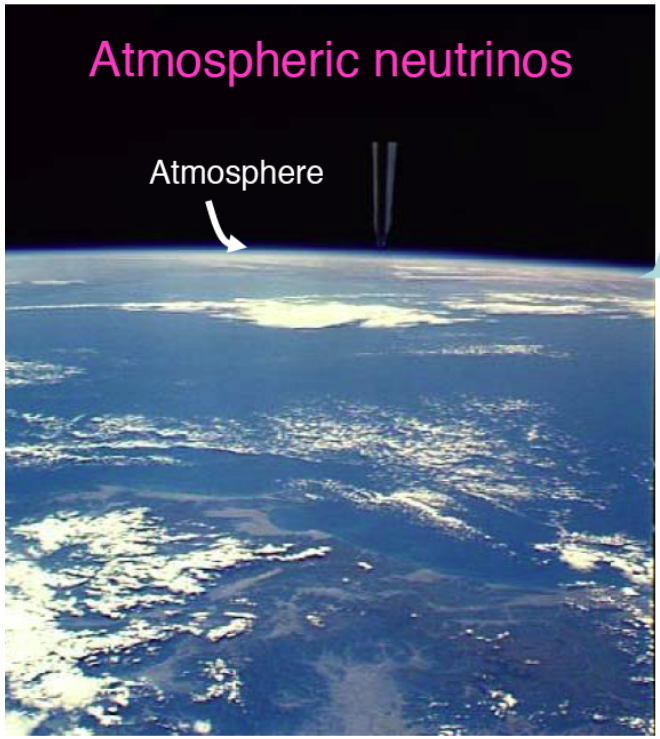
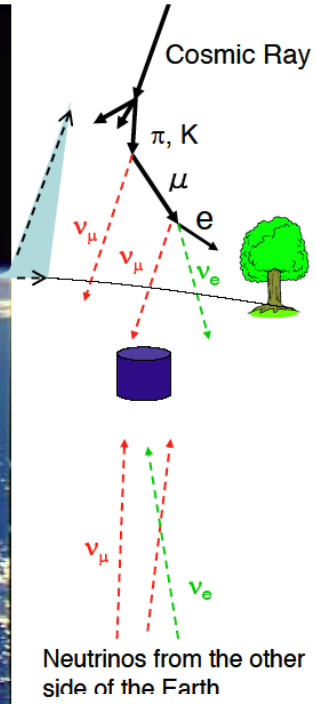
The State of Neutrino Physics

Hisakazu Minakata ~~Yachay Tech, Ecuador~~ See Science
http://www.sciencemag.org/news/2017/07/plans-research-powerhouse-andes-begin-unravel

3 flavor neutrino mixing established

Long discovery phase finally ended





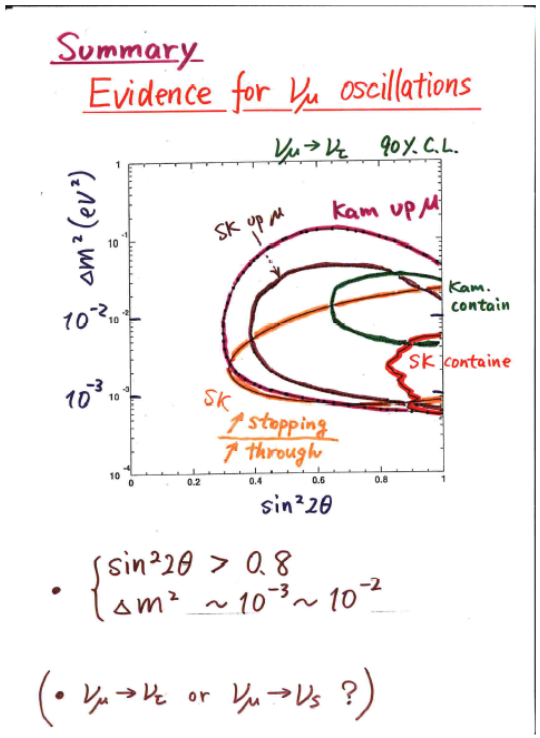
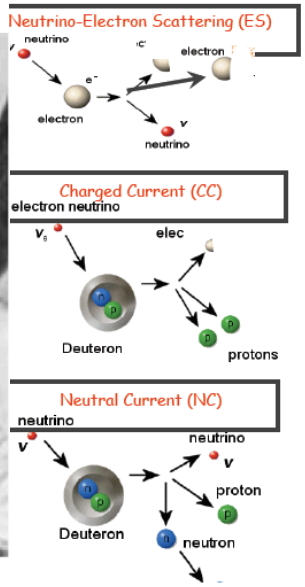


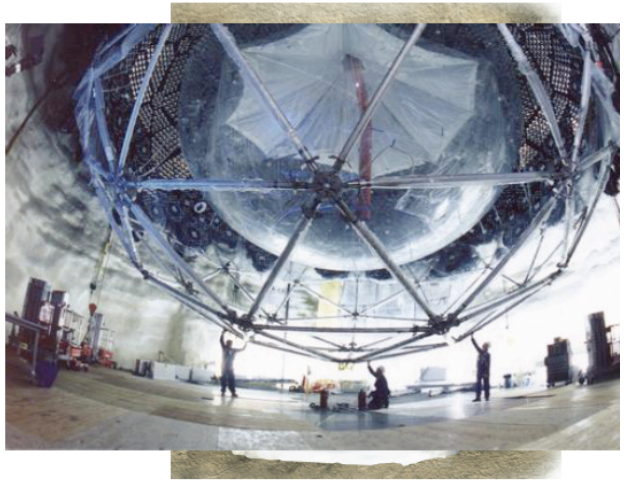
Photo: A. Mahmoud
Takaaki Kajita

Solar Neutrino Appearance

➢SNO neutrino reactions on deuterons

Raymond David Jr. (left) and John Bahcall in miner's





National Geographic

Signal rates determined by statistical fit

Photo: A. Mahmoud
Arthur B. McDonald

Physics 2015

All the angles are measured !
lepton CP phase δ left (1998-2012)

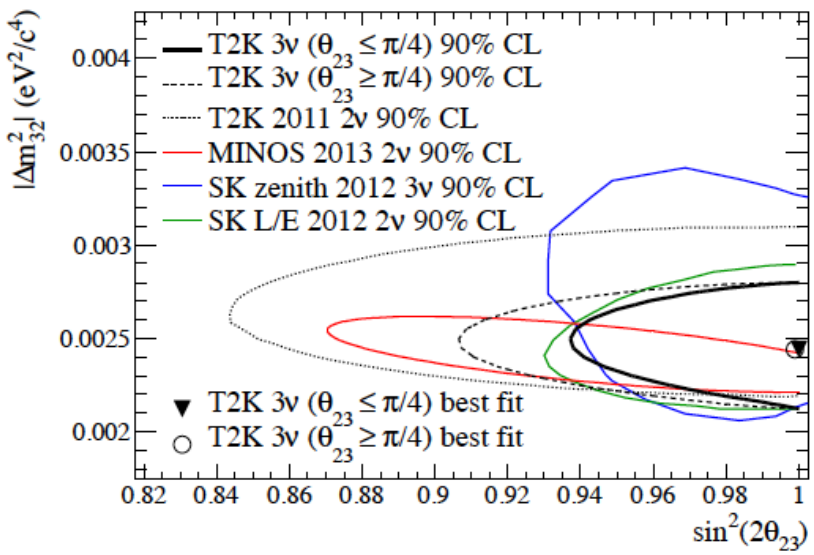
$\nu_\alpha = U_{\alpha i}\, \nu_i$

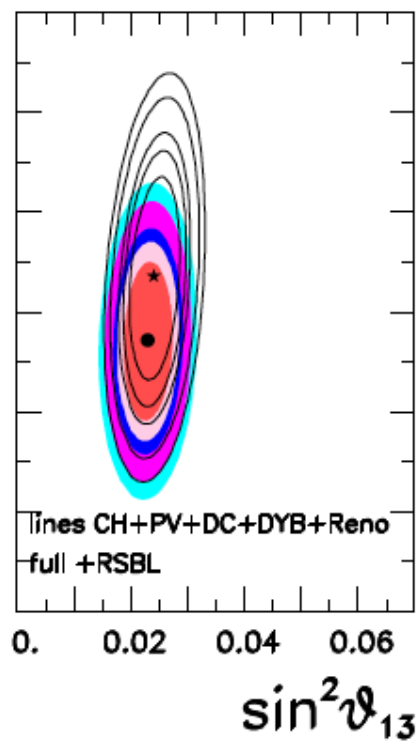
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

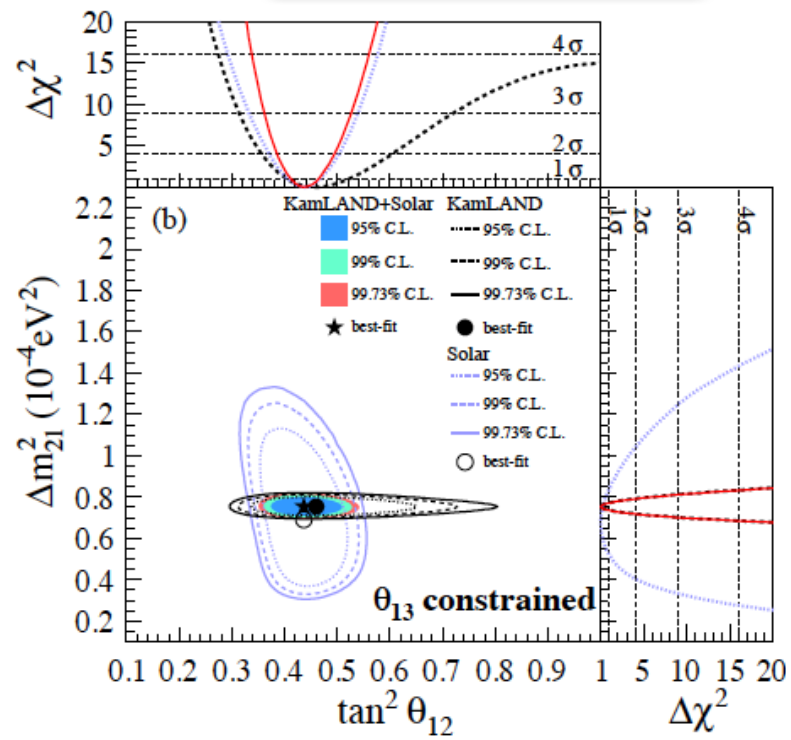
SK-atm+MINOS+T2K

T2K-MINOS-DC-DB-RENO

solar+KamLAND

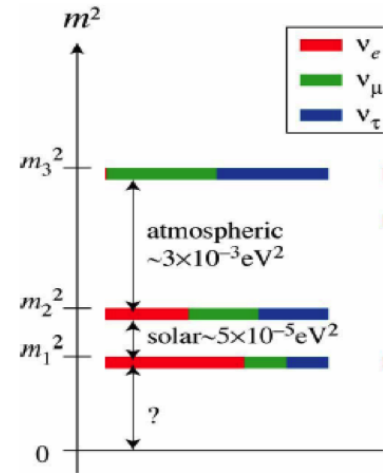






One can measure θ_{12} and θ_{13} by reactor neutrino oscillation

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



ν_e–bar survival probability

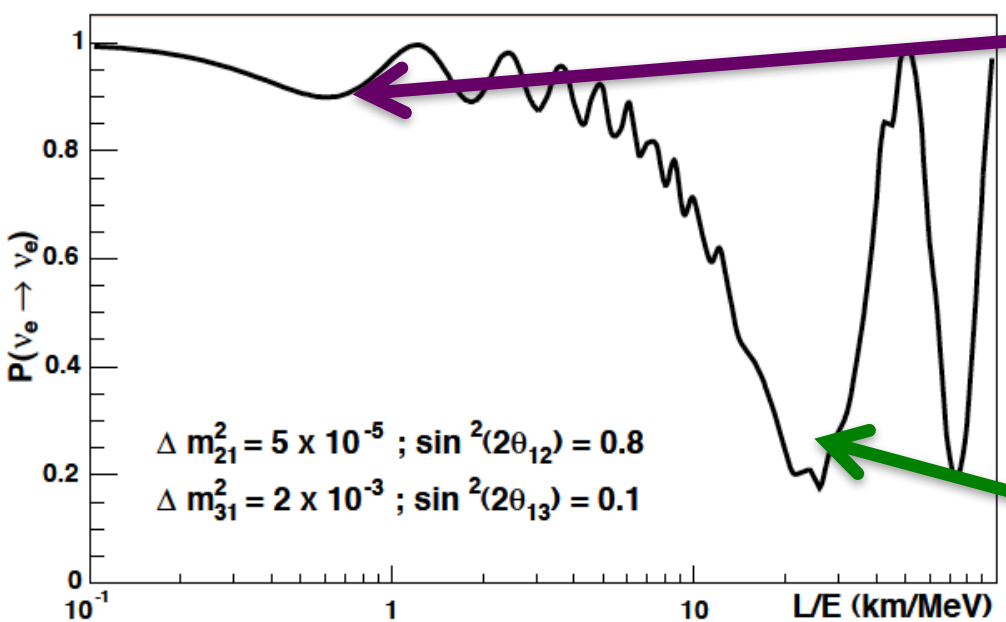


Figure 3: Probability of ν_e disappearance versus L/E for θ_{13} at its current upper limit

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(\epsilon s^2_{13}) + O(\epsilon^2)$$

$$\epsilon \equiv \Delta m^2_{21}/\Delta m^2_{31} \simeq 0.03$$

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

θ_{23} atmospheric oscillation decoupled from θ_{12} and θ_{13} oscillation

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

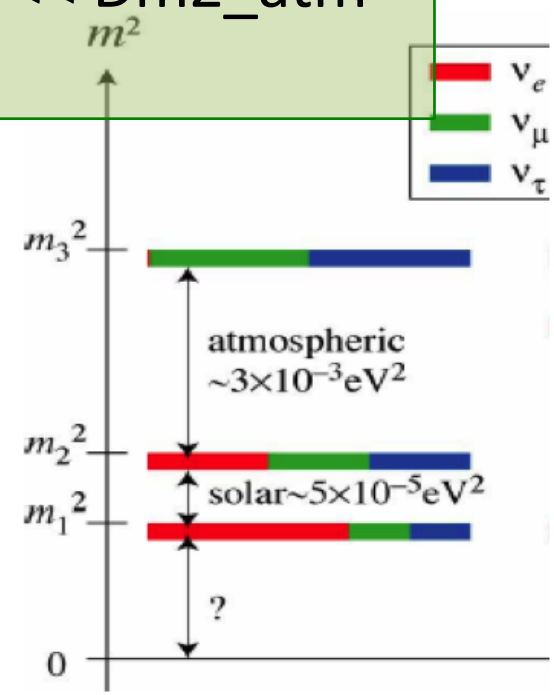
Solar oscillation ~ decoupled because Dm2_solar << Dm2_atm and θ_{13} small

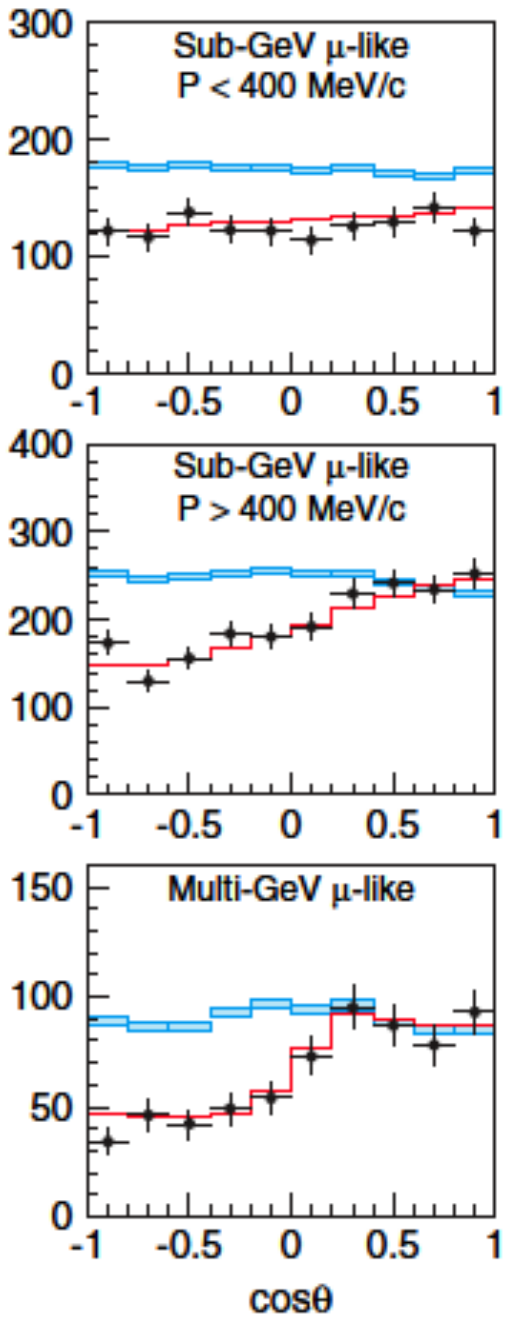
ν_μ survival probability

$$P_{\mu\mu} = 1 - 4s_{23}^2 c_{13}^2 \left(c_{23}^2 + s_{23}^2 s_{13}^2\right) \sin^2 \Delta_{31}$$

+ order ε

$$\Delta_{ji} \equiv \frac{\Delta m_{ji}^2 L}{4E},$$





Atmospheric neutrinos: Focus in on μ-like events

- High-energy sample shows an interesting feature:
- => no deficit in down-going μ-like events, whereas large deficit in up-going events
- => neutrino oscillation with characteristic length of ~1000 km

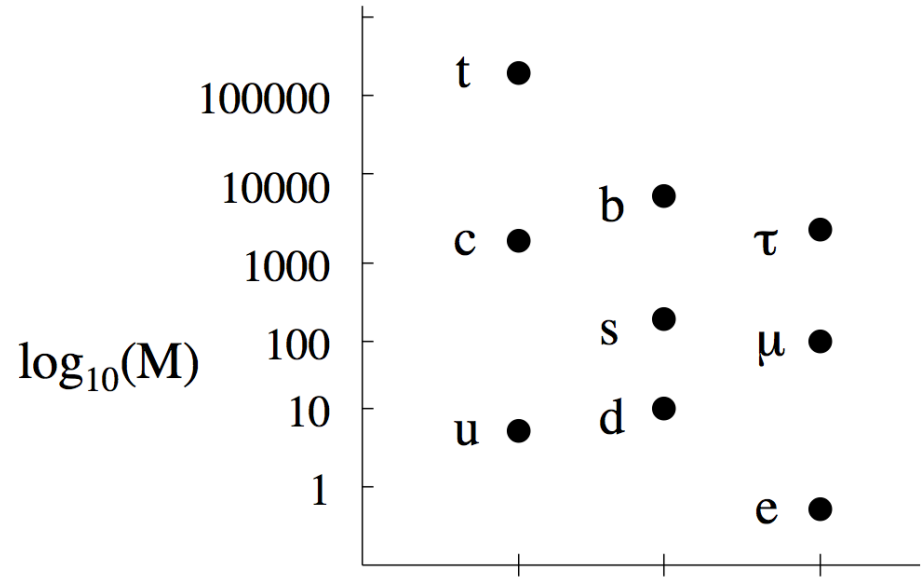
Diamond in a garbage can !!

All three angles are measured: Random angles?

- θ_{23} ~ 45 degree
- θ_{12} ~ 33 degree
- θ_{13} ~ 8 degree
- What do they mean?

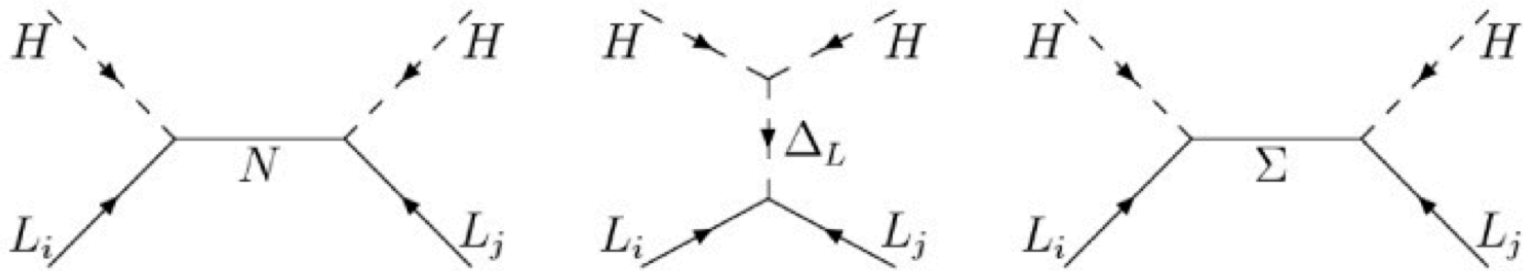
Quark mixing:
angles are tiny except for $\theta_{Cabibbo}$ = 13 deg.

