Physics | Lancaster University

Short-baseline Neutrinos

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IOP Conference, Imperial College

Tuesday 9th April, 2019

Posters & Talks

Many great posters and talks related to short-baseline neutrinos:
(MicroBooNE, SBND, ProtoDUNE, HP-TPC, ARIADNE, DUNE-ND)

POSTERS

P11. Measuring Space Charge in ProtoDUNE.
J. Thompson (Sheffield)

P28. Measuring Pion-Argon Cross-Section at ProtoDUNE.
S. Vergani (Cambridge)

P29. Track/shower Classification using Deep Learning in LAr-TPC Experiments.
S. Vergani (Cambridge)

P35. SBND Recombination Study for Shower Calorimetry.
E. Tyley (Sheffield)

P39. A High Pressure TPC for Future Neutrino Experiments
E. Atkin (Imperial)

P48. The High Pressure gas TPC: a Future Neutrino Detector
T. Nonnenmacher (Imperial)

P51. Electron Neutrino Selection in MicroBooNE using the Pandora Pattern Recognition
W. van de Pontseele (Oxford)

TALKS

A Preliminary Charged-Current Muon Neutrino Inclusive Selection in SBND.
T. Brooks (Sheffield)

An Electron Neutrino Event Selection Procedure in SBND.
D. Barker (Sheffield)

The High Pressure gas TPC: a Future Neutrino Detector.
T. Nonnenmacher (Imperial)

Approaching the Neutrino Mass Problem with a Beam Dump Experiment.
T. Boschi (QMUL)

ARIADNE: a 1-ton Dual-Phase LAr-TPC With Optical Readout.
J. Vann (Liverpool)

Electron Neutrino Selection in MicroBooNE using the Pandora Pattern Recognition.
W. van de Pontseele (Oxford)

Outline

- Neutrino Oscillations
- Short-baseline Anomalies
  - LSND & MiniBooNE low-energy excess
  - Gallium & reactor anomalies
- Null Results
  - Daya Bay & MINOS/MINOS+
  - Global fit tensions
- New Experiments
  - Short-baseline reactor experiments
  - Fermilab short-baseline programme

(Lots of other interesting threads: neutrino interaction physics, DUNE prototypes, Near Detector concepts for future neutrino experiments, …)

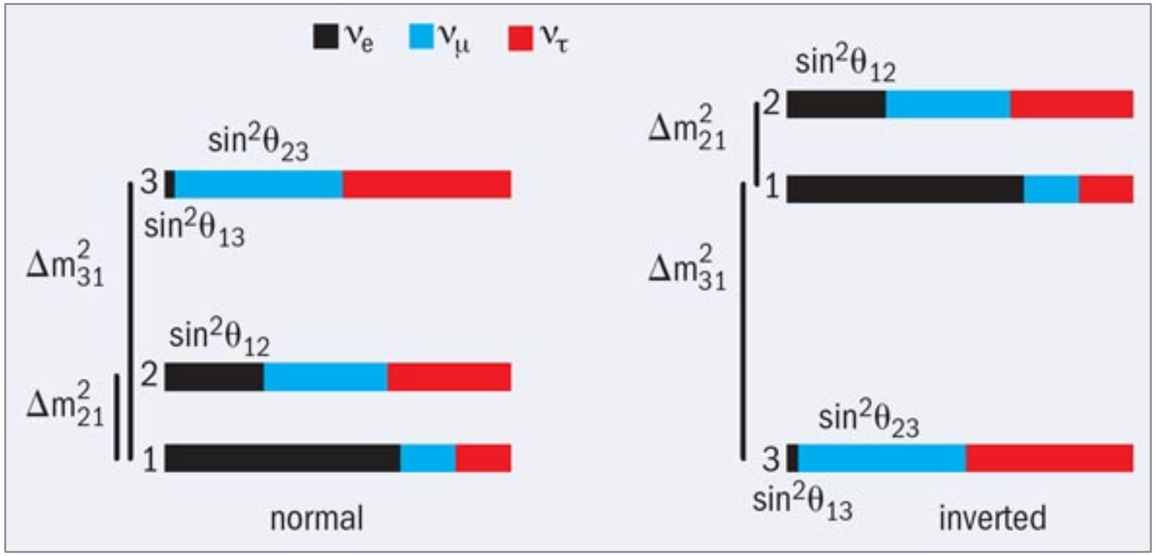
Neutrino Oscillations

- Our picture of neutrino flavour mixing is almost complete!
- The current generation of experiments has performed precise measurements of the mass splittings and mixing parameters.
  - Including first hints of non-zero δ_{CP}!
- A number of well-defined questions remain (mass ordering, θ_{23} octant, precision measurements of δ_{CP}, etc.).

Current knowledge (simplified!)

$\lvert\Delta m^2_{32}\rvert \approx 2.5\times10^{-3}\ \mathrm{eV}^2$
$\Delta m^2_{21} \approx 7.5\times10^{-5}\ \mathrm{eV}^2$
$\theta_{13} \approx 9^\circ$
$\theta_{12} \approx 33^\circ$
$\theta_{23} \approx 45^\circ$
$\delta_{CP} \approx -90^\circ$

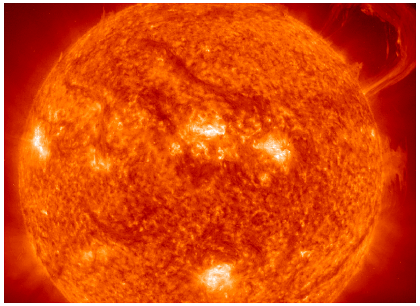
Normal Ordering   Inverted Ordering



Long-baseline Neutrinos

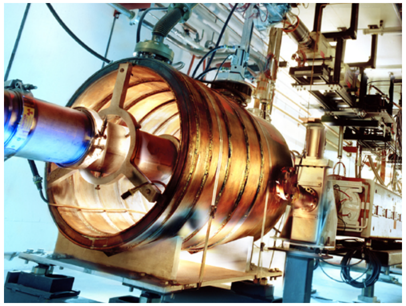
◆ Our understanding of neutrino mixing comes from experiments which probe regions of large oscillation probability ($L_\nu/E_\nu > \Delta m^2$):

Solar



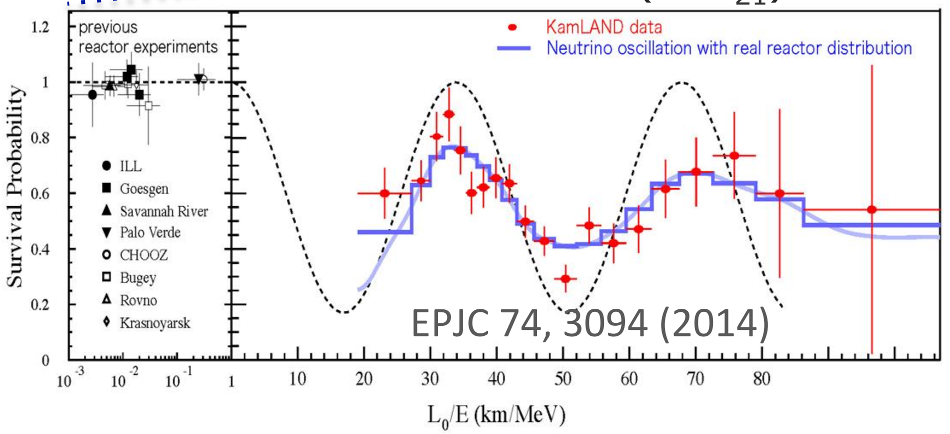
Atmospheric

Accelerator



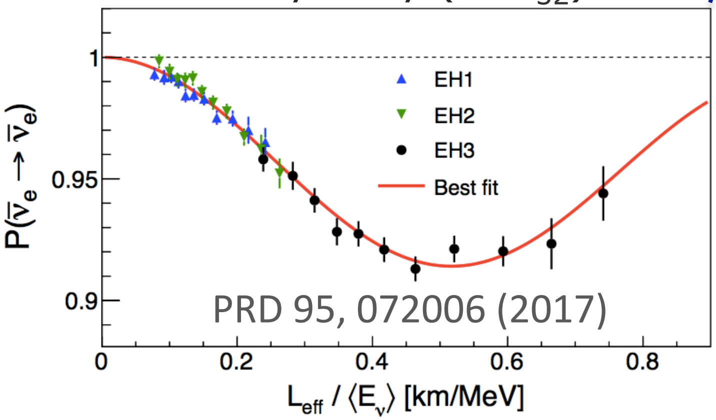
Reactor

KamLAND (Δm^2_{21})



EPJC 74, 3094 (2014)

Daya Bay (Δm^2_{32})

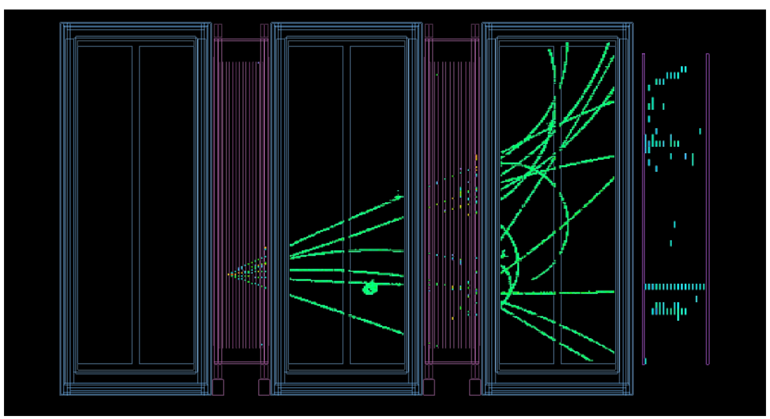


PRD 95, 072006 (2017)

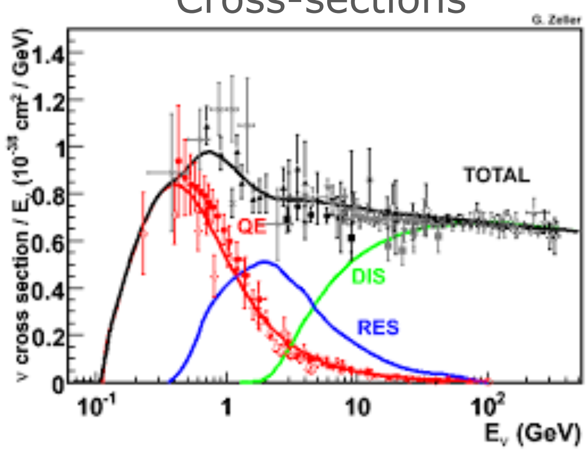
Short-baseline Neutrinos

- Roles of short-baseline neutrino detectors:
  - **Near Detectors** for multi-detector oscillation measurements *(enabling cancellations of systematic uncertainties)*.
  - Dedicated measurements of **neutrino interaction physics** *(often with Near Detectors from long-baseline experiments)*.
  - Studies of **anomalous neutrino appearance/disappearance** in regions of L_ν/E_ν where three-flavour oscillation probability is expected to be small **[Main focus of this talk]**.

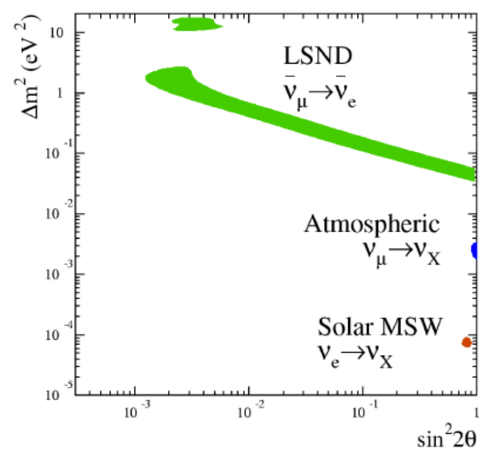
Near Detector



Cross-sections



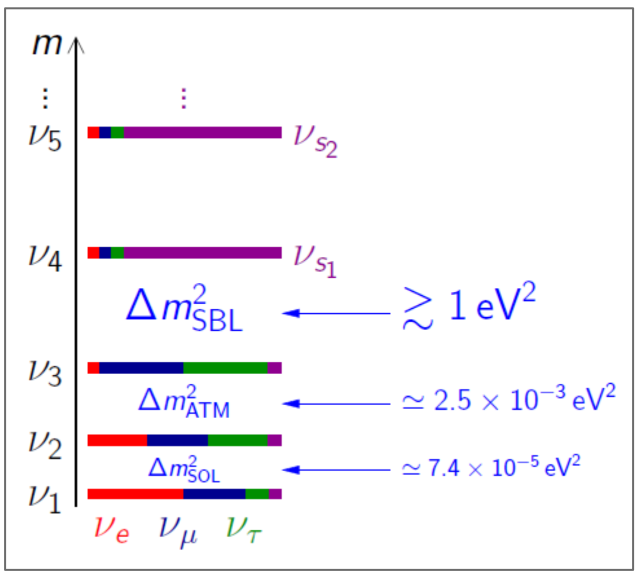
Oscillations



Sterile Neutrinos?

