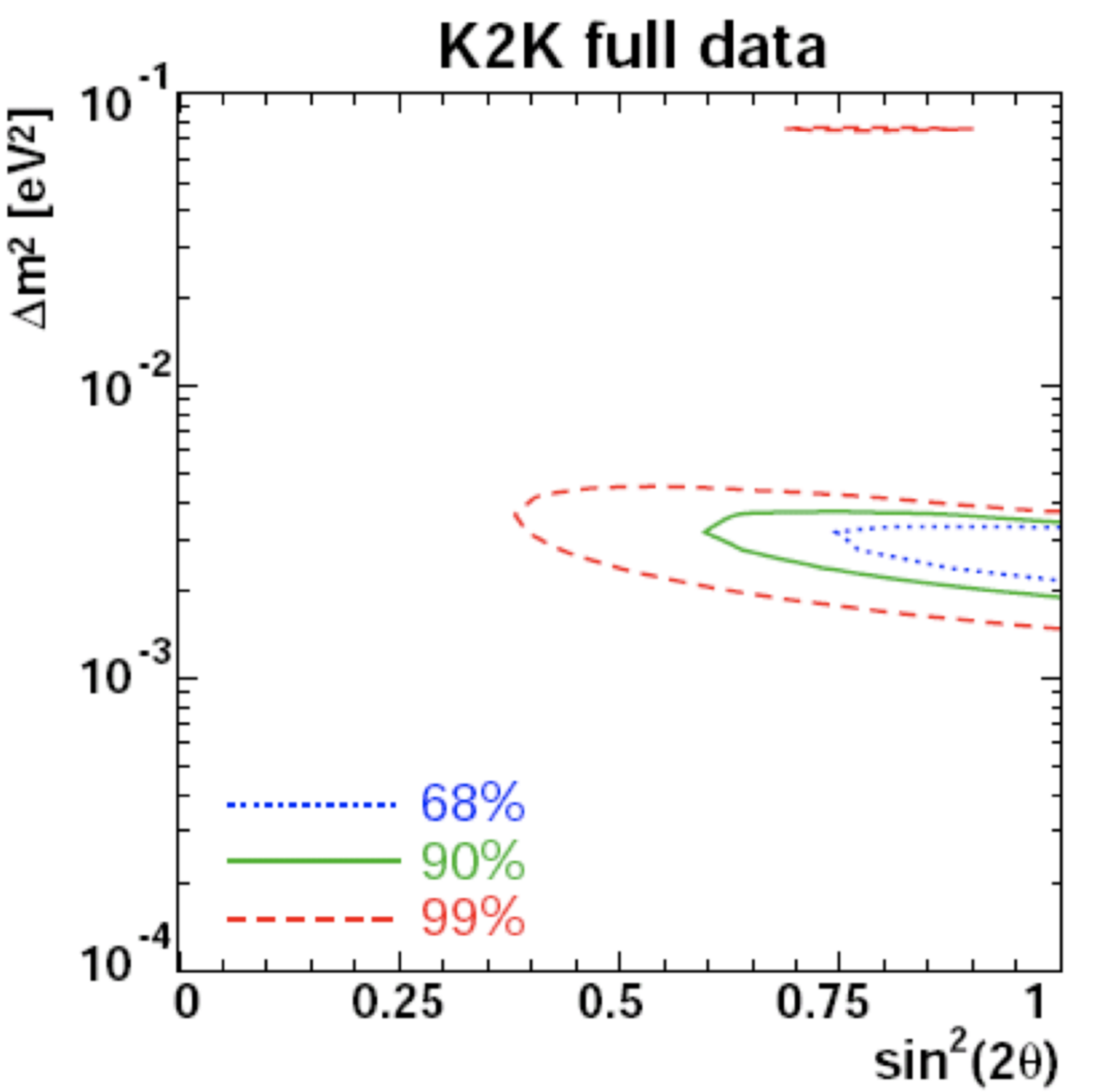


50kton water Cerenkov detector



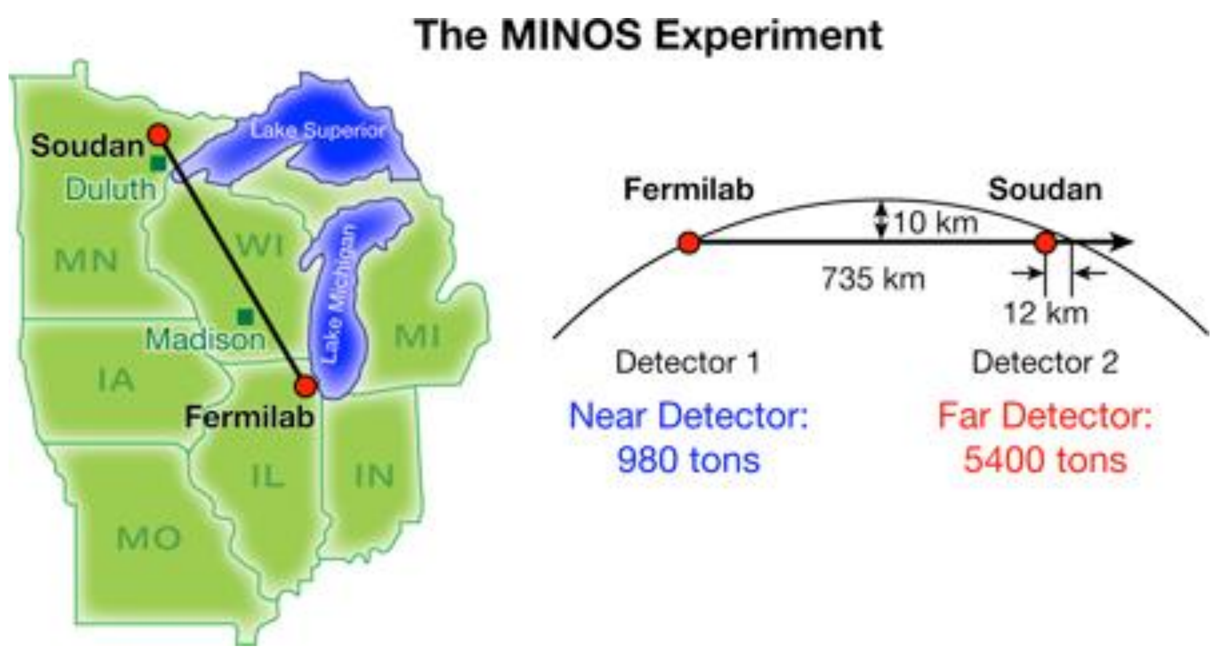
K2K oscillation results





- $\Delta m^2 = \Delta m_{23}^2$ and $\theta = \theta_{23}$ here
- Mixing seems maximal, i.e. $\theta_{23} \sim \pi/4$

The MINOS experiment at Fermilab

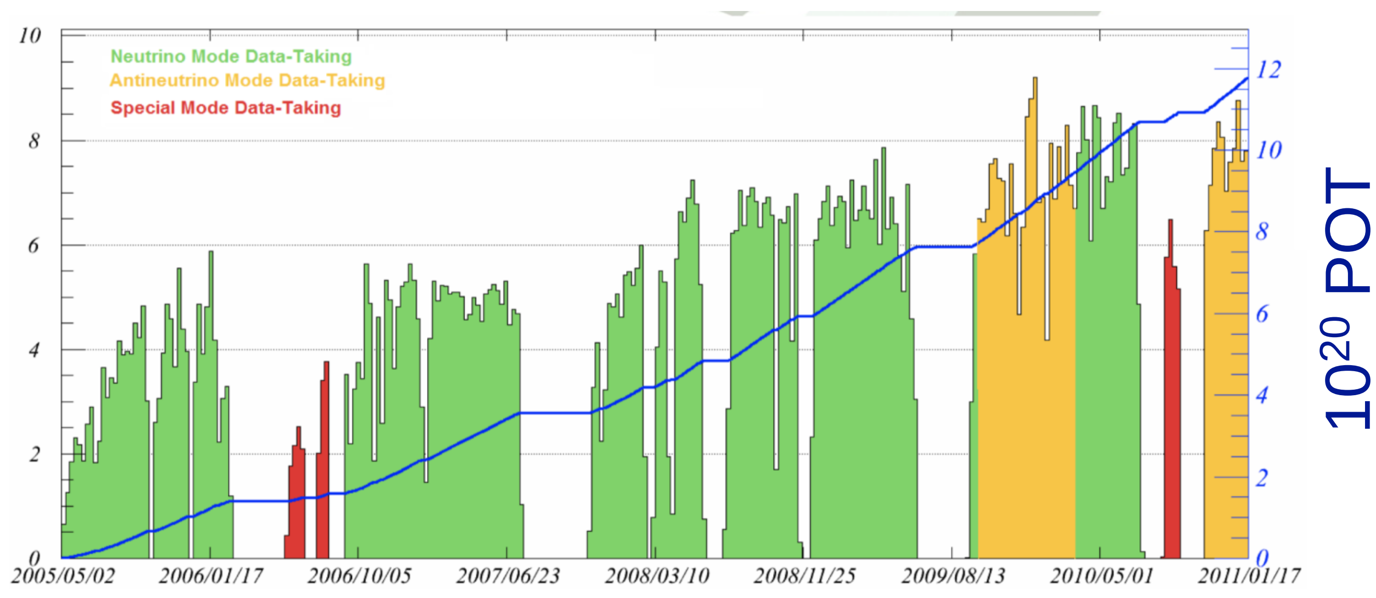


- Long baseline neutrino oscillation experiment
- Uses the NuMI (Neutrino Main Injector) neutrino beam at Fermilab
- Neutrino energy ~1-5 GeV
- Baseline 735km
- Atmospheric neutrino L/E!
- Able to measure both ν_μ and anti-ν_μ disappearance

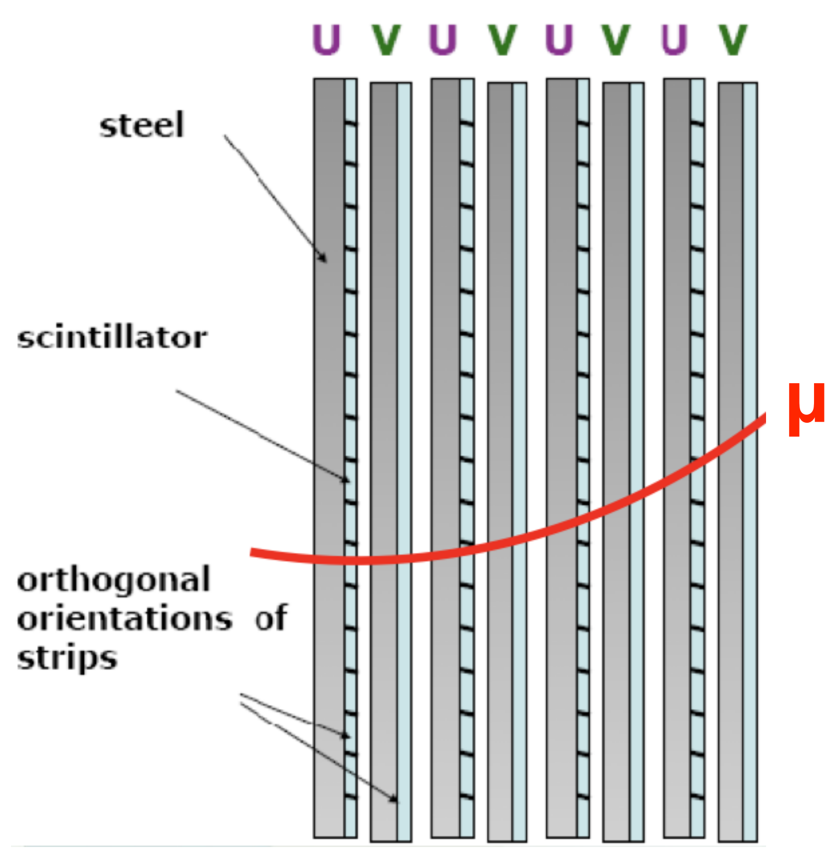
Near Detector

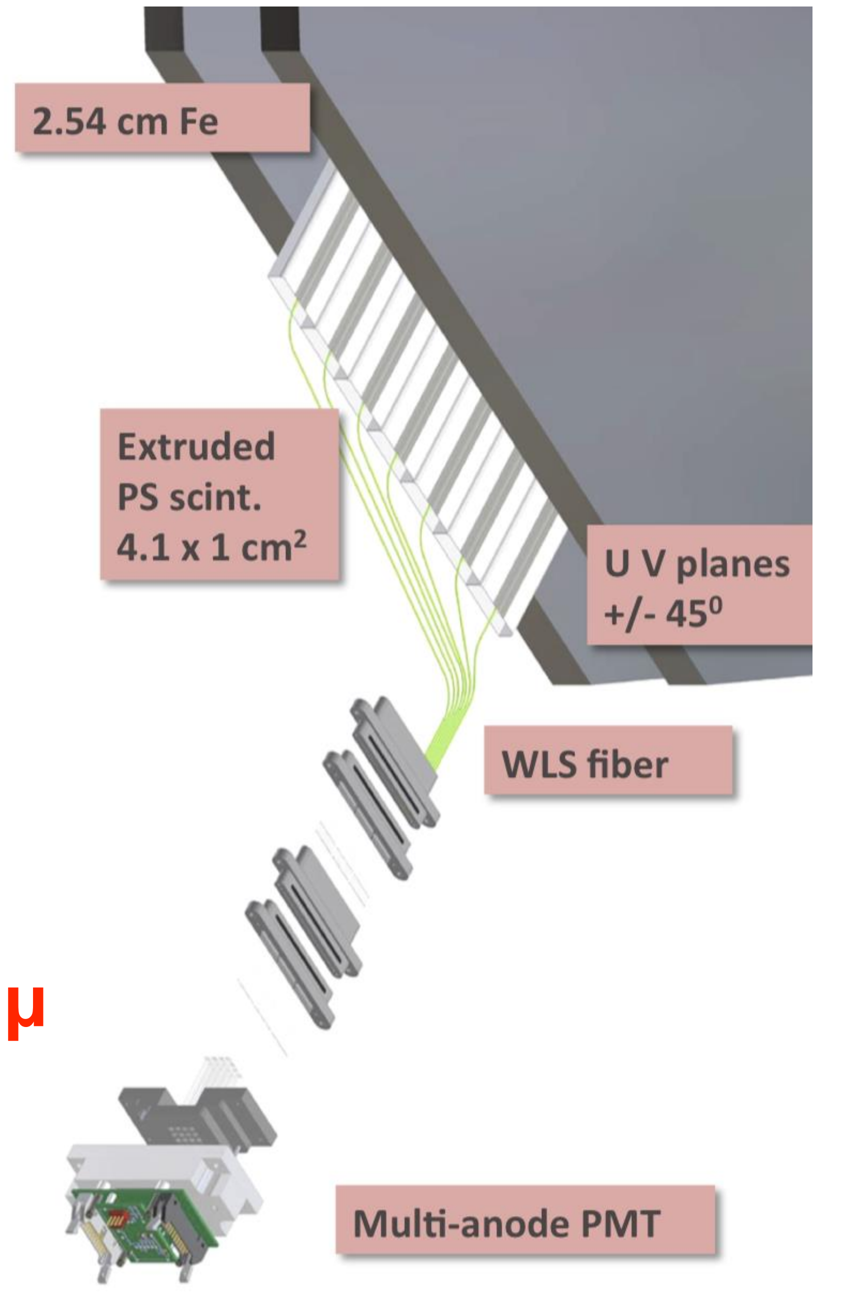
Far Detector

Detector technology



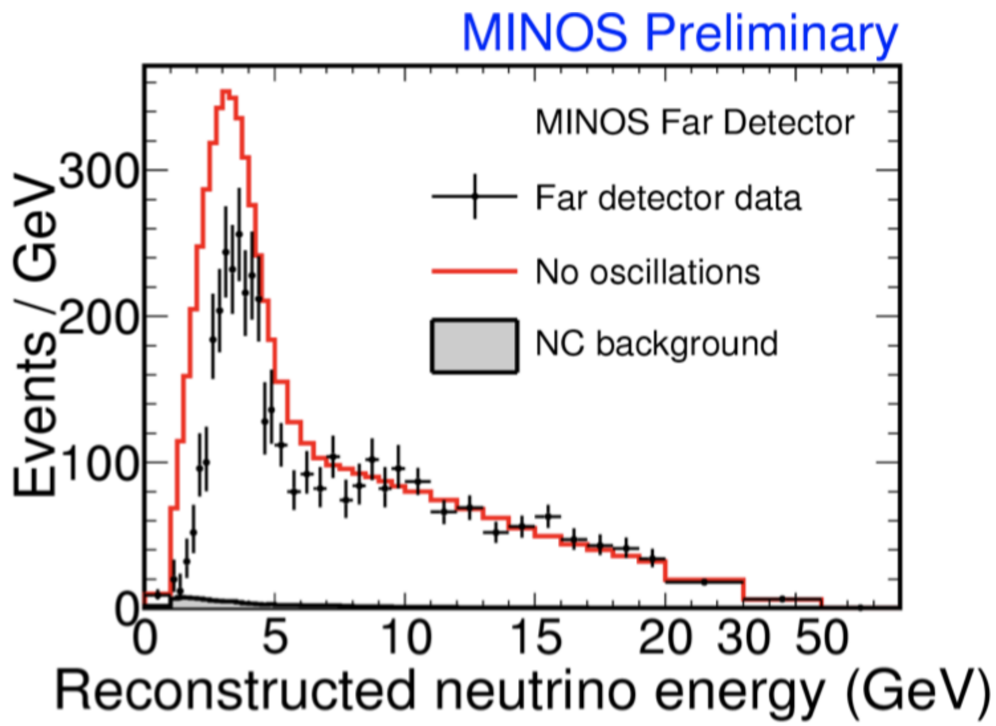
- Tracking sampling calorimeters:
  - steel absorber 2.5cm thick (1.4 X_0)
  - scintillator strips 4.1cm wide (1.1 Moliere radii)
- Magnetized (1.3 T)
  - can distinguish between μ^- and μ^+
- Near and Far detector are functionally identical

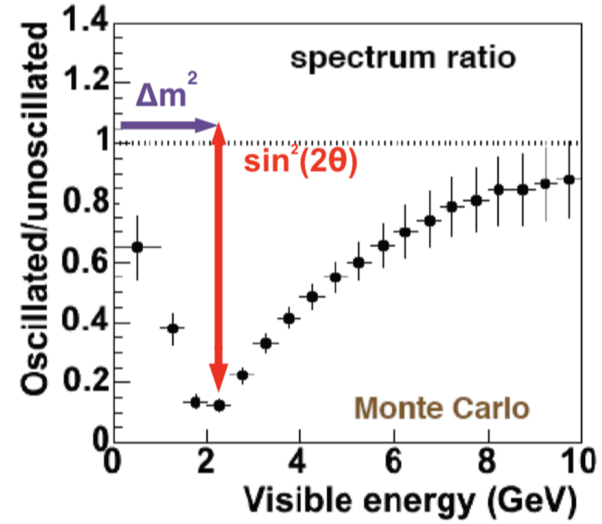


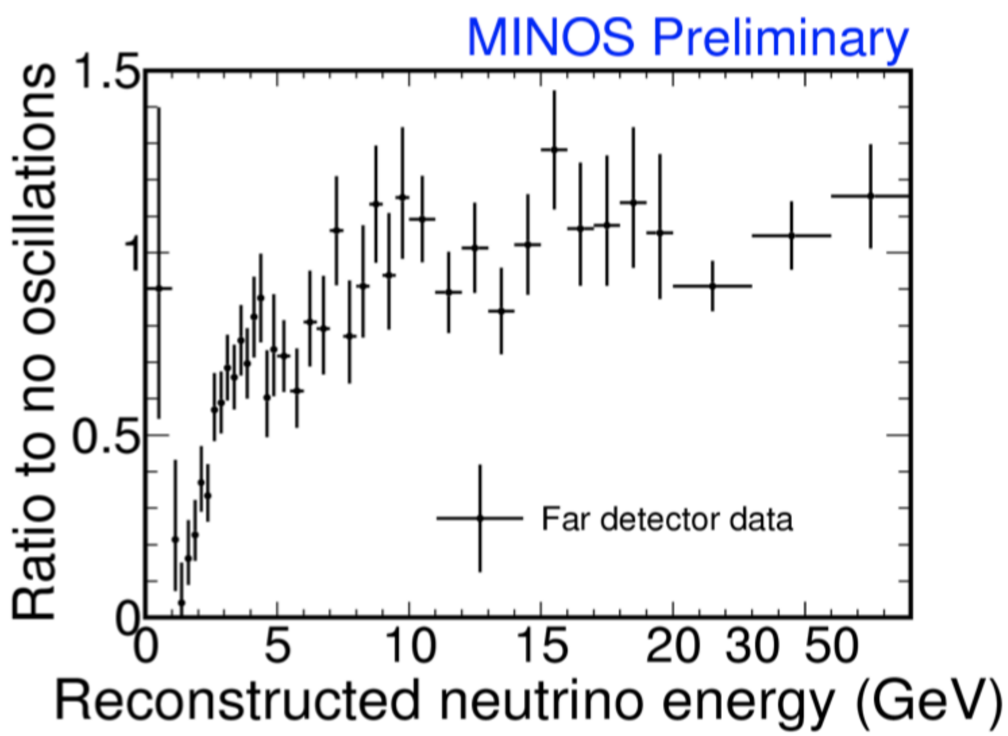


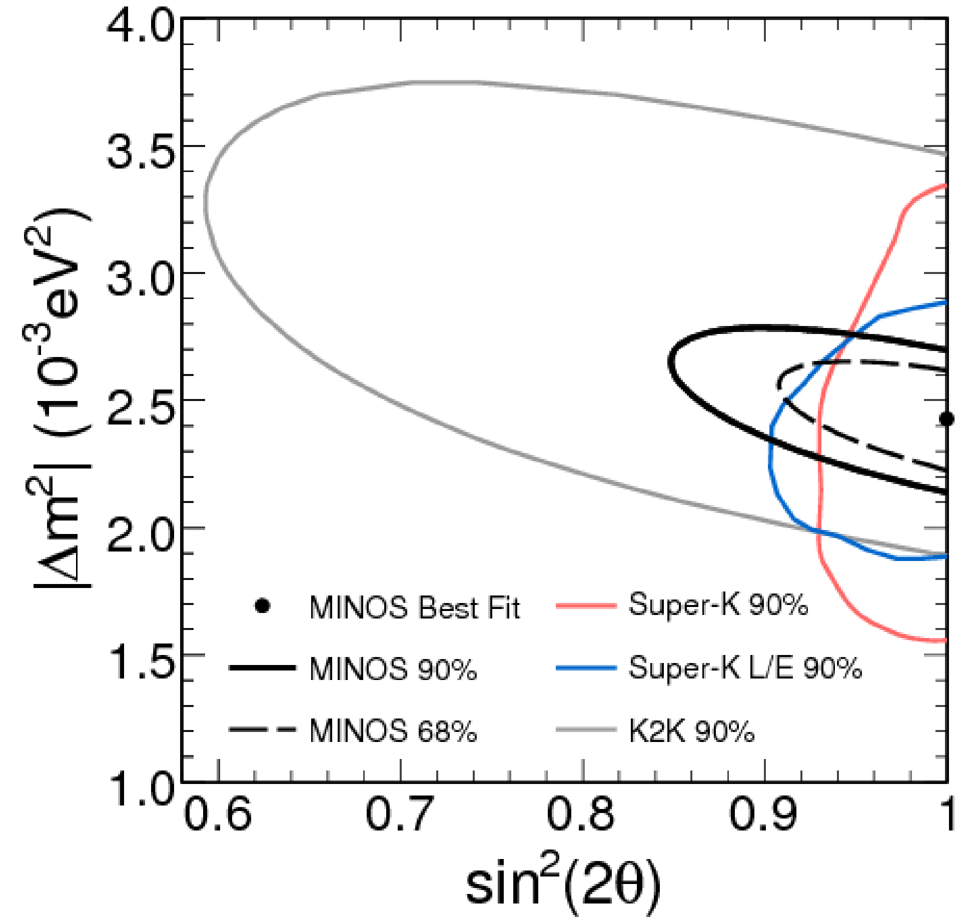
MINOS oscillation results

consistent results with K2K and Super-K! ✔



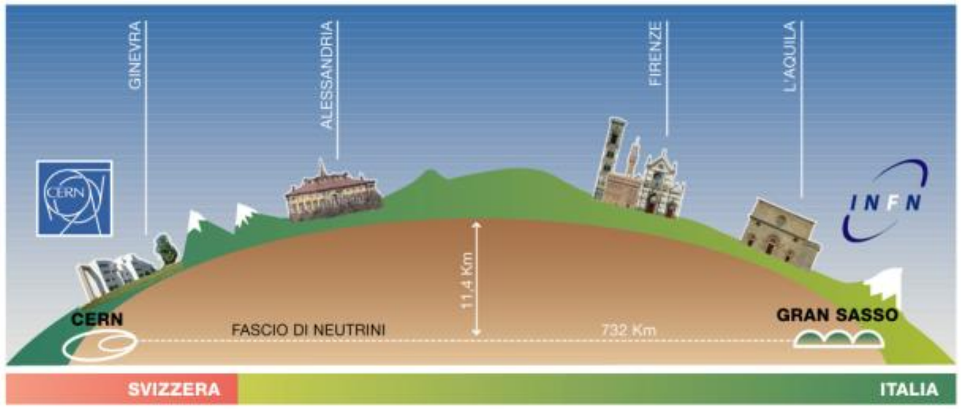


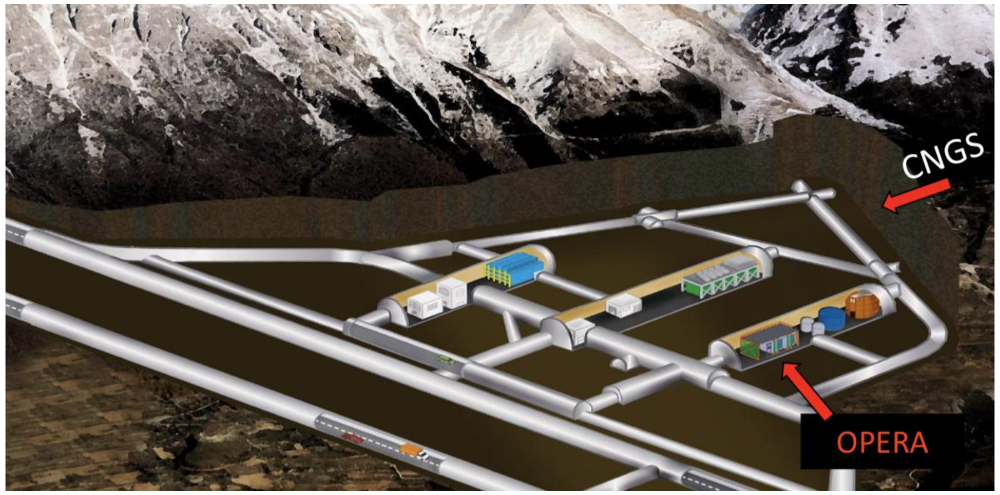


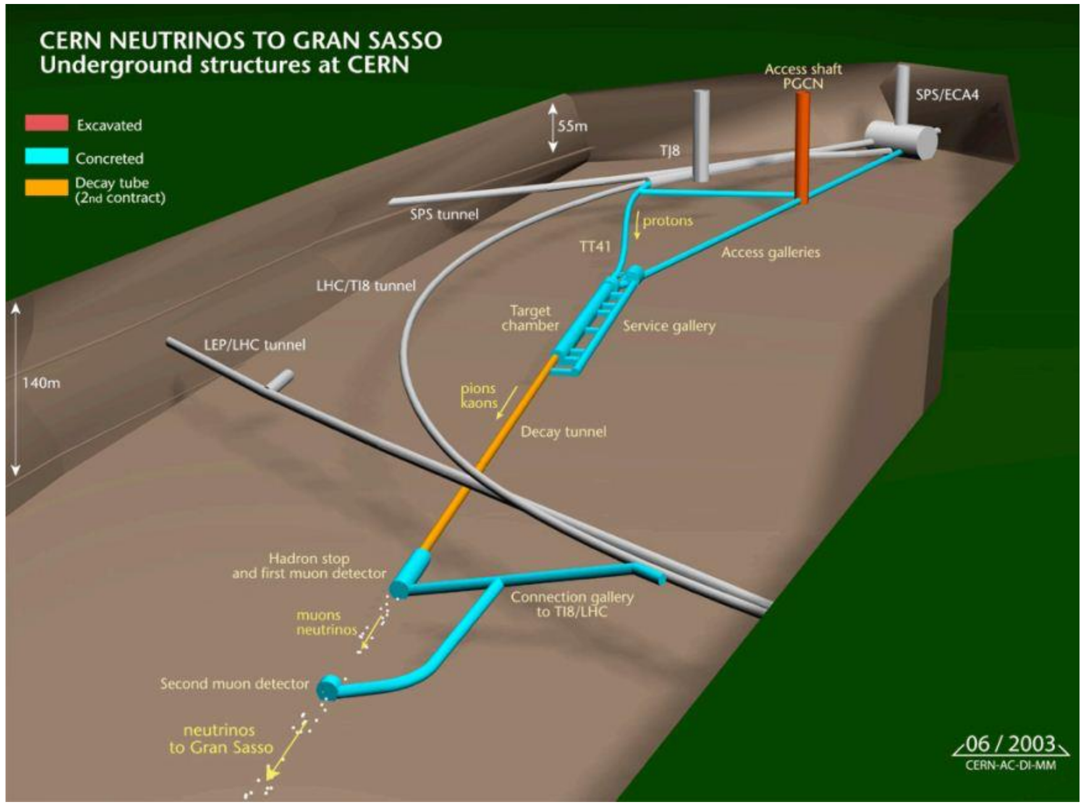


How about ν_τ appearance in a ν_μ beam?

- The picture of ν_μ disappearance looks consistent. But **we need evidence of ν_τ appearance to definitely confirm the model**
- You need a very energetic neutrino beam to directly detect τ's from ν_τ's (M_τ~1.7GeV): $E_\nu > 3.5$ GeV
- CNGS (Cern to Gran Sasso) neutrino beam and the OPERA experiment!

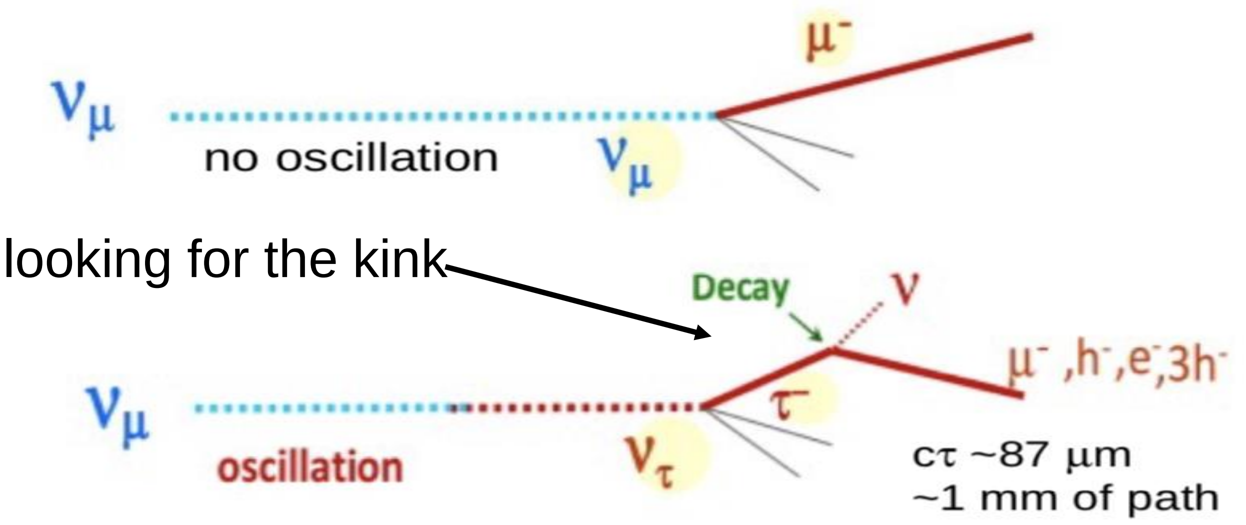


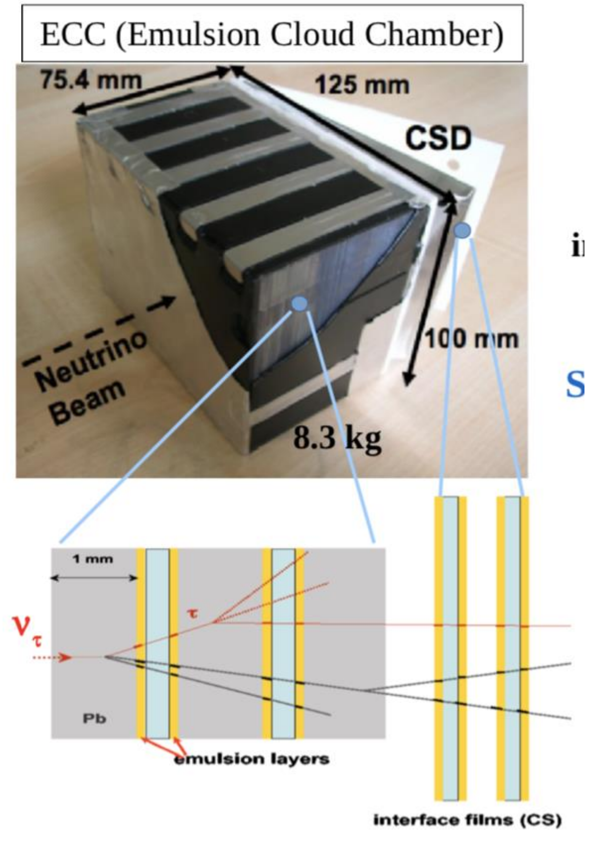


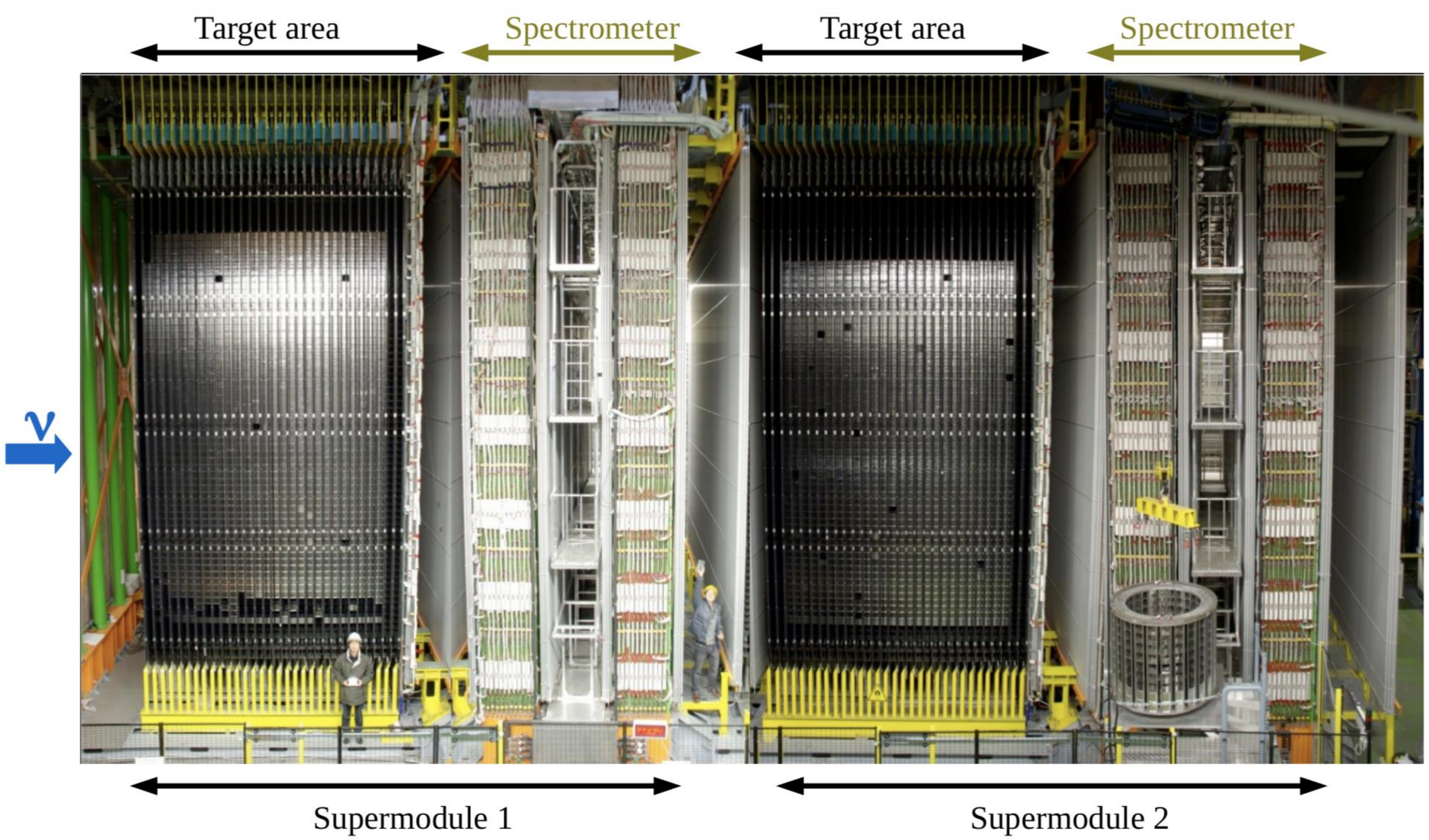


The OPERA experiment

- 730km baseline
- average ν_μ energy 17GeV
- basically zero contamination of ν_τ in the beam. So no need for a far detector!
- nuclear emulsion technology





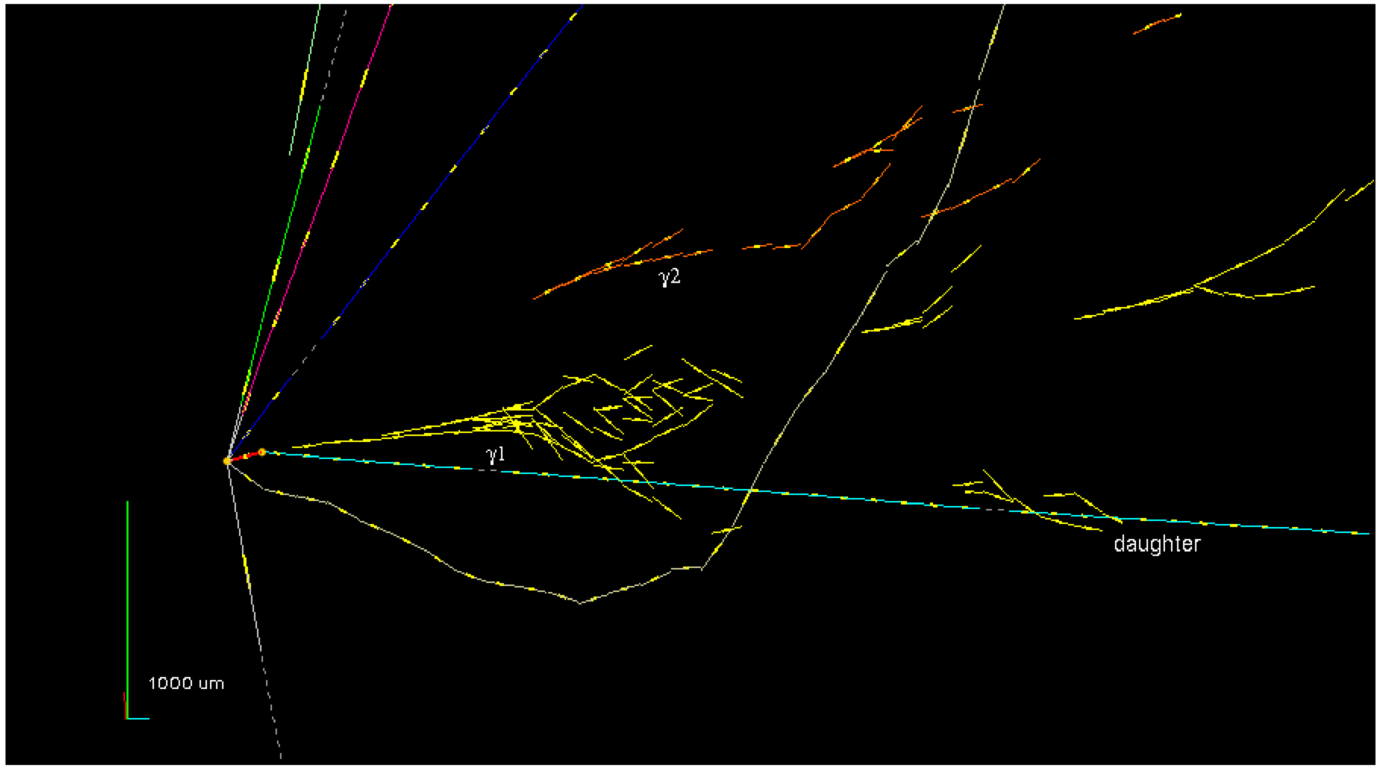


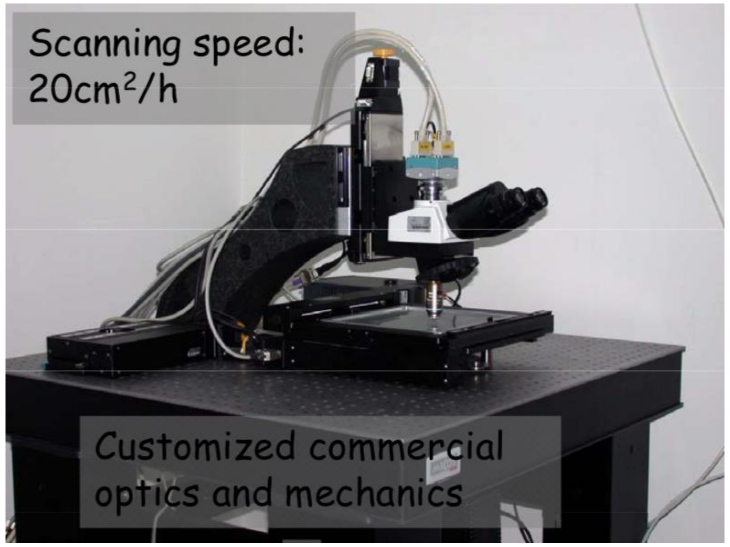
150k ECC for 1.25kton total!

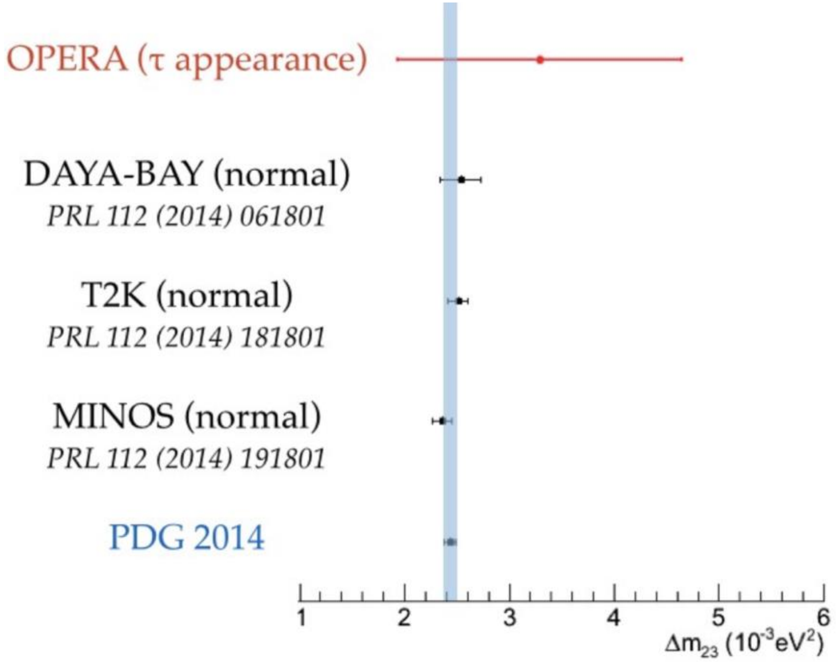
OPERA results

- running 2008-2012 and collecting 1.8 10^{20} POTs
- …observed 10 candidate ν_τ events with an expected background of 2 events
- 6.1σ evidence of ν_τ appearance in a ν_μ beam
- Final results just released: [10.1103/PhysRevLett.120.211801](https://doi.org/10.1103/PhysRevLett.120.211801)
- Every ν_τ observation is a publication. Including DONUT, the total number of observed ν_τ is <20 !!

Phys. Lett. B 691 (2010) 138-145

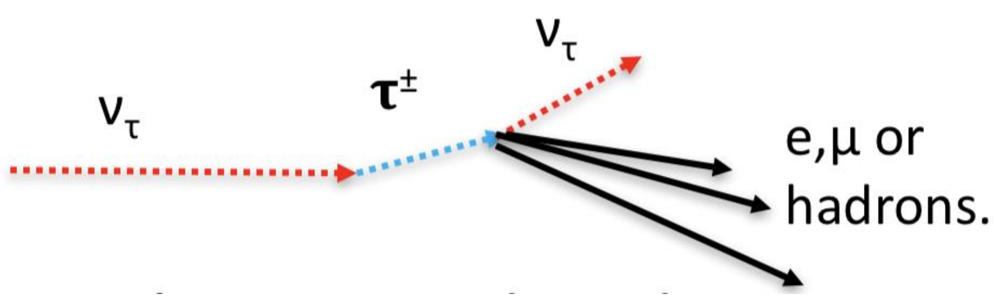


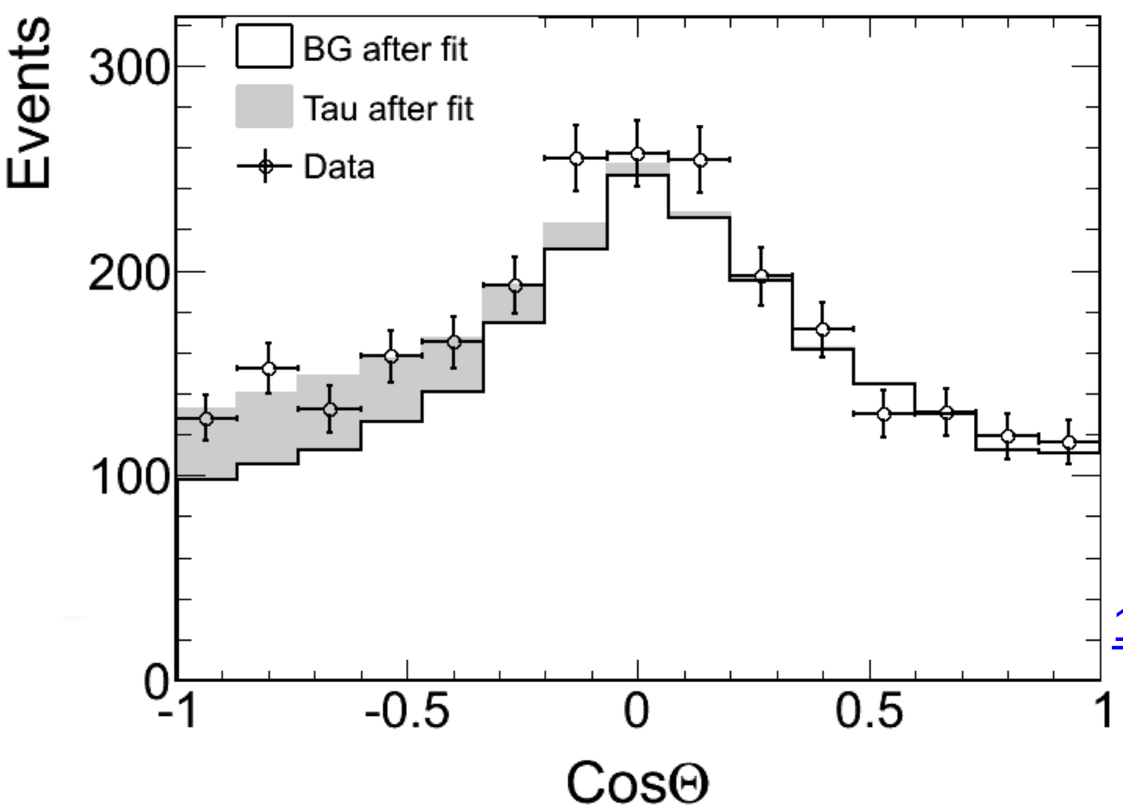




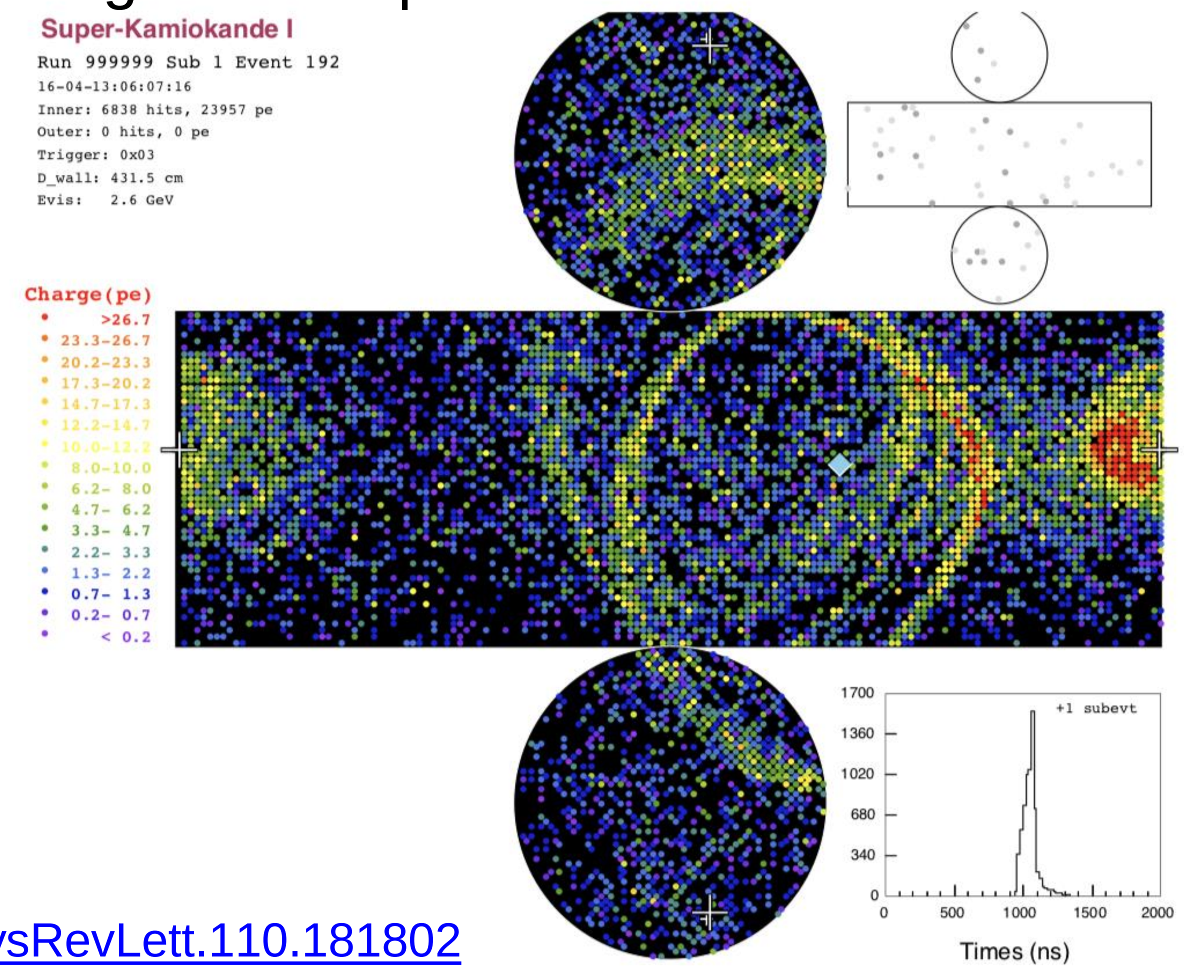
ν_τ appearance is discovered and is compatible with what observed in disappearance channels

Super-K evidence of ν_τ appearance in atmospheric





signal example



10.1103/PhysRevLett.110.181802

Decay mode	Branching ratio (%)
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.41 ± 0.04
$e^-\bar{\nu}_e\nu_\tau$	17.83 ± 0.04
$\pi^-\nu_\tau$	10.83 ± 0.06
$\pi^-\pi^0\nu_\tau$	25.52 ± 0.09
$\pi^-2\pi^0\nu_\tau$	9.3 ± 0.11
$\pi^-3\pi^0\nu_\tau$	1.05 ± 0.07
$\pi^-\pi^+\pi^-\nu_\tau$	8.99 ± 0.06
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$	8.99 ± 0.06
$h^-\omega\nu_\tau$	2.00 ± 0.08

- With a sophisticated analysis, they were able to show an excess of events compatible with ν_τ appearance: but SK is not able to detect directly the τ

Recap

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

U is the PMNS matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

“atmospheric”

1. Atmospheric neutrinos (Super-K), ν disappearance. L/E~ 10^4km / 10GeV
2. K2K and MINOS: accelerator based ν_μ disappearance, L/E ~ 250km / 1GeV
3. OPERA ν_τ appearance, L/E ~ 730 km /17 GeV

“reactor”

We have not discussed this yet. Until a few years ago, θ_{13} was thought to be ~0. This explains this convention: no CP violation if one of the angles is zero!

“solar”

1. Solar neutrino experiments (SNO, Borexino, Ga-Cl), energies ~MeV - NO oscillations but mixing (ve)
2. KamLAND reactor experiment (anti-ve)
3. L/E ~ 100 km/ 10MeV

The hunt for θ_{13}

- After the atmospheric and solar oscillations were fully established, neutrino physicists wanted **to measure θ_{13} : is it zero?**
- **θ_{13} is responsible for ν_e appearance in ν_μ beams**
  - accelerator experiments seem good candidates!
- but also, θ_{13} is needed to describe precisely in the 3 oscillation framework **anti-ν_e disappearance at ~MeV energy**
  - reactor experiments!

Accelerator ve appearance in ν_μ beam L~800 km and E~2GeV are sensitive to θ_{13}

$$\boxed{\Delta m^2_{23}(eV^2)\frac{L(km)}{E(GeV)} \sim 2.5\cdot 10^{-3}\frac{800}{2} \sim 1}$$

$$\Delta m^2_{12}(eV^2)\frac{L(km)}{E(GeV)} \sim 7\cdot 10^{-5}\frac{800}{2} \sim 0.03$$

$$P(\nu_\mu \to \nu_e) \approx \left|\sqrt{P_{\mathrm{atm}}}e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\mathrm{sol}}}\right|^2$$

$$\sqrt{P_{\mathrm{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

Reactor anti-ν_e disappearance searches with L~1km and E~3MeV are sensitive to θ_{13}

$$\boxed{\Delta m^2_{23}(eV^2)\frac{L(km)}{E(GeV)} \sim 2.5\cdot 10^{-3}\frac{1}{3\cdot 10^{-3}} \sim 1}$$

$$\Delta m^2_{12}(eV^2)\frac{L(km)}{E(GeV)} \sim 7\cdot 10^{-5}\frac{1}{3\cdot 10^{-3}} \sim 0.02$$

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1-\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}+\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)$$

Long baseline searches of θ_{13}

- **Long baseline** (~1000km @ ~GeV) accelerator experiments have the potential to measure **θ_{13} through ν_e appearance in a ν_μ beam**
  - this oscillation probability depends on many parameters: mass ordering, δ_{CP}, θ_{23} precise value
  - the probability appearance is *small* (a few %)
- Experiments: NOvA and T2K

- The first indication of θ_{13} != 0 was reported by T2K in 2011: 6 candidate ν_e events (expectation 1.5 events). 2.5σ indication!

10.1103/PhysRevLett.107.041801

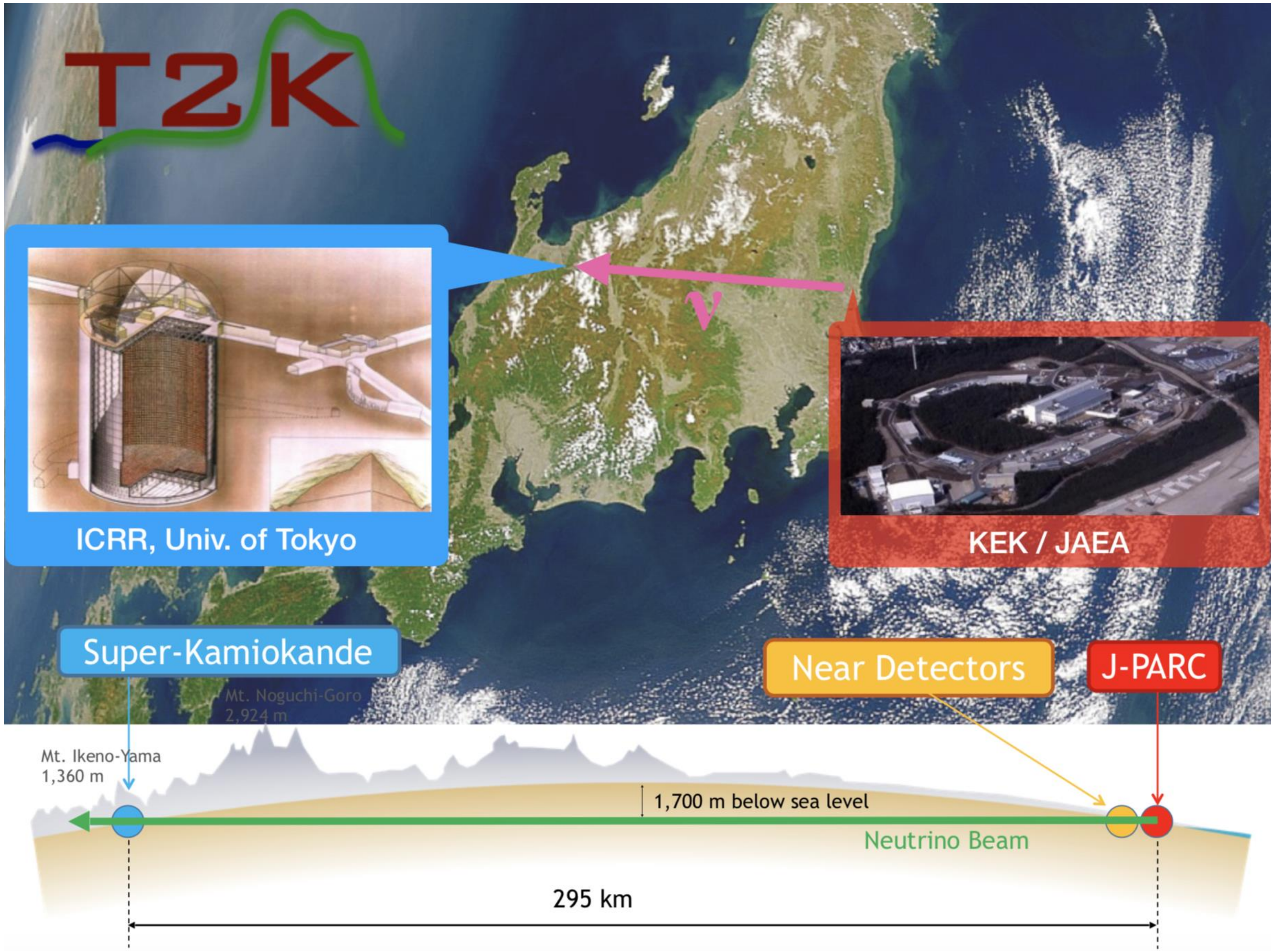
Selected for a Viewpoint in *Physics*

PRL **107,** 041801 (2011) PHYSICAL REVIEW LETTERS week ending 22 JULY 2011

Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam

The T2K experiment

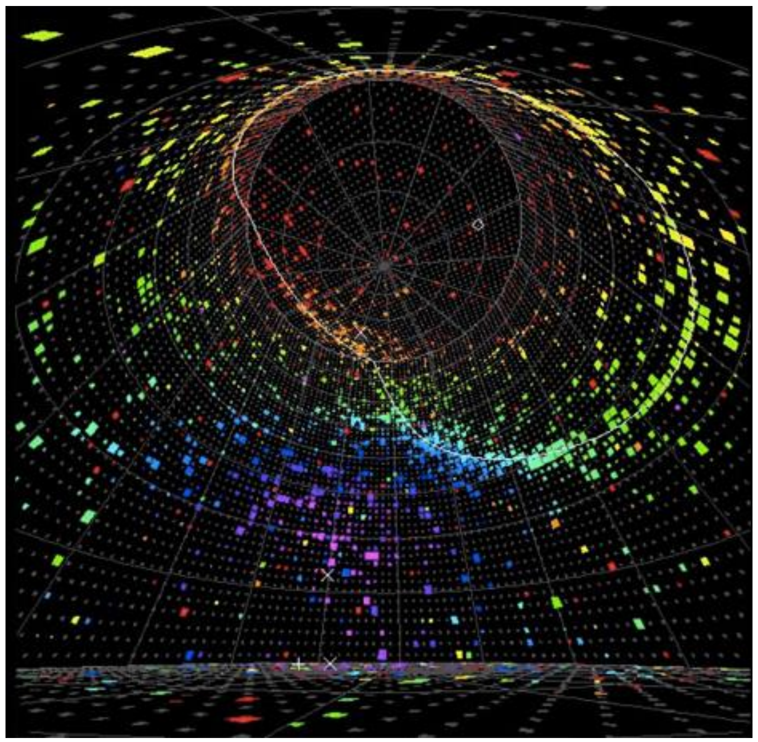
from T2K's Neutrino 2018 talk



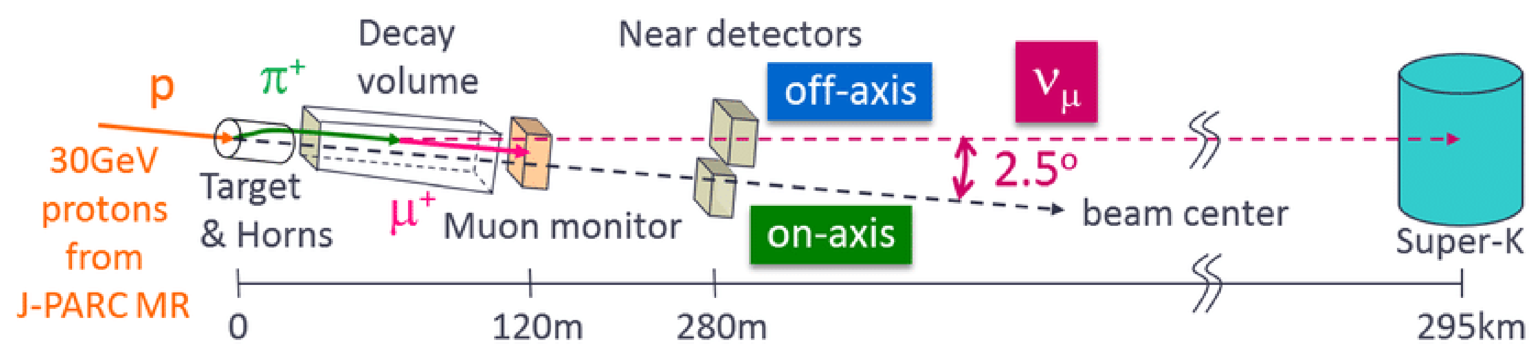
more on this tomorrow!

