BSM From Reactors

December 19, 2023

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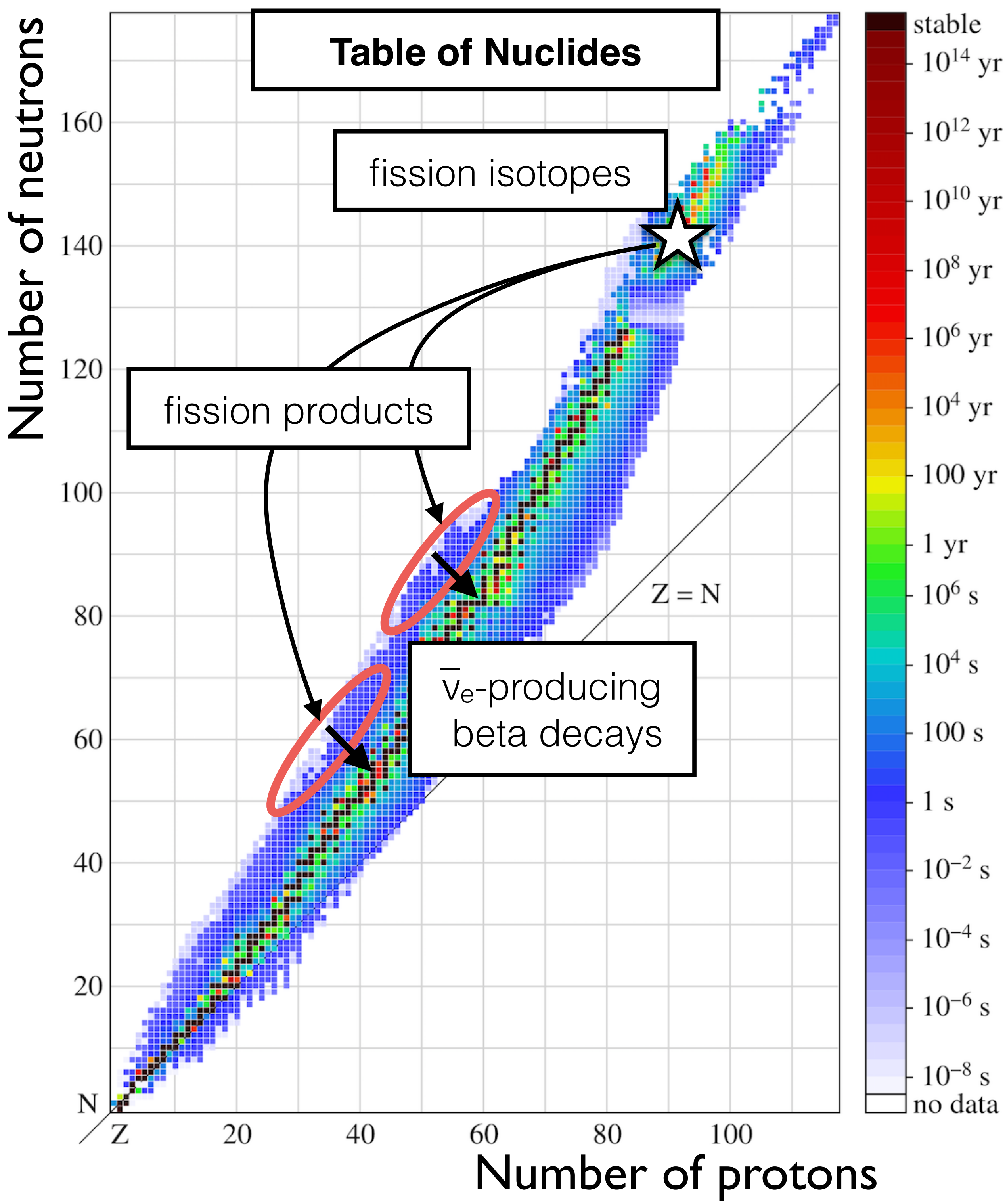
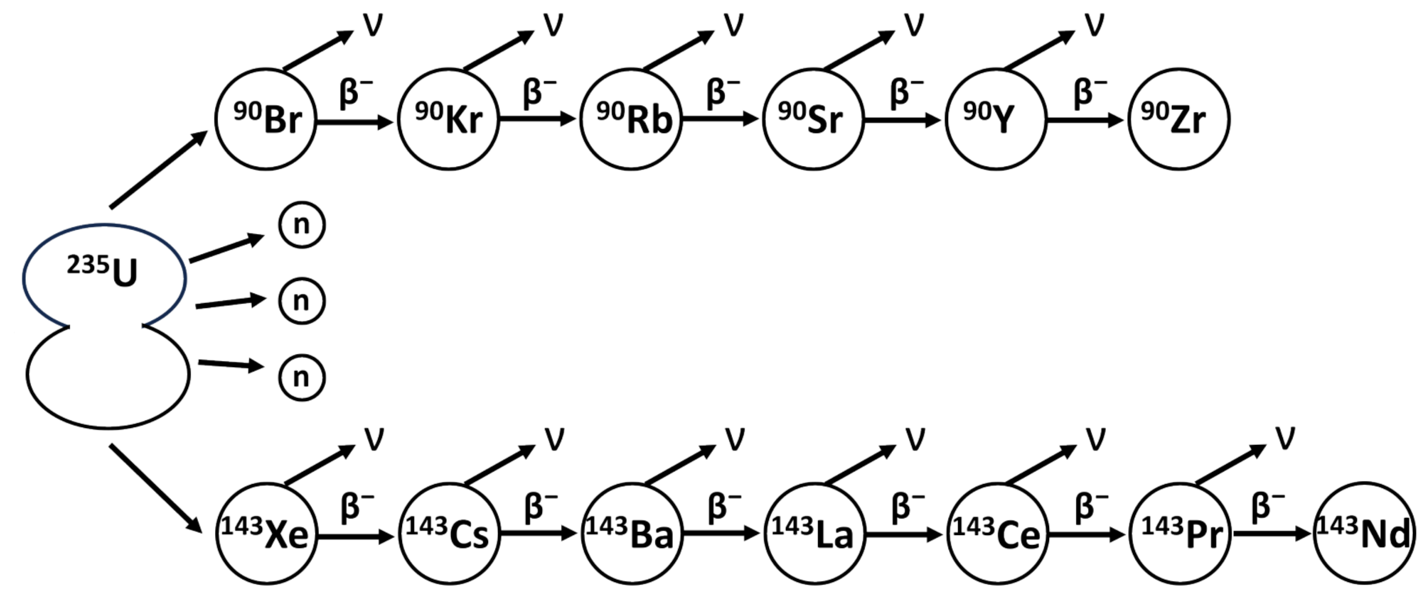
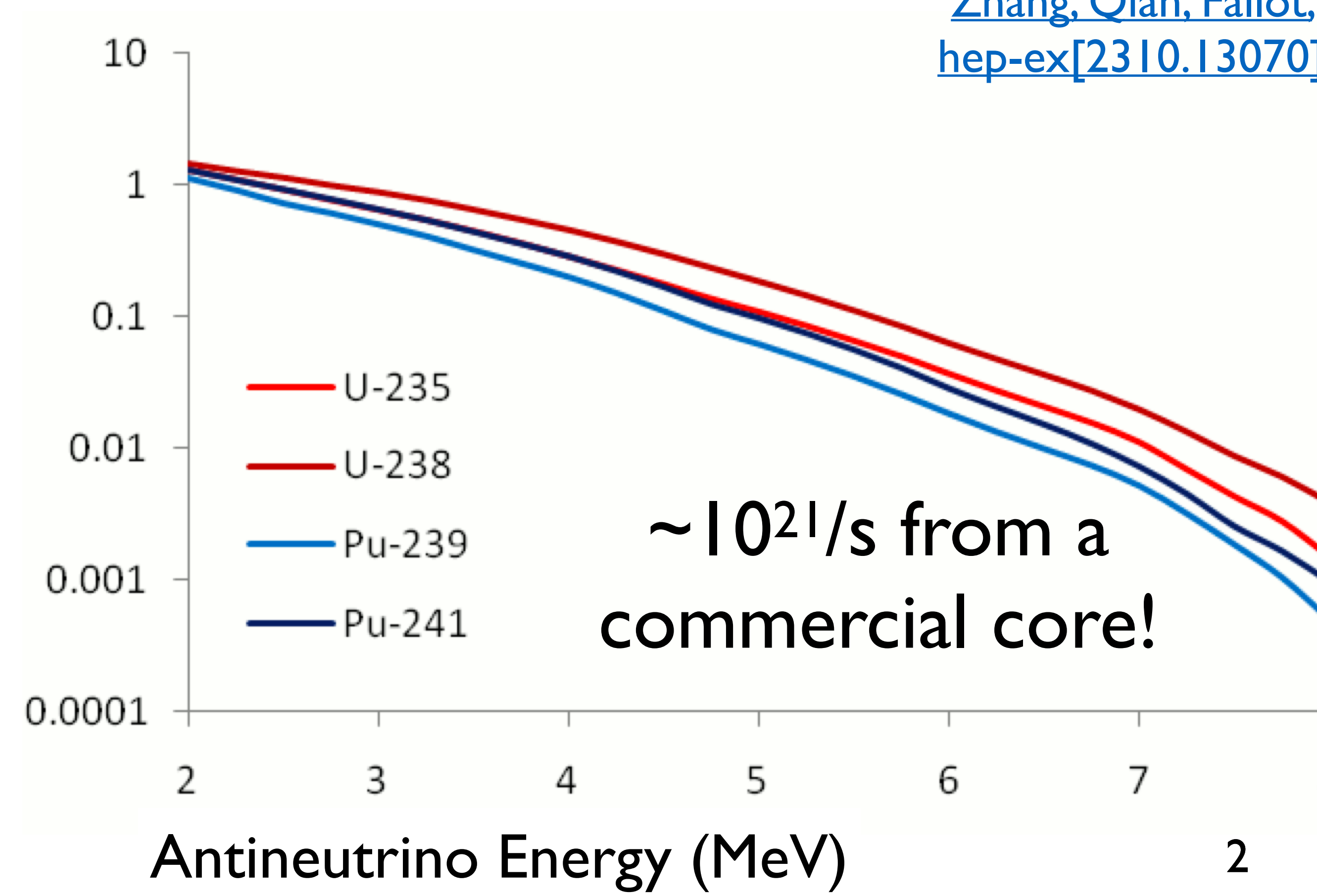
How Do Reactors Make Neutrinos?

- Heavy isotopes fission make lighter isotopes and energy… and neutrons, betas, gammas and **electron antineutrinos**



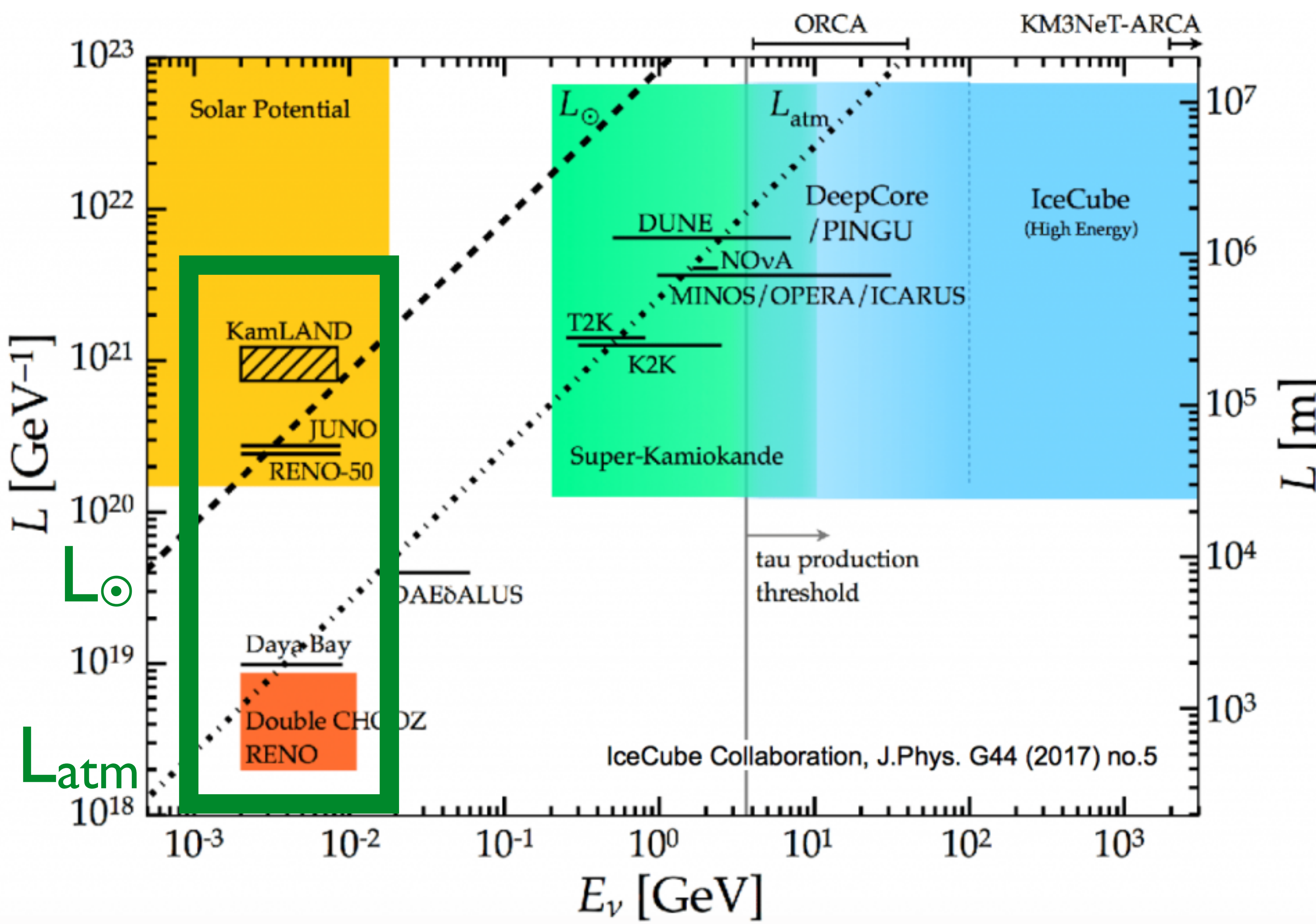


Zhang, Qian, Fallot, hep-ex[2310.13070]



