Short Baseline Neutrino Experiments: Overview and Outlook

Josh Spitz, University of Michigan
Aspen Winter Conference, 3/28/2019

Short baseline summary

- Why are there short baseline neutrino experiments?
    - Mainly: various hints of anomalous electron-flavor appearance and disappearance may be indicative of a new neutrino participating in oscillations and/or some other new physics.
    - But, also:
        - Neutrino cross sections for informing long-baseline oscillations measurements.
        - Neutrino cross sections for understanding the neutrino interaction with matter.
        - Exotic searches (e.g. dark matter production) with high luminosity, fixed target.
        - Detector R&D.

Outline

- Non-oscillation physics
- Short review of the existing anomalies at short-baseline
- Discussion of the MiniBooNE anomaly
- A quick tour of current/future experiments

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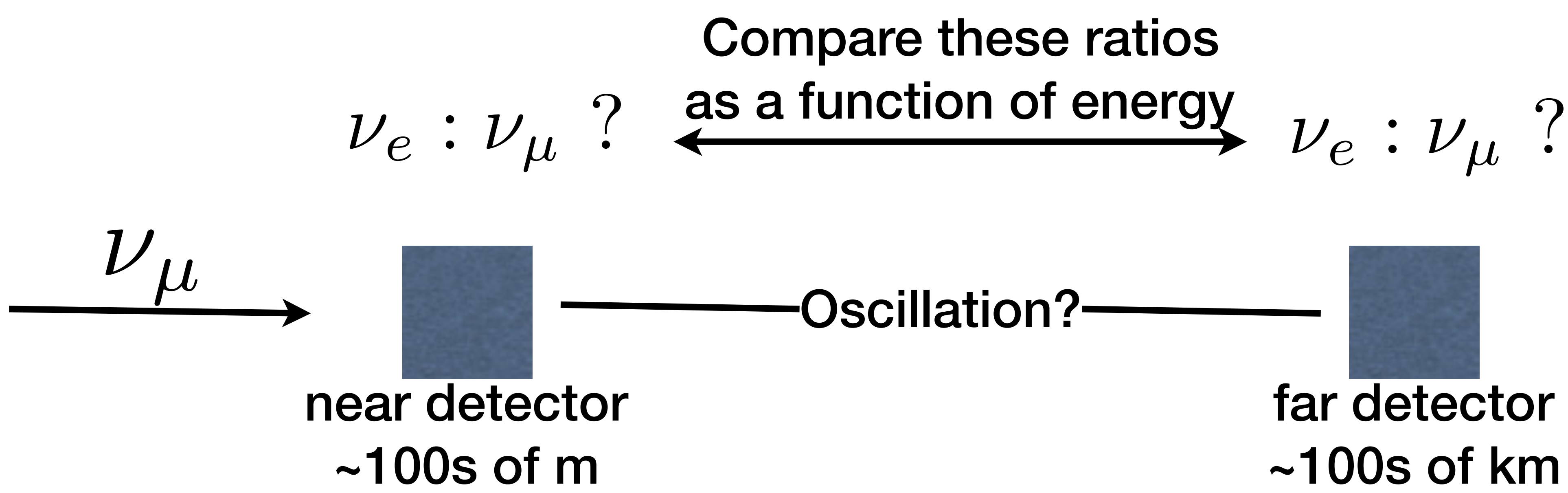
Why neutrino cross section measurements at short-baseline?

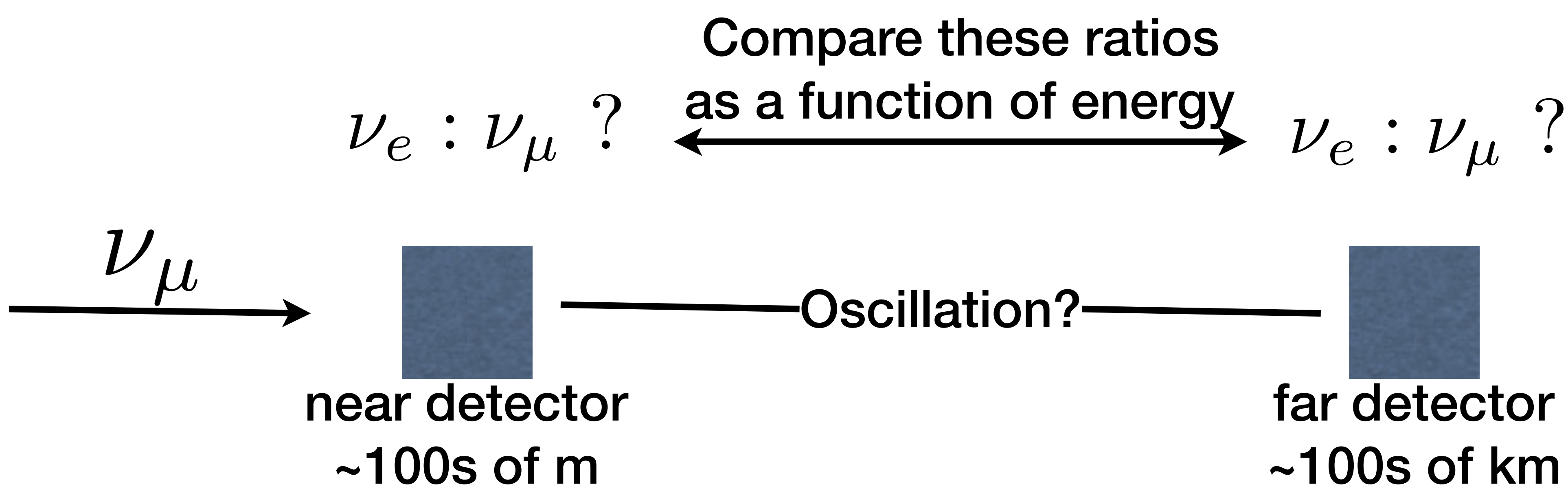
Reminder



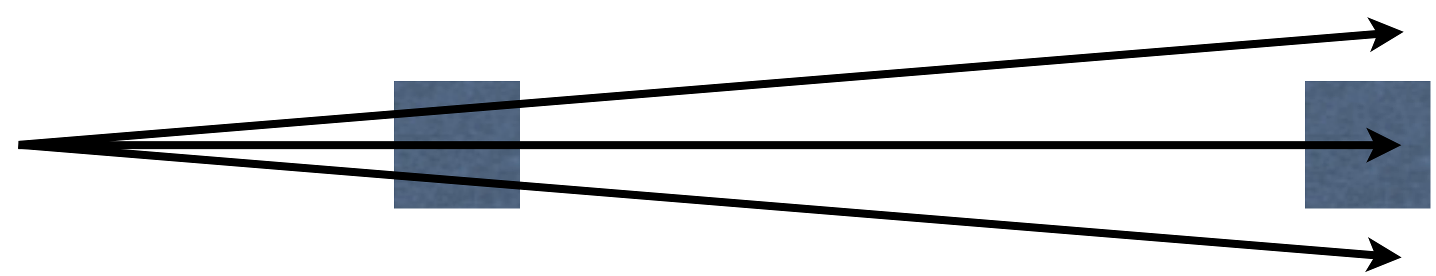
CP violation in the lepton sector?

$$P[\nu_\mu \to \nu_e] \neq P[\overline{\nu}_\mu \to \overline{\nu}_e] \ ?$$

A problem

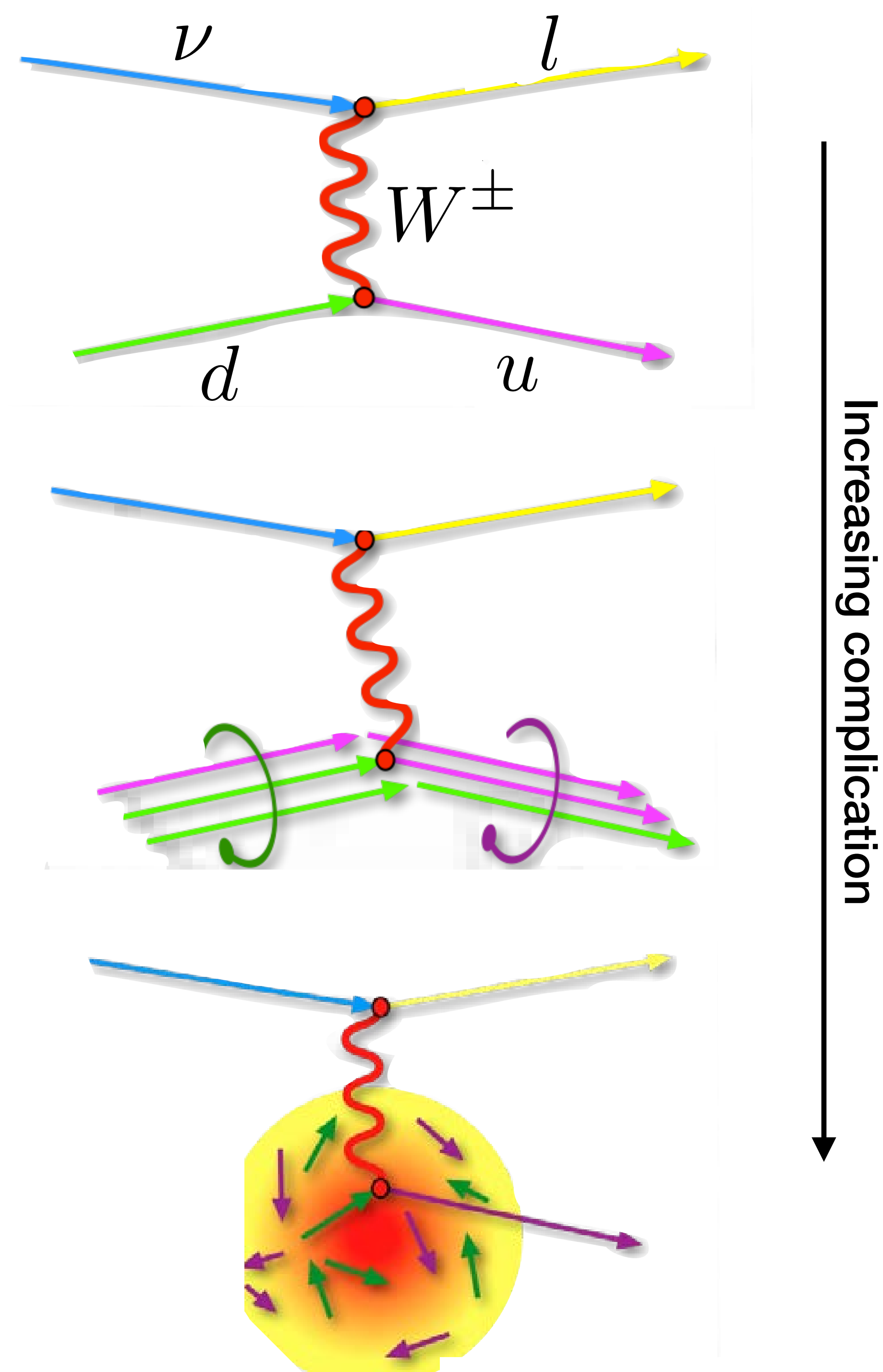


The near and far fluxes are inherently different! So, we need to rely on cross section knowledge for a proper comparison.



Why neutrino cross section measurements at short-baseline?

- Neutrino interactions with nuclei are complicated!
    - Fermi motion.
    - Correlations between nucleons.
    - Final state interactions.
    - One nucleus is different than the next.
- Detector limitations
    - Energy resolution.
    - Event classification issues.
    - Cerenkov threshold.



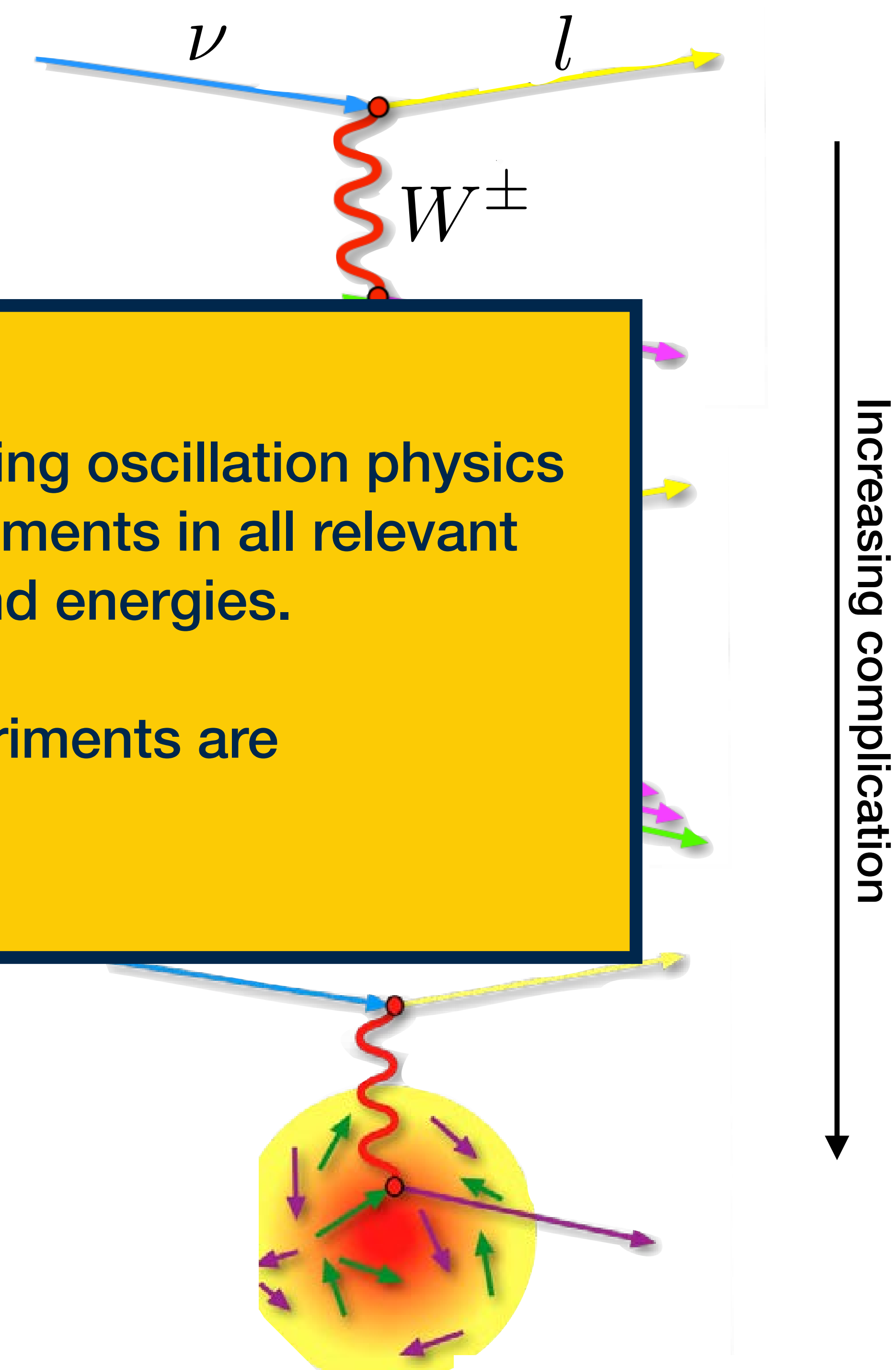
Adapted from K. McFarland

Why neutrino cross section measurements at short-baseline?

- Neutrino interactions with nuclei are complicated!
  - Fermi motion
  - C
  - F
  - O
- Dete
  - Energy resolution.
  - Event classification issues.
  - Cerenkov threshold.

Solving these problems for the purposes of informing oscillation physics requires neutrino-nucleus cross section measurements in all relevant interaction channels, nuclear targets, and energies.

Accelerator-based short-baseline experiments are tackling these issues.

