Status of Neutrino Short-Baseline Anomalies

July 3, 2024

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Illinois Institute of Technology

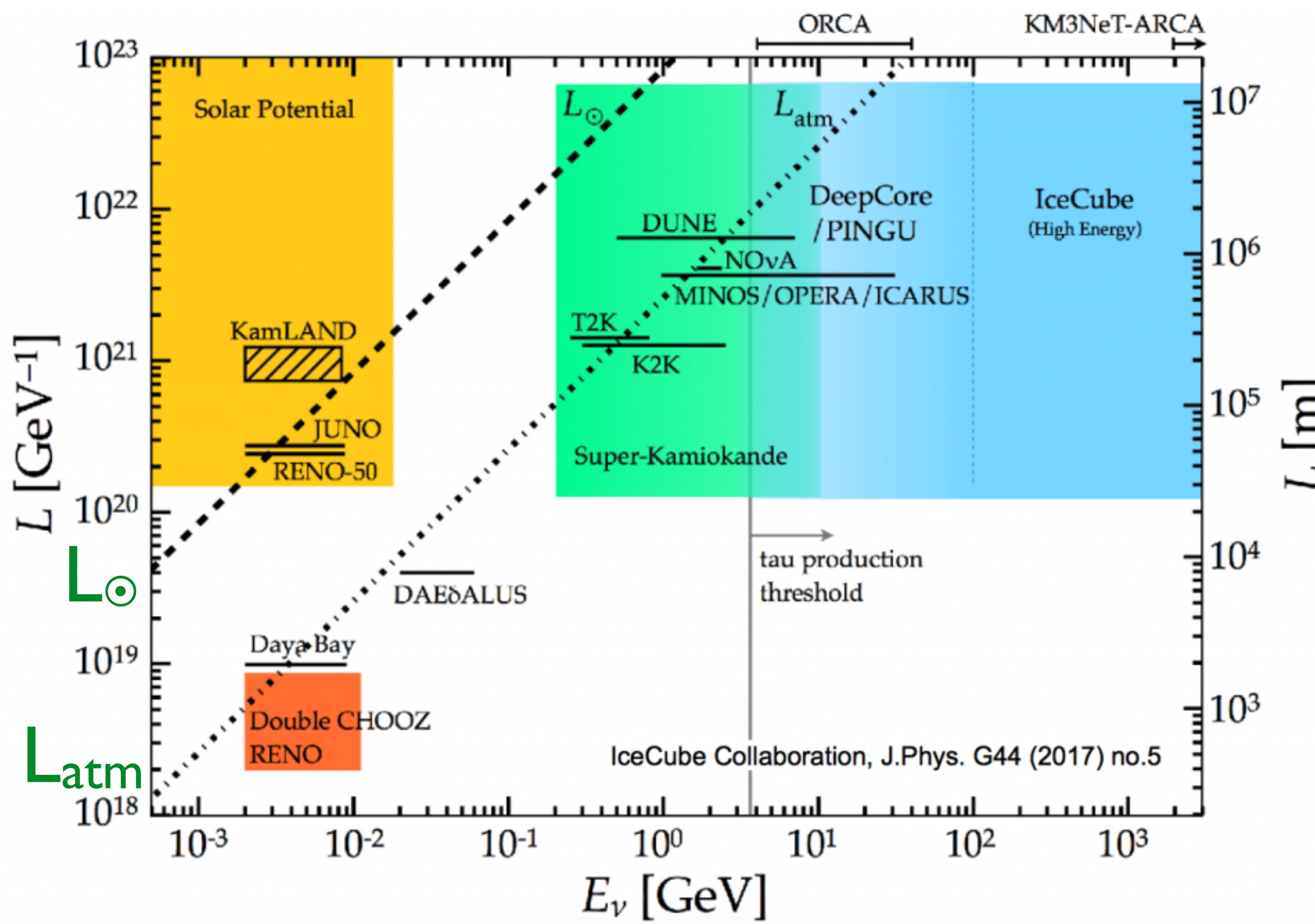
Standard Model Oscillations

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Took many experiments to get us here!

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

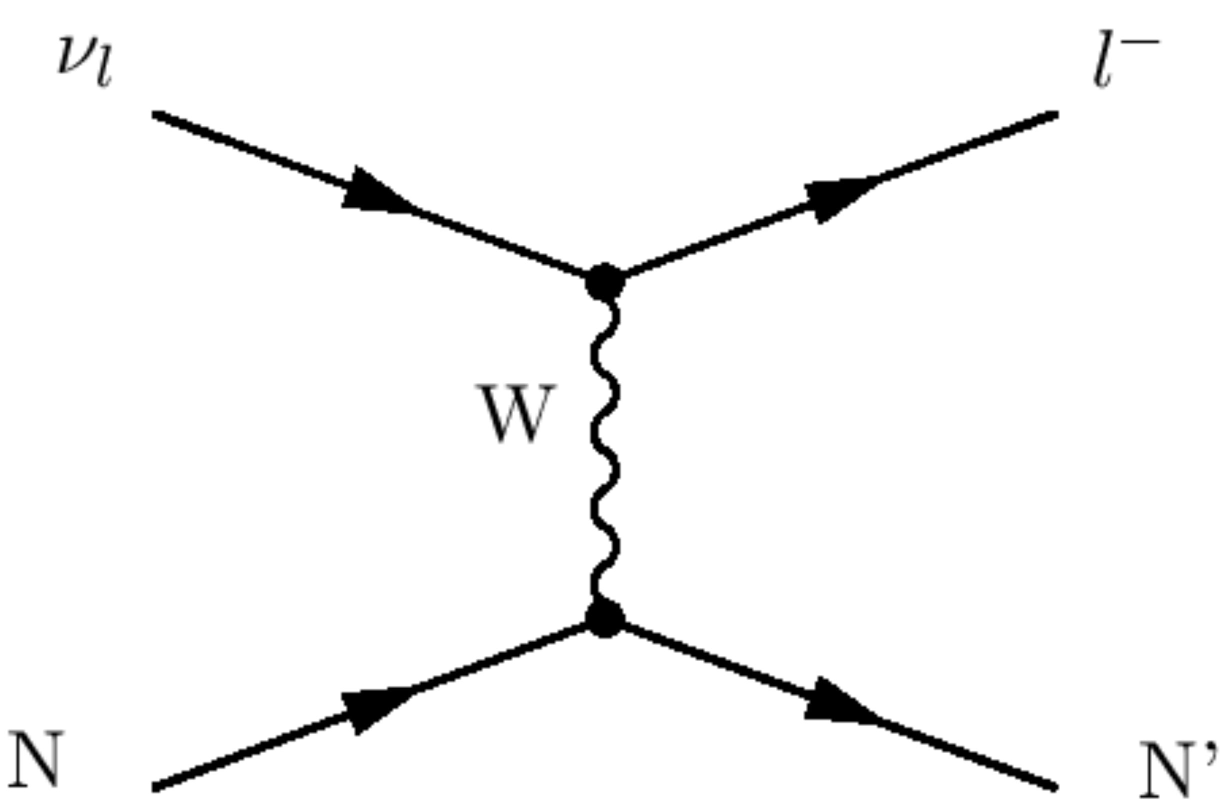
+ etc. etc.…

- Baselines (L): >km-scale



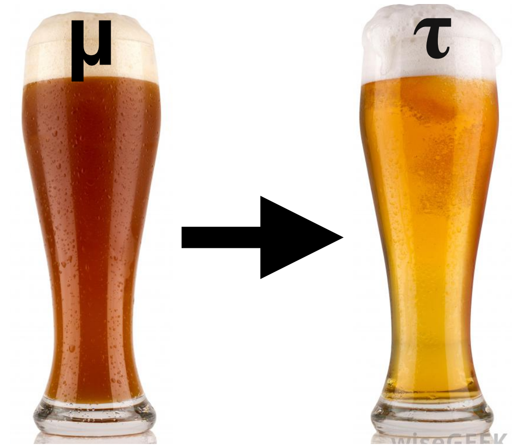
Sampling Neutrino Flavors

- We want to see the flavor!
  - Want to make sure I <u>taste</u> the flavor that was produced: pilsner, stout, amber?
- For neutrinos, charged current interactions enable this
  - Want to make sure I <u>detect</u> the flavor that was produced: e, μ, or τ ?

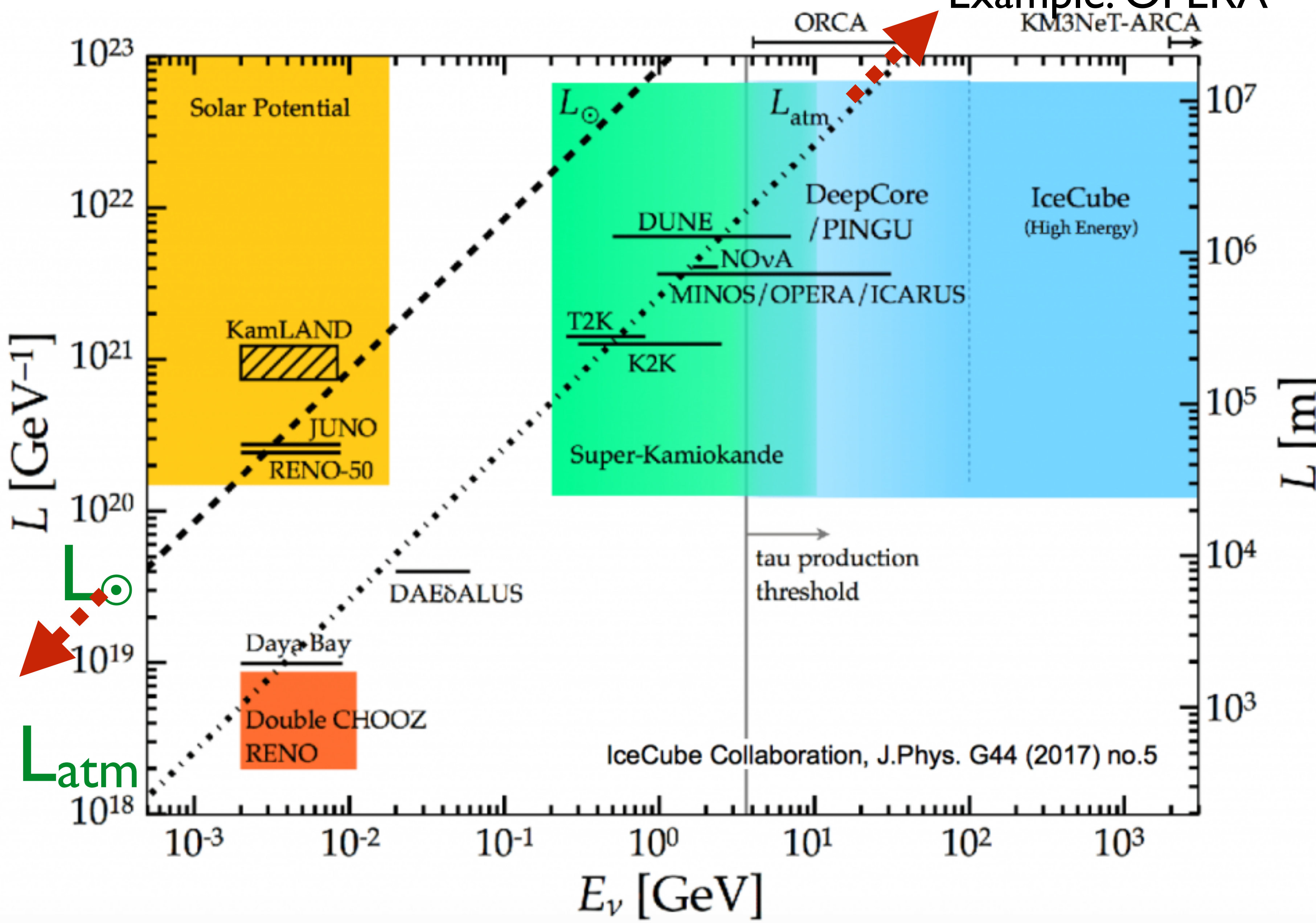


Standard Model Oscillations

- Have a beautiful picture of three oscillating SM neutrinos coming into focus
- Took many experiments to get us here!
- Baselines (L): >km-scale



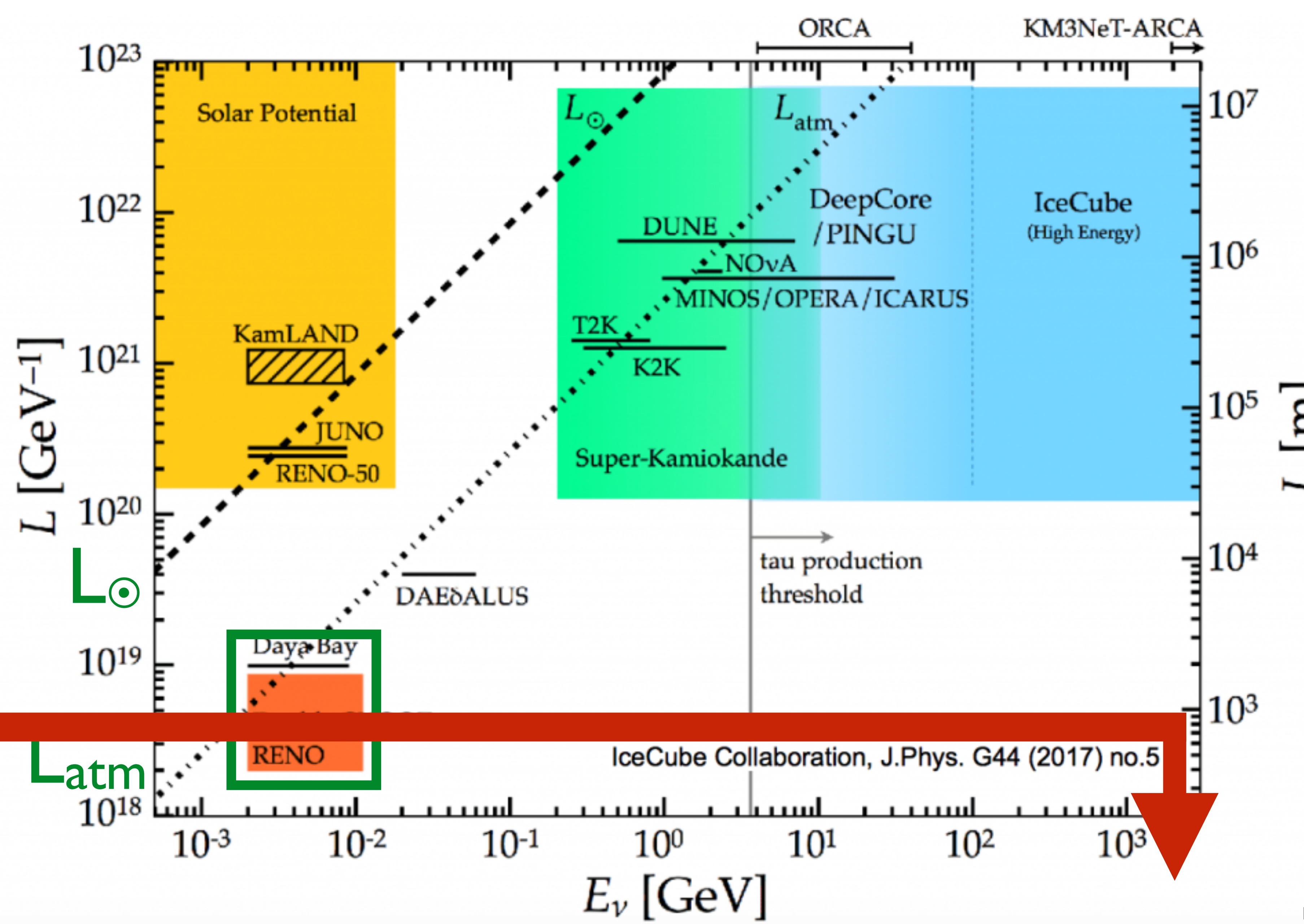
Example: OPERA



Example: KamLAND

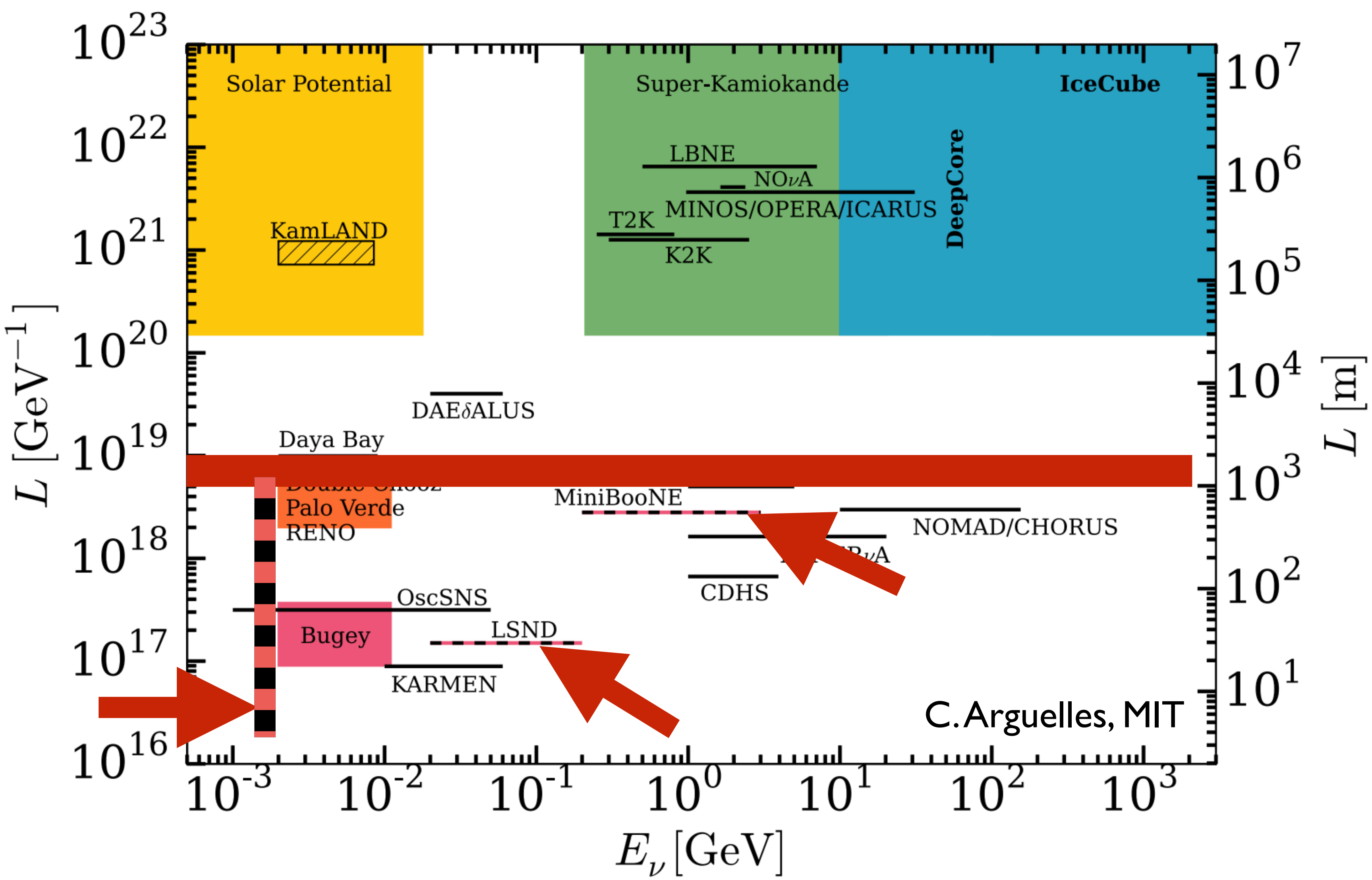
Standard Model Oscillations

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Took many experiments to get us here!
- Baselines (L): >km-scale
- Let's go HERE!
- WHY go here?



Neutrino Flavor Anomalies

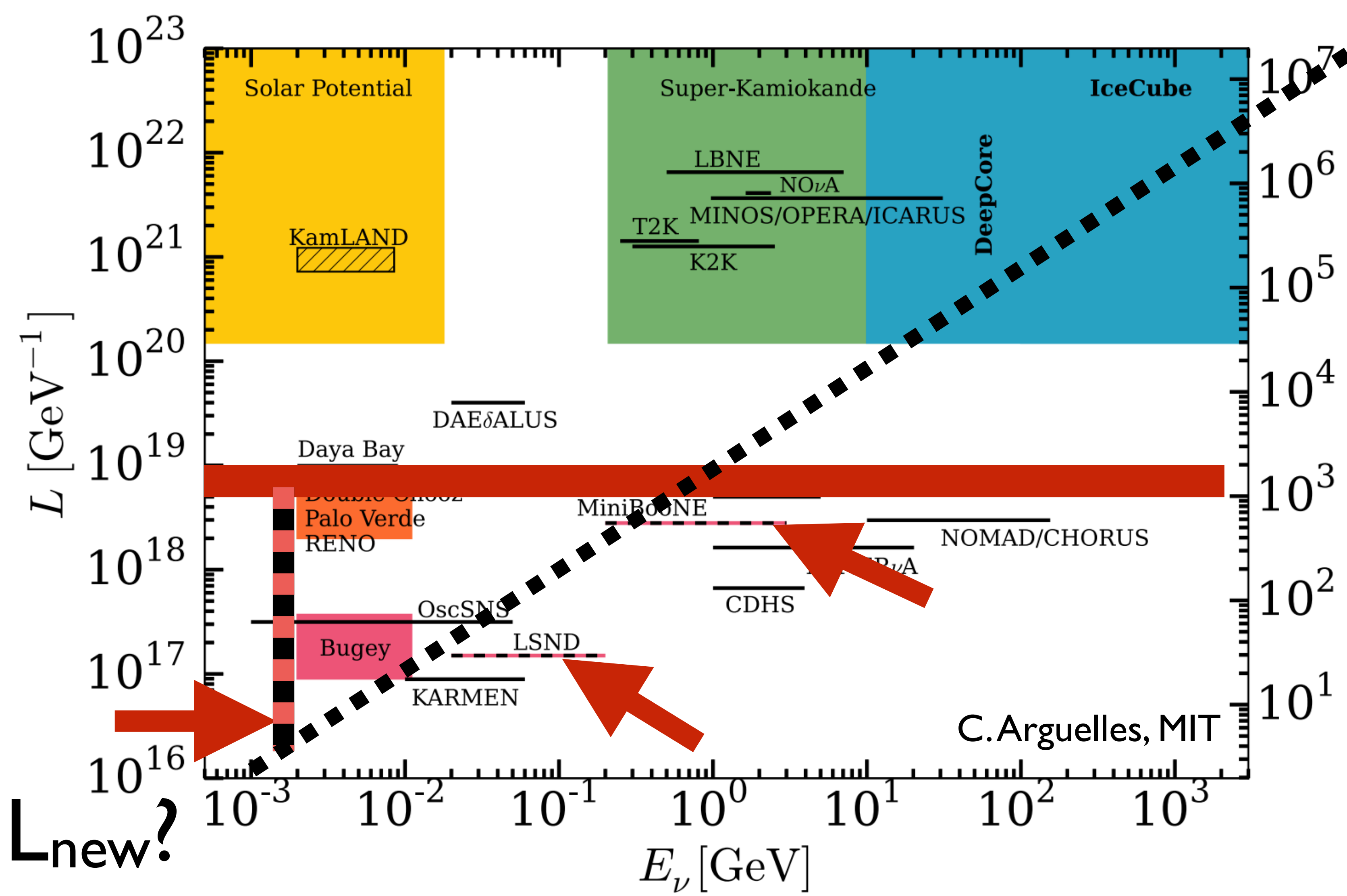
- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Hints of new physics beyond Standard Model oscillations?!



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!?

