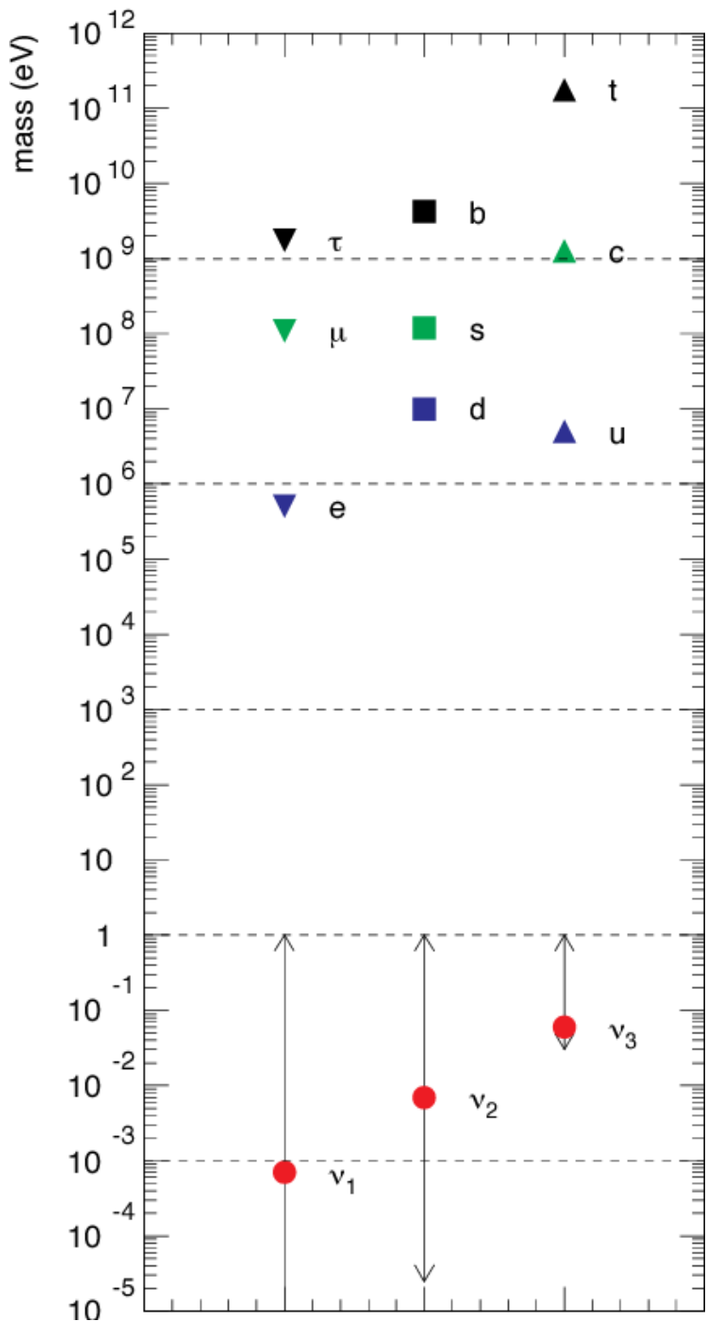
# Status Update on Short-Baseline Neutrino Oscillation Experiments

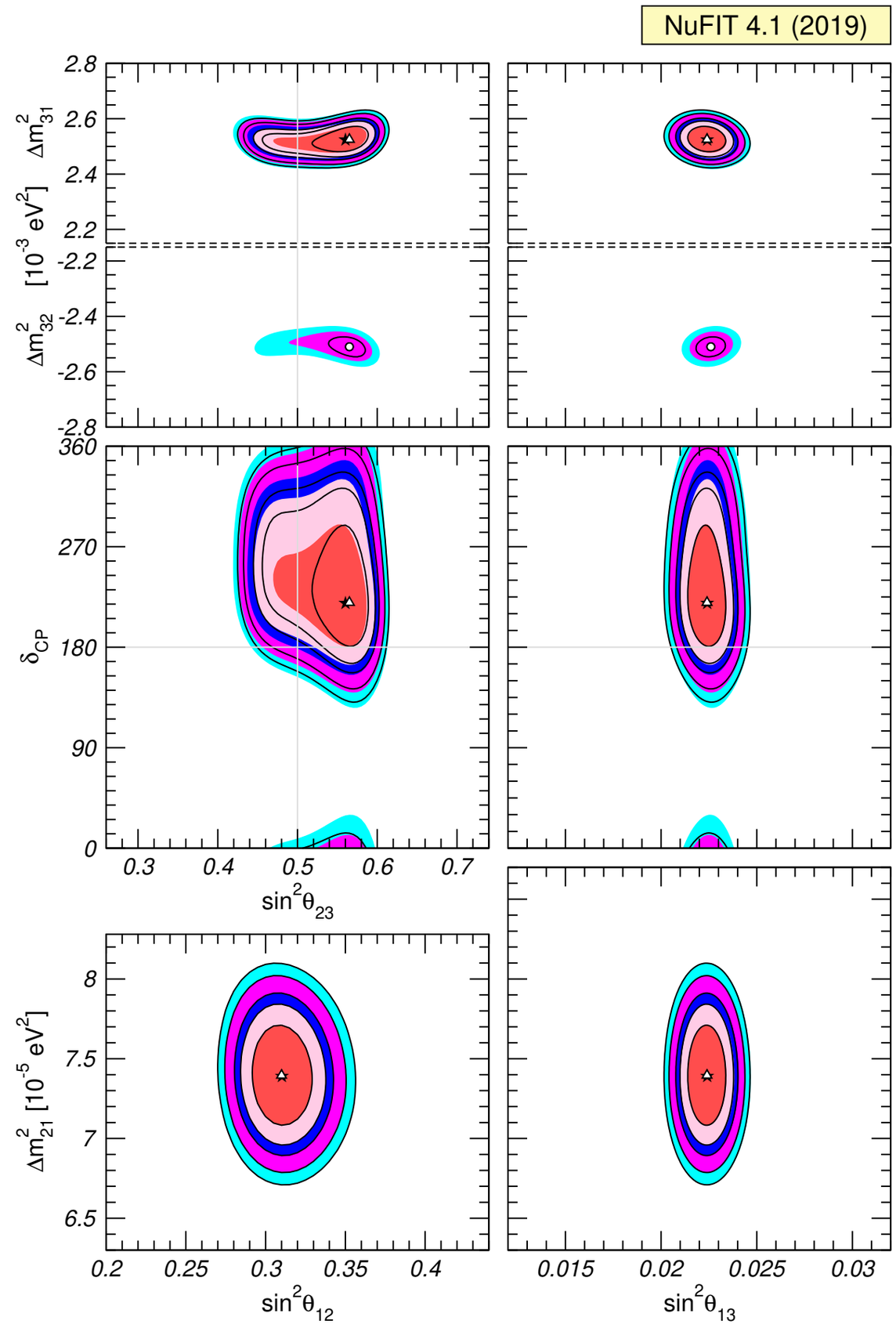
August 9, 2019

Bryce Littlejohn
Illinois Institute of Technology

# Neutrino Oscillation Picture

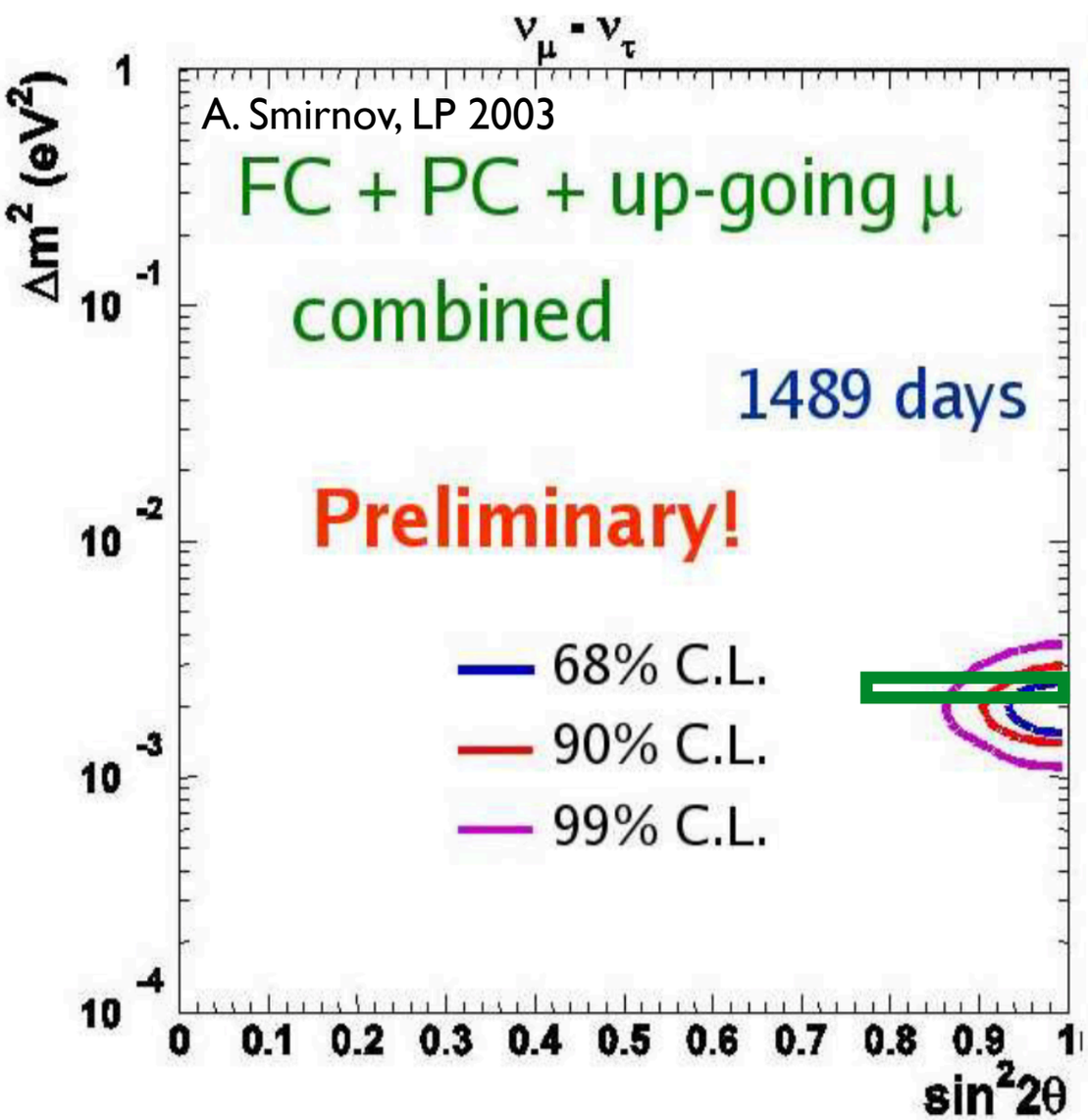
- Have a beautiful picture of Standard Model oscillations coming into focus

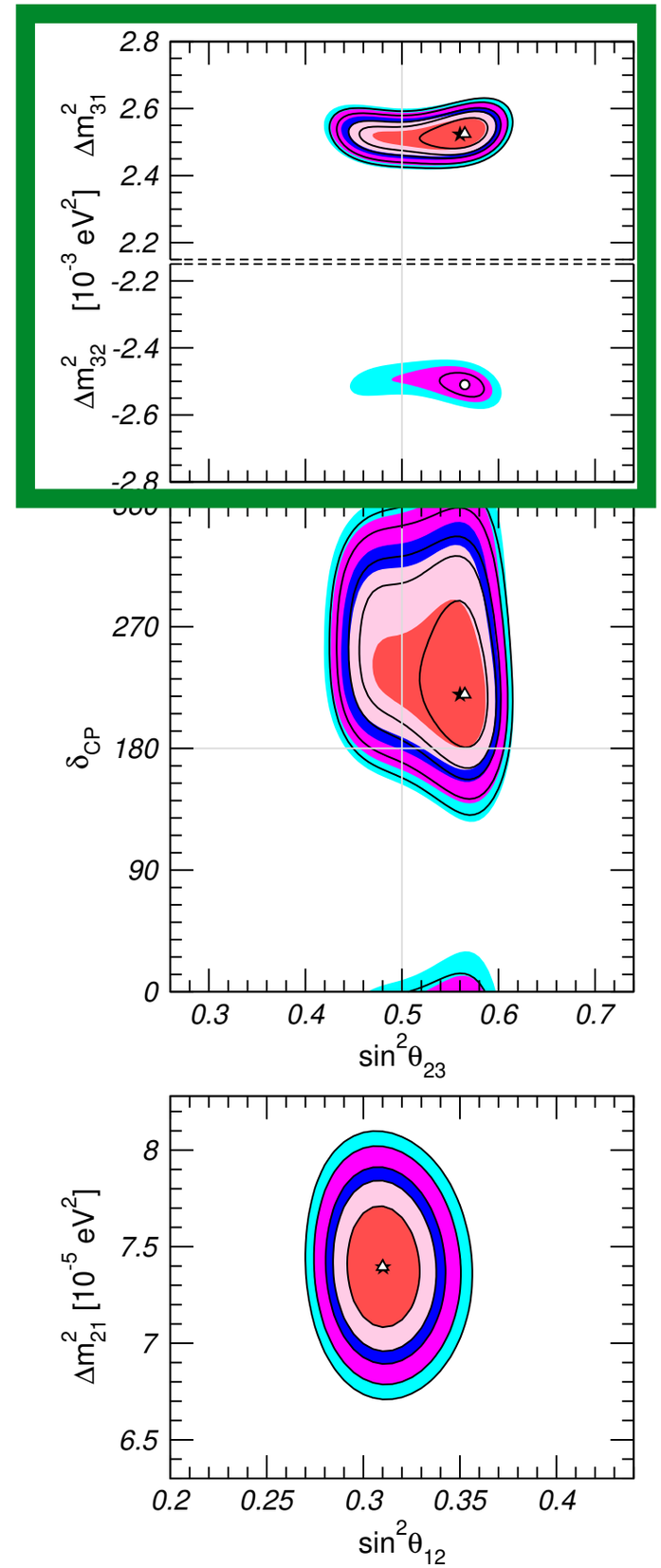


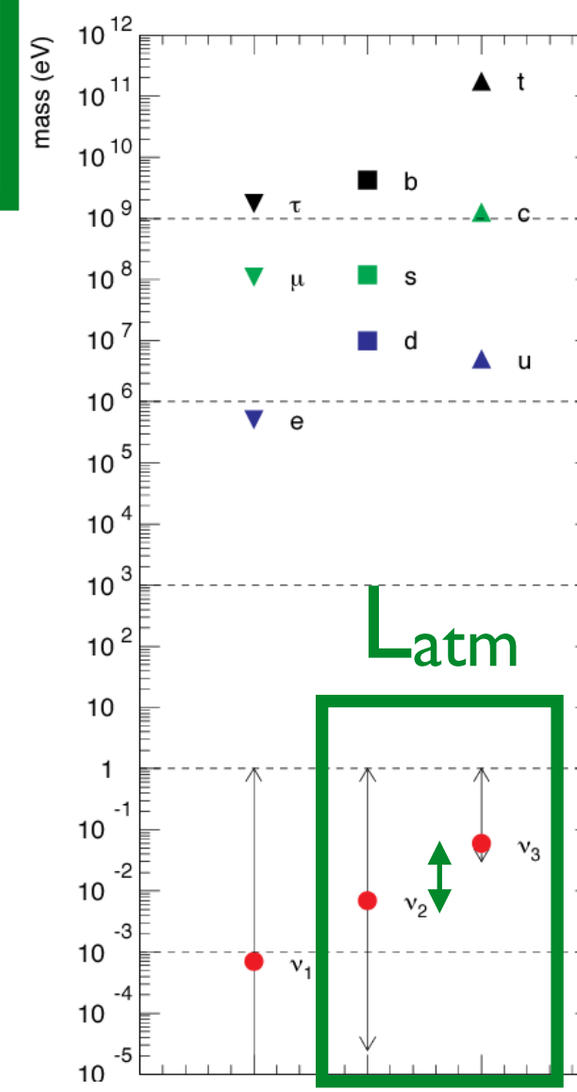



# Neutrino Oscillation Picture

- Just a reminder: ~15 years, Lepton-Photon 2003
- Atmospheric Sector:



# Neutrino Oscillation Picture

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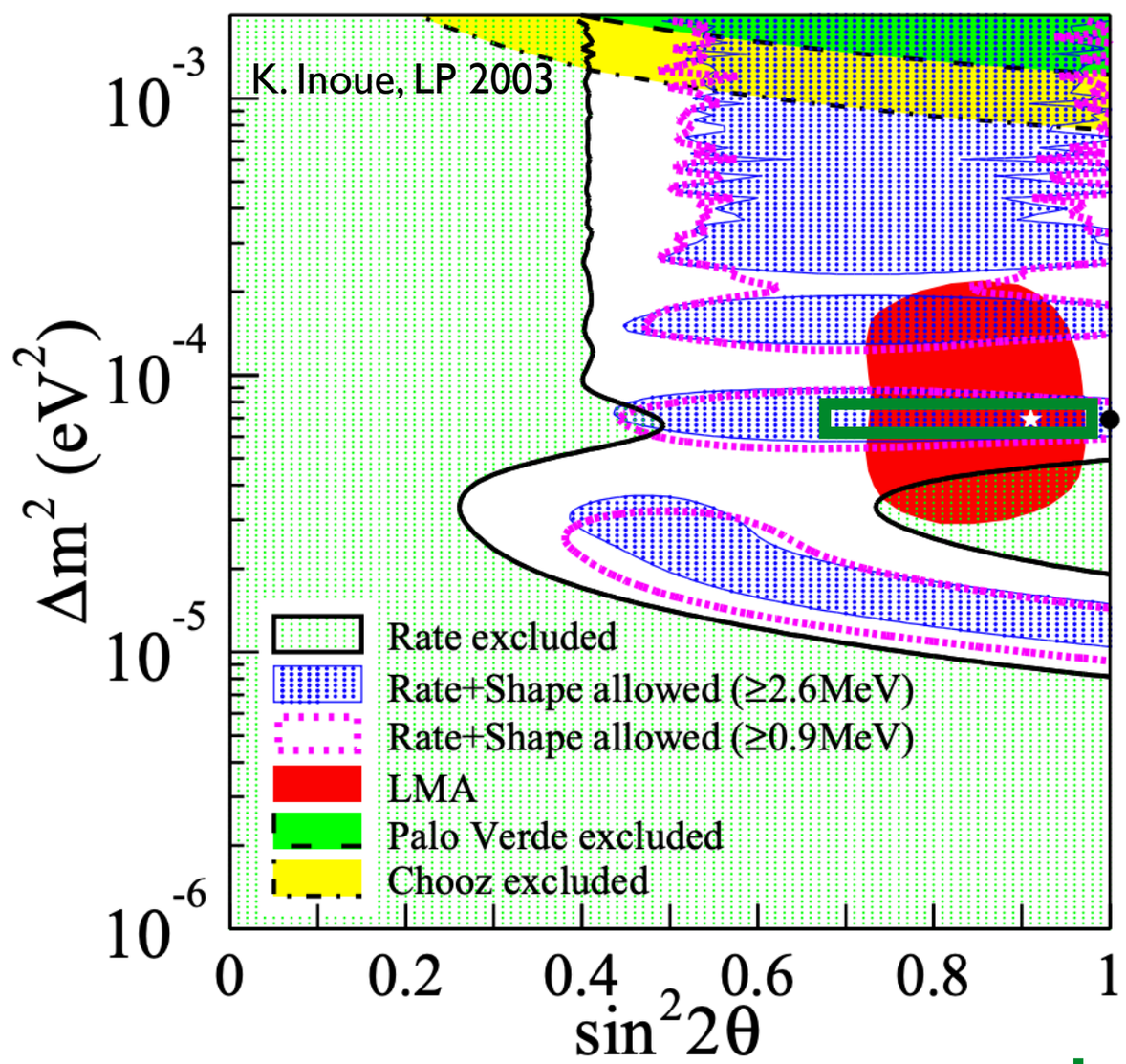
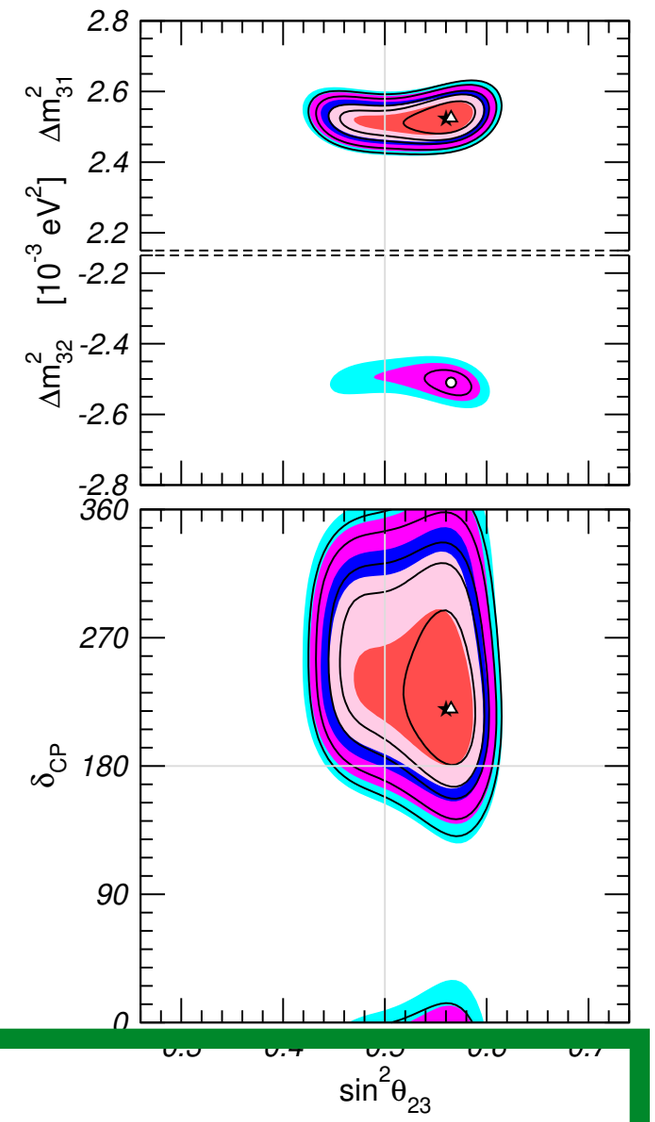
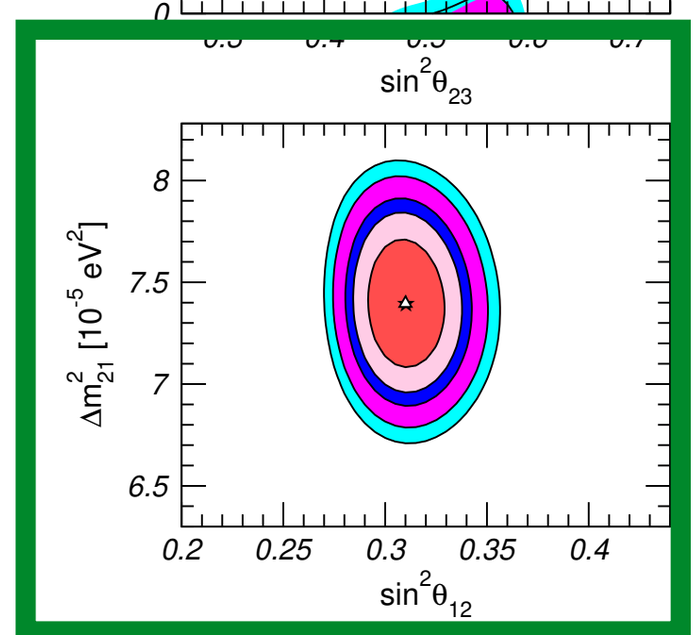
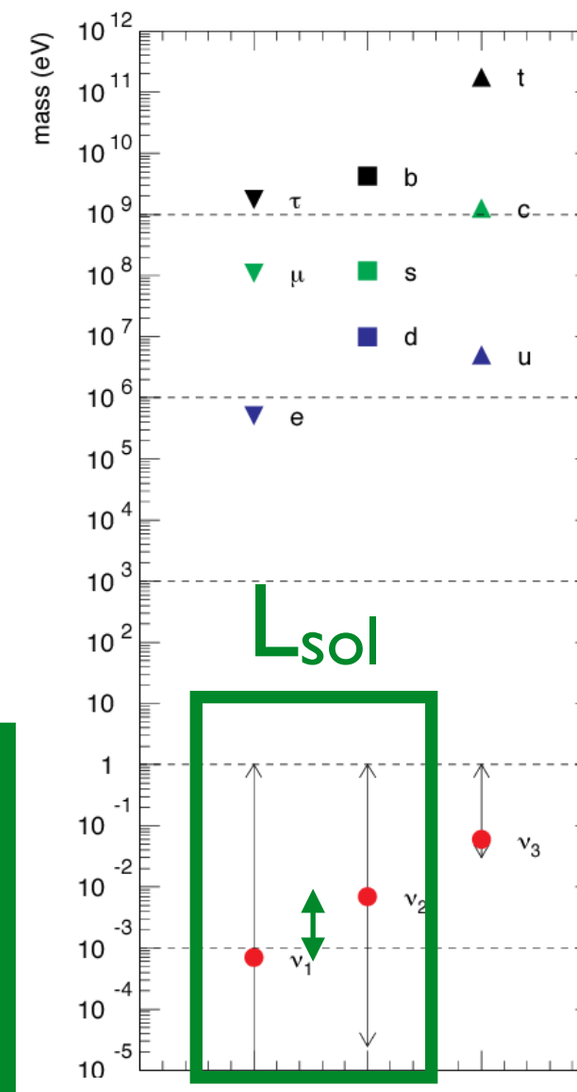
- Solar Sector:




