Sterile Neutrino Searches (an unfinished story)

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Special thanks to Jiajie Ling
White paper: 1204.5379

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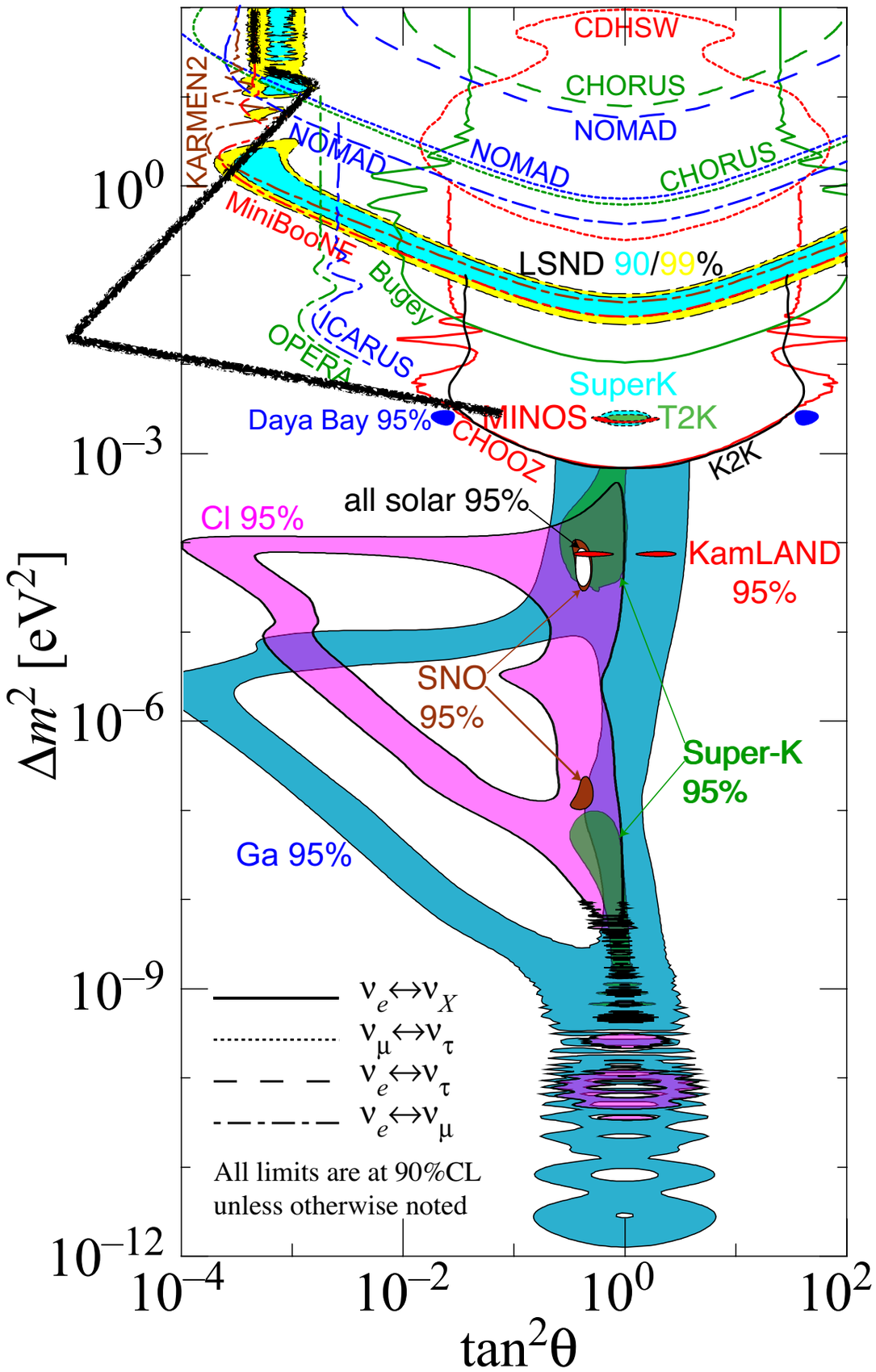
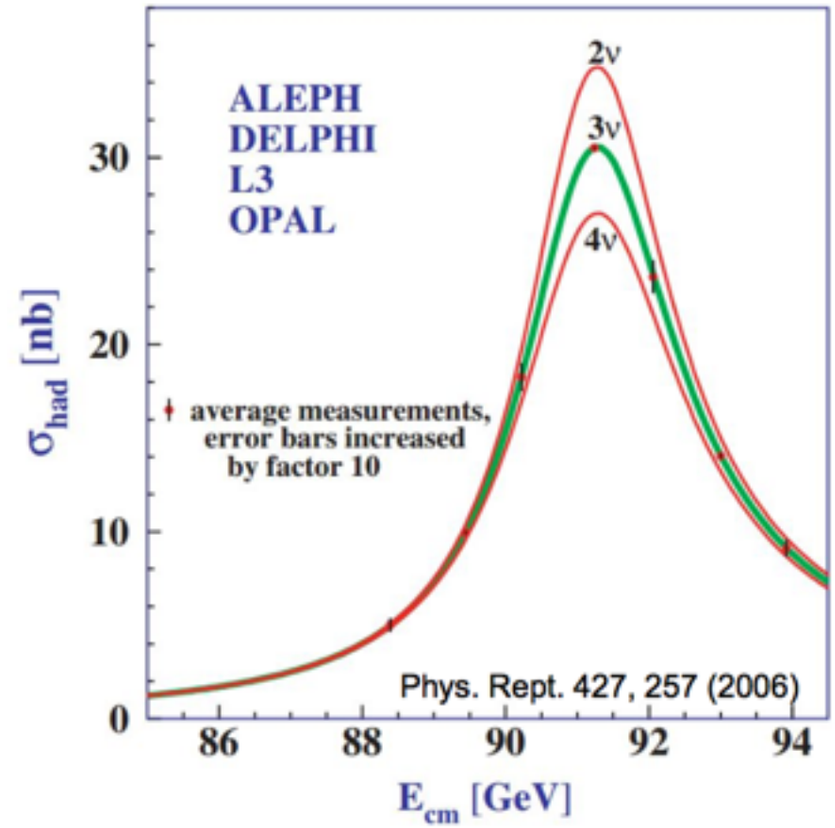
Outline

- ***Generalities***
  - ***The search for fundamental neutral states is extremely well motivated because of the known mystery of dark matter and the unknown nature of the neutrino.***
- ***3 neutrinos and phase space for a 4th light state***
- ***Experiments and Techniques with anomalies***
- ***Near term experiments***
- ***Experimental Outlook***

new result MINOS+DB



http://hitoshi.berkeley.edu/neutrino



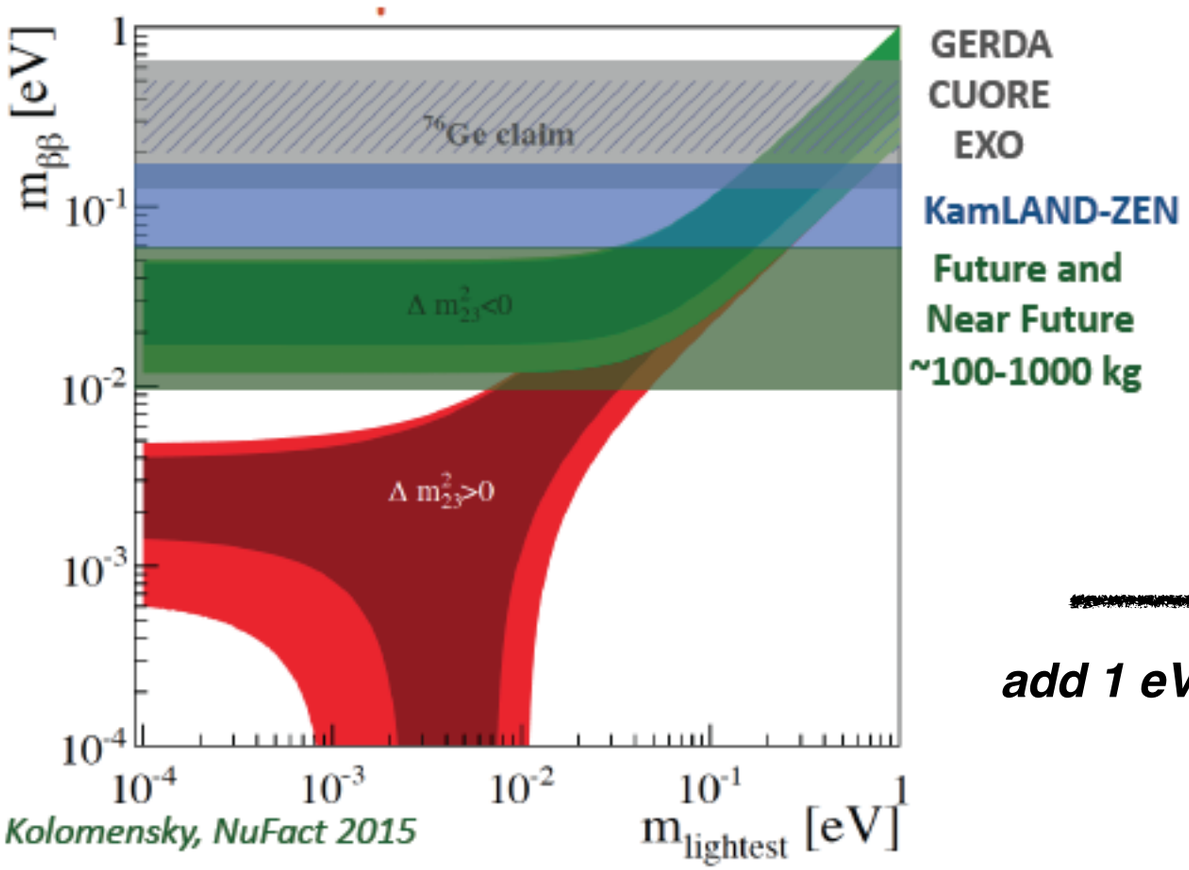
The electroweak and the most compelling neutrino oscillation data is consistent with 3 active neutrinos that have small masses and large mixings.

But sterile neutrinos that do not have electroweak coupling are allowed at any mass scale.

- **Very Heavy right-handed (~10^{12} GeV) considered to be natural partners of light left-handed neutrinos**
- **Light (<10 eV) could be observable through mixing.**
- **keV scale could form dark matter. observable through decays.**

Large mixing of ν_s with active neutrinos is excluded across ~10 orders of mag. For <1eV ν_s is effectively excluded 1204.5379

Neutrino less double beta decay with sterile



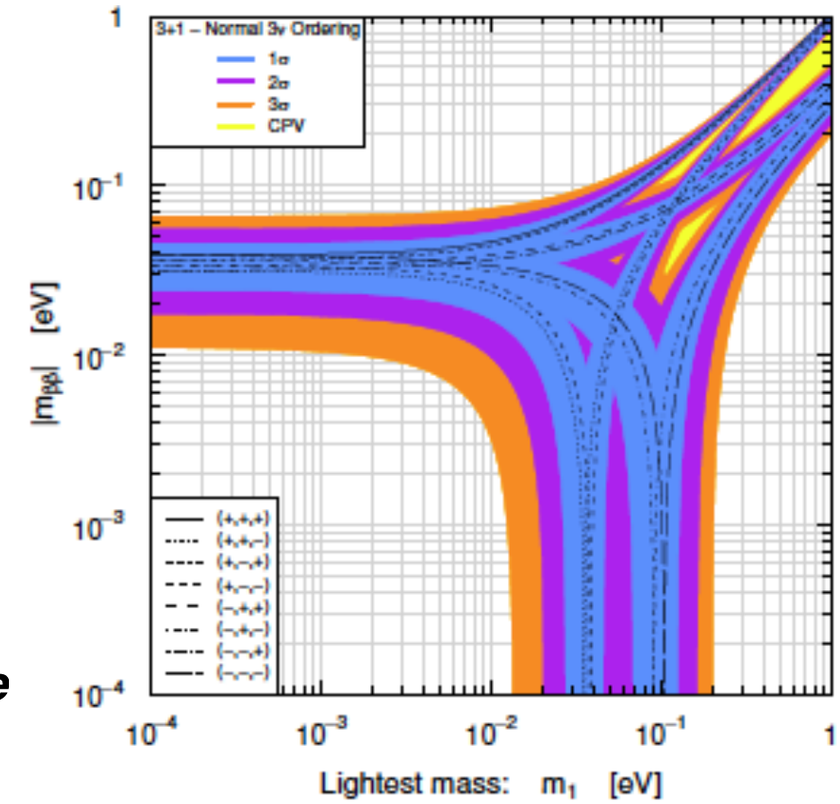
Y. Kolomensky, NuFact 2015

$$\left|m_{\beta\beta}\right| = \left|\sum \left|U_{ej}\right|^2 m_j e^{i\alpha_j}\right|$$

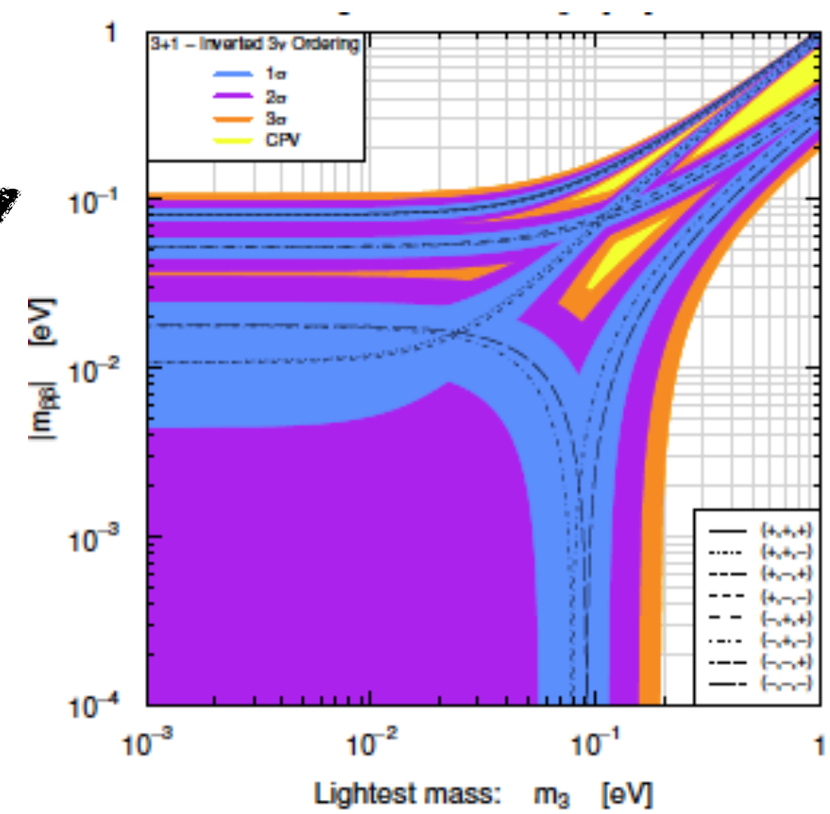
$$T_{1/2} \propto 1/\left|m_{\beta\beta}\right|^2$$

If there is a 1 eV sterile neutrino with mixing according to global fit then NLDBD could be accessible over a larger range of values. 1507.08204

add 1 eV sterile

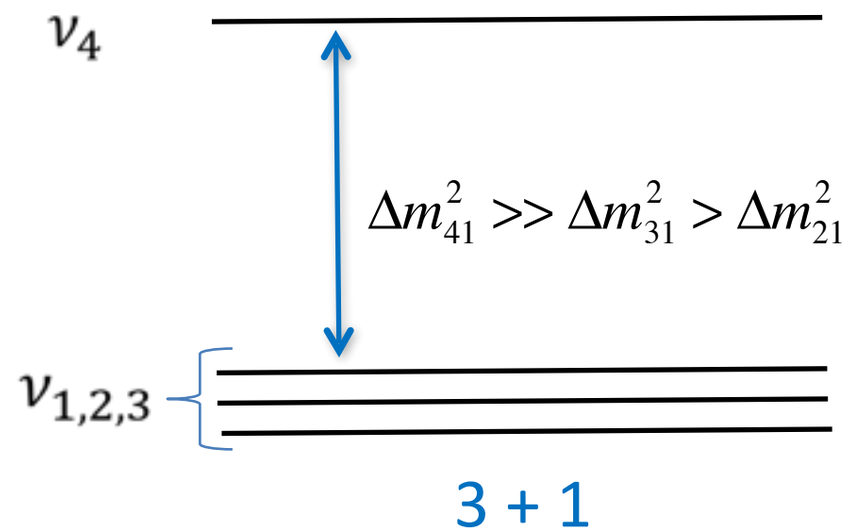


inverted 3ν



3(active)+1(sterile) formalism

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$



- ***The 3 active neutrinos have much lower masses and so this is an effective 2 neutrino system with a new $\Delta m^2 > 1\ eV^2$***
- ***Oscillations will be at much smaller L/E ~1 km/GeV or 1 m/MeV where atmospheric and solar oscillations can be ignored.***

Appearance:

$$P(\nu_\alpha \to \nu_\beta) \cong 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

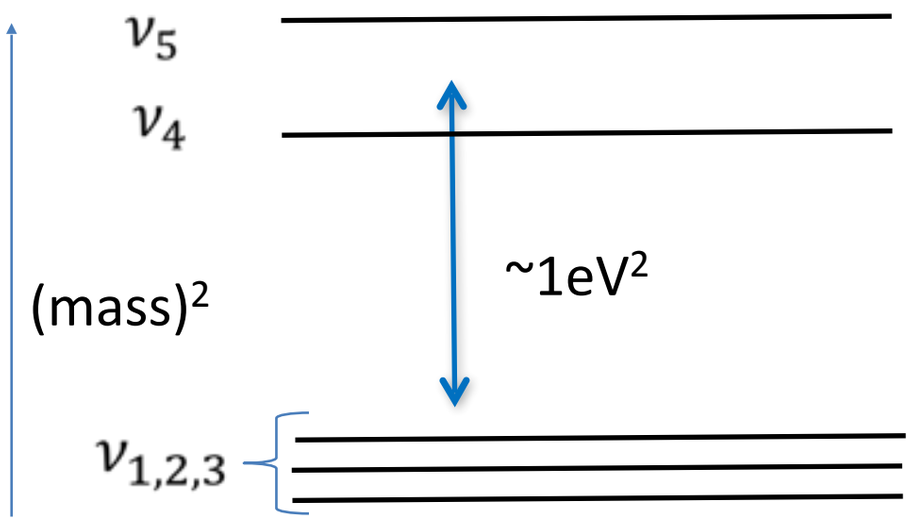
$$\cong sin^2 2\theta_{\alpha\beta}\ sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Disappearance:

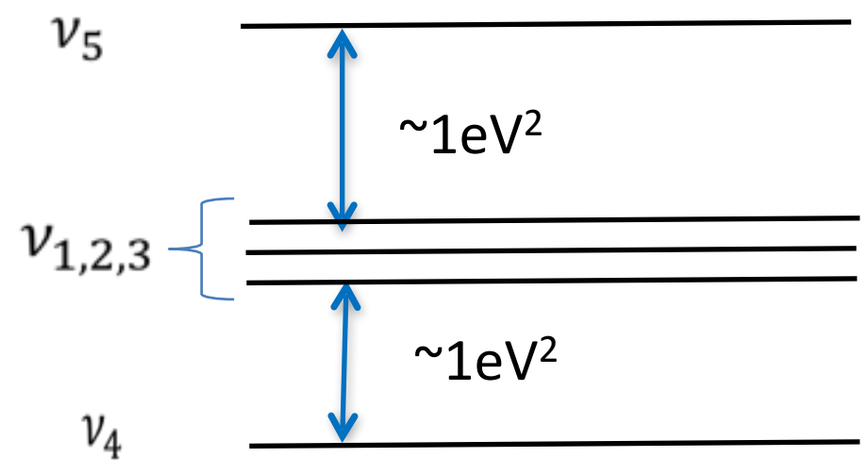
$$P(\nu_\alpha \to \nu_\alpha) \cong 1 - 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\cong 1 - sin^2 2\theta_{\alpha\alpha}\ sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

More than 1 sterile neutrino ?