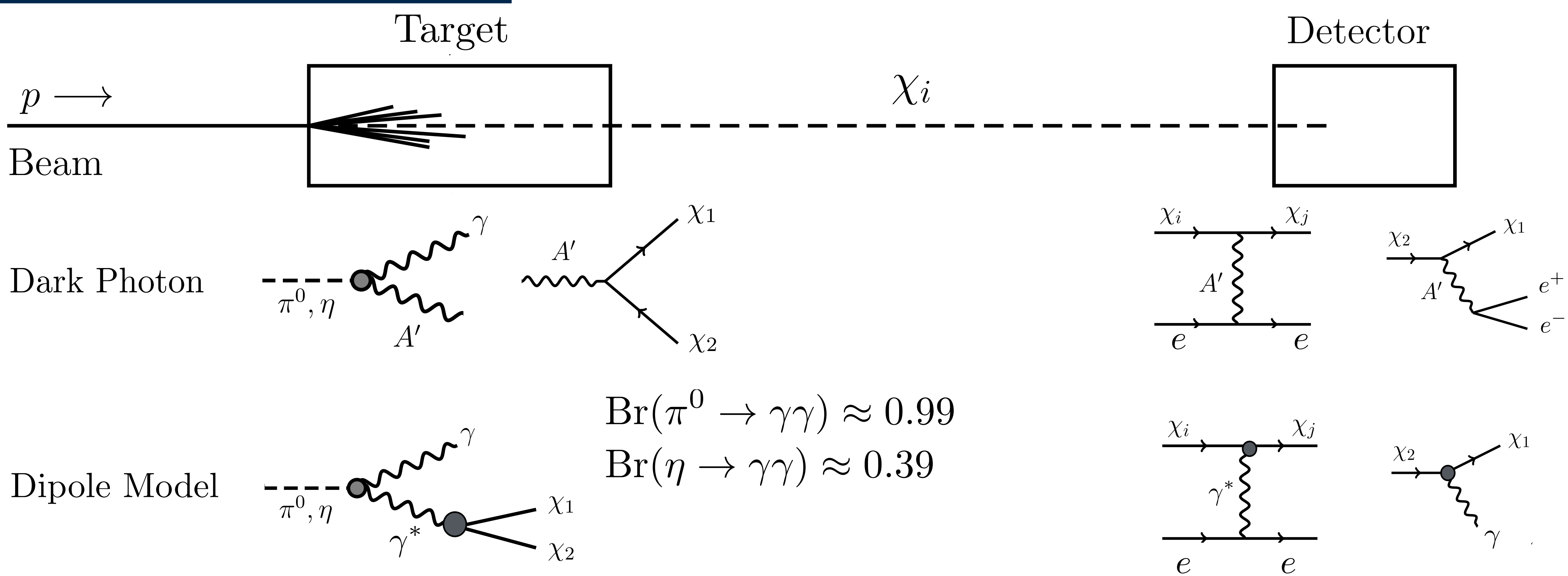


Adapted from K. McFarland

Exotic searches at short-baseline

Simple idea: make a new particle with your $10^{20\text{-something}}$ protons on target and then watch it decay or interact in your neutrino detector

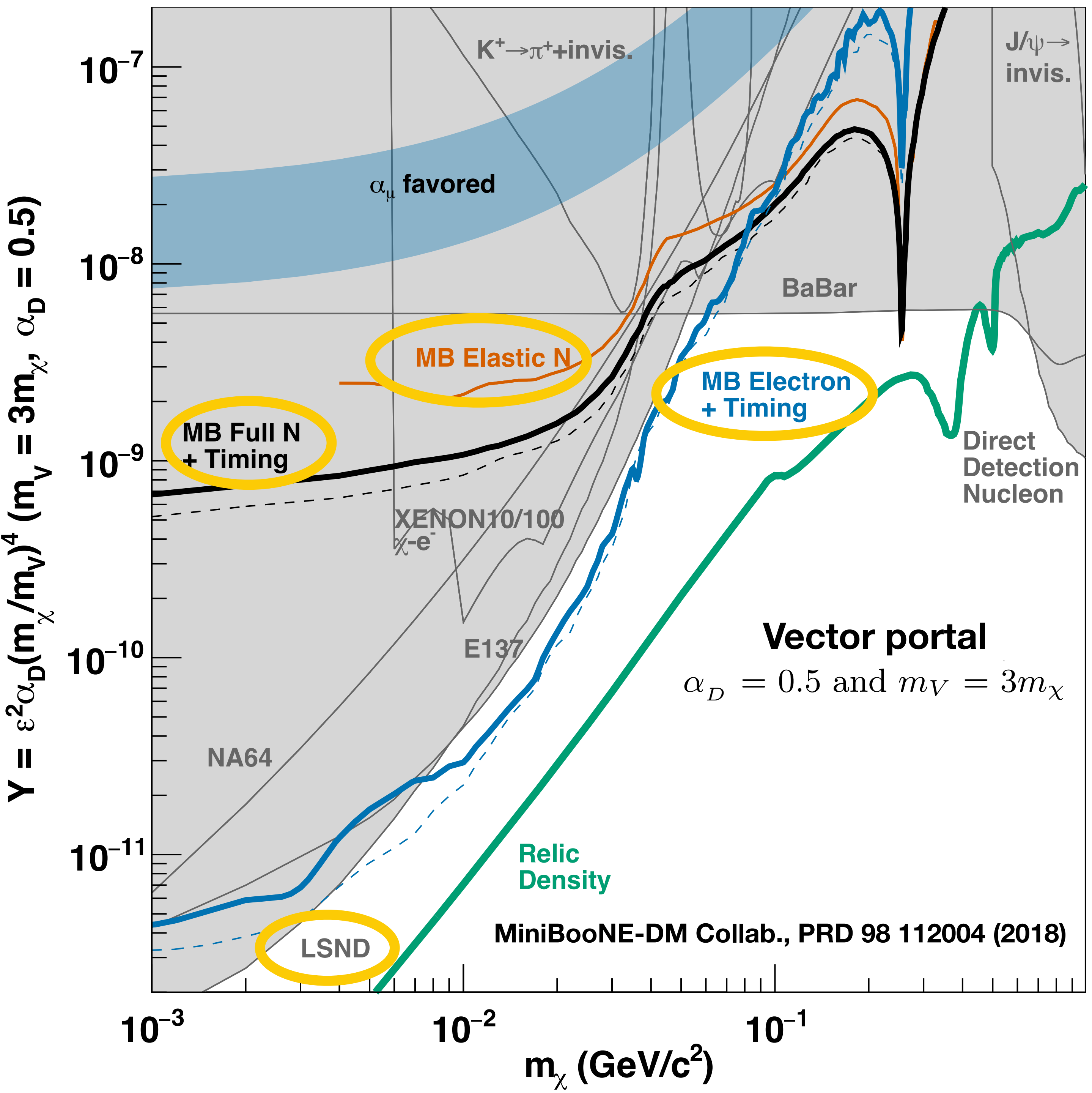
High luminosity proton beam (100s of MeV to 10s of GeV)



$$\mathrm{Br}(\pi^0 \to \gamma\gamma) \approx 0.99$$
$$\mathrm{Br}(\eta \to \gamma\gamma) \approx 0.39$$

Large boost means there are less kinematic constraints on the scattering, compared to traditional direct DM searches

Exotic searches at short-baseline



Short-baseline neutrino experiments are very competitive with other techniques when it comes to exotic searches.

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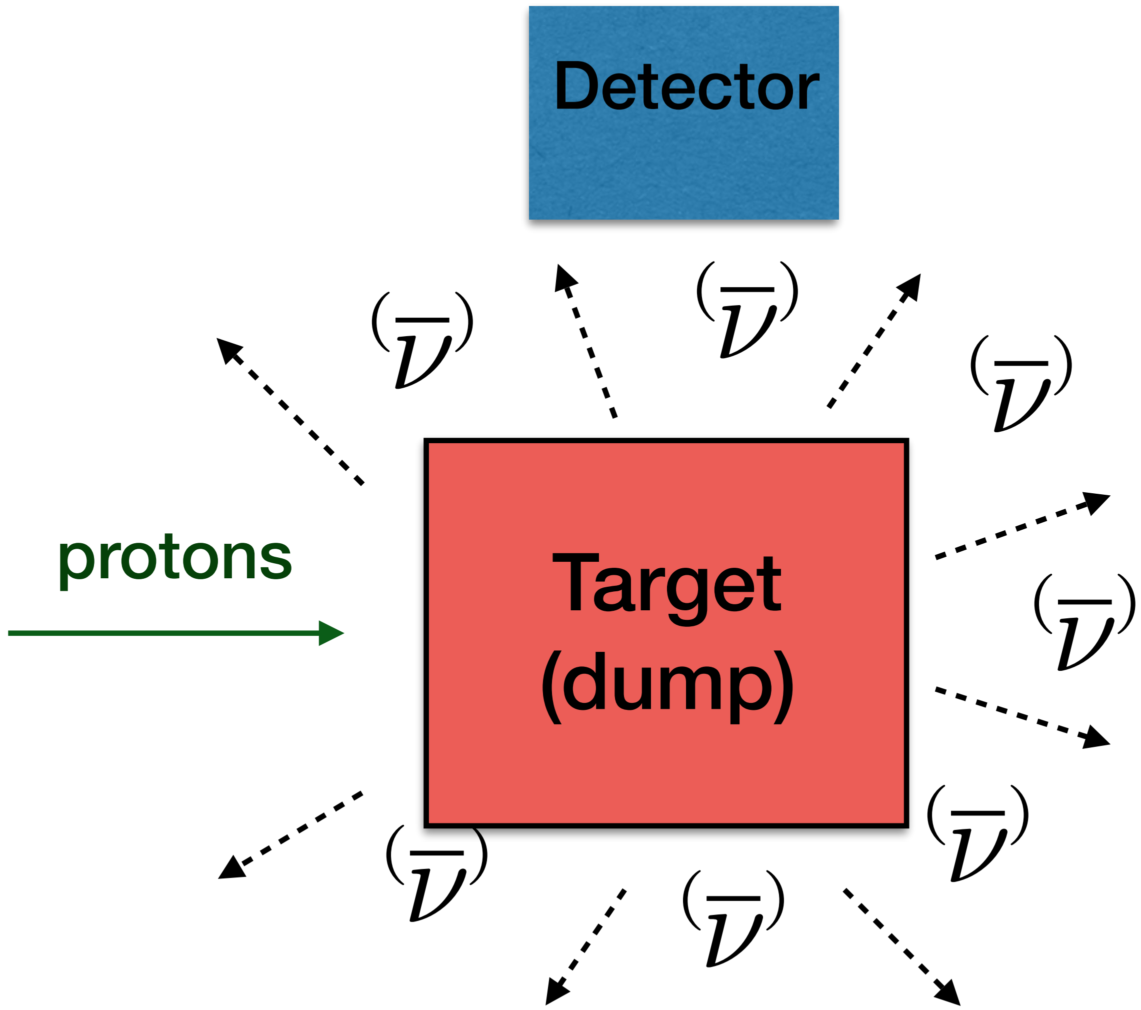
A number of anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

Experiment name	Type	Oscillation channel	Significance
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	4.5σ
Reactors	Beta decay	electron disappearance (antineutrino)	(varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

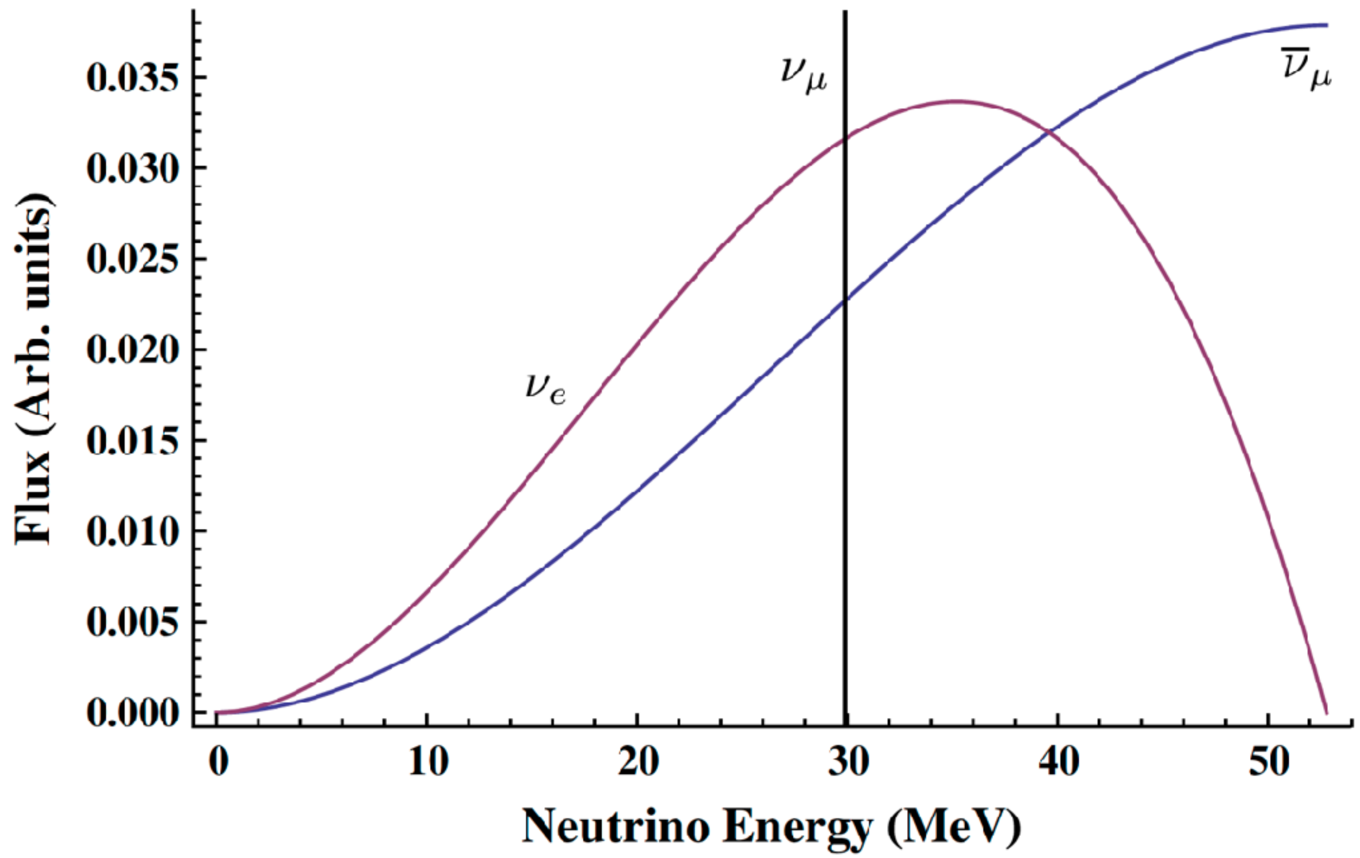
Now: 4.8σ (combined)

(there are also various null results in this "high-frequency oscillation" parameter space); MINOS(+), IceCube, KARMEN, CDHS, OPERA, …

Pion and muon decay-at-rest neutrinos

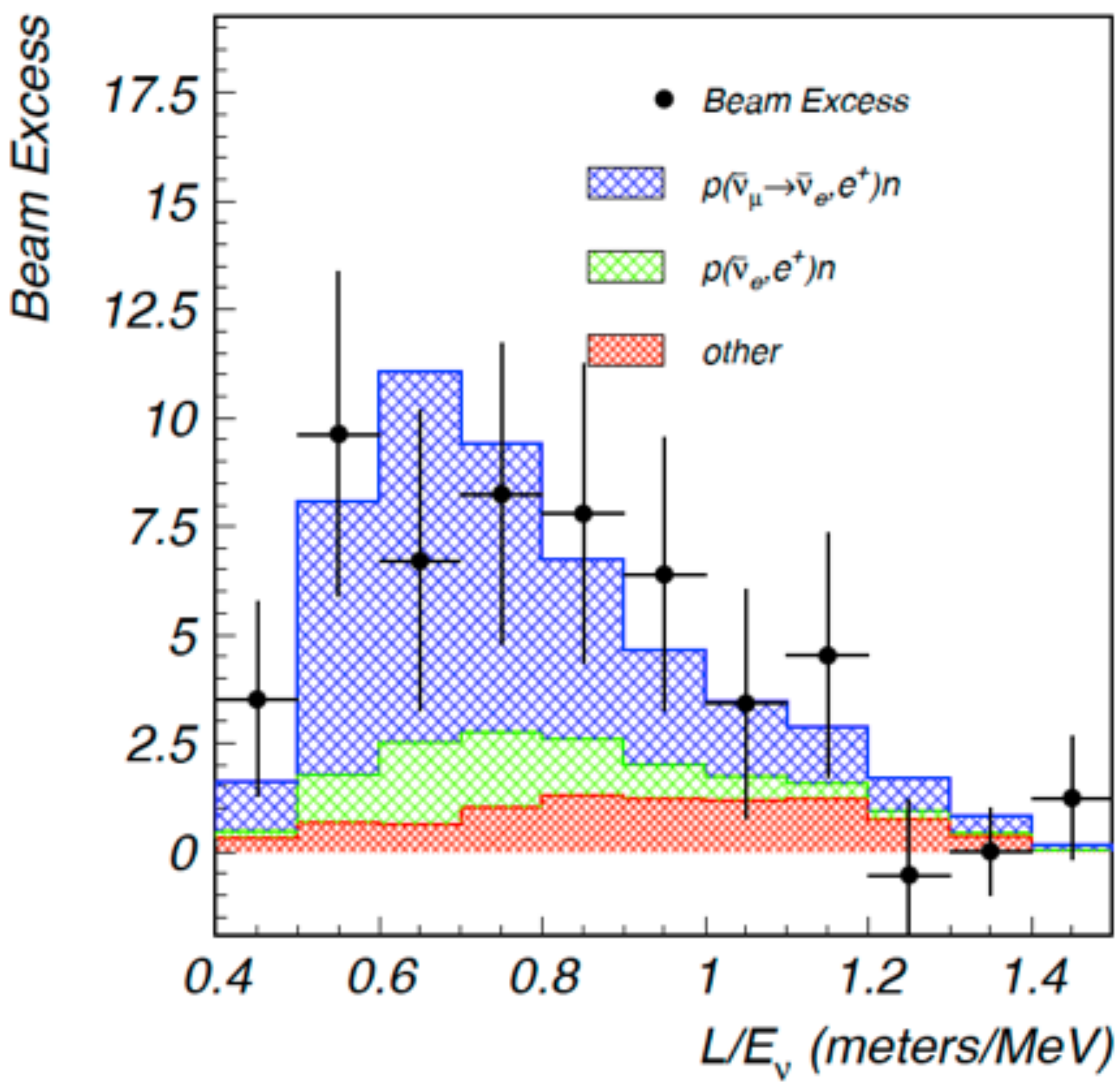


$\overline{\nu}_\mu \to \overline{\nu}_e$?