Double Fruit Smoothie Sour

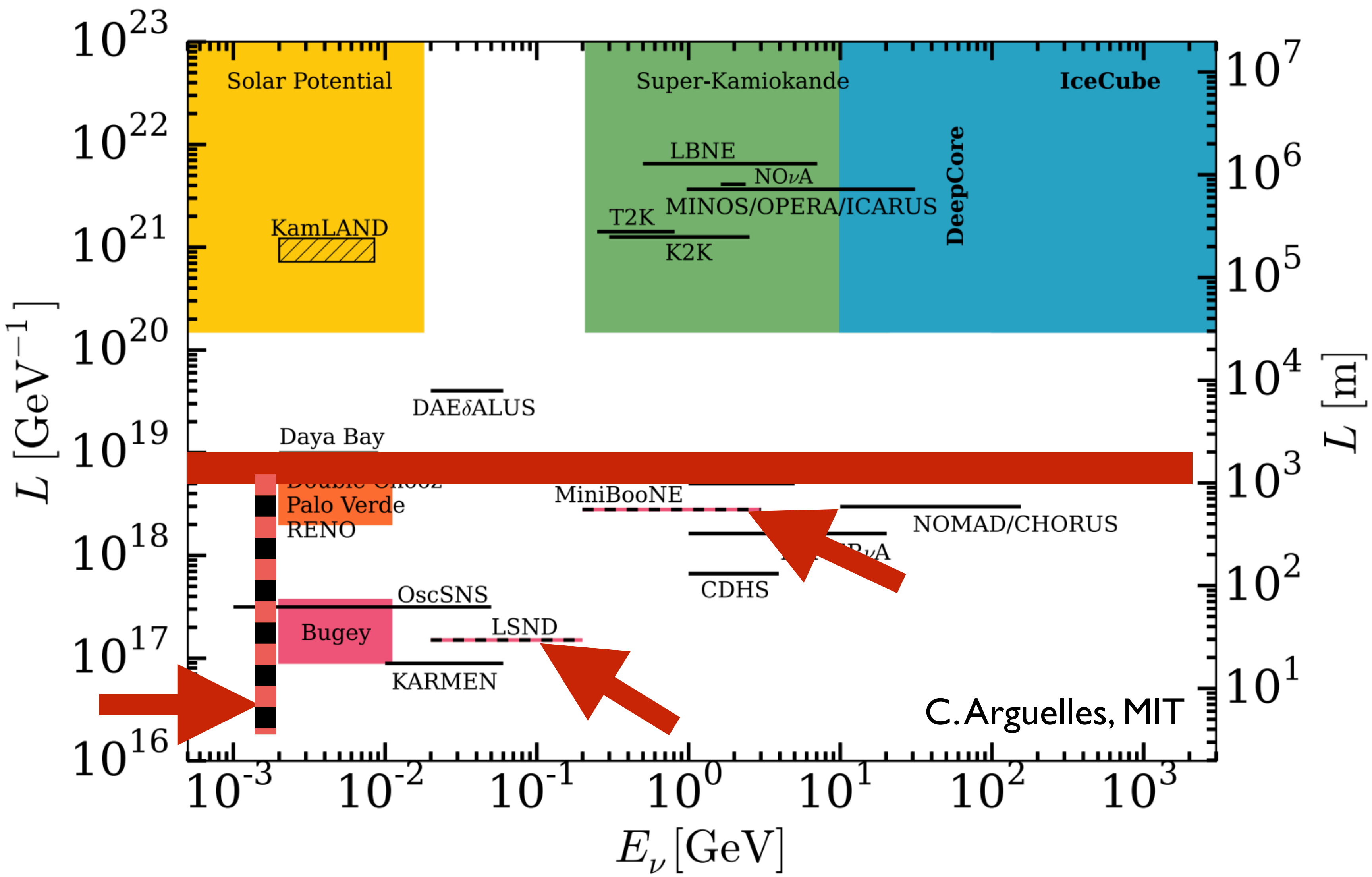
but also:

Pastry Stout

Coffee Blonde Ale

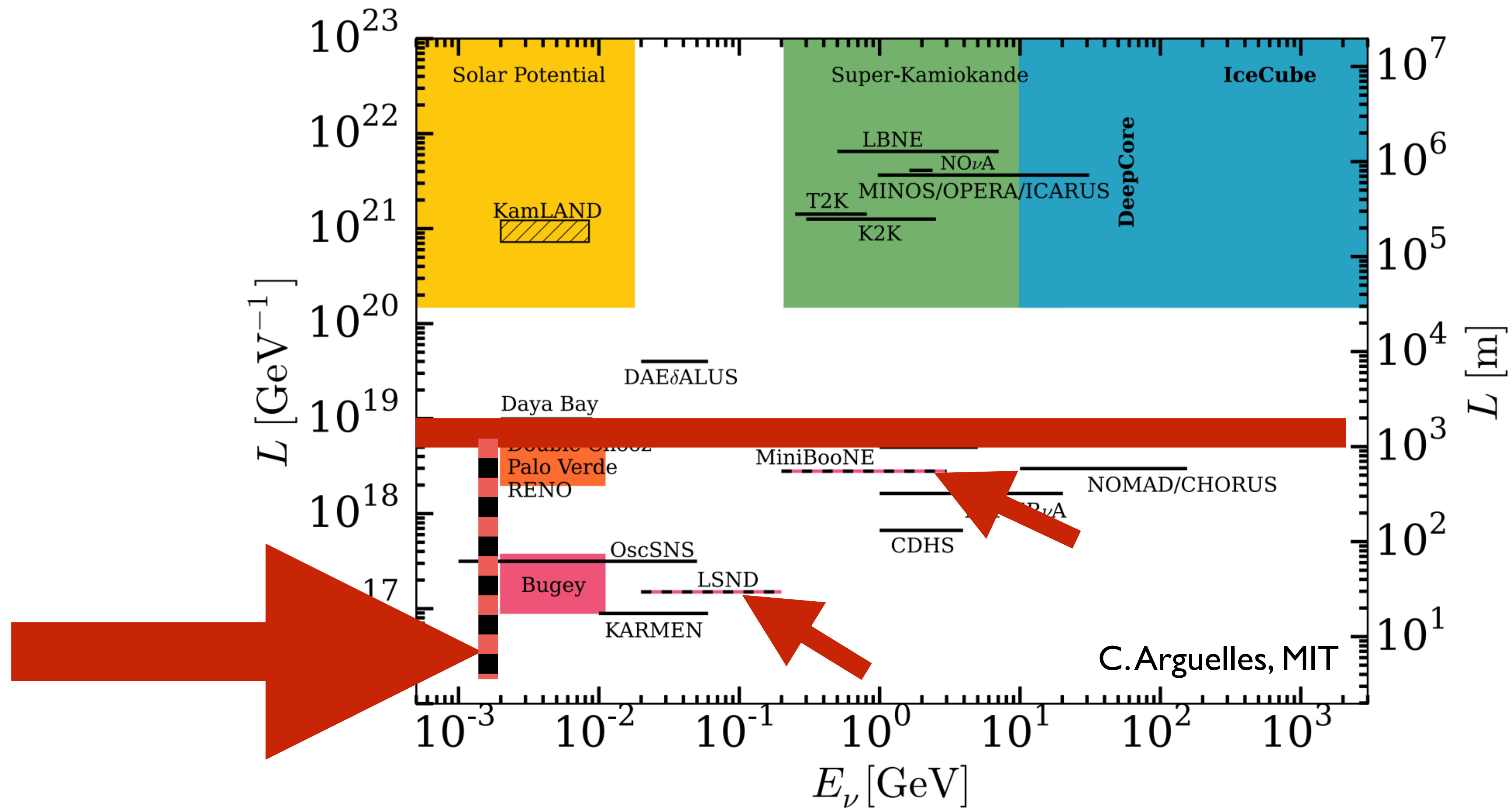
Neutrino Anomalies

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



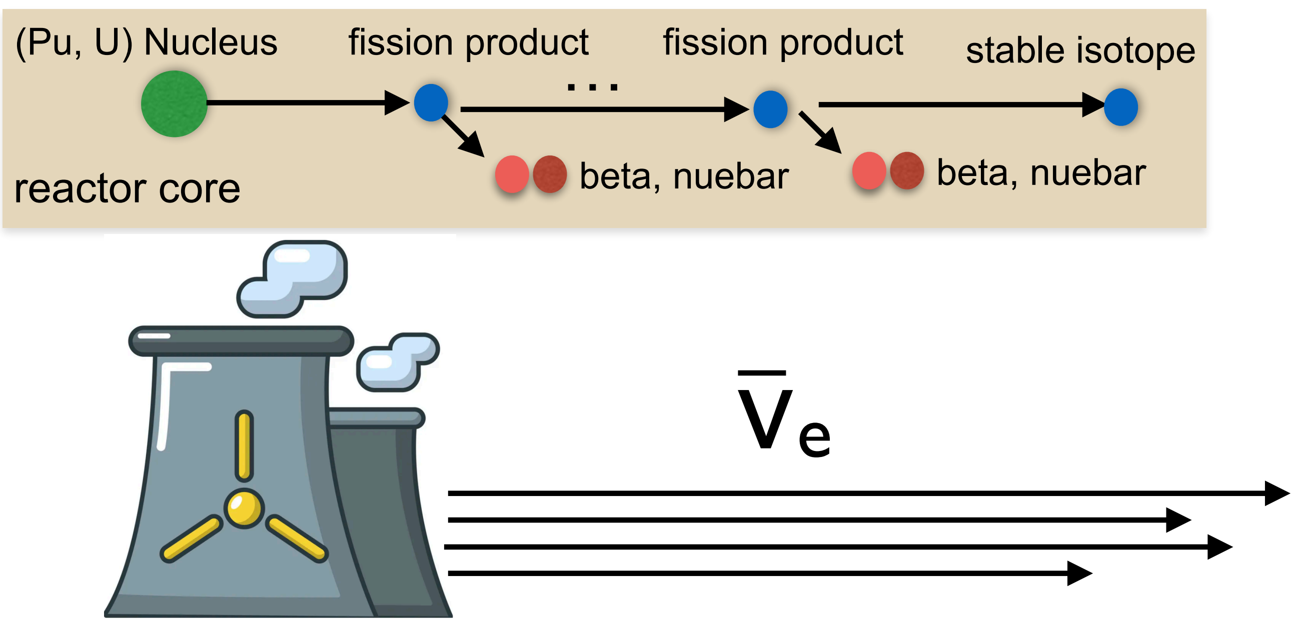
Electron-Flavor Disappearance

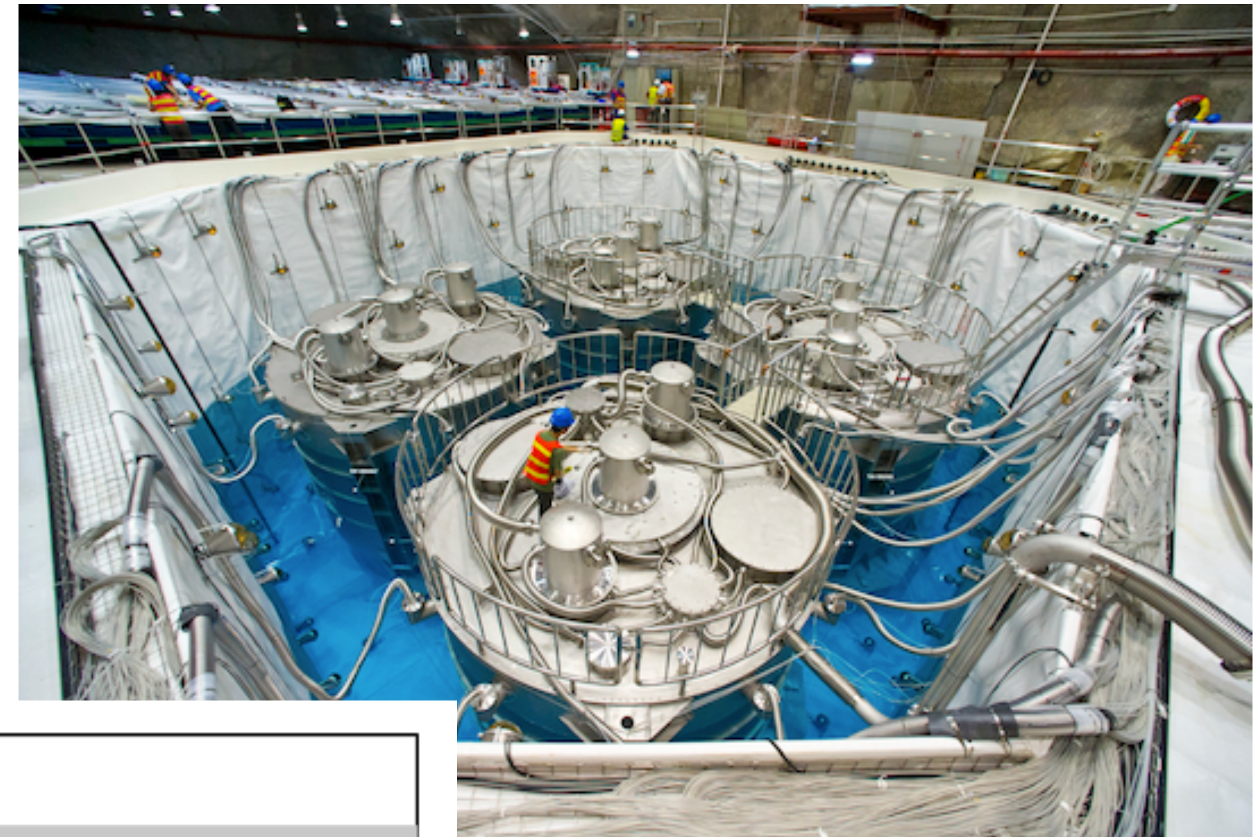
- Let's zoom in and explore the non-miniBooNE anomalies
  - What's their status?
  - How does this relate to the broader neutrino program?

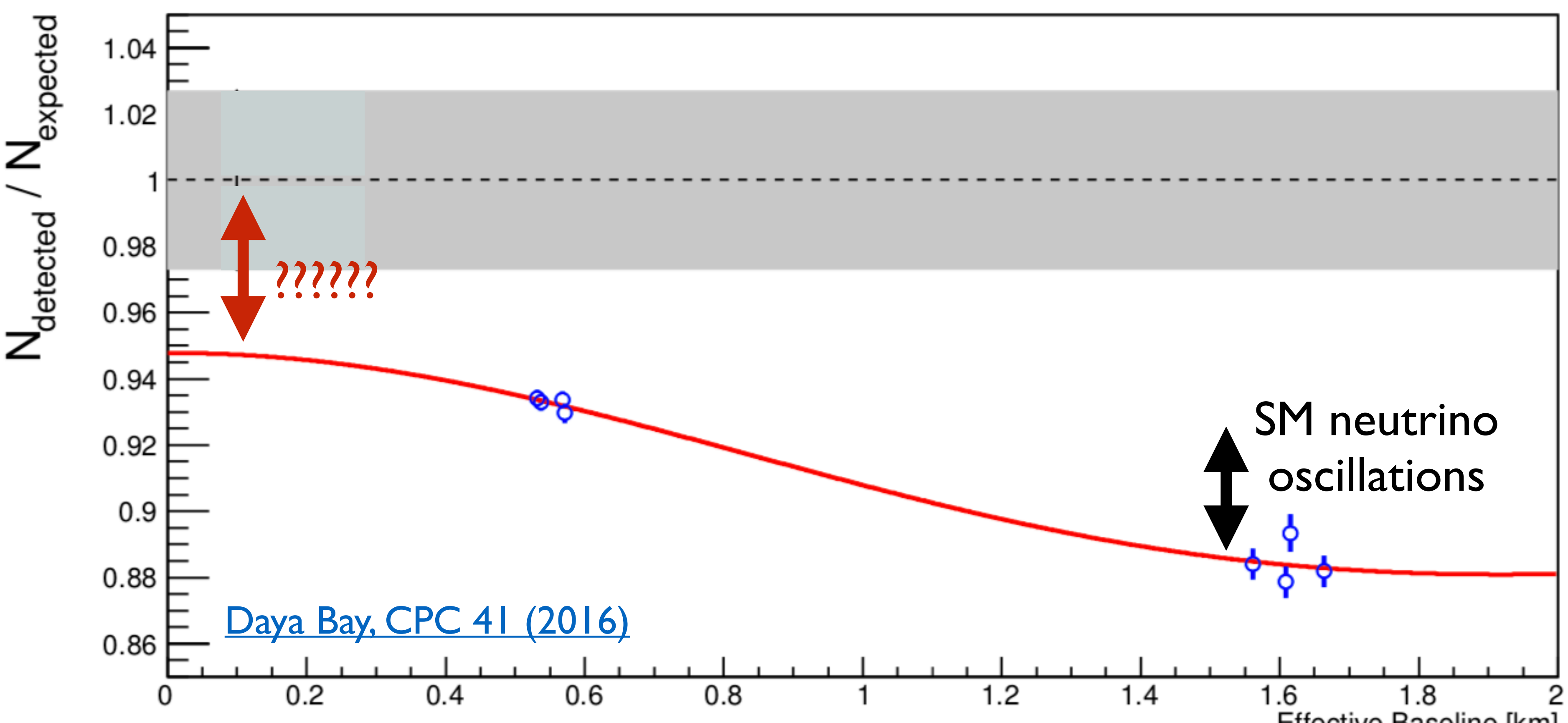


Reactor Antineutrino Anomaly (RAA)?

- 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

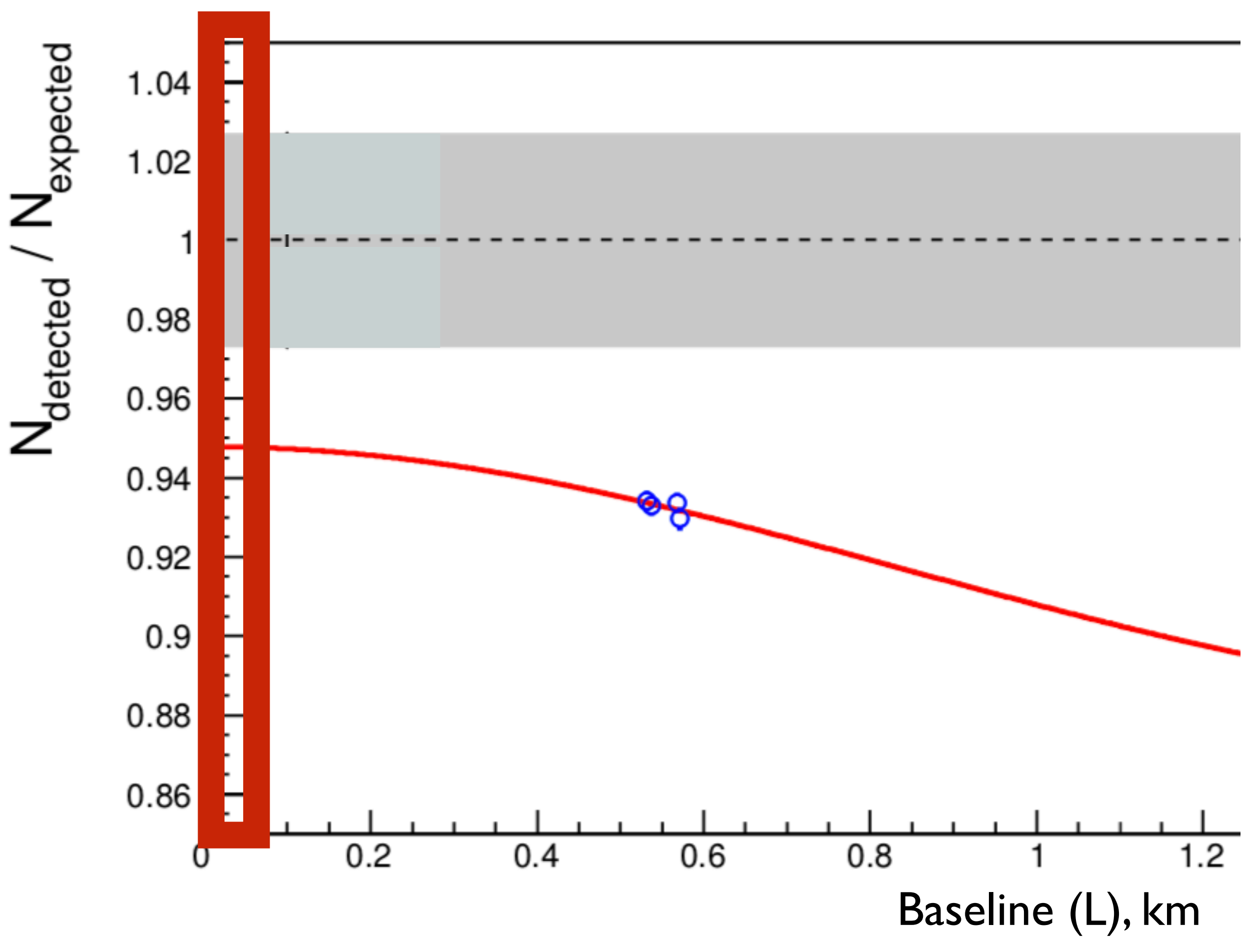
'RAA'

Exploring the Quantum Universe

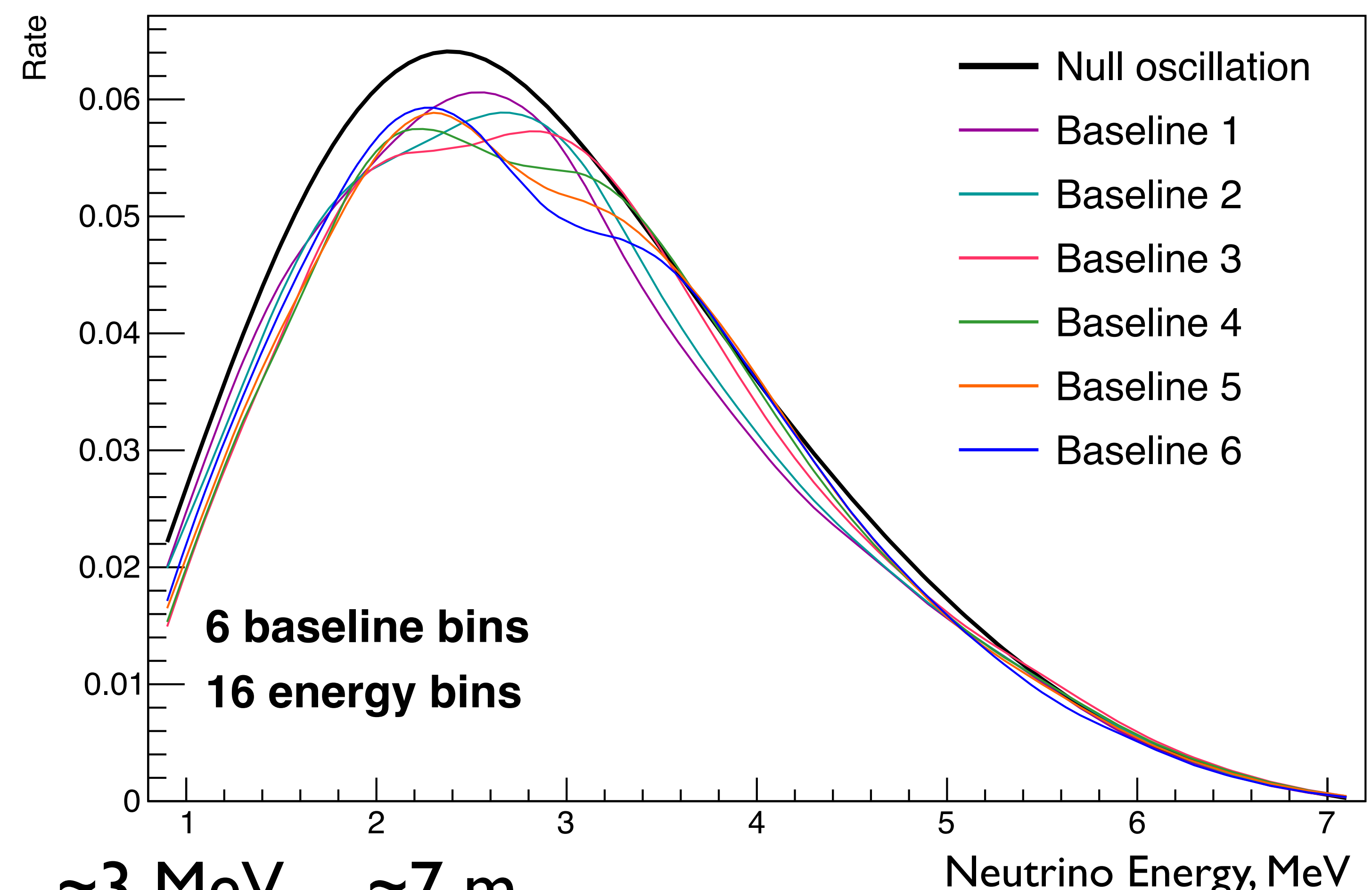
RAA Resolution: Clear Sterile Searches

- 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

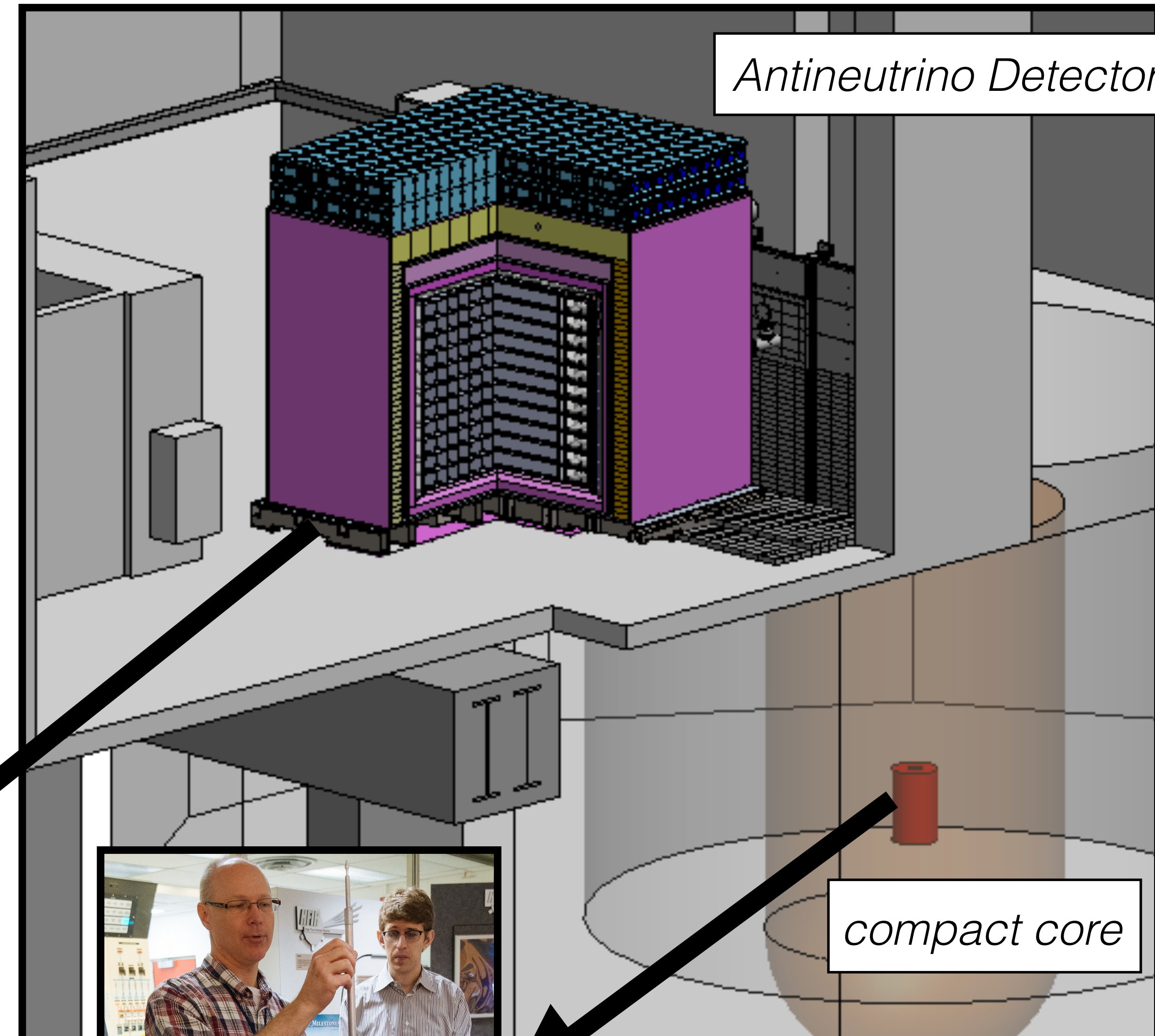
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \boxed{\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}\right]}$$

