Experimental Sterile Neutrino Overview

- or -

Status Update on Short-Baseline Neutrino Oscillation Experiments

October 11, 2019

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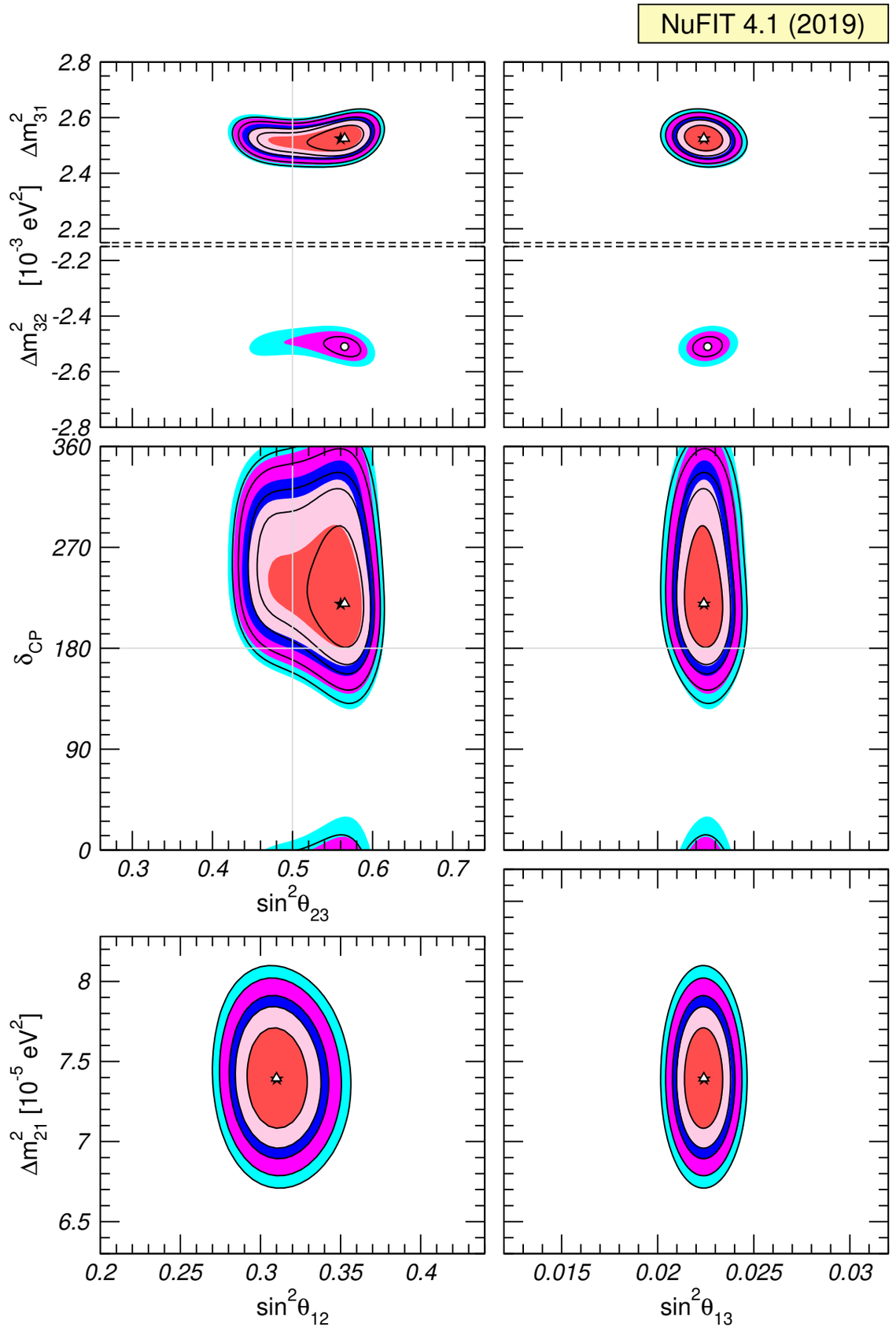
Illinois Institute of Technology

Neutrino Oscillation Picture

- Have a beautiful picture of Standard Model oscillations coming into focus
  - Provides a primary handle on knowledge of the minimum active neutrino mass in the universe



Neutrino Oscillation Picture

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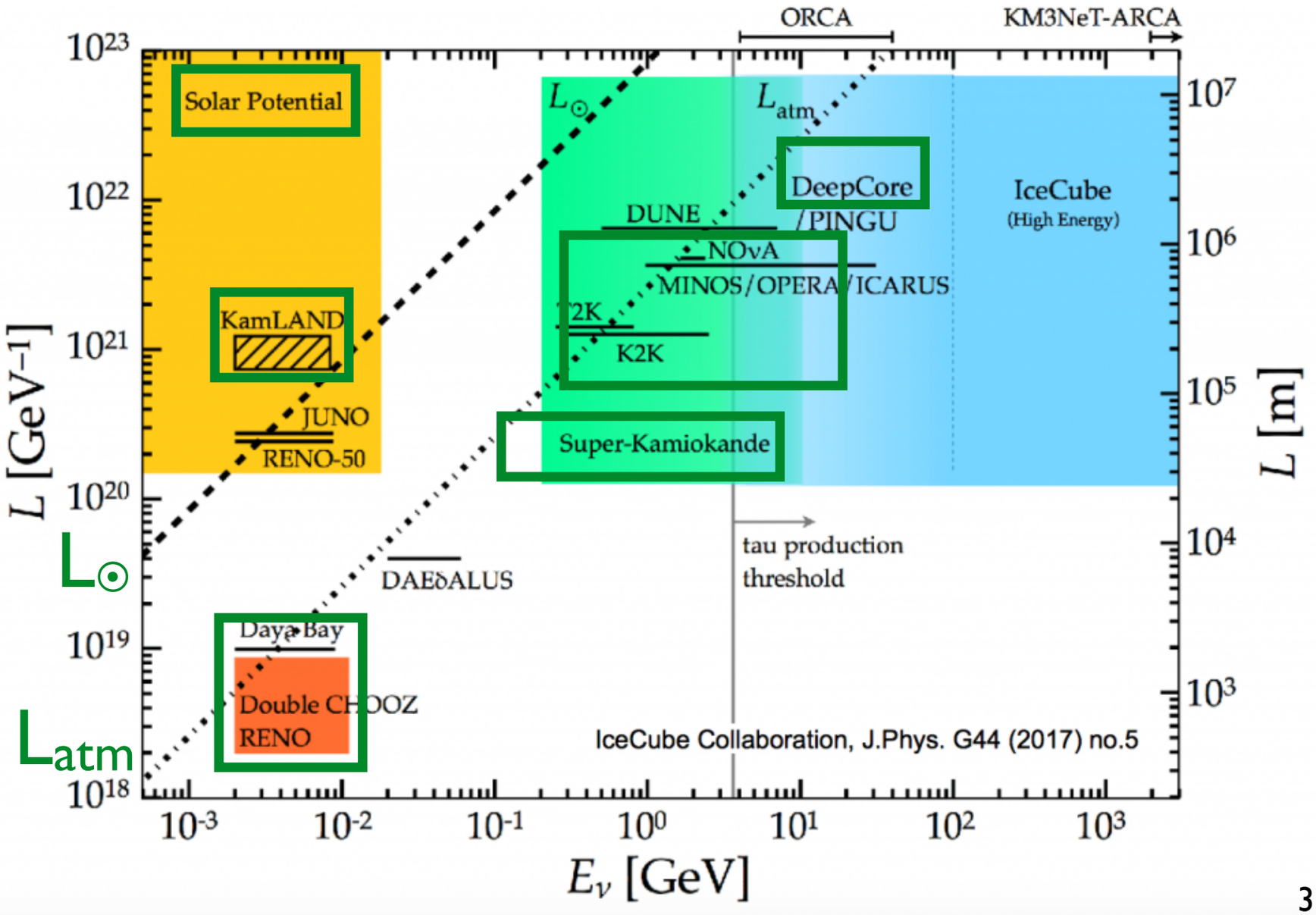
- What experiments got us here?
- Baselines: >km-scale



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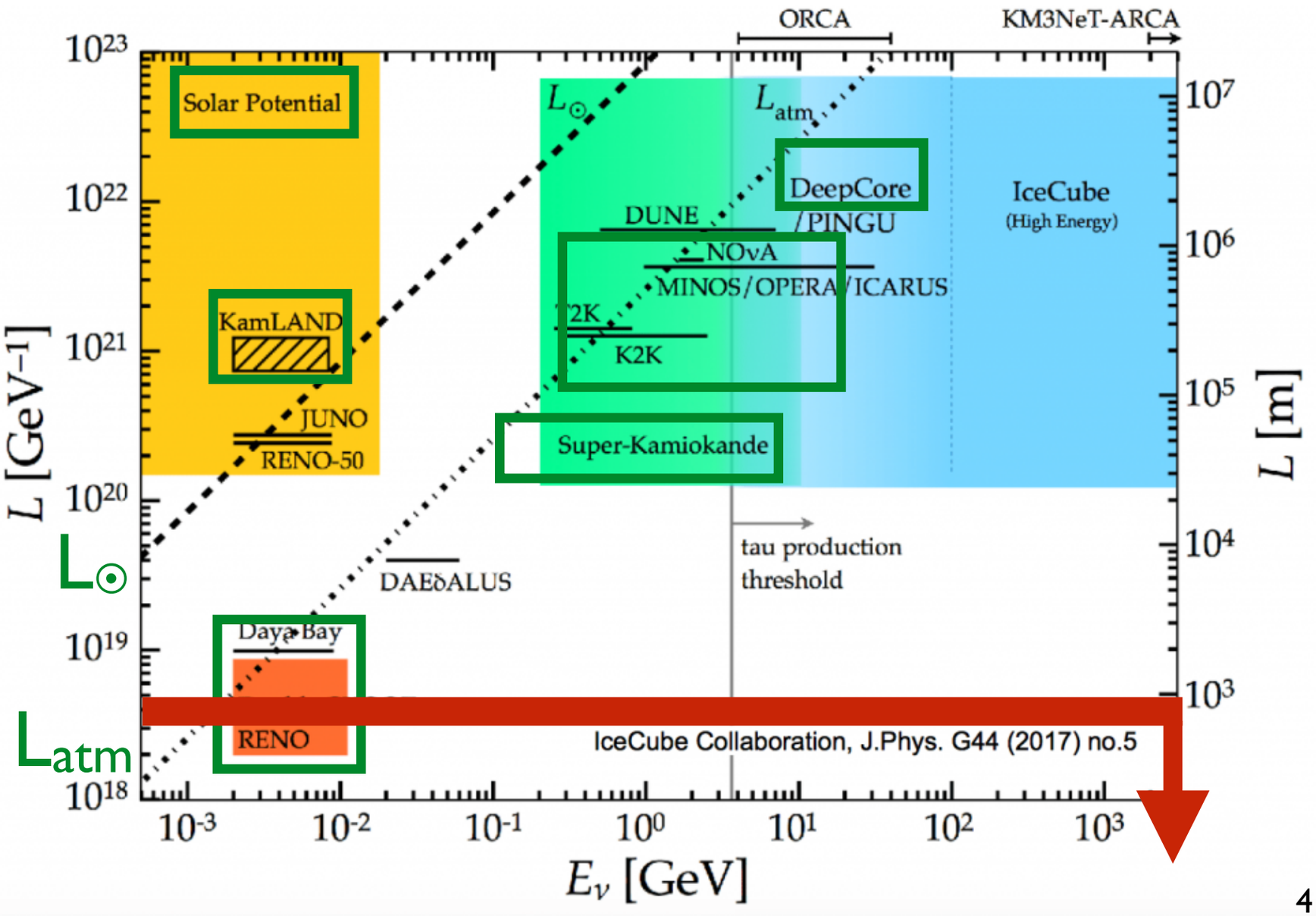
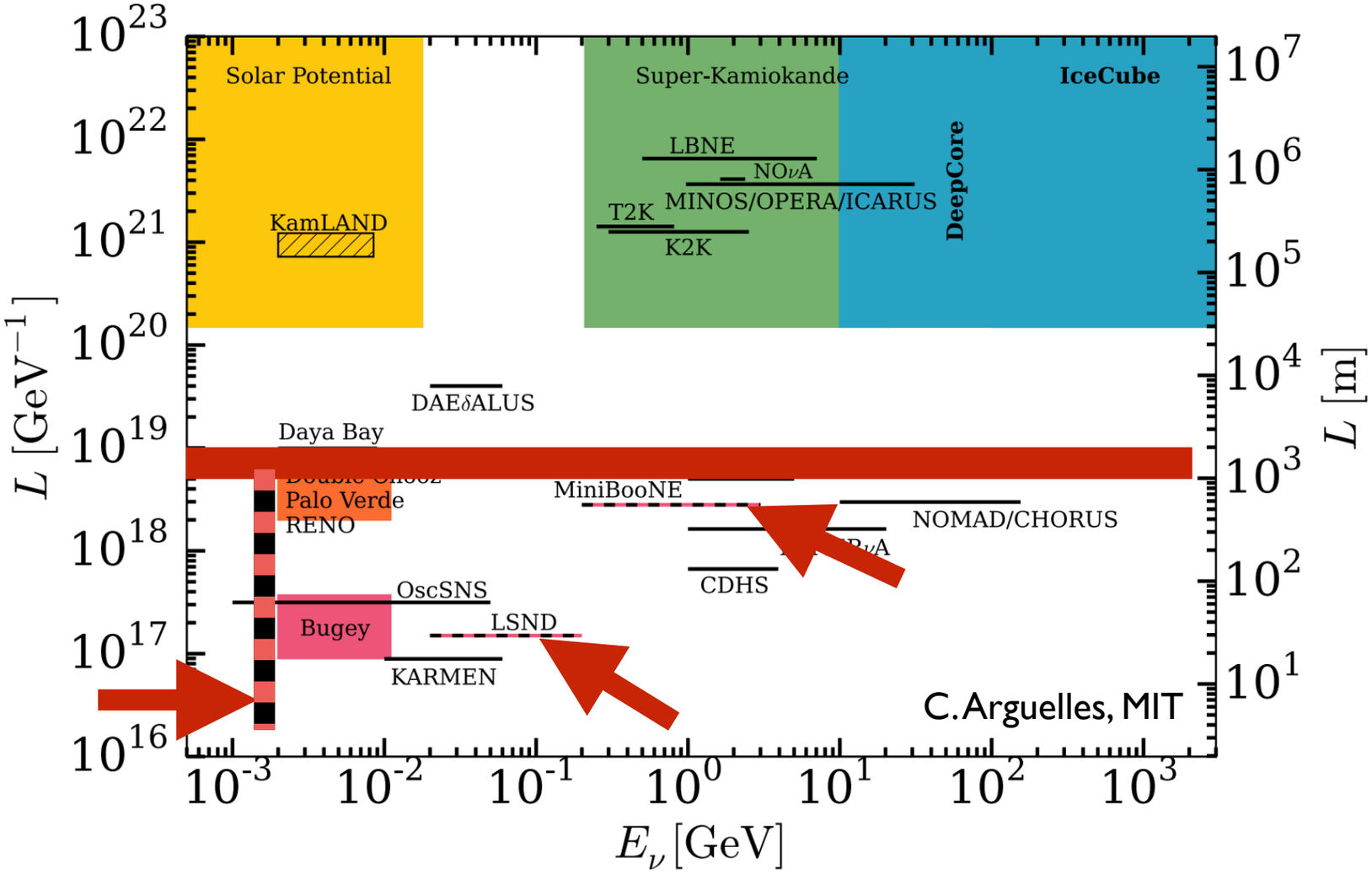
- WHY go here?



Existing Experimental 'Anomalies'

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



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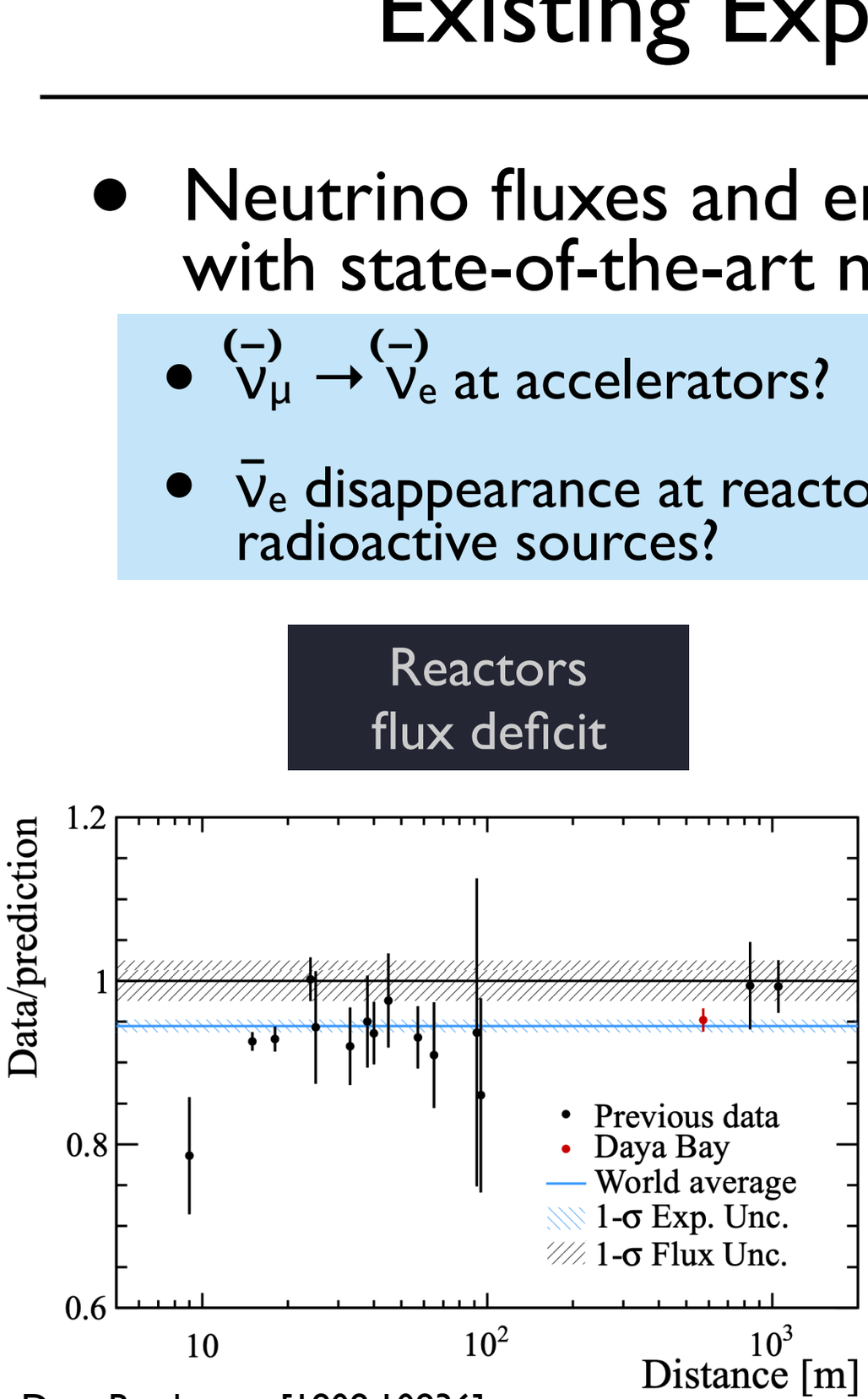
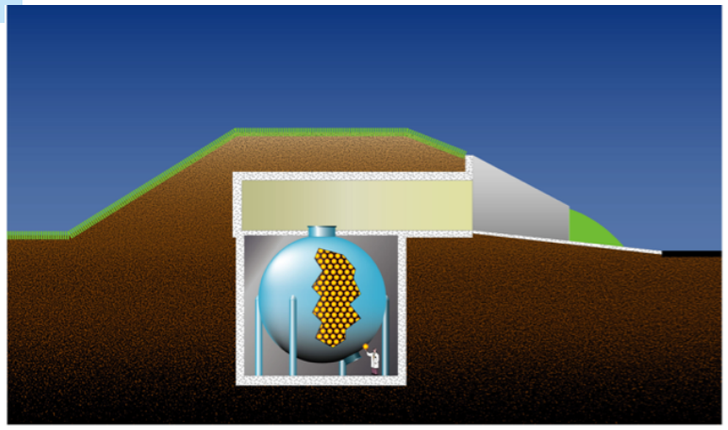
  - $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ at accelerators?
  - $\bar{\nu}_e$ disappearance at reactors, radioactive sources?

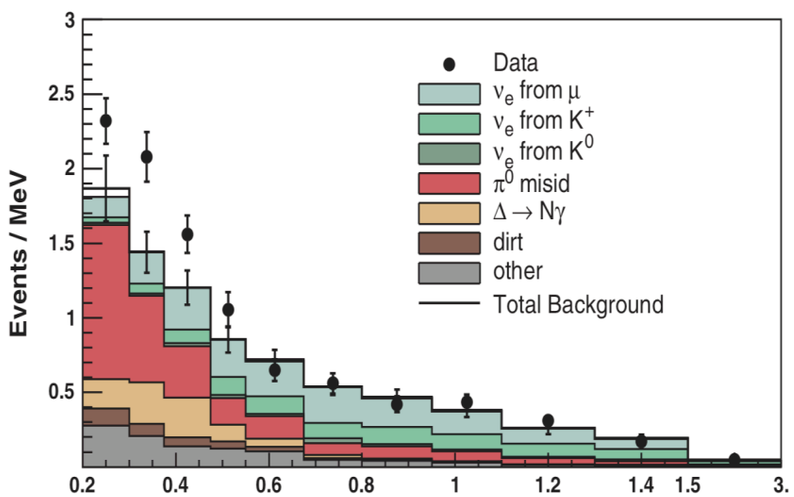
Reactors
flux deficit



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

MiniBooNE
short baseline accelerator

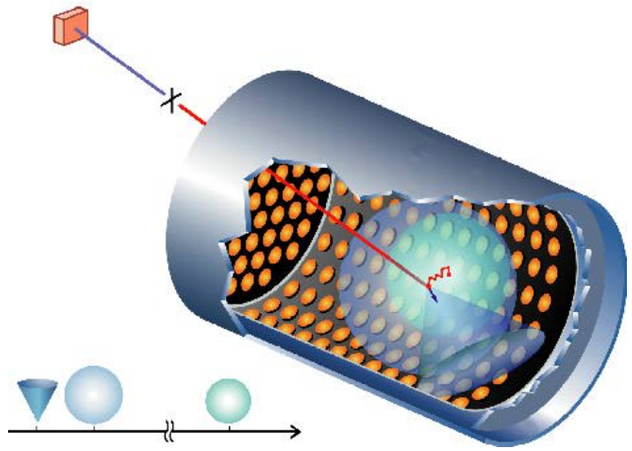


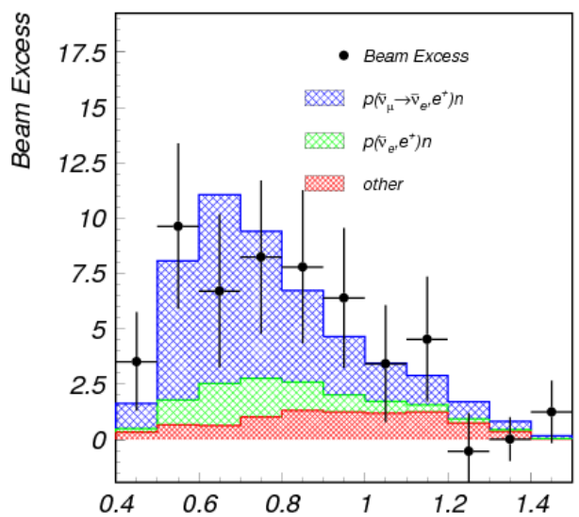


PRL 102, 101802

flux deficit

LSND
decay at rest



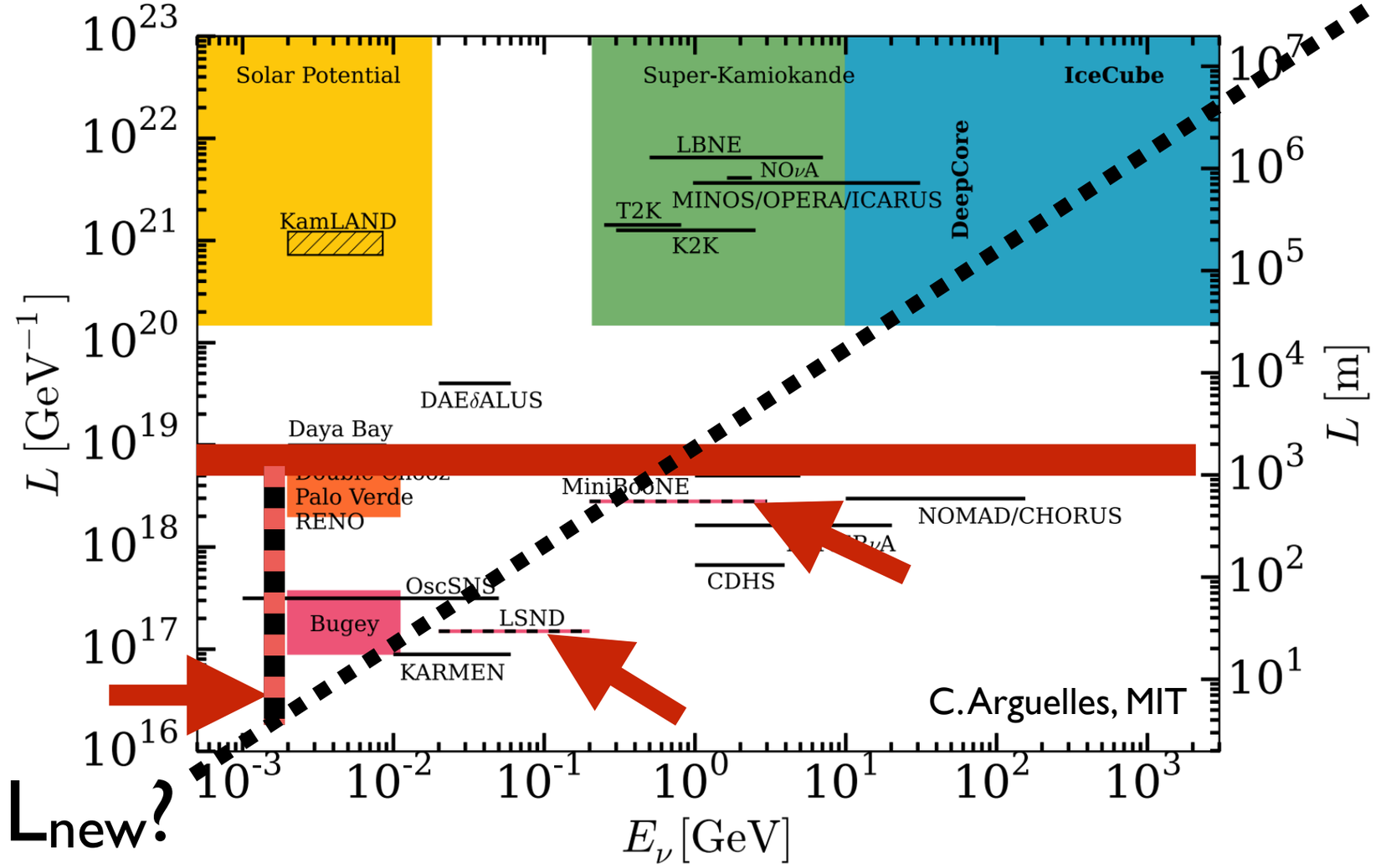


PRD 64, 112007

anti-ν_e appearance

Existing Experimental 'Anomalies'