$L_\odot$



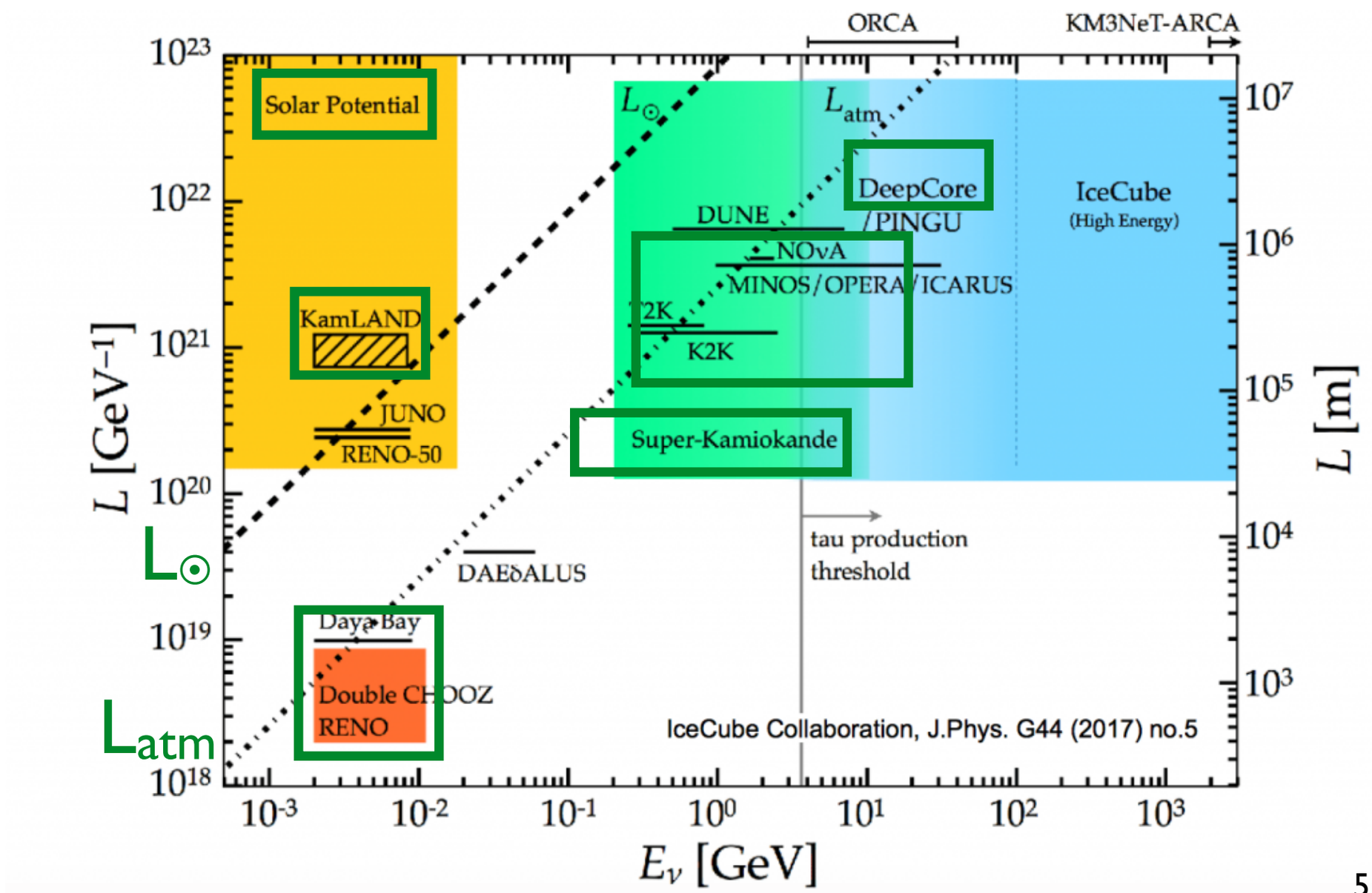




$L_{sol}$

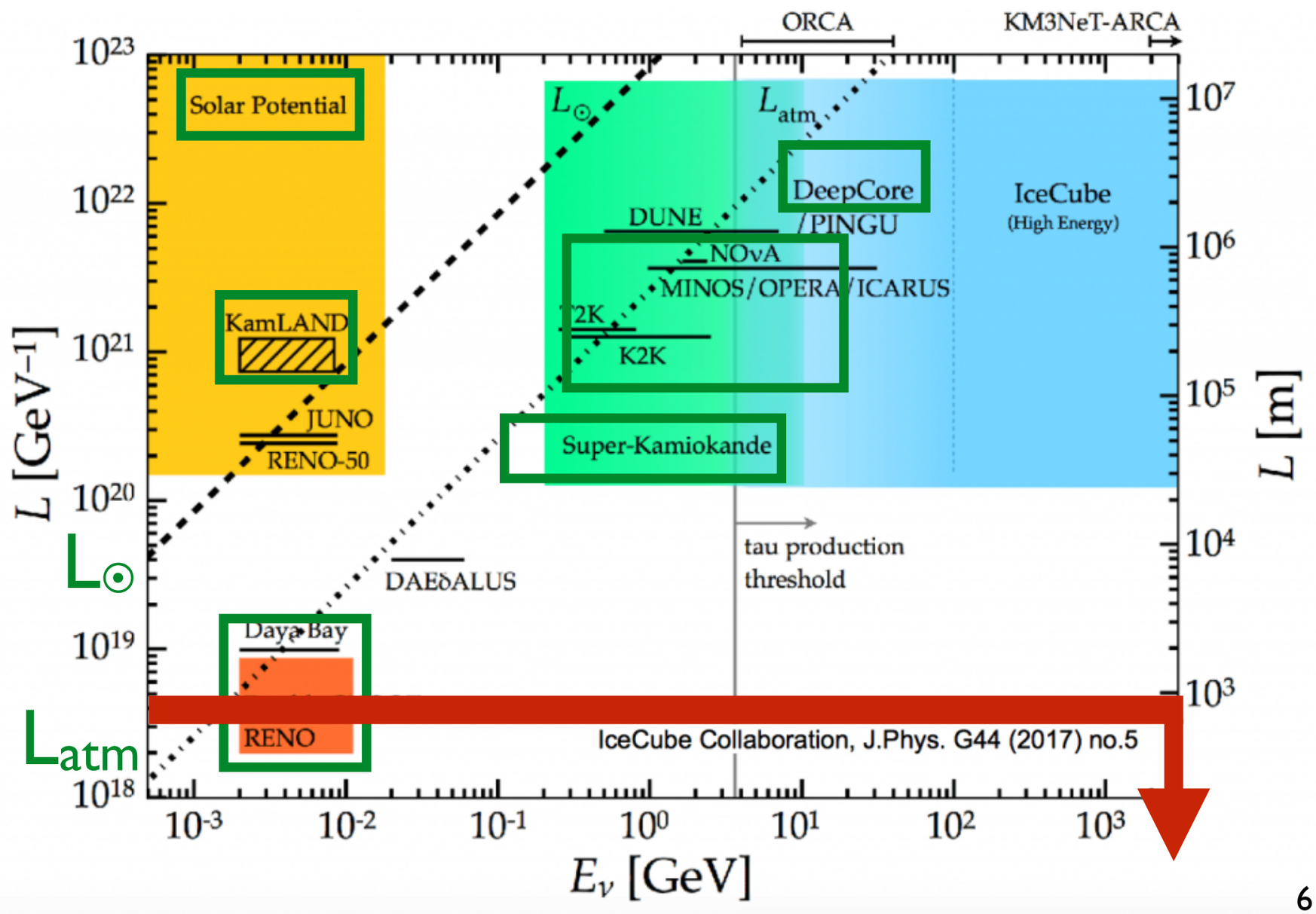
# Neutrino Oscillation Picture

- Have a beautiful picture of Standard Model oscillations coming into focus
- What experiments got us here?
- Baselines: >km-scale



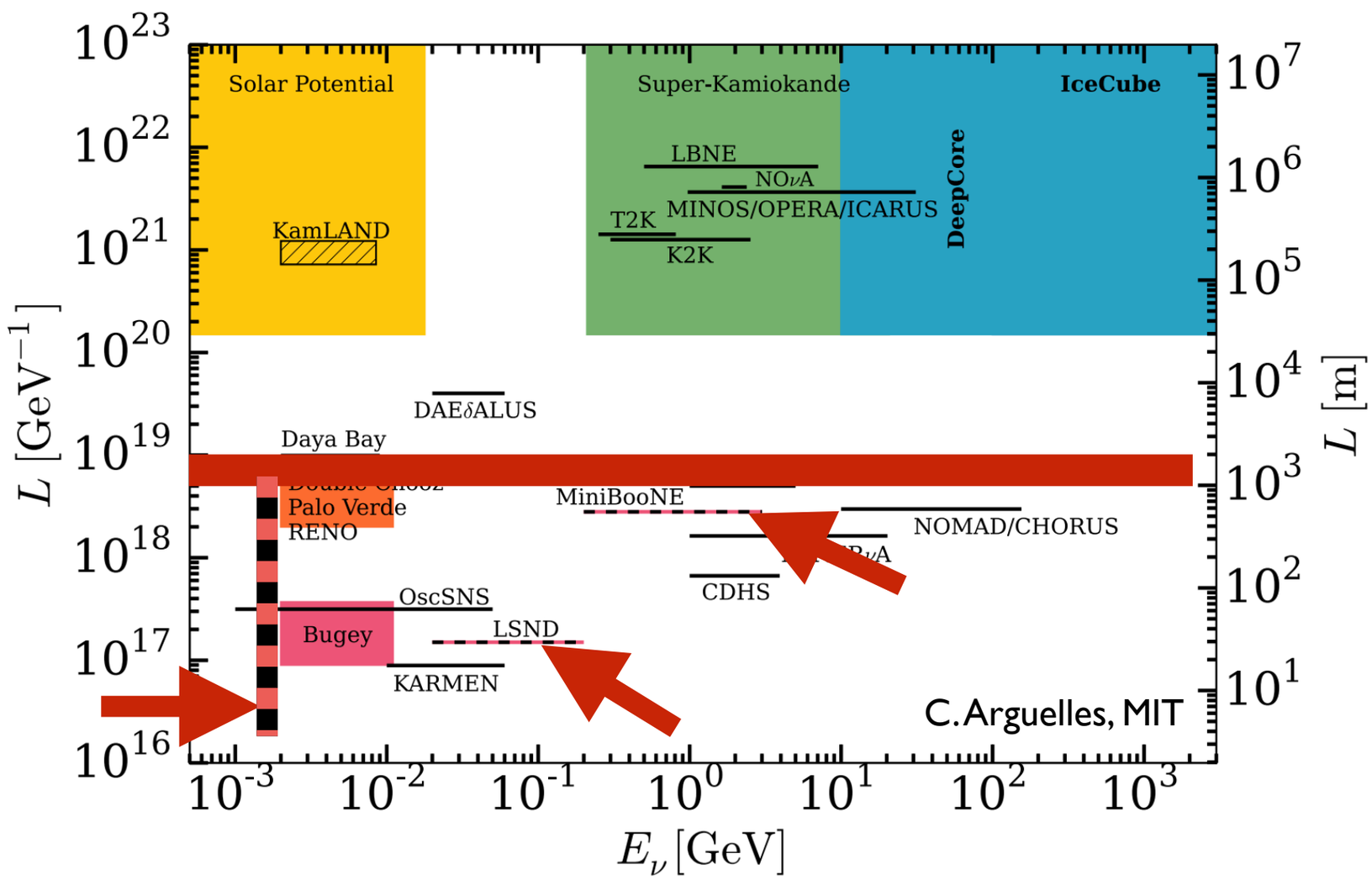
# Neutrino Oscillation Picture

- Have a beautiful picture of Standard Model oscillations coming into focus
- What experiments got us here?
- Baselines: >km-scale
- WHY go here?



# Existing Experimental 'Anomalies'

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions



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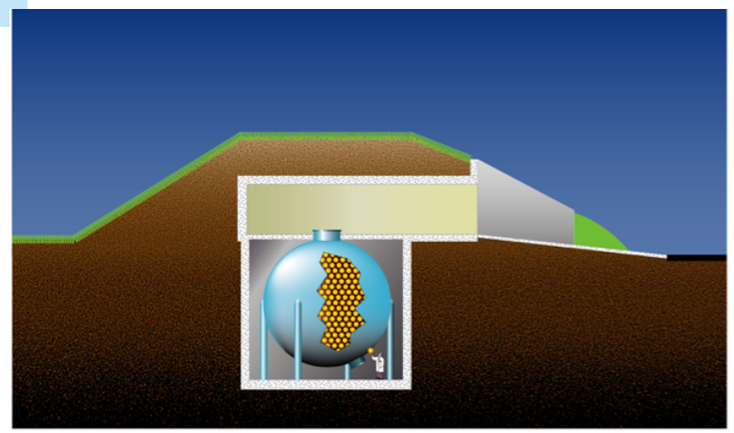
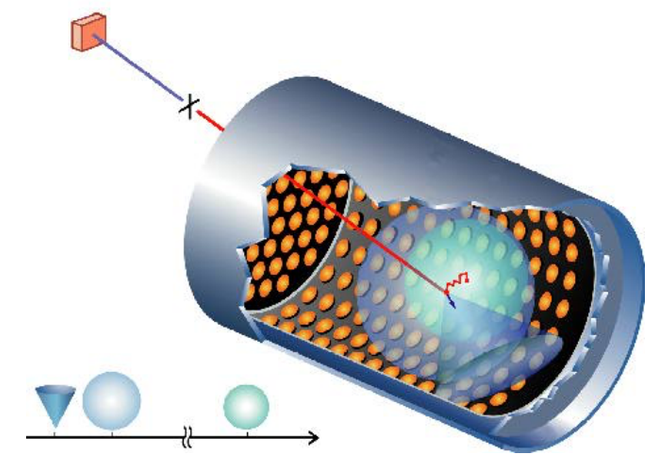
  - $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ at accelerators?
  - $\bar{\nu}_e$ disappearance at reactors, radioactive sources?

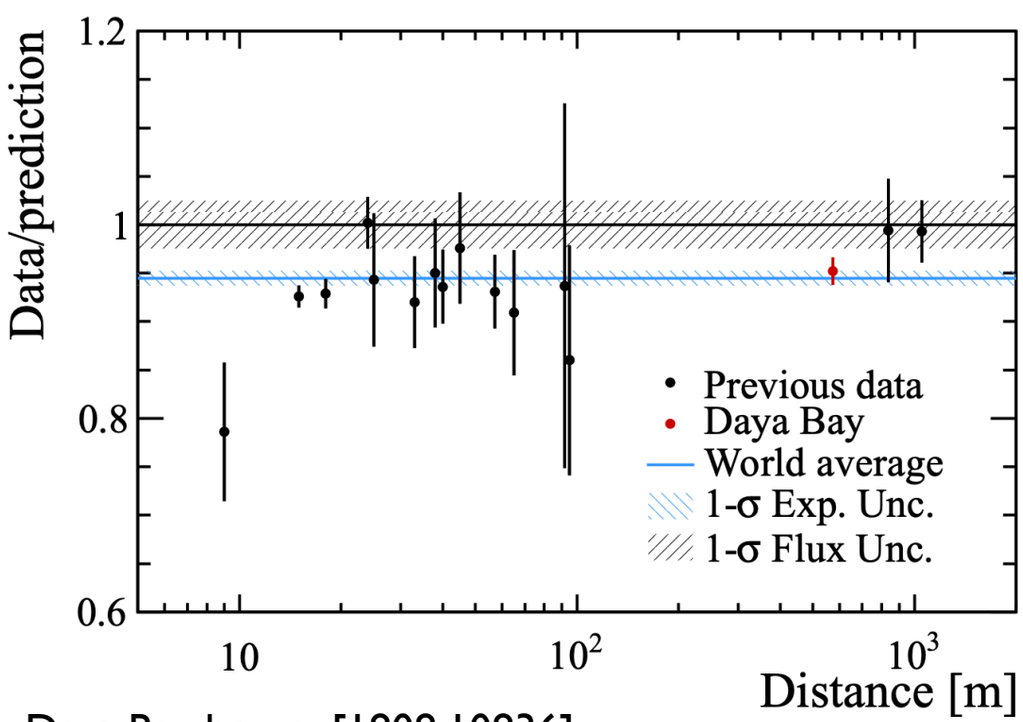
MiniBooNE
short baseline accelerator

LSND
decay at rest

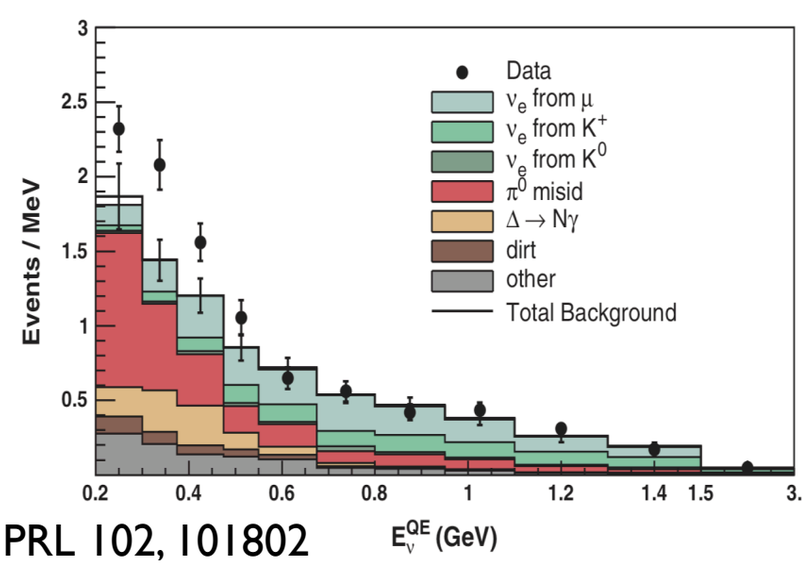
Reactors
flux deficit



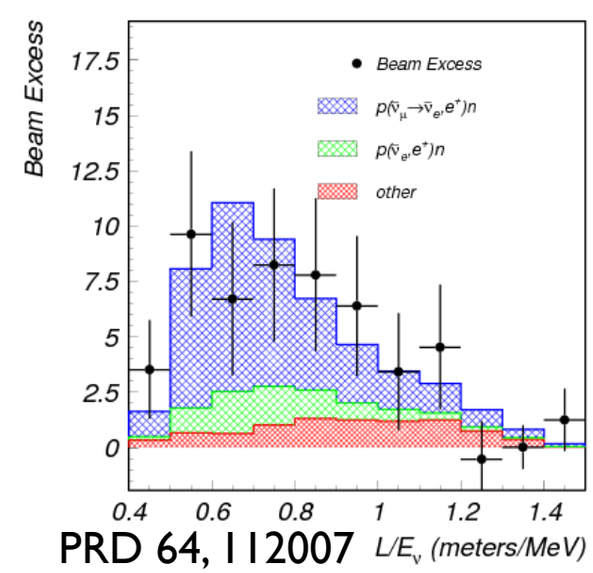





Daya Bay, hep-ex[1808.10836]
(accepted to PRD)




PRL 102, 101802




PRD 64, 112007

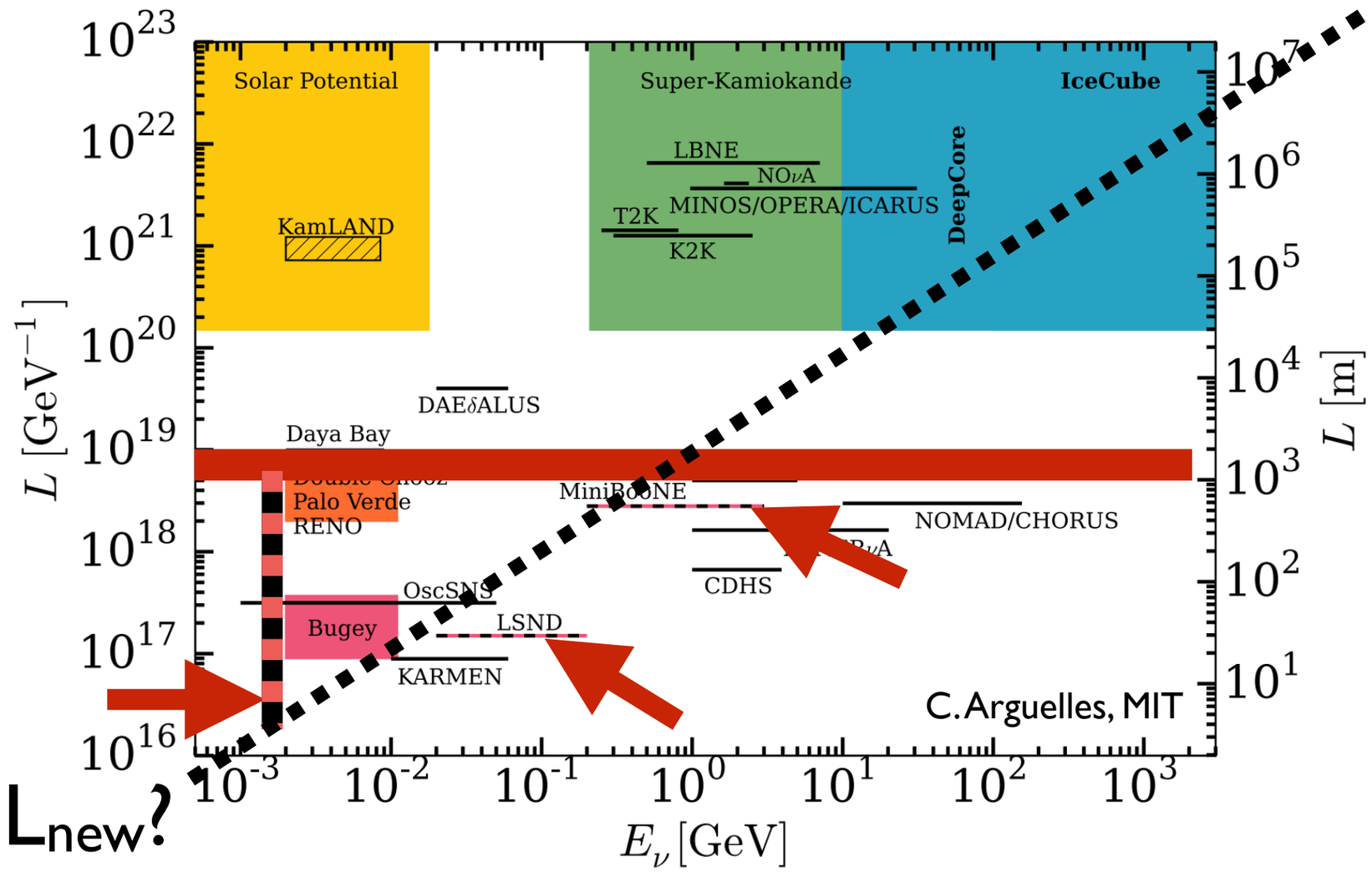
flux deficit

low energy excess

anti-$\nu_e$ appearance

# Existing Experimental 'Anomalies'

- Some neutrino rates/energies measured at <km disagree with state-of-the-art neutrino predictions
- Indications of new physics beyond 'SM oscillations'?(!)
  - Additional neutrino mass states, sterile neutrinos? Other new physics?
  - <u>Goal</u>: try to test parameter space of new physics models