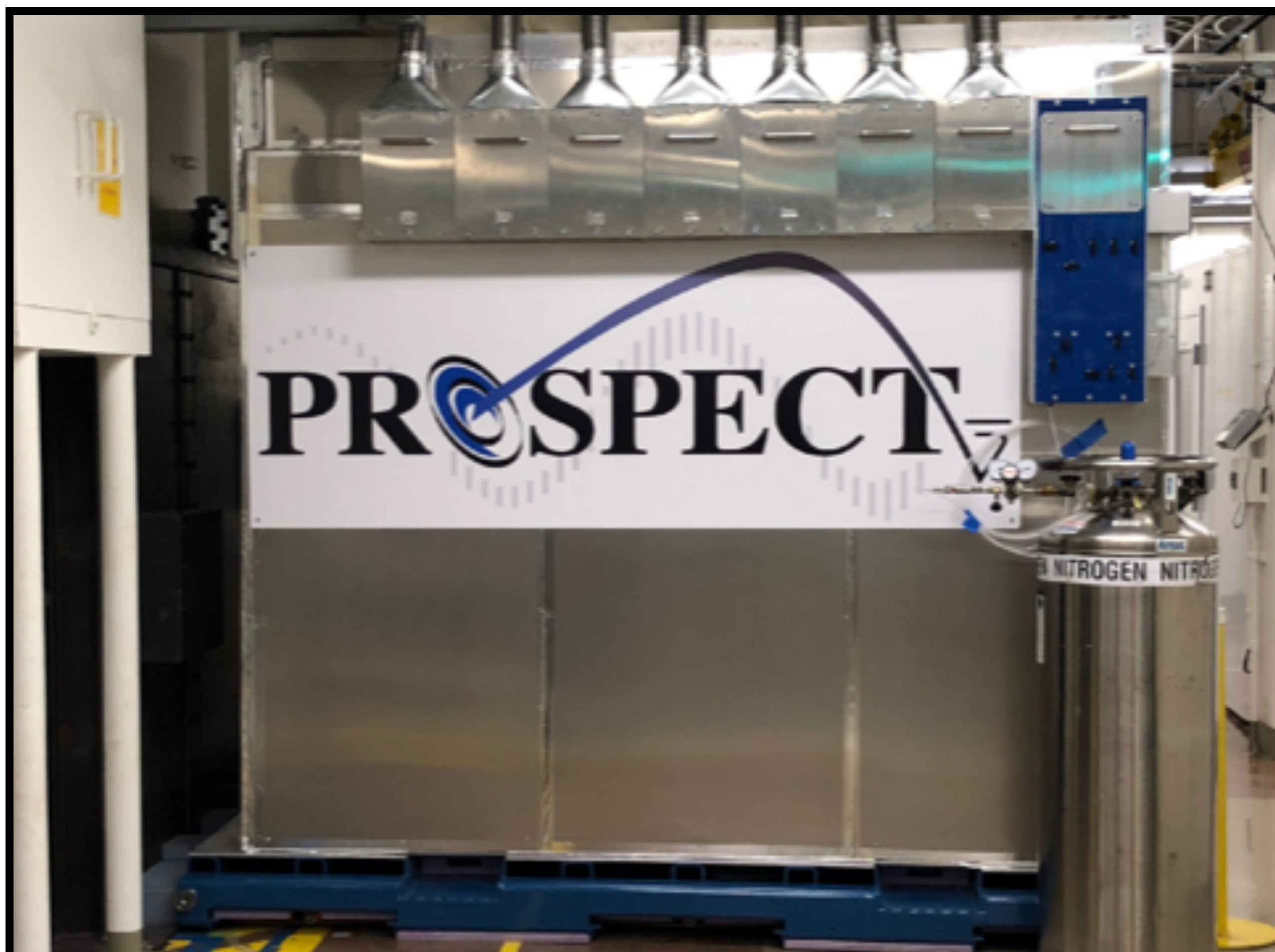
Probing $\Delta m^2 \sim 0.6$ eV^2

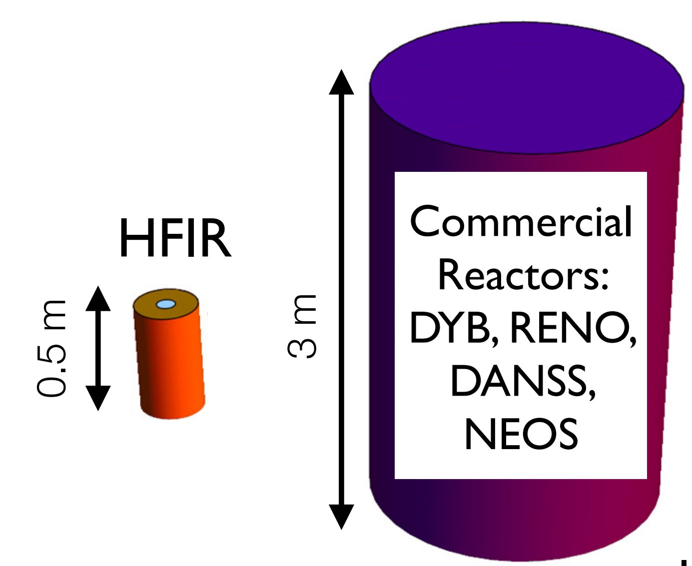
~Same as mB; uB; SBN.

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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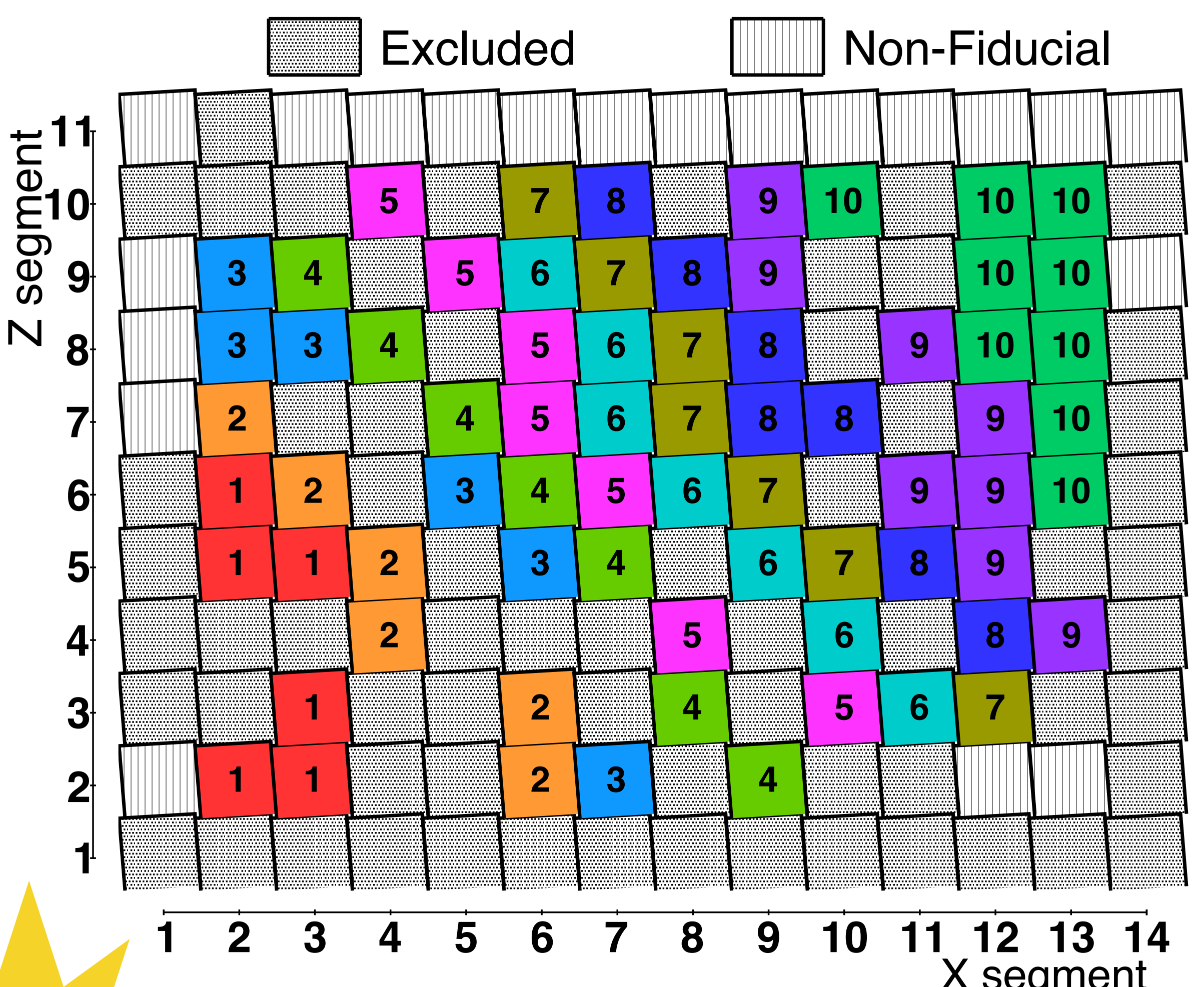
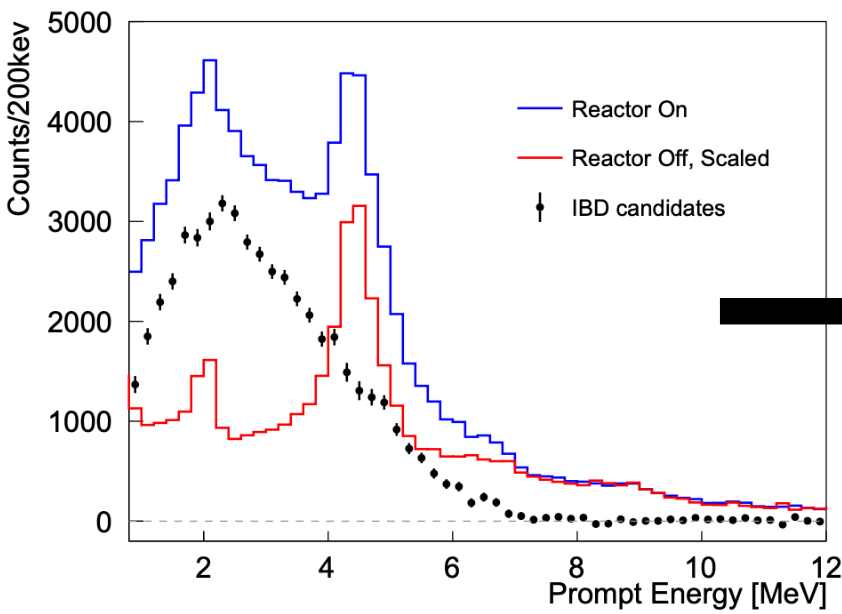


HEU core

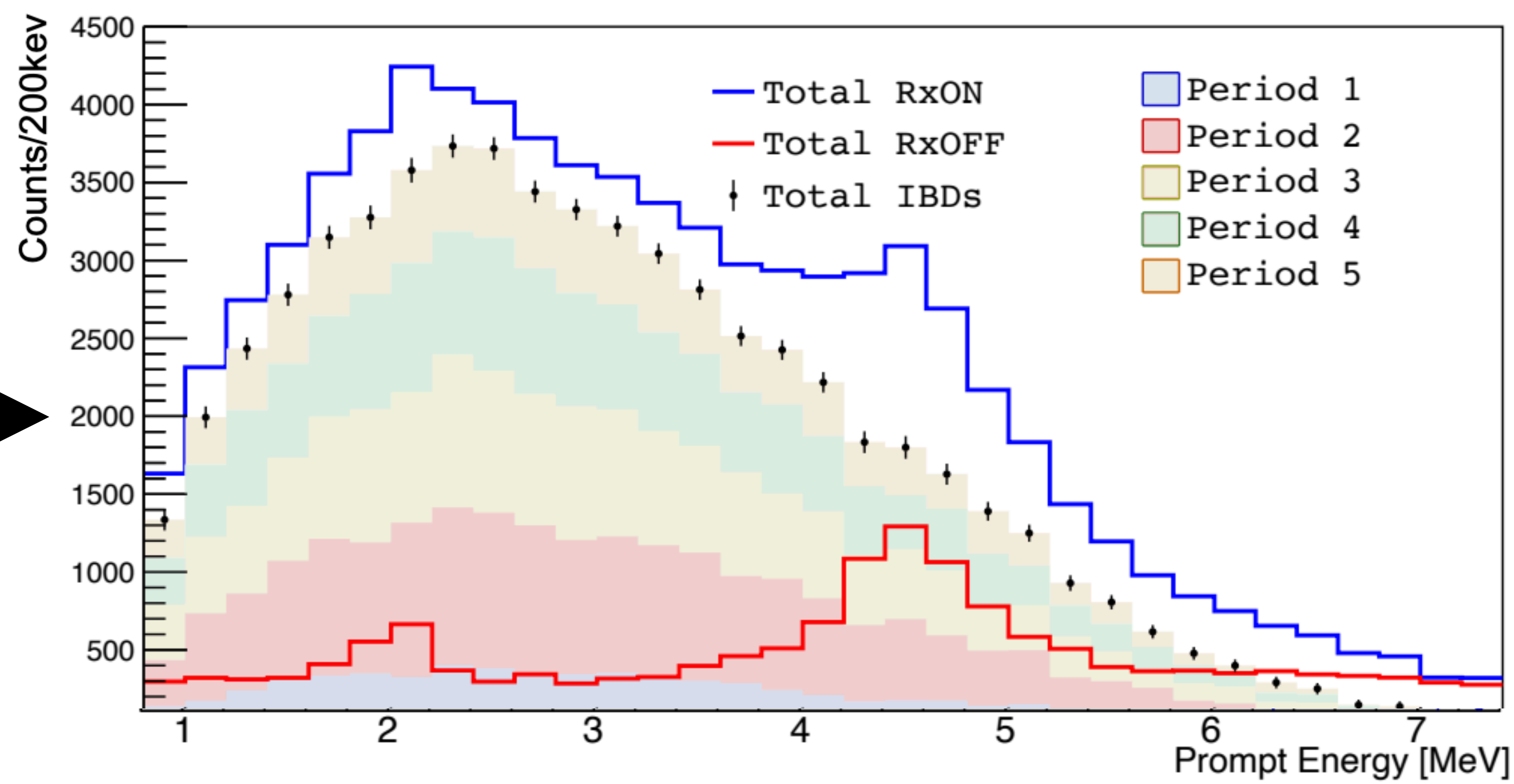
[PROSPECT Collaboration, PRD 103 (2021)]

PROSPECT Final IBD Selection

- Improved PROSPECT’s IBD selection in light of gradual PMT failures (62 of 398 PMTs)
  - Split dataset into 5 periods: 1 reactor cycle per period.
  - Used segments with 1 functioning PMT to veto cosmic neutron backgrounds
  - Ratio of signal to cosmic background increases from 1.4 to 3.9, and IBD counts increase by 20%. Total statistical power is more than doubled.



PROSPECT, PRD 103 (2021)

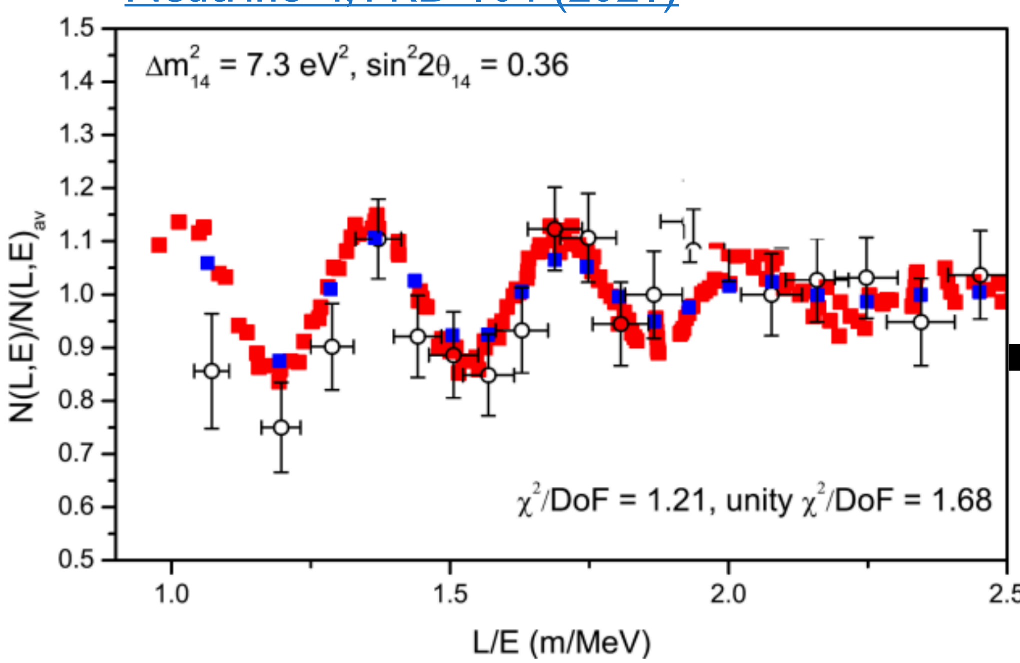


PROSPECT, PRL 131 (2023)

PROSPECT Final Osc: Probing L/E

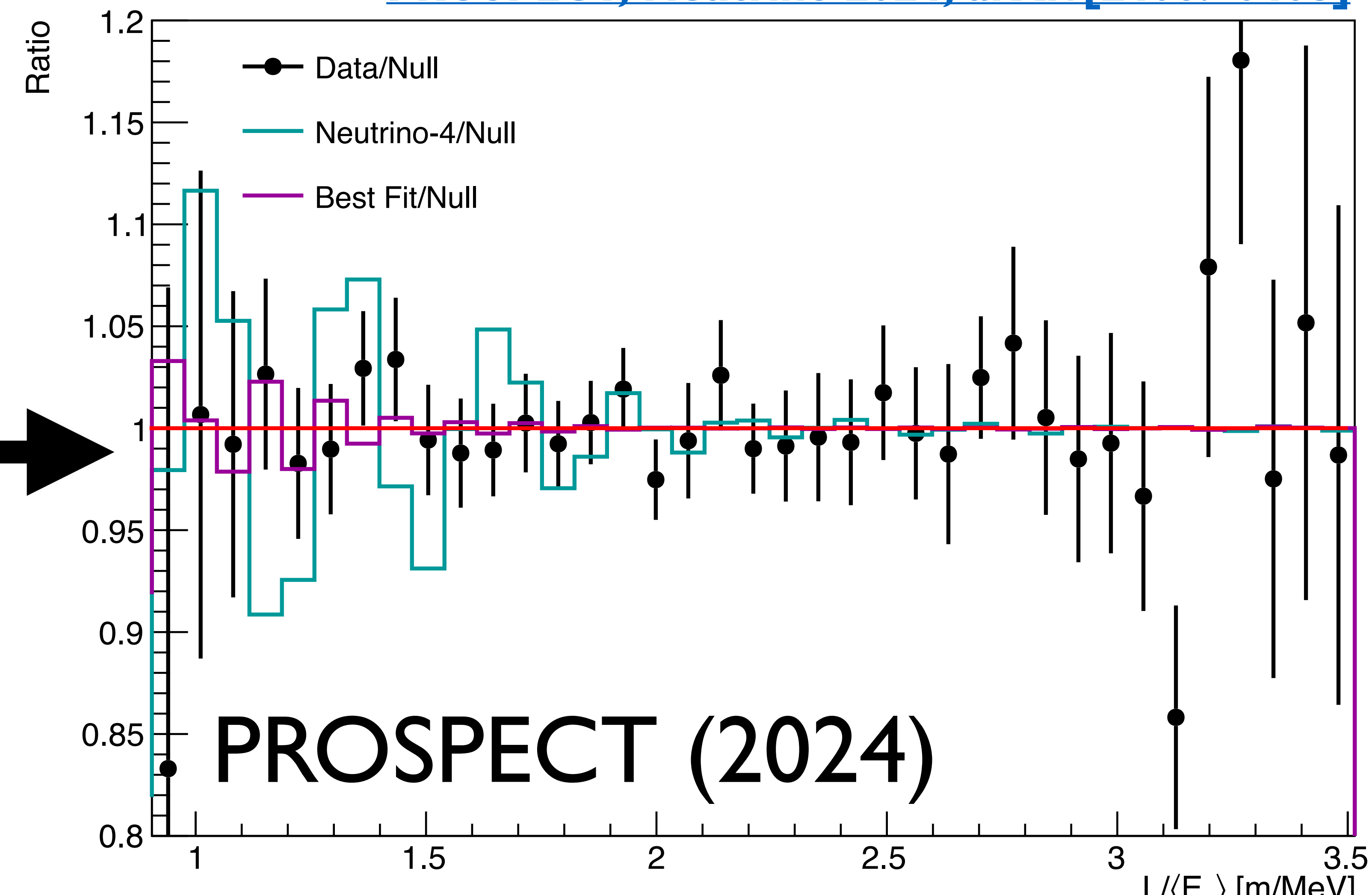
- Qualitatively examined PROSPECT's IBD dataset in bins of L/E_ν
- No obvious oscillatory features are visible in the ratio of L/E_ν spectra between data and the null-oscillation prediction
  - One would expect to see substantial features in the presence of oscillations matching the Neutrino-4 best fit point.

