Complimentary BSM Oscillation Experiments and Constraints

April 3, 2024

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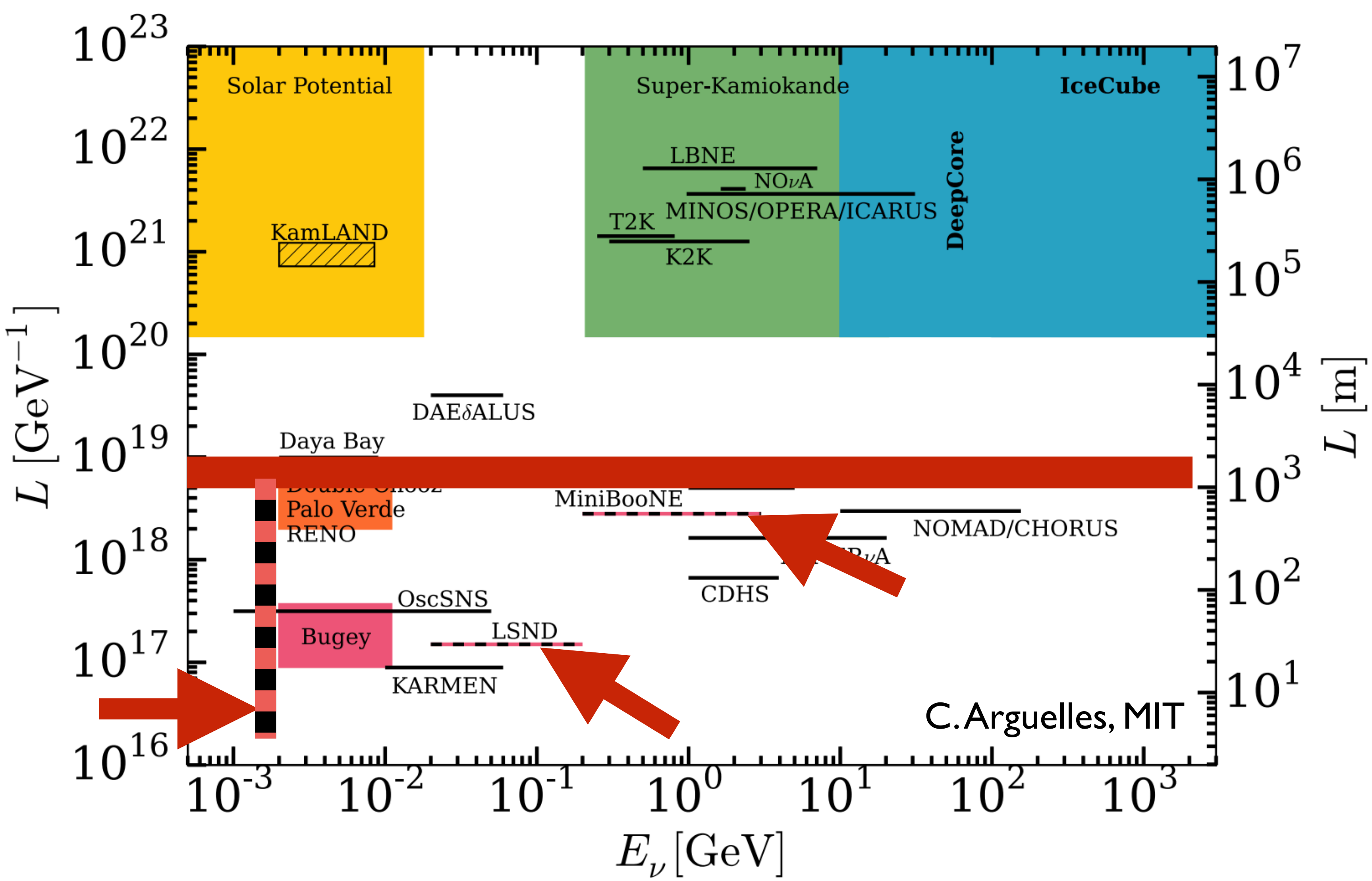
Illinois Institute of Technology

Neutrino Anomalies

- Let's zoom in and explore the non-FNAL anomalies
  - What's their status?
  - How does this relate to the broader neutrino program (and SBN)?

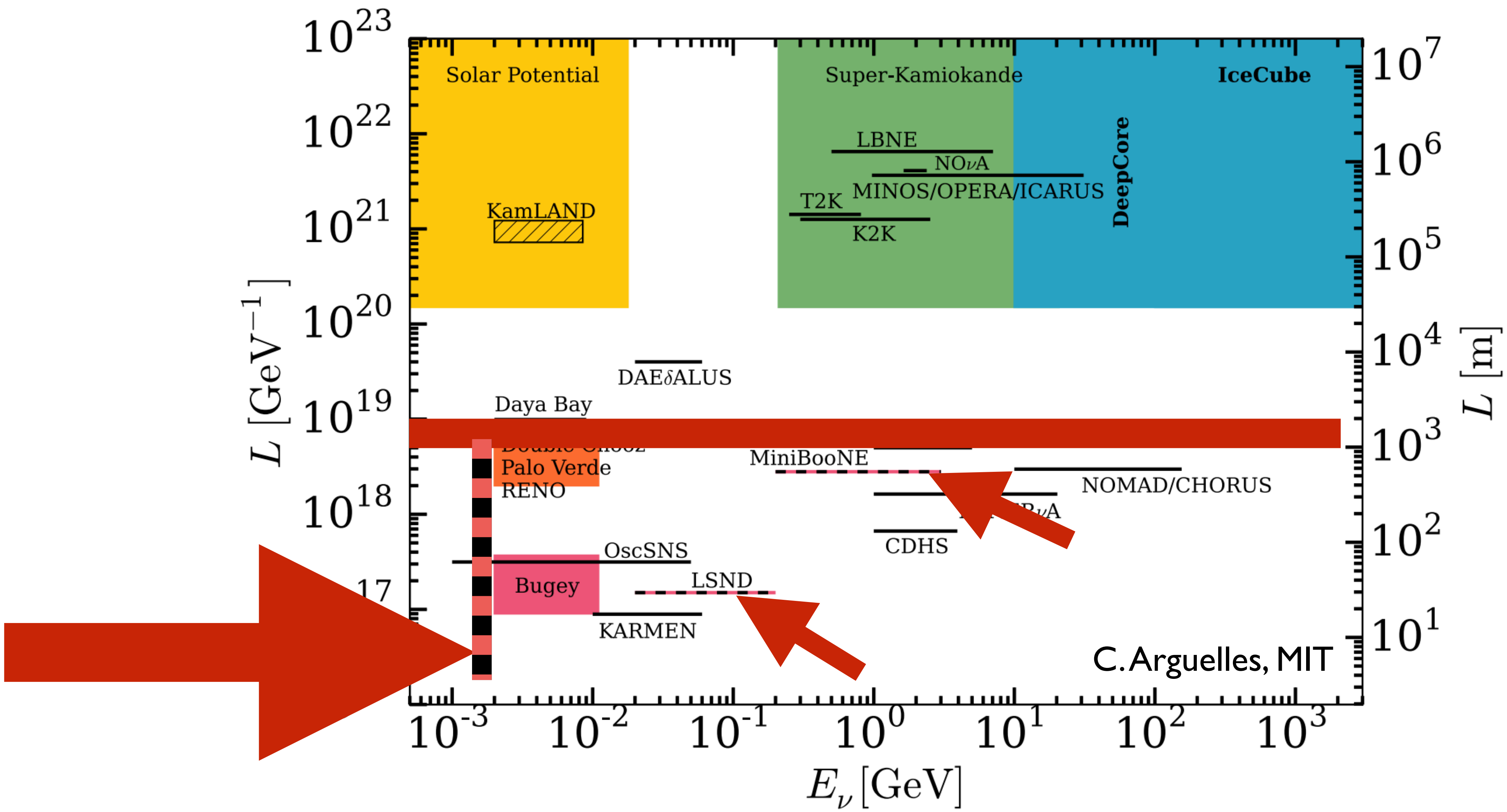


Note: no mention of IceCube or BEST in my slides here.

Note: I know others have covered global 3+1 picture; so I'll look forward

Electron-Flavor Disappearance

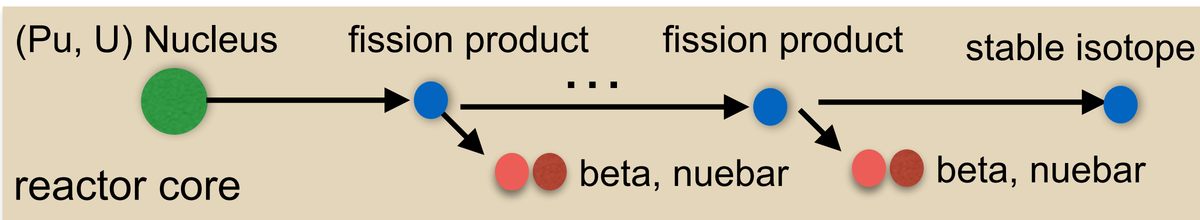
- **Let's zoom in and explore another of these anomalies**
  - What's their status?
  - How does this relate to the broader neutrino program (and SBN)?

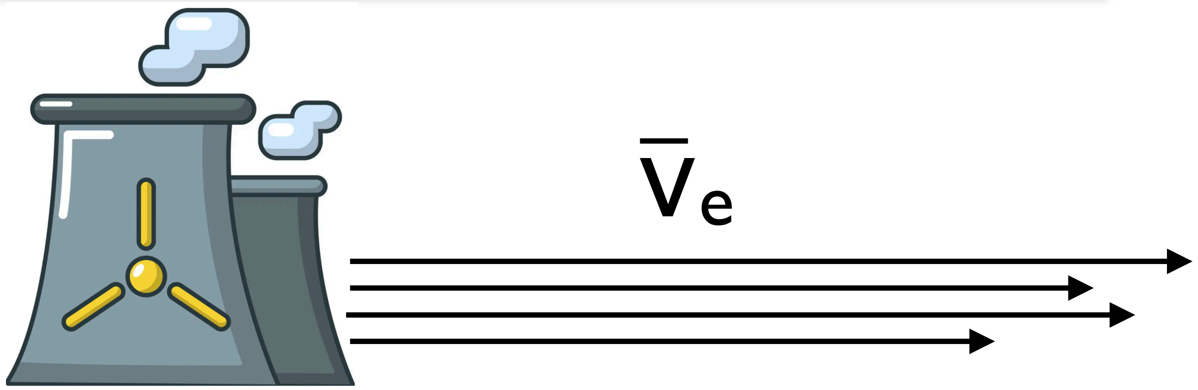


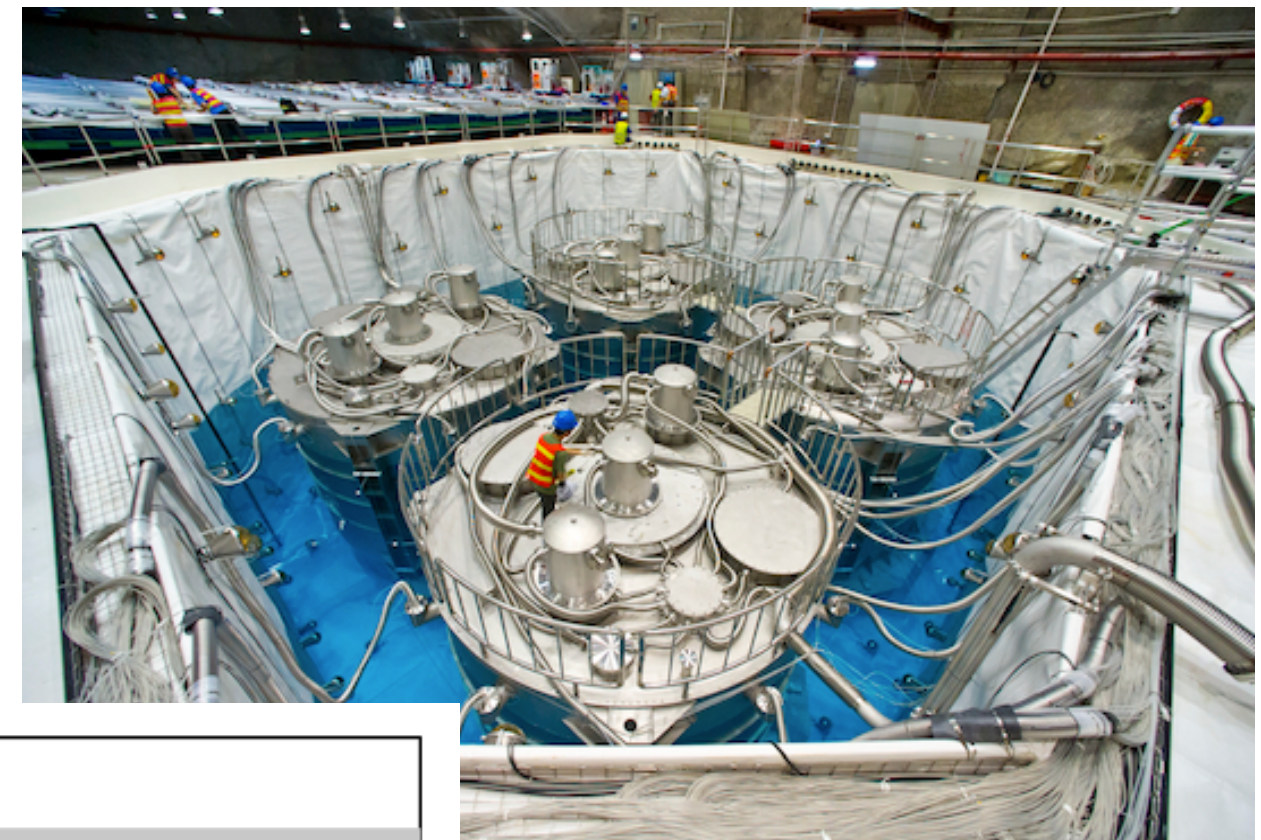
(Most of this talk…)

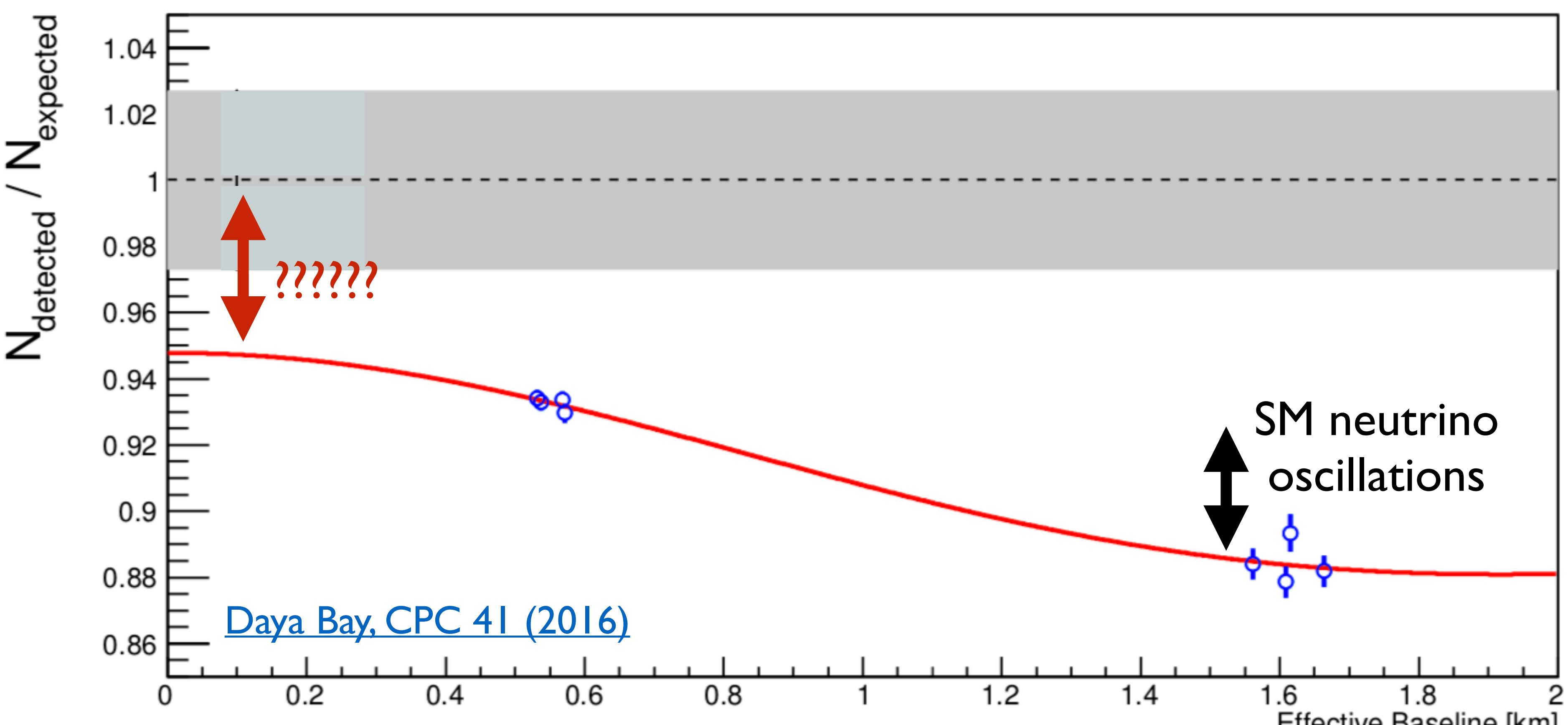
Reactor Antineutrino Anomaly (RAA)?

- 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

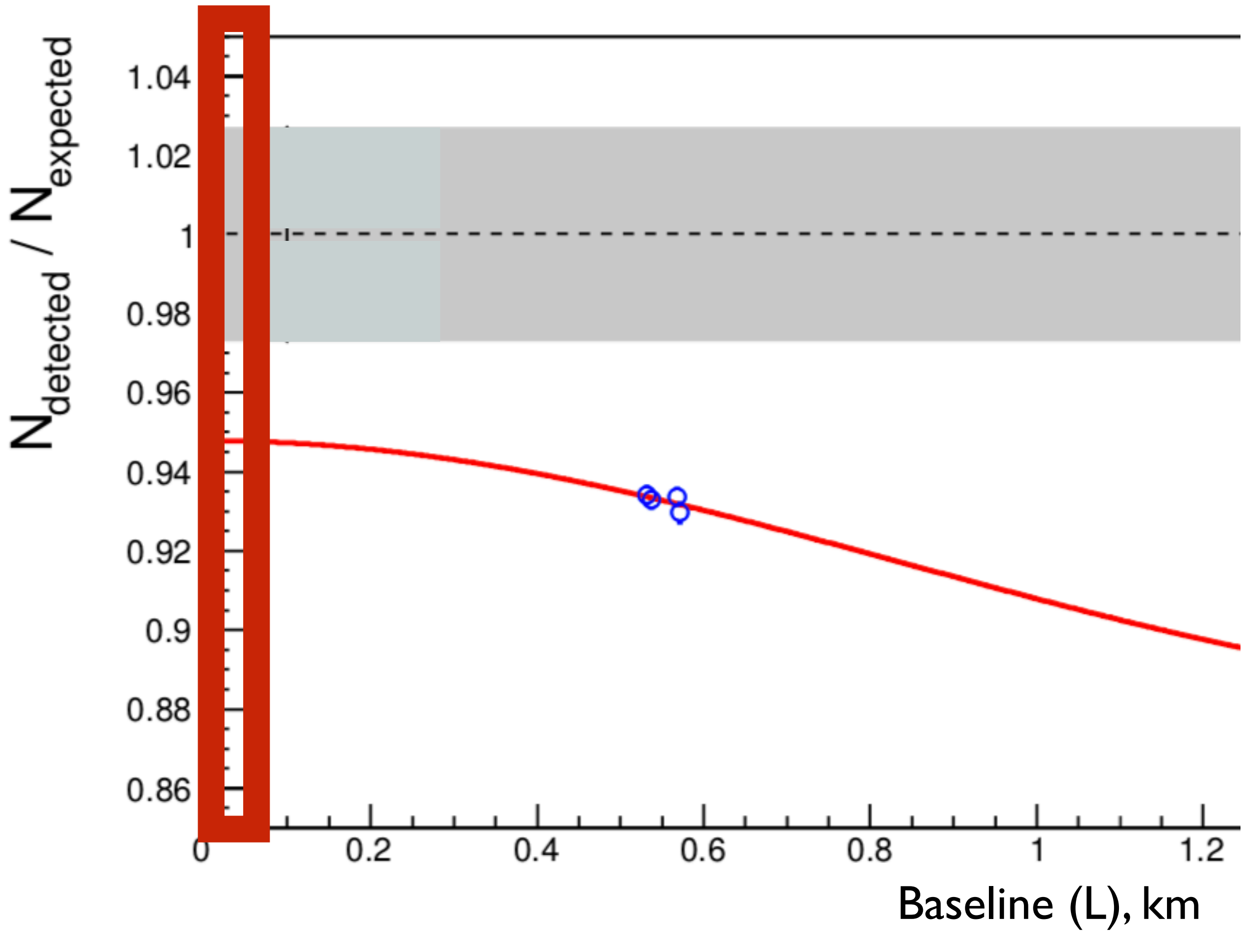
'RAA'

Exploring the Quantum Universe

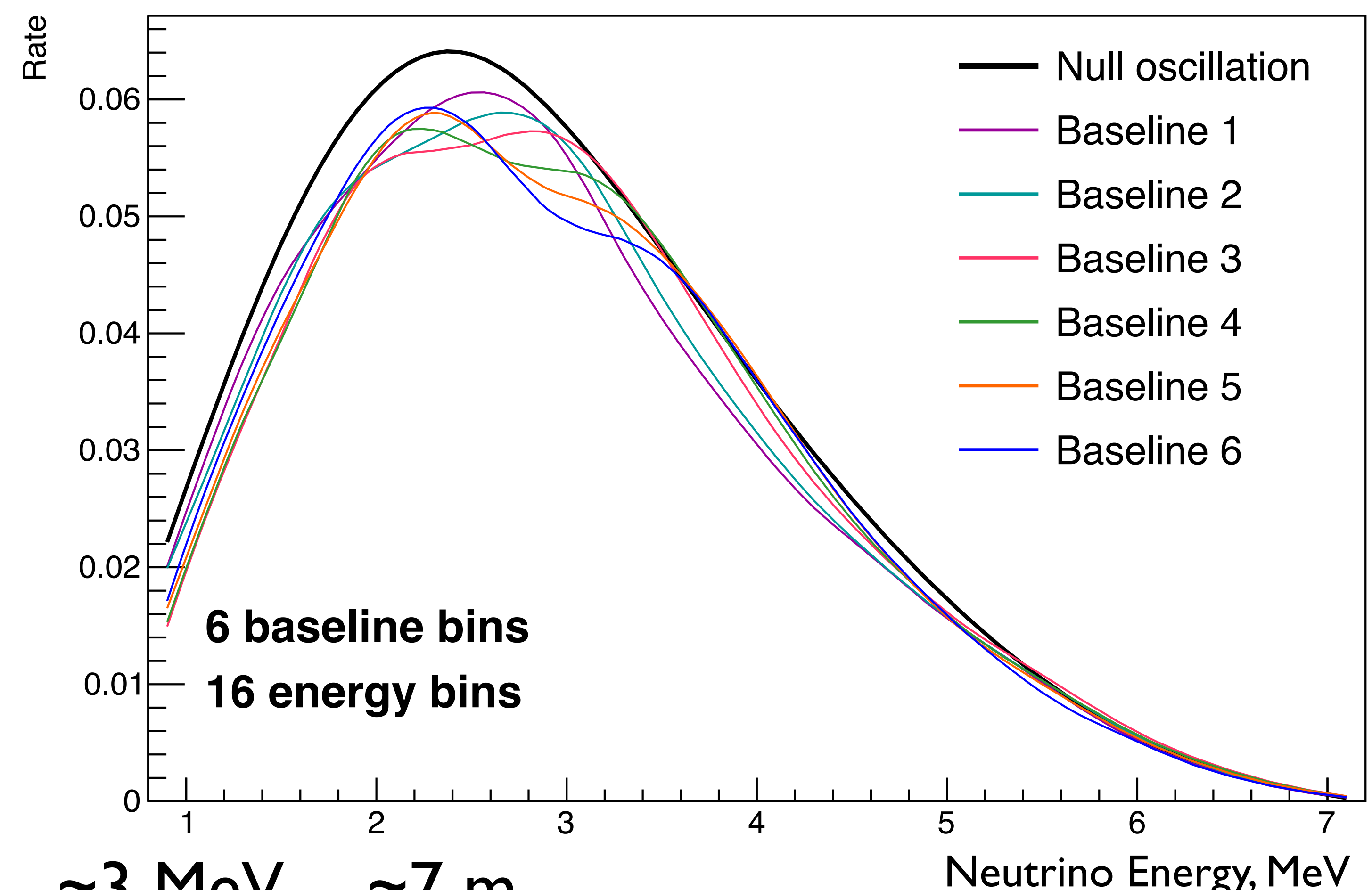
RAA Resolution: Clear Sterile Searches

- 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!



