Current Status of Search for Sterile Neutrinos

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Sep 16, 2021

40^{th} International Symposium on Physics in Collisions

Yale

Wright Laboratory

Disclaimers

Focus of this talk

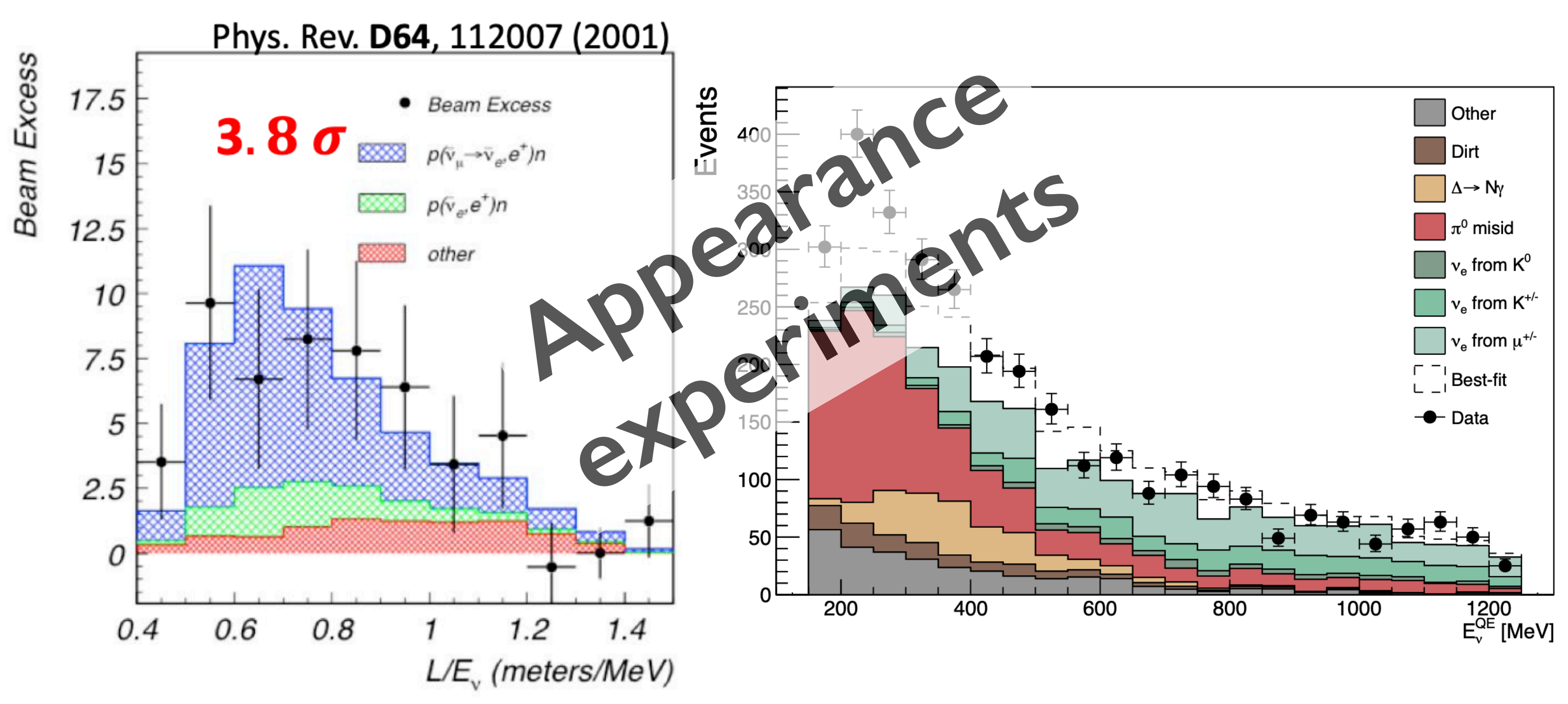
- eV scale sterile neutrinos
- Finished or currently running experiments
- Experiments built to search for eV-scale sterile neutrino oscillations

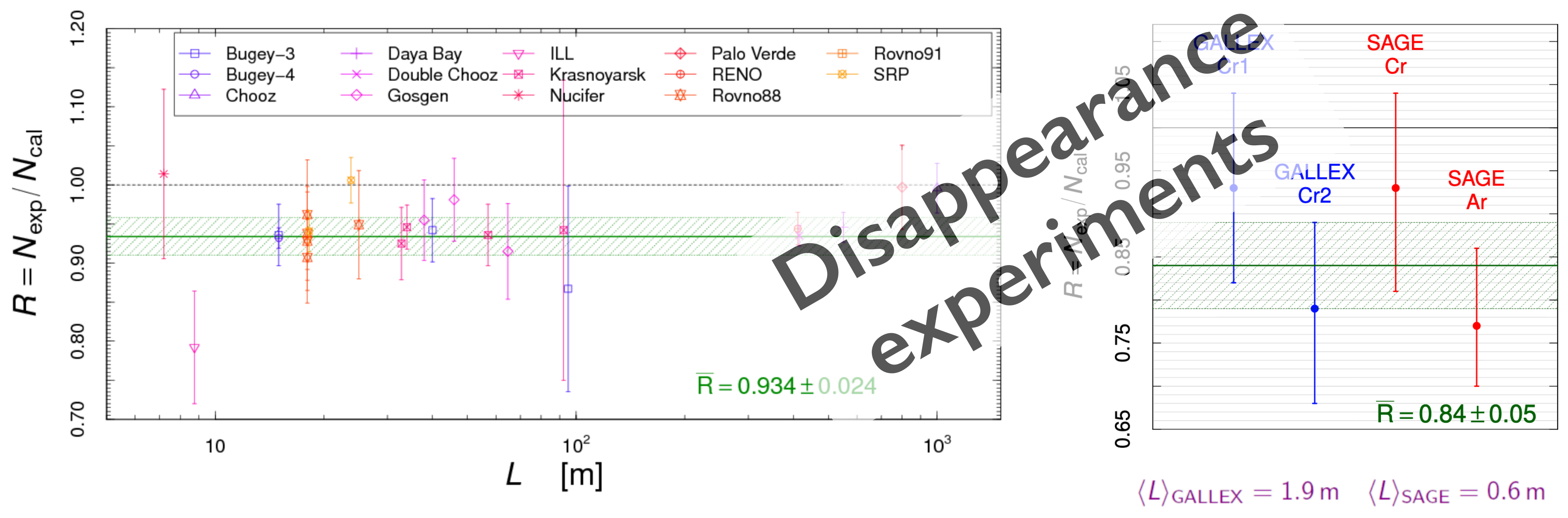
* I am collaborator on the PROSPECT reactor neutrino experiment

	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

Anomalies





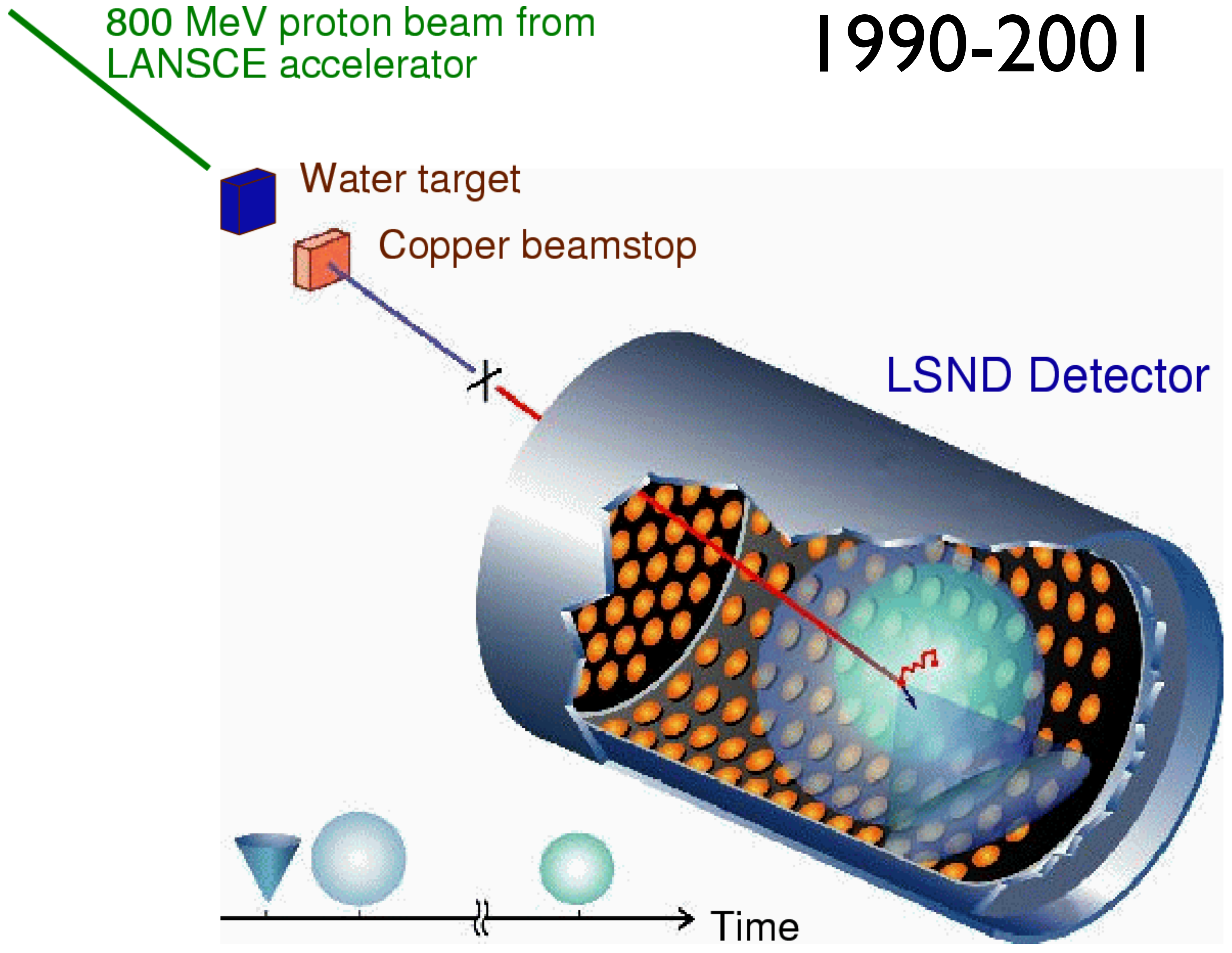
Anomalies drive searches for eV-scale sterile neutrinos

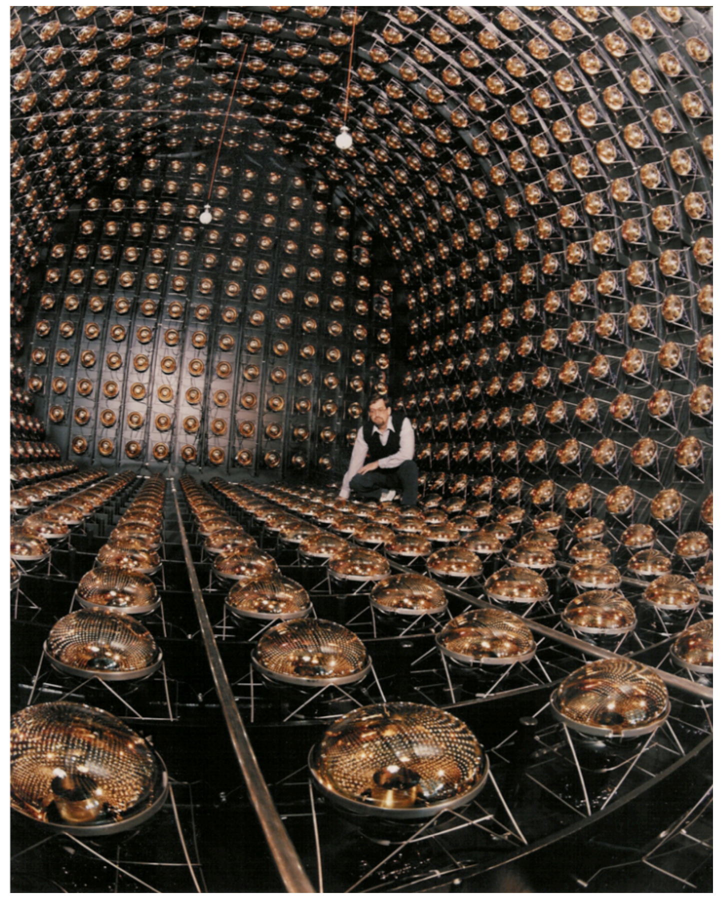
LSND Anomaly

Neutrino source

$$p + X \rightarrow \pi^+ + X'$$
(800 MeV) $\quad \hookrightarrow \mu^+ \nu_\mu$ (DAR)
$\quad\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

1990-2001



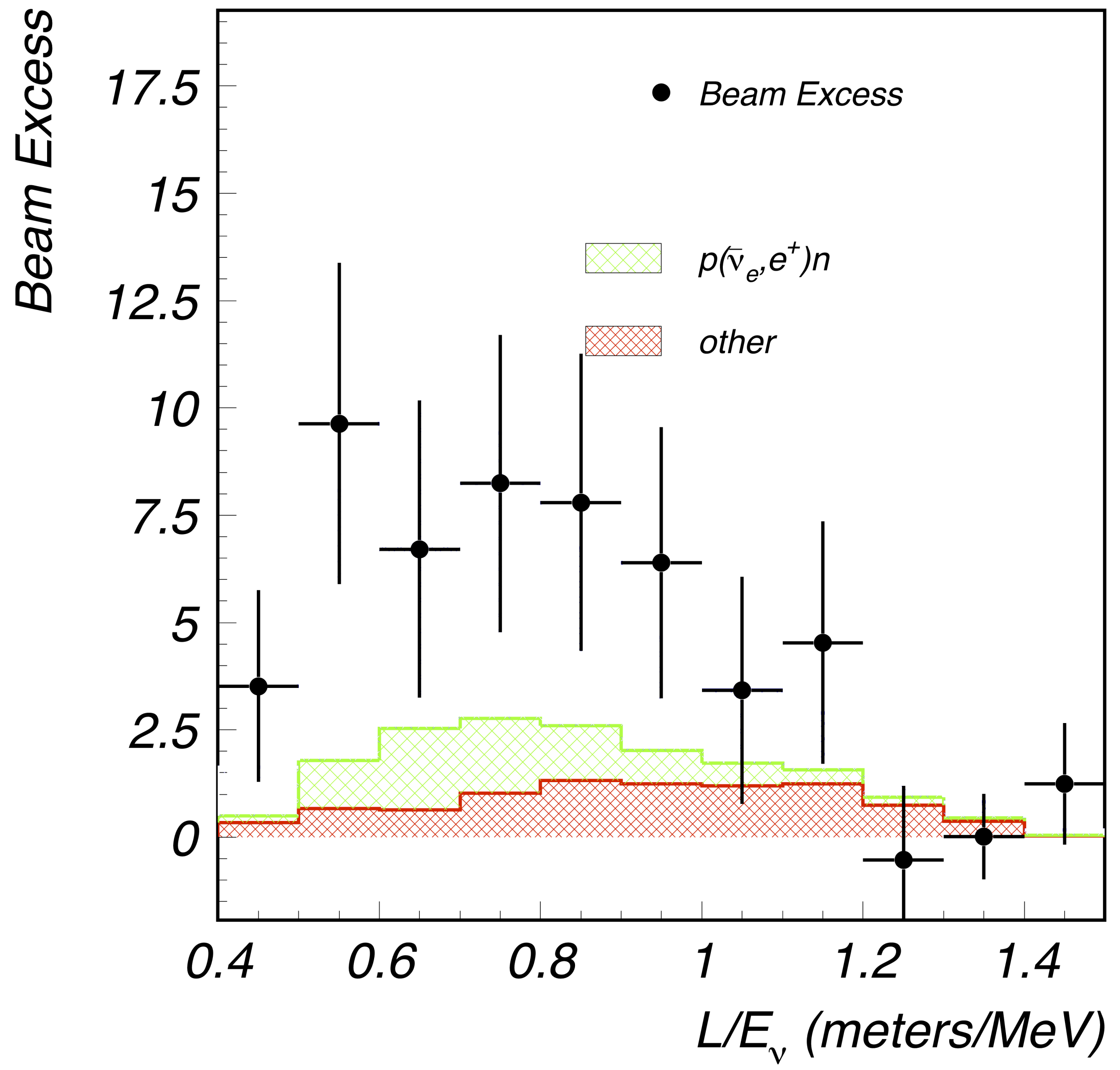


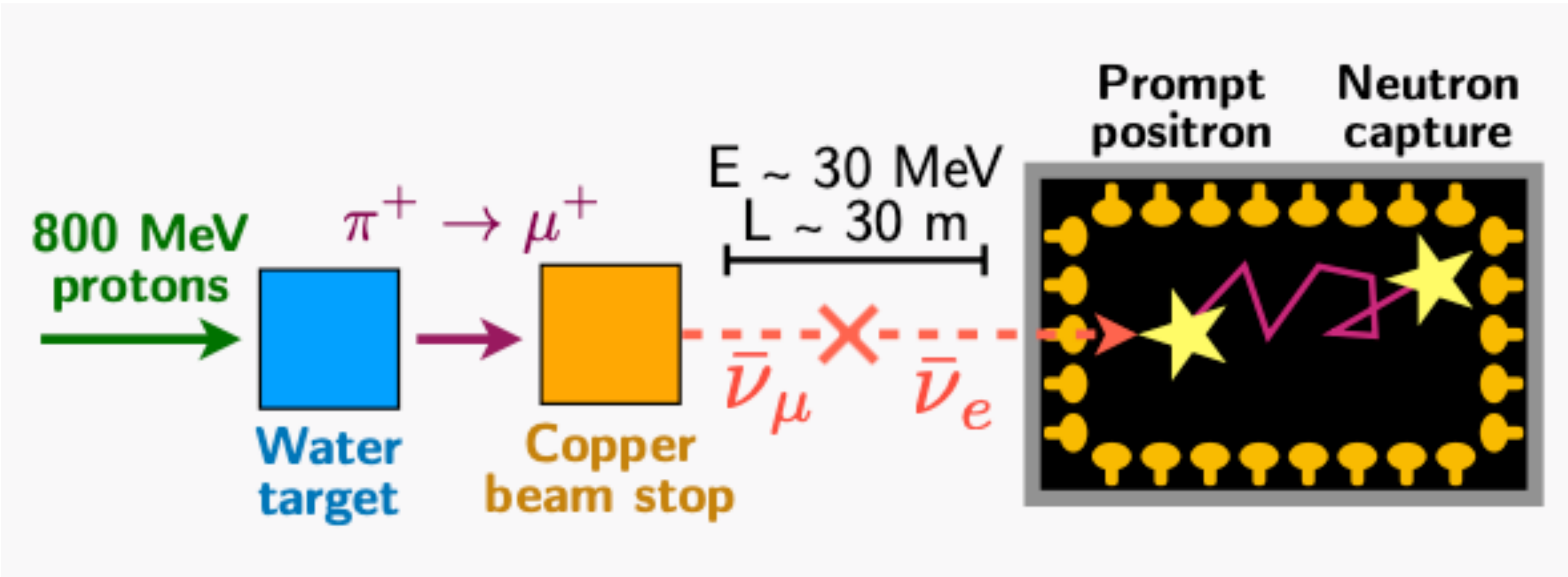
Detection:
Liquid scintillator + PMT

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Scintillation + Cherenkov (e^+)

Capture on H (n)