3 + 2



1 + 3 + 1

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

Disappearance in neutrinos and antineutrinos must be the same.

CP-violation: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

But this can happen only if there are $\geq 2\ \Delta m^2$ participating, and so there cannot be CP violation in a 3(active)+1(sterile) system which is effectively 2-ν

Addition of more than 1 sterile neutrino can introduce CP Violation allowing different appearance results for neutrinos and anti-neutrinos.

A 3 (active)+2(sterile) system is effectively a 3-ν system if the sterile masses are much larger than the active ones.

Muon and electron neutrino oscillations in 3+1

For any two flavors there is a triplet of observable oscillations.

$$P(\nu_\mu \to \nu_e) \cong 4\left|U_{\mu 4}\right|^2 \left|U_{e4}\right|^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) = \sin^2 2\theta_{\mu e} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P(\nu_\mu \to \nu_{\not\mu}) \cong 4\left|U_{\mu 4}\right|^2 (1-\left|U_{\mu 4}\right|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) = \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P(\nu_e \to \nu_{\not e}) \cong 4\left|U_{e4}\right|^2 (1-\left|U_{e4}\right|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) = \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P(\nu_\alpha \to \nu_{\not\alpha}) \approx P(\nu_\alpha \to \nu_s)$$

For small mixing

$$\sin^2 2\theta_{\mu e} = \frac{1}{4}\sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee} \quad \text{and} \quad \theta_{\mu\mu} \sim \theta_{24} \quad \theta_{ee} \sim \theta_{14}$$

This gives an upper bound after averaging over the oscillations

$$P(\nu_\mu \to \nu_e) \le \frac{1}{2} P(\nu_\mu \to \nu_{\not\mu}) \times P(\nu_e \to \nu_{\not e})$$

Although derived for 3+1 this should be independent of number of sterile neutrinos.

Regardless, the triplet of oscillations must be consistent if appearance is found.

Each of the disappearances separately is allowed without appearance.

See talk from Minakata.

Some history pre-LSND

- *Many accelerator oscillations experiments were carried out >1eV^2 because the large laboratories had L/E=1 km /1 GeV.*
- *Motivation from astrophysics in the past to find a ~1eV state.*
- *Almost all experiments struggled with backgrounds to the electron neutrino signal.*
- *"A value of a candidate depends on the background" — Maurice Goldhaber*

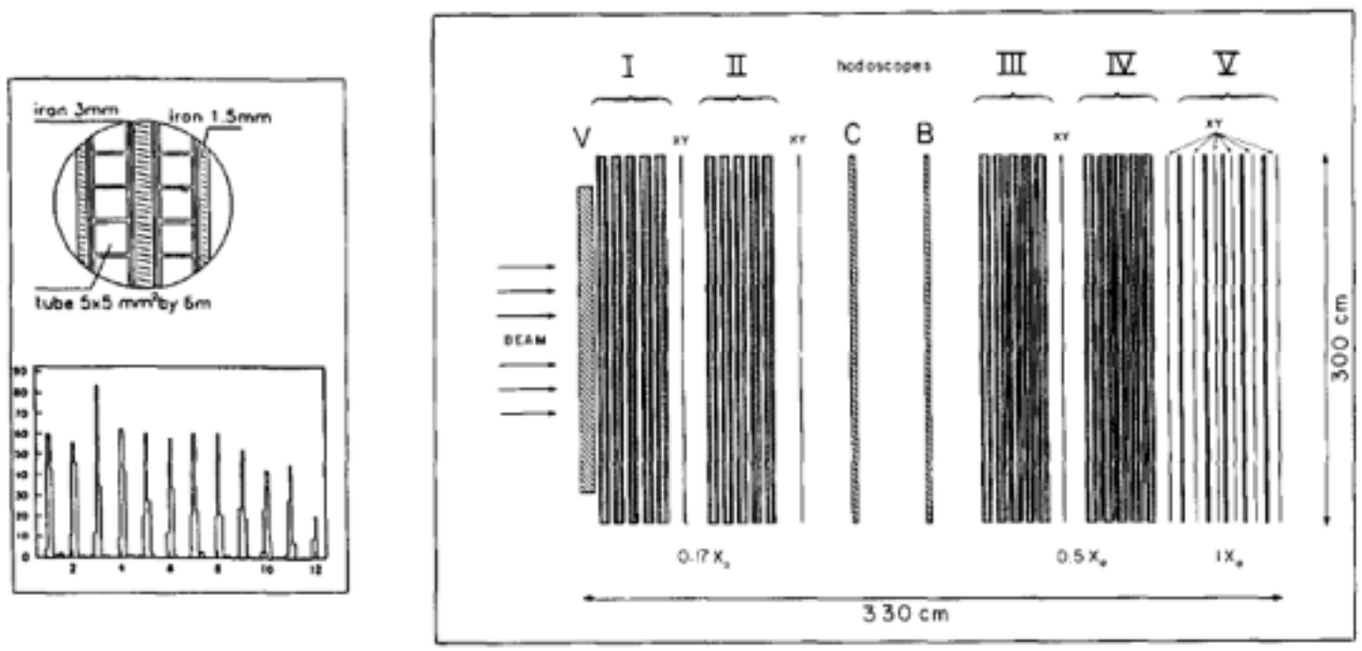
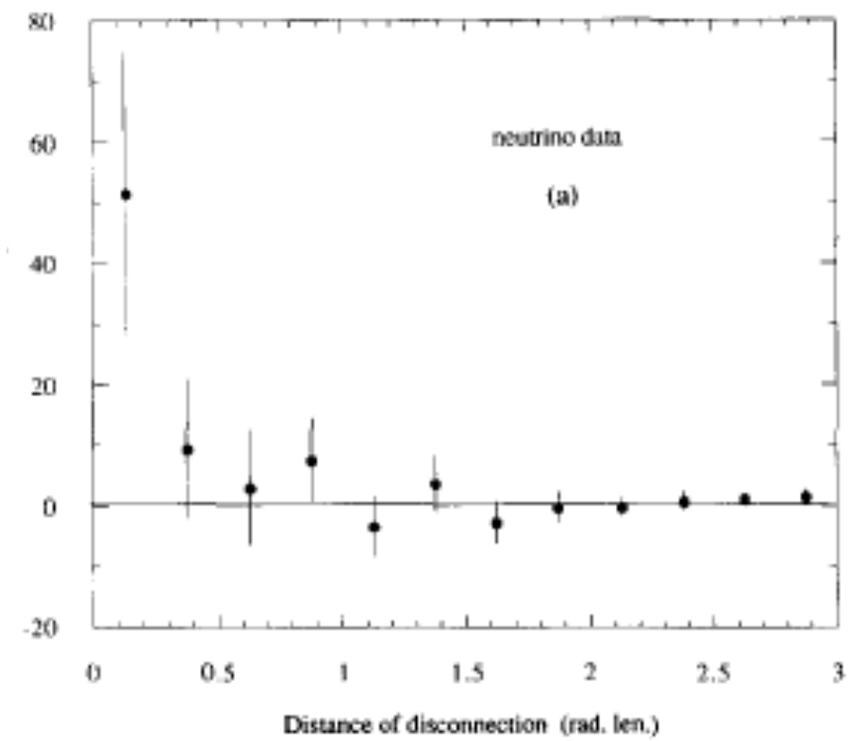


Fig. 1. The detector. The inset shows details of the flash chamber and the beam burst structure as measured by the experiment (horizontal scale gives time in units of 224 ns).



Example: AGS-816 had 1 view readout to measure e/gamma showers.

ref: CERN-EP-89-128,

Search for Neutrino Oscillations P. Astier et al.. Jan 1989. 18 pp.
Published in Phys.Lett. B220 (1989) 646

A signal was found using the gap between vertex and shower.

also see summary by Aronson, Murtagh: bnl-42369

Status in 1993

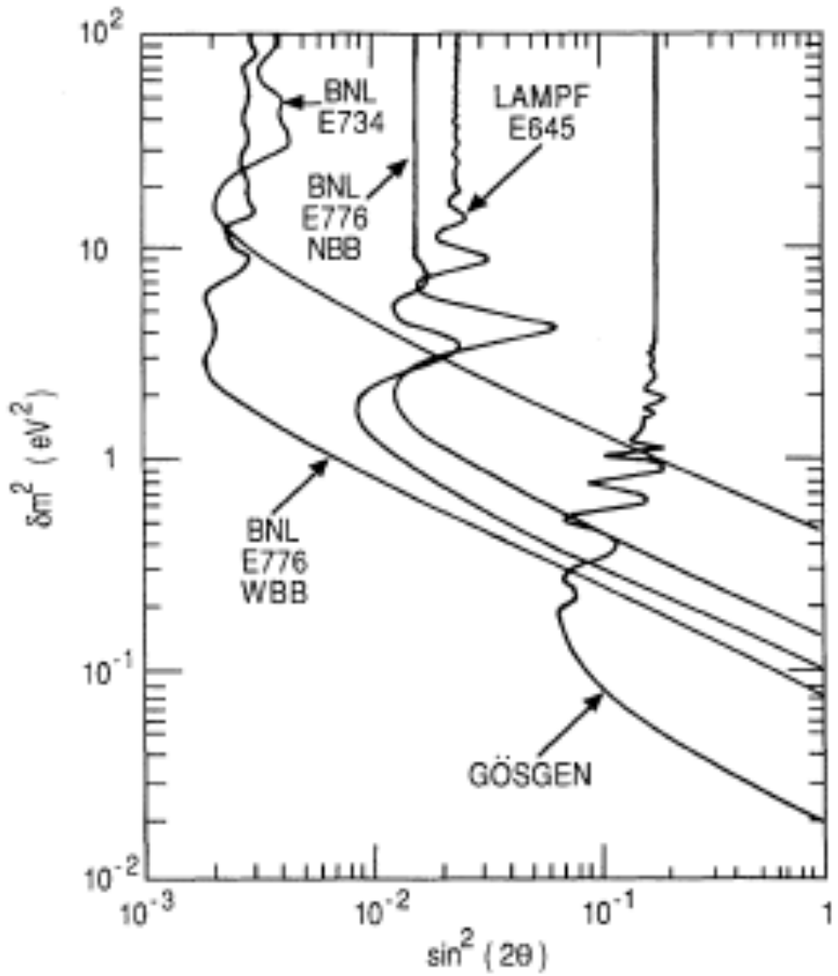


FIG. 31. Comparison of selected flavor-changing neutrino oscillation limits. The figure combines limits from appearance experiments with neutrinos and antineutrinos with the best limits from reactor disappearance experiments. The limits are comparable under the simplest assumptions of two-flavor neutrino mixing. See (Blumenfeld *et al.*) Ref. [10], BNL 776 NNB (narrow band beam); (Borokovsky *et al.*) Ref. [10], BNL WBB (wide-band beam); (Ahrens *et al.*) Ref. [9], BNL E734; and (Zacek, *et al.*), Ref. [6], Gösgen.

S.J. Freedman et al. (E645 collaboration), PRD 47 no. 3, 811 (1993)

Status 2015

- LSND Excess
  - $\bar{\nu}_\mu \to \bar{\nu}_e$ (3.8σ)
- MiniBoone Excess
  - $\bar{\nu}_\mu \to \bar{\nu}_e$ (2.8σ)
  - $\nu_\mu \to \nu_e$ (3.4σ)
  - combined (3.8σ)
- Reactor anomaly
  - $\bar{\nu}_\mu \to \bar{\nu}_s$ (3.0σ)
- Gallium anomaly
  - $\nu_e \to \nu_s$ (2.7σ)

An eV scale sterile neutrino would fit all of these, except for MiniBoone neutrino excess.

This status is changing rapidly with disappearance results from accelerator and reactor.

Evidence from LSND anti-$\nu_\mu \rightarrow$ anti-ν_e

p-beam: LAMPF in Los Alamos National Lab. 798 MeV at 1 mA
Neutrinos from decay at rest (DAR)

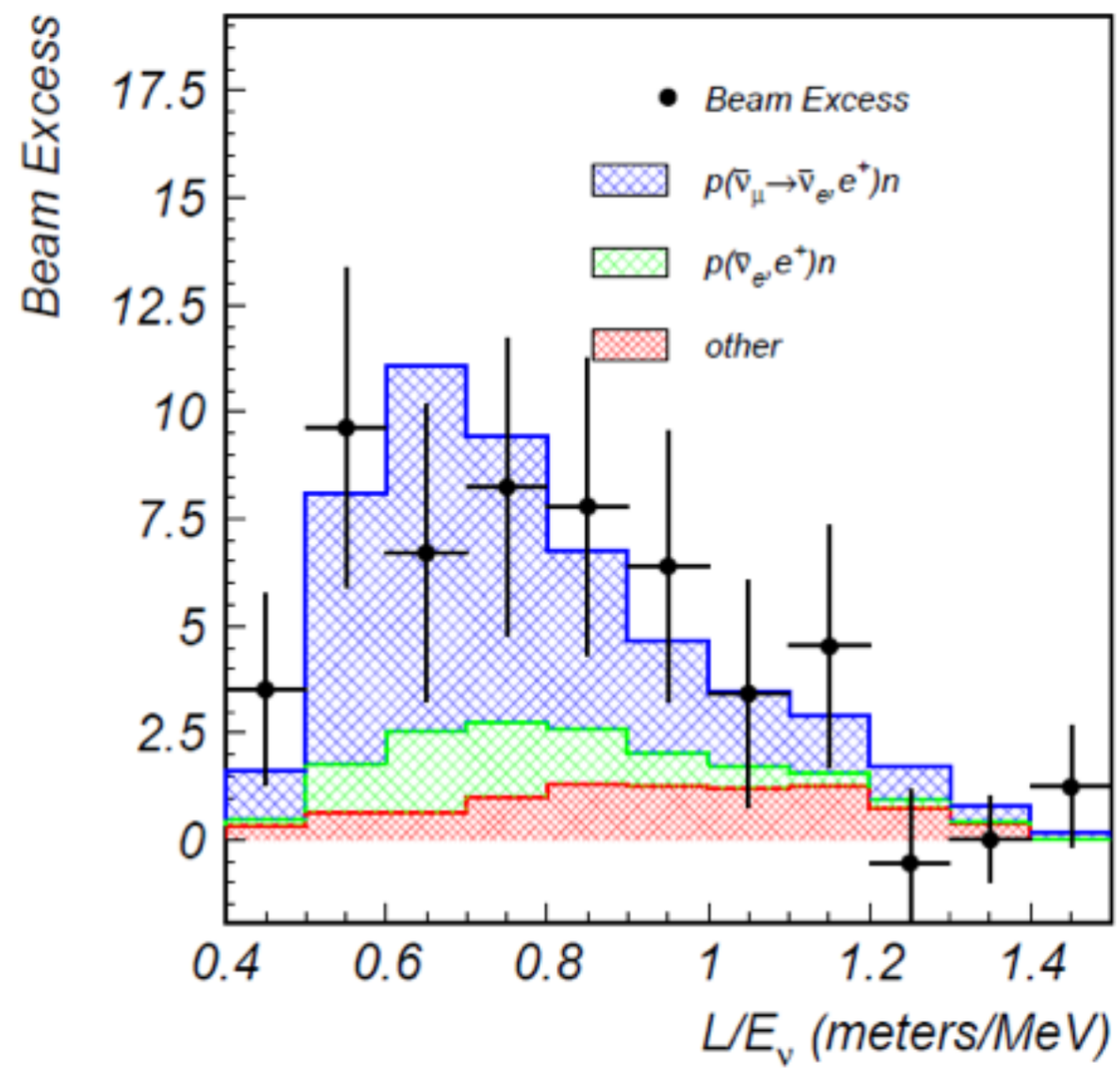
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Oscillation mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Detection mode: $\bar{\nu}_e + p \rightarrow e^+ + n$
Baseline: 30 m
Energy range: 20 – 60 MeV
L/E : ~ 1 m / MeV

Signal: inverse beta decay positron with a gamma from n absorption

Event excess: 87.9+-22.4+-6.0 (3.8σ)

Phys. Rev. D64, 112007 (2001)



plot of a subset of data with good n-tag

- backgrounds: beam-off, μ^- DAR, and π^- Decay in flight.
- implies at least 4 mass eigenstates: $\Delta m^2_{sol} << \Delta m^2_{atm} << 1\ eV^2$

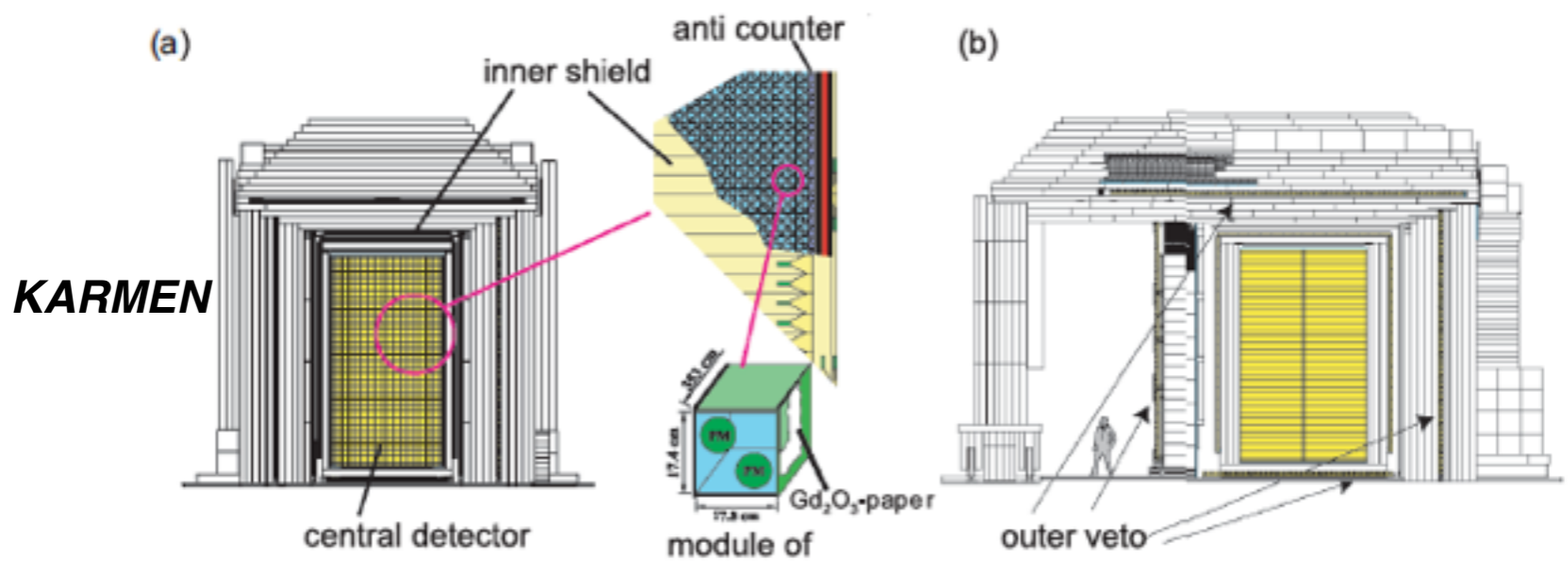
LSND versus KARMEN

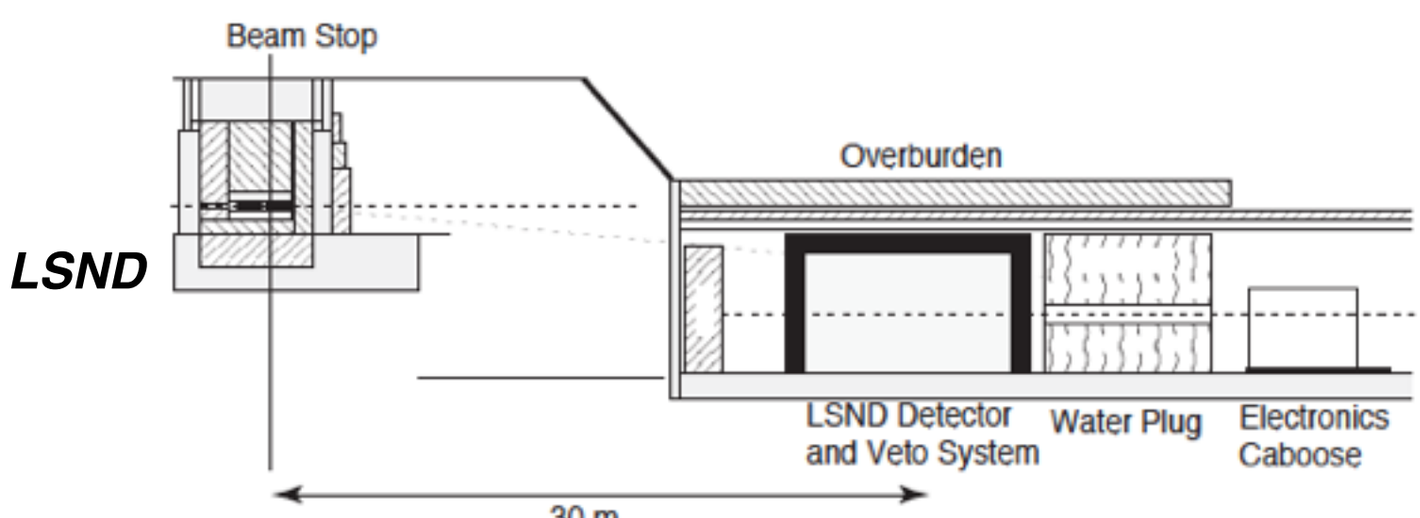
KARMEN p-beam: ISIS in RAL, 800 MeV, 50 Hz, 100 ns double pulse separated by 325 ns

