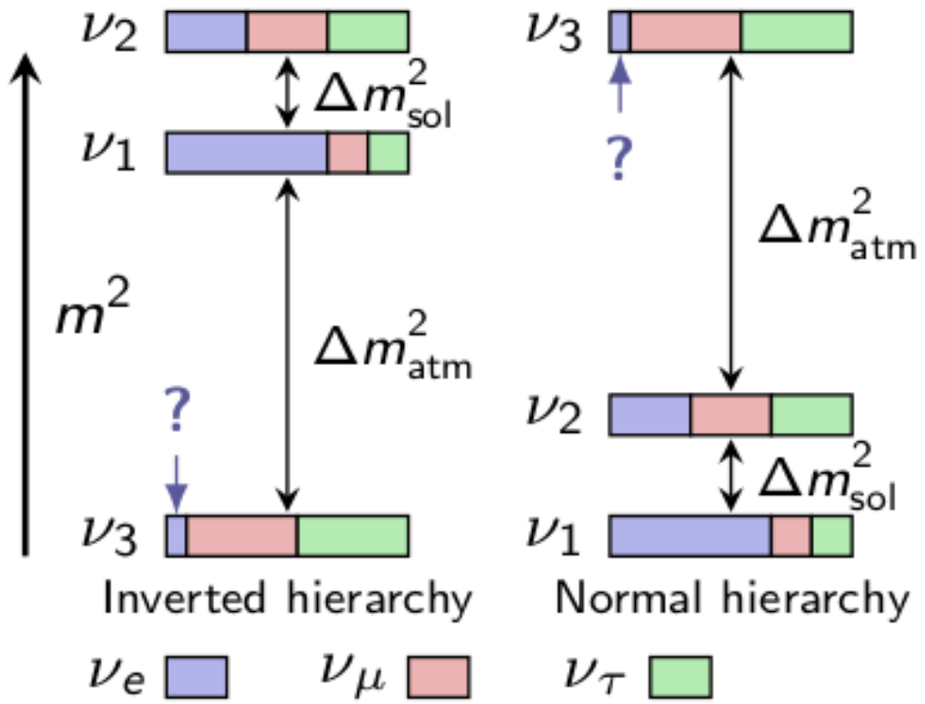
Shedding Light on the Dark Sector With Neutrino Oscillations

Bryce Littlejohn
University of Cincinnati
6/13/14

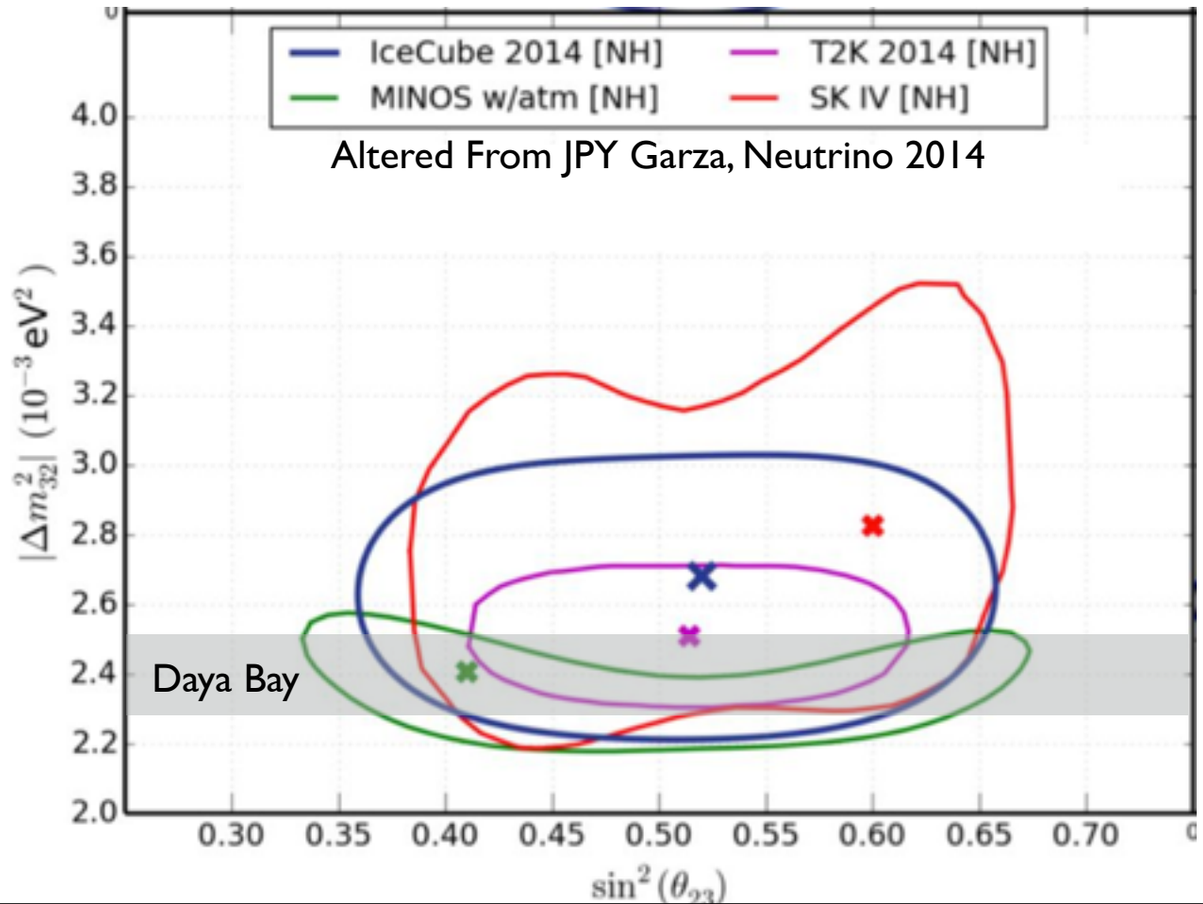
Three-Neutrino Oscillation Picture

- Consistent results from disparate experimental methods confirm three-neutrino mixing paradigm:
  - Three mass splittings observed
  - Observed oscillation to or from each active flavor: clear that 3x3 PMNS relates three mass states to three active neutrino states.
  - Have plenty of mass splittings to go around. Don't need any more!



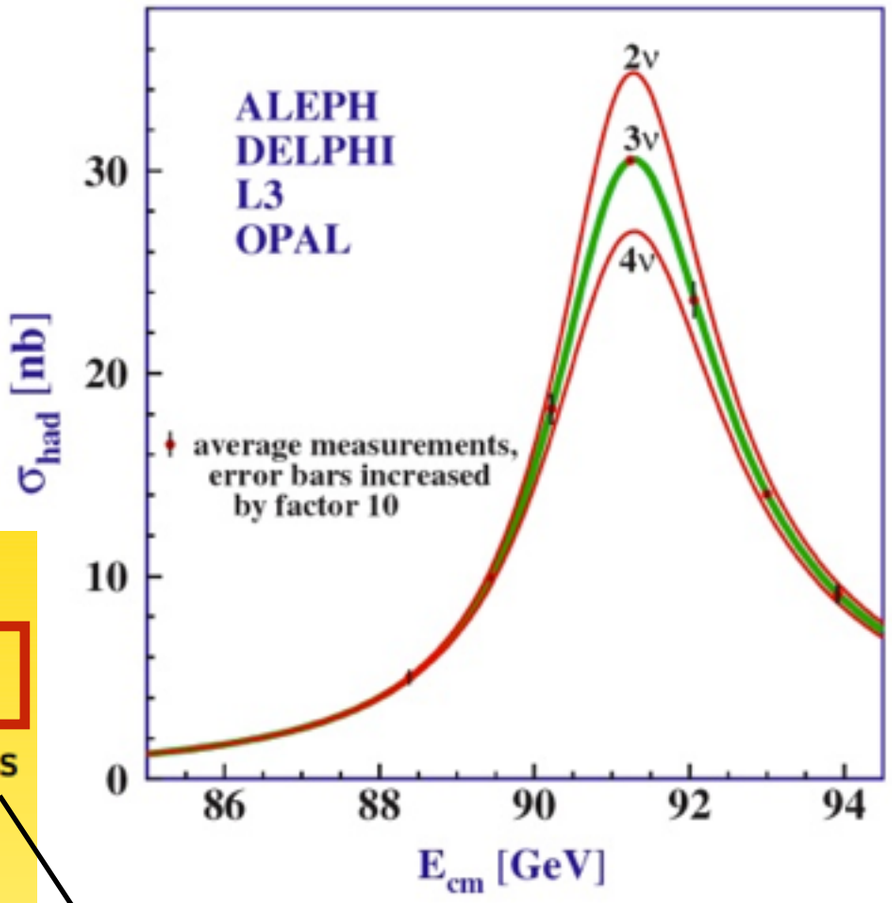
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \left[1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}\right]$$

$$U_{\text{PMNS}} \approx \begin{pmatrix} 0.820 & 0.554 & 0.146 \\ 0.482 & 0.528 & 0.699 \\ 0.310 & 0.644 & 0.699 \end{pmatrix}$$



Additional Mass Splittings, Sterile Neutrinos

- Numerous anomalous results in neutrino physics can be explained by oscillation via a fourth mass splitting
- Resort to ‘sterile neutrinos’ to mesh with Z mass peak width
- Sterile neutrinos look like different things to different people…
- Focus on hints of eV^2 steriles from neutrino oscillation experiments



arxiv:hep-ex[0509008] (2006)

Next Talk (K. Smith)

Summary slides in backup if you have questions here.

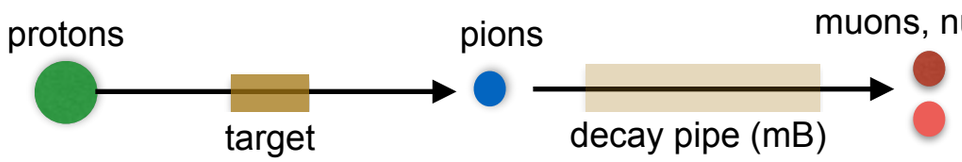
Sterile Neutrinos

- eV: SBL Anomalies
- eV: N_{eff} (Cosmology, BBN), r-process
- eV: BICEP-2 and Planck
- $\ll$ eV: missing upturn of $P_{ee}^{\odot}$
- keV: Warm Dark Matter
- TeV: Z-width, NuTeV
- 10^{10} GeV: Leptogenesis
- 10^{15} GeV: Seesaw Mechanism

W. Rodejohann

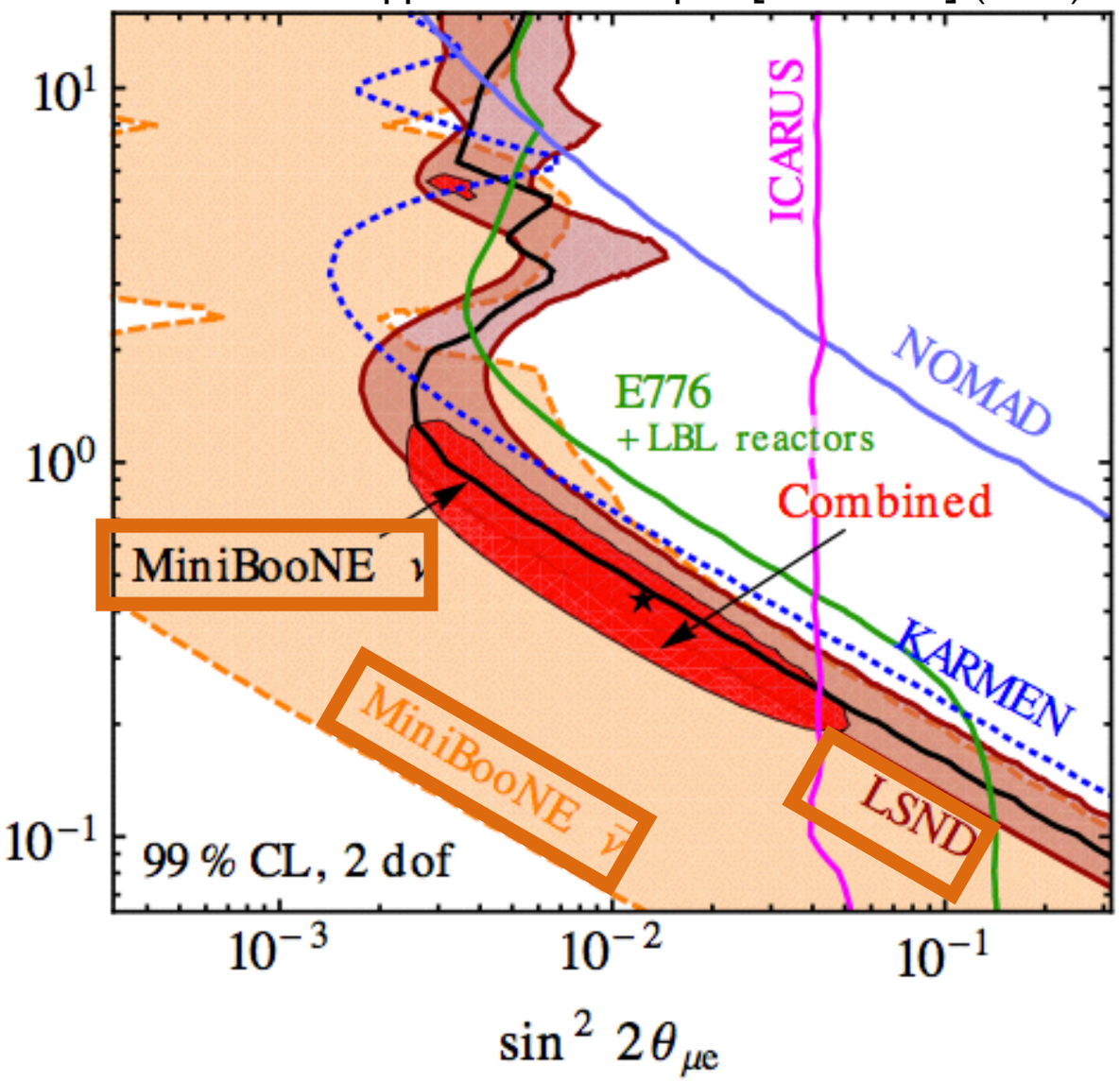
Hints For Alternate Δm^2 : $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

- LSND: Pion decay-at-rest $\overline{\nu}_\mu$ beam (1990s)
- MiniBooNE experiments: decay-in-flight (2000-10s)
- Observed excess of $\overline{\nu}_e$-like interactions at L/E ~ 1 GeV/km, indicating appearance via oscillation, ~eV^2 mass splitting
- Widely divergent methods



Parameter	LSND	mBooNE
Bunch Width	600 us	1.6 us
Proton E	<1 GeV	8 GeV
Neutrino E	<50 MeV	>200 MeV
Interaction	Inverse Beta	Nuclear CCQE
Detector Type	Liquid Scint	Oil Cerenkov

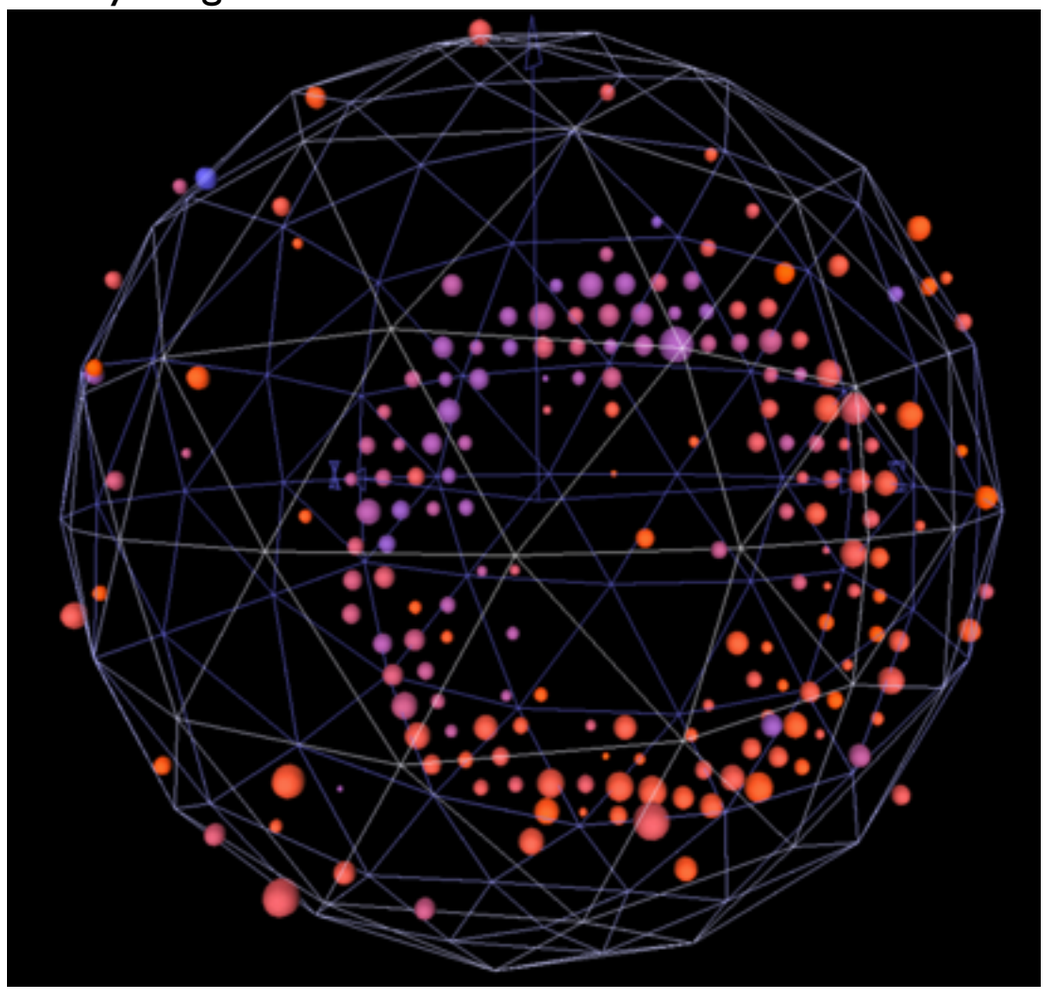
Kopp, et. al, arxiv:hep-ex[1303.3011] (2014)



For The Skeptics…

- Alternate (untested!) theories for appearance results exist
  - LSND detector is on-axis with a large duty factor: affected by not-understood beam-related products? Cosmic ray flux?
  - MiniBooNE: Really electrons? Or maybe gammas?
- Other experiments show null results at nearby Δm^2

Fuzzy Ring From EM Shower: A Gamma? Or Electron?