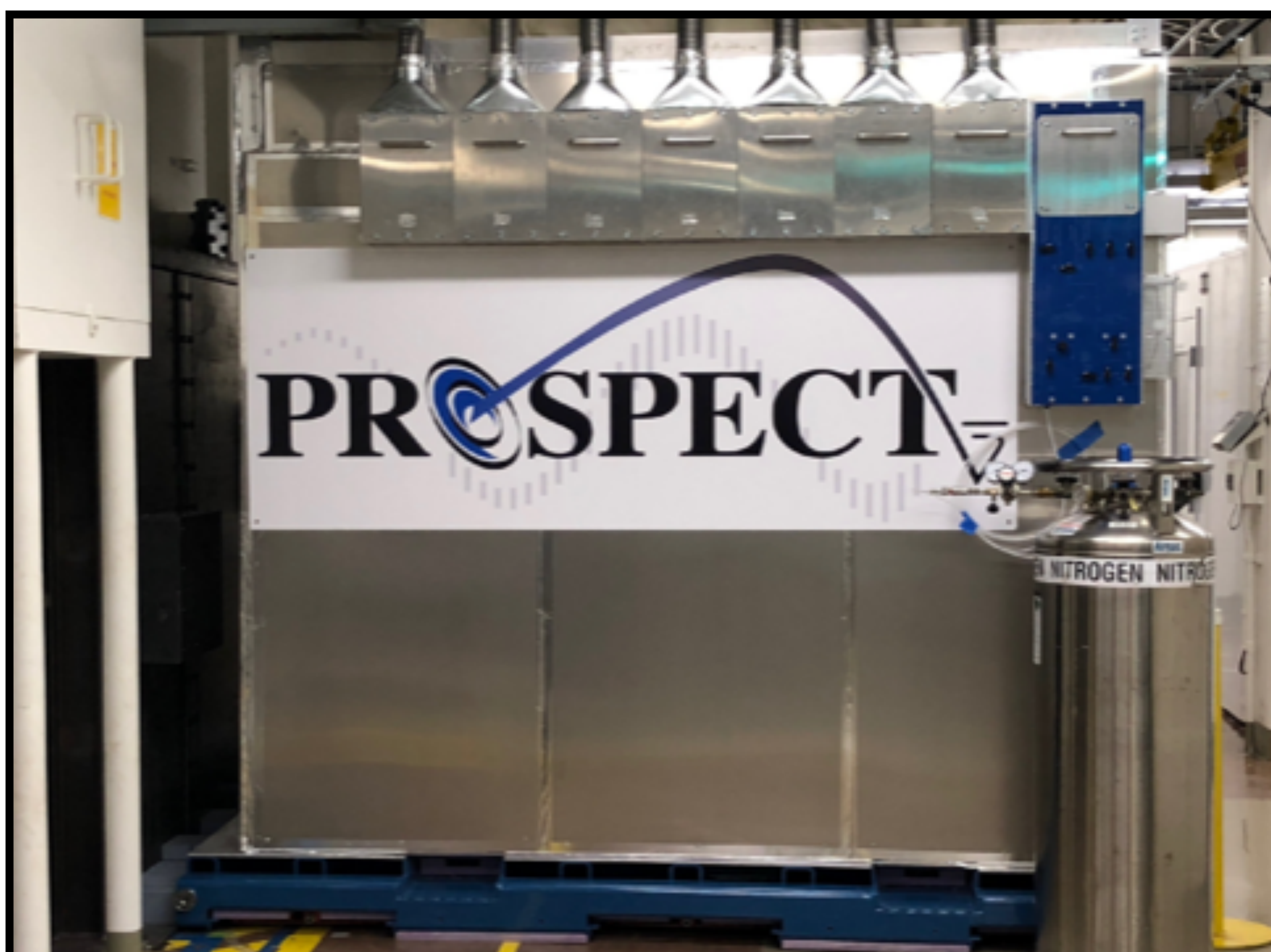
~3 MeV ~7 m

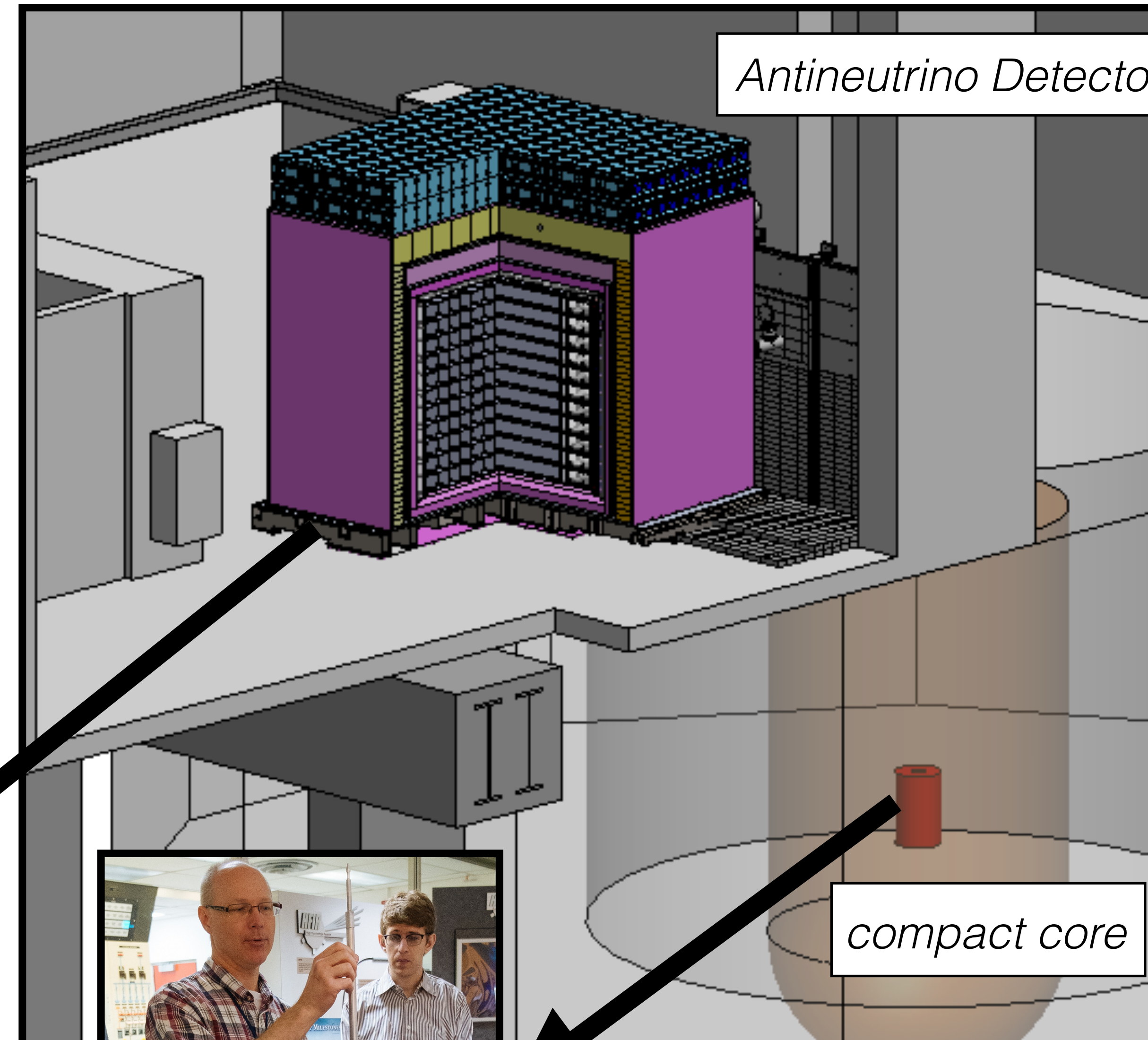
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left[1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)} \right]$$

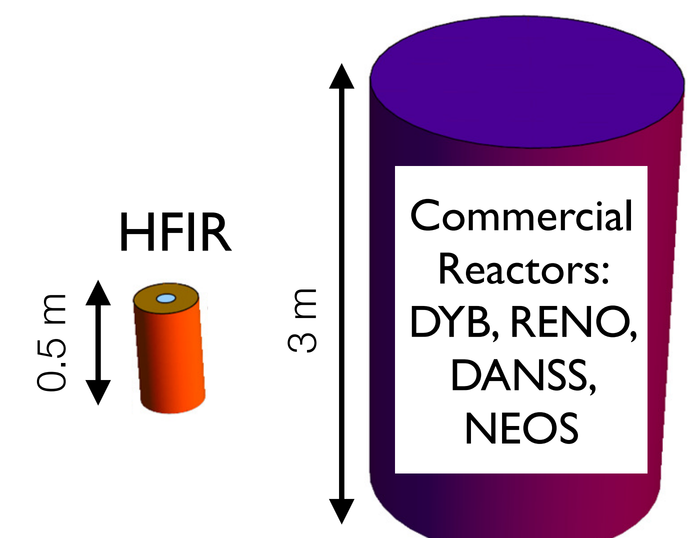
Probing Δm² ~ 0.6 eV²
~Same as mB; uB; SBN.

Example: The PROSPECT Experiment

- A 4-ton ^{6}Li-doped segmented liquid scintillator detector at the HFIR 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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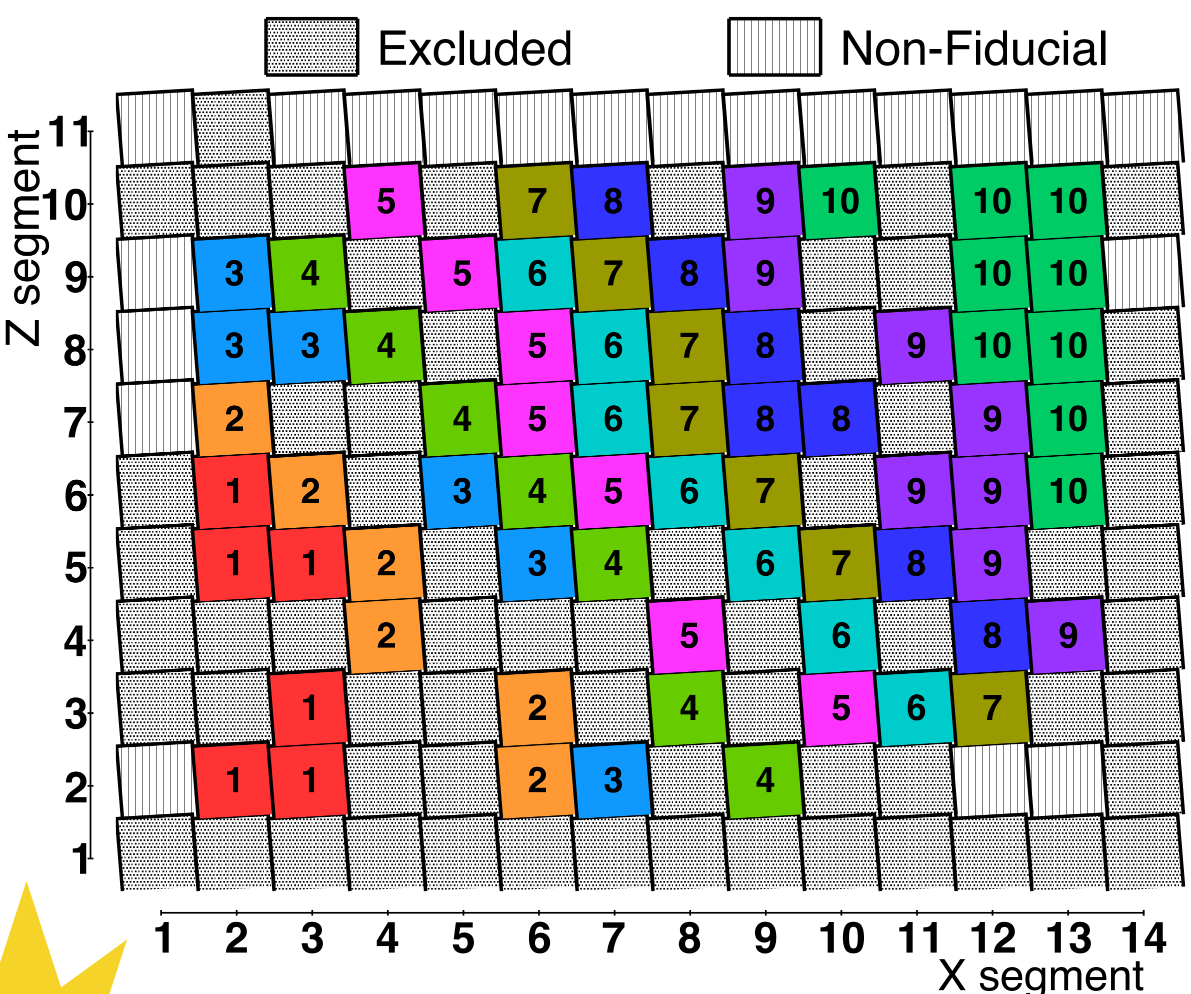


HEU core

PROSPECT Collaboration, PRD 103 (2021)

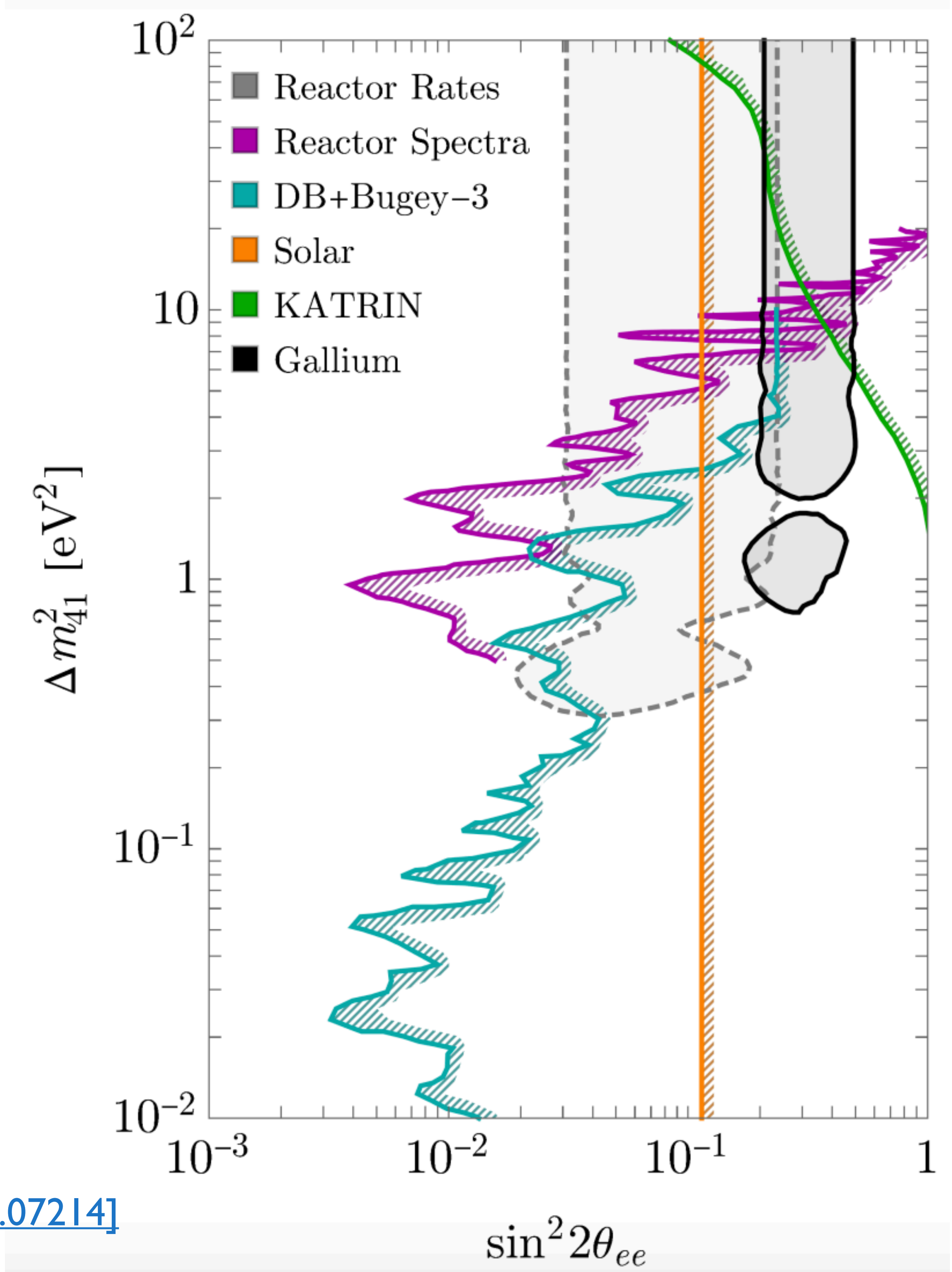
RAA Resolution: Clear Sterile Searches

- 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) eV²

- 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.

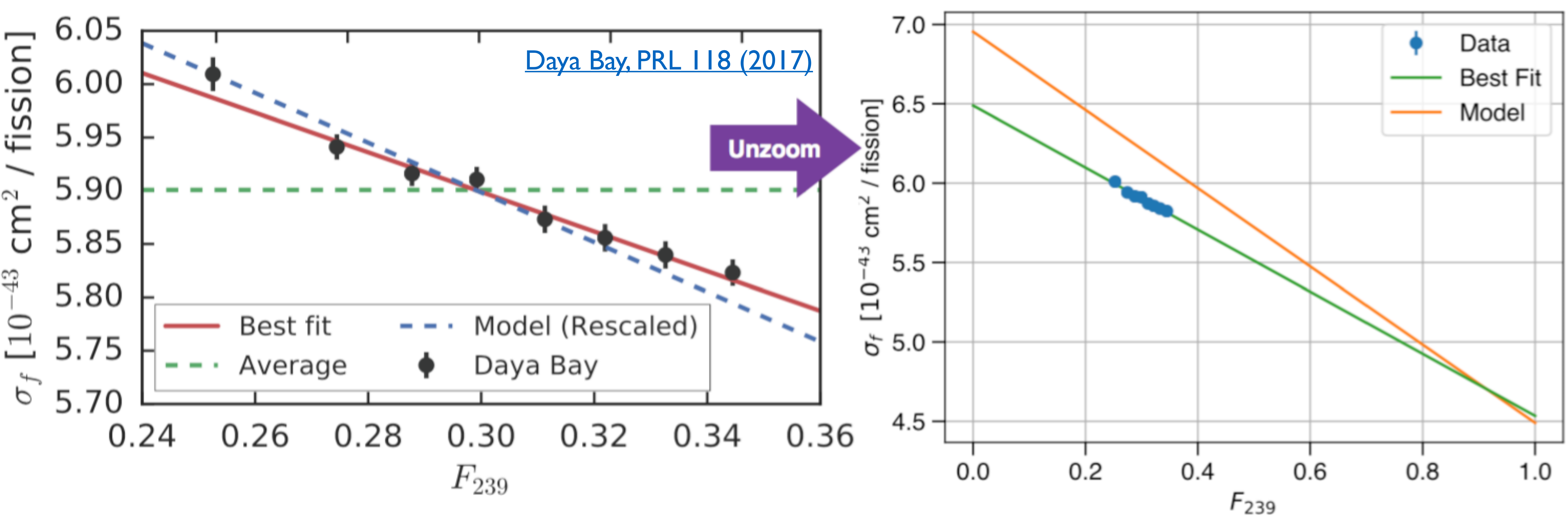


T.Akindele et al, hep-ex[2203.07214]

RAA Resolution: New Flux Measurements

- Resolve by probing the RAA deficit from reactor fuels with differing content ('fuel 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
- Recent curiosities here: can comment more (in back-up…)

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



New P5 Period: Why SBL Reactors?

- Well-tailored reactor neutrino measurements have resolved a key outstanding neutrino physics question!
- With the RAA problem 'solved,' why do we still need short-baseline reactor experiments in the next P5 period?
  - Let's ask this Q in general for e-flavor disappearance, too.

