Status of Searches for Sterile Neutrinos with Reactor and Radioactive Sources

Pranava Teja Surukuchi

July 21, 2022

Snowmass 2021 Community Summer Study

Yale

Wright Laboratory

Disclaimers

Focus of this talk:

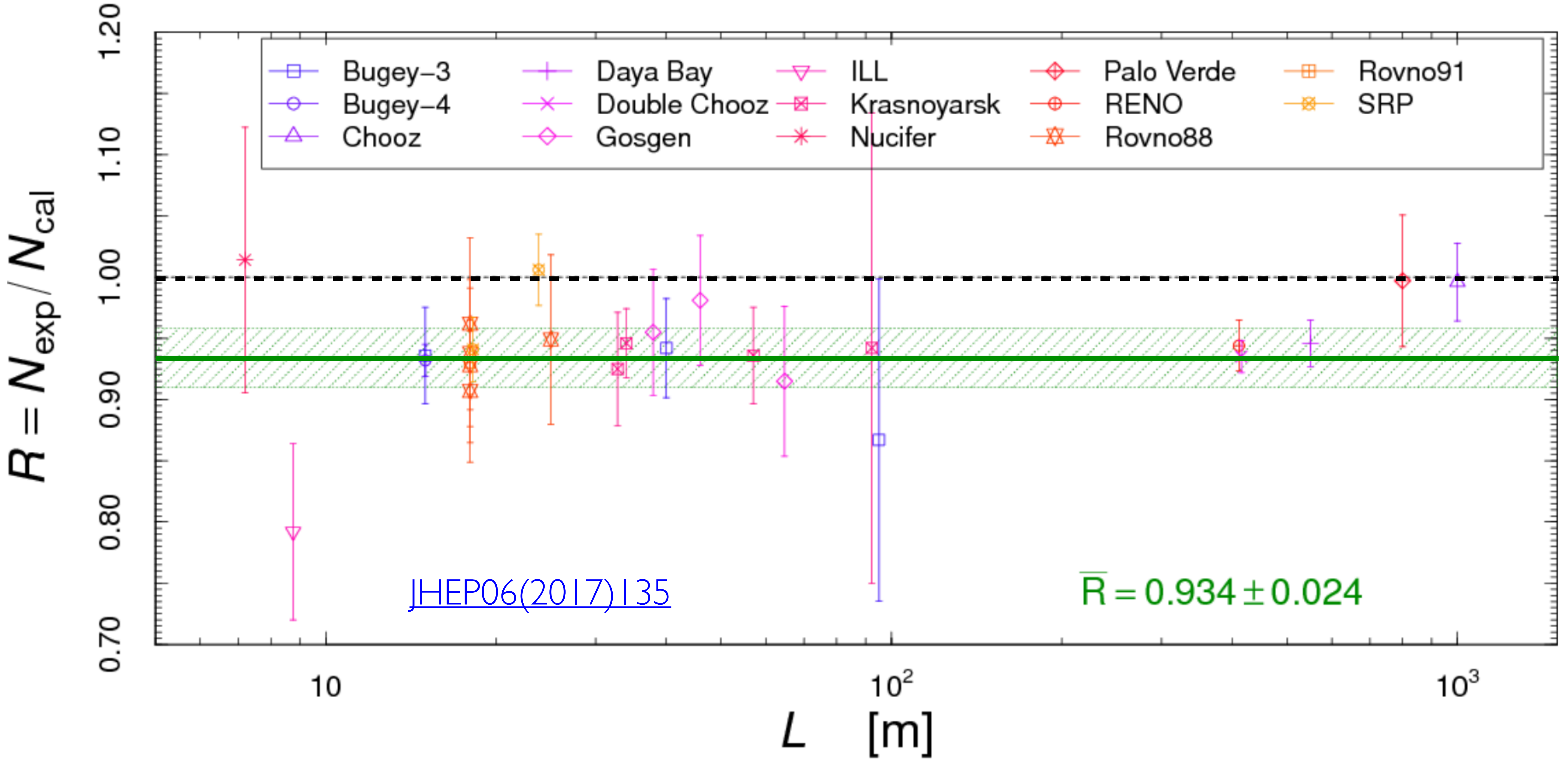
- eV-scale sterile neutrinos
- Finished or currently running experiments
- A bit US-centric

	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

arXiv: 1301.5516

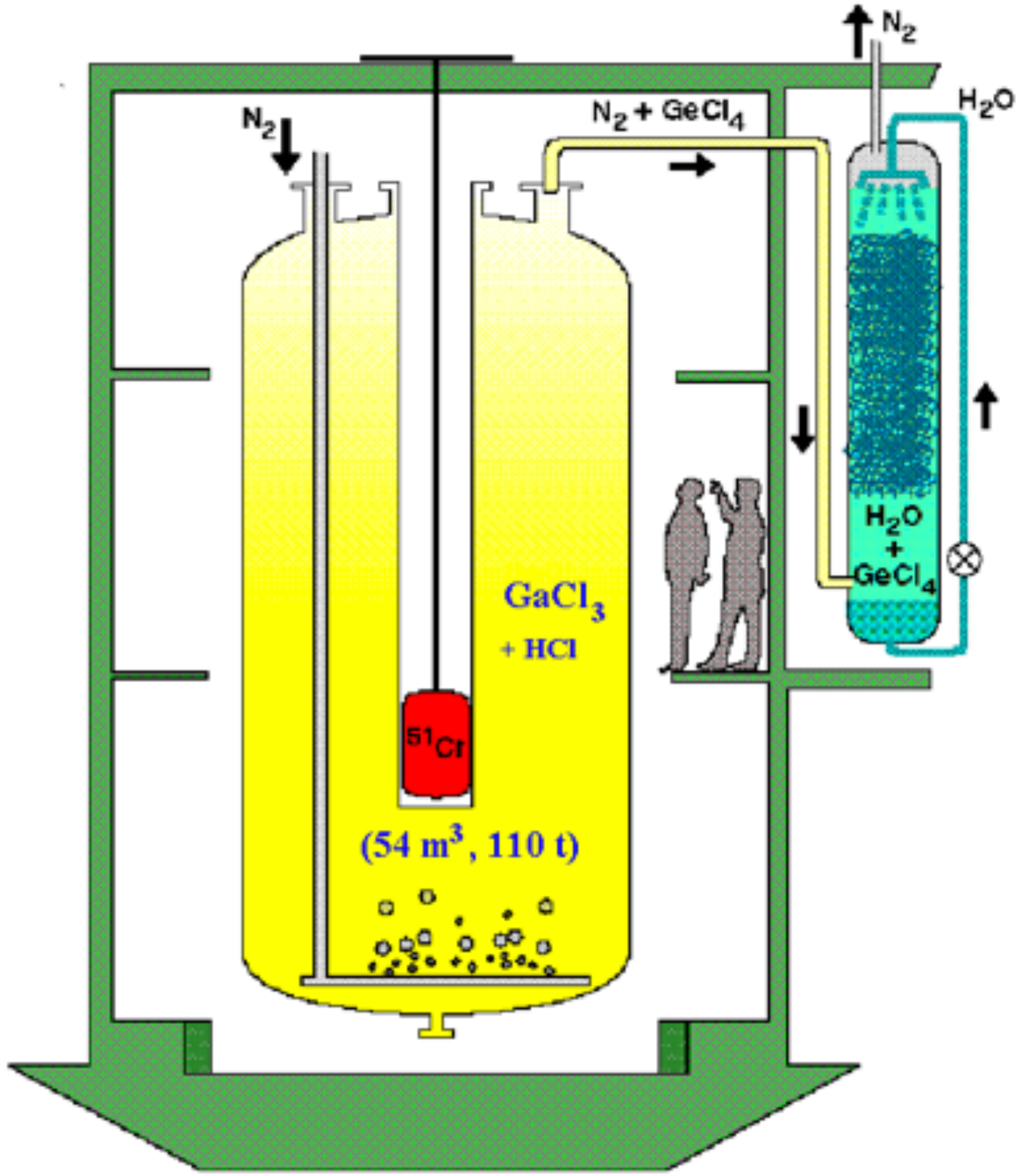
Reactor Antineutrino Anomaly (RAA)

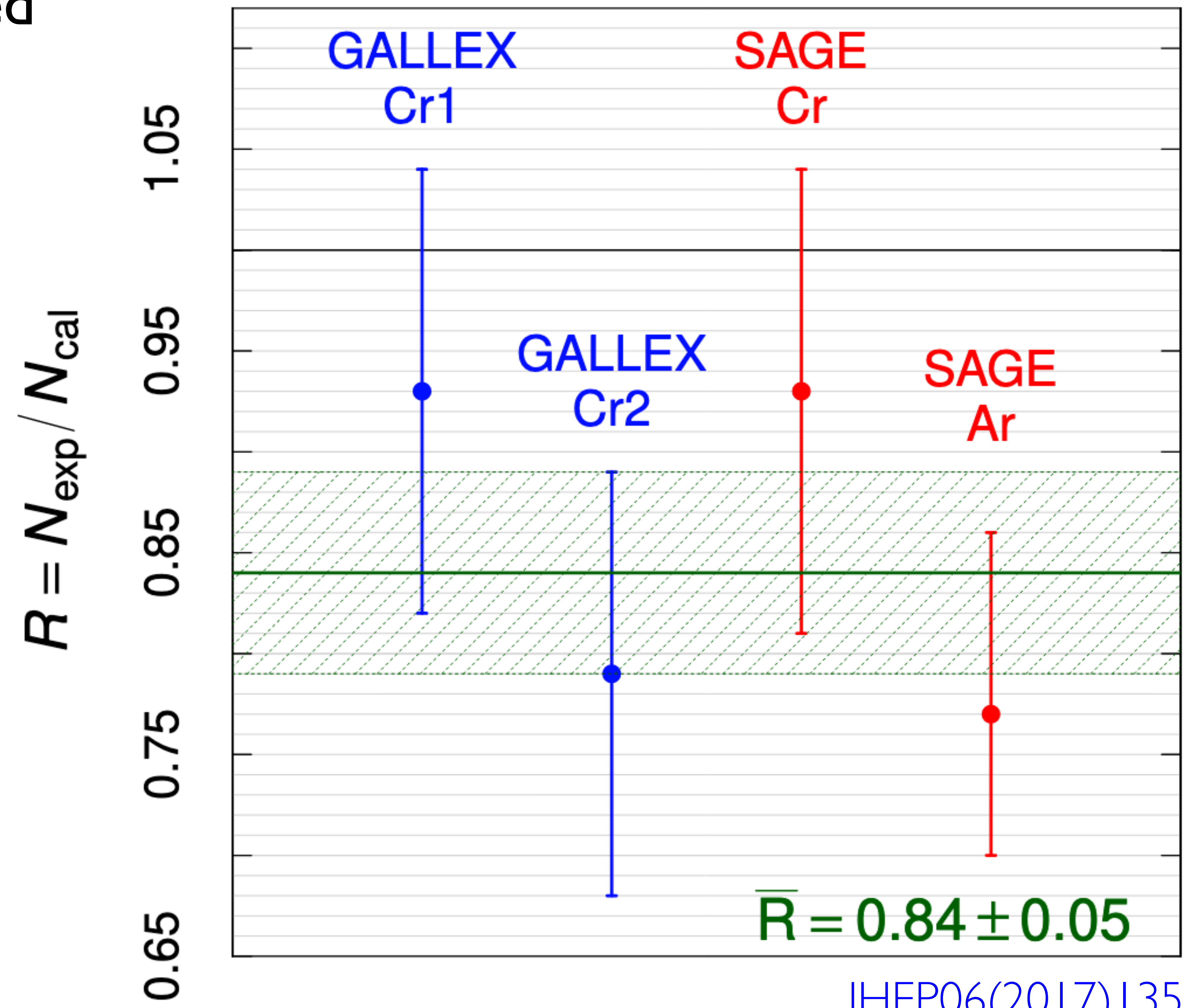
- Reactor Antineutrino Anomaly (RAA)
  - Measured data show ~6% (~3σ) deficit w.r.t updated reactor models



Galium Anomaly (GA)

- Solar neutrino experiments GALLEX and SAGE used ^{51}Cr and ^{37}Ar as calibration sources
- Measured electron neutrinos 16% (~3σ) lower than predicted



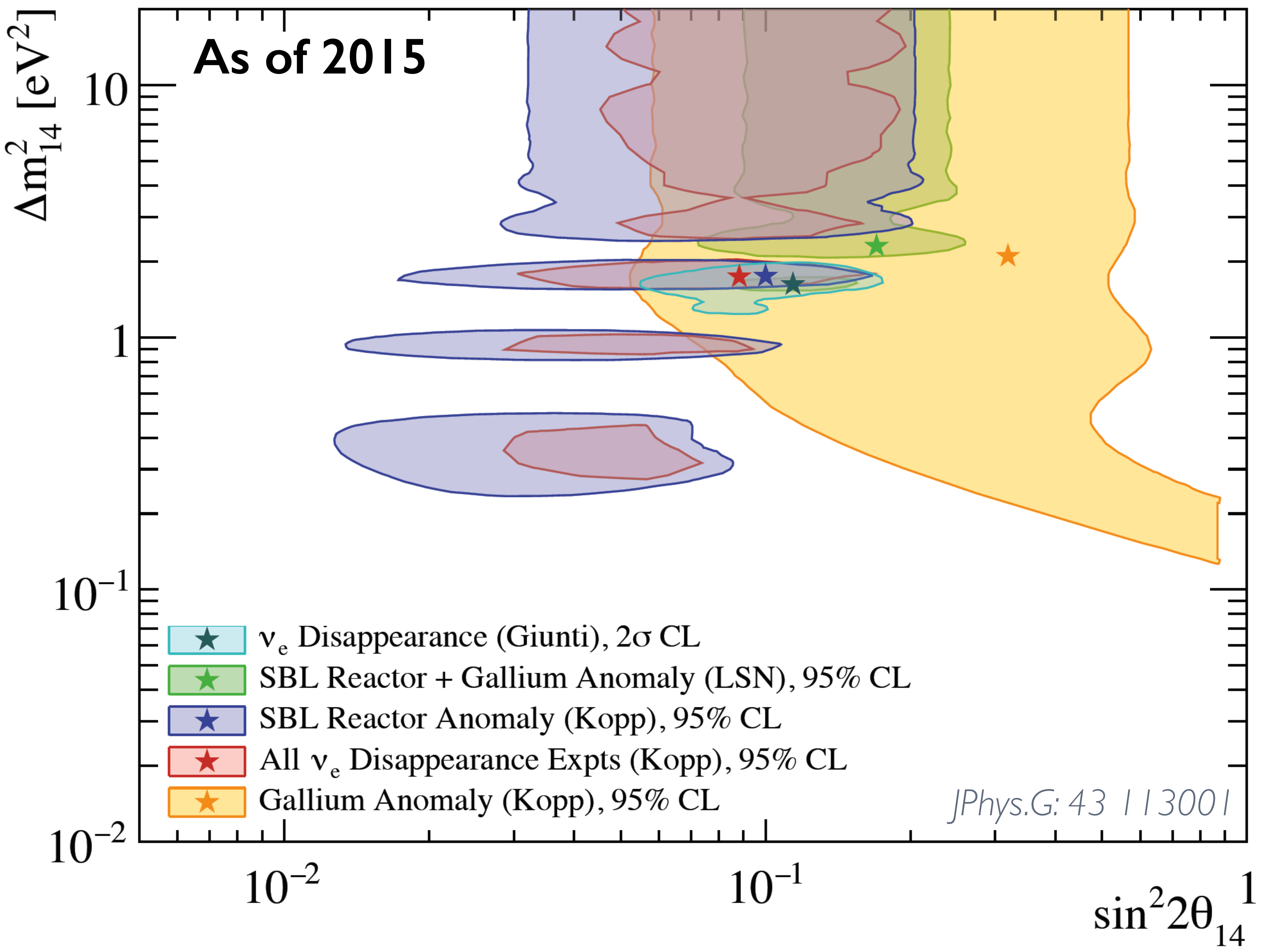


JHEP06(2017)135

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m} \quad \langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

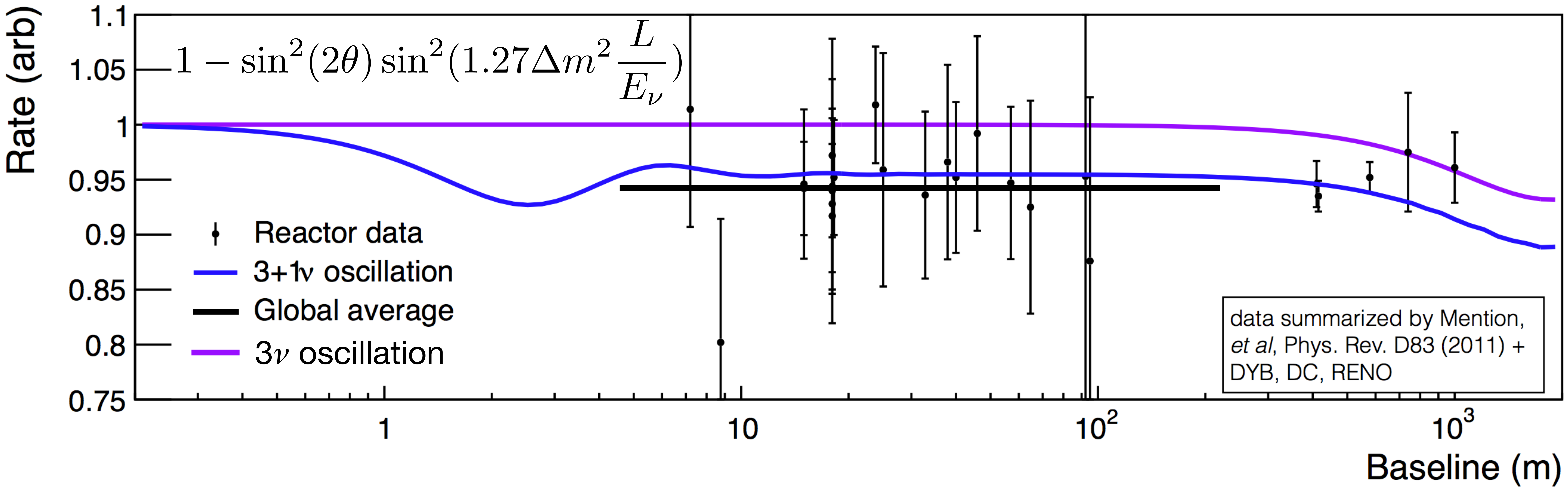
Interpretation of Anomalies

- Both RAA and GA could be explained by eV-scale sterile neutrinos
- Similar parameter space as suggested by the appearance experiments (*see M. Ross-Lonergan's talk*)
- Catalyzed several (particularly reactor neutrino) experiments



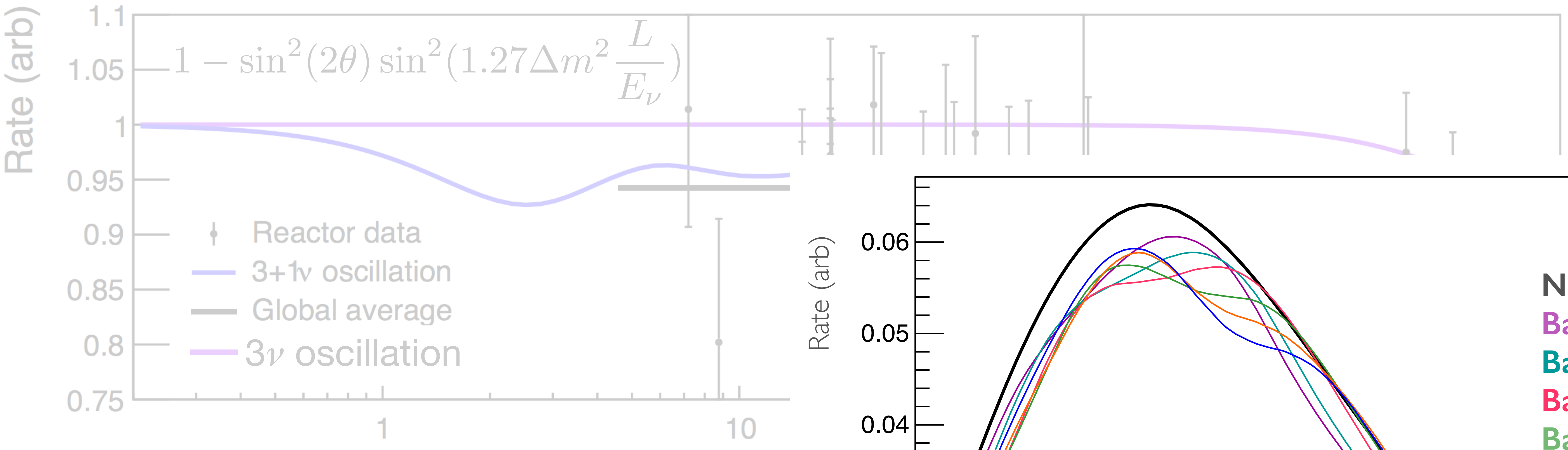
Anomalies motivated searches for eV-scale sterile neutrinos

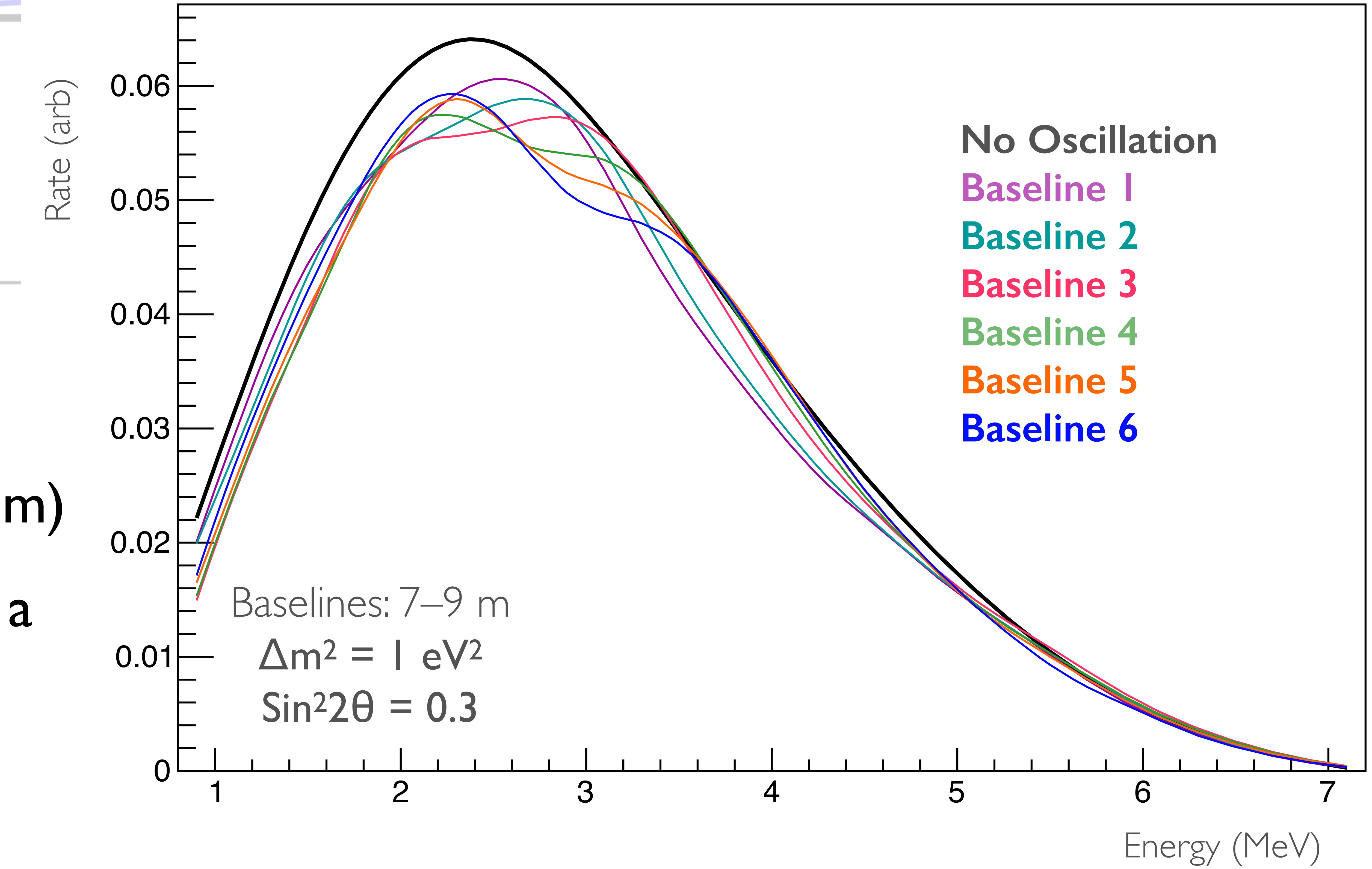
Testing RAA: Searching for Sterile Neutrinos with Reactors



- Sterile neutrinos at eV scale:
  => High frequency oscillations at short distances (<10 m)

Testing RAA: Searching for Sterile Neutrinos with Reactors





- Sterile neutrinos at eV scale:
  => High frequency oscillations at short distances (<10 m)
- Spectrum measured as a function of baseline would be a smoking gun evidence for sterile neutrino oscillations
- Measure spectrum within a single detector, move the detector, or both

Relative spectral searches essential to irrefutably test eV-scale sterile neutrinos

Testing RAA: Recent Reactor Experiments

Experiment	Baseline(m)	Reactor type	Reactor power (MW_{th})	Mass	Target	Search strategy
DANSS	11-13 m	LEU	3000	~1 m^3	PS +Gd coating	Movable
NEOS	24 m	LEU	2800	~1 m^3	GdLS	Relative to Daya Bay
Neutrino-4	6-12	HEU	100	~1.8 m^3	GdLS	Movable
PROSPECT	7-9 m	HEU	85	~4 ton	^{6}LiLS	2D Segmentation
STEREO	9-11 m	HEU	57	~2.4 m^3	GdLS	2D Segmentation

* *Other reactor neutrino SBL experiments that haven't performed oscillation search not included*

