

# Accelerator-based Neutrino Experiments at Short-Baselines

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HEISING-SIMONS  
FOUNDATION



# 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

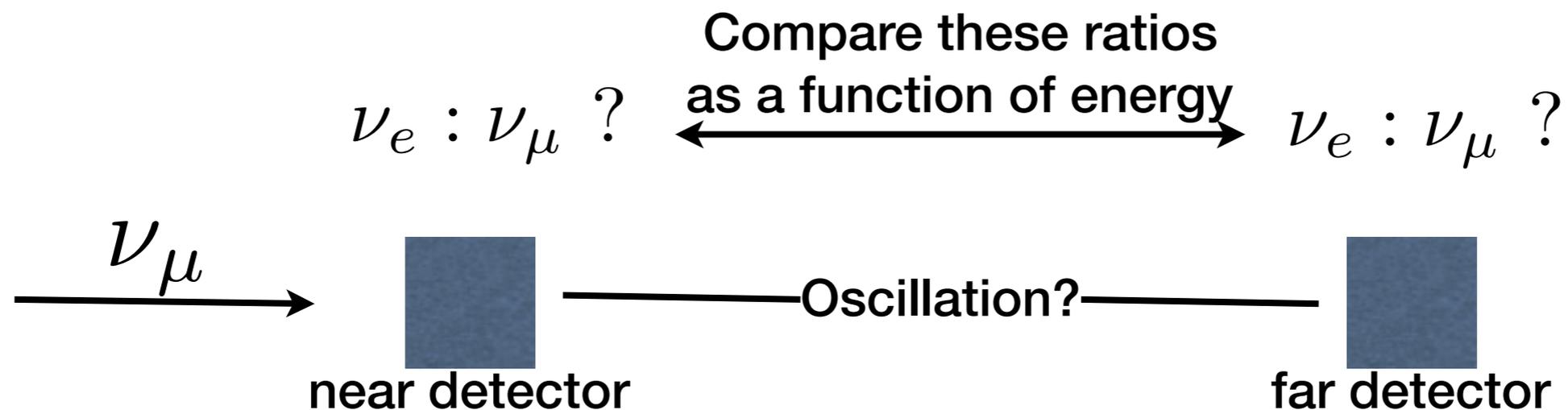
- **Non-oscillation physics**
- **Short review of the existing anomalies at short-baseline**
- **Discussion of the MiniBooNE anomaly**
- **A quick tour of current/future experiments**

# Outline

- **Non-oscillation physics**
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**Why neutrino cross section  
measurements at short-baseline?**

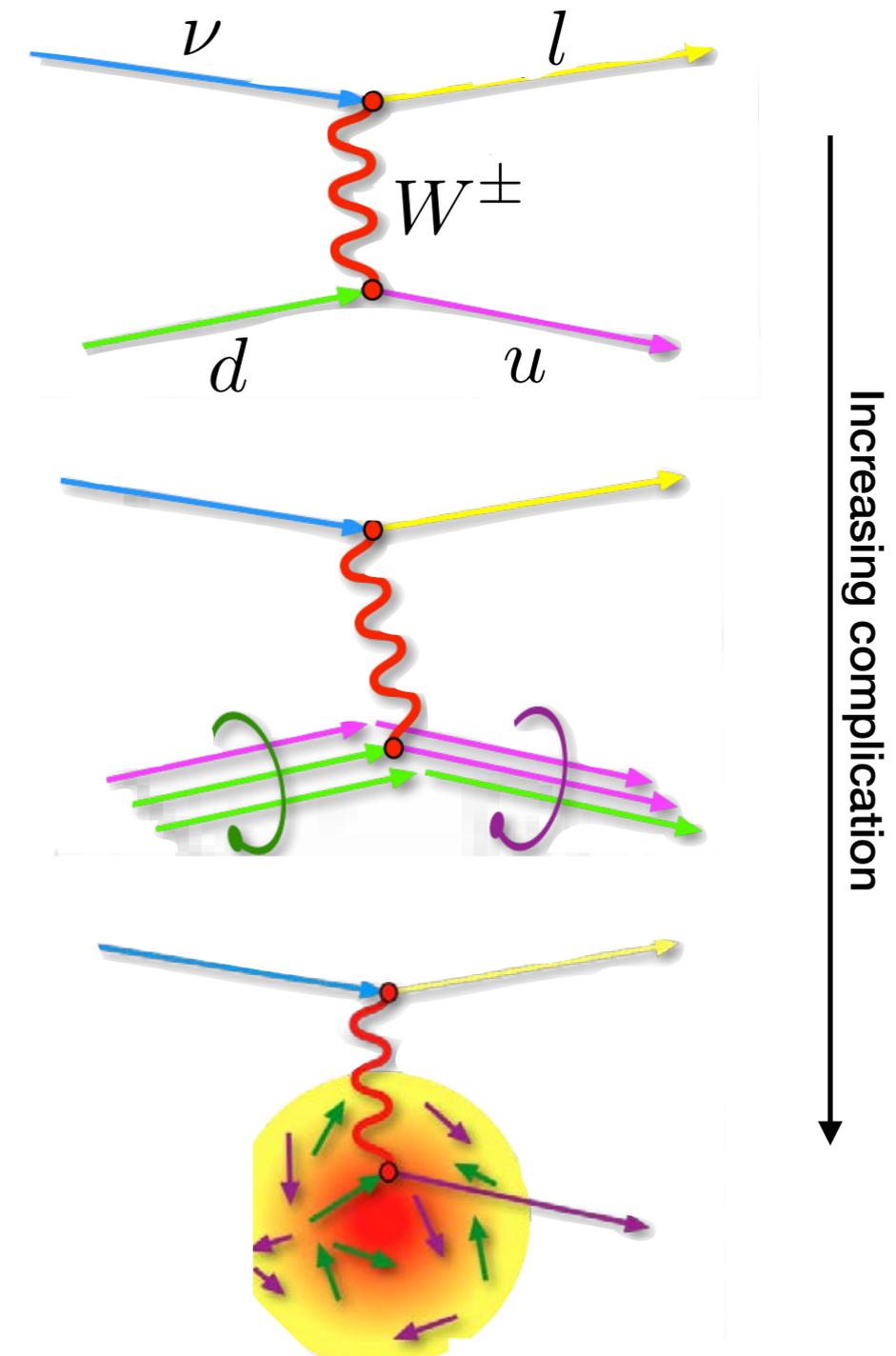
# Reminder



**Turning near and far rate measurements into flux evolution (oscillation) measurements requires cross section knowledge.**

# 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.



# Why neutrino cross section measurements at short-baseline?

- Neutrino interactions with nuclei are complicated!

- Fermi motion

- C

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.

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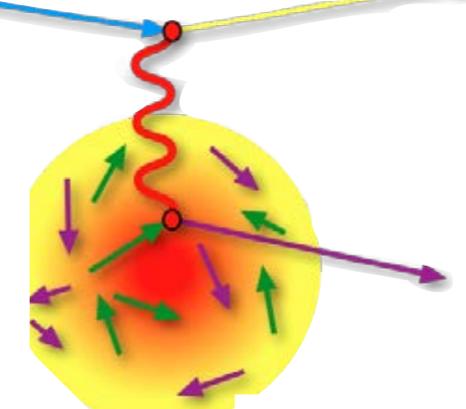
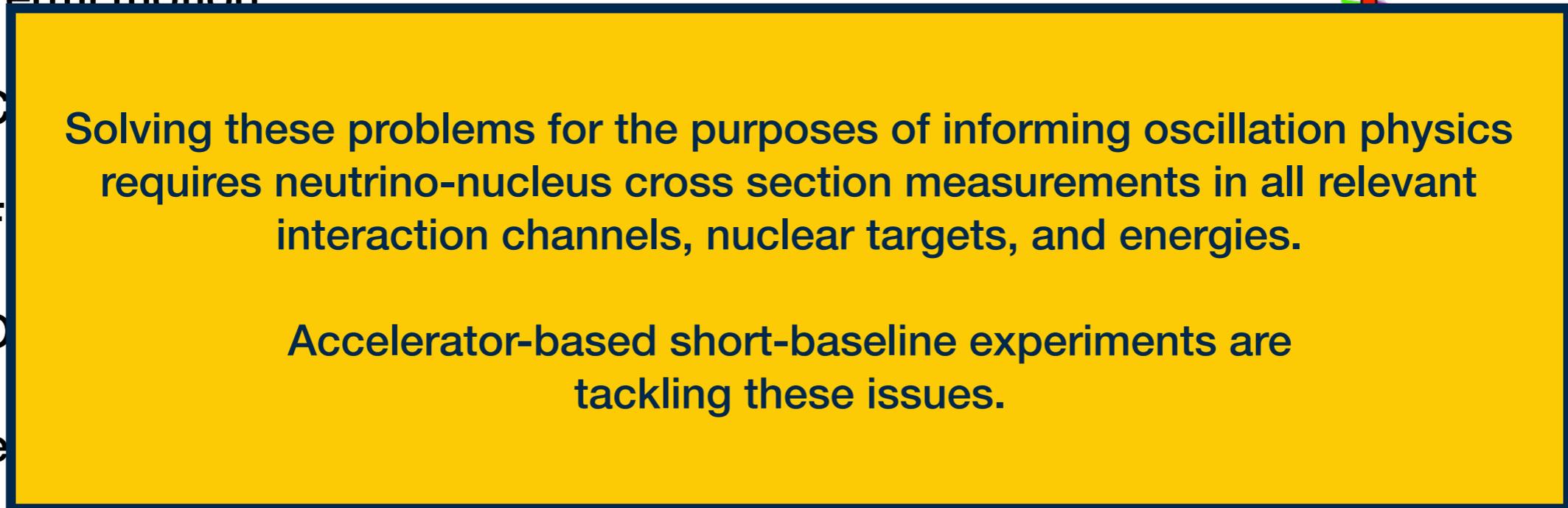
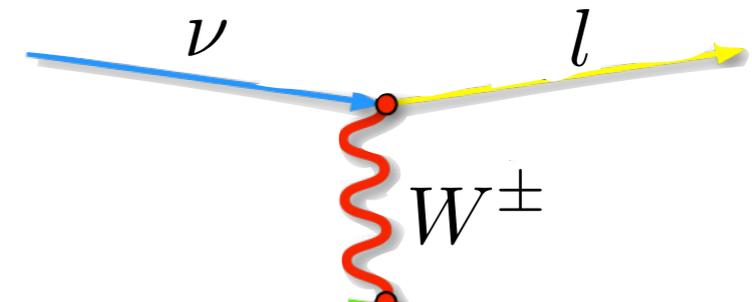
Accelerator-based short-baseline experiments are tackling these issues.

- Dete

- Energy resolution.

- Event classification issues.

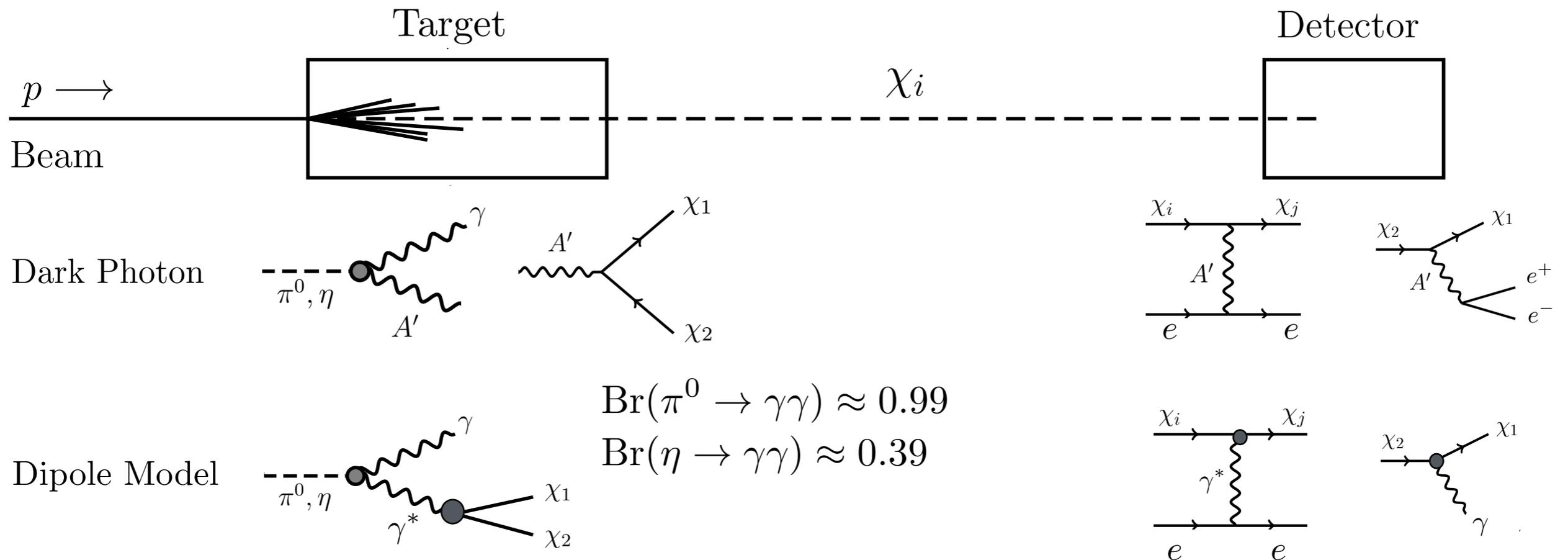
- Cerenkov threshold.