Reactors and Standard Model Oscillations

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Took many experiments to get us here!
- Baselines (L): >km-scale
- Note reactors straddling both key L/E sectors



Reactors and Standard Model Oscillations

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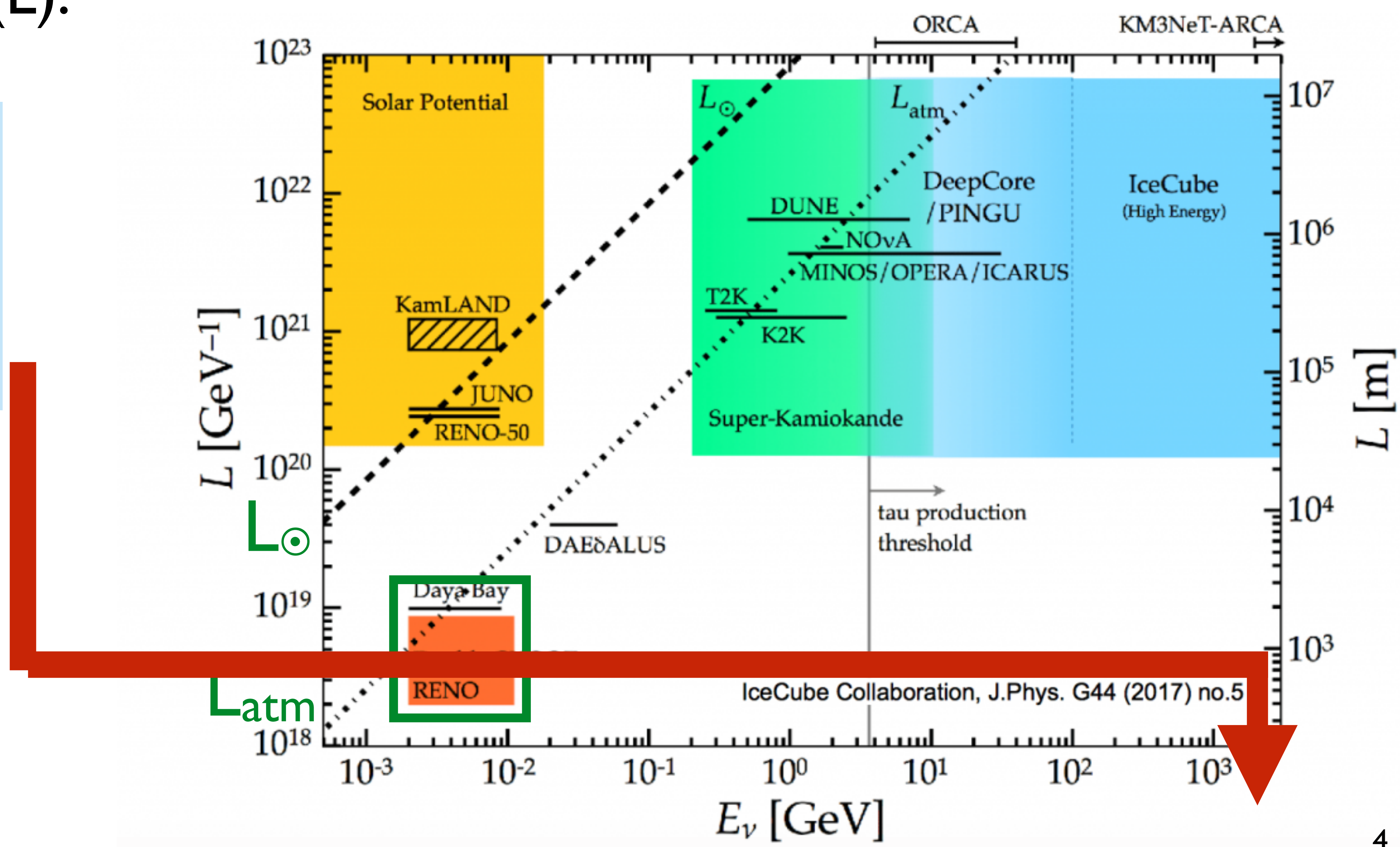
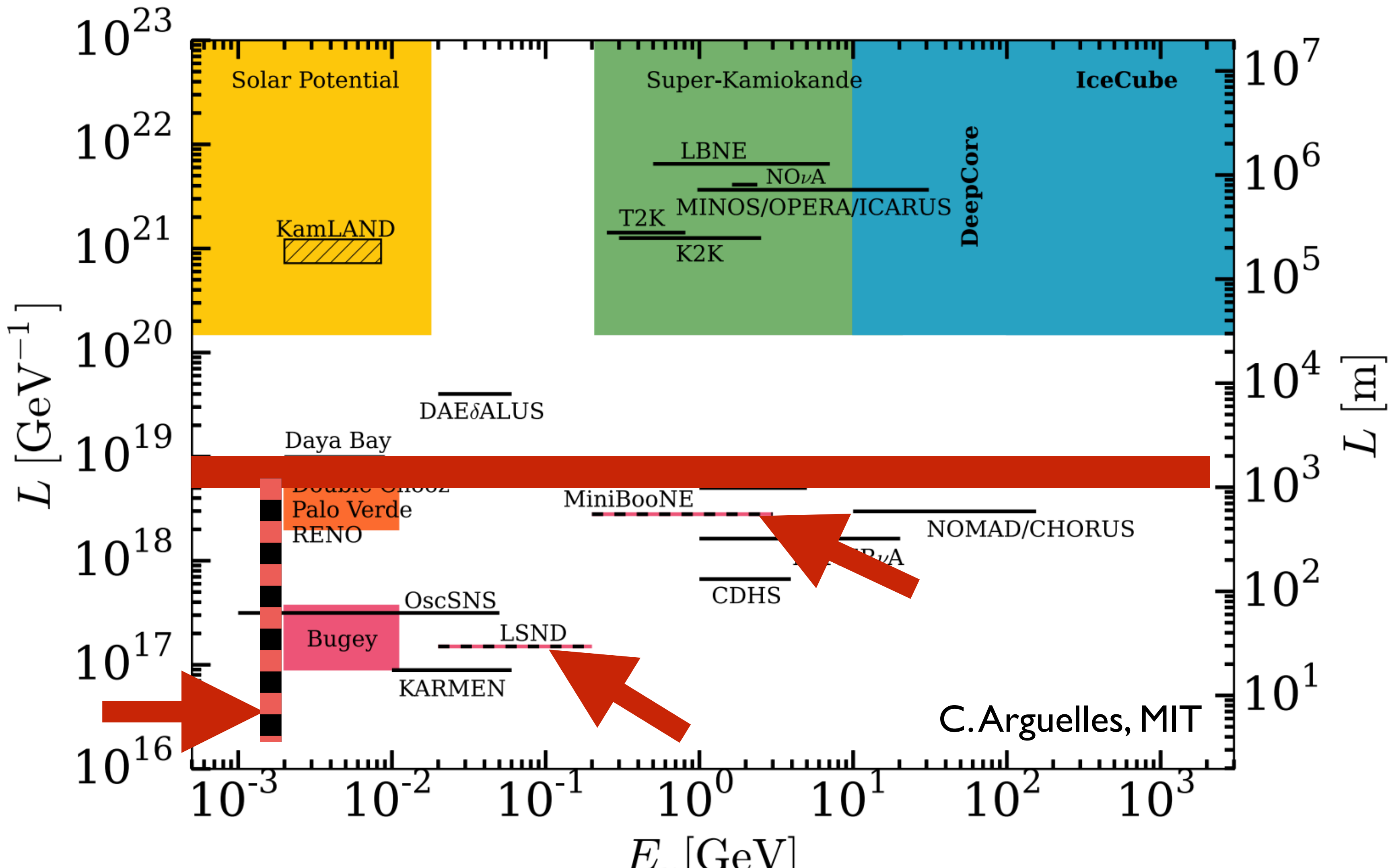
  >km-scale

- Let’s go HERE!
- WHY go here?



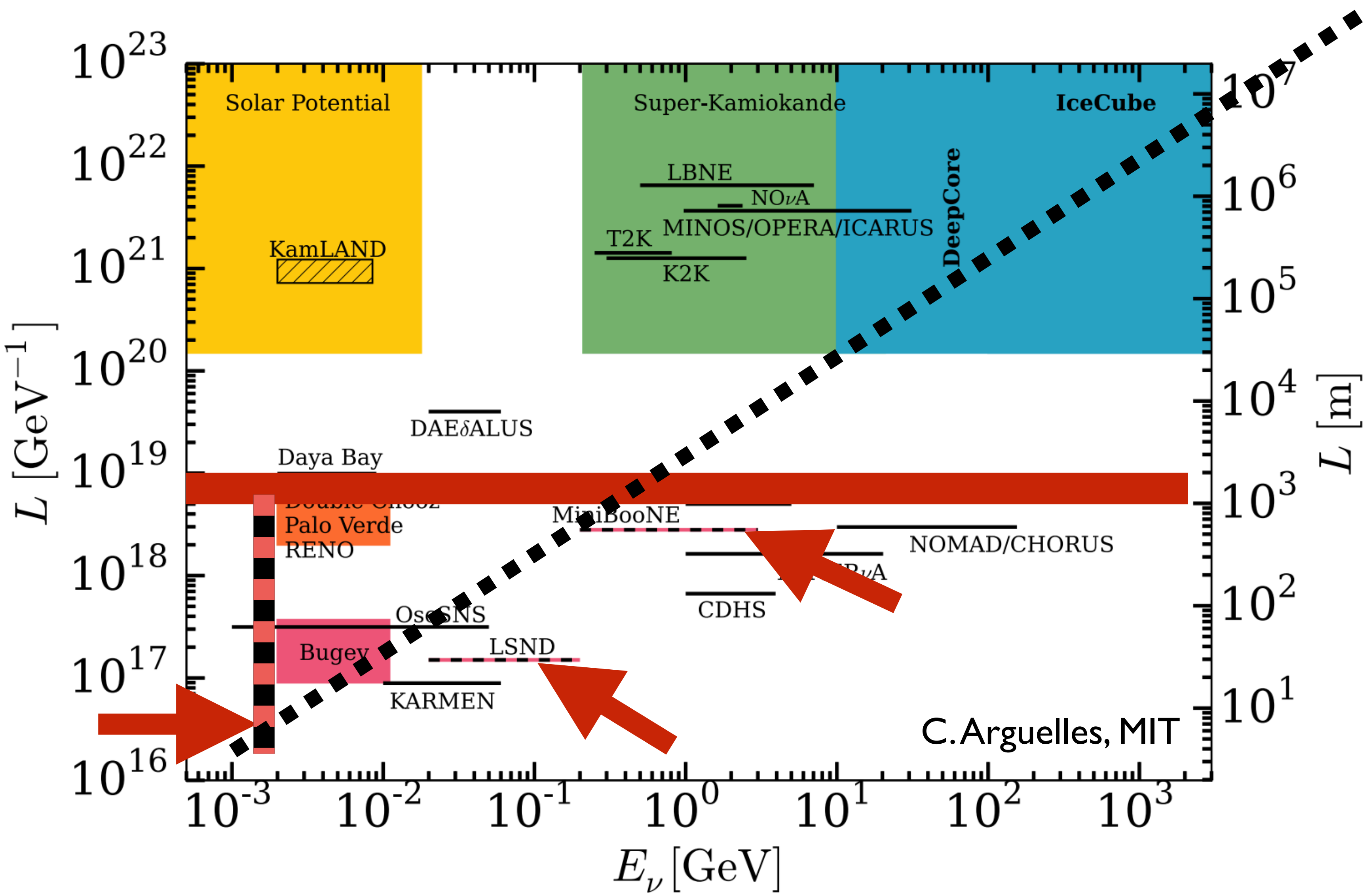
Neutrino Anomalies

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Hints of new physics beyond Standard Model oscillations?!



New Neutrino Mass States?

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Hints of new physics beyond Standard Model oscillations?!
  - Additional neutrino mass states: **sterile neutrinos?** Other new physics?



Other New Physics?

- Once you’ve made new mass states, how do they behave?
  - Do they decay? Palomares-Ruiz et al, JHEP 09 (2005) DeGouvea, et al, JHEP 2019:141 Balantekin et al, PLB 789 (2019) Dentler, et al, PRD 101 (2020)
  - Do they have couplings to larger hidden sector? Magill, et al, PRD 98 (2018) Ballett, et al, PRD 99 (2019)
  - Why not have more than one new state? Kopp et al, JHEP 2013:50 Vergani et al, PRD 104 (2021) Abdullah et al, PRD 104 (2021)

    Summary Snowmass Whitepaper:[hep-ex]2203.07323
- If we crack open a hidden sector, who knows what we’ll find!?

Dark Ale Lager

but also:

Double Fruit Smoothie Sour

‘Lighter HNL?