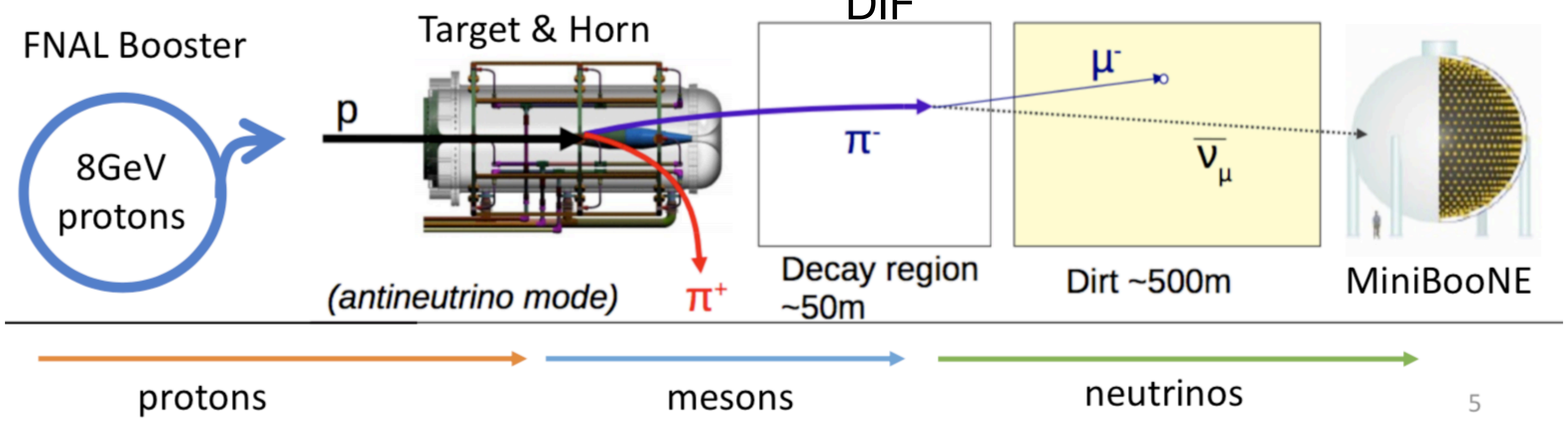


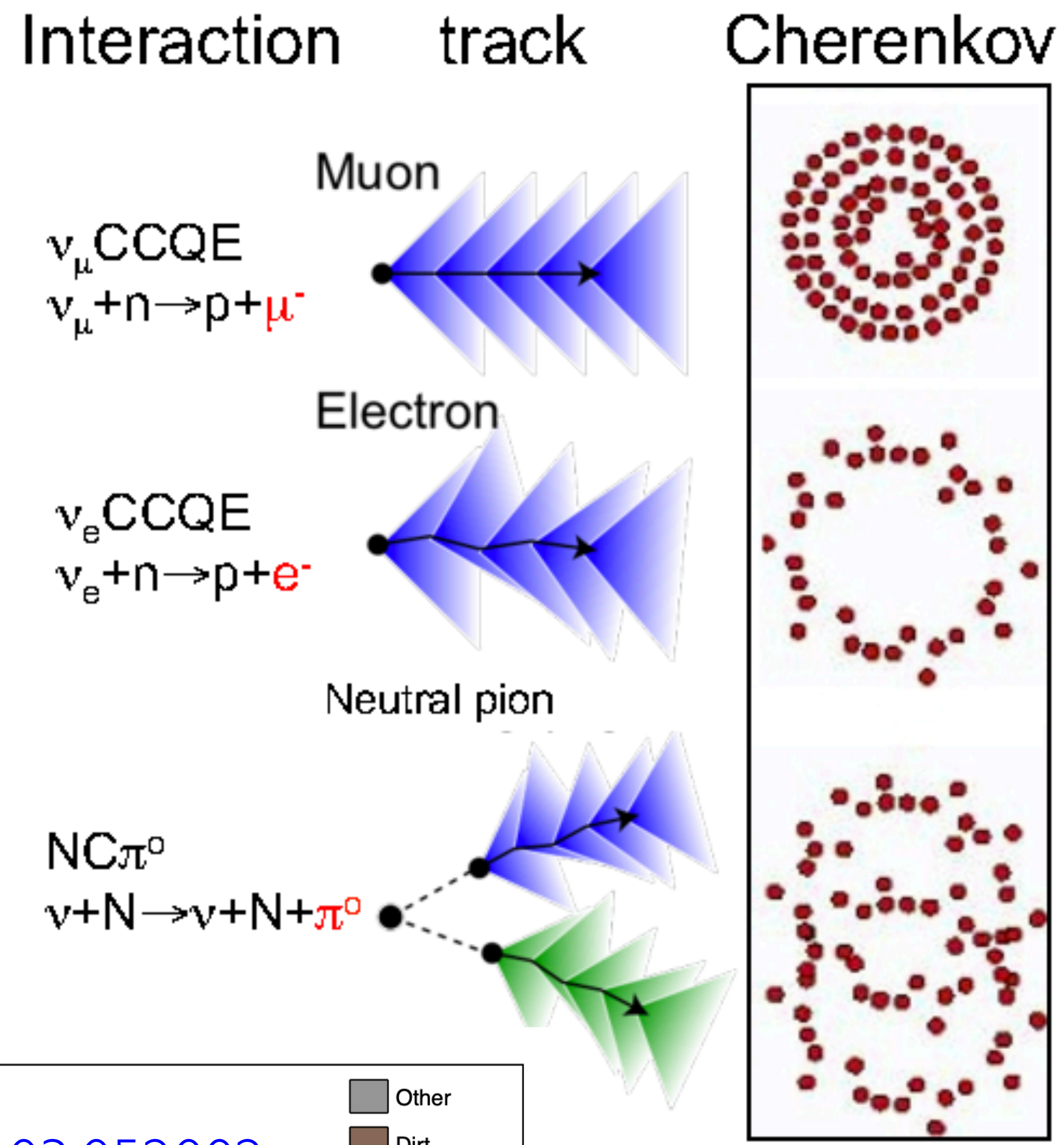


LSND detected 87.9 ± 23.2 (3.8σ) excess $\bar{\nu}_e$ events

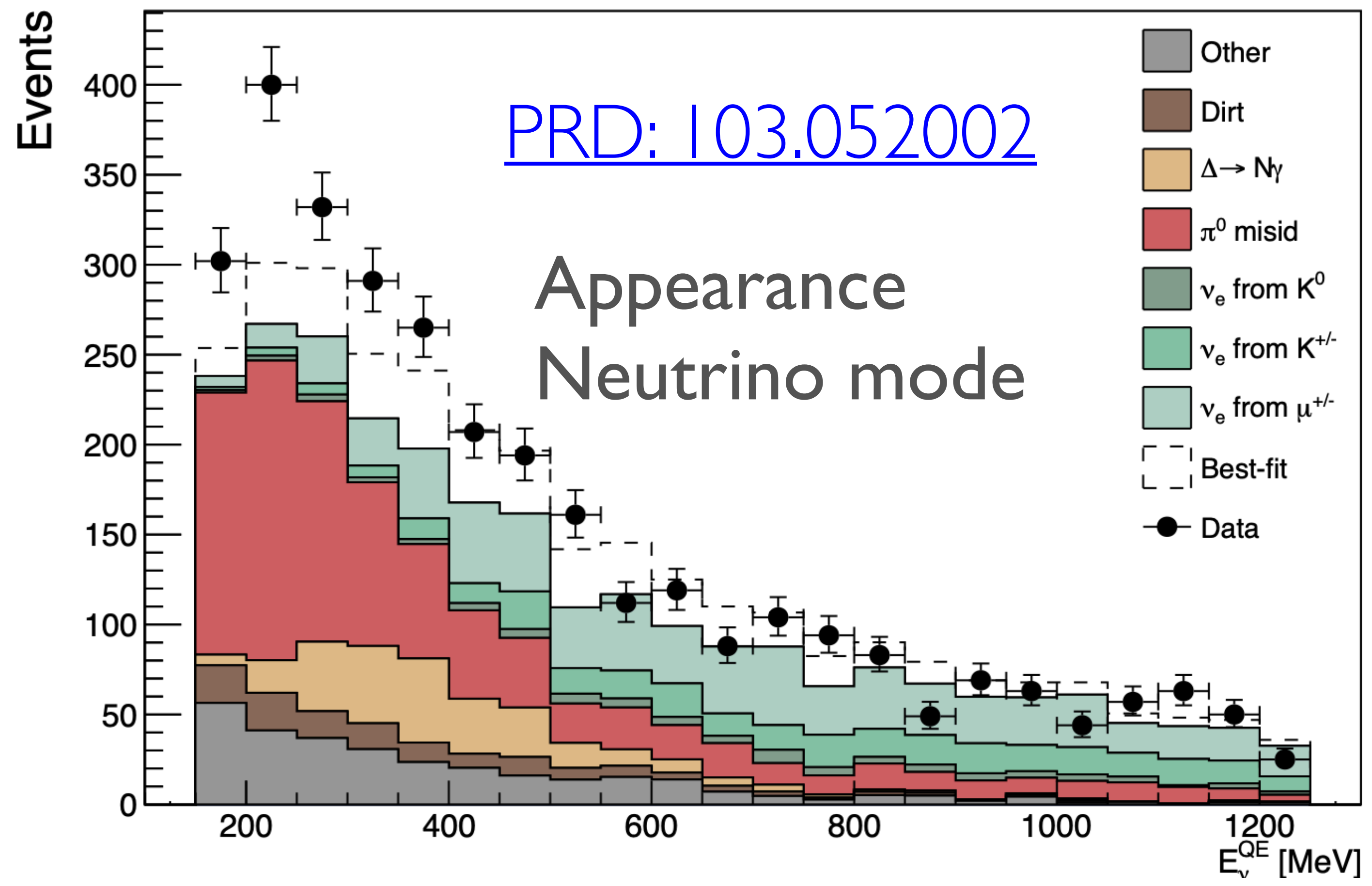
MiniBooNE Anomaly

1998-2020





- Built to test LSND results
- Protons hit Be target; mesons focused
- Muons and Kaons decay in decay pipe to produce neutrinos
- Focus horn polarity to switch (anti)neutrino mode
- Particle identification through Cherenkov radiation



MiniBooNE observed excess in appearance primarily in the neutrino mode

Reactor Antineutrino Anomaly (RAA)

- Double Chooz initially only had one detector and so an oscillation measurement had to be done by comparing to a model
  - Improvement in reactor neutrino model to make a precise θ_{13} measurement
  - Change in neutron lifetime
  - Inclusion of off-equilibrium effects
- Predicted flux higher with improved model
- ~6% global experimental deficit
- Discrepancy is called Reactor Antineutrino Anomaly (RAA)

Improved predictions of reactor antineutrino spectra

Th. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, and F. Yermia

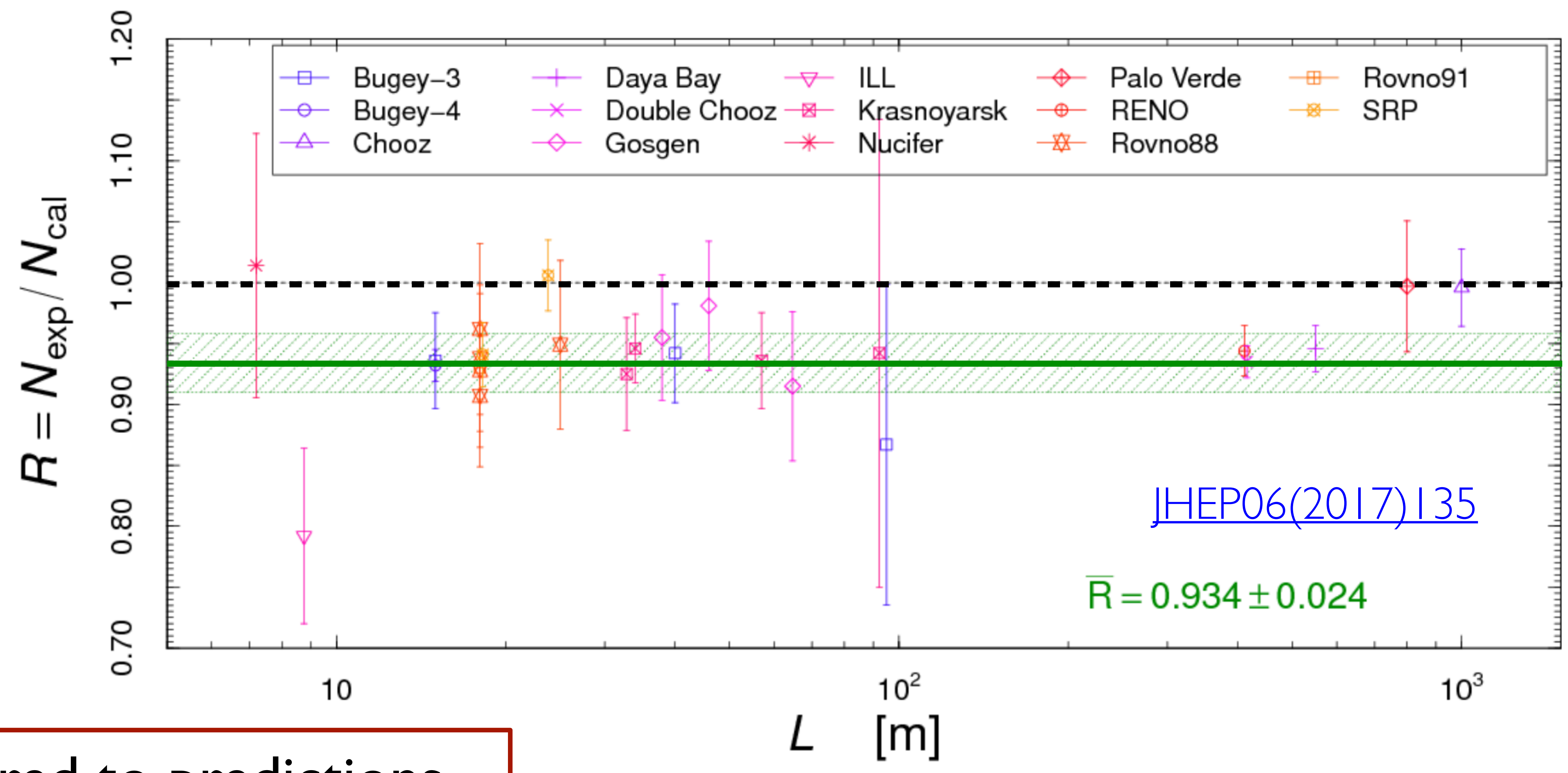
Phys. Rev. C **83**, 054615 – Published 23 May 2011

Determination of antineutrino spectra from nuclear reactors

Patrick Huber*

Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA

(Received 16 June 2011; published 29 August 2011)

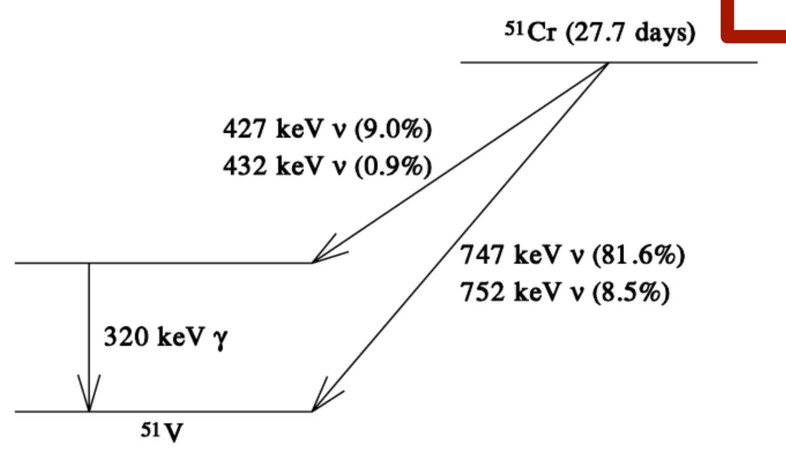


Reactor experiments observe ~3σ deficit compared to predictions

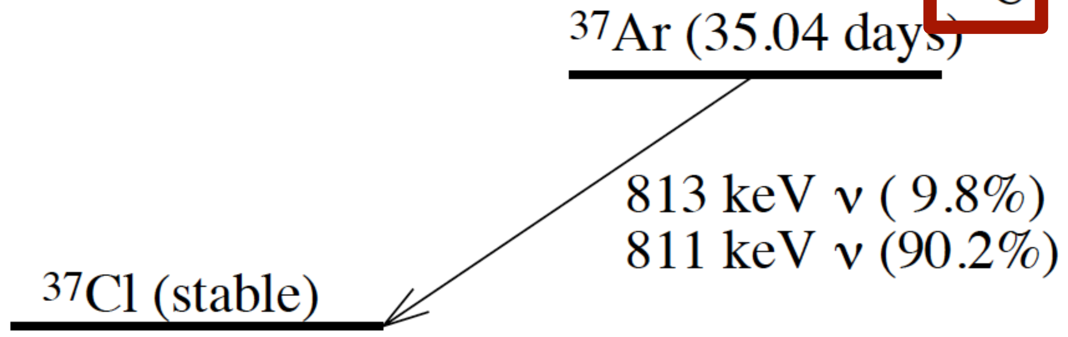
Galium Anomaly

Radioactive sources

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

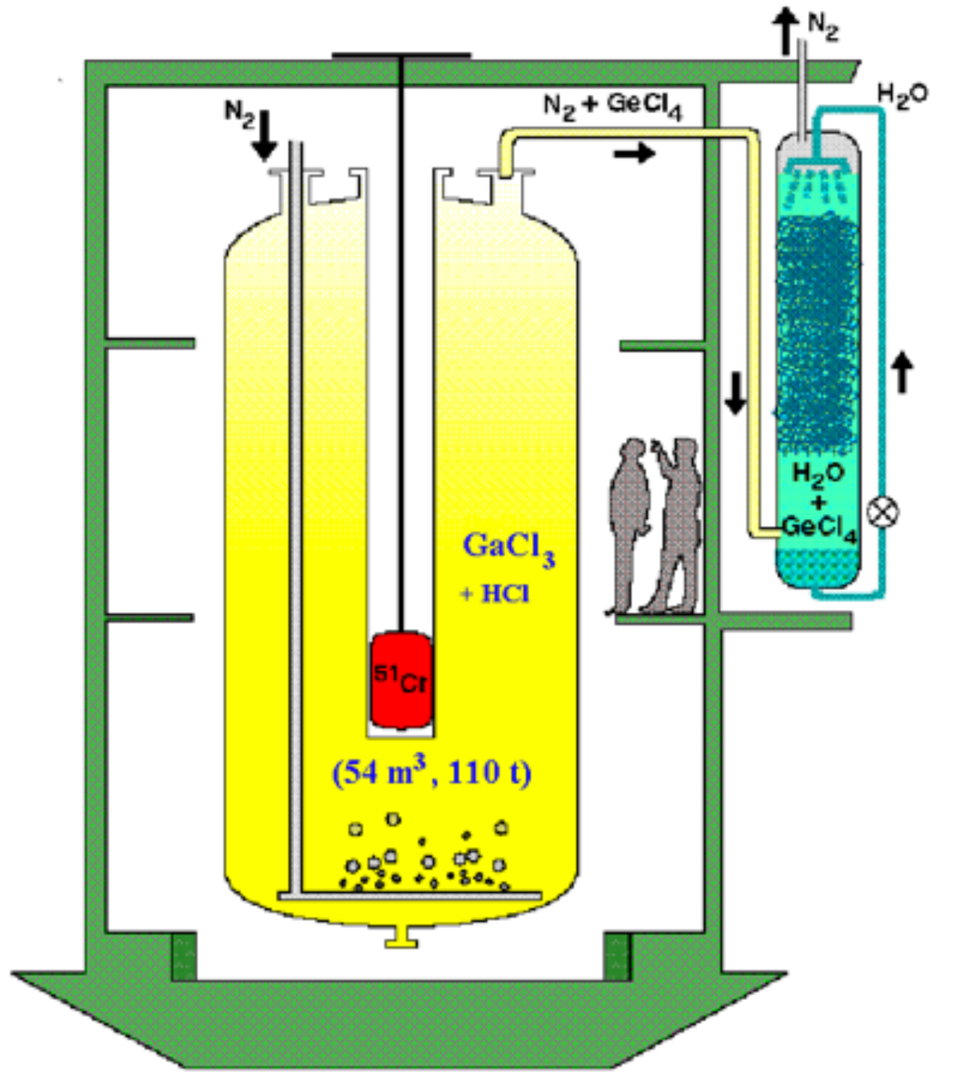


$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$

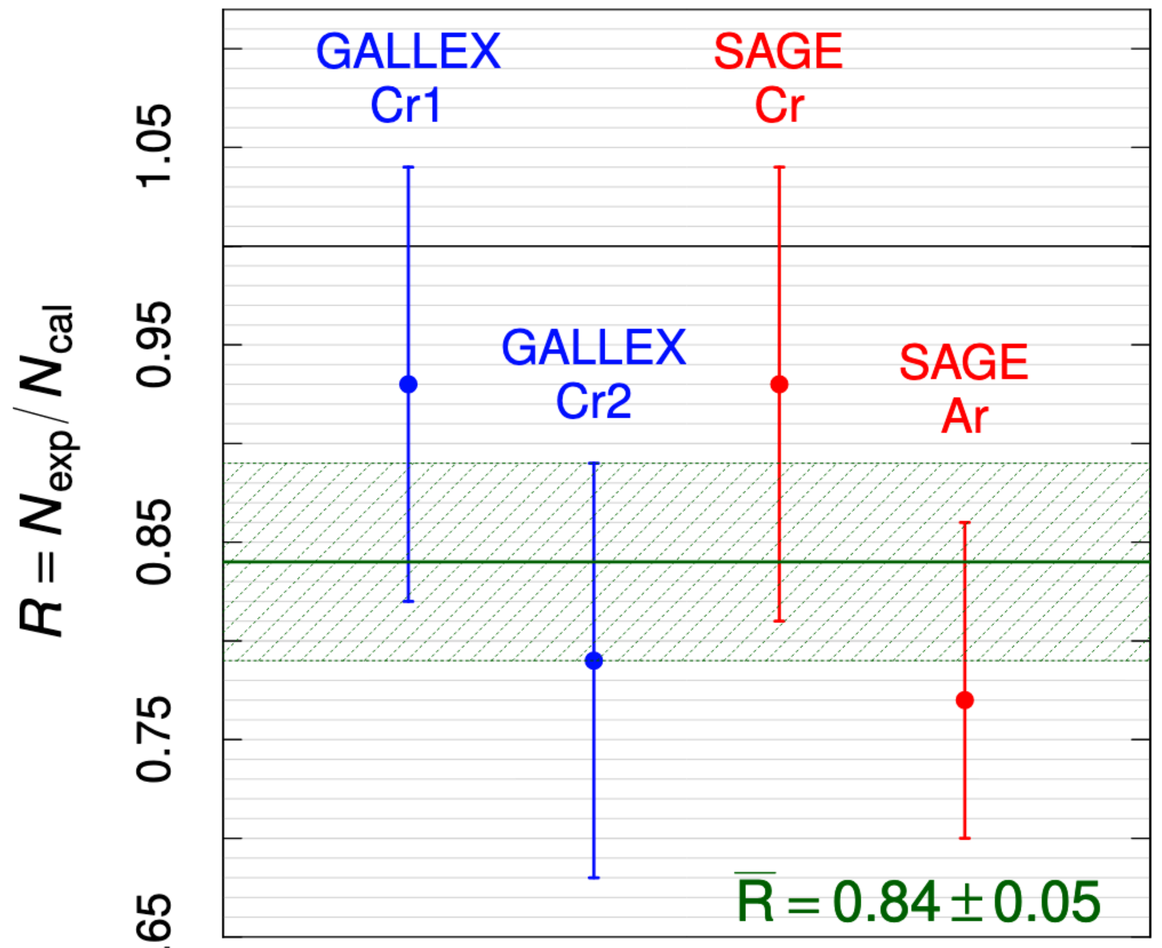


Detection:

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



- Solar neutrino experiments GALLEX and SAGE used ^{51}Cr and ^{37}Ar as calibration sources
- Measured electron neutrinos lower than predicted



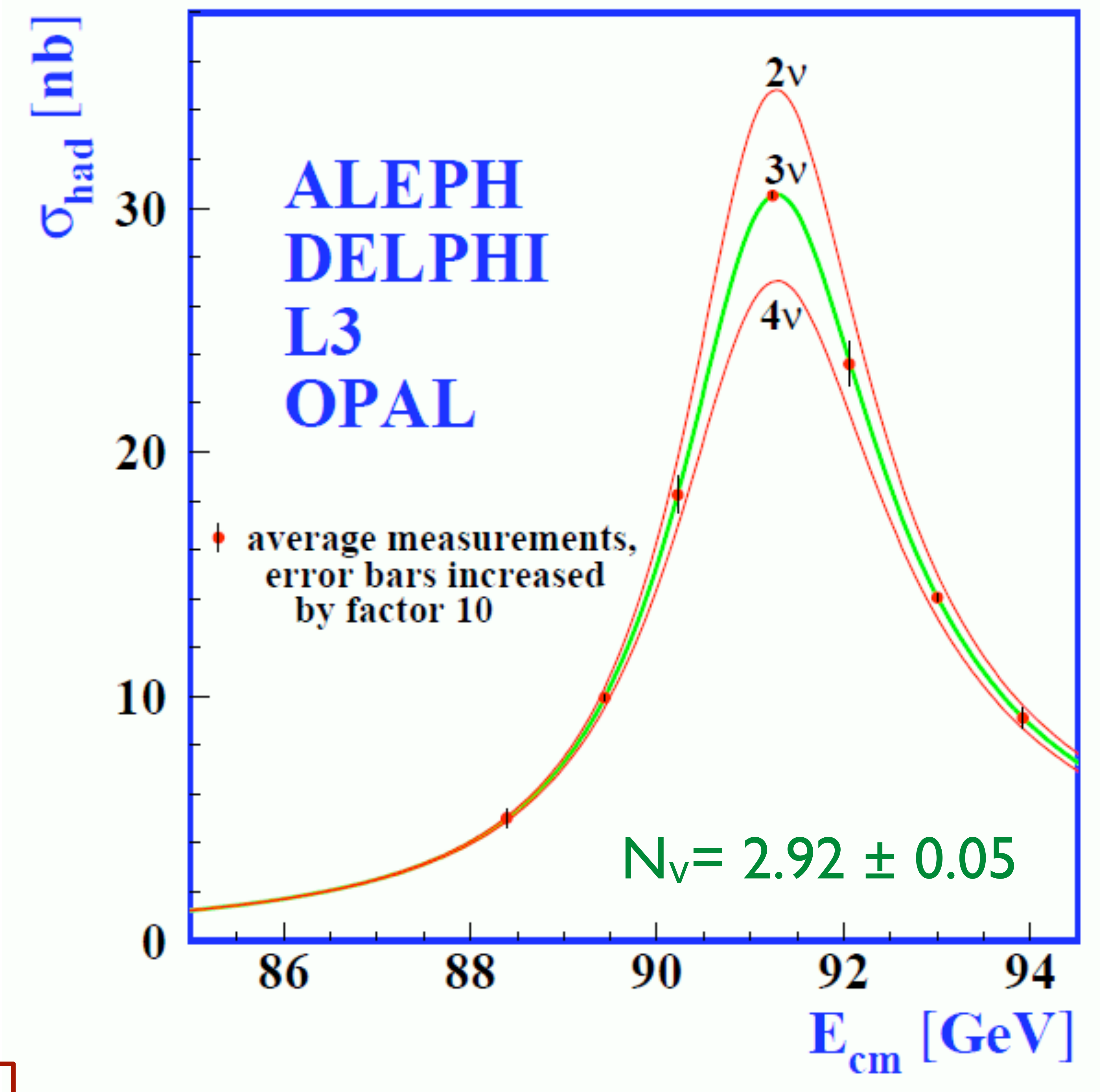
JHEP06(2017)135

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

Gallium experiments measure ~3σ deficit compared to predictions

Interpretation of Anomalies

- LSND and MiniBooNE (appearance experiments) see excess
- Reactor and Gallium experiments (disappearance) see deficit
- If interpreted as neutrino oscillations, suggests eV-scale neutrinos
- Active neutrino flavors constrained by Z boson invisible decay width measurements at LEP
- Another light neutrino state must be a sterile state



Sterile neutrinos could explain anomalies independently

Sterile Neutrino Refresher

Extended PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

Two oscillation approximation valid for $\Delta m_{43} >> \Delta m_{21}, |\Delta m_{31}|$

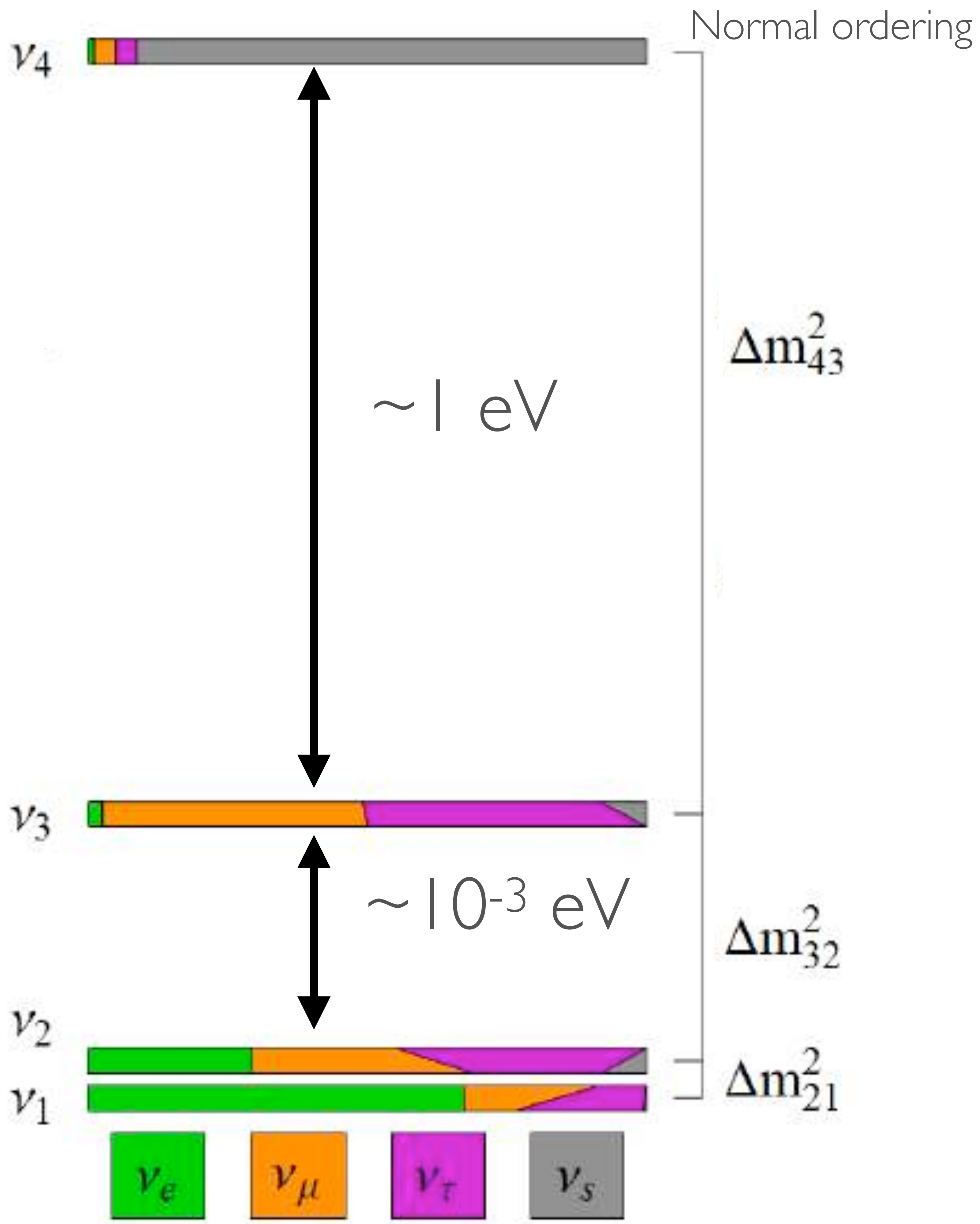
Appearance experiments

$$\nu_\mu \to \nu_e: \ \sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$$

Disappearance experiments

$$\nu_e \to \nu_e: \ \sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1-|U_{e4}|^2)$$

$$\nu_\mu \to \nu_\mu: \ \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$$



J. Coelho: Neutrino Telescopes

*Similar situation in inverted ordering

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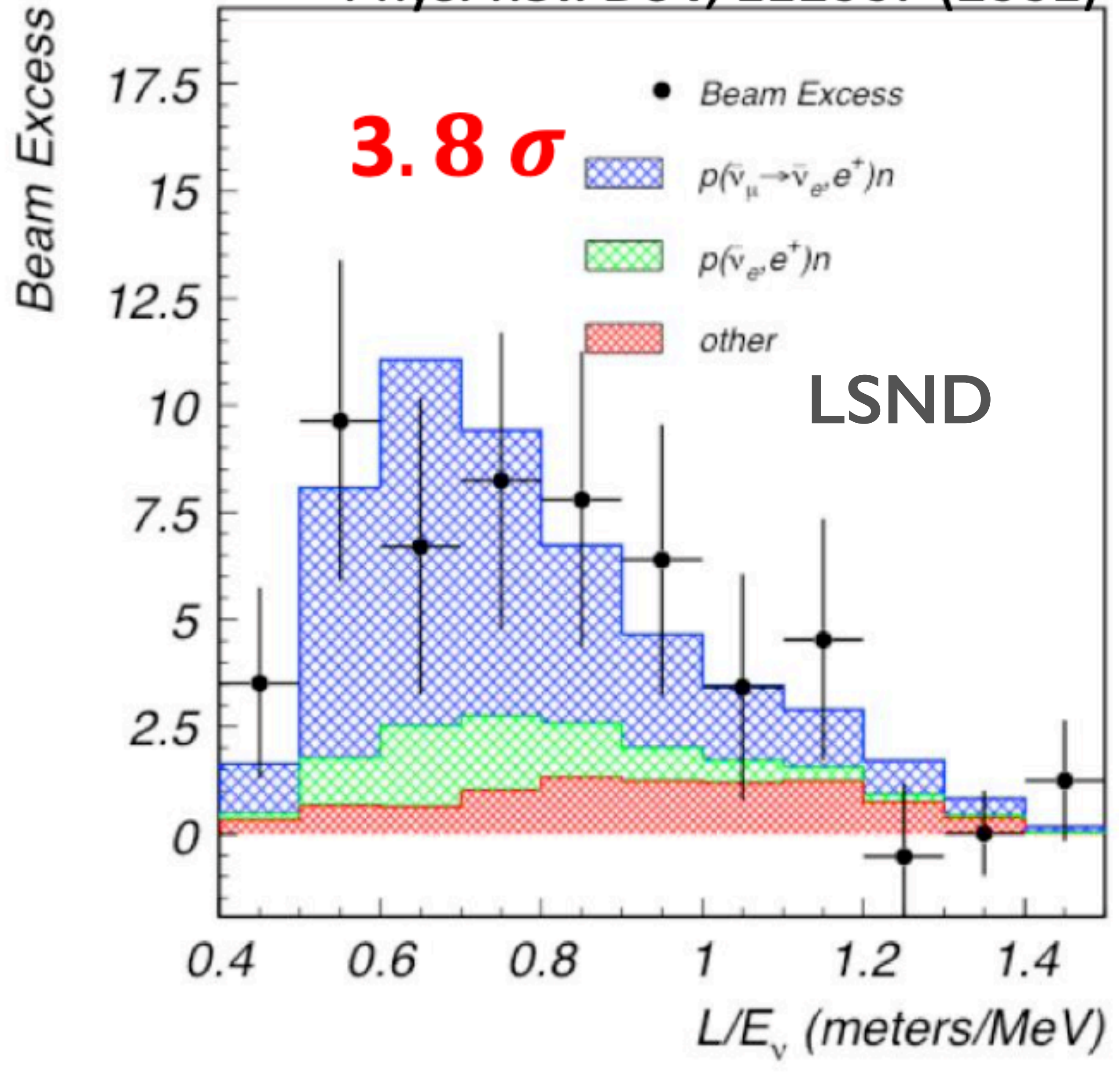
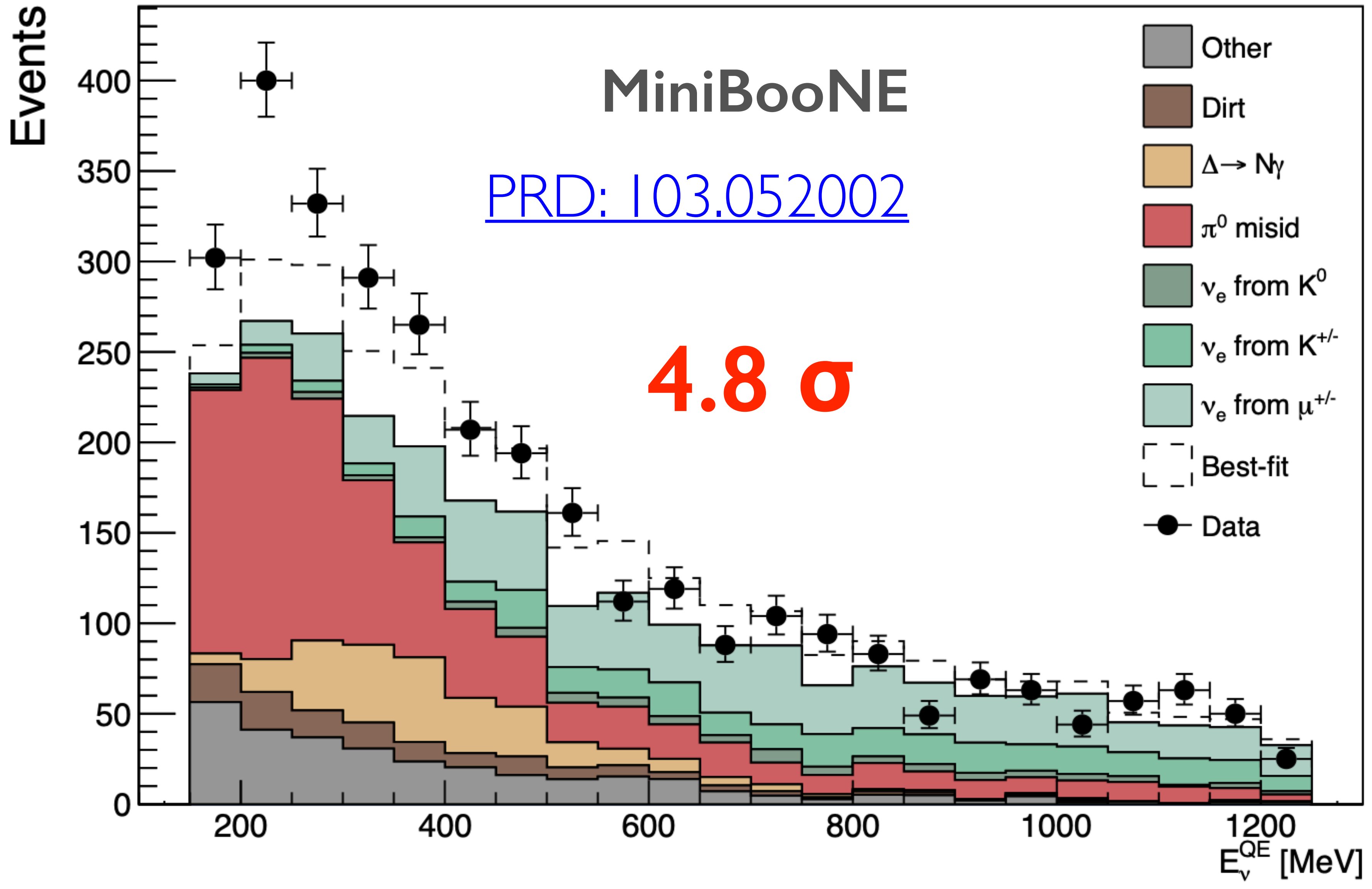
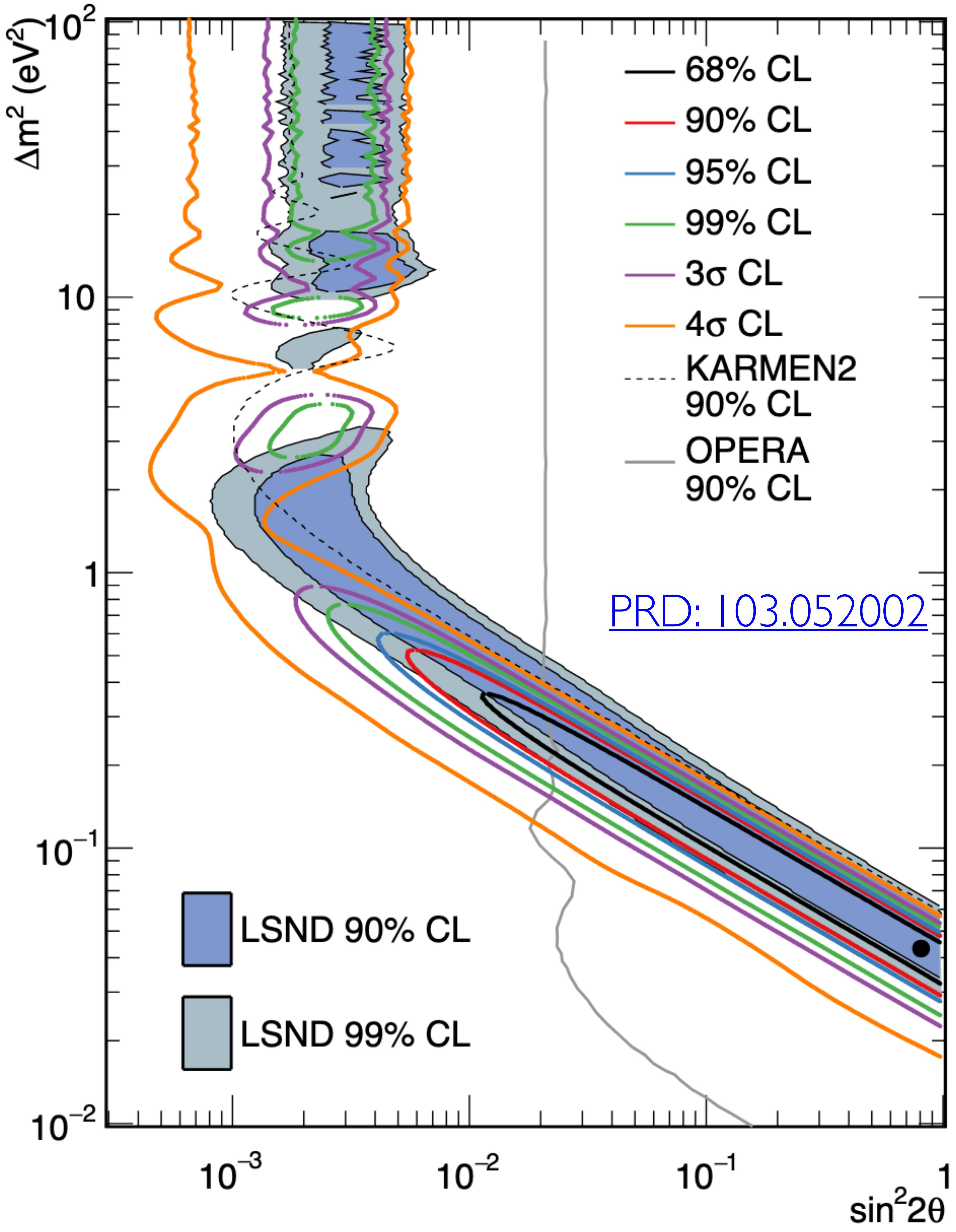
Interpretation of Anomalies: Appearance Experiments