Small ν masses



Pedro described seesaw models

Seesaw scenarios

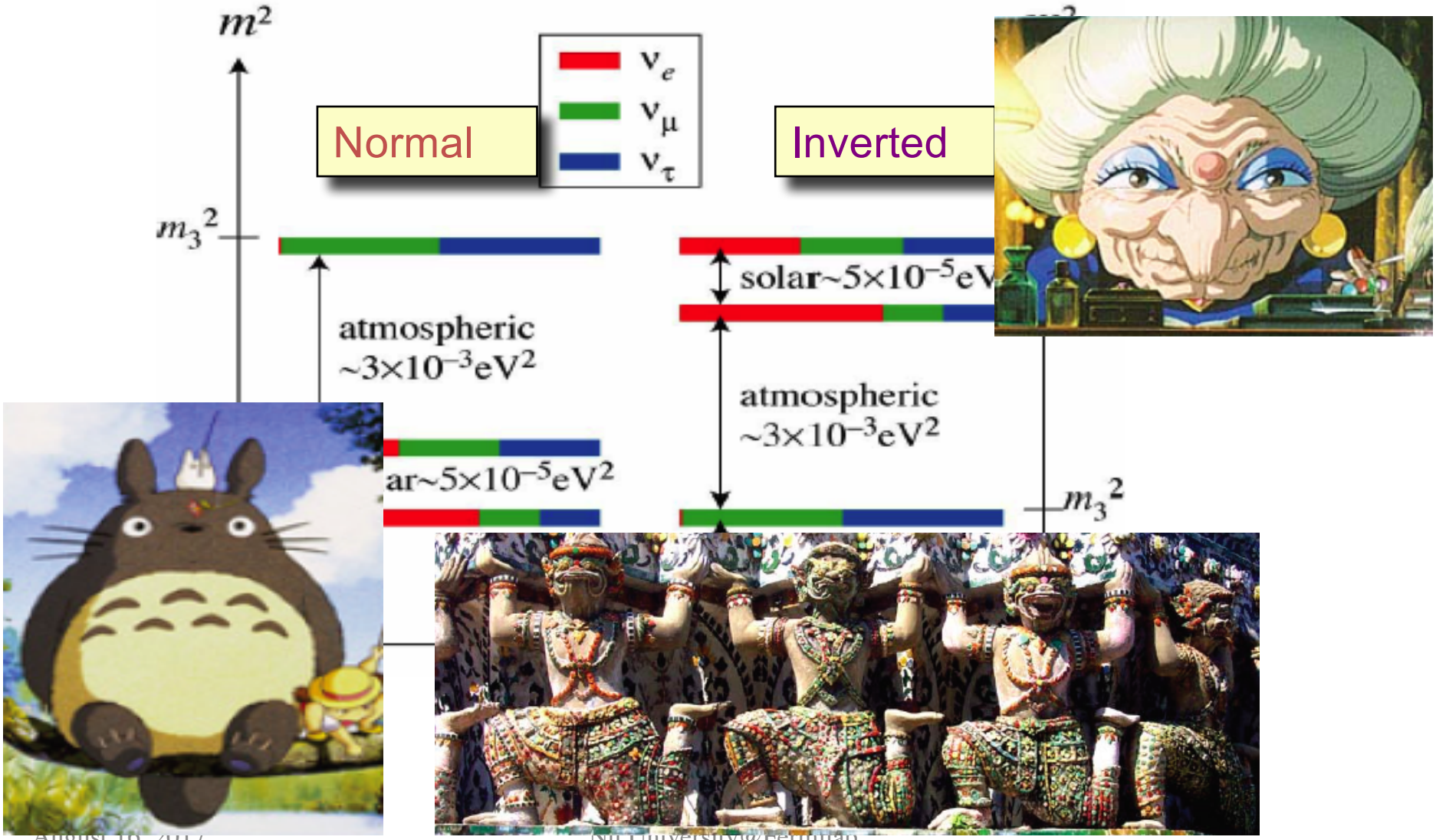


- More generically, one can write down the higher dimensional operator $(1/M_{NP})\ \phi\phi\nu\nu$
- Large mass scale M_{NP} involved → ν mass is telling us about world with huge energy scale ~10^{15} GeV

We don't know ν mass pattern & absolute mass scale

← Cosmology would help → Planck 2015

$$\sum m_\nu < 0.23\,\mathrm{eV}.$$



CP violation?(new data from T2K)

T2K (Tokai-to-Kamioka)

30 GeV proton beam

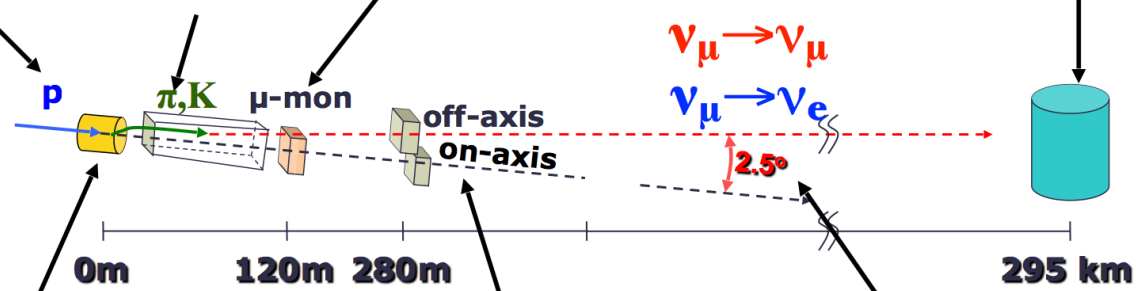
Decay volume:

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

MUMON measures muons from pion decay

Off-axis **far detector** at 295 km: SK Cherenkov detector measures event rates after oscillations



Off-axis = narrow band beam

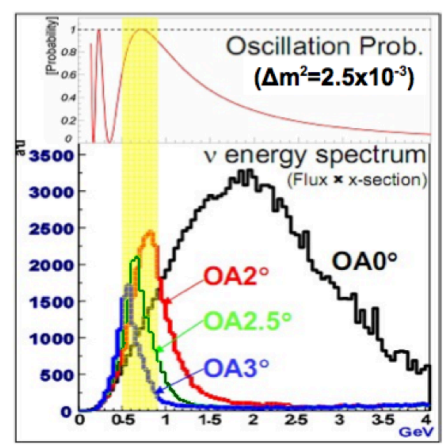
Beam on graphite target

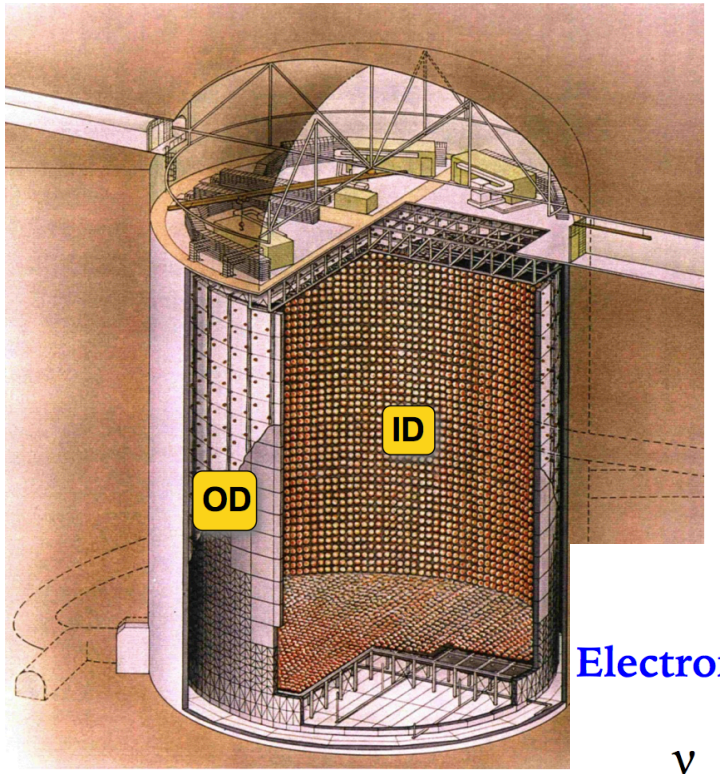
3 magnetic horns focus:
π^+ for neutrino mode

π^- for antineutrino mode

Off-axis **near detector**: ND280 detector measures spectra interactions

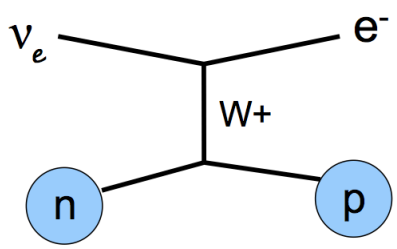
INGRID on-axis detector monitors beam direction and neutrino rate



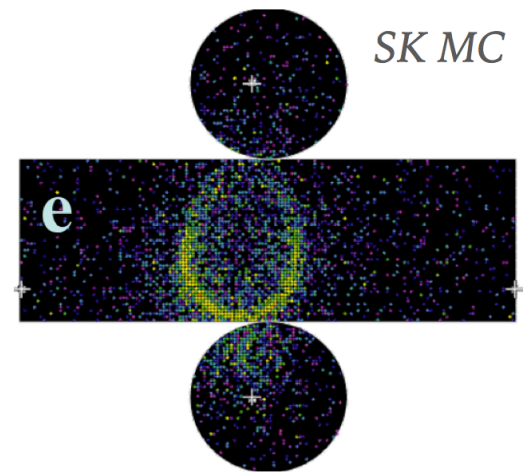


Super-K as far detector

Electron neutrino appearance signal:

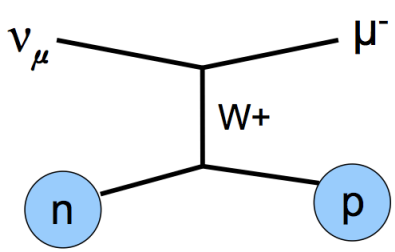


Detected electron produces a shower: "fuzzy" ring

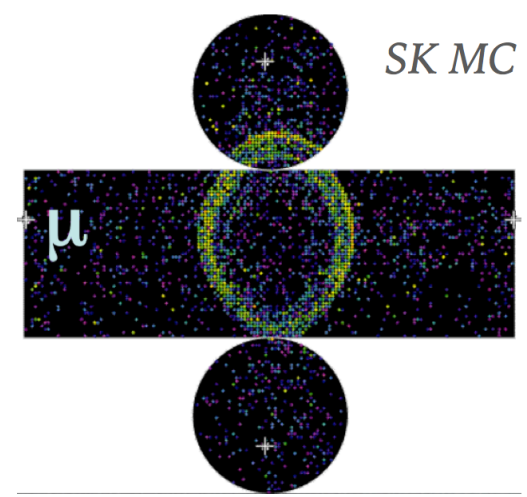


Target nucleon is bound in nucleus (more later)

Muon neutrino survival signal:



Detected muon produces a sharp ring



PREDICTED AND OBSERVED EVENT RATES

Mark Hartz, KEK Colloquium: August 4, 2017

Sample	Predicted Rates				Observed Rates
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

nu

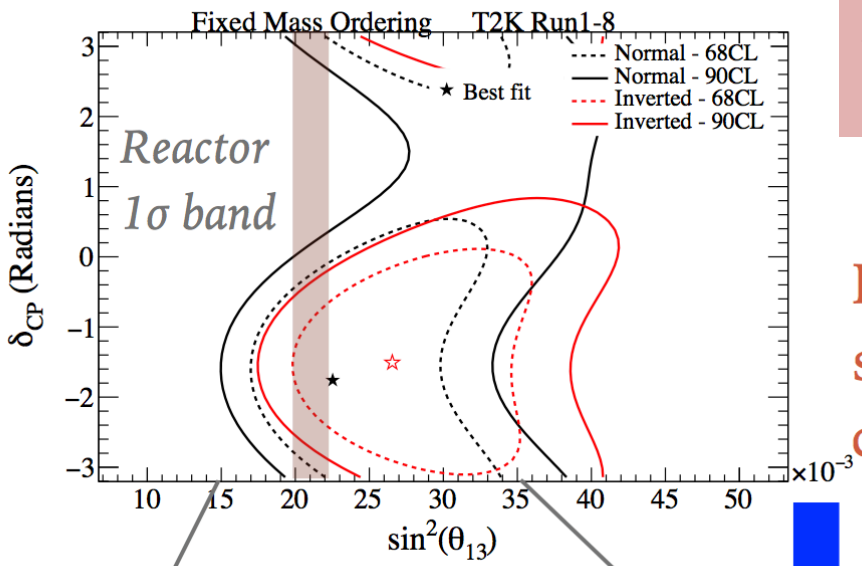
anti-nu

- The number of observed events are largely in line with the predictions after oscillations
  - The e-like samples have rates most consistent with the $\delta_{cp}=-\pi/2$ hypothesis
- The observed μ-like rate in neutrino mode is lower than prediction
  - Consistent within statistical and systematic errors

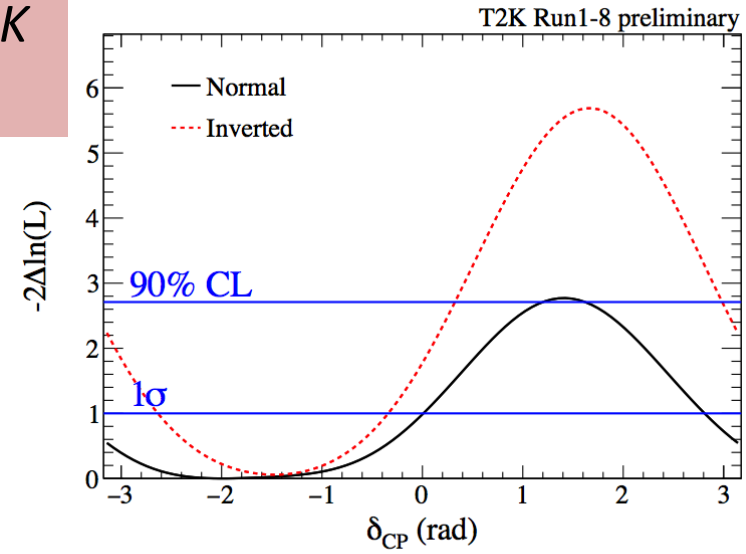
OSCILLATION PARAMETER SENSITIVITIES (2017)

Without the reactor experiment constraint on $\sin^2 2\theta_{13}$

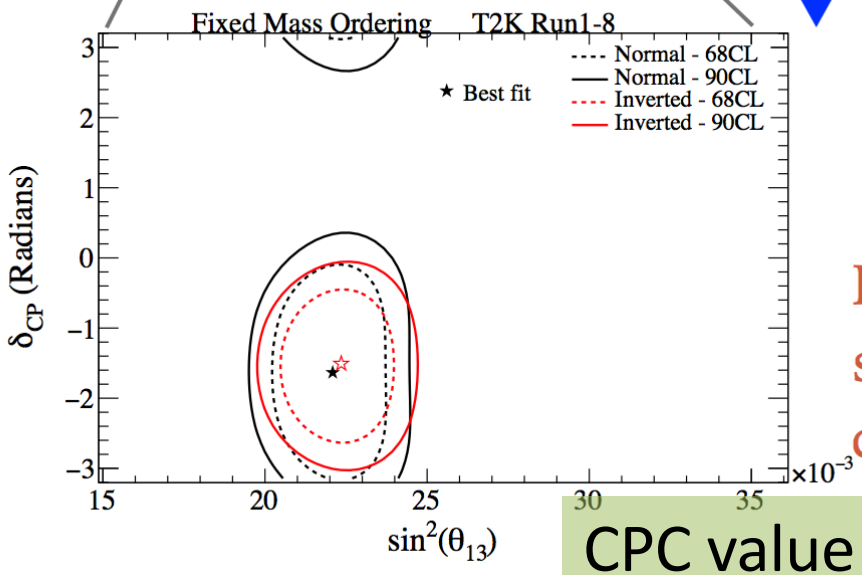
Mark Hartz, KEK Colloquium



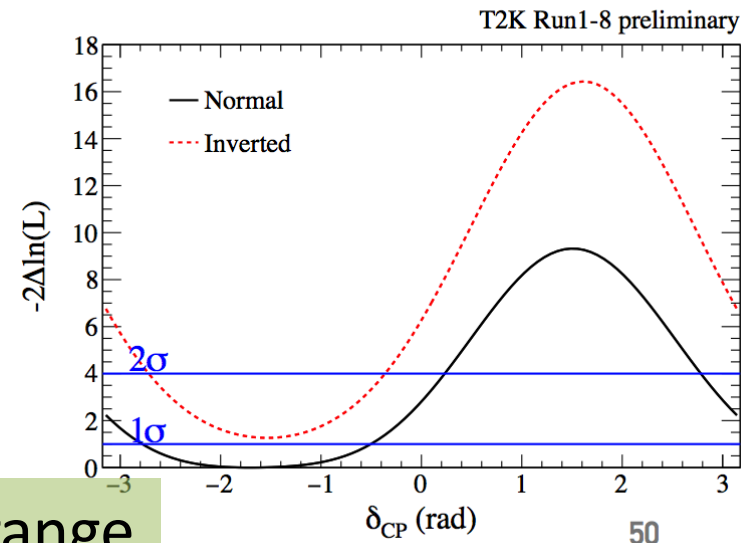
Integrate out $\sin^2\theta_{13}$ dependence



Reactor constraint on $\sin^2(2\theta)_{13}$ (PDG2016)



Integrate out $\sin^2\theta_{13}$ dependence

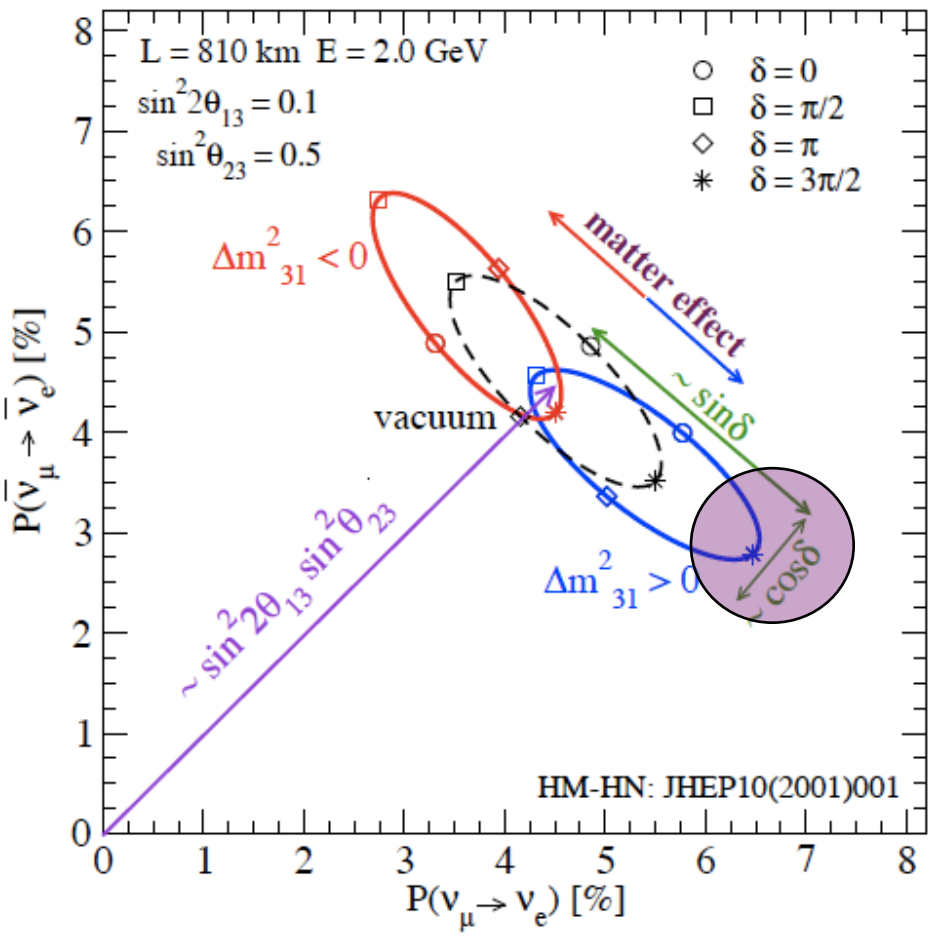


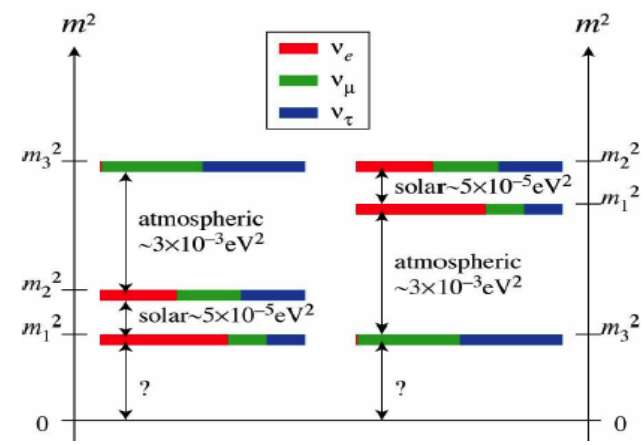
CPC value outside 2σ range

If so it's a great news for NOvA!

$\delta=3\pi/2$ (or $-\pi/2$) implies that we are at the tip of the ellipse → the best case for NOvA

P-\bar{P} bi-probability diagram, proposed by HM-H.Nunokawa, JHEP 2001





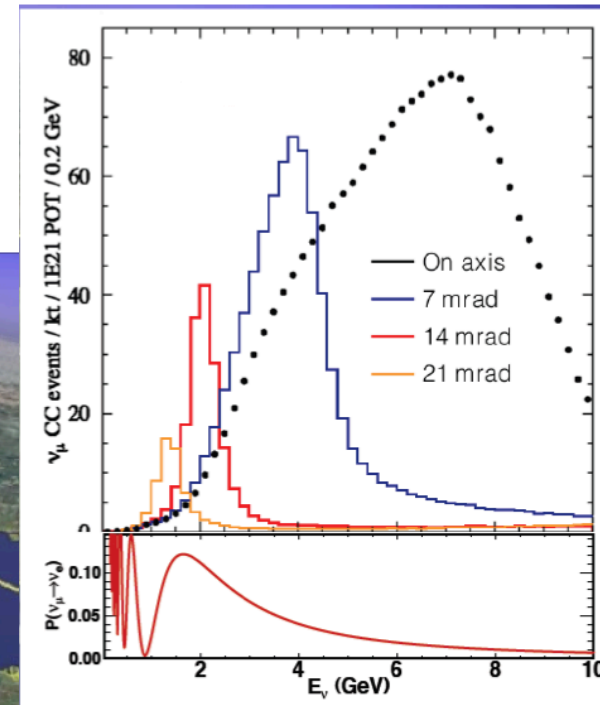
Sign of Δm_{13} distinguishes normal vs inverted mass ordering

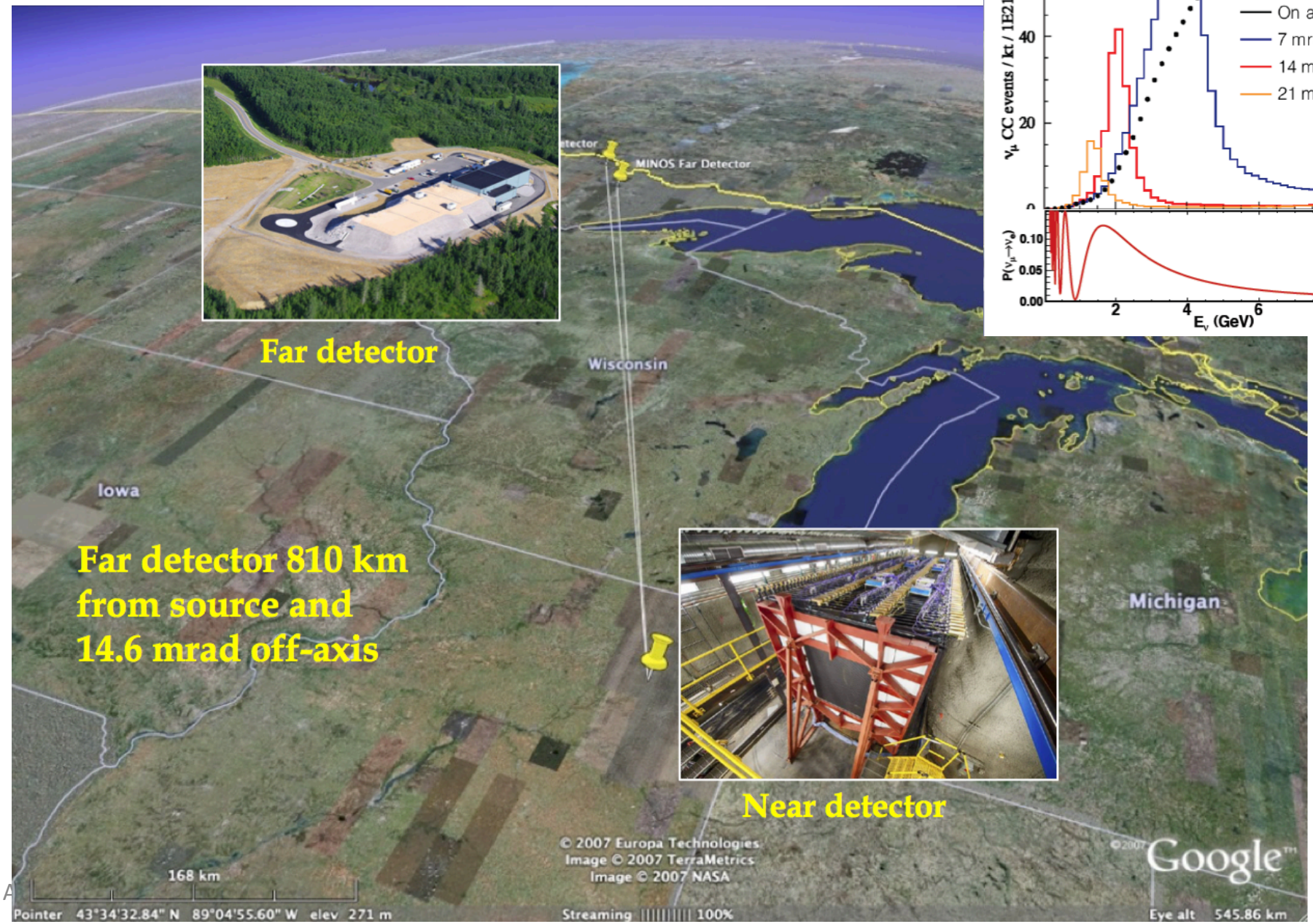
δ and sign of Δm_{13} couple because ($\Delta m_{13} \to \Delta m_{13}$, $\delta \to \pi-\delta$) symmetry in vacuum