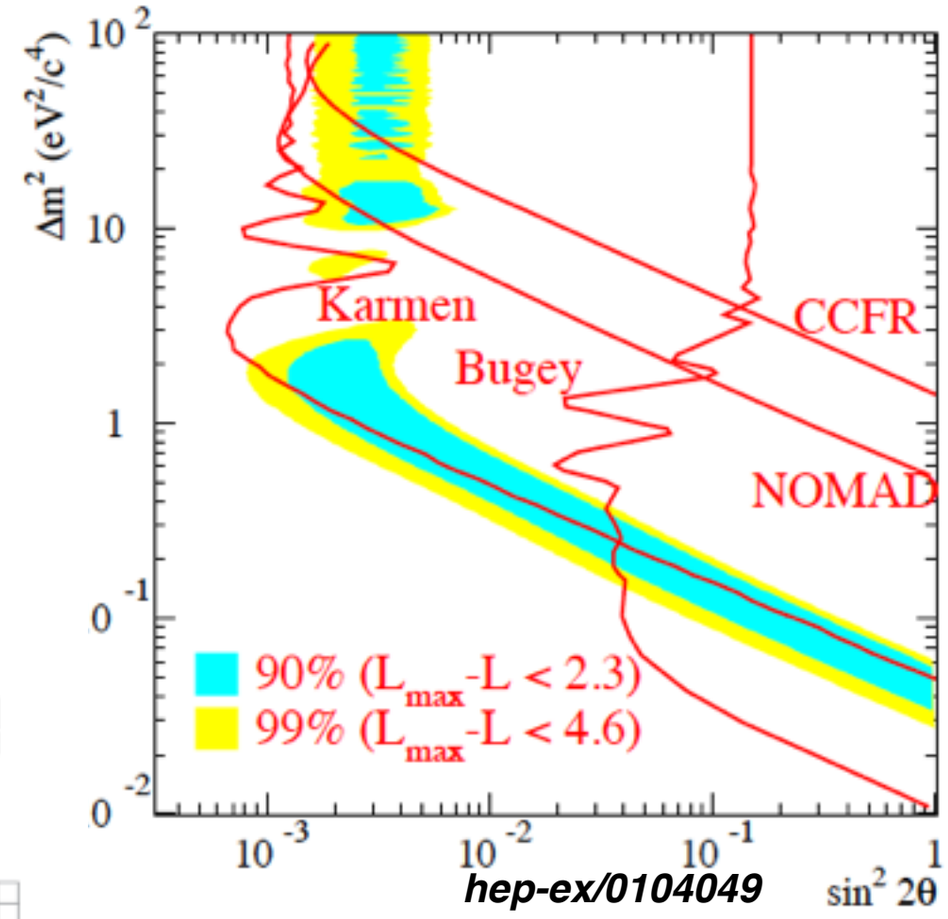
neutrinos: DAR from π and μ stops.

baseline: 17.7 m Phys. Rev. D65, 112001 (2002)

observation: 15 events with 15.8 expected bckg.







hep-ex/0104049

Key differences

beam duty factor
- ***LSND (continuous)***
- ***KARMEN (pulsed)***

neutron tag
- ***LSND (2.2 MeV γ in LS)***
- ***KARMEN (Gd ~8 MeV γ tag)***

Hint from MiniBooNE: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$

p beam: Booster in FNAL, 8 GeV
ν beam: π Decay-in-flight

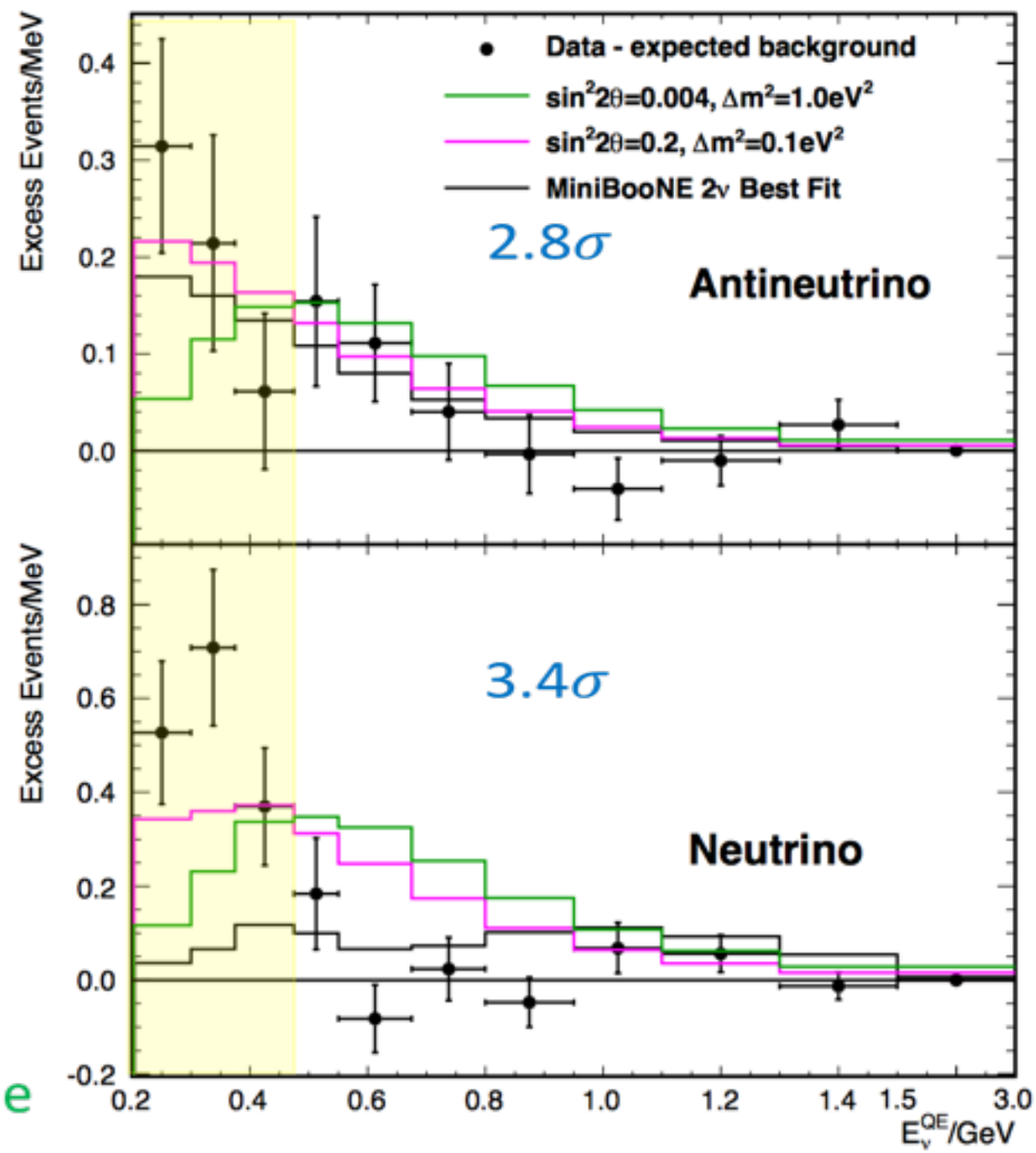
$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

Oscillation modes: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$
Detection mode: $\nu_e + n \to e^- + p$
$\bar{\nu}_e + p \to e^+ + n$
Baseline: 500 m
Peak Energy: 600 / 400 MeV
L/E : ~ 1 m / MeV

Event excess:
ν mode - 162.0 ± 47.8 (3.4σ)
$\bar{\nu}$ mode - 78.4 ± 28.5 (2.8σ)

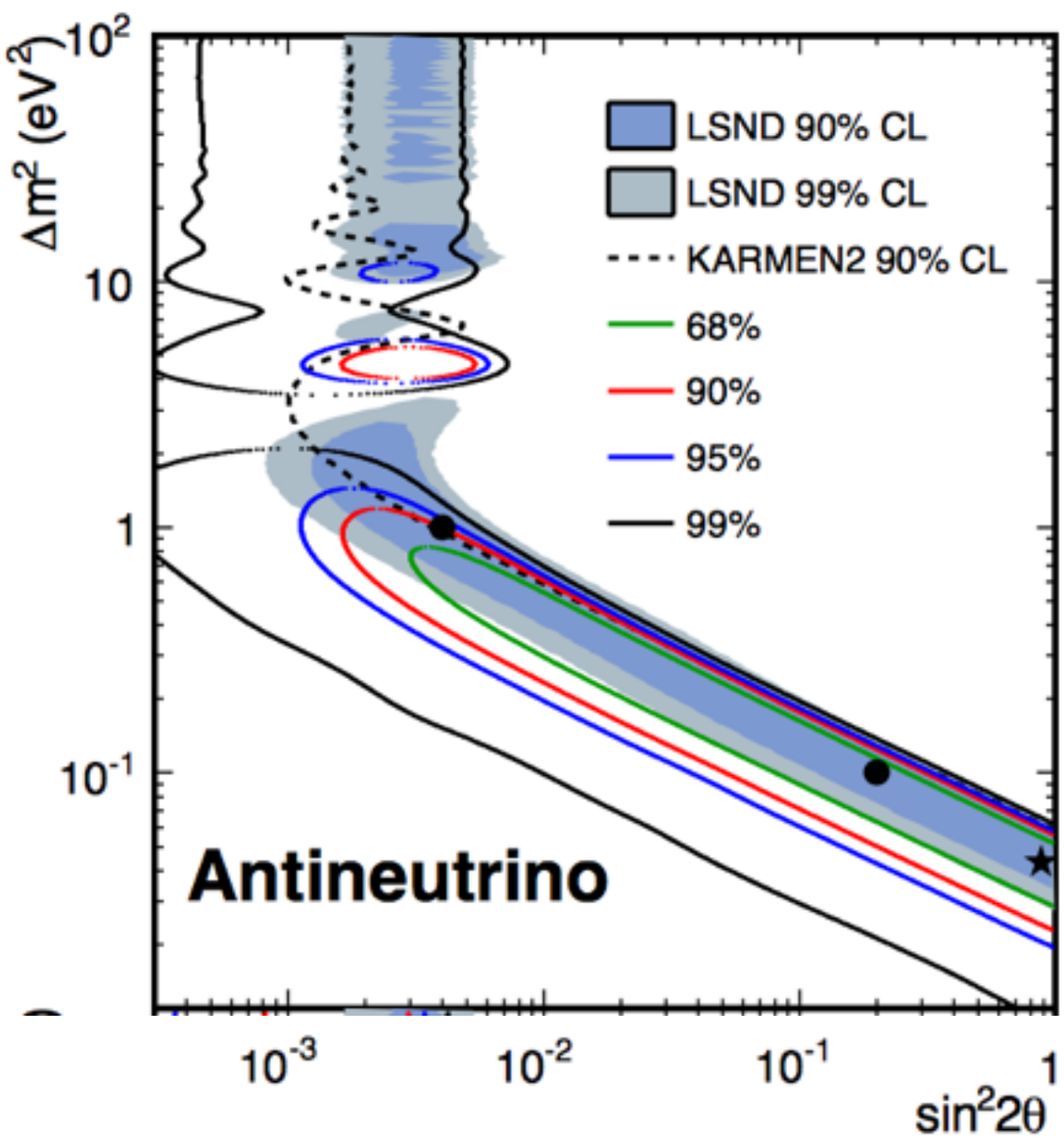
Above 475 MeV, no event excess for ν mode

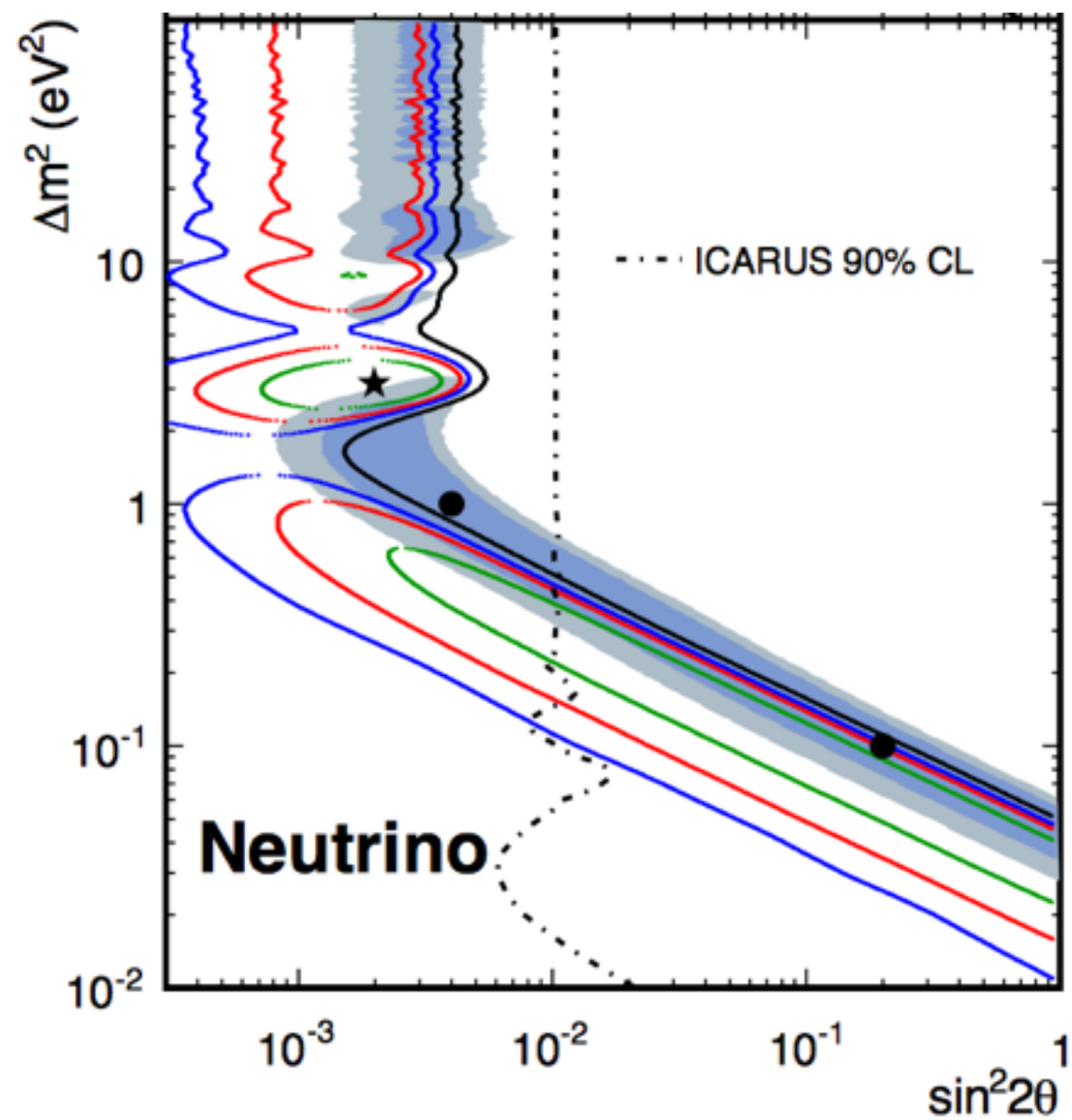
Phys. Rev. Lett.110, 161801 (2013)



MiniBooNE/LSND Results Comparison

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





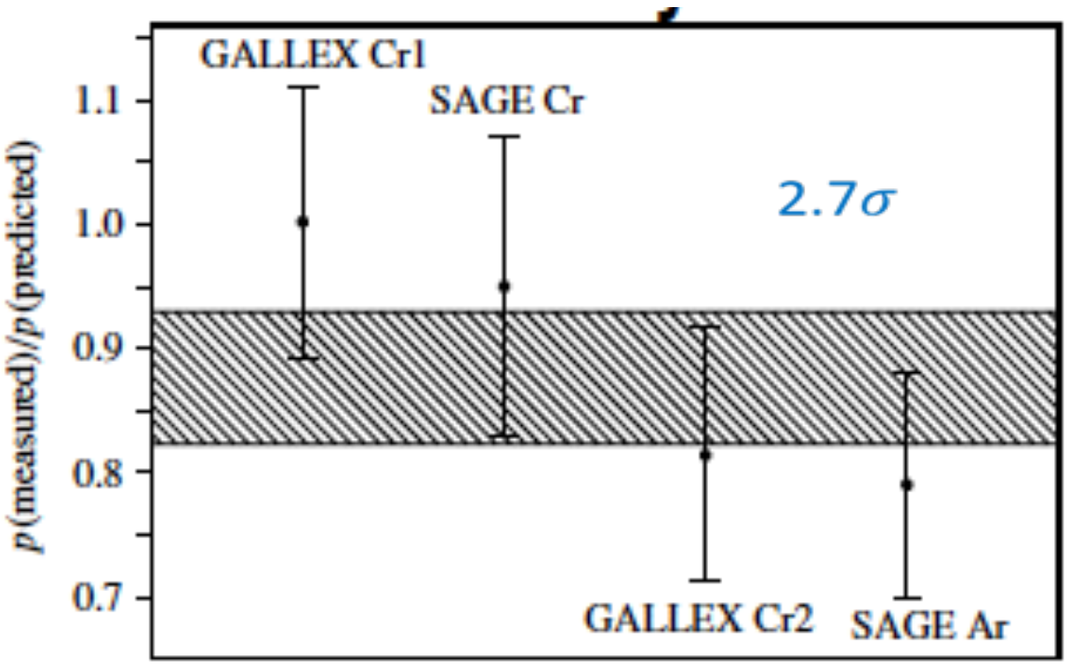
$\bar{\nu}$ mode is more compatible with LSND result compared with ν mode.