Pastry Stout

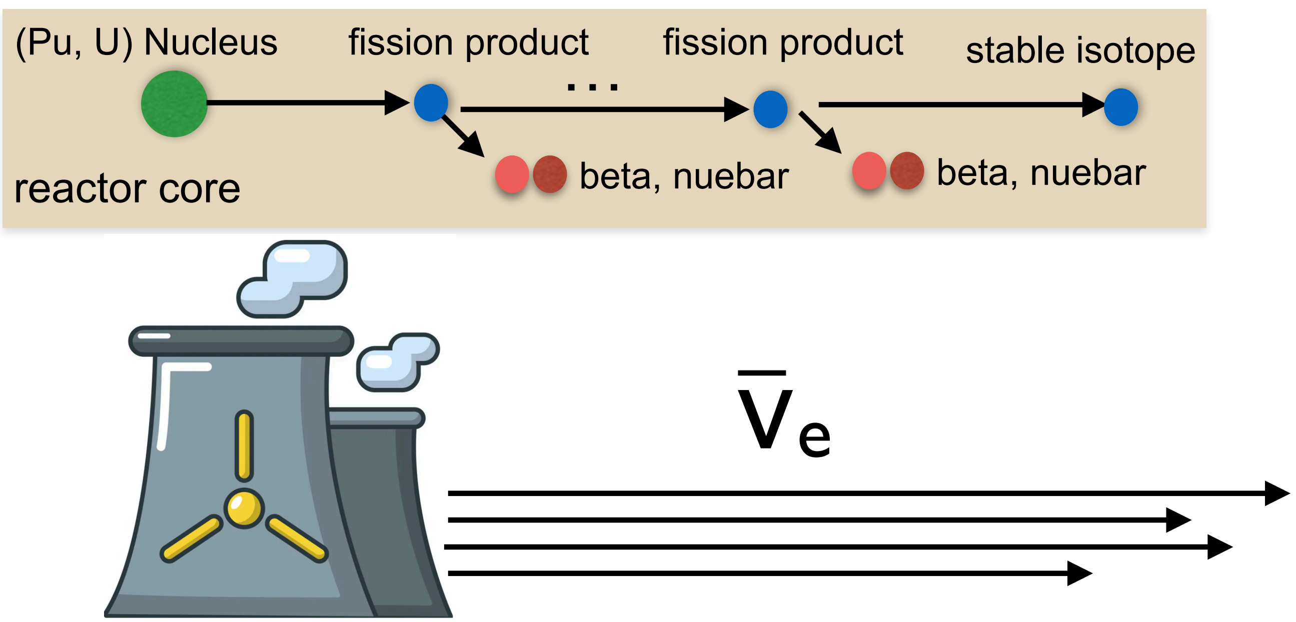
‘Heavier’ HNL?

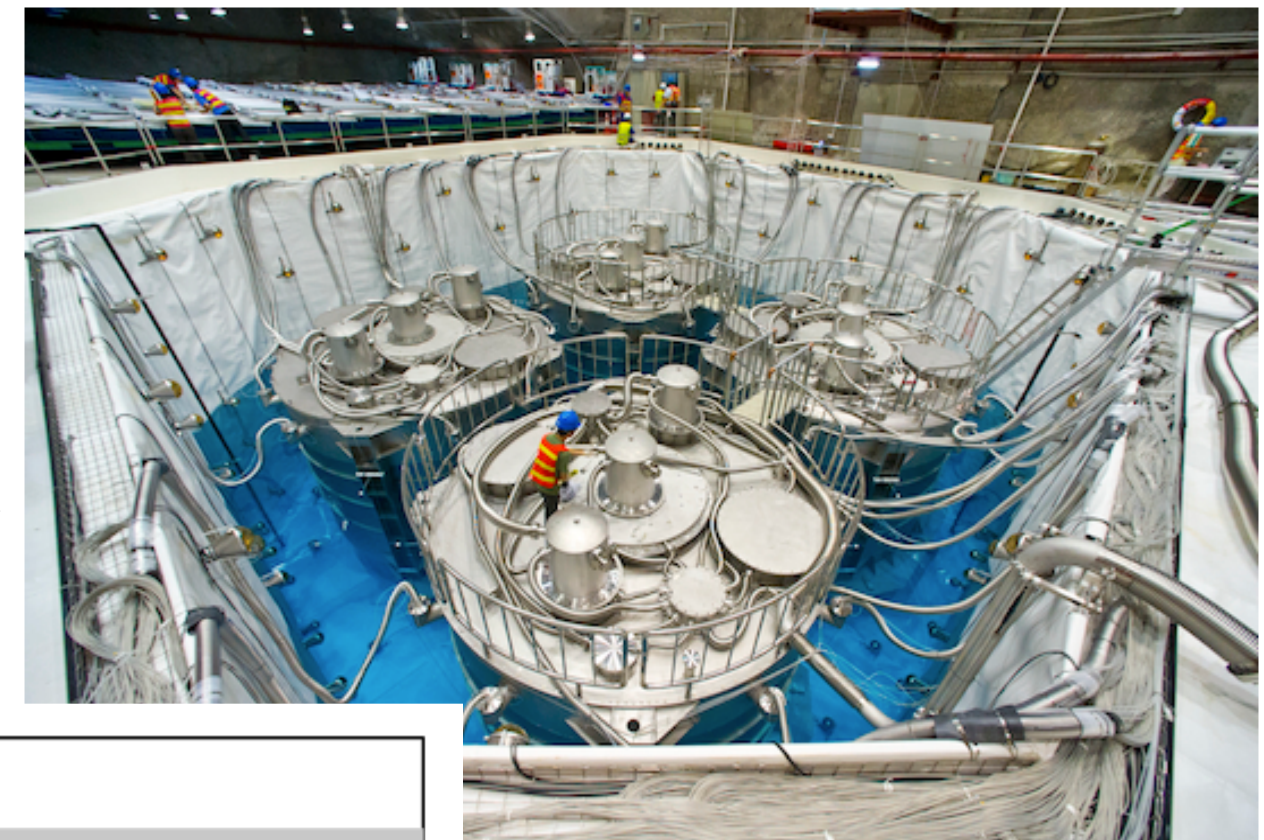
Coffee Blonde

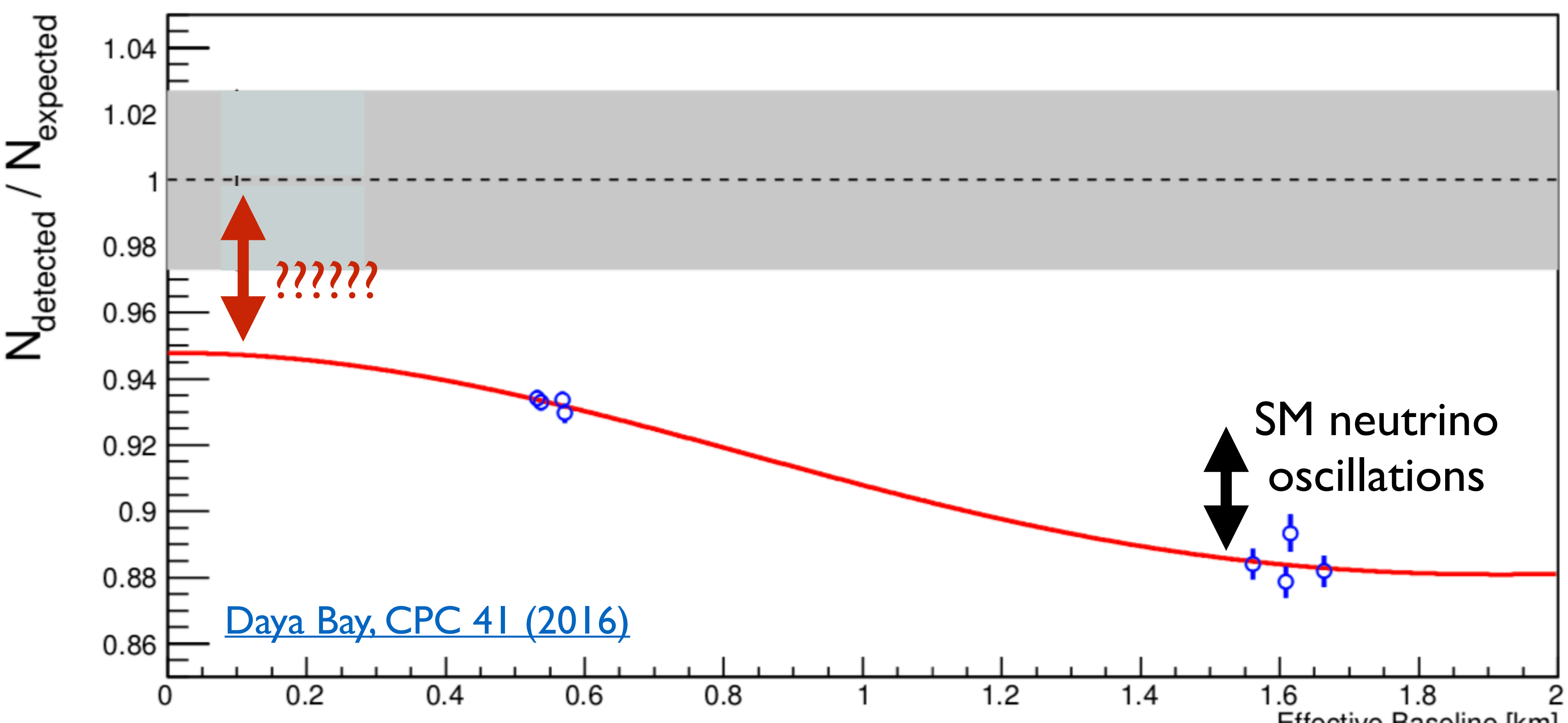
New Mediator?

Reactor Anomaly?

- Deficits in electron flavor detection rates at nuclear reactors







So We've Heard From P5…

- From the P5 Report, recapping the last decade, and outlining US particle physics strategy for the next decade:

> Over the past decades neutrino oscillation searches at length/distance scales of 1 MeV/m have found a number of anomalous results: The liquid scintillator neutrino detector (LSND) anomaly, the reactor antineutrino anomaly, the MiniBooNE low-energy excess and the gallium anomaly. These anomalies have not been confirmed, and the reactor antineutrino anomaly has been recently resolved. The remaining phase space

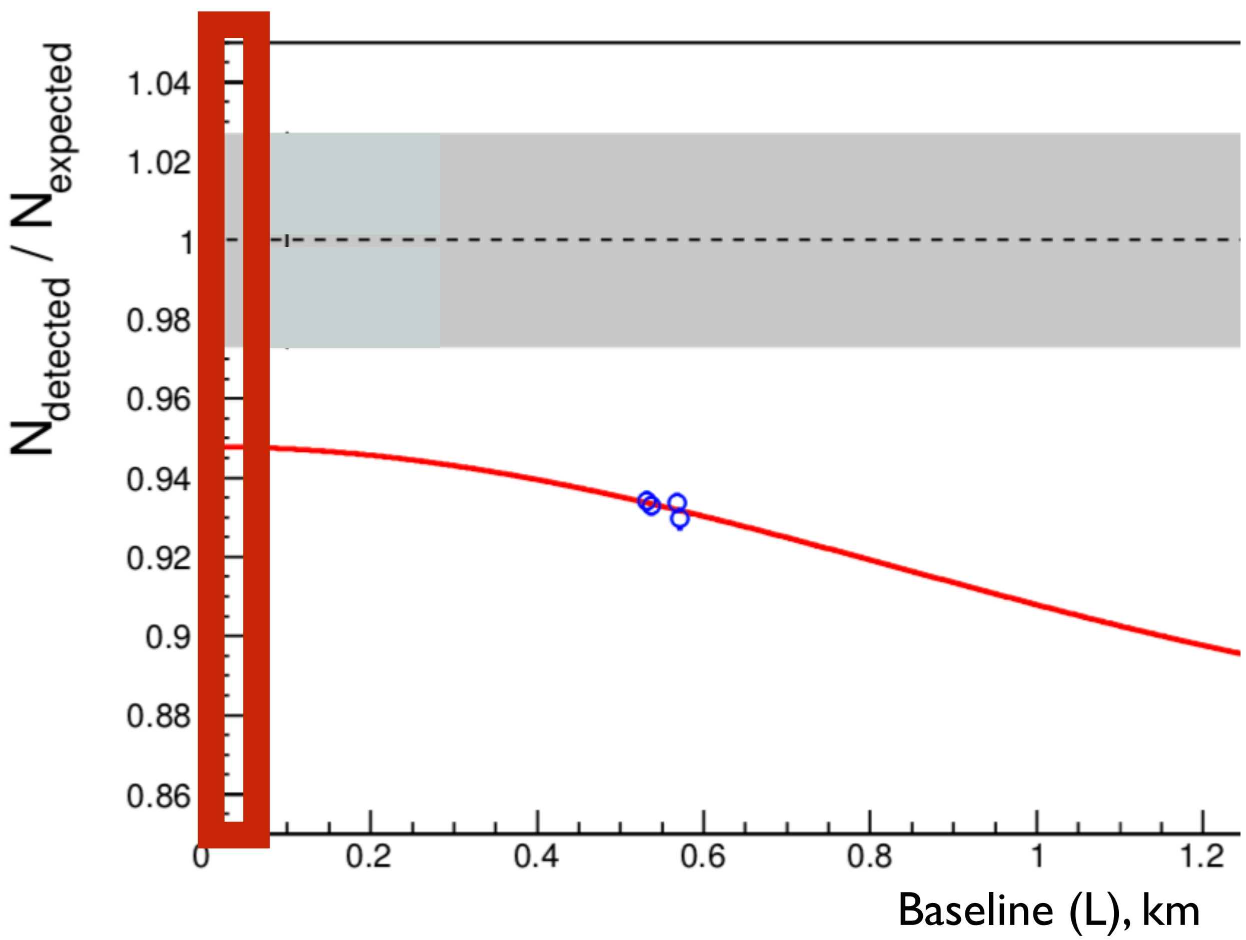
'RAA'