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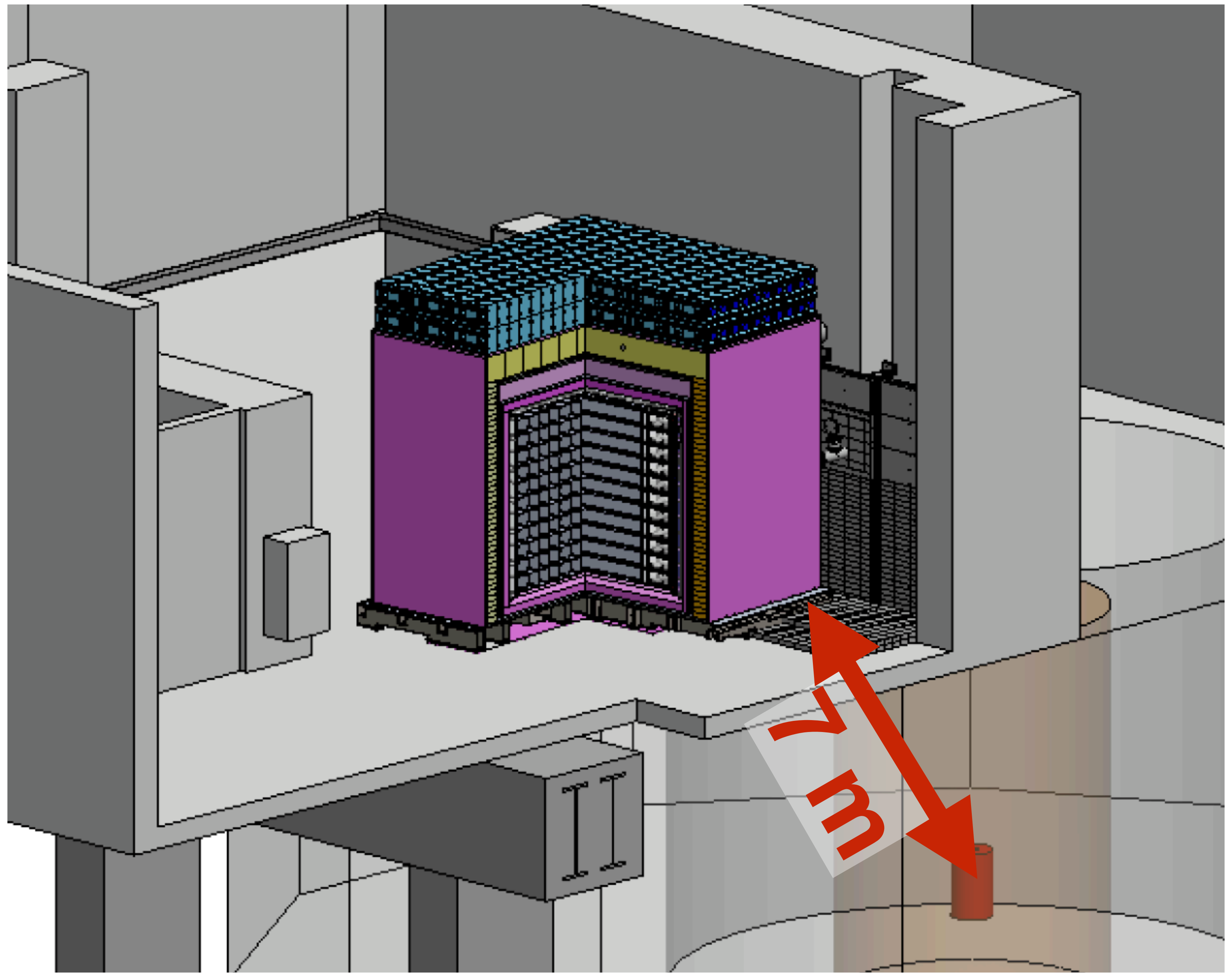
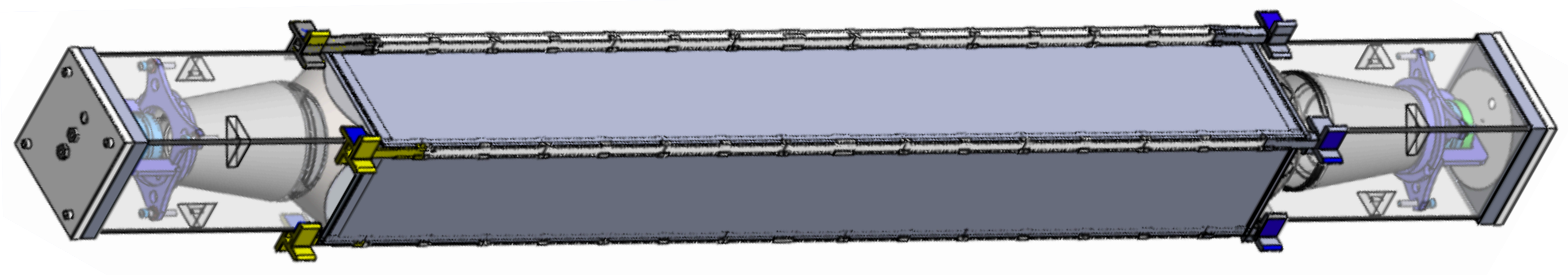
PROSPECT is a US-led domestic experiment

* *Other reactor neutrino SBL experiments that haven't performed oscillation search not included*

PROSPECT Experiment: Leveraging Unique Domestic Facility

- Source: HFIR reactor at ORNL in Tennessee
- Detector:
  - Segmented detector at 7-9 m baselines

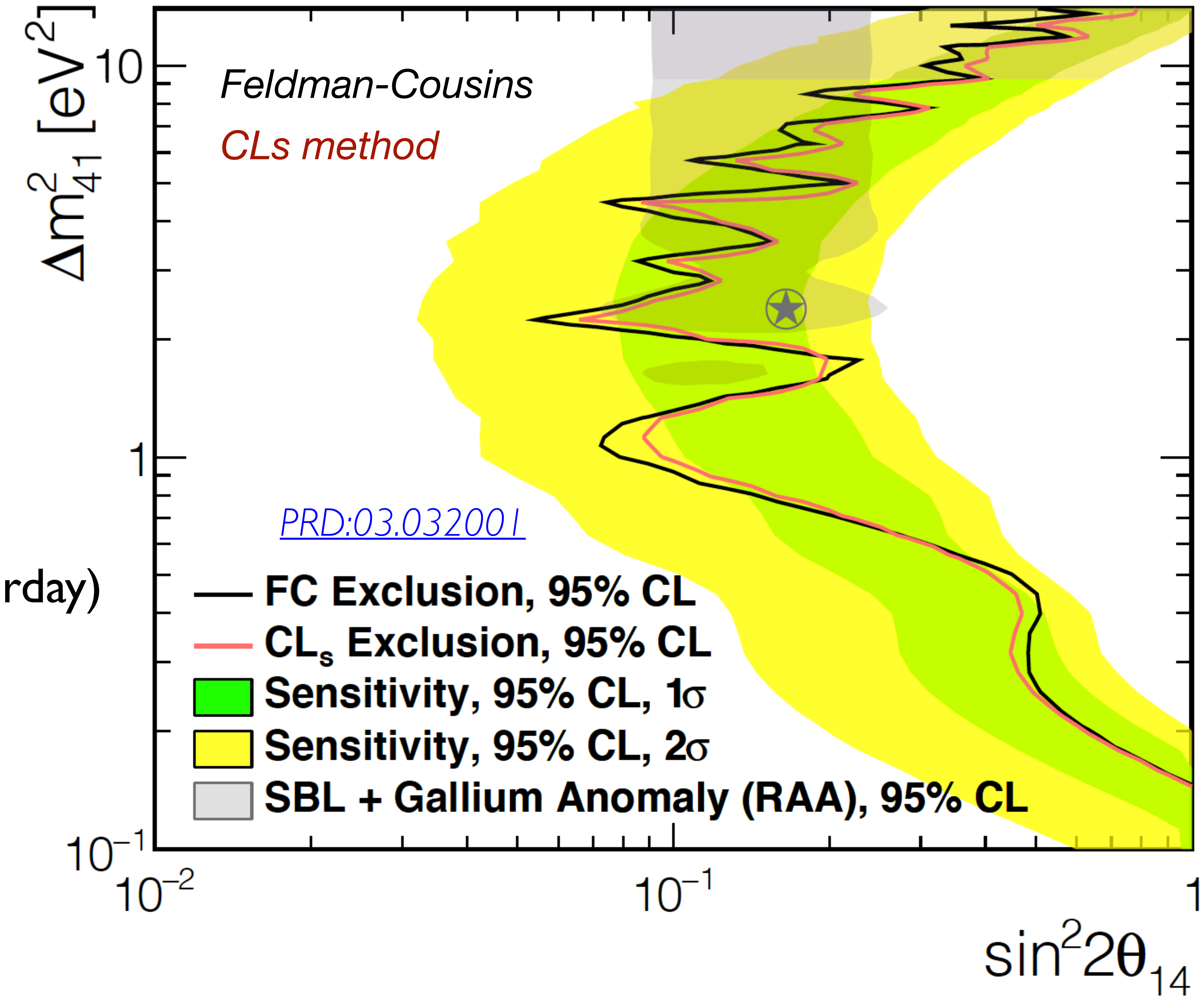




PROSPECT detector as installed at Oak Ridge National Laboratory

PROSPECT Experiment: Leveraging Unique Domestic Facility

- Source: HFIR reactor at ORNL in Tennessee
- Detector:
  - Segmented detector at 7-9 m baselines
- Excluded best fit point at 2.5σ
- Limited by statistics (~50k events)
- Improvements in analysis underway (D. Venegas-Vargas on Saturday)
- Phase-II detector is at an advanced design stage (F. Sutanto on Saturday)



Yale

PROSPECT Experiment: Leveraging Unique Domestic Facility

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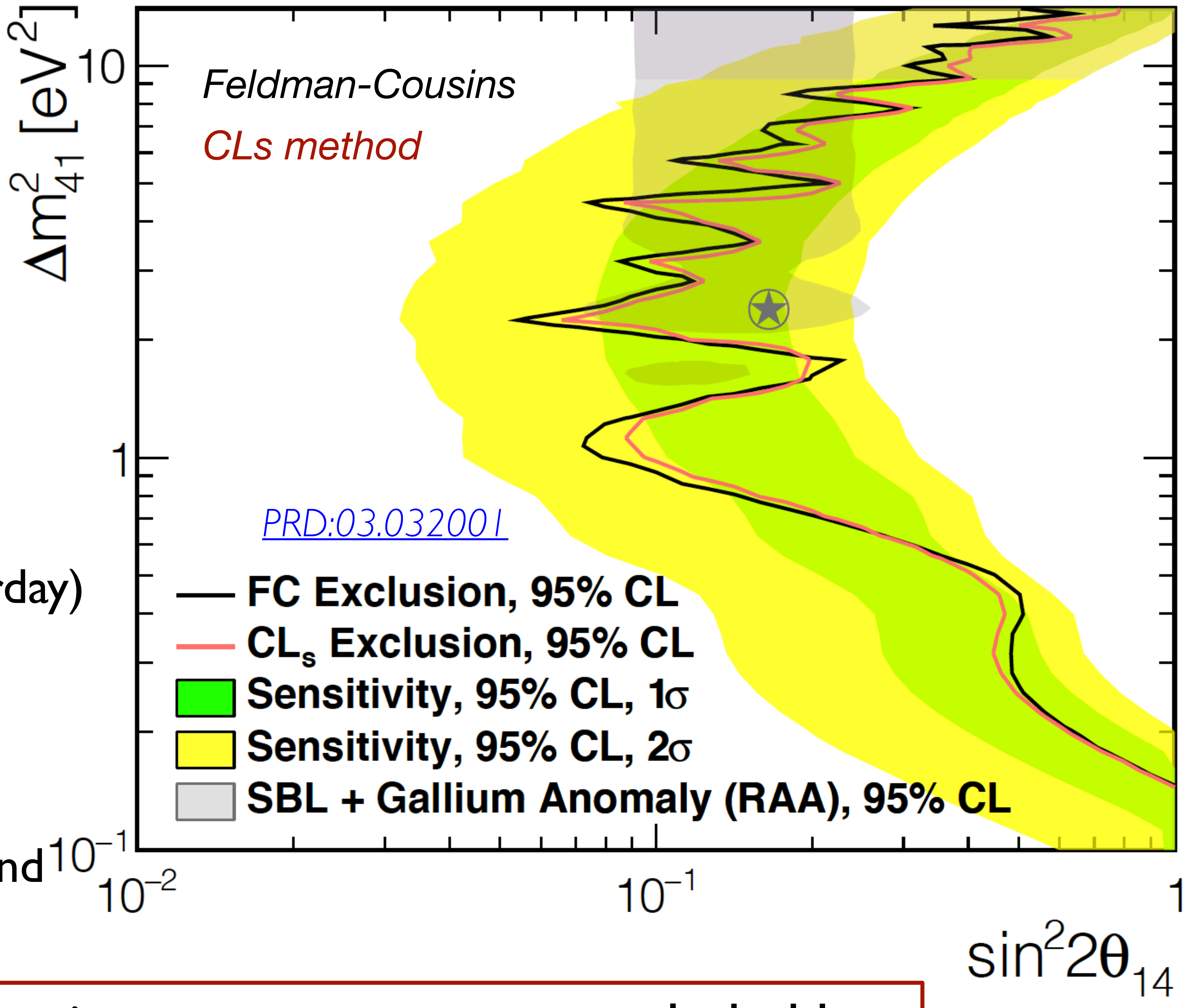
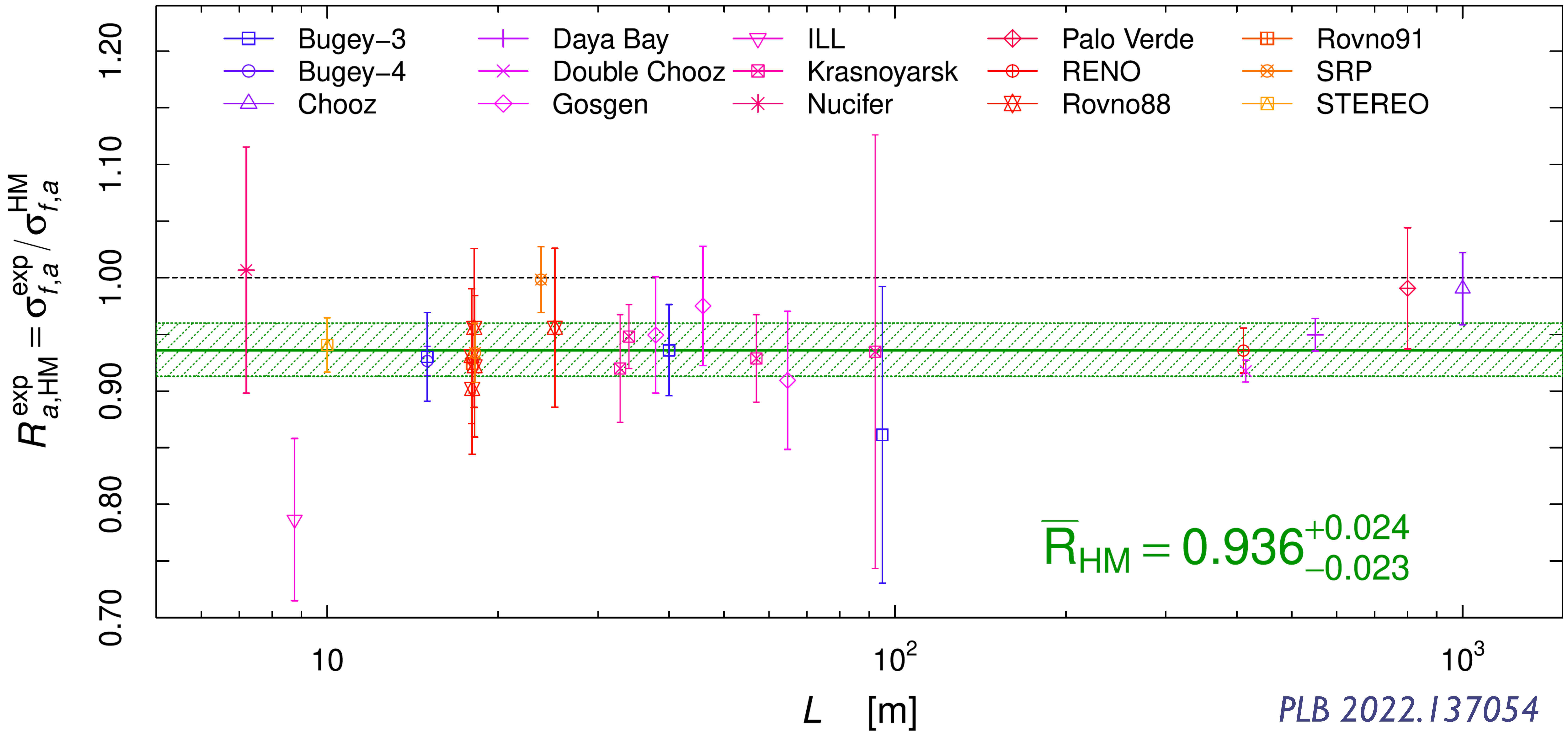
- Limited by statistics (~50k events)
- Improvements in analysis underway (D.Venegas-Vargas on Saturday)
- Phase-II detector is at an advanced design stage (F. Sutanto on Saturday)
- Not discussed here: Spectrum measurements by PROSPECT (and others) help understand issues with modeling



Major portion of the suggested sterile neutrino parameter space excluded by PROSPECT and other reactor neutrino experiments (except Neutrino-4)

Conventional Explanation for Flux Anomaly

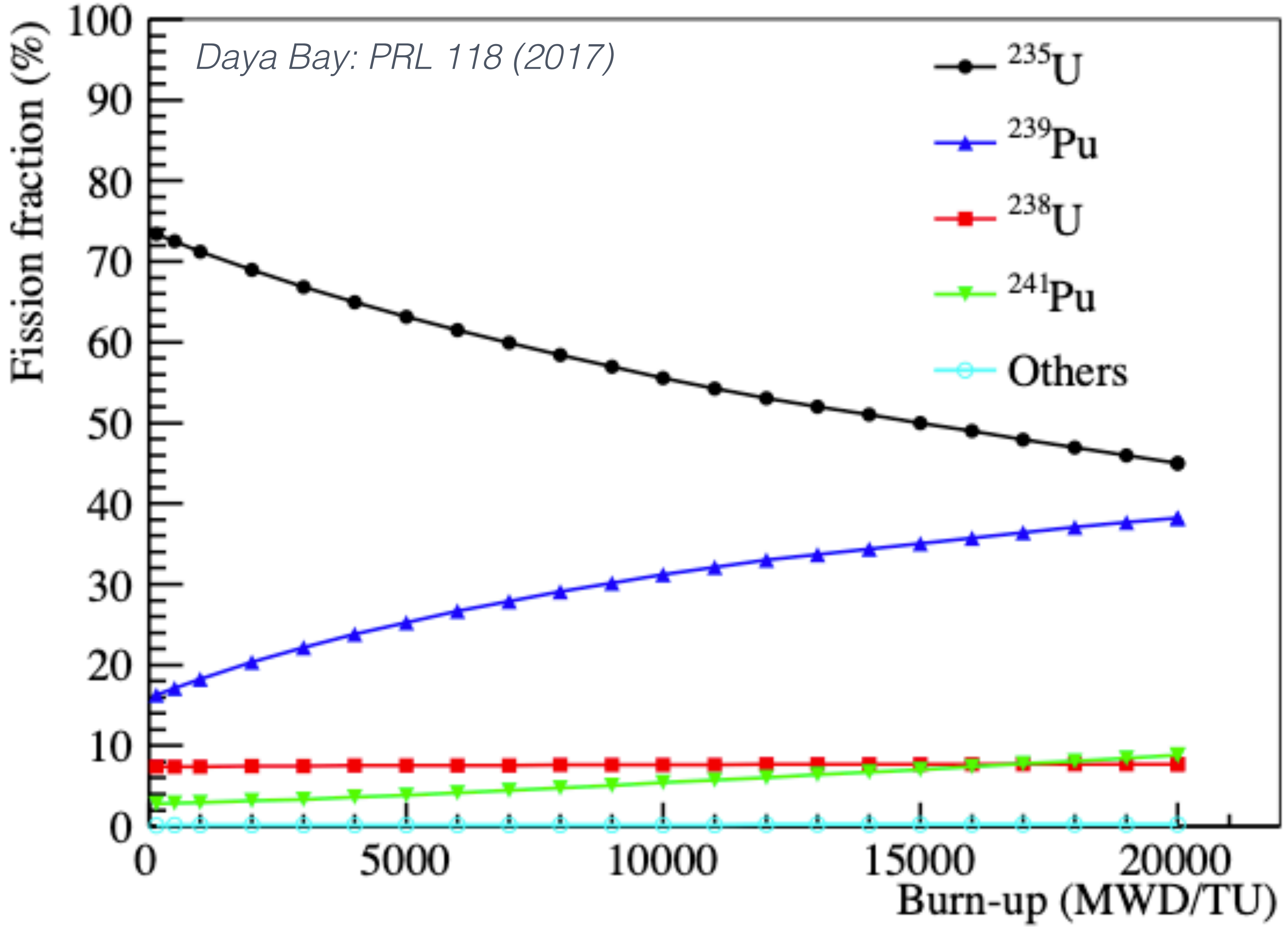
- Reactor Antineutrino Anomaly: Flux predictions disagree with measurements
- Could the flux predictions be wrong ?



PLB 2022.137054

Individual IBD Yields Disagree with Models

- Neutrino flux at LEU reactors could be measured as a function of fission fractions of $^{235}U/^{239}Pu$
- One can extract the contribution (IBD yield) of single isotope to the measured flux



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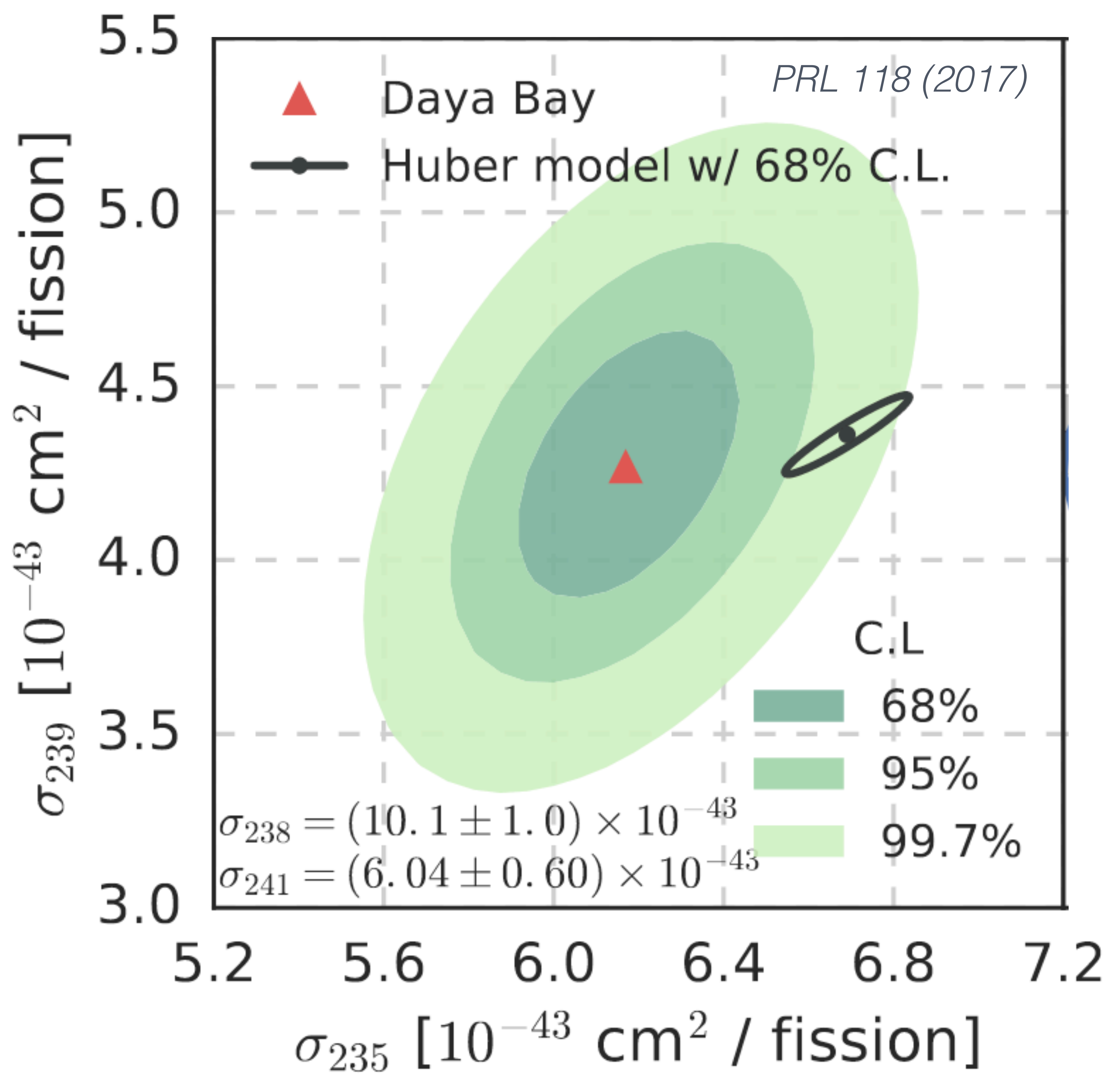
- One can extract the contribution (IBD yield) of single isotope to the measured flux
- ^{239}Pu yield agrees with models
- But ^{235}U yield disagrees
- STEREO's modern pure ^{235}U IBD yield measurement also agrees with Daya Bay/RENO

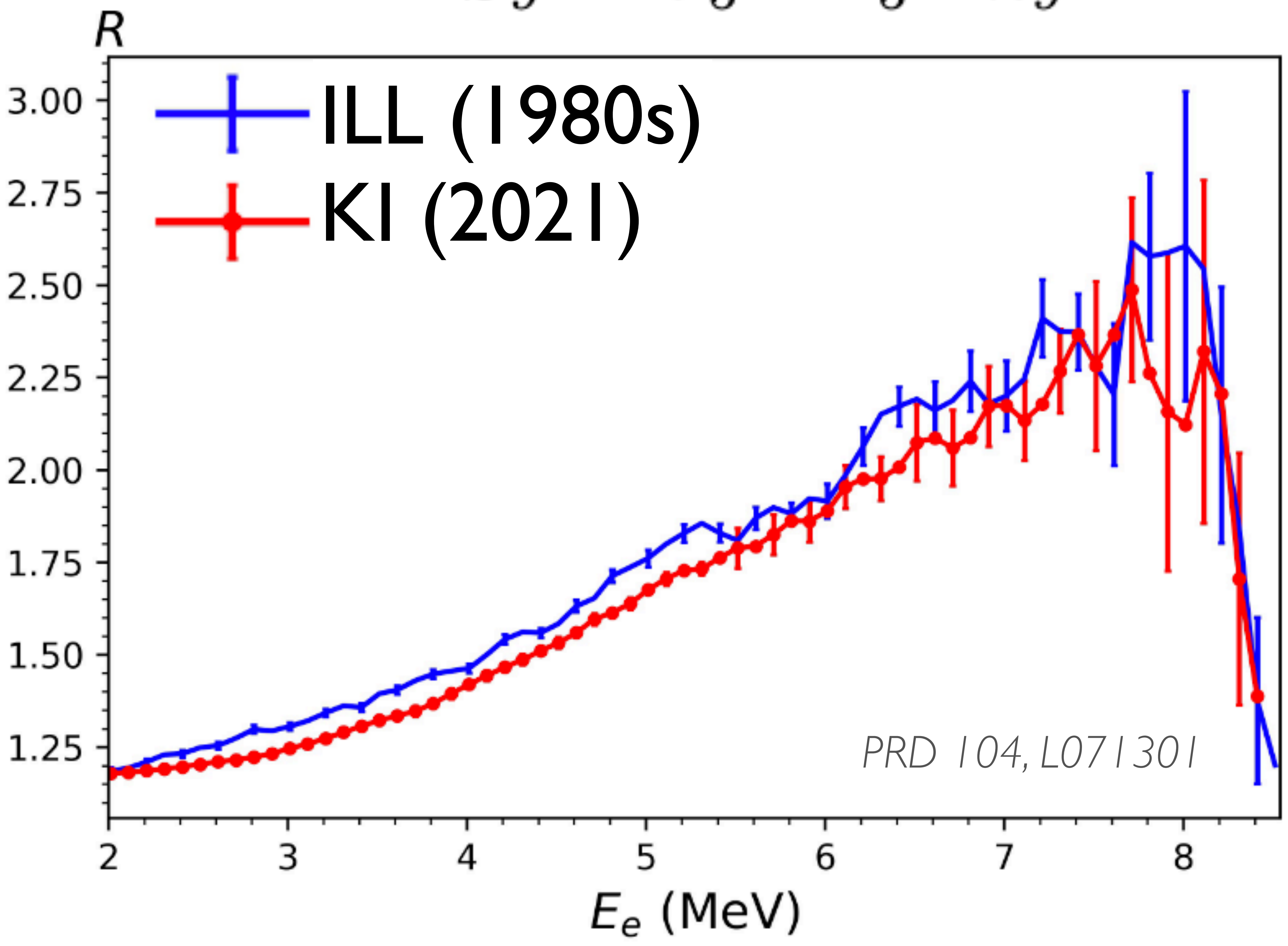


Reactor neutrino modeling of ^{235}U disputed by modern IBD yield measurements

Beta Decay Measurements Point Toward ^{235}U Mismodeling

- Reactor (conversion) models reliant on the β-decay measurements done in 1980s
- Recent claim: Issue with calibration in the original β-decay measurements
- New measurement of ^{235}U/^{239}Pu β-decay spectra performed at Kurchatov Institute
- Shows that ^{235}U normalization was overestimated (assuming ^{239}Pu normalization is correct)