The Gallium Anomaly: $\nu_e \rightarrow \nu_s$

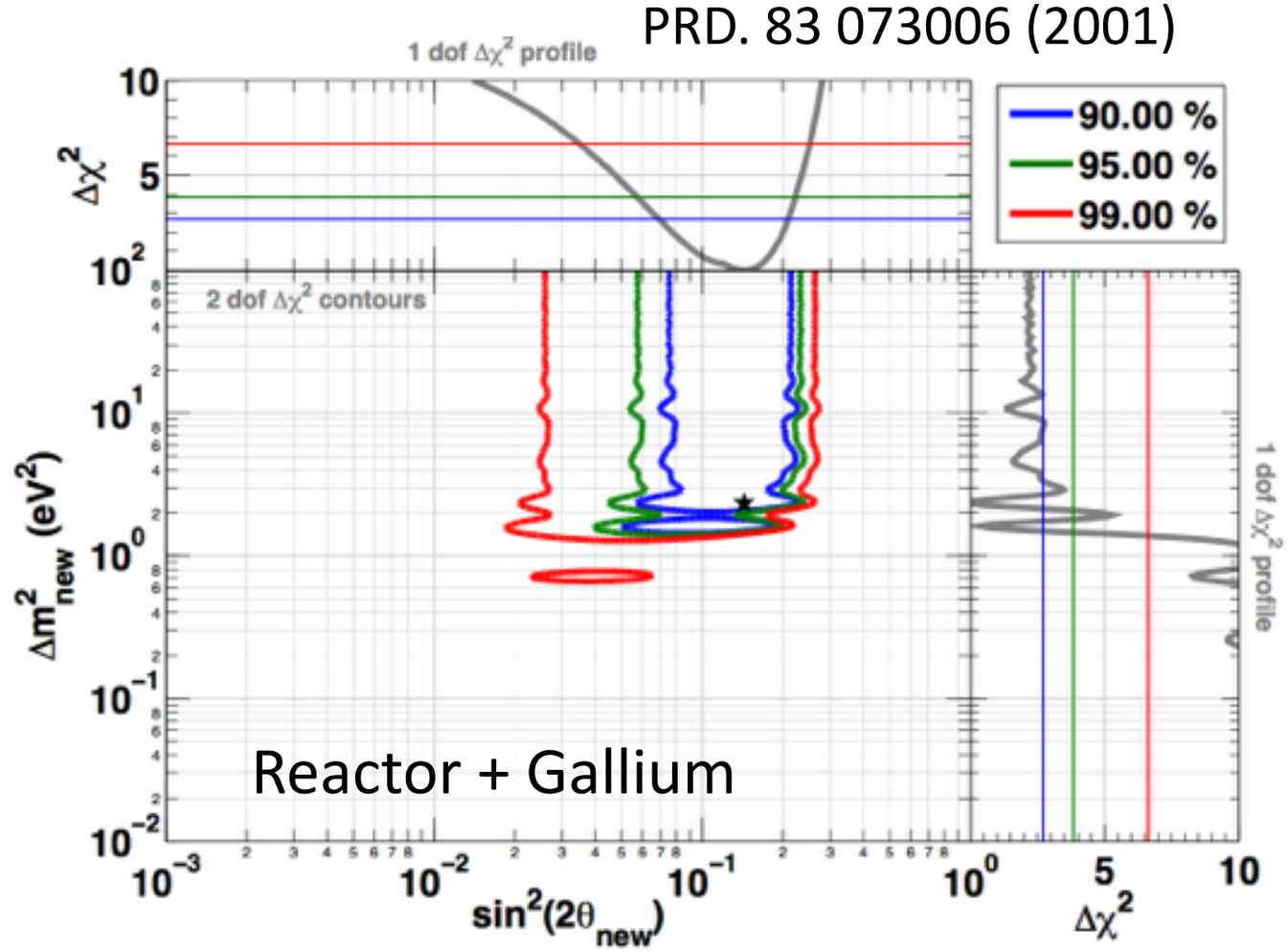
The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources (^{51}Cr and ^{37}Ar) to calibrate the detector.

$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e\,,$$

$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e\,,$$



PRD. 83 073006 (2001)

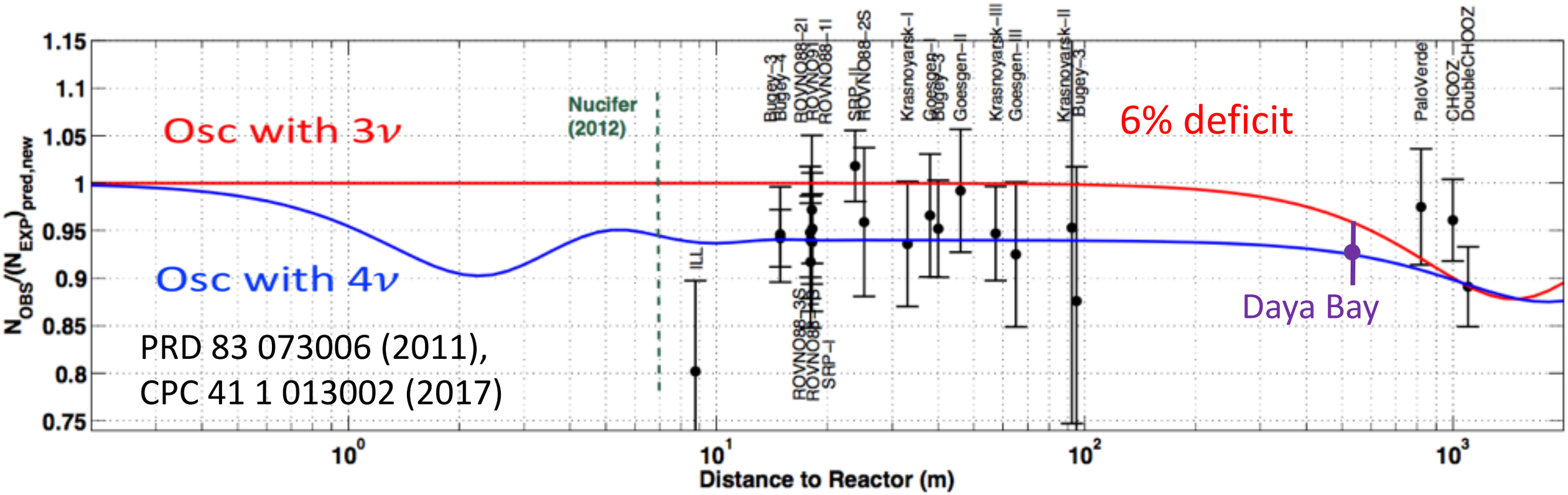


Oscillation mode: $\nu_e \rightarrow \nu_e$ (disappearance)

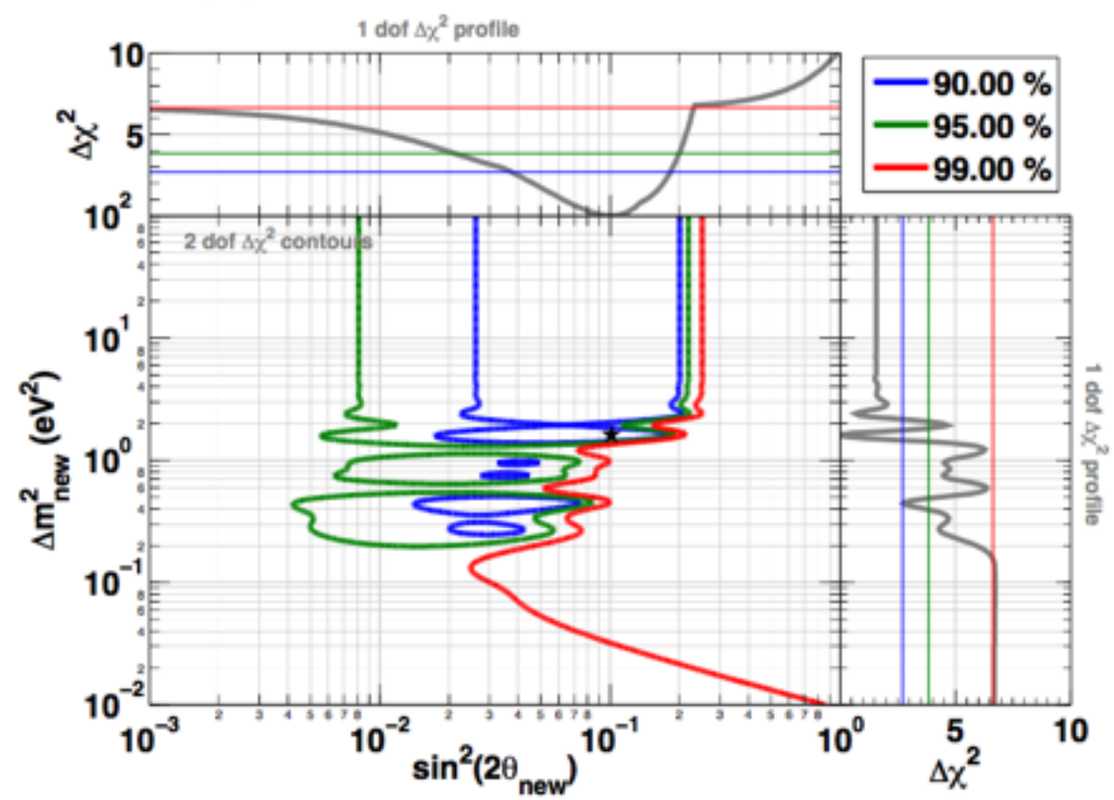
R = 0.86 $\pm$ 0.05 (Giunti, Laveder)

No oscillation is disfavored by 99.8% C.L.

The Reactor Anomaly: $\bar{\nu}_e \rightarrow \bar{\nu}_s$

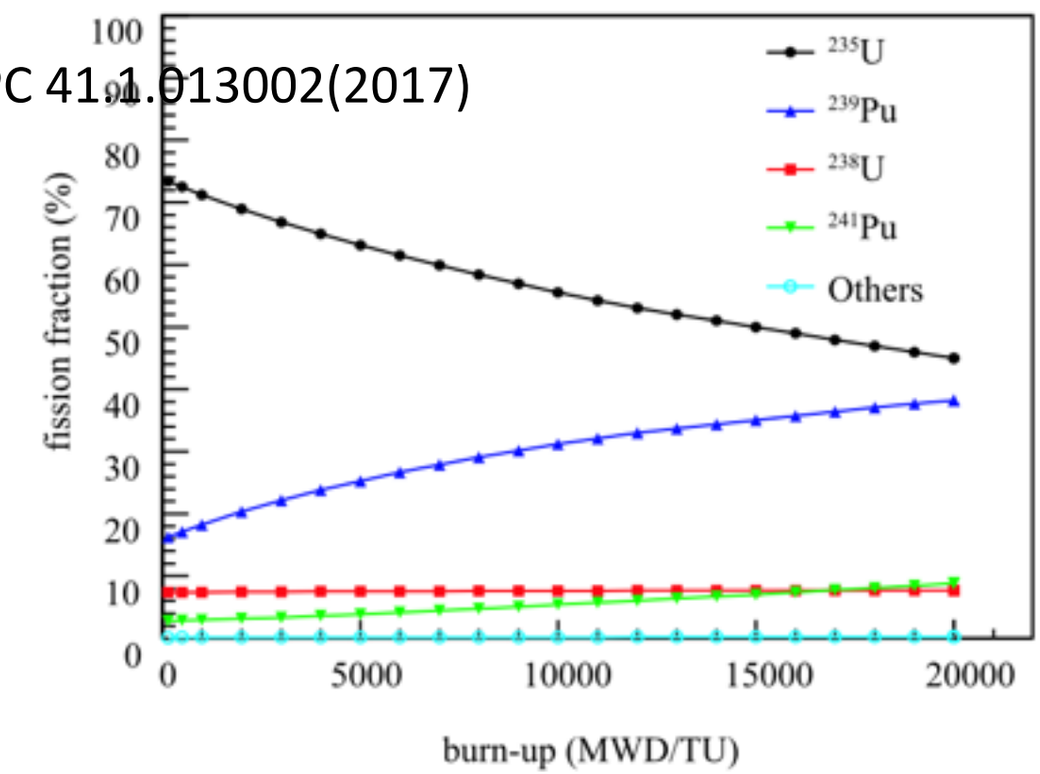


- Oscillation mode: $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- The measured $\bar{\nu}_e$ flux at 10-100 m from reactor cores is ~6% below the theoretical calculation
- Absence of oscillation is disfavored at 98.6% C.L.

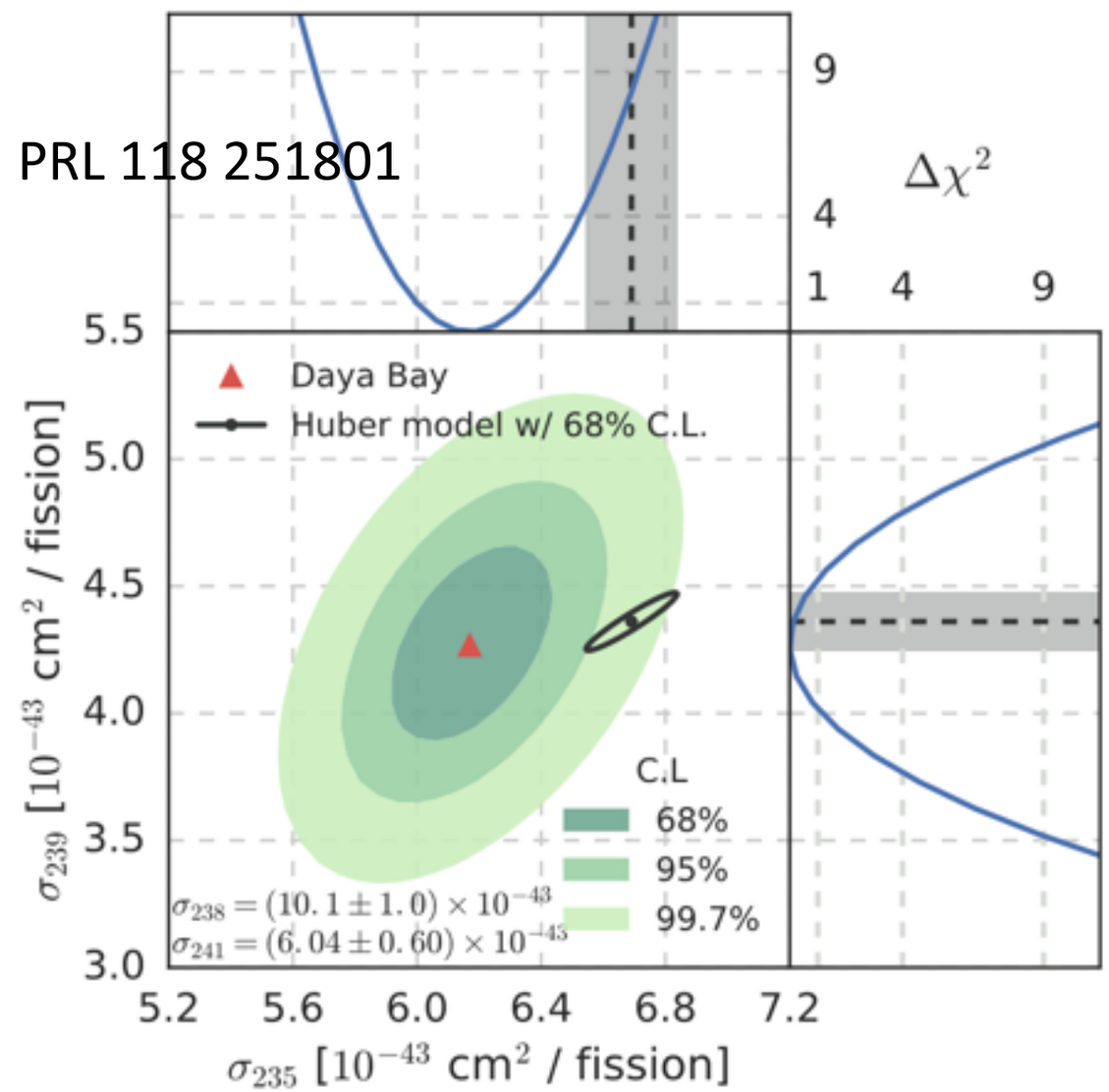


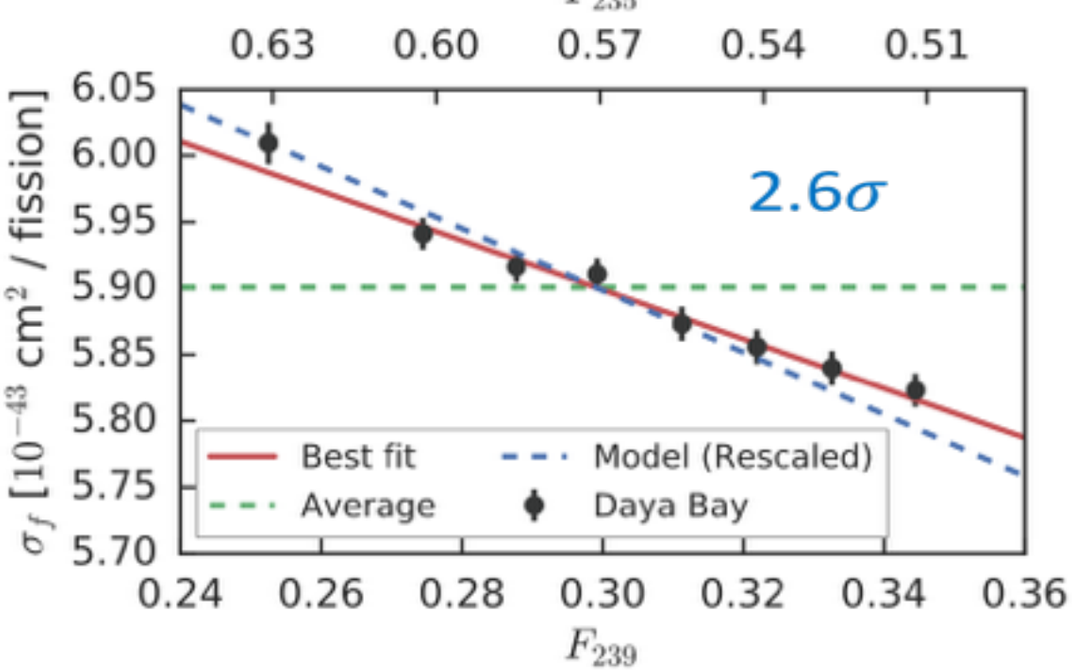
Dayabay Reactor Fuel Evolution Measurement

CPC 41.1.013002(2017)



PRL 118 251801



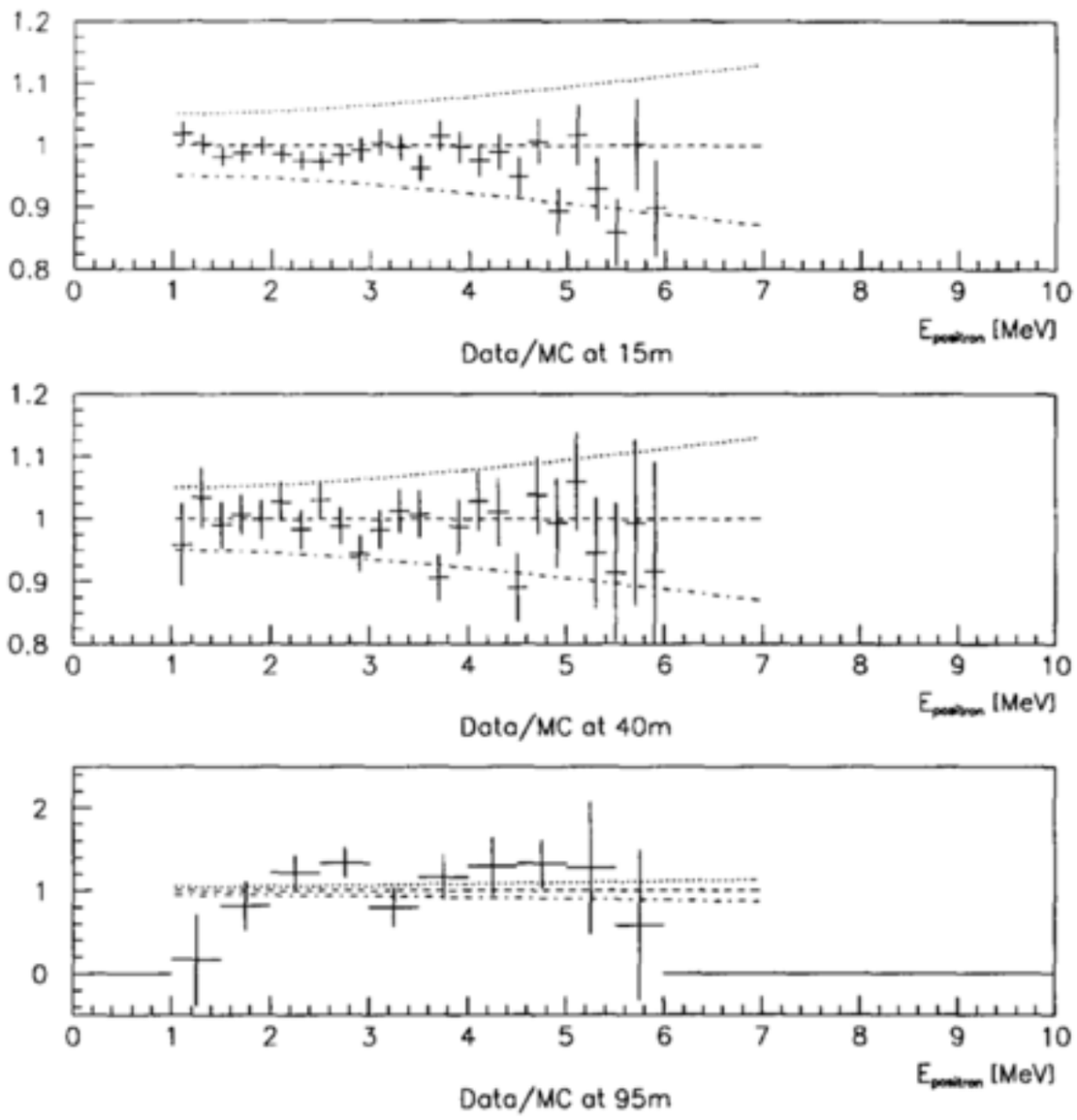


- Sterile neutrino oscillation requires equal deficit for ^{235}U and ^{239}Pu
- Daya Bay data prefer ^{235}U to be mainly responsible for the reactor anomaly
- talk from David Martinez Caicedo