# Exotic searches at short-baseline

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

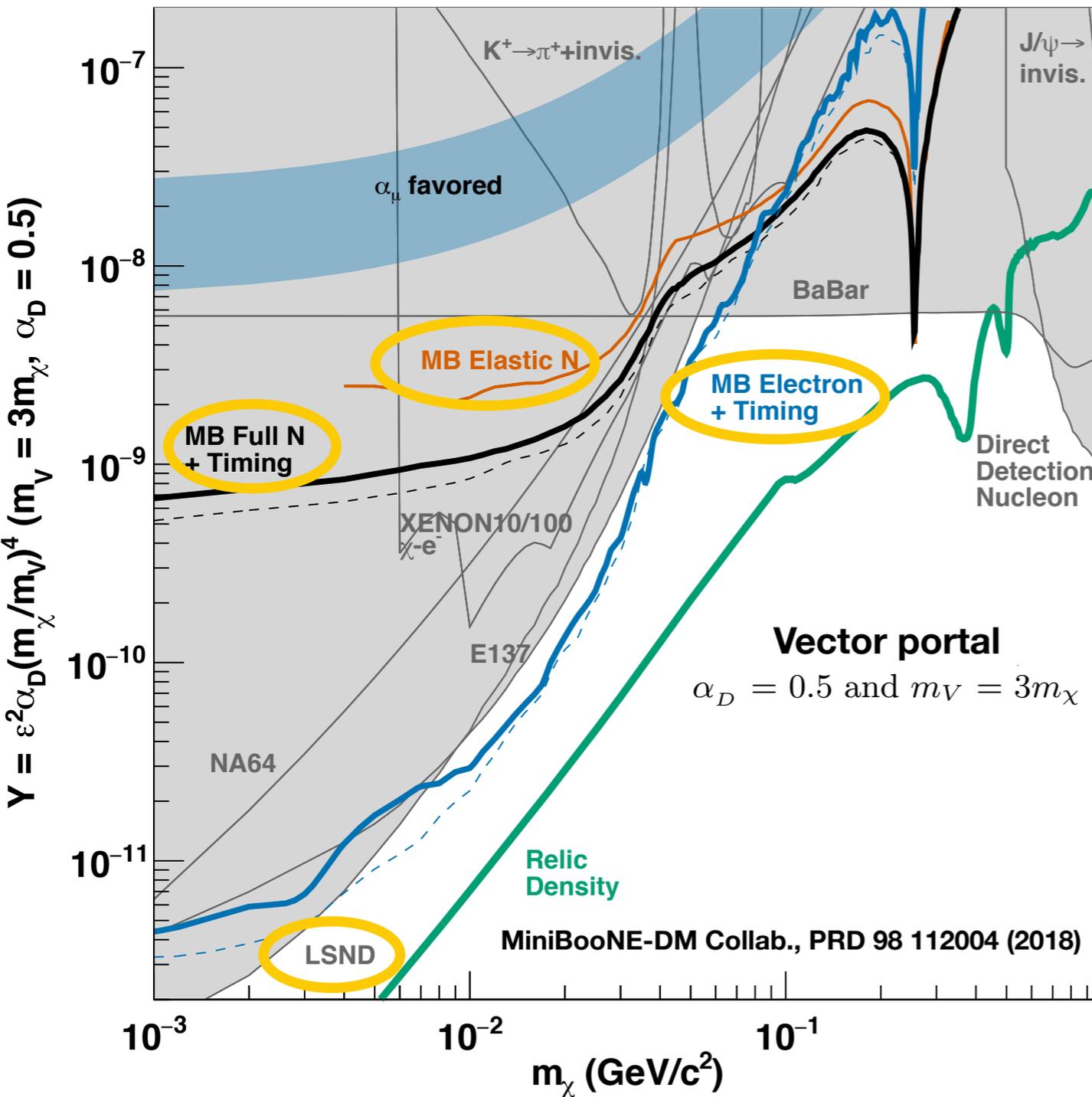
Simple idea: make a new particle with your  $10^{20}$ -something protons on target and then watch it decay or interact in your neutrino detector



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

# Exotic searches at short-baseline

example: vector portal



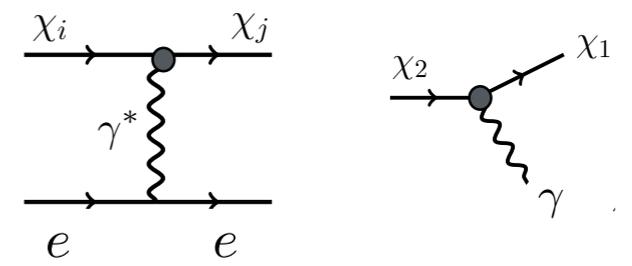
Detector

$\chi_i$

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

$\approx 0.99$   
 $\approx 0.39$



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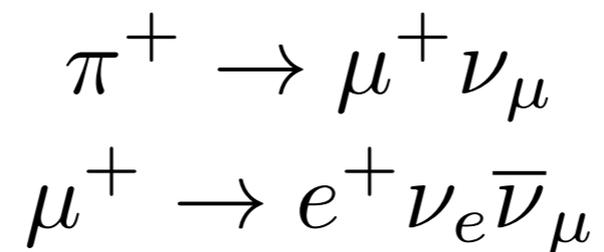
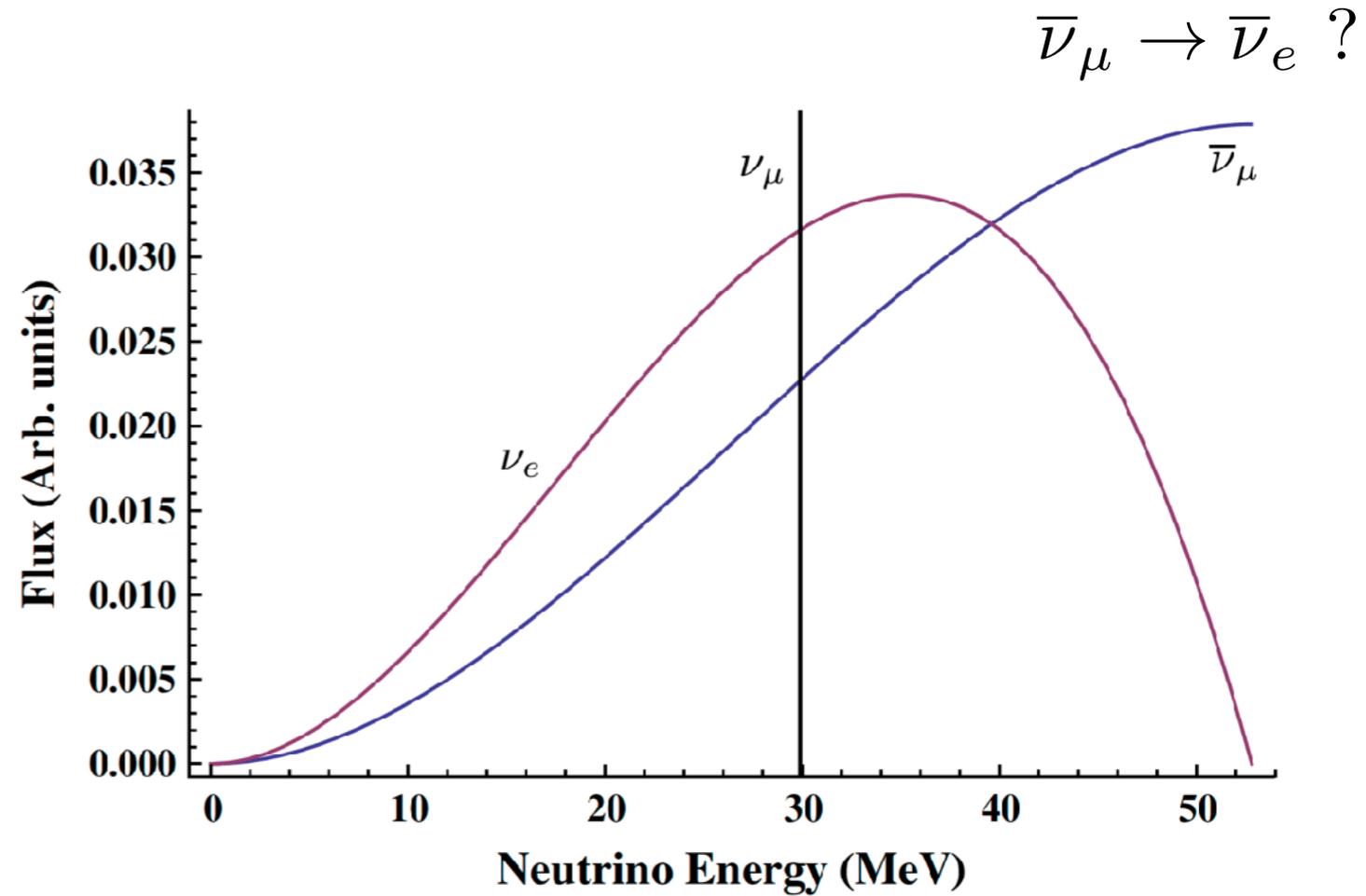
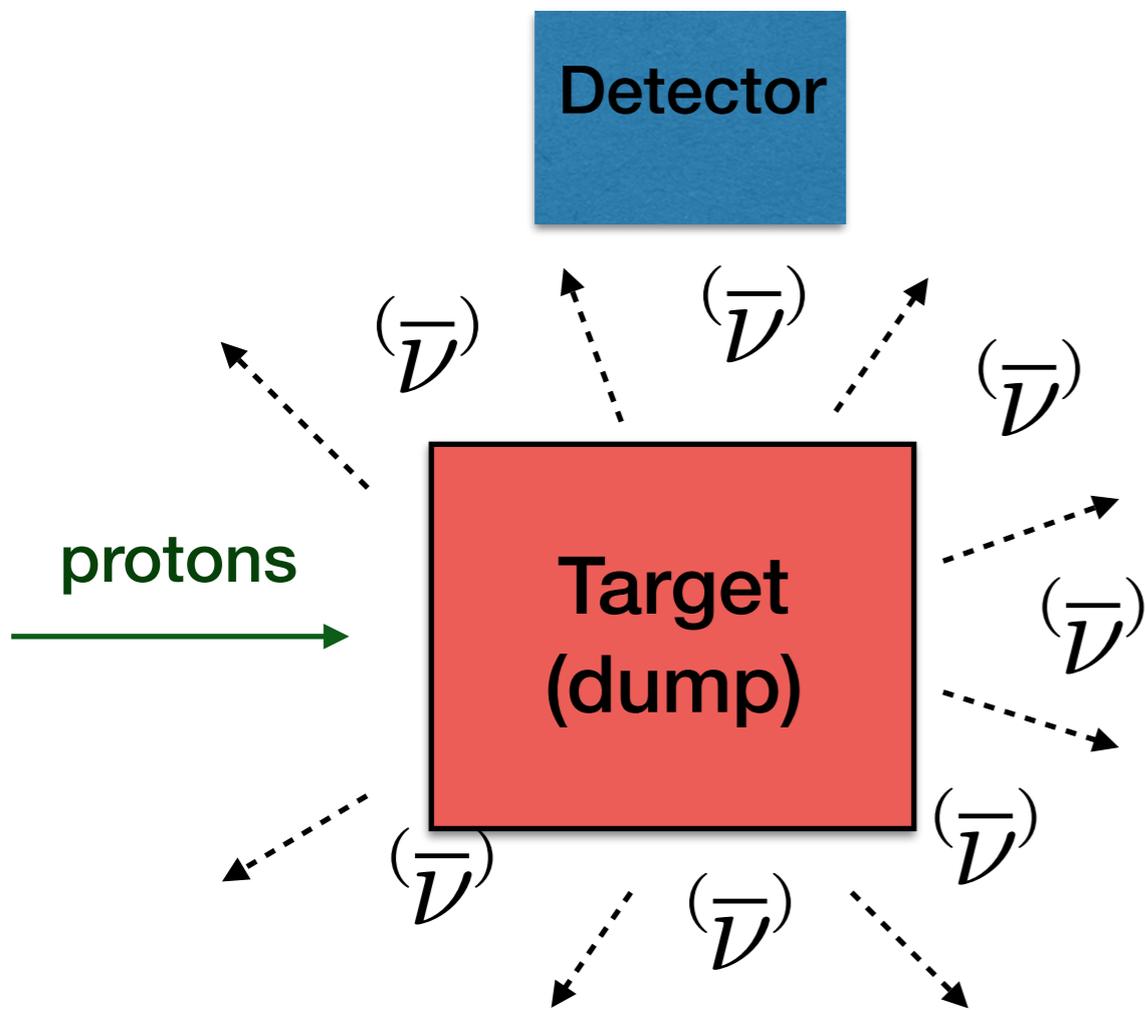
A number of anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