$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

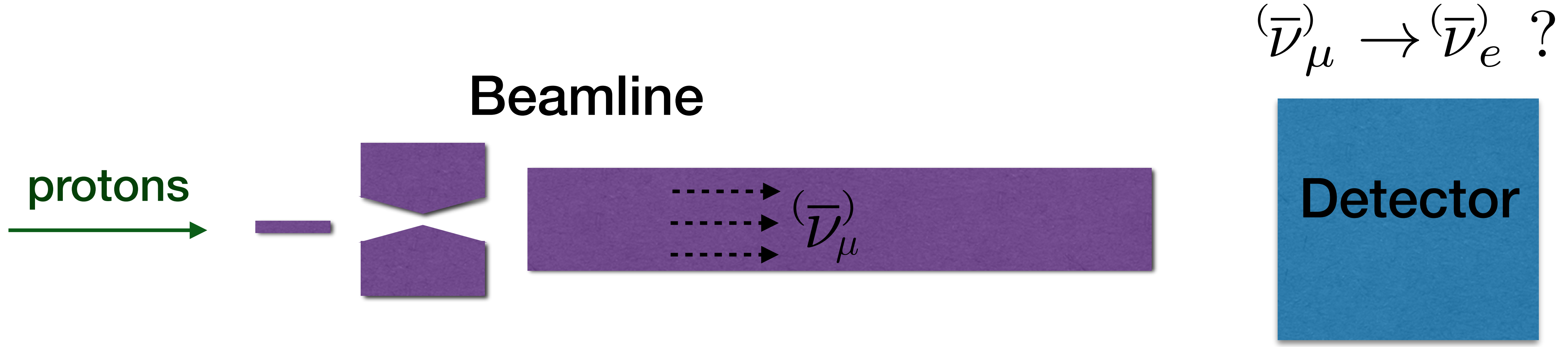
The Liquid Scintillator Neutrino Detector anomaly



- **LSND observed $\overline{\nu}_\mu \to \overline{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1$ eV^2.**
- **That's odd. There are two characteristic oscillation frequencies in the three neutrino picture and they are precisely measured.**

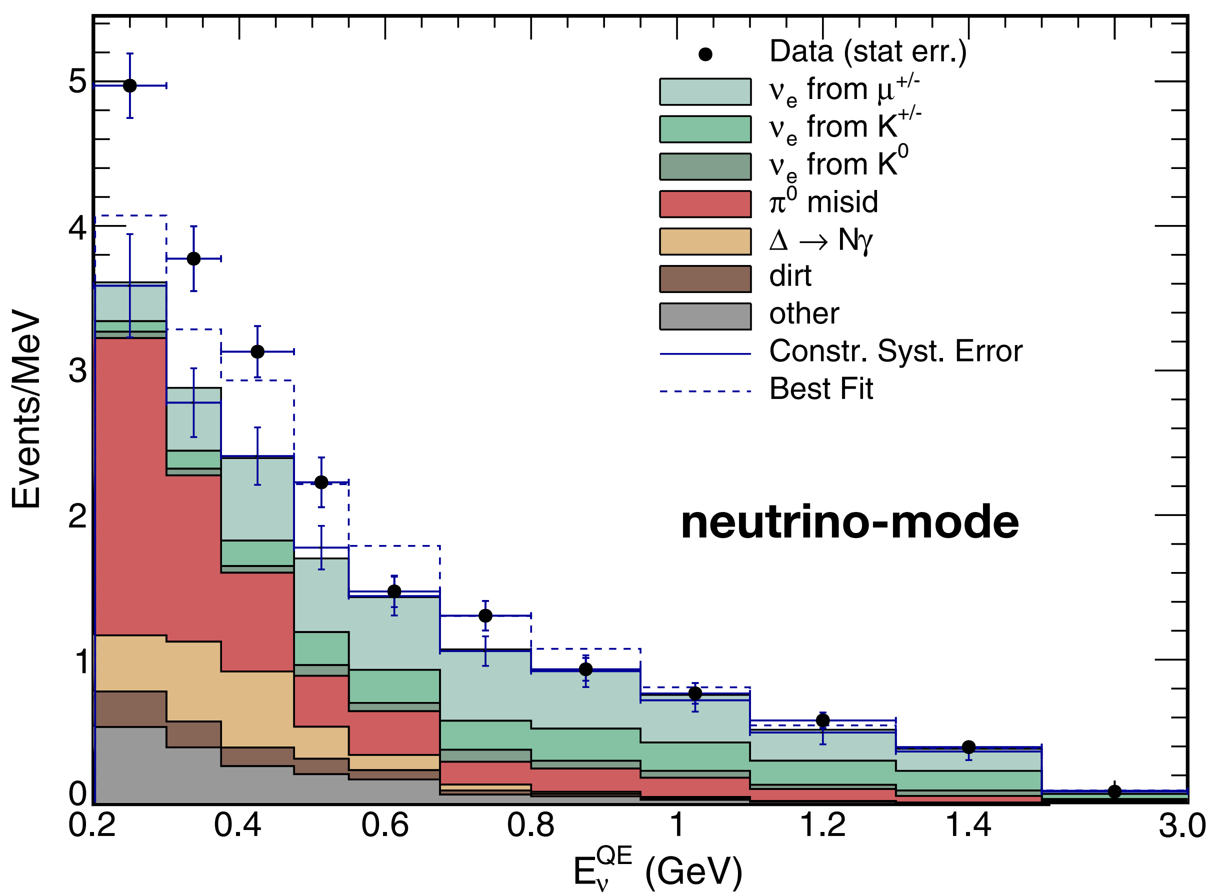
$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}})$$

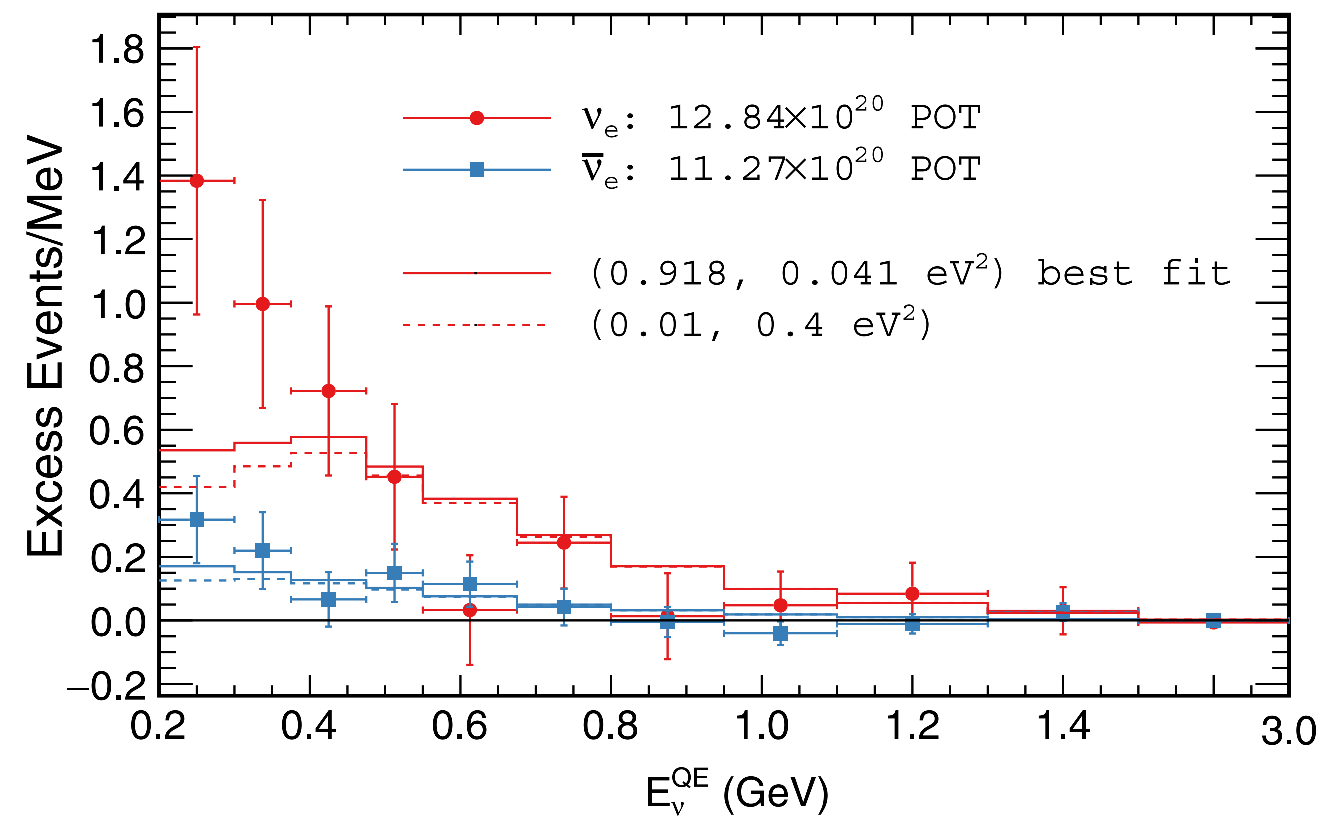
Pion decay-in-flight



The MiniBooNE anomalies

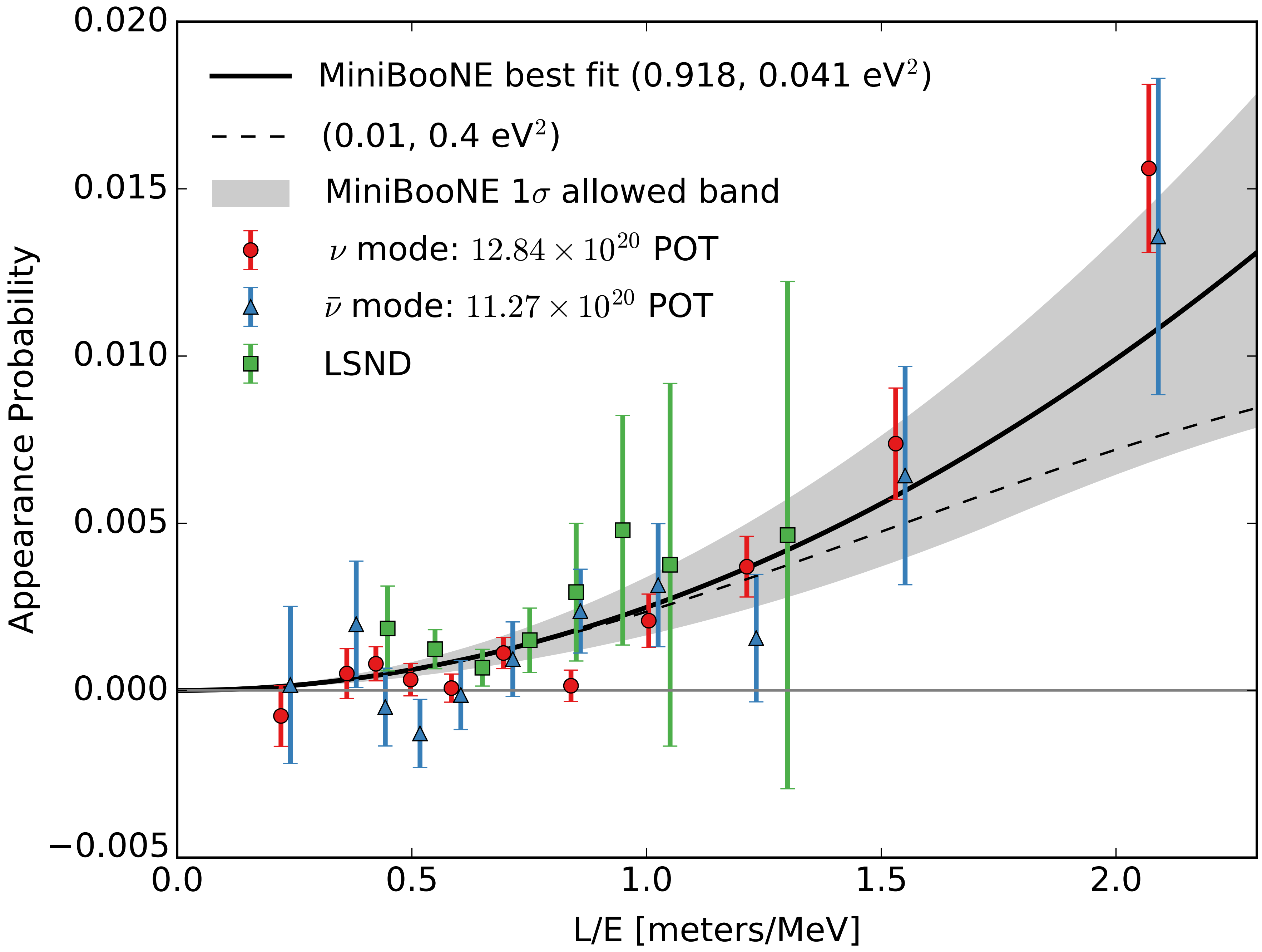
MiniBooNE Collab., PRL 122 221801 (2018)





Note: MiniBooNE does not have the ability to distinguish between electrons and single-gammas.