- Theories of short-baseline neutrino disappearance/appearance typically extend the standard three-flavour oscillation model.
  - ➢ If there are additional oscillation modes, then there must be additional mass splittings, and therefore new mass states.
  - ➢ Since there are only three active flavours of neutrino, **sterile neutrinos** are invoked in these extended models.

Neutrino mixing and oscillations driven by sterile neutrinos



$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

(Yu-Fung Li, NuFact'2018)

Short-baseline Anomalies

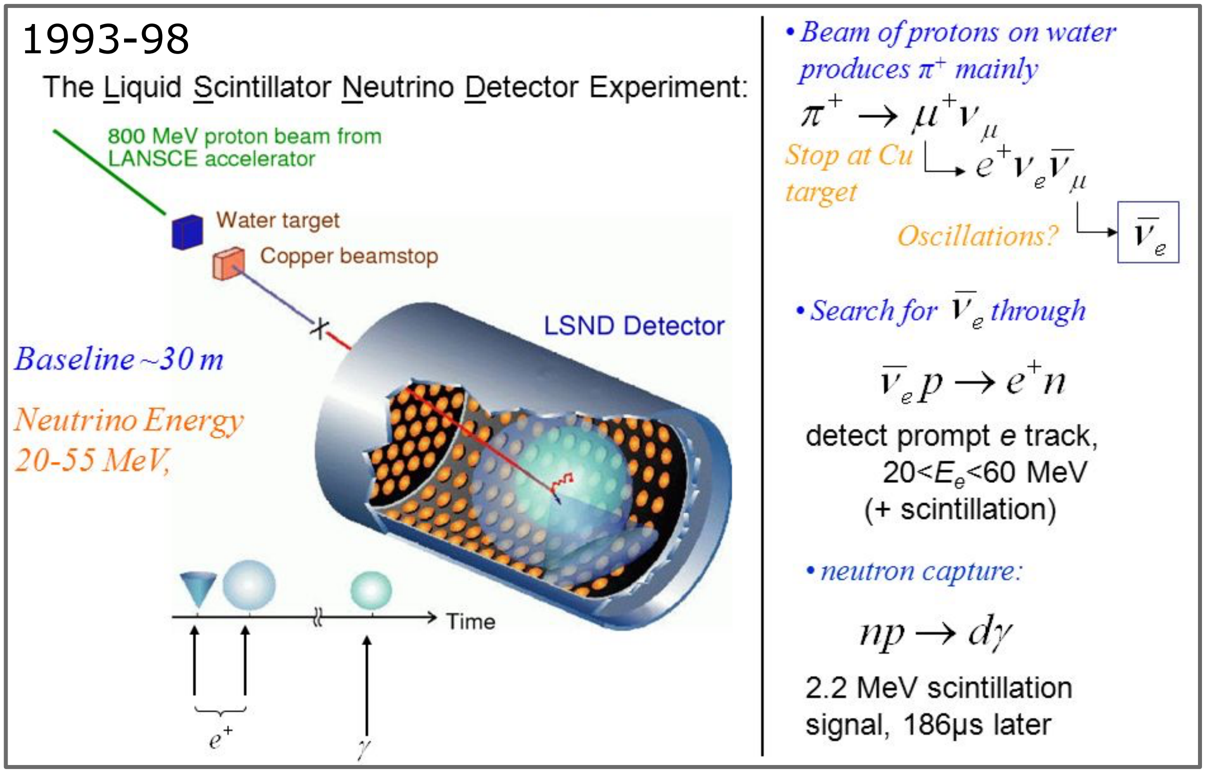
- While the bulk of the world's data agree well with the standard three-flavour formalism, several short-baseline results are in tension with this picture.
- The anomalous results fall into a number of different categories, involving either ν_e disappearance or $\nu_\mu \rightarrow \nu_e$ appearance:

Experiment	Type	Oscillation mode	Significance
LSND	Accelerator (DAR)	anti-ν_e appearance	3.8 σ
MiniBooNE	Accelerator (SBL)	ν_e appearance	4.5 σ
		anti-ν_e appearance	2.8 σ
GALLEX/SAGE	Source (e-capture)	ν_e disappearance	2.8 σ
Reactors	Radioactive β decay	anti-ν_e disappearance	2.8 σ

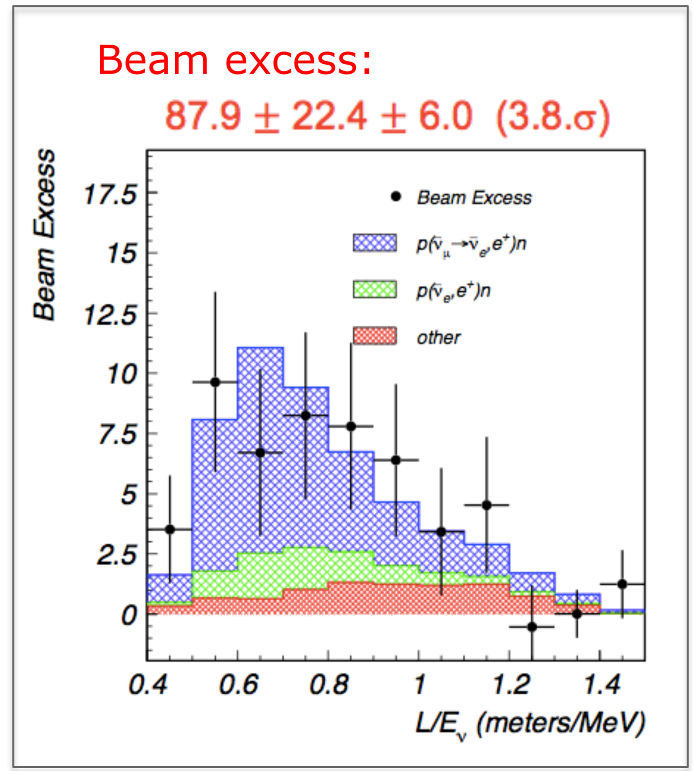
- Each of these results can be described by sterile oscillations with $\Delta m^2_{new} \approx 1$ eV^2 and a relatively small $\sin^2(2\vartheta_{new})$ - but no model is successful in fitting all the results at once!

LSND

- The LSND experiment at Los Alamos observed an excess of anti-ν_e neutrino events in a decay-at-rest beam of anti-ν_μ neutrinos.
  - ➢ Appearance signal is consistent with $\Delta m^2 \sim 1 eV^2$ oscillations.



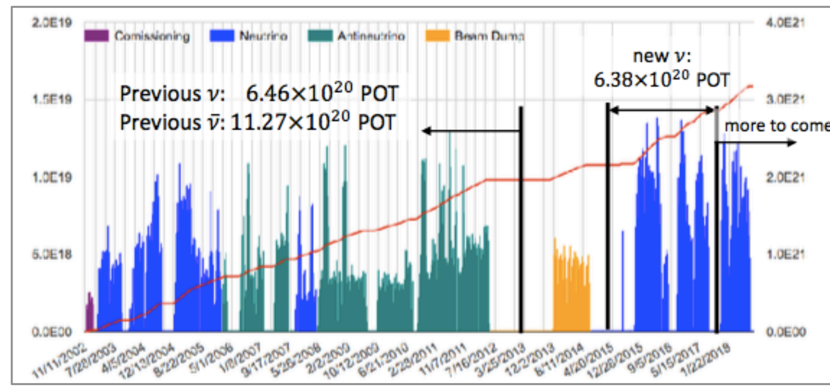
(Pedro Ochoa)



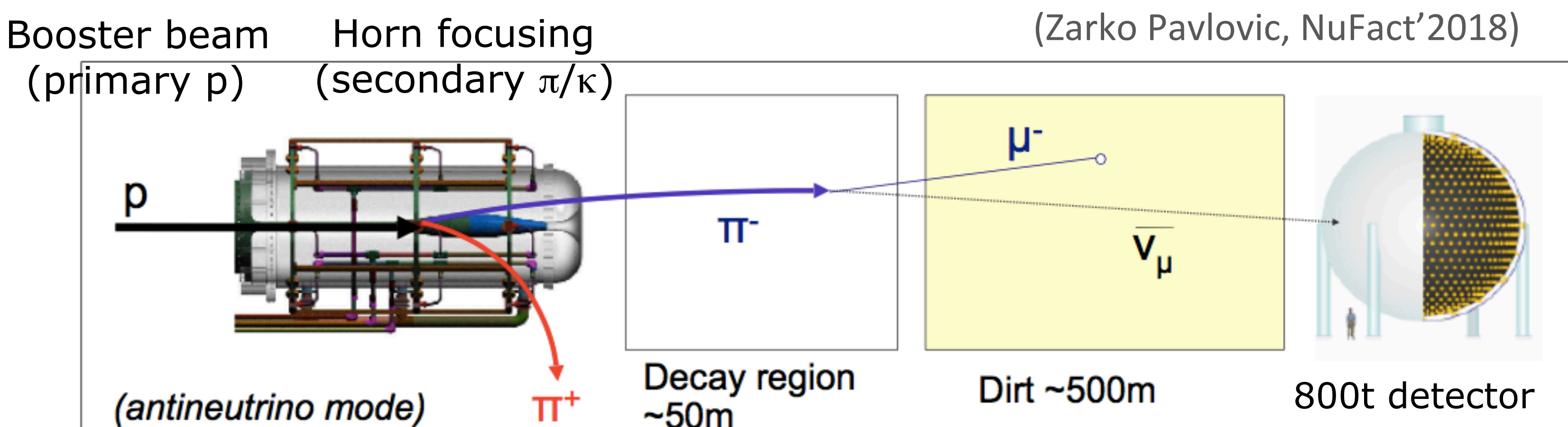
PRD 64, 112007 (2002)

MiniBooNE

- The MiniBooNE experiment at Fermilab was designed to investigate the LSND result.
  - ➢ Searching for an excess of ν_e events in an accelerator ν_μ beam.
  - ➢ Same L_ν/E_ν as LSND, but different neutrino source, baseline, energy and event signature.
  - ➢ Still operating after 15+ years!
    (Detector is well-understood and extremely stable)

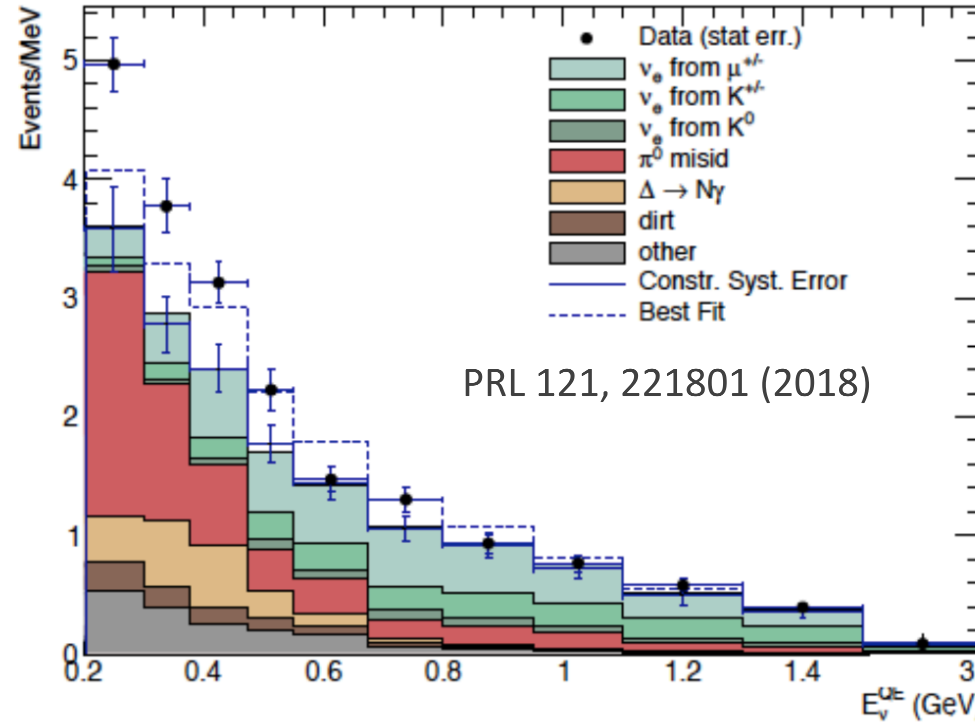


(Zarko Pavlovic, NuFact'2018)



MiniBooNE

- MiniBooNE observes a low energy ν_e excess in both neutrino and antineutrino running modes.
  - ➢ Including the latest data, significance of excess is now approaching 5σ.
- A robust analysis:
  - ➢ All major backgrounds are measured in data and their errors are constrained.
  - ➢ Neutrino flux model also based on real data (HARP).
  - ➢ Reconstruction and analysis techniques have stood the test of time.