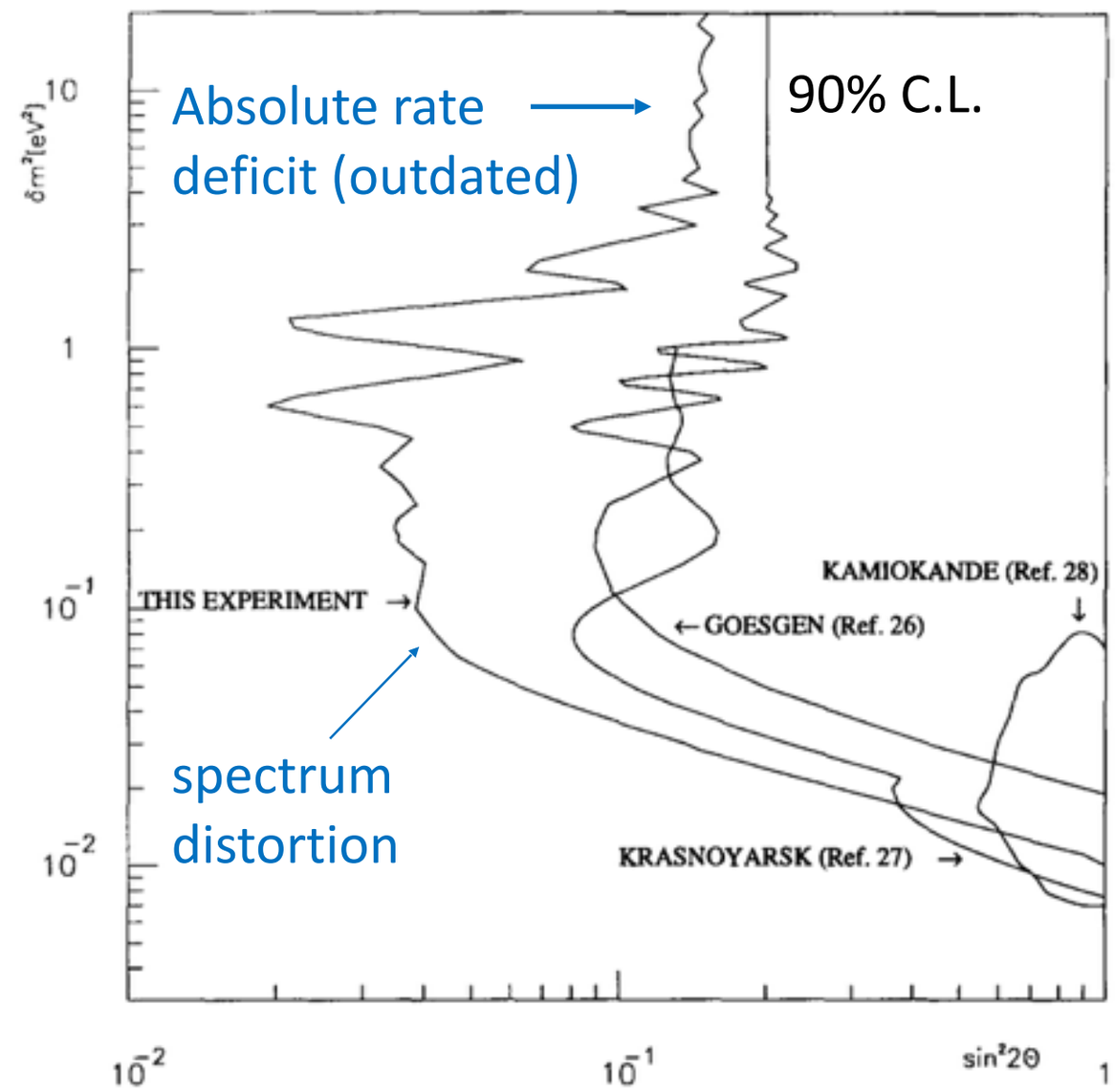
$$\text{IBD Yield:} \quad \text{Events}_x = \sigma_x \times \text{Total no. of fissions} \times \frac{N_{\text{Targets}}}{4\pi R^2}$$

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ from Bugey-3

- Bugey, France, PWR, 2.8 x 4 GW
- ^{6}Li-LS, segmented
- Baselines: 15, 40 and 95 m



Nucl. Phys. B 434, 503 (1995)

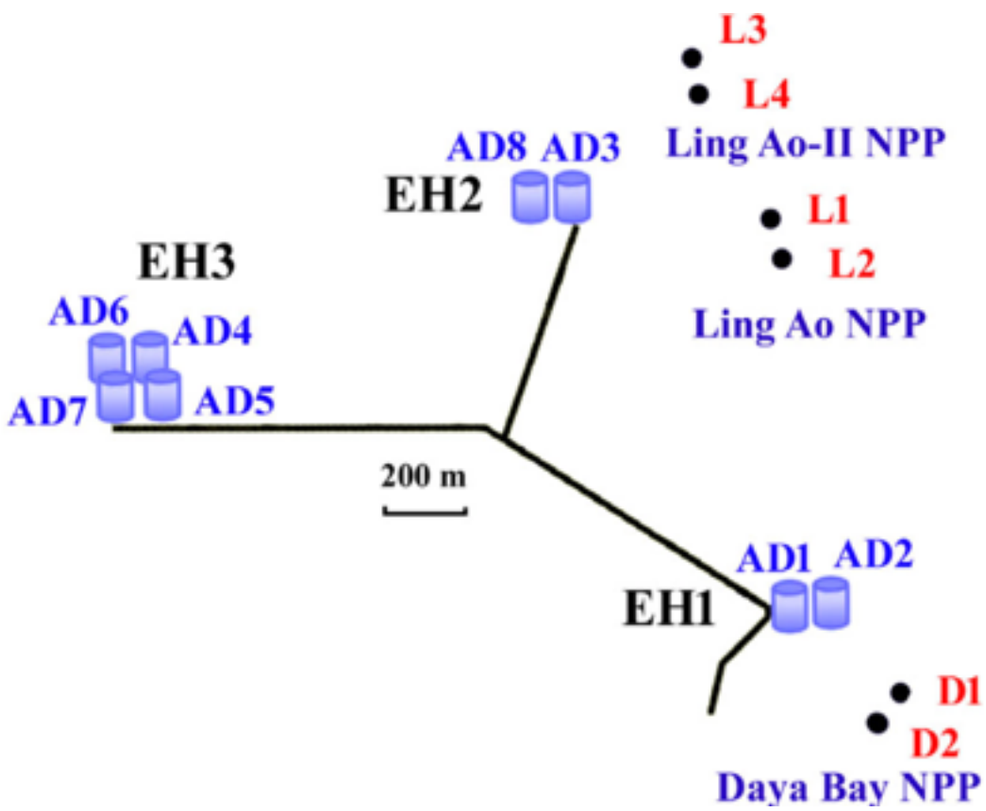


Disfavor sub-eV^2 oscillation

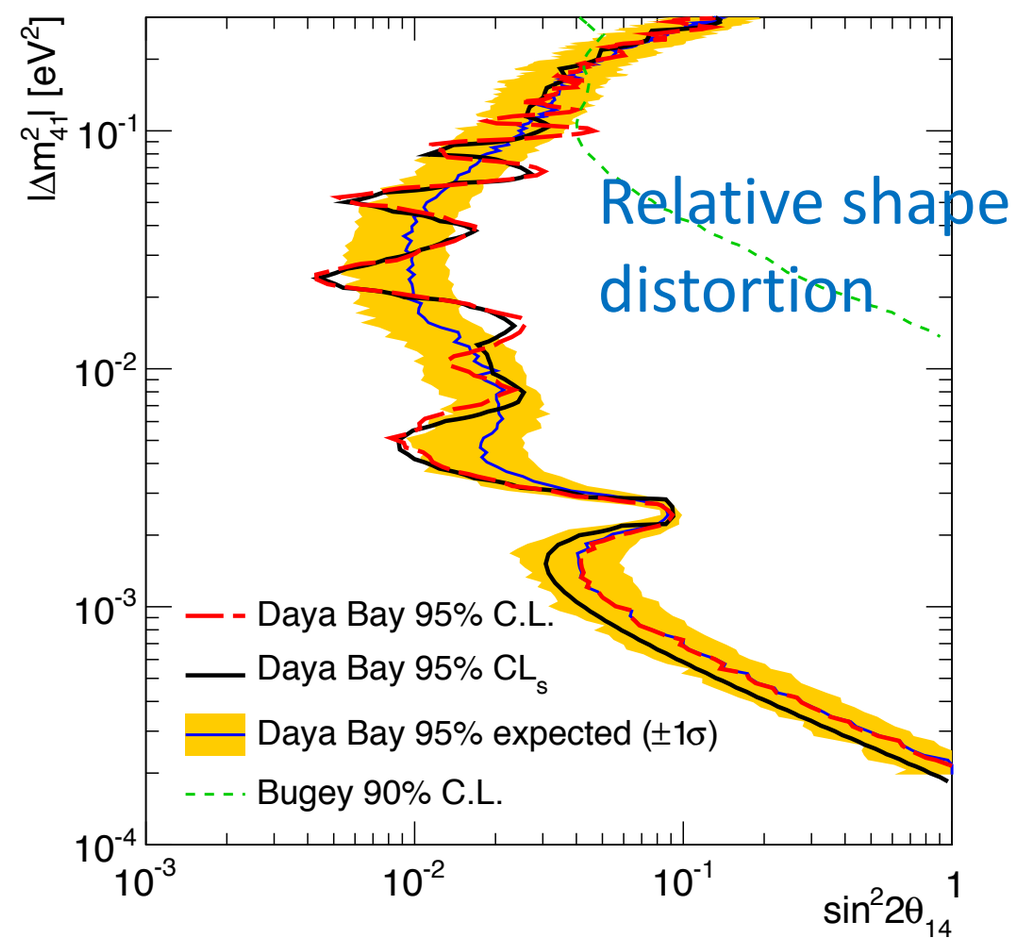
The Daya Bay Experiment

Daya Bay reactor complex: 2.9 x 6 GW_{th}, PWR

PRL 117, 151802 (2016)



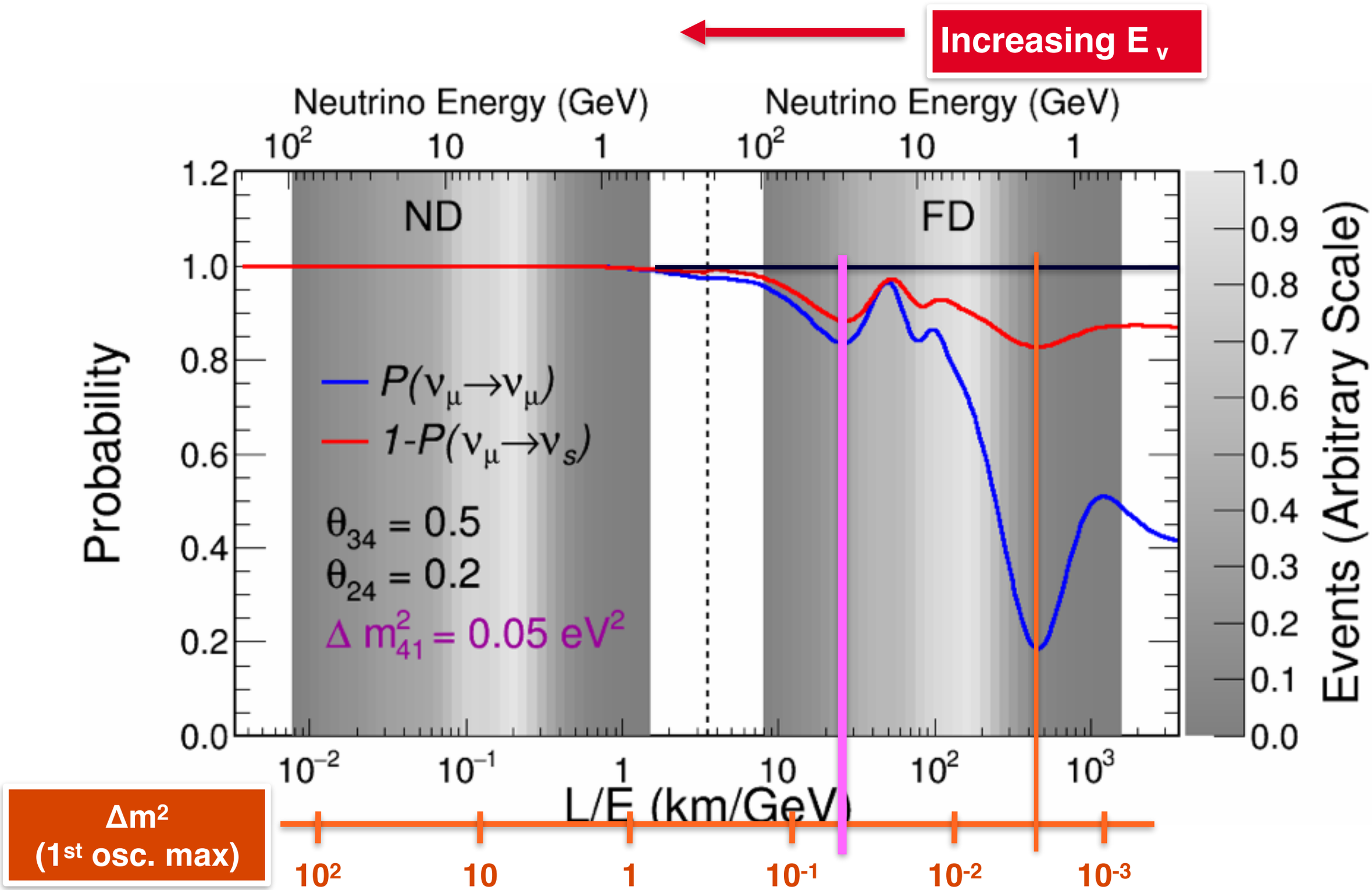
Site	Mean distance to reactor cores (m)		
	Daya Bay	Ling Ao	Ling Ao–II
EH1	365	860	1310
EH2	1348	481	529
EH3	1909	1537	1542



No very light sterile neutrino ($\Delta m^2 < 0.2$ eV^2) signal found

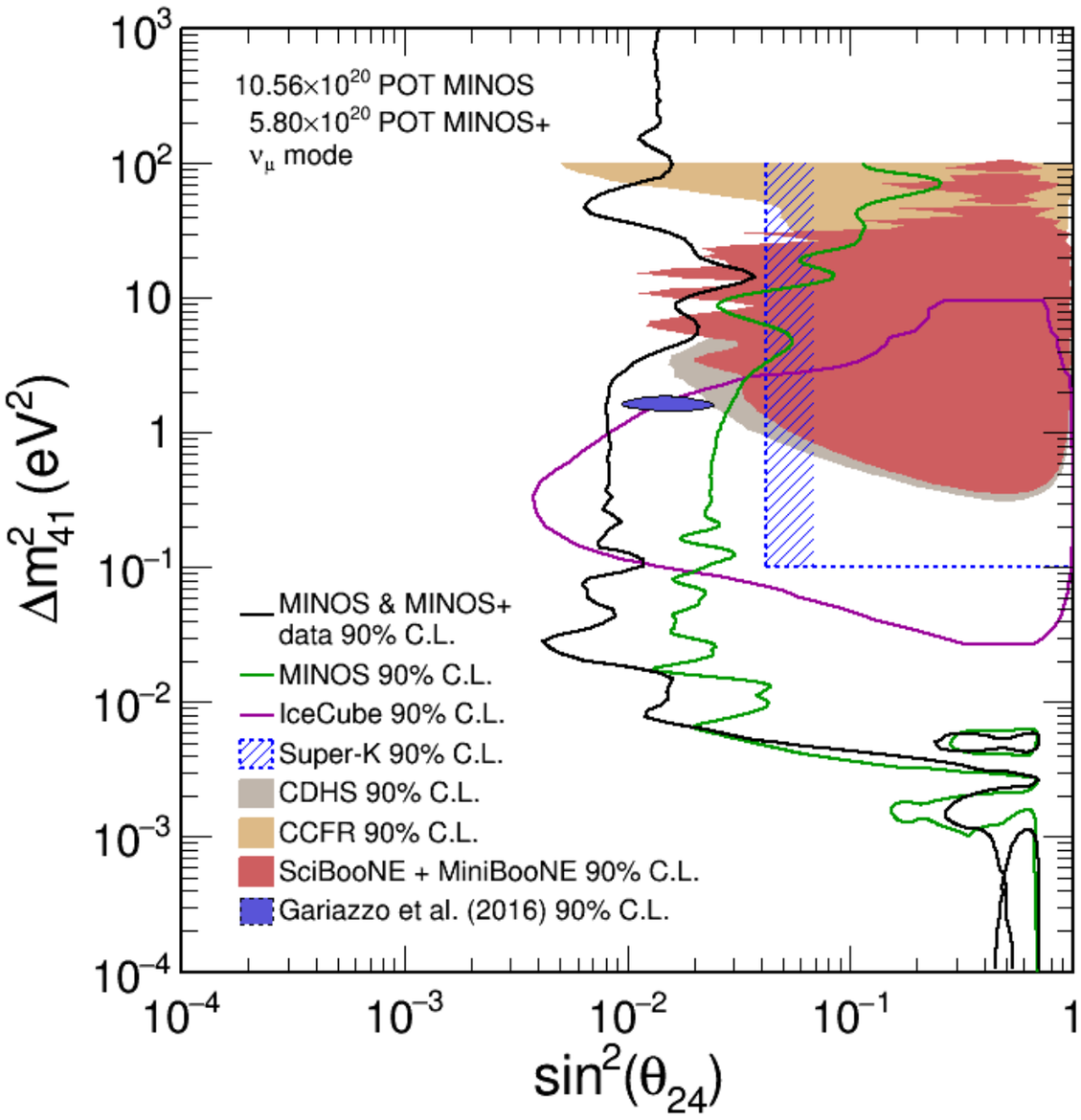
Wide L/E range allows sensitivity over 3 decades.