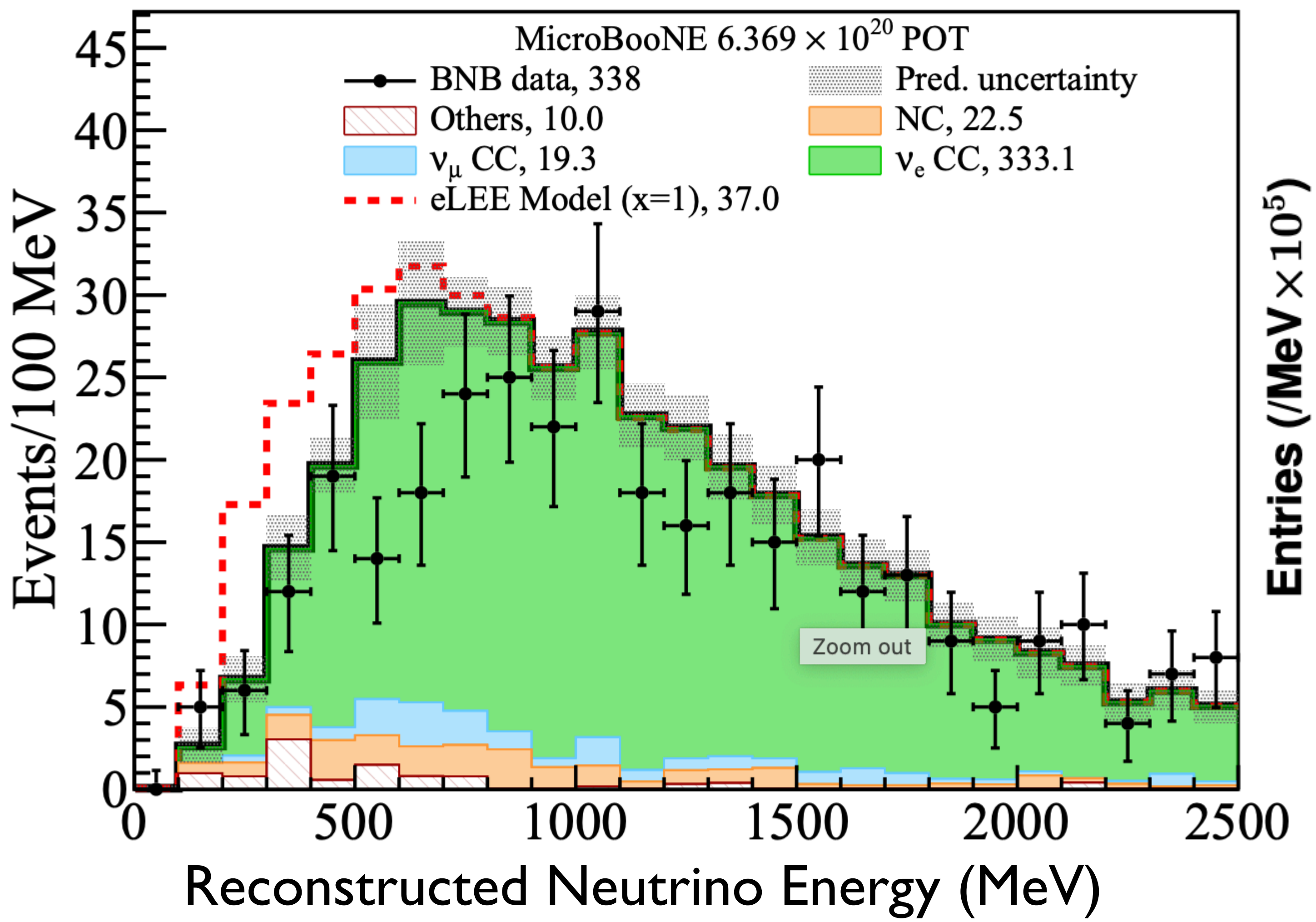
Exploring the Quantum Universe

> 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

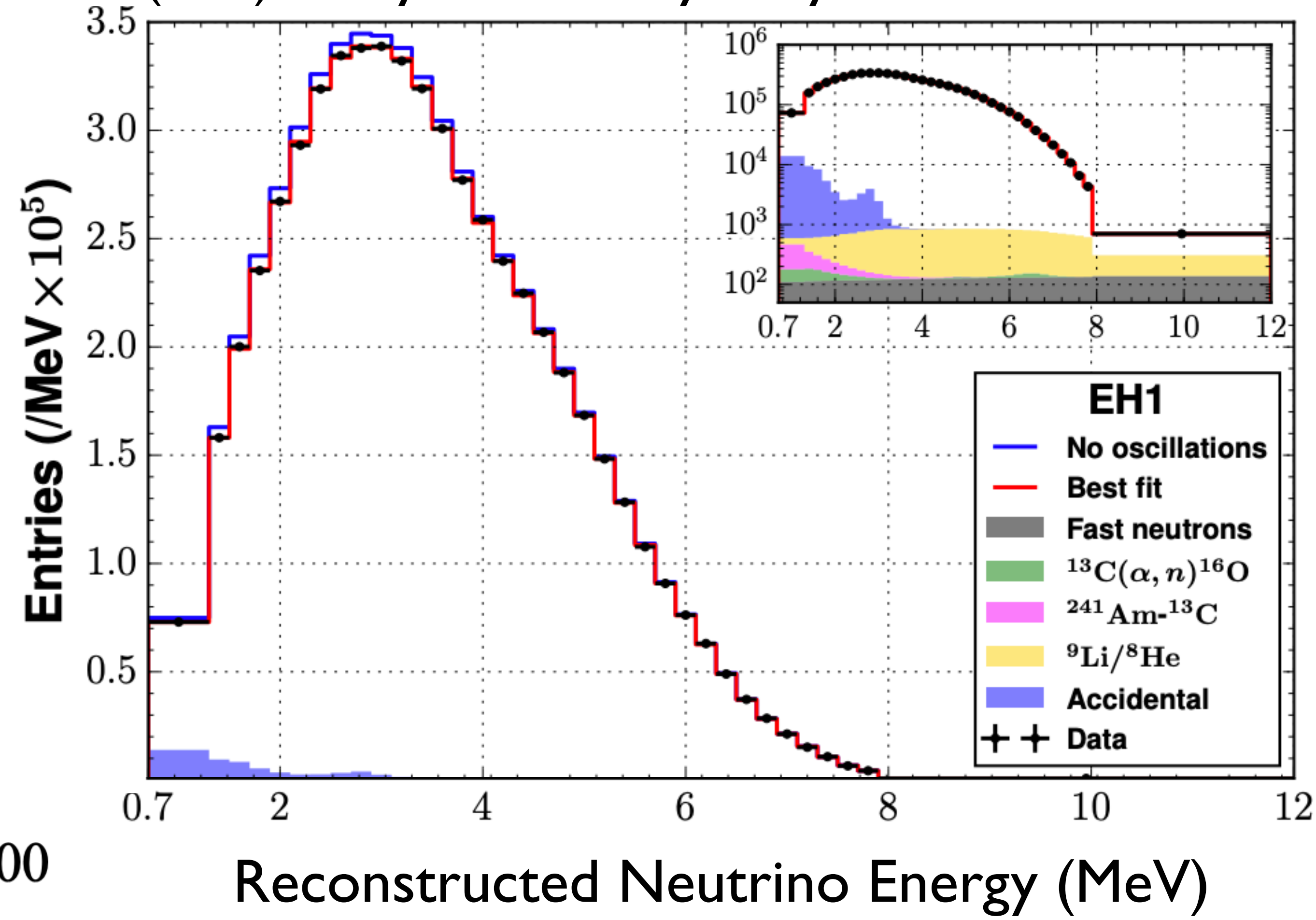
- Reactors are the purest, highest-intensity source of electron-flavor neutrinos that we have to work with
  - Purity and high stats are complimentary to mixed-flavor accelerator fluxes

O(100) ton-years at Fermilab: 350 ν_e



[MicroBooNE, PRL 128 (2022)](https://example.com)

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



Daya Bay, PRD 95 (2017)

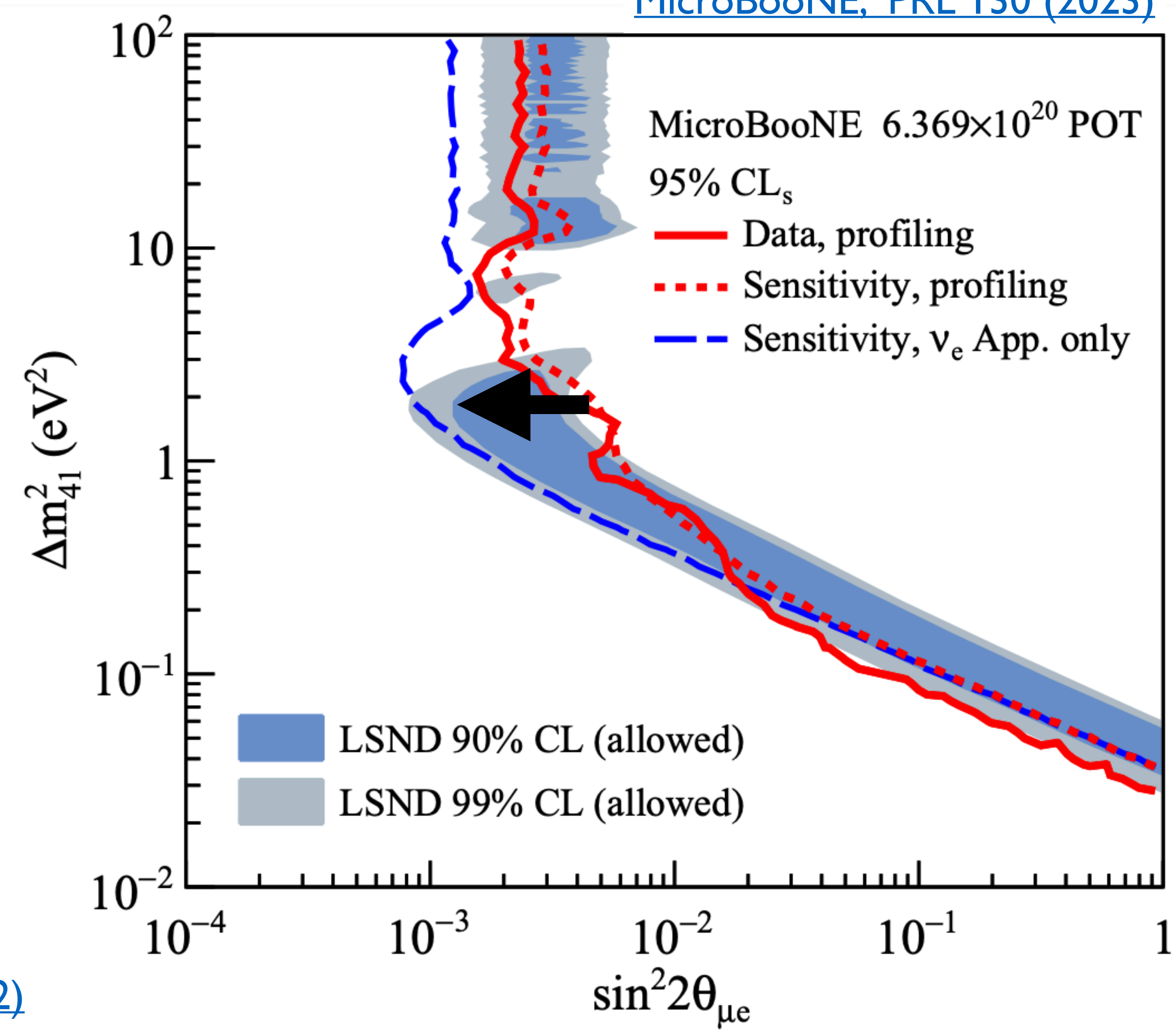
Reason 2: Remaining Anomalies

- **<u>Three</u>** other short-baseline anomalies remain unexplained: Gallium, LSND, and MiniBooNE

- Many pheno explanations impact reactor signatures, too
  - `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 <u>and</u> GeV; muon <u>and</u> electron; appearance <u>and</u> disappearance
  - Example: Testing MiniBooNE with MicroBooNE data Arguelles et al, PRL 128 (2022)

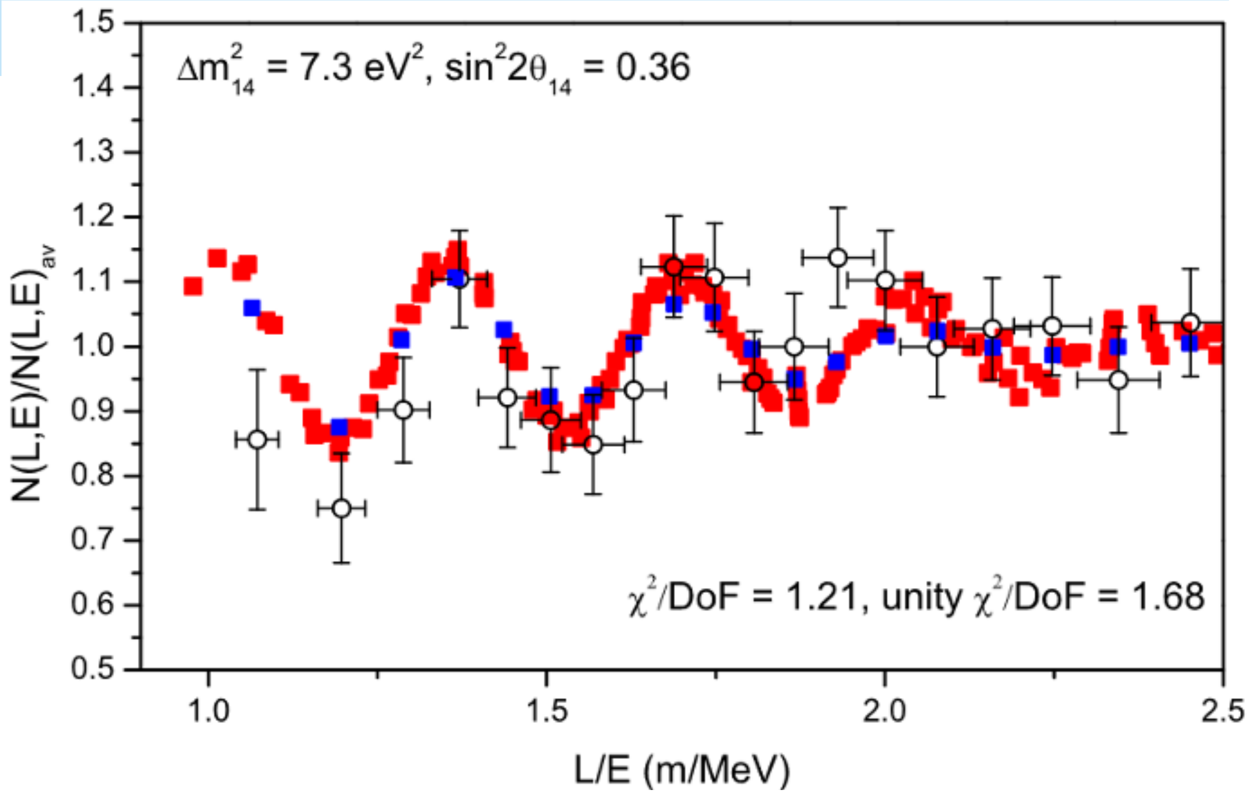
MicroBooNE, PRL 130 (2023)

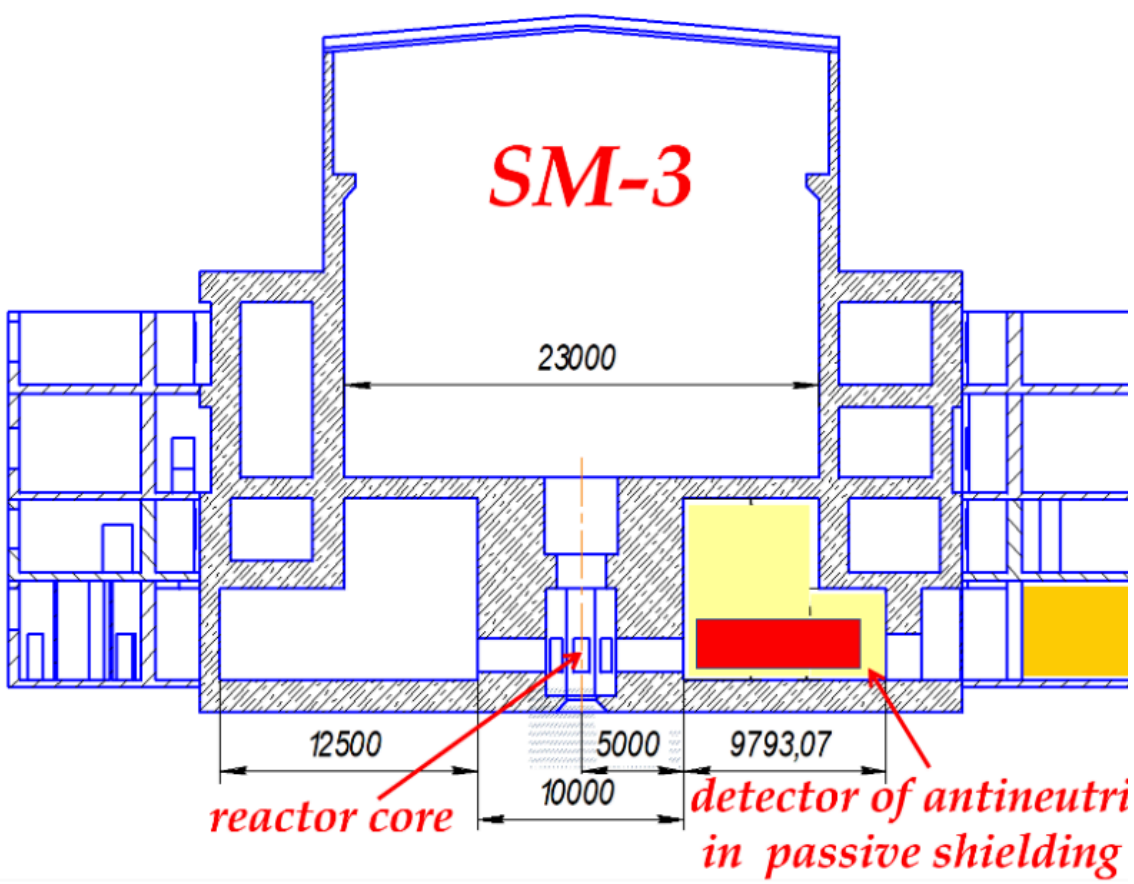


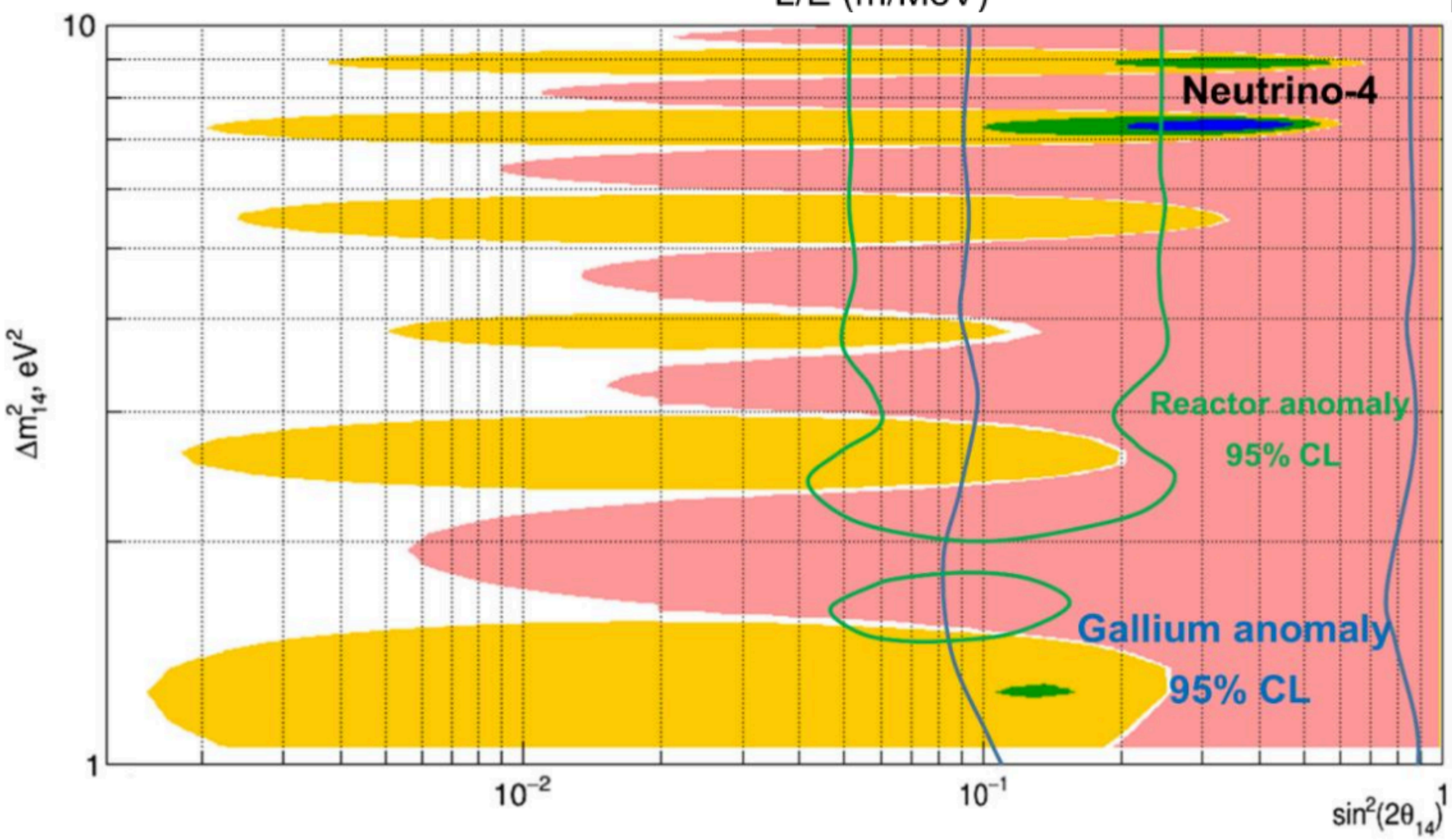
- Short-baseline reactor experiments play a unique role in an integrated global effort to understand these anomalies.

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 settle the issue



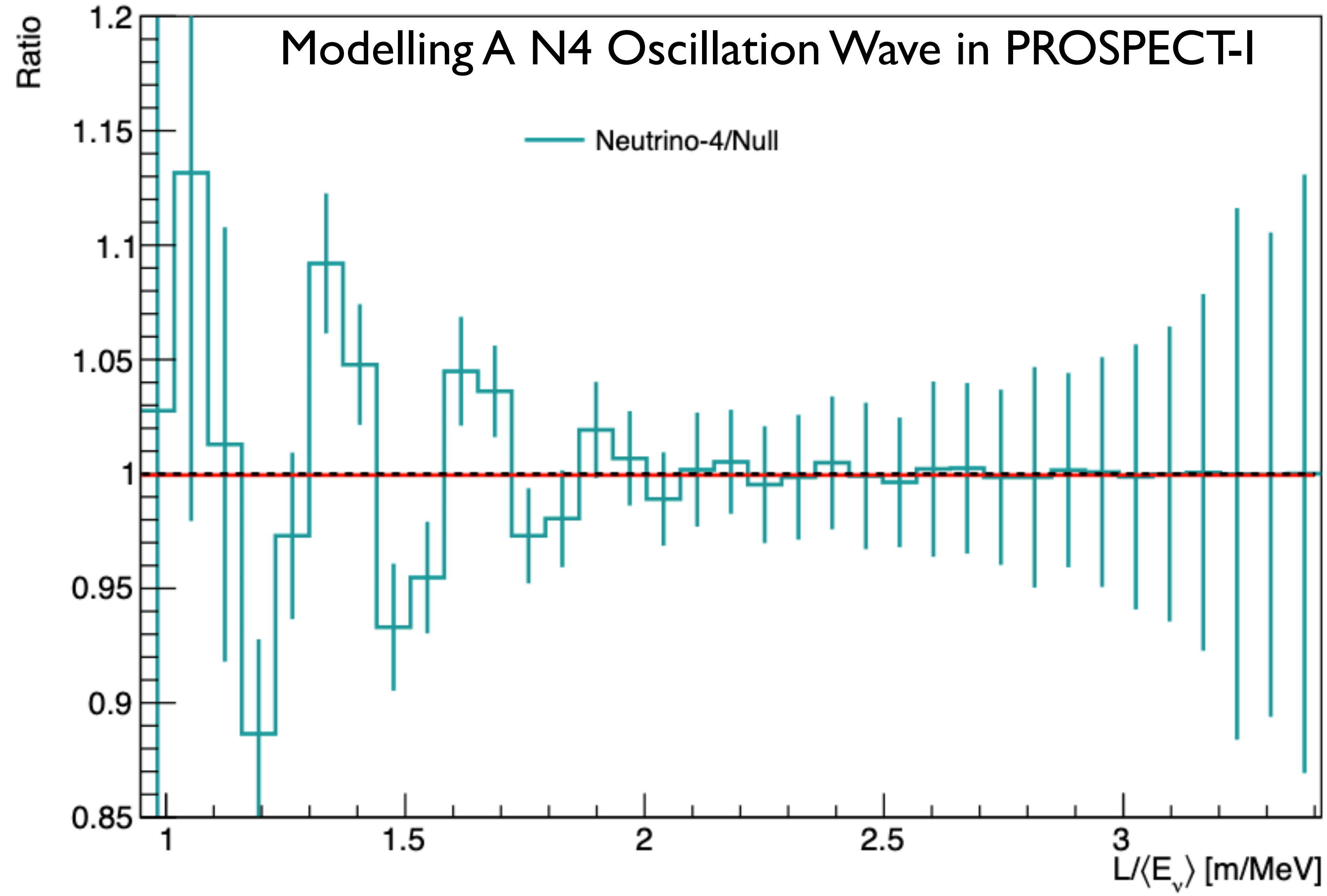




A. Serebrov et al, Phys Rev D 104 (2021)

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



	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

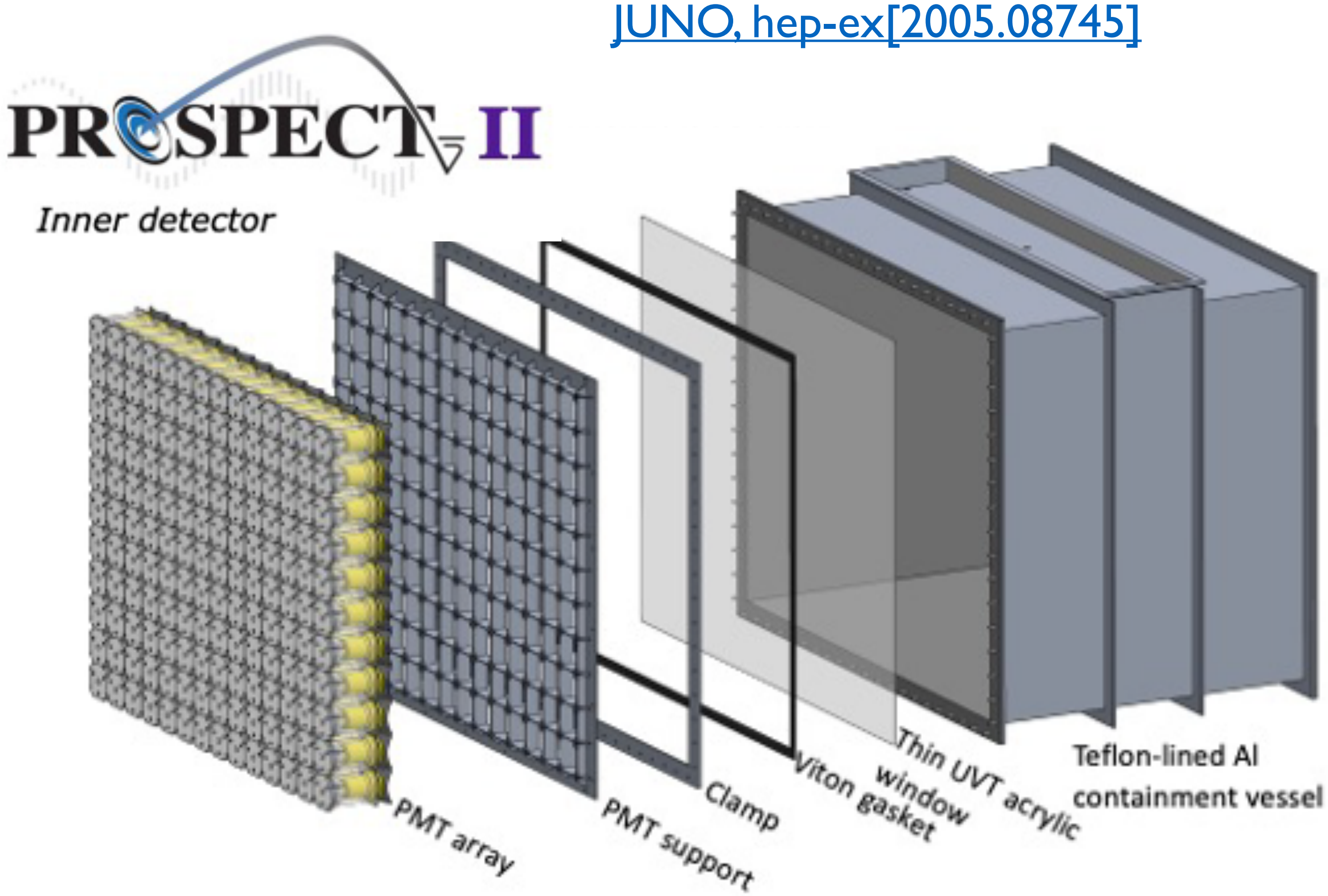
- In the new P5 period, major enhancements in sensitivity can come from 'ultimate' next-generation SBL reactor experiments