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

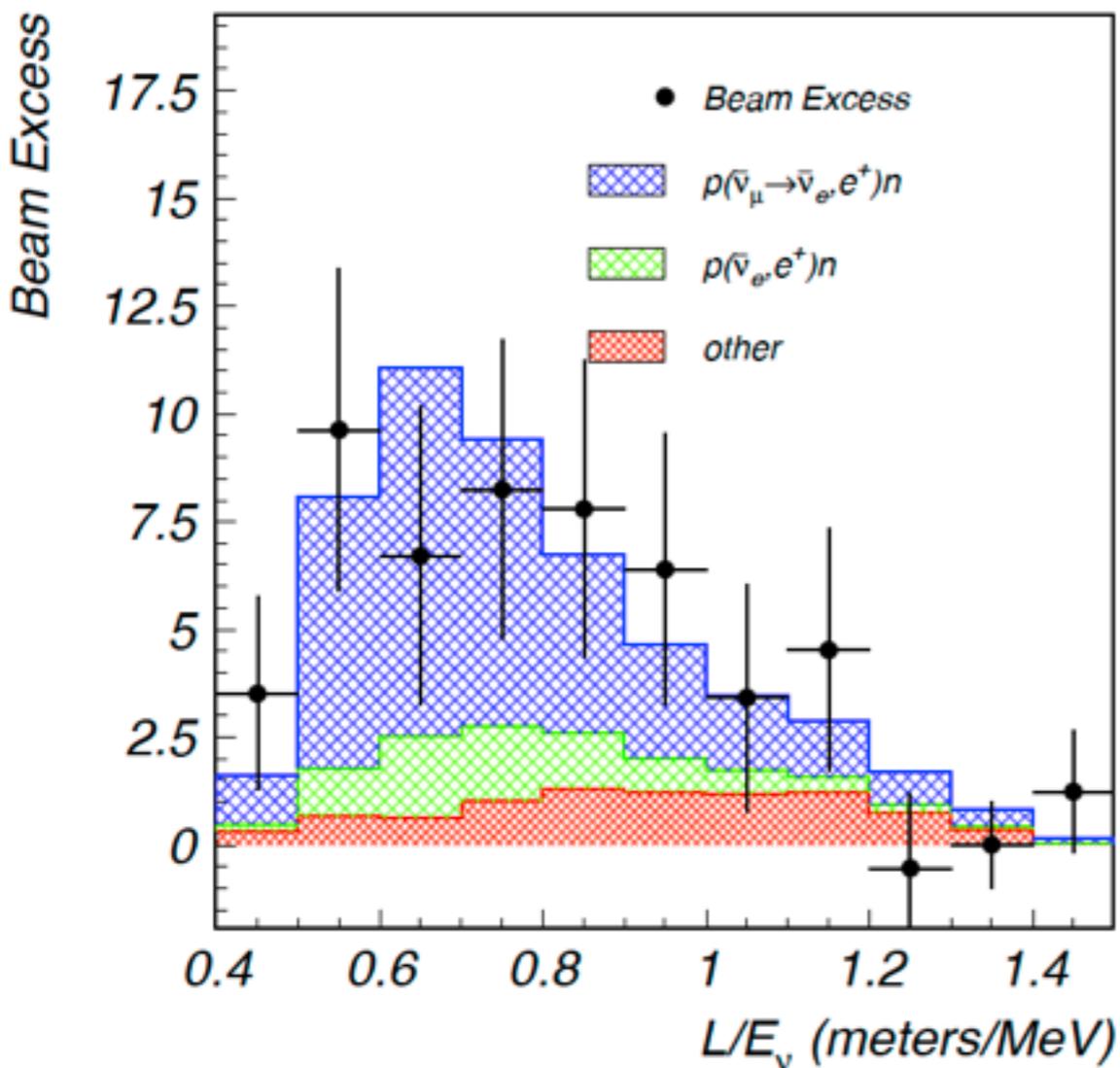
Now:  $4.8\sigma$  (combined)

(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



# The Liquid Scintillator Neutrino Detector anomaly

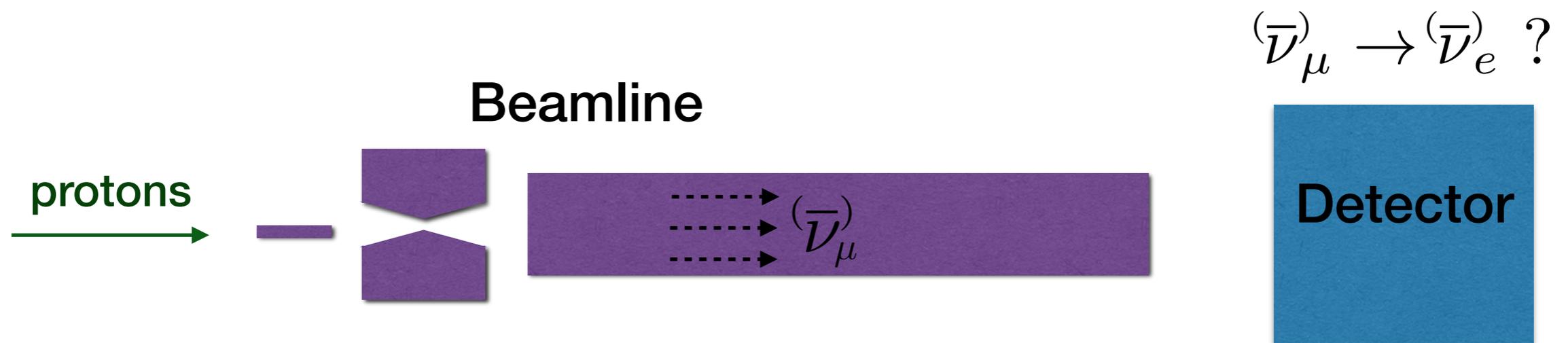


- LSND observed  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  at  $3.8\sigma$  significance with a characteristic oscillation frequency of  $\Delta m^2 \sim 1 \text{ eV}^2$ .
- That's odd. There are two characteristic oscillation frequencies in the three neutrino picture and they are precisely measured.

$$\Delta m_{\text{LSND}}^2 \gtrsim 0.2 \text{ eV}^2$$

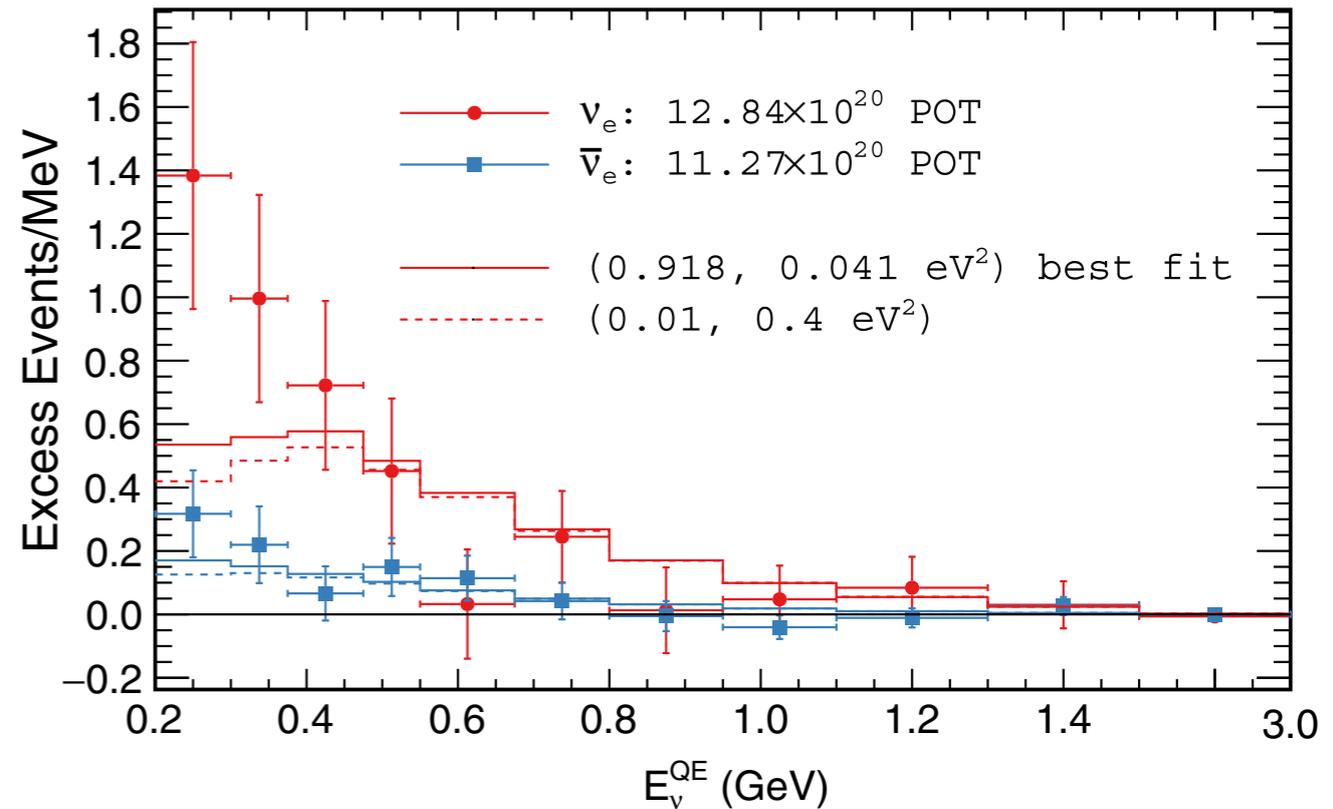
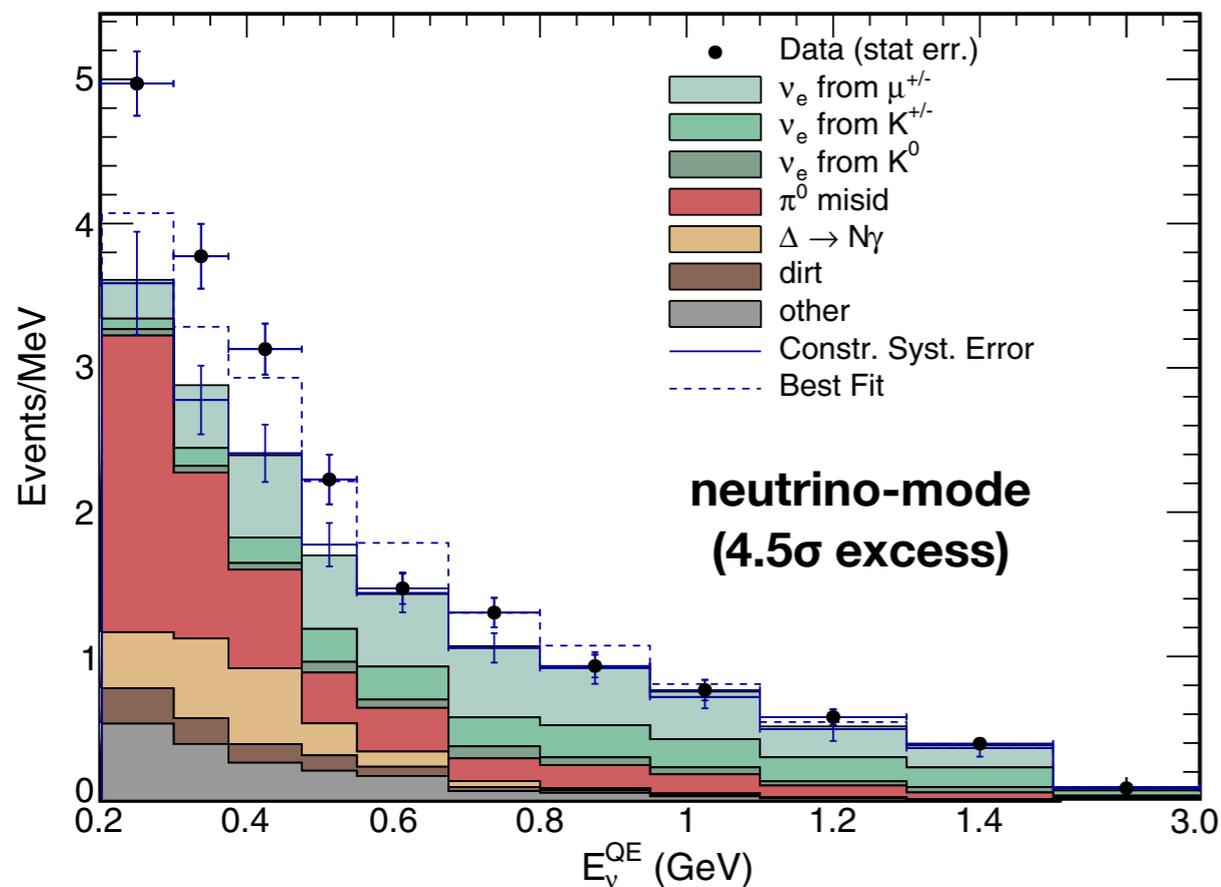
$$(\gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2)$$