3(active)+1(sterile) oscillation pattern in MINOS detectors

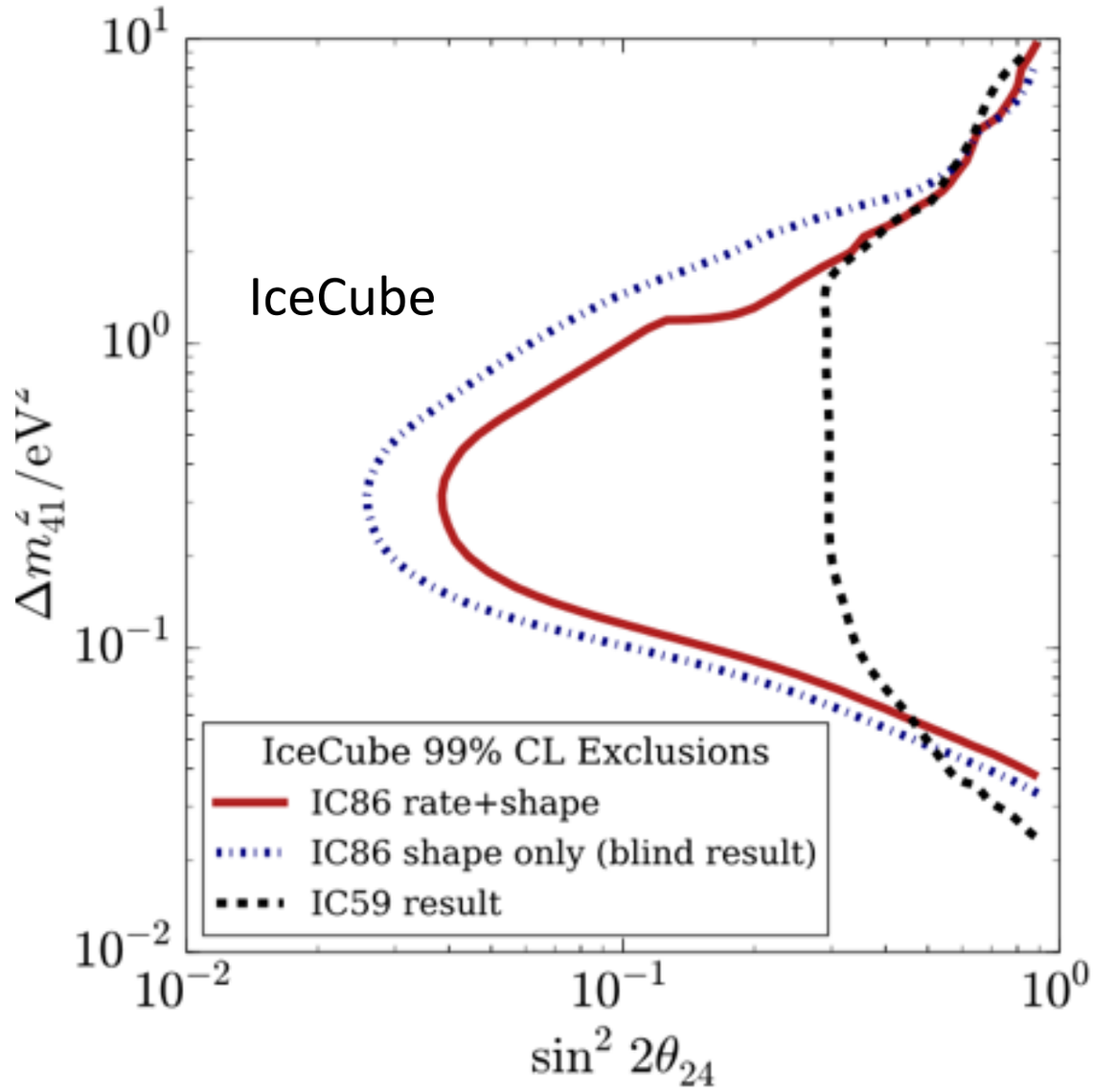


ν_s Search in $\nu_\mu \rightarrow \nu_\mu$ Channel

PRL 117, 151803 (2016)+new results from MINOS+



PRL 117, 071801 (2016)



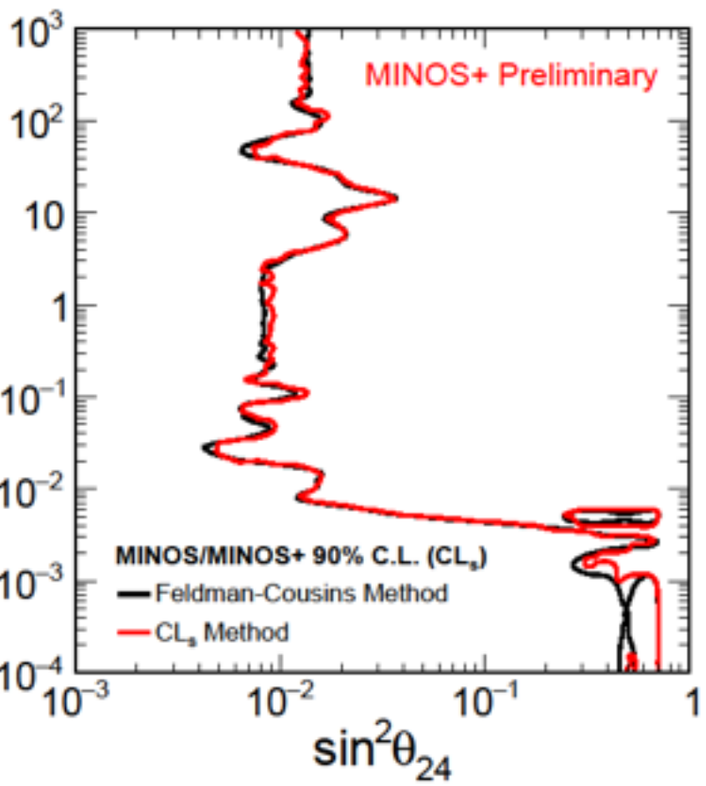
No sterile neutrino hints from ν_μ disappearance channel.

New MINOS+ result has improved for higher masses using ND. (see FNAL W&C by J.Todd)

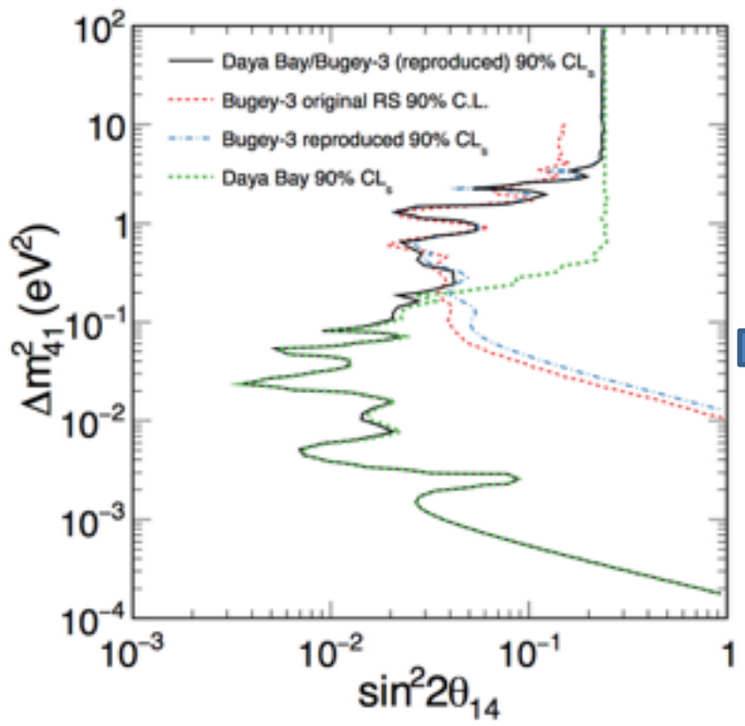
Joint Analysis of Daya Bay/Bugey-3/MINOS

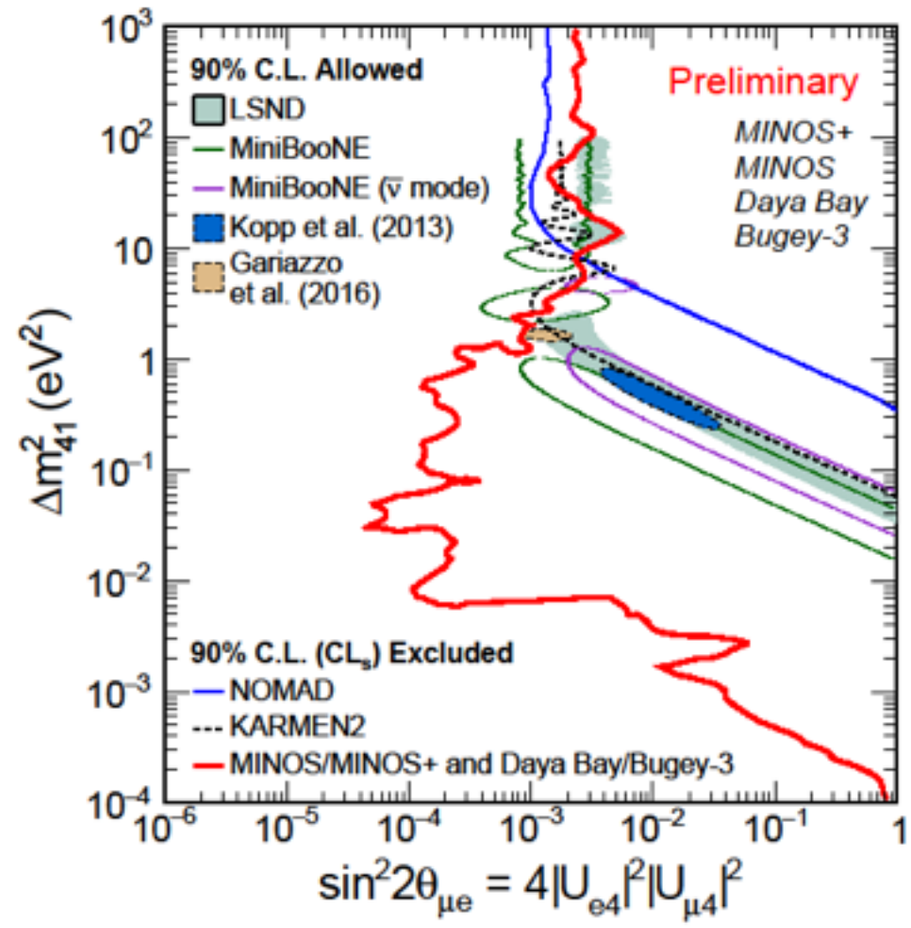
PRL 117, 151801 (2016)+MINOS+ results

MINOS/MINOS+



Daya Bay + Bugey-3





- The combined results can largely exclude the LSND and MiniBooNE region assuming 3+1 neutrino model

Combined : Phys. Rev. Lett. 117, 151801
MINOS : Phys. Rev. Lett. 117, 151803
Daya Bay : Phys. Rev. Lett. 117, 151802

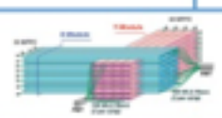
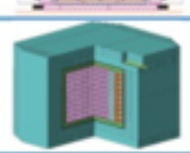
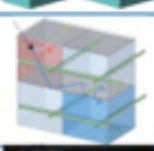
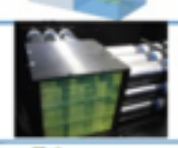
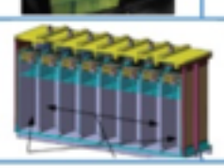
Short baseline reactor experiments

Experimental considerations are

Commercial versus research reactor: size of the core. (~4 m vs ~50cm)

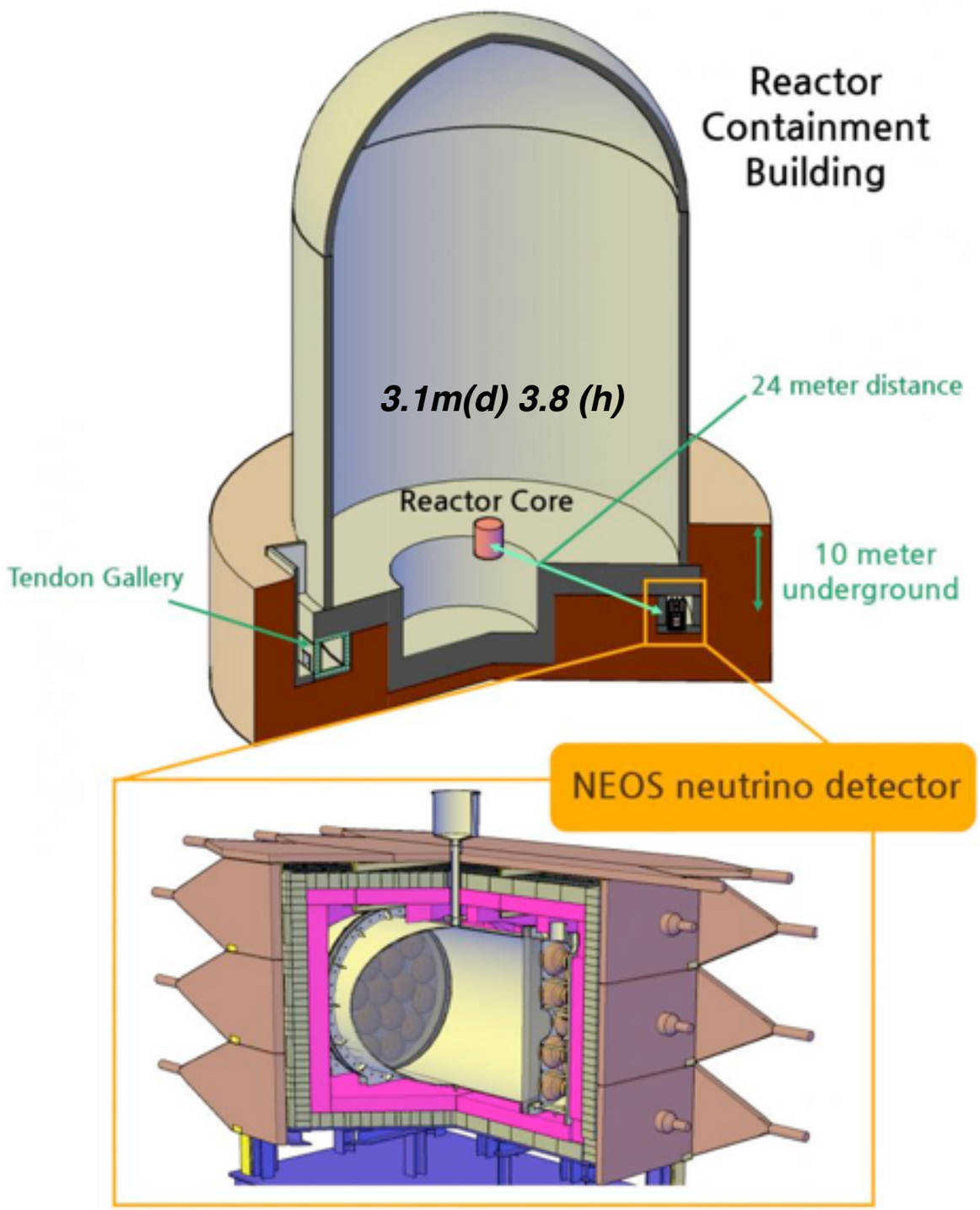
Segmentation and overburden for the detector: background suppression

Mauro Mezzetto, 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

DANSS and NEOS have reported preliminary results. Neutrino-4 has some data

NEOS experiment (new result)



2.8 GW_{th} LEU fuel Hanbit NPP

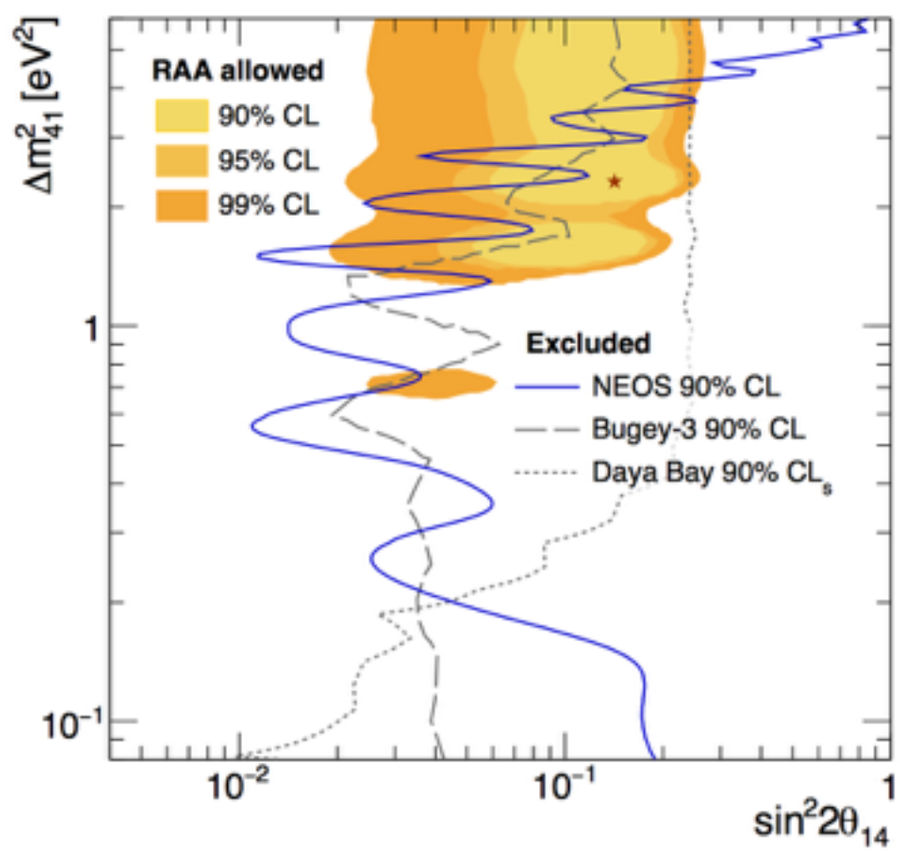
- Yeonggwang, Korea
- Core size: 3.1 m (⌀), 3.8m (H)

Baseline: 23.7 ± 0.3 m

Overburden: > 20 m.w.e.

