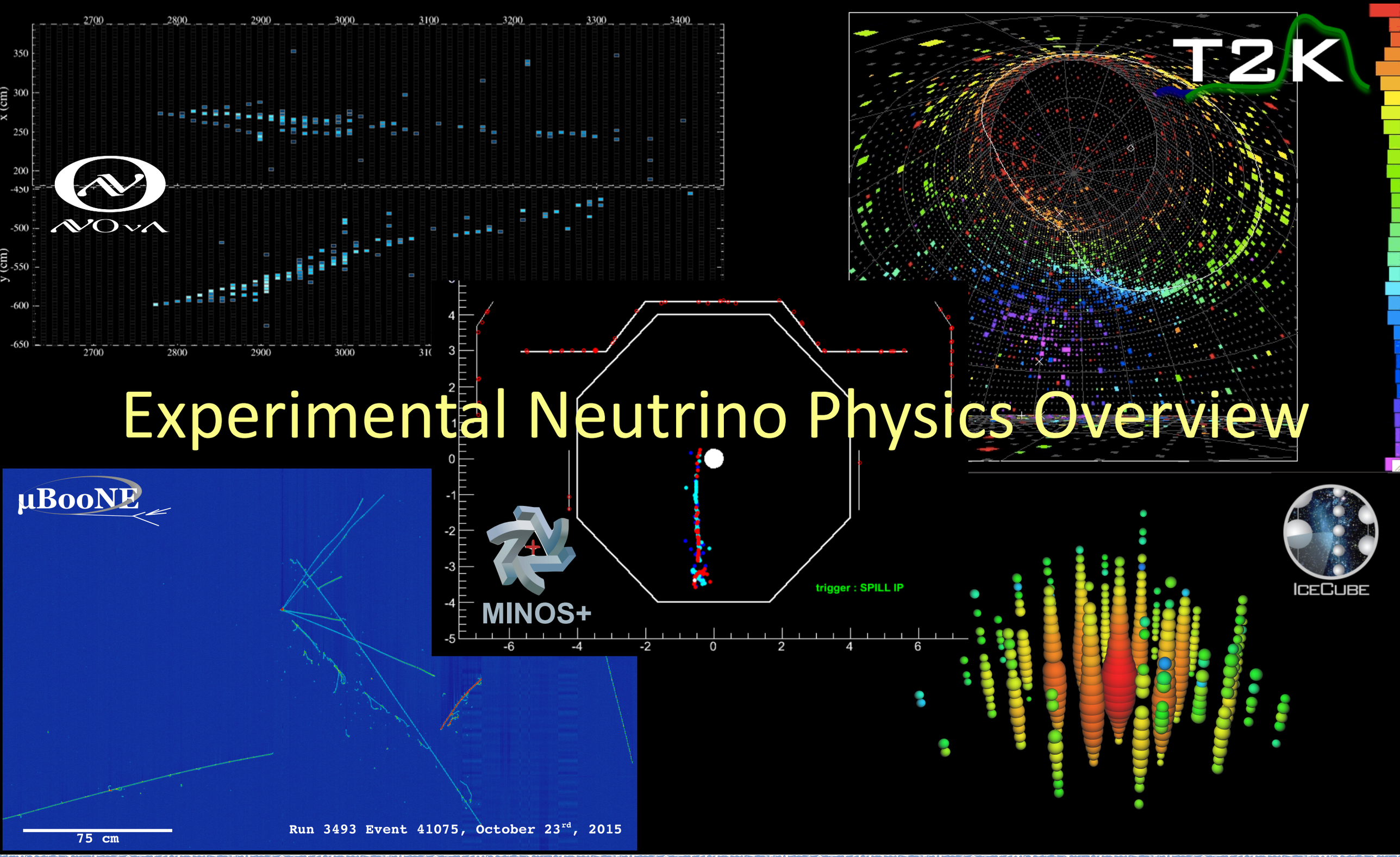


Experimental Neutrino Physics Overview

Alexandre Sousa
University of Cincinnati

26th International Workshop on
Weak Interactions and Neutrinos

WIN 2017 - UC Irvine, CA

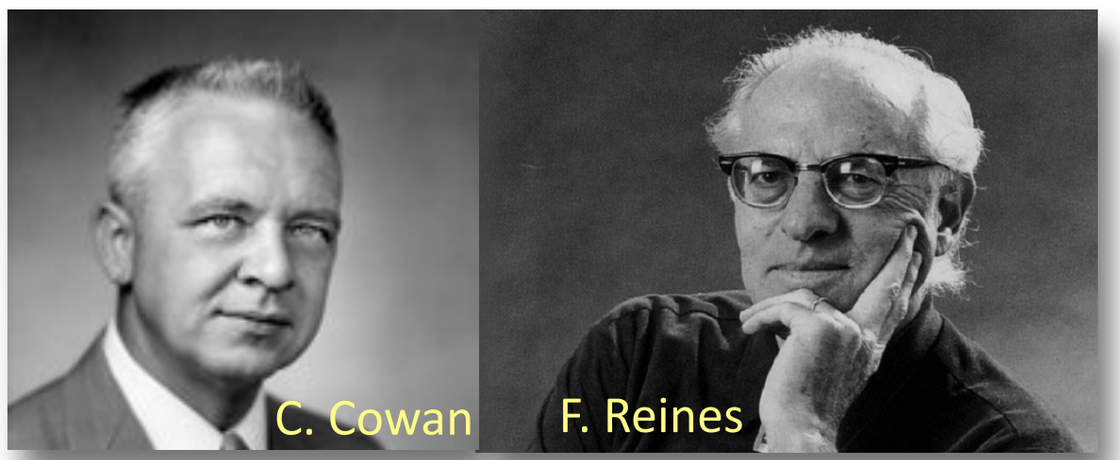
June 19, 2017

University of California, Irvine

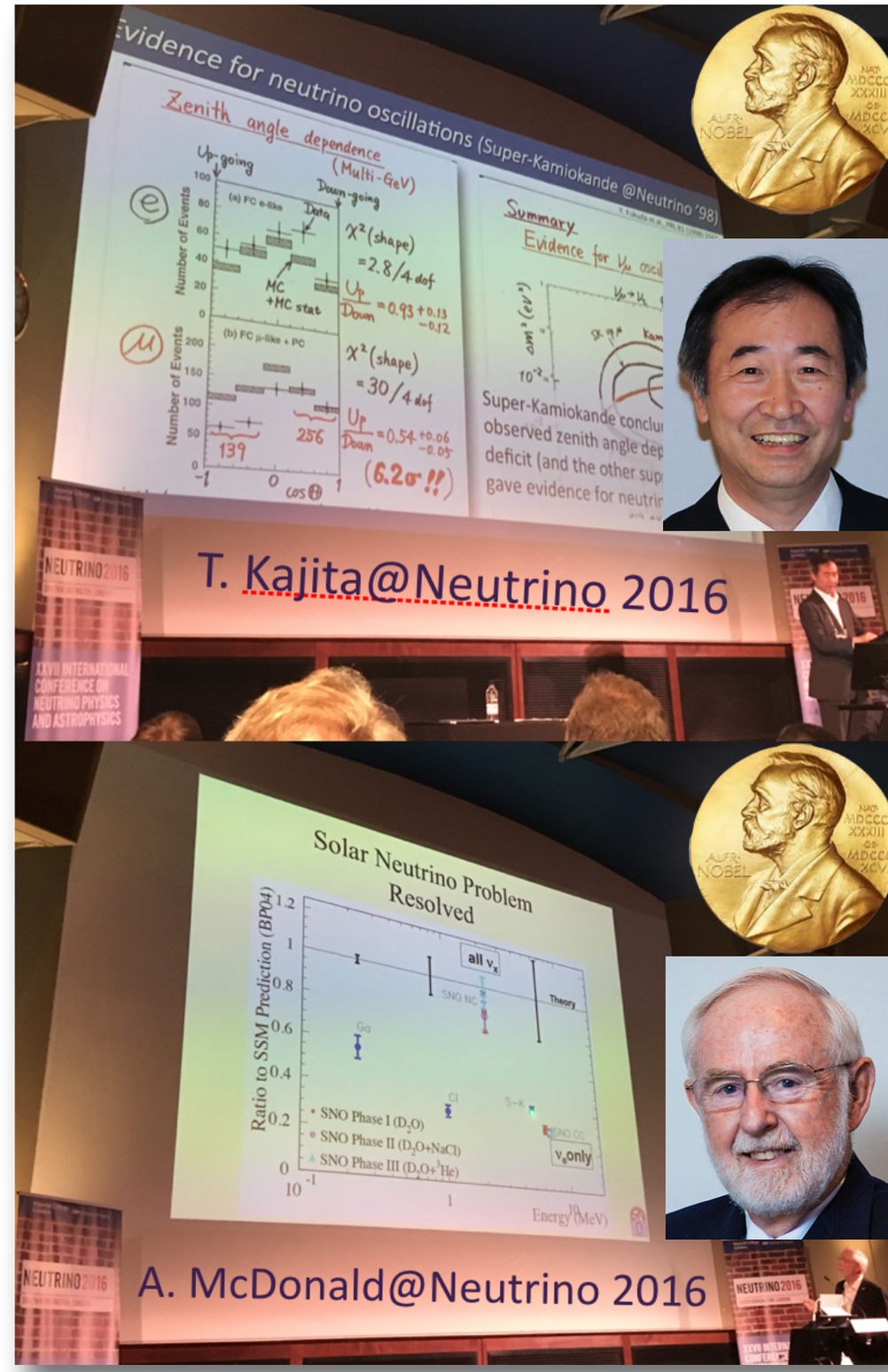
Much more than just missing E_T!

1988 Nobel Prize - First ν Beam and ν_μ Discovery

1995 Nobel Prize - Direct ν Detection



2002 Nobel Prize - Cosmic ν Detection



2015 Nobel Prize - ν Oscillations

What do we know?

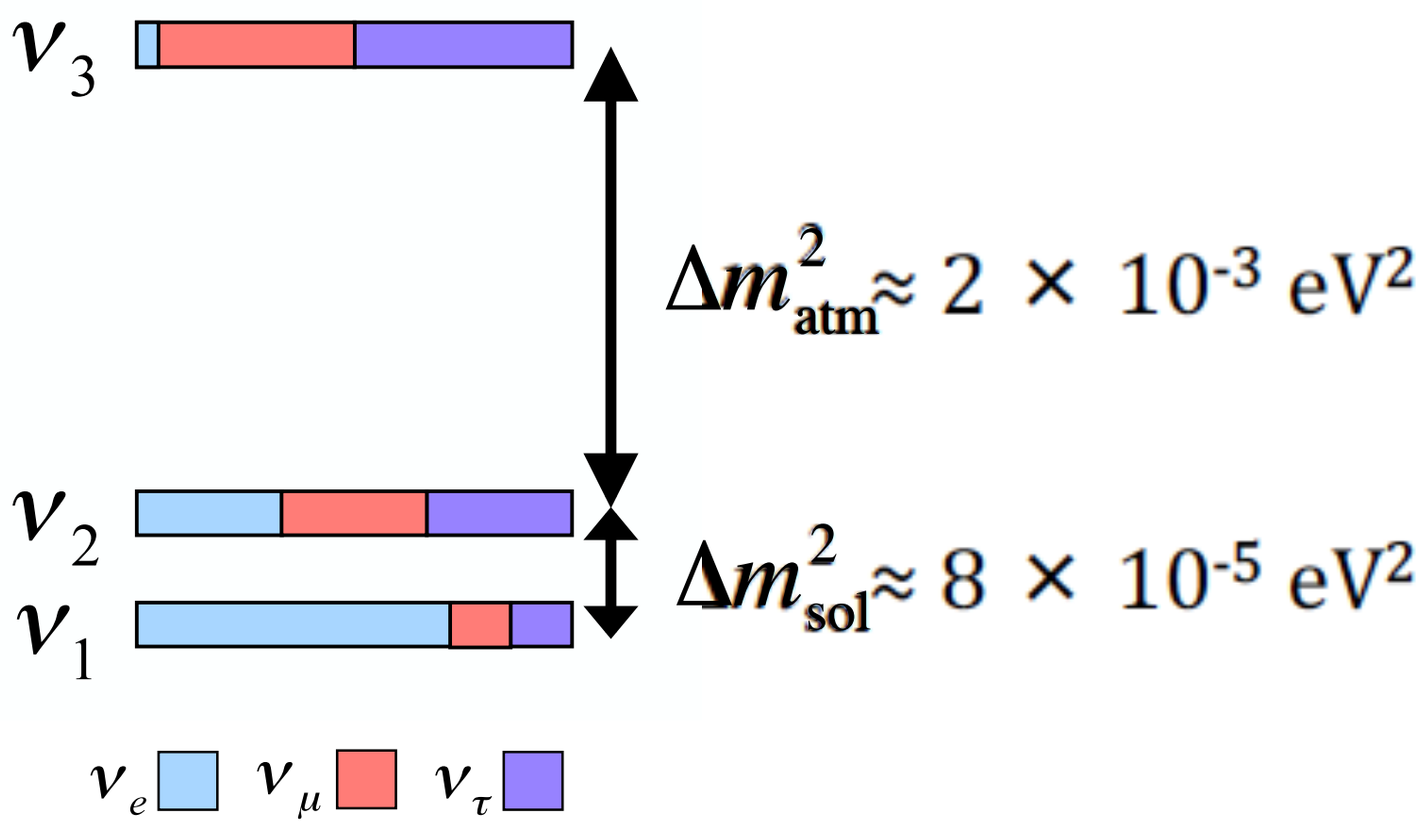
atmospheric accelerator ν_μ | short baseline reactor accelerator ν_e | solar long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

$\theta_{23} \approx 45^\circ$ $\theta_{13} \approx 9^\circ$ $\theta_{12} \approx 34^\circ$



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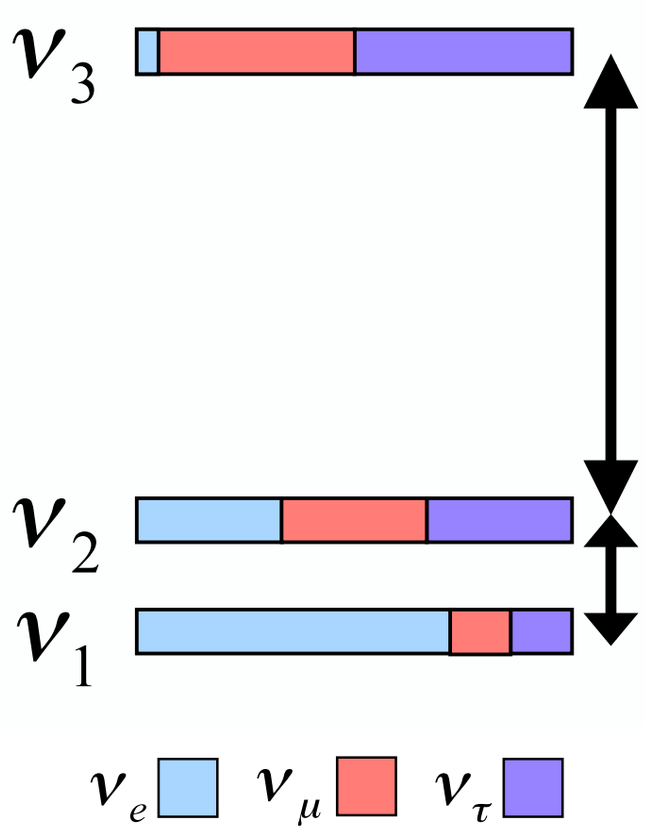


$\Delta m^2_{atm} \approx 2 \times 10^{-3}\ eV^2$

$\Delta m^2_{sol} \approx 8 \times 10^{-5}\ eV^2$

How precisely do we know it?

Δm^2_{sol}	2.3%
Δm^2_{atm}	1.6%
$\sin^2\theta_{12}$	5.8%
$\sin^2\theta_{23}$	9.6%
$\sin^2\theta_{13}$	4.0%

F. Capozzi et al., Phys. Rev. D 95, 096014 (2017)

What we don't know

atmospheric accelerator ν_μ | short baseline reactor accelerator ν_e | solar long baseline reactor

Flavor

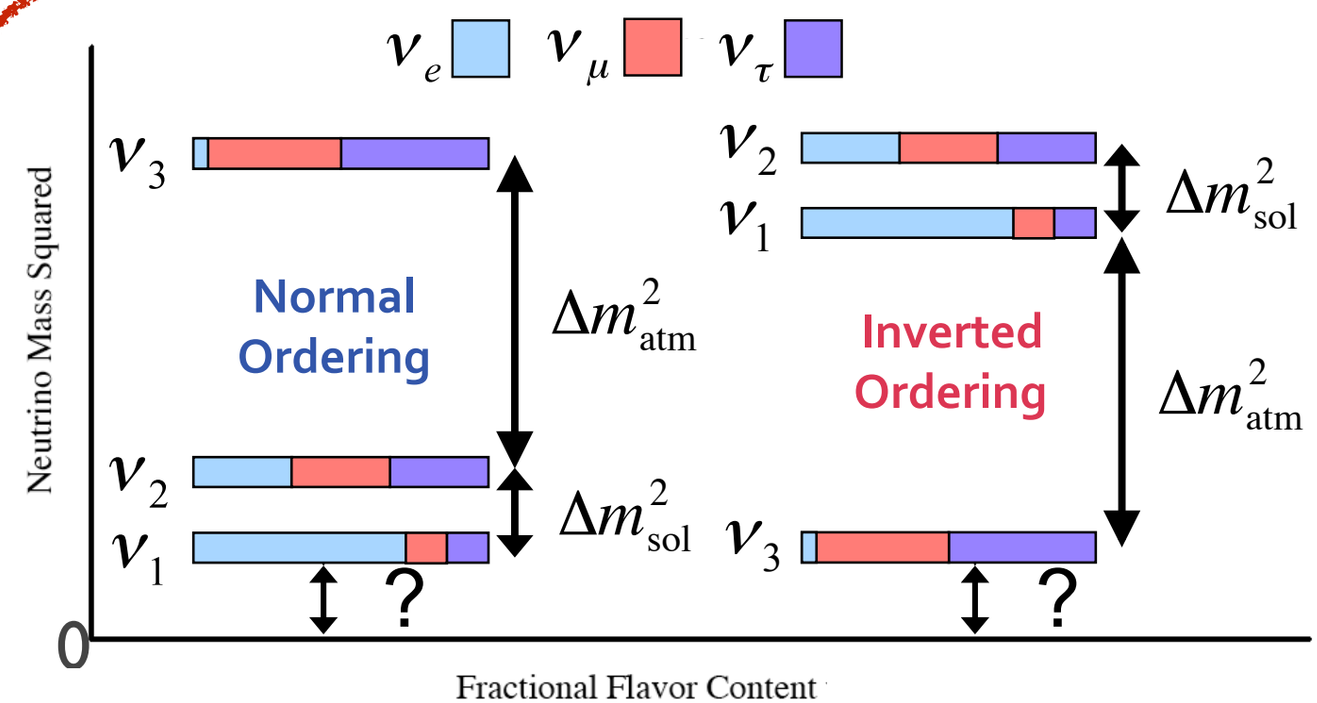
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

Is θ_{23} really 45°?

Is there CP violation in the lepton sector? Value of δ_{CP}

Are there more than 3 neutrinos?



What is the ν mass ordering, the sign of Δm^2_{atm}

What is the absolute neutrino mass scale?

Are neutrinos Majorana or Dirac particles?

Answering the Questions…

- Neutrino Oscillations
  - Solar Sector
  - Atmospheric Sector
  - Measuring θ_{13}
  - Determining the Mass Ordering and Looking for CP violation
  - Digression: Systematic Uncertainties
  - Beyond the Three-Flavor Paradigm
- Measuring the Absolute Neutrino Mass Scale
- Are Neutrinos Majorana Particles?
  - Neutrinoless Double Beta Decay Experiments

Answering the Questions…

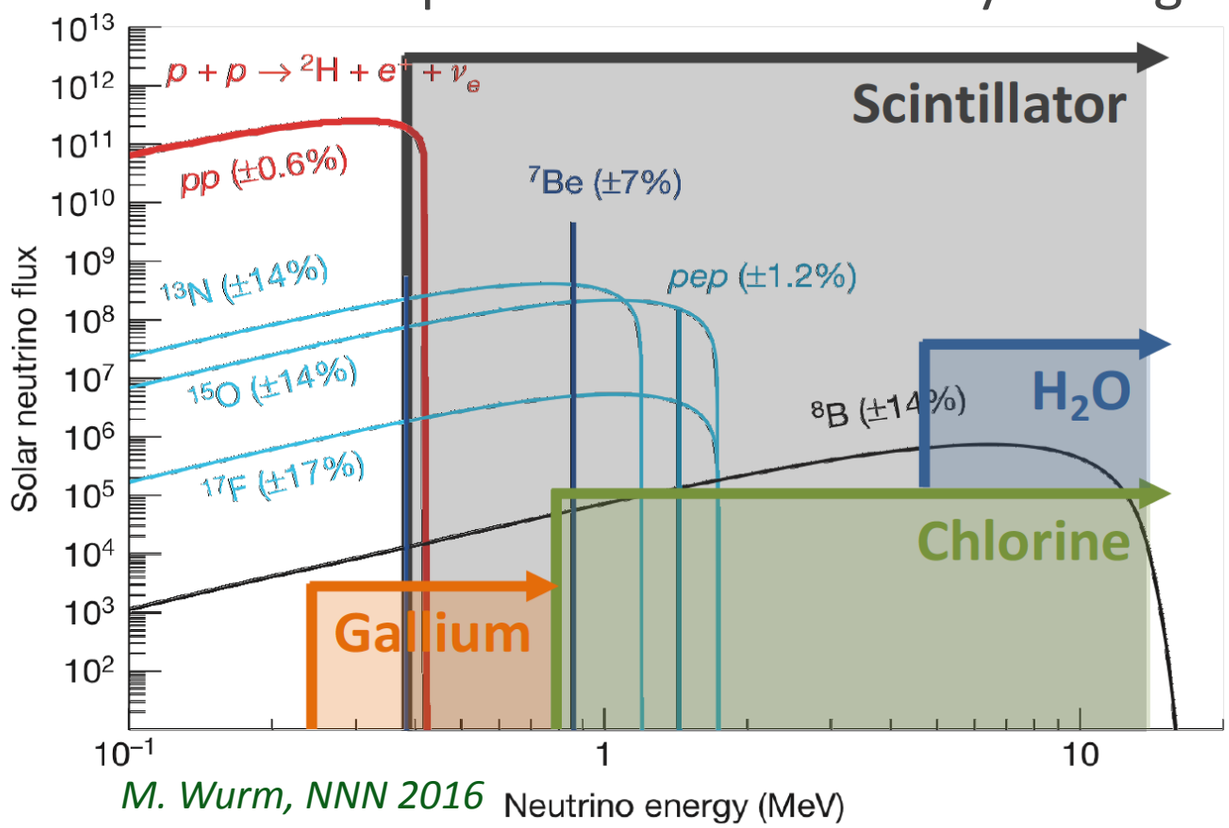
Solar Sector

Solar Neutrinos

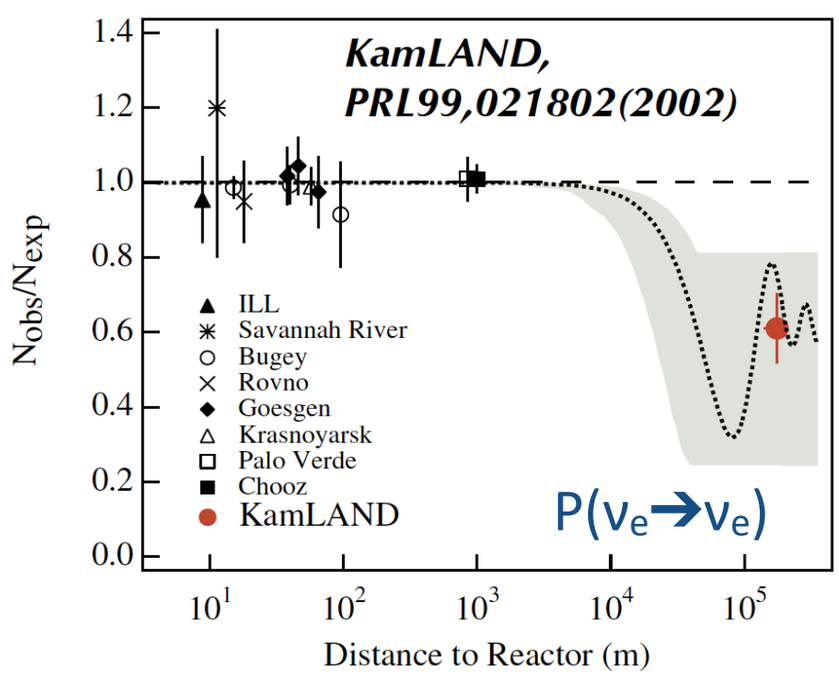
From Symmetry Magazine, 06/30/15

Solar Expts. and KamLAND Results

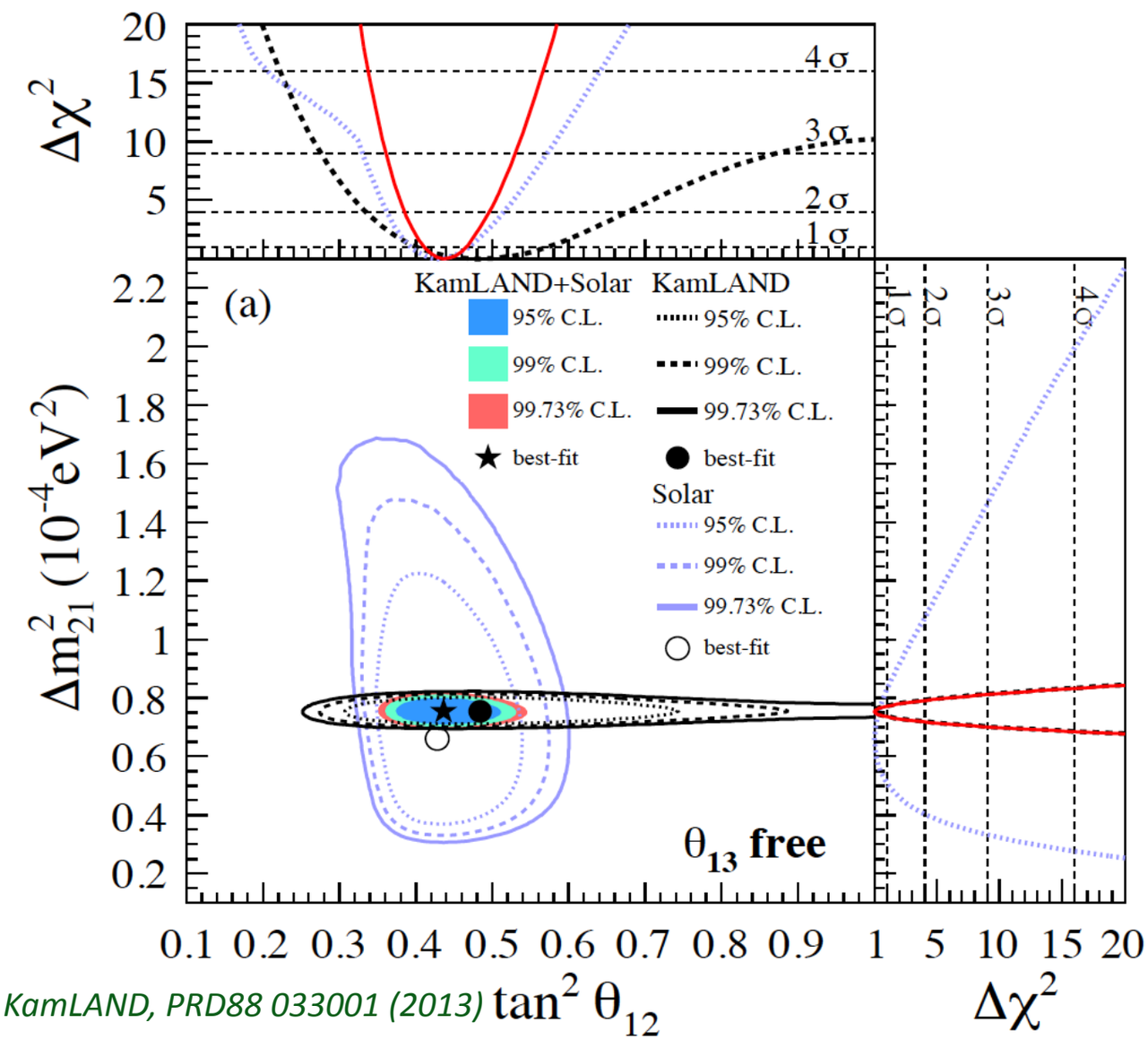
- First indication of solar ν_e disappearance from Homestake experiment started ~50 years ago



M. Wurm, NNN 2016



- SNO confirmed solar ν_e oscillate to ν_μ, ν_τ
- KamLAND long-baseline reactor experiment made precision measurement of Δm^2_{Sol}
- SNO+KamLAND combination provides most precise measurement of solar mixing params.



KamLAND, PRD88 033001 (2013)

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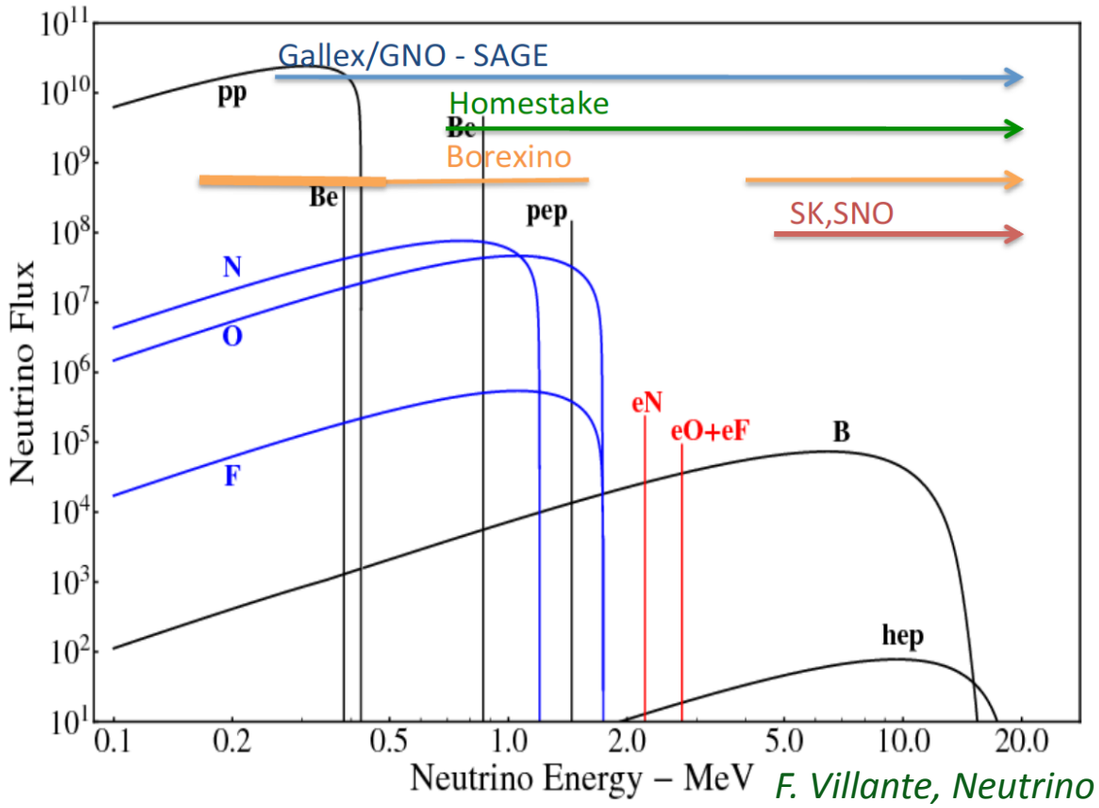
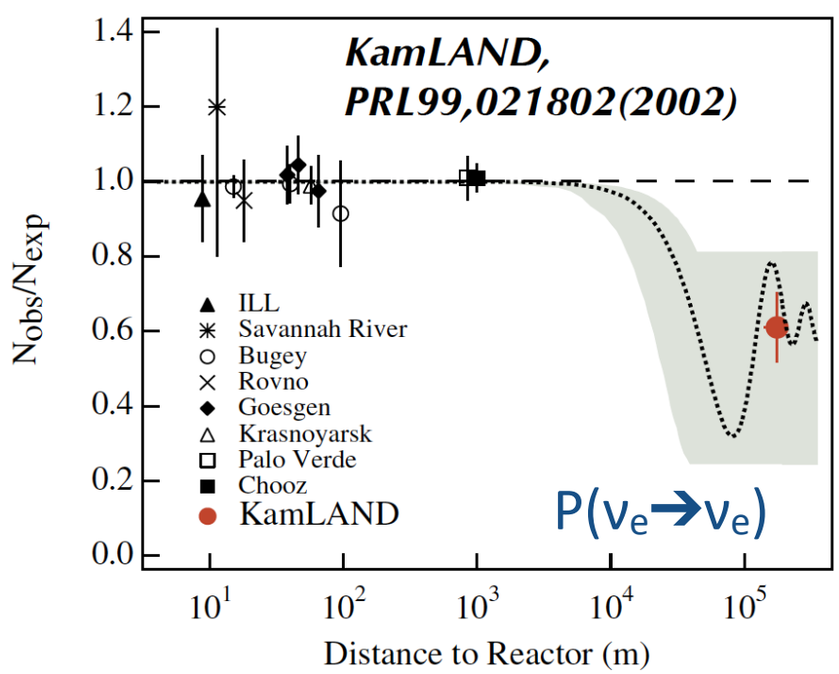


F. Villante, Neutrino 2016



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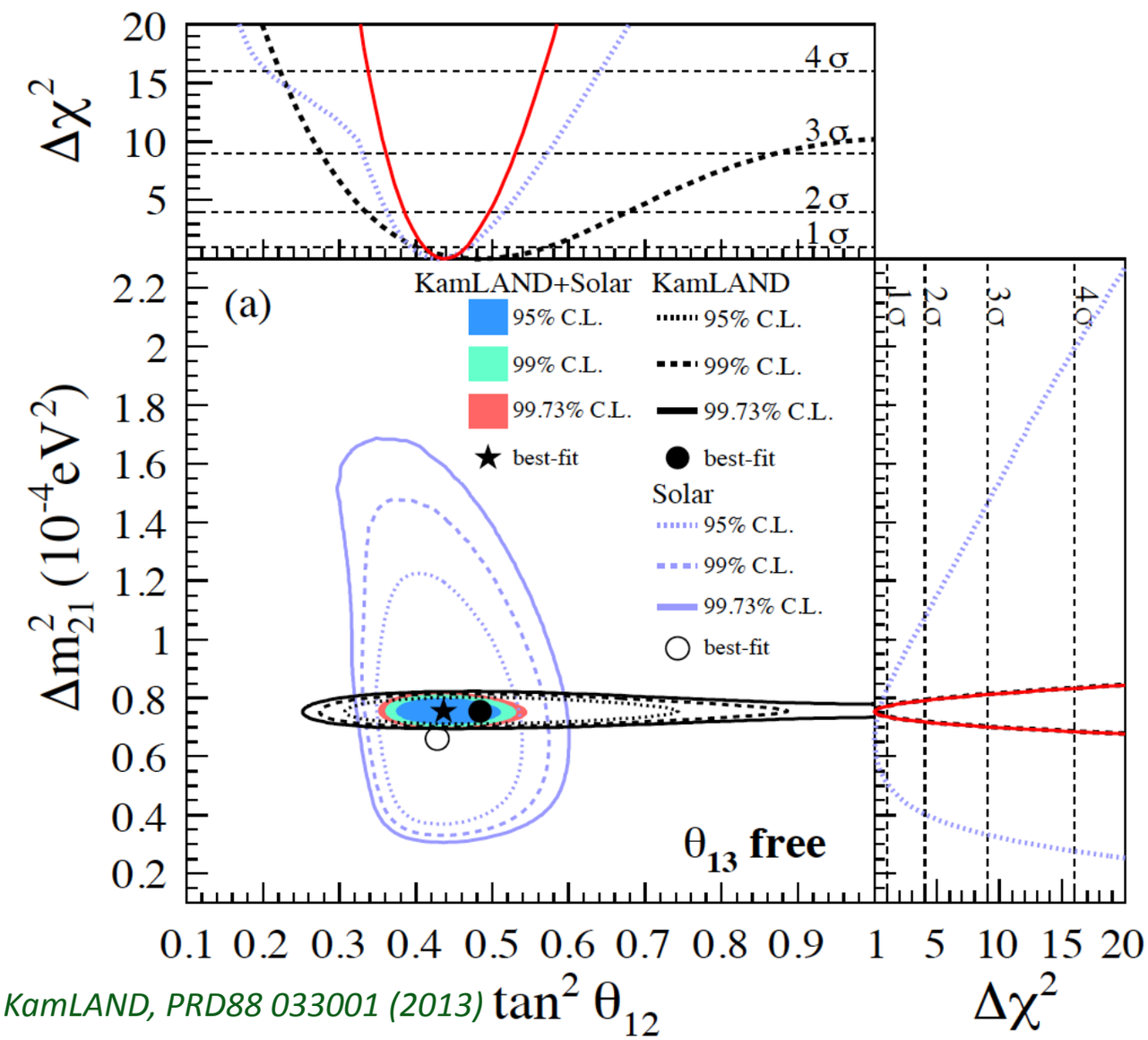
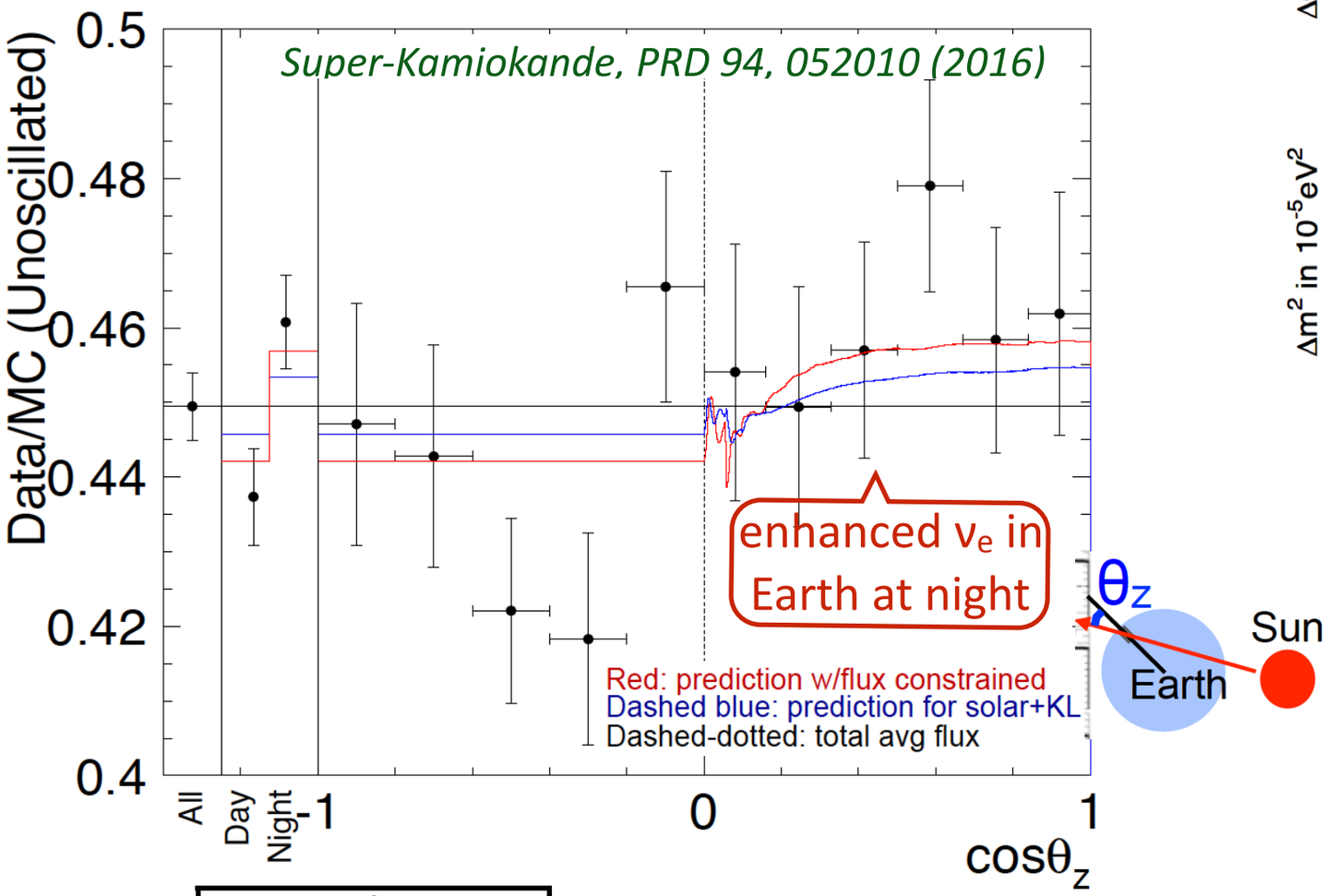


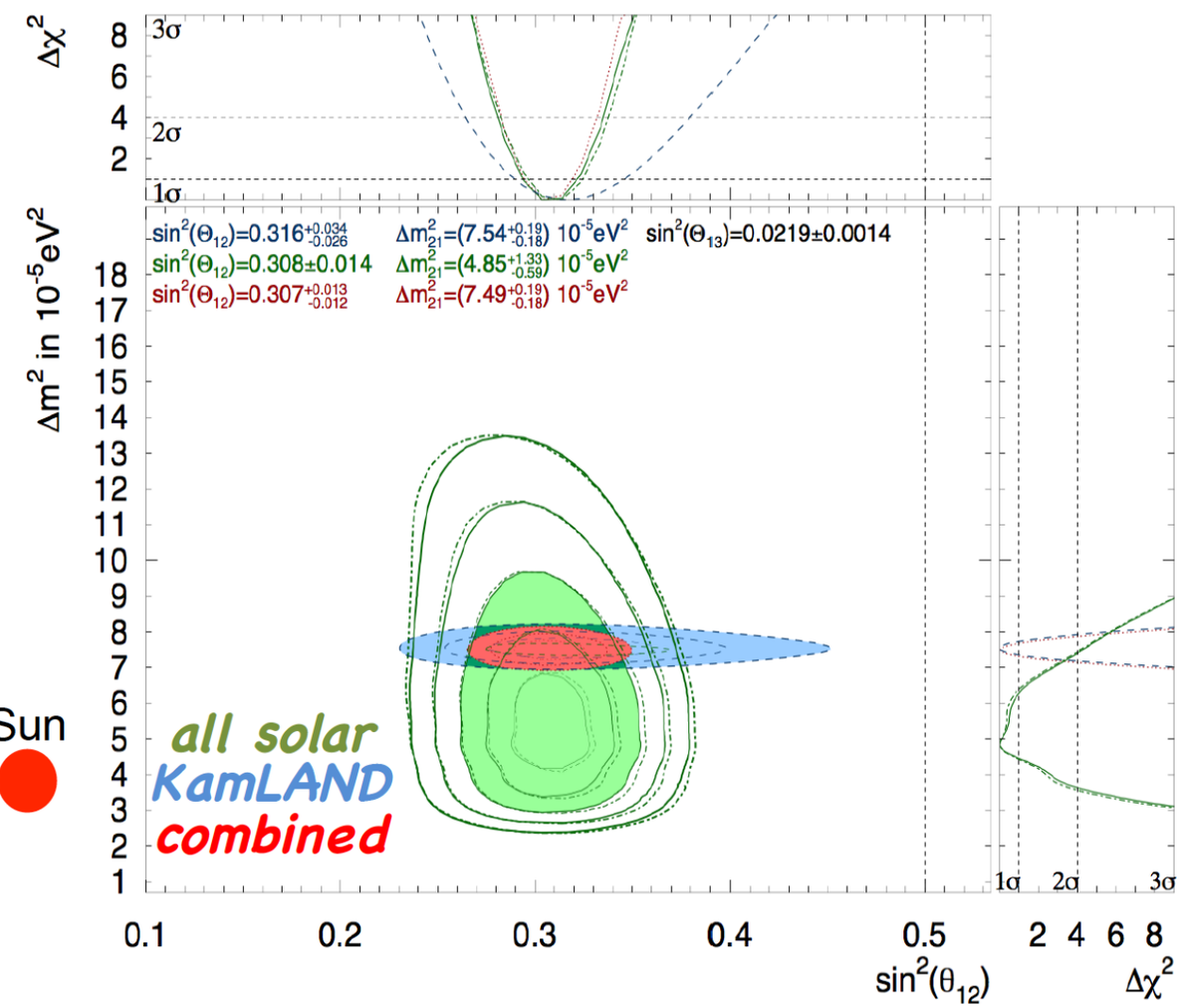
KamLAND, PRD88 033001 (2013)

SuperK Results

- Day/Night Asymmetry
  - Direct observation of matter effects



S. Moriyama, Neutrino 2016



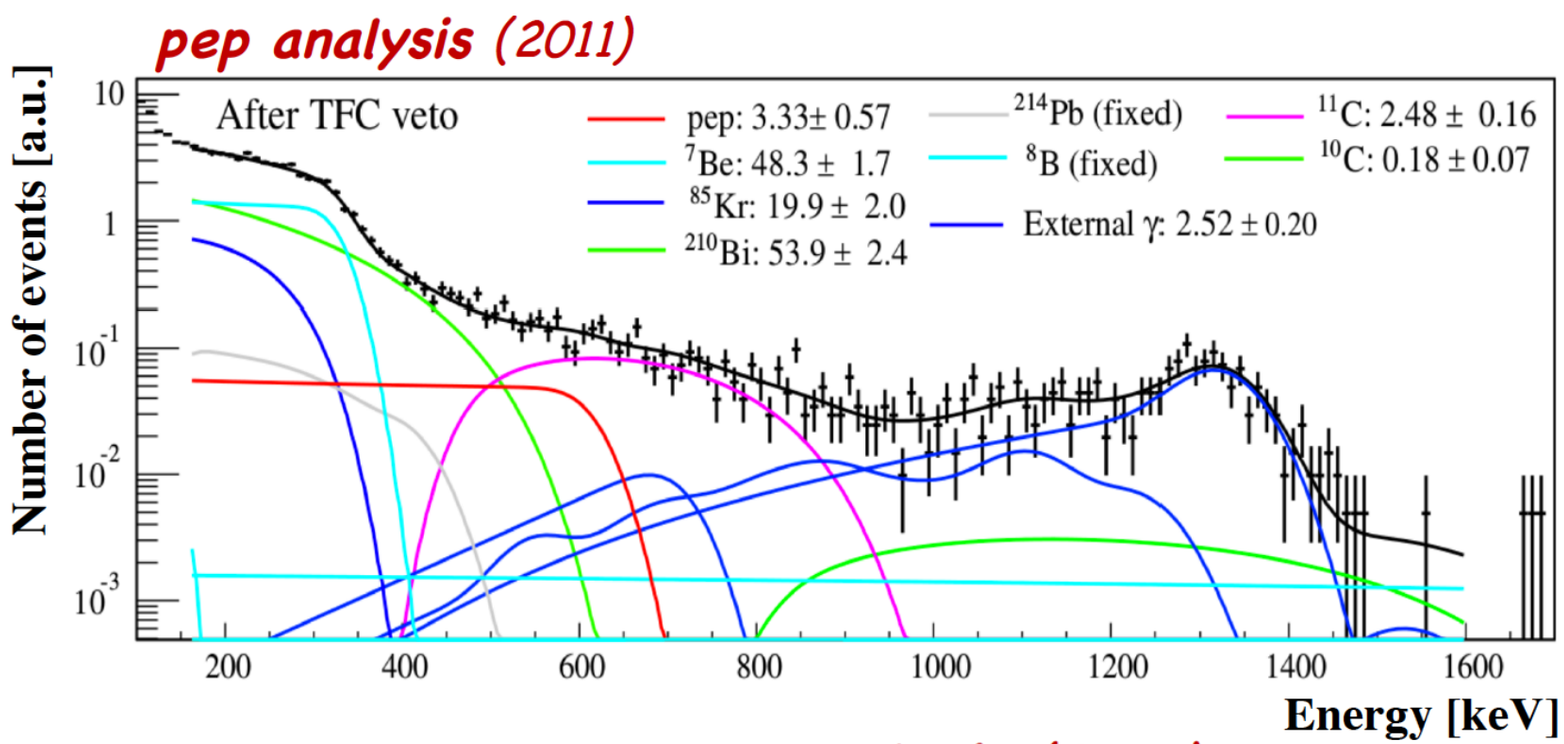
	A_{DN}^{fit}
SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	**-3.3±1.0±0.5%**
non-zero significance	3.0 σ

S. Moriyama, Neutrino 2016

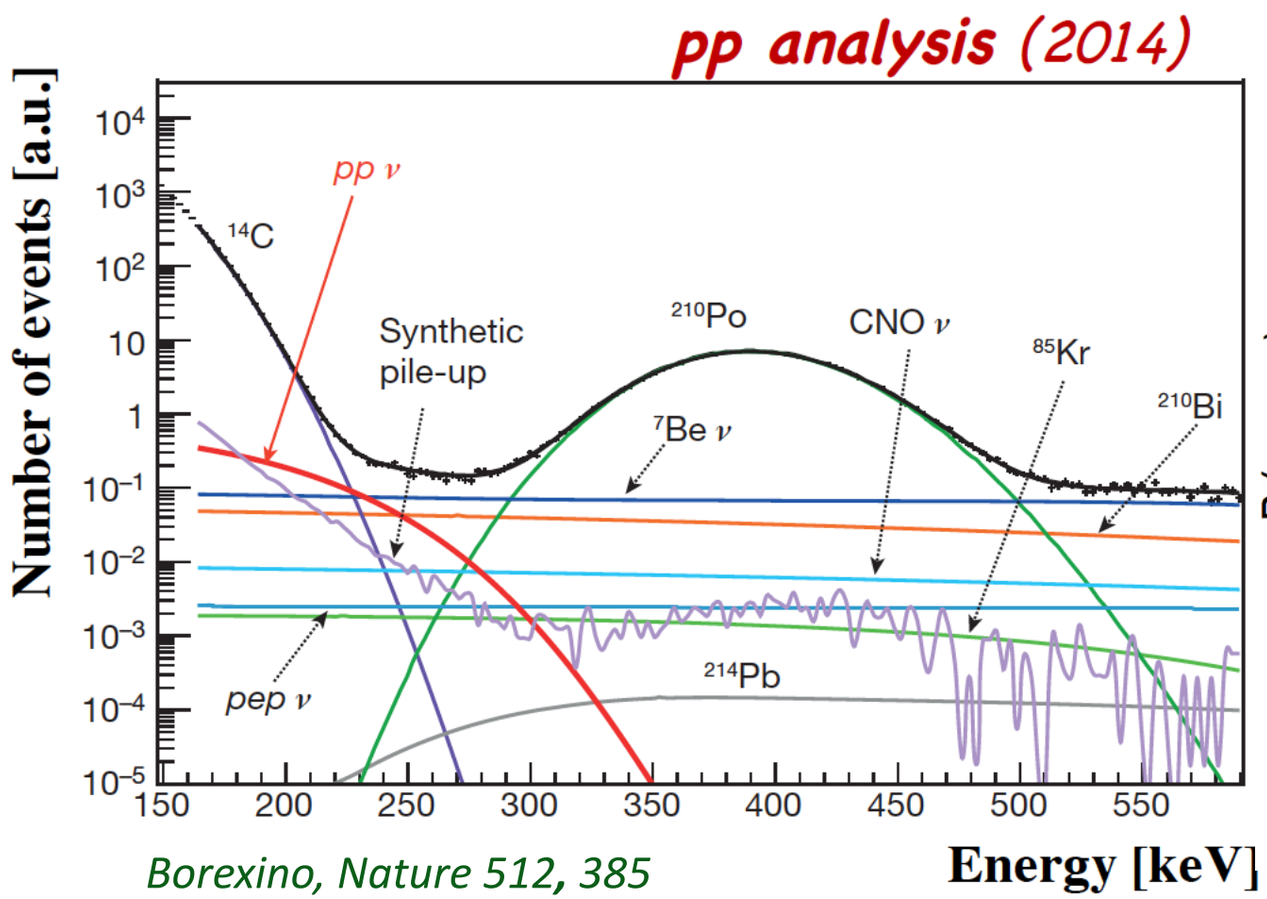
$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$

- SuperK data prefers lower value of Δm^2_{Sol}
  - 5×10^{-5} vs. 7×10^{-5} eV^2
  - 2σ tension with KamLAND

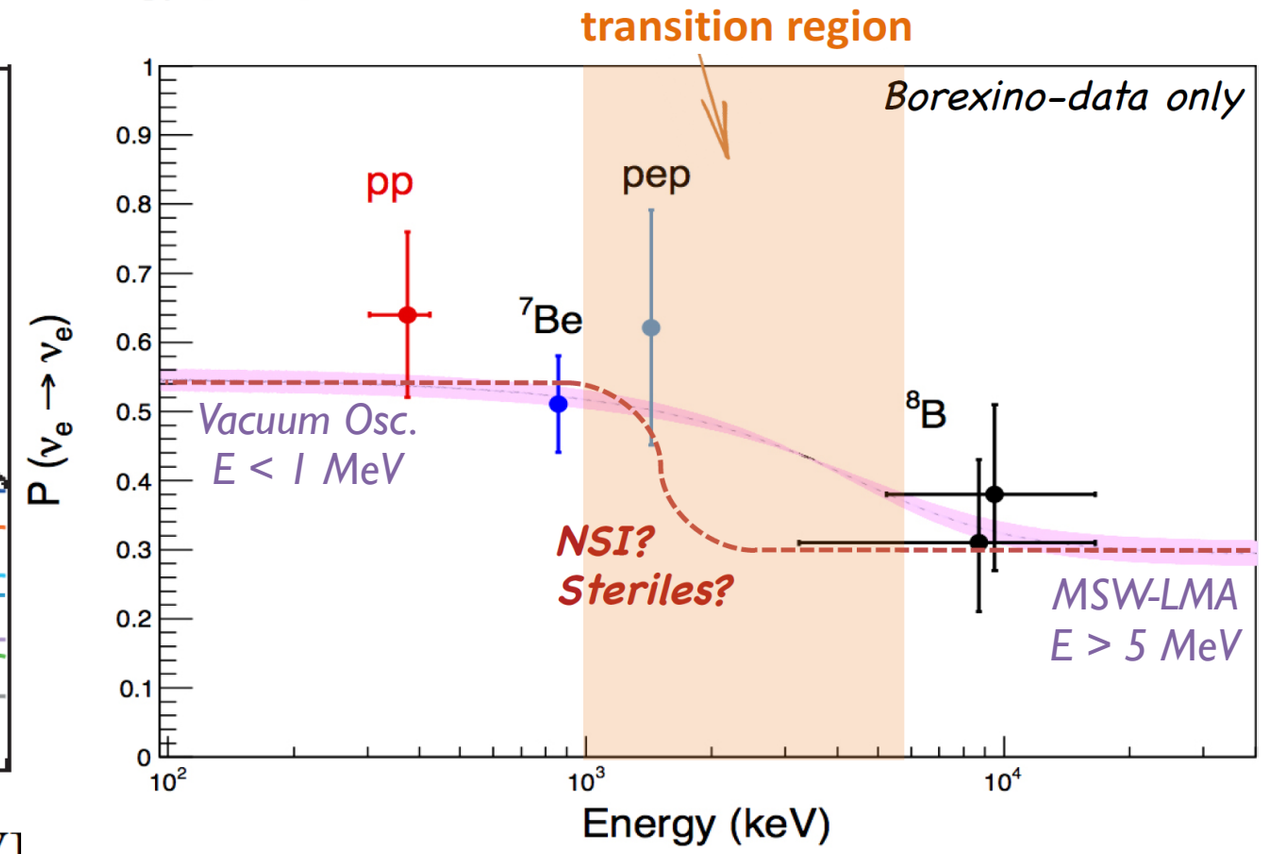
Borexino Results



- Measurements in real-time of *pp* and *pep* neutrinos
- New physics may be hiding in transition region
  - Borexino phase-2 data
  - SuperK with 2.5 MeV threshold
- Future efforts: SNO+, JUNO, HyperK, THEIA, LENS, CLEAN, DARWIN, Argo…