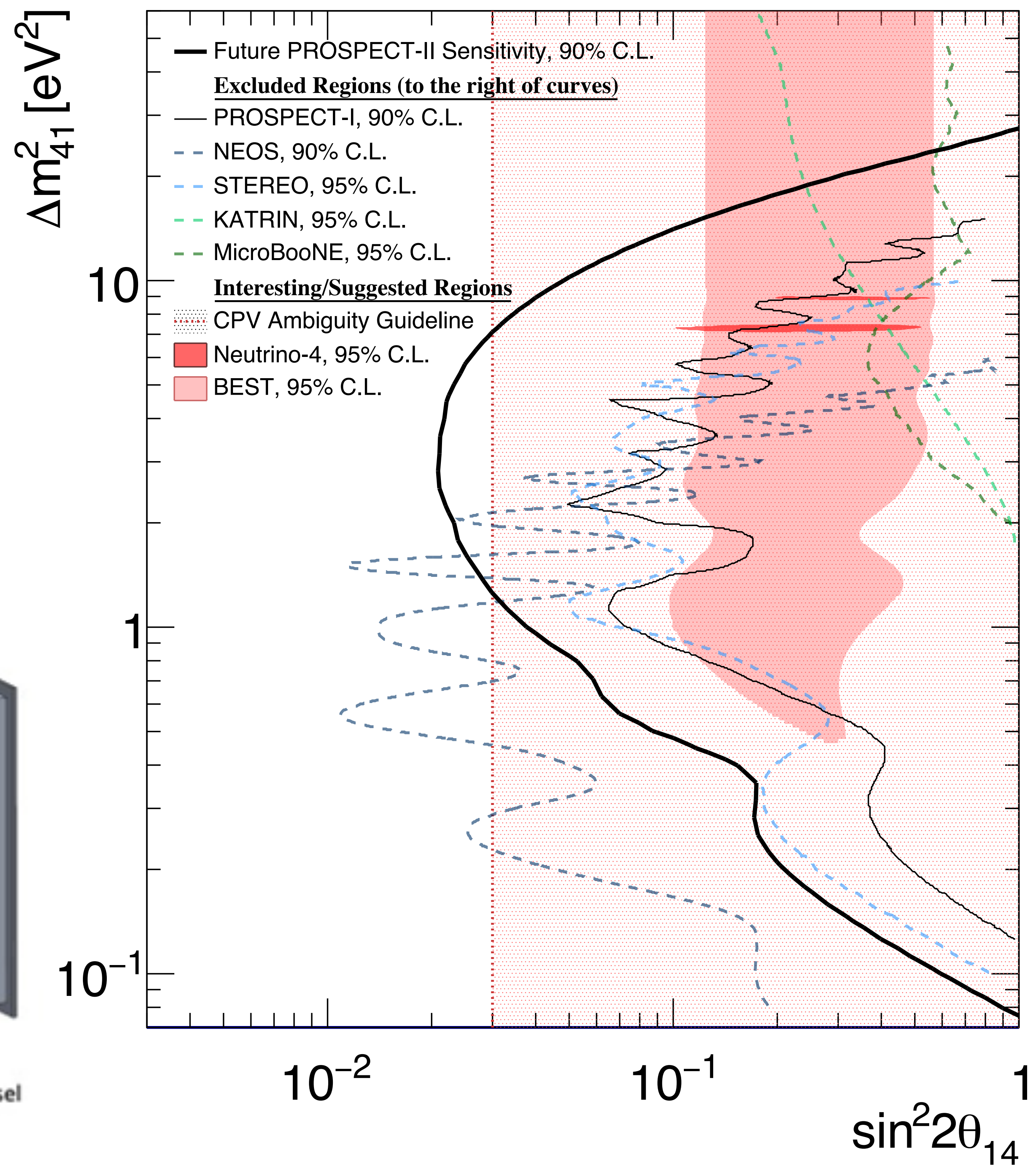
- PROSPECT-II:
  - Correlated HEU and LEU measurements in a mobile, robust tons-scale detector

PROSPECT, J Phys G 49 (2022)

- JUNO-TAO:
  - Percent-level energy resolution in a LEU-based short-baseline measurement

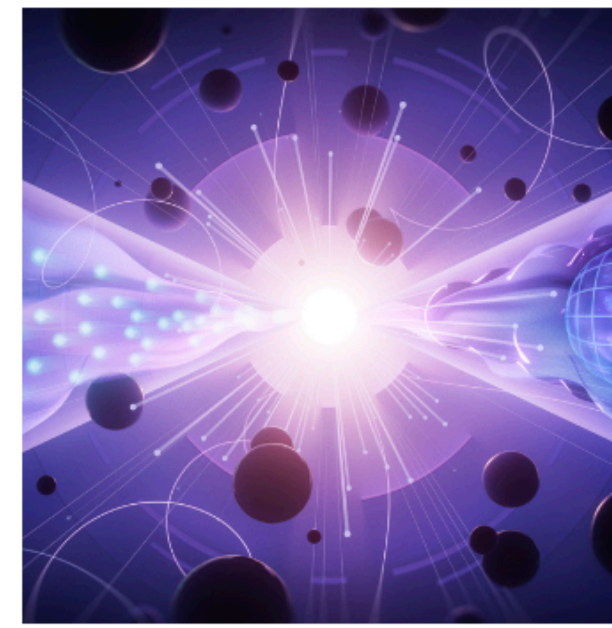
JUNO, hep-ex[2005.08745]





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,

Reason 4: Exploring New Paradigms

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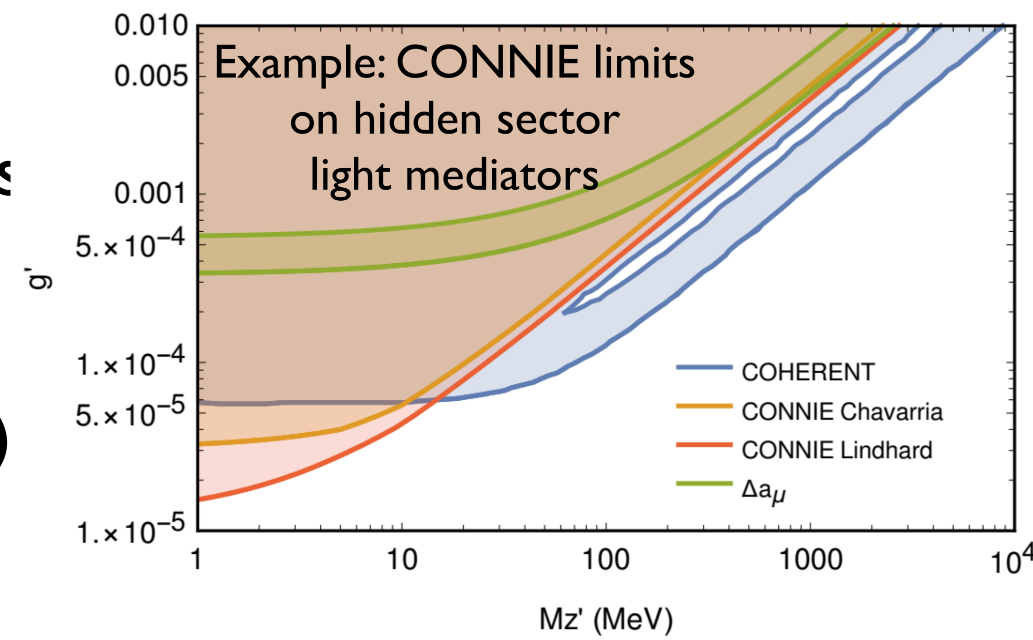
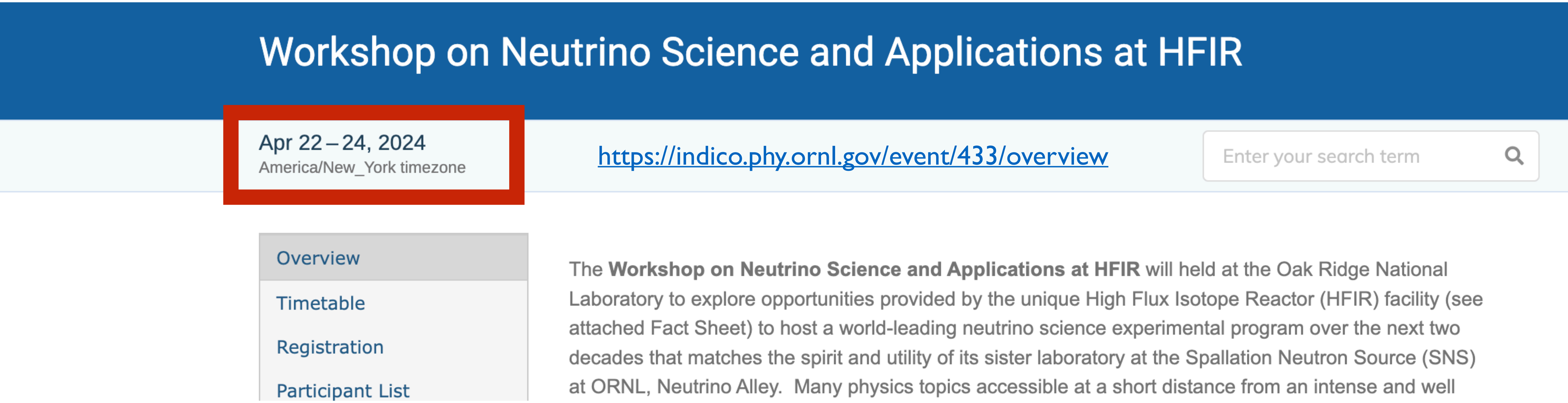
T.Akindele et al, hep-ex[2203.07214]

CONNIE, JHEP 54 (2020)





Workshop on Neutrino Science and Applications at HFIR

Apr 22 – 24, 2024
America/New_York timezone

https://indico.phy.ornl.gov/event/433/overview

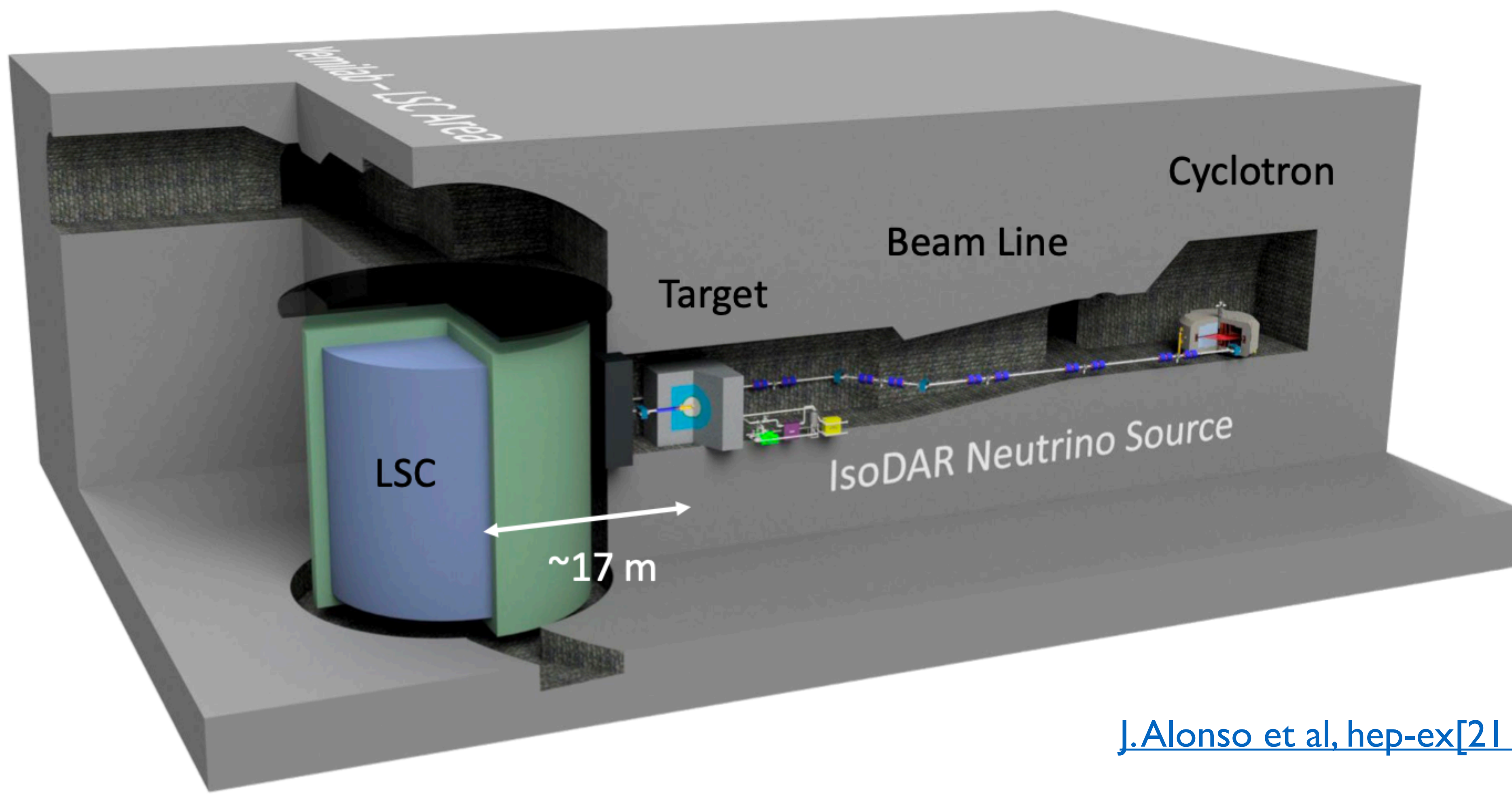
Enter your search term

Overview
Timetable
Registration
Participant List

The **Workshop on Neutrino Science and Applications at HFIR** will held at the Oak Ridge National Laboratory to explore opportunities provided by the unique High Flux Isotope Reactor (HFIR) facility (see attached Fact Sheet) to host a world-leading neutrino science experimental program over the next two decades that matches the spirit and utility of its sister laboratory at the Spallation Neutron Source (SNS) at ORNL, Neutrino Alley. Many physics topics accessible at a short distance from an intense and well

Back to Reason 1: Electron Flavor

- "Reactors are the purest, highest-intensity source of electron-flavor neutrinos that we have to work with"… *<u>CURRENTLY.</u>*
- A new experiment type provides another option: IsoDAR!

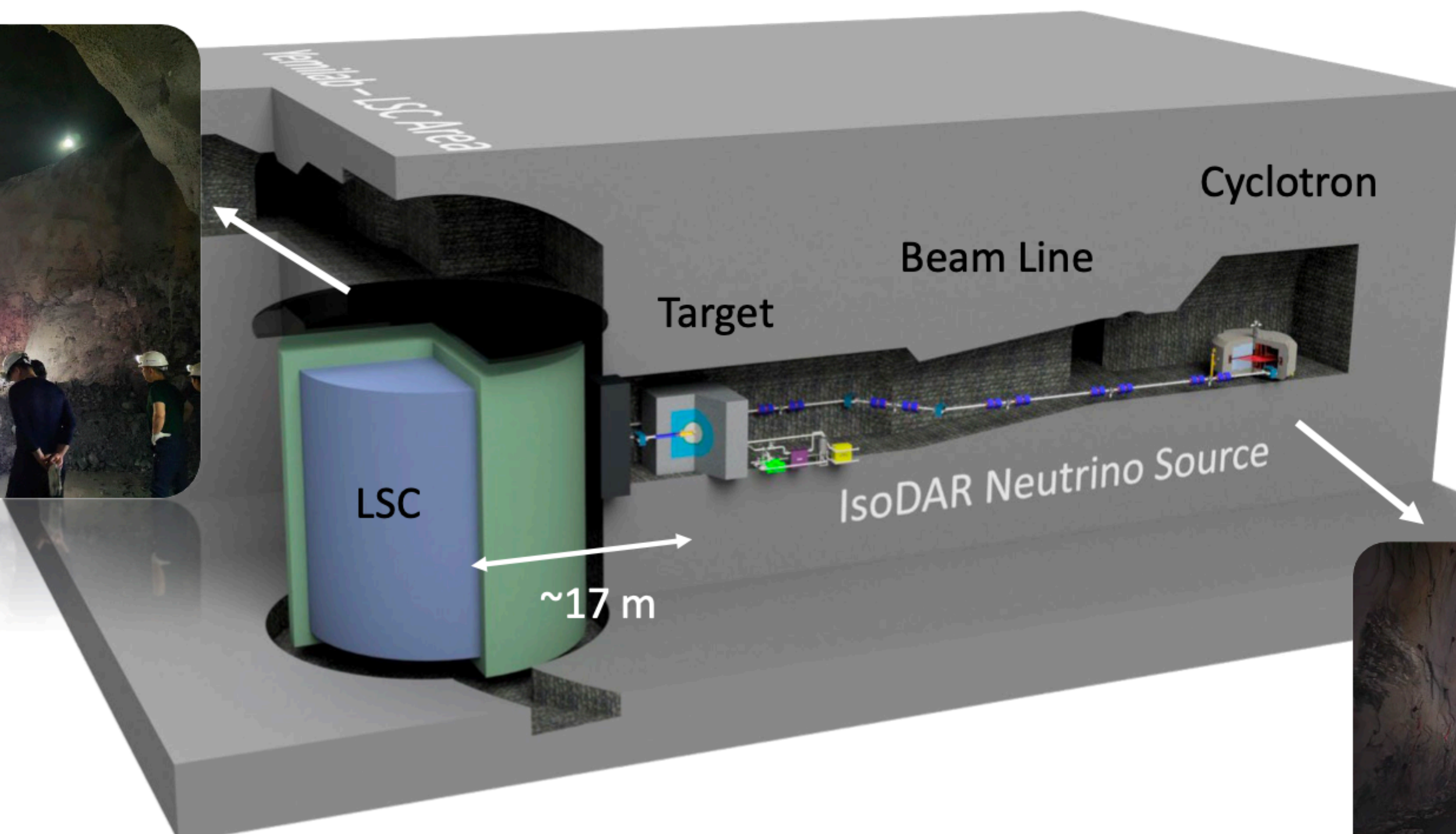


J. Alonso et al, hep-ex[2111.10635]

- Compact Cyclotron → 10 mA protons @ 60 MeV (10x more current than existing)
- Target → 600 kW power deposited → ~1 mole $\bar{\nu}_e$ produced in 5 years from pure ^{8}Li DAR
- Liquid Scintillator Counter → ~2M Inverse Beta Decay ev., ~7000 $\bar{\nu}_e - e^-$ ES ev.

New P5: More Electron Flavor!

- **IsoDAR at Yemilab in South Korea: existing civil construction!**
  - Accelerator and LSC R&D work continues; approaching shovel-ready status
  - Funding explorations active on both sides of the Pacific



Caverns are already constructed

Physics Paper: http://arxiv.org/abs/2111.09480, PRD 2022
IsoDAR@Yemilab – CDR: http://arxiv.org/abs/2110.10635 arXiv 2021

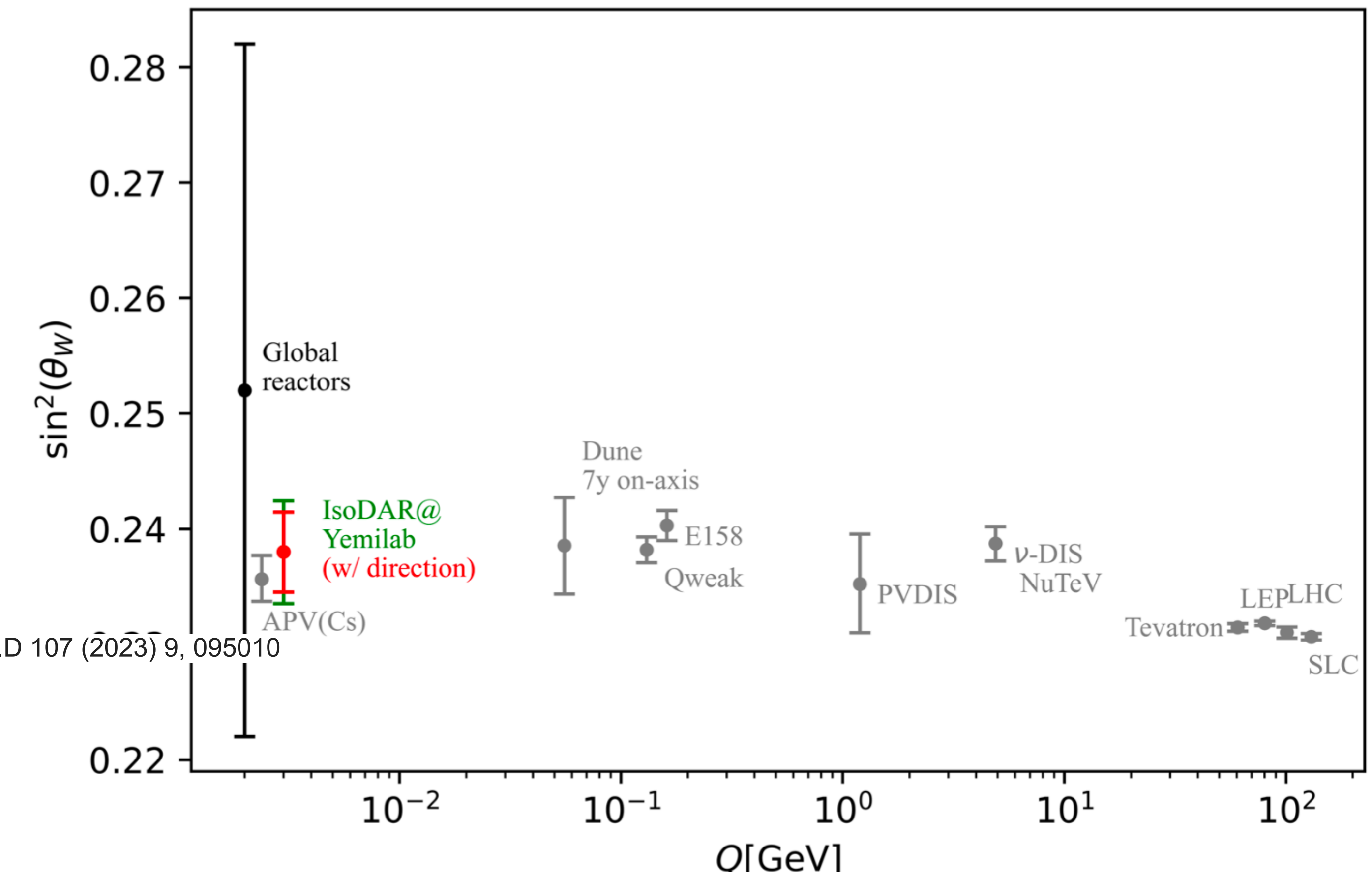
Thanks to J. Spitz for input.