# Pion decay-in-flight



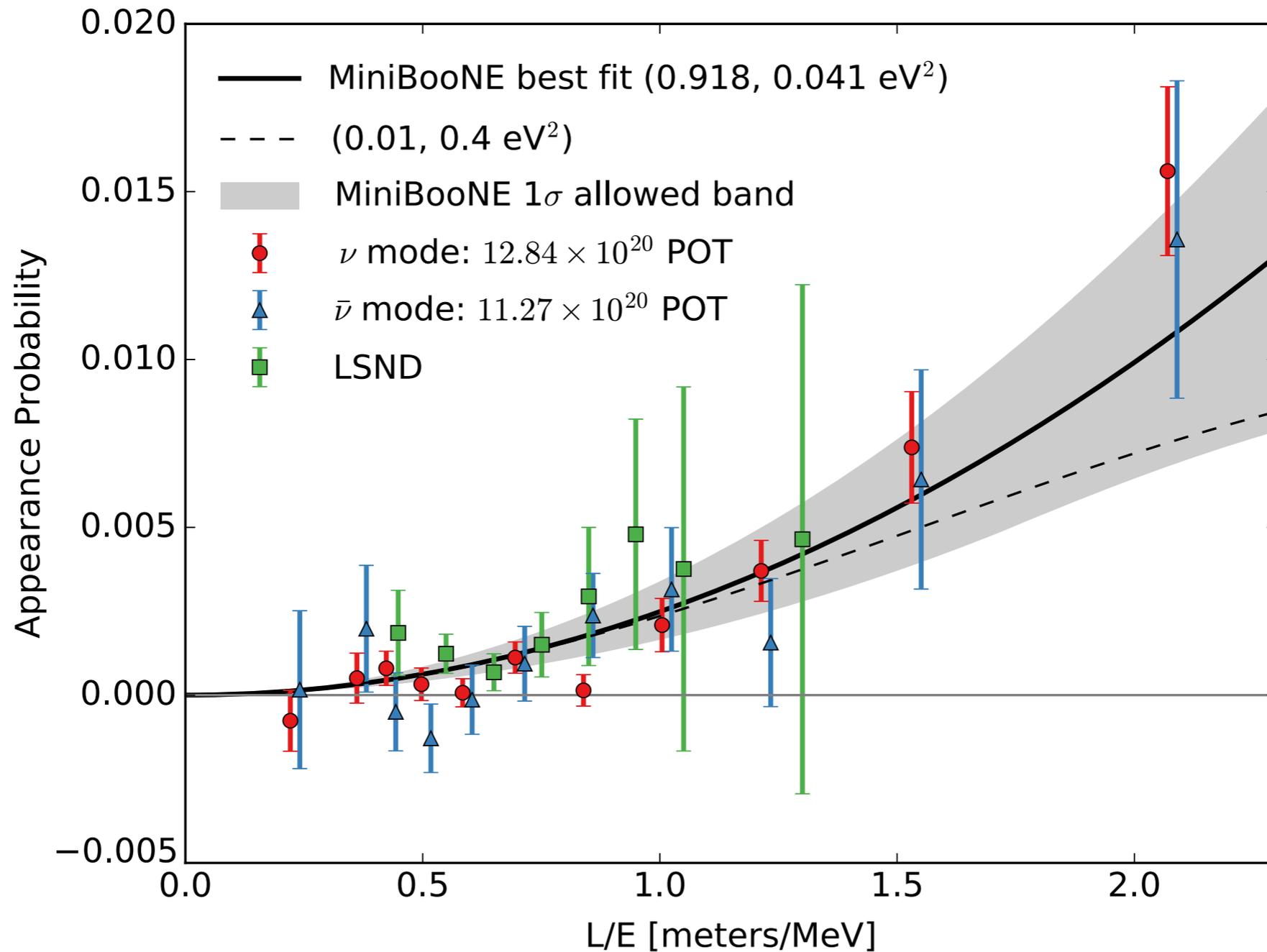
# The MiniBooNE anomalies

MiniBooNE Collab., PRL 122 221801 (2018)



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

# LSND and MiniBooNE



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

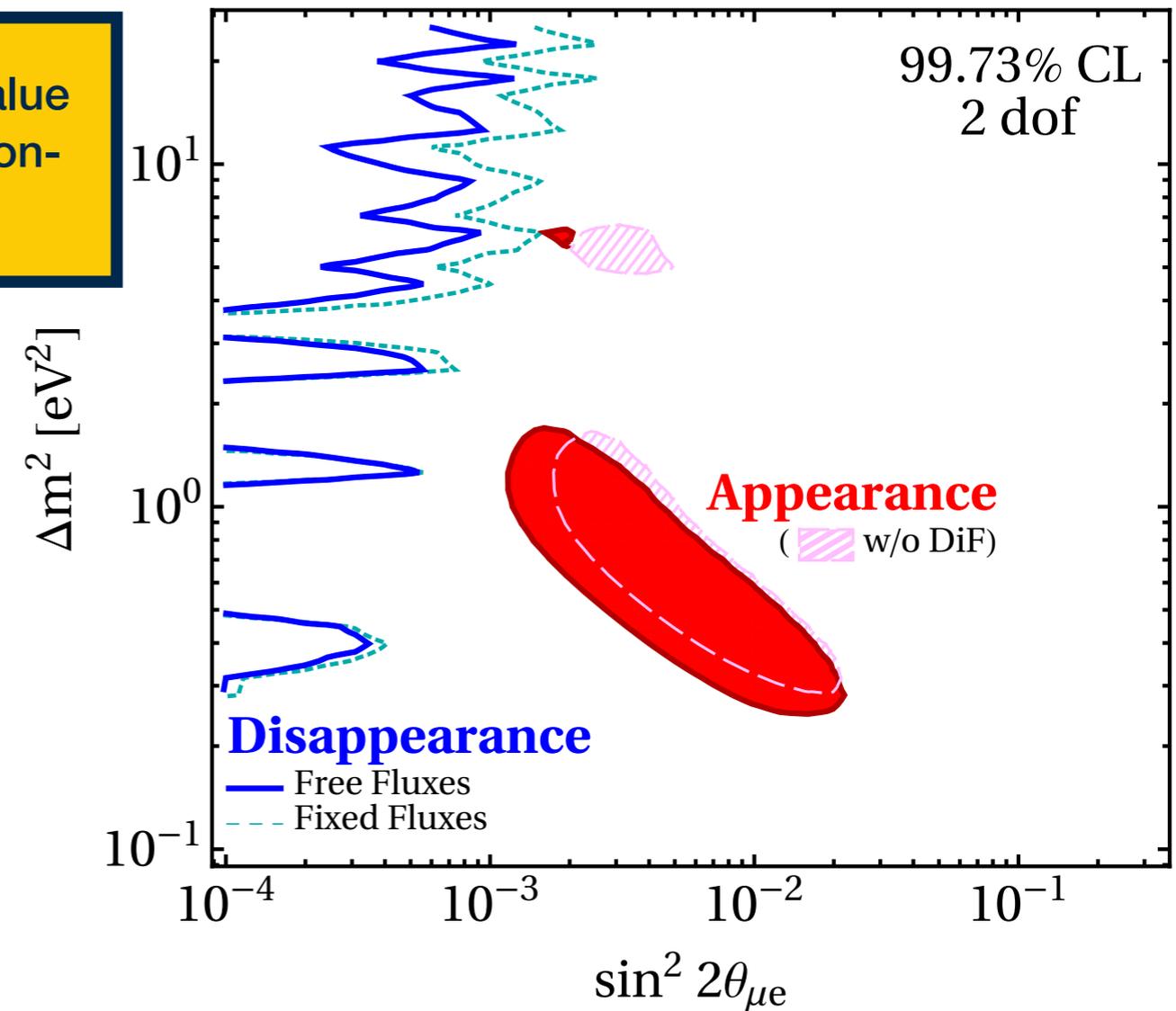
IceCube, MINOS(+), NOvA, MiniBooNE, OPERA, CDHS see no muon-flavor disappearance at high- $\Delta m^2$

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.

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

$$P_{\mu\mu} = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)$$

$$P_{\mu e} = 4|U_{\mu4}|^2|U_{e4}|^2 \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)$$



$$\sin^2 2\theta_{\mu e} = 4|U_{\mu4}|^2|U_{e4}|^2$$

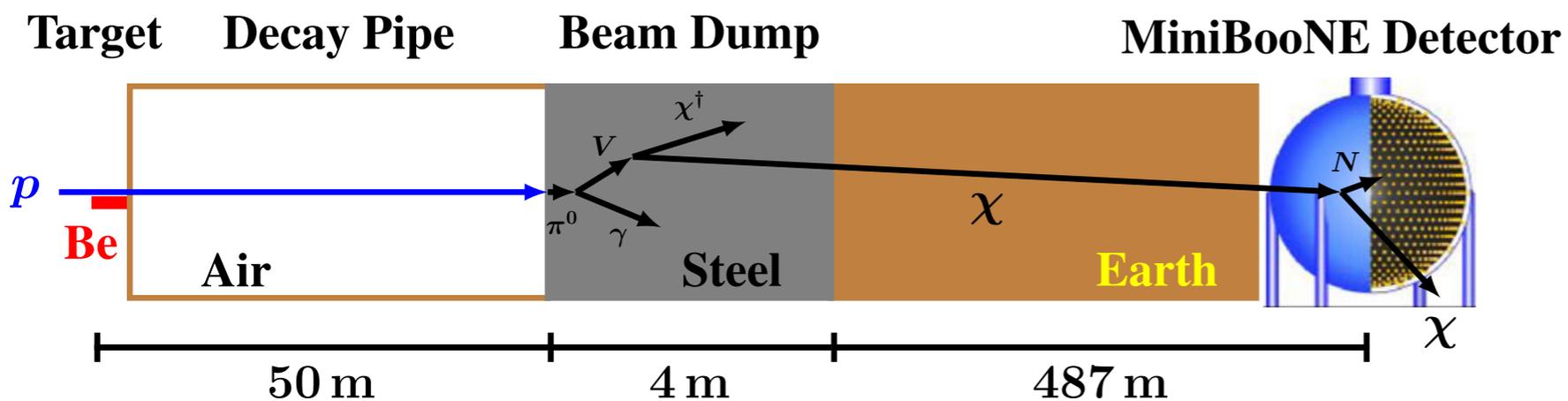
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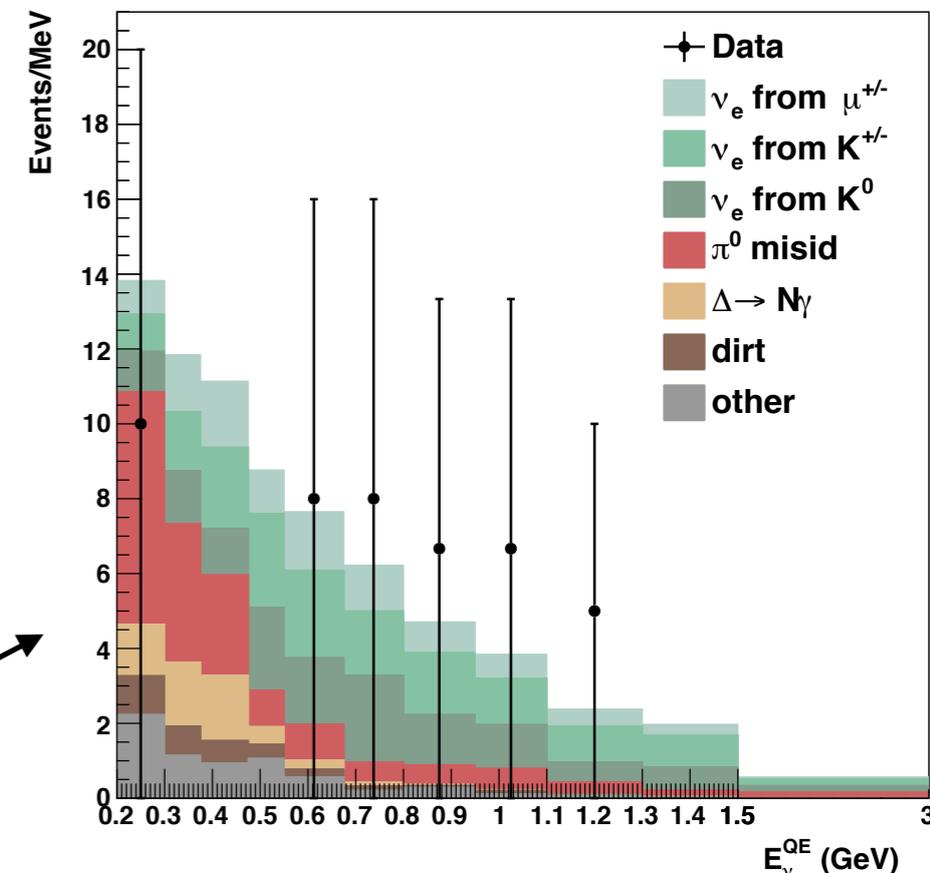
# Ok, so 3+1 is ruled out.