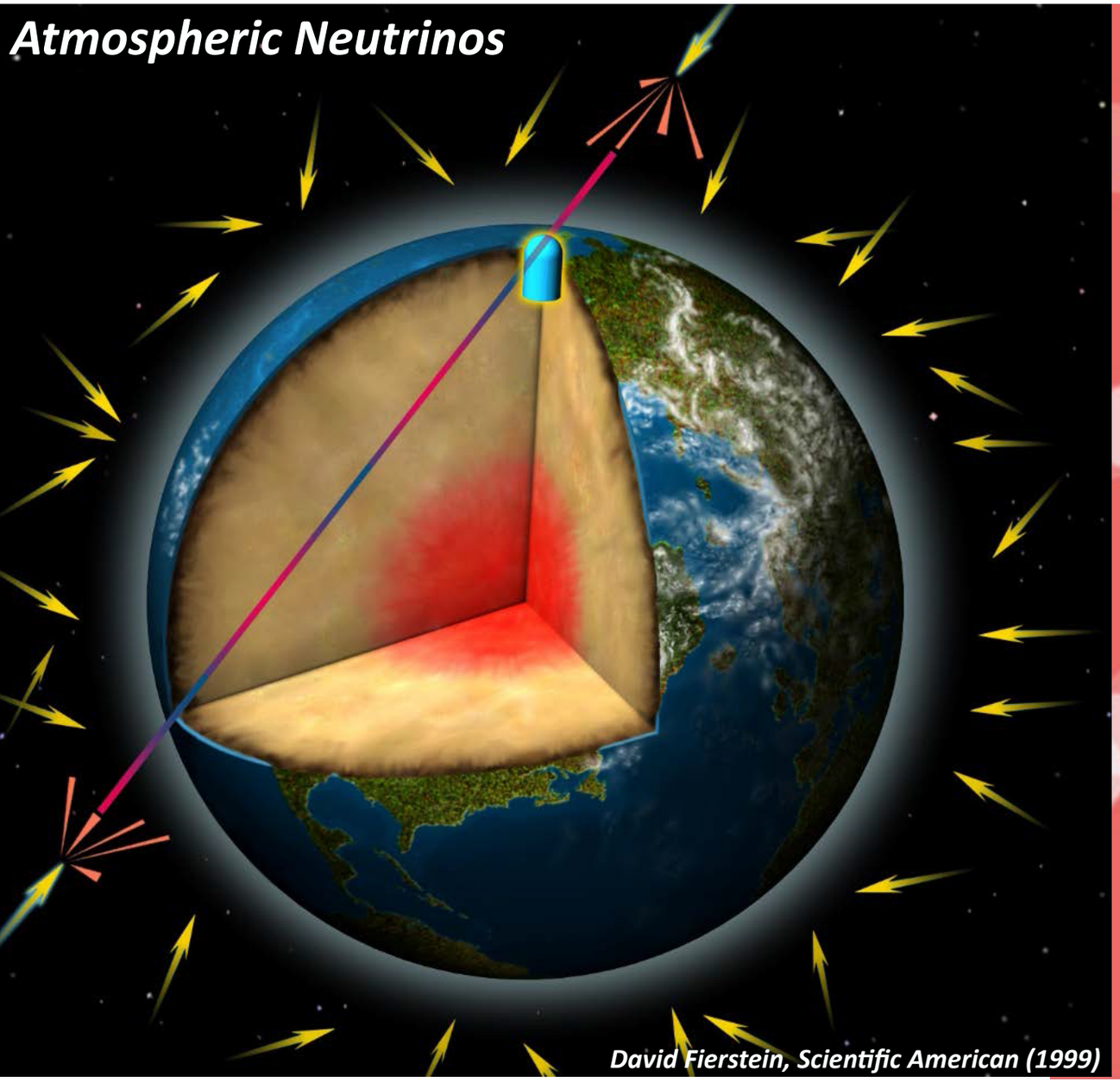


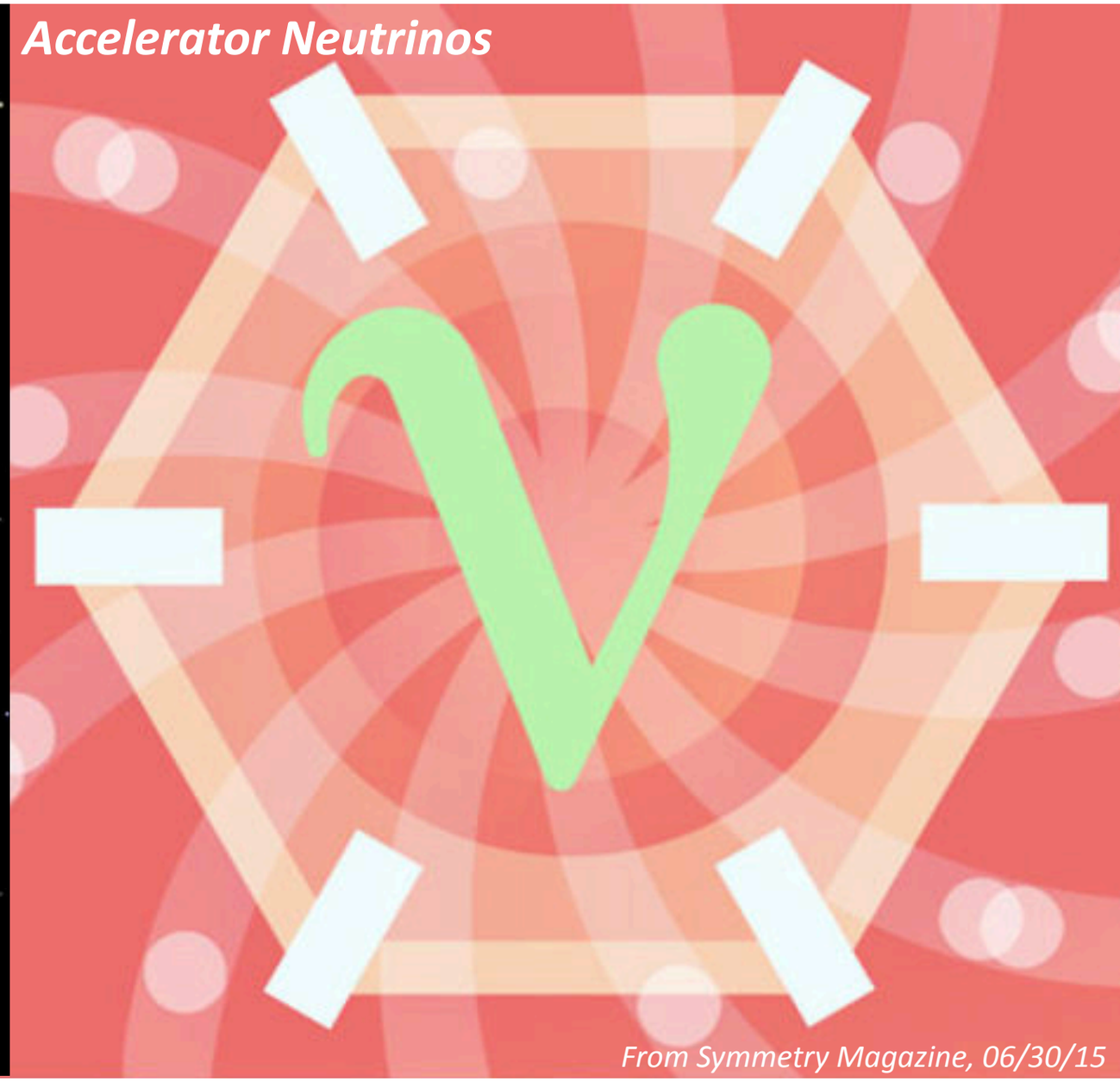
Borexino, Nature 512, 385



M. Wurm, NNN 2016

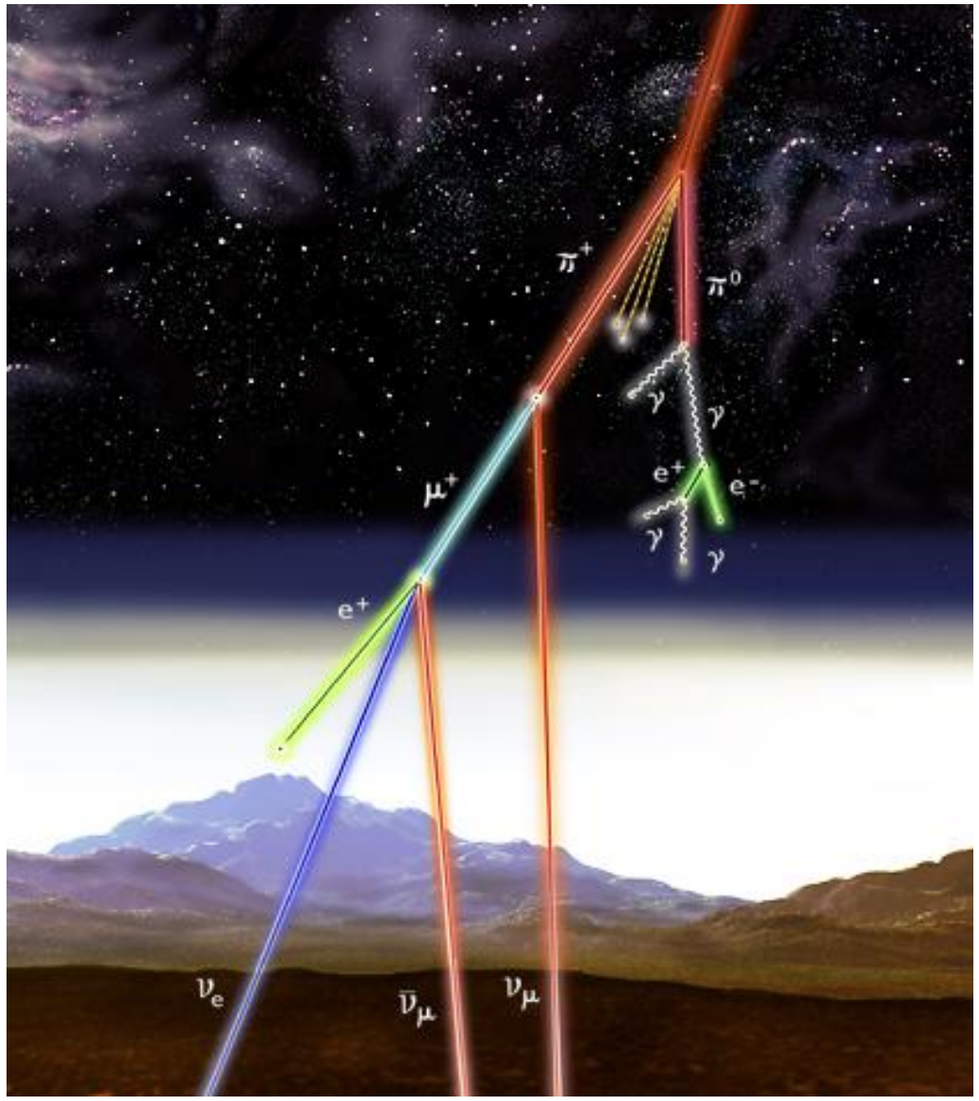
Answering the Questions…



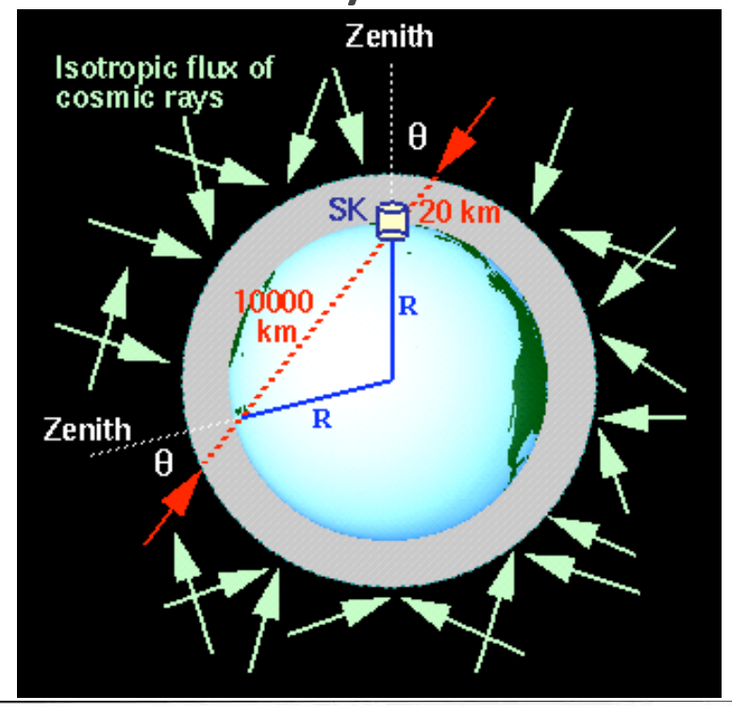


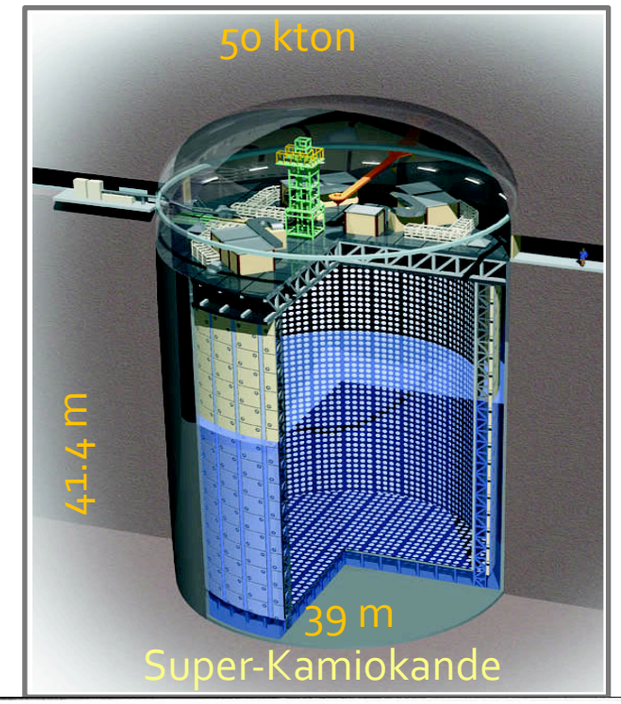
Atmospheric Sector

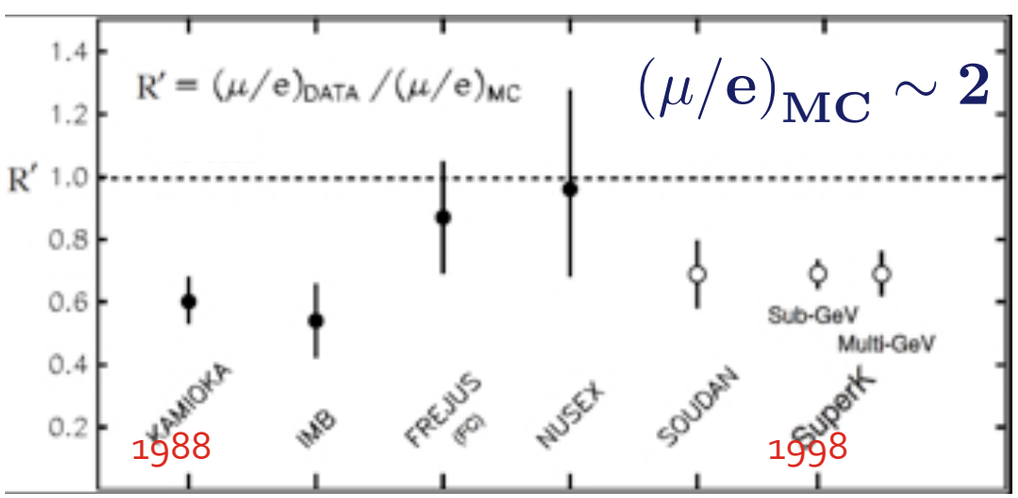
Atmospheric Sector

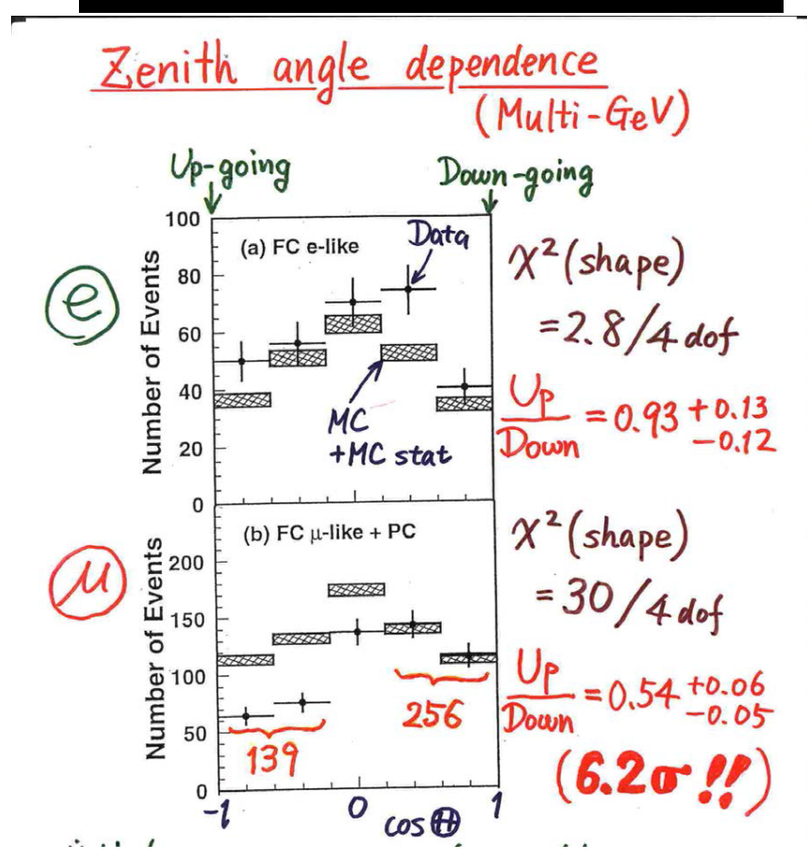


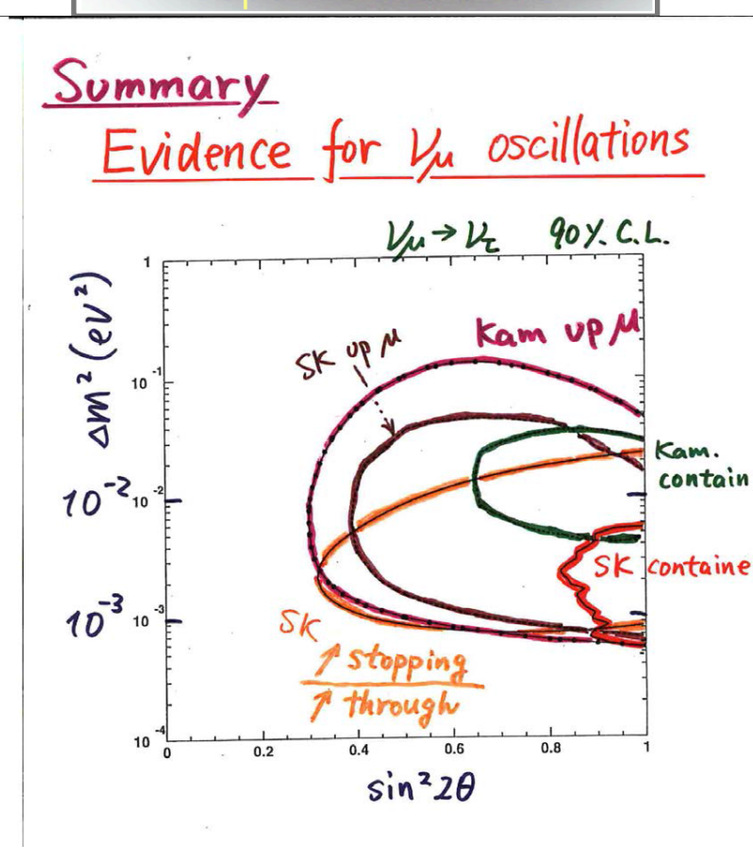
- Discovery of Neutrino Oscillations





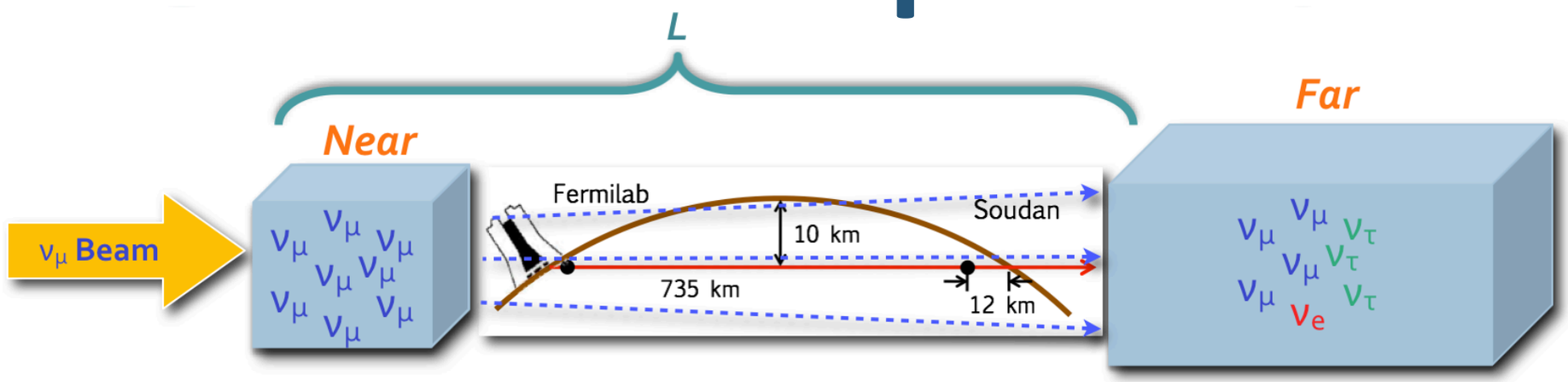




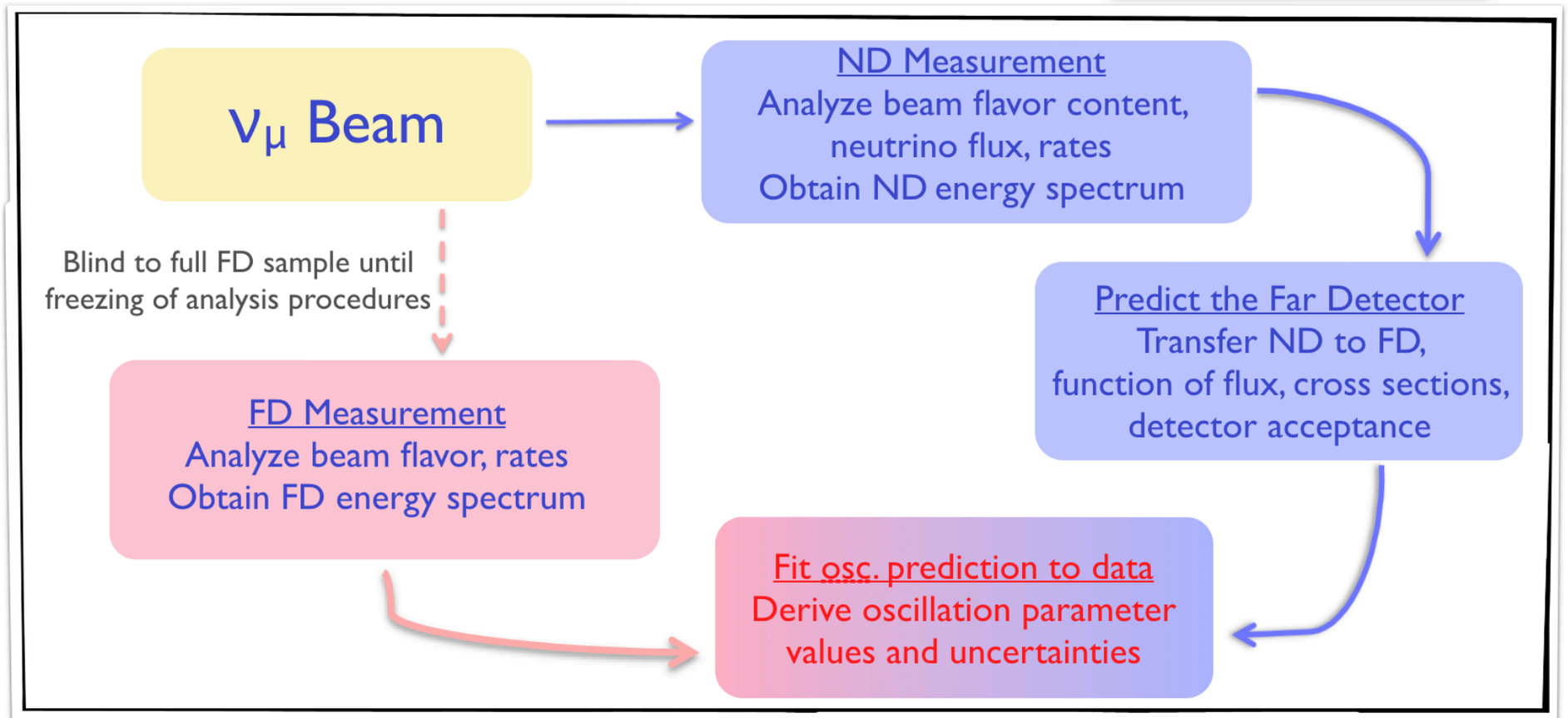


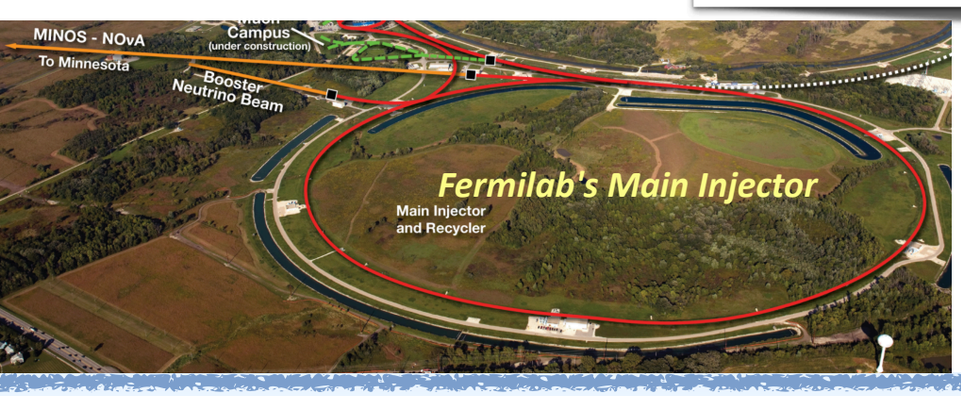
T. Kajita, Nobel Lecture (2015)

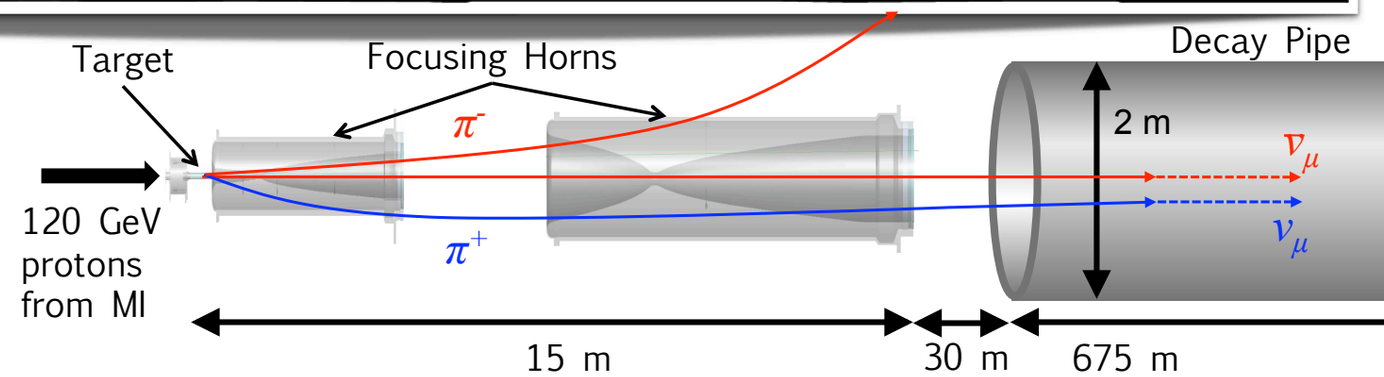
Accelerator Neutrino Experiments



- Create intense neutrino source with well-understood flux
- Multi-detector approach allows for partial cancellation of systematic uncertainties







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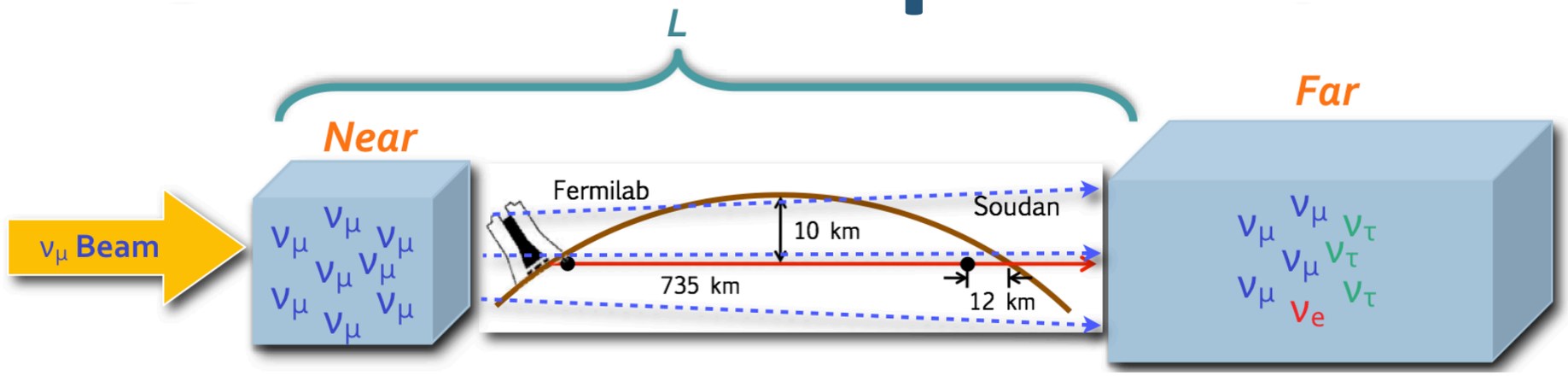
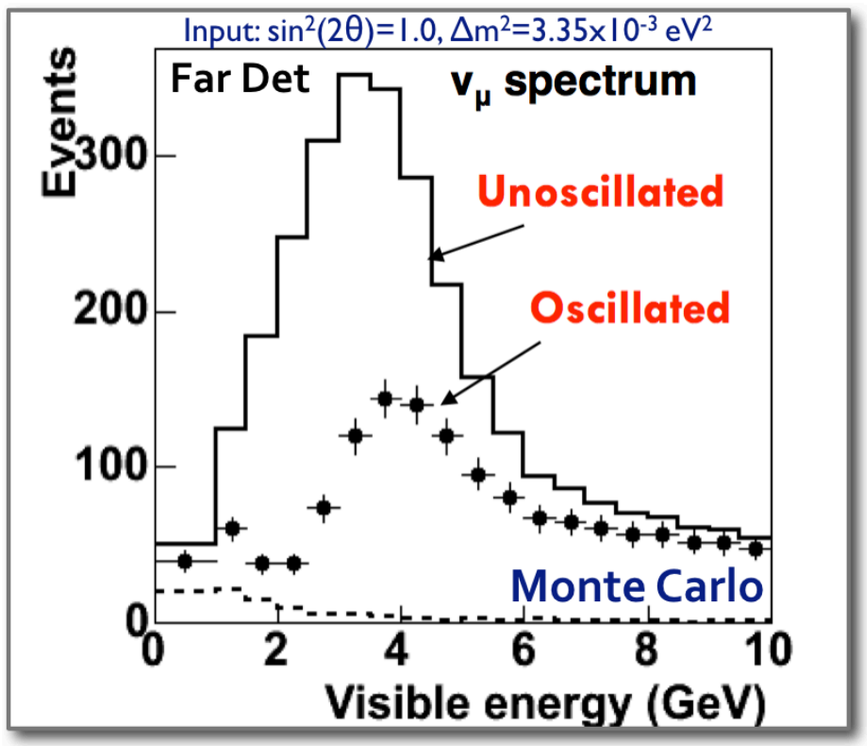
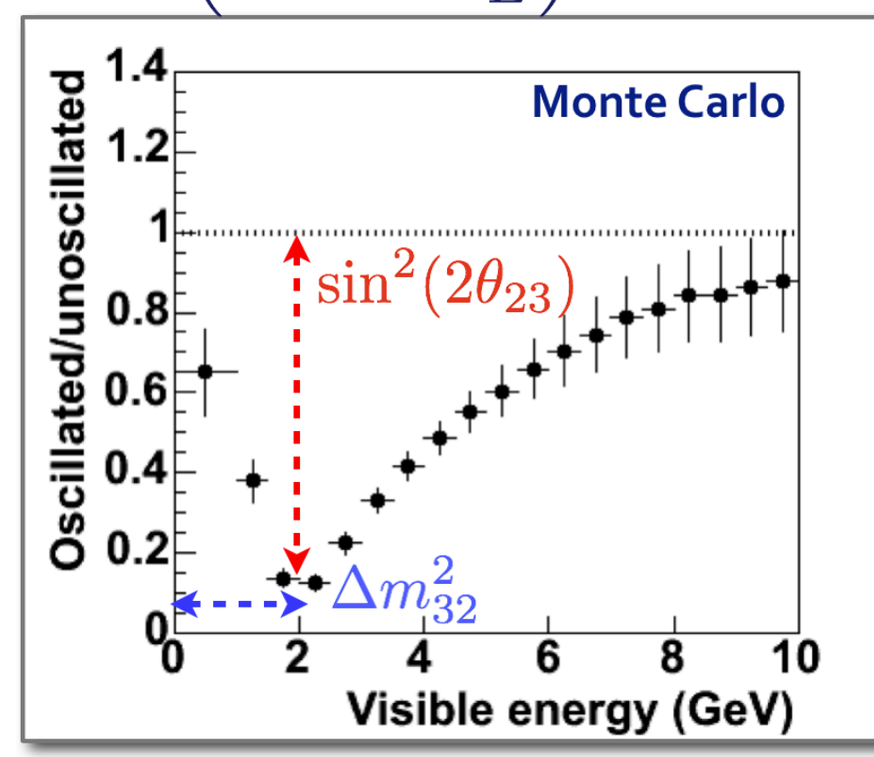
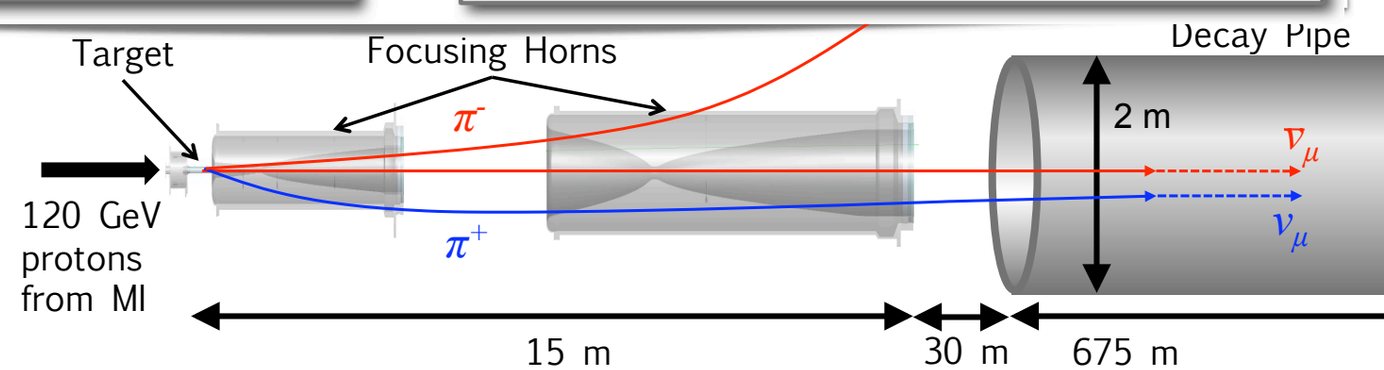


$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$

- Create intense neutrino source with well-understood flux
- Multi-detector approach allows for partial cancellation of systematic uncertainties







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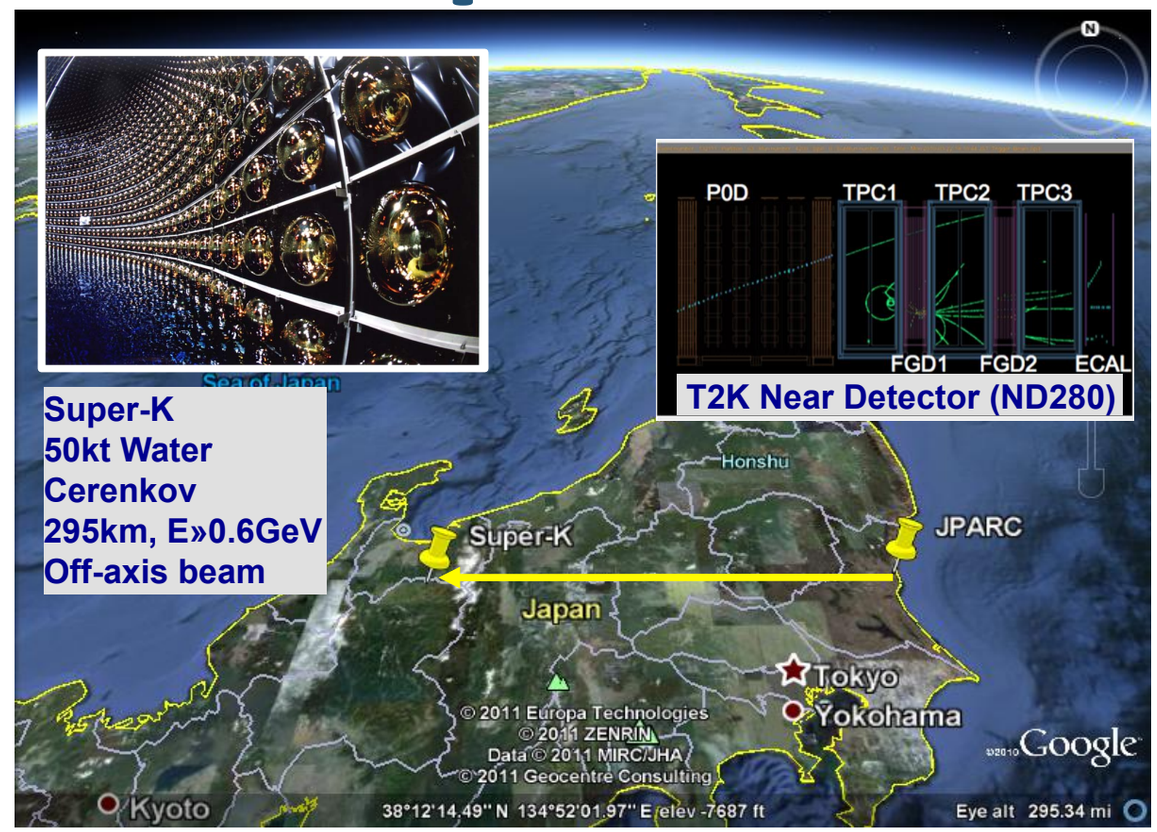
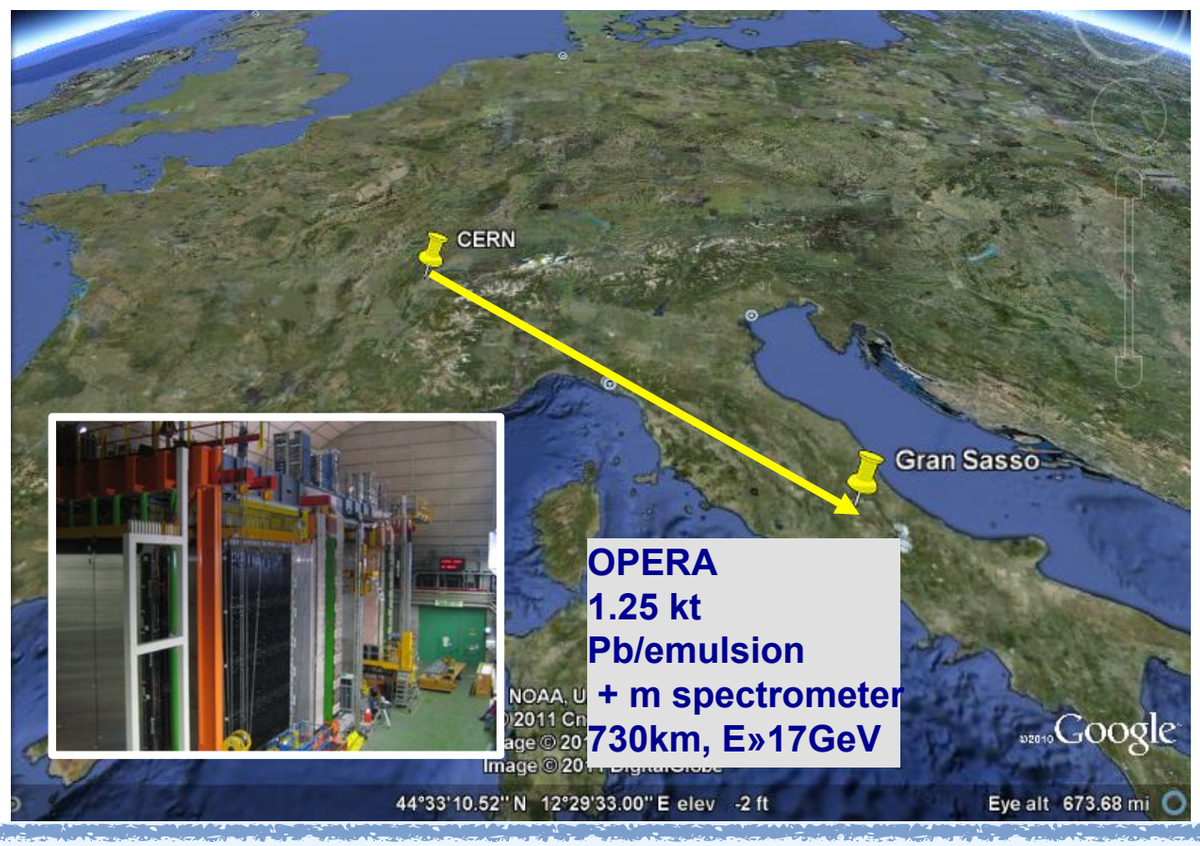
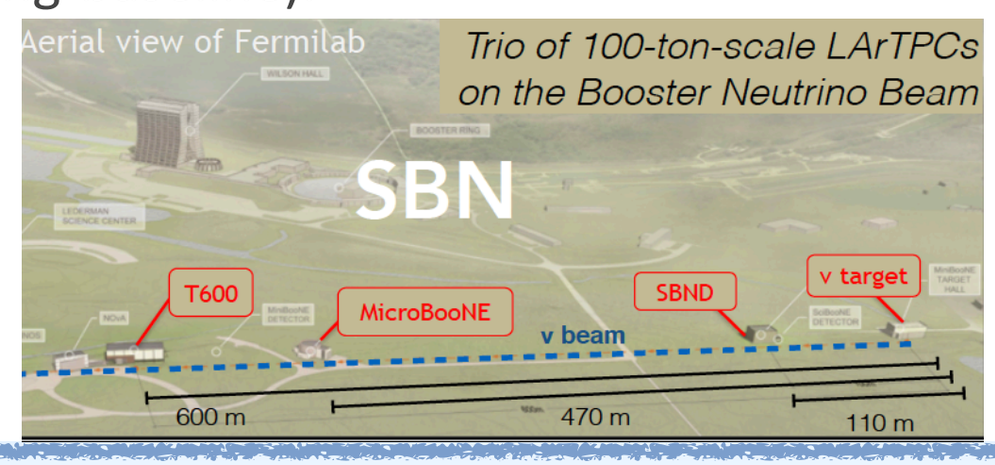
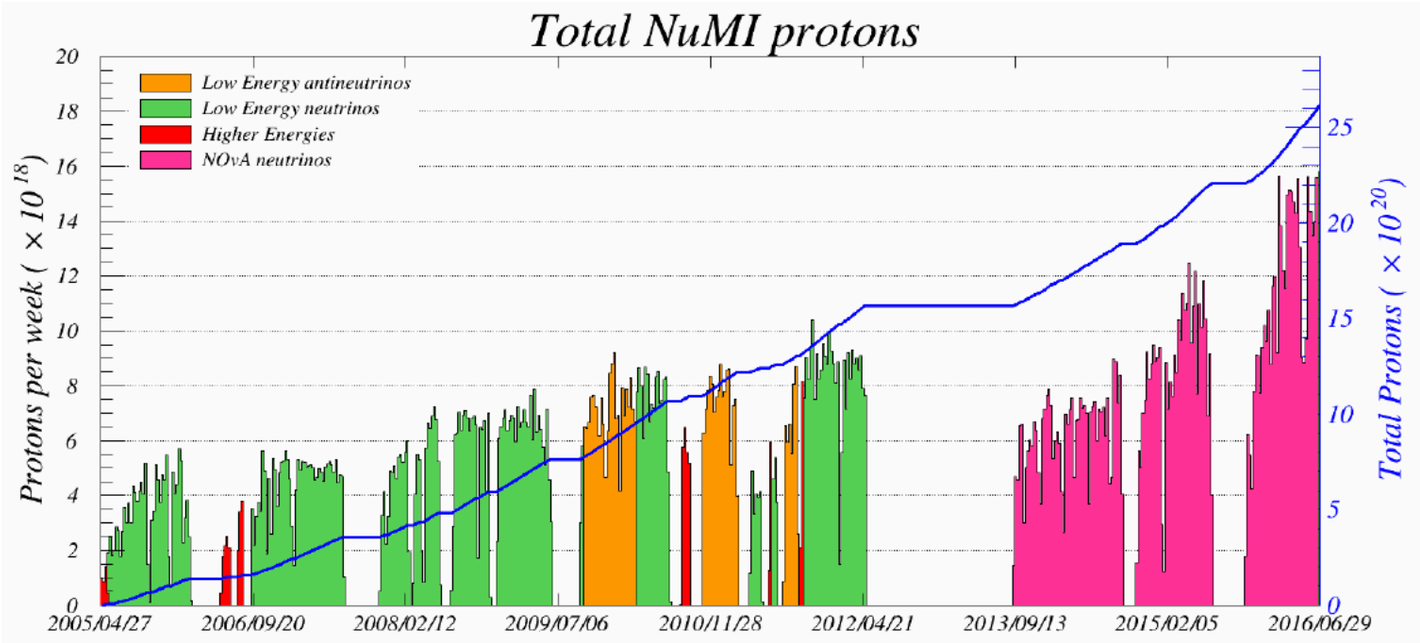




- Neutrino beams around the World: US (NuMI and Booster), Europe (CNGS) and Japan (JPARC)
- Baselines range from a few hundreds of meters (short-baseline) to hundreds (300-1300) of km (long-baseline).



MINOS/MINOS+ Results



Normal hierarchy

$$\Delta m^2_{32} = 2.42 \pm 0.09 \times 10^{-3}\ \mathrm{eV}^2\ (68\%\ \mathrm{C.L.})$$

$$\sin^2\theta_{23} = 0.35 - 0.65\ (90\%\ \mathrm{C.L.})$$

Inverted hierarchy

$$\Delta m^2_{32} = -2.48^{+0.09}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2\ (68\%\ \mathrm{C.L.})$$

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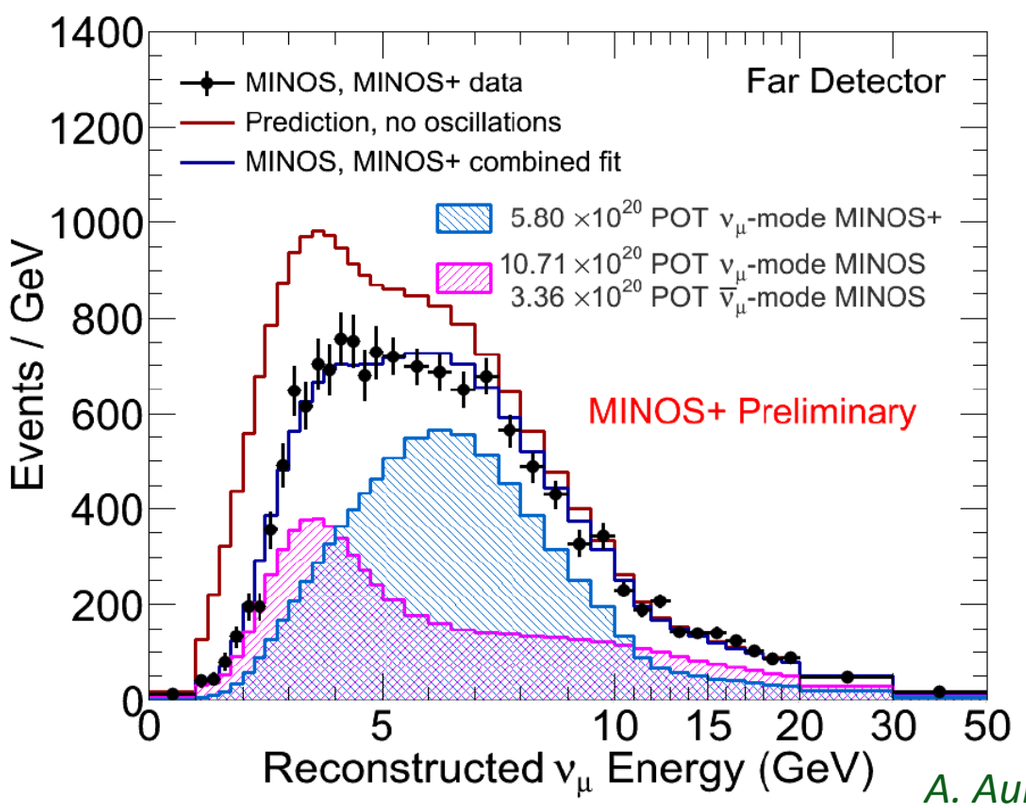
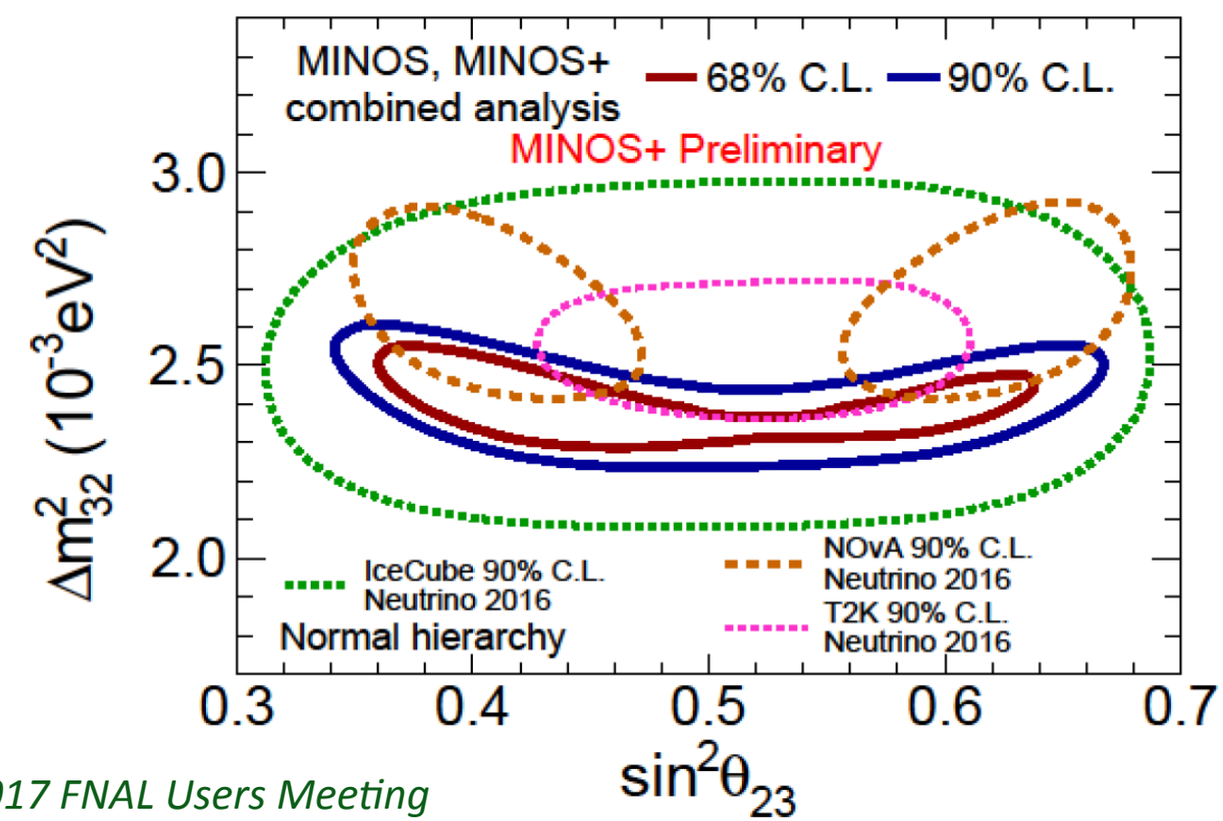
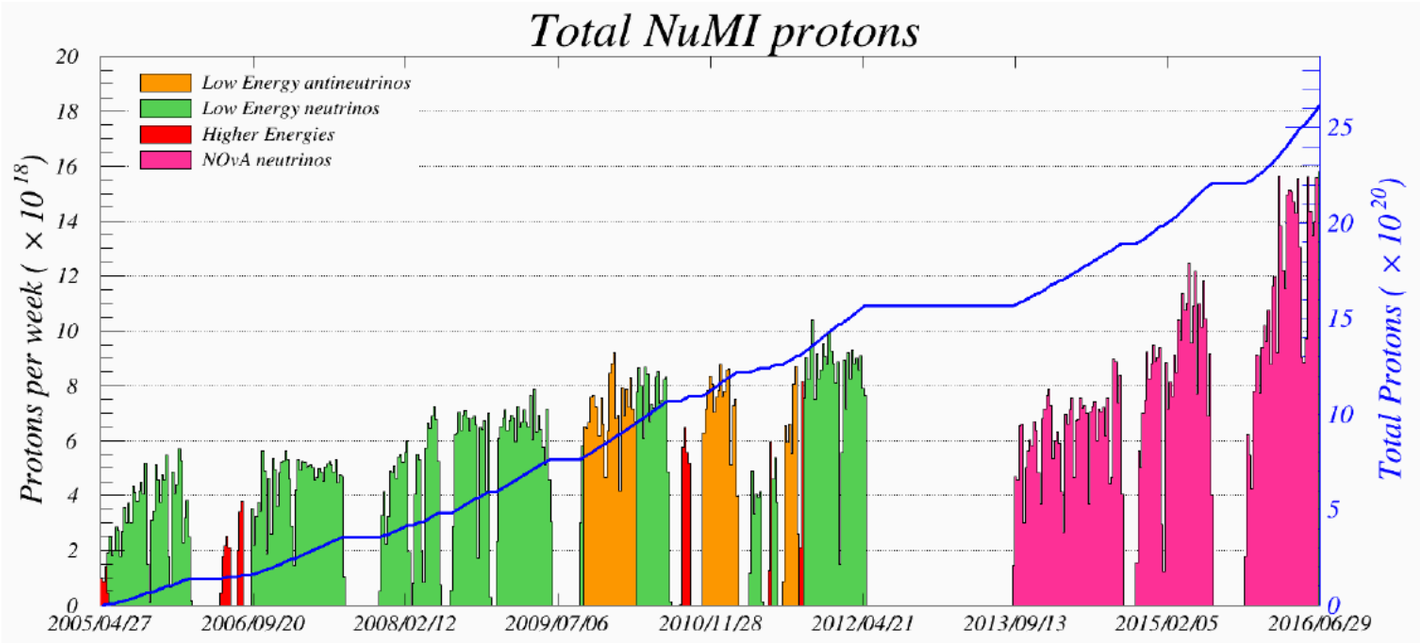
- Exposure of 25x10^{20} POT collected in 11 years of running
- MINOS+ running used higher-energy beam
- Look for ν_μ disappearance - Most precise measurement of Δm^2_{32}





A. Aurisano, 2017 FNAL Users Meeting

MINOS/MINOS+ Results



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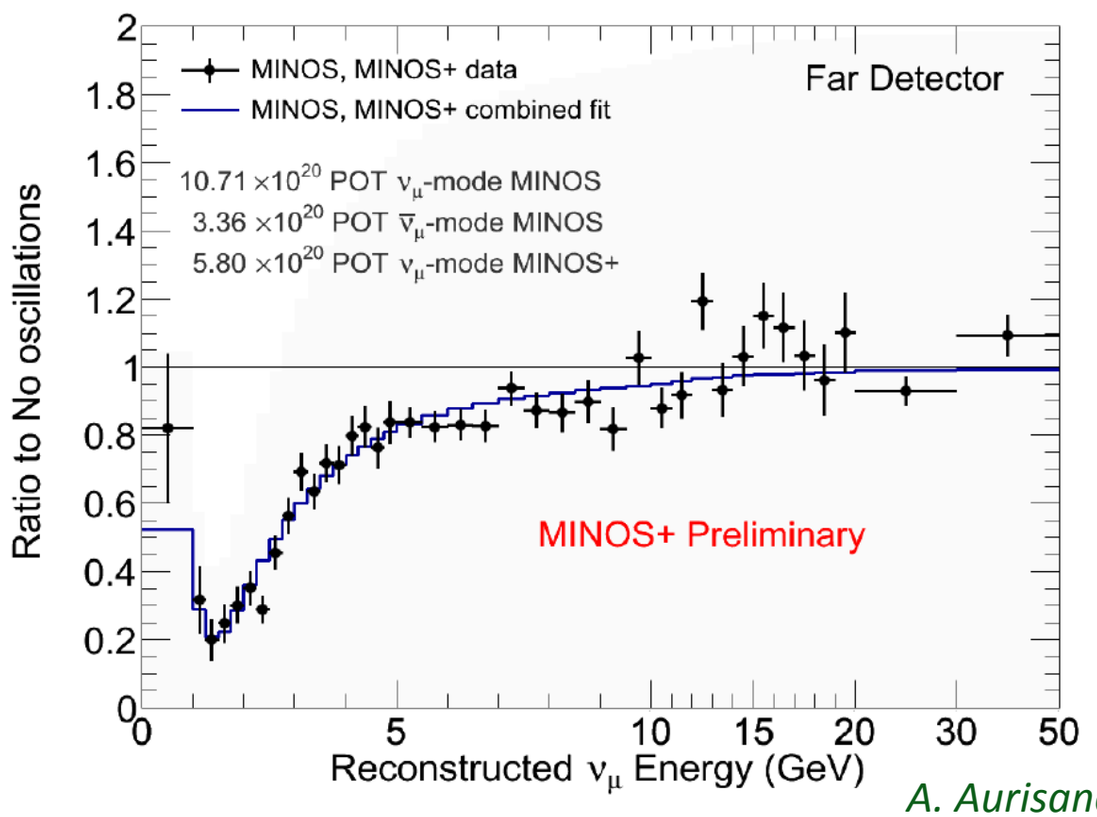
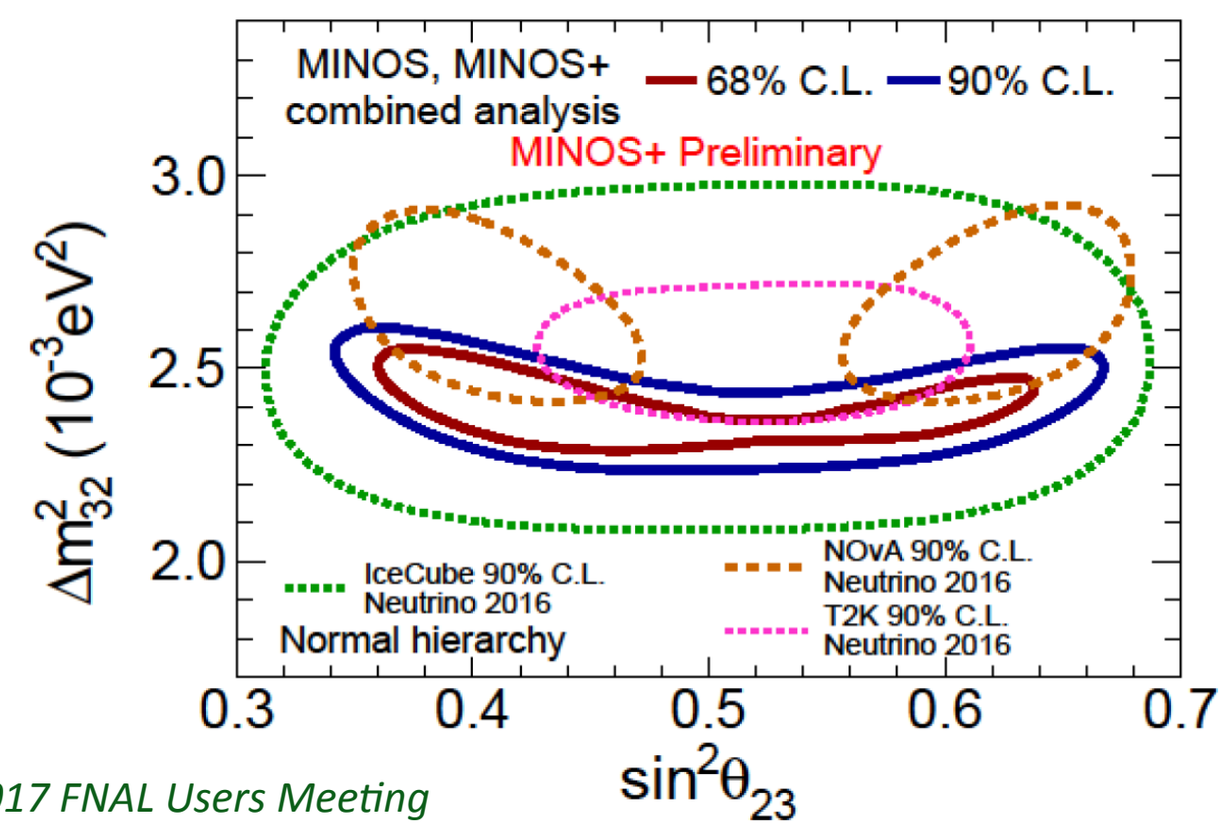
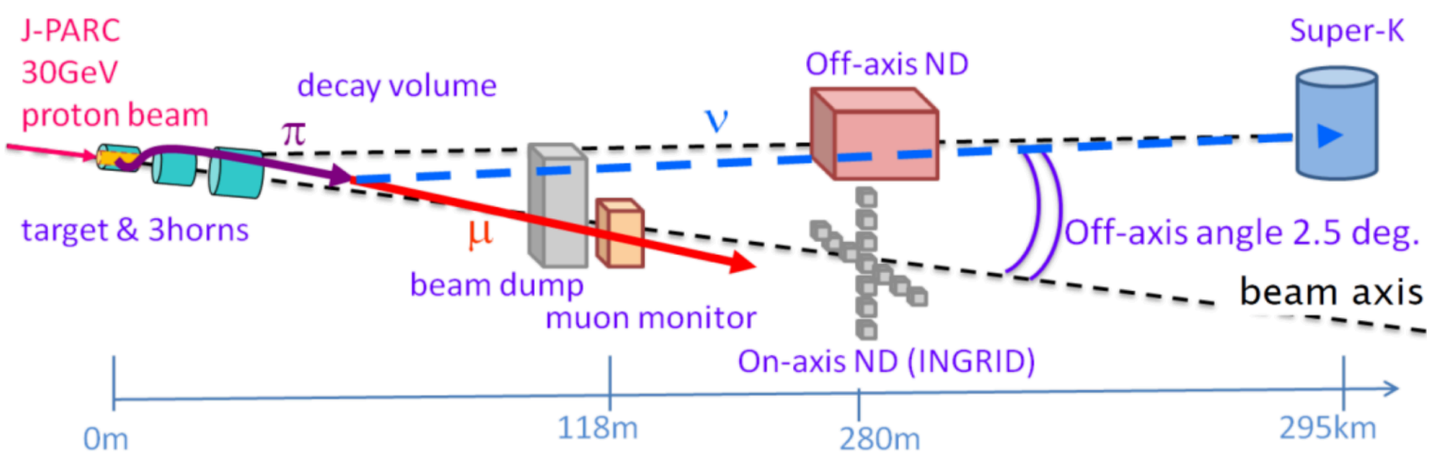
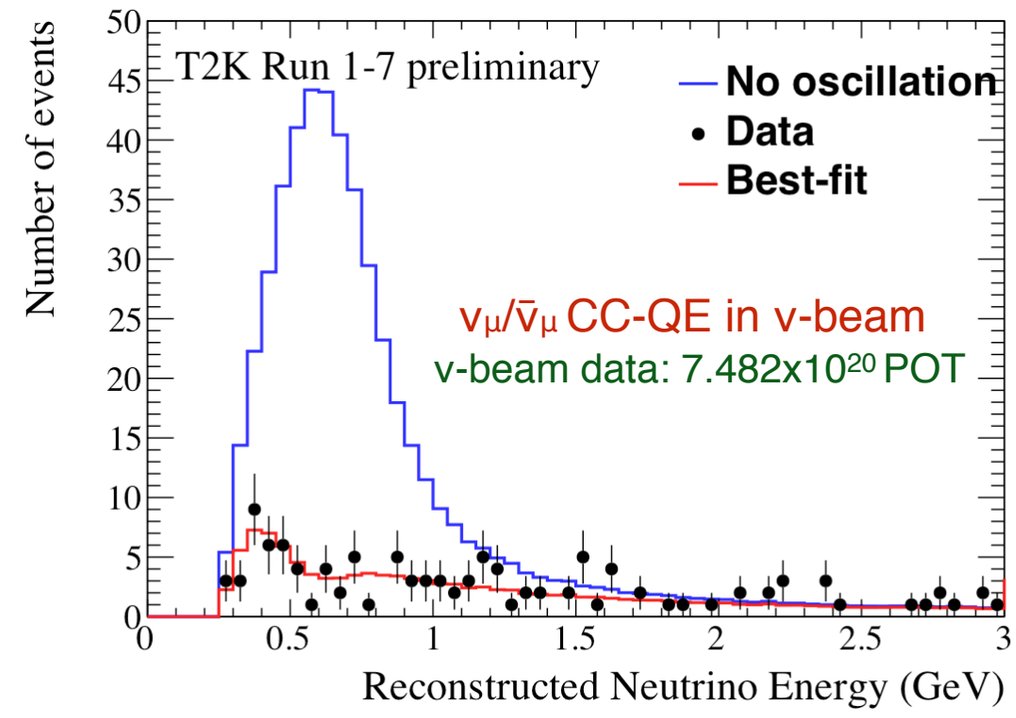