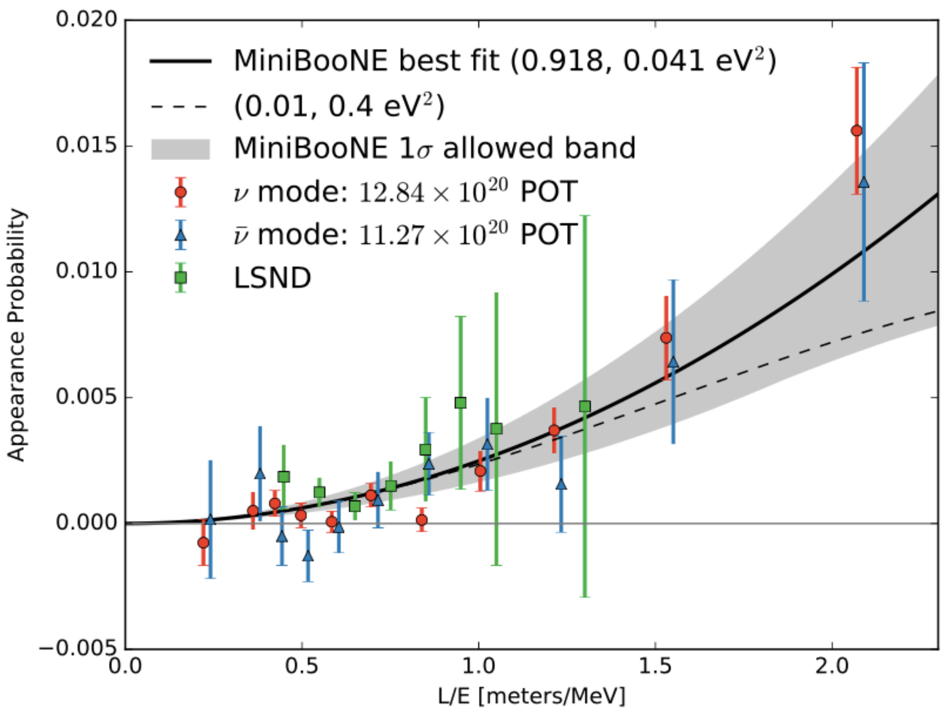


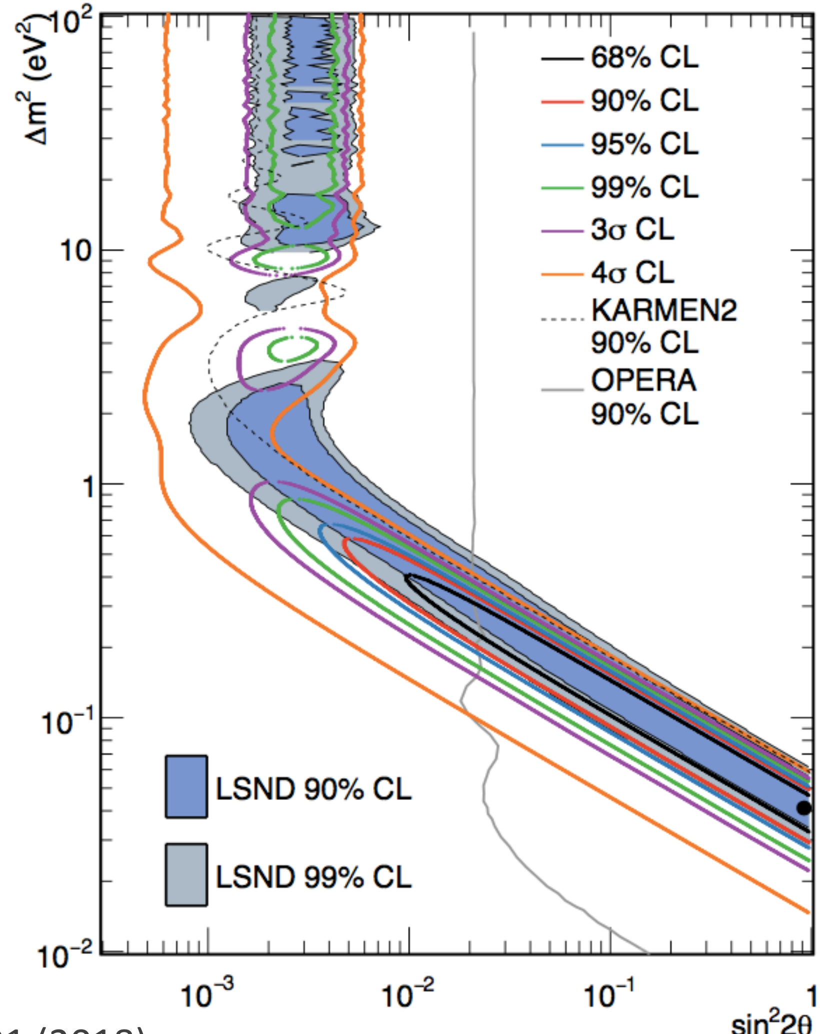
PRL 121, 221801 (2018)

	ν mode $12.84{\times}10^{20}$ POT	$\overline{\nu}$ mode $11.27{\times}10^{20}$ POT	Combined
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 99.0 4.7σ

MiniBooNE

- MiniBooNE results are consistent with high-Δm^2 oscillations.
  - ➢ (But not a great fit to the data…)
  - ➢ L_ν/E_ν dependence of low-energy excess also consistent with LSND.

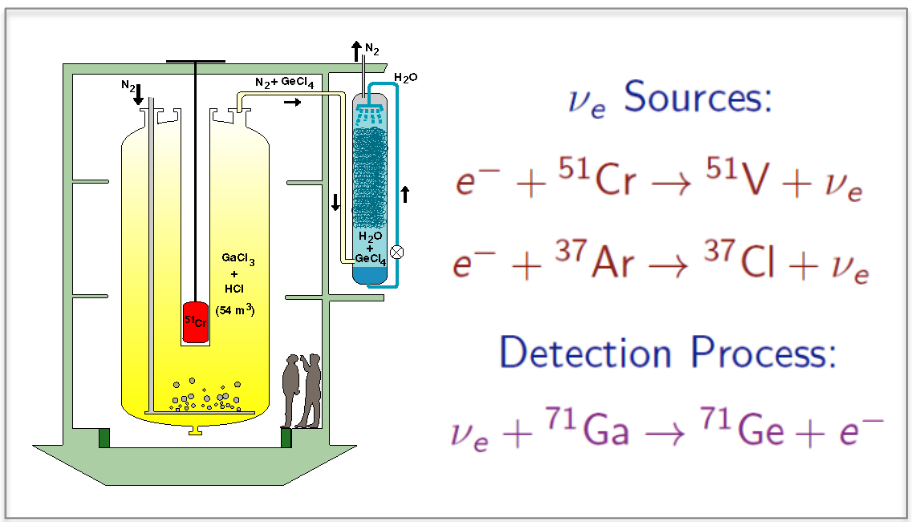


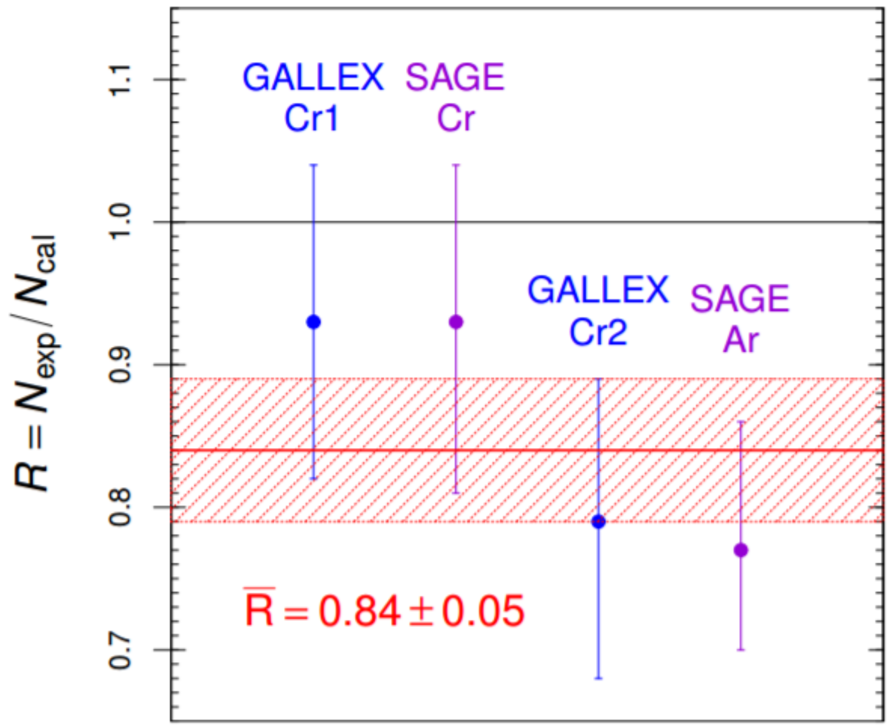


PRL 121, 221801 (2018)

Gallium Anomaly

- The GALLEX and SAGE experiments were designed for the radiochemical detection of solar neutrinos.
- The detectors were calibrated using the radioactive sources ^{51}Cr and ^{37}Ar, which emit neutrinos via electron capture.
- The neutrino interaction rates were found to be 2.7σ lower than expected.