## 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]

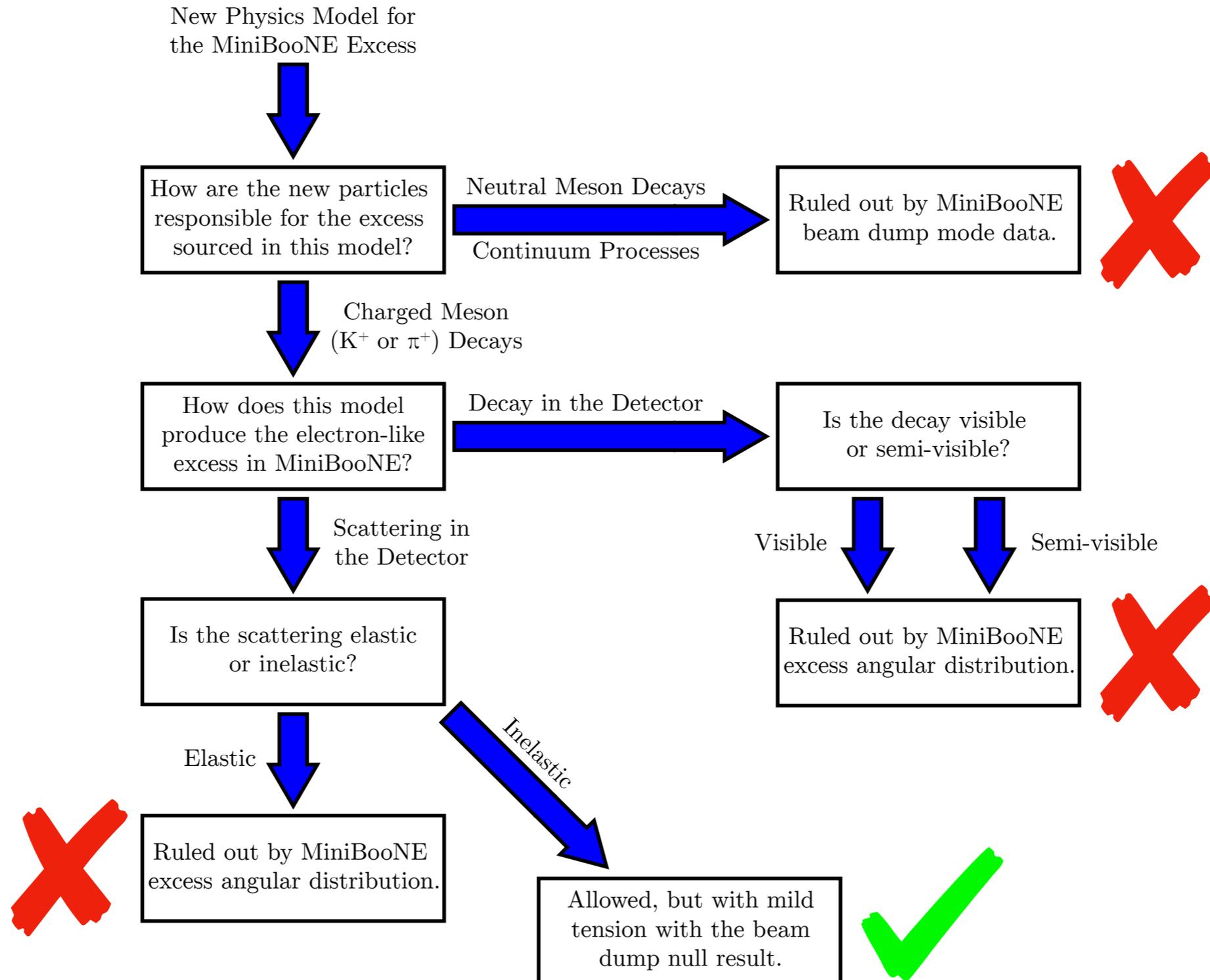


beam dump mode electron-like search  
 is consistent with background



# What is the source of the MiniBooNE anomaly?

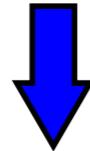
J. Jordan, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz, PRL 122 081801 (2019)



# What is the source of the MiniBooNE anomaly?

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

New Physics Model for  
the MiniBooNE Excess



How are the new particles

Neutral Meson Decays

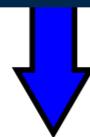
Ruled out by MiniBooNE



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?

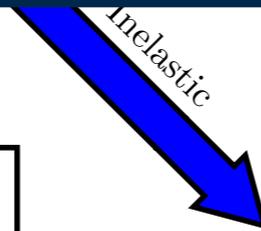
Also, it's very hard to imagine new physics explaining both LSND and MiniBooNE simultaneously without invoking oscillations.

Elastic



Ruled out by MiniBooNE  
excess angular distribution.

Inelastic



Allowed, but with mild  
tension with the beam  
dump null result.



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

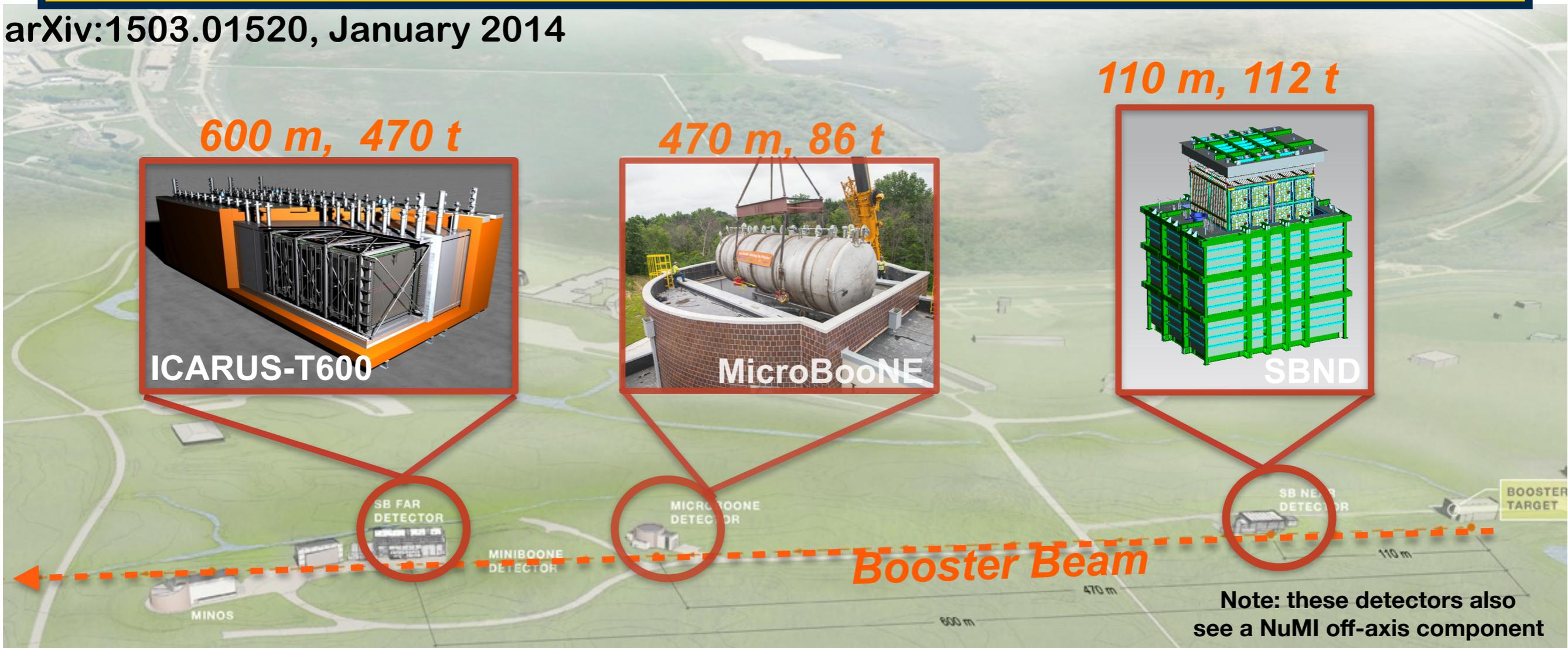
- SBN at Fermilab (pion decay-in-flight)
- JSNS<sup>2</sup> (pion/muon/kaon decay-at-rest)

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

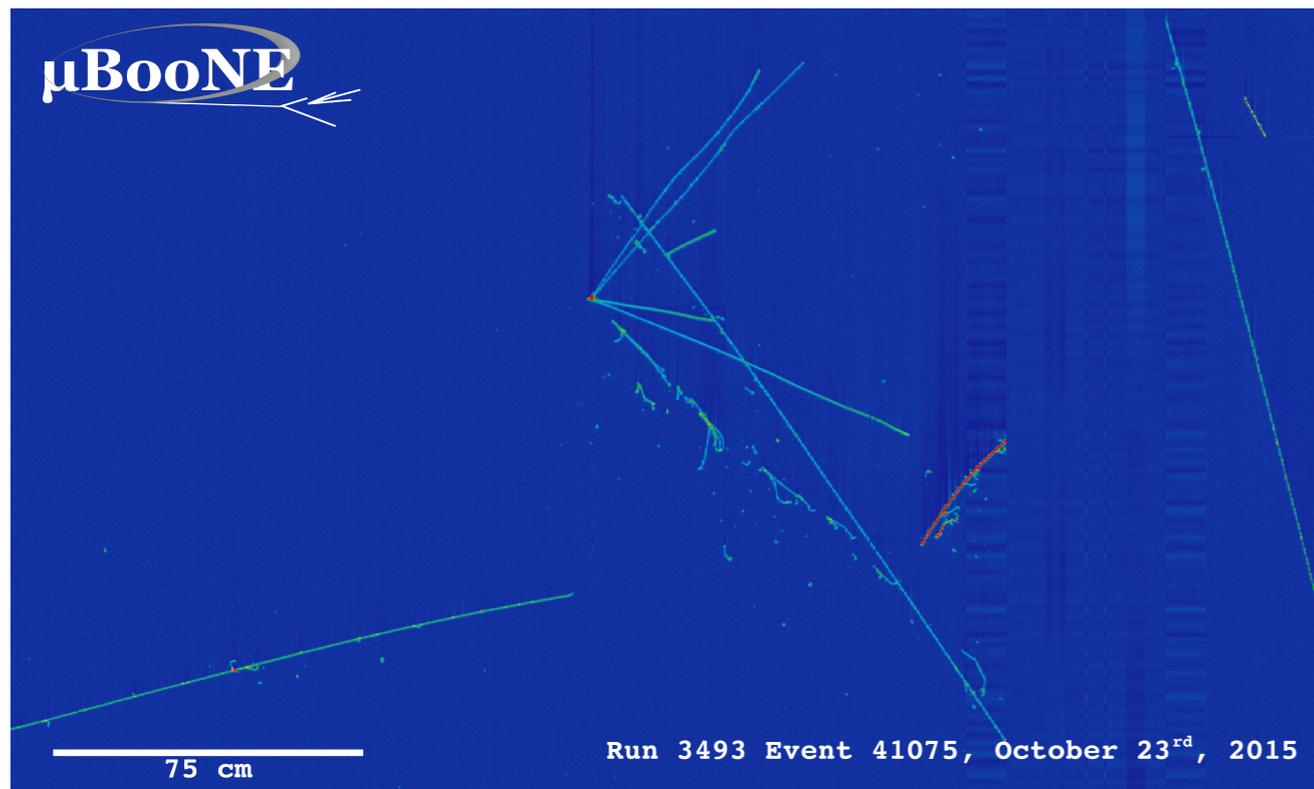
arXiv:1503.01520, January 2014



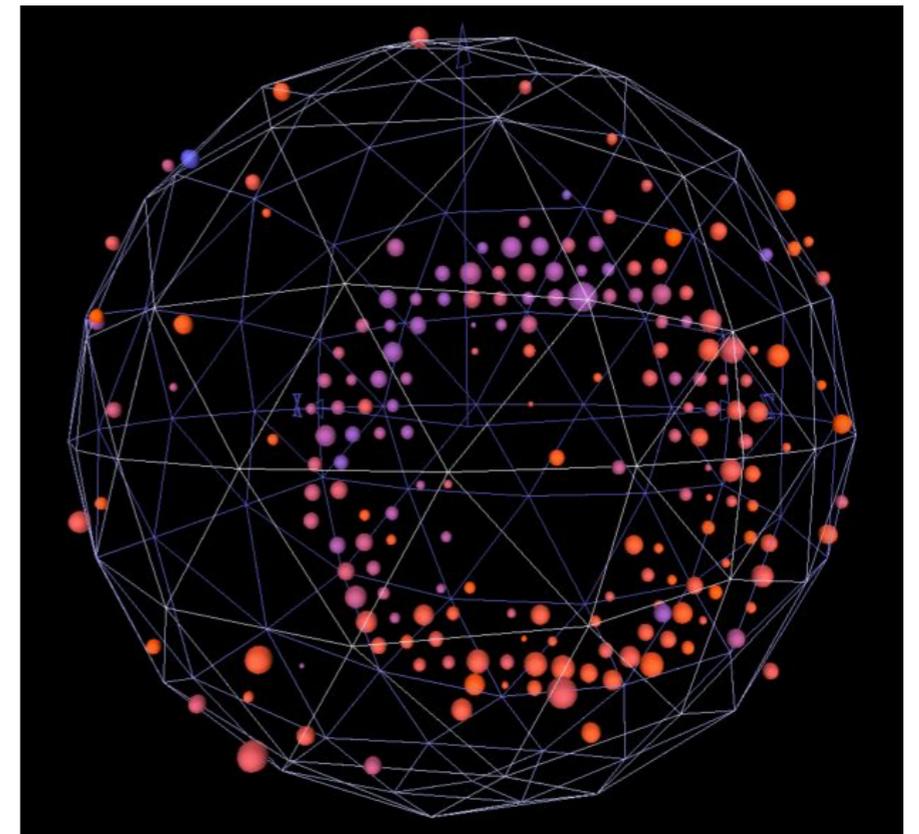
SBND (first data in 2020/2021)  
 MicroBooNE (running since late-2015)  
 ICARUS (first data in 2019/2020)