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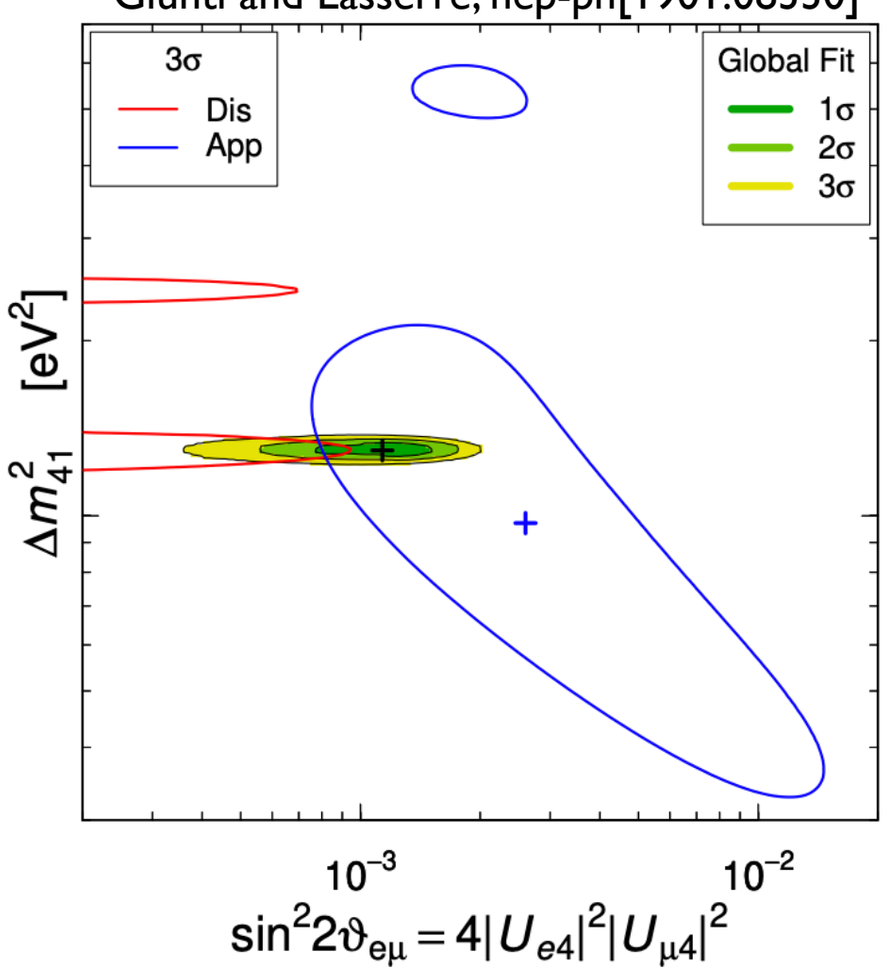
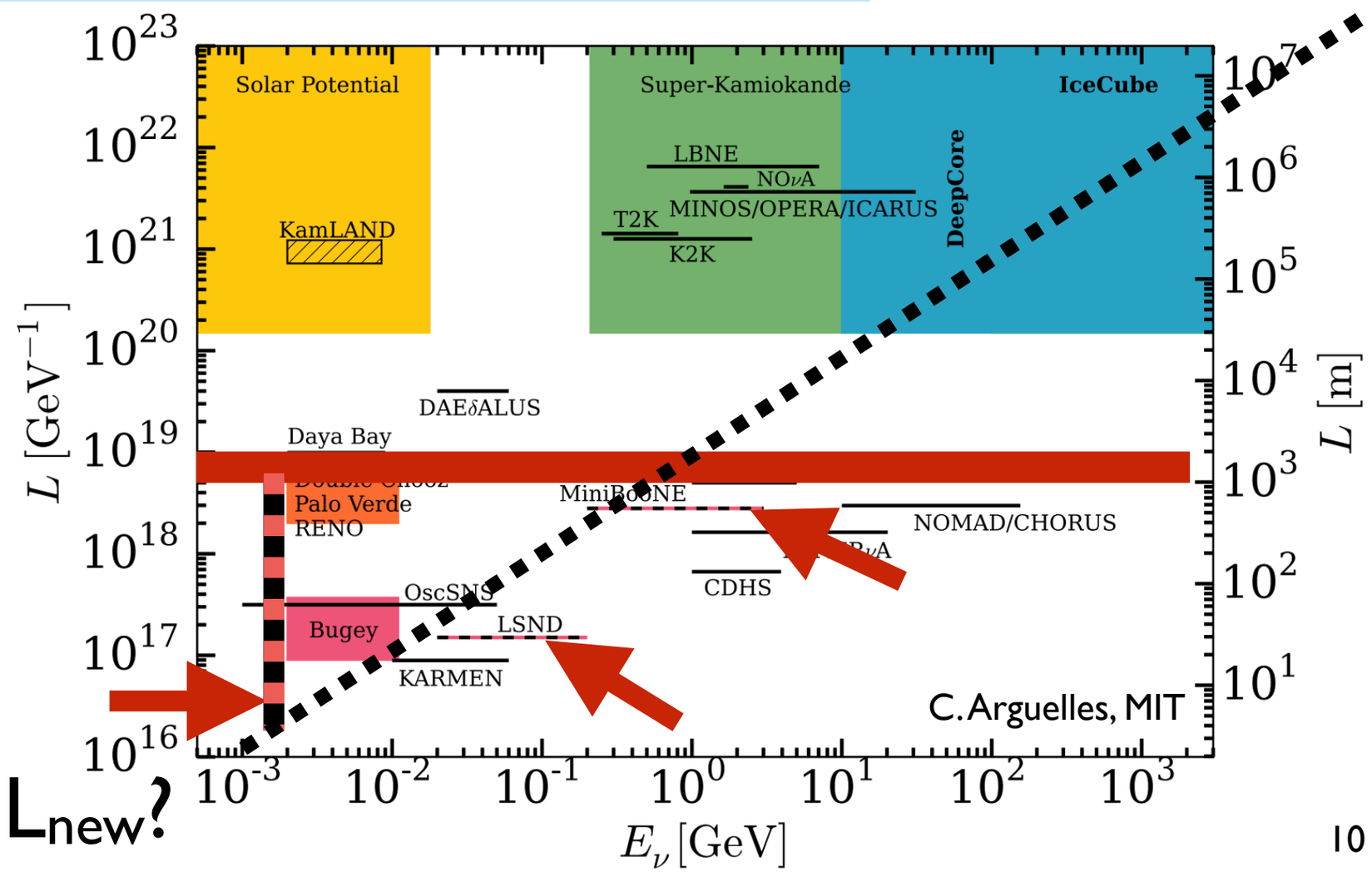
Giunti and Lasserre, hep-ph[1901.08330]

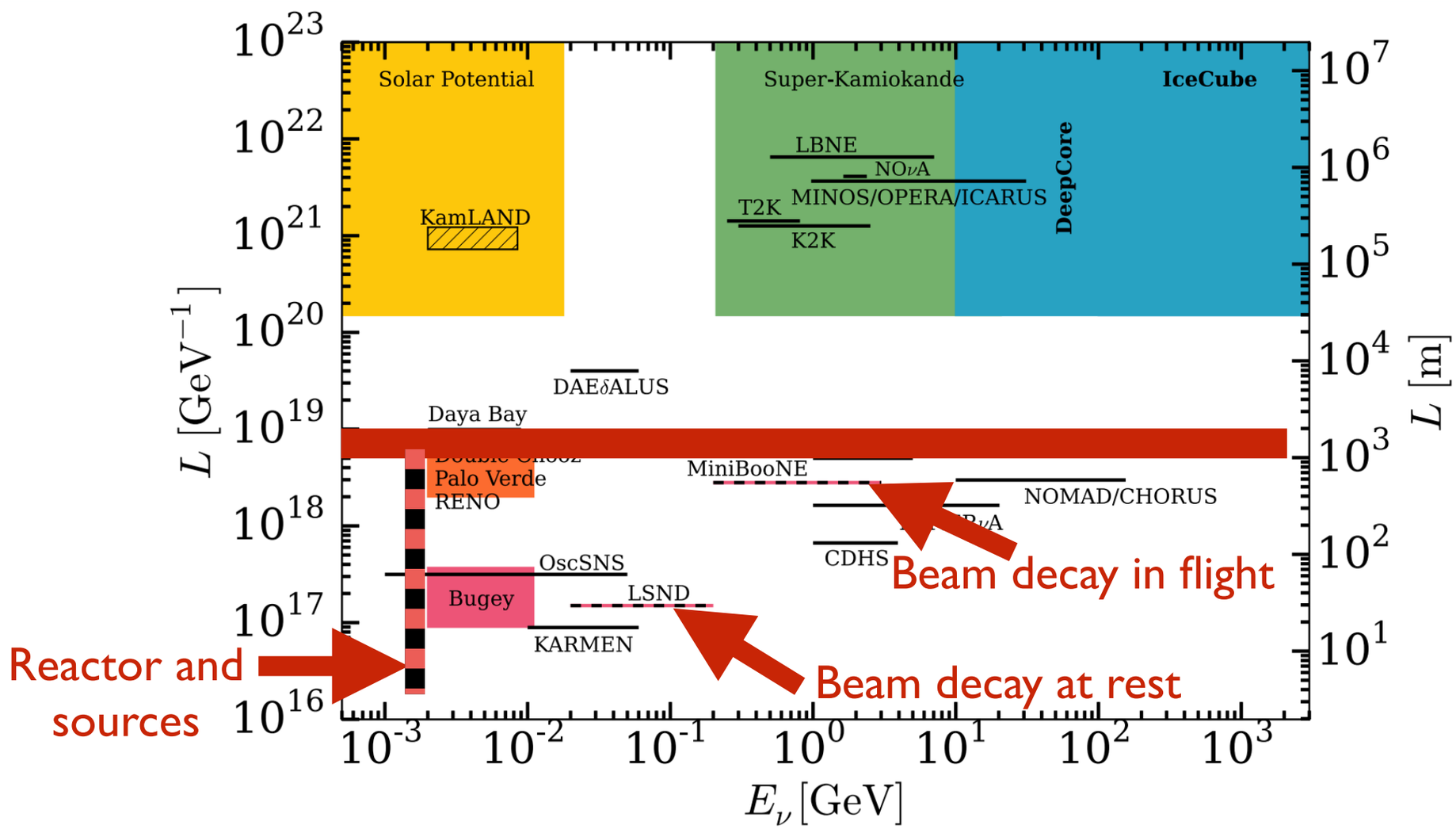



$L_{new}$?

# Existing Experimental 'Anomalies'

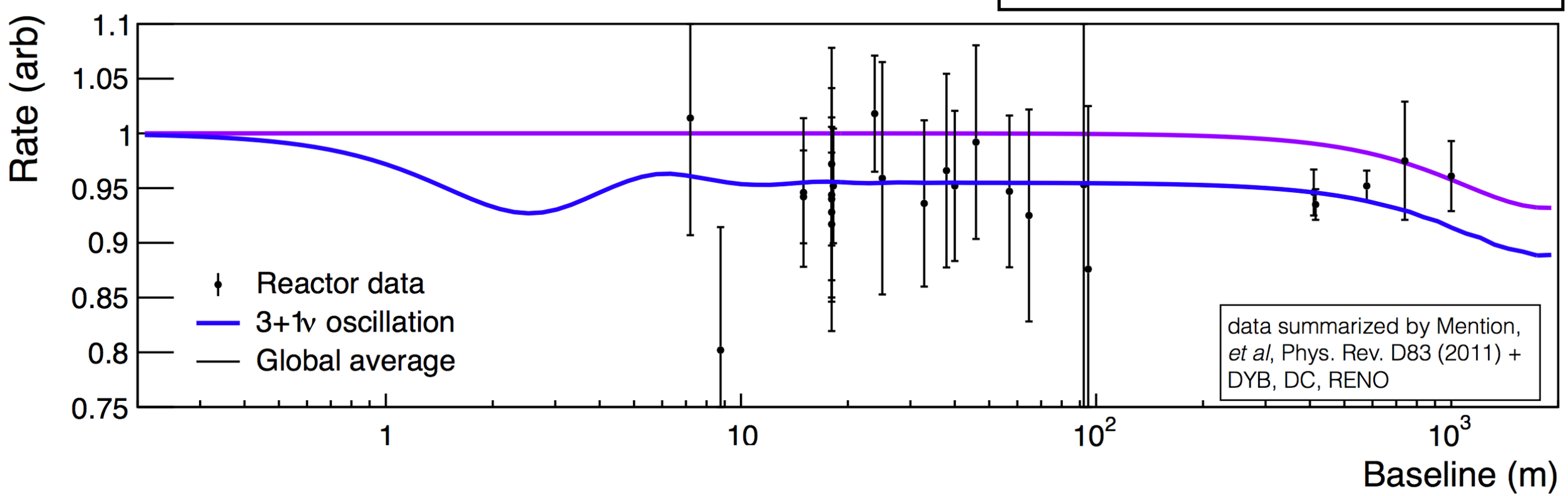
- Some neutrino rates/energies measured at <km disagree with state-of-the-art neutrino predictions
- Four 'anomalies,' four different neutrino source types
  - No 'silver bullet' experiment for understanding anomalies' origin(s)
  - <u>Goal</u>: probe each anomaly individually to improve understanding



# Reactor Anomaly Cause: Steriles

- Models of $\bar{\nu}_e$ production in reactors appear higher than data.
- Hypothesis 1: Some $\bar{\nu}_e$ oscillated to unobservable types
  - Can fit this hypothesis to flux data well with an eV-scale mass splitting
  - Hypothesis indicates a deficit that should be baseline- and energy-dependent
  - Flux data doesn't demonstrate either very well. Other data types needed!

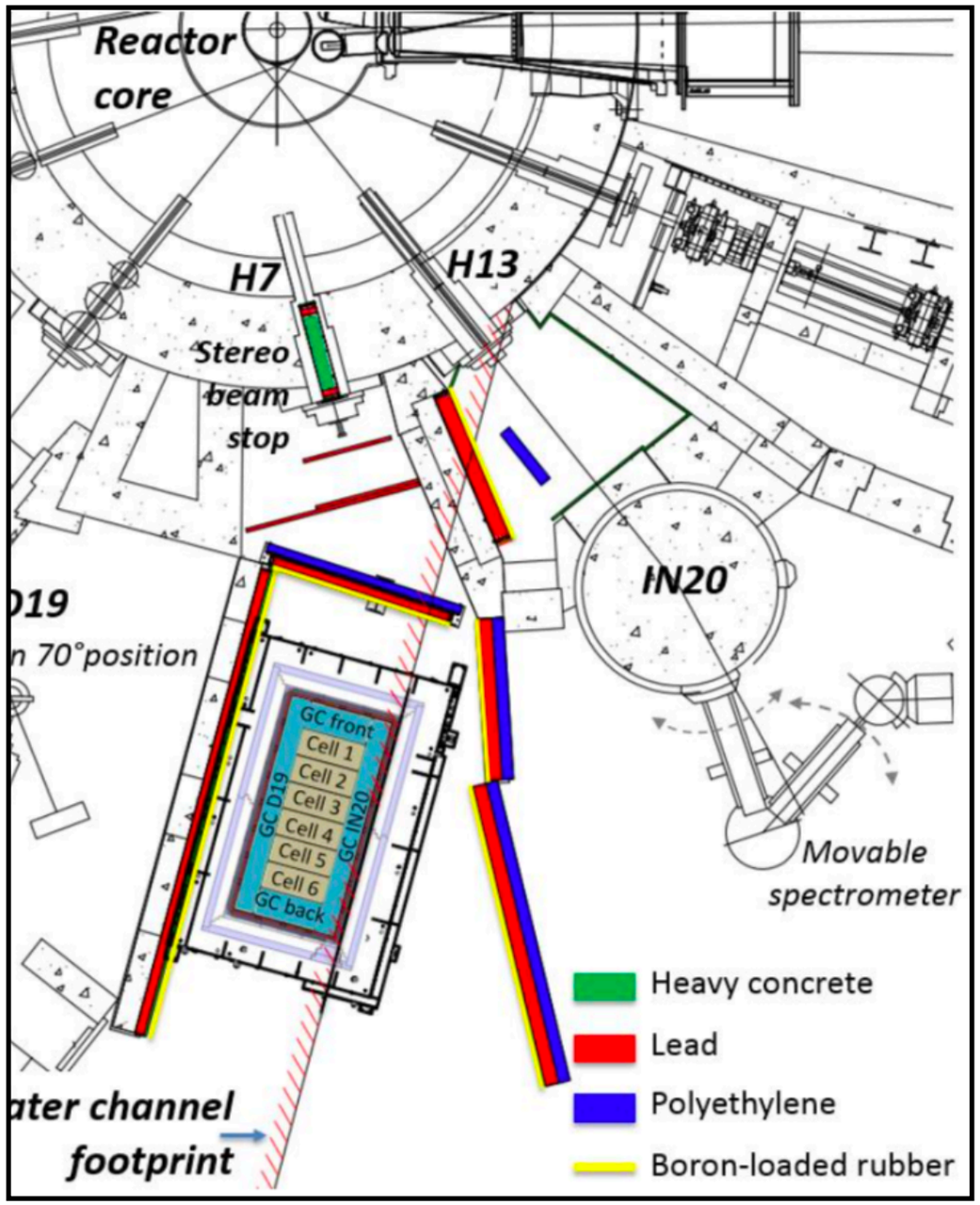
$$sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$



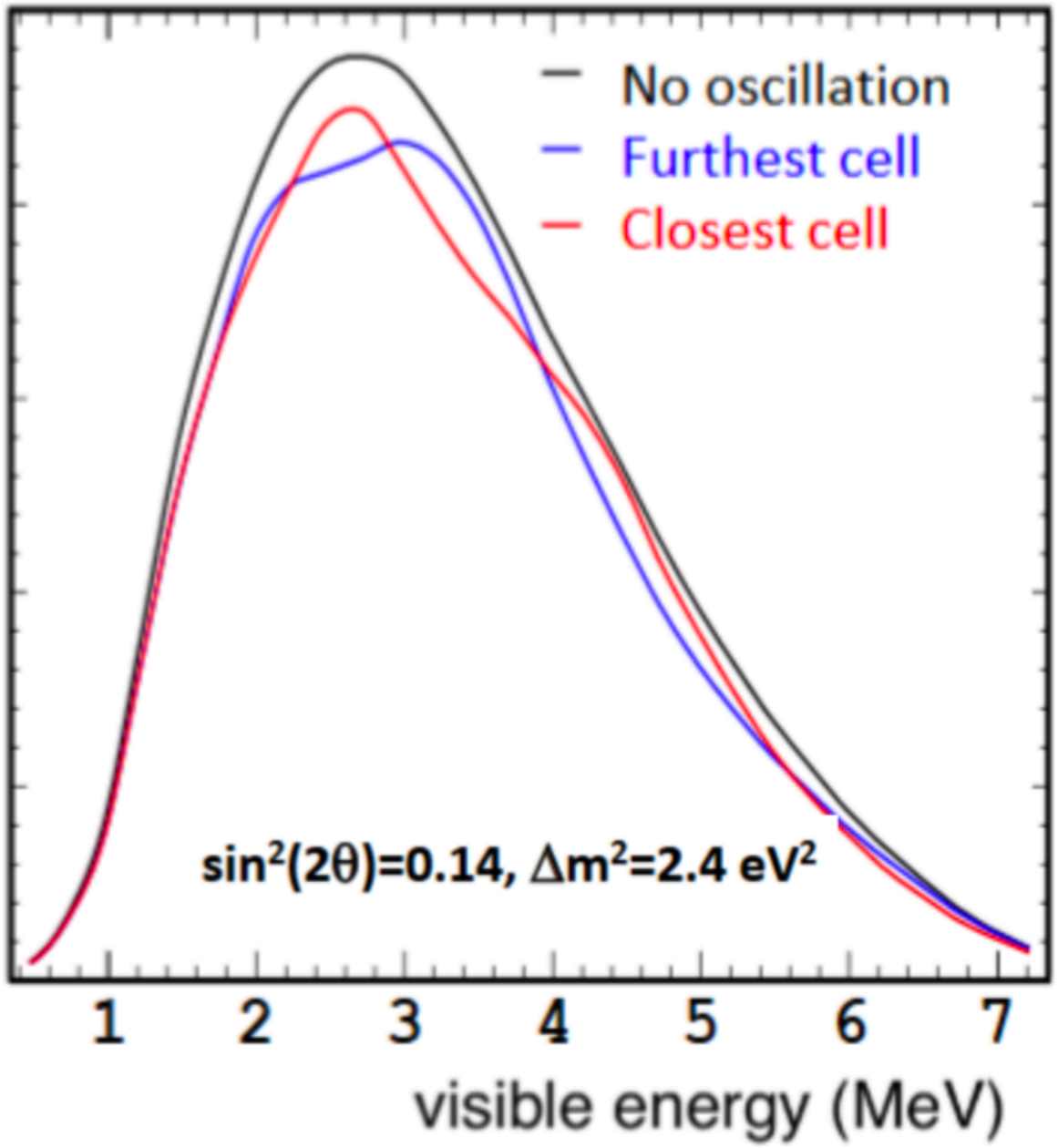
# Spectral Ratio Reactor Experiments

- Compare spectra between baselines within one stationary (PROSPECT, STEREO) or mobile (DANSS) detector

STEREO Experimental Layout



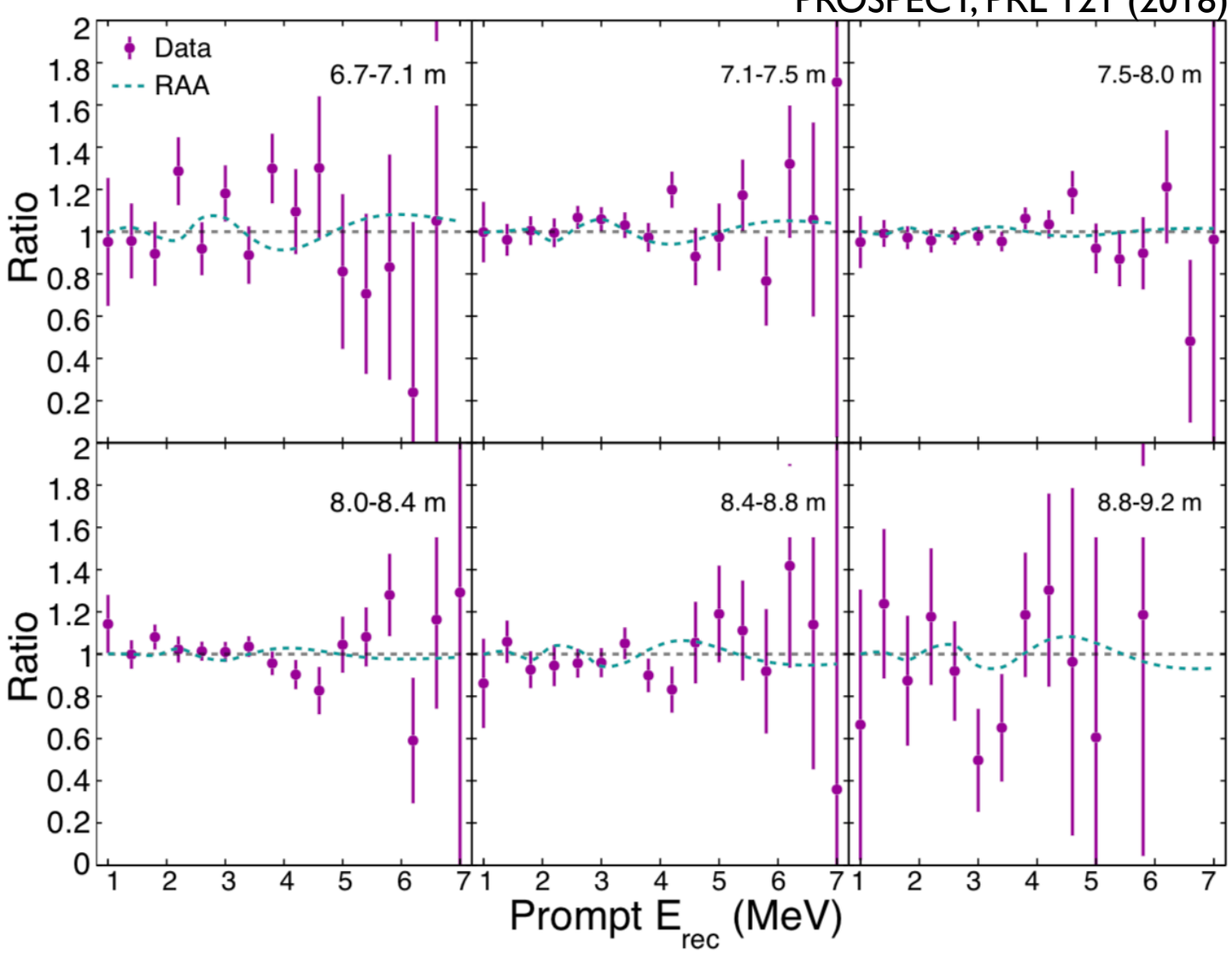

STEREO Toy Prompt Spectra From RAA Best-Fit Osc



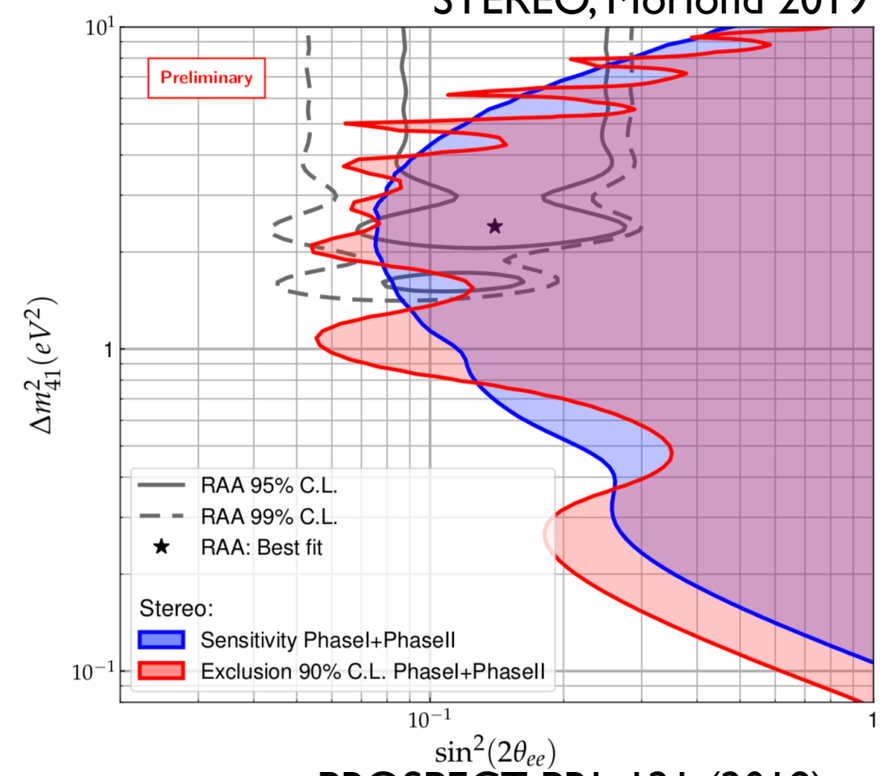
# Testing Steriles: HEU Experiments

- PROSPECT, STEREO: measure compact $^{235}U$ (HEU) reactors
- No evidence for steriles so far
  - More statistics will bring sensitivity improvements very soon
  - PROSPECT@LP2019