- Neutrino fluxes and 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?
  - Goal: try to test parameter space of new physics models



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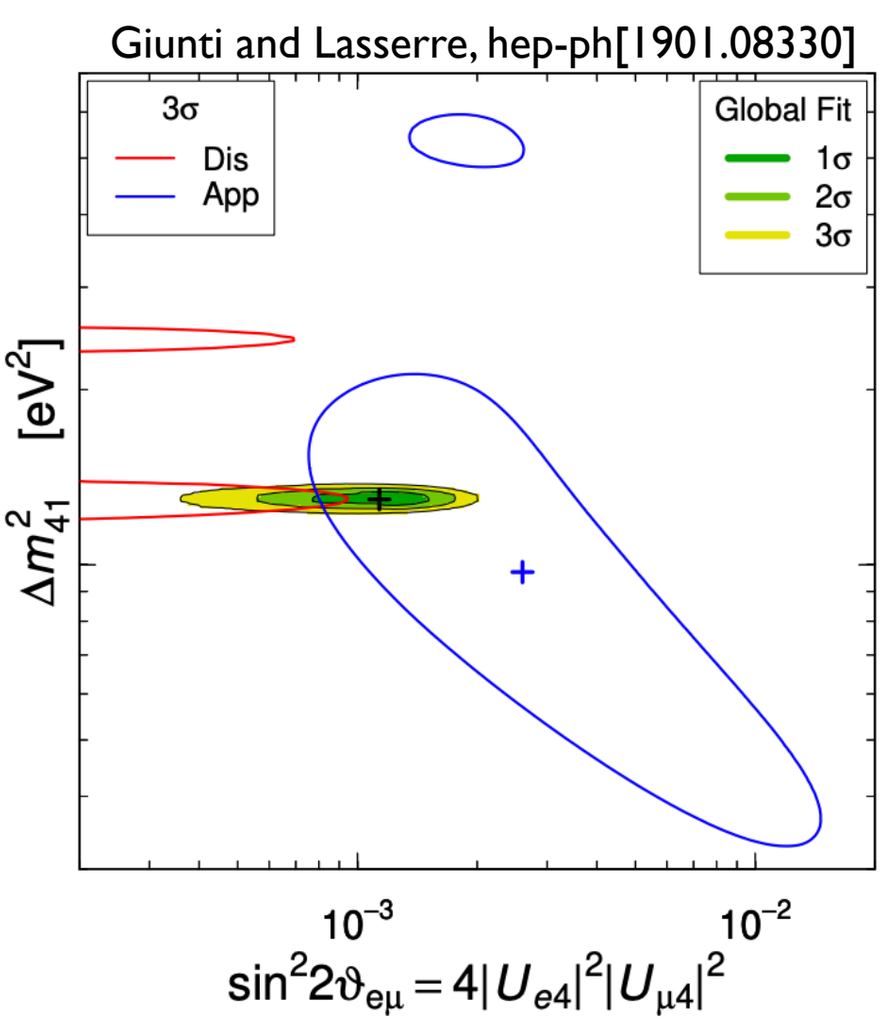
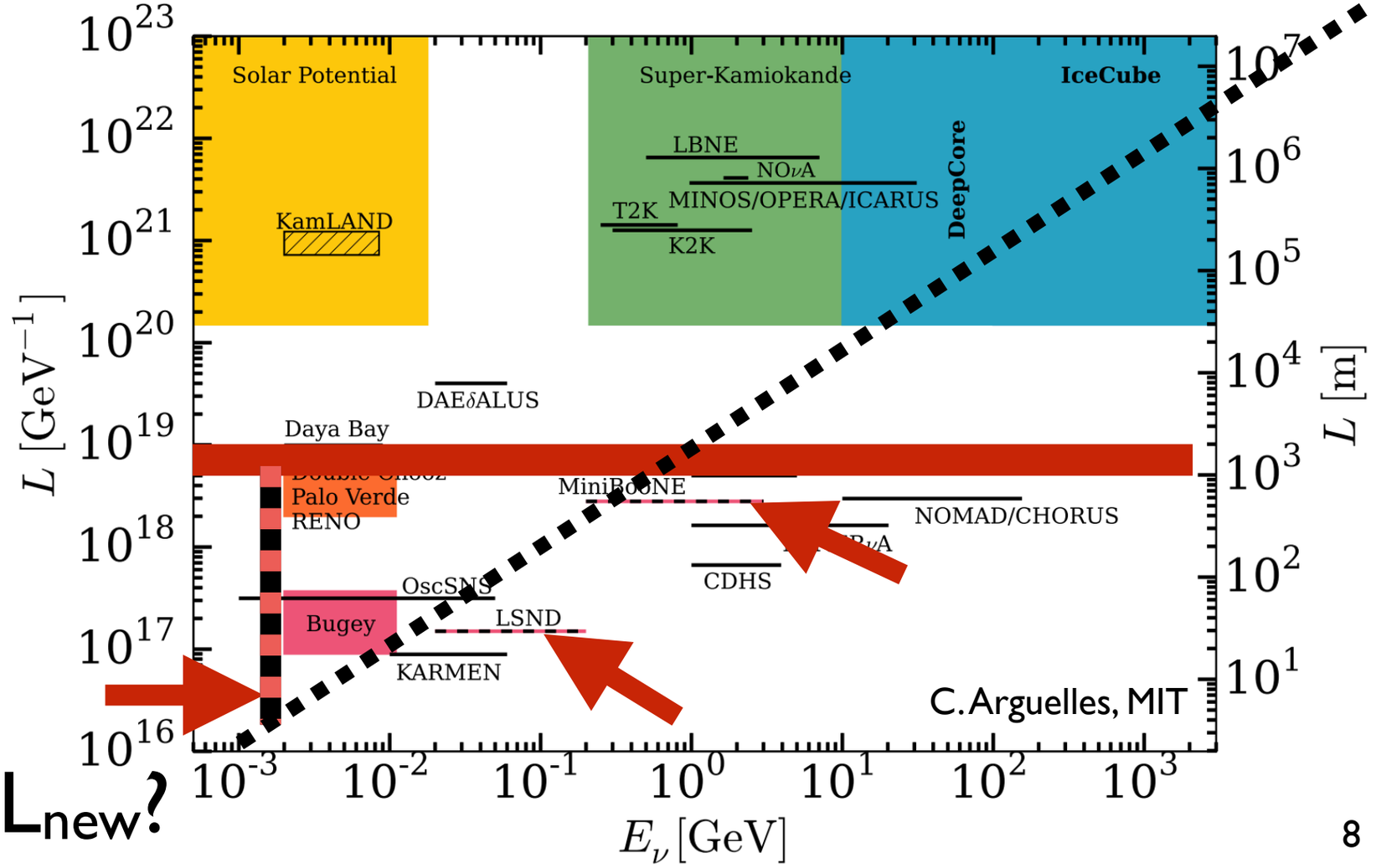
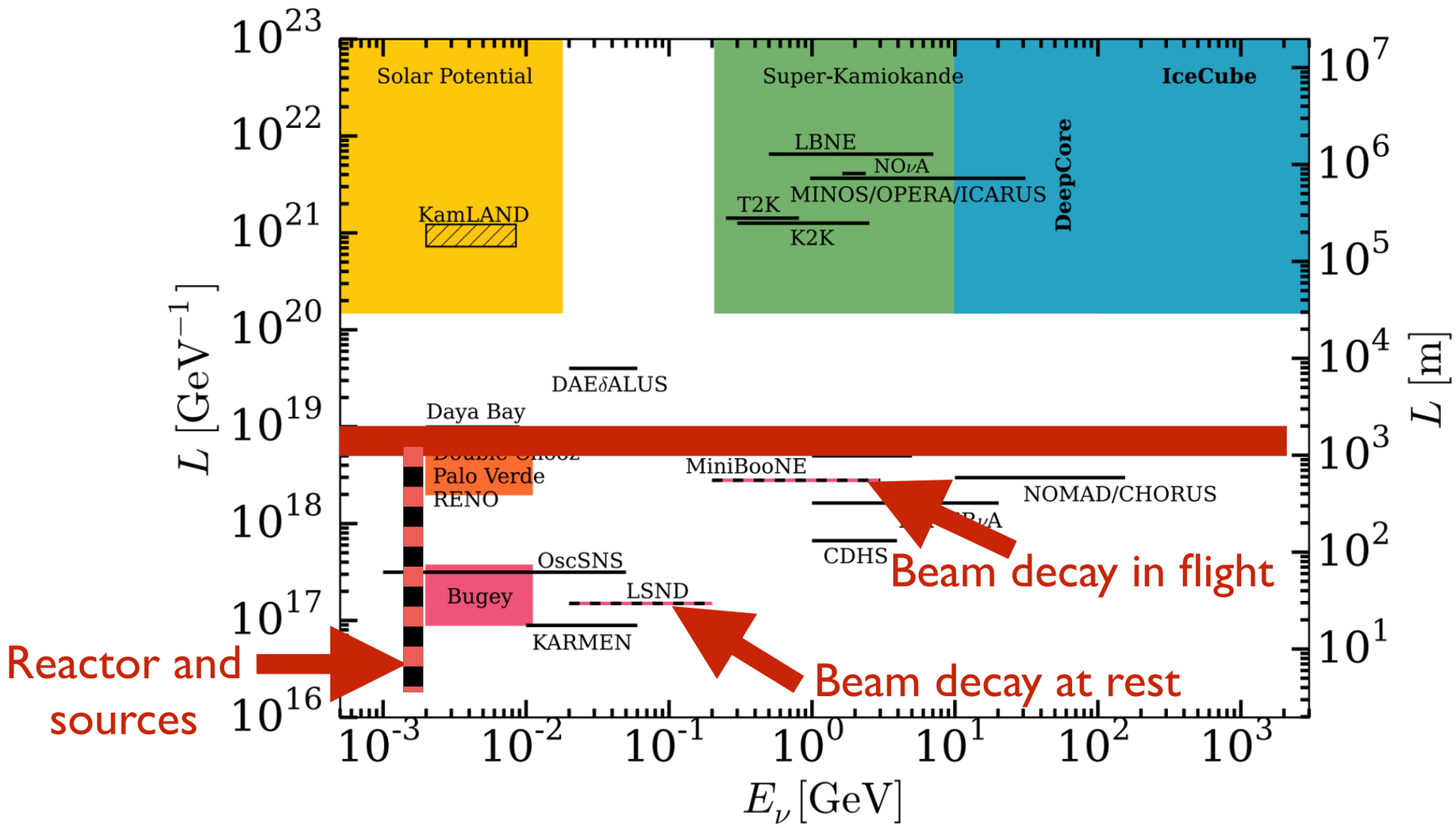




Existing Experimental 'Anomalies'

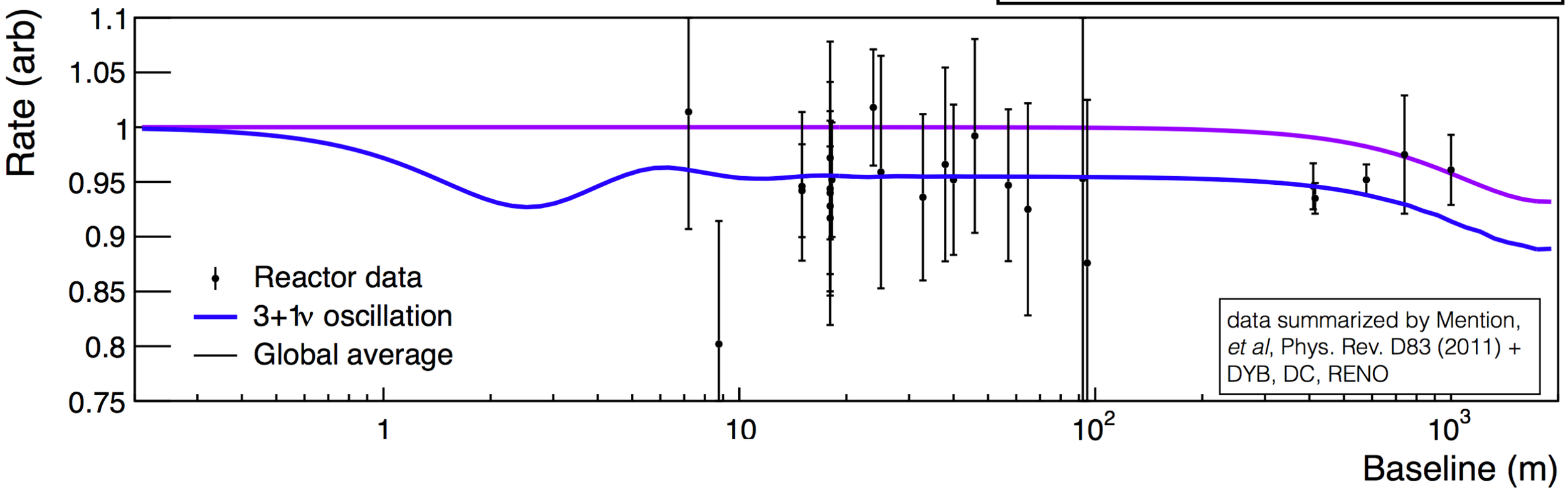
- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Four 'anomalies,' four different neutrino source types
  - No 'silver bullet' experiment for understanding anomalies' origin(s)
  - Goal: probe each anomaly individually to improve understanding



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!

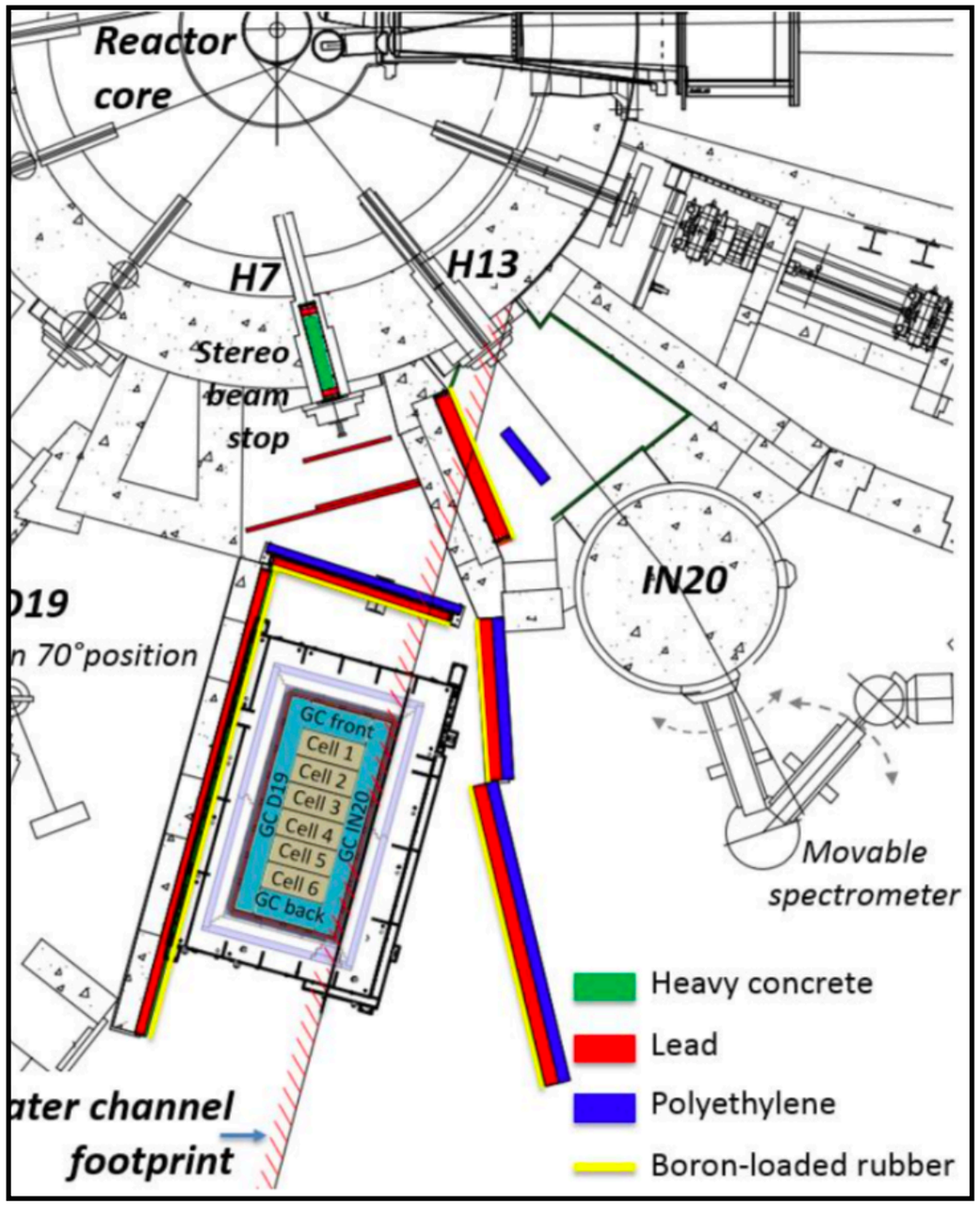
$$sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$



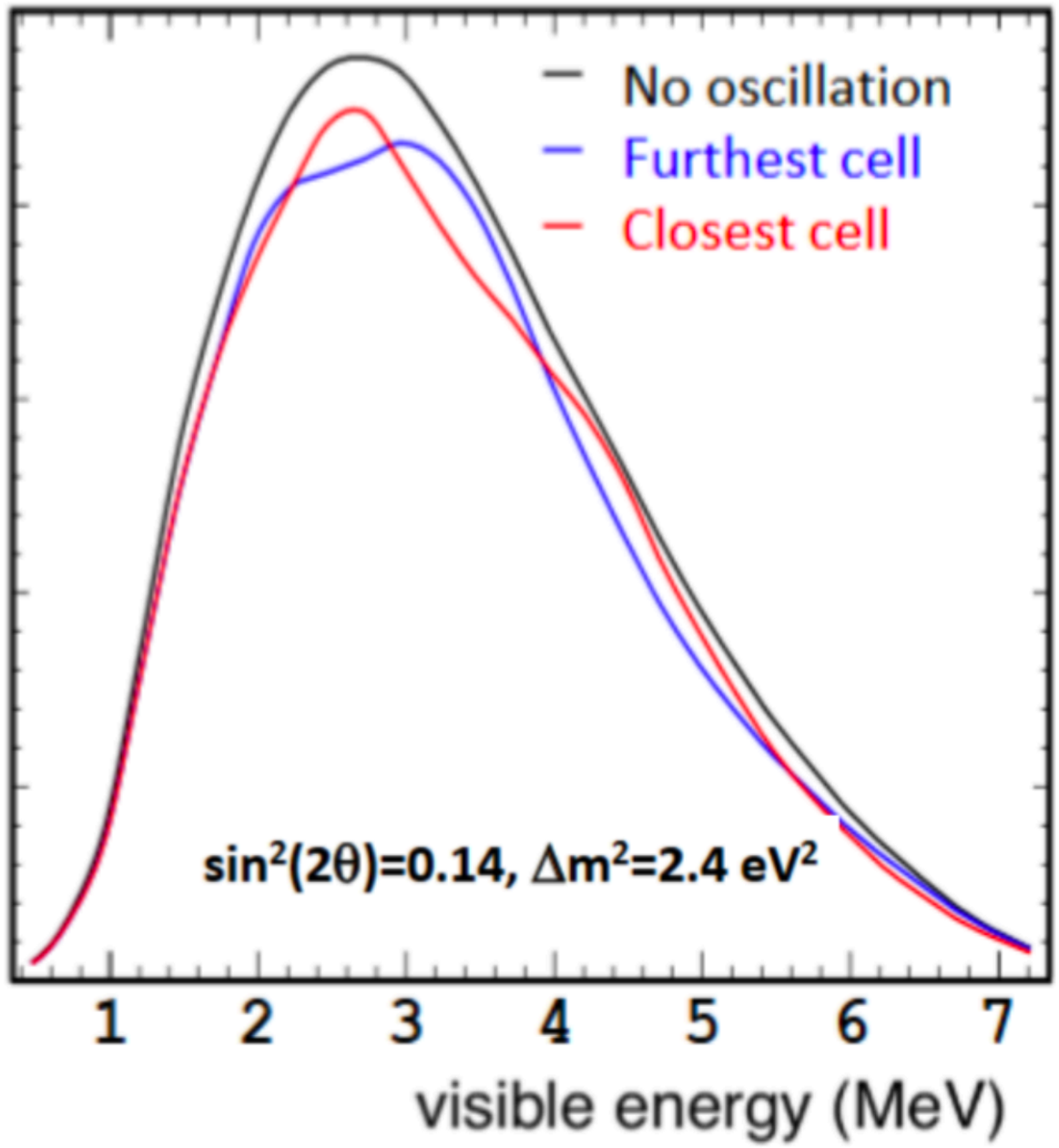
Spectral Ratio Reactor Experiments

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

STEREO Experimental Layout



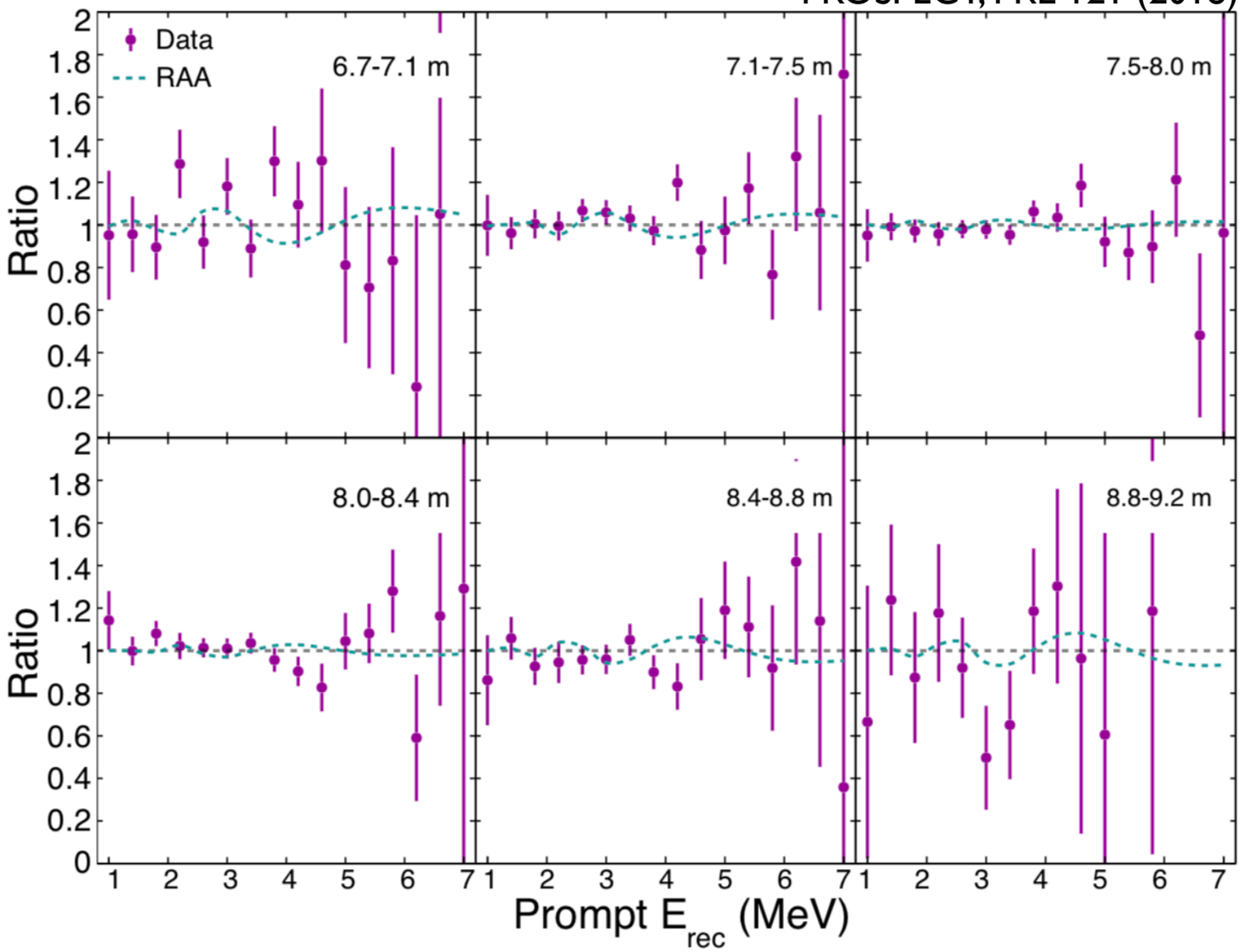
STEREO Toy Prompt Spectra From RAA Best-Fit Osc