LSND and MiniBooNE



MiniBooNE Collab., PRL 122 221801 (2018)

Lack of observed muon disappearance rules out a generic 1 sterile neutrino model

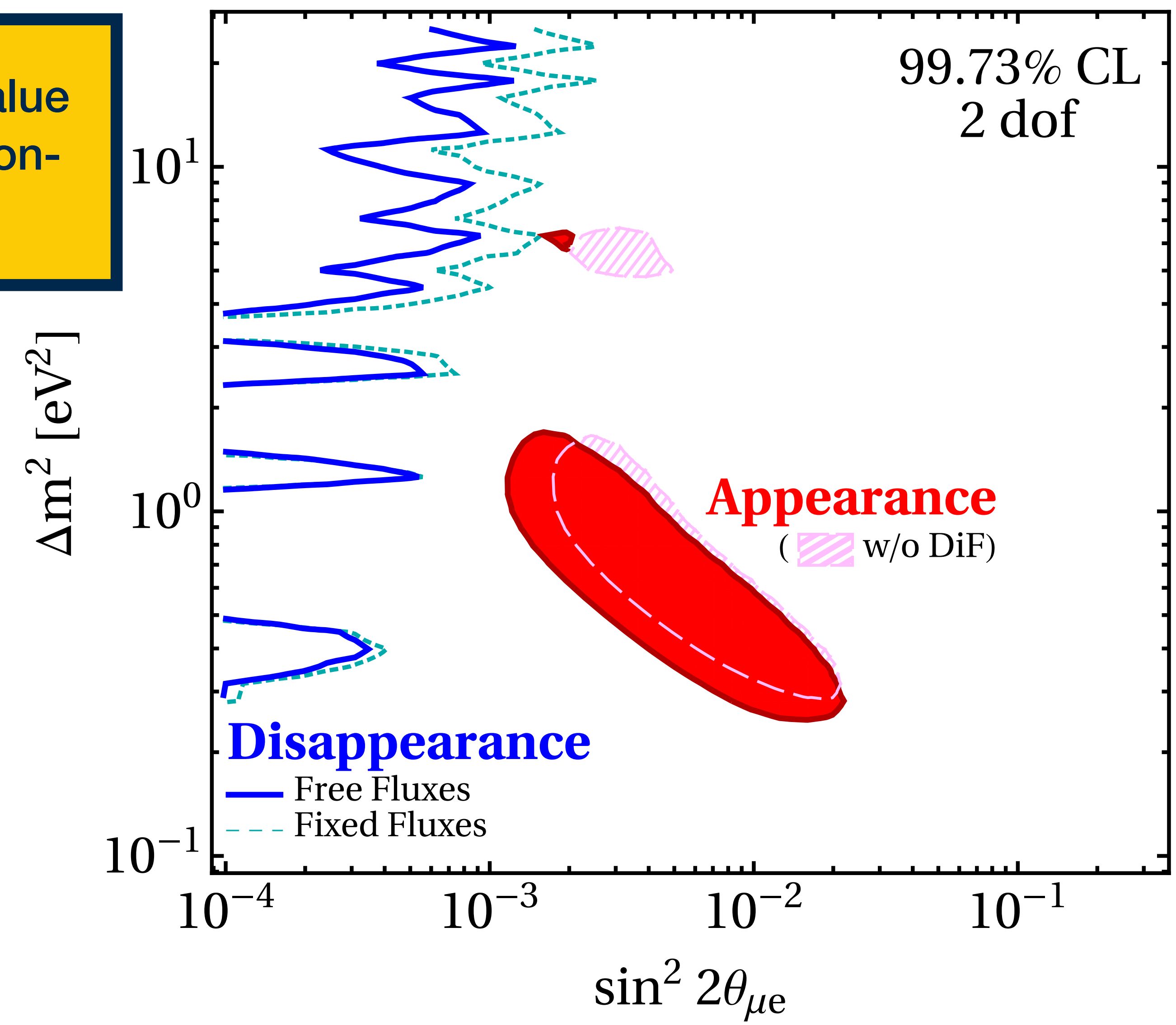
IceCube, MINOS(+), NOvA, MiniBooNE, OPERA, CDHS see no muon-flavor disappearance at high-Δm^2

Taking the observed MiniBooNE+LSND results at face value and assuming the addition of 1 light sterile neutrino, muon-flavor disappearance should have been seen by now.

$$P_{ee} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$



$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$$

M. Dentler et al., JHEP **08**, 010 (2018), 1803.10661

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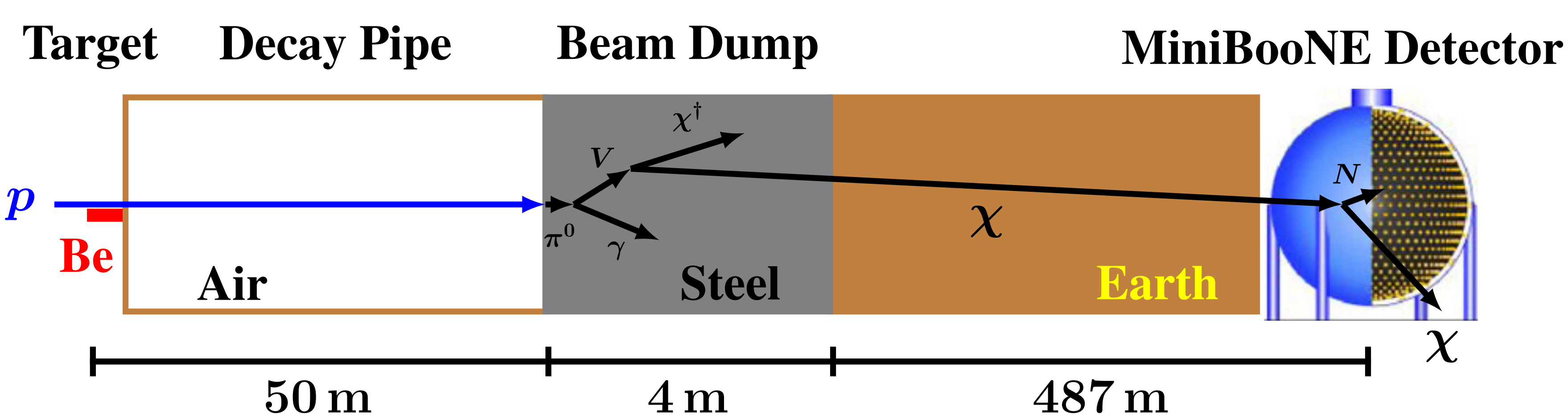
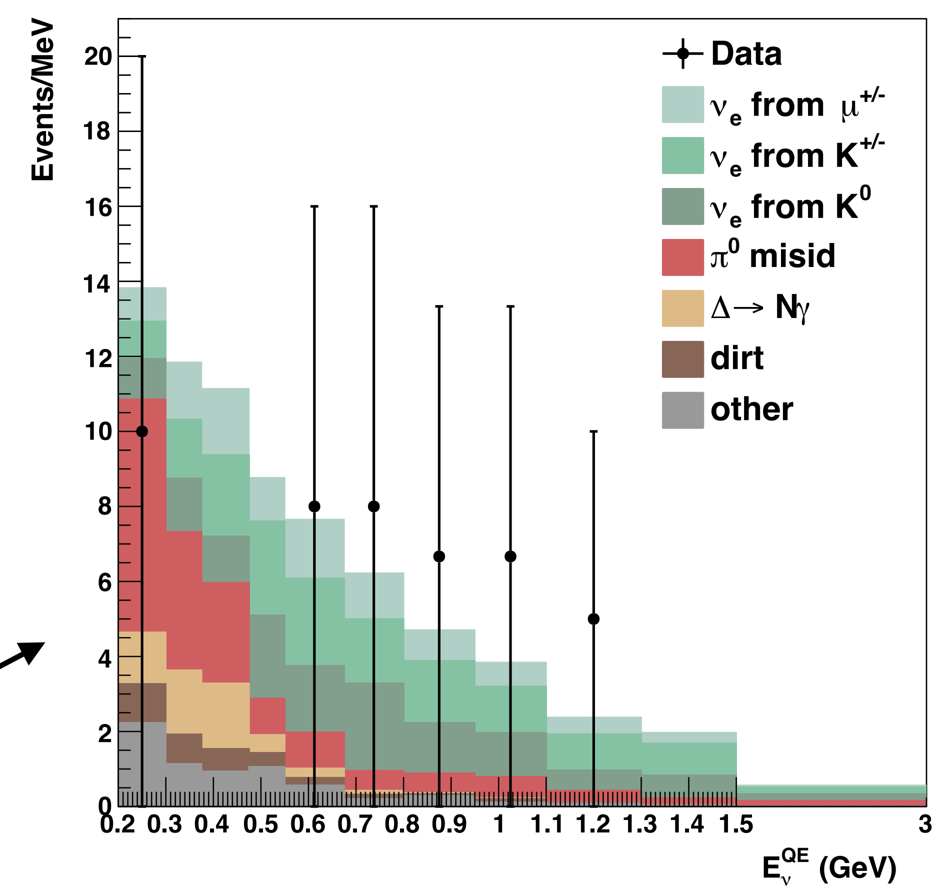
Ok, so 3+1 is ruled out. Can the MiniBooNE anomaly be due to something else exotic, perhaps not involving neutrinos?

The MiniBooNE beam dump null result provides a pretty good answer to this question.
Answer: probably not.
[The exotic particle should probably be produced in beam dump running as well… but no excess is seen]

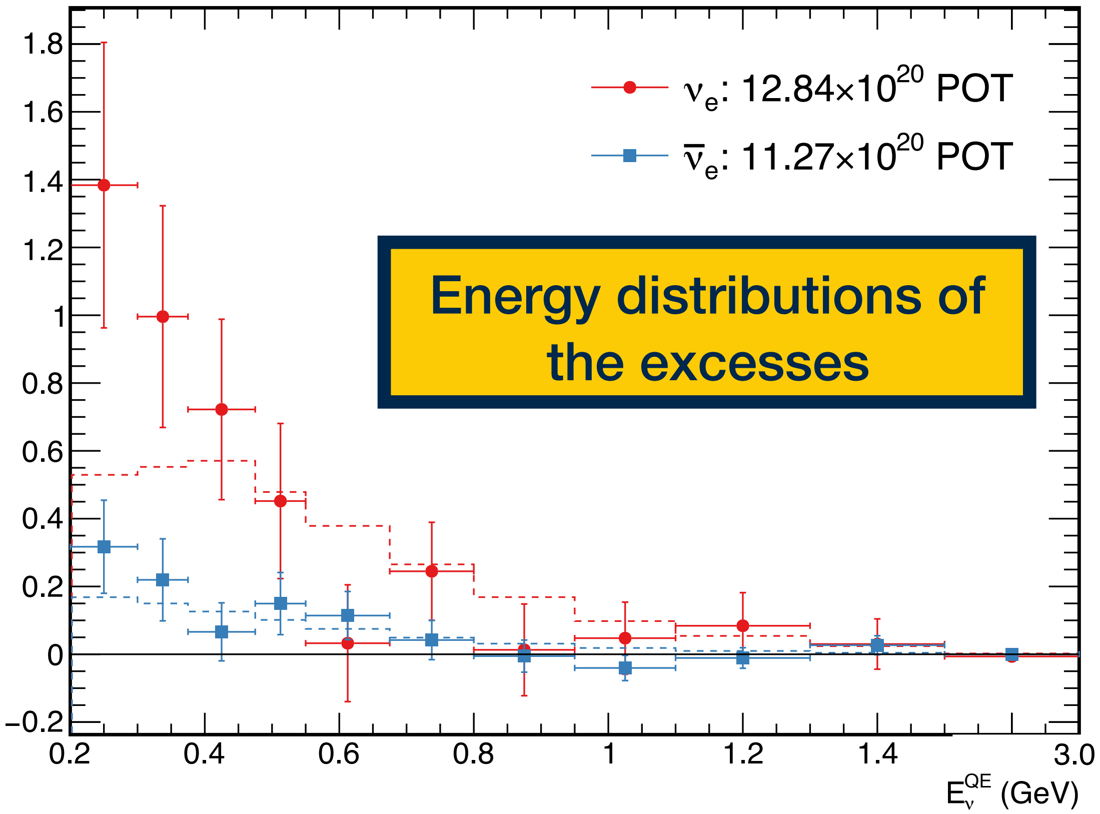


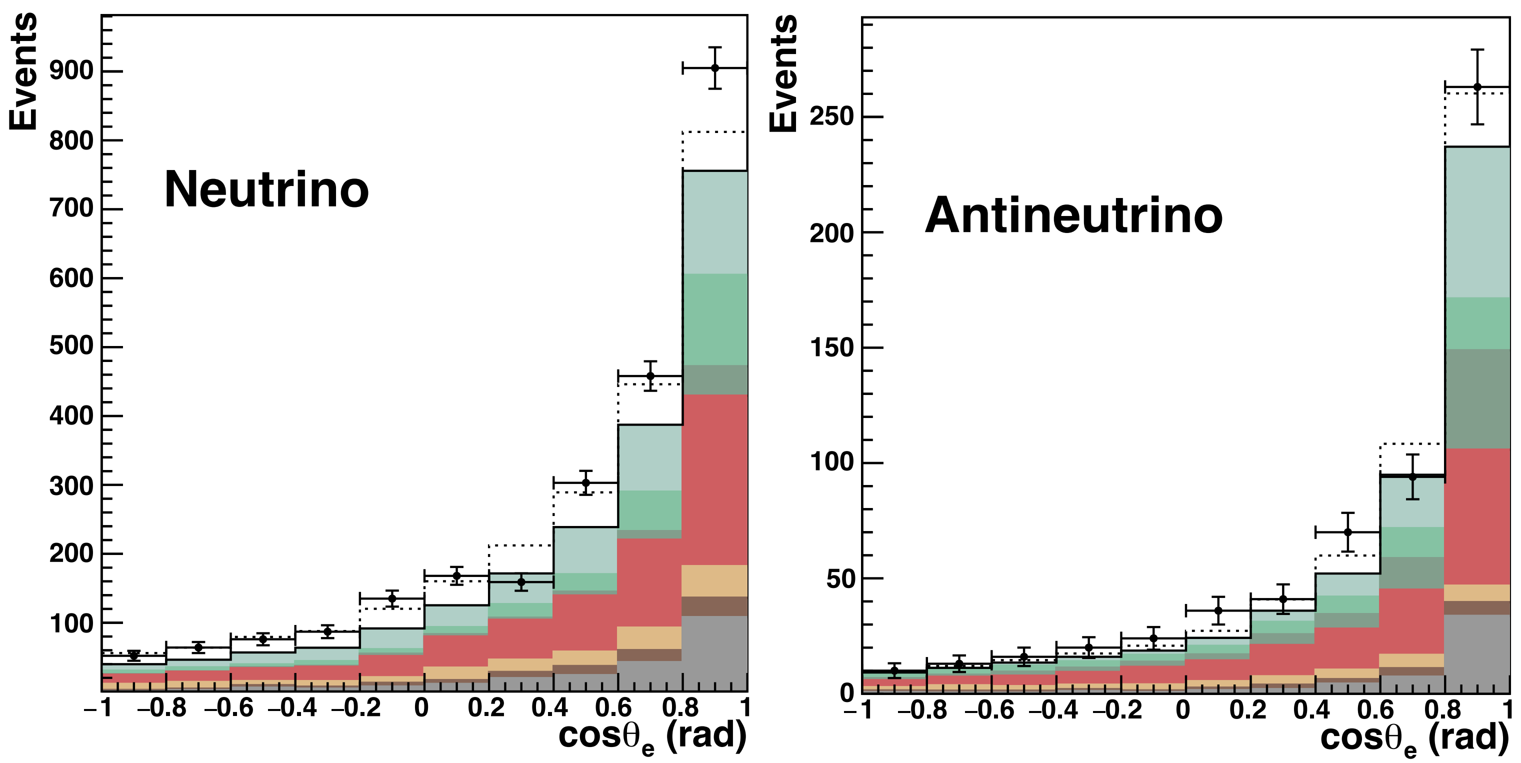
beam dump mode electron-like search is consistent with background



MiniBooNE-DM Collab., PRD 98 112004 (2018)

What is the source of the MiniBooNE anomaly?