Exploring the Quantum Universe

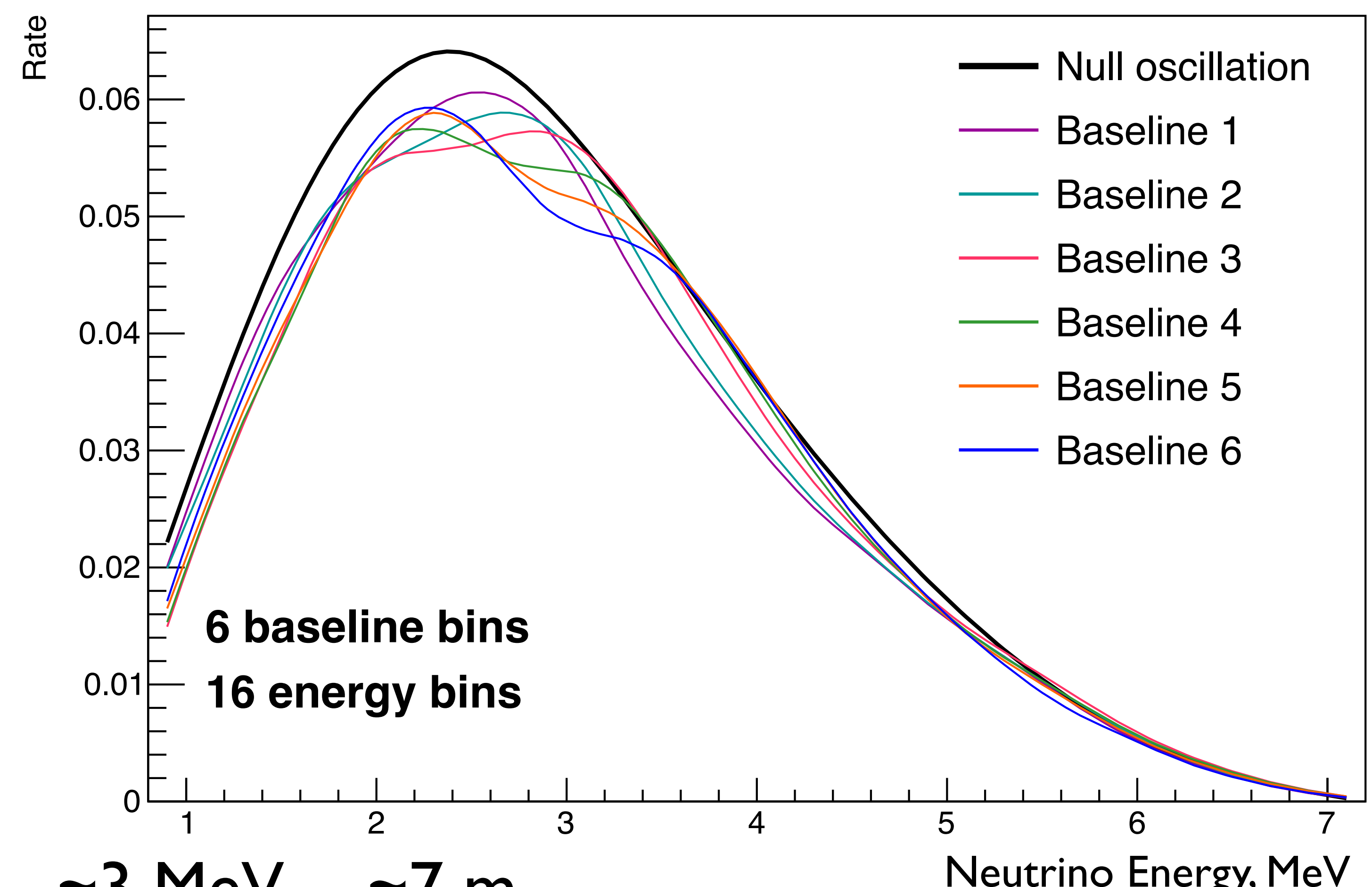
RAA Resolution: Clear Sterile Searches

- Resolve the reactor anomaly by looking for variations between energy spectra of full detector versus individual baselines
  - Any wiggles in ratio is evidence of L/E nature of sterile neutrino oscillations

Look here…



…for this!



~3 MeV ~7 m

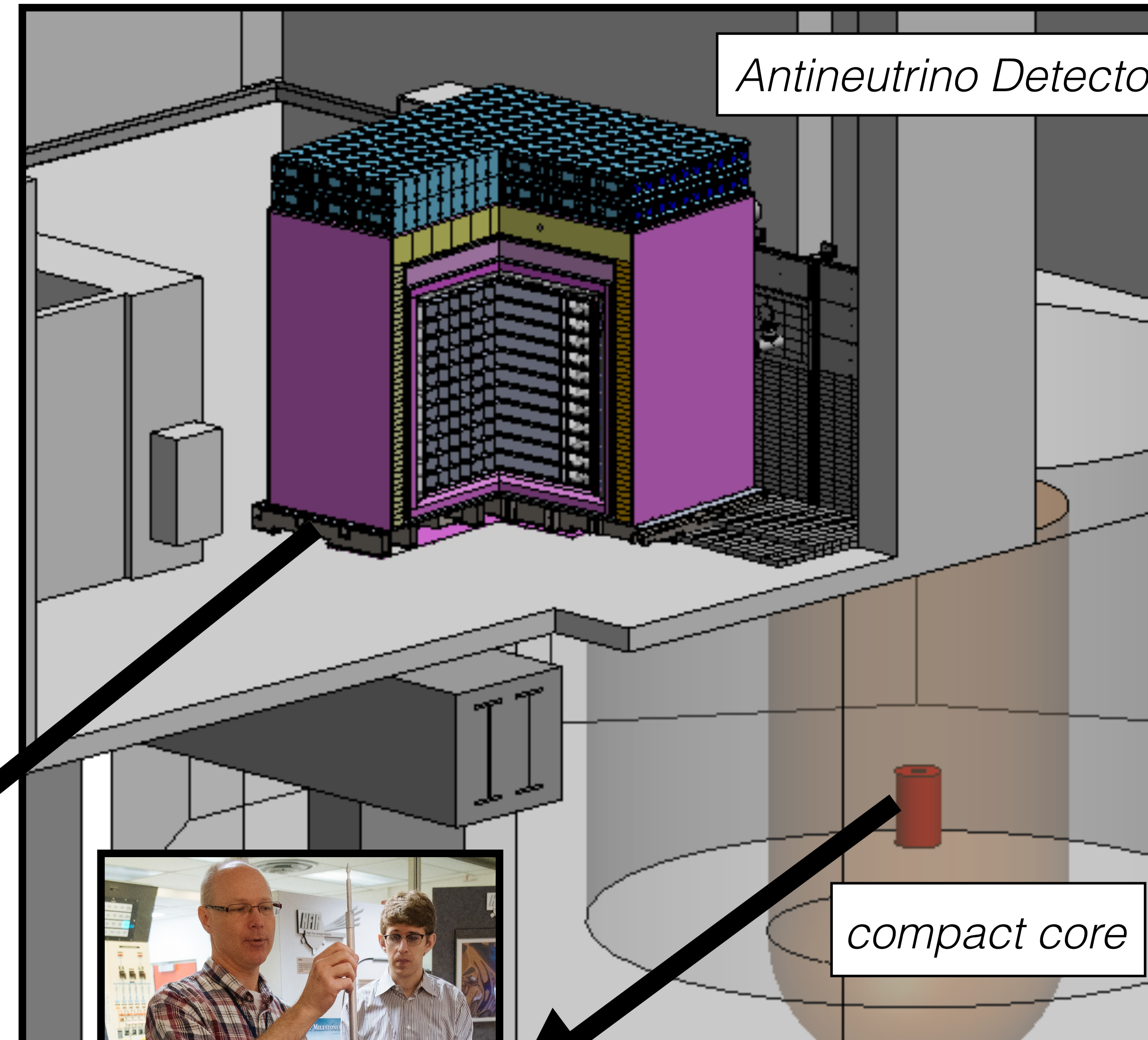
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}\right]$$

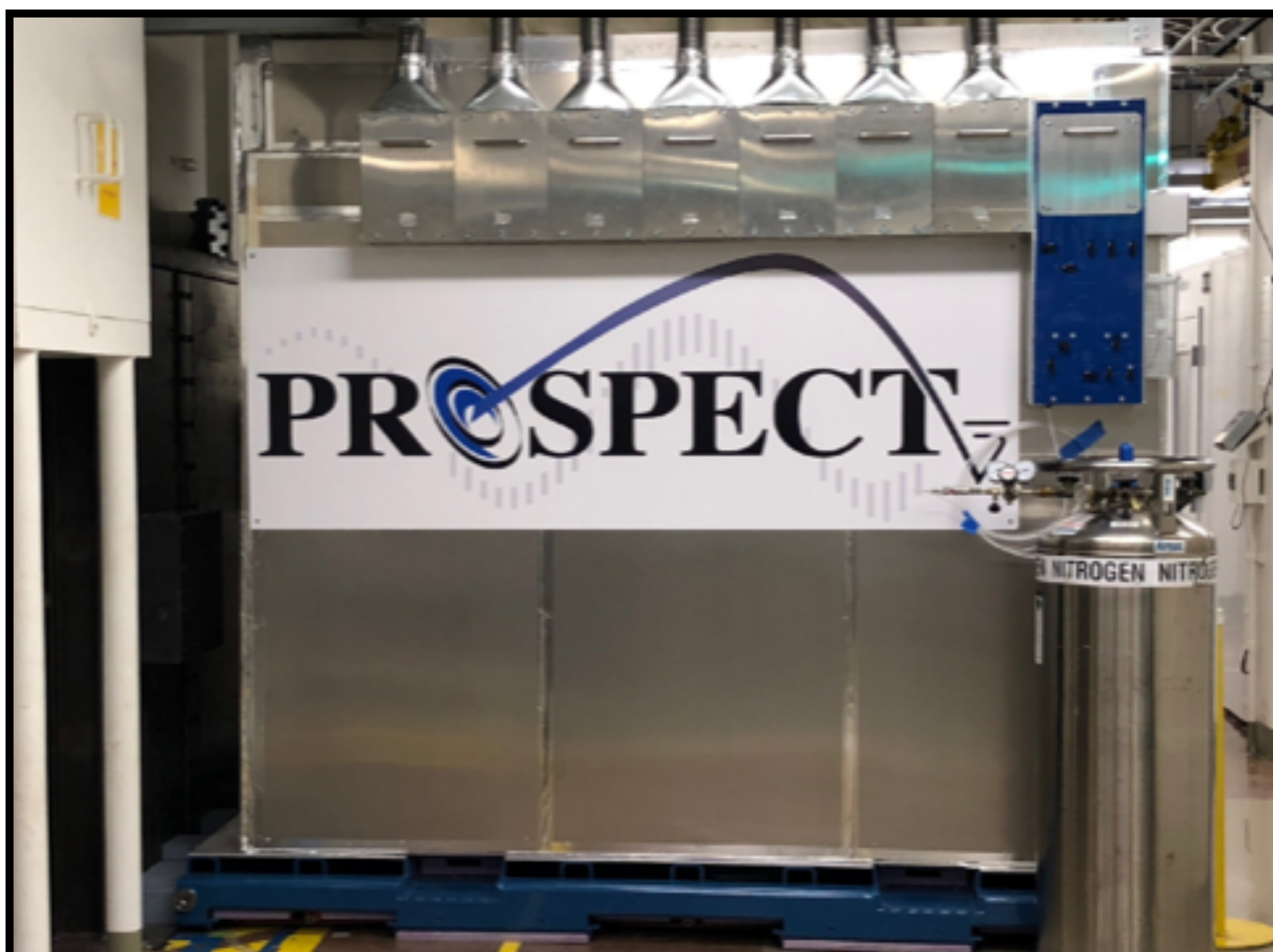
Probing Δm^2 ~ 0.6 eV^2

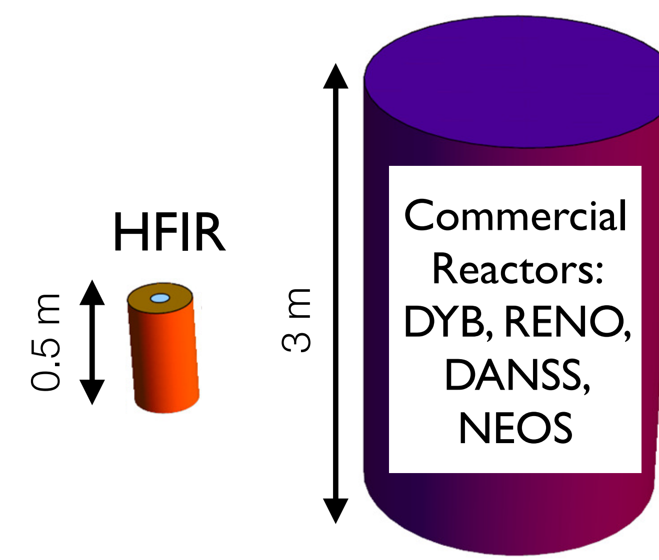
~Same as miniBooNE

Example: The PROSPECT Experiment

- A 4-ton ^{6}Li-doped segmented liquid scintillator detector at theHFIR research reactor
  - US-based: Oak Ridge Lab (Tennessee)
  - Very short baseline: 6.7-9.2 meters
  - Compact core: <50cm height, diameter







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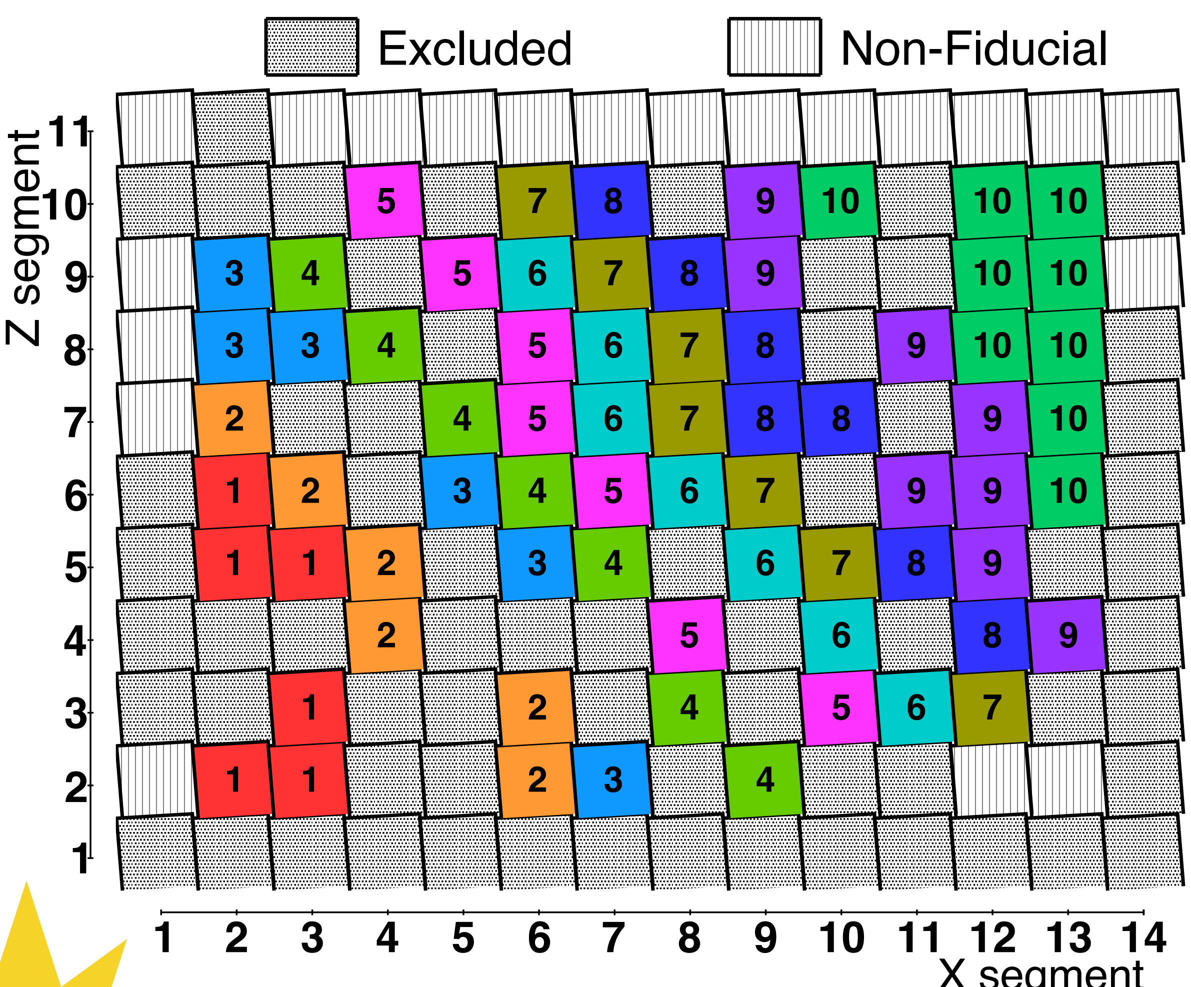