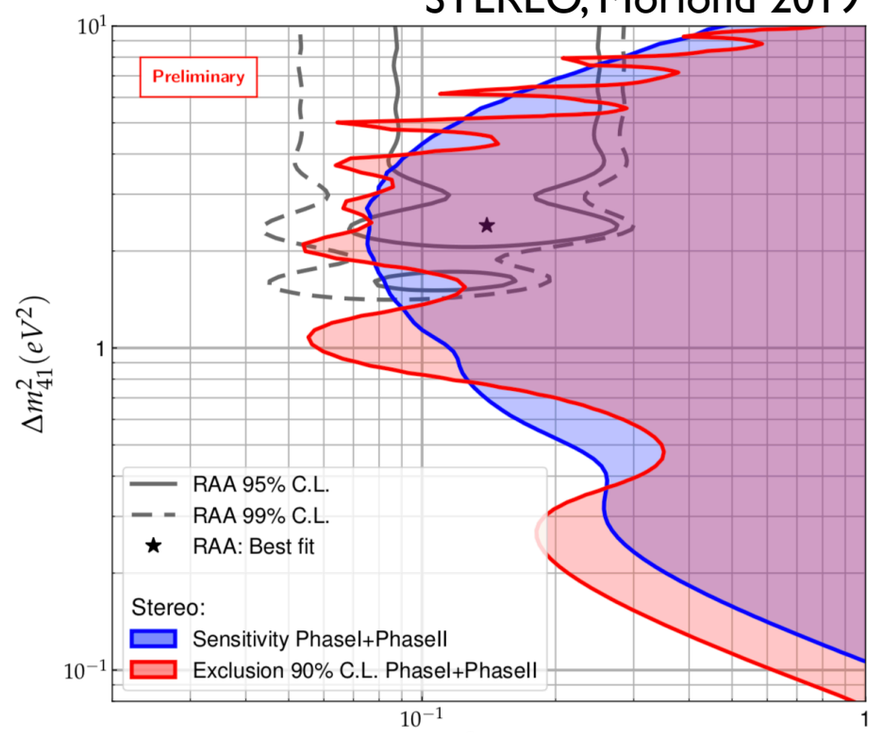
Testing Steriles: HEU Experiments

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

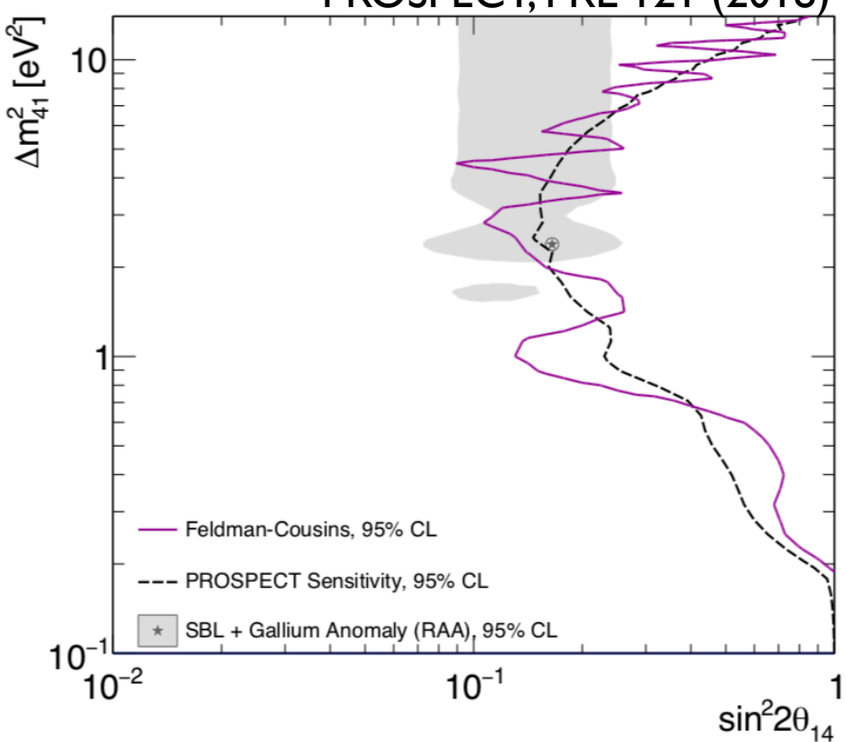
PROSPECT, PRL 121 (2018)



STEREO, Moriond 2019

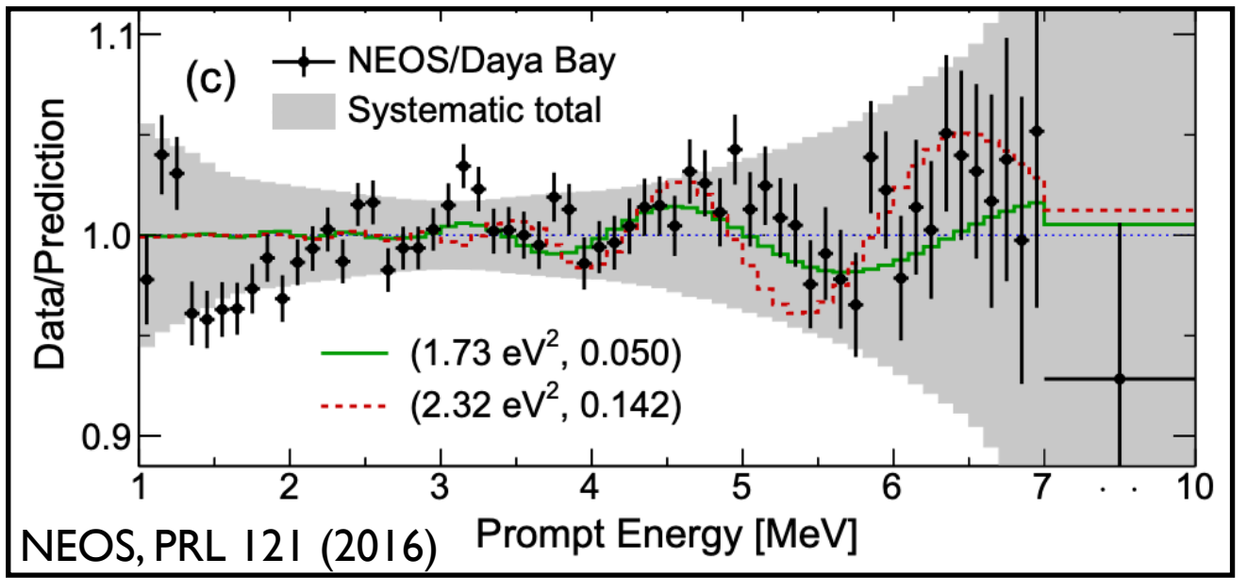


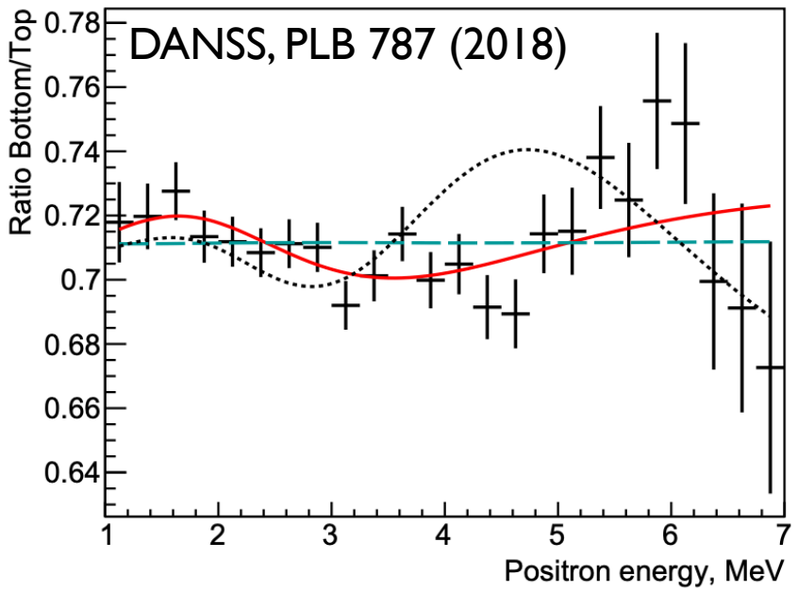
PROSPECT, PRL 121 (2018)

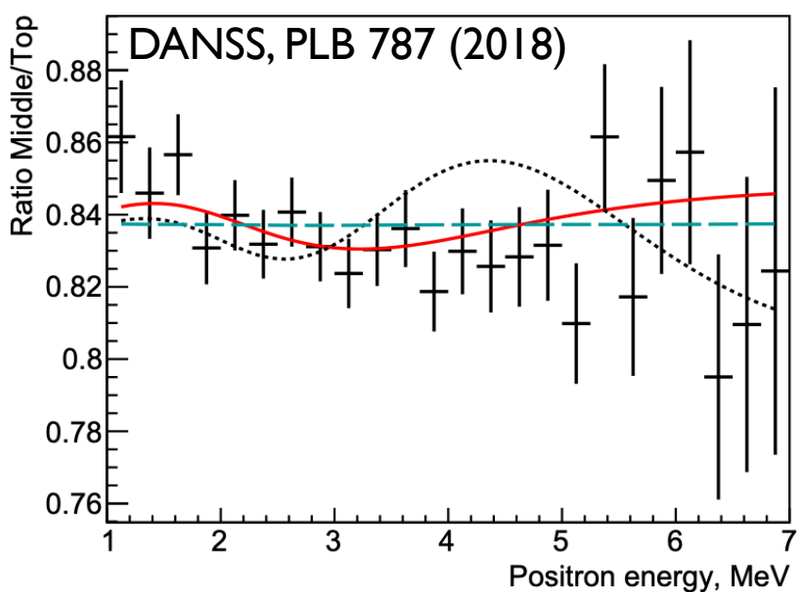


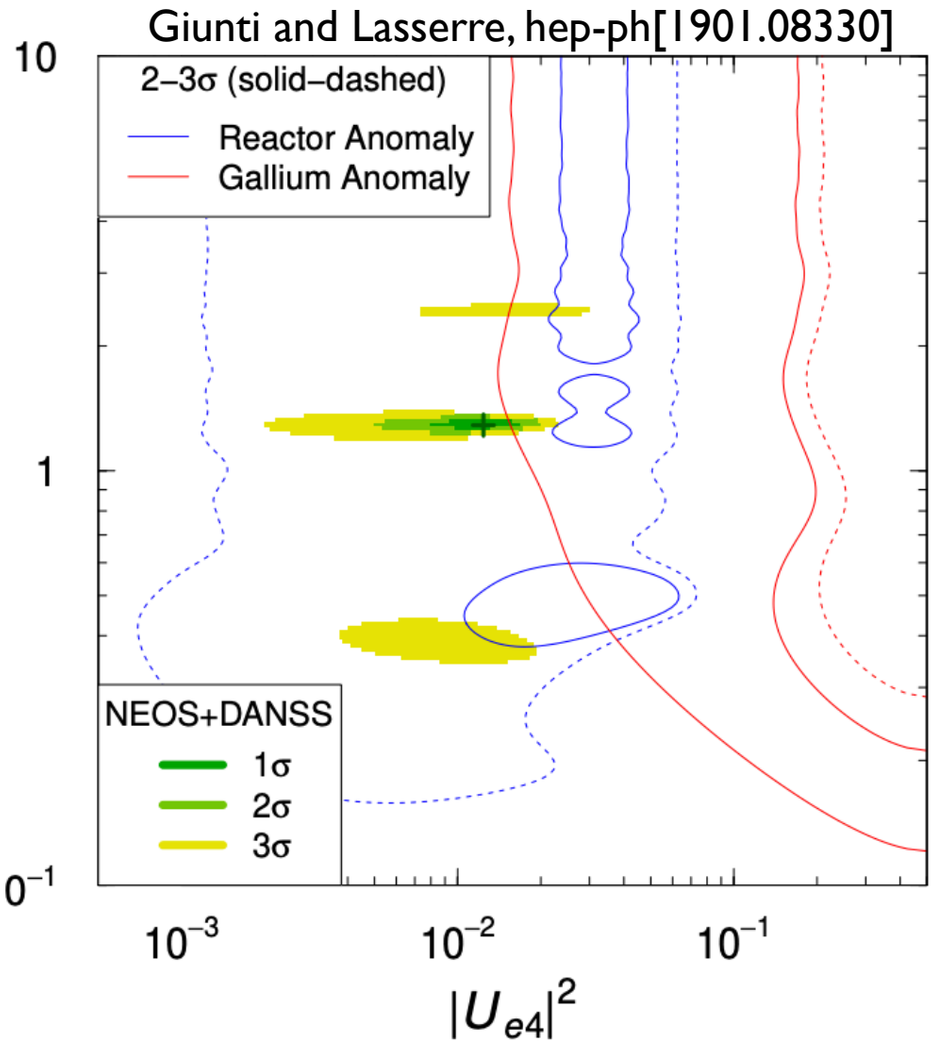
Testing Steriles: LEU Experiment Hints?

- 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





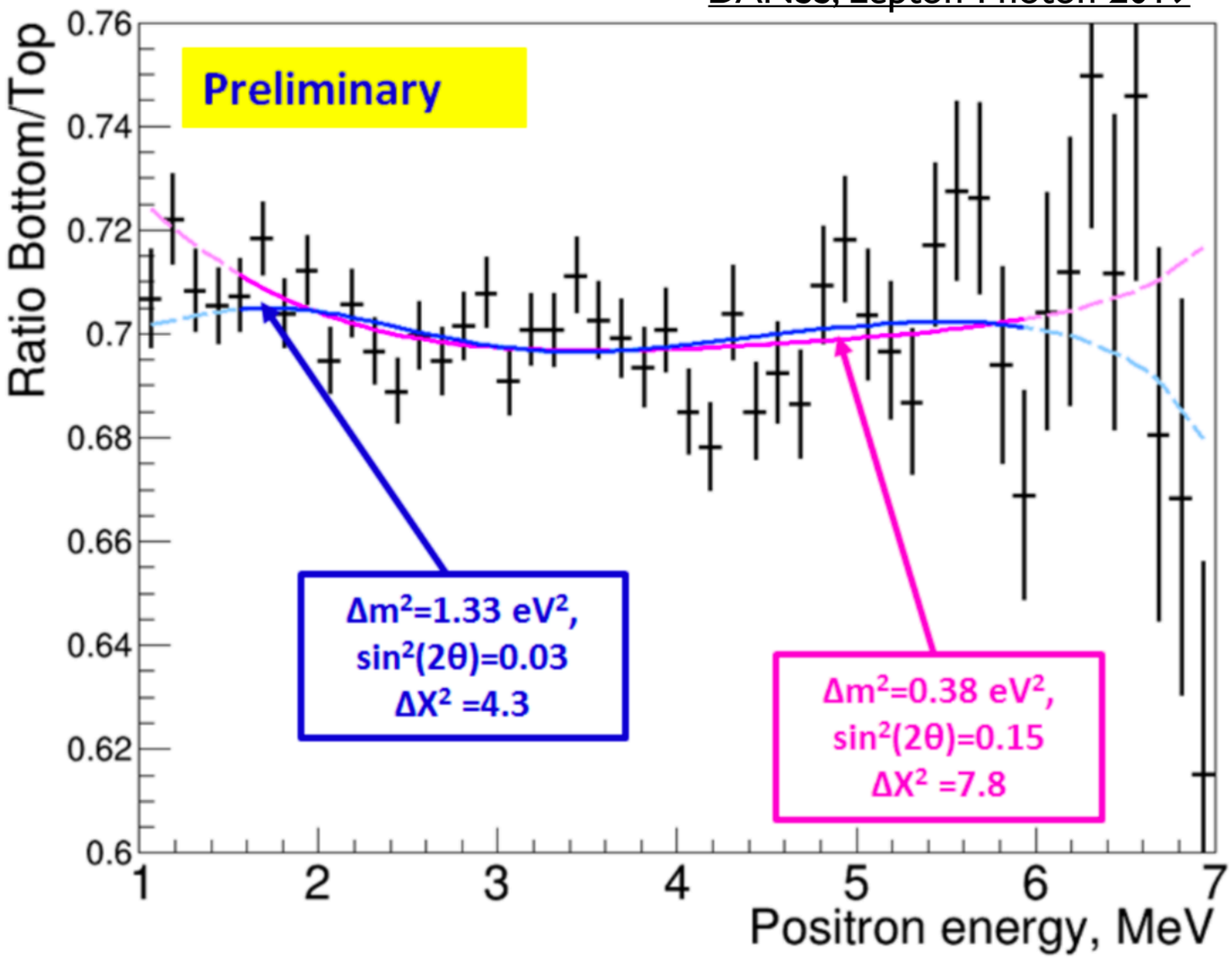




Testing Steriles: LEU Experiment Update

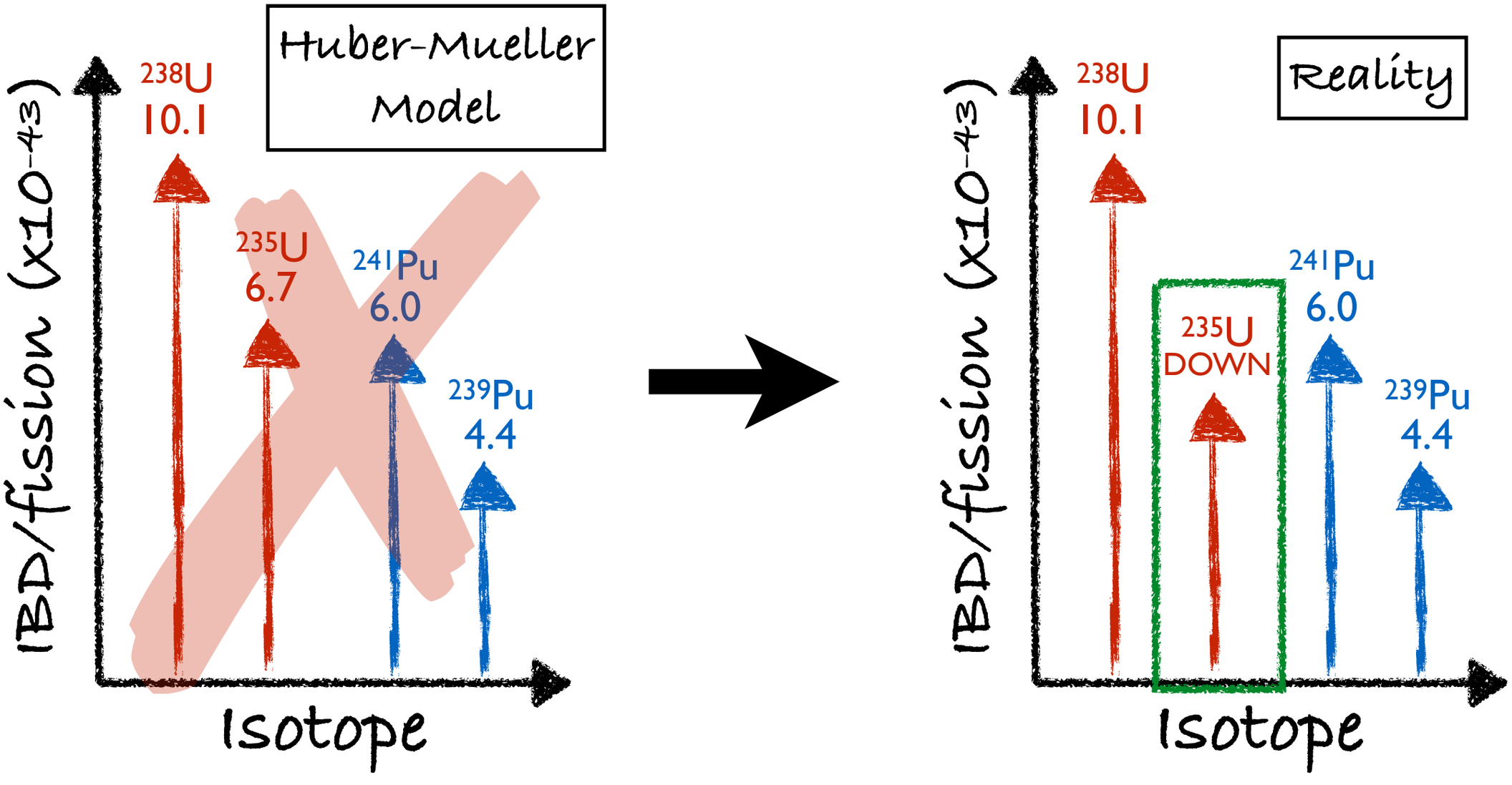
- Hints for steriles from commercial core (LEU) spectrum ratios?
- New DANSS results with improved stats, systematics handling
  - No-oscillation is only disfavored with respect to best-fit at 1.8σ
  - Even less disfavored compared to 'old best fit'
- Primary sterile hint from reactor spectra appears 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

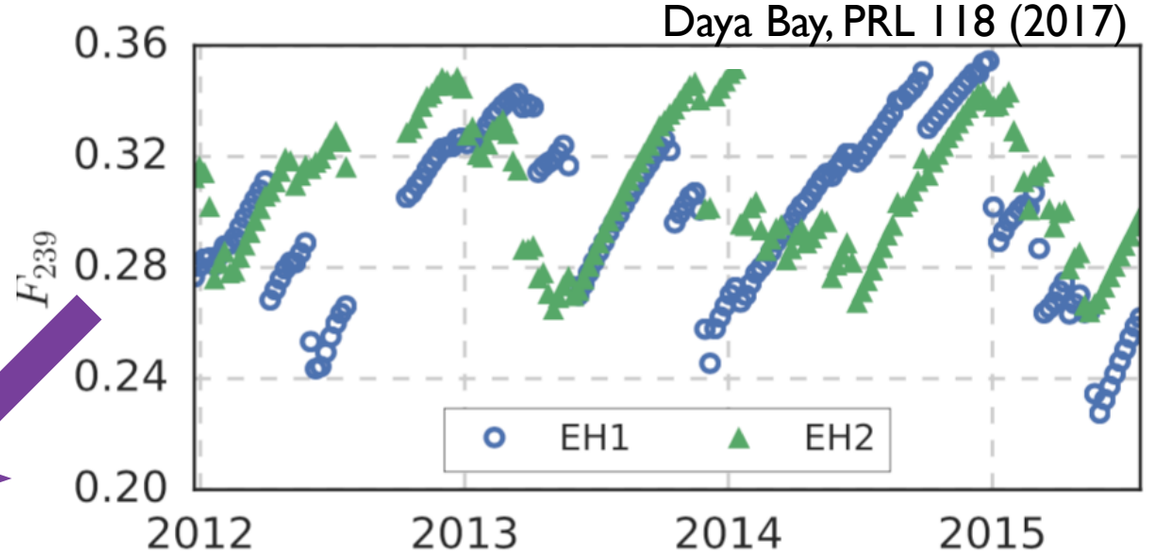
- Hypothesis 2: Something is wrong with the flux predictions
  - Theorists have come up with lots of reasons why predictions could be bad
  - Could be just **one** fission isotope; or could be **all** fission isotopes.