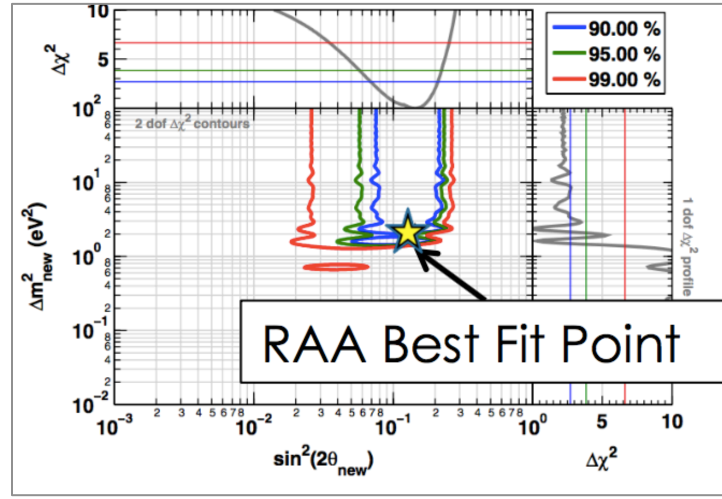


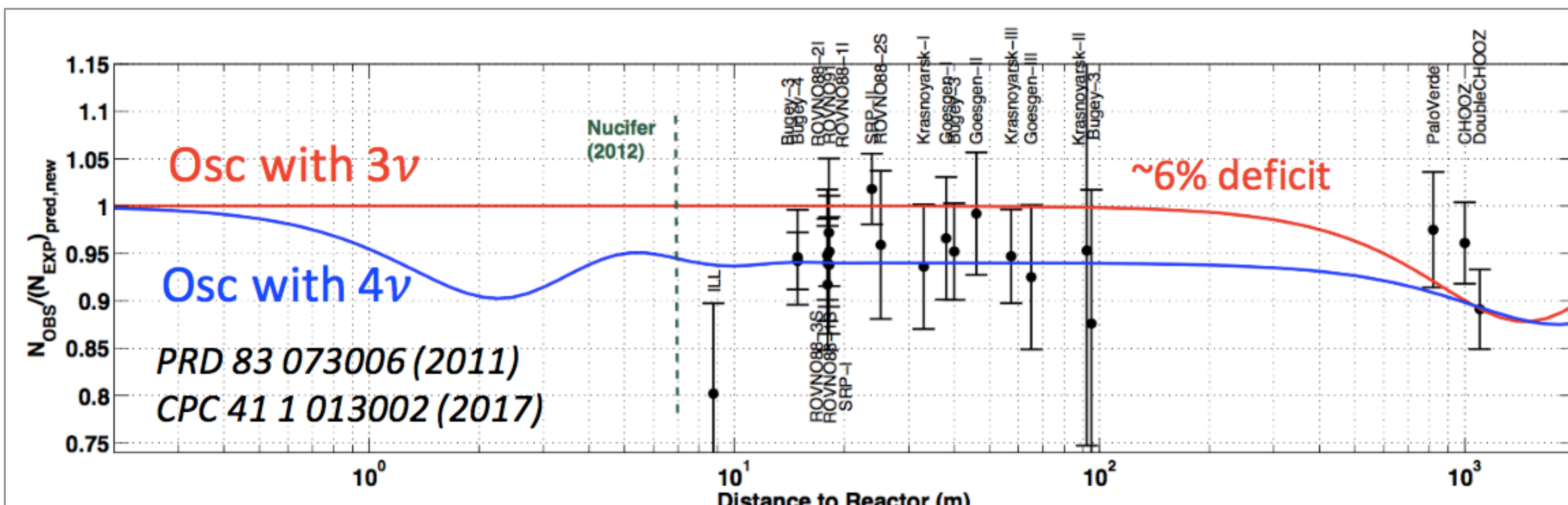


Gariazzo et al. J.Phys. G43, 033001 (2016)

Reactor Antineutrino Anomaly

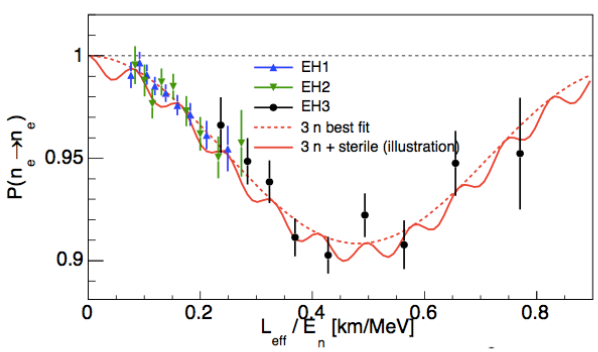
- The measured reactor anti-ν_e flux is ~6% below the theoretical prediction.
  - Corresponds to ~2.8σ effect, depending on exact uncertainties.
  - Consistent with rapid oscillations (Δm^2~1-10eV^2).
  - Anomaly arose following recalculation of fluxes (Huber & Mueller, 2011).





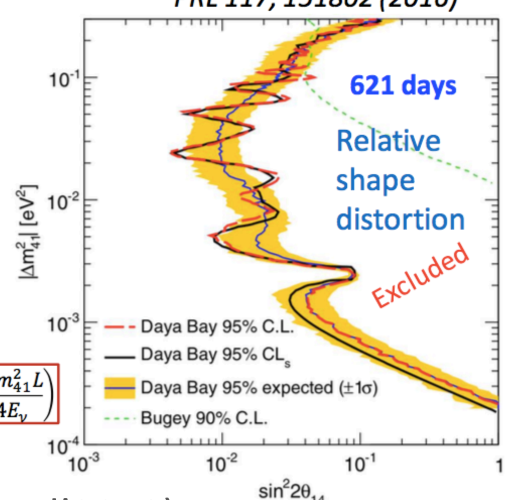
Null Results: Daya Bay

- However, recent reactor neutrino measurements by Daya Bay disfavour both the reactor anomaly and sterile neutrino hypothesis.
  - ➢ Detailed analysis of fission isotope yields indicates that an incorrect prediction of ^{235}U is the primary source of the reactor anomaly.
  - ➢ An analysis of the data assuming a minimal 3+1 model of sterile neutrinos yields no evidence of oscillations at $\Delta m^2 < 0.2$ eV^2.

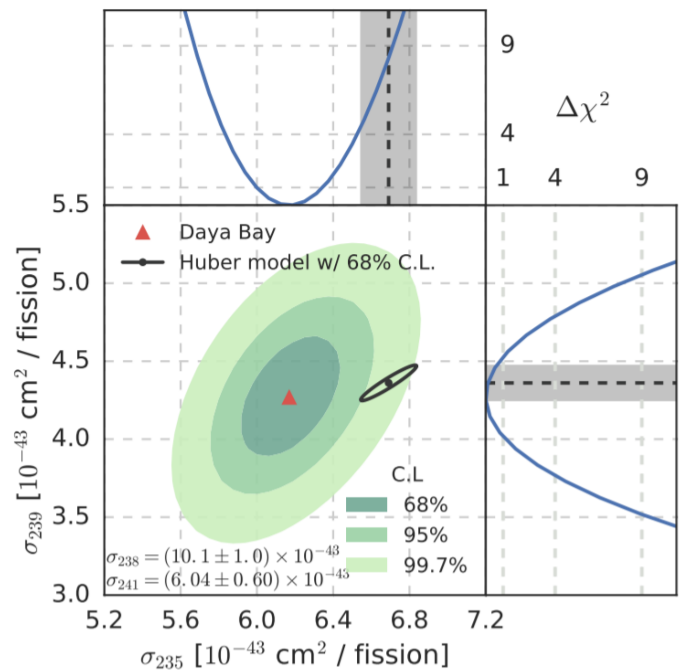


$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - cos^4\theta_{14} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - sin^2 2\theta_{14} sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

PRL 117, 151802 (2016)



(Jiajie Ling, Neutel'2019)



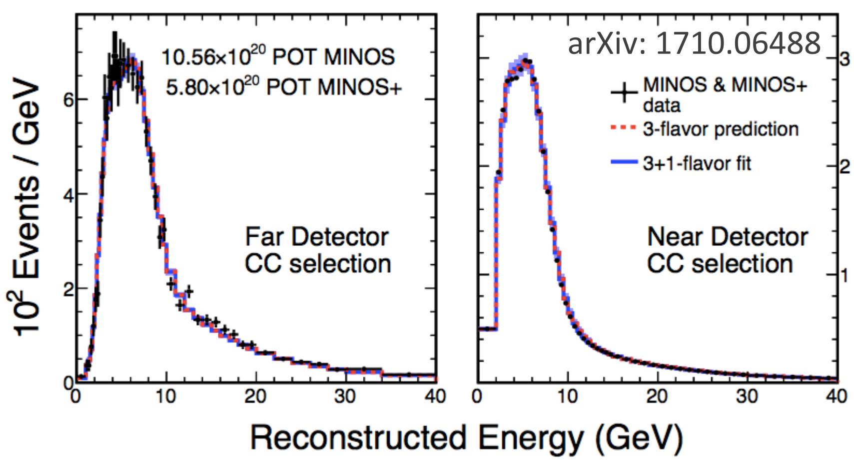
PRL 118, 251801 (2017)

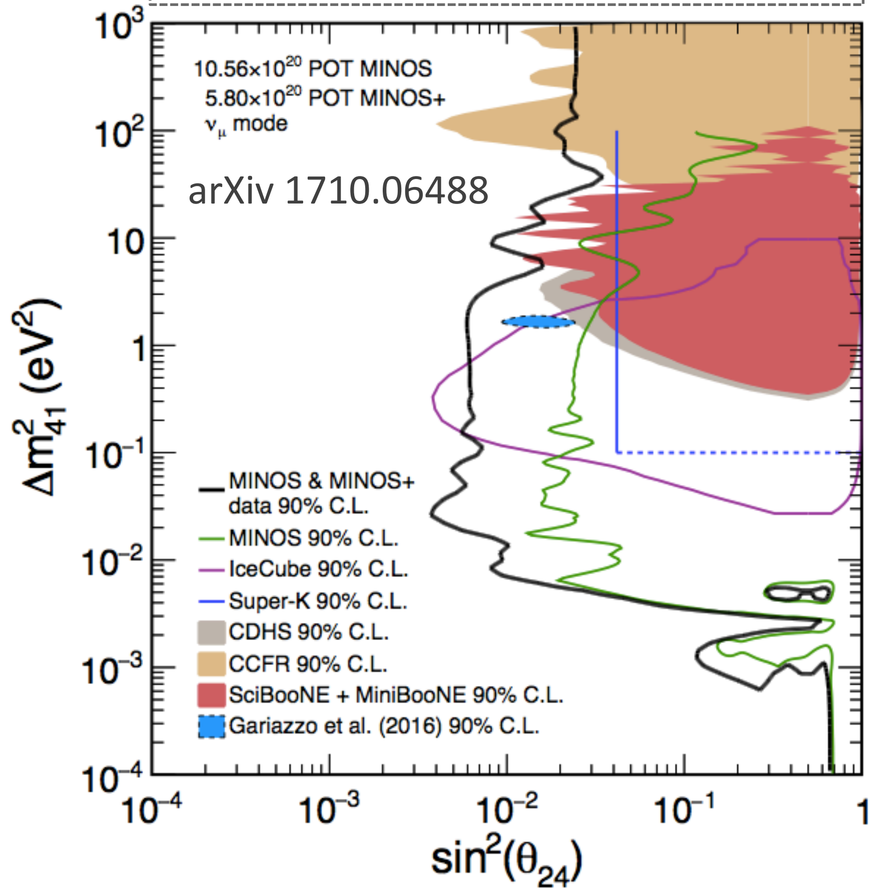
Null Results: ν_μ disappearance

- No evidence for non-standard oscillations in ν_μ disappearance.
  - ➢ This is an important null result, as ν_μ disappearance is a prerequisite for ν_e appearance!
  - ➢ In particular, MINOS & MINOS+ and IceCube strongly disfavour sterile neutrino mixing across a range of Δm^2 values.

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right).$$

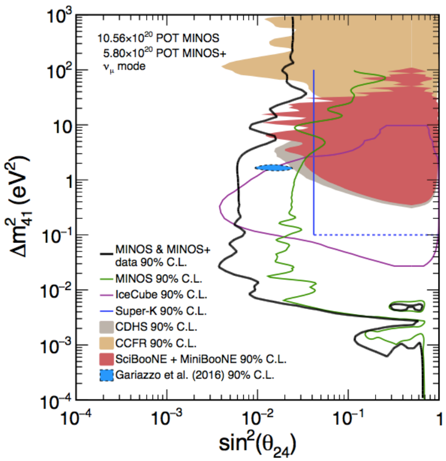


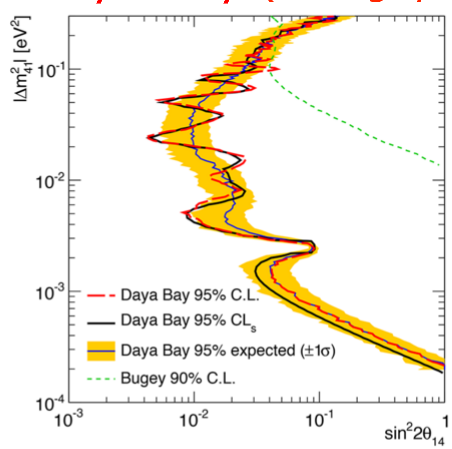


Null Results: Joint Fit

- Can probe $\nu_\mu \rightarrow \nu_e$ appearance signal by combining measurements of accelerator ν_μ disappearance and reactor anti-ν_e disappearance:

MINOS/MINOS+ Daya Bay (& Bugey-3)