@Fermilab

θ_{23}: Maximal or not ? (NOvA vs. T2K)

NOvA: Fermilab → Ash River

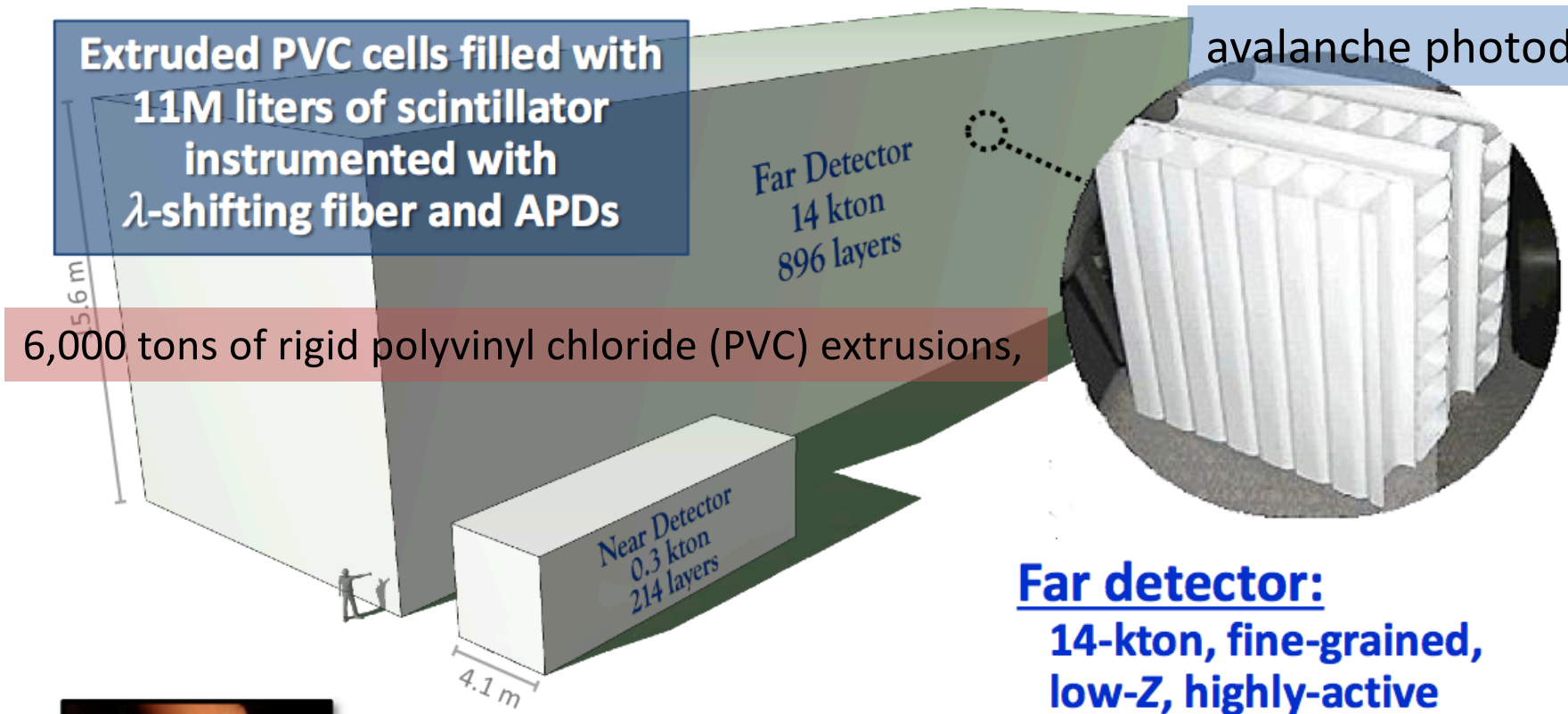




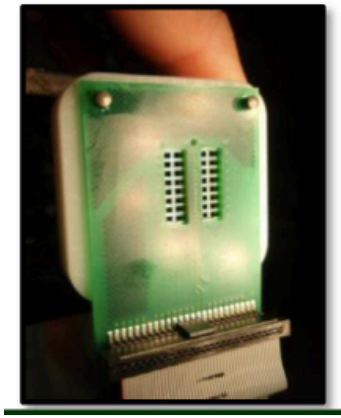
NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs

6,000 tons of rigid polyvinyl chloride (PVC) extrusions,

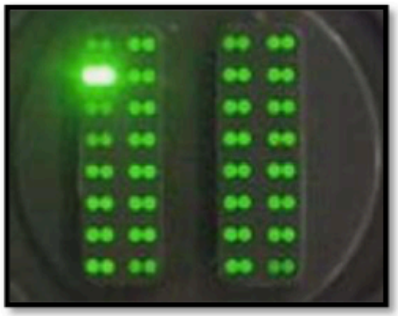


A NOνA cell



32-pixel APD ←

Fiber pairs from 32 cells →



Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter

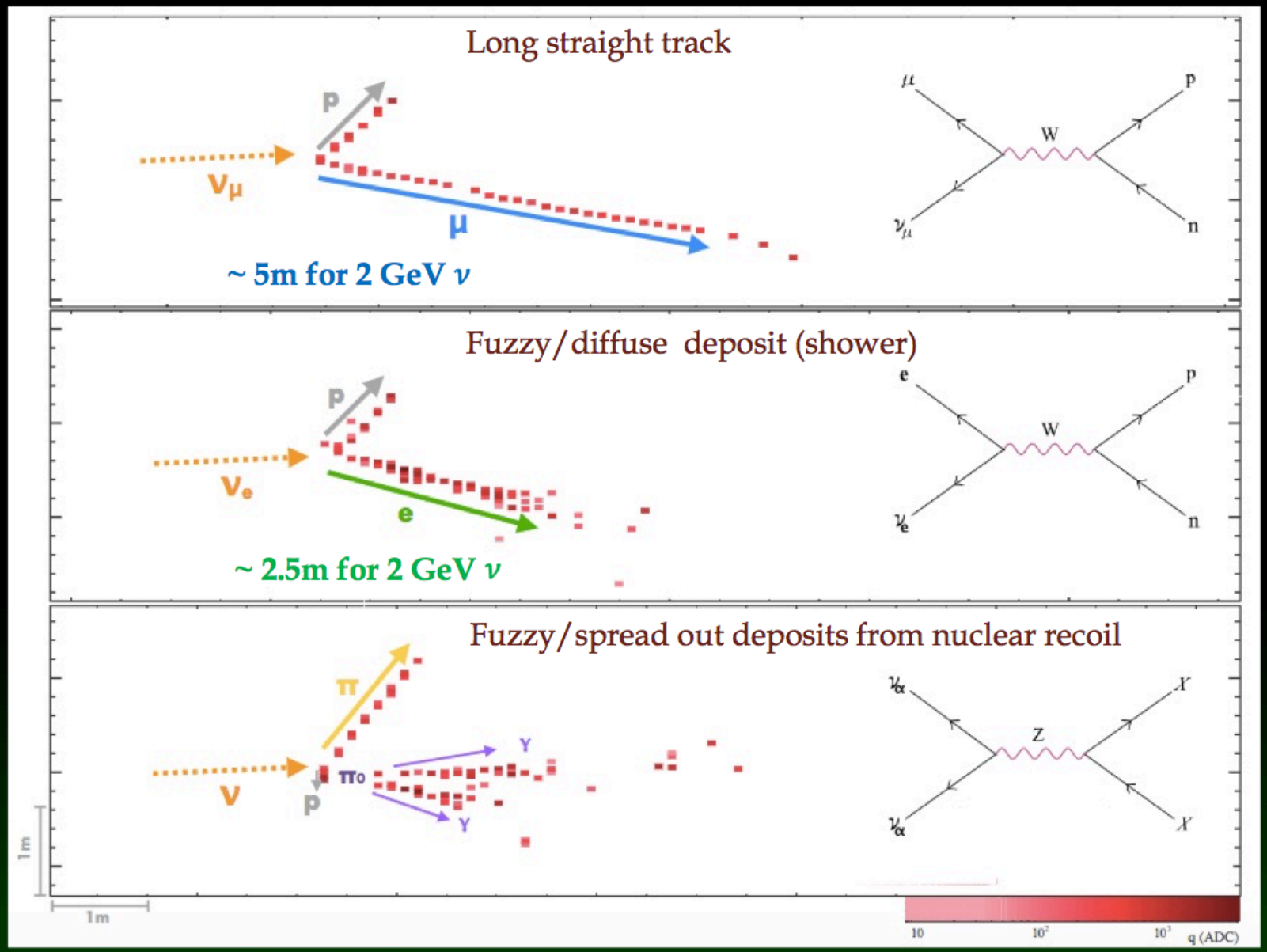
→ 344,000 channels

Near detector:

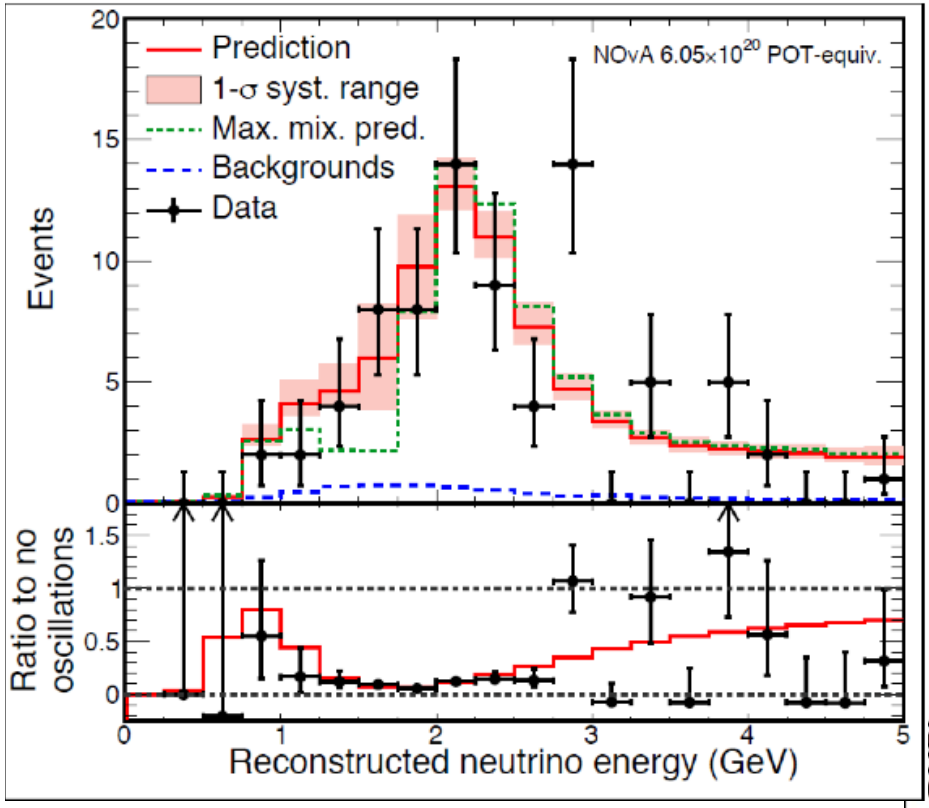
0.3-kton version of the same

→ 20,000 channels

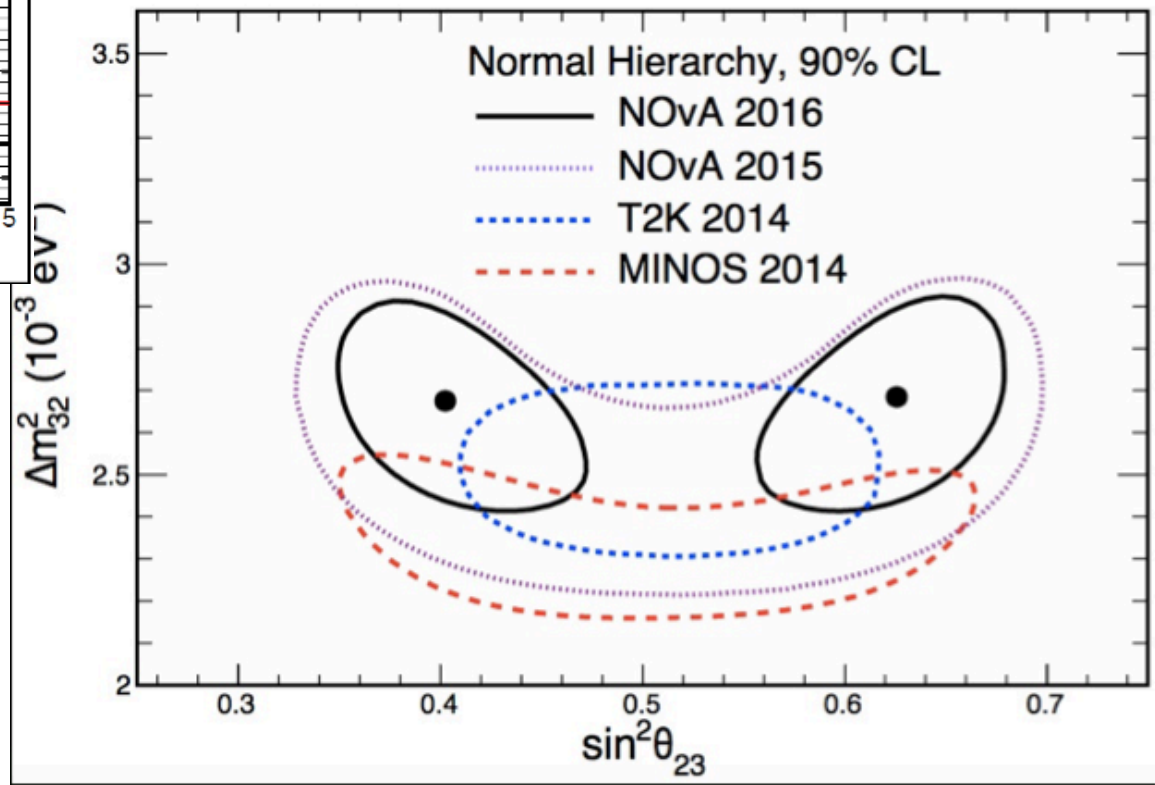
NOvA Event Topologies



Maximal mixing excluded at 2.6 σ



Nuclear effects discussed also in the context of Minerva results

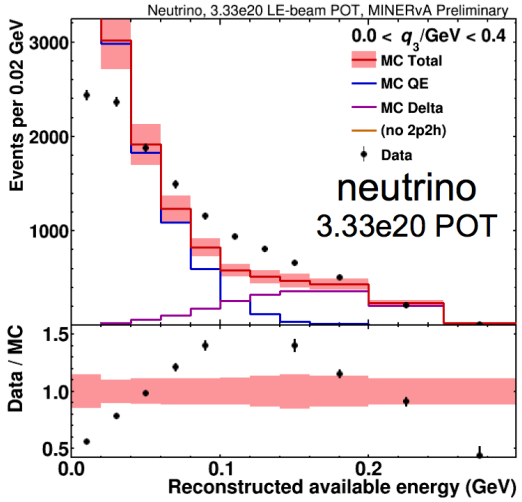


Phys. Rev. Lett. 118,151802

Minerva: RPA & 2p2h improves fit

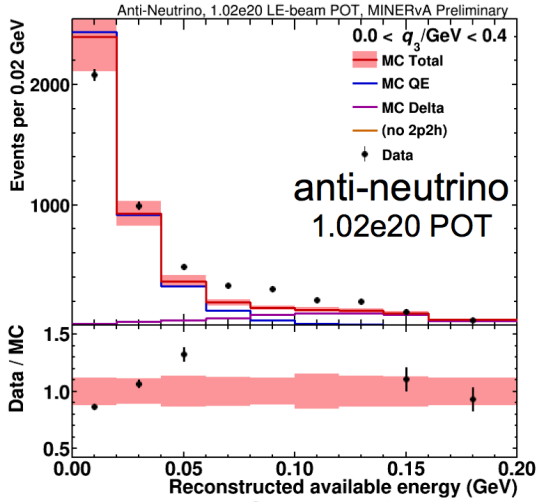
GENIE, pion base, no RPA, no 2p2h, zoom Y axis

X2 = 407 for 21 bins



Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

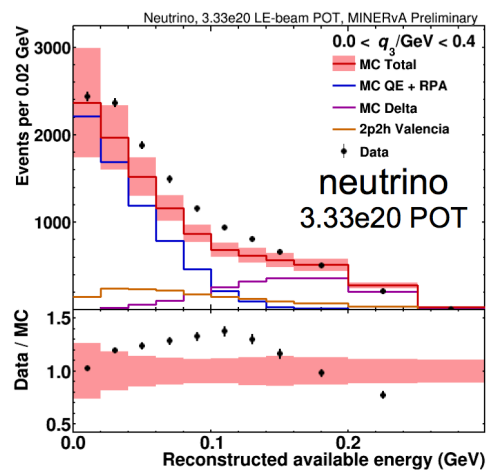
X2 = 245 for 19 bins



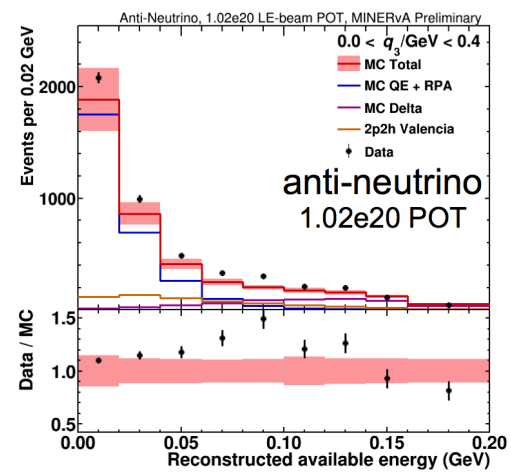
new for NuInt17
equivalent anti-neutrino distribution

GENIE, Pion base, RPA, Valencia 2p2h

X2 = 138 for 21 bins

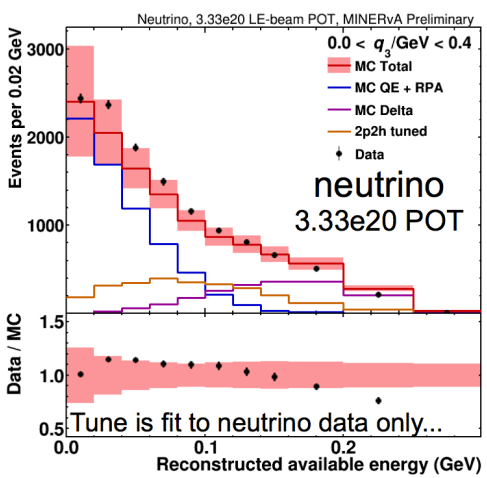


X2 = 84 for 19 bins



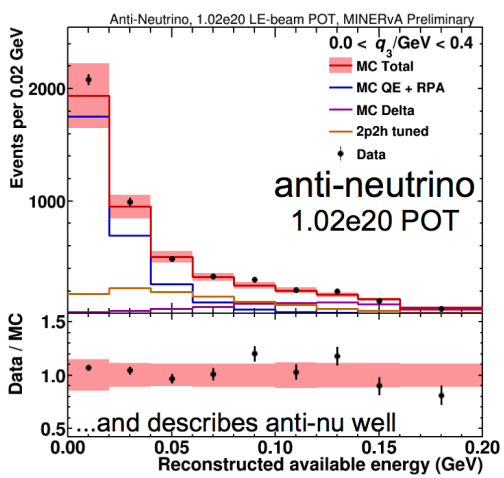
GENIE, Pion base, RPA, 2017 Tuned 2p2h

X2 = 76 for 21 bins



Tune is fit to neutrino data only...