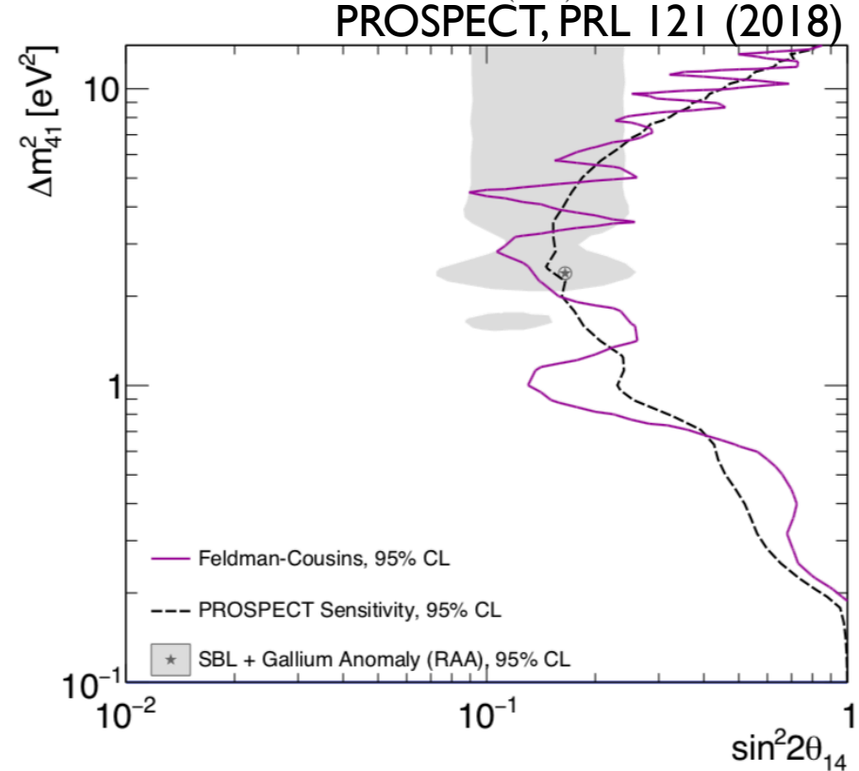
PROSPECT, PRL 121 (2018)




STEREO, Moriond 2019

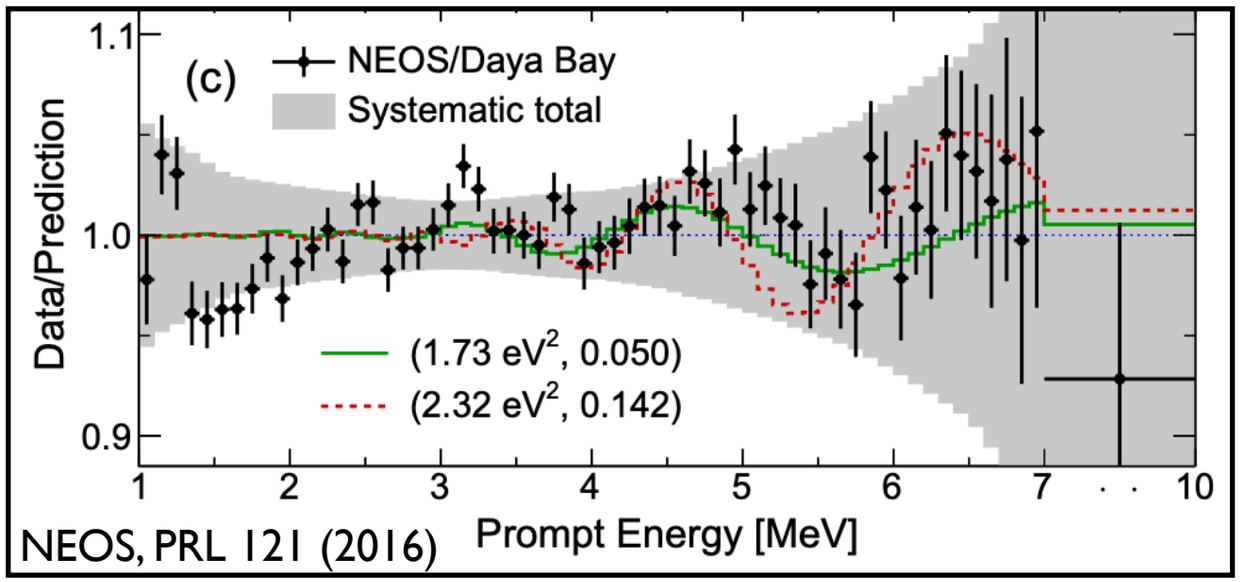


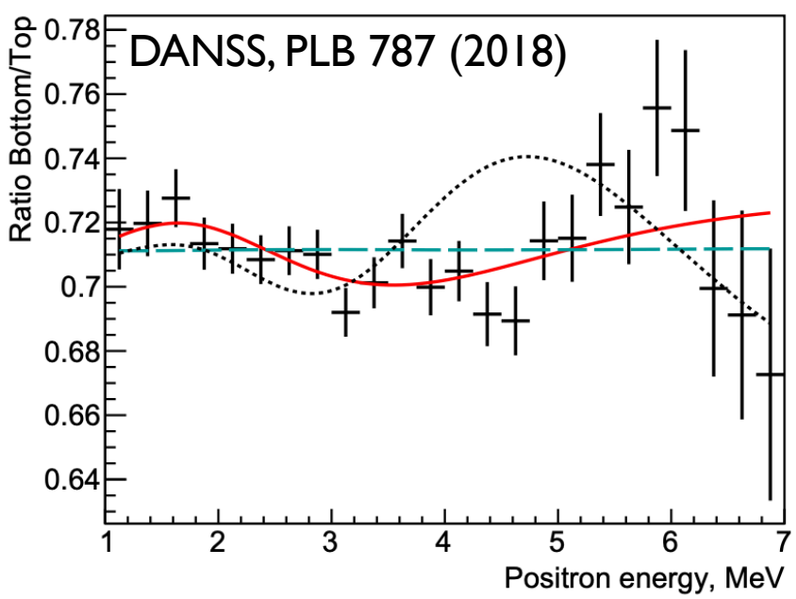

PROSPECT, PRL 121 (2018)

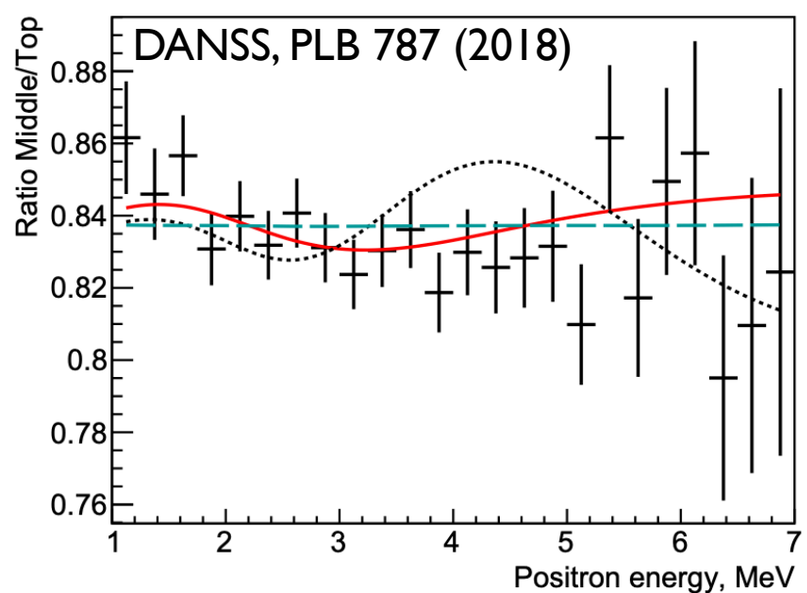


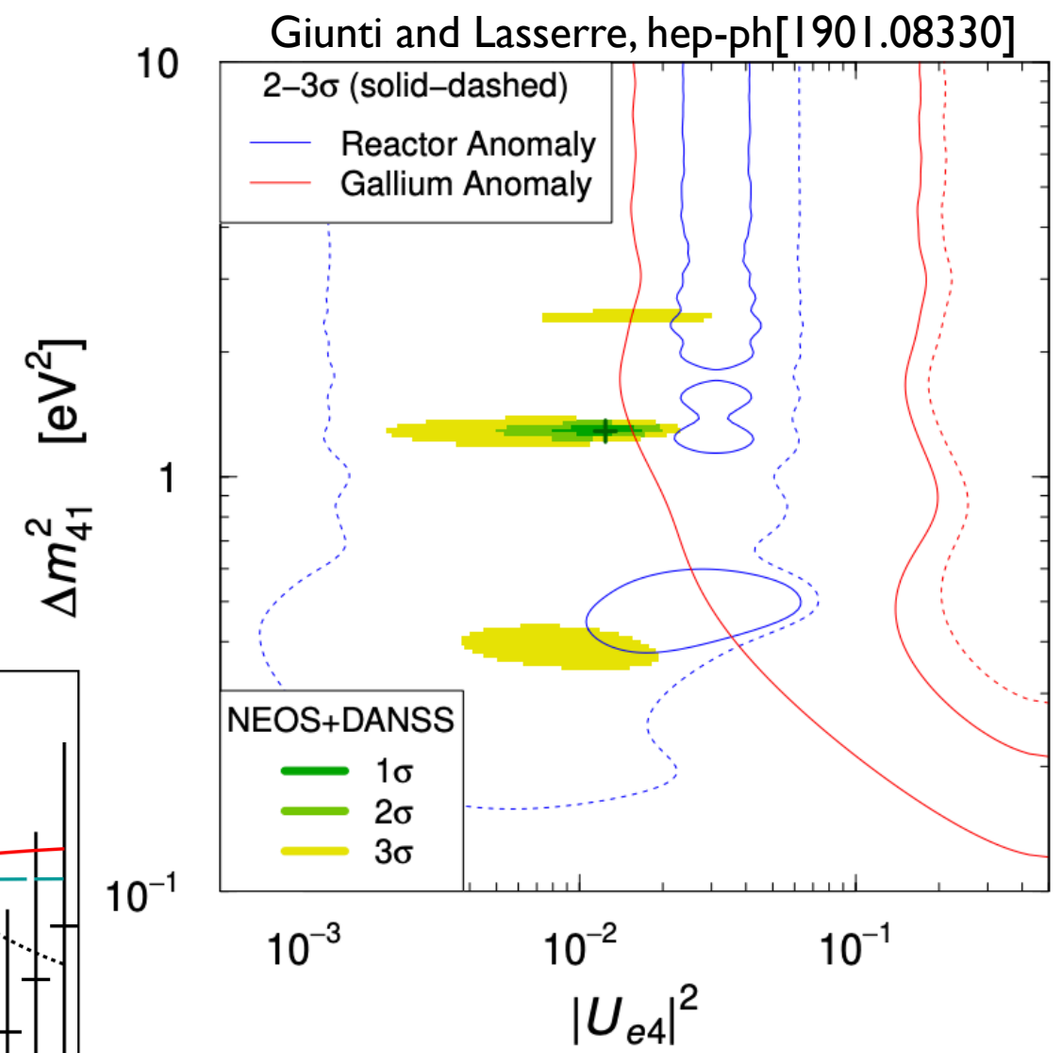
# Testing Steriles: LEU Experiment Hints?

- Hints for steriles from commercial core (LEU) spectrum ratios?
  - Global fit of DANSS+NEOS ratios: ~5% osc amplitude best-fit at ~1.5 eV$^2$
  - Note: Individual experiments don't claim a statistically significant observation



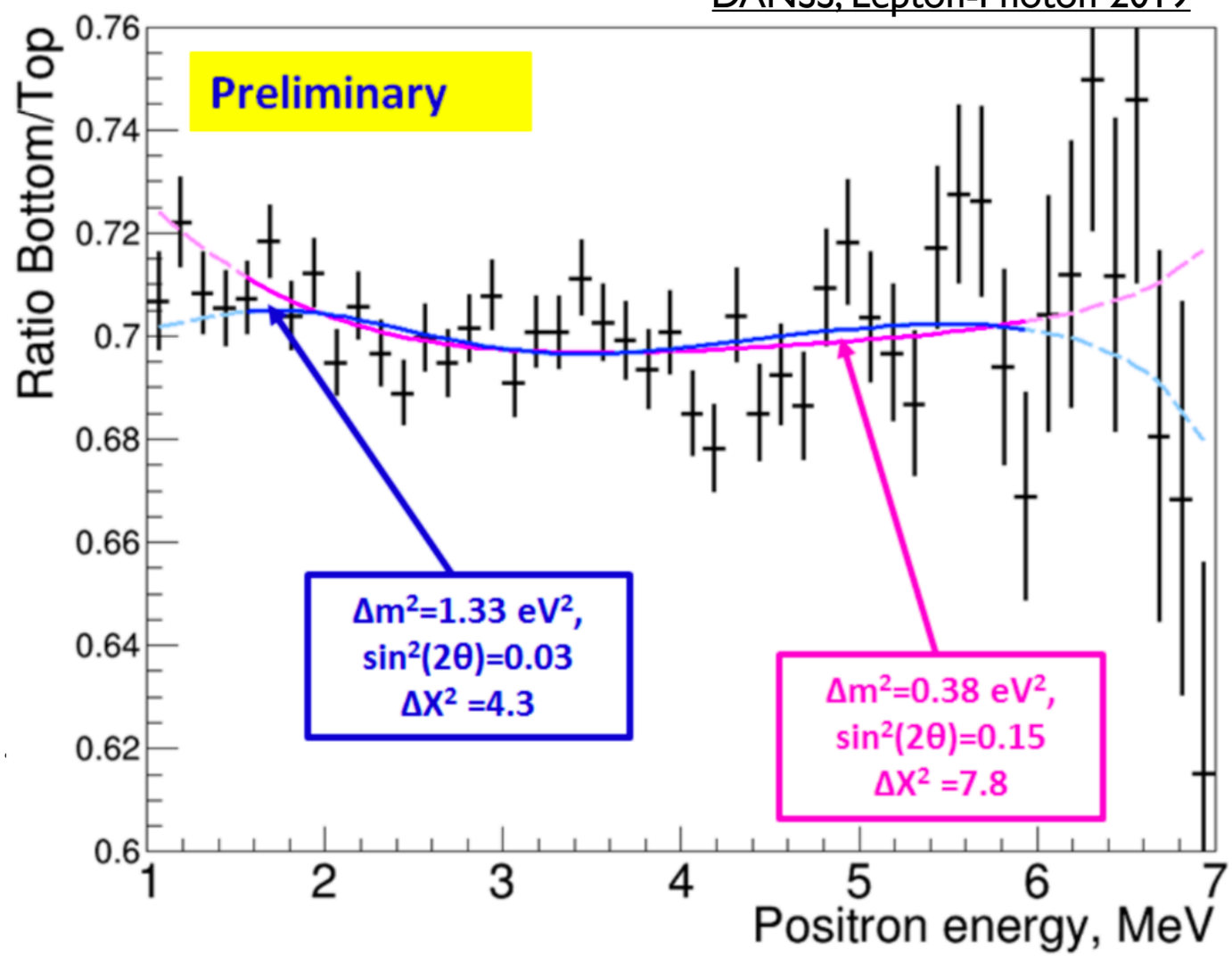



# Testing Steriles: LEU Experiment Update

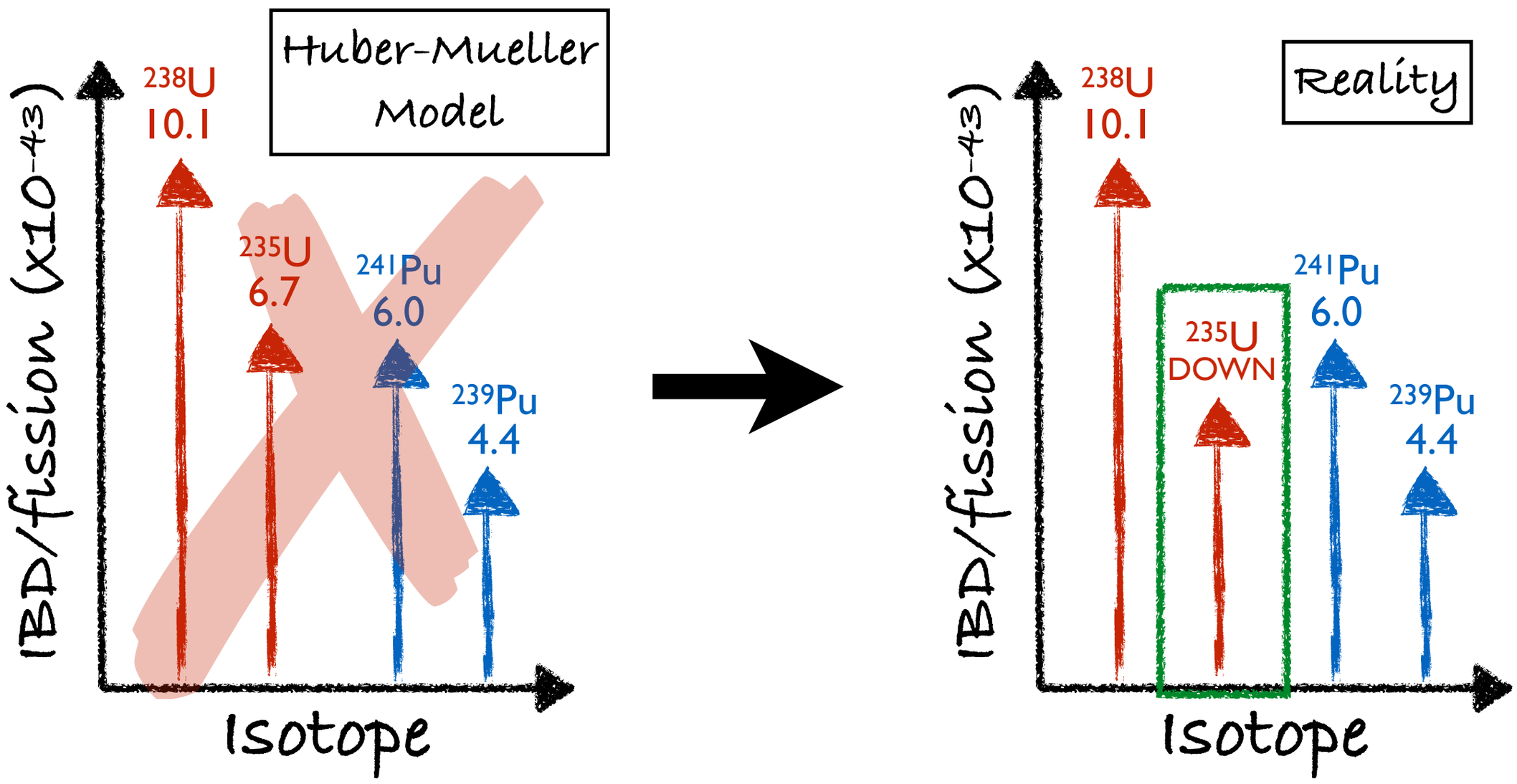
- Hints for steriles from commercial core (LEU) spectrum ratios?
- New DANSS results with improved stats, systematics handling
  - No-oscillation is only disfavored with respect to best-fit at 1.8σ
  - Even less disfavored compared to 'old best fit'
- Primary sterile hint from reactor spectra appears to have faded.
  - Looking forward to a full publication and systematics details
  - New data from a new NEOS deployment also on the horizon.

DANSS, Lepton-Photon 2019



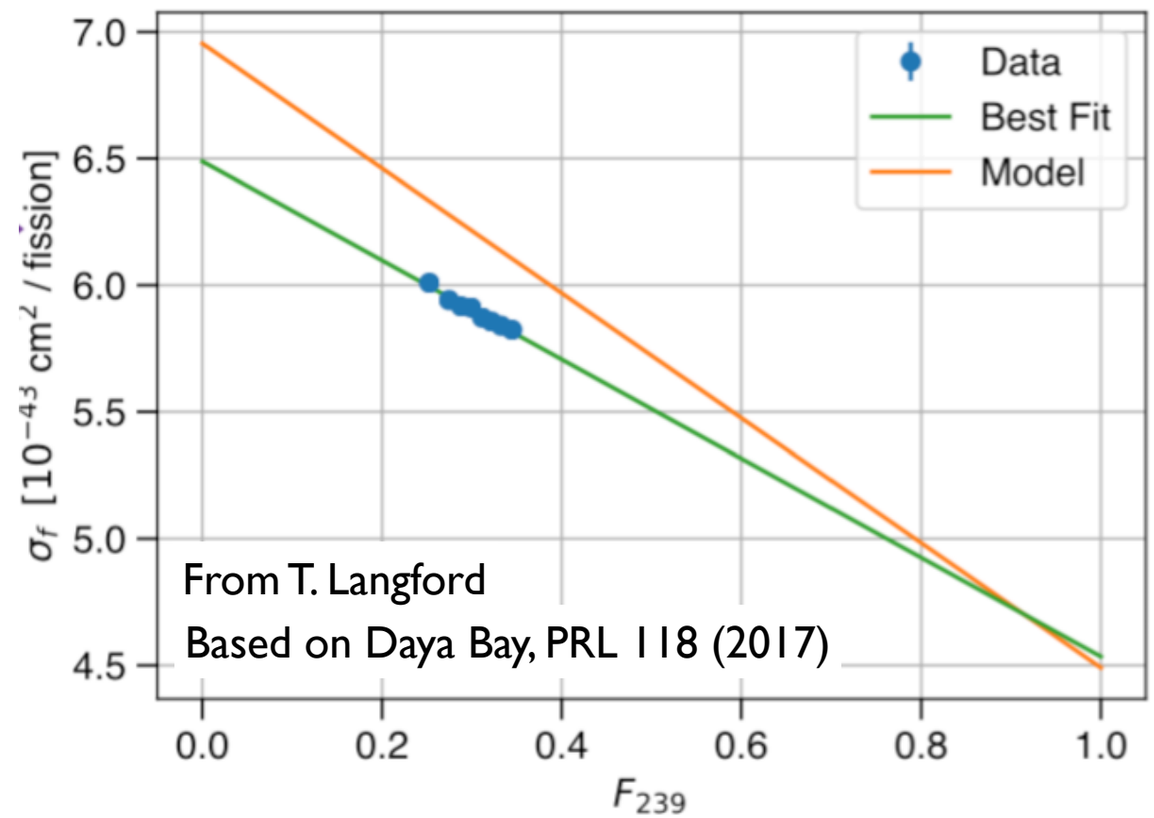
# Reactor Anomaly Cause: Bad Models

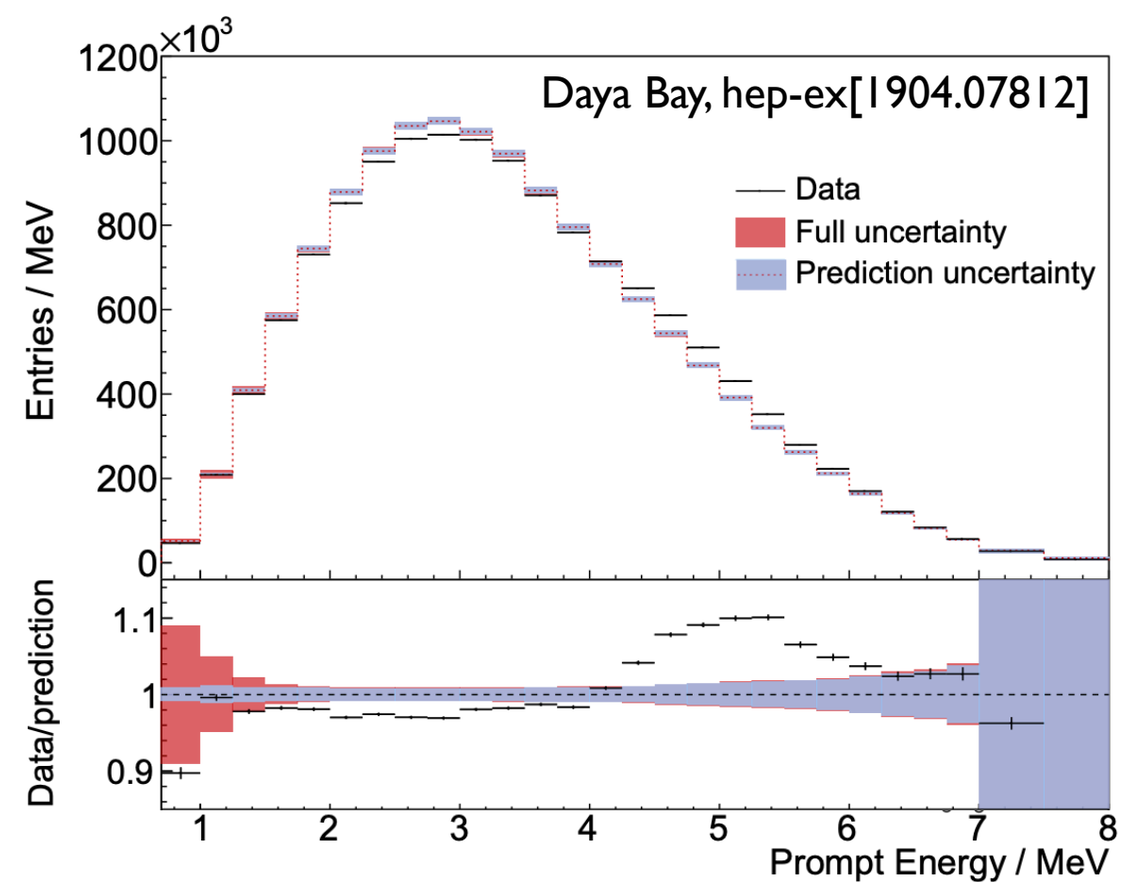
- Hypothesis 2: Is something wrong with the flux predictions
  - Theorists have come up with lots of reasons predictions could be bad
  - Could be just **one** fission isotope; or could be **all** fission isotopes.