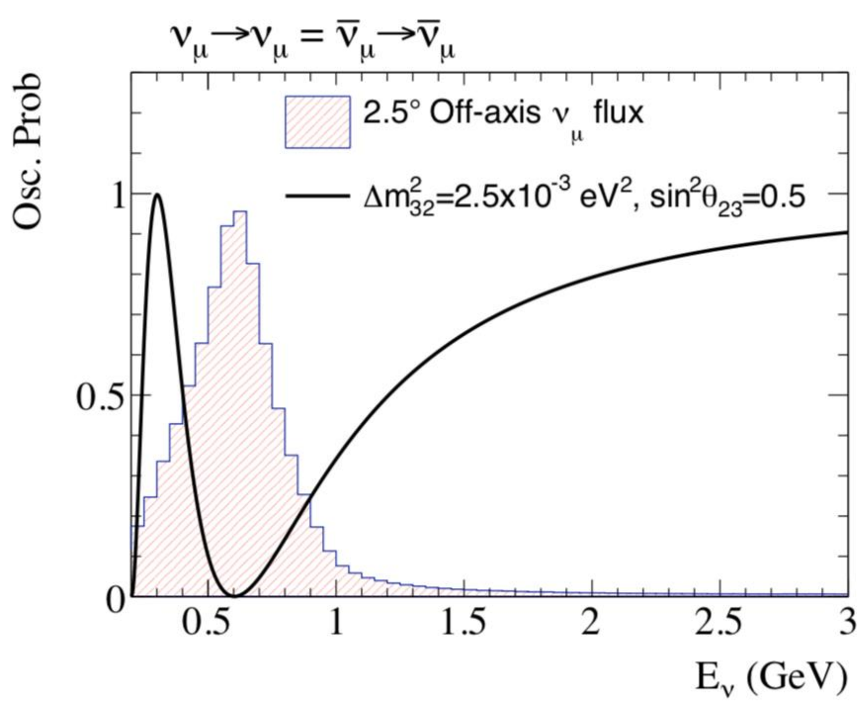
The T2K experiment

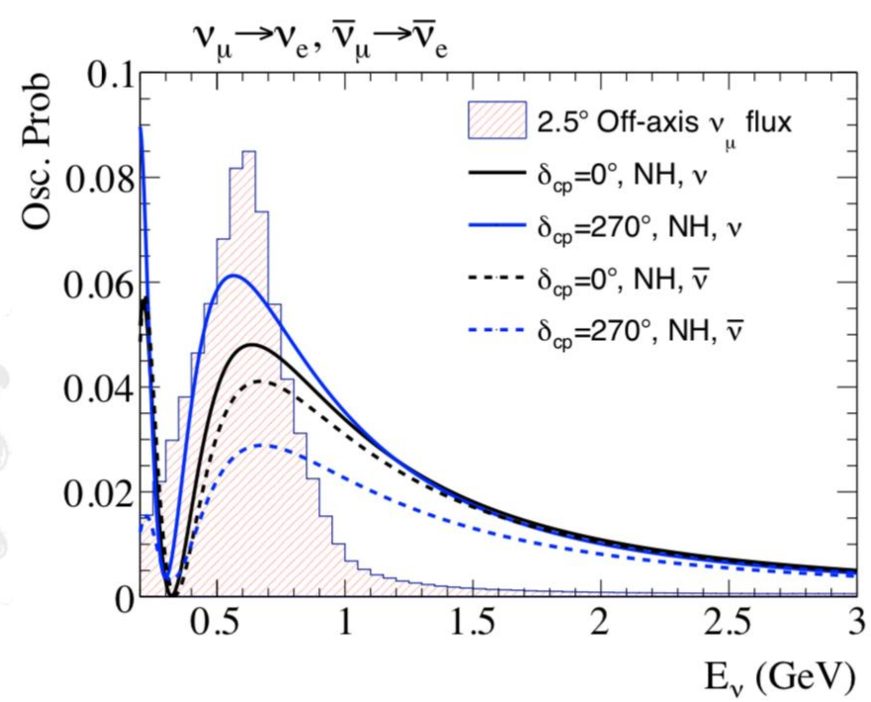
from T2K's Neutrino 2018 talk



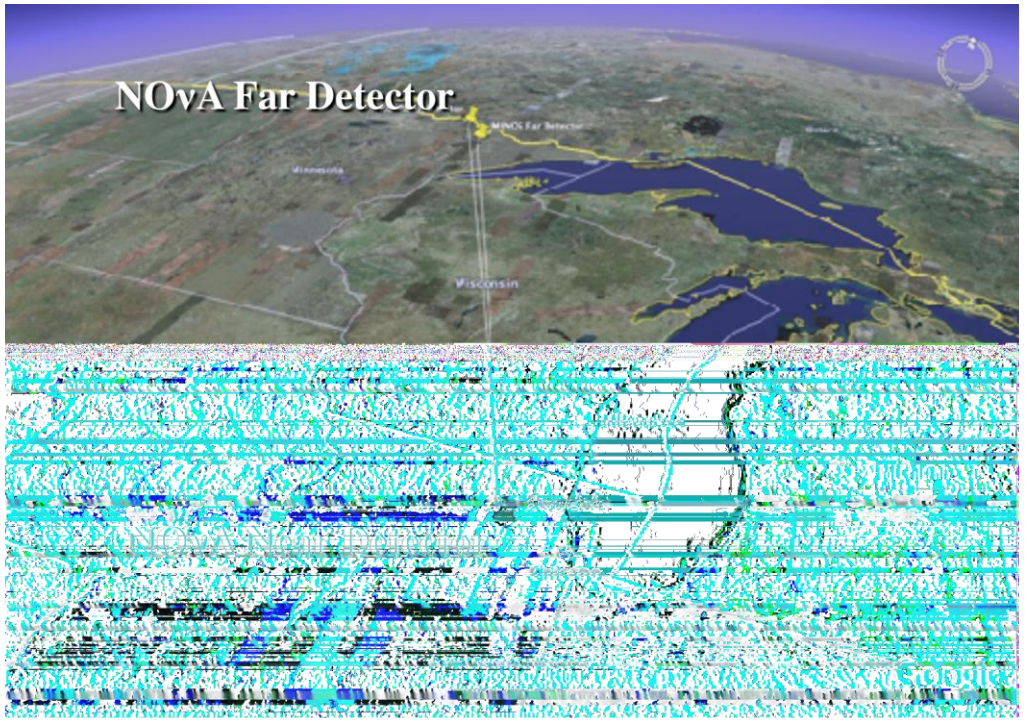
yes, again Super-K!

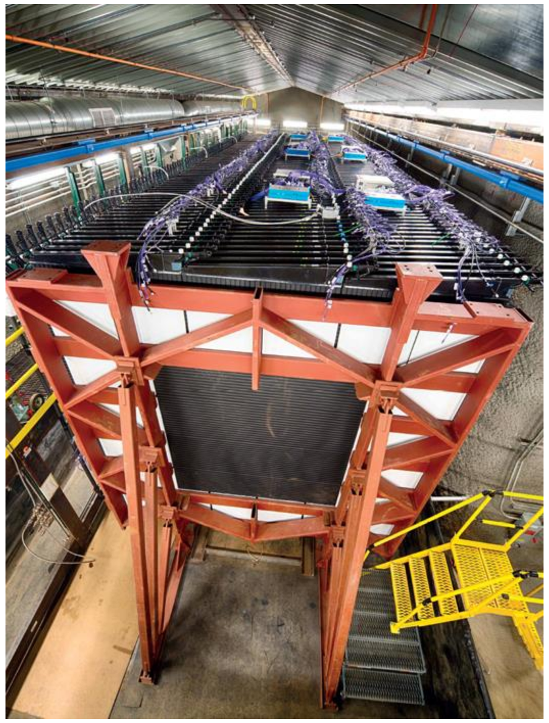




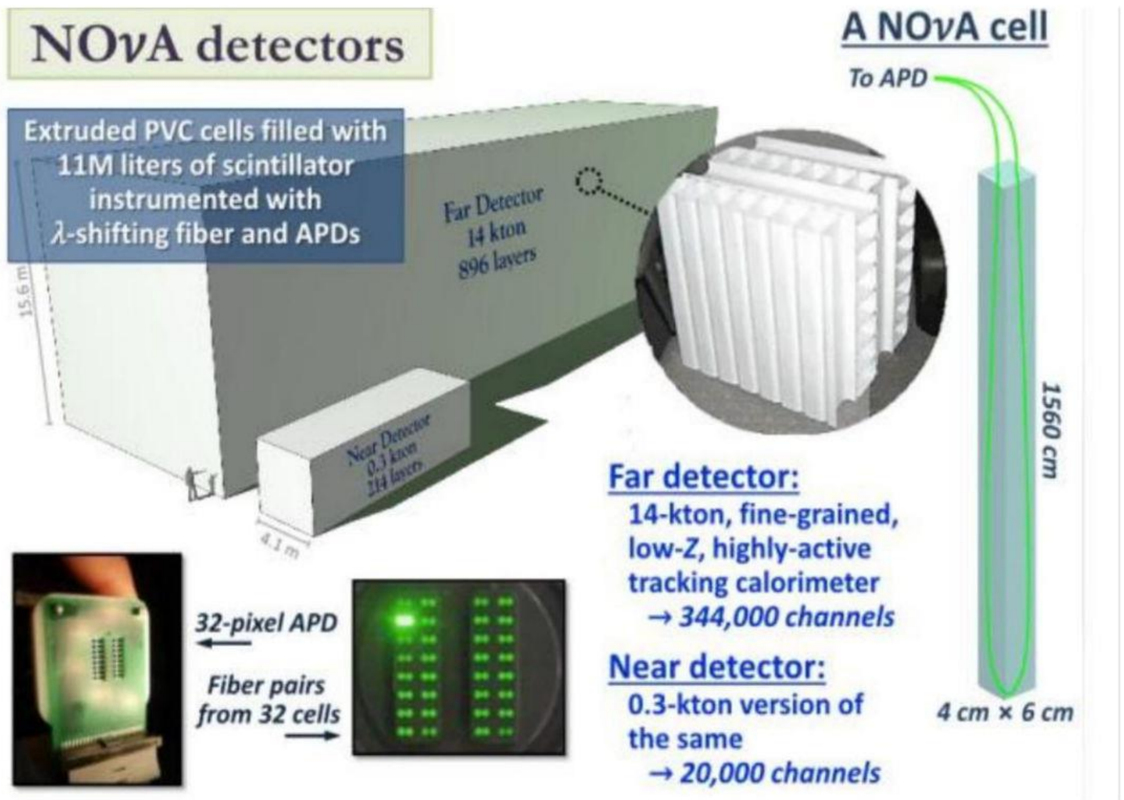


The NOvA experiment



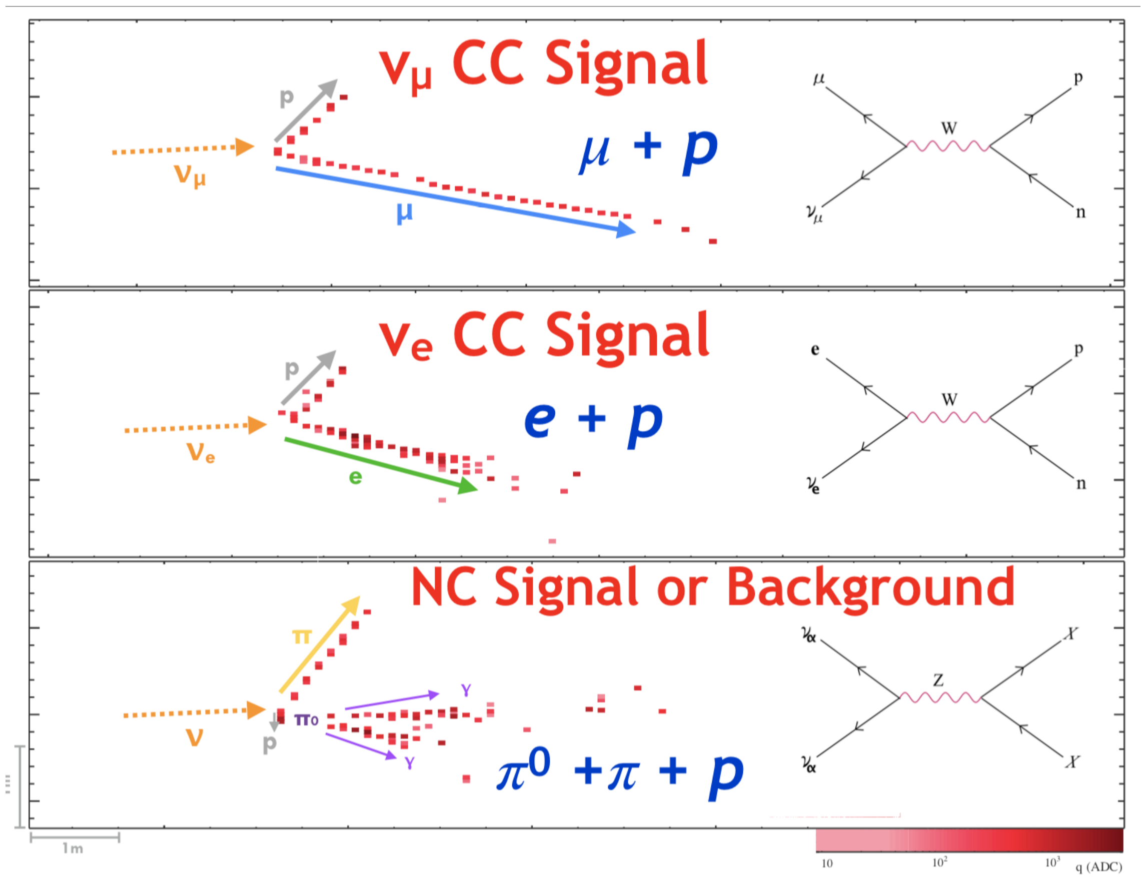


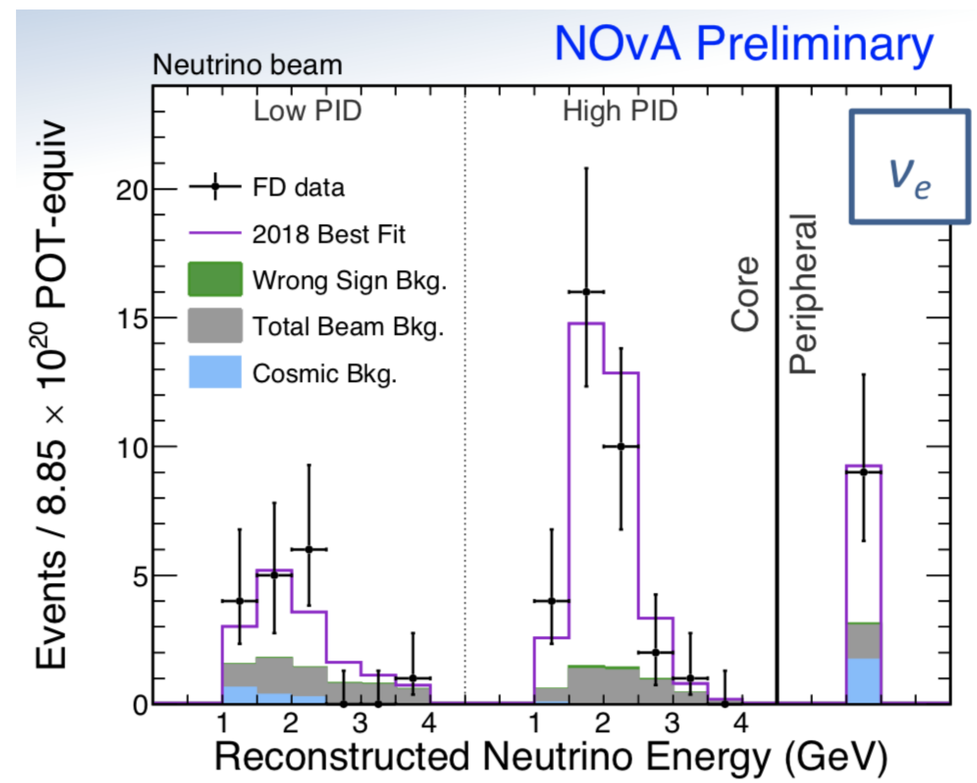
- Highest intensity neutrino beam (NuMI, 700kW of 120GeV protons)
- 14kton far detector
- Neutrino energy ~2GeV, baseline ~800km
- Far Detector at Ash River, northern Minnesota



more on this tomorrow!

The NOvA experiment





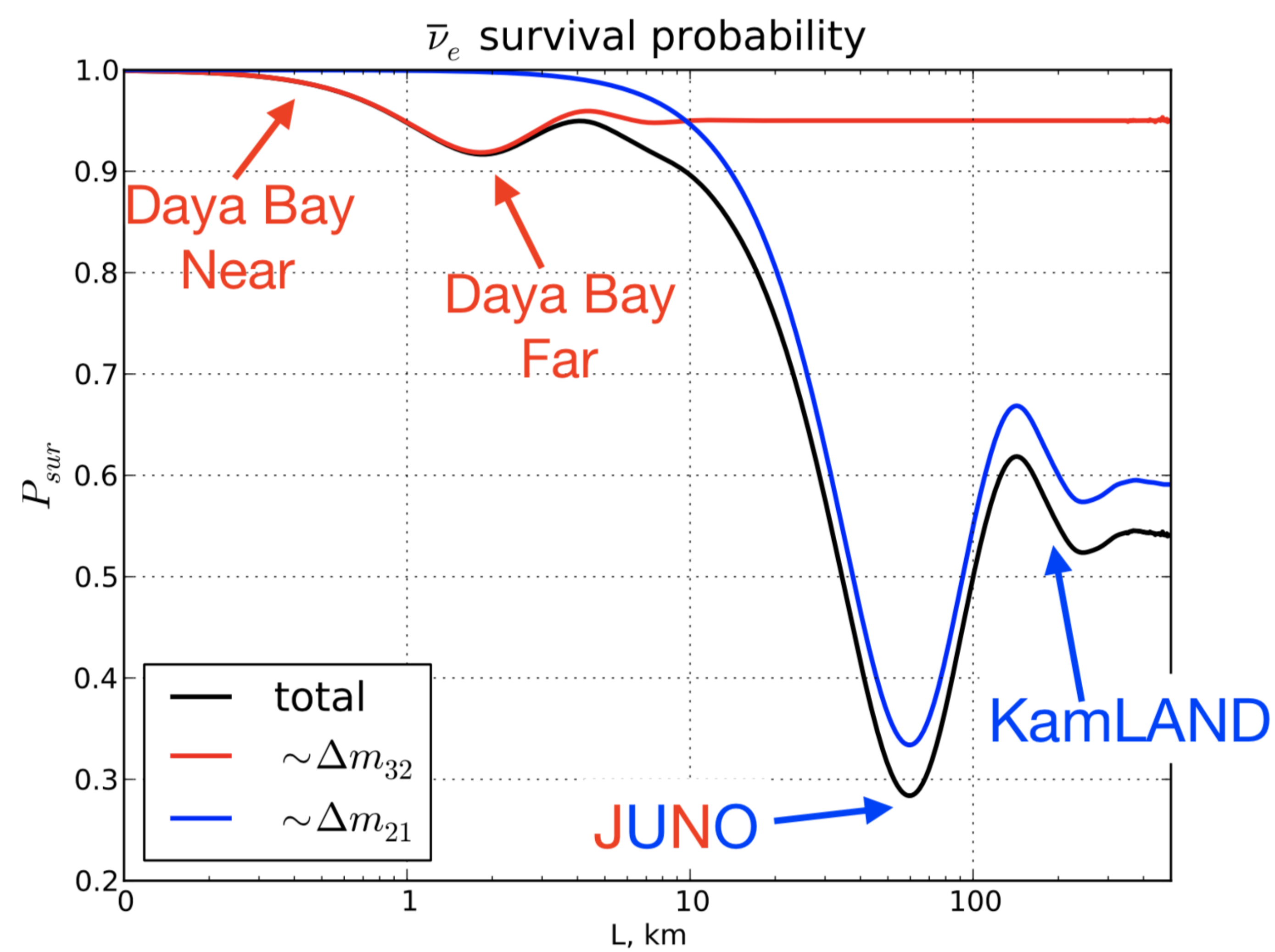
Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

Strong (>4σ) evidence of $\bar{\nu}_e$ appearance

more on this tomorrow!

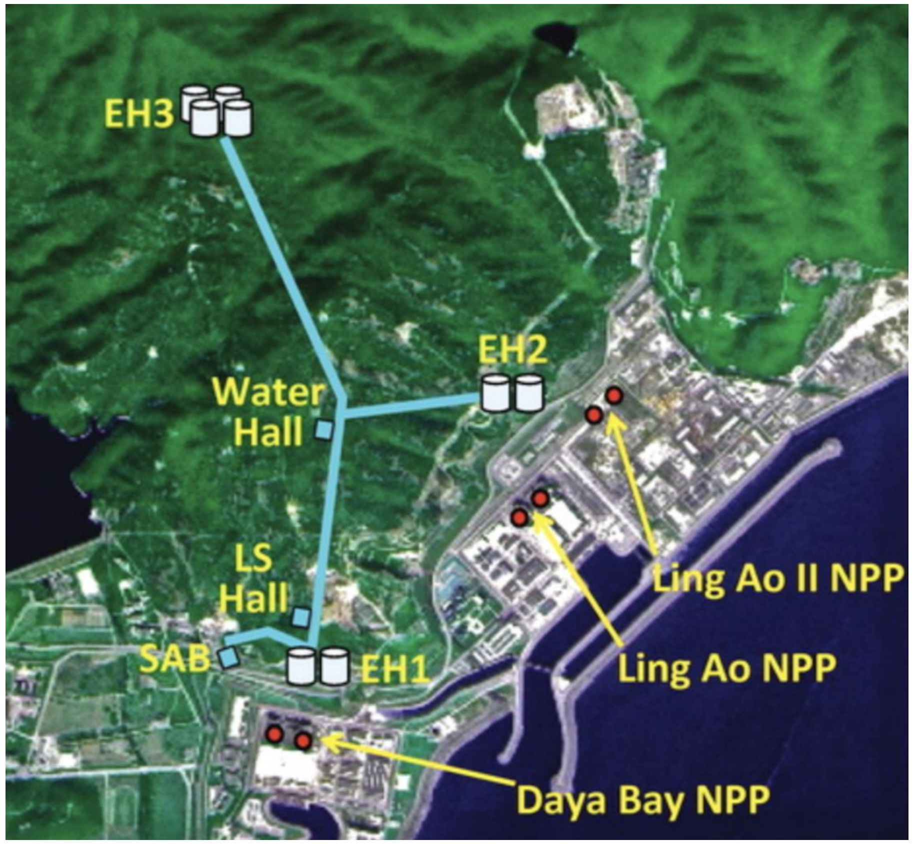
Reactor measurements θ_{13}

- **θ_{13} can be best measured with short baseline (~km) reactor disappearance (anti-ν_e) searches**
- Reactor experiments:
  - Daya Bay (China)
  - RENO (Korea)
  - Double Chooz (France)
- The idea is the same, I am describing only Daya Bay

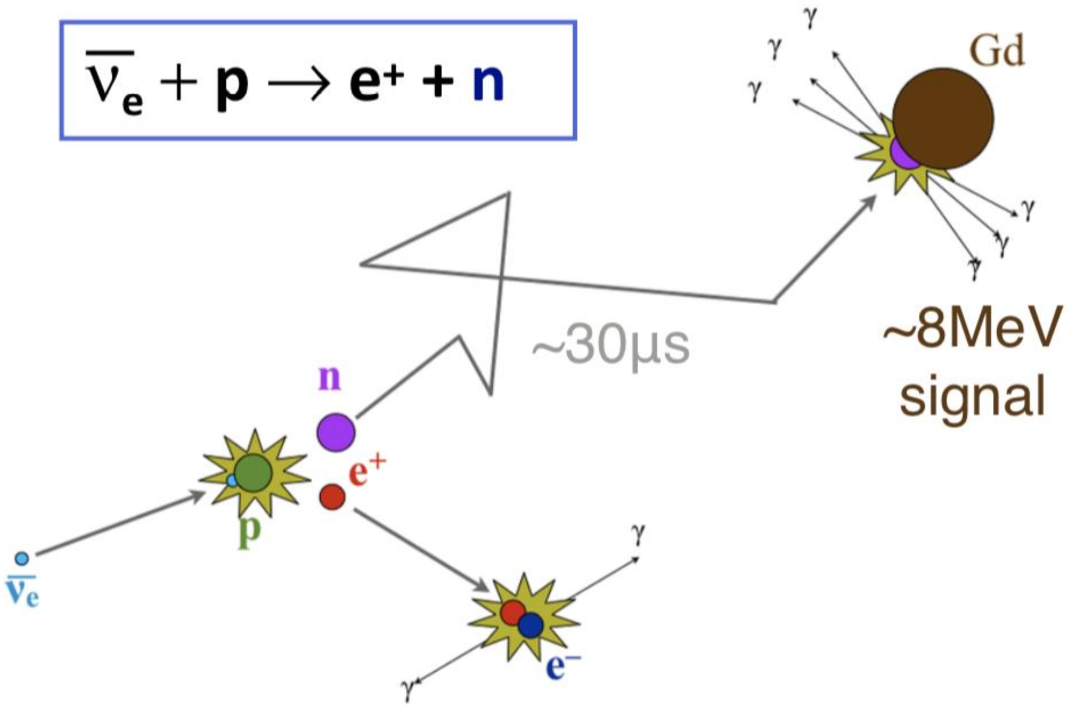


$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \boxed{\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)} - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}}$$

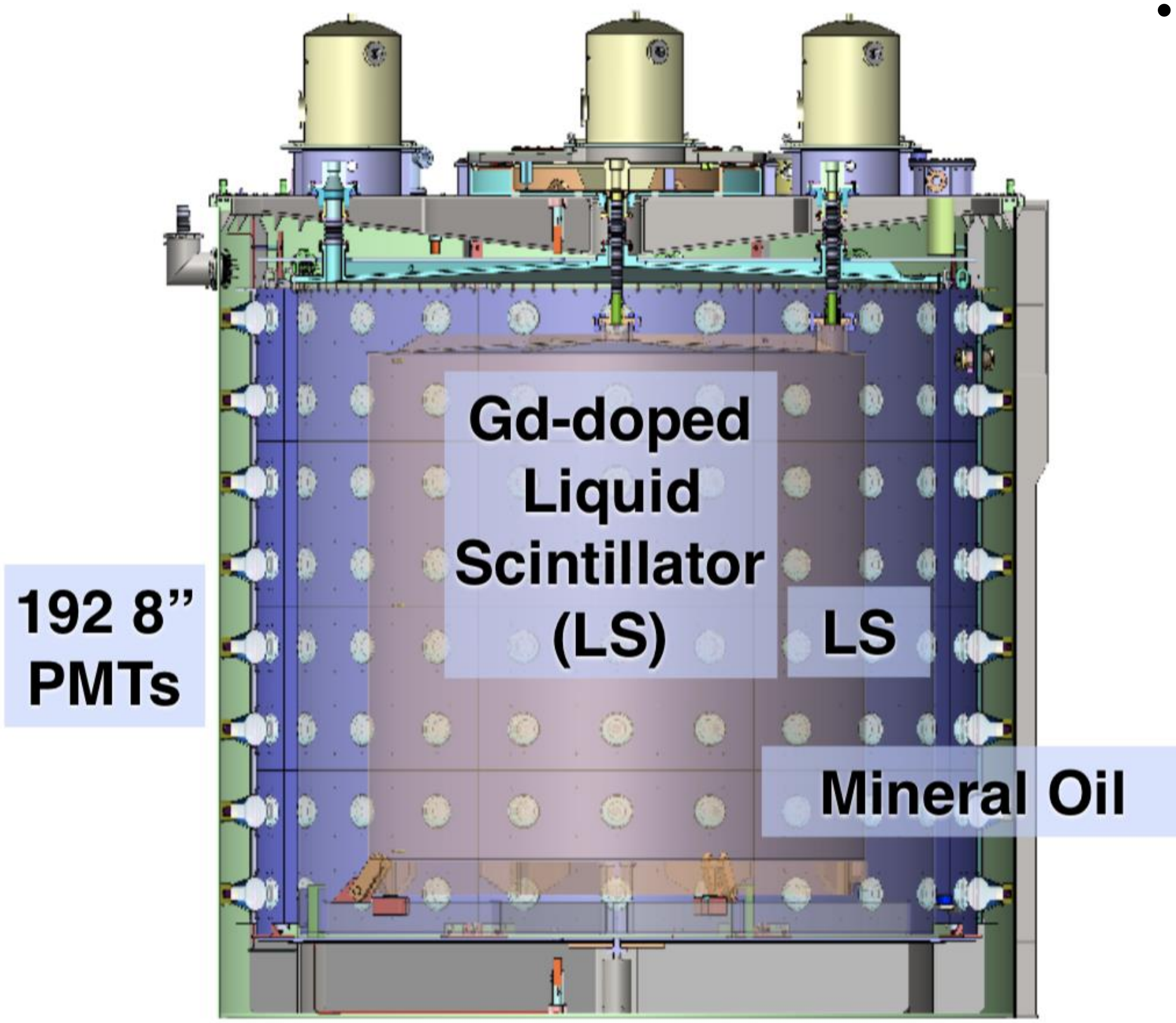
Daya Bay



- 8 identically designed detectors
- 3 experimental halls at three different baselines
- 6, 2.9 GW_{th} reactors in 3 Nuclear Power Plants
- anti-ν_e detected via IBD in Gd doped liquid scintillator



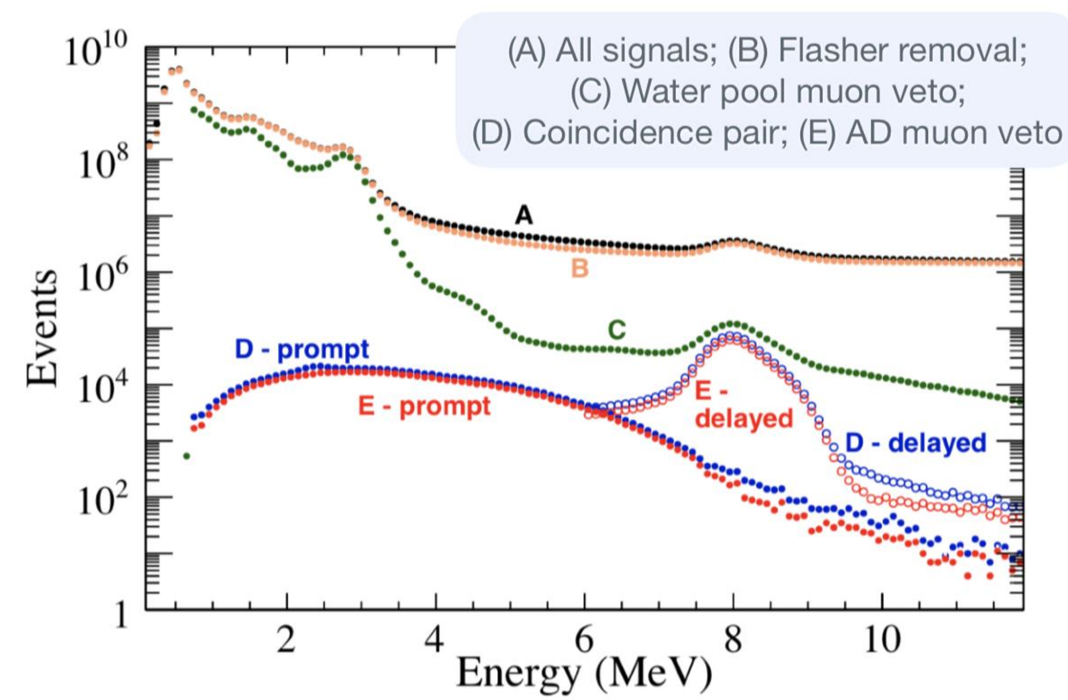
Daya Bay



Energy resolution:
$\sigma_E/E \cong 8.5\%/\sqrt{E[\mathrm{MeV}]}$

NIM A 811, 133 (2016)

- They have just released new results at Neutrino 2018 with 1958 days of data!

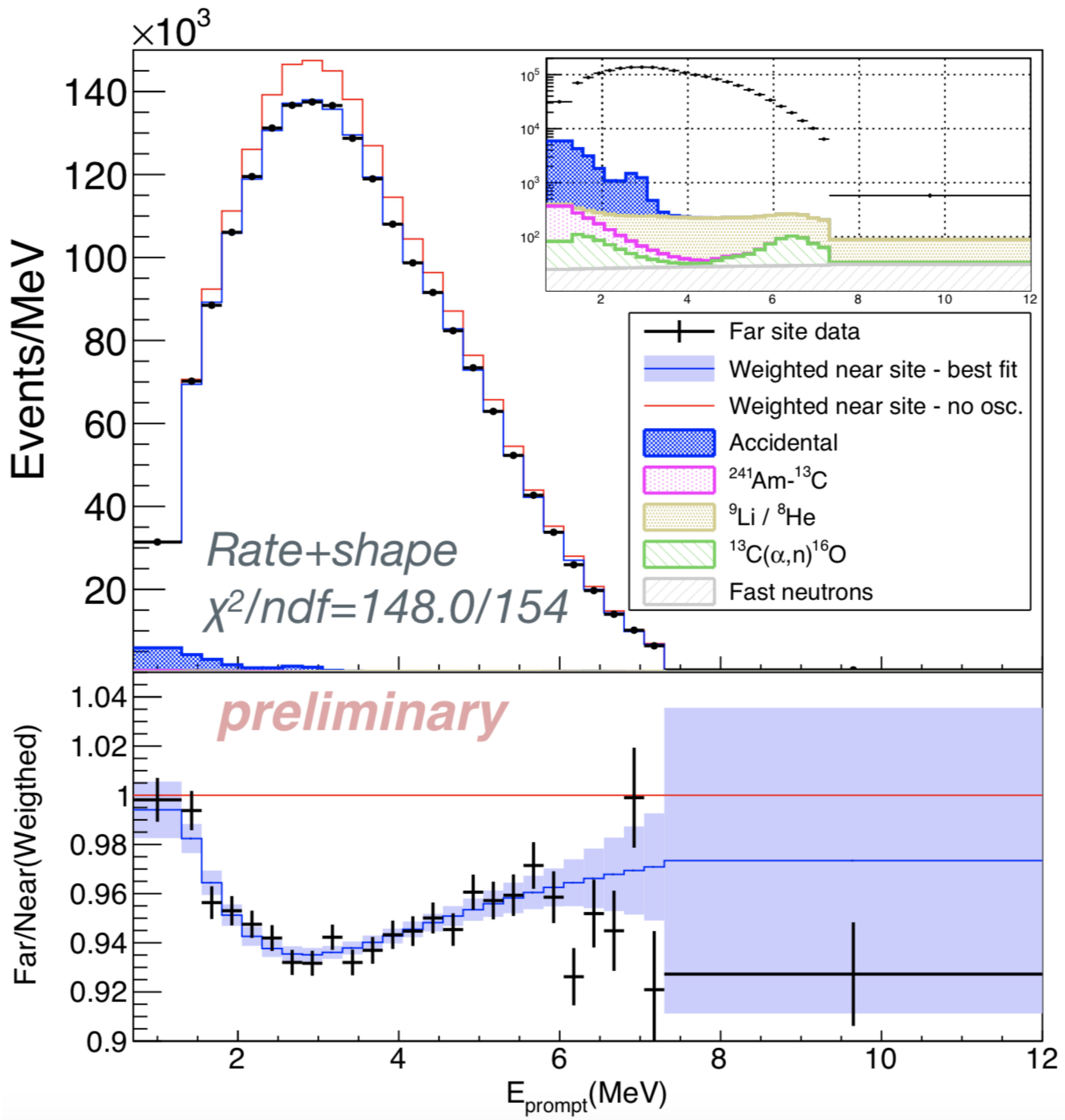


$1\ \mu s < \Delta t < 200\ \mu s$

$0.7\ \mathrm{MeV} < E_{prompt} < 12\ \mathrm{MeV}$

$6\ \mathrm{MeV} < E_{delayed} < 12\ \mathrm{MeV}$

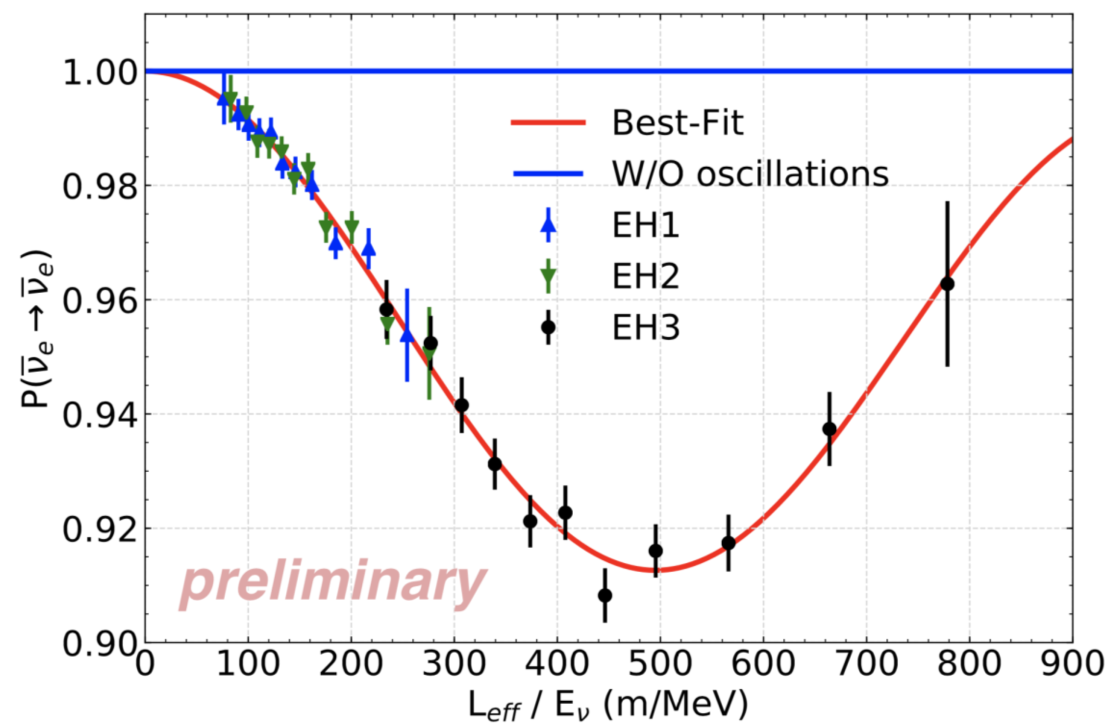
Daya Bay results



3.4% precision !

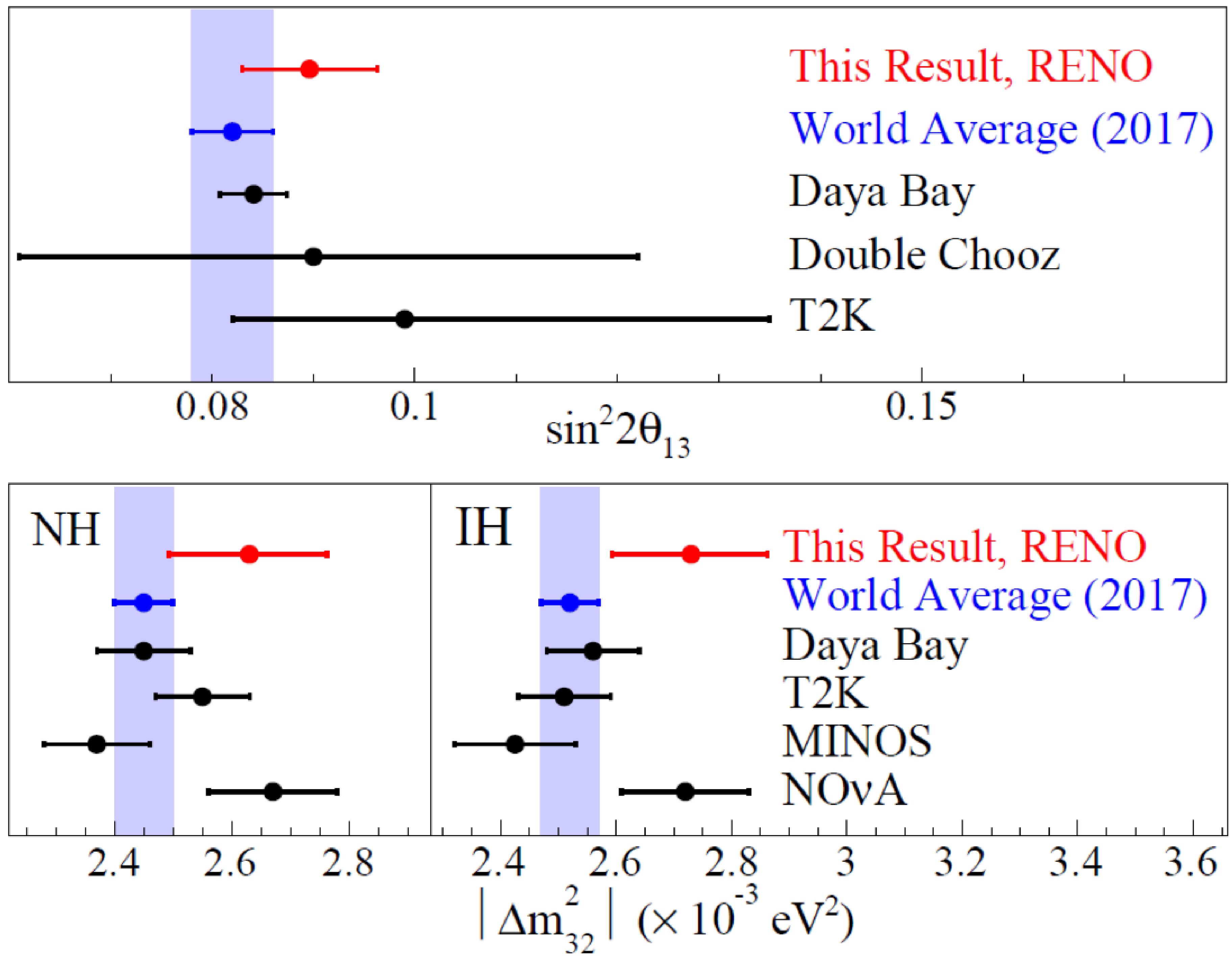
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

- Daya Bay will run until 2020 and will reach the accuracy of 3%!
- θ_{13} is now the best measured leptonic mixing angle



θ_{13} global results

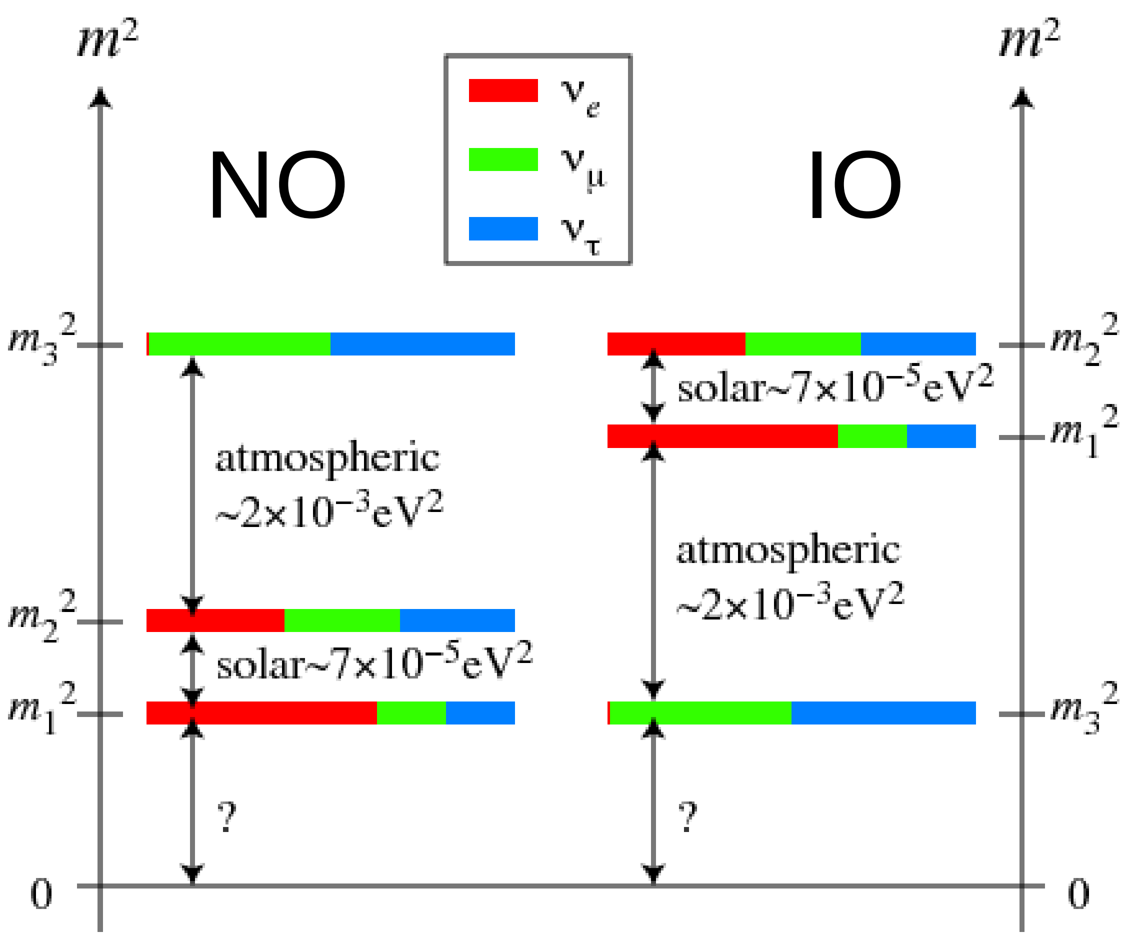
Intae Yu - Neutrino 2018



Open questions and prospects

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"atmospheric" **"reactor"** **"solar"**



- All mixing angles are not zero. **Is there CP violation?**
- **Is θ_{23} maximal (i.e. $\pi/4$)?** This is usually rephrased to: "what is the octant of θ_{23}?"
- **What is the mass ordering?**
- These can be answered by long baseline oscillation experiments (accelerators)

Summary

- Neutrino oscillations discovered ~20 yr ago
  - **Many measurements at different L/E** and with different techniques needed to confirm the theory
  - Really exciting field with a lot of open questions (still)

- Future long baseline neutrino oscillation experiments will be mostly looking for **CPV in the leptonic sector**, which could explain the matter/anti-matter asymmetry in the universe

- Future short baseline neutrino oscillation experiments will hunt for light **sterile neutrinos**

- And I haven’t even mentioned anything about lepton number violation searches, absolute mass scale, Majorana vs Dirac…

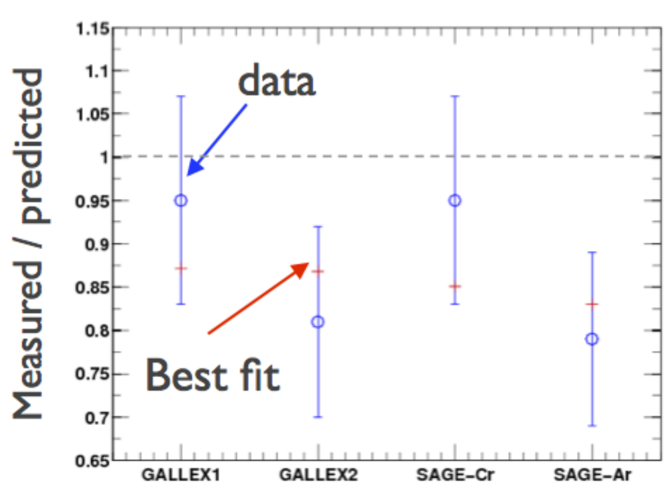
Outline (today's lecture!)

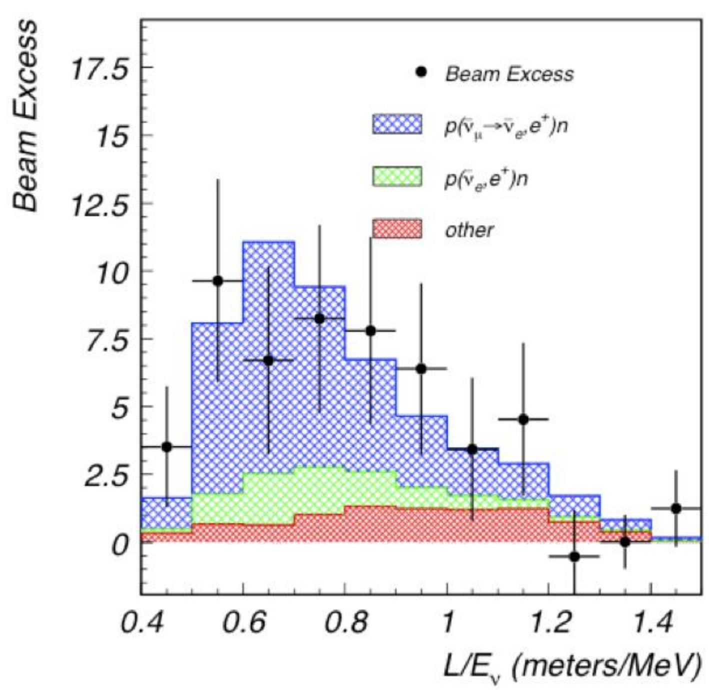
1. Neutrino "anomalies"
2. The search for sterile neutrinos
3. The Short Baseline Program at Fermilab
4. CP violation in the neutrino sector
5. Prospects for future long baseline searches

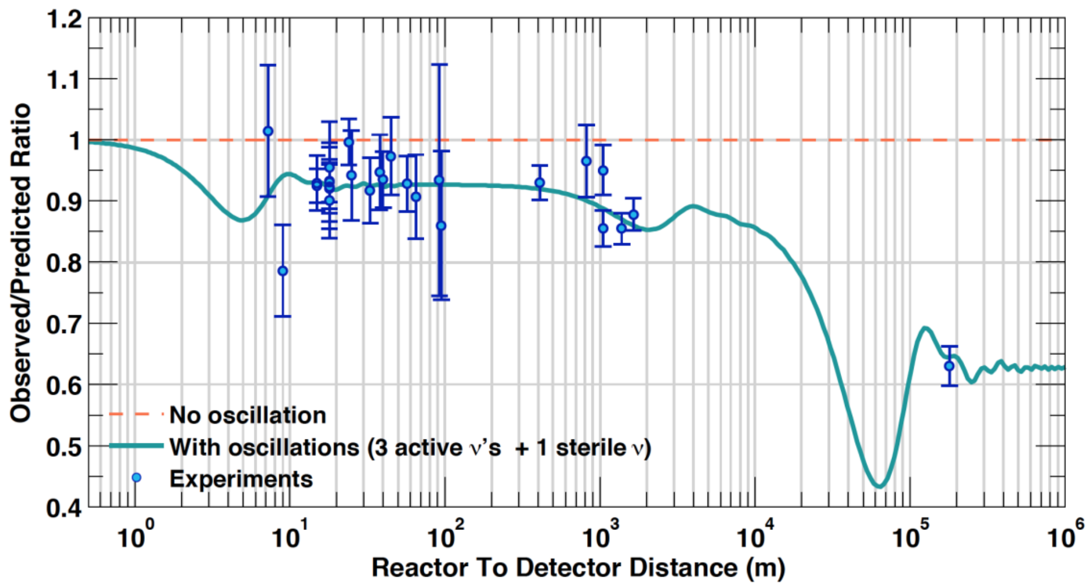
In this case, I will be biased towards the neutrino program at Fermilab. There is a lot going on and it's a very exciting time!

Anomalies?

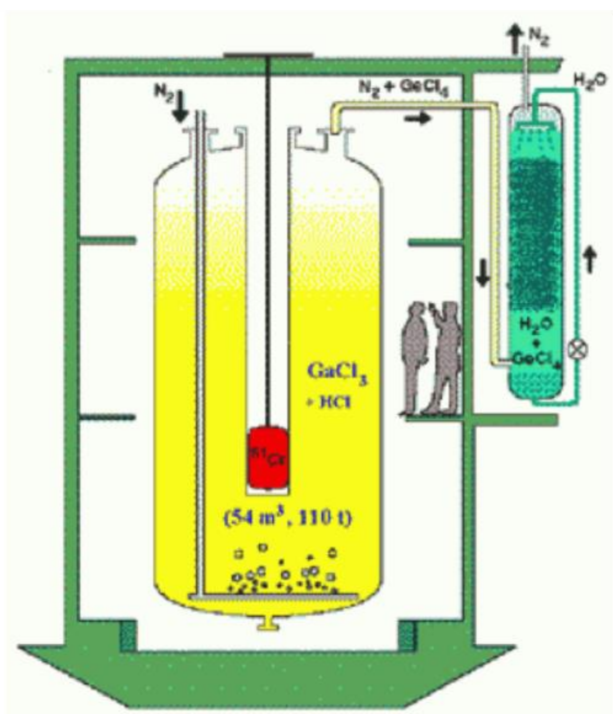
- There are hints of anomalous neutrino behaviors at very short baseline **(L/E ~ m/MeV)**
  - **deficit of ν_e** observed in neutrino source experiments
    - “Gallium anomalies”
  - **deficit of anti-ν_e** observed at reactor experiments
    - “Reactor anomaly”
  - **excess of ve/anti-ν_e** observed at accelerator experiments
    - LSND and MiniBooNE

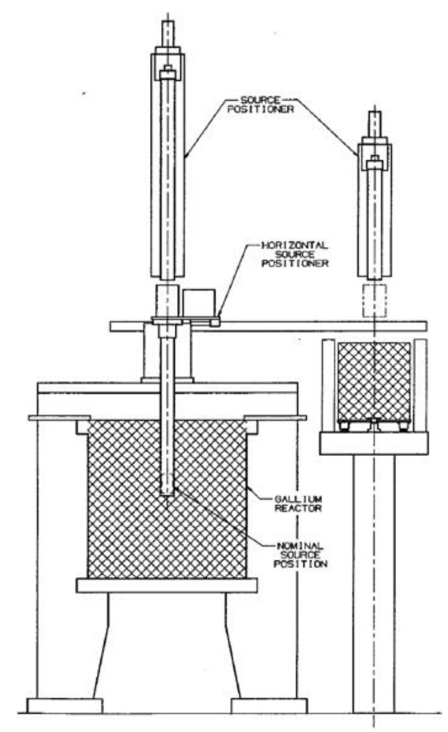


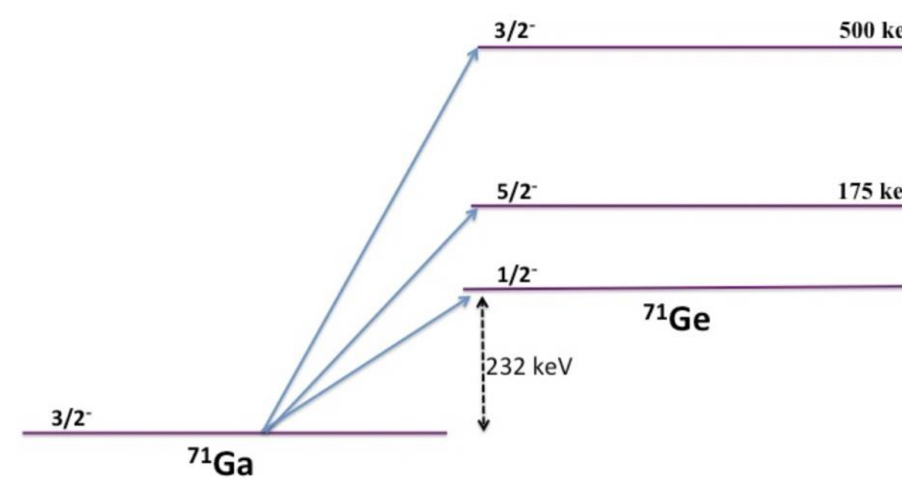




Gallium experiments: Gallex/GNO and SAGE



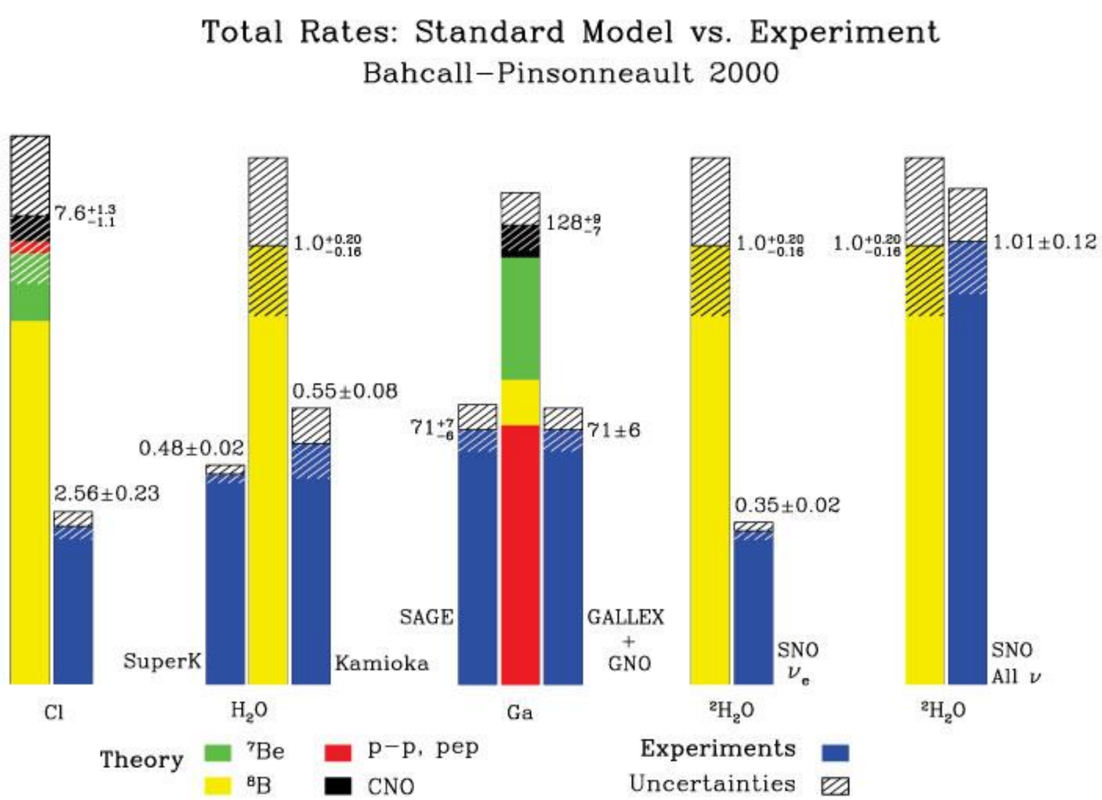


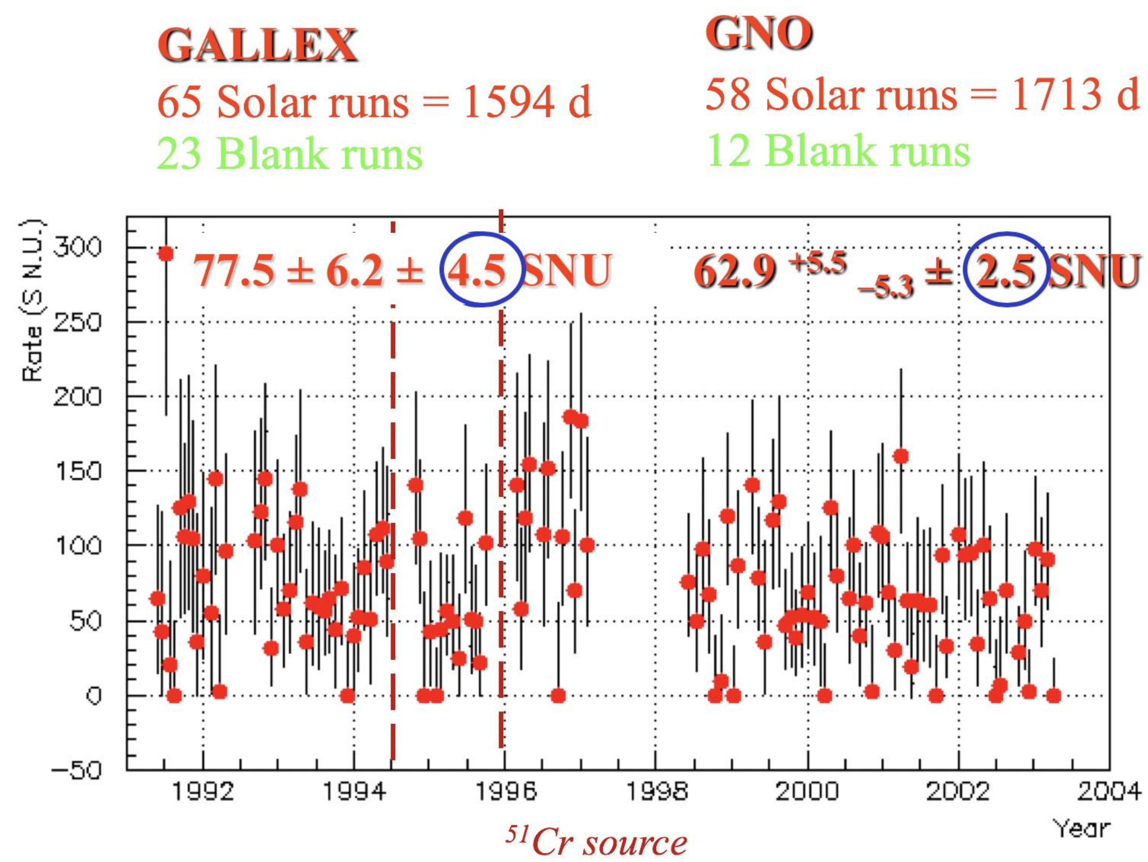


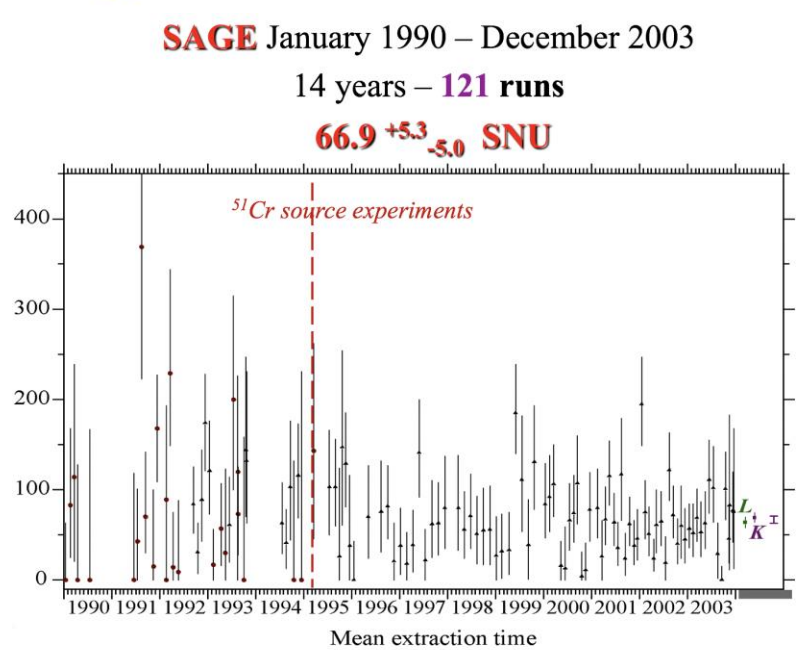
- Solar neutrino experiments. Same concept as Ray Davis' chlorine experiment. Use Ga for a lower threshold (233keV)

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

Gallium experiments: solar results







- Multi year measurements
- Consistent results with Super-K and Homestake (Ray Davis)
- Solar neutrino “problem”!