- LSND and MiniBooNE excess in appearance channels could be explained by eV-scale sterile neutrinos
- Both in roughly similar parameter space
- Experiments have different source and detection techniques
- MiniBooNE disappearance shows no evidence of oscillations

Phys. Rev. **D64**, 112007 (2001)



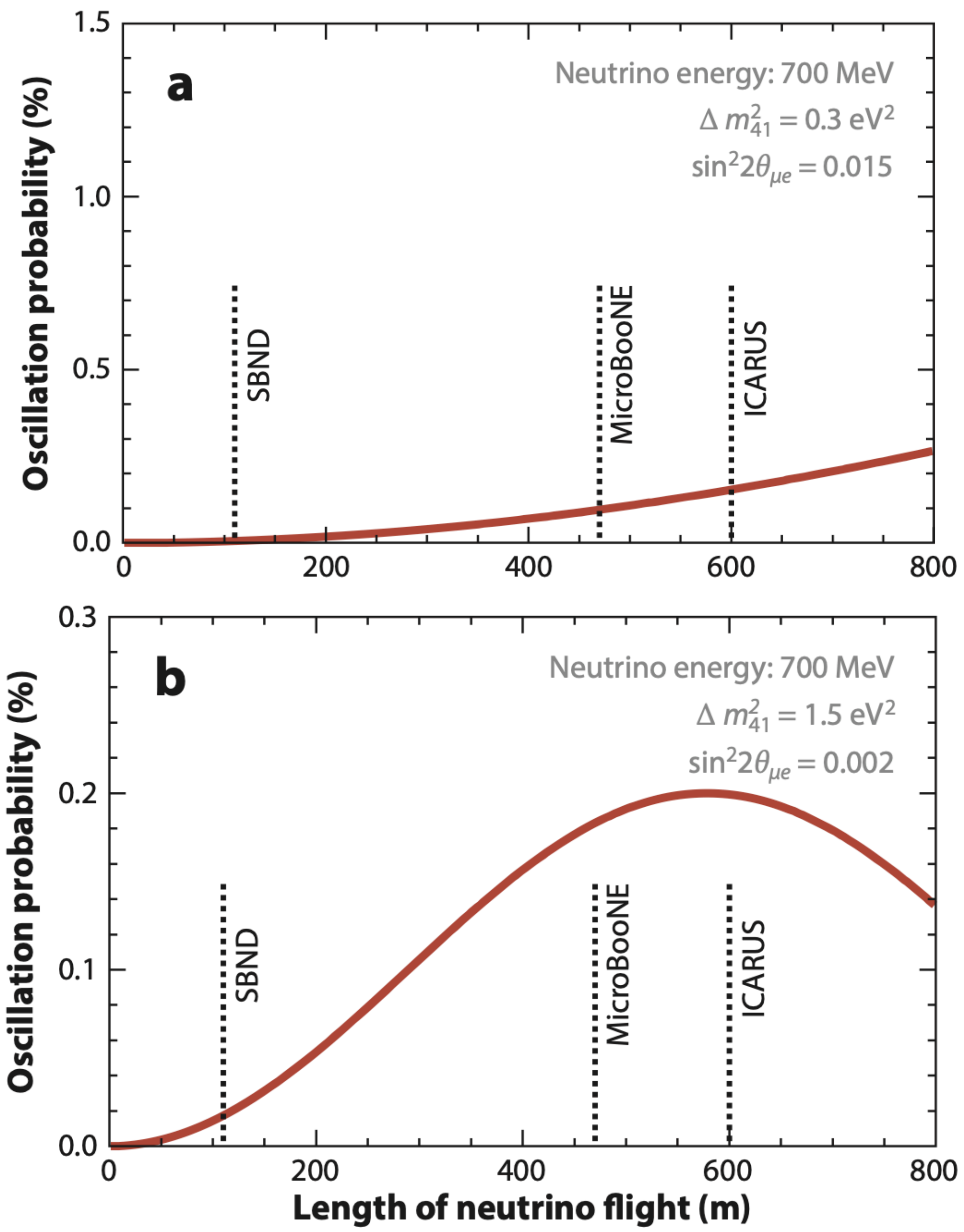




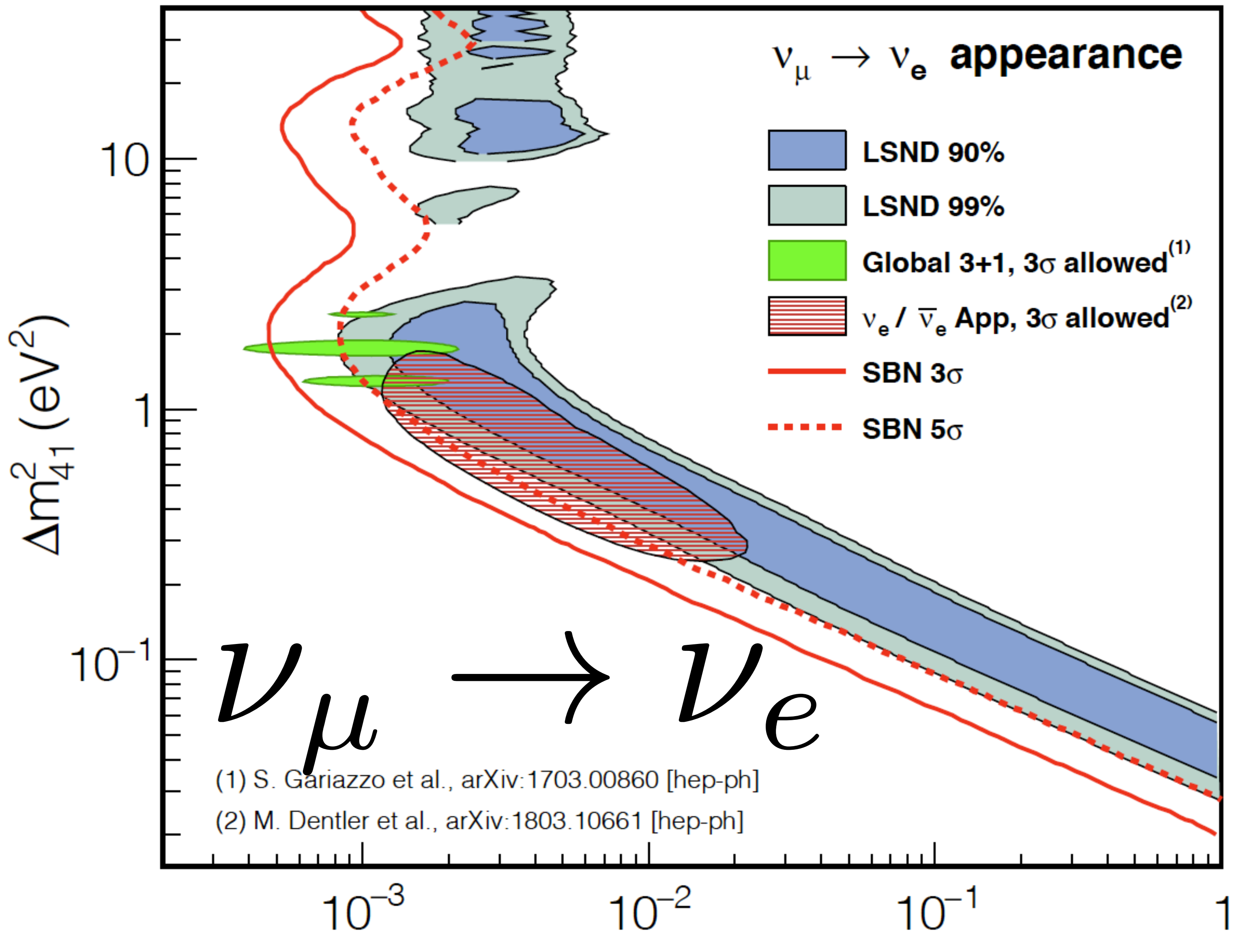
Testing LSND and MiniBooNE Anomalies: SBN Program

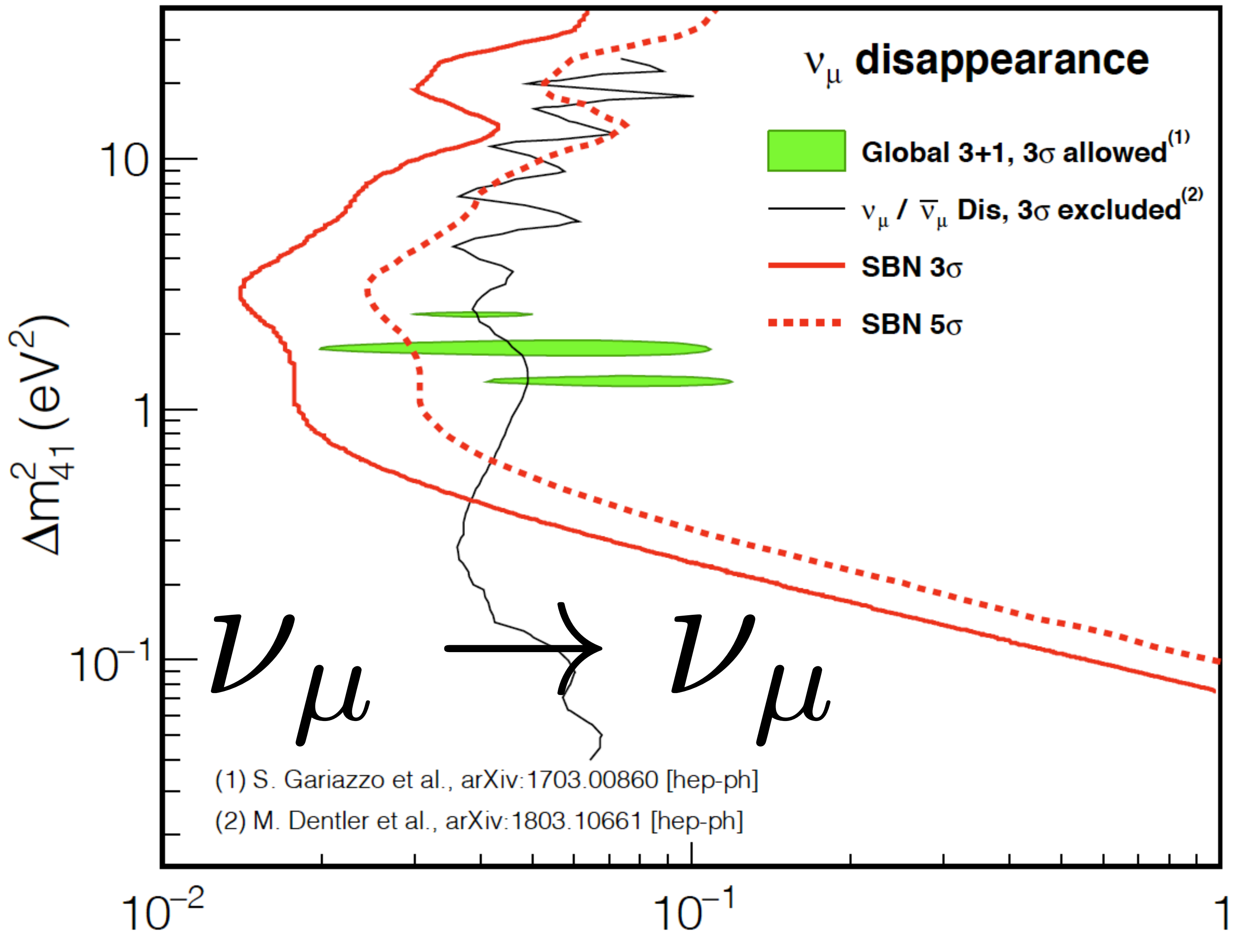
- SBN program to test both LSND and MiniBooNE anomalies
- Three detectors share same beam line (booster neutrino beam at Fermilab) and uses Liquid Argon TPC

Testing LSND and MiniBooNE Anomalies: SBN Program



- Detectors baselines optimized for eV-scale sterile neutrino search
- Relative measurements provide significant cancellation of systematic uncertainties
- Test both appearance and disappearance modes





$\sin^2 2\theta_{\mu e}$ Annu. Rev. Nucl. Part. Sci. 2019 $\sin^2 2\theta_{\mu\mu}$

SBN Program Status

- ICARUS commissioning: neutrinos from BNB and NUMI have been collected since the end of March 2021 to setup the data processing workflow and event reconstruction tools.
- Beam data with ICARUS will be collected this fall, SBND will be operational late 2022.

- SBN: a conclusive ve
with a direct test of
both in appearance
data-taking (6.6 10^{20} pot).
- ICARUS alone: can confirm or refute in less than one year the results from the Neutrino-4 experiment, which reports 2.9σ indications for oscillation consistent with Δm^2_{14} = 7.3 eV^2 (*Phys. Rev. D 104, 032003*).

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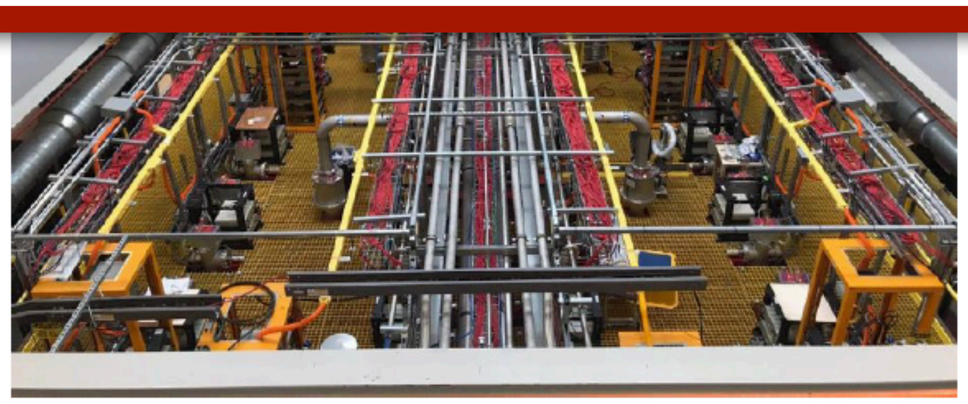
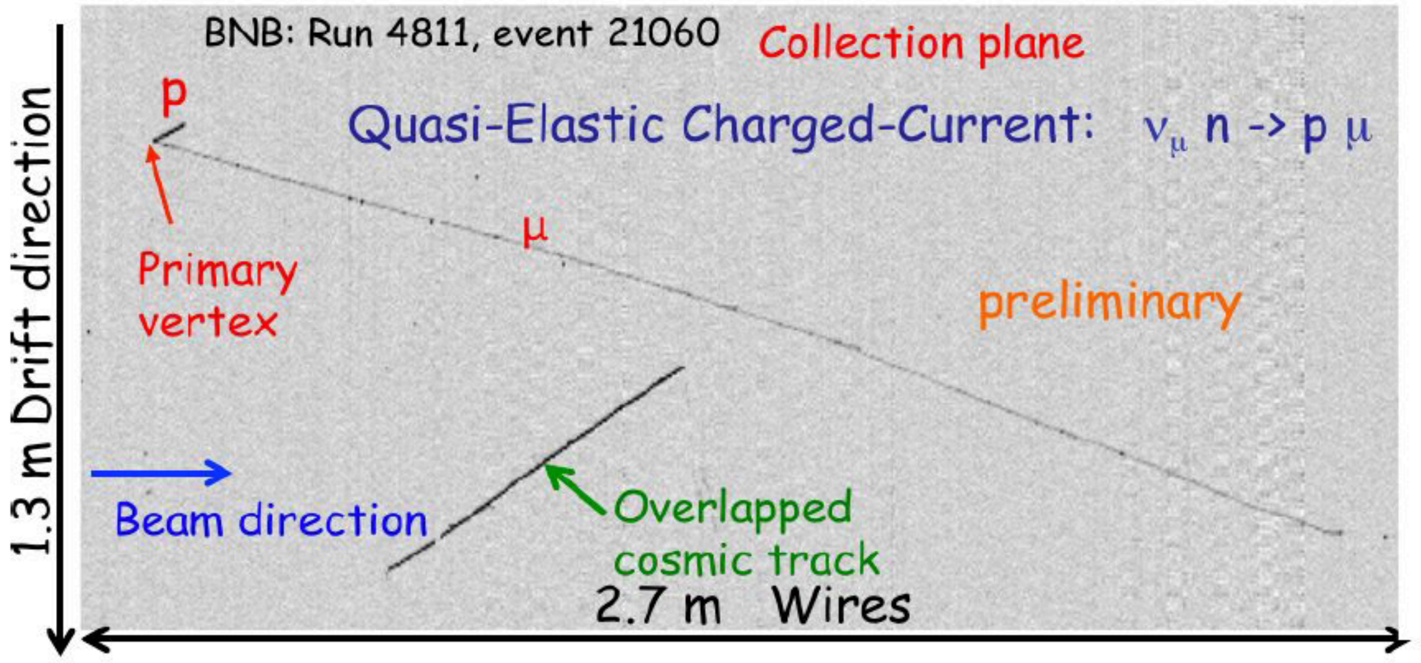
- Beam data with ICARUS will be collected this fall, SBND will be operational late 2022.