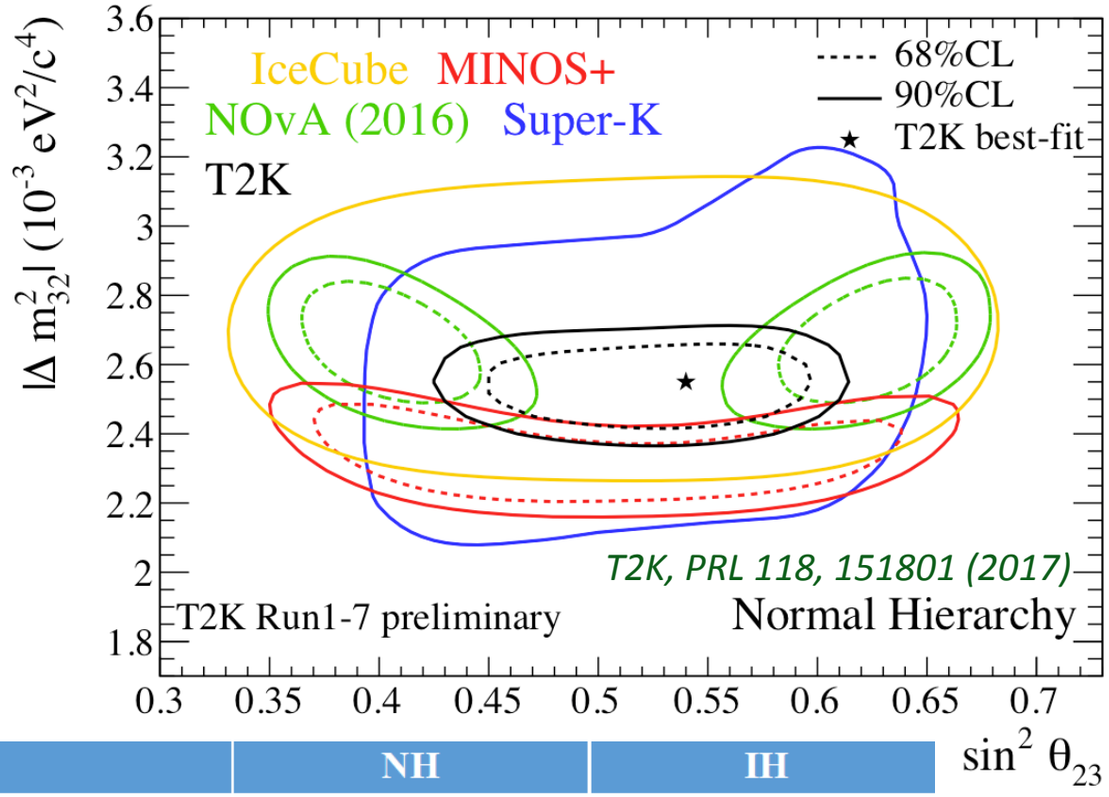
A. Aurisano, 2017 FNAL Users Meeting

T2K Results

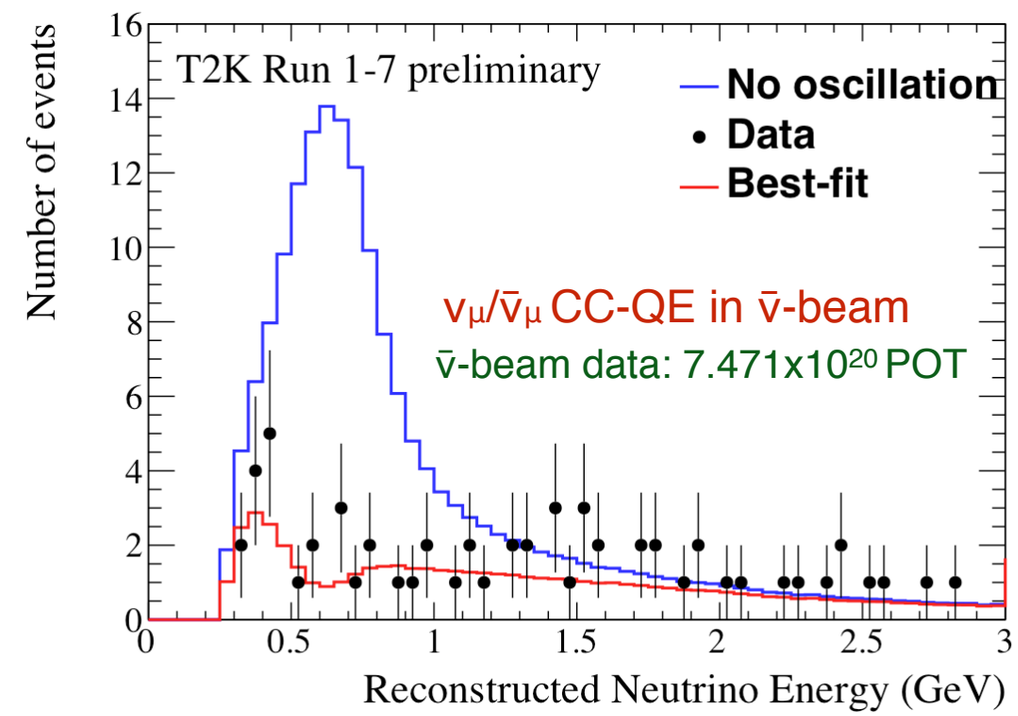




- Detectors placed 2.5° off-axis - narrow-band beam and large reduction of feed-down backgrounds
- Combined $\nu_\mu/\bar{\nu}_\mu$ disappearance analysis consistent with maximal mixing ($\sin^2\theta_{23}$=0.5) and maximal disappearance ($\sin^2\theta_{23}$=0.514)



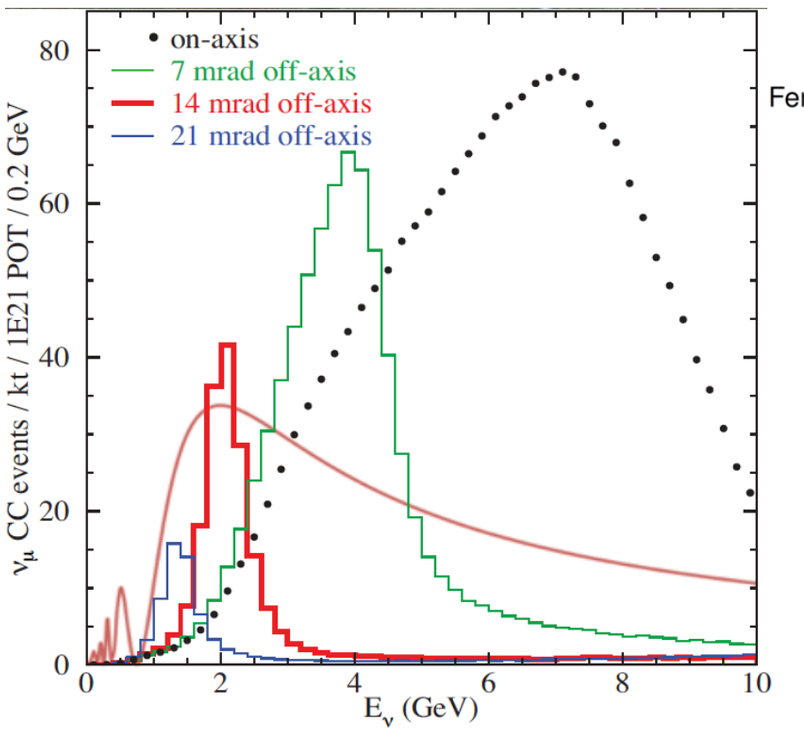
	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\mathrm{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

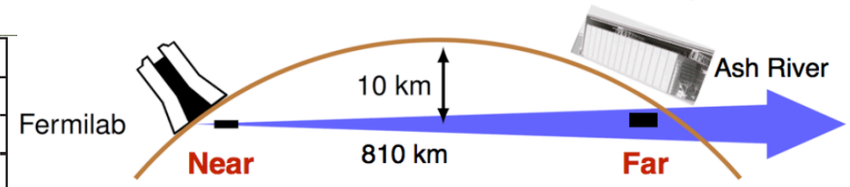


T. Nakadaira, Rencontres de Moriond 2017

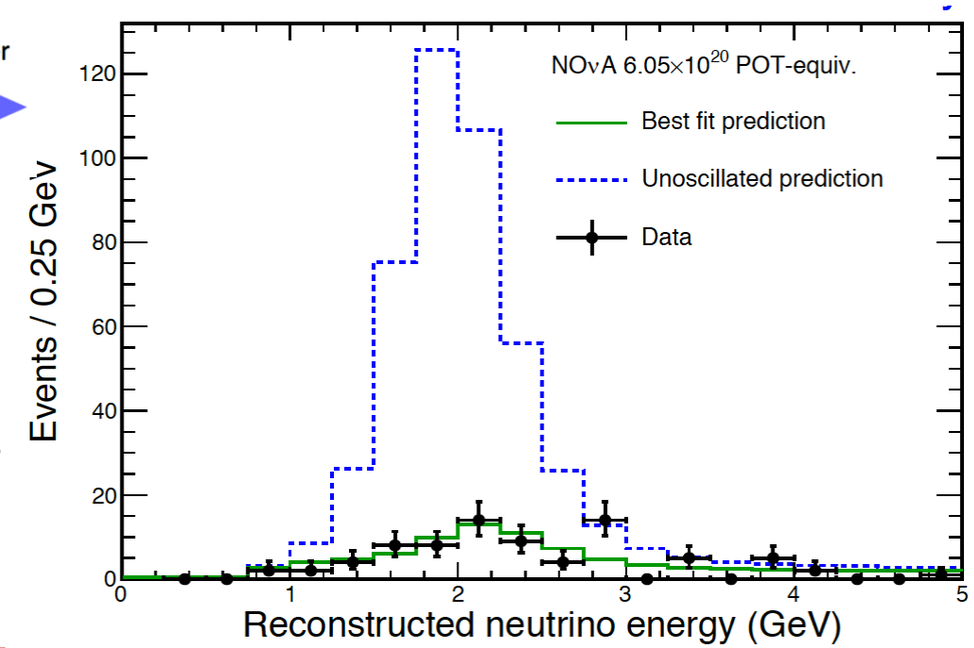
Most precise measurement of θ_{23}

NOvA Results



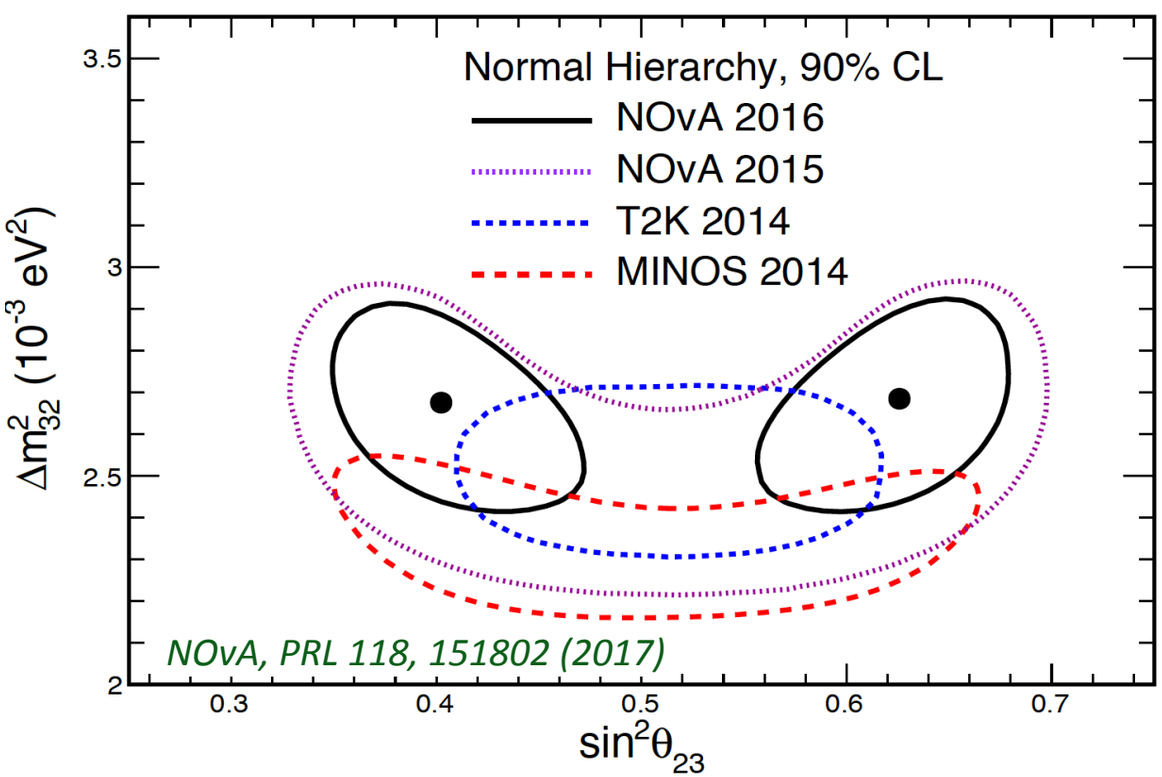


- 810 km baseline
- 700 kW NuMI beam
- Detectors placed 0.8° off-axis

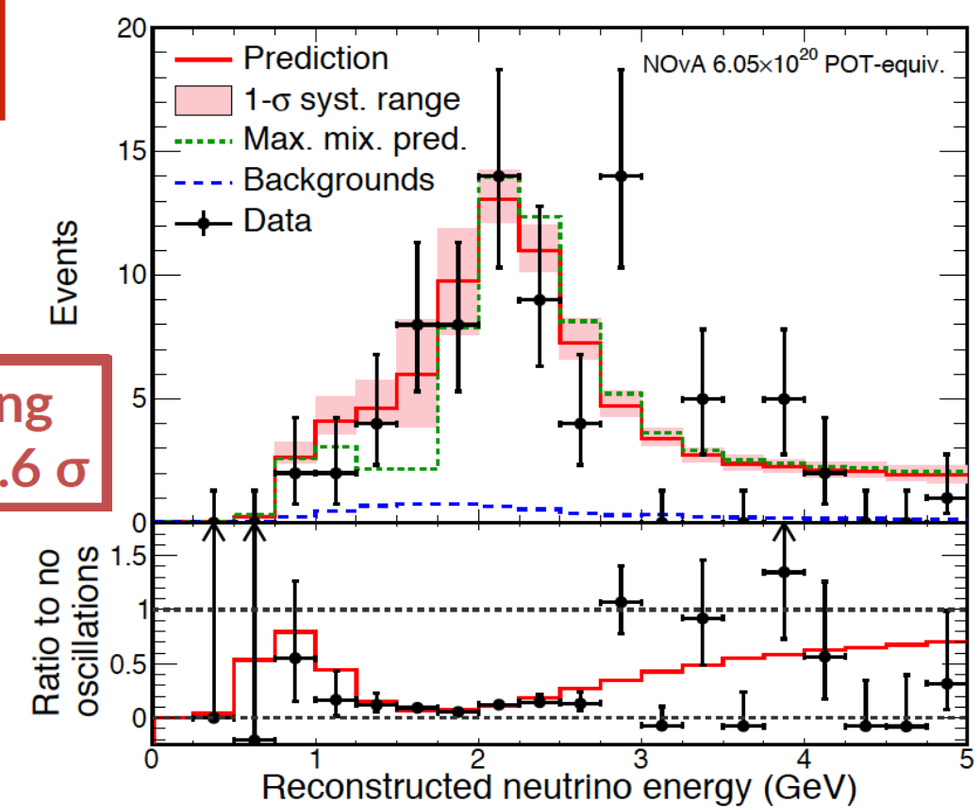


$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}(0.624^{+0.022}_{-0.030})$$



Maximal mixing disfavored at 2.6 σ

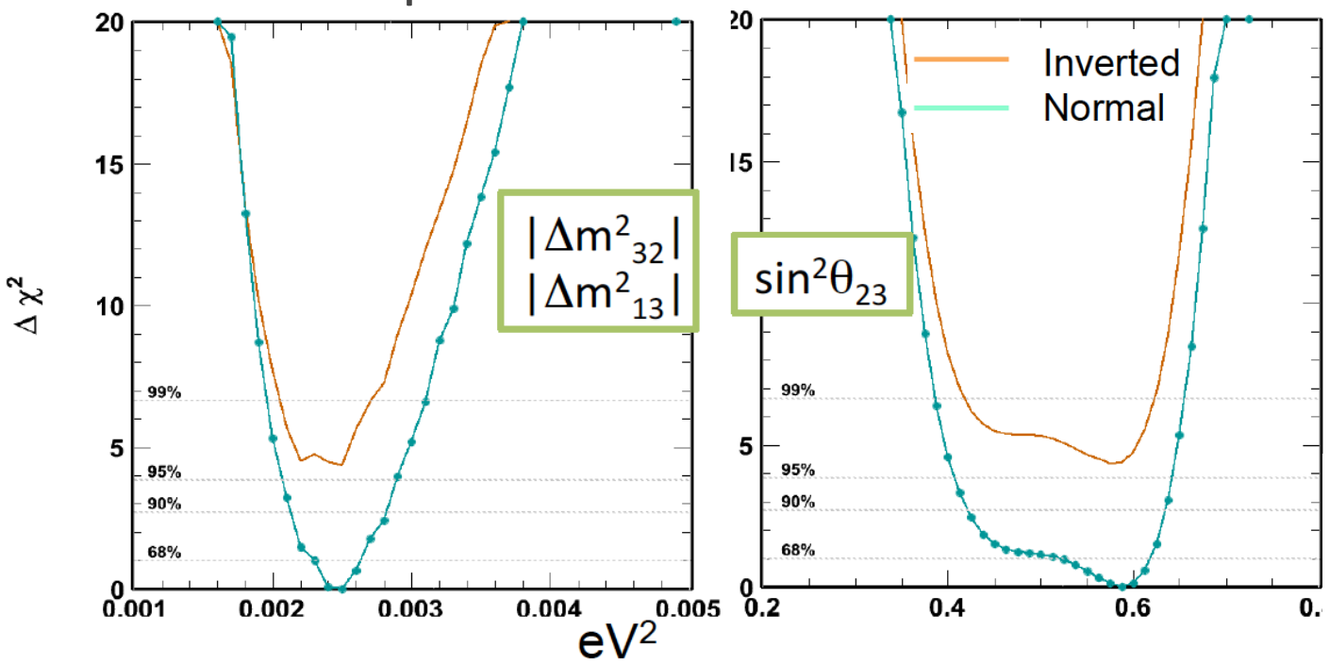


- Analysis with ~50% more data ongoing
- Antineutrino running ongoing

See Session Nu-1

SuperK, IceCube Results

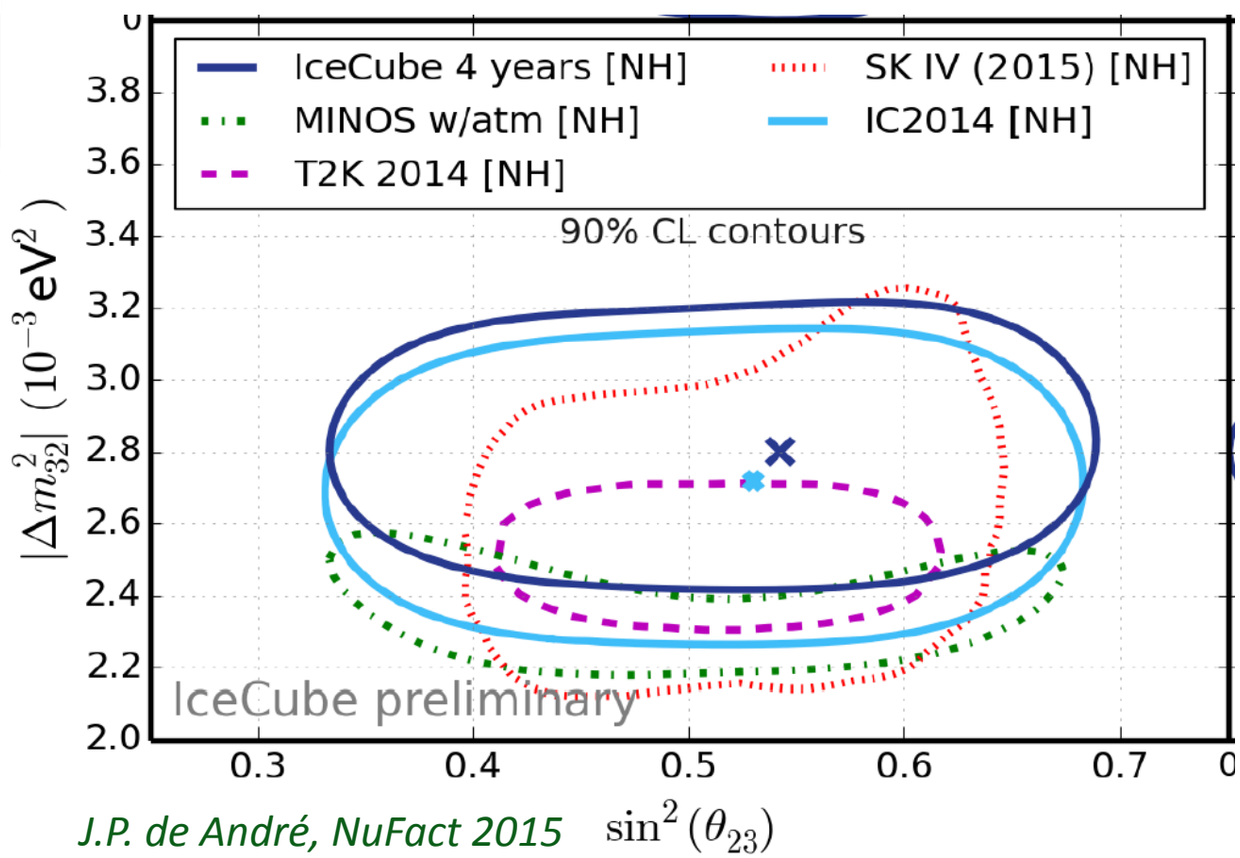
- Direct measurements of atmospheric neutrinos continue to contribute to precision of oscillation parameters



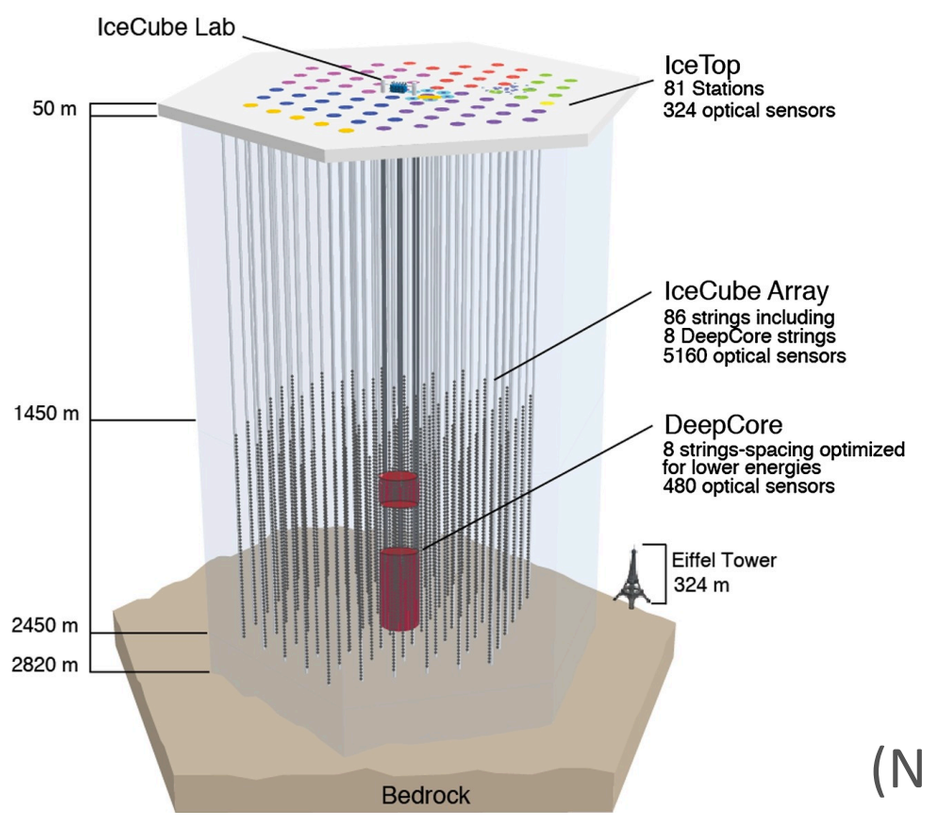
- Sk-I/II/III/IV results - 0.33 MtonYr exposure

Fit (517 dof)	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert eV^2$
SK (IH)	0.575	2.5×10^{-3}
SK (NH)	0.587	2.5×10^{-3}

J. Kameda, NuFact 2016



J.P. de André, NuFact 2015

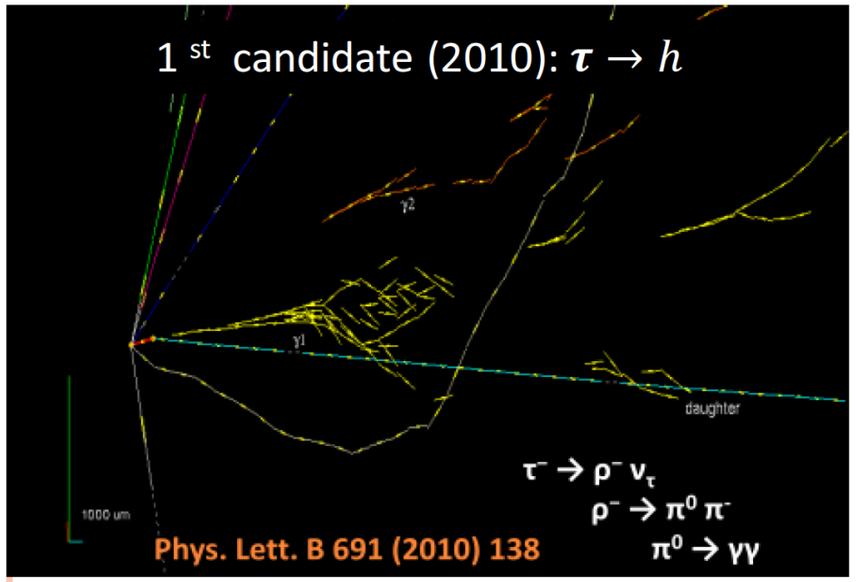


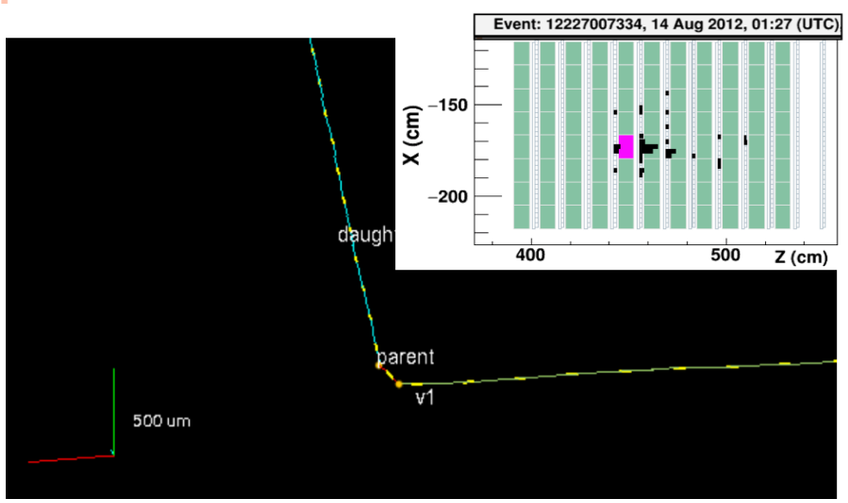
Best Fit:
(Normal Ordering)

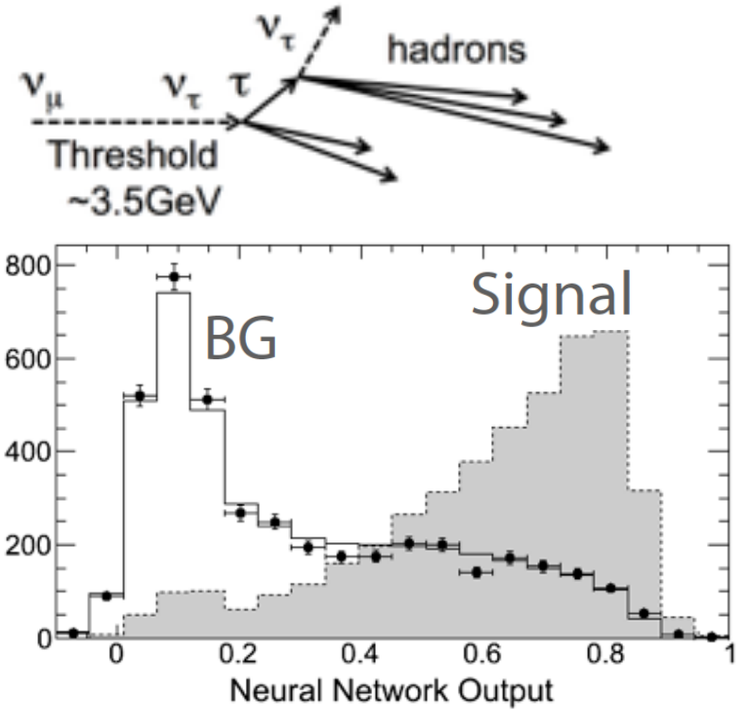
$$\sin^2\theta_{23} = 0.54^{+0.08}_{-0.13}$$
$$|\Delta m^2_{32}| = 2.80^{+0.16}_{-0.20}\times10^{-3}\mathrm{eV}^2$$

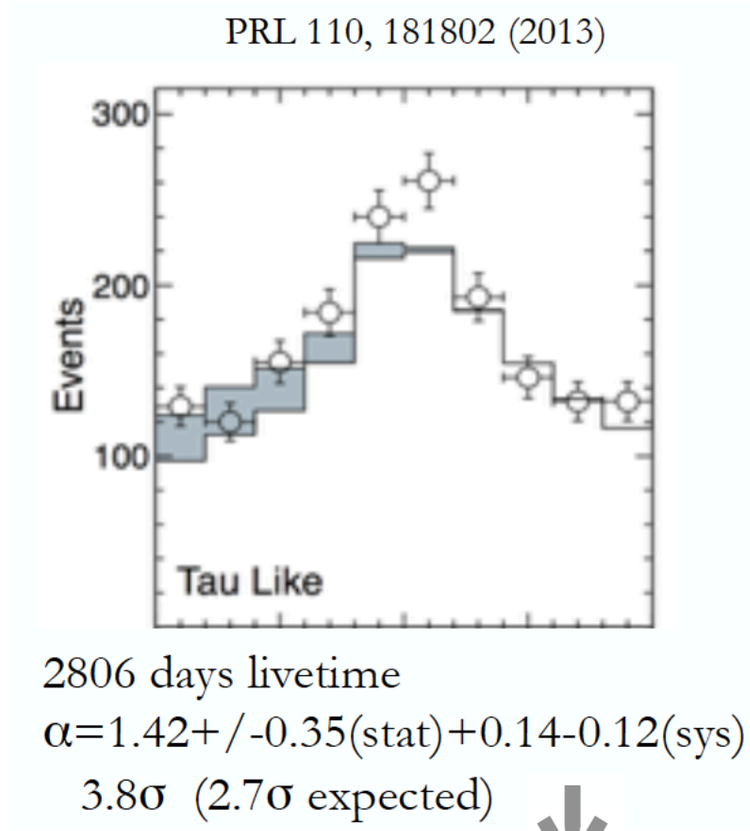
ν_τ Appearance

- What are ν_μ disappearing into? OPERA established $\nu_\mu \rightarrow \nu_\tau$ oscillations









Channel	Expected background	Expected signal	Observed
$\tau \rightarrow 1h$	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

P-value $=1.1 \cdot 10^{-7}$ *OPERA, PRL 115, 121802 (2015)*

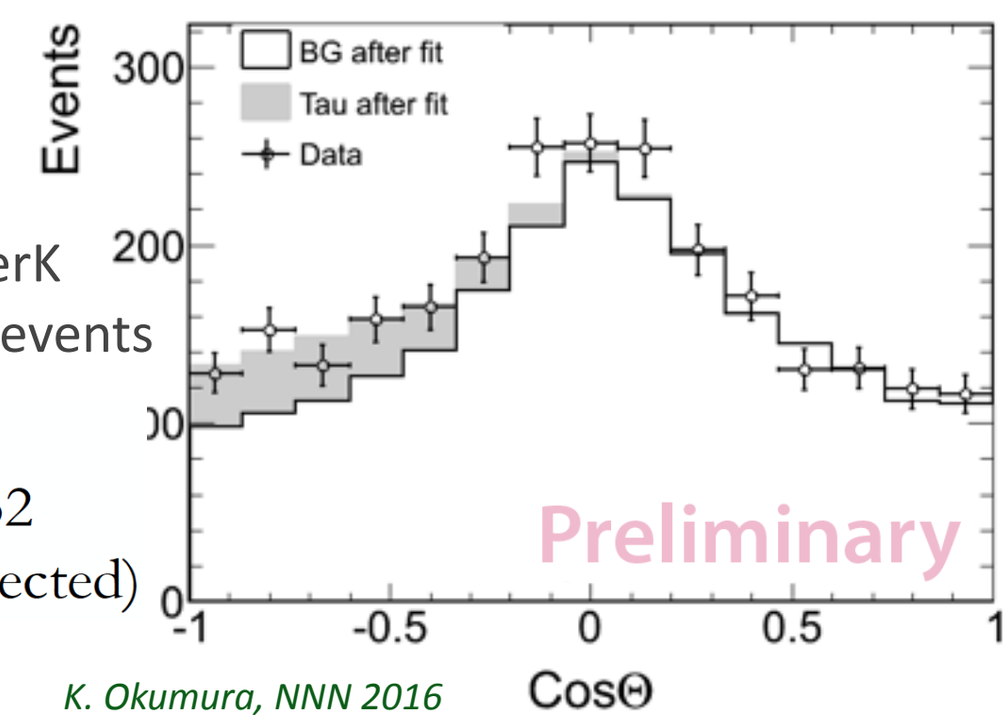
Exclusion of background-only hypothesis: 5.1 σ

- Confirmed by SuperK search for tau-like events

Fit result:

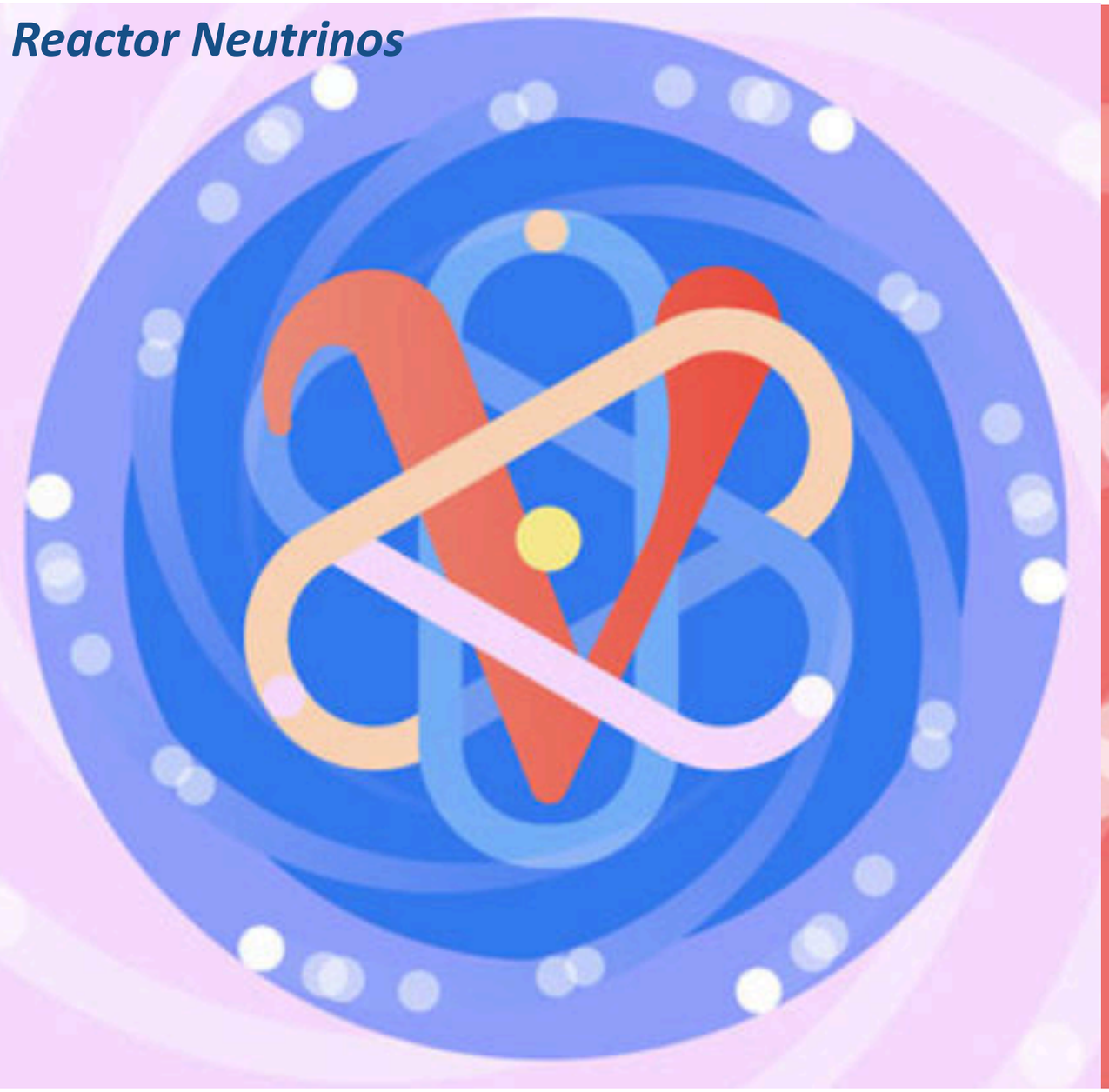
$\alpha = 1.47 \pm 0.32$

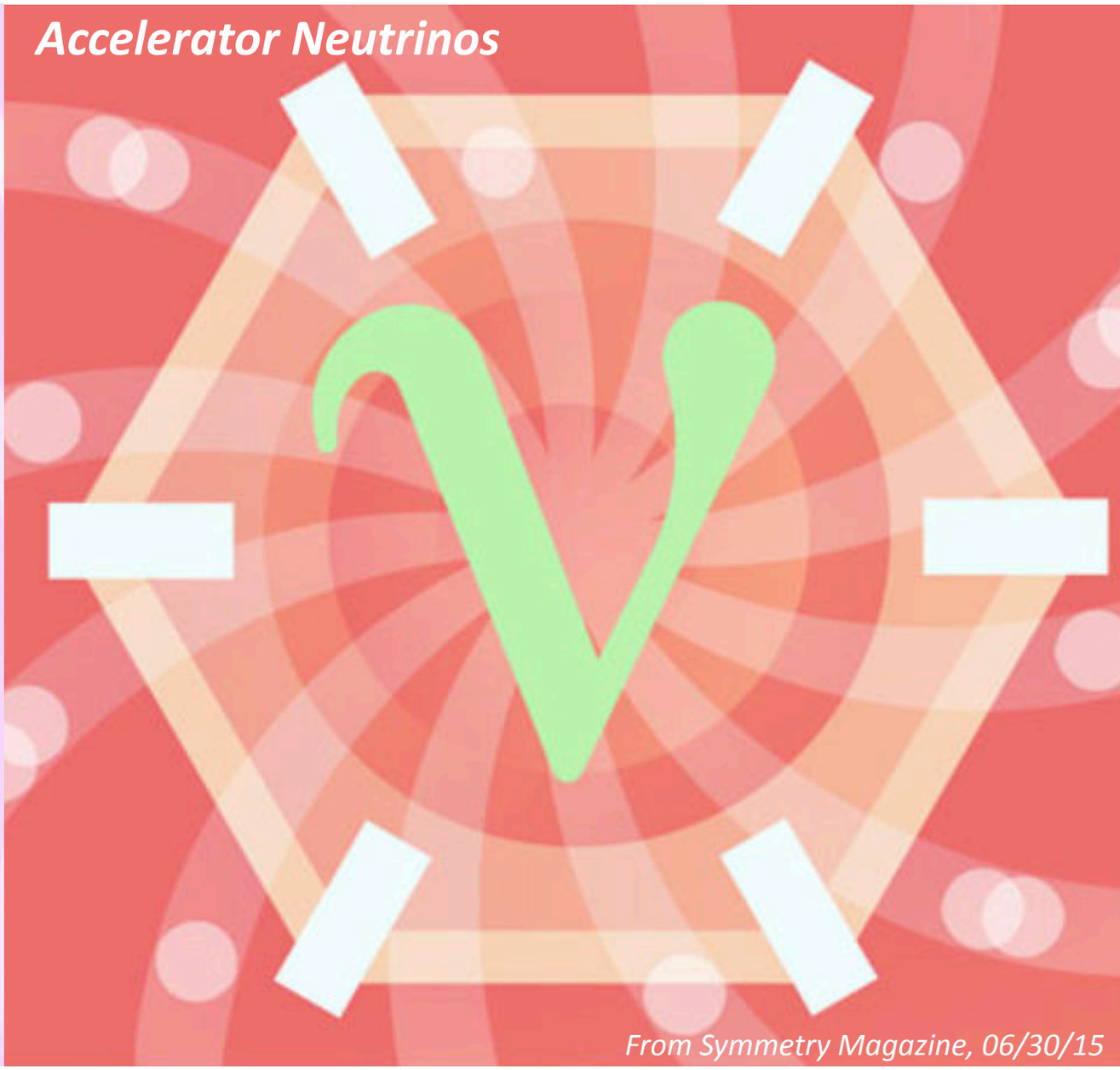
4.6σ (3.3σ expected)



K. Okumura, NNN 2016

Answering the Questions…



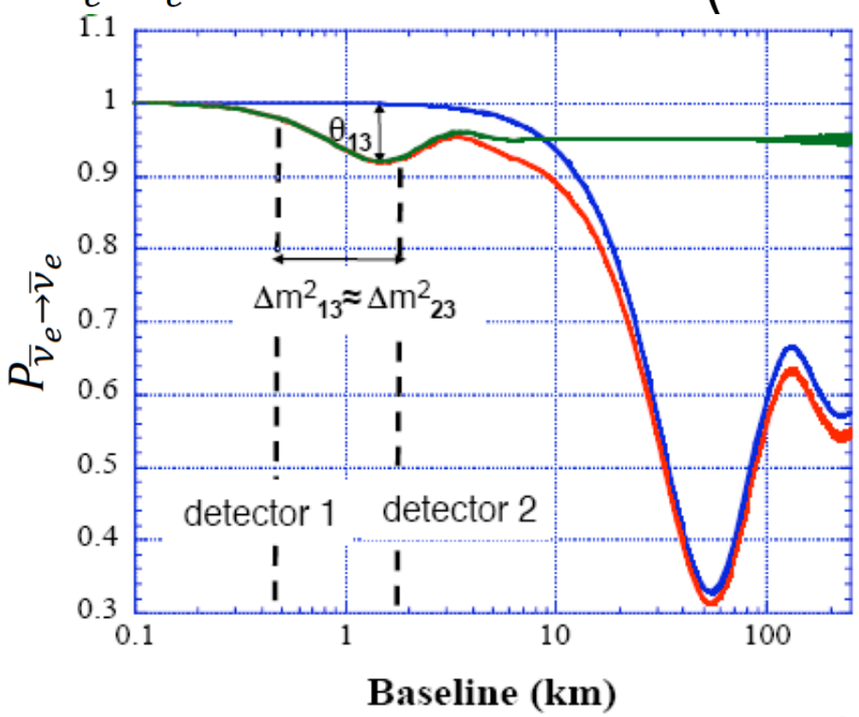


Measuring θ_{13}

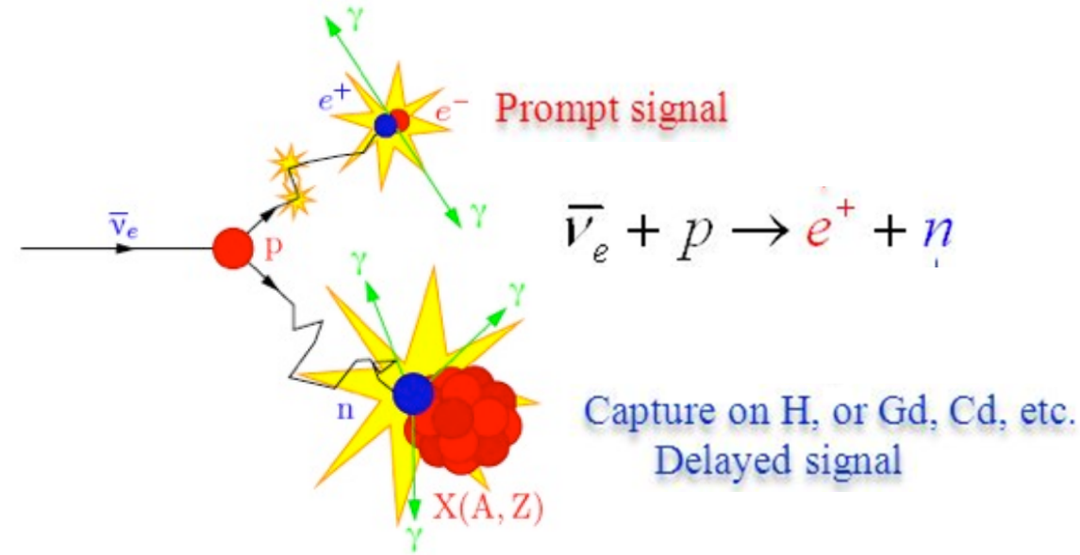
Daya Bay Results

- Measure disappearance of reactor $\overline{\nu}e$. Look for inverse beta decay (IBD) signal in detectors

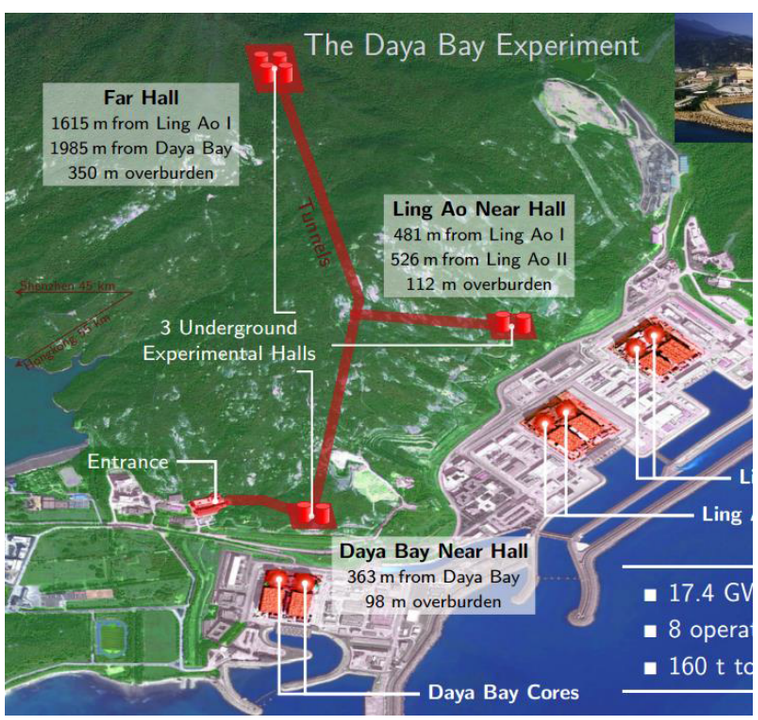
$$P_{\overline{\nu}_e \to \overline{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(1.27 \Delta m^2_{ee} \frac{L}{E}\right)$$

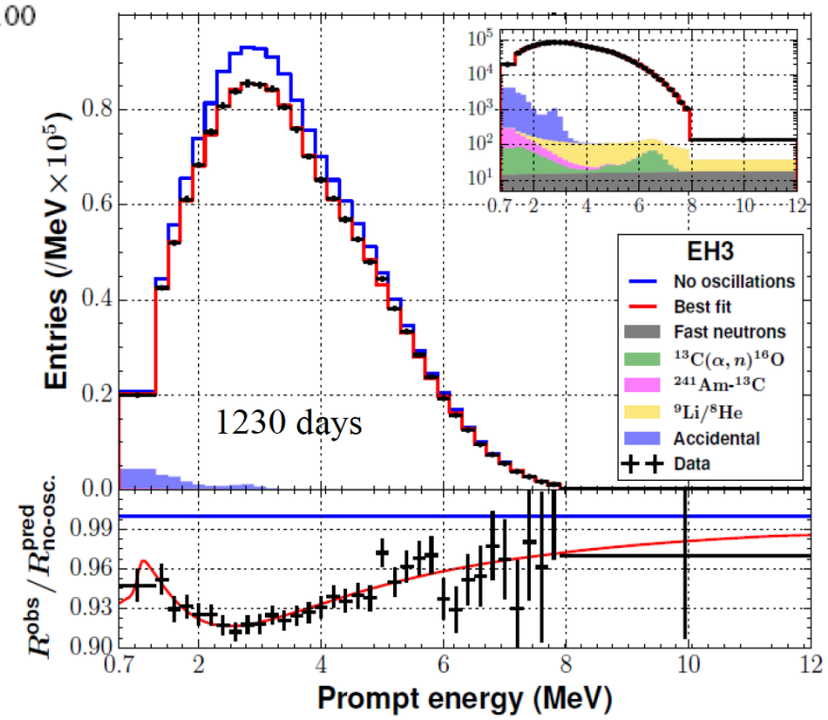


$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

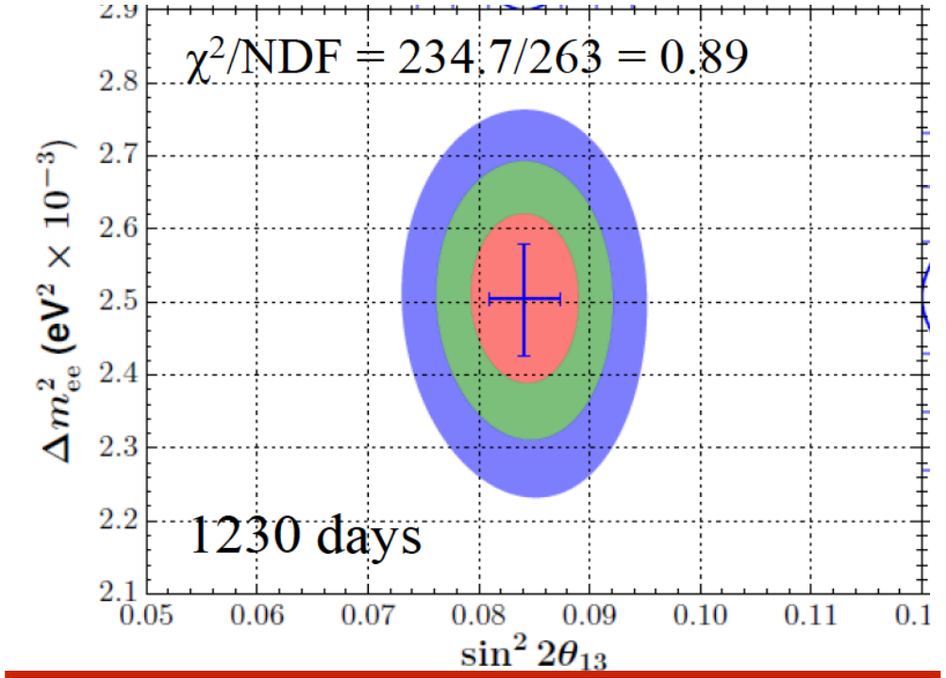


- Daya Bay discovered non-zero θ_{13} in 2012
- Latest result is the most precise measurement of θ_{13} and Δm^2_{ee}





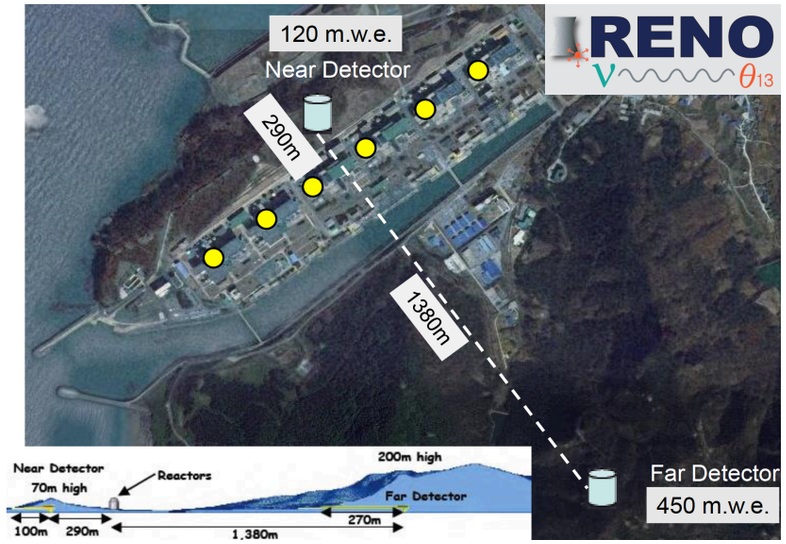
L. Lebanowski, NNN 2016



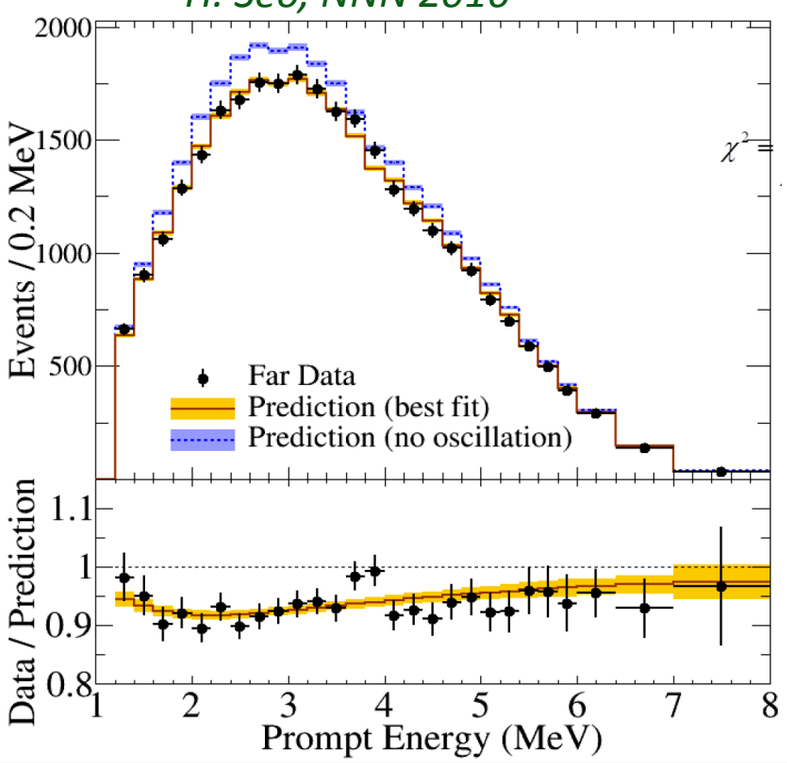
$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$
$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3}\, eV^2$$

RENO, Double Chooz Results

- RENO's Far/Near rate+shape analysis



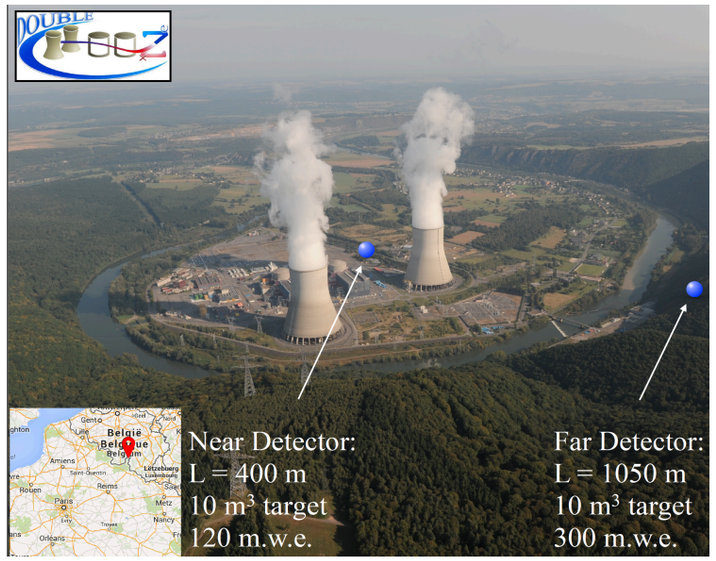
H. Seo, NNN 2016



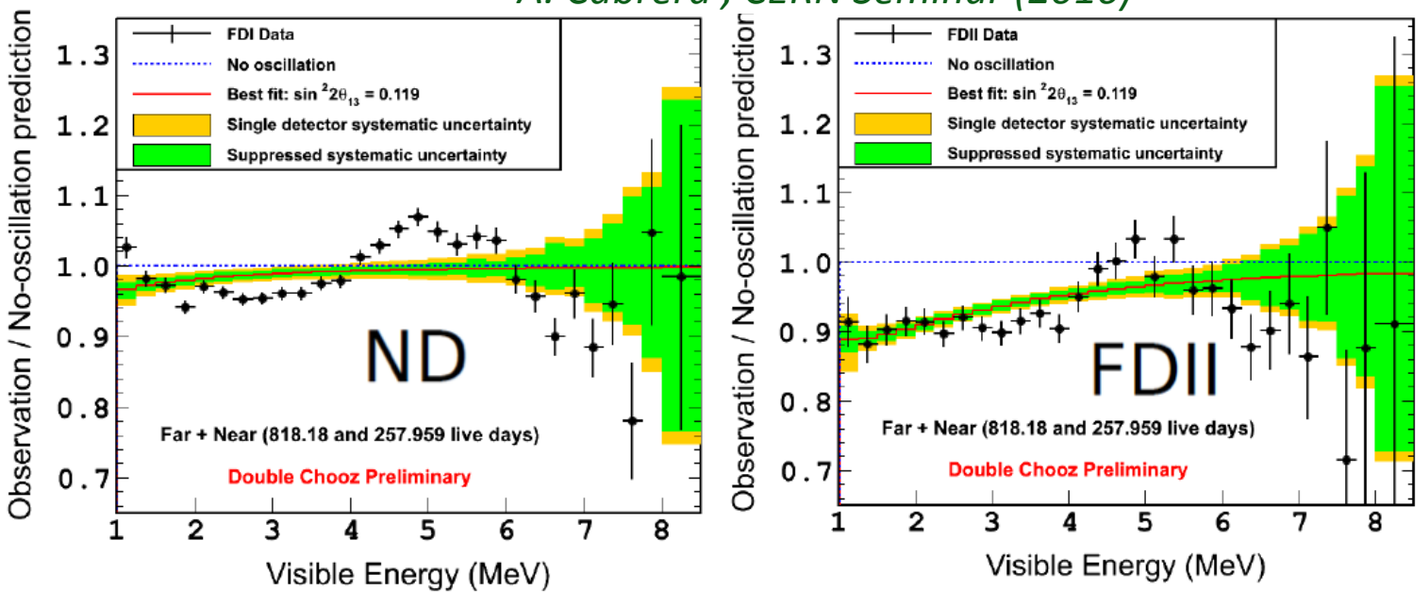
$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$$
$$|\Delta m^2_{ee}| = [2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})] \times 10^{-3}\ \text{eV}^2$$

- Consistent with Daya Bay measurement

- First multi-detector results from Double Chooz in 2016



A. Cabrera , CERN Seminar (2016)



$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ (stat.+syst.)

- 2.2σ higher value than Daya Bay's

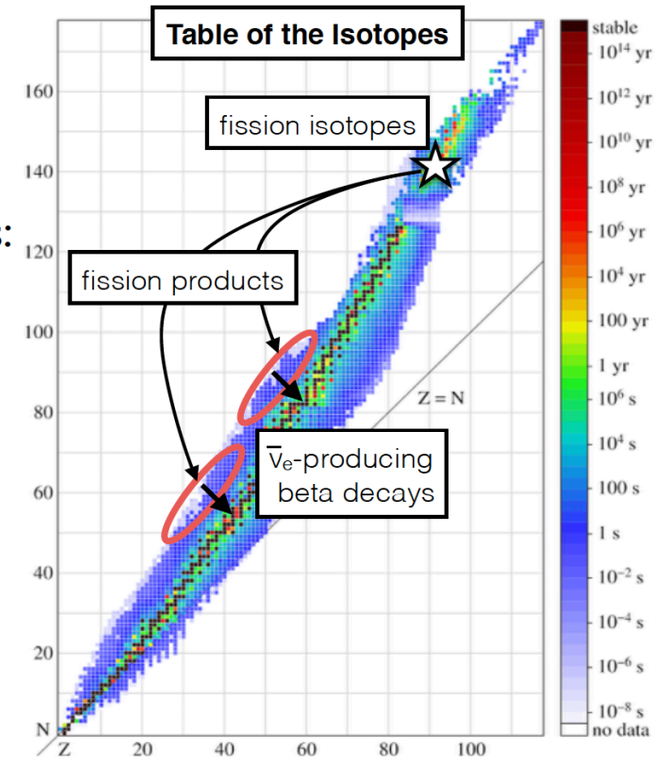
- All experiments see a "bump" at ~5 MeV

See Session Nu-1

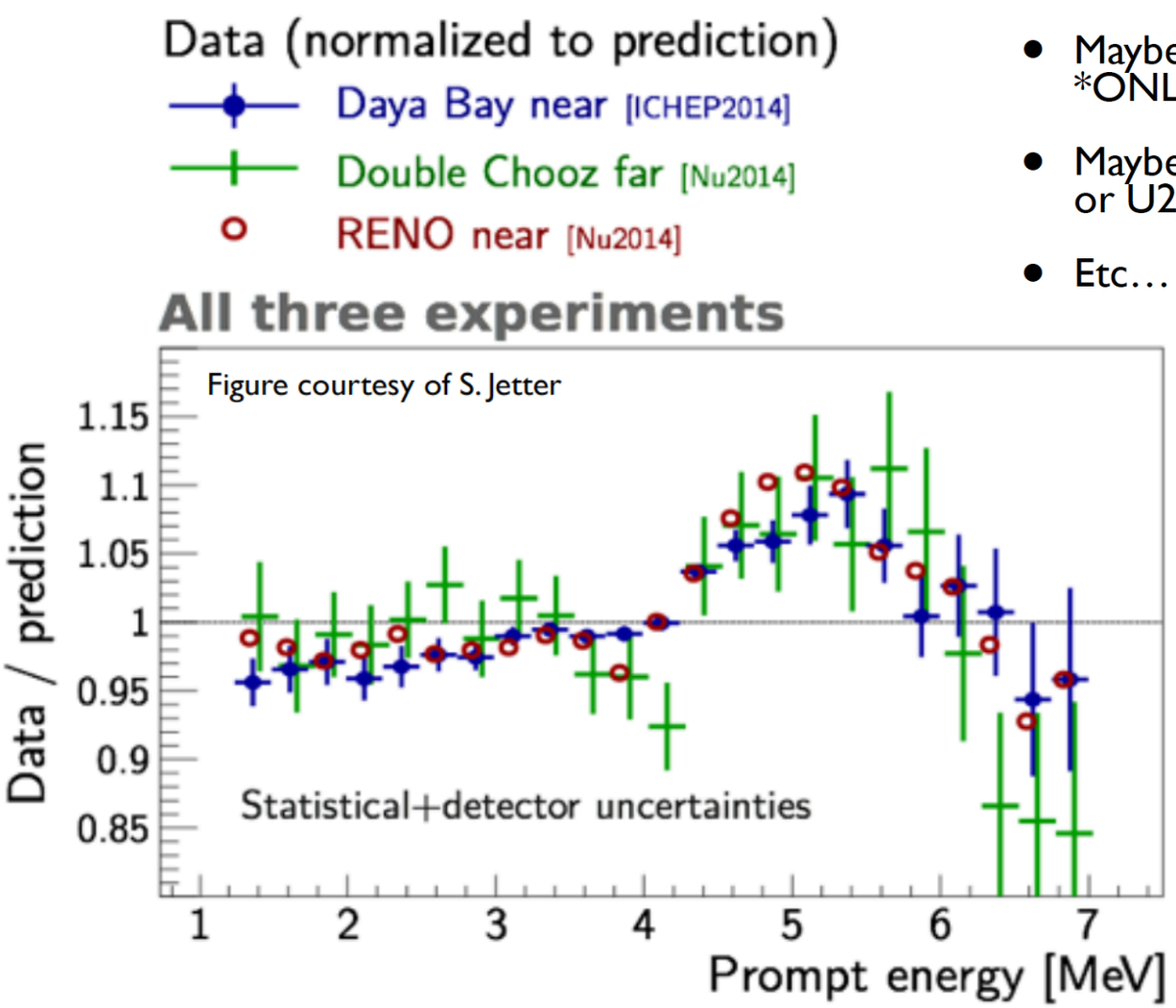
The "5 MeV Bump"

- Multiple explanations advanced…

- Maybe it's specifically related to beta-decays:
  - Maybe forbidden decays aren't treated properly. Hayes, et al, **PRL** 112 (2014), **PRD** 92 (2016)
  - Maybe prominent beta branches measurements are incorrect. See TAS measurements…
  - Maybe fission isotope beta spectrum measurements are wrong. Dwyer+Langford, **PRL** 114 (2015)
- Maybe it's specifically related to fission yields:
  - Fission yield databases are incorrect! Sonzogni, et al **PRL** 116 (2016)
  - Fission yield dependence on neutron energy not considered correctly. Hayes, et al, **PRD** 92 (2016)
- Maybe there's an issue with *ONLY* U238 Hayes, et al **PRD** 92 (2016)
- Maybe there's an issue with *ONLY* Pu239 or U235 Buck, et al, hep-ex[1512.06656] (2015)
- Etc…



B. Littlejohn, NNP 2016



- Will likely need multiple reactor experiments with diverse reactor compositions to explain effect
- Good News! - Several coming online or proposed

See Sessions Nu-1, 4

Measuring θ_{13} with LBL Expts.