# Ample 'Bad Model' Evidence

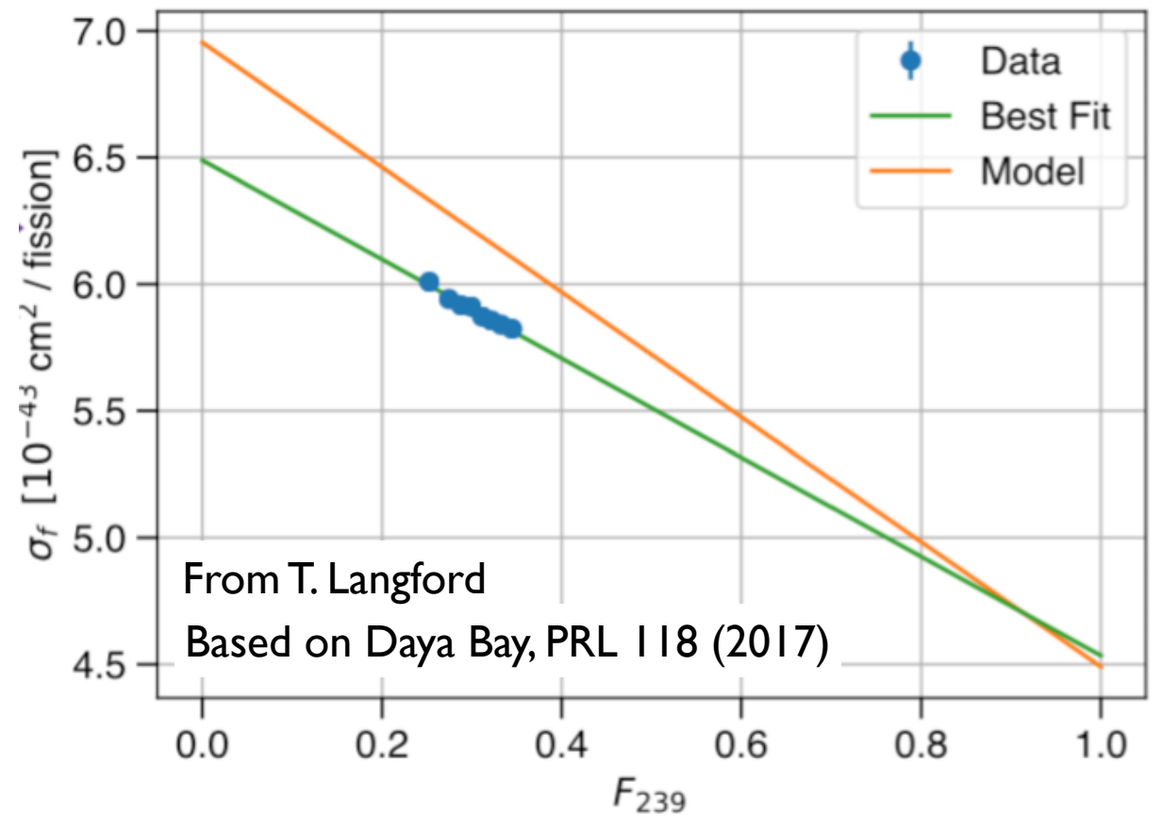
- Flux evolution looks wrong.
- Spectrum looks wrong.
- Neither of these can be caused by oscillations

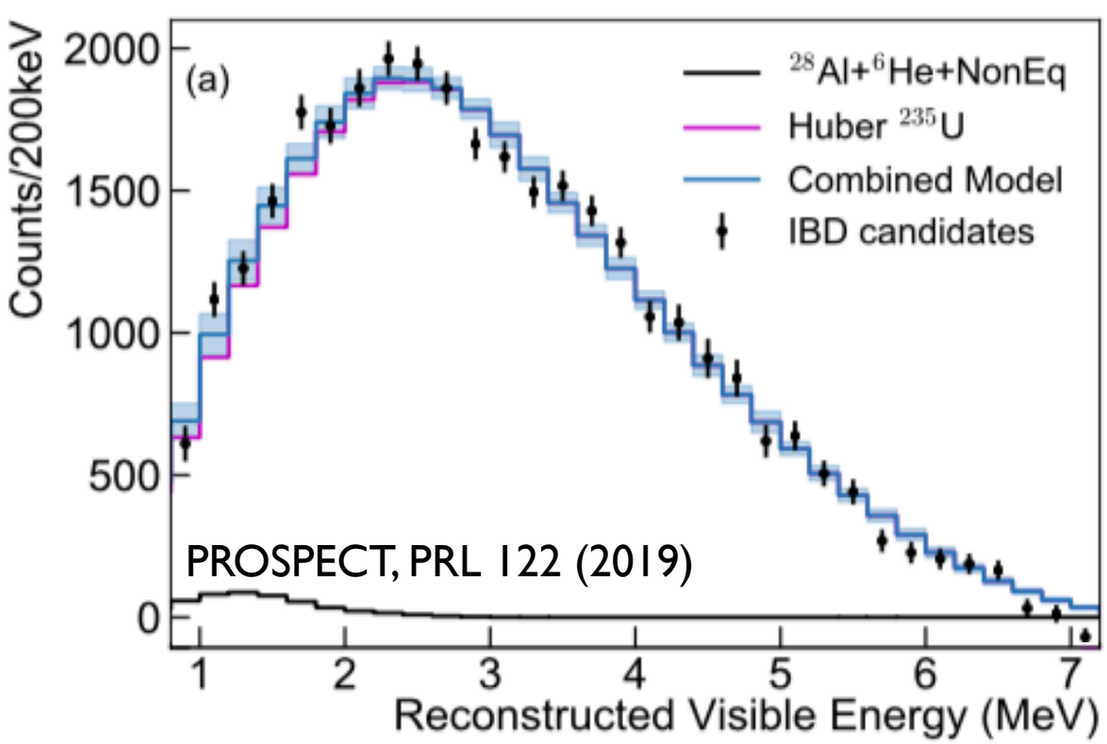


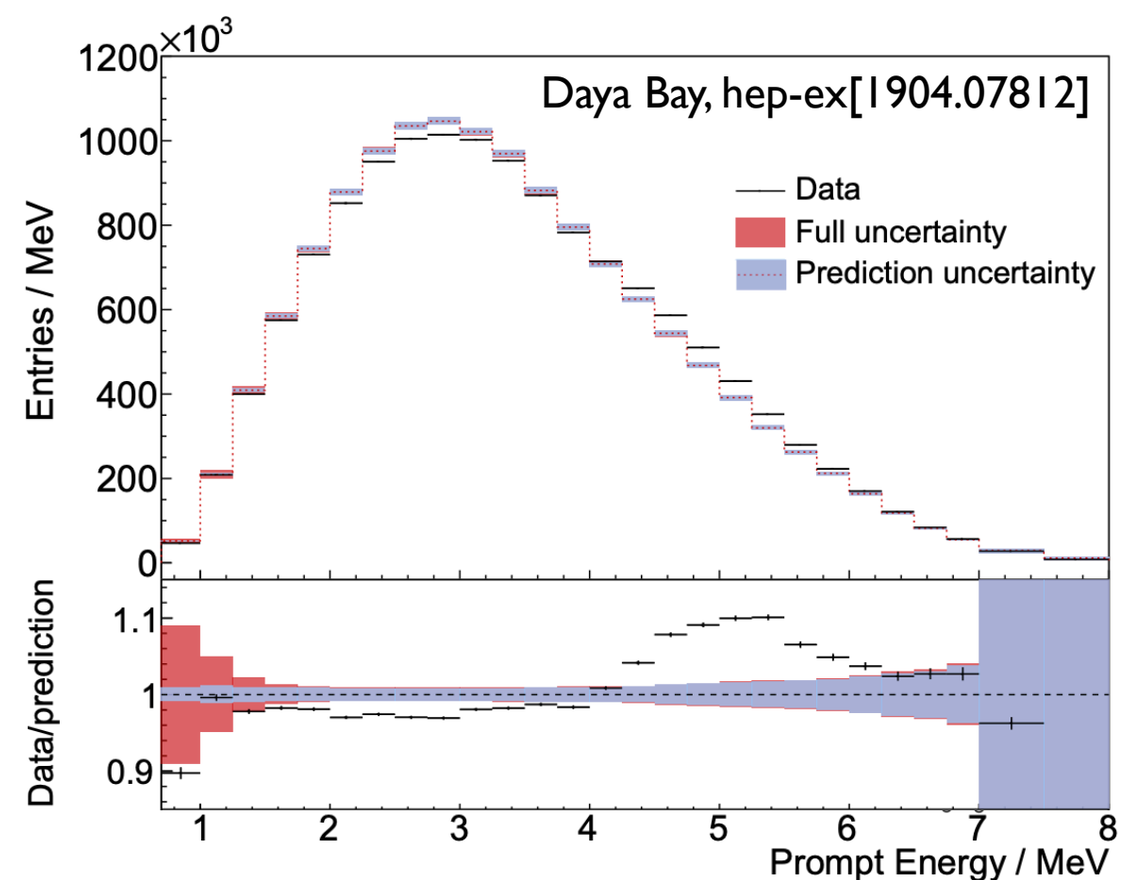



# Ample 'Bad Model' Evidence

- Flux evolution looks wrong.
- Spectrum looks wrong.
- Further insight into both can come from $^{235}$U exps (PROSPECT, STEREO)
  - Also from detailed comparison of LEU exps to these HEU exps
  - Valuable for testing BSM physics, CEvENS, JUNO, nuclear applications

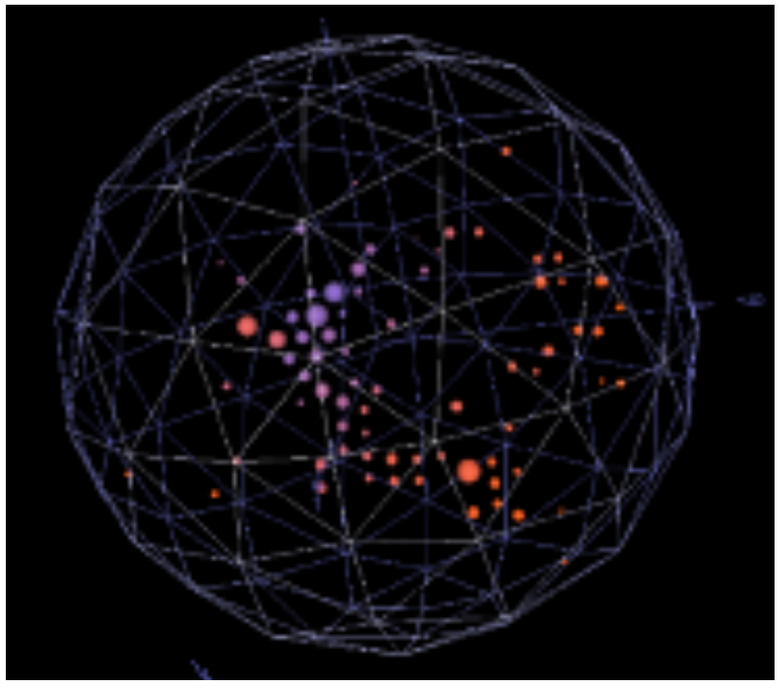


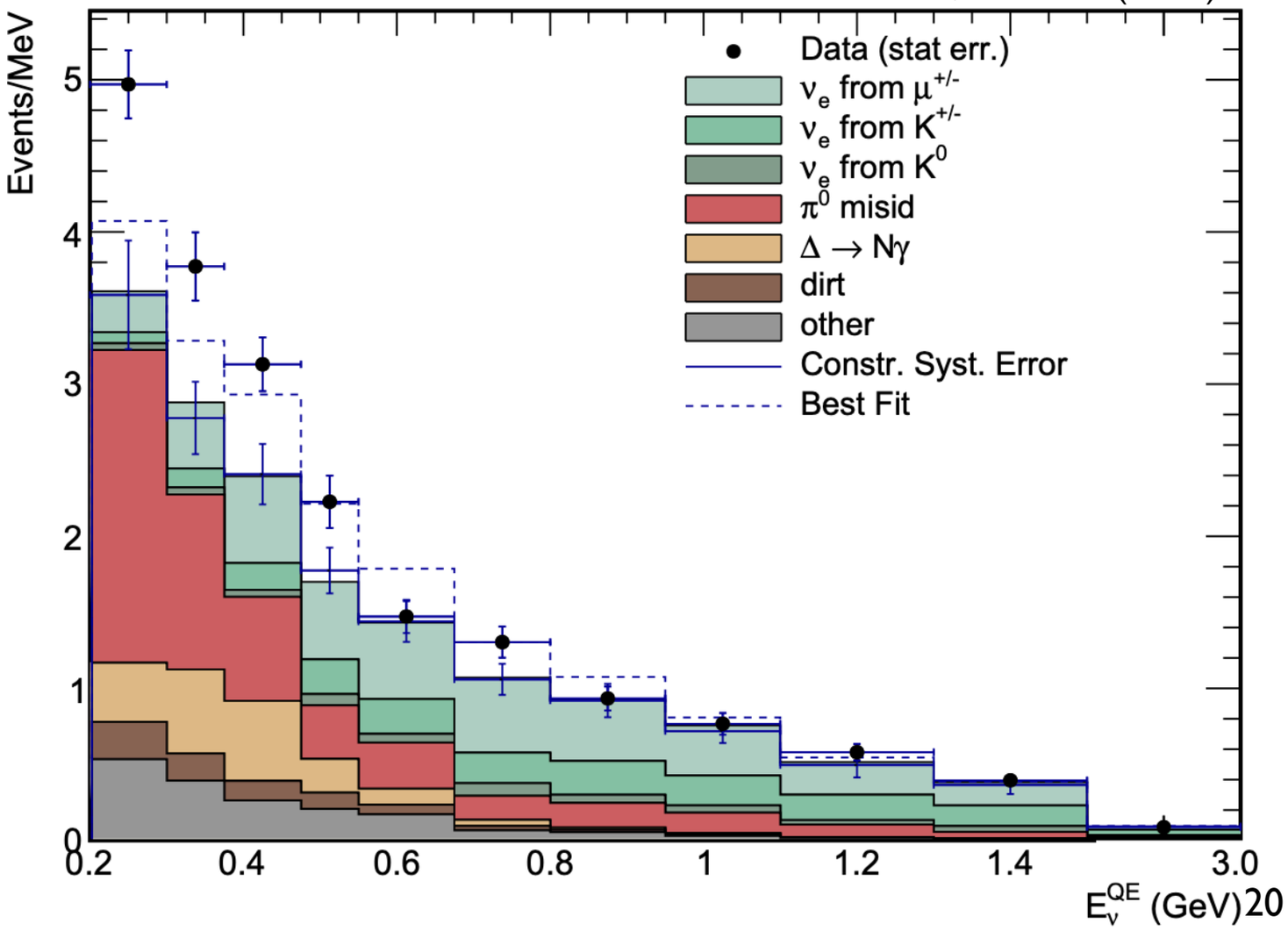



# MiniBooNE Anomaly

- An excess of sub-GeV EM showers in the MiniBooNE Cherenkov detector at ~km
  - Excess went from ~3σ to ~5σ with new data and 2018 publication.
- To match eV-scale sterile neutrino description, excess must be from electrons.
  - MiniBooNE cannot tell electrons from photons; need different technology.



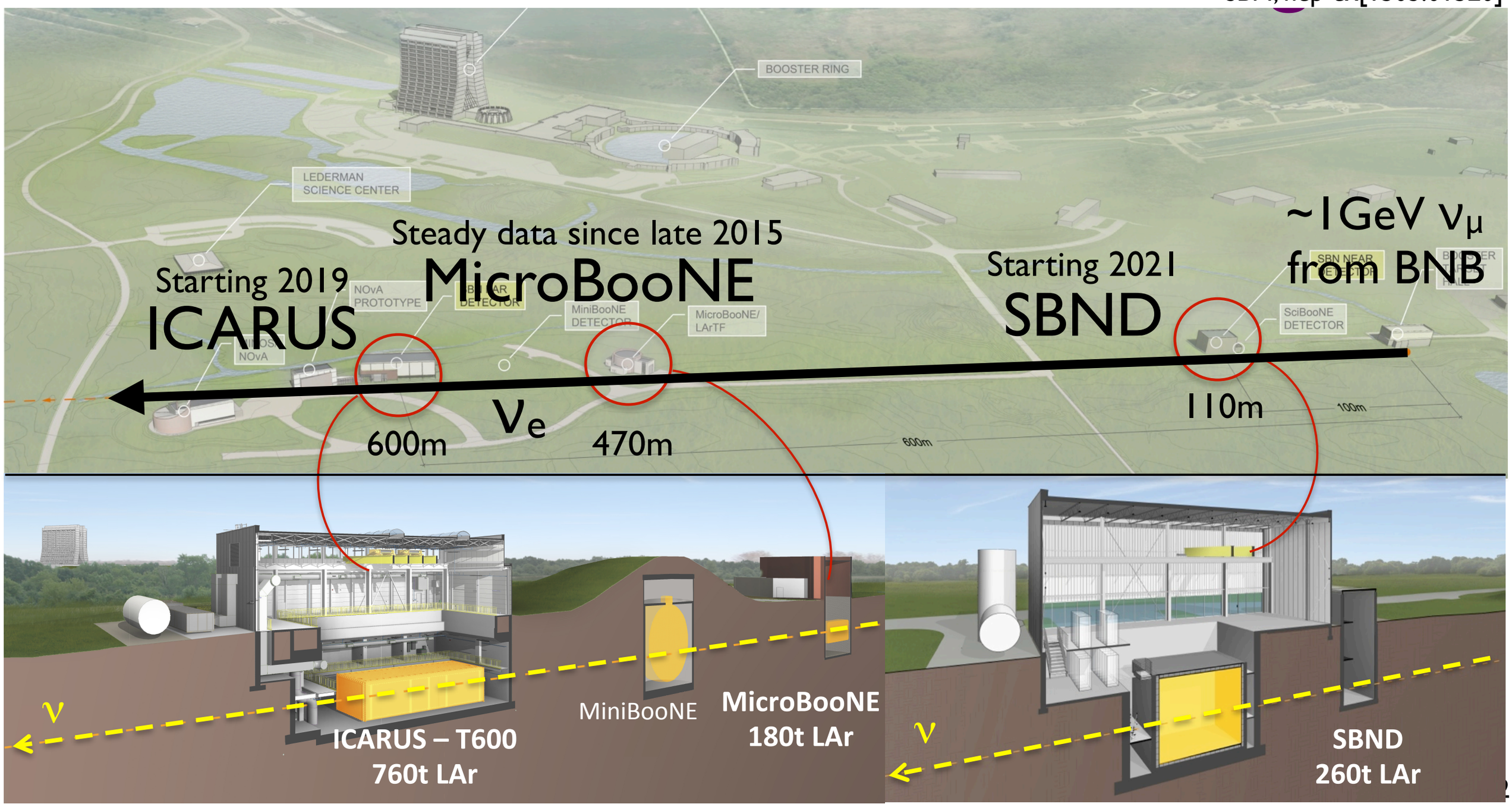
MiniBooNE, PRL 121 (2018)



# Fermilab's SBN Program

- Address electron/gamma ambiguity with LArTPC technology
- 3 baselines increases osc sensitivity for both $\nu_\mu$, $\nu_e$ channels

SBN, hep-ex[1503.01520]



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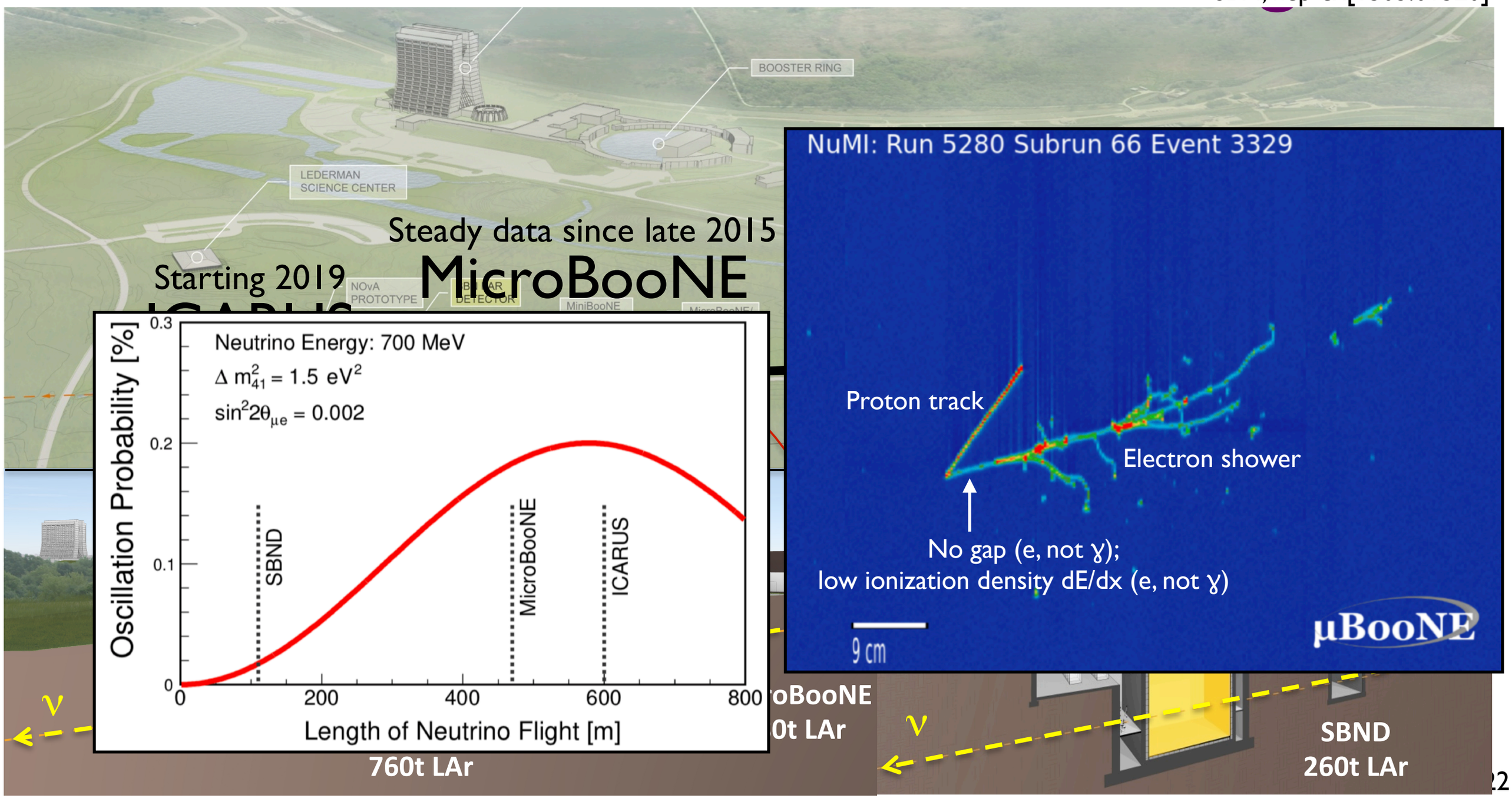


# MicroBooNE: Shower Reconstruction

- Working in phases towards uBooNE low-energy excess result
- Pursuing multi-pronged strategy:
  - Inclusive versus exclusive (1e+1p) searches

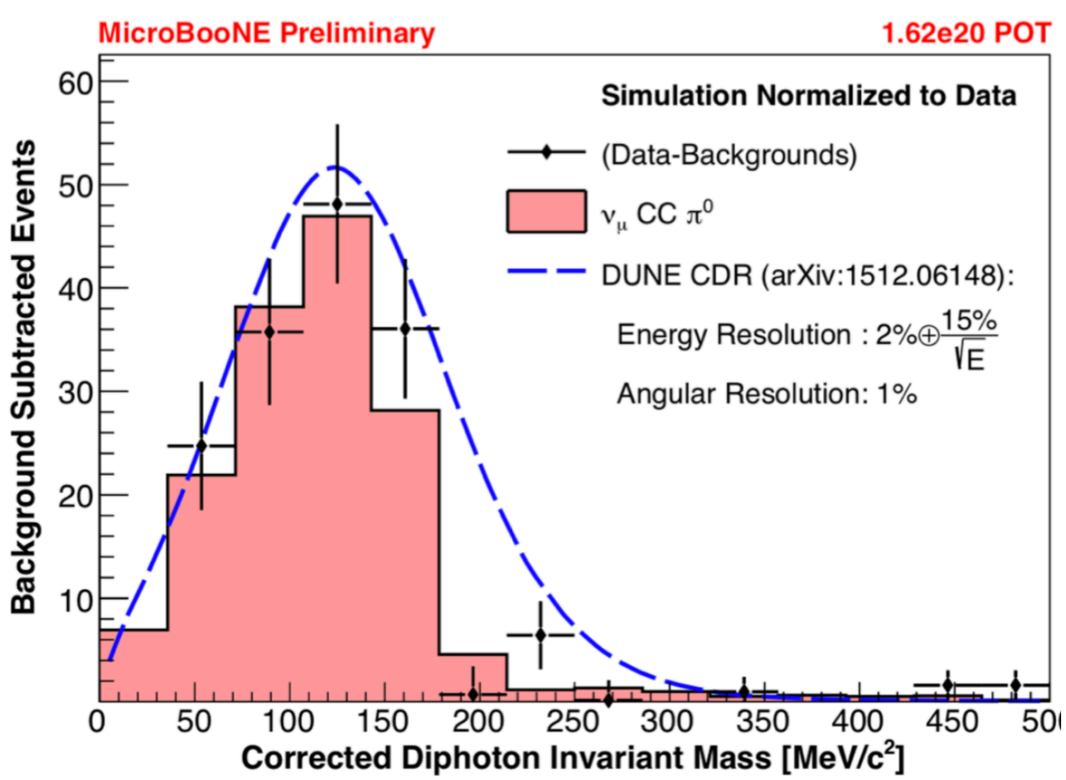
    MicroBooNE Public Note 1051 (2018) MicroBooNE Public Note 1054 (2018)
  - Pandora versus Deep Learning event reconstruction tools

    MicroBooNE, Eur. J. Phys. C 78 (2018) MicroBooNE PRD 99 092001(2019) MicroBooNE, JINST 12 P03001 (2017)
- All strategies built upon robust foundational analyses and low-level signal processing