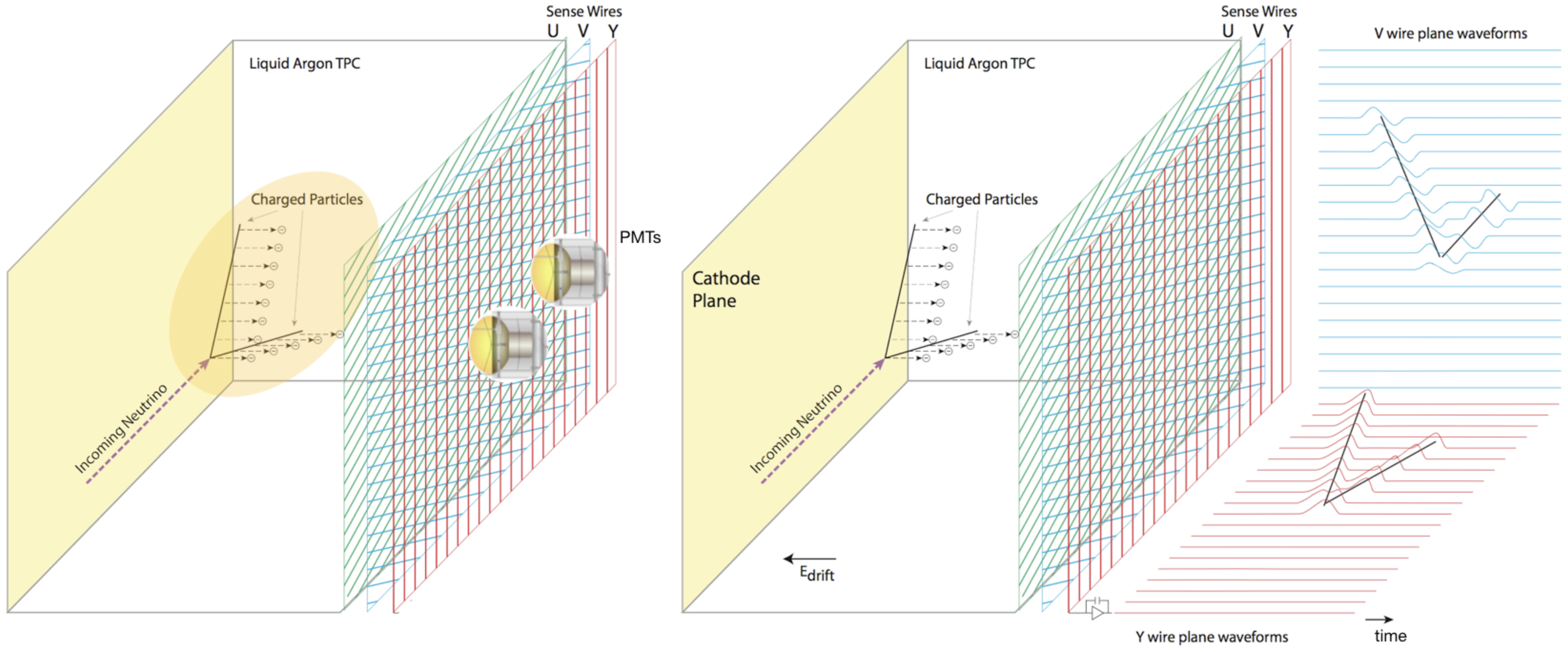
First ICARUS neutrino candidates (BNB): CCQE

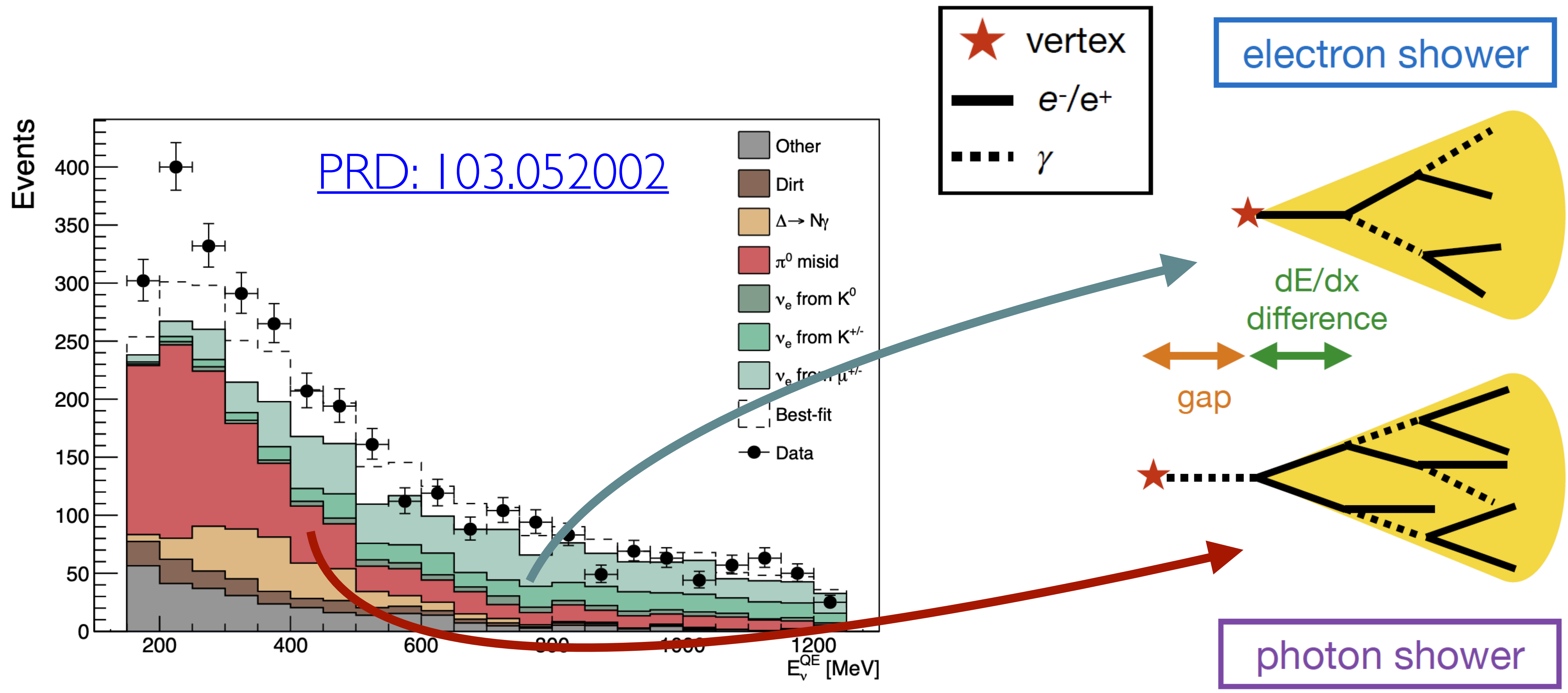


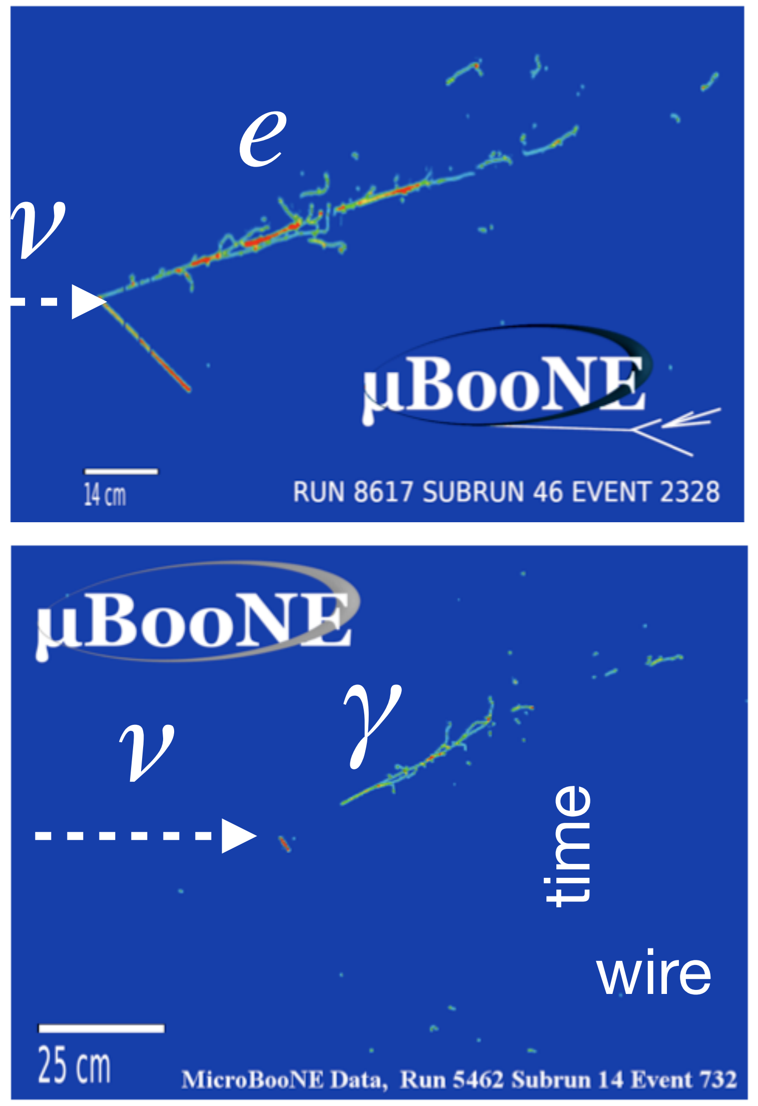
Slide from ICARUS collaboration

Testing MiniBooNE Anomaly: MicroBooNE

- SBN and MicroBooNE uses LArTPC detectors
- LArTPC: Ionization drift (energy, tracking) and scintillation (timing)
- MicroBooNE designed to directly test the MiniBooNE anomaly
  - Same beamline
  - Differentiate e/γ type events
- Data since 2015-2020
- Soon to release first low energy excess results







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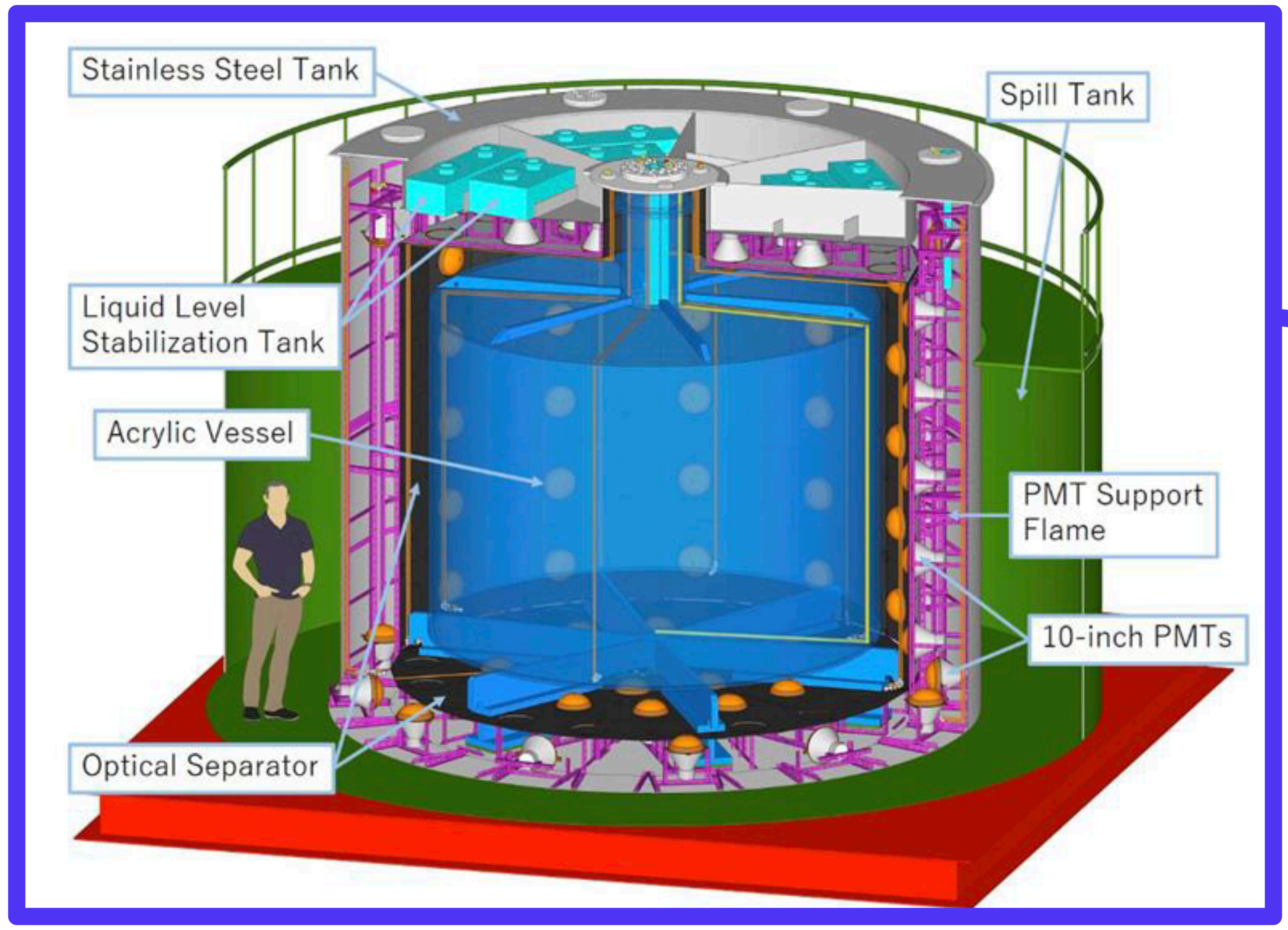
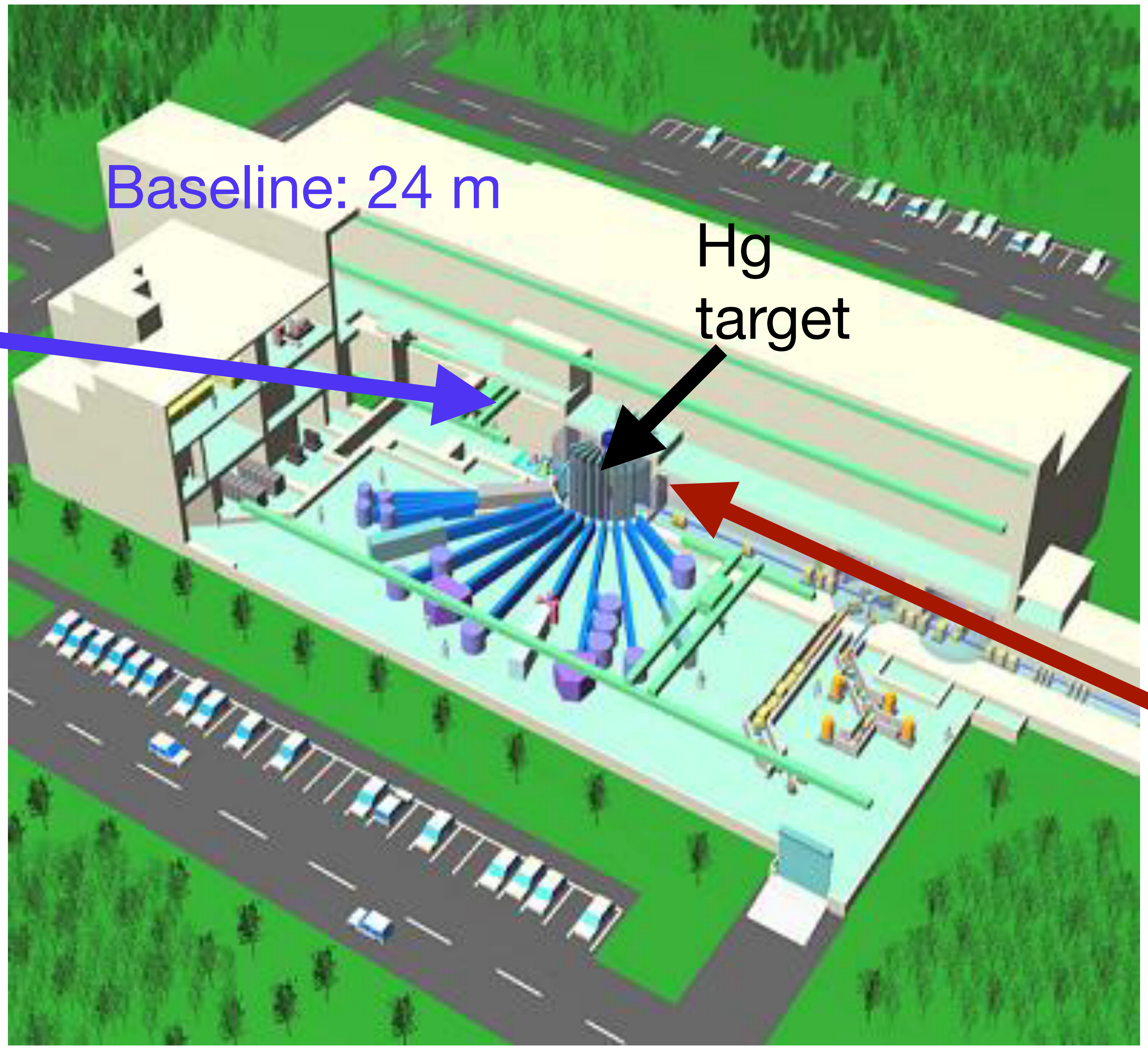
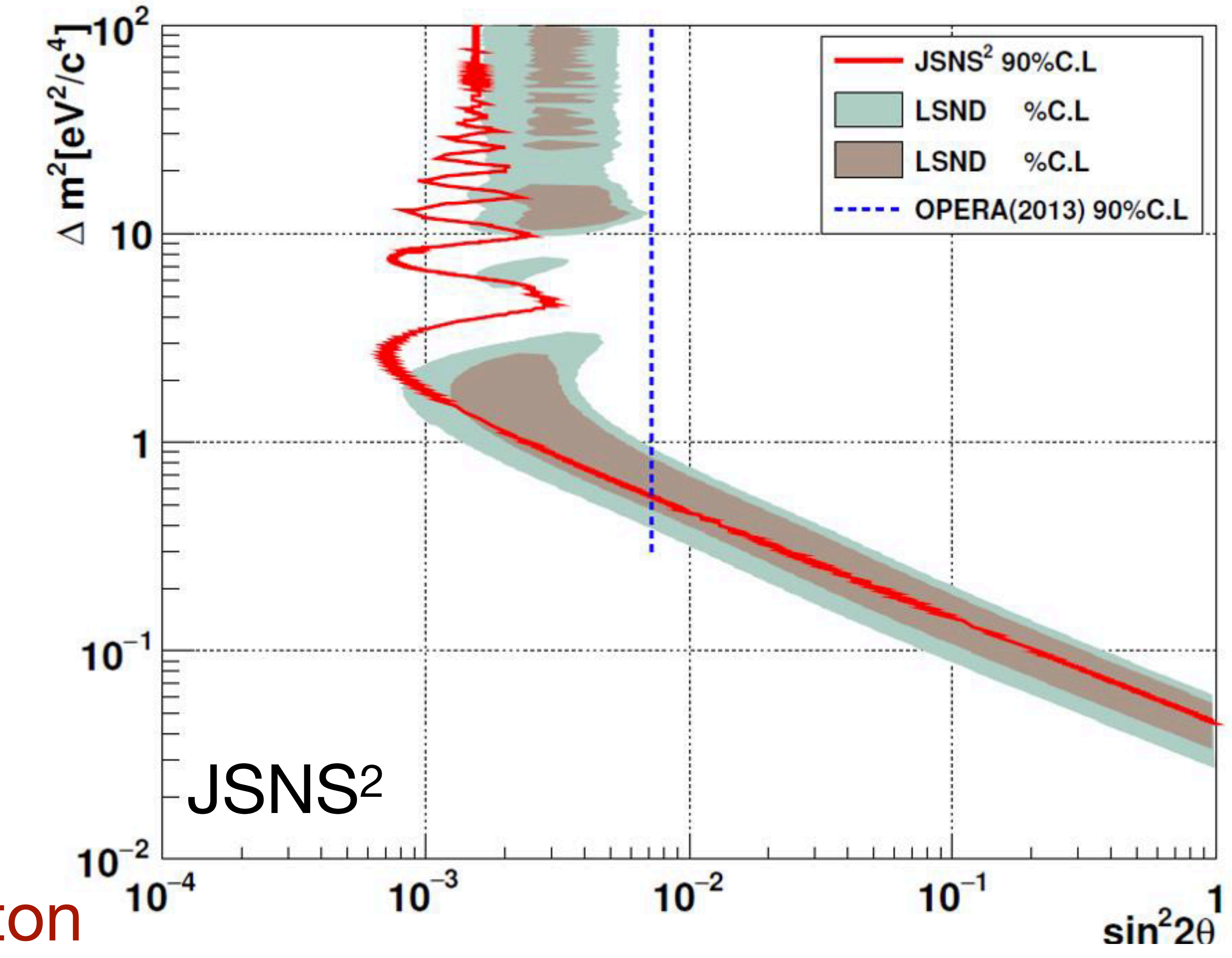
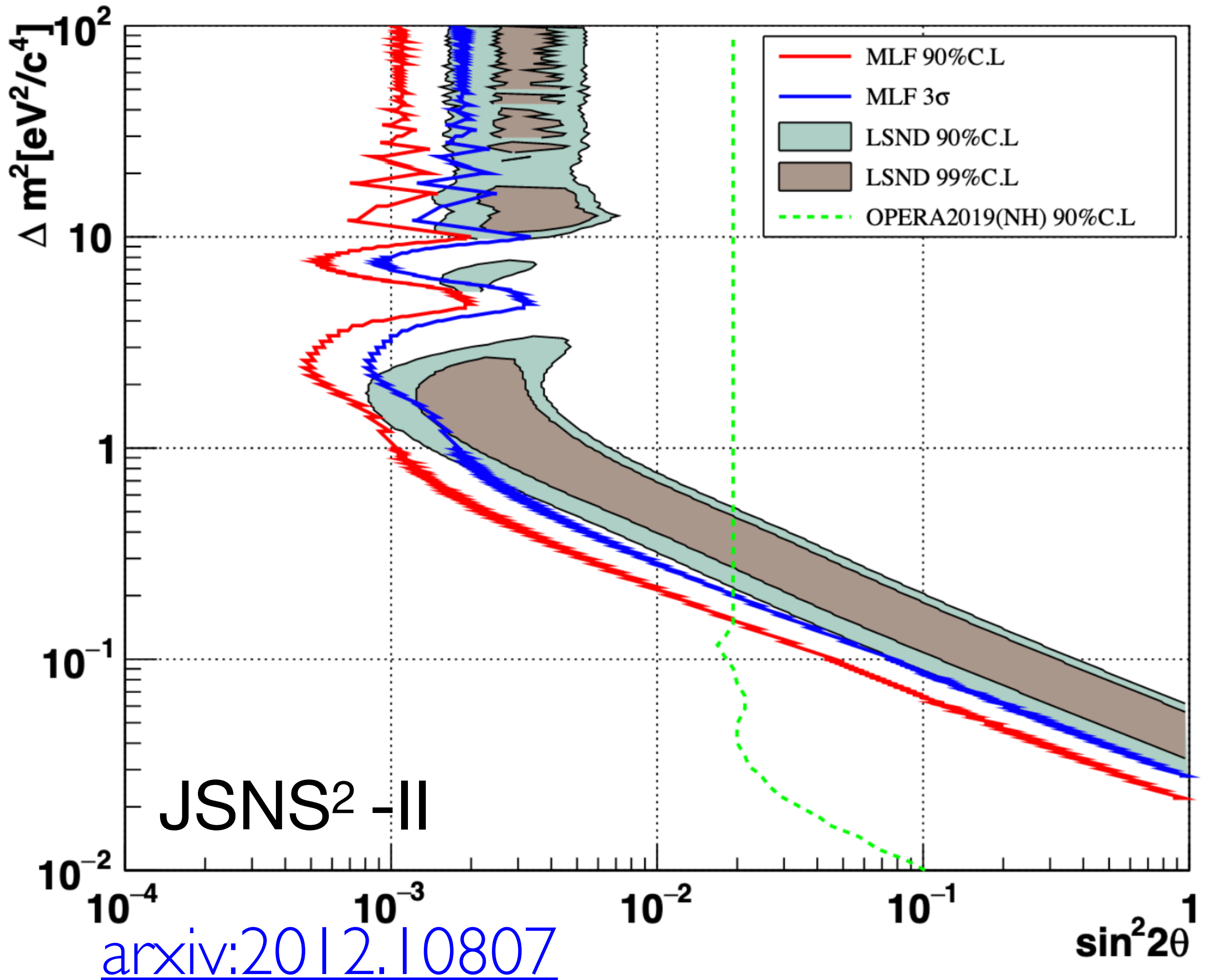
Testing LSND Anomaly: JSNS²