Neutrino-4, PRD 104 (2021)



Neutrino-4 (2020)

PROSPECT, Neutrino 2024, arXiv[2406.10408]

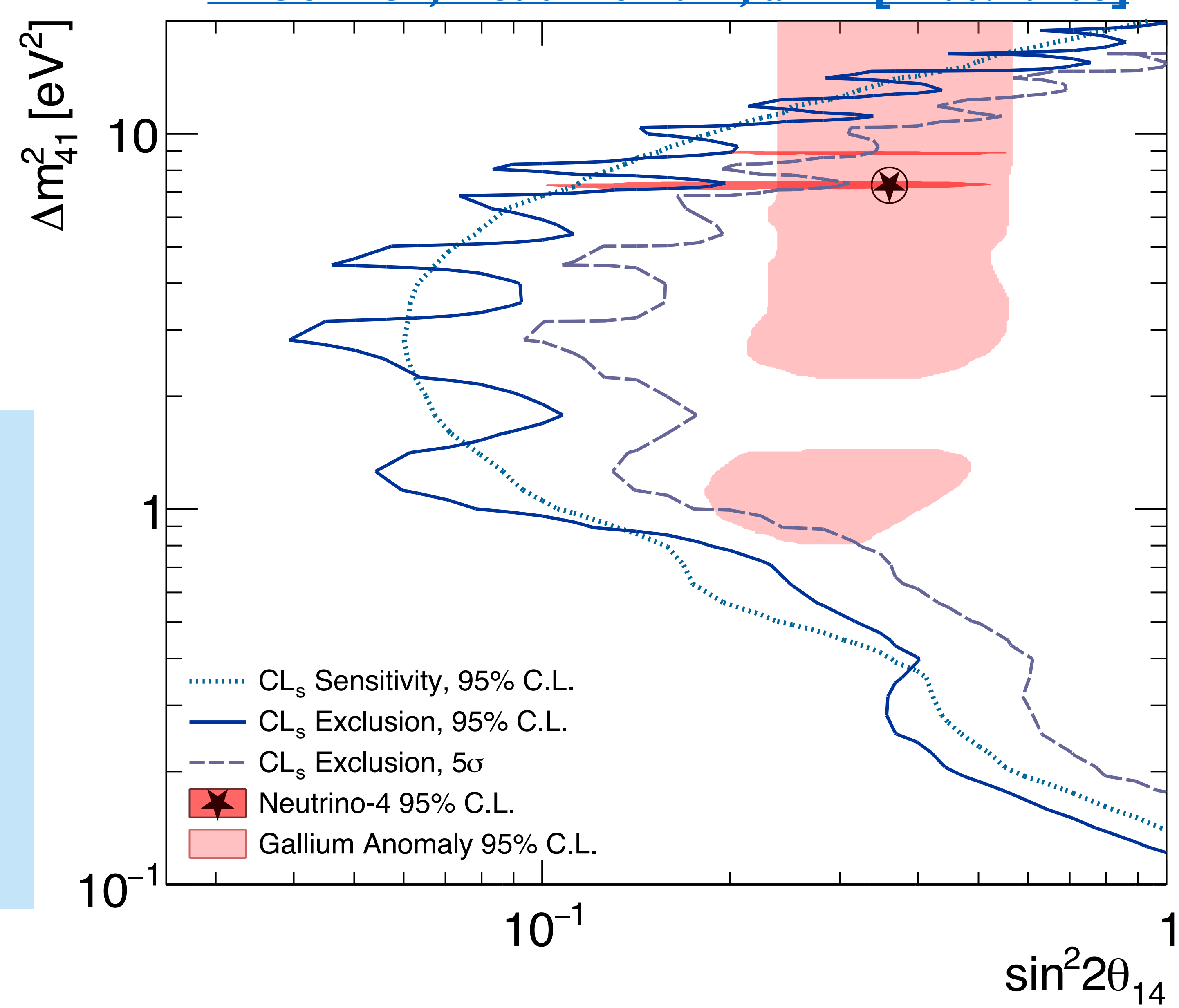


PROSPECT (2024)

PROSPECT Final Osc: Exclusion

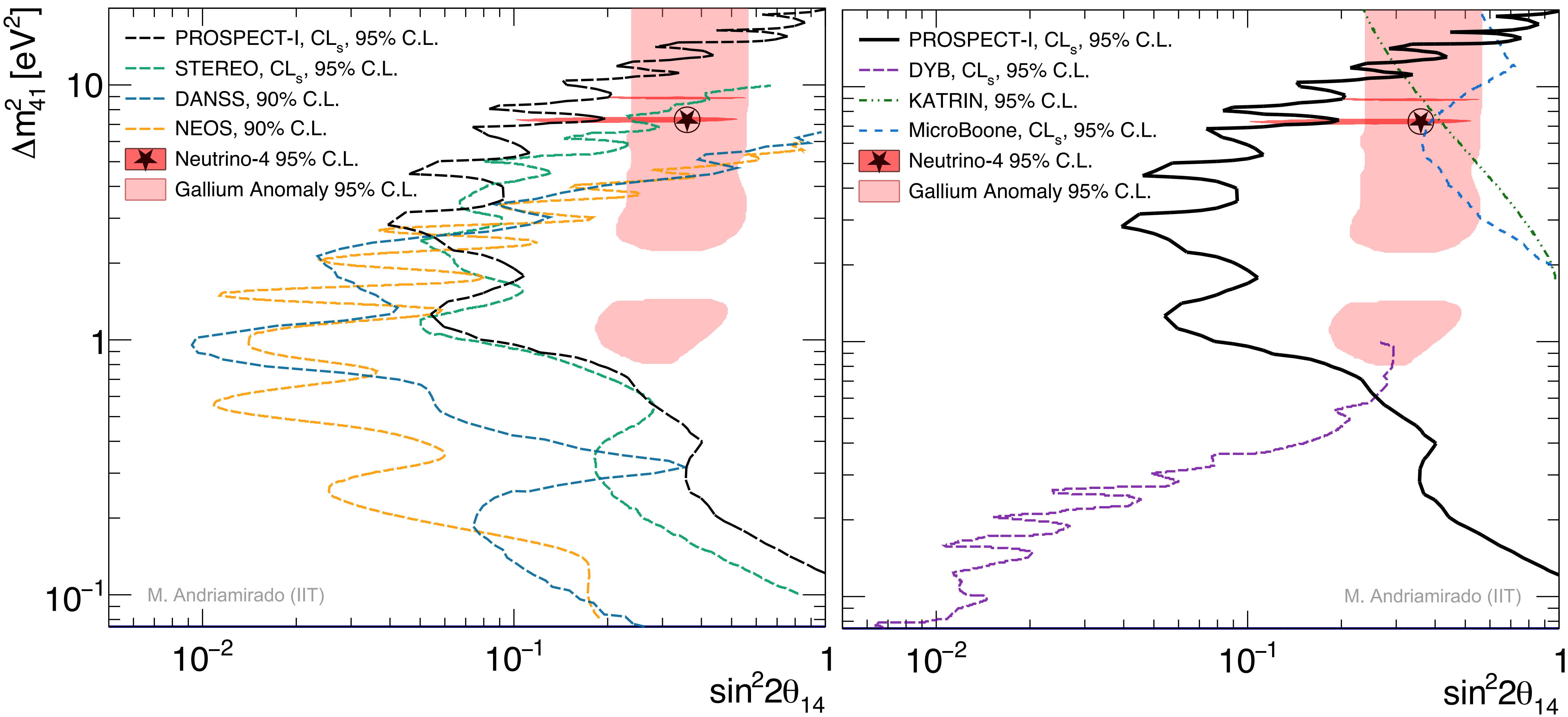
- Tested sterile neutrino phase space using 990 energy (33) x baseline (6) x period (5) bins.
  - 'Relative spectral ratio' approach: compare each baseline's energy spectrum to the baseline-integrated spectrum
  - Final result is still statistics-limited!
- PROSPECT provides new world-leading limits on sterile neutrino oscillations
  - New regions of high-Δm^2 space are excluded at >95% CL, including all space below 10 eV^2 suggested by the Gallium Anomaly
  - Neutrino-4 best-fit point is ruled out at >5σ CL

PROSPECT, Neutrino 2024, arXiv[2406.10408]



Global ν_e Disappearance Picture

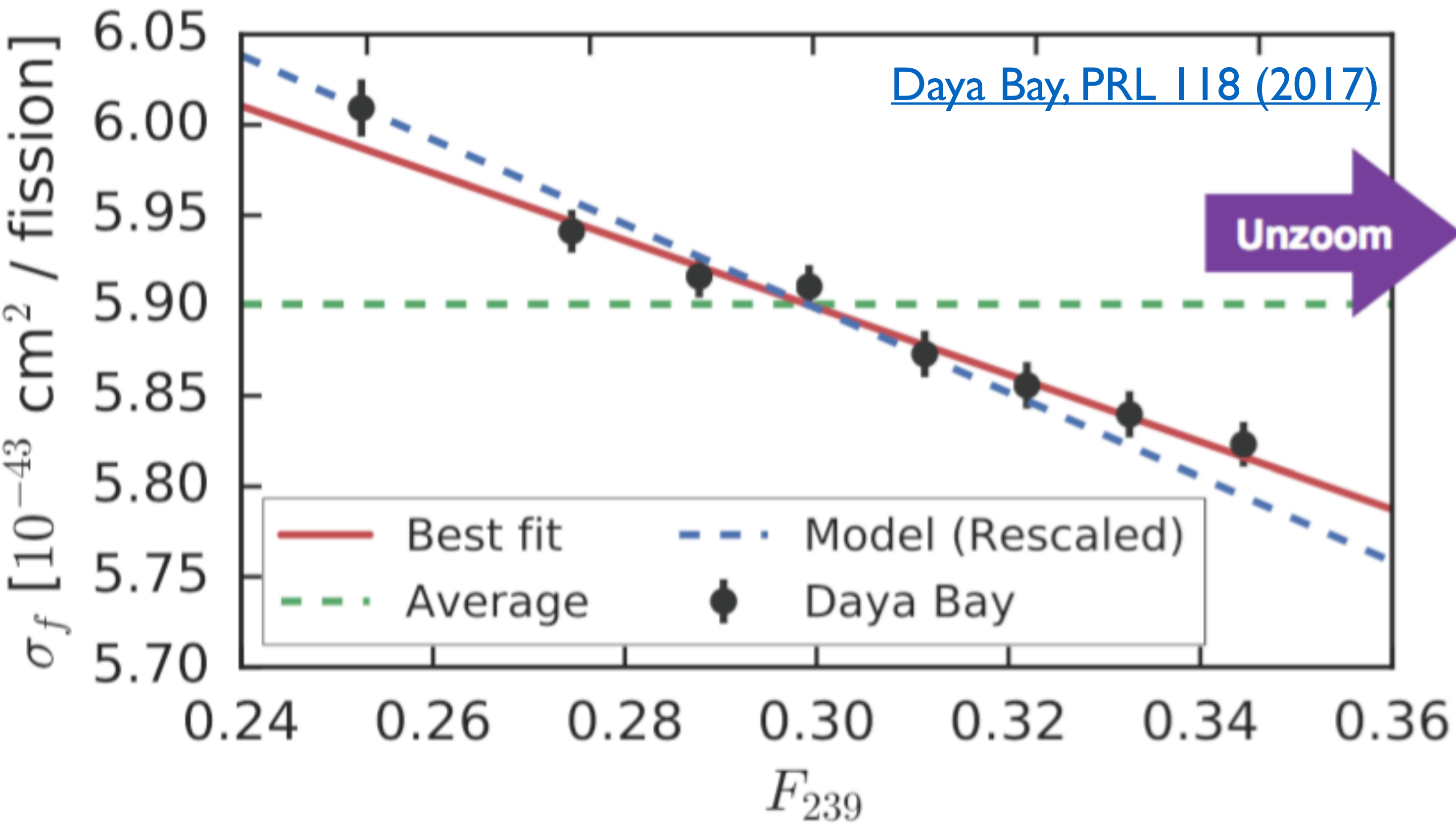
- For ν_e disappearance (θ_{14}), reactor-based limits are stronger than other sectors over most of the pictured phase space.
- After PROSPECT, it seems not possible that BEST and Neutrino-4 can be explained by the same 3+1 BSM physics.

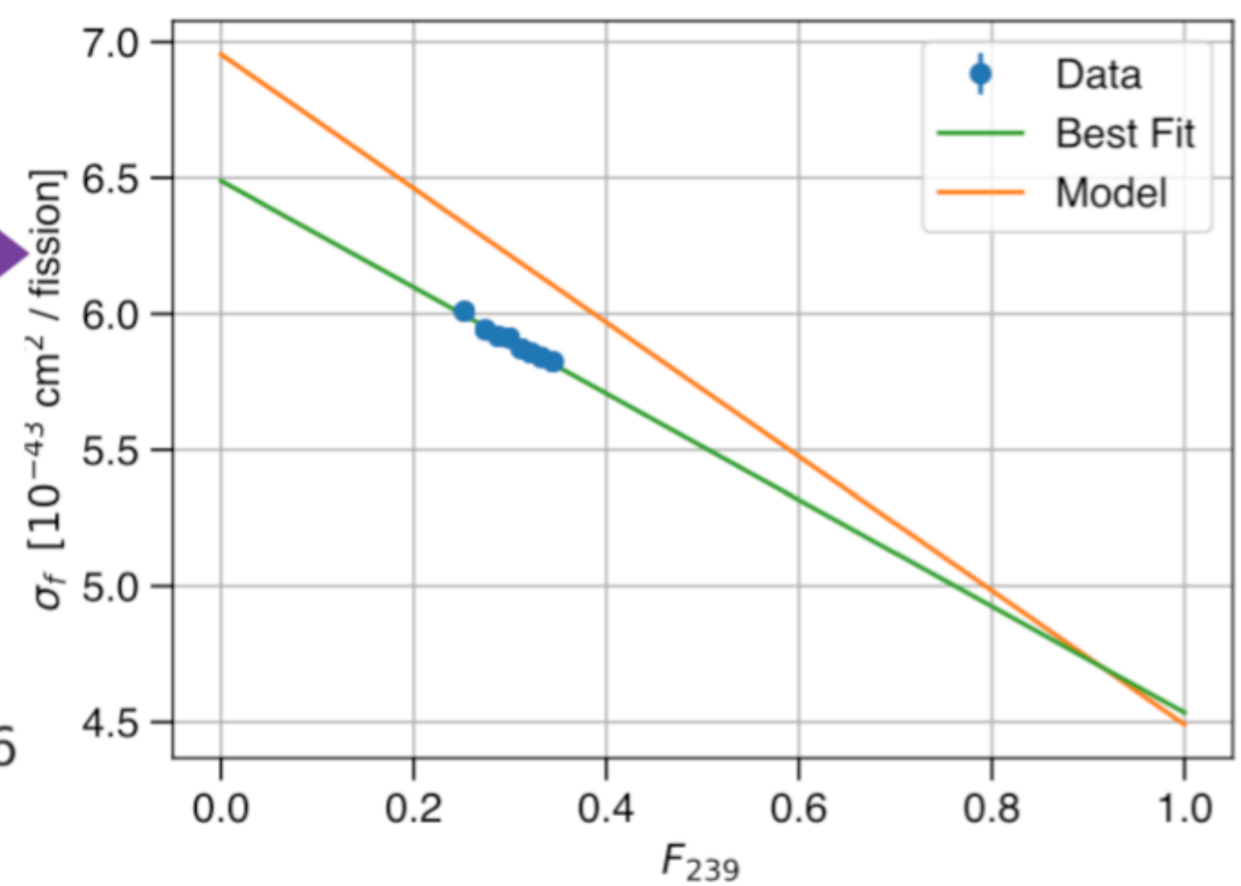


RAA Resolution: New Flux Measurements

- 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

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

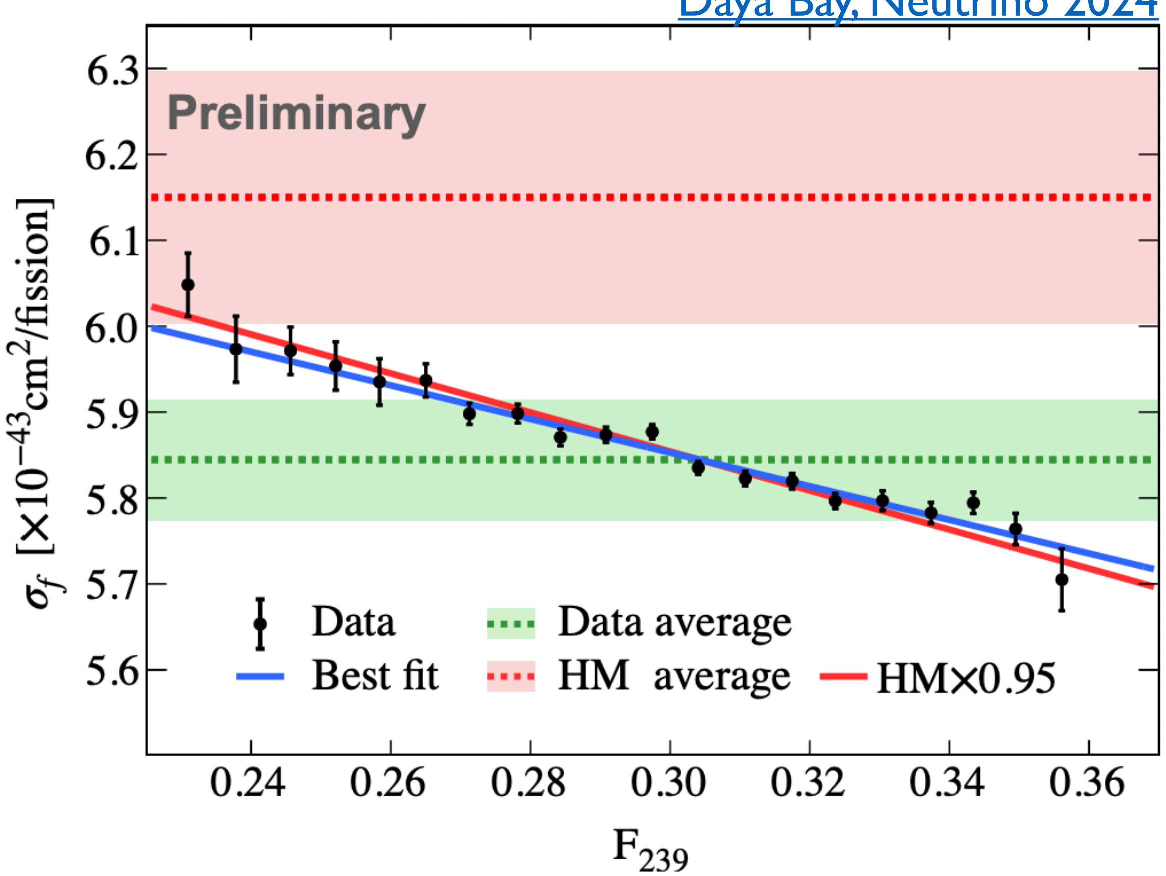


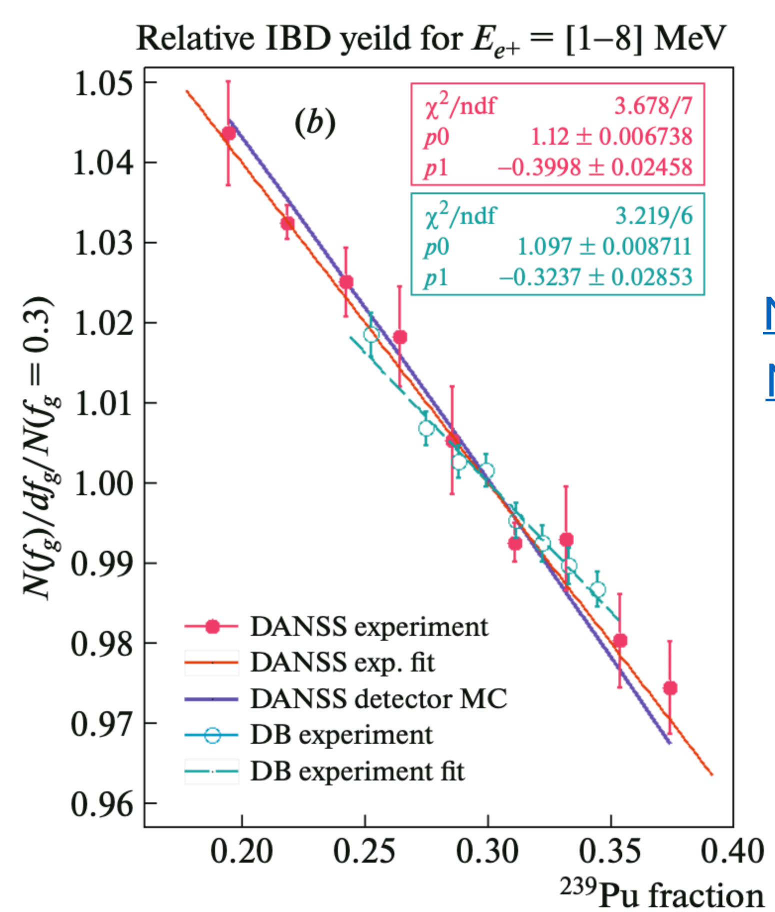


OTOH: New Flux Results

- The neutrino side of the picture, is no longer quite as definitive: final Daya Bay flux evolution results, new DANSS results
  - Flux evolution slope shifted; unclear whether RAA size is fuel-dependent now…
- While combined picture (nucl-th; nucl-ex; hep-ex) still seems to point towards flux modelling problems, the picture isn't as clear-cut as it was a year or two ago.
  - Instead of 'slammed shut,' let's consider the RAA door 'opened by a crack'

Daya Bay, Neutrino 2024

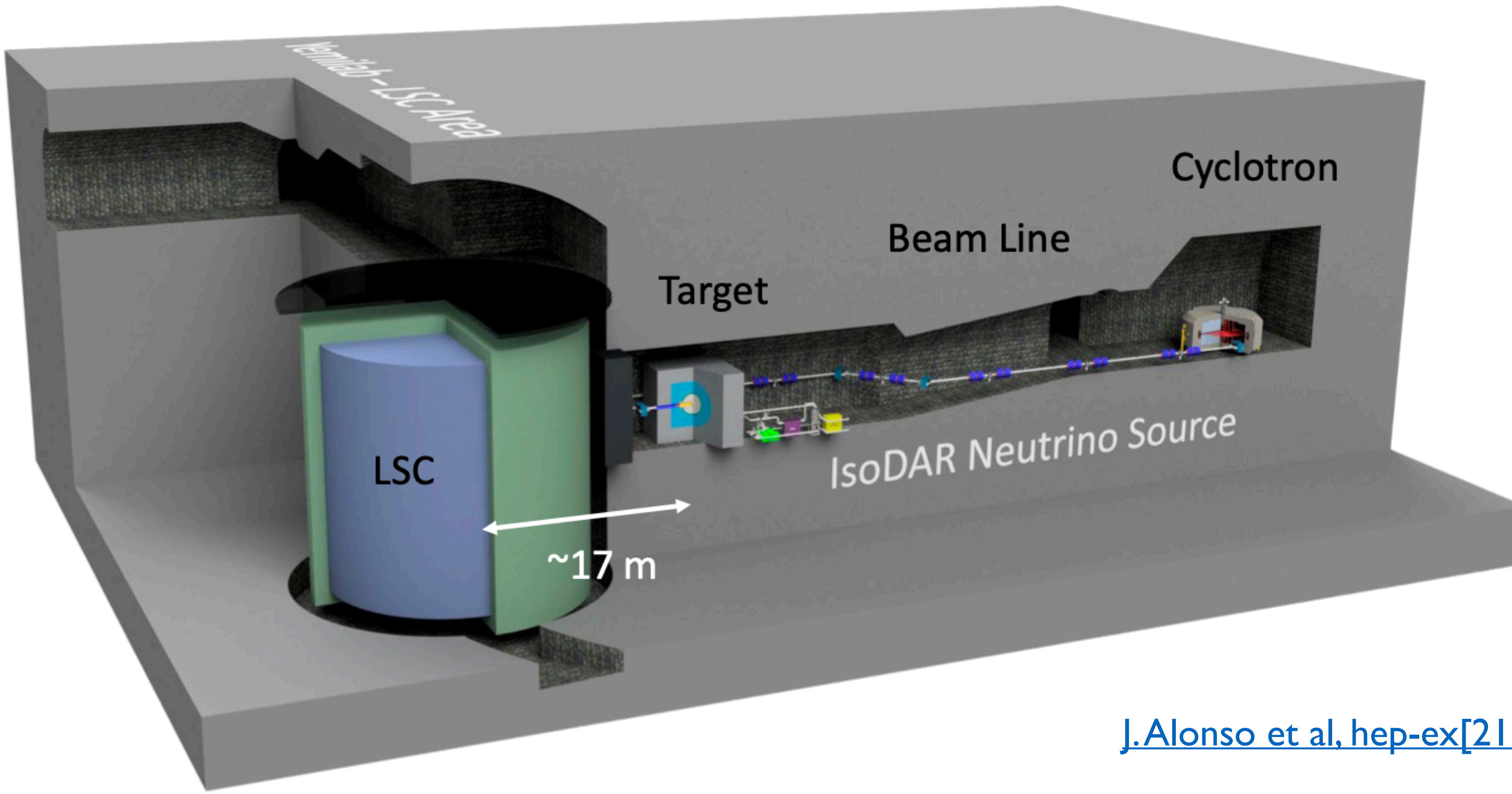




M. Danilov (DANSS), Neutrino 2024

Future Electron Flavor Probes

- 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!