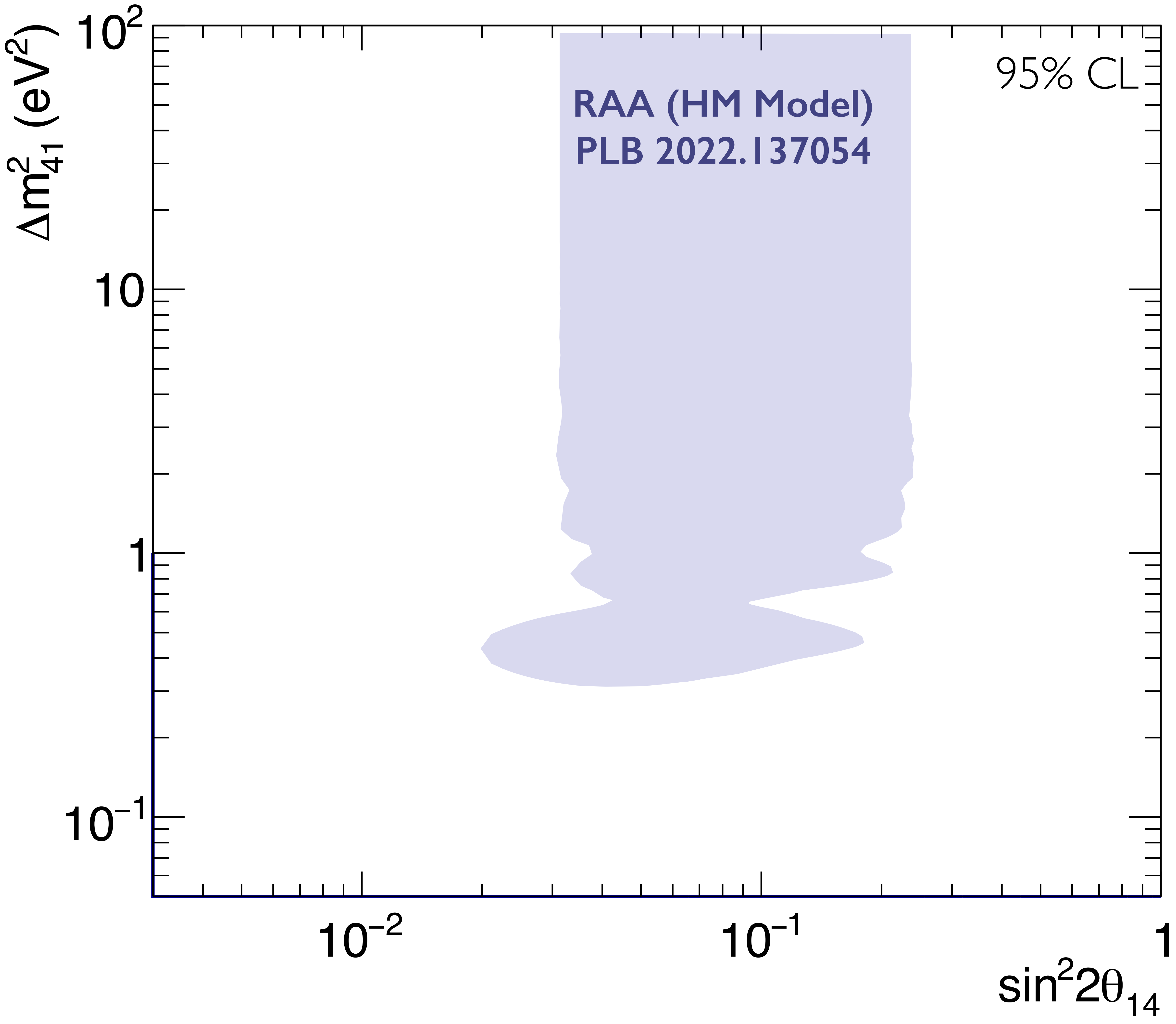
$$R \equiv \frac{{}^{e}S_5}{{}^{e}S_9} = \frac{\sigma_9}{\sigma_5} \cdot \frac{N_9}{N_5} \cdot \frac{n_5}{n_9},$$



^{235}U mismodeling seem to be the source of RAA

Current Reactor Neutrino Status

- Updated models don't agree with canonical Huber-Mueller (HM) model
- Updated models agree with Daya Bay + RENO evolution + STEREO



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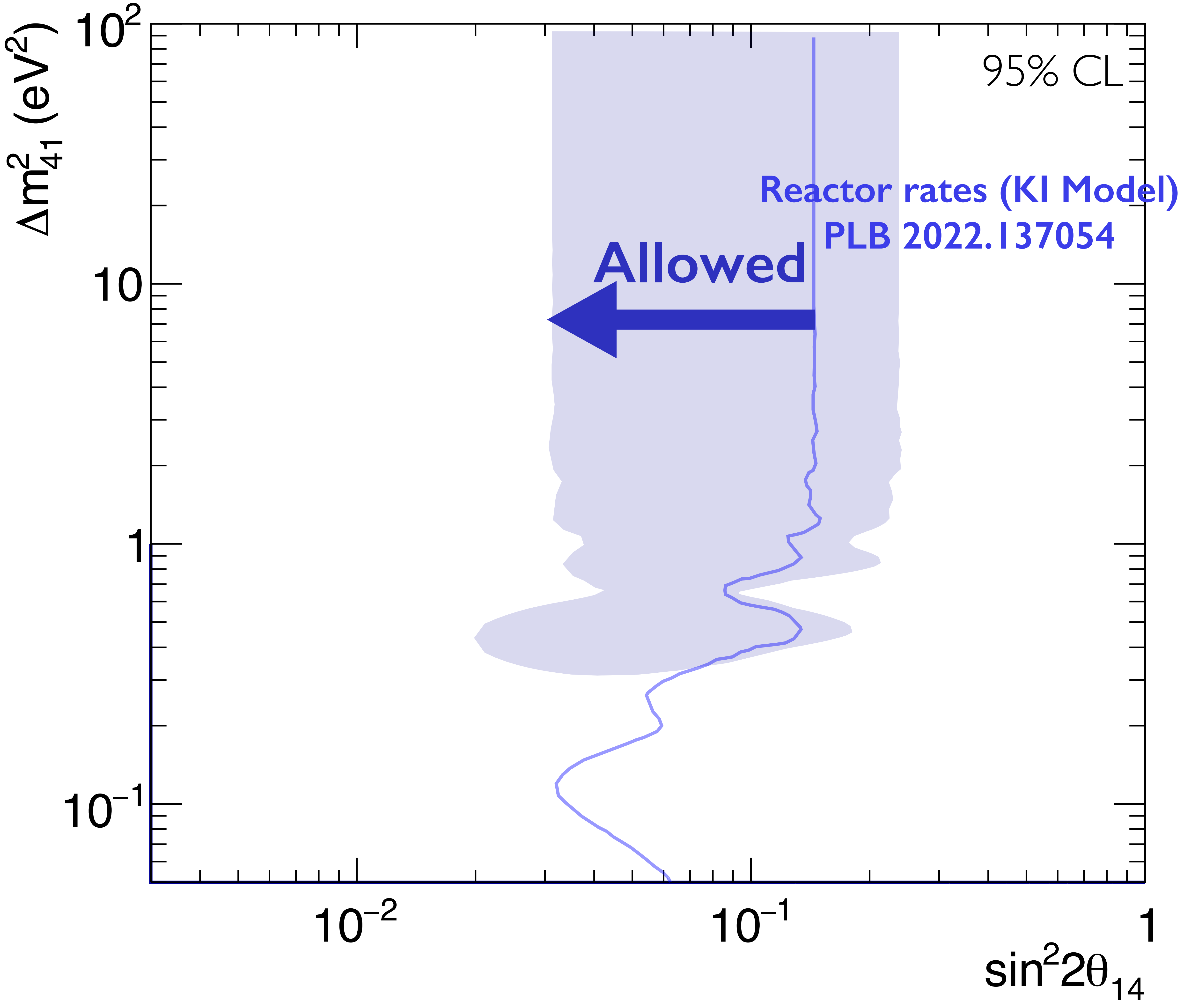
- **Reactor mismodeling and sterile neutrinos not (yet) mutually exclusive**



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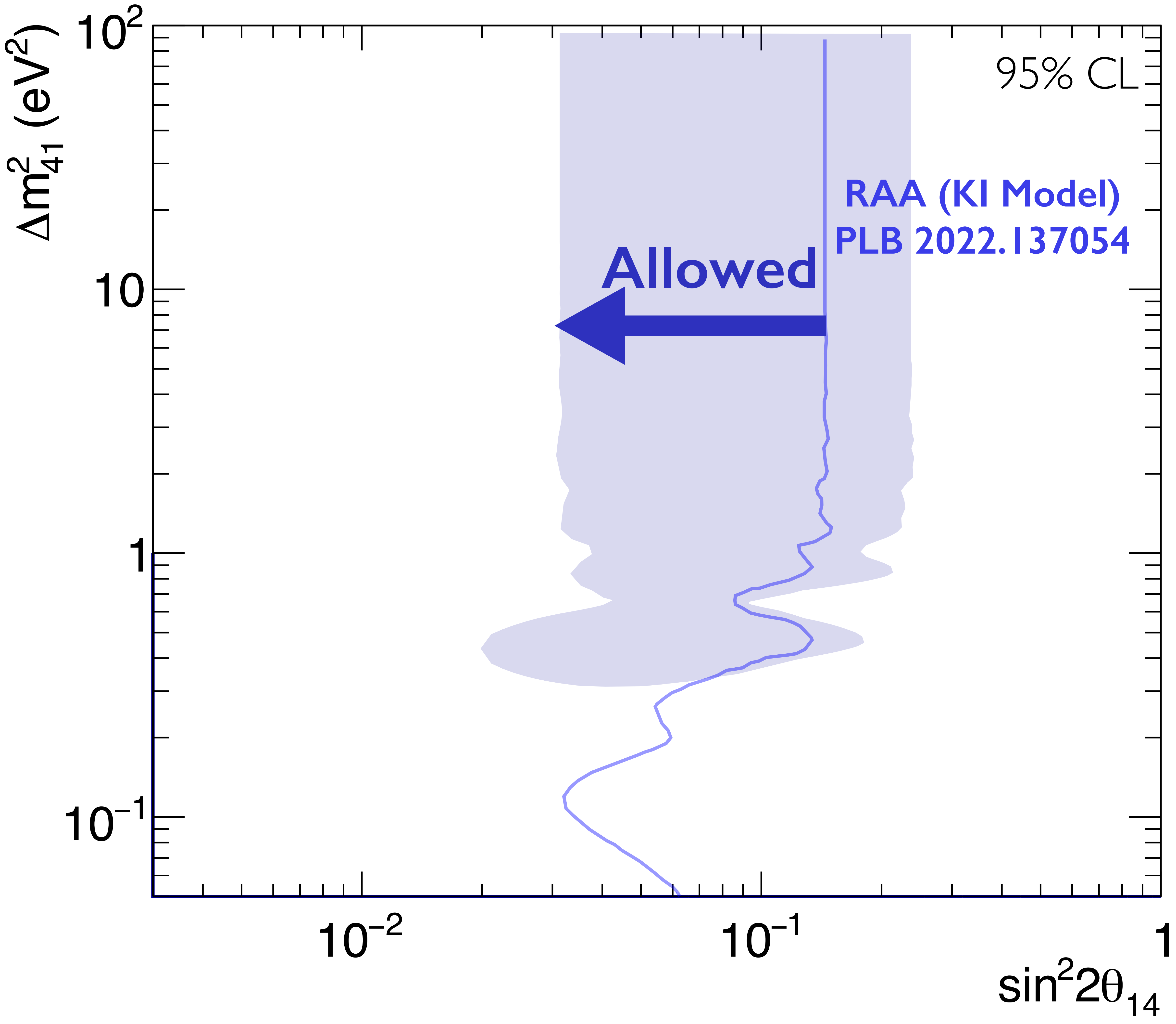

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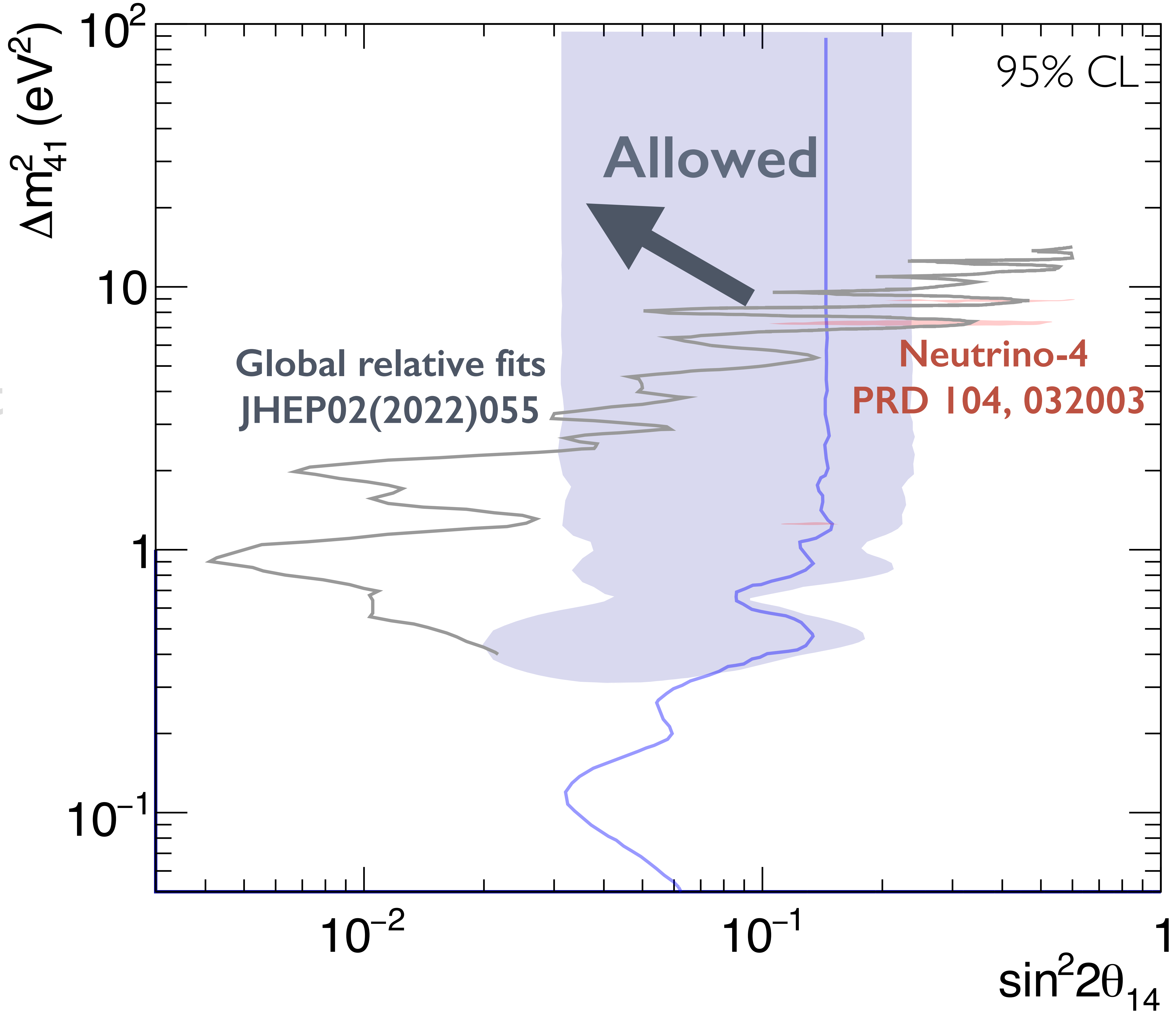
- Significant portion of the suggested parameter space excluded
- ~Δm^2 > 5 eV^2 yet to be excluded



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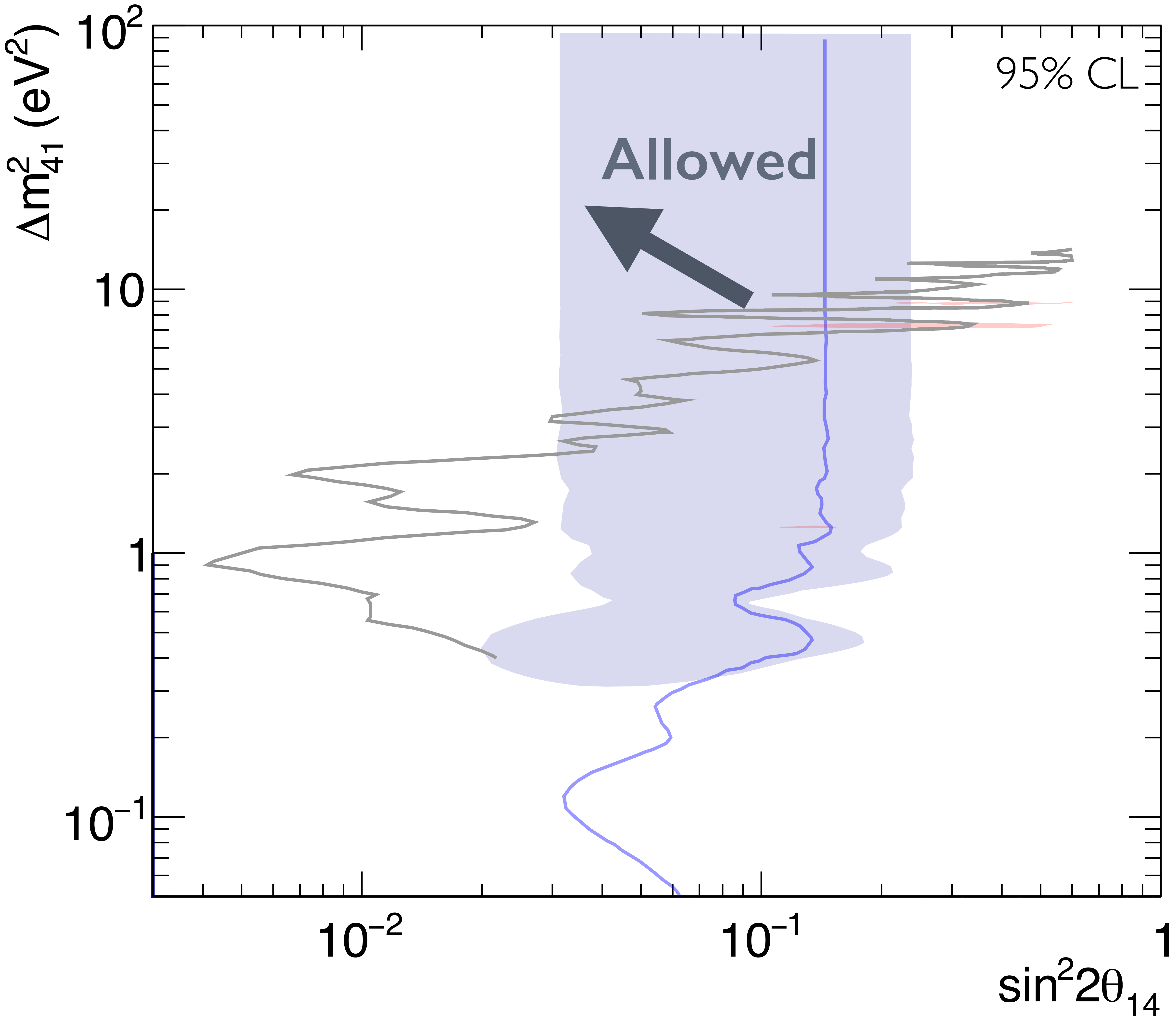


Baseline-dependent reactor spectra are essential to probe flavor transformation scenarios

Testing Galium Anomaly: BEST Experiment

- BEST: Gallium source experiment similar to GALLEX and SAGE
- Source: 3 MCi of ^{51}Cr source

752 keV (8.49%)
747 keV (81.63%)
432 keV (0.93%)
427 keV (8.95%)

$$e^- + \boxed{^{51}\mathrm{Cr}} \rightarrow {}^{51}\mathrm{V} + \boxed{\nu_e}$$

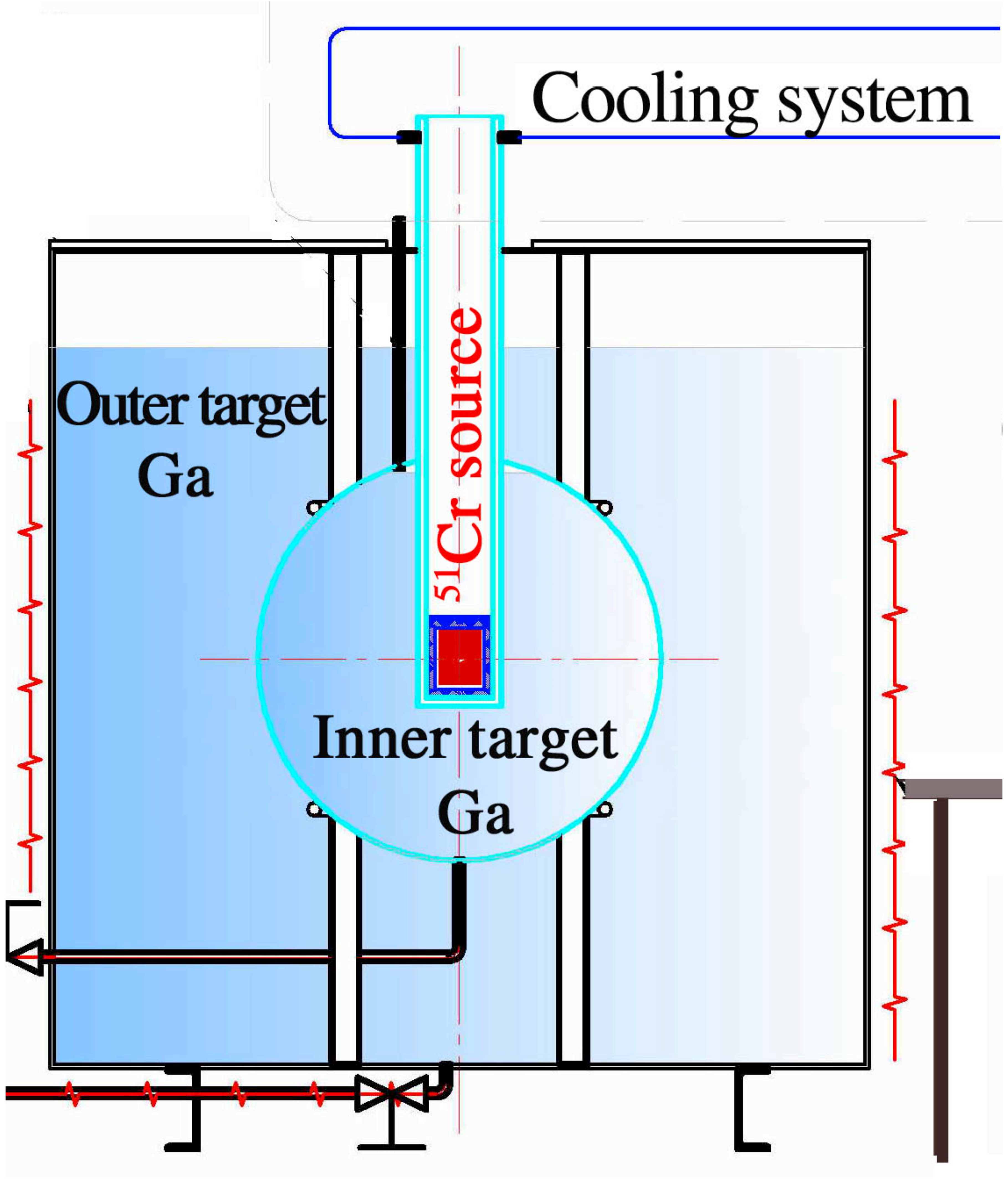
^{51}Cr (27.7 days)

$$\boxed{\nu_e} + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$$

- Two zones:

1. Inner sphere (L ~ 0.660 m)
2. Outer cylinder (L ~ 1.096 m)

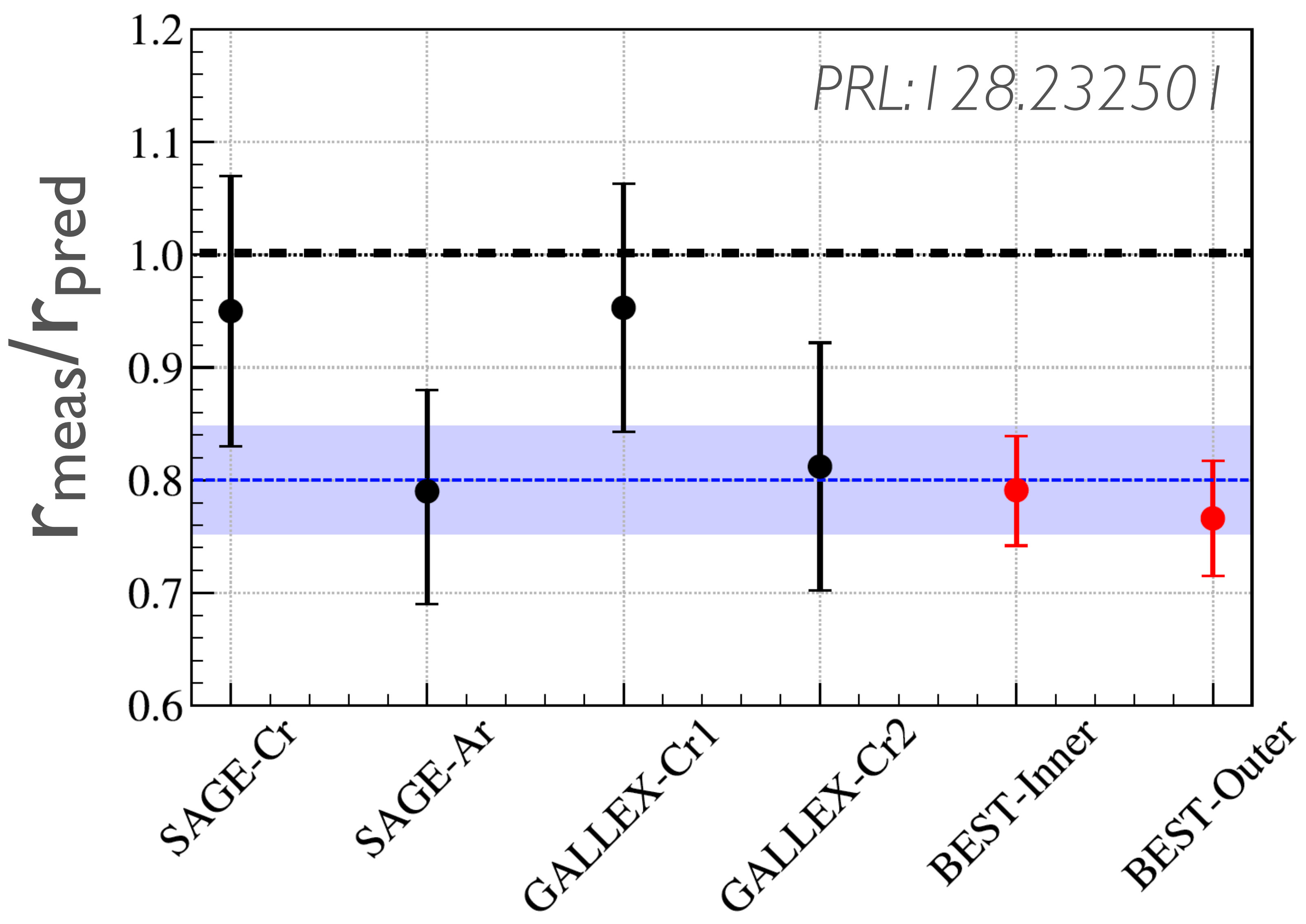
  - ^{71}Ge production at each distance measured separately