Ample 'Bad Model' Evidence: Flux

- Measure flux during periods with differing fuel content
- Flux anomaly's size depends on how much ^{235}U is burning
- Can't be explained by steriles
  - CAN be caused by bad ^{235}U flux predictions (among other things)

Daya Bay, PRL 118 (2017)



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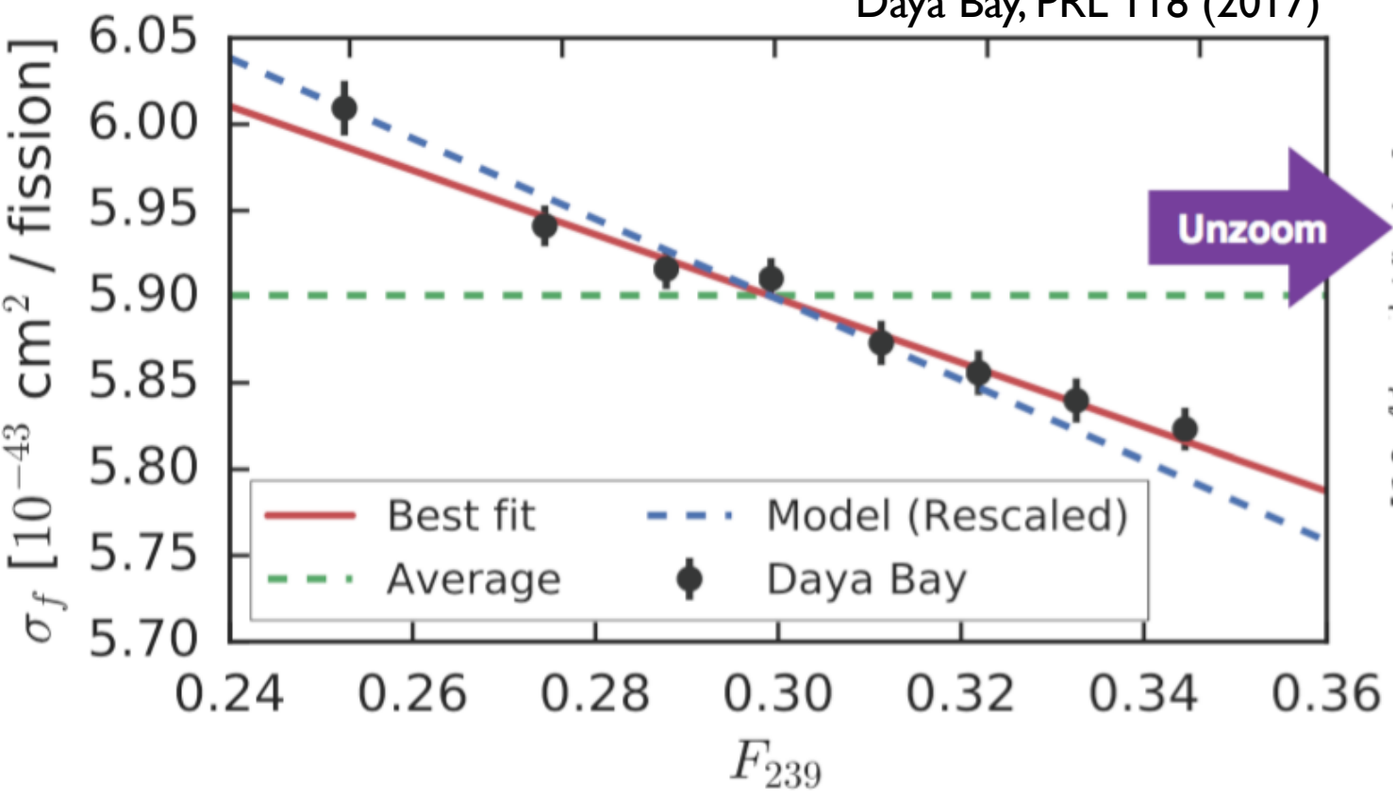
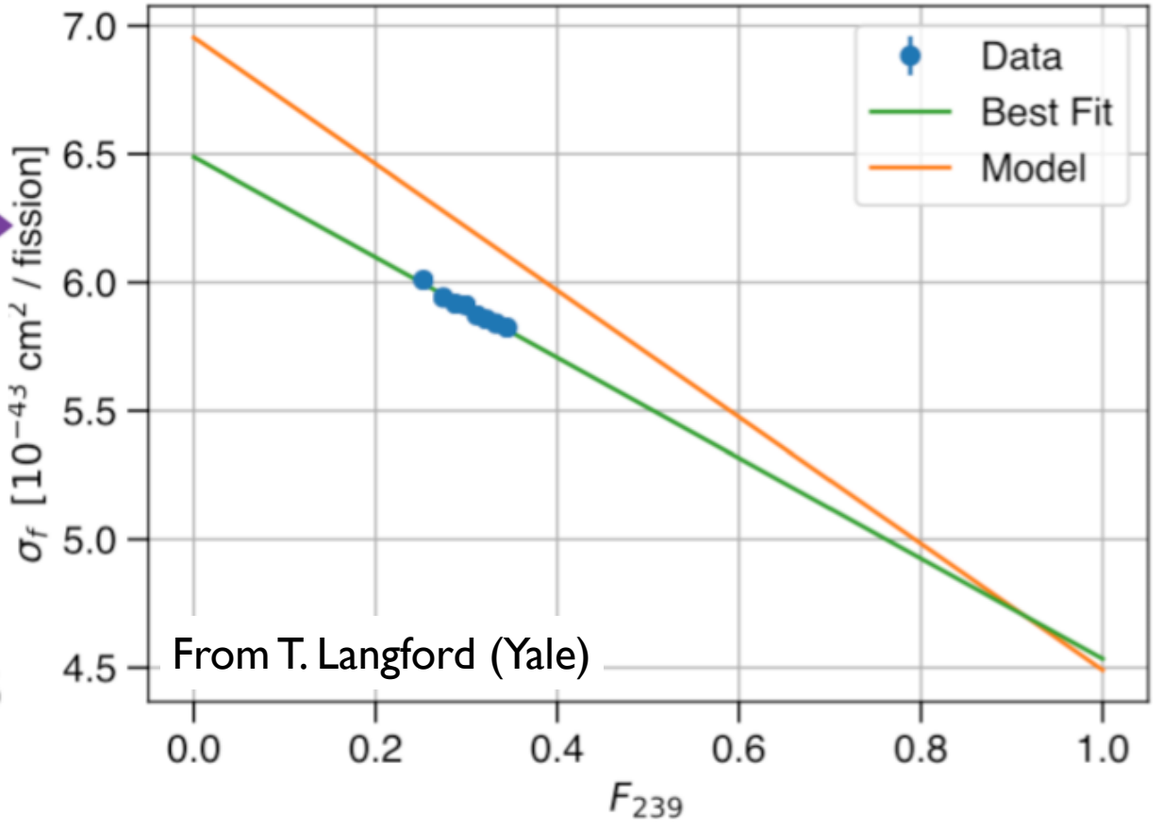


Unzoom

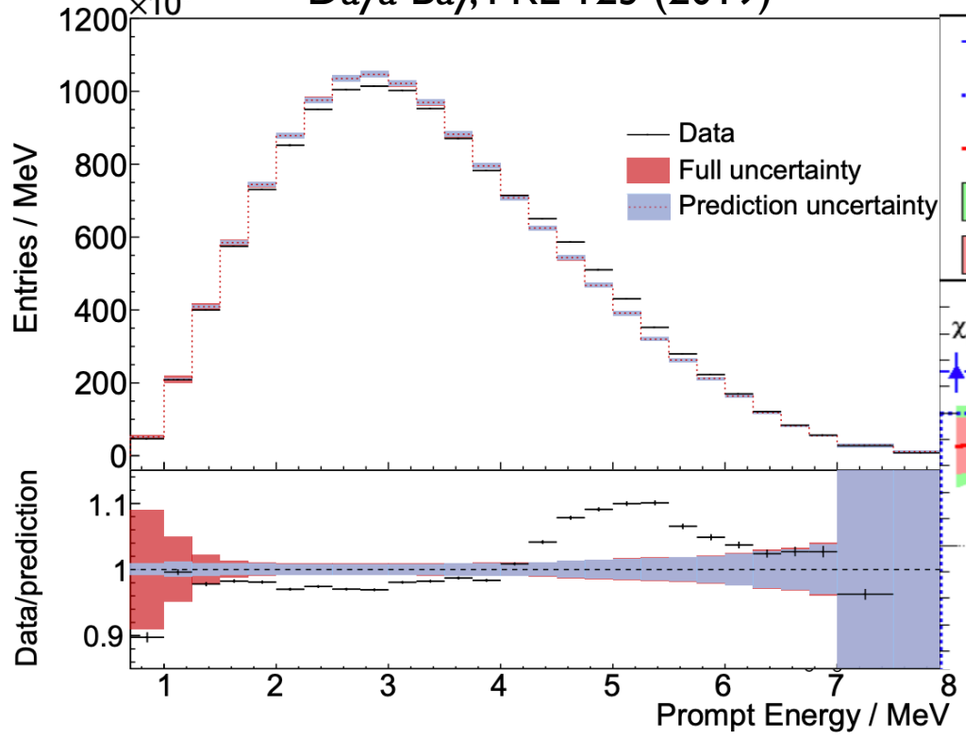
From T. Langford (Yale)



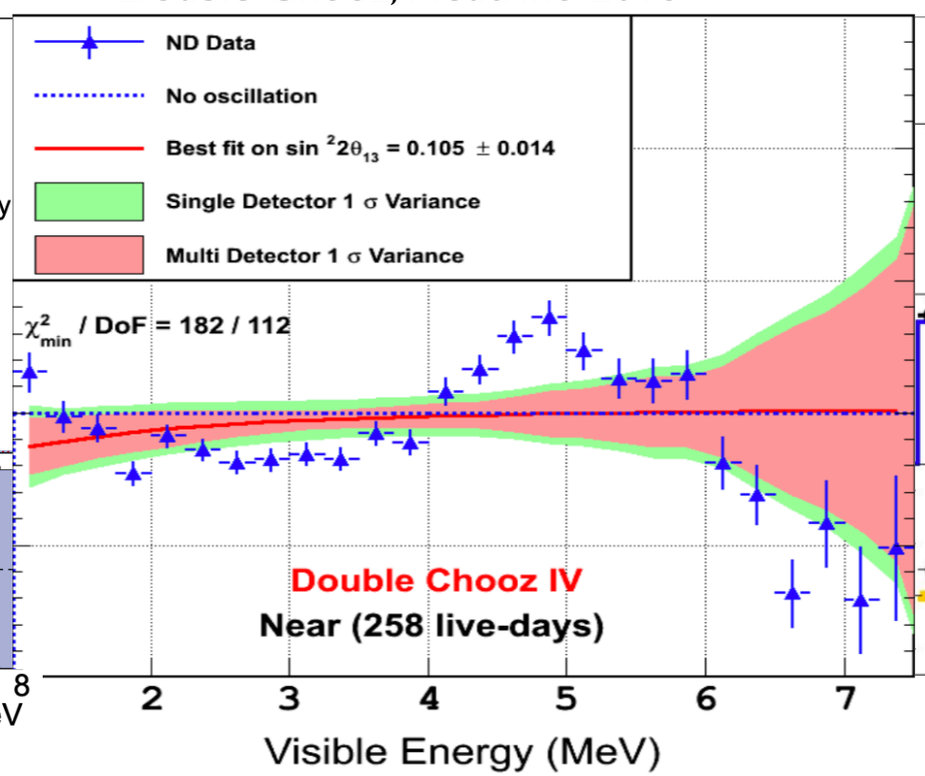
Ample ‘Bad Model’ Evidence: Spectrum

- Reactor spectrum predictions also do not match the data.
- Effect observed by Daya Bay, RENO, Double Chooz, others
- Again, cannot be explained by steriles

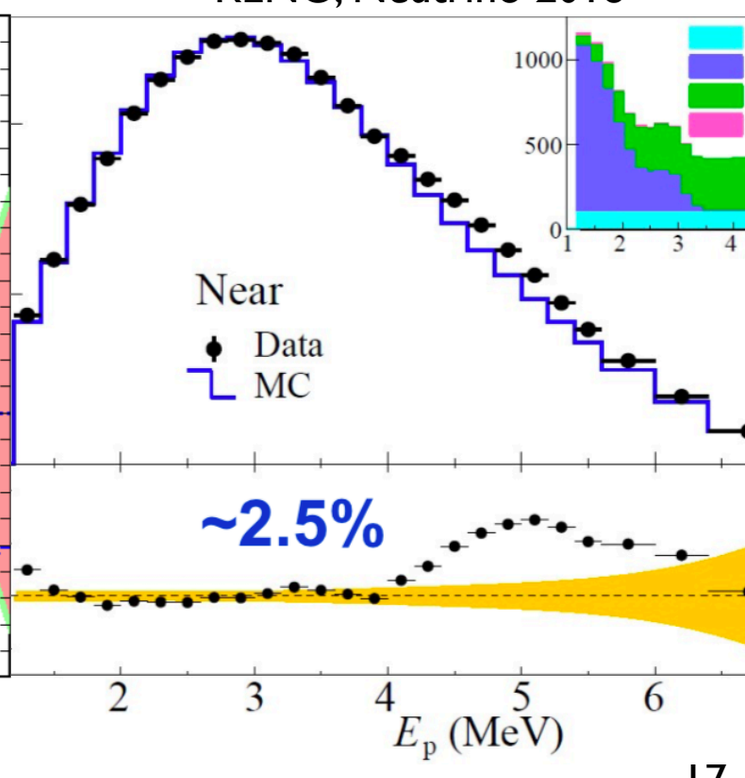
Daya Bay, PRL 123 (2019)



Double Chooz, Neutrino 2018



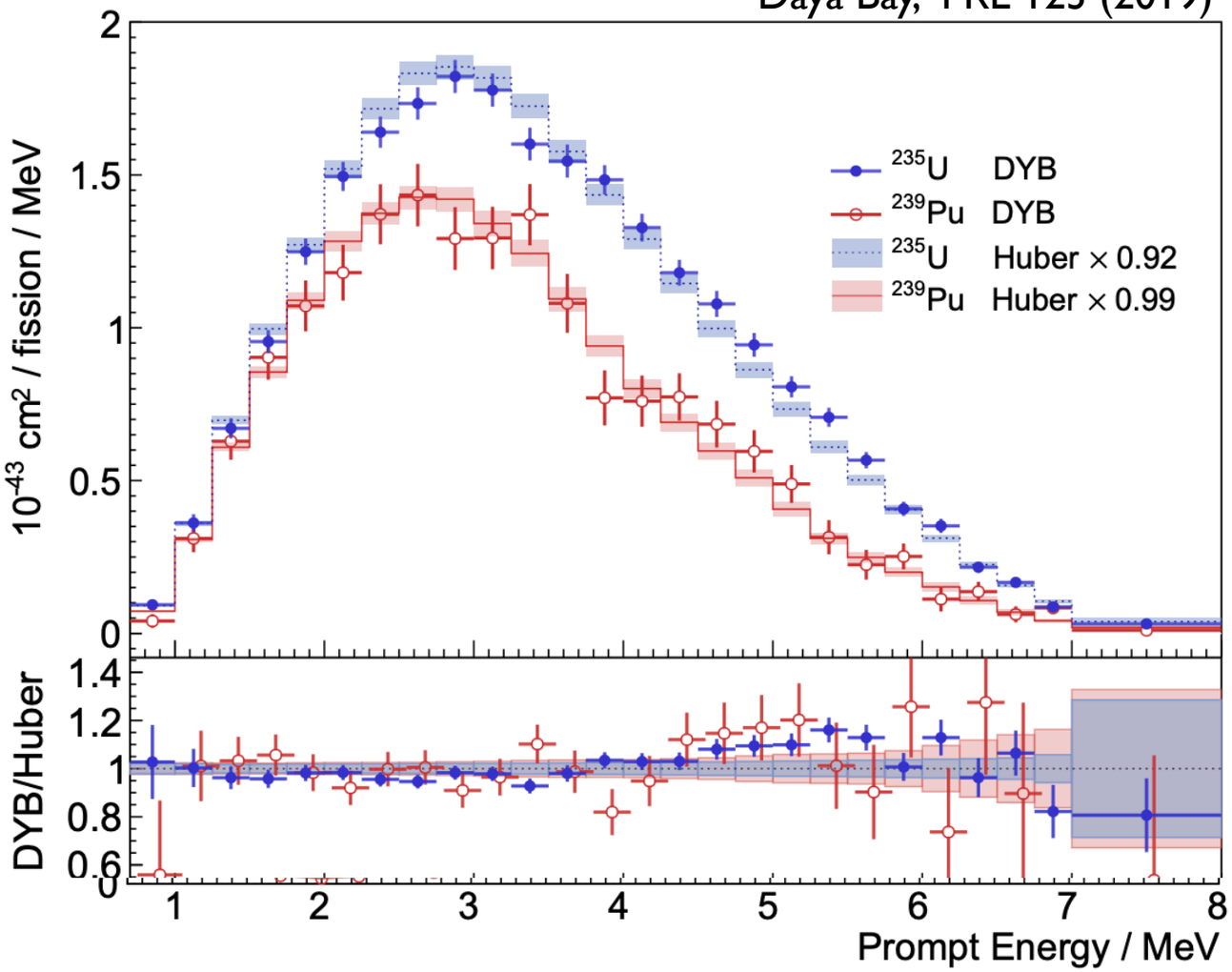
RENO, Neutrino 2018



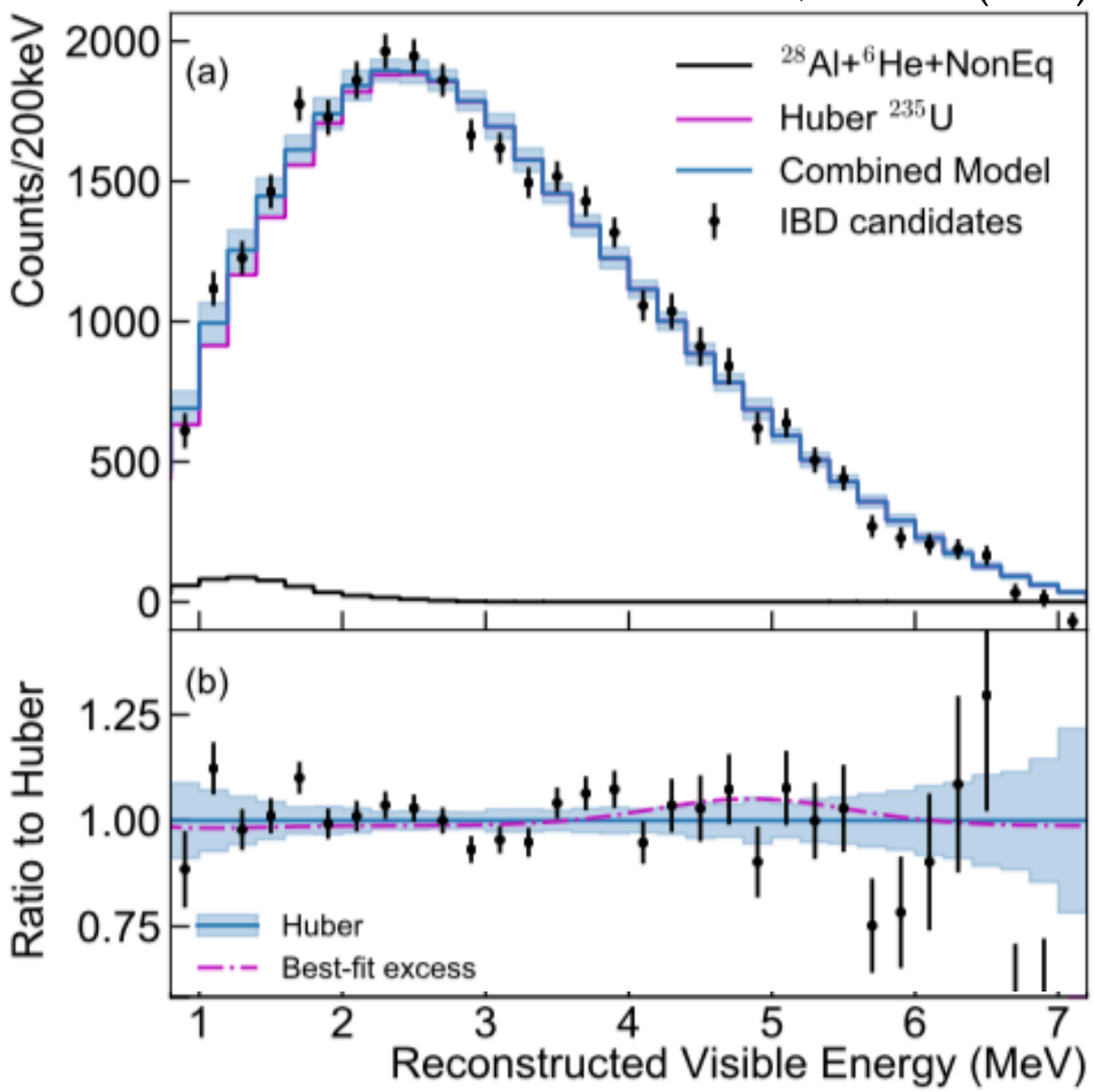
Ample 'Bad Model' Evidence: Spectrum

- Reactor spectrum predictions also do not match the data.
- Again, cannot be explained by steriles
  - Look to LEU 'spectrum evolution,' and detailed HEU-LEU comparisons to better understand the origin of this disagreement.

Daya Bay, PRL 123 (2019)

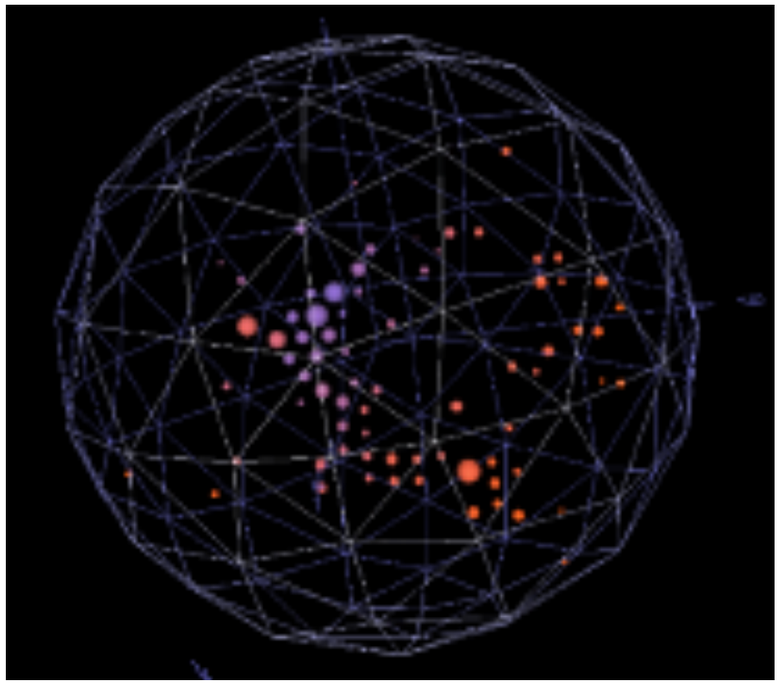


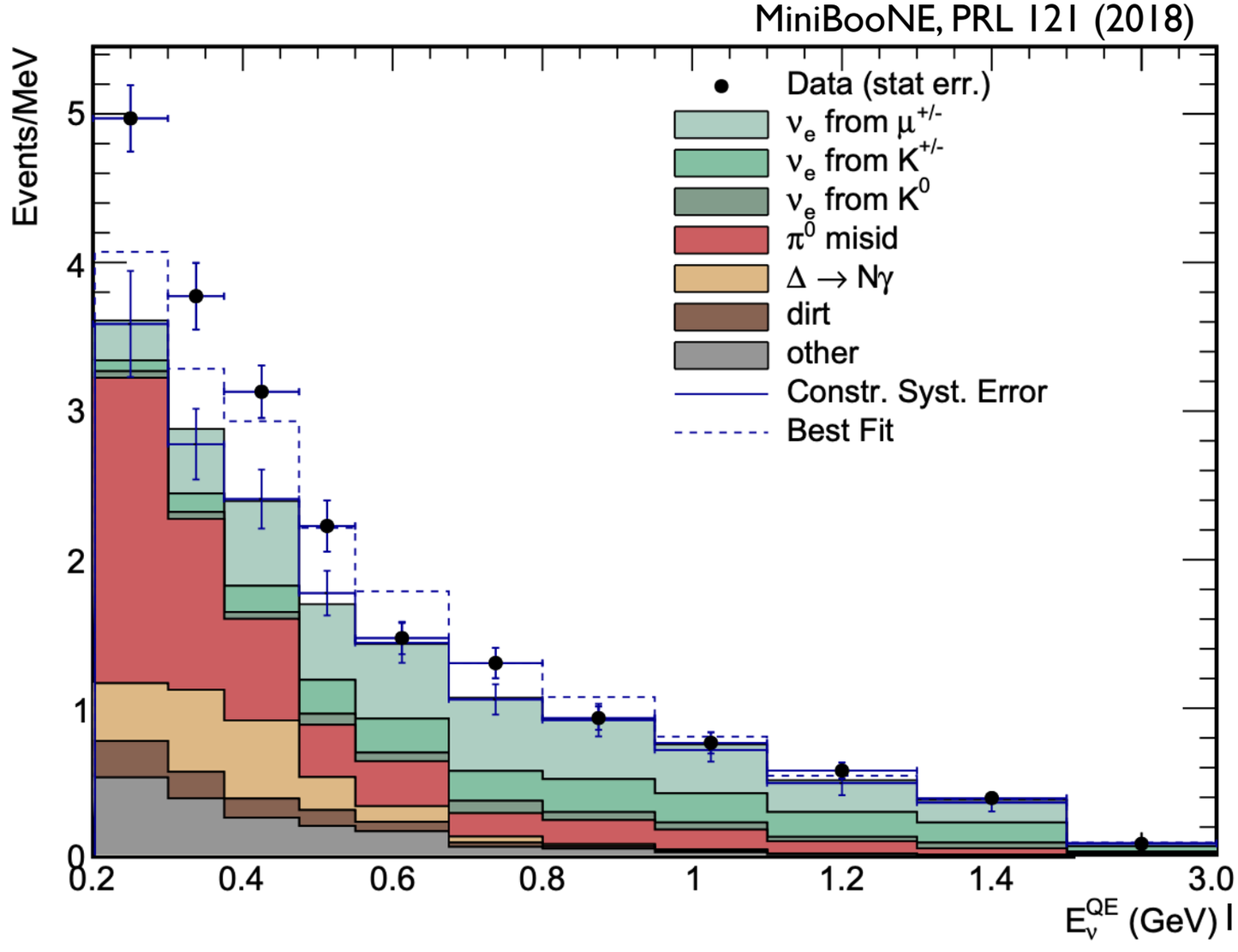
PROSPECT, PRL 122 (2019)



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.