HEU core

[PROSPECT Collaboration, PRD 103 (2021)]

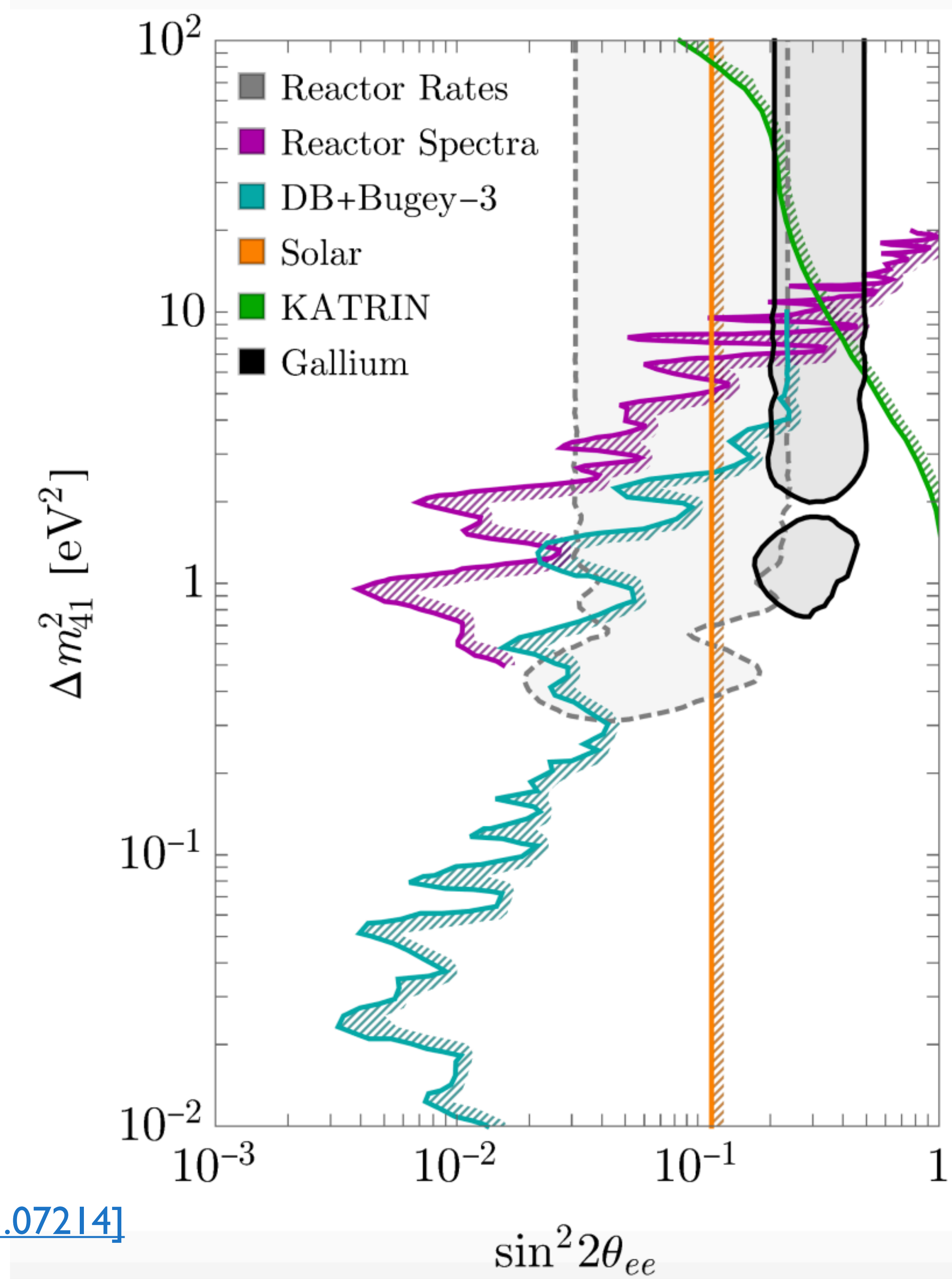
RAA Resolution: Clear Sterile Searches

- Resolve the reactor anomaly by looking for variations between energy spectra of full detector versus individual baselines

- We have not observed any such effect so far, setting new bounds on oscillation at O(0.01-10) eV^2

- Reflects decade's worth of effort from many continents: Daya Bay, DANSS, NEOS, RENO, PROSPECT, STEREO, and more.

- Note: Could use more coverage at high dm2… will get back to this later.

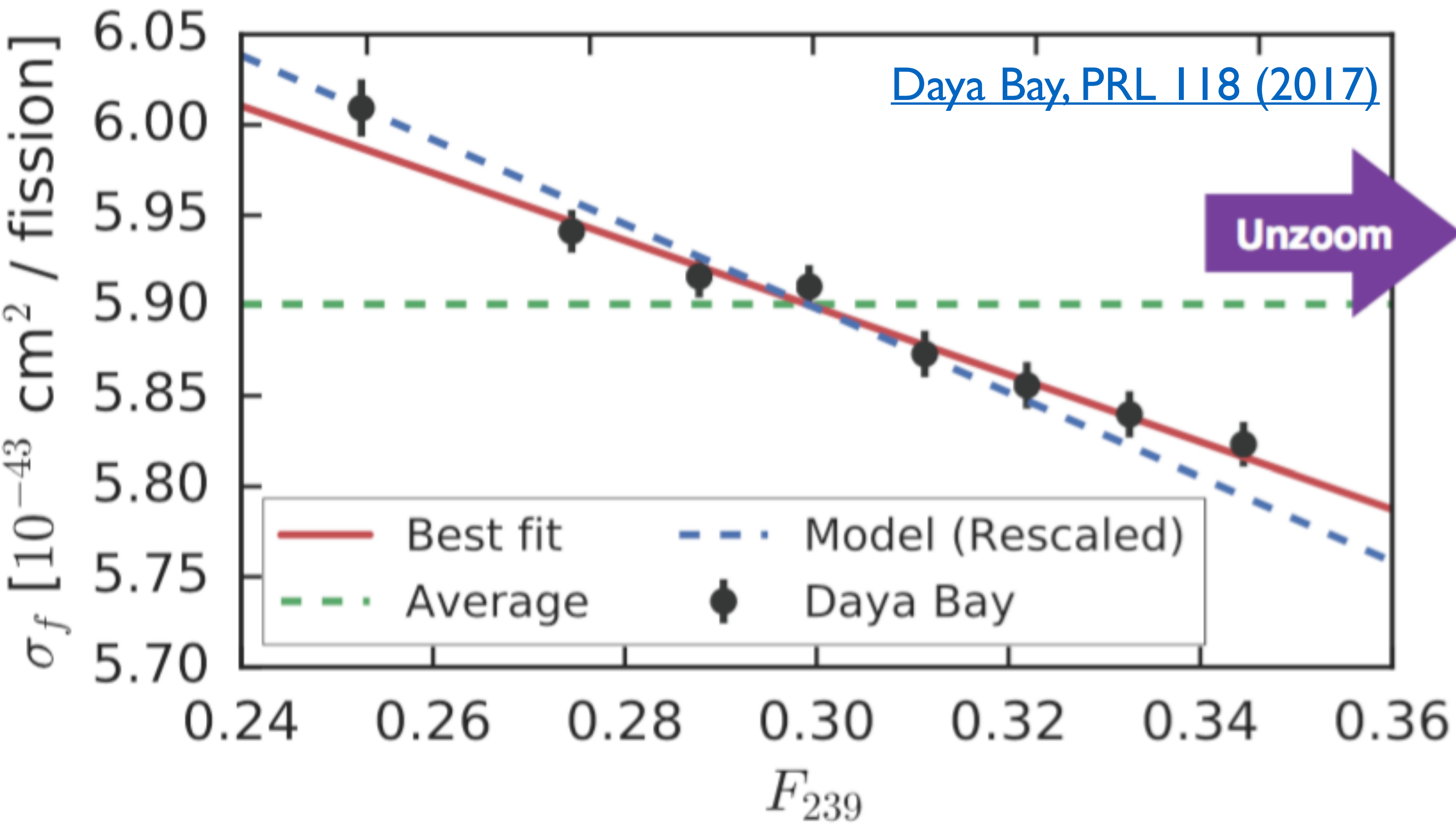


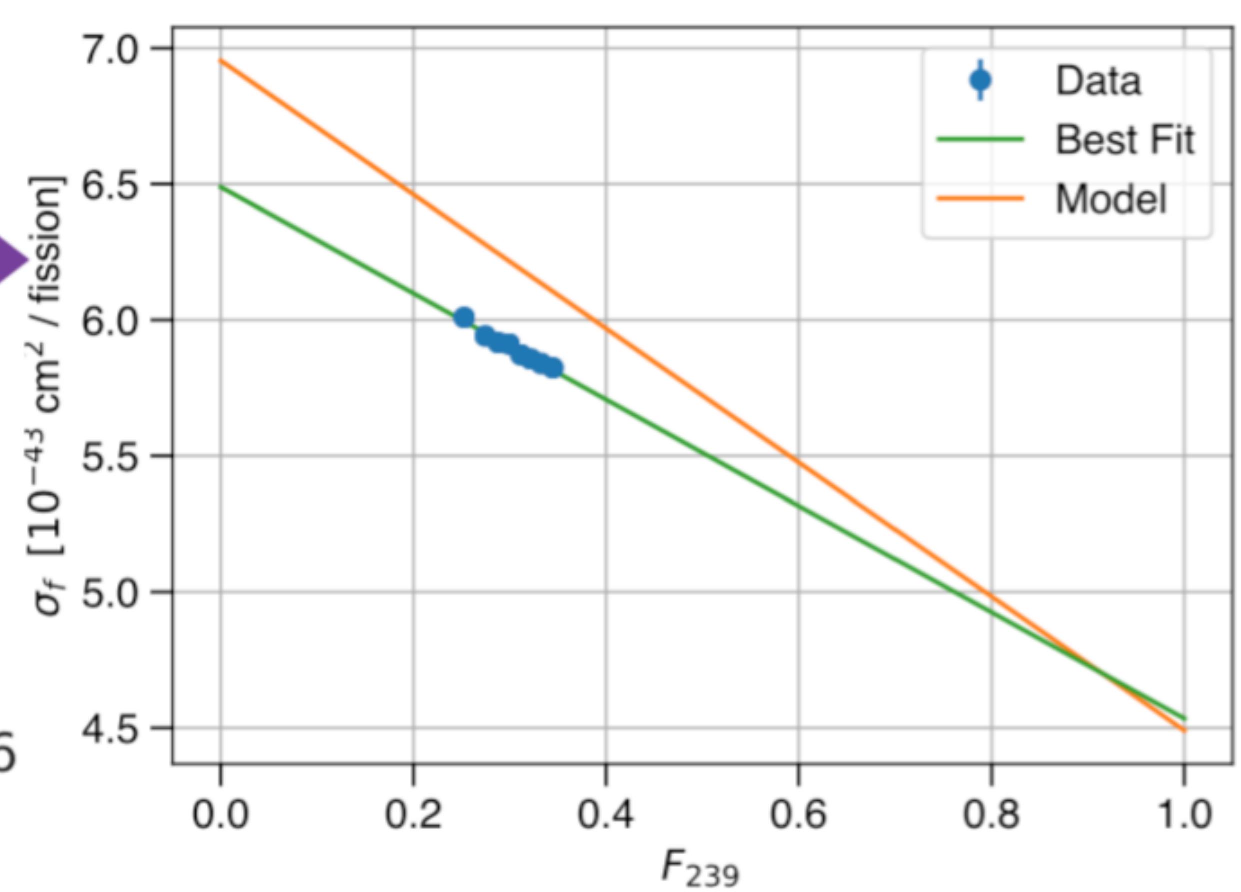
T. Akindele et al, hep-ex[2203.07214]

RAA Resolution: New Flux Measurements

- Resolve by probing the RAA deficit from reactor fuels with differing content ('flux evolution' measurements)
- The more ^{235}U a reactor is burning, the bigger the measured deficit. Indicates that bad flux predictions cause the RAA!
  - Parallel developments in nuclear theory and experiment support this picture

Zhang, Qian, Fallot, hep-ex[2310.13070]





New P5 Period: Why Reactors?

- Well-tailored reactor neutrino measurements have resolved a key outstanding neutrino physics question!
  - Seems to happen a lot at reactors… LMA-MSW solar neutrino solution; θ_{13}
- With the RAA problem licked, why do we still need short-baseline reactor experiments in the next P5 period?