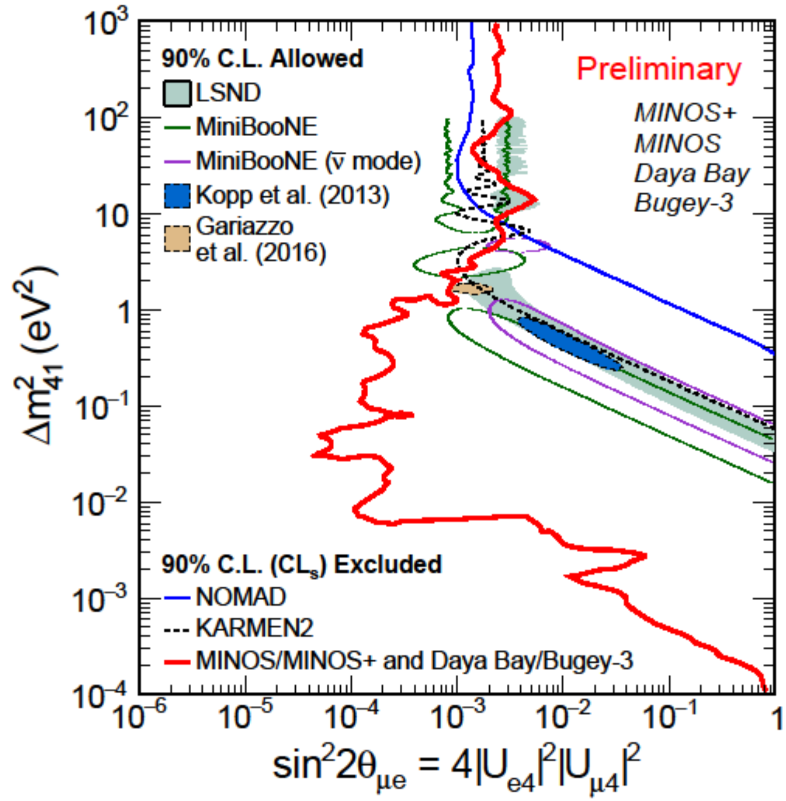


$$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

$$|U_{e4}|^2 = \sin^2\theta_{14}$$

$$\Rightarrow 4|U_{\mu 4}|^2|U_{e4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

PRL 117, 151801 (2016)

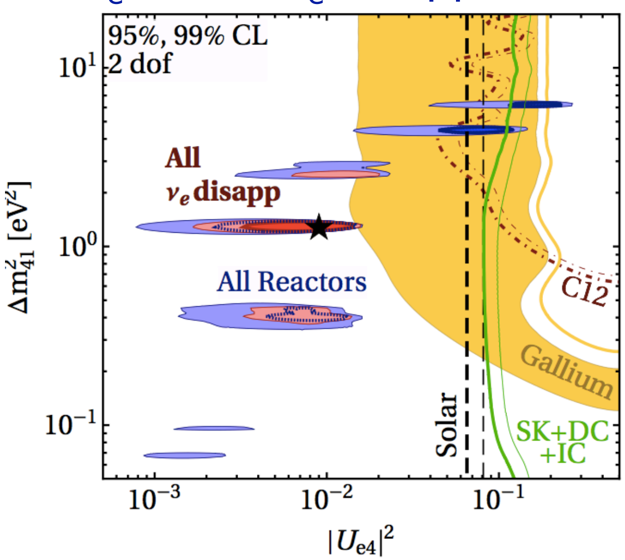


- A joint analysis of MINOS/MINOS+, Daya Bay and Bugey-3 excludes most of the LSND/MiniBooNE region, assuming a 3+1 model.

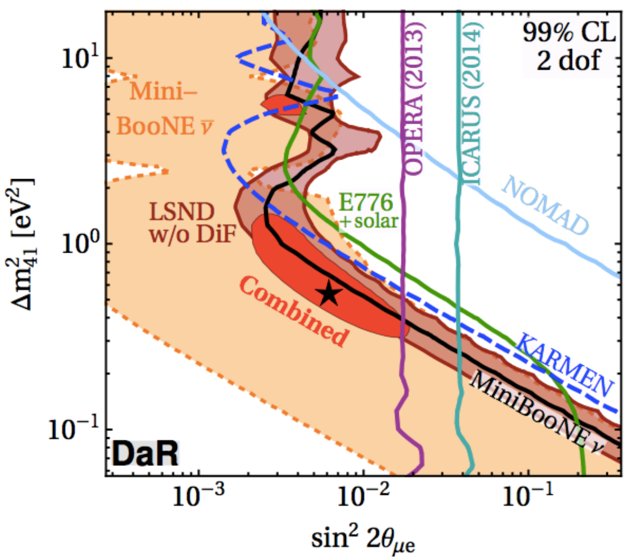
Global Fits

- Attempts to fit the world's neutrino data assuming a 3+1 model do not produce a clear or consistent picture.

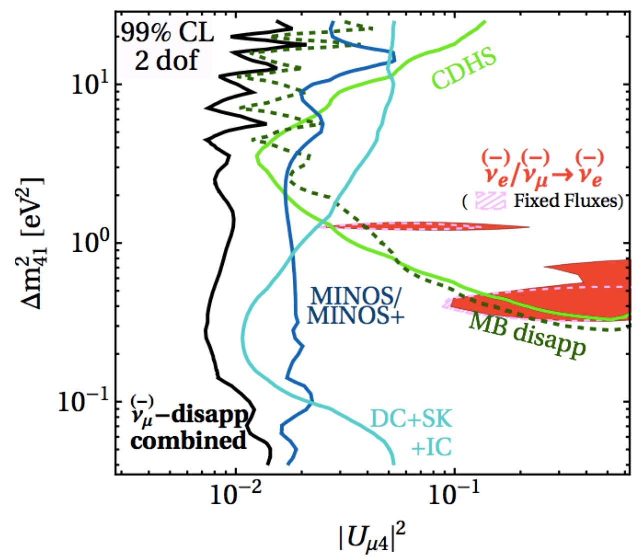
ν_e & anti-ν_e disappearance



ν_e & anti-ν_e appearance



ν_μ & anti-ν_μ disappearance



➢ Some of the issues:
- – Tension between reactor and gallium disappearance data.
- – MiniBooNE low-energy data is a poor fit to the 3+1 model.
- – Severe tension between ν_e data and ν_μ disappearance data.

M. Dentler et al. arXiv 1803.10661

New Experiments

- A new programme of neutrino experiments is now taking shape, with the goal of addressing the short-baseline anomalies.

➢ **Reactor antineutrino anomaly:**

– Perform model-independent searches for sterile neutrinos, by measuring relative spectral distortions at different baselines.

– Extend L/E reach of reactor programme.

⇒ **Several new short-baseline experiments in progress.**

➢ **Accelerator $\nu_\mu \rightarrow \nu_e$ appearance:**

– Determine whether low-energy excess is e-like or γ-like (i.e. ν_e appearance or anomalous NC backgrounds).

– Perform multi-detector search for short-baseline oscillations (where systematics cancel, like long-baseline programme).

⇒ **Fermilab short-baseline neutrino programme.**

Reactor Programme

Experiment	Reactor	Baseline (m)	Overburden (m.w.e.)	Segmented	Energy resolution (@ 1 MeV)
NEOS (South Korea)	LEU 2.8 GW	23.7	~20	none	5%
DANSS (Russia)	***LEU 3.1 GW***	***11 – 13***	***~50***	***2D***	***17%***
SoLid (UK Fr Bel US)	***HEU 70 MW***	***6 - 9***	***~10***	***3D***	***14%***
STEREO (France)	HEU 58 MW	9 - 11	~15	1D	8%
Neutrino-4 (Russia)	HEU 100 MW	6 - 12	~5	2D	
PROSPECT (USA)	HEU 85 MW	7 - 12	<1	2D	4.5%

Power Reactor: NEOS, DANSS. Research Reactor: SoLid, STEREO, Neutrino-4, PROSPECT.

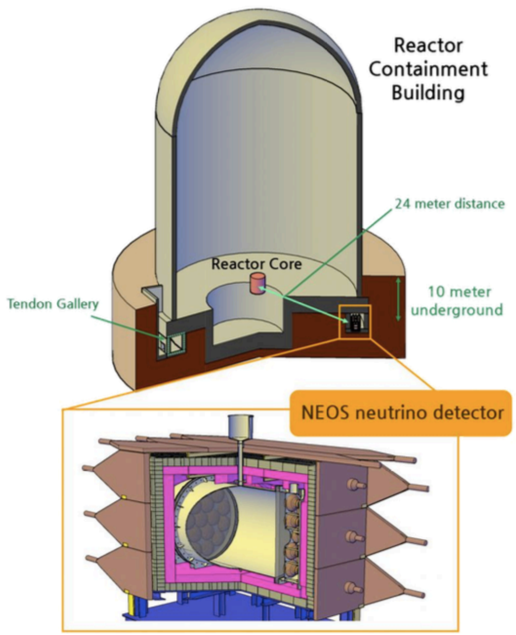
Liquid: NEOS. Plastic Scintillator: DANSS, SoLid. Liquid Scintillator: STEREO, Neutrino-4, PROSPECT.

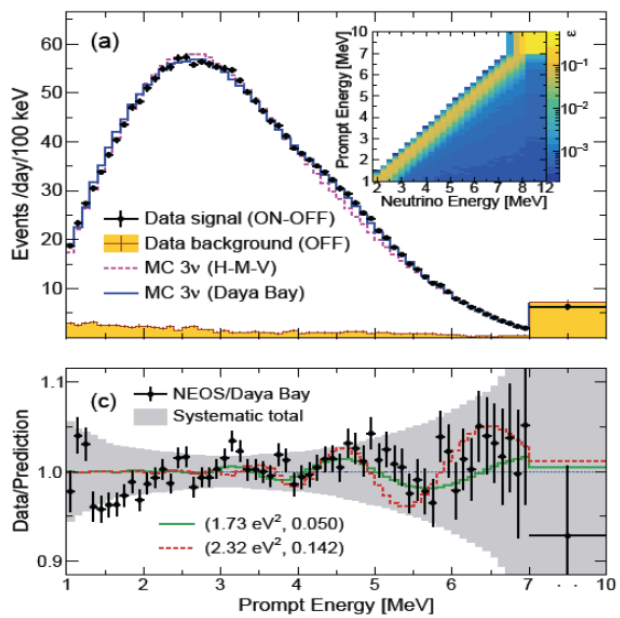
Global efforts are using a wide variety of experimental techniques

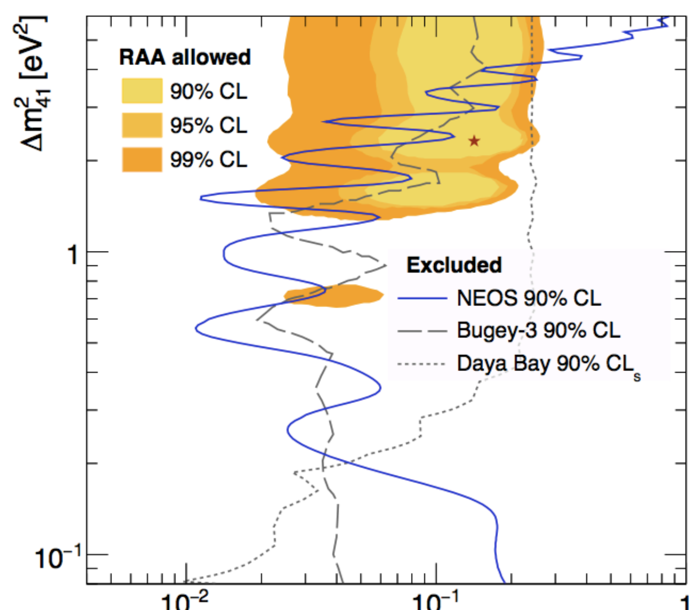
(Jeremy Gaison, NuPhys'2018)

NEOS

- NEOS operates 24m from the Hanbit-5 reactor (Yeong-gwong, Korea) using a 1-ton Gd-loaded scintillator detector.
  - ➢ Phase 1: Sep'2015 – May'2016
    - – No evidence for sterile neutrinos (disfavour RAA best fit at 90% CL)
  - ➢ Phase 2: Ongoing since 2018
    - – Plan to operate over a full fuel cycle.



