29 October, 2024

NNN24
Rio de Janeiro

ILLINOIS INSTITUTE OF TECHNOLOGY

PROSPECT-I final oscillation results and PROSPECT-II physics goals and detector design

arXiv: 2406.10408

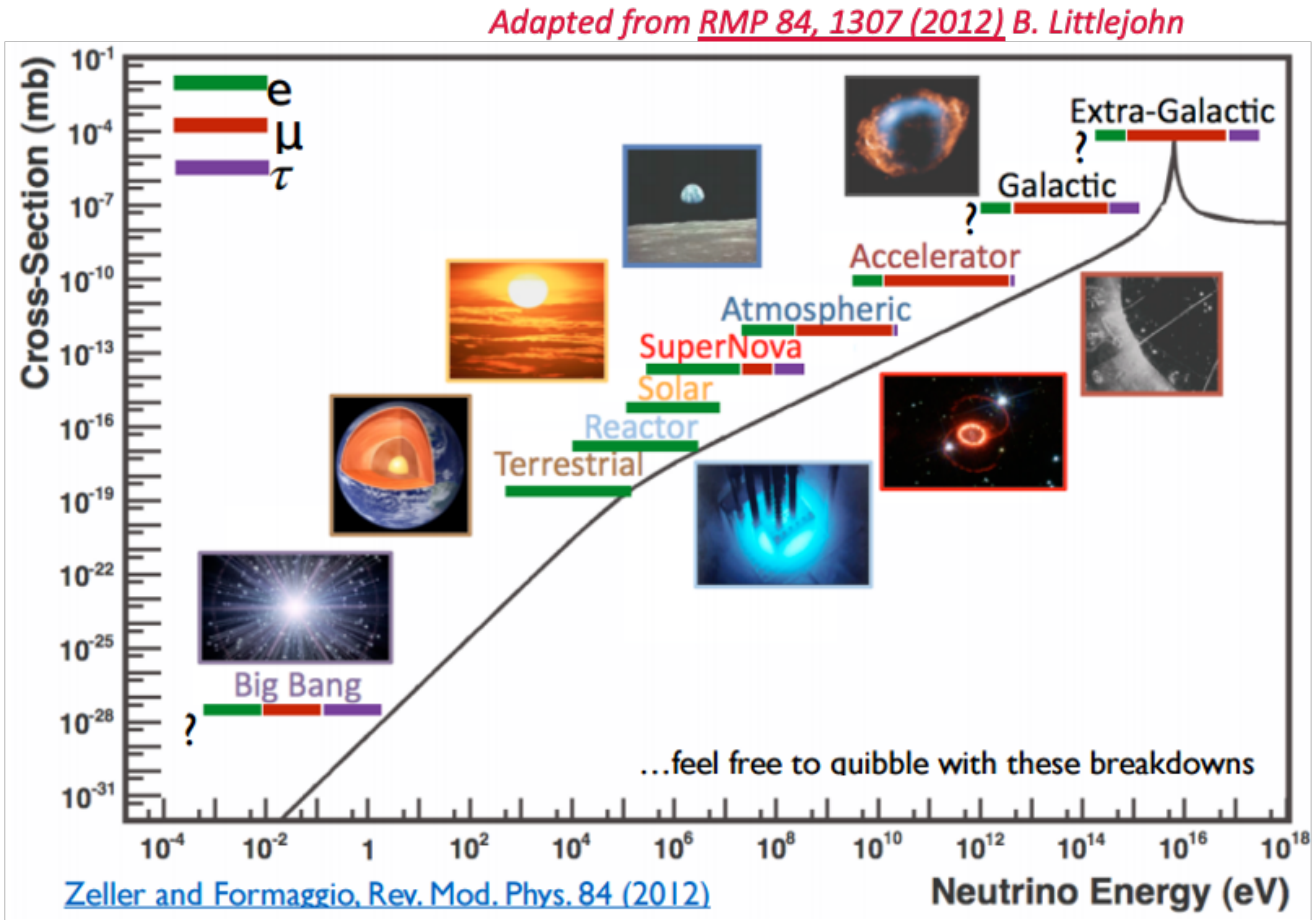
arXiv: 2107.03934

Ohana B. Rodrigues, on behalf of the PROSPECT Collaboration

obenevidesrodrigues@iit.edu

1 Neutrinos

- Neutrinos are produced multiple sources:
    - Natural (sun, supernovas, etc)
    - Man-made (accelerators, reactors, etc)



1 Neutrinos

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  - Natural (sun, supernovas, etc)
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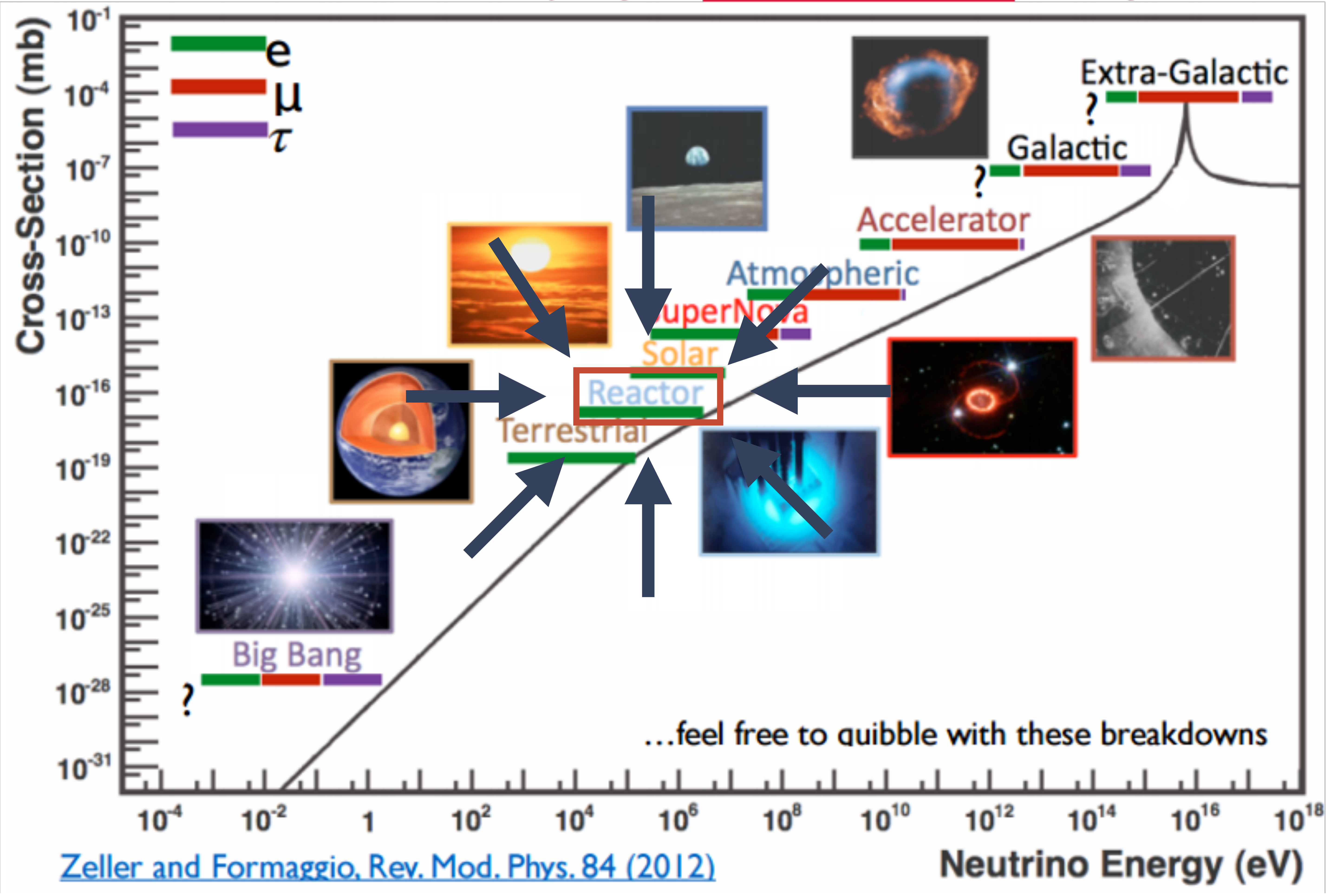
- Reactor neutrinos:

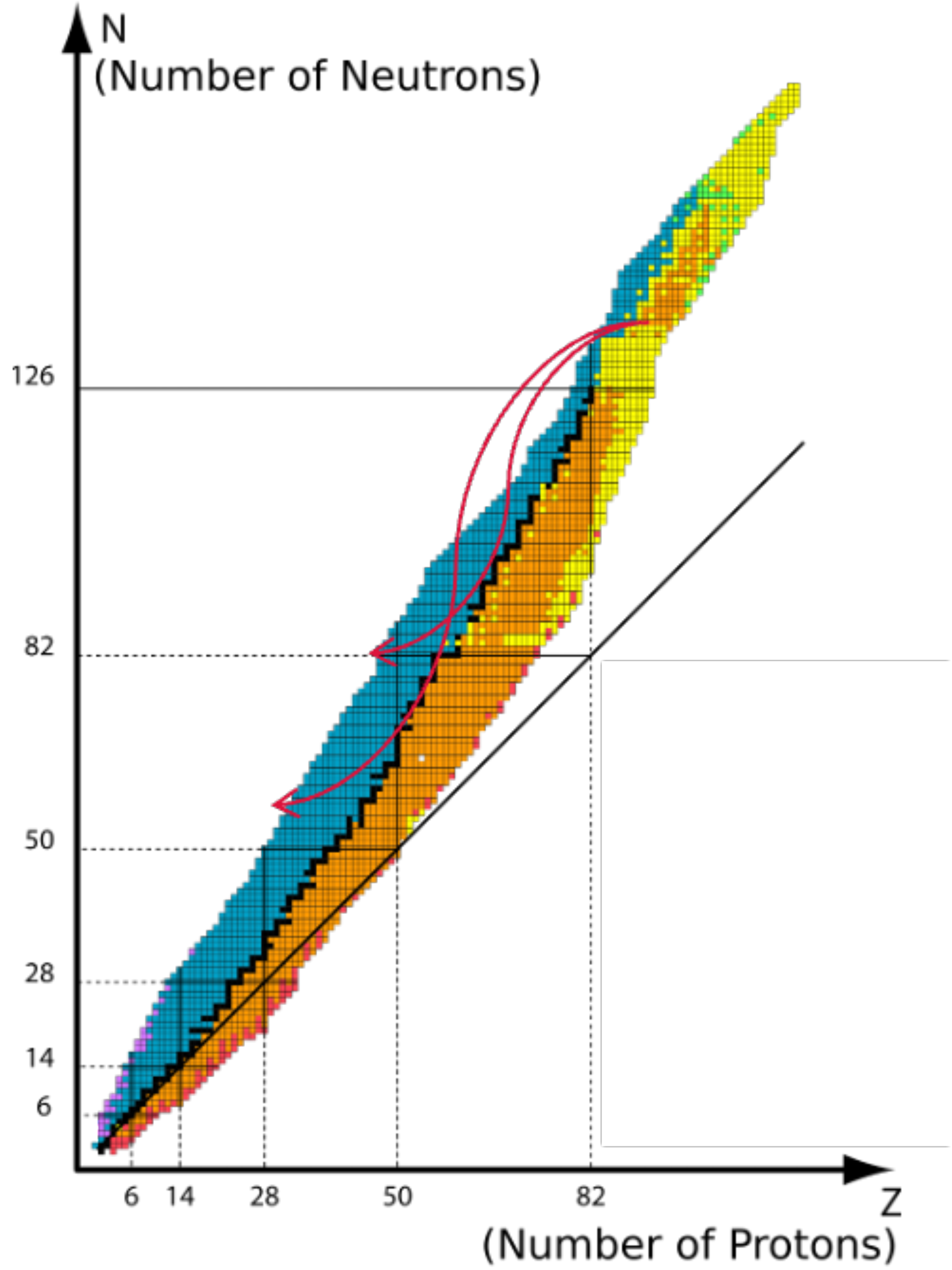
  - MeV regime.
  - electron only antineutrinos.

Adapted from RMP 84, 1307 (2012) B. Littlejohn



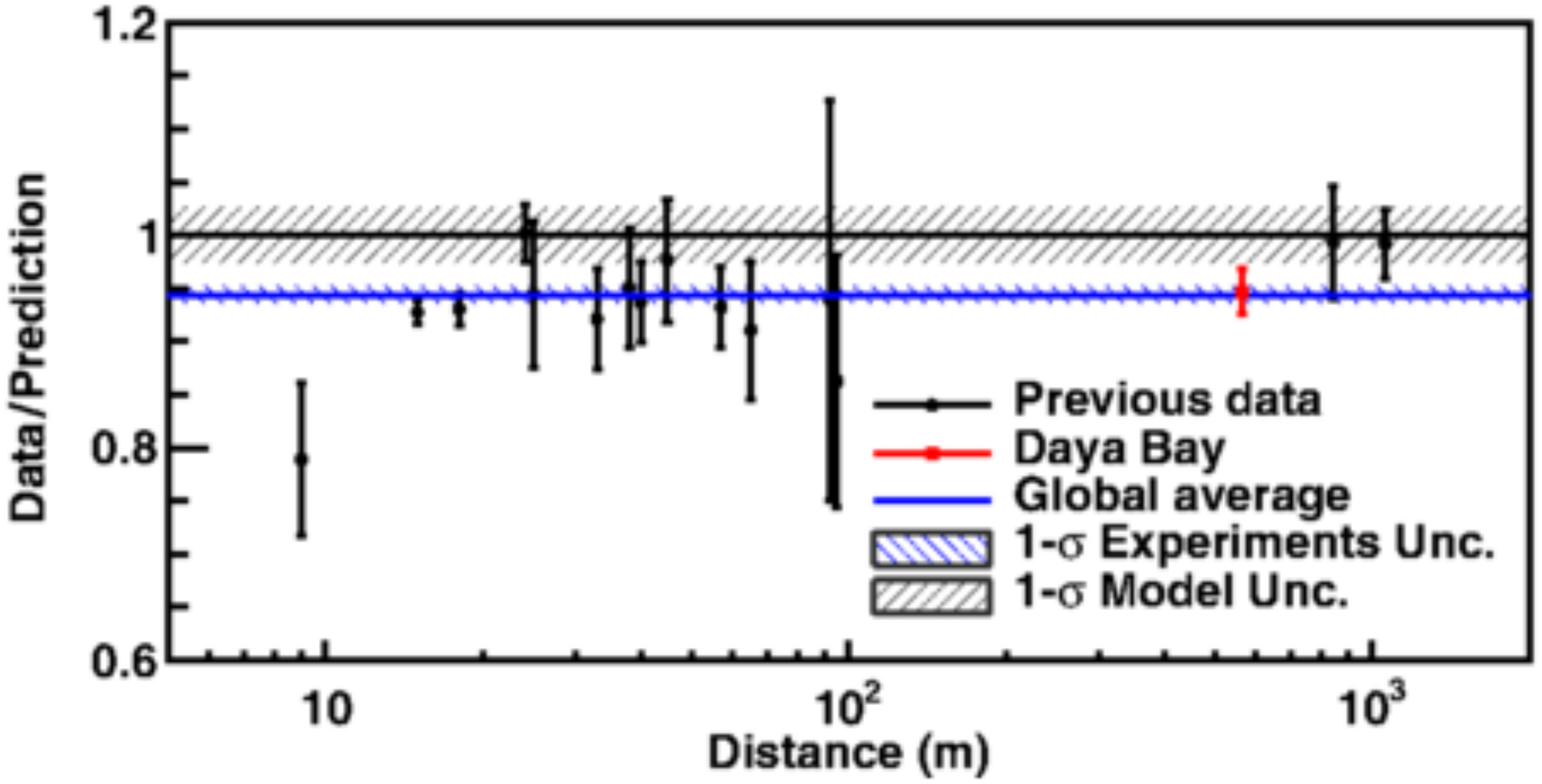
1 Reactor Antineutrinos

- Fission isotopes are bombarded with neutrons, producing neutron-rich daughters:
  - Unstable nuclei beta decay
  - ~6 antineutrinos/fission
- 99% of antineutrinos in nuclear reactor are produced by fissions in $^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu$
  - Highly-Enriched Uranium (HEU) only burns ^{235}U
  - Low-Enriched Uranium (LEU) is a mixture of isotopes.



2 Reactor Antineutrino Anomaly

- When comparing the antineutrino flux data and the predictions (from Huber-Mueller model) differ

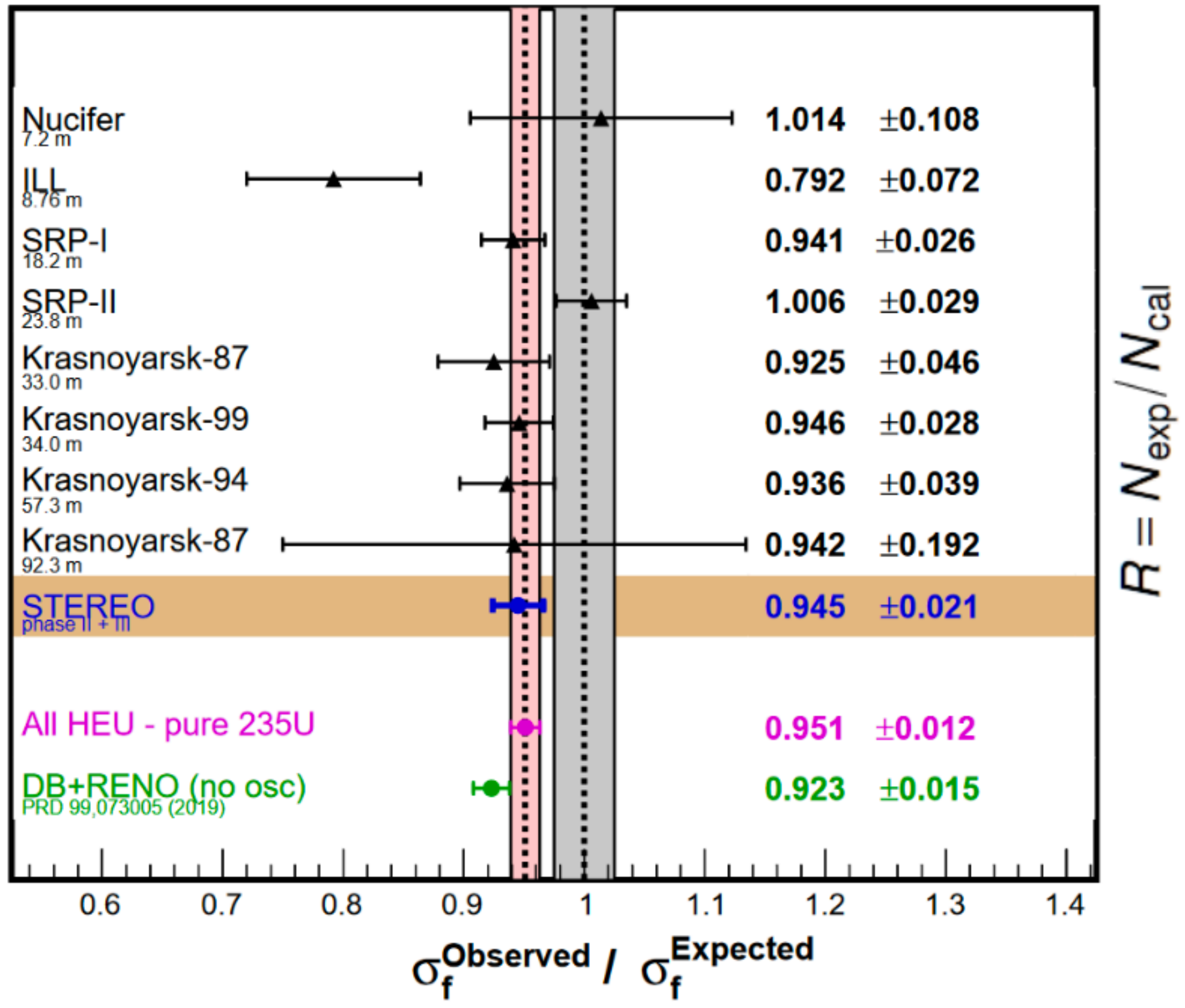


PRL 116.061801 (2016)

2 Short Baseline Anomalies

Reactor Antineutrino Anomaly

Nature 613, 257-261 (2023)



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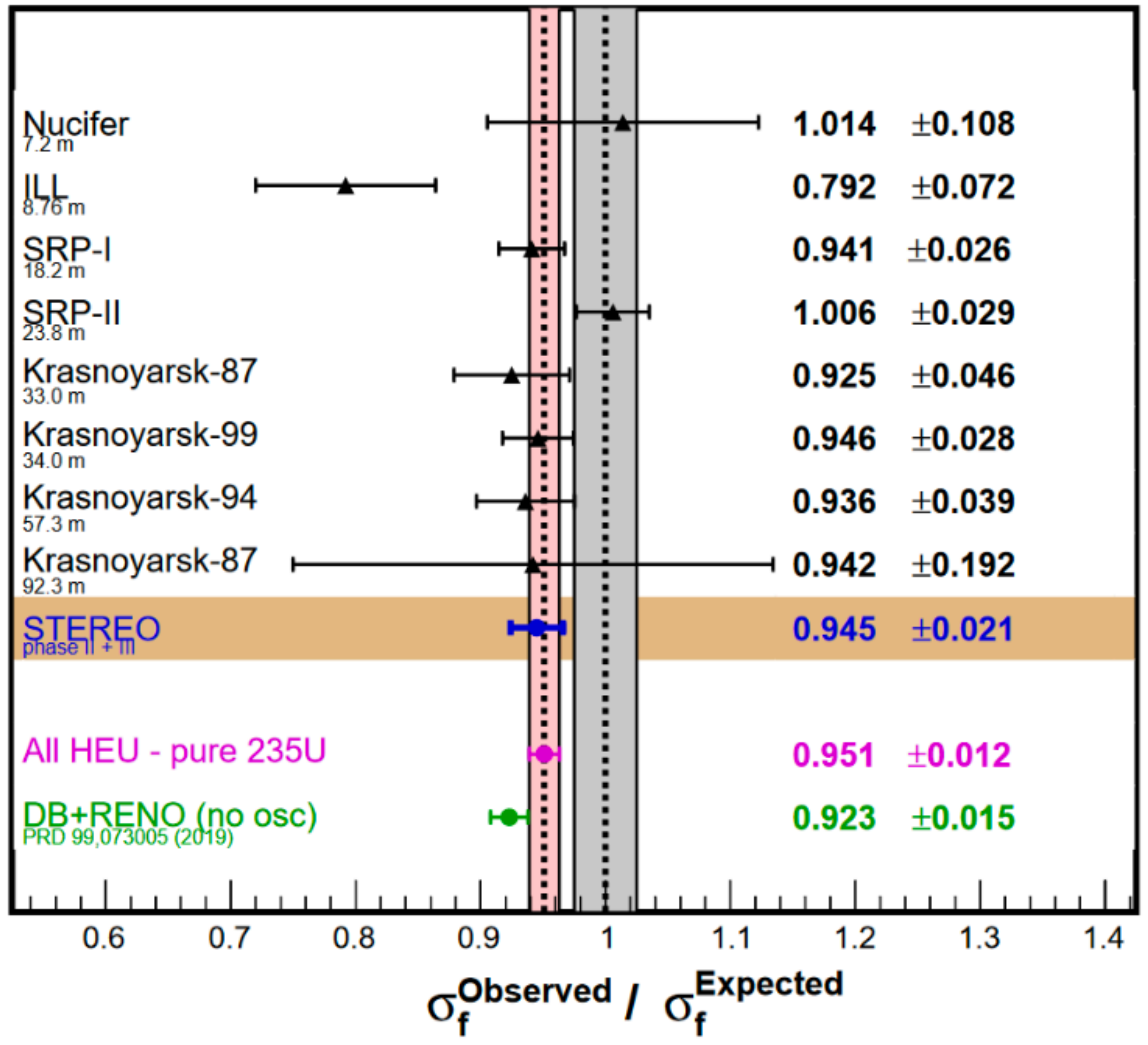
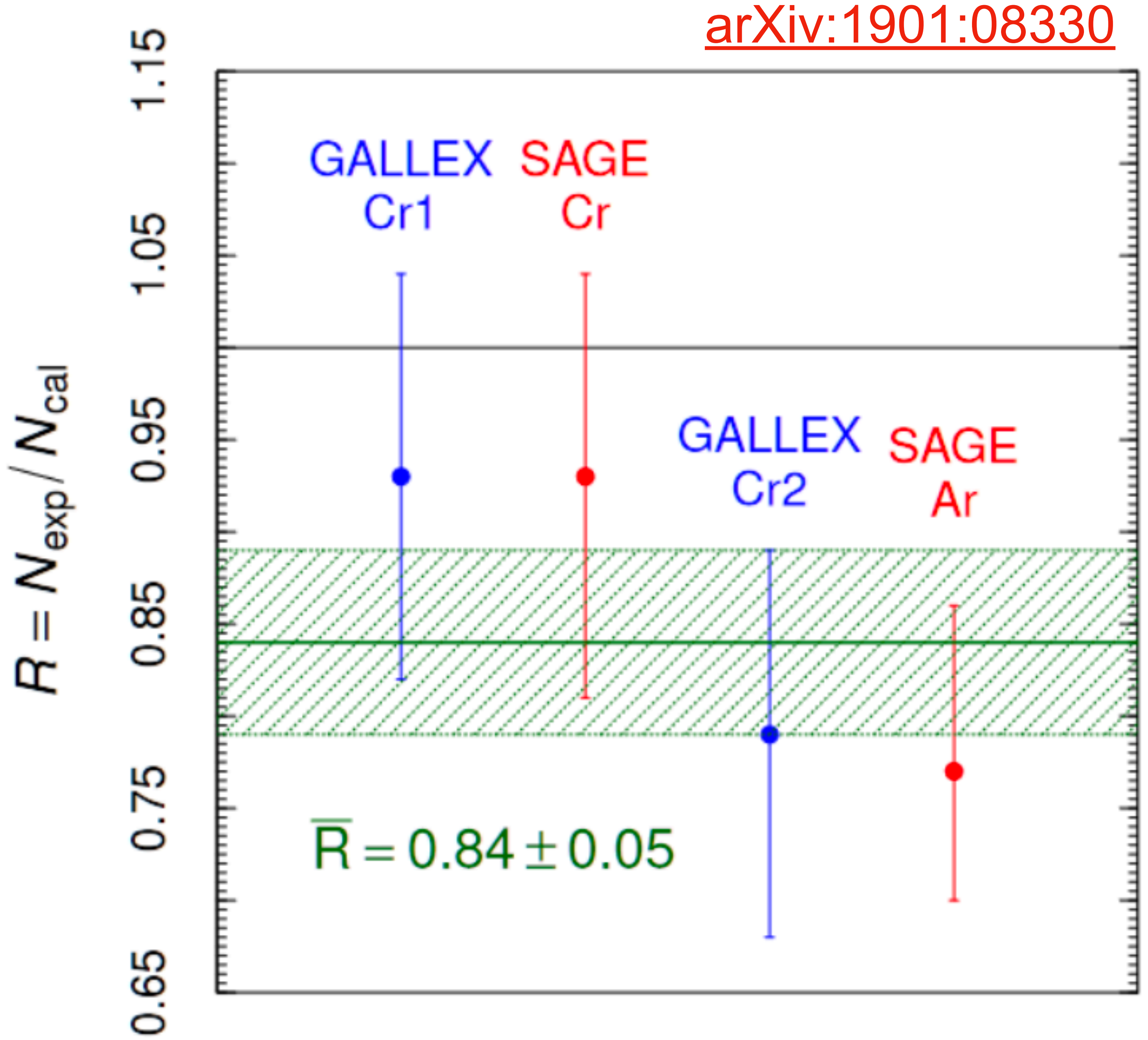


Gallium Anomaly

arXiv:1901:08330



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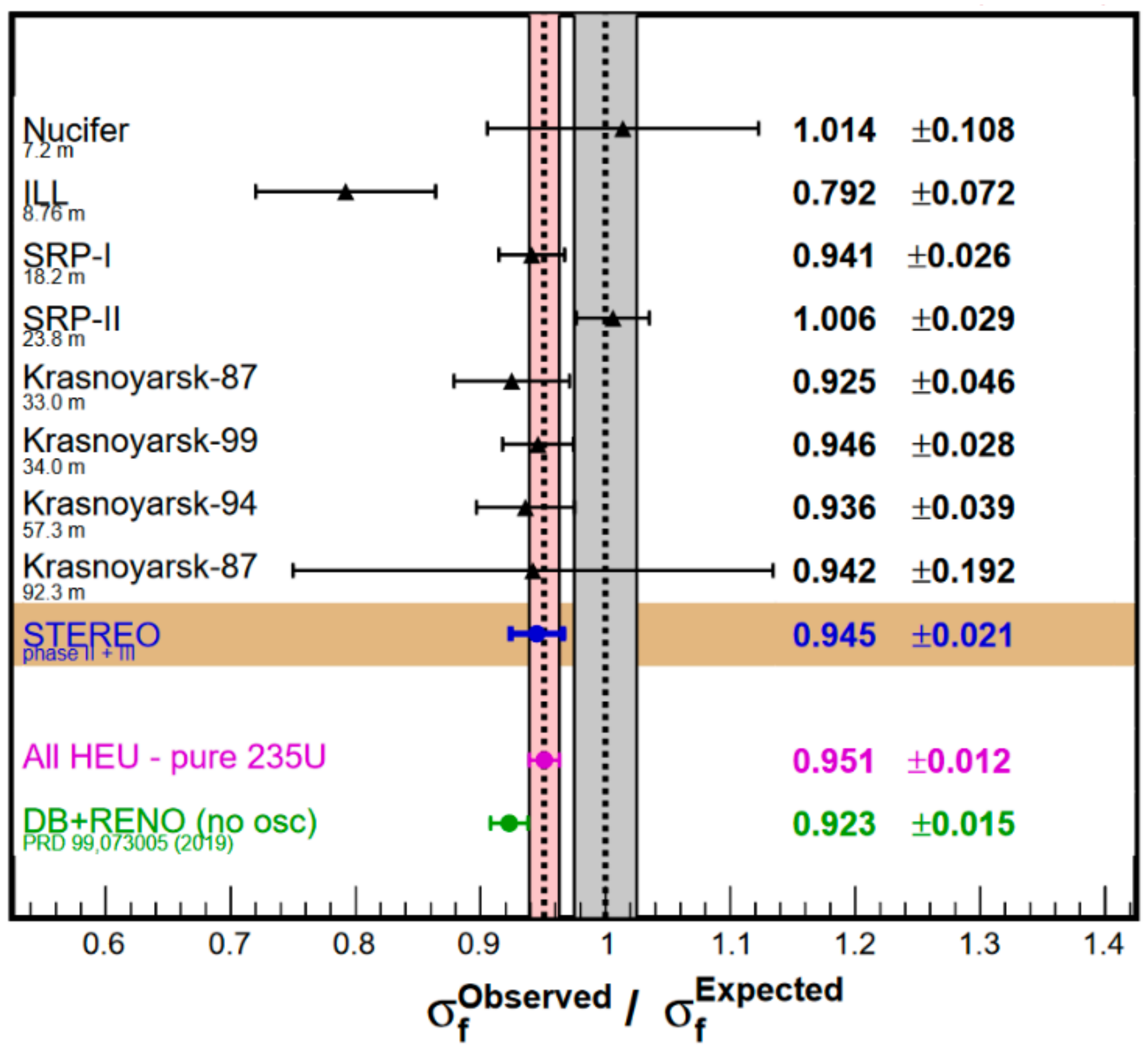

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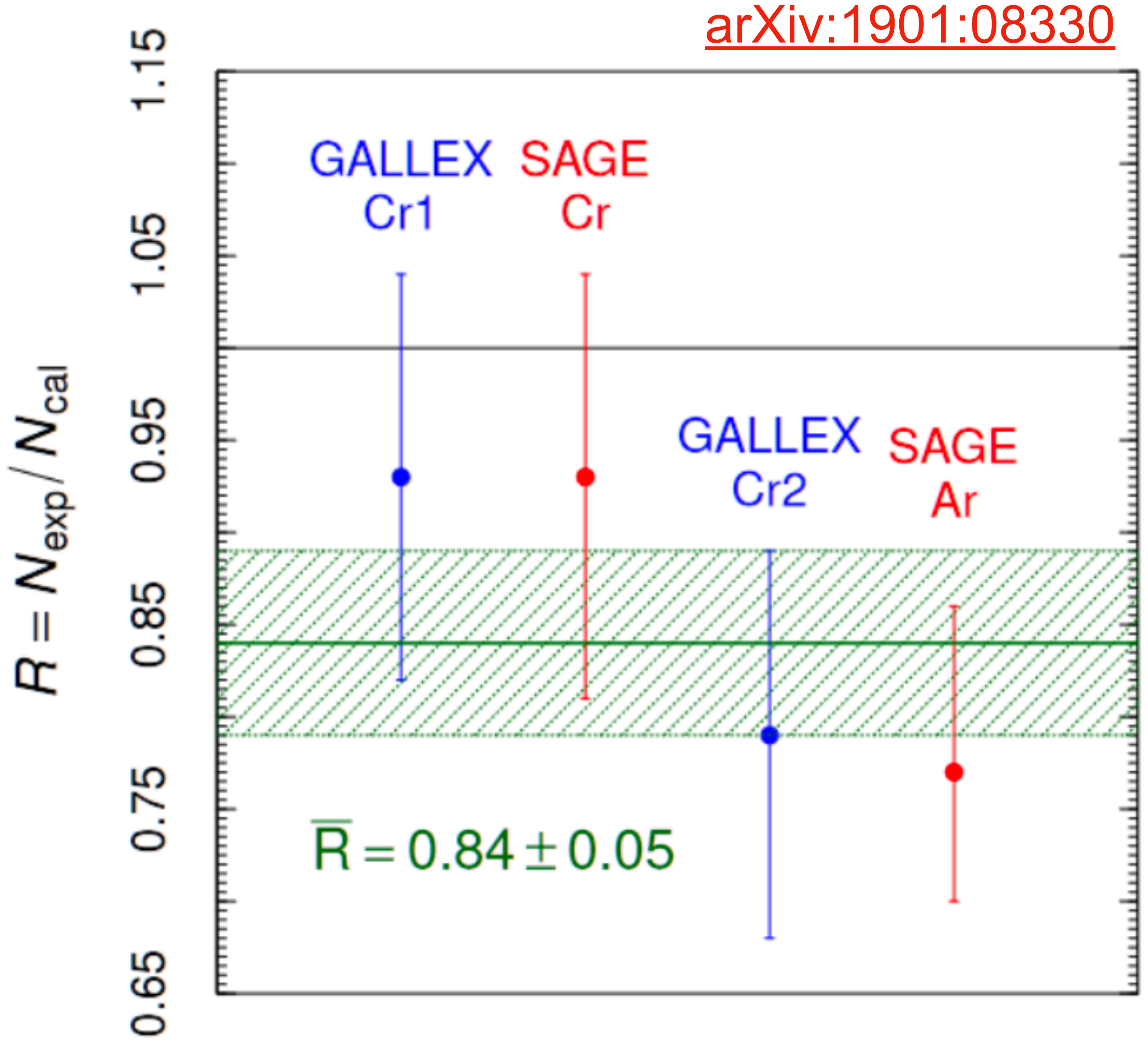
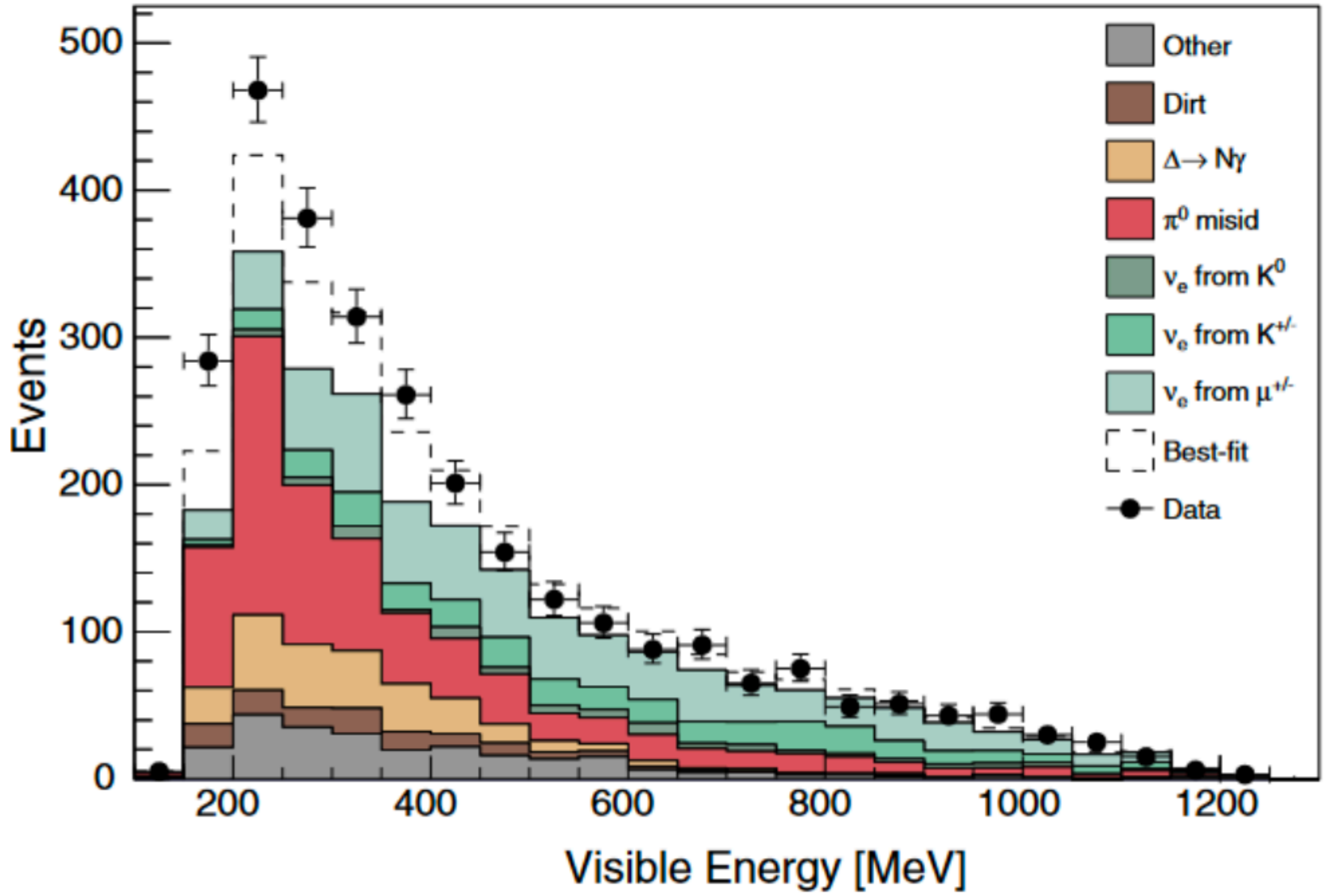


LSND/MiniBooNE Anomaly

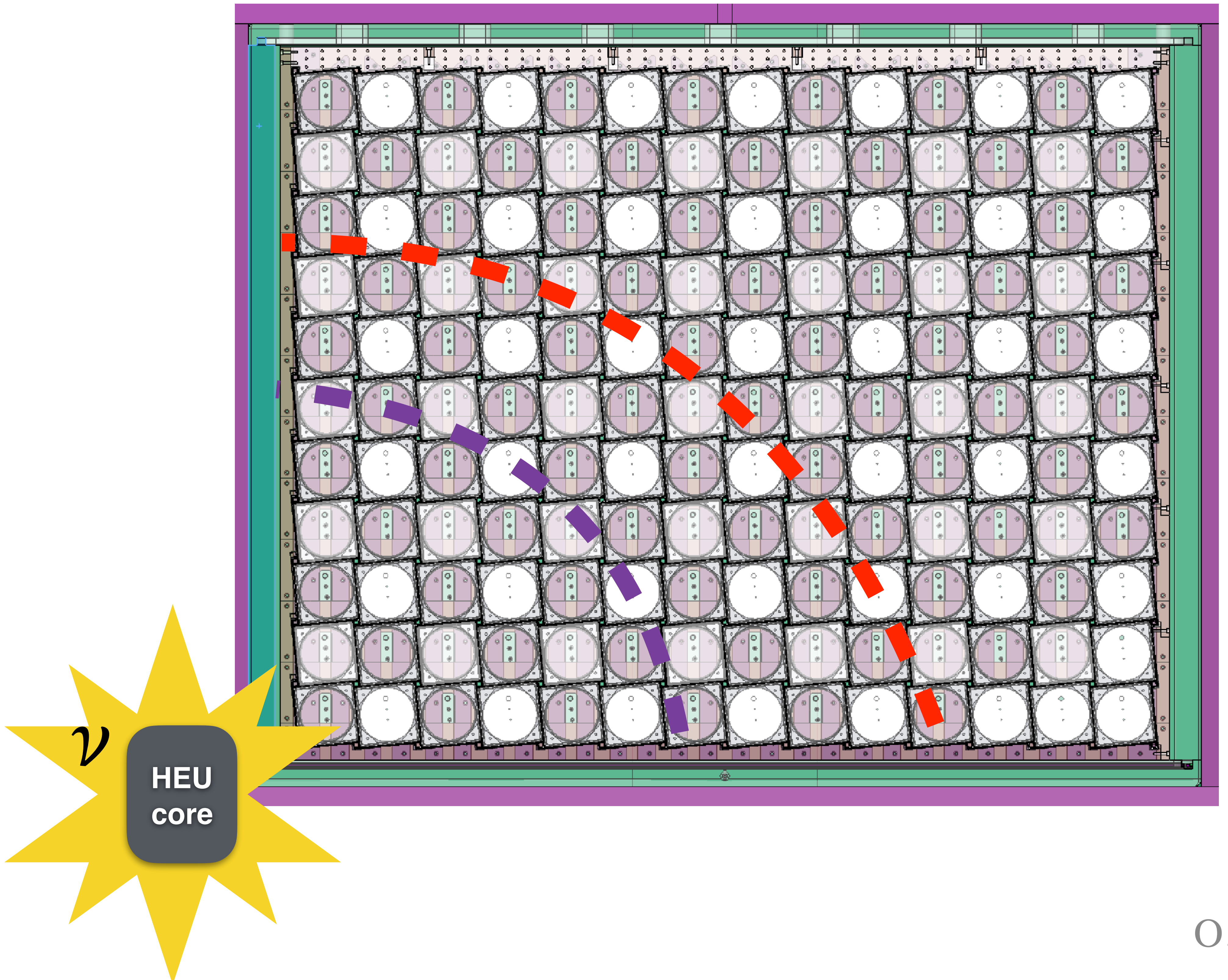
PRD 103, 052002 (2021)

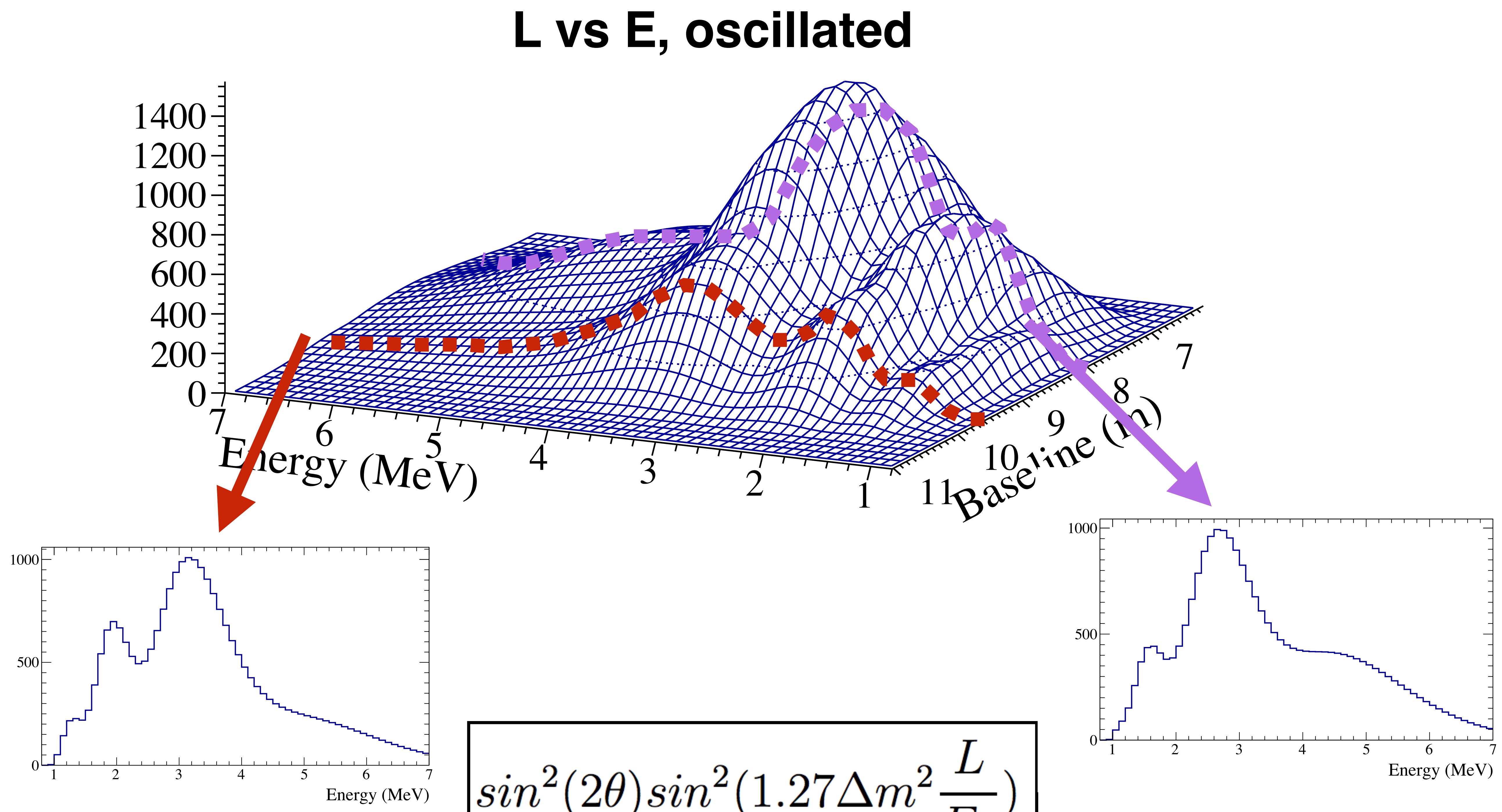


Could the explanation be sterile neutrinos?