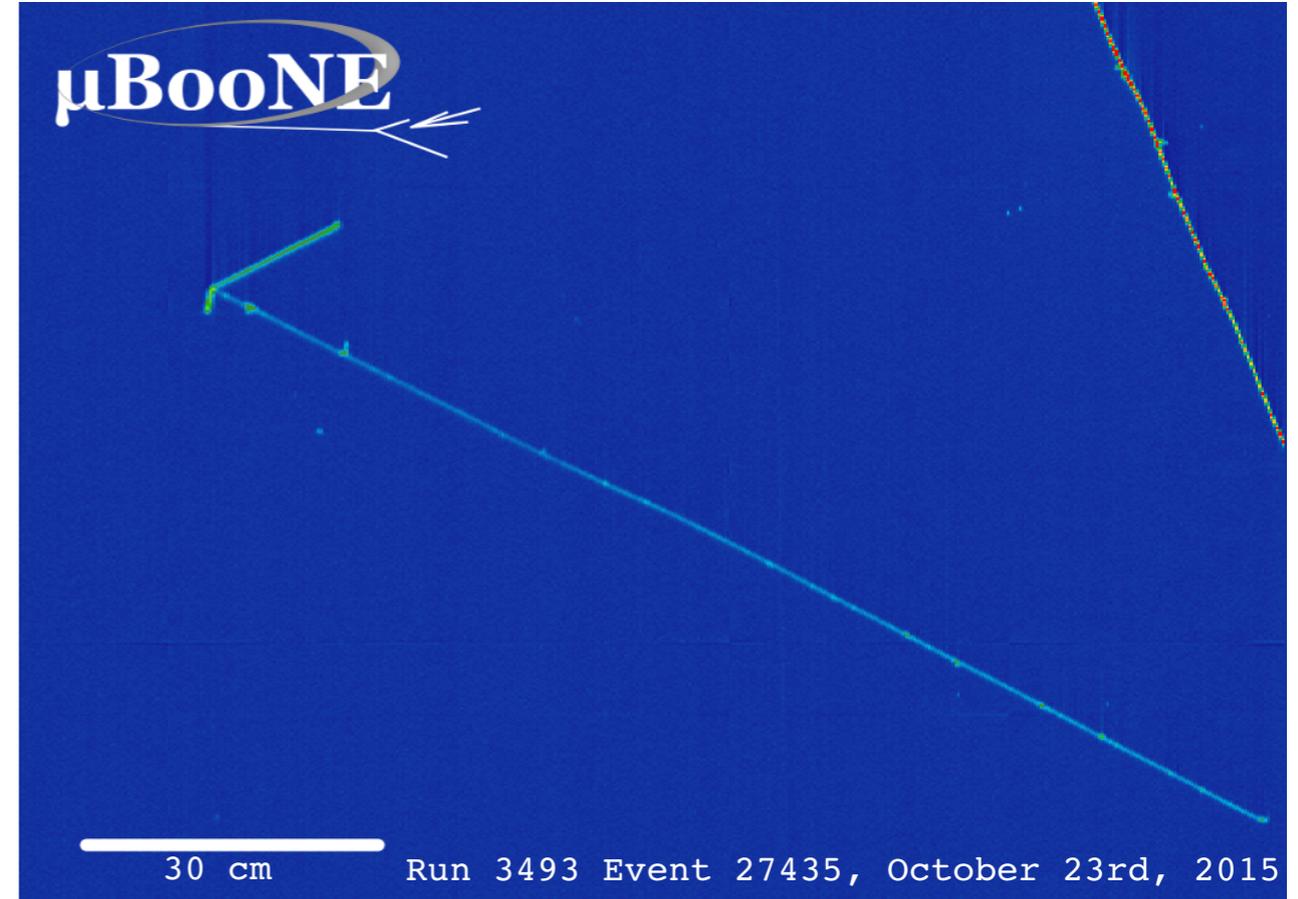
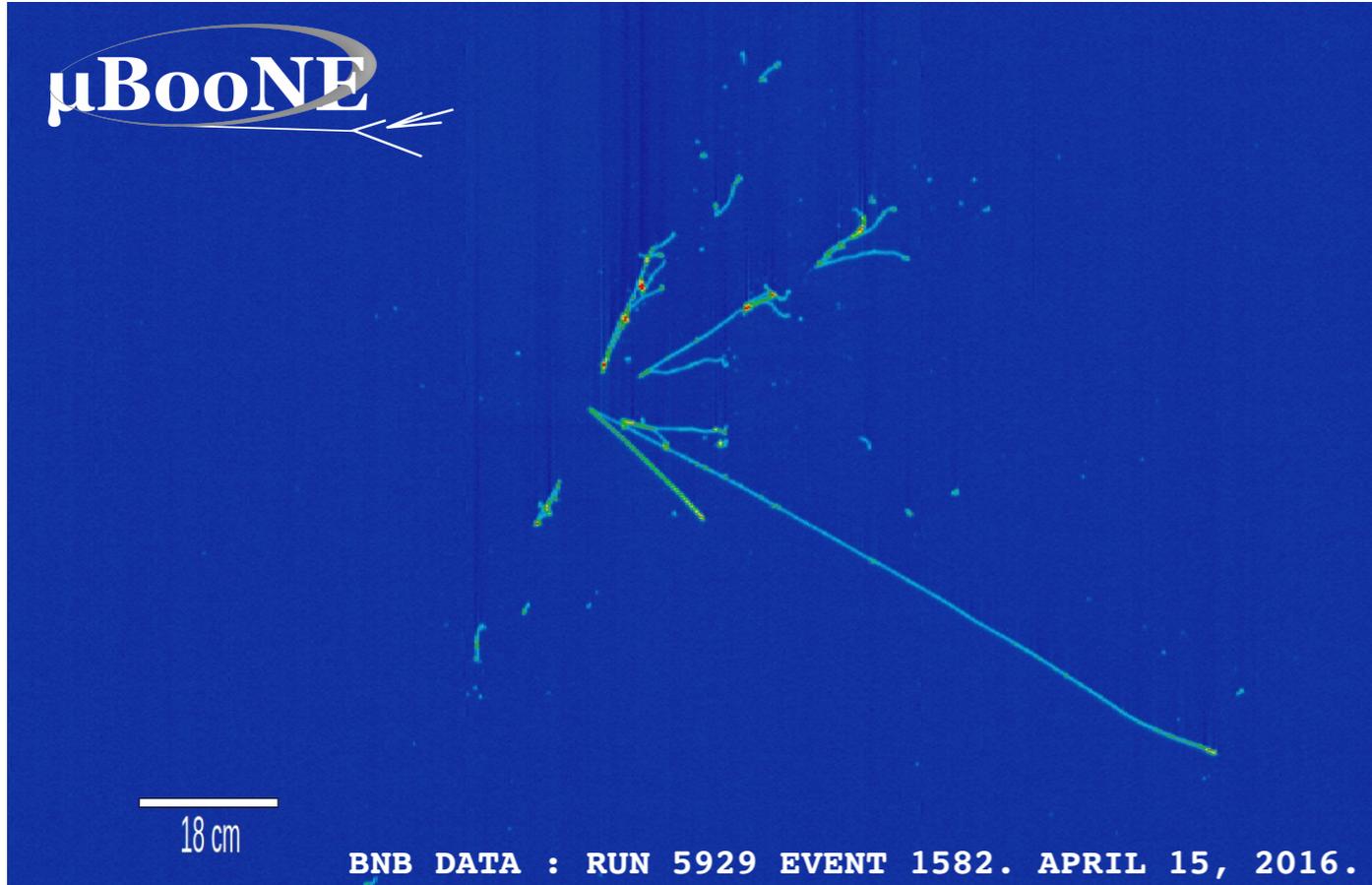
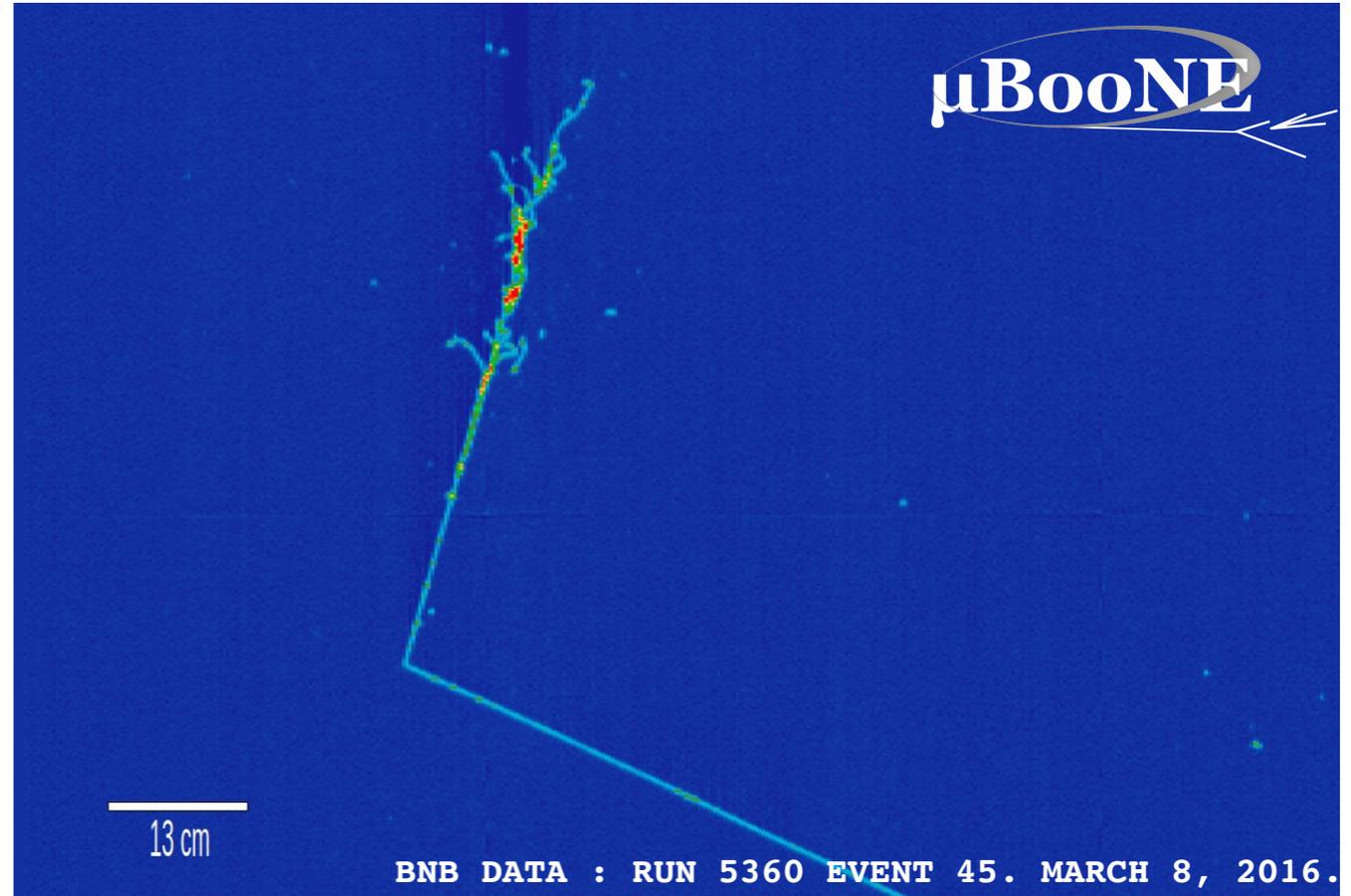
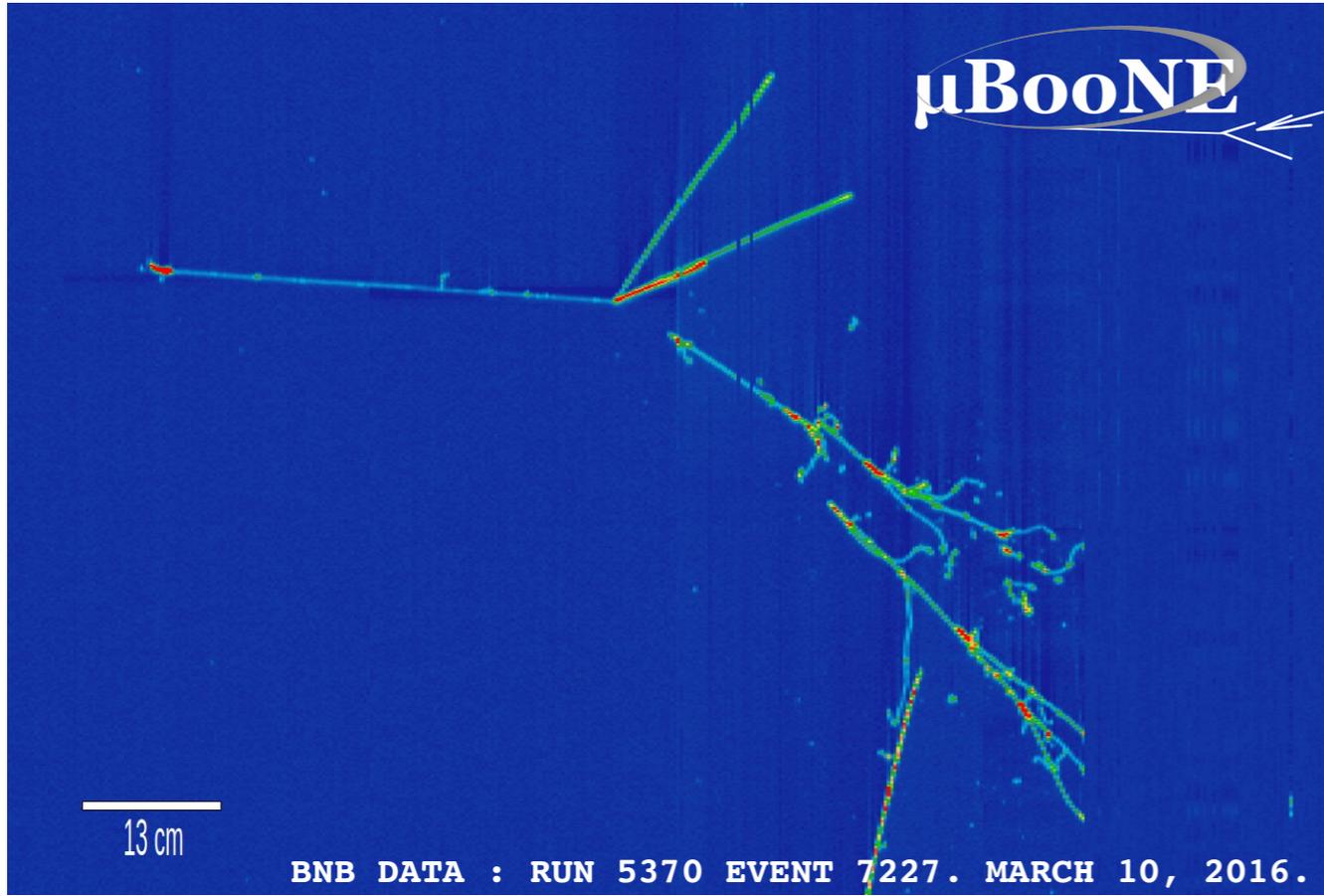
SBN's LArTPC technology provides the ability to "see" all aspects of a neutrino interaction (w/ few exceptions) and differentiate between electrons and gammas