- Look for $\nu_\mu \rightarrow \nu_e$ appearance over long-baselines

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij} \qquad \Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E_\nu} \qquad a = 2\sqrt{2}G_F n_e E$$

$$P(\nu_\mu \rightarrow \nu_e) = 4c^2_{13}s^2_{13}s^2_{23}\sin^2\Delta_{31}\times\left(1 \pm \frac{2a}{\Delta m^2_{31}}(1-s^2_{13})\right)$$ Leading term

$$+8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Conserving

$$\mp 8c^2_{13}s^2_{13}s^2_{23}\cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s^2_{13})$$ Matter effect

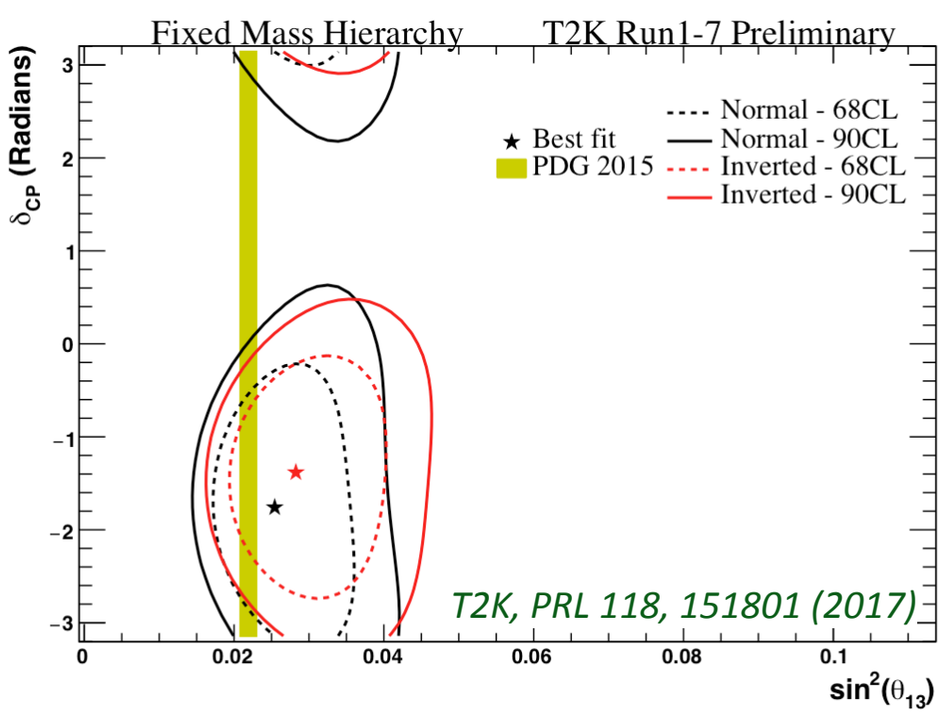
$$\mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

$$+4s^2_{12}c^2_{13}(c_{12}c_{23}+s^2_{12}s^2_{13}s^2_{23}-2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ Solar term

ν vs. $\bar{\nu}$ sign change

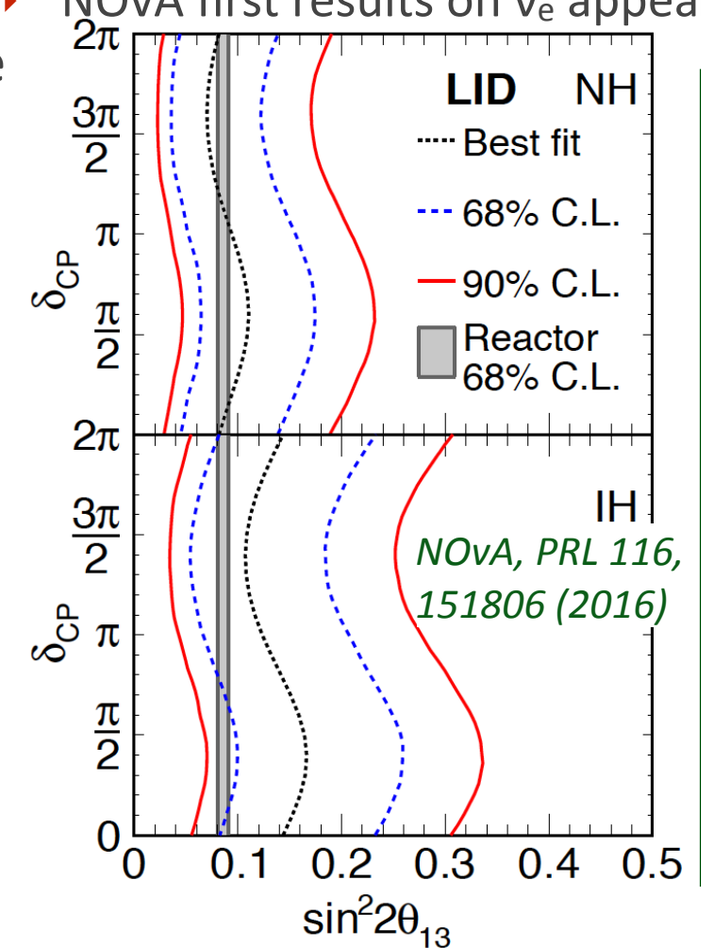
J.Imber, NNN 2016

- T2K latest results on ν_e appearance



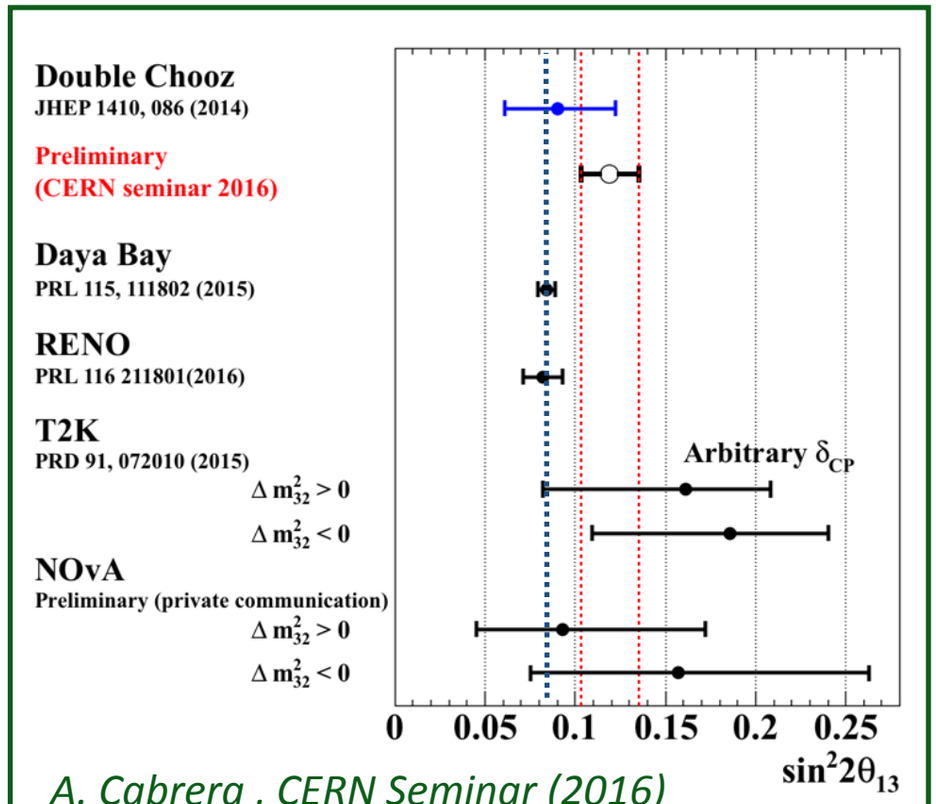
T2K, PRL 118, 151801 (2017)

- NOvA first results on ν_e appearance



NOvA, PRL 116, 151806 (2016)

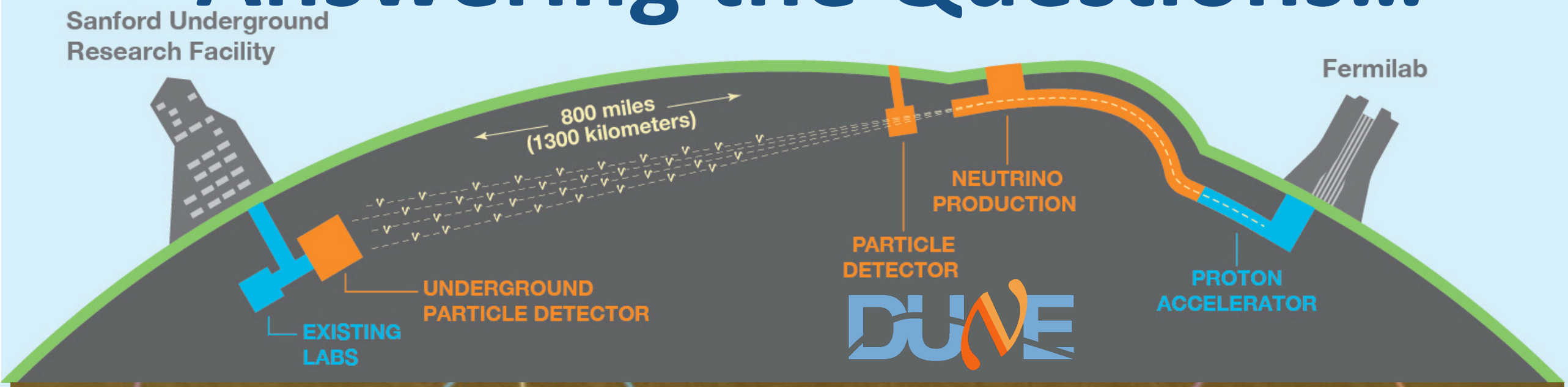
- Global Picture

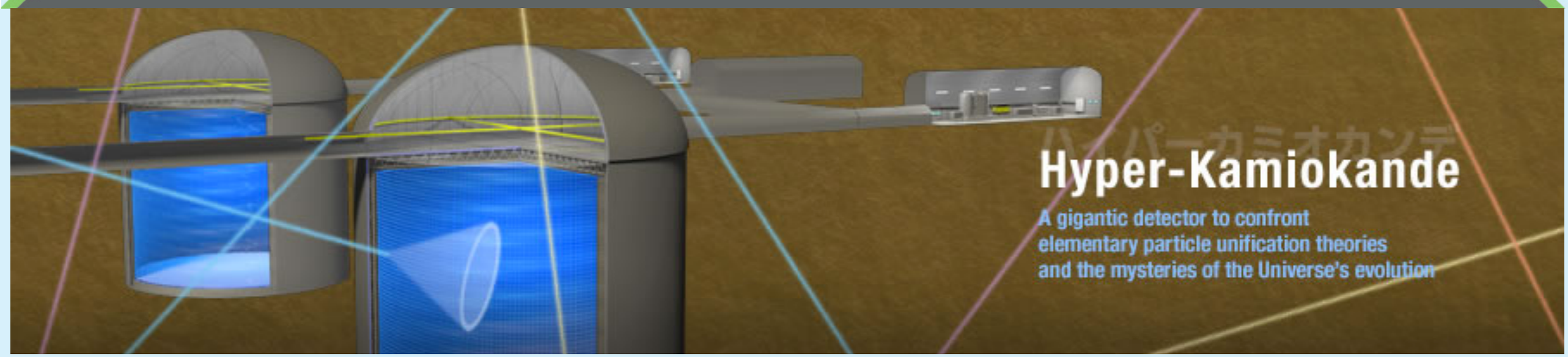


A. Cabrera , CERN Seminar (2016)

See Session Nu-1

Answering the Questions...



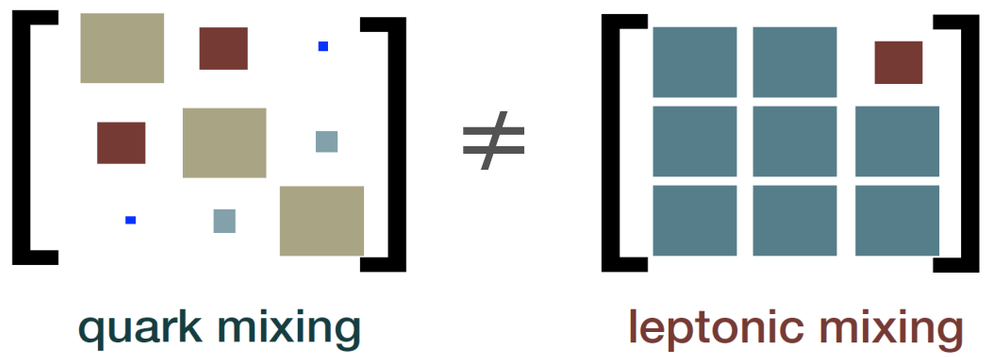


NOvA T2K IceCube SOUTH POLE NEUTRINO OBSERVATORY ORCA KM3NeT JUNO

Mass Ordering and CP Violation

Mass Ordering, δ_{CP} (and octant of θ_{23})

- Why do we want to measure these?
- sin δ_{CP} determines the size of CP violation in the lepton sector
  - May explain matter-antimatter asymmetry through ***Leptogenesis***
  - Measuring δ_{CP} precisely is needed to understand structure of PMNS matrix and underlying symmetries

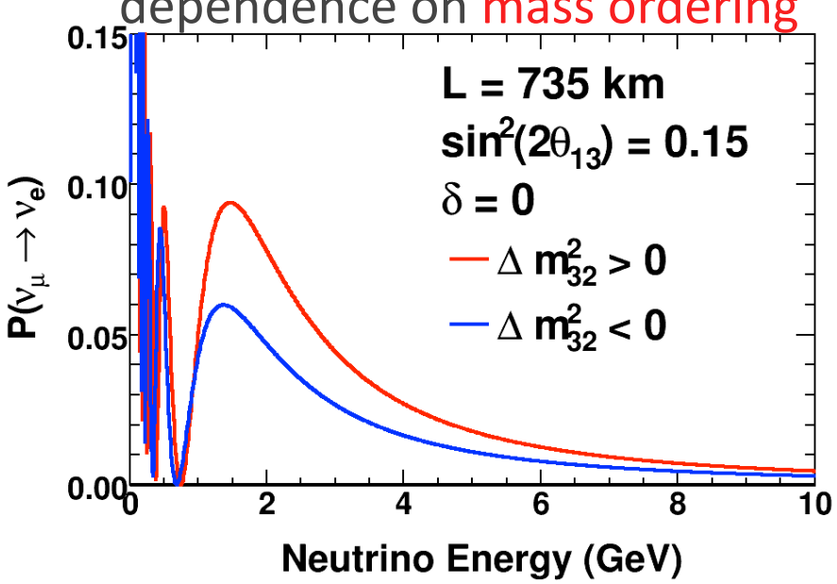


- Mass Ordering is a good model discriminator
  - Important to understand if neutrinos are Majorana or Dirac particles
- θ_{23}=45° could be a hint for a not yet understood symmetry
  - Precision needed to test PMNS unitarity and for neutrino model building

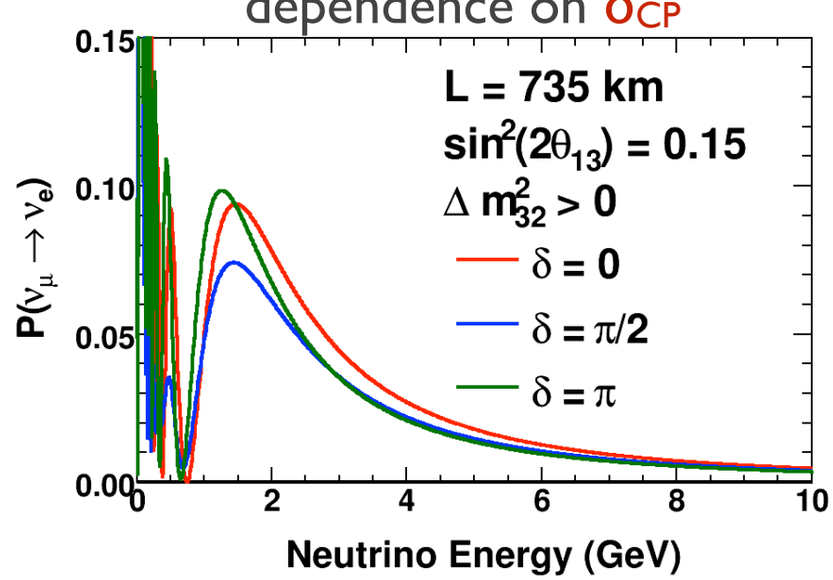
Reference		Hierarchy
Anarchy Model:		
dGM	[18]	Either
$L_e - L_\mu - L_\tau$ Models:		
BM	[35]	Inverted
BCM	[36]	Inverted
GMN1	[37]	Inverted
GL	[38]	Inverted
PR	[39]	Inverted
S_3 and S_4 Models:		
CFM	[40]	Normal
HLM	[41]	Normal
		Normal
KMM	[42]	Inverted
MN	[43]	Normal
MNY	[44]	Normal
MPR	[45]	Normal
RS	[46]	Inverted
		Normal
TY	[47]	Inverted
T	[48]	Normal
A_4 Tetrahedral Models:		
ABGMP	[49]	Normal
AKKL	[50]	Normal
Ma	[51]	Normal
SO(3) Models:		
M	[52]	Normal
Texture Zero Models:		
CPP	[53]	Normal
		Inverted
		Inverted
WY	[54]	Either
		Either
		Either

Albright, Chen, PRD 74, 113006 (2006)

dependence on mass ordering



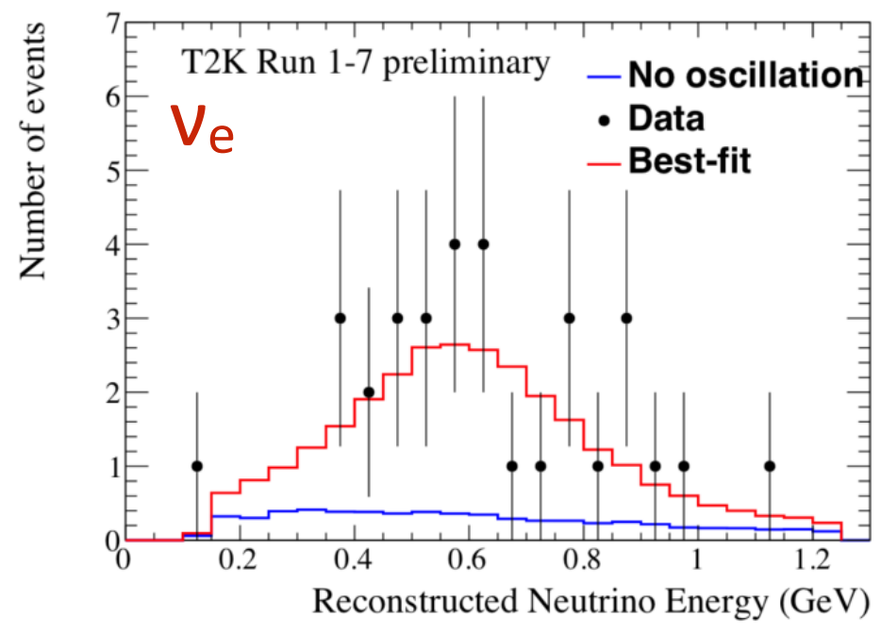
dependence on δ_{CP}

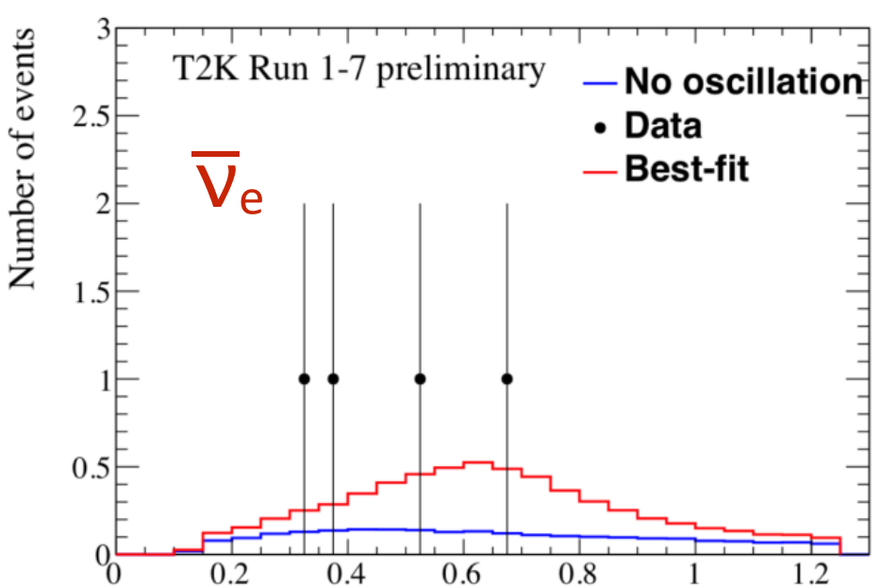


T2K Results

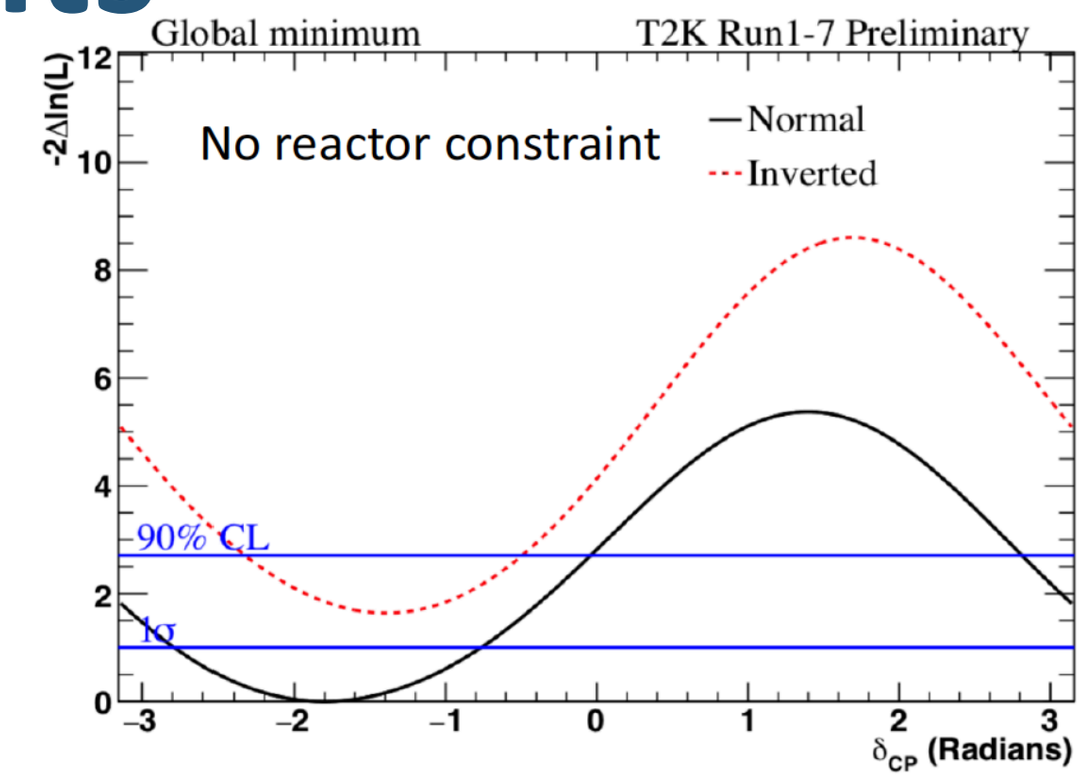
$\delta_{CP} \neq 0 \Rightarrow P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$

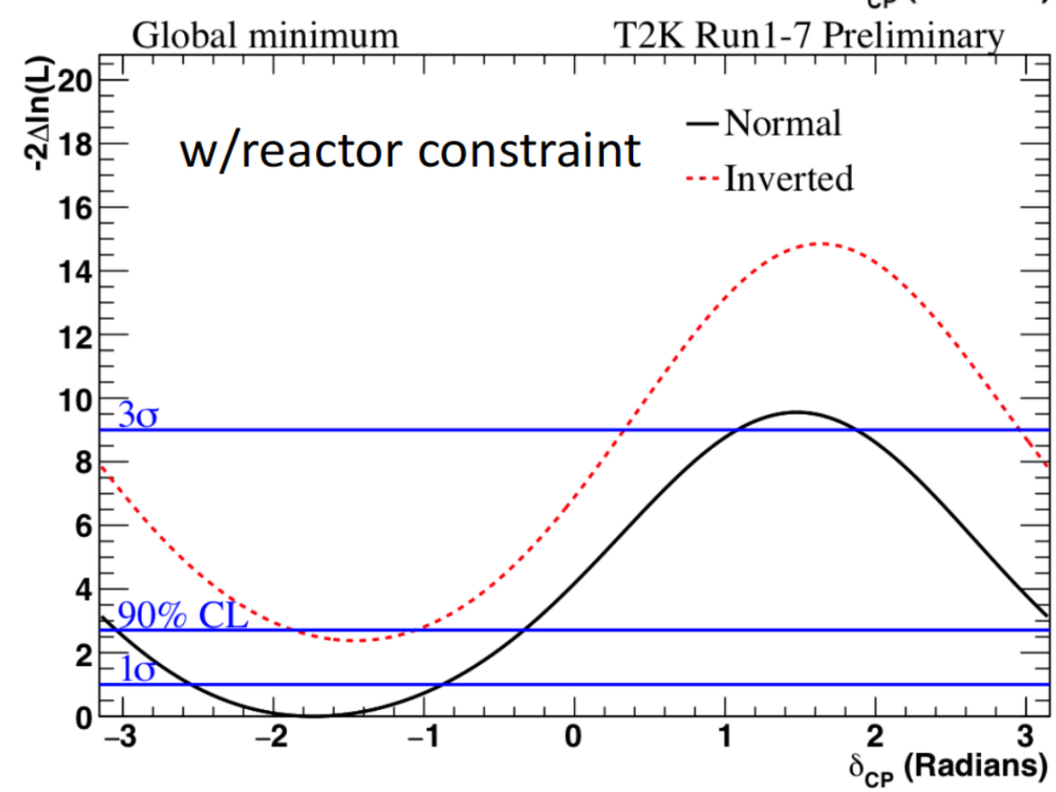
- T2K observes 32 ν_e and 4 $\bar{\nu}_e$
  - Expected 29 ν_e and 6 $\bar{\nu}_e$ for Normal Ordering, δ_{CP}=-π/2 (or 3π/2)





J. Haigh, FPCP 2017

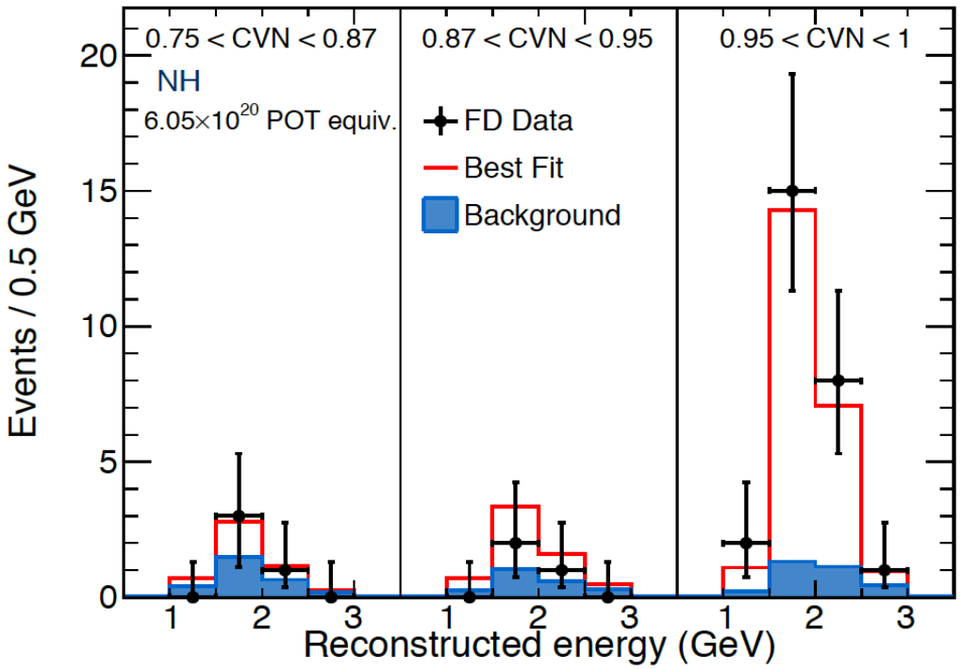




- Prefers large CP violation, δ_{CP}=0 disfavored at 90% C.L.
- In combination with reactor results, disfavors δ_{CP}=0 at 2σ

NOvA Results

- NOvA observes 33 ν_e events
  - background 8.2±0.8

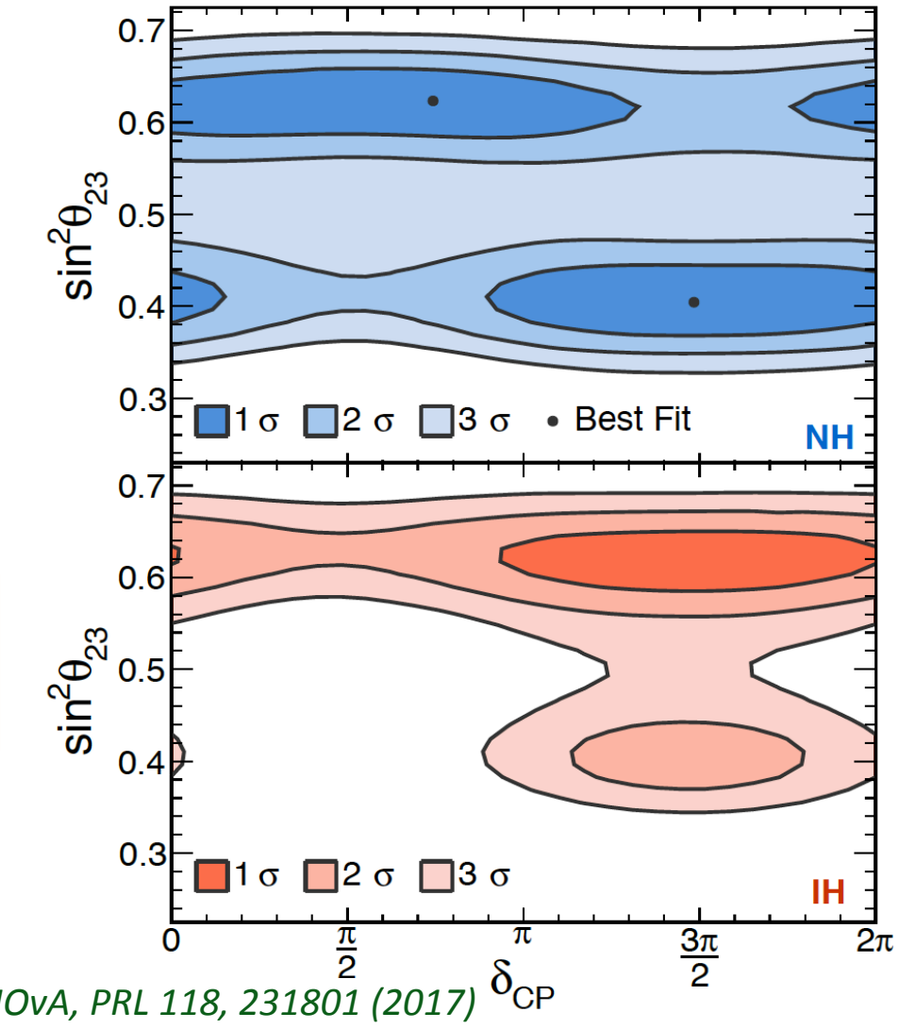


- Also prefer large CP violation
- Two degenerate best fit points in N.O.

$$\sin^2\theta_{23} = 0.404, \delta_{CP} = 1.48\pi$$

$$\sin^2\theta_{23} = 0.623, \delta_{CP} = 0.74\pi$$

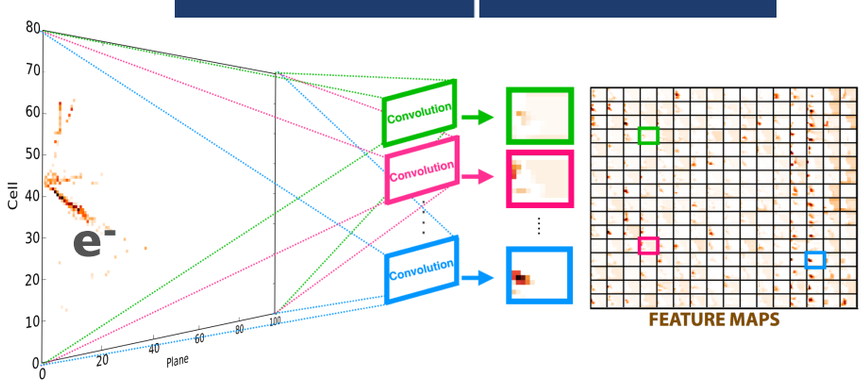
- NOvA sees a 3σ exclusion at IH, lower octant around $\delta_{CP}=\pi/2$



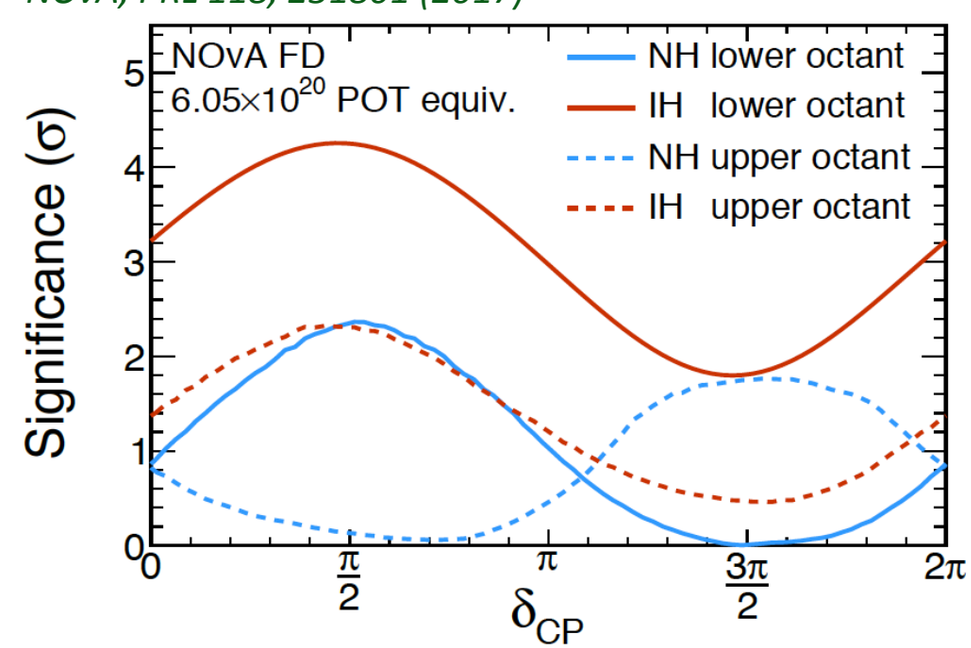
NOvA, PRL 118, 231801 (2017)

- Predictions depend on oscillation parameters. For maximal θ_{23} mixing:

NH, 3π/2,	IH, π/2,
36	19



- Inverted Ordering in the lower θ_{23} octant disfavored at 93% CL for all δ_{CP} values



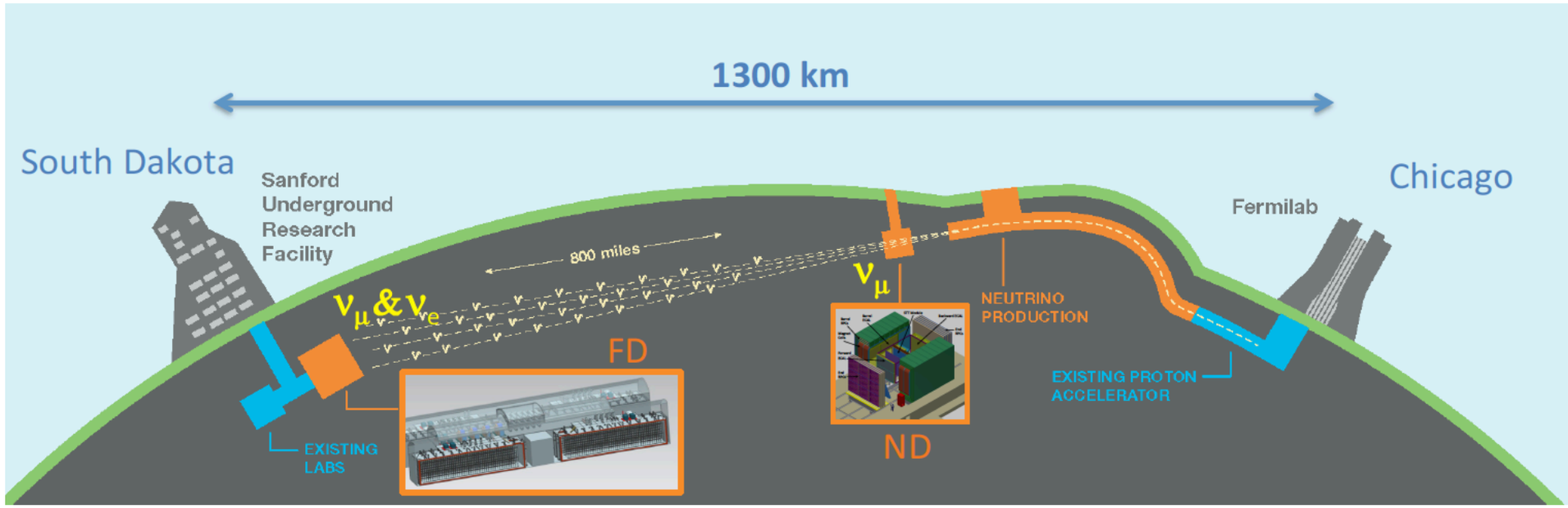
- CVN - Deep Learning-based event selection

A. Aurisano et al., JINST 11 P09001 (2016)

See Session Nu-1

- Antineutrino running (ongoing) will help resolve degeneracies

The Future - DUNE/LBNF

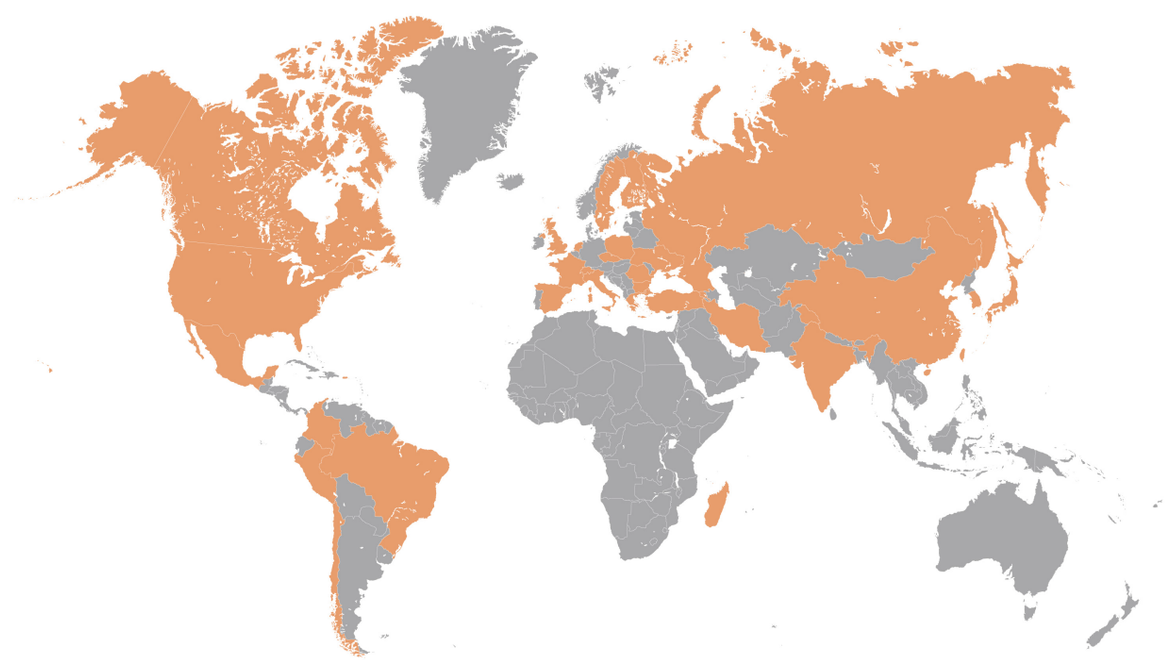


- High-intensity source, large detector mass, high-resolution detectors, large matter effects
- High-power ν_μ / $\overline{\nu}_\mu$ beam produced at Fermilab
  - Start at 1.2 MW, upgradable to 2.4 MW
- Large underground LArTPC detectors at Homestake
  - 4x17 kton (fiducial mass > 40 kton)
  - 1300 km baseline, detectors on-axis
- Near Detector to characterize beam
- Large international science Collaboration

The DUNE Collaboration

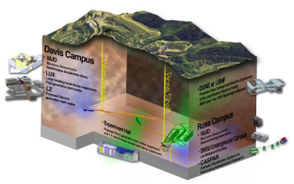
60 % non-US

970 collaborators from 162 institutions in 31 nations



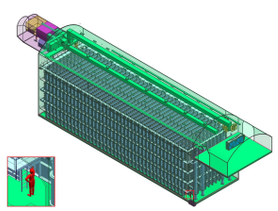
The Future - DUNE/LBNF

DUNE Timeline

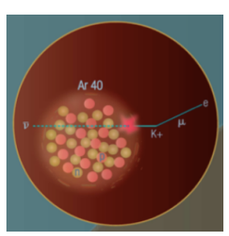


2017: Far Site Construction Begins

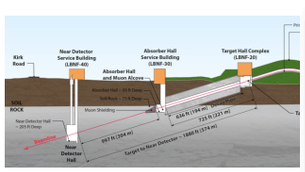
2018: protoDUNEs at CERN



2021: Far Detector Installation Begins

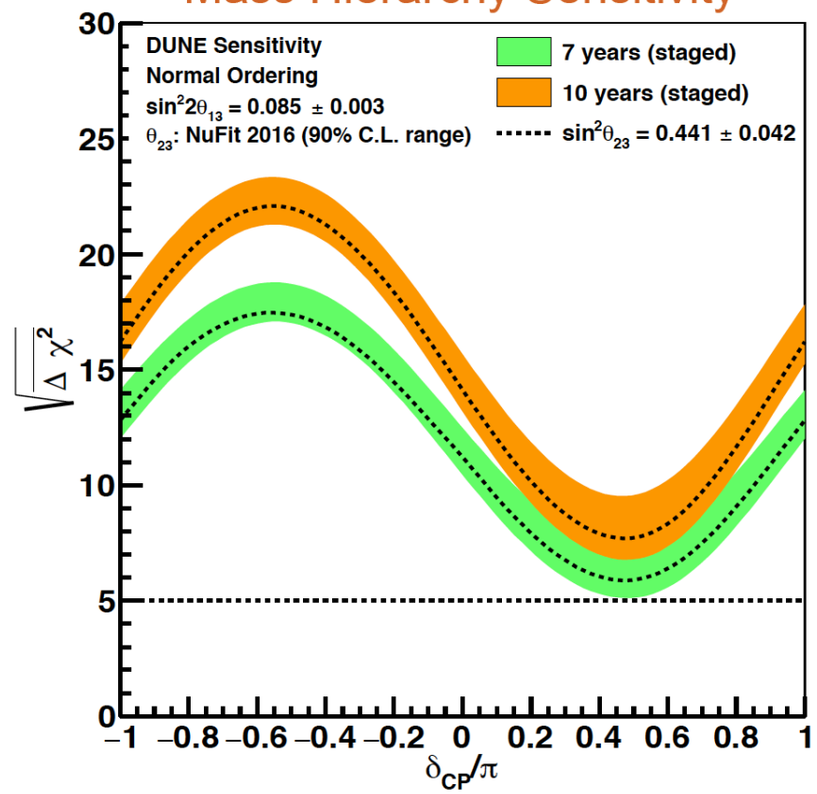


2024: Physics Data Begins

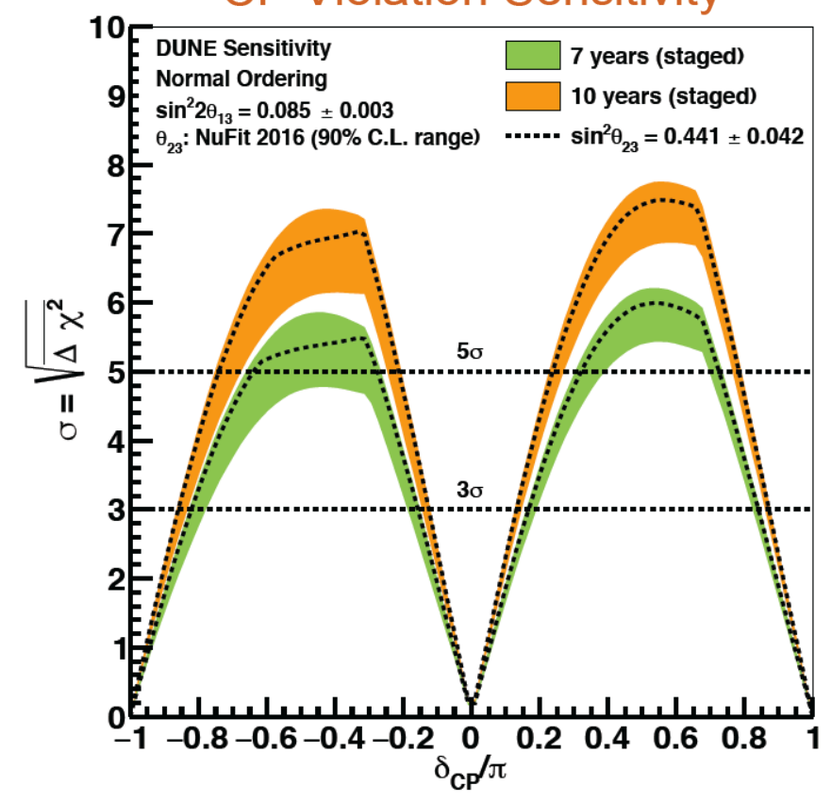


2026: Neutrino Beam Available

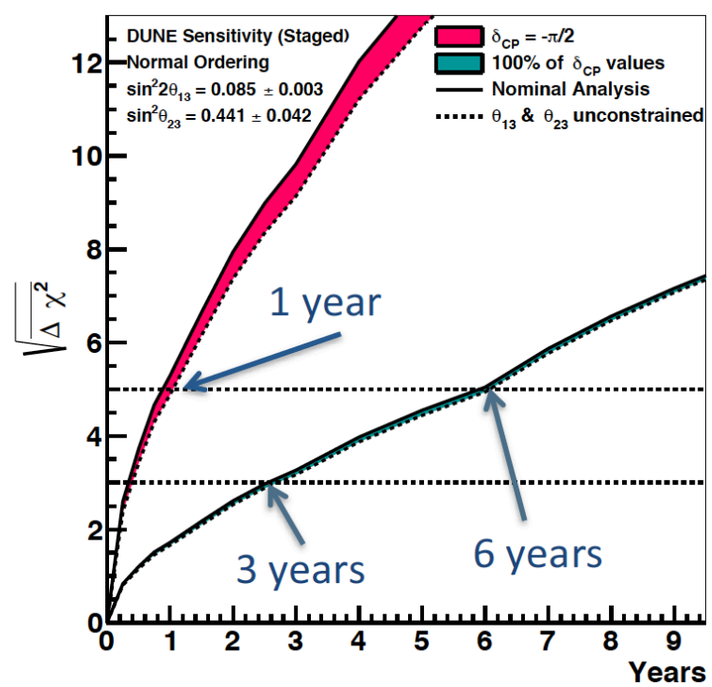
Mass Hierarchy Sensitivity

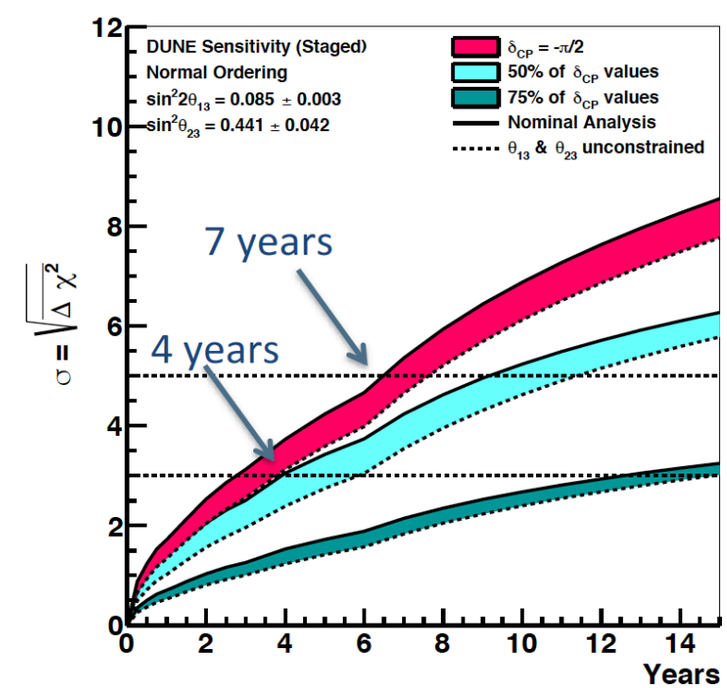


CP Violation Sensitivity



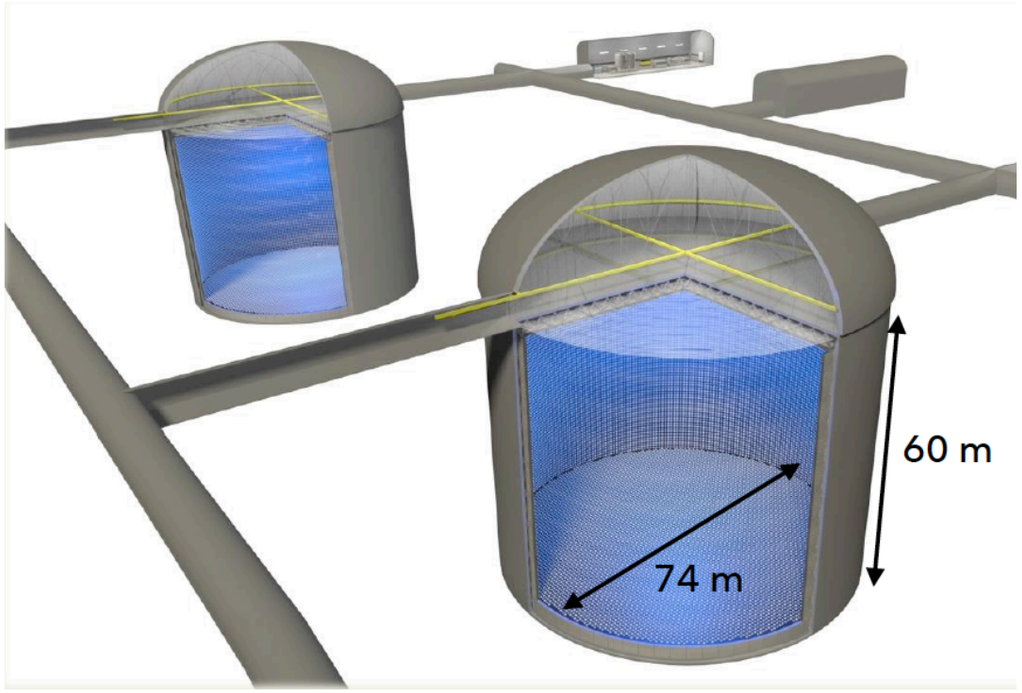
- Neutrino mass ordering determined at > 5σ for all parameter values
- 5σ discovery of CP violation if δ_{CP} near $-\pi/2$; 3σ over 65% of δ_{CP} range

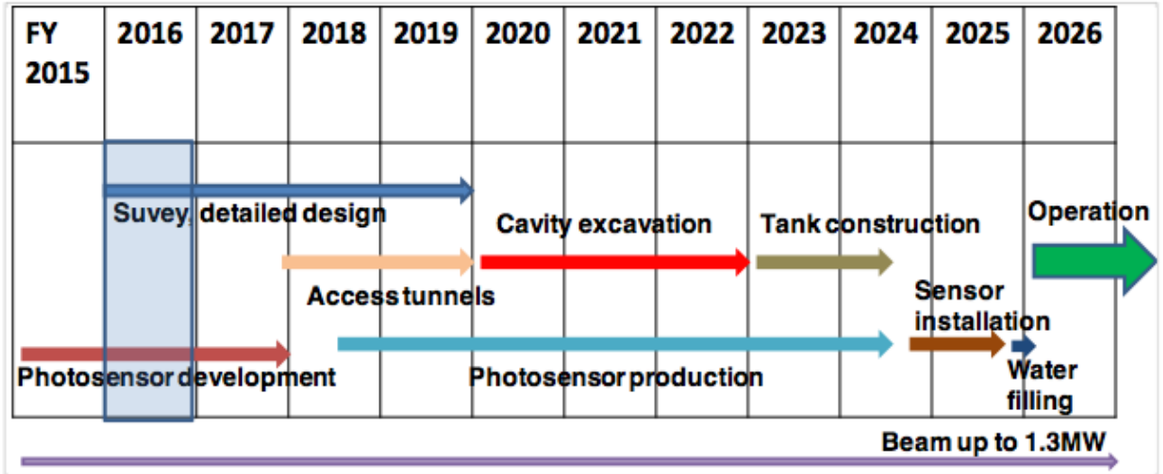




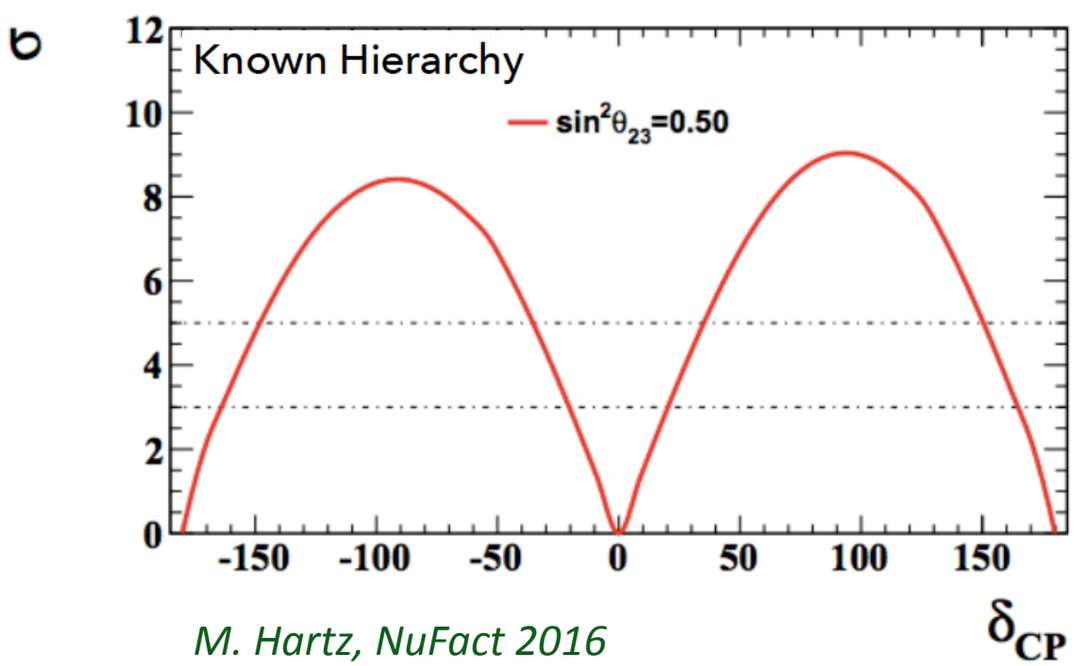
The Future - HyperK

- High-power ν_μ / $\bar{\nu}_\mu$ beam produced at JPARC
  - 1.3 MW beam power by 2026
- Large Water Cherenkov detectors near Kamioka
  - 2x260 kton (fiducial mass ~200 kton = 10 x SuperK)
  - 295 km baseline, detectors 2.5° off-axis
  - 46700 PMTs (40000 50 cm, 6700 20 cm)
- 300 members from 15 countries in protoCollaboration

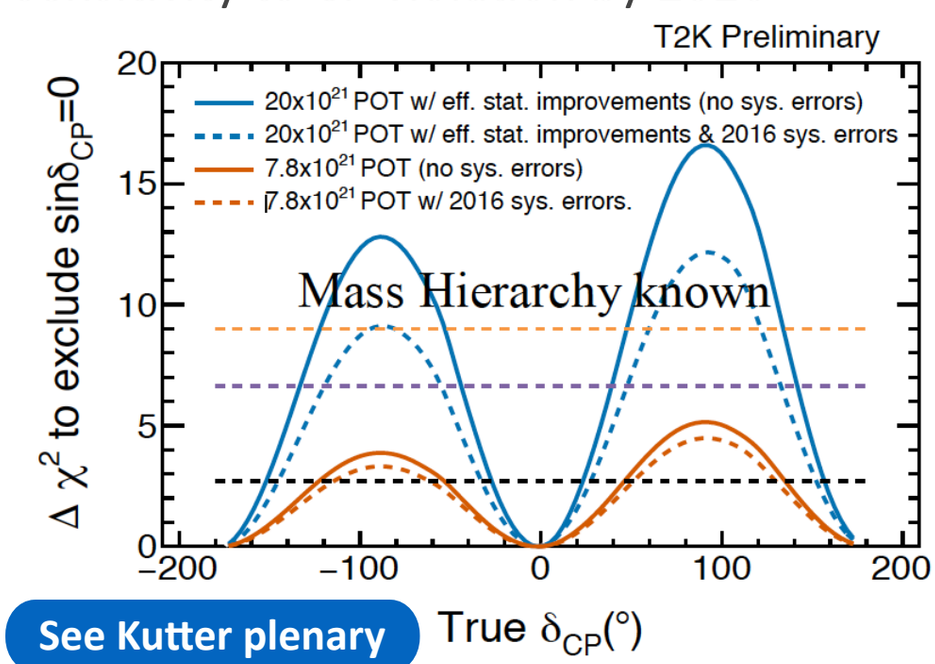




- Exclusion of $\sin(\delta_{CP})=0$ at 3σ for 78% of δ_{CP} values and at 5σ for 62%
- T2K-II will continue operation during construction, can reach 3σ sensitivity to CP violation by 2026