PRL:128.232501

BEST Results

- Data taking July - Nov 2019
- Measured rate lower than expected in **both volumes**
    - R_{in} = 0.79 ± 0.05, R_{out} = 0.77 ± 0.05
- BEST reinforces Gallium Anomaly at > 5 σ
- Conventional nuclear physics can't resolve the large discrepancy



Gallium Anomaly Persists after BEST

- Data taking July - Nov 2019
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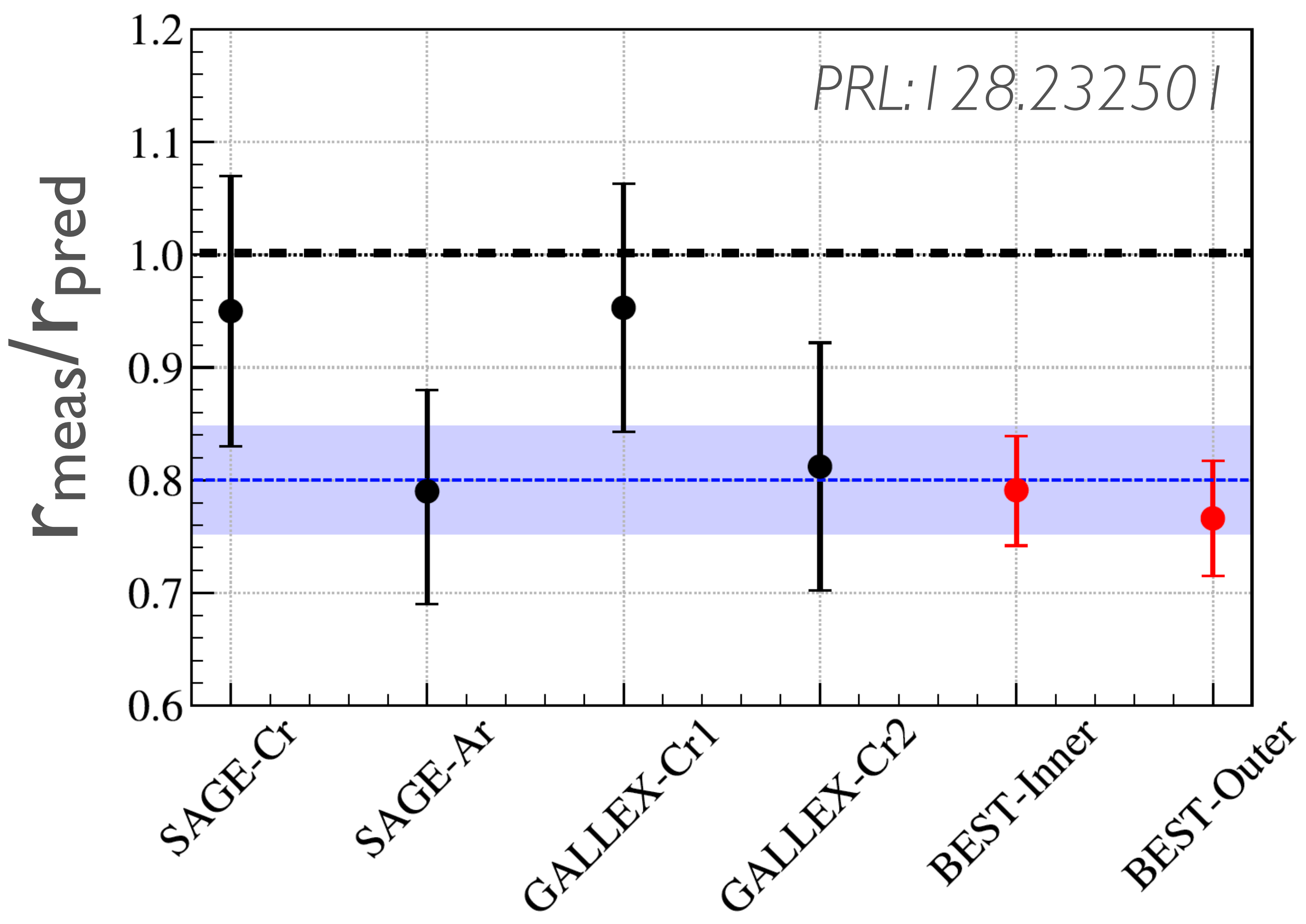
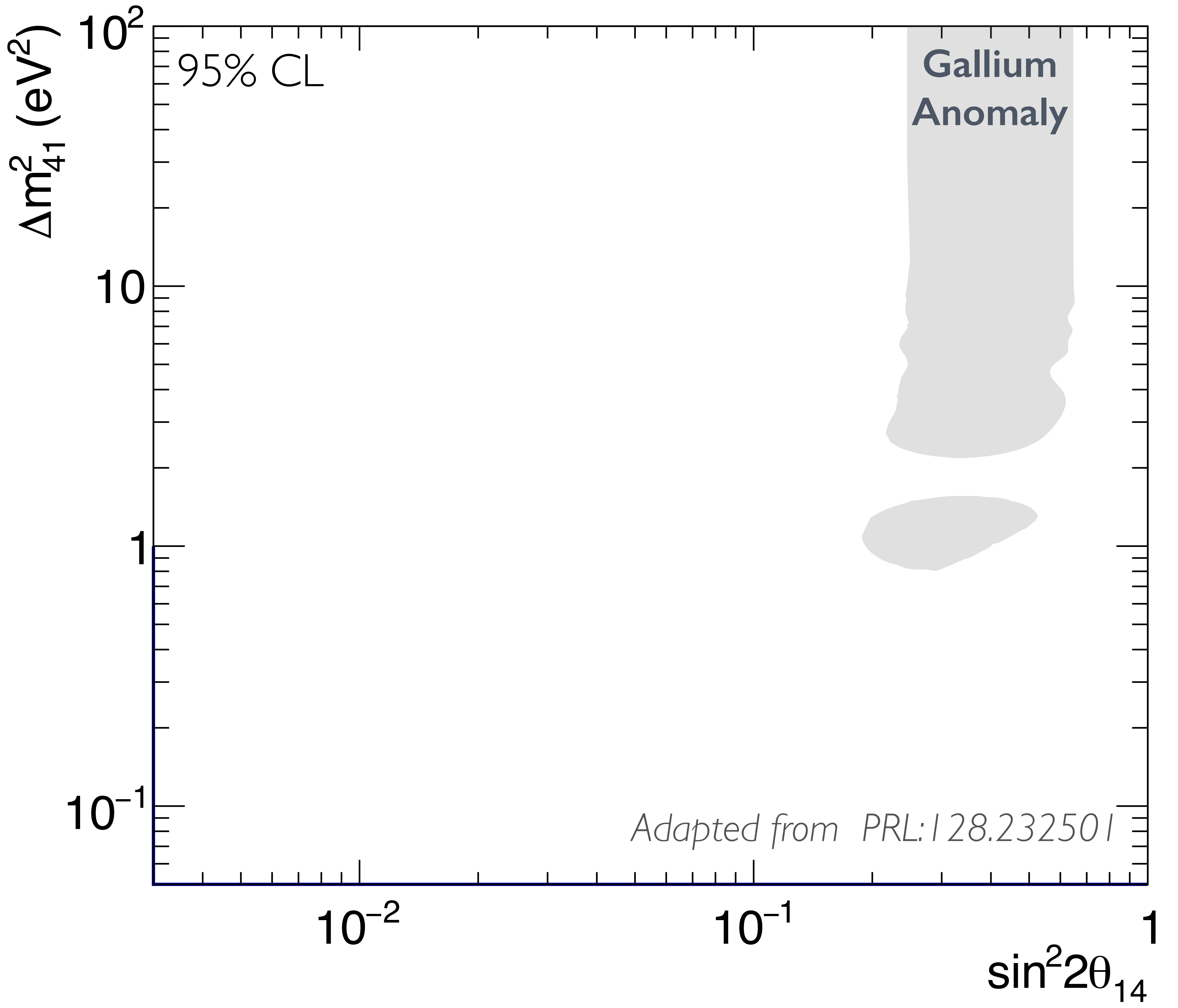
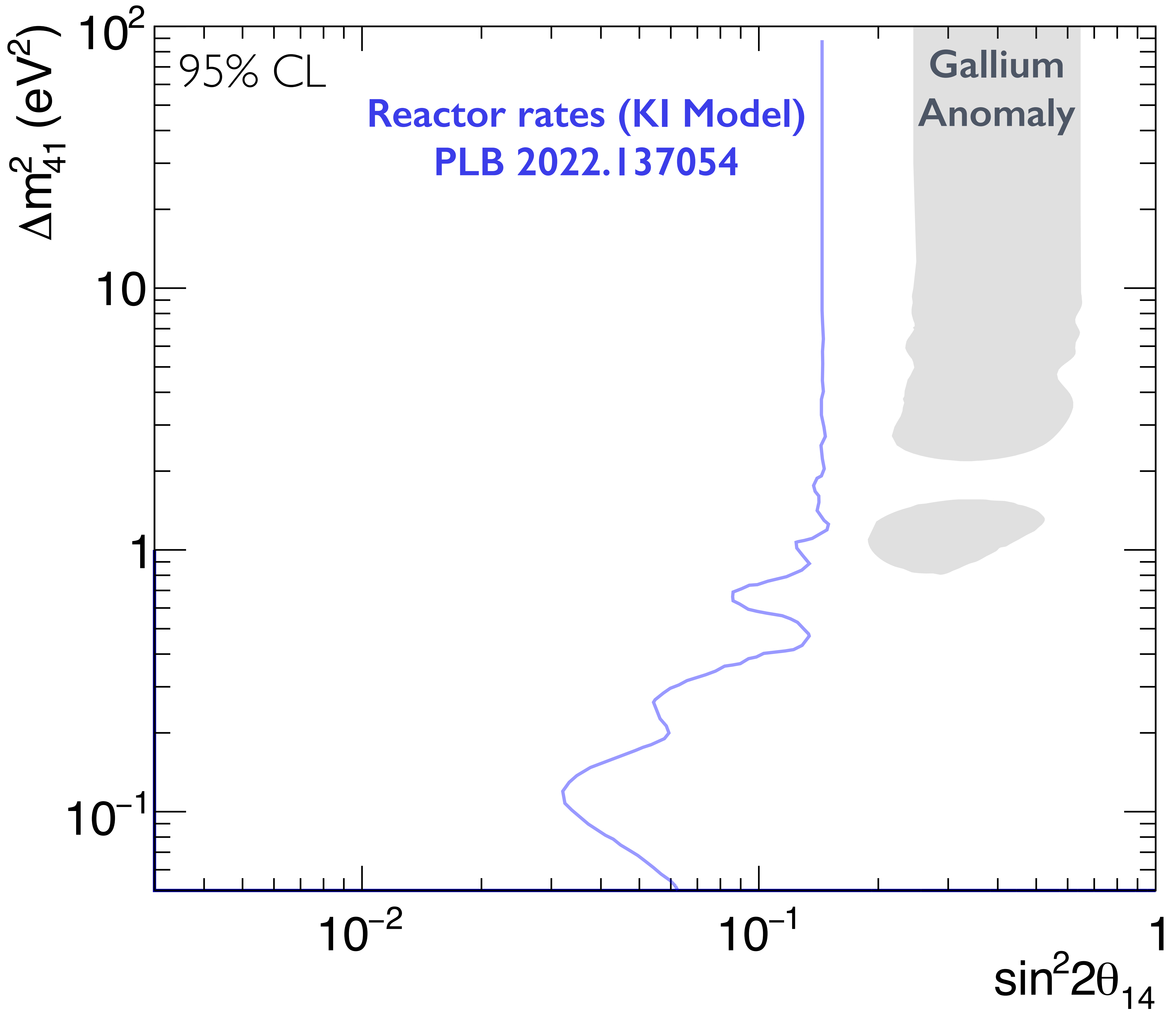




BEST reinforces Gallium Anomaly and is consistent with eV-scale sterile neutrino hypothesis

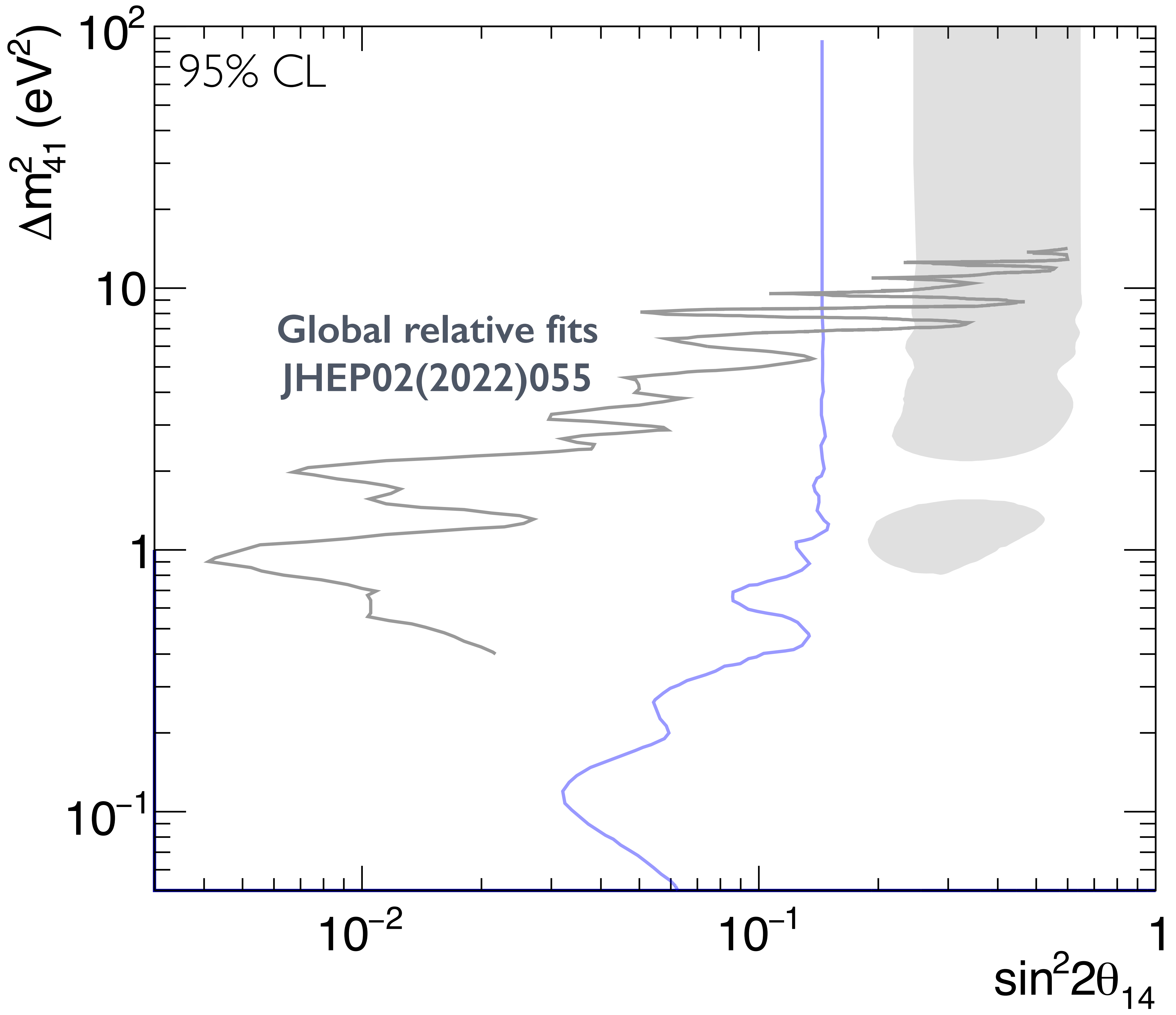
Reactor + Gallium Experiments

- The deficit from GA is too high to be compatible with updated reactor rates



Reactor + Gallium Experiments

- The deficit from GA is too high to be compatible with updated reactor rates
- Also major portions of 3+1 suggested parameter space by GA excluded by relative reactor spectral data



Reactor + Gallium + β-decay Experiments

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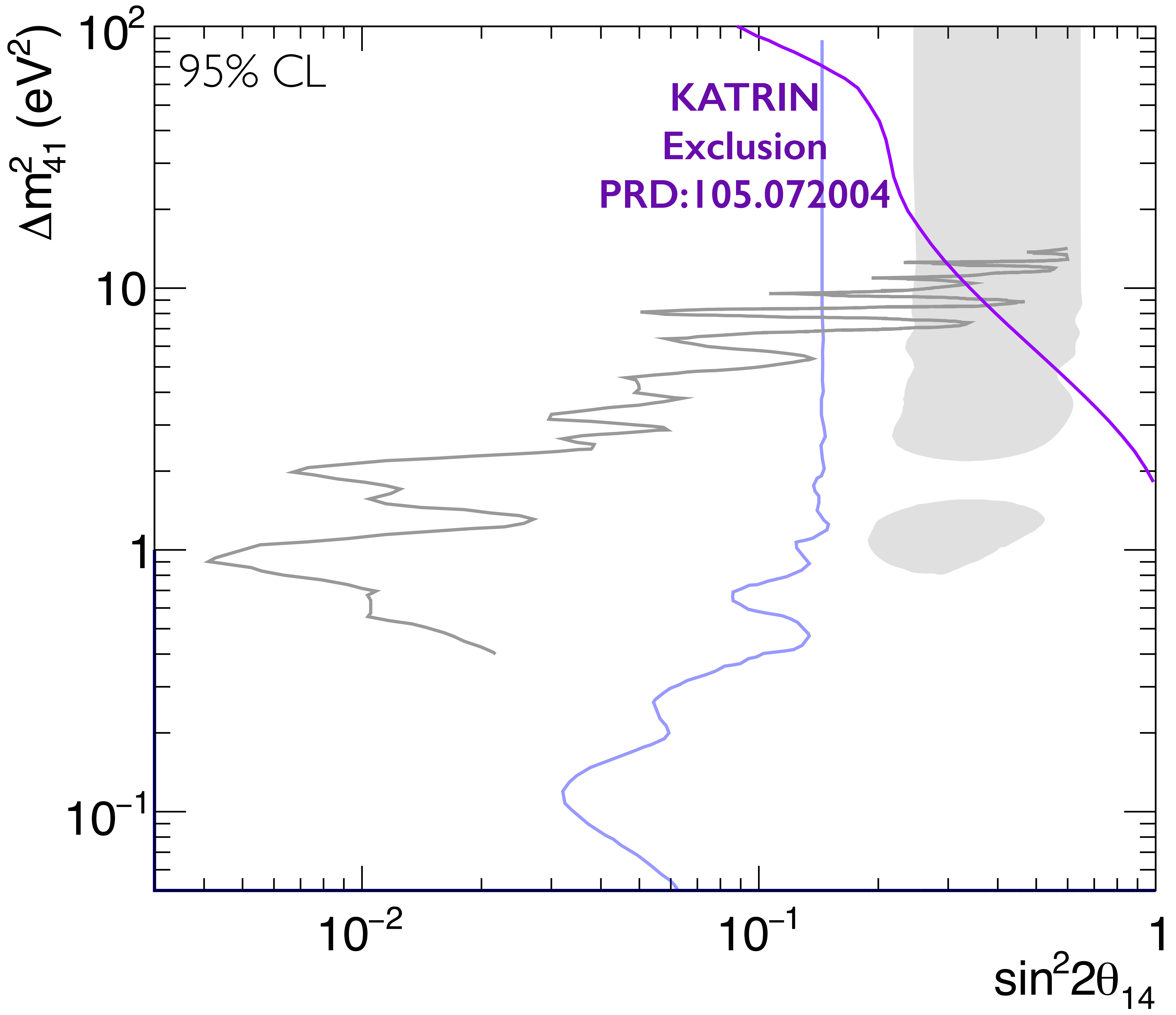
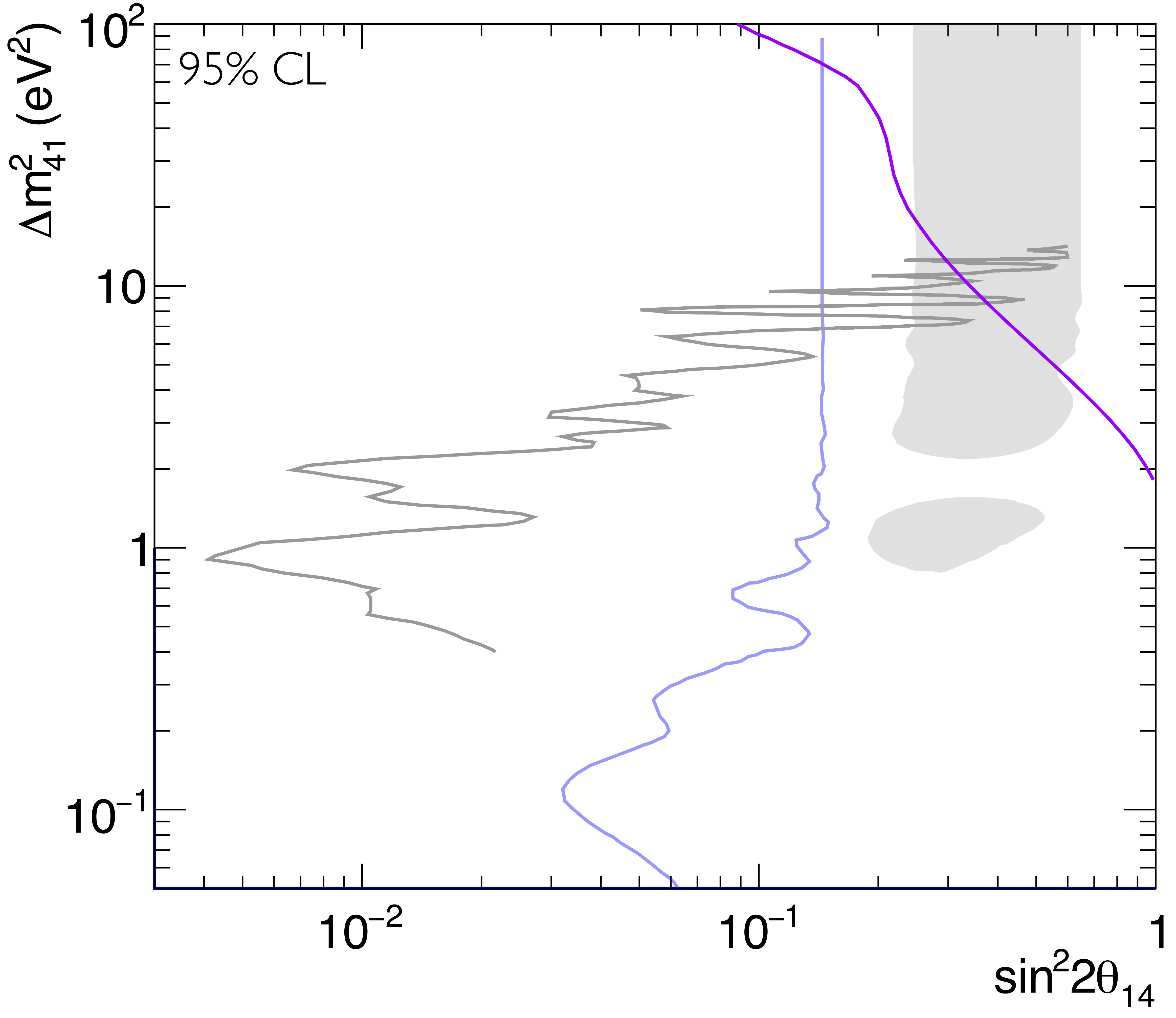
- KATRIN is starting to exclude parameter space from high Δm^2



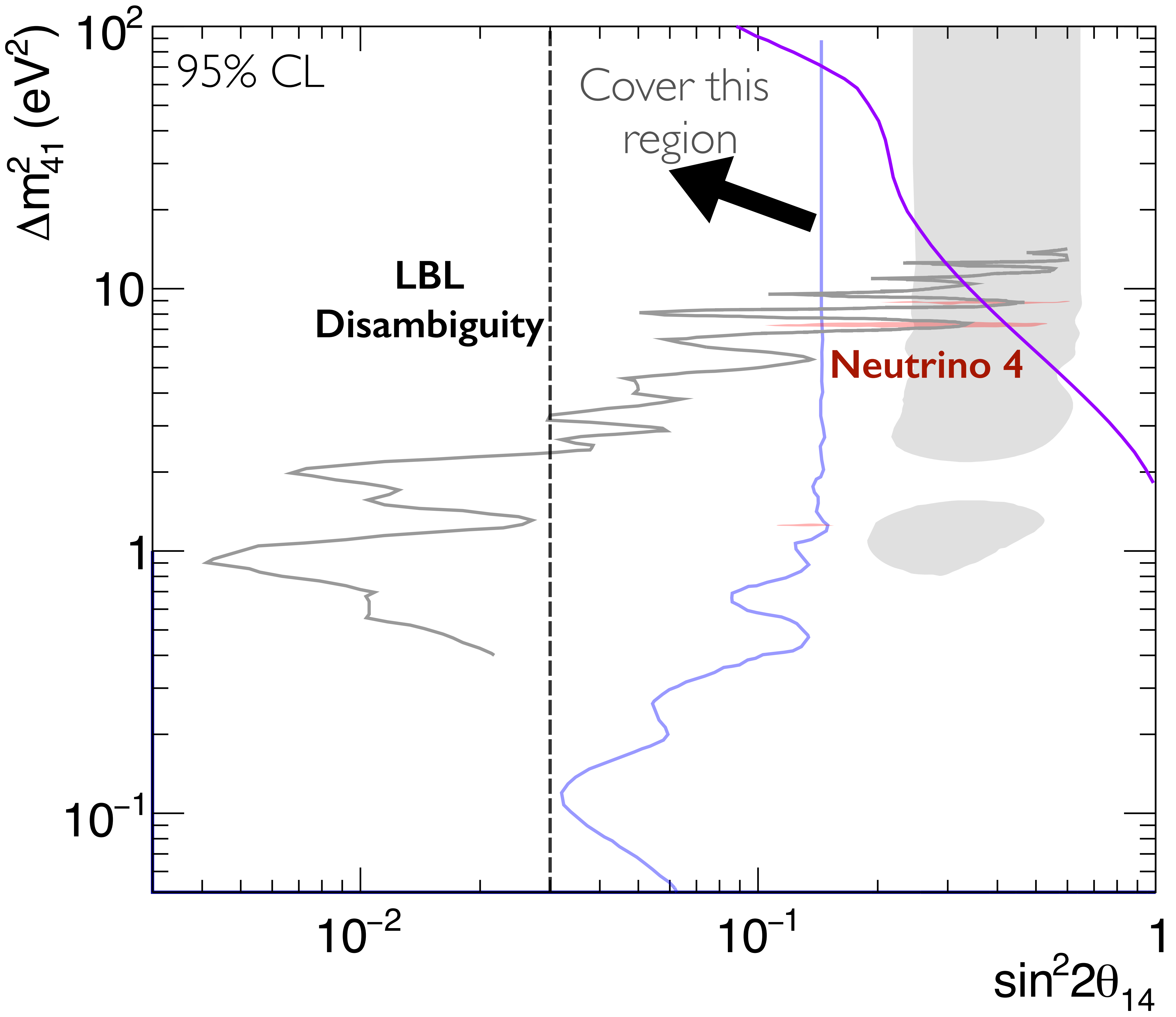
Complex Situation

- The deficit from GA is too high to be compatible with updated reactor rates
- Also major portions of 3+1 suggested parameter space by GA excluded by relative reactor spectral data
- KATRIN is starting to exclude parameter space from high Δm^2
- Complex situation: Vanilla 3+1 model seems increasingly less likely to explain combinations of datasets (*see M. Hostert's talk*)