X2 = 50 for 19 bins



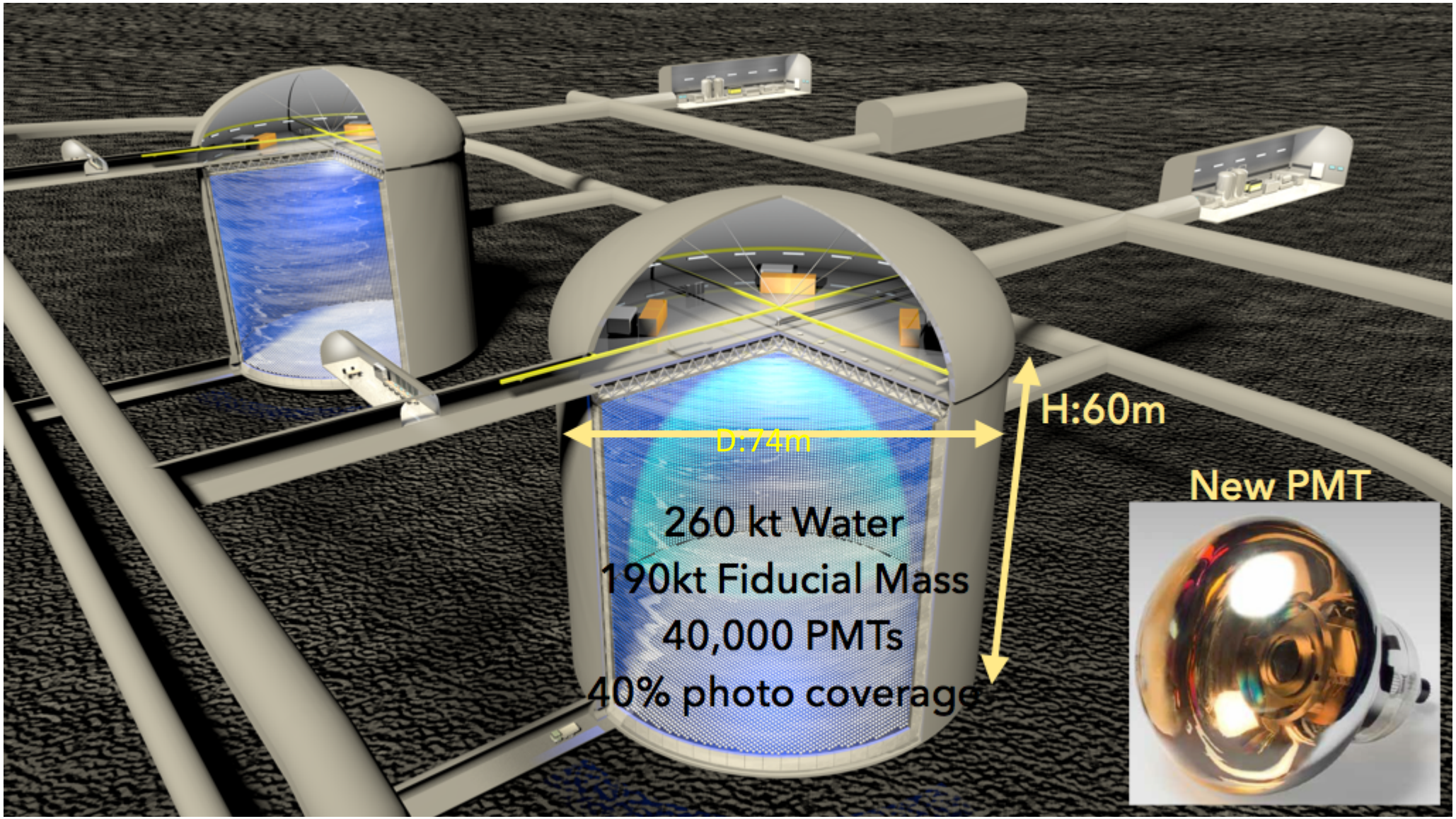
...and describes anti-nu well

Rik Gran @ Nuint 2017

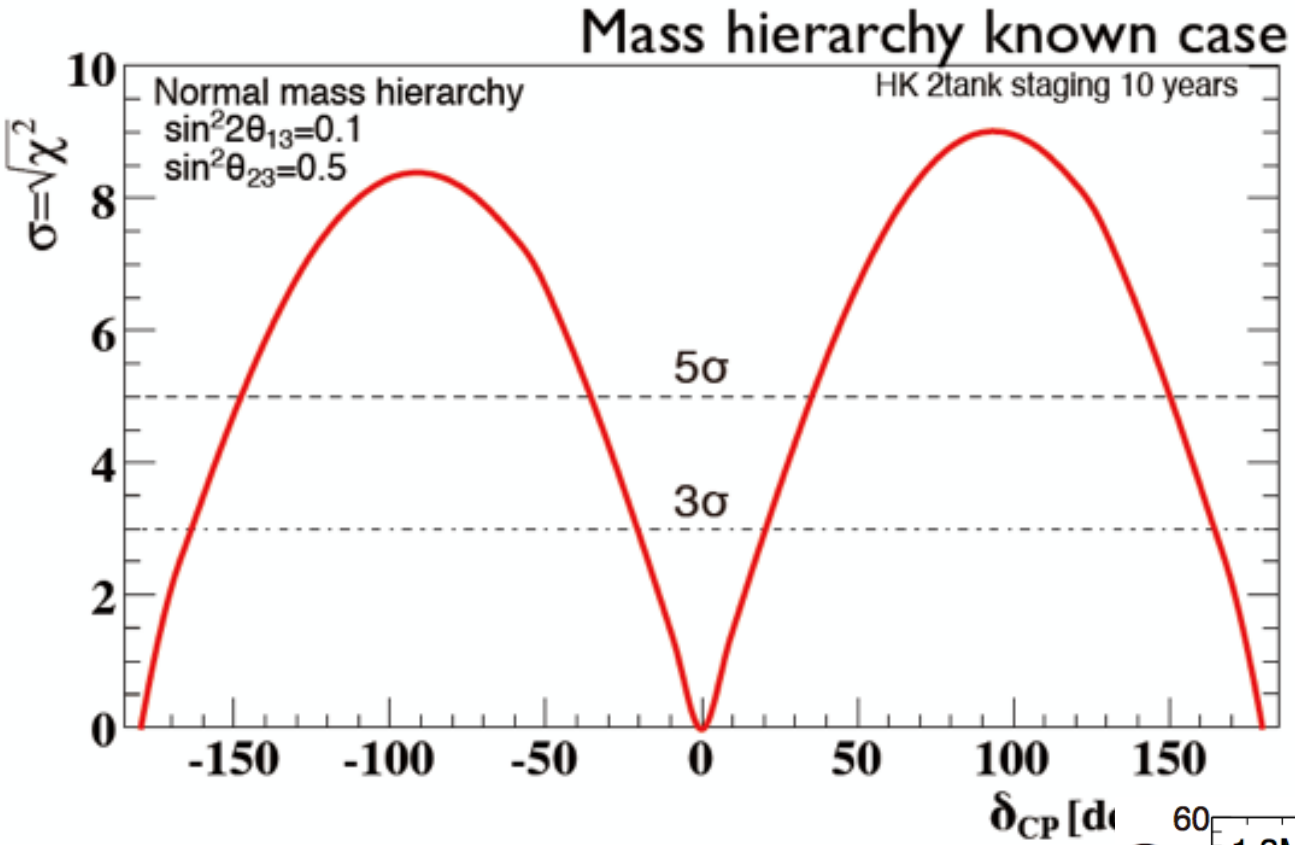
Next generation experiments

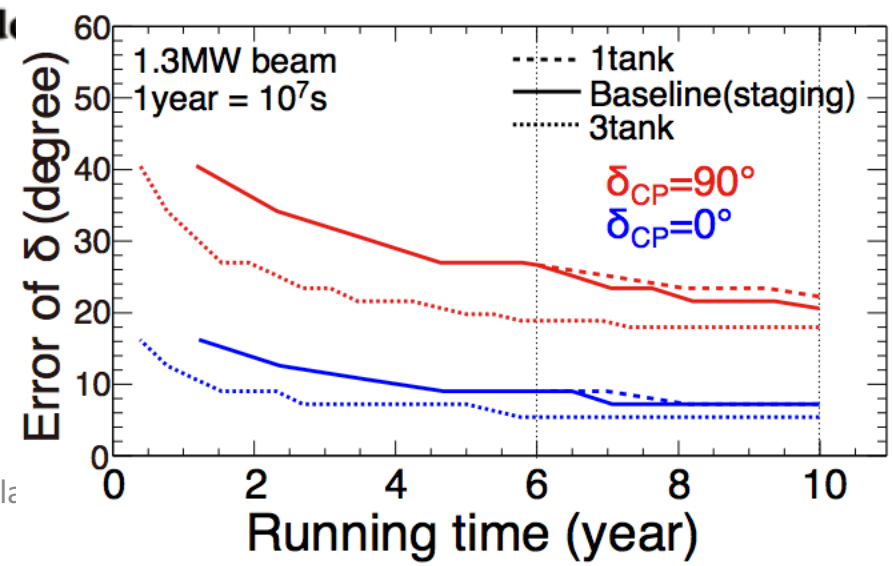
Hyper-Kamiokande

HK included in the MEXT Roadmap !!



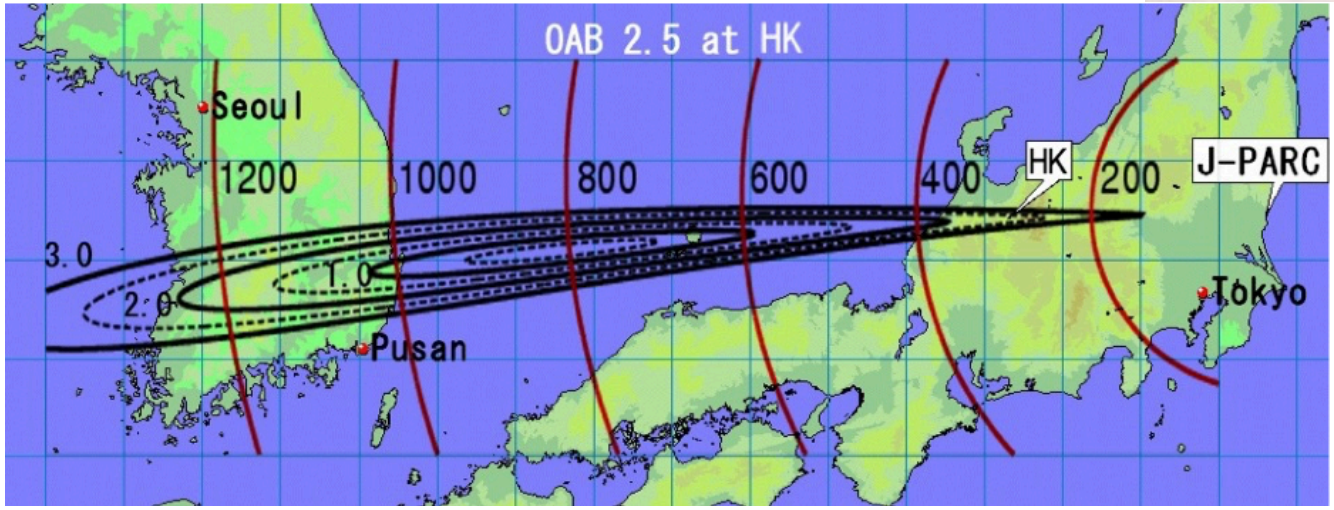
Sensitivity to CP phase





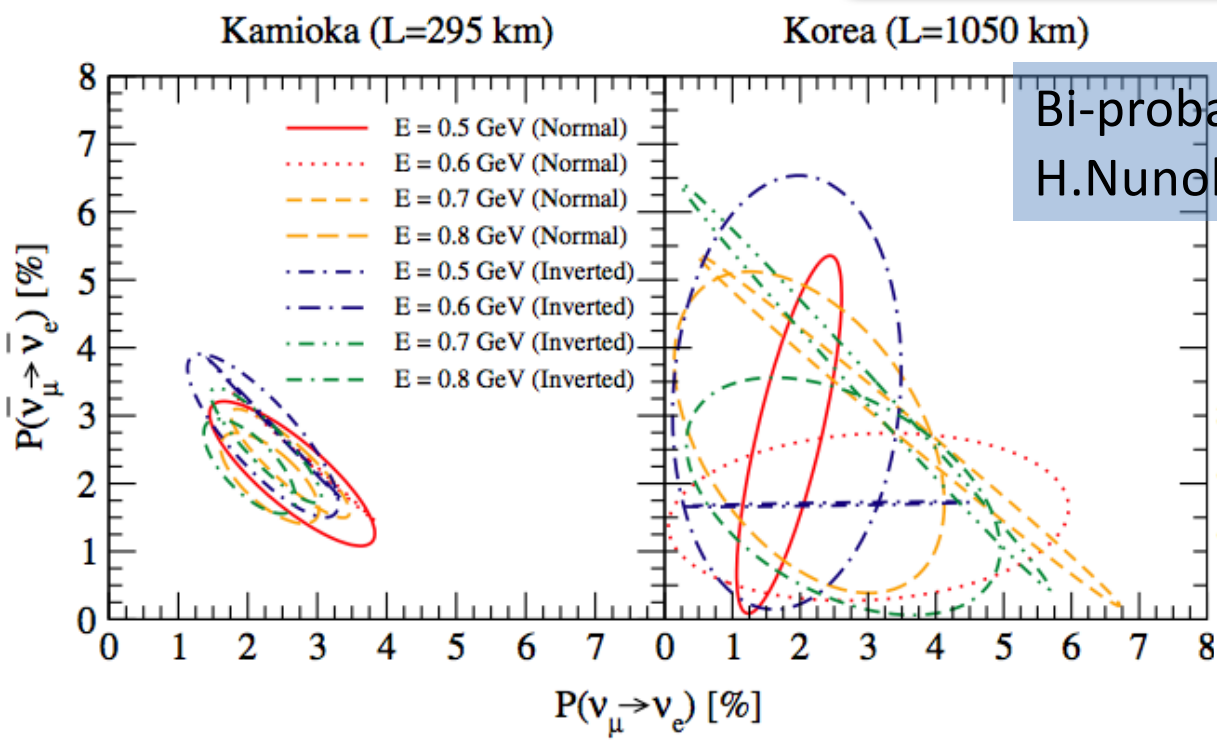
If CP is known to 3 σ, HK (or next generation machines) may have to have capability to measure something else

Tokai-to-Kamioka-Korea (T2KK), or T2HKK

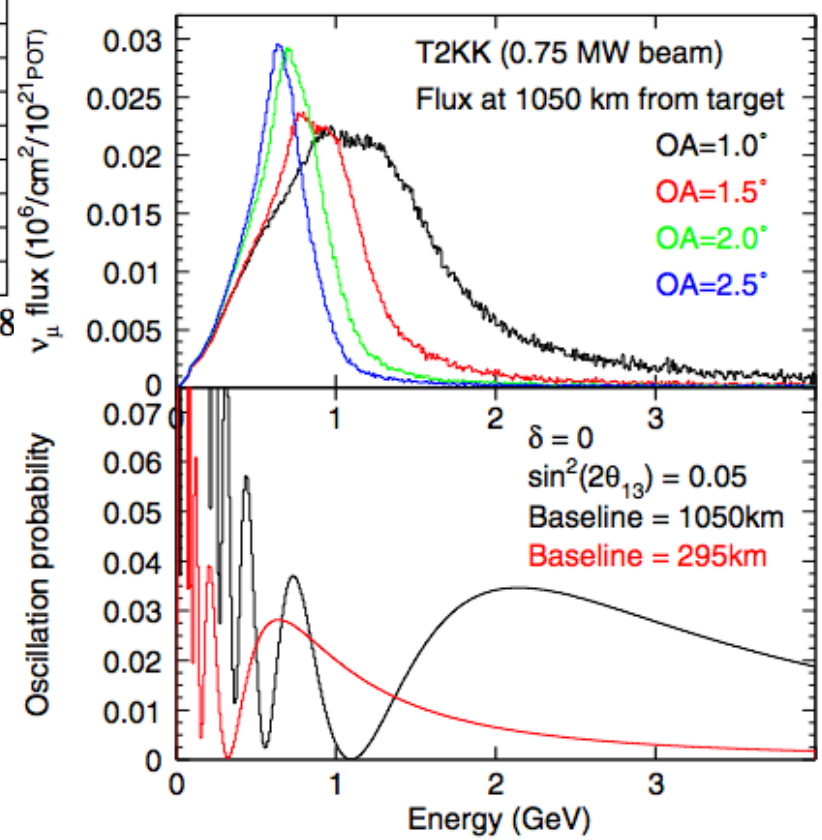


T2KK (or T2HKK)

Ishitsuka-Kajita-HM-Nunokawa, PRD 2005

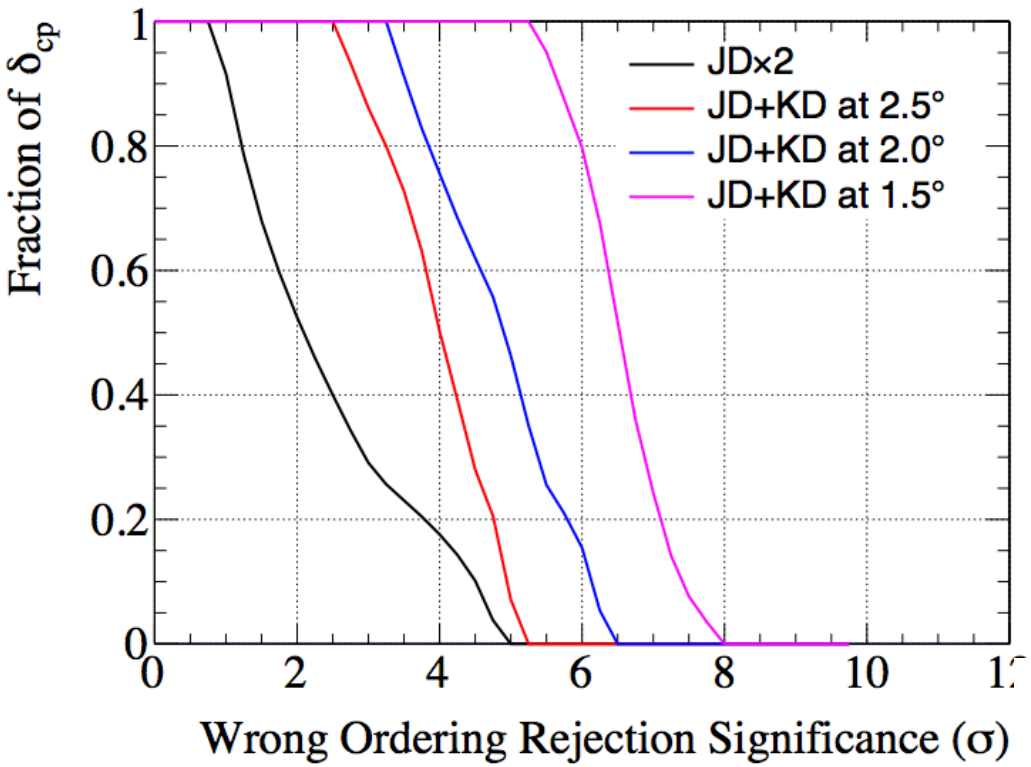


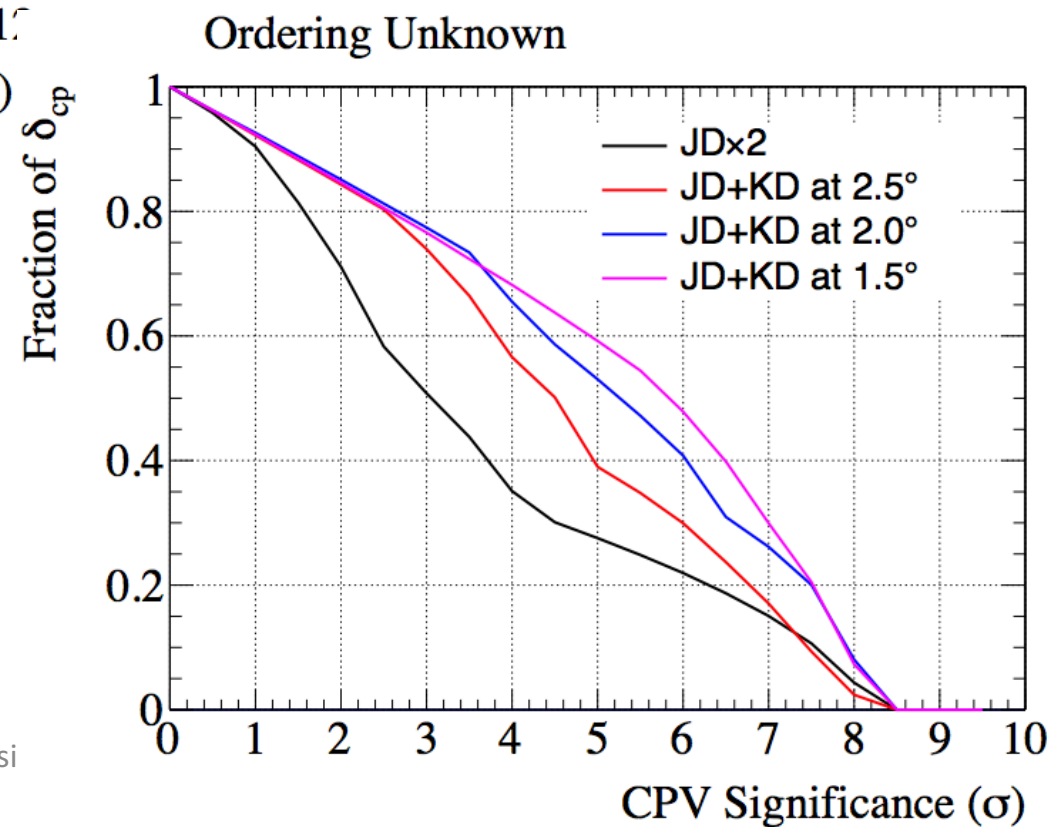
Bi-probability plot: HM-H.Nunokawa, JHEP 2001



E dependence far more dynamic at 2nd oscillation maximum

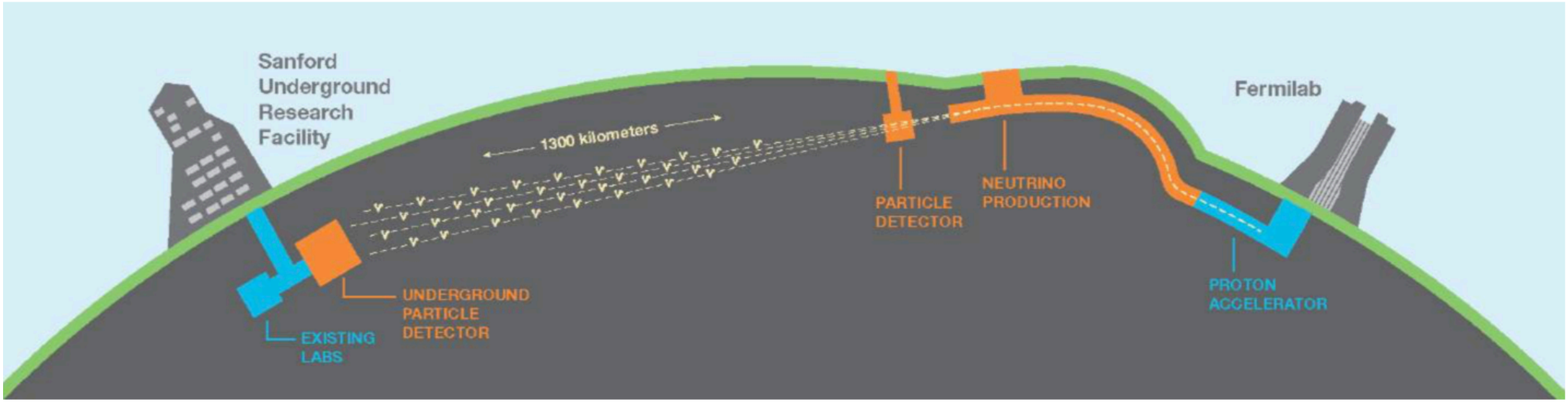
T2HKK: Mass ordering and CP sensitivities