M. Hartz, NuFact 2016

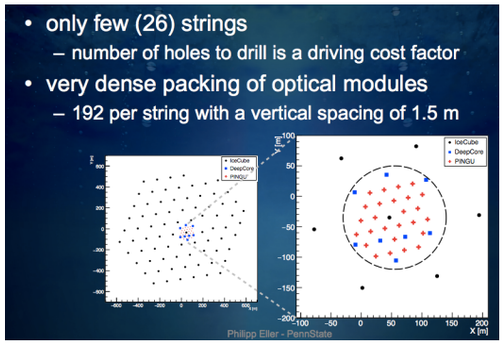


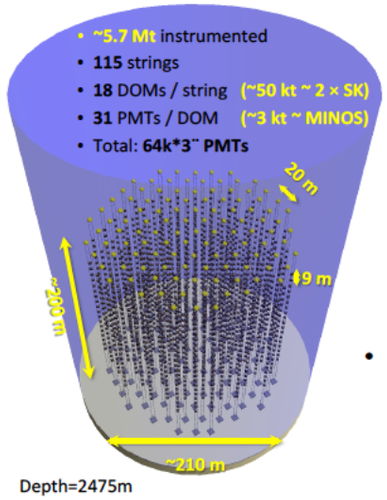
See Session Nu-2

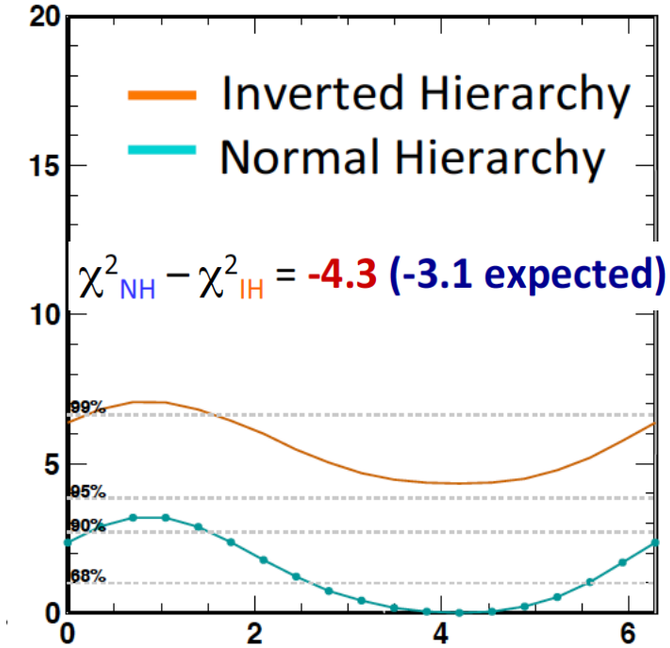
See Kutter plenary

The Future - PINGU, ORCA, JUNO

- PINGU - Upgrade to IceCube
- ORCA - Upgrade to KM3NeT

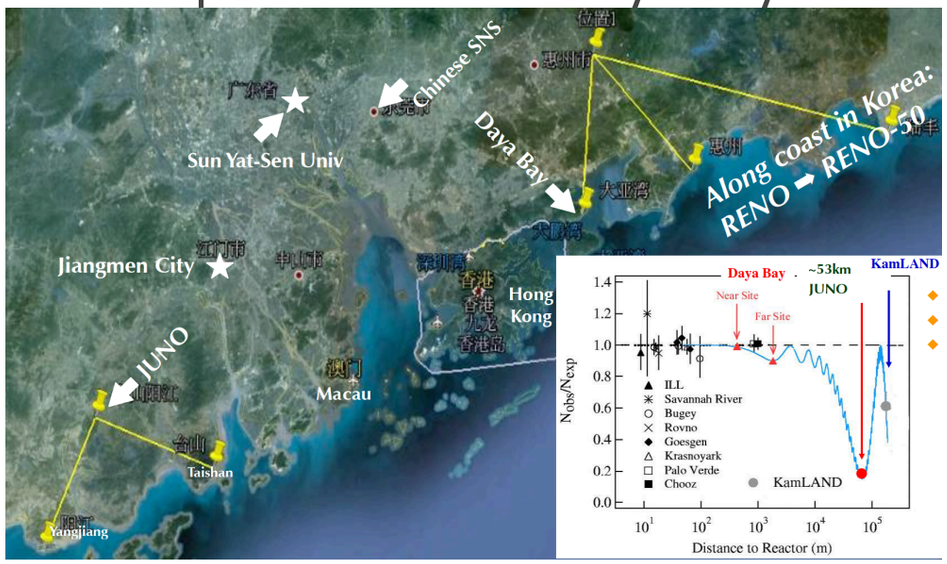


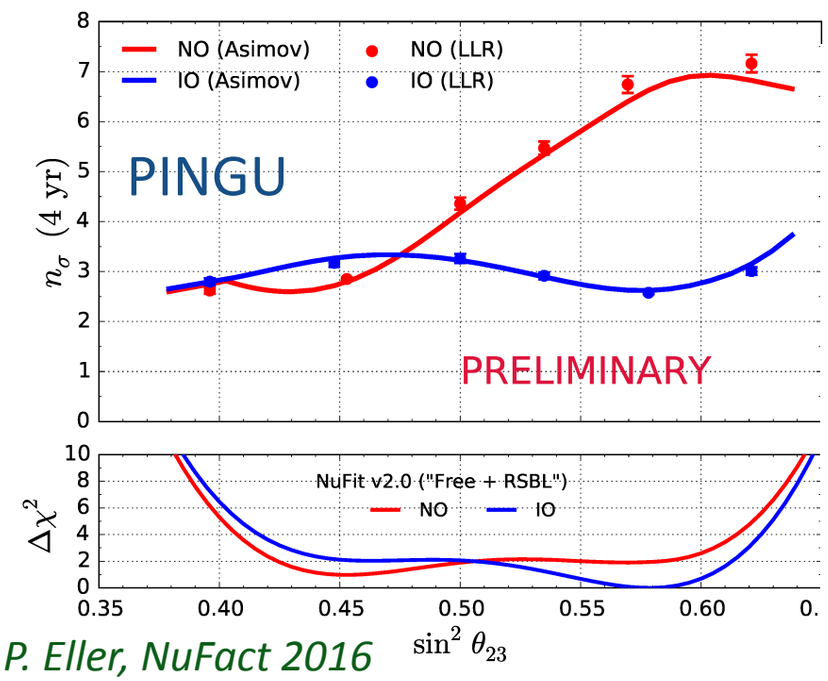




J. Kameda, NuFact 2016

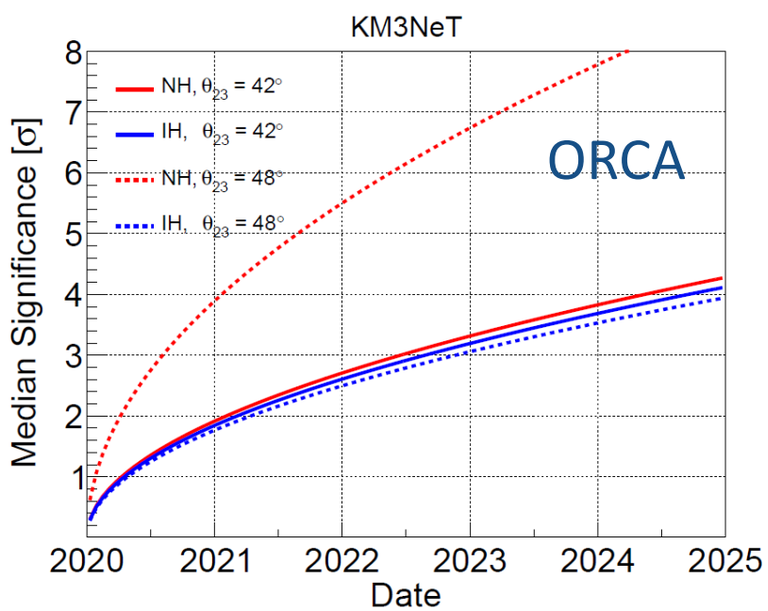
- JUNO - 60 km baseline reactor experiment near Daya Bay site

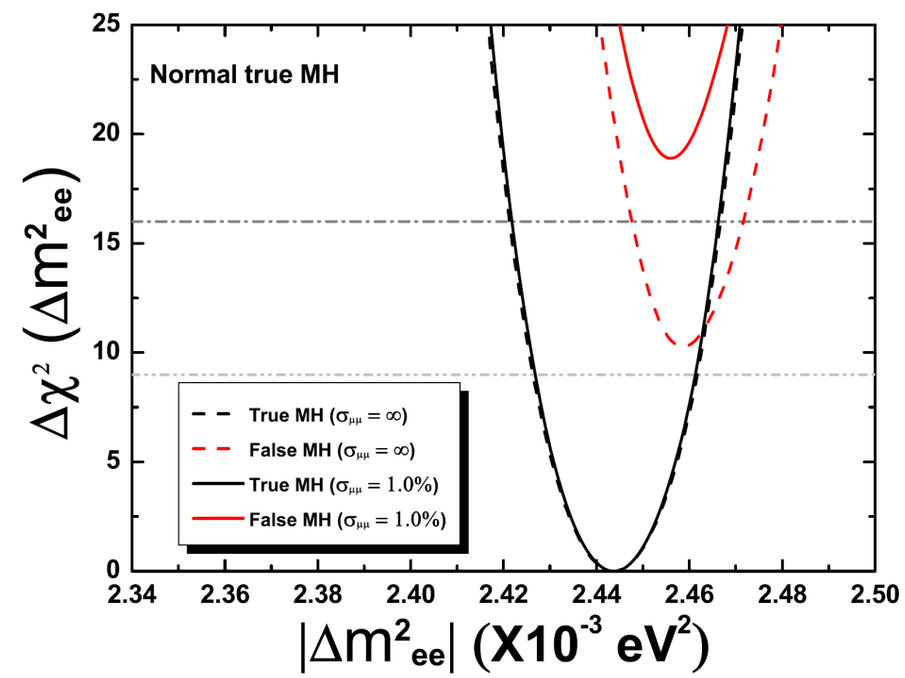




P. Eller, NuFact 2016

- SuperK favors N.O. at ~2σ from atmos. neutrinos





- Can determine N.O at 3σ over 3- 4 years

- 3σ determination of mass ordering with 6 years of running
- Under construction, operations starting in 2020 *W. Wang, NuFact 2016*

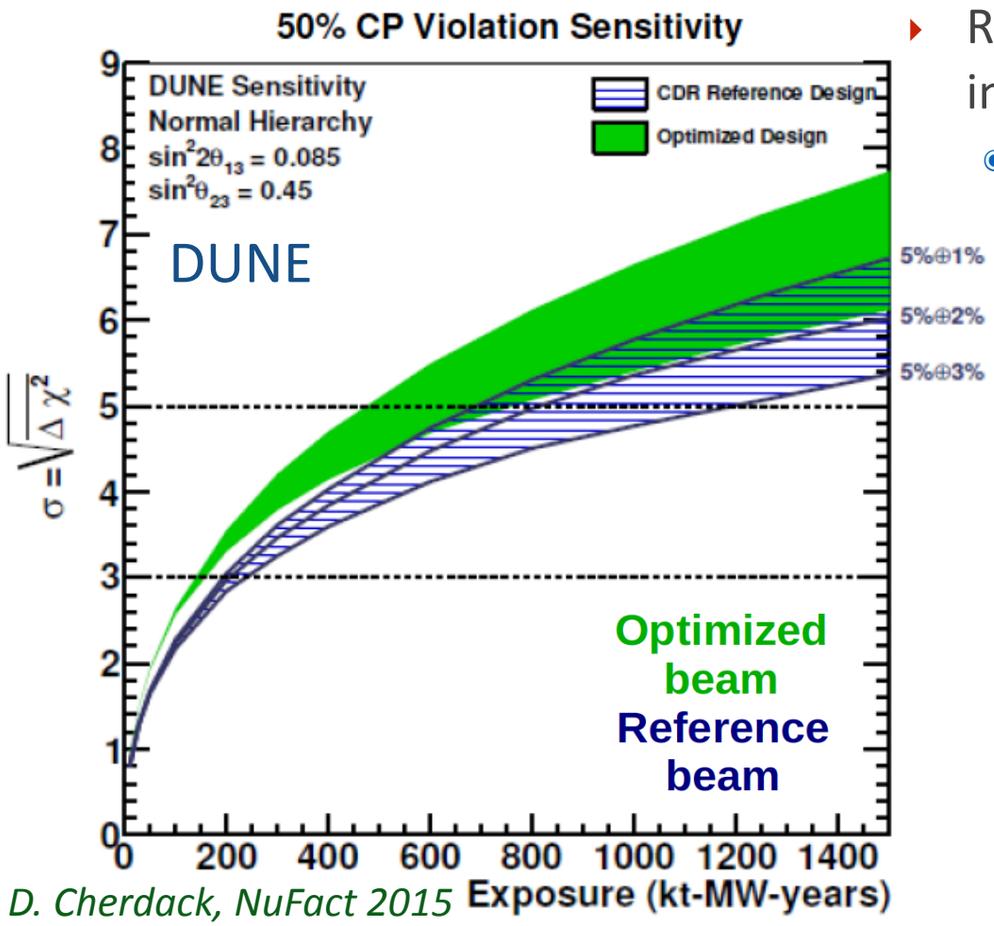
See Session Nu-2

Answering the Questions…

Systematic Uncertainties

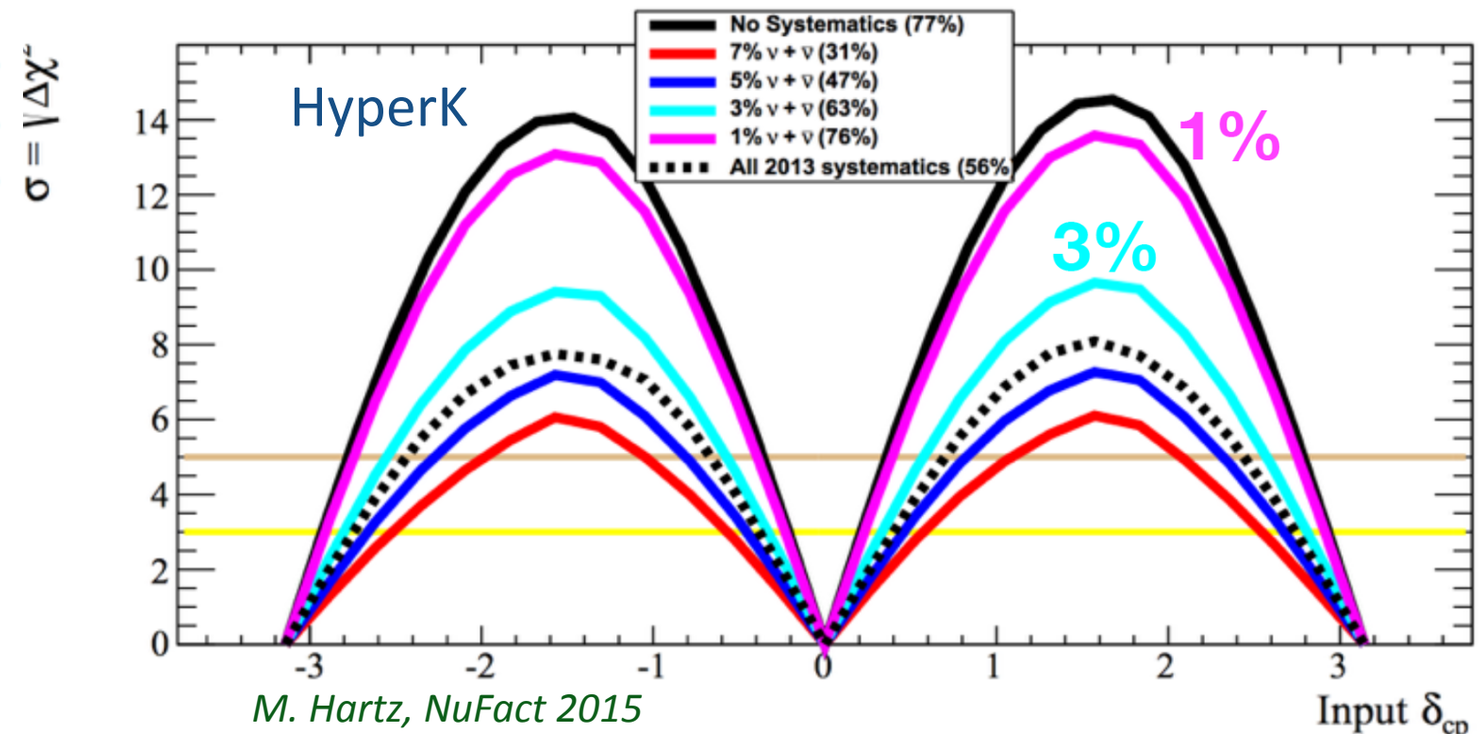
NuMI Beam Horn, January 2015

Effect of Systematic Uncertainties



D. Cherdack, NuFact 2015

- Reduction of systematic uncertainties essential to timely get to the physics in future experiments
  - Note: NOvA and T2K report 11% syst on their sample bgs and 6-7% in signal



M. Hartz, NuFact 2015

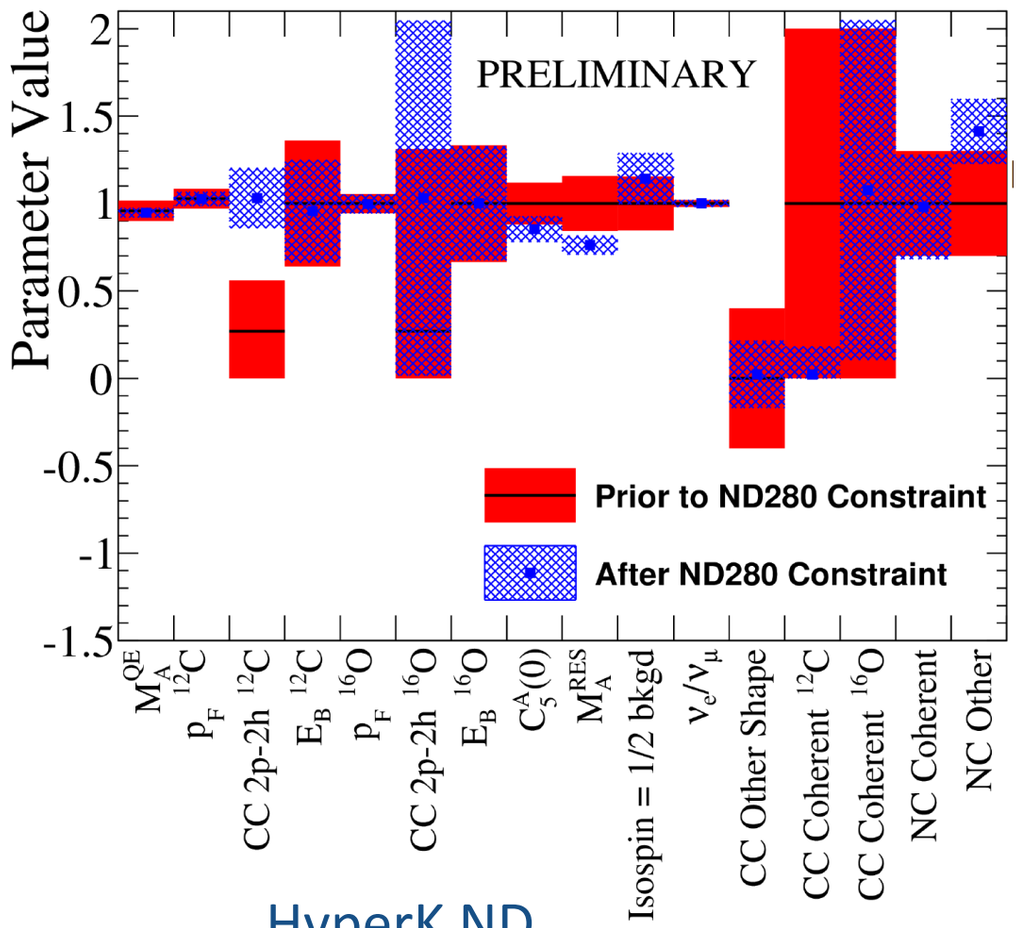
$\nu_\mu \rightarrow \nu_e$ osc. signal →

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\to\nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$

A. Weber, DUNE Meeting (2017)

- Near Detector is essential
- Cross sections of $\nu_e, \bar{\nu}_e$ measured in FD not directly cancelled by ND measurements of $\nu_\mu, \bar{\nu}_\mu$
  - Need better knowledge of $\nu_e, \bar{\nu}_e$ cross sections and uncertainties on $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$
- Precise understanding of absolute flux rate and shape necessary to disentangle convolution of hadron production and beam optics, cross sections, and detector effects to determine energy scale
  - Hadron production experiments, test beams, and detector R&D

Near Detectors

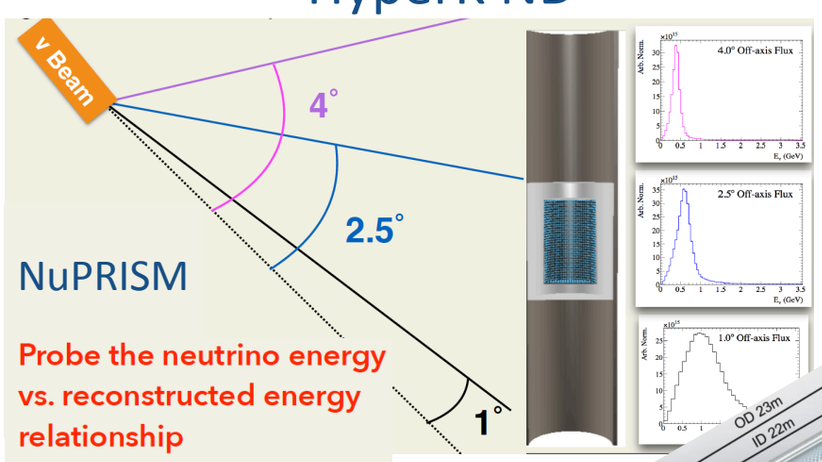


$\bar{\nu}_\mu$ disappearance analysis		w/o ND measurement	w/ ND measurement
ν flux and cross section	flux	7.1%	3.5 %
	cross section cmn to ND280	5.8%	1.4 %
	(flux) × (cross section cmn to ND280)	9.2%	3.4 %
	cross section (SK only, include ↓)	10.0 %	
	multi-nucleon effect on oxygen	9.5%	
	total	13.0%	10.1%
Final or Secondary Hadronic Interaction		2.1%	
Super-K detector		3.8%	
total		14.4%	11.6%

K. Mahn, NuFact 2015 Fractional error on number-of-event prediction

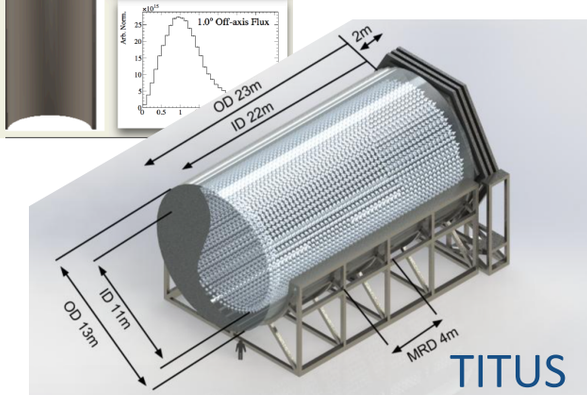
- Impact of ND280 in T2K analysis
  - Large reductions in flux and cross section uncertainties
  - Motivated improved modeling of neutrino interactions with correlated nucleon pairs (2p2h)

HyperK ND



NuPRISM

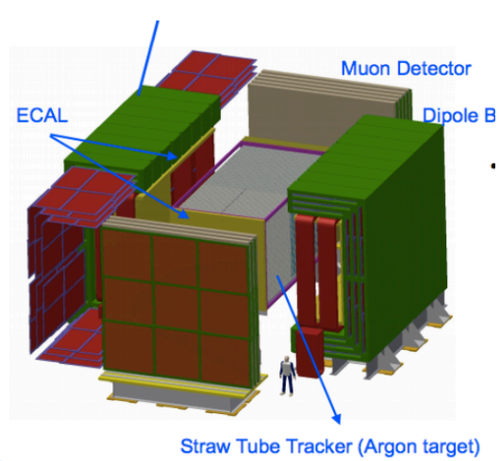
Probe the neutrino energy vs. reconstructed energy relationship



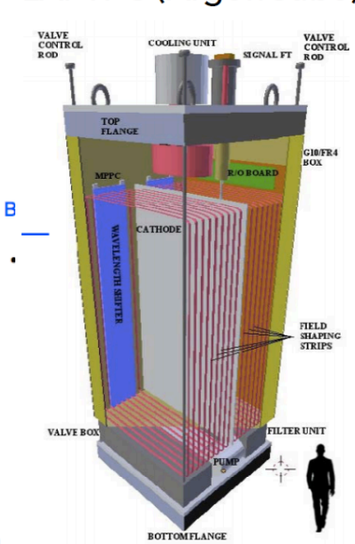
TITUS

DUNE ND

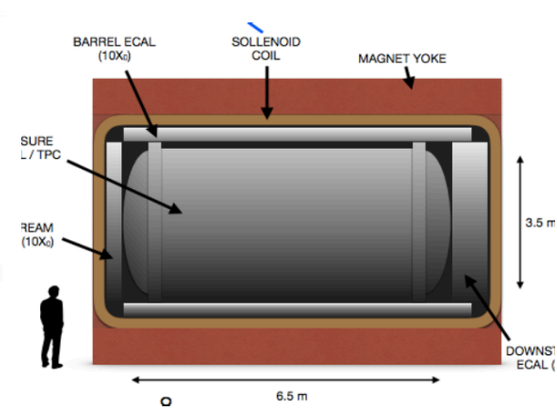
Fine-Grained Tracker



LAr TPC (ArgonCube)

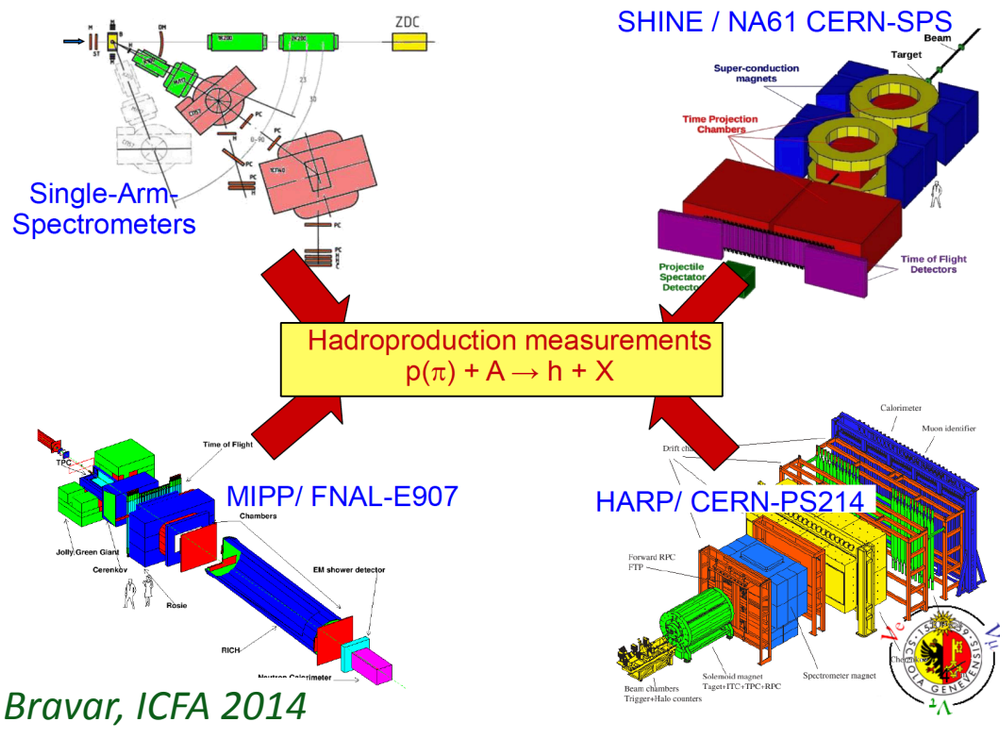


High Pressure Ar Gas TPC



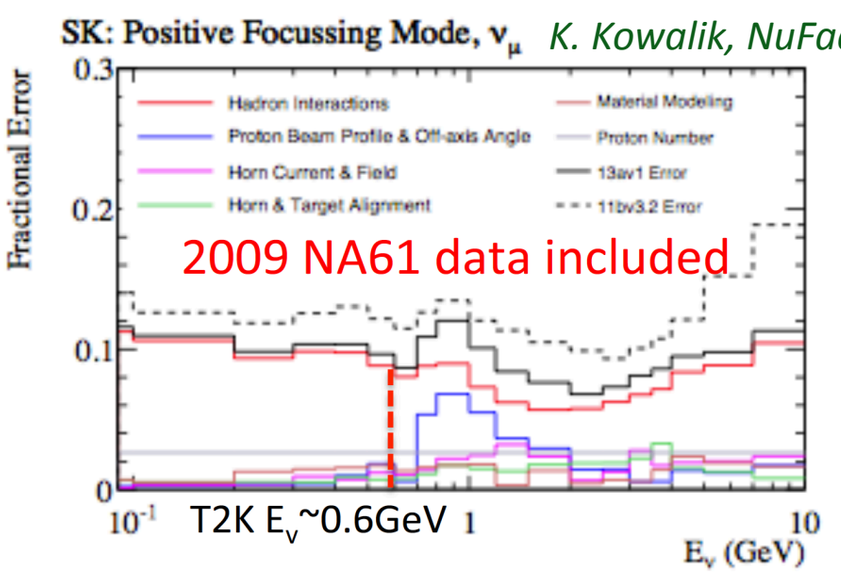
See Session Nu-2

Hadron Production, Cross Section Measurements



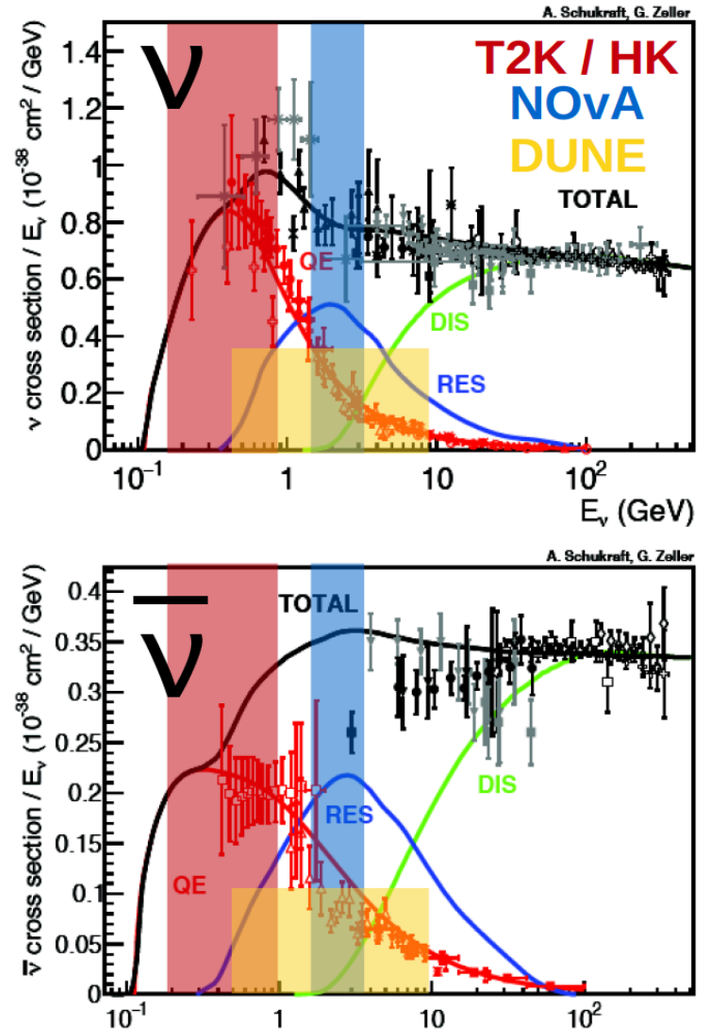
A. Bravar, ICFA 2014

- In 50 years we have gone from 30% uncertainties on ν fluxes to ~10% while increasing proton fluxes on target by ~10^3 – 10^4



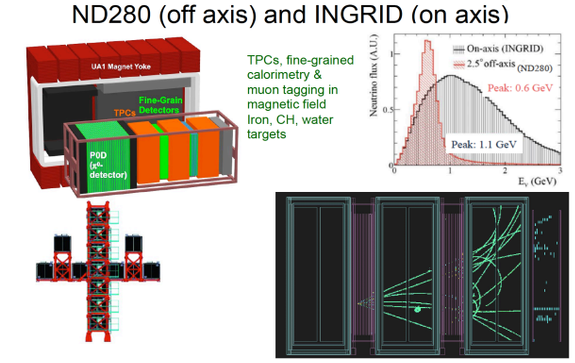
K. Kowalik, NuFact 2016

- Ongoing 2-year NA61/SHINE program for LBNF/NuMI. Aim to reduce flux uncertainties to ~5%

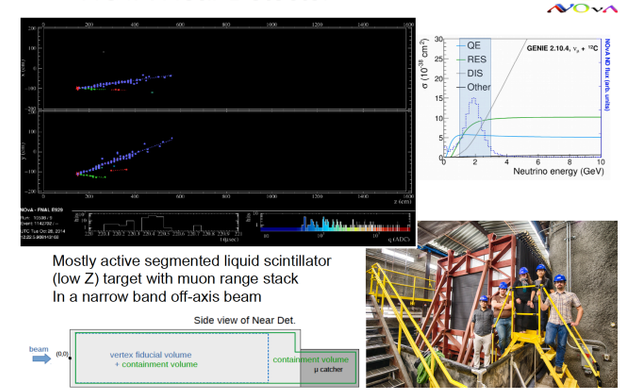


J. Nelson, NuFact 2016

T2K near detectors
ND280 (off axis) and INGRID (on axis)

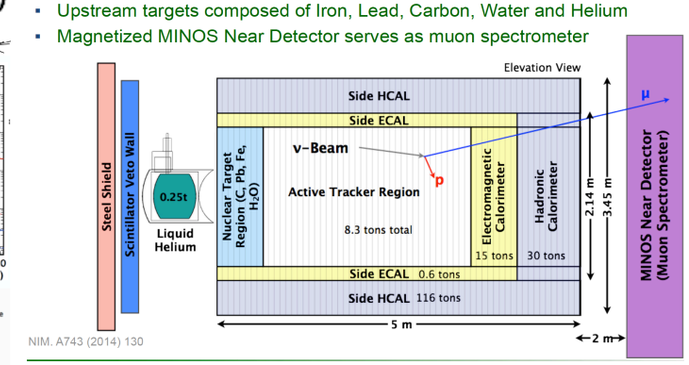


NOvA Near Detector



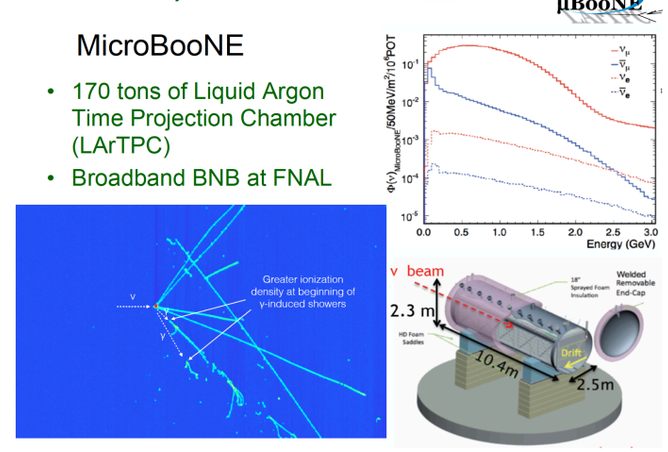
MINERvA

- Finely segmented solid scintillator detector in NuMI
  - Active tracker is made completely of scintillator
  - Calorimeters are scintillator with either Iron or Lead
- Upstream targets composed of Iron, Lead, Carbon, Water and Helium
- Magnetized MINOS Near Detector serves as muon spectrometer



MicroBooNE

- 170 tons of Liquid Argon Time Projection Chamber (LArTPC)
- Broadband BNB at FNAL



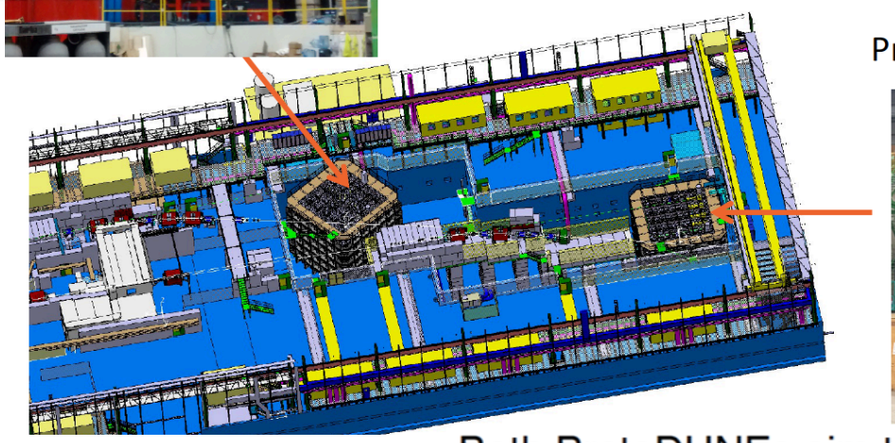
See Session Nu-3

Systematics - R&D, Test Beams

ProtoDUNE Dual Phase

Major CERN investment to support DUNE

- EHN1 extension in the North area
- Two tertiary charged-particle beam lines
- Two 8m×8m×8m cryostats & cryogenic systems

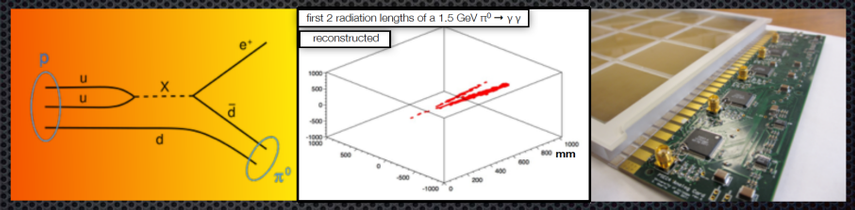


ProtoDUNE Single Phase

Both ProtoDUNEs aim to begin data taking in mid 2018.

The ANNIE experiment

- ANNIE, seeks to measure the abundance of final state neutrons from neutrino interactions in water, as a function of energy (see arXiv:1409.5864 and arXiv:1504.01480).
- It is also the first application in a HEP experiment of LAPPDs (Large-Area Picosecond Photo-Detectors).

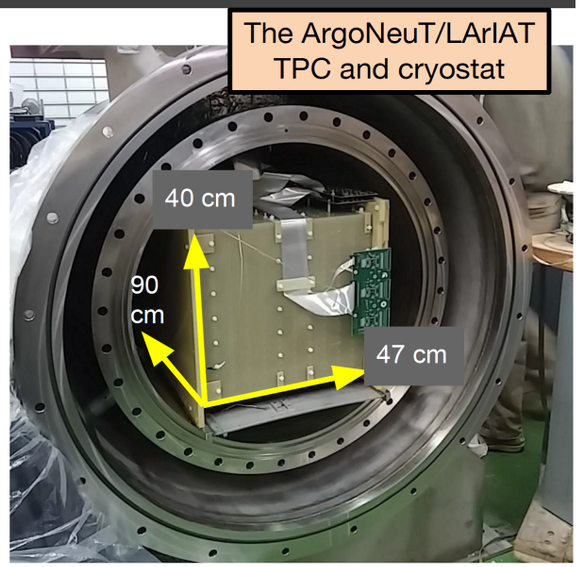


- A key physics measurement in understanding the nature neutrino-nucleus interactions.
- Application of a promising technology for detecting neutrinos.

LArIAT

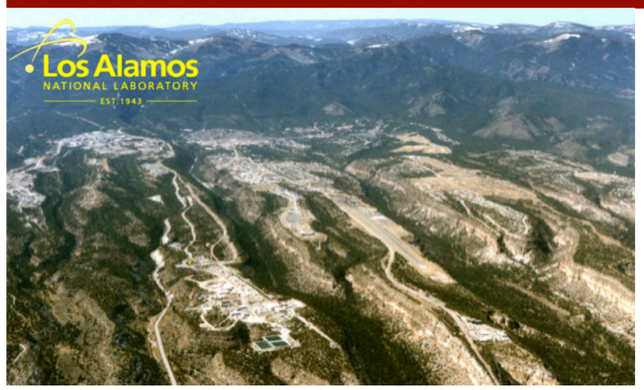
"Table-top" (170L) LArTPC in a test beam at Fermilab Test Beam Facility

- Repurposed ArgoNeuT detector
- **Physics goals:**
  - π-Ar interactions
  - e/γ shower ID
  - μ-Ar capture
  - non-magnetic charge determination
  - kaon studies
  - Geant4 validation
- **R&D goals:**
  Optimize PID algorithm, calorimetry with charge & light, and 2D/3D event reconstruction

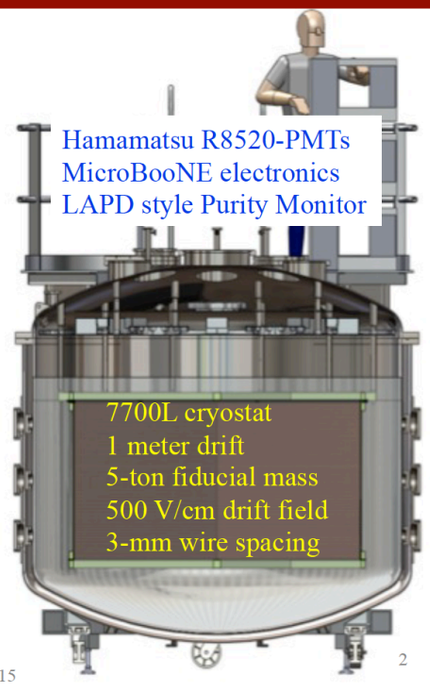


- See session nu-4

Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos - CAPTAIN



•Funded by Los Alamos National Lab (LANL) Laboratory Director Research & Development (LDRD). Now a multi-instituitional collaboration.
• A portable full-scale liquid argon TPC (CAPTAIN) and a prototype (Mini-CAPTAIN).
• Study interactions in liquid argon with neutron source at LANL and neutrino beams at Fermilab.

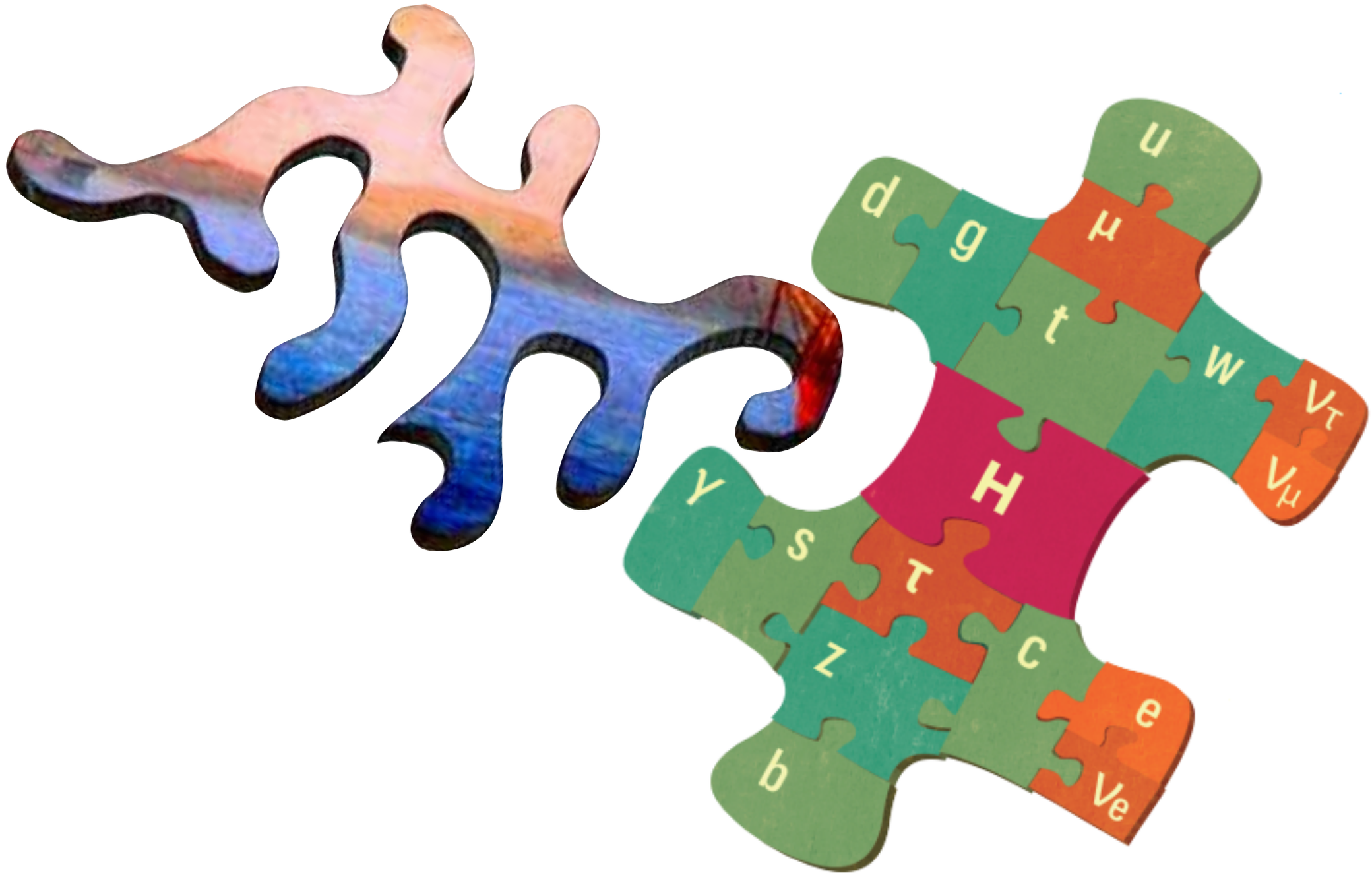


Jianming Bian - DPF2015

2

See Sessions Nu-2, 7

Answering the Questions…

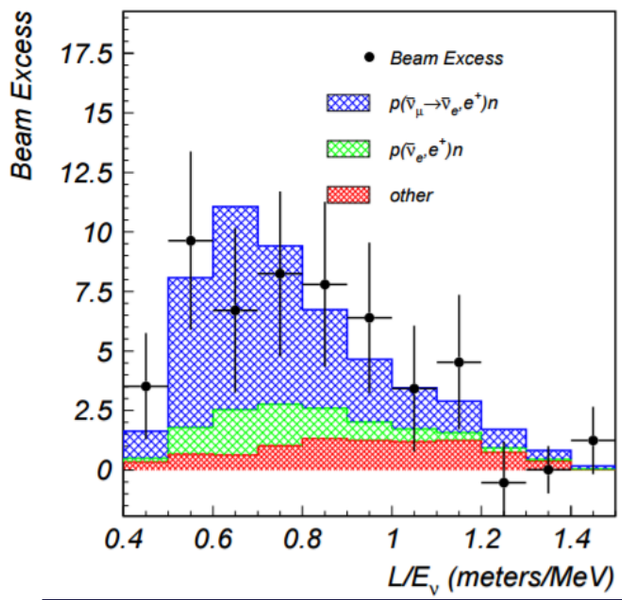


Beyond the Three-Flavor Paradigm

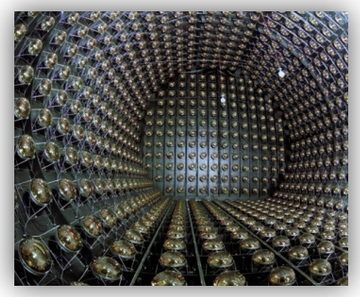
"Anomalies"

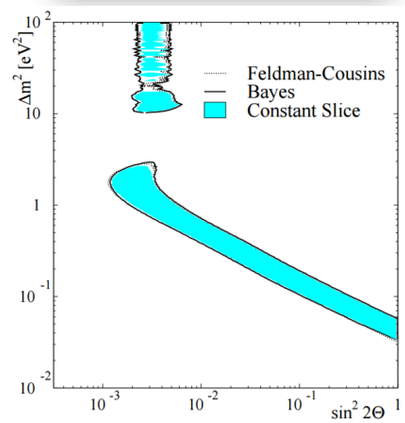
See Giunti, Cao, Diwan talks

- **LSND** $\bar{\nu}_\mu \to \bar{\nu}_e$
  - Excess of electron antineutrinos from decay-at-rest (~3.8σ)

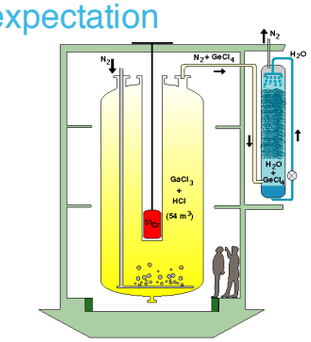


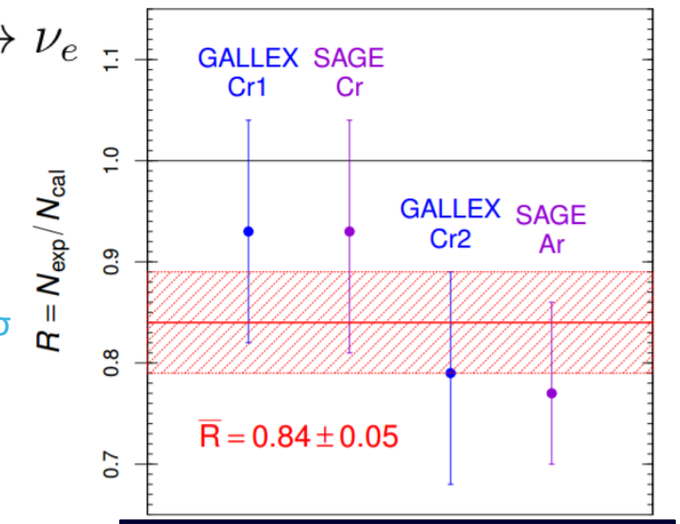
A. Aguilar-Arevalo et al. Phys. Rev. D64 (2001), p. 112007.





- **Gallium Anomaly** $\nu_e \to \nu_e$
  - GALLEX & SAGE
    - Designed for radiochemical detection of solar neutrinos
  - Measured rates for calibration sources ^{51}Cr and ^{37}Ar was ~2.7σ below expectation

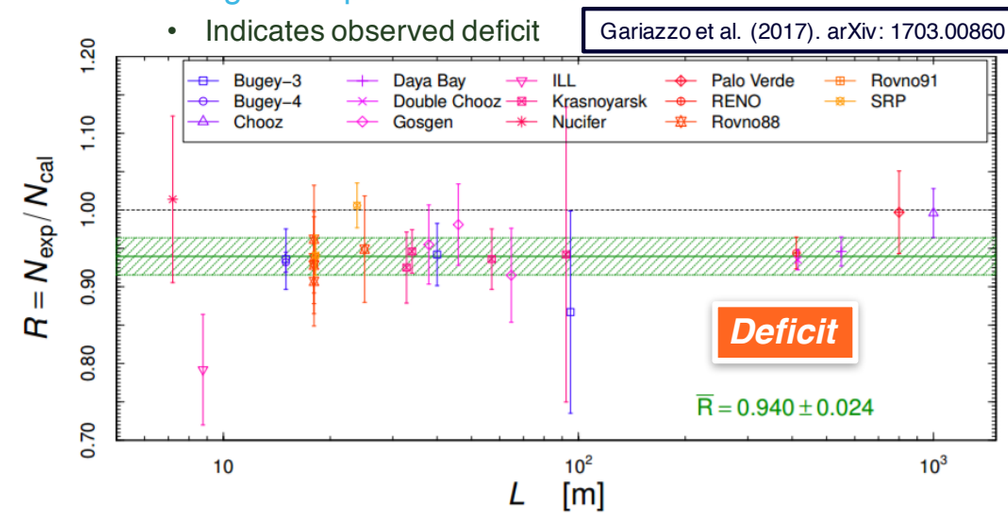




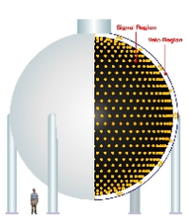
Gariazzo et al. J.Phys. G43 (2016) 033001
DOI:10.1088/0954-3899/43/3/033001

- **Reactor Flux** $\bar{\nu}_e \to \bar{\nu}_e$
  - Recalculation of expected reactor flux found systematic bias in previous predictions
  - New prediction is ~6%(~2.5σ) greater than world average of experimental measurements
    - Indicates observed deficit

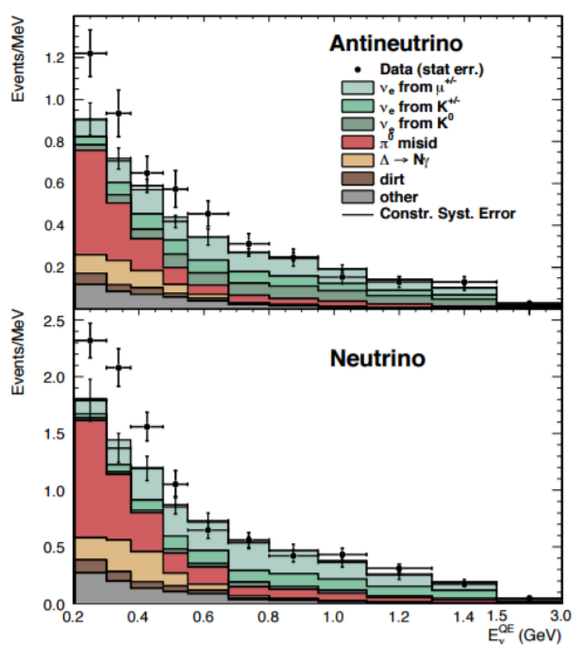
Gariazzo et al. (2017). arXiv: 1703.00860 [hep-ex]



- **MiniBooNE** $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$
  - Designed motivated by LSND KARMEN results
  - Observed Low-energy excess in electron flavor
    - Neutrinos (~3.4σ)
    - Antineutrinos (~2.8σ)



A. Aguilar-Arevalo et al. Phys. Rev. Lett. 110 (2013), p. 161801.



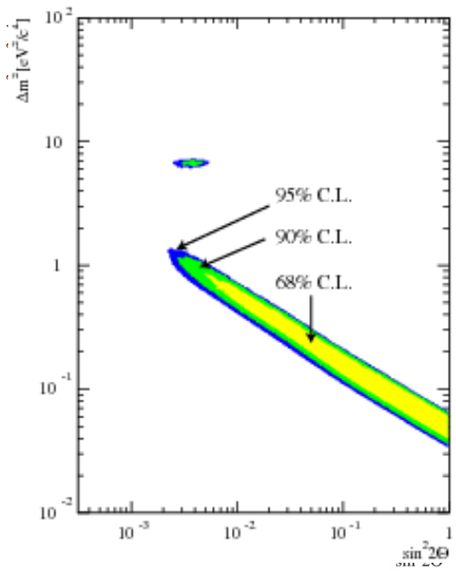
J. Todd, MINOS+ Wine&Cheese (2017)

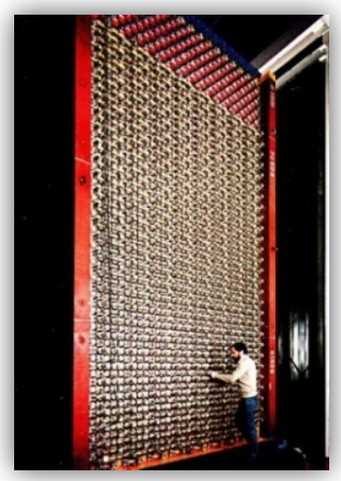
- Oscillation interpretation requires Δm^2~1 eV^2
  - Mixing with sterile neutrinos?

Null Results

See Giunti, Cao, Diwan talks

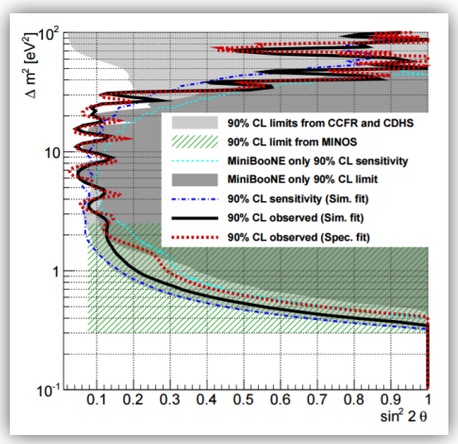
- **KARMEN2** $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$
  - No excess above background from spallation source with decay-at-rest

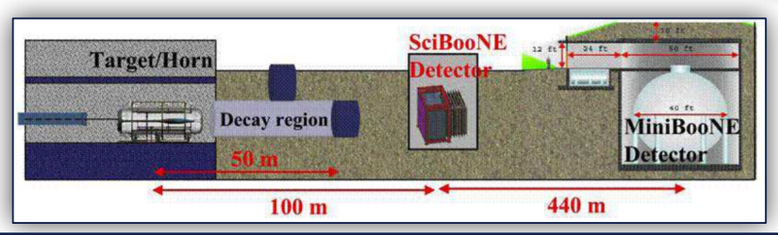




Church et al. Phys. Rev. D66 (2002), p. 013001.

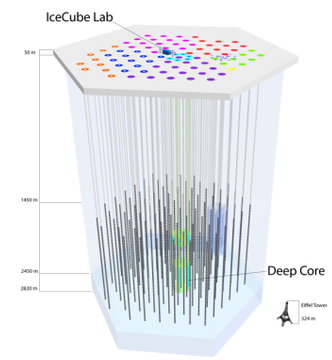
- **MiniBooNE/SciBooNE** $\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$
  - Search for muon (anti)neutrino disappearance in neutrino beam
  - Dual-detector fit over short baselines
    - SciBooNE as near detector and MiniBooNE as far detector
  - No evidence seen in either neutrino or antineutrino channels



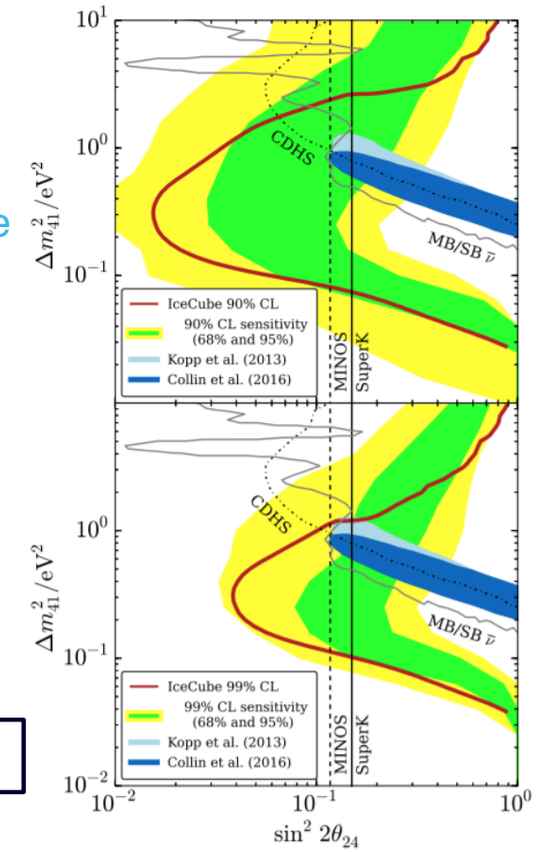


Mahn, K et al. Phys. Rev. D85 (2012), p. 032007.