2 Flux-Independent Reactor Oscillation Search

- 2 explanations:
  - Flux miss-prediction
  - Sterile antineutrinos
- Search for baseline-dependent energy spectrum distortion inside a stationary, segmented, short-baseline detector





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

2 Flux-Independent Reactor Oscillation Search

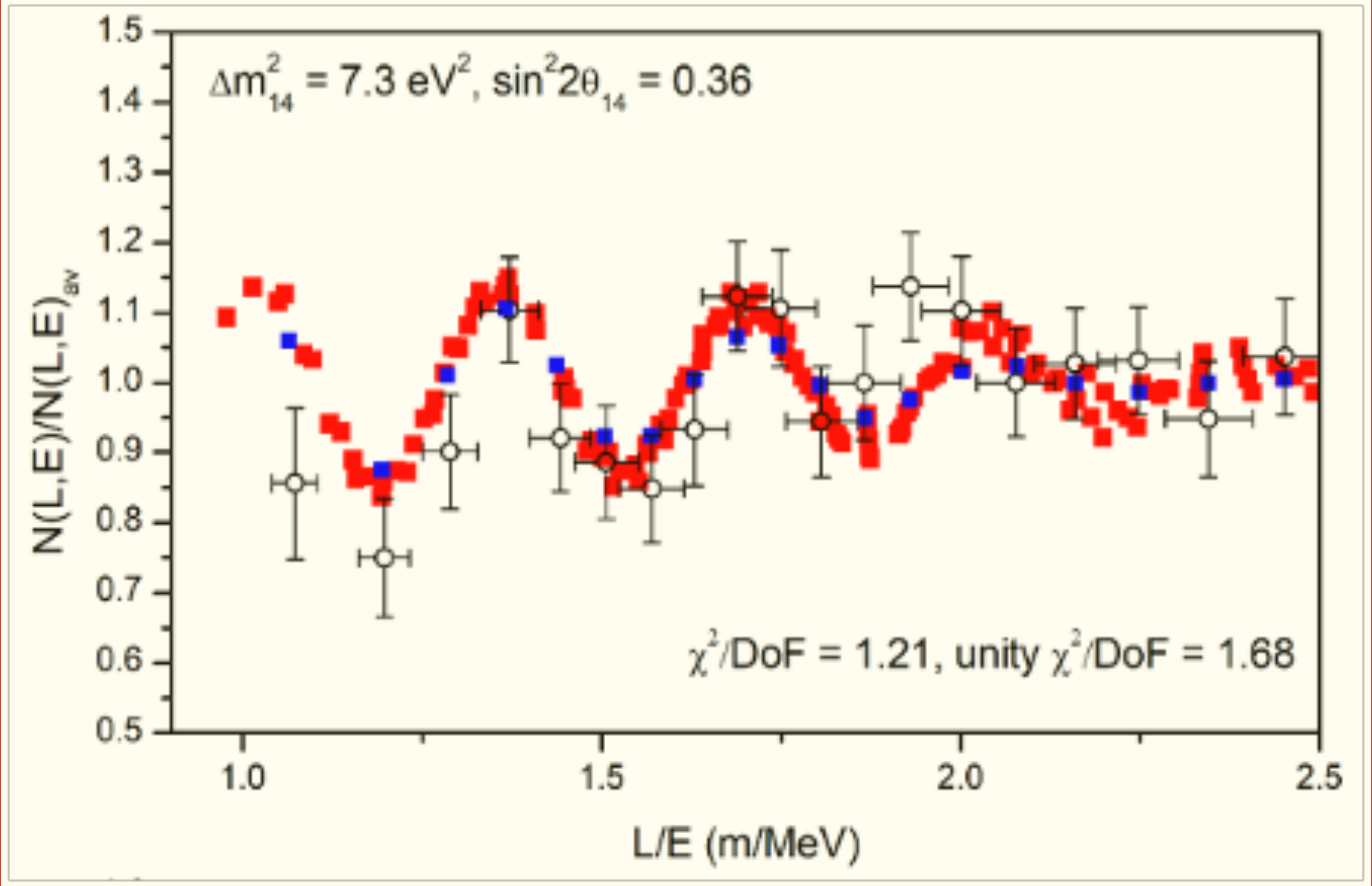
So far nothing has been seen yet at existing experiments PROSPECT, STEREO, NEOS and DANSS.

2 Status of the Sterile Neutrino Hypothesis at SBL

The Neutrino-4 claimed to had seen non-zero oscillation $(Sin^2 2\theta_{14}, \Delta m^2_{14}) = (0.36, 7.3)$, with ~2.9σ

Reactor Antineutrino Anomaly

PRD 104, 032003 (2021)



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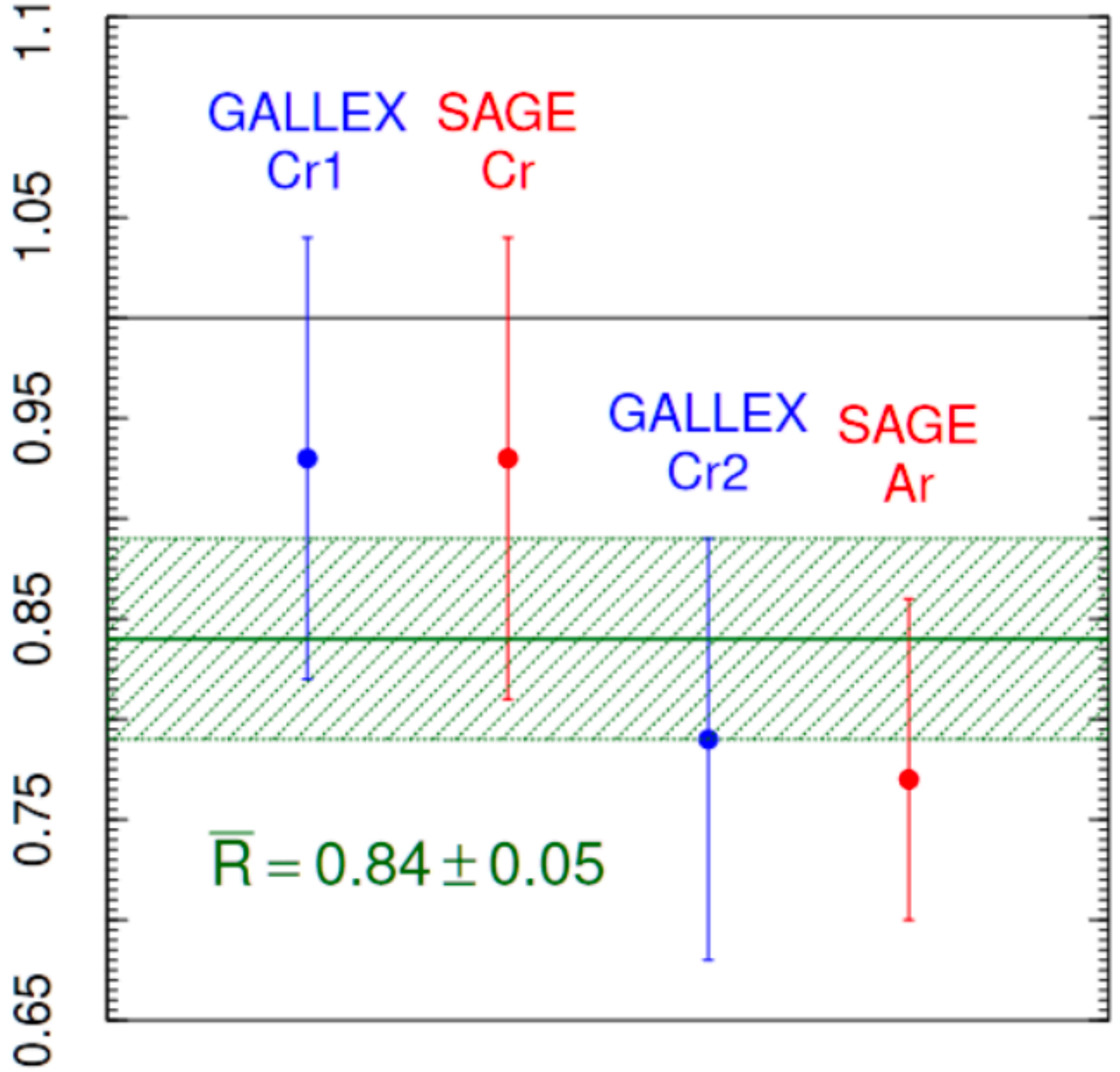
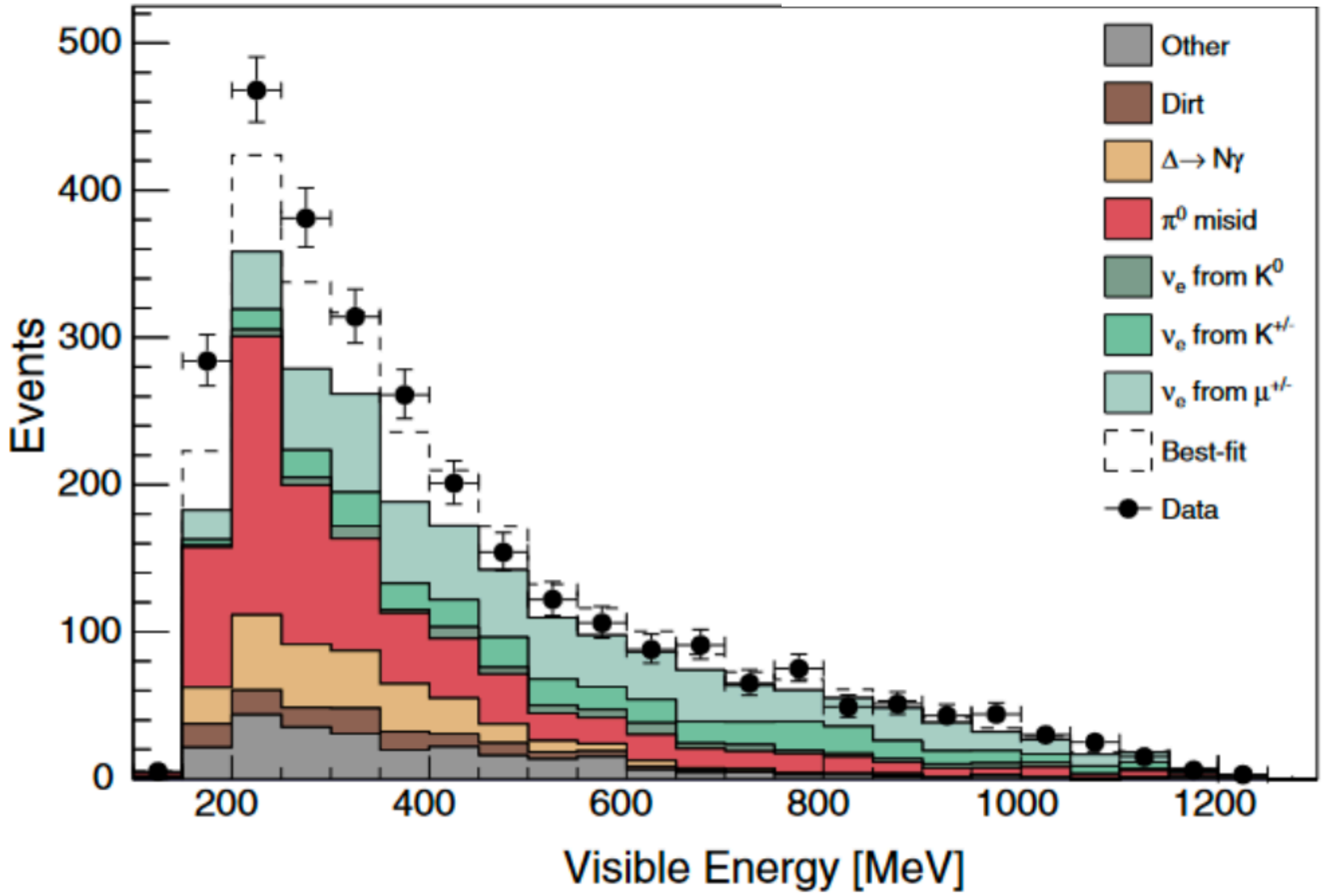


Electron-flavor disappearance ?

LSND/MiniBooNE Anomaly

PRD 103, 052002 (2021)



Electron-flavor appearance ?

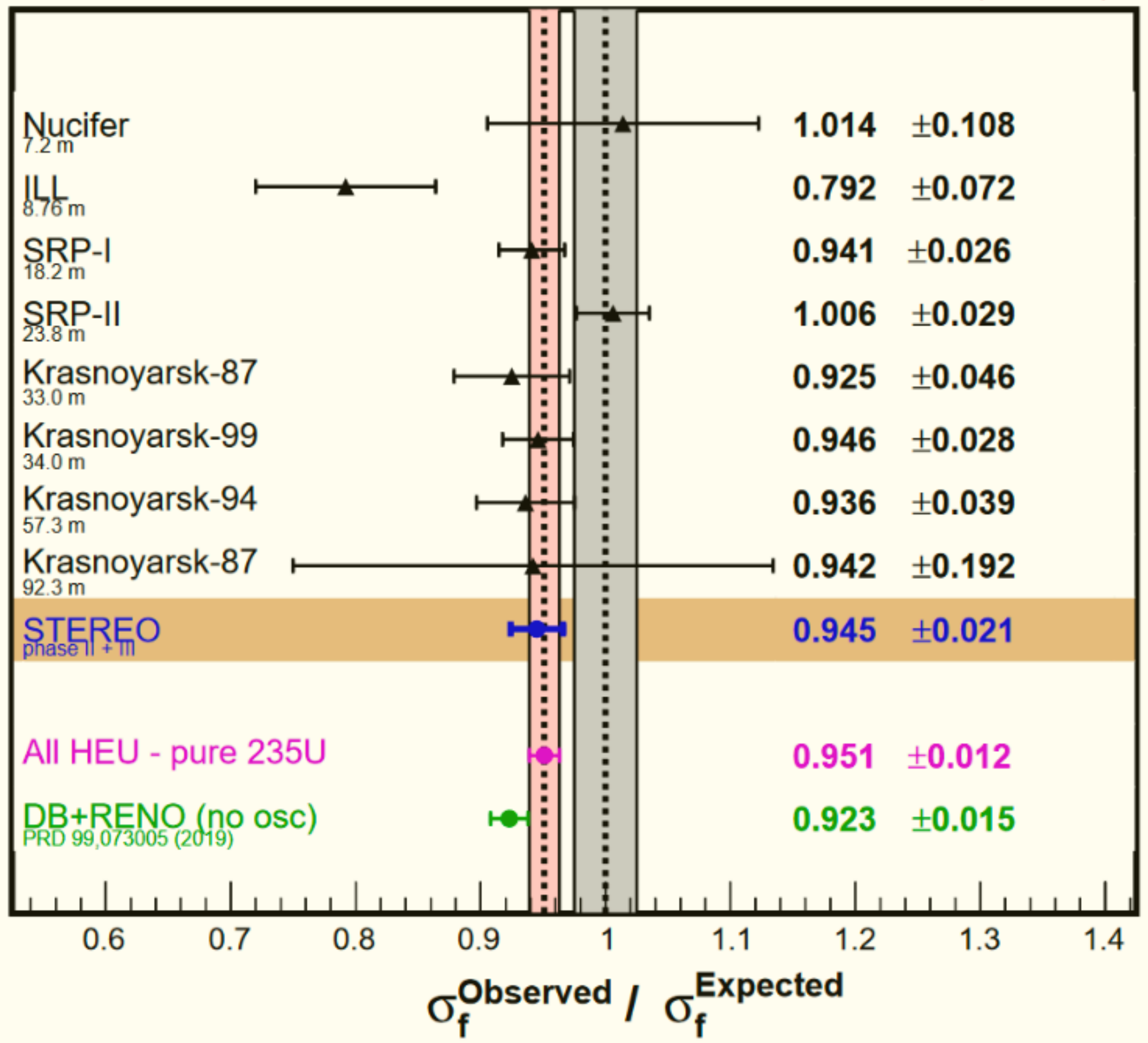
There is a lot of controversy about the legitimacy of those results

2 Status of the Sterile Neutrino Hypothesis at SBL

Reactor Antineutrinos Anomalies are fading away…

Reactor Antineutrino Anomaly

Nature 613, 257-261 (2023)



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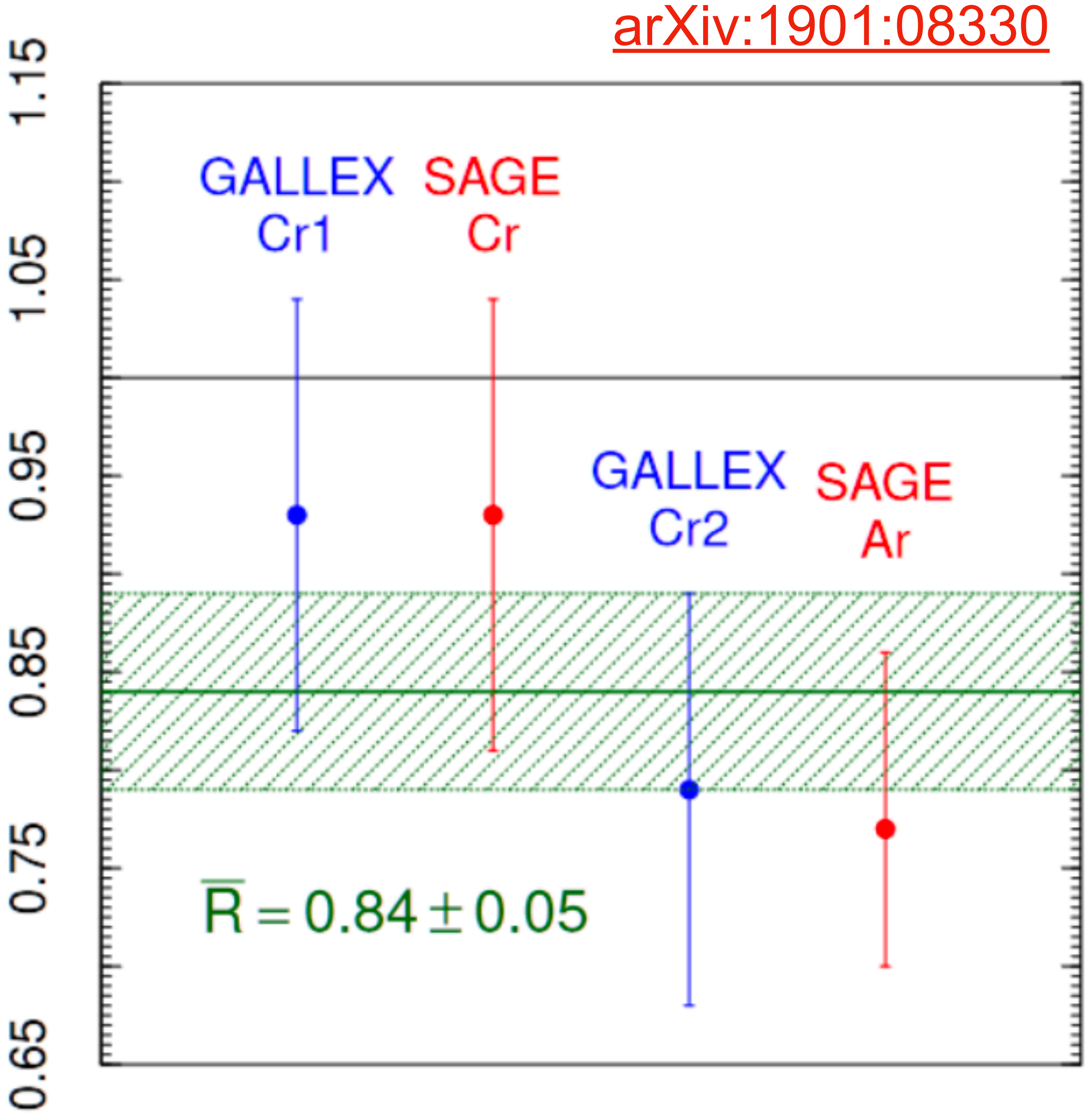

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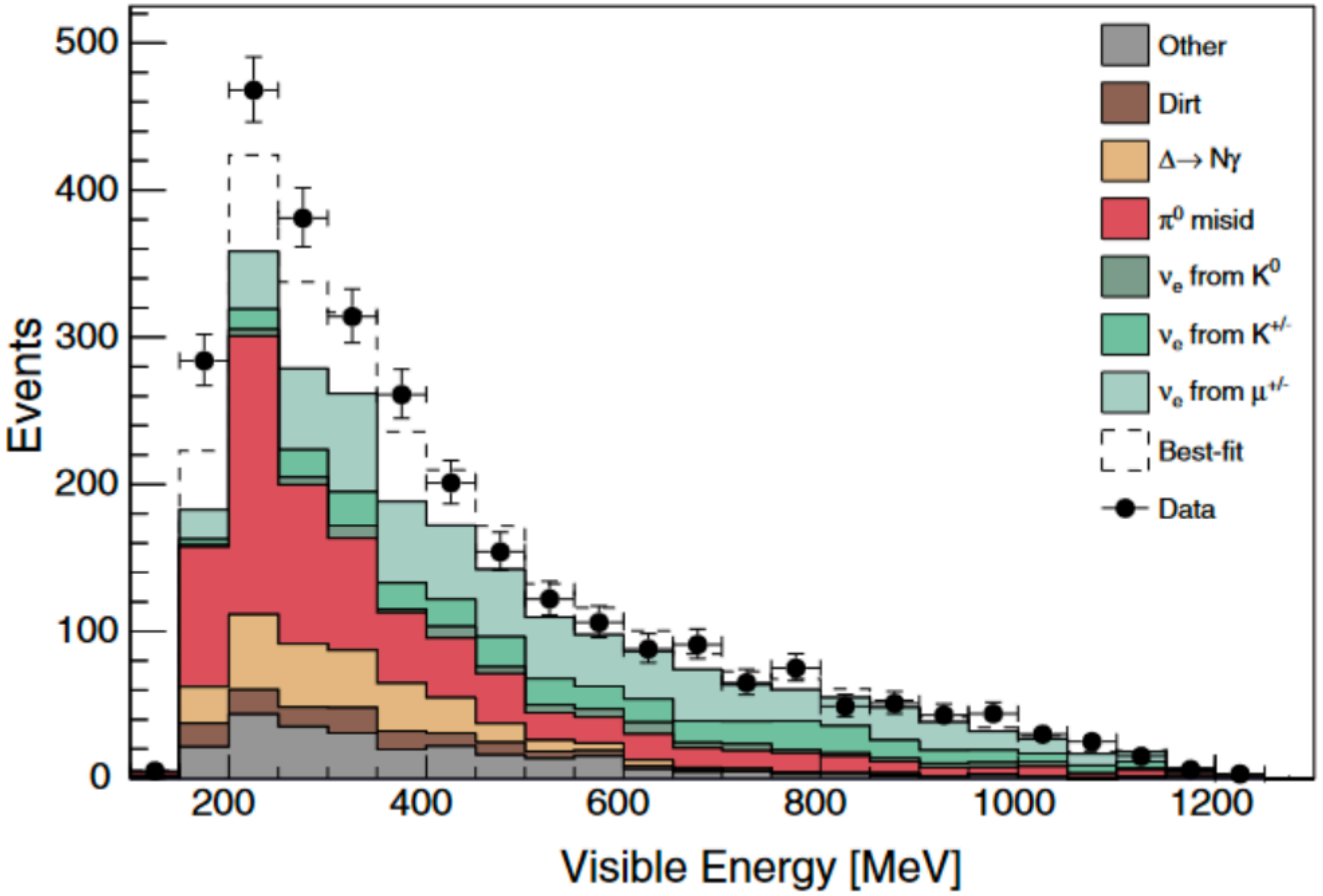


Electron-flavor appearance ?

PLB 829,137054 (2022) PRD 104, L071301 (2021)

PRL 118, 251801 (2017)

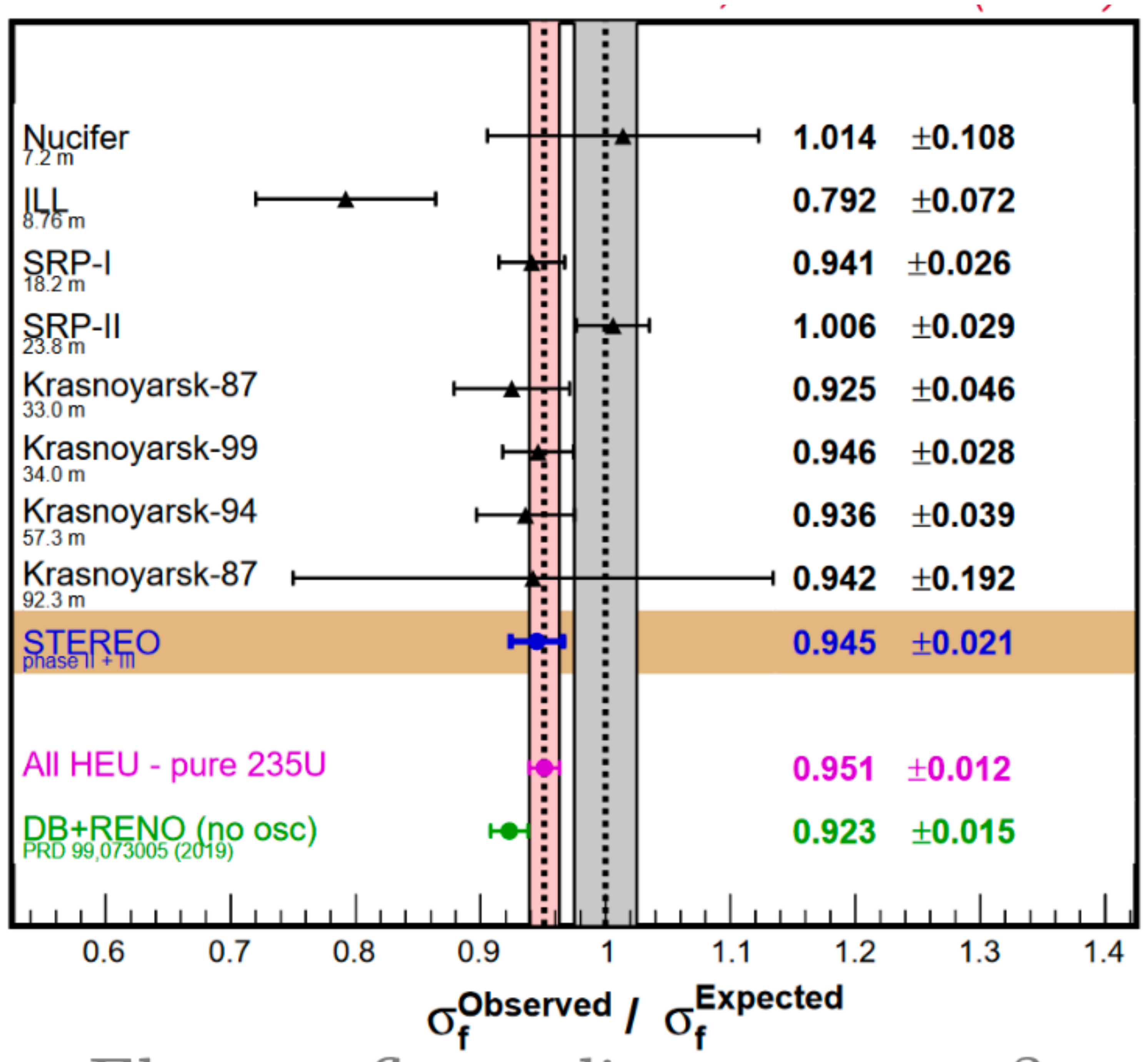
2 Status of the Sterile Neutrino Hypothesis at SBL

μBooNE seems to be disfavoring oscillations, but mBooNE excess remains

Could mB be a mix of BSM phenomena?

Reactor Antineutrino Anomaly

Nature 613, 257-261 (2023)



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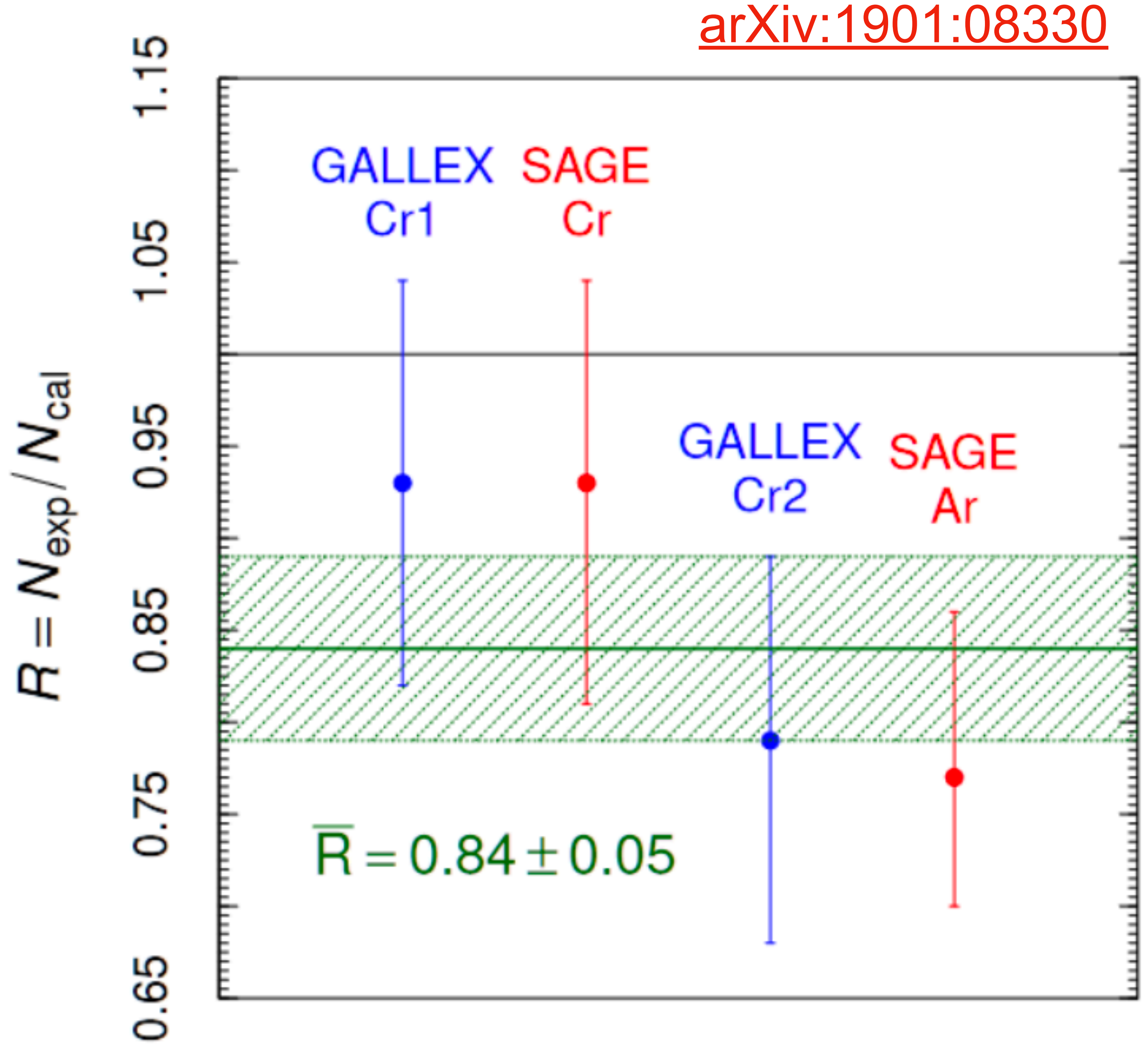

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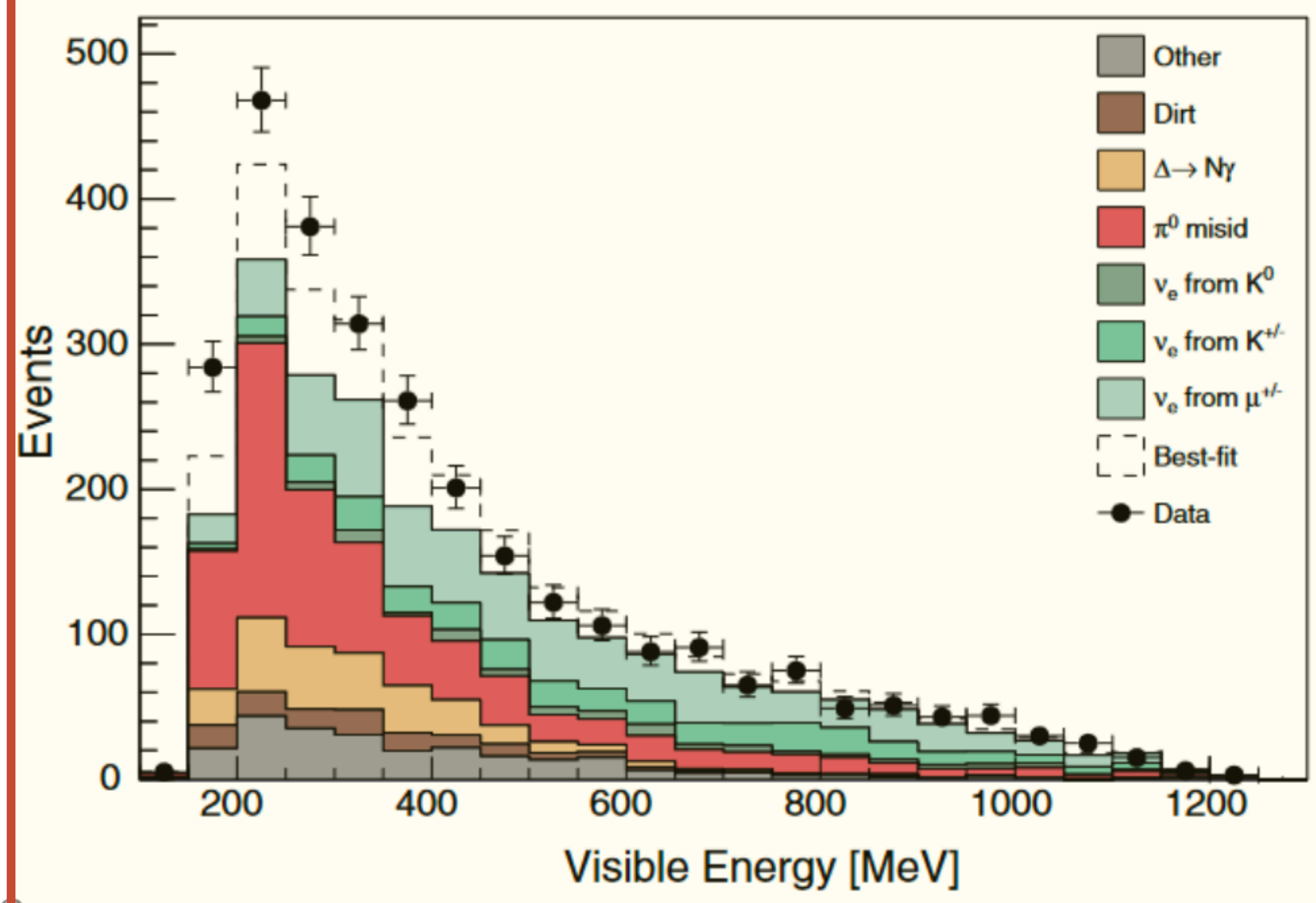

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PLB 829,137054 (2022) PRD 104, L071301 (2021)

PRL 118, 251801 (2017)

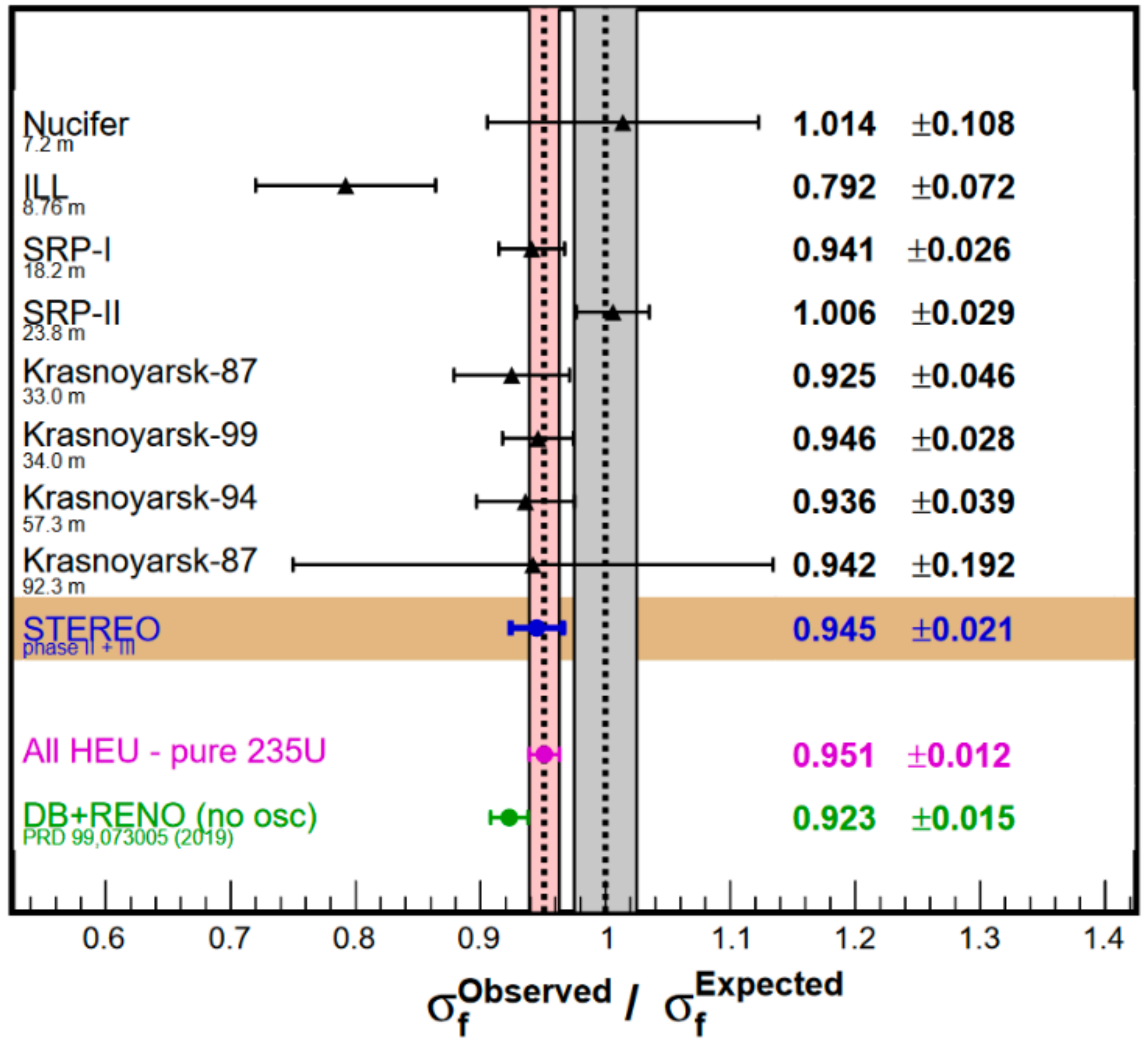
uBooNE public note # 127

2 Status of the Sterile Neutrino Hypothesis at SBL

Gallium Anomaly was strengthened recently by the BEST experiment and the evidence is solid

Reactor Antineutrino Anomaly

Nature 613, 257-261 (2023)



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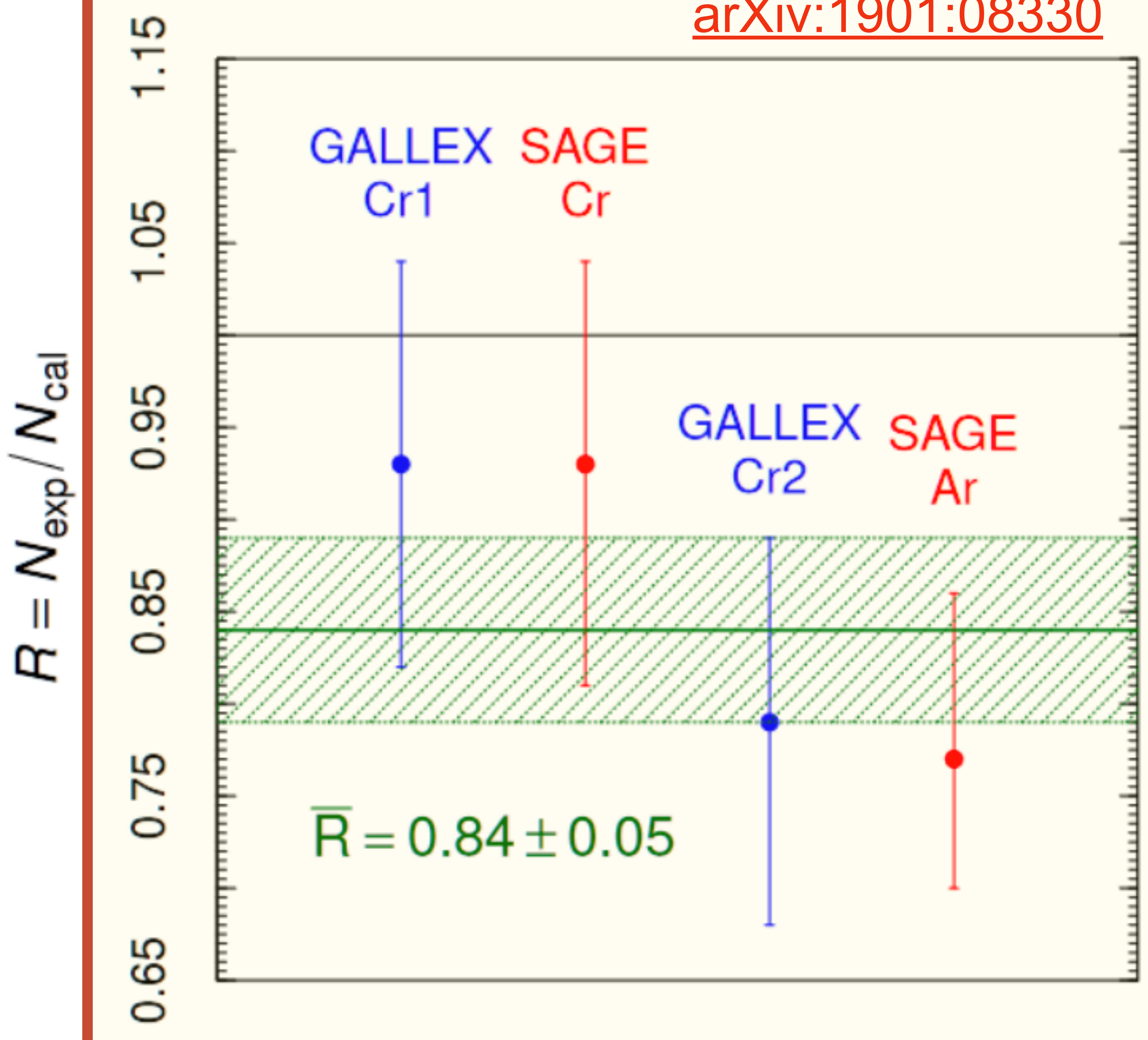

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PPNP 2023.104082

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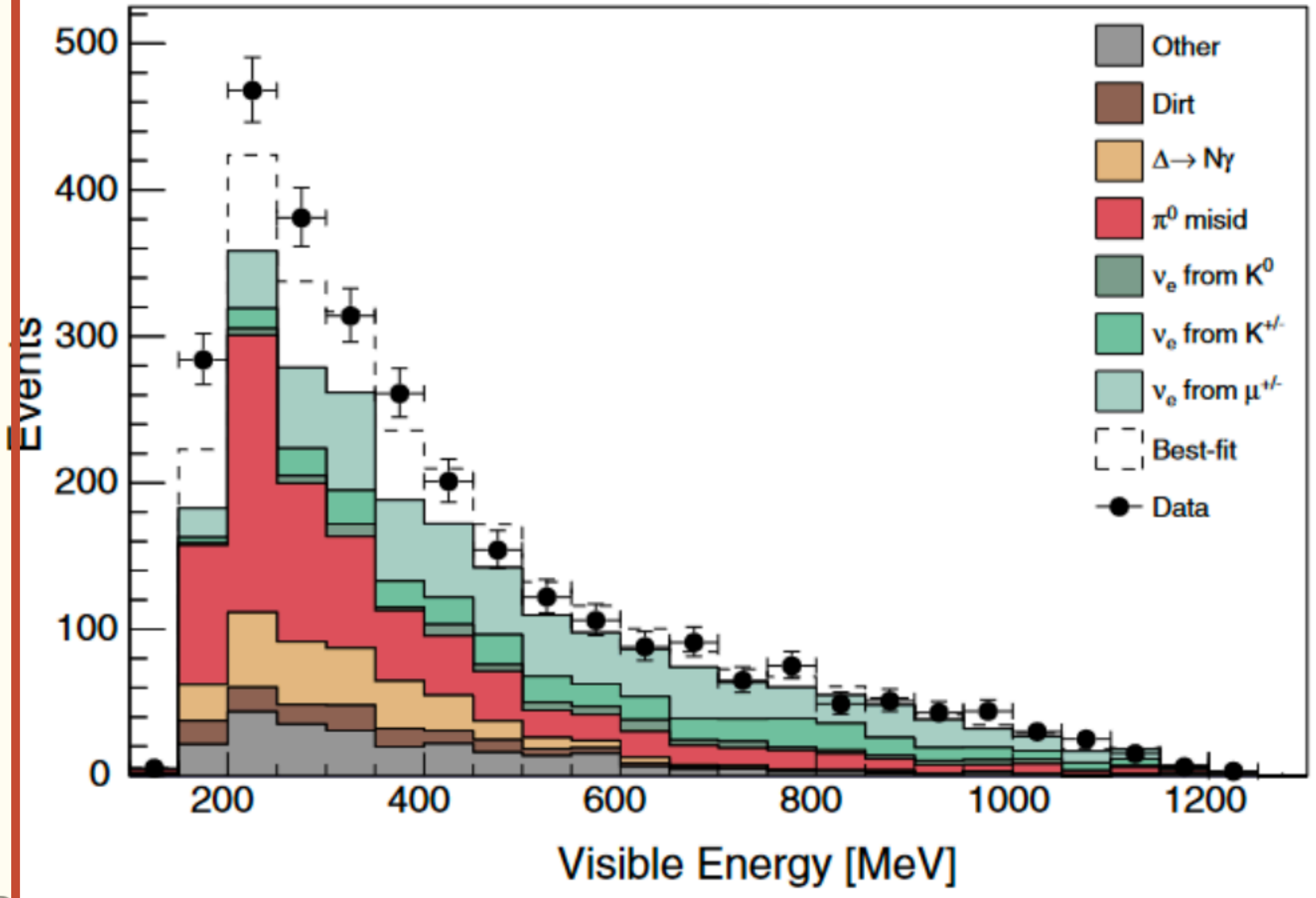

Electron-flavor appearance ?

2 Status of the Sterile Neutrino Hypothesis at SBL

How can the Reactor Anomaly ($\bar{\nu}_e$ disappearance) be 'fading away' if the Gallium Anomaly (also $\bar{\nu}_e$ disappearance!) is getting strengthened?

3 Going Forward

- Vanilla 3+1 – oscillation from a single additional sterile neutrino – cannot be the full solution
- Around/after Snowmass 2022, the community has gravitated towards more diverse, potentially interlocking explanations:
  - 3+1 … plus more: decoherence, decays, etc.
  - Neutrino couplings to hidden sector particles
  - Combination of different phenomena

PRD 107, 036004 (2023)

arxiv:2209.05352

3 The Puzzle

1 - Short-Baseline Neutrino

- Direct MiniBooNE test.
- Access to rich hidden sector in > GeV beam.
- Two-beam osc capabilities.

2 - DUNE

- Highest ν/BSM flux.
- High beam energy.
- PRISM ND concept.

3 - IceCube

- Probe non-standard matter effects.
- Very high energy ν's also accessible

All experiments can contribute to the resolution of the puzzle.

6 - JSNS^2

- Direct LSND test.
- Access to rich 'lowmass' hidden sector.
- Probe LFV models.

5 - Reactor

- Pure e-flavor.
- Low (MeV) ν energies.
- Pure probe of vacuum oscillations.

4 - Sources

- Direct Gallium Anomaly Test.
- Pure e-flavor.
- Lowest ν energy.