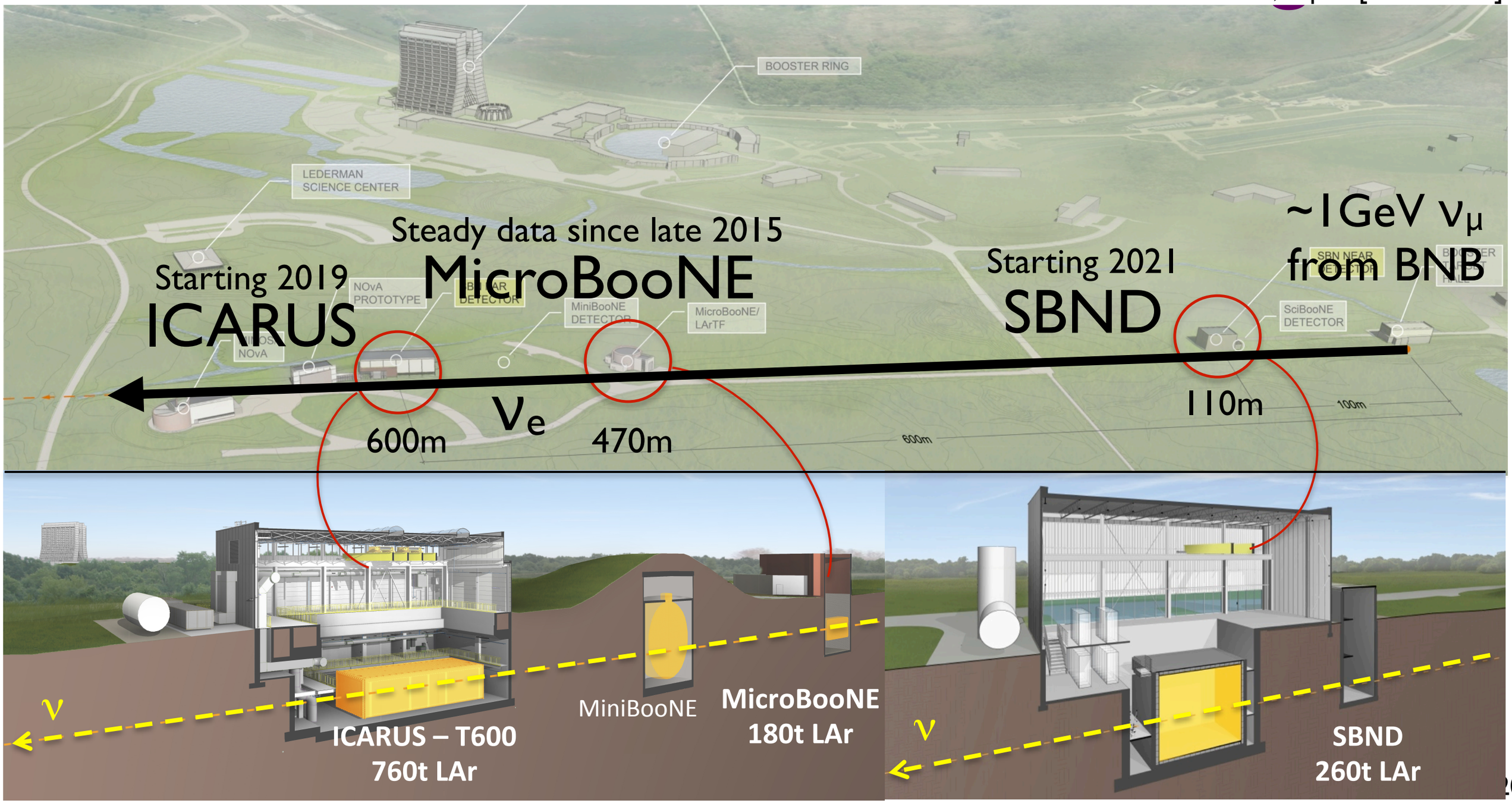




Fermilab's SBN Program

- Address electron/gamma ambiguity with LArTPC technology
- 3 baselines increases osc sensitivity for both ν_μ, ν_e channels

SBN, hep-ex[1503.01520]



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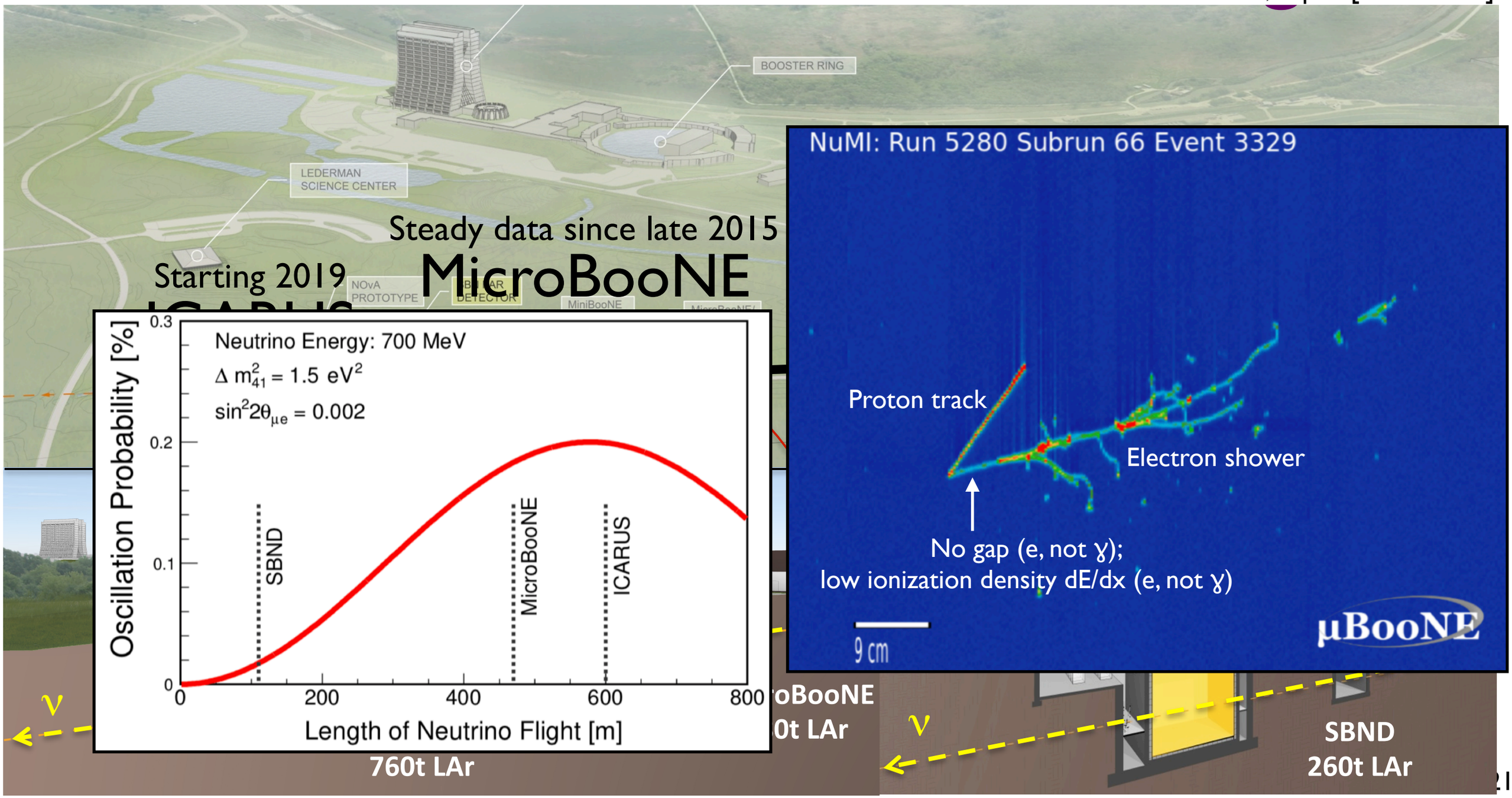


MicroBooNE: Shower Reconstruction

- 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)

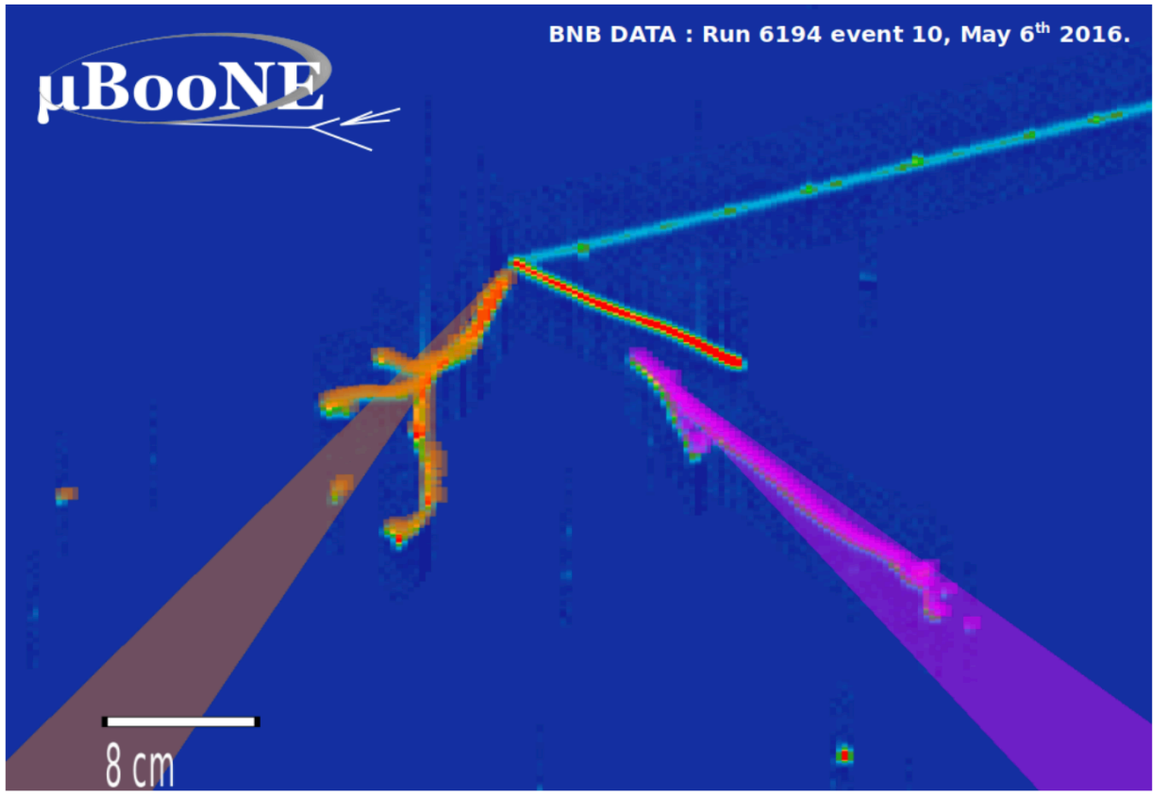
- All strategies built upon robust foundational analyses and low-level signal processing

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

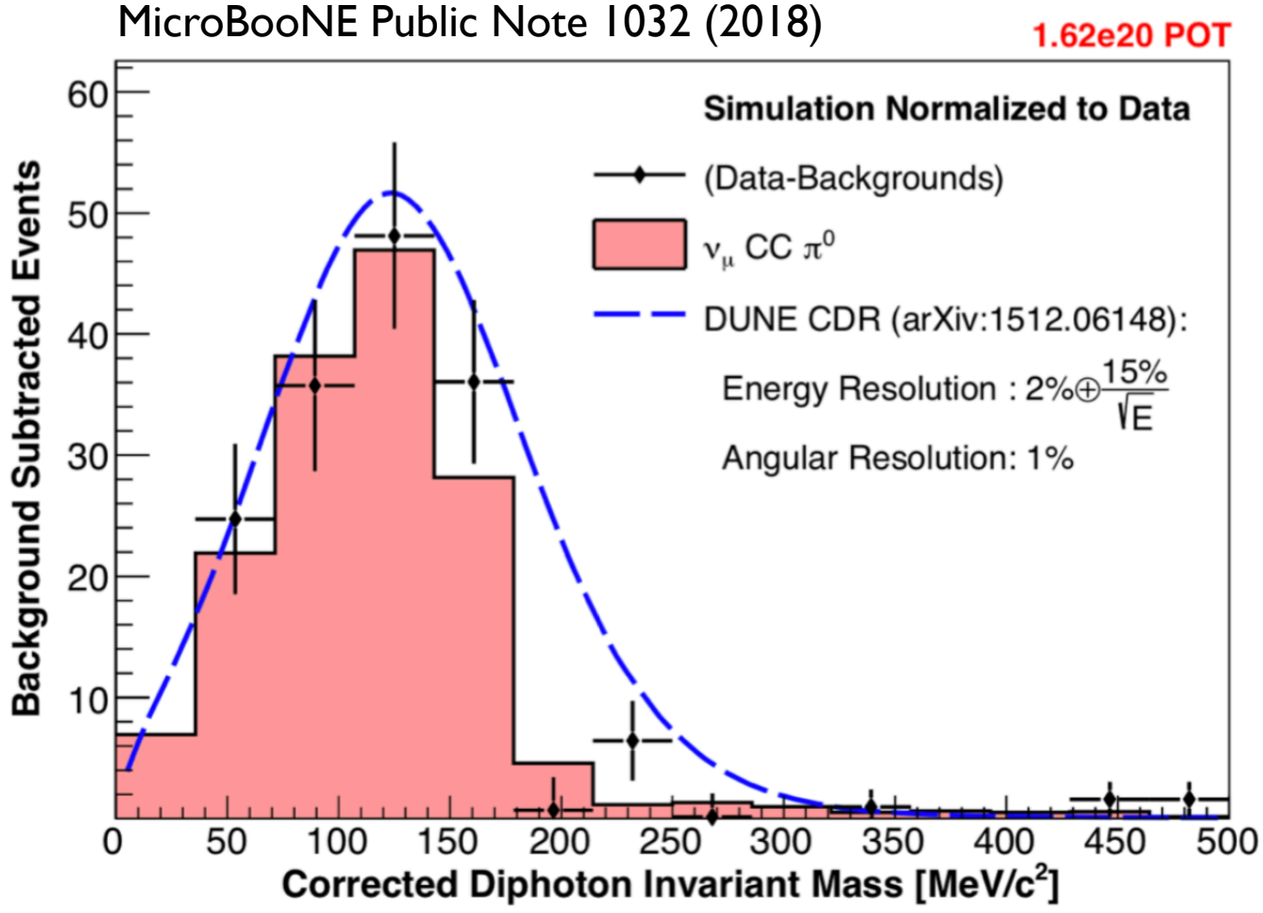
MicroBooNE: Shower Reconstruction

- Working in phases towards uBooNE low-energy excess result
- First: can we acceptably reconstruct shower qualities?
- Demonstration with ν_μCC + 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)

MicroBooNE, hep-ex[1910.02166]



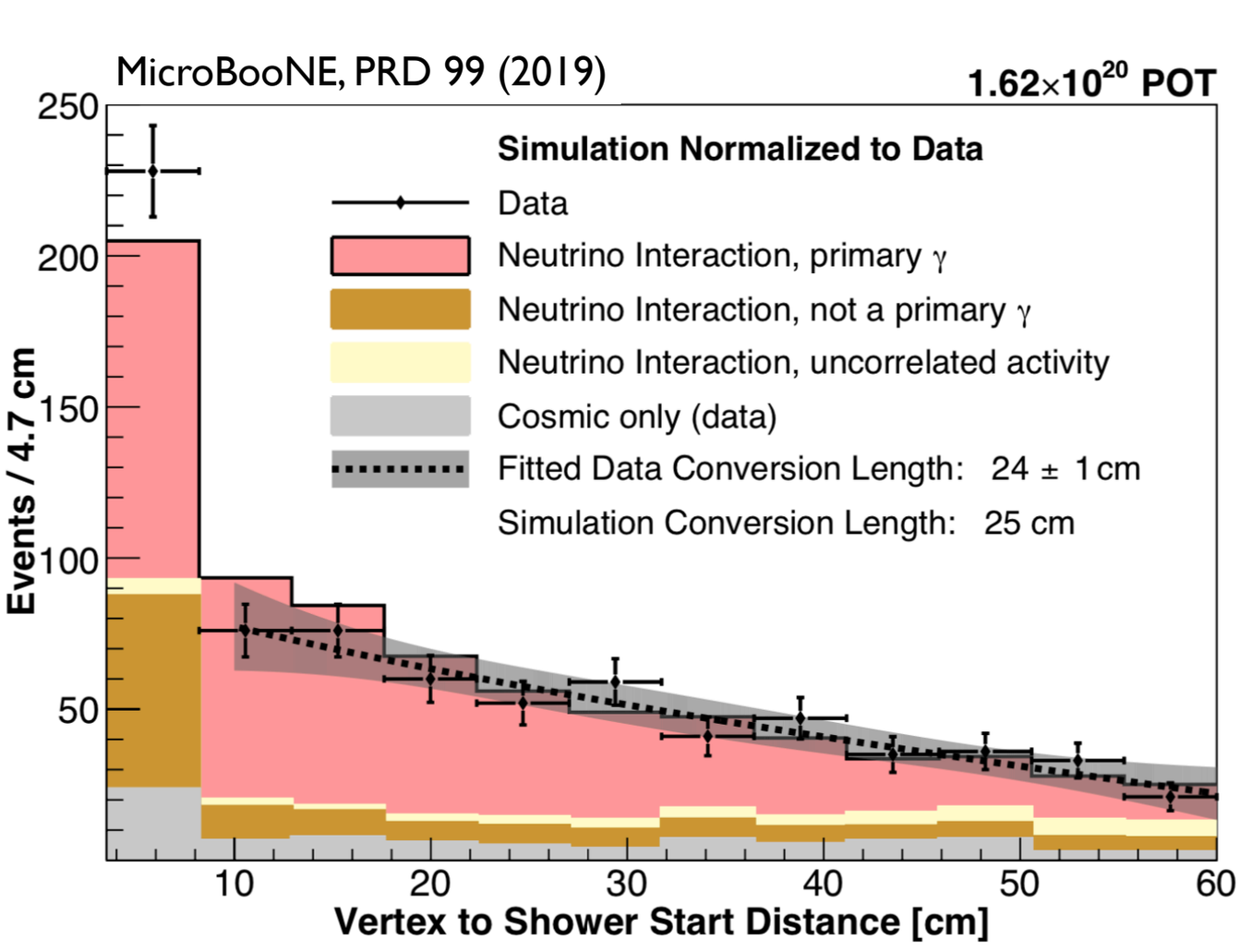
MicroBooNE Public Note 1032 (2018)

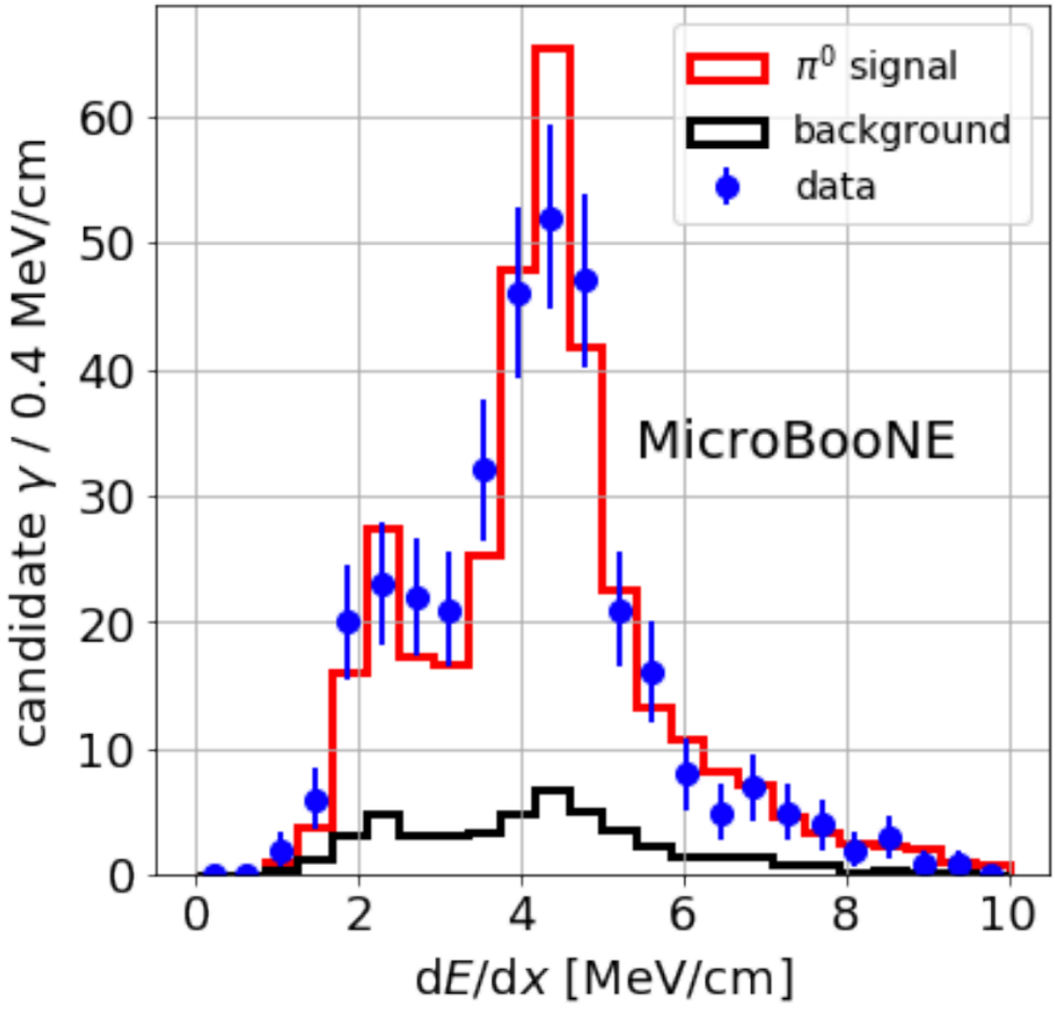


MicroBooNE: Shower Reconstruction

- Working in phases towards uBooNE low-energy excess result
- First: can we acceptably reconstruct shower qualities?
- Demonstration with ν_μCC + Pi0 cross-section analysis
  - Vertex locations match what we'd expect for photons in LAr
  - Pi0 trunk dE/dx distributions match MC

MicroBooNE, hep-ex[1910.02166]