Gallium experiment calibration

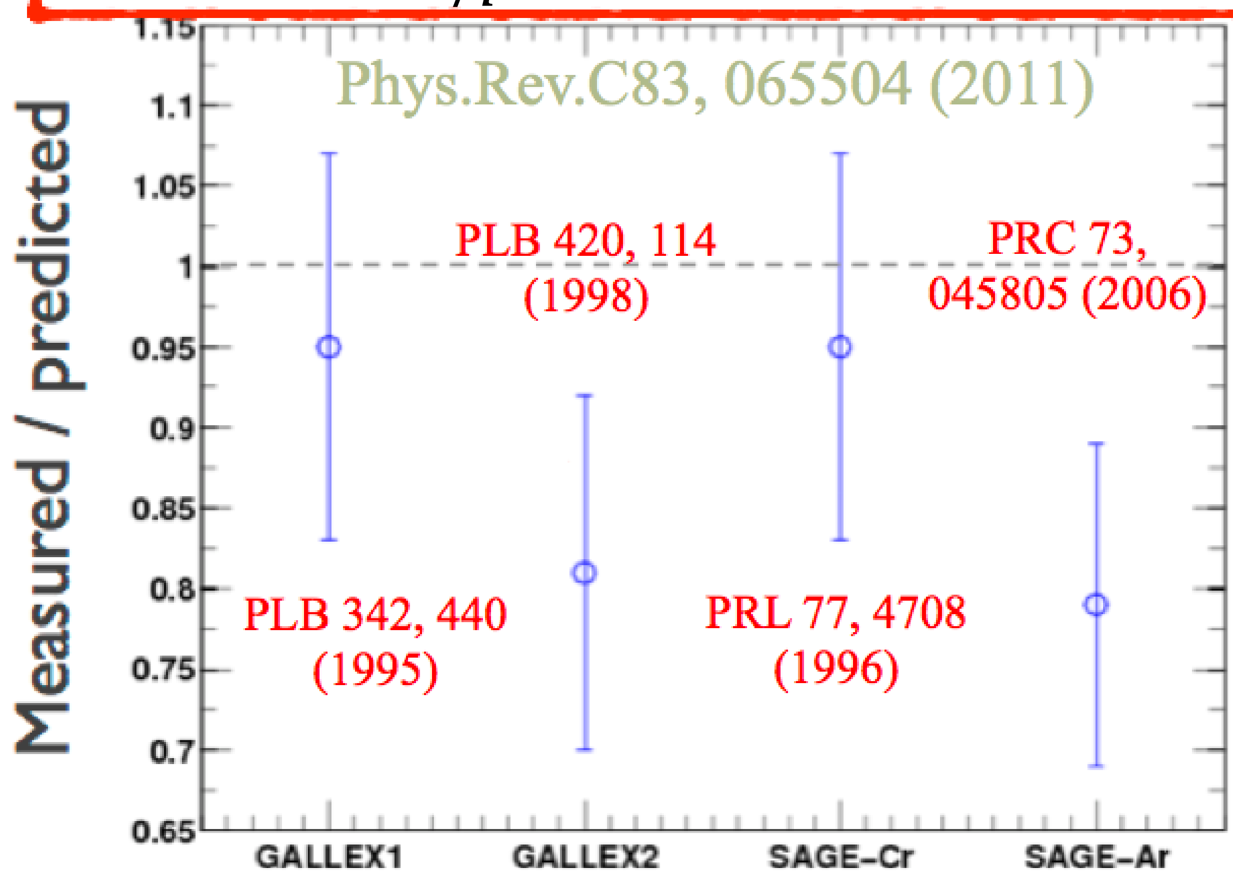
$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$
$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$$

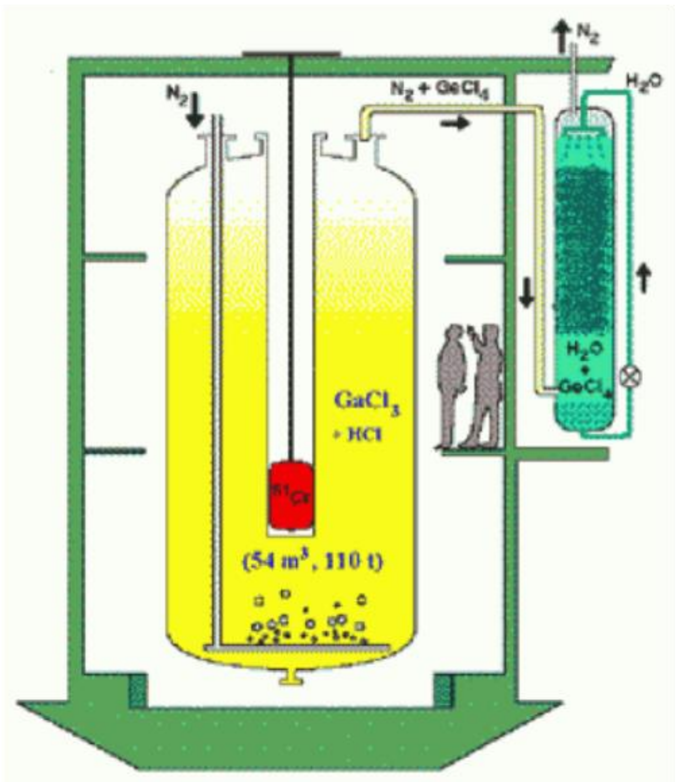
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
branching ratio	0.8163	0.0849	0.0895	0.0093	0.902	0.098

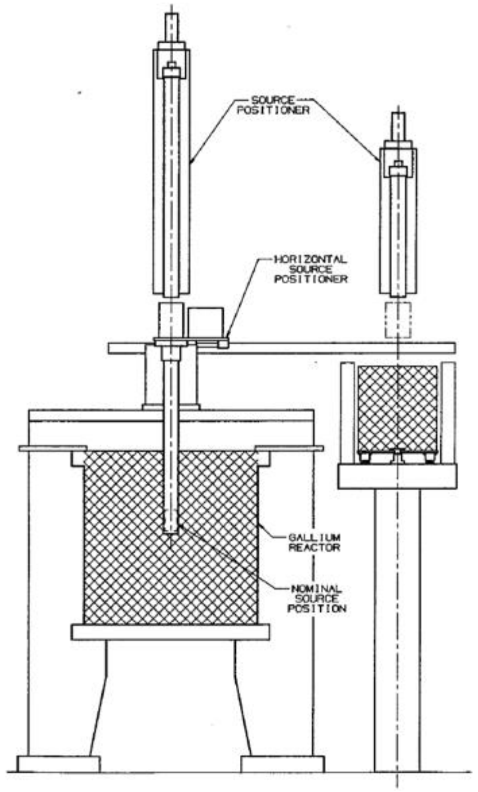
GALLEX Sources: 1.7 MCi of ^{51}Cr
1.8 MCi of ^{51}Cr

SAGE Sources: 680 kCi of ^{51}Cr
409 kCi of ^{37}Ar

$$R_{measured/predicted} = 0.86 \pm 0.05$$

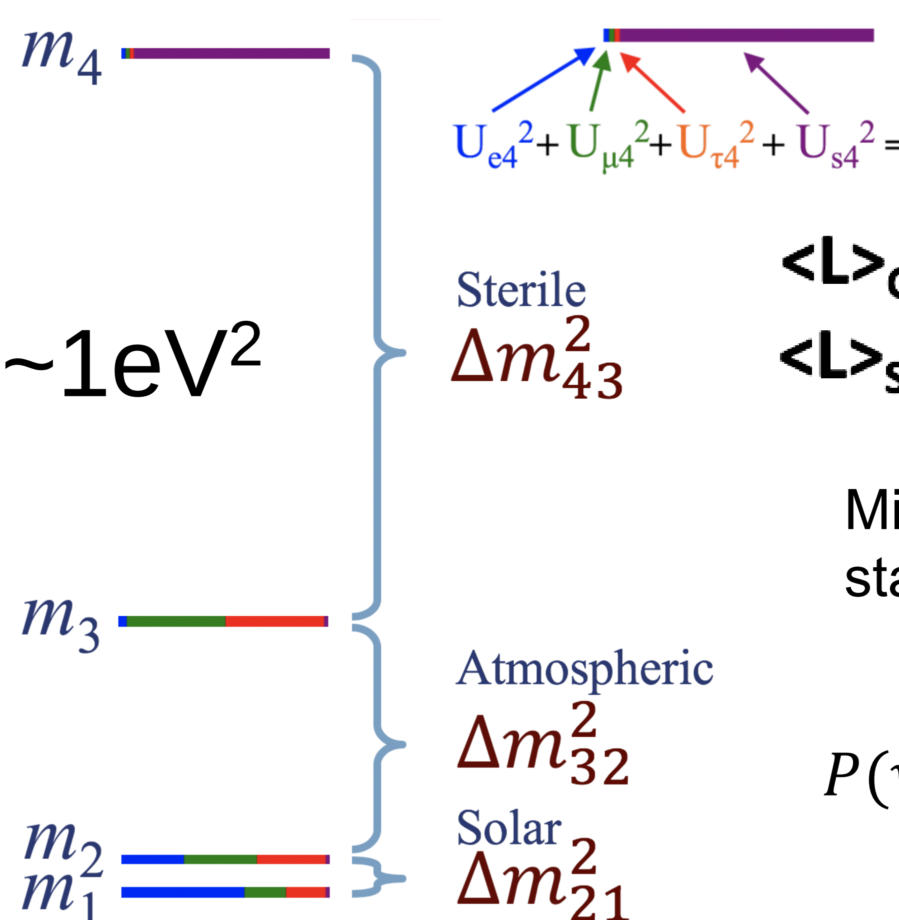






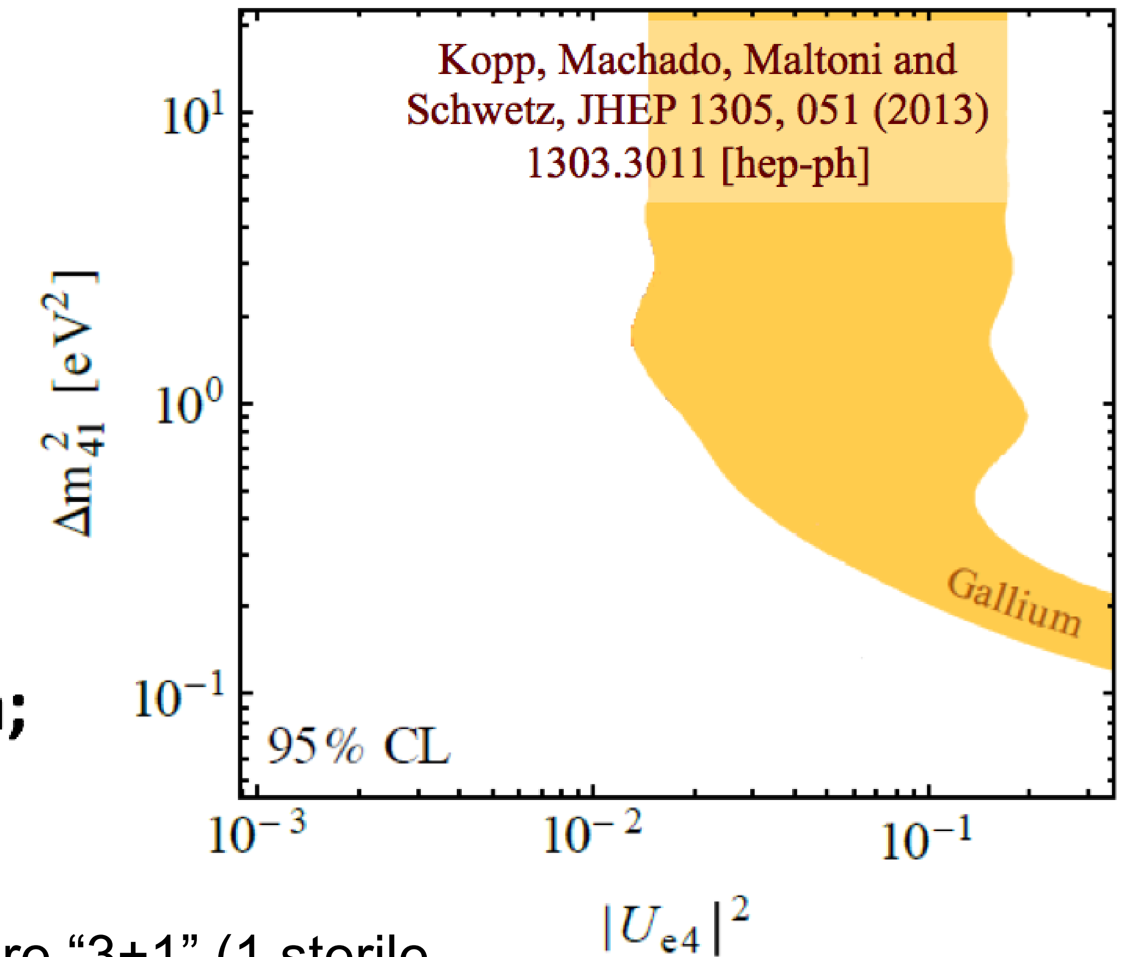
Gallium anomaly: oscillations?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



<L>$_{\text{GALLEX}}$ = 1.9 m;

<L>$_{\text{SAGE}}$ = 0.6 m



Minimal models are “3+1” (1 sterile state), but there also are 3+2, 3+2…

$$P(\nu_\mu \to \nu_e) = 4U^2_{e4}U^2_{\mu 4}\sin^2\left(1.27\Delta m^2_{43}(eV^2)\frac{L(km)}{E(GeV)}\right)$$

$$P(\nu_e \to \nu_x) \approx P(\nu_e \to \nu_s) = 4U^2_{e4}U^2_{s4}\sin^2\left(1.27\Delta m^2_{43}(eV^2)\frac{L(km)}{E(GeV)}\right) x \neq e$$

Investigations on Gallium anomaly

from J. Link

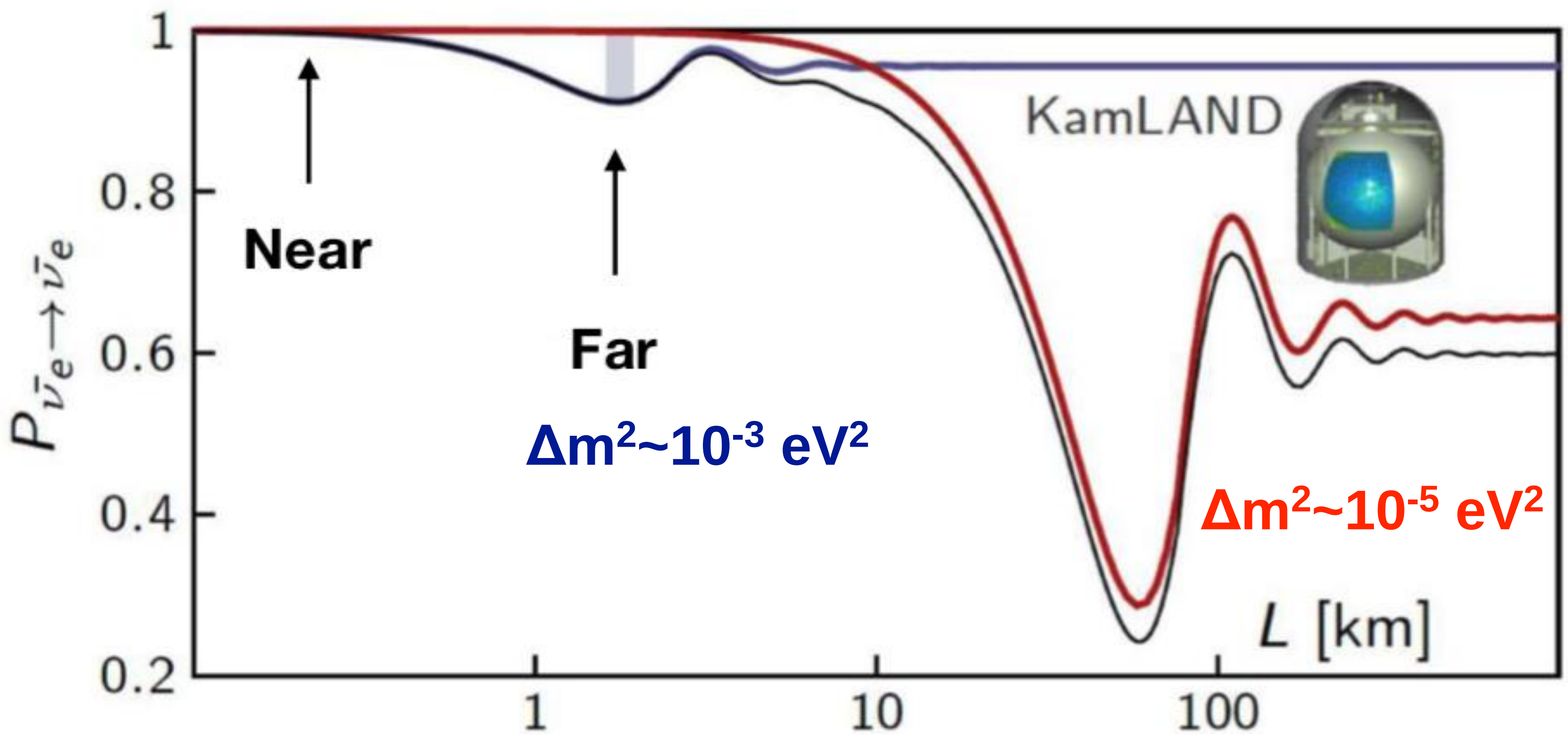
Source Experiment Proposals	Source	Detector
LENS-Sterile (Phys.Rev.D 75, 093006, 2007)	^{51}Cr	LENS (Solar)
Zoned Radio-chemical (arXiv:1006.2103 [nucl-ex], 2010)	^{51}Cr	SAGE (Solar)
CeLAND (Phys.Rev.Lett. 107, 201801, 2011)	^{144}Ce	KamLAND (Reactor)
Neutral Current Coherent (Phys.Rev.D 85, 013009, 2012)	^{37}Ar	Bolometers (DM)
IsoDAR (Phys.Rev.Lett. 109, 141802, 2012)	^{8}Li	KamLAND (Reactor)
SOX (JHEP 1308, 038, 2013)	^{51}Cr & ^{144}Ce	Borexino (Solar)
Liquid Xe + Source (JHEP 1411, 261, 2014)	^{51}Cr	LZ (DM)

Many ideas for short baseline radioactive source experiments: unfortunately none of them is being actively pursued right now

Reactor anti-ν_e disappearance

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

anomalies? **Δm^2~1 eV^2**



“Reactor” anomaly

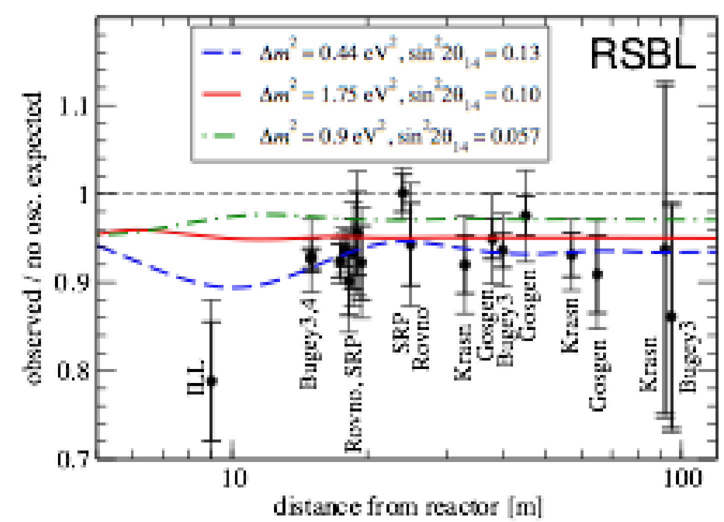
M. Maltoni - Neutrino 2018

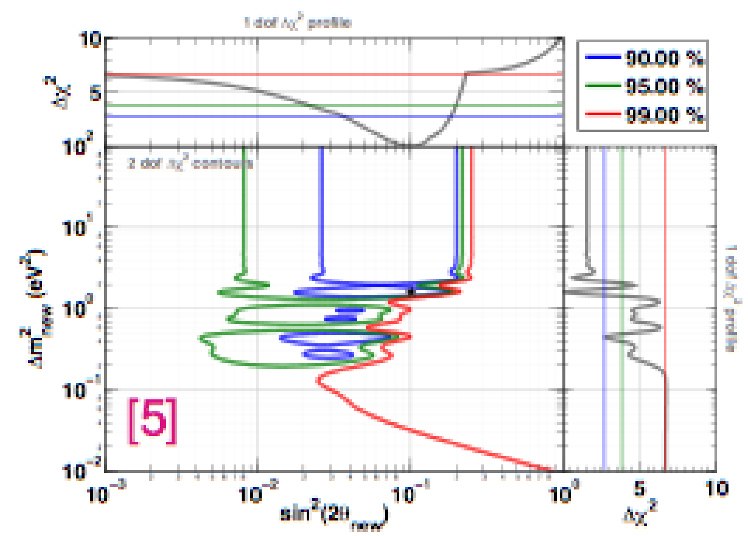
I. Oscillation anomalies: ν_e disappearance

$\bar{\nu}_e$ disappearance: the reactor anomaly

- In [3, 4] the reactor $\bar{\nu}$ fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- no visible dependence on $L \Rightarrow \Delta m^2 \gtrsim 1$ eV^2;
- global data (3σ): $\begin{cases} \Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5} \text{ eV}^2, \\ |\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3} \text{ eV}^2; \end{cases}$

$\Rightarrow$ solutions: **add new neutrinos** or **revise fluxes**.



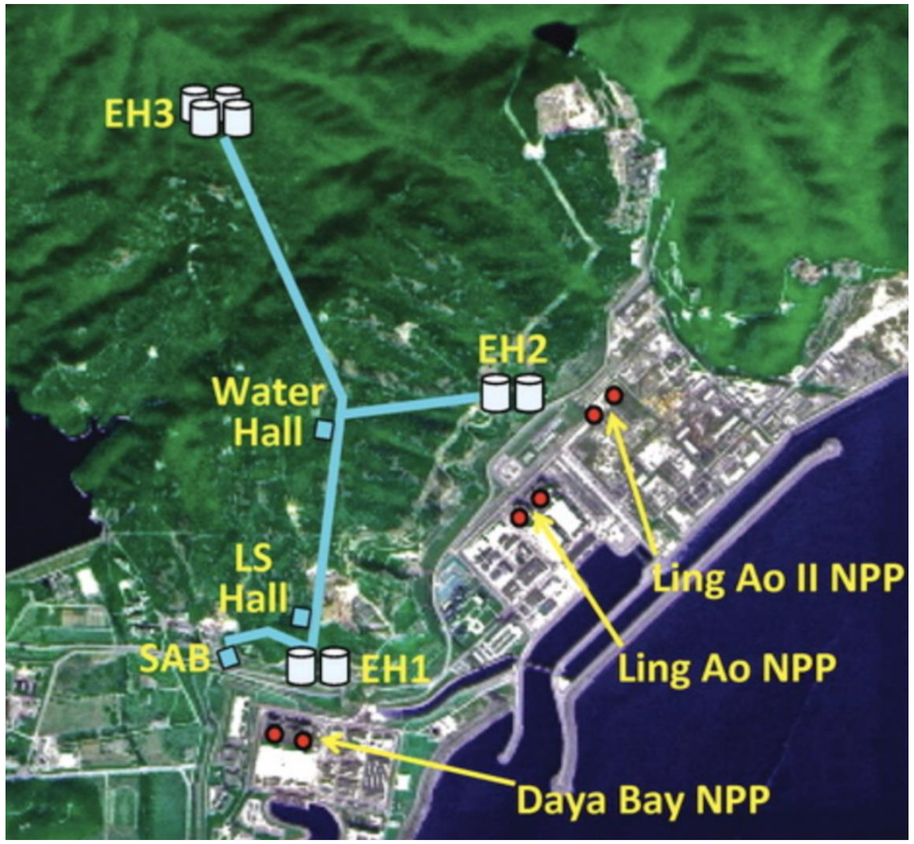


[3] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663].
[4] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687].
[5] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755].

$\Rightarrow$ Talk: Hayes
$\Rightarrow$ Talk: Suhonen

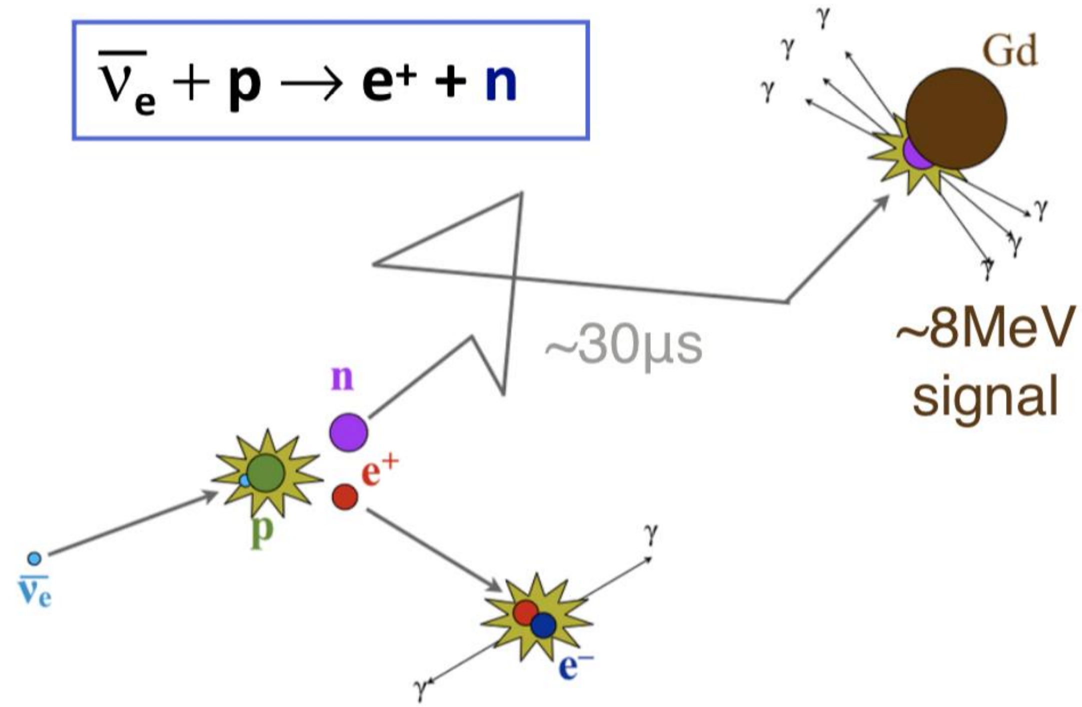
Michele Maltoni <michele.maltoni@csic.es>

Daya Bay experiments

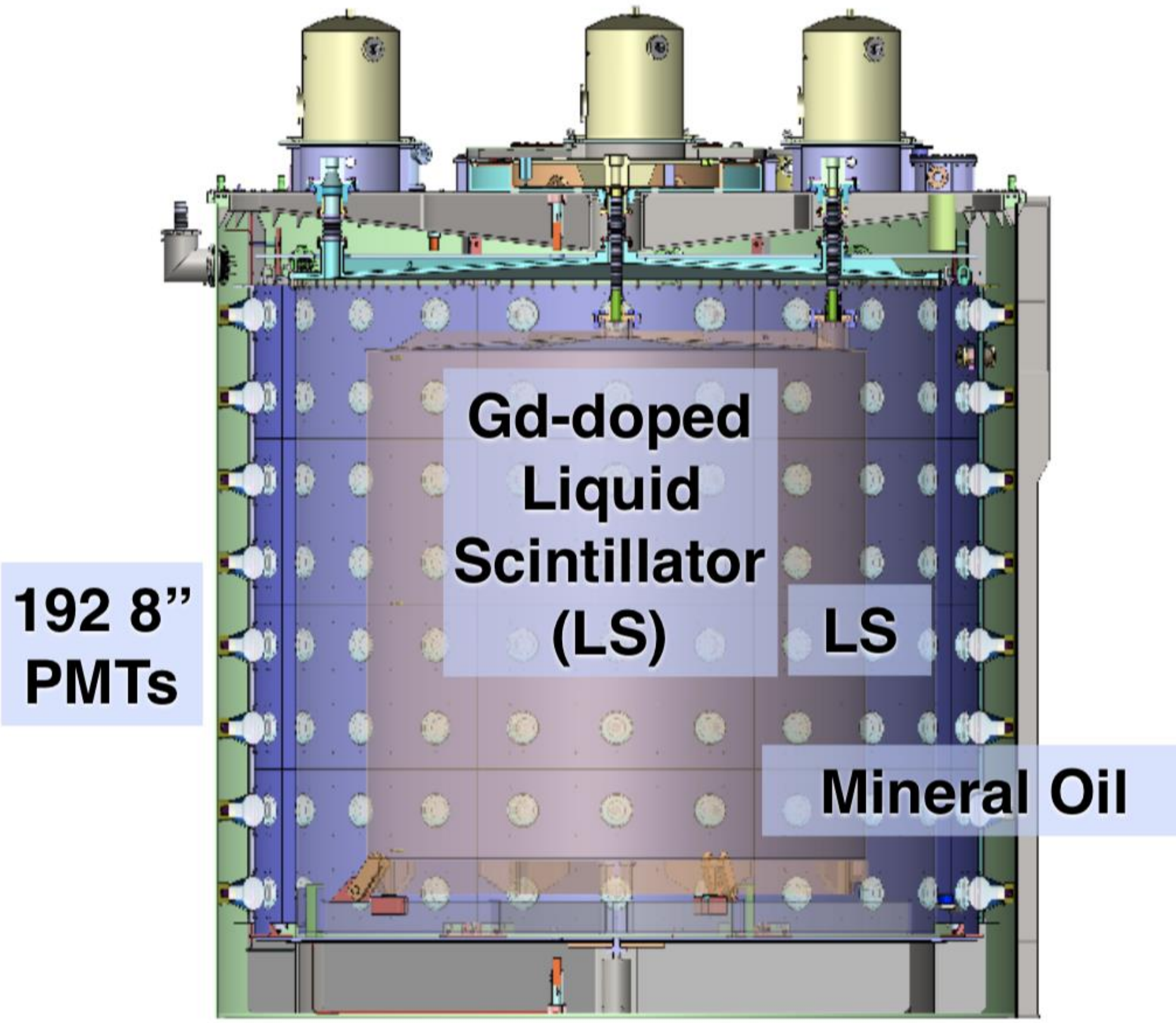


- 8 identically designed detectors
- 3 experimental halls at three different baselines
- 6, 2.9 GW_{th} reactors in 3 Nuclear Power Plants
- anti-ν_e detected via IBD in Gd doped liquid scintillator

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



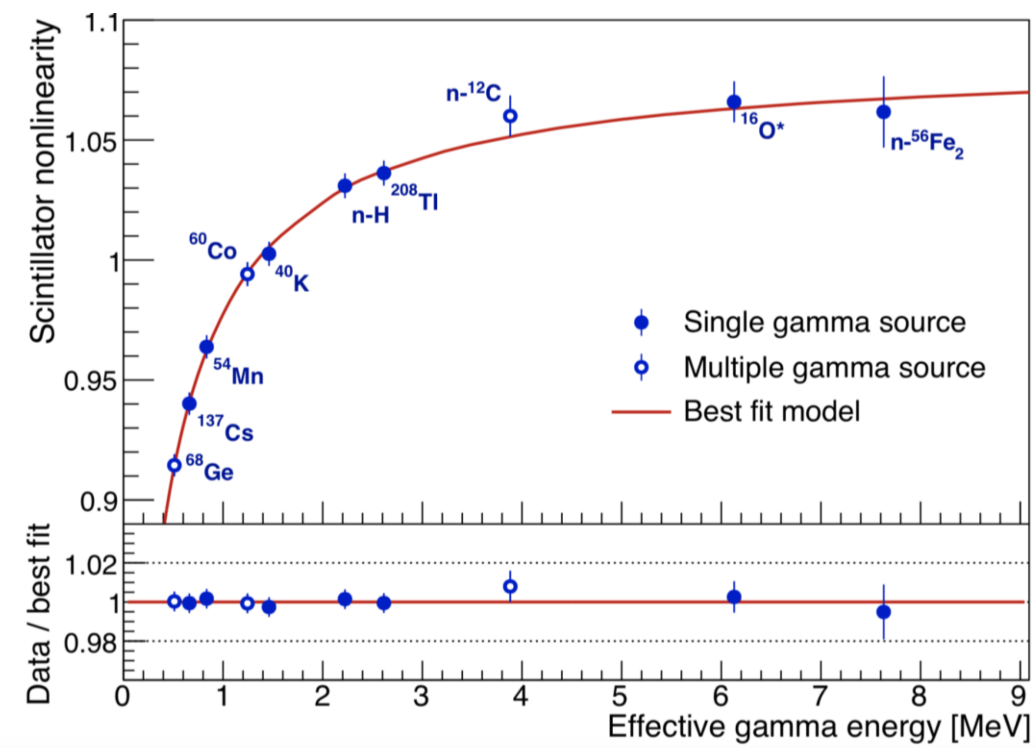
Daya Bay



Energy resolution:
$\sigma_E/E \cong 8.5\%/\sqrt{E[MeV]}$

NIM A 811, 133 (2016)

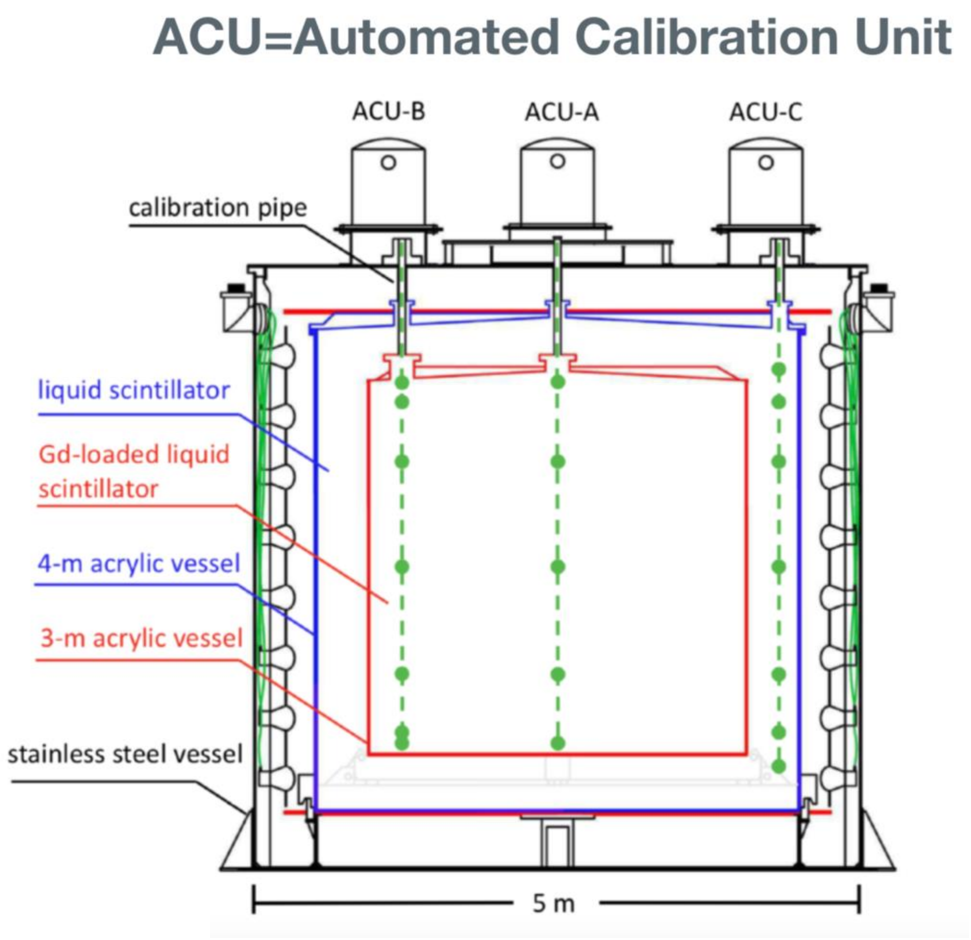
Need for a **precise detector response modeling** for an accurate anti-neutrino spectrum measurement



Daya Bay’s goal was to measure θ_{13} using the ratios between near and far detectors

It can also measure very precisely the absolute anti-ν_e flux as well as their spectrum

Daya Bay: absolute anti-ν_e flux measurement



- Thorough calibration of all the 8 detectors with Am-C and Am-Be sources to constrain the neutron detection efficiency
- Comparison with Huber+Mueller model

results with 1230 days

$$R_{\text{data/pred}} = 0.952 \pm 0.014(\text{exp.}) \pm 0.023(\text{model})$$

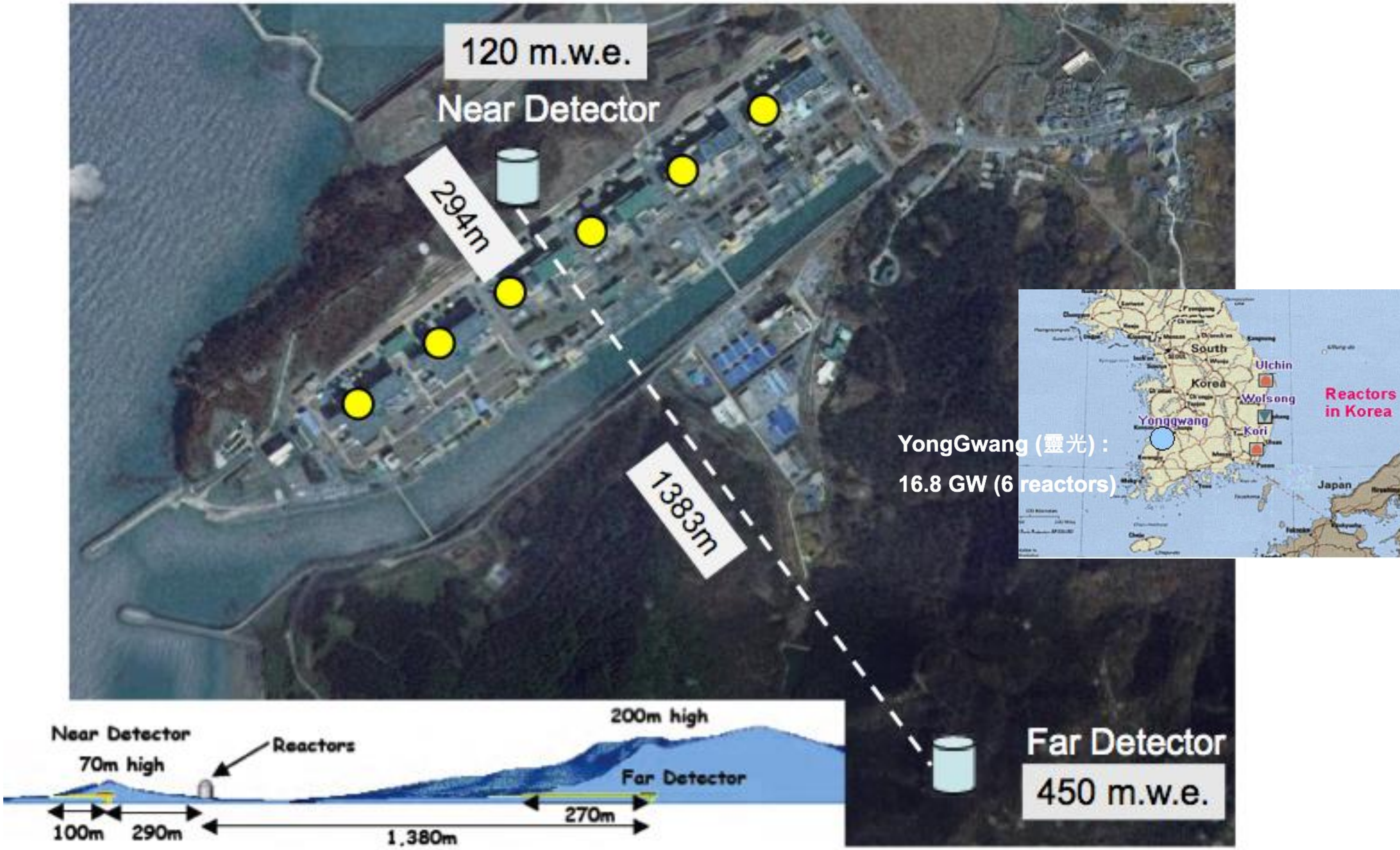
$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43}\ \text{cm}^2/\text{fission}$$

J. Pedro Ochoa-Ricoux, Neutrino 2018

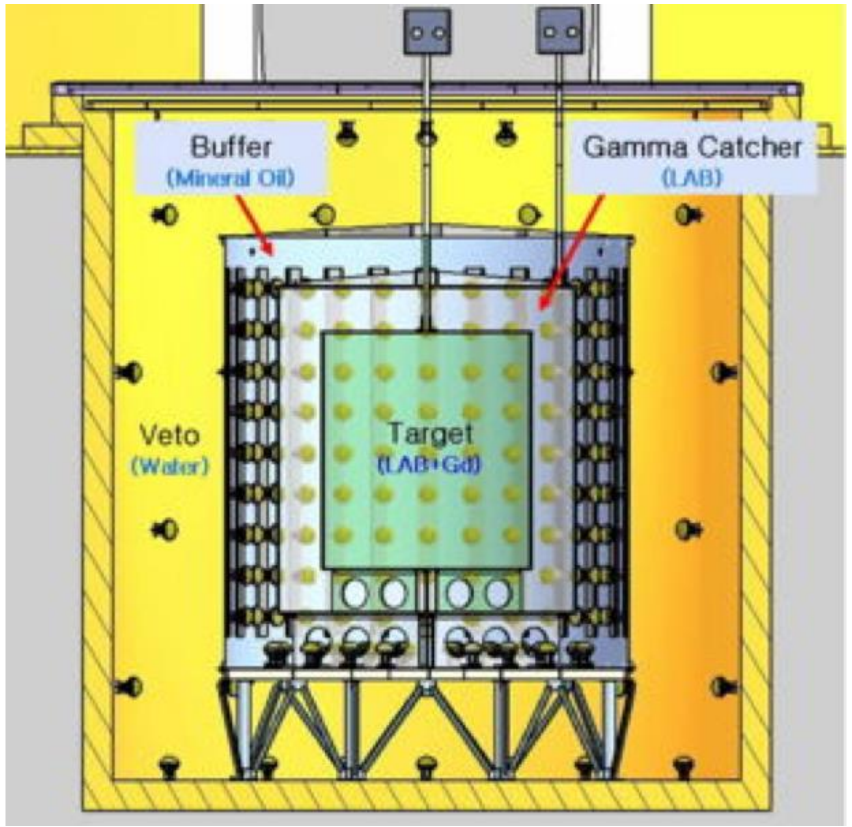
Is this a problem with the modelling of the reactor anti-ν_e fluxes?
Are these sterile neutrinos?

RENO

Intae Yu - Neutrino 2018

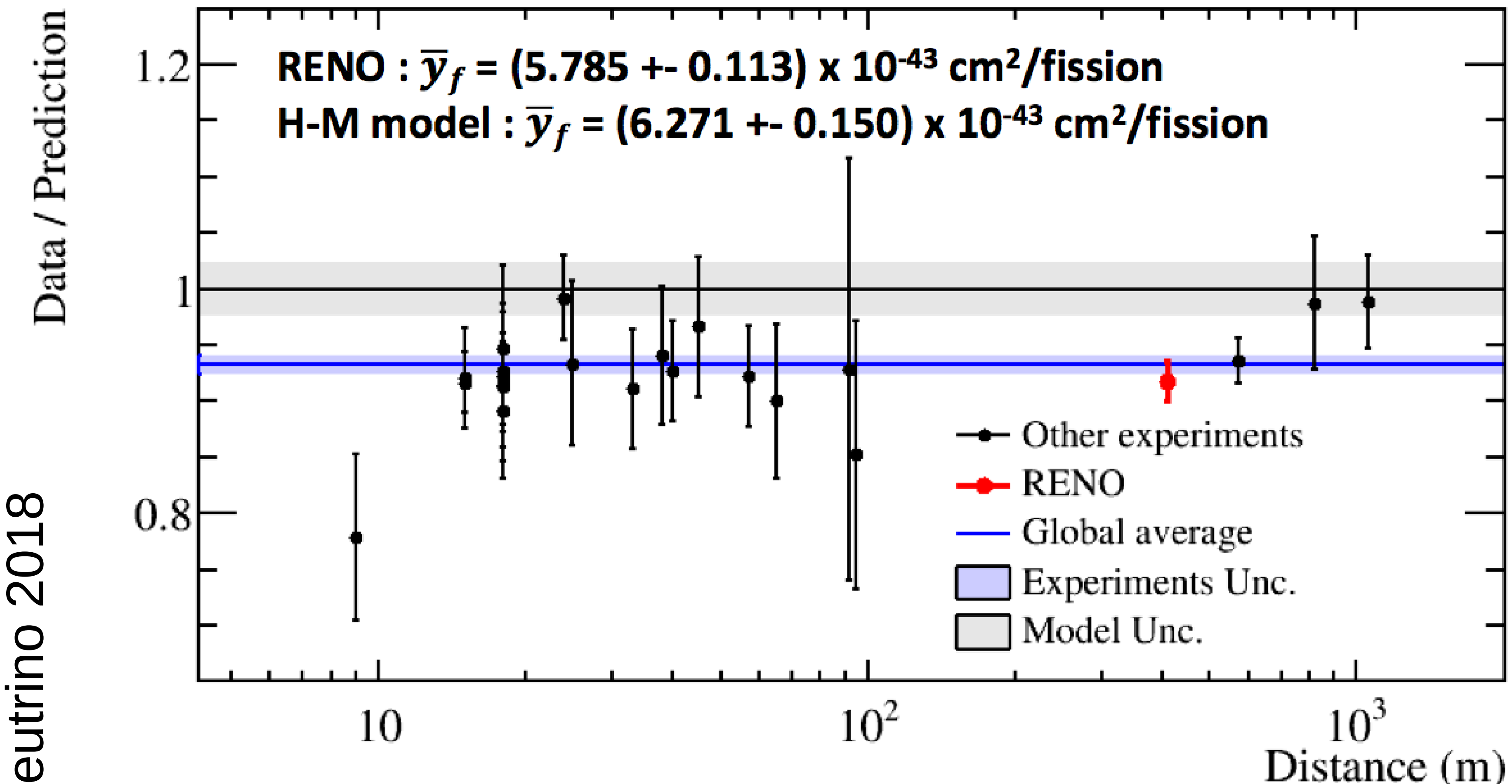


RENO experiment



- Gd doped liquid scintillator - functionally identical to Daya Bay
- 354 ID + 67 OD 10'' PMTs
- 16.5ton Gd-LS, R=1.4m, H=3.2m
- 30ton LS Gamma Catcher
- 350ton water for veto

RENO results



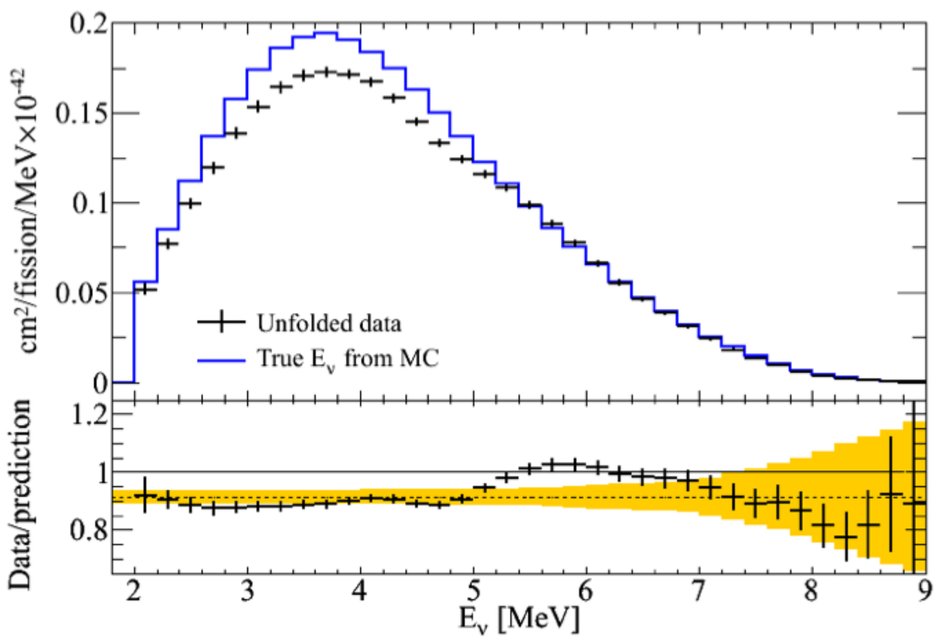
Data / Prediction, RENO 2200 days at near detector
0.918 +- 0.018 (for Huber + Mueller model)
0.959 +- 0.018 (for ILL + Vogel model)

- The core composition and power are known by the power reactor company
- **The observed rate shows a tension (deficit) with the model**, as it did for Daya Bay data

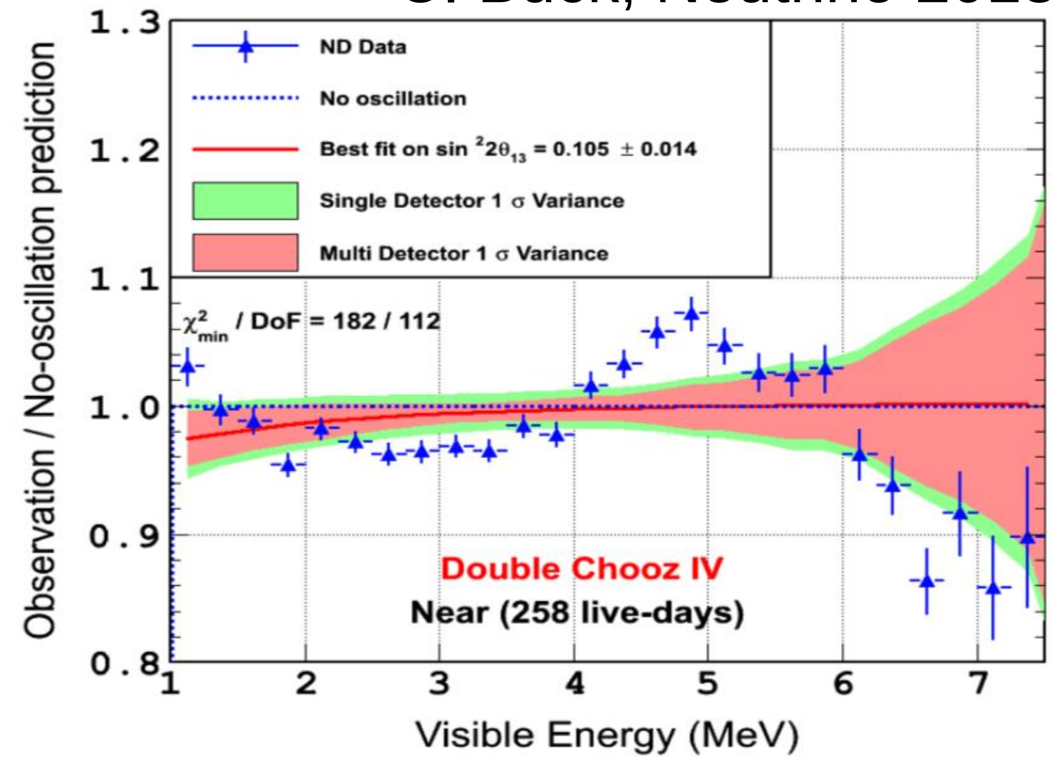
Intae Yu - Neutrino 2018

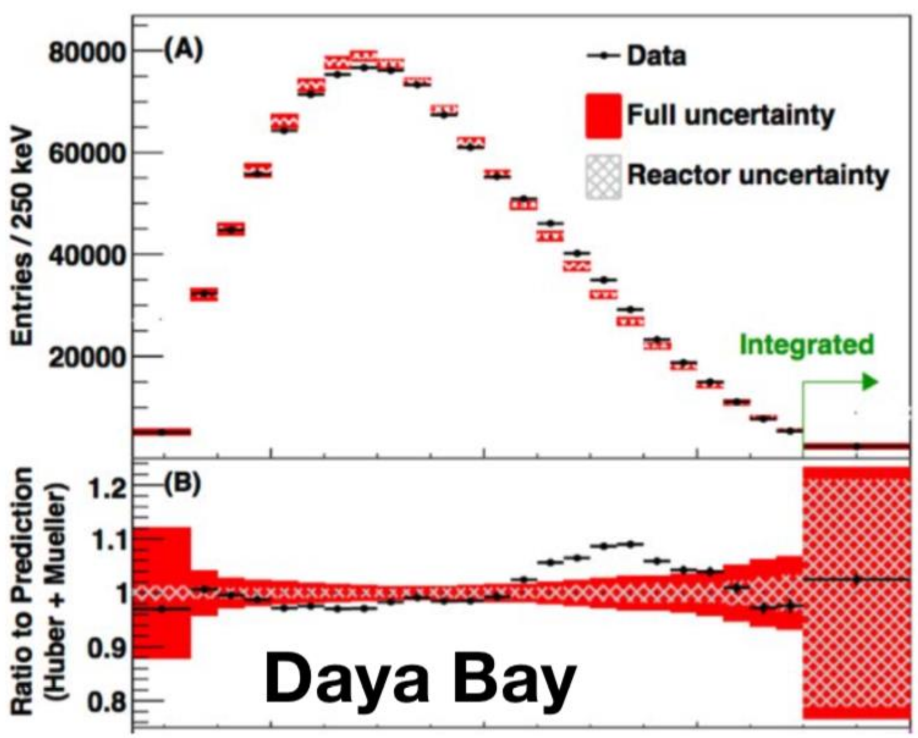
The 5 MeV bump?