B. Littlejohn: summarizing Snowmass22 NF02 Report and Whitepaper.

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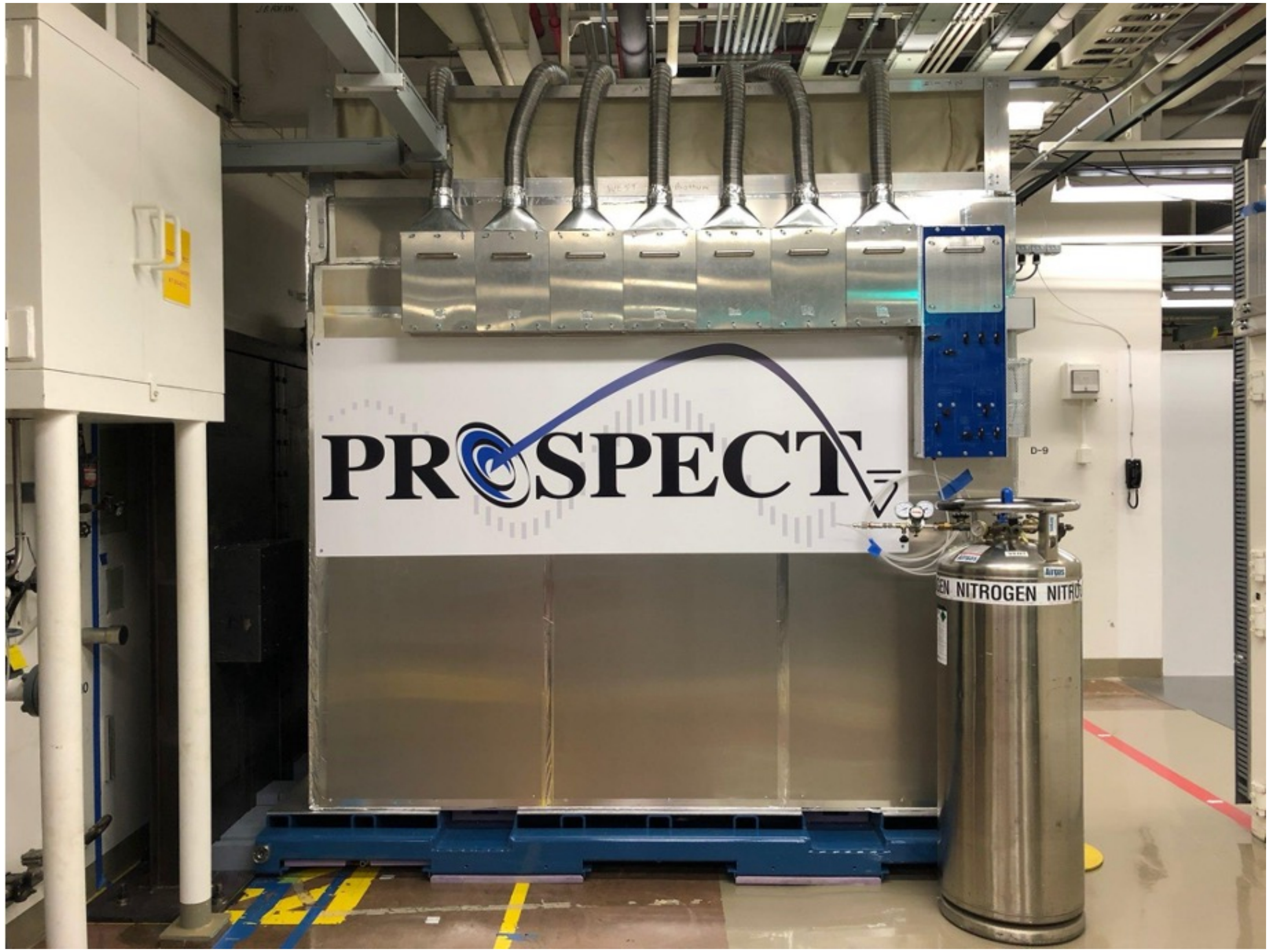
4 The Precision Reactor Oscillation and SPECTrum Experiment

PROSPECT: The Goals

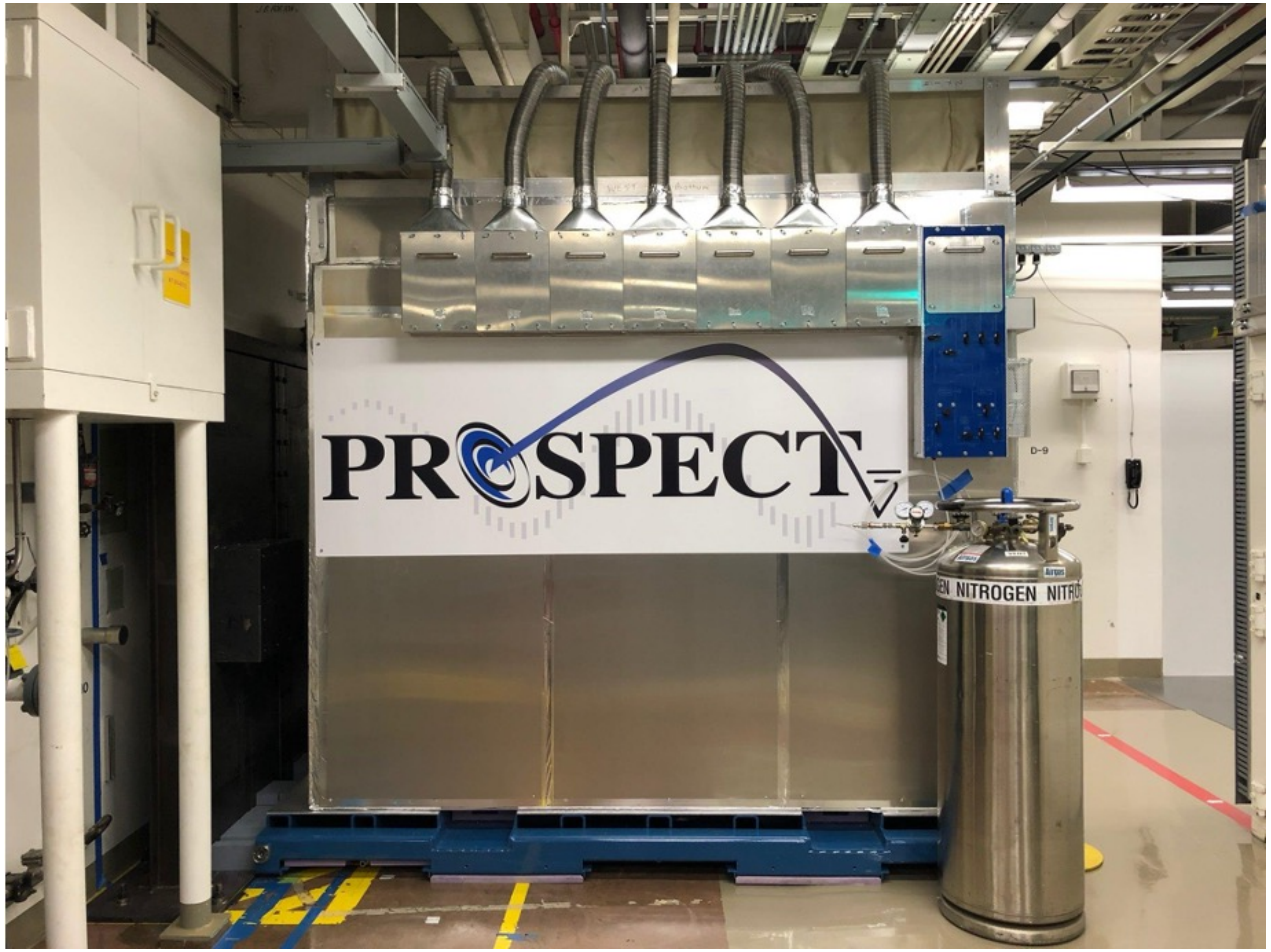
- Search for sterile neutrino oscillations
- Precise measurement of the ^{235}U antineutrino spectrum



4 The Precision Reactor Oscillation and SPECTrum Experiment

PROSPECT: The Detector

- Located at HFIR, Oak Ridge, TN.



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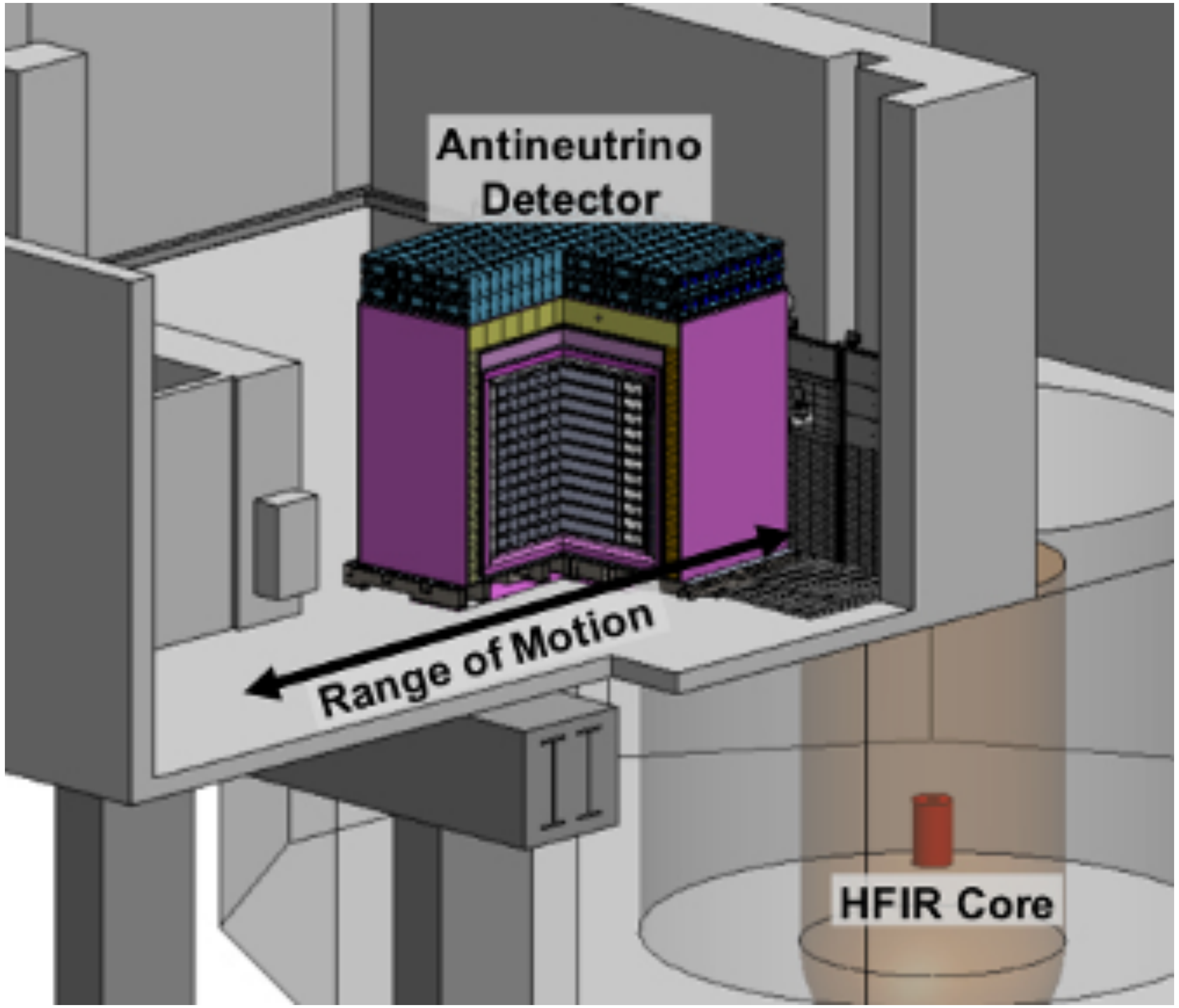
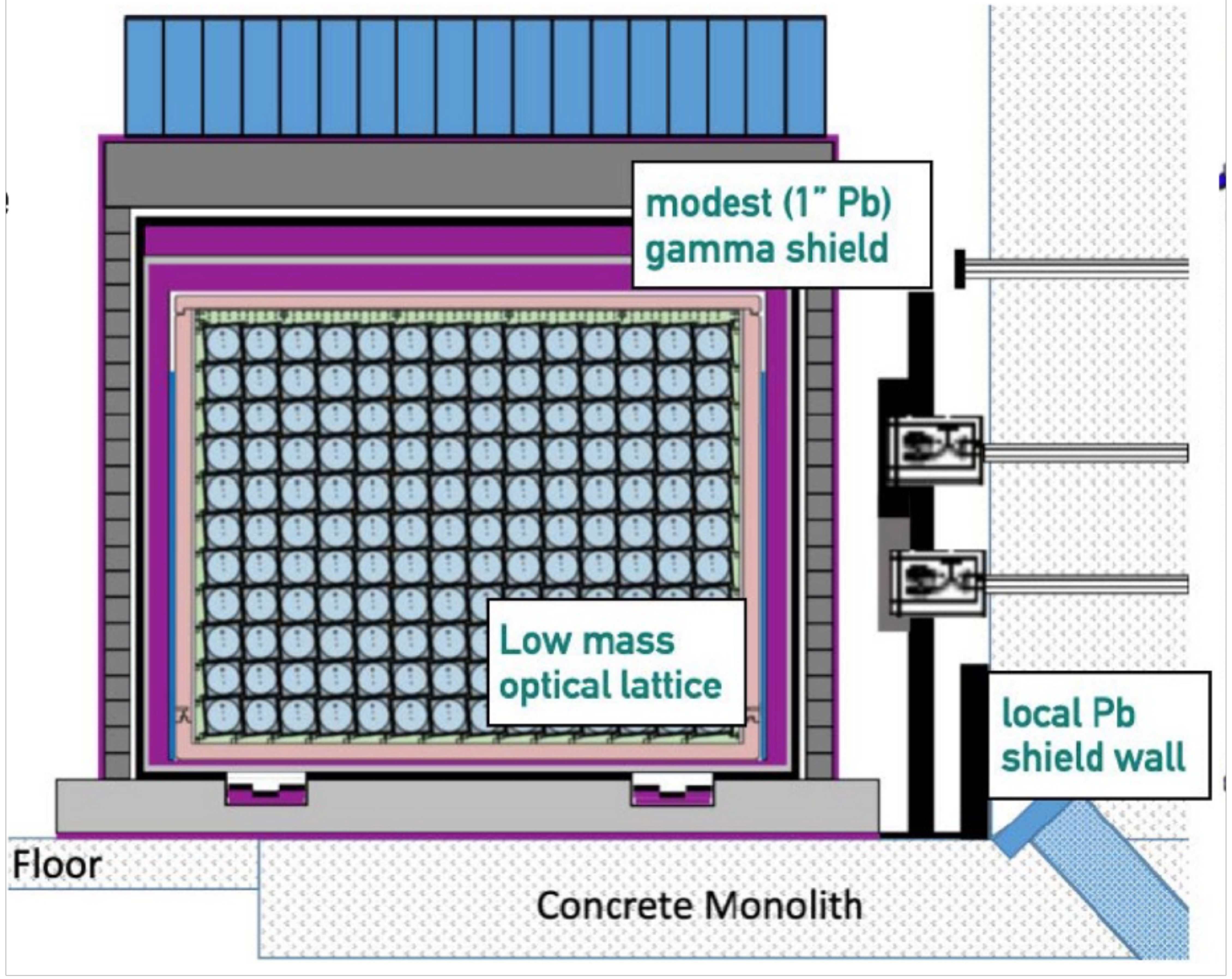


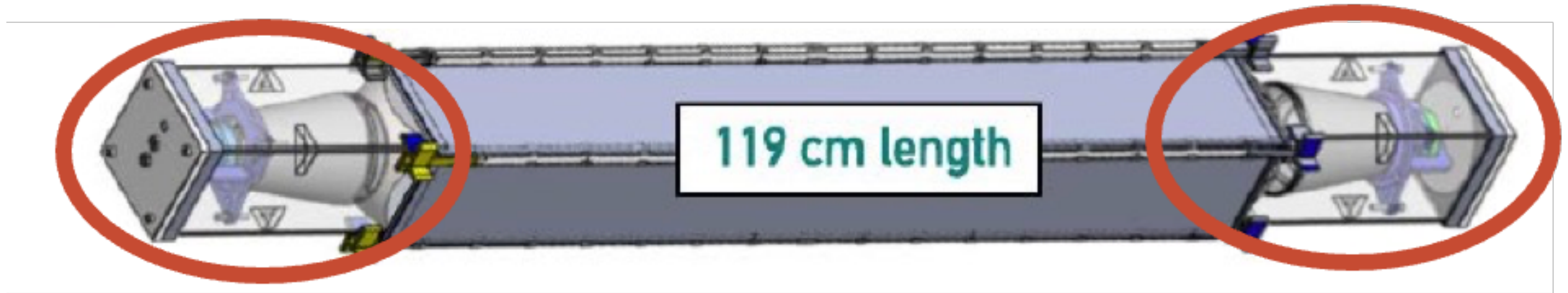
4 The Precision Reactor Oscillation and SPECTrum Experiment

PROSPECT: The Detector

- Located at HFIR, Oak Ridge, TN.
- Proximity of the reactor: 6.7 – 9.2m
- 154 segments - 14 x 11 grid
- Each segment:
  - 2 PMTs

Schematic of the active detector volume

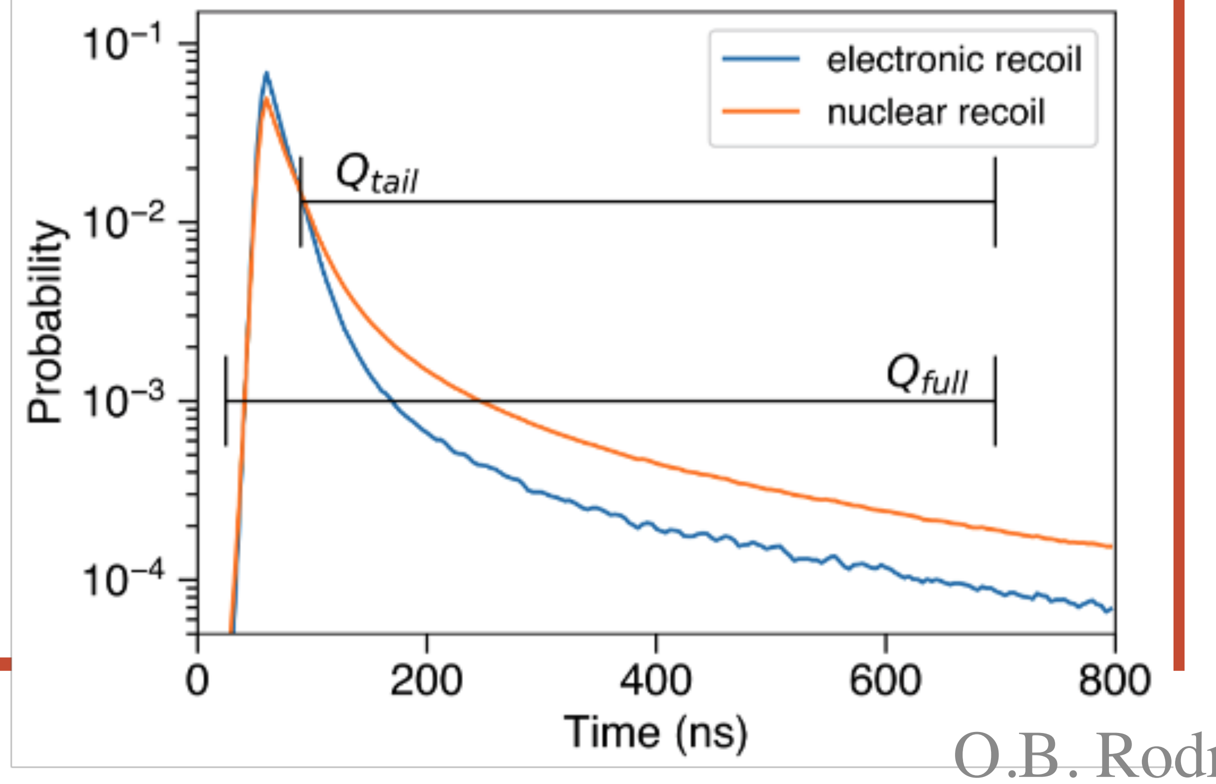




4 The Precision Reactor Oscillation and SPECTrum Experiment

PROSPECT: The Detector

- Located at HFIR, Oak Ridge, TN.
- Proximity of the reactor: 6.7 – 9.2m
- 154 segments - 14 x 11 grid
- Each segment:
  - 2 PMTs
  - Filled with LiLS
    - Pulse Shape Discriminator
    - Electronic recoil emit light faster than nuclear recoil



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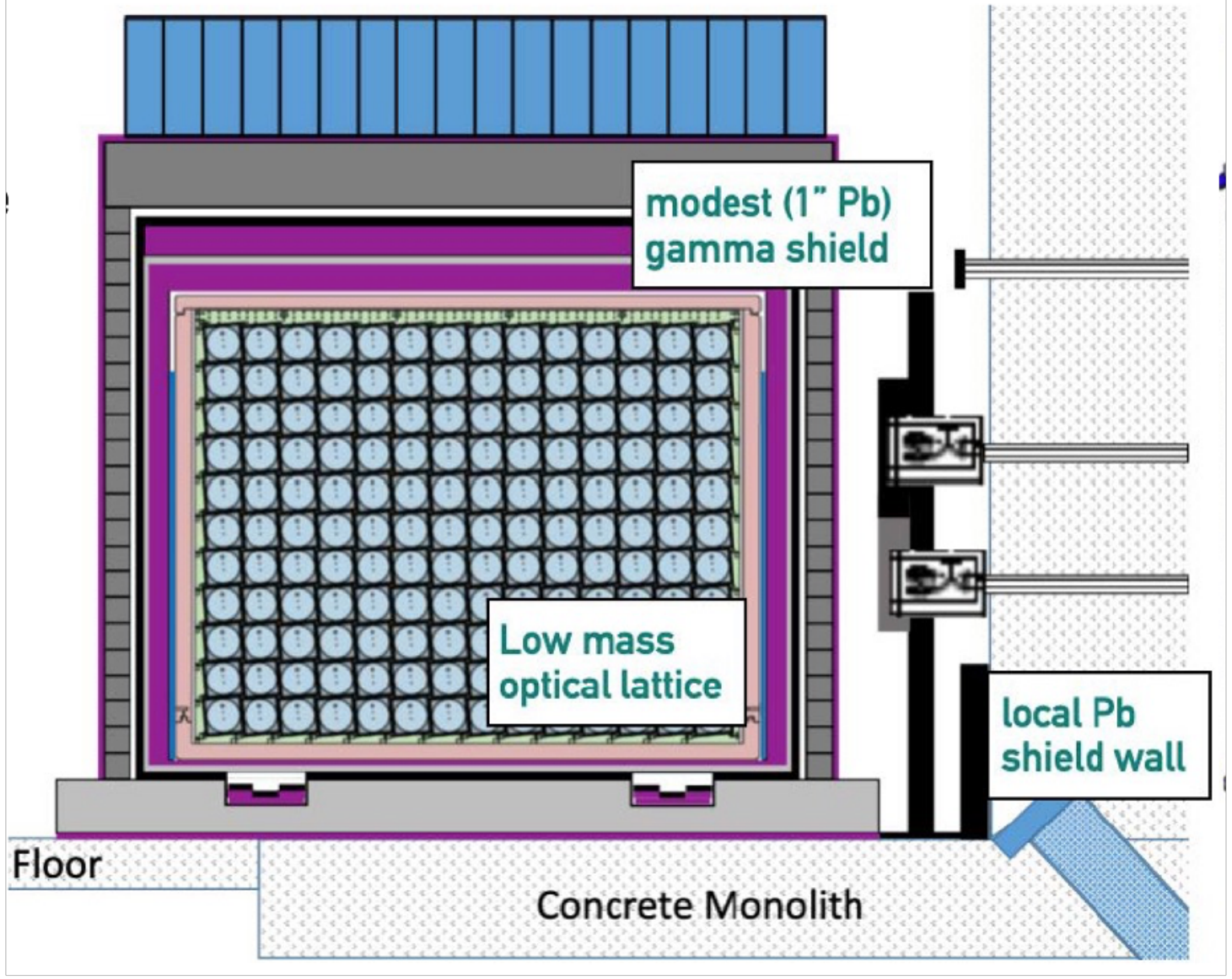
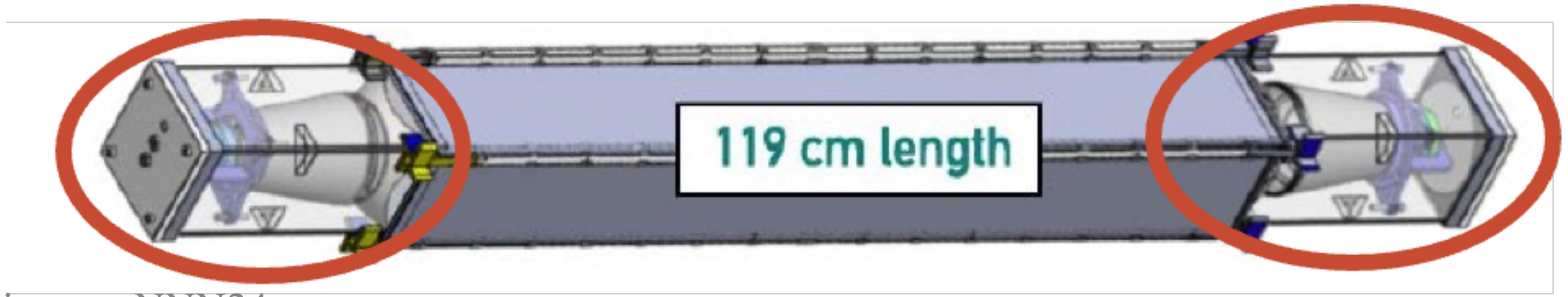
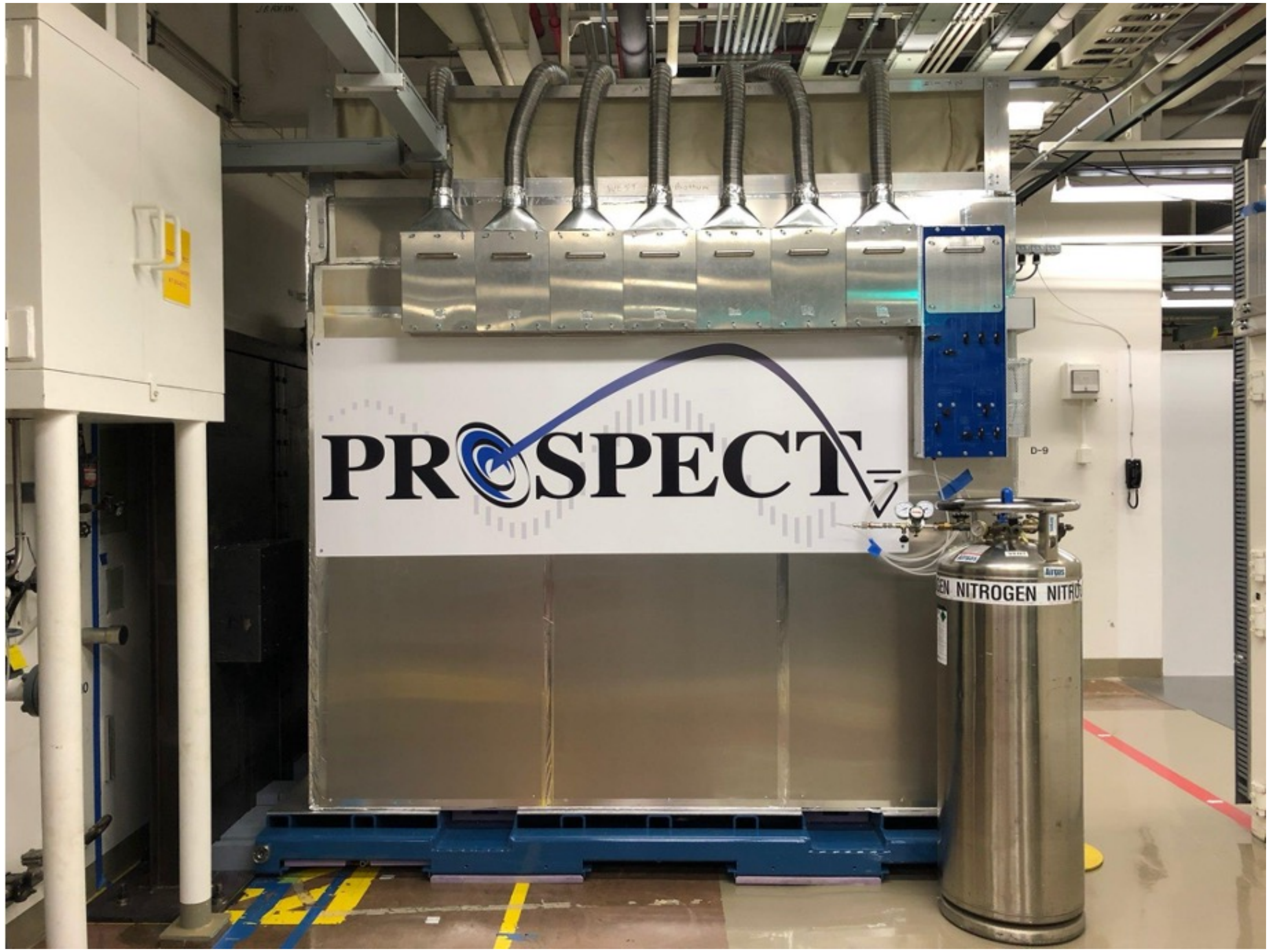




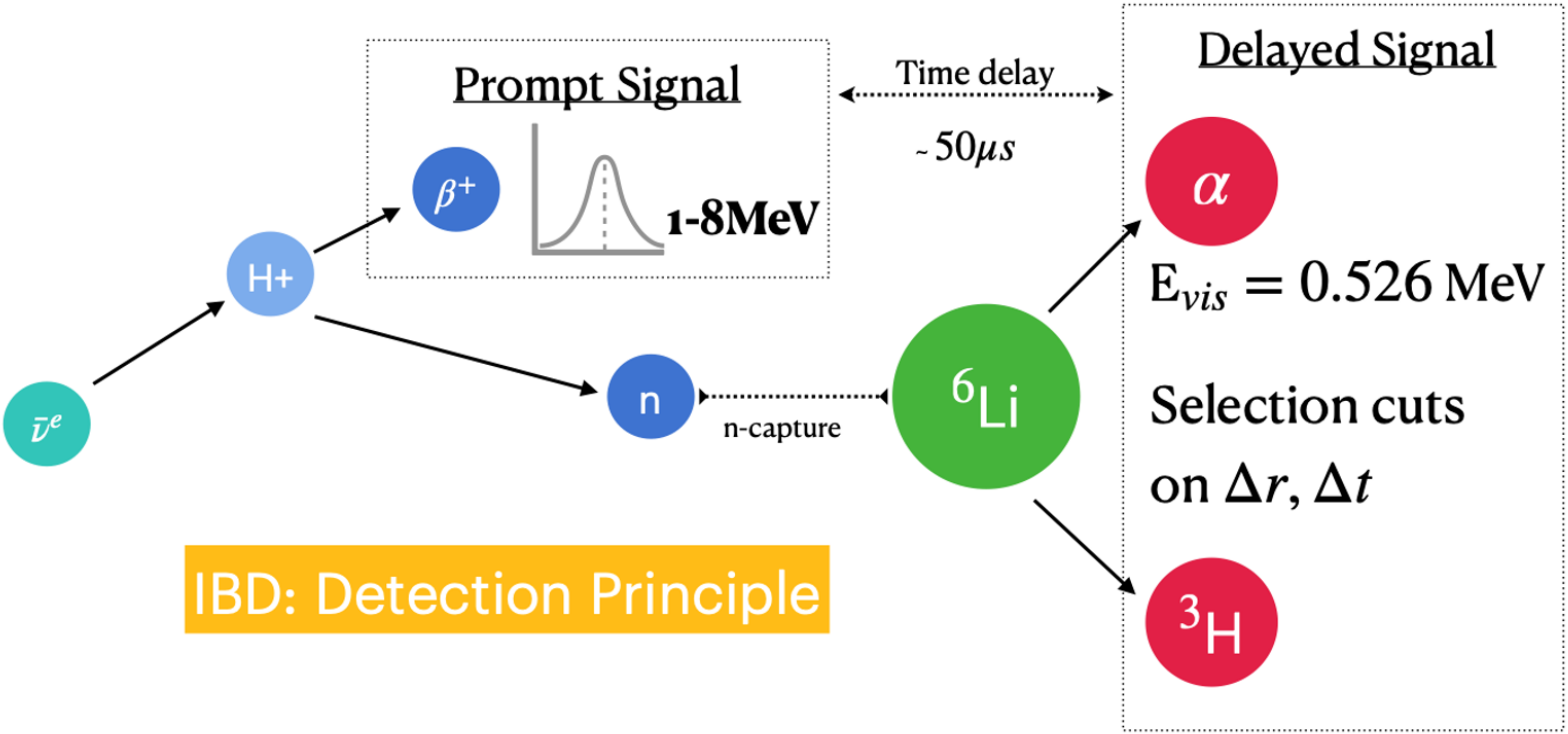
4 The Precision Reactor Oscillation and SPECTrum Experiment

PROSPECT: The Challenges

- Minimal overburden.
- Backgrounds: cosmogenic fast neutrons and reactor gammas.

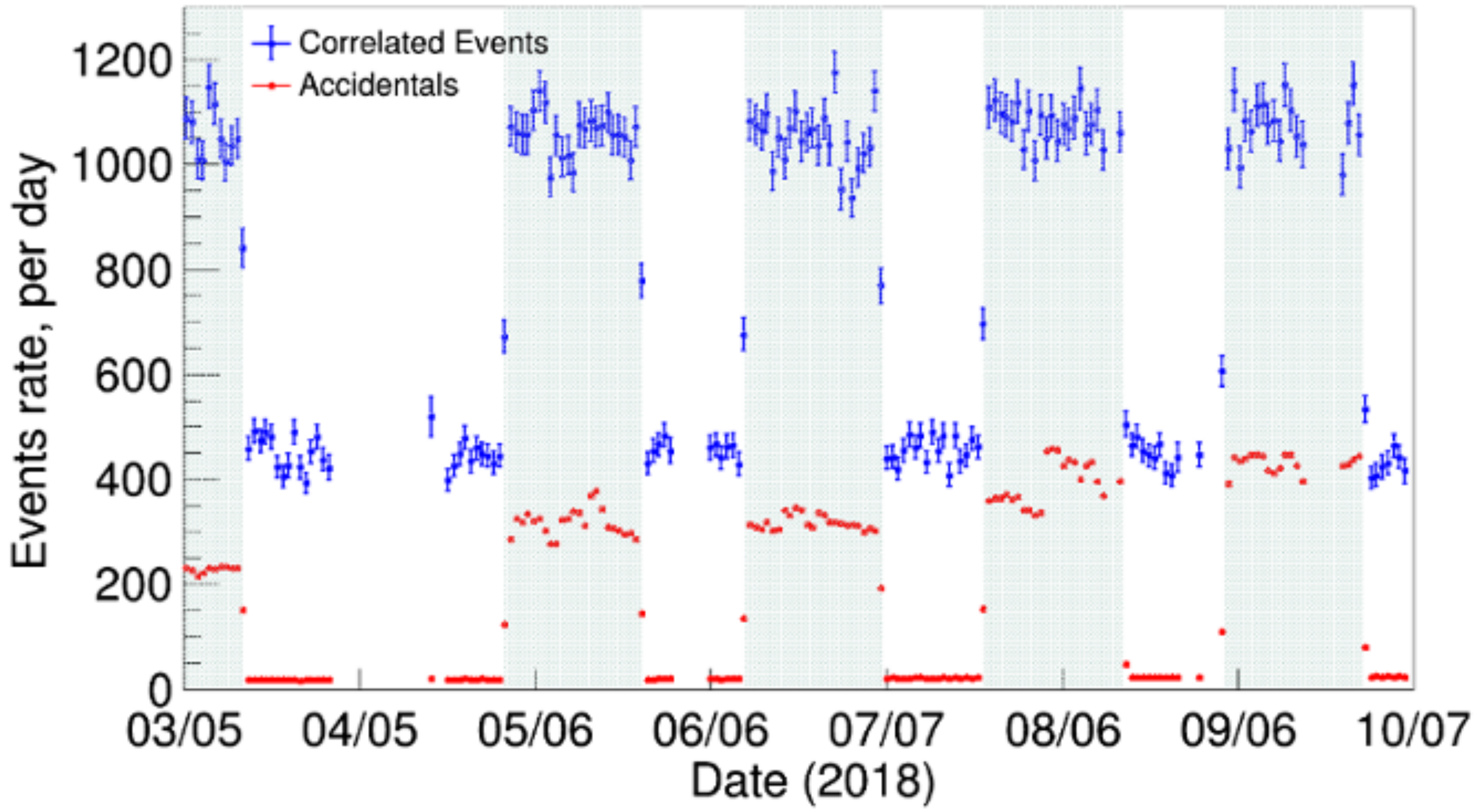


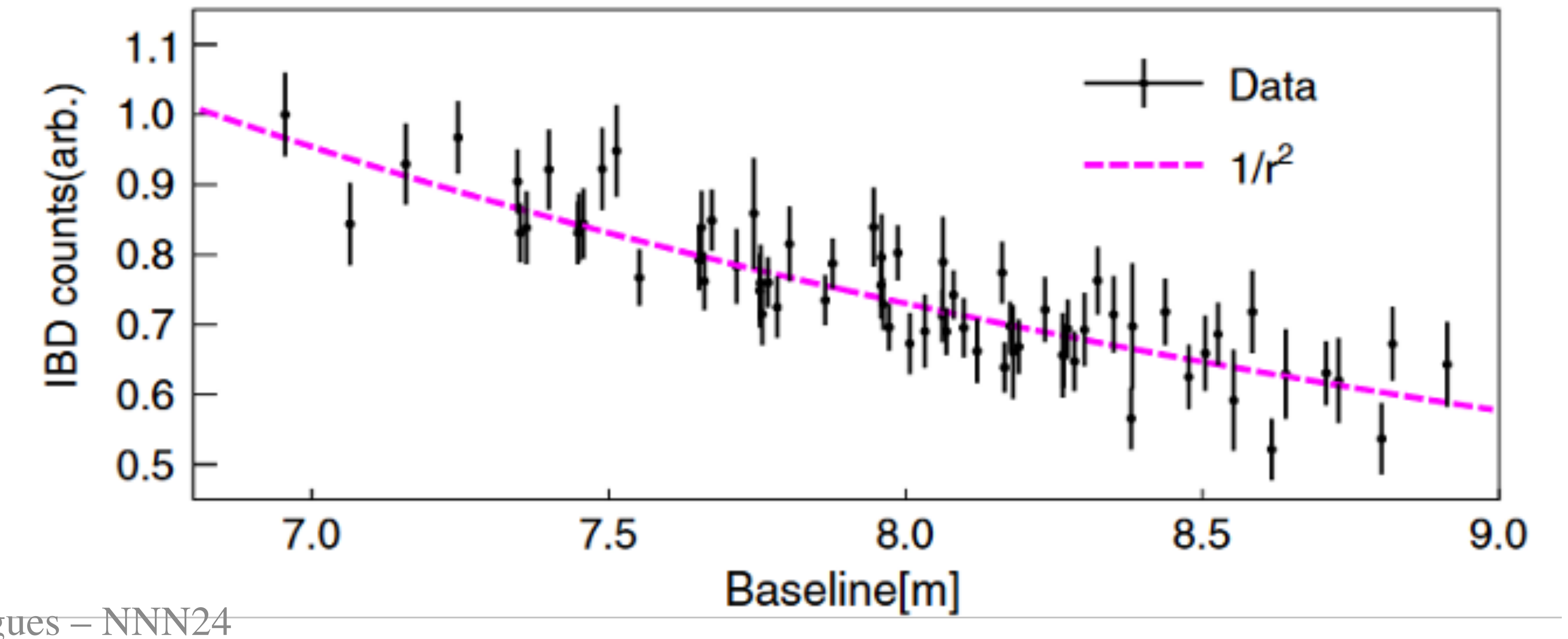
4 IBD Detection Principle



4 PROSPECT data

- PROSPECT detector took data from March 5 to October 6, 2018:
  - 105 days reactor-on.
  - 78 days reactor-off.
  - 8 days of calibration.
  - Discard candidates from 36 fiducial segments experiencing PMT current instabilities.
  - Average of 500 IBD per day.
  - IBD rate follow $1/r^2$ distribution.

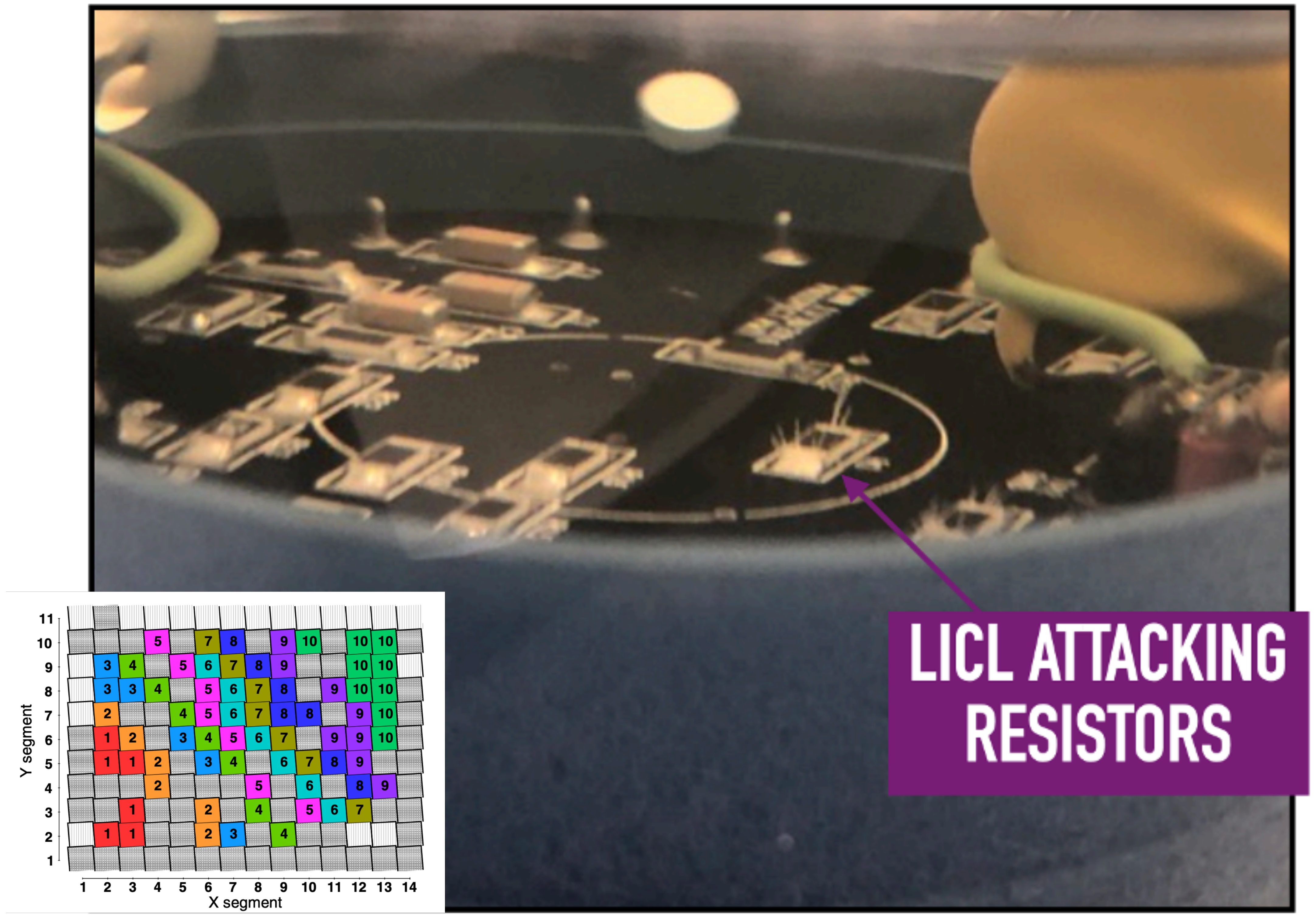




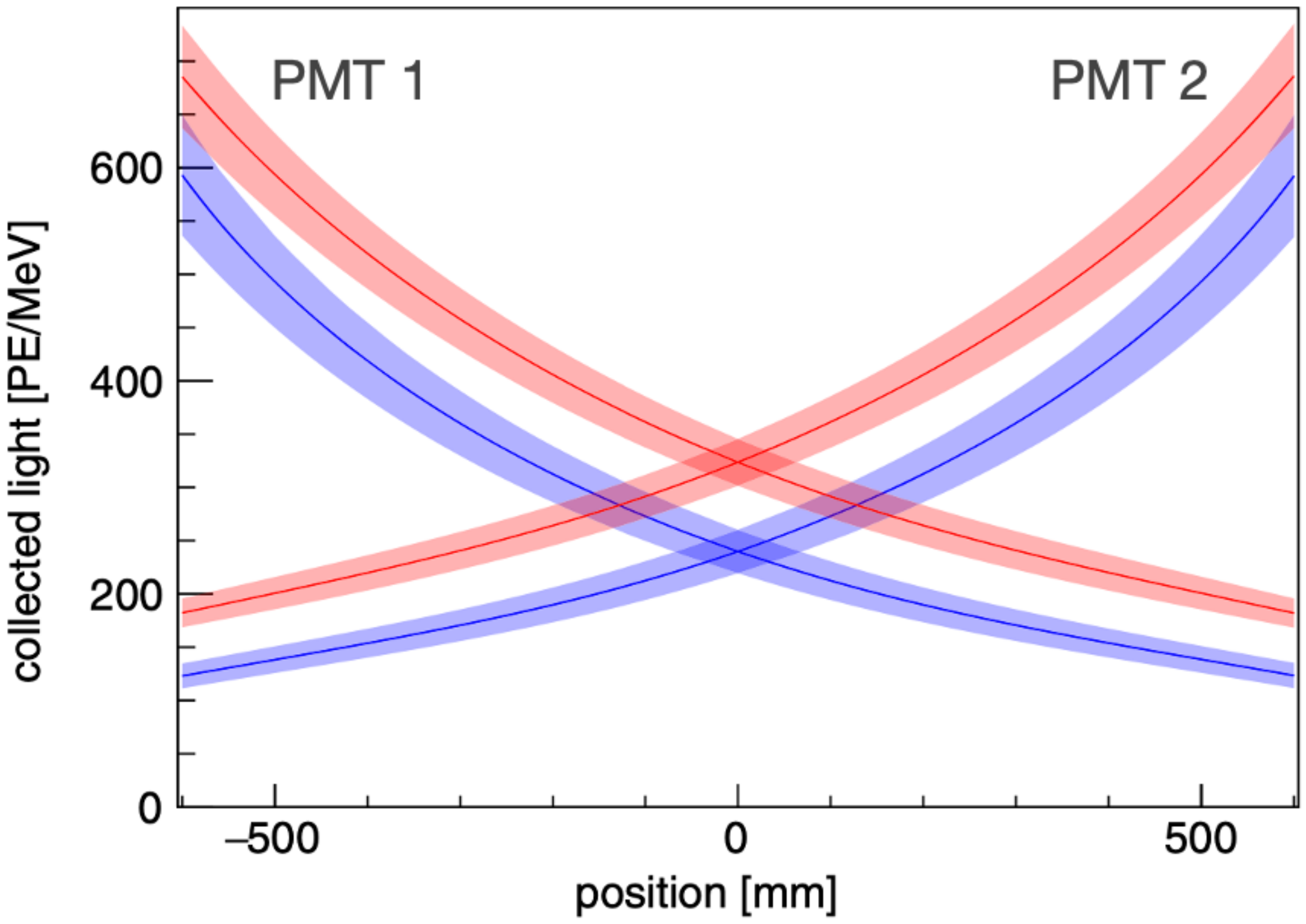
4 Challenges during operation

LiLS ingress into the PMT housing

- ~20% of the total segment turned off by end of operations



LiLS degradation



4 Challenges during operation

LiLS ingress into the PMT housing

Go around this one with some clever data analysis

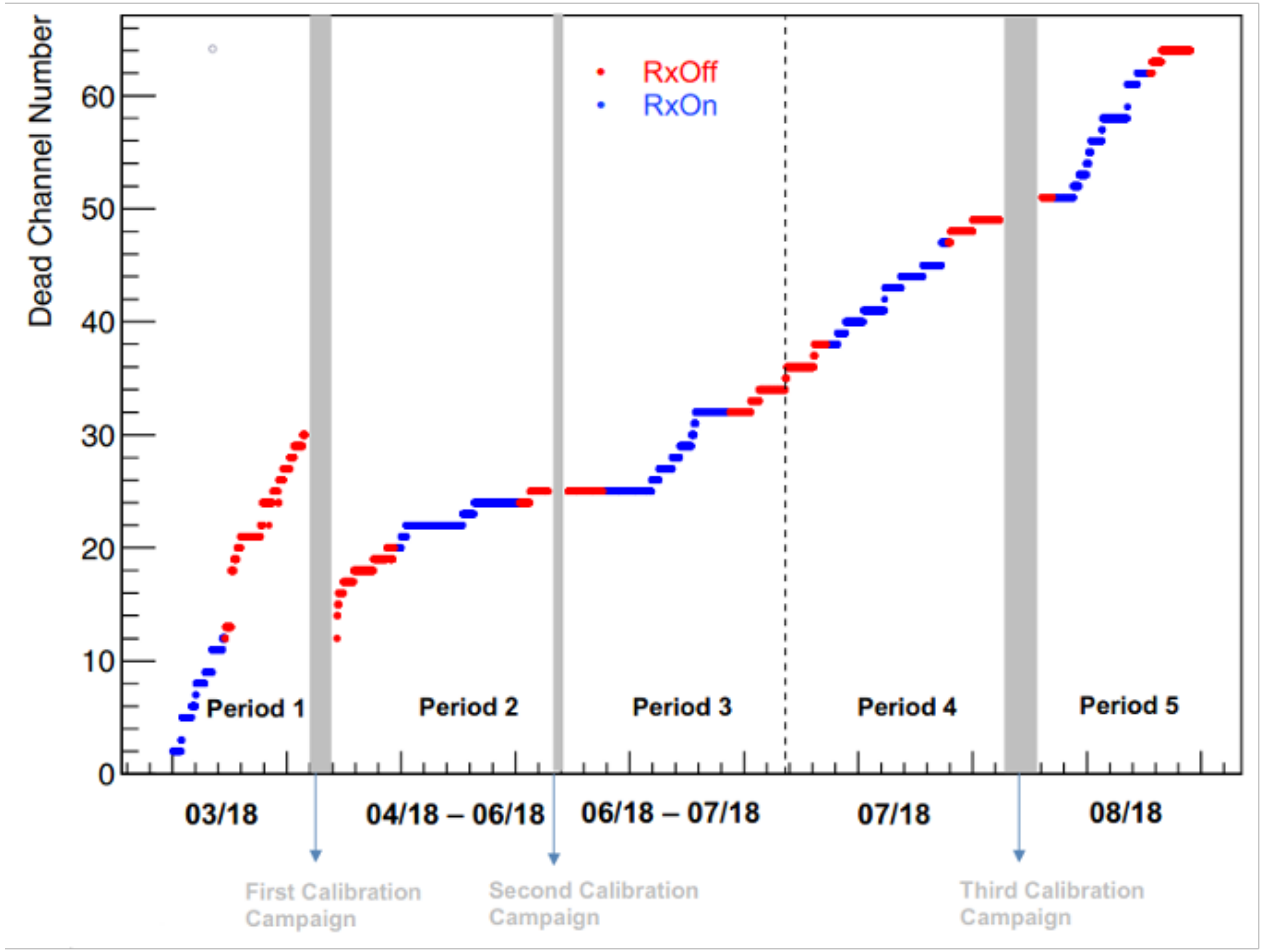
LiLS degradation

It was minor and it has been adressed in previous analysis already

5 Final data analysis treatment

Maximize the PROSPECT-I data set:

- Data splitting (DS)
  - Maximize number of live segments in each period.
- Splitting criteria:
  - Each period must contain one full RxOn cycle.
  - Each period should start immediately after a new calibration campaign.
  - All periods should have RxOff data before and after each corresponding RxOn cycle



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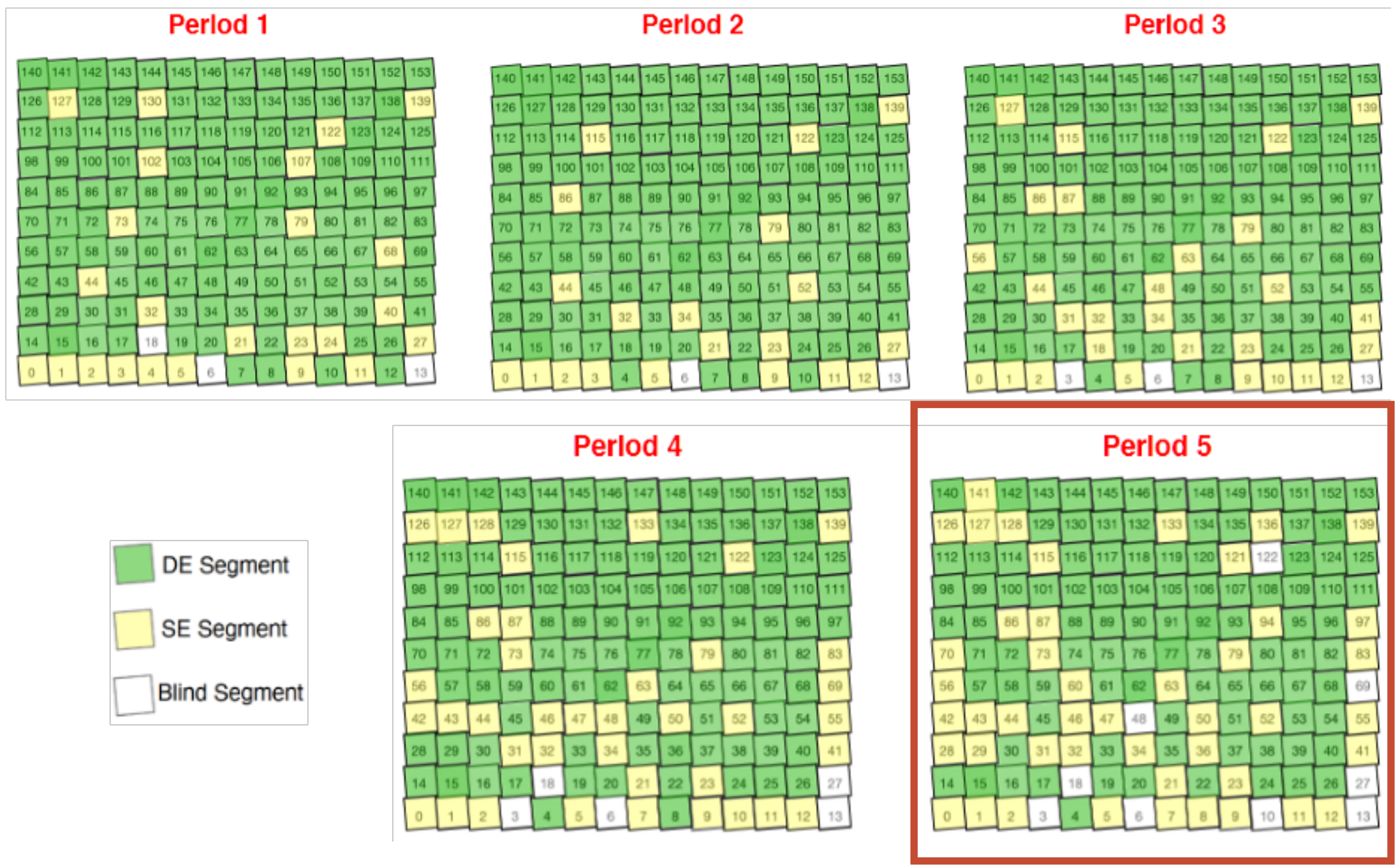
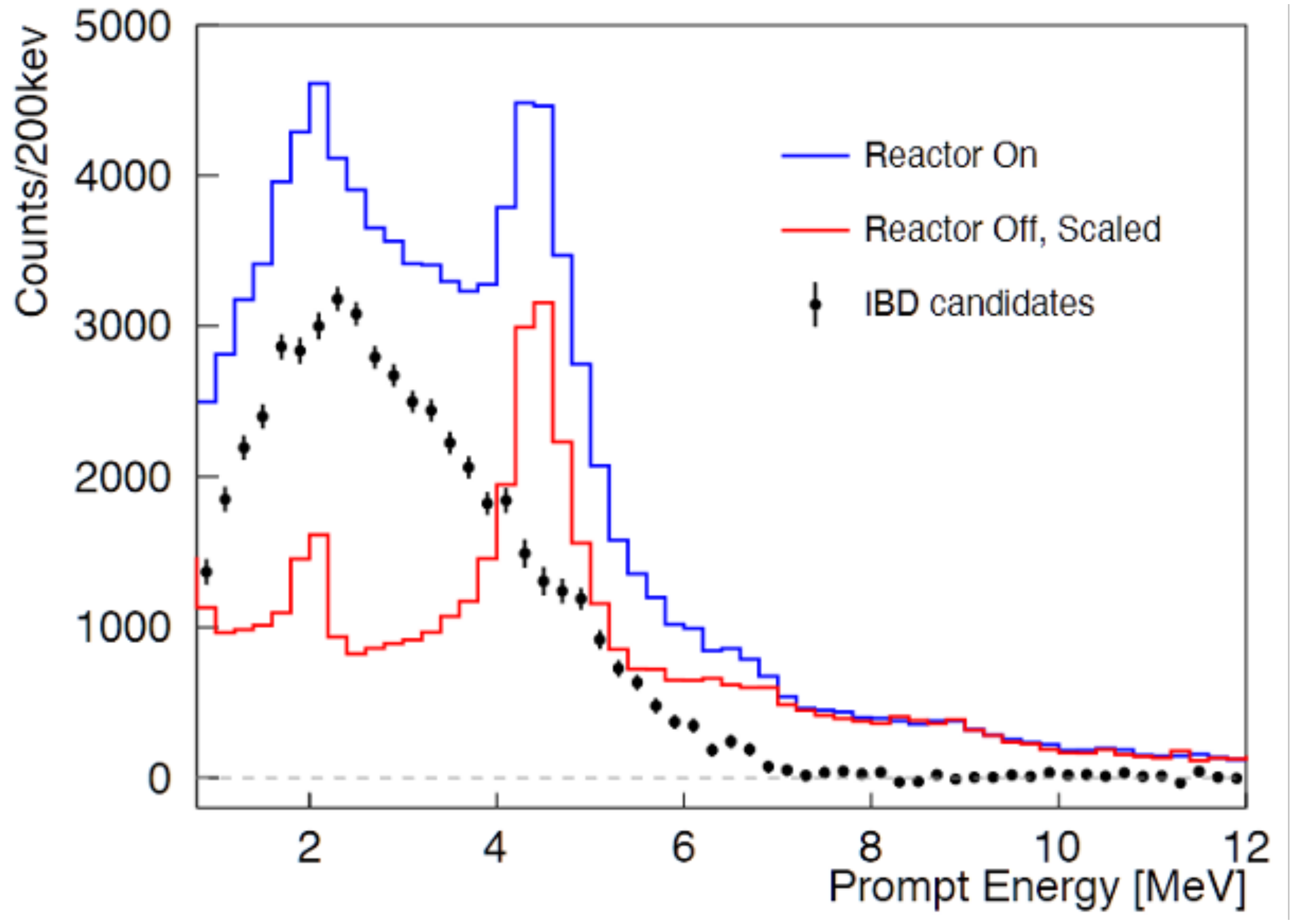
  - Each period should start immediately after a new calibration campaign.
  - All periods should have RxOff data before and after each corresponding RxOn cycle
- Previous analysis considered P5 configuration as the final
- Use single ended segments for background rejection



5 Final Optimized Dataset

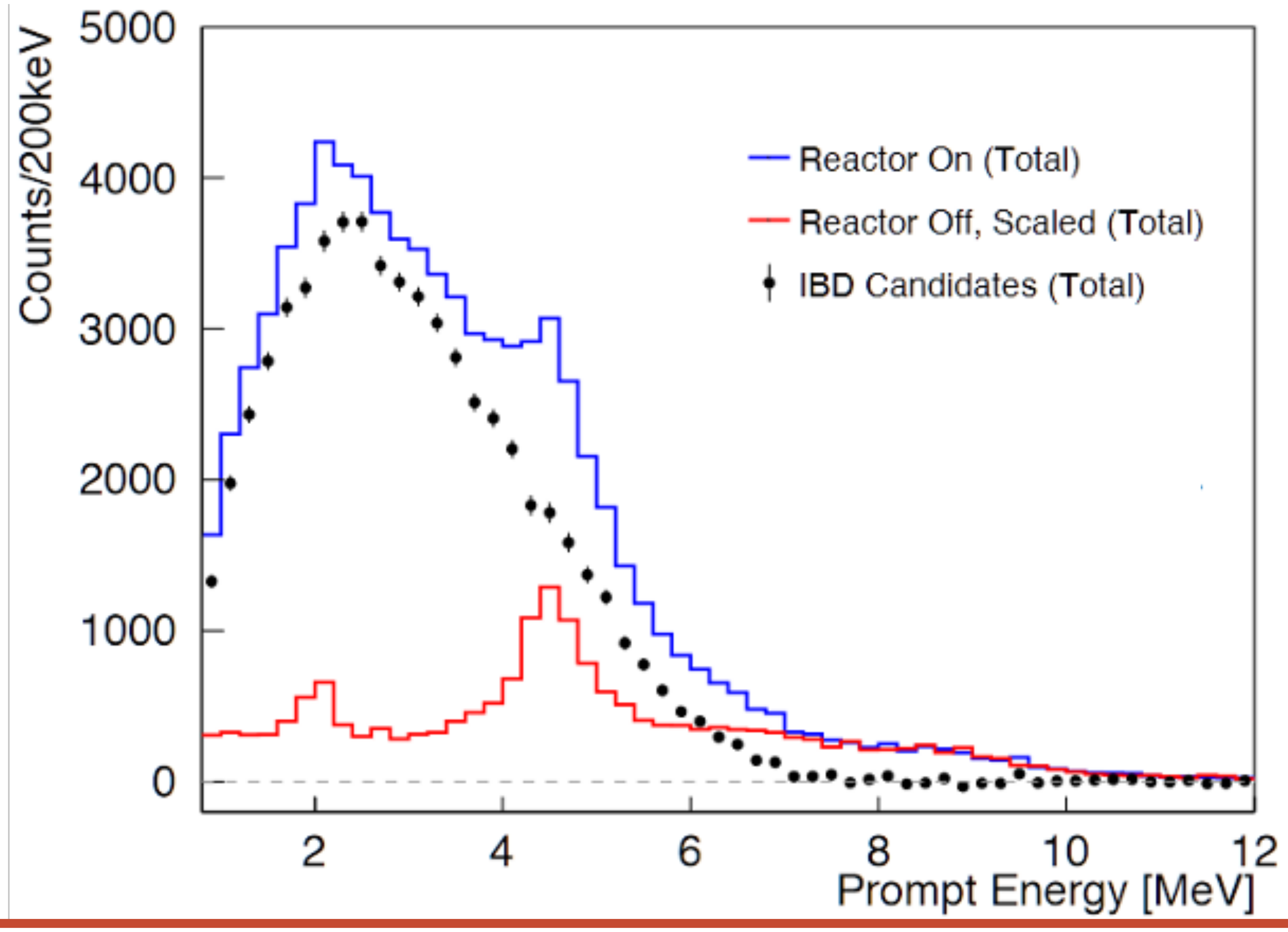
Previous analysis

- Phys. Rev. D 103, 032001, using only DE-segments
- 50,560 IBD signal
- 1.37 S/B ratio



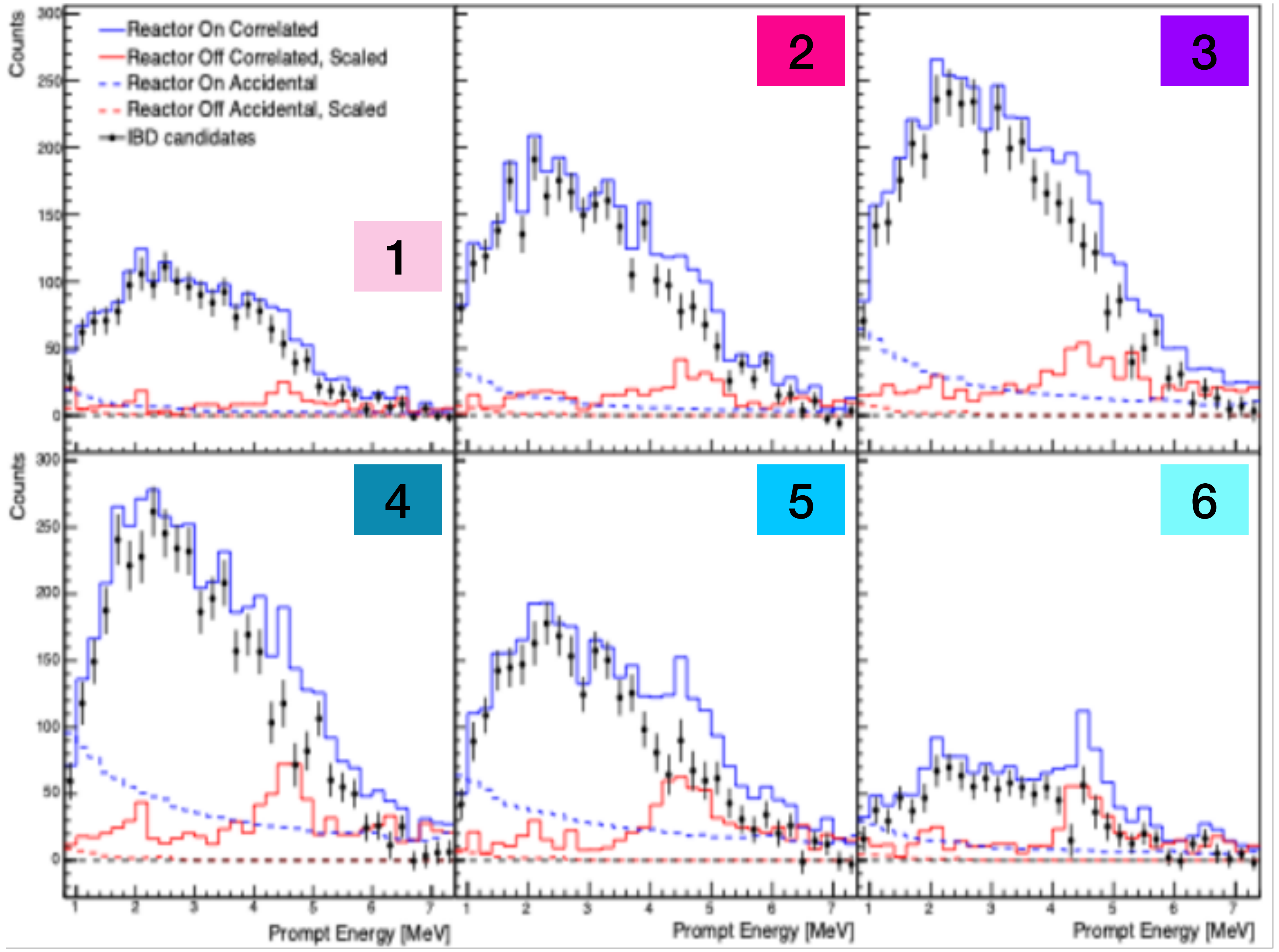
Current analysis

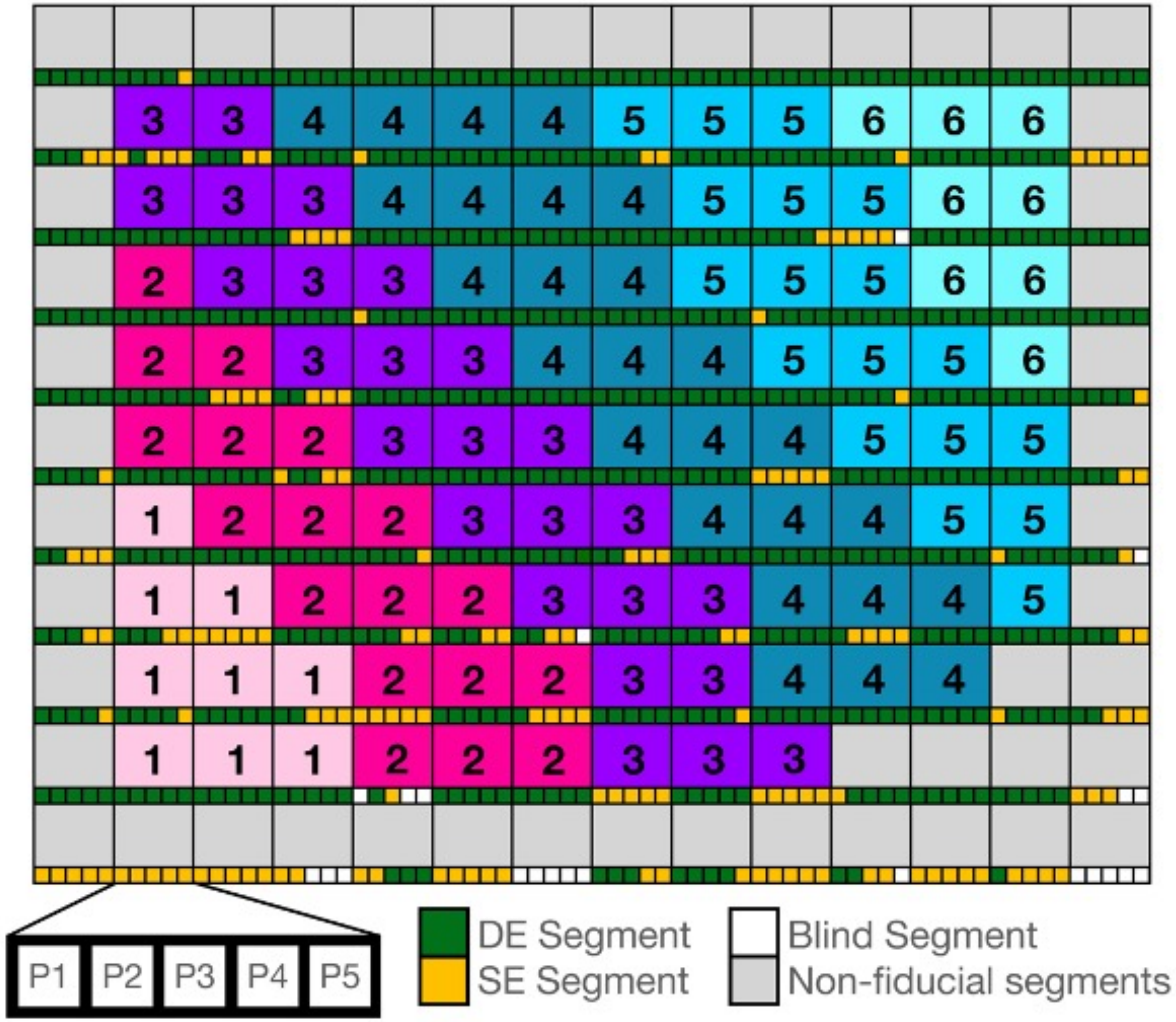
- arXiv:2406.10408, using DS and SEER
- 61,029 IBD signal
- 3.90 S/B ratio



5 Oscillation Analysis Strategy

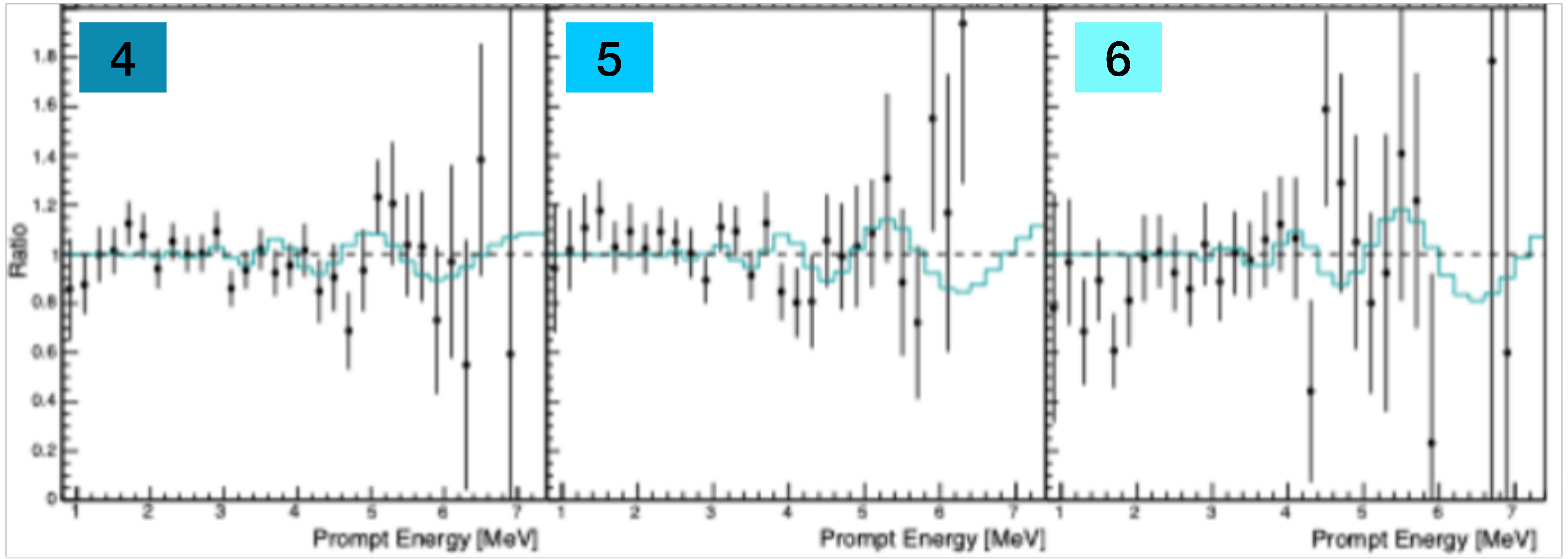
- Combine spectra from segments into baseline
- 6 baseline bins x 33 energy bins x 5 periods.



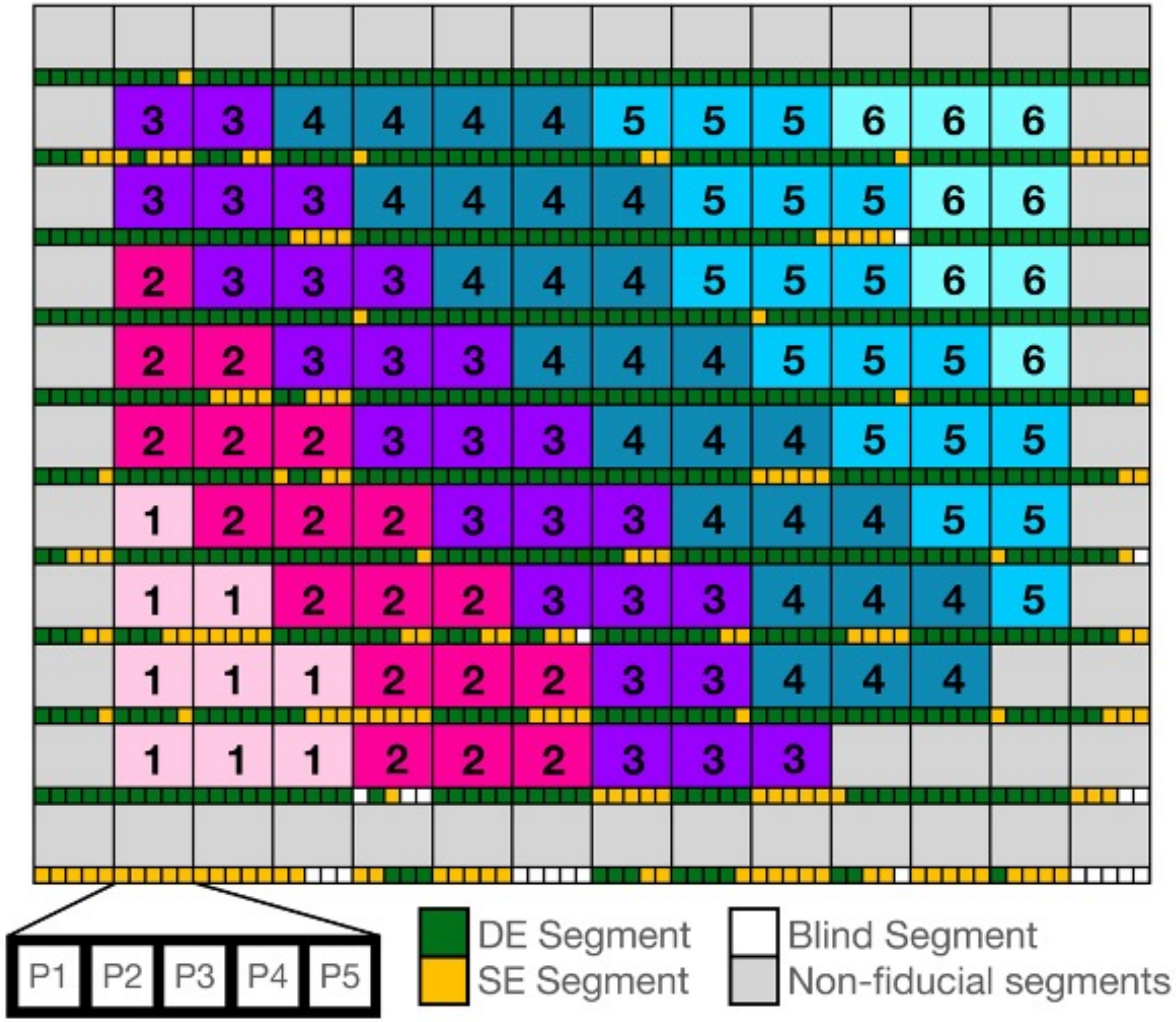


5 Oscillation Analysis Strategy

- Combine spectra from segments into baseline
- 6 baseline bins x 33 energy bins x 5 periods
- Search for spectral distortion by comparing each baseline to the detector integrated average (flux independent).



Subset of period 2



5 Oscillation Analysis Strategy

- Use Chisquare test to quantitatively assess the parameter fitting the dataset:
  - Combined Neyman-Pearson to minimize bias from low statistics bins

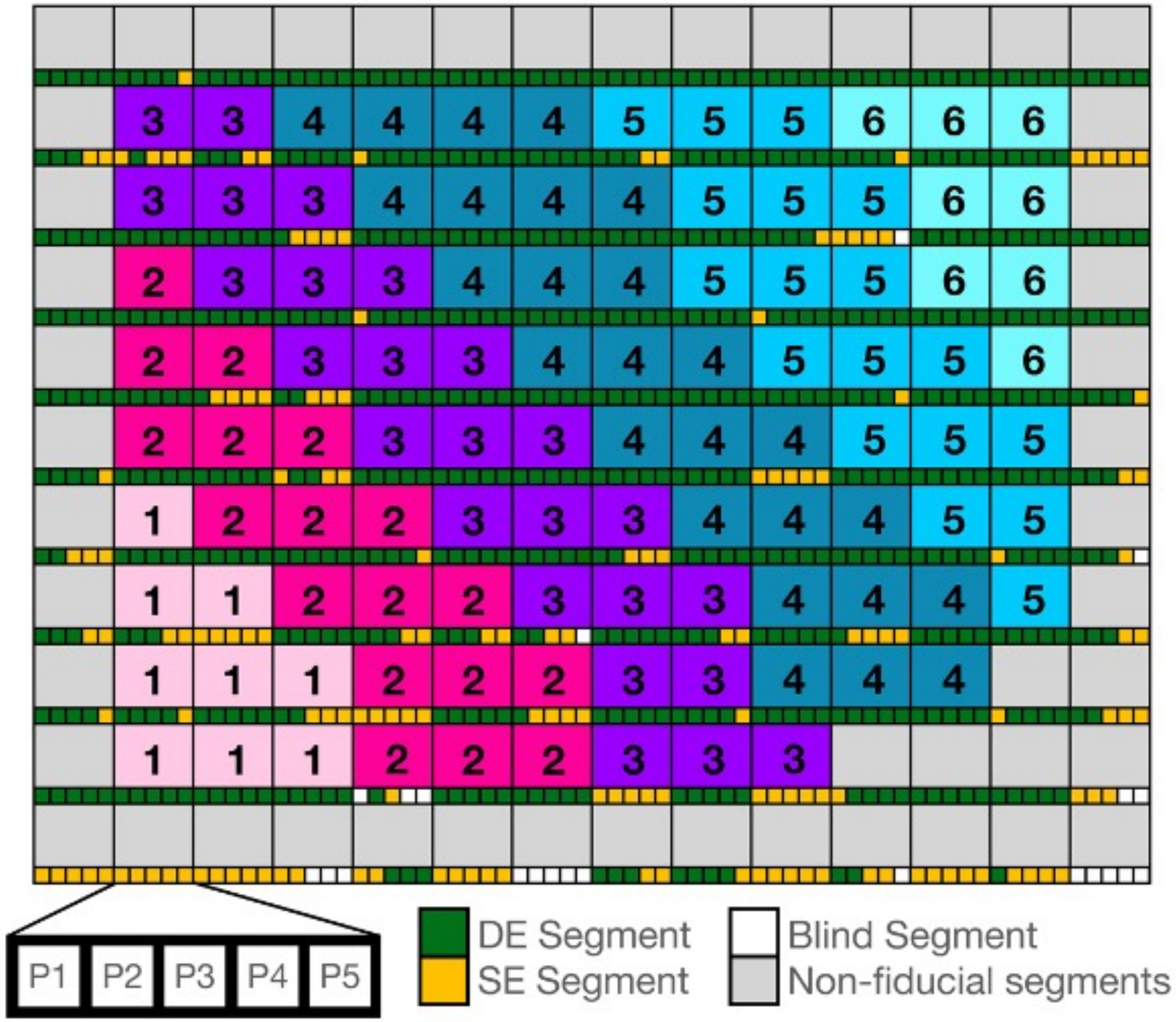
NIMA 961, P163677 (2020)

$$\chi^2_{min}(\sin^2 2\theta, \Delta m^2) = \Delta^T V_{Tot}^{-1} \Delta$$

V: Stat + Sys uncertainty

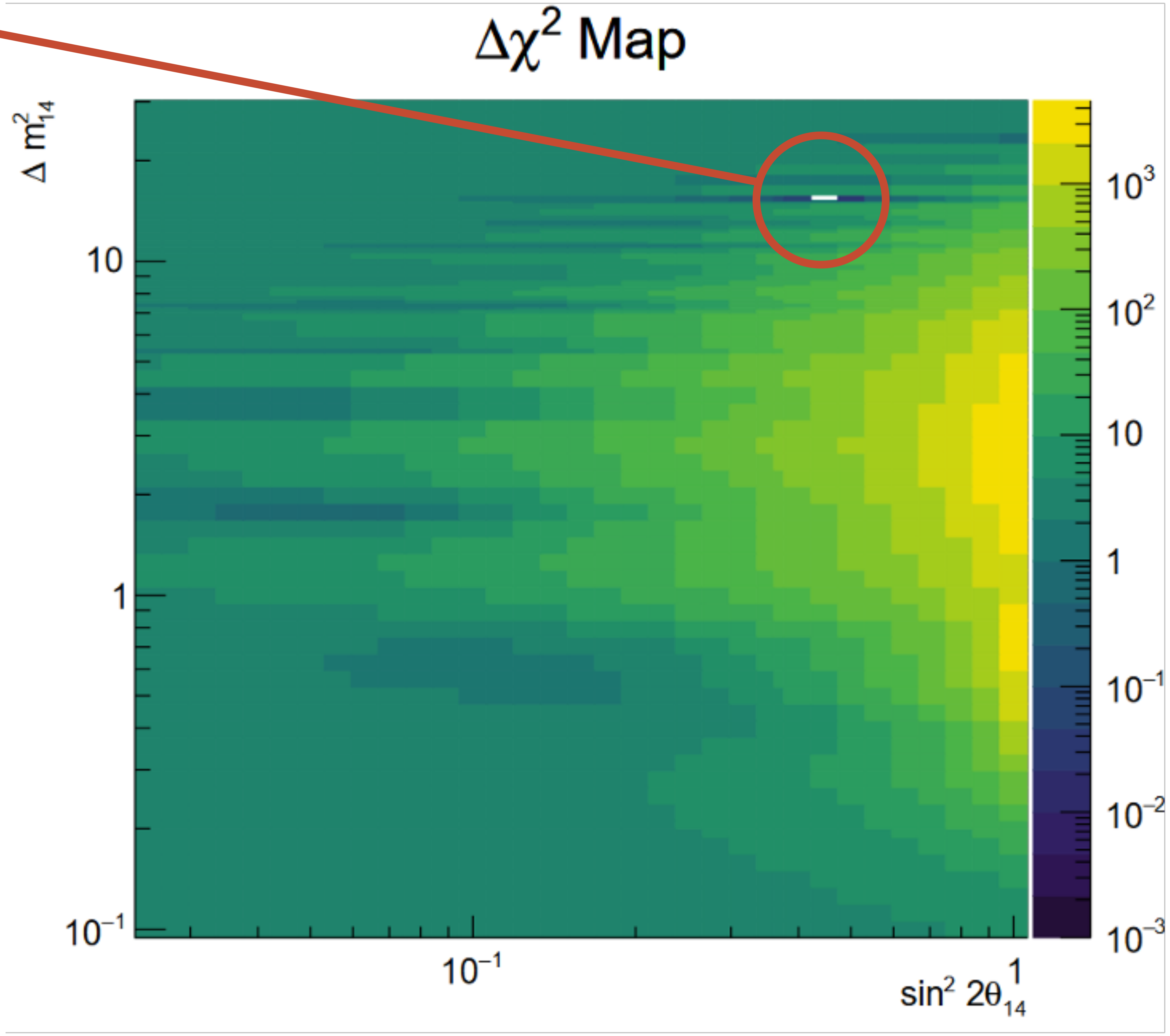
$$\Delta_{l,e} = O_{l,e} - O_e \frac{P_{l,e}}{P_e}$$

$O_{l,e}$: Observed
$P_{l,e}$: Prediction



5 Final Oscillation Analysis Results

- Best-fit point($sin^2 2\theta_{14}$, Δm^2_{14}) = (0.42, 15.2)
  - $\Delta\chi^2$ of 3.56 wrt to the null hypothesis



5 Final Oscillation Analysis Results

- Best-fit point($sin^2 2\theta_{14}$, Δm^2_{14}) = (0.42, 15.2)
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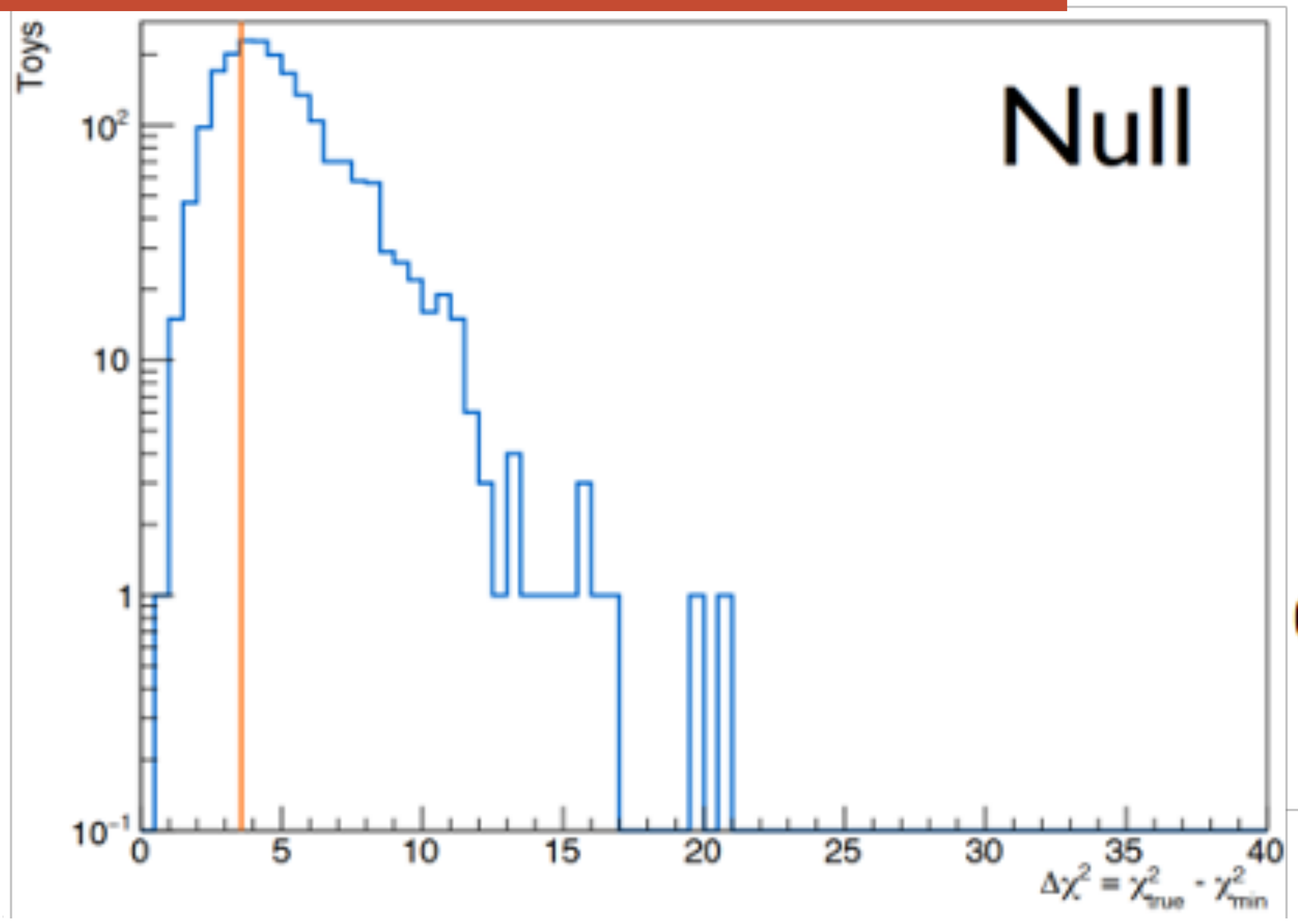
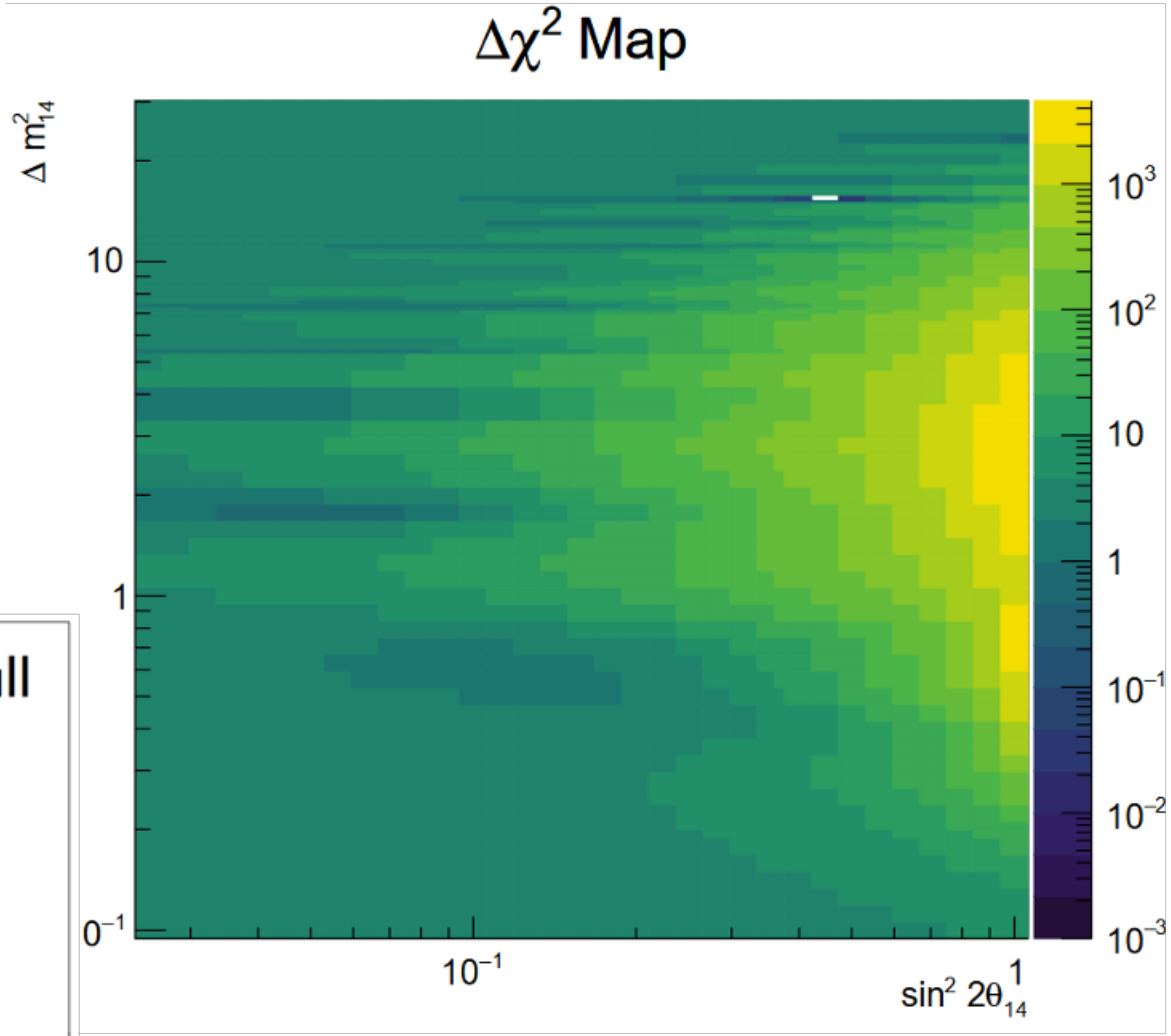
  - Data is highly consistent with null-oscillation toys (p=0.73)





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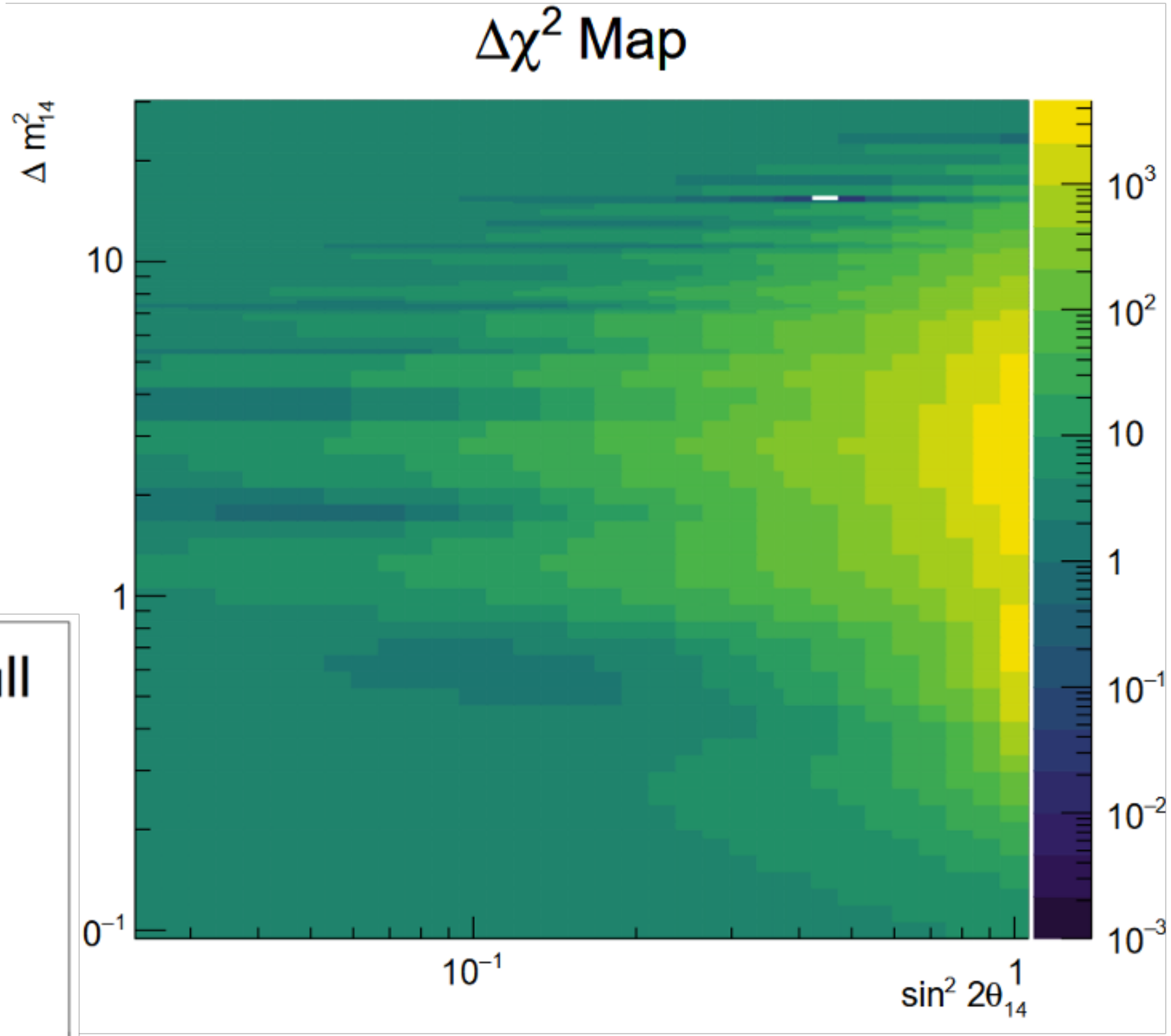