Monolithic Gd-LS

PRL 118, 121802 (2017)

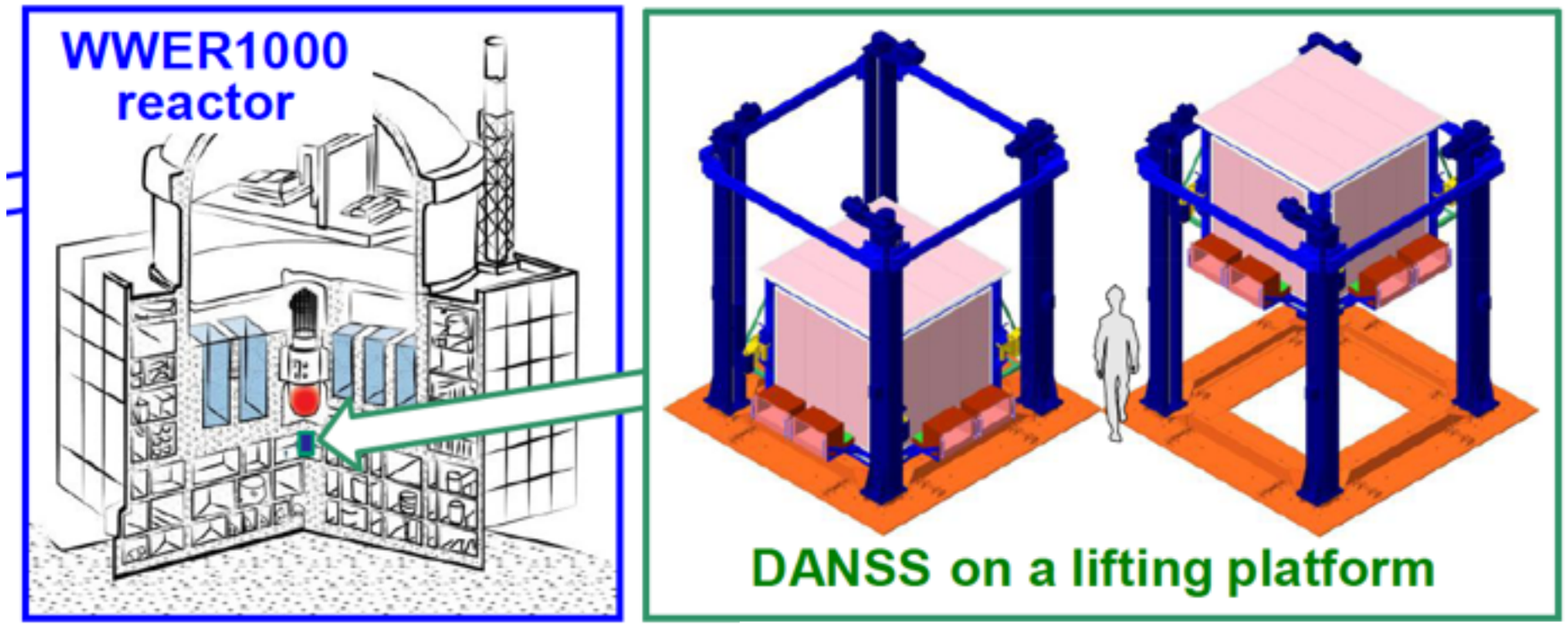


Consistent with Bugey-3's result

Talk from Yoomin Oh

DANSS experiment (new result)

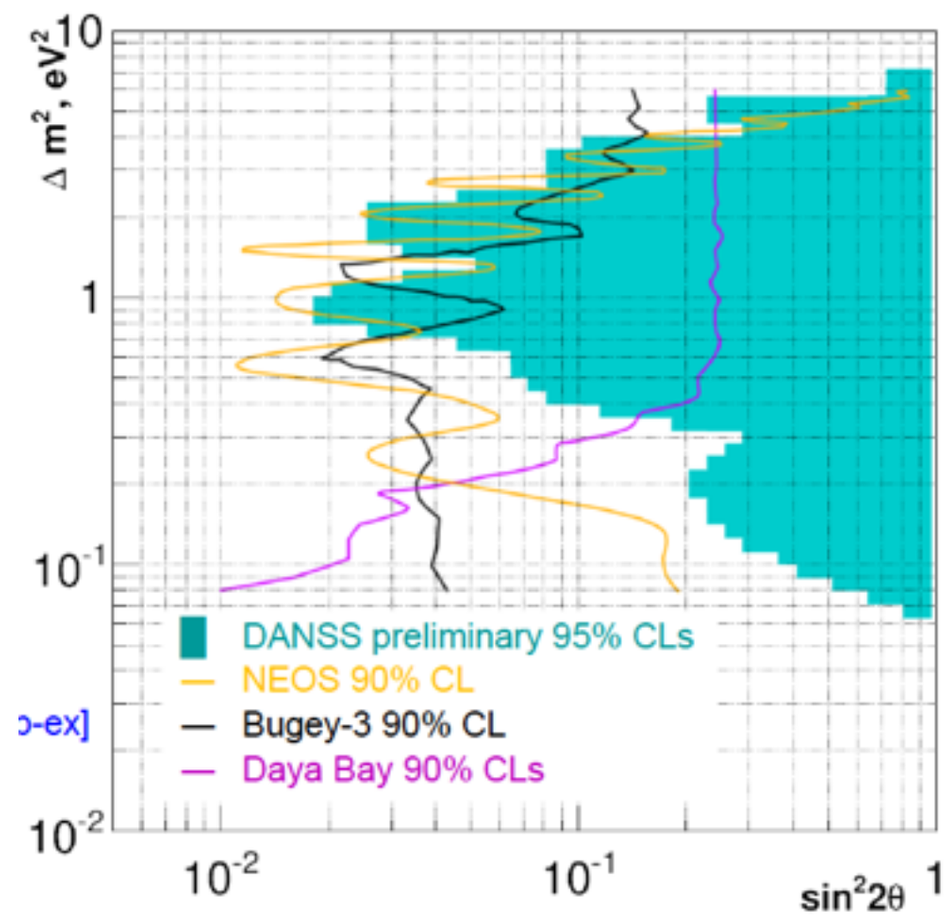
Talk by Dmitry Svirida



Key design features

- *3.1 GW commercial reactor*
- *50 m.w.e overburden*
- *movable L= 10.7 to 12.7 m*
- *~5k evts/day with*

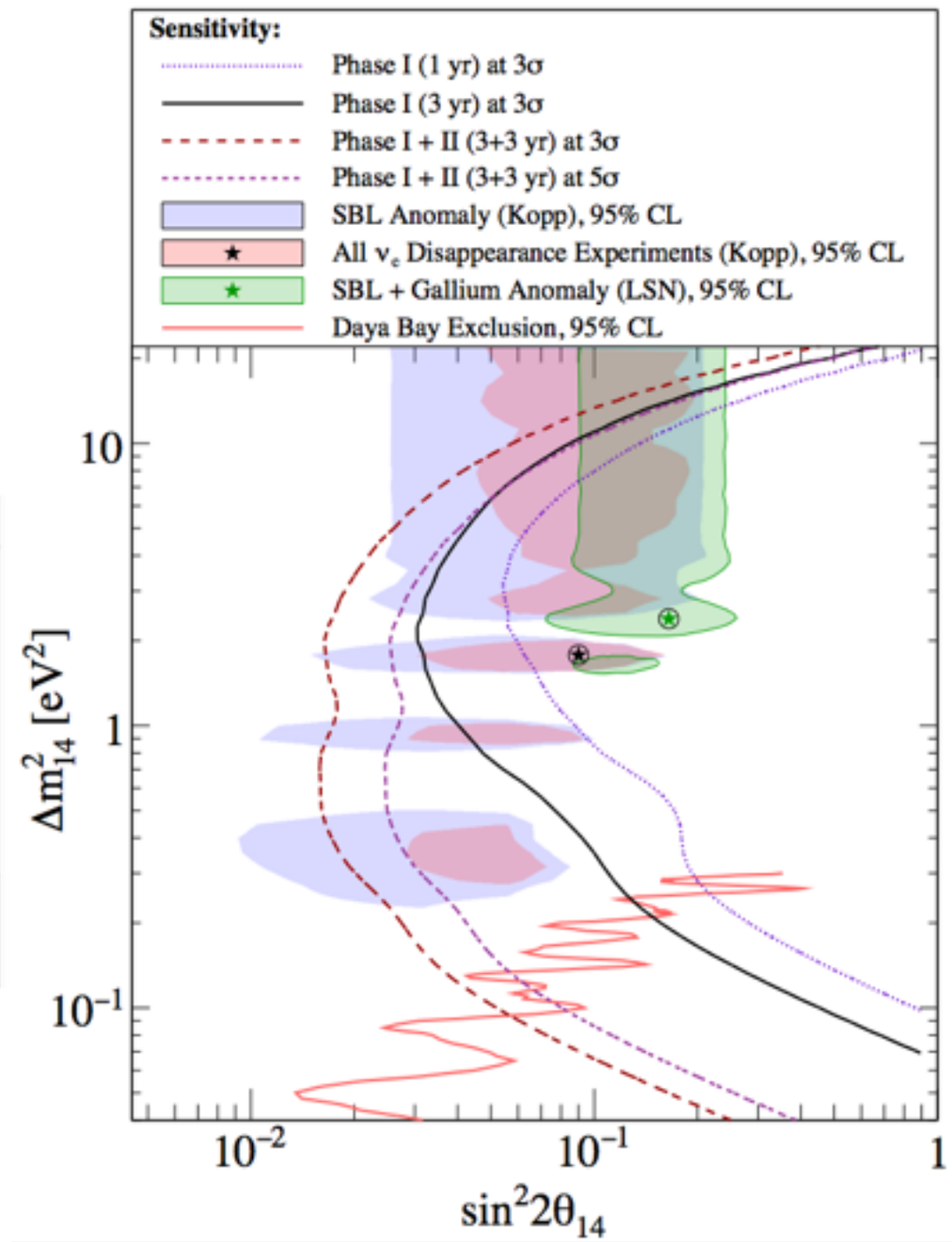
Analysis - compares spectra at two positions (up/down)

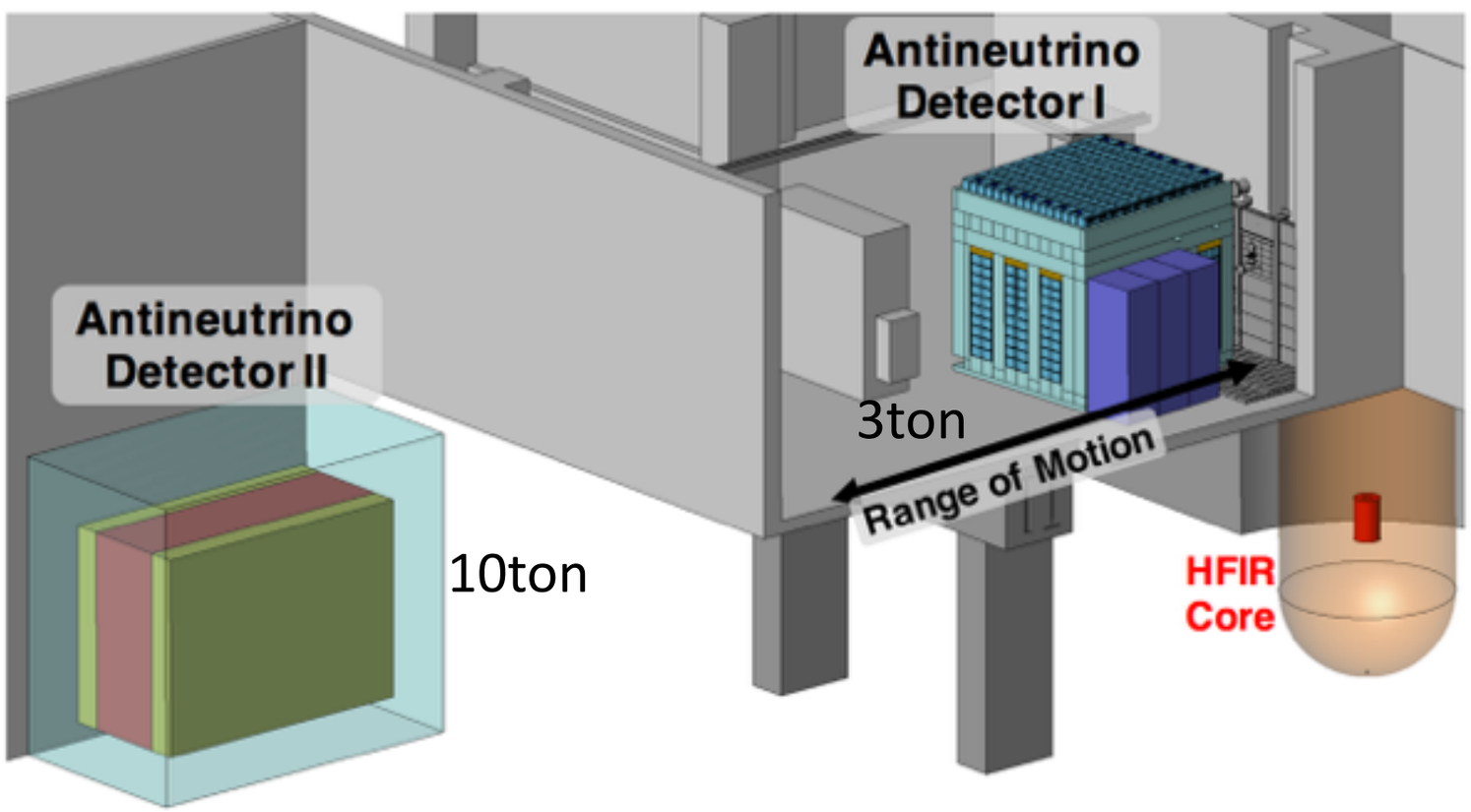


The PROSPECT Experiment (near future)

- 85MW ^{235}U HEU HFIR in ORNL
  - Core size: 0.38 m (①), 0.61m (H)
- Baseline: 6-12 m (AD1), 15-19 m (AD2)
- ^{6}Li-LS, segmented, PSD
- Phase R&D in progress and AD1 will be ready in 2017

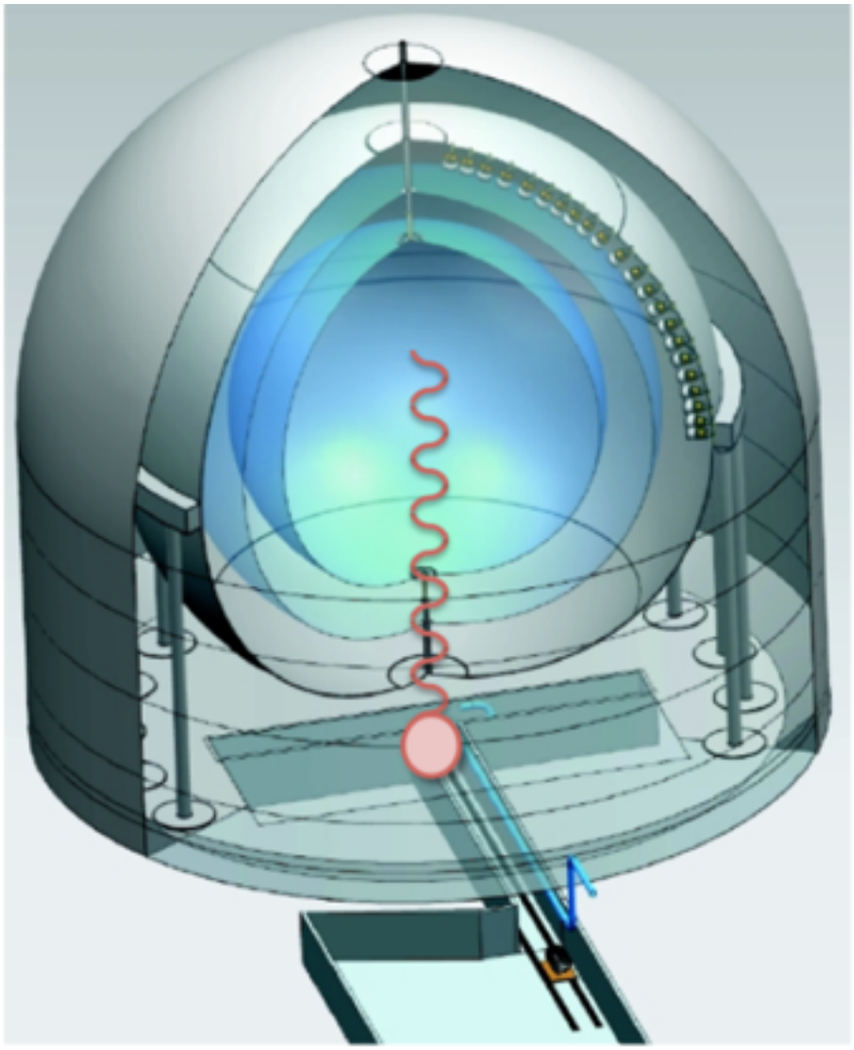
arXiv: 1512.02202





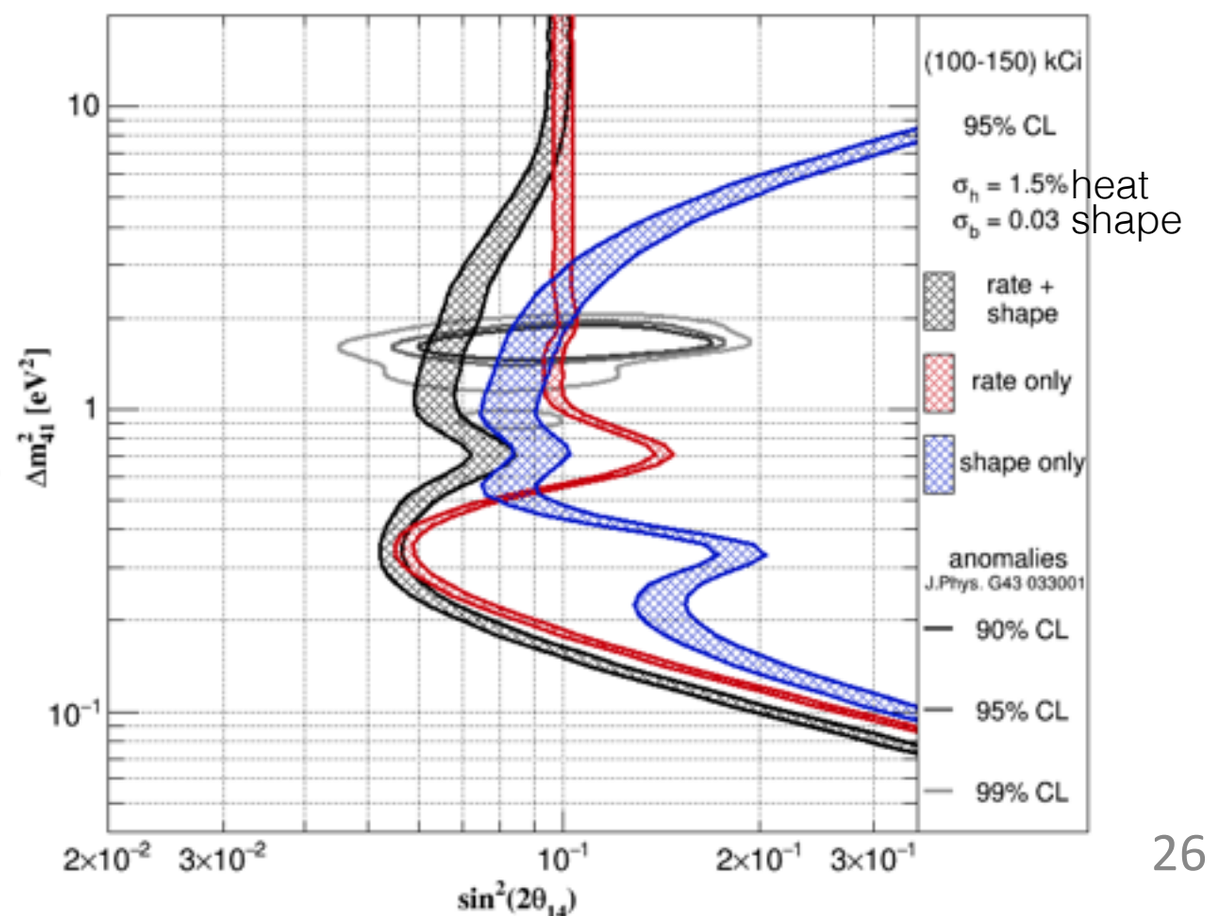
Talk: James Matta

The SOX Experiment



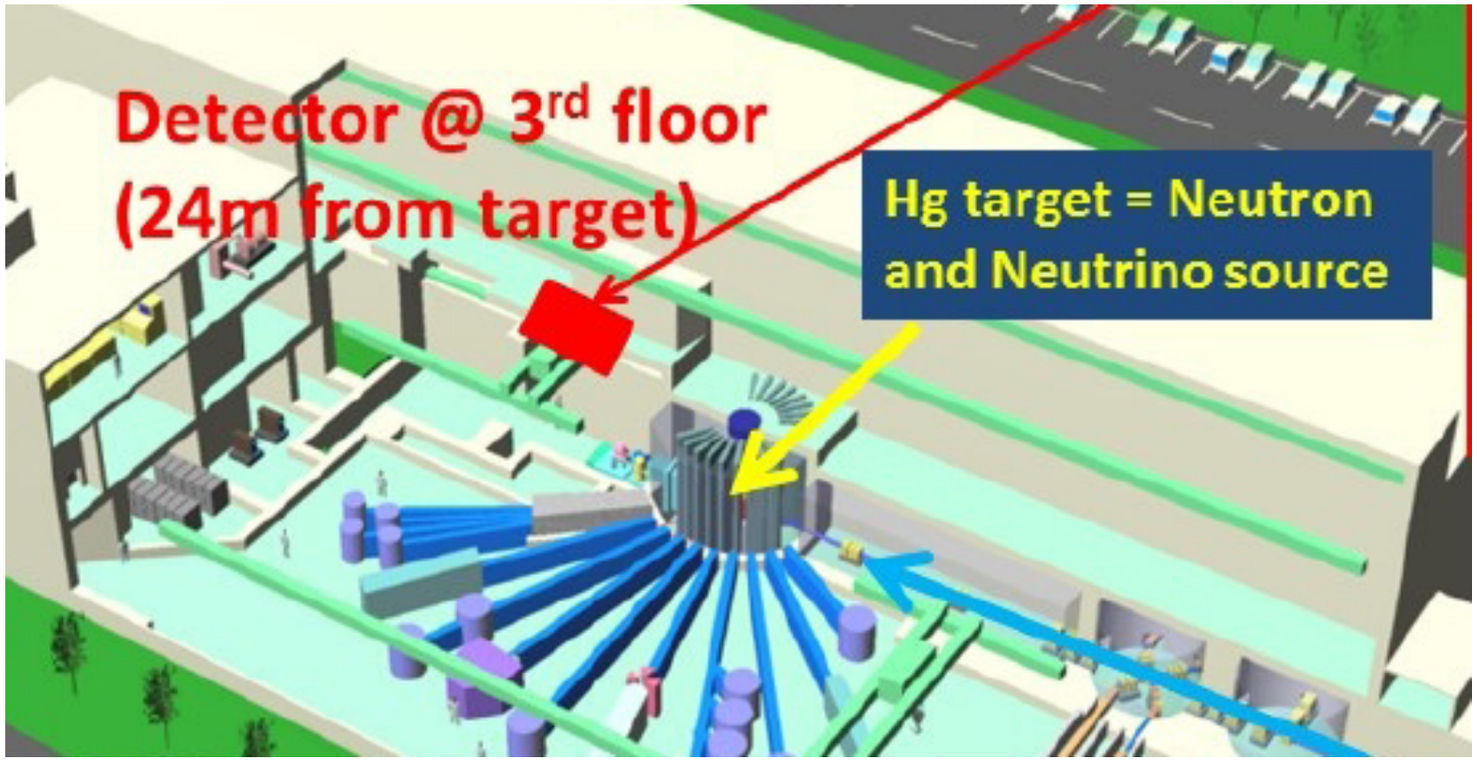
- 100-150 kCi ^{144}Ce $\bar{\nu}_e$ source (calorimeter)
- Baseline: 8.5 m from center
- 270 ton LS of Borexino in LNGS (3800 m.w.e.
- Rate+Shape measurement
- Data taking starts 2017-2018