Broad IsoDAR Physics

- IsoDAR @ Yemilab aims for broad, long-term physics program
  - IBD: Osc-related searches: 3+1; 3+2; 3+1+decay, etc.
  - Nu-e like signatures: θ_W, ALPs, and more.
  - Non-beam signatures: solar neutrinos

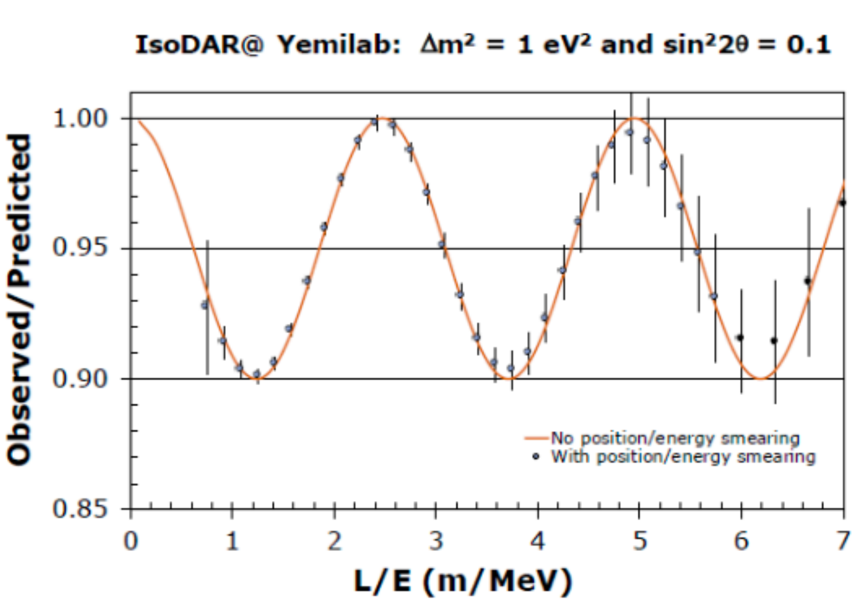
[J. Alonso, et al, Phys Rev D 105 (2022)]

[L. Waites et al, Phys Rev D 107 (2023)]

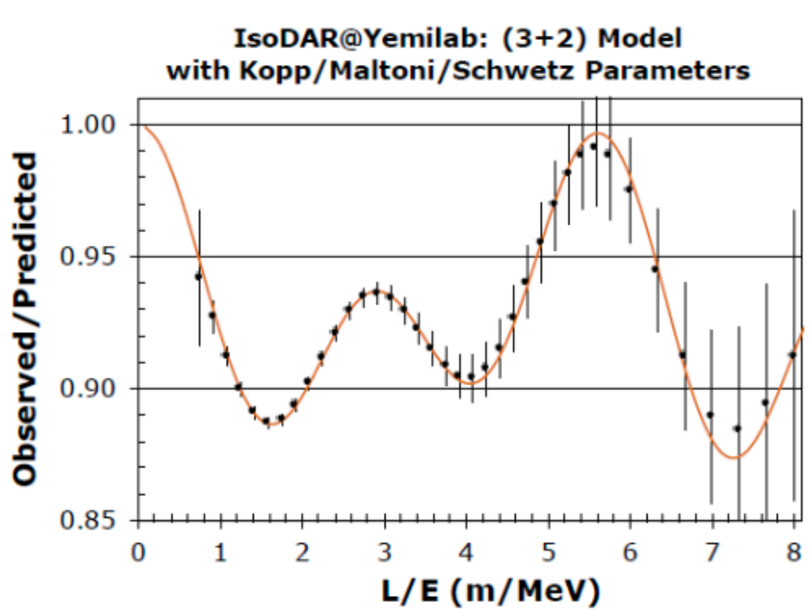


Phys.Rev.D 107 (2023) 9, 095010

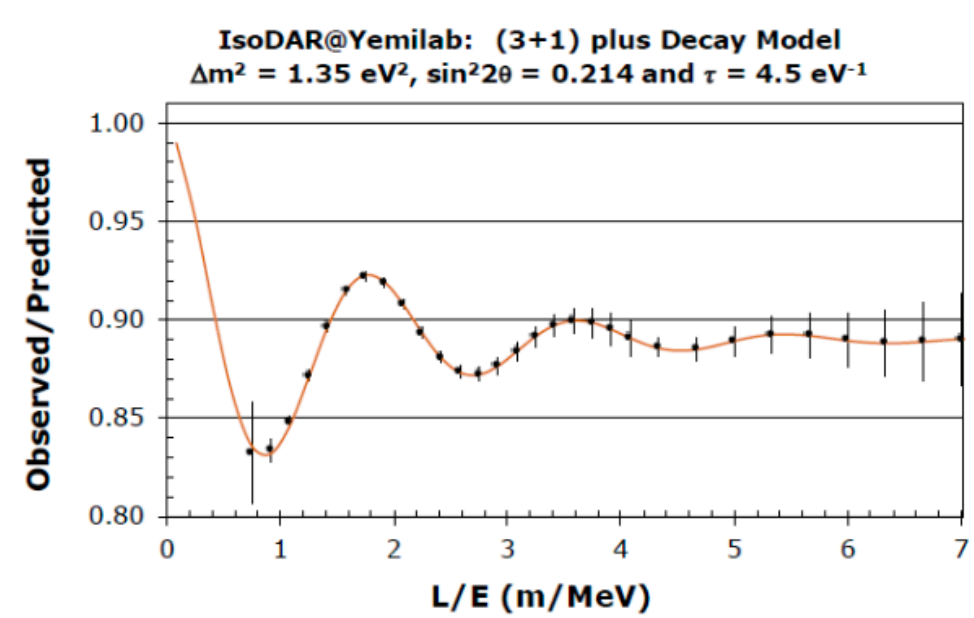
one exotic neutrino



two exotic neutrinos



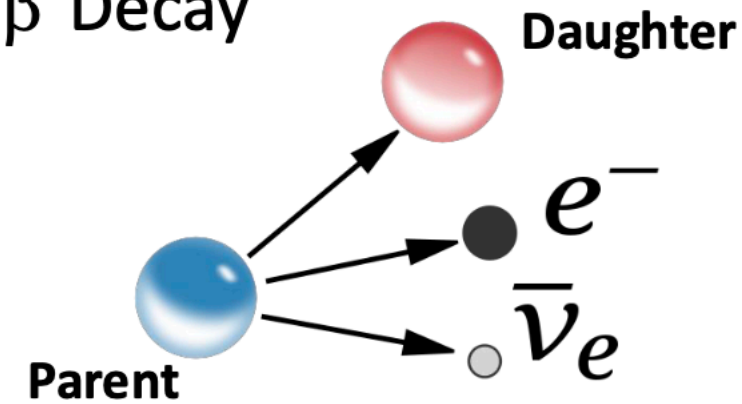
one that decays...



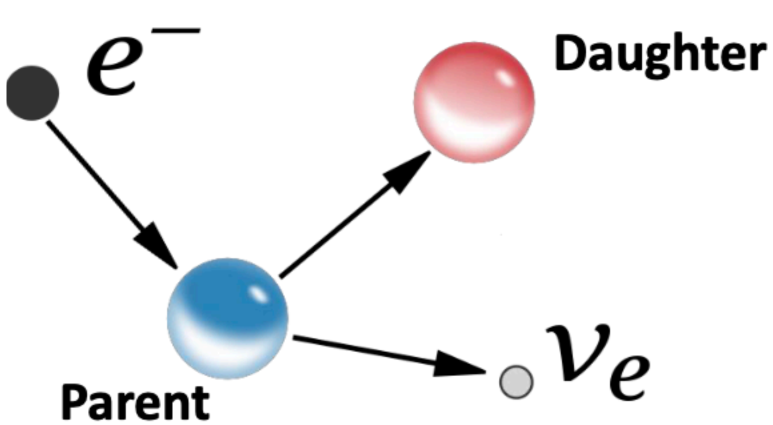
More About High Δm^2: Decay Experiments

- Electron-flavored weak decay: great coverage at very high Δm^2
  - Measure tritium beta, or measure EC nuclear recoil
  - Below ~100 eV^2, future limits from KATRIN, Project-8

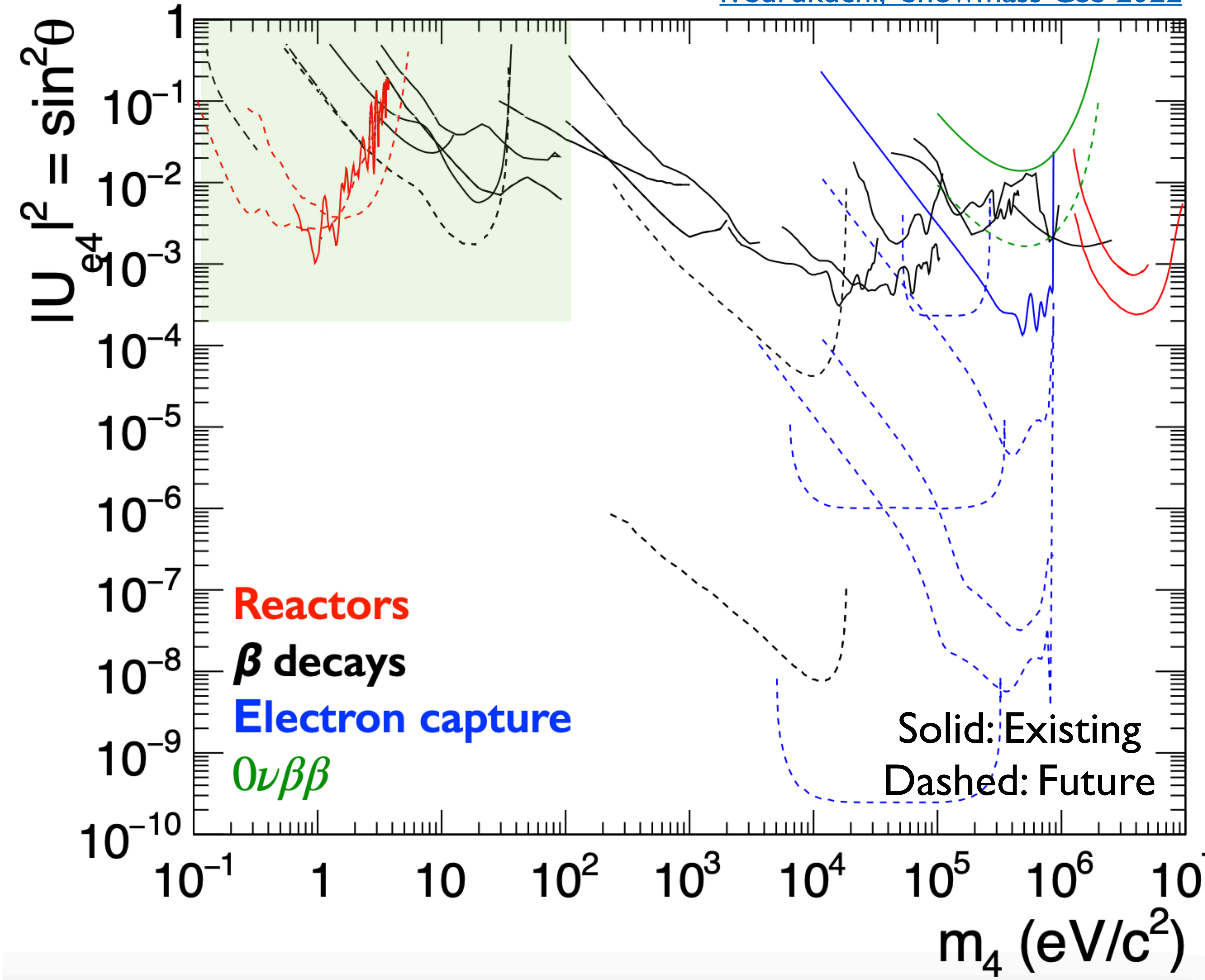
β^- Decay



EC Decay

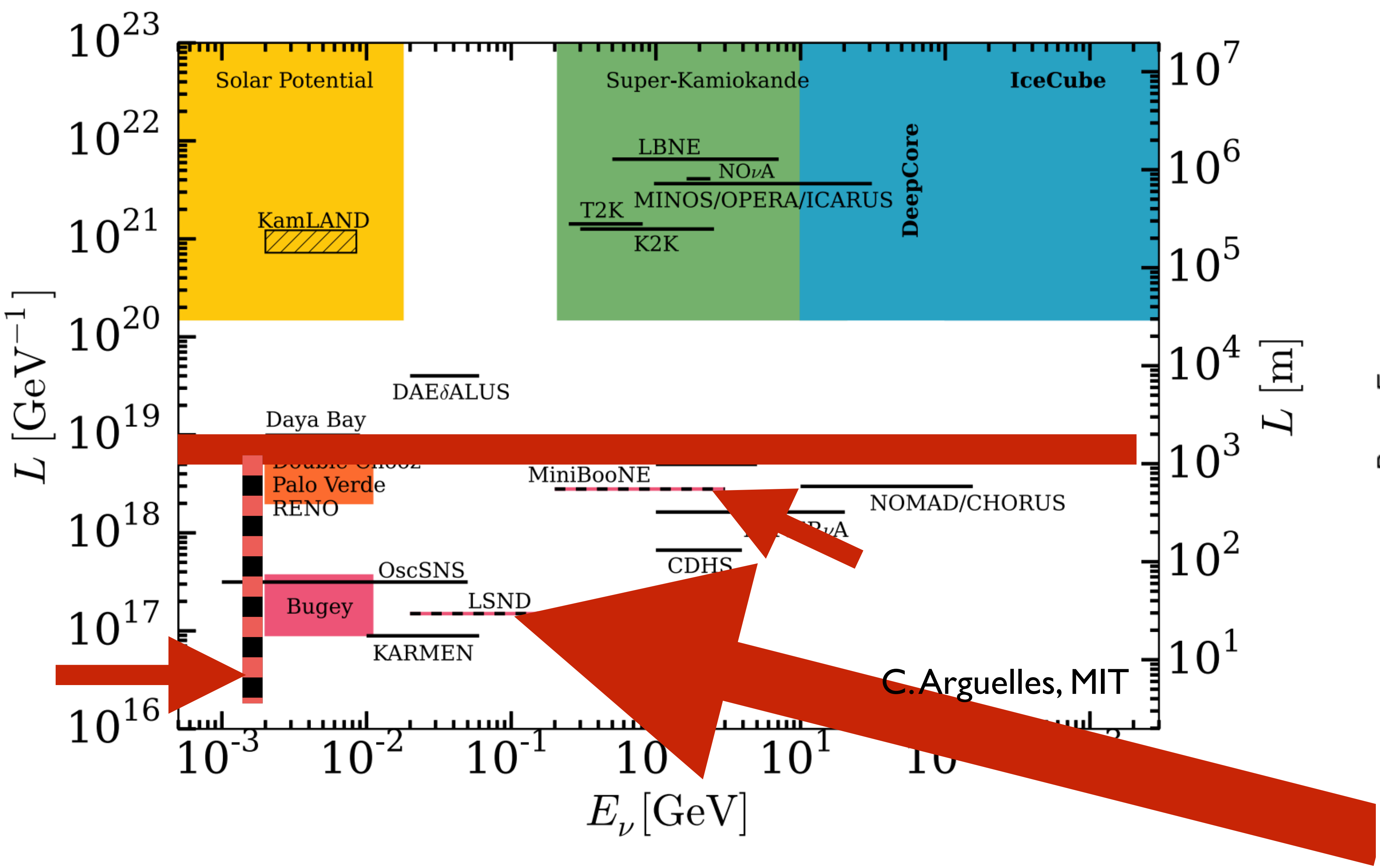


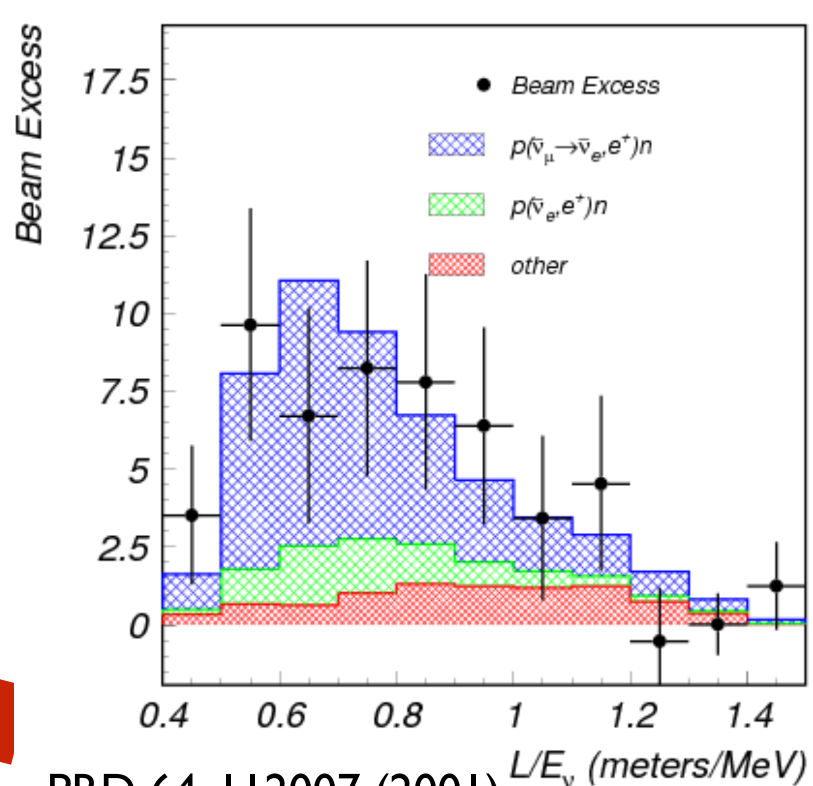
P. Surukuchi, Snowmass CSS 2022



Decay-At-Rest Electron Appearance (LSND)

- Let's zoom in and explore another of these anomalies
  - What's their status?
  - How does this relate to the broader neutrino program (and SBN)?