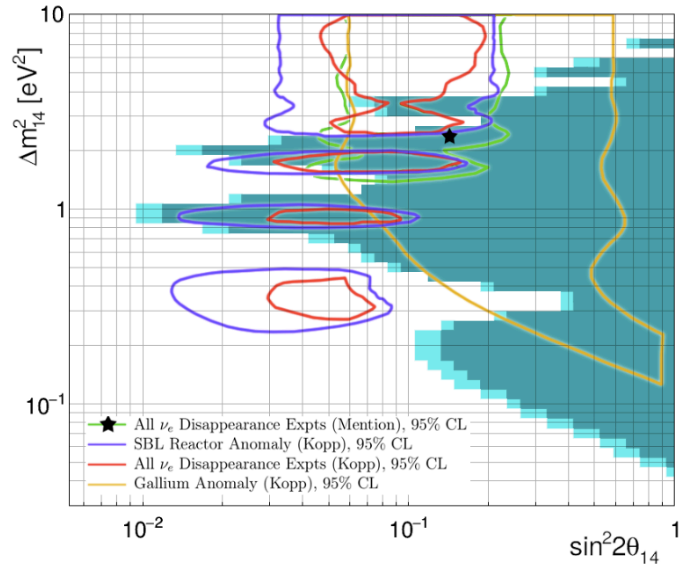


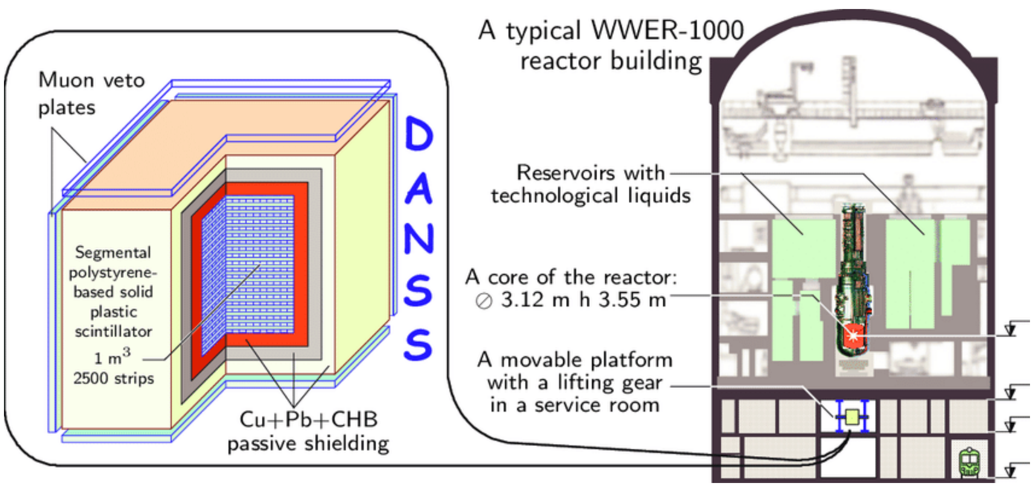


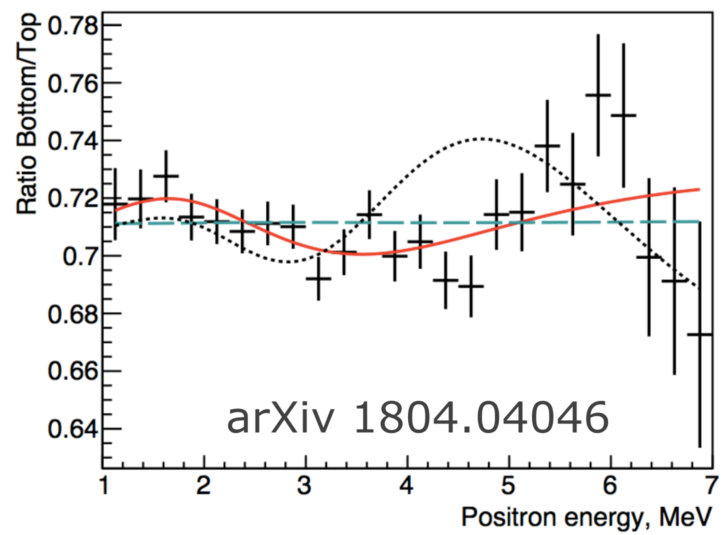
PRL 118, 121802 (2017)

DANSS

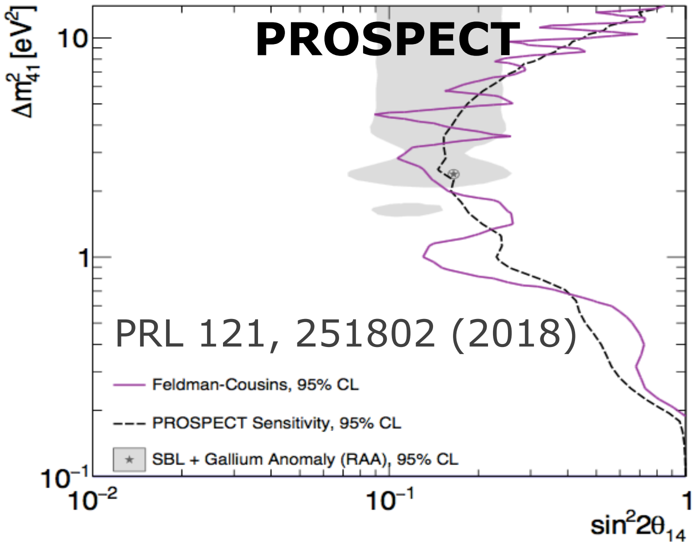
- DANSS operates at the Kalinin reactor (Russia) using a 1m^3 highly-segmented plastic scintillator detector.
- Detector is moveable! Distance to core can be varied from 10.7m to 12.7m.
- Oscillation analysis based on ratio of “top” and “bottom” energy spectra.
- No evidence for oscillations.

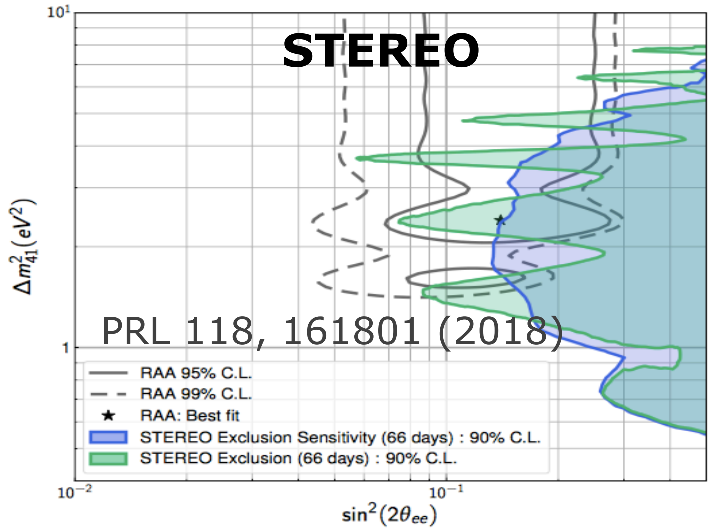


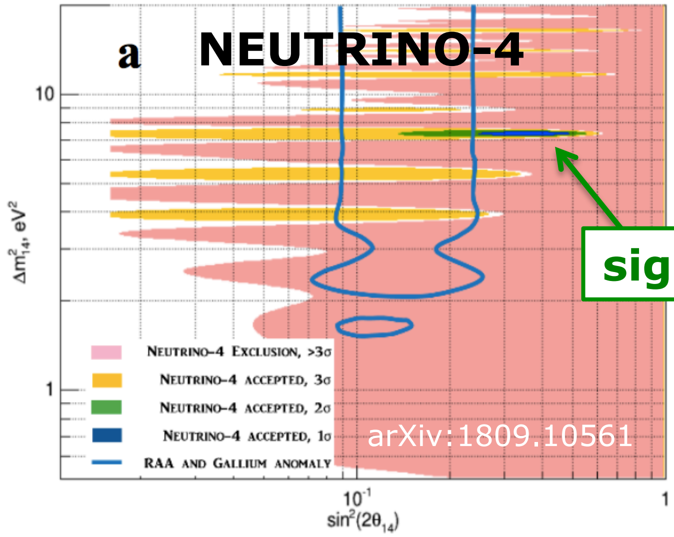


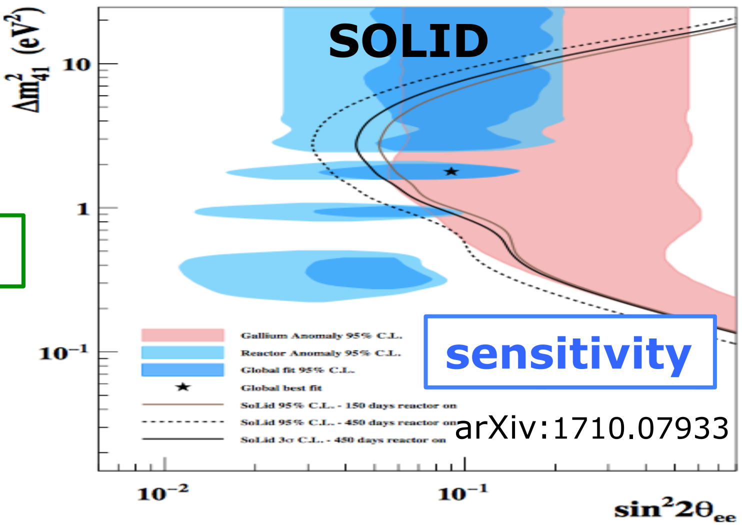


Broad Program!



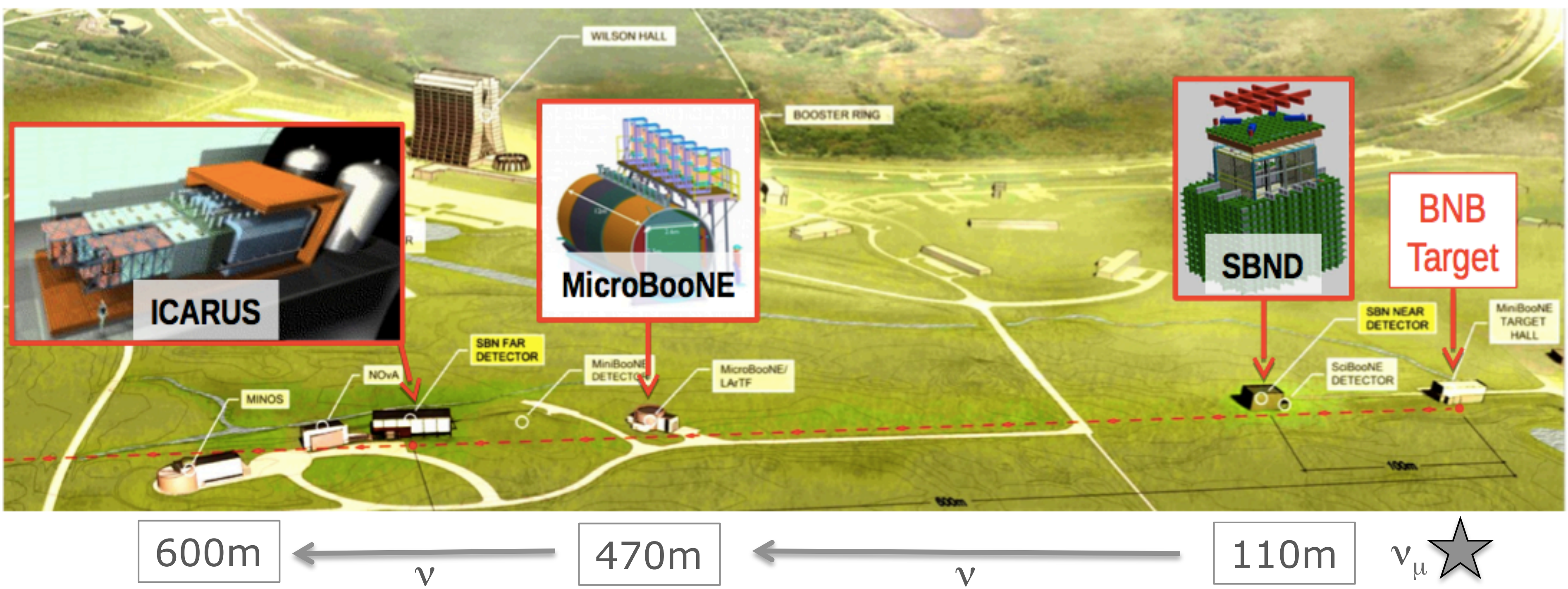






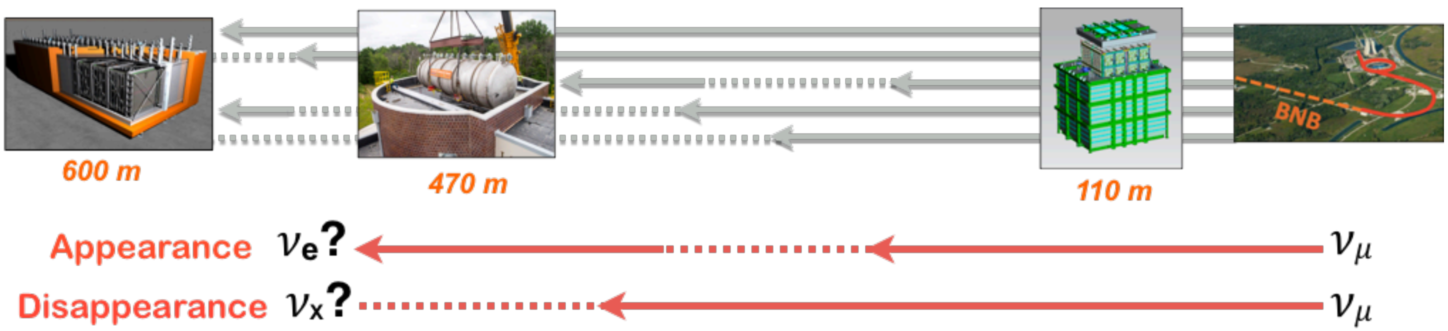
FNAL Short-baseline Program

- The short-baseline neutrino program at Fermilab aims to definitively understand the MiniBooNE low-energy excess:
  - Use the well-characterised Booster accelerator neutrino beam.
  - Deploy three detectors based on liquid argon TPC techology.