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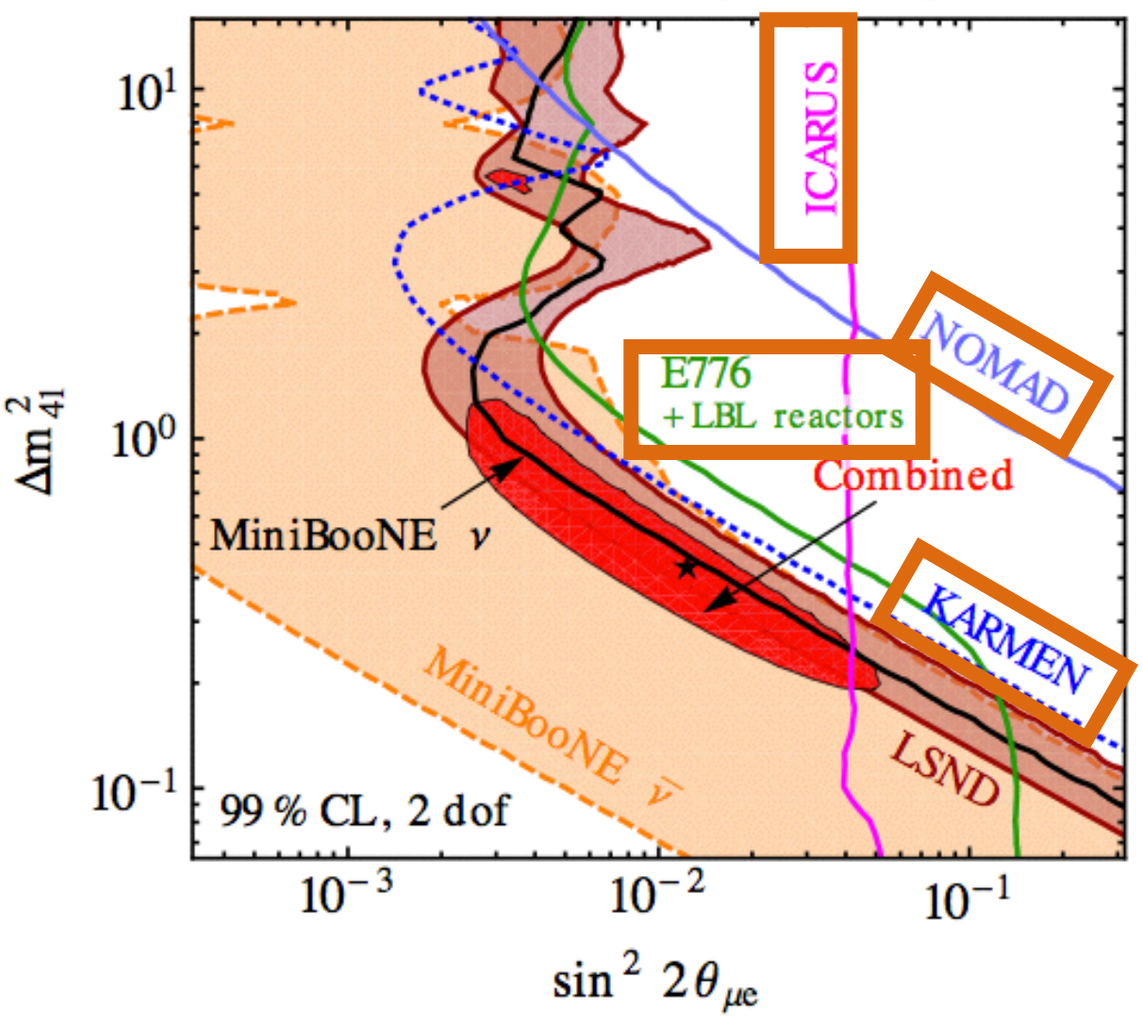
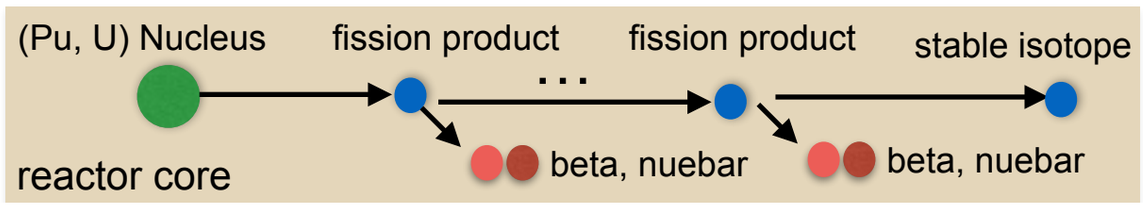
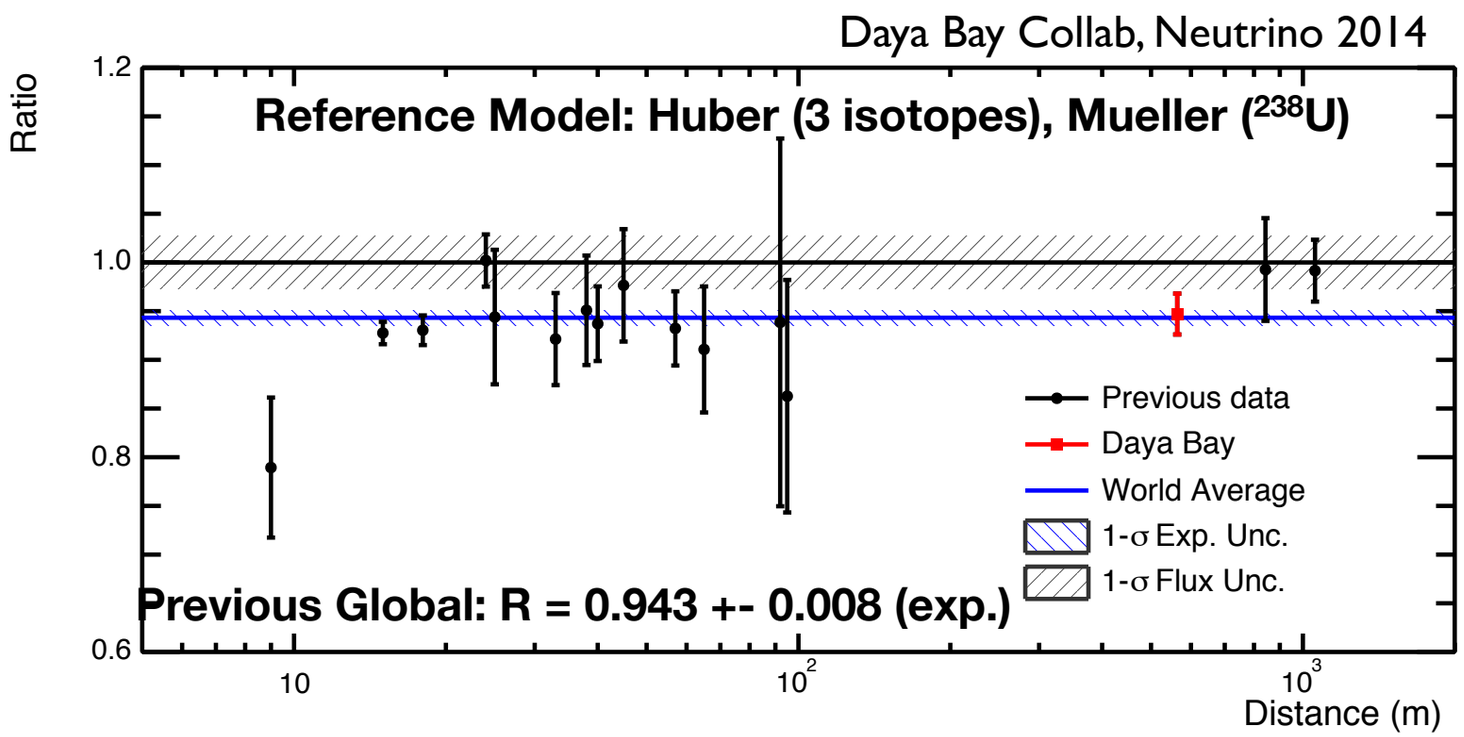
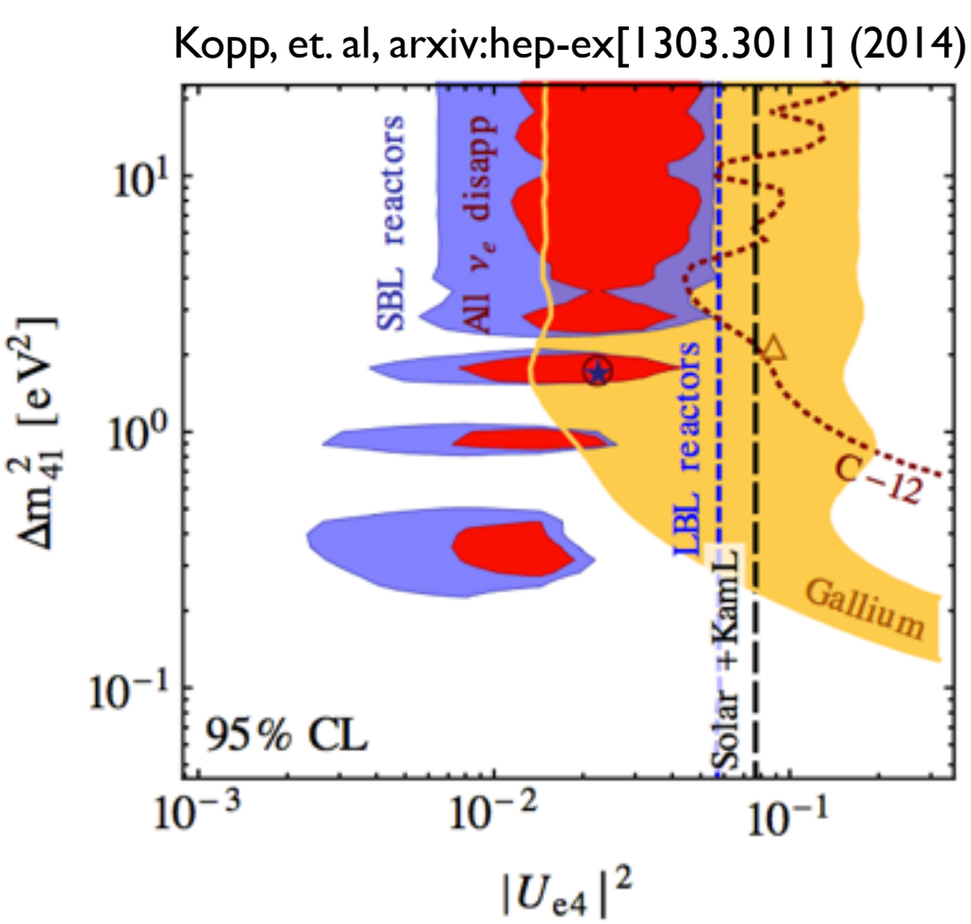


Hints For Alternate Δm^2 : $\overline{\nu}_e \rightarrow \overline{\nu}_e$

- 'Reactor anomaly': ~6% deficit in measured reactor $\overline{\nu}_e$ flux
  - Recently re-confirmed at Daya Bay (Neutrino 2014)
  - Also weak hints of spectral distortions at shortest baselines (ILL)
- 'Gallium anomaly': deficit in ν_e flux measured from large radioactive source
  - Observed with both Ar and Cr neutrino sources



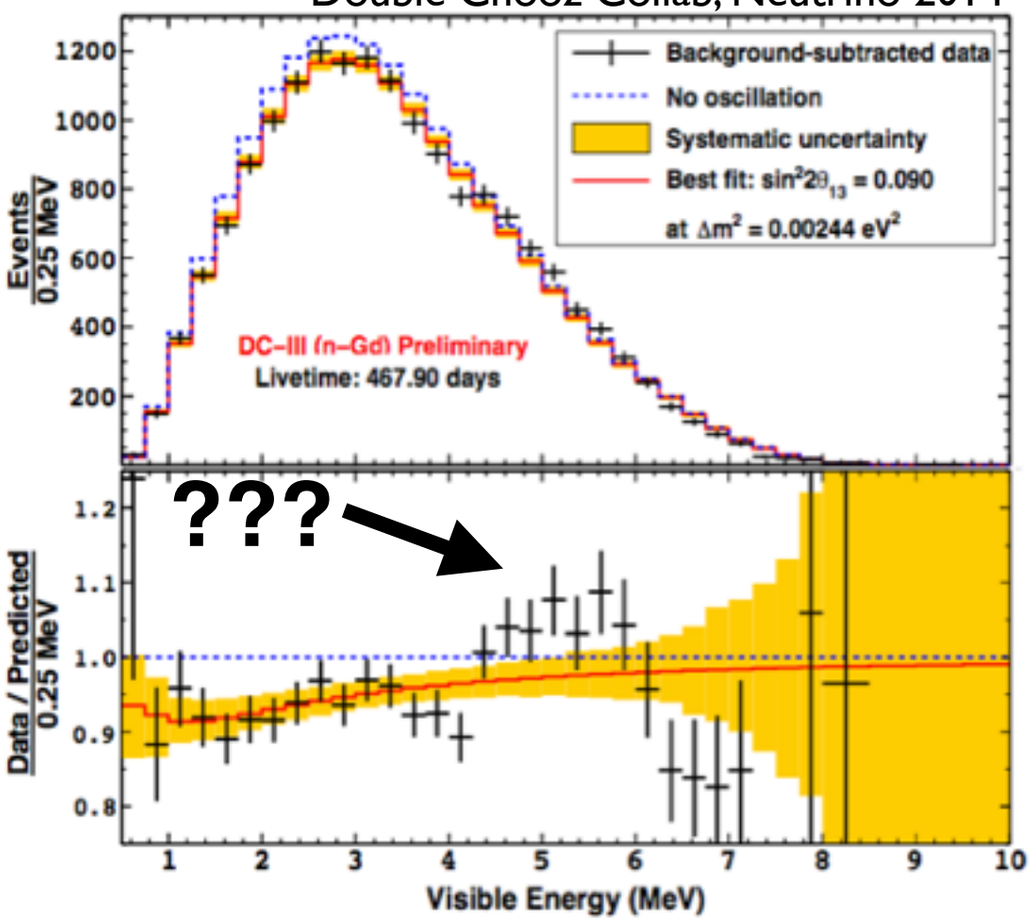




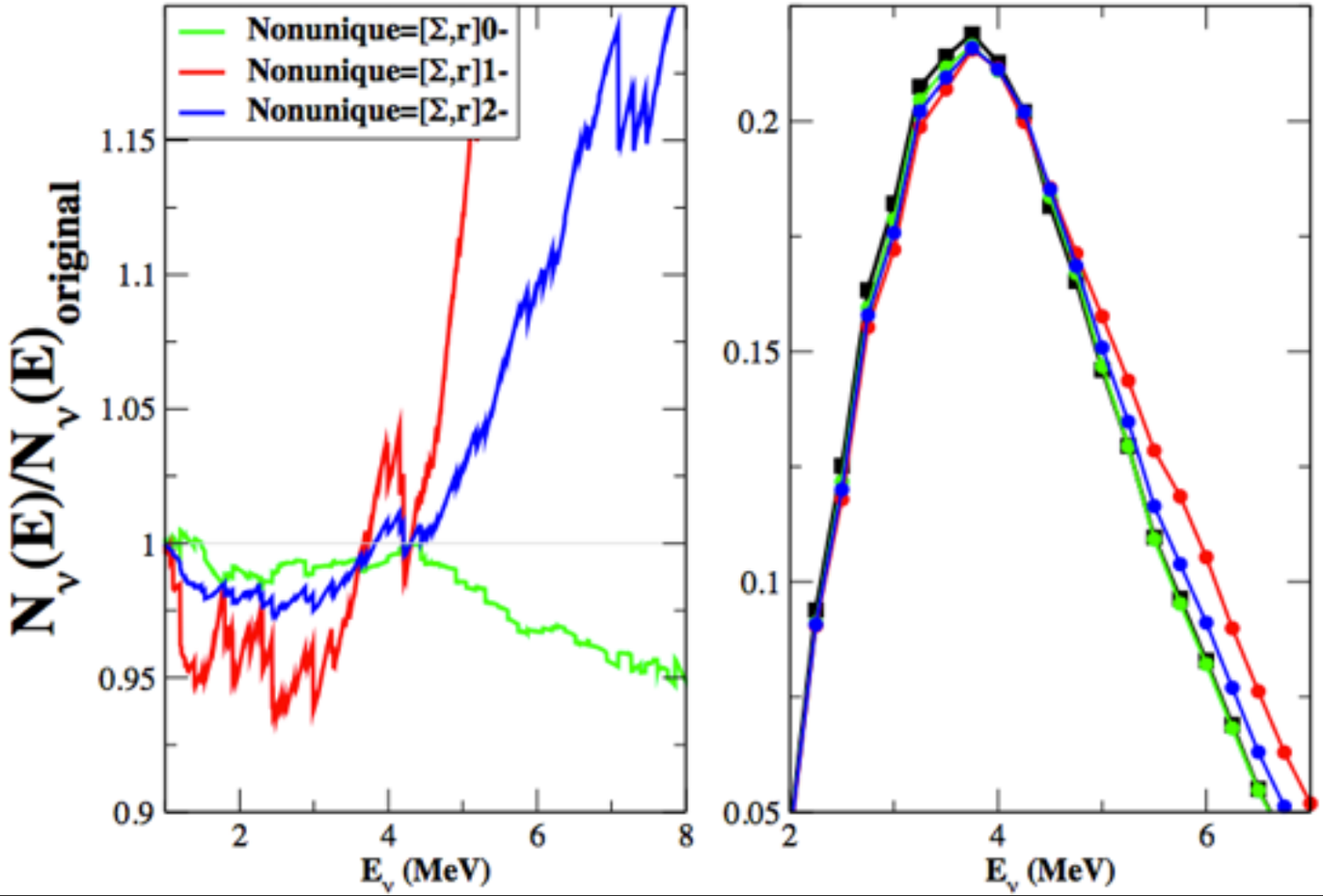
For The Skeptics…

- Alternate (untested!) theories for disappearance results exist
  - How to model spectral shapes 10k+ reactor fission product beta branches, many of which are highly forbidden?
  - A. Hayes, *et. al.,* PRL 112 (2014): Flux/spectral uncertainties more like 5%?
  - Hints of improper spectral modeling (Double Chooz, RENO, Neutrino 2014)
  - Decay rate to excited Cr, Ar states are also ‘uncertain in uncertain ways’