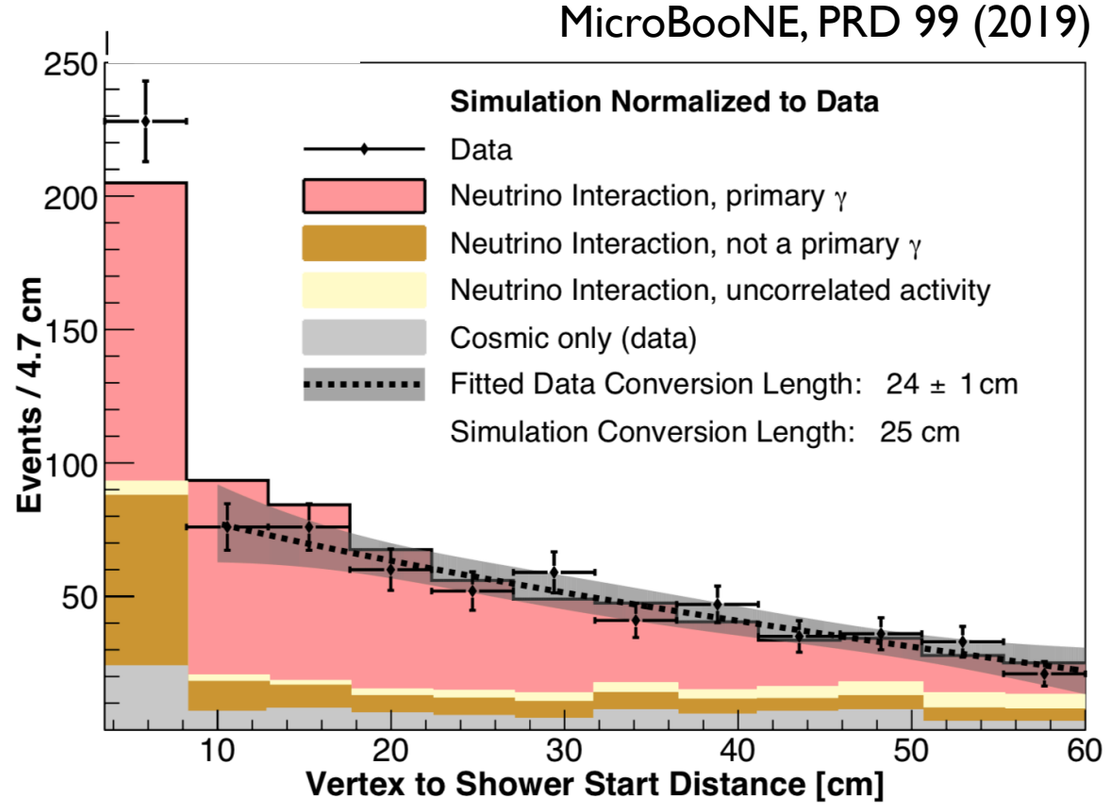
  MicroBooNE, JINST 13 P07006 (2018) MicroBooNE, JINST 13 P07007 (2018) MicroBooNE, JINST 12 P08003 (2017)

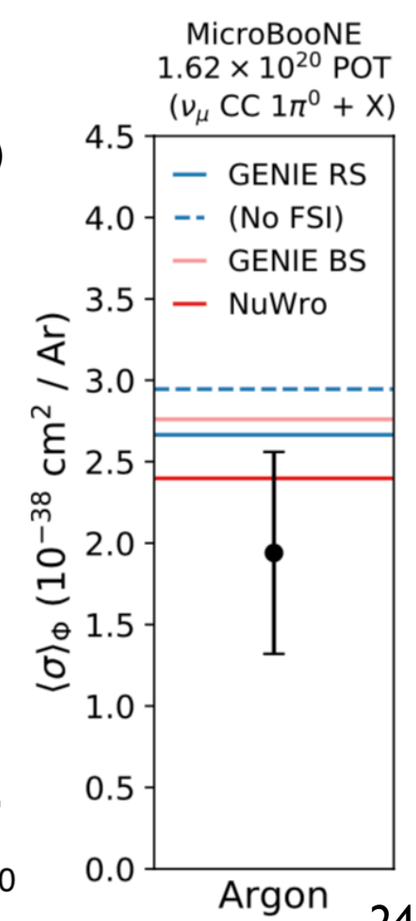
# MicroBooNE: Shower Reconstruction

- Working in phases towards uBooNE low-energy excess result
- First: can we acceptably reconstruct shower qualities?
- Demonstration with $\nu_\mu$CC + Pi0 cross-section analysis
  - Pi0 mass peak is where we expect it to be (unbiased energy, angle reco)
  - Energy resolution is acceptable (better than DUNE CDR assumption)
  - Vertex locations match what we'd expect for photons in LAr



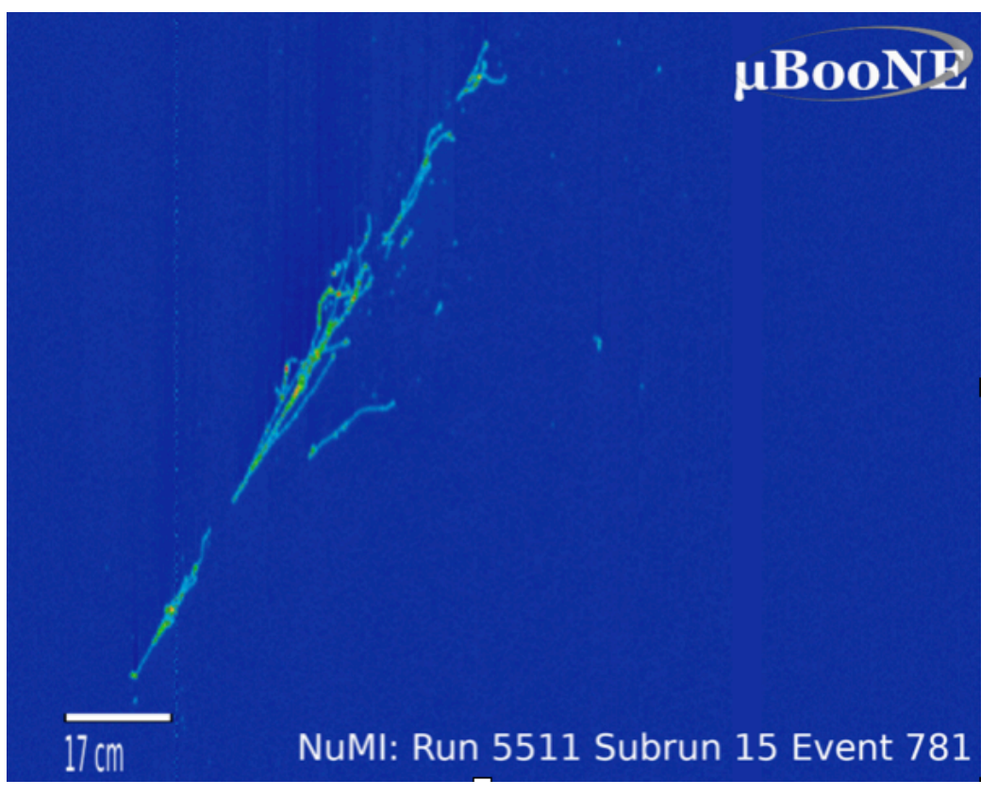

MicroBooNE, PRD 99 (2019)

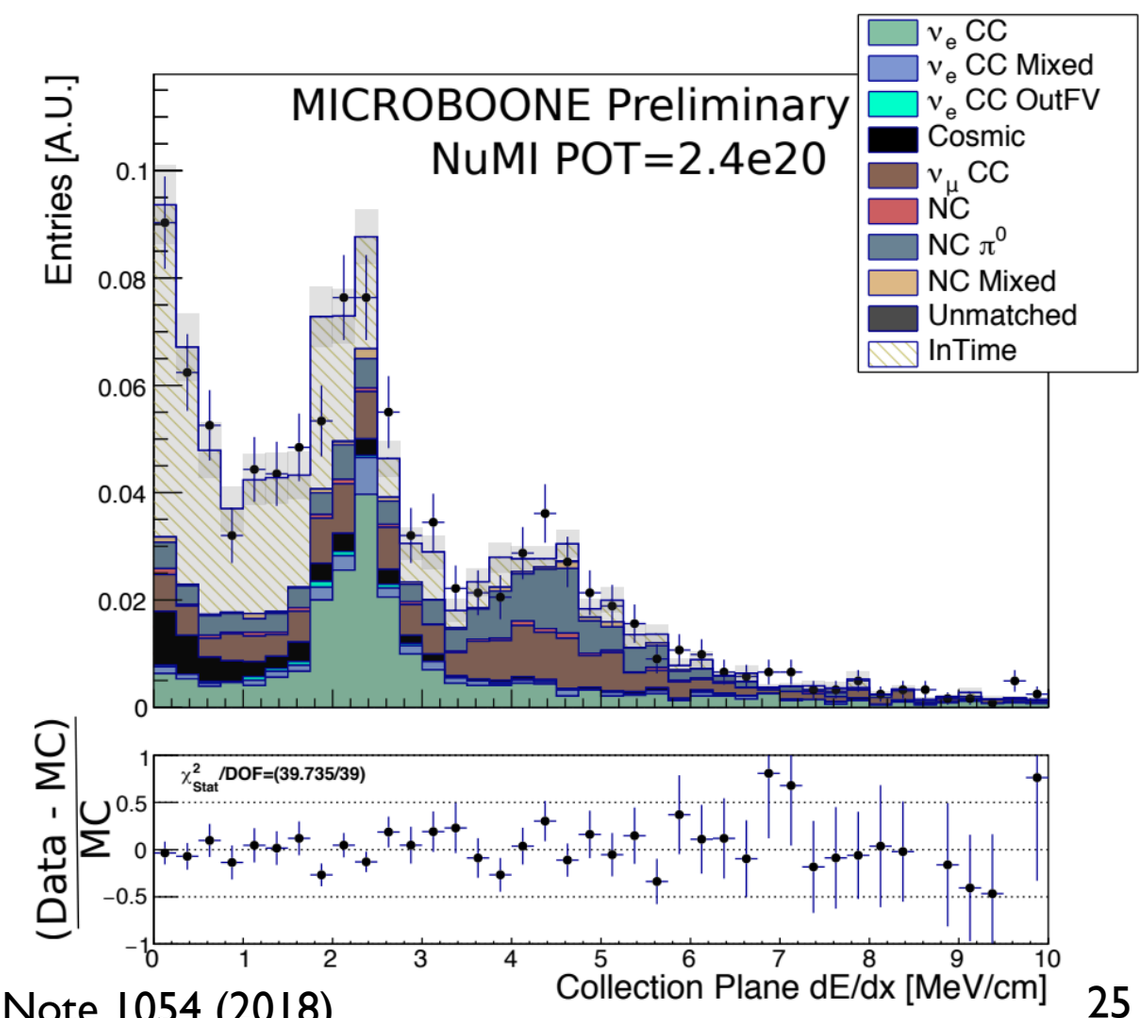


# MicroBooNE: $\nu_e$ Selection

- Working in phases towards uBooNE low-energy excess result
- Second: can we select $\nu_e$CC events in a sideband dataset?
- Demonstration with NuMI beam events
  - NuMI beam $\nu_e$ contamination is higher (less sensitive to $\nu_\mu \rightarrow \nu_e$)
  - Automated selection IDs ~100 $\nu_e$CC events in 2.4e20 POT
  - Also: good data-MC dE/dx agreement



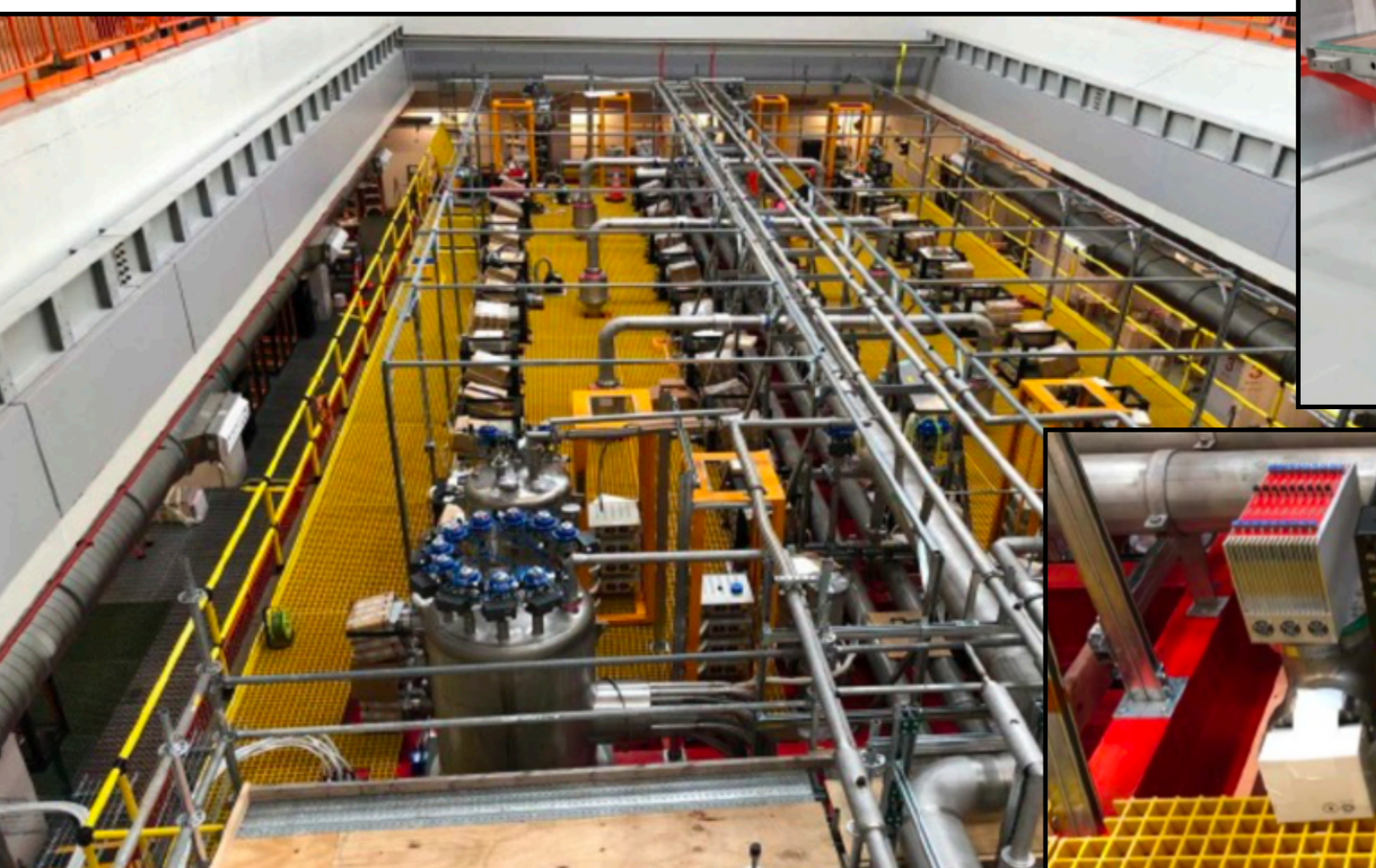

MicroBooNE Public Note 1054 (2018)

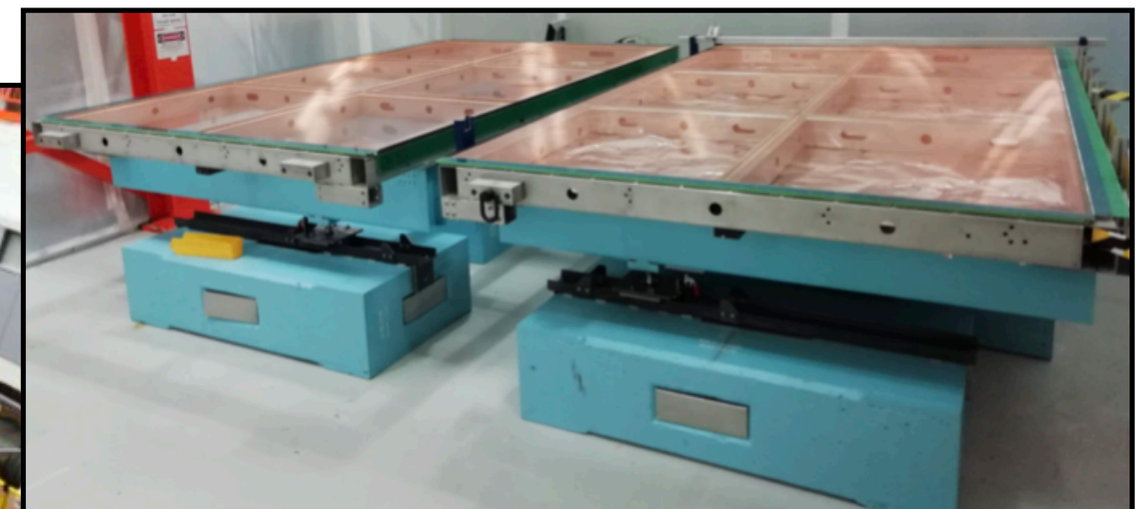
# ICARUS and SBND

- ICARUS is well on its way: LAr filling in September
- SBND assembly underway at Fermilab: 2021 physics start

Completed SBND Building at Fermilab

Installed ICARUS@SBN: Top view!





SBND anode wire planes at Fermilab

ICARUS commissioned Installed PMT electronics

# Other Disappearance Channels

- Other experiments forego direct checks of 'anomalies' in favor of directly assessing sterile neutrino oscillations

  - NC: active neutrino disappearance (MINOS+, NoVA)

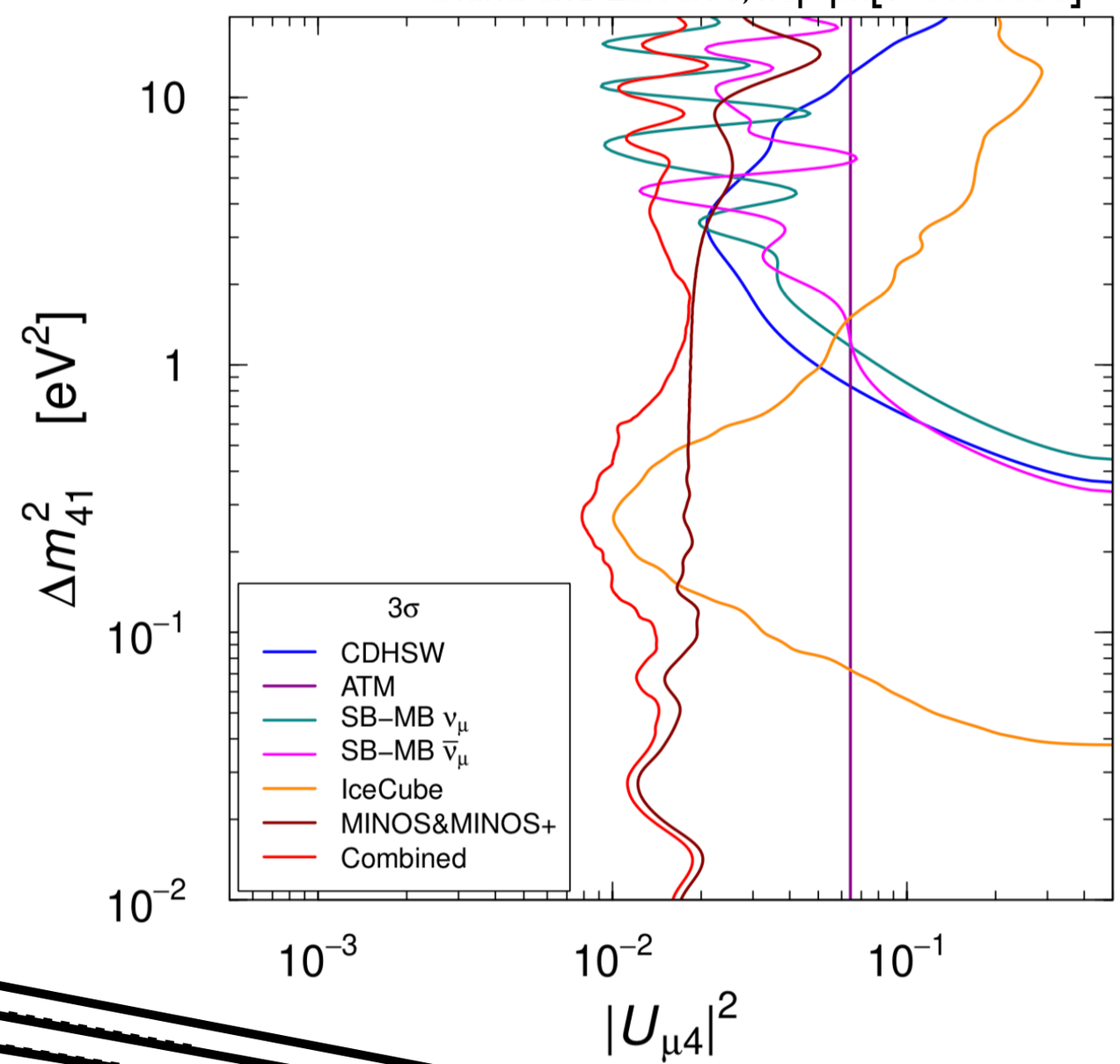
    MINOS(+), PRL 122 (2019)  NoVA, PRD 96 (2017)

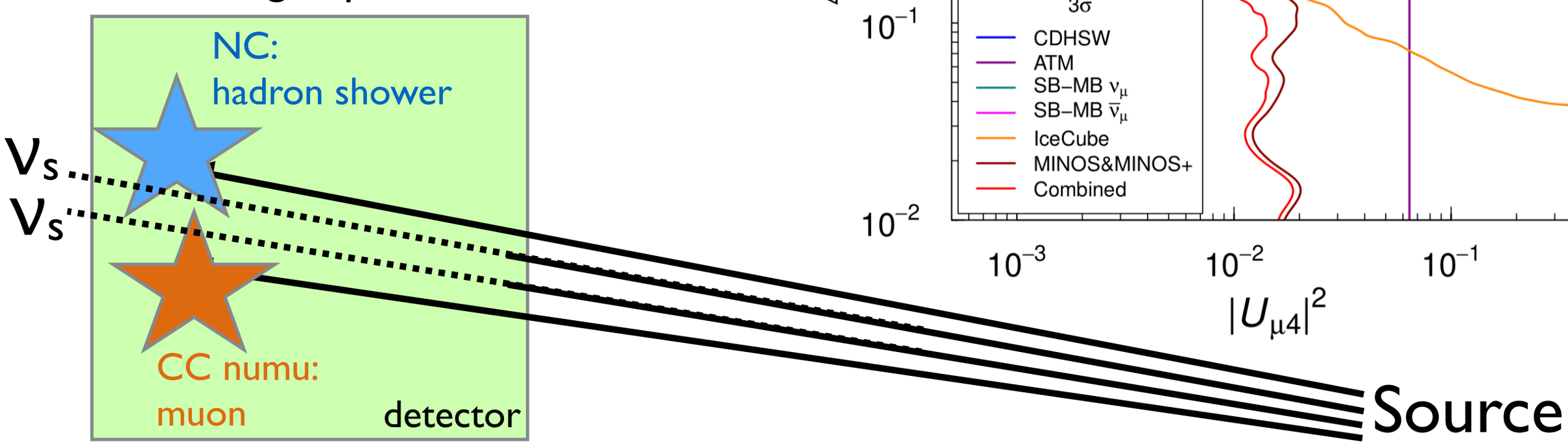
  - CC: muon neutrino disappearance (MINOS+, IceCube)

    MINOS(+), PRL 122 (2018)  IceCube, PRL 117 (2016)

  - New analyses of these types are expected in the near future with existing experiments.