More Data to Clarify the Complex Situation

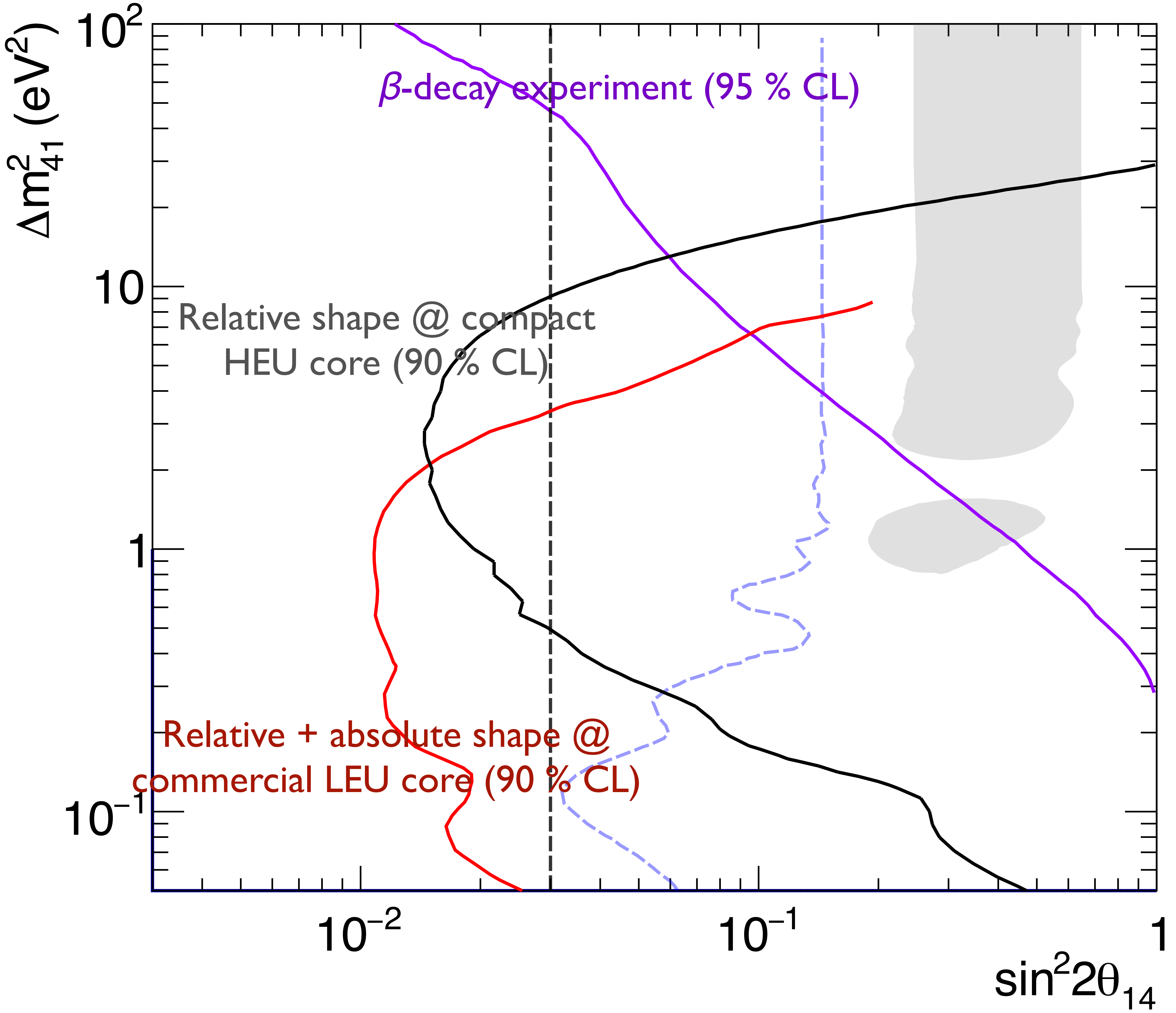
- The deficit from GA is too high to be compatible with updated reactor rates
- Also major portions of 3+1 suggested parameter space by GA excluded by relative reactor spectral data
- KATRIN is starting to exclude parameter space from high Δm^2
- Complex situation: Vanilla 3+1 model seems increasingly less likely to explain combinations of datasets (*see M. Hostert's talk*)
- Upcoming and planned experiments will clear up the controversial Neutrino-4 hints and help deambiguate future LBL data



Improved reactor and radioactive source experiments are essential to probe flavor transformations scenarios

Summary and Outlook

- Past decade experimental program successfully followed through the recommendations from Snowmass 2011
- New data and updated models increasingly suggest reactor $\bar{\nu}_e$ mismodeling as the cause for RAA
- The significance of gallium anomaly is strengthened by the BEST experiment
- Complicates the situation and highlights the need for more data
- Models beyond 3+1 sterile neutrinos increasingly need to be invoked to reconcile all data
- **Complementary data from upcoming and planned reactor and radioactive source experiments essential to address the anomalies**



Back up

Reactor Neutrino Predictions

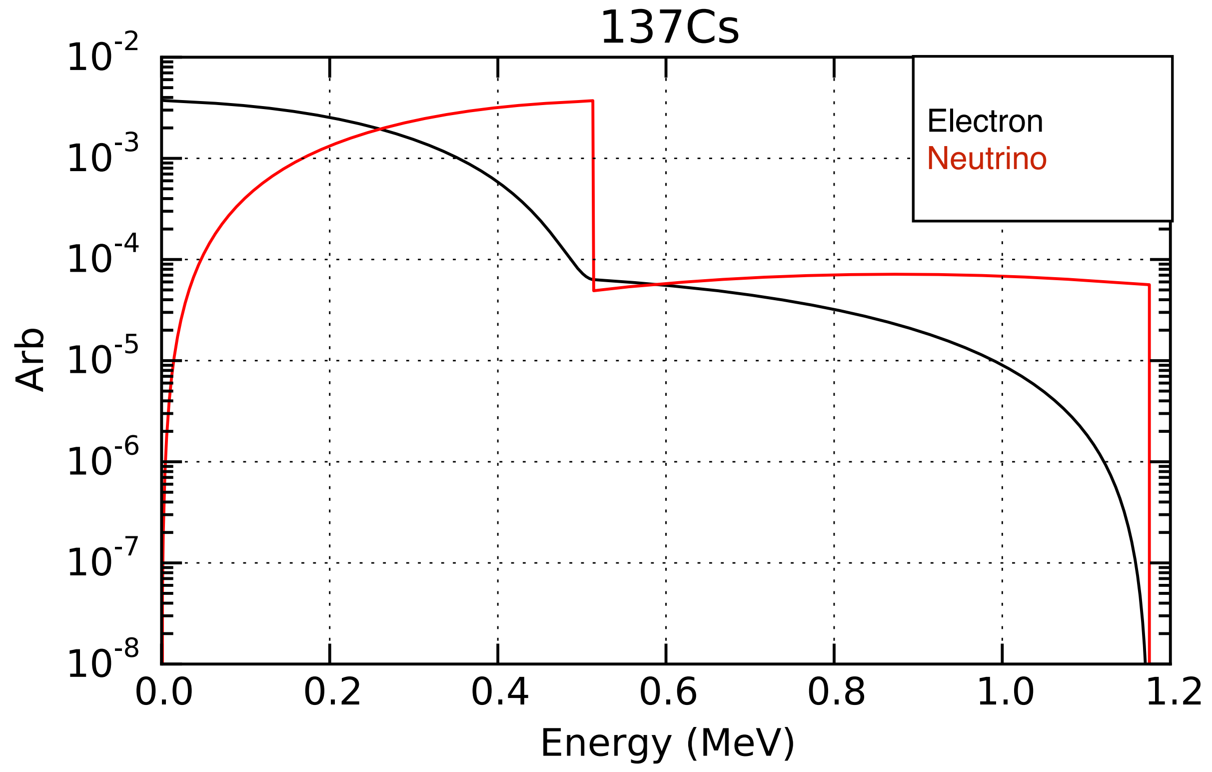
Predicted Spectrum

Decay Rate

Spectrum

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} \boxed{R_i} \sum_{j=0}^{m} \boxed{f_{ij}} \boxed{S_{ij}(E_{\bar{\nu}})}.$$

Branching Fraction

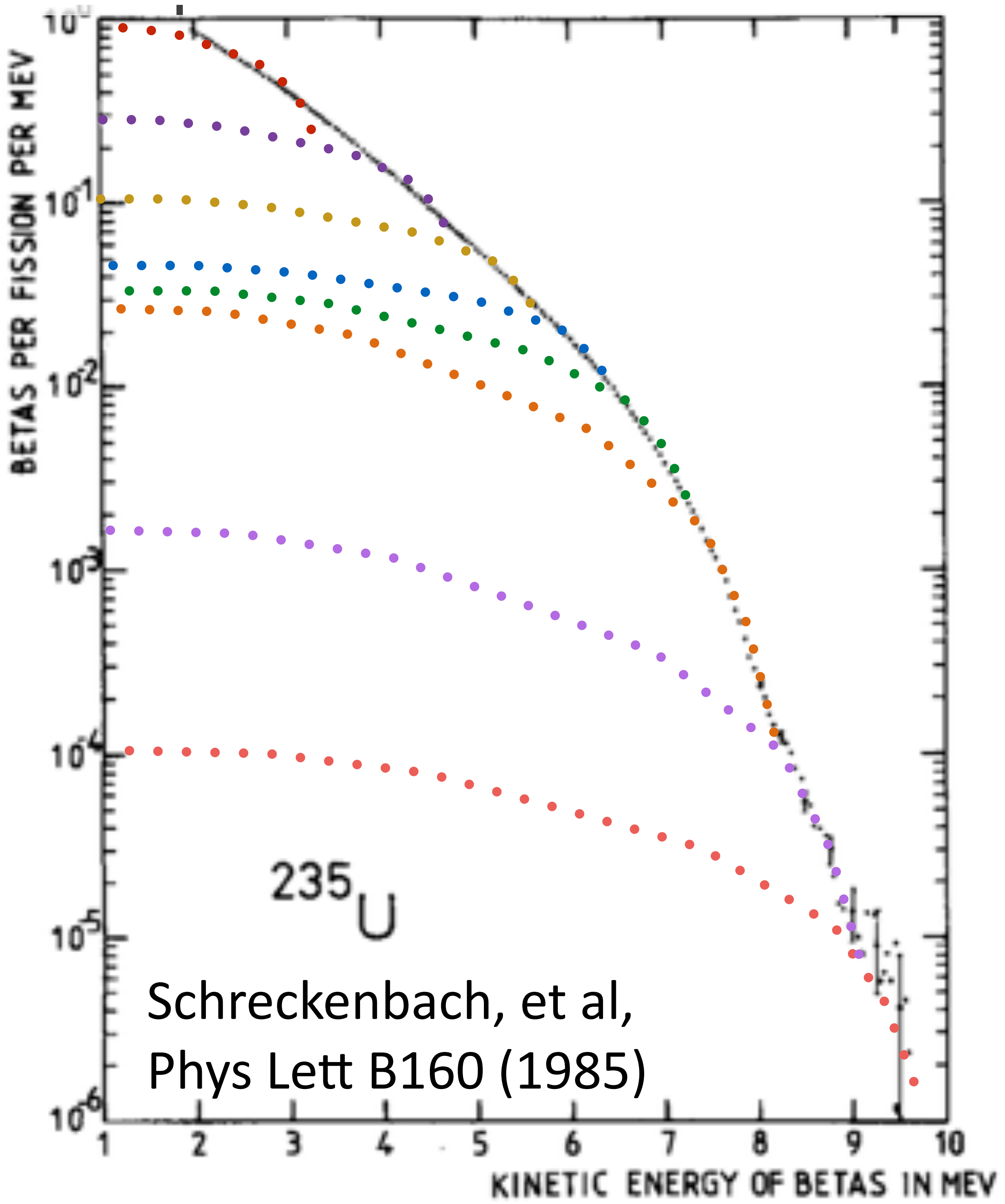


Summation approach

- Use existing databases and sum the spectra from all the beta decay branches
- *1000s of branches; Databases are incomplete/wrong*

Conversion method

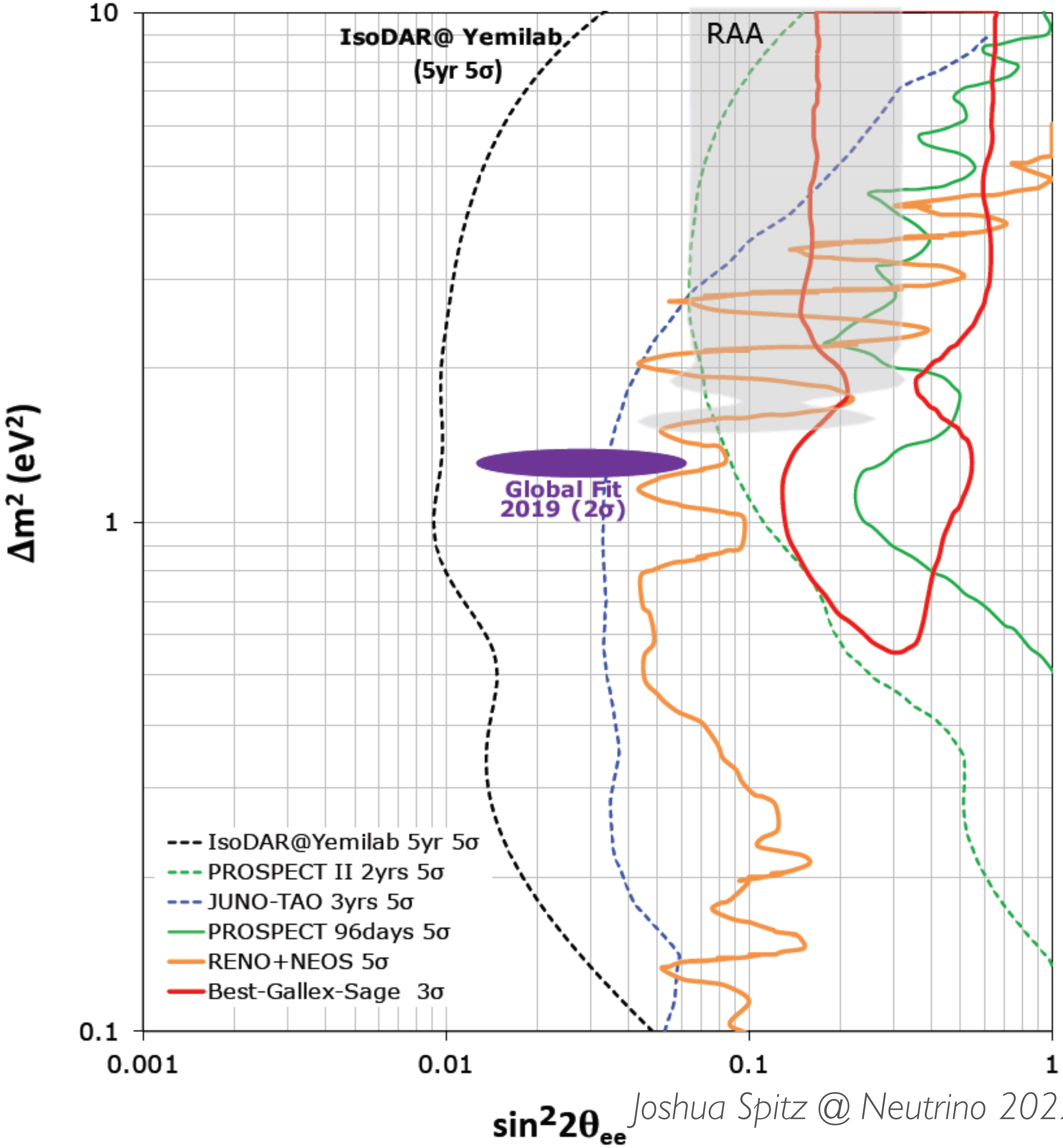
- Measure beta spectrum and fit it to virtual branches to convert to neutrino spectrum
- *Is all relevant physics captured by virtual beta branches*



Reactor antineutrino predictions are very complicated

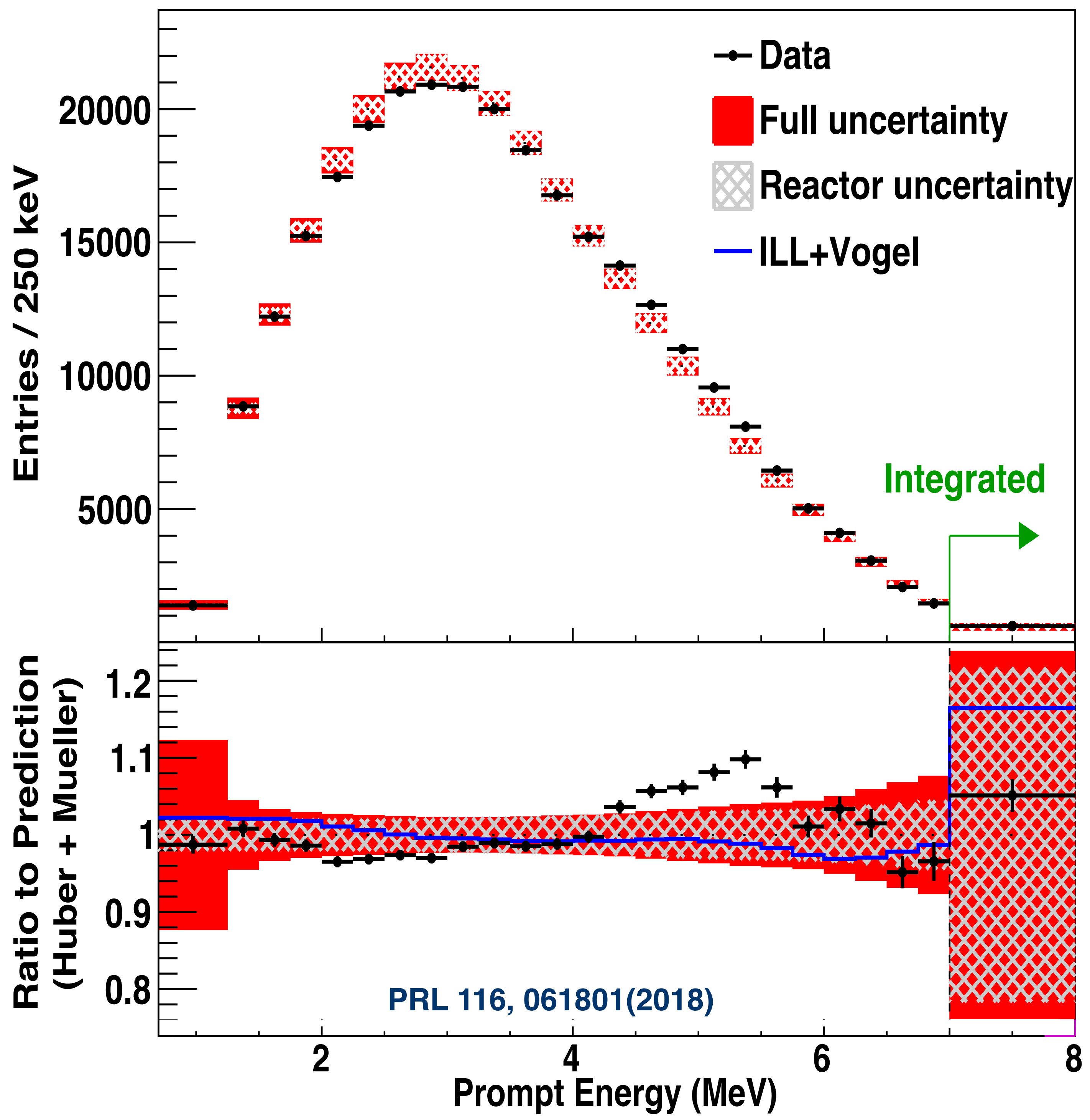
eV-scale Sterile Searches: Prospects

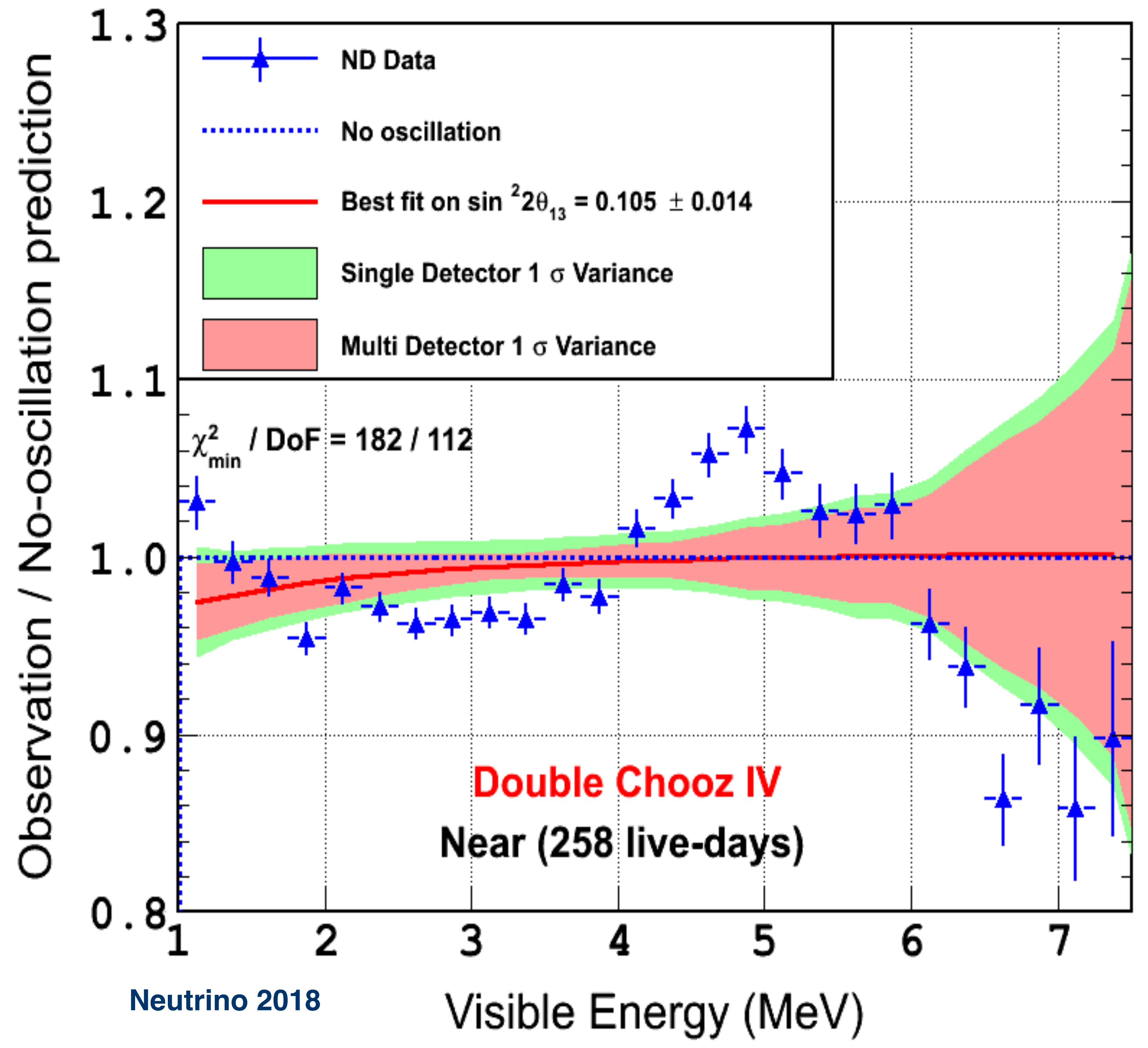
- Experimental progress in the past decade successfully followed through recommendations from Snowmass 2011
- New data and updated models increasingly suggest reactor $\bar{\nu}_e$ mismodeling as the cause of RAA
- Meanwhile, the significance of gallium anomaly is strengthened by BEST experiment, making situation complex, highlighting need for more data
- Models beyond 3+1 sterile neutrinos increasingly need to be invoked to reconcile all data
- **Complementary data from upcoming and planned reactor and radioactive source experiments will be needed to identify the sources of the anomalies**
- Addressing the anomalies will clear up the N4 and LBL situation

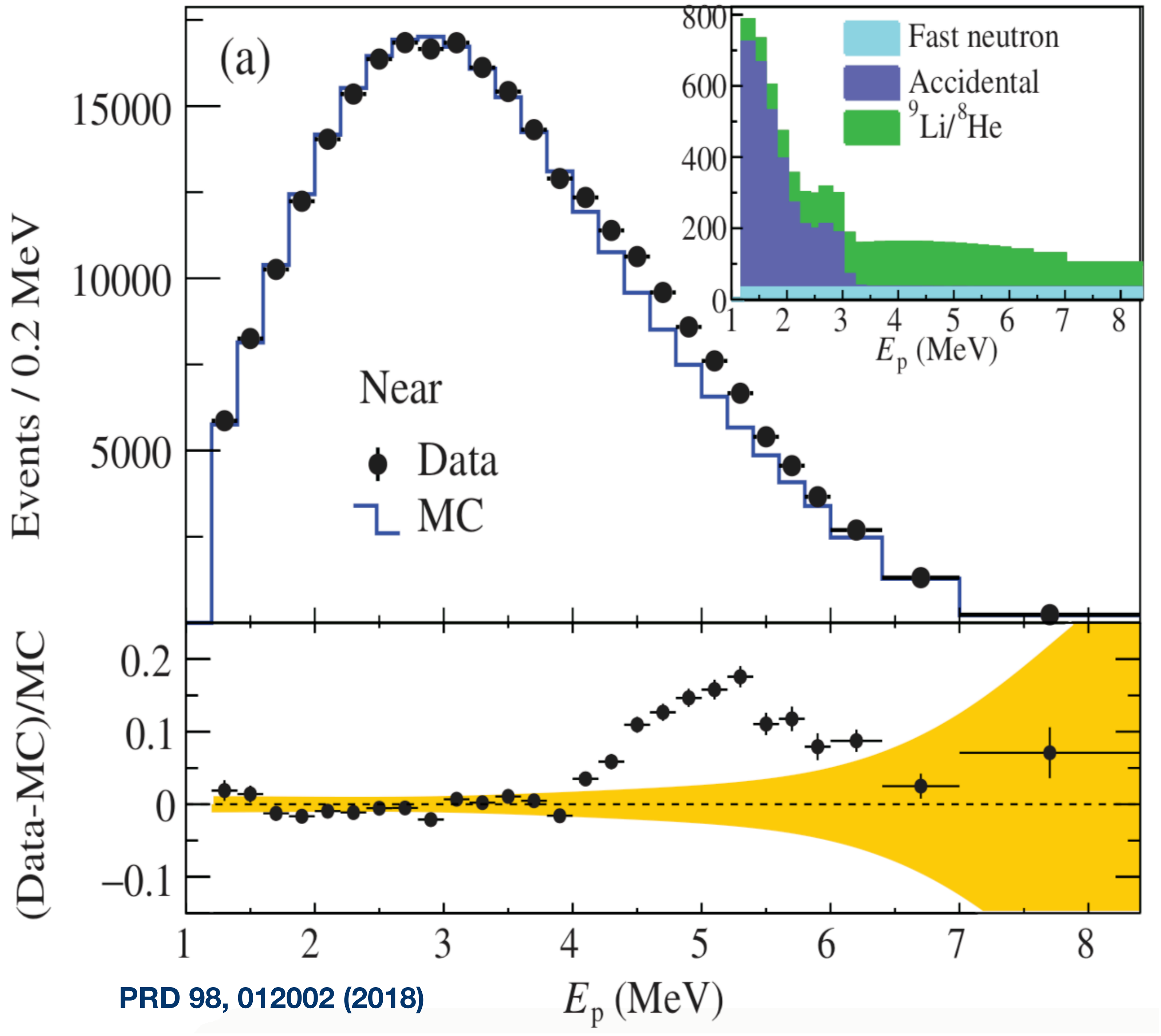


Joshua Spitz @ Neutrino 2022

More Reactor Neutrino Context



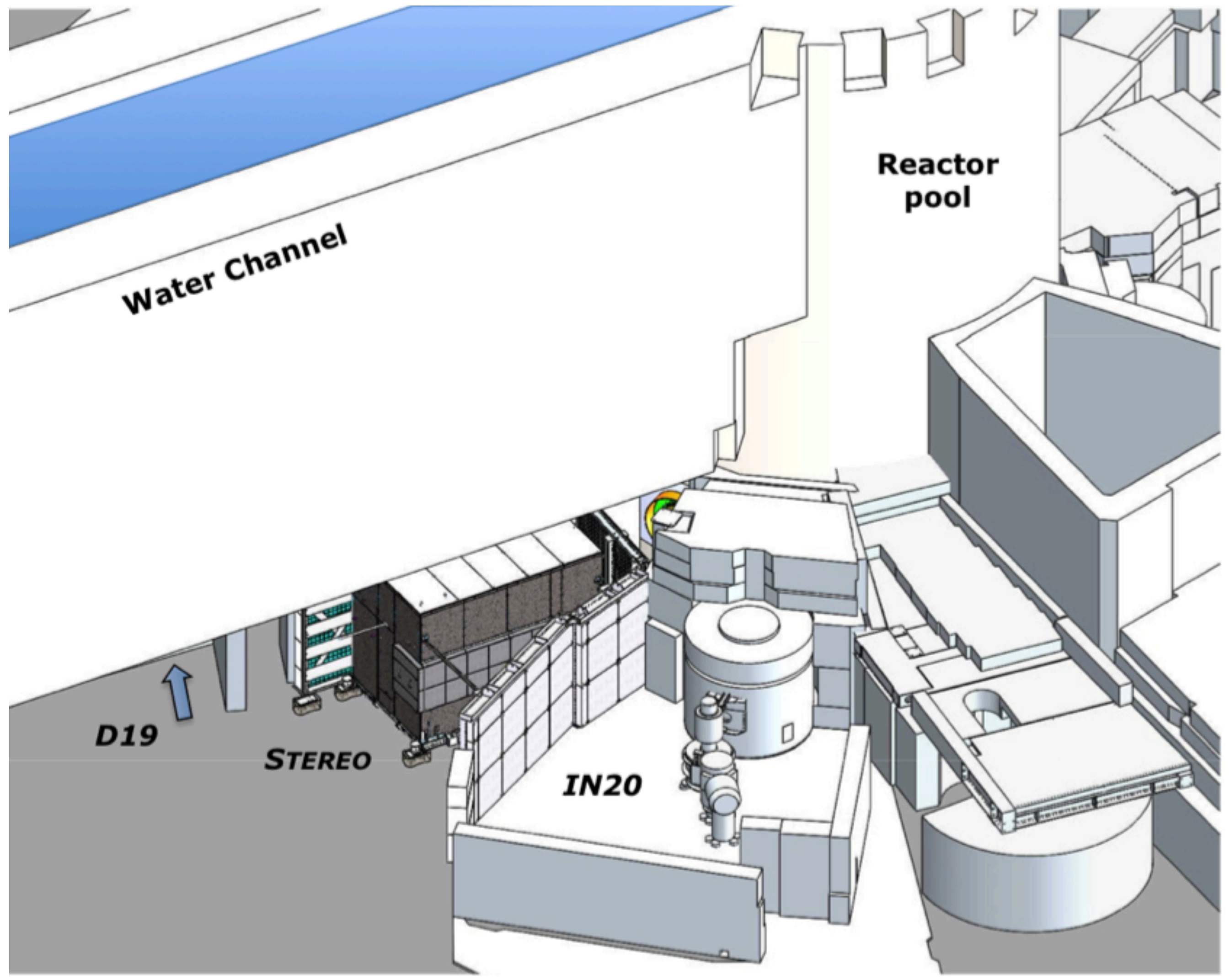




- Spectra shapes measured by θ_{13} experiments at LEU reactors disagree with state-of-the art models
- Sterile neutrinos cannot explain this anomaly
- **Points towards reactor models being wrong**