Double Chooz Collab, Neutrino 2014



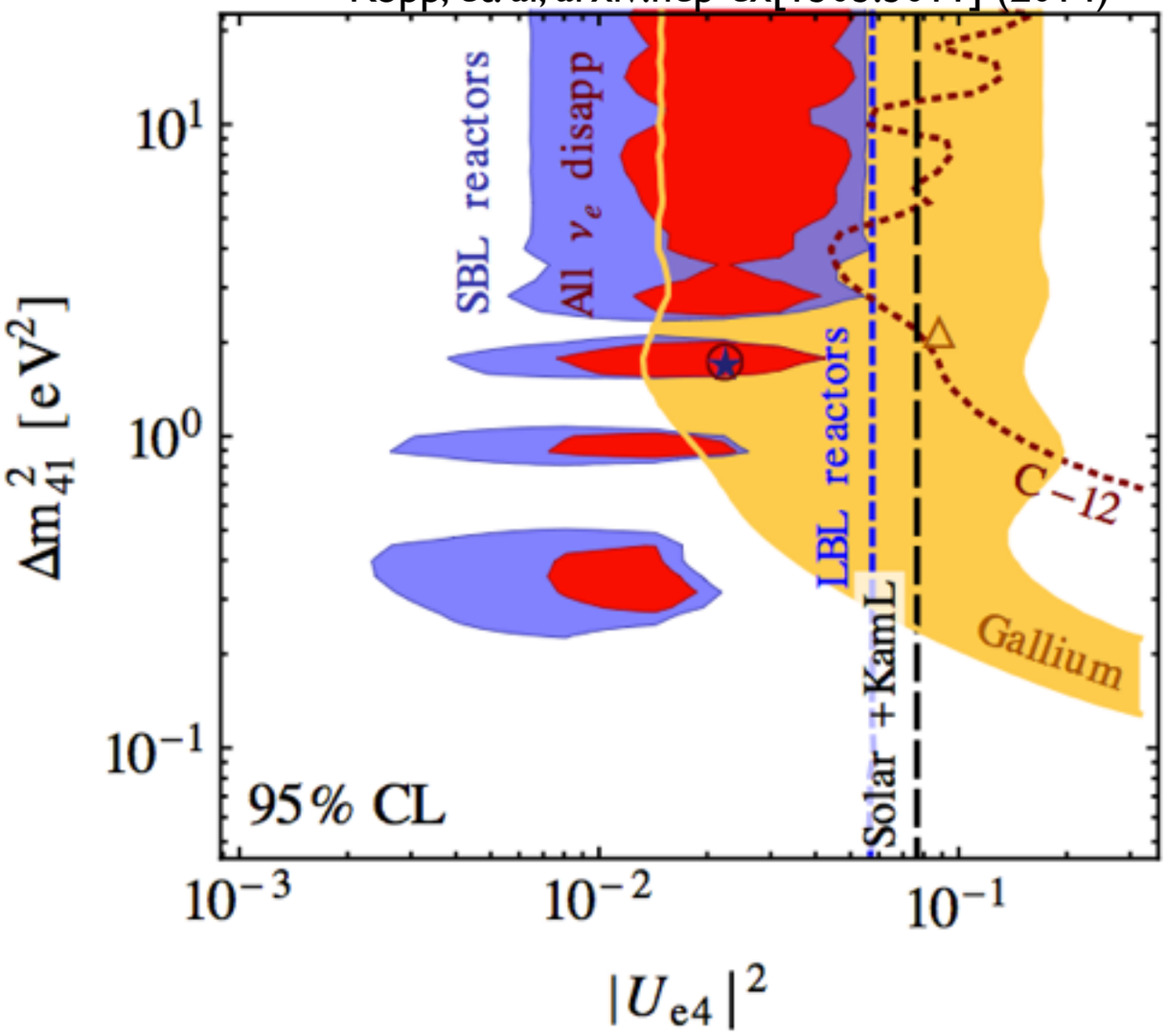
G. Garvey, Neutrino 2014



Anomalous Results: A Consistent Picture

- LSND, MiniBooNE, reactor, and gallium data all point to a similar region of Δm^2 space: ~0.2-10 eV^2
- Indicates that all anomalies could be caused by the same sterile neutrino(s)

Kopp, et. al, arxiv:hep-ex[1303.3011] (2014)



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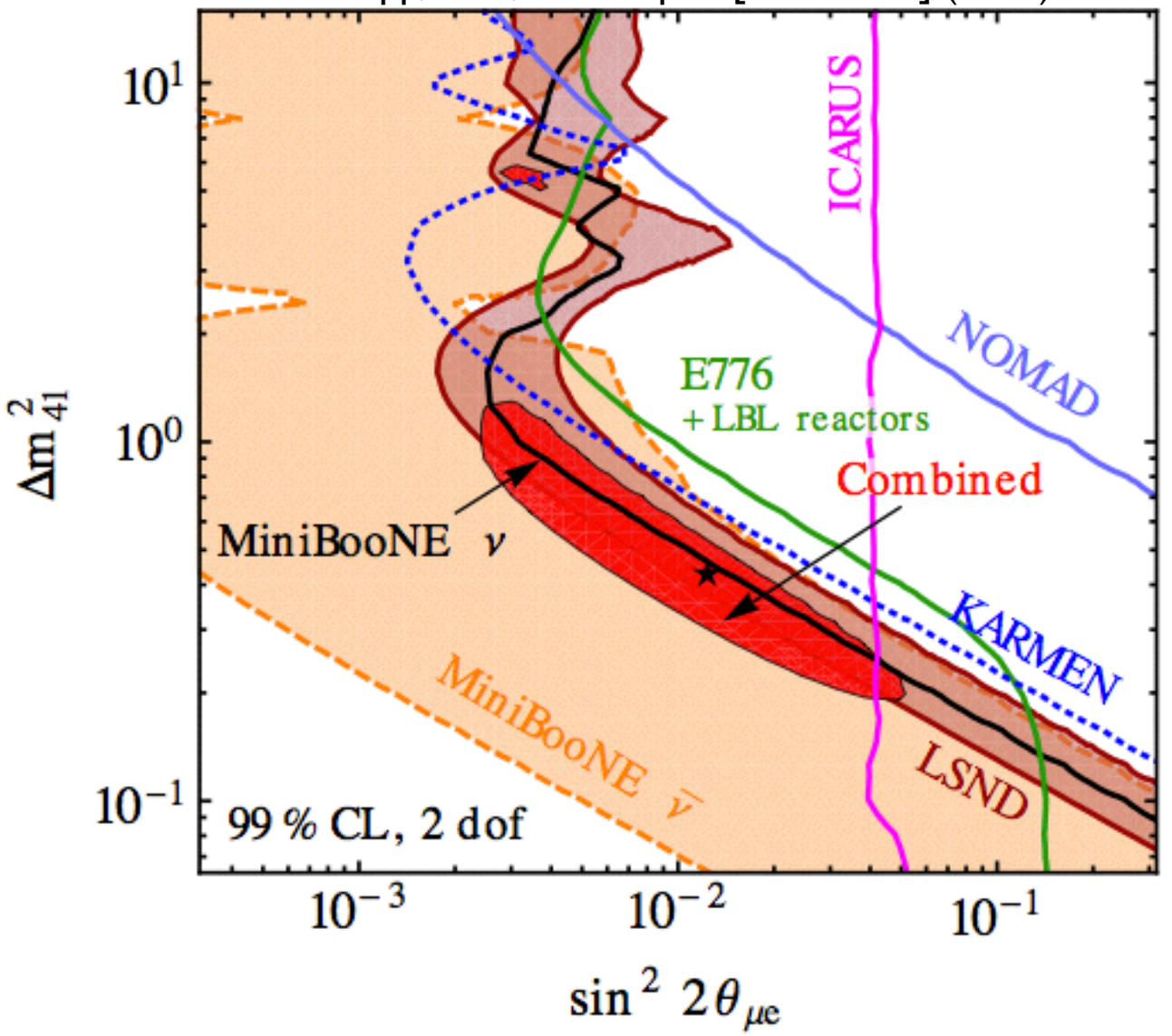
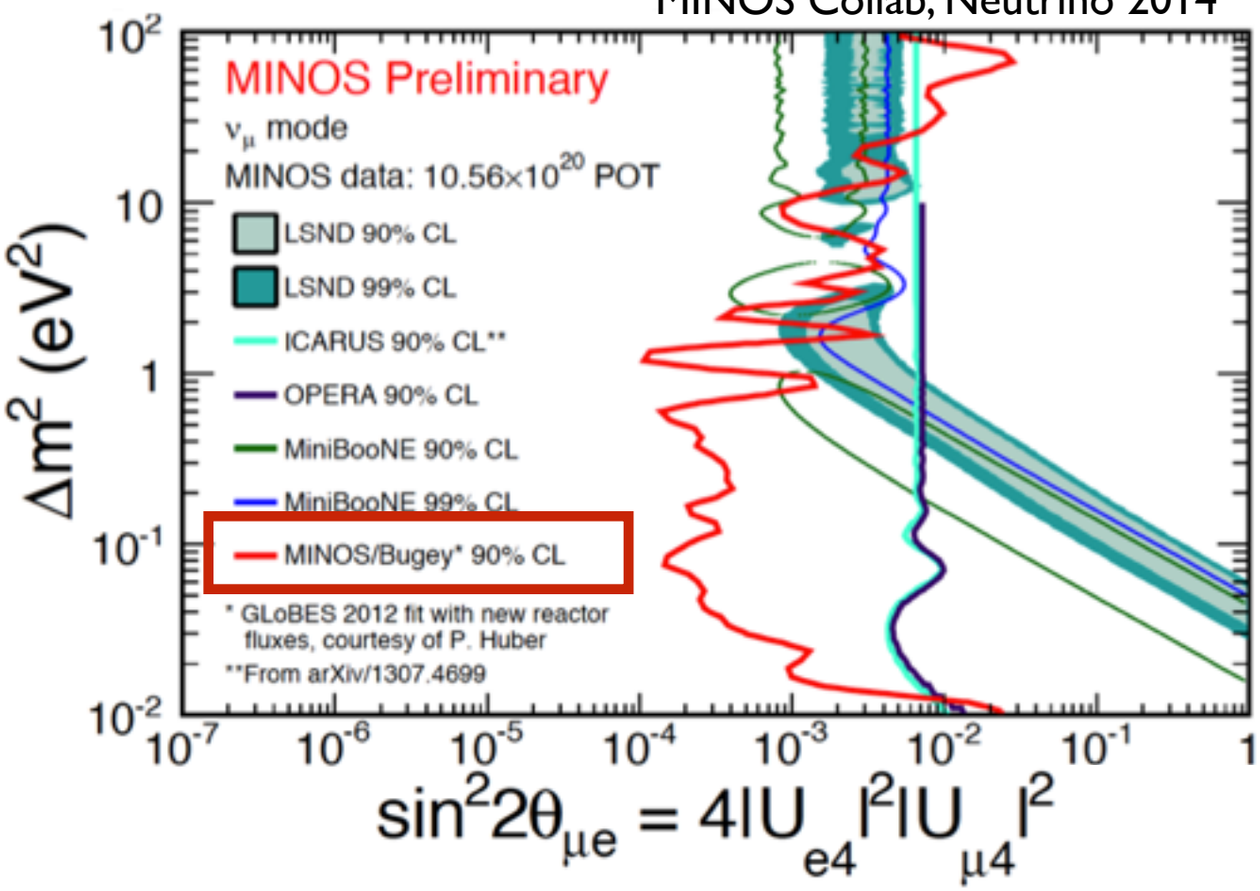


For The Skeptics…

- No evidence of ν_μ disappearance at these Δm^2
  - New, more sensitive null result from MINOS at Neutrino 2014
  - Combination of disappearance experiments highly disfavors regions suggested by anomalies
- 3+1 hypothesis does not even fit mBooNE data all that well...