RENO, Neutrino 2018



C. Buck, Neutrino 2018



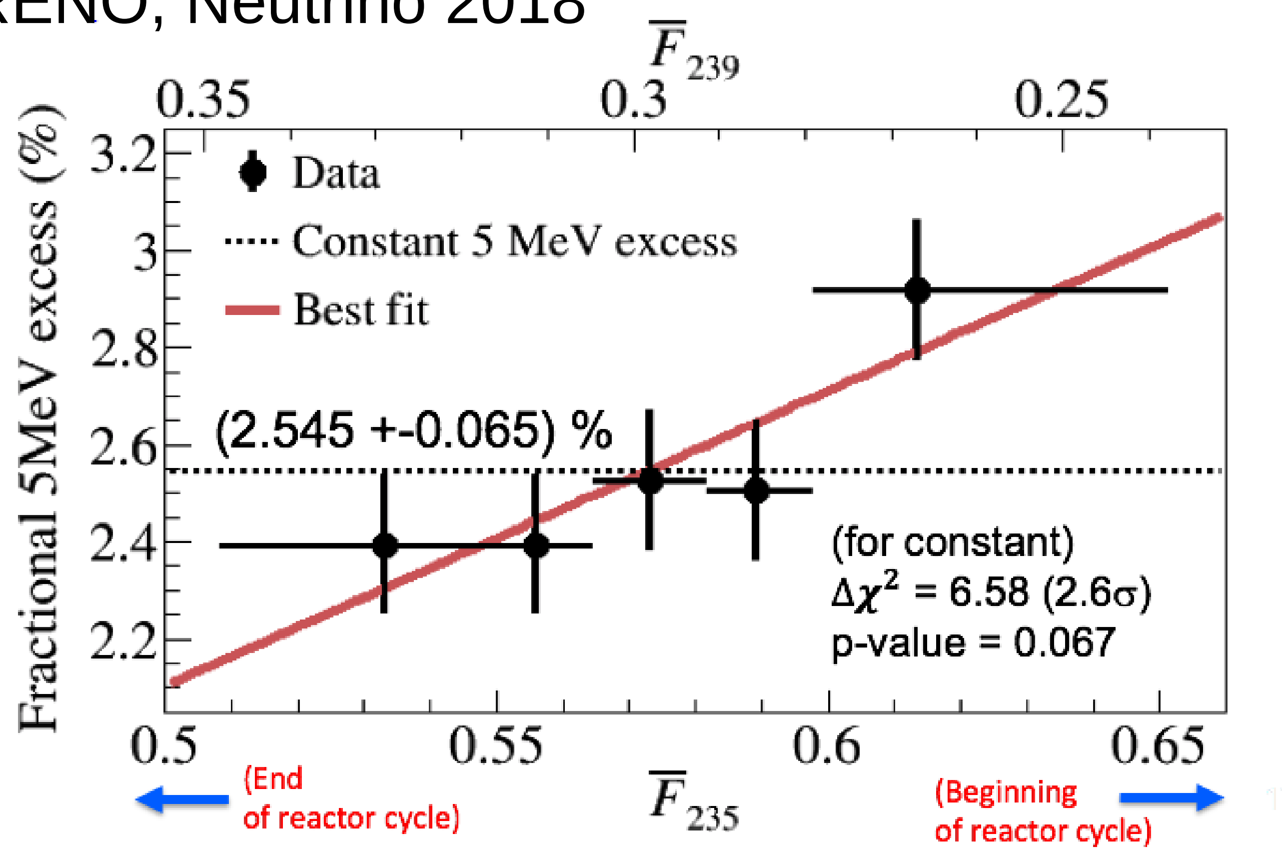


- First reported by RENO @ Neutrino 2014, later seen by Daya Bay, Double Chooz
- **Nuclear fission (mis)modeling or new neutrino properties?**

5 MeV bump: nuclear fission mis-modeling

- It's an excess and not a deficit
- It's independent of L (seen both at near at far detectors)
- Different experiments (different reactors) are compared: the bump depends on the fuel composition

RENO, Neutrino 2018



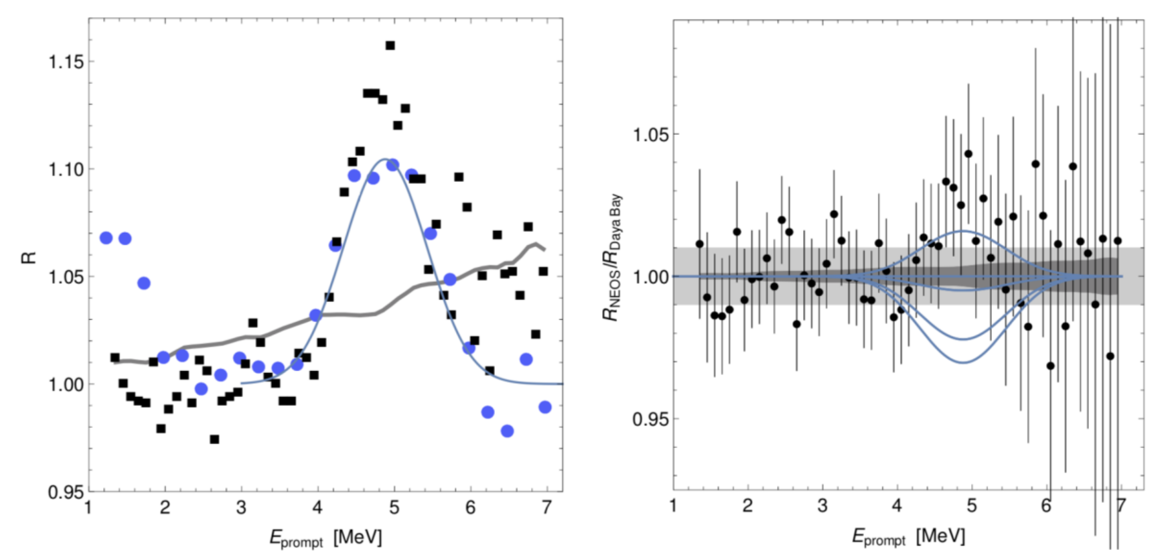
2.6σ indication that 5MeV excess is coming from ^{235}U isotope fission mis-modeling

Daya Bay

$$^{235}\mathrm{U} = 56.1\%,\ ^{239}\mathrm{Pu} = 30.7\%$$

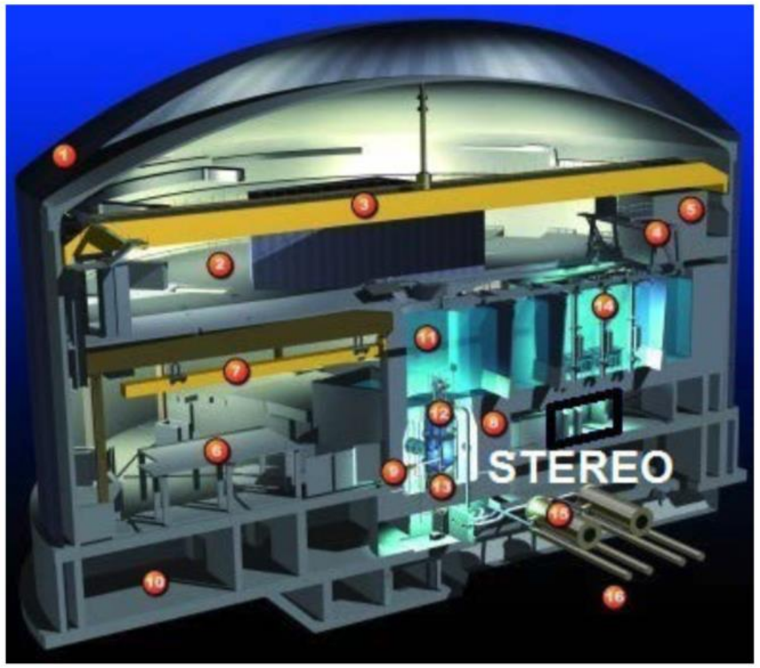
NEOS (Korea)

$$^{235}\mathrm{U} = 65.5\%,\ ^{239}\mathrm{Pu} = 23.5\%$$

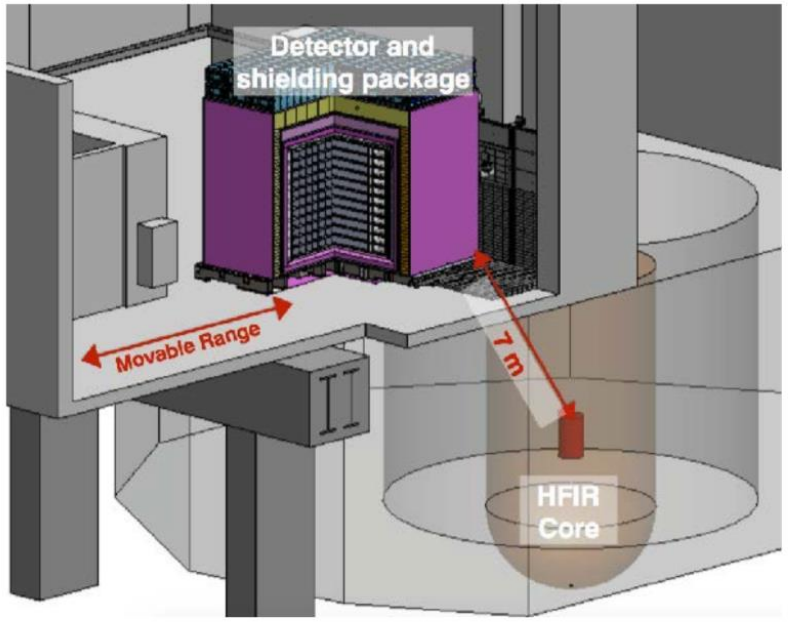


Data is better reproduced when the bump is ascribed to ^{235}U (M. Maltoni, Neutrino 2018

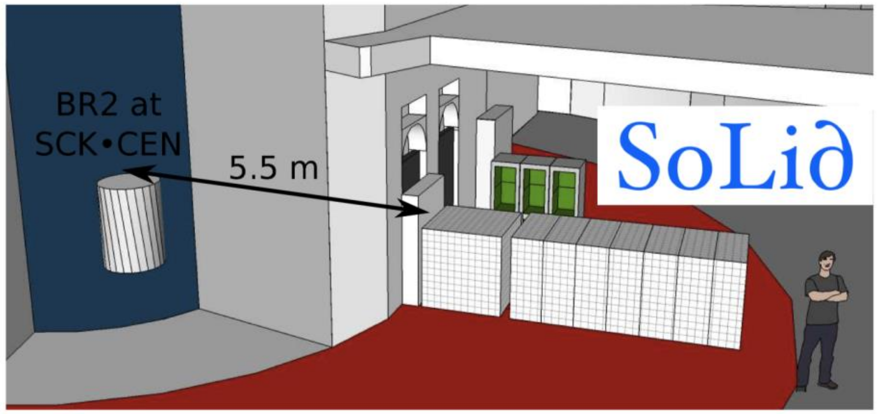
Very short baseline anti-ν_e experiments



- @ILL (Grenoble)
- Baseline: 8.9-11.1m
- Gd-loaded liquid scintillator
- Analysis+data taking in progress



- @HFIR (Oak Ridge)
- Multiple baseline
- Cd doped liquid scintillator
- First results just released!



- @SCK-CEN BR2 (Belgium)
- Baseline 6-9m
- Li doped scintillator bars
- Data taking!

The underlying idea is similar: scintillator (liquid/plastic) doped with neutron absorber. Maybe segmented and movable, very close (a few m) from the reactor core.

+DANSS, NuLat, Neutrino4, Chandler

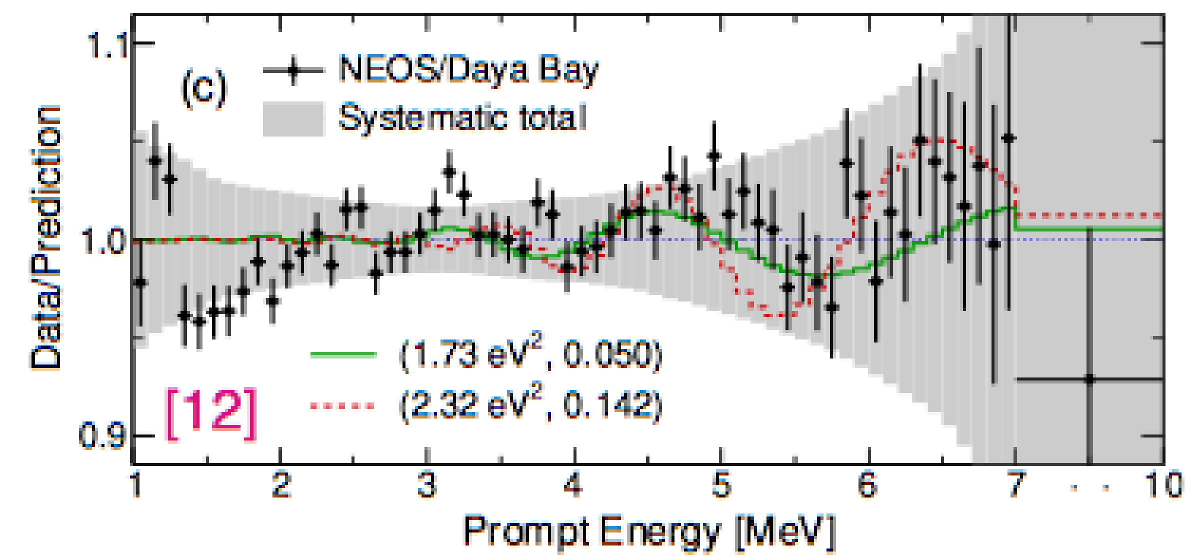
Some hints/confirmations but more data needed

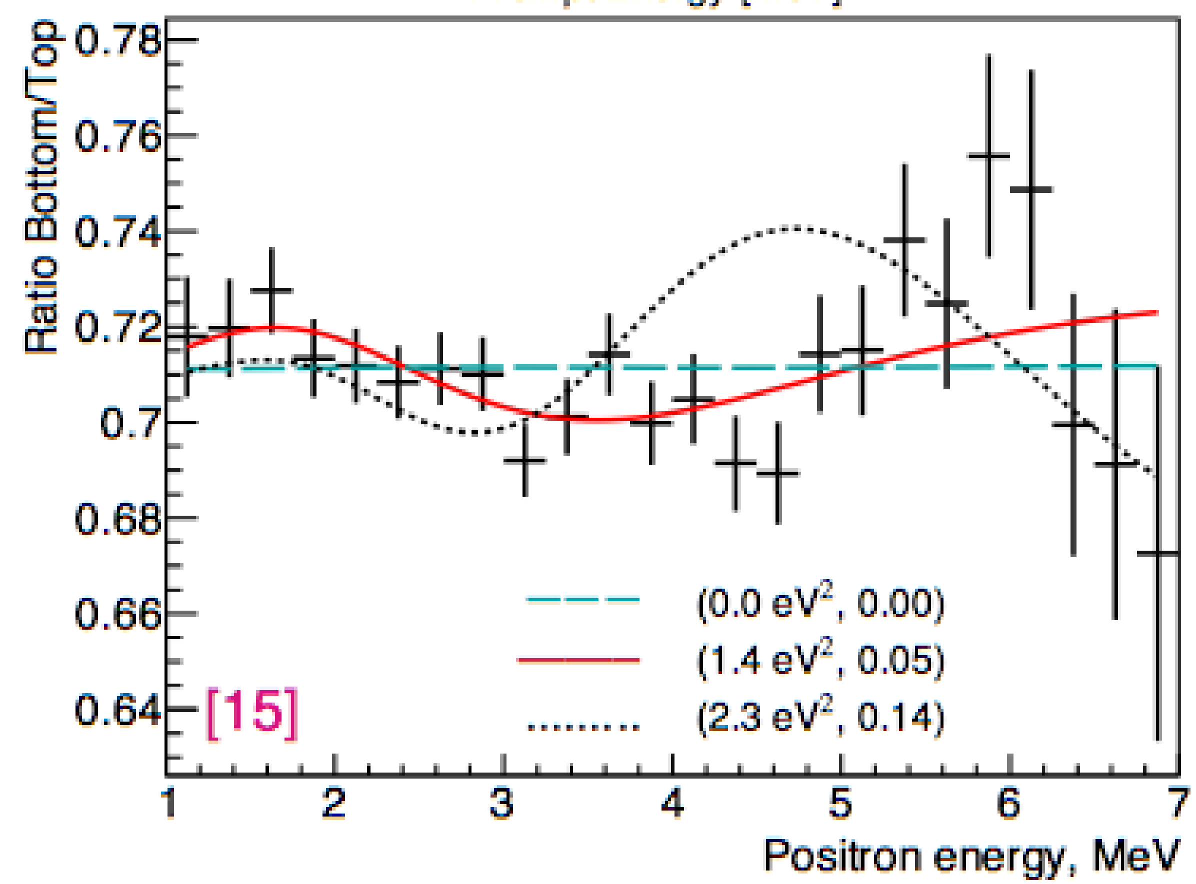
M. Maltoni Neutrino 2018

NEOS and DANSS results

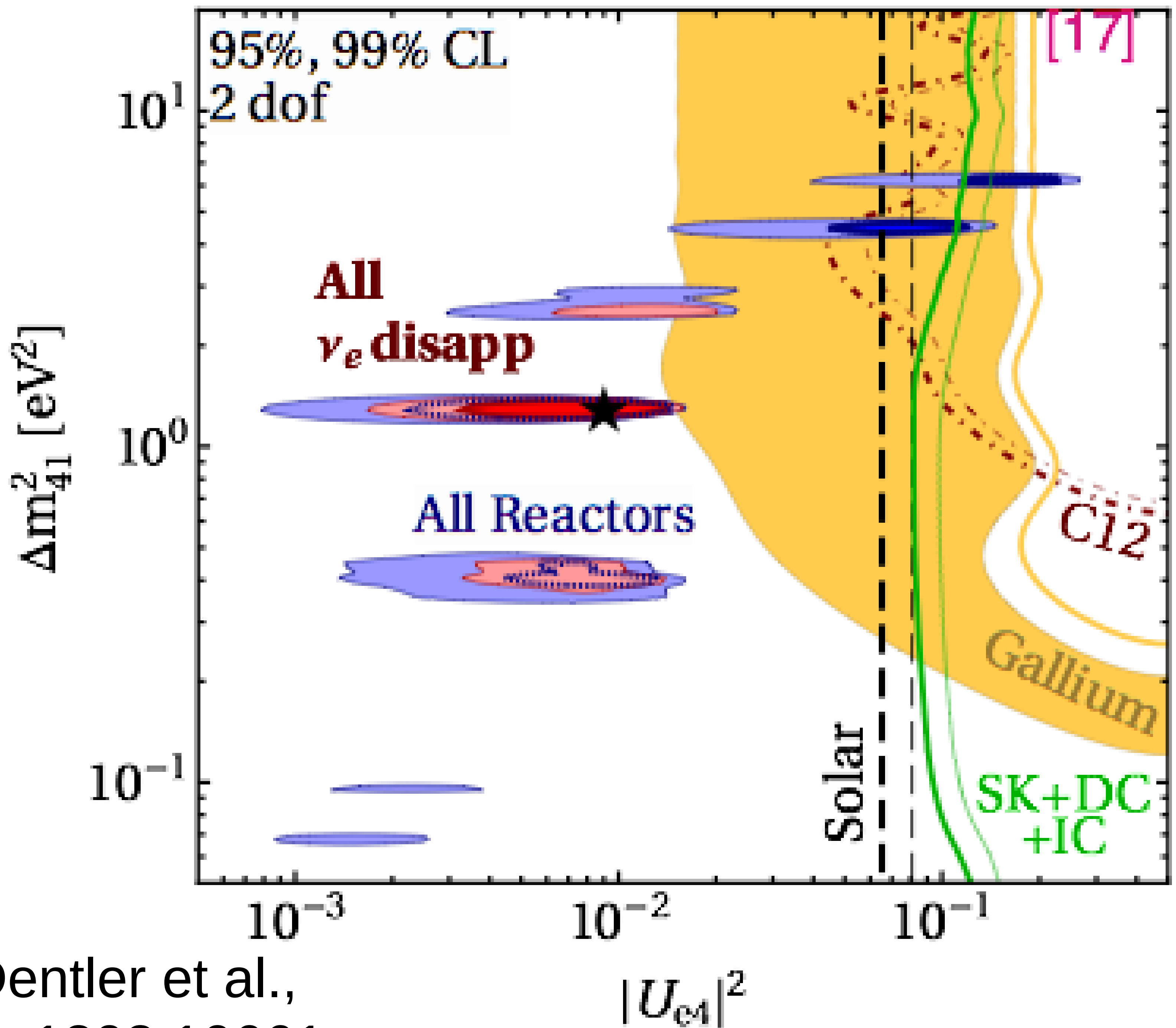
- Both detectors have measured reactor neutrinos at very short baseline:
  - NEOS [12]: 24 m;
  - DANSS [15]: 10.7 m → 12.7 m;
- data: near/far spectral ratios ⇒ insensitive to flux shape & normalization:
  - NEOS: normalized to Daya-Bay;
  - DANSS: movable detector;
- both detectors observe small energy modulations ⇒ hints of sterile ν.

[12] Y. J. Ko *et al.* [NEOS collab], PRL **118** (2017) 121802 [arXiv:1610.05134].
[15] I. Alekseev *et al.* [DANSS collabortion], arXiv:1804.04046.





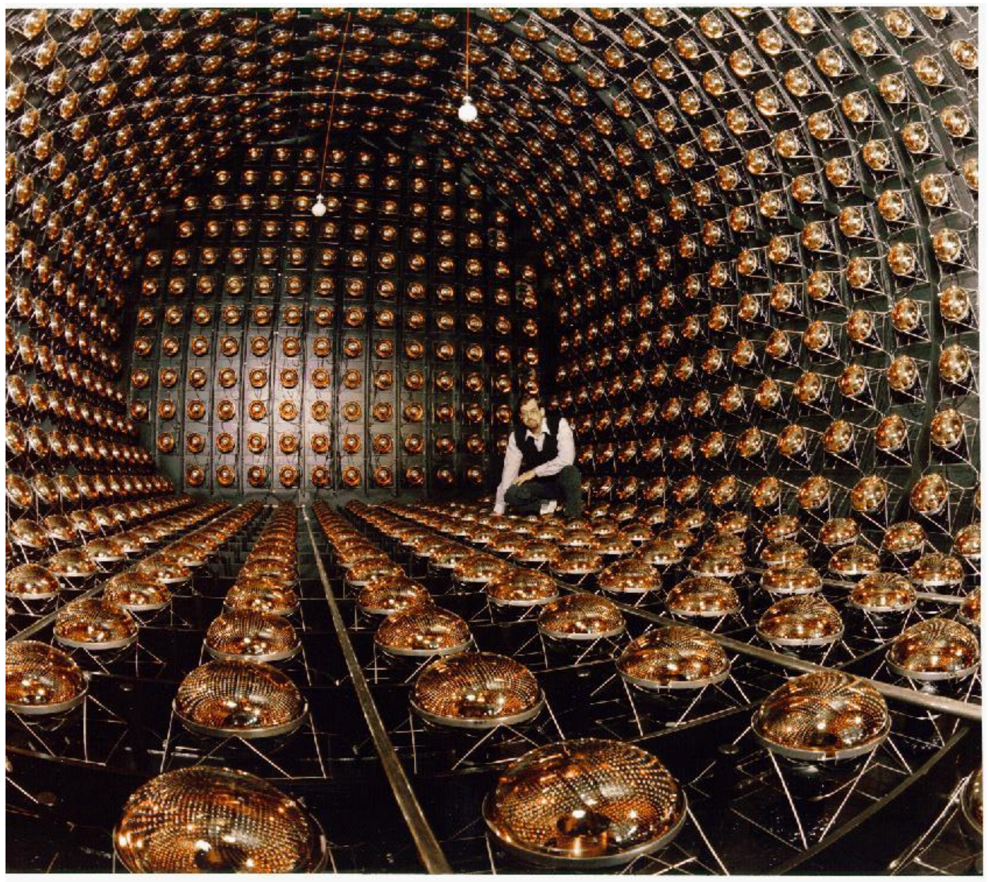
Global ν_e and anti-ν_e disappearance



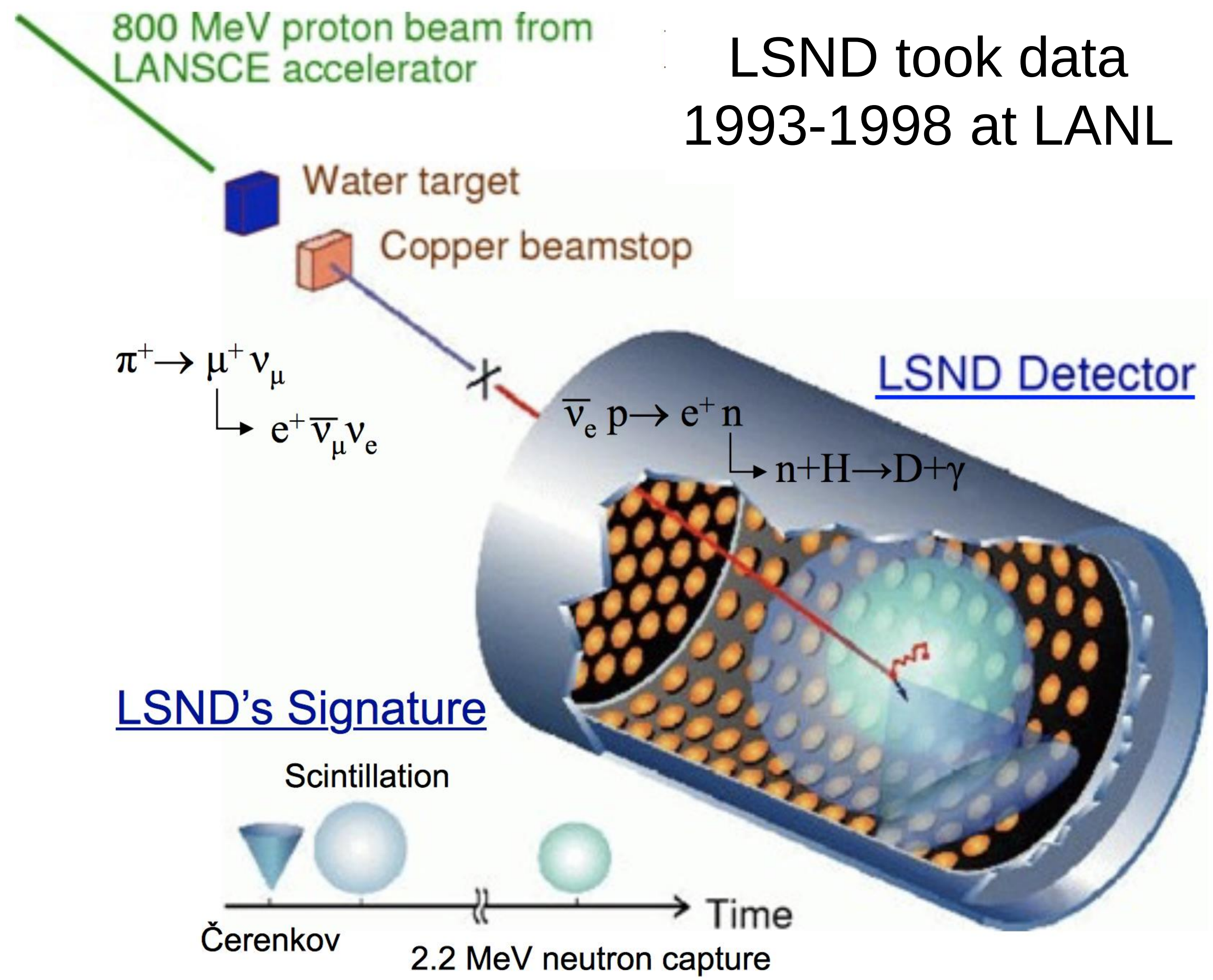
M. Dentler et al., arXiv:1803.10661

2.1σ tension between Gallium (ν_e disappearance) and reactors (anti-ν_e disappearance)

Accelerator anomaly: LSND



LSND took data
1993-1998 at LANL

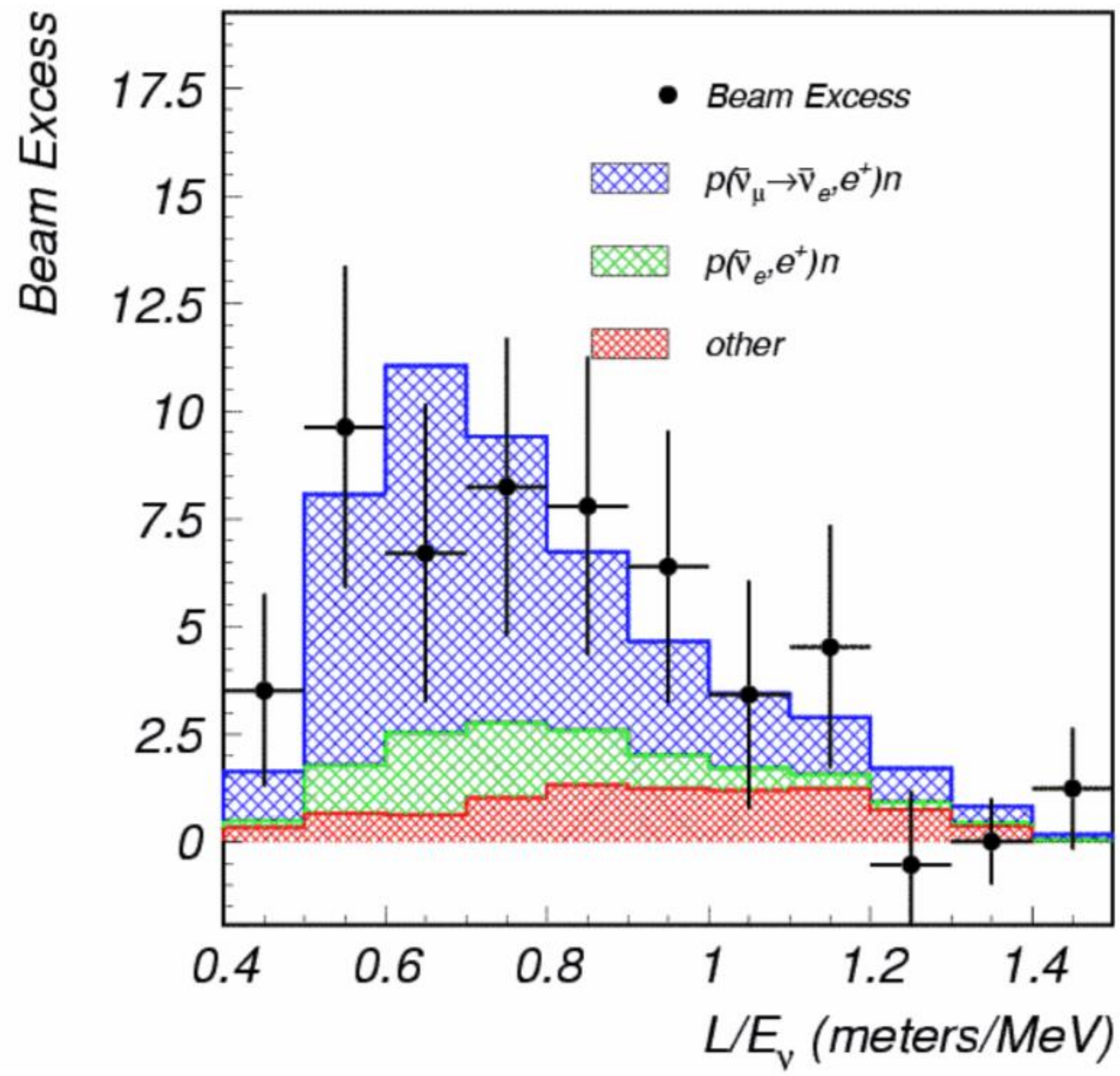


- IBD in liquid scintillator
- Baseline ~30 m
- Energy ~20-50 MeV
- L/E ~ 1m / MeV

μ^+ decay at rest experiment

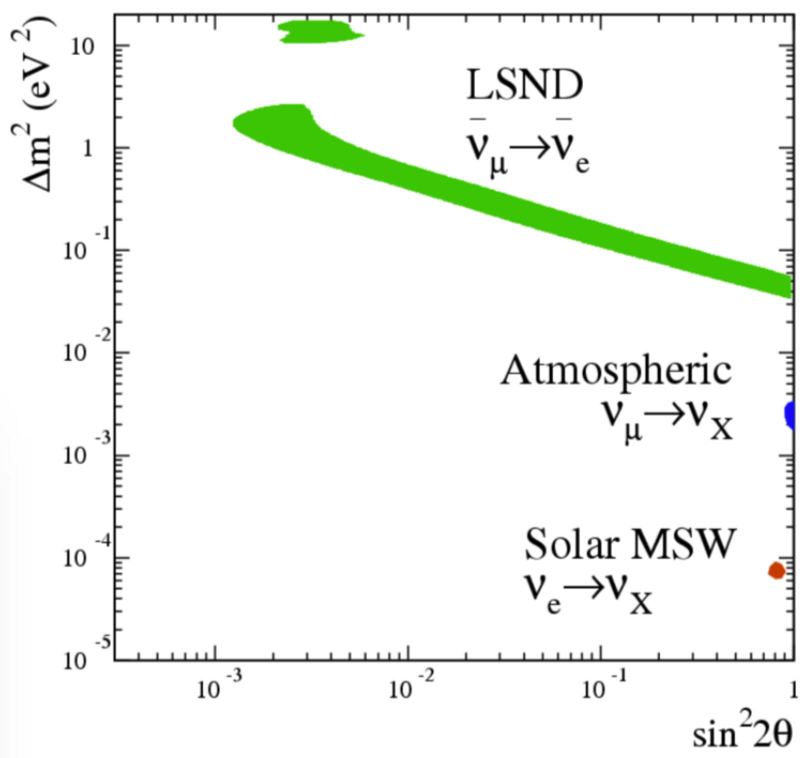
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\overset{?}{\hookrightarrow} \bar{\nu}_e$$

LSND signal

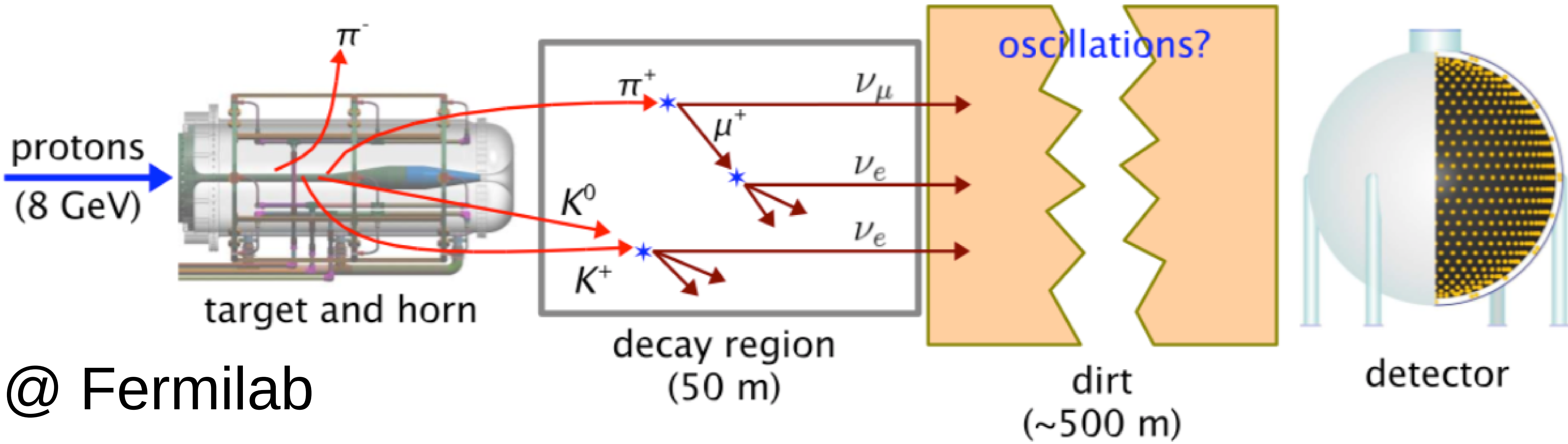


- Excess of anti-ν_e in an anti-ν_μ beam
- Excess events: 87.9±22.4±6.0
- 3.8σ evidence

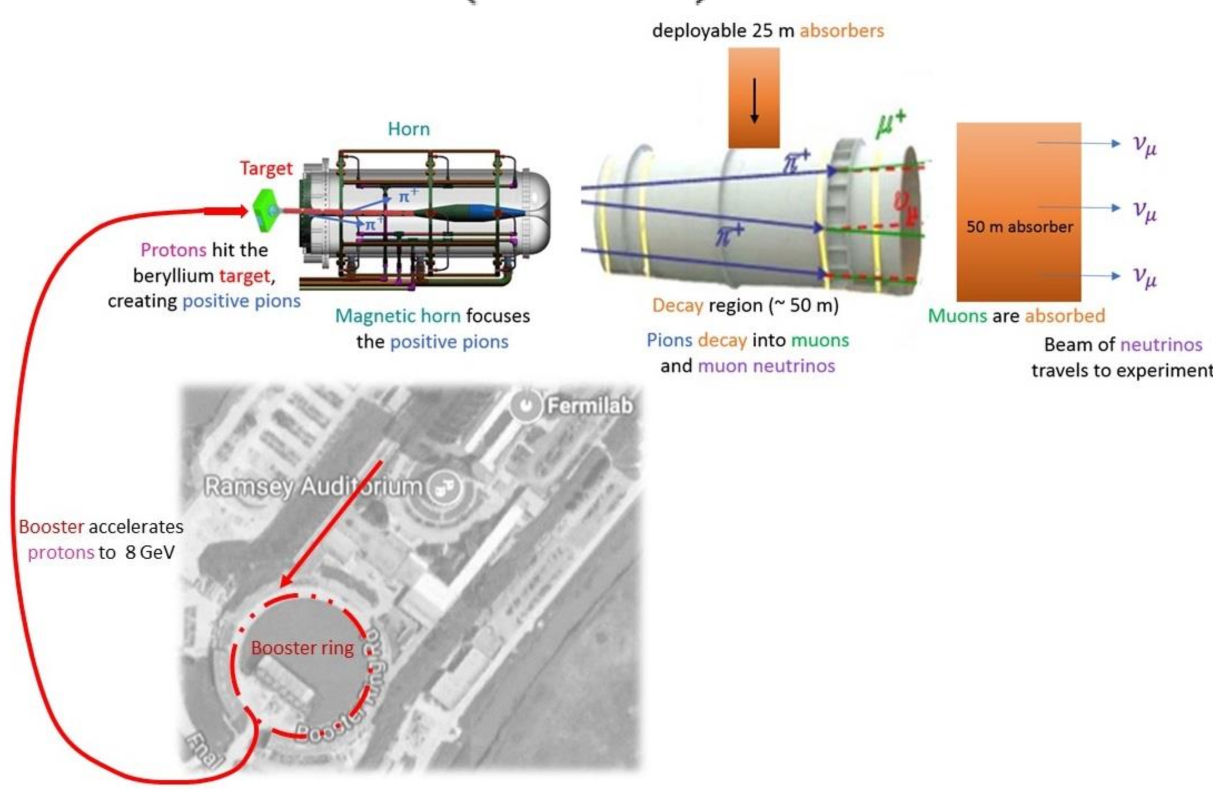
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$



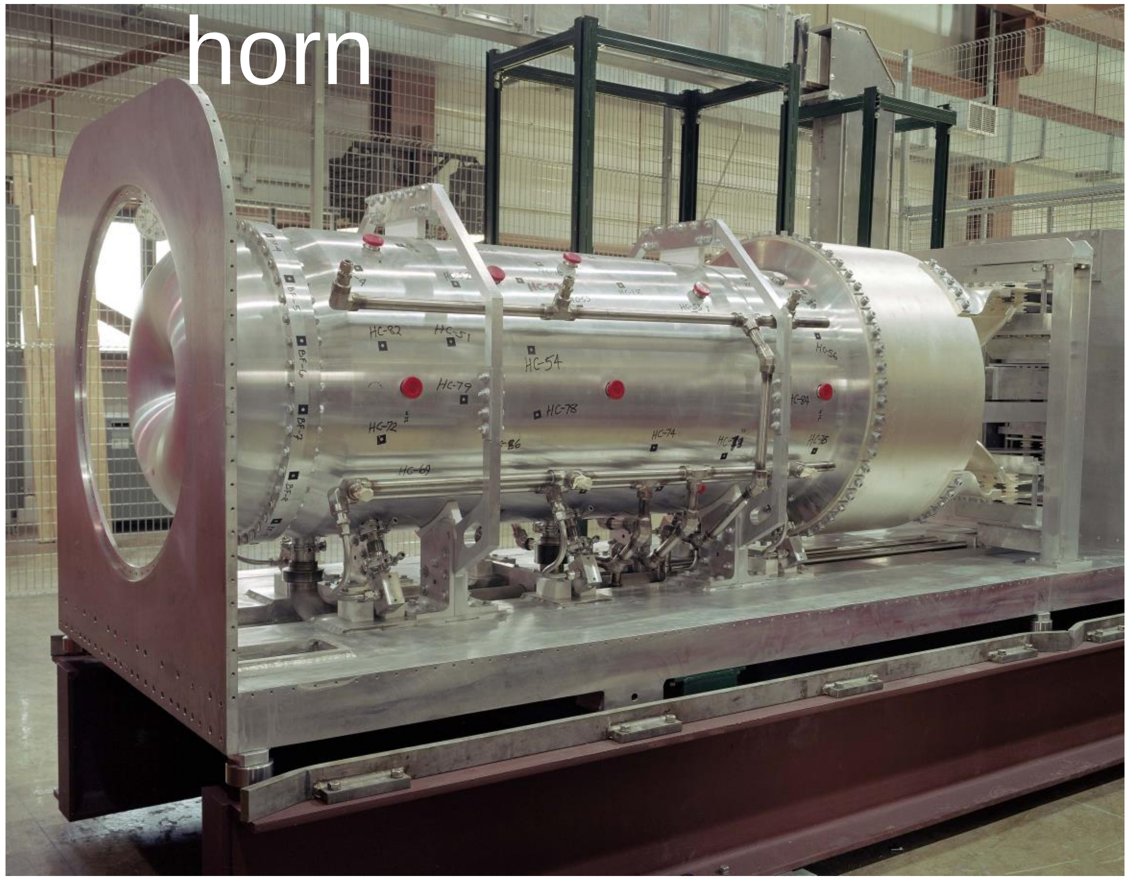
MiniBooNE to test LSND

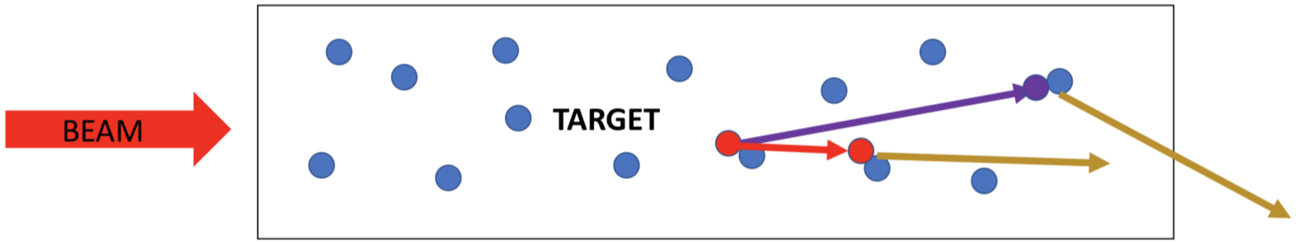


@ Fermilab

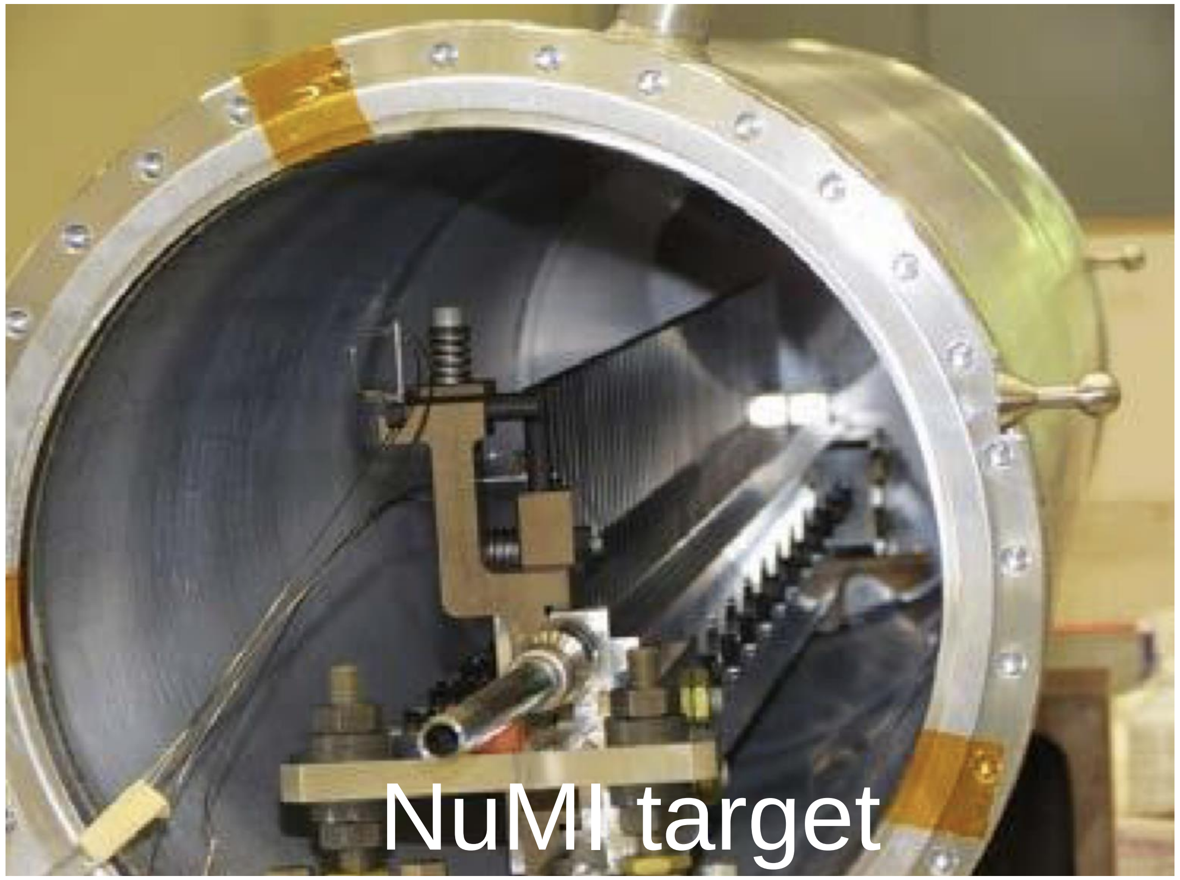


Aside on neutrino production

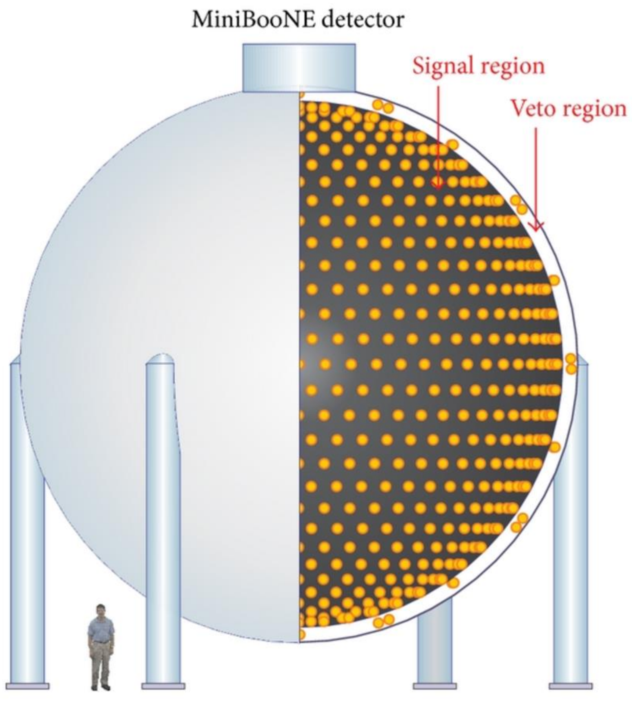




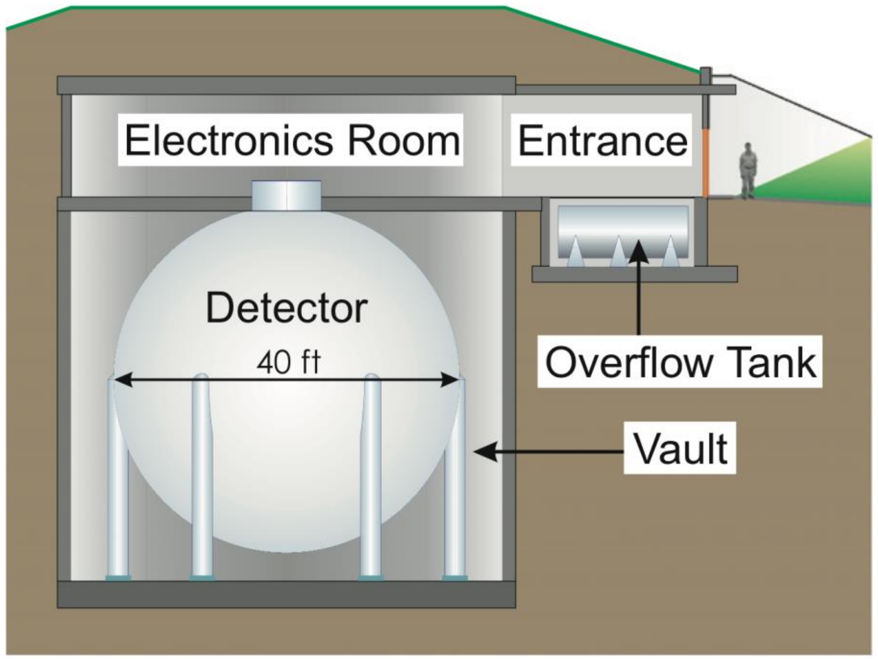
- The target needs to be able to get rid of the beam power (BNB ~38kW, NuMI ~700kW)
- Be or C
- ~2 interaction lengths
- segmented for better heat dissipation and temperature dilatation/contraction handling
- Air or He cooled

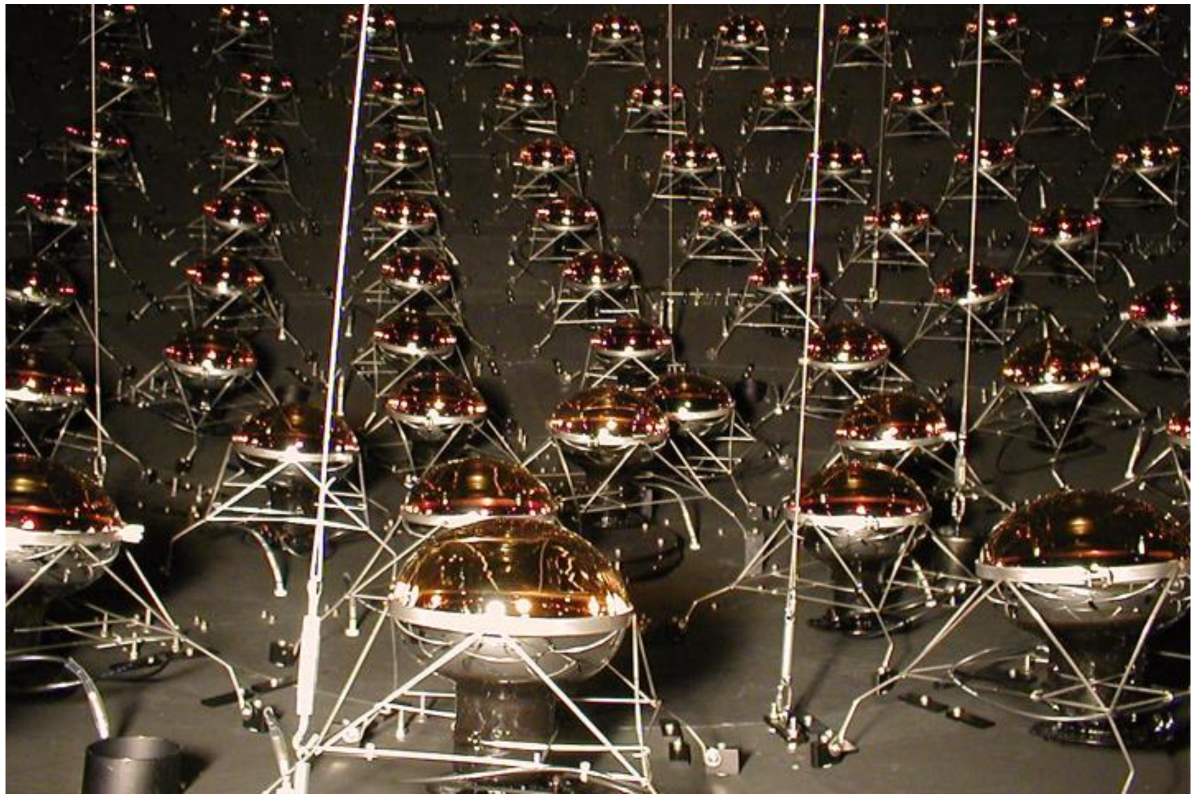


MiniBooNE detector

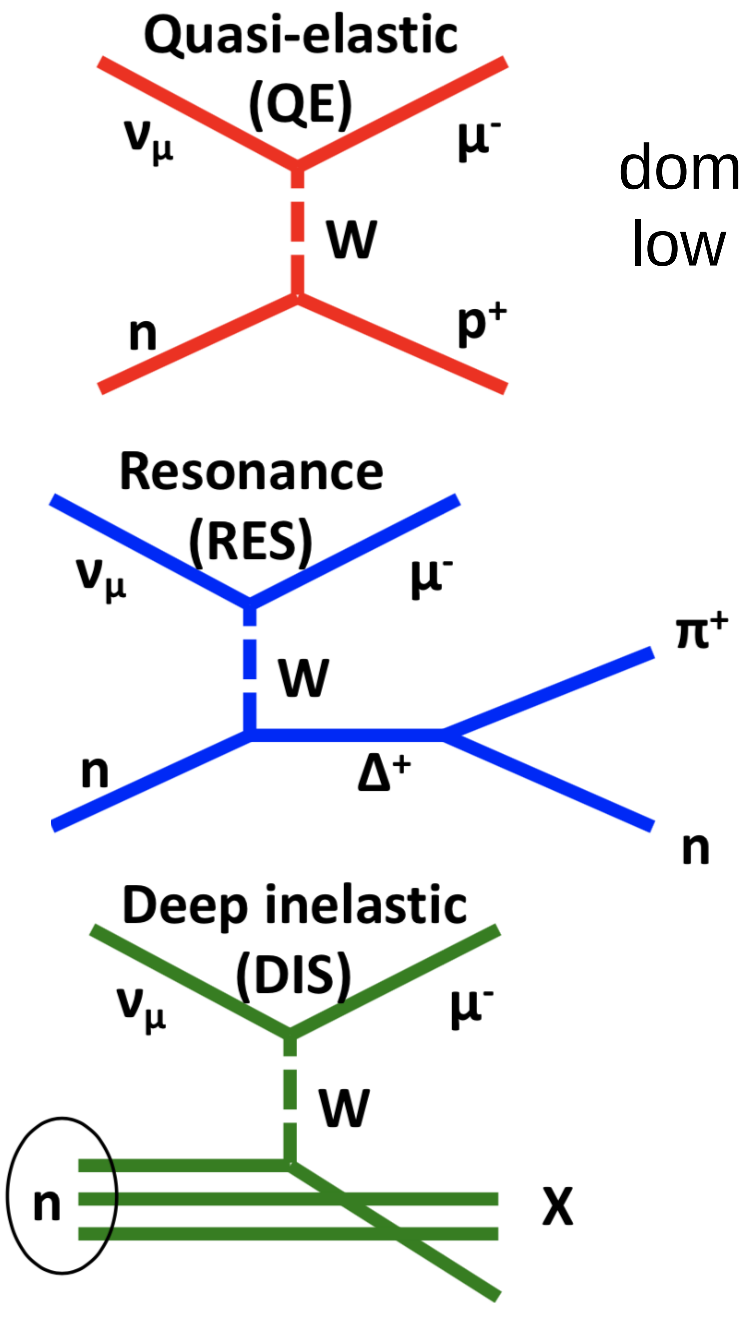


- Pure mineral oil, Cerenkov:scintillation=3:1
- 800tons (445 fiducial, 5m radius)
- ~1500 PMTs for ~10% coverage
- E_ν~800MeV
- Baseline ~500m

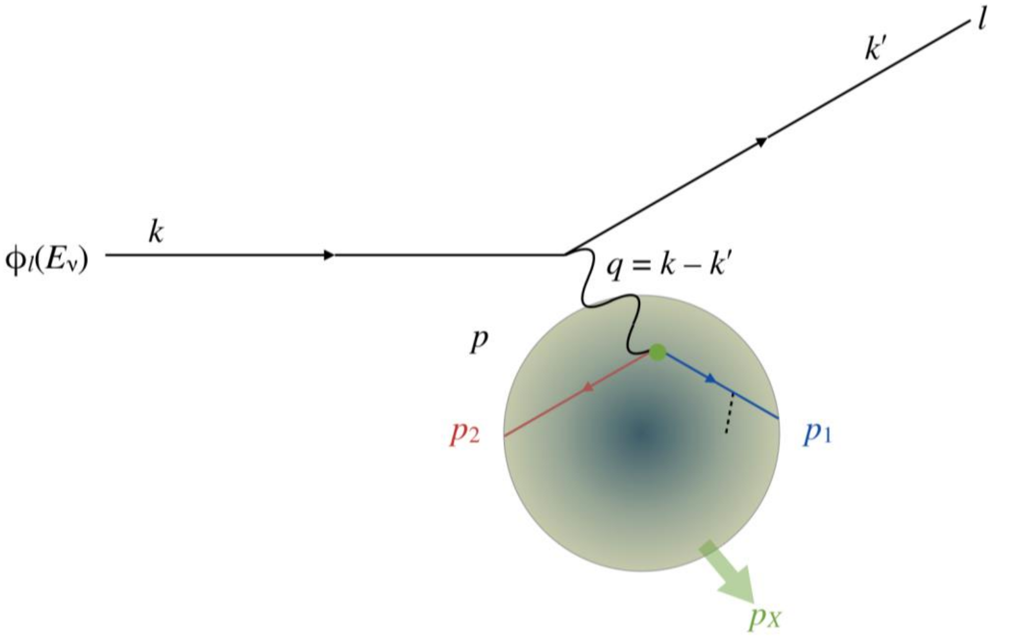




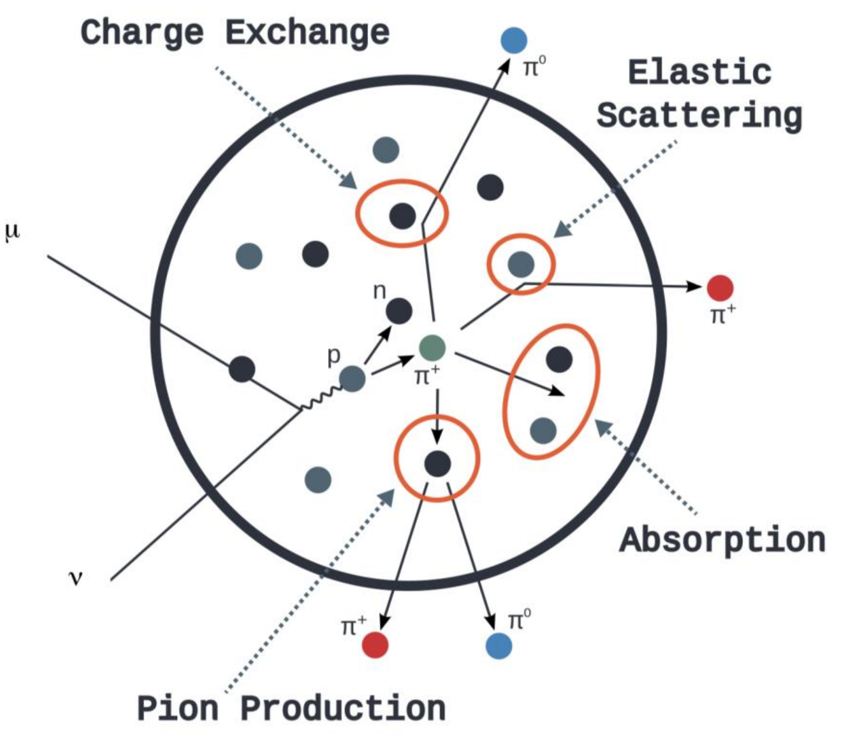
Neutrino interactions



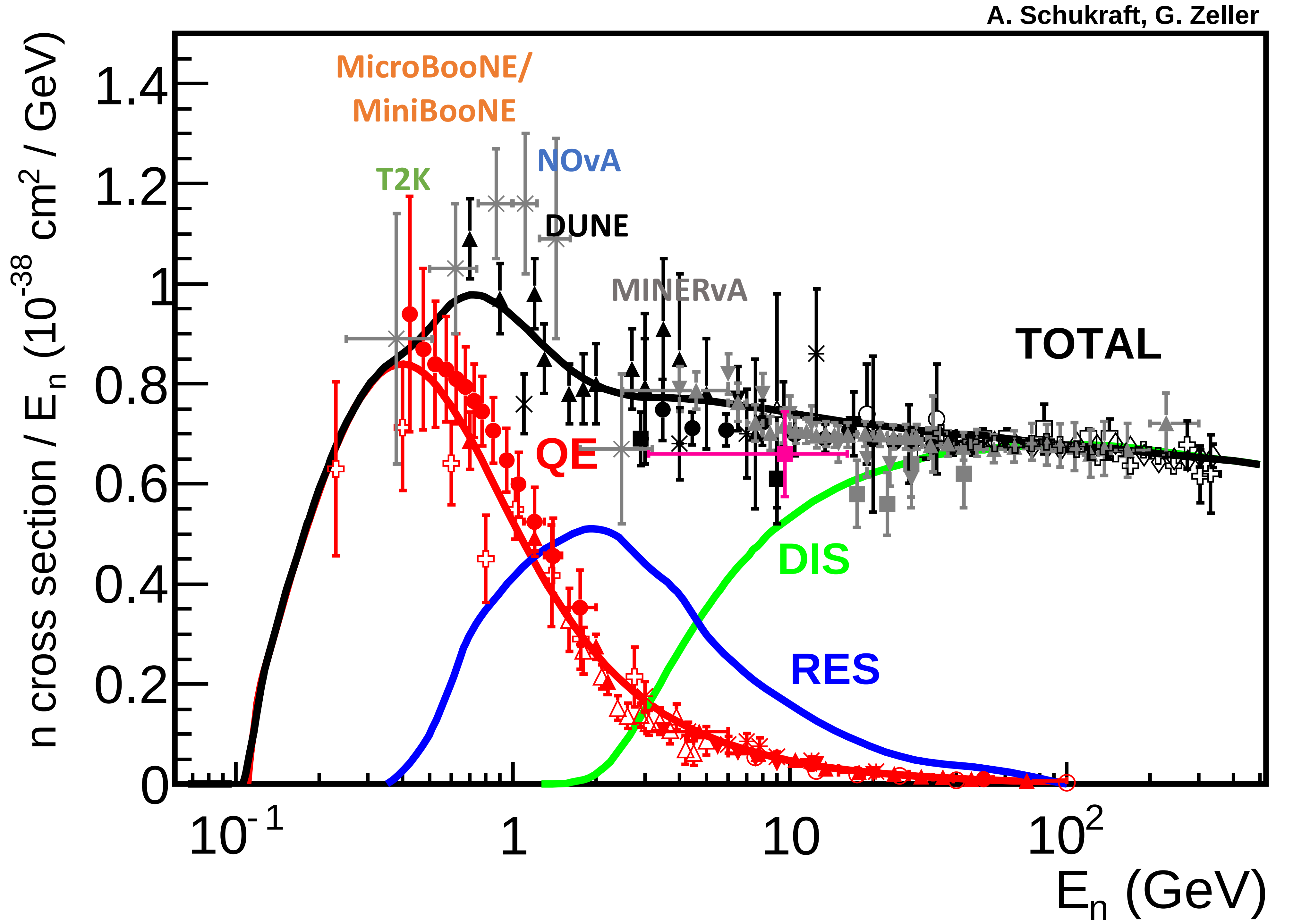
dominant at low energy



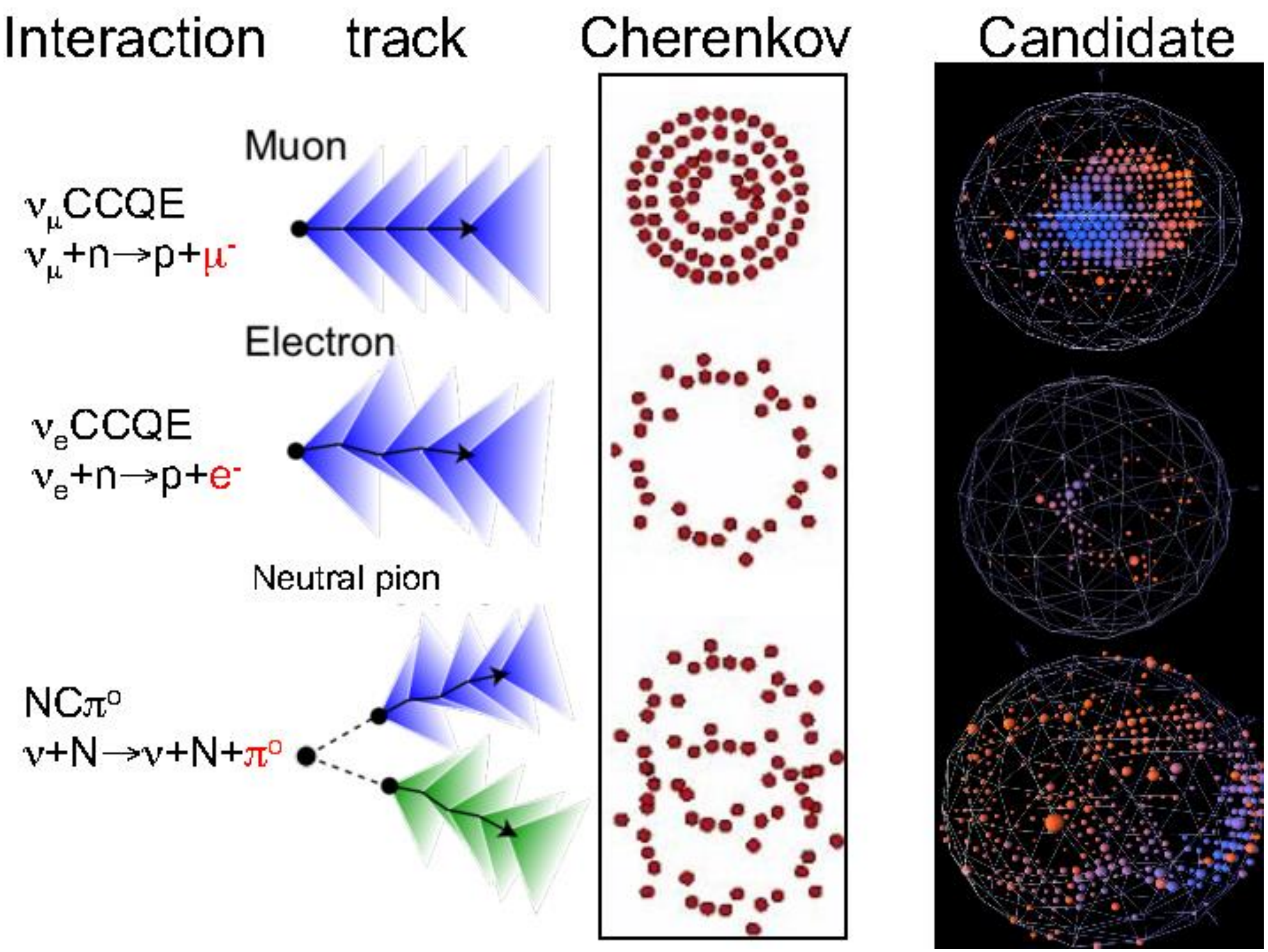
Scattering on nuclei is different that scattering on nucleons: there is a lot of very complicated nuclear physics going on
Also: Final State Interactions!