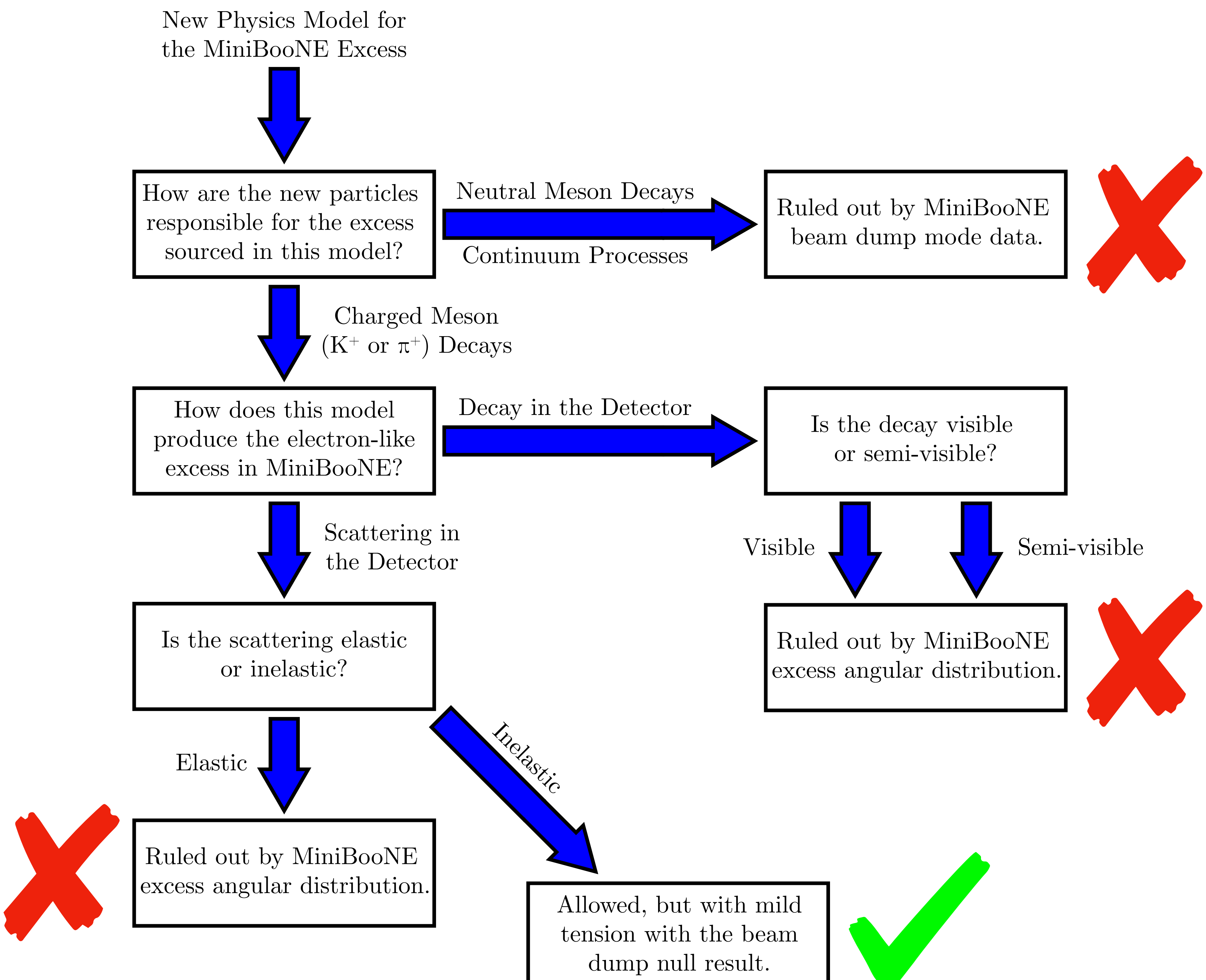




Angular distributions of the excesses

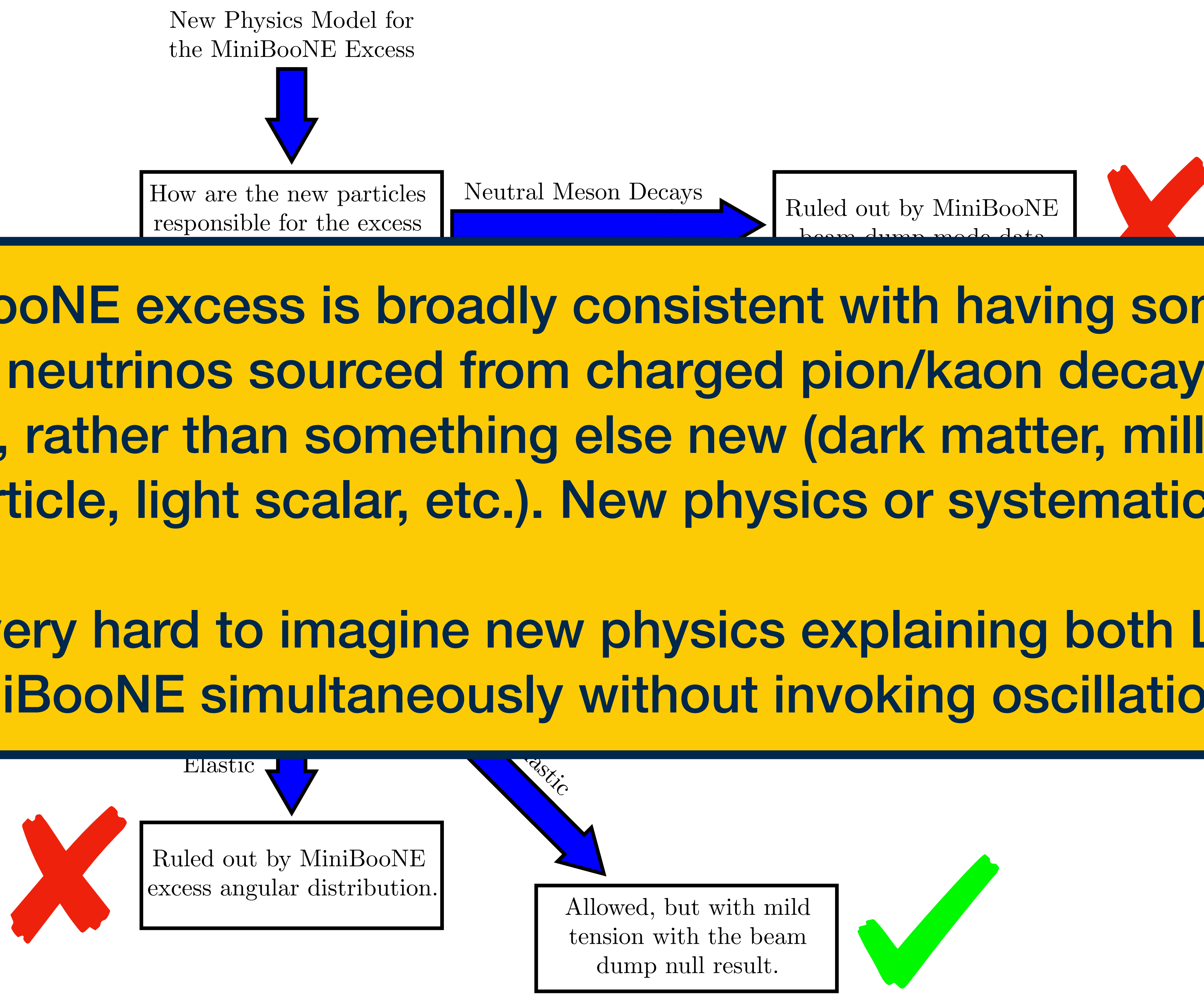
A good model for the excess must agree with all of these distributions simultaneously and the beam-dump mode results

What is the source of the MiniBooNE anomaly?



J. Jordan, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, PRL 122 081801 (2019)

What is the source of the MiniBooNE anomaly?



The MiniBooNE excess is broadly consistent with having something to do with neutrinos sourced from charged pion/kaon decays in the beamline, rather than something else new (dark matter, millicharged particle, light scalar, etc.). New physics or systematics?

Also, it's very hard to imagine new physics explaining both LSND and MiniBooNE simultaneously without invoking oscillations.

J. Jordan, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, PRL 122 081801 (2019)

What is going on?

- 3+1 doesn't work.
    - A number of global-fit papers consider the removal of an experiment or class of experiments when performing a 3+1 or 3+0 fit. In general, it is still hard to perform a reasonable fit in these cases.
- It is fairly clear that any new physics explanation likely requires 'multiple layers' to explain all the results.
    - One sterile neutrino and a new interaction or decay? Two/three sterile neutrinos?
- There may be new physics here. But, the possibility of underestimated/unknown systematics ("bad data") remains. Global fits suffer badly from the very real possibility of a wrong experiment.
- Unfortunately, we have entered the realm of 'sigmas doesn't matter', recalling that the MiniBooNE+LSND combo (w/o considering others) is now 6.1σ.
    - **A wiggle in L/E, observation in multiple channels with *coherence* among the results (and cosmology), or some other smoking gun needs to be seen for discovery!**
- What to do? Keep pushing with better detectors and better neutrino sources.
    - Even in the absence of an actual light sterile neutrino or other new physics, short-baseline experiments remain highly compelling.

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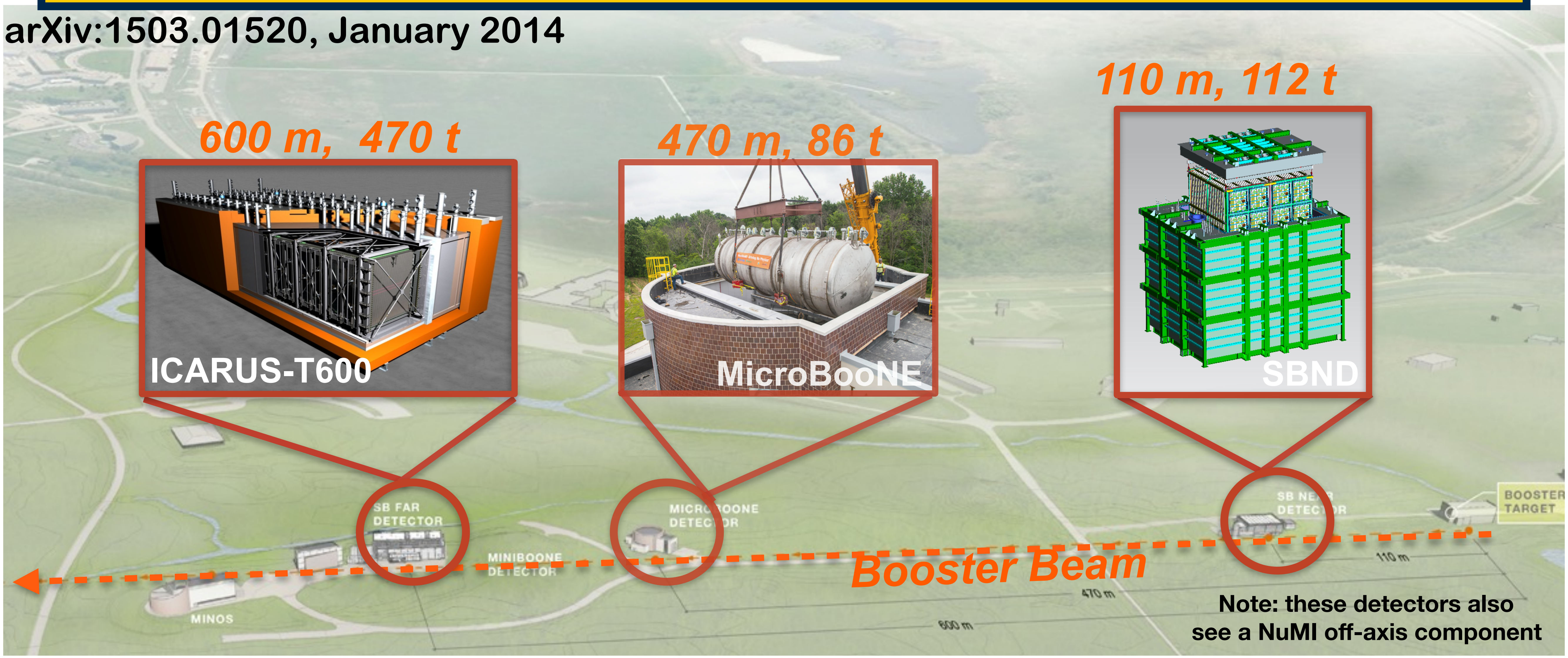
A quick tour of *selected* and *representative* running and ‘next-two-years’ short-baseline experiments

- SBN at Fermilab (pion decay-in-flight)
- JSNS^2 (pion/muon/kaon decay-at-rest)
- PROSPECT (reactor)

Please see: C. Giunti, T. Lasserre, arXiv:1901.08330 for a recent review on eV-scale sterile neutrinos, including current/future experiments

SBN Program at Fermilab

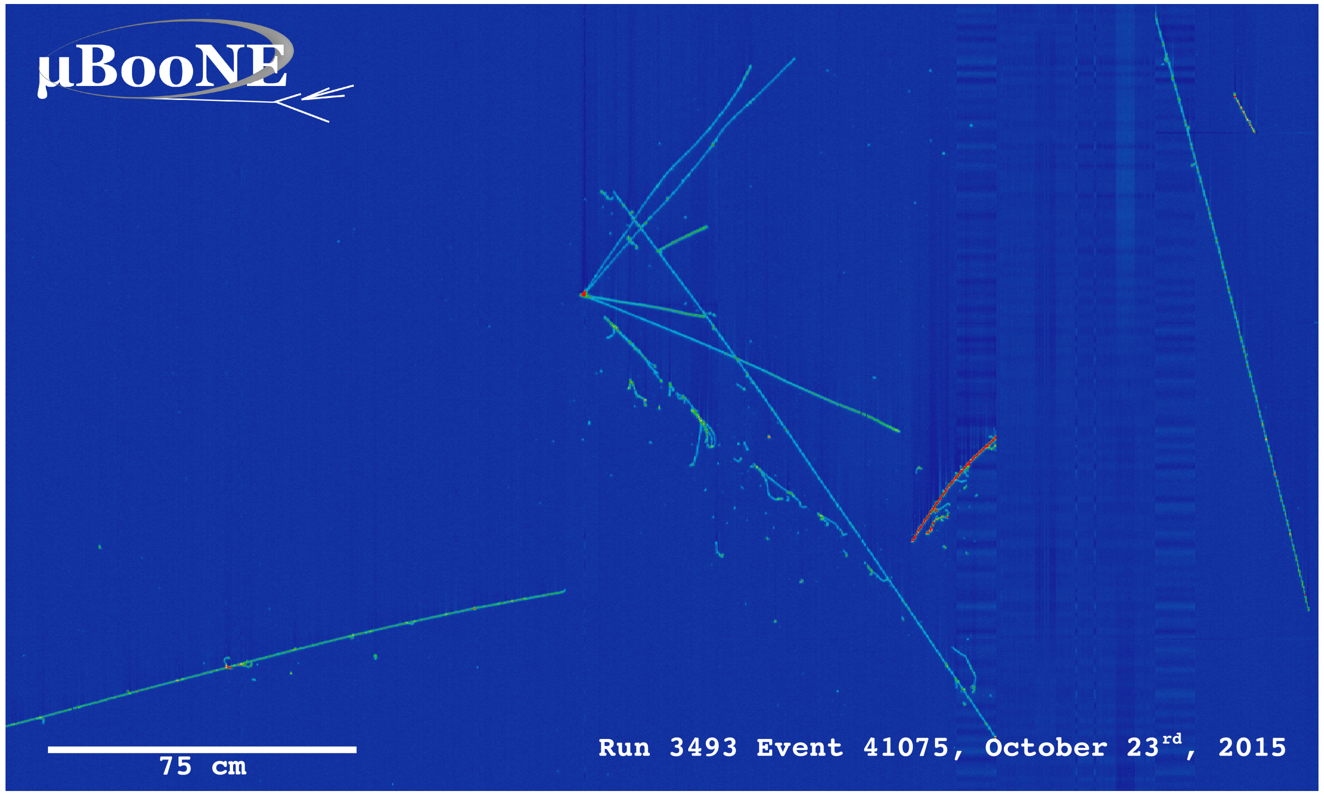
3 LArTPCs in the Booster Neutrino Beamline, looking for (among other things) muon->electron flavor oscillations as a function of L/E



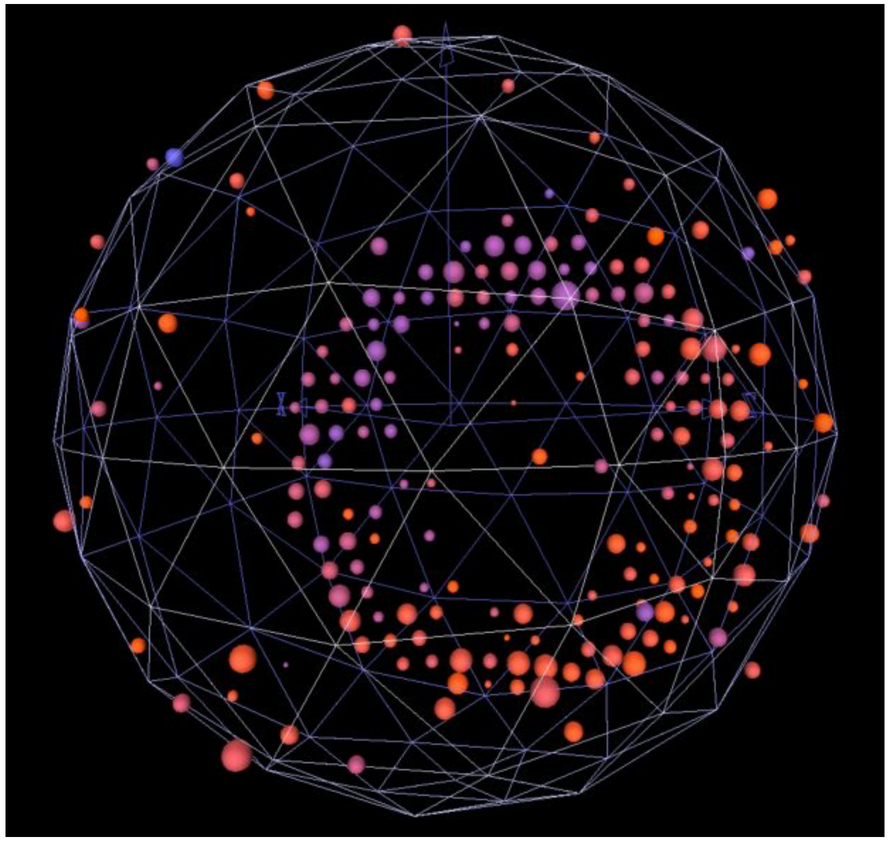
SBND (first data in 2020/2021)
MicroBooNE (running since late-2015)
ICARUS (first data in 2019/2020)