LEU Reactors:
^{235}U ~ 45-65%
^{239}Pu ~ 25-35%
^{238}U,^{241}Pu < 10% each

STEREO Experiment



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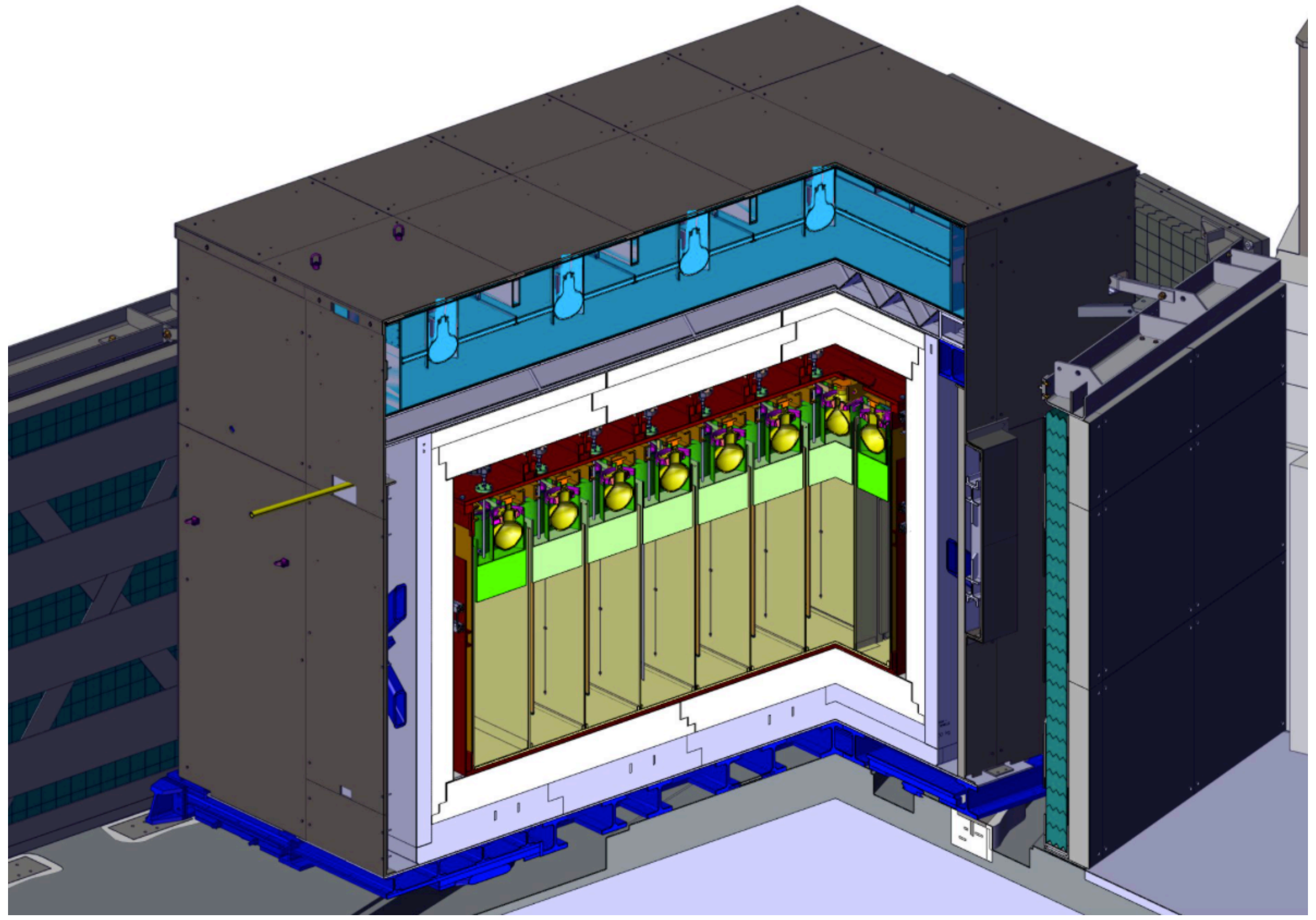
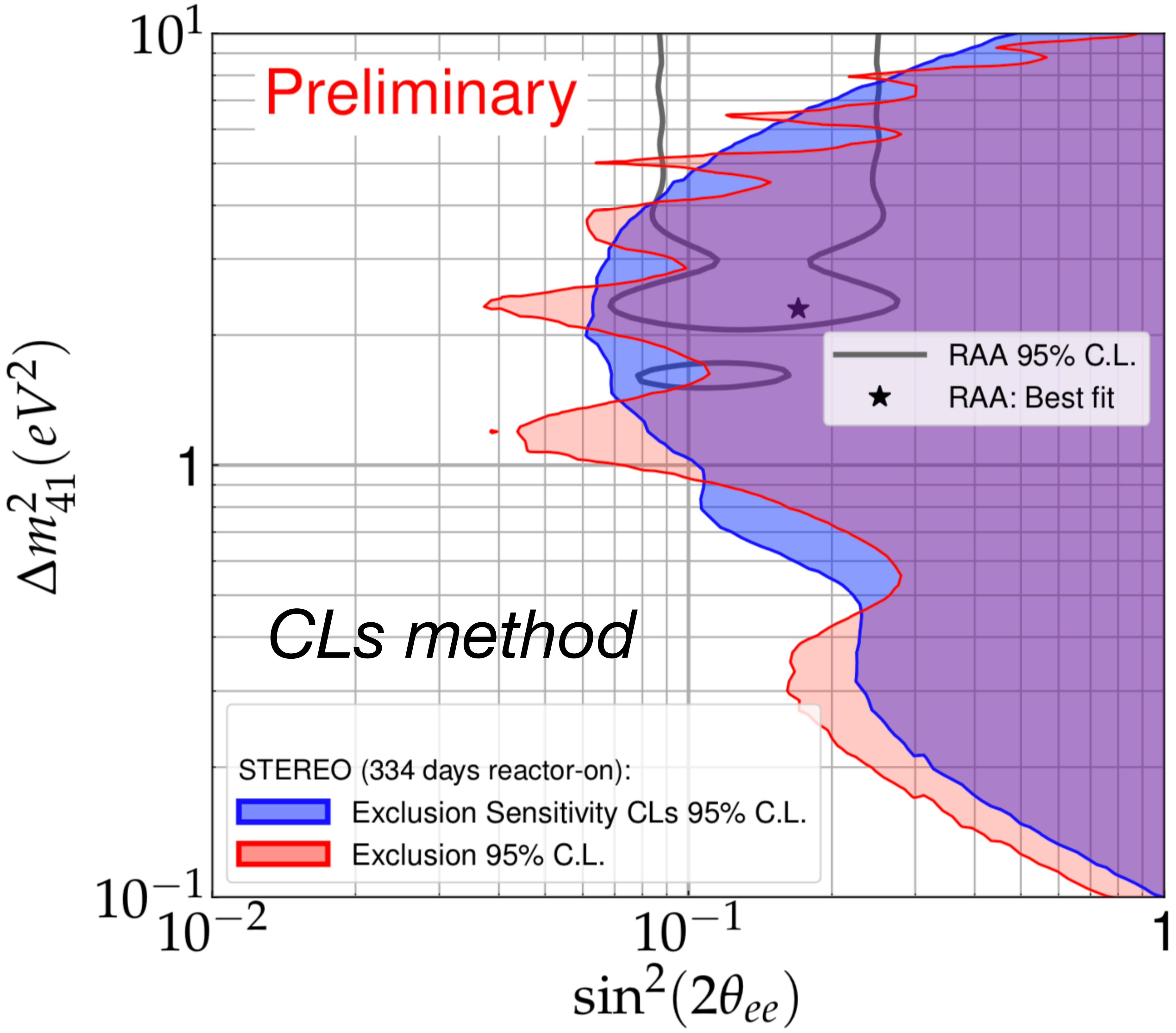
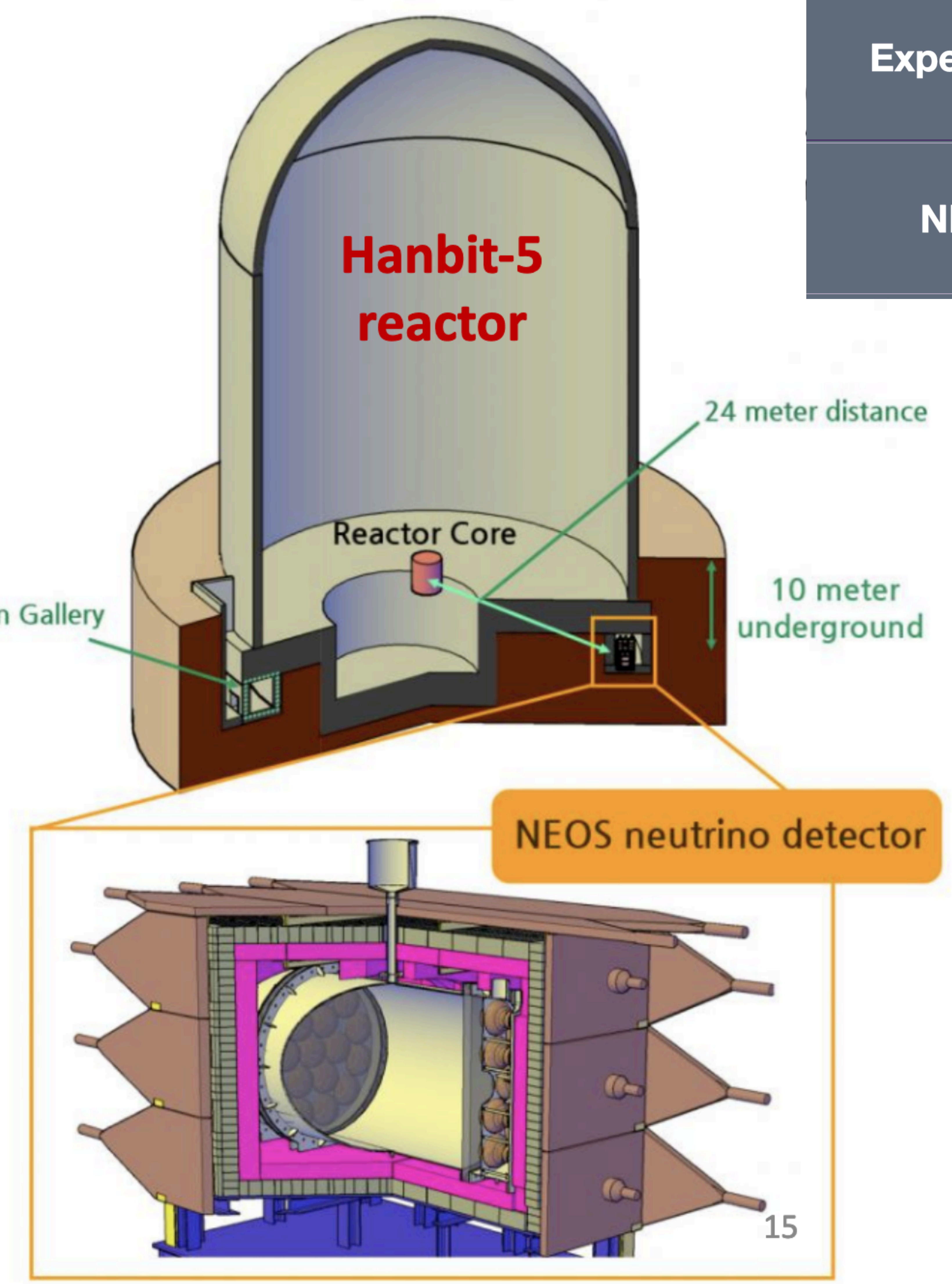


- 334 (543) rx-on (rx-off) days
- Segmentation provides baselines
- Excluded RAA best-fit at >4σ
- Data taking ended

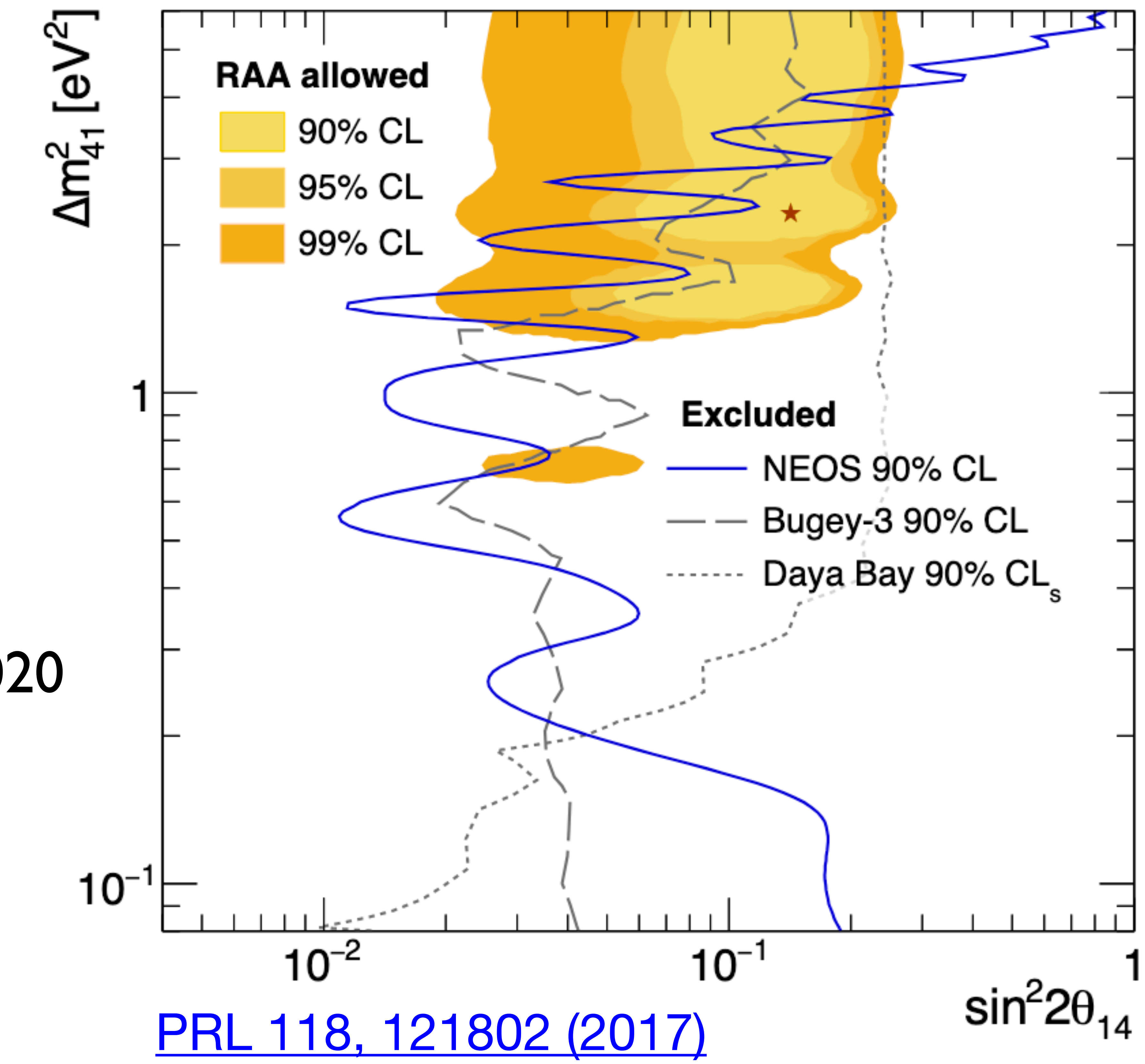


NEOS Experiment

Experiment	Baseline(m)	Reactor type	Reactor power (MW_{th})	Mass	Target	Search strategy
NEOS	24 m	LEU	2800	~1 m^3	GdLS	Relative to Daya Bay



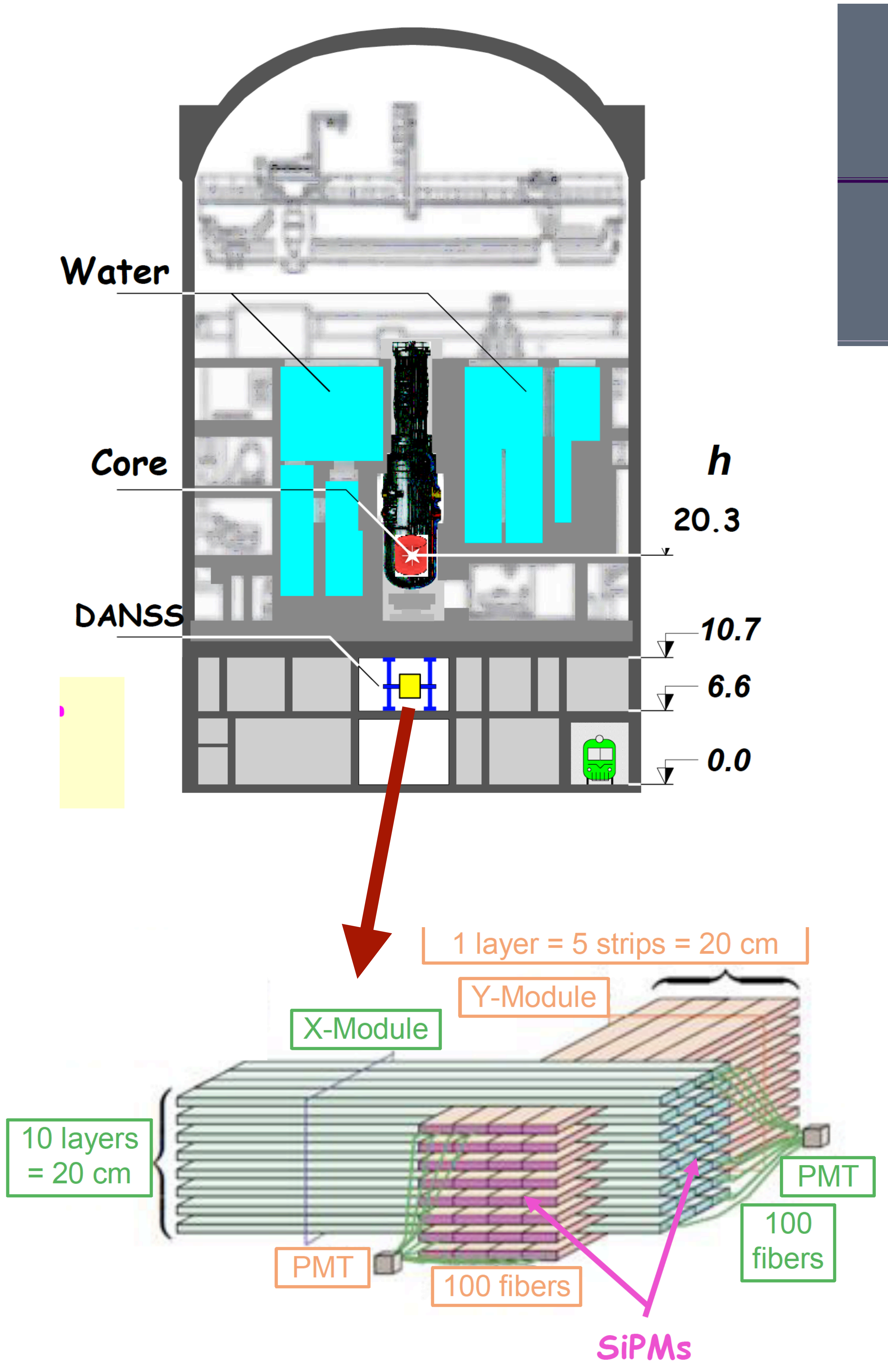
- 180 (46) days reactor-on(off)
- Single volume stationary detector
- Excluded RAA best-fit at >4σ
- NEOS-II: Refurbished NEOS detector
  - Data taking finished: Sep 2018 - Oct 2020
  - Results expected this year



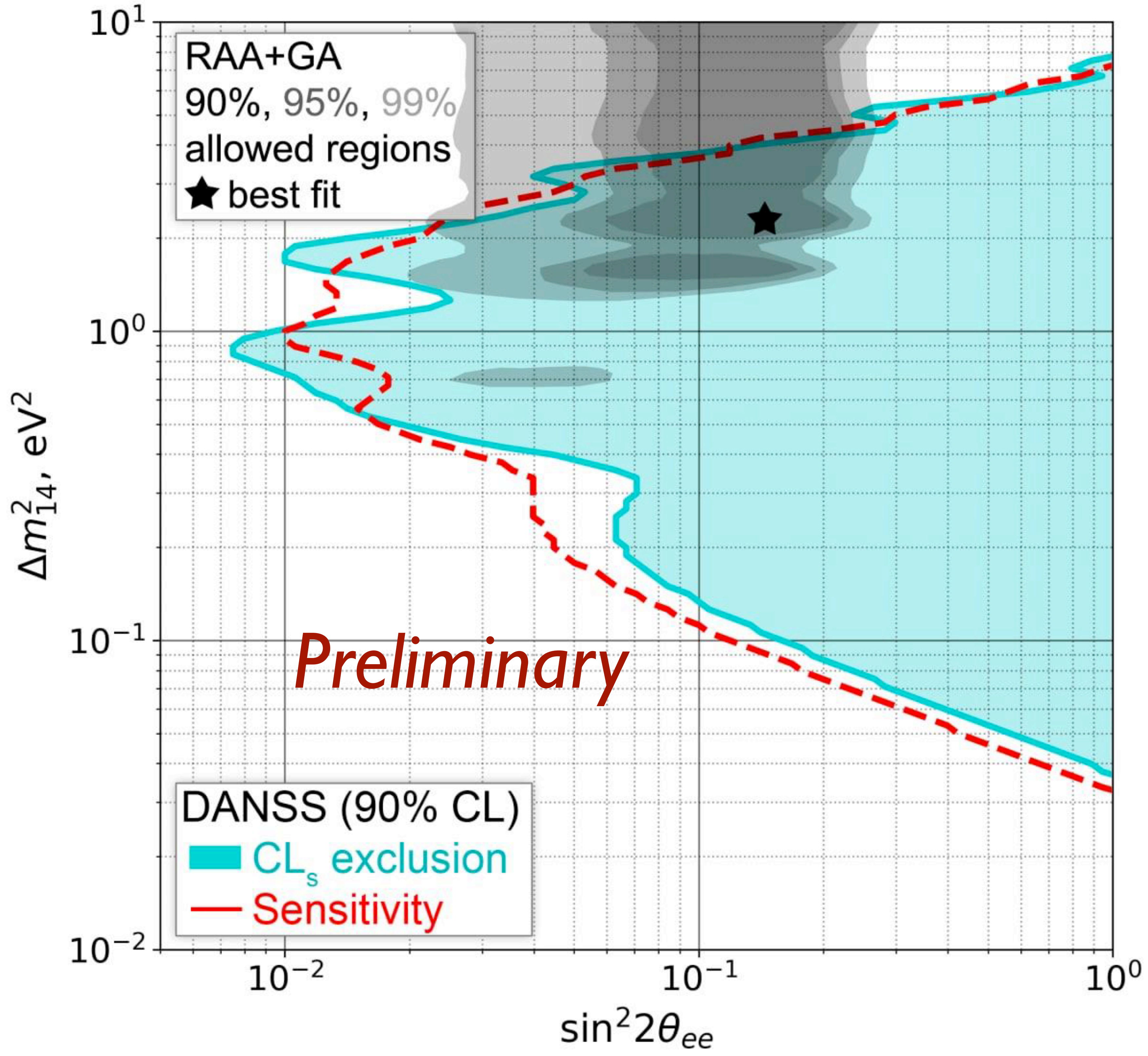
PRL 118, 121802 (2017)

DANSS Experiment

Experiment	Baseline(m)	Reactor type	Reactor power (MW_{th})	Mass	Target	Search strategy
DANSS	11-13 m	LEU	3000	~1 m^3	PS +Gd coating	Movable