MINOS Collab, Neutrino 2014



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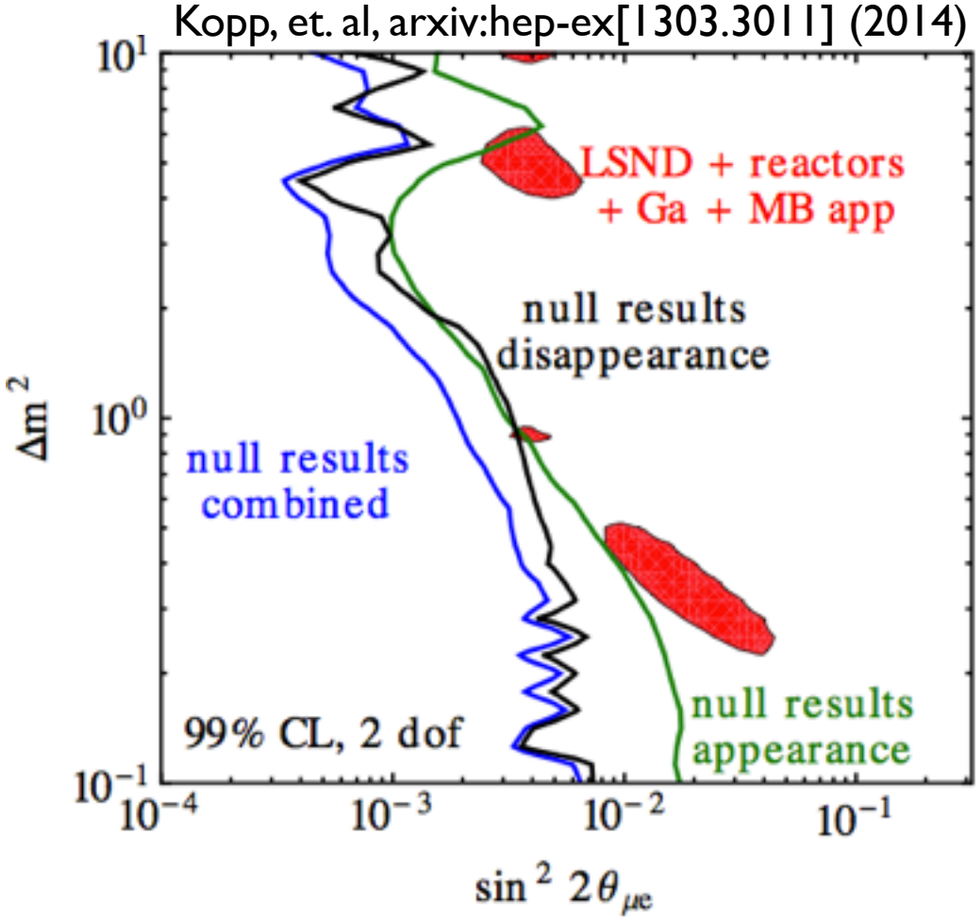
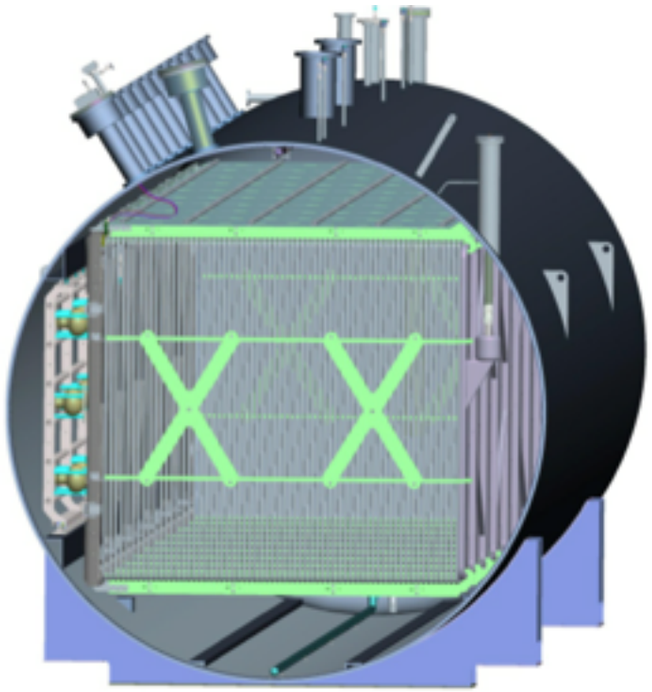
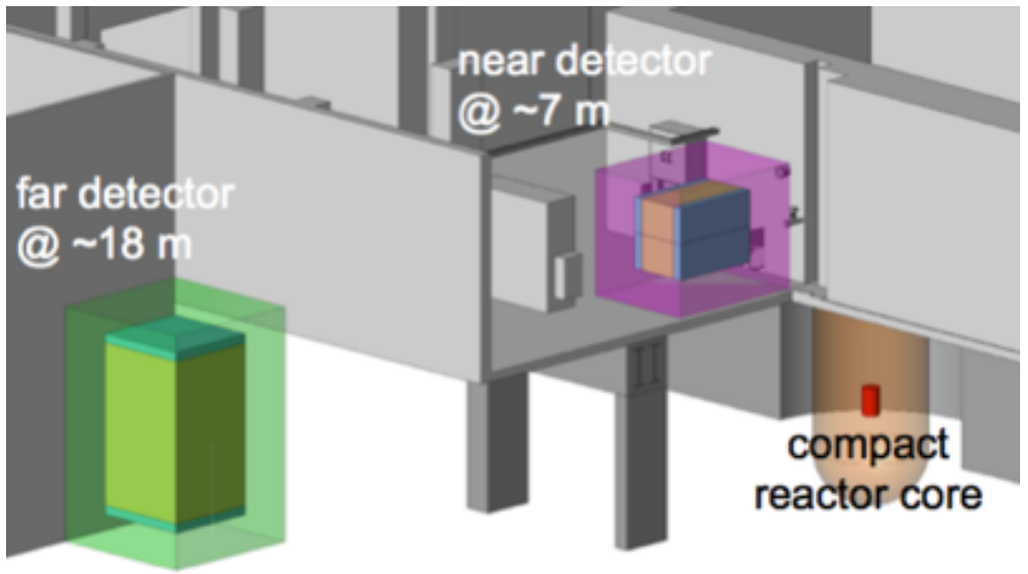


A Path Forward

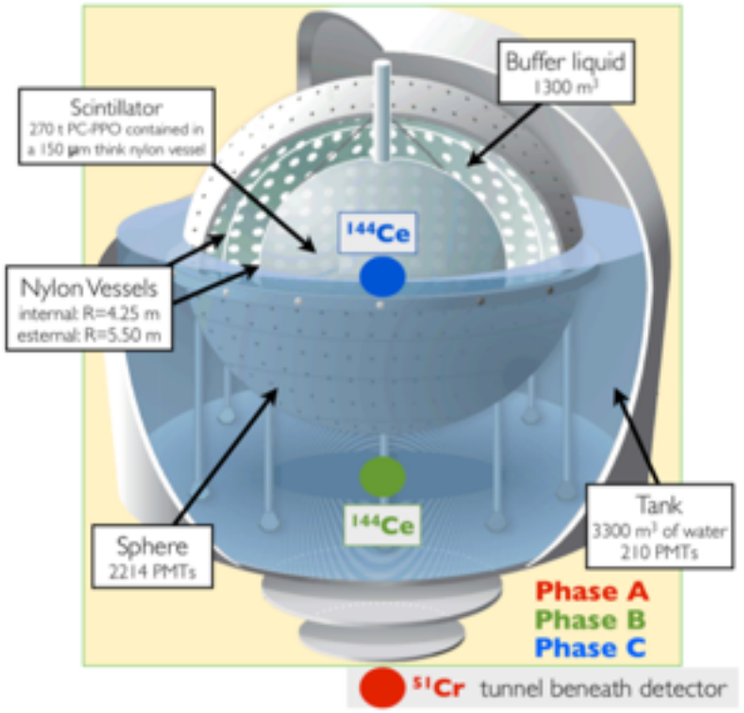
- Experimental evidence is clearly not sufficient to conclude that sterile neutrinos exist
- And yet, no single existing experimental result directly refutes the entirety of any of the existing anomalies.
- Need new direct tests of anomalies, ν_s hypothesis
  - $\nu_\mu \rightarrow \nu_e$: A new generation of SBL experiments in Fermilab Booster beamline
  - $\nu_e \rightarrow \nu_e$: A new generation of radioactive source and SBL reactor experiments



MicroBooNE in BNB at Fermilab



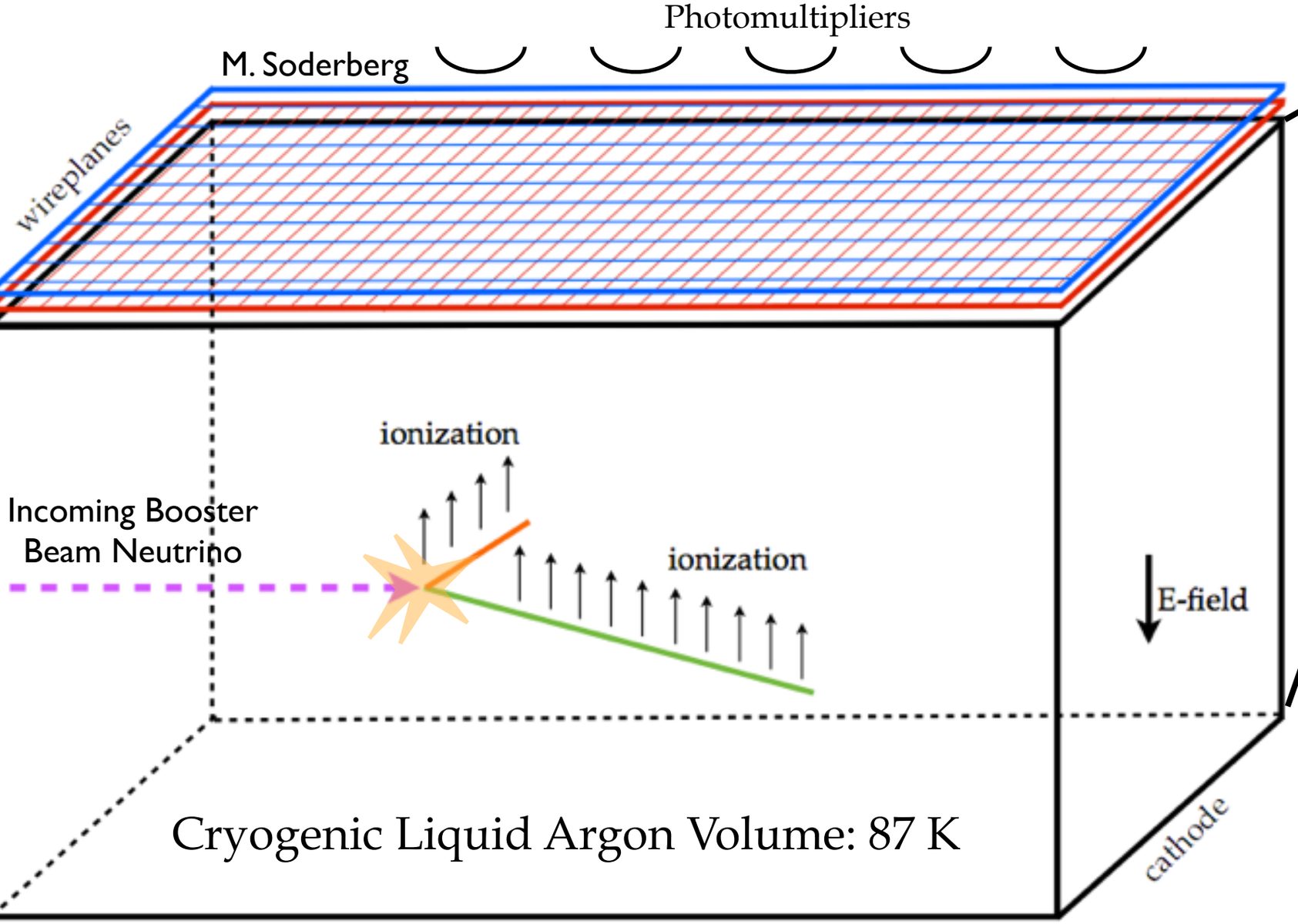
PROSPECT Experimental Setup

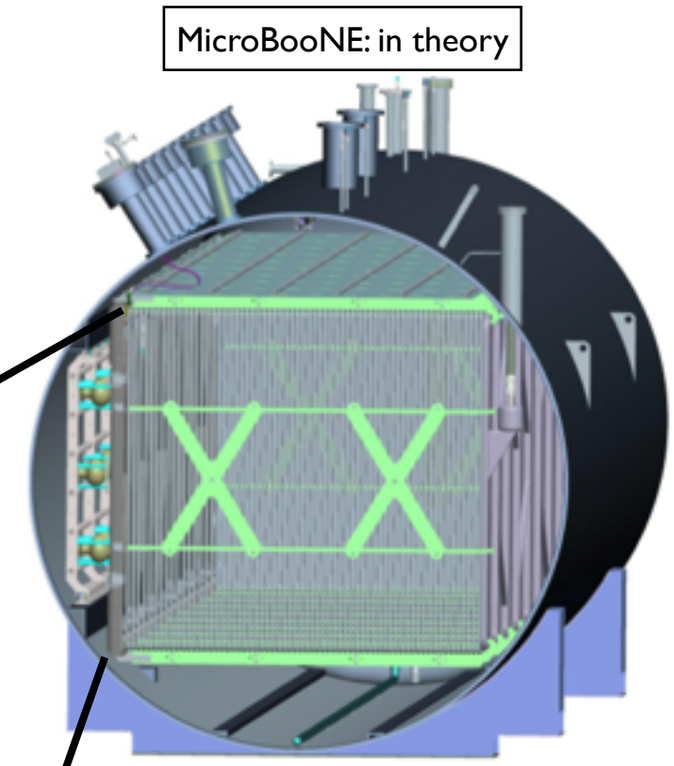


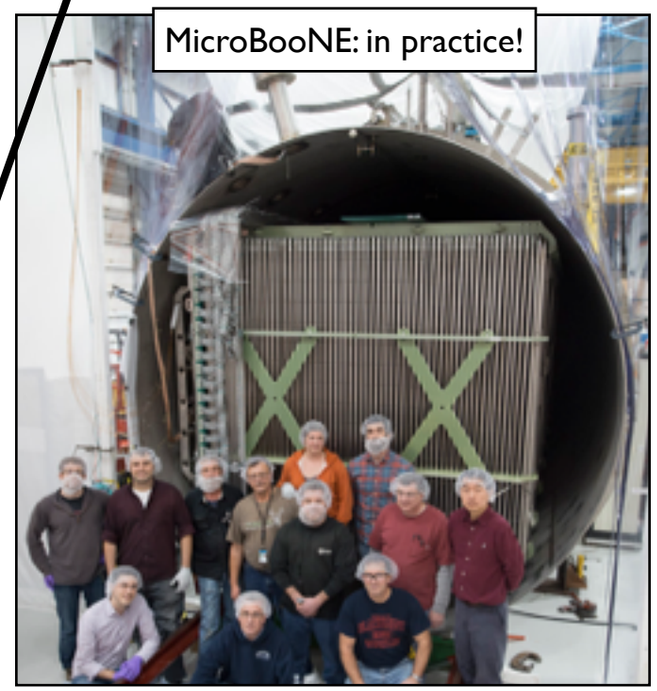
CeSox Experimental Setup

Short-Baseline LArTPCs

- Interaction ionization drifted meters along uniform E-field toward finely spaced wire planes; 3D position from position + scintillation light timing

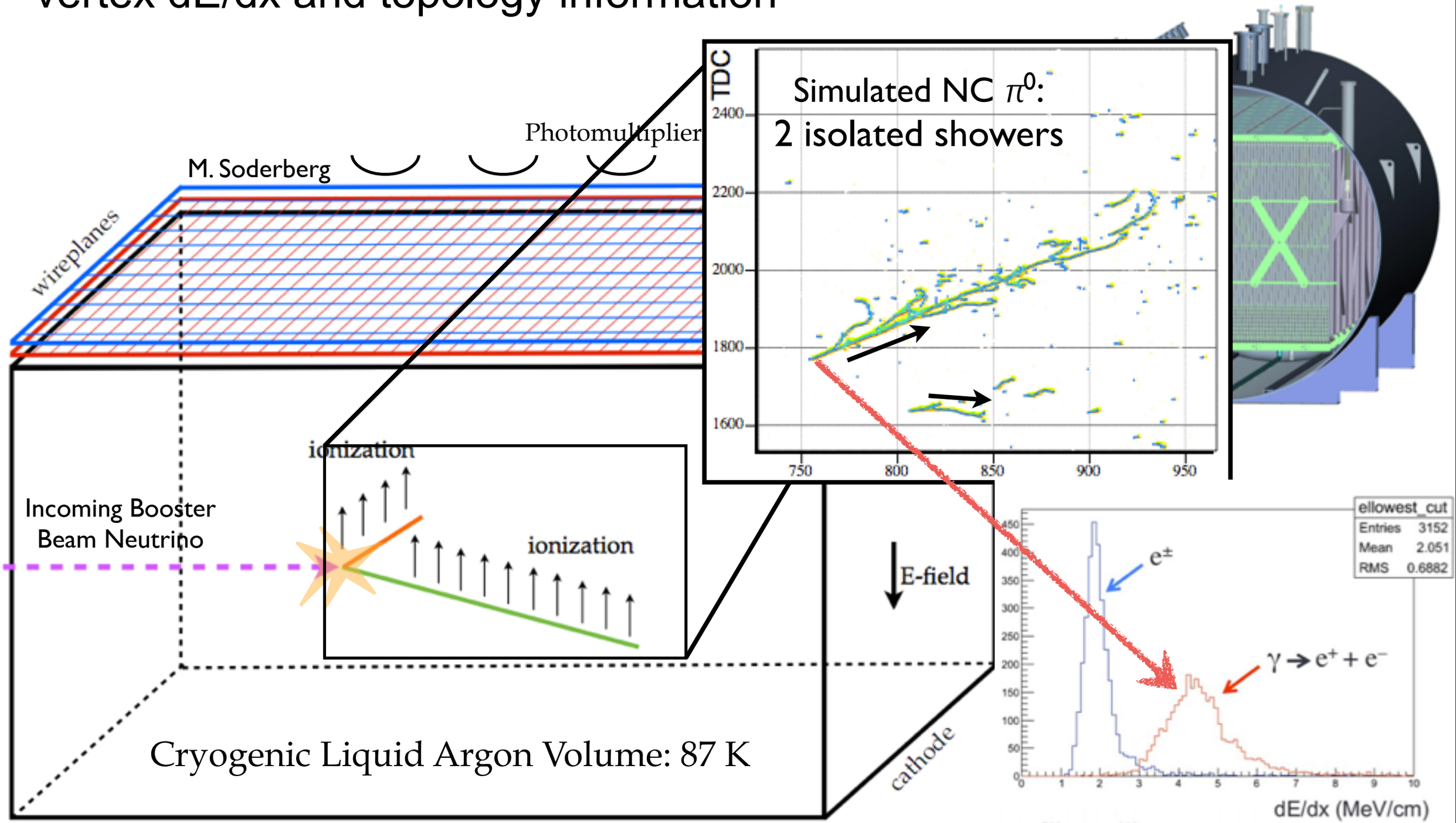






Short-Baseline LArTPCs

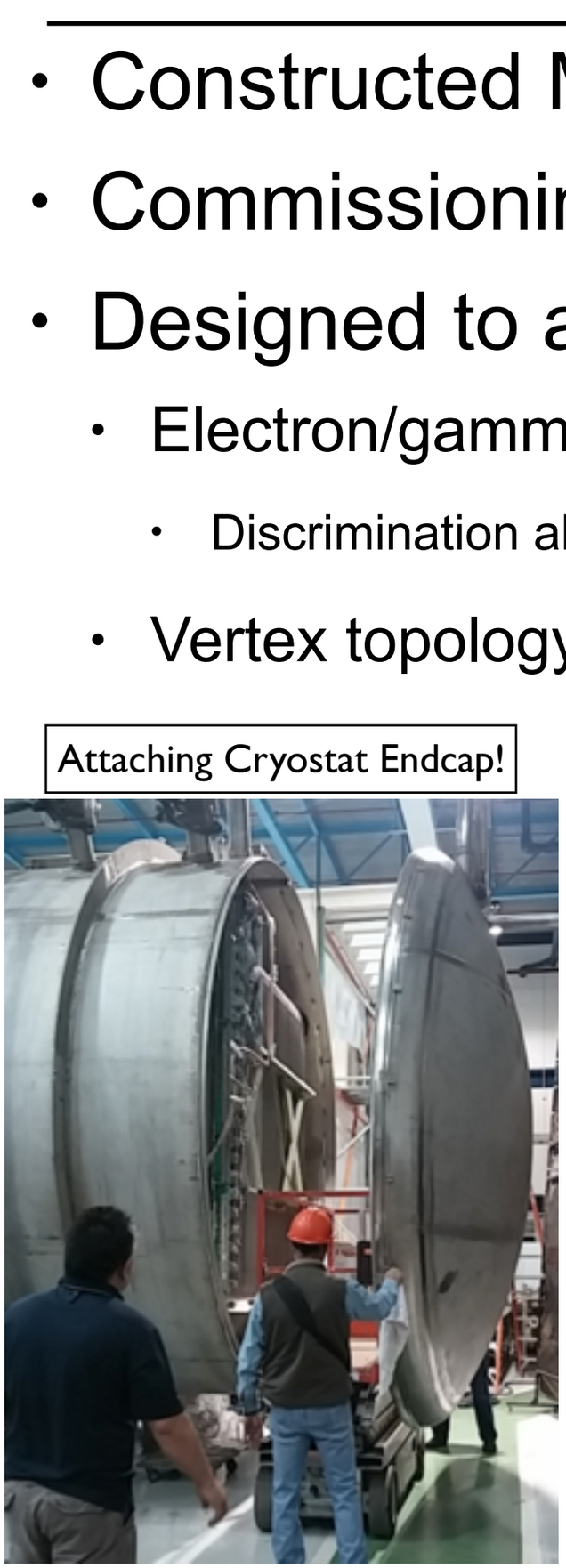
- Interaction ionization drifted meters along uniform E-field toward finely spaced wire planes; 3D position from position + scintillation light timing
- Discriminate major MiniBooNE background, gammas, using vertex dE/dx and topology information