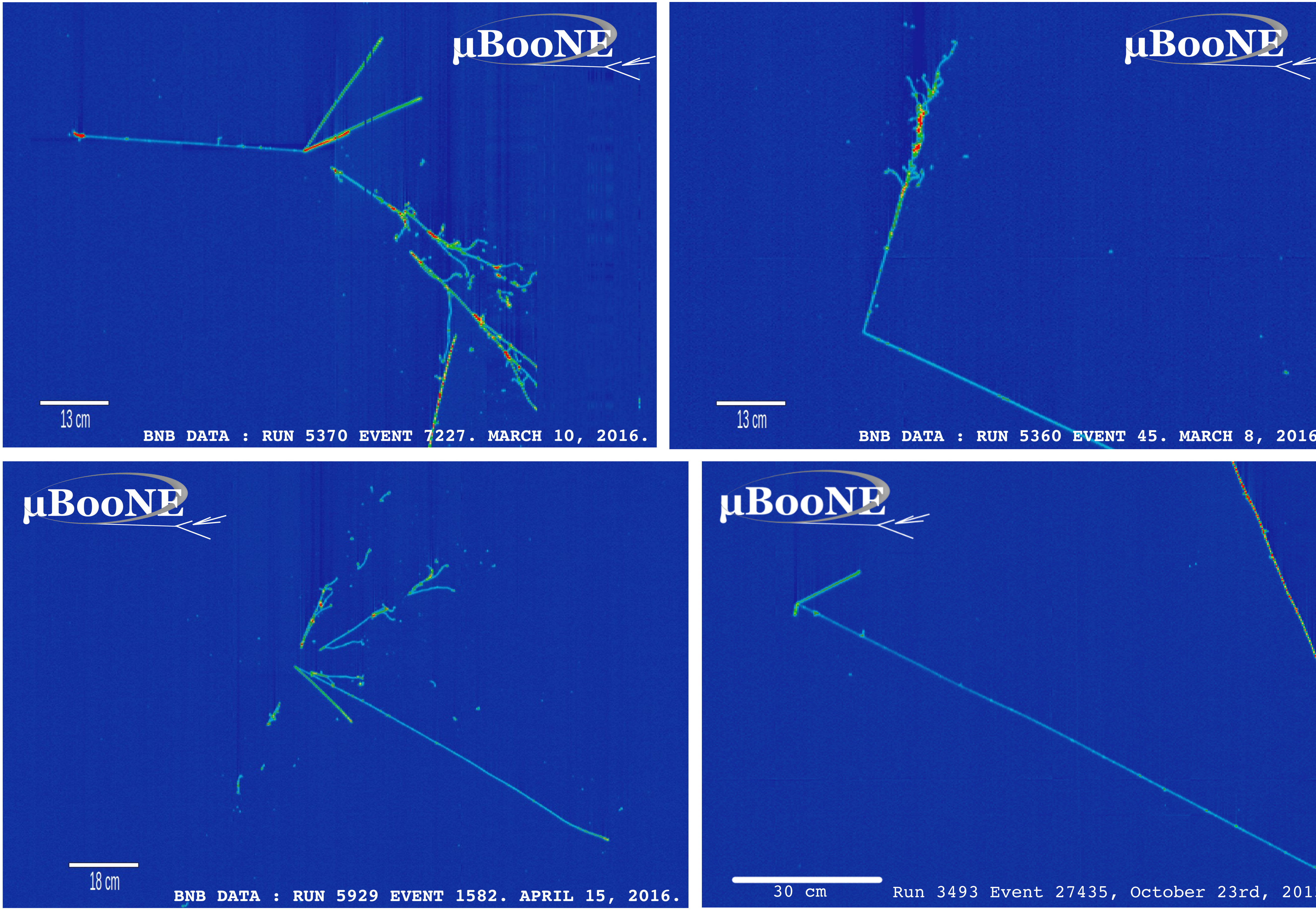
SBN's LArTPC technology provides the ability to "see" all aspects of a neutrino interaction (w/ few exceptions) and differentiate between electrons and gammas

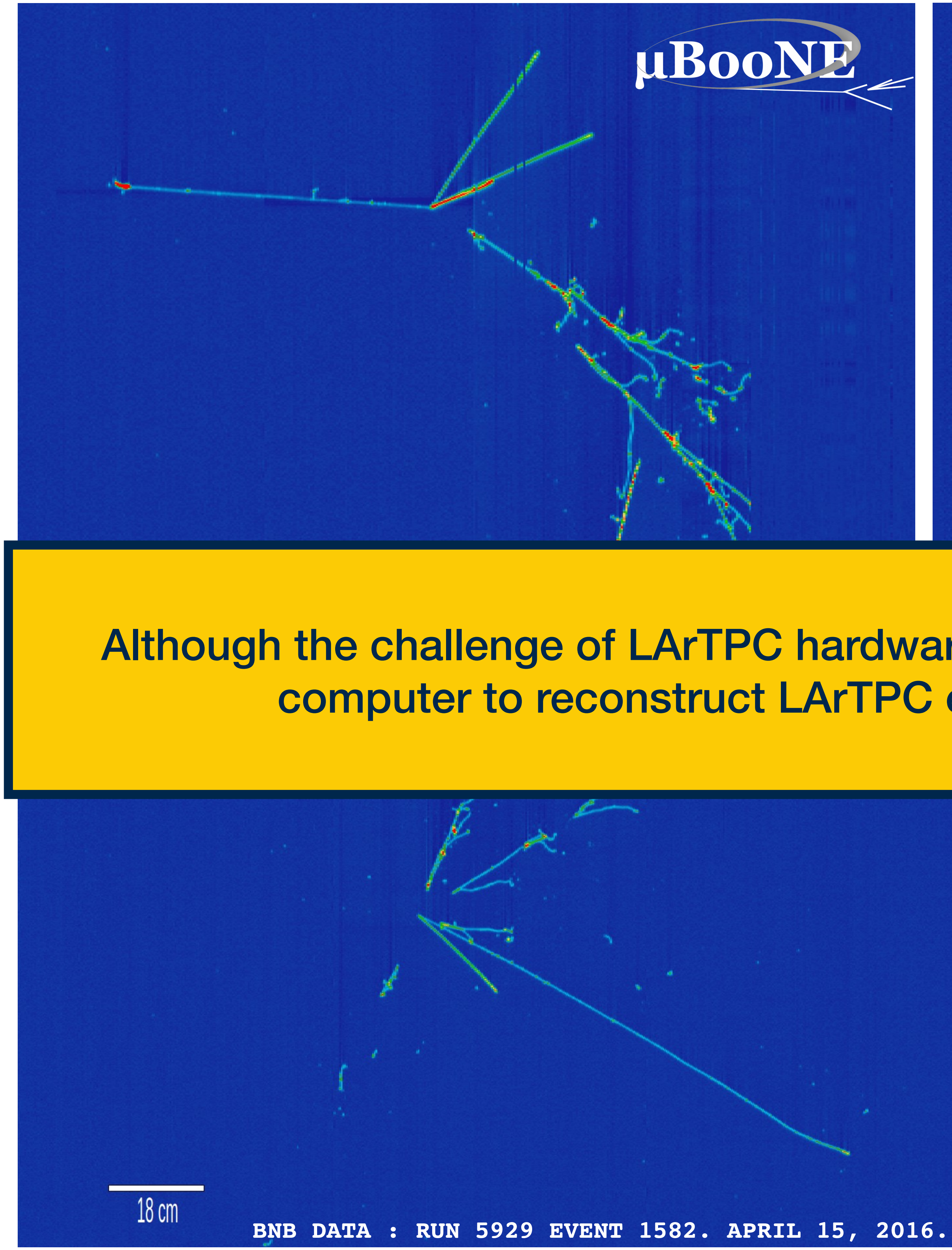
LArTPC



(compare to MiniBooNE)




μBooNE
13 cm
BNB DATA : RUN 5370 EVENT 7227. MARCH 10, 2016.
μBooNE
13 cm
BNB DATA : RUN 5360 EVENT 45. MARCH 8, 2016.
μBooNE
18 cm
BNB DATA : RUN 5929 EVENT 1582. APRIL 15, 2016.
μBooNE
30 cm
Run 3493 Event 27435, October 23rd, 2015



Although the challenge of LArTPC hardware gets most of the attention, teaching a computer to reconstruct LArTPC events is just as difficult IMHO.

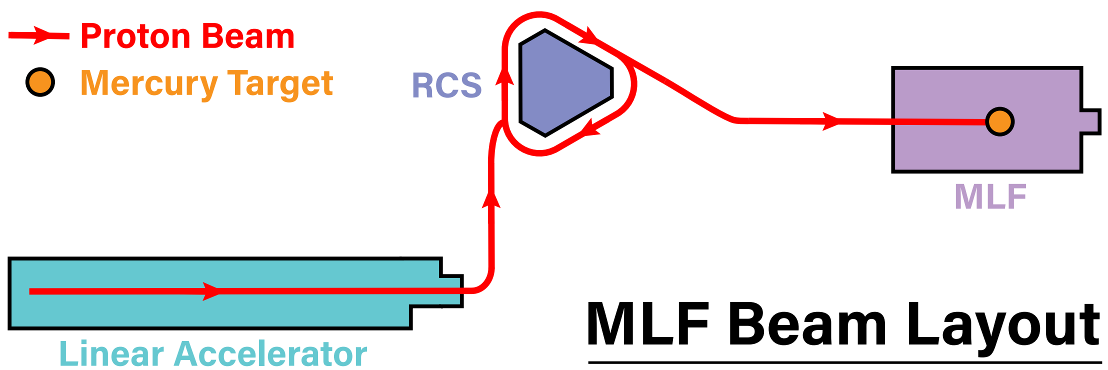
MicroBooNE is laying the groundwork for SBN+DUNE

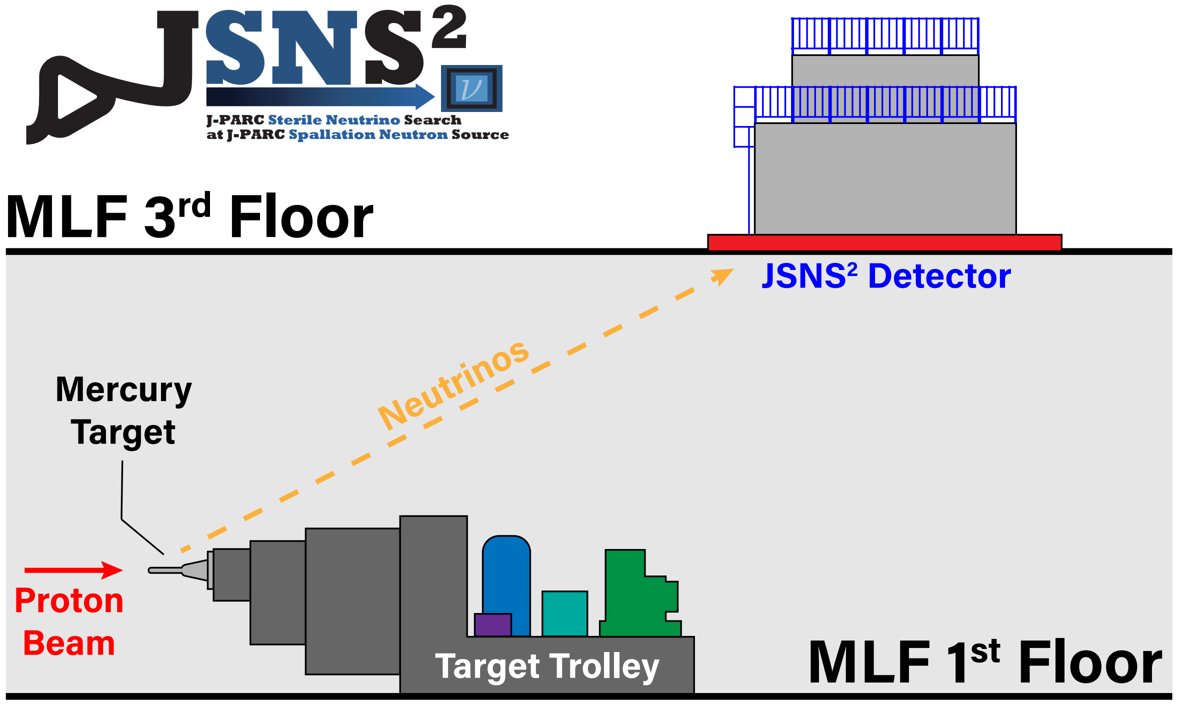
So far: LArTPC hardware R&D, reconstruction and pattern recognition, detector physics and calibration, and cross section measurements…with lots more to come, including a detailed study of the MiniBooNE excess region.

Publications/Documents by the MicroBooNE Collaboration

- MicroBooNE collaboration, "Design and Construction of the MicroBooNE Cosmic Ray Tagger System", arXiv:1901.02862, submitted to JINST
- MicroBooNE collaboration, "Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector", arXiv:1812.05679, submitted to PRC
- MicroBooNE collaboration, "First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE LAr TPC", arXiv:1811.02700, submitted to PRL
- MicroBooNE collaboration, "A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber", arXiv:1808.07269, accepted by PRD, Fermilab News article (09/12/18), DOE HEP Science Highlight (01/30/19)
- MicroBooNE collaboration, "Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, Eur. Phys. J. C79, 248 (2019), Fermilab News article (05/31/18)
- MicroBooNE collaboration, "Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE", arXiv:1804.02583, JINST 13, P07007 (2018), Fermilab News article (07/09/18)
- MicroBooNE collaboration, "Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation", arXiv:1802.08709, JINST 13, P07006 (2018), Fermilab News article (07/09/18)
- MicroBooNE collaboration, "The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", arXiv:1708.03135, Eur. Phys. J. C78, 1, 82 (2018)
- MicroBooNE collaboration, "Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter", arXiv:1707.09903, JINST 12, P12030 (2017)
- MicroBooNE collaboration, "Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", arXiv:1705.07341, JINST 12, P08003 (2017), Fermilab News article (07/05/17), DOE HEP Science Highlight (05/16/18)
- MicroBooNE collaboration, "Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC", arXiv:1704.02927, JINST 12, P09014 (2017)
- MicroBooNE collaboration, "Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering", arXiv:1703.06187, JINST 12 P10010 (2017)
- MicroBooNE collaboration, "Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber", arXiv:1611.05531, JINST 12, P03011 (2017)
- MicroBooNE collaboration, "Design and Construction of the MicroBooNE Detector", arXiv:1612.05824, JINST 12, P02017 (2017)

J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source (JSNS²)

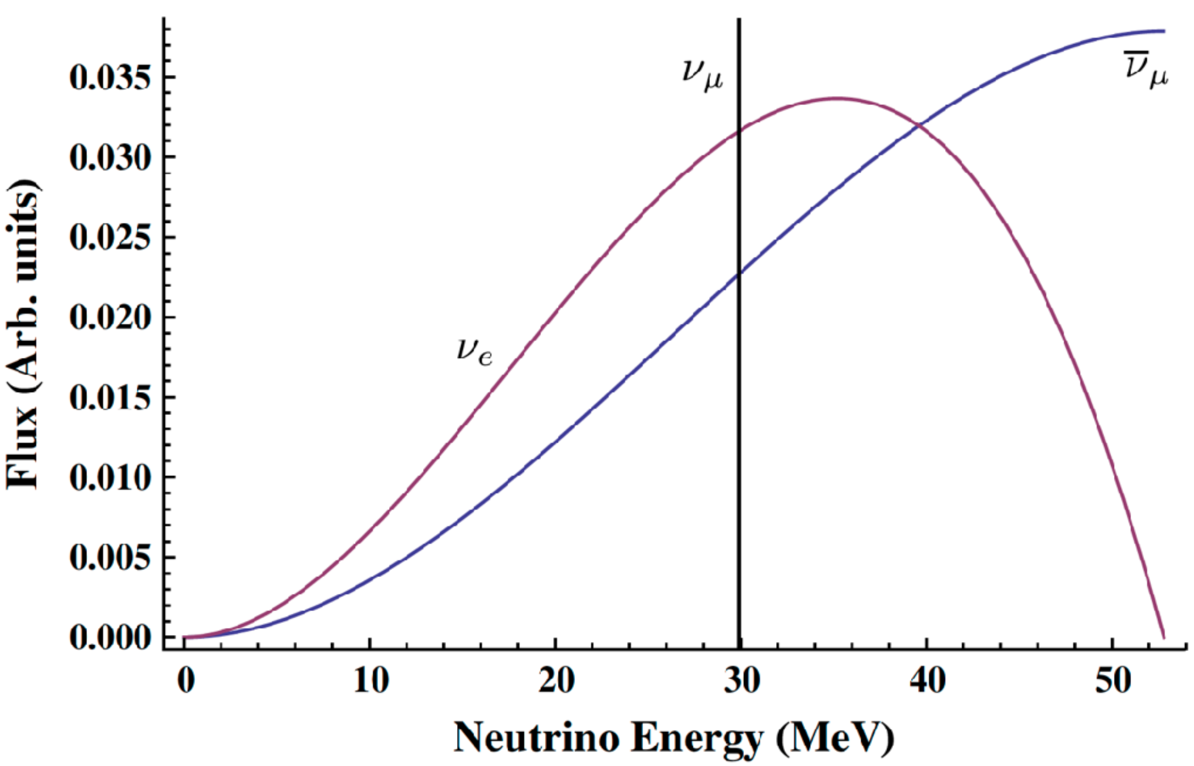




$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$

- Direct test of LSND
- Target volume is Gd-loaded liquid scintillator
  - Phase 0: 17 tons w/ ~200 10” PMTs @ 24 m
  - Future phase: multi-detector
- Energy resolution $\sim 15\% \sqrt{\mathrm{E\ (MeV)}}$
- Beam: 525 kW @ 3 GeV (w/ duty factor ~5x10^{-6})
  - Eventually 1 MW
- First data in late-2019!