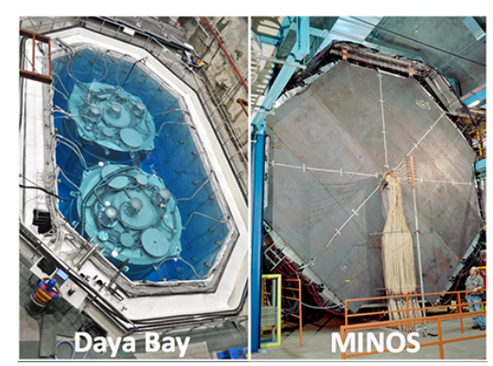
- **IceCube**
  - Detects no evidence of beyond three flavor oscillations in atmospheric neutrinos traversing the earth



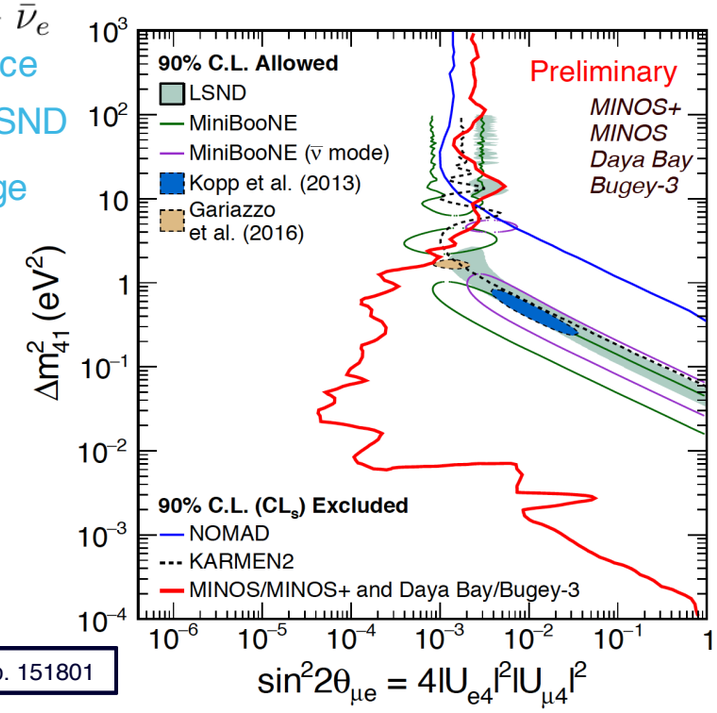
M.G. Aartsen et al. Phys. Rev. Lett. 117 (2016) 071801



- **MINOS+, Daya Bay** $\nu_\mu \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_e$
  - Combination of two disappearance measurements comparable to LSND
  - Disfavors sterile mixing over large regions of parameter space



P. Adamson, et al. Phys. Rev. Lett. 117 (2016), p. 151801

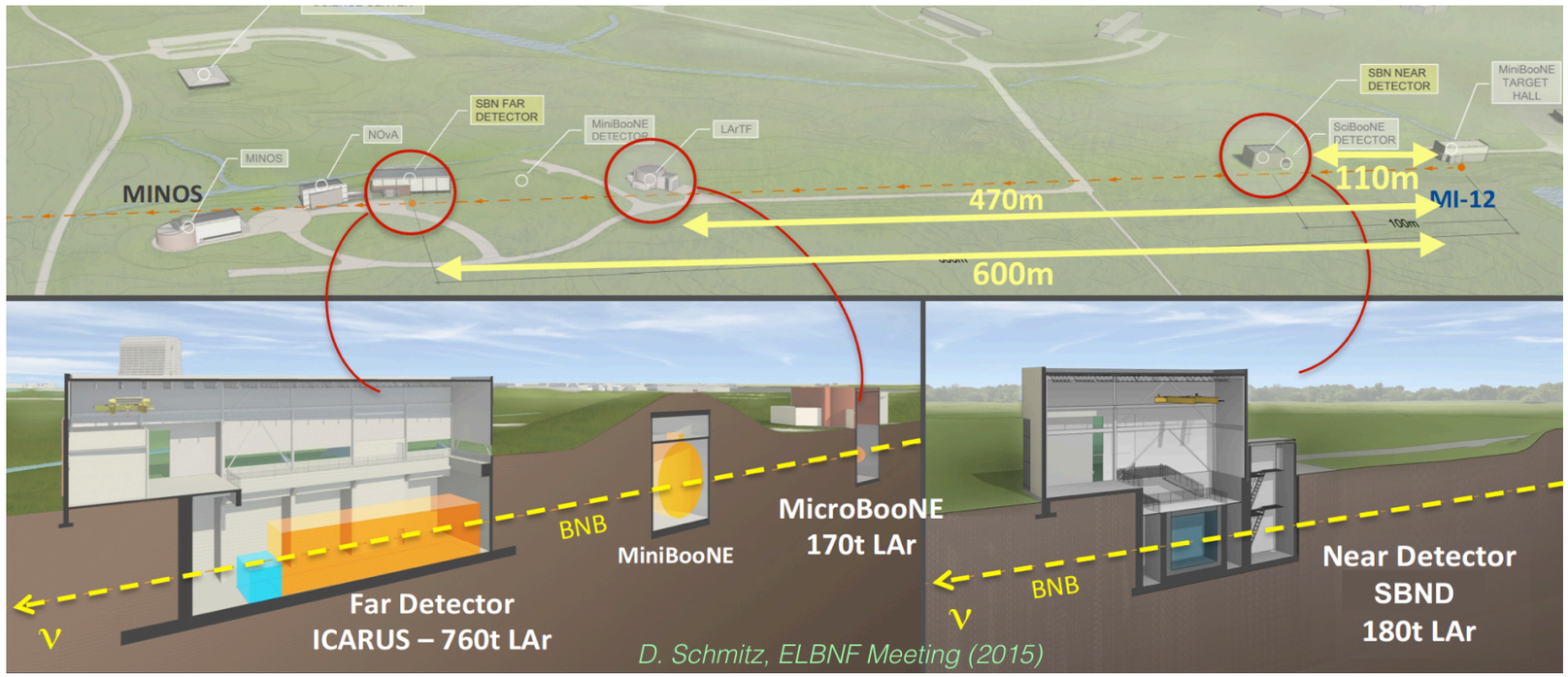


J. Todd, MINOS+ Wine&Cheese (2017)

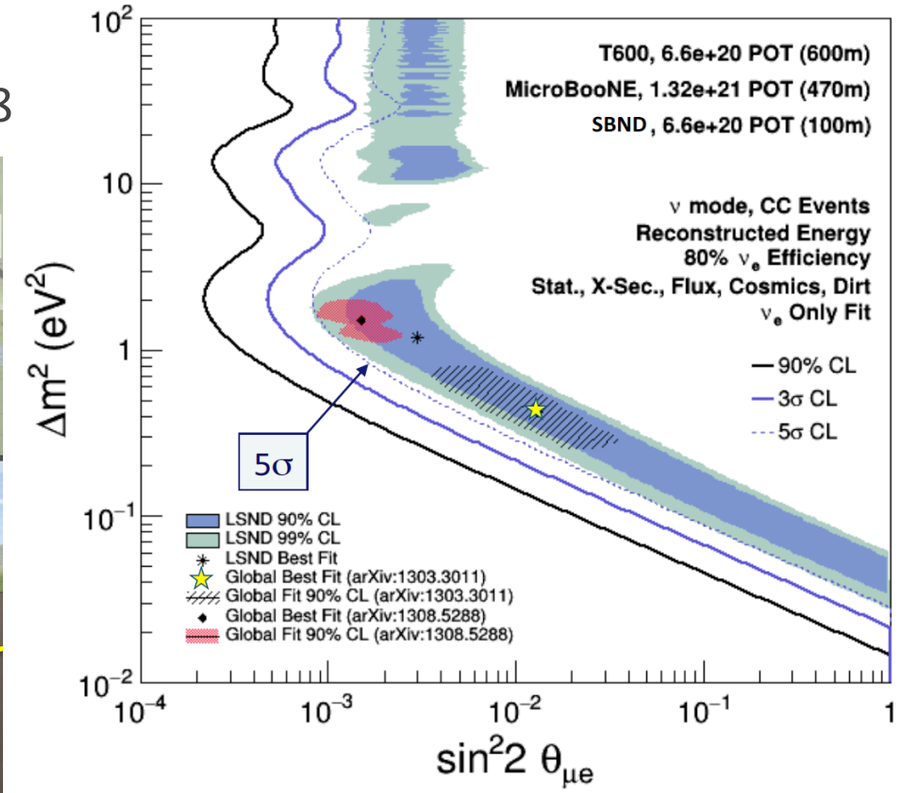
- Also SuperK, IceCube-DeepCore, NOvA, OPERA, ICARUS, CDHS, CCFR, NOMAD, …

Future - SBL Experiments

- Short-Baseline Neutrino Program at Fermilab
  - Three LArTPC detectors in the Booster beam, data taking starts in 2018

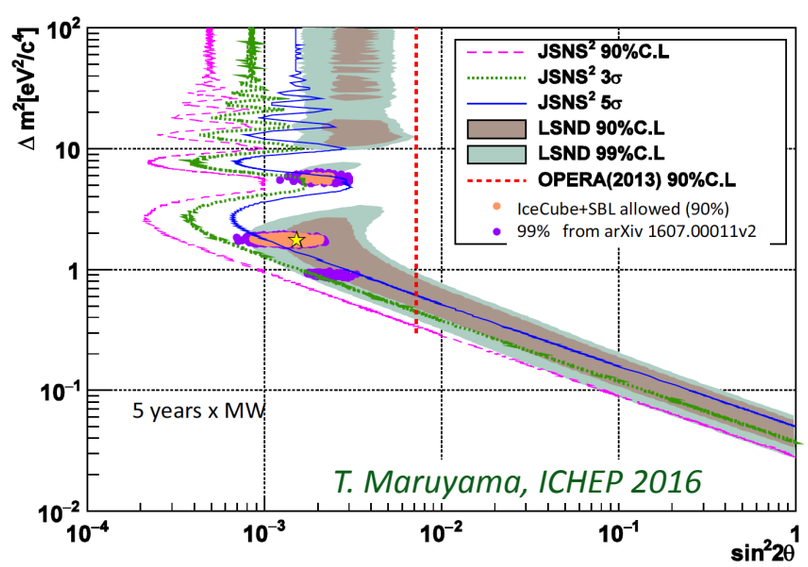


D. Schmitz, ELBNF Meeting (2015)

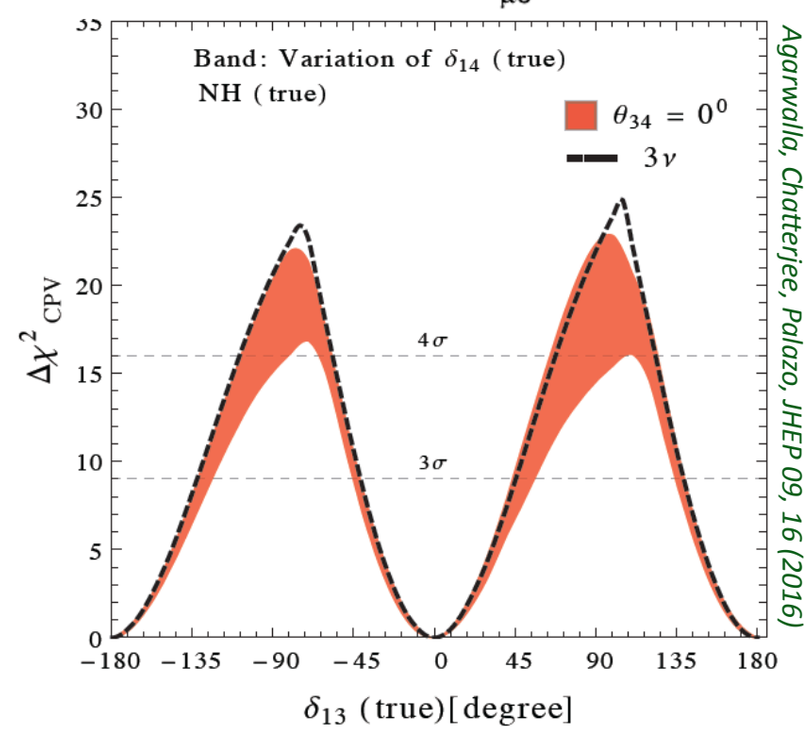


- JSNS^2 will use decay-at-rest beam from spallation source
  - Direct test of LSND, potential exclusion at 3σ, data taking starts in 2018

Searching for neutrino oscillation : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up



T. Maruyama, ICHEP 2016



Agarwalla, Chatterjee, Palazo, JHEP 09, 16 (2016)

- If sterile neutrinos present, they will impact interpretation of future results on δ_{CP}

See Sessions Nu-3, 7 **See Cao plenary**

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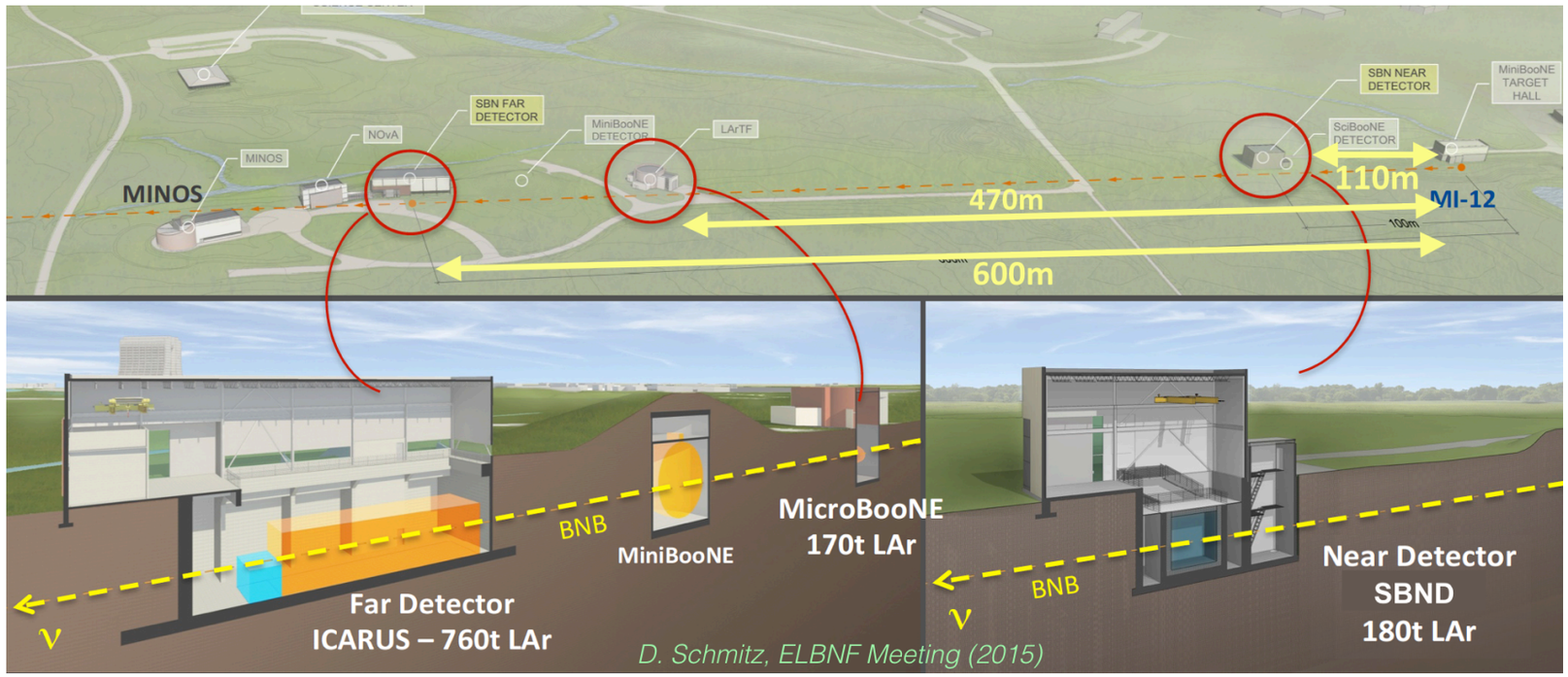

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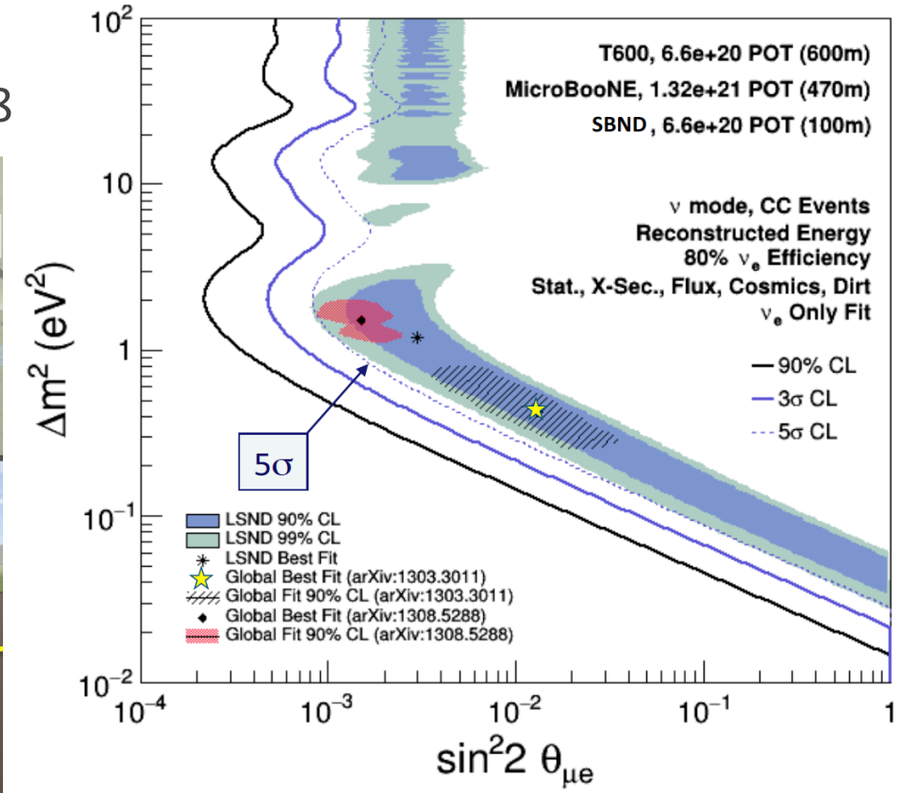

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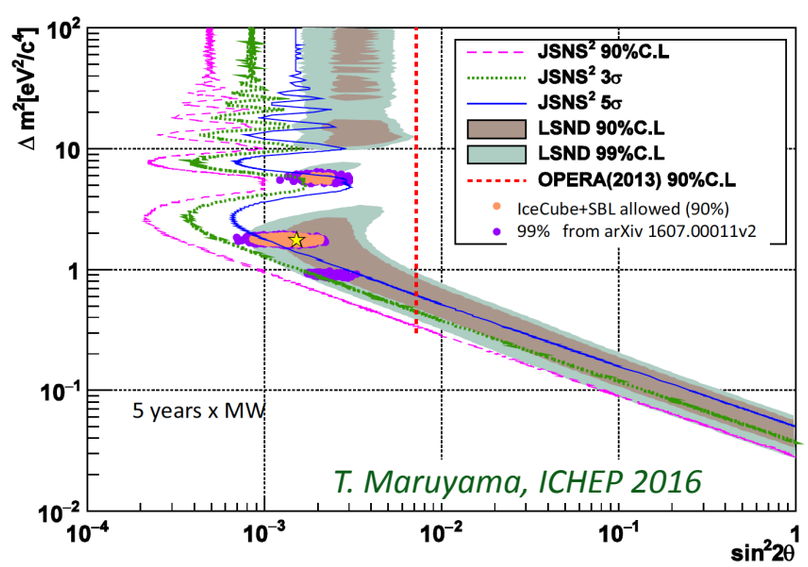

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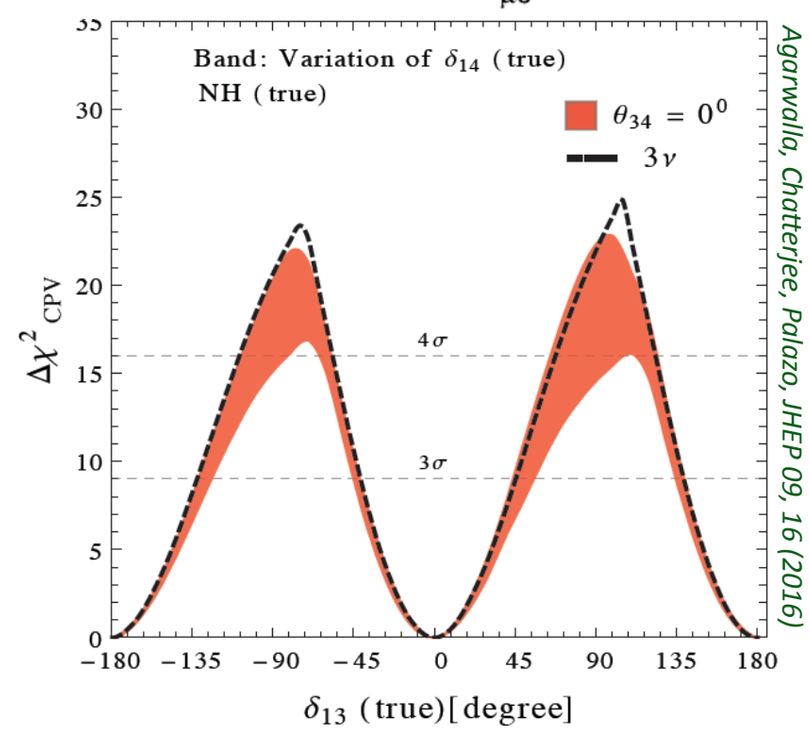

Agarwalla, Chatterjee, Palazo, JHEP 09, 16 (2016)

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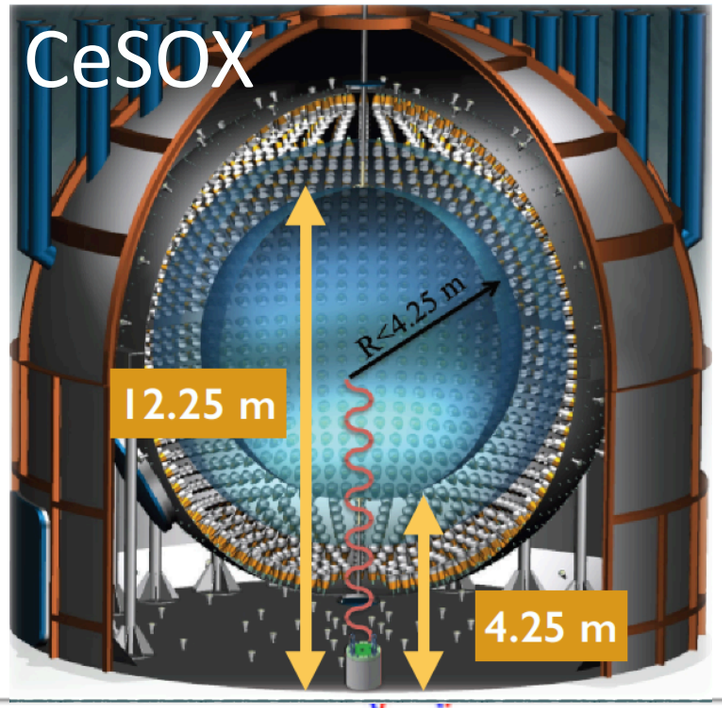
See Sessions Nu-3, 7

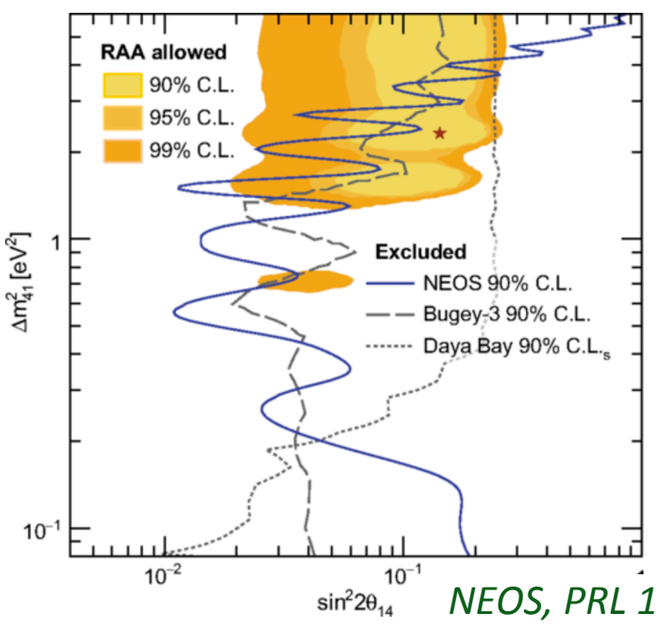
See Cao plenary

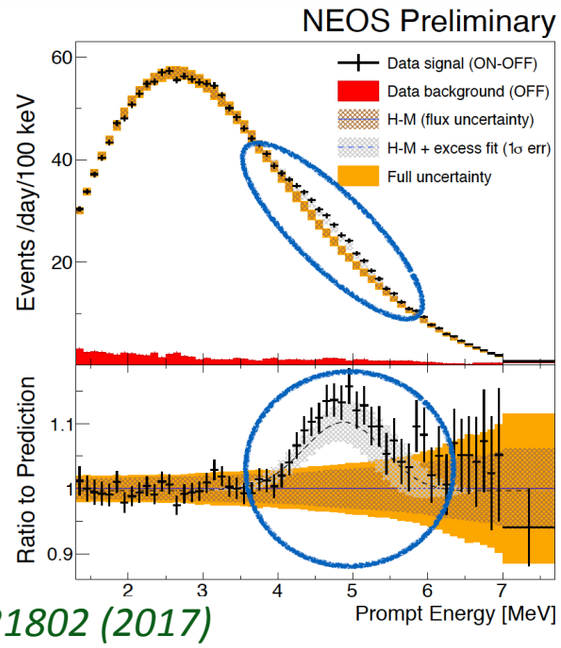
Future - Non-Accelerator Expts.

N. Bowden, Neutrino 2016

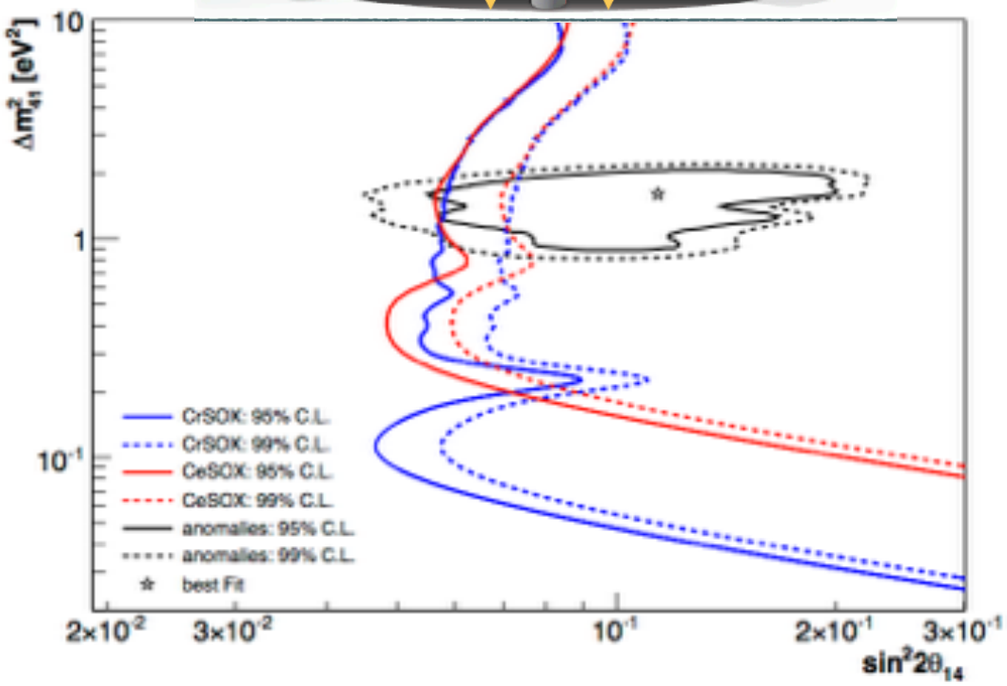
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD







NEOS, PRL 118, 121802 (2017)

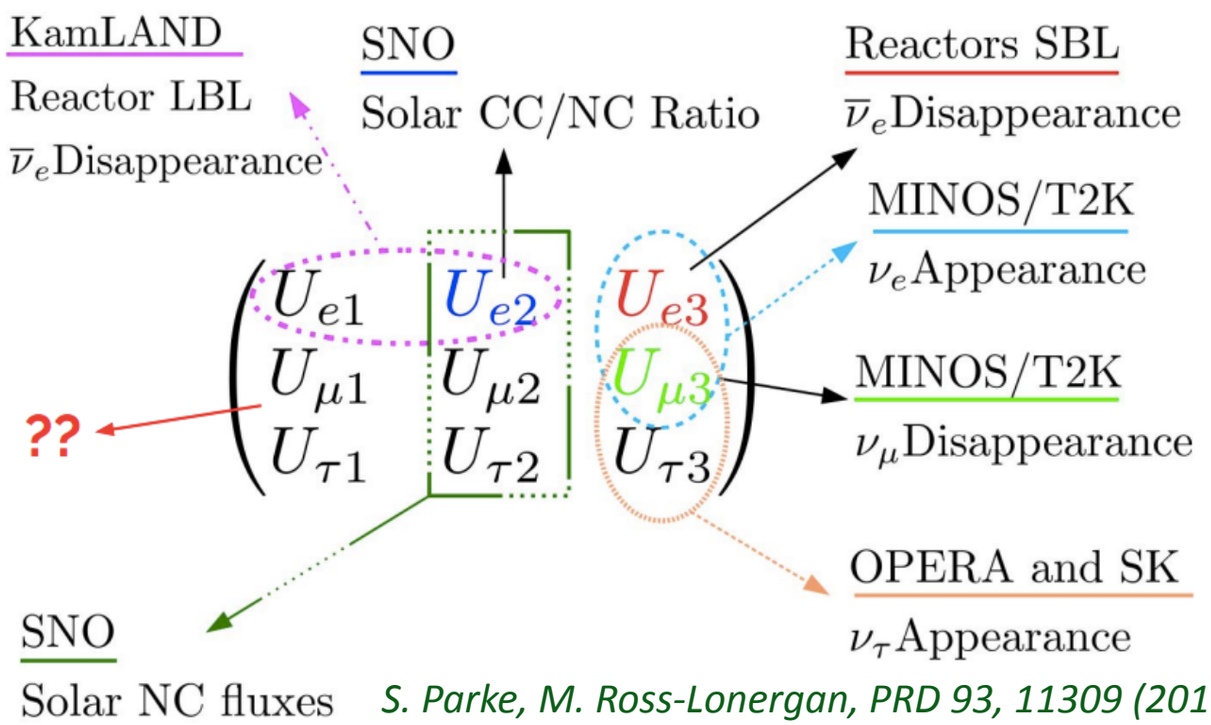


- Multiple reactor experiments will address reactor anomaly and "5 MeV bump"
- CeSOX - Use powerful ^{144}Ce $\overline{\nu}_e$ source in Borexino detector. Use "oscillometry" within detector to look for sterile neutrino mixing

See Sessions Nu-1, 4

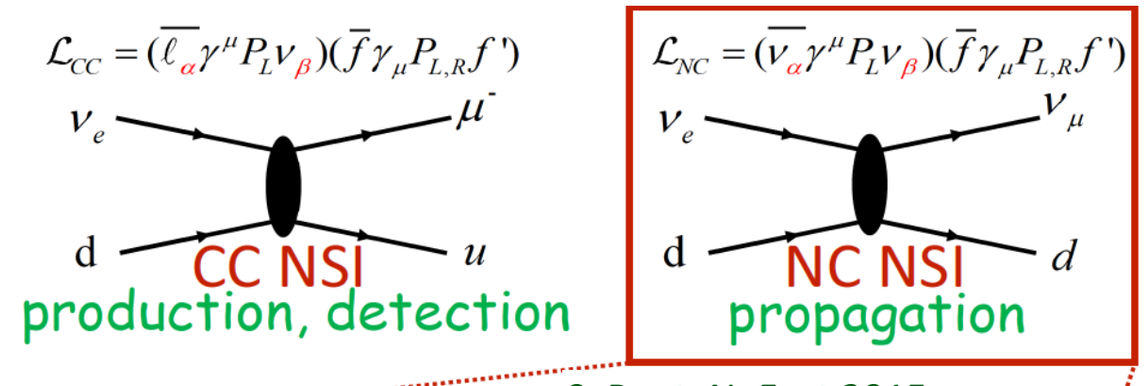
Other BSM Searches

- Non-Unitarity of PMNS matrix



S. Parke, M. Ross-Lonergan, PRD 93, 11309 (2016)

- Non-Standard Neutrino Interactions

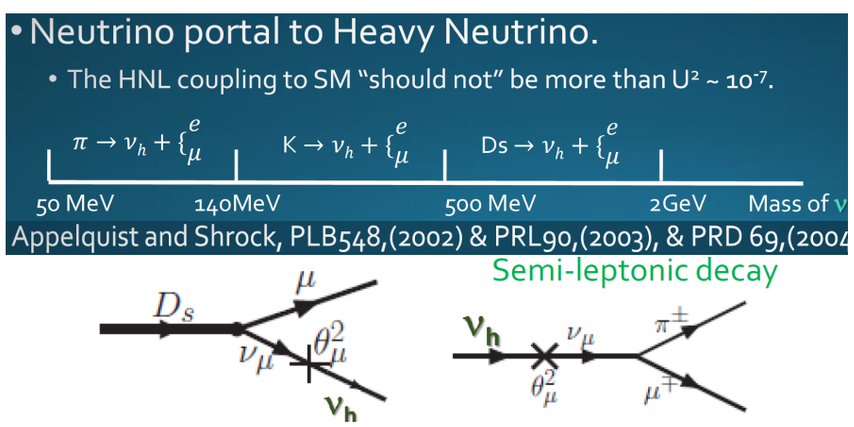


S. Raut, NuFact 2015

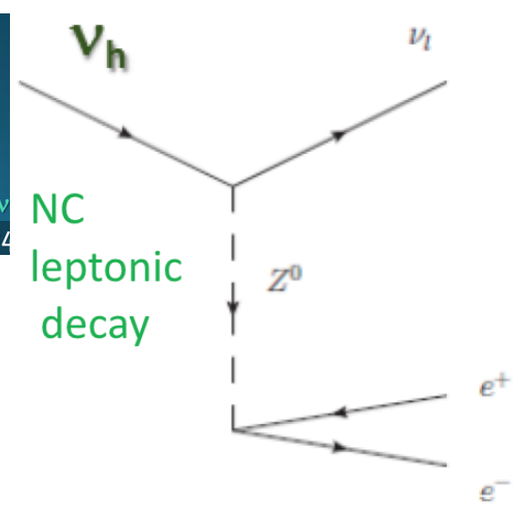
$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}$$

$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

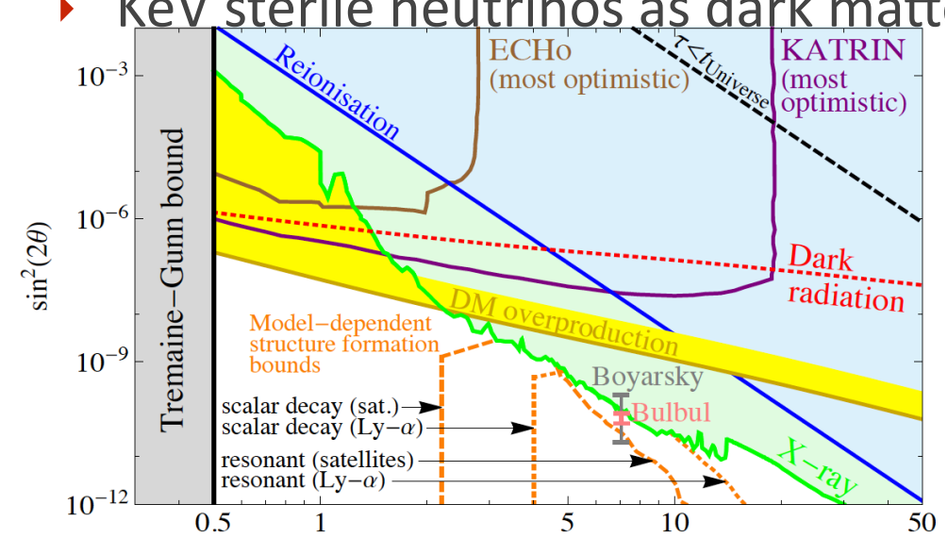
- Heavy Neutral Leptons



A. Hatzikoutelis, DUNE Meeting (2016)



- KeV sterile neutrinos as dark matter

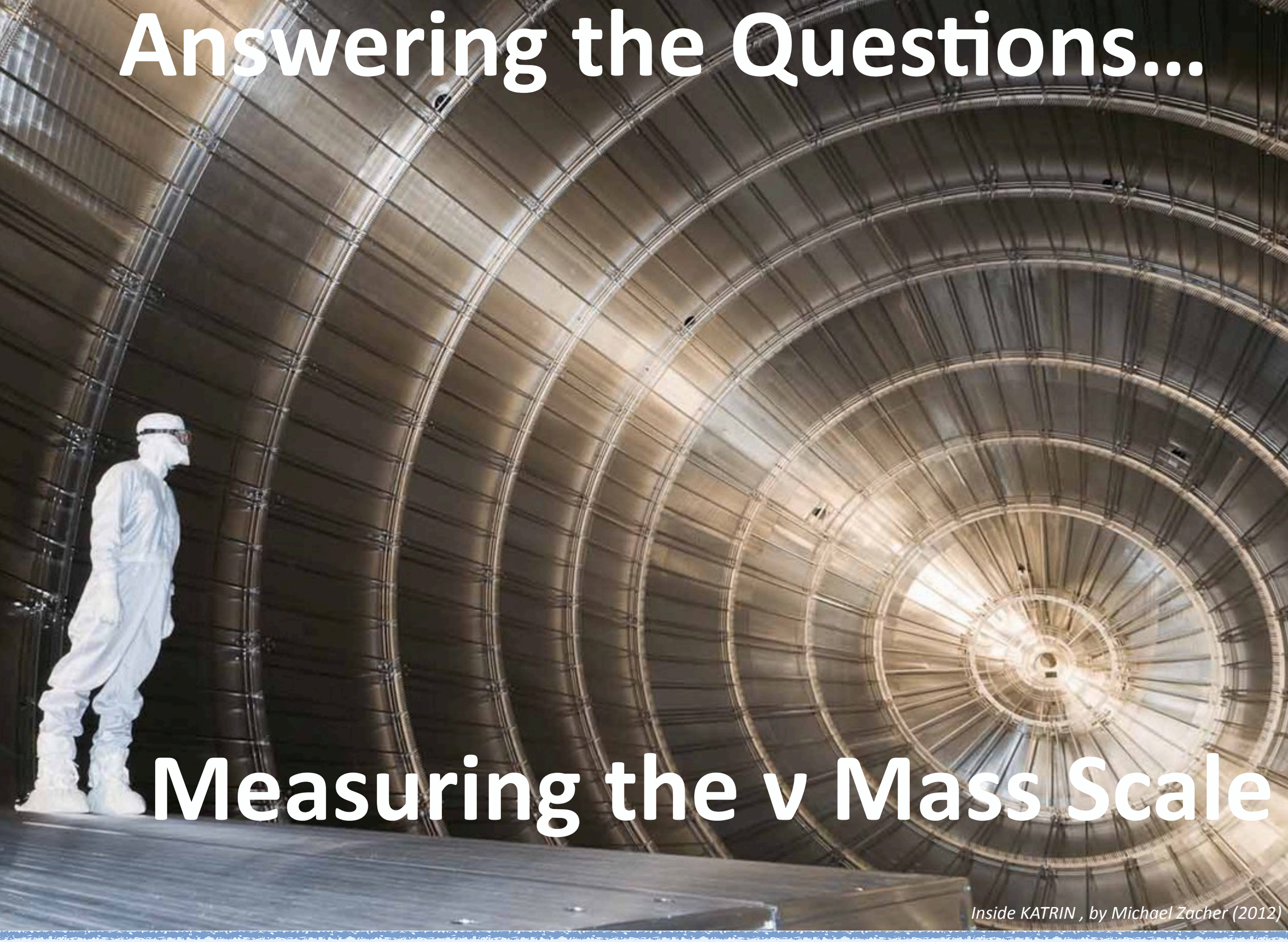


M. Drewes, NuFact 2016

- And many more…

See Sessions Nu-1, 4, 5, 6, 8

Answering the Questions…

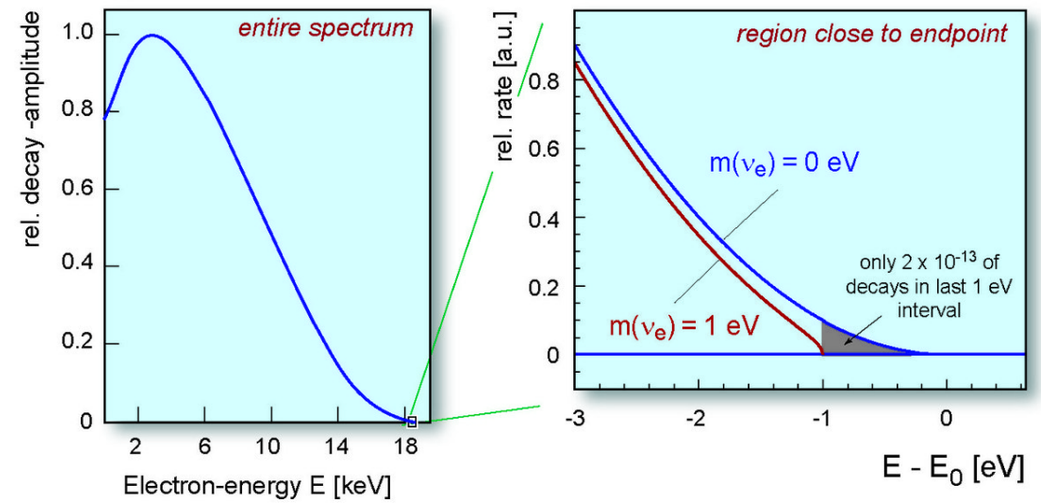


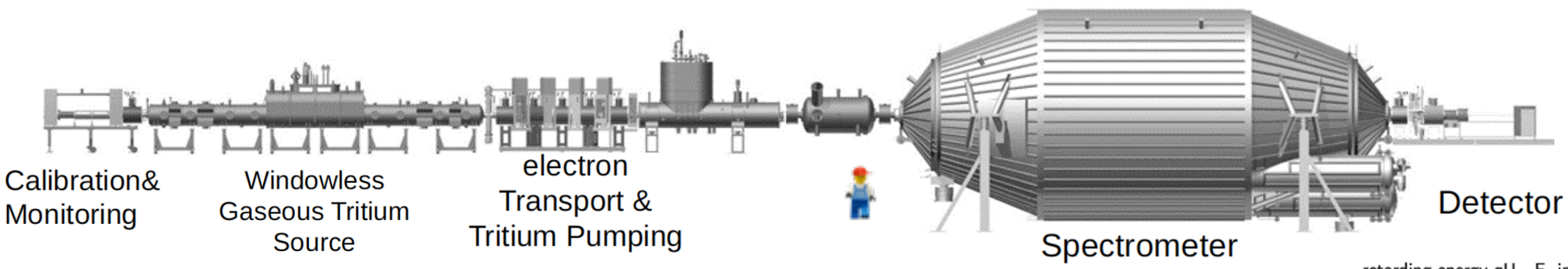
Measuring the ν Mass Scale

Inside KATRIN , by Michael Zacher (2012)

Neutrino Mass from β-decay

- Measure deviation from $m(\nu_e)=0$ eV in endpoint of β-decay spectrum. Need:
  - high-luminosity source
  - low-energy endpoint
  - low background
  - extremely good energy resolution, calibration and stability

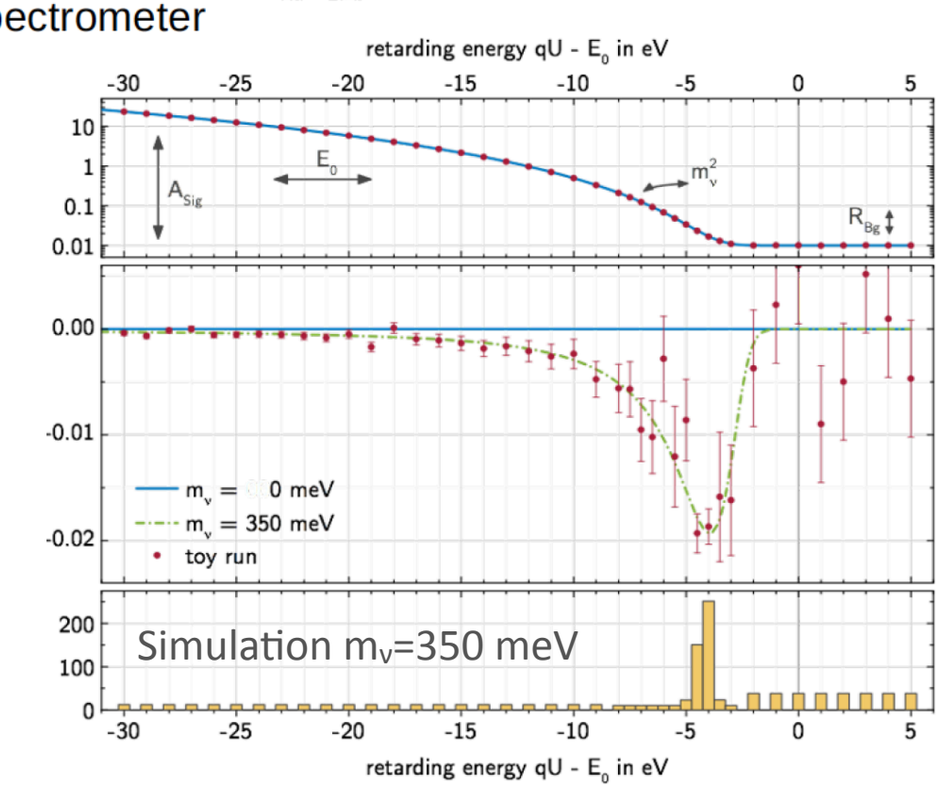




- KATRIN uses a tritium source and a giant spectrometer

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \mathrm{e}^- + \bar{\nu}_e$$

  - 0.2 eV 90% C.L sensitivity on m_ν, factor of 10 improvement over current limit.
  - "First -Light" in October 2016, electrons went through the full 70-m beam line
  - First tritium data with entire beam line in 2018
  - 5 years of operation



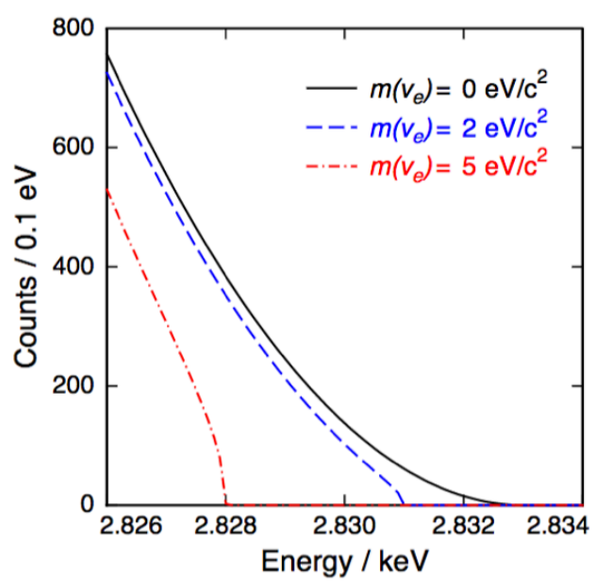
J. Wolf, SURF 2017

Neutrino Mass from β-decay

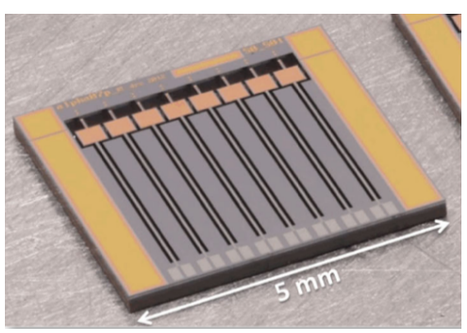
- Thermal calorimetry using Holmium

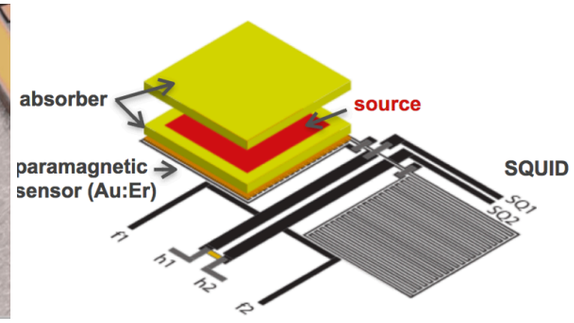
$^{163}Ho \rightarrow {}^{163}Dy^* + \nu_e$

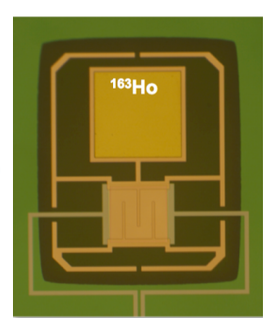
Low Q_{EC} ~2.8 keV and $T_{1/2}$ ~ 4570 years



- **NuMECS/ECHO/HOLMES**
- R&D for calorimeter arrays







- 1k-channel arrays will reach 10 eV (90% CL) sensitivity by 2019
- 10^5 1k-channel detectors can reach sub-eV sensitivity in 2 years

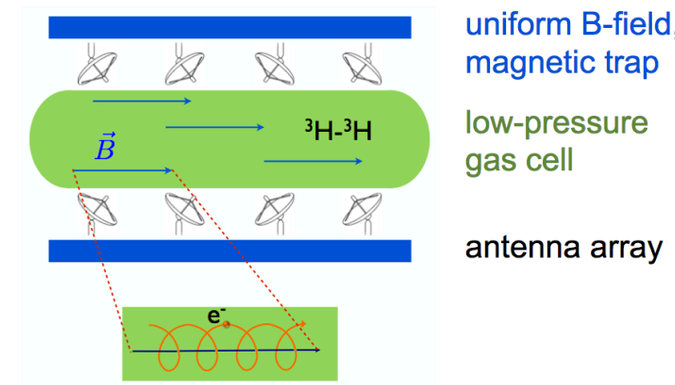
K. Valerius, Neutrino 2016

PROJECT 8

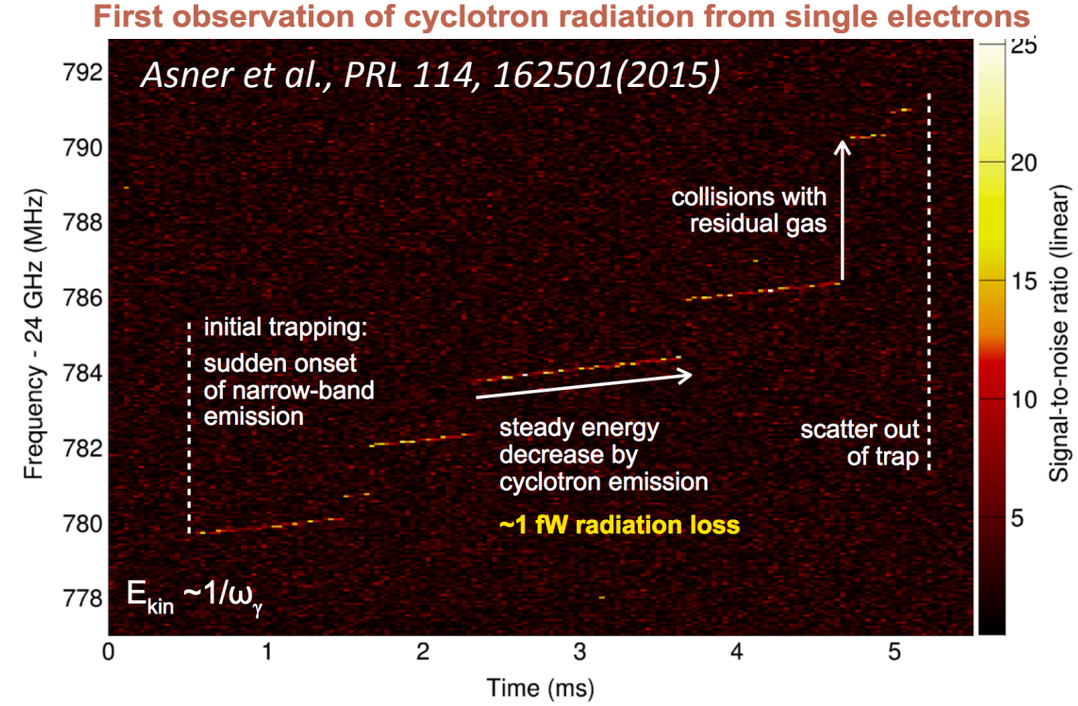
- Cyclotron radiation from tritium spectrometer

Non-destructive measurement of electron **energy** via **cyclotron frequency:**

$$\omega(\gamma) = \frac{\omega_c}{\gamma} = \frac{eB}{E_{kin} + m_e}$$



First observation of cyclotron radiation from single electrons

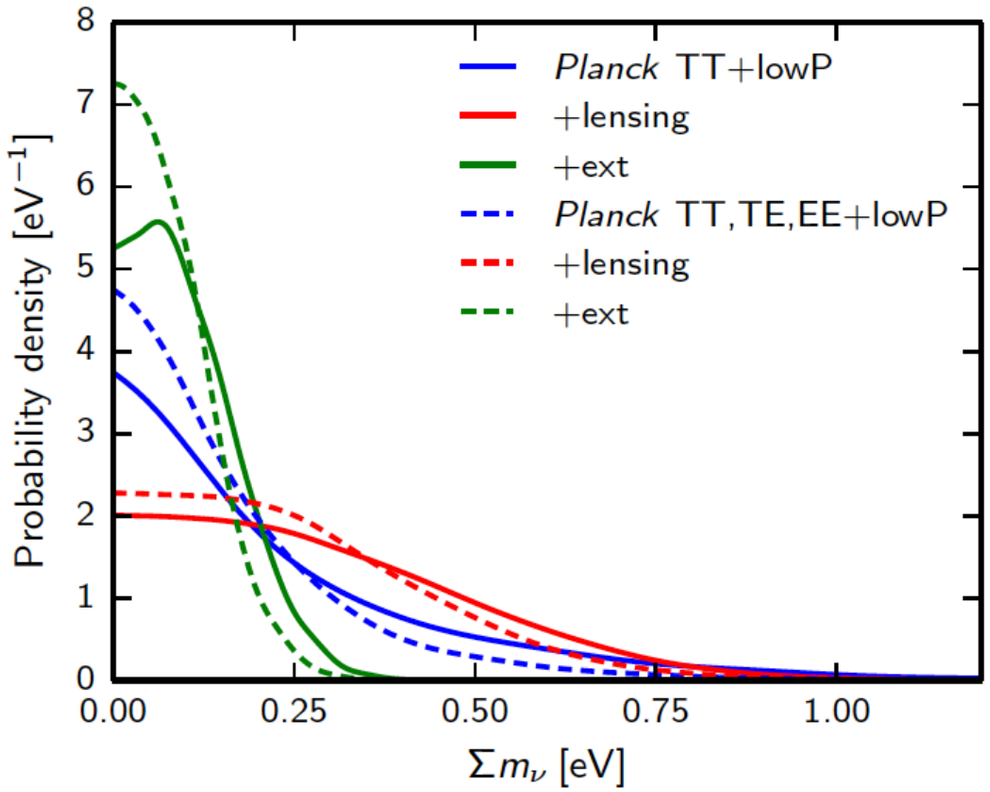


- Aiming to reach 2 eV (90% CL) by 2020
- Following large-scale experiment to reach sub-eV sensitivity

See Formaggio plenary

Neutrino Mass from Cosmology

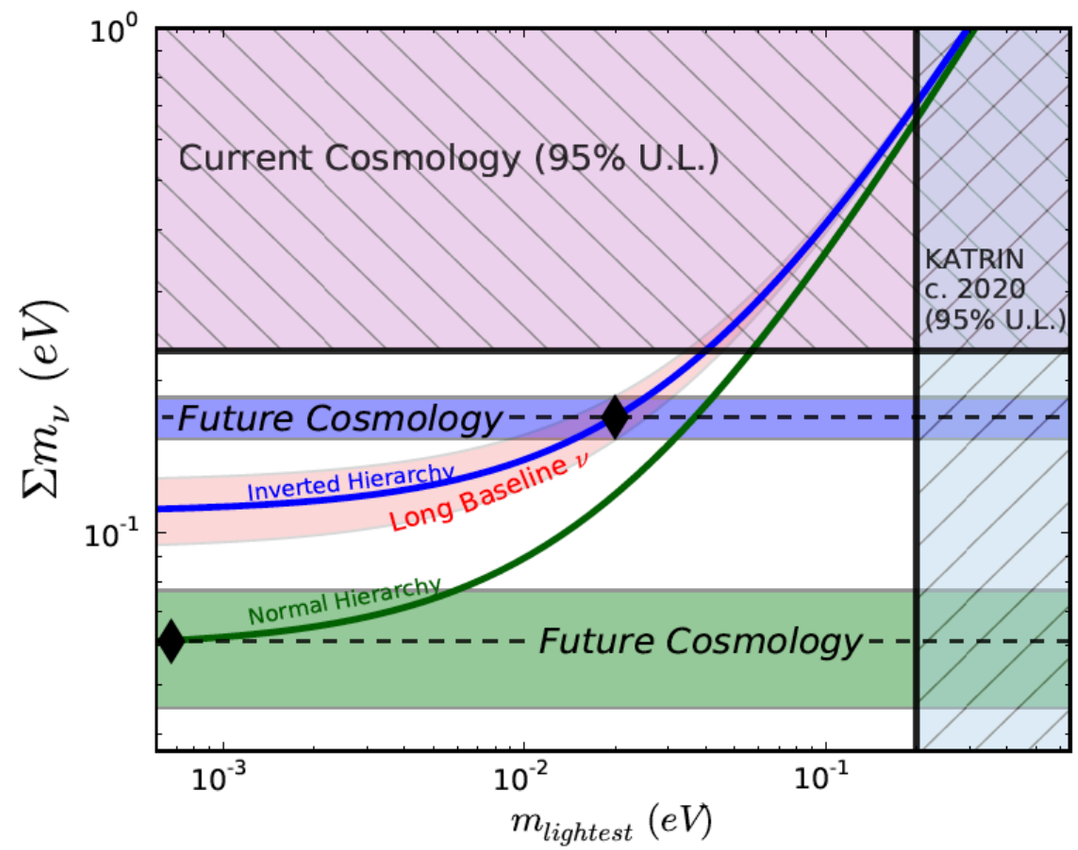
- Cosmological limits on sum of neutrino masses are dominated by Planck CMB data
- Constraints are model-dependent and vary with data sets used



$$\sum m_\nu < 0.23 \text{ eV } (95\,\%\text{ CL})$$

Planck, A&A 594, A13 (2016)

$N_{eff} = 3.15 \pm 0.46$ (95% CL)



K. Abazajian et al., Astrop. Phys. 63, 66 (2013)

- **TT**: temperature power spectrum
- **TE**: temperature-polarization cross spectrum
- **EE**: polarisation power spectrum.
- **lowP**: Planck polarization data in low-ℓ likelihood
- **lensing**: CMB lensing reconstruction
- **ext**: External data (BAO+JLA+H0)
  - BAO: Baryon acoustic oscillation
  - JLA: Joint Light-curve Analysis (of supernovae)
  - H0: Hubble constant

- Upcoming dark energy Experiments DESI, EUCLID, LSST (starting between 2018-2021) will have sub-eV sensitivity to neutrino masses

See Wong plenary

Answering the Questions...

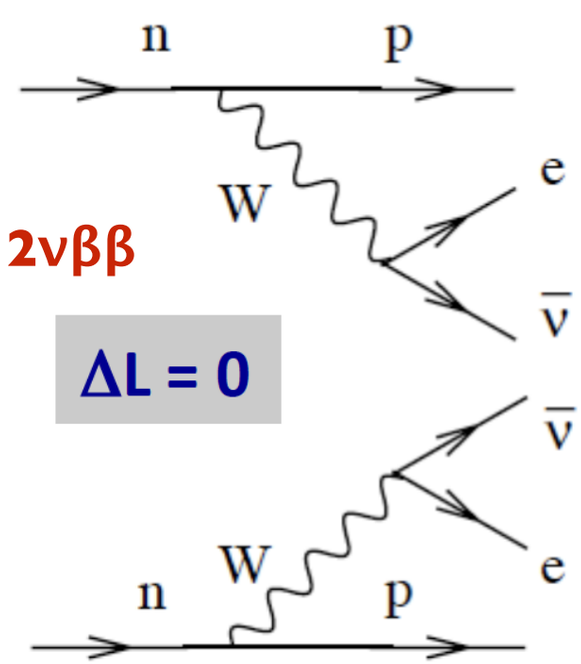
Are Neutrinos Majorana Particles?