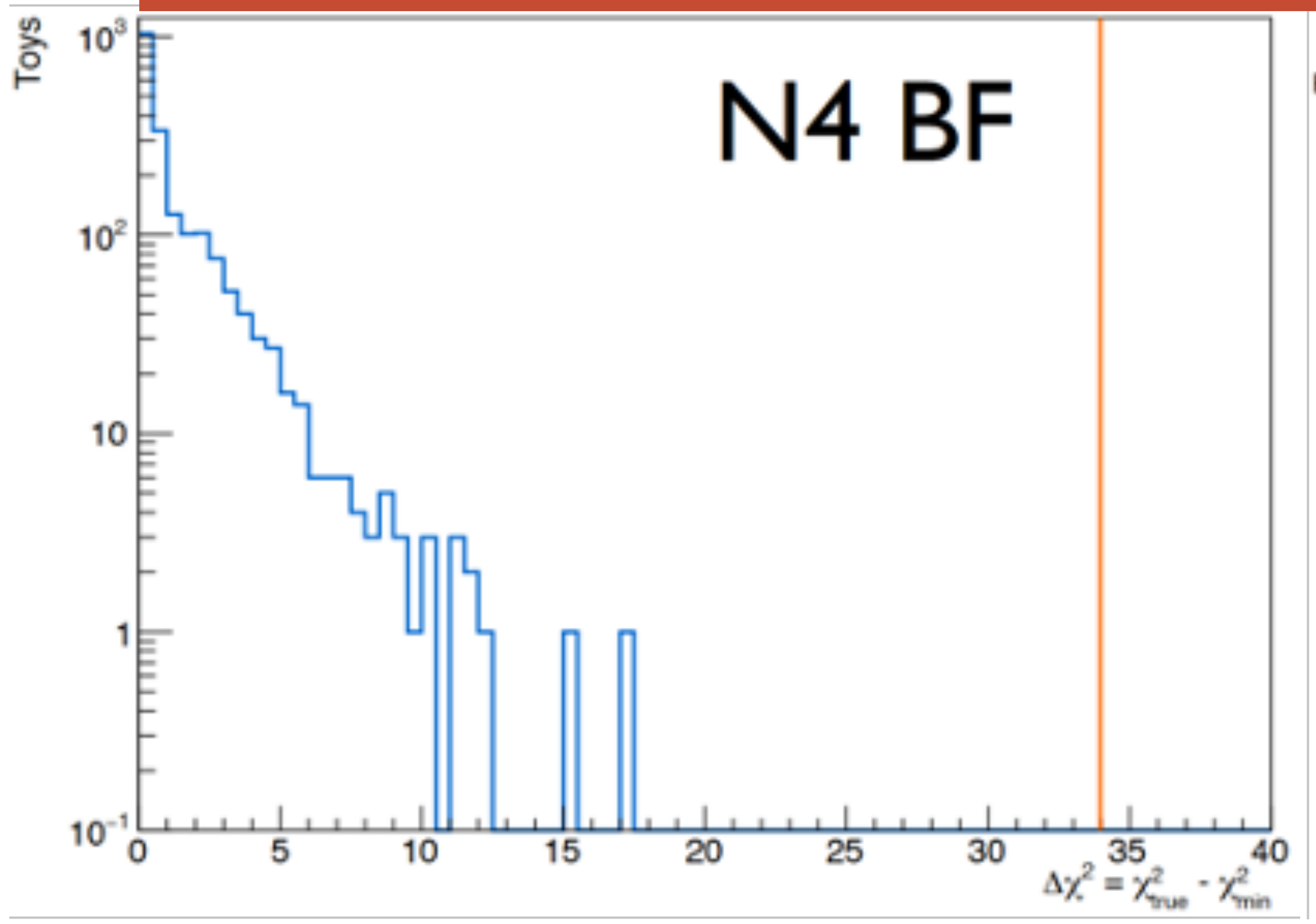

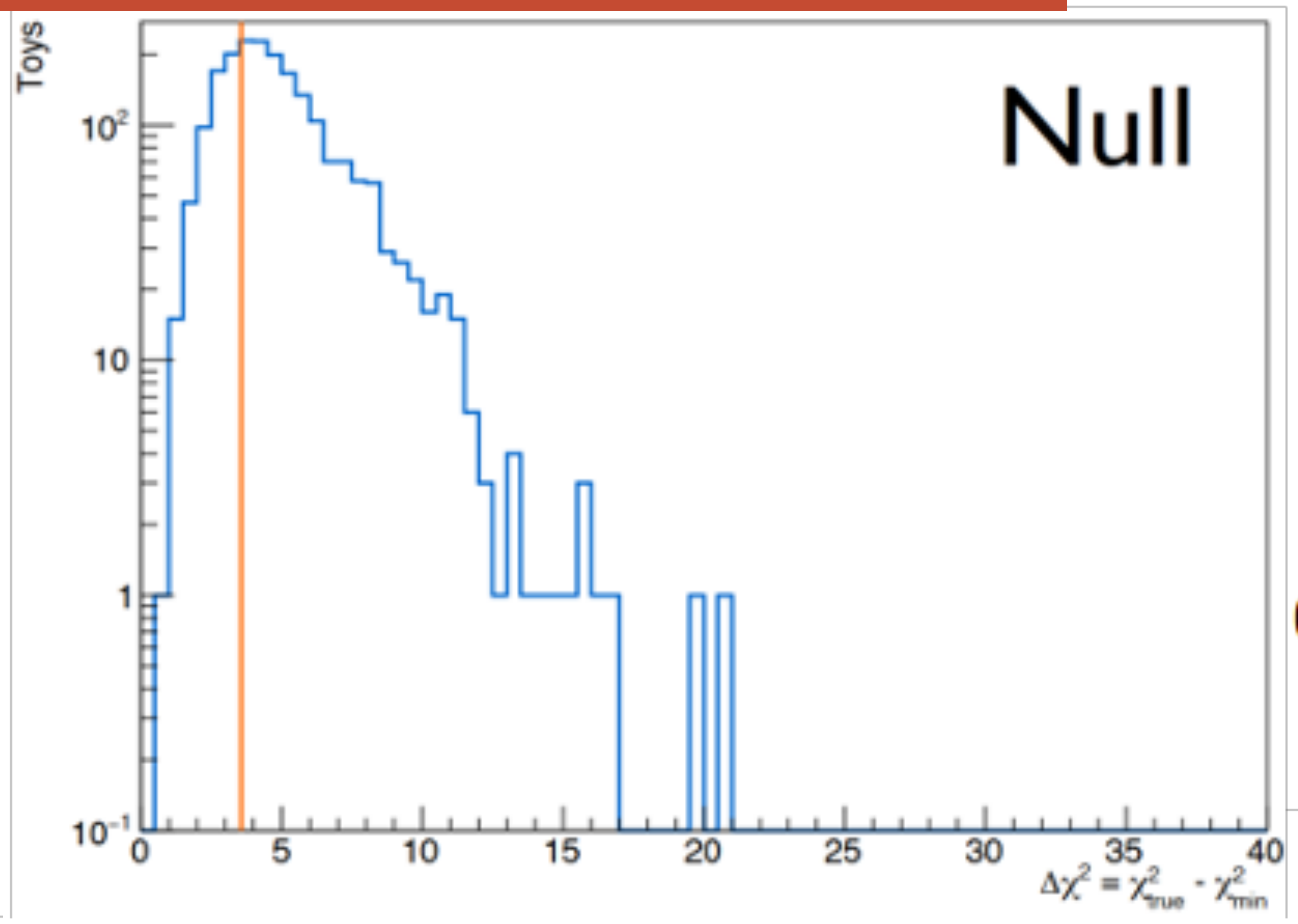

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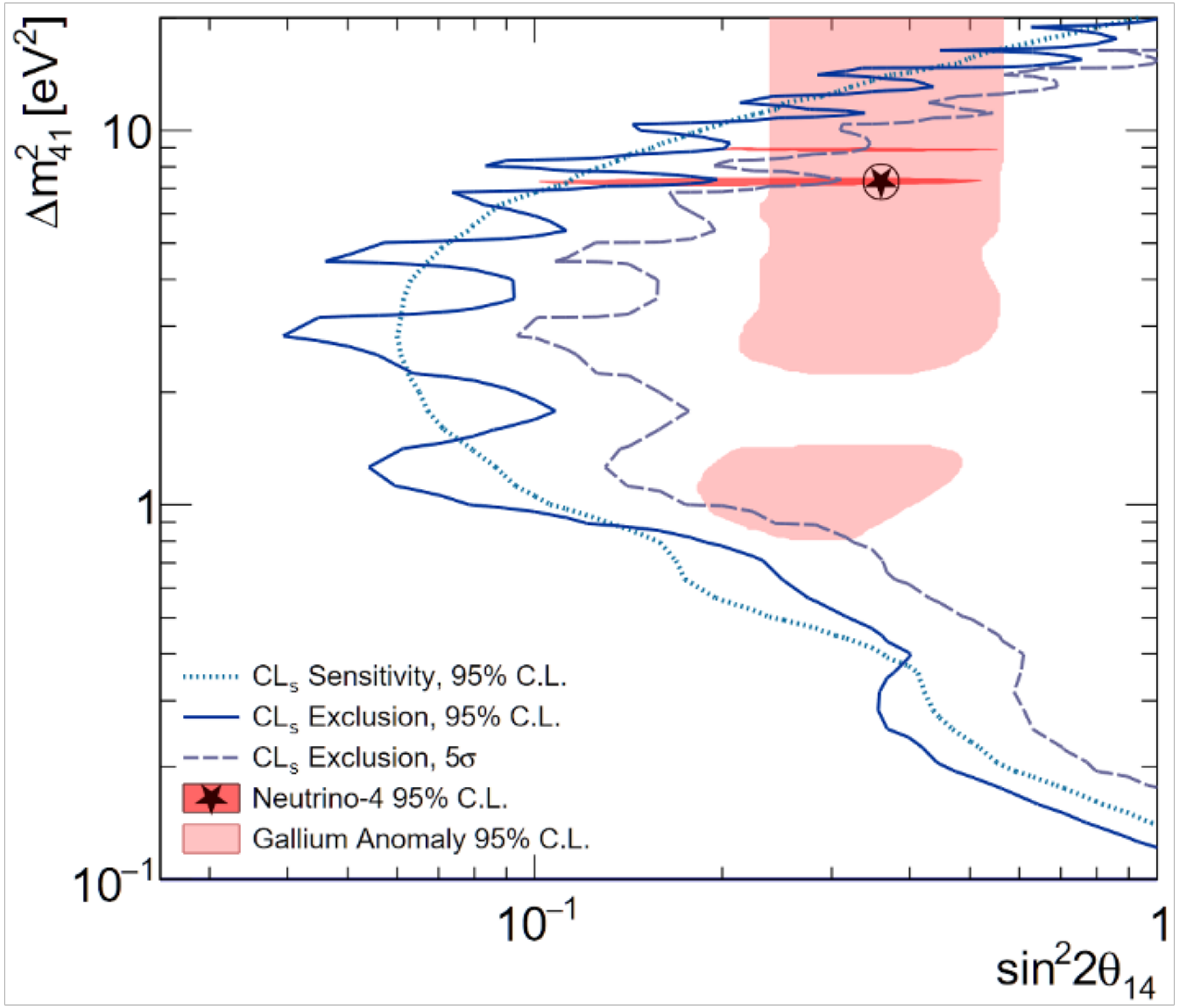

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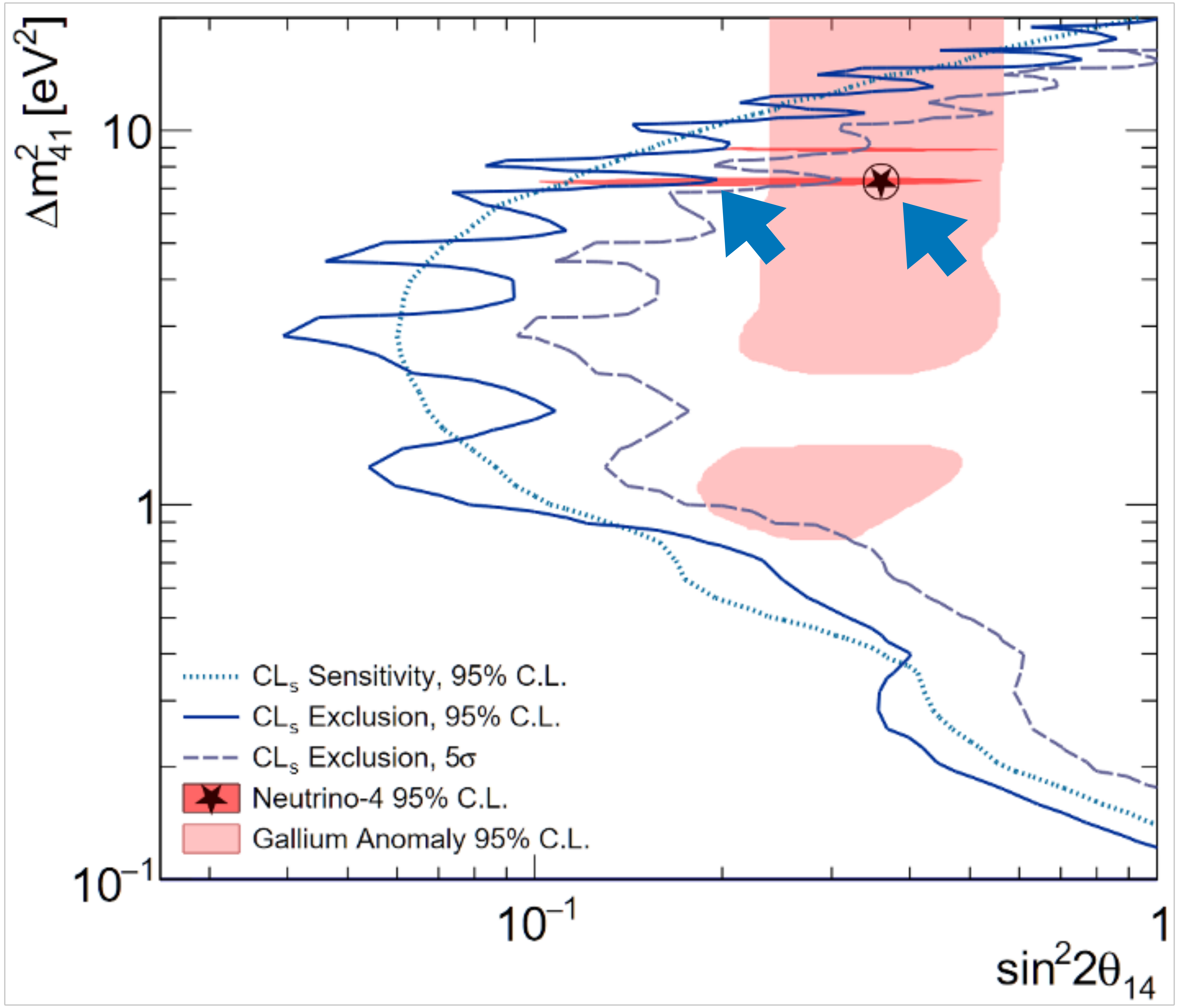
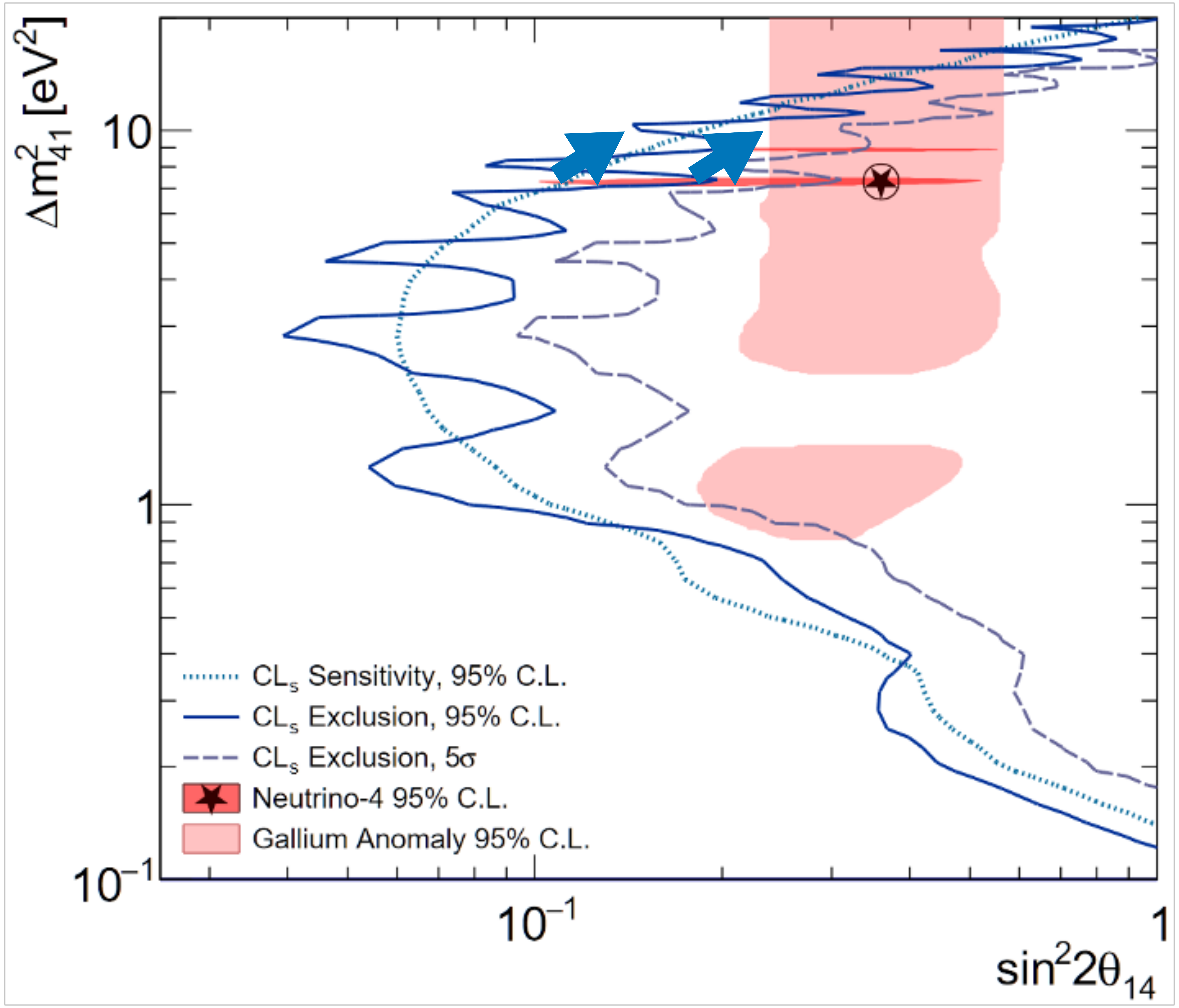


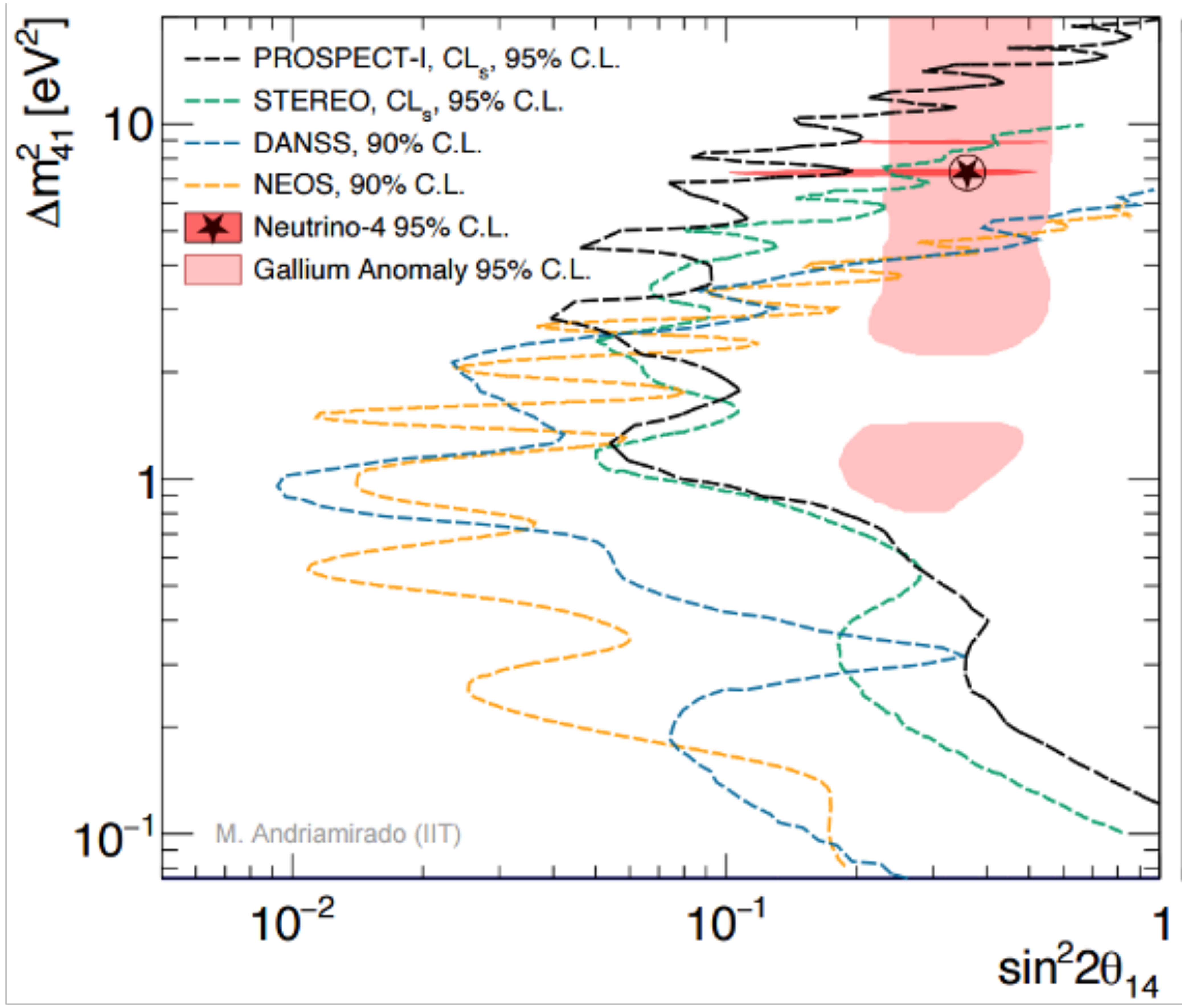
5 Final Oscillation Analysis Exclusion Results

- Given the compatibility of the data with null hypothesis, we use the Gaussian CLs method to draw an exclusion contour
- Claimed observation of short-baseline oscillation from the Neutrino-4 experiment is ruled out at more than 5σ
- Exclude all phase-space for Δm^2 below 10 eV^2 suggested by the recently strengthened Gallium Anomaly at 95% CL



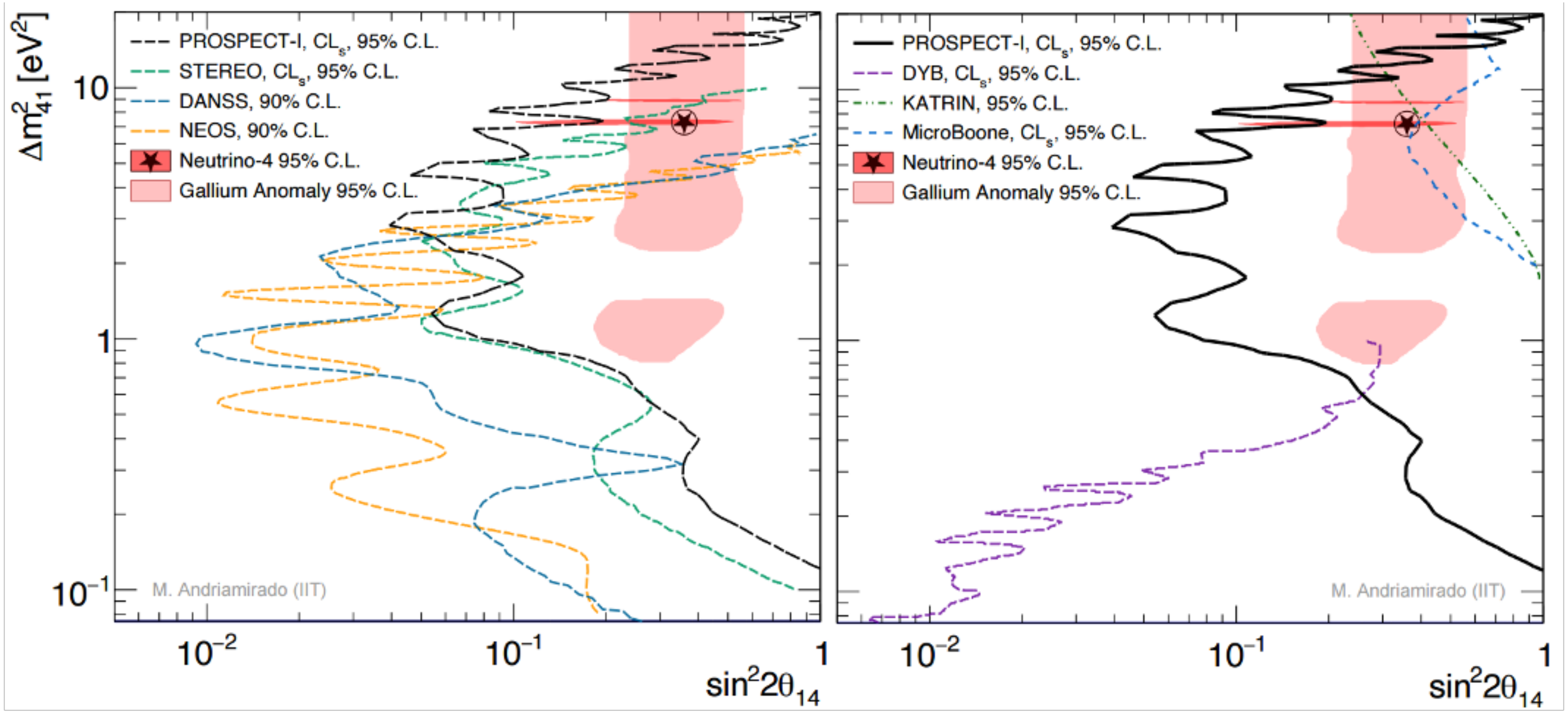
5 Final Oscillation Analysis Global Results

- New PROSPECT limits lead short-baseline reactor efforts for most Δm^2 values above 3 eV^2.



5 Final Oscillation Analysis Global Results

- New PROSPECT limits lead short-baseline reactor efforts for most Δm^2 values above 3 eV^2.
- Reactor-based θ_{14} limits are much stronger than other experiment sectors over most of the pictured phase space

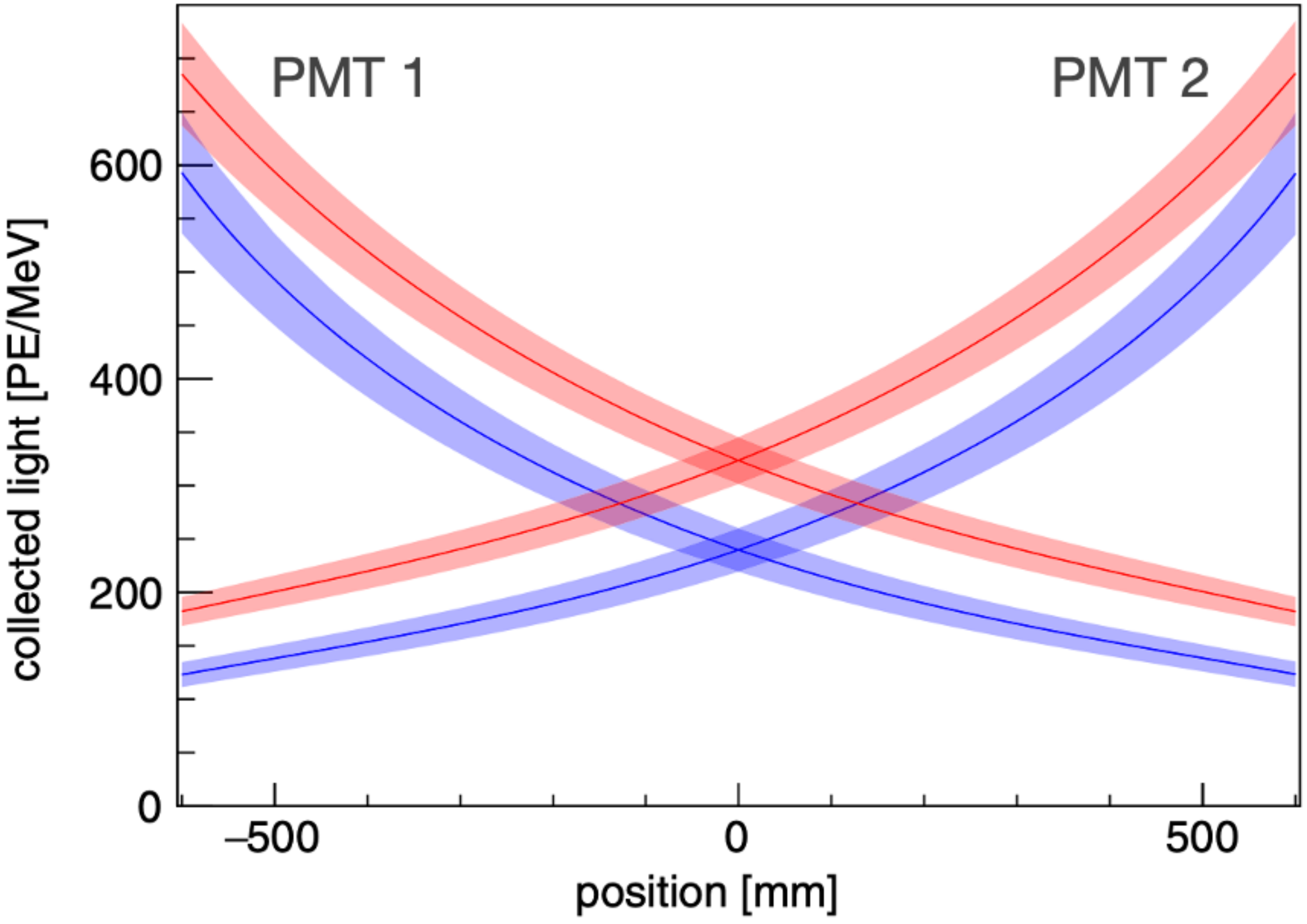


Beyond PROSPECT-I: PROSPECT-II

6 From PROSPECT-I to PROSPECT-II

PROSPECT-I

- LiLS ingress into PMT housing caused PMT degradation
- LiLS degradation caused effective attenuation length and light yield reduction



6 From PROSPECT-I to PROSPECT-II

PROSPECT-I

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PROSPECT-II

- Maintain PROSPECT-I performance
- Improve stability
  - Avoid PMT exposure to LiLS

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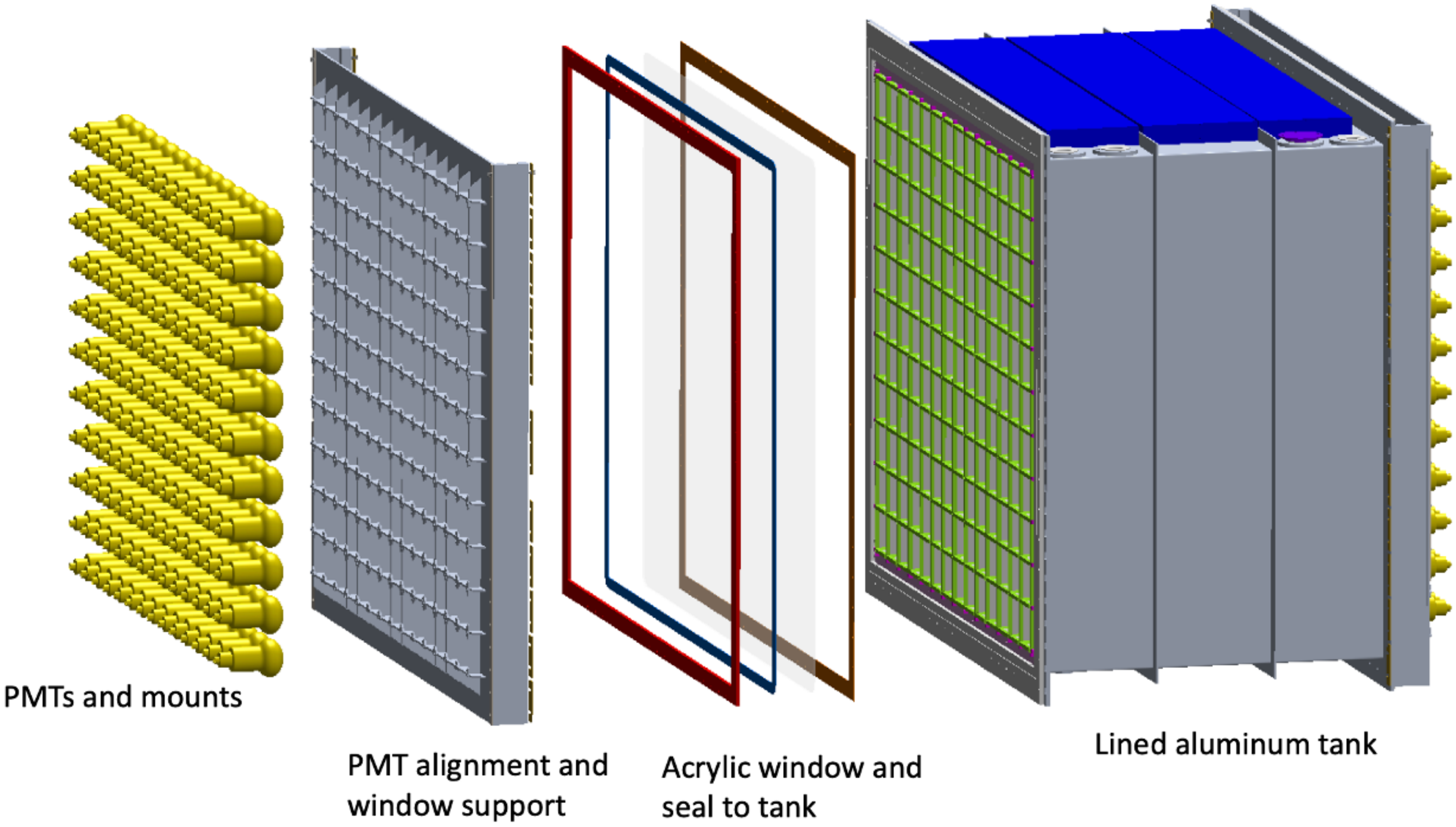
PROSPECT-II

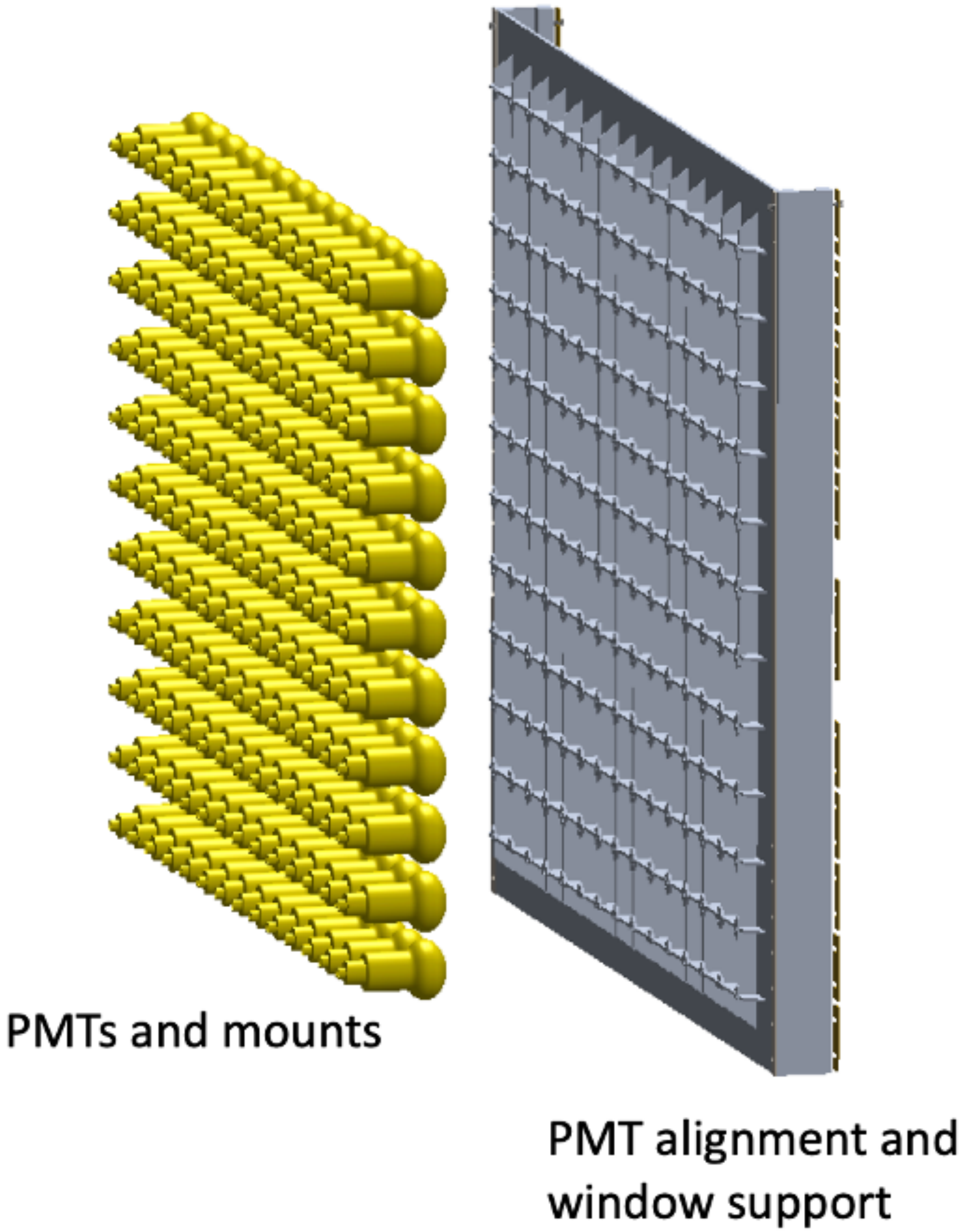
- Maintain PROSPECT-I performance
- Improve stability
  - Avoid PMT exposure to LiLS
  - Minimize LiLS contact with other materials
  - Optimize LiLS isolation

6 Design overview of the PROSPECT-II detector

Let me walk you through the details!

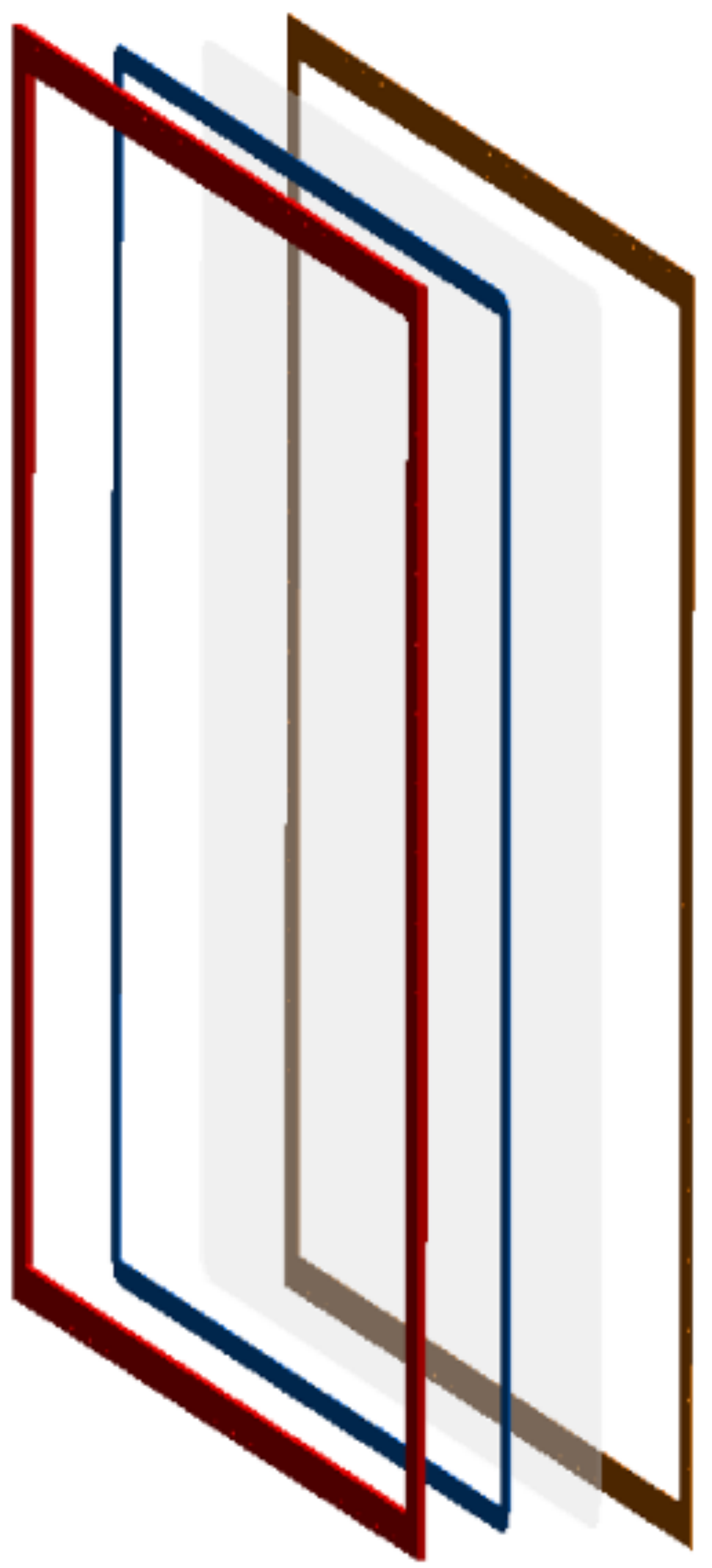


6 Design overview of the PROSPECT-II detector



- PMTs removed from the active volume
- Re-using most of P-I PMTs

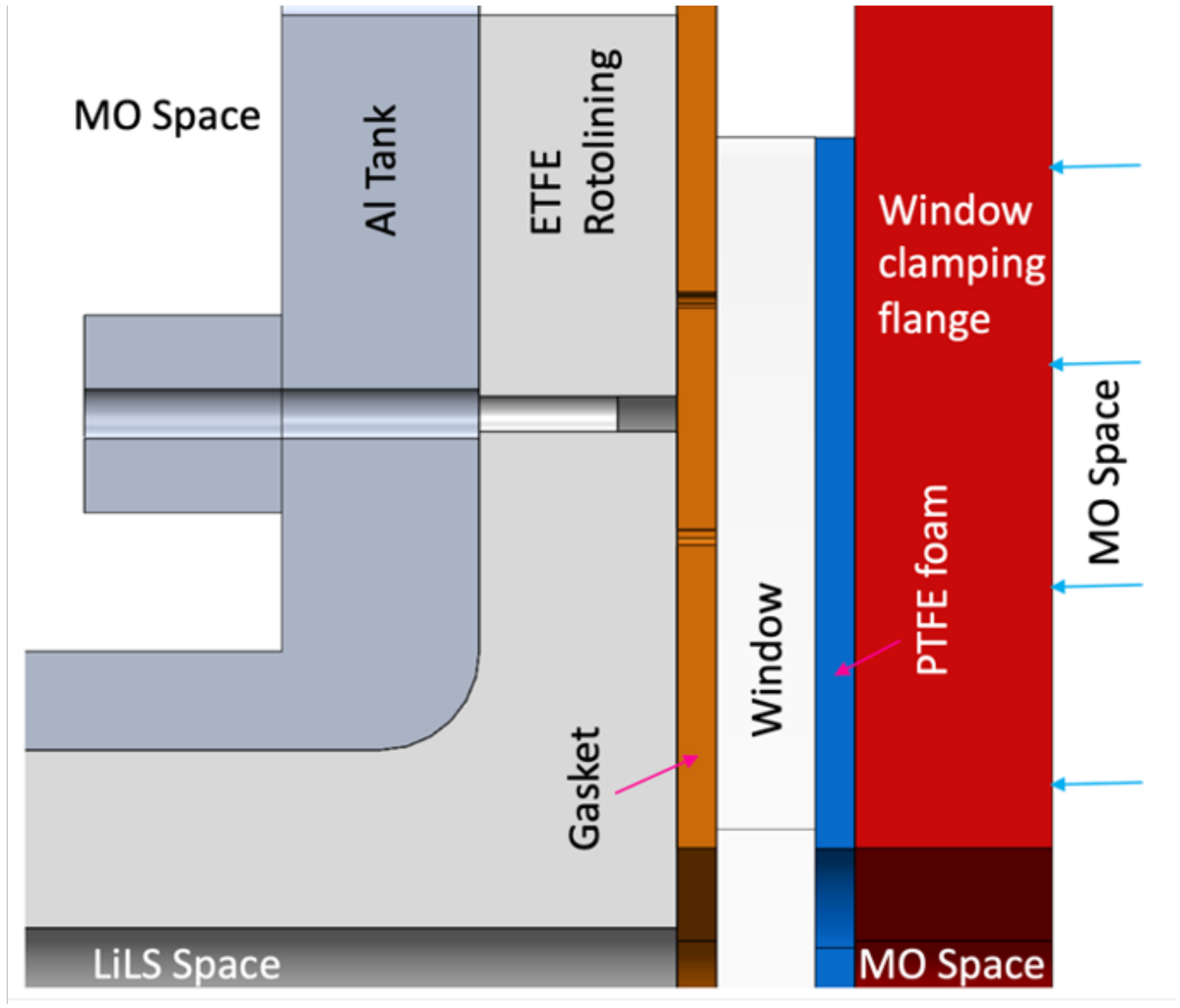
6 Design overview of the PROSPECT-II detector

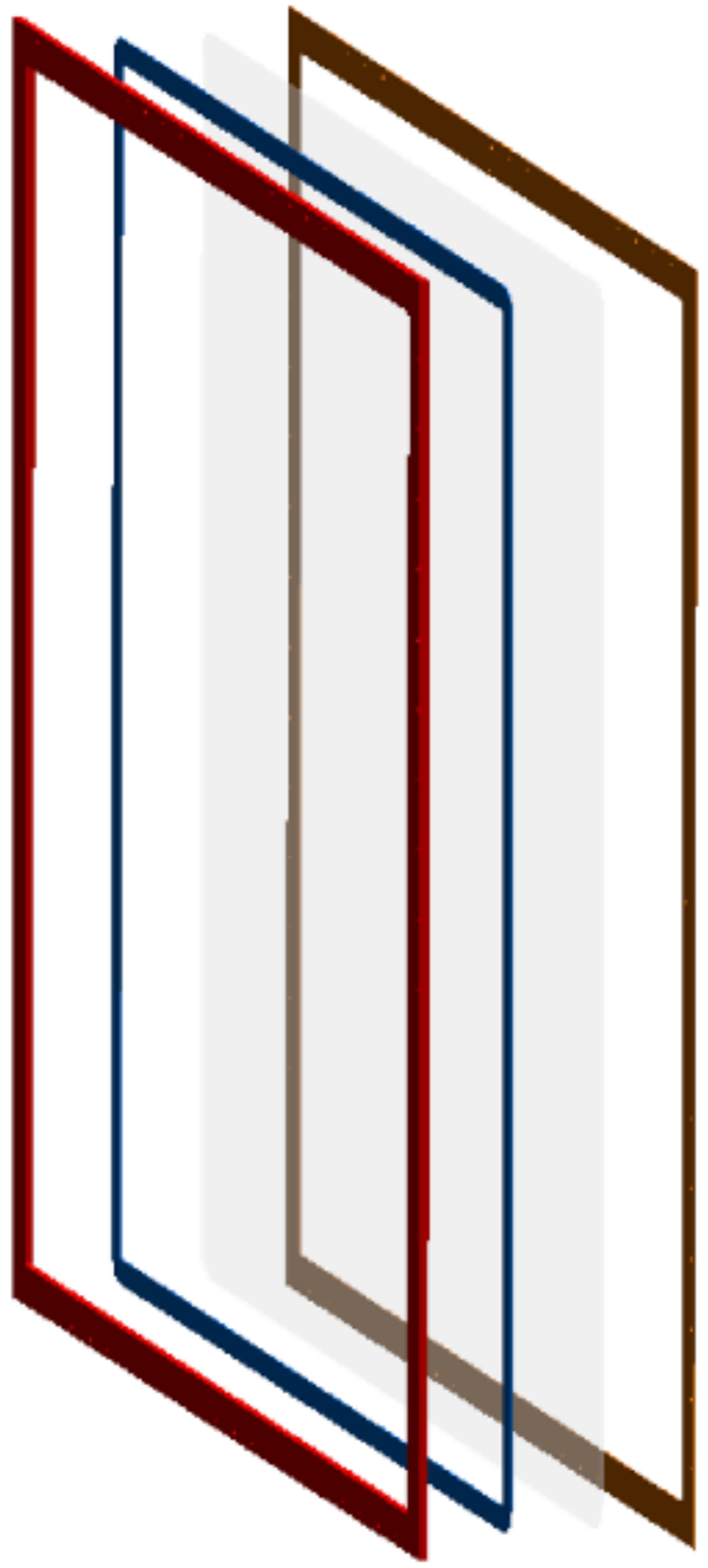


Acrylic window and seal to tank

- Thin (1/4 in) UVT acrylic windows serve as the optical interface between the PMTs and LiLS
- Double-layer seal design