JSNS2 is sensitive to the smoking gun signature of oscillations: a wiggle in L/E



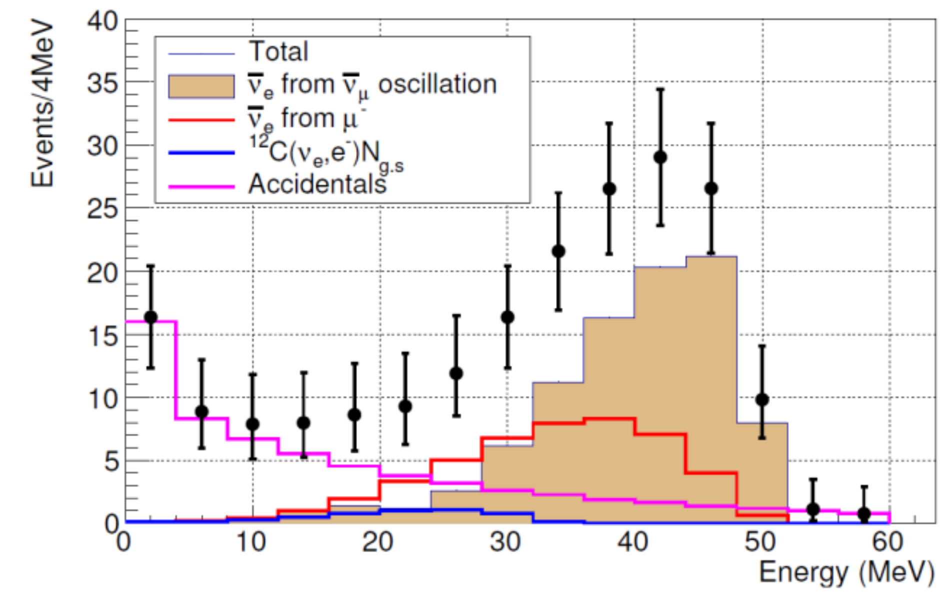
$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e \ ?$$

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e, \quad \overline{\nu}_e + p \rightarrow e^+ + n$$

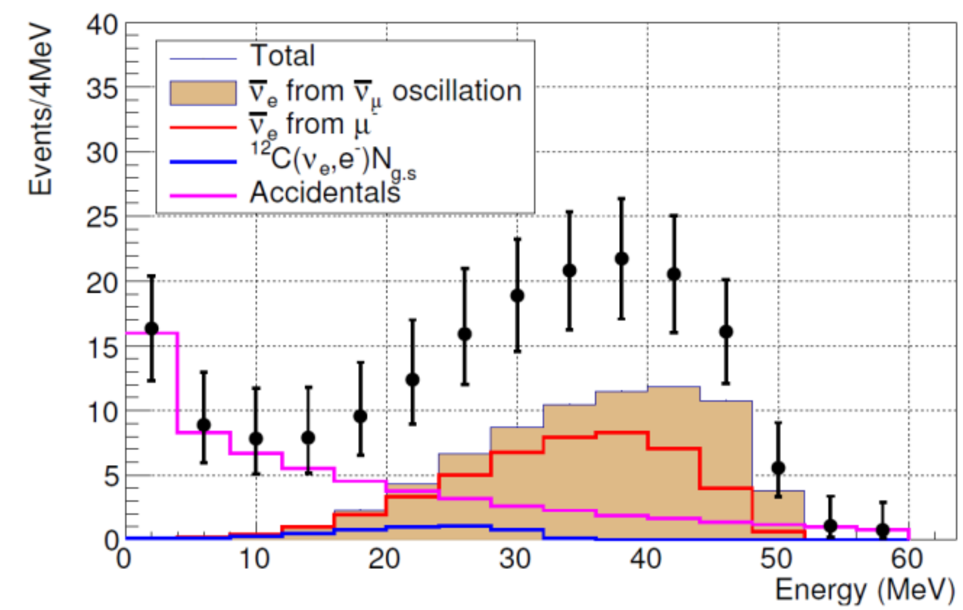
prompt signal

delayed signal
(n-capture)

Expected spectrum



Case $\Delta m^2 = 2.5 eV^2, \sin^2 2\theta = 0.003$



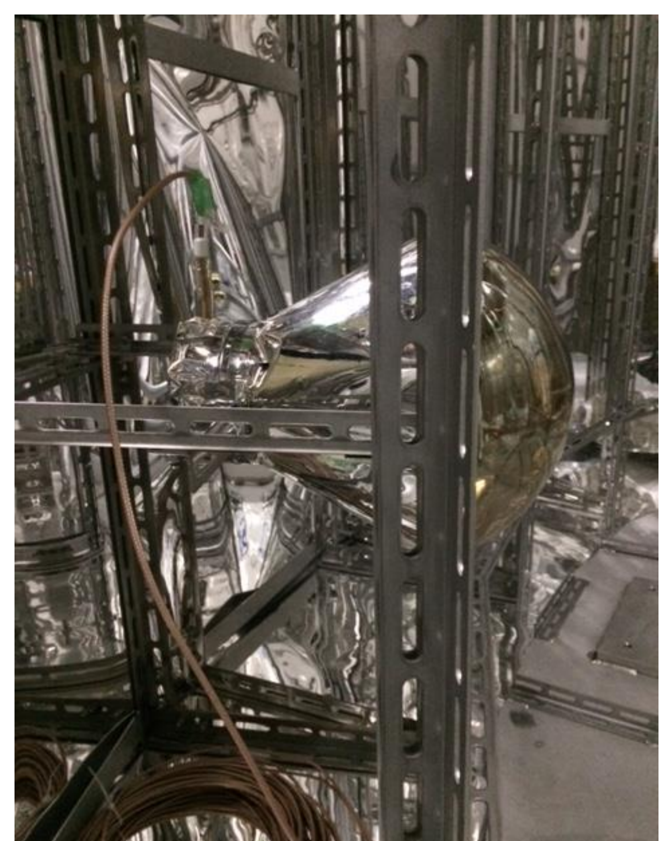
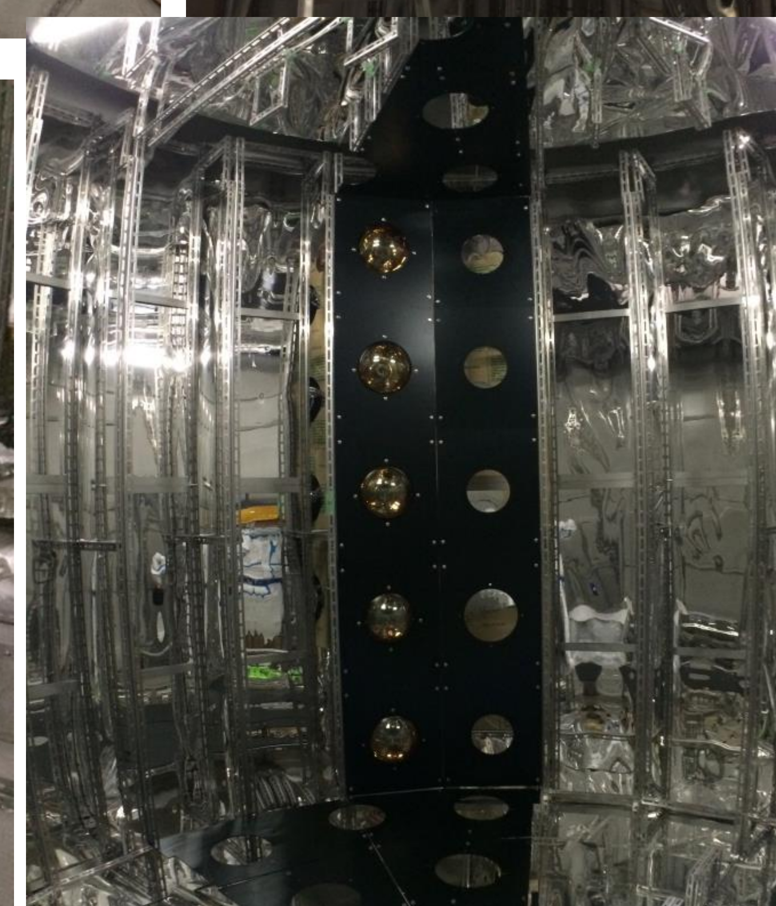
Case $\Delta m^2 = 1.2 eV^2, \sin^2 2\theta = 0.003$

(3 years of running)

JSNS^2 status as of Summer-2018 (first data will be taken in late-2019)

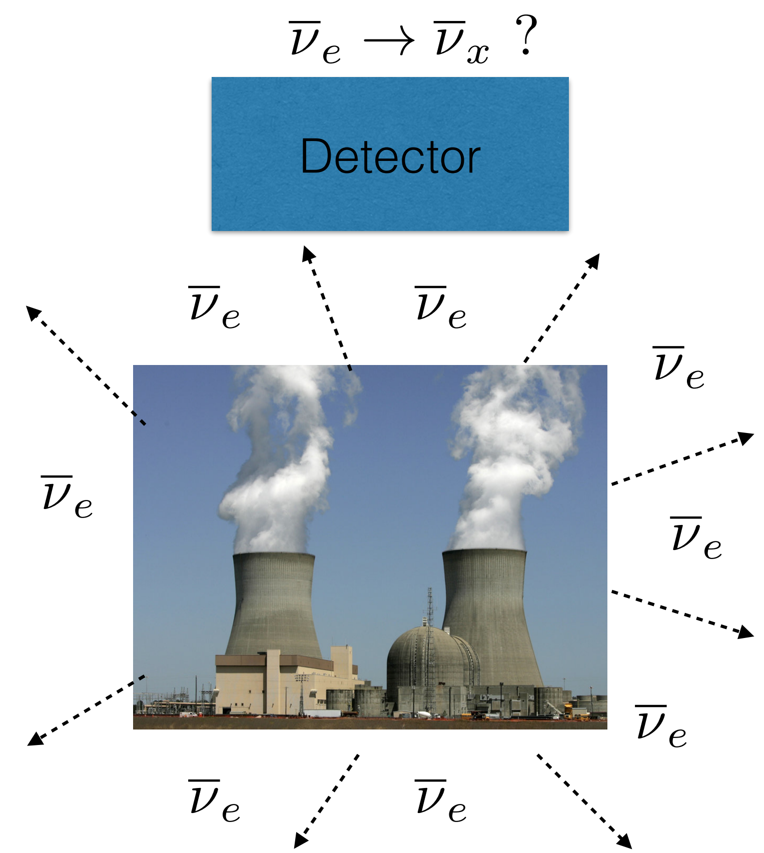


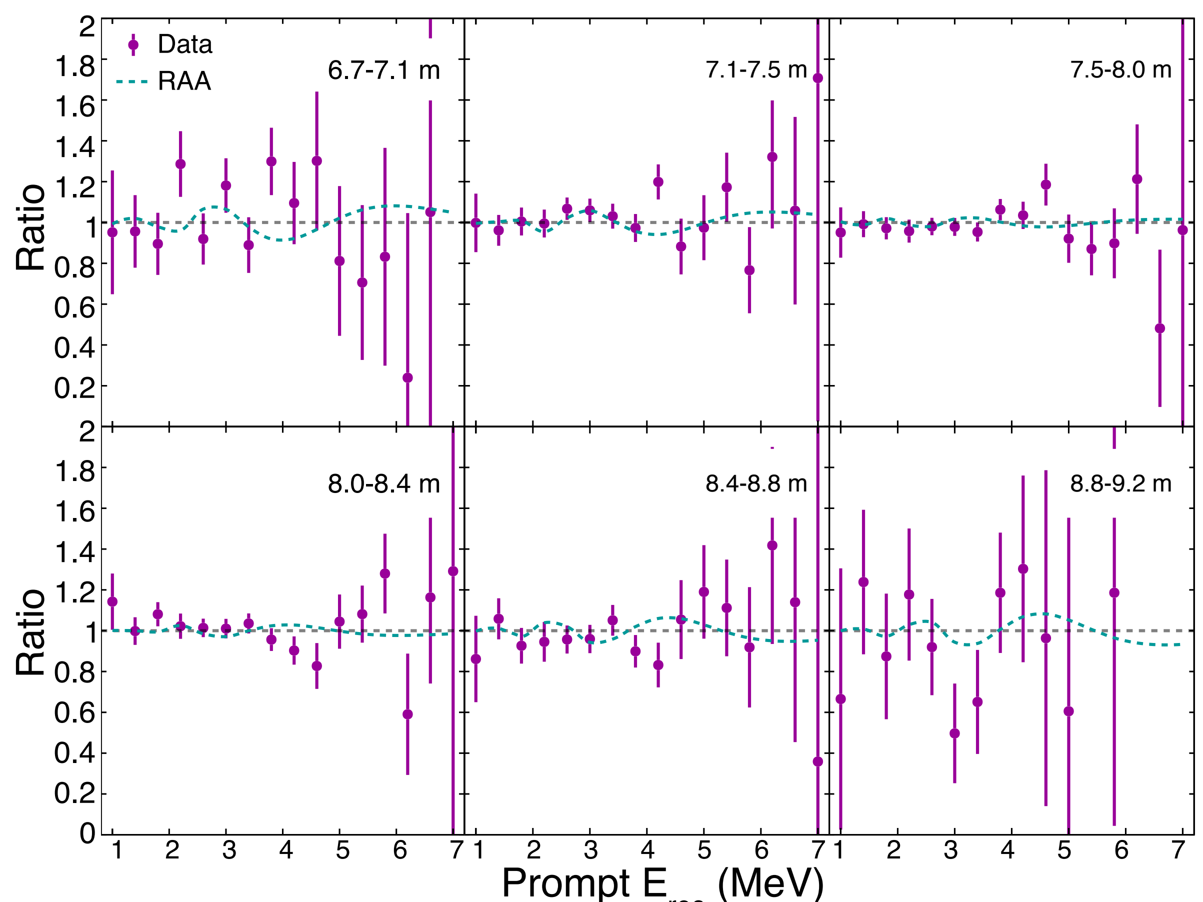


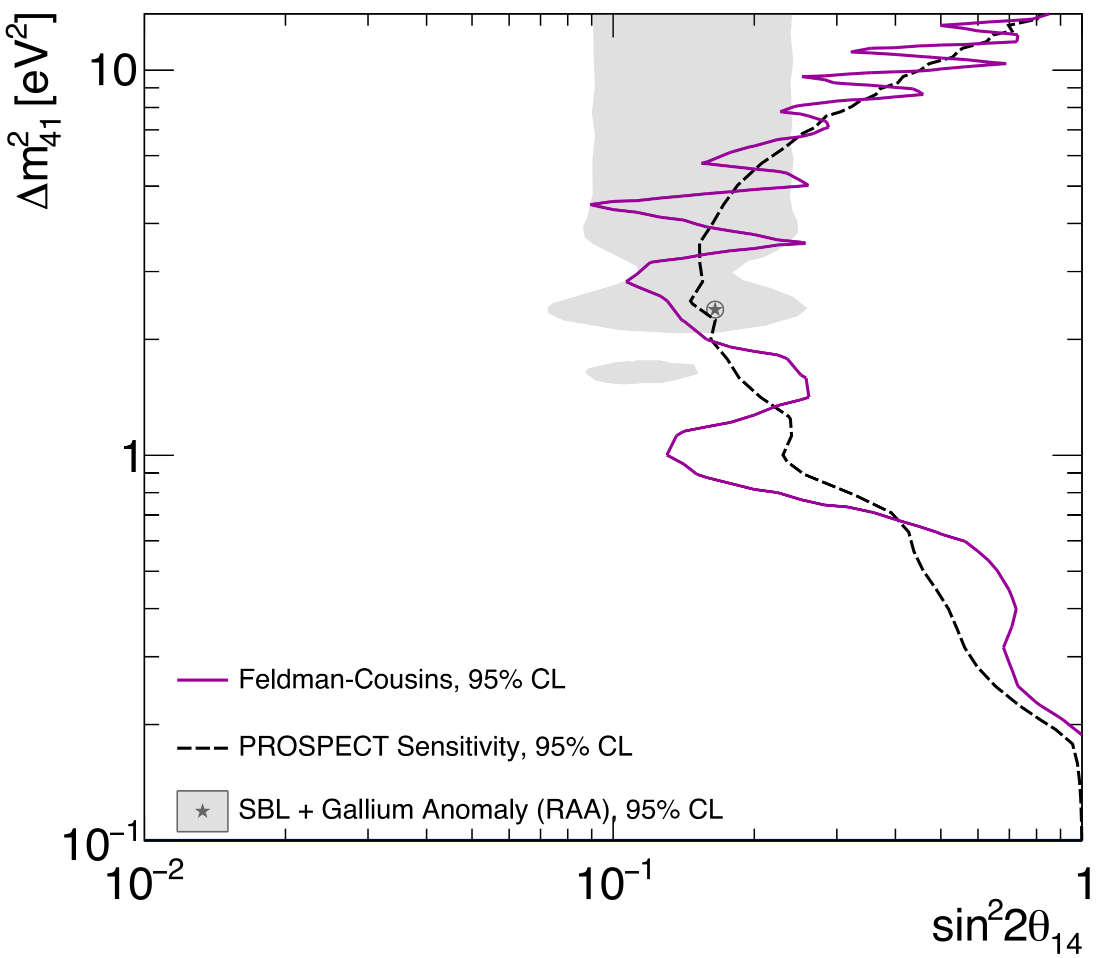



PROSPECT

- Segmented liquid scintillator (4 tons in Phase 1)
- Highly-enriched uranium reactor @ 85 MW
- Moveable w/ 7-12 m baselines
- Initial results reported for 33 days of reactor-on (750 IBD events/day).
- First oscillation analysis excludes Reactor Antineutrino Anomaly best-fit at 2.3σ.