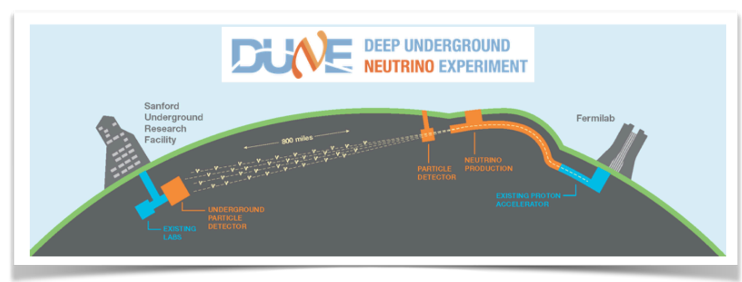


SBN Goals

- **Phase 1 – MicroBooNE**
  - Understand the nature of the MiniBooNE low-energy excess, using the same accelerator neutrino beam.
- **Phase 2 – SBND & ICARUS**
  - Search for short-baseline oscillations in both the appearance and disappearance channels.

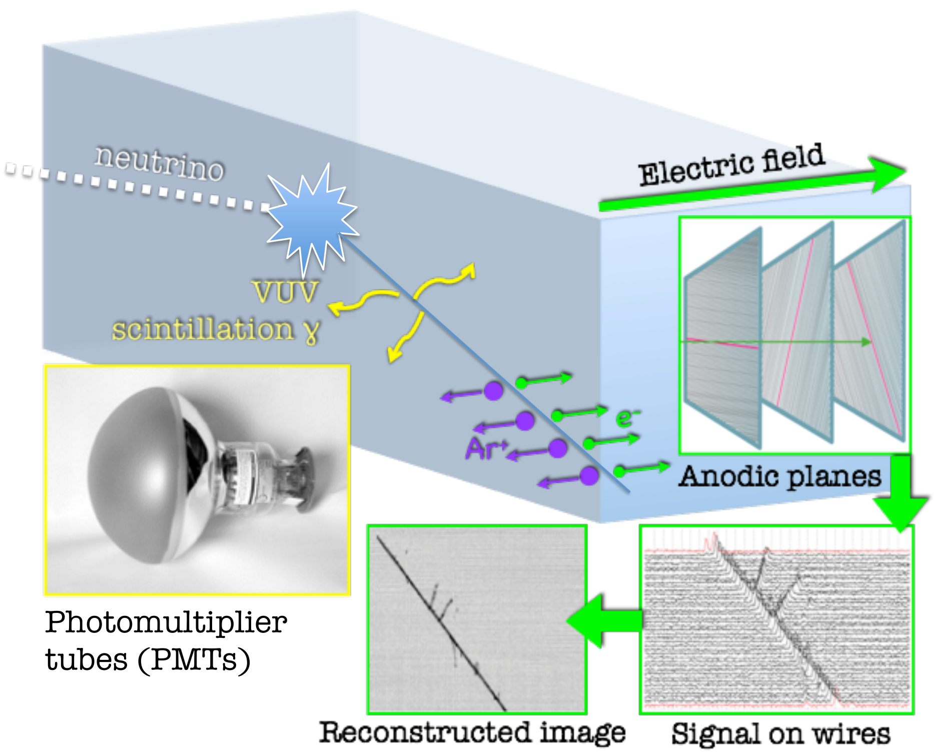


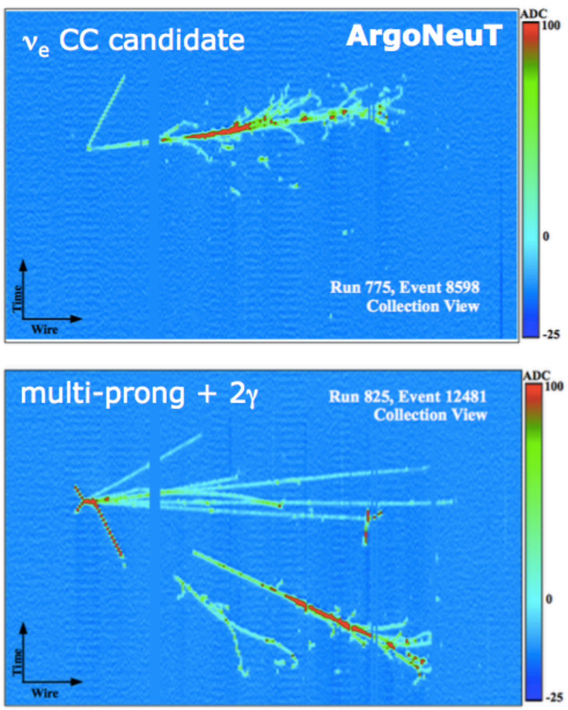
- **Prepare ground for DUNE:**
  - Further develop LAr-TPC technology.
  - Measure ν-Ar cross-sections at energies of relevance to DUNE.



LAr-TPC Detectors

- The superb spatial and calorimetric resolution of LAr-TPC detectors offers excellent reconstruction and particle identification capabilities.
  - ➢ Enables e/γ separation (crucial for characteristion of low-energy excess and precision searches for short-baseline oscillations).

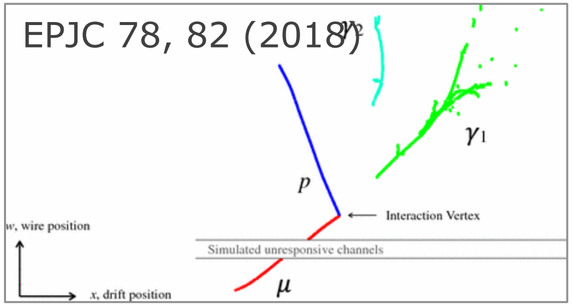


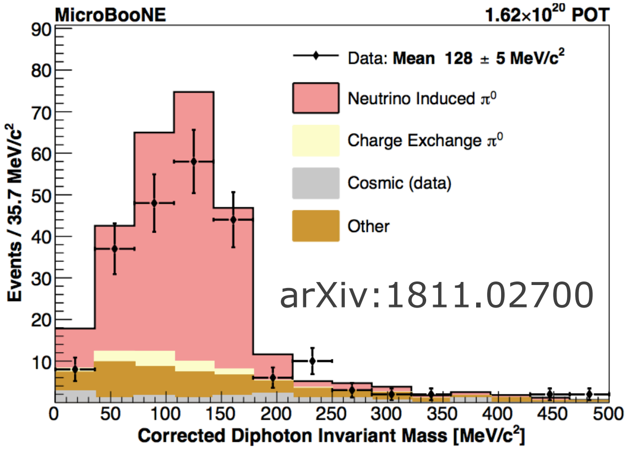


R. Acciarri *et al*, Phys. Rev. D 95, 072005 (2017)

MicroBooNE

- First large LAr-TPC detector in an intense neutrino beam.
  - ➢ 87-ton active mass.
- Stable operation since October 2015.
- Understanding detector effects:
  - ➢ Noise, diffusion, recombination, space charge (crucial for physics!)
- Significant progress on automated neutrino event reconstruction.
- First physics results:
  - ➢ ν_μ CC differential cross-section.
  - ➢ CC π^0 total cross-section.
- First fully-automated ν_e selections:
  - ➢ Towards low-energy excess analysis.

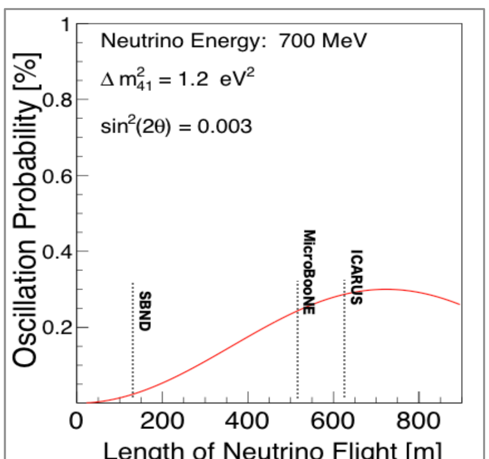


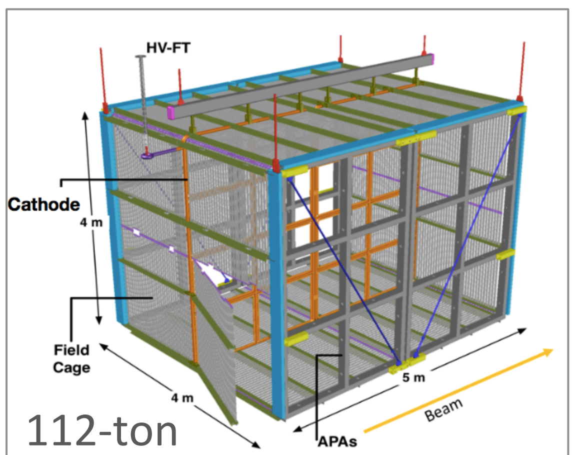


SBND

- The Short Baseline Near Detector will sit upstream of MicroBooNE, and will measure the beam before oscillations.
- SBND will also amass the largest sample of ν-Ar interactions in the world for the foreseeable future.
  - Expect 7M neutrino interactions, including 12,000 ν_e CC events.