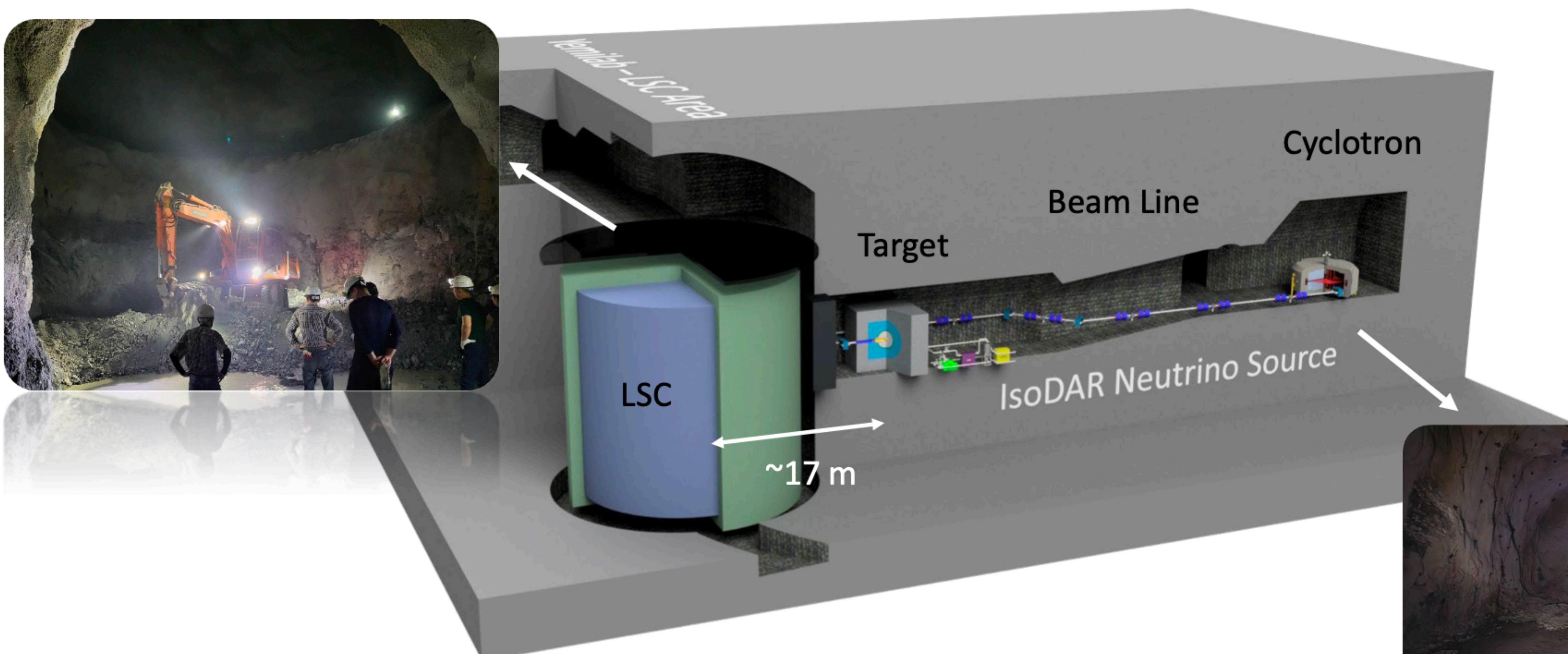


[J. Alonso et al, hep-ex[2111.10635]](https://arxiv.org/abs/2111.10635)

- Compact Cyclotron → <u>10 mA protons @ 60 MeV</u> (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



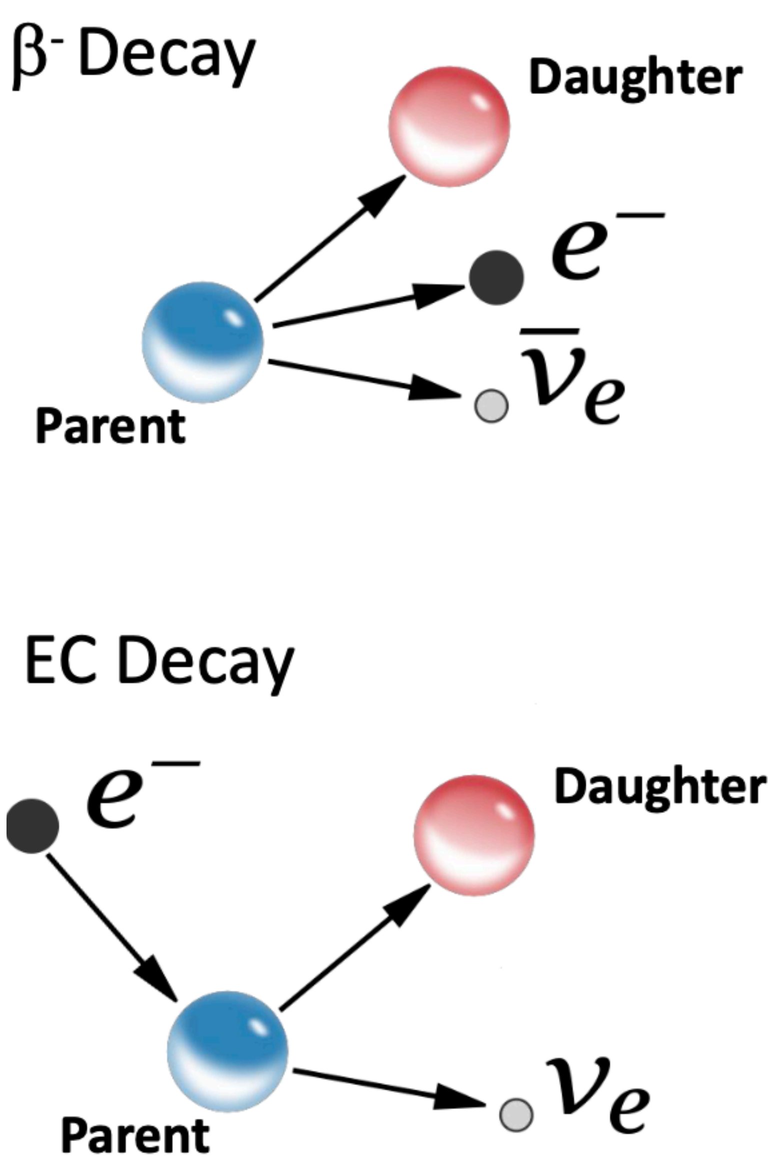
Caverns are already constructed

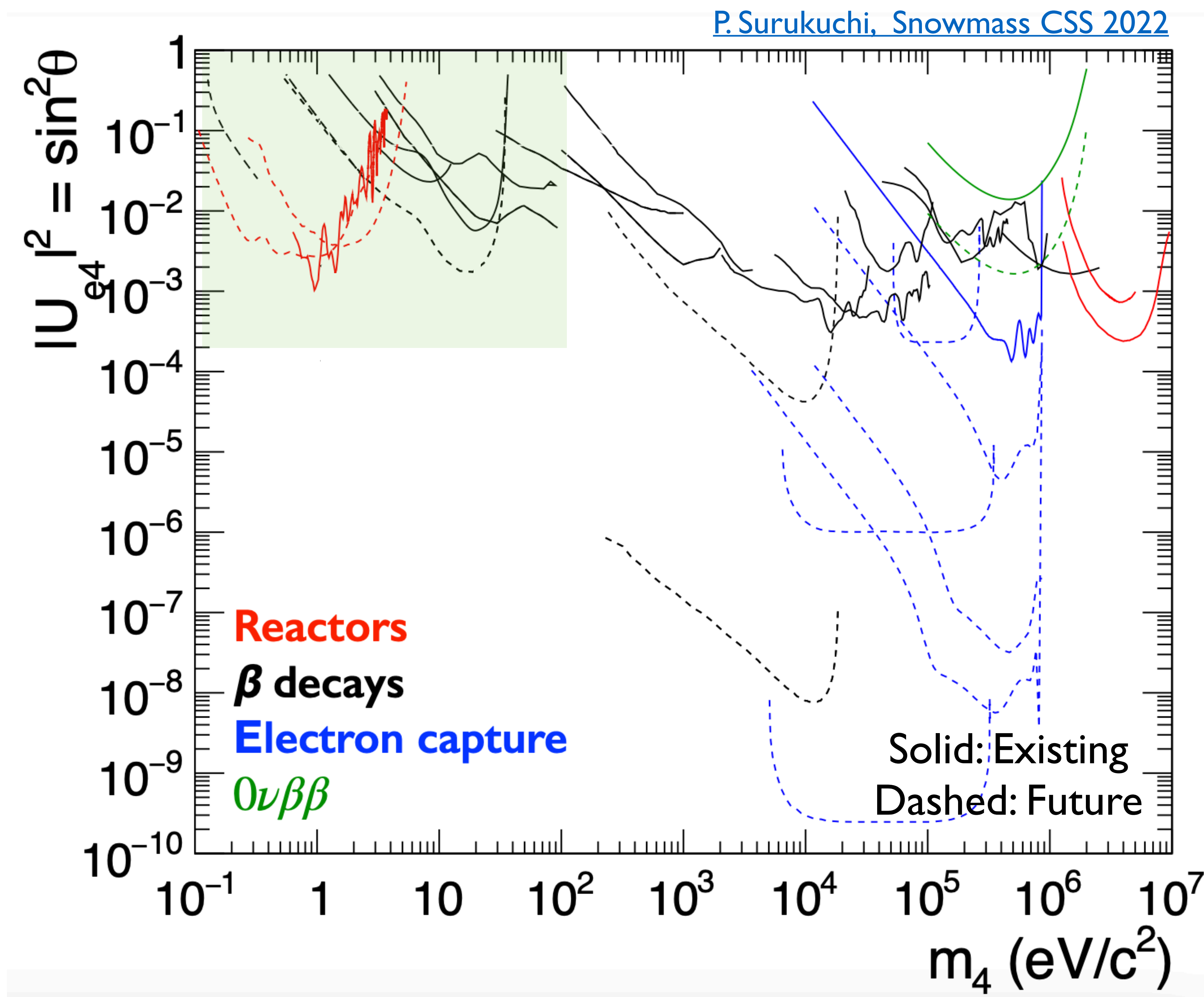
Physics Paper: http://arxiv.org/abs/2111.09480, PRD 2022
IsoDAR@Yemilab – CDR: http://arxiv.org/abs/2110.10635 arXiv 2021

Thanks to J. Spitz for input.

More Electron Flavor: Decay Experiments

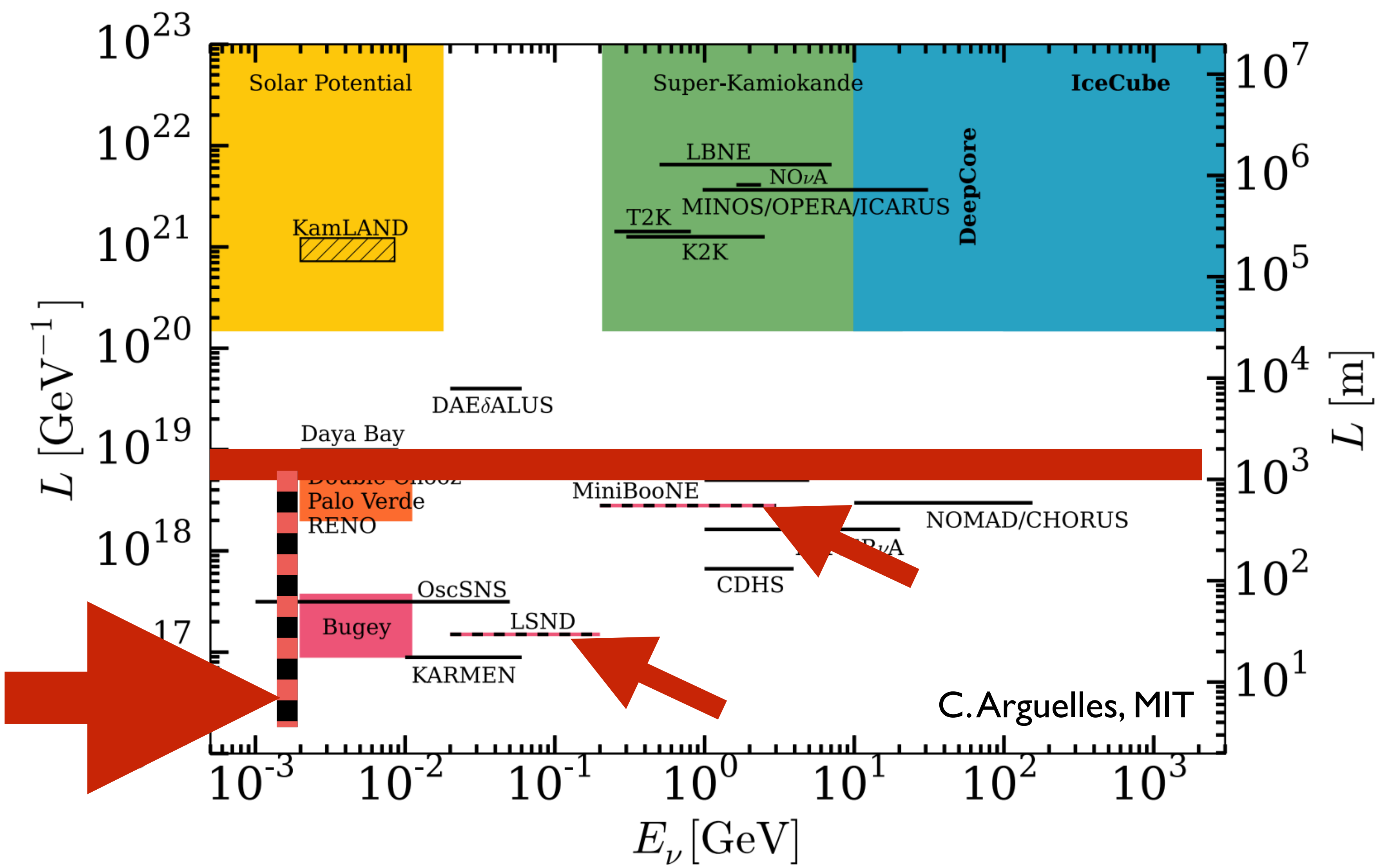
- Electron-flavored weak decay: great coverage at very high Δm^2
  - Measure tritium beta, or measure EC nuclear recoil
  - Below ~100 eV^2, future limits from KATRIN, Project-8

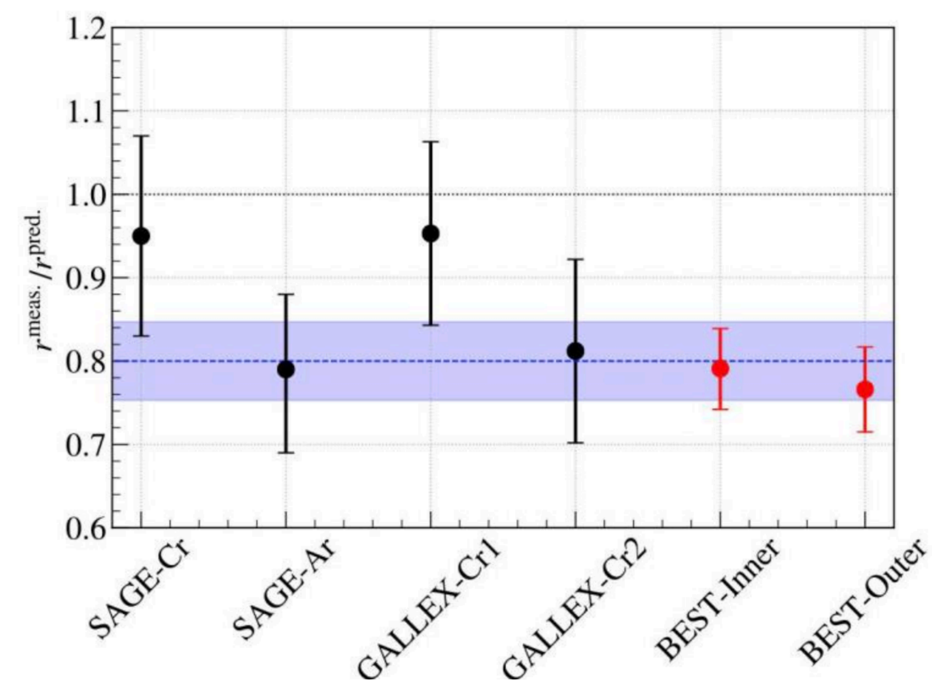




Gallium Anomaly

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

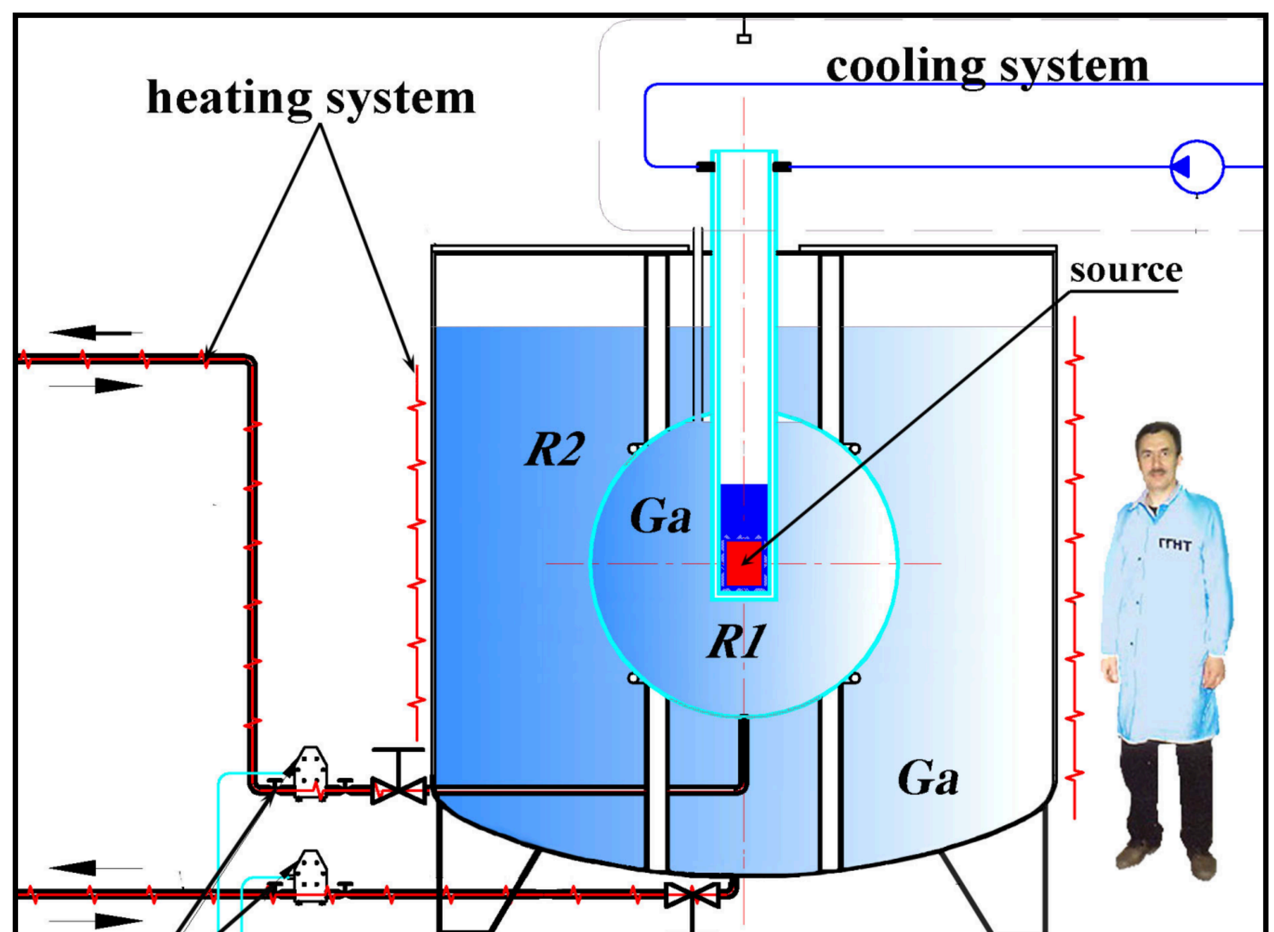




Some content from D. Gorbunov, Neutrino 2024

Gallium Anomaly: Quick Summary

- Make a crazy hot (PBq) Cr-51 source using a nuclear reactor
- Measure its heat release w/ calorimeter to determine activity
- Drop it in a double-zone Ga-71 bath
- Count Ge-71 made by via neutrino capture
- See a 20% deficit in detected rates with respect to prediction



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Gallium Anomaly: What Is It?

- What could bias detected electron-capture source nue counts?
  - Sterile neutrinos?
  - Incorrect Cr-51 decay branching ratios?
  - Incorrect Ga-71 neutrino capture cross-sections?
  - Incorrect Ge-71 half-life?
  - Measurement systematic uncertainties in Ge-71 counting?
  - Some other bespoke BSM that affects <MeV electron-capture nue but not >MeV reactor beta-decay nuebar?

Gallium Anomaly: What It Isn't.

- What could bias detected electron-capture source nue counts?
  - Sterile neutrinos?
    - Already explained this: PROSPECT, other reactor experiments, reactor fluxes say 'no.'
  - Incorrect Cr-51 decay branching ratios?
    - Seems very unlikely — pretty basic…: Brdar, Gerhlein, Kopp, JHEP 05:143 (2023)
  - Incorrect Ga-71 neutrino capture cross-sections?
    - Nope: Elliott, et al, PRC 108 (2023)
  - Incorrect Ge-71 half-life?
    - Nope: Norman, et al, PRC 109 (2024)
  - Measurement systematic uncertainties in Ge-71 counting?
    - Nope: Brdar, Gerhlein, Kopp, JHEP 05:143 (2023)
  - Some other bespoke BSM that affects <MeV electron-capture nue but not >MeV reactor beta-decay nuebar?
    - No really compelling models built to date; i.e.: Brdar, Gerhlein, Kopp, JHEP 05:143 (2023)
    - Nue-nuebar distinction? Haven't seen this exploited in the literature yet?

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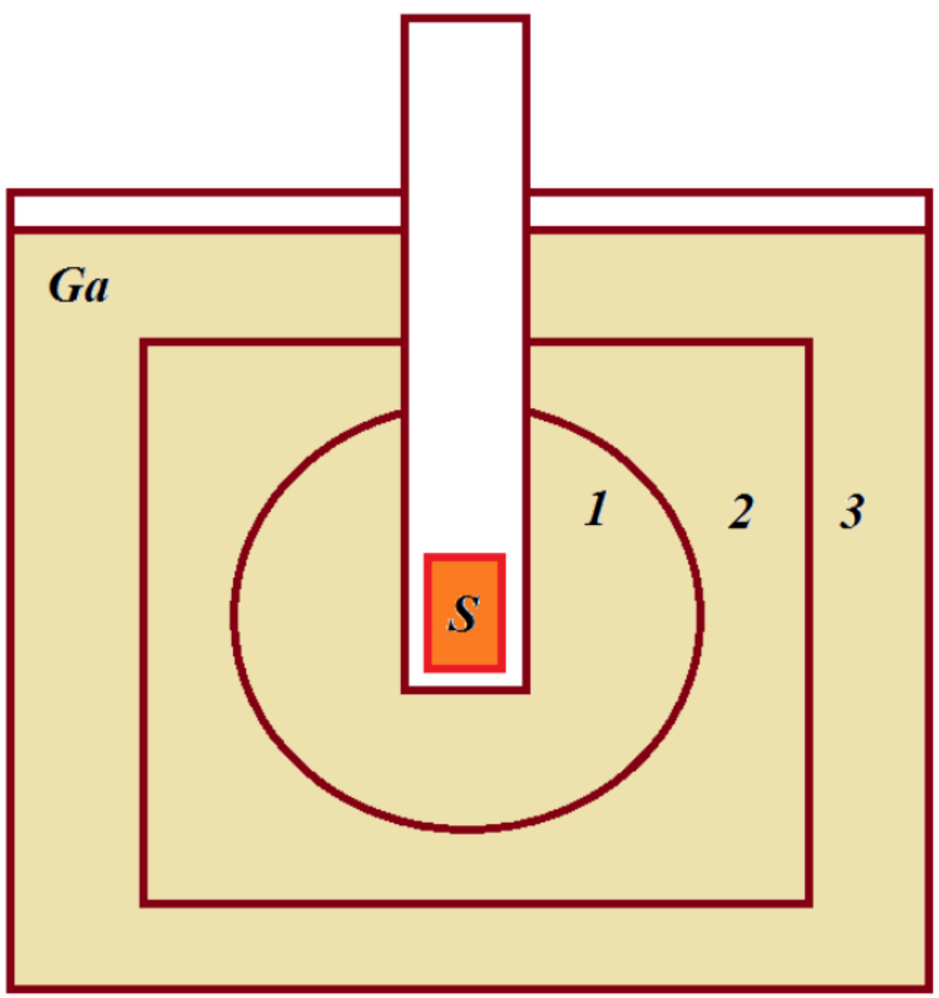
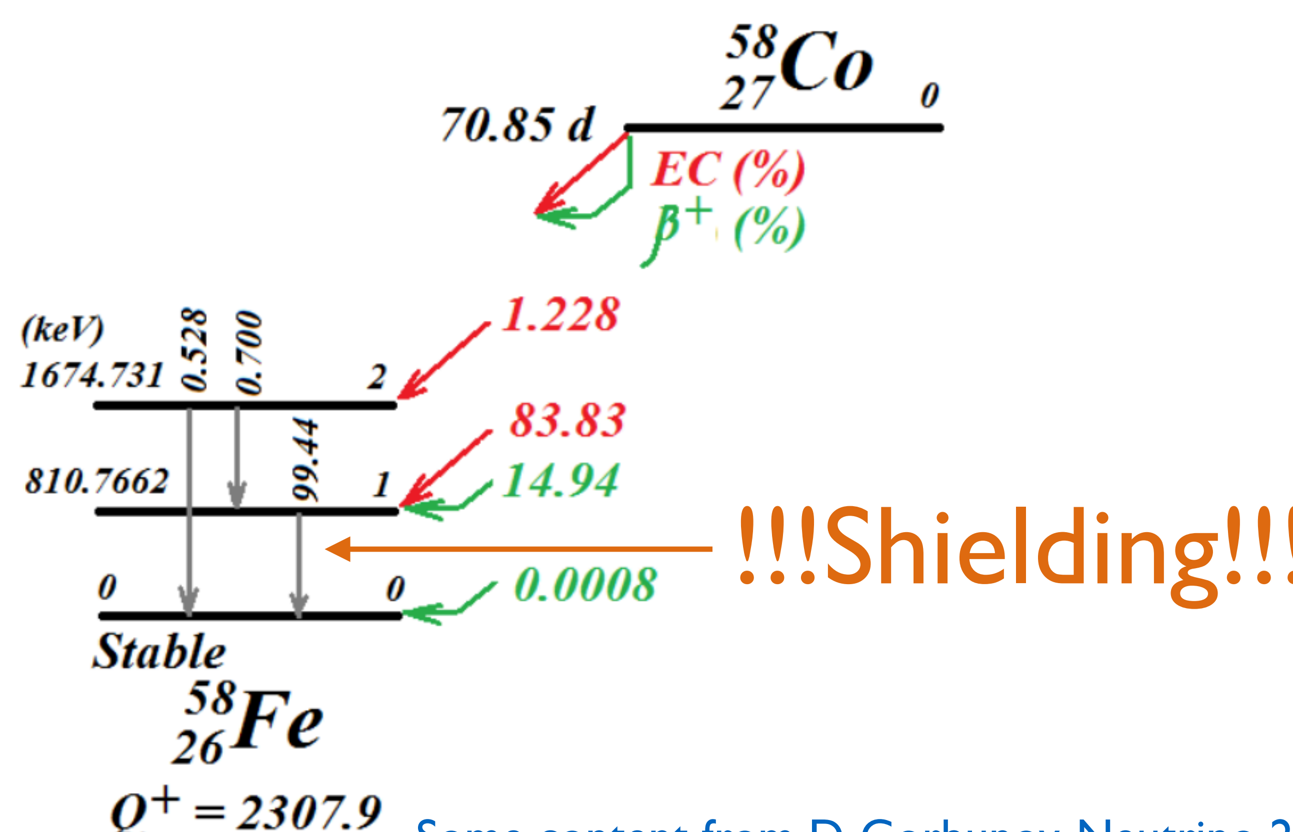
SHRUG.