6 Design overview of the PROSPECT-II detector

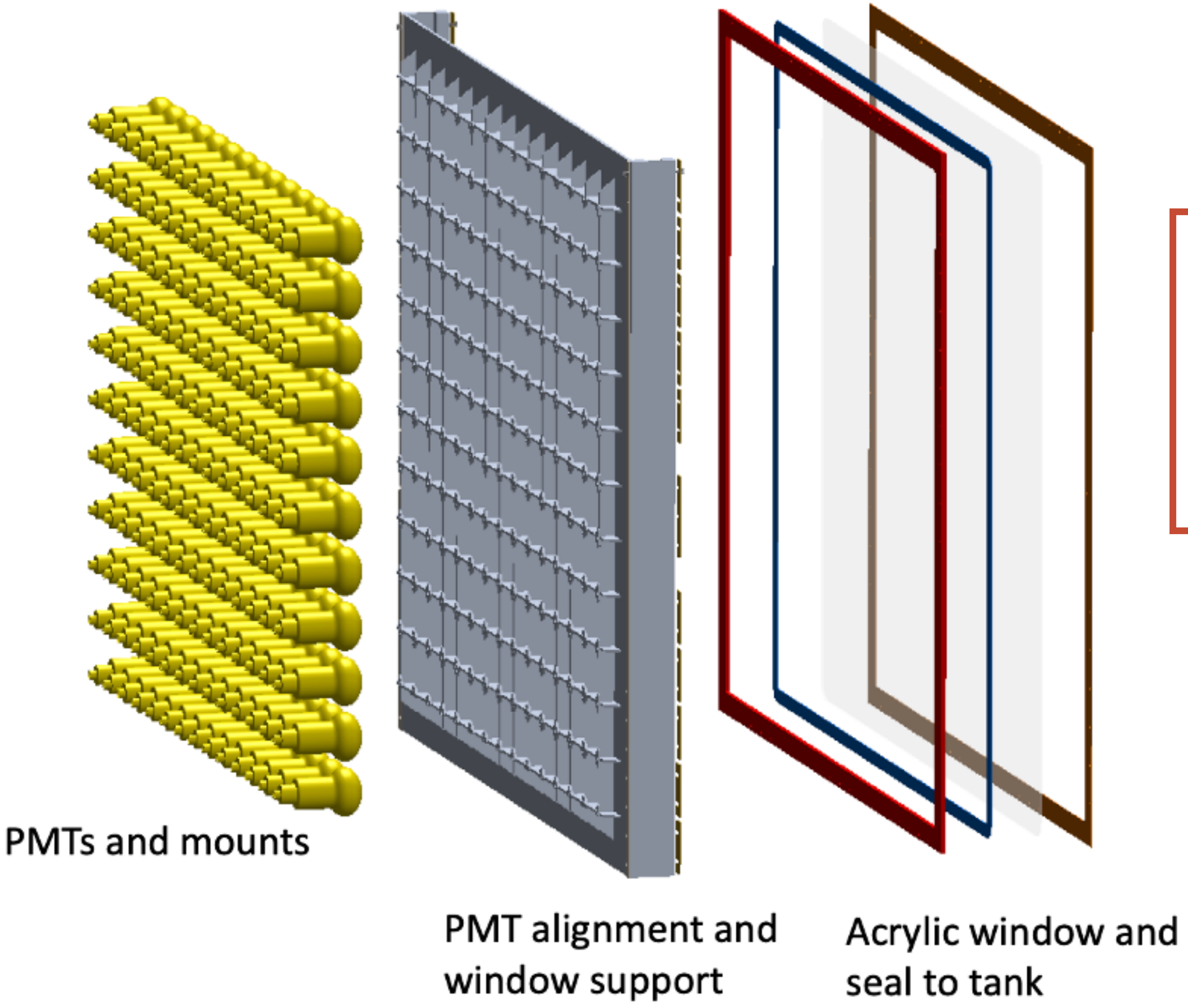




Acrylic window and seal to tank

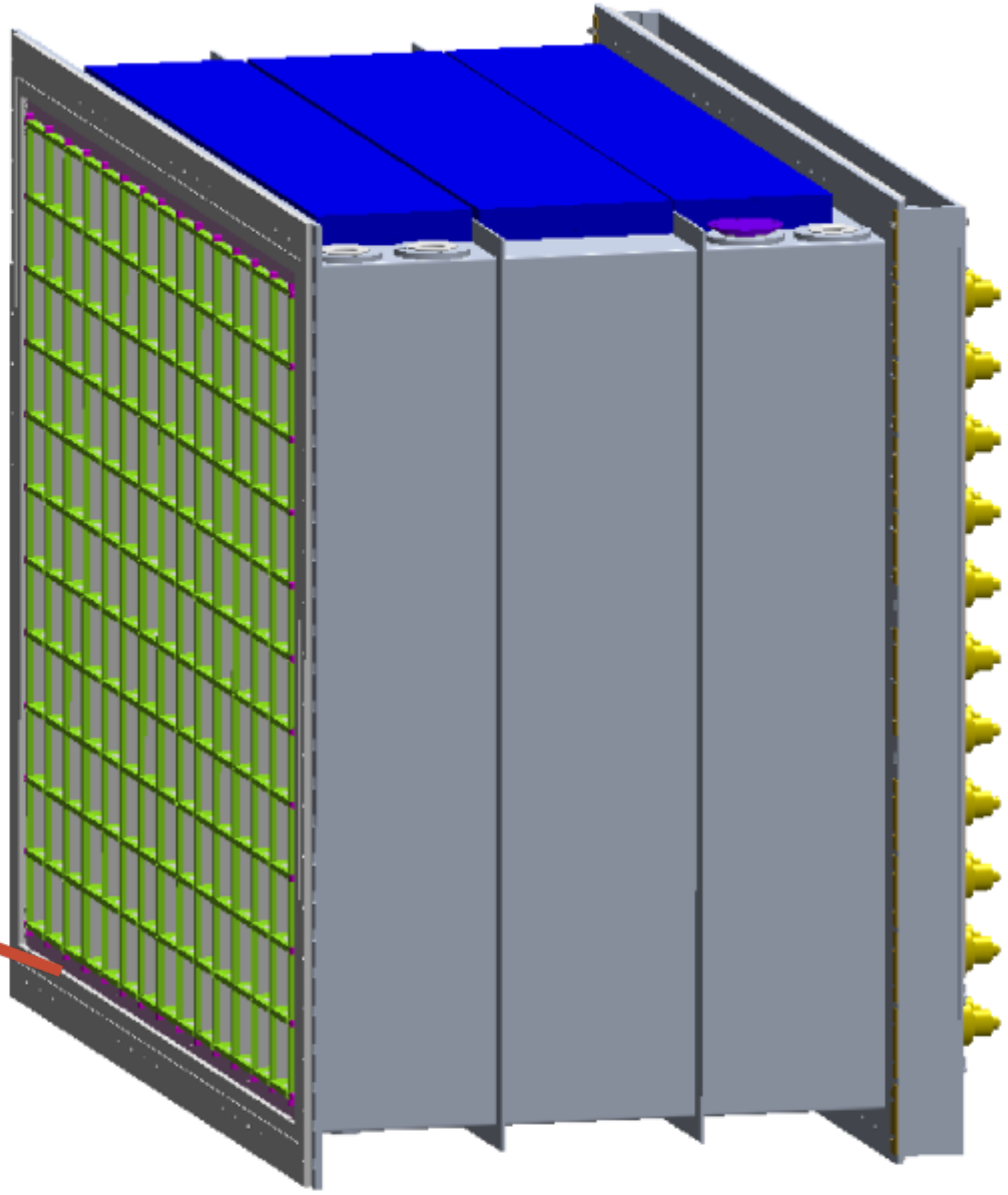
- Thin (1/4 in) UVT acrylic windows serve as the optical interface between the PMTs and LiLS
  - Double-layer seal design
  - Perforated gasket designed for leak inspection before filling and during operations
  - Engineering studies on-going with industrial vendor

6 Design overview of the PROSPECT-II detector



- This new structure is slimmer, allowing 20% more active volume while keeping the vessel the same size!

6 Design overview of the PROSPECT-II detector

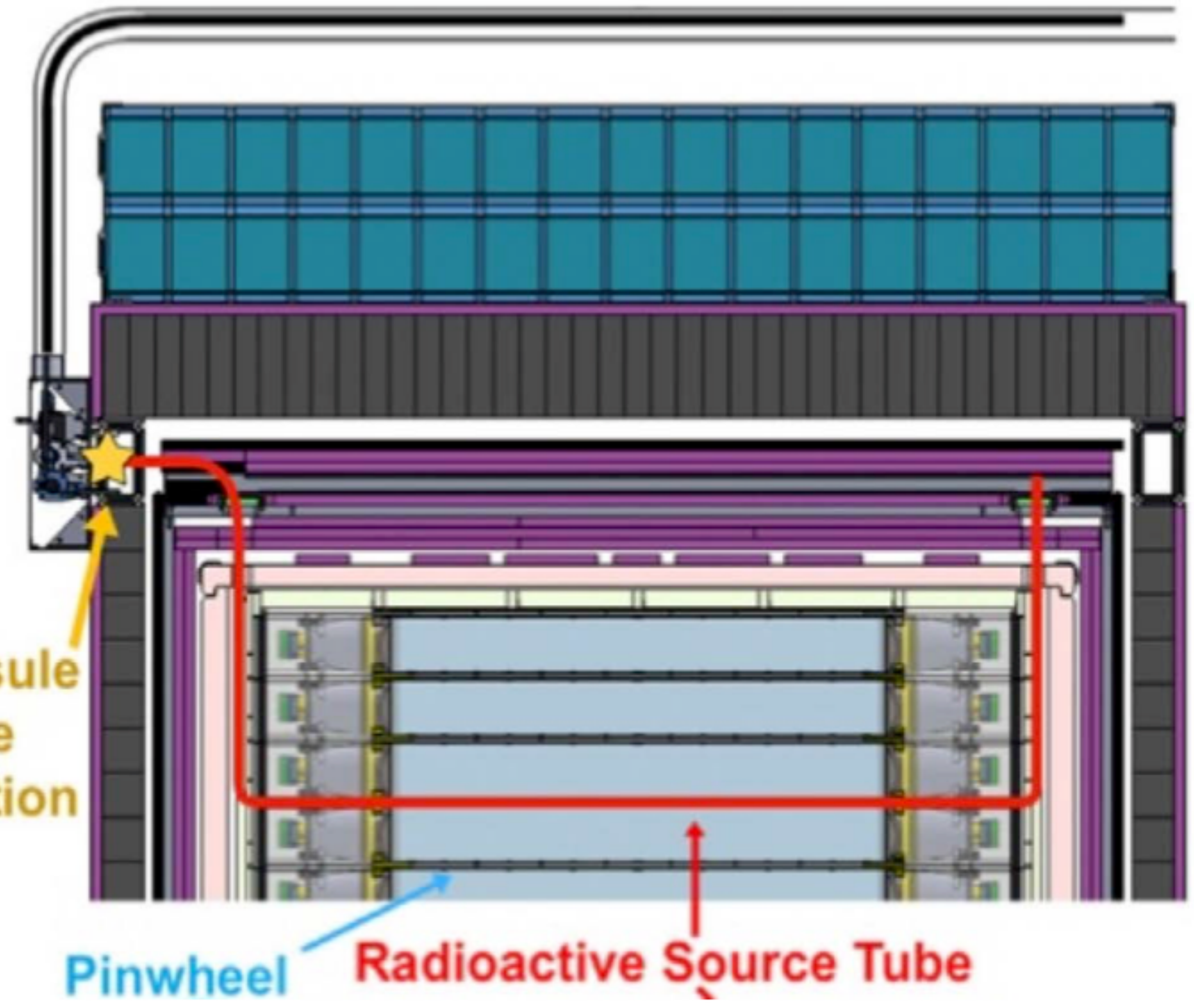


Lined aluminum tank

- Teflon lining -> barrier between LiLS and metal tank
- Keeping the 154 segments

6 Design overview of the PROSPECT-II detector

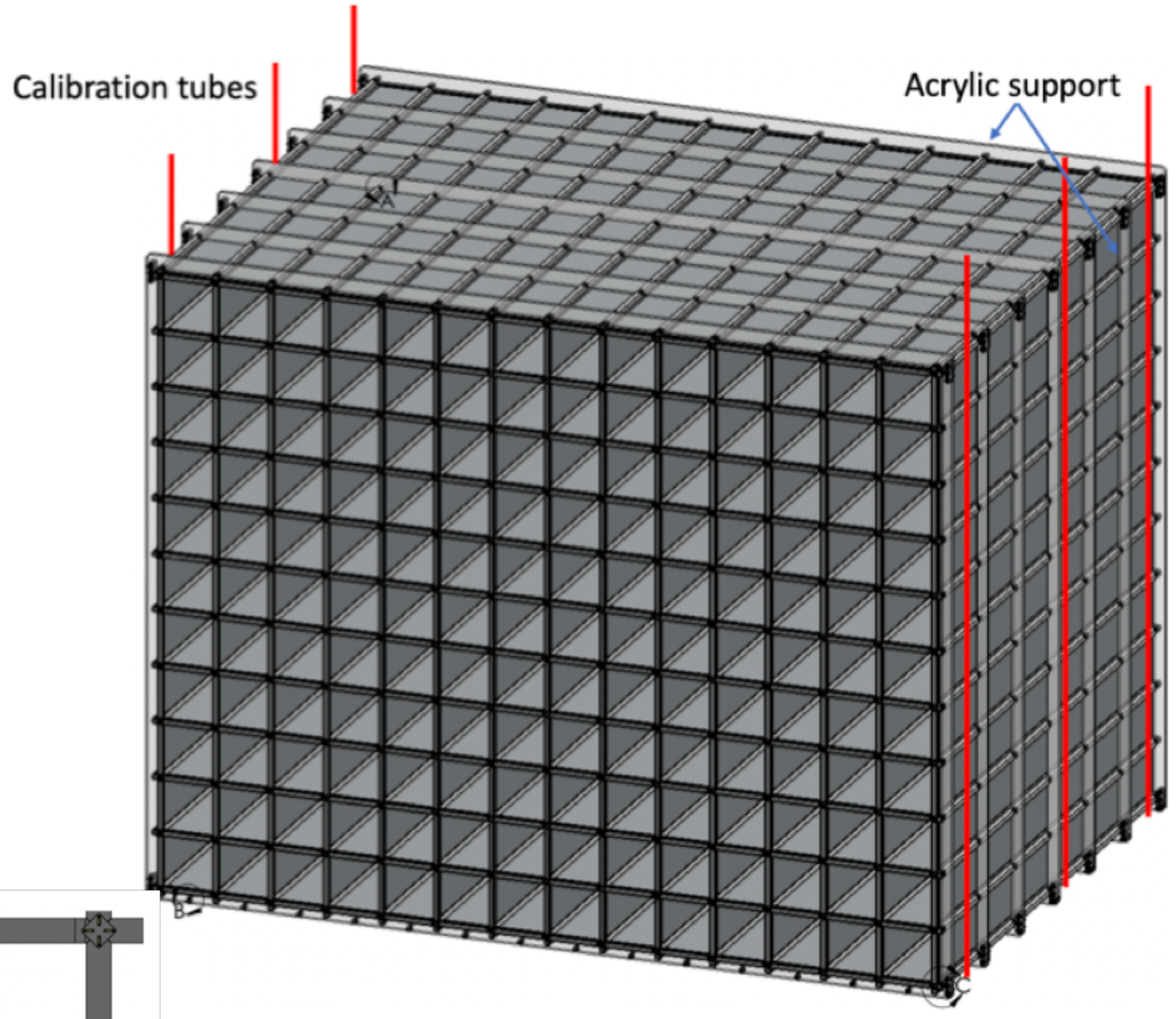
PROSPECT-I

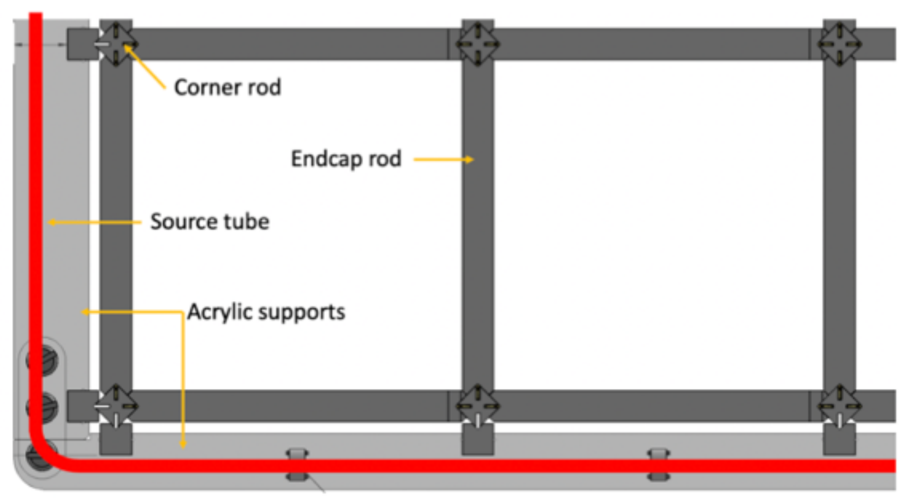


NIMA 944, 162465 (2019)

PROSPECT-II

- New external calibration system design
  - Fewer penetrations
  - Simplified design





JINST 18 P06010 (2023)

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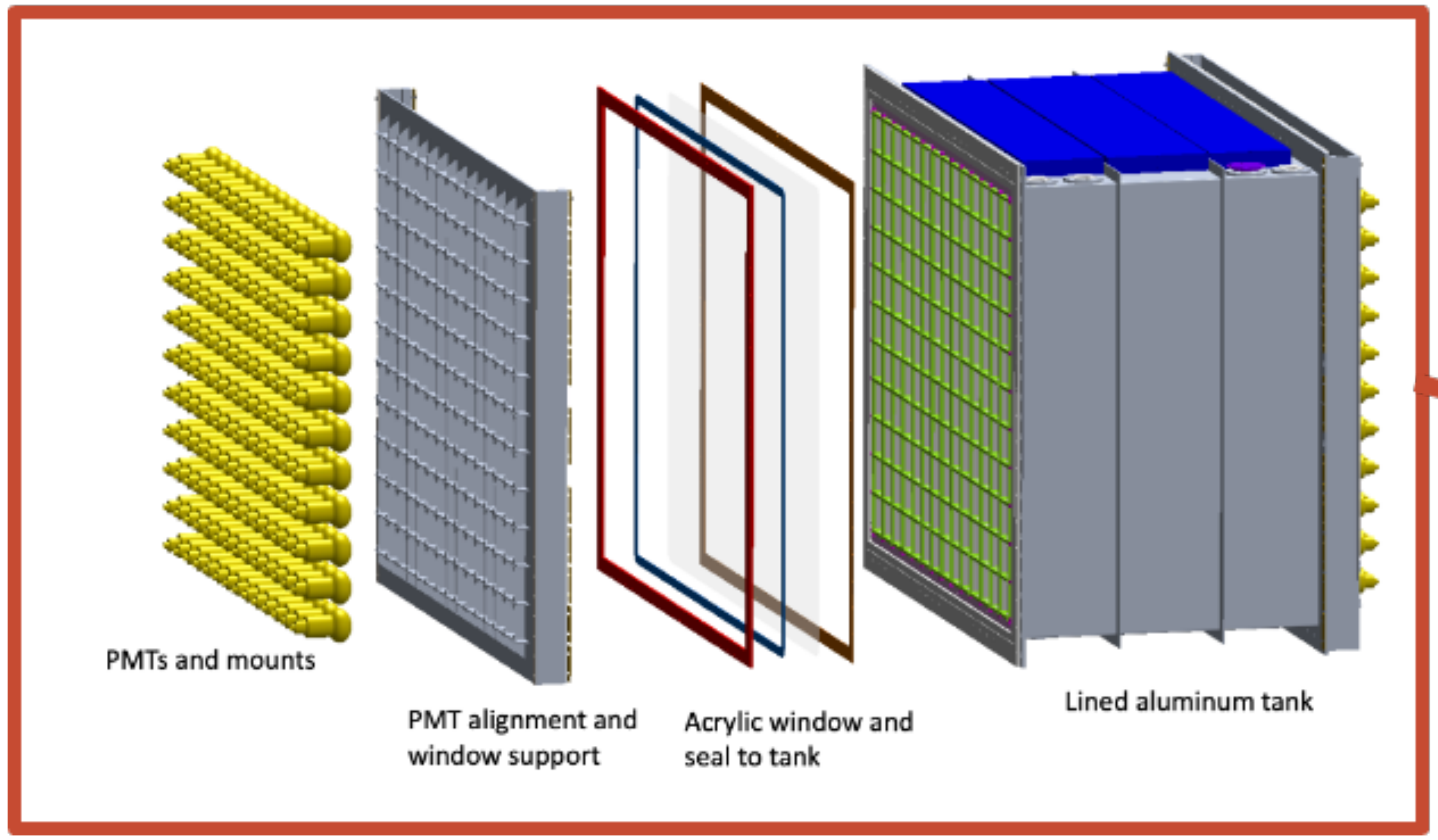

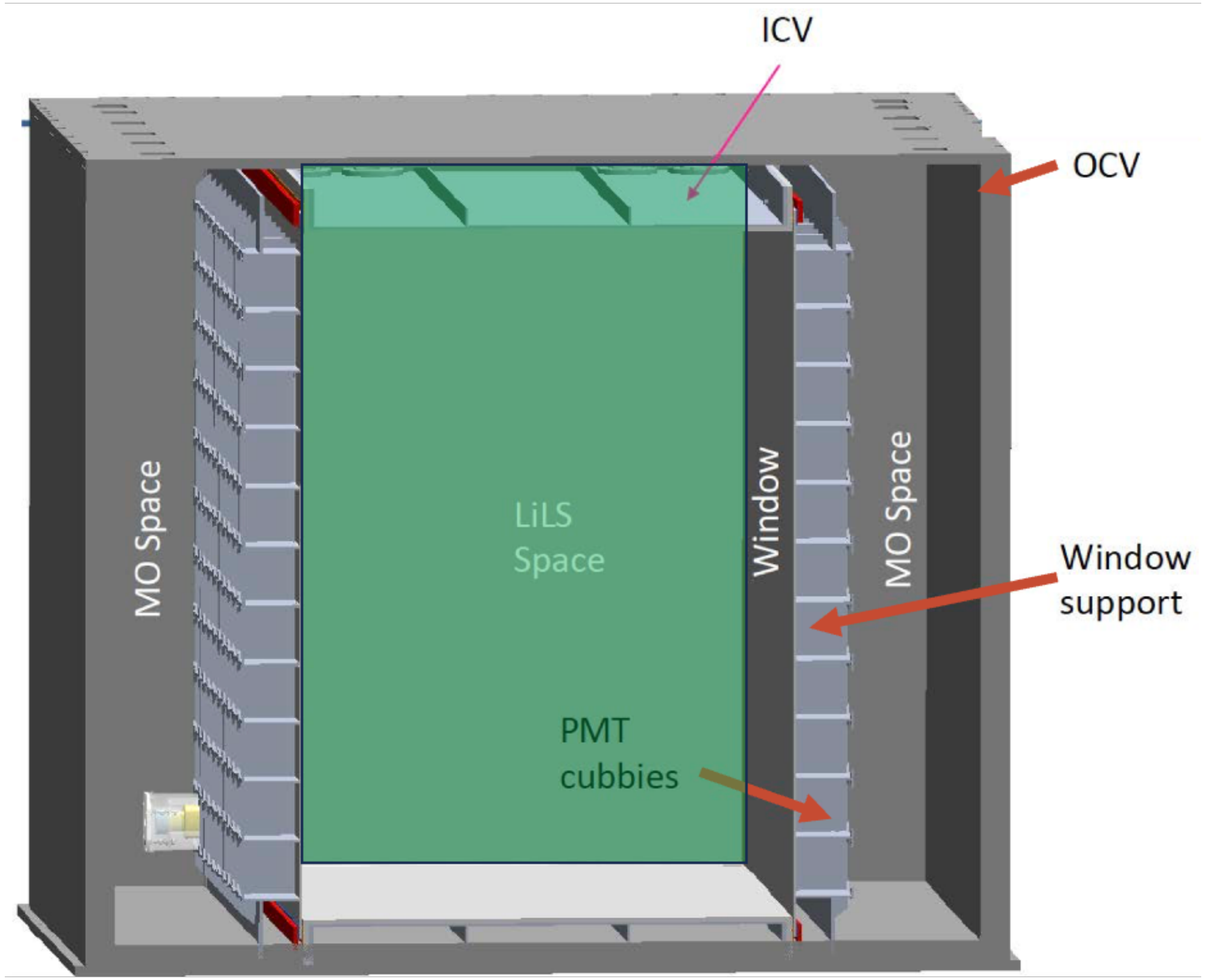

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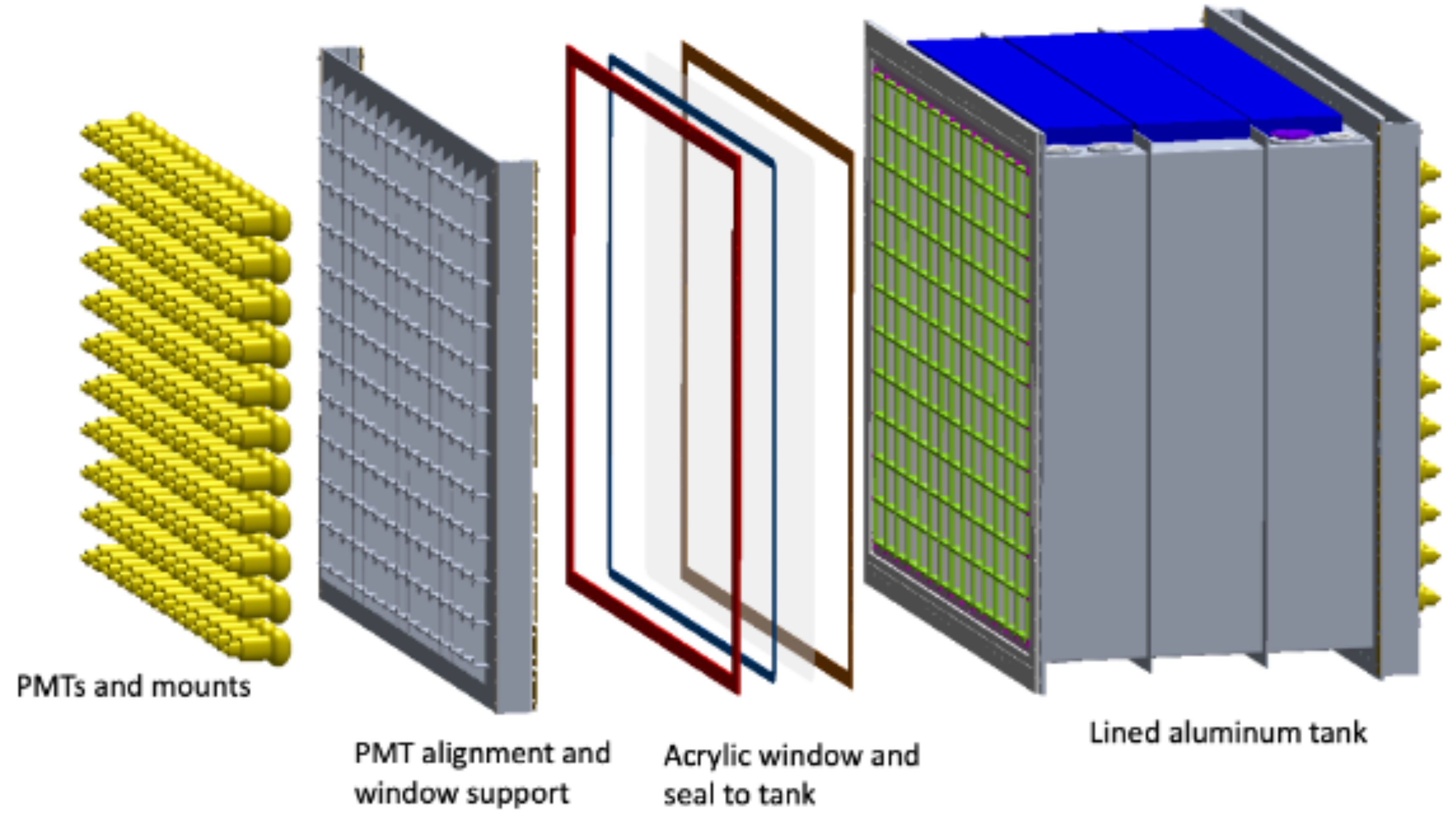
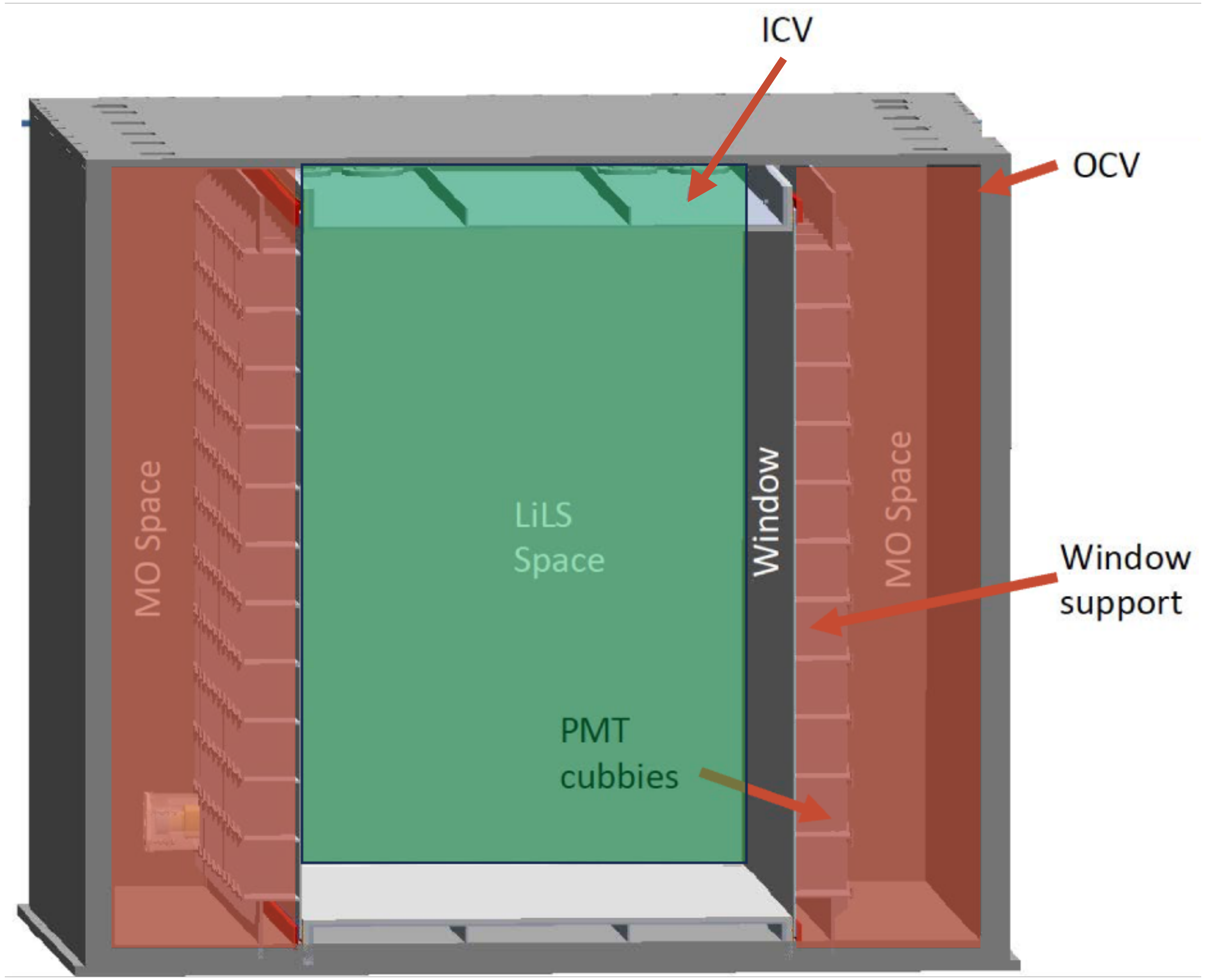
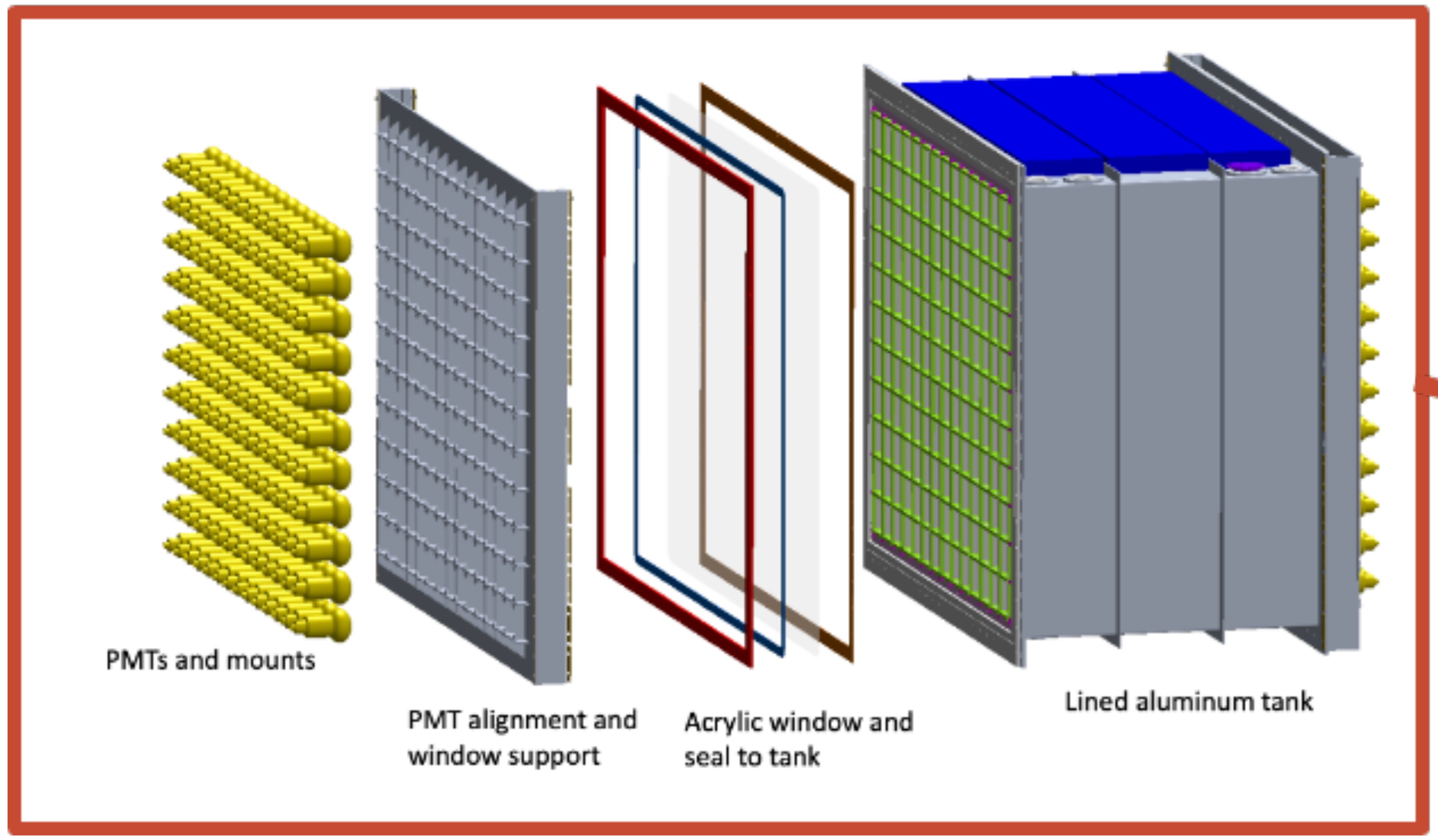
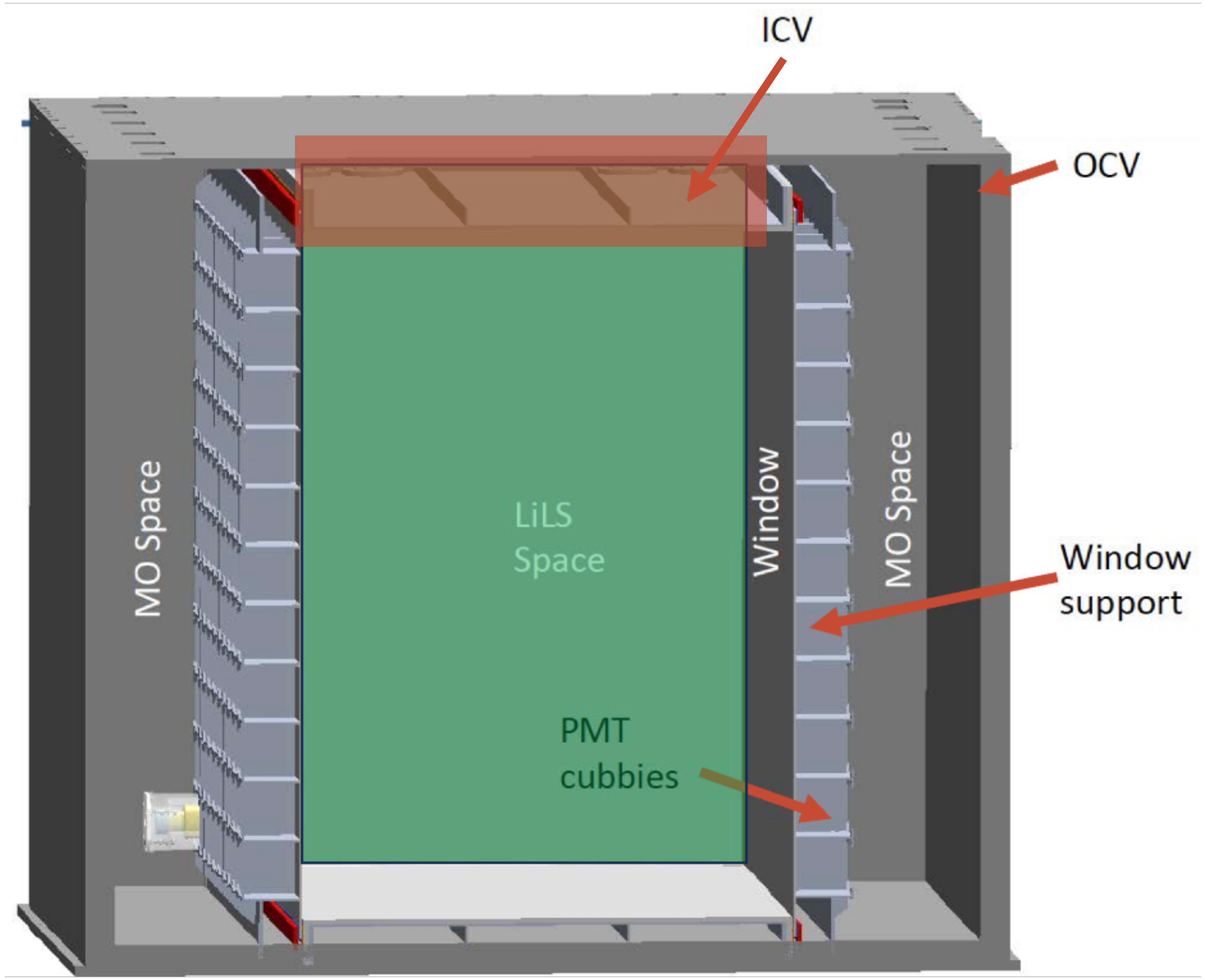




- Mineral oil between ICV and OCV provides optical coupling and shielding

6 Design overview of the PROSPECT-II detector





- Mineral oil between ICV and OCV provides optical coupling and shielding
- LiLS overflow

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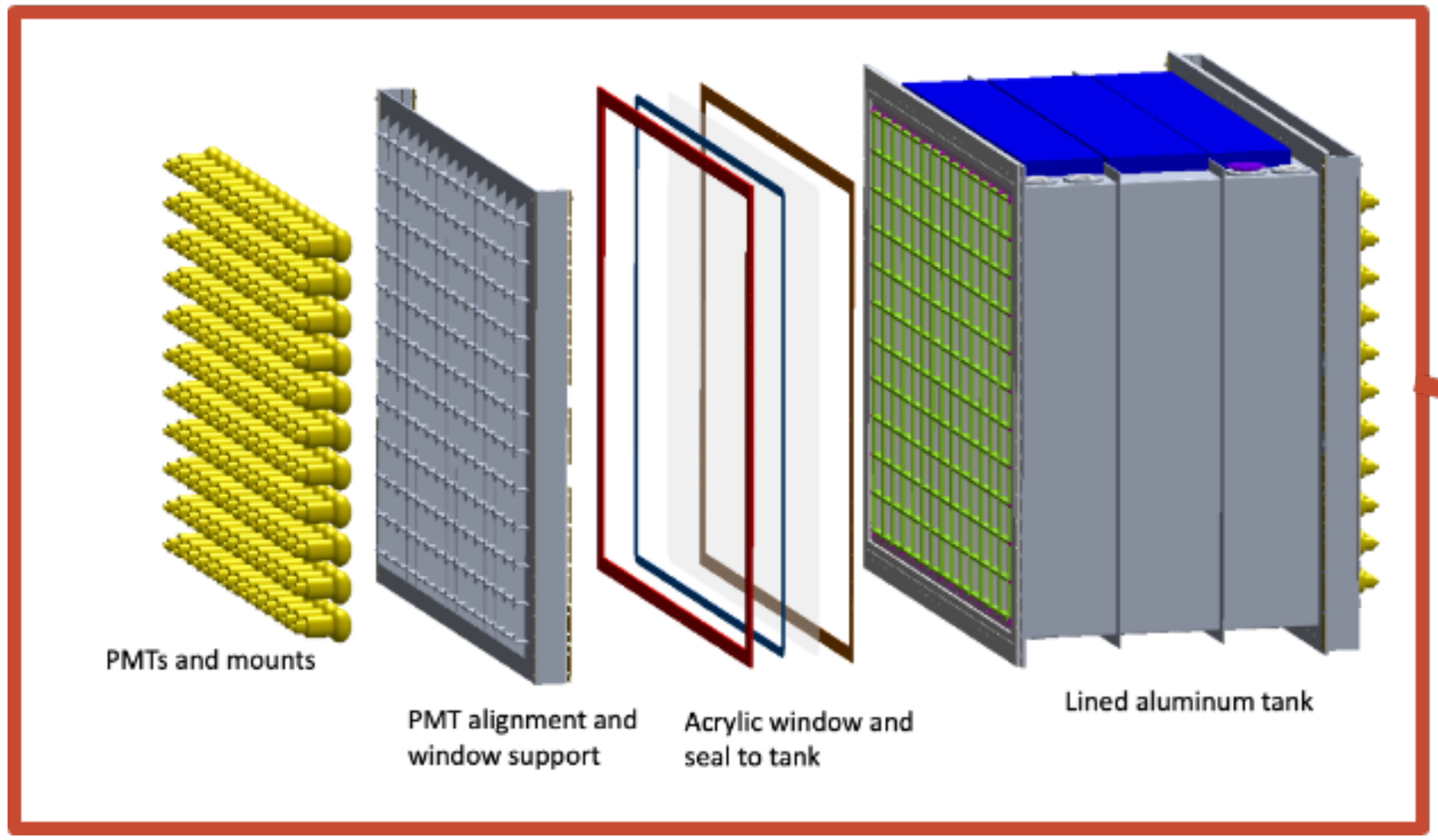
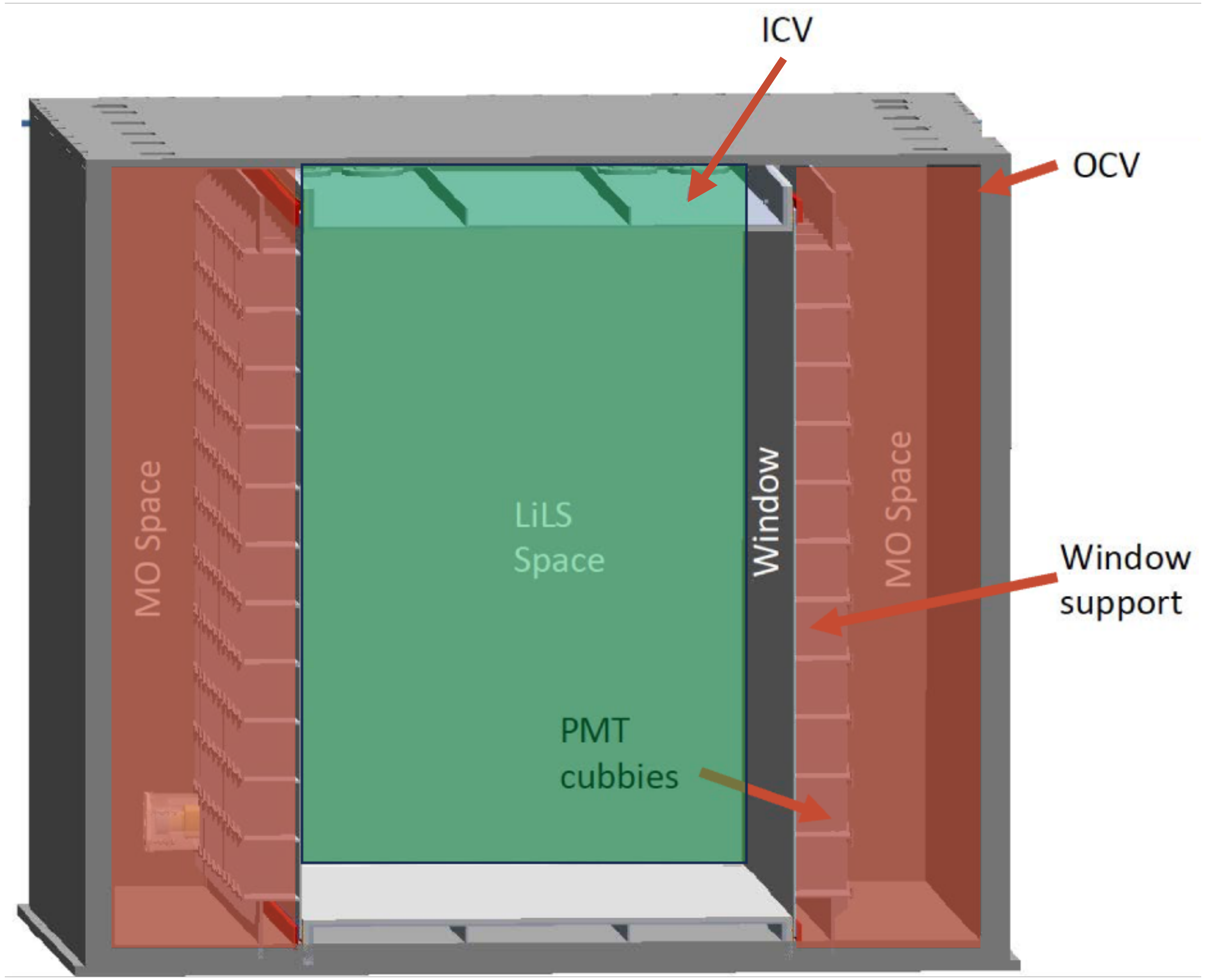