## LArTPC

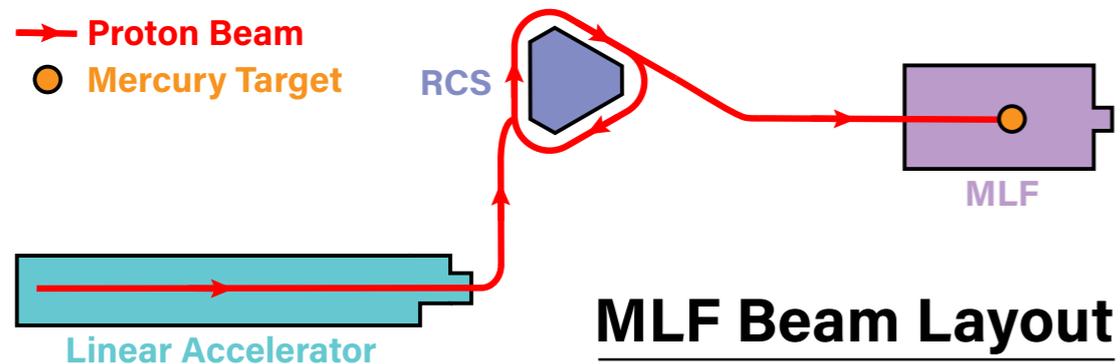


## (compare to MiniBooNE)

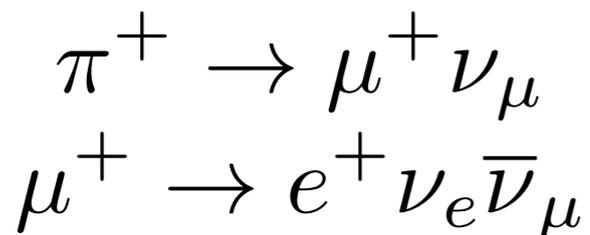
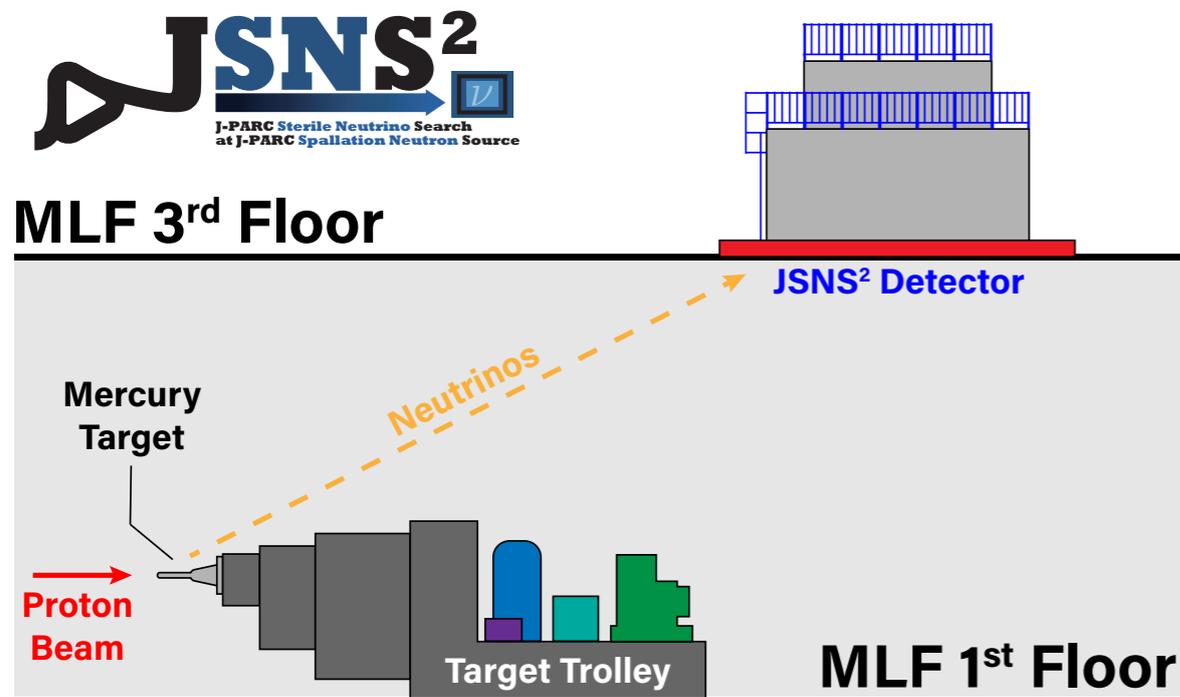




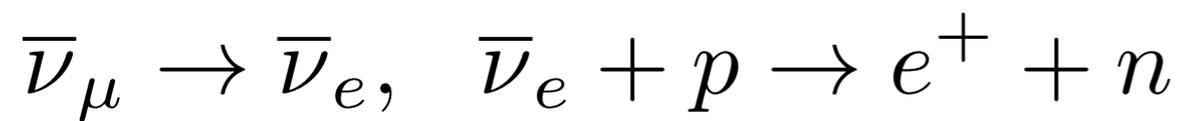
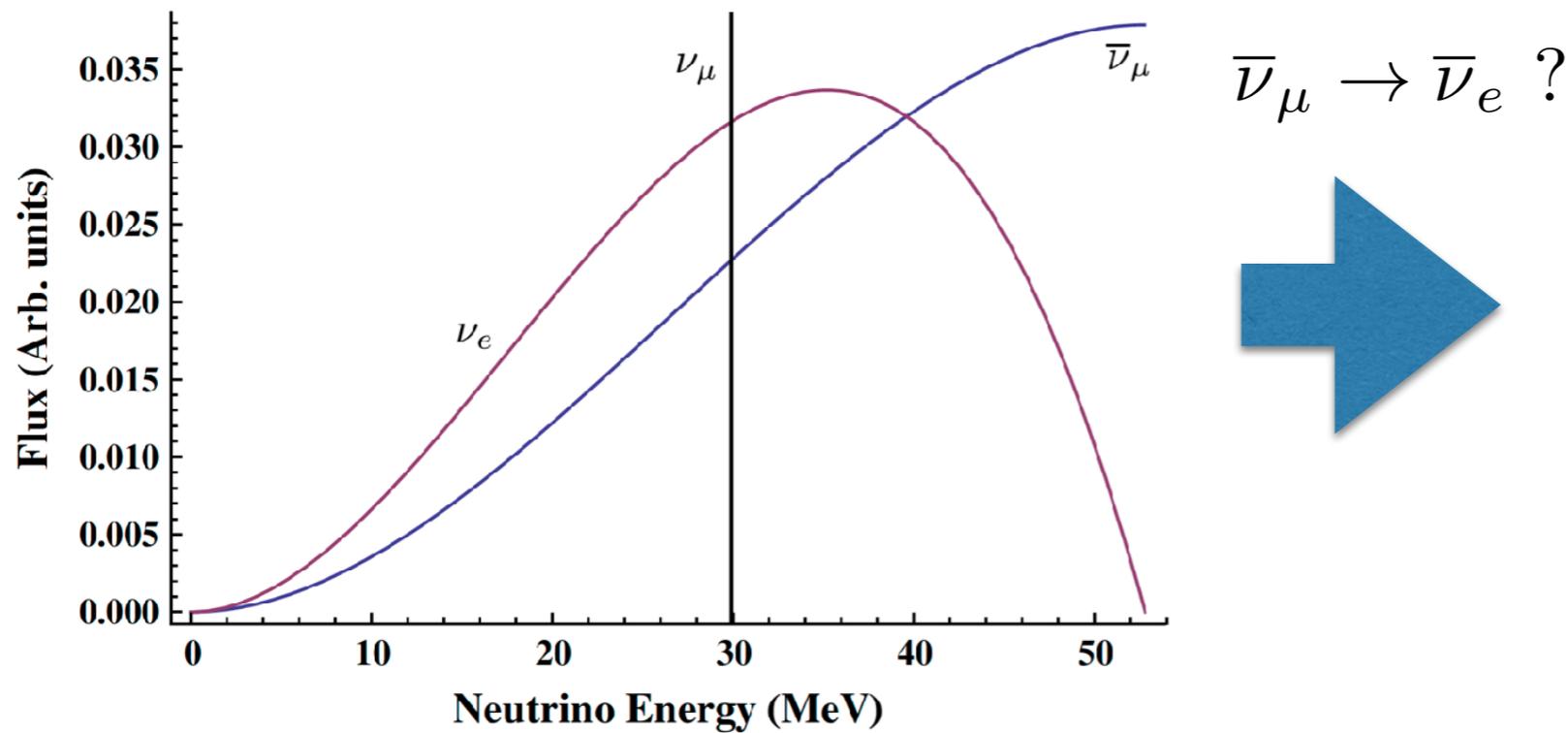
# J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source (JSNS<sup>2</sup>)



- 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  $\sim 15\% \sqrt{E}$  (MeV)
- Beam: 525 kW @ 3 GeV (w/ duty factor  $\sim 5 \times 10^{-6}$ )
  - Eventually 1 MW
- First data in late-2019!



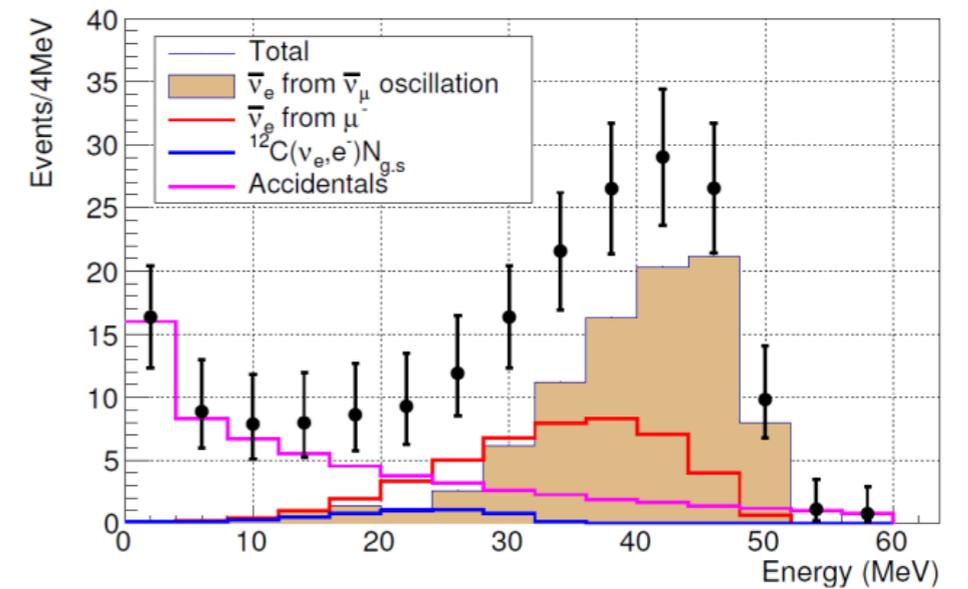
JSNS2 is sensitive to the smoking gun signature of oscillations: a wiggle in L/E