Gallium Anomaly: Next Steps

- Next steps by BEST, stated at Neutrino 2024:
  - Turn BEST into a 3-zone gallium detector
    - This is 'easy'
  - Try a different source: ^{65}Zn or ^{58}Co
    - This is 'hard:' need to shield ~MeV-scale gammas… A LOT OF THEM!
  - R&D will take years, so follow-up is not happening soon…





Some content from D. Gorbunov, Neutrino 2024

Decay-At-Rest Electron Appearance (LSND)

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  - What's their status?
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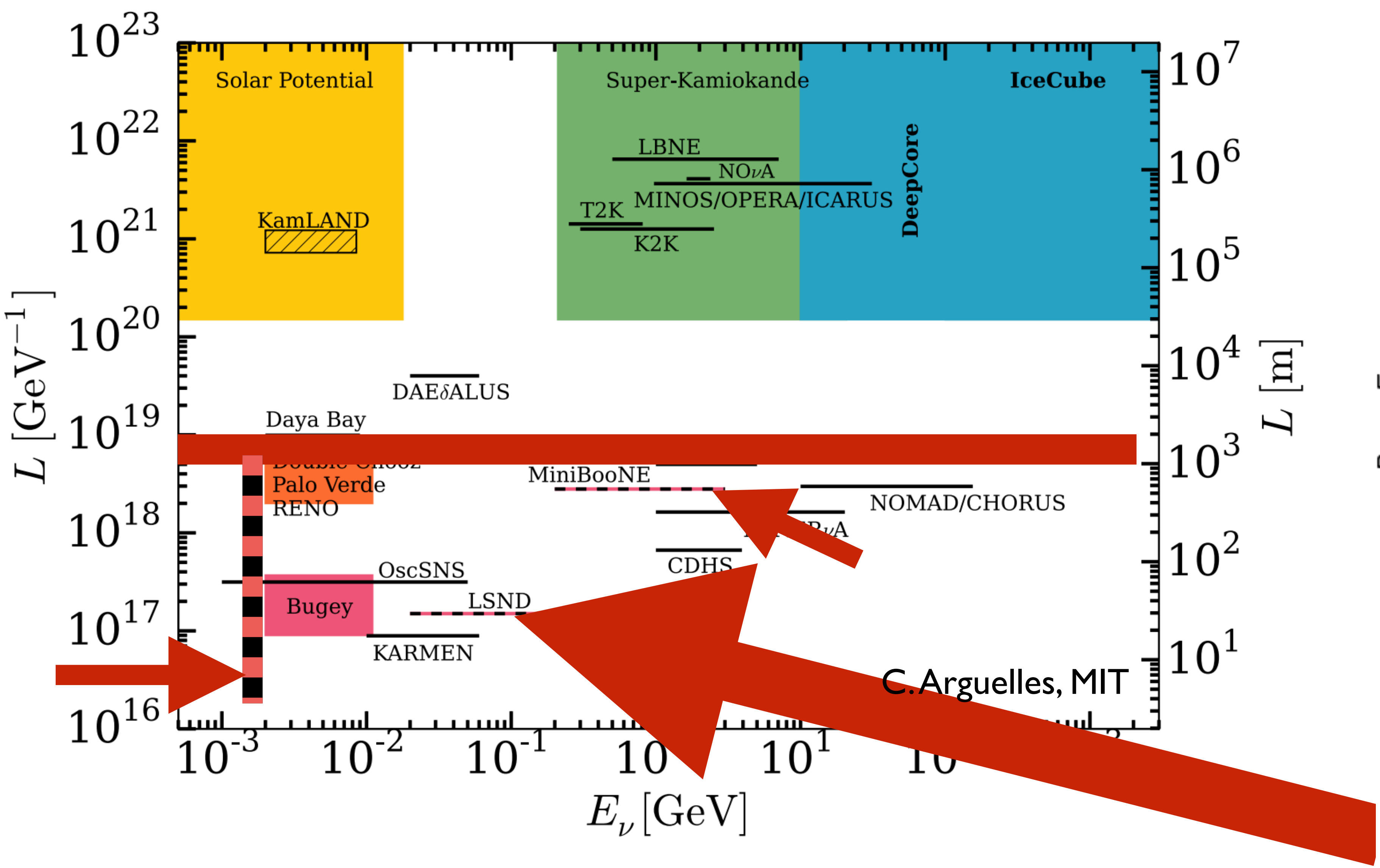
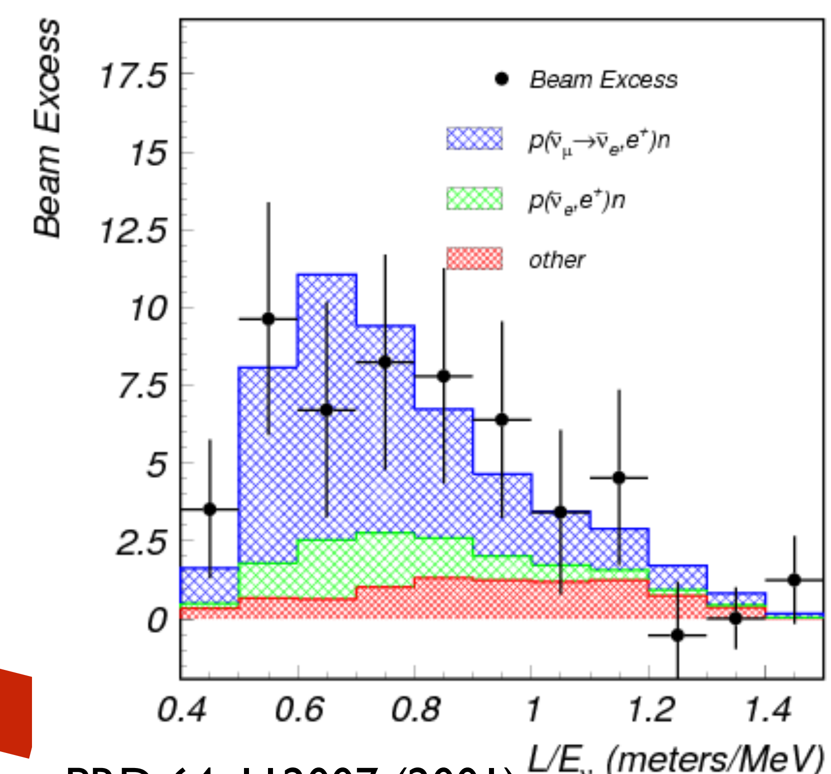
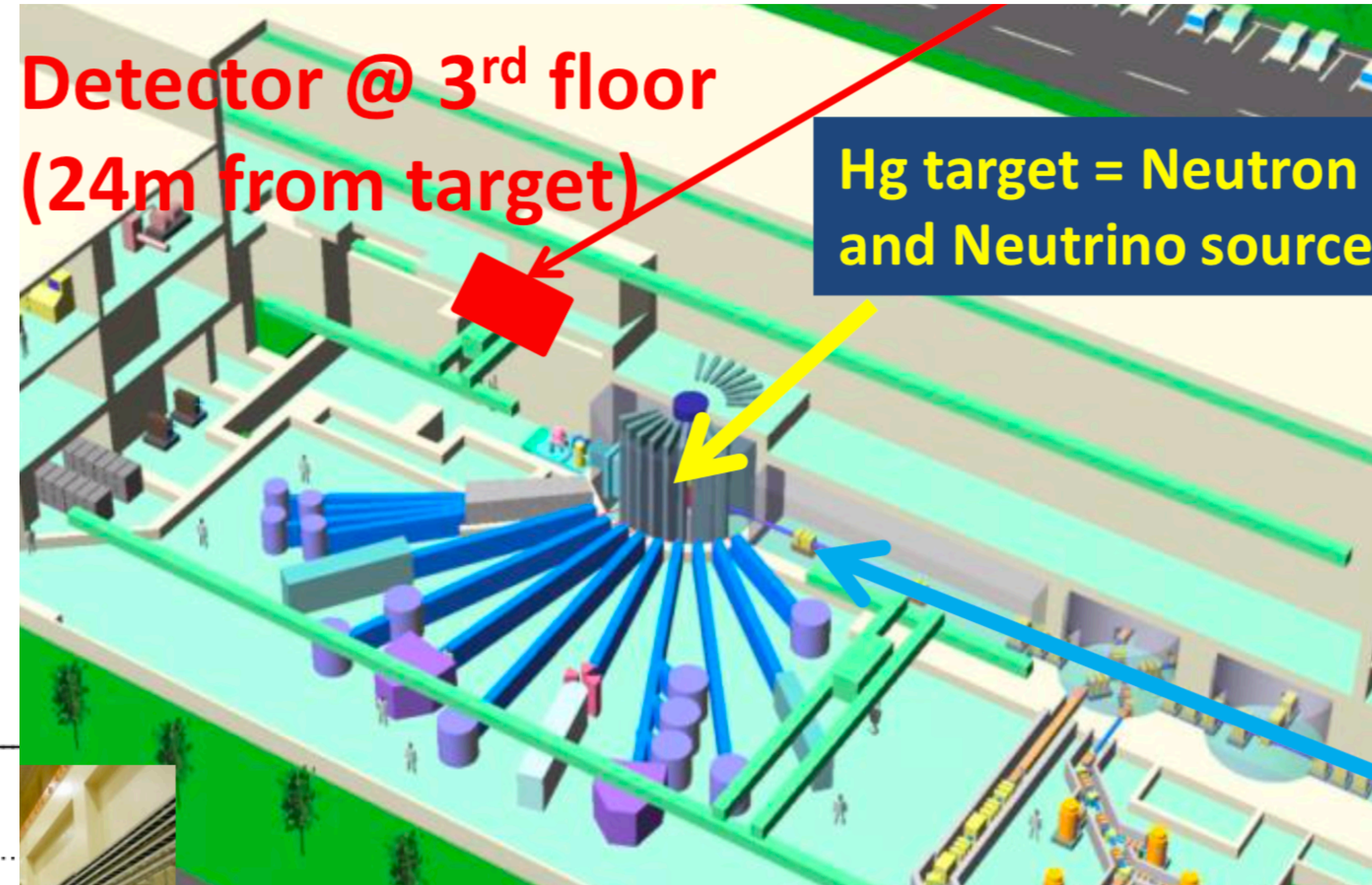




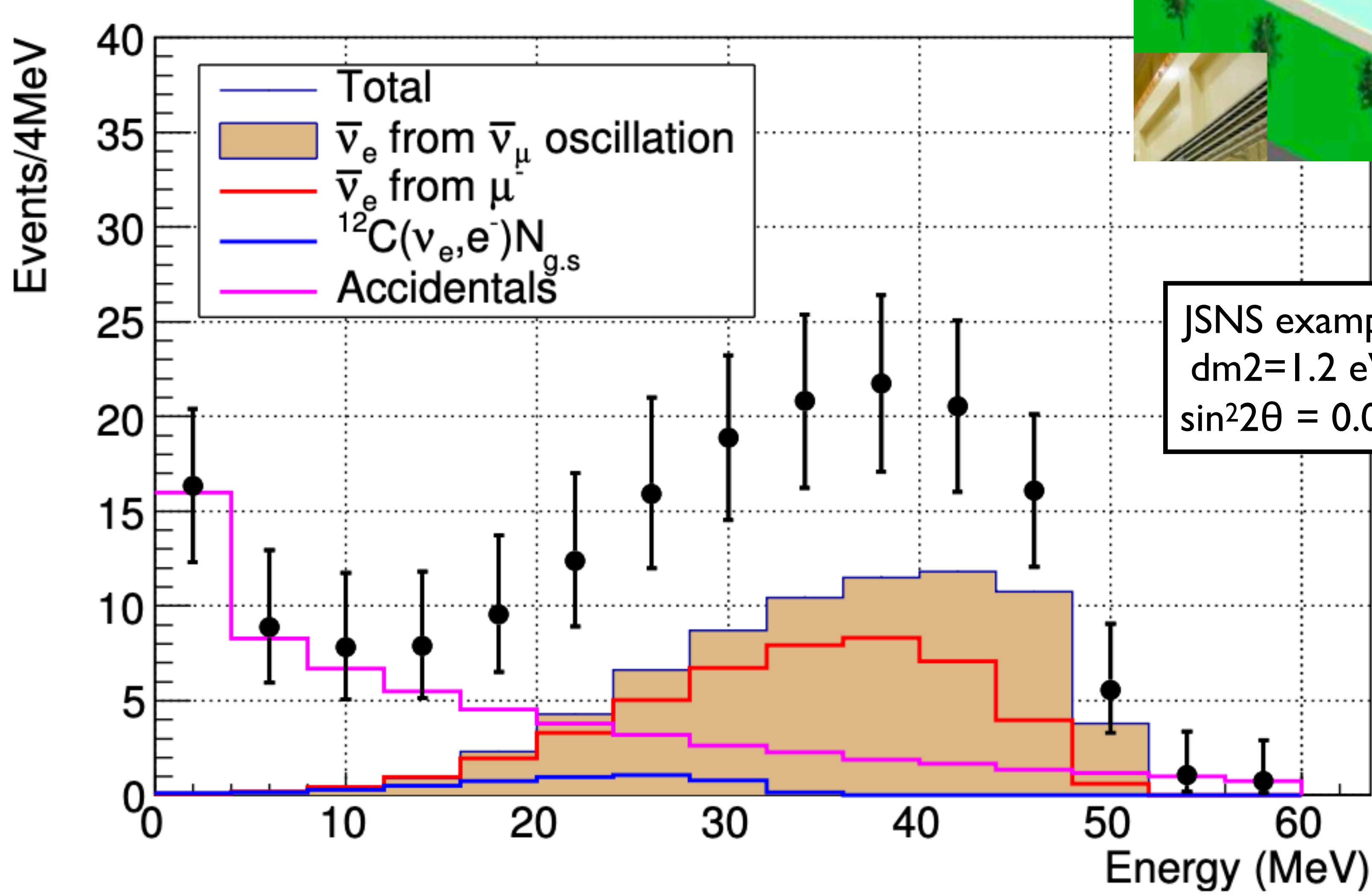
PRD 64, 112007 (2001)

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



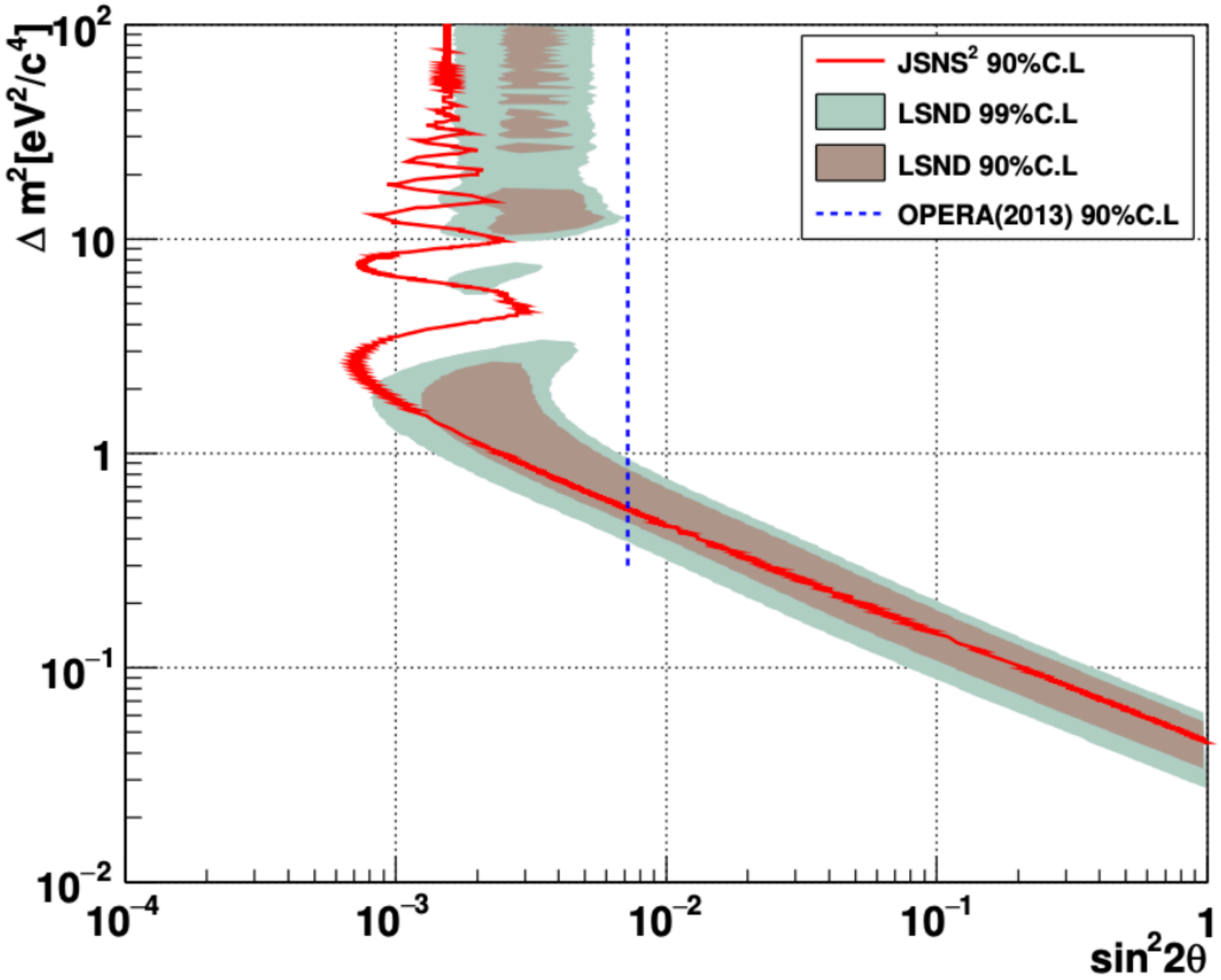
JSNS2, hep-ex[1705.08629]



Thanks to J. Spitz for input.

Into the New P5: JSNS^2

- 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 (JSNS^2-II) planned to start data-taking in late 2024.



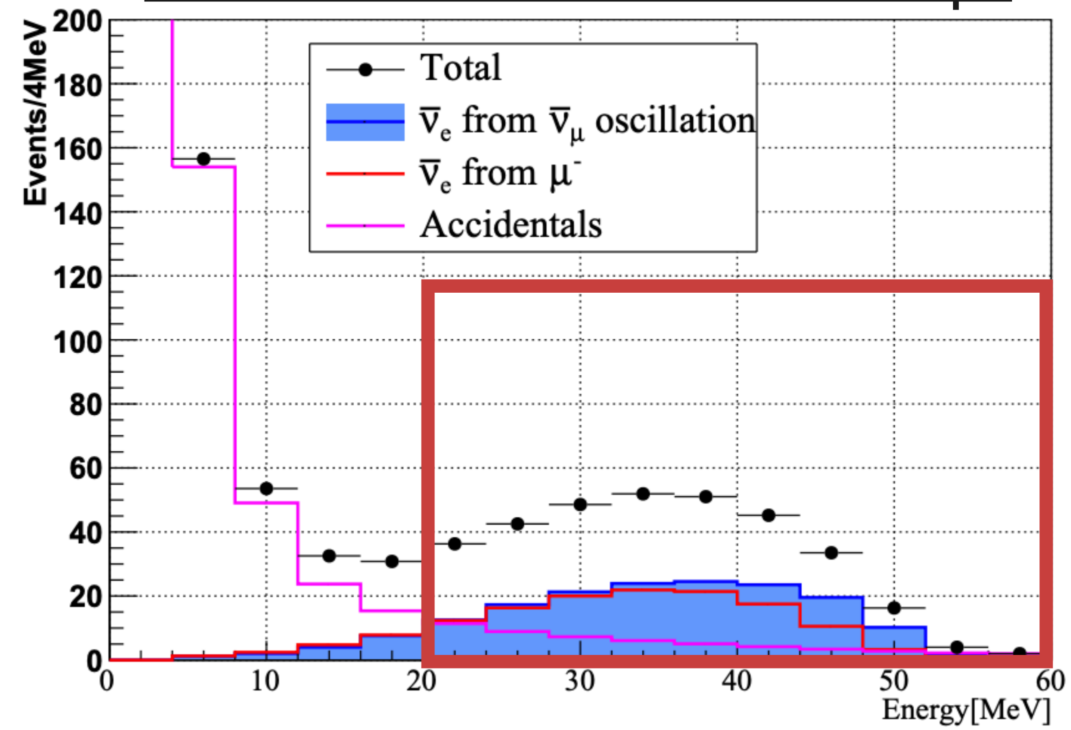
JSNS2, hep-ex[2012.10807]

Thanks to J. Spitz for input.