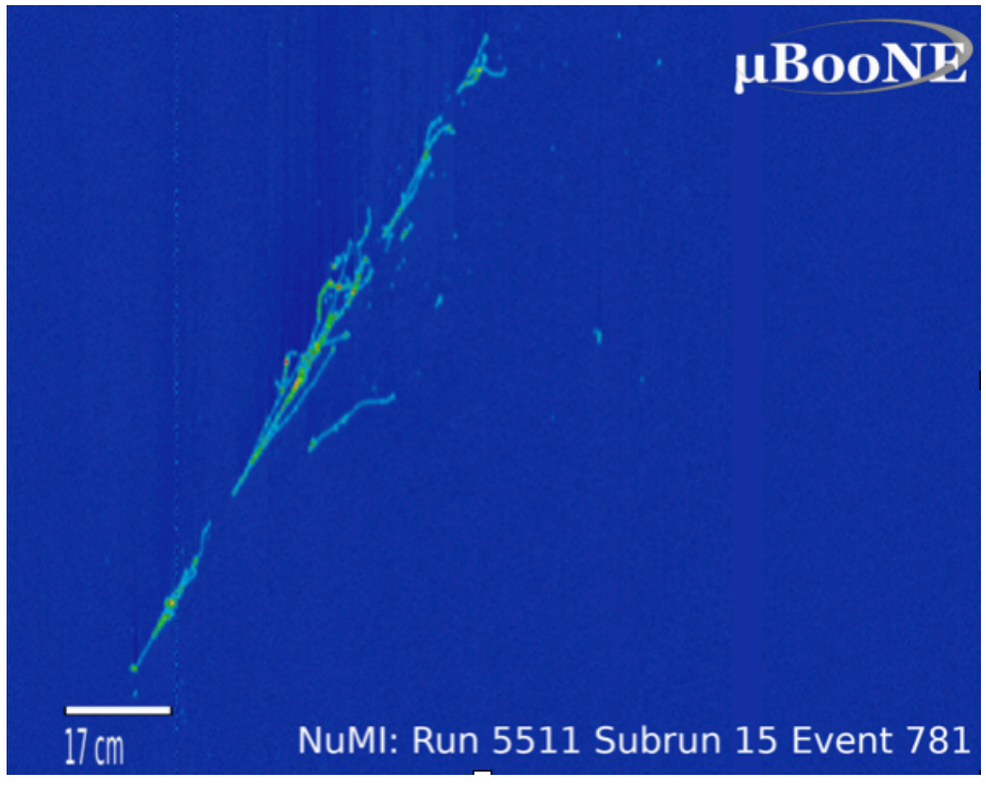


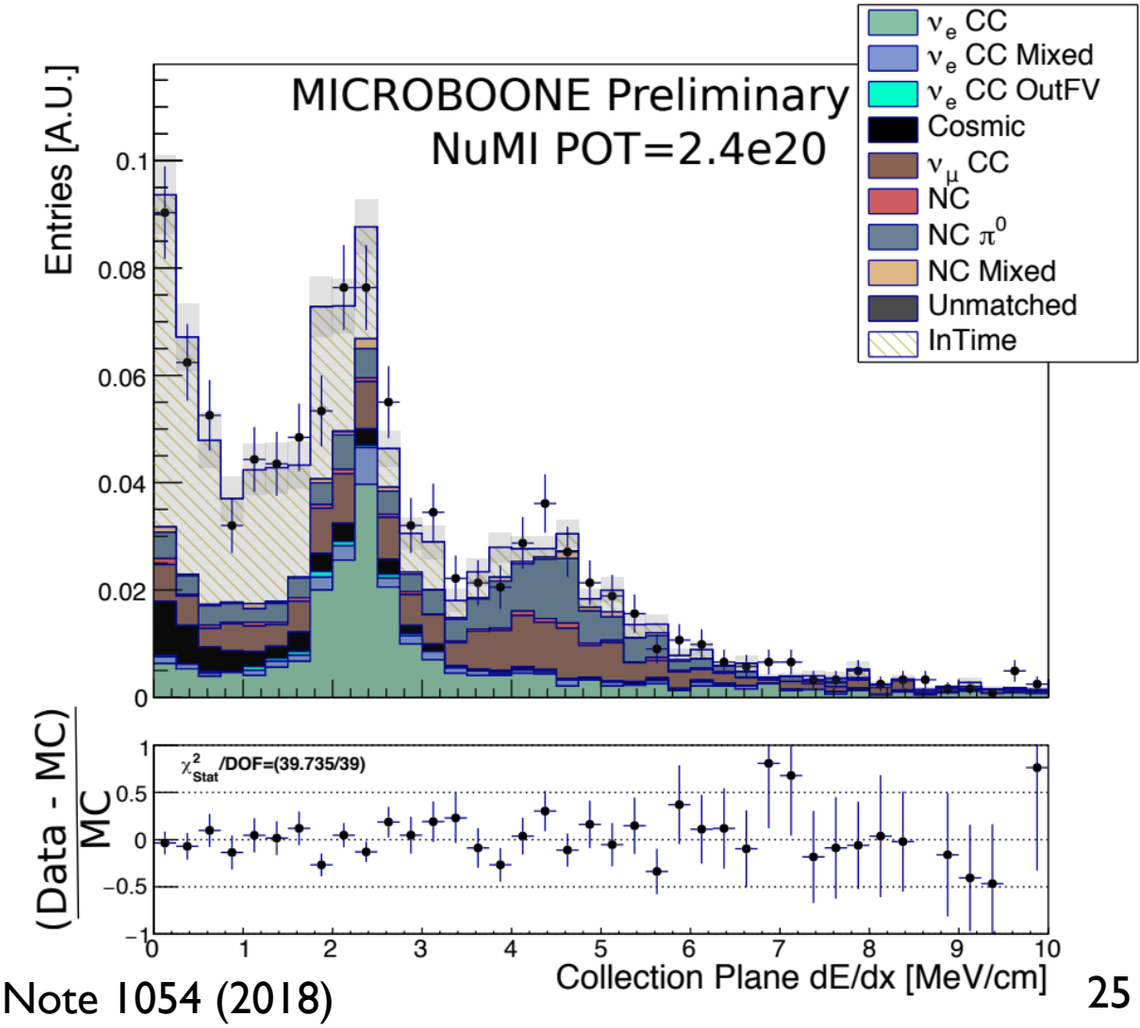


MicroBooNE: ν_e Selection

- Working in phases towards uBooNE low-energy excess result
- Second: can we select ν_eCC events in a 'sideband' dataset?
- Demonstration with NuMI beam events
  - NuMI beam ν_e contamination is higher (less sensitive to $\nu_\mu \rightarrow \nu_e$)
  - Automated selection IDs ~100 ν_eCC events in 2.4e20 POT

- Also: good data-MC dE/dx agreement



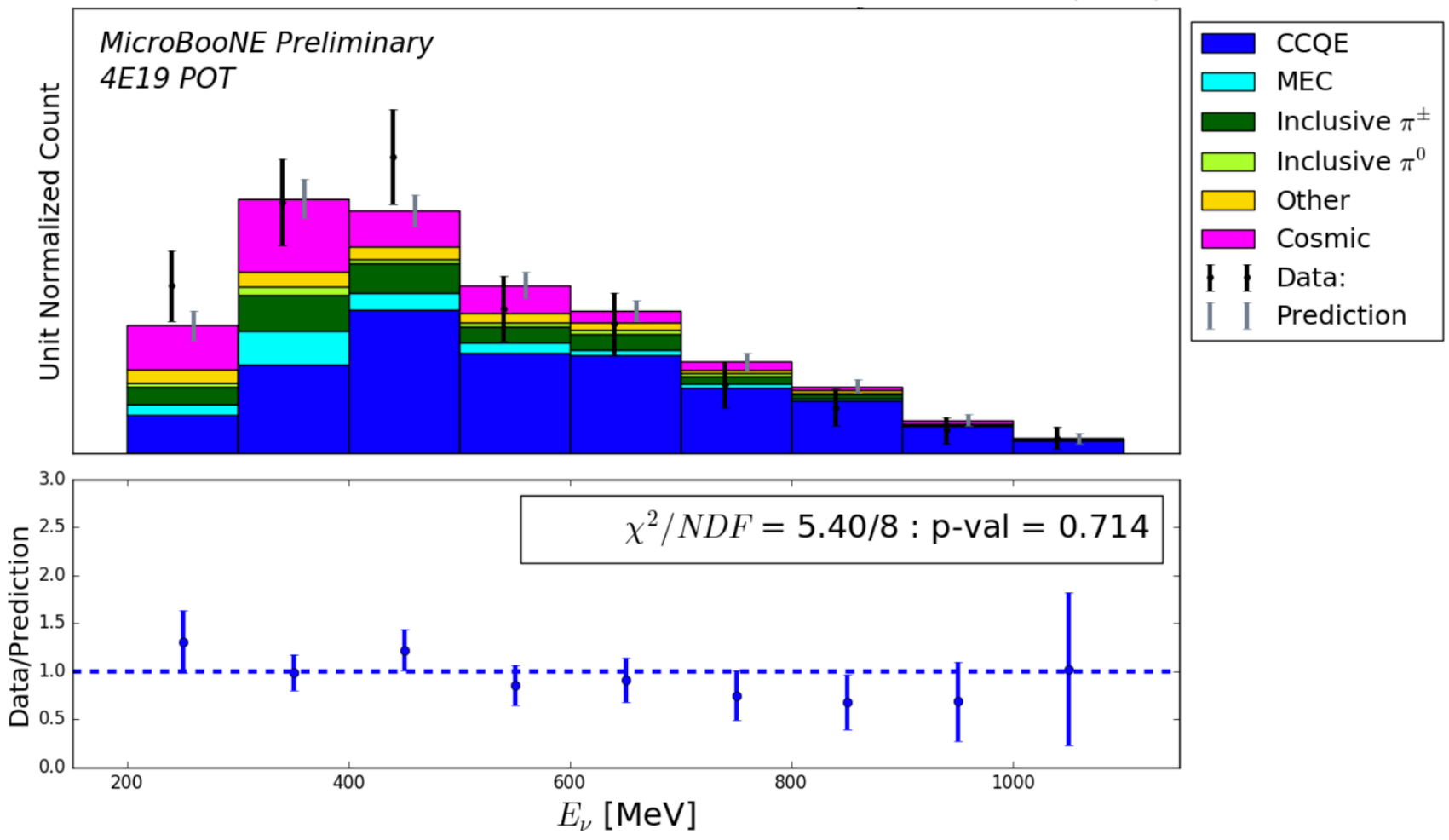


MicroBooNE Public Note 1054 (2018)

MicroBooNE: ν_μ Selection

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

MicroBooNE Public Note 1051 (2018)

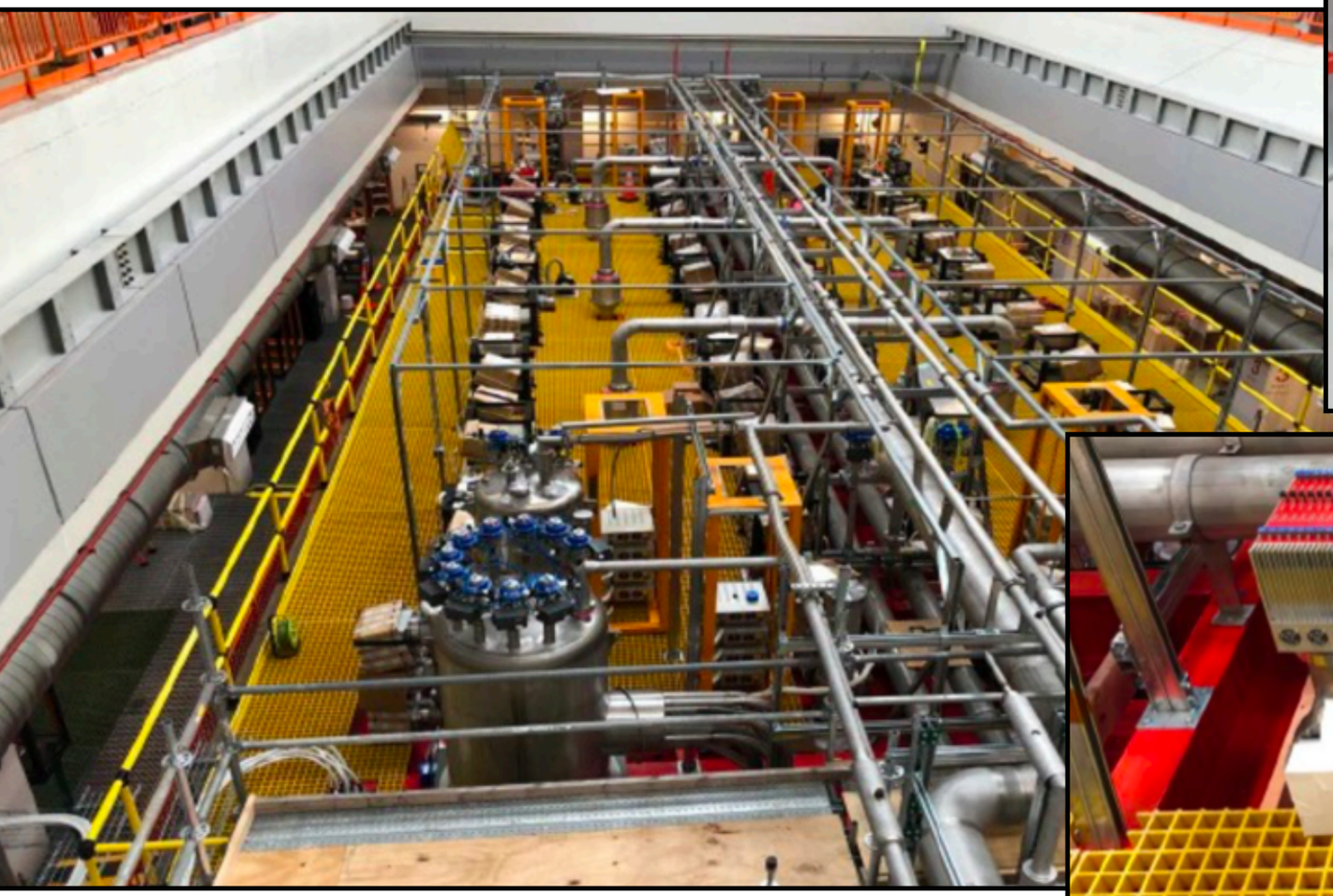


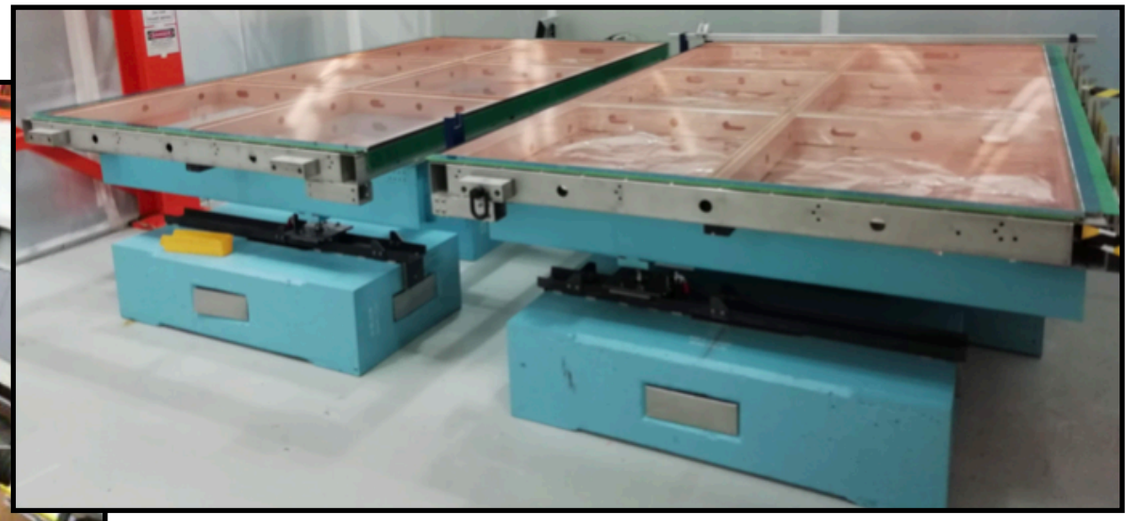
ICARUS and SBND

- ICARUS is well on its way:
  LAr filling is imminent: end 2019!
- 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

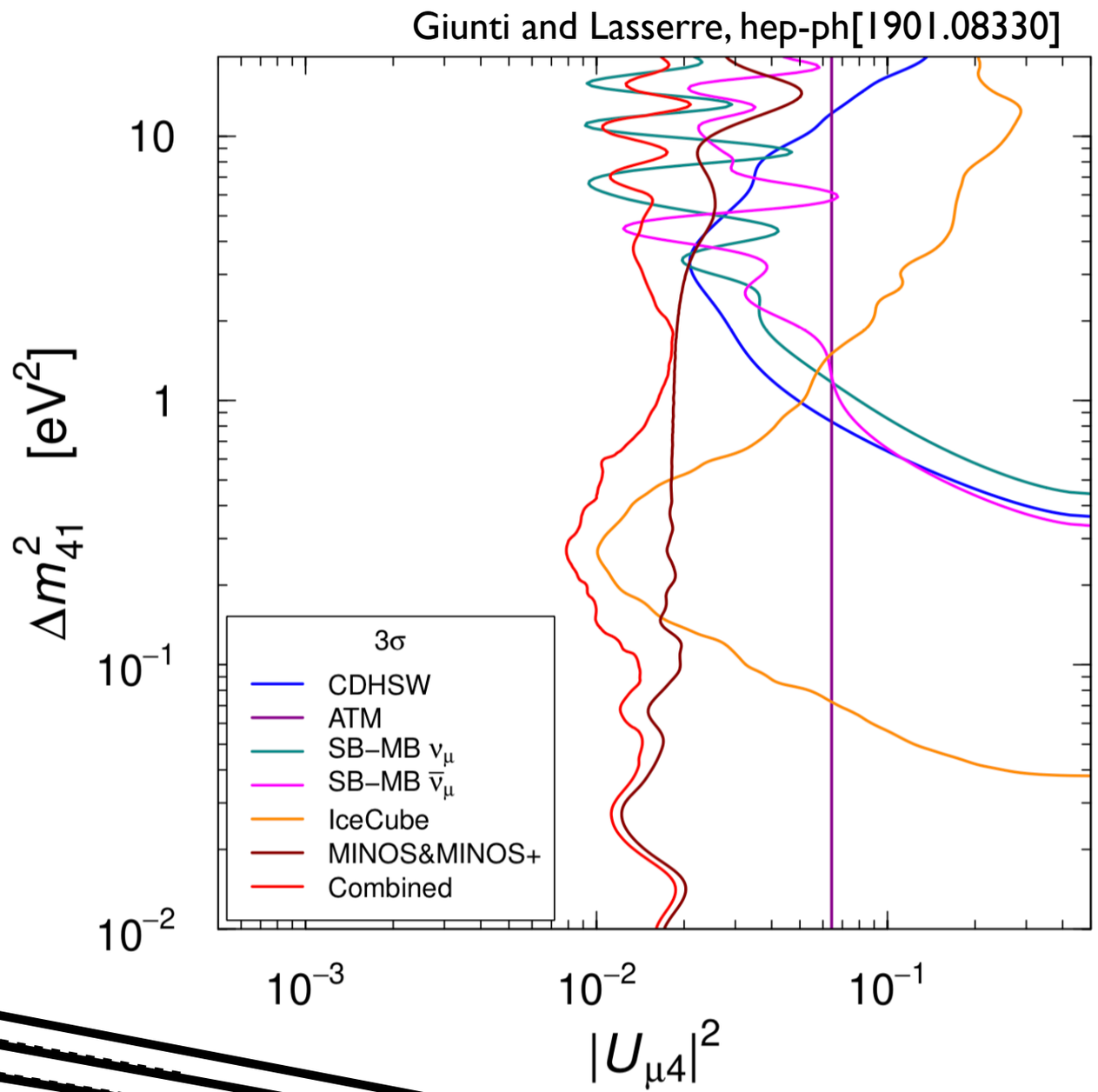
Taking off the Blinders: Disappearance

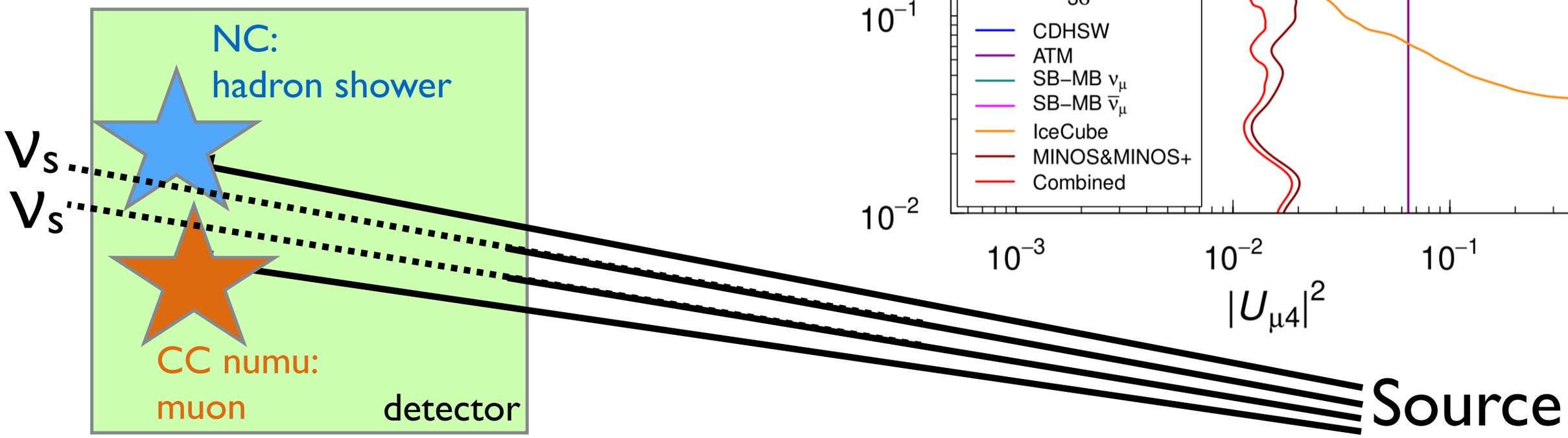
- Other experiments forego direct checks of 'anomalies' in favor of directly assessing sterile neutrino oscillations
  - NC: active neutrino disappearance (MINOS+, NoVA)

    MINOS(+), PRL 122 (2019) NoVA, PRD 96 (2017)
  - CC: muon neutrino disappearance (MINOS+, IceCube)

    MINOS(+), PRL 122 (2019) IceCube, PRL 117 (2016)

Giunti and Lasserre, hep-ph[1901.08330]

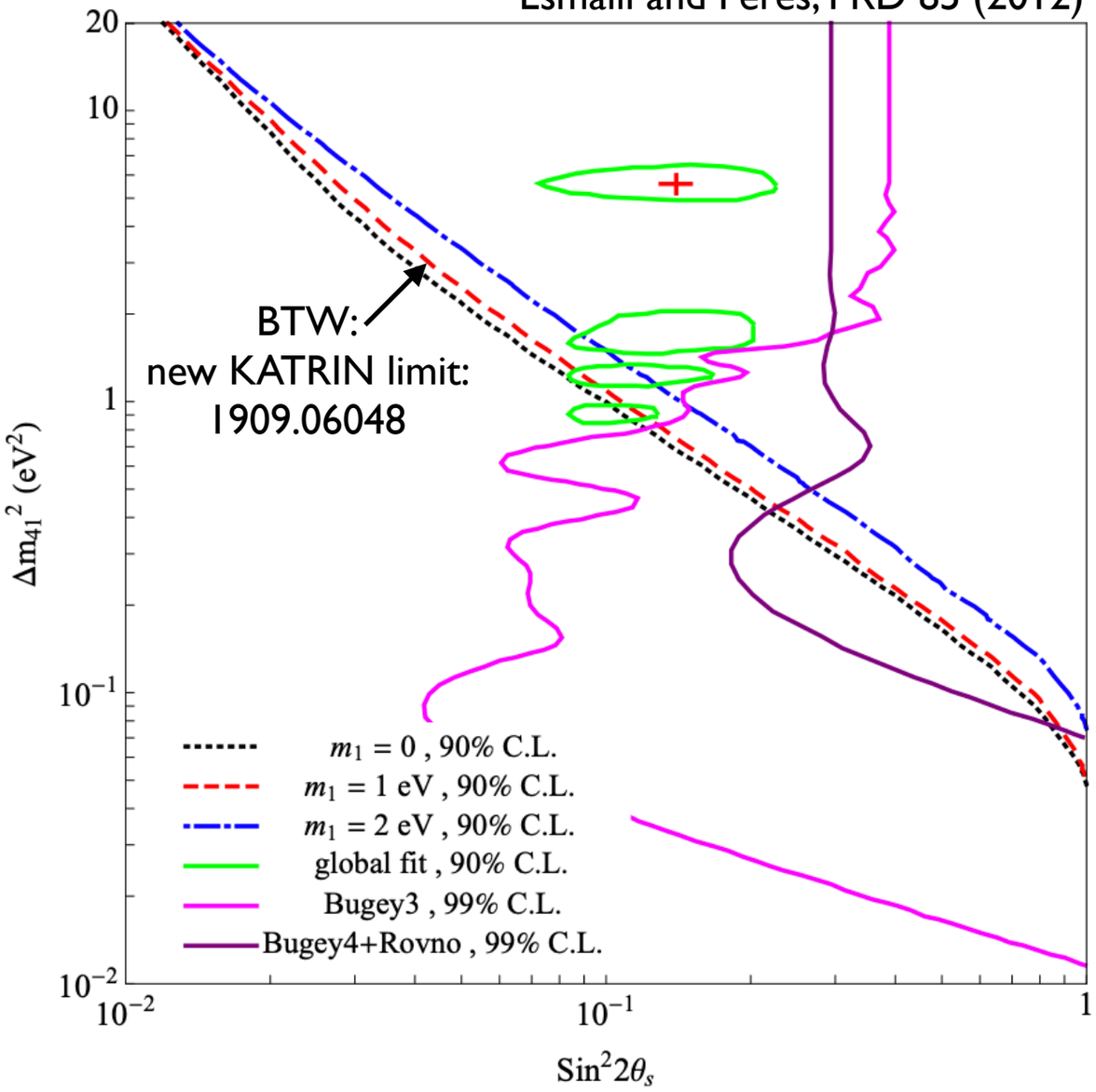




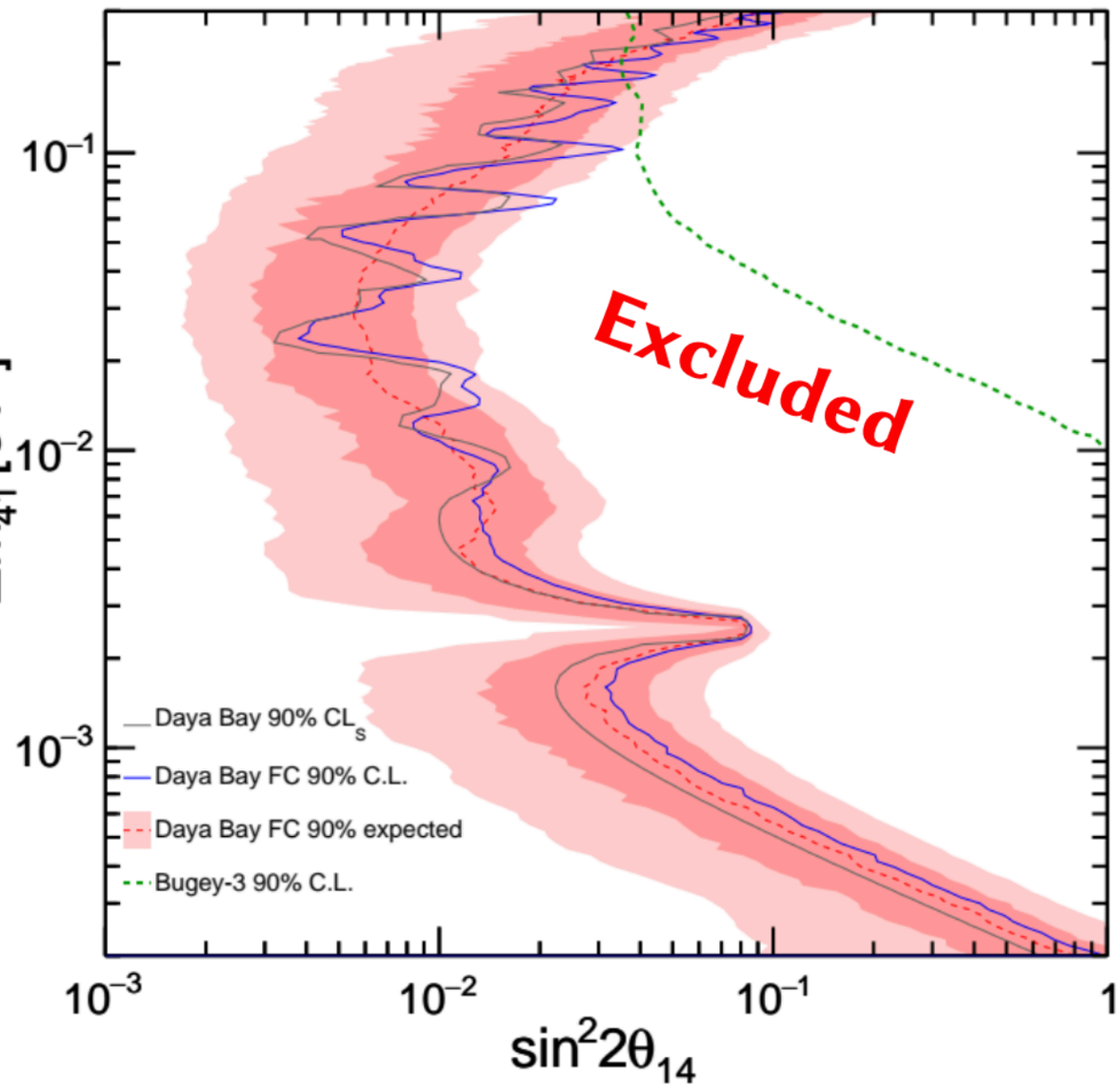
Taking off the Blinders: Other Δm^2

- Other experiments forego direct checks of 'anomalies' in favor of powerfully assessing oscillations at other Δm^2
  - Lower Δm^2: longer baseline reactor disappearance with Daya Bay
  - Higher Δm^2: beta spectrum distortion in direct mass experiments