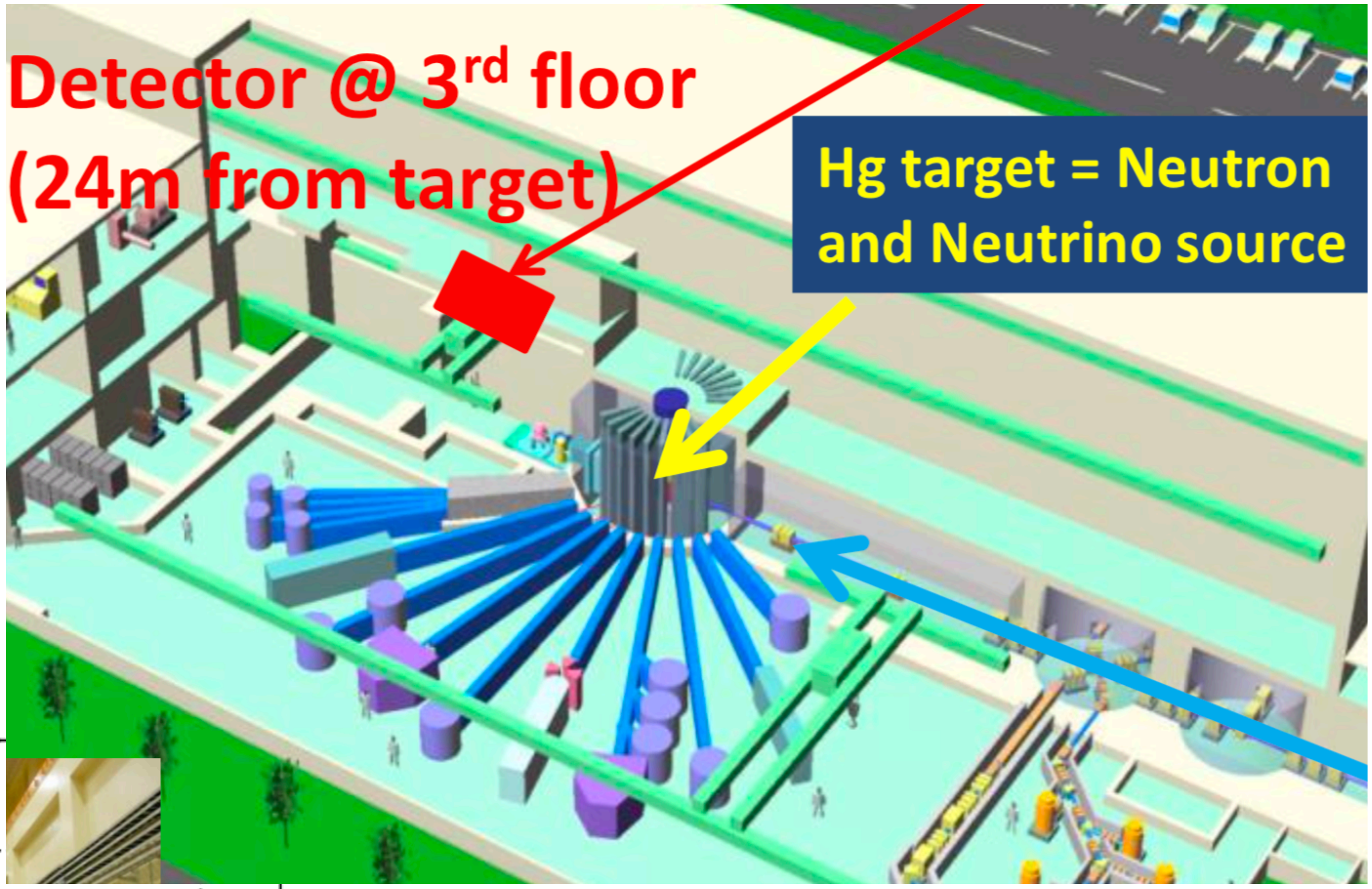




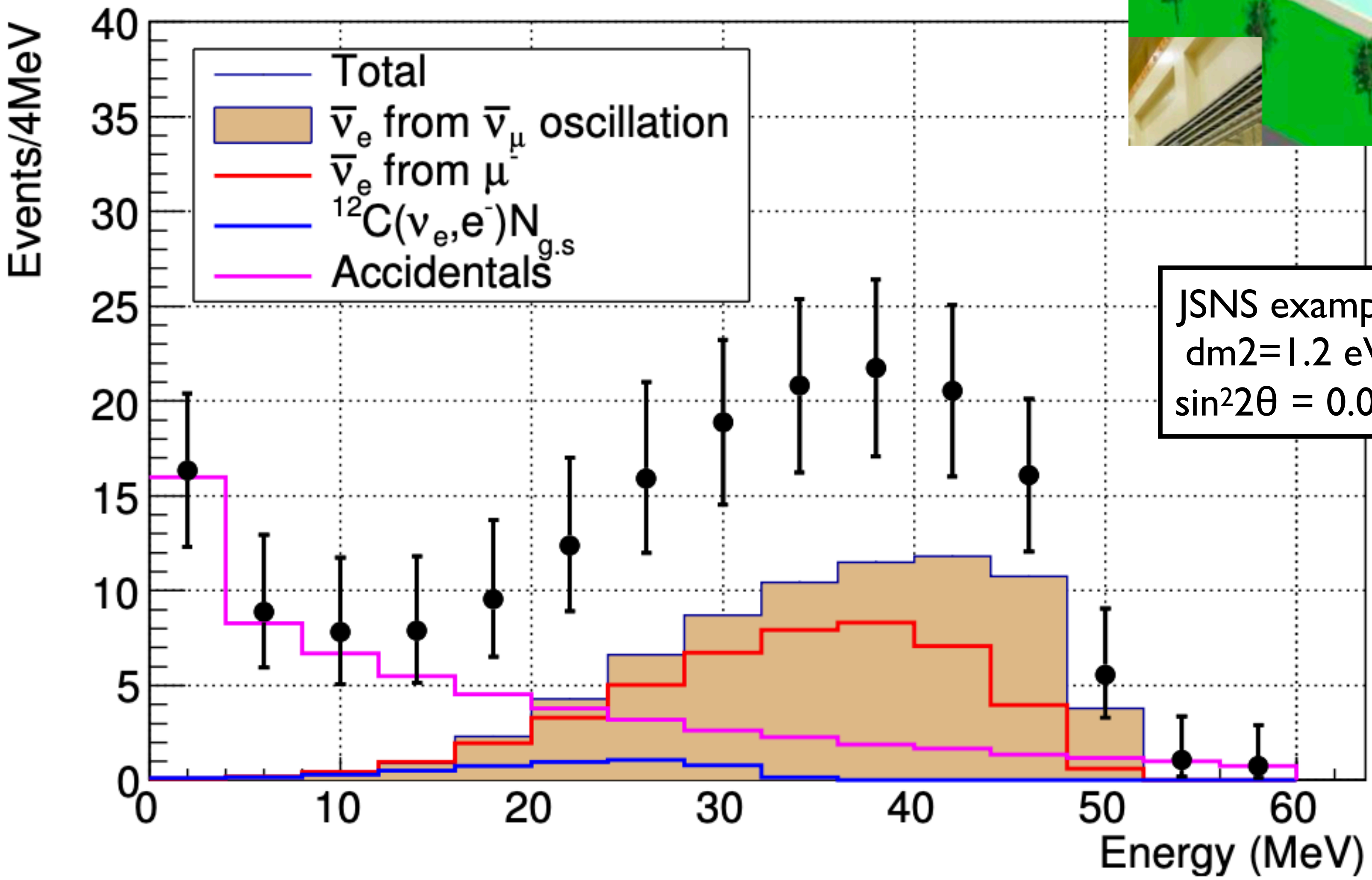
PRD 64, 112007 (2001)

Into the New P5: JSNS²

- JSNS² at JPARC: like LSND, source nearly free of all $\bar{\nu}_e$
- Higher beam power (1MW), and higher statistics
- Shorter beam width (100ns), lower backgrounds



JSNS2, hep-ex[1705.08629]

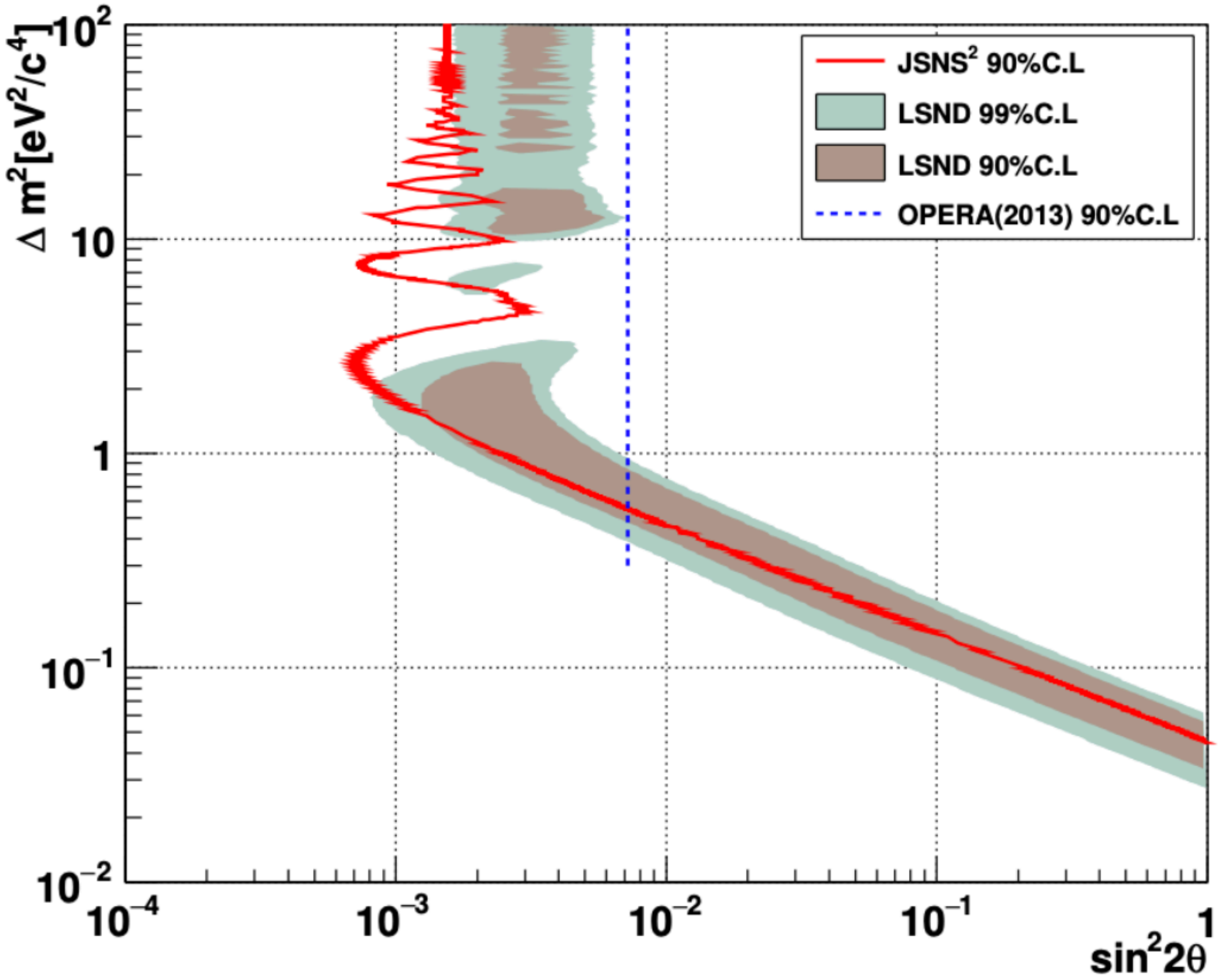


JSNS example: dm2=1.2 eV²; $\sin^2 2\theta$ = 0.003

Thanks to J. Spitz for input.

Into the New P5: JSNS²

- In the new P5 period, we will directly test the LSND anomaly
  - Experiment is constructed and already taking data: 4e22 POT (36% of total)
  - 2nd detector (JSNS²-II) planned to start data-taking in late 2024.



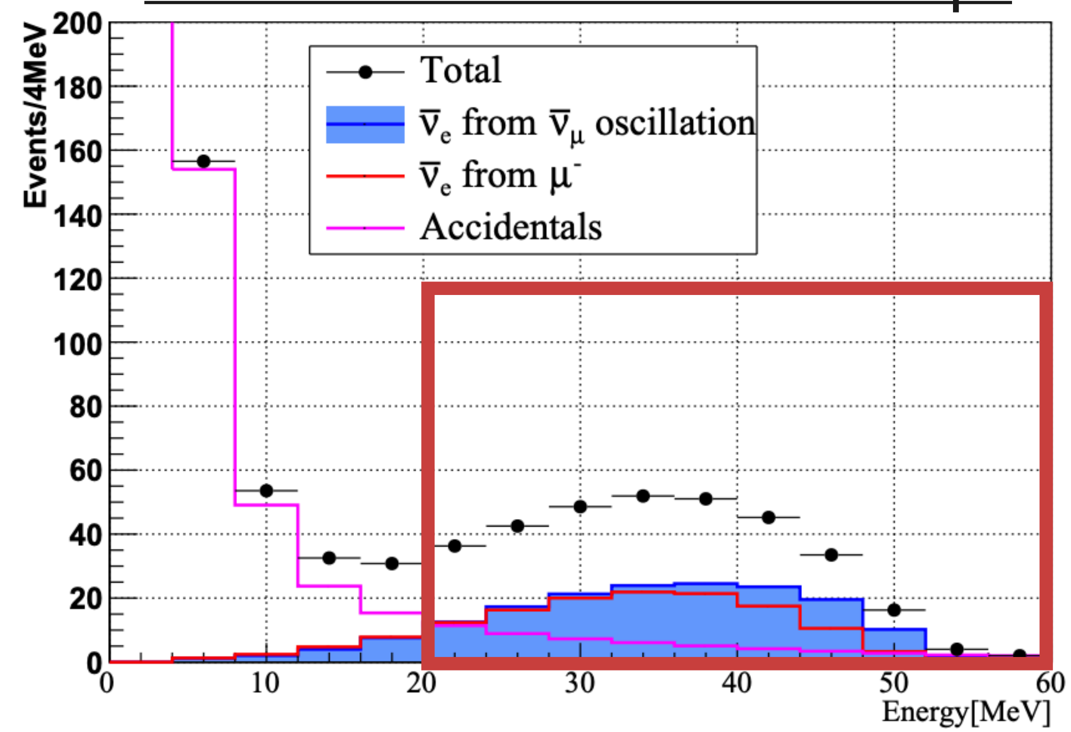
JSNS2, hep-ex[2012.10807]

Thanks to J. Spitz for input.

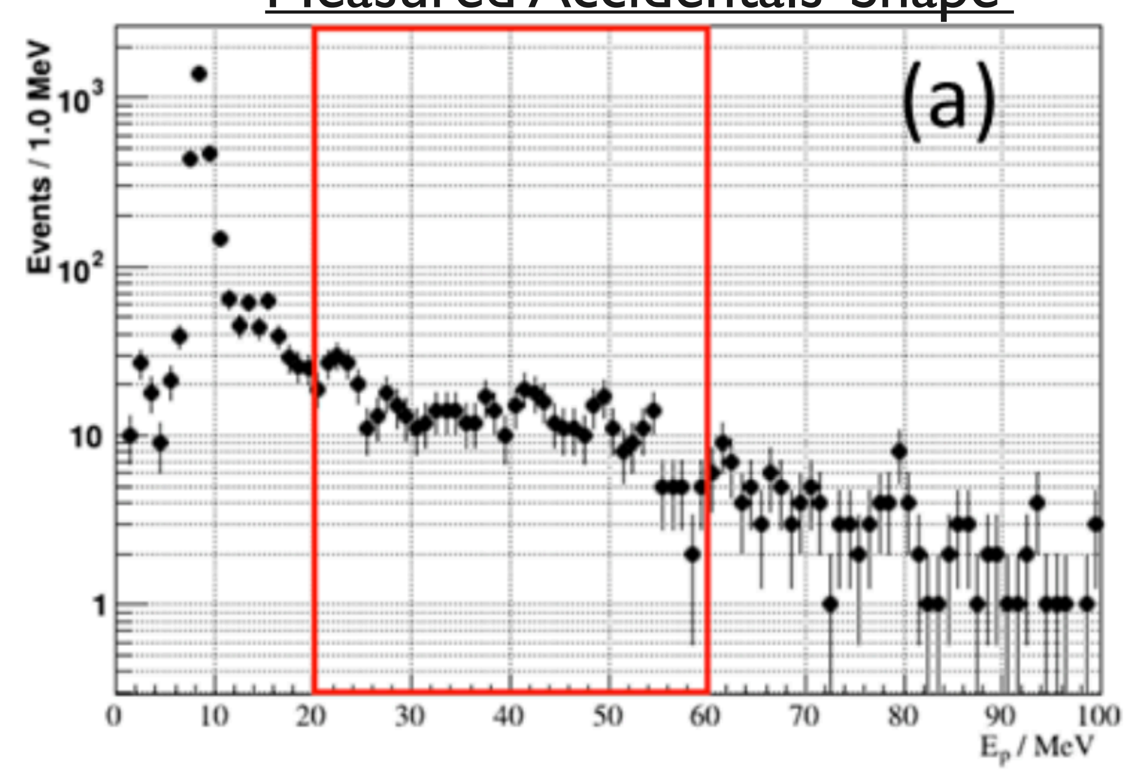
First Public Analysis of JSNS² Data

- Some JSNS² data analysis is public: accidentals rates
  - Accidentals (pink): 9e-8/spill/0.75MW
  - Osc signal (LSND BF) : 5e-8/spill/0.75MW
  - While shape+rate can be easily measured, it looks like accidentals may be higher than initially anticipated
- Collaboration is hard at work at both oscillation and KDAR analyses
  - These results will both be highly relevant to the SBN program; different JSNS results may point SBN towards different new physics scenarios of interest!

2021 Predicted Accidentals Shape



Measured Accidentals 'Shape'



JSNS2, hep-ex[2012.10807]

JSNS2, hep-ex[2308.02722]

Summary

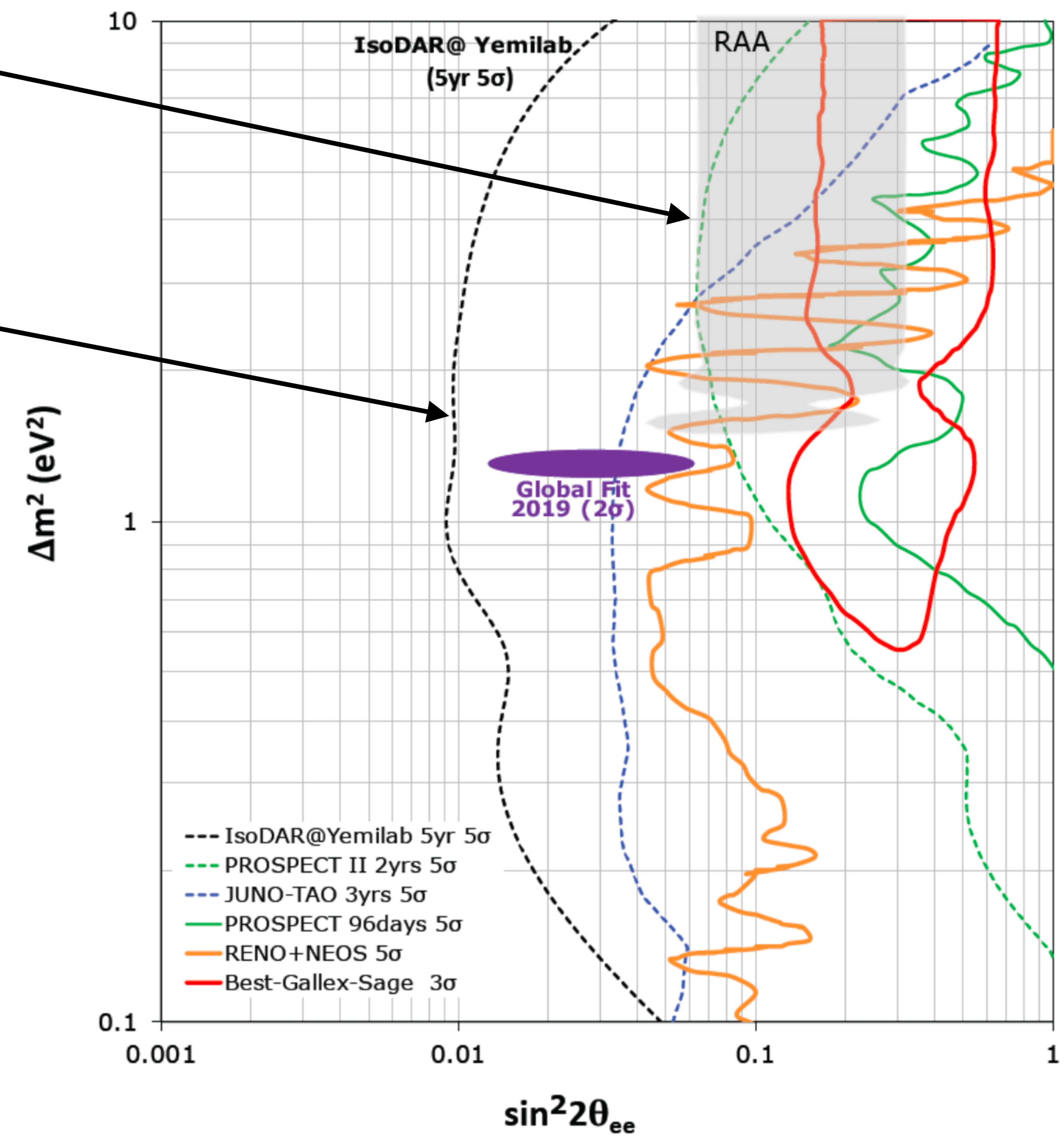
- In the new P5 period, there will be a lot more going on at short baselines than just FNAL SBN!
- We can expect new electron-flavor disappearance limits from reactors and weak decay experiments, and we have a new generation of Reactor-nu/IsoDAR-nu/weak-decay experiments that can be initiated in the new P5 period
- For electron disappearance, $JSNS^2$ has data in the can, and we can expect 1- and 2-detector results in the new P5 period

Thanks!

Backup

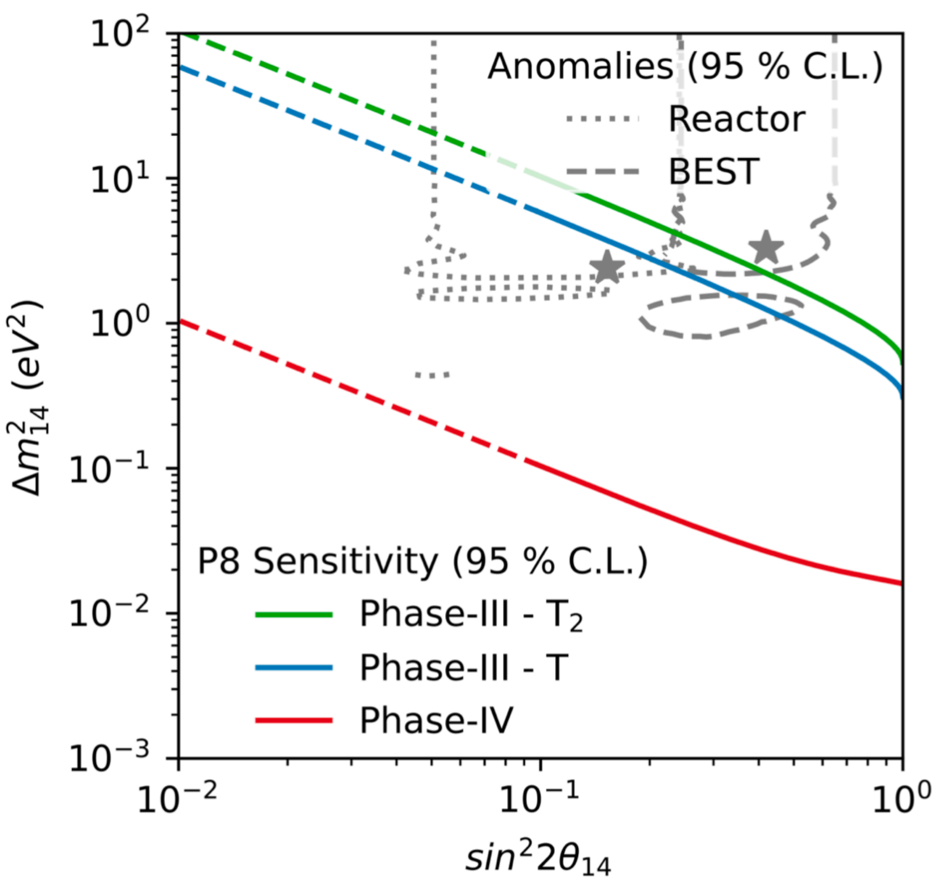
Future Electron-Disappearance Limits?

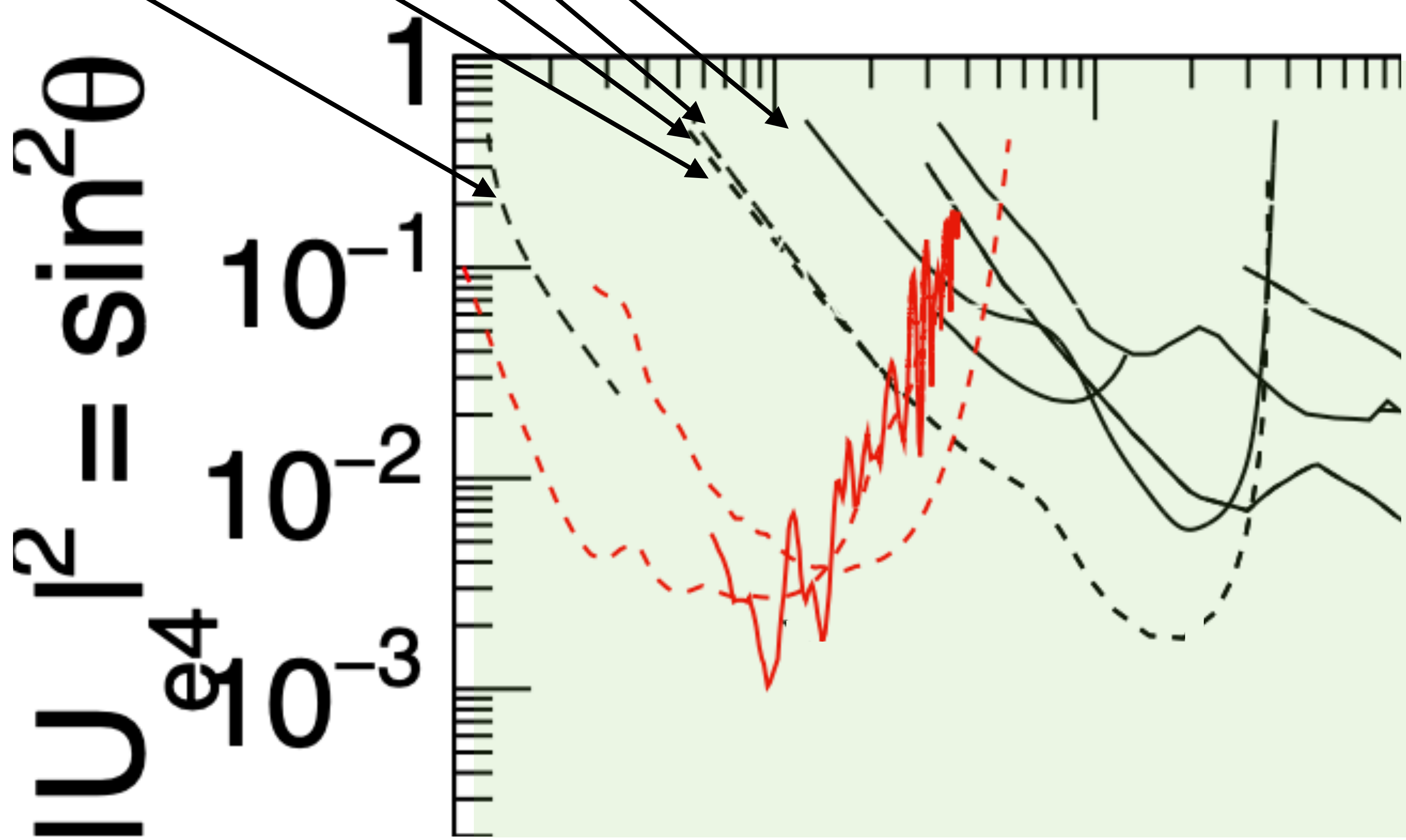
- Let's make a hypothetical scenario where we started building IsoDAR and PROSPECT-II today:
  - Assume 1 year PROSPECT construction; 2 year IsoDAR + LSC construction
  - 2027: P2@HFIR final results
  - ~2027: BNB Long shutdown?
  - 2031: IsoDAR final results
  - ~2031: DUNE+Beam startup?
- This is a pretty nice picture of what we might know by DUNE start-up time!
- Note all curves are 5sigma



Future E-Flavor Weak Decay Limits?