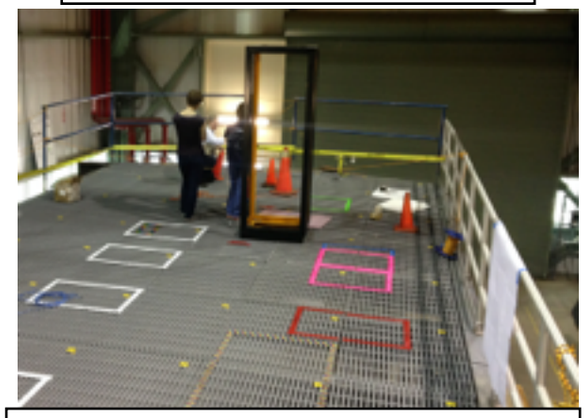
MicroBooNE: Status and Potential

- Constructed MicroBooNE TPC will be installed this month
- Commissioning in Fall 2014, beam data afterwards
- Designed to address MiniBooNE excess at 5σ CL
  - Electron/gamma dE/dx separation expected to be 90% or betterL
    - Discrimination ability demonstrated for first time in Argoneut data (Neutrino 2014)
  - Vertex topology information could further increase rejection factor

Attaching Cryostat Endcap!

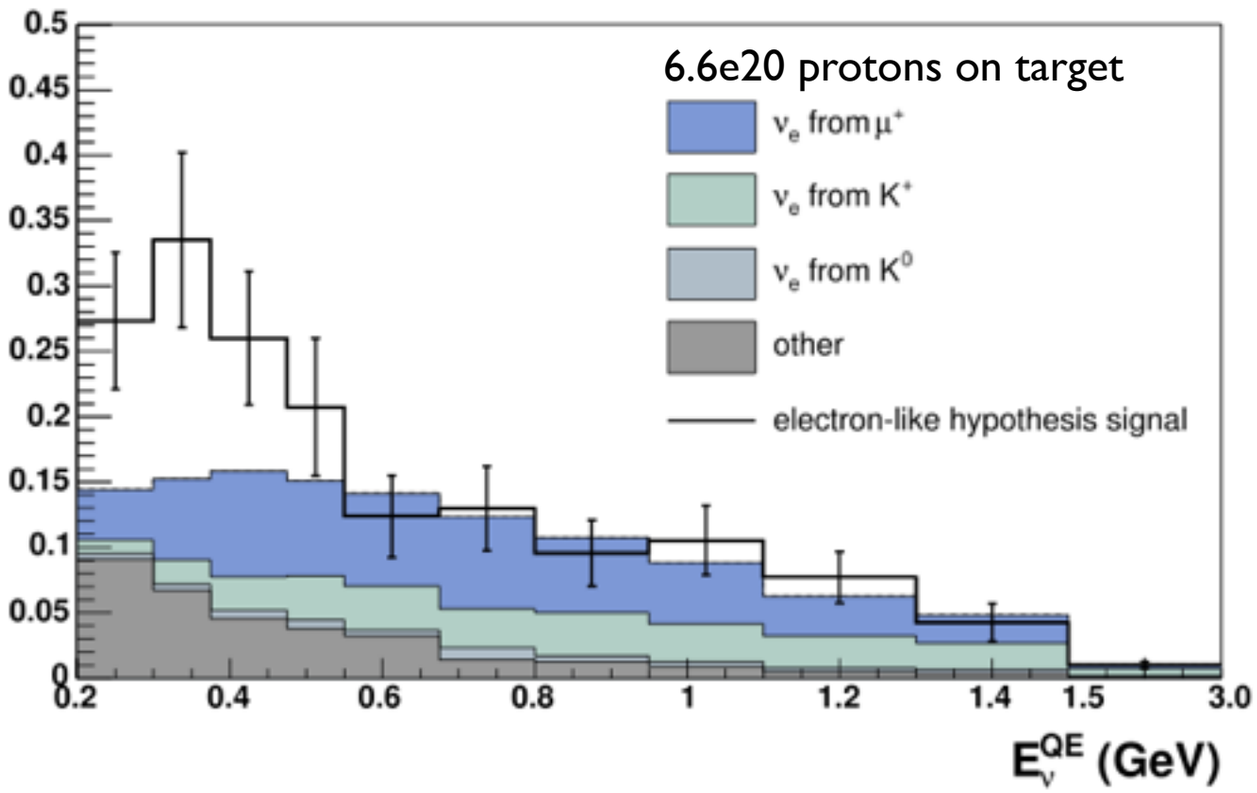


DAQ, Network Installed



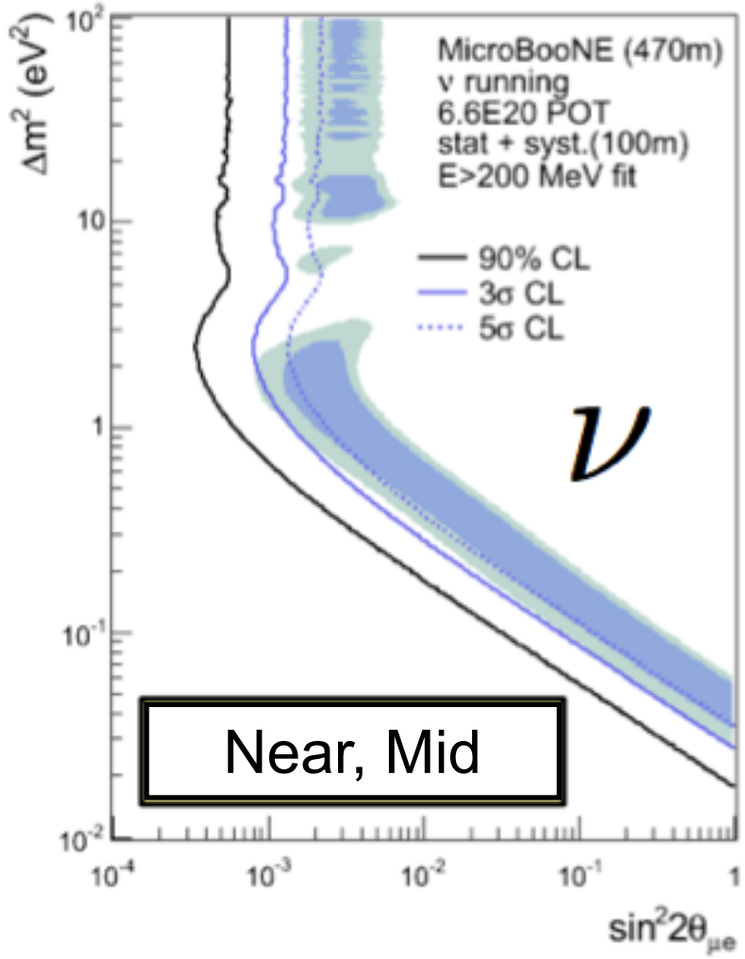
Prepping Above-TPC Platform

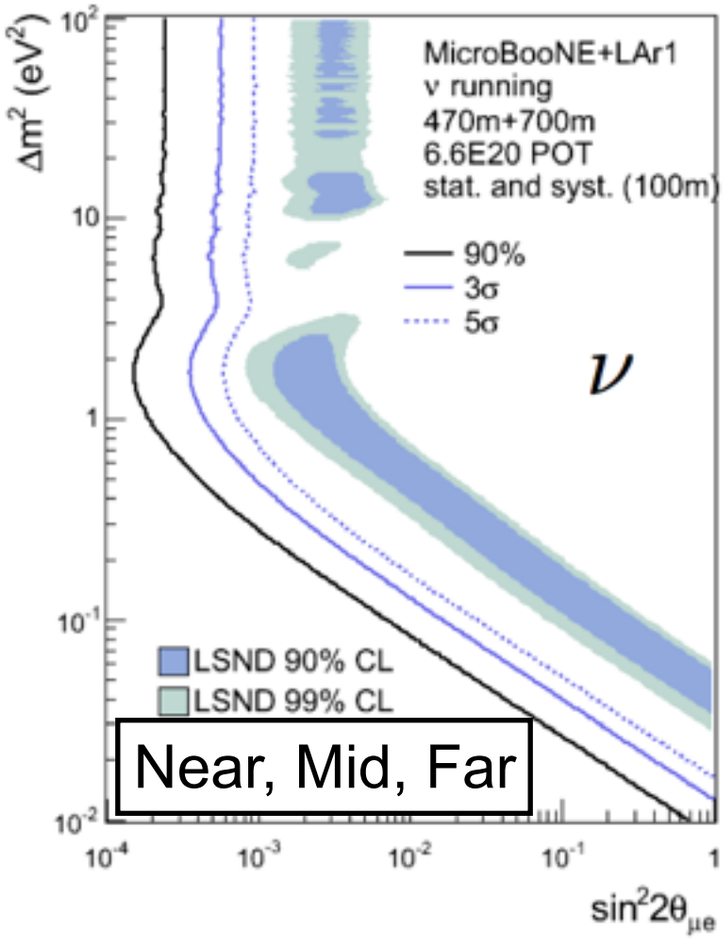
MicroBooNE, if excess is ν_e-like

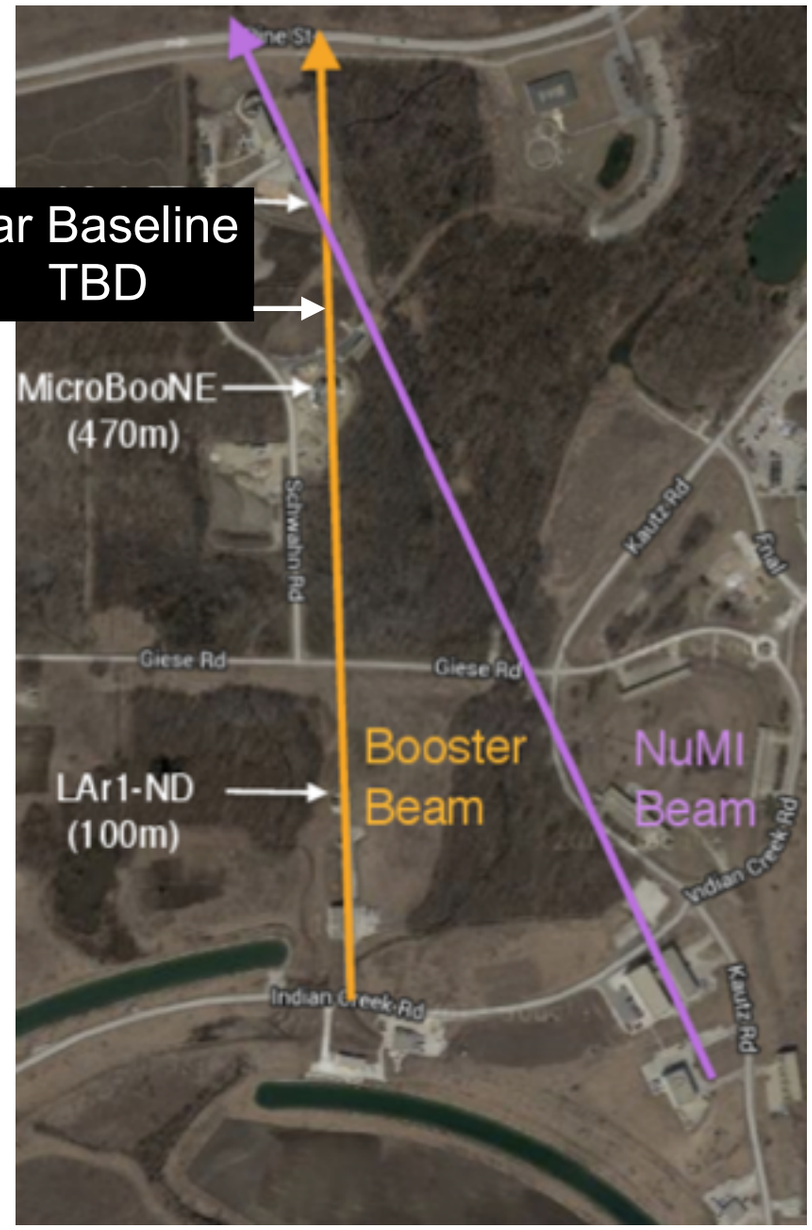


Fermilab Short-Baseline LArTPC Program

- Proposals to install additional near LArTPC (LAr-ND), additional LArTPC (ICARUS) closer to oscillation maximum
- Relative appearance measurement goes well beyond MicroBooNE in sensitivity



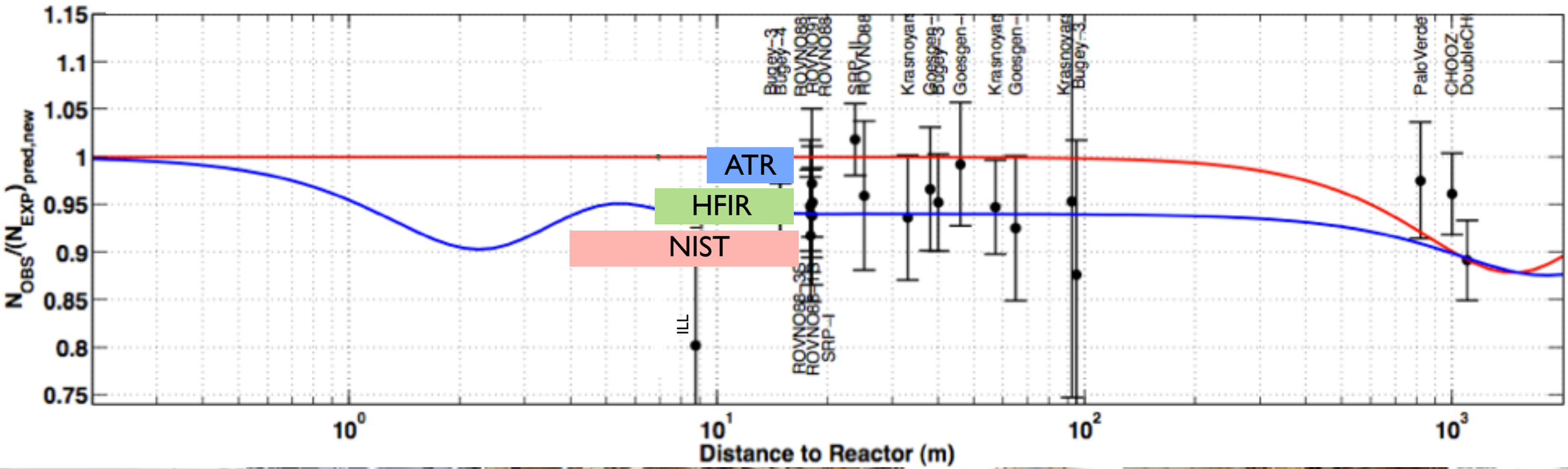




- P5-endorsed plan encourages pre-LBNF US-Europe LAr collaboration, Demonstrate design principles for LBNF TPC