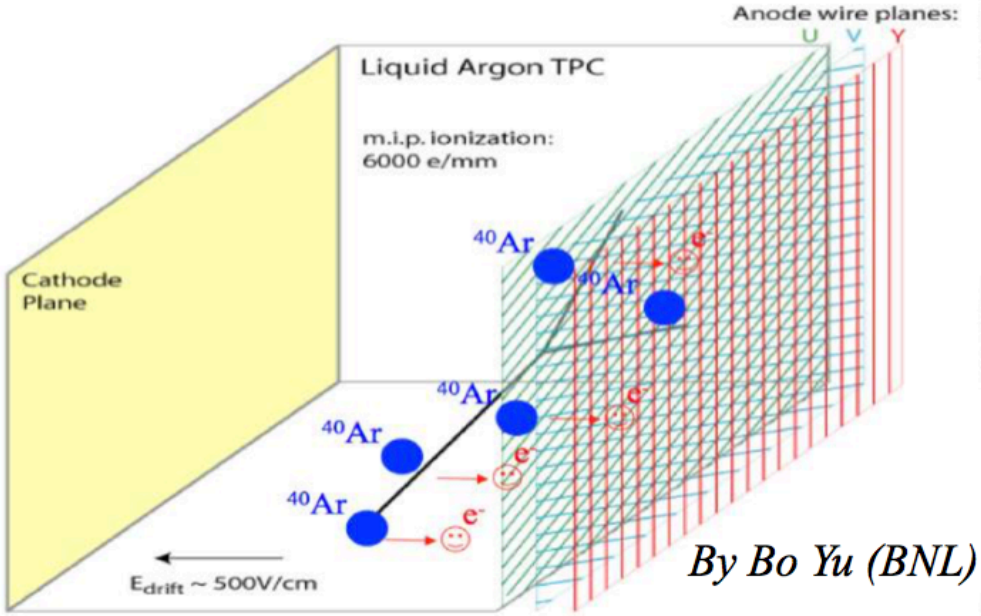
T2HKK White paper
arXiv 1611.06118

DEEP UNDERGROUND NEUTRINO EXPERIMENT

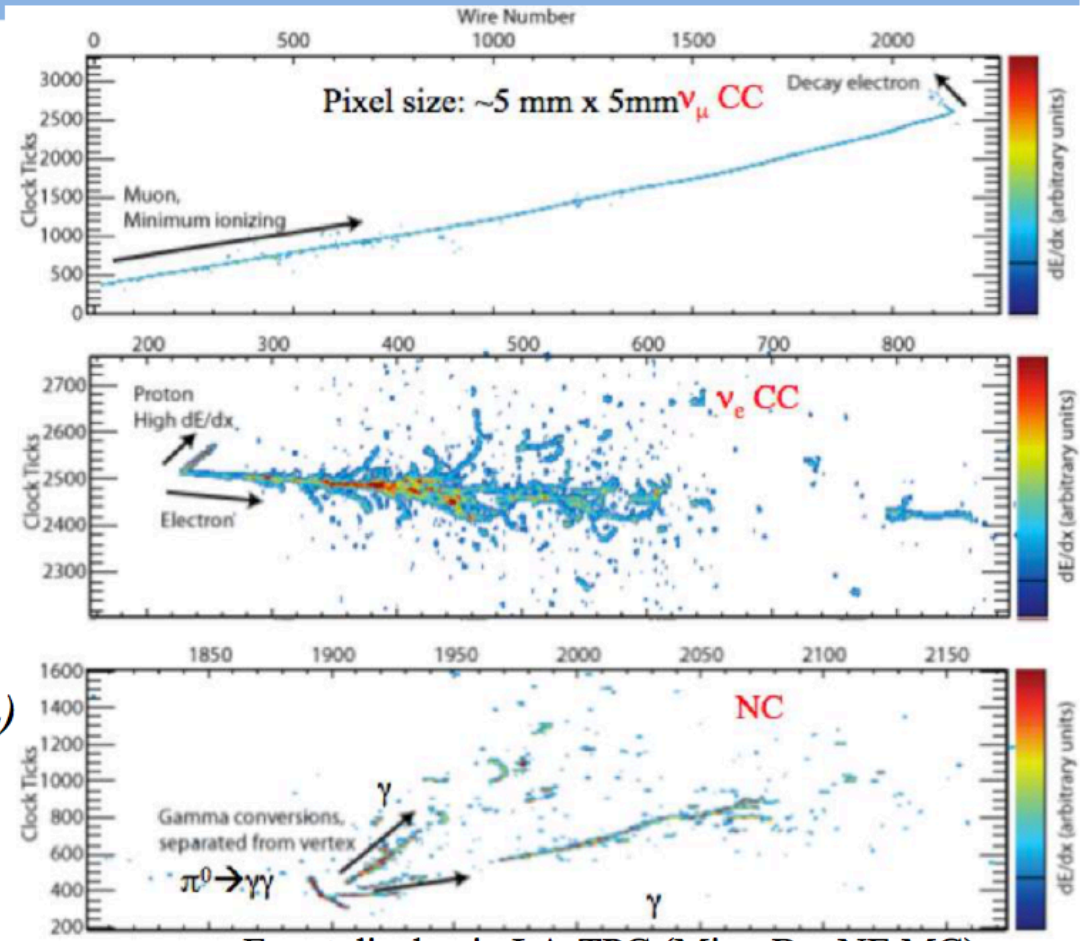


- New beam at Fermilab (1.2 MW@120 GeV protons, upgradeable to 2.4 MW), 1300 km baseline
- On-Axis 40 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Highly-capable near detector at Fermilab
- ν_e appearance and ν_μ disappearance → Measure MH, CPV and mixing angles
- Large detector, deep underground → Nucleon decay, supernova burst neutrinos, atmospheric neutrinos, etc (Juergen Reichenbacher (SDSMT)'s talk, Wed.)

Far Detectors: Liquid Argon Time Projection Chamber (LArTPC)



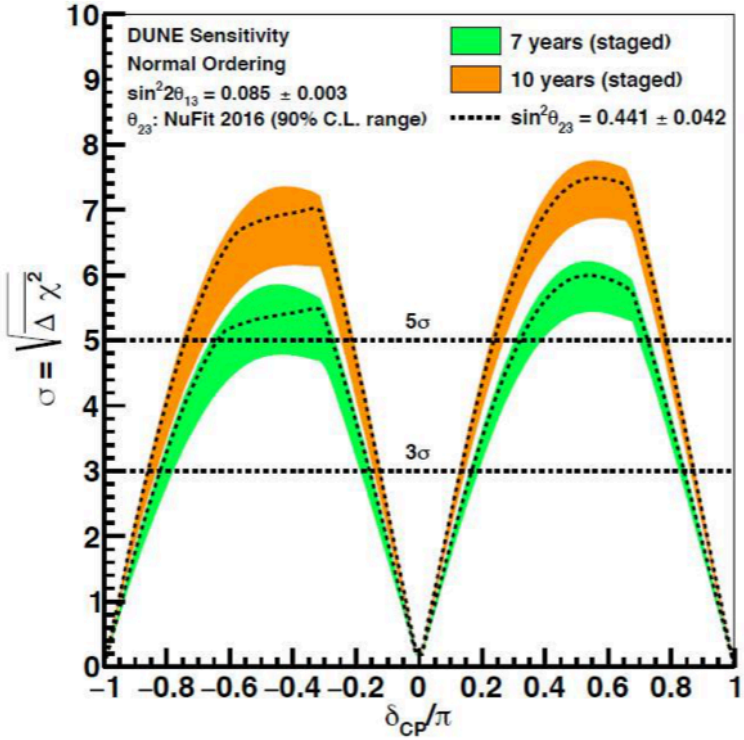
By Bo Yu (BNL)



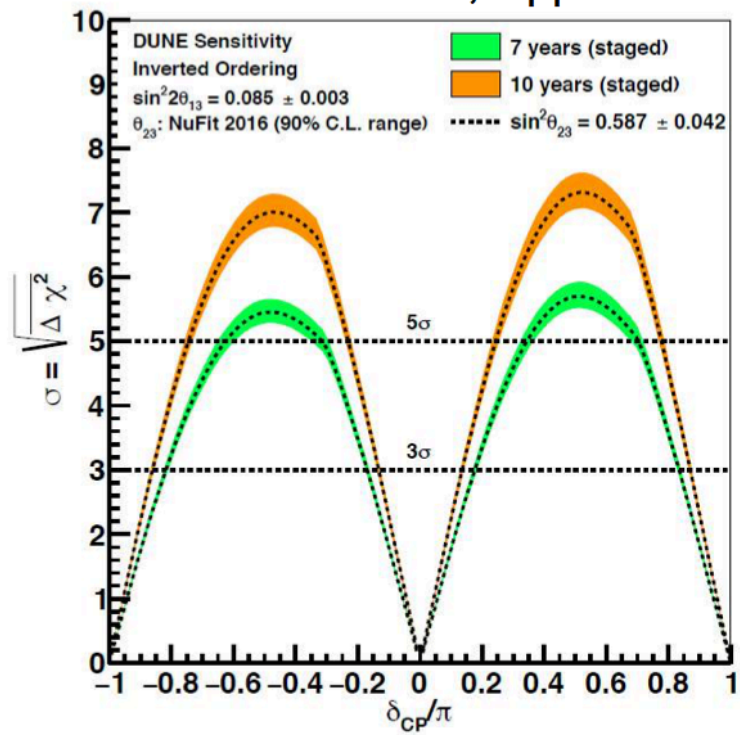
Event display in LArTPC (MicroBooNE MC)

- High resolution 3D track reconstruction
  - Charged particle tracks ionize argon atoms
  - Ionized electrons drift to anode wires (~ms) for XY-coordinate
  - Electron drift time projected for Z-coordinate
- Argon scintillation light (~ns) detected by photon detectors, providing t_0

Normal Hierarchy, Lower octant

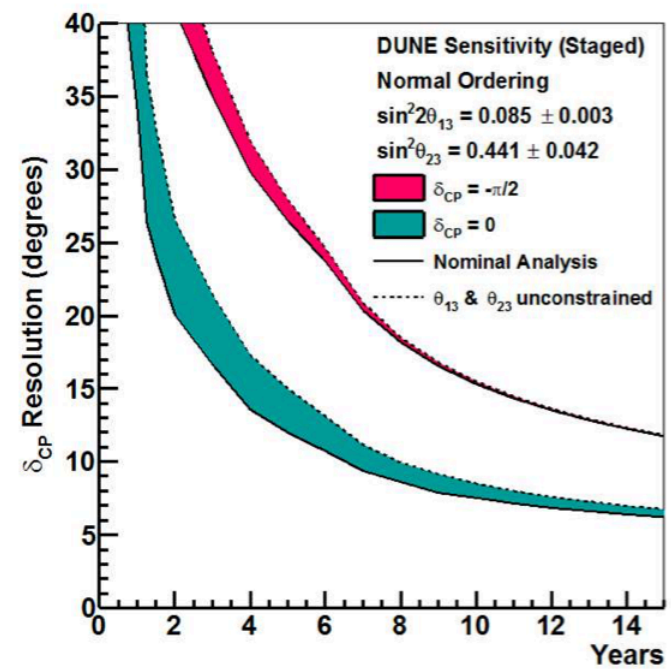


Inverted Hierarch, Upper Octant



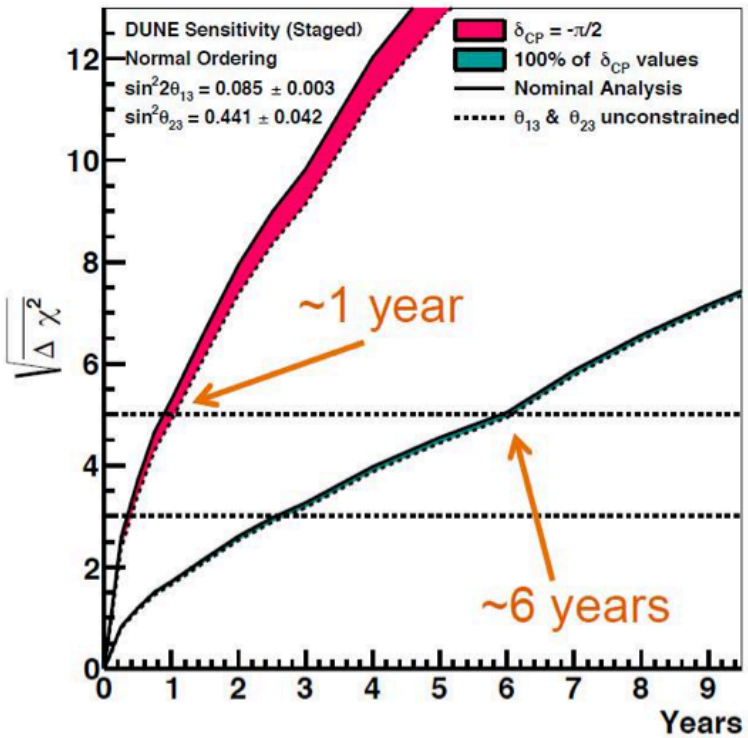
DUNE: CP sensitivity

δ_{CP} Resolution

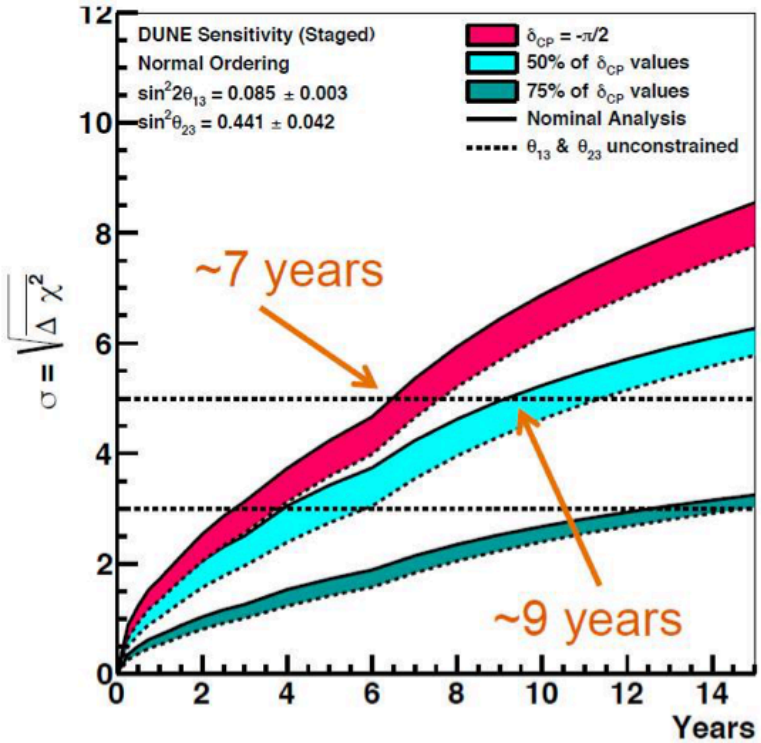


MH & CPV Sensitivity vs. Time

Mass Hierarchy Sensitivity

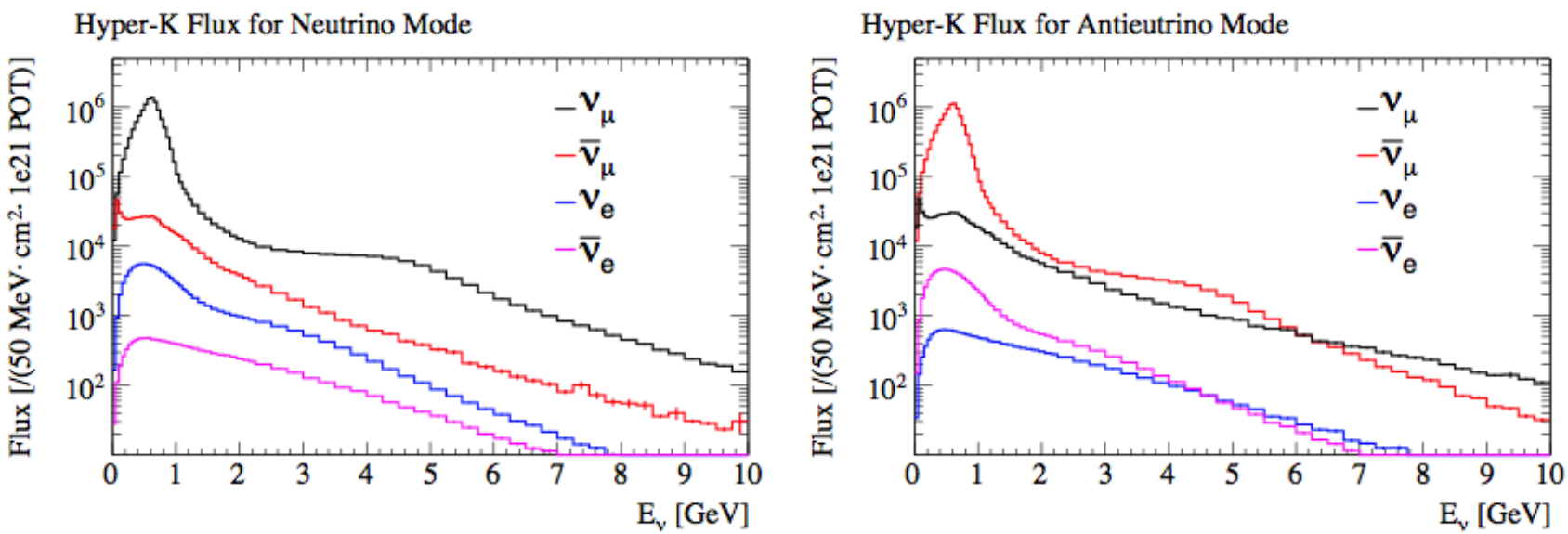


CP Violation Sensitivity

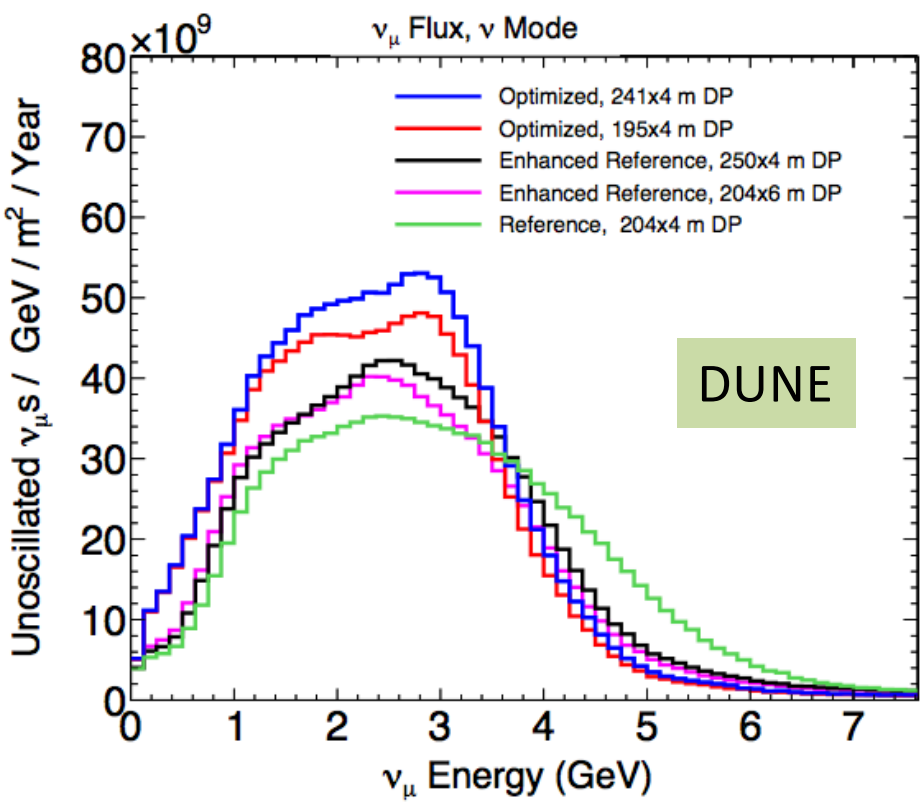


300 kt-MW-yrs
40kt @ 1.07 MW, 80GeV protons
Equal neutrino and anti-neutrino running

Narrow off-axis vs. wide-band beams



Hyper-K



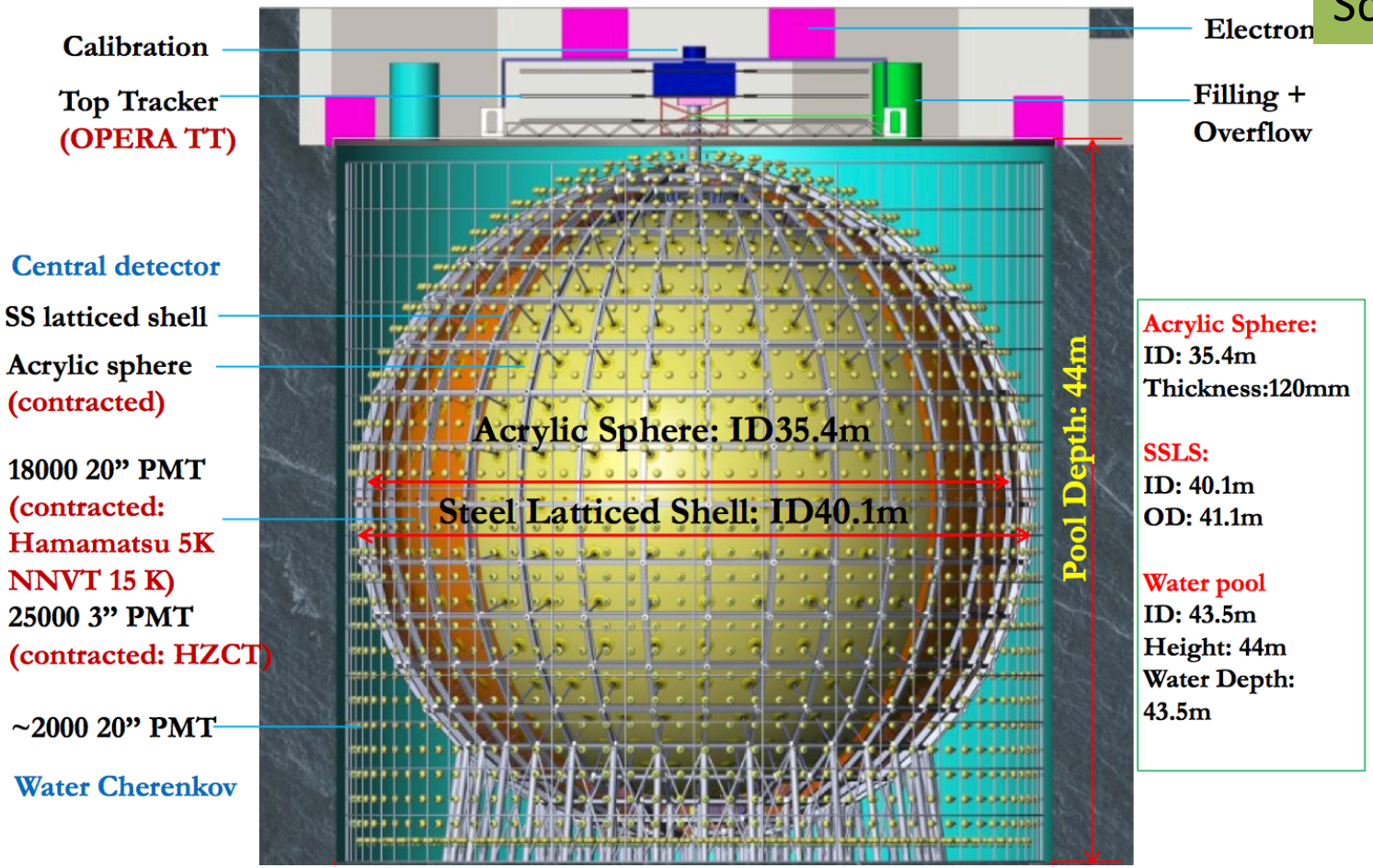
DUNE

- Complementarity or synergy?
- Detector technology very different
- Sensitivity to new physics, NSI etc ?