50 ton (17 Gd-loaded + unloaded) LS









arxiv:2012.10807

- Directly test LSND anomaly
  - DAR 40 MeV ν, baseline 24 m (30 m for LSND), Gd-loaded LS
- Data taking: June 5-15, 2020 (10 days) + Jan12 - Jun 23 2021(6 months)
- Analysis underway
- Plan for a second detector at 48 m

Interpretation of Anomalies: Disappearance

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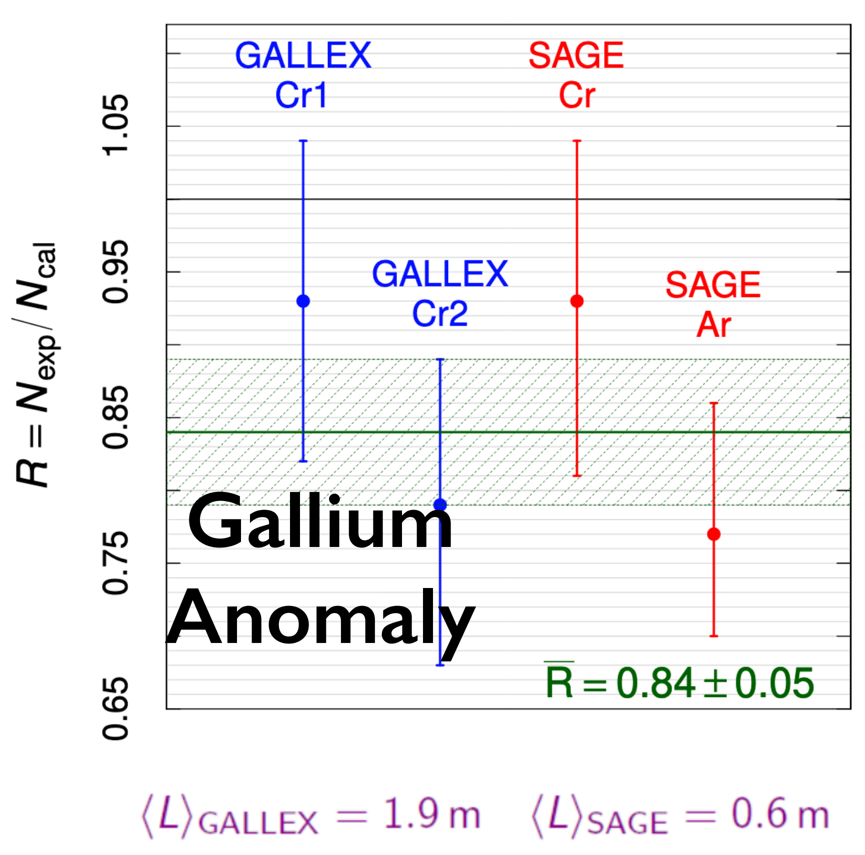
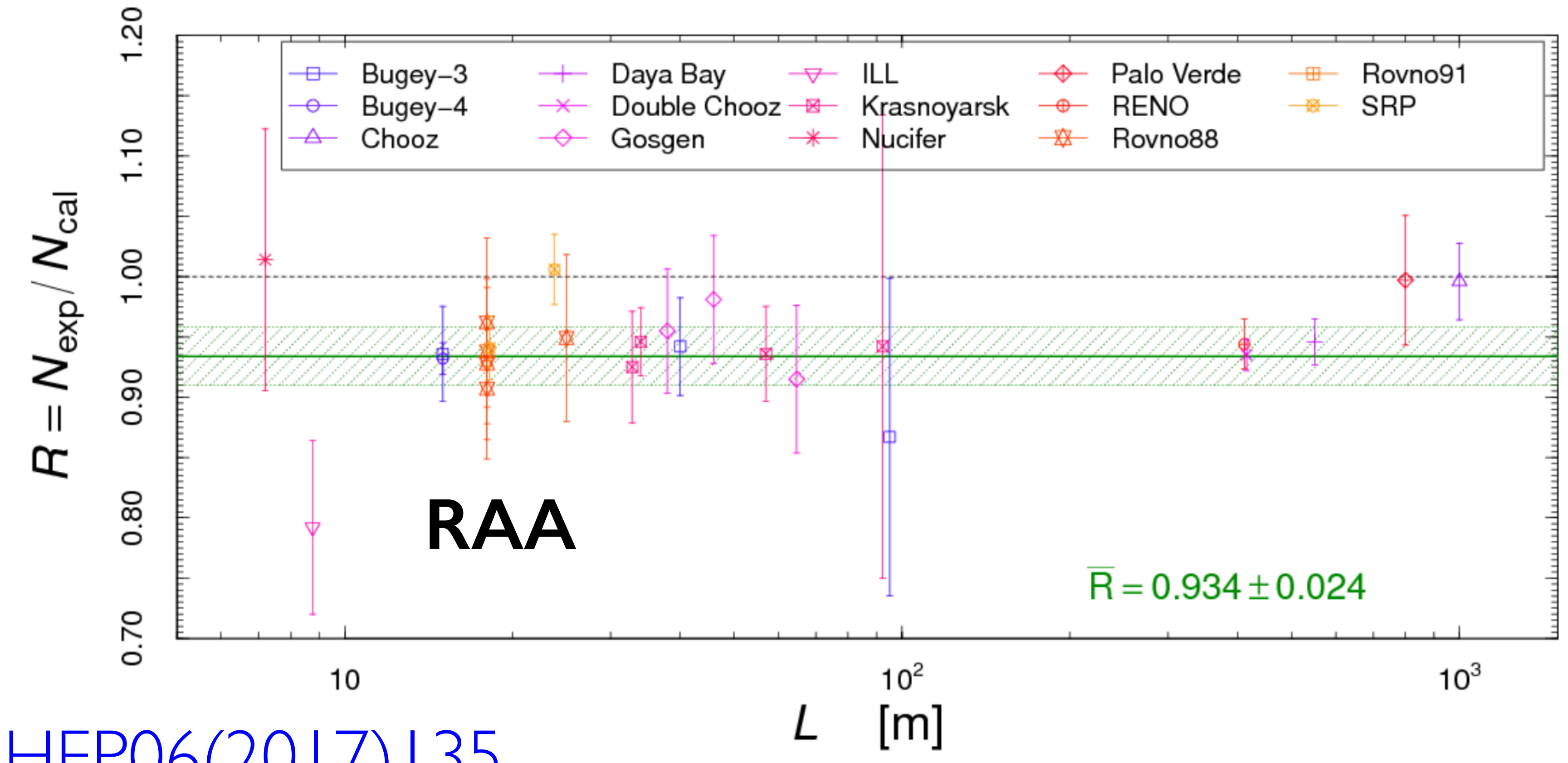
Interpretation of Anomalies: Disappearance





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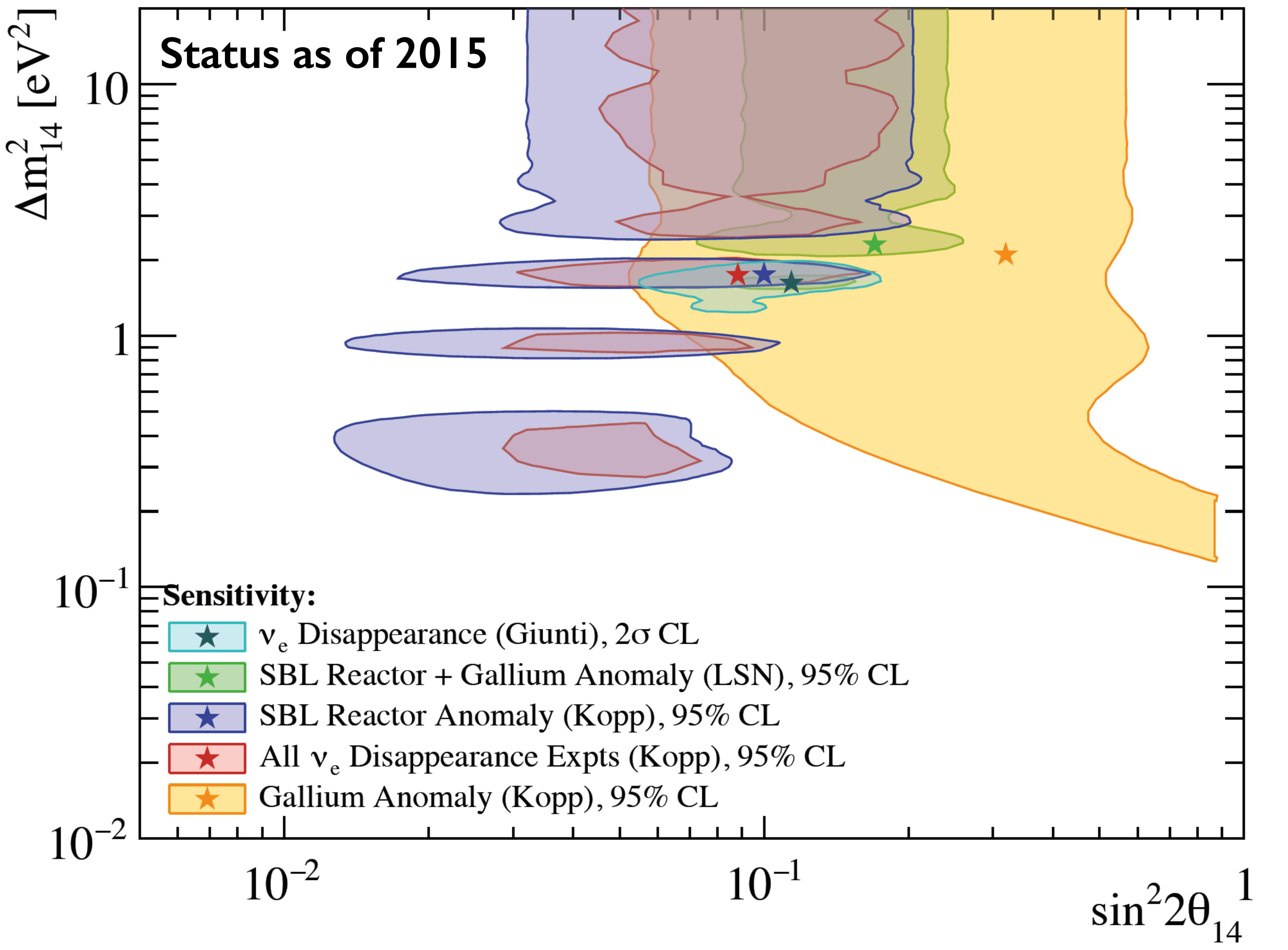
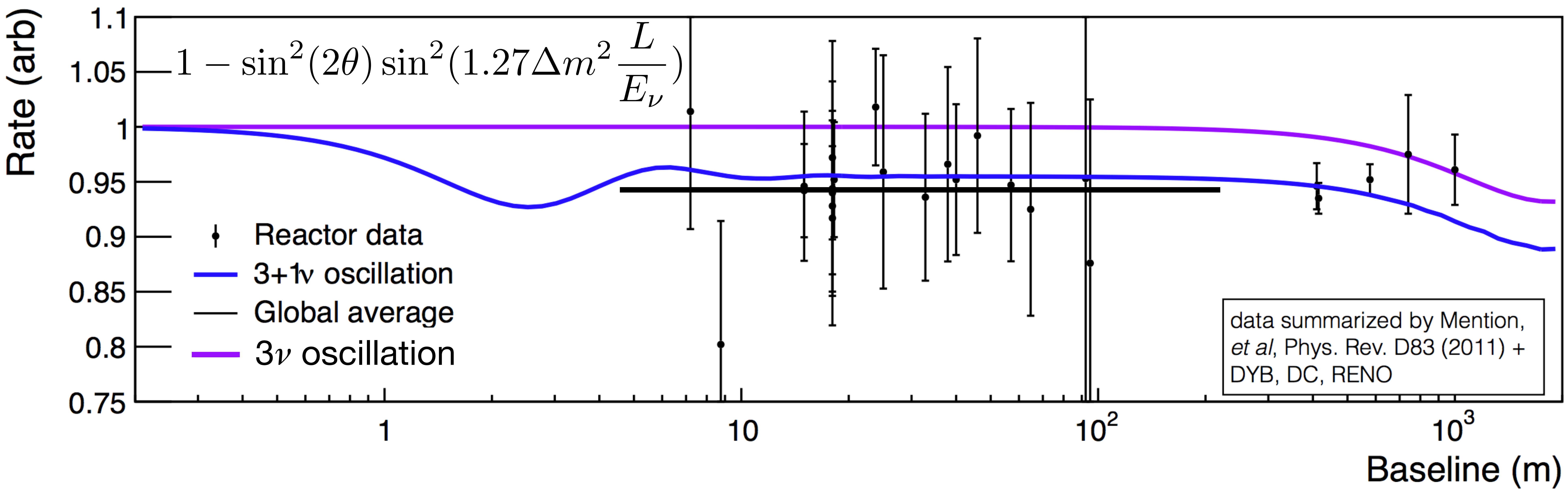
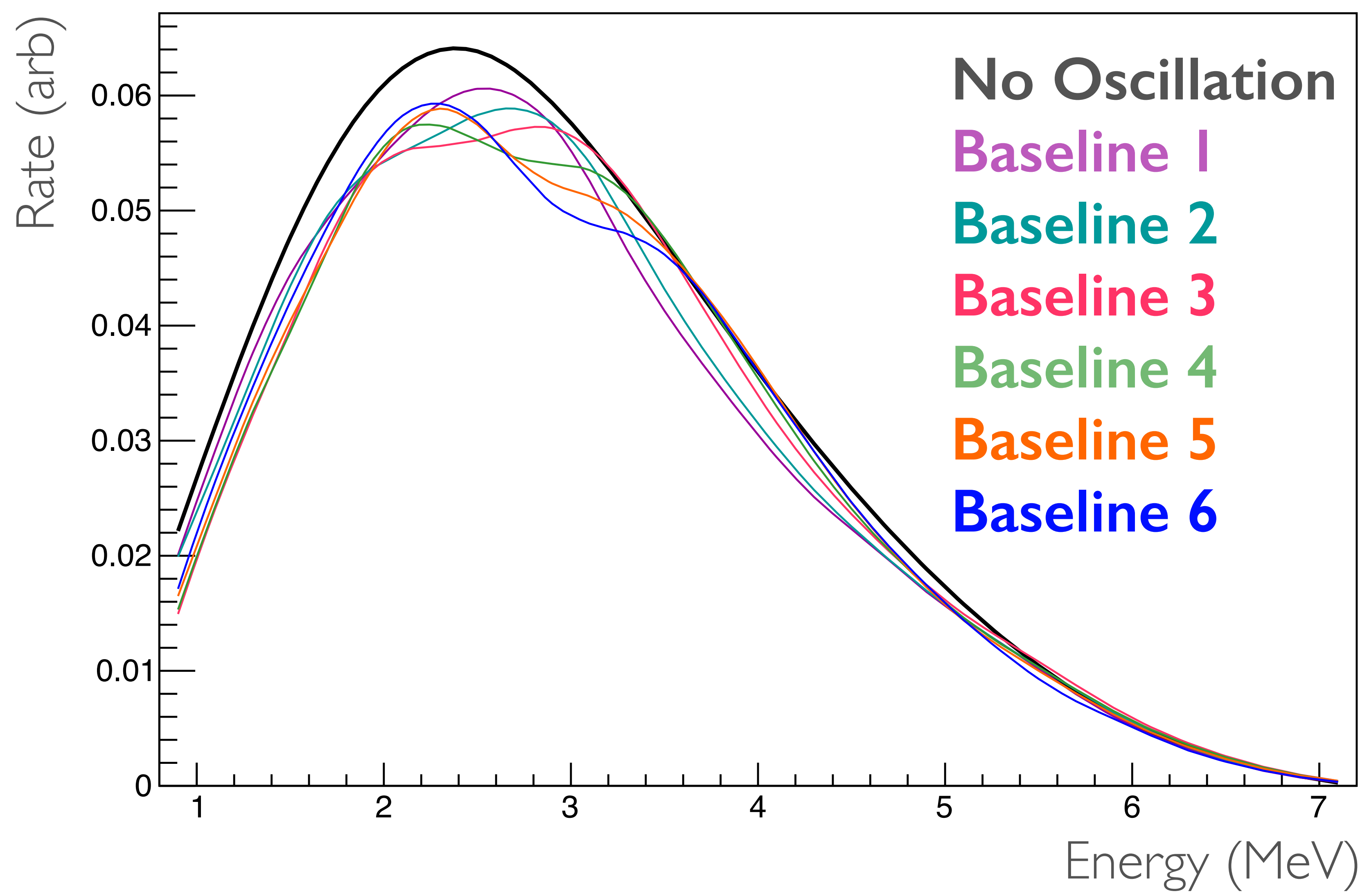