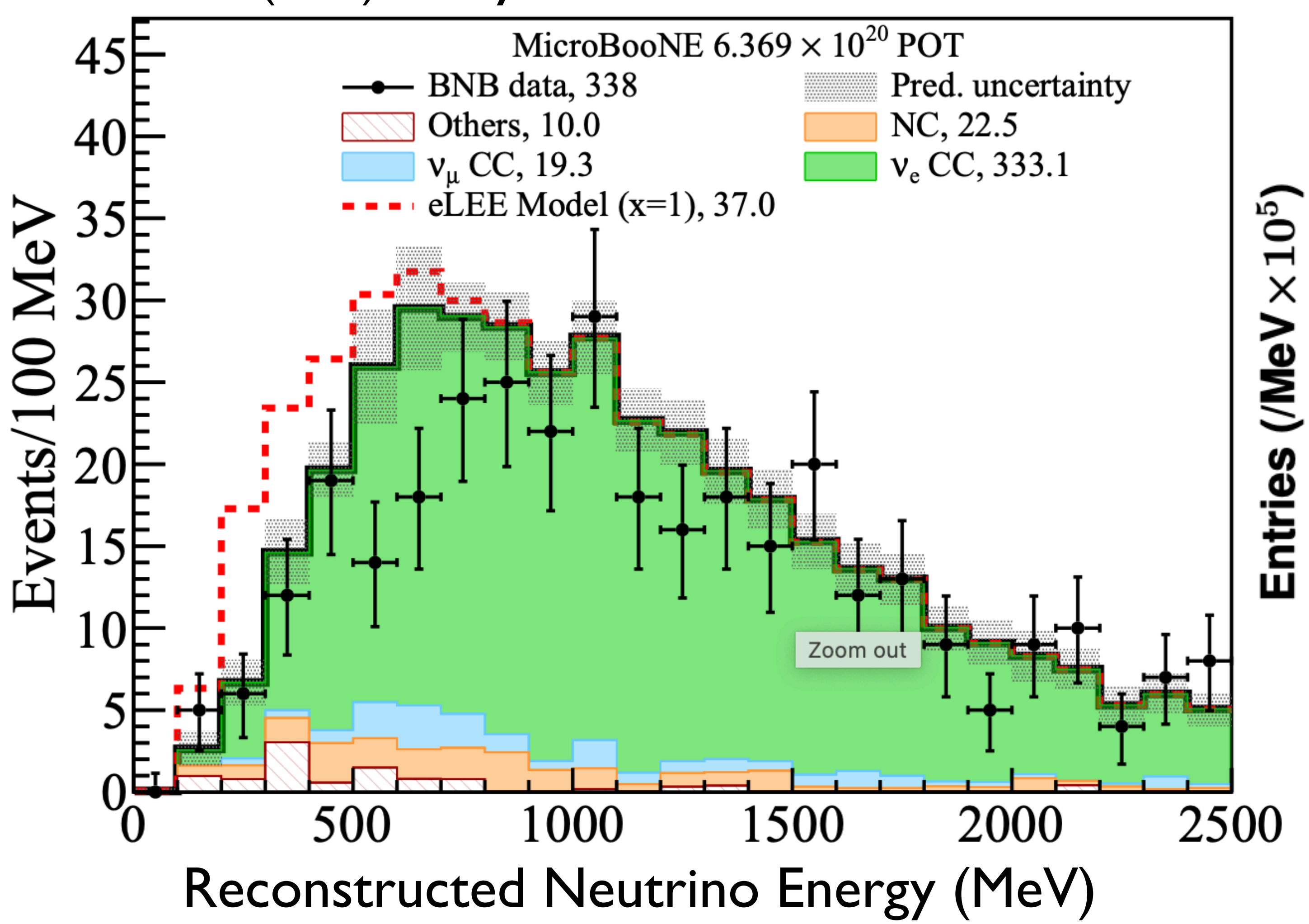
Exploring the Quantum Universe

Over the past decades neutrino oscillation searches at length/distance scales of 1 MeV/m have found a number of anomalous results: The liquid scintillator neutrino detector (LSND) anomaly, the reactor antineutrino anomaly, the MiniBooNE low-energy excess and the gallium anomaly. These anomalies have not been confirmed, and the reactor antineutrino anomaly has been recently resolved. The remaining phase space

Reason 1: Electron Flavor

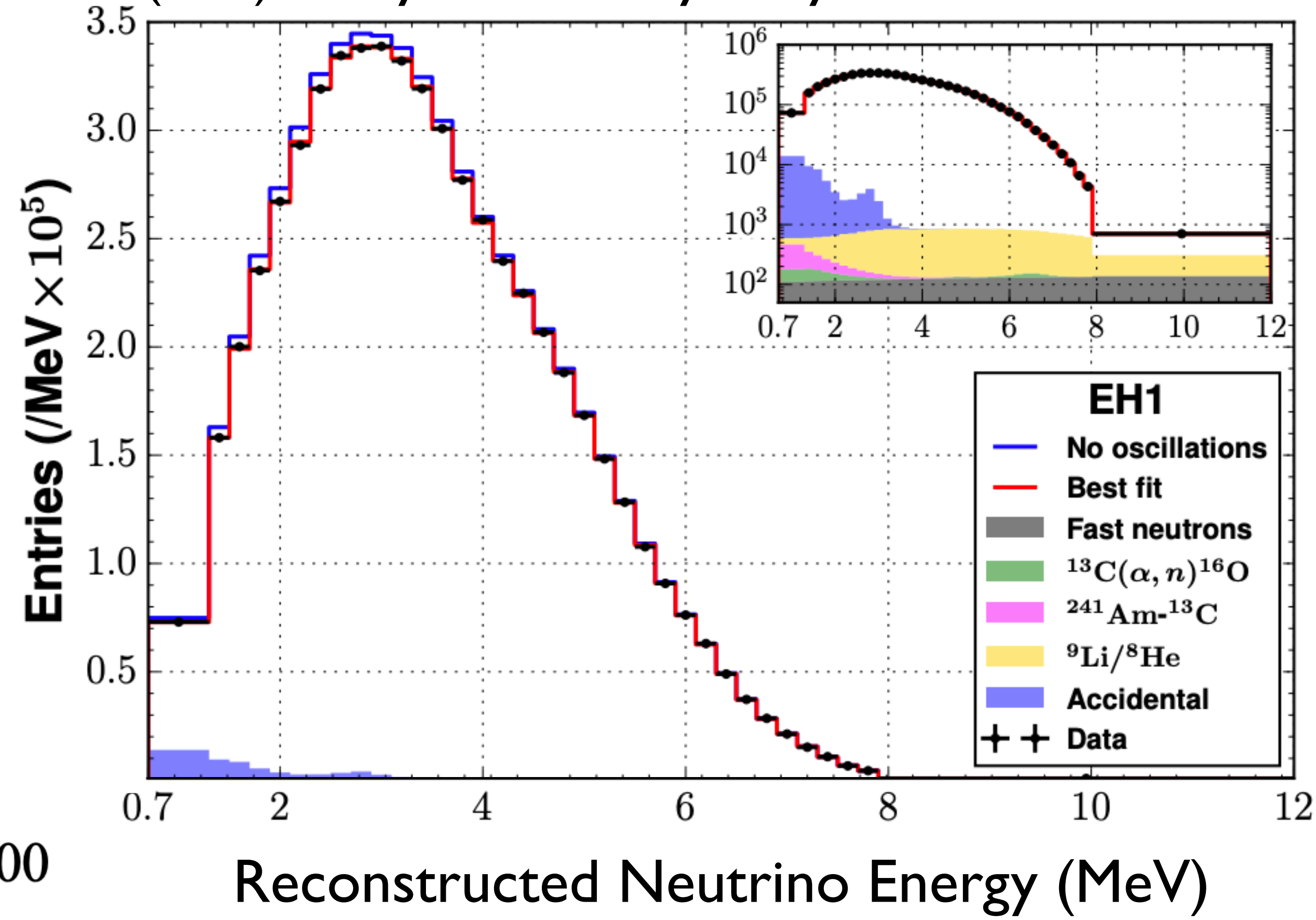
- Reactor neutrinos are the purest, highest-intensity source of electron-flavor neutrinos that we have to work with!
  - To broadly probe short-baseline oscillation phenomena, this source is essential!
  - Purity and high stats are complimentary to mixed-flavor accelerator fluxes

O(100) ton-years at Fermilab: 350 ν_e



MicroBooNE, PRL 128 (2022)

O(100) ton-years at Daya Bay reactors: 2.5M ν_e



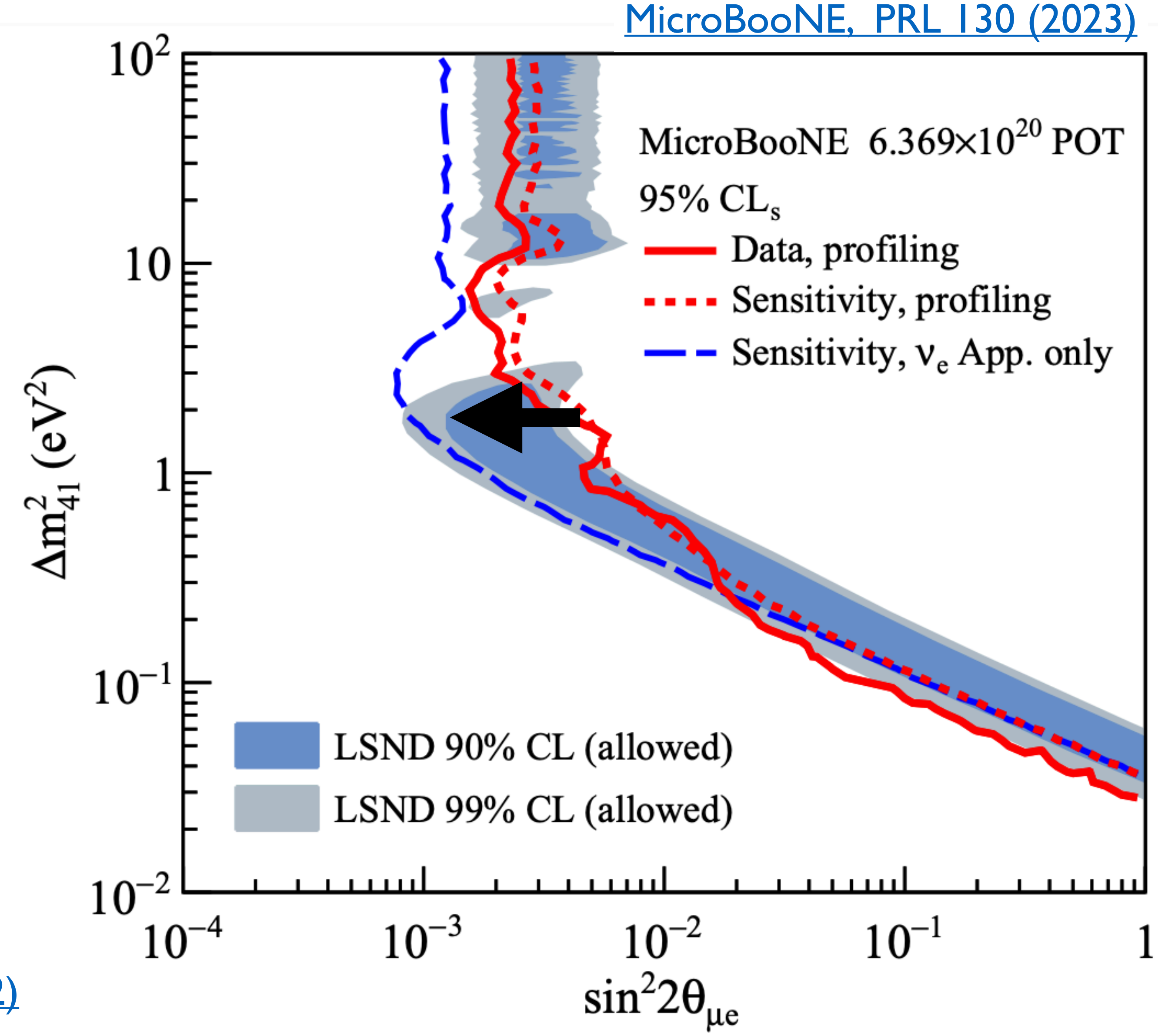
Daya Bay, PRD 95 (2017)

Reason 2: Remaining Anomalies

- **Three** other short-baseline anomalies remain unexplained: Gallium, LSND, and MiniBooNE

- Many pheno explanations impact reactor signatures
  - `3+1' sterile picture, for example
  - 'Non-vanilla' models too: 3+1+NSI, 3+1+decay, others
- Key to unravelling/excluding BSM causes: dataset diversity
  - MeV and GeV; muon and electron; appearance and disappearance
  - Example: Testing MiniBooNE with MicroBooNE data Arguelles et al, PRL 128 (2022)