Esmaili and Peres, PRD 85 (2012)

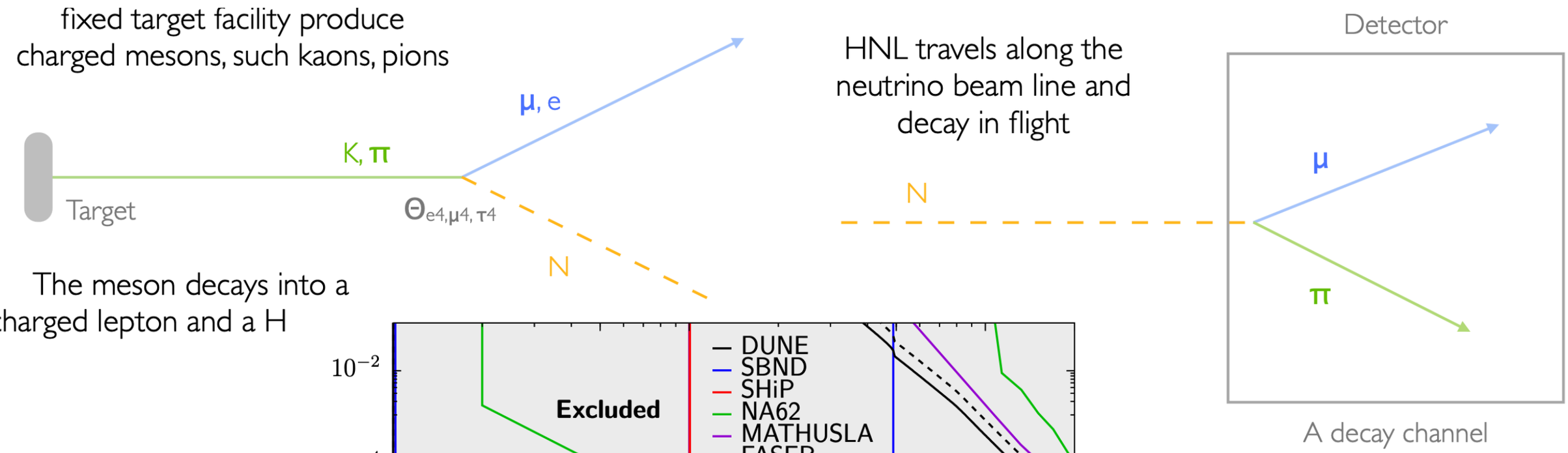


Daya Bay, NuFact 2019



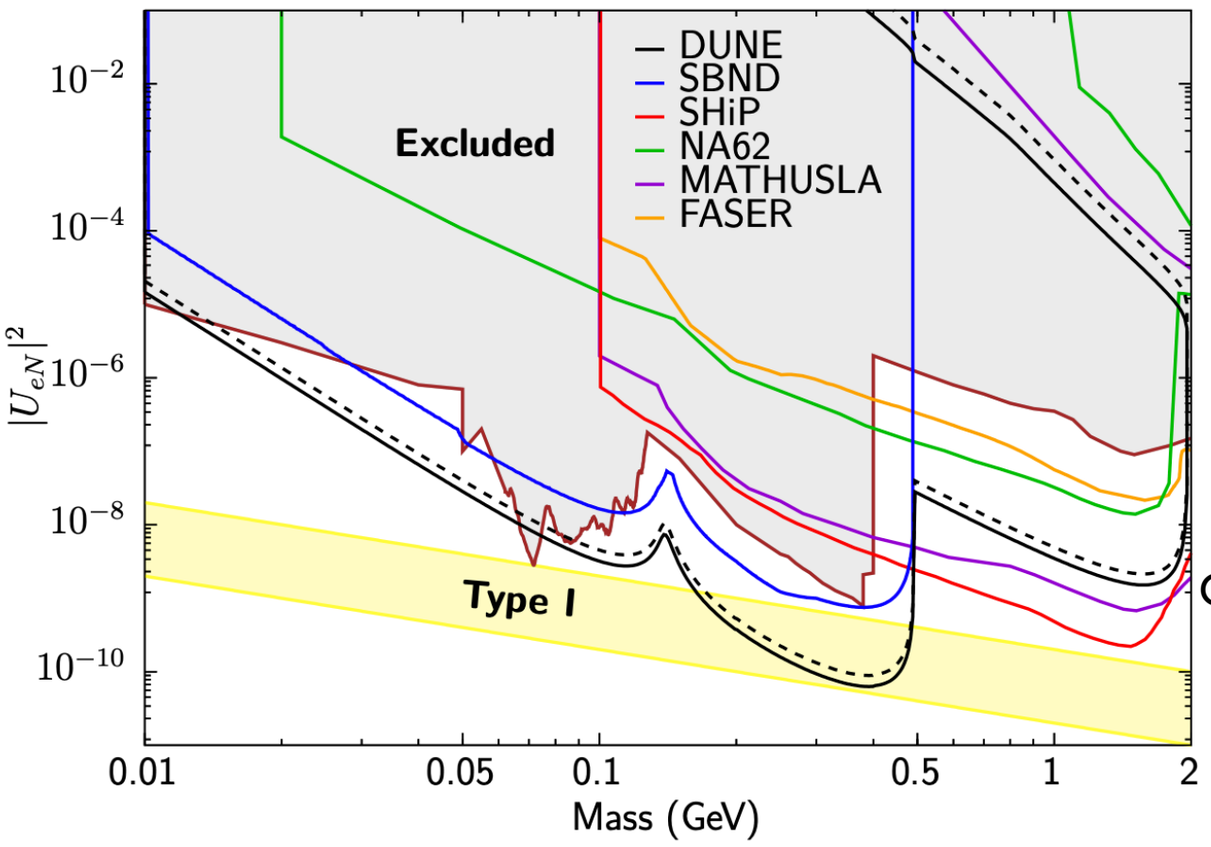
Taking off the Blinders: Mass Decades

- Other efforts completely leave the eV regime behind, and seek other sterile neutrinos — heavy ones, for example
  - Imminent plans for broader searches in MicroBooNE, Fermilab SBN



The meson decays into a charged lepton and a H

Diagrams from Y. Tsai, PONDD 2019

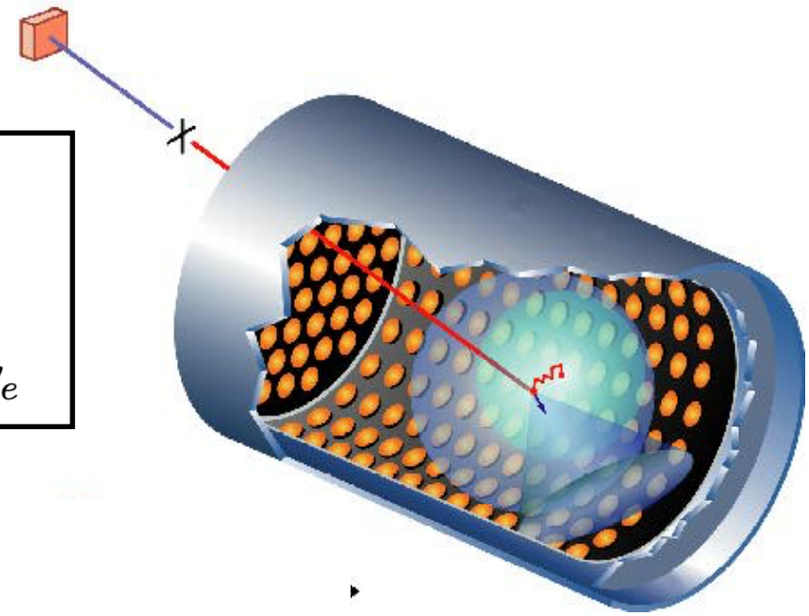


Next-Gen Neutrino Opportunities White Paper
C. Arguelles, et al,
[hep-ph]1907.08311

LSND Anomaly

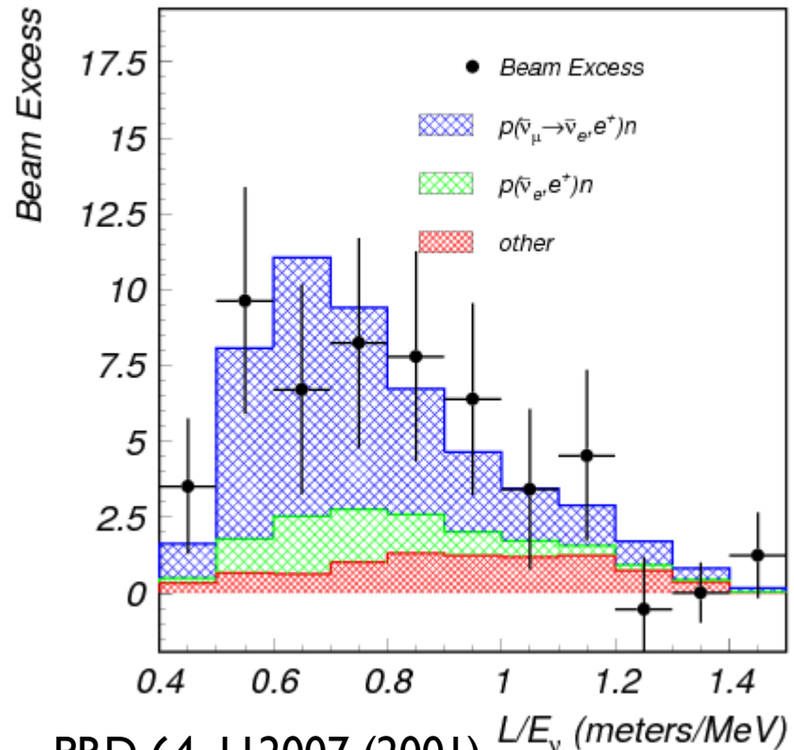
- LSND: the oldest of the 'anomalies' from beam decay-at-rest (DAR) neutrinos

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



  - 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

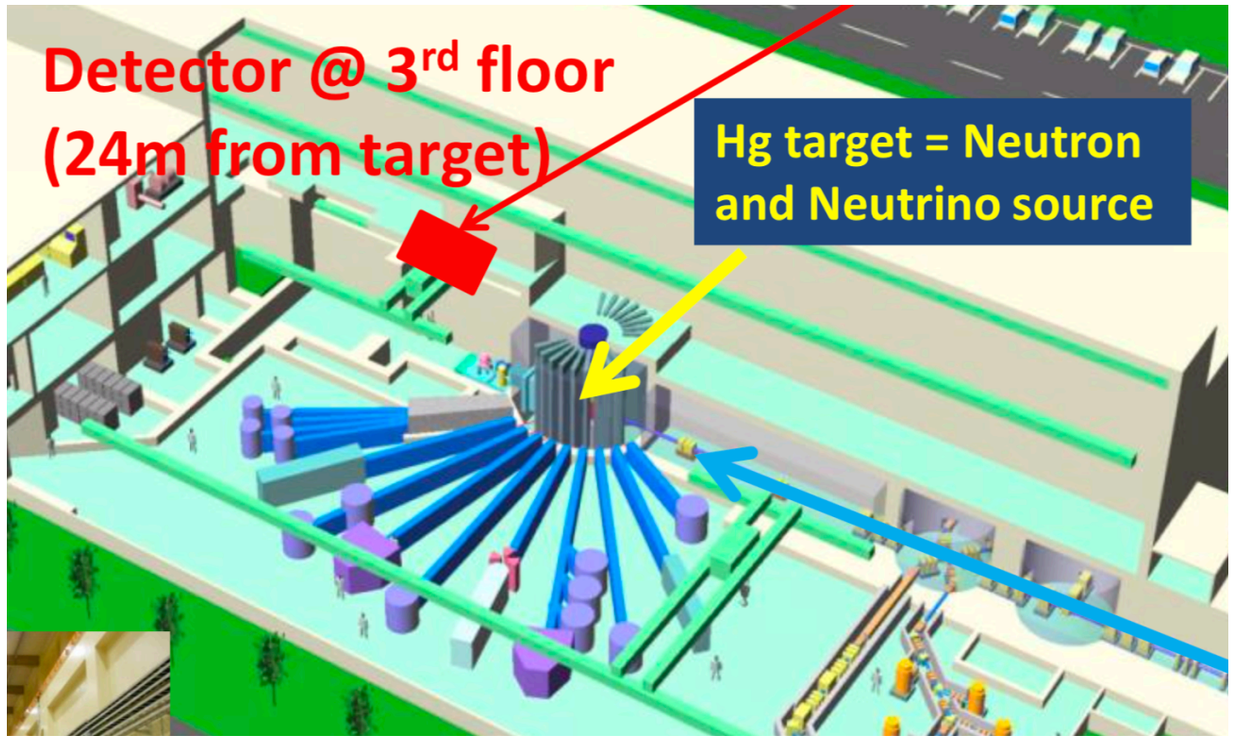
- Can we directly double-check DAR approach with an improved setup?
  - More powerful beam?
  - Lower backgrounds?

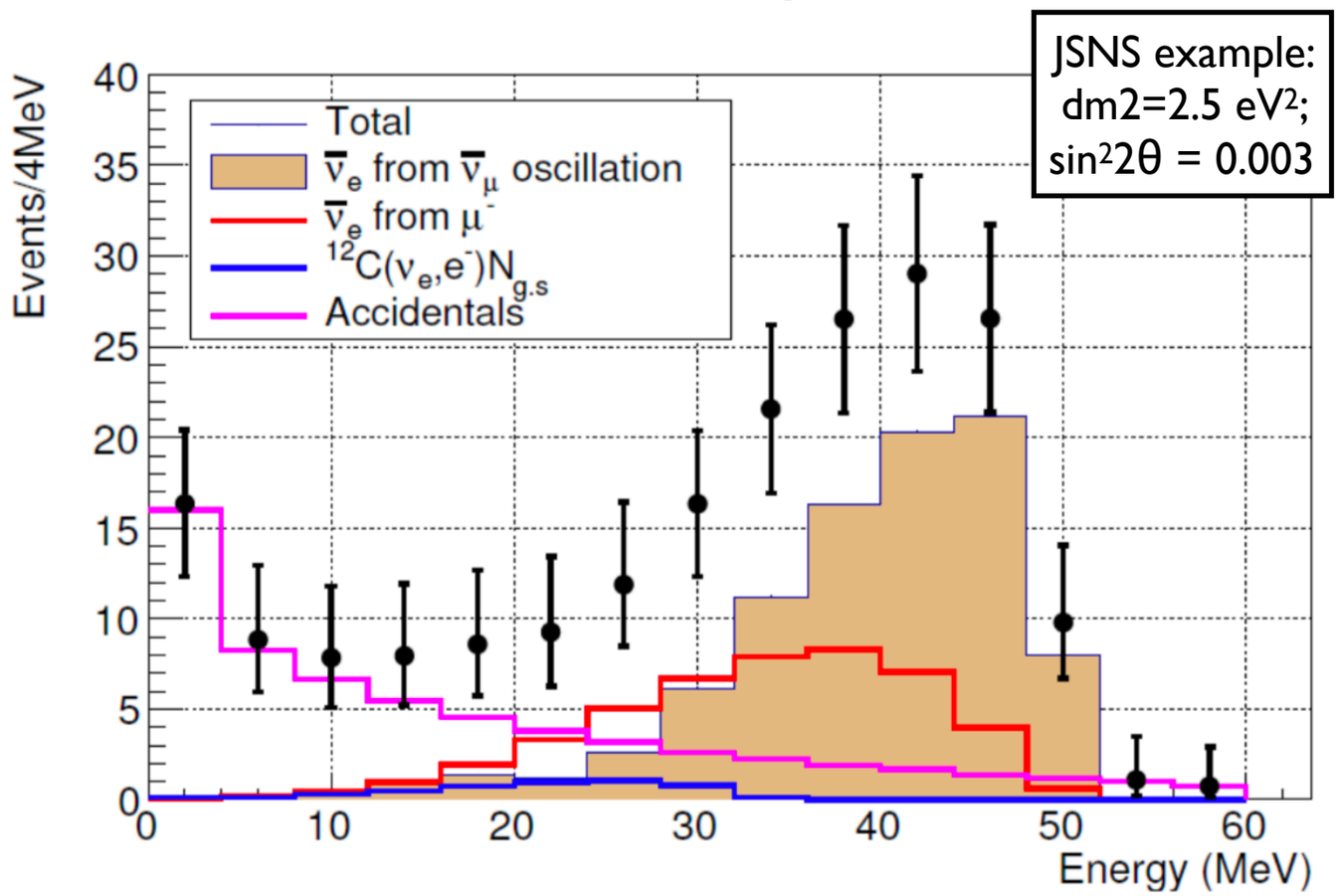


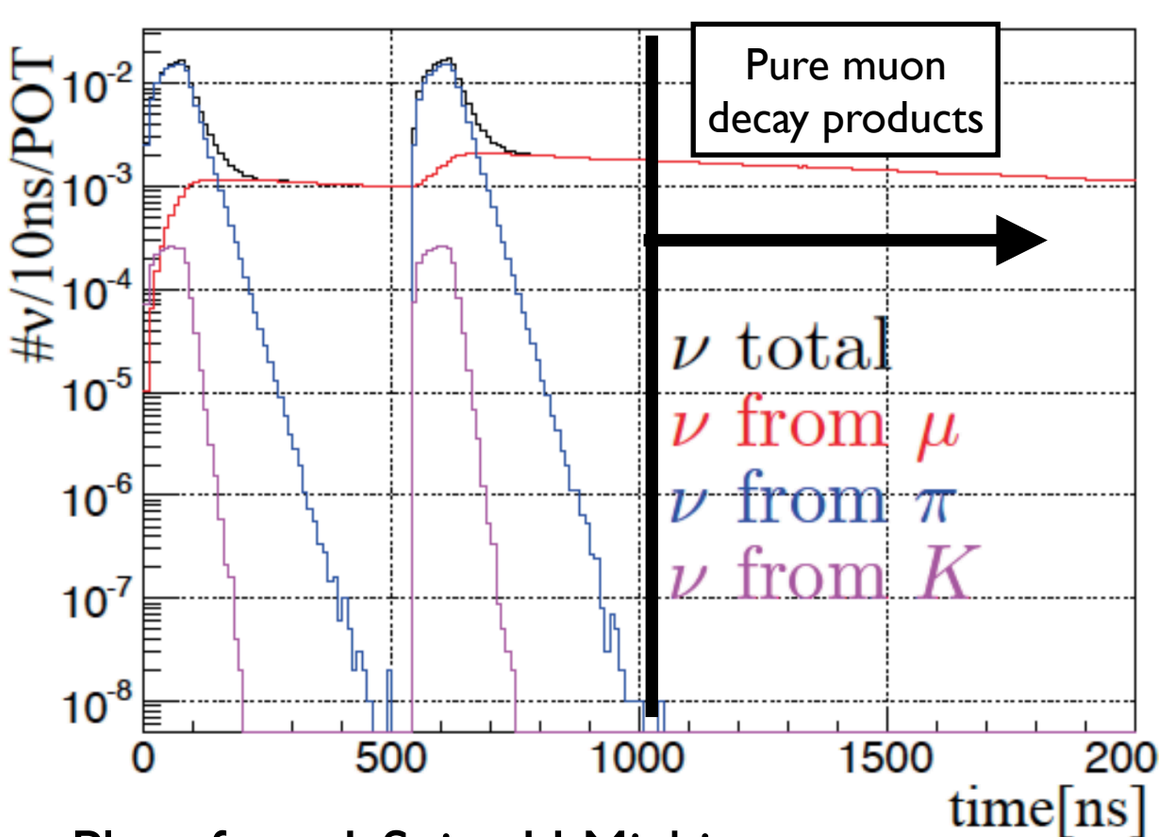
PRD 64, 112007 (2001)

JSNS^2

- JSNS^2 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 in early 2020

Acrylic vessel test installation

PMTs in transit to Japan

Tested baseline readout electronics

GdLS in ISO tank storage

Photos from J. Spitz, U Michigan

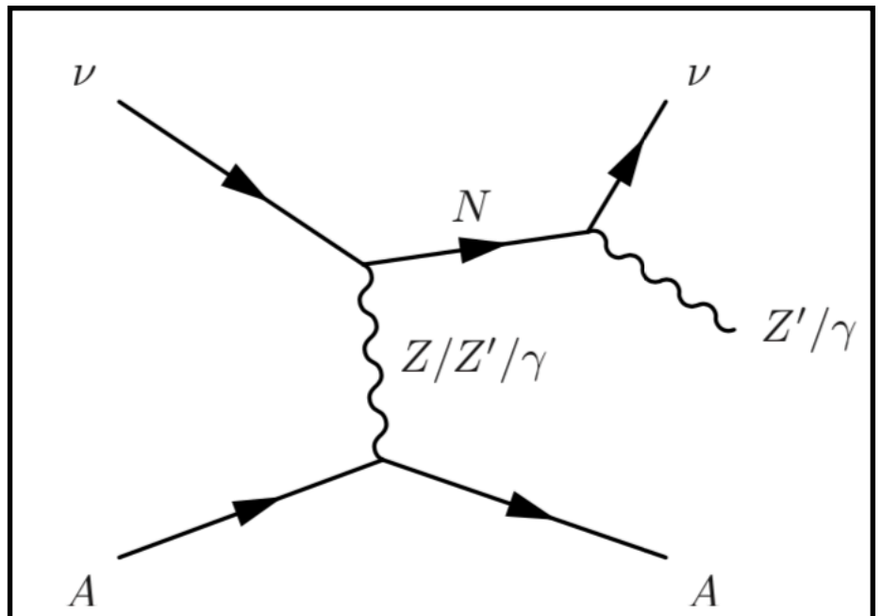
Summary

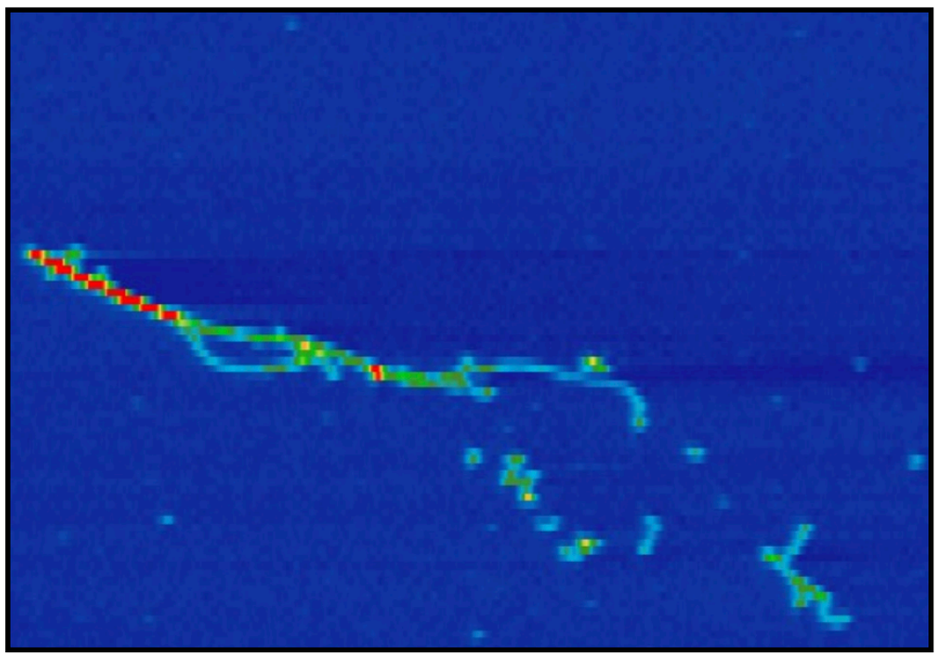
- We need short-baseline neutrino efforts to:
  - Probe the parameter space of new physics models (sterile neutrinos)
  - Directly address anomalous results that blur our picture of SM neutrinos
- Recent results have had a substantial impact:
  - Null-osc results from HEU and LEU spectral ratio measurements have eaten away at reactor-based sterile neutrino hints, while improved flux/spectrum results have clearly demonstrated inadequacy in flux models
  - MicroBooNE has made crucial steps in addressing MiniBooNE's excess: automated ν_e and ν_μ 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

SBN: Other BSM Goals Too!