JUNO: exploring 12 sector & mass ordering

JUNO Detector

20 kt Liquid Scintillator Detector



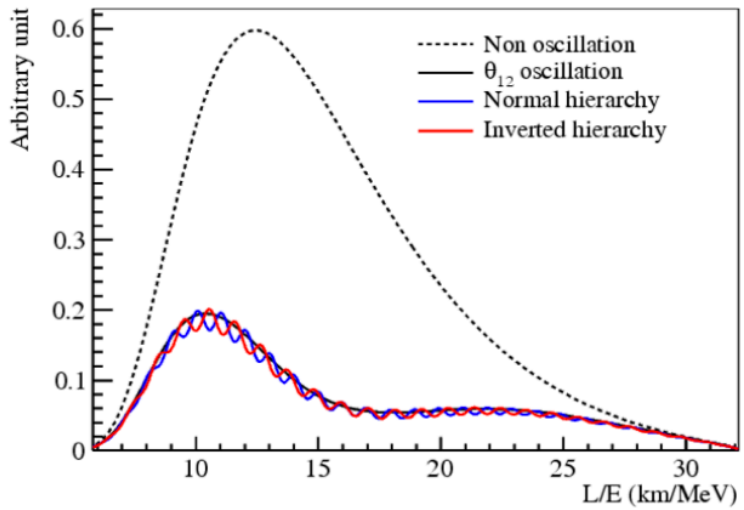
Capozzi et al PRD2014

Parameter	% error (prior)	% error after fit (NH true) All data	All – far	All – geo	% after fit (IH true) All data	All – far	All – geo
α	∞	59.2	59.0	57.0	56.2	55.3	54.0
Δm^2_{ee}	2.0	0.26	0.25	0.26	0.26	0.25	0.25
δm^2	3.2	0.22	0.21	0.16	0.21	0.21	0.16
s^2_{12}	5.5	0.49	0.47	0.39	0.49	0.46	0.42
s^2_{13}	10.3	6.95	6.88	6.95	6.84	6.77	6.84
f_R	3.0	0.66	0.66	0.64	0.65	0.65	0.64
f_{Th}	20.0	15.3	14.6	...	15.5	15.4	...
f_U	20.0	13.3	13.3	...	13.3	13.3	...

My slide in Neutrino 2012@Kyoto

Reactor ν at 60 km

Daya Bay II, HanoHano



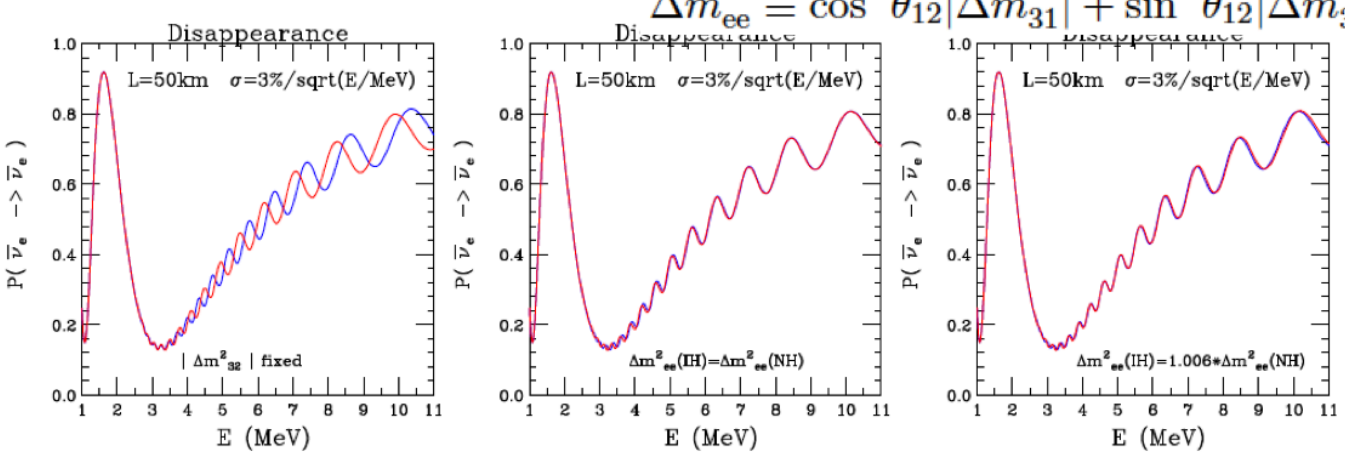
S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

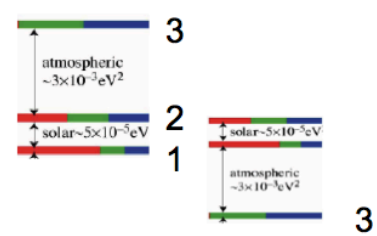
L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

J.Cao@ NuTURN12

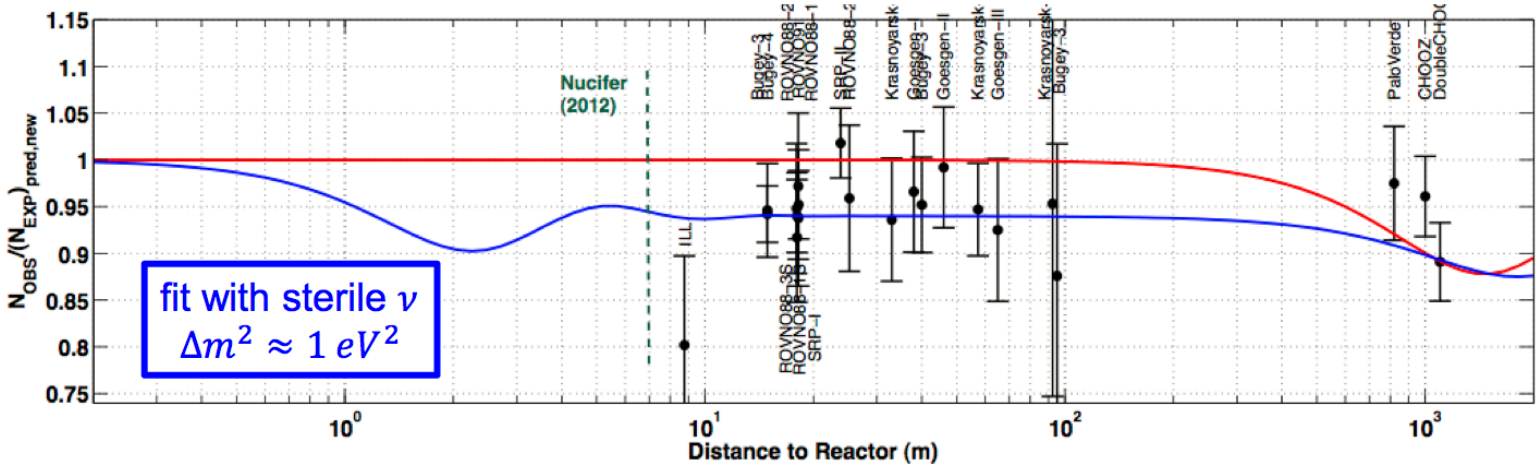
Sensitive to Δm^2 error and Δm^2 def: Parke et al. PRD07

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|.$$





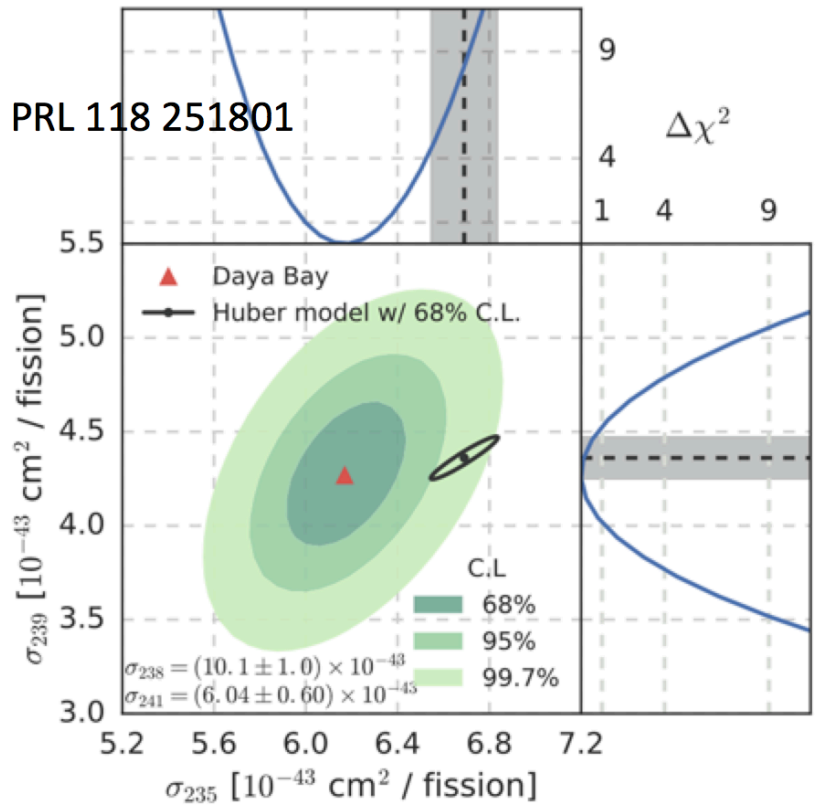
Anomaly?
Sterile ν?



Reactor neutrino anomaly?

- Calculated nu flux ~3% higher than measured
- Sterile nu?
- But the discrepancy is in ^{235}U, not in ^{239}Pu (Daya Bay)

PRL 118 251801

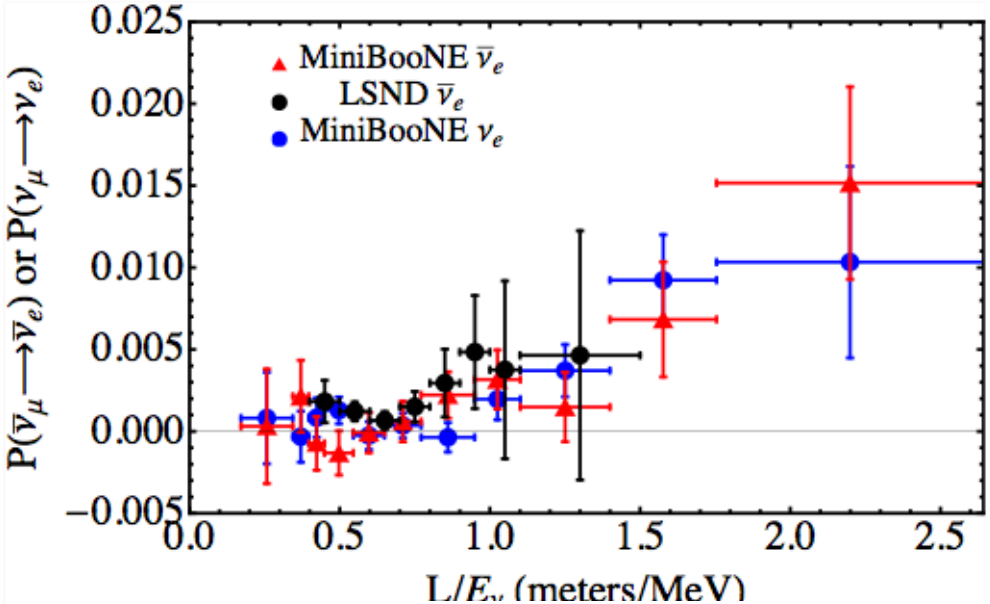


Sterile neutrino oscillation requires equal deficit for ^{235}U and ^{239}Pu

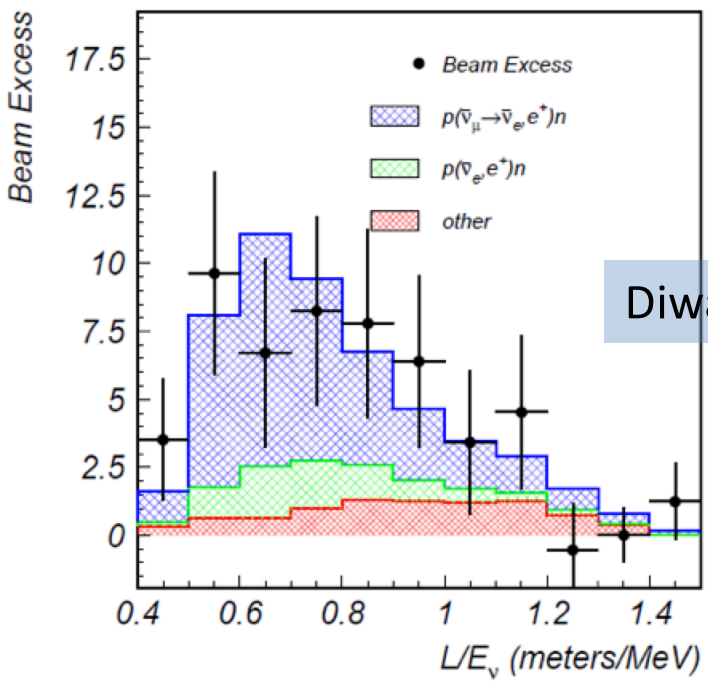
Daya Bay data prefer ^{235}U to be mainly responsible for the reactor anomaly

talk from David Martinez Caicedo

LSND-MiniBooNE anomaly



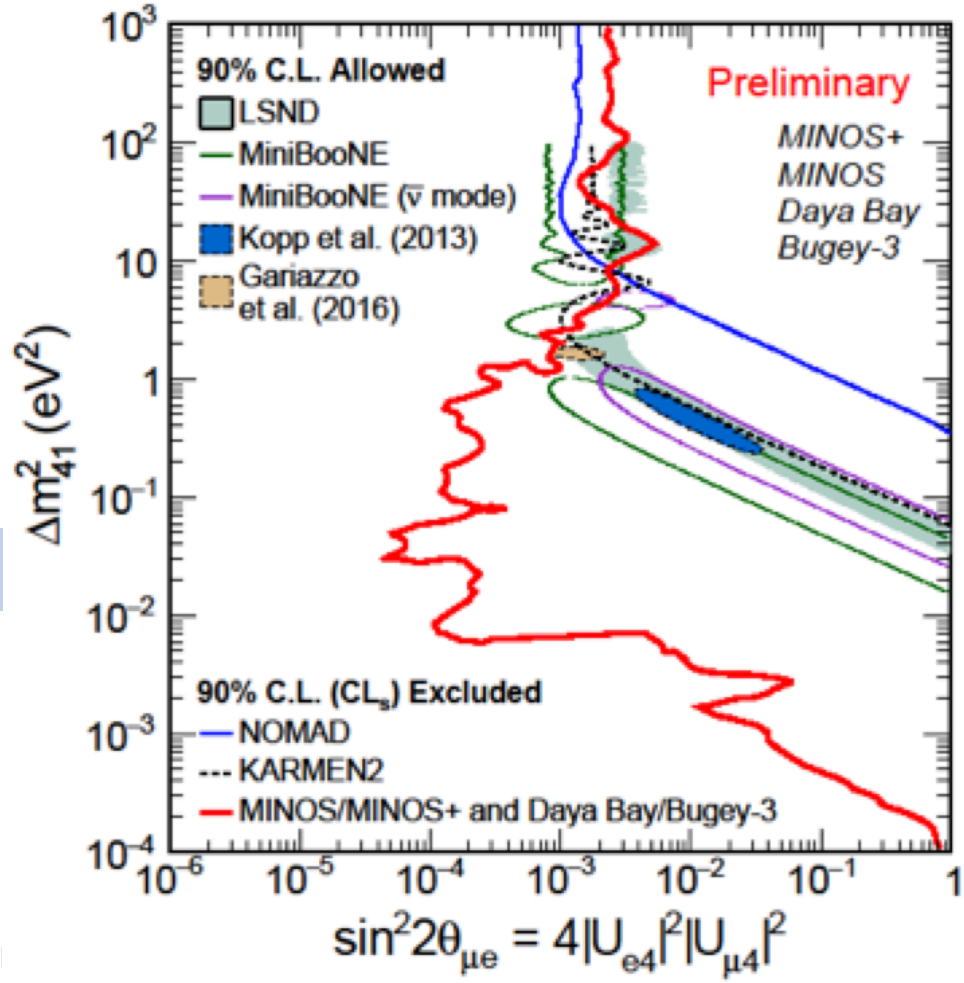
Phys. Rev. D64, 112007 (2001)



plot of a subset of data with good n-tag

Diwan@WIN2017

PRL 117, 151801 (2016)+MINOS+ results



New experiments ongoing/planned 1

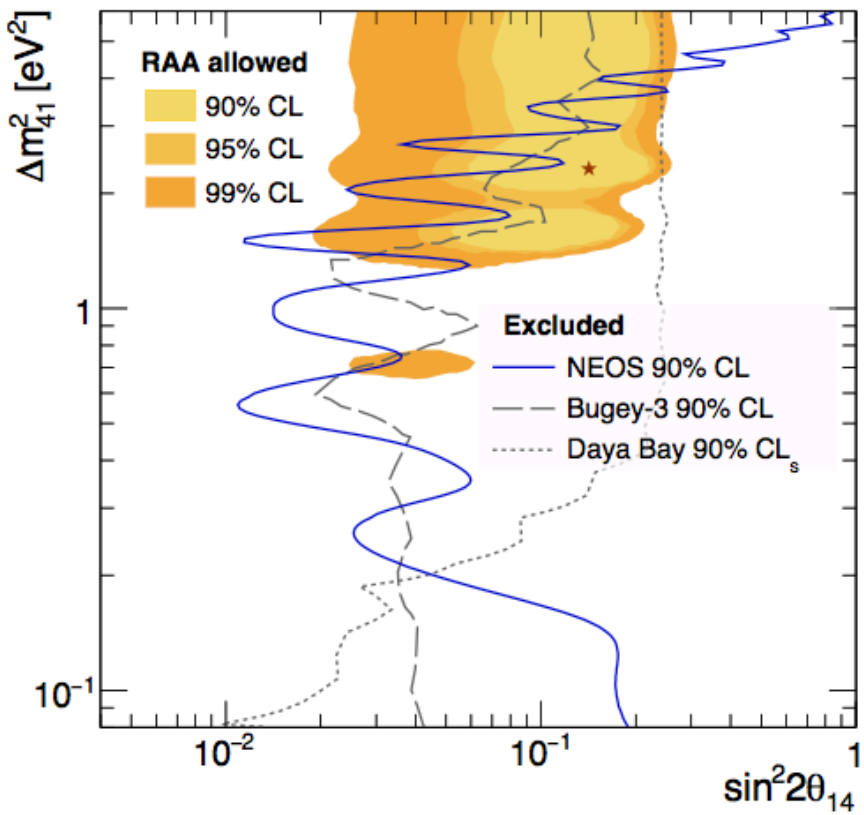
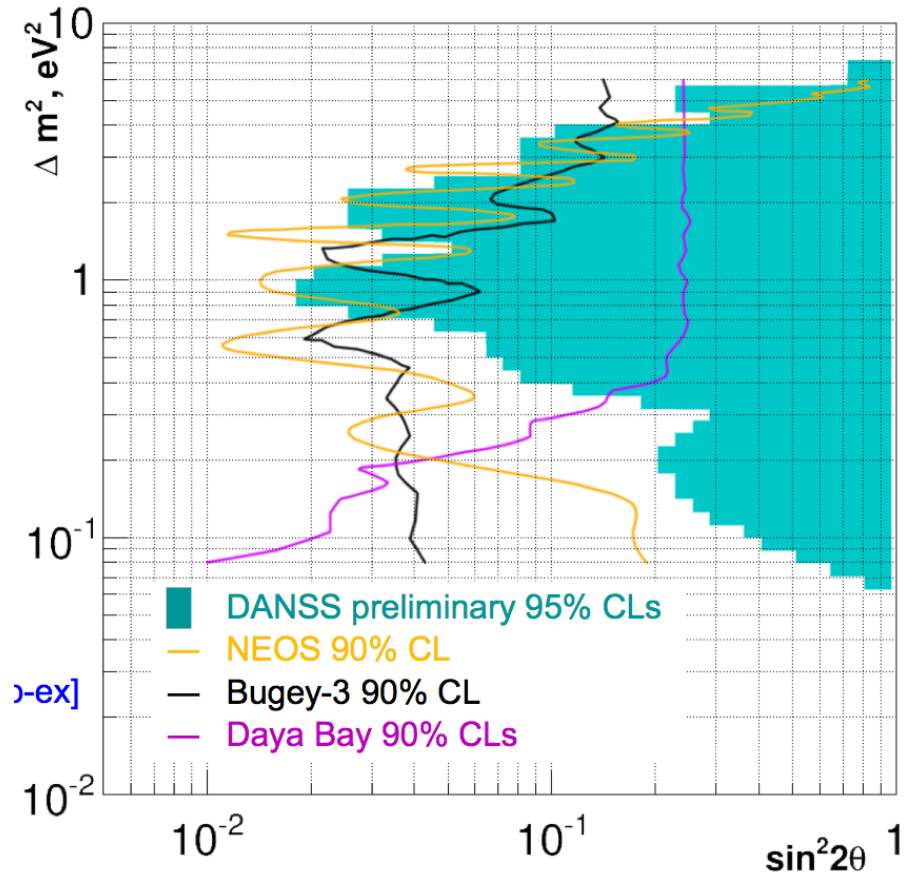


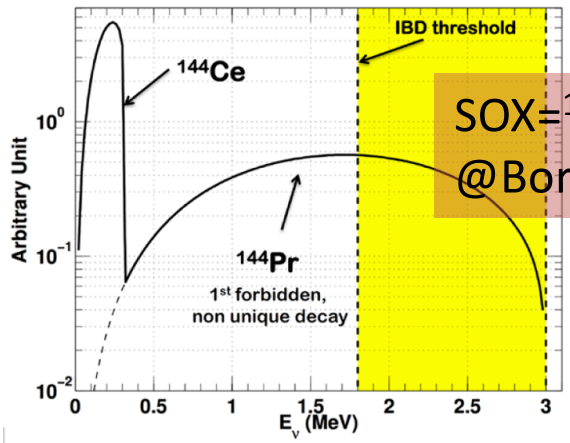
FIG. 4. Exclusion curves for 3+1 neutrino oscillations in the $\sin^2 2\theta_{14} - \Delta m^2_{41}$ parameter space. The solid blue curve is 90% C.L. exclusion contours based on the comparison with the Daya Bay spectrum, and the dashed gray curve is the Bugey-3 90% C.L. result [10]. The dotted curve shows the Daya Bay 90% CL$_s$ result [34]. The shaded area is the allowed region from the reactor antineutrino anomaly fit, and the star is its optimum point [12].