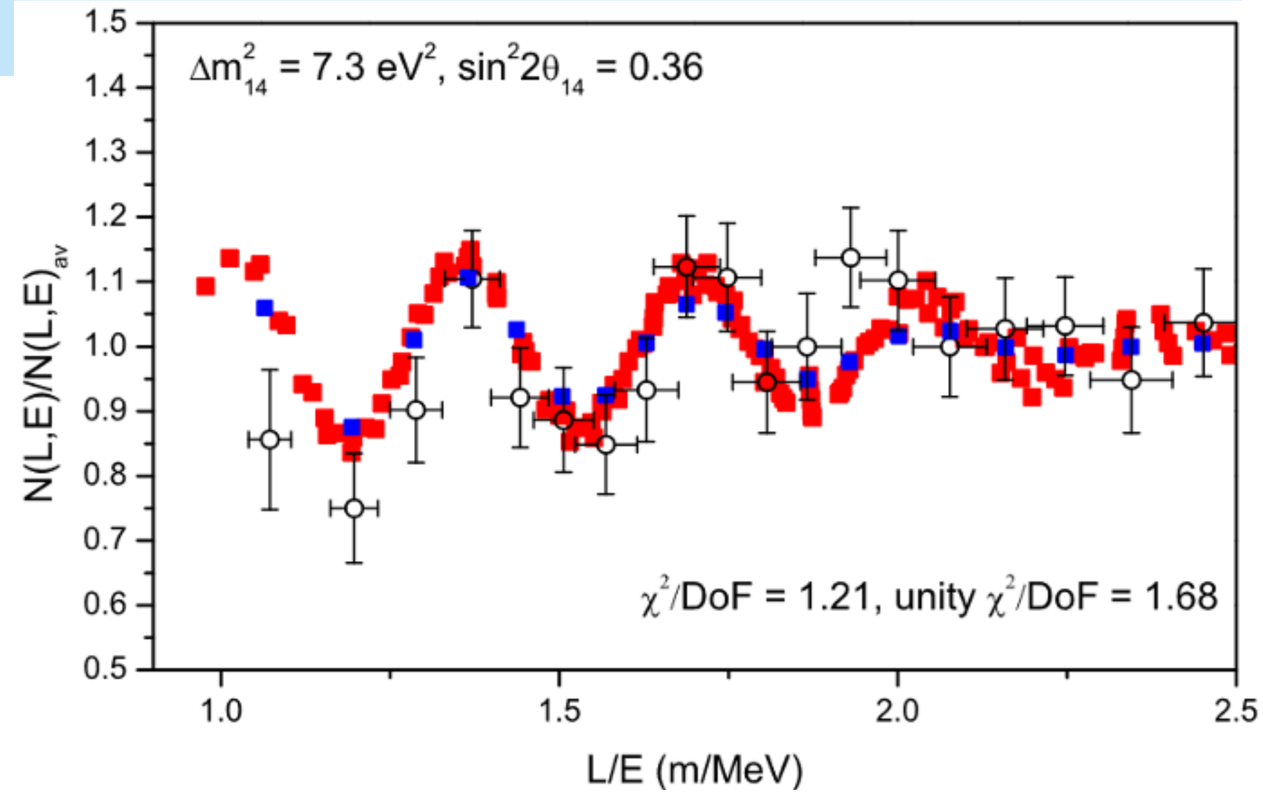
MicroBooNE, PRL 130 (2023)



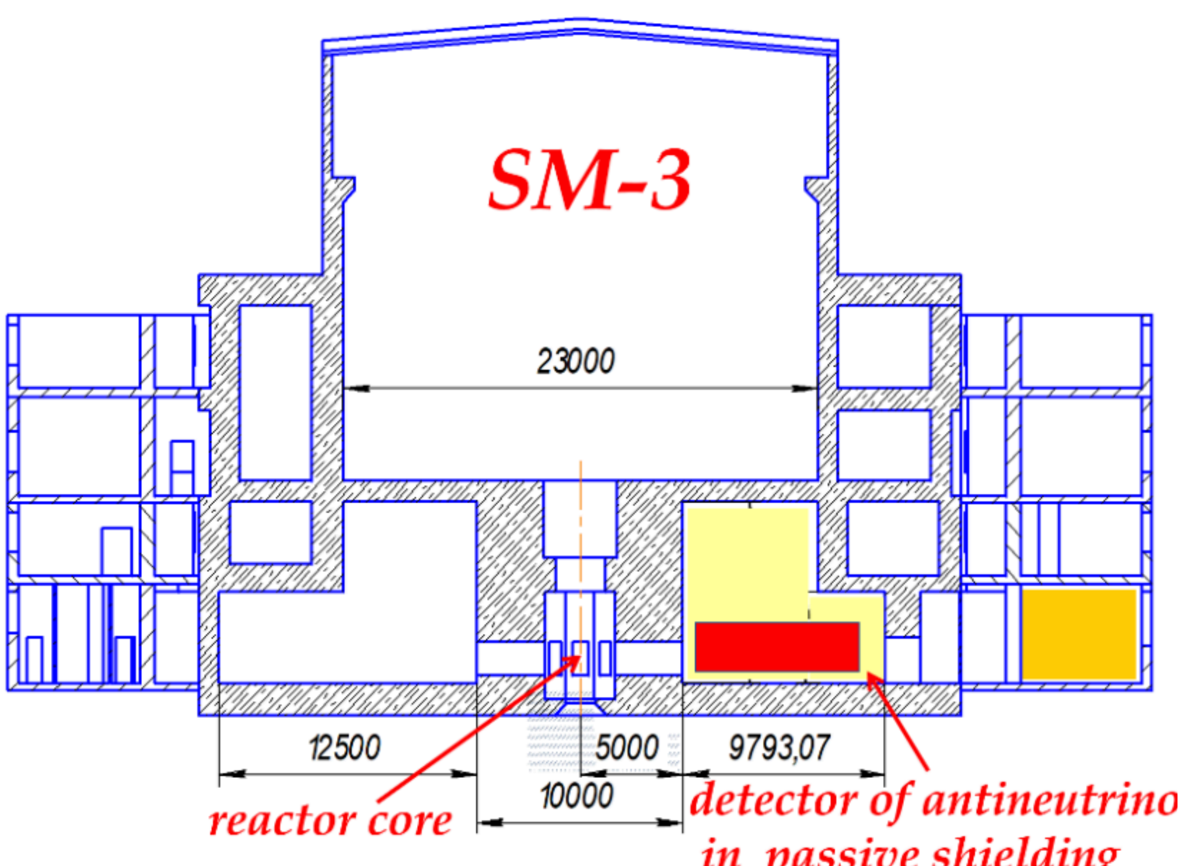
- Short-baseline reactor experiments play a unique role in an integrated global effort to understand these anomalies.

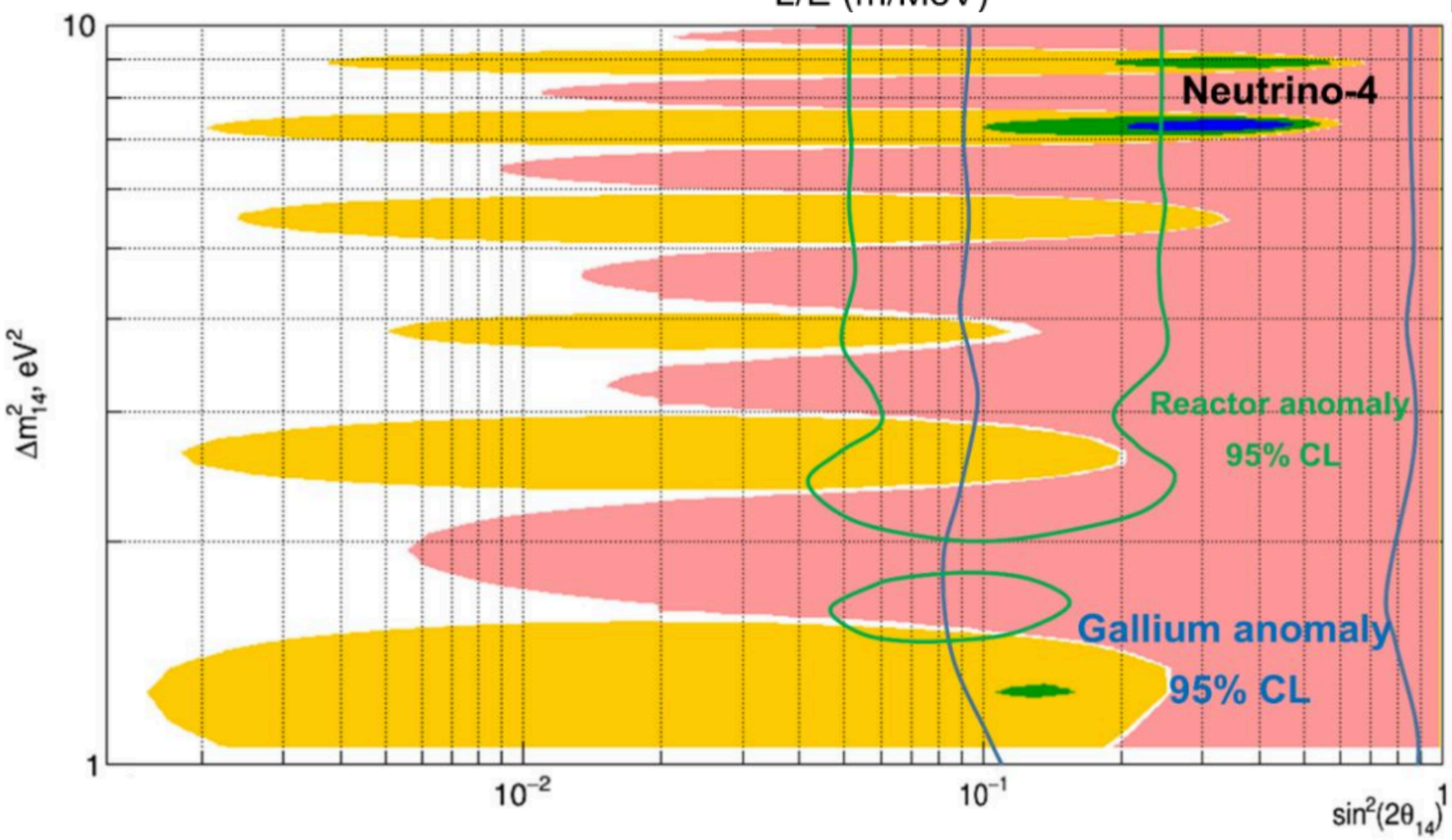
Reason 3: Outstanding Reactor Issues

- While the RAA is largely resolved, the oscillation picture from short-baseline reactors is not.



- Specifically: Neutrino-4 claims to observe high-amplitude, high-dm2 sterile oscillations
  - Other sources (accelerators) are insufficient to fully address this issue.

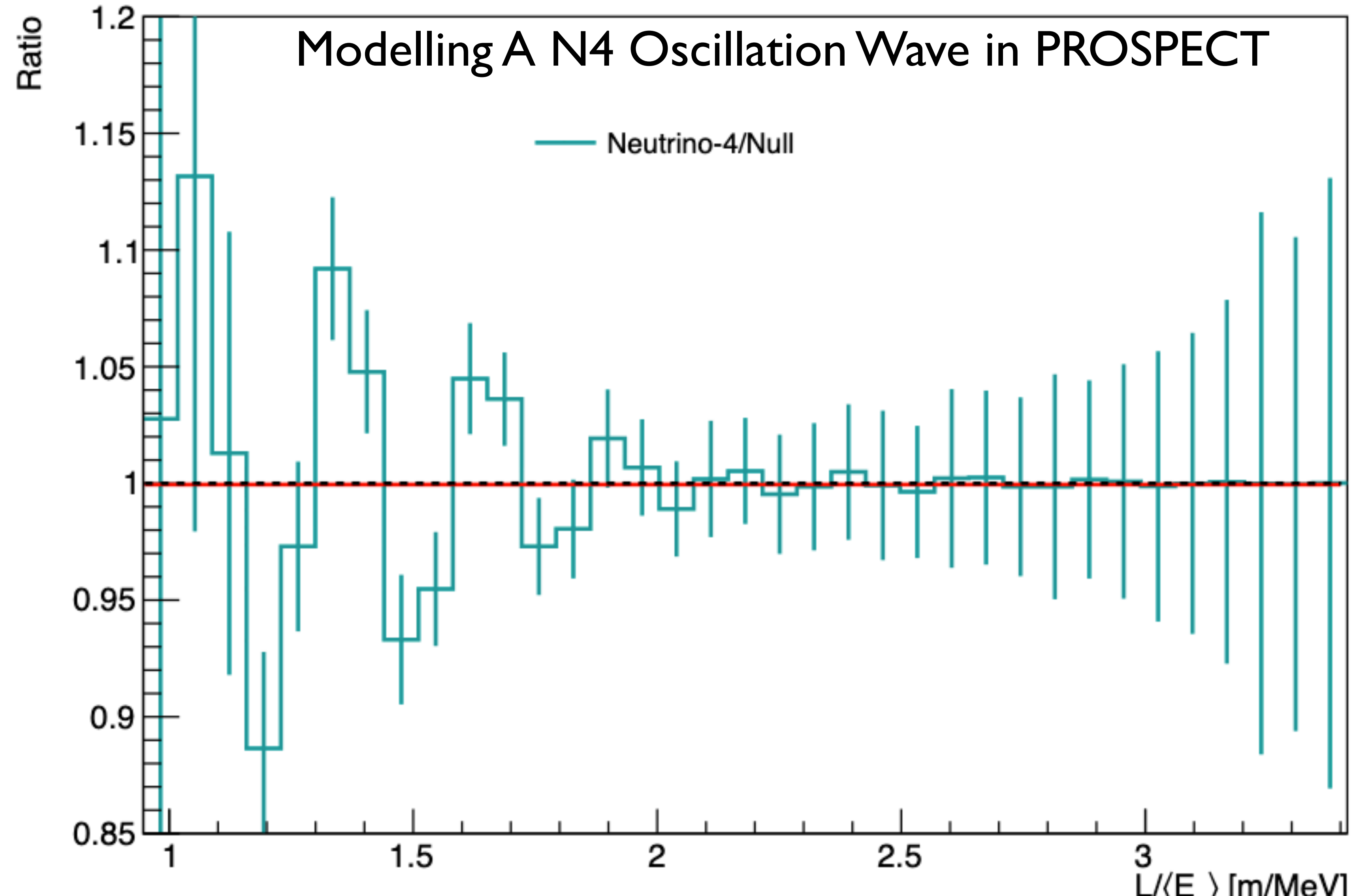




Horizons: Data From Existing Experiments

- In the new P5 period, we can use existing short-baseline datasets to learn more about BSM phenomena