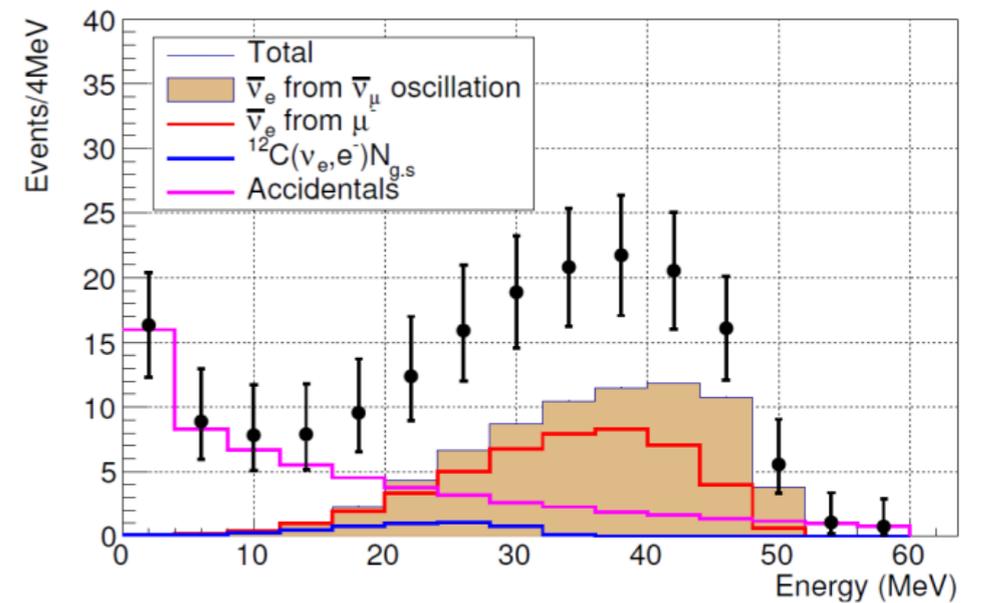
prompt signal

delayed signal  
(n-capture)

Expected spectrum



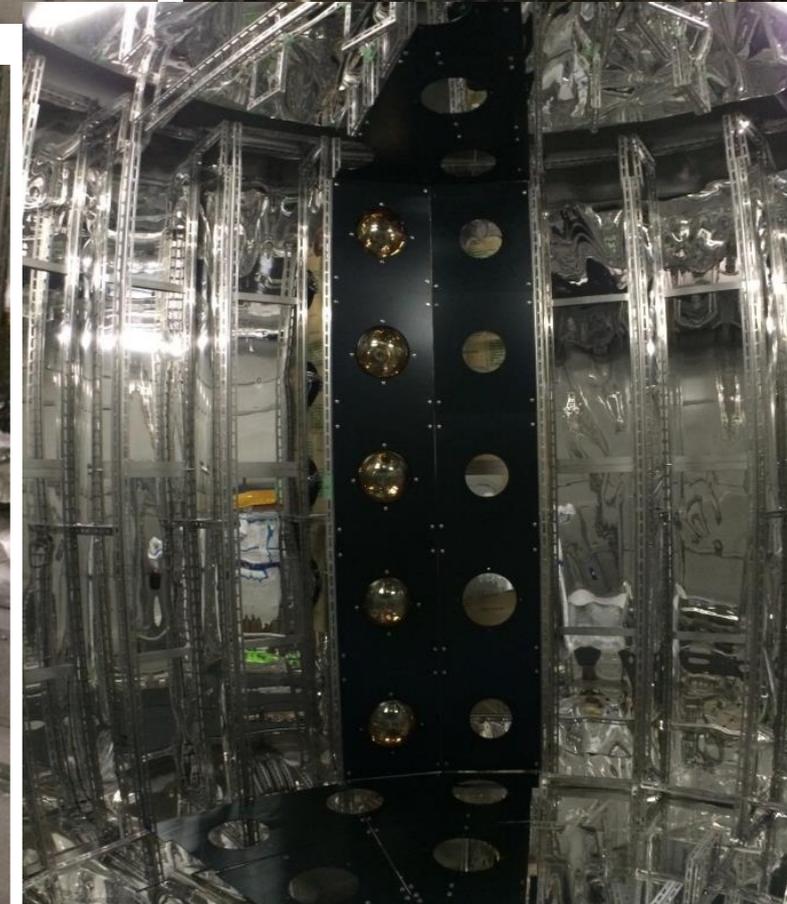
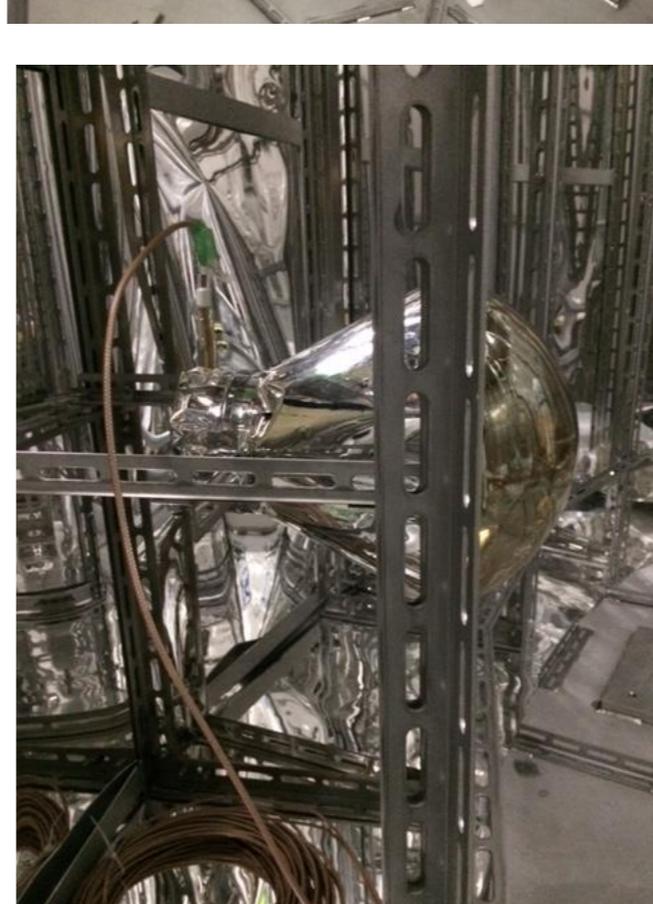
Case  $\Delta m^2 = 2.5 \text{eV}^2, \sin^2 2\theta = 0.003$



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

(3 years of running)

# JSNS<sup>2</sup> status as of Summer-2018 (first data will be taken in late-2019)



# Conclusion

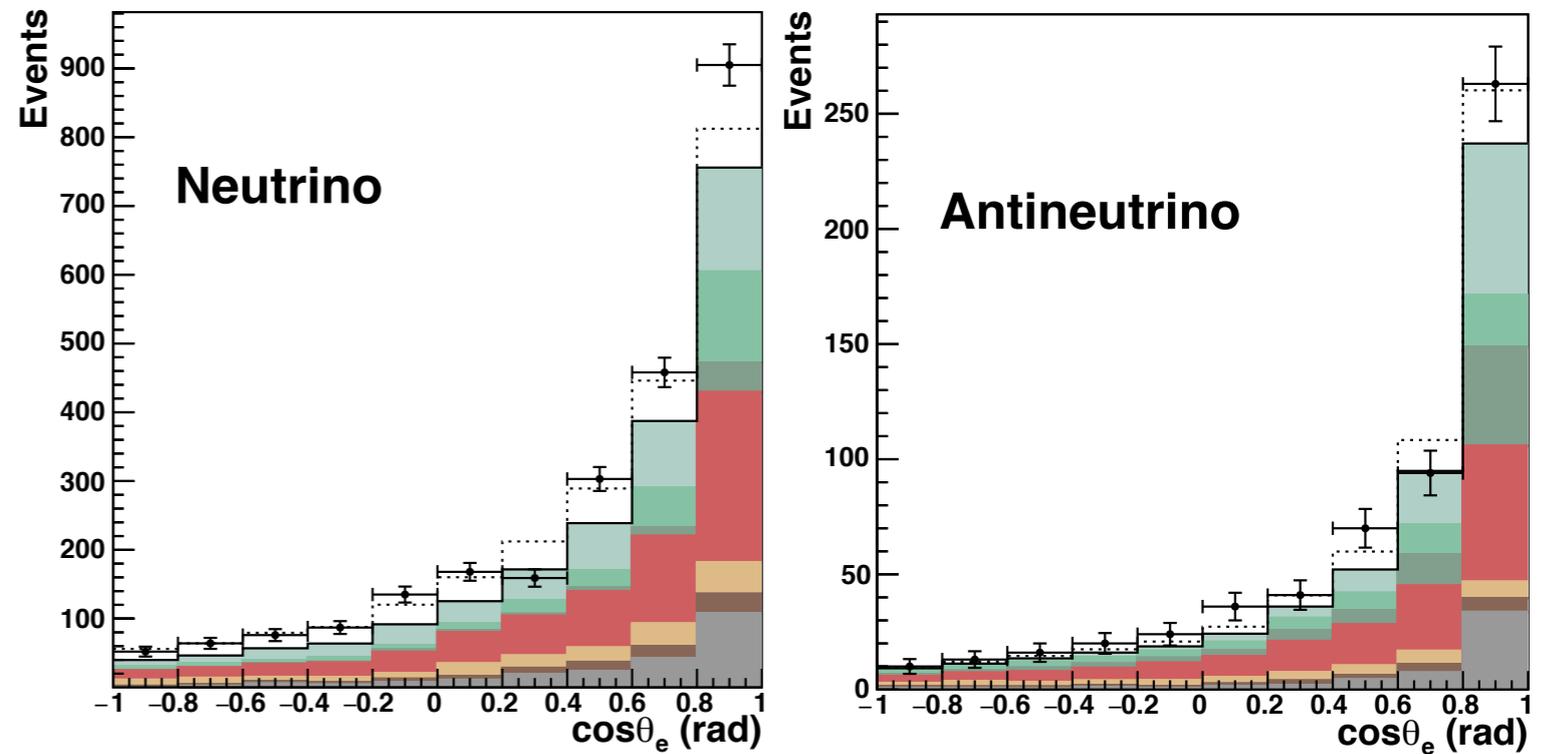
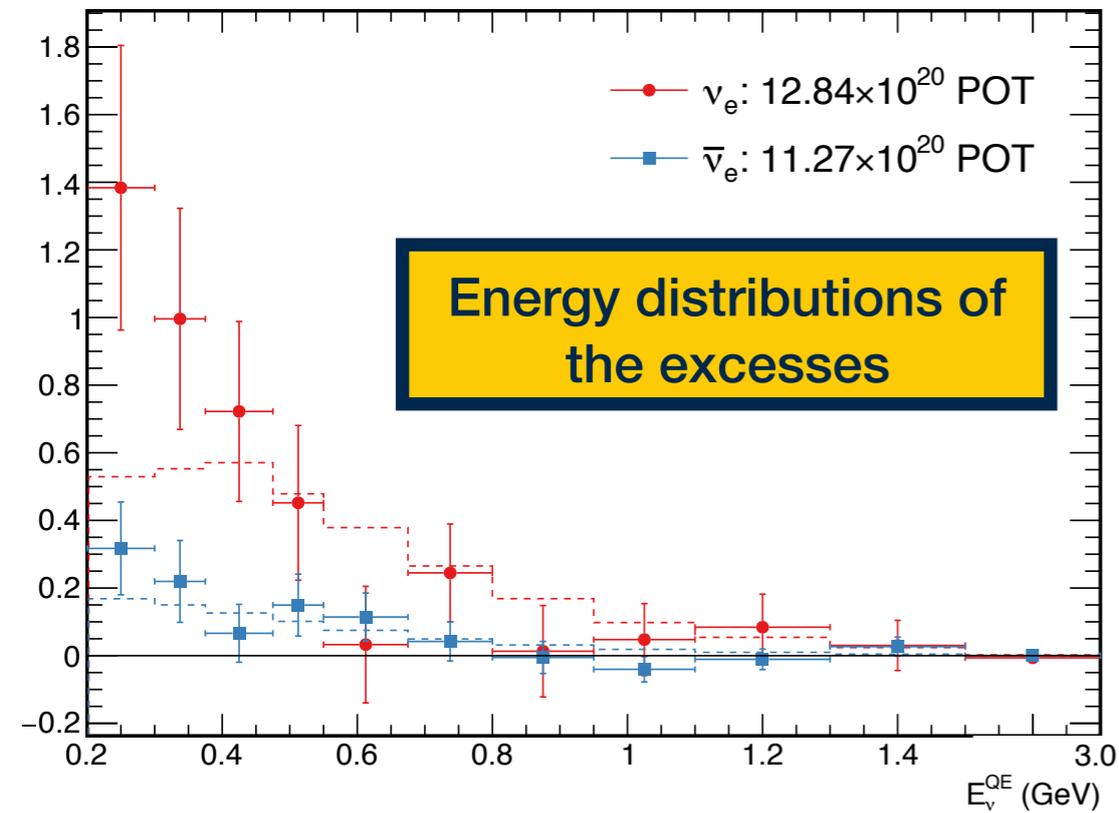
- A number of neutrino anomalies at short baseline may be indicative of new physics.
- The parameter space of new oscillations/interactions continues to be explored with accelerator-based, including decay-in-flight and decay-at-rest, and reactor-based experiments.
- We can look forward to many more results 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**

# 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  $6.1\sigma$ .
  - **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.

# What is the source of the MiniBooNE anomaly?



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

# Reactor anomaly

The oscillation modes associated with reactor neutrinos