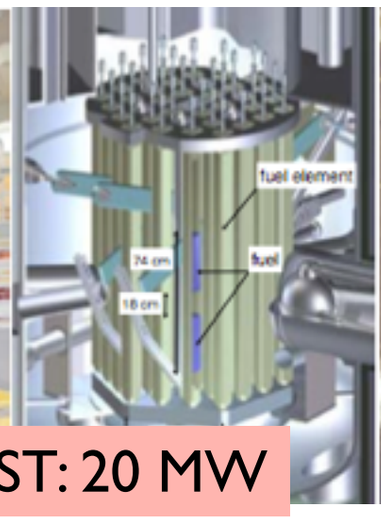
Short-Baseline Reactors: PROSPECT

- Need an MeV-scale short-baseline (SBL) probe of L/E behavior
  - Absolute reactor flux checks are nice, but not good enough
- Research reactors provide a venue for oscillation searches at shortest-ever reactor baselines



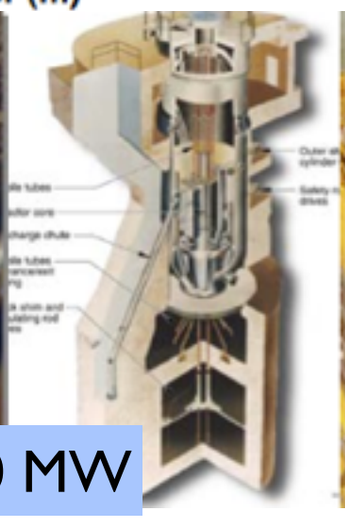
NBSR@NIST: 20 MW

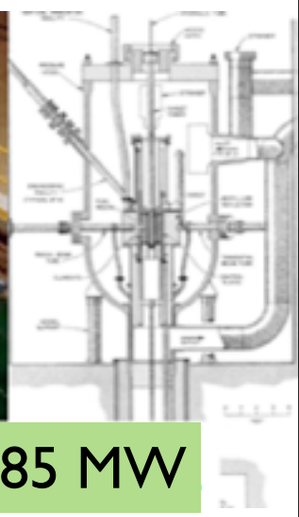
Gaithersburg, MD



ATR@INL: 110 MW

Idaho Falls, ID





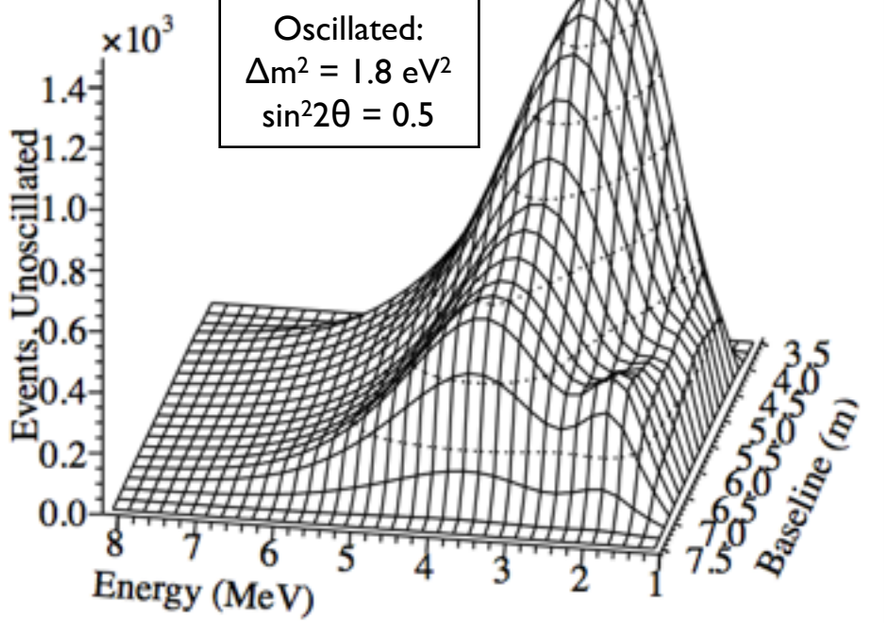
HFIR@ORNL: 85 MW

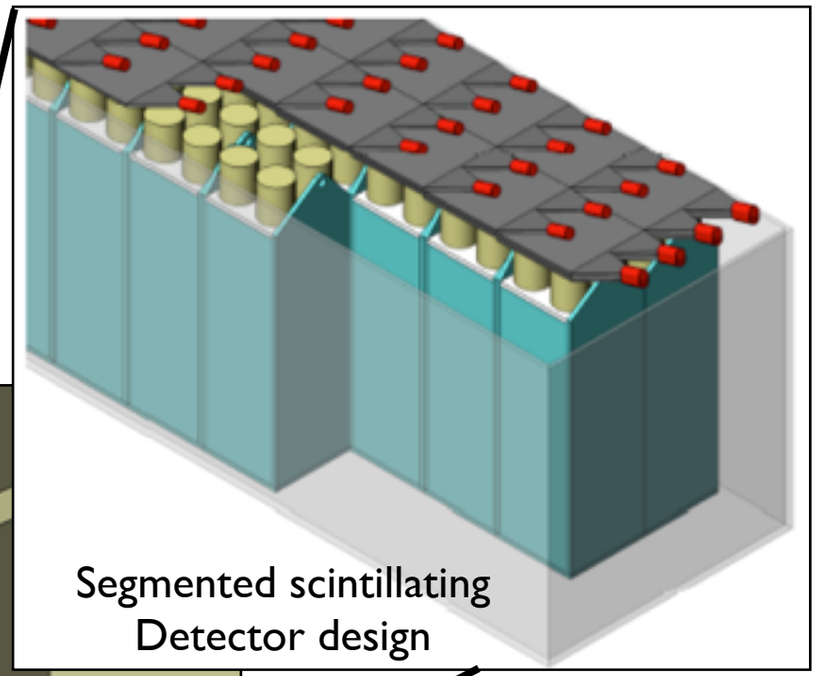
Oak Ridge, TN

Short-Baseline Reactors: PROSPECT

- Segmented scintillator detectors at short baselines from compact reactor core detect IBD e+ spectrum distortion with position

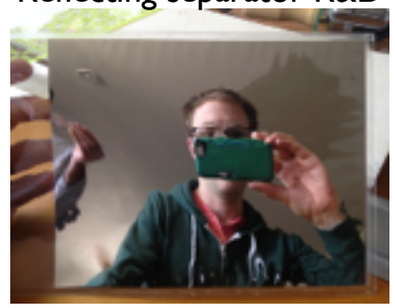
σ_p = 15cm; σ_E = 10% /$\sqrt{E}$



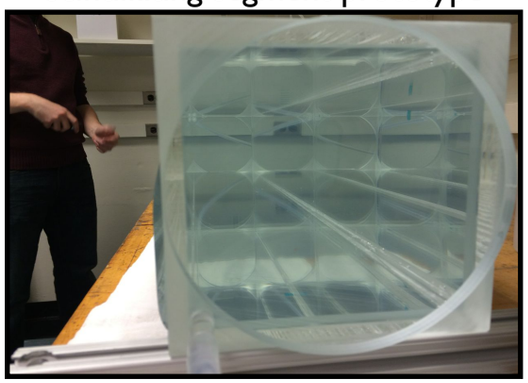


Segmented scintillating Detector design

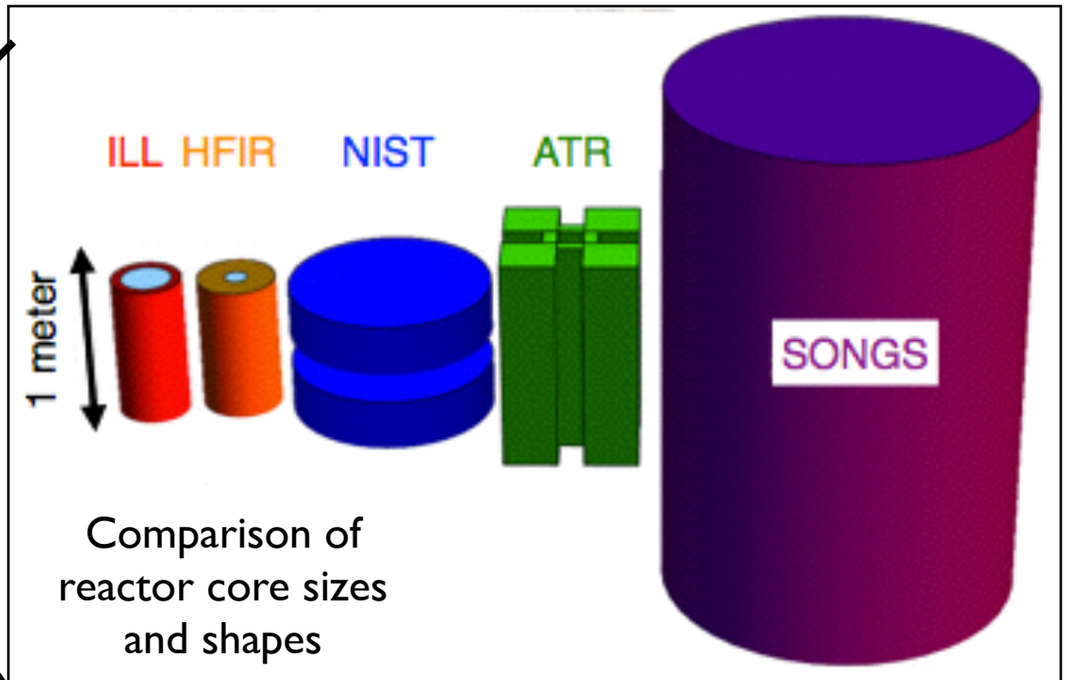
Reflecting separator R&D



Scintillating segment prototype



Example detector placement: HFIR

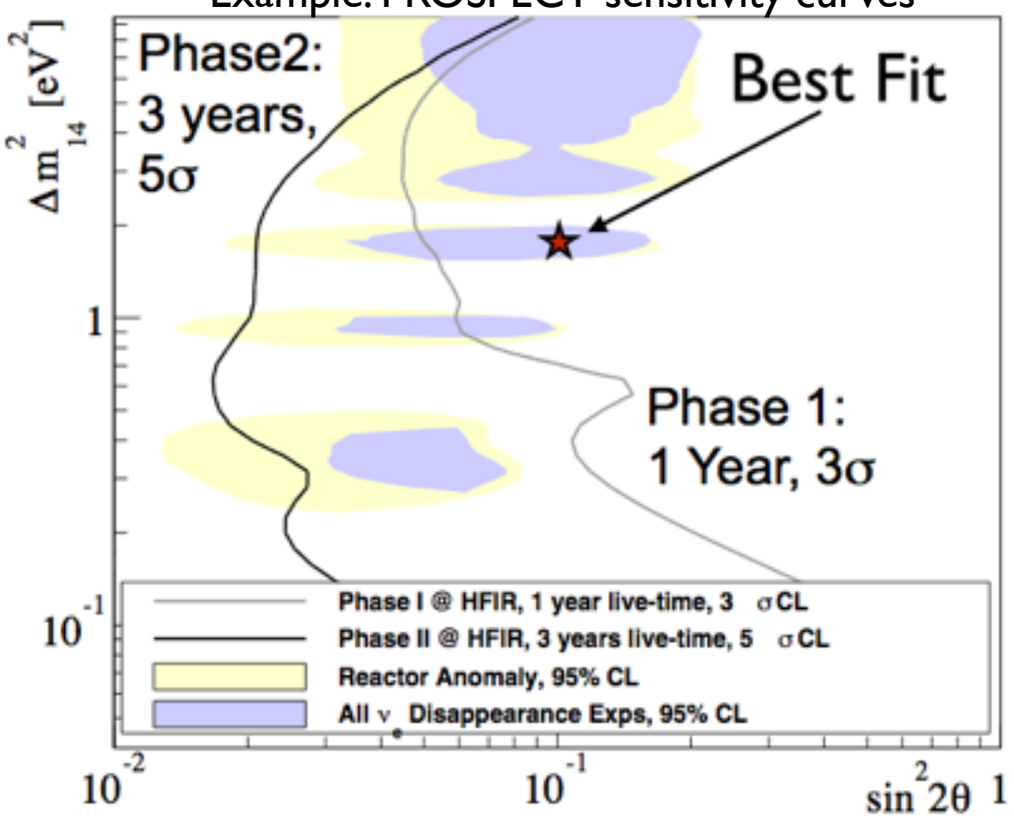


Comparison of reactor core sizes and shapes

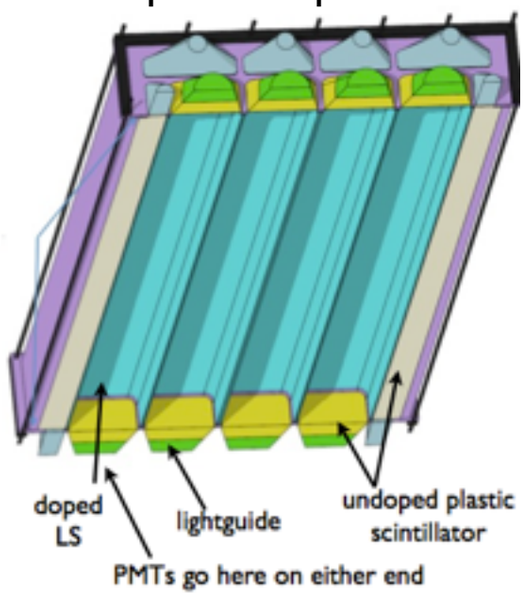
SBL Reactors: Sensitivity, Challenges

- Competing global efforts; complementary technologies for mitigating reactor, near-surface cosmogenic backgrounds
- Short timescales for data-taking: 2015-2016 start dates proposed for many efforts
- Potential to probe majority of suggested oscillation parameter space at high confidence level
- Low cost, high discovery potential (P5-recommended)

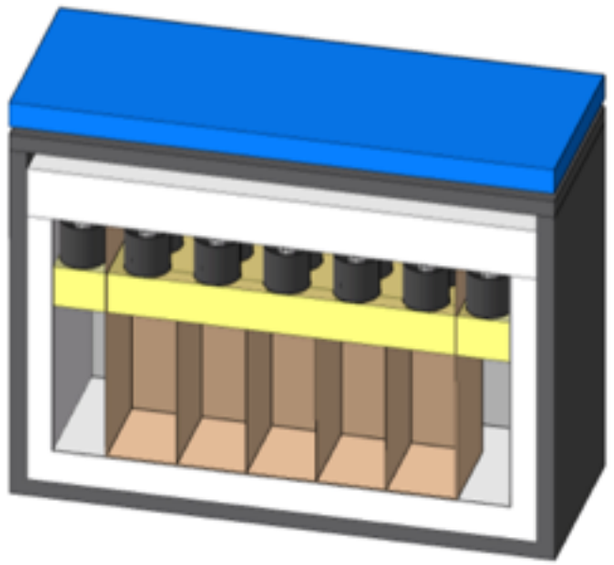
Example: PROSPECT sensitivity curves



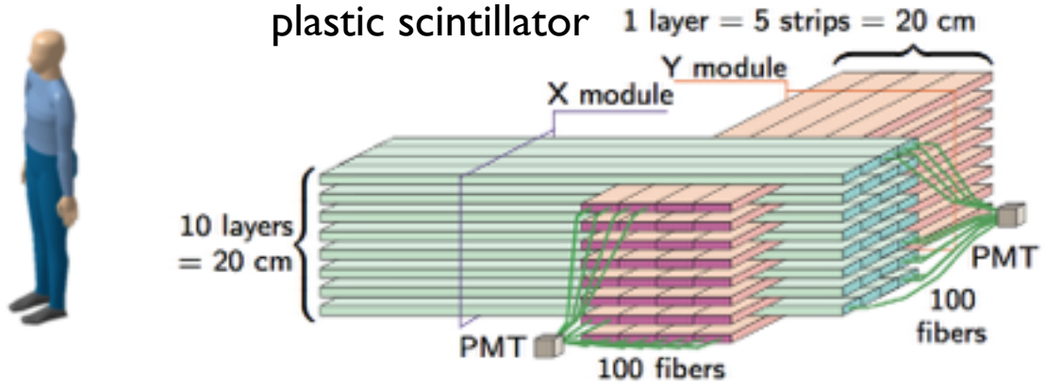
Prospect: Lithium-doped LS, with pulse-shape discrimination