Giunti and Lasserre, hep-ph[1901.08330]

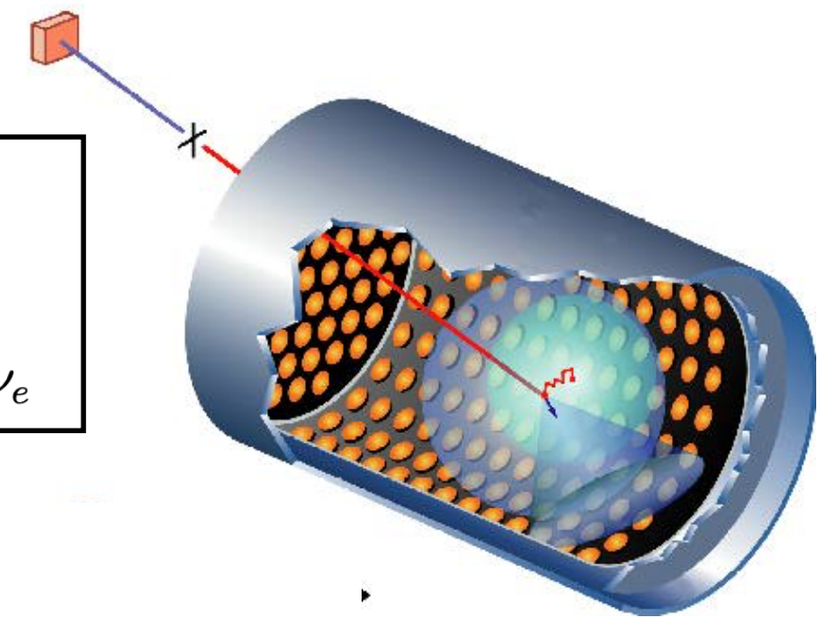


# LSND Anomaly

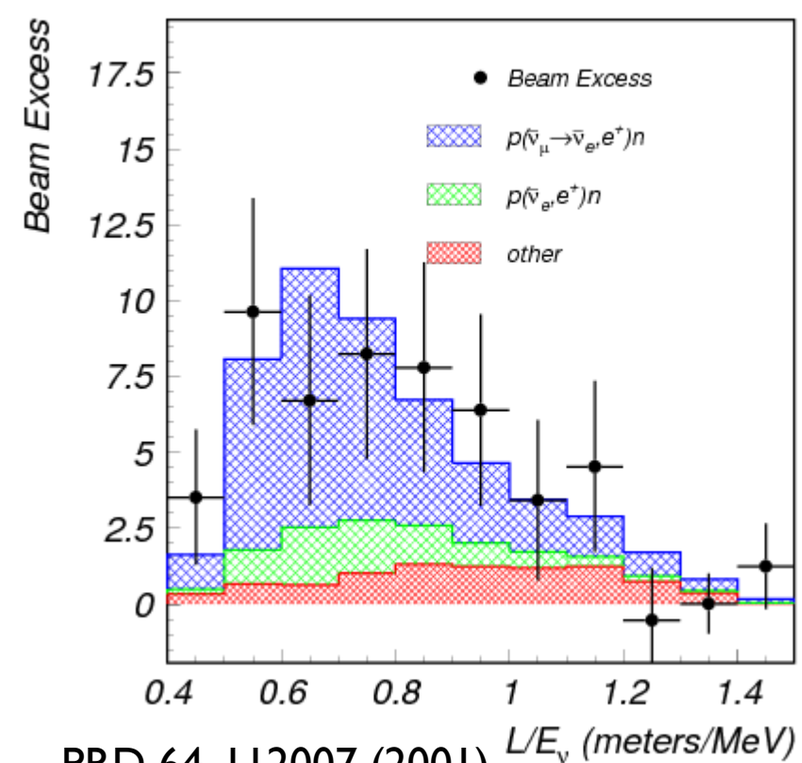
- LSND: the oldest of the 'anomalies' from beam decay-at-rest (DAR) neutrinos

$$p + \text{target} \rightarrow \pi^+/\text{K}^+ + X$$
$$\hookrightarrow \pi^+/\text{K}^+(\text{stop}) \xrightarrow{\tau=26/12\text{ns}} \mu^+ + \nu_\mu(E_\nu = 30/236\ \text{MeV})$$
$$\hookrightarrow \mu^+(\text{stop}) \xrightarrow{\tau=2.2\mu\text{s}} e^+ + \overline{\nu}_\mu + \nu_e$$



  - Very distinctive IBDs only occur if $\overline{\nu}_\mu$ oscillate to $\overline{\nu}_e$
  - Non-osc $\overline{\nu}_e$ greatly suppressed as pi- are bound and captured by + nuclei

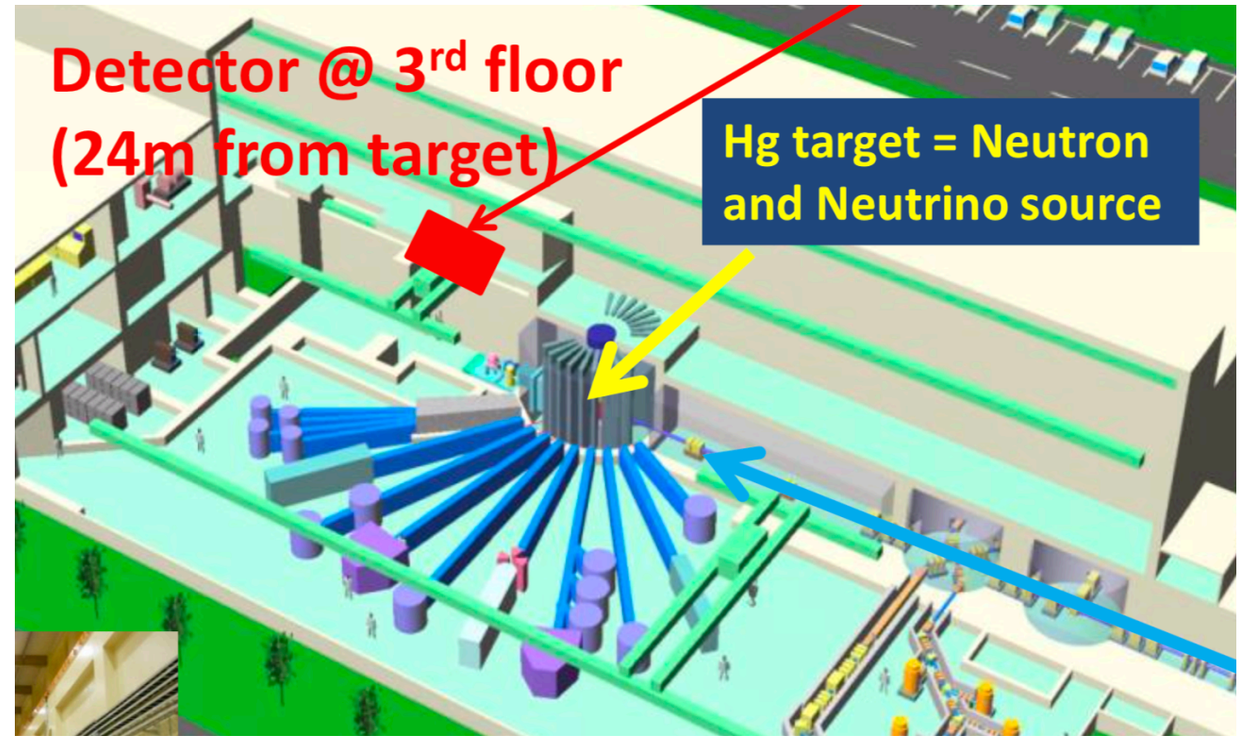
- Can we directly double-check DAR approach with an improved setup?
  - More powerful beam?
  - Lower backgrounds?

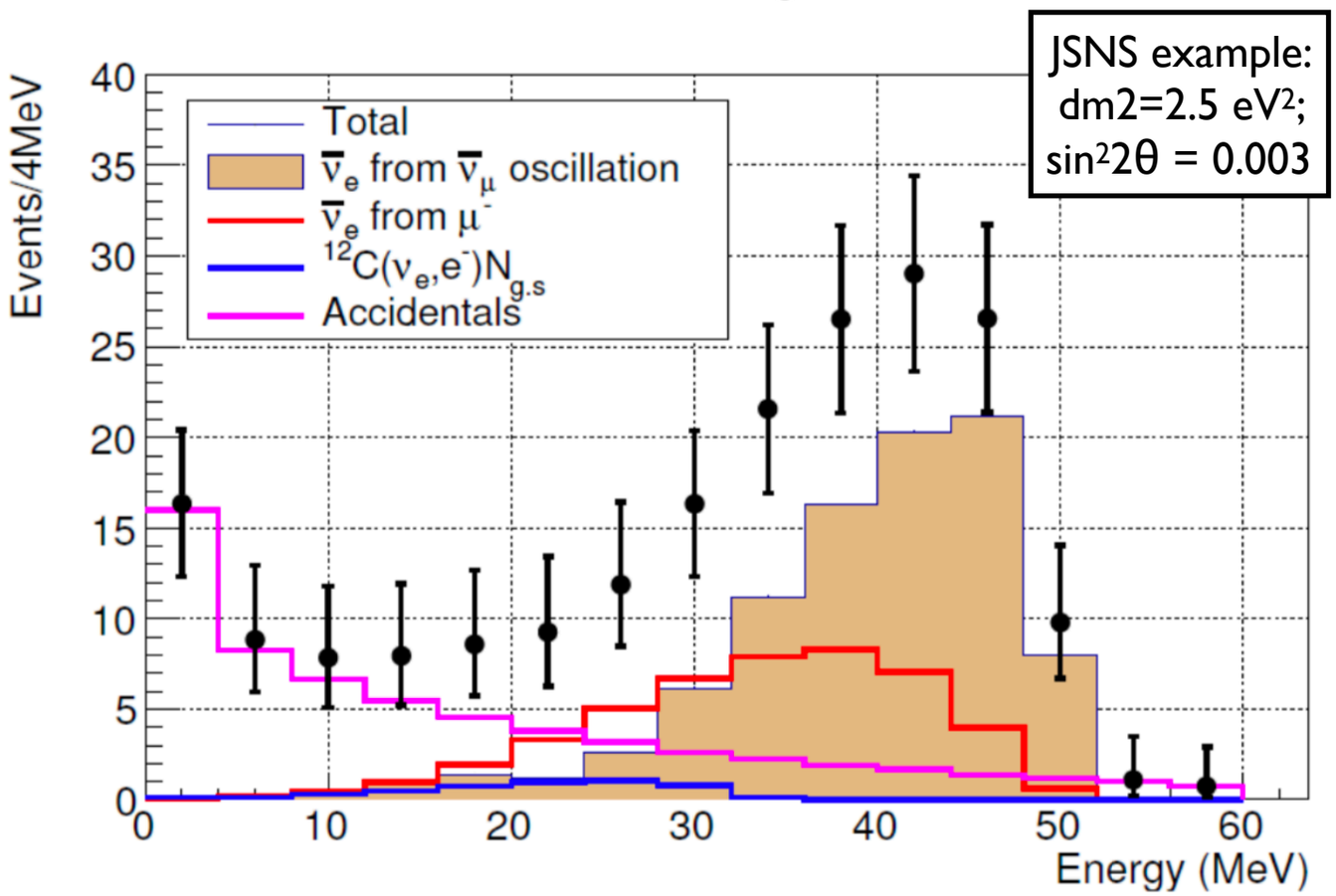


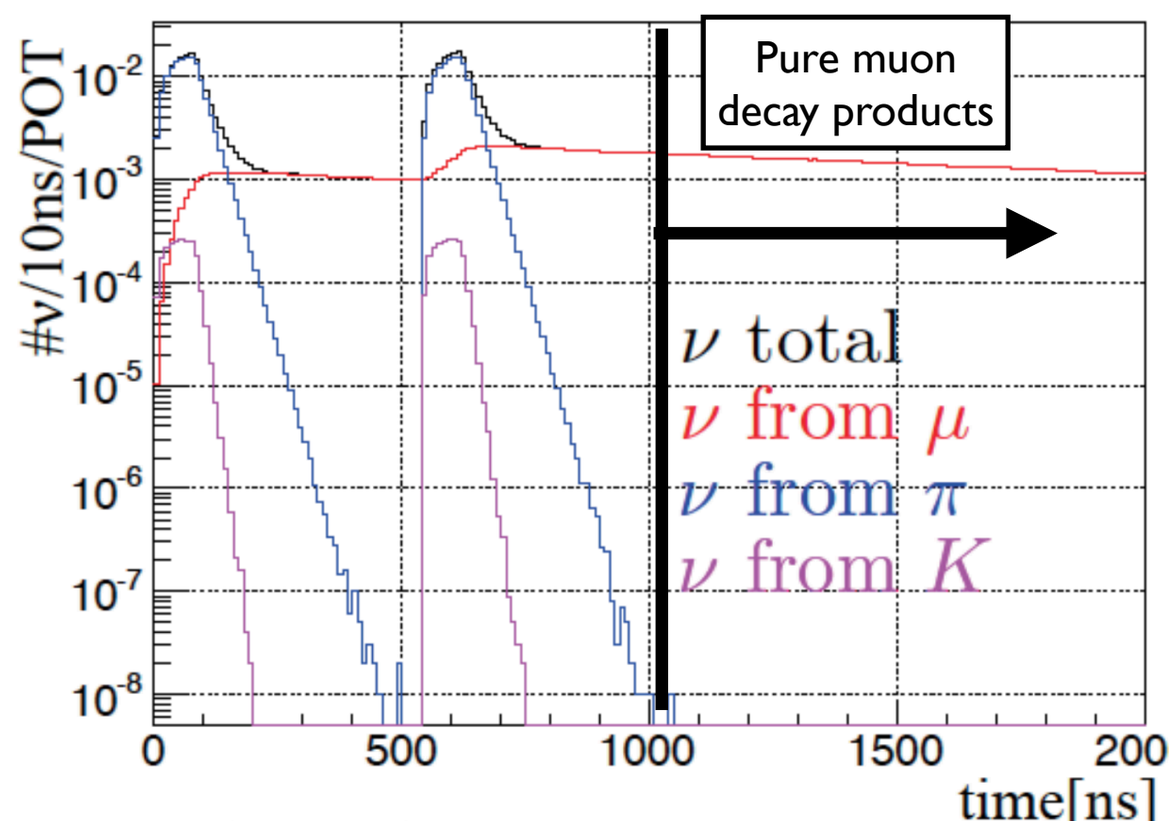

PRD 64, 112007 (2001)

# JSNS²

- JSNS² at JPARC MLF
- Higher beam power: 1MW
  - If caused by oscillations, anomaly signal substantially higher than LSND
- Shorter beam width: 100ns
  - Better ability to reduce on-beam and off-beam backgrounds




Plots from J. Spitz, U Michigan

# JSNS$^2$ Progress

- Vessels, Daya Bay scintillator, and PMTs for a 17t GdLS IBD detector are now all in Japan
- Aiming for data-taking prior to November 2019 beam time

Tested baseline readout electronics

Acrylic vessel test installation


PMTs in transit to Japan

GdLS in ISO tank storage


Photos from J. Spitz, U Michigan

# Summary

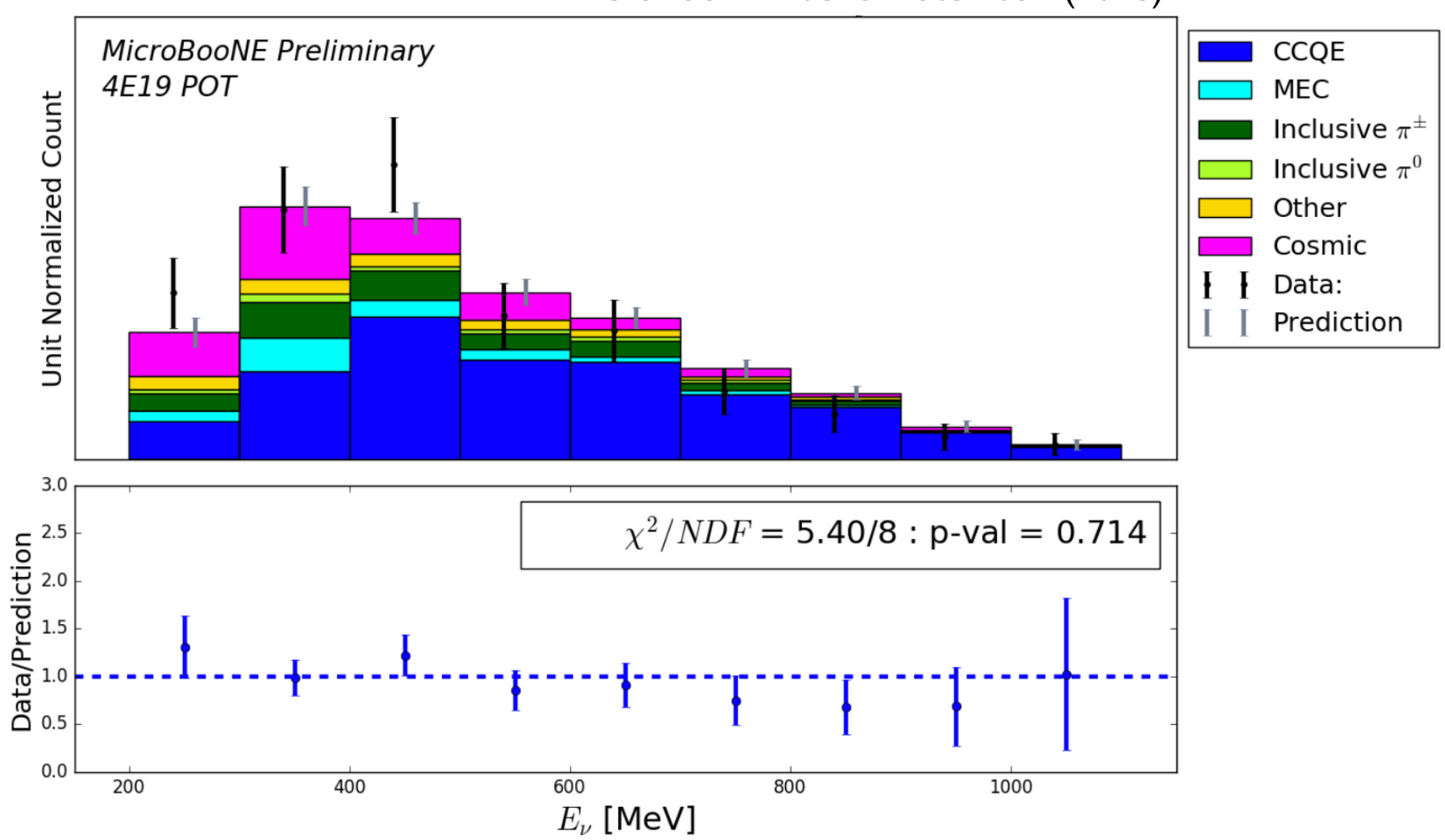
- We need short-baseline neutrino efforts to:
  - Probe the parameter space of new physics models (sterile neutrinos)
  - Directly address anomalous results that blur our picture of SM neutrinos
- Recent results have had a substantial impact:
  - Null-osc results from HEU and LEU spectral ratio measurements have eaten away at reactor-based sterile neutrino hints, while improved flux/spectrum results have clearly demonstrated inadequacy of flux models
  - MicroBooNE has made crucial steps in addressing MiniBooNE's excess: automated $\nu_e$ selection and unbiased EM shower reconstruction
- In the next year, we will have new data for addressing all three SBL neutrino anomalies I've mentioned today
  - New data/analysis from reactors and from MicroBooNE
  - New experiments online very soon! (JSNS$^2$, ICARUS)

# Backup Slides

# MicroBooNE: $\nu_e$ Selection

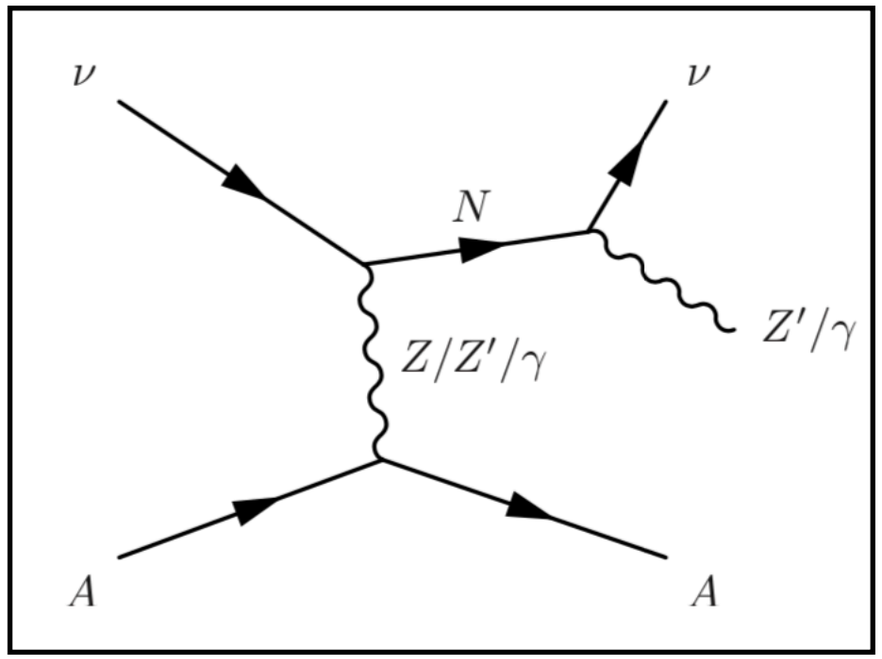
- Working in phases towards uBooNE low-energy excess result
- Third: can we also select $\nu_\mu$ using similar algorithms?
  - $\nu_\mu$ constrains beam $\nu_e$ if selection systematics for $\nu_\mu$ and $\nu_e$ are correlated
- Demonstration with BNB beam events
  - Bulk of $\nu_\mu$ selection identical to that used for $\nu_e$
  - Exclusive 1μ + 1p 1e + 1p search strategy
  - Solid data-MC agreement

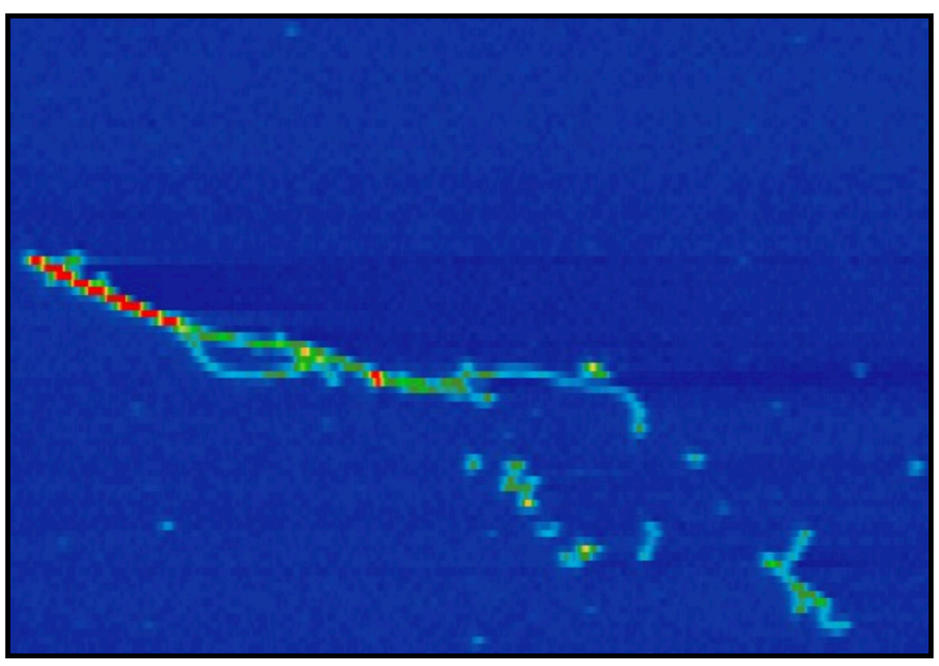
MicroBooNE Public Note 1051 (2018)



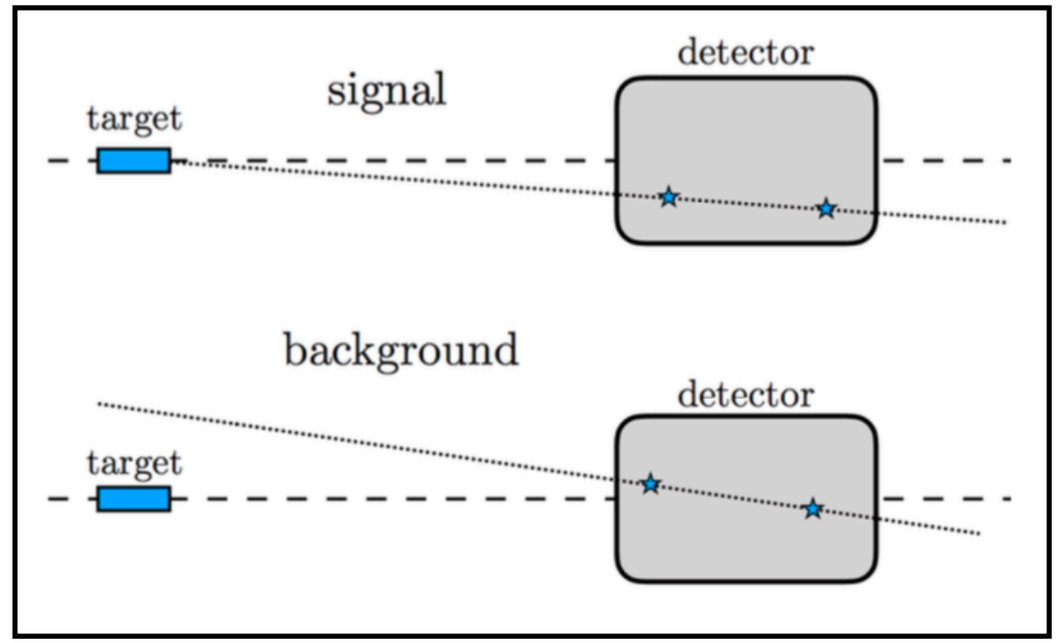
# SBN: Other BSM Goals Too!