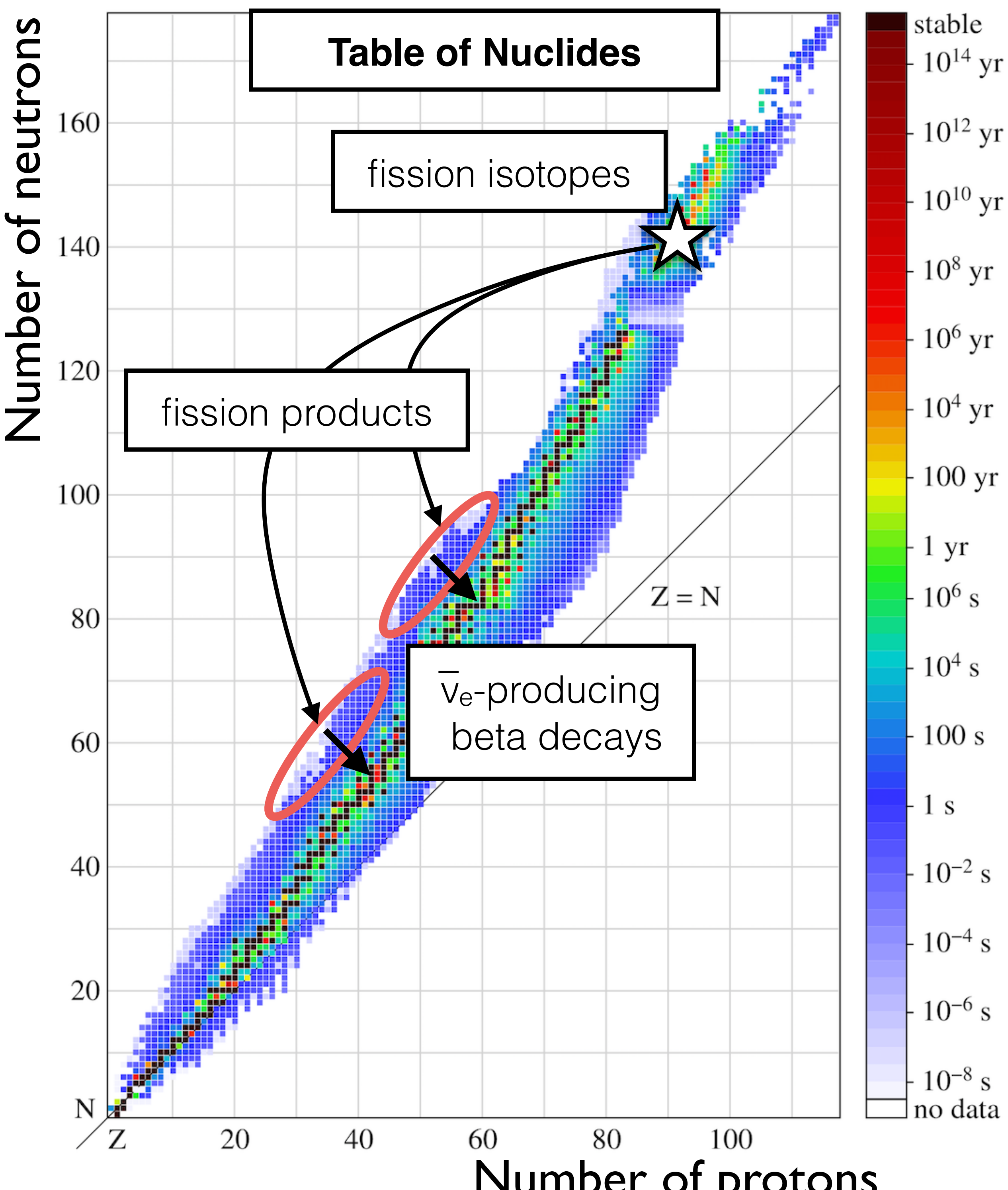
- When do weak decay limits come into existence?
  - KATRIN Current: 2021
  - KATRIN Completion: 2025
  - Project-8, Phase III (T2): 2030
  - Project-8, Phase III (T): 2033
  - Project-8, Phase IV: 2040

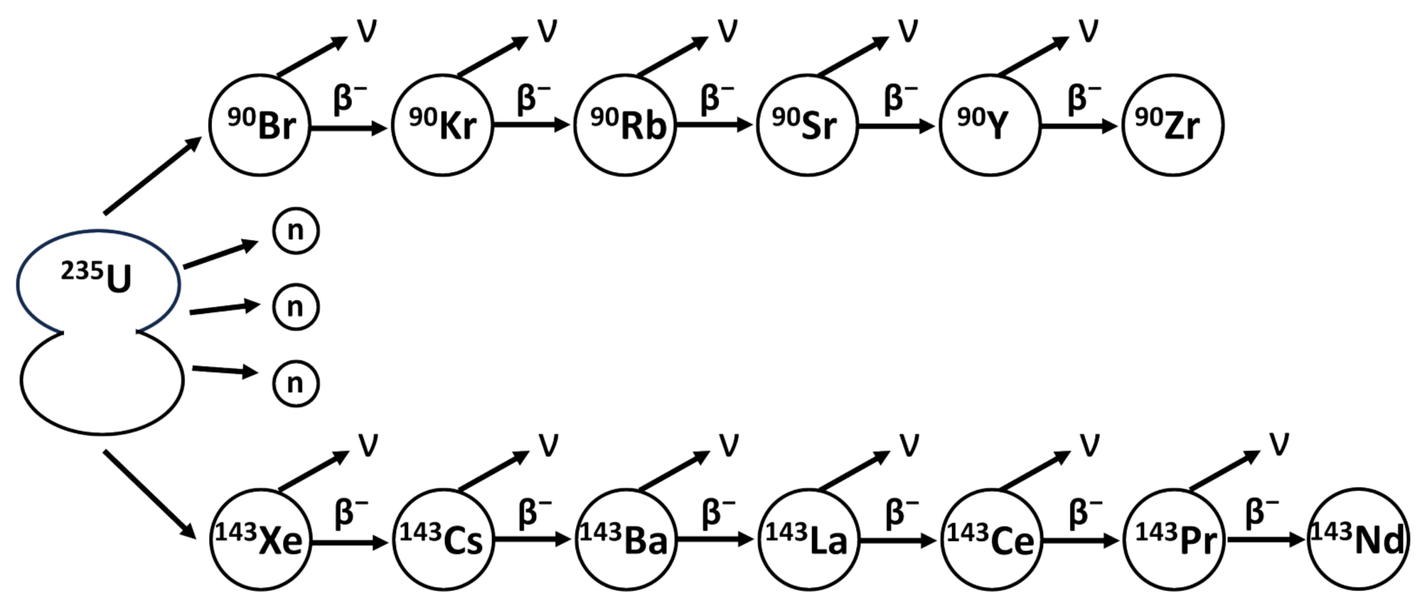




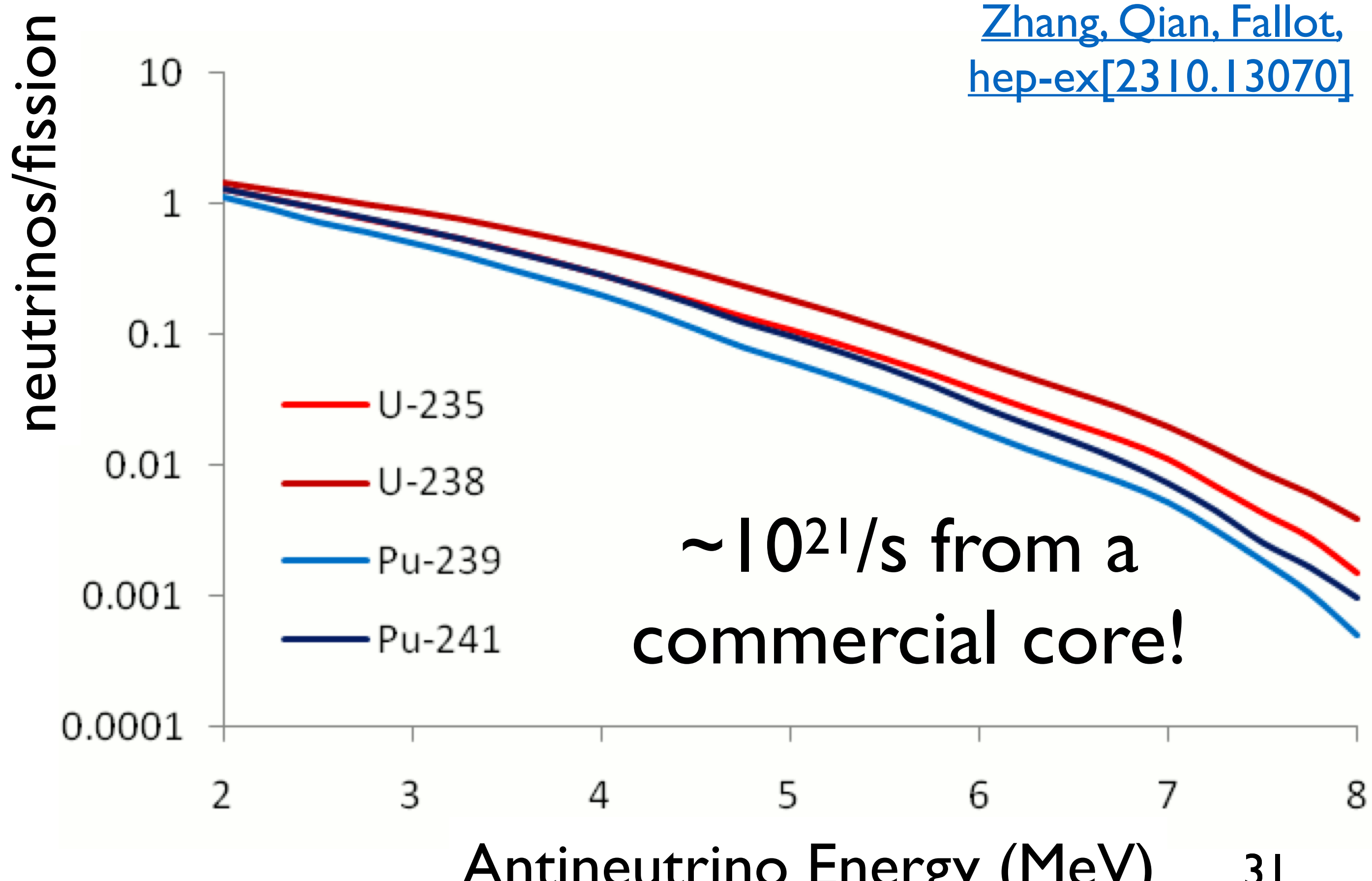
How Do Reactors Make Neutrinos?

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





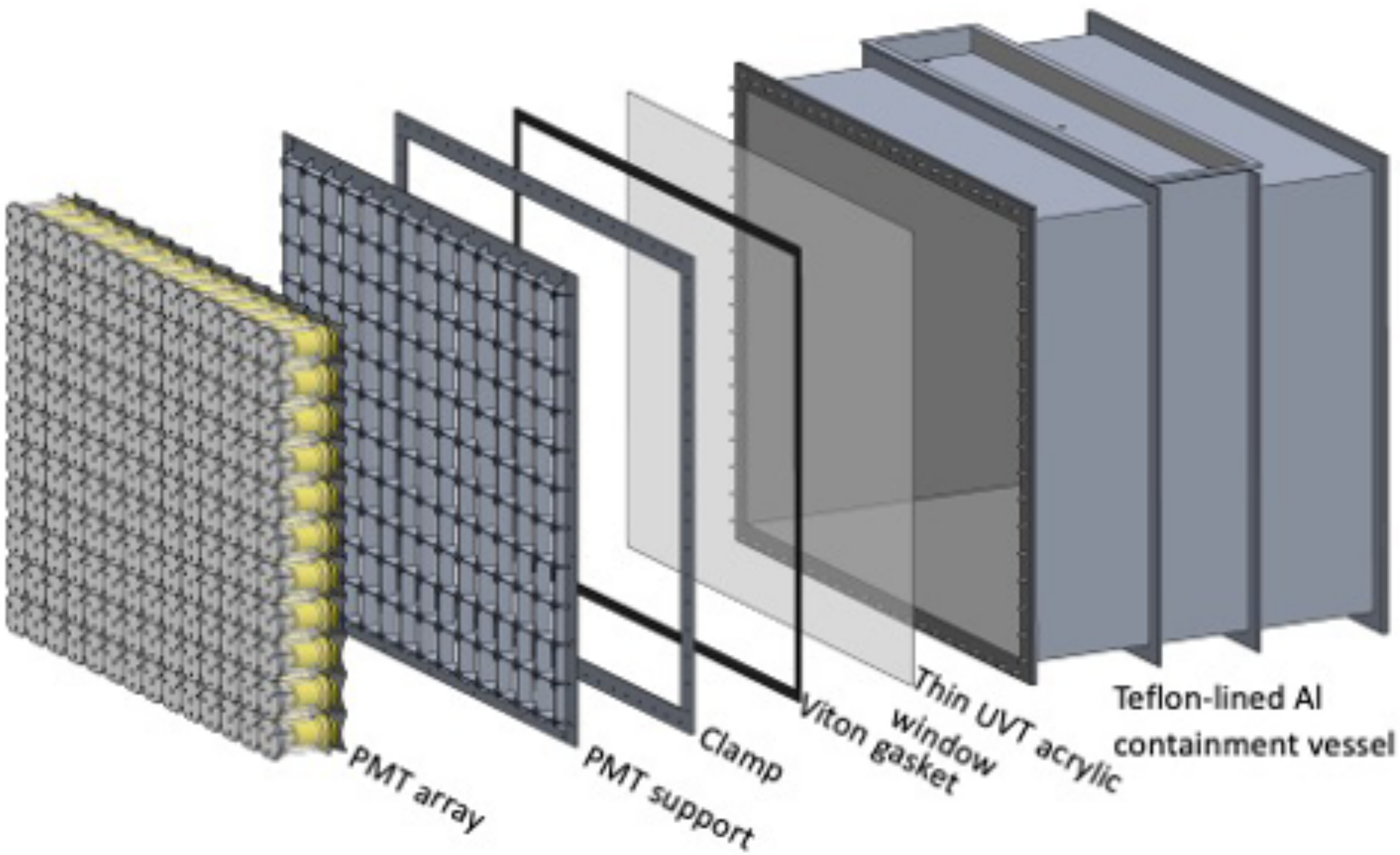
Zhang, Qian, Fallot, hep-ex[2310.13070]

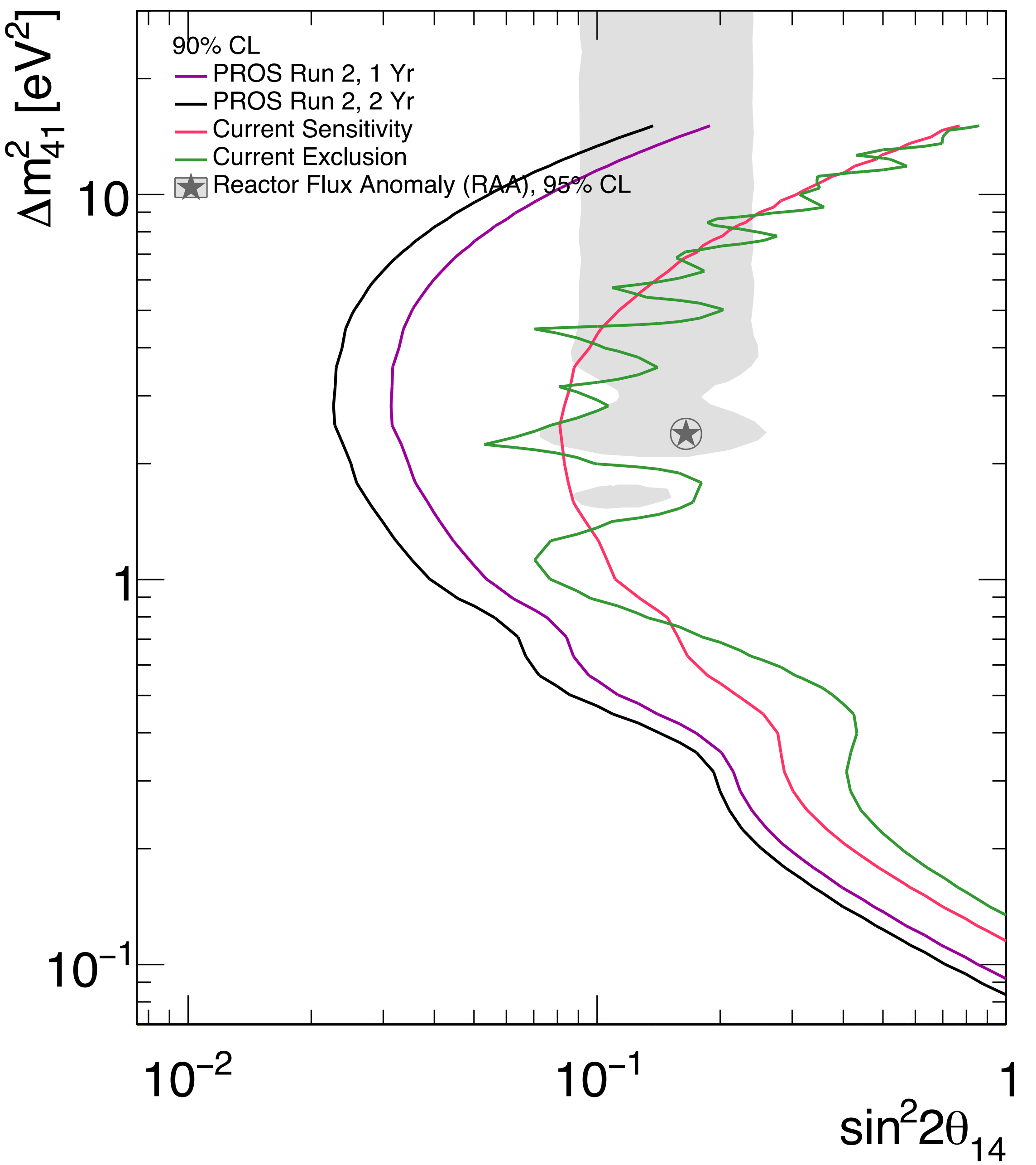


Next Steps: PROSPECT-II

- PROSPECT-II will deliver x10 more IBD at HFIR than P-I, extending our statistics-limited oscillation limits
- Designed to be mobile and perform correlated measurements at different reactor types (commercial and highly-enriched)
  - Probe oscillation <u>and</u> neutrino emissions by different reactor fuel components

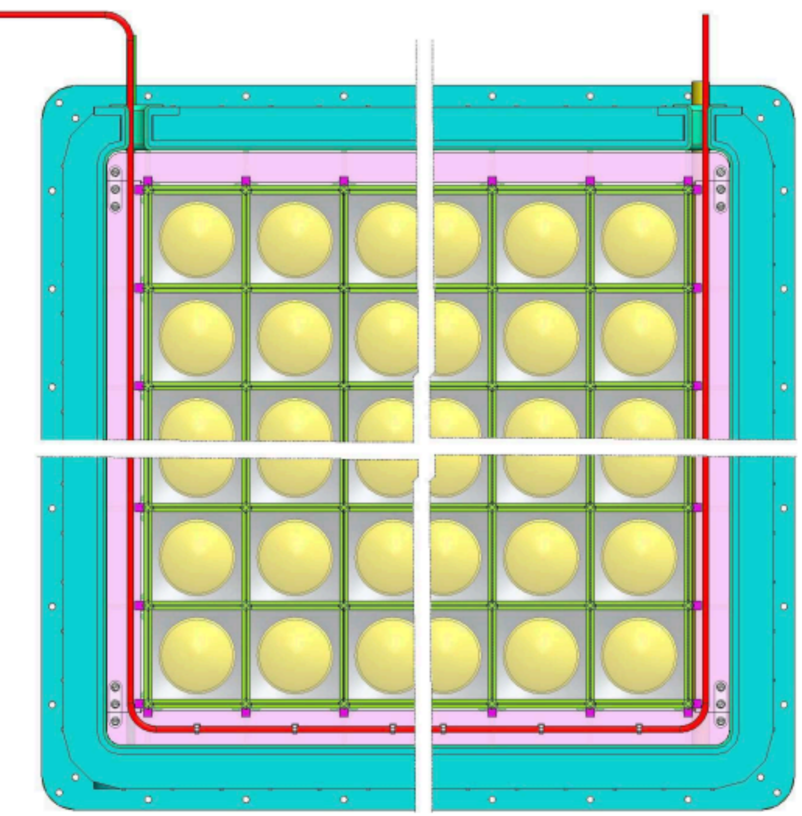
[PROSPECT, J. Phys. G49 (2022)](#)
[PROSPECT, JINST P06010 (2023)](#)
[Fujikake, BRL, Rodrigues, Surukuchi, PRD 107 (2023)](#)