STEREO: Large overburden, Gd-doped liquid scintillator

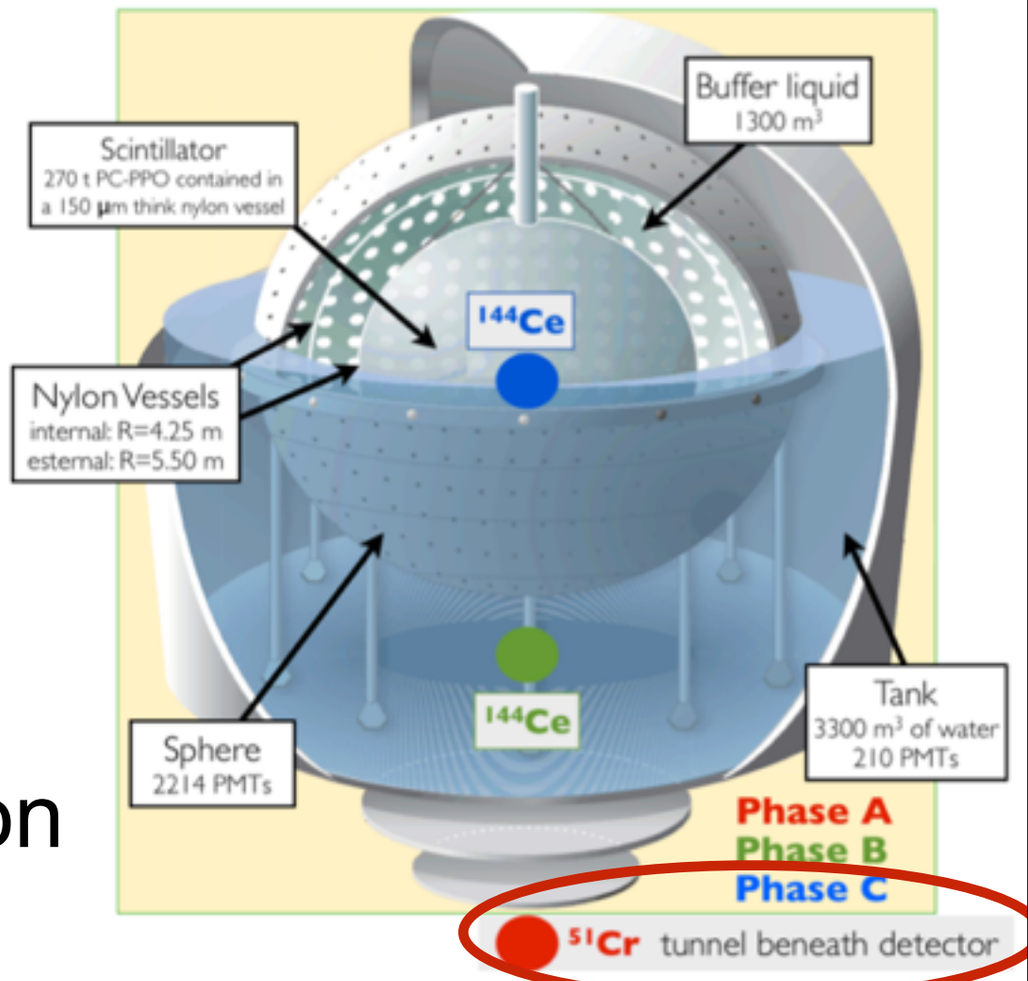


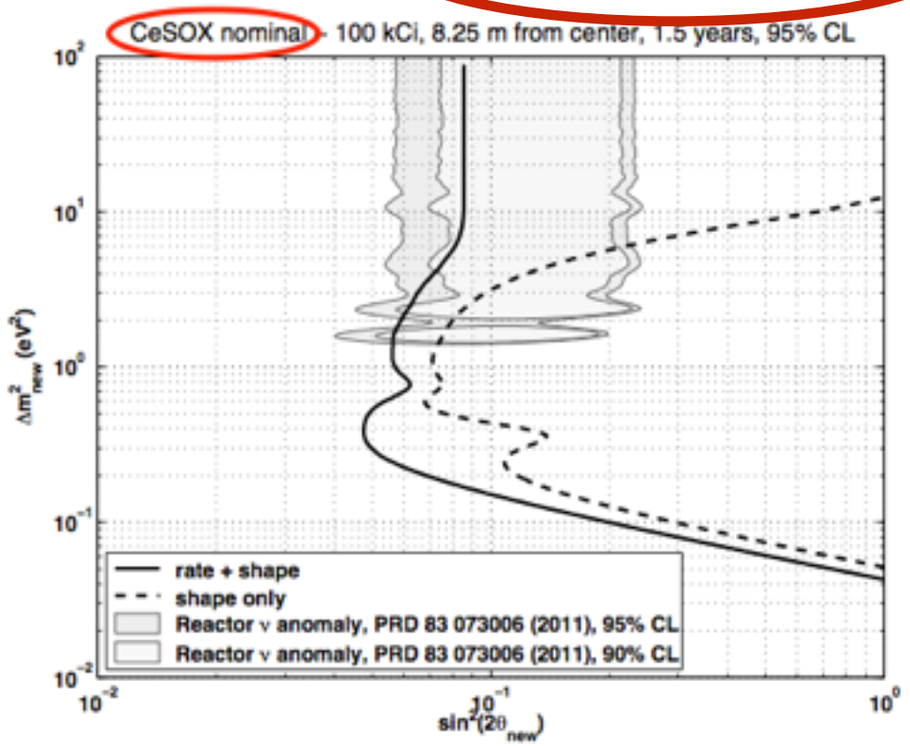
DANSS: Finely segmented plastic scintillator



Short-Baseline Source: CeSOX

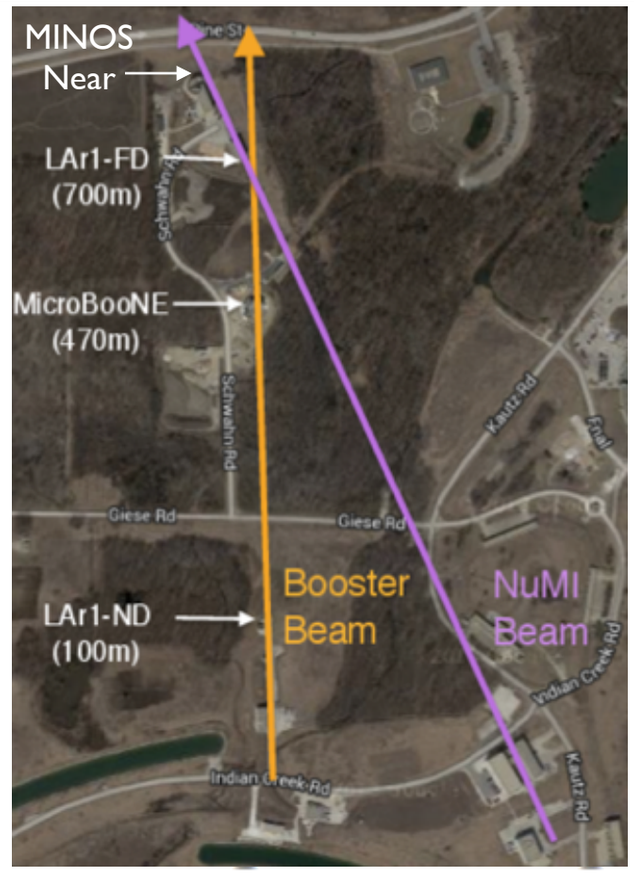
- ^{144}Ce $\bar{\nu}_e$ source (0-3 MeV) produced at Mayak (Russia) by 2015
- Source deployed in tunnel 8.25 m underneath Borexino target in 2015
- 10,000 detected ν_e in 1.5 years in un-altered Borexino detector
- Attempt to measure spectral distortion along with absolute flux deficit using calorimetric measurement
- Probe best-fit reactor anomaly space
- If something is seen, can optimize detector and/or deploy new source in closer location



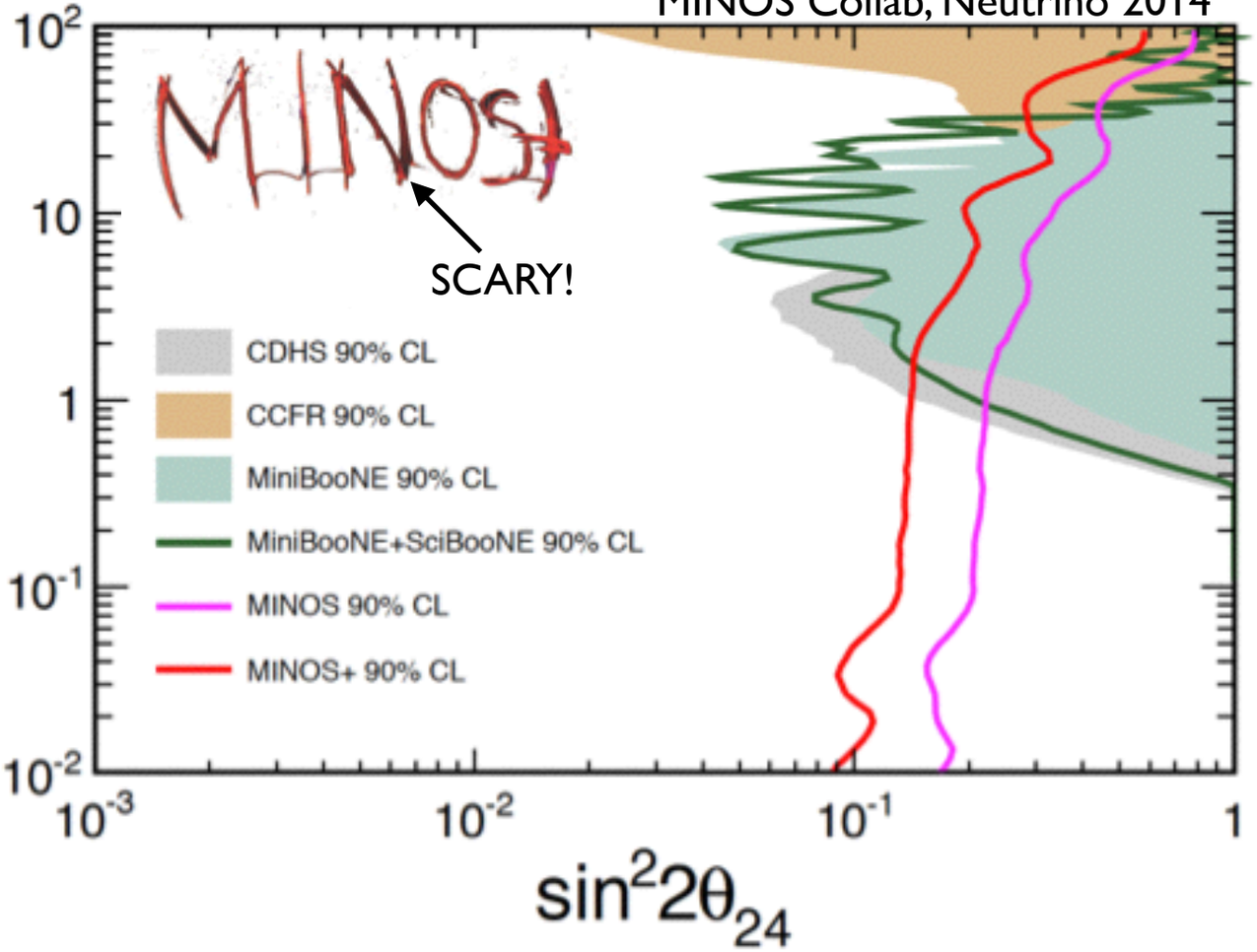


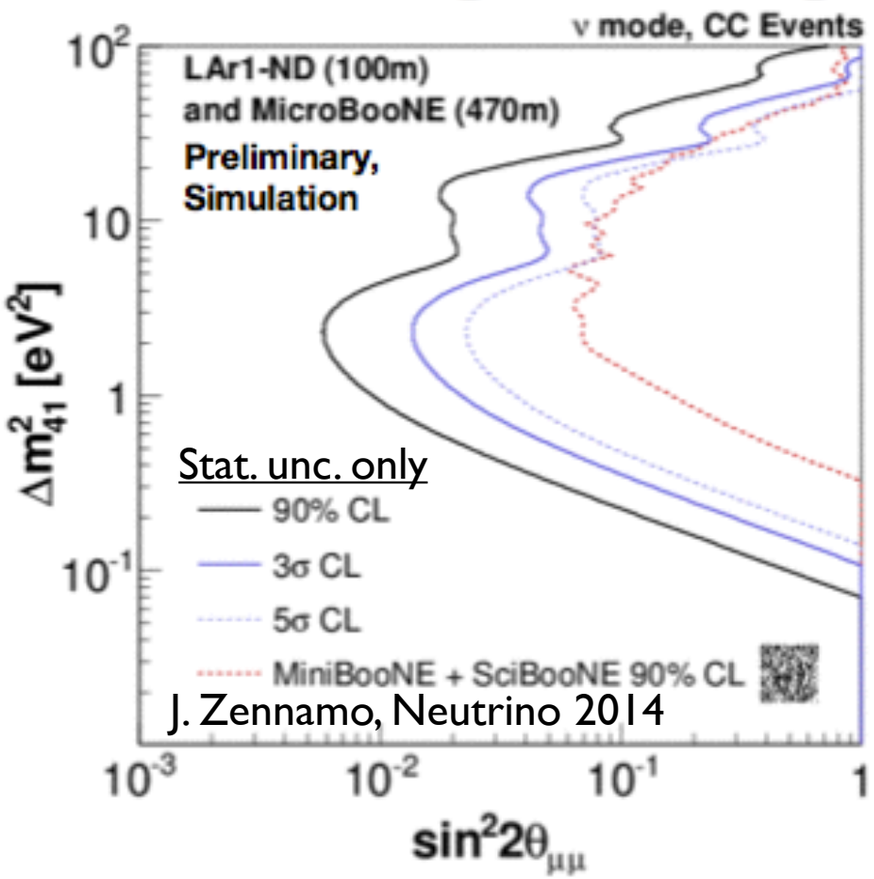
Future ν_μ Disappearance Measurements

- MINOS+: Higher energies, more statistics
- IceCube: Higher-energy atmospherics
- Combined ν_μ measurements at LAr1-ND, MicroBooNE, ICARUS cancels systematics
  - Not a direct test of existing anomalies, but still useful!



MINOS Collab, Neutrino 2014

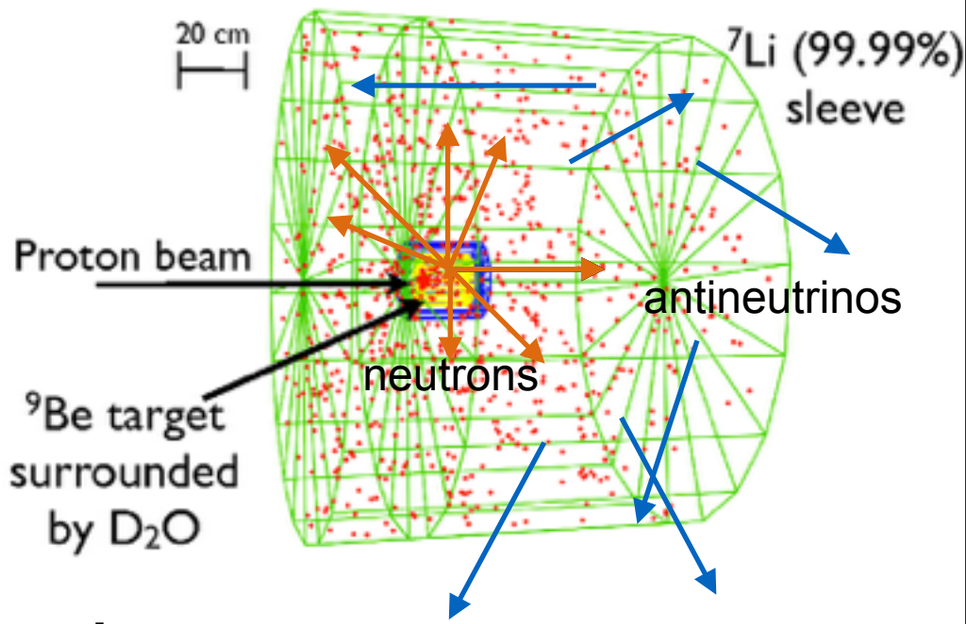




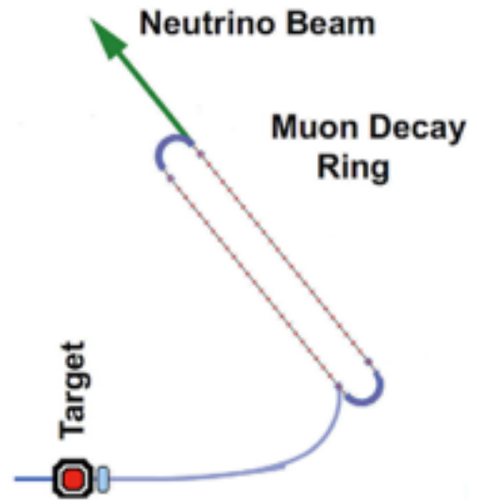
J. Zennamo, Neutrino 2014

Other Developed Experiment Proposals

- IsoDAR: 10+ MeV $\bar{\nu}_e$ from cyclotron-produced beta decays
  - High-statistics, low-background, low-systematics measurement
  - High-intensity compact cyclotron technology under intense development
  - Funding source and host detector still TBD



- OscSNS: Redo LSND completely off-axis
  - Build new larger scintillating detector below grade in/near SNS facility
- NuSTORM: Oscillation search with muon storage ring source
  - Extremely high confidence level (<10sigma) test of appearance anomaly
  - $100M+: Not recommended in P5 report



Summary

- Tantalizing hints support the existence of eV-scale ν_s
- A number of valid reasons to doubt the validity of these hints
- A diverse array of upcoming experiments will provide much-needed new data to conclusively resolve the issue

Thanks!

MicroBooNE: nue appearance data on the way!

Thoughts About 'Definitiveness'

- Definitive proof of sterile neutrinos? Definitive experiments? Definitive resolution of current anomalies?

- What metrics to consider when building/funding experiments?