Neutrino interactions: all together

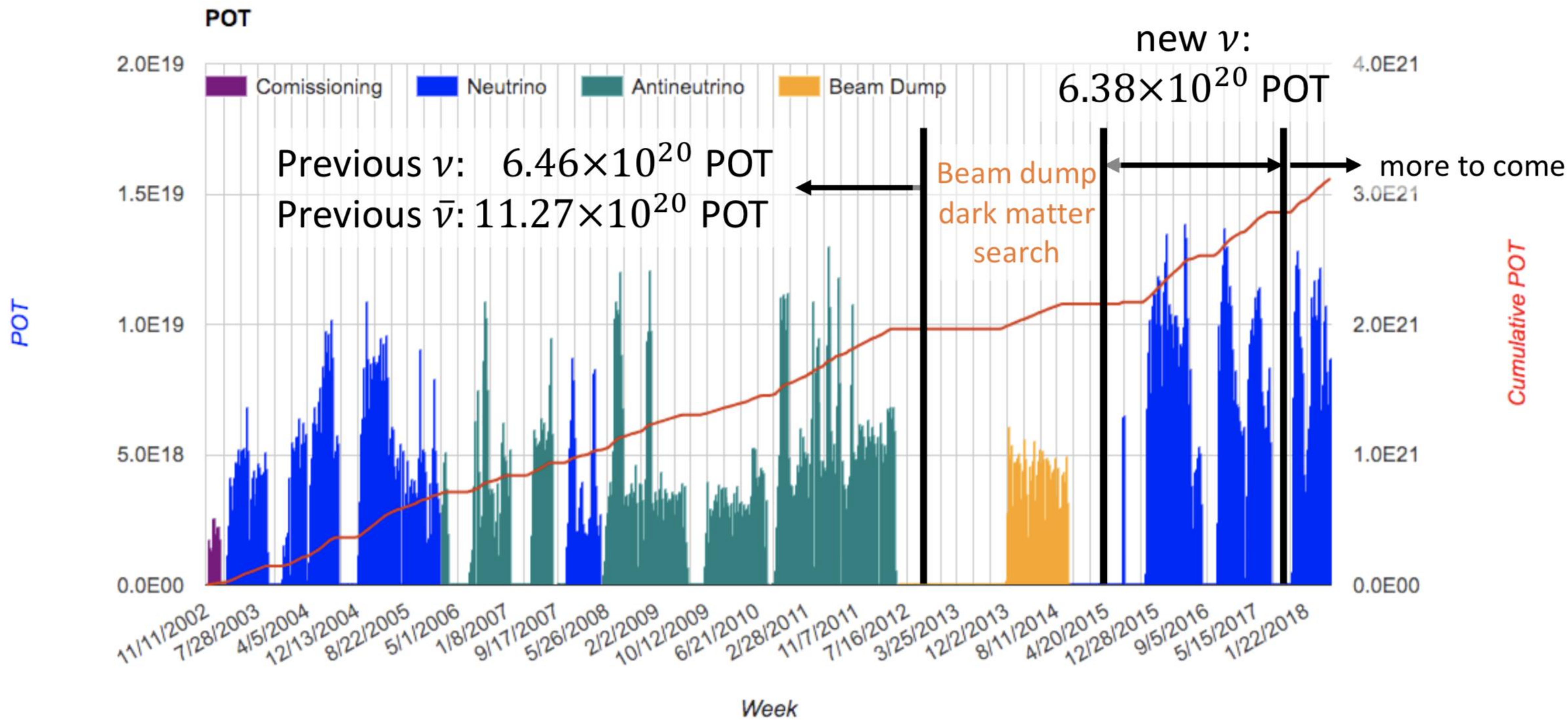


Signatures in Cerenkov detector (MiniBooNE)



- Examples of CCQE (Charged Current Quasi Elastic) ν_μ and ν_e and NC (Neutral Current) π^0 topologies
- Use primarily Cerenkov light
- **Insensitive to difference between electron and photons**

New combined analysis (June 2018)

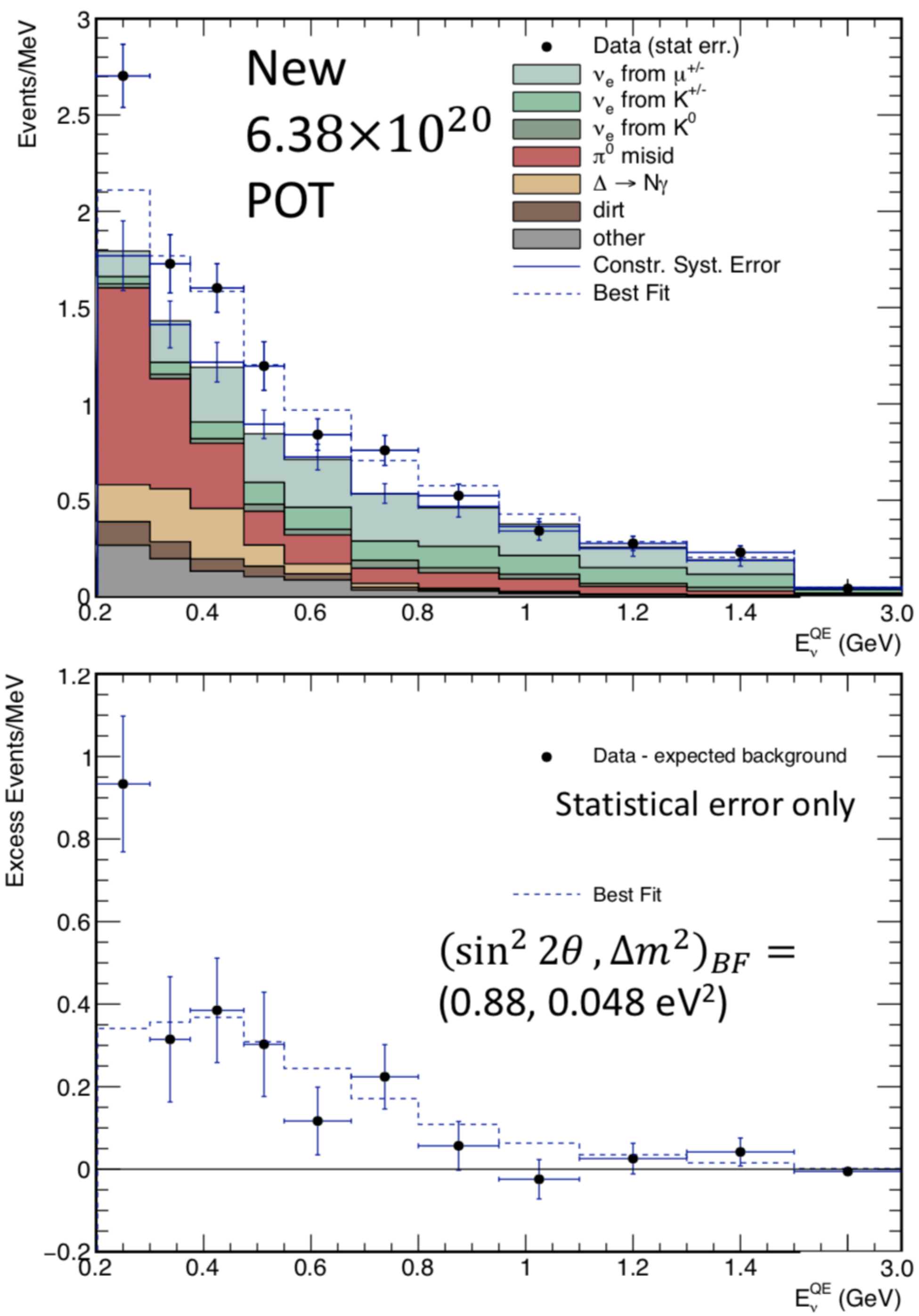


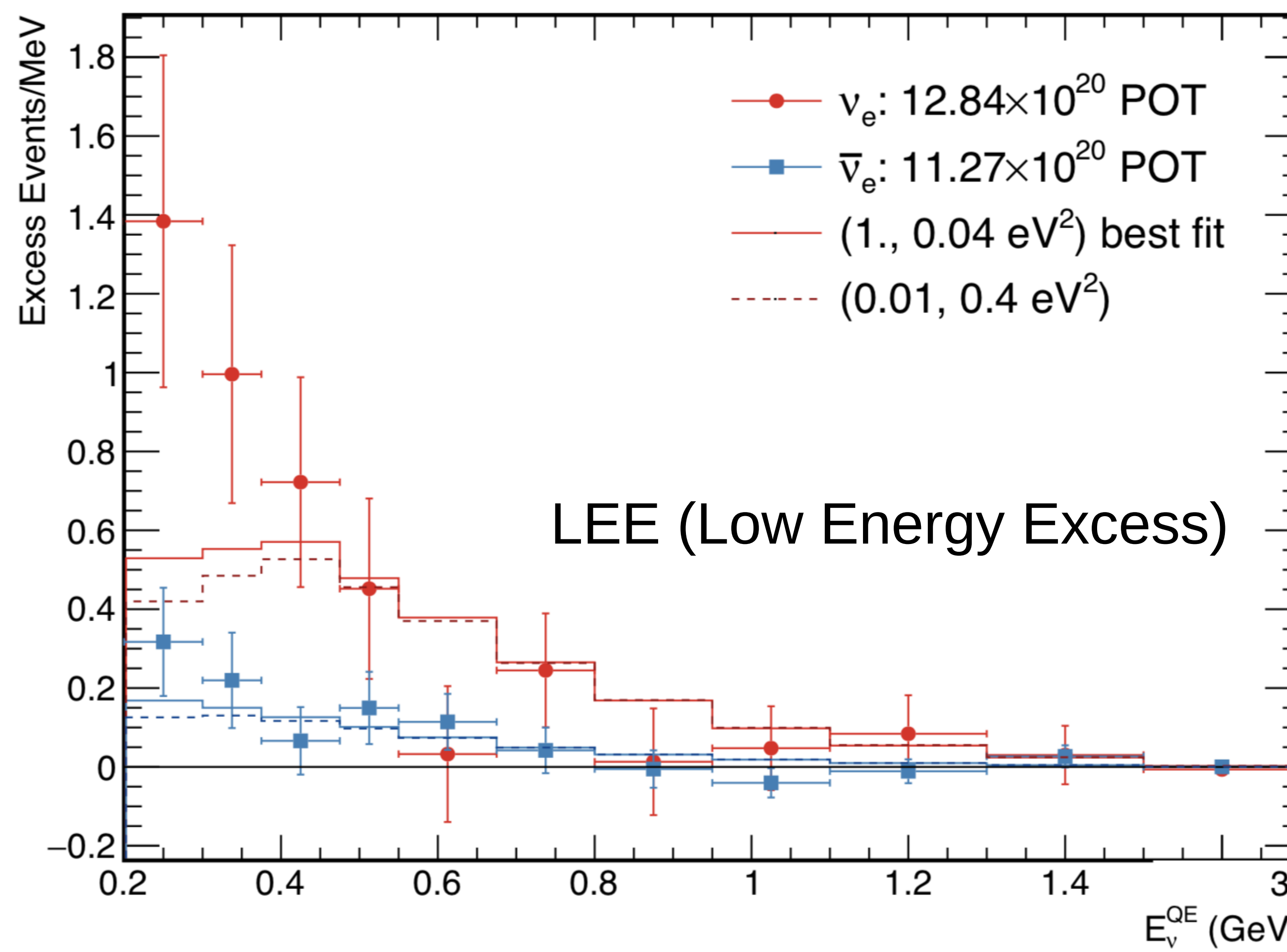
Huang, Neutrino 2018

- New results just released used both neutrino and anti neutrino datasets (ν_μ and anti-ν_μ) spanned over many years (started in 2002)
- Same analysis as carried out before, in 2012

MiniBooNE results

Huang, Neutrino 2018

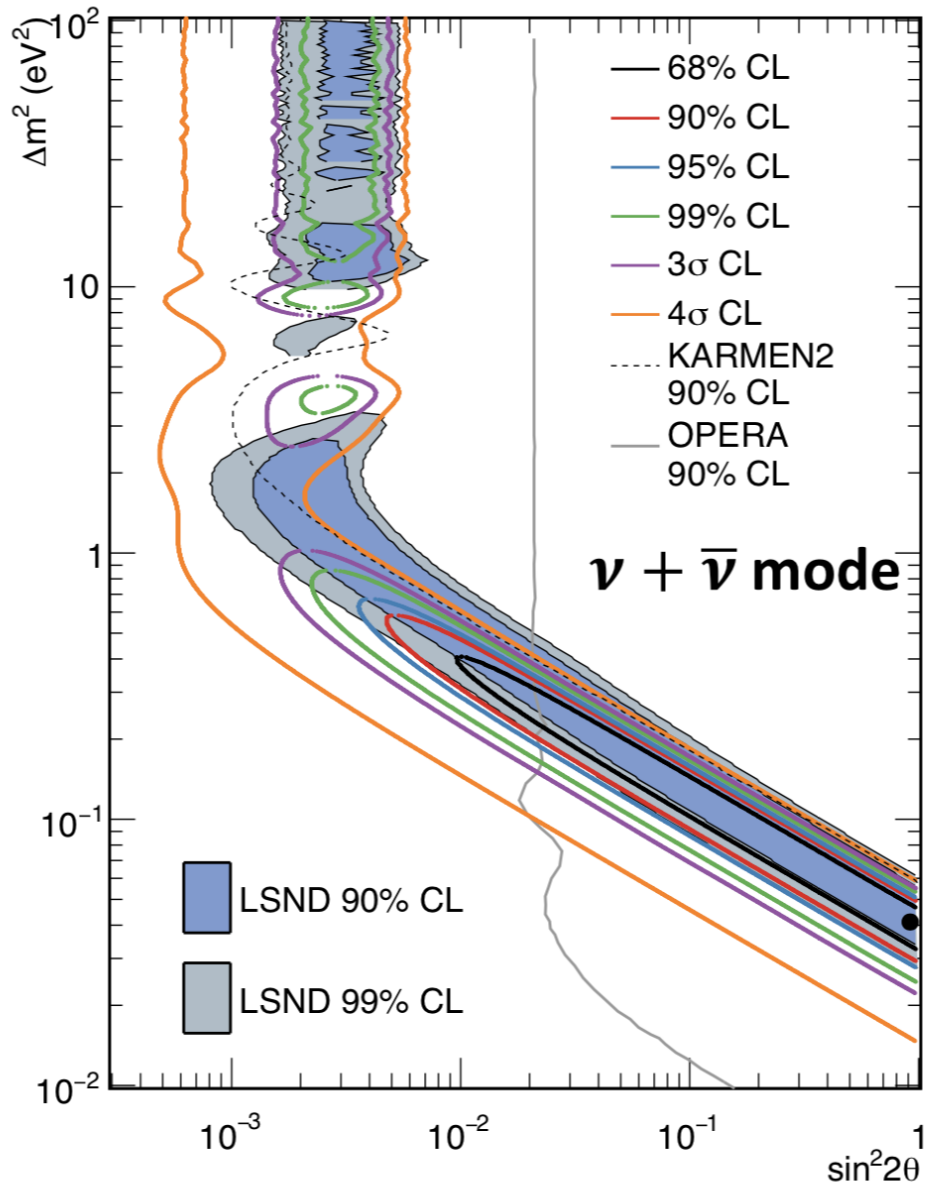




4.8σ evidence of excess of ν_e and anti-ν_e

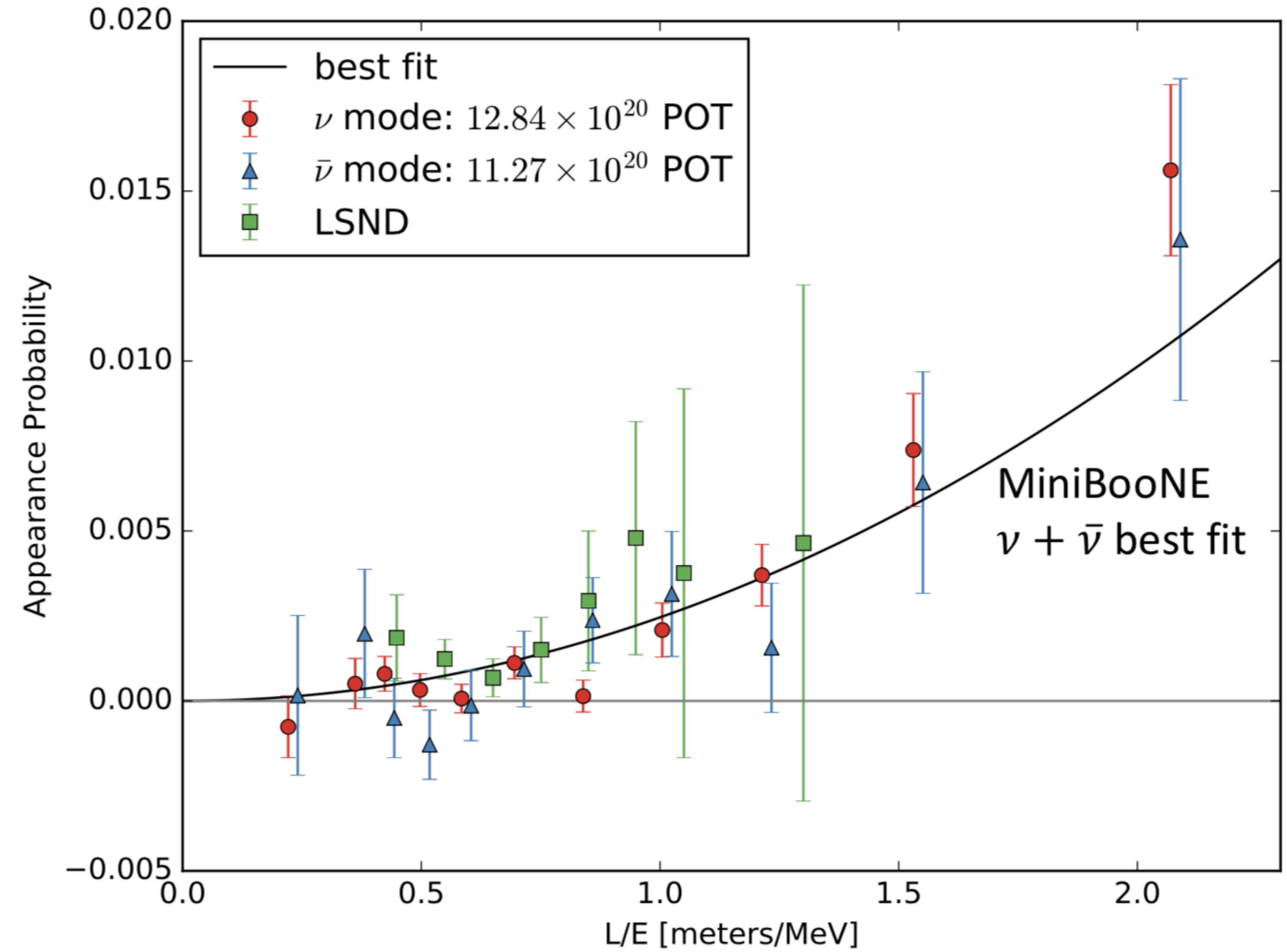
are these oscillations? or not well understood backgrounds (gammas, Δ radiative decays…)?

Consistency with LSND



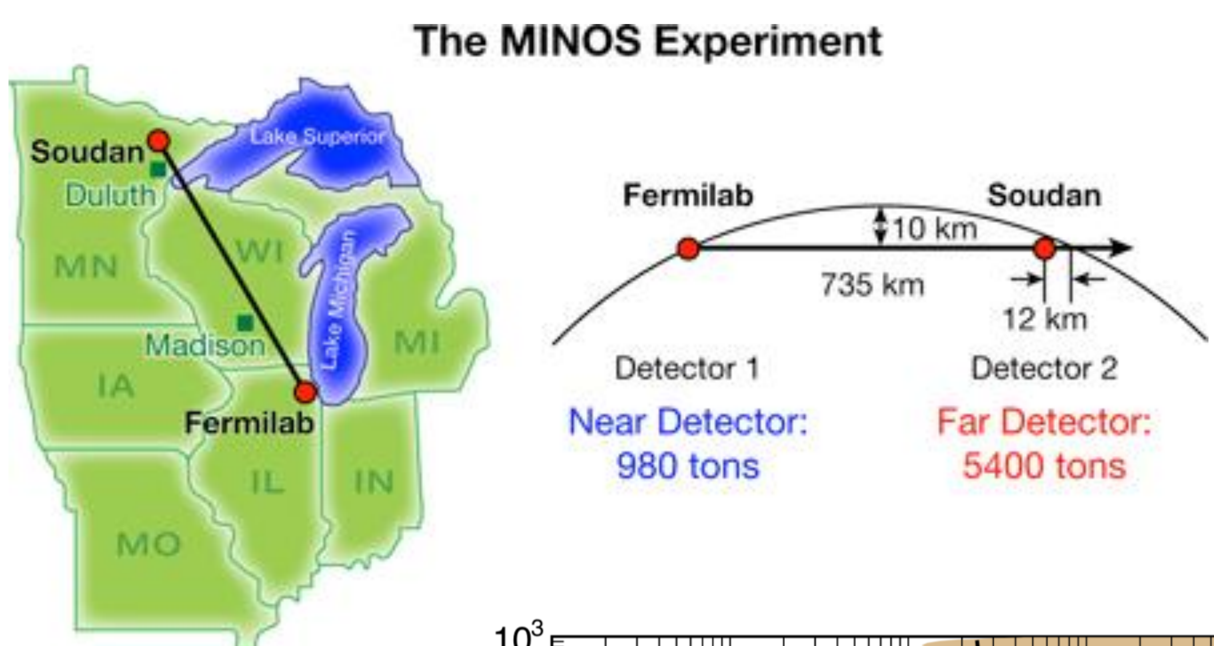
$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$

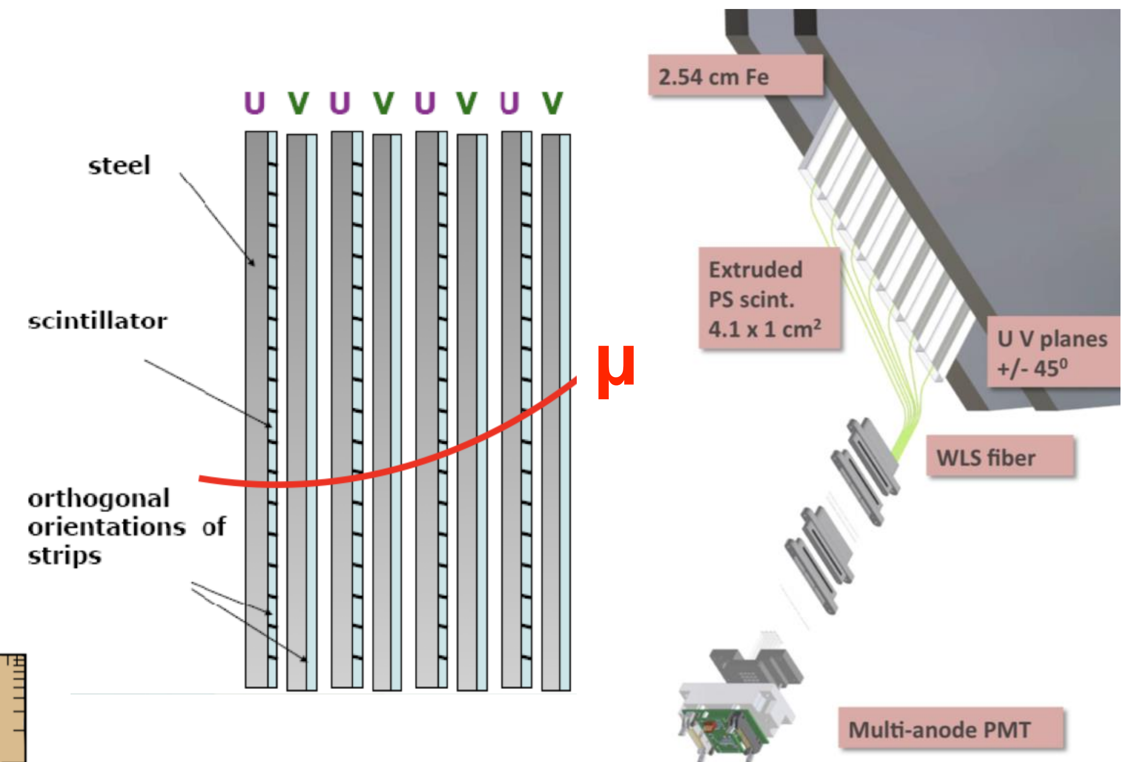
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

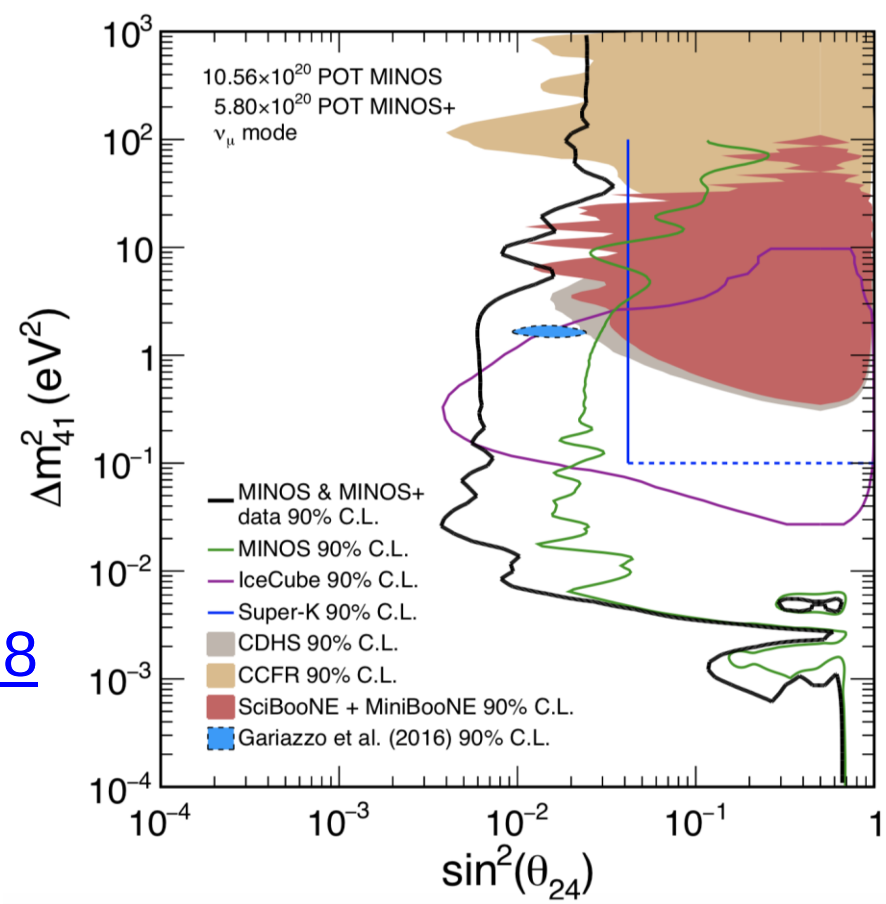


MiniBooNE claims they are consistent with LSND…many people are not convinced.

ν_μ disappearance? MINOS results







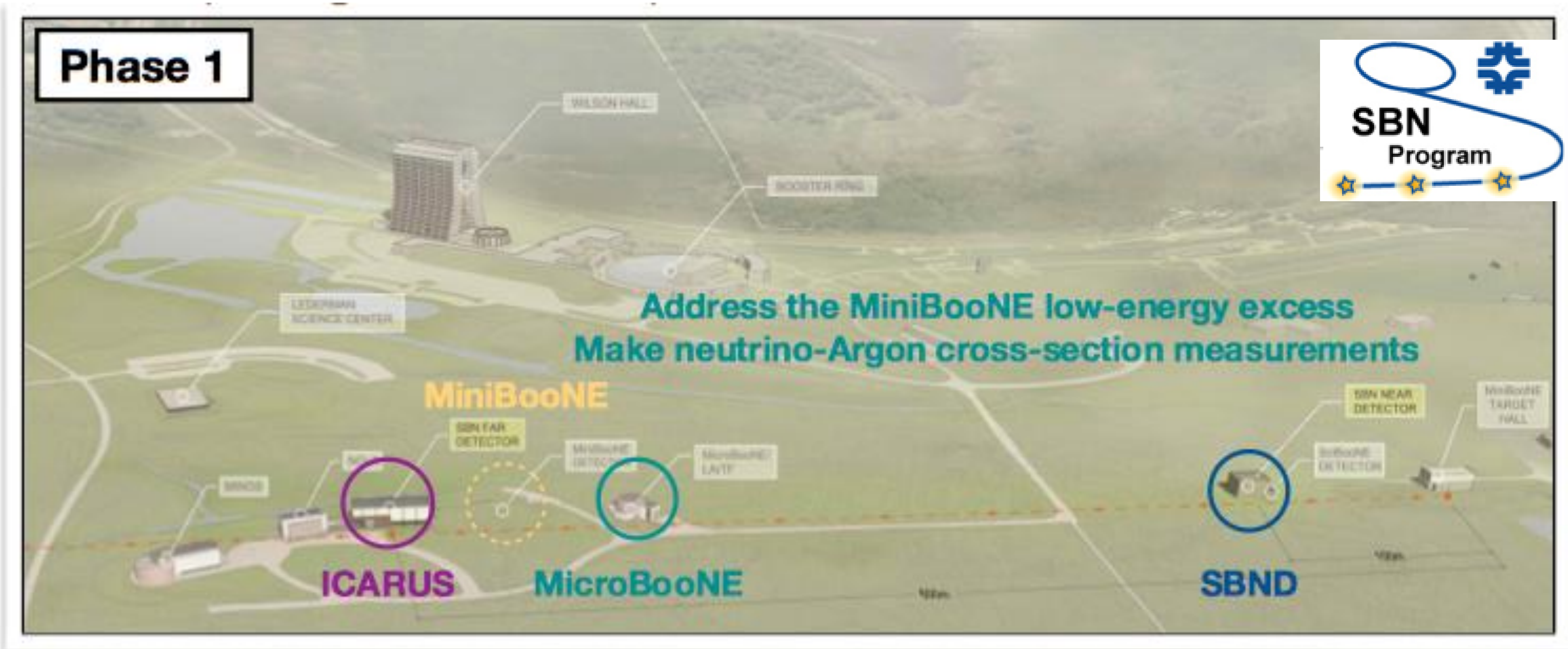
[arXiv:1710.06488]()

Very stringent limits on oscillation interpretation of LSND and MiniBooNE results

No ν_μ disappearance observed with L/E ~ 1m/MeV

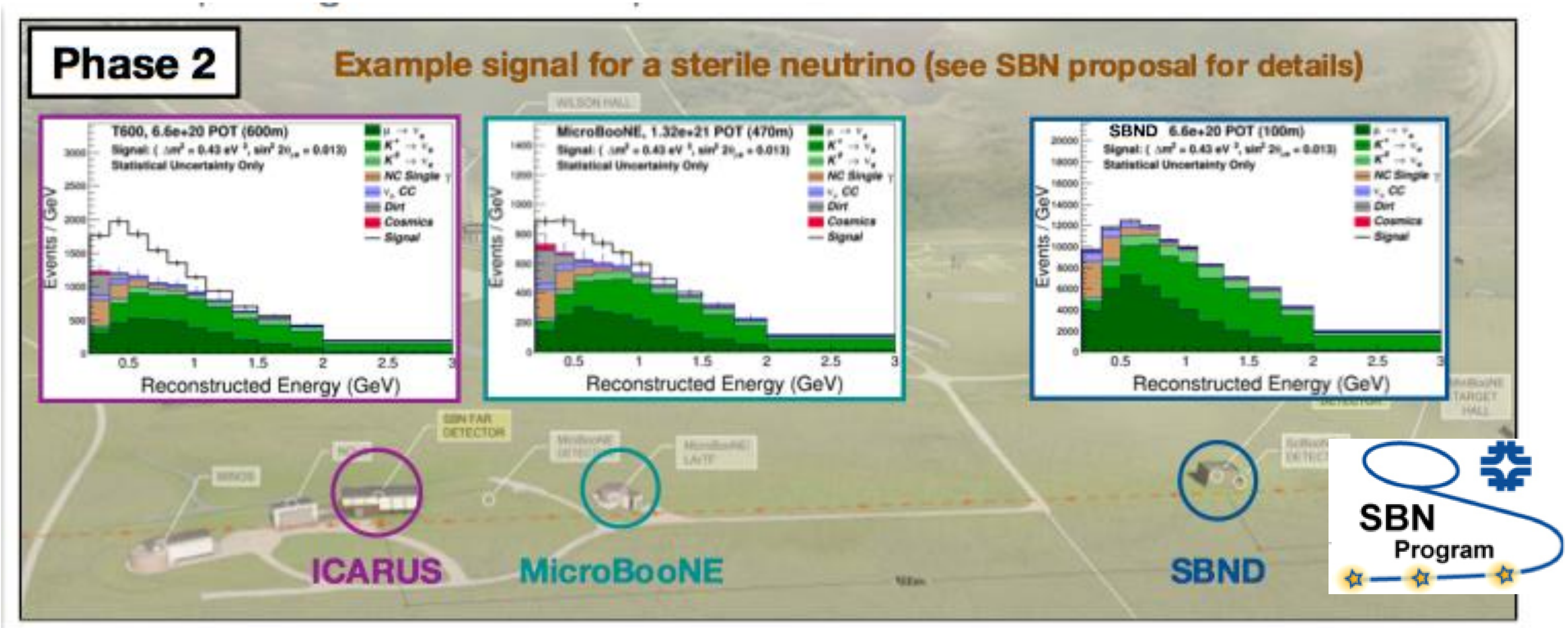
Moving forward: the SBN program at Fermilab

R. Guenette, Neutrino 2018



~100 ton LArTPC, taking data since 2015, first results out NOW!
Primary goal: address LEE

Moving forward: the SBN program at Fermilab



R. Guenette, Neutrino 2018

Far detector
L = 600 m
M = 476 ton

First detector
L = 470 m
M = 85 ton

Near detector
L = 110 m
M = 112 ton

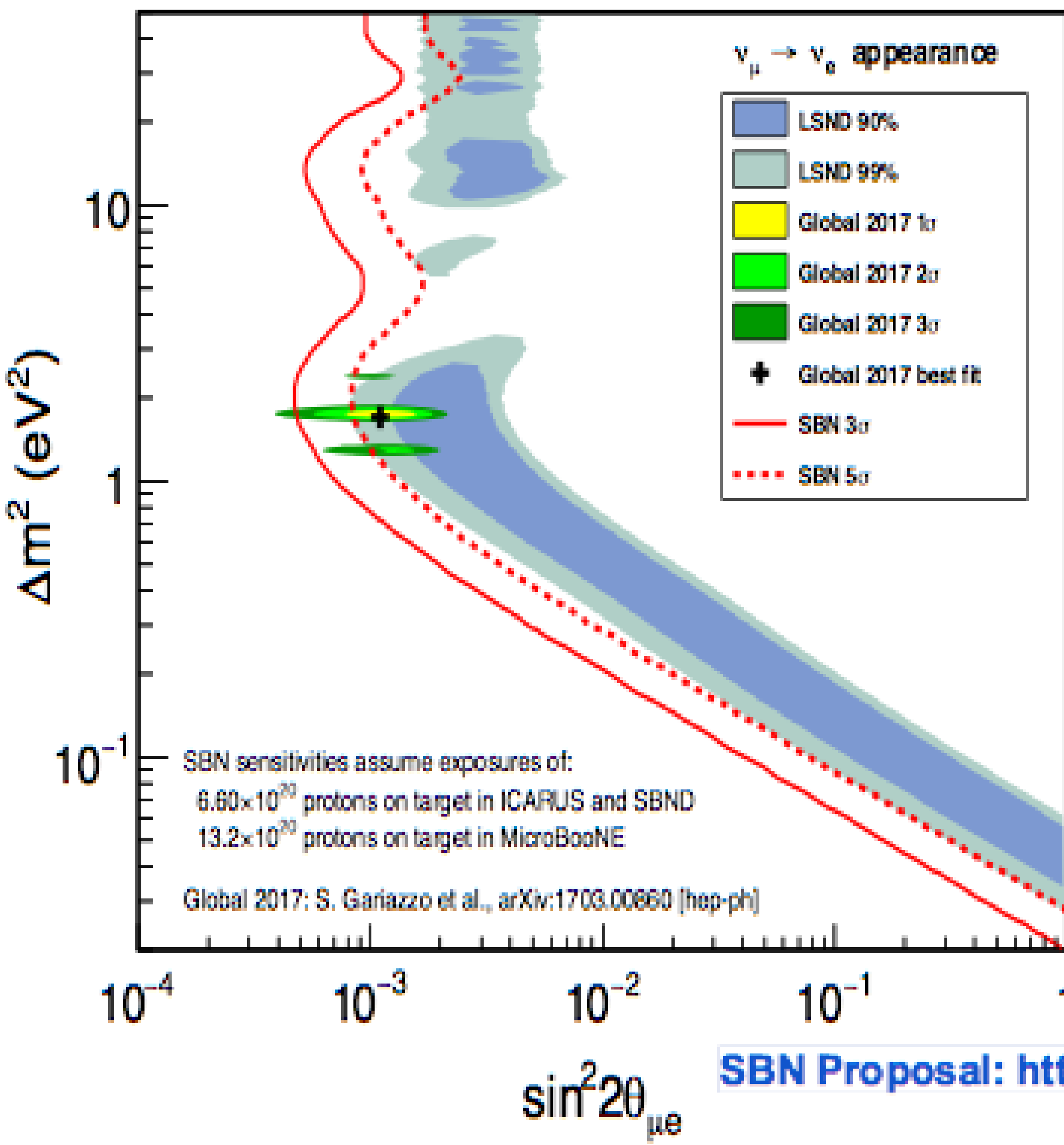
Advantages and goals of the program

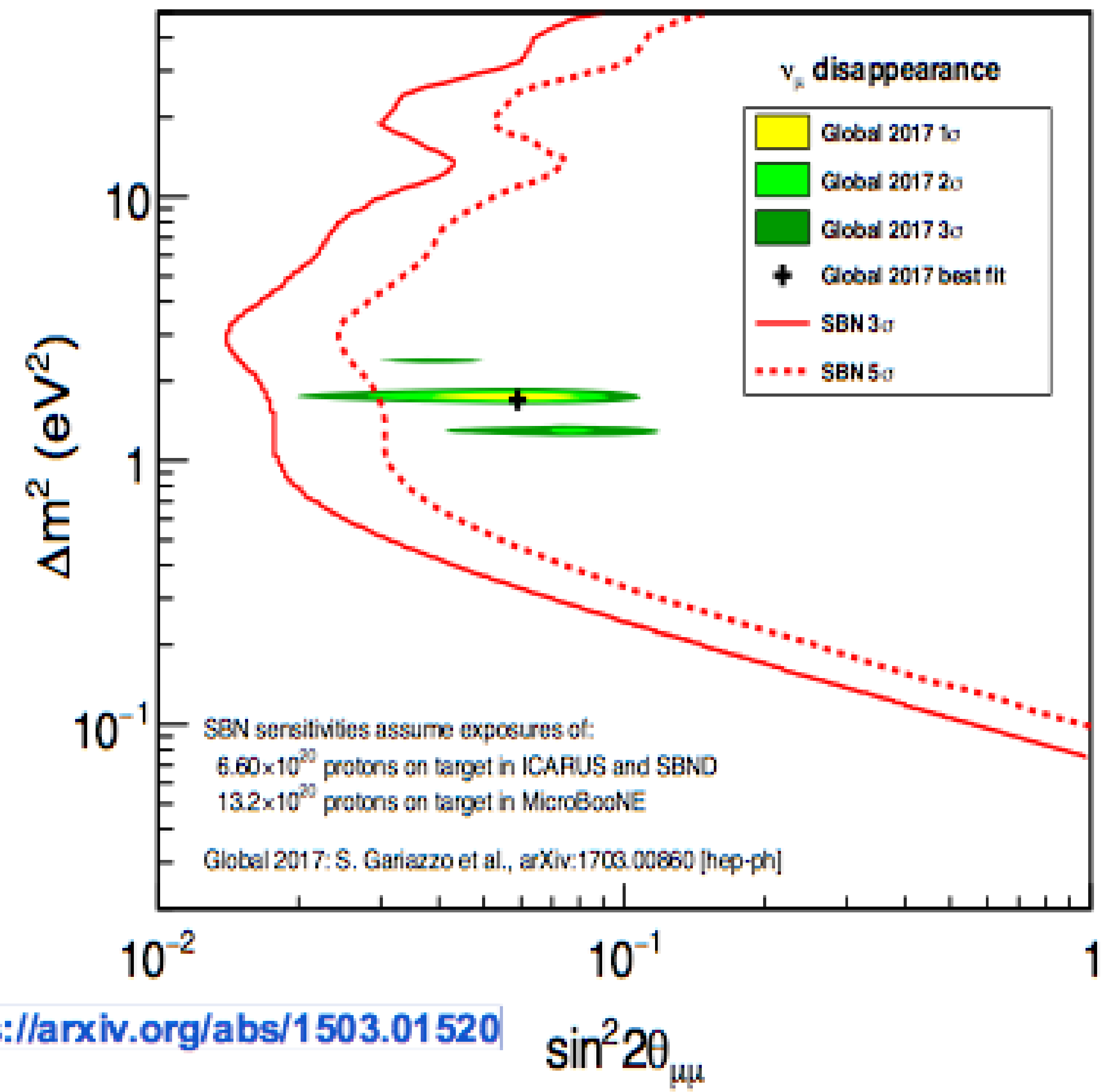
- Ability to address separately:
  - MiniBooNE **Low Energy Excess** (LEE) by MicroBooNE
  - LSND/sterile signals with simultaneous searches:
    - **ν_μ disappearance**
    - **ν_e appearance**

- **The Liquid Argon TPC technology provides bubble-chamber quality pictures of neutrino interactions**
  - can discriminate electrons and gammas
  - can study exclusive topologies with high precision
  - can thoroughly study ν-Ar interactions

SBN sensitivity

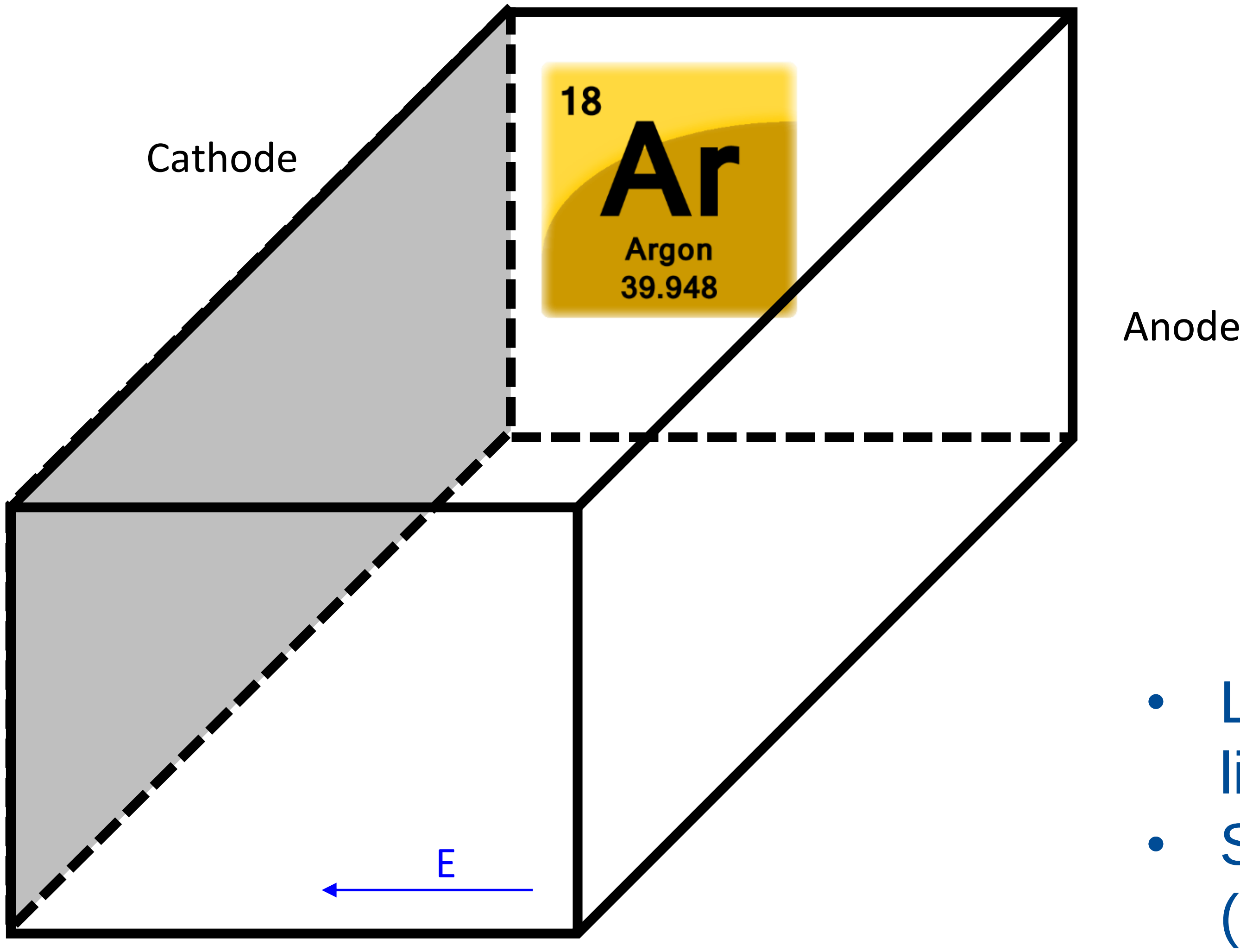
R. Guenette, Neutrino 2018





SBN Proposal: https://arxiv.org/abs/1503.01520

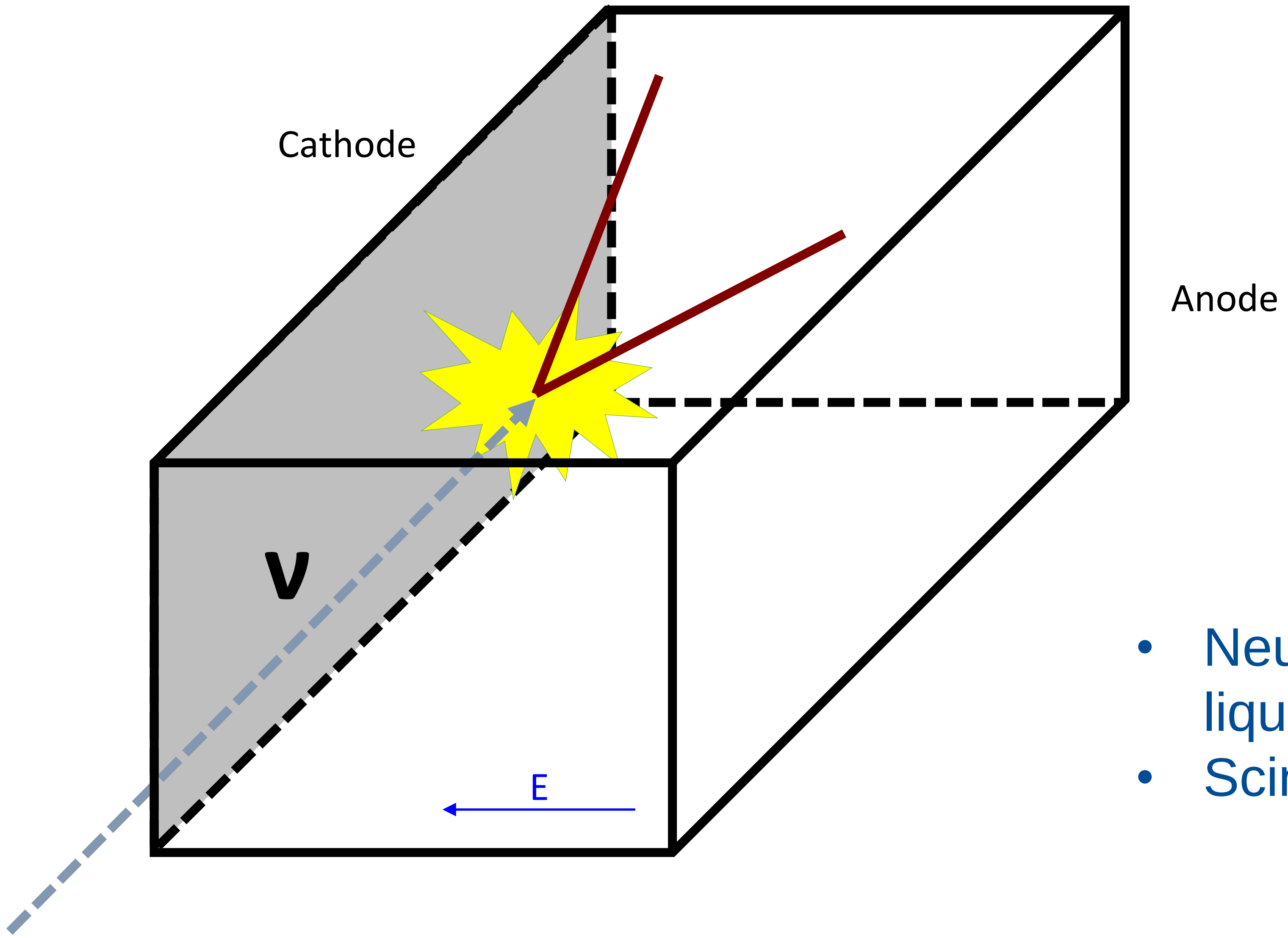
LArTPC: how does it work?



- Large volume filled with liquid-argon
- Strong electric field (~500V/cm)

Credit: A. Schukraft

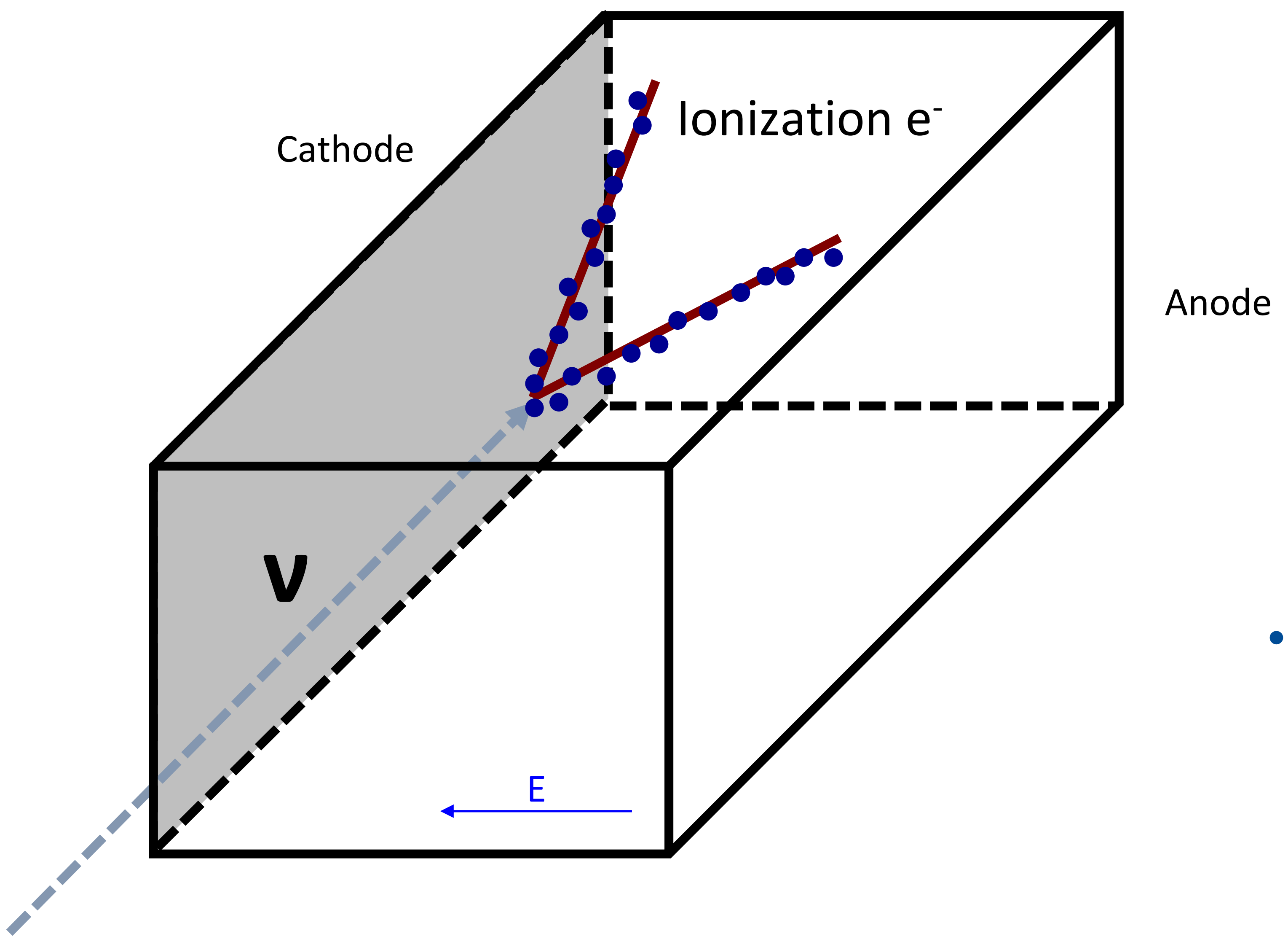
LArTPC: how does it work?



- Neutrinos interact within the liquid argon volume
- Scintillation light production

Credit: A. Schukraft

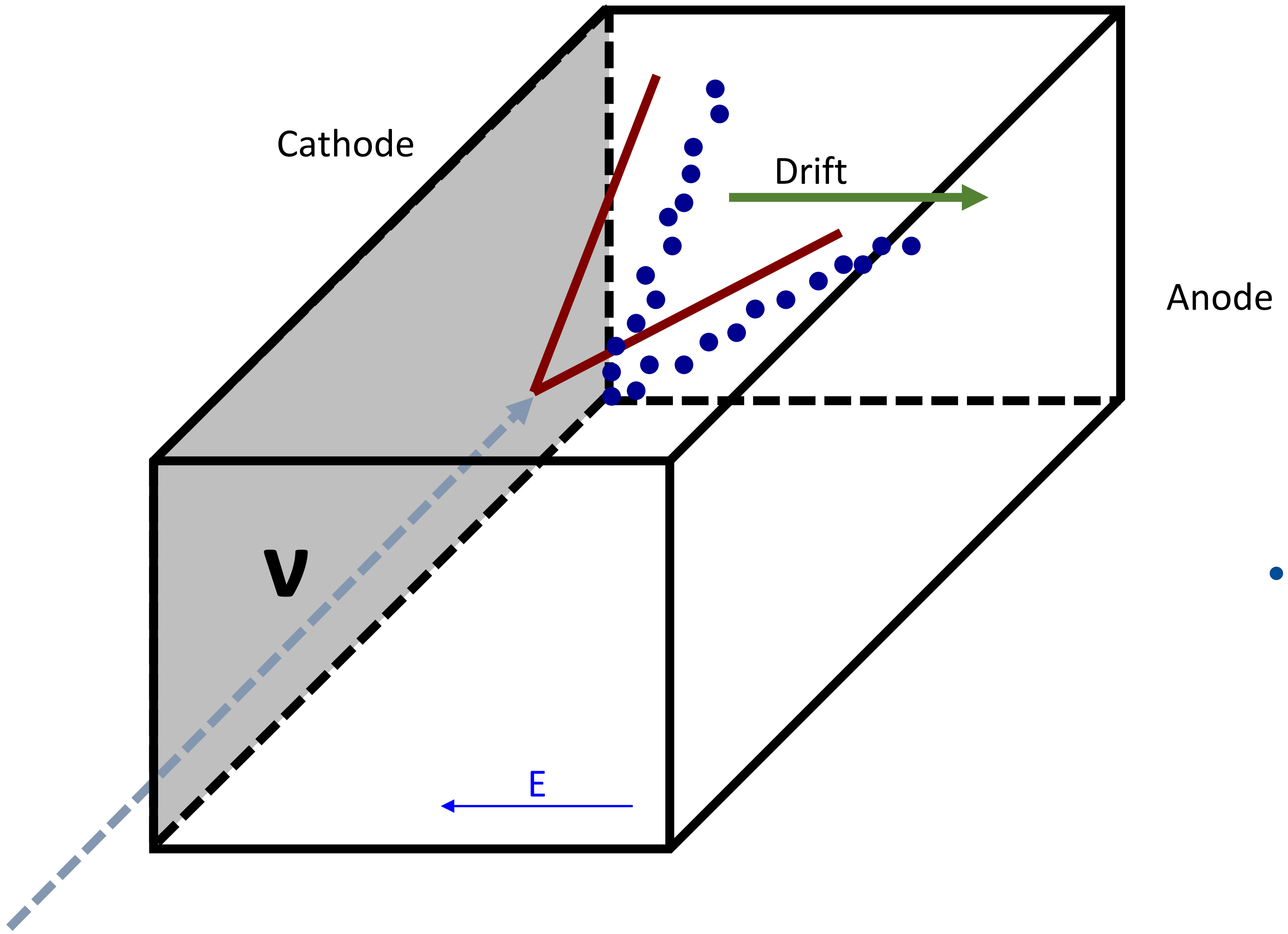
LArTPC: how does it work?