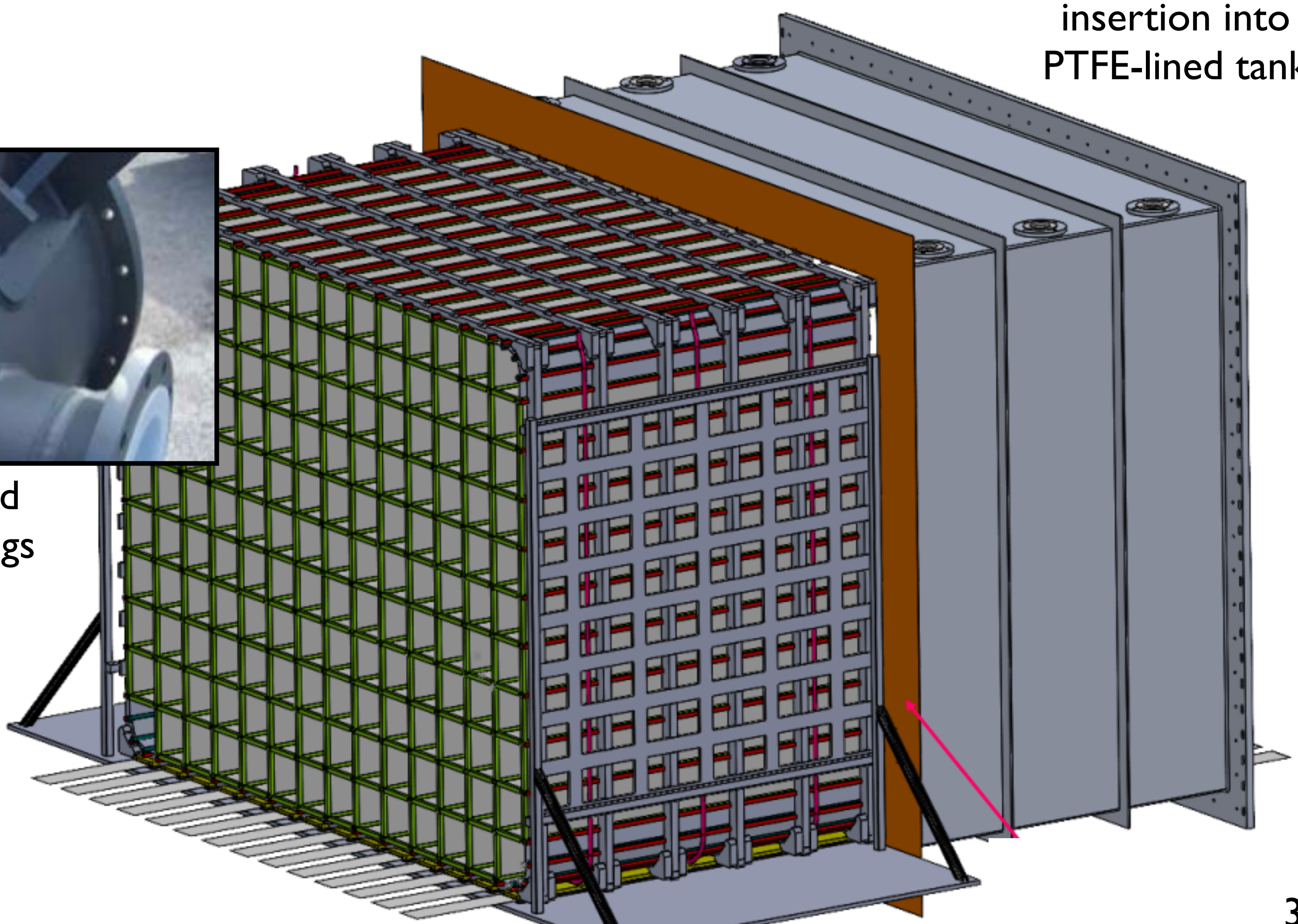


PROSPECT-II R&D Highlights

- Developed/validated external calibration design JINST 18 P06010 (2023)
- Retired risks associated with segment cross-talk J Phys G 49 (2022)
- Engineering design for inner tank underway; fabrication in 2024!
- Initiate Eng. design for PMT supports in 2024
- Details: P-II IAEA Talk

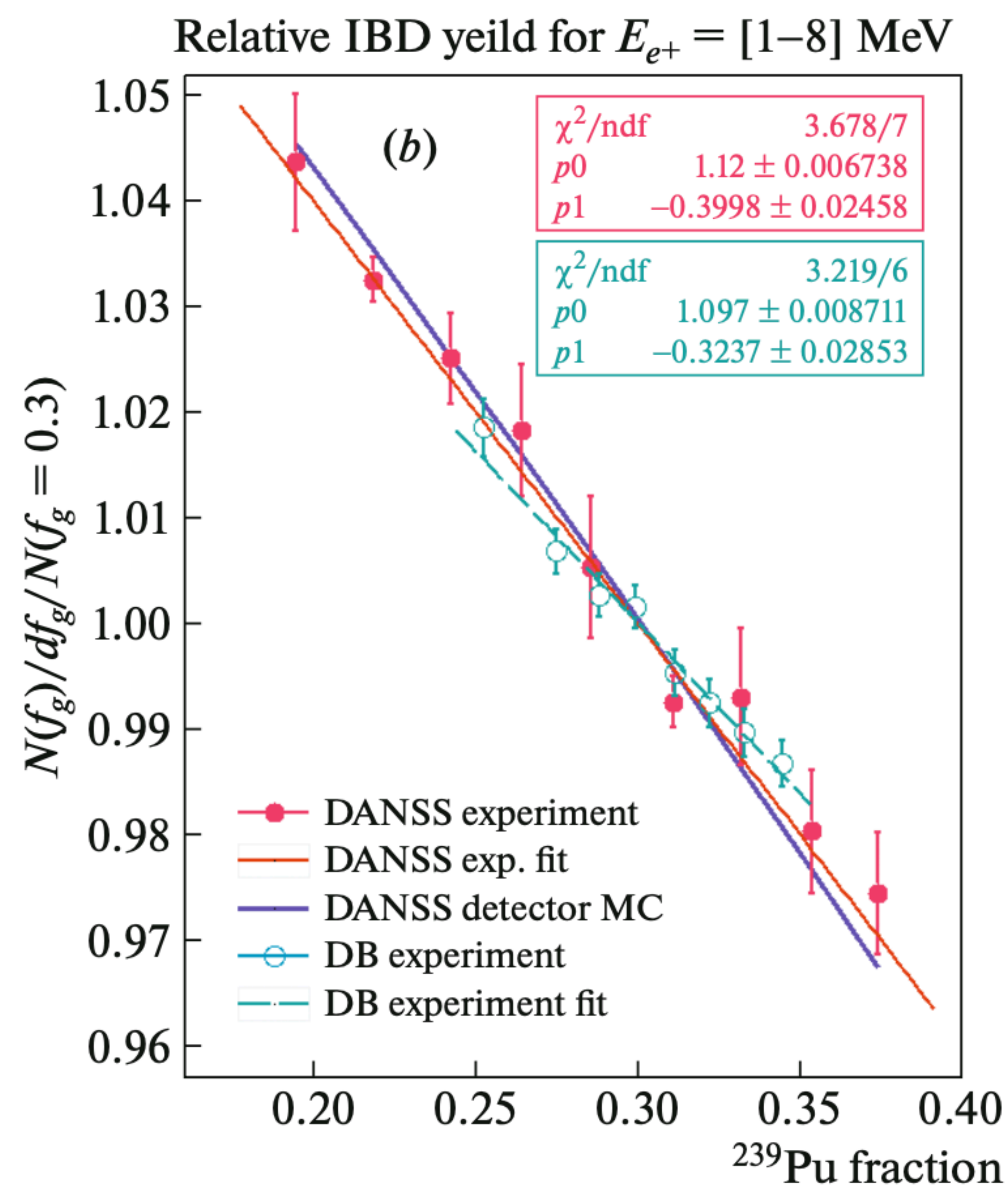

Segment-external calibration axes


Example: rotolined PTFE flange coatings


Optical grid insertion into PTFE-lined tank

Recent Flux Evolution Curiosities

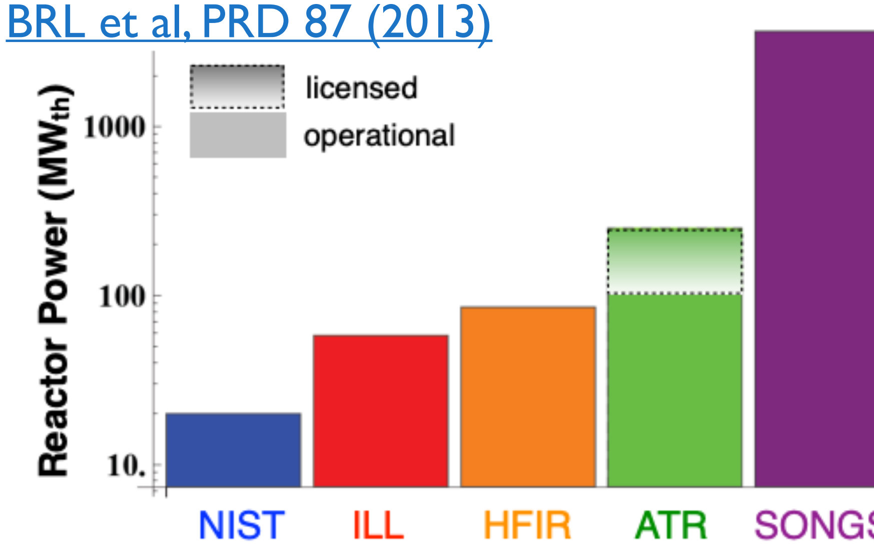
- I said: neutrinos (Daya Bay) and nuclear experiment/theory all agree that U-235 could be largely to blame for the RAA
- Recent DANSS results disagree? NEOS-II as well?
  - No longer perfect consonance in the picture above?
- We have yet to see Daya Bay's final results here; stay tuned.
- PROSPECT-II HEU+LEU can further hone this picture from the neutrino side

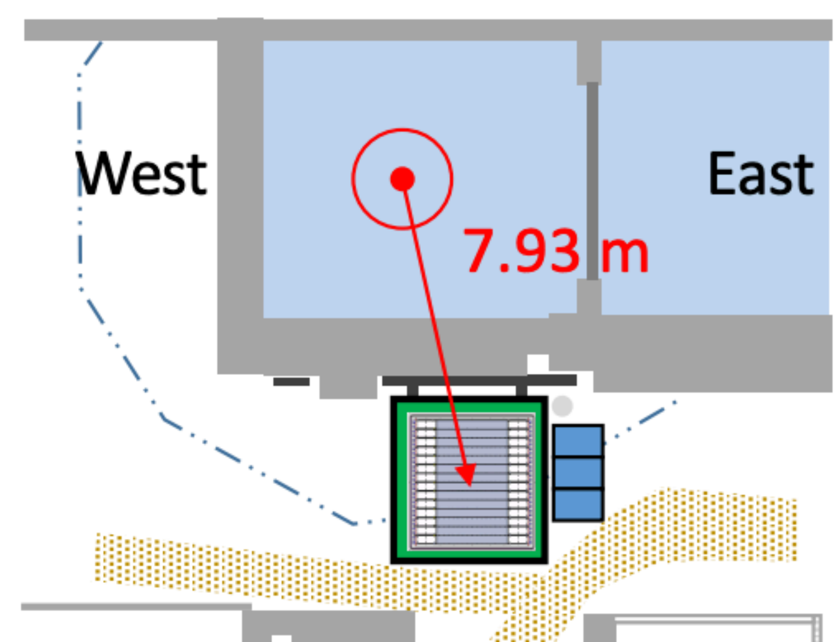


Key HFIR Features

- Reactor:
  - 85 MW core burns only ^{235}U
  - <50cm height, diameter
- Facilities:
  - Many m^2 of floor (~3m wide) 6-10m from core
  - Concrete monolith beneath: high floor loading
  - Adjacent to ground-level exterior doors
- Backgrounds:
  - Lead wall shields gammas from reactor direction
  - Neutron experiments below shielded by monolith
  - <1 mwe overburden: little to no cosmic shielding
- Access:
  - 24/7 data/physical access for authorized personnel
  - HFIR ops rarely (<<1/y) require detector movement

BRL et al, PRD 87 (2013)

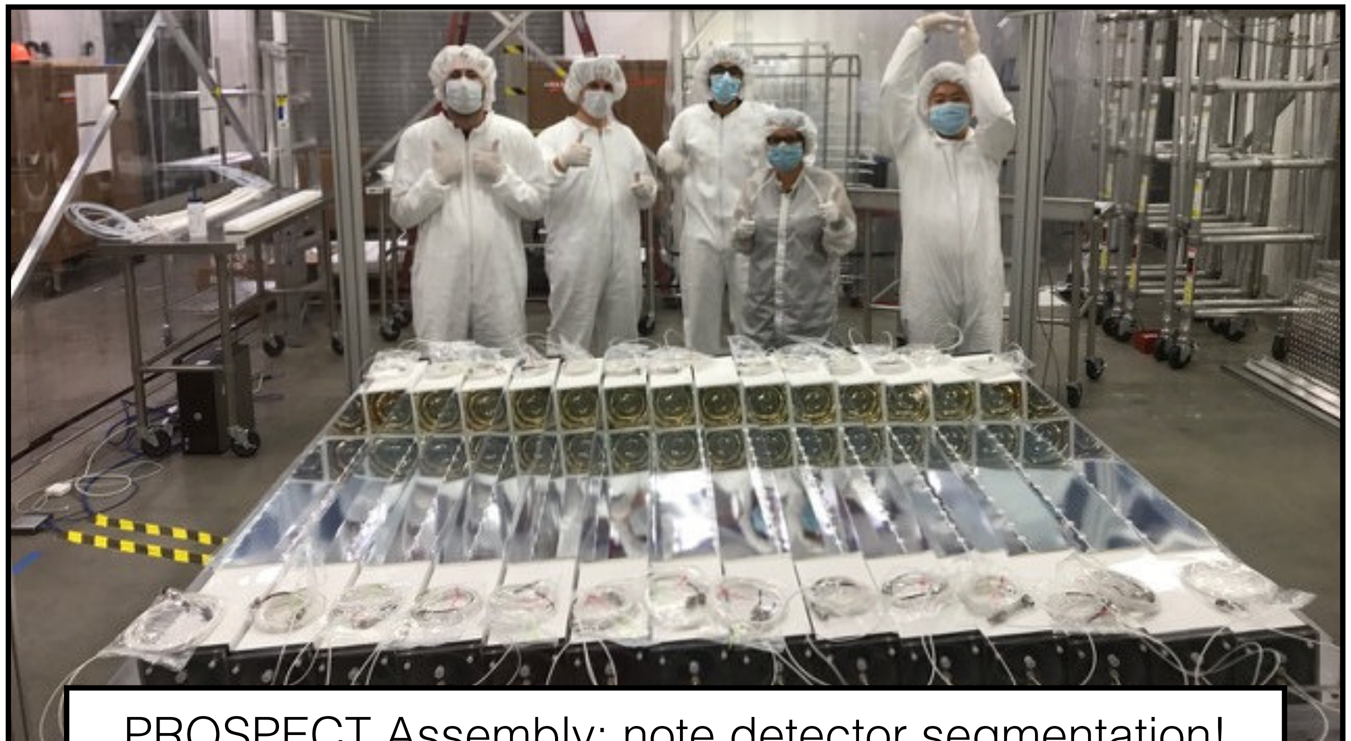




NIM A 922 (2018)

PROSPECT: Pretty Pictures

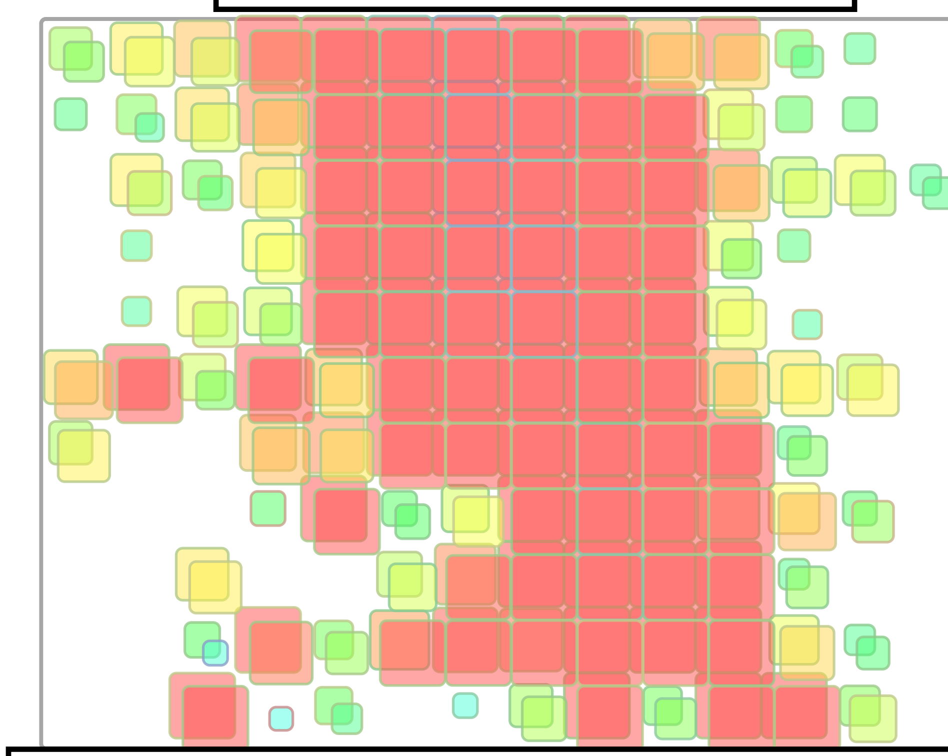
- Assembly start to first data @ HFIR by March 2018: <5 months!



PROSPECT Assembly: note detector segmentation!

PROSPECT arrival at ORNL

PROSPECT Installation: Rx on other side of the wall!

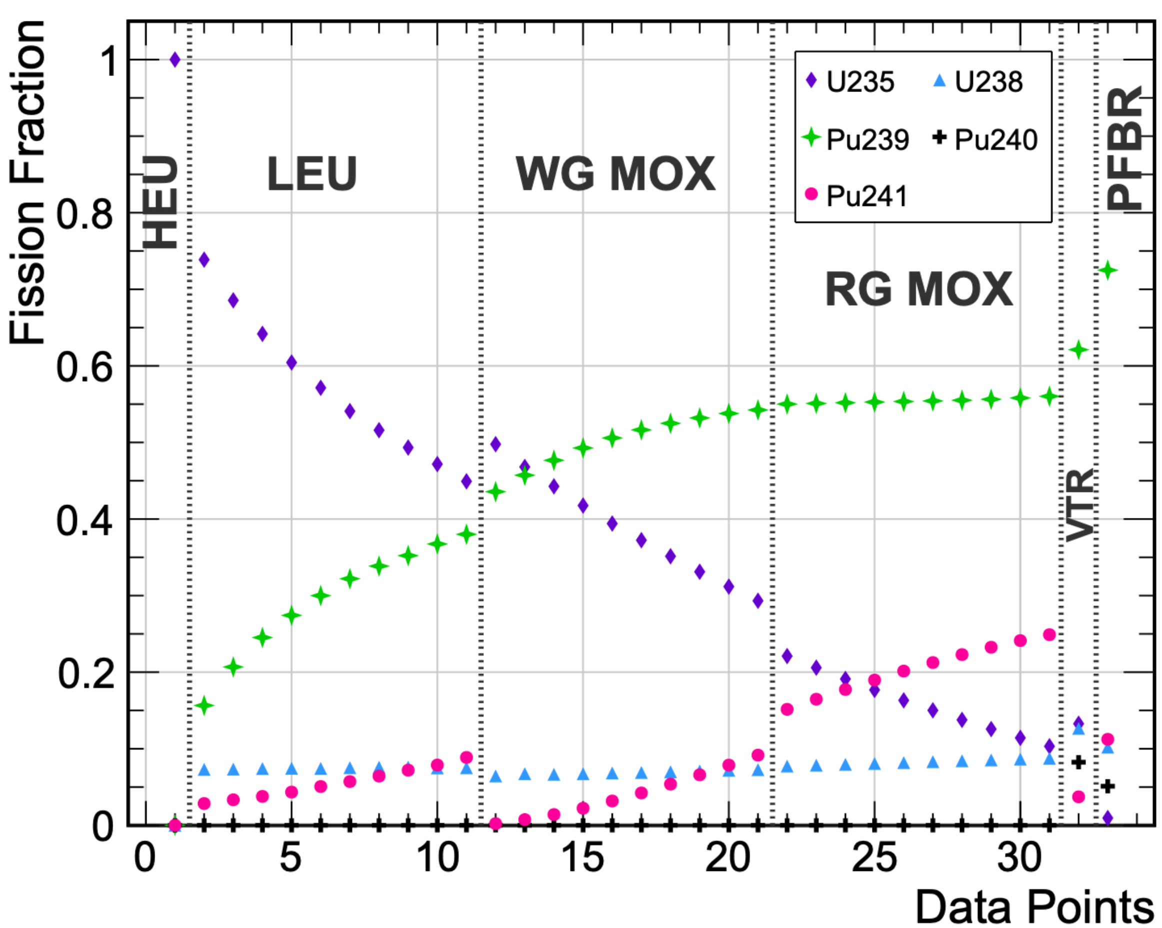


First fun event: cosmic hadronic shower!

Multi-Site Physics With PROSPECT-II

- Q: If we deploy one IBD detector at different reactor types, how well can we measure isotopic IBD yields?
  - A: with combined HEU+LEU measurement, four fission isotopes' yields can be measured at 10%-level accuracy (^{241}Pu, ^{238}U) or much better (^{235}U, ^{239}Pu)
  - **JOIN US** in fully developing the (detector-agnostic) physics case for correlated HEU+LEU deployment (isotopic spectra, oscillations, etc)!

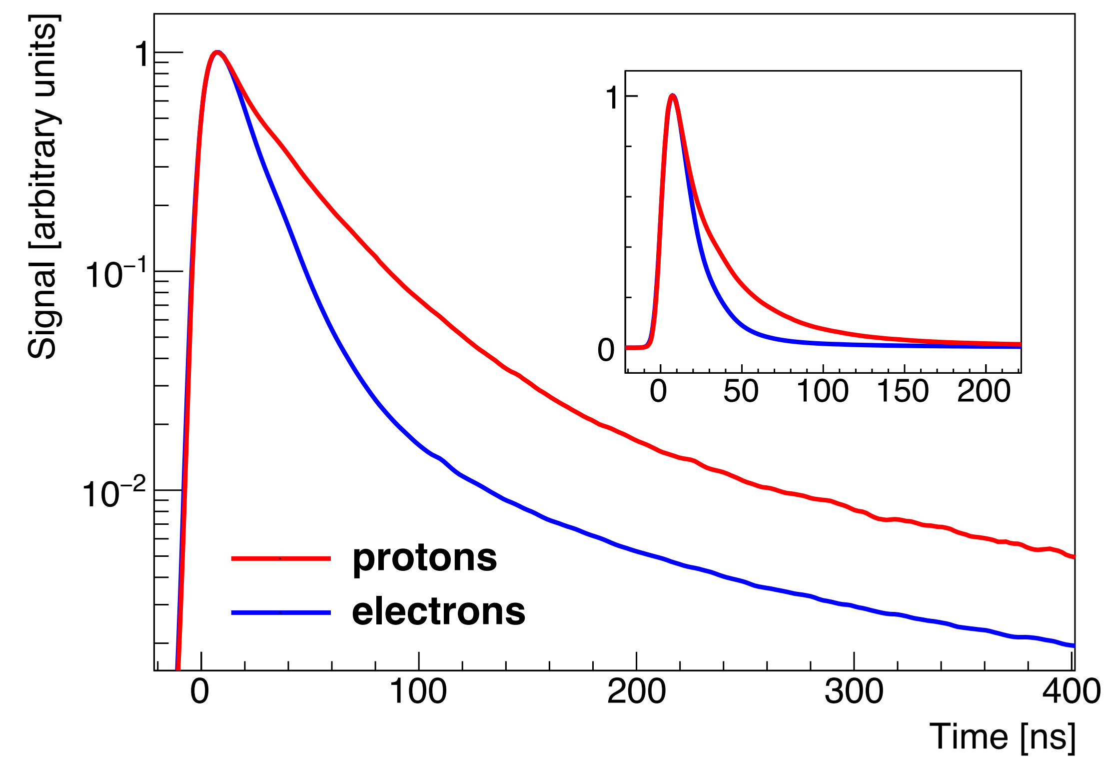
Fujikake, BRL, Rodrigues, Surukuchi, PRD 107 (2023)



Case	Description	Precision on σ_i (%)				
		^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
-	Existing Global Data	1.3	26.4	25.2	-	42.6
1	HEU + LEU	1.6	11.1	4.6	-	10.5
3	HEU + LEU + RG-MOX	1.6	9.7	2.2	-	3.4
2	HEU + LEU + WG-MOX	1.6	9.9	2.5	-	3.6
4	HEU + LEU + Fast	1.6	10.9	4.6	27.2	10.3
5	**All**	**1.6**	**9.5**	**2.1**	**23.6**	**3.3**
6	All, Uncorrelated	1.5	14.3	2.1	36.2	4.2
-	Model Uncertainty [66]	2.1	8.2	2.5	-	2.2

Key Detector Features

- Prompt e^+ gives $\bar{\nu}_e$ energy estimate (>400 pe/MeV)
- Fully-contained, single-cell delayed n-^{6}Li signal
- Prompt, delayed PSD differ from common background classes
- Double-end PMT readout and segmentation allows XYZ reco and topology cuts
- Reactor-on data rates are only manageable with zero-suppression of segments and PMT waveforms!



PRD 103 (2021)