My charge
(From organizers)

J. Spitz, Neutrino 2014

I would like to invite you to give a critical review talk on future short baseline experiments at the 26th International Conference on Neutrino Physics and Astrophysics (Neutrino 2014)…

By short baseline, I mean the search for sterile neutrinos whose masses are well above the atmospheric mass scale. There appear to be many different proposals. I see one of main functions of this talk is to clarify which can be conclusive in confirming or refuting the present anomalies.

From Snowmass 2013 Executive Summary on Neutrinos,
arXiv:1310.4340 [hep-ex]

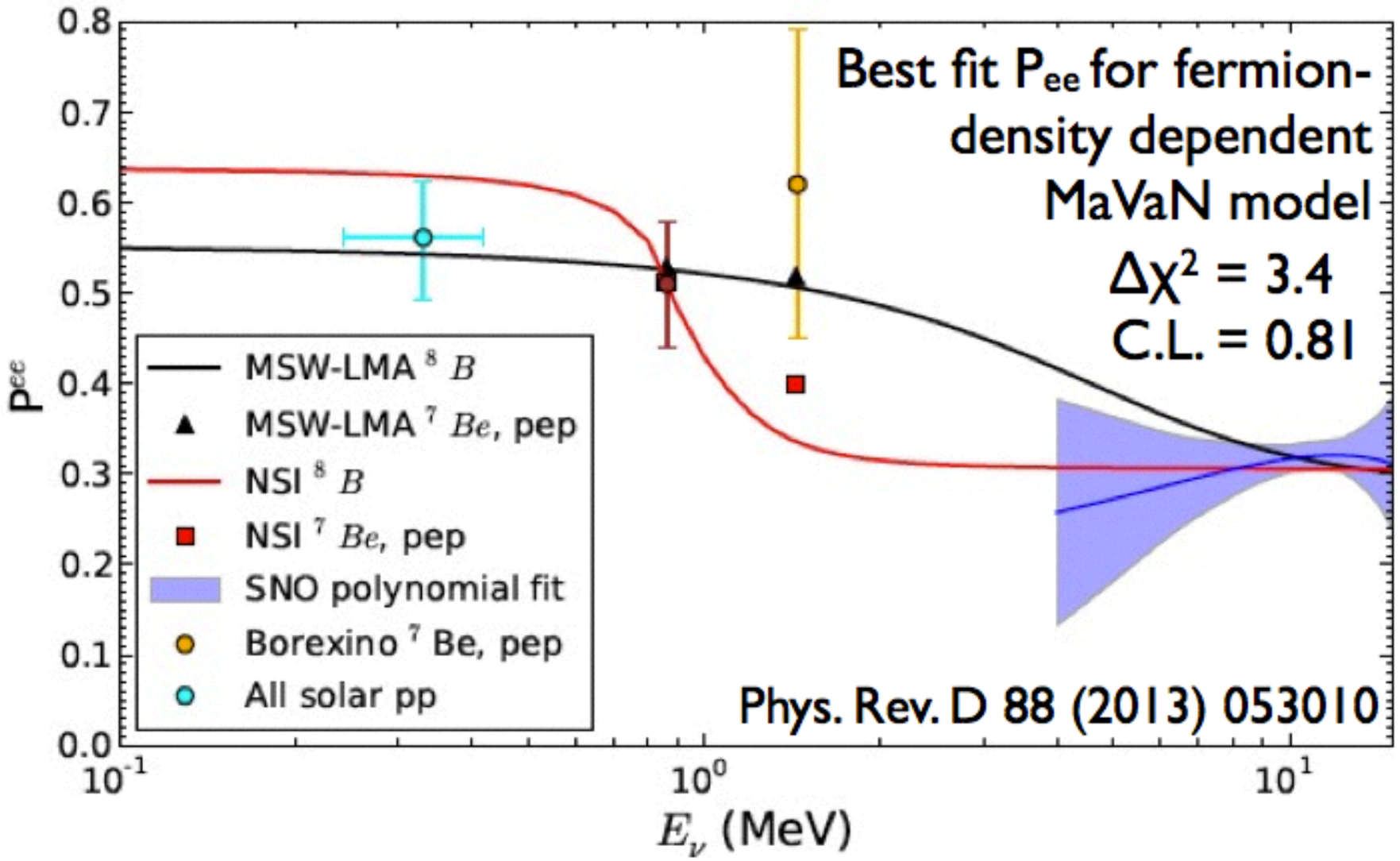
– *Definite resolution of the current short-baseline anomalies.* These will (probably) require neutrino sources other than pion-decay-in-flight and the pursuit of different flavor-changing channels, including $\nu_{e,\mu}$ disappearance and $\nu_\mu \to \nu_e$ appearance, using a combination of reactor, radioactive source and accelerator experiments. In addition to small-scale dedicated experiments, such experiments can be carried out as part of R&D projects related to next-next generation neutrino beams (e.g., nuSTORM, IsoDAR).

Thoughts About ‘Definitive’ Experiments

- What do we mean by ‘definitive’ sterile neutrino results?
  - High-CL exclusion/acceptance of anomaly sterile neutrino parameter space
    - This is arguably already in existence (ν_μ disappearance): Kopp, et al: “In a 3+1 scheme the compatibility of appearance and disappearance data is at the level of 10^{-4} “
    - After Neutrino2014 MINOS, etc. results, exclusion space via disappearance will only expand.
    - It seems, based on attitudes at Neutrino14, this is not a sufficient test (worrying, but not sufficient)
  - Directly reproduce existing anomalies using more sensitive experimental methods
    - Design experiments to investigate systematic weaknesses of previous experiments
  - Eventually, we would obviously want both of these
- Rather than stressing ‘definitiveness’ of individual experiments, focus on making new datasets available in short order that directly test the systematics assumptions of the anomalous results
- Joe Lykken: “We will never ever stop looking for steriles”
  - So easy to motivate theoretically, so much parameter space available

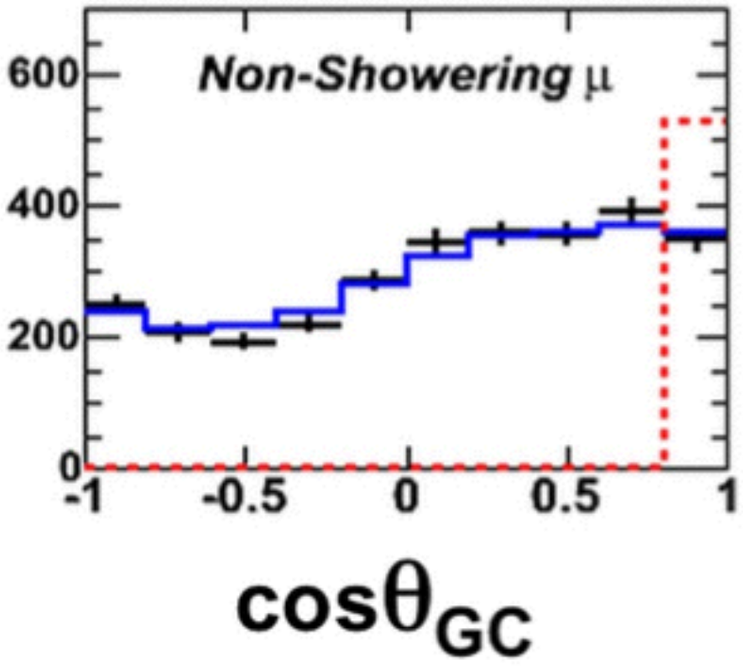
<< eV^2 Steriles

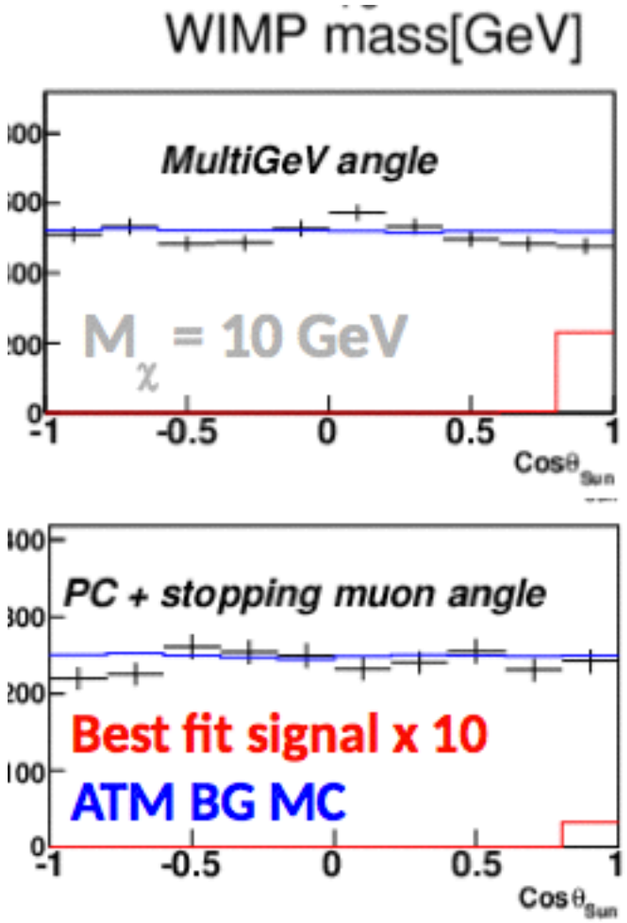
- MSW resonance in sun affects solar neutrino oscillations
- Non-standard resonance transition could be explained by new very light sterile neutrinos
- Also explained by other phenomena (mass varying neutrinos…?)

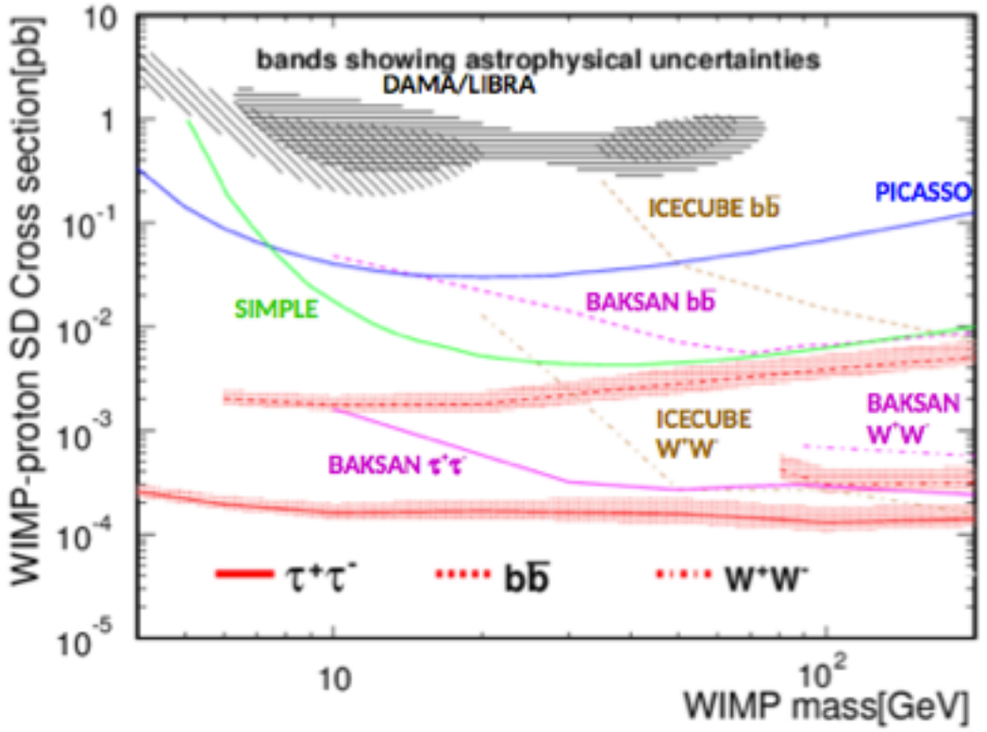


Dark Matter Searches

- Signature of Dark Matter annihilation to nu-nubar in Sun or galactic center, or elsewhere
- SuperK: no evidence of such a signature in ~GeV range





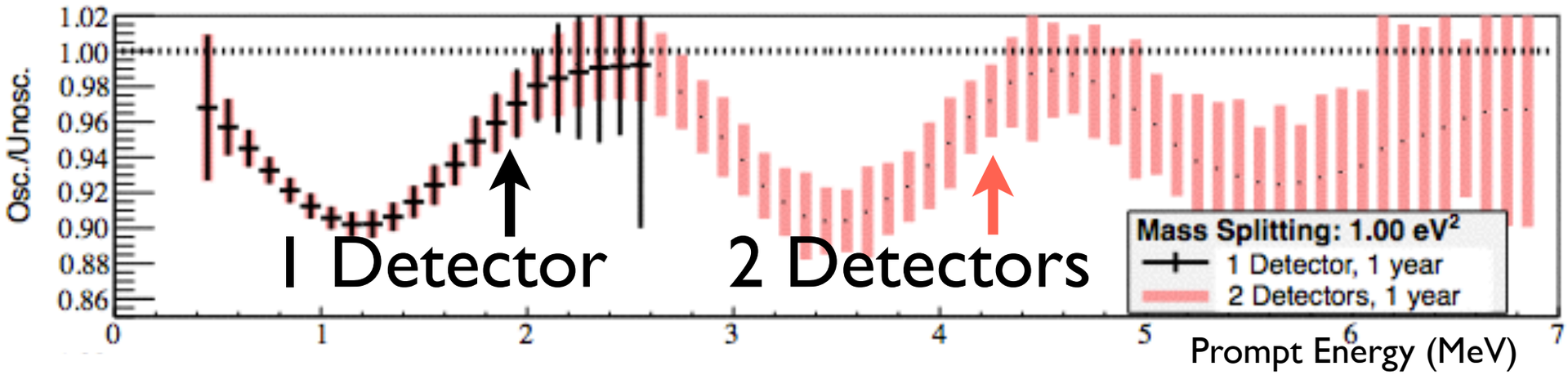


- Some evidence of ~keV signatures from sources using X-ray astronomy

Reactor Oscillation Signature

- Multiple detectors give better L/E coverage
  - Example: 2m long detectors at 4 and 15 m closest distances to a 20 MW reactor

Heeger, Mumm, BRL
arXiv:1307.2859 (2013)



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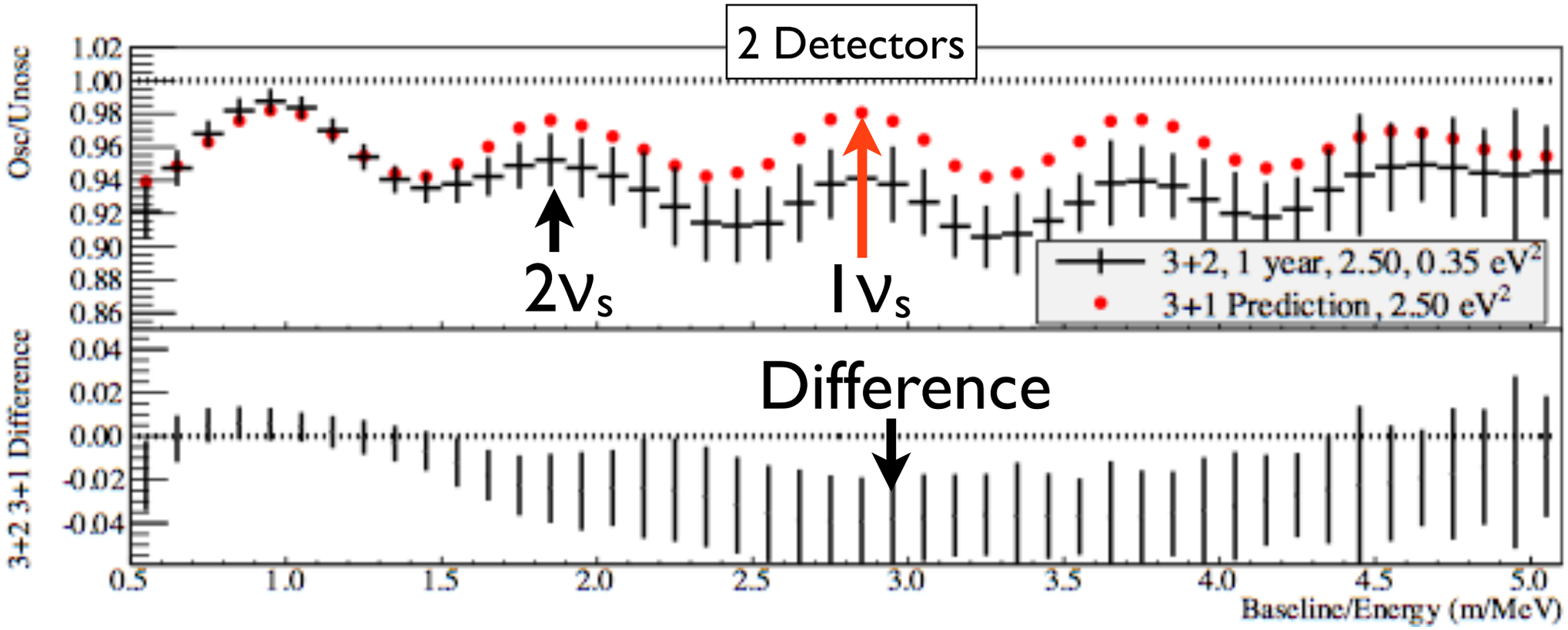
- Ability to distinguish existence of multiple sterile ν



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