- Production of ionization electrons

Credit: A. Schukraft

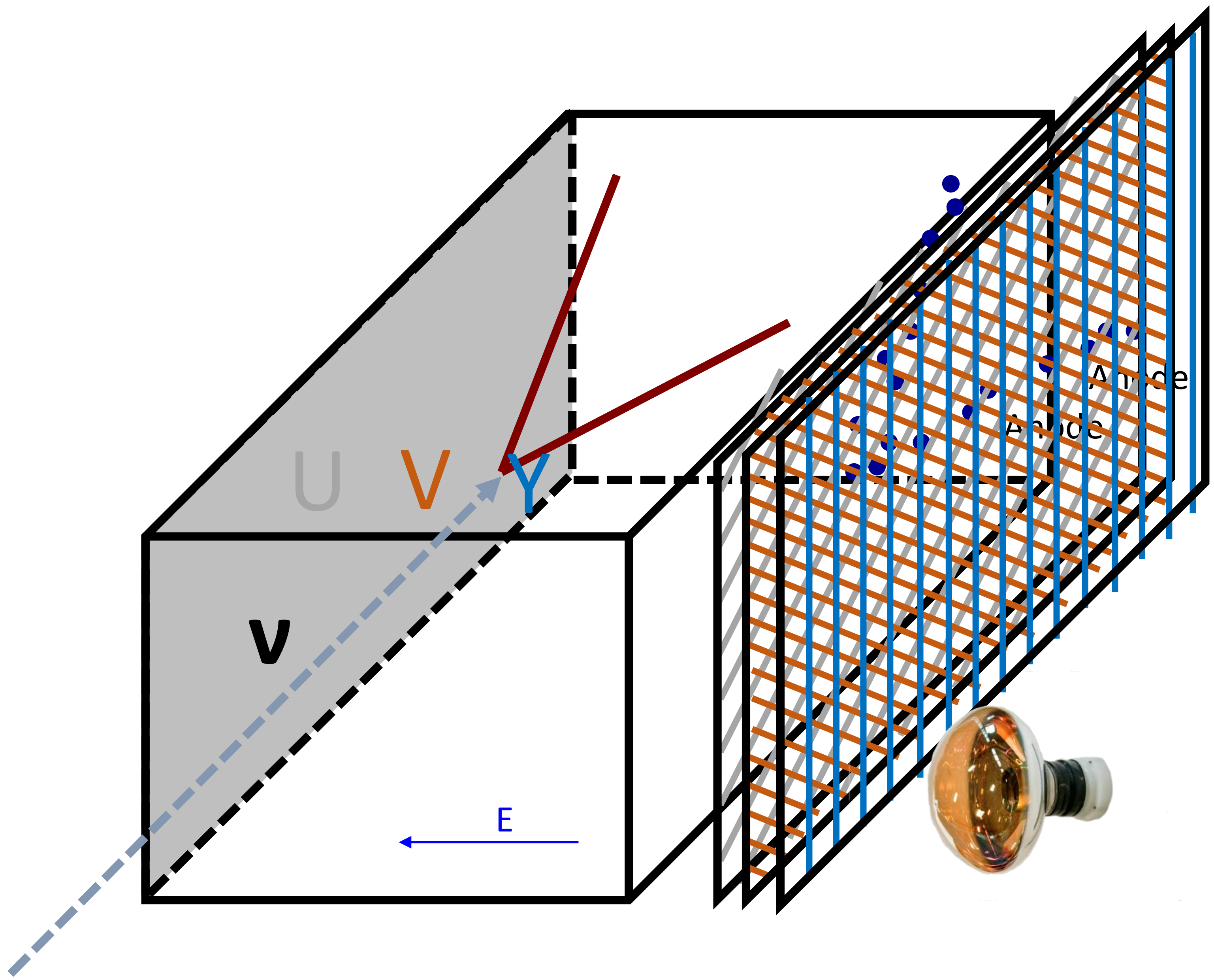
LArTPC: how does it work?

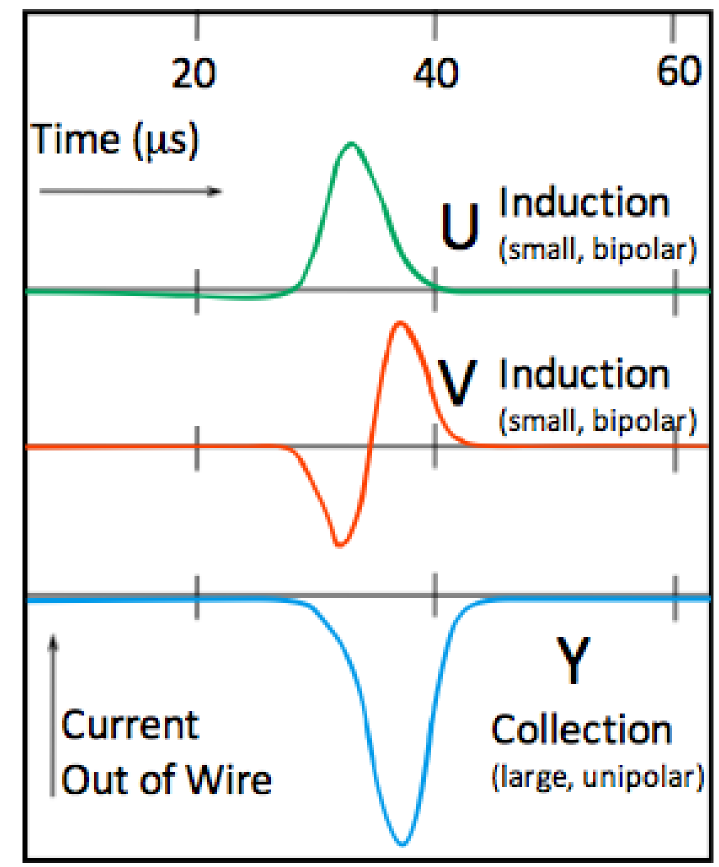


- Electrons drift towards anode plane

Credit: A. Schukraft

LArTPC: how does it work?

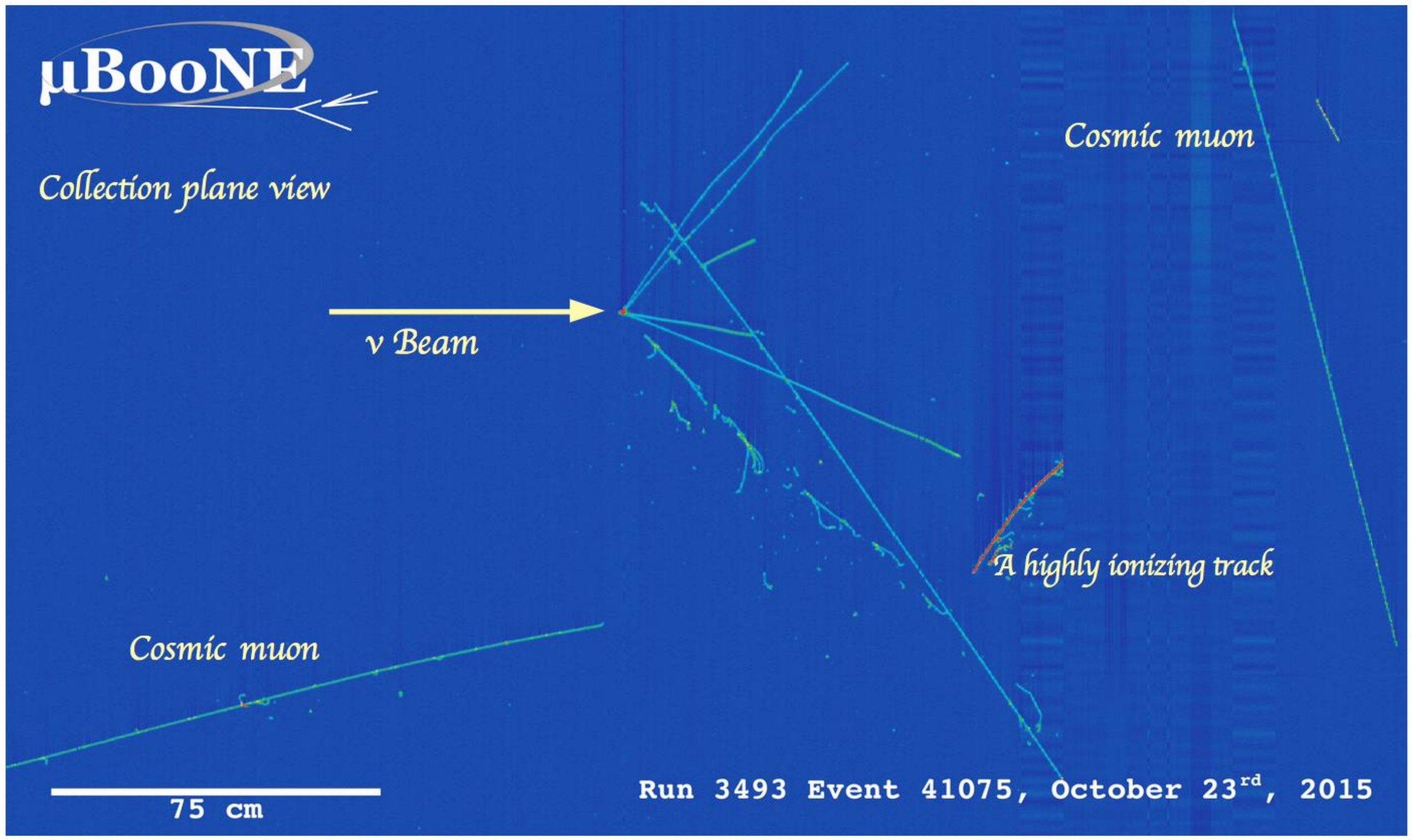


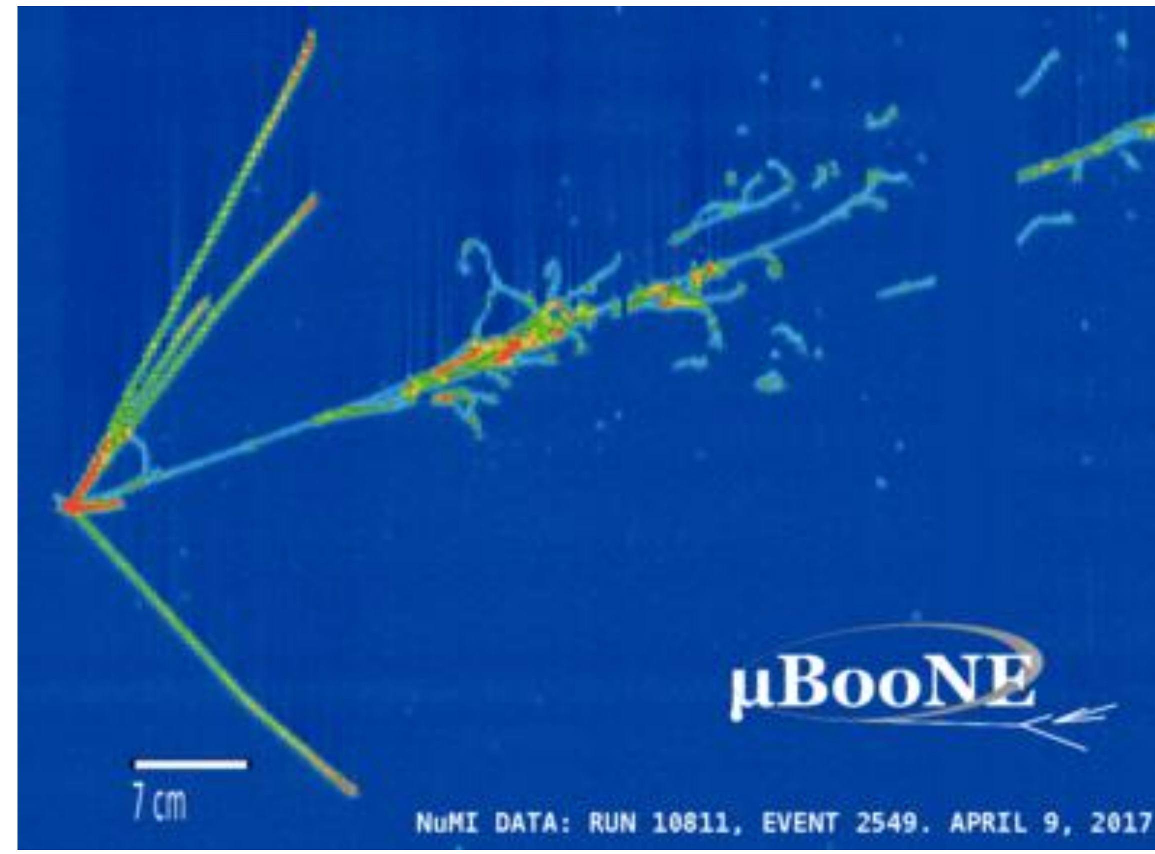


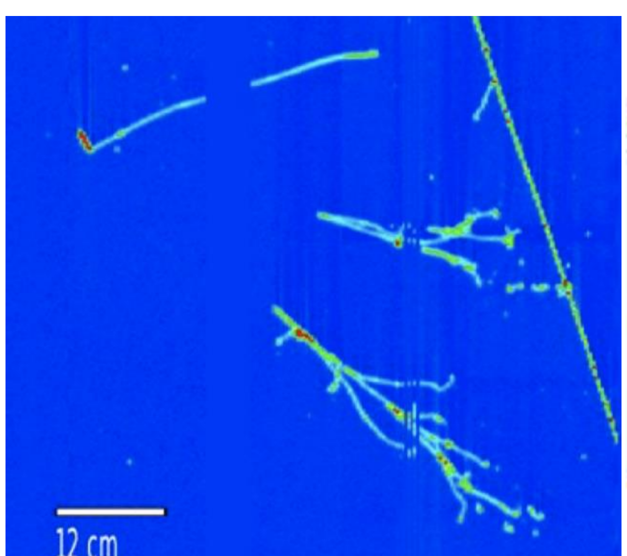
- Readout on wire planes
- Scintillation light captured by PMTs

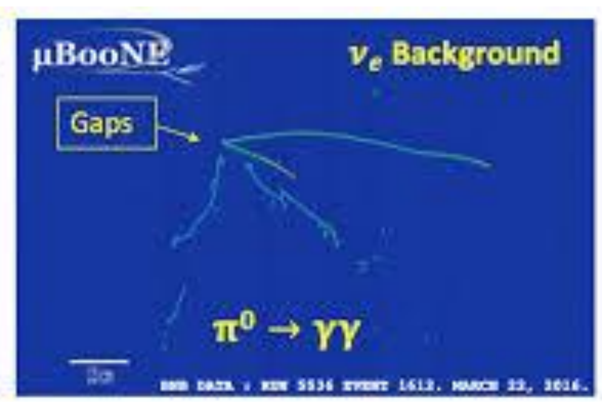
Credit: A. Schukraft

Neutrino interactions in LArTPC



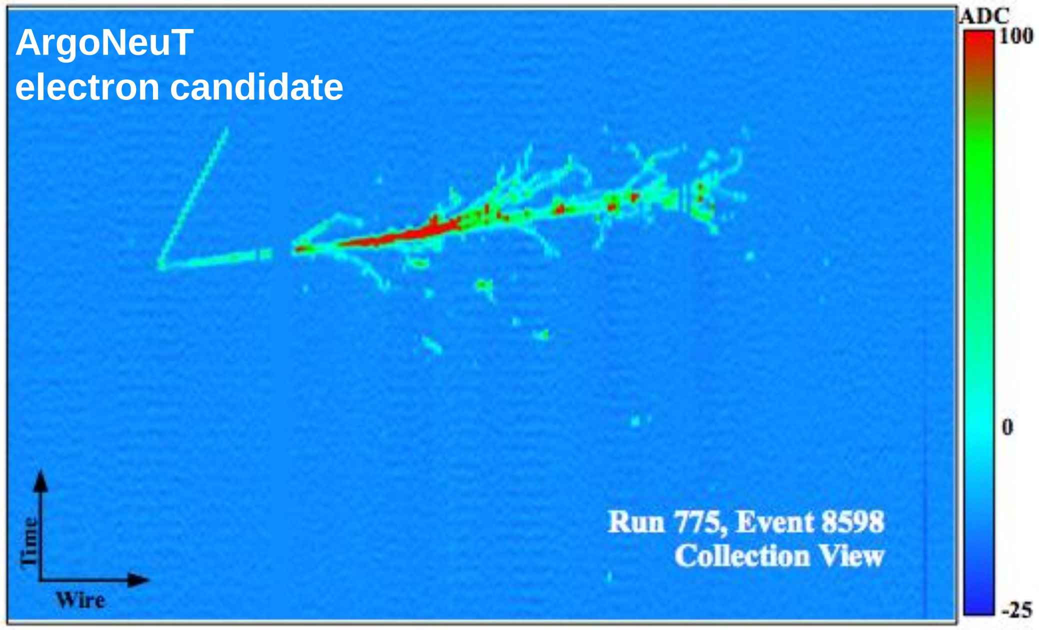


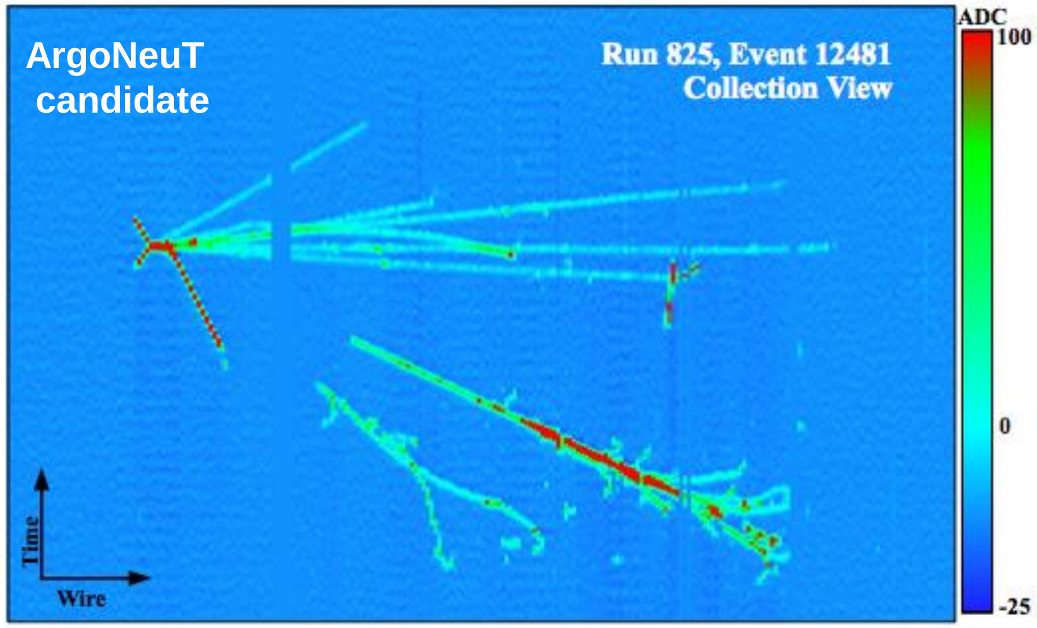




Bubble chamber quality images with ~mm resolution and calorimetric capability

e/γ separation

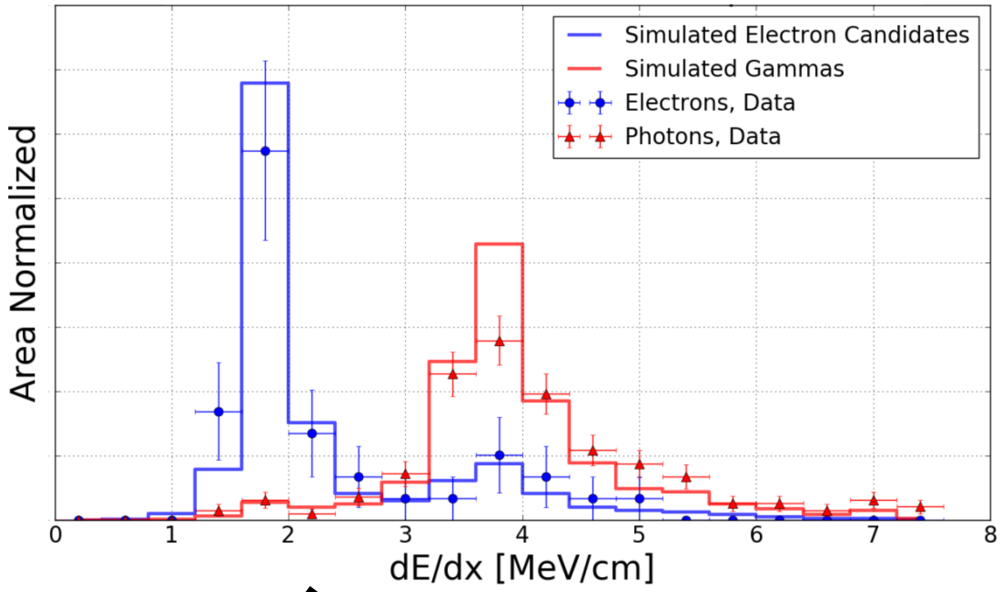


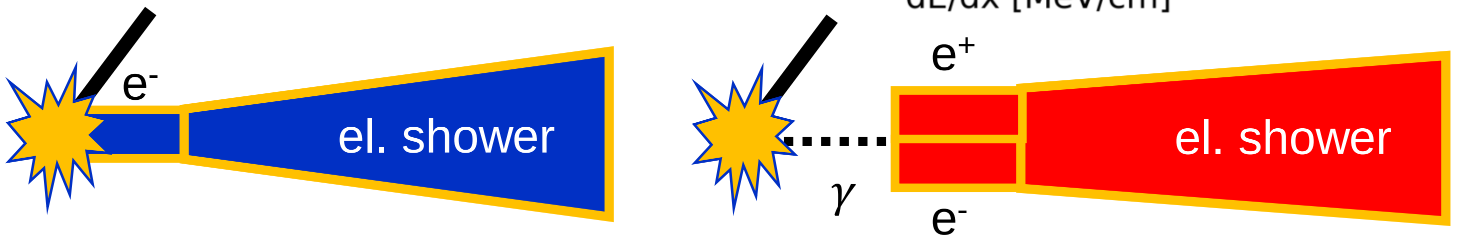


Credit: A. Schukraft

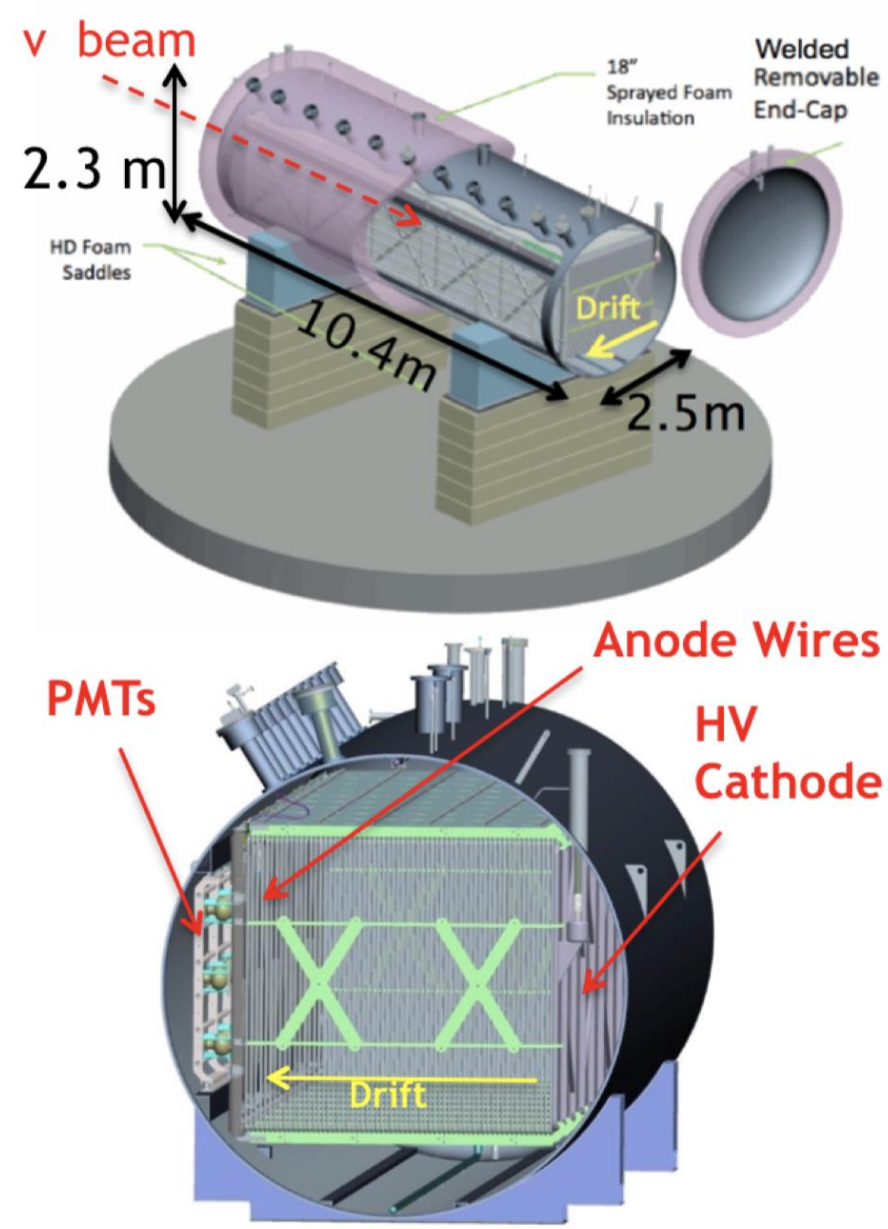
Technique well demonstrated:
ArgoNeuT, Phys. Rev. D 95, 072005 **(2017)**

- mm resolution allows you to “see” γ as a gap after the vertex
- Calorimetric capabilities can distinguish e^- from γ at the shower start





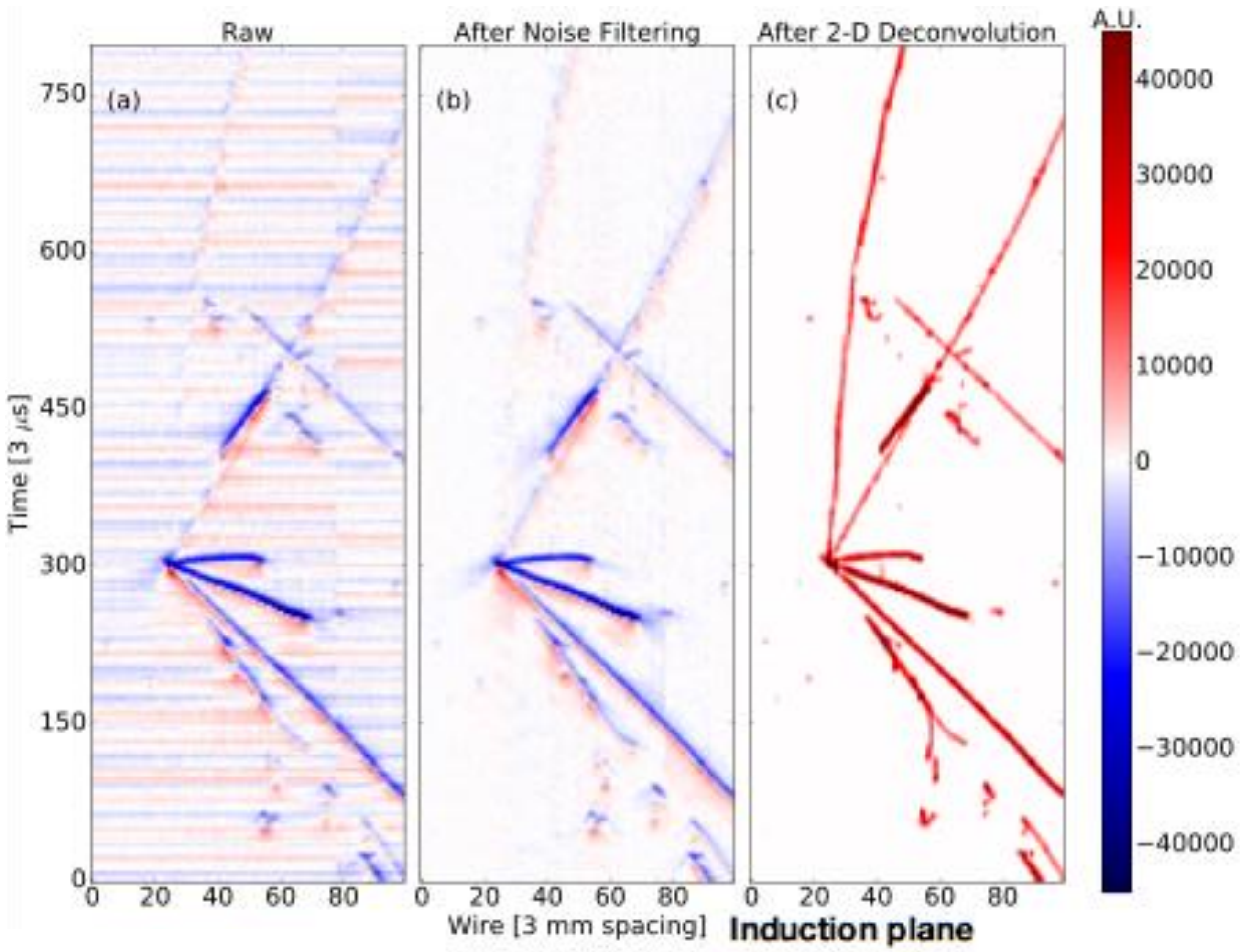
MicroBooNE: the first large LArTPC in the US

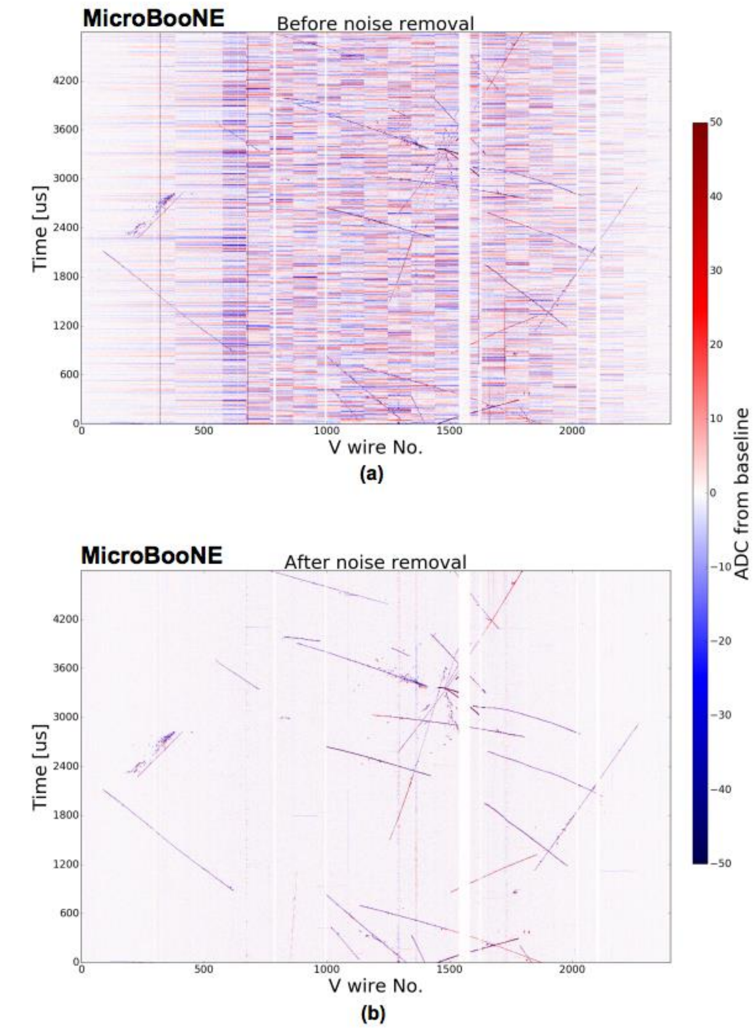


- Three wire planes with 3mm pitch, 8256 channels
- 170ton purified LAr (85ton fiducial)
- 2.5 drift distance
- 32 PMTs
- UV calibration system
- External Cosmic Ray Tagger

Understanding a LArTPC

R. Guenette, Neutrino 2018





- Powerful filtering techniques can address many sources of noise
- Excellent characterization of multiple wire signal response (2D deconvolution)
- Robust signal processing allows calorimetry in all three planes (enabling induction planes)

Reconstruction

- MicroBooNE is pioneering the advancements in track and shower reconstruction in a LArTPC
- Multiple, complementary approaches

Pandora

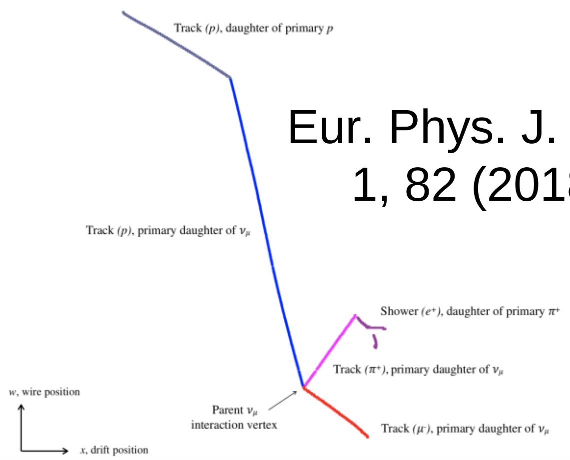
✓ multi-algorithm approach to pattern recognition (many decoupled algorithm to build up the image of the event)
✓ "traditional" approach: clusters the 3, 2D views, then projects in 3D

Deep Learning

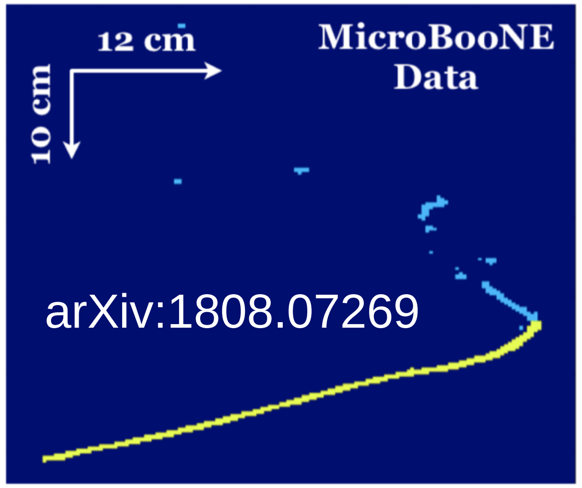
✓ first demonstration of application of convolutional neural networks to LArTPC data
✓ track-shower identification
✓ takes advantage of recent AI advancements

Wire Cell

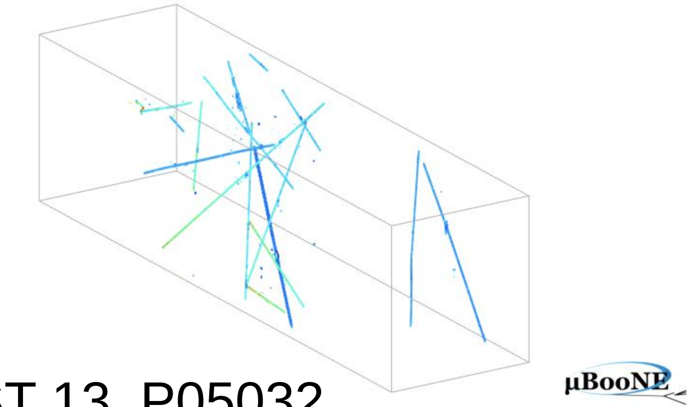
✓ tomographic approach to reconstruction
✓ immediate 3D reconstruction and clustering



Eur. Phys. J. C78, 1, 82 (2018)

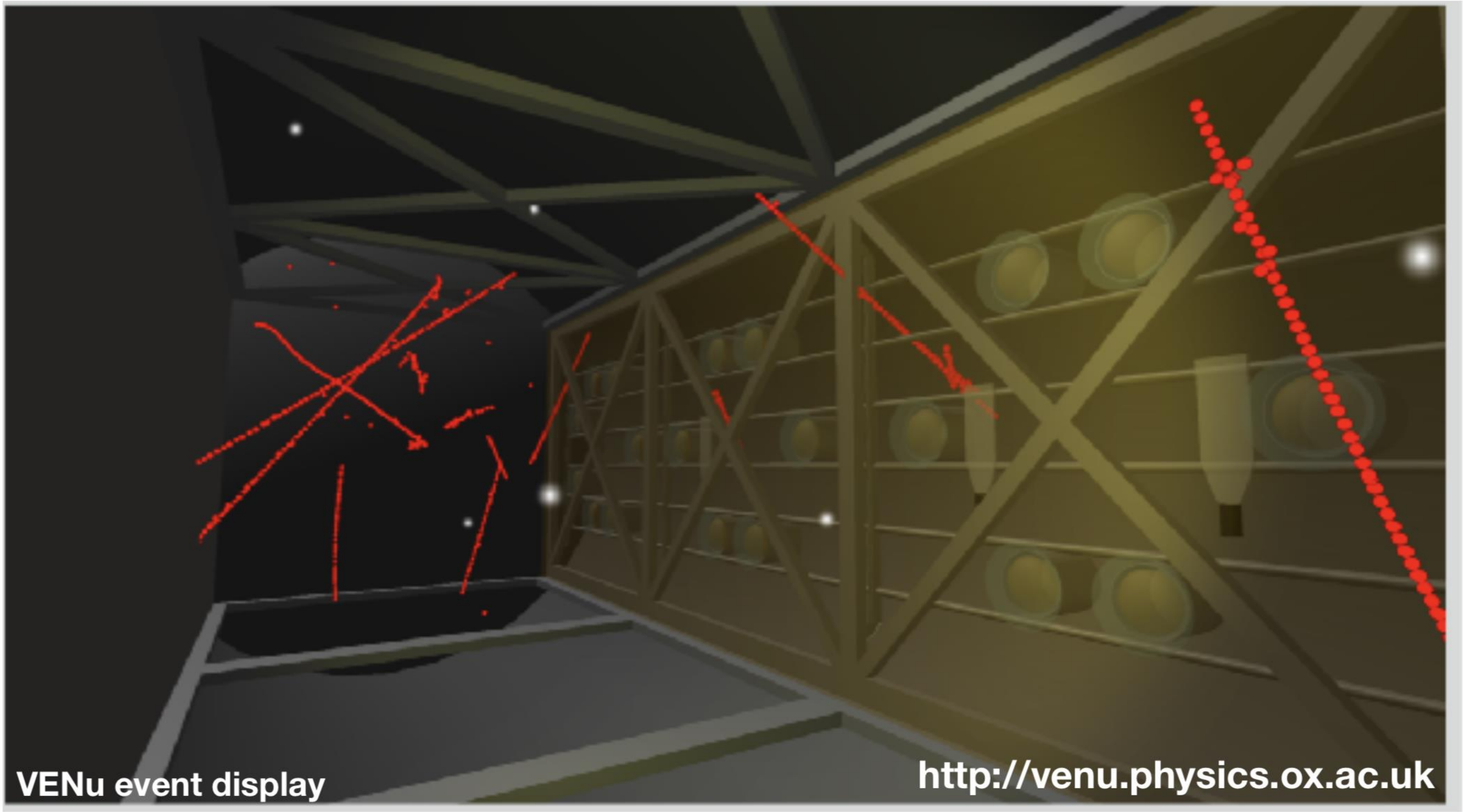


arXiv:1808.07269



JINST 13, P05032

Can you find the neutrino?



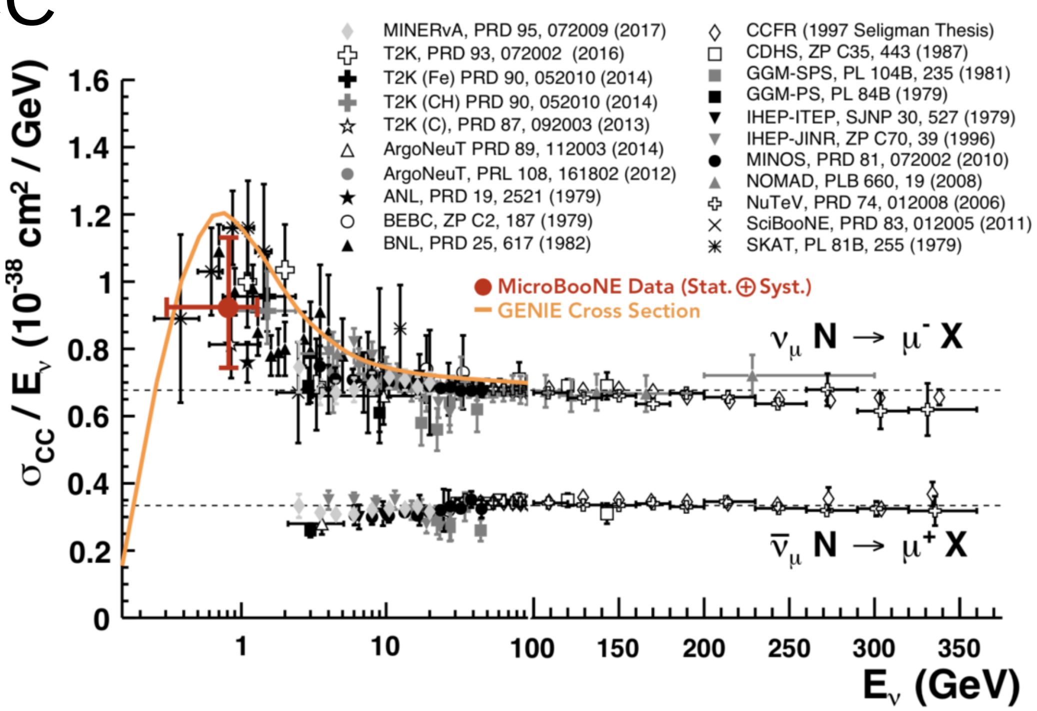
Google Play: https://play.google.com/store/apps/details?id=com.marcodeltutto.venu&hl=en_US
Apple Store: https://itunes.apple.com/us/app/venu/id1189851951?mt=8

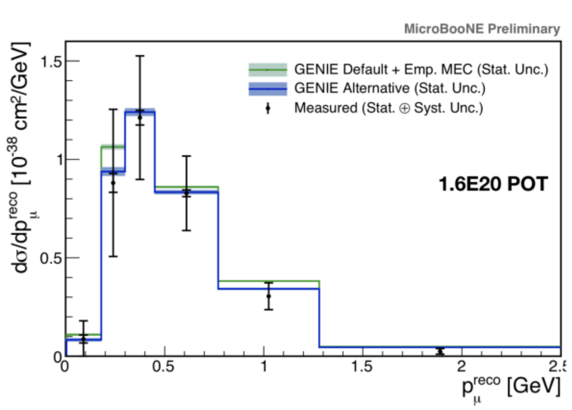
First results

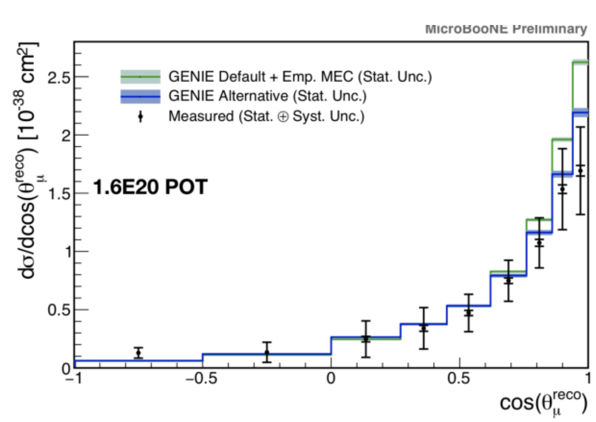
- MicroBooNE is on its way to address MiniBooNE's LEE
- The first step is to understand ν-Ar interactions

R. Guenette, Neutrino 2018

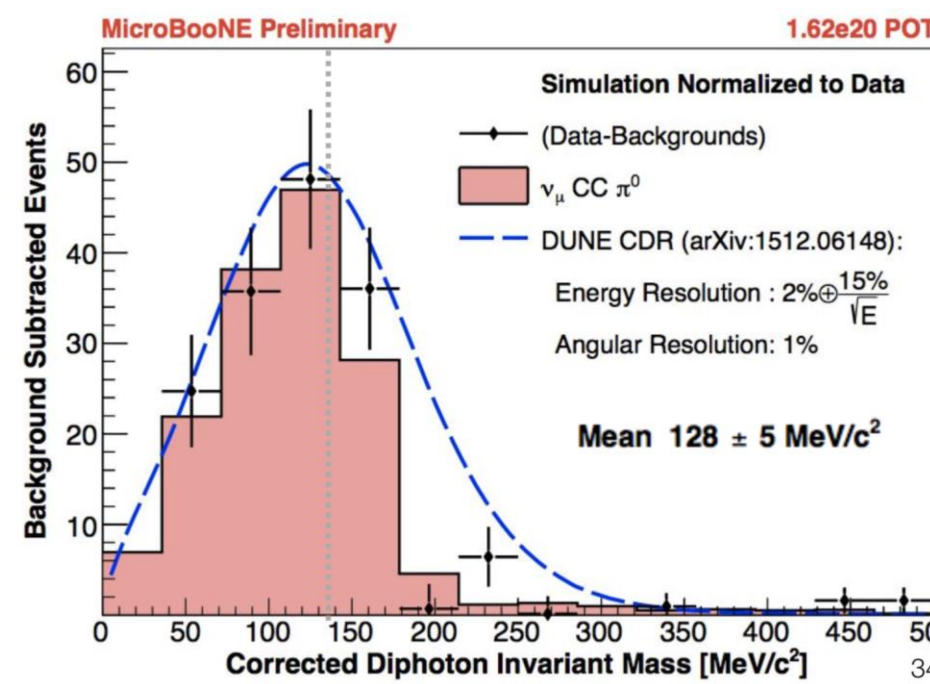
ν_μ CC







ν_μ CC π^0



Mass of π^0: 135 MeV/c²

$$\left\langle \sigma^{\nu_\mu \mathrm{CC}\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16\ [\mathrm{stat.}] \pm 0.60\ [\mathrm{syst.}]) \times 10^{-38}\ \frac{\mathrm{cm}^2}{\mathrm{Ar}}$$

Question

Why do you care so much about ν-Ar interactions?
You'll have a near detector which will allow to cancel out all the systematic uncertainties!

is this true?

From S. Bolognesi (INSS 2017)

background subtraction and efficiency corrections

$$N_{\nu_{\alpha'}}^{FD} = \frac{N_{\nu_{\alpha'}}^{measured-at-FD} \times p^{FD}}{\epsilon^{FD}} \qquad N_{\nu_\alpha}^{ND} = \frac{N_{\nu_\alpha}^{measured-at-ND} \times p^{ND}}{\epsilon^{ND}}$$

$$\boxed{\epsilon = \frac{N_{\nu_\alpha}^{signal-measured}}{N_{\nu_\alpha}^{signal}}}$$

efficiency corrects for events which escape the detection
(threshold, acceptance, containment...)

$$\boxed{p = \frac{N_{\nu_\alpha}^{measured} - N^{background}}{N_{\nu_\alpha}^{measured}} = \frac{N_{\nu_\alpha}^{signal-measured}}{N_{\nu_\alpha}^{measured}}}$$

purity corrects for background
(events wrongly identified as ν_α)

Need to know efficiency and purity in order to correct for them → any possible mis-modeling of them causes a **systematic uncertainty in the oscillation analysis**

$$P_{\nu_\alpha \to \nu_{\alpha'}} \approx \frac{N_{\nu_{\alpha'}}^{measured-at-FD}}{N_{\nu_\alpha}^{measured-at-ND}} \times \frac{\epsilon^{ND}}{\epsilon^{FD}} \times \frac{p^{FD}}{p^{ND}}$$

What really matter is the difference between ND and FD, common systematics cancel out (to first order...)

5

Dependence on neutrino energy (S. Bolognesi)

To extract the oscillation parameters, the oscillation probability must be evaluated **as a function of neutrino energy,** since the neutrino beams are not monochromatic:

$$P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2_{21} L}{4 E_\nu}\right)$$

→ we need to know the **number of neutrinos as a function of E_ν** at near and far detectors

$$\boxed{N^{ND}_{\nu_\alpha}(E_\nu) = \varphi(E_\nu) \times \sigma(E_\nu)\, dE_\nu}$$

flux= number of neutrinos produced by the accelerator per cm^2, per bin of energy, for a given number of protons on target

$$\left[\int \varphi(E_\nu)\, dE_\nu\right] \equiv [\Phi] = [cm^{-2}\, POT^{-1}]$$

cross-section = probability of interaction of the neutrinos in the material of the detector

$$[\sigma] = [cm^2]$$

Flux and cross-section (S. Bolognesi)

- So the oscillation probability becomes:

predicted number of neutrino interactions at the FD (w/o oscillations)

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) \times \boxed{\frac{\varphi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\varphi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}} \times \frac{\epsilon^{ND}}{\epsilon^{FD}} \times \frac{p^{FD}}{p^{ND}}$$

measured number of neutrino interactions at the ND

We measure flux and xsec for ν_α (and $\nu_{\alpha'}$) at the ND and *<u>we use our models to extrapolate</u>* at the far detector (like a ratio measurement...)
→ systematic minimized if same flux (eg, same off-axis angle) and same target material

- But the most complicated part is :

1) the neutrino energy spectrum is different at ND (before oscillation) and at the FD (after oscillation)
→ so we measure the xsec and flux at a given energy and we need to extrapolate to a different energy

2) flux and xsec extrapolation from ND to FD are different → we need to separately estimate flux and xsec at the ND

But we measure only the product of the two (strong anti-correlation between them) 8

ICARUS: SBN's far detector

T600 leaving from CERN June 12th 2017

T600 in Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Michigan lake)

T600 arriving at SBN Far site building @FermiLab, July 26th 2017

Slide# : 13

G. Raselli, NOW 2018

ICARUS: SBN's far detector

G. Raselli, NOW 2018

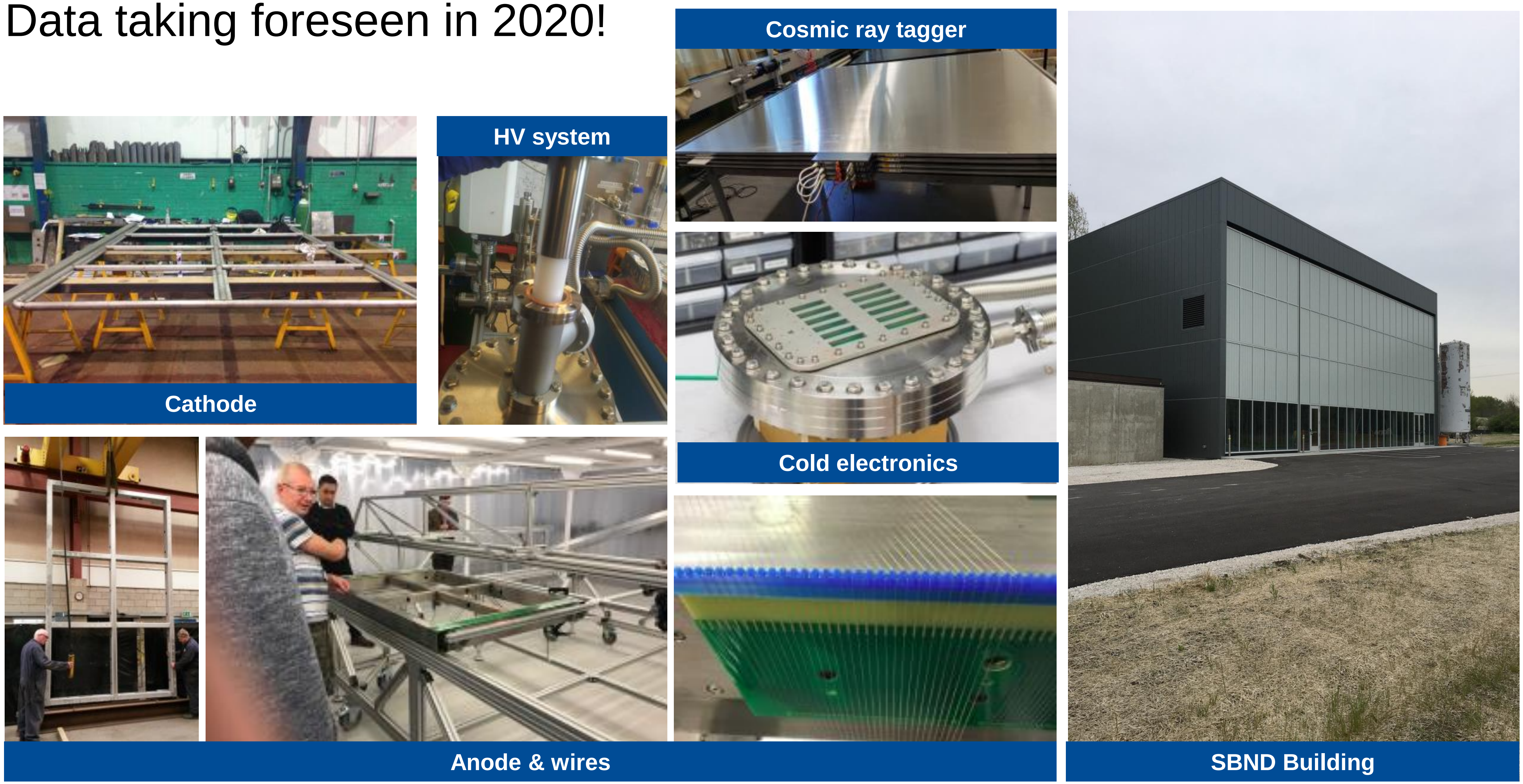
ICARUS: SBN’s far detector

- 4 TPCs with a total mass of 476 ton (fiducial)
- **Largest LArTPC ever operated**
- Great timing capabilities (light detection system) and external cosmic ray tracker
- Successfully operated at Gran Sasso for 3 years in the CNGS neutrino beam

- **Installation is ongoing and commissioning will come along soon**
- Exciting time for the SBN program!

SBND: SBN’s near detector

Construction ongoing
Data taking foreseen in 2020!

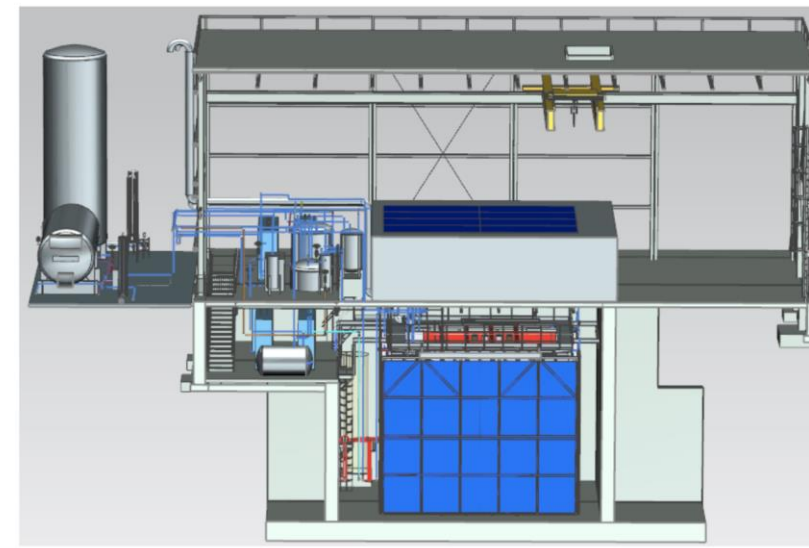


SBND: SBN's near detector

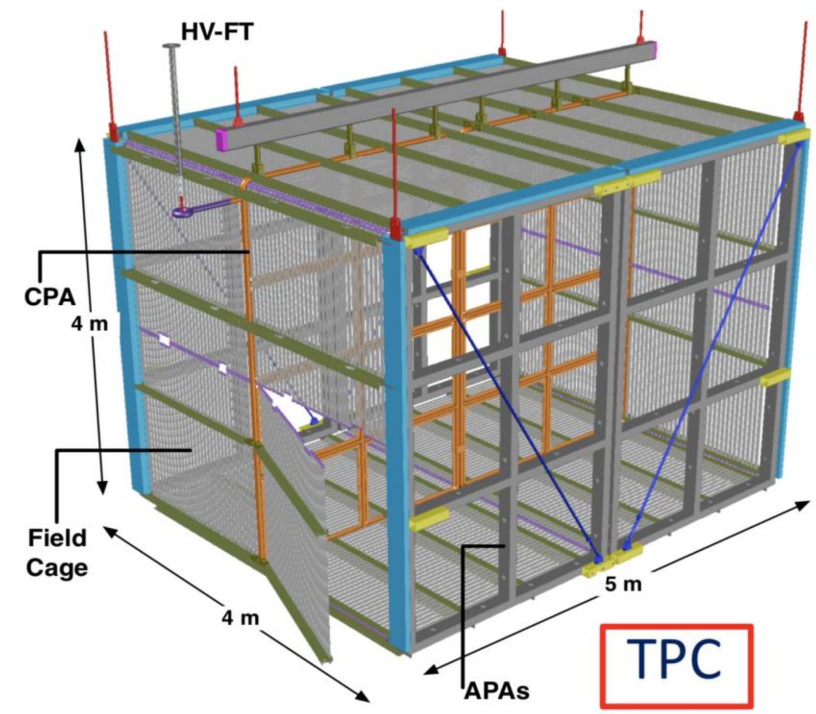
Baseline ~110m, Mass ~100ton
SBND will be able to measure with great accuracy (huge statistics) ν-Ar interactions

Process		No. Events	Events/ ton	Stat. Uncert.
	ν_μ Events (By Final State Topology)			
CC Inclusive		5,212,690	46,542	0.04%
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830	31,713	0.05%
	$\cdot\ \nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	$\cdot\ \nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	$\cdot\ \nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	$\cdot\ \nu_\mu N \to \mu + \geq 3p$	371,347	3,316	0.16%
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to \text{nucleons}$	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to \text{nucleons} + 1\pi^\pm$	260,924	2,330	0.20%
NC $\geq 2\pi^\pm$	$\nu_\mu N \to \text{nucleons} + \geq 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	358,443	3,200	0.17%
	ν_e Events			
CC Inclusive		36798	329	0.52%
NC Inclusive		14351	128	0.83%
Total ν_μ and ν_e Events		7,251,948	64,750	
	ν_μ Events (By Physical Process)			
CC QE	$\nu_\mu n \to \mu^- p$	3,122,600	27,880	
CC RES	$\nu_\mu N \to \mu^- \pi N$	1,450,410	12,950	
CC DIS	$\nu_\mu N \to \mu^- X$	542,516	4,844	
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	18,881	169	

SBN proposal: arXiv:1503.01520



Cryogenics and Building



Summary on short baseline oscillations

- **"Gallium anomaly" - ν_e disappearance**
  - no experiment currently planned to test it directly

- **"Reactor anomaly" - anti-ν_e disappearance**
  - many experiments planned and taking data
  - hits of fission modeling origin
  - results soon!

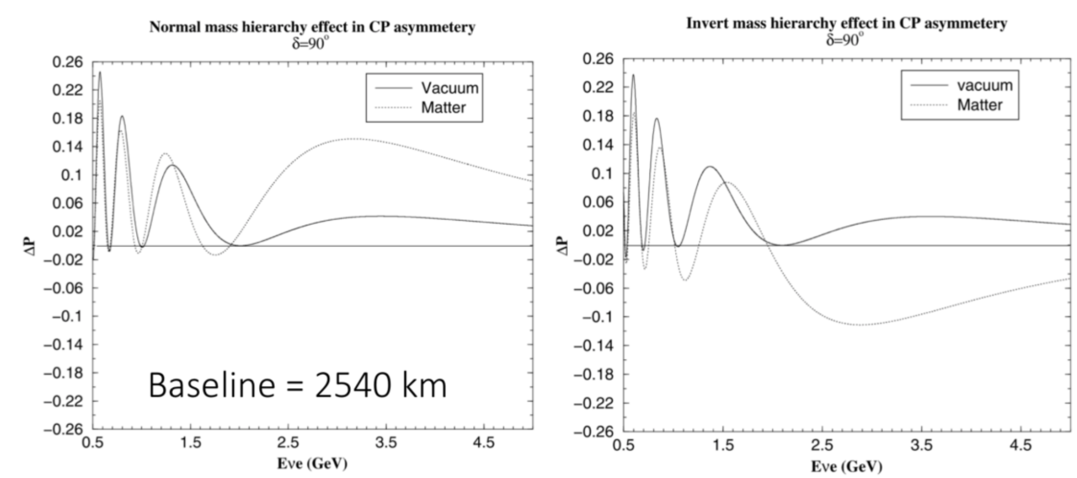
- **"LSND" and "MiniBooNE" anomalies - ν_e appearance**
  - SBN program at Fermilab
  - will probe MiniBooNE's LEE and the full LSND oscillation picture

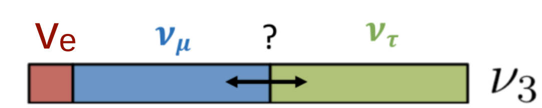
Questions for long baseline

- Oscillation parameters:
  - θ_{13}, $\boxed{\theta_{23}}$, θ_{12}, Δm_{12}^2, $\boxed{\Delta m_{23}^2}$, $\boxed{\delta_{CP}}$, $\boxed{\text{mass ordering}}$

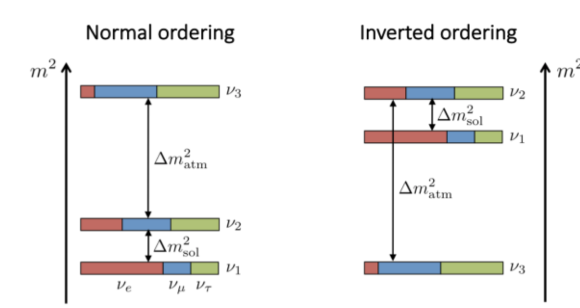
precision measurements with anti-ν_e disappearance at reactors

KamLAND + solar (JUNO in the future)



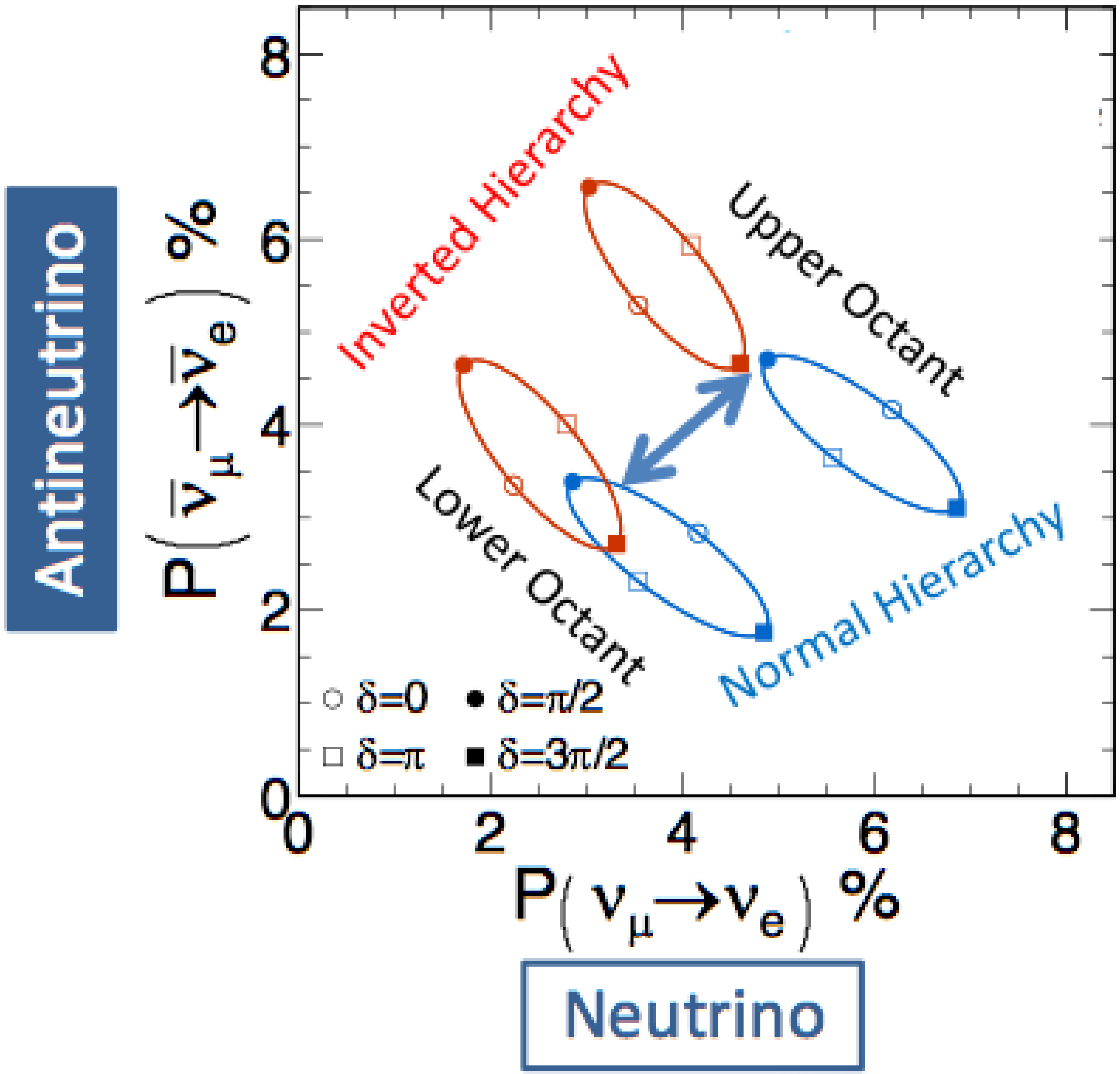


- What is the octant of θ_{23}? i.s. θ_{23} <45 or >45?
- What's the value of δ_{CP}?
- What's the mass ordering?