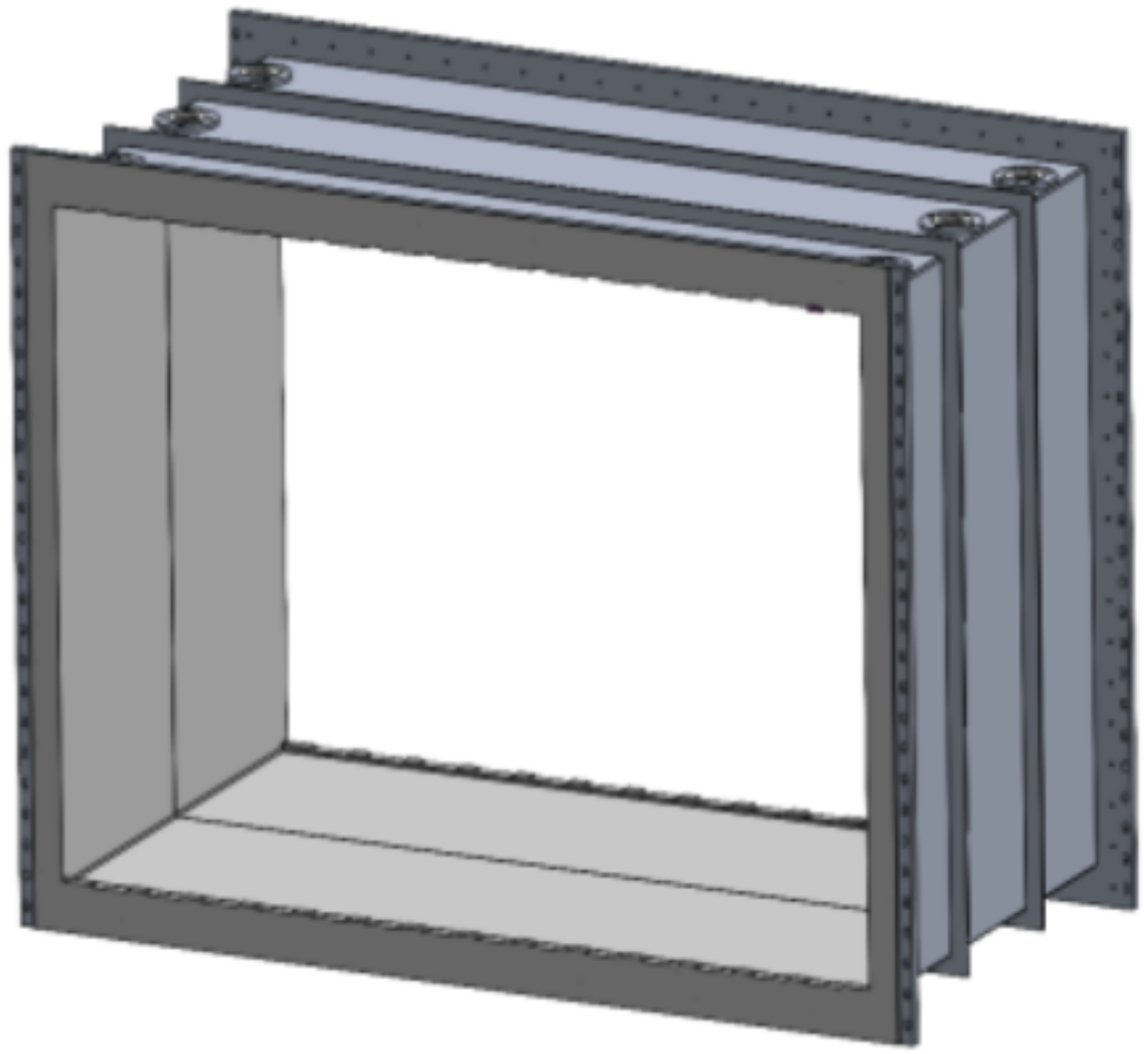


- Mineral oil between ICV and OCV provides optical coupling and shielding
- LiLS overflow
- Added temperature control system
- Cabling out of LiLS volume

6 PROSPECT-II R&D Milestones

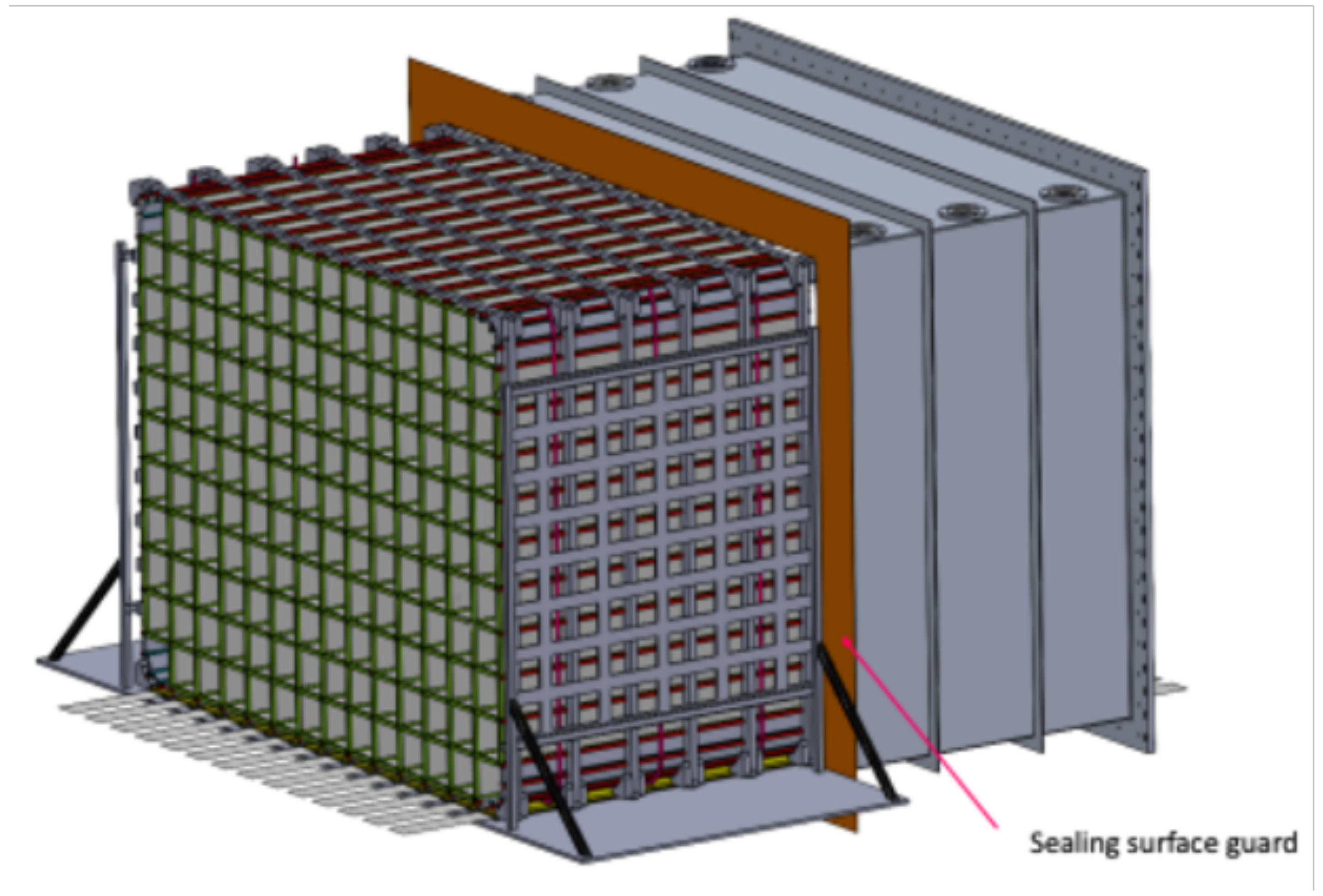
Stage 1 (Current):

- Design and build the inner containment vessel
- Engineering Test: full fill with complete liquid control/ monitoring systems



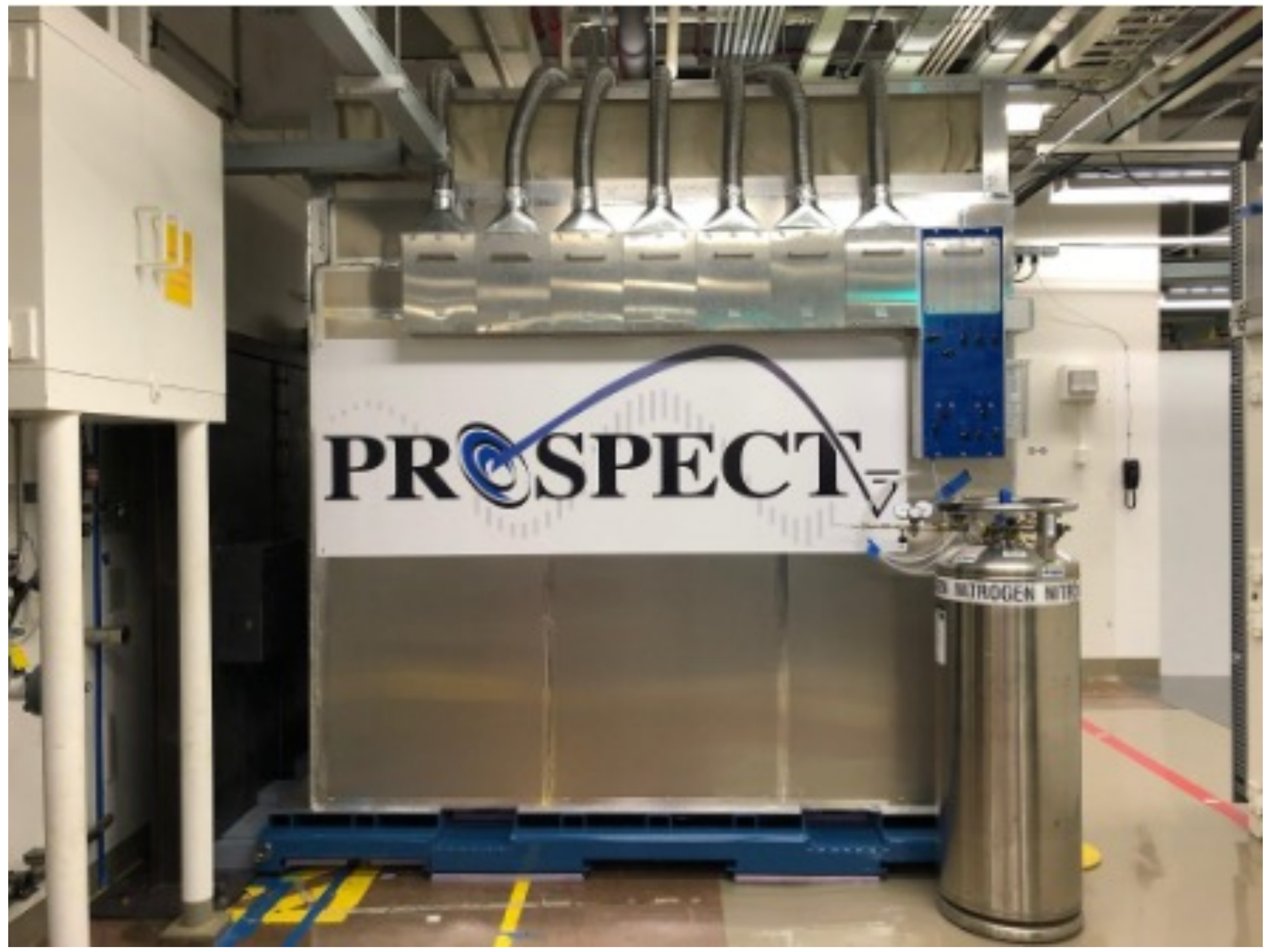
Stage 2:

- Build optical grid and PMT support structure, and other systems
- Mechanically integrate the full PROSPECT-II detector package
- Small prototype LiLS test



Stage 3:

- Procure large batch of production LiLS
- Fill the detector



7 PROSPECT-II Projected Results

Higher stats -> Higher sensitivity!

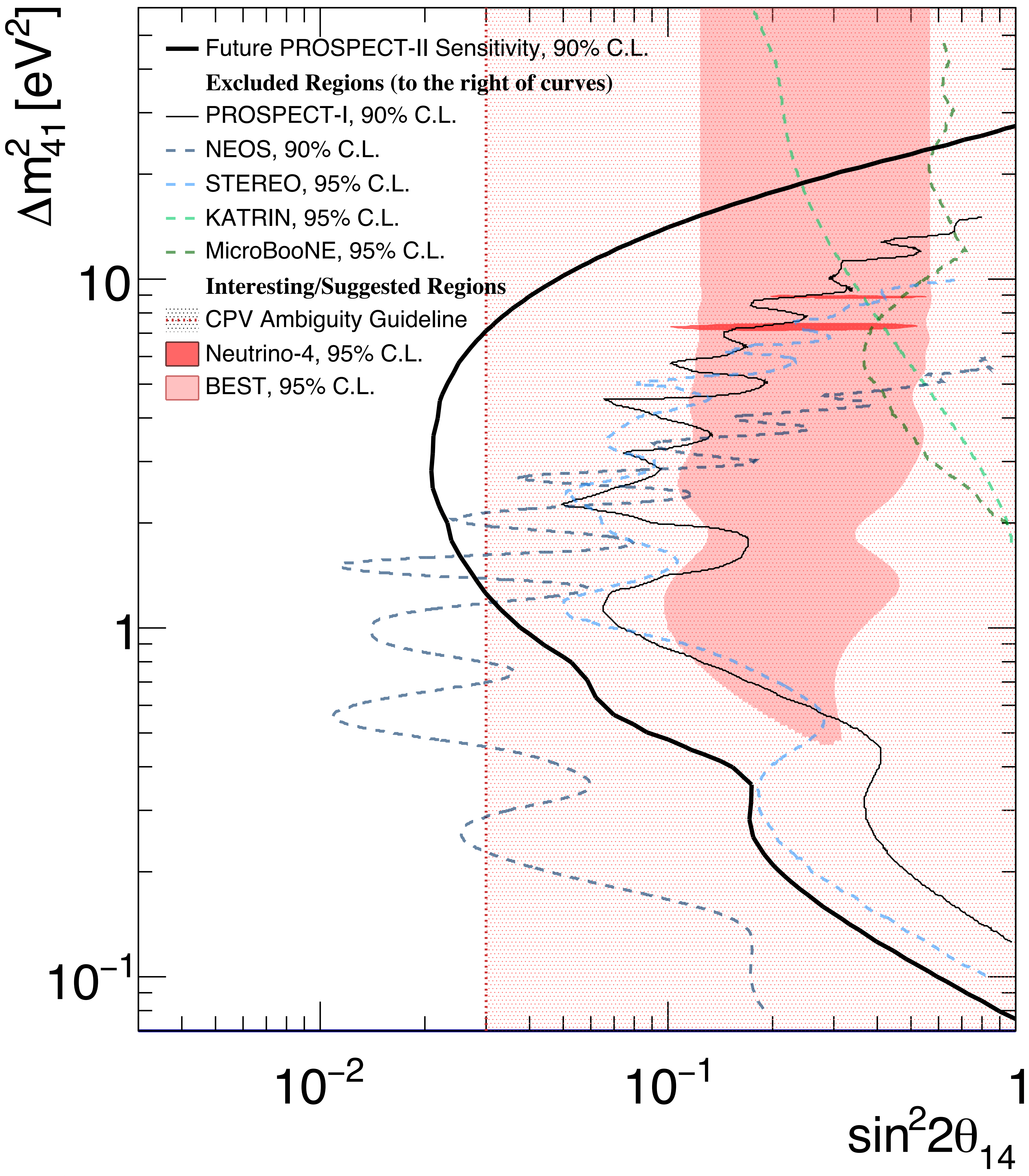
	Parameter	P1	P2 at HFIR	P2 at LEU
Exposure	Average Baseline (m)	7.9	7.9	25
	Reactor-On Days (d)	105	336	548
	Reactor-Off Days (d)	78	360	61
	Signal:Background	1.4	4.3	19.3
	IBD Statistics (N_{IBD})	50560	3.74×10^5	2.72×10^6
	Effective Statistics (N_{eff})	15195	2.08×10^5	1.79×10^6

arxiv:2107.03934

~ 5 times

7 PROSPECT-II Projected Results

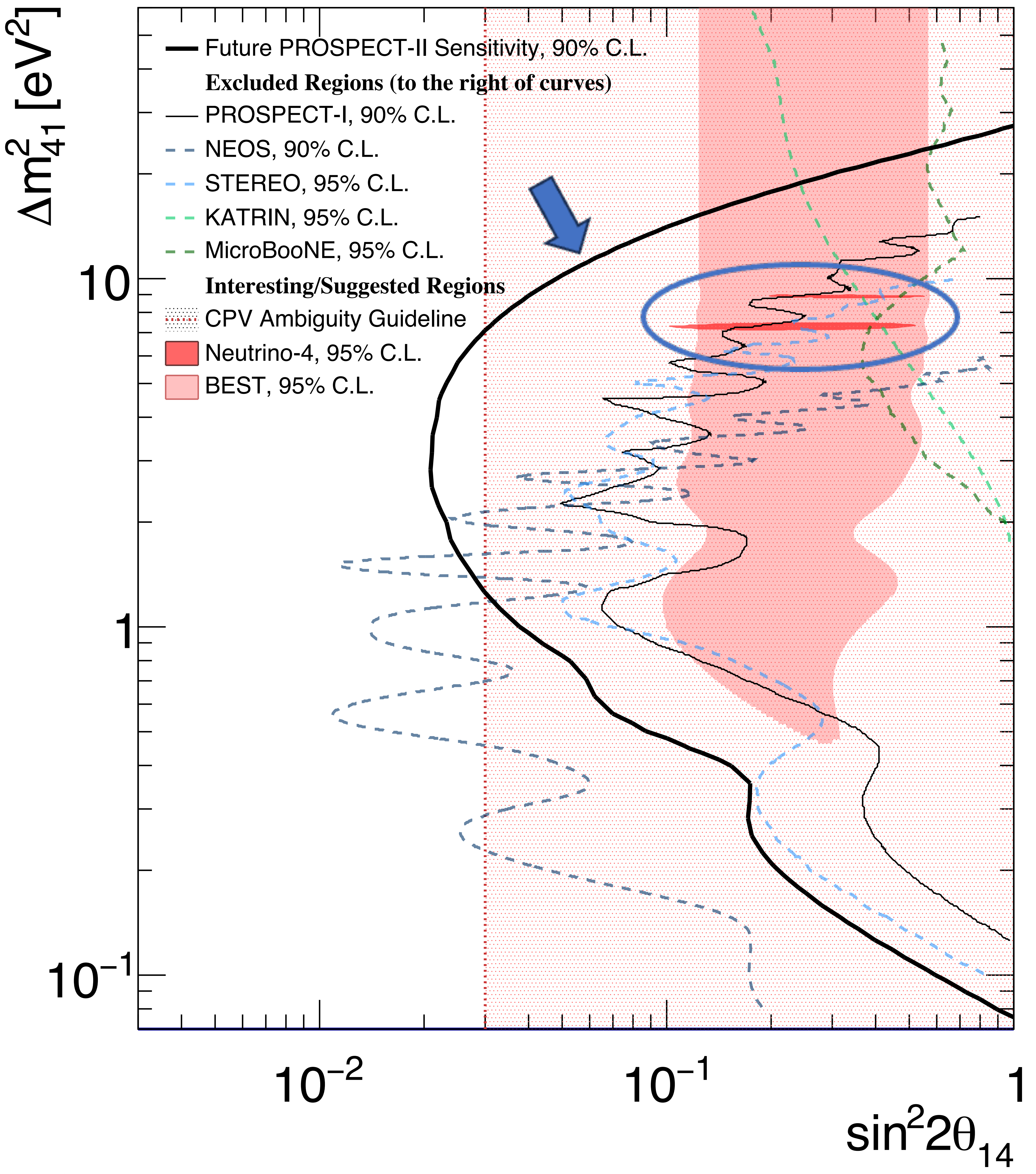
Sensitivity Contour



7 PROSPECT-II Projected Results

Sensitivity Contour

- More phase-space coverage, specially at higher Δm^2_{41}
- Addresses Neutrino-4



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Sensitivity Contour

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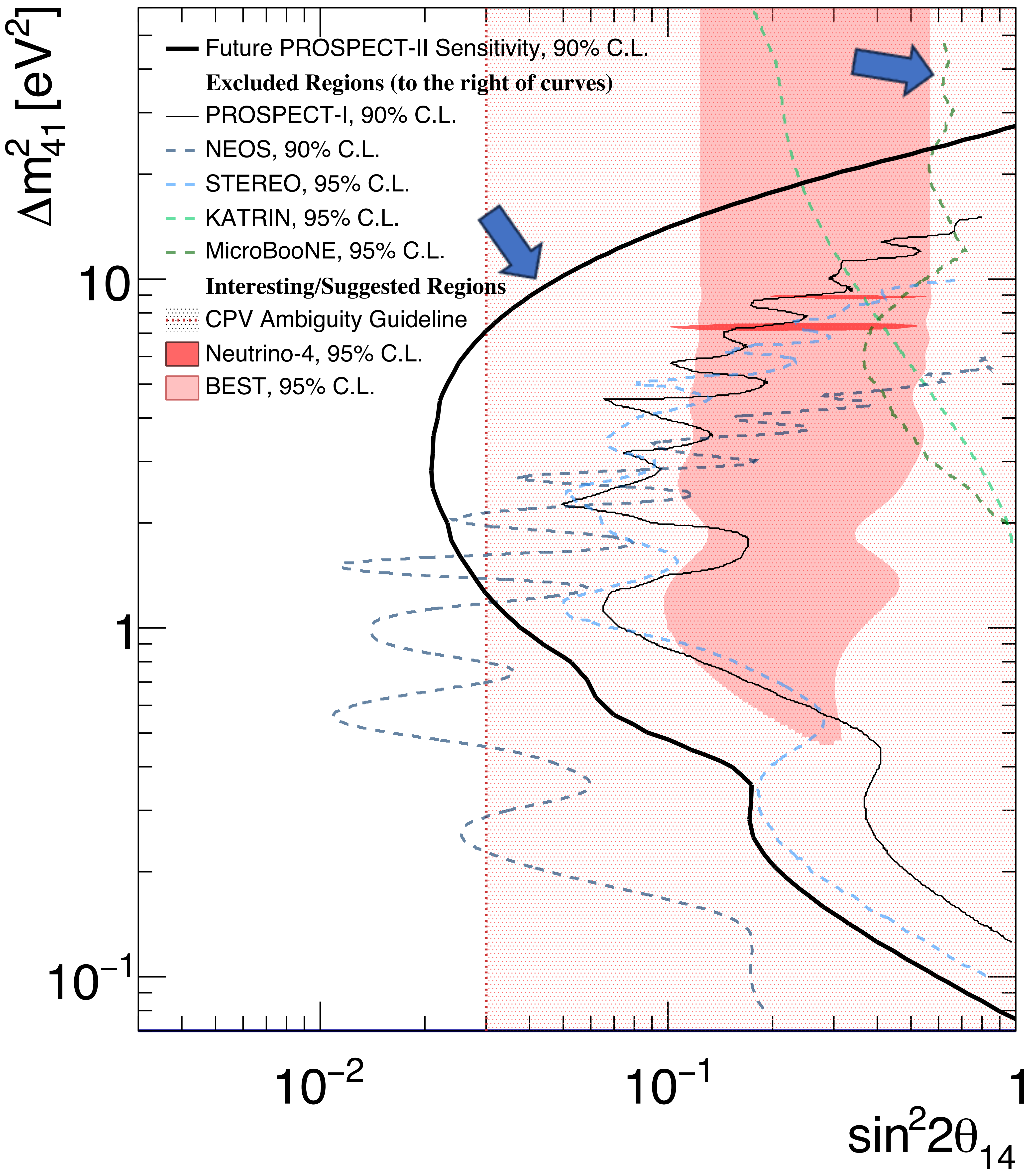
- Better coverage at higher Δm^2_{41} than beam experiments



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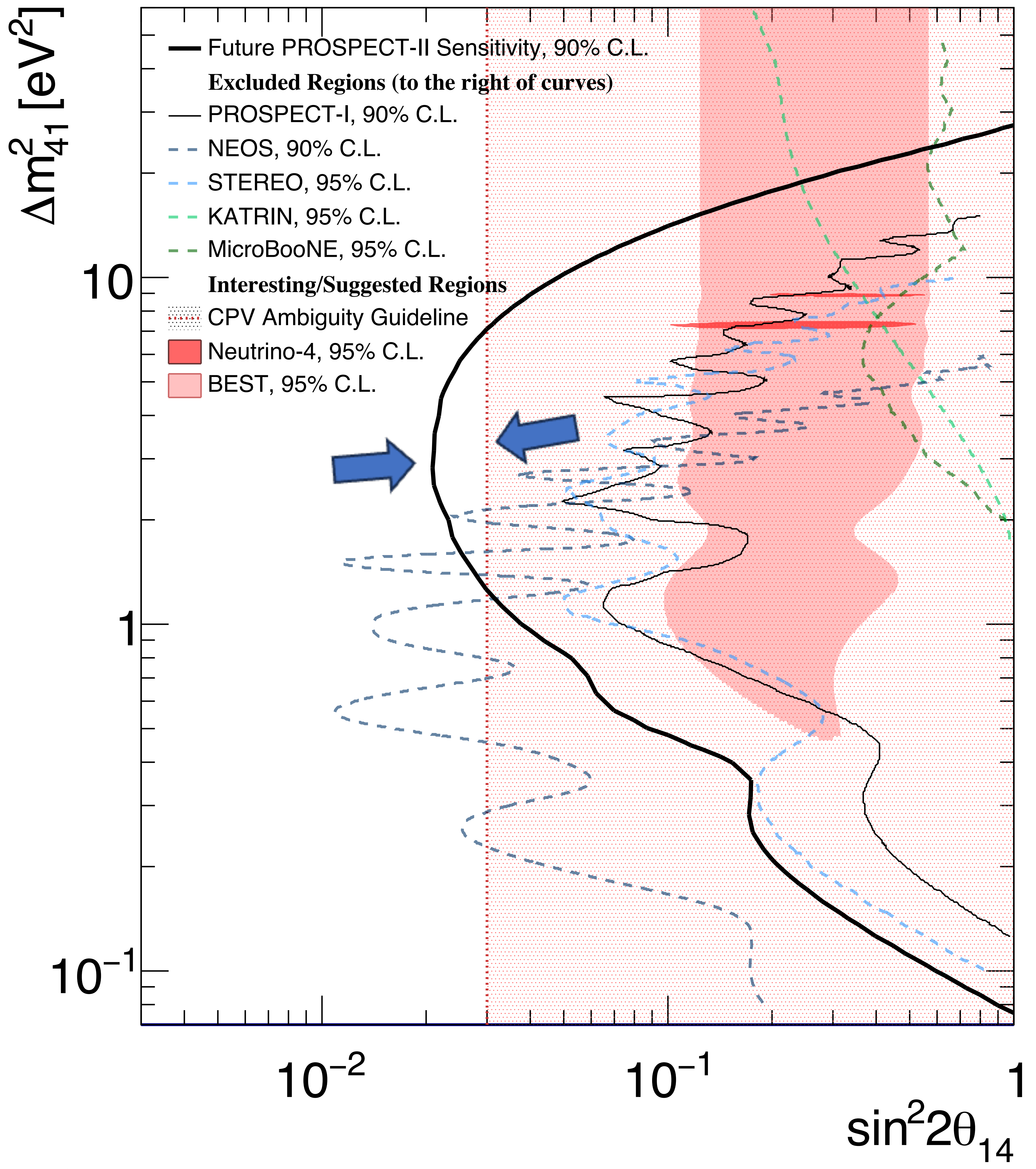

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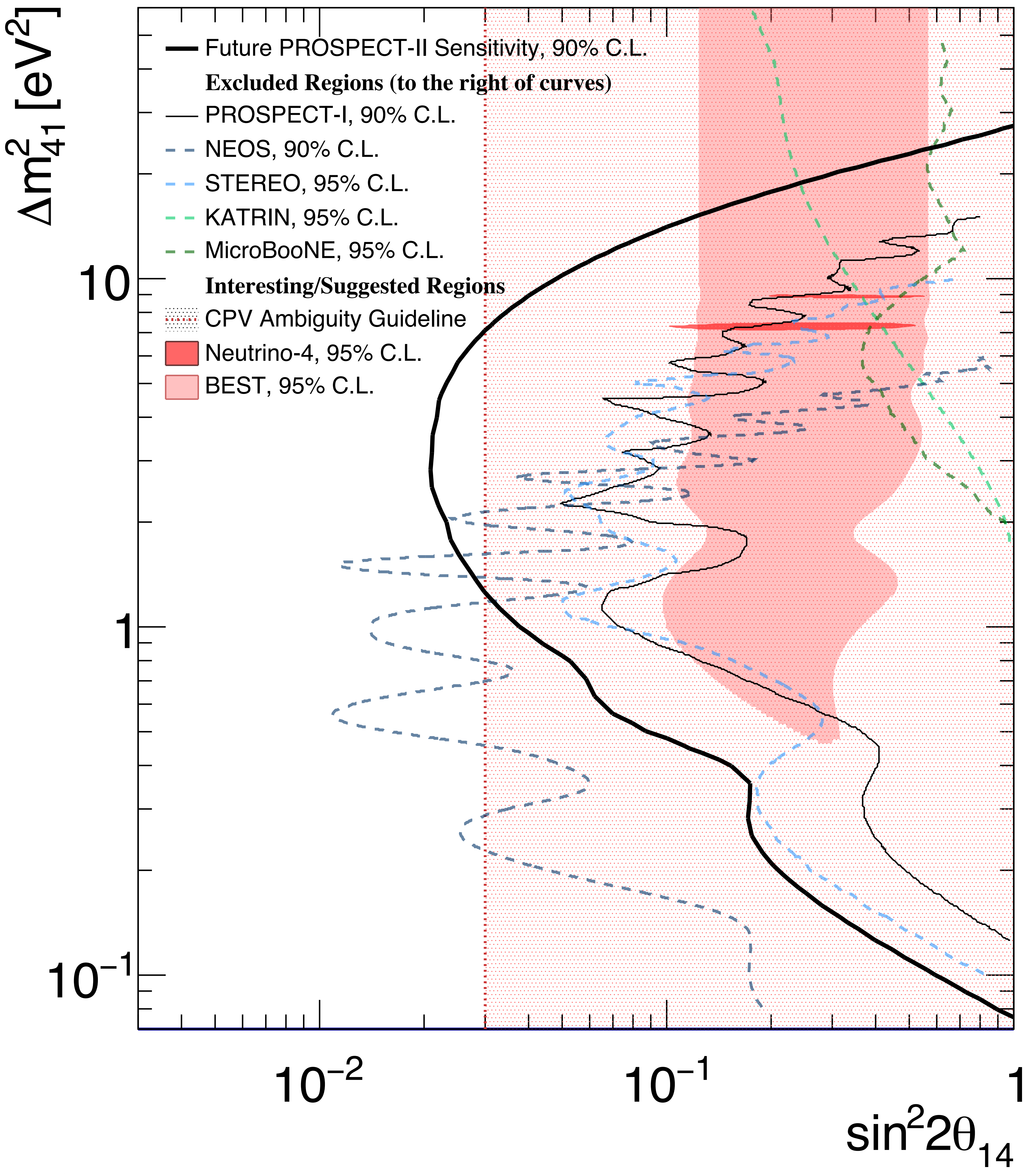

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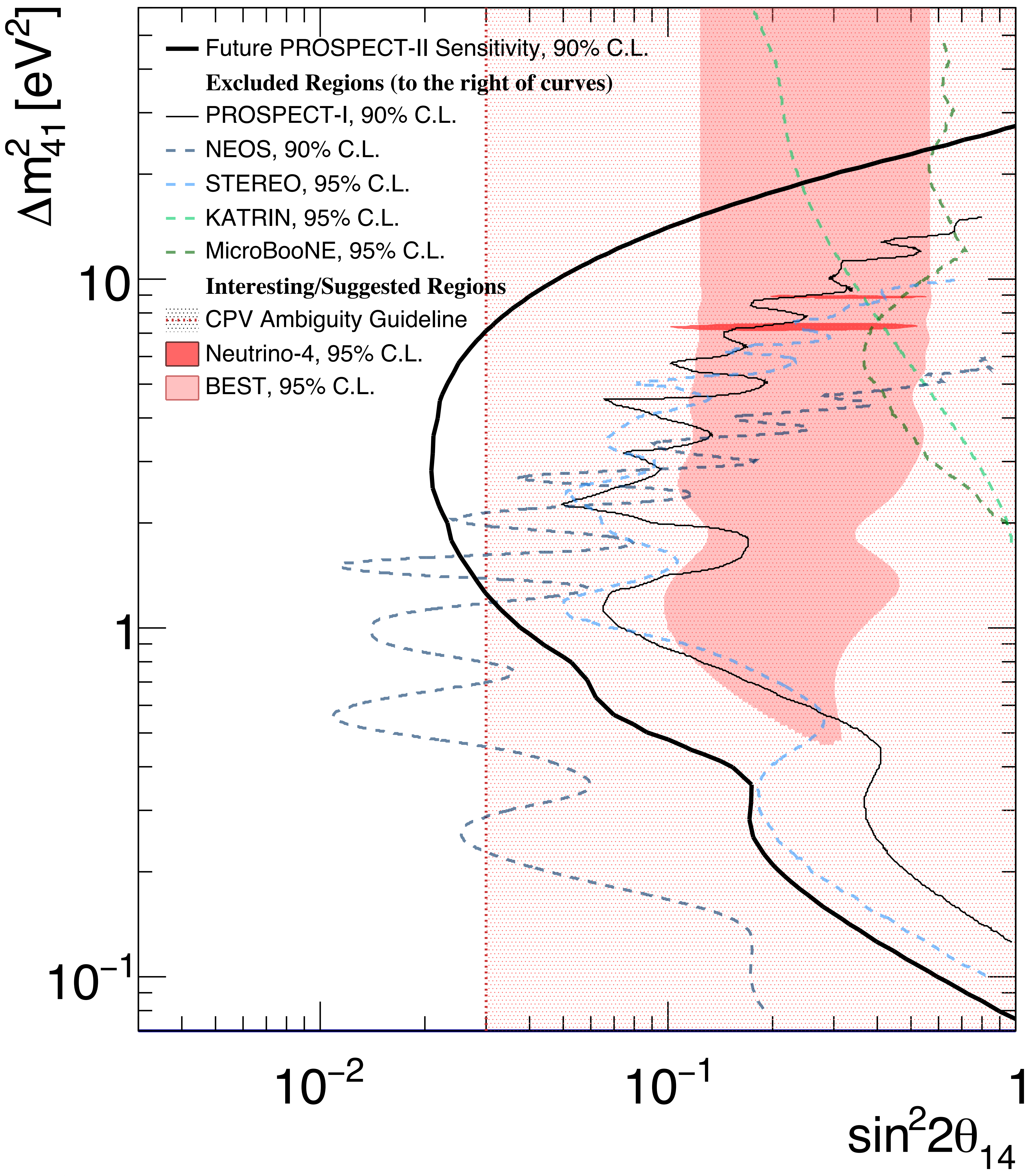
- Help us have a clearer picture on the LB CPV JHEP11(2015)039
- Constrain reactor antineutrino flux for CEvNS measurements
- Understand antineutrino production by different isotopes during fuel consumption

arXiv:2301.13123



8 Conclusion

- We have set world-leading limits on sterile neutrino oscillations with the final PROSPECT-I dataset
  - Neutrino-4 BF ruled out at > 5σ
  - Gallium Anomaly allowed Δm2 < 10 eV^2 rule out at 95% C.L.
  - Leads global SBL electron-flavor disappearance limits over most of the 3-10 eV2 phase space
- PROSPECT-II robustness give us the chance to push even further the borders of knowledge we currently have in the field

Obrigada!

Thank you!

1 Other Sterile Neutrino Hints

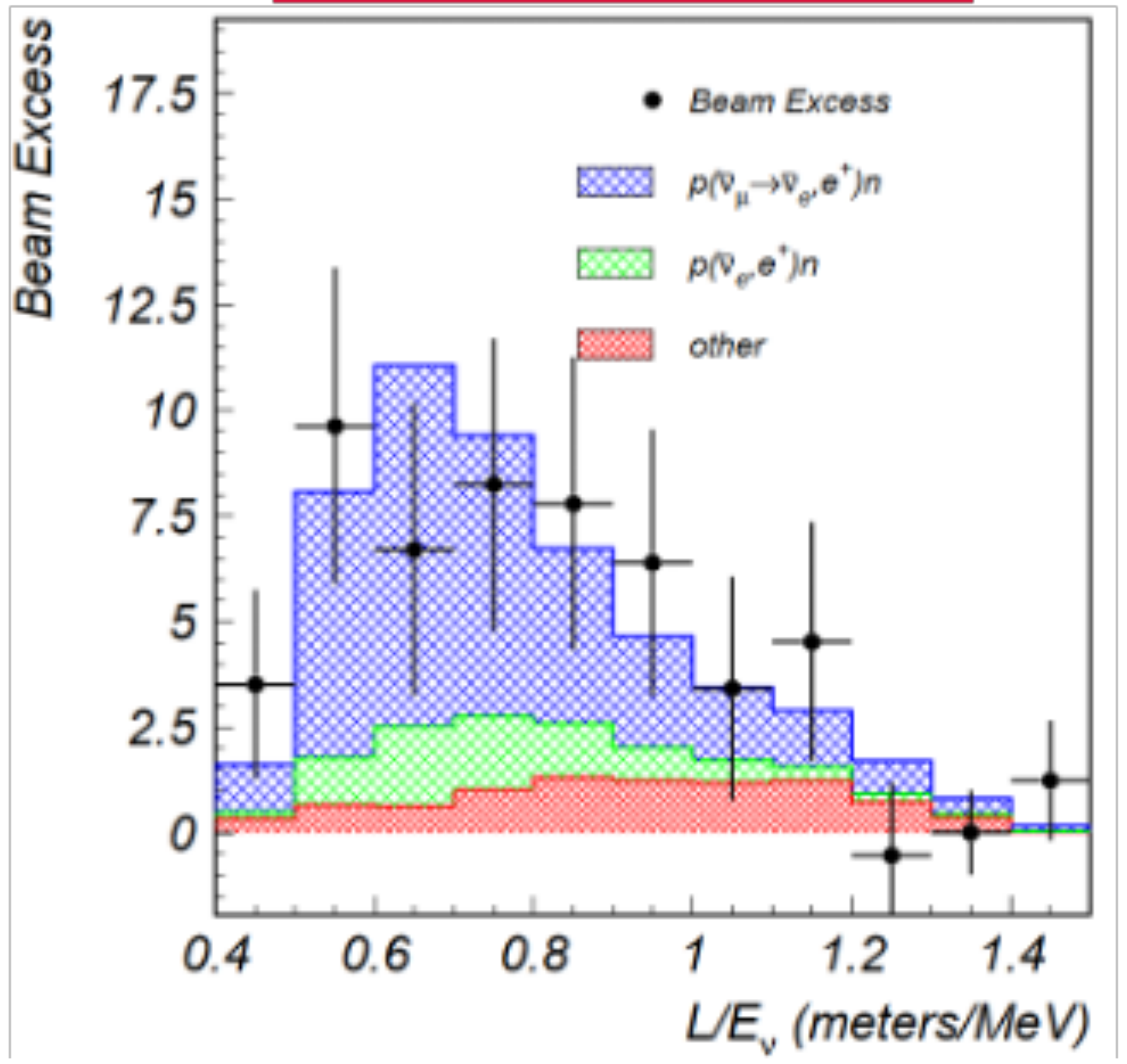
Ab-initio/Summation

- LSND/MiniBooNE anomaly
  - Excess of electron (anti)neutrinos in muon (anti)neutrino beam
  - Significant of ~6σ

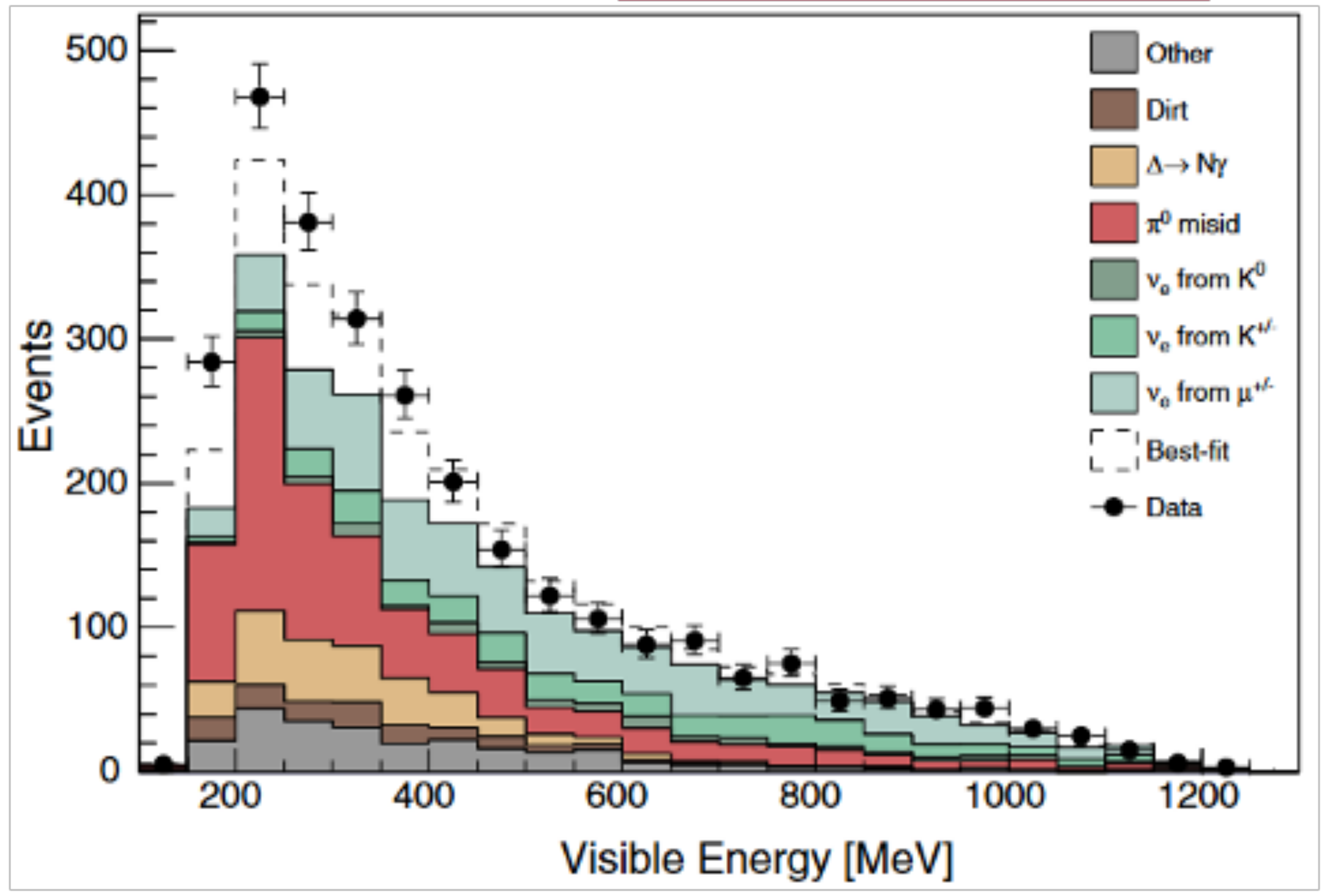
- Gallium anomaly
  - Deficit of electron neutrinos from radioactive sources in Gallium-based detectors

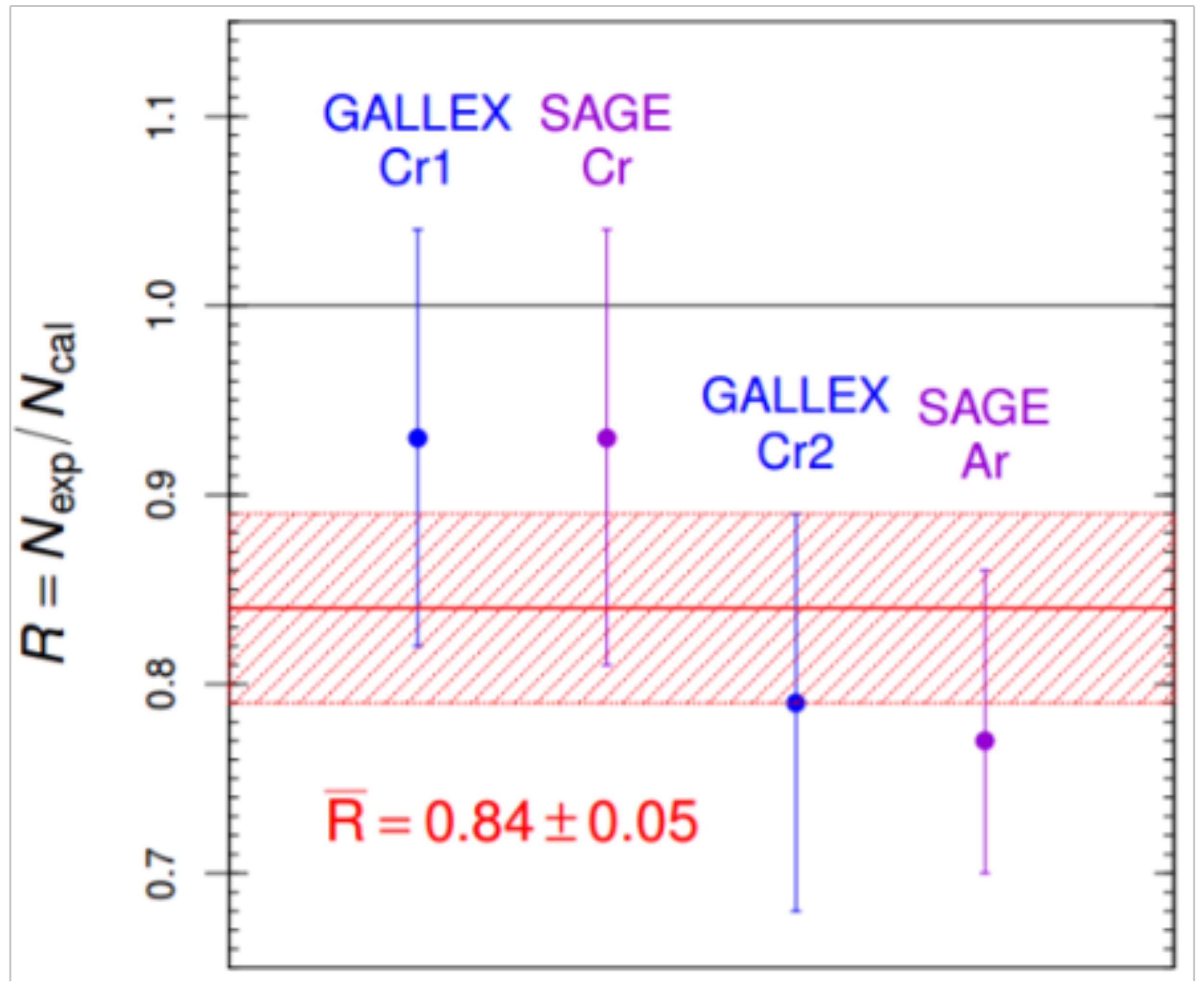
3+1 eV-scale sterile neutrino oscillations?