NEOS (Korea)

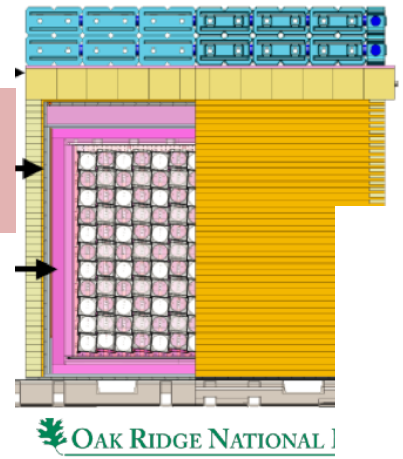


DANSS (Russia)

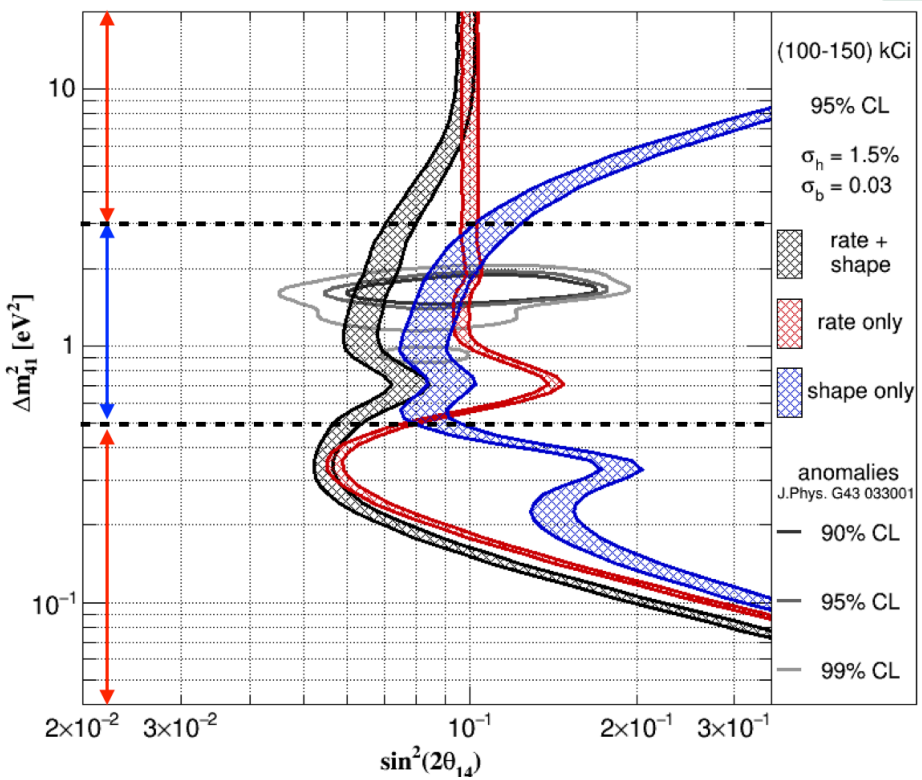
New experiments ongoing/planned 2

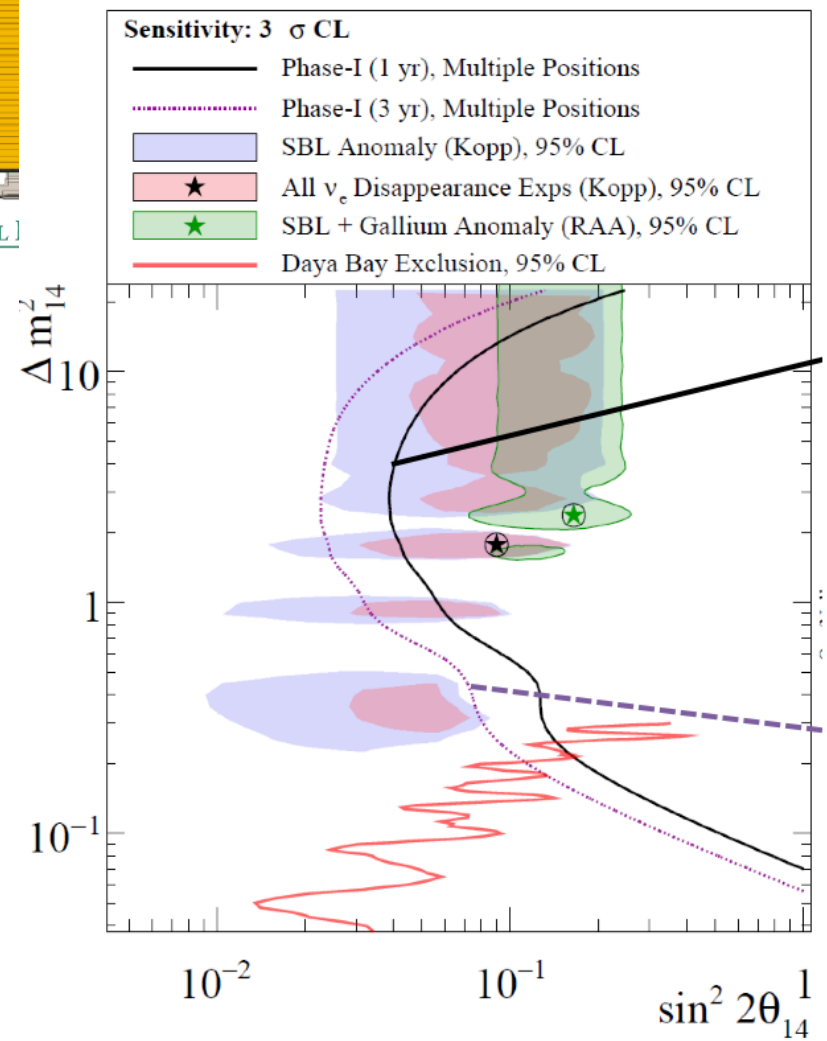


SOX=^{144}Ce source @Borexino



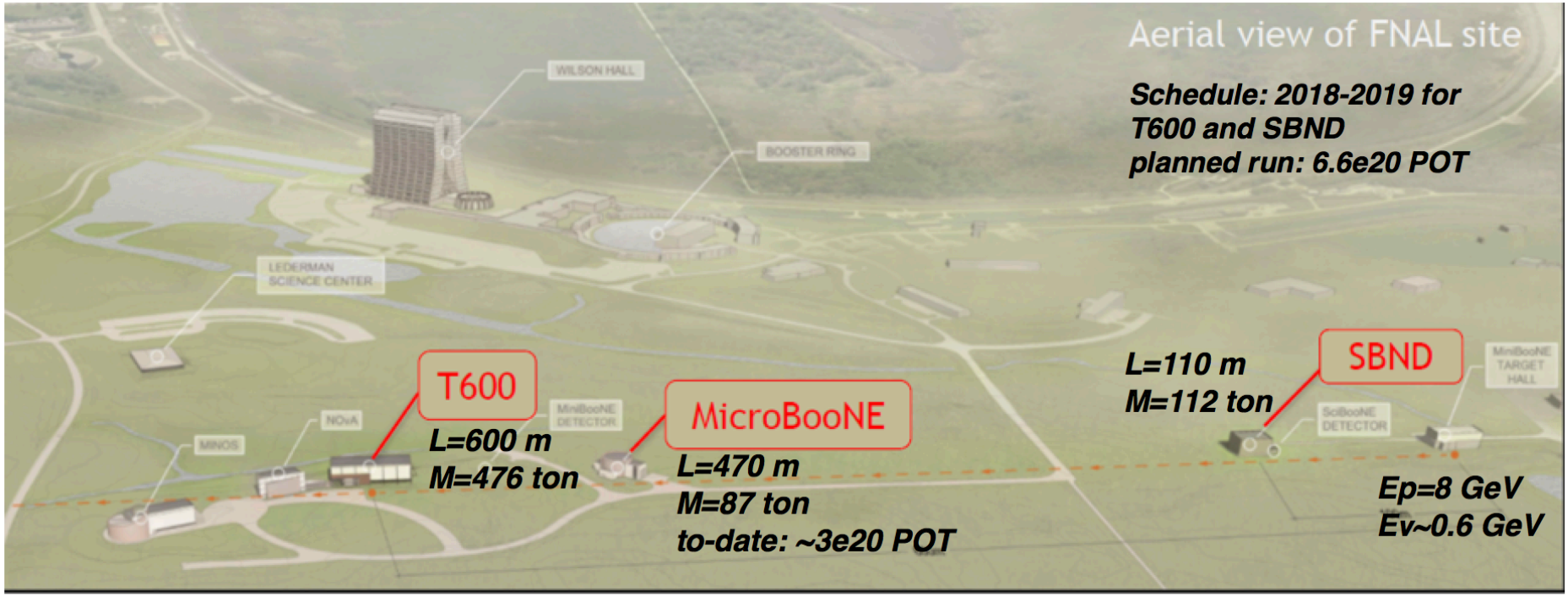
PROSPECT@Oak Ridge

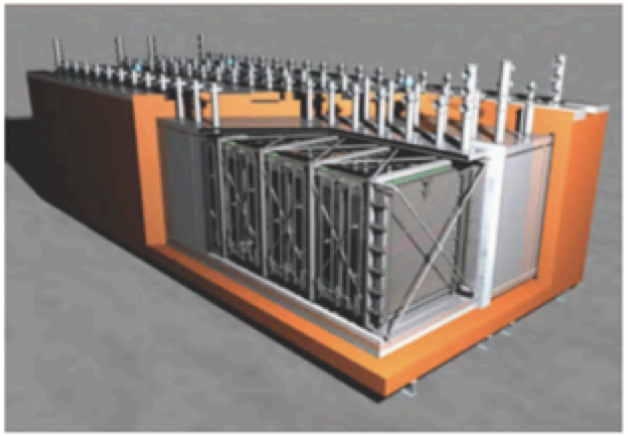


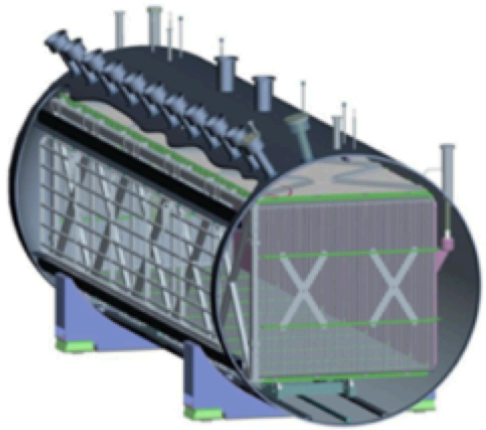


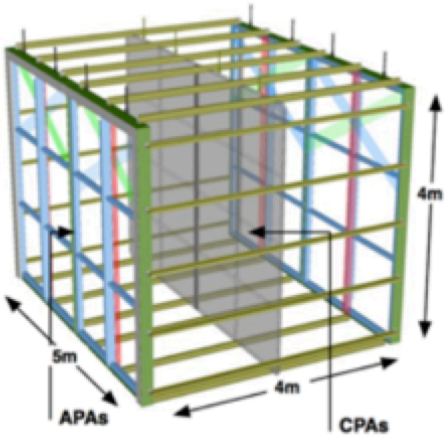
We want to hear the last words

Fermilab Short Baseline program

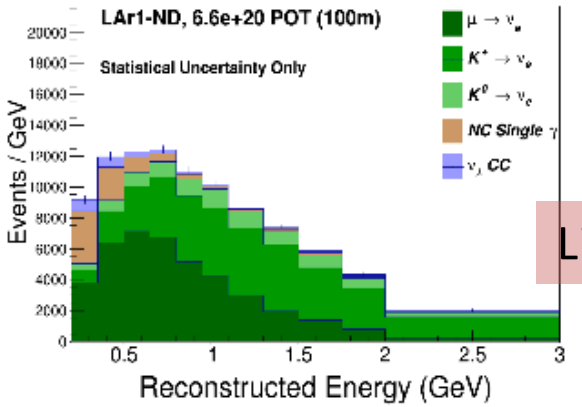




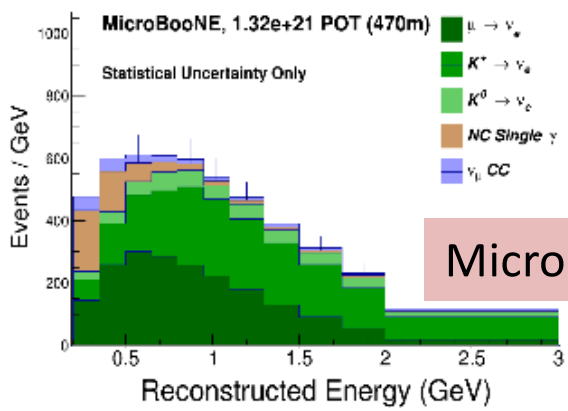




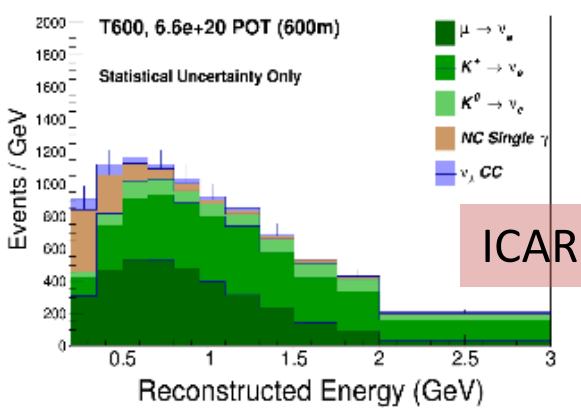
Fermilab SBL program: 5σ coverage!



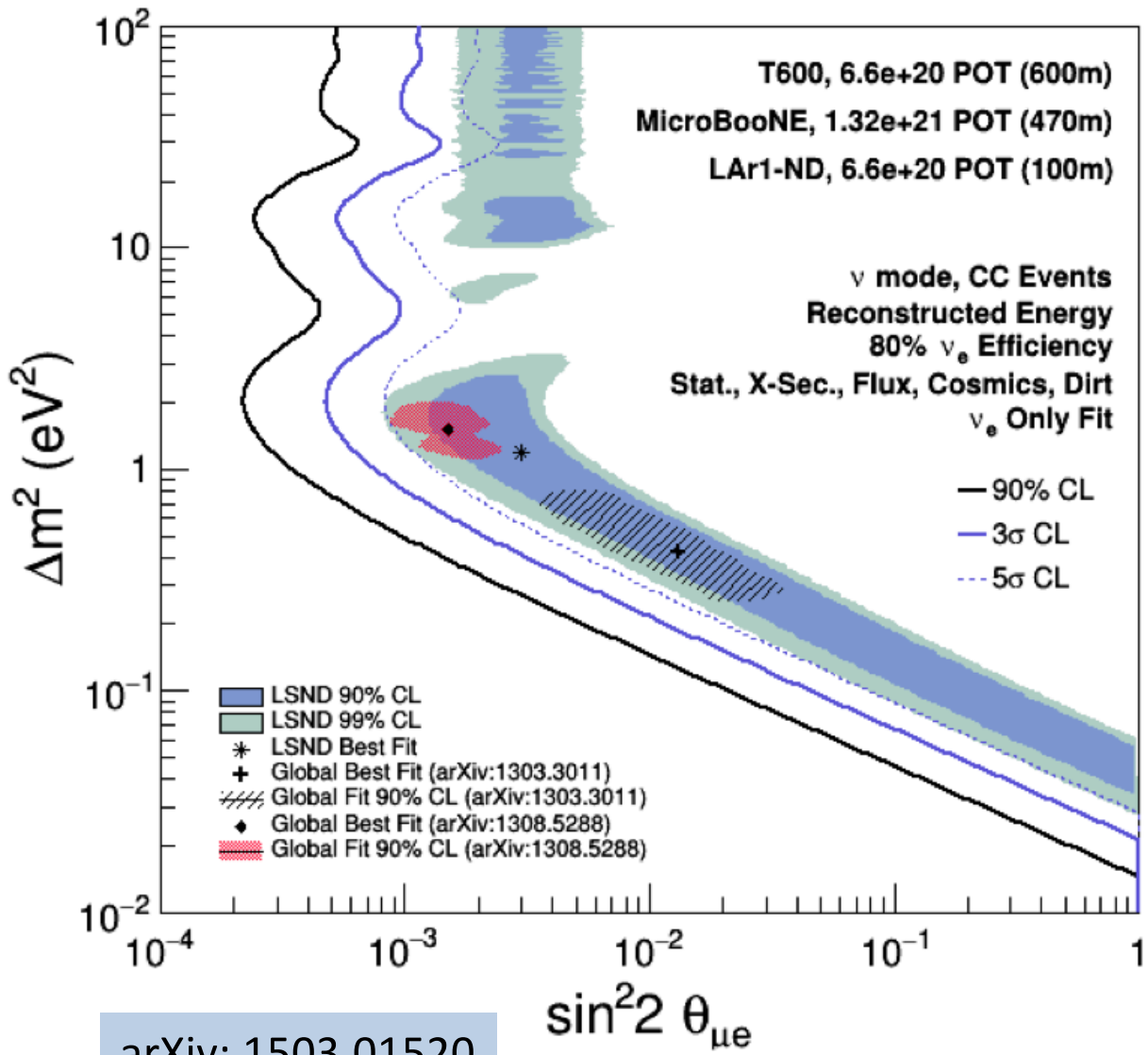
LiqAr ND



MicroBooNE



ICARUS T600



arXiv: 1503.01520

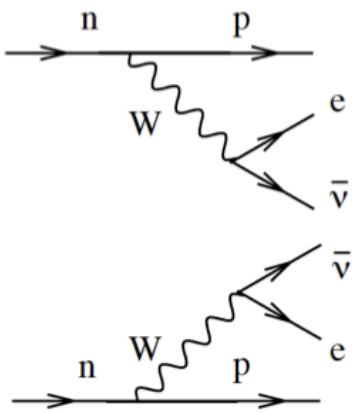
If they see sterile …

- If they see sterile, what that means? Curious guy without SM interactions exists
- For what reason?
- If they exist do they affect cosmology?
- If too much and fully thermalized, conflict with data…

Majorana vs. Dirac neutrinos

Double beta decay (DBD)

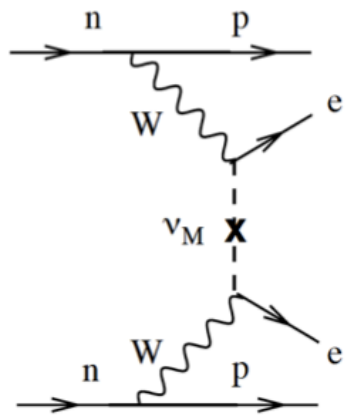
2ν DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$



- proposed in 1935 by Maria Goeppert-Mayer;
- 2nd order process allowed in the Standard Model;

$$\tau \sim 10^{19-21}\, yr$$

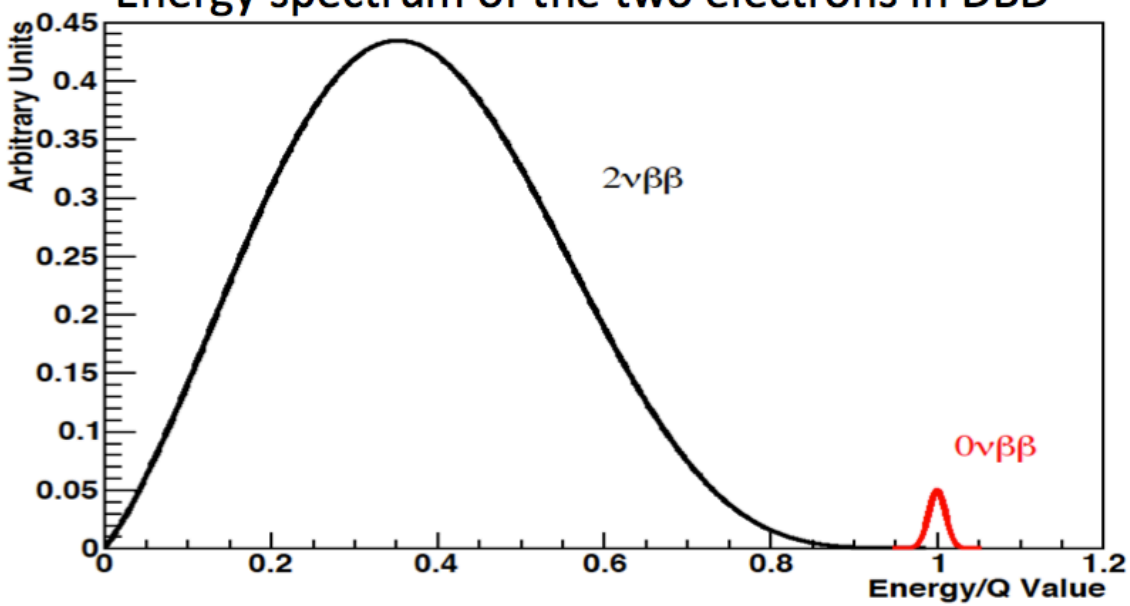
0ν DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^-$



- proposed in 1937 by Ettore Majorana;
- requires physics beyond Standard Model;

$$\tau > 10^{24-25}\, yr$$

Energy spectrum of the two electrons in DBD

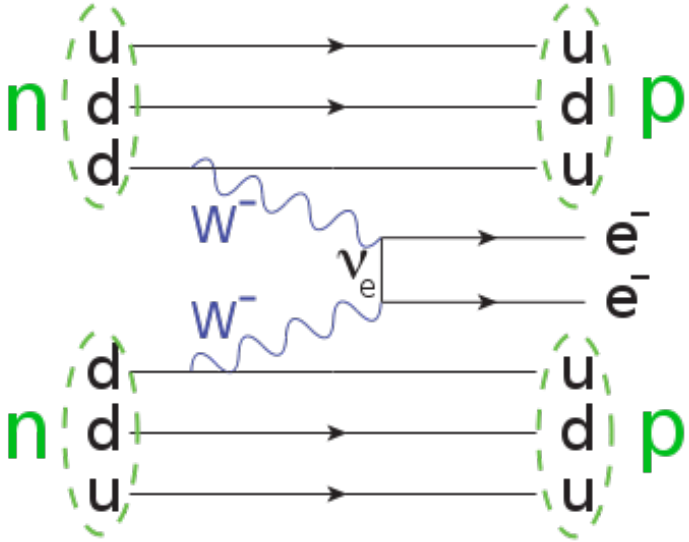


0ν DBD Signature: monochromatic line in the energy spectrum at the energy value

$$Q_{\beta\beta} = M_p - (M_d + 2\, m_e)$$

smeared by detector resolution!