Interplay between parameters

Alex Himmel



It is crucial to use all available channels (appearance, disappearance, ν and anti-ν) to break degeneracies

CP: are we descendant of heavy neutrinos?

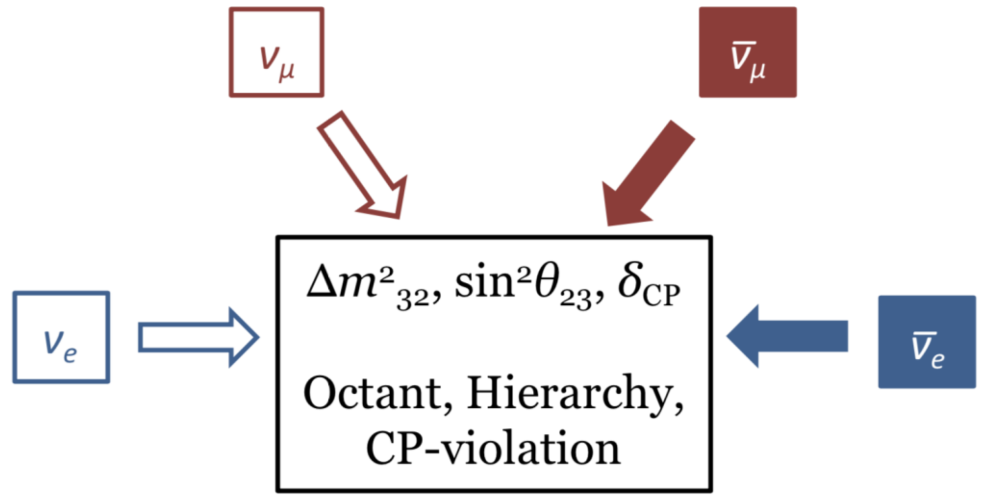
$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha) \quad CPT = 1$$

$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \;\; if \;\; CP = 1$$

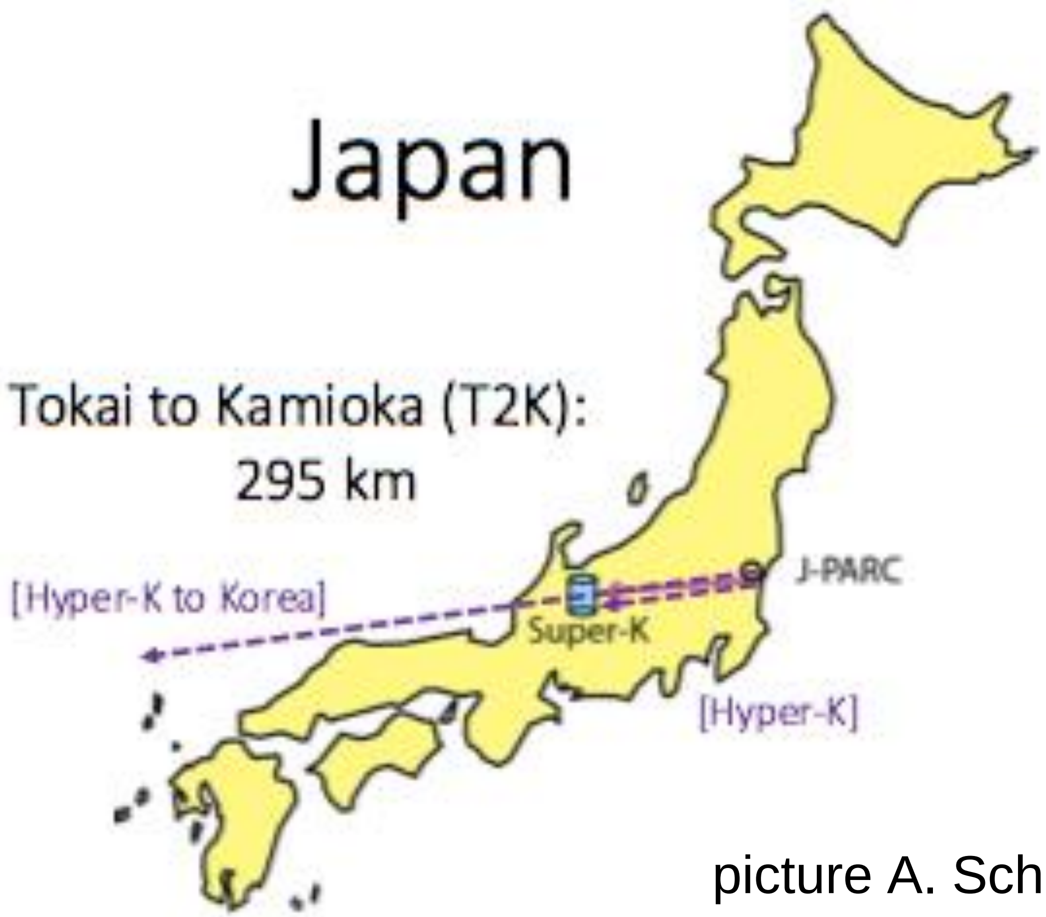
- **What created the asymmetry in matter/anti-matter in the universe?** CP violation in the quark sector cannot explain it
- **Leptogenesis**: CP violation in the lepton sector could generate a B violation large enough to explain what we see today
  - standard scenario is that of heavy Majorana neutrinos (see saw mechanism)
  - heavy Majorana neutrinos, violating CP, could have produced more matter than anti-matter
- **CP violation in the leptonic sector (most of the phase space) could explain the matter/anti-matter asymmetry that we observe in the universe**

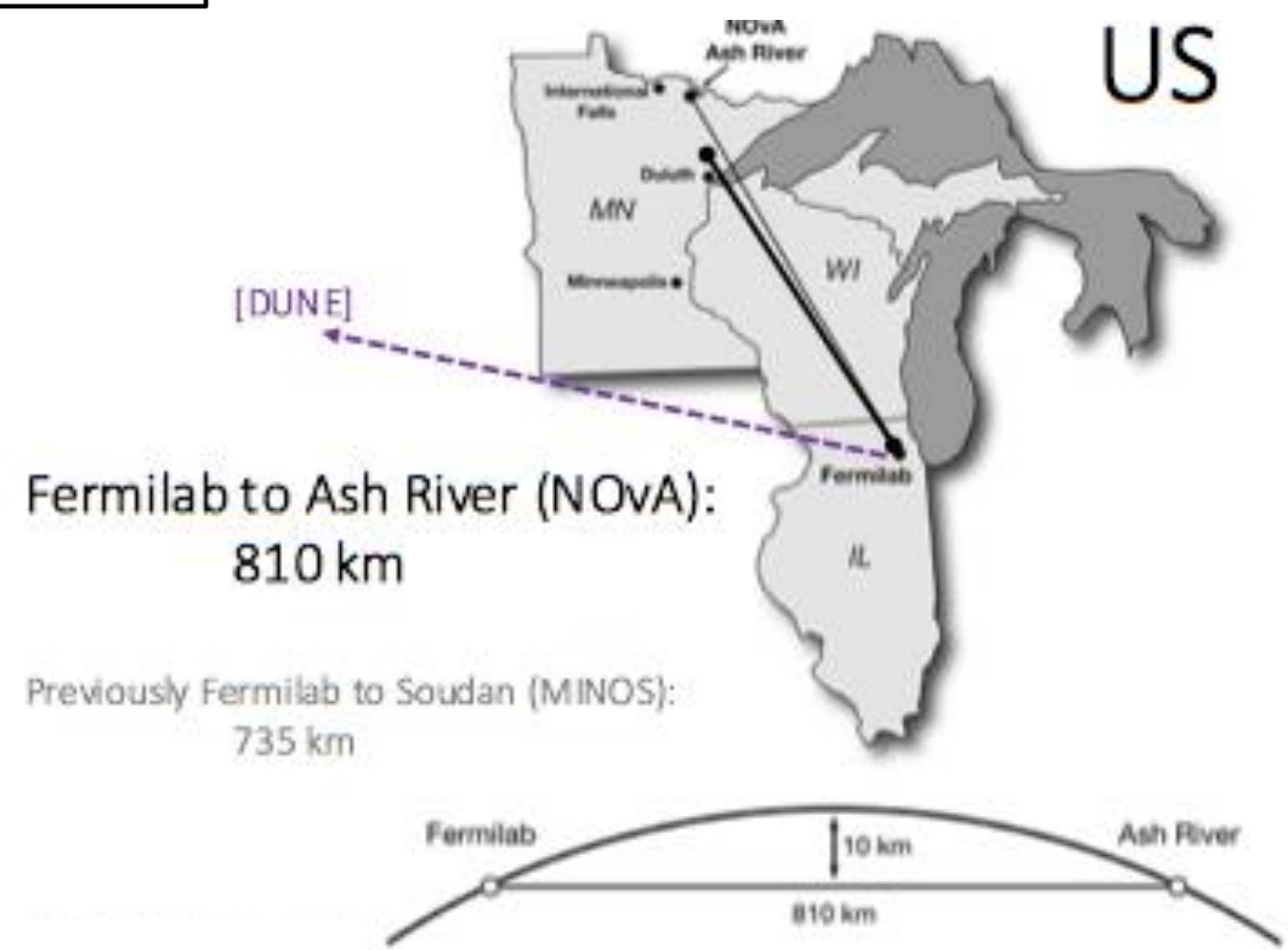
Long baseline experiments

T2K
T2HK



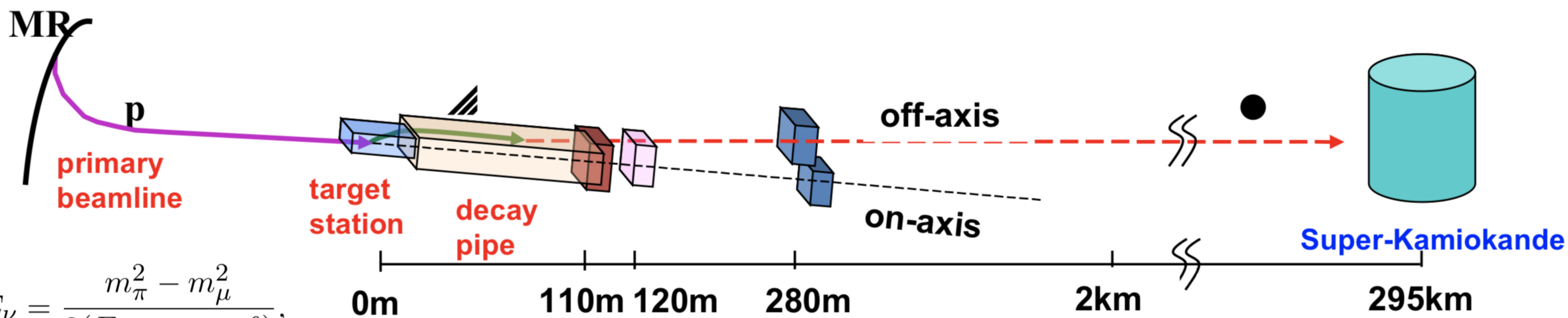
NOvA
DUNE



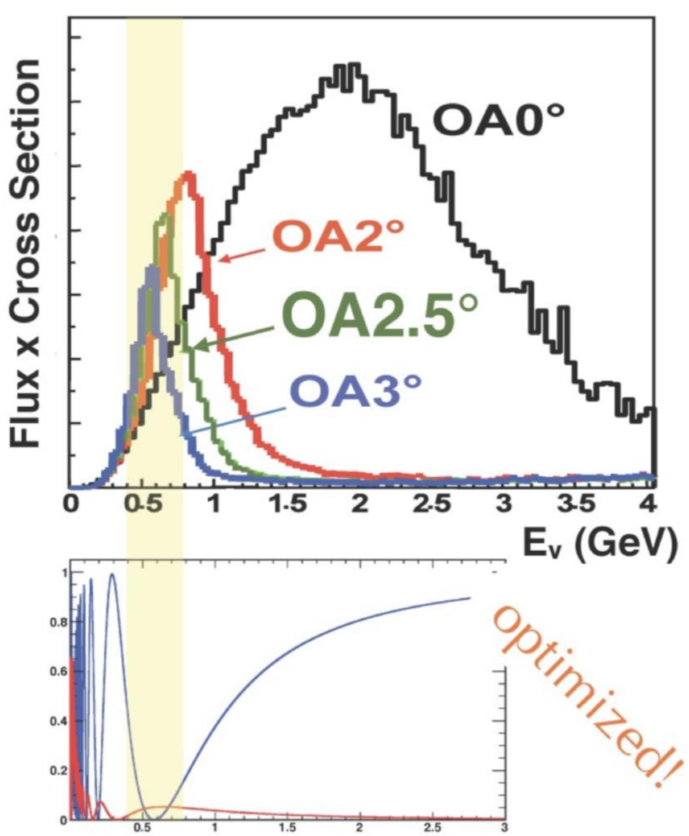


picture A. Schukraft

T2K

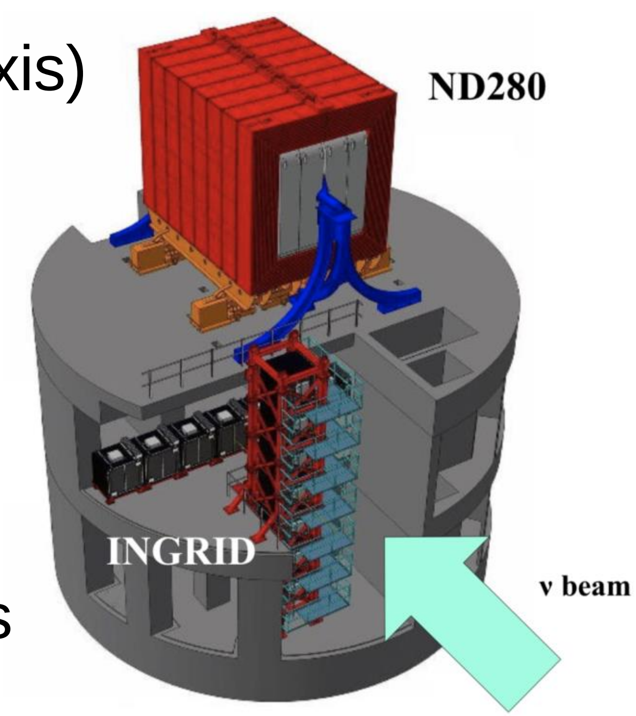


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)},$$

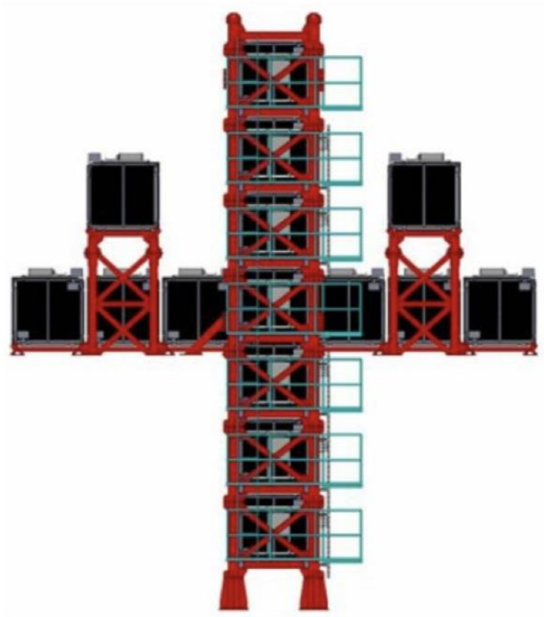


Near Detector (2.5deg off-axis)

beam (μ) monitor, on-axis



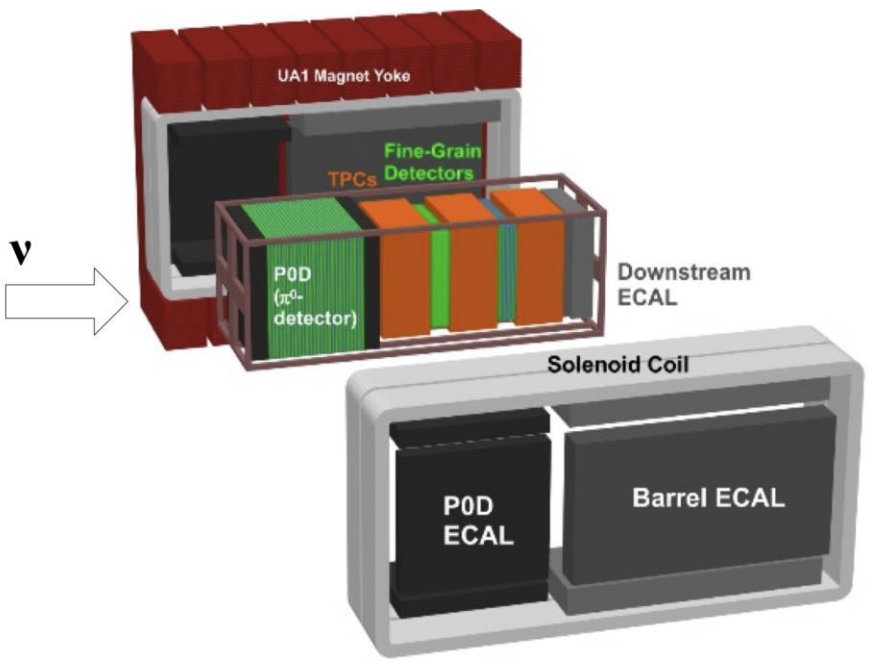
T2K near detectors

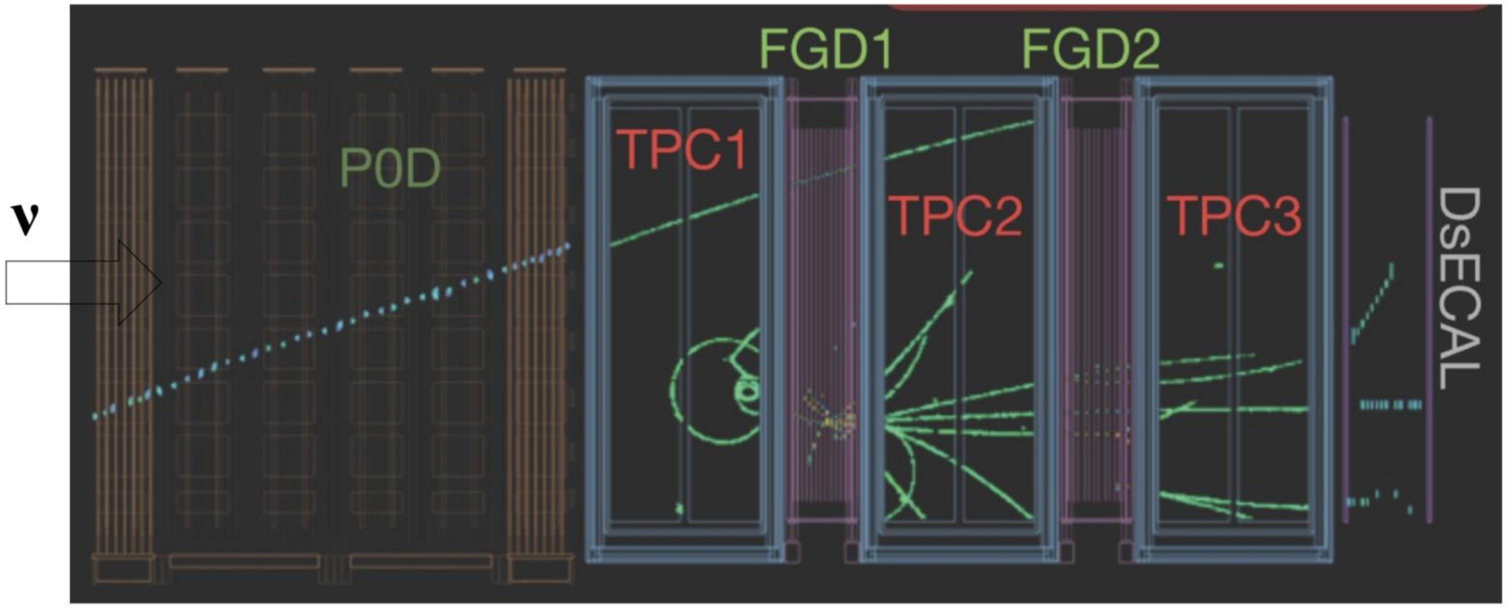


INGRID: monitor beam stability, iron/scintillator planes in a cross shape

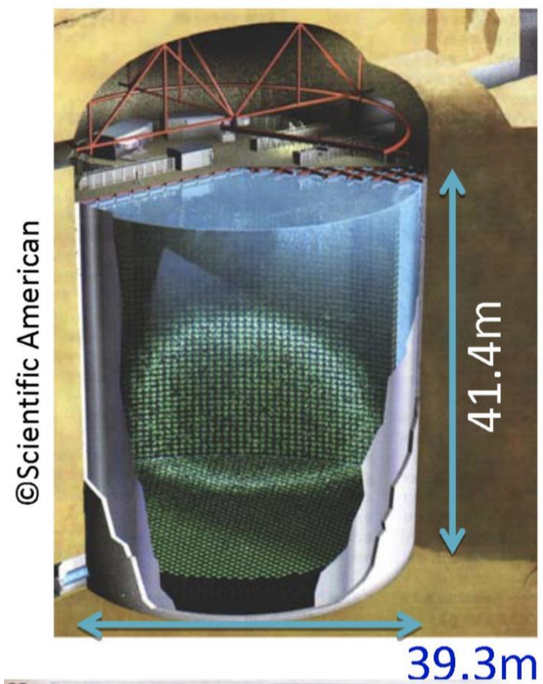
ND280: Tracker with 3TPC and 2 FGD (Fine Grained Detectors

- FGD, scintillator tracker, 1cm^2 bars
- TPC, microMEGAS technology
- P0D (π^0 detector), scintillator w/ water target
- ECAL, Pb/scintillator calorimeter

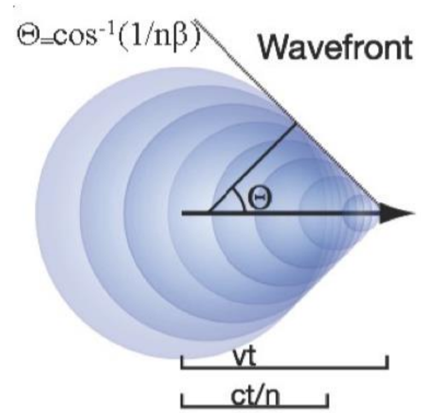


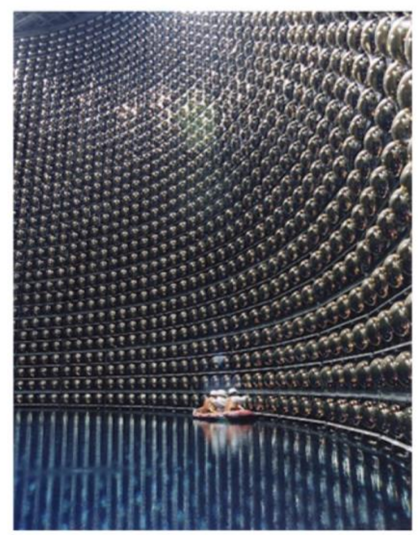


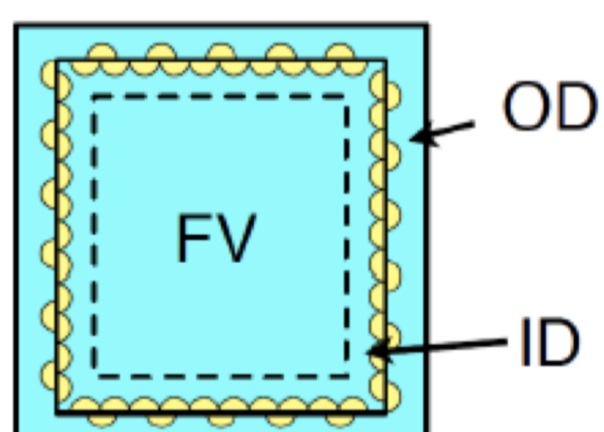
T2K far detector: Super-K

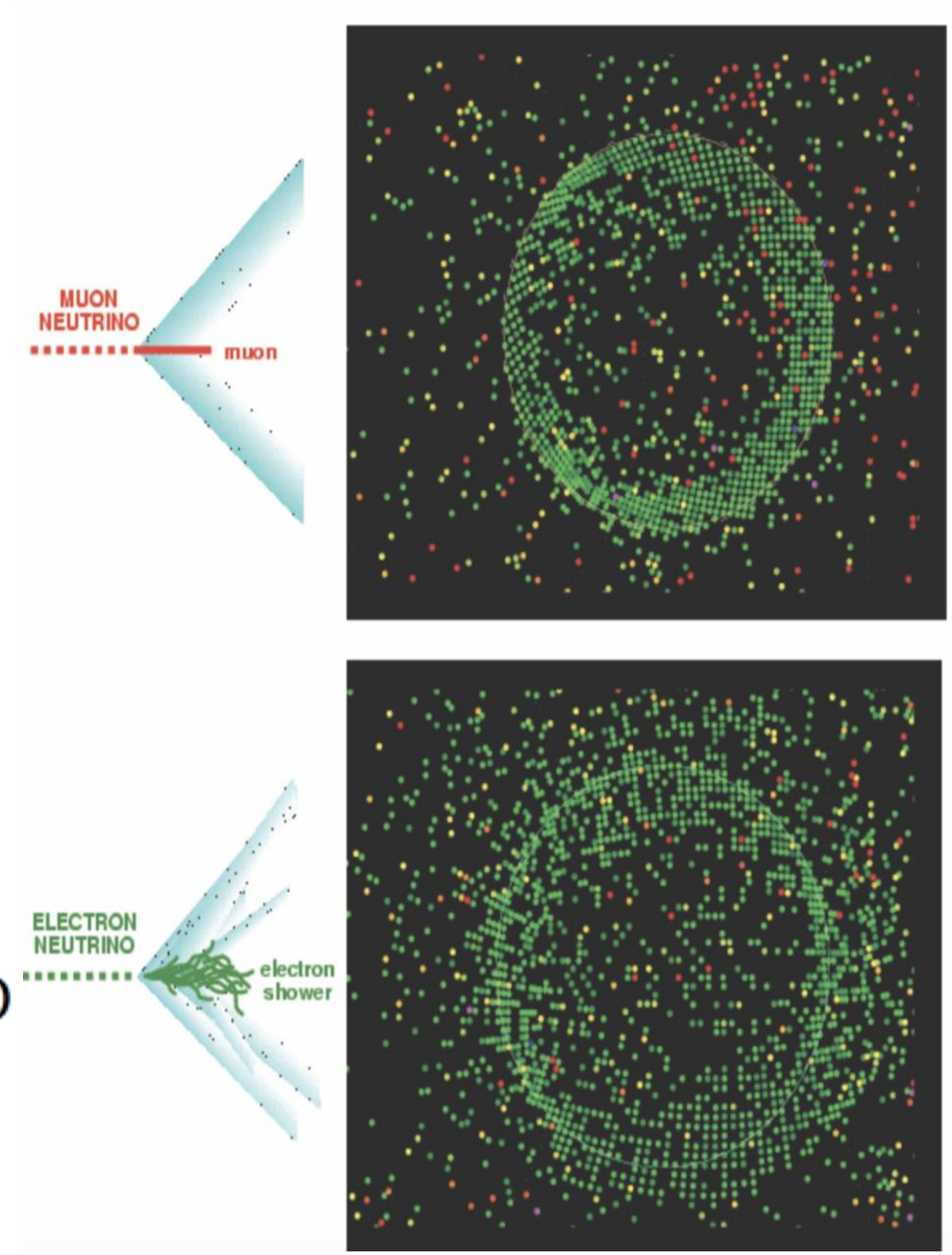


20inch (~50cm) PMT



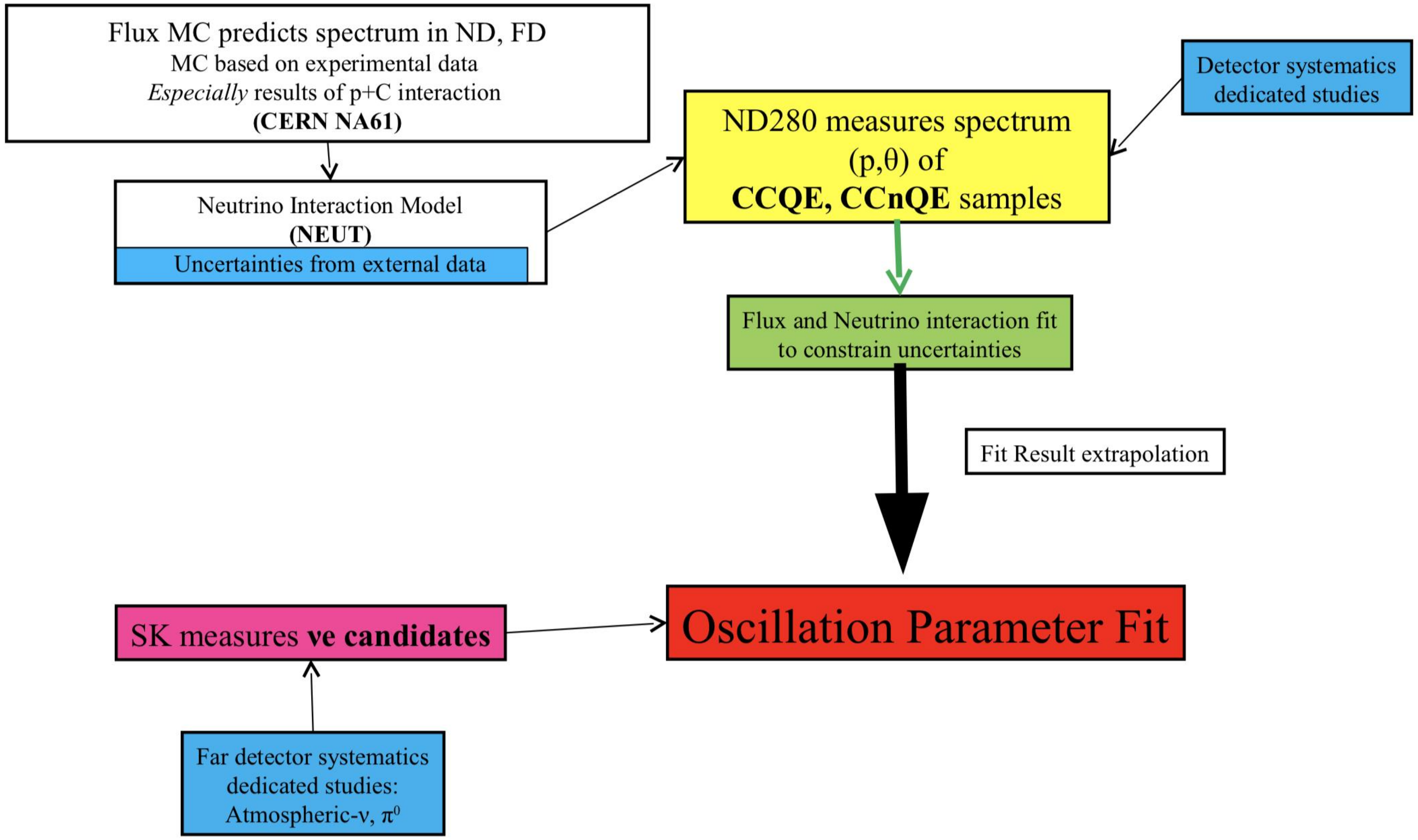






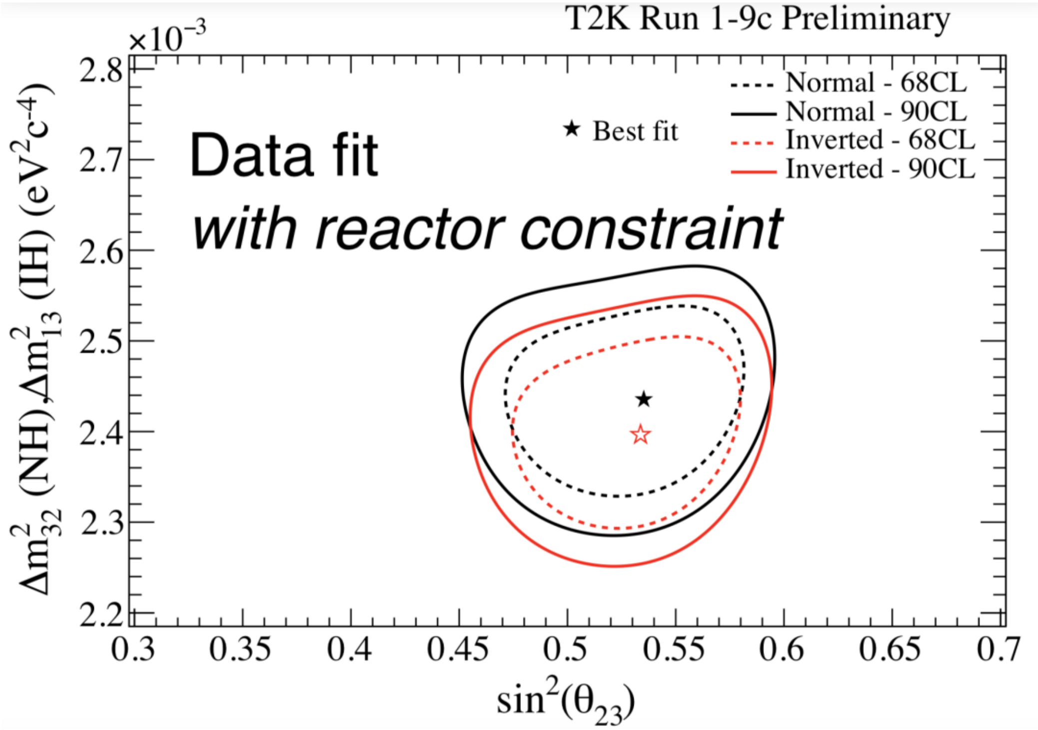
T2K strategy

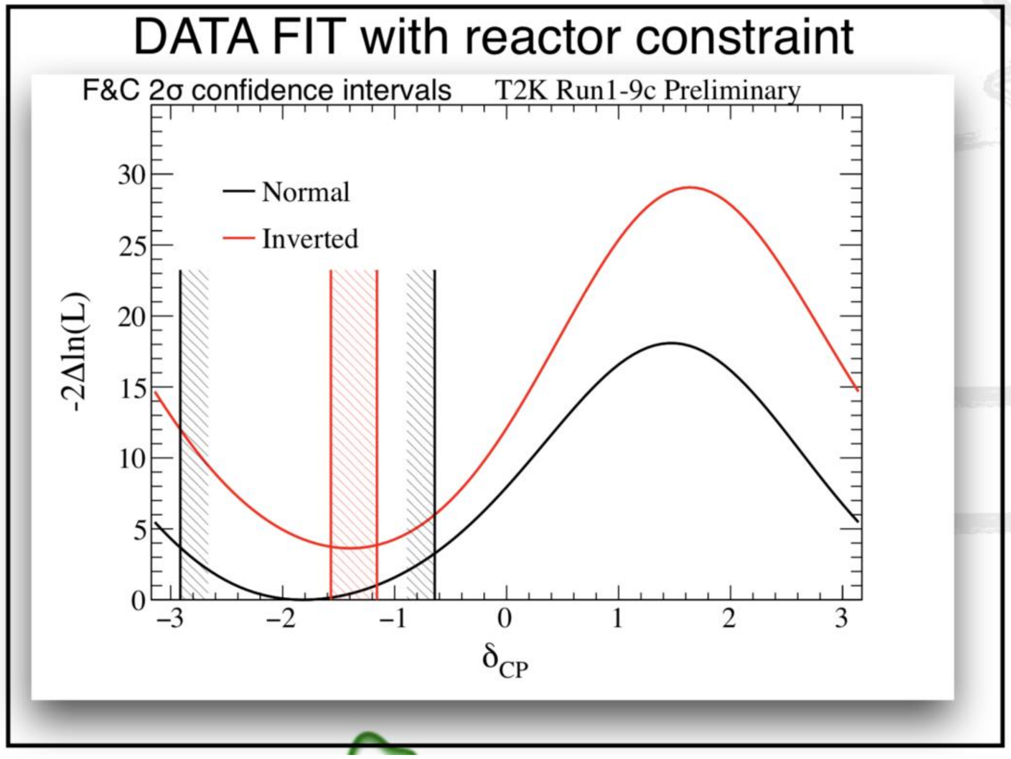
- **Use ND280 to constrain the flux and the neutrino interaction model to predict the ν rate at Super-K**
- Since ND and FD are not functionally identical, a direct extrapolation is not possible

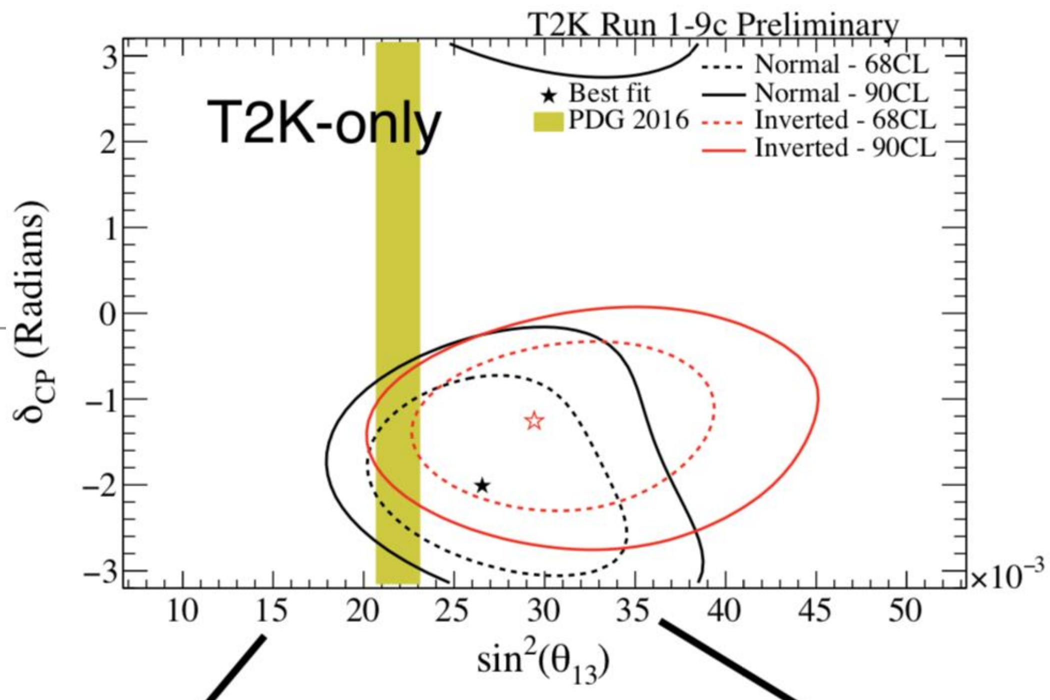


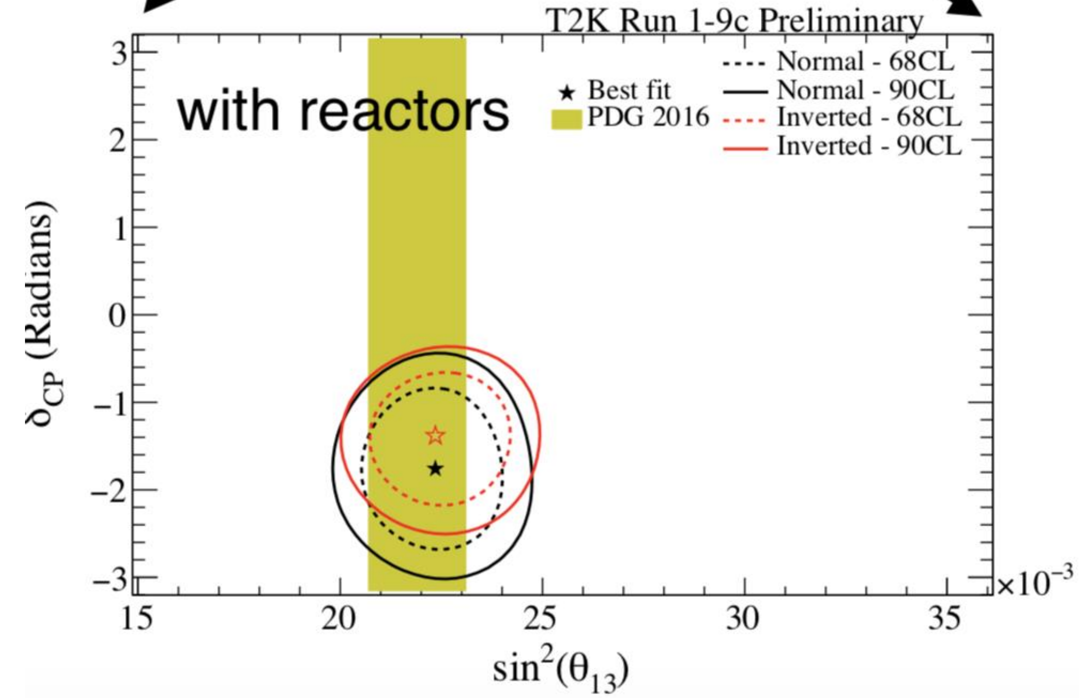
T2K results

Wascko, Neutrino 2018



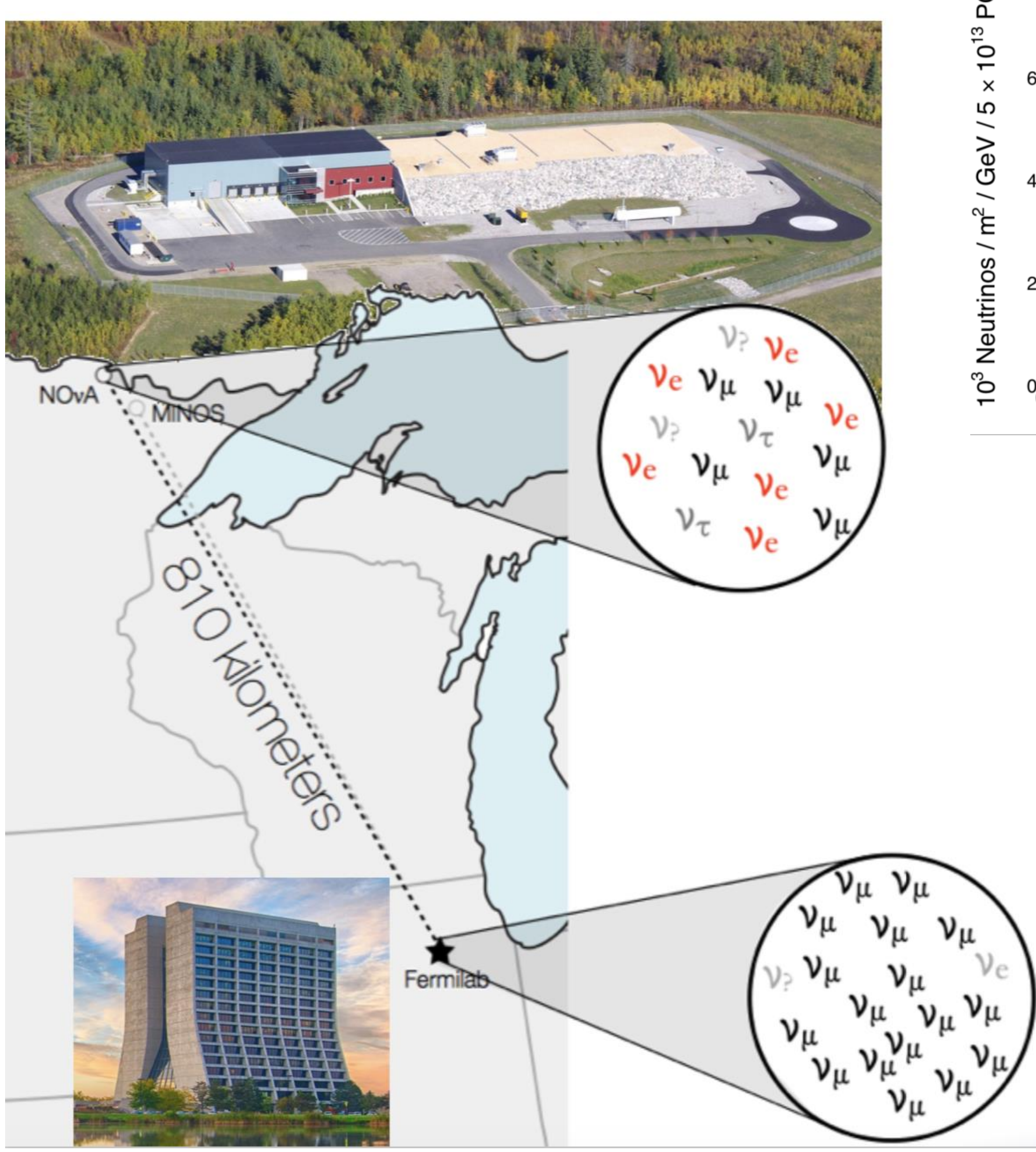


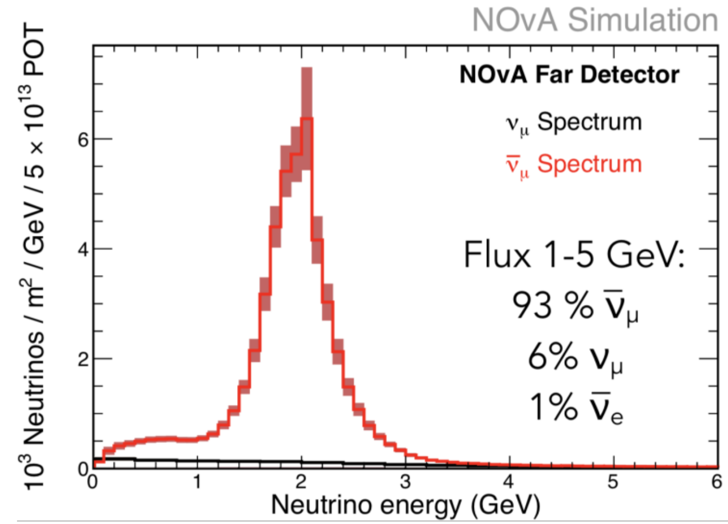


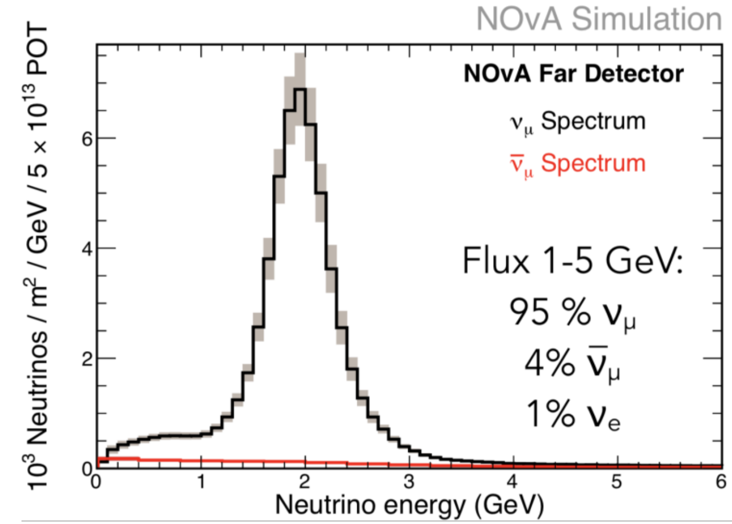


CP conserving values outside 2σ bands for both hierarchies!

NOvA



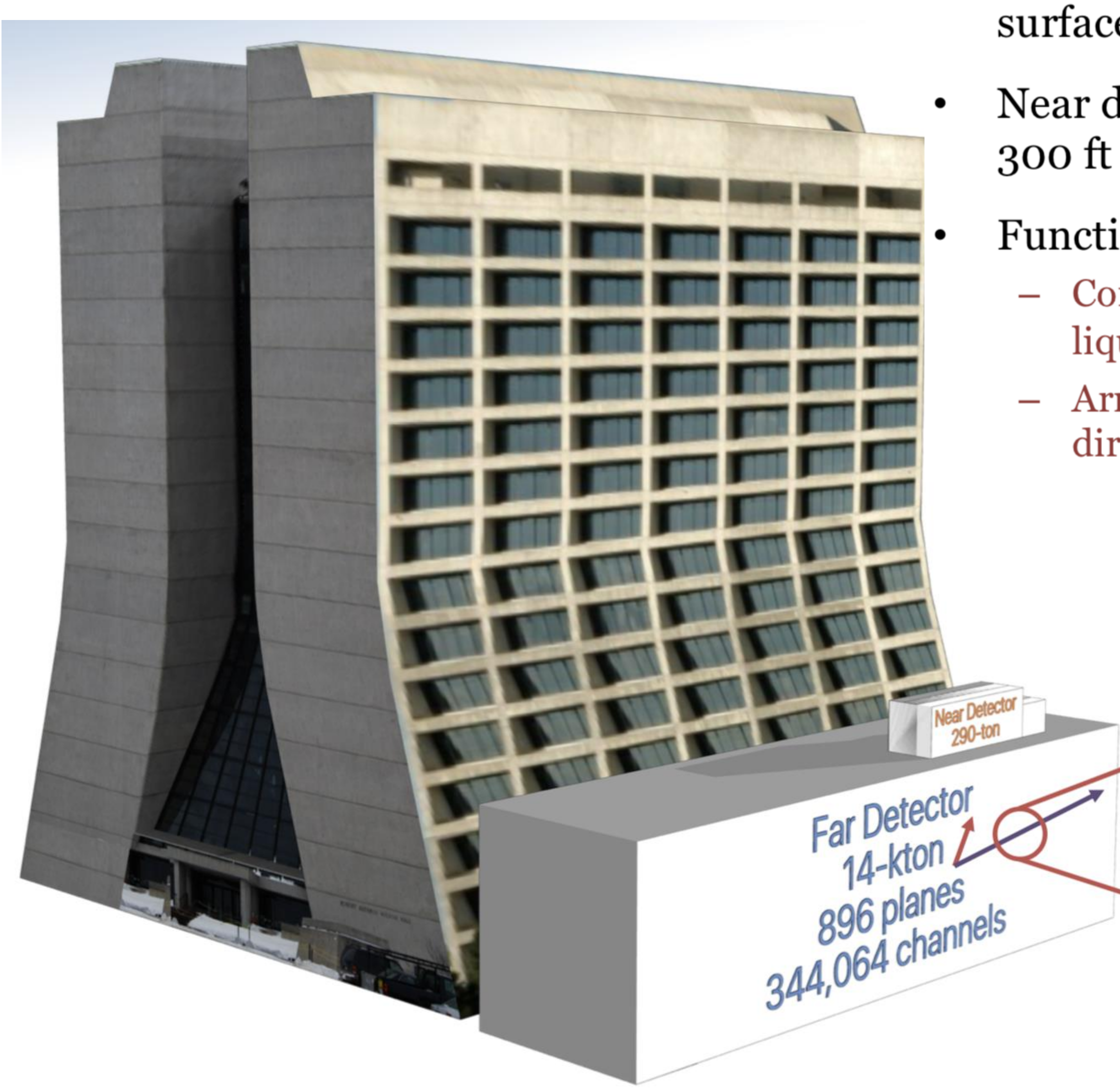




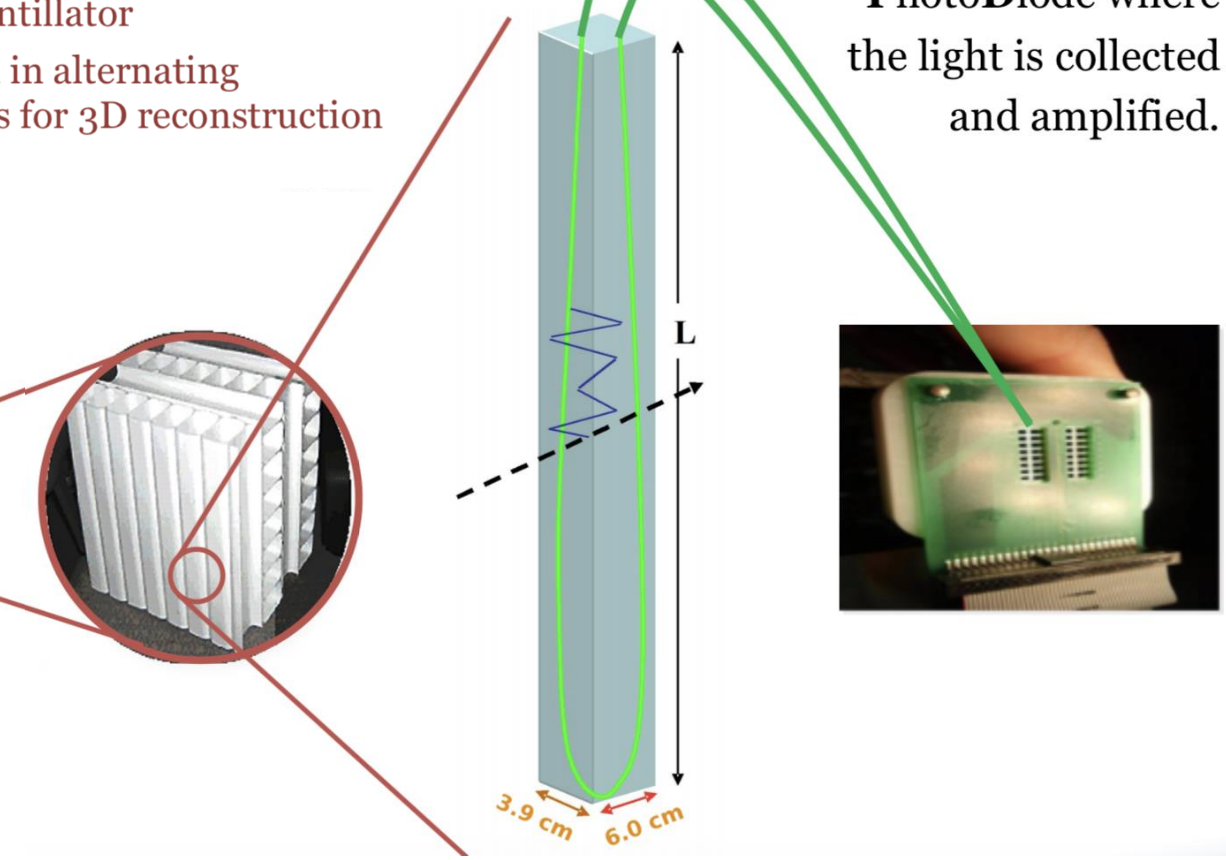
- 14mrad off axis ν and anti-ν beam
- functionally identical ND and FD
- 0.3kton ND, 14kton FD
- 700kW NuMI beam from Fermilab (the most powerful!)
- ND ~1km from source (100m underground), FD ~810km from source (on the surface)

NOvA detectors

- Far detector is 14 ktons, sits at the surface in Minnesota
- Near detector is 290 tons placed 300 ft underground at Fermilab.
- Functionally identical
  - Consist of plastic cells filled with liquid scintillator
  - Arranged in alternating directions for 3D reconstruction



It is then transported to an **A**valanche **P**hoto**D**iode where the light is collected and amplified.