Neutrinoless Double Beta Decay

From Symmetry Magazine, 06/30/15

Neutrinoless ββ decay

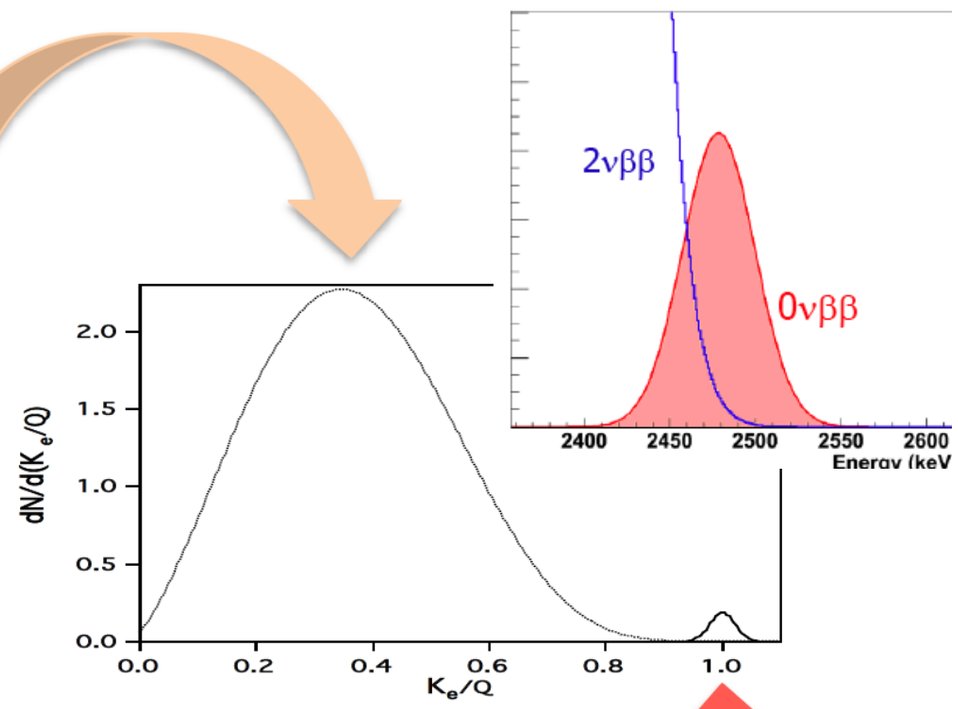
- Observation of 0νββ decay would establish
  - Neutrinos are Majorana particles
  - Lepton number violation
  - Neutrino mass scale
- Majorana neutrinos are required in seesaw mass models and leptogenesis



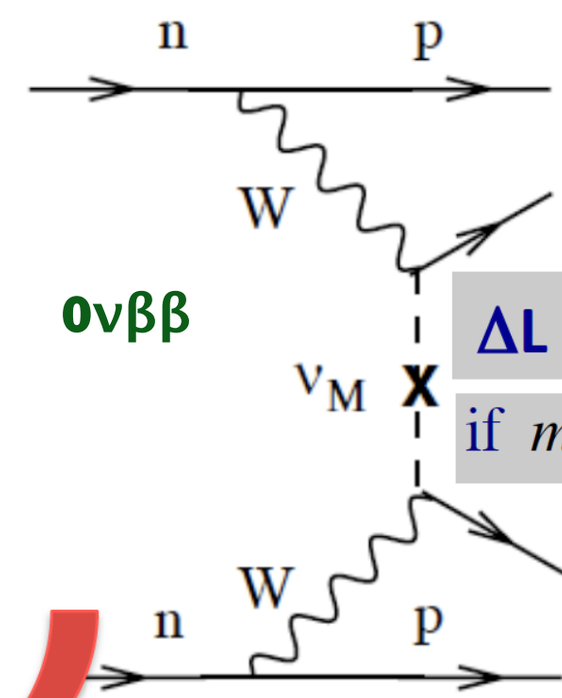
2νββ

ΔL = 0

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



K. Lang, SILAFAE 2010



0νββ

ΔL = 2

if $m_\nu \neq 0$

$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$
$$(0\nu\beta\beta)$$

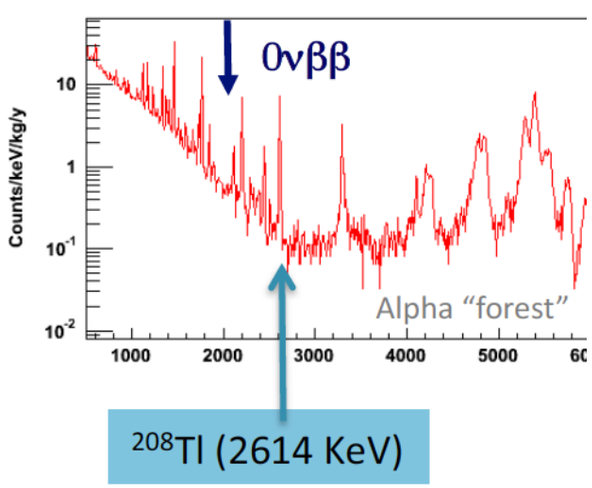
Neutrinoless ββ decay

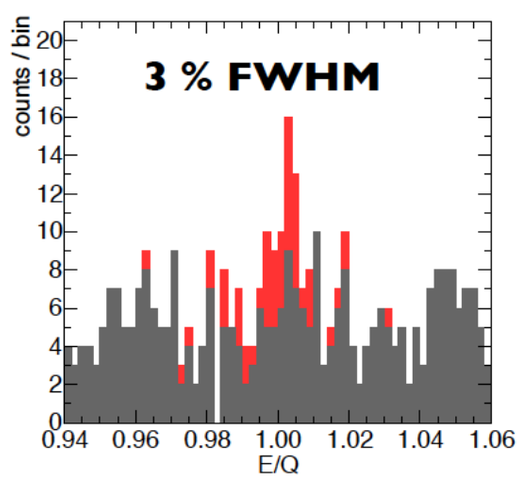
- Sensitivity to Majorana mass is a compromise between statistics, background rejection, and detector energy resolution

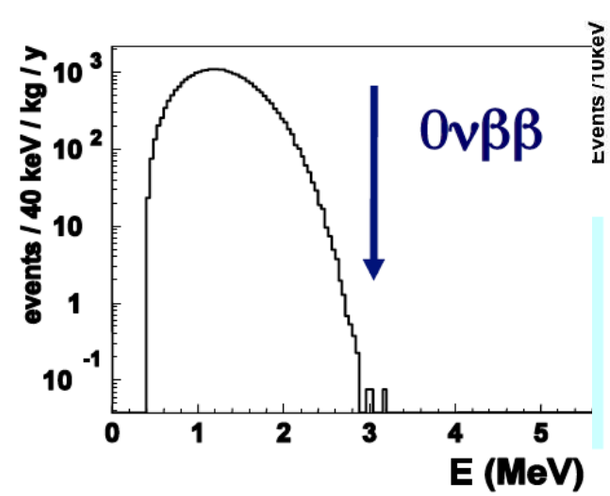
$$m_{\beta\beta} = K\sqrt{1/\epsilon}\left(\frac{b\ \Delta E}{Mt}\right)^{1/4}$$

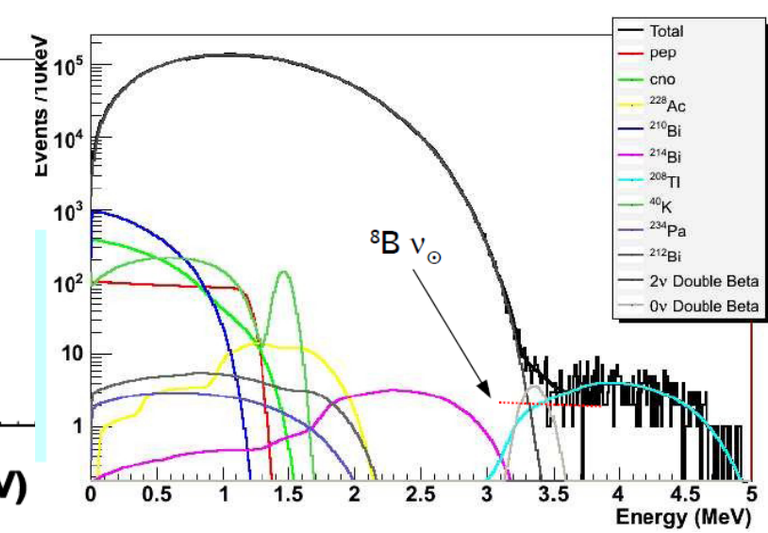
$K \rightarrow$ isotope yield
$\varepsilon \rightarrow$ detection efficiency
$M \rightarrow$ isotope mass
$t \rightarrow$ running time
$b \rightarrow$ background rate
$\Delta E \rightarrow$ energy resolution

- Different approaches and technologies in next generation experiments:
  - **Calorimeter/bolometer high energy resolution and efficiency**
  - **TPC (Xe) high efficiency, large mass**
  - **Tracking calorimeter good bg rejection, multiple isotope choices**
  - **Liquid scintillator + isotope - high efficiency, large mass**









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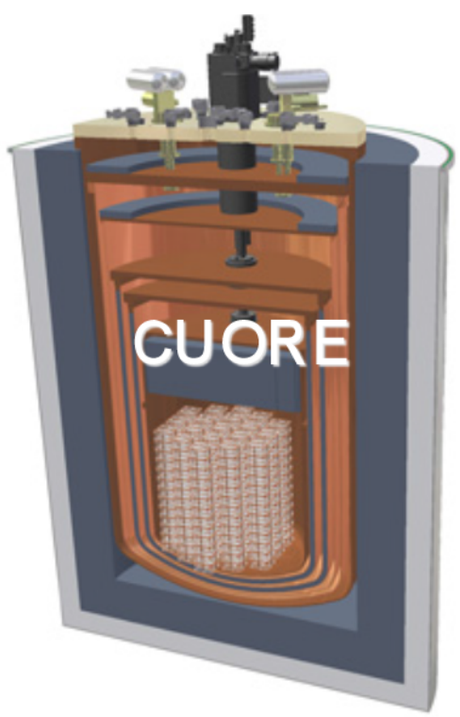
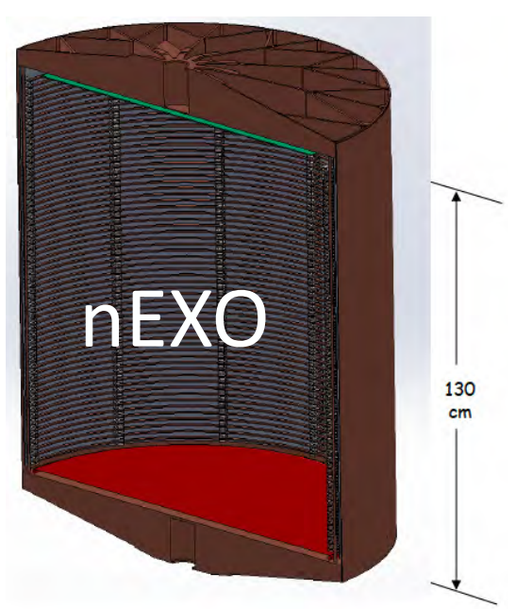
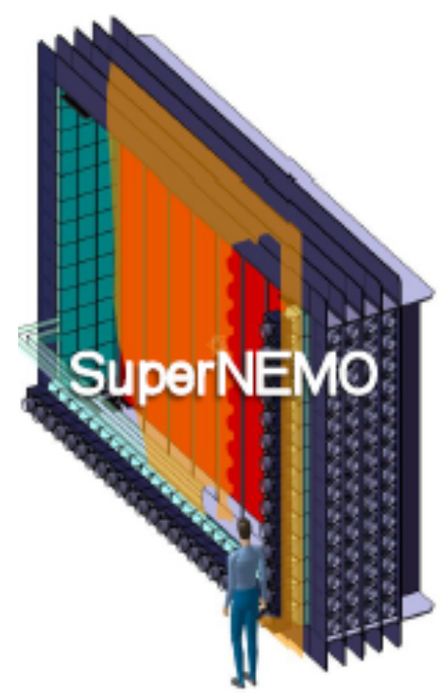
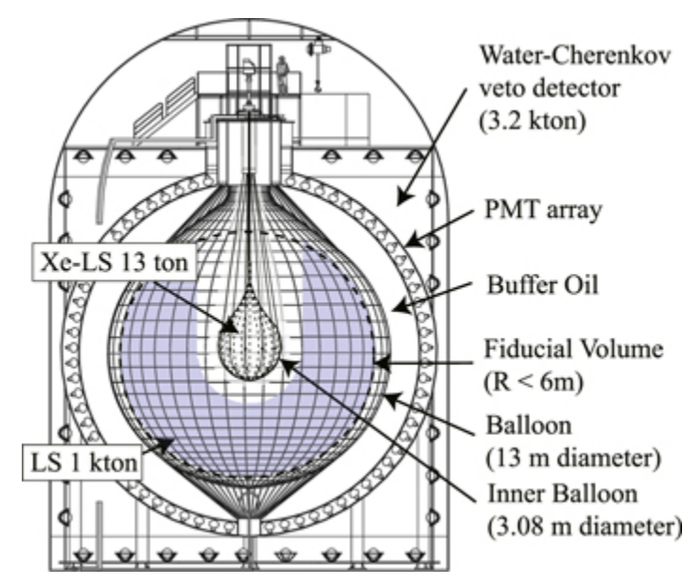




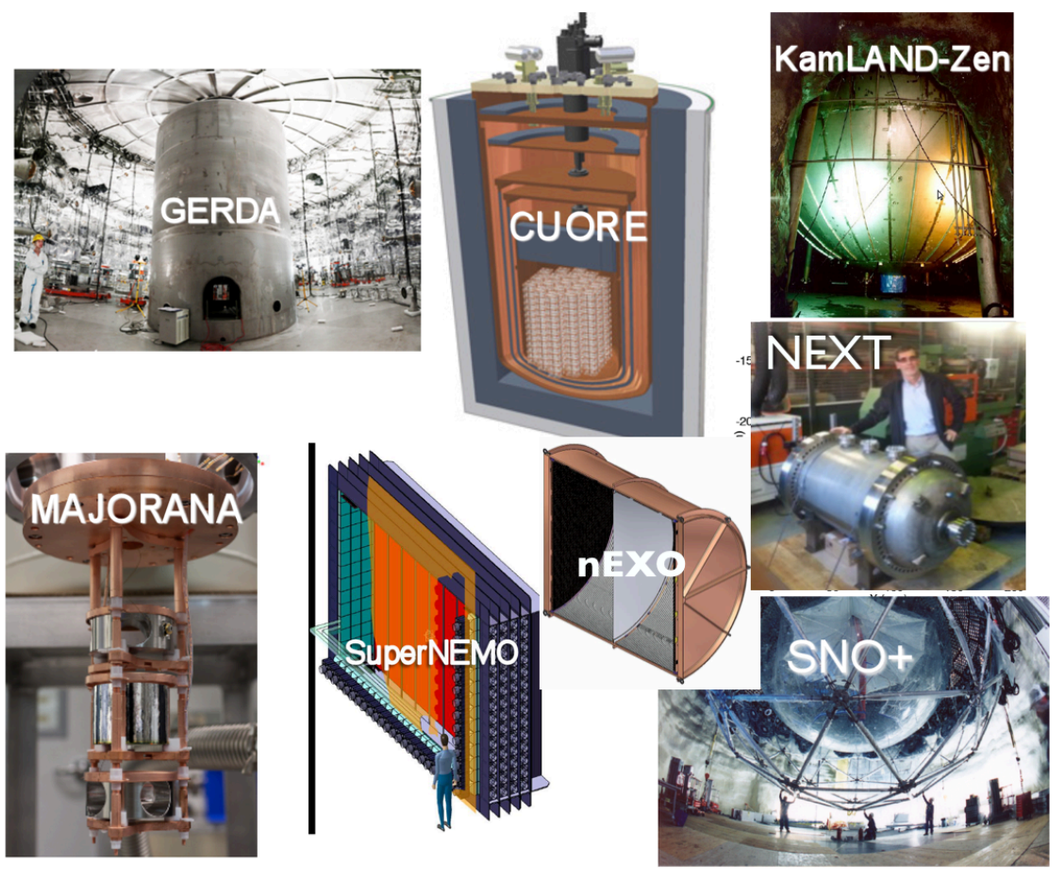


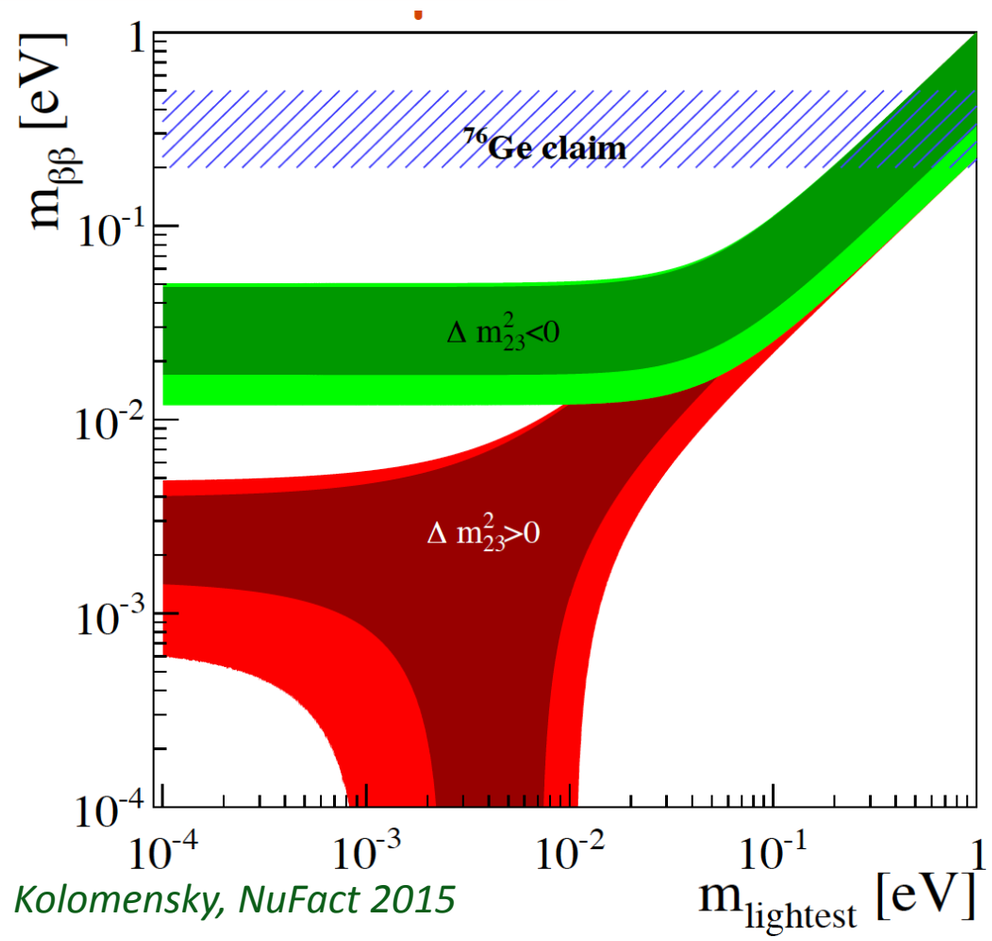


KamLAND-ZEN

0νββ decay - Results and Prospects

Experiment	Isotope	limit on $T_{1/2}^{0\nu}$	limit on $m_{\beta\beta}$
GERDA	^{76}Ge	5.3×10^{25} yr	150-330 meV
CUORE	^{130}Te	4.0×10^{24} yr	270-650 meV
EXO	^{136}Xe	1.1×10^{25} yr	190-450 meV
KamLAND-Zen	^{136}Xe	1.07×10^{26} yr	61-165 meV





Y. Kolomensky, NuFact 2015

- Also AMoRE, CUPID, CANDLES, COBRA, PANDAX-III, THEIA

See Session Nu-8 **See Winslow plenary**

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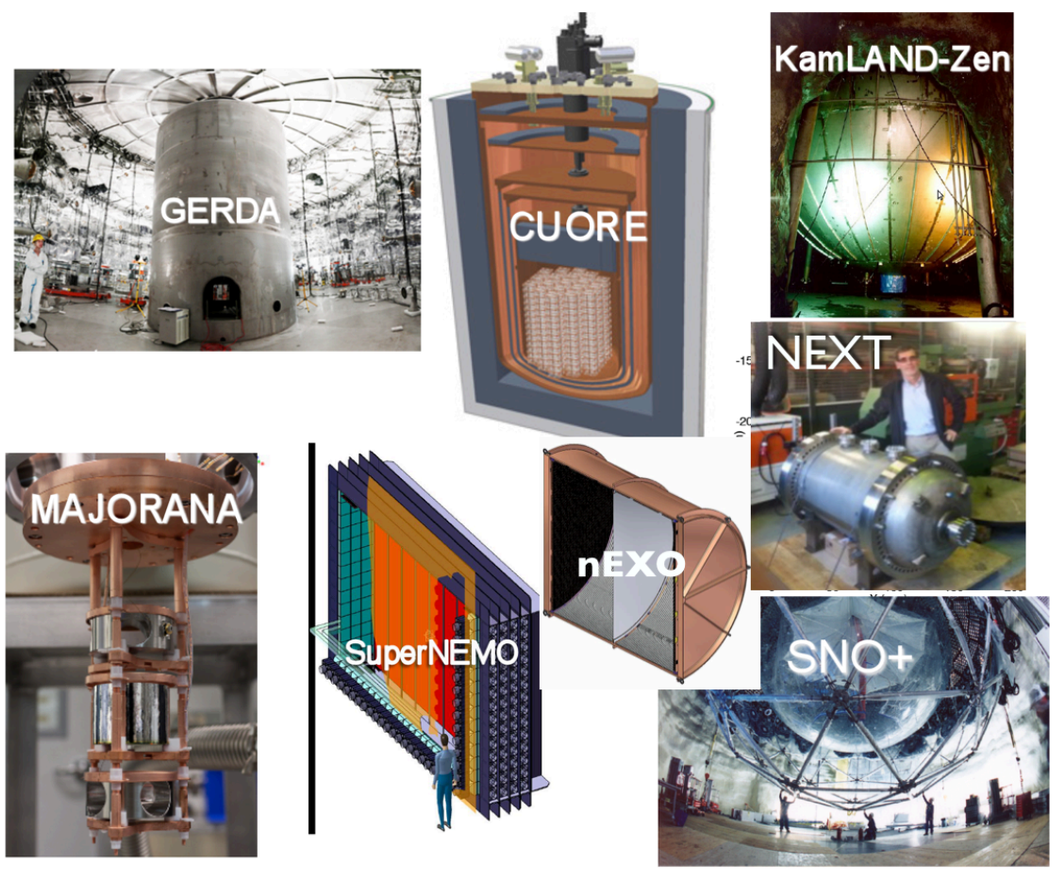

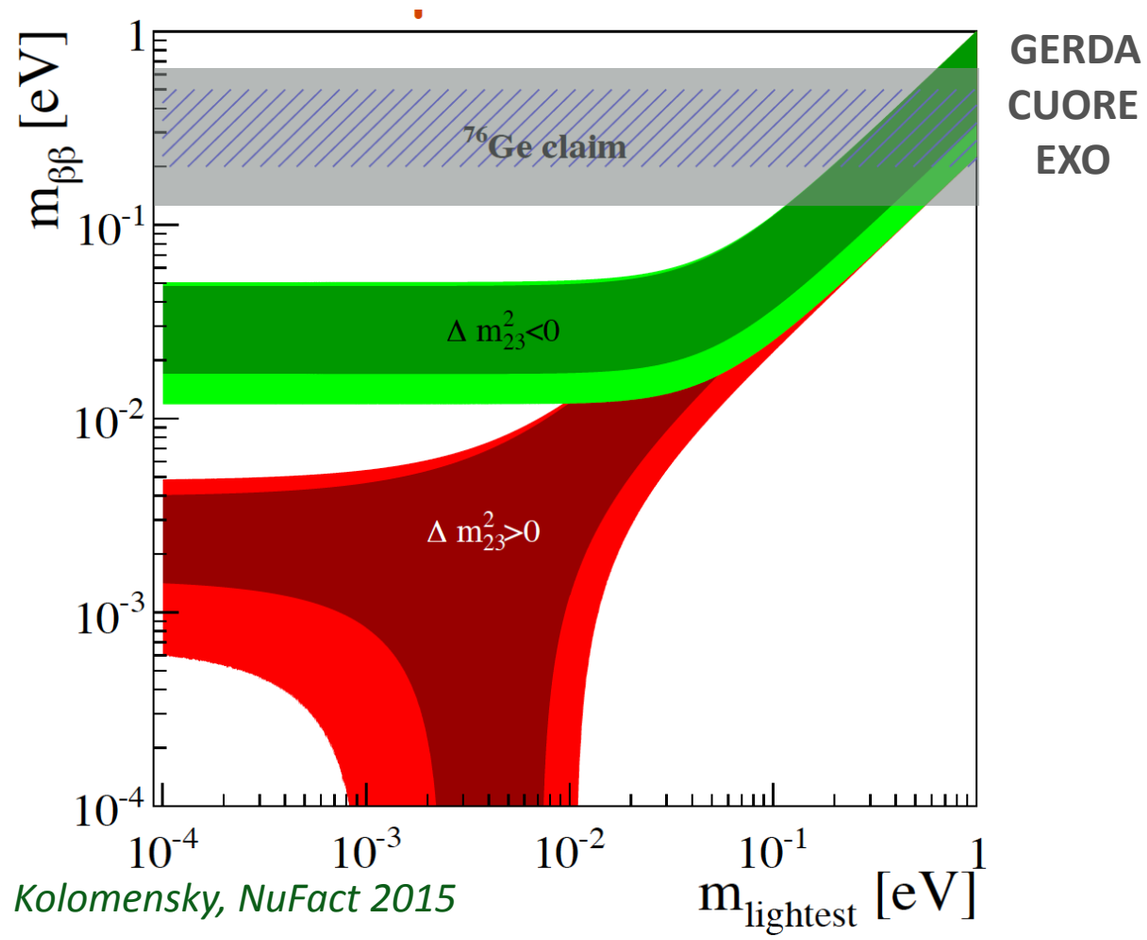

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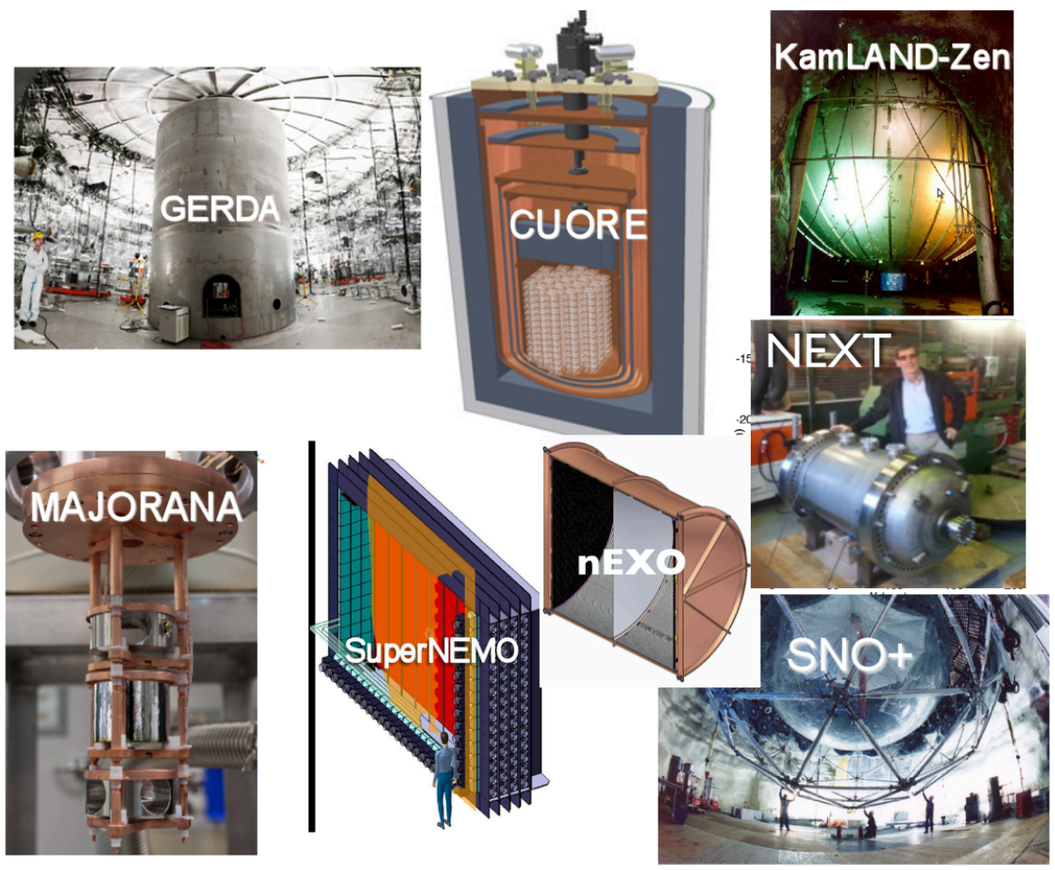

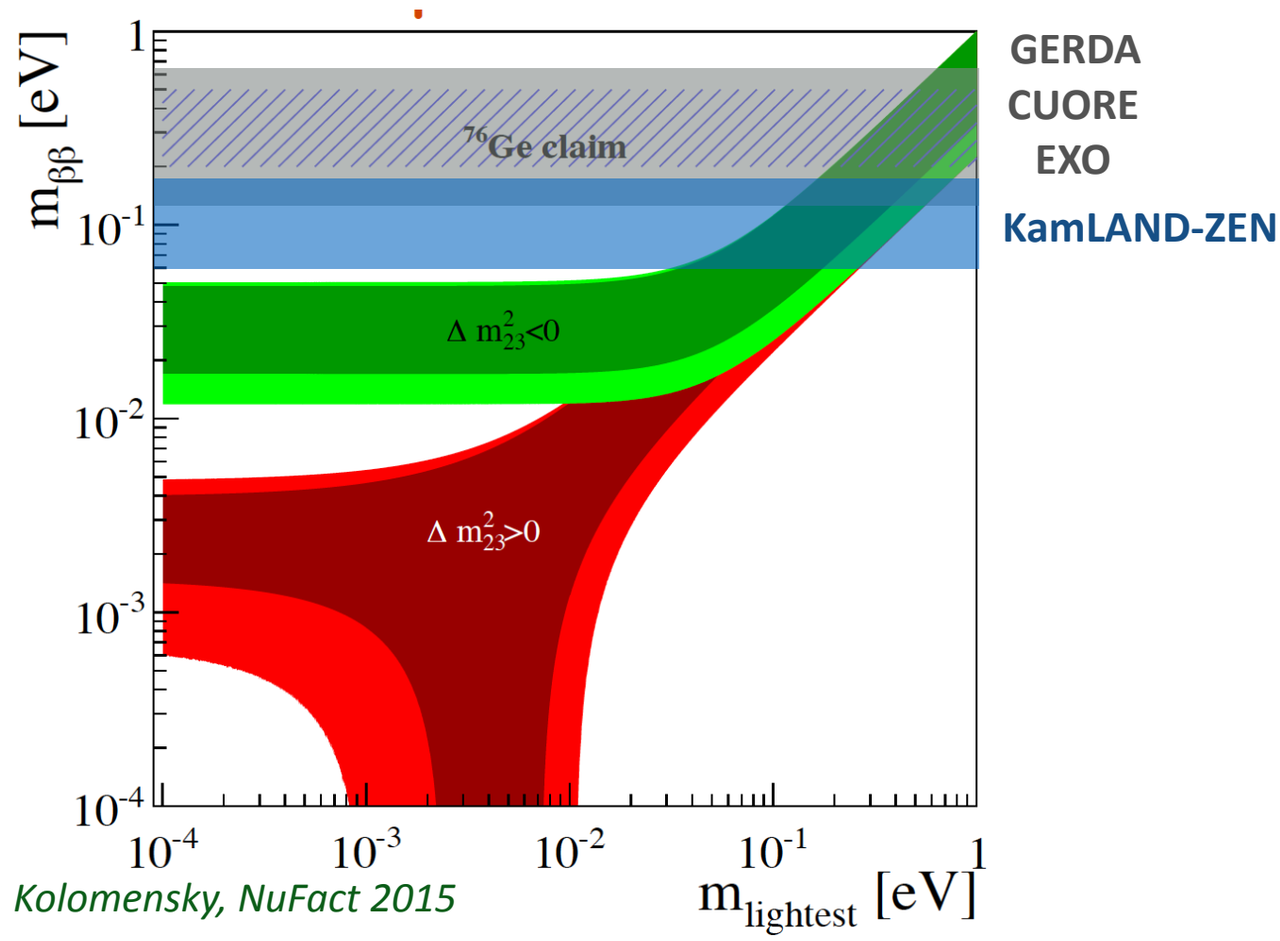

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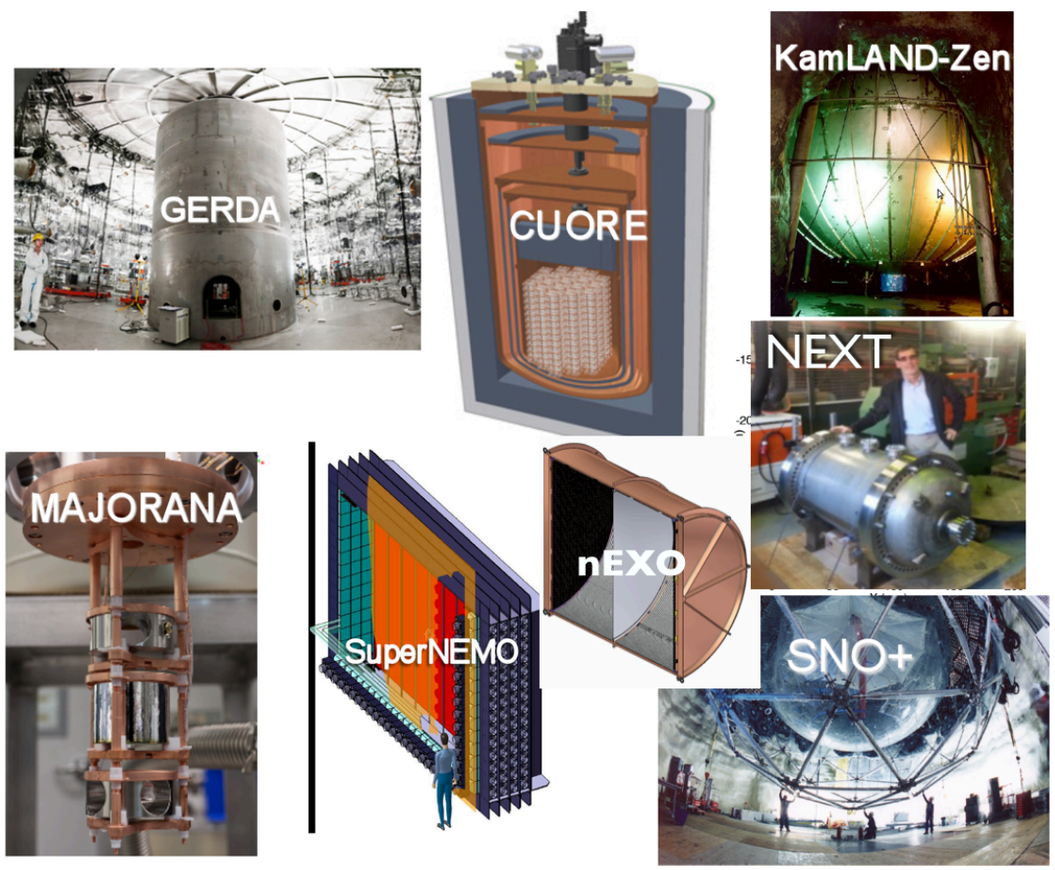

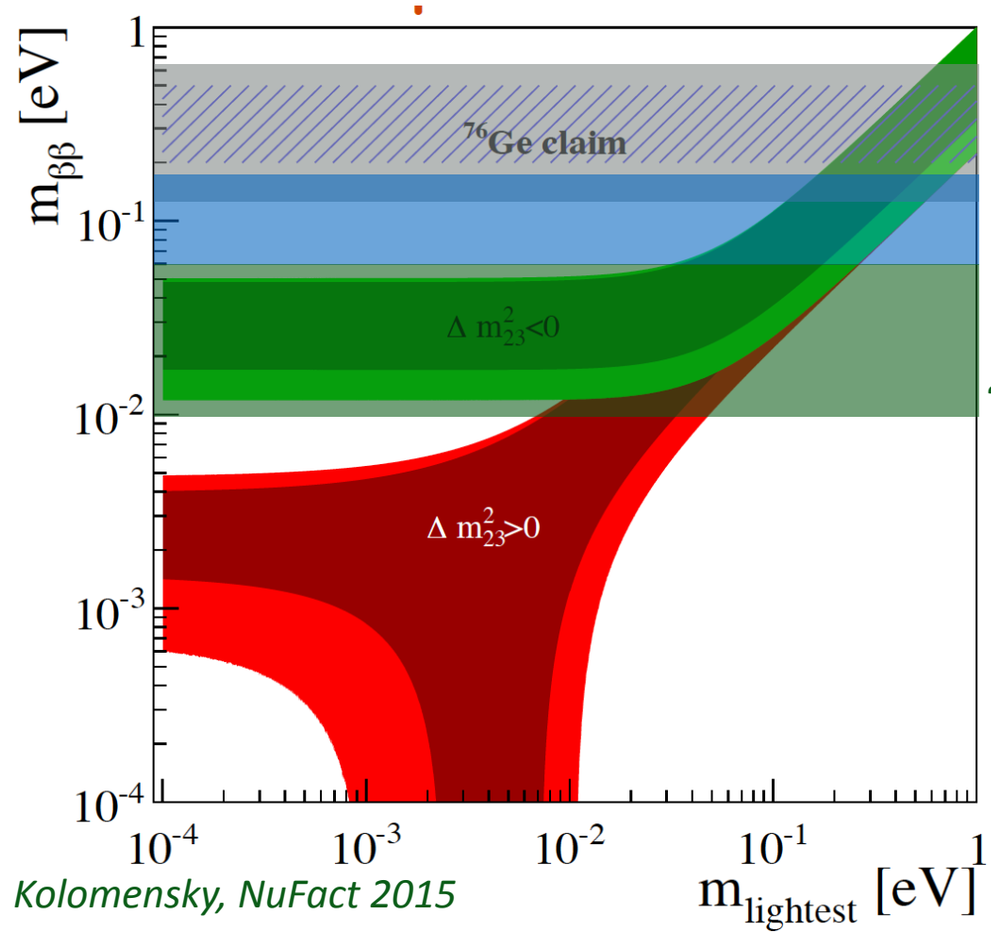

GERDA
CUORE
EXO
KamLAND-ZEN
Future and Near Future ~100-1000 kg

Y. Kolomensky, NuFact 2015

- Also AMoRE, CUPID, CANDLES, COBRA, PANDAX-III, THEIA

See Session Nu-8 **See Winslow plenary**

- Next generation of experiments will go beyond the degenerate region and start probing the inverted ordering regions

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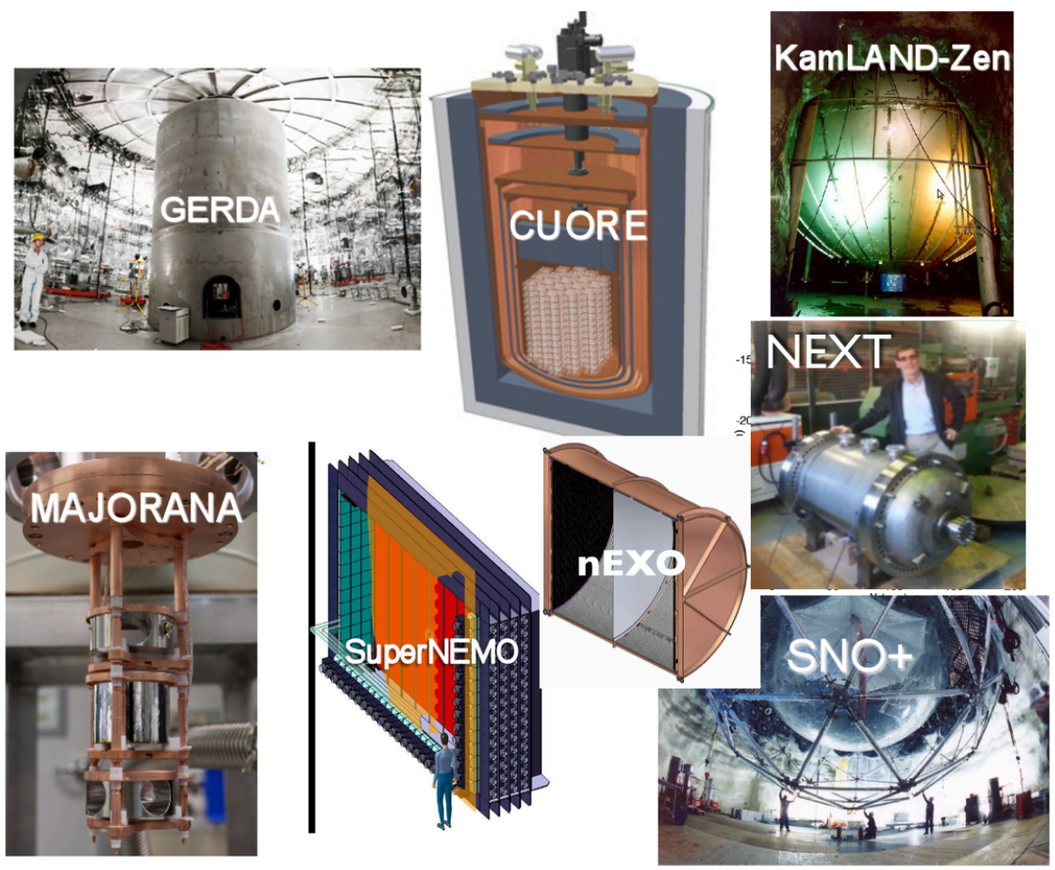

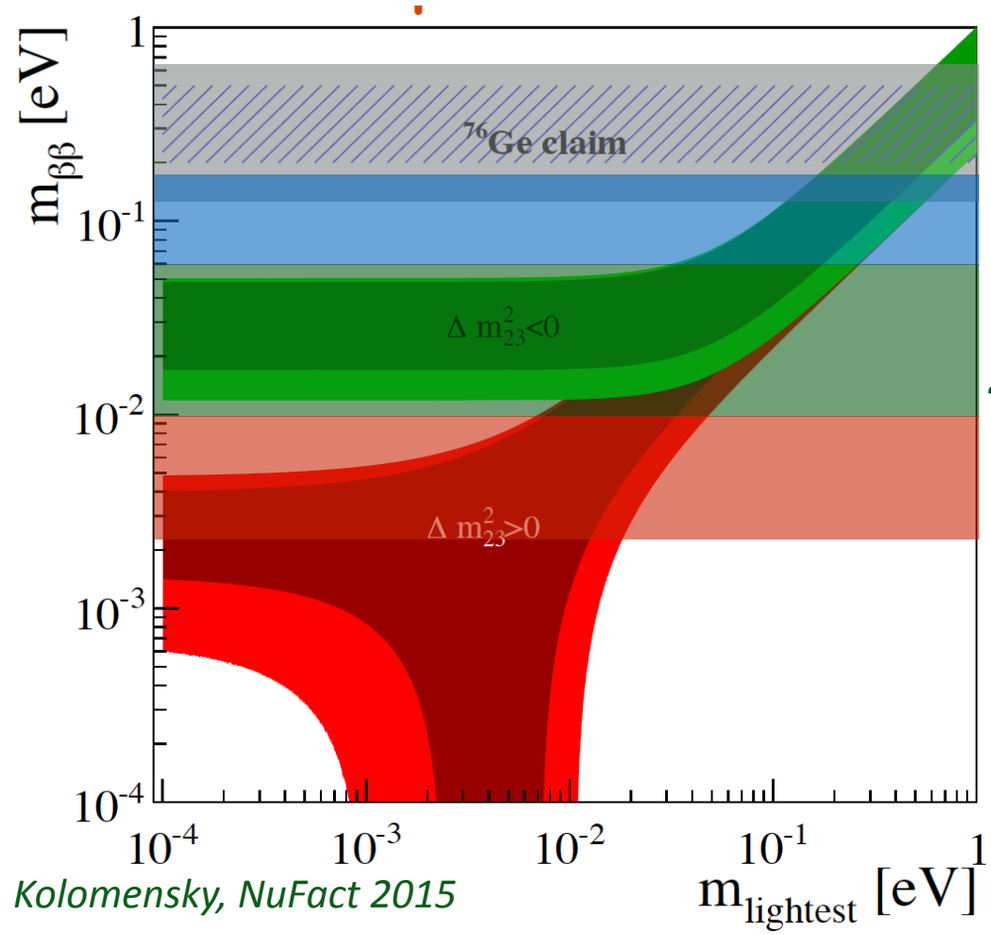

Y. Kolomensky, NuFact 2015

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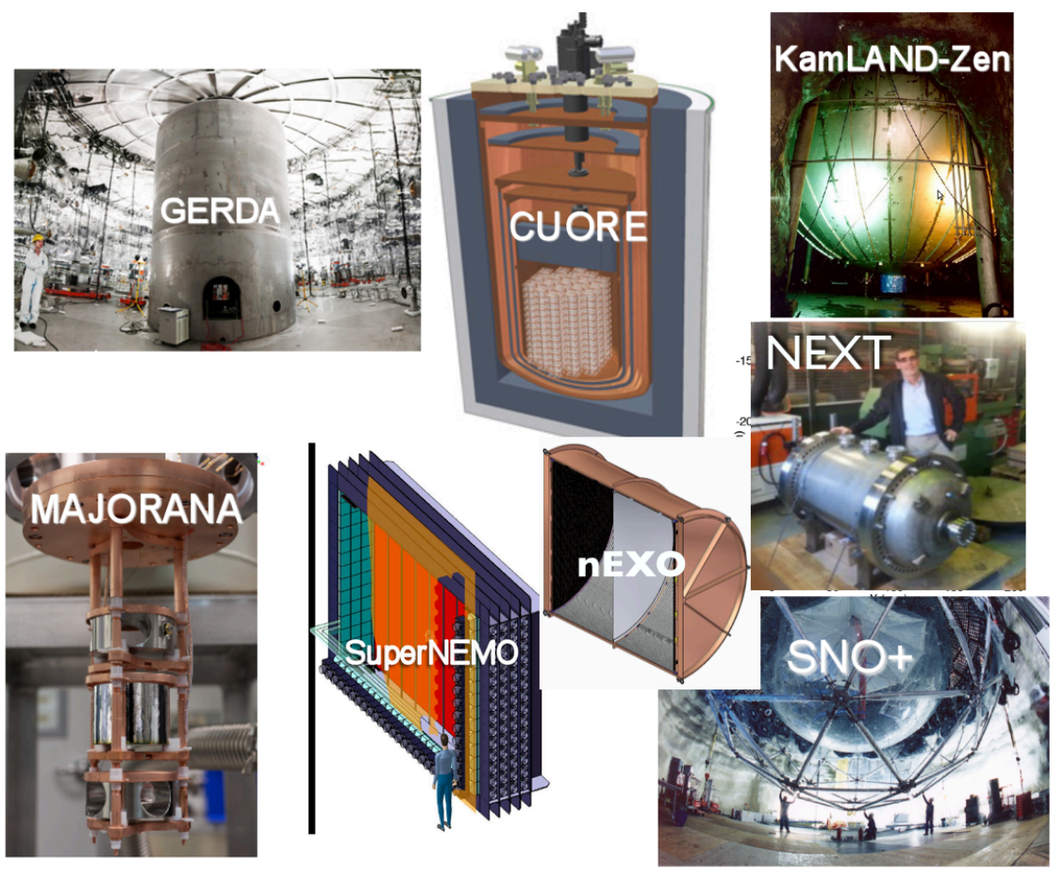

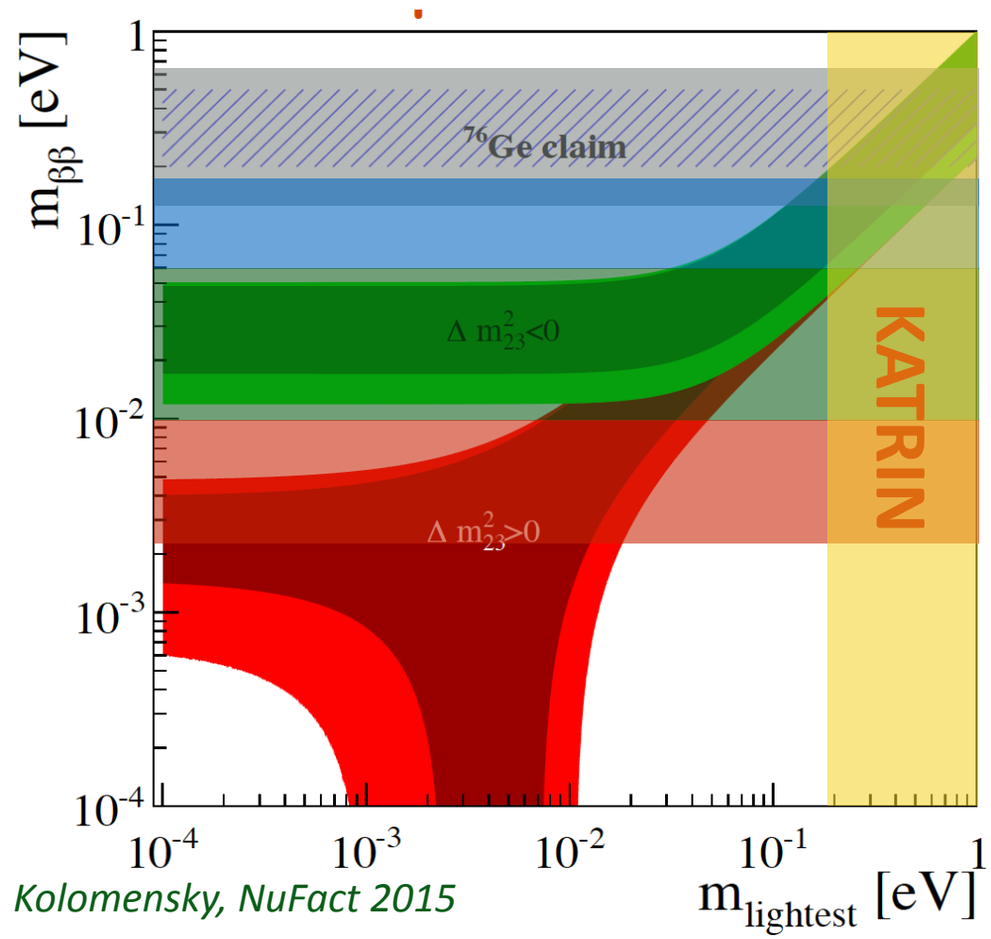

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See Session Nu-8 | See Winslow plenary

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Conclusions

- We are living in a precision era in neutrino physics

- Exciting results:
  - T2K disfavors CP conservation at >90% CL.
  - NOvA excludes CP region of inverted mass ordering for the lower θ_{23} octant
  - NOvA sees hints of non-maximal mixing
  - Unexpected "5 MeV bump" in reactor flux measurements
  - Sensitivity of neutrinoless double beta decay experiments approaching I.O. region

- Very rich experimental program will address (and provide definitive answers to?) some of the major questions in neutrino physics over the next 10-15 years
  - Experiments with larger mass, longer baseline, and higher resolution being planned - DUNE groundbreaking at Homestake this Summer
  - Suite of new dedicated experiments will probe deviations from three-flavor mixing

- As always with neutrinos, expect the unexpected!

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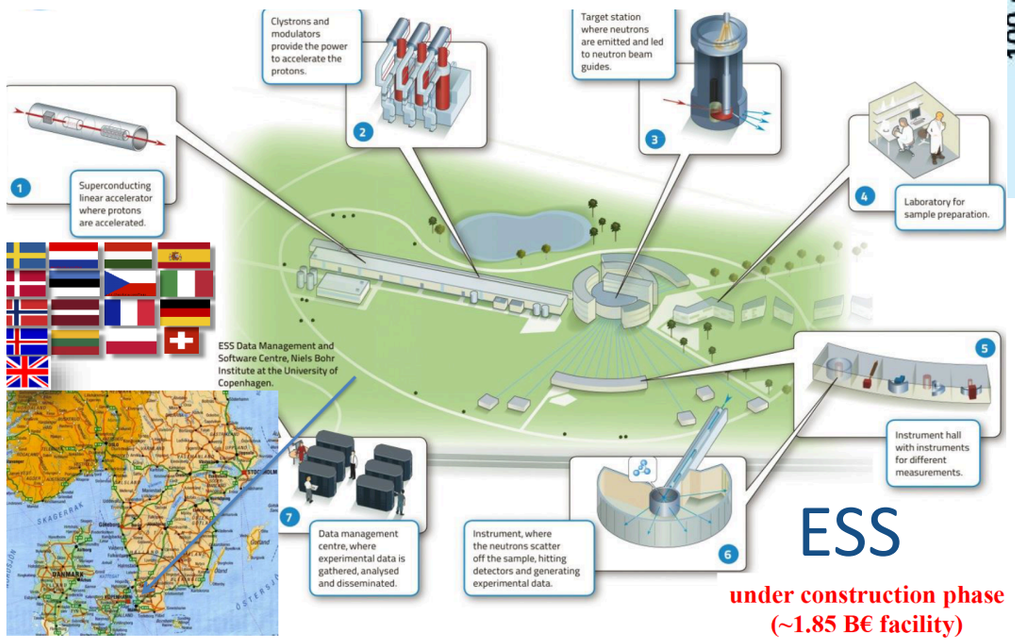
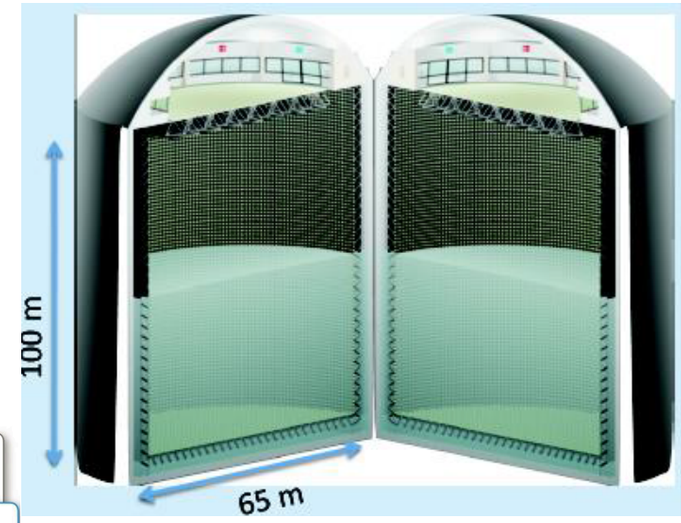
Thank You!

Supplements

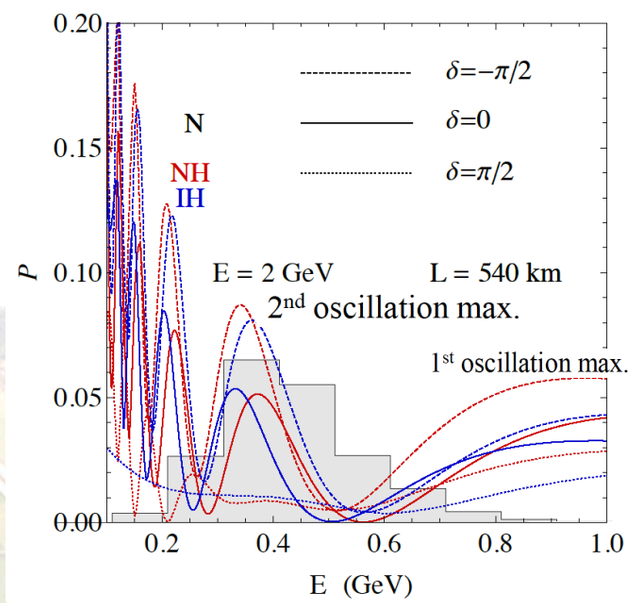
The Future - ESSνSB

- European Spallation Source Neutrino SuperBeam
  - 5 MW beam power by 2023
- Large Water Cherenkov detector





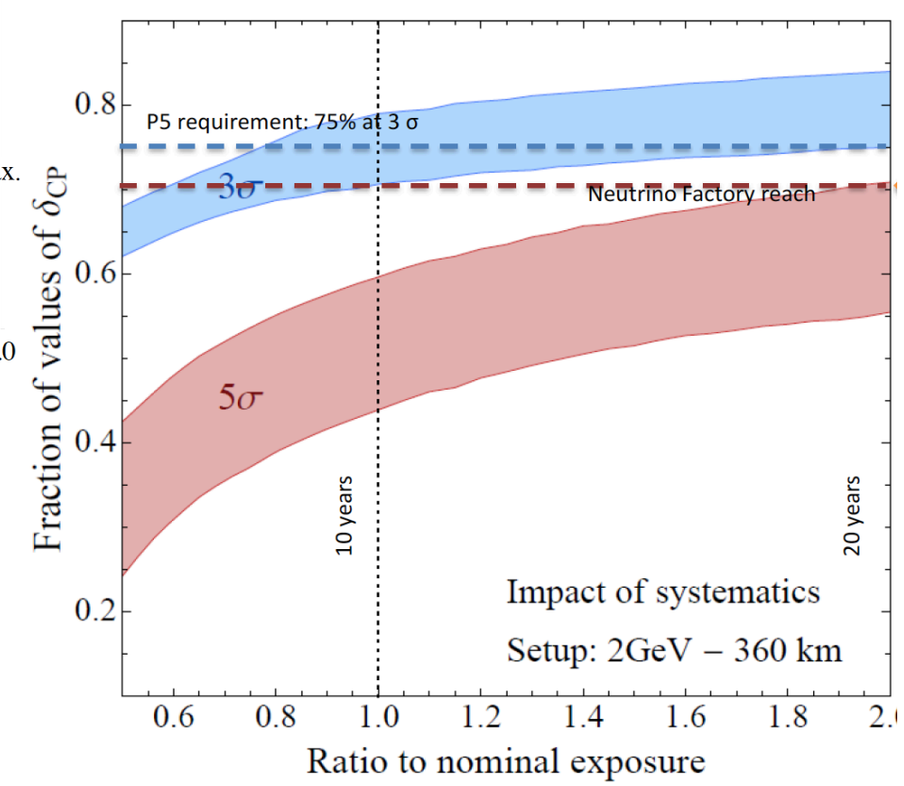
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8" PMTs
- 30% optical coverage



- COST CA15139: 2016-2019 (just networking)
- EU H2020 Design Study: 2018-2021
- Decision for ESSνSB: 2022
- End of Linac construction: 2023
- Construction of ESSνSB: 2023-2030
- Data taking: 2030-2040.

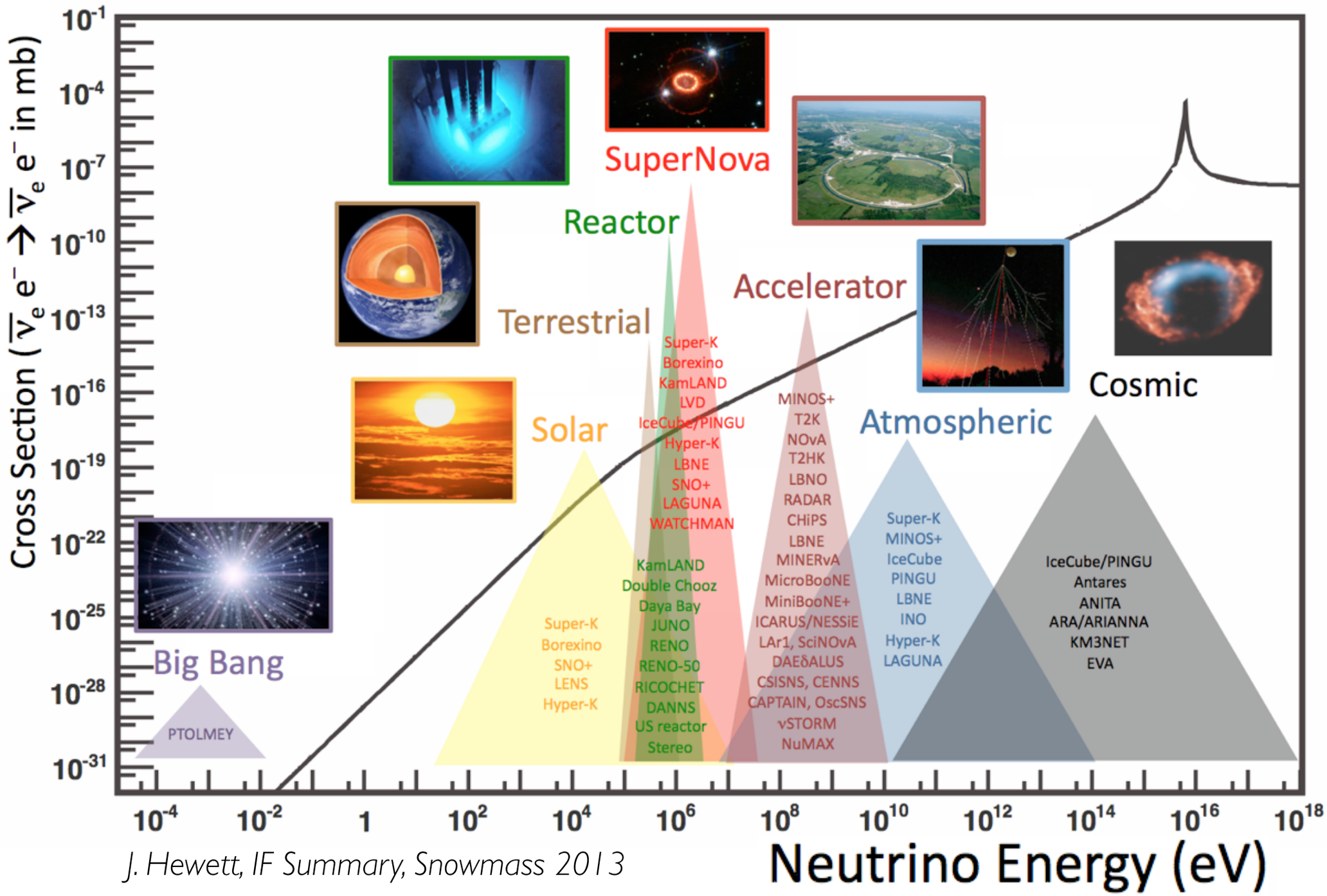
M. Dracos, ICHEP 2016

- 75% δ_{CP} coverage at 3σ after 10 years
- 50% δ_{CP} coverage at 5σ after 10 years



Running and Future Experiments

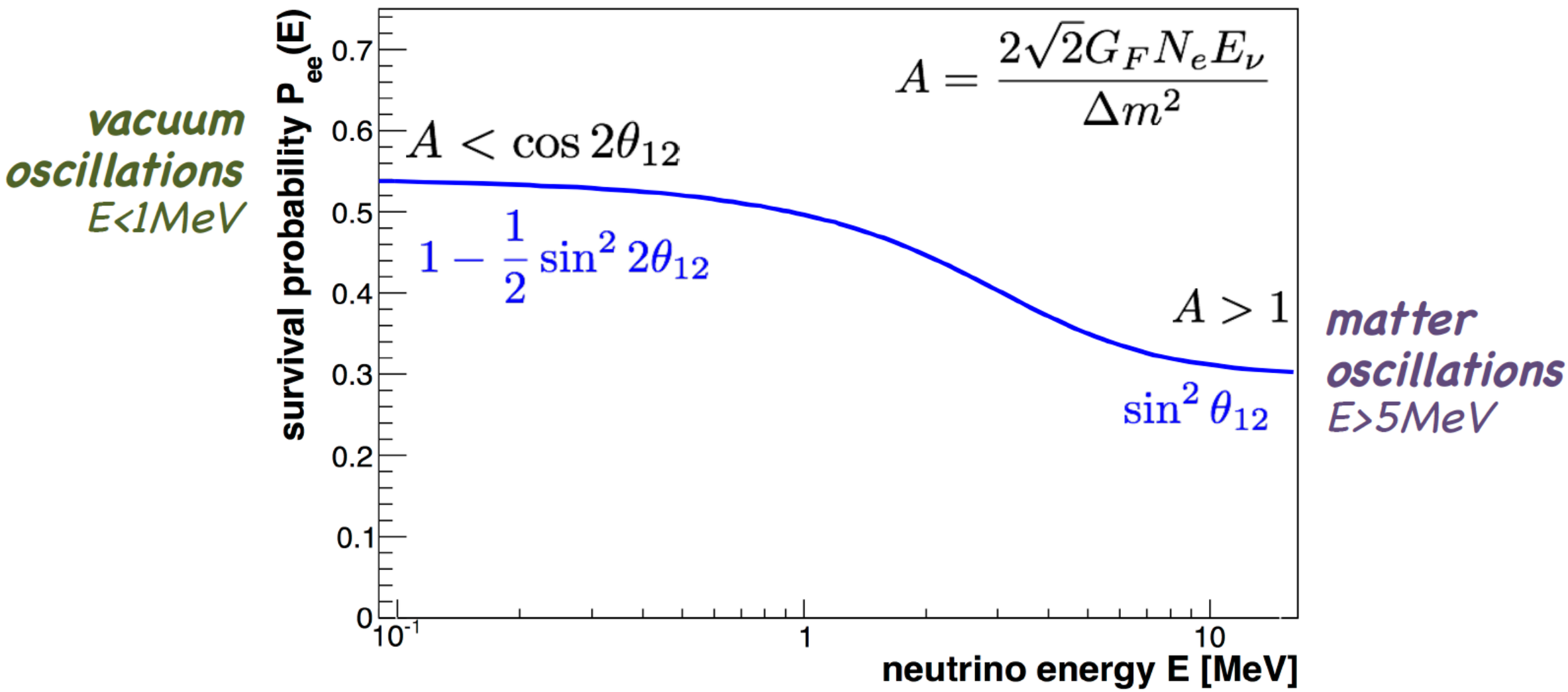
- Many new neutrino projects proposed during Community Summer Study (Snowmass) 2013 process.