PROSPECT Collab., PRL 121 251802 (2018)

Conclusion

- A number of neutrino anomalies at short baseline may be indicative of new physics.

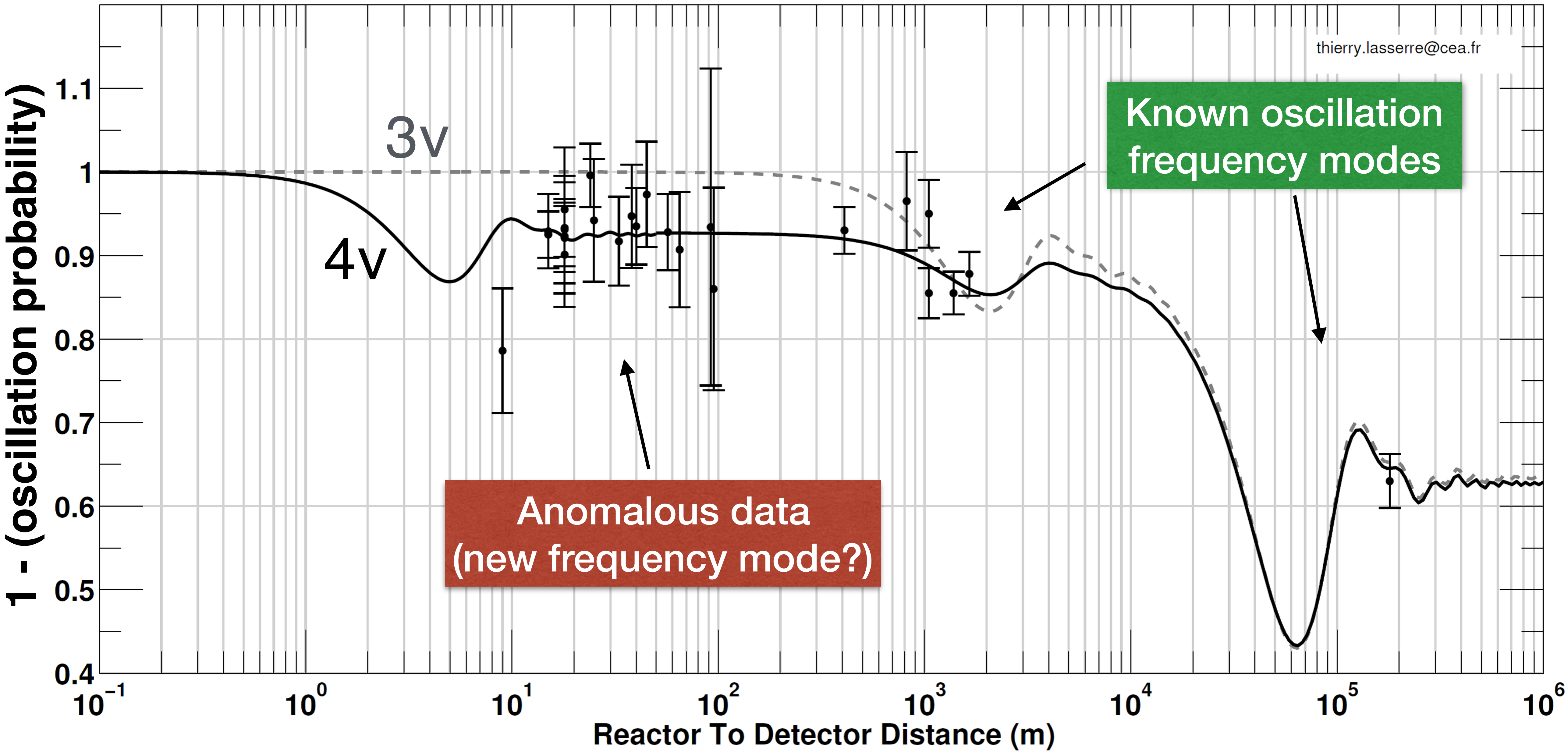
- The parameter space of new oscillations/interactions continues to be explored with accelerator-based, including decay-in-flight and decay-at-rest, and reactor-based experiments.

- We can look forward to many more results with short-baseline experiments in the future, including impactful cross section measurements, exotic searches, and R&D, all in addition to the anomaly probes.

Backup

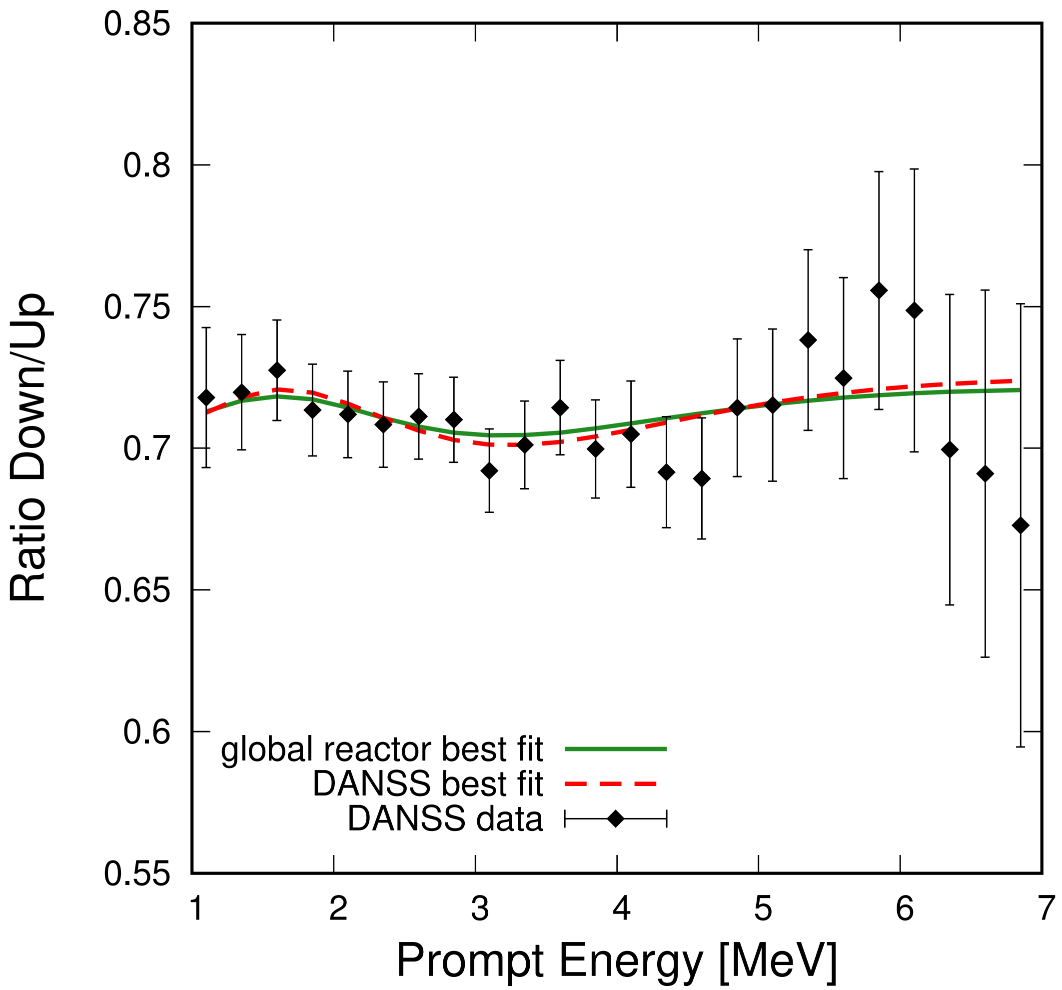
Reactor anomaly

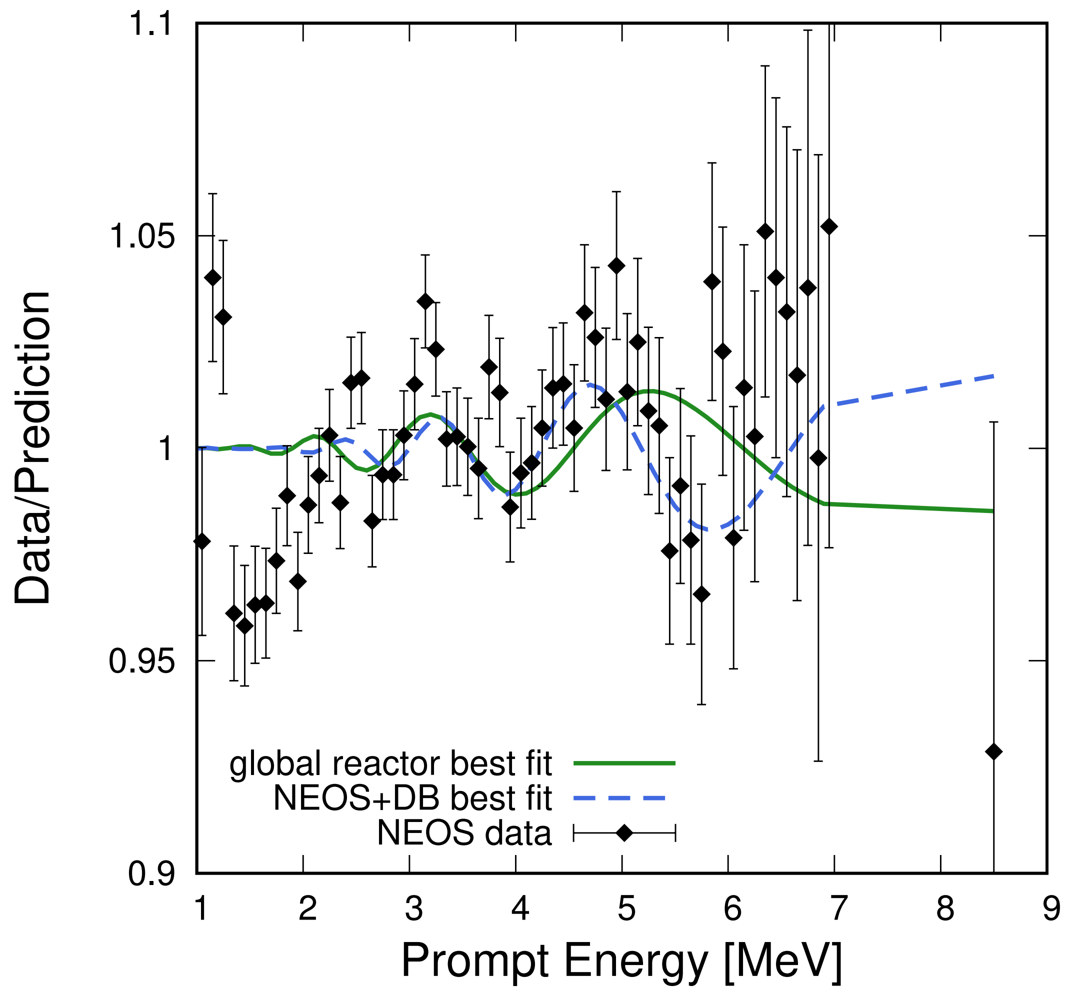
The oscillation modes associated with reactor neutrinos



Update: recent reactor results

arXiv:1803.10661

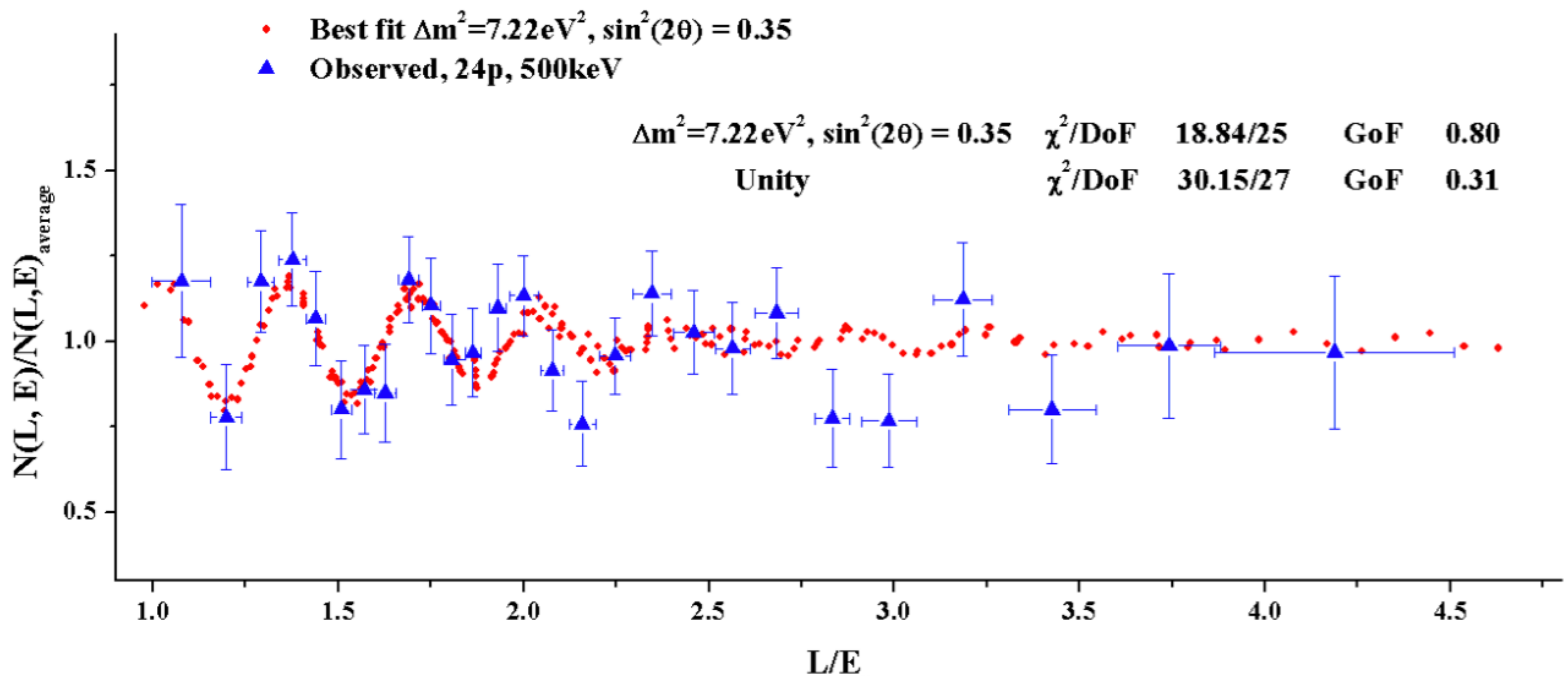




DANSS and NEOS

Update:
recent reactor results

arXiv:1809.10561



Neutrino-4