Charged Current	
ν_μ Inclusive	5,389,168
$\rightarrow 0\pi$	3,814,198
$\longrightarrow 0p$	27,269
$\longrightarrow 1p$	1,261,730
$\longrightarrow 2p$	1,075,803
$\longrightarrow \geq 3p$	1,449,394
$\rightarrow 1\pi^+ + X$	942,555
$\rightarrow 1\pi^- + X$	38,012
$\rightarrow 1\pi^0 + X$	406,555
$\rightarrow 2\pi + X$	145,336
$\rightarrow \geq 3\pi + X$	42,510
$\rightarrow K^+K^- + X$	521
$\rightarrow K^0\bar{K}^0 + X$	582
$\rightarrow \Sigma_c^{++} + X$	294
$\rightarrow \Sigma_c^{+} + X$	98
$\rightarrow \Lambda_c^{+} + X$	672
ν_e Inclusive	**$\approx$ 12,000**
Neutral Current	
Inclusive	2,170,990
$\rightarrow 0\pi$	1,595,488
$\rightarrow 1\pi^\pm + X$	231,741
$\rightarrow \geq 2\pi^\pm + X$	343,760
$\rightarrow e(^-)$	374

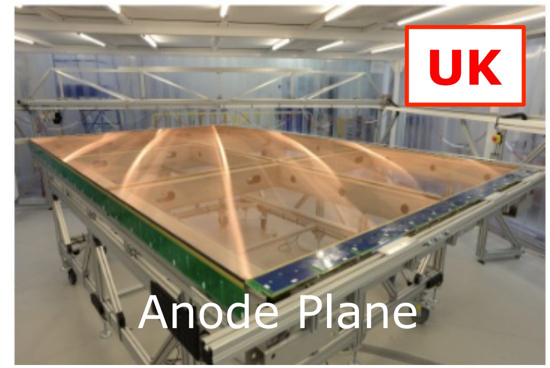


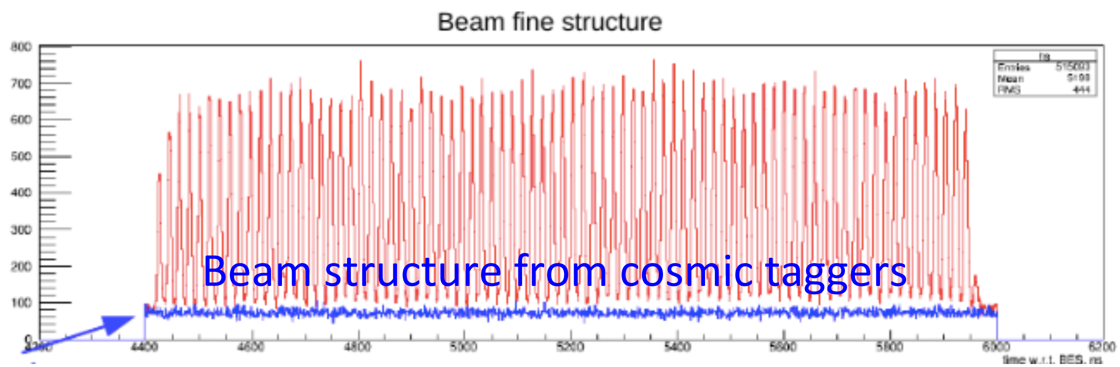


(Andzej Szelc, NuINT'2018)

SBND Construction

UK have a key role in all aspects of SBND - particularly construction.





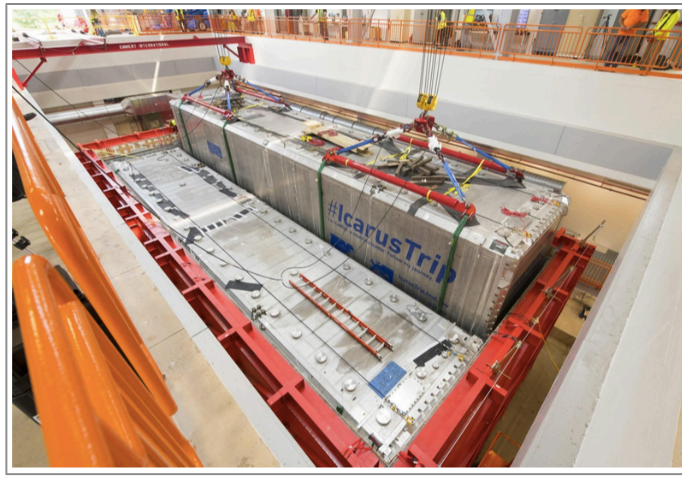
- Building is completed, and cosmic taggers installed (and taking data!)
- UK-built Cathode and Anode Plane Assemblies shipped to Fermilab.

First data expected in 2020

ICARUS

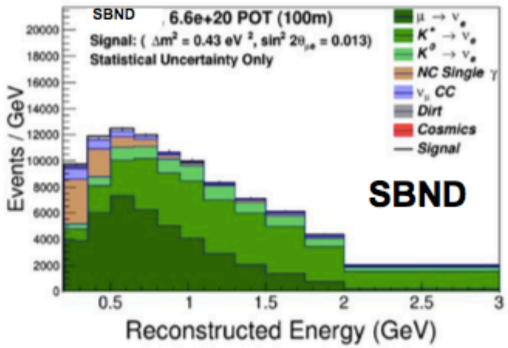
- ICARUS will be the Far Detector of the SBN program.
  - ➢ Previously operated at Gran Sasso, but now refurbished and installed in the Booster beamline.
- Given its large active mass (476-ton) and far location, ICARUS will enable a precision search for short-baseline oscillations.
- Status:
  - ➢ Installation of two modules was completed in August 2018.
  - ➢ Ongoing work includes cryogenics, cabling, etc.

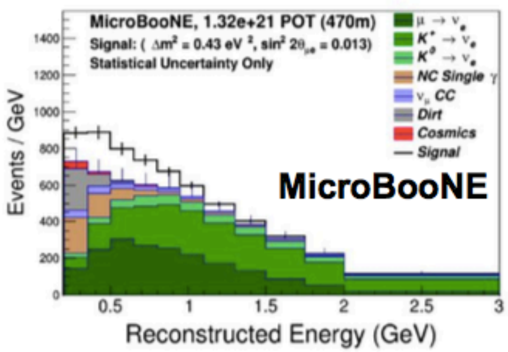
Data-taking planned in 2019.

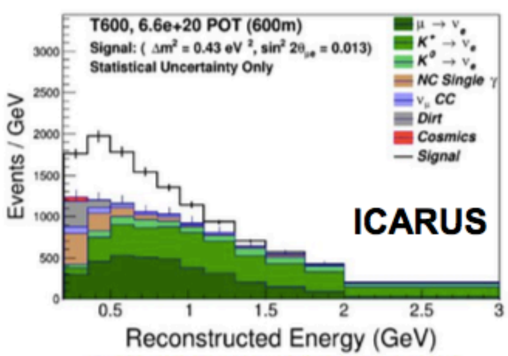


(Serhan Tufanli, NuPhys'2018)

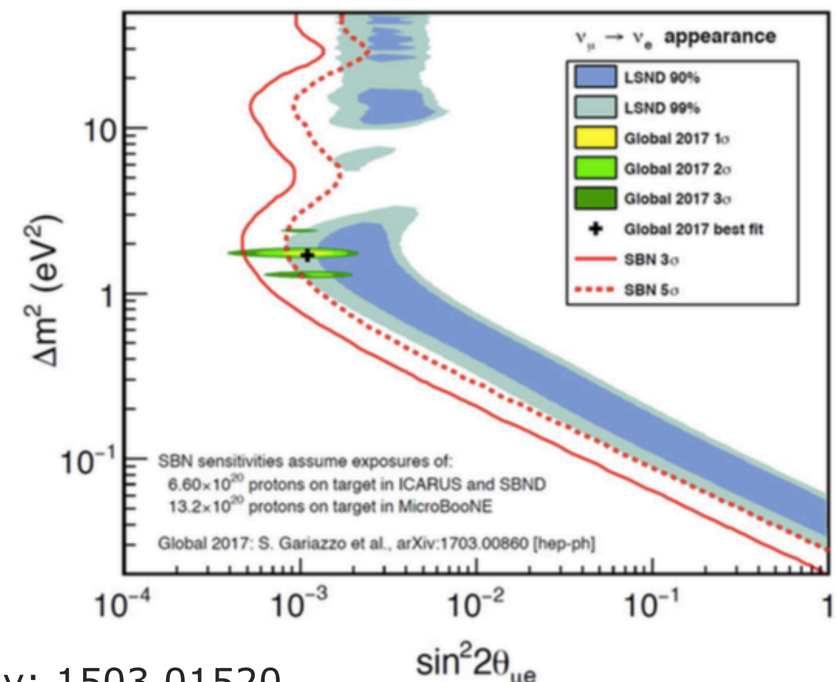
Sensitivity (ν_e appearance)





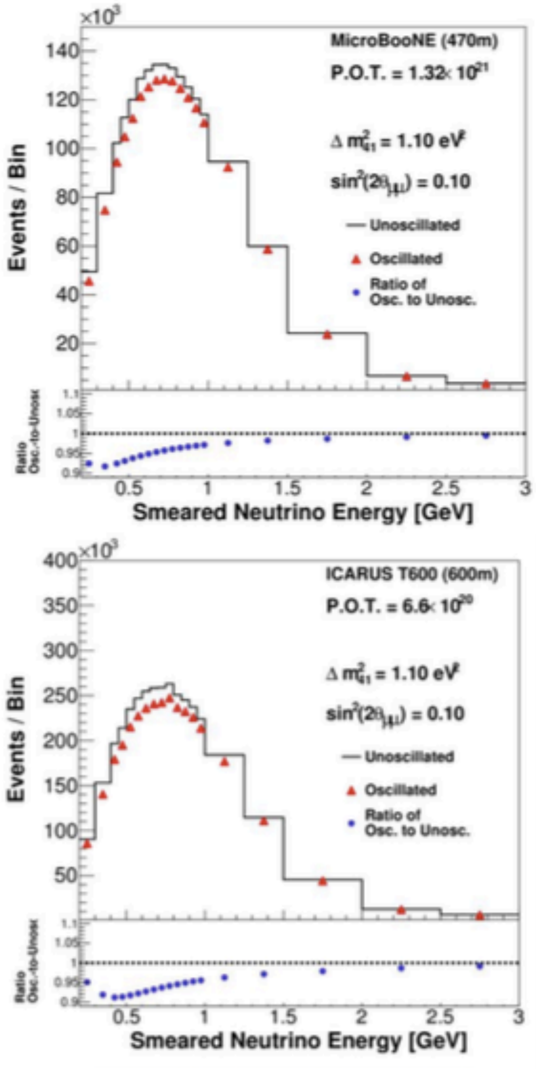


- A massive Far Detector with a Near Detector of similar technology reduces both statistical and systematic uncertainties.
- SBN detectors enable 5σ coverage of the 99% C.L. allowed region of the LSND signal and the global best-fit.

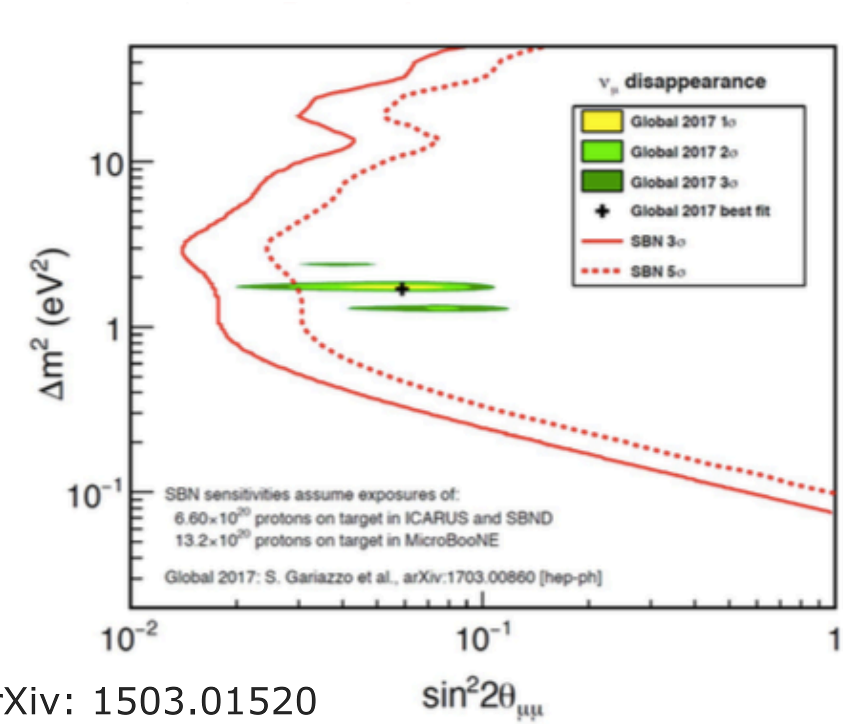


arXiv: 1503.01520

Sensitivity (ν_μ disppearance)



- The SBN program will also perform a precision search for ν_μ disappearance, pushing back the current limits.
- This is a critical analysis in verifying any oscillation hypothesis.



arXiv: 1503.01520

Summary

- Our picture of standard neutrino oscillations is almost complete. However, short-baseline anomalies are observed.
  - Sterile neutrinos are typically used to describe anomalous appearance and disappearance.
- Global fits to world data do not yield a consistent picture.
  - e.g. no evidence for short-baseline oscillations in ν_μ disappearance data.
- The new short-baseline programs will deliver precision data that will shed new light on these anomalies.
  - Short-baseline reactor neutrino experiments.
  - Fermilab short-baseline neutrino program.
- Watch this space!