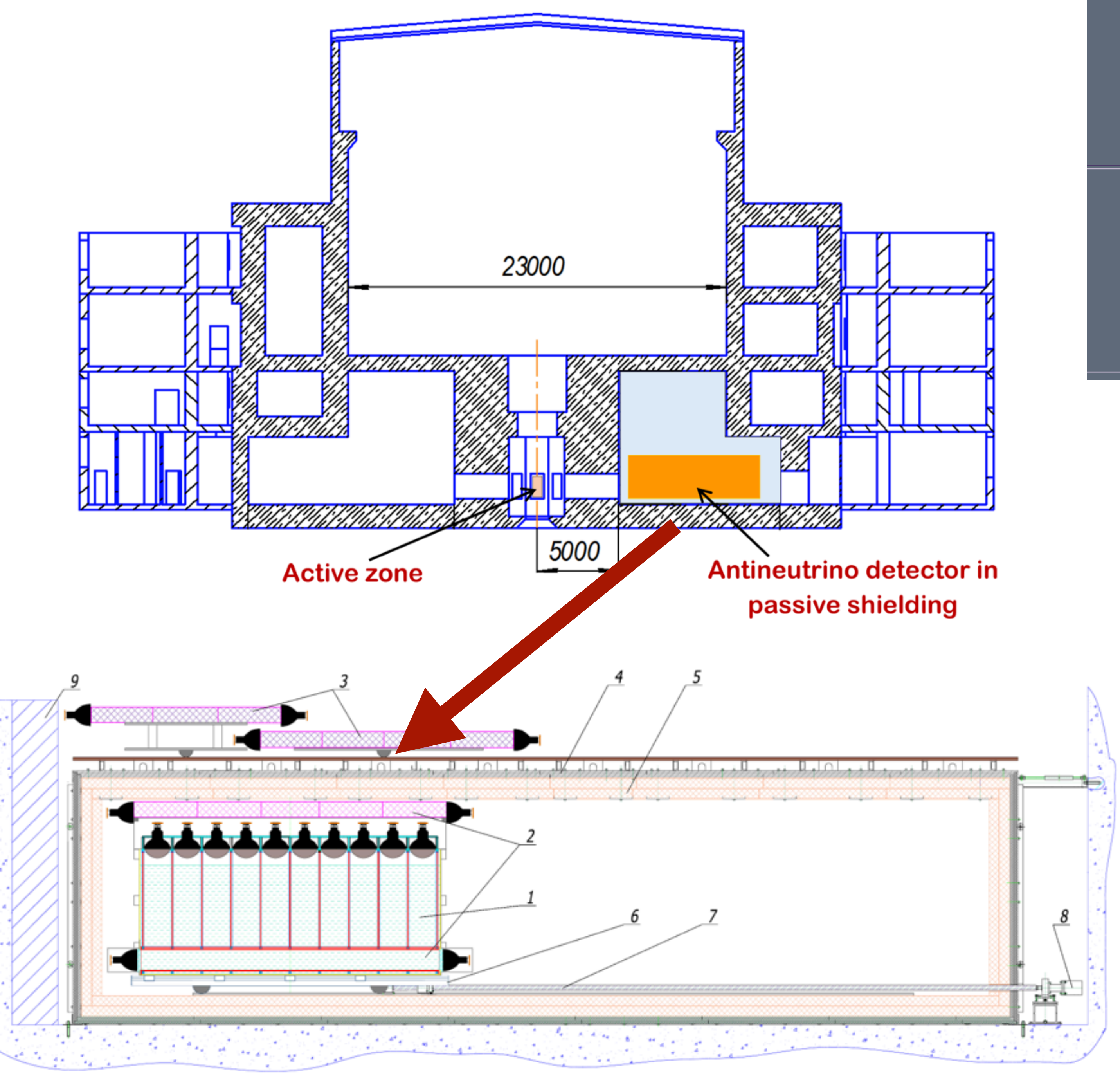


- 5 years of data: 5.5 million events
- Oscillation search using movable detector
- Excluded RAA best-fit at >5σ
- Detector upgrade underway

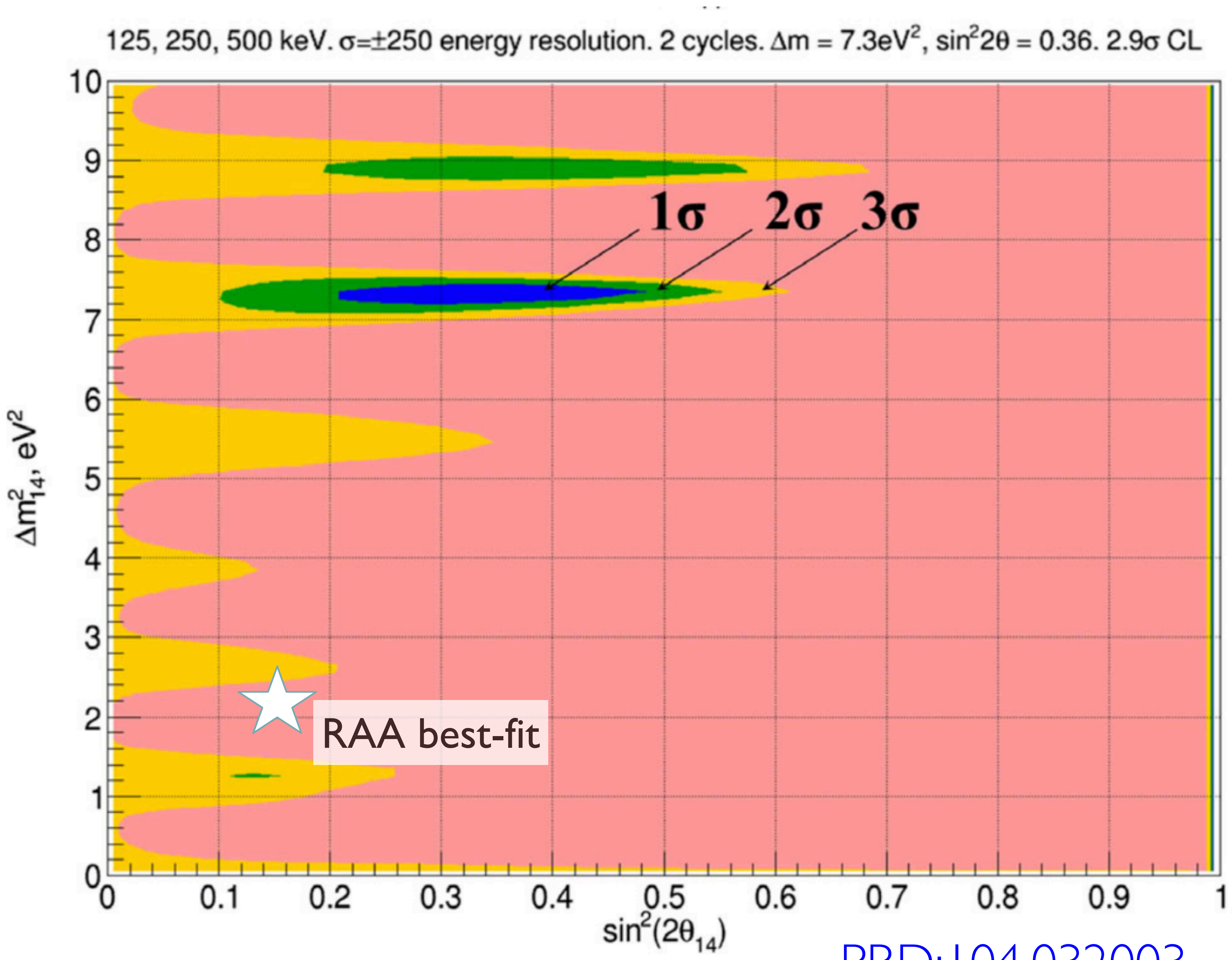


Neutrino-4 Experiment: Claim

Experiment	Baseline(m)	Reactor type	Reactor power (MW_{th})	Mass	Target	Search strategy
Neutrino-4	6-12	HEU	100	~1.8 m³	GdLS	Movable



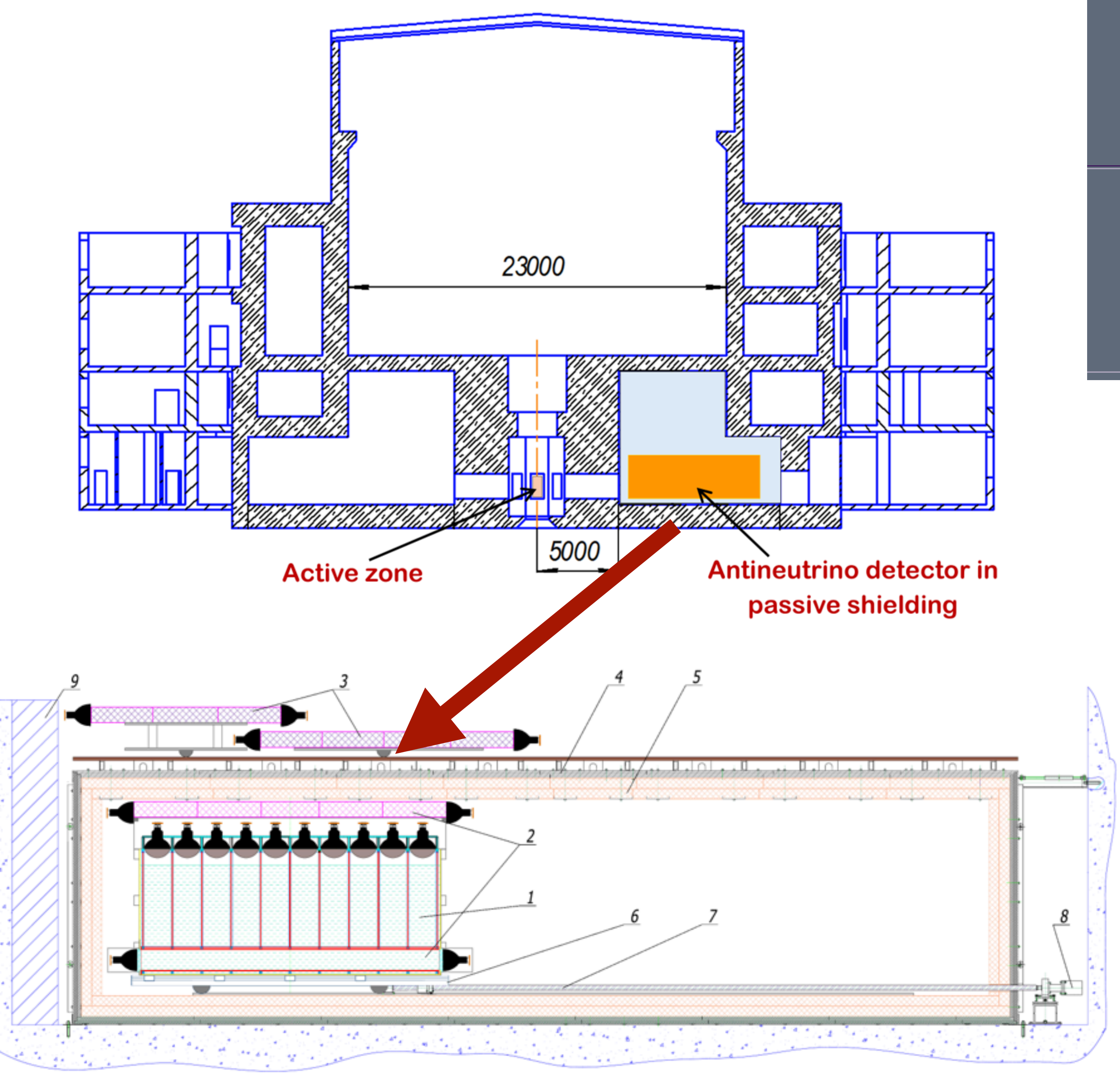
- 5 years of data
- Oscillation search using movable detector
- Claim oscillation:
  - ($\Delta m2 = 7.3, \sin 22\theta = 0.36$) @ 2.9σ
- Detector upgrade underway



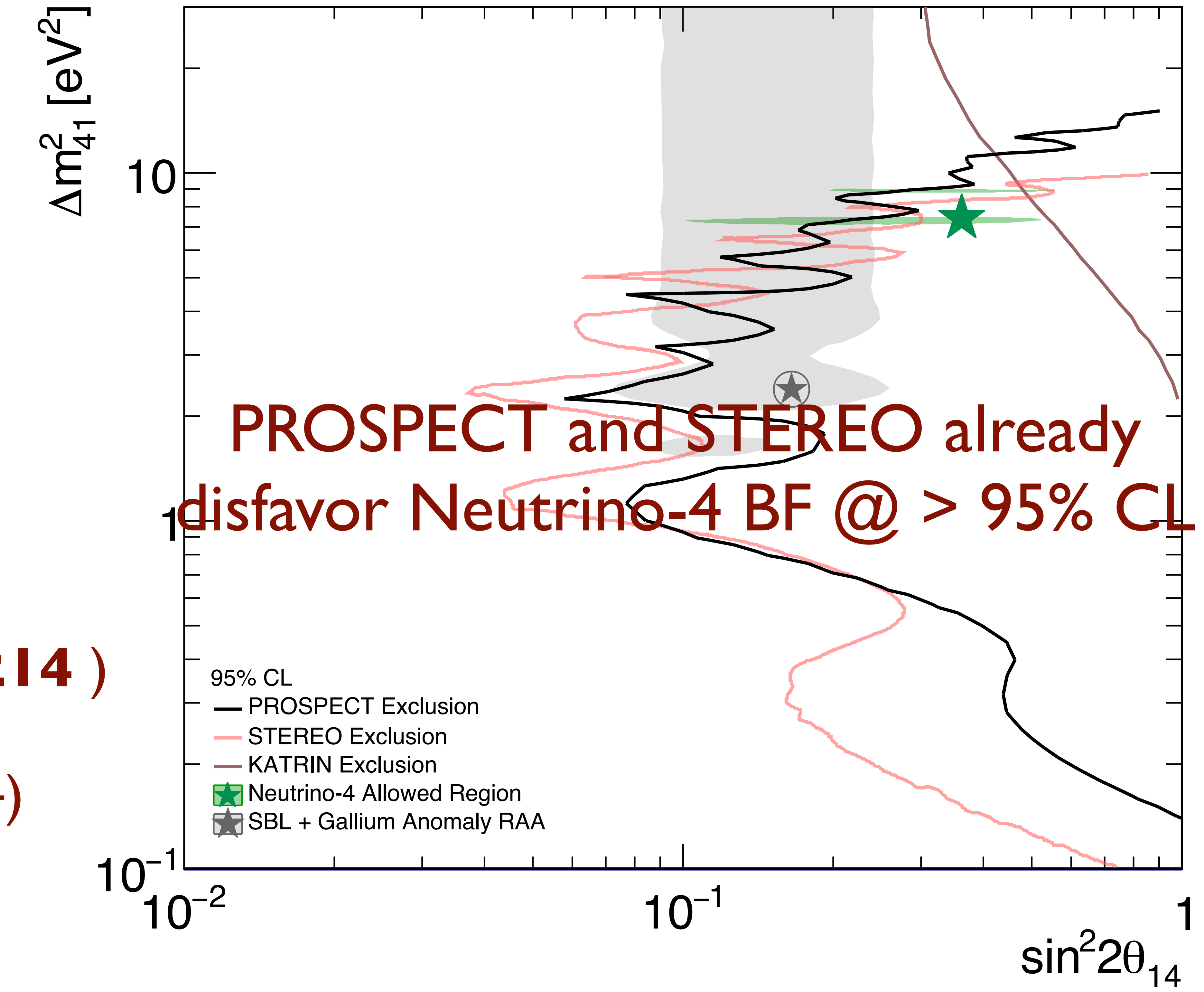
PRD:104.032003

Neutrino-4 Experiment: Questions

Experiment	Baseline(m)	Reactor type	Reactor power (MW_{th})	Mass	Target	Search strategy
Neutrino-4	6-12	HEU	100	~1.8 m³	GdLS	Movable



- 5 years of data
- Oscillation search using movable detector
- Claim oscillation:
  - ($\Delta m2 = 7.3, \sin 2 2\theta = 0.36$) @ 2.9σ
- Detector upgrade underway

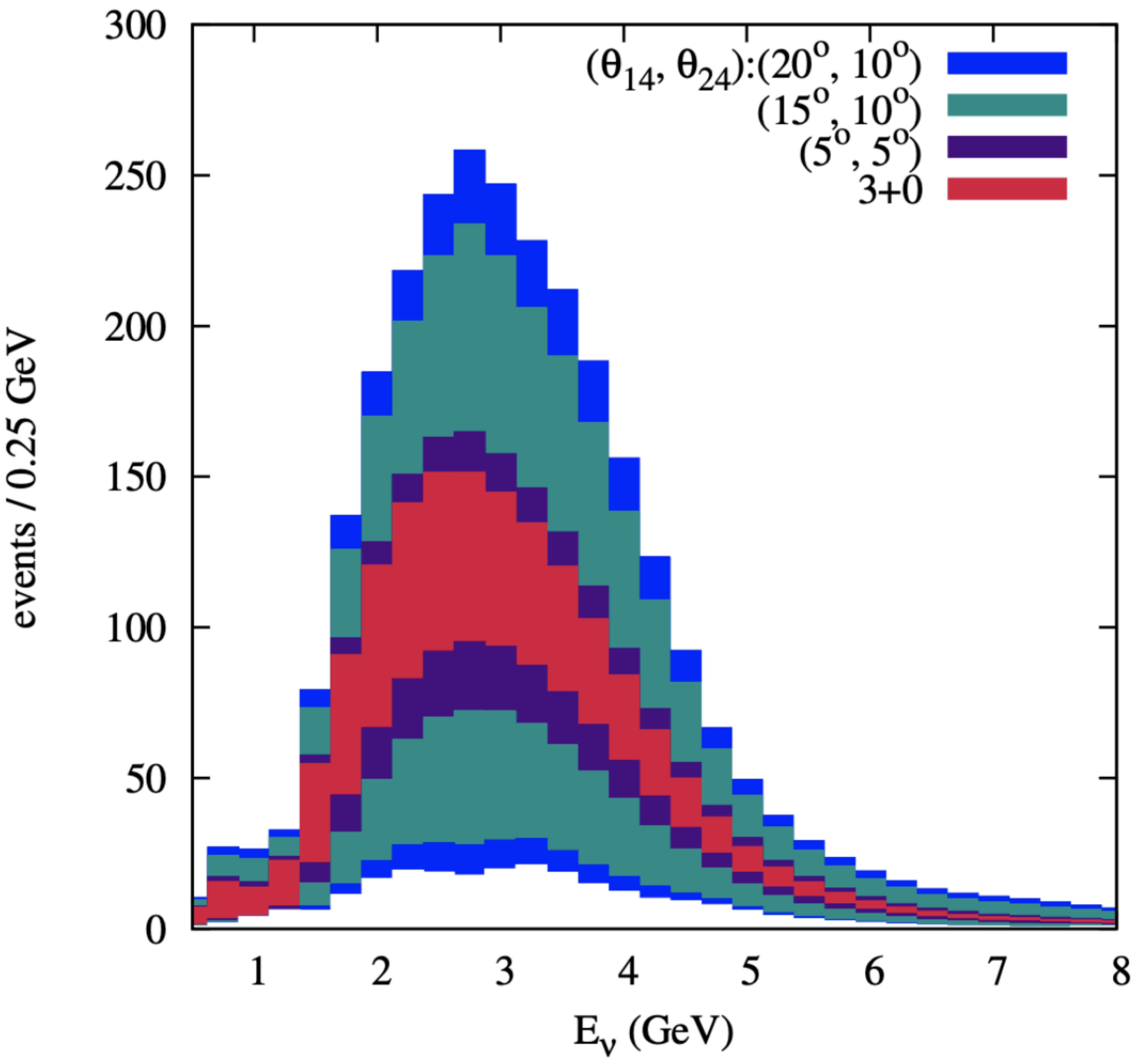


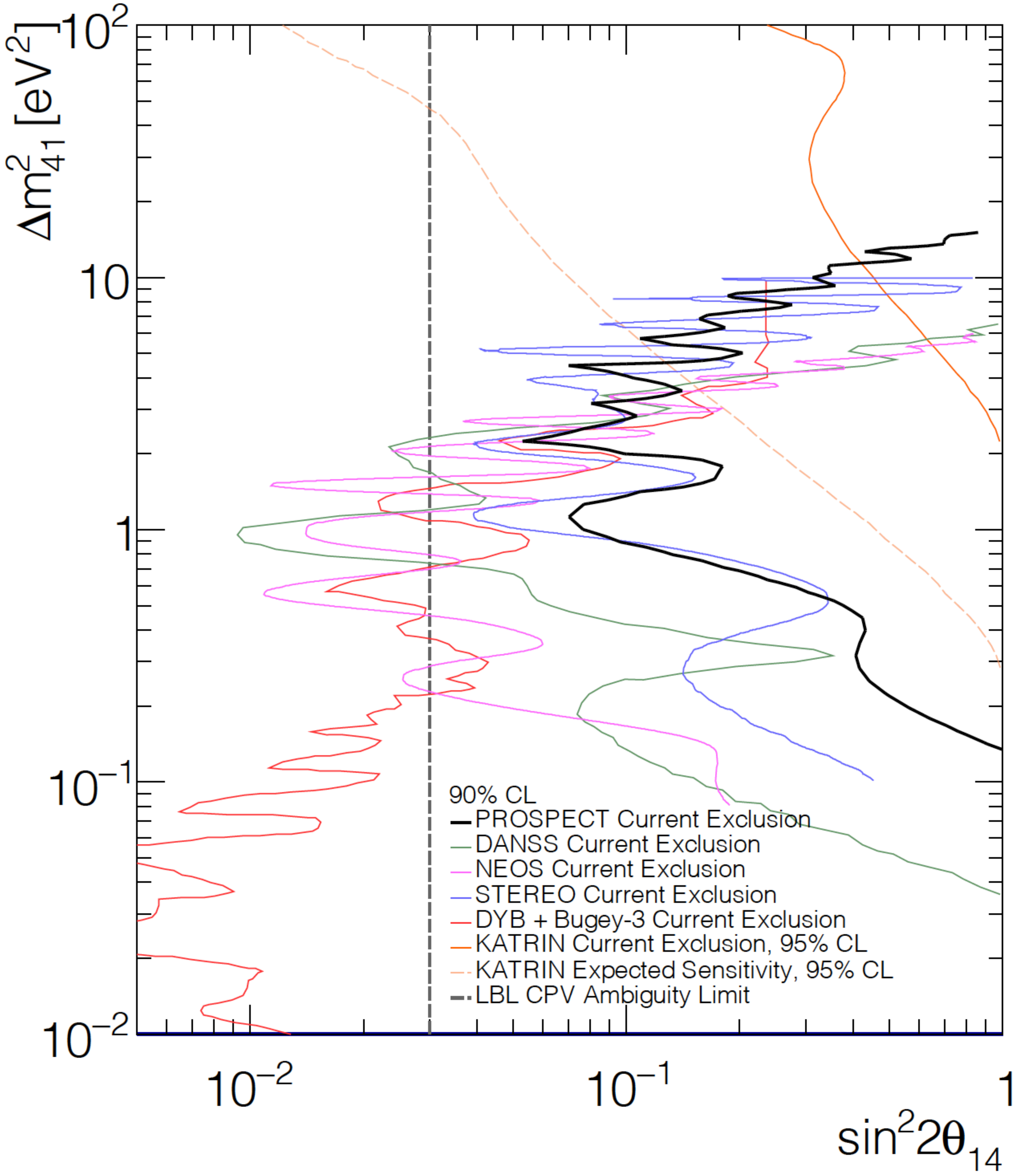
PROSPECT and STEREO already disfavor Neutrino-4 BF @ > 95% CL

! Several questions raised:

* Statistical approach to oscillation search (arXiv:**2006.13147**; EPJC.**81**,2; PLB.**136214**)
* Inclusion of systematics in the analysis (arXiv:**2006.13147**, JETP Lett **112**, 452–454)
* Impact of backgrounds on the results (JETP Lett **112**, 452–454)

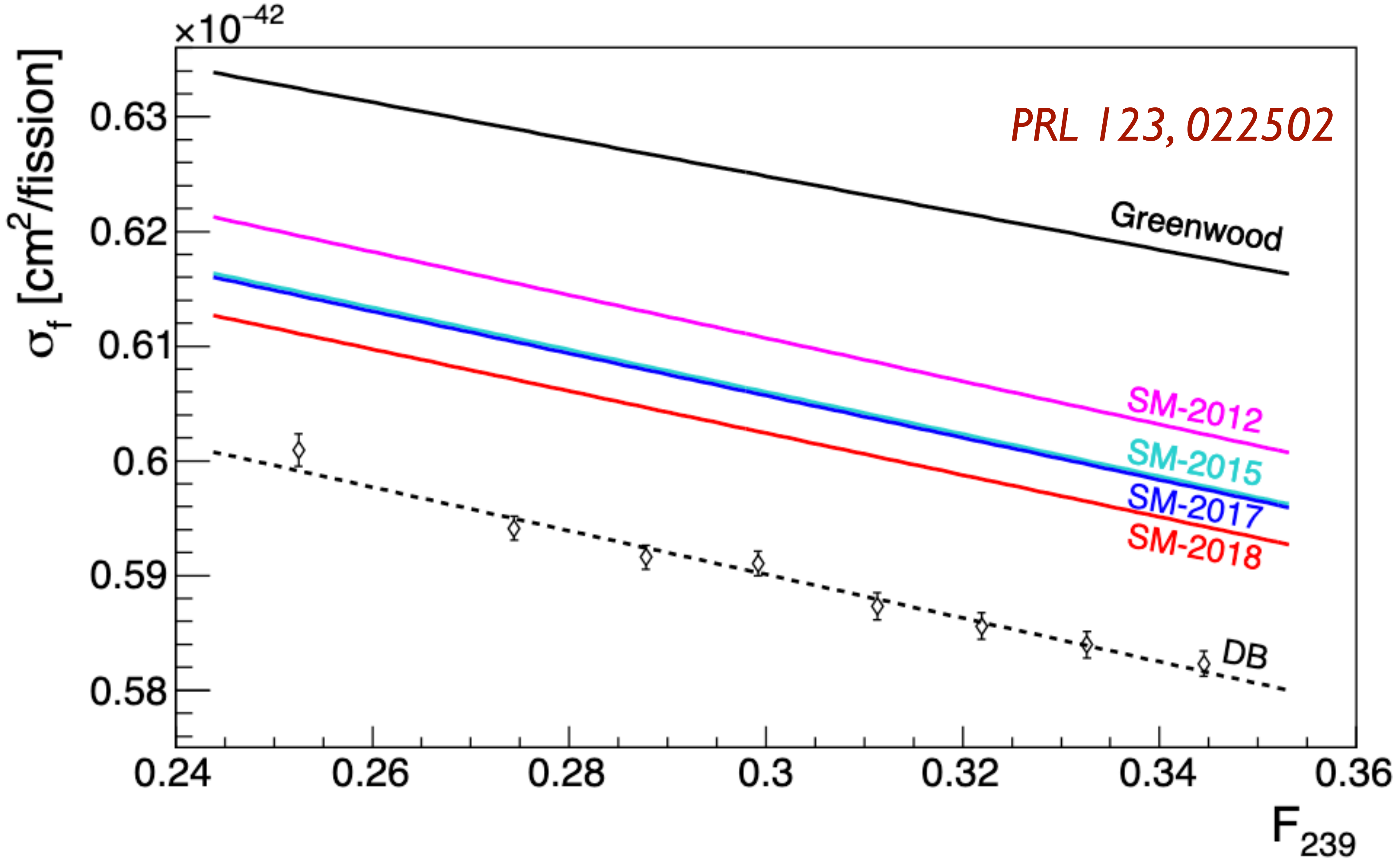
Why Do We Care ?