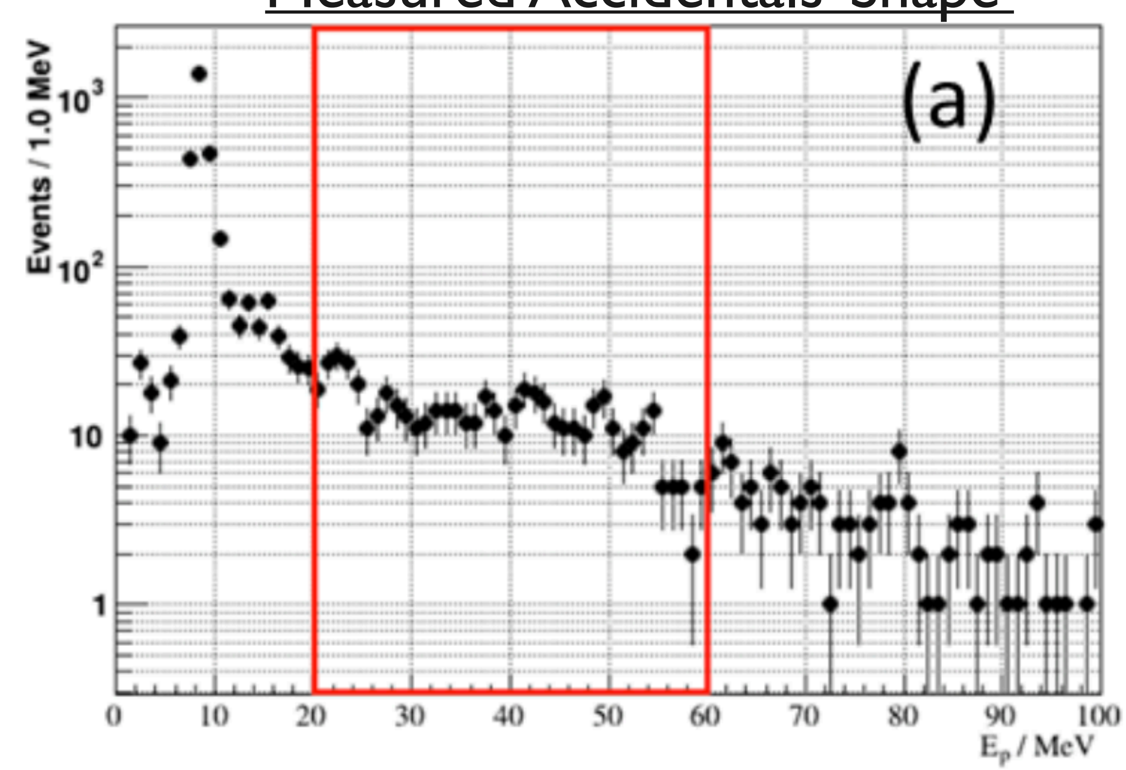
First Public Analysis of JSNS² Data

- 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

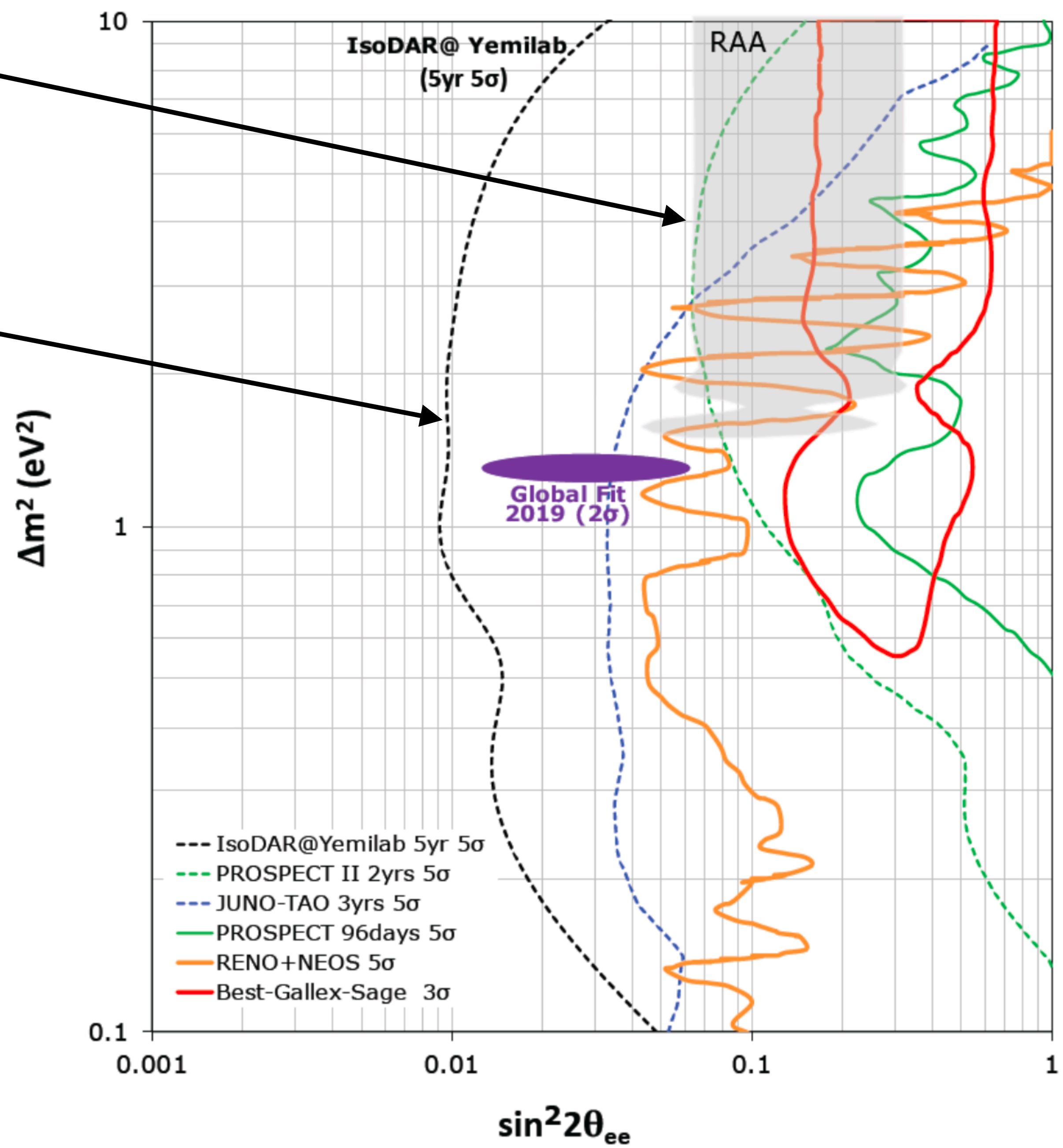
- While some seem (mostly) dead, many of the neutrino short-baseline anomalies are alive and well.
- After PROSPECT, it seems not possible that BEST and Neutrino-4 can be explained by the same simple 3+1 BSM.
- There are clear paths toward improved electron-flavor disappearance measurement improvements:
  - Powerful new sources/methods: IsoDAR@Yemilab
  - PROSPECT-II, TAO: more short-baseline reactor statistics, at HEU and LEU
- In contrast: you should expect it to be a long time before the Gallium Anomaly is directly experimentally resolved.
- To directly address LSND, JSNS^2 has data in the can, and we can expect 1- and 2-detector results in the next 5 years
  - Exciting, but there are risks to achieving their sensitivity targets (backgrounds!)

Thanks!

Backup

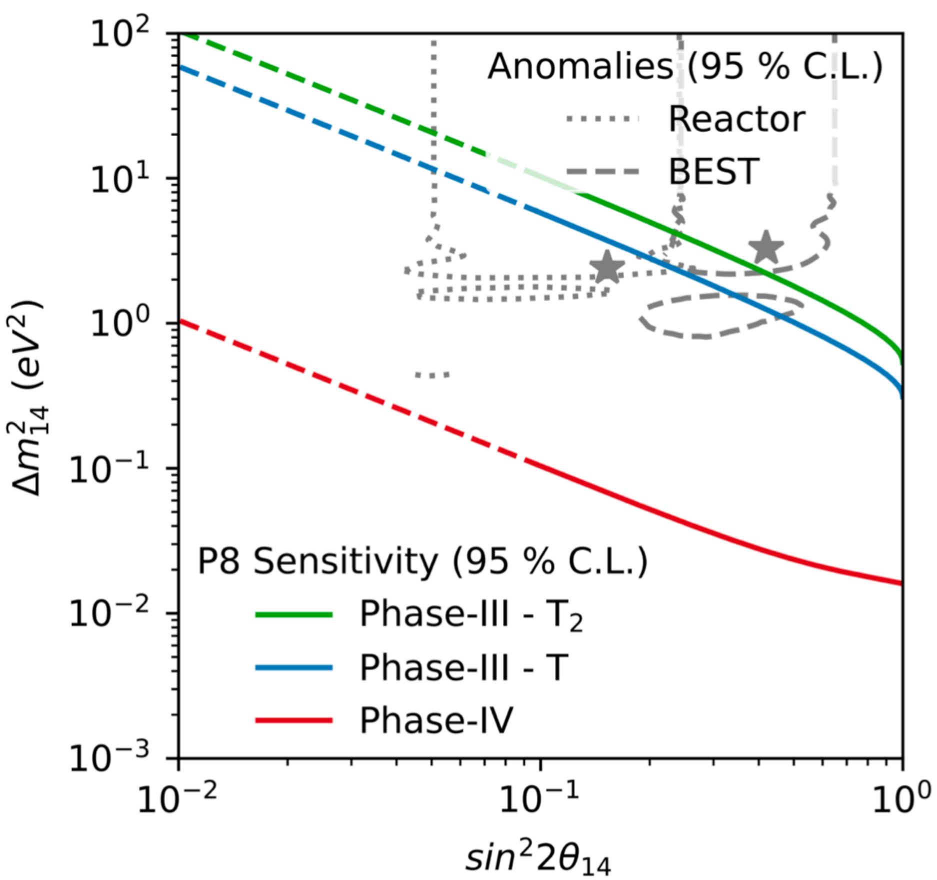
Future Electron-Disappearance Limits?

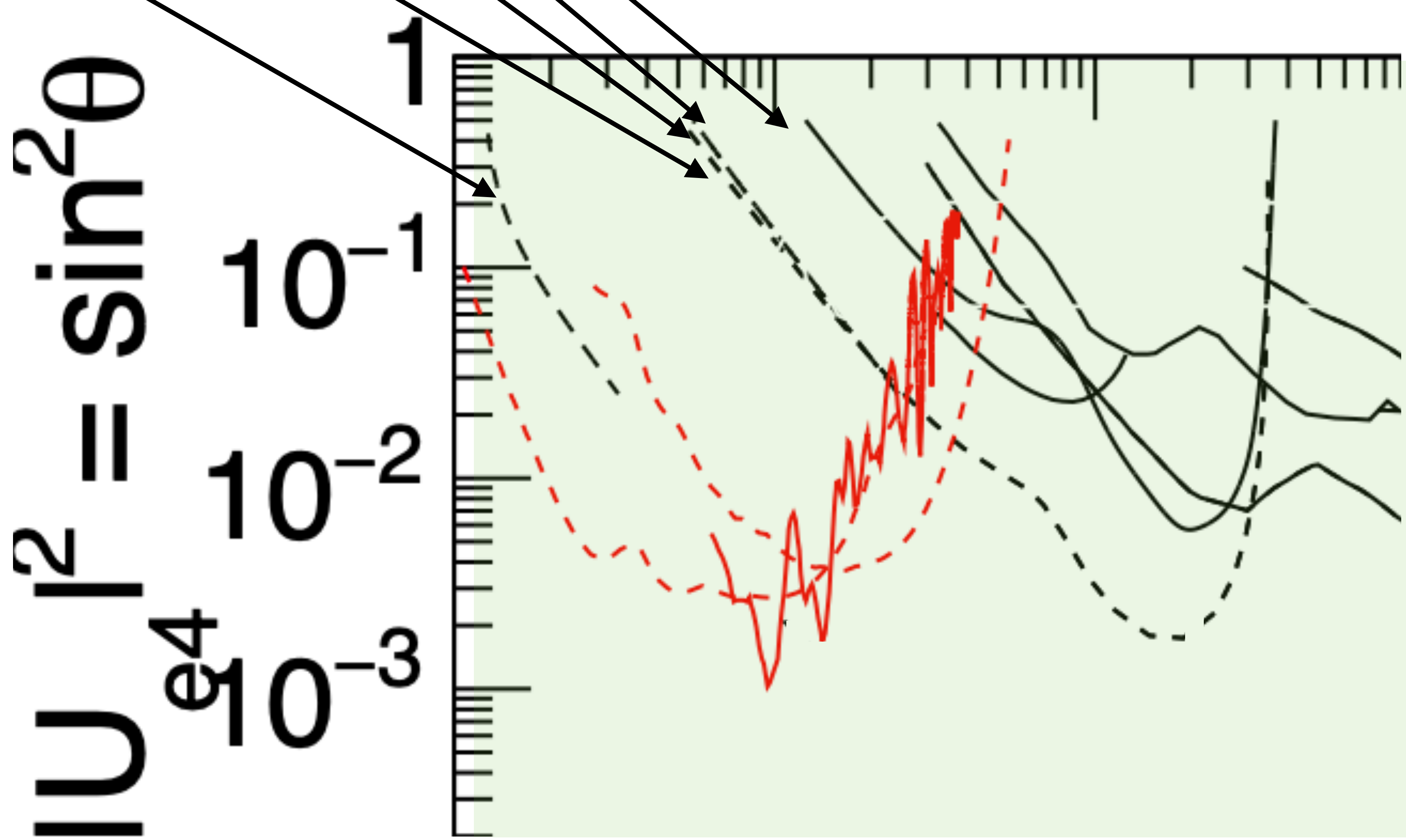
- Let's make a hypothetical scenario where we started building IsoDAR and PROSPECT-II today:
  - Assume 1 year PROSPECT construction; 2 year IsoDAR + LSC construction
  - 2027: P2@HFIR final results
  - ~2027: BNB Long shutdown?
  - 2031: IsoDAR final results
  - ~2031: DUNE+Beam startup?
- This is a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



Future E-Flavor Weak Decay Limits?

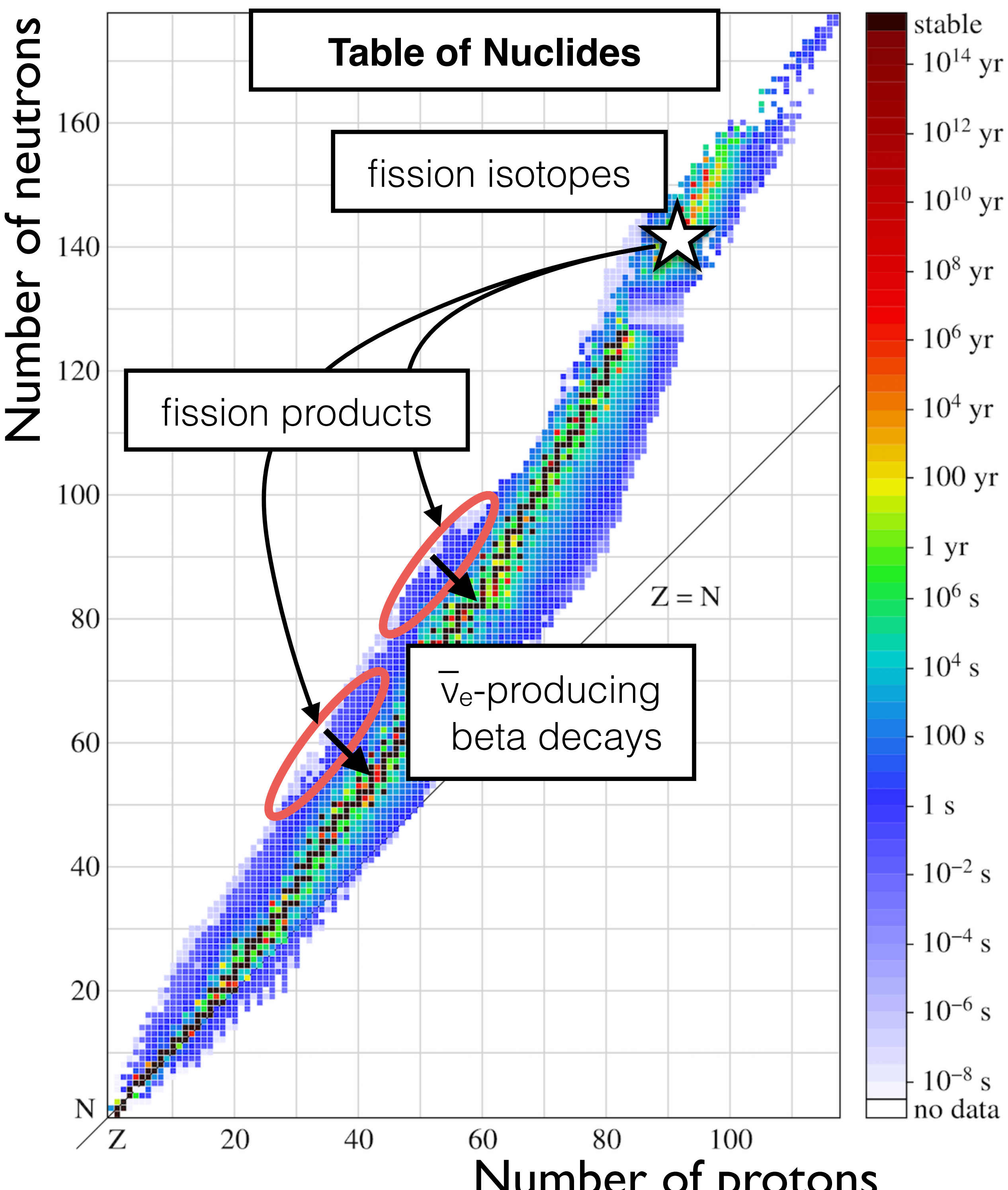
- When do weak decay limits come into existence?
  - KATRIN Current: 2021
  - KATRIN Completion: 2025
  - Project-8, Phase III (T2): 2030
  - Project-8, Phase III (T): 2033
  - Project-8, Phase IV: 2040

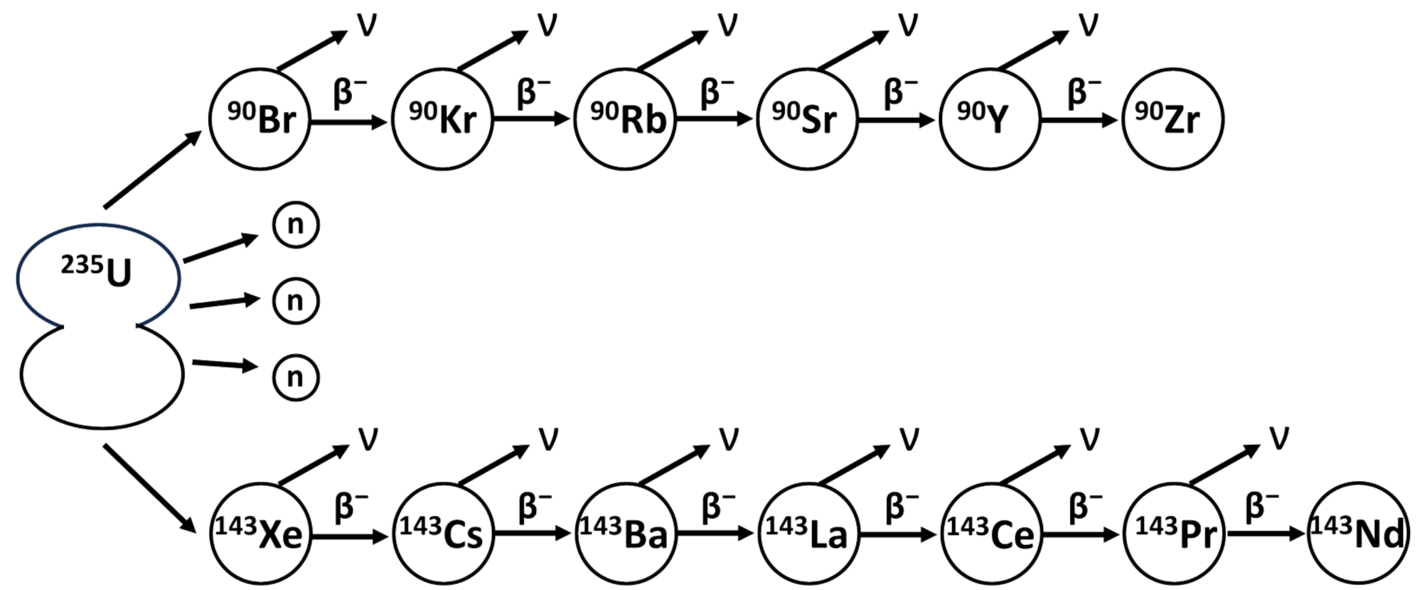




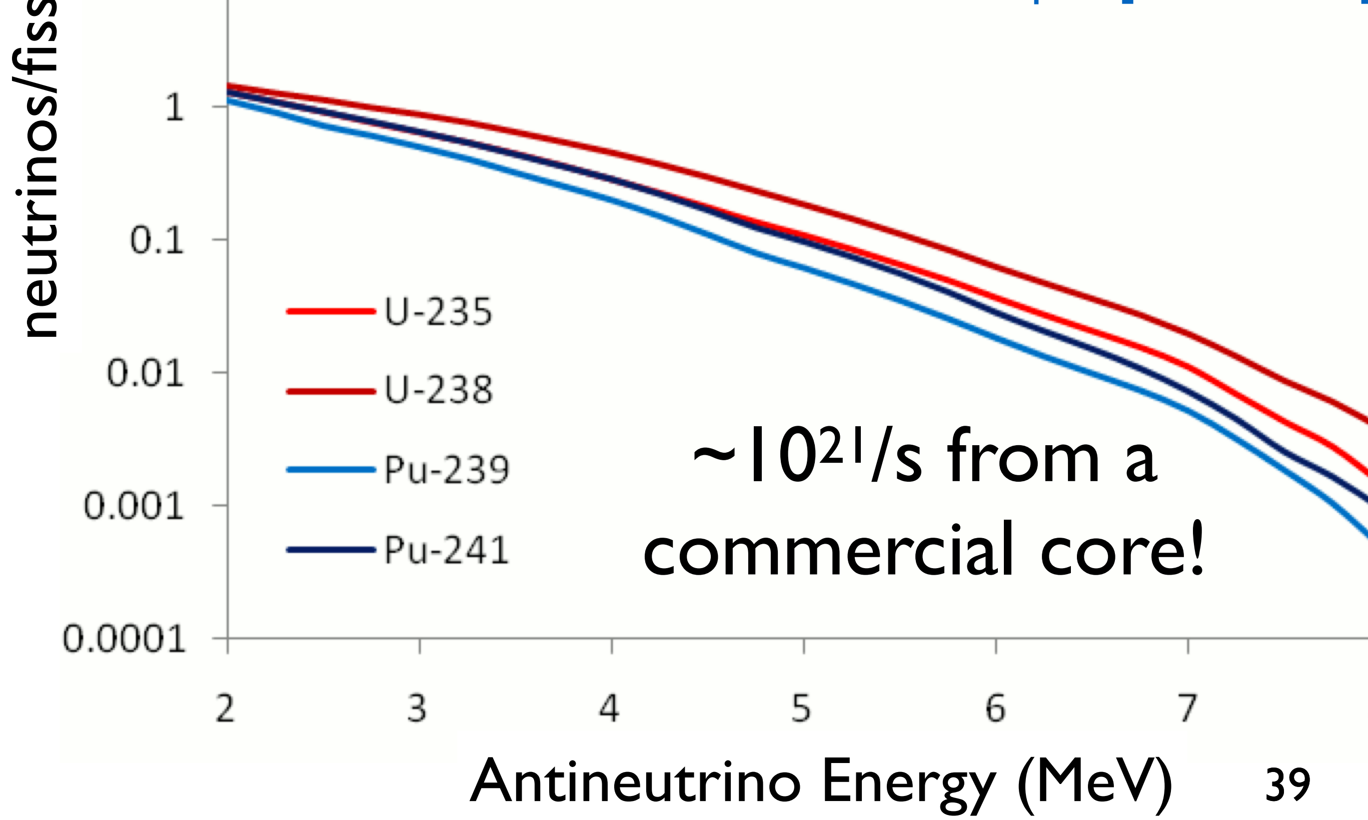
How Do Reactors Make Neutrinos?

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





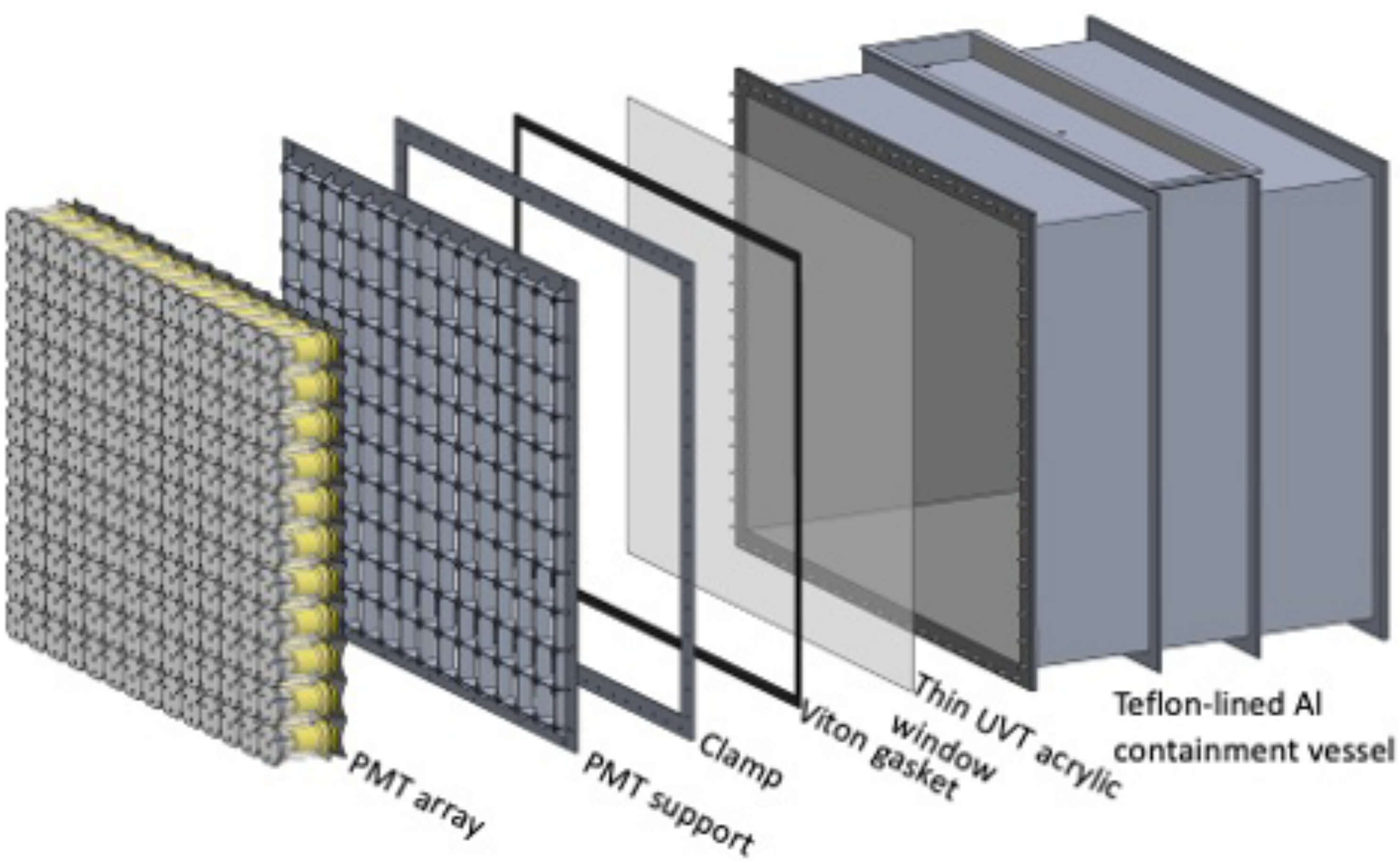
Zhang, Qian, Fallot, hep-ex[2310.13070]