J. Hewett, IF Summary, Snowmass 2013

Solar neutrino oscillations: MSW-LMA

Solar neutrino oscillations are observed via ν_e survival probability:

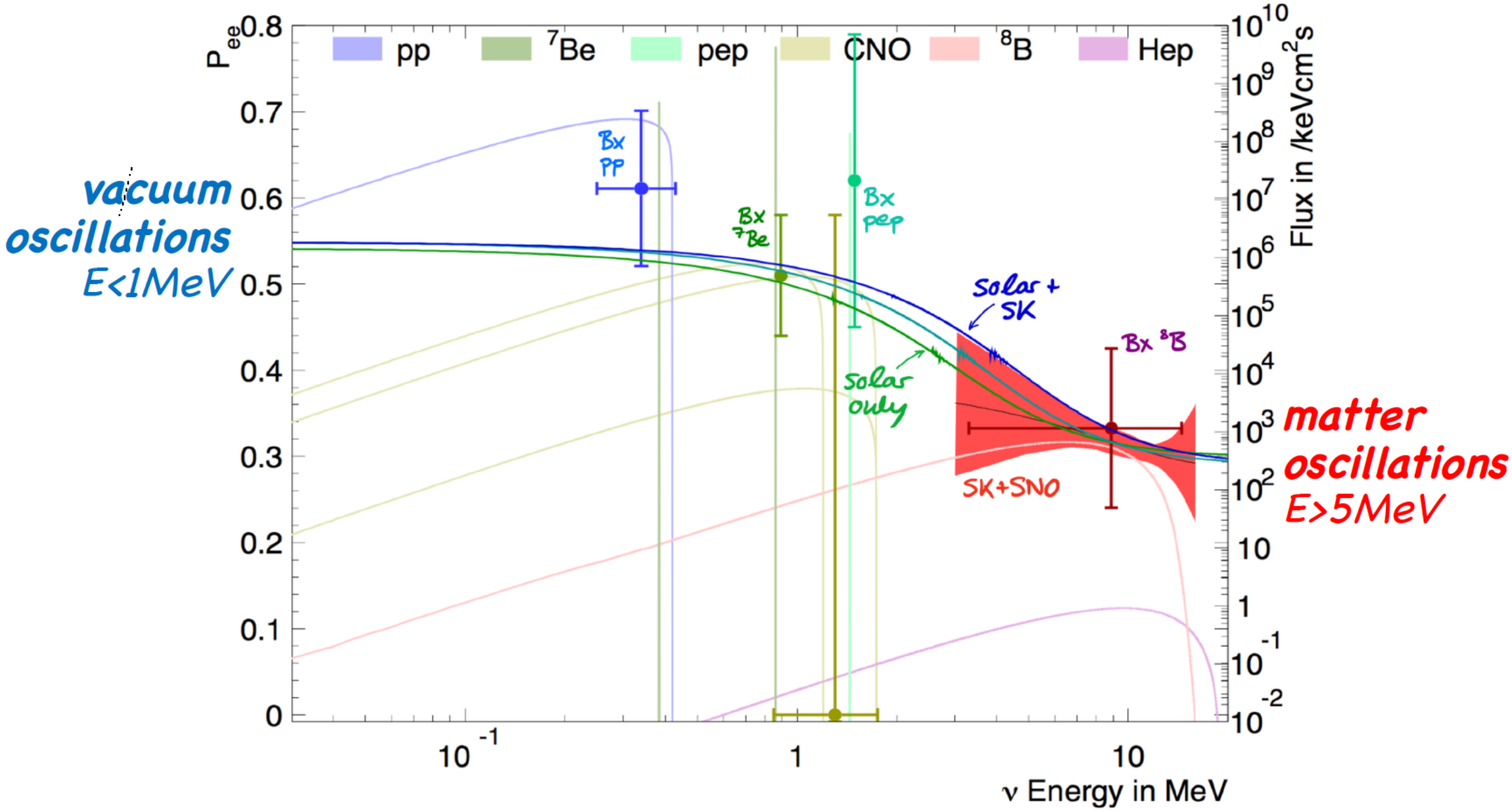


→ **Three distinctive regions:**

vacuum oscillations, **transition region**, **matter-dominated** oscillations

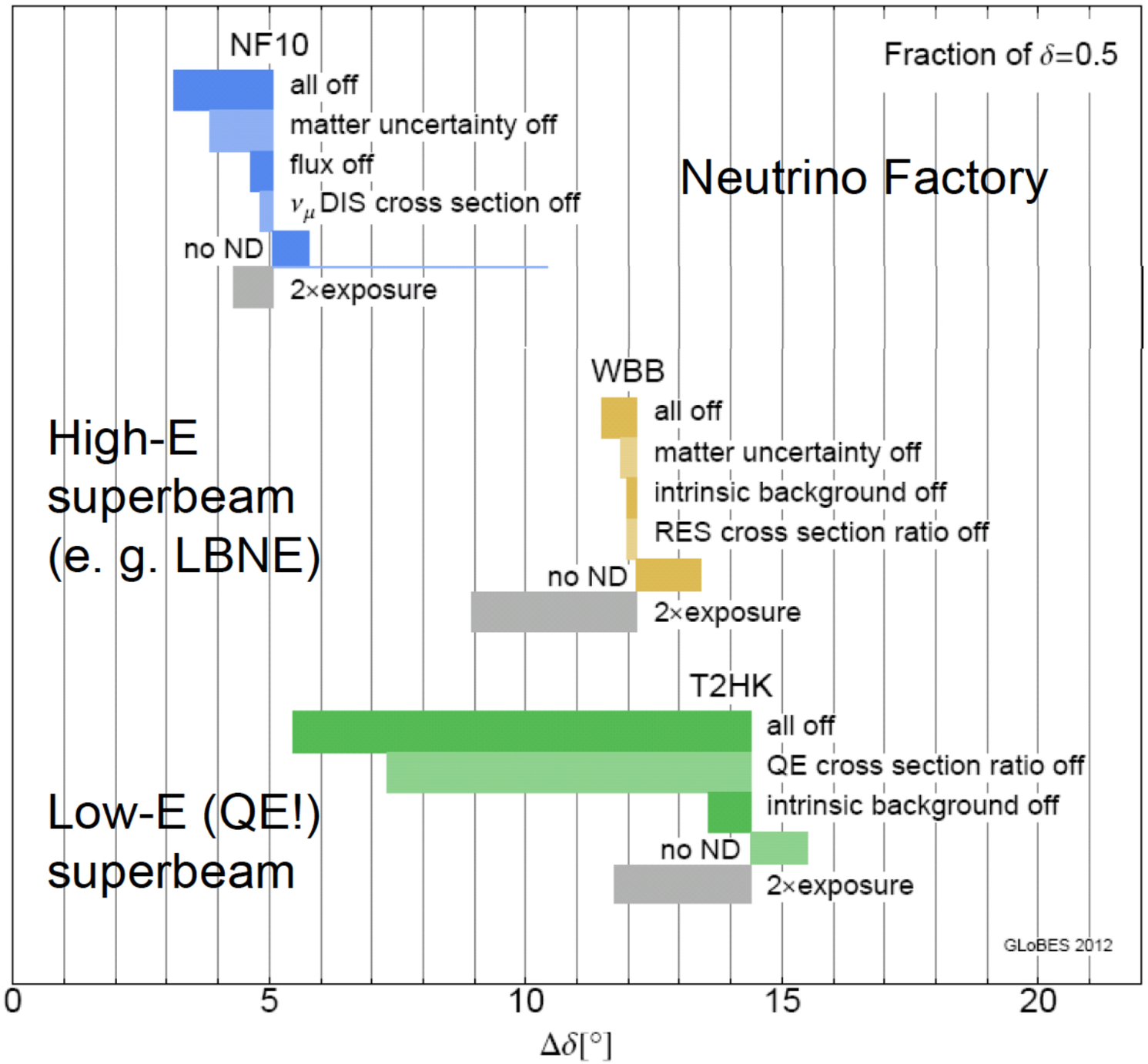
Michael Wurm (Mainz) Solar neutrino spectroscopy

Solar neutrino Measurements



→ *full agreement with basic MSW-LMA scenario*

More on Systematics



(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

Robust wrt systematics

Main impact:
Matter density uncertainty

Operate in statistics-limited regime

Exposure more important than near detector

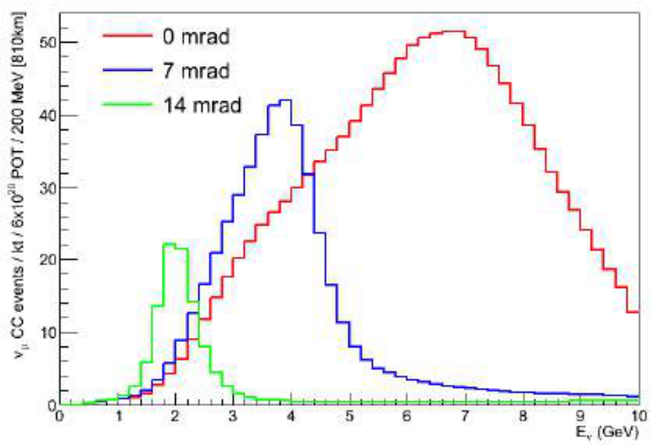
QE ν_e X-sec critical: cannot be measured in near detector

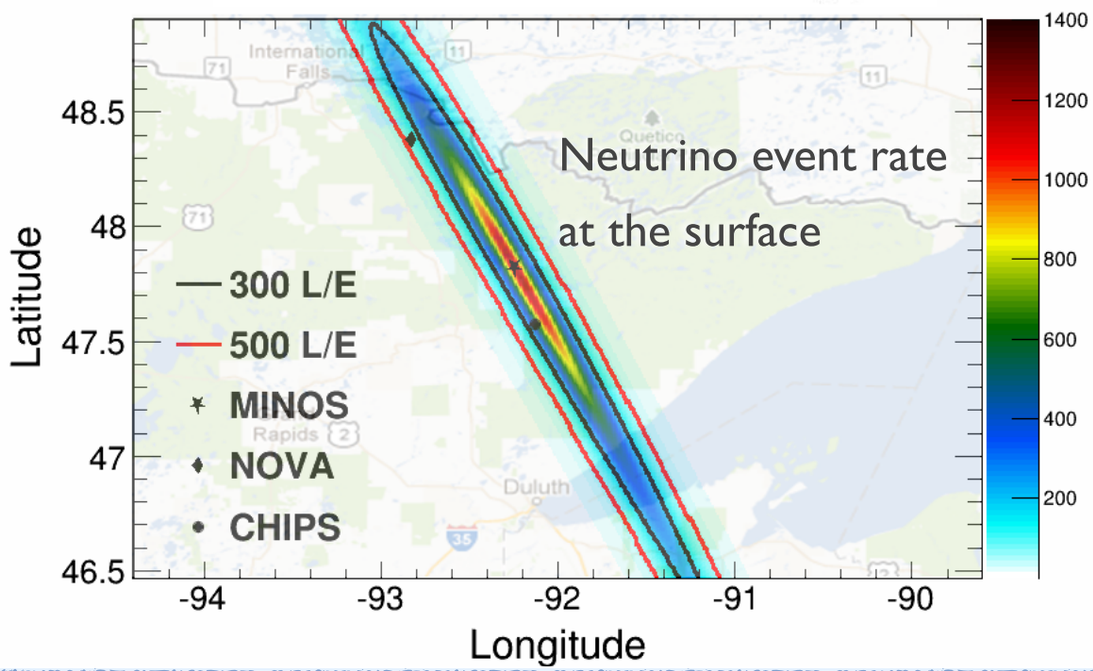
Theory: ν_e/ν_μ ratio?
Experiment: νSTORM

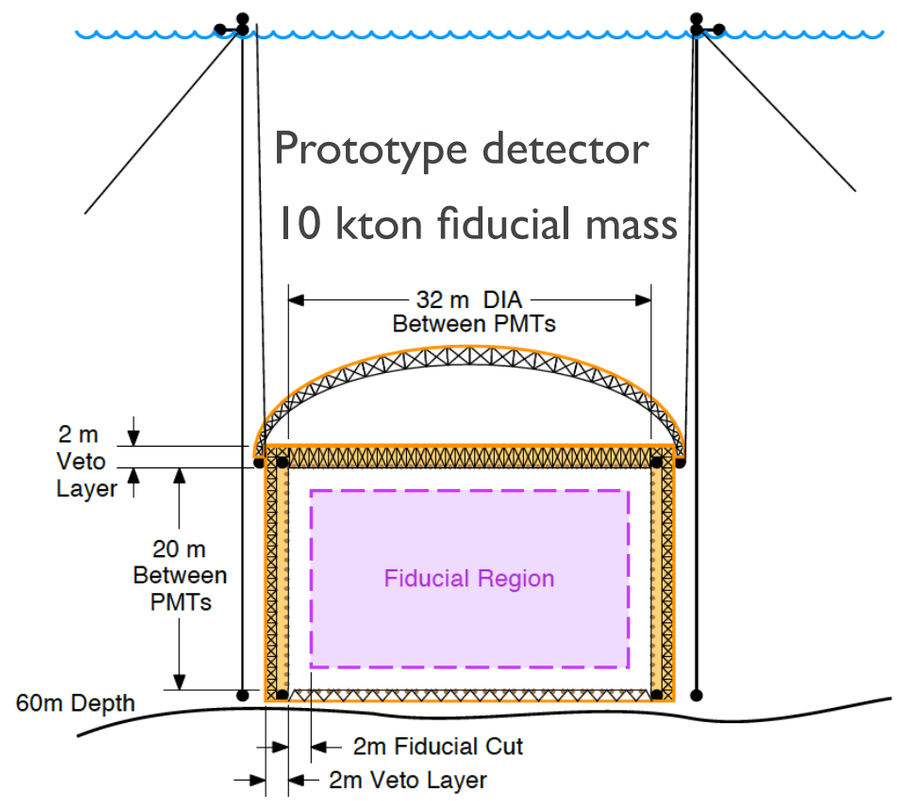
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

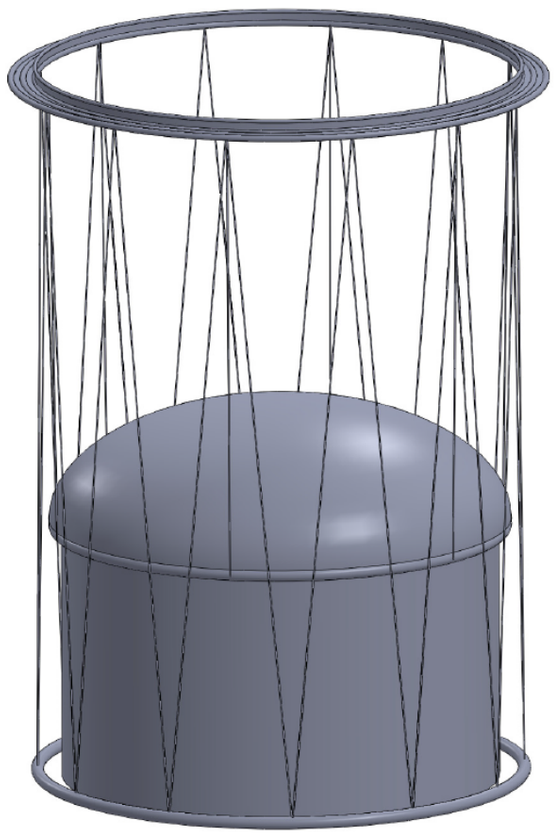
CP Violation, Mass Hierarchy, θ_{23} Octant

- **CHIPS (Cherenkov detectors In Mine PitS) in the US**
- Uses existing NuMI beam — Pion decay-in-flight off-axis (7 mrad) ν_μ beam with 700 kW power and 712 km baseline to Wentworth Pit in Minnesota
- Plan to instrument up to 100 kton of water to measure CP violation at 0.2-0.5M/kton cost







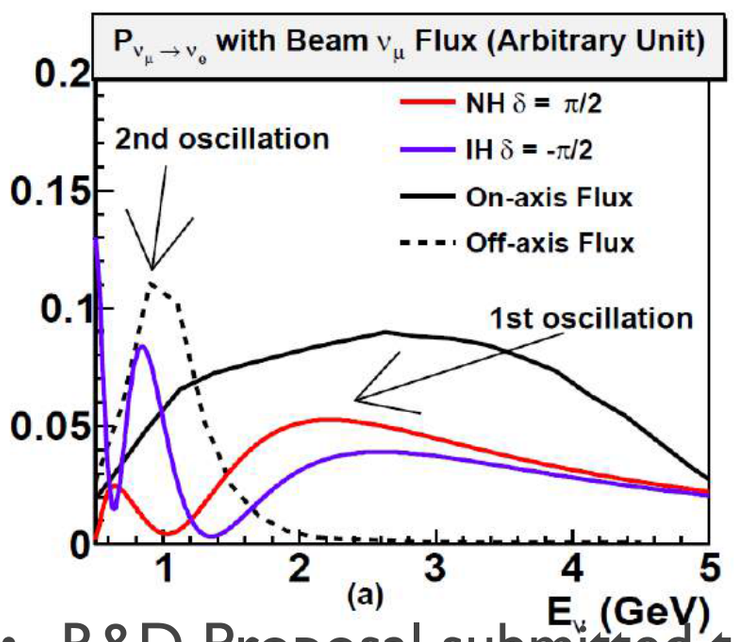


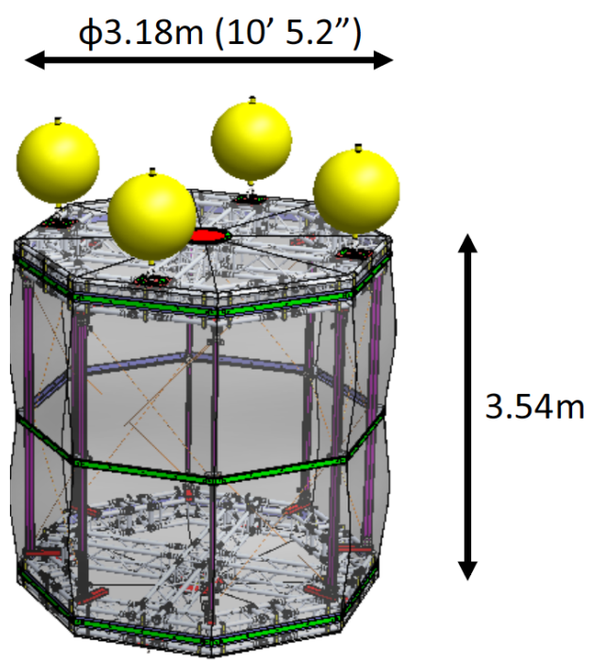
J.Thomas, ICFA Neutrino Panel, Paris (Jan. 2014)

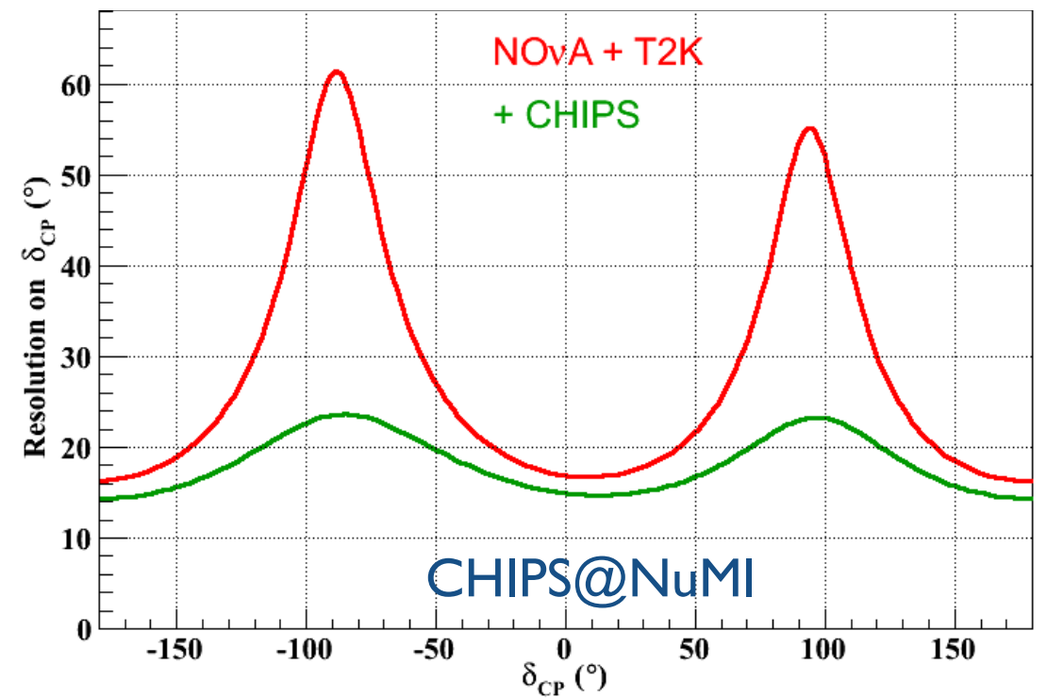
CP Violation, Mass Hierarchy, θ_{23} Octant

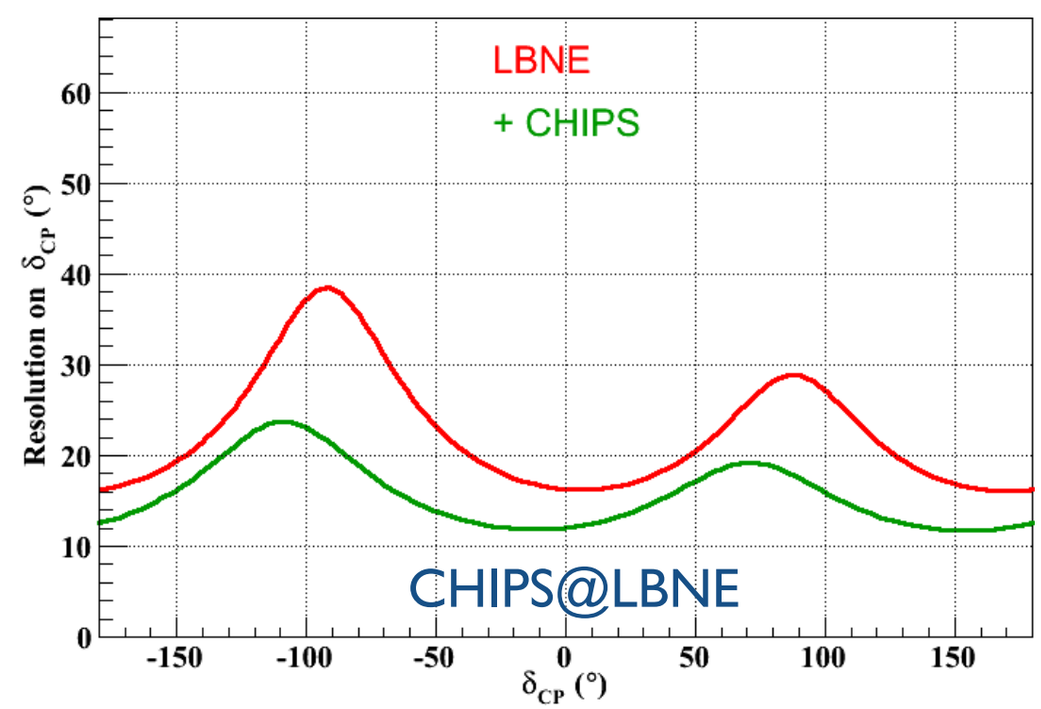
- **CHIPS (Cherenkov detectors In Mine PitS) in the US**

- Assuming 6 years of running with a 100 kton detector in NuMI, CHIPS can improve significantly sensitivity to CP violation from NOvA+ T2K
- In second phase, running 20 mrad off-axis from LBNE beam with 1250 km baseline, would help LBNE measurement





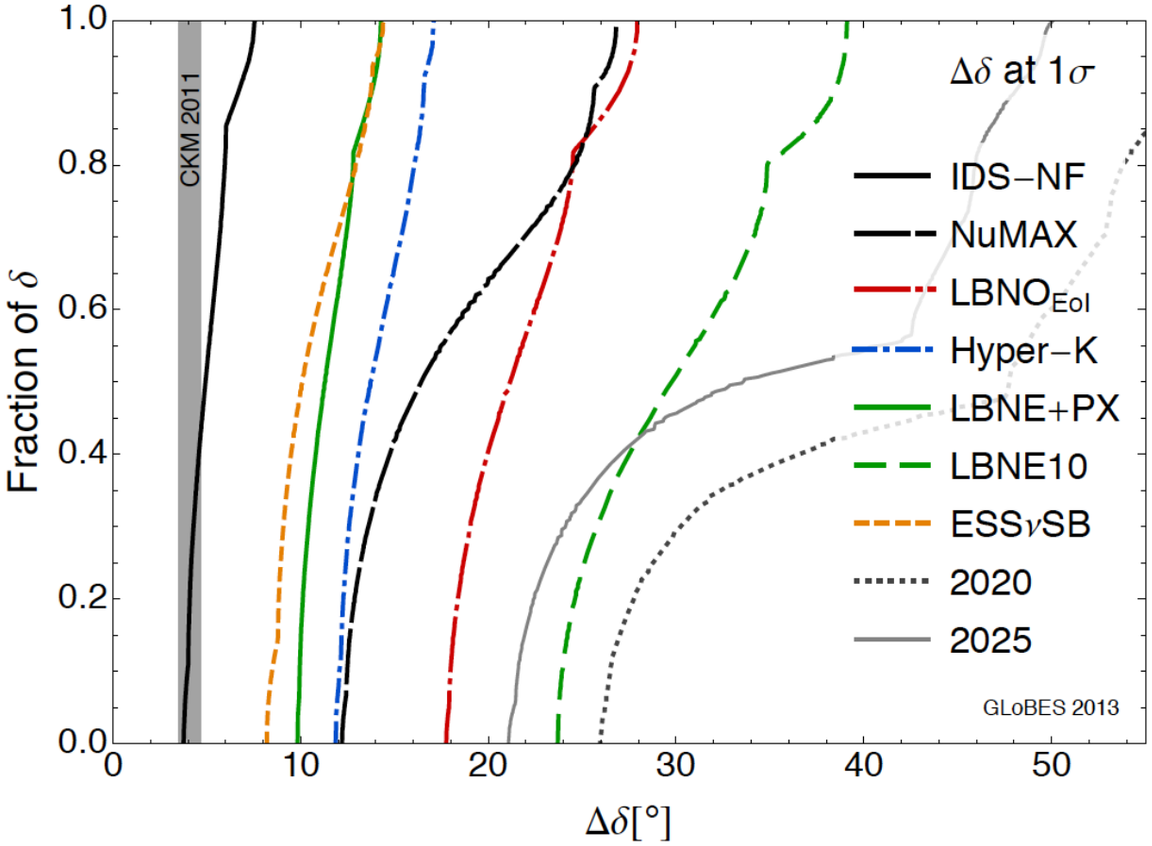




- R&D Proposal submitted to PAC and encouraged.
- 10 ton proof-of-principle detector to be deployed at Wentworth Pit this Summer
- LOI to Snowmass: arXiv:1307.5918

CP Violation, Mass Hierarchy, θ_{23} Octant

- **Other Proposed Experiments**
  - RADAR - 5 kton LAr TPC in NOνA Far Detector Hall using the NuMI beam, arXiv:1307.6507
  - DAEAδALUS - Pion decay-at-rest ν beam produced by 100 kW cyclotron. Use multiple baselines (1-20 km) to measure δ_{CP}. Hyper-K as detector would be ideal, arXiv:1307.2949
  - NuMAX - Low-energy neutrino factory, muon storage ring to produce muon decay-in-flight $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, ν_μ beam, use 1 MW PIP-II 5 GeV protons, and magnetized LBNE Far Detector, arXiv:1308.0494
  - IDS-NF - High-energy neutrino factory, 4 MW beam, muon cooling, 100 kton magnetized Fe detector arXiv:1112.2853



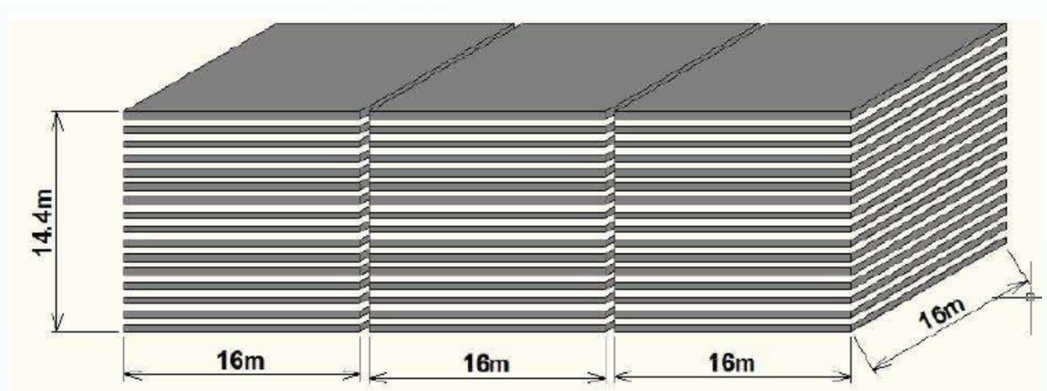
	detector vol. (kt)/type	dist. (km)	power (MW)	proton driver energy (GeV)	years $\nu/\bar{\nu}$
ESSνSB-360	500/WC	360	5	2.0/3.0	2/8
ESSνSB-540	500/WC	540	5	2.0/3.0	2/8
Hyper-K	560/WC	295	0.75	30	3/7
LBNE-10	10/LAr	1290	0.72	120	5/5
LBNE-PX	34/LAr	1290	2.2	120	5/5
LBNO-EoI	20/LAr	2300	0.7	400	5/5
IDS-NF	100/MIND	2000	4	10*	10**
NuMAX	10/LAr (magnetized)	1300	1	5*	5/5

E. Baussan et al., arXiv:1309.7022

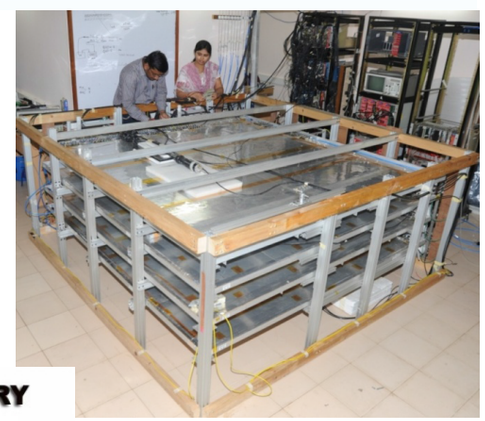
CSS 2013 (Snowmass) Neutrino Report, arXiv:1310.4340 (2013), based on P. Coloma, P. Huber, J. Kopp, W. Winter: Phys. Rev. D 87, 033004 (2013)

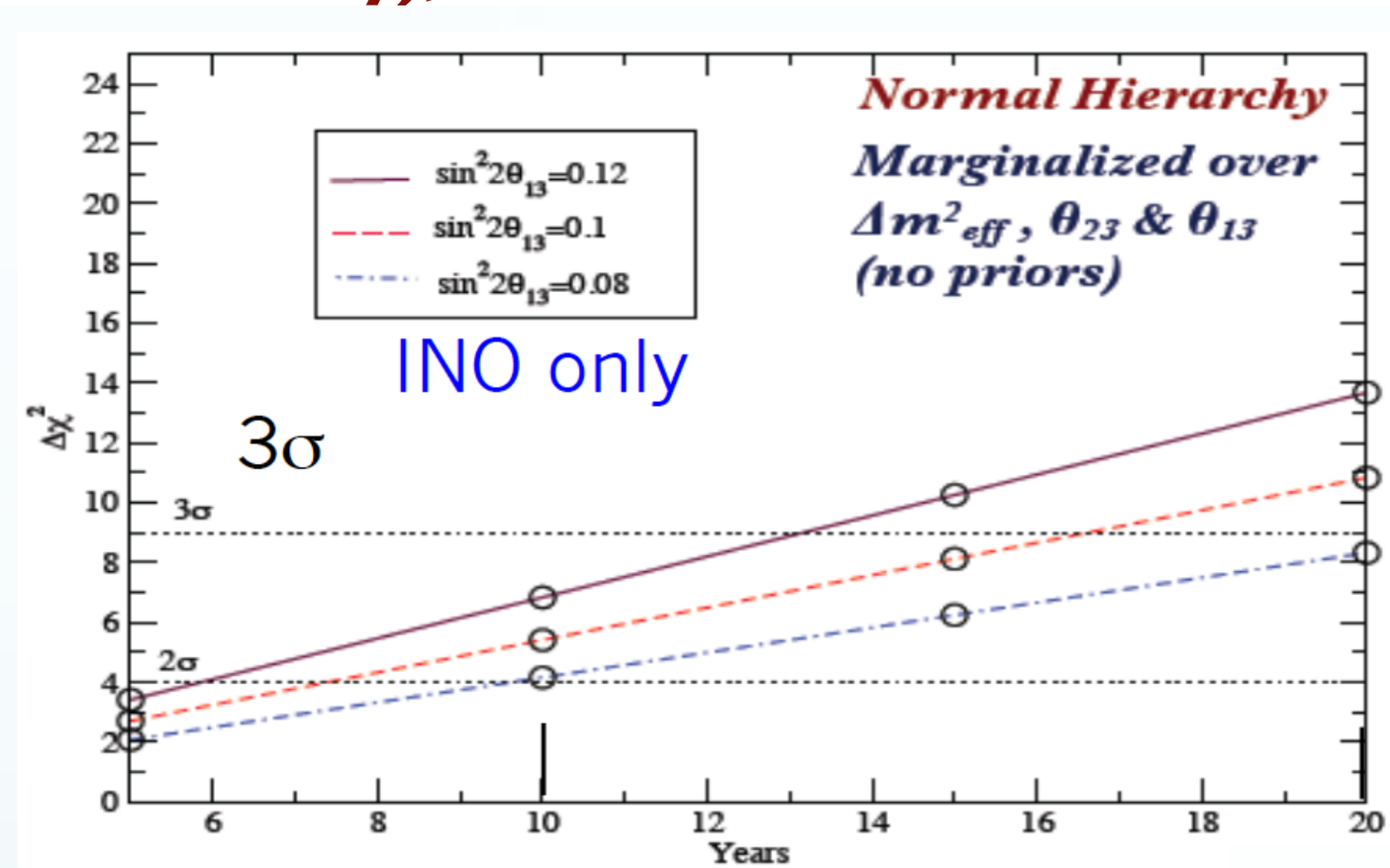
Mass Hierarchy, θ_{23} Octant

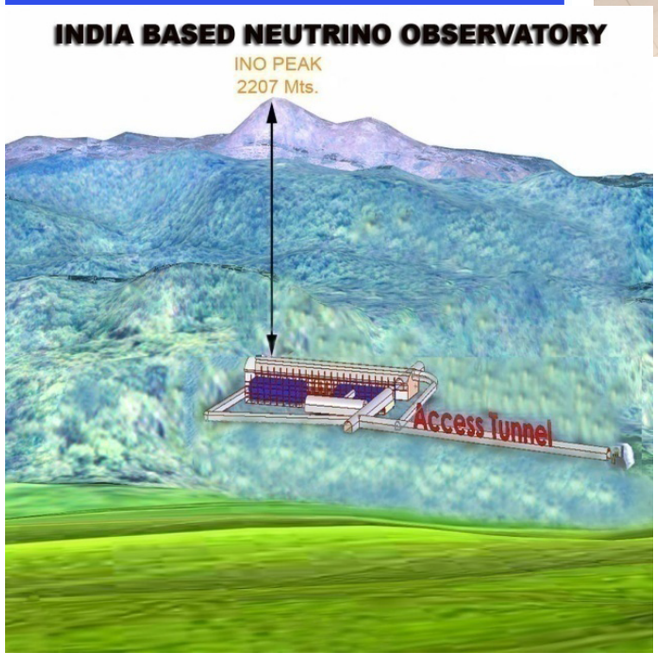
- **Dedicated Atmospheric Experiments:**
  - **INO (India-based Neutrino Observatory), in India**



- ✓ *50Kton Fe-RPC Detectors*
- ✓ *# of layers = 140*
- ✓ *Fe thickness = 5.6 cm*
- ✓ *Magnetic Field ~ 1.3T*
- ✓ *# of RPCs ~ 27K*
- ✓ *# of channels ~ 3.6M*







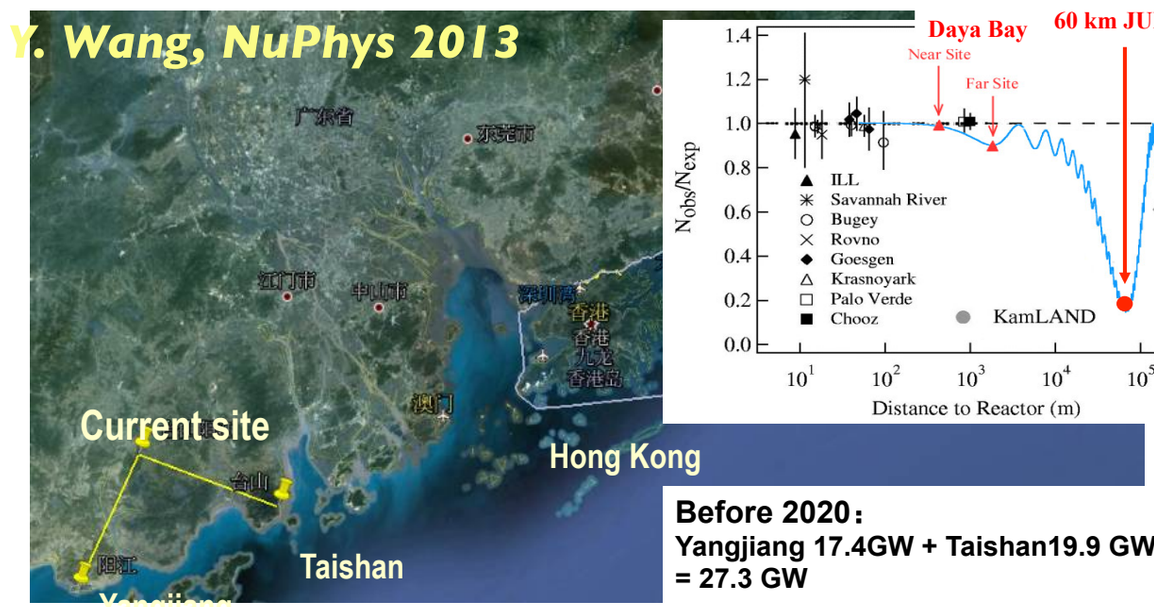
- Need over 10 years of running to reach 3σ resolution of mass hierarchy, but complementary to other measurements
- Status
  - Location chosen in Pottipuran, 100 km west of Madurai
  - Work started on facilities in Madurai HEP Center
  - Waiting for full approval by Indian government. Operations to start circa 2020

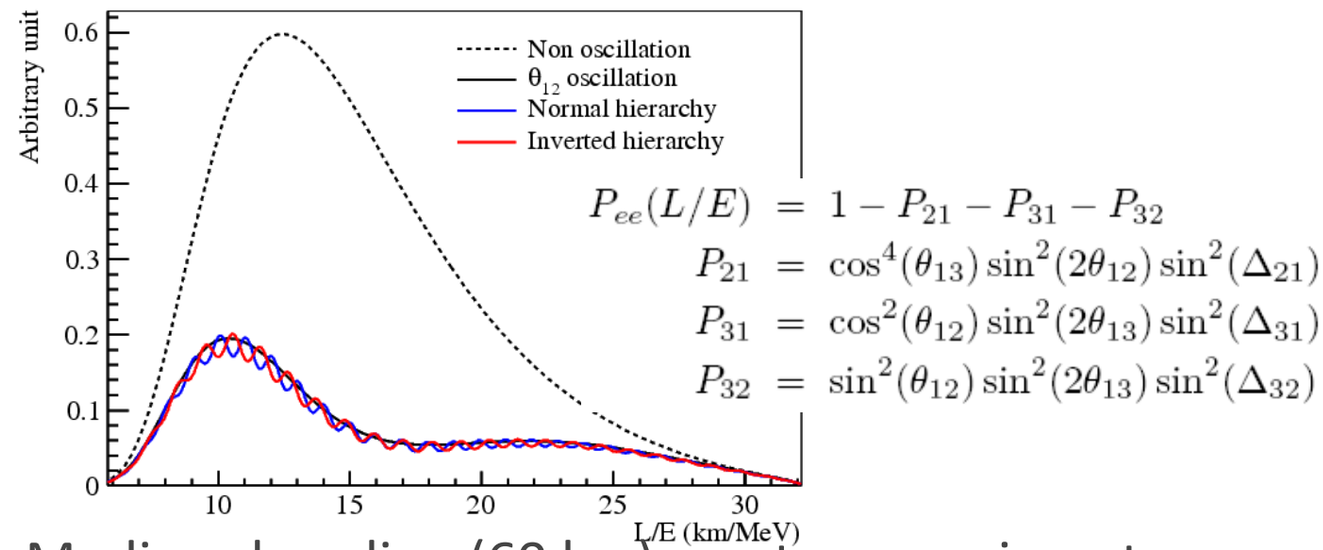
- **NB: Also sensitivity from atmospherics in DUNE, HyperK**

Mass Hierarchy

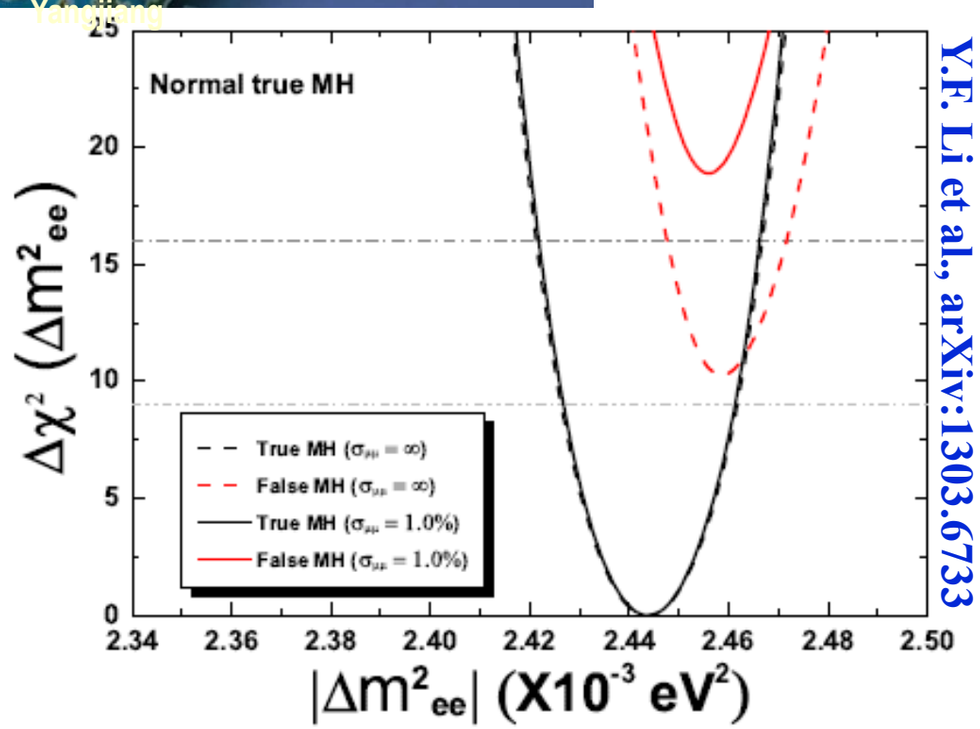
- **Reactor Experiments:**
  - **JUNO (Jiangmen Underground Neutrino Observatory), in China**

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4





$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

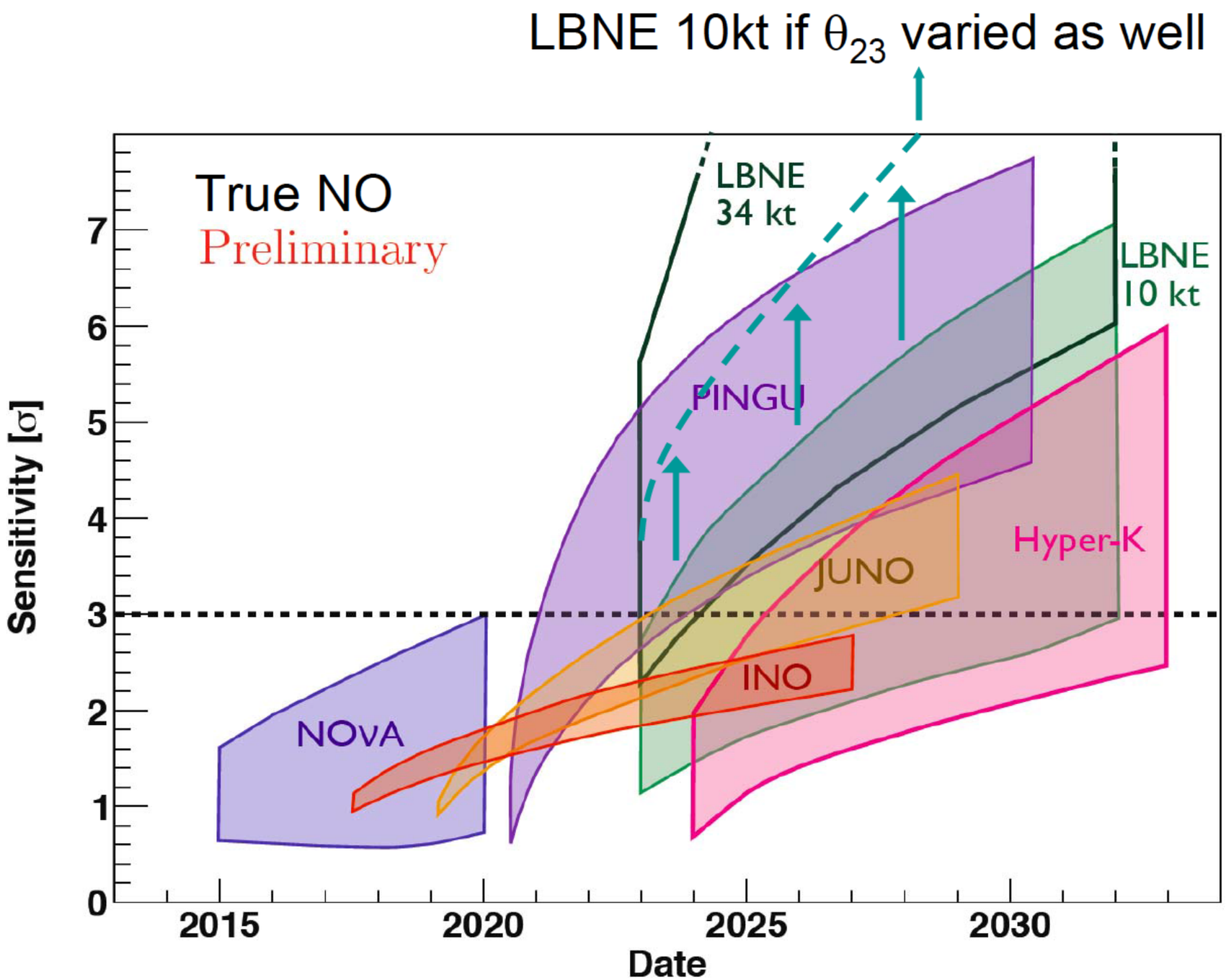


Y.F. Li et al., arXiv:1303.6733

- Medium-baseline (60 km) reactor experiment
- Need to distinguish between NH and IH in rapid oscillations in $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ driven by Δm^2_{31-2}
- Requires 20 kton liquid scintillator det. with 3% /√E energy resolution, and reactors with 36 GW power
- Can determine MH at 4σ level with 6 years of running if Δm^2 can be determined with 1% precision; < 2% precision measurement of θ_{12} and Δm^2_{21}
- Status: Detector design underway, prototype to be started by end of the year, R&D funding approved, construction approval in progress
  - First data expected in 2020
- **Also RENO-50 proposal, in Korea, with same concept and same challenges**

Mass Hierarchy Summary

- Comparison of reach in determining the mass hierarchy for current and future experiments

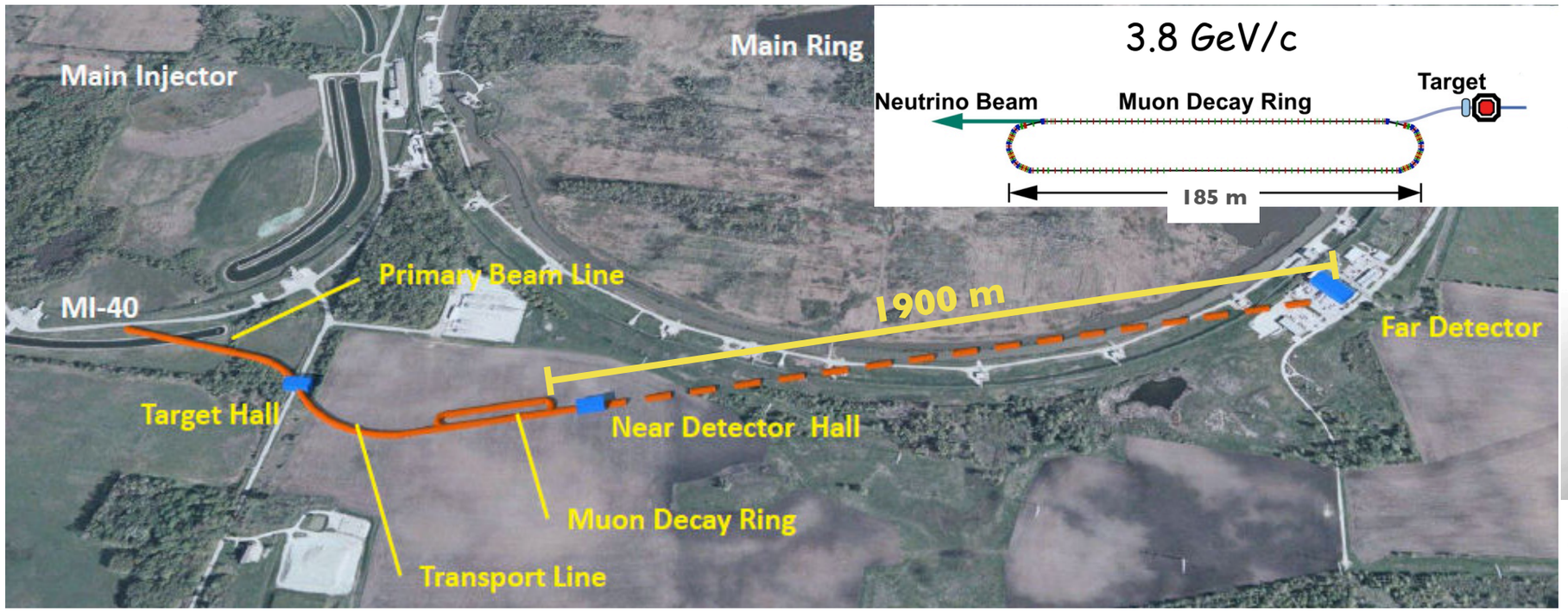


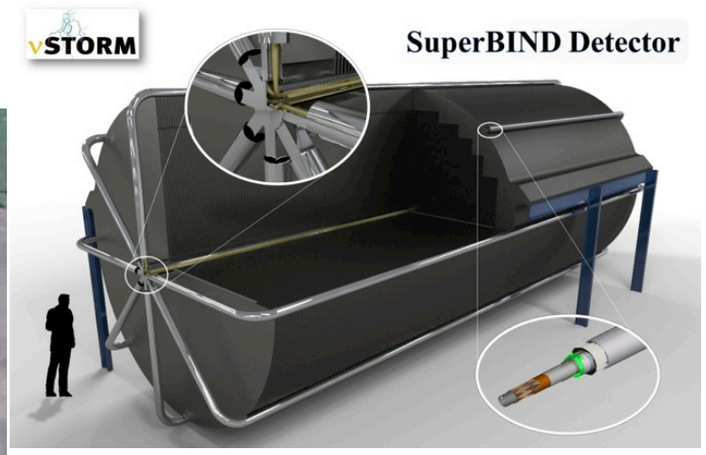
- Bands cover maximum sensitivity differences due to variation of δ_{CP} (NOνA, LBNE), θ_{23} (PINGU, INO, HyperK), and energy resolution (JUNO)
- Expected LBNE sensitivity for most favorable θ_{23} values also included.

W. Winter, Frontiers in HEP 2014, Aspen, based on Blennow, Coloma, Huber, Schwetz, arXiv:1311.1822

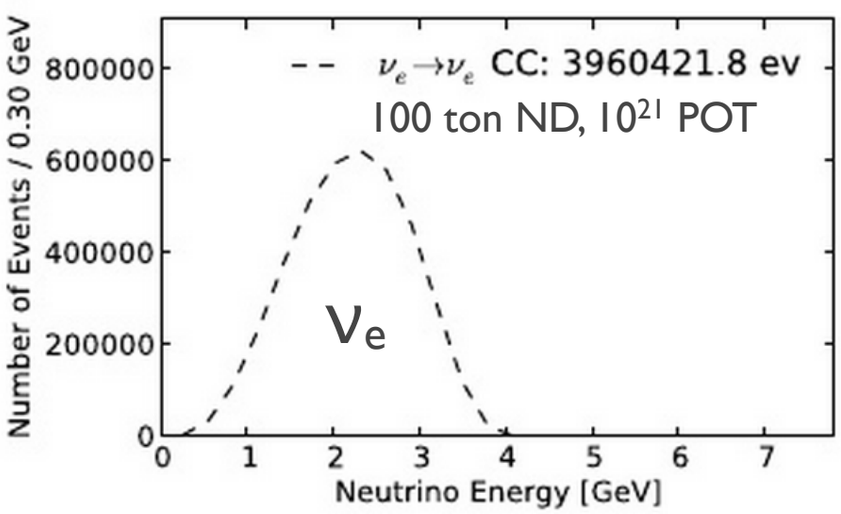
Sterile Neutrinos

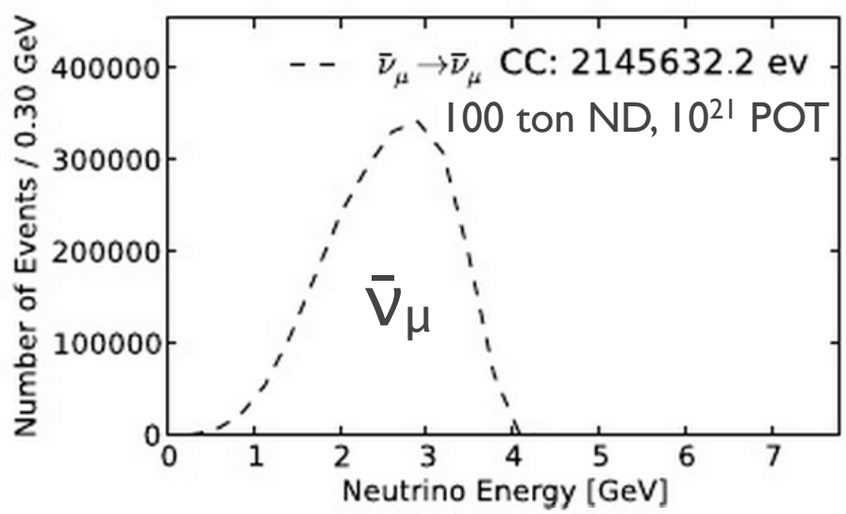
- **Short-Baseline Accelerator Experiments**
  - **nuSTORM (Neutrinos from STORed Muons), to be hosted at Fermilab or CERN**
- $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, ν_μ beams from muon decay-in-flight in muon storage ring. 3.8 GeV/c muons from 100 kW 120 GeV/c proton beam incident in graphite target





- Proposed FD is a 1.3 kton iron-scintillator tracking calorimeter similar to MINOS, but ~2.3 T B field is generated by a superconducting transmission line

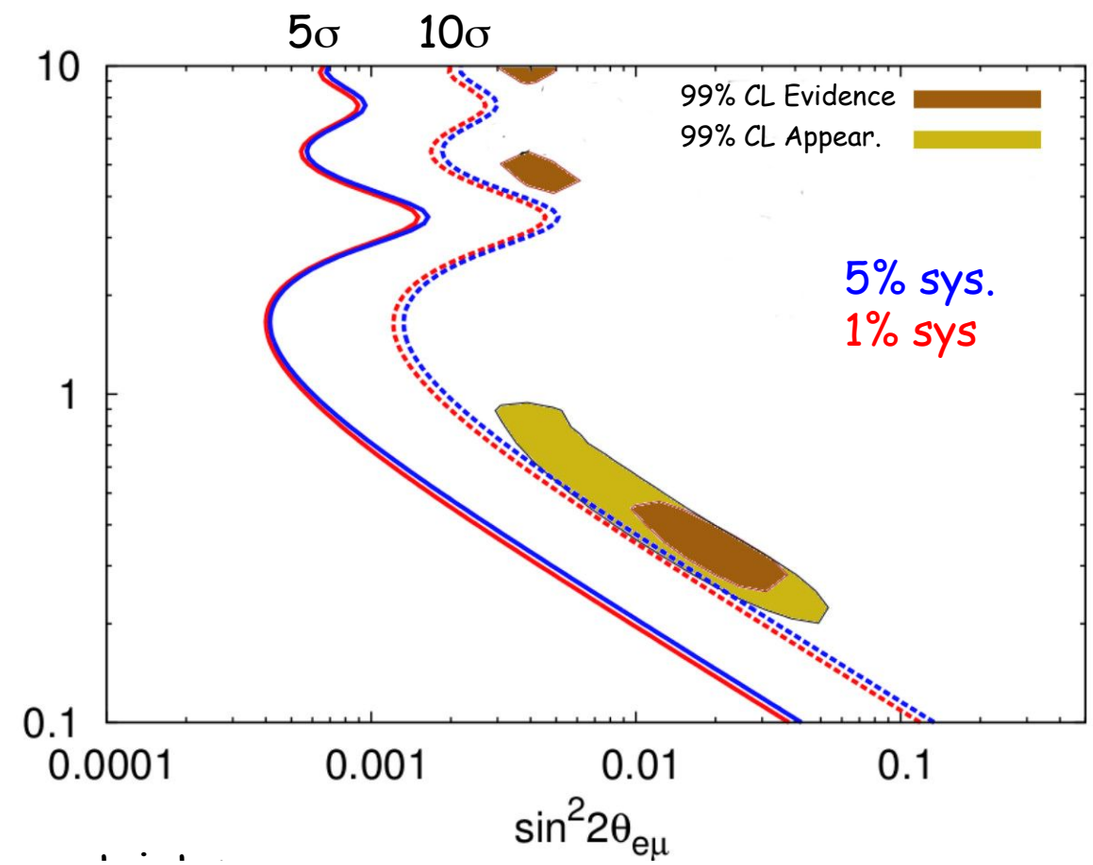




Sterile Neutrinos

- **Short-Baseline Accelerator Experiments**
  - **nuSTORM (Neutrinos from STORed Muons), to be hosted at Fermilab or CERN**
  - Experimental setup has access to 8 of 12 possible channels from stored μ^+ or μ^-
  - Using the very large statistics in the CPT invariant mode of LSND, $\nu_e \rightarrow \nu_\mu$, can rule out sterile neutrino allowed regions at 10σ
  - With Near Detector(s), can potentially measure ν_e, $\bar{\nu}_e$ cross-sections to ~1-2%, essential for future long-baseline experiments

$\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$	$\mu^- \rightarrow e^-\overline{\nu}_e\nu_\mu$	
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\overline{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$	appearance (atm. oscillation)
$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	disappearance
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	appearance: "silver" channel



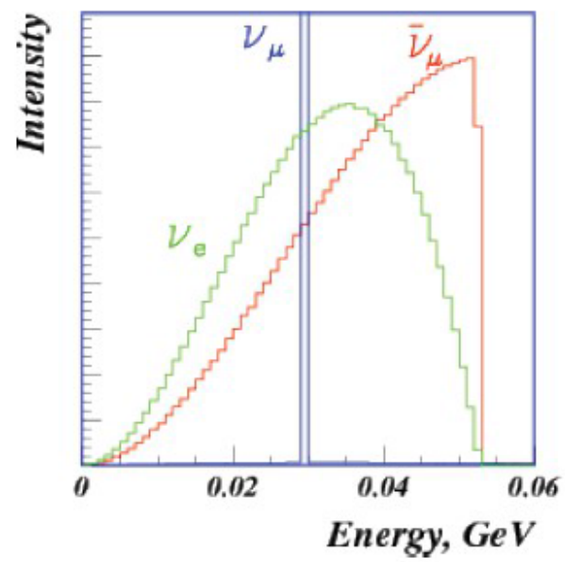
nuSTORM paper submitted to PRD(RC), arXiv:1402.5250 (2014)

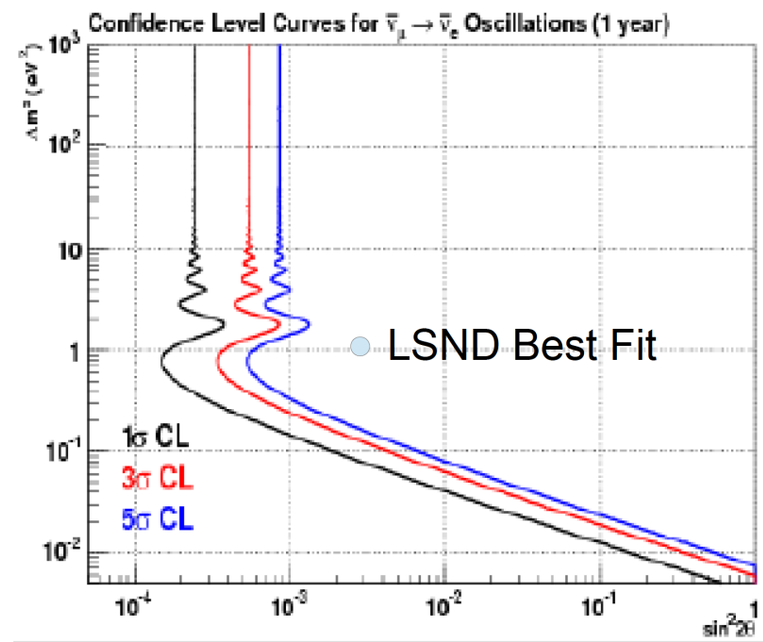
- Status: Full proposal submitted to Fermilab PAC in June 2013, granted Stage I approval, expecting to produce Technical Design Report in 2 years; LOI to Snowmass
- EOI to CERN in April 2013: support to study where to site the facility at CERN, and also define decisive european contributions

Sterile Neutrinos

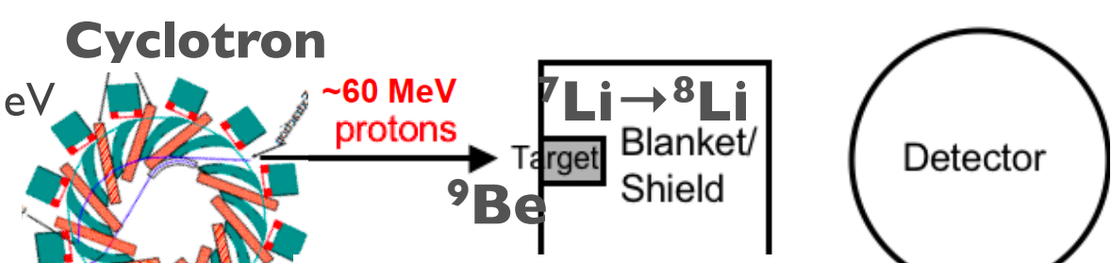
- **Short-Baseline Accelerator Experiments**
  - **OscSNS (Oscillations at the Spallation Neutrino Source), at Oak Ridge Nat. Lab, US**
- Redo LSND experiment with a more intense and well understood pion decay-at-rest beam (1 GeV protons on Hg target) with 1.4 MW power
- Use 450 ton fiducial detector with same type of mineral oil as LSND, but better electronics (200 MHz vs 10 MHz)
- LOI submitted to Snowmass

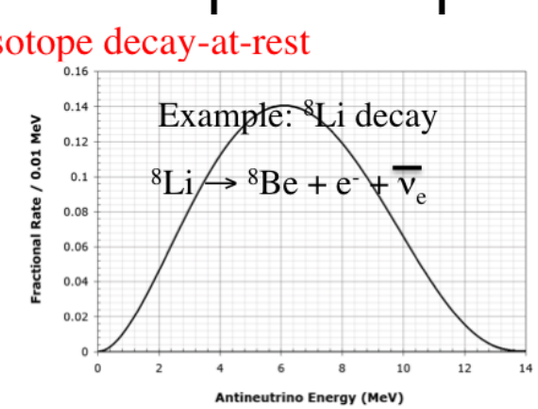
  arXiv:1307.7097

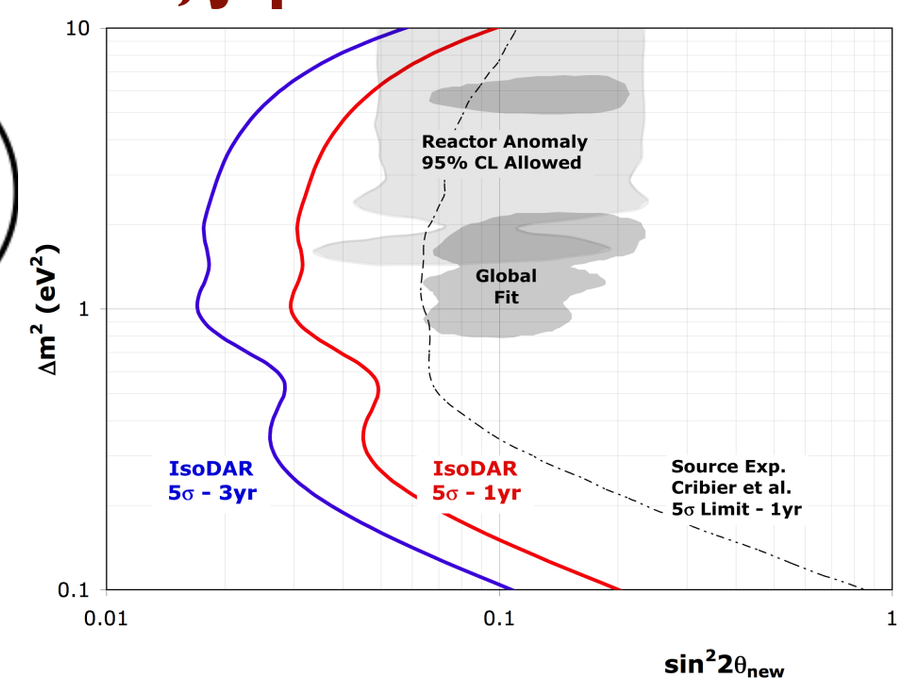




- **IsoDAR (Isotope Decay-At-Rest Experiment), at KamLAND, Japan**
- Mean $\bar{\nu}_e$ energy of 6.5 MeV
- Neutrino source placed 16 m from center of KamLAND
- Look for changes in inverse beta decay rate as a function of L/E inside detector to look for sterile neutrinos
- Proposal in arXiv:1205.4419







Sterile Neutrino Summary

CSS 2013 (Snowmass) Neutrino Report, arXiv:1310.4340 (2013)

	Experiment	ν Source	ν Type	Channel	Host	Cost Category[1]
radioactive	CeLAND [259]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
	Daya Bay Source [260]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
	SOX [261]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
		^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
	BEST [64]	^{51}Cr	ν_e	disapp.	Russia	small
reactor	PROSPECT [262]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
	STEREO	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	N/A[4]
	DANSS [263]	Reactor	$\bar{\nu}_e$	disapp.	Russia	N/A[4]
π-DAR	OscSNS [205]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.	ORNL, U.S.	medium
π-DIF	LAr1 [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
	LAr1-ND [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
	MiniBooNE+ [203]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	small
	MiniBooNE II [265]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
	ICARUS/NESSiE [266]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	N/A[4]
Other DAR	IsoDAR [111]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
μ-storage ring	nuSTORM [192]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab/CERN	large

[1] Rough recost categories: small: <$5M, medium: $5M-$50M, large: $50M-$300M.

- Also constraints on sterile neutrino mixing from long-baseline experiments (à la MINOS/MINOS+) and atmospheric experiments like PINGU
- SBL accelerator experiments will also contribute to improving ν cross sections knowledge