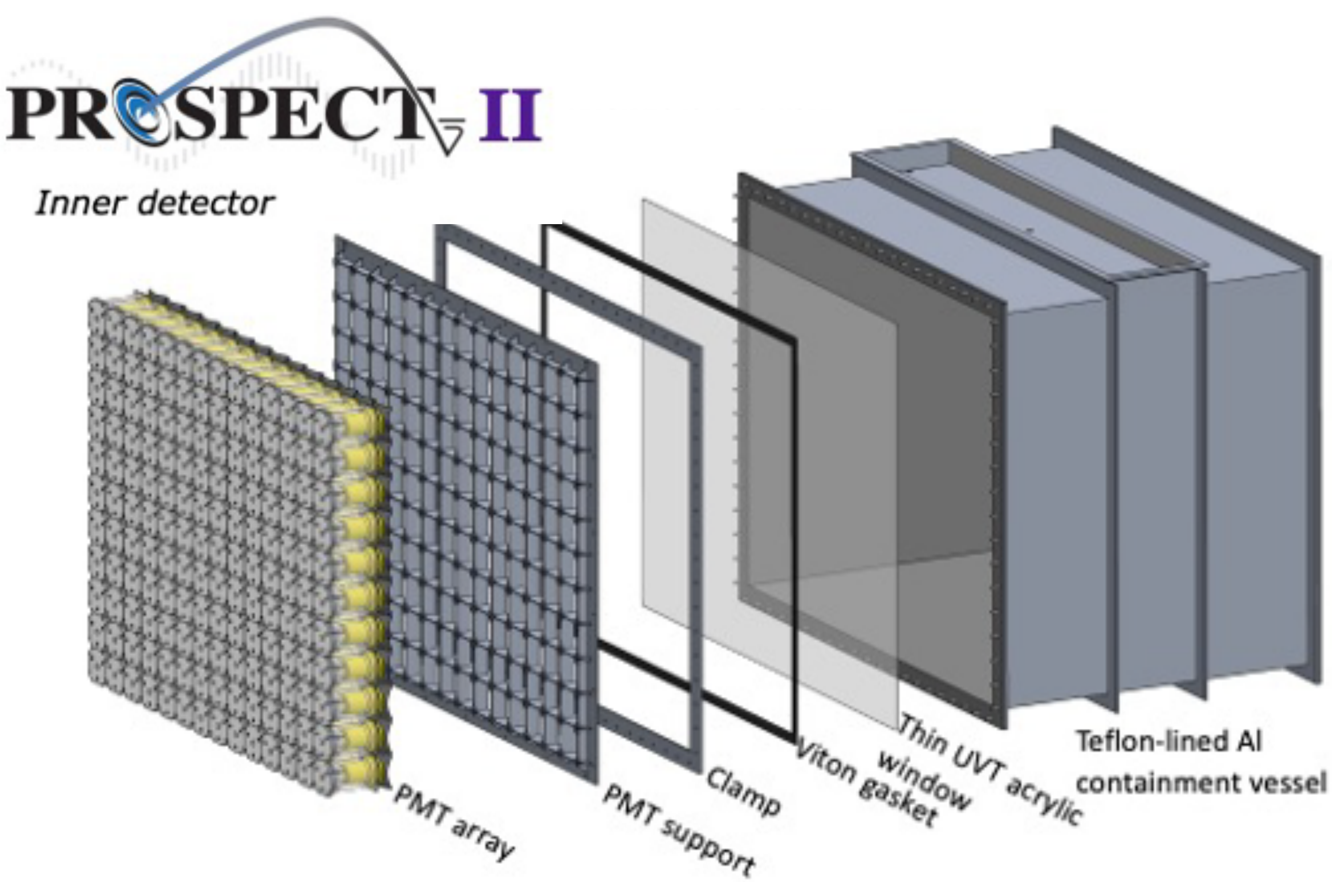
  - PROSPECT's final dataset will provide a high-CL test of most of N4-suggested phase space
  - Joint oscillation analyses from DYB, PROSPECT, and STEREO will address new space while giving a comprehensive exclusion region

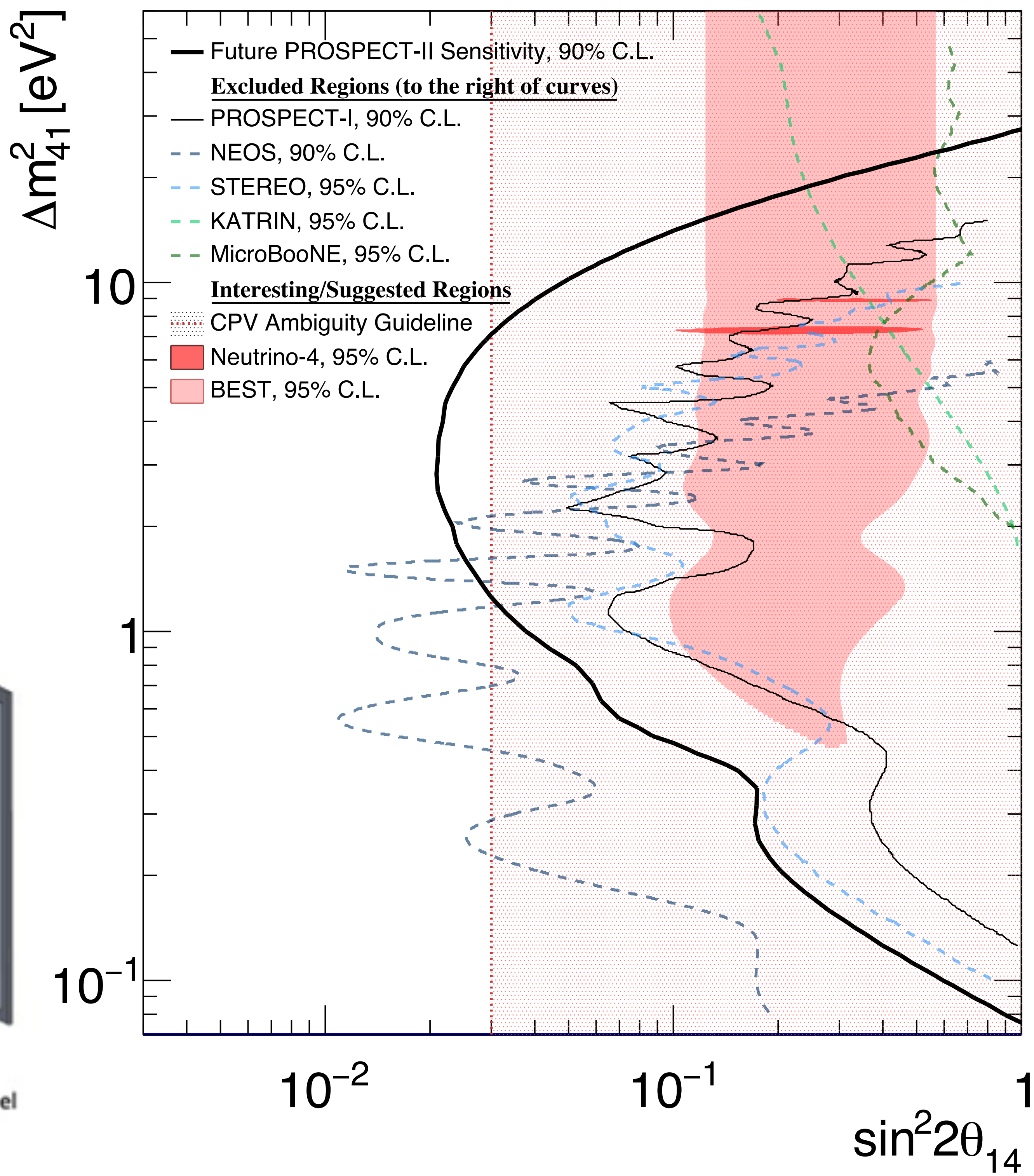


	Data Set	Rx-On(Off) Days	N_{IBD}	N_{eff}	S:CB(AB)
PROSPECT, PRD 103 (2021) →	Prev. Analysis	95.65(73.09)	50560 ± 406	18100	1.37(1.78)
COMING SOON! →	This Analysis	95.62(72.69)	61029 ± 338	36204	3.90(4.31)

Horizons: New P5 Period Experiments

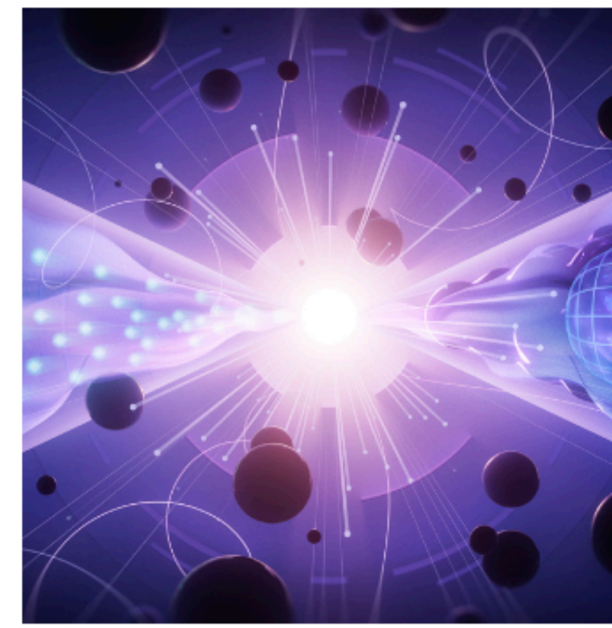
- In the new P5 period, major enhancements in sensitivity can come from 'ultimate' next-generation SBL reactor experiments
  - PROSPECT-II:
    - Correlated HEU and LEU measurements in a mobile, robust tons-scale detector
  - JUNO-TAO:
    - Percent-level energy resolution in a LEU-based short-baseline measurement





Reason 4: Exploring New Paradigms

- **Reactors would be the most intense terrestrial source of hidden sector particles below the ~10 MeV scale!**
  - Production of new MeV-scale hidden sector particles in the radioactive crucible of a reactor
  - BSM imprints in reactor-based CEvNS signatures
  - Low-threshold detection with QIS sensors
  - Enabling support measurements (flux, spectrum) from IBD detectors



T. Akindele et al, hep-ex[2203.07214]

Exploring the Quantum Universe

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

> ical phenomena and long-baseline neutrino oscillation experiments. The adaptability and deployment flexibility of agile experiments, whether near beams or reactors offer promise for synergistic explorations of hidden sector particles and other phenomena in the evolving BSM field. Technology development, such as innovative materials and unique sensors,

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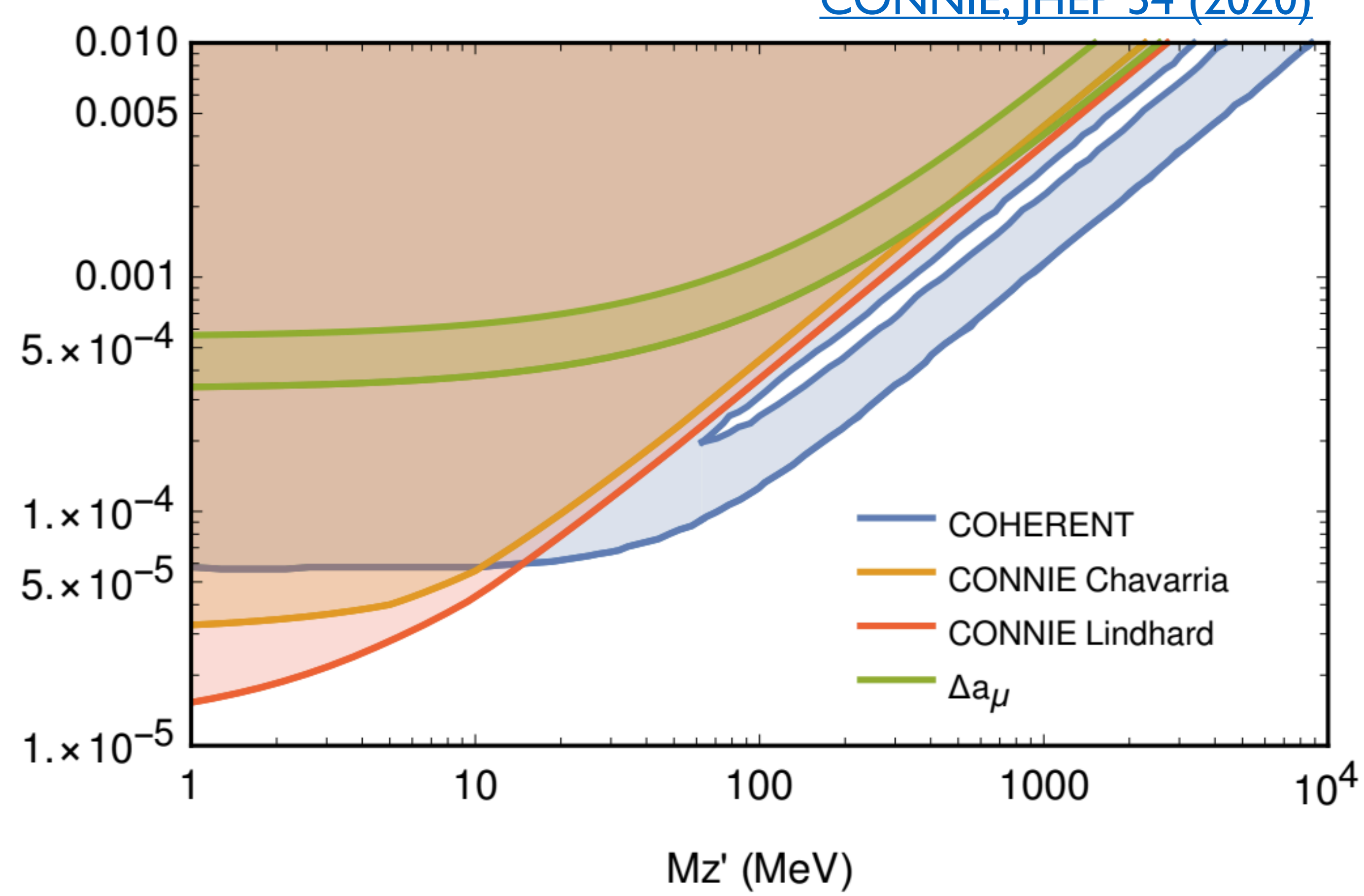
CONNIE, JHEP 54 (2020)

Example: CONNIE limits on hidden sector light mediators



Summary

- Reactor neutrino experiments are an essential piece of a global effort to achieve precision tests of lepton flavor mixing and complete understanding of long-standing neutrino anomalies.
- Many reactor experiments can be initiated, run, and completed within timescales/budgets associated with the new P5 period.
- Reactor neutrino efforts are drivers of applied and QIS-oriented technology development in particle physics.
- More questions? See the Snowmass 2021 Reactor Whitepaper

Thanks!

Backup