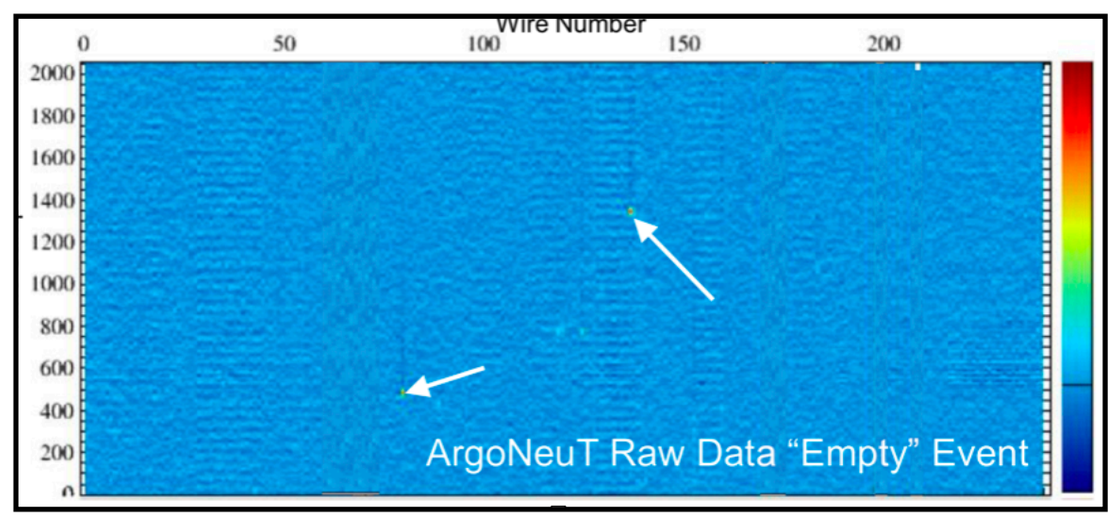
## Dark Neutrino Portal



## Millicharged Particles



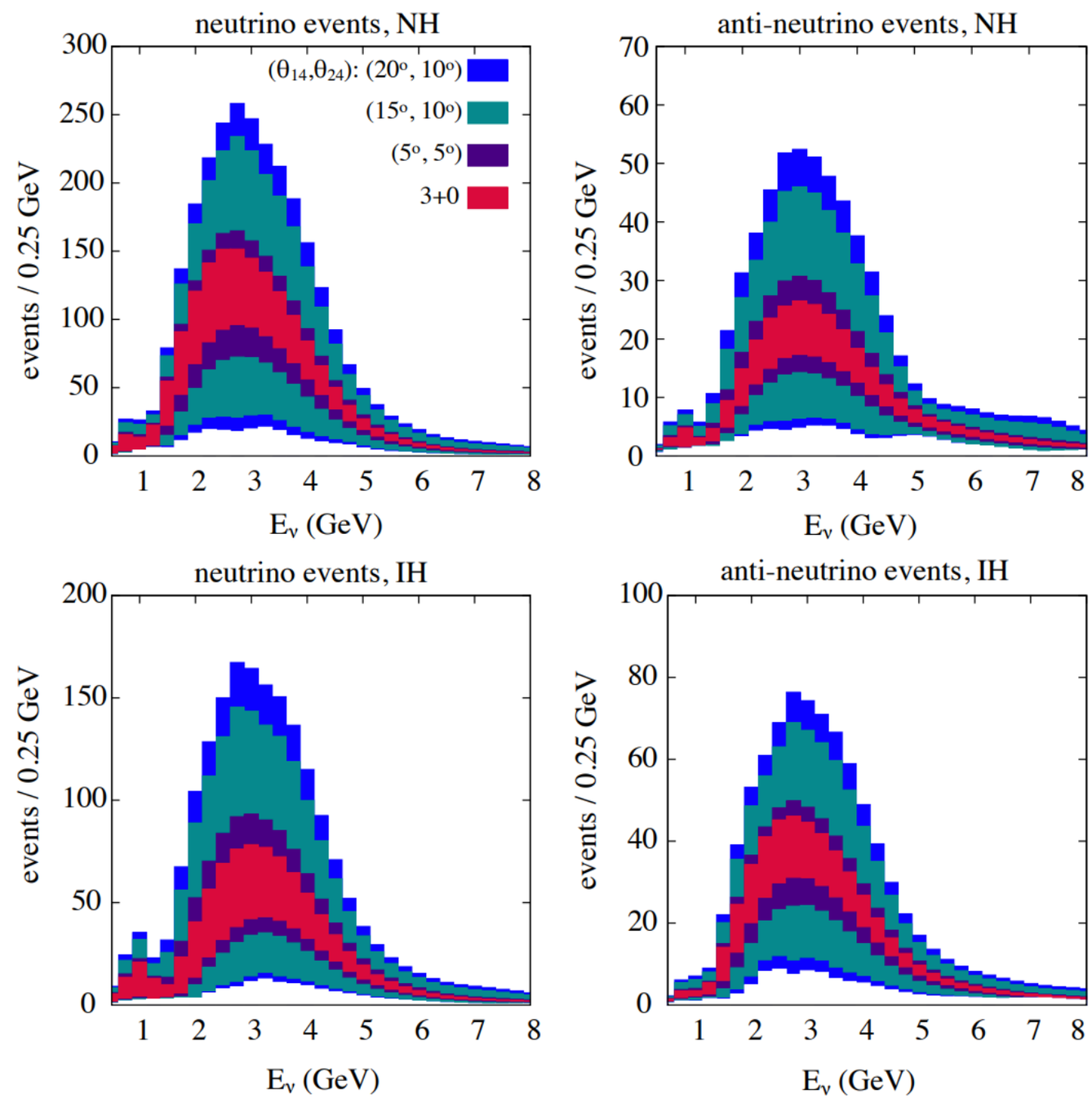

Bertuzzo et al, PRL 121 241801 (2018)
Machado, Palamara, Schmitz, hep-ex[1903.04608]

Harnik, Liu, Palamara JHEP 07:170 (2019)

And more!

# Note: LBL CP-Violation

- If bounds on sterile mixing angles are too loose, LBL bar($nu_e$), $nu_e$ appearance signals can vary a TON.
- Once you get $\theta_{14}$ and $\theta_{24}$ below the 5 degree level ($\sin^2 2\theta_{14} \sim 0.035$), the 3+1 effects start becoming more close to negligible.
  - https://arxiv.org/pdf/1607.02152.pdf
  - https://arxiv.org/pdf/1508.06275.pdf

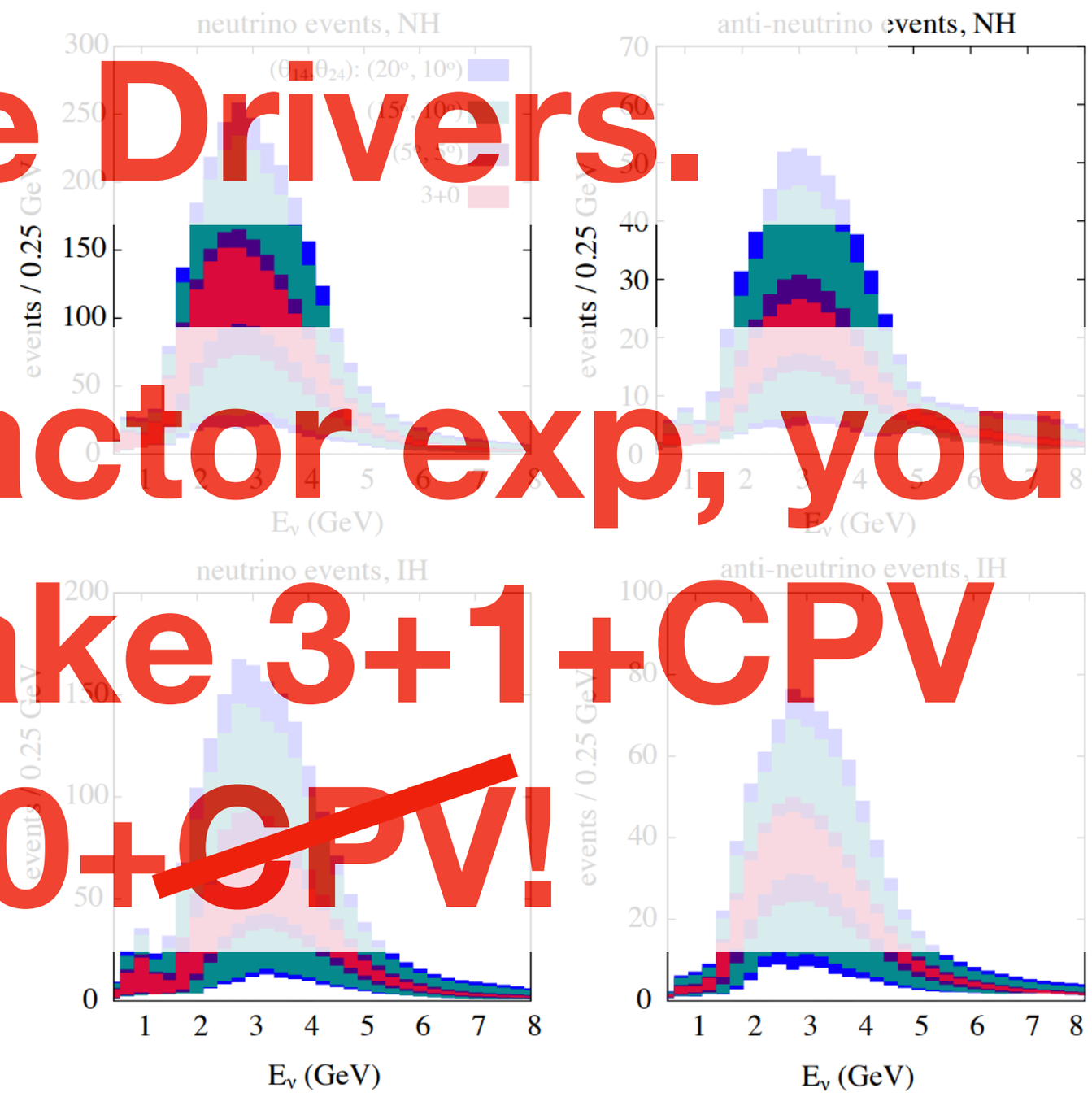


# Note: LBL CP-Violation

**NOTE: This is highly relevant to the P5 Science Drivers.**

- Remember our J Phys G: there was a big reason to shoot at the sensitivity range we were going for – enabling interpretation of LBL CP-violation!
  - If bounds on sterile mixing angles are too loose, LBL bar($\nu_e$), $\nu_e$ appearance signals can vary a TON.
  - Once you get $\theta_{14}$ and $\theta_{24}$ below the 5 degree level ($\sin^2 2\theta_{14} \sim 0.035$), the 3+1 effects start becoming more close to negligible.
    - https://arxiv.org/pdf/1607.02152.pdf
    - https://arxiv.org/pdf/1508.06275.pdf
  - So no moving goalposts here, this is what we've been aiming at since late 2015 when the first of these articles came out!

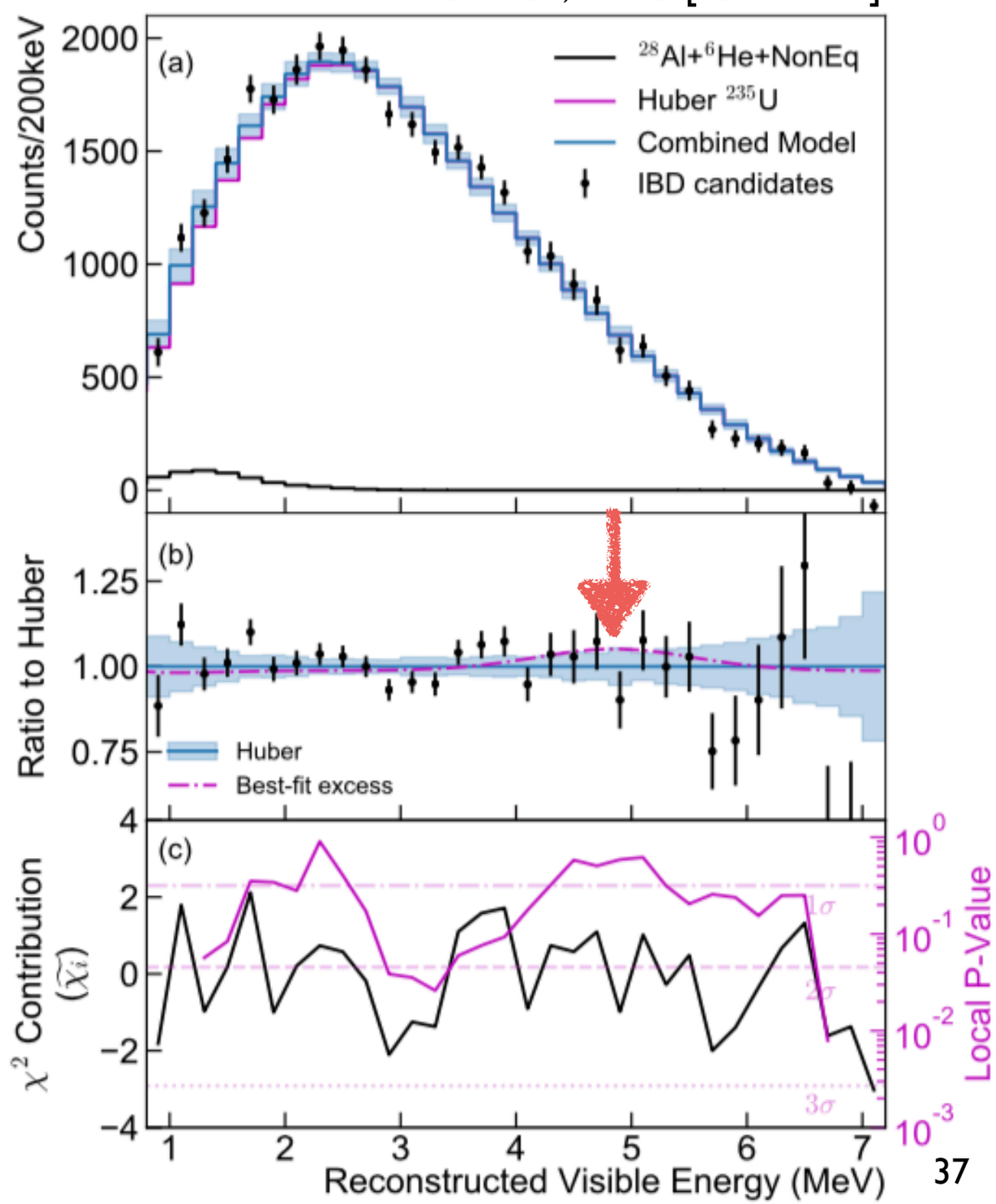
**W/O SBL reactor exp, you might mistake 3+1+CPV for 3+0+~~CPV~~!**



# Isotopic Origins: PROSPECT

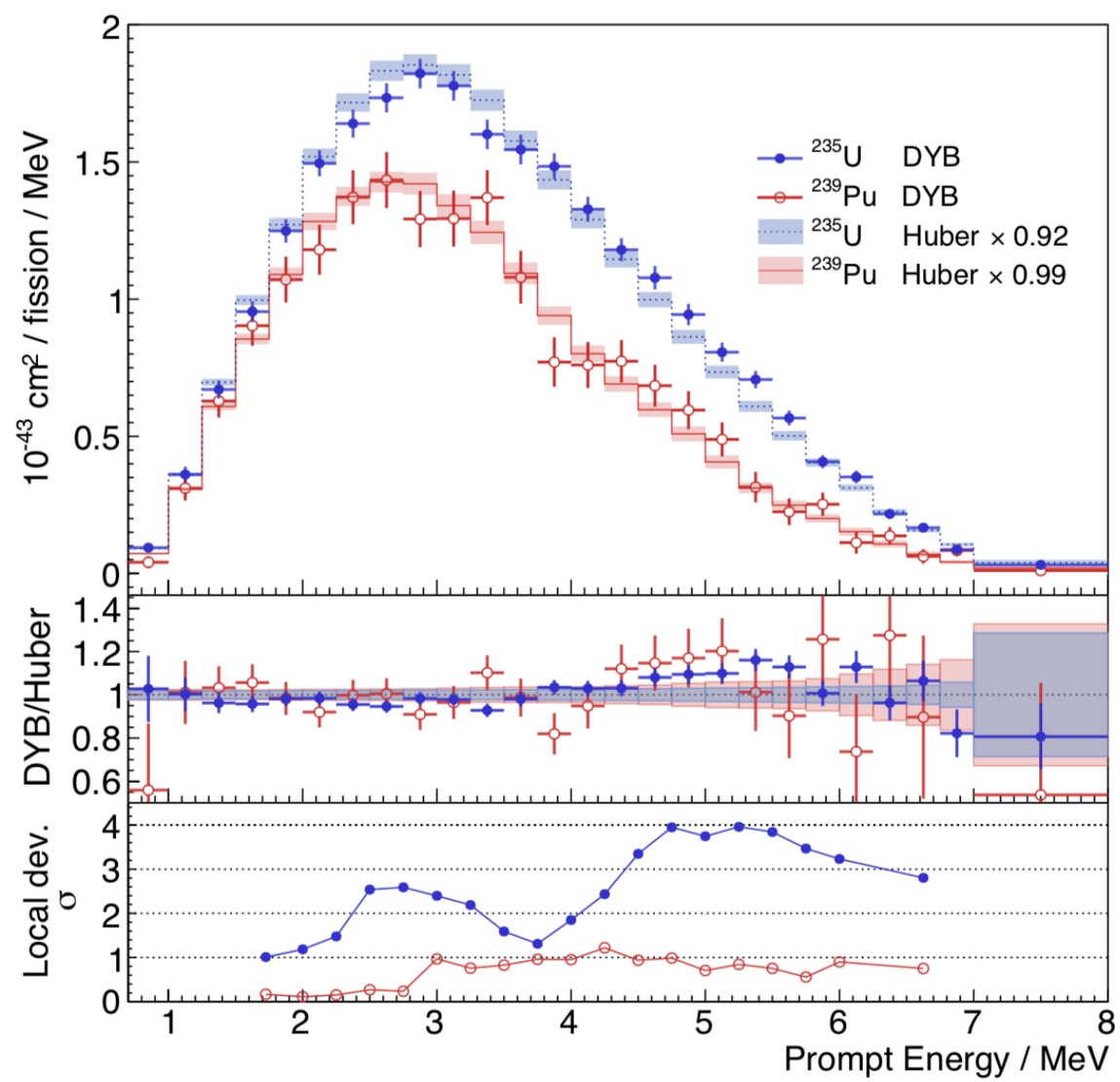
- Measure spectrum when burning <u>only</u> $^{235}U$
- PROSPECT has done this!
- How does PROSPECT compare to 'bump' in $\theta_{13}$ experiments?
  - PROSPECT relative bump size WRT to Daya Bay: 69% ± 53%
  - ~consistent with 'no bump' (0%) and 'DYB-sized bump' (100%)
    - Need more stats to differentiate
  - 'Big bump' (178%) if $^{235}U$ is the sole bump contributor
    - Disfavored at 2.1σ

PROSPECT, nucl-ex[1812.10877]



# Daya Bay Isotopic Spectra

- New Daya Bay U235 and Pu239 measurement!
  - Forget 'where the bump comes from' — let's just measure the full spectra
- However, staying with the bump paradigm for a moment:
  - 'Equal contribution' 0.4sigma away from best-fit
  - 'No U235 bump' is 4.0sigma away from best-fit
  - 'No Pu239 bump' (i.e. 'mostly 235') is 1.2sigma away from best-fit



# Experimental Recap

- Experimental studies trying to understand the nature of the spectrum data-prediction disagreement have formulated their research question as: 'Which isotopes produce the bump?'
- Studies weighing in so far (note - I'm oversimplifying, obs…)

| Study | ~Only 235 (~No 239 bump) | Equal | No 235 bump (~Pu only) |
|---|---|---|---|
| Huber (w/ NEOS+DYB) | **OK** | **OK** | **NO** |
| DYB | **OK** | **OK** | **NO** |
| RENO | **OK** | **NO** | **NO** |
| PROSPECT | **NO** | **~OK** | **~OK** |

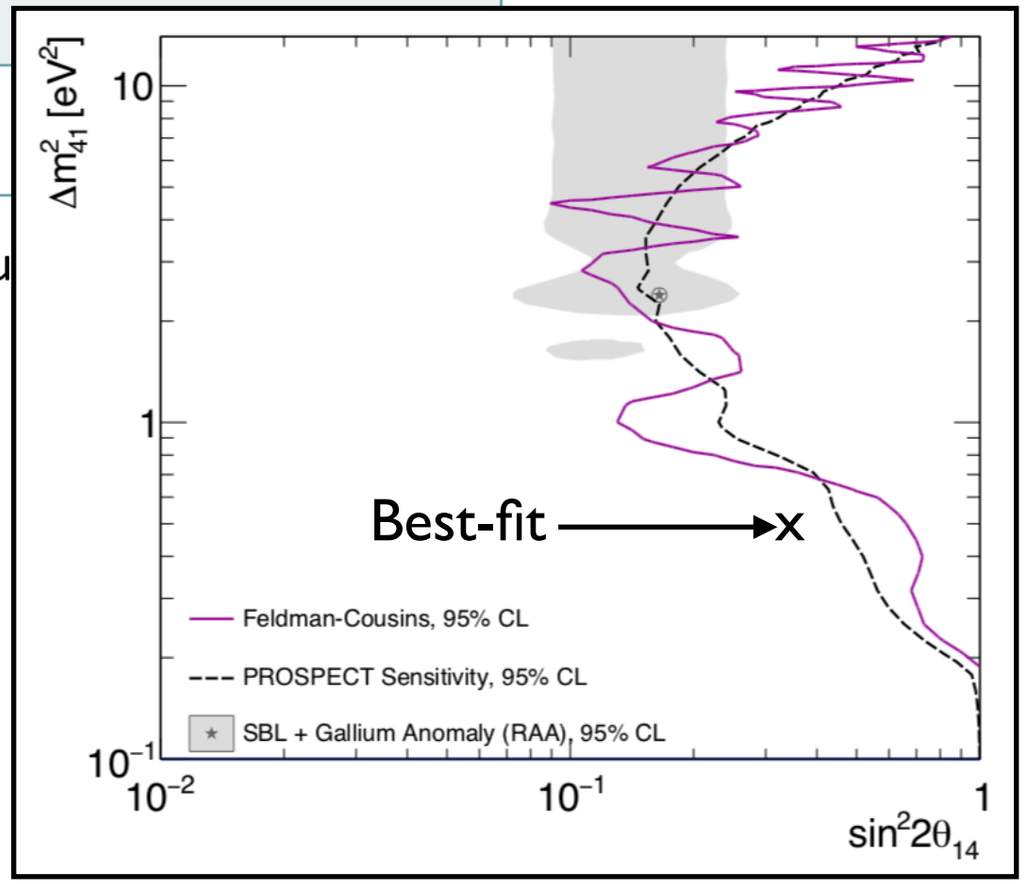
- All datasets are ~compatible with a bump of some kind existing in HM
- No single hypothesis is compatible with all claims; 'Equal' would be a good hypothesis, if not for RENO's (questionable?) result

# Feldman-Cousins Approach

- Standard (incorrect) method does not handle boundary features such as bounded nature of $sin^2 2\theta$ (0,1) or cases when oscillation frequency approaches energy bin size. Feldman-Cousins method solves those problems
- Comparing p-values for Feldman-Cousins and standard (incorrect) methods:

| P-values | 3ν-oscillation hypothesis | RAA sterile ν oscillation hypothesis |
|---|---|---|
| Feldman-Cousins | 0.58 | 0.013 |
| Standard (incorrect) confidence intervals assignment | 0.14 | 0.005 |

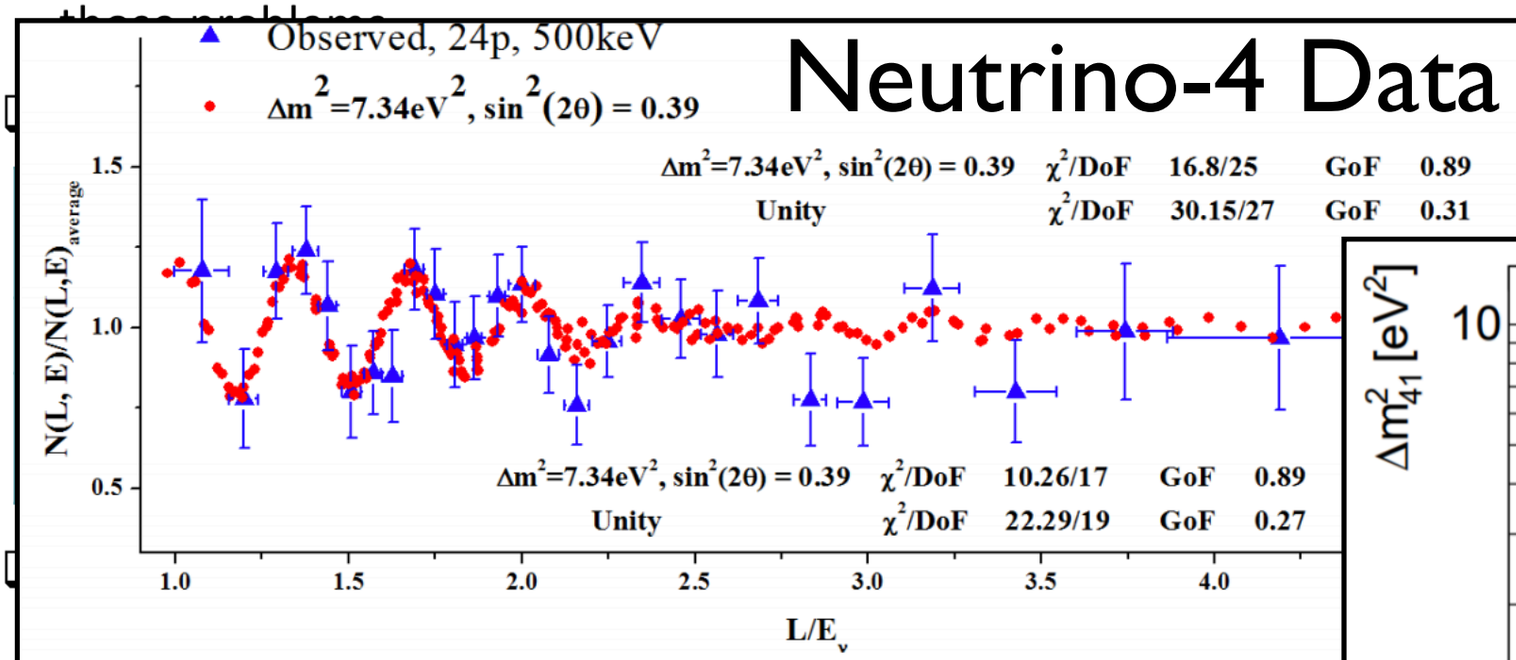
- If standard (incorrect) confidence levels used instead of Feldman-Cou
  - We say 3ν is less compatible with data than it actually is
- Illustrates an importance of using Feldman-Cousins



# Neutrino-4

## Feldman-Cousins Approach

- Standard (incorrect) method does not handle boundary features such as bounded nature of $sin^2 2\theta$ (0,1) or cases when oscillation frequency approaches energy bin size. Feldman-Cousins method solves




- Illustrates an importance of using Feldman-Cousins