- Similar parameter space as suggested by the appearance experiments
- Initiated a lot of short baseline reactor experiments
- At 1 eV^2
  => High frequency oscillations
  => Short distance (preferably at <10 m)

Testing RAA



- Sterile neutrino interpretation of RAA motivated by flux rates
  - Depends on the predicted flux
- Irrefutable way to test would be performing a relative spectral search
- At reactor neutrino energies (~1— 8 MeV), baselines < 10m



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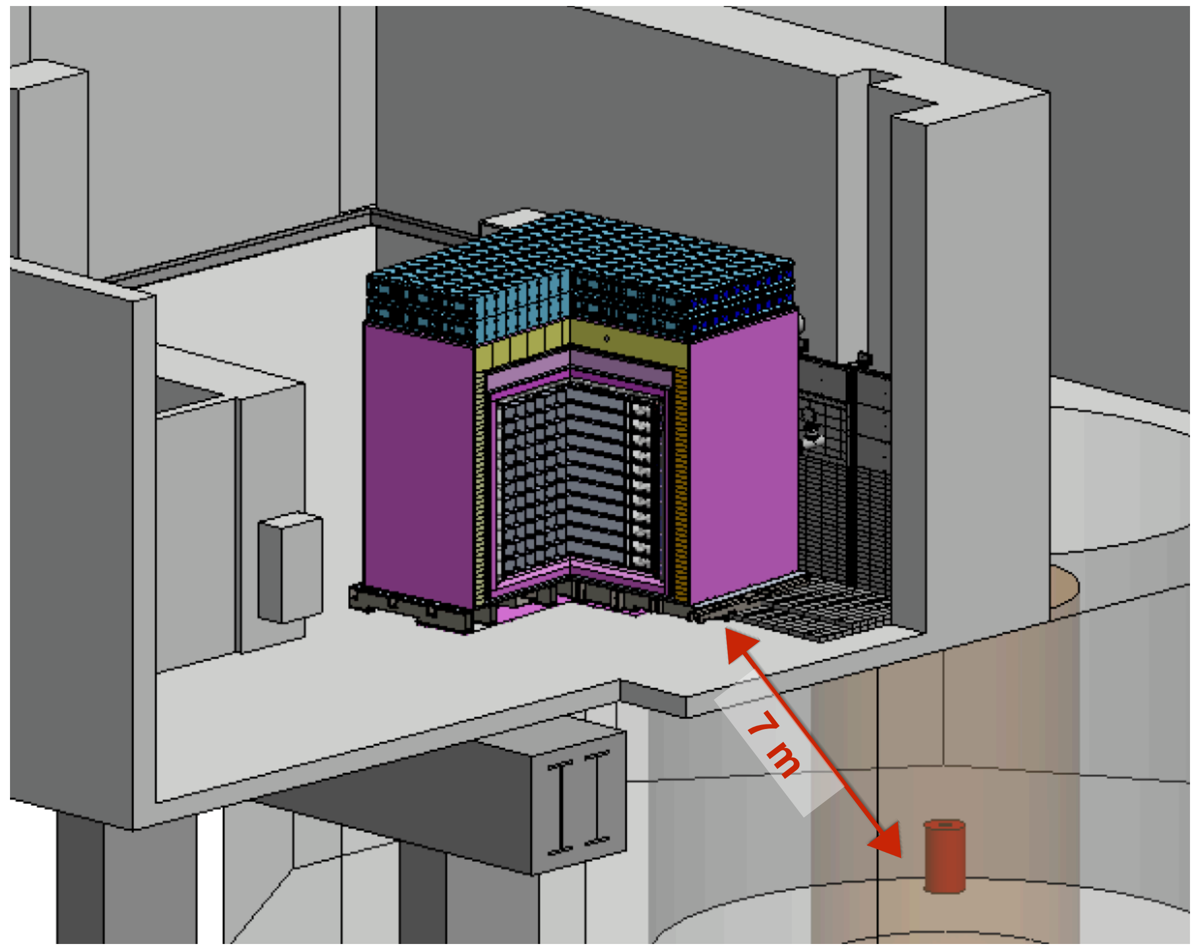
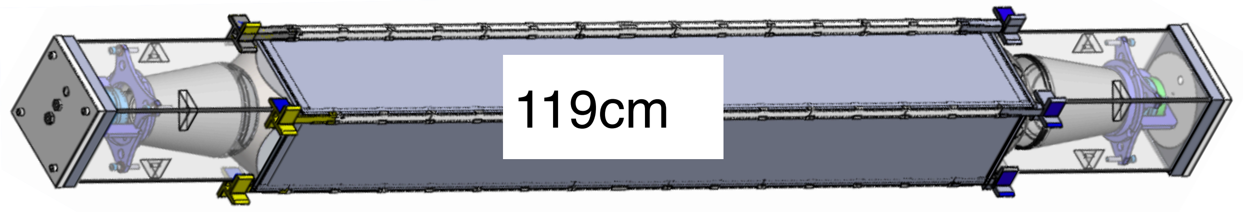
Testing RAA: Short Baseline Reactor Experiments

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

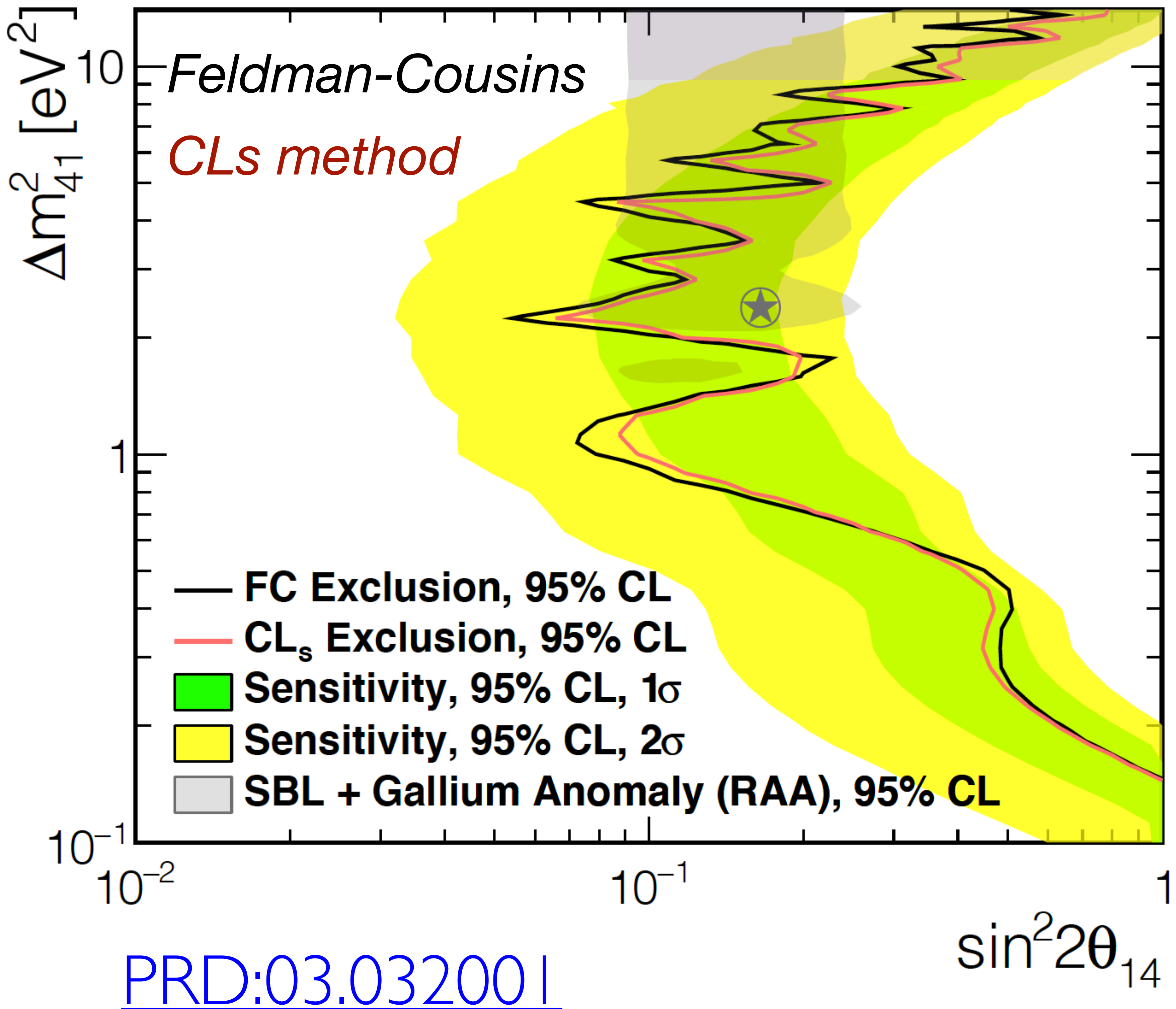
* Other reactor neutrino SBL experiments that haven't performed oscillation search not included

PROSPECT Experiment

Experiment	Baseline(m)	Reactor type	Reactor power (MW_{th})	Mass	Target	Search strategy
PROSPECT	7-9 m	HEU	85	~4 ton	^{6}LiLS	2D Segmentation

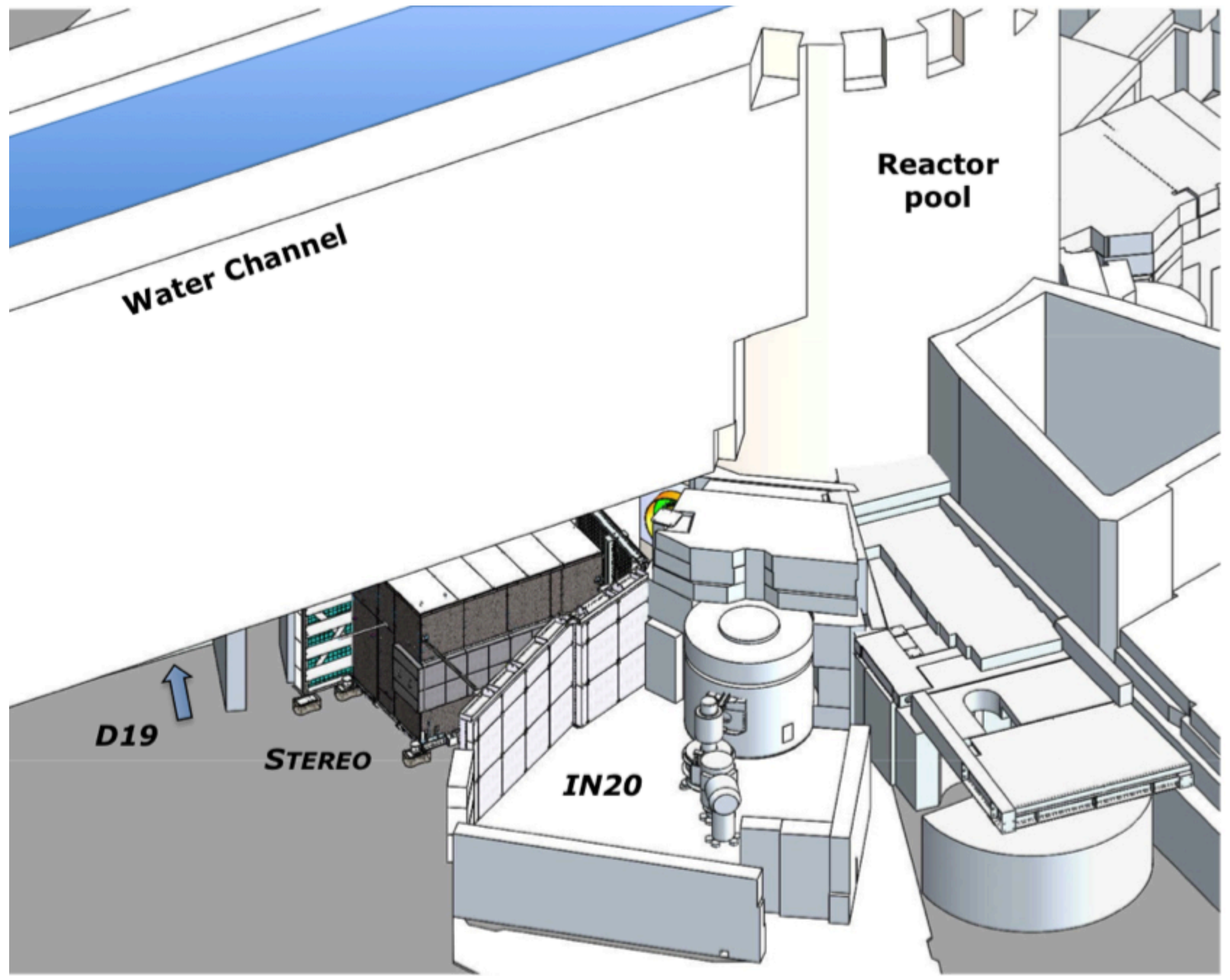
- 96 (73) rx-on (rx-off) days
- Segmentation provides baselines
- Excluded RAA best-fit at 2.5σ
- Limited by statistics (~50k events)
- Phase-II detector planned

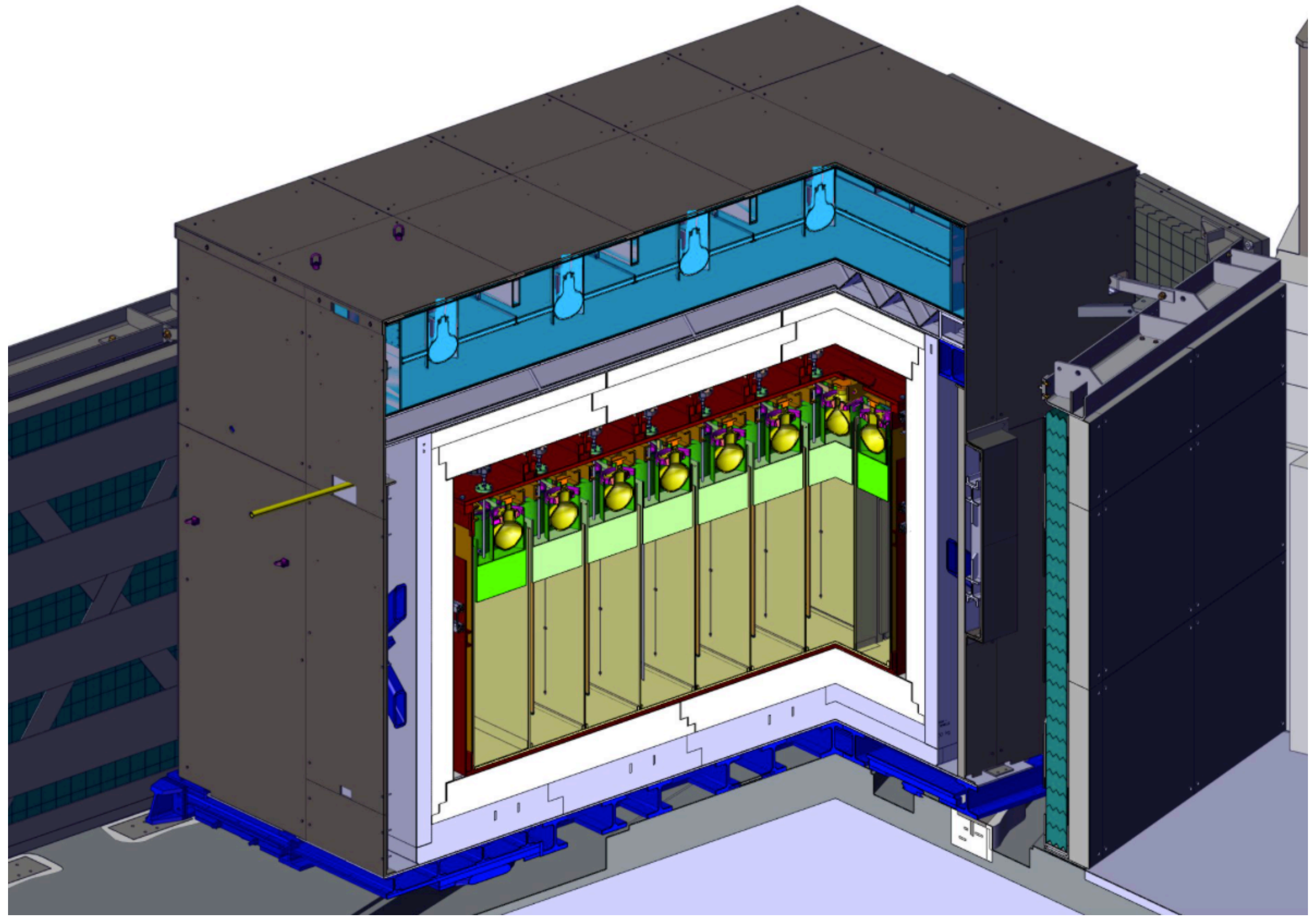


PRD:03.032001

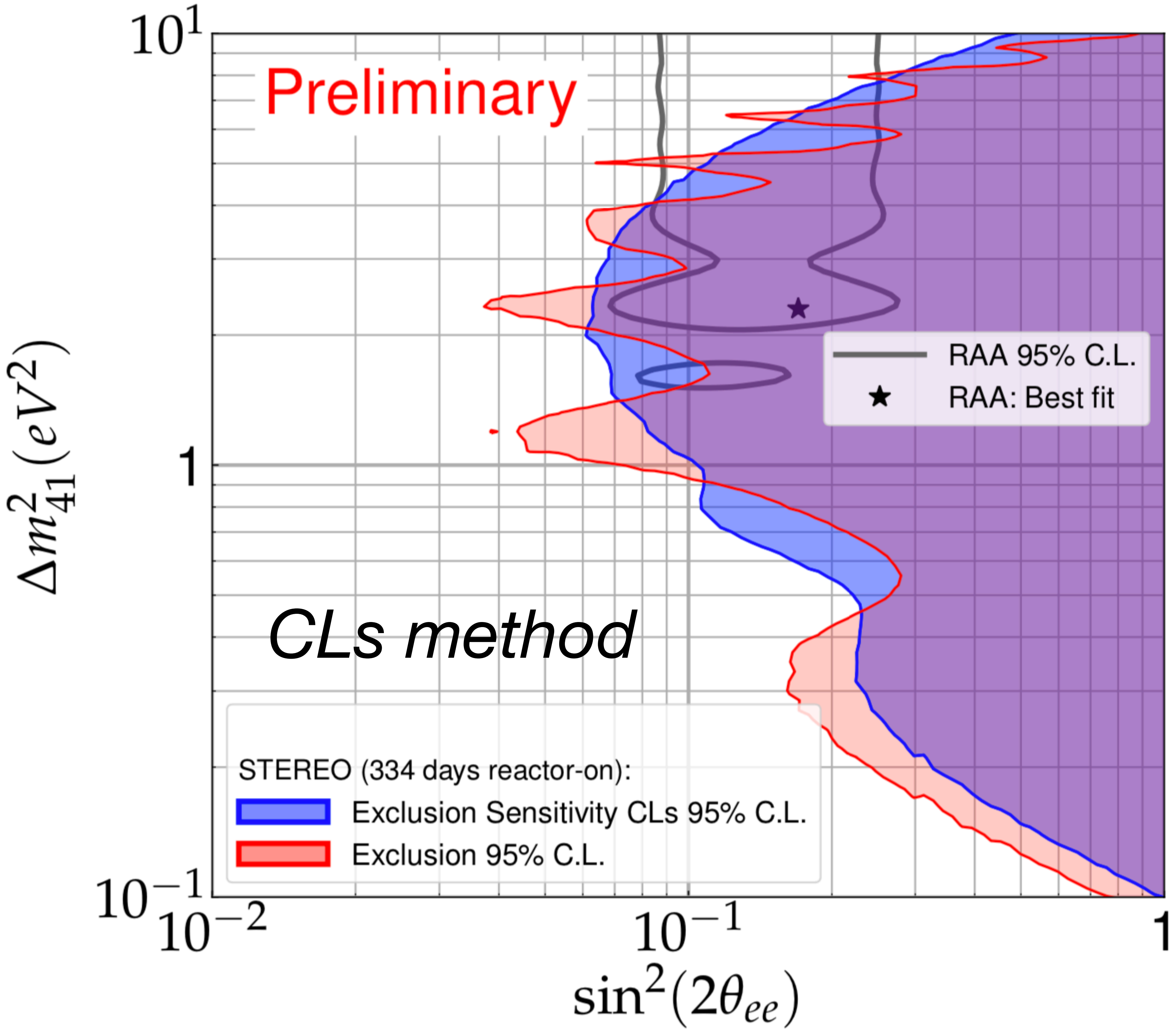
STEREO Experiment

Experiment	Baseline(m)	Reactor type	Reactor power (MW_{th})	Mass	Target	Search strategy
STEREO	9-11 m	HEU	57	~2.4 m^3	GdLS	2D Segmentation