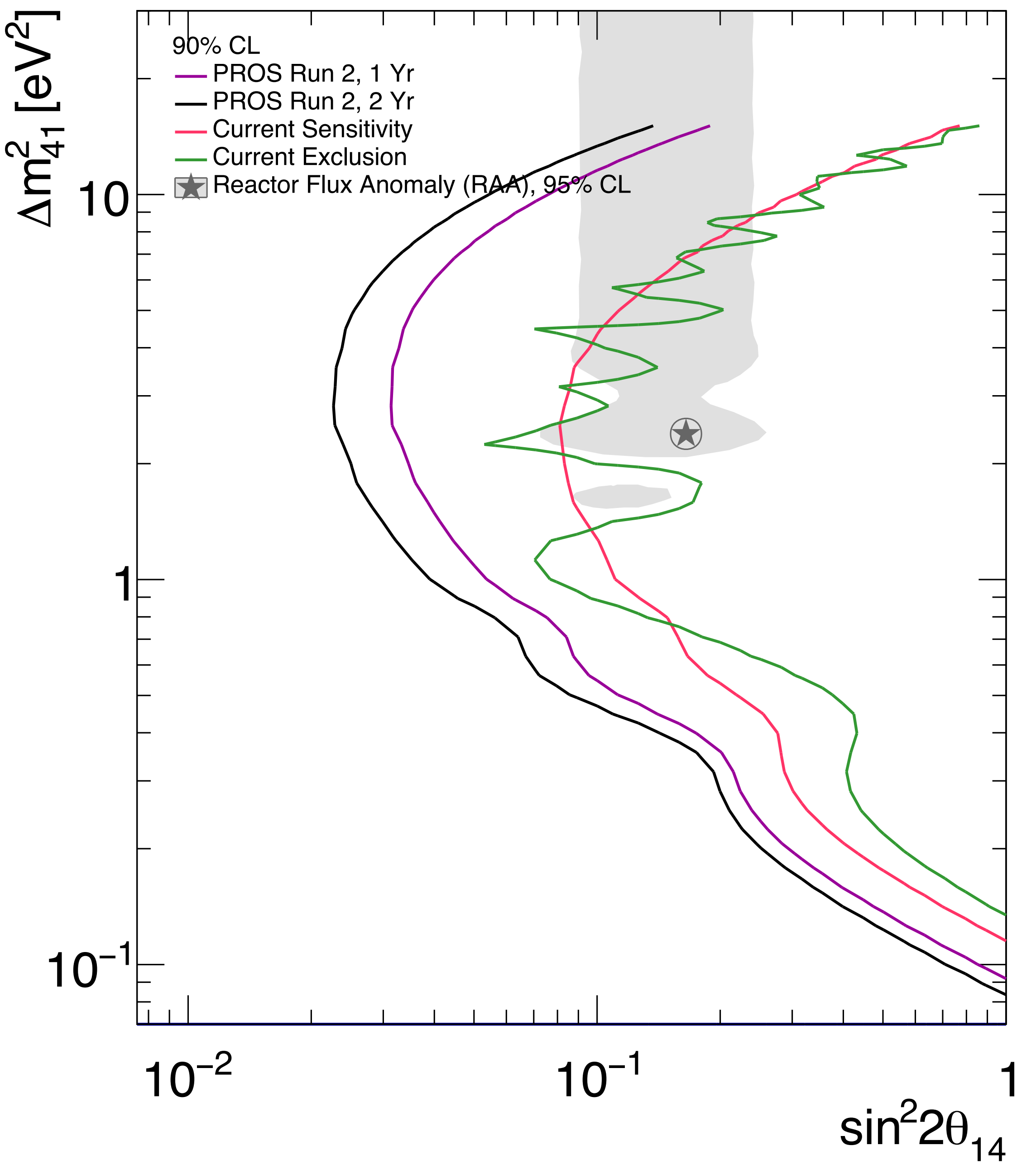


Next Steps: PROSPECT-II

- 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 and neutrino emissions by different reactor fuel components

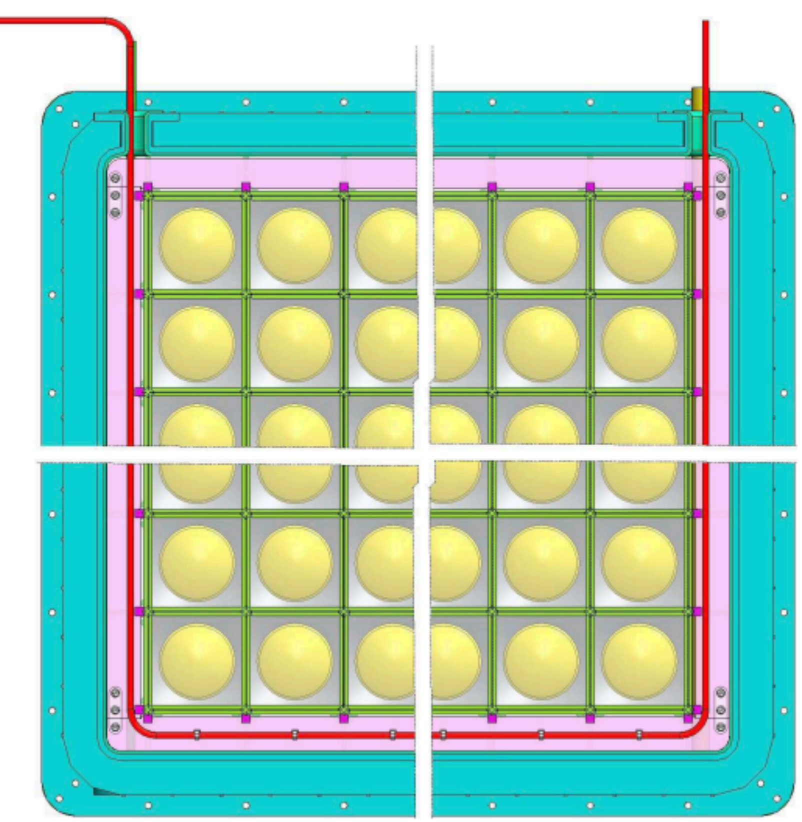
PROSPECT, J. Phys. G49 (2022)
PROSPECT, JINST P06010 (2023)
Fujikake, BRL, Rodrigues, Surukuchi, PRD 107 (2023)





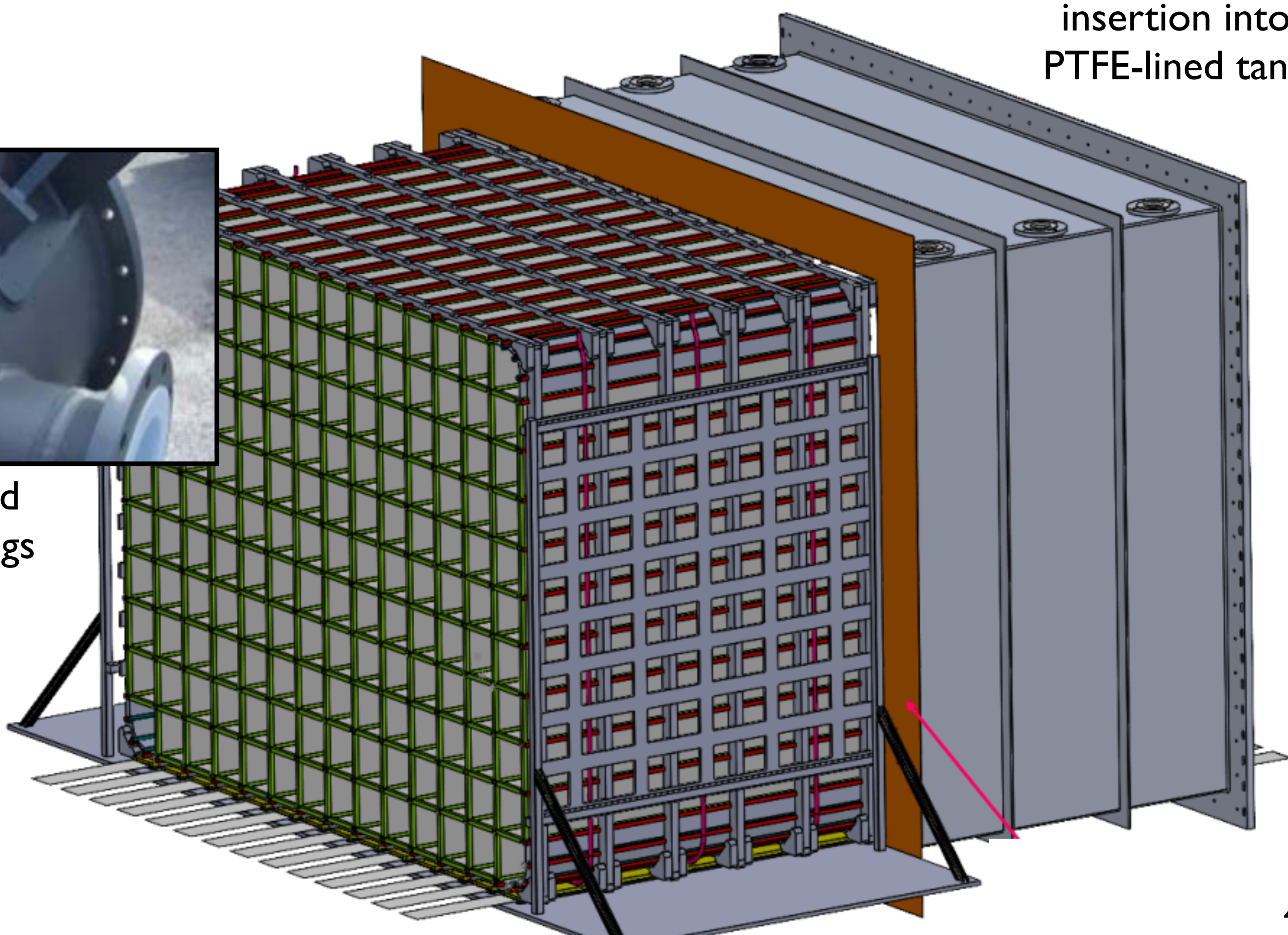
PROSPECT-II R&D Highlights

- 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

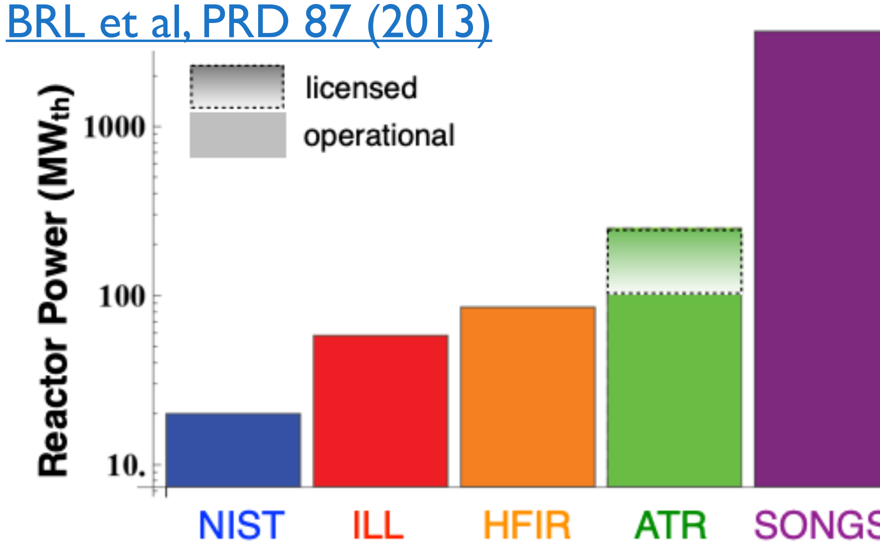


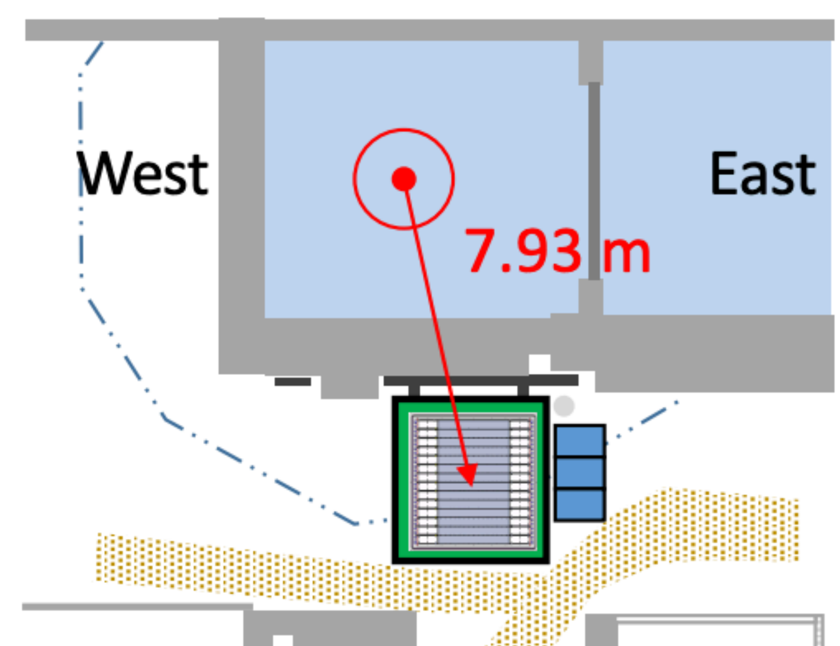
Optical grid insertion into PTFE-lined tank

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)

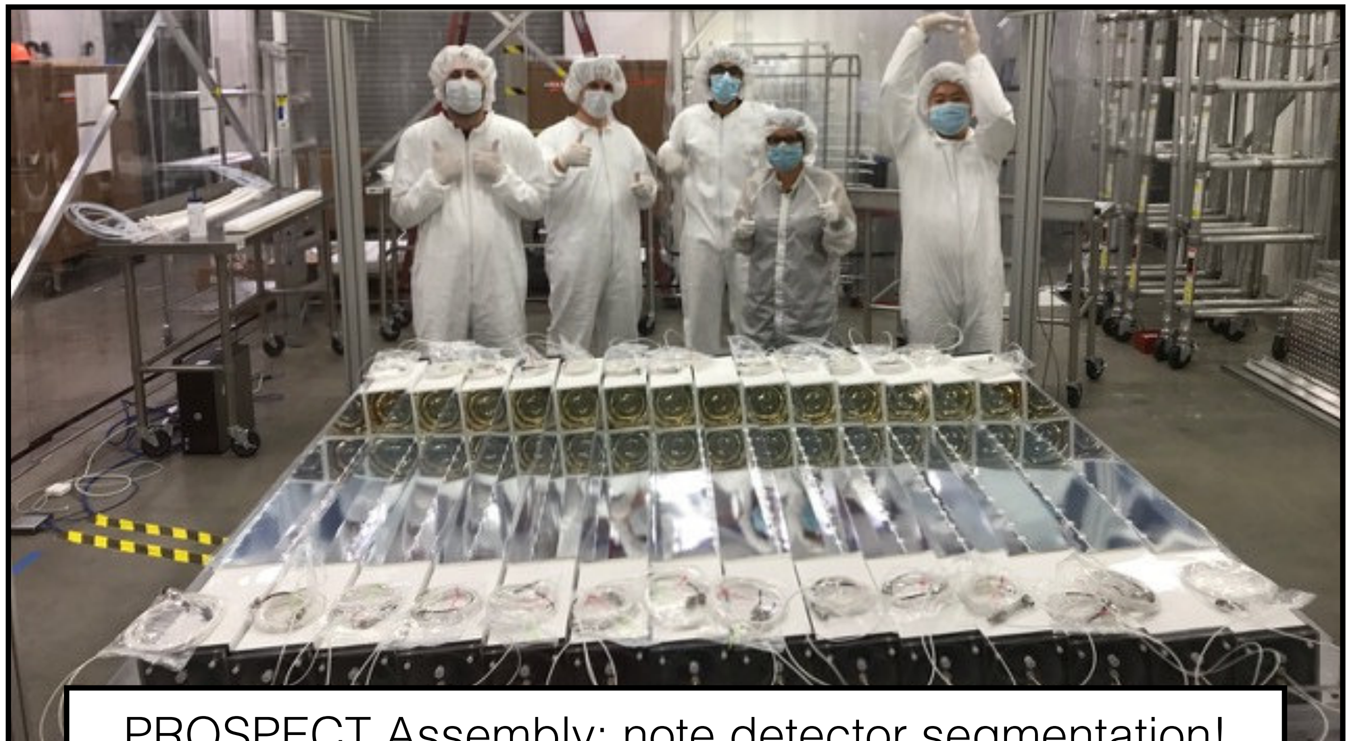




NIM A 922 (2018)

PROSPECT: Pretty Pictures

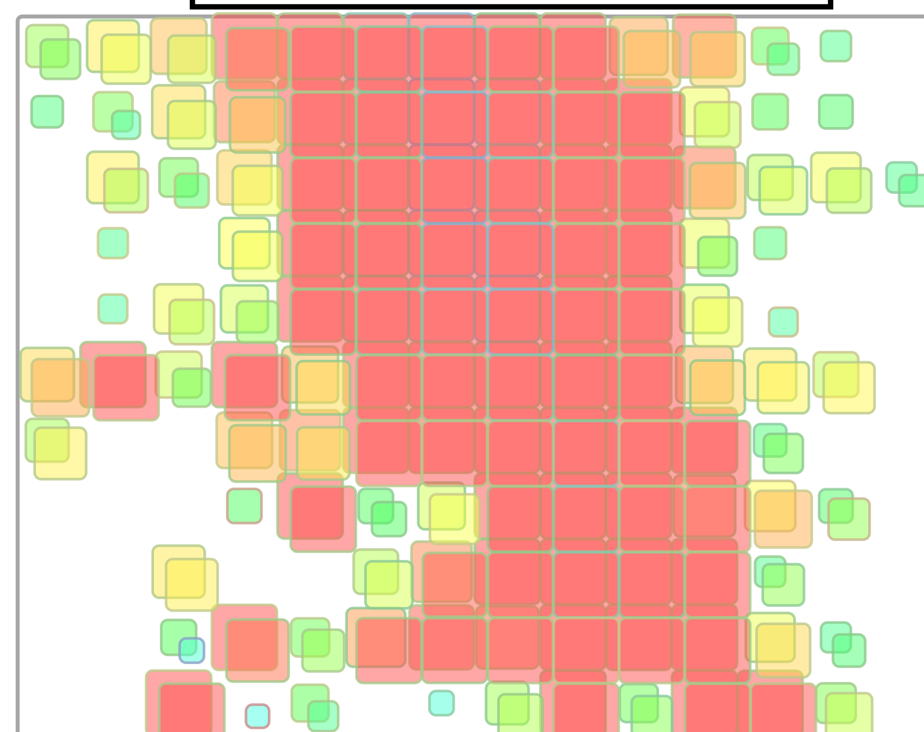
- Assembly start to first data @ HFIR by March 2018: <5 months!



PROSPECT Assembly: note detector segmentation!

PROSPECT arrival at ORNL

PROSPECT Installation: Rx on other side of the wall!

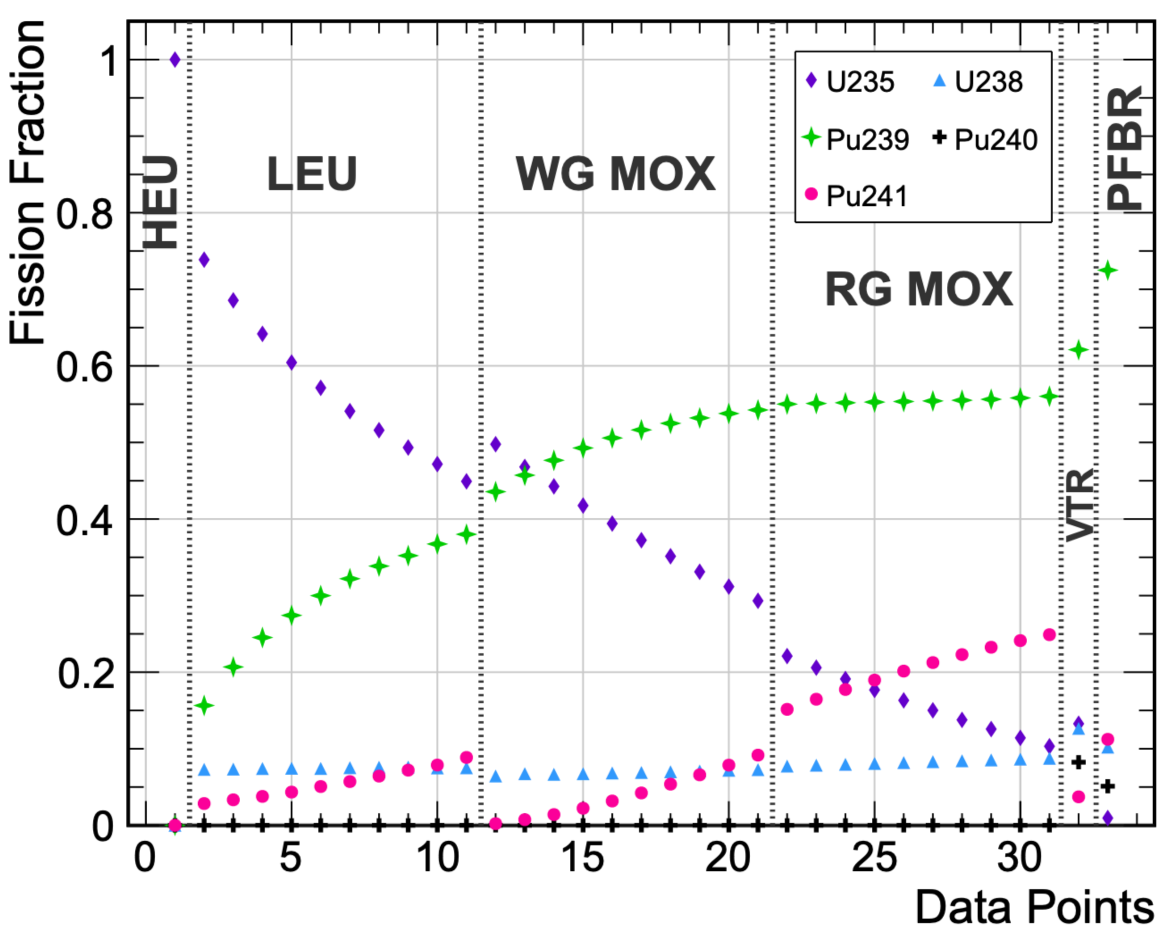


First fun event: cosmic hadronic shower!

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)!

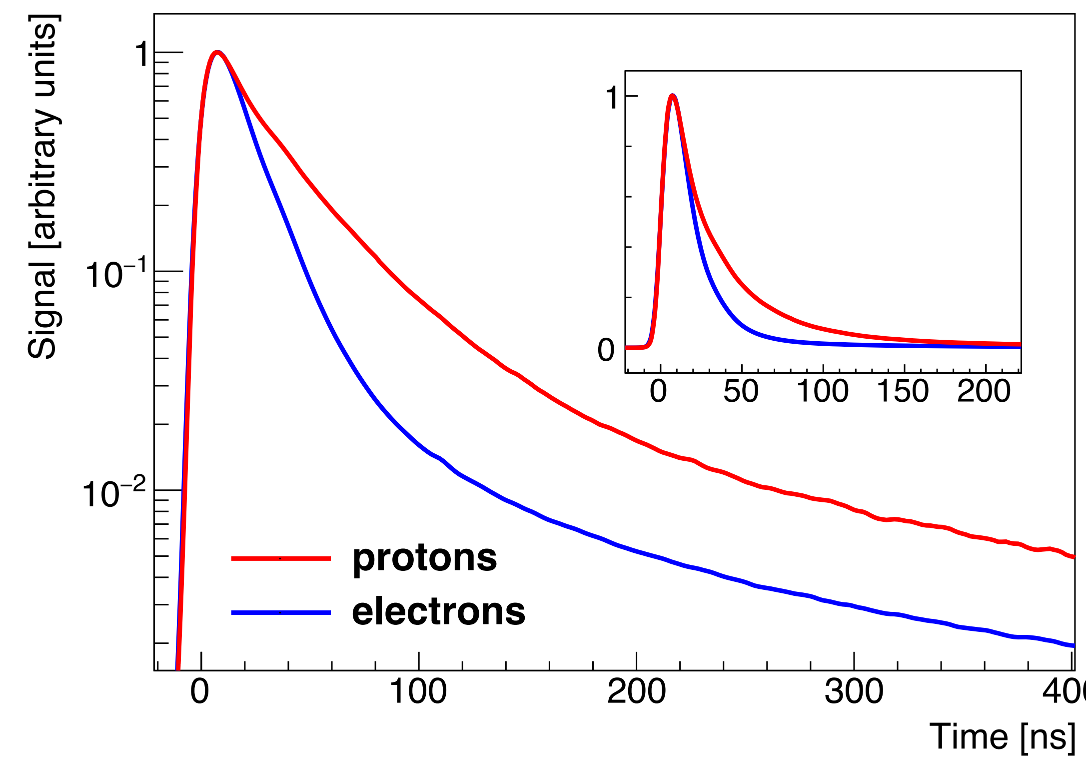
Fujikake, BRL, Rodrigues, Surukuchi, PRD 107 (2023)



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)