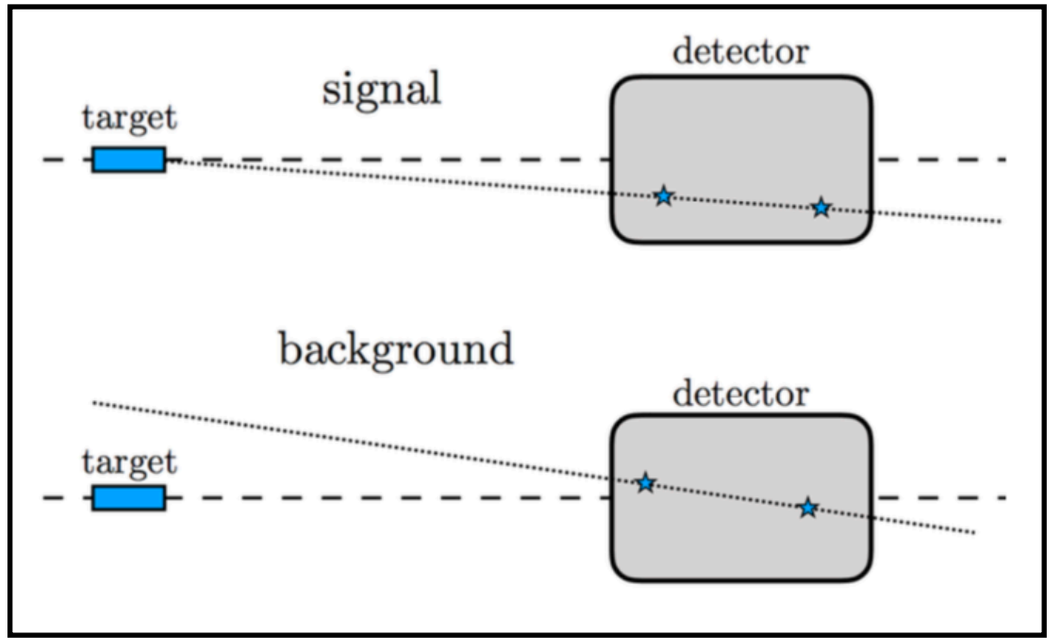
Dark Neutrino Portal

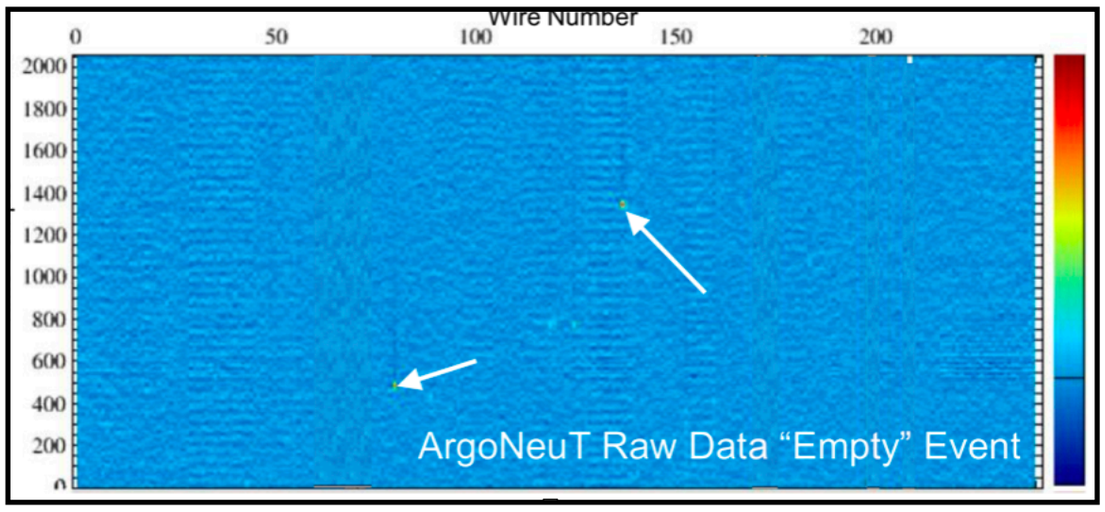




Bertuzzo et al, PRL 121 241801 (2018)
Machado, Palamara, Schmitz, hep-ex[1903.04608]

Millicharged Particles



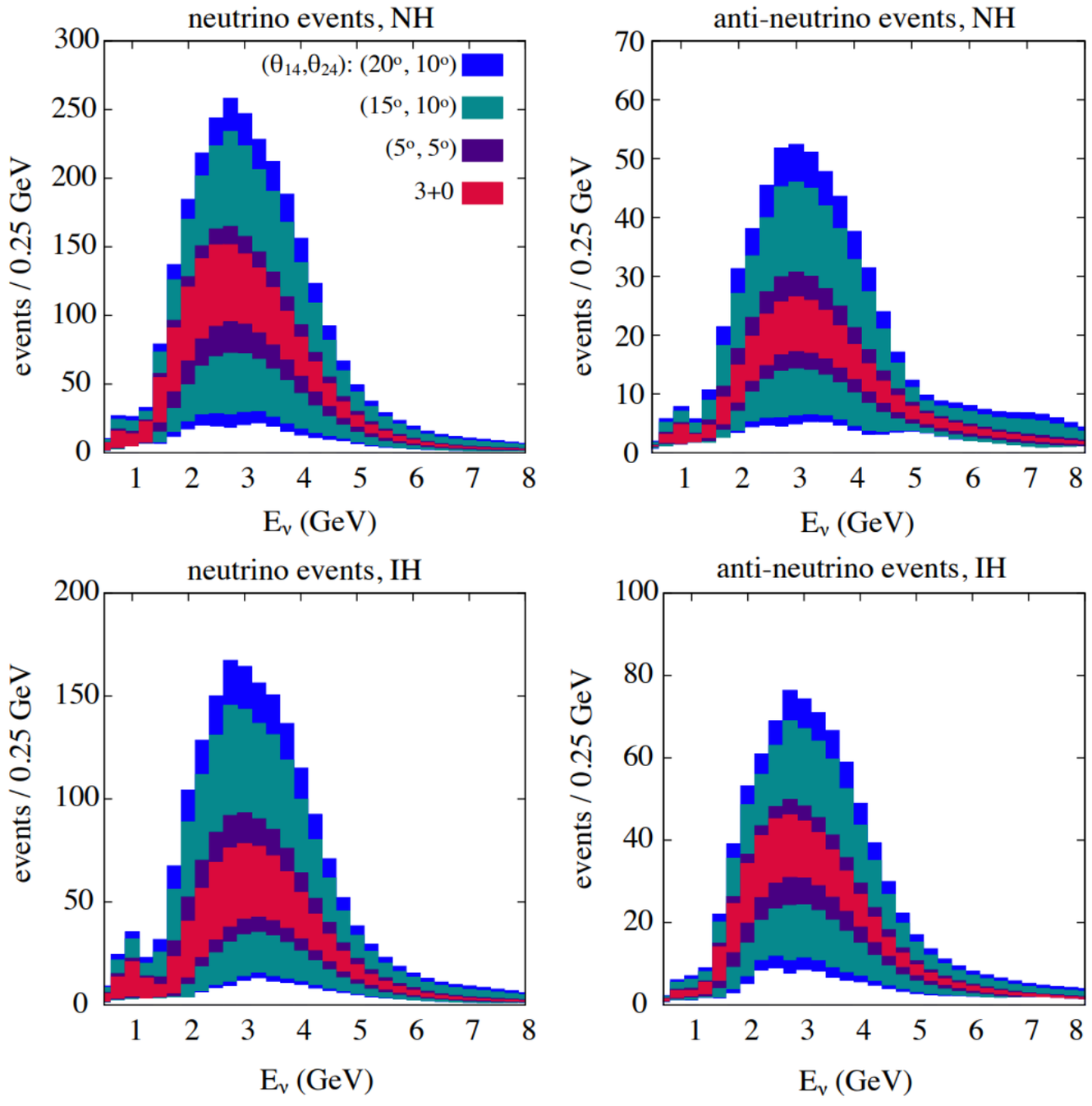


Harnik, Liu, Palamara JHEP 07:170 (2019)

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 θ_{14} and θ_{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

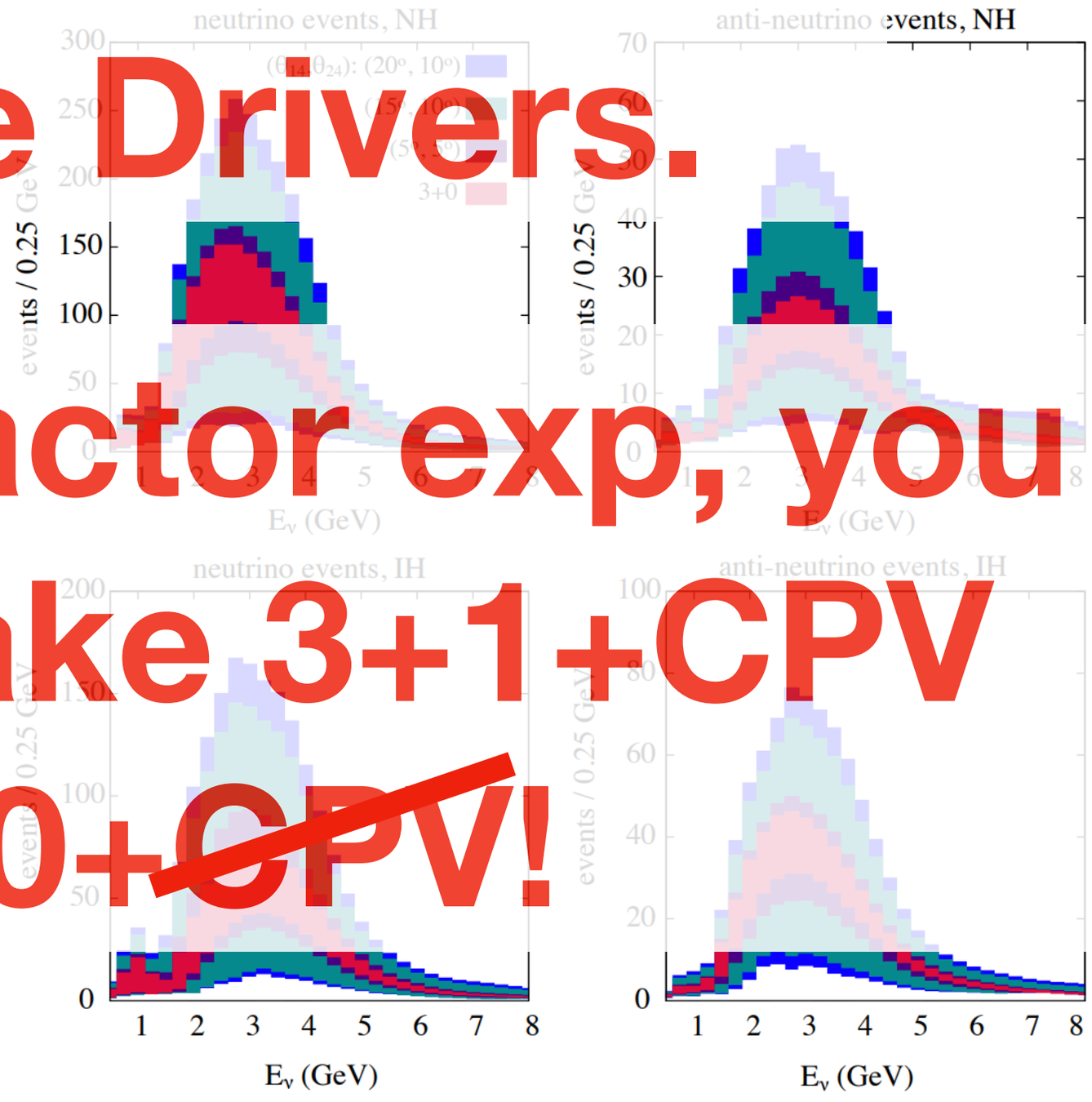


Notes: LBL CP-Violation

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(ν_e), ν_e appearance signals can vary a TON.
  - Once you get θ_{14} and θ_{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!

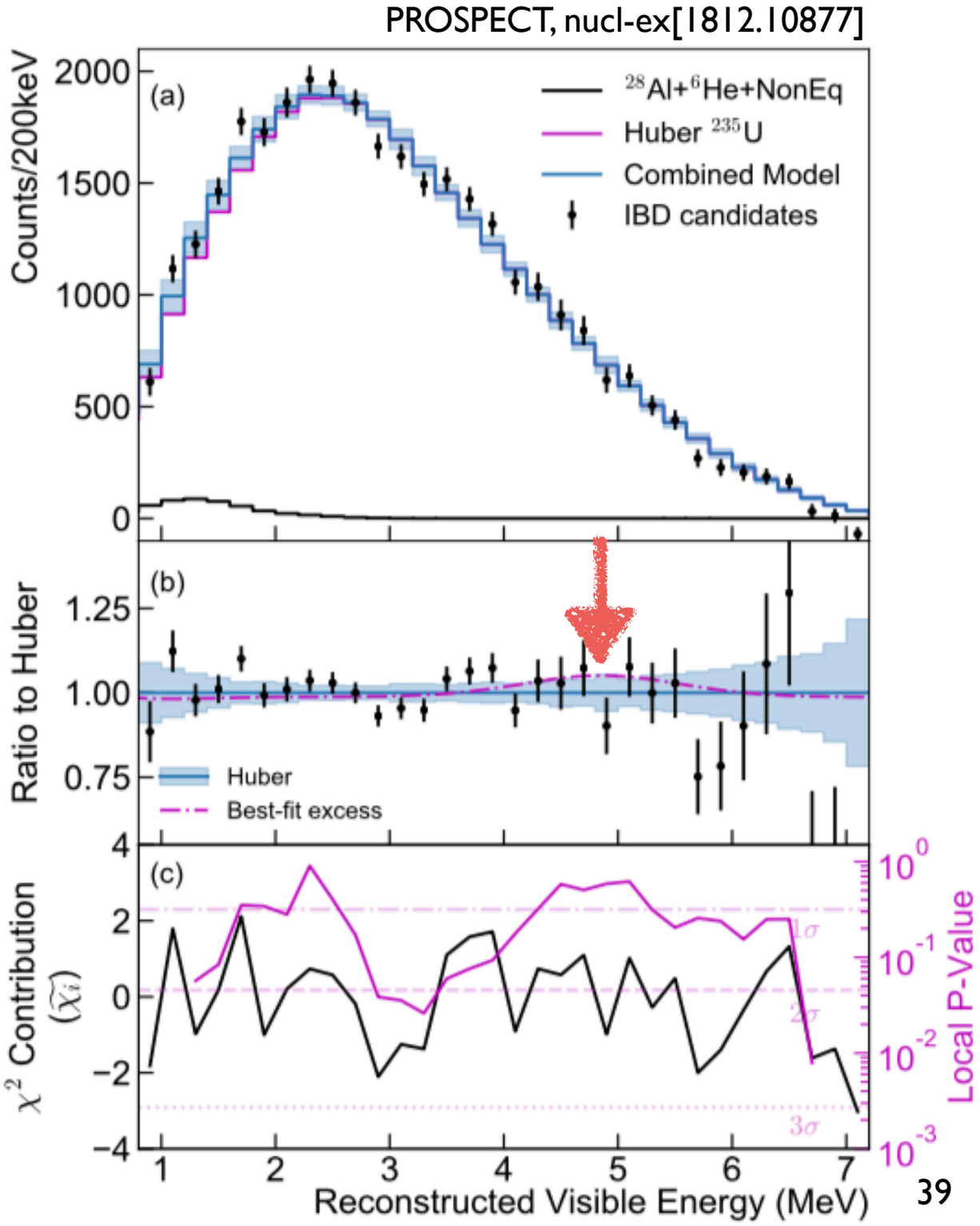
W/O SBL reactor exp, you might mistake 3+1+CPV for 3+0+~~CPV~~!



Isotopic Origins: PROSPECT

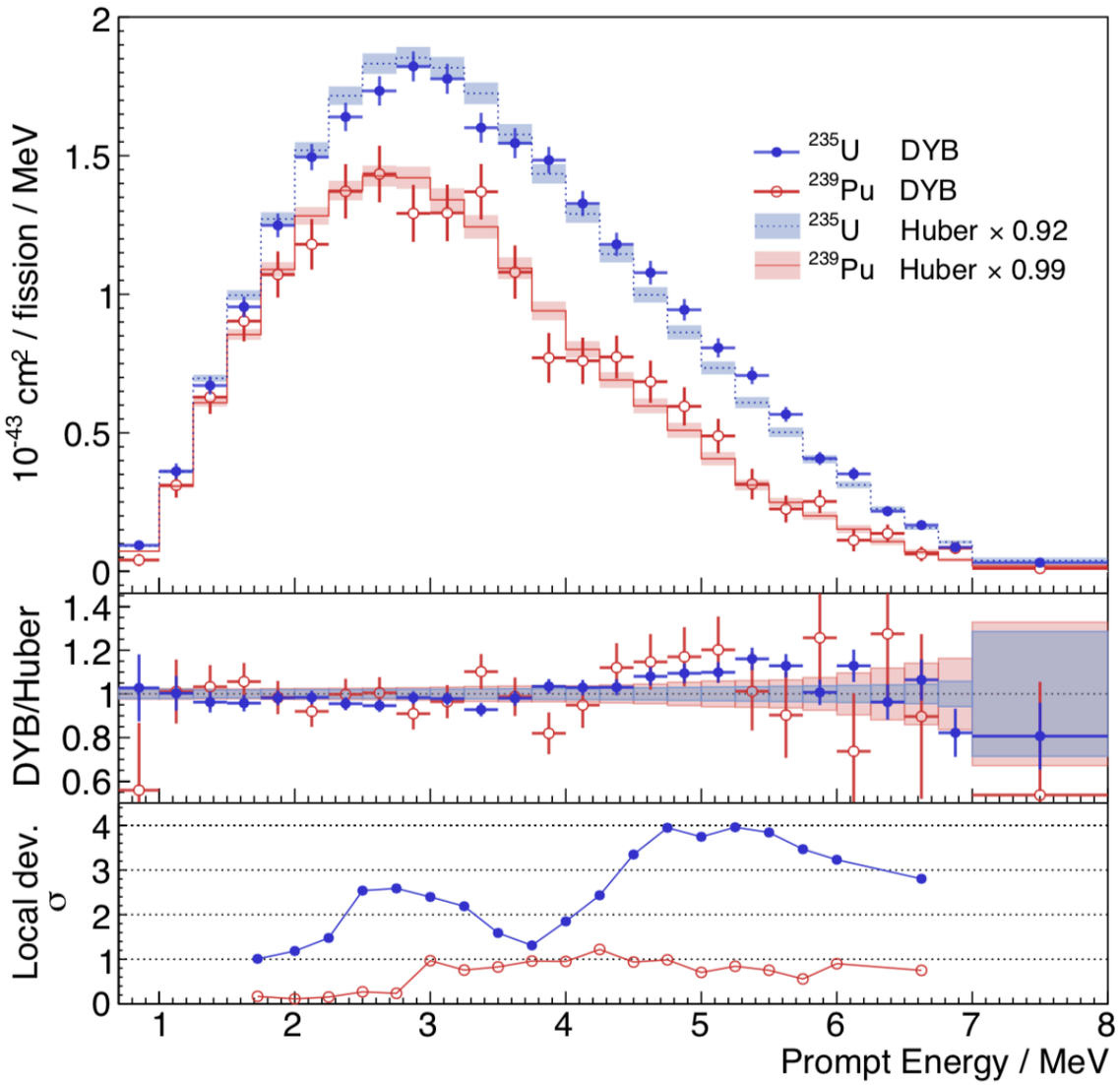
- Measure spectrum when burning <u>only</u> ^{235}U
- PROSPECT has done this!
- How does PROSPECT compare to 'bump' in θ_{13} experiments?
  - PROSPECT relative bump size WRT to Daya Bay: 69% ± 53%
  - ~consistent with 'no bump' (0%) and 'DYB-sized bump' (100%)
    - Need more stats to differentiate
  - '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**

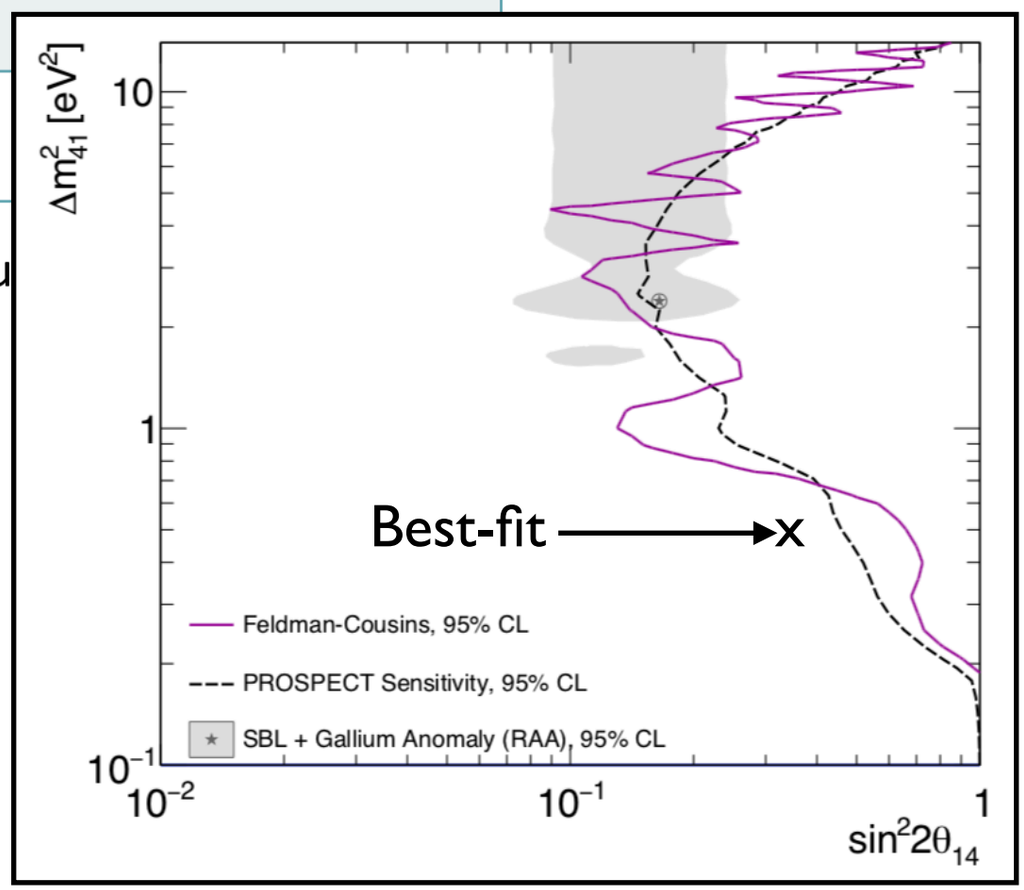
- All datasets are ~compatible with a bump of some kind existing in HM
- No single hypothesis is compatible with all claims; 'Equal' would be a good hypothesis, if not for RENO's (questionable?) result

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 those problems

- [illegible] methods:
  - [illegible] ile ν oscillation

- We say SV is less compatible with data than it actually is

- Illustrates an importance of using Feldman-Cousins