PRD 64, 112007 (2001)



PRD 103, 052002 (2021)



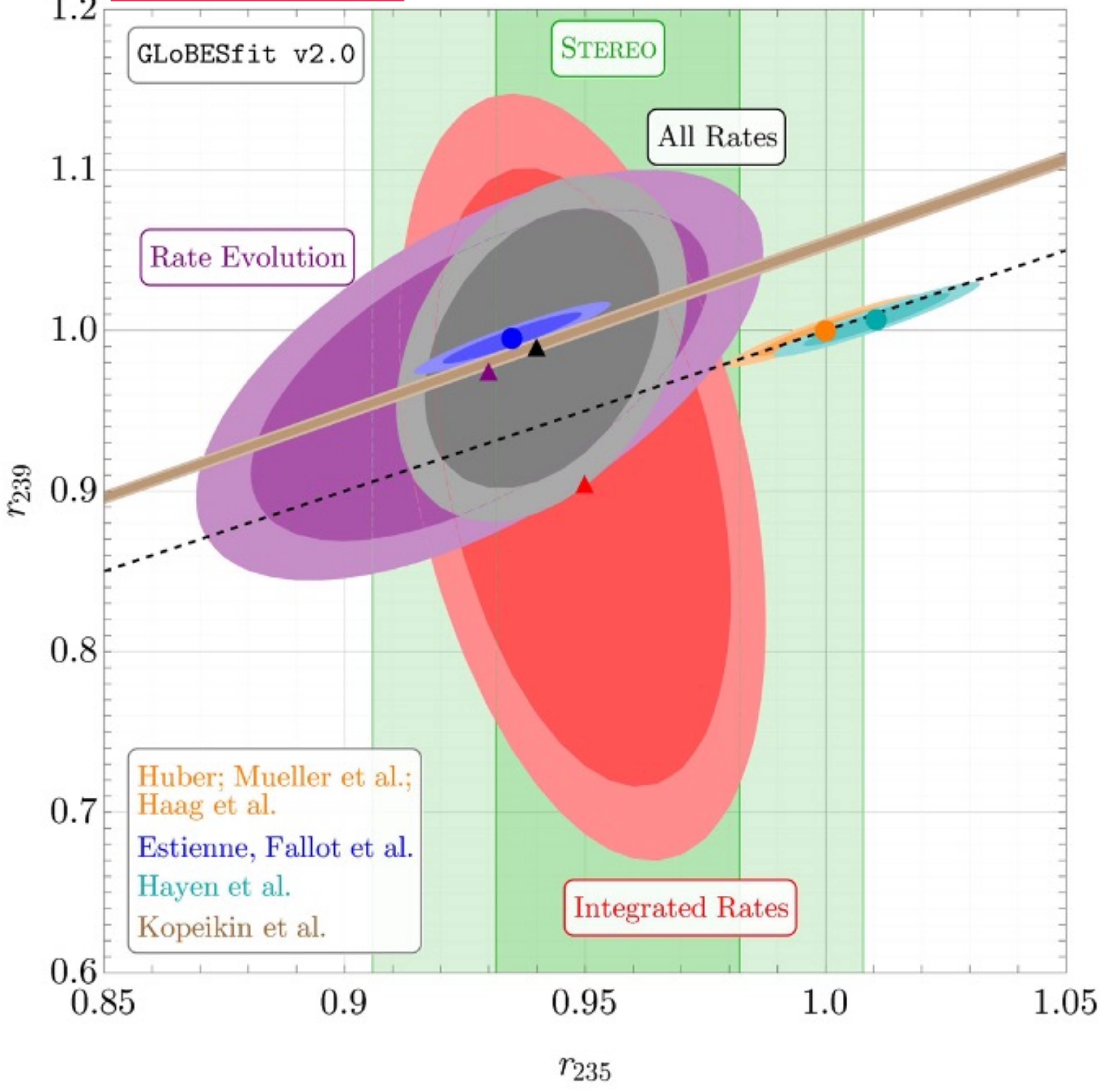


1 Current Landscape

The Reactor Antineutrino Anomaly is fading:

- Daya Bay fuel evolution measurement suggests over-prediction of ^{235}U flux PRL 118, 251801 (2017)
- New fission beta measurement suggests lower ^{235}U is needed PRD 104, L071301 (2021)
- Ab-initio prediction shows reduced deficit with improved beta data PRL 123, 022502 (2019)

JHEP 01, 167 (2021)



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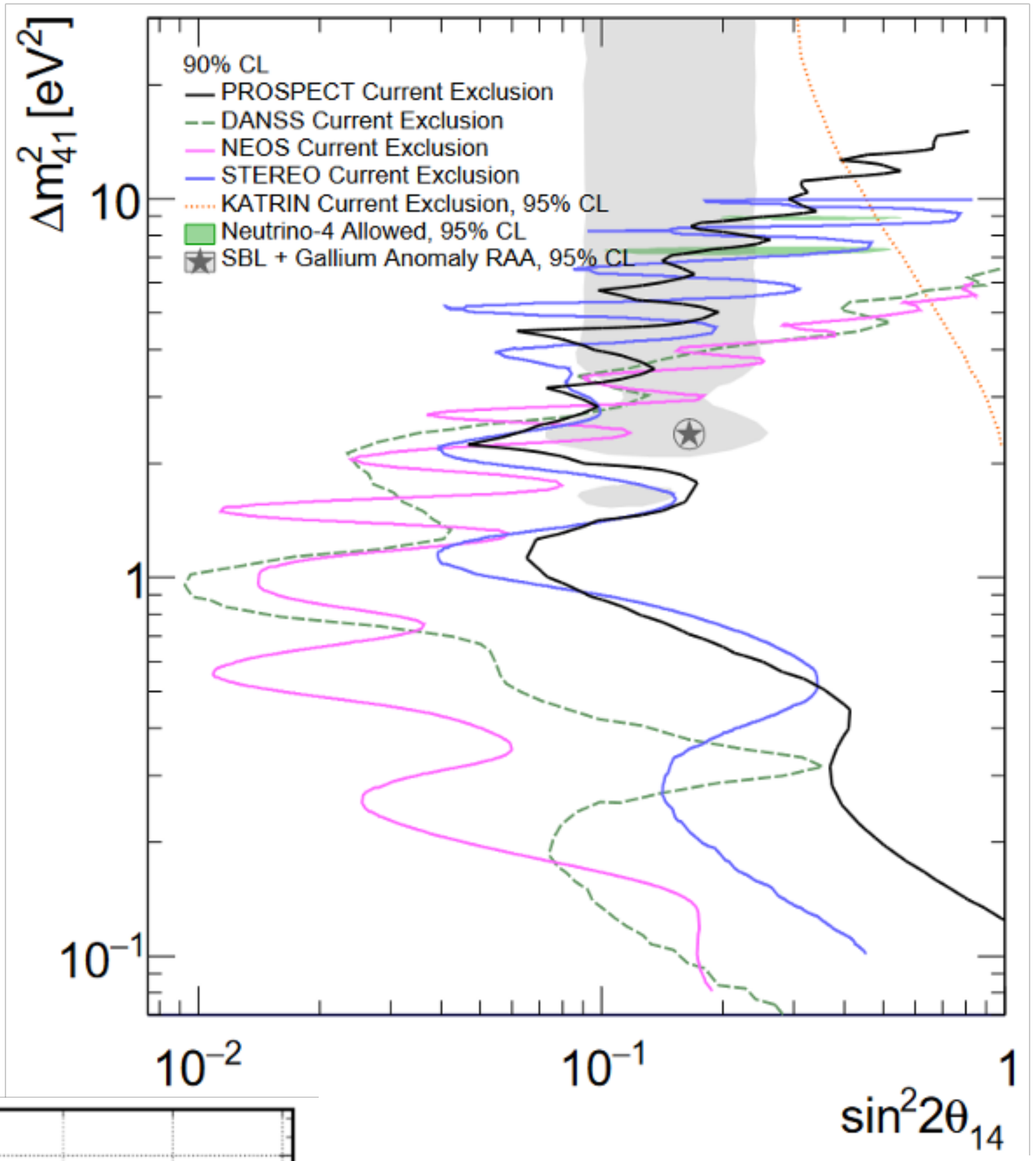
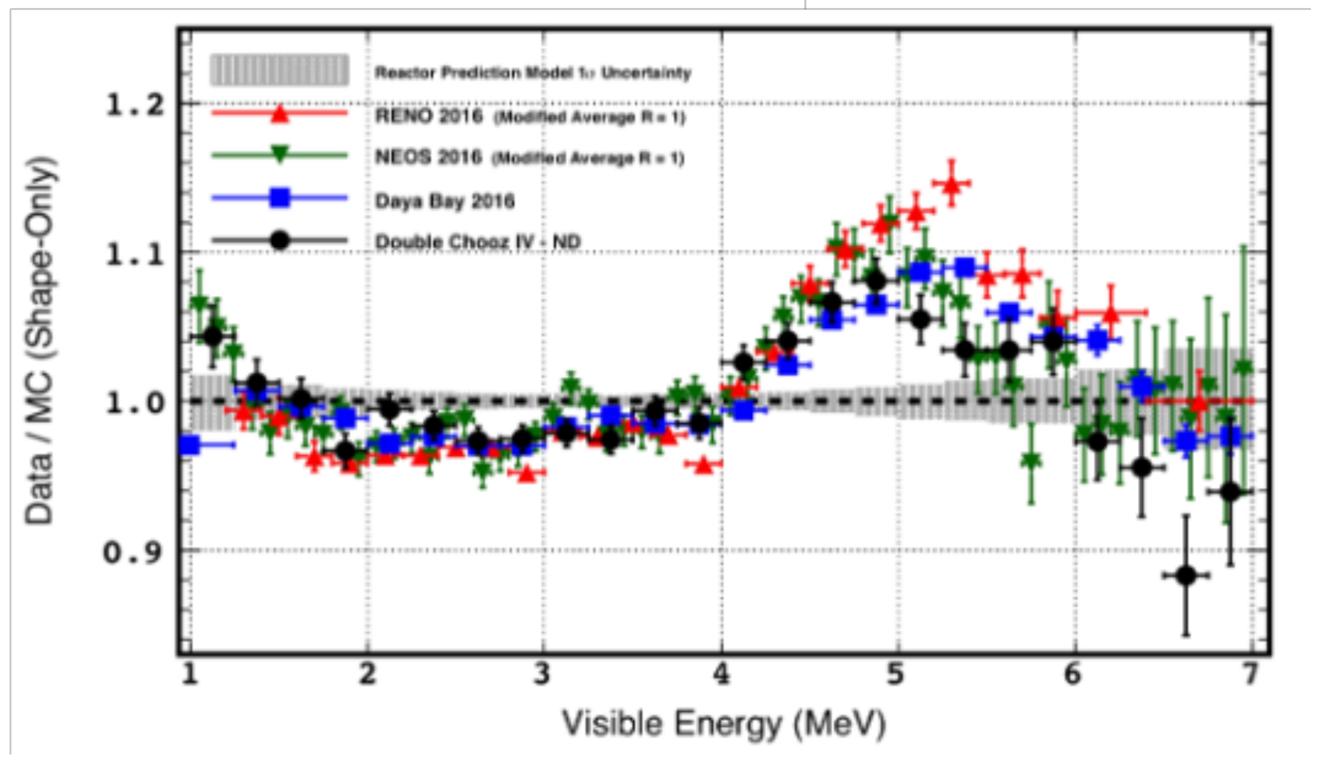
- Beta conversion unable to predict neutrino spectrum: Distortion around 5 MeV
- Many SBL reactor oscillation experiments have ruled out much of ‘sterile neutrino hypothesis’ space: DANSS, NEOS, PROSPECT, STEREO
- LSND/MiniBooNE anomaly and Gallium anomaly are still present is still present





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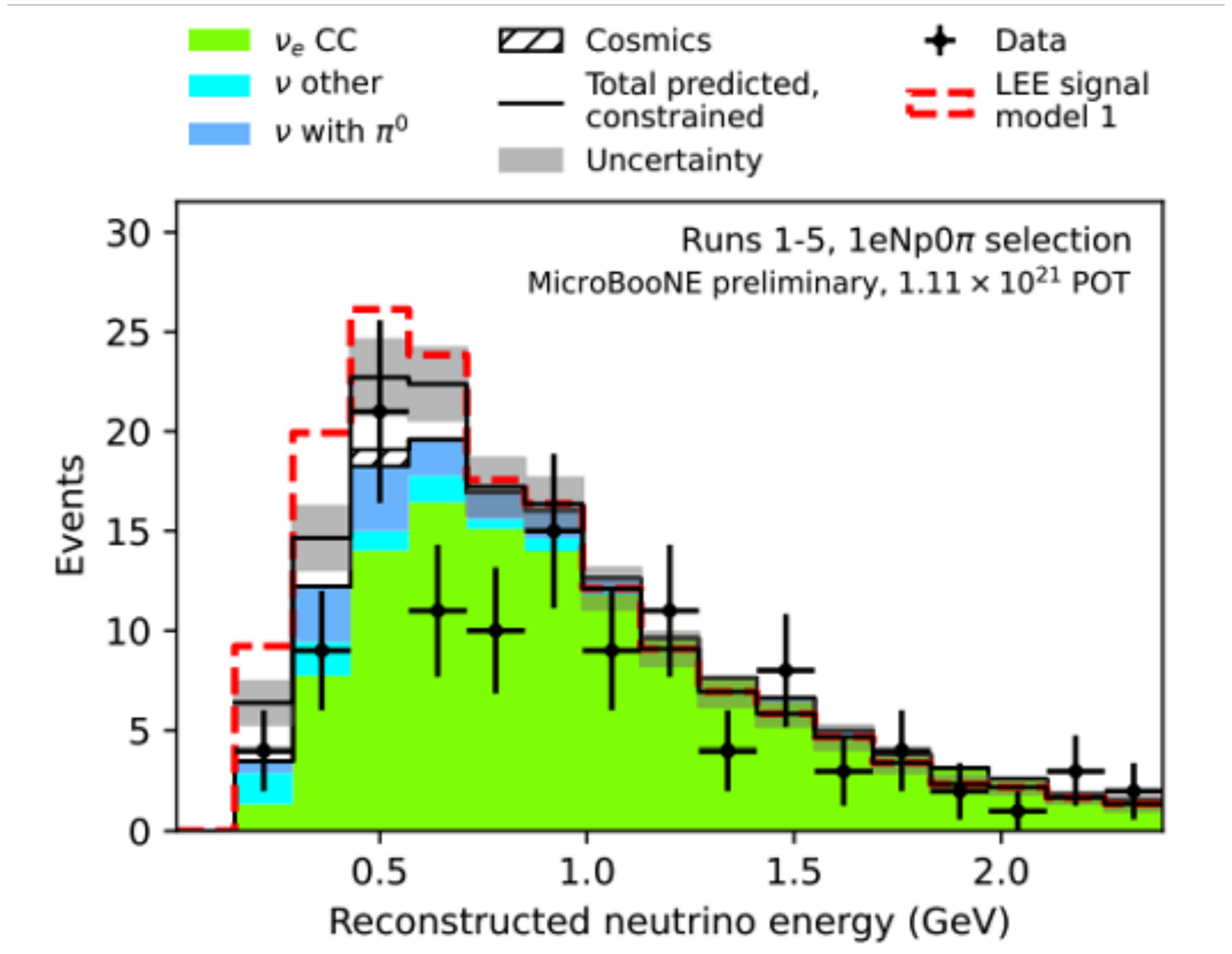
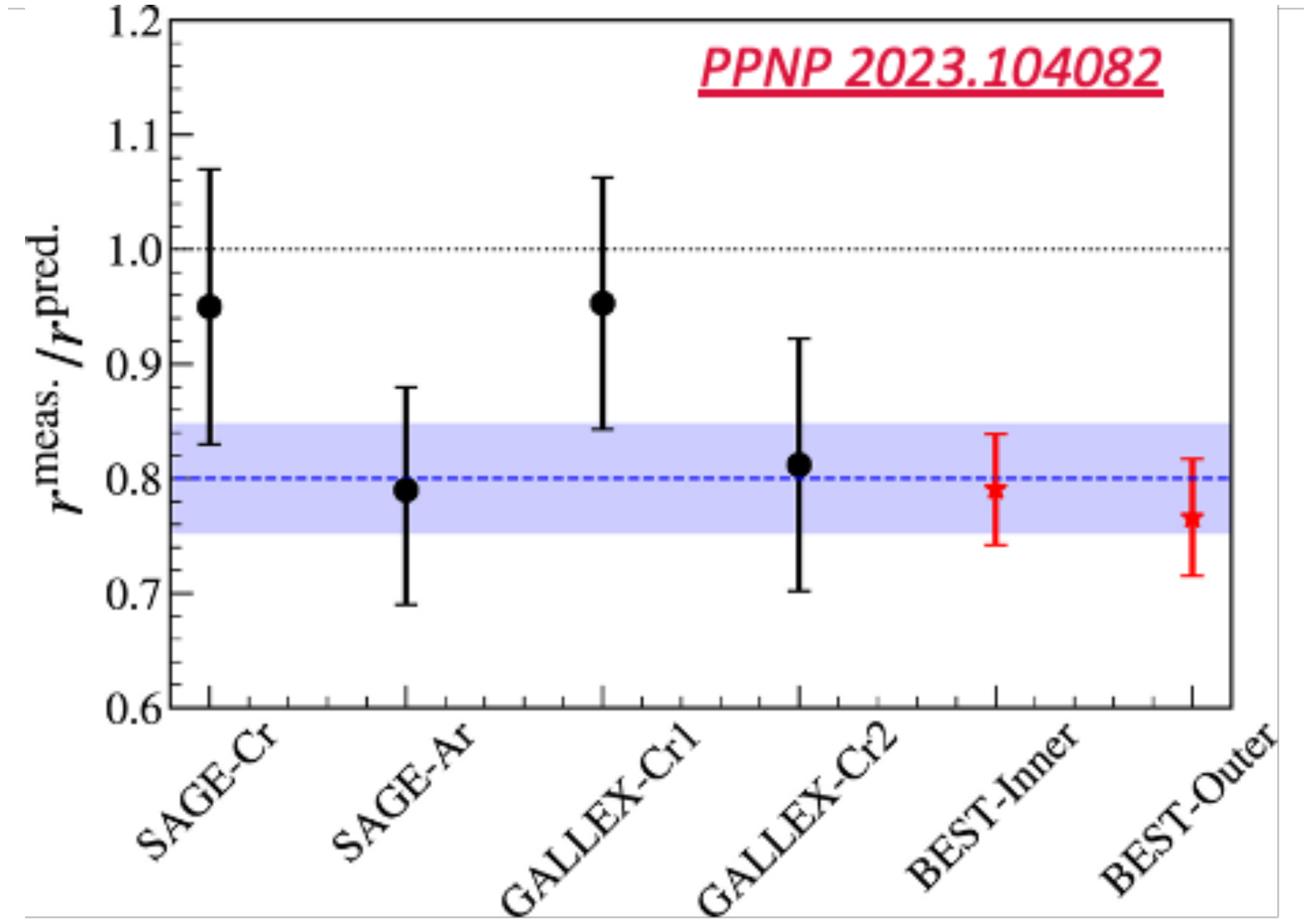
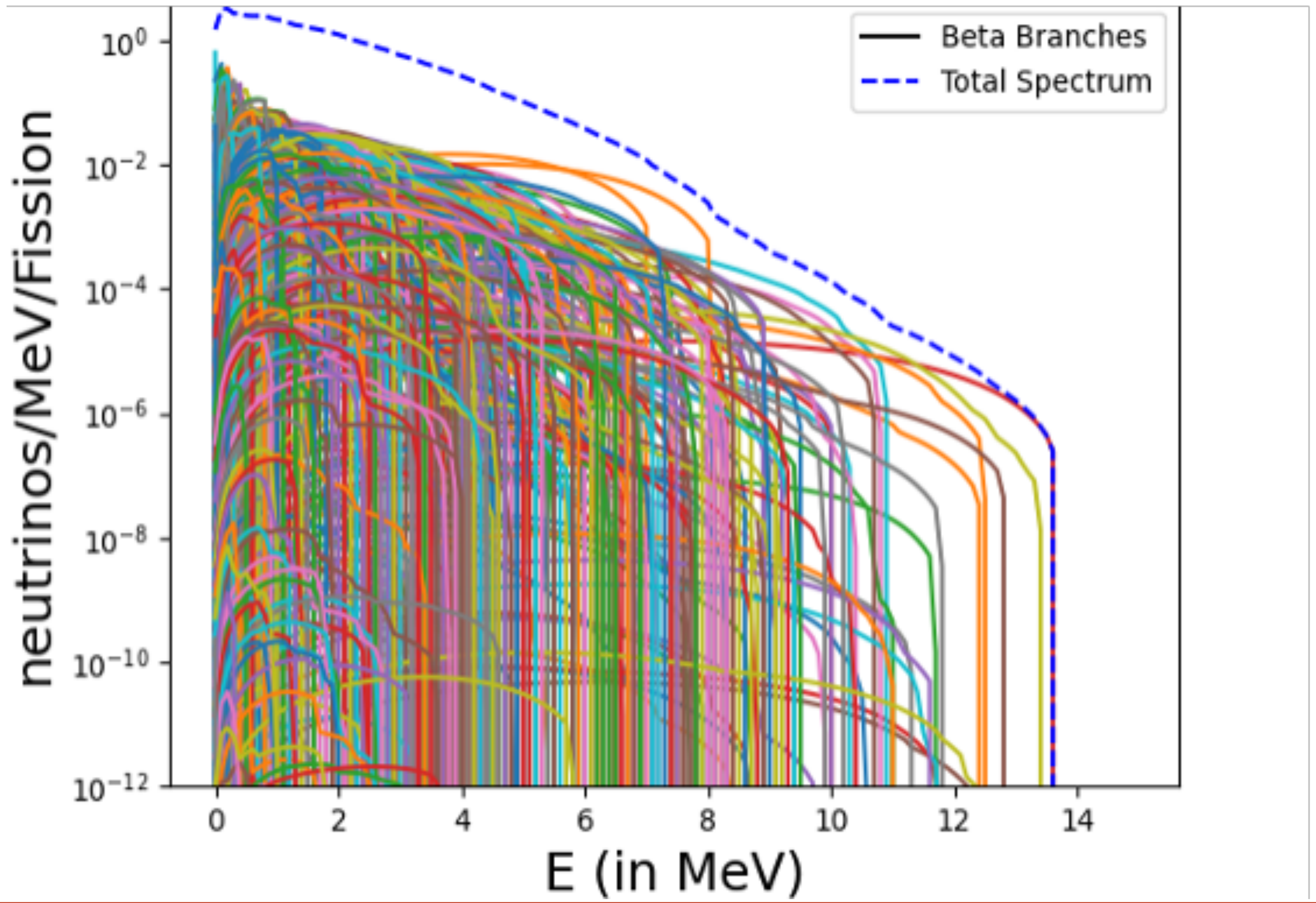




1 Prediction of Antineutrino Spectrum

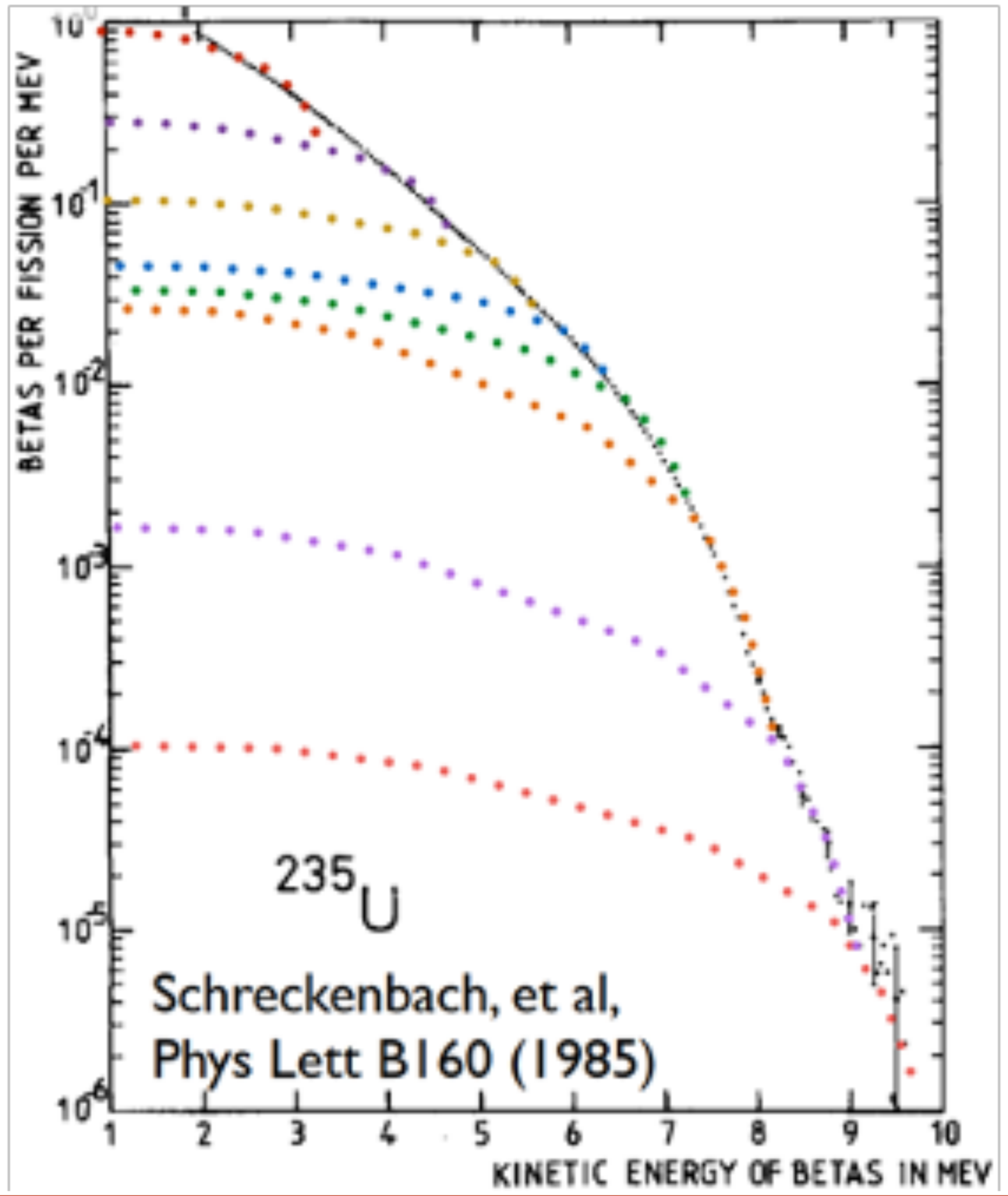
Ab-initio/Summation

- Summation of all β-branches of all fission products using database
- Huge uncertainty in the database: rare isotopes/beta-branches



Conversion

- Measure beta spectra then convert into ve using 'virtual beta branches'
- Legacy dataset from the 80s
- Claimed smaller error than ab-initio



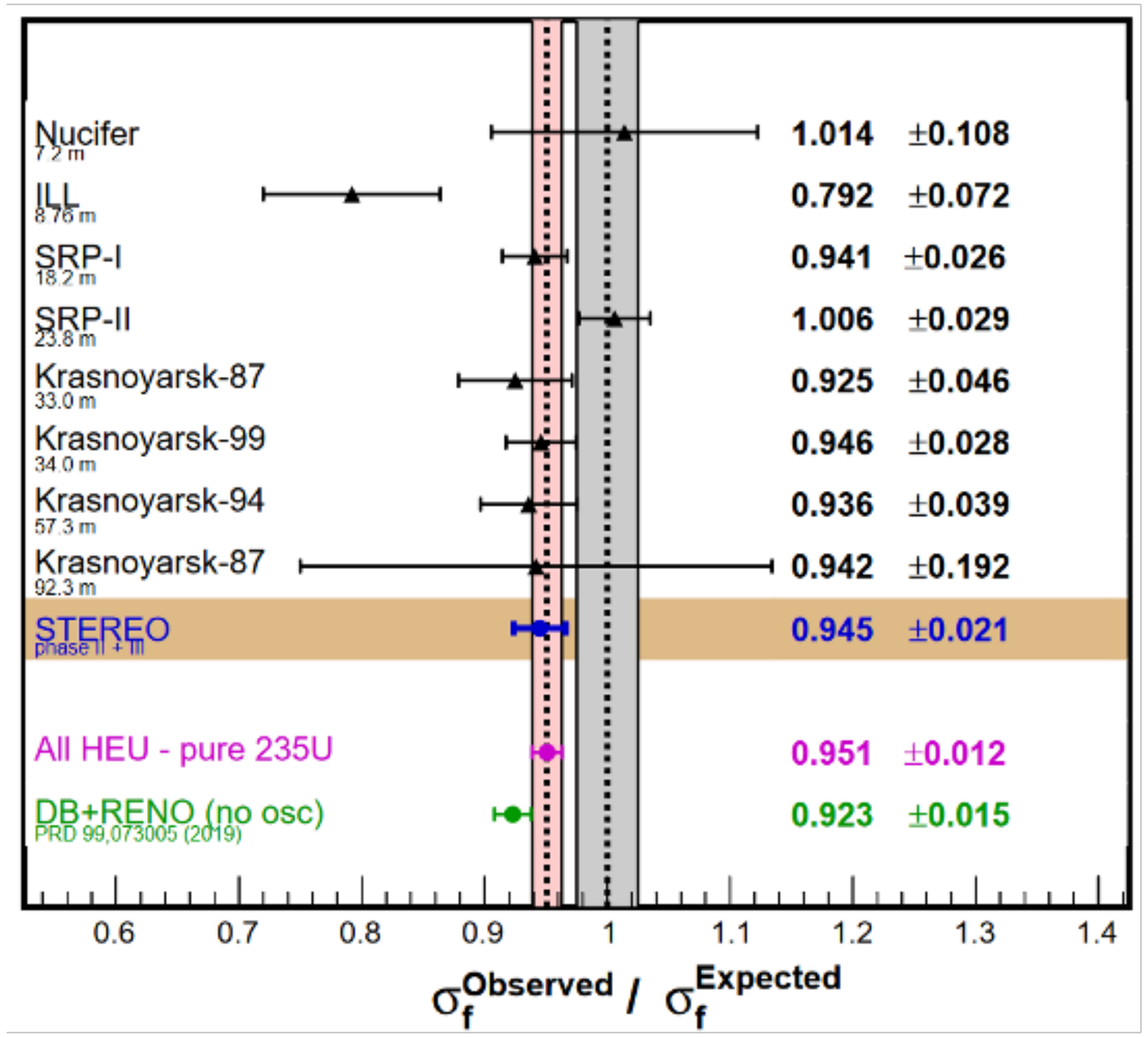
1 Reactor Antineutrino Anomaly

Re-evaluation of the antineutrino spectrum model:

- Th. A. Mueller et al., PRC 83, 054615 (2011): Combine summation and conversion methods
- Huber, PRC 84, 024617 (2011): %-level correction factor in the conversion
- Currently: Huber-Mueller model is what is used to benchmark for all reactor experiments

Tension with the experimental data:

- 5.7% flux deficit: Reactor Antineutrino Anomaly.
- ~ 3σ tension with previous experiments.

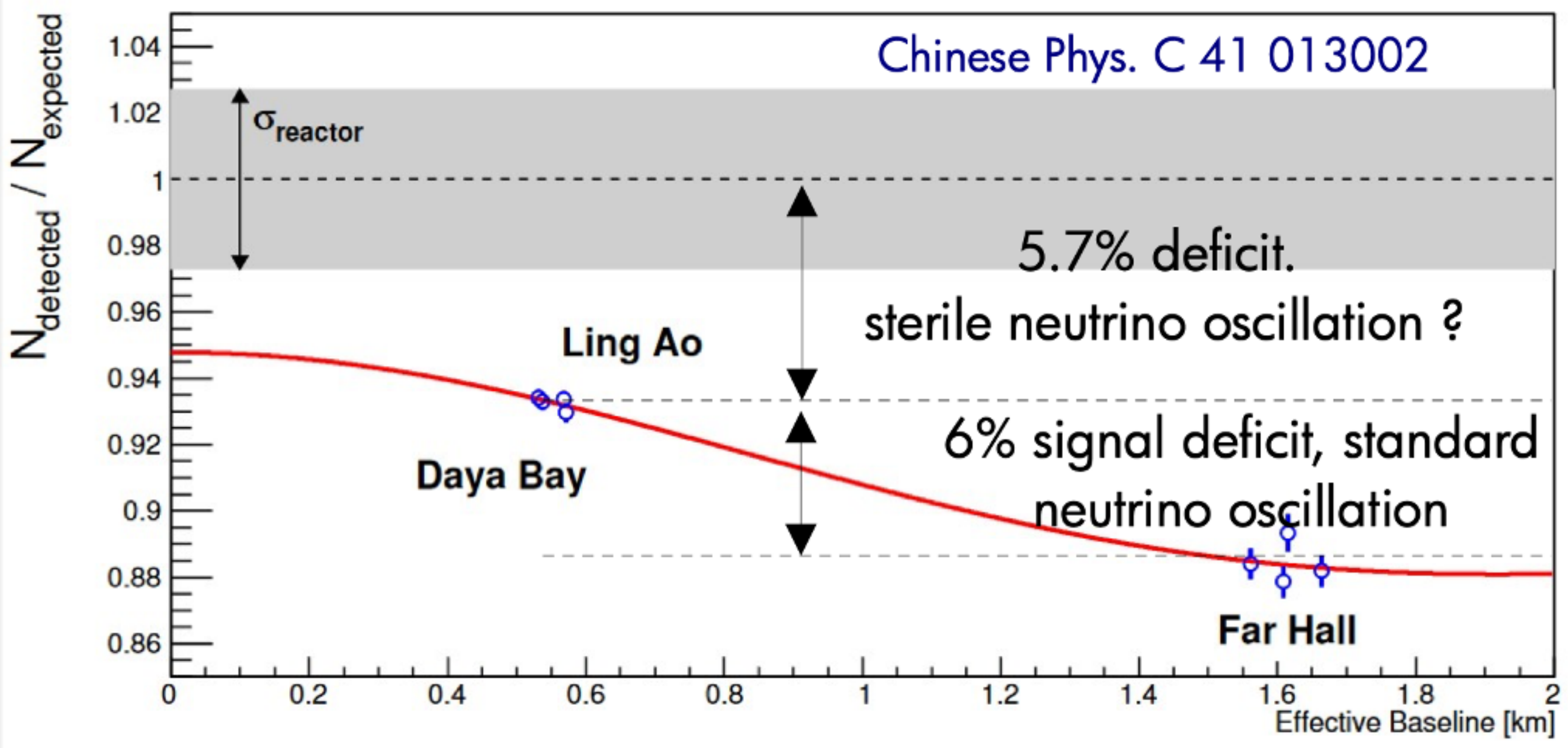


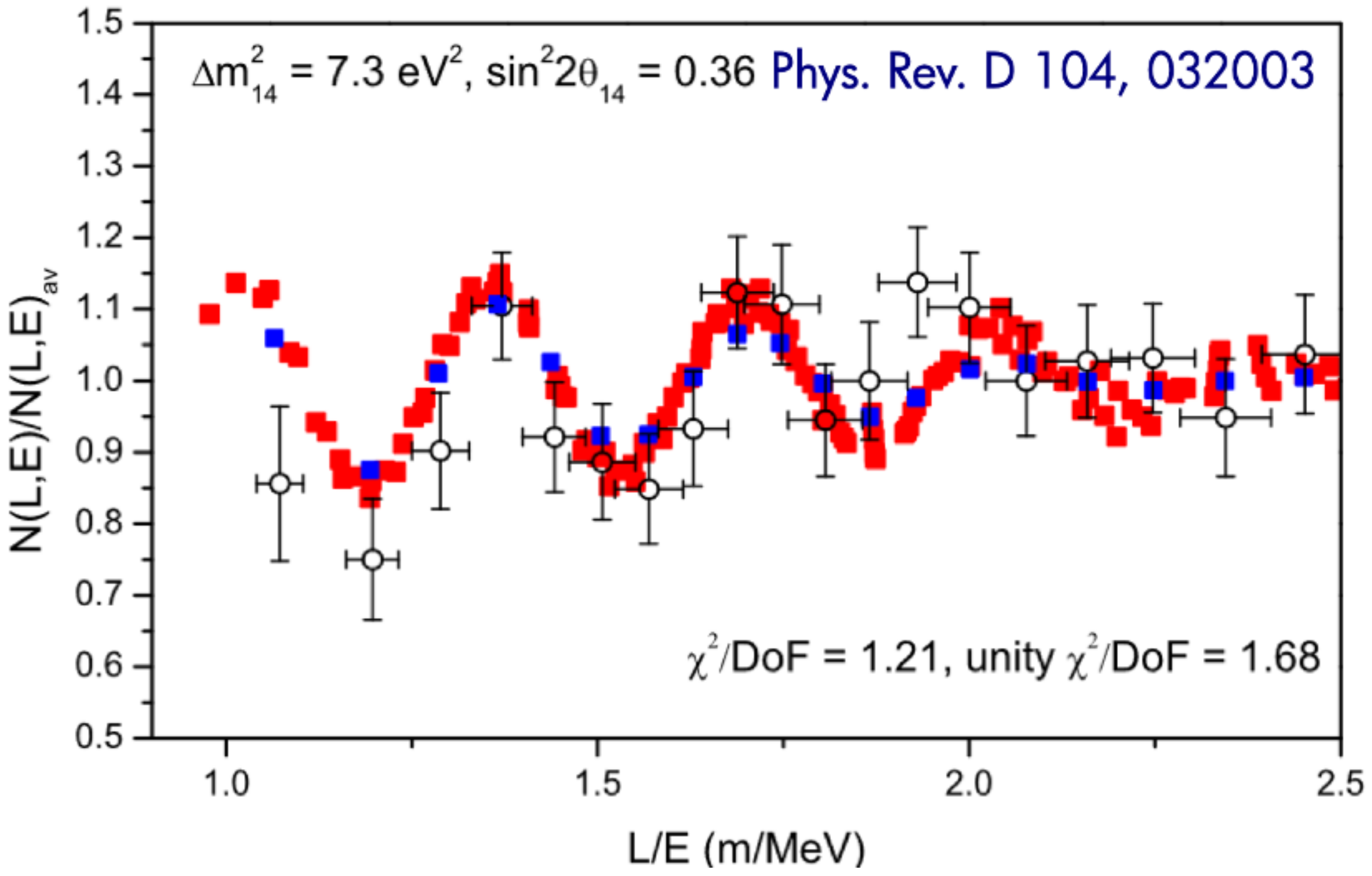
Nature 613, 257–261 (2023)

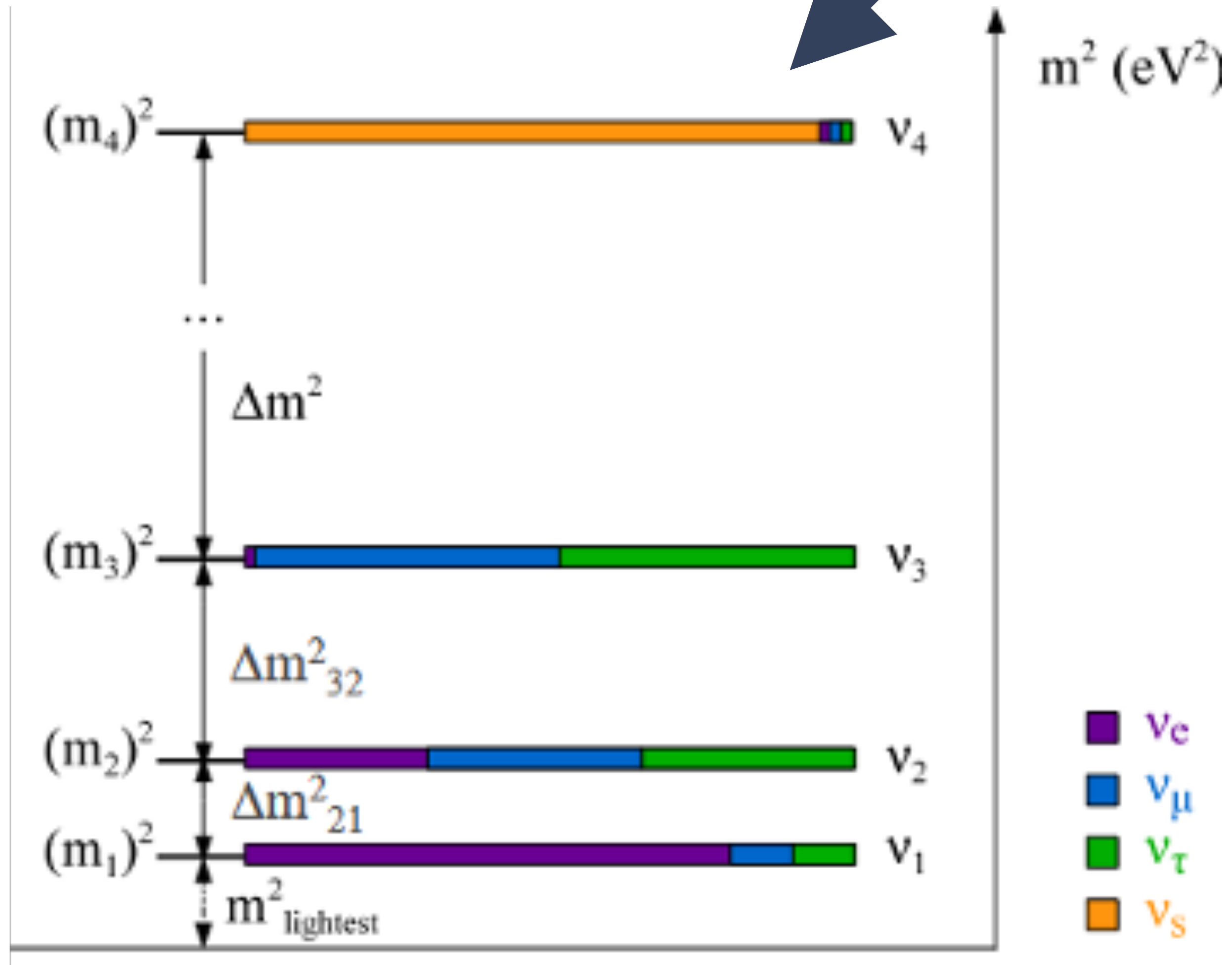
1 Reactor Antineutrino Anomaly

What could be the origin of this deficit?

- Miscalculation of the flux prediction?
- Could this be an eV-scale sterile neutrino oscillation at short-baseline ('3+1' model)?

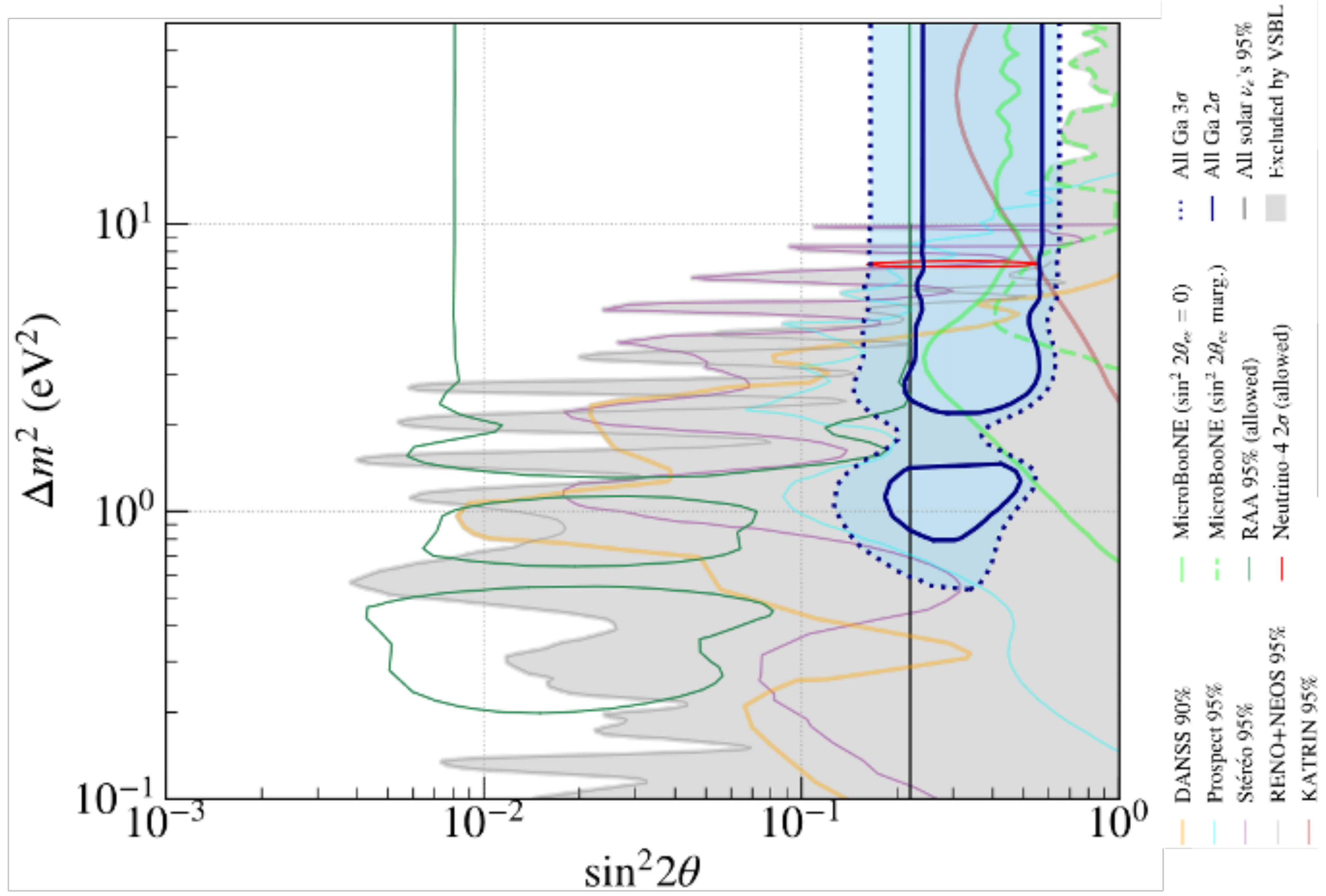




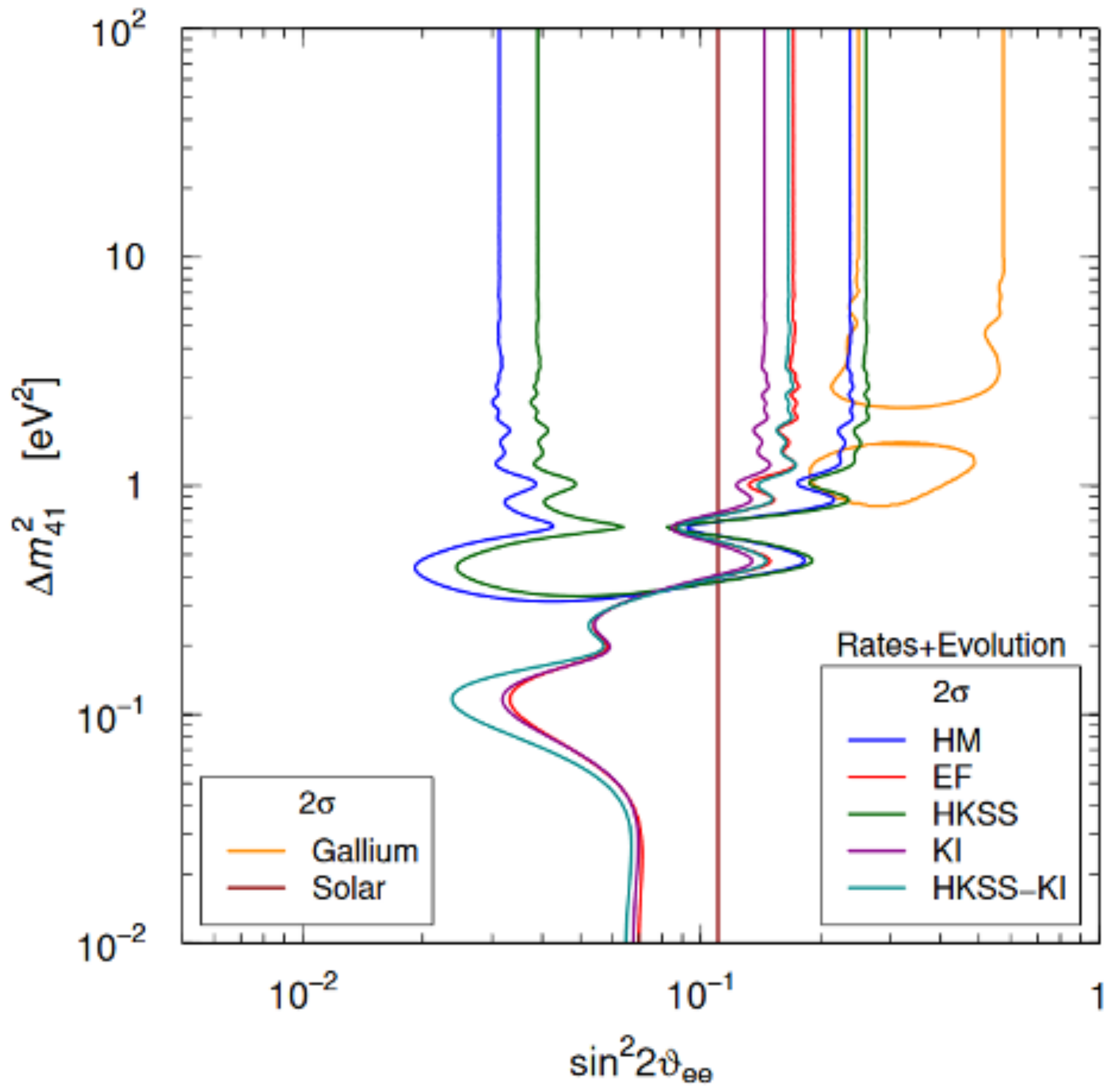


2 Current tension: Reactor

- The gallium anomaly and Neutrino-4 seems mostly ruled out by other SBL reactor measurements.
- If the Gallium anomaly is caused by electron-flavor disappearance, then how can the electron-flavor Reactor Anomaly be 'fading away'?



PRL 128, 232501 (2022)



PLB 829,137054 (2022)