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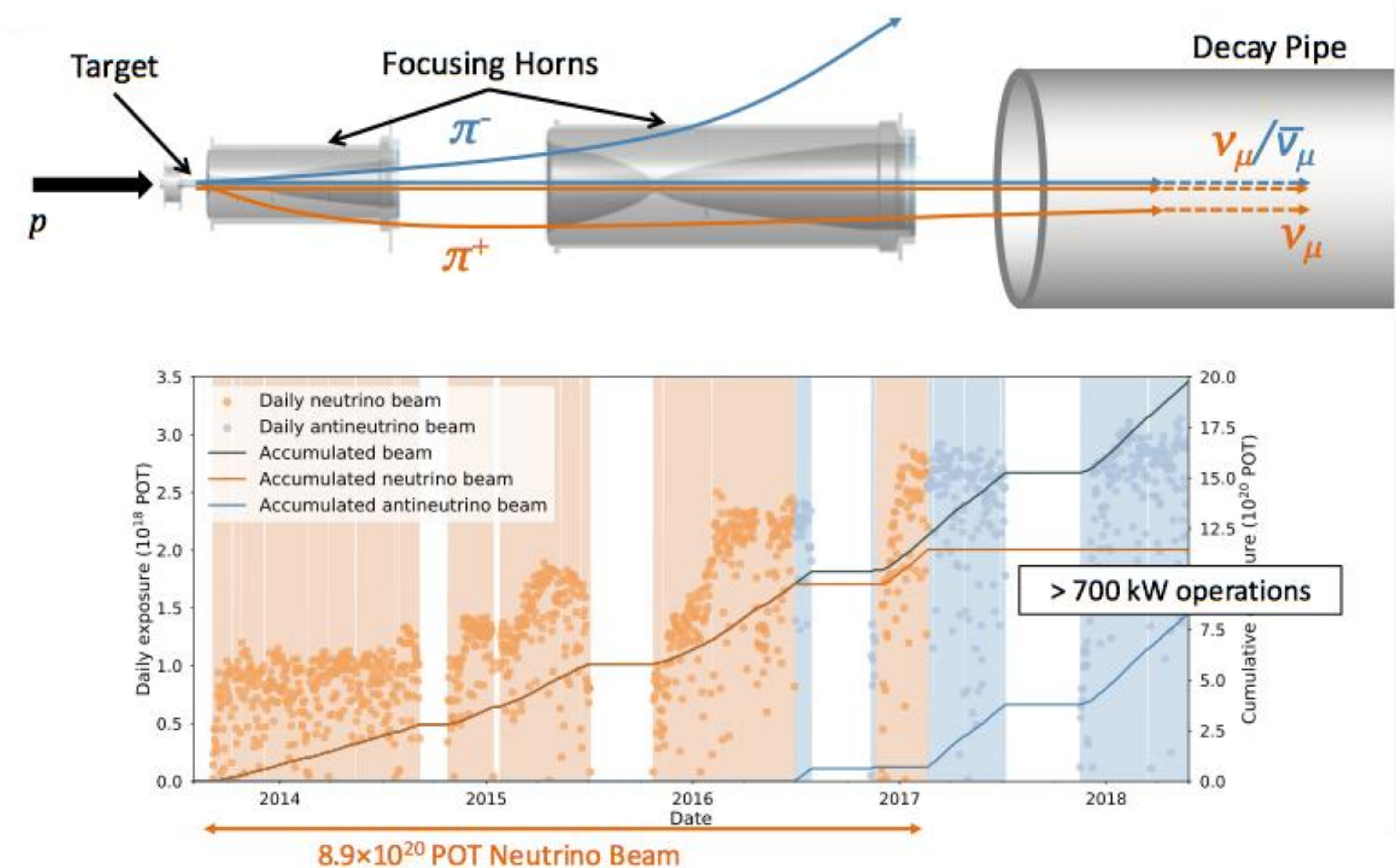
NOvA: the NuMI beam



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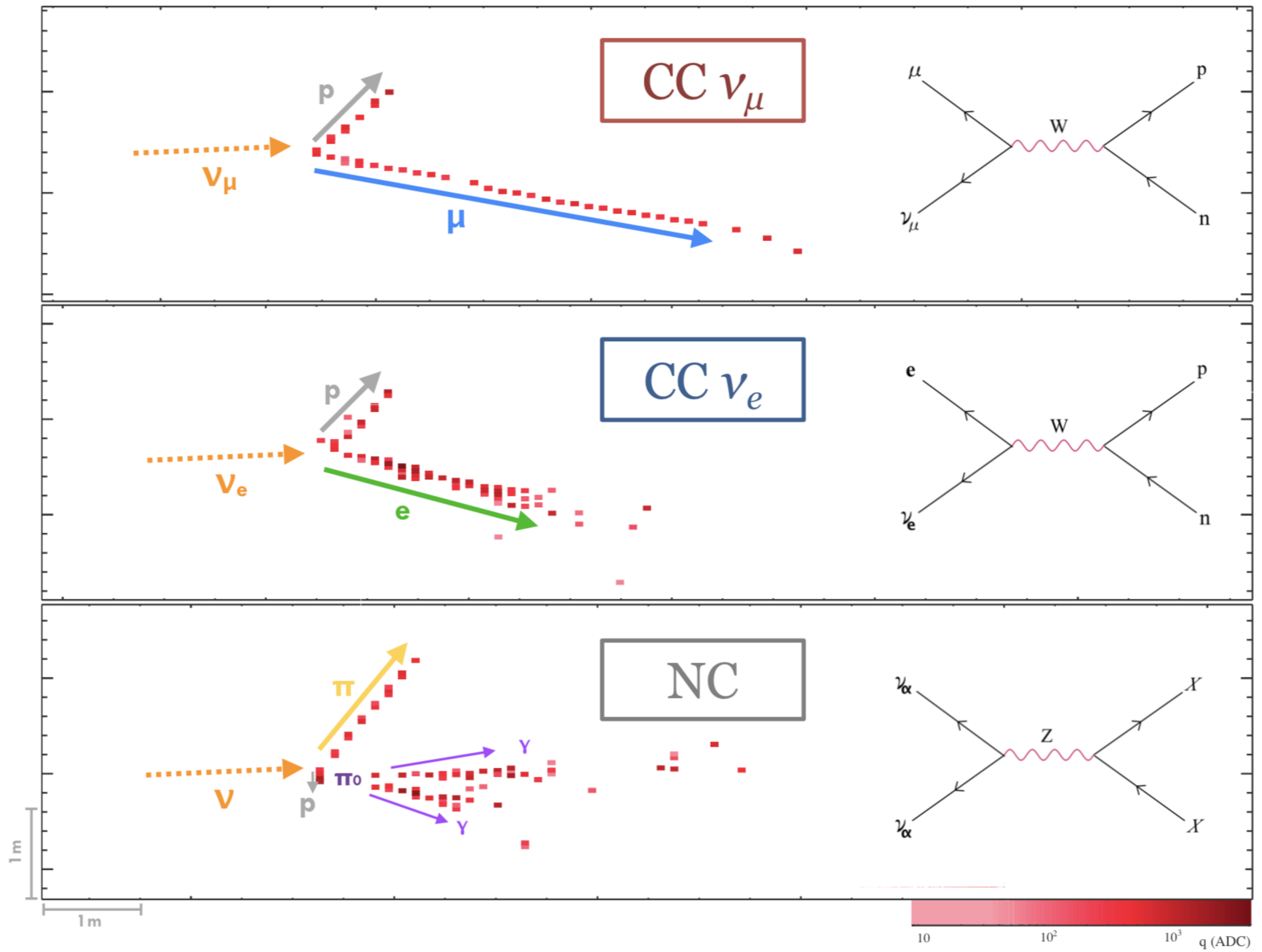
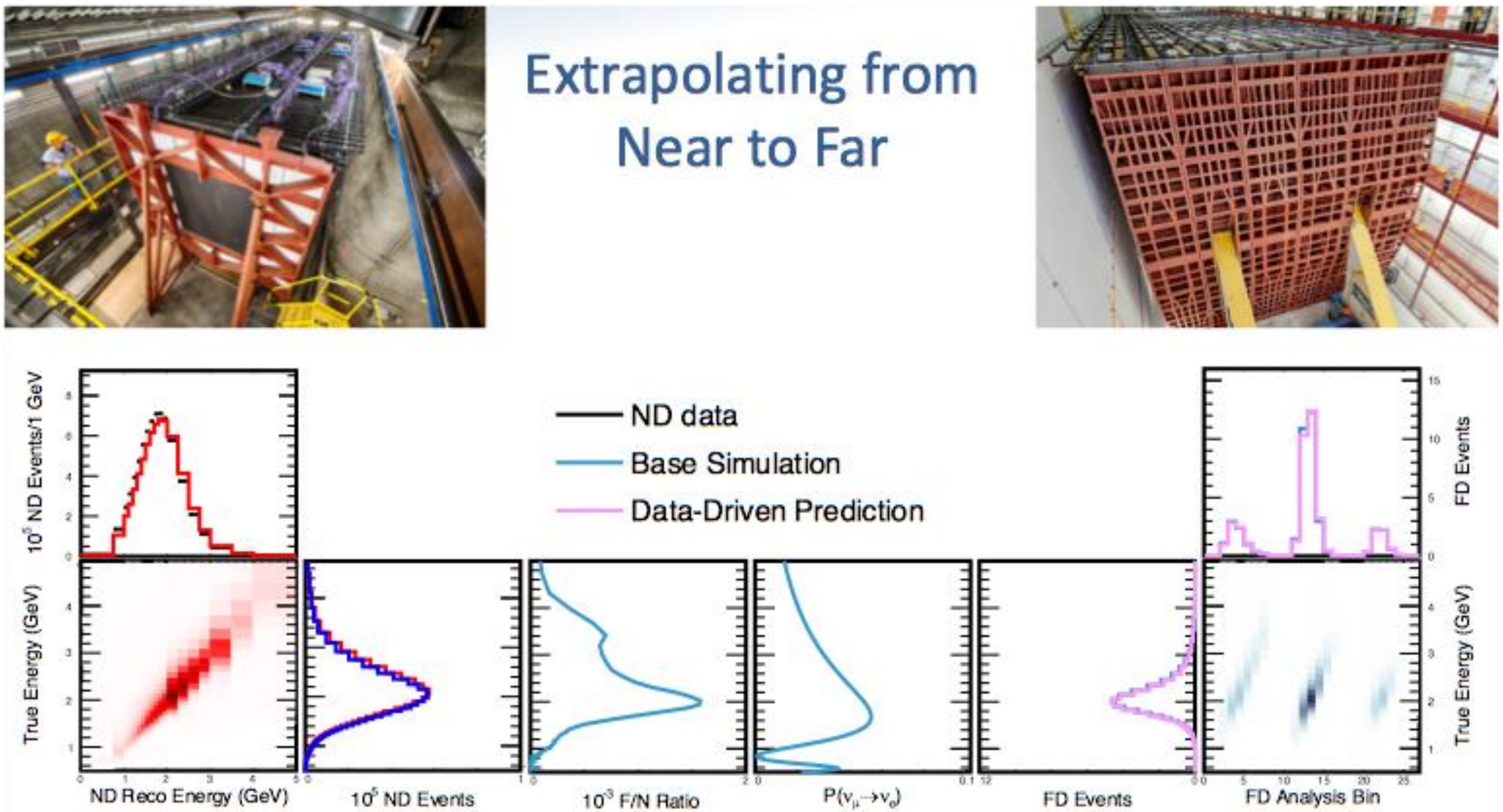
NOvA neutrino candidates



NOvA's strategy



- Use the ND ν_μ sample to predict the FD ν_μ sample.
- Use the ND ν_μ sample to predict the FD ν_e signal.

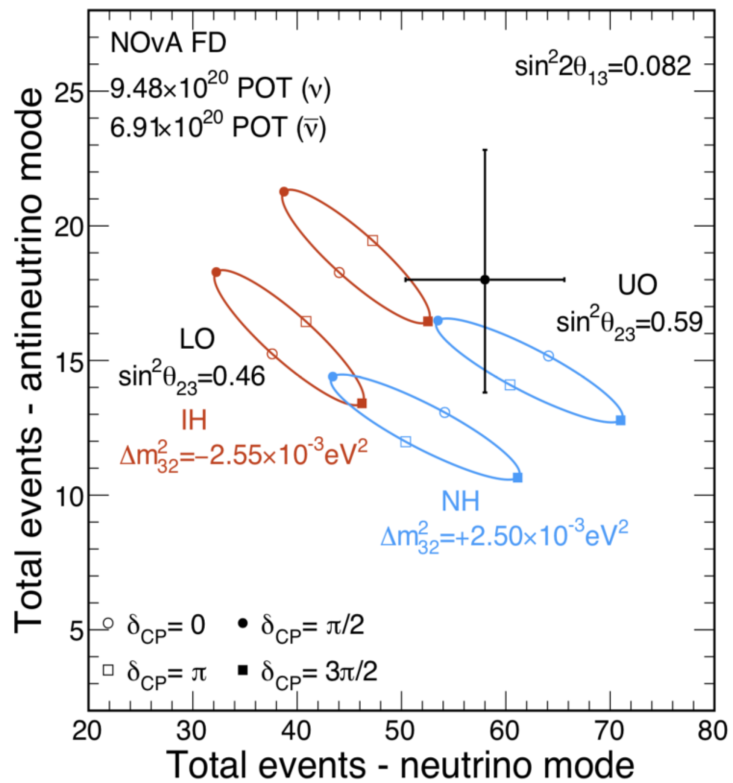
slightly different approach w.r.t. T2K

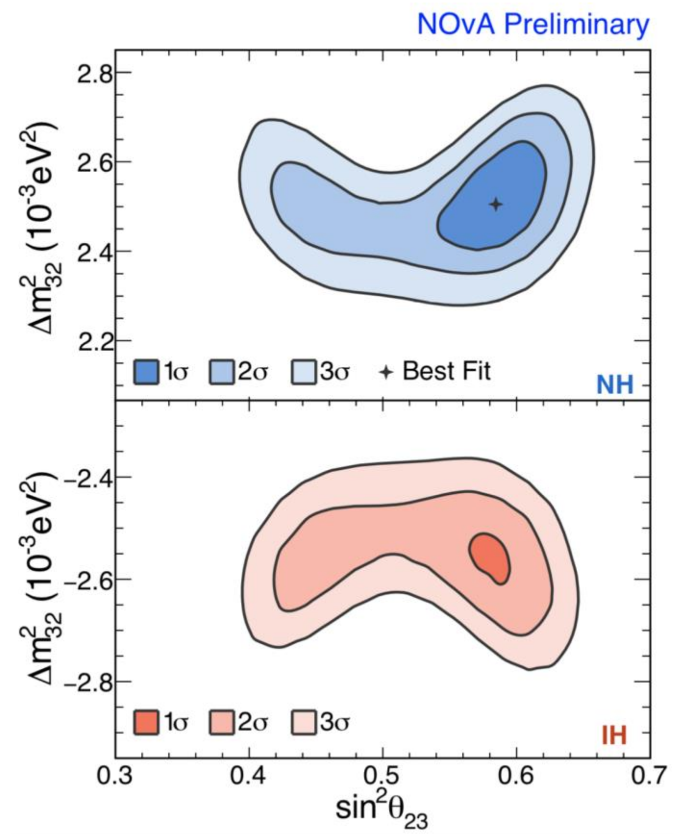
Alex Himmel

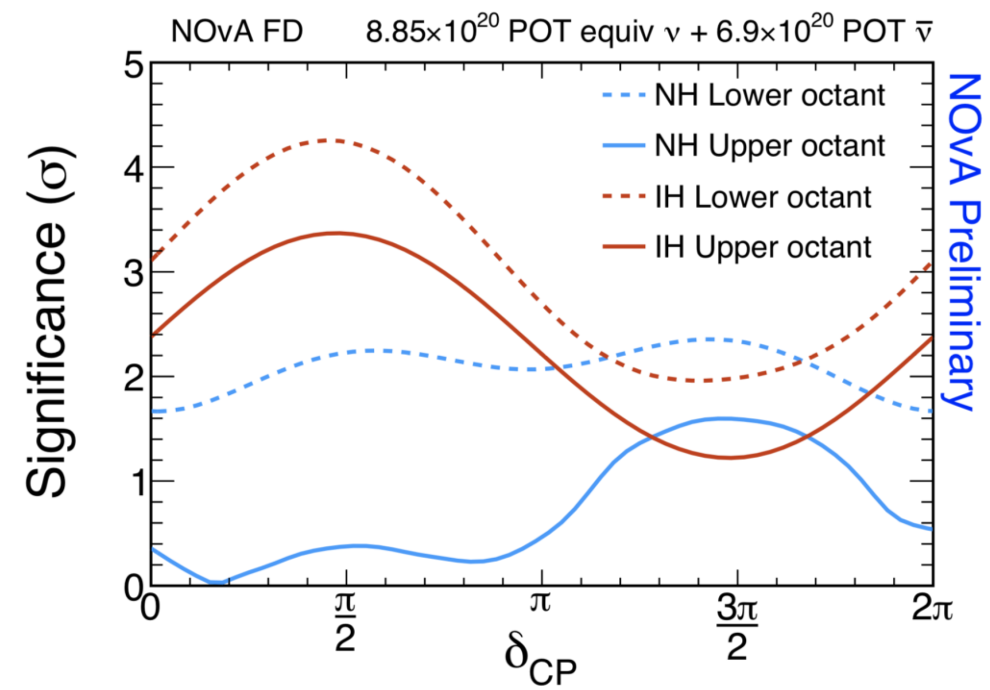
NOvA's results

ν_e appearance:

M. Sanchez, Neutrino 2018







- expect 30-70 events in ν mode, and 10-22 in anti-ν mode
- observed 58 νe and 18 anti-νe
- >4σ evidence of ν_e appearance

- Best fit: NH, $\sin^2\theta_{23}$=0.58±0.03 (upper octant)
- Prefer non maximal mixing at 1.8σ

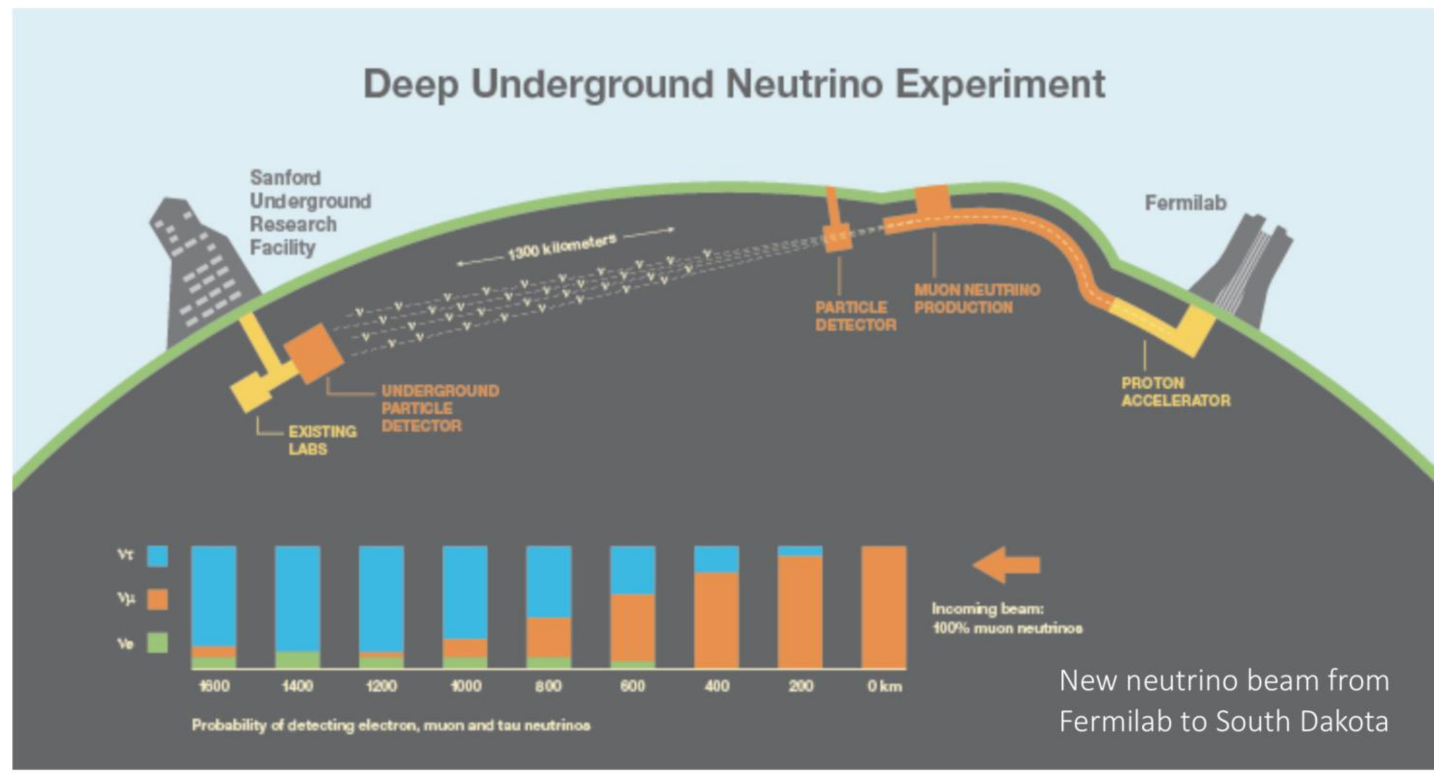
- Prefer NH at 1.8σ
- Exclude δ_{CP} in IH at > 3σ

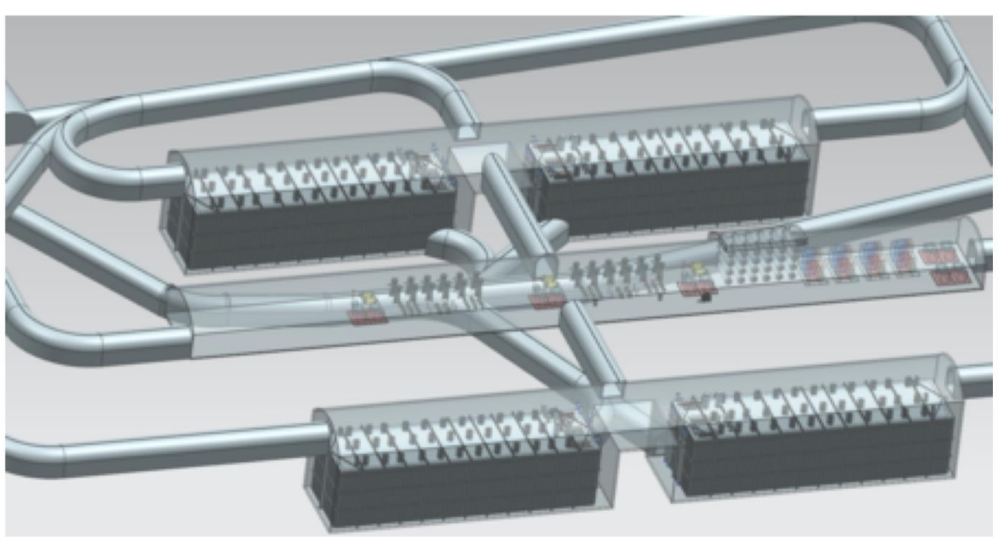
What next?

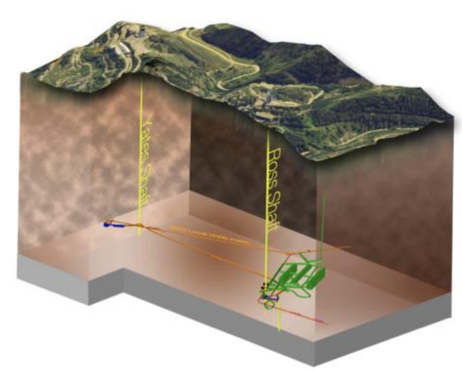
- 4 x 10kton modules filled with LAr
- underground @ Lead, South Dakota to reduce cosmic backgrounds
- LArTPC provides amazing imaging capability

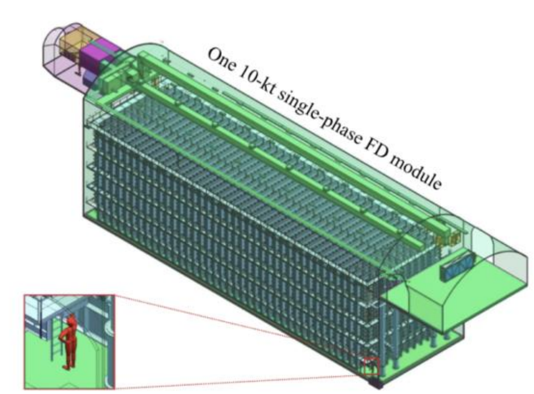
- **Goals: discover CP violation in the neutrino sector and look for proton decay**

DEEP UNDERGROUND NEUTRINO EXPERIMENT

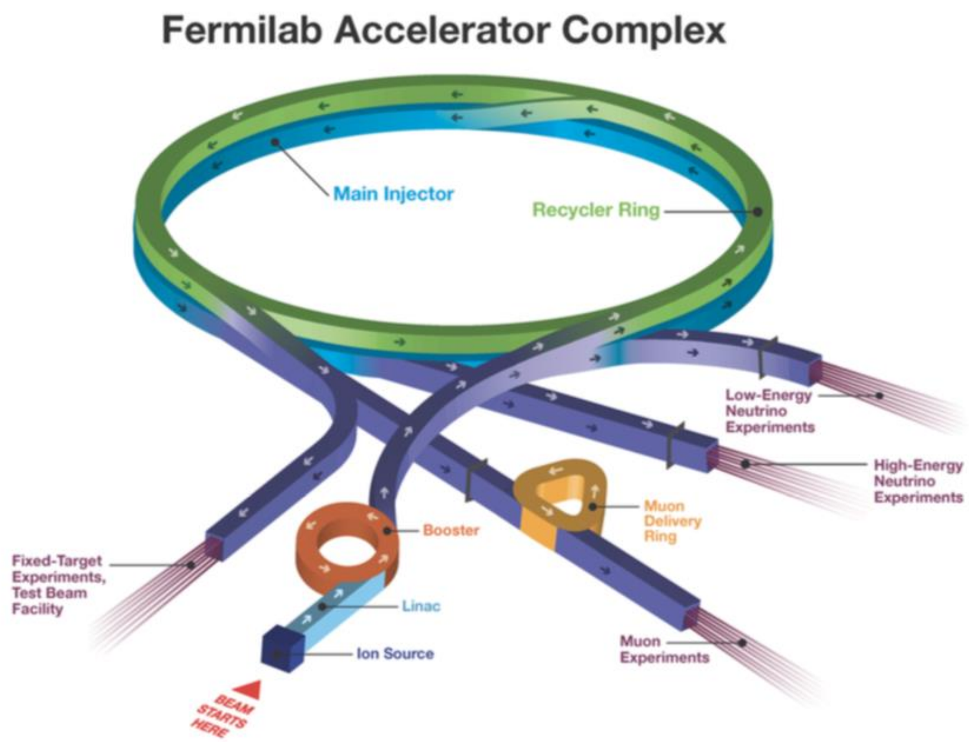


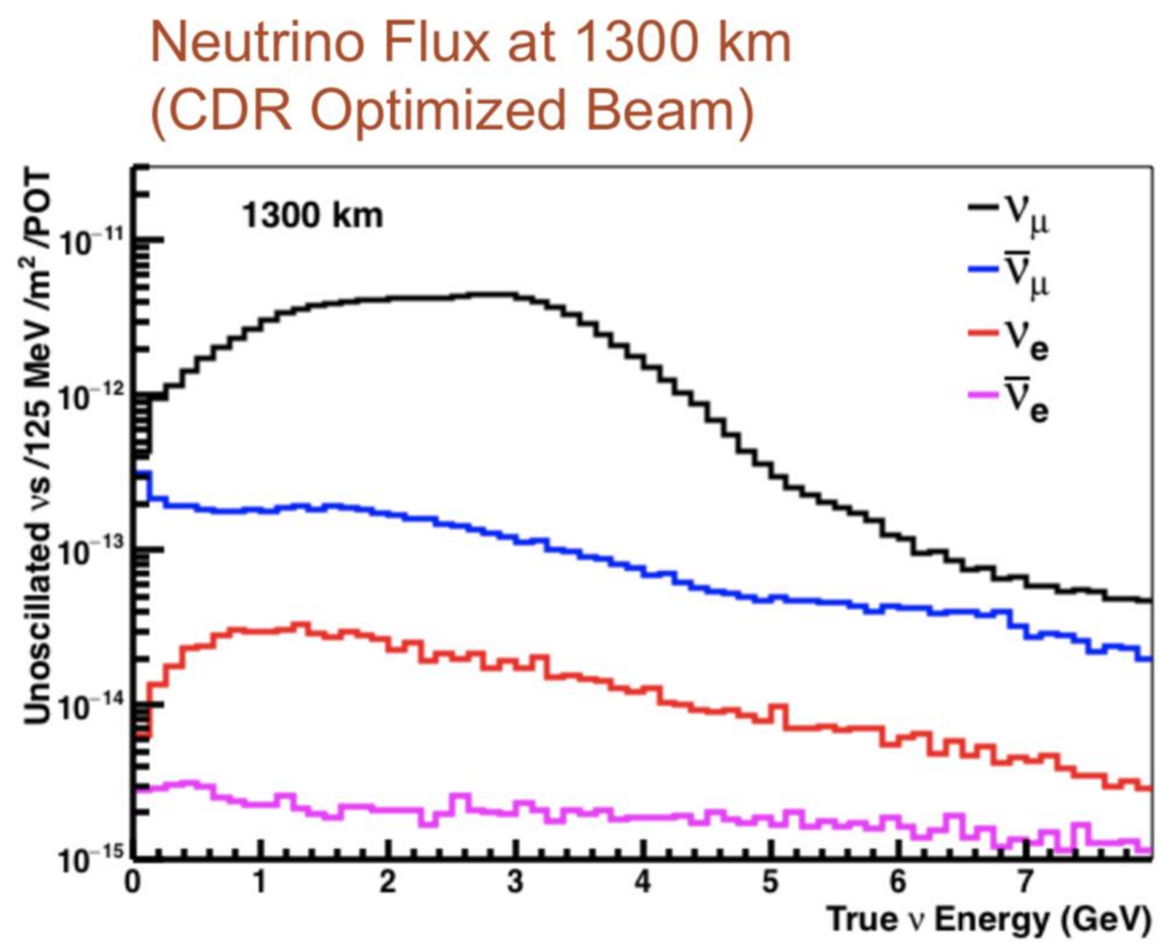






New high intensity beam

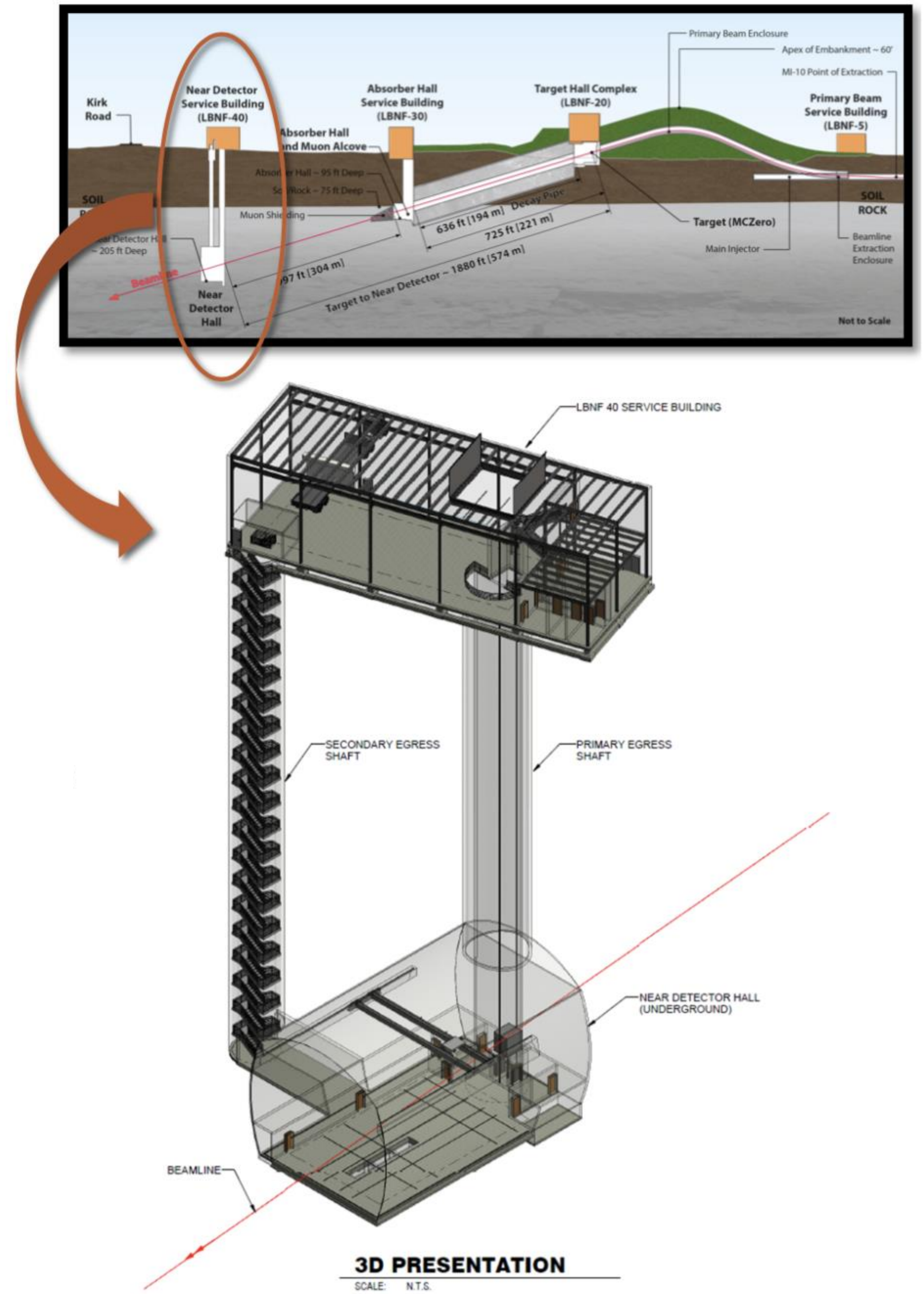




- Very powerful new neutrino beam:
  - horn focused, 1.2MW upgradable to 2.4MW
  - 60-120GeV proton beam
- Wideband neutrino spectrum to study multiple oscillation maxima and enhance sensitivity to δ_{CP} (remove degeneracies)

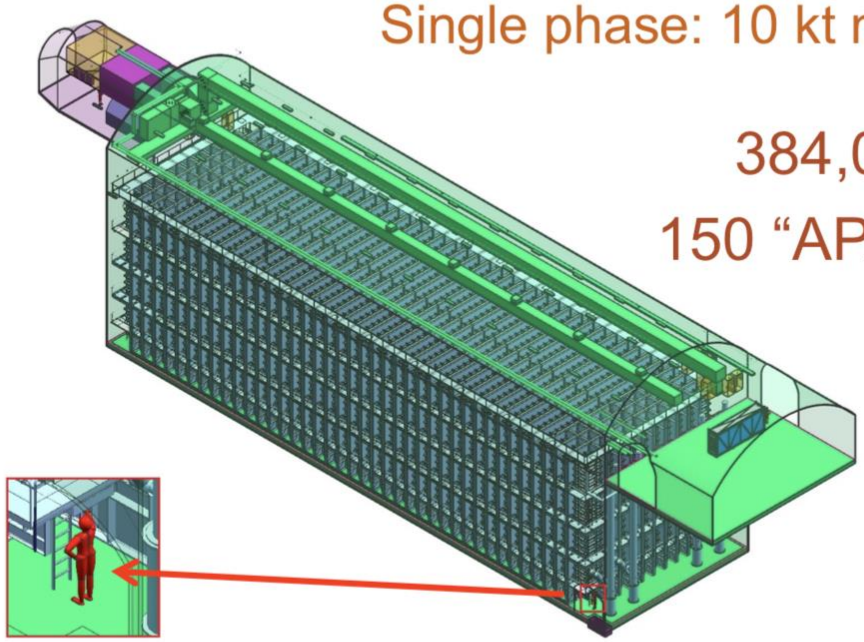
DUNE Near Detector

- Crucial to constrain systematic uncertainties for oscillation studies
- Huge statistics will allow precision measurement of neutrino interactions
- Will contain a LArTPC plus other tracker detectors to collect all the necessary info on the events:
  - **highly segmented LArTPC**
  - **magnetized multi-purpose tracker**
  - **electromagnetic calorimeter**
  - **muon chambers**

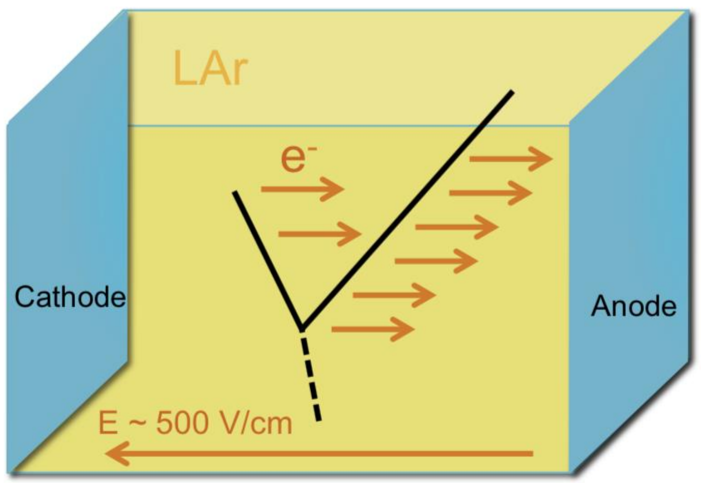


DUNE Far Detectors

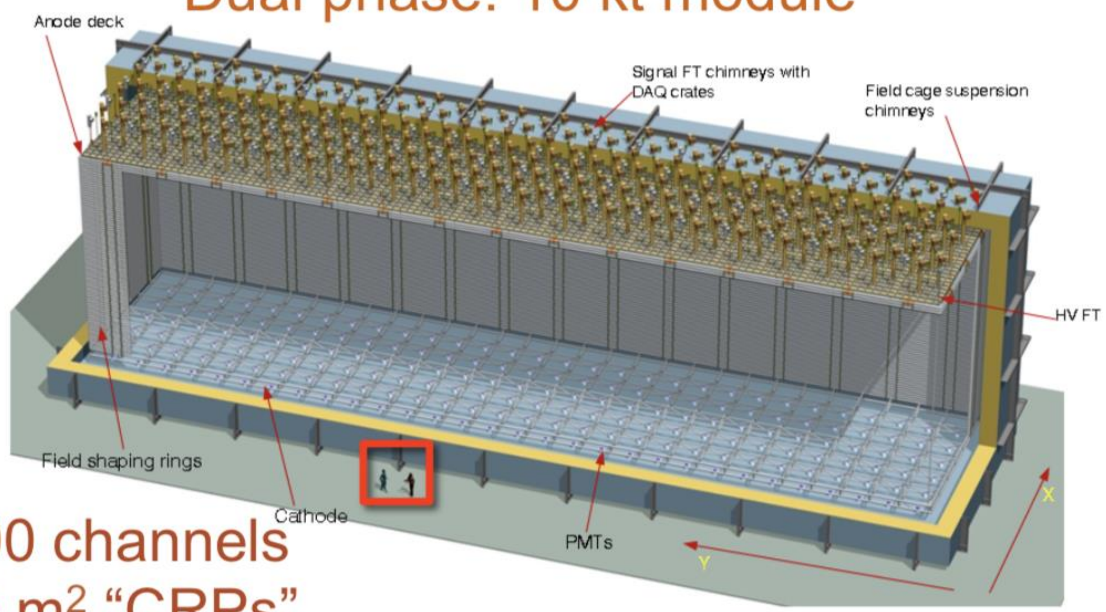
Single phase: 10 kt module



384,000 readout wires
150 “APAs” (2.3 m x 6 m)
12 m high
15.5 m wide
58 m long

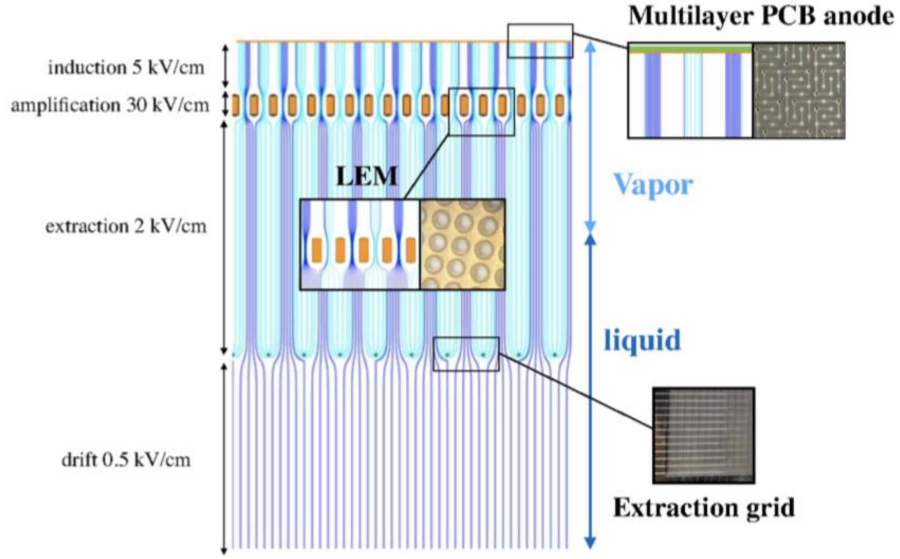


Dual phase: 10 kt module

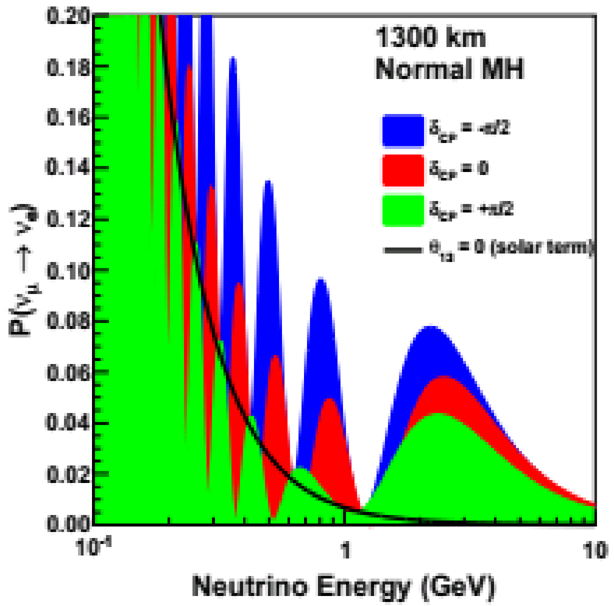


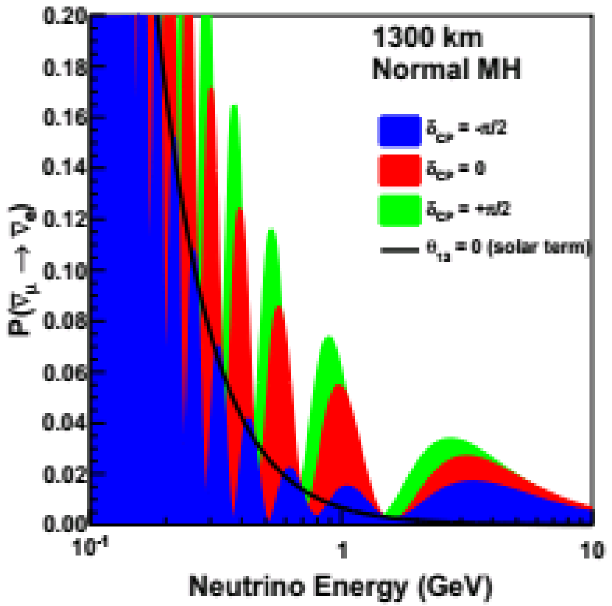
153,600 channels
80 3x3 m^2 “CRPs”
(Charge Readout Planes)

Dual phase: signal extracted; amplified in gas phase

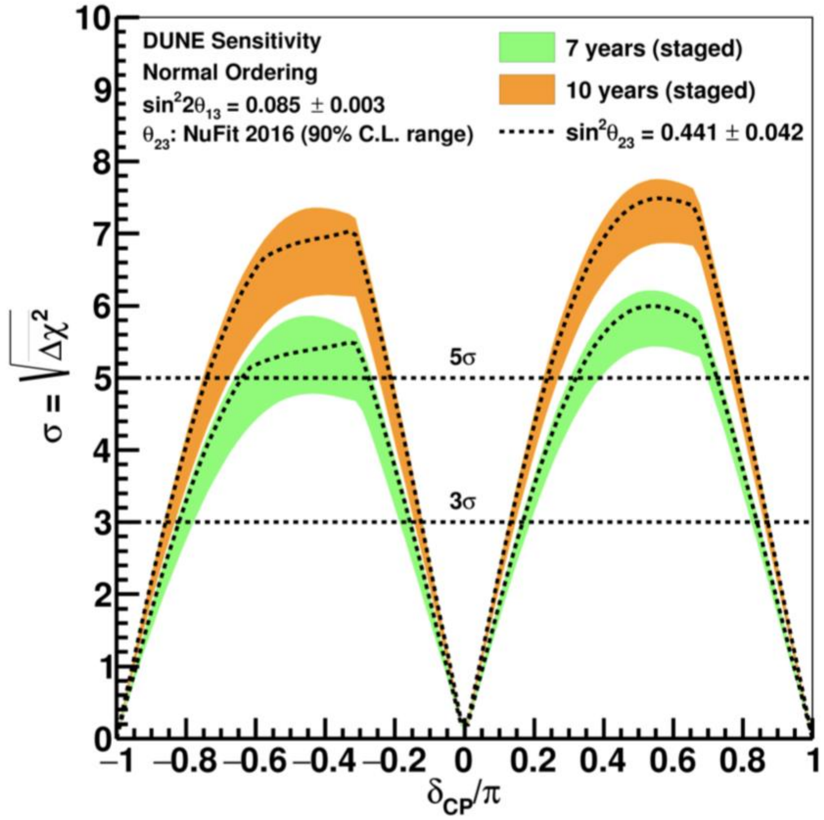


DUNE oscillation physics



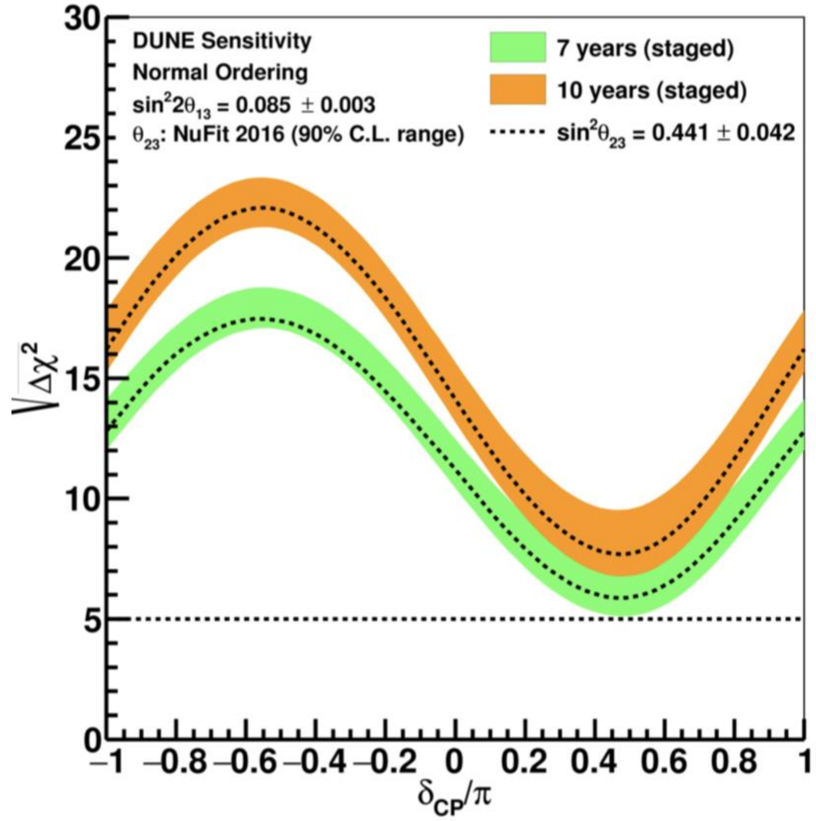


CP Violation



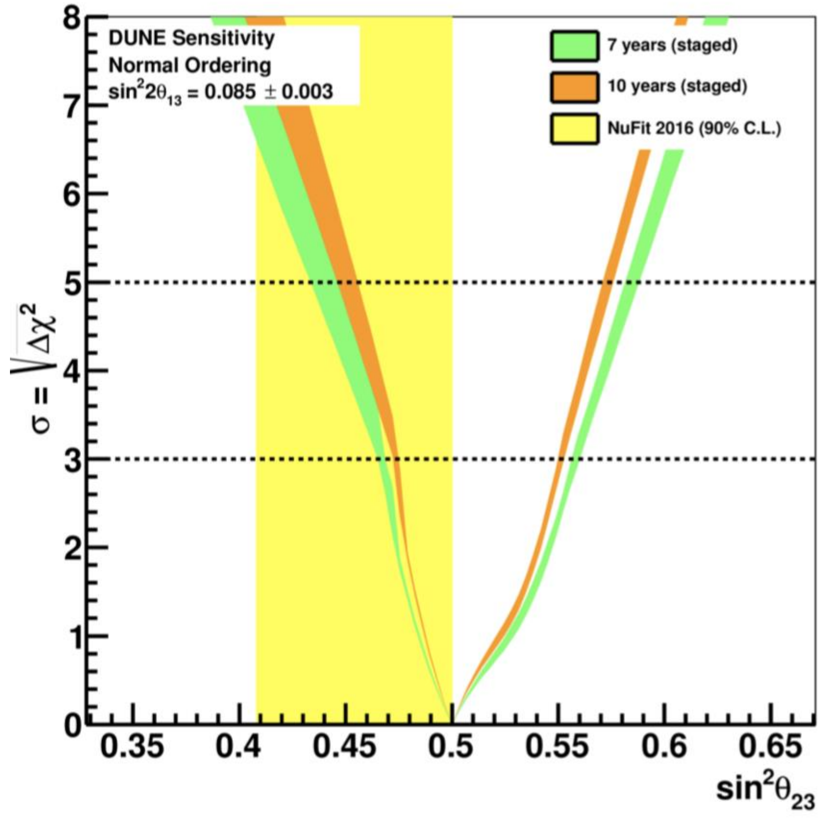
Width of band indicates variation in possible central values of θ_{23}

Mass Ordering



Width of band indicates variation in possible central values of θ_{23}

Octant



Width of band indicates variation in possible true value of δ_{CP}

DUNE timeline

E. Worchester, Neutrino 2018

2018: protoDUNEs at CERN

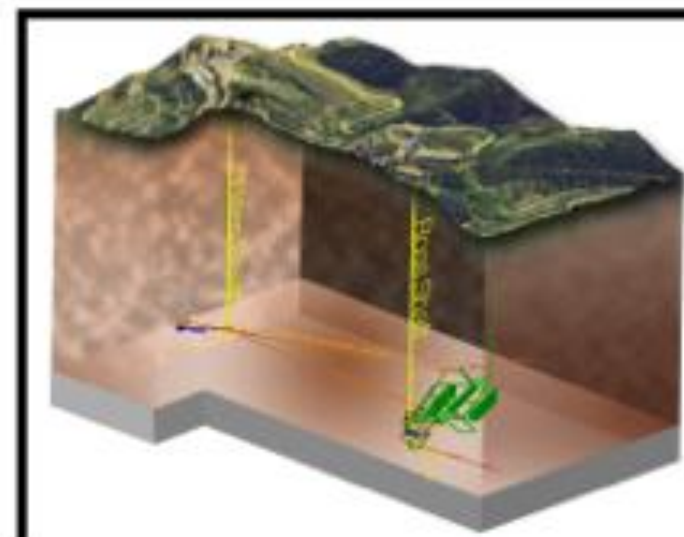
2019: Technical Design Report

2019: Far Site Primary Excavation Begins

2022: First Module Installation Begins

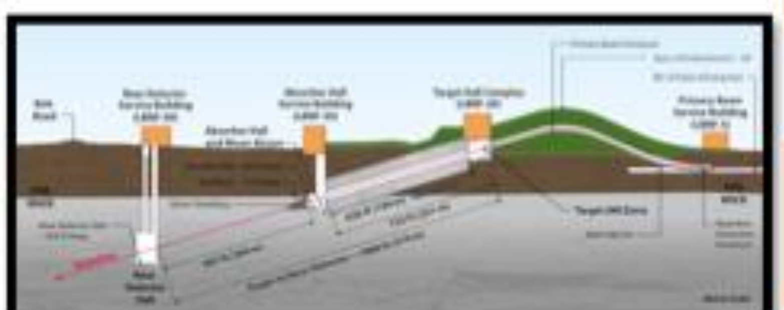
2026: Neutrino Beam Available

DUNE Far Detector Interim Design Report (2018)
Will be made public soon…



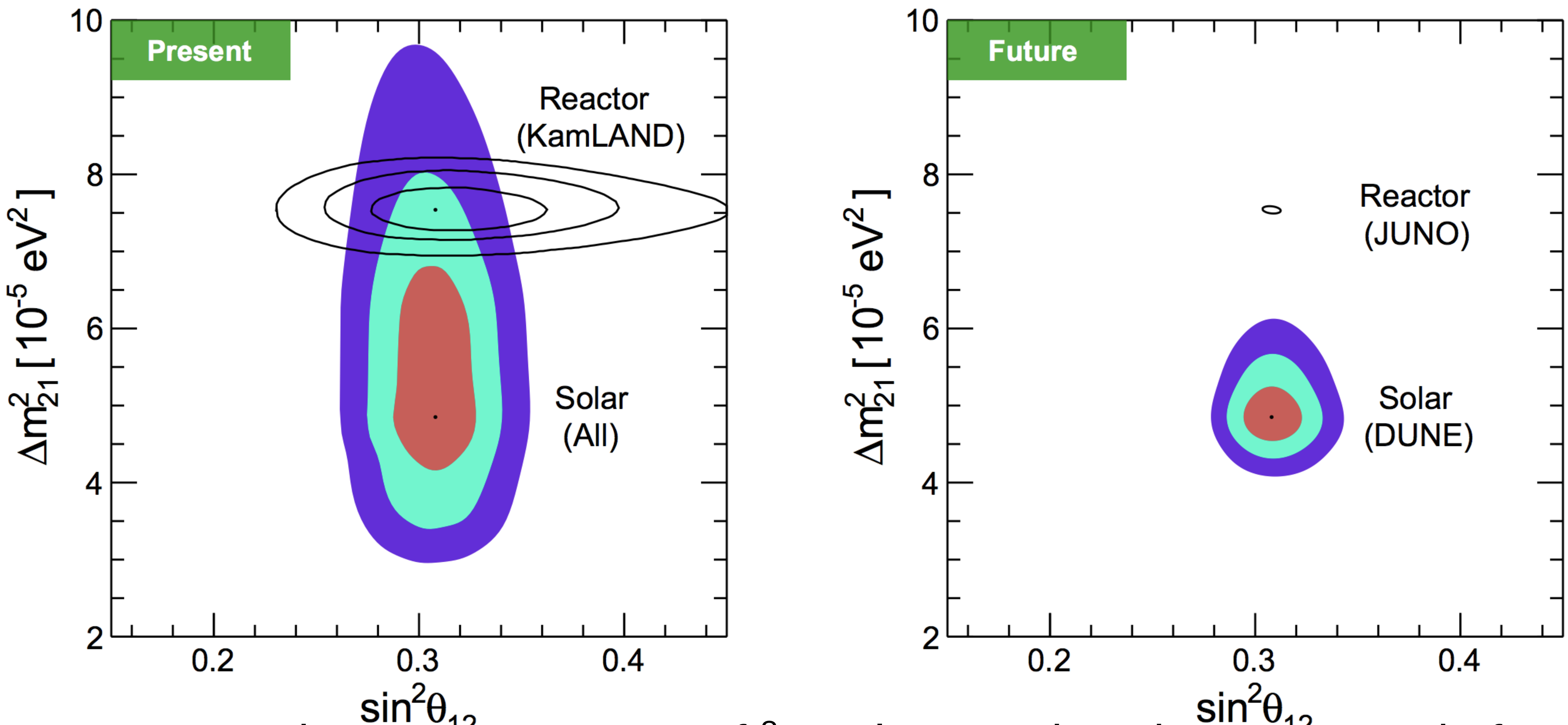
Physics data as soon as 1st module complete

- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration



Solar and θ_{12} physics

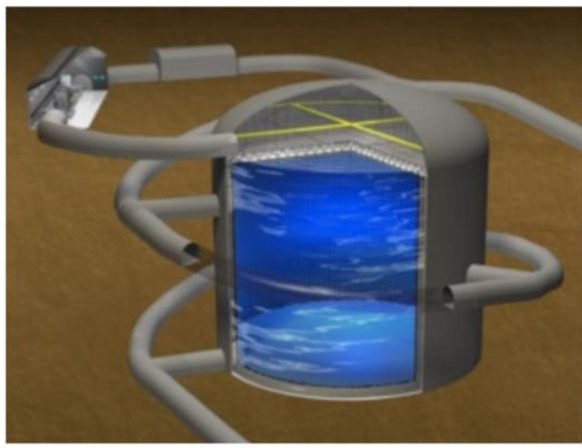
arXiv:1808.08232



By precise measurements of ^{8}B solar neutrinos by DUNE and of θ_{12} by the future reactor experiment JUNO, it will be possible to solve the long standing 2σ tension between KamLAND and solars!

T2HK

Construction starting in 2020! last week's news!



Hyper-K

J-PARC
Accelerator Complex

- Gigantic nucleon decay and neutrino detector
  - 186kton FV, ~10 times Super-K
  - ~x2 higher photon sensitivity than Super-K
  - 2nd oscillation maximum with a second tank in Korea is under study
- Upgrade of J-PARC accelerator to MW intensities

Summary

- **“Anomalies”**
  - “Gallium anomaly” - ν_e disappearance
  - “Reactor anomaly” - anti-ν_e disappearance
  - “LSND” and “MiniBooNE” anomalies - ν_e appearance

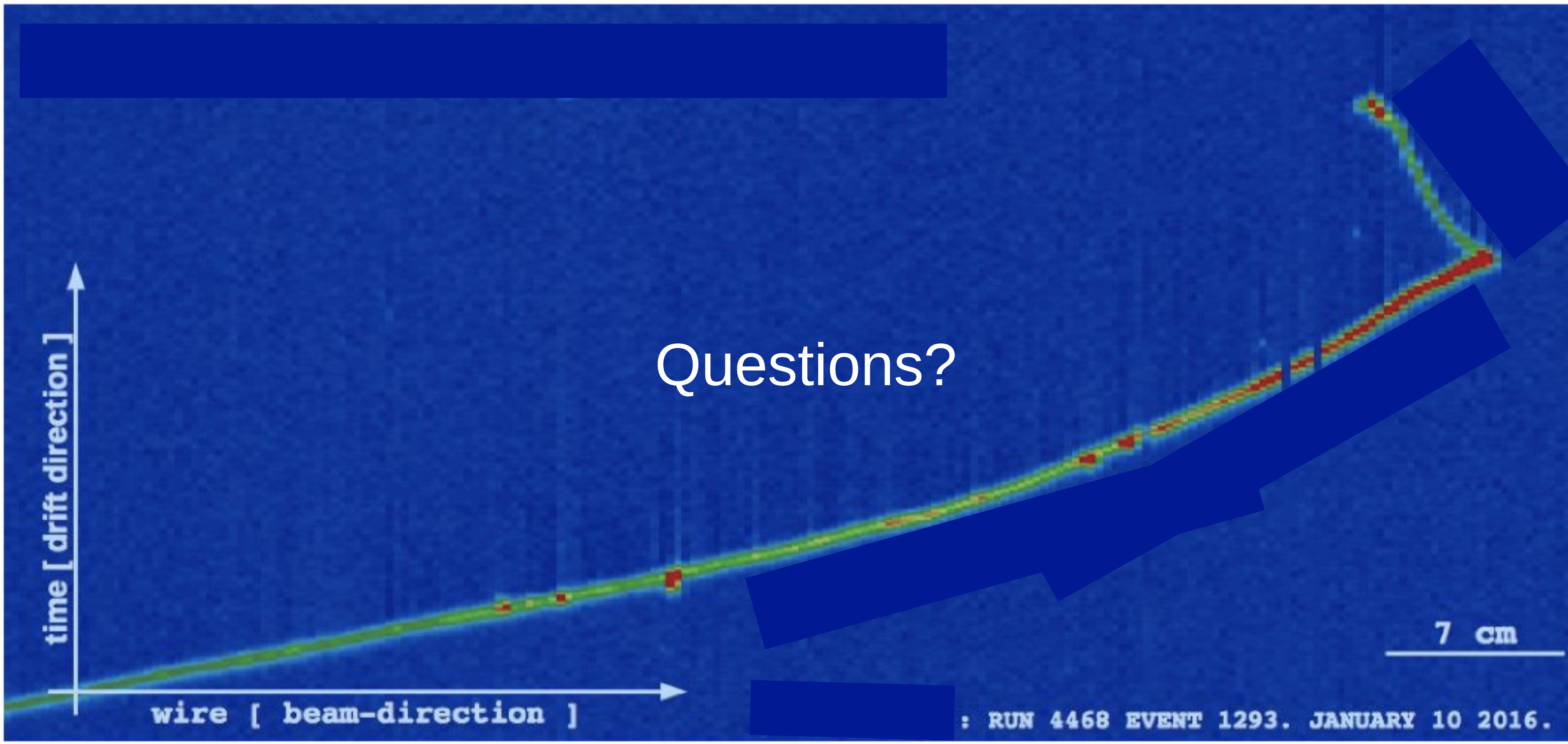
- **Current and future experiment are investigating the anomalies and will provide answers soon**

- Exciting long baseline oscillation measurements being carried out now
  - T2K and NOvA are getting hints for CP violation

- **CP violation is the goal of the next decade**
  - it could explain the matter/anti-matter asymmetry in the universe

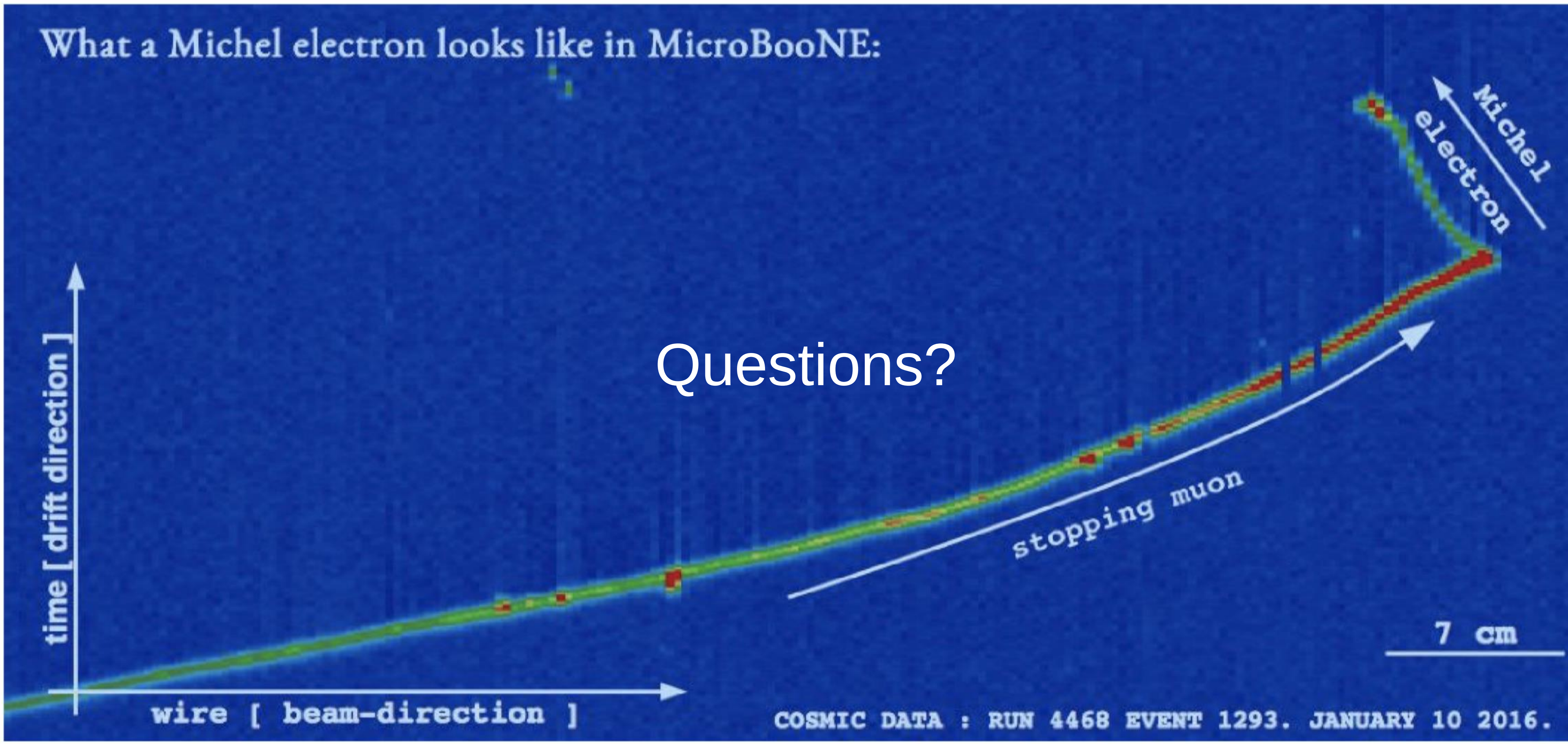
- **DUNE and Hyper-K are ramping up**
  - a lot of exciting physics coming along
  - many R&D opportunities

Thank you!



Questions?

Thank you!



Questions?