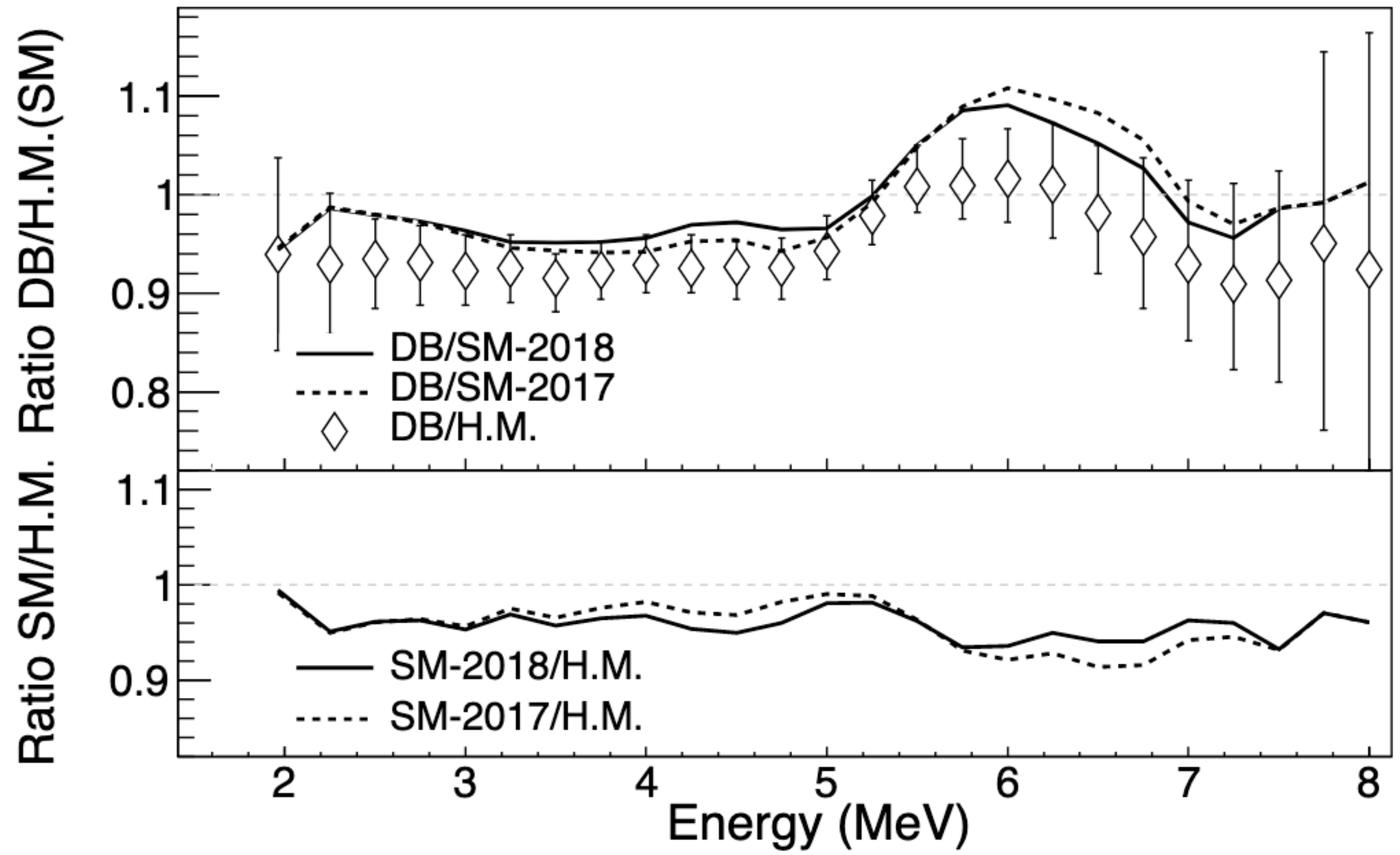
Reactor Neutrino Flux: Modeling

- Questions on the validity of *conversion* method
- Inclusion of forbidden decays, doesn't change the picture much
- For *summation* method: corrections in databases (*Sonzogni et.al., PRL 116, 132502*)
- Pandemonium effect also plays a systematics effect
- TAGS measurements of the individual β spectra of various high yield and high Q isotopes (*Estienne et.al. and Rasco et.al.*)
- Summation data:
    - Agrees with DYB for ^{239}Pu
    - For ^{235}U agreement gets better by day
- Caveat: No uncertainties assigned, expected to be at ~5% level



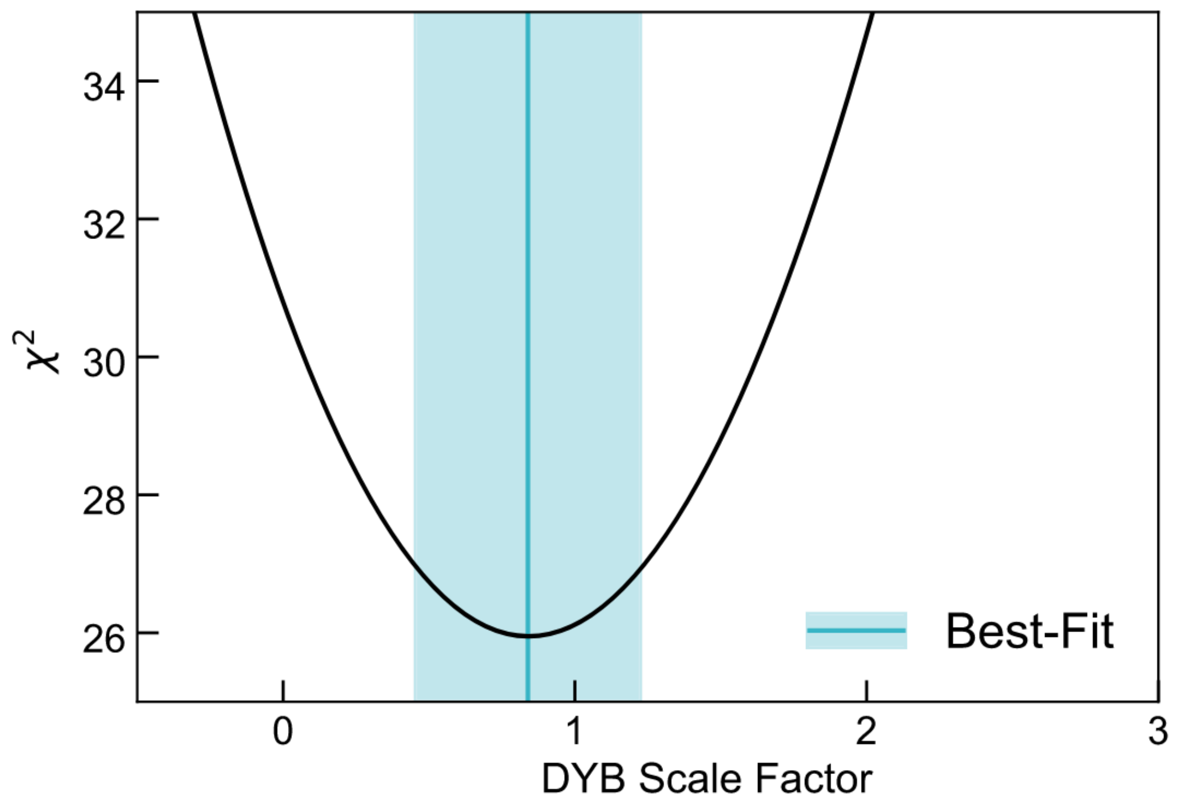
Reactor Neutrino Flux: Modeling

- Initially the spectral deviation were thought to be with the conversion approach
- Databases updated
- Included new data TAGS data
- Shows a better agreement b/w conversion and summation => Disagreement between LEU data and conversion method
- Treatment of forbidden decays called into question
- Proper understanding of the shape factors important in modeling the spectra

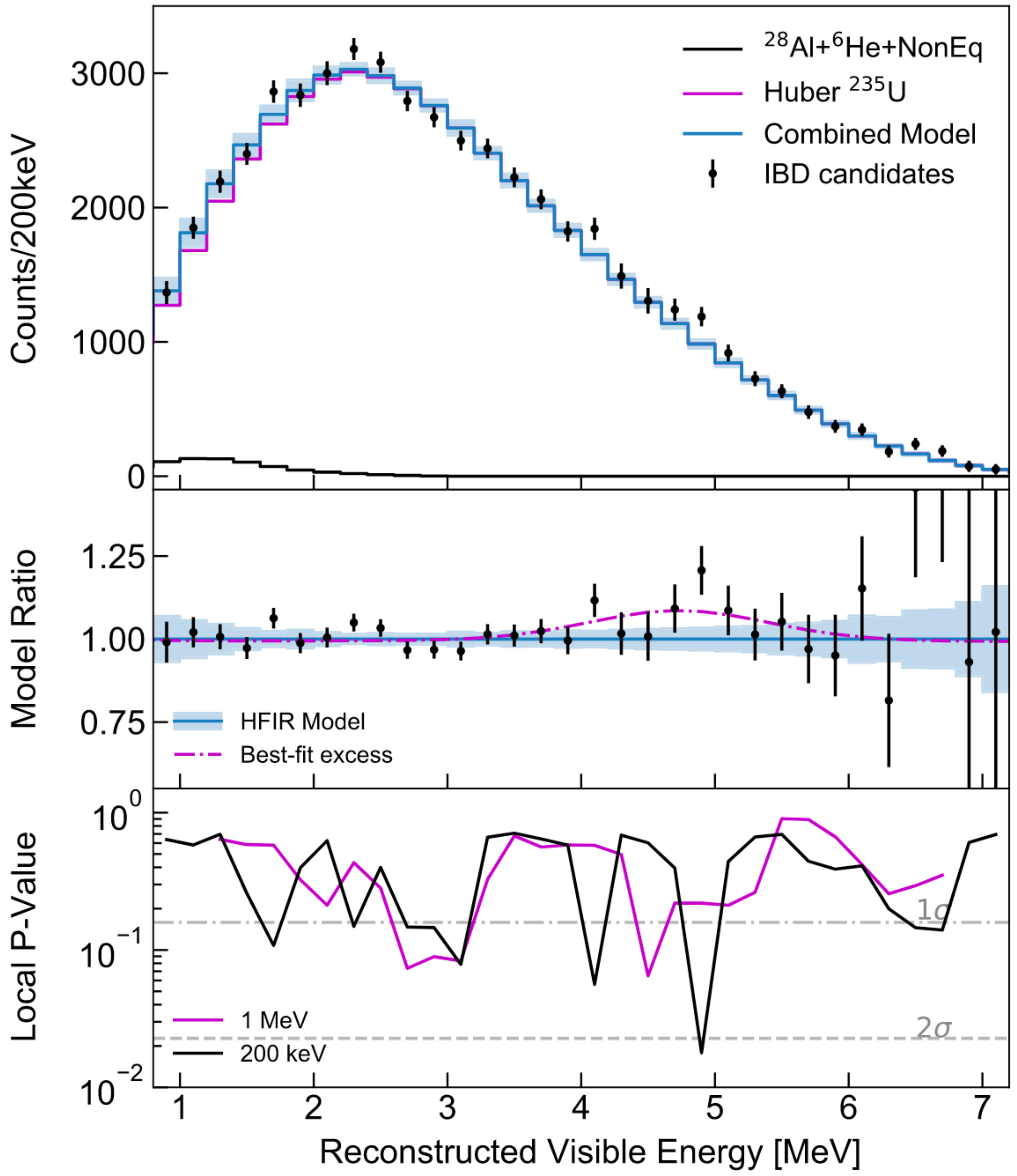


PROSPECT

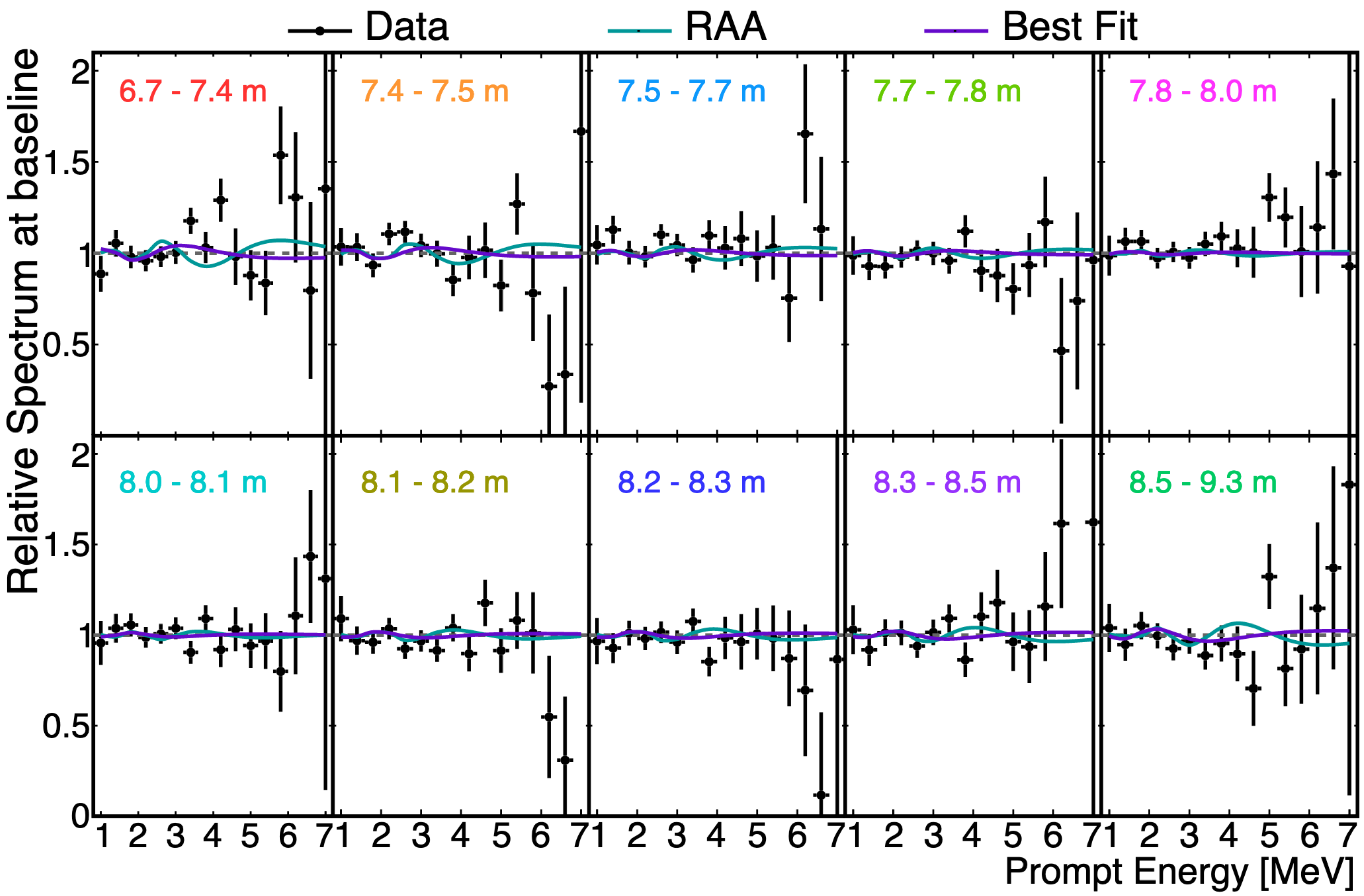
- PROSPECT and STEREO experiments highest statistics HEU experiment
- PROSPECT
  - 50k events
  - S:B = 1.4:1
- Spectrum not in disagreement with Huber
- ^{235}U solely (not at all) responsible disfavored at 2.1σ (2.2σ)



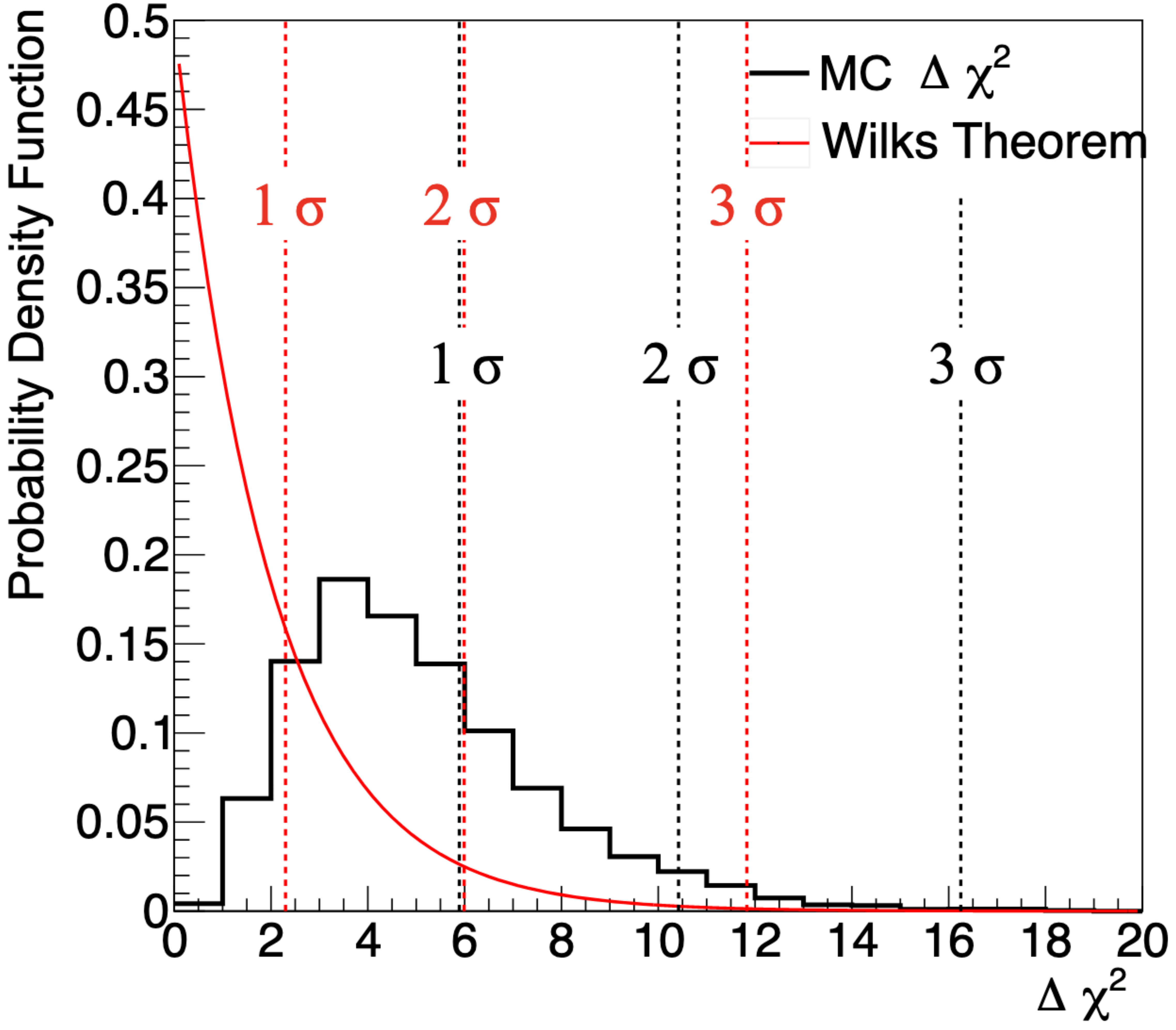
PhysRevD.103.032001

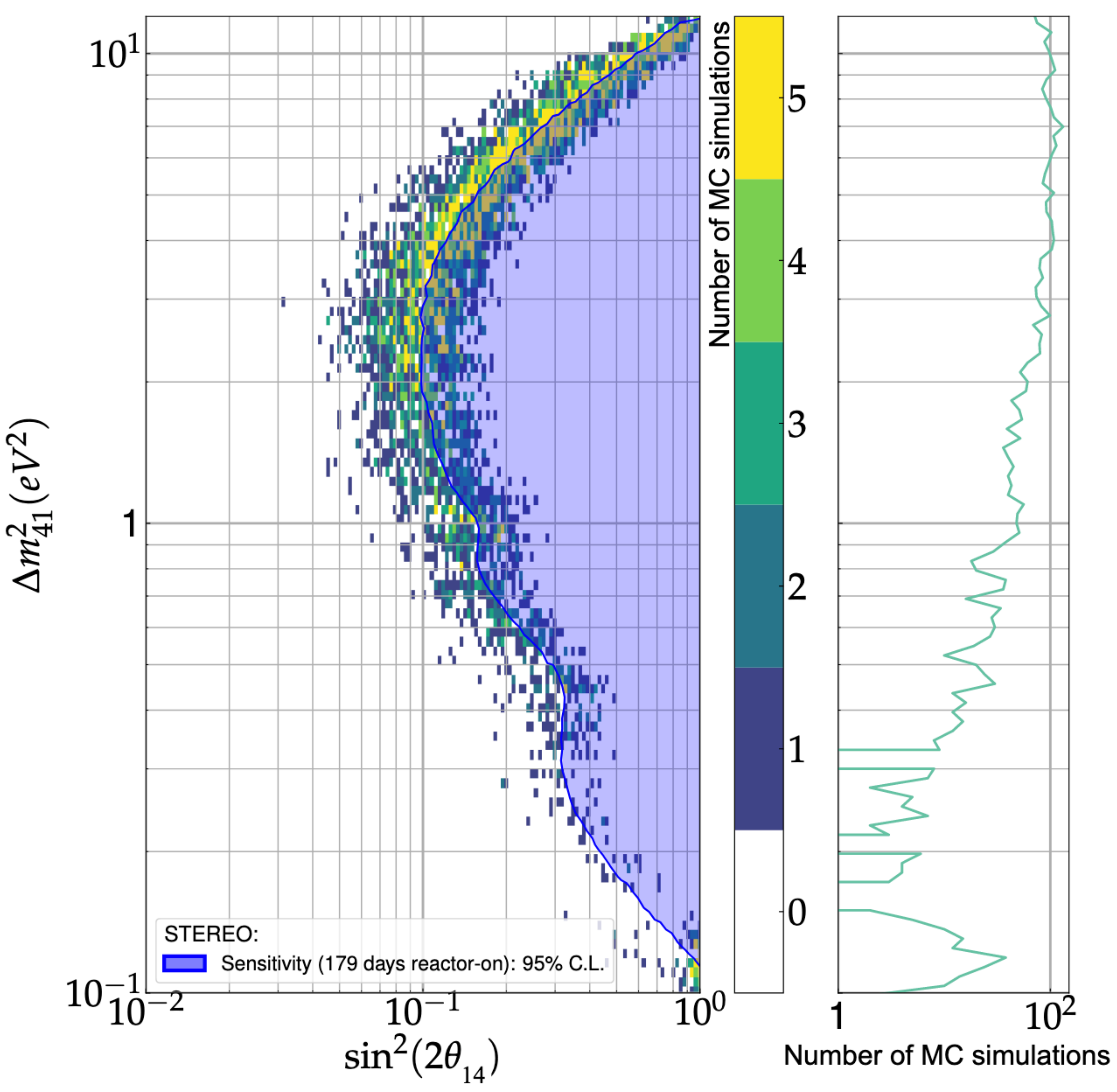


PROSPECT


Data
RAA
Best Fit
Relative Spectrum at baseline
6.7 - 7.4 m
7.4 - 7.5 m
7.5 - 7.7 m
7.7 - 7.8 m
7.8 - 8.0 m
8.0 - 8.1 m
8.1 - 8.2 m
8.2 - 8.3 m
8.3 - 8.5 m
8.5 - 9.3 m
0
0.5
1
1.5
2
1 2 3 4 5 6 7
Prompt Energy [MeV]

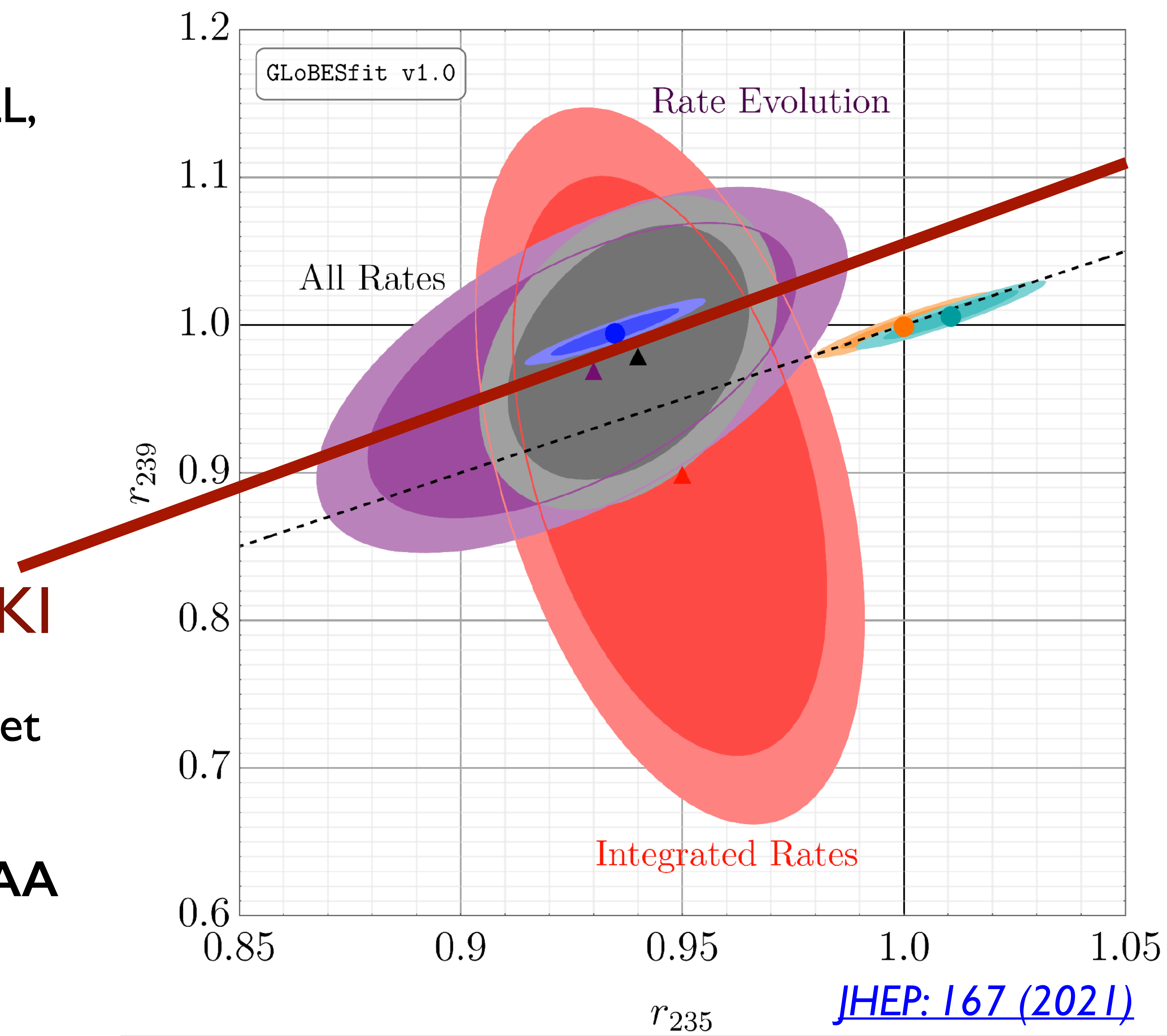
N4 Stats


Probability Density Function
MC Δ χ2
Wilks Theorem
1 σ
2 σ
3 σ
1 σ
2 σ
3 σ
Δ χ2


STEREO:
Sensitivity (179 days reactor-on): 95% C.L.
$\Delta m^2_{41}(eV^2)$
$\sin^2(2\theta_{14})$
Number of MC simulations
Number of MC simulations

Even More Reactor Neutrino Context

- Conversion method is reliant on the β-decay measurements done at ILL, France in 1980s
- Recent claim: Issue with calibration for the original ILL β-decay measurements
- Kopeikin et.al., (*arXiv 2103.01684*) performed a measurement of ^{235}U/^{239}Pu β-decay spectra
- Shows that ^{235}U normalization was overestimated (assuming ^{239}Pu normalization is correct)
- No systematic uncertainties presented and peer-reviewed results not yet published
- **If confirmed, it would effectively resolve the original motive for RAA**



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