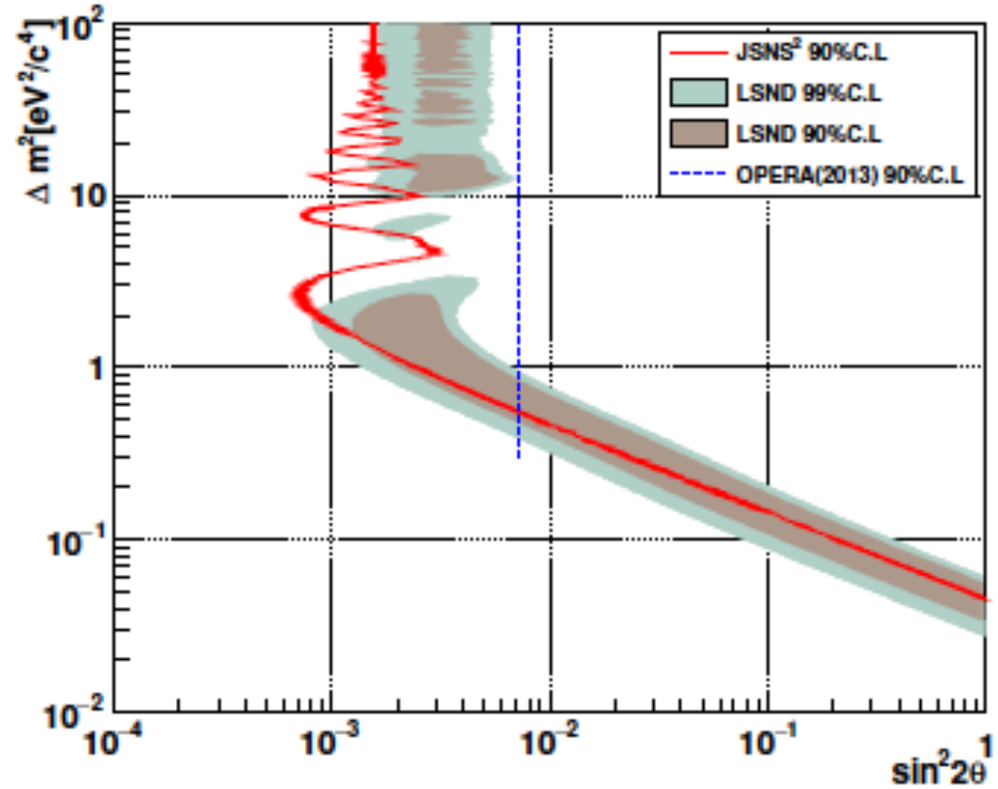
Considerations: systematics due to spectrum and the heat measurement of the source.



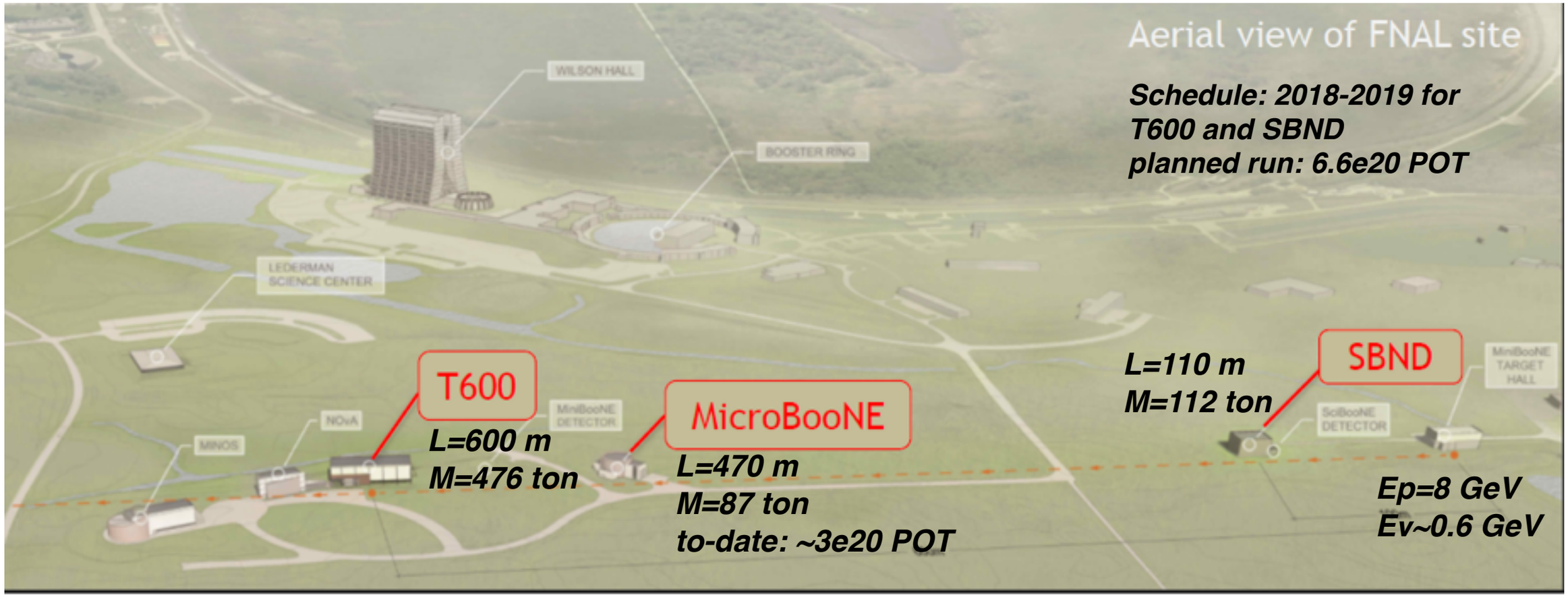
JSNS² / J-PARC E56 in Japan

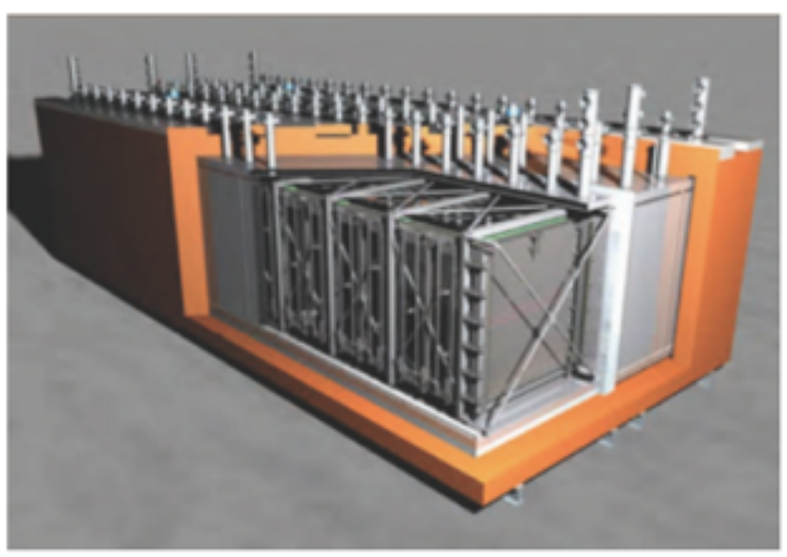
- Technical Design Report 1705.08629, May 2017
- Direct test on LSND anomaly with the same signal (start JFY2018)
- p-beam: J-PARC spallation neutron source. 1 MW 3 GeV
- pulsed beam: 25 Hz, double pulse 100 ns separated by 540 ns
- Neutrino beam: pion and muon DAR (also includes ~1% flux from Kaon-DAR)
- GD loaded LS detector. Fid mass: 17 ton at baseline 24 m
- The JLF facility has constraints on placement of detector.
- 5000 hrs/yr X 3 yrs of exposure.

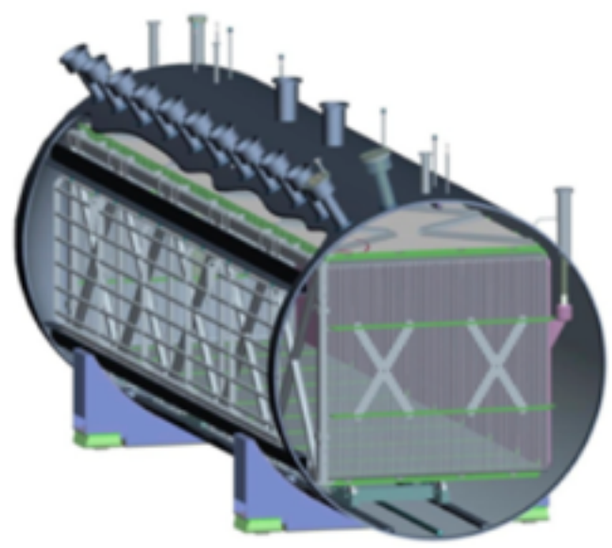


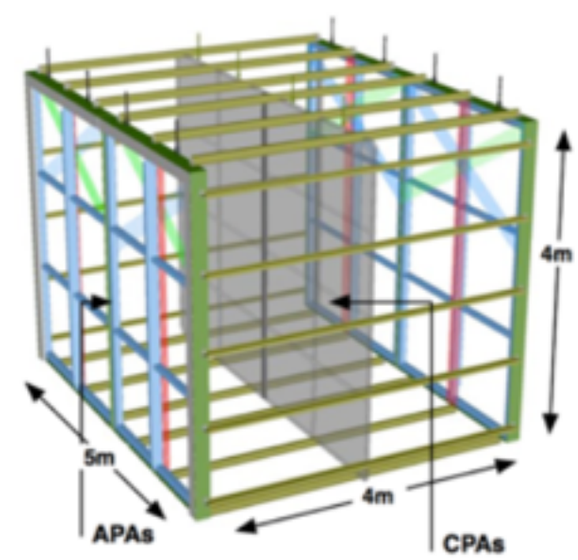


Fermilab Short Baseline program

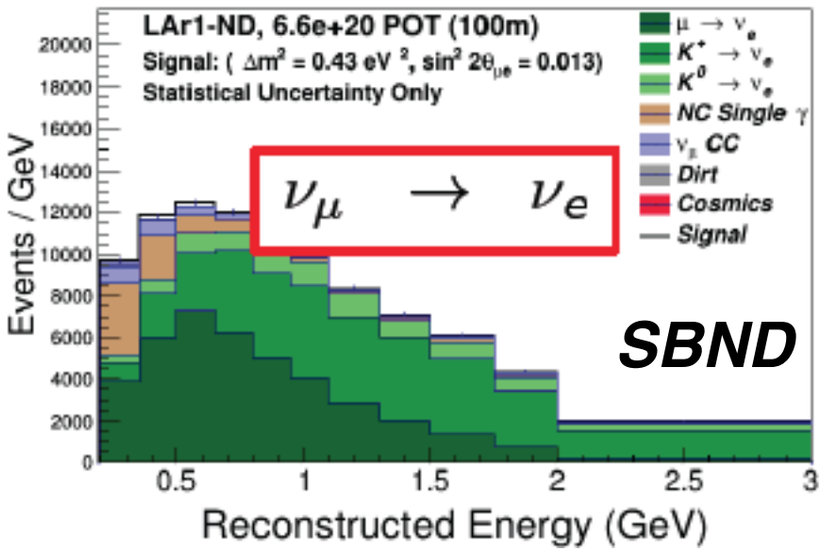


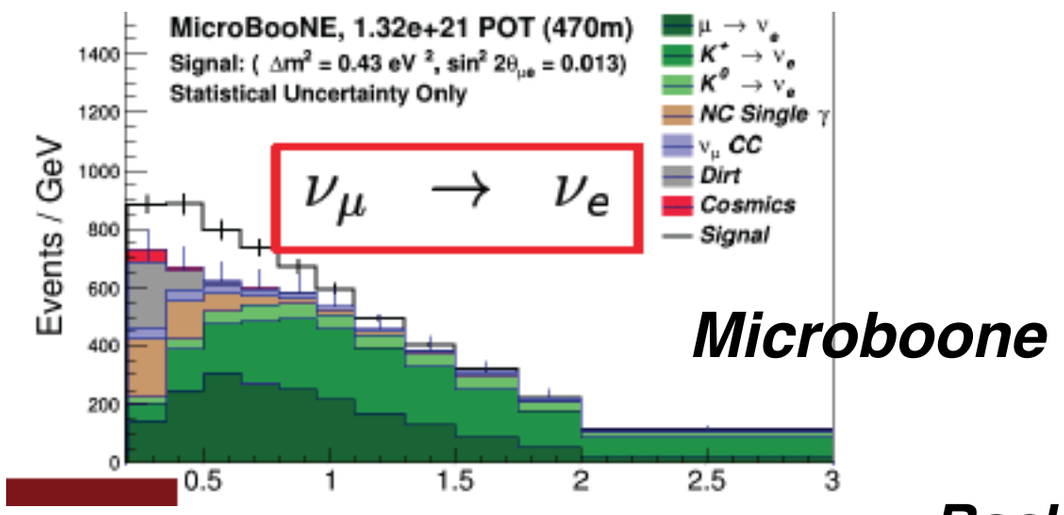


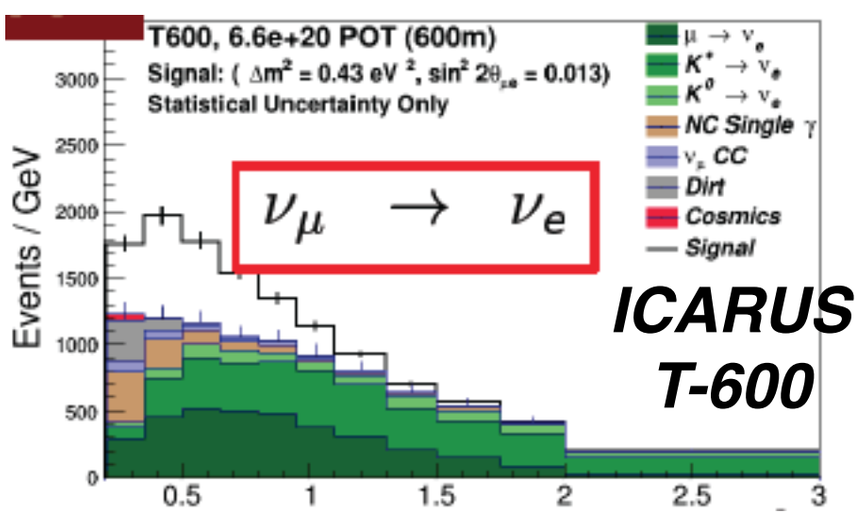




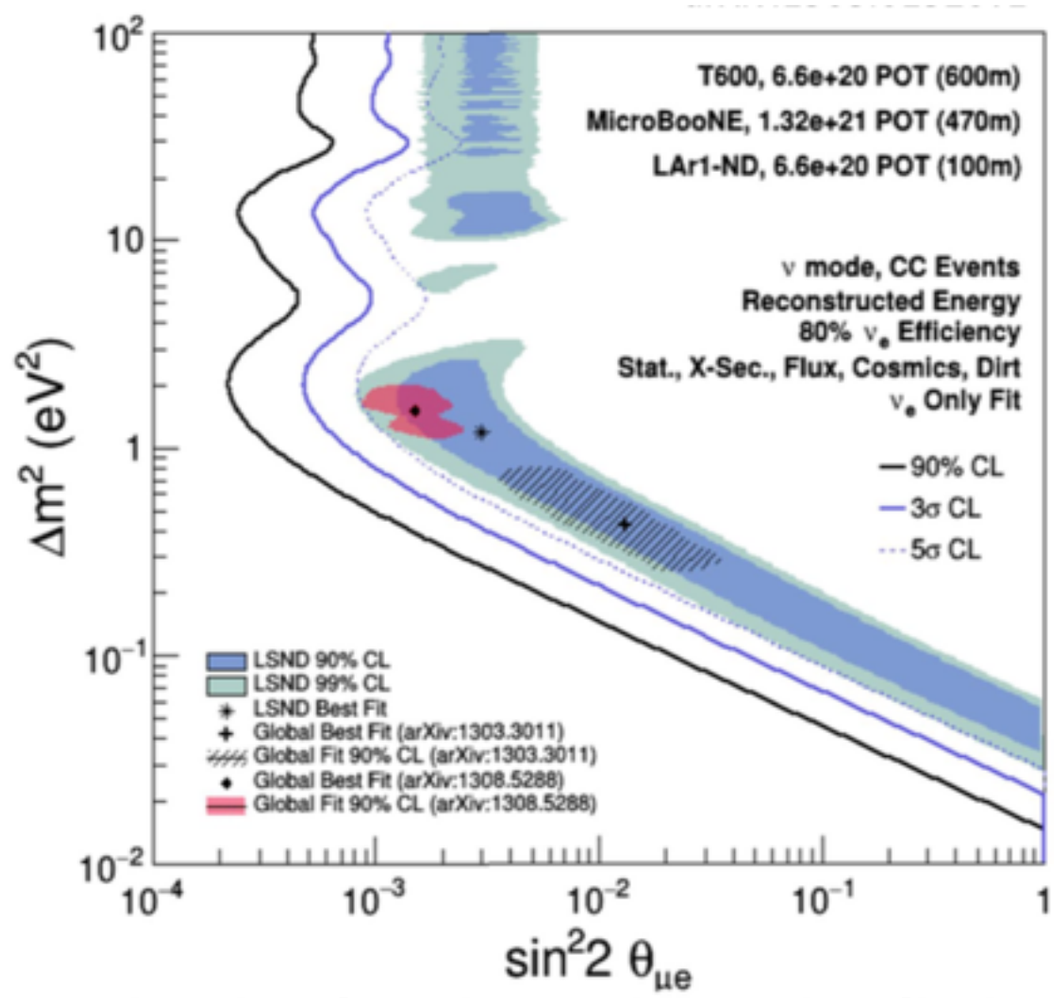
FNAL Short-baseline program.







arXiv: 1503.01520



Background reduction depends on detailed event reconstruction and e/γ separation by gap and dedx.

Performance depends on geometry/electronic noise. (mind the gap).

The 3-detector approach should be an excellent cross check on the backgrounds and systematics

Conclusions

- ***There is good motivation for sterile neutrino search over a wide mass range. Such a broadband search is very difficult.***

- ***We should pay attention to results from cosmology, astrophysics, beta decay, and neutrino-less double beta decay, and CLFV (e.g., $\mu \rightarrow e$). Surprises might emerge.***

- ***Current search of oscillations around 1 eV is likely to conclude in the near future with many new experimental results.***

- ***Are sterile neutrinos 1) relevant ?(probably yes), 2)experimentally accessible ? (partly), 3) already observed ? (we will soon settle this).***

- ***There are important technical lessons to be learnt from previous experiments regarding backgrounds and systematics.***