Observable: 0ν DBD half life



The 0ν DBD half-life:

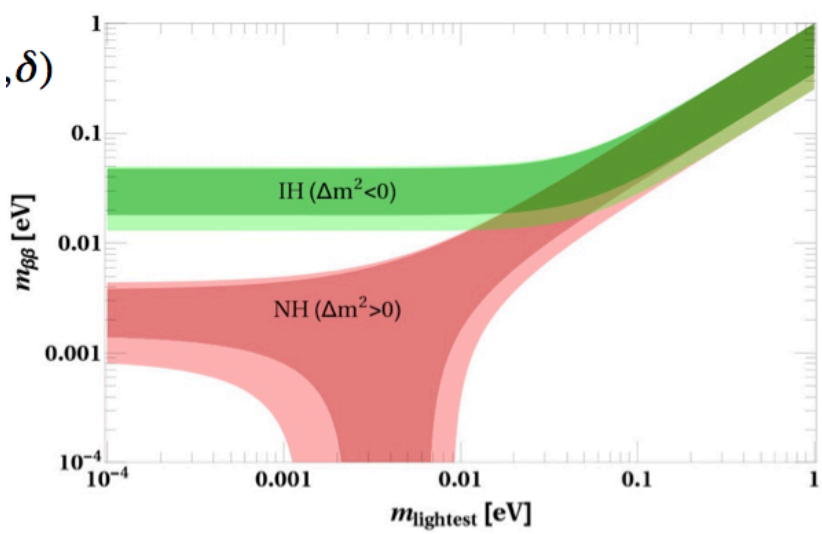
Effective Majorana mass

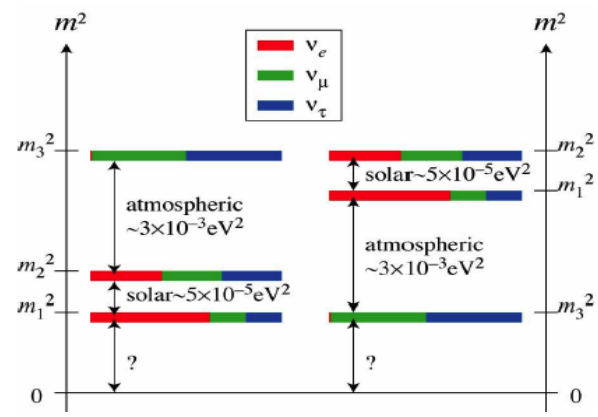
$$m_{\beta\beta} = f(\Delta m_{1,2}, \Delta m_{2,3}, m_1, \alpha_1, \alpha_2, \delta)$$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor ~$Q^5_{\beta\beta}$ (accurately calculable)

Nuclear Matrix Element (theoretical uncertainty ~2-3)





$$m_{0\nu\beta\beta} = \left| m_1 c_{13}^2 c_{12}^2 + m_2 c_{13}^2 s_{12}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i\alpha_{31}} \right|$$

Currently, Xe constraint seems the strongest

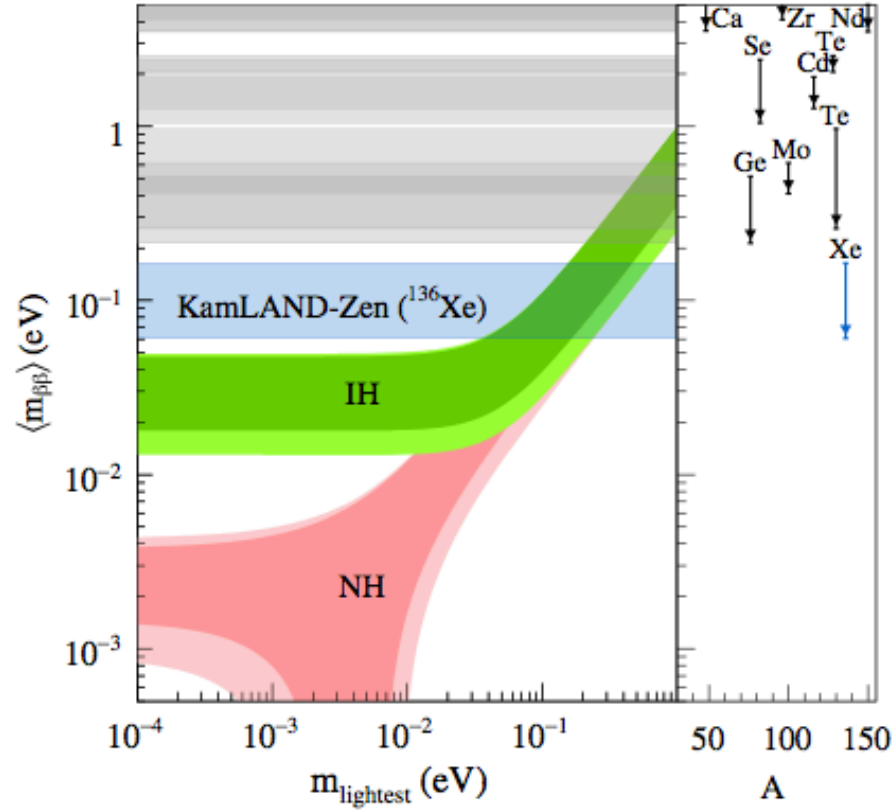
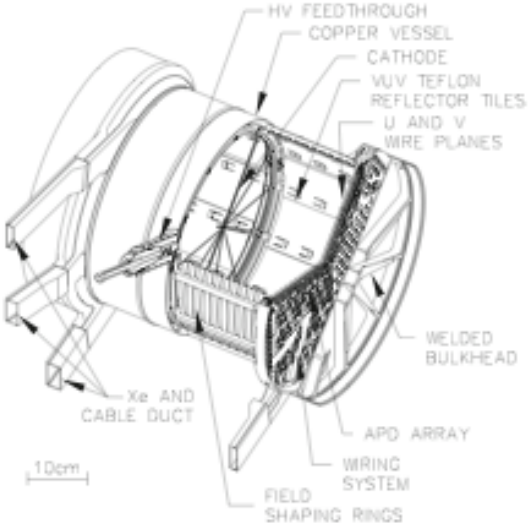
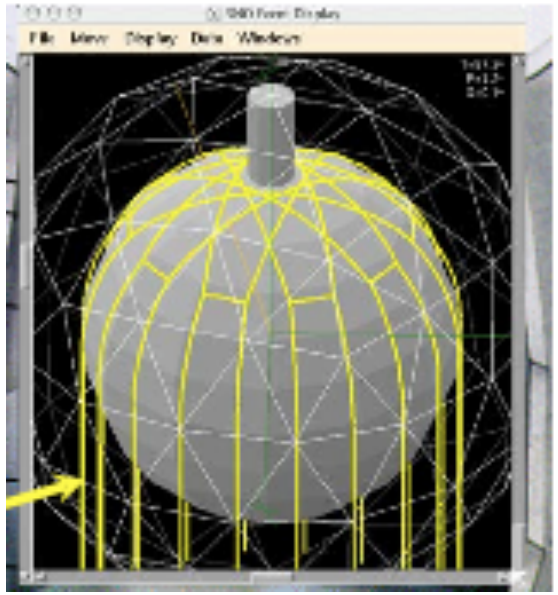
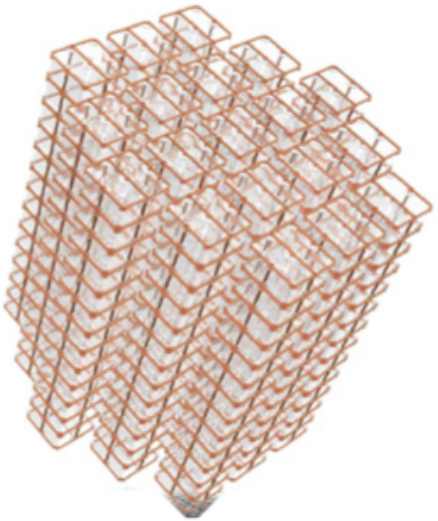


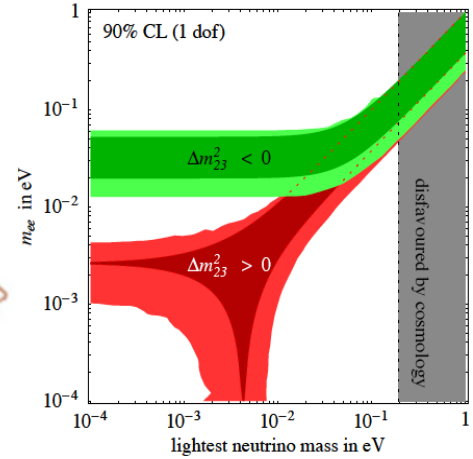
FIG. 3. Effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ as a function of the lightest neutrino mass m_{lightest}. The dark shaded regions are the predictions based on best-fit values of neutrino oscillation parameters for the normal hierarchy (NH) and the inverted hierarchy (IH), and the light shaded regions indicate the 3σ ranges calculated from the oscillation parameter uncertainties [29,30]. The horizontal bands indicate 90% C.L. upper limits on $\langle m_{\beta\beta} \rangle$ with ^{136}Xe from KamLAND-Zen (this work), and with other nuclei from Refs. [2,26–28], considering an improved phase space factor calculation [17,18] and commonly used NME calculations [19–25]. The side panel shows the corresponding limits for each nucleus as a function of the mass number.

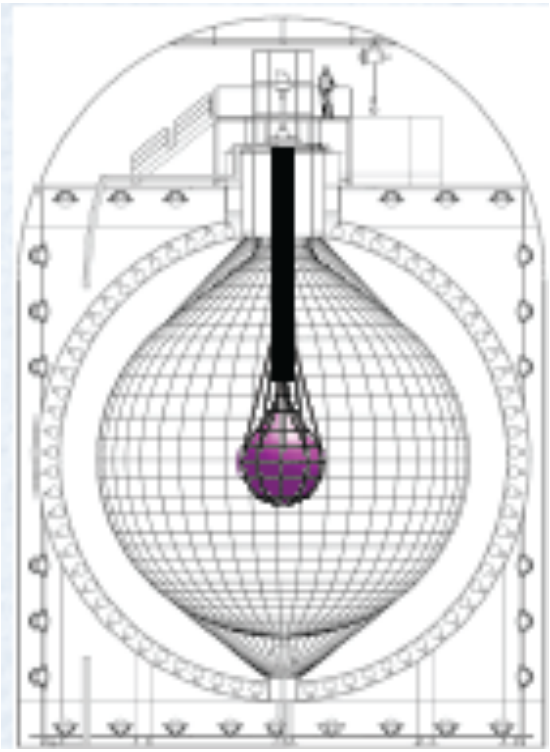
Many double beta decay experiments are either ongoing or coming



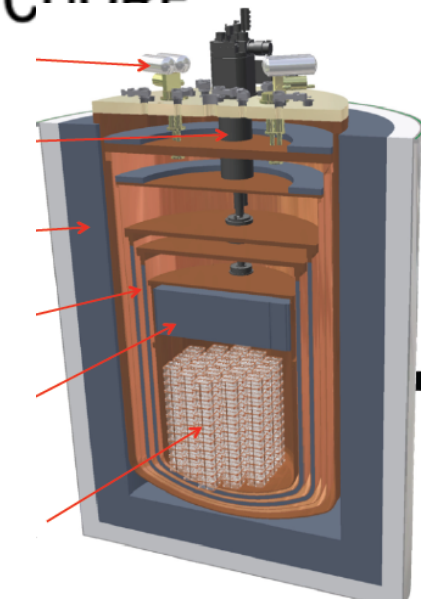


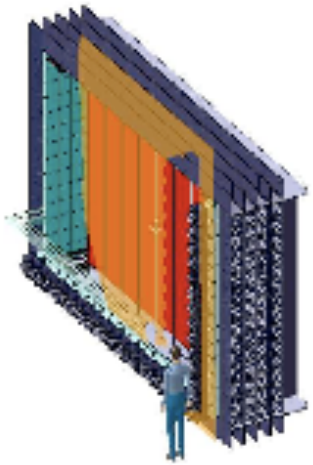






CUORE





If 0ν DBD is discovered ..

- If 0ν DBD is discovered what that means?
- Neutrinos are Majorana particle
- Lepton number is violated by 2 units
- $(1/M_{NP})\ \phi\phi\nu\nu$ (=Majorana mass) favored but not proven

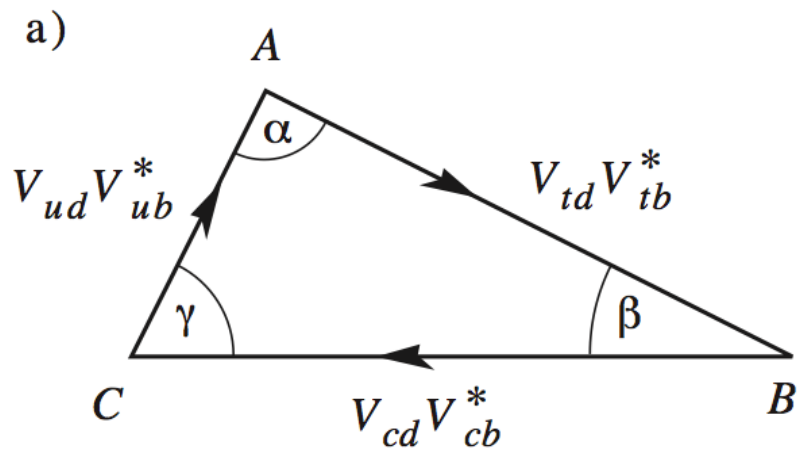
What is next?

What is next?

- Suppose in some day we come to know lepton CP phase and the neutrino mass ordering
- Then, the question is "what is next?", or could be "what is the last?"
- High precision measurement? JUNO!
- Paradigm Test ! → Prove that 3 nu mixing is our world
- But, how?

Unitarity test

- If one could prove that flavor mixing matrix U is unitary it indicates that 3 nu system spans complete set
- Unitarity triangle?



- Apparently, in neutrino case, hard to measure each side of the triangle
- Model of unitarity violation + experimental tests

High-energy vs. Low-energy unitarity violation

- Feature of unitarity violation different for
- High-energy ($E >> M_W$) unitarity violation vs.
- Low-energy ($E << M_W$) unitarity violation
- For Low-E case probability leakage to "sterile" sector → small but observable effect

C-S. Fong, HM, H. Nunokawa, JHEP 2017

- Other differences are more subtle, like zero distance transition in High-E case

Conclusion

- Breakthrough at around 1994-2002 led to discovery of nu mass
- Current status of our understanding of neutrino oscillation/mixing briefly reviewed
- Accumulating hints for lepton CP violation → $\delta \sim 3\pi/2$?? → δ could me measured earlier than we thought??
- Current weak hints for Nu mass ordering not conclusive, but $\delta \sim 3\pi/2$ great news for NOvA

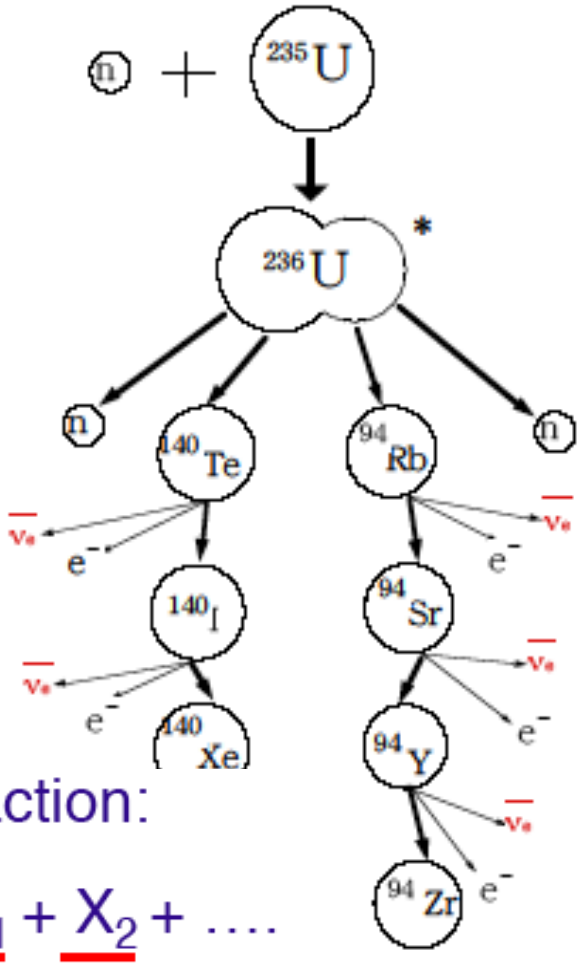
Conclusion

- LSND-MiniBooNE anomaly + reactor neutrino anomaly → hints for sterile neutrinos?
- Less likely for the reactor anomaly
- The former anomaly needs to be settled → either confirmation at high, σ or rejection
- 0ν double beta decay discussed as a mean to determine Majorana vs Dirac neutrinos
- How to close the neutrino story? → $3\ \nu$ paradigm test

Backup slides

Reactor produces neutrinos

Reactor $\bar{\nu}_e$



Fission reaction:

$U + n \rightarrow X_1 + X_2 + \ldots$

Neutron rich

$$X_i \rightarrow Y + e^- + \bar{\nu}_e$$

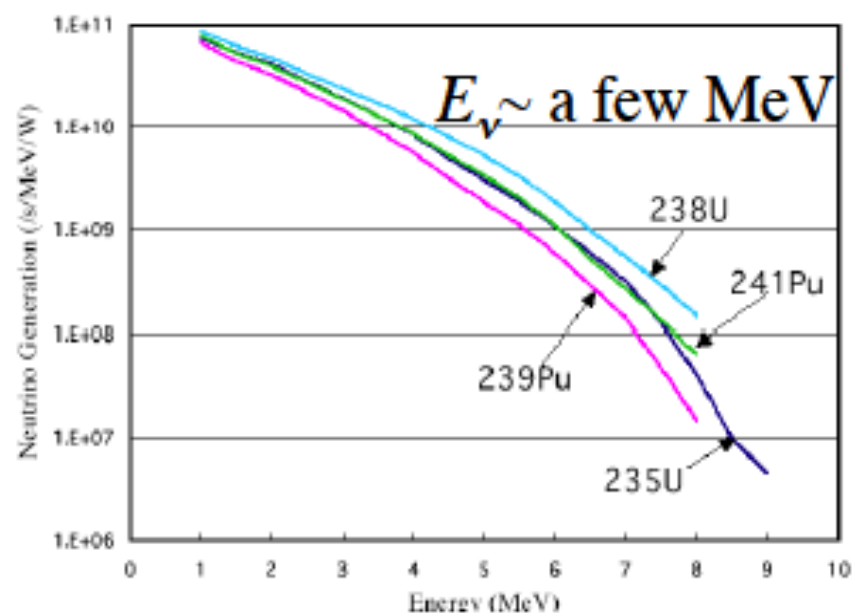
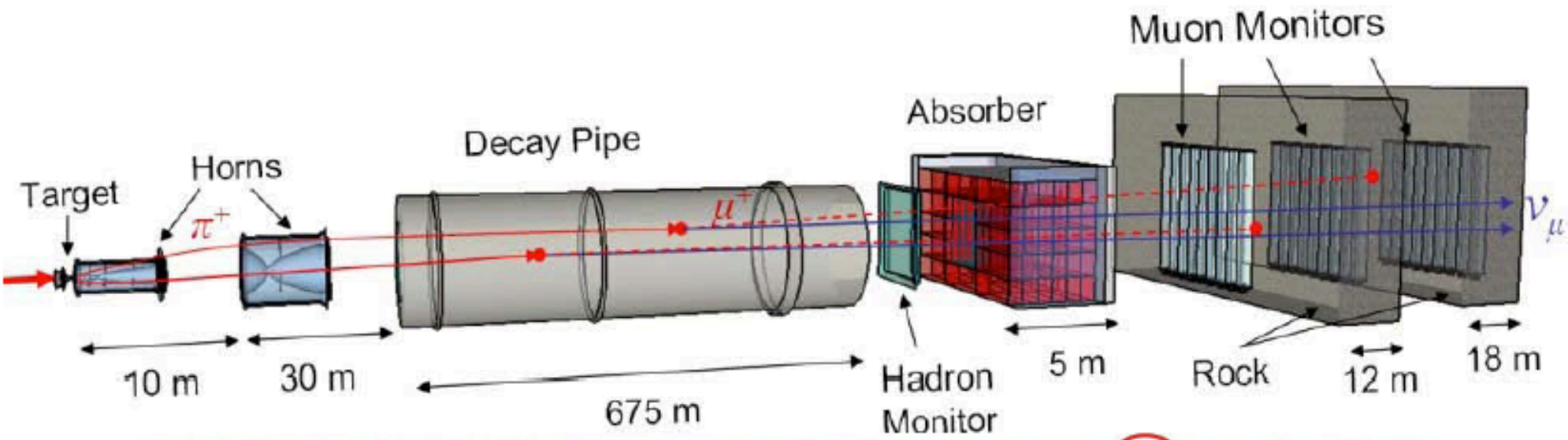
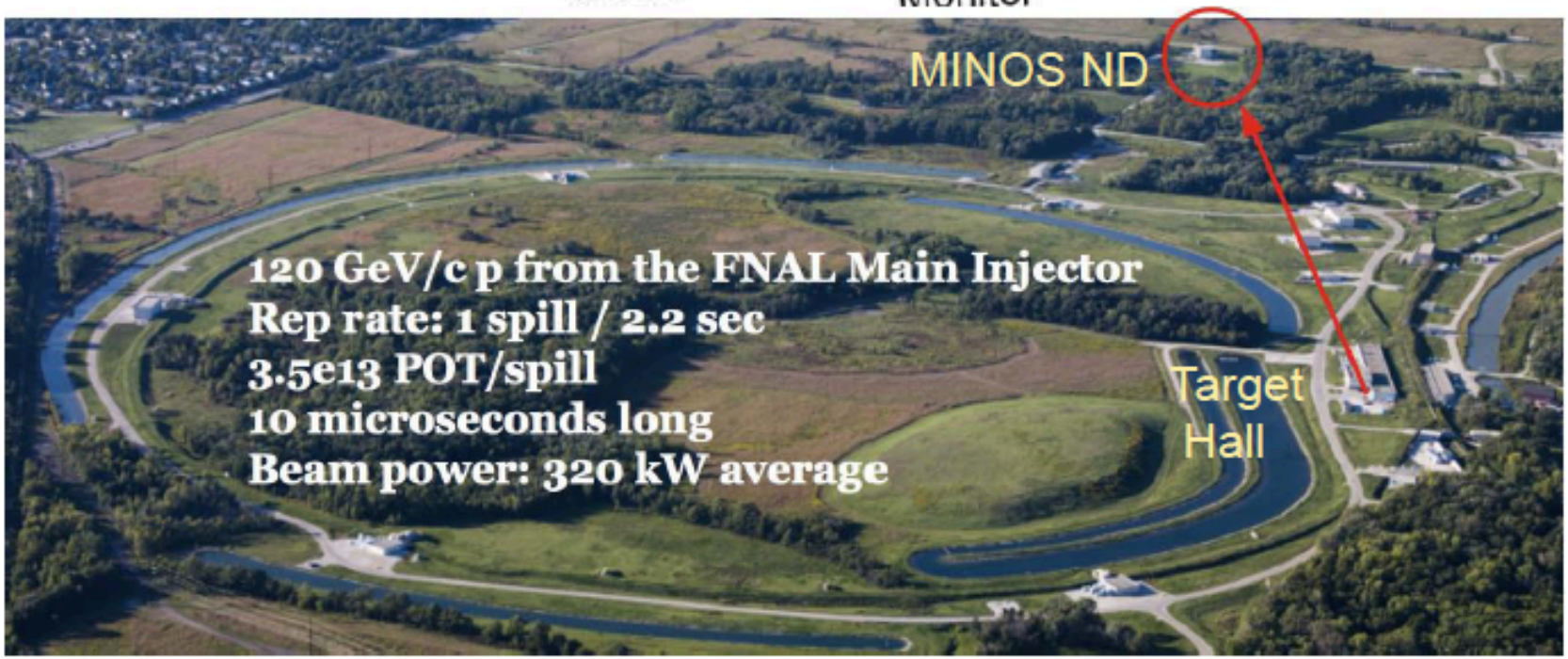
Reactor ν is free!

~6ν/fission & ~200MeV/fission

$\Downarrow$

$$\sim 6 \times 10^{20}\, \bar{\nu}_e / s / reactor \quad (1\text{GWe})$$

Energy Spectra



The NuMI Beam