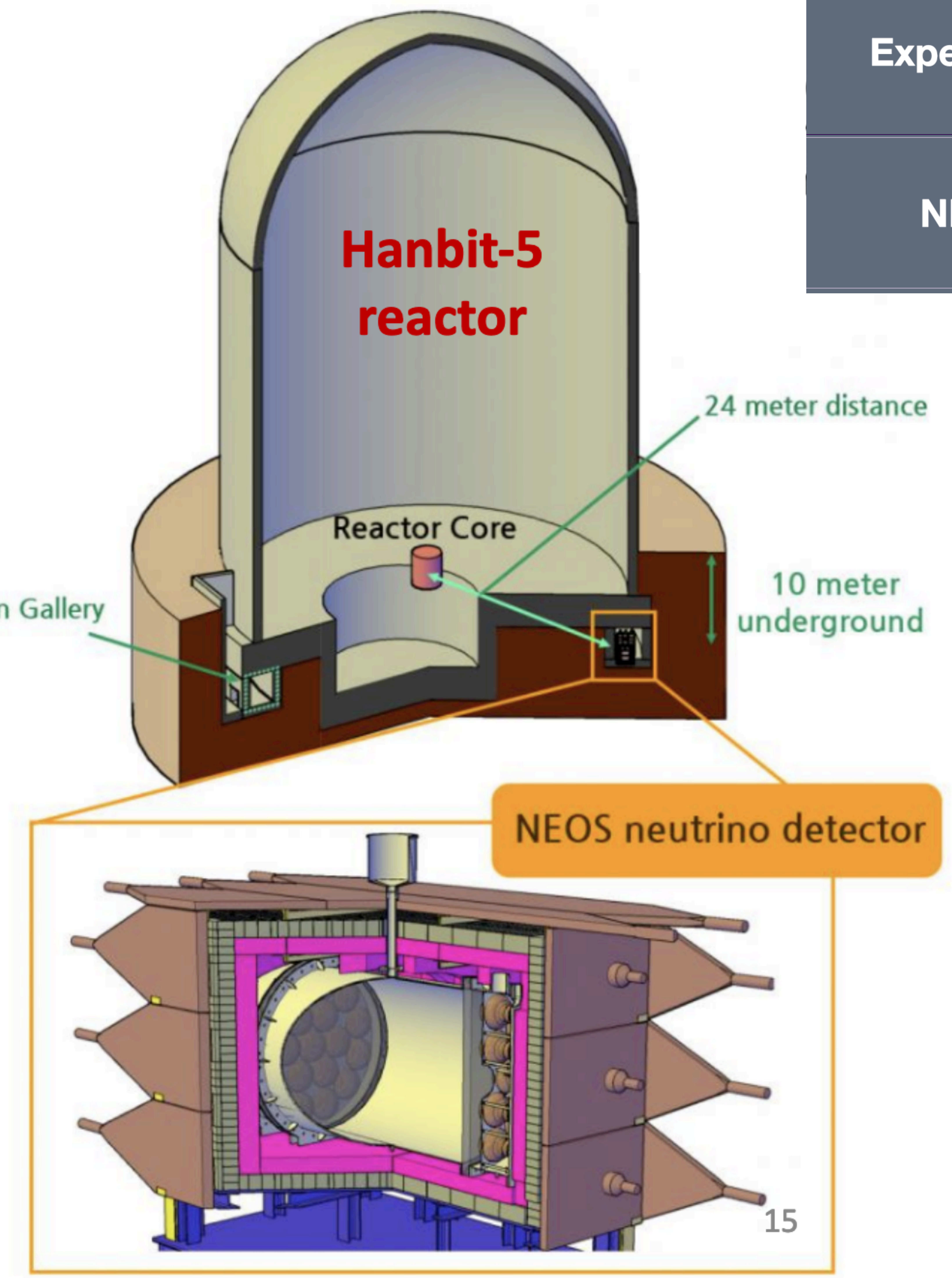


- 334 (543) rx-on (rx-off) days
- Segmentation provides baselines
- Excluded RAA best-fit at >4σ
- Data taking ended

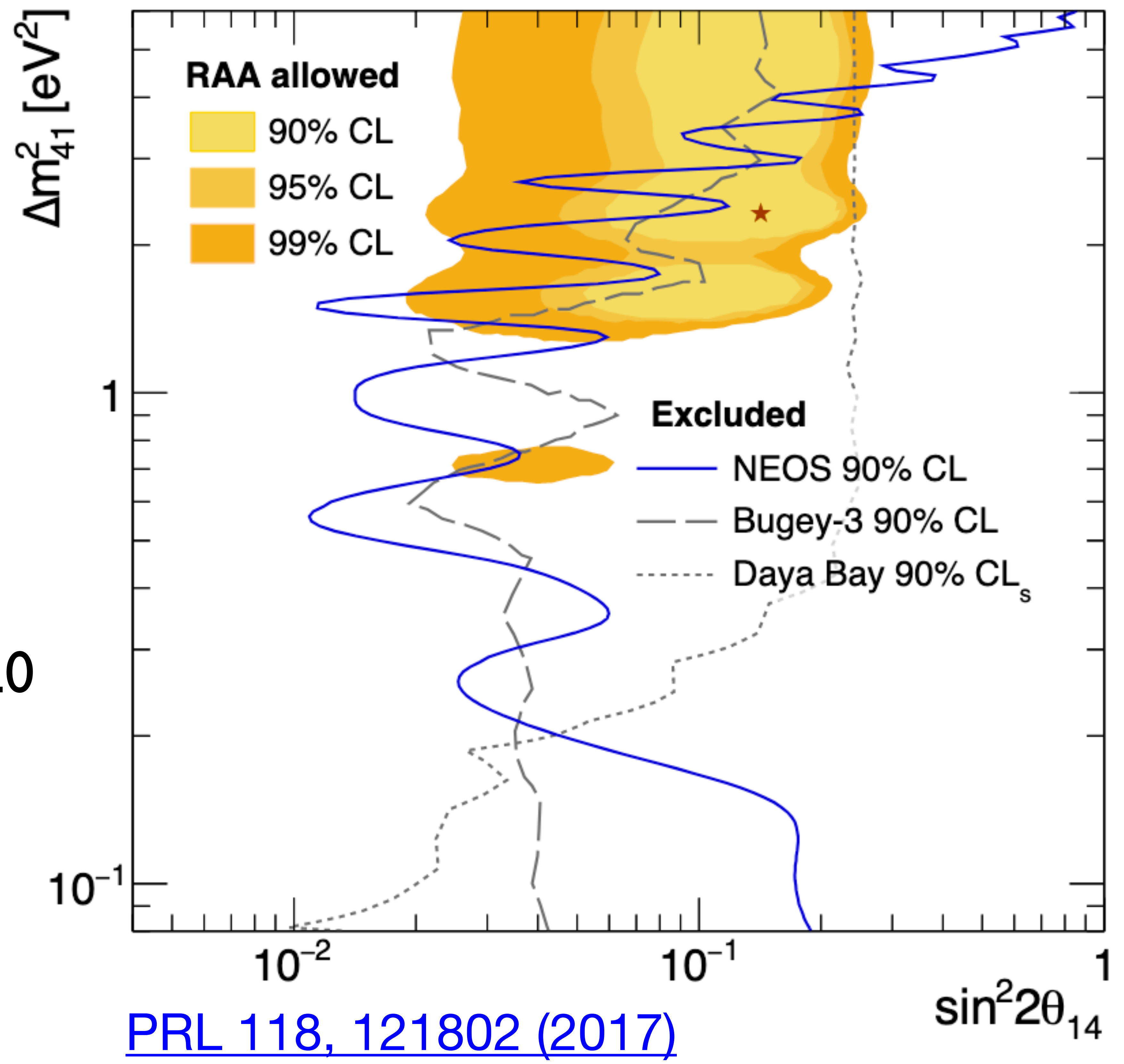


NEOS Experiment

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



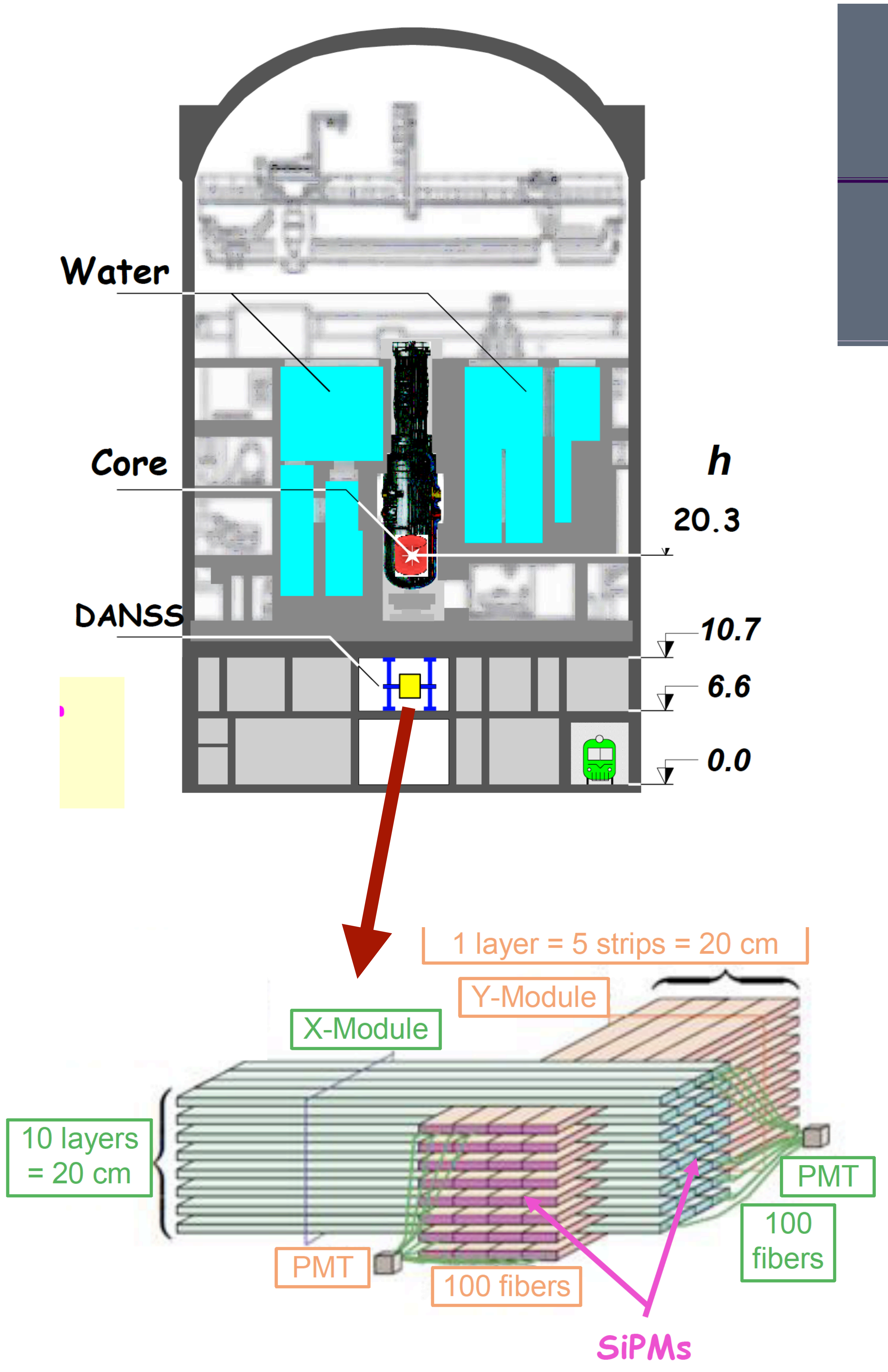
- 180 (46) days reactor-on(off)
- Single volume stationary detector
- Excluded RAA best-fit at >4σ
- NEOS-II: Refurbished NEOS detector
  - Data taking finished: Sep 2018 - Oct 2020
  - Results expected this year



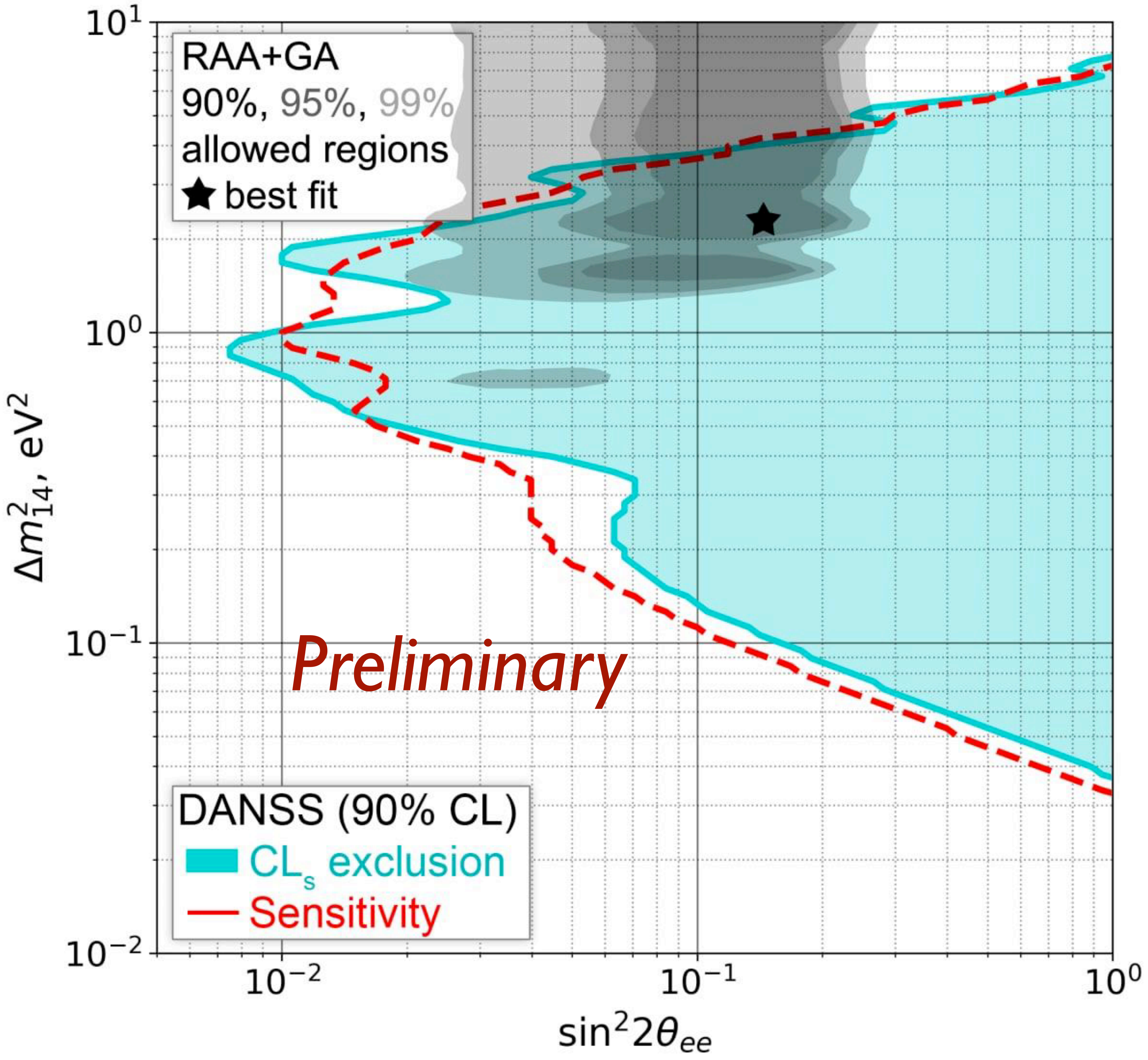
PRL 118, 121802 (2017)

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

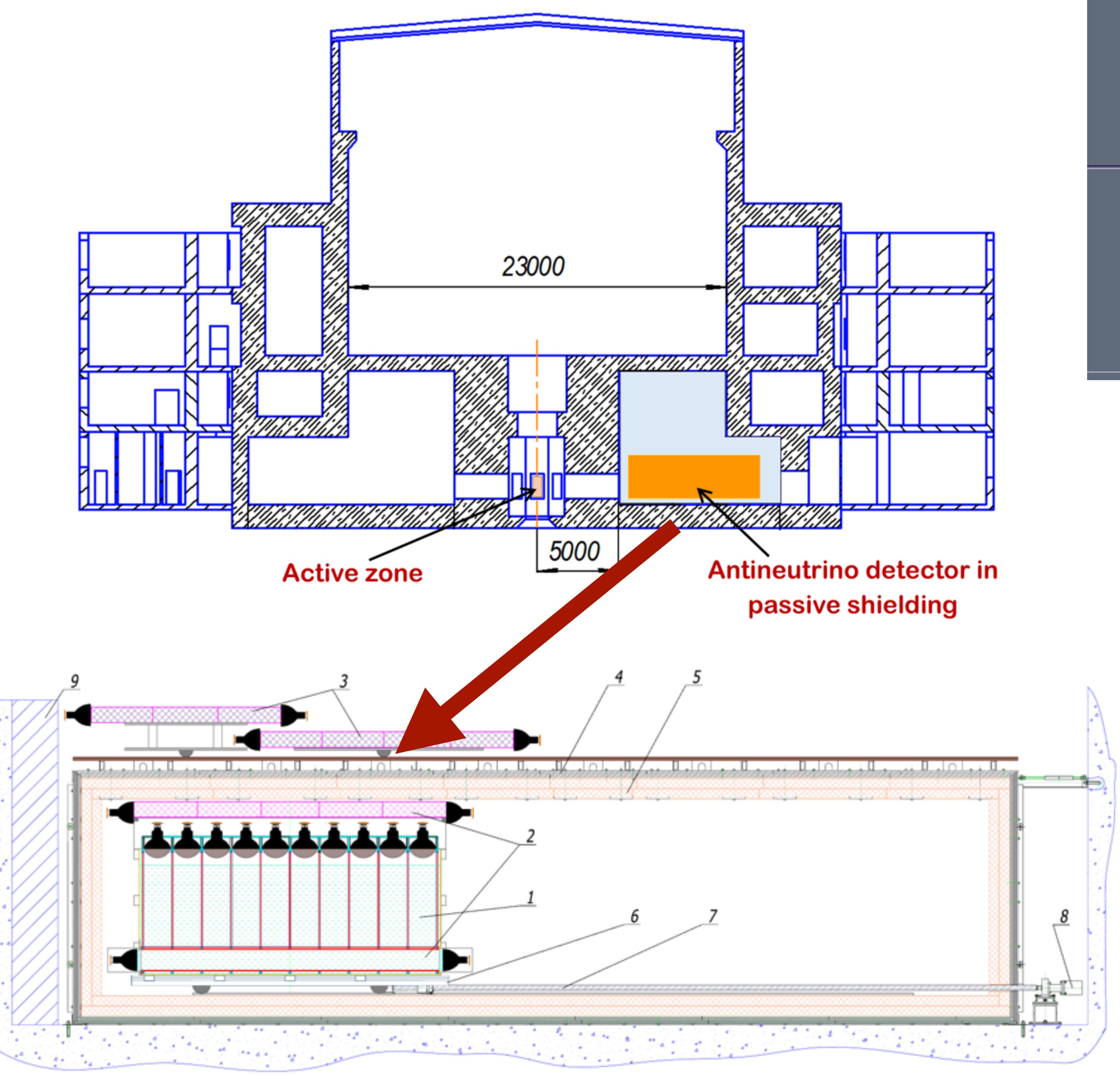


- 5 years of data: 5.5 million events
- Oscillation search using movable detector
- Excluded RAA best-fit at >5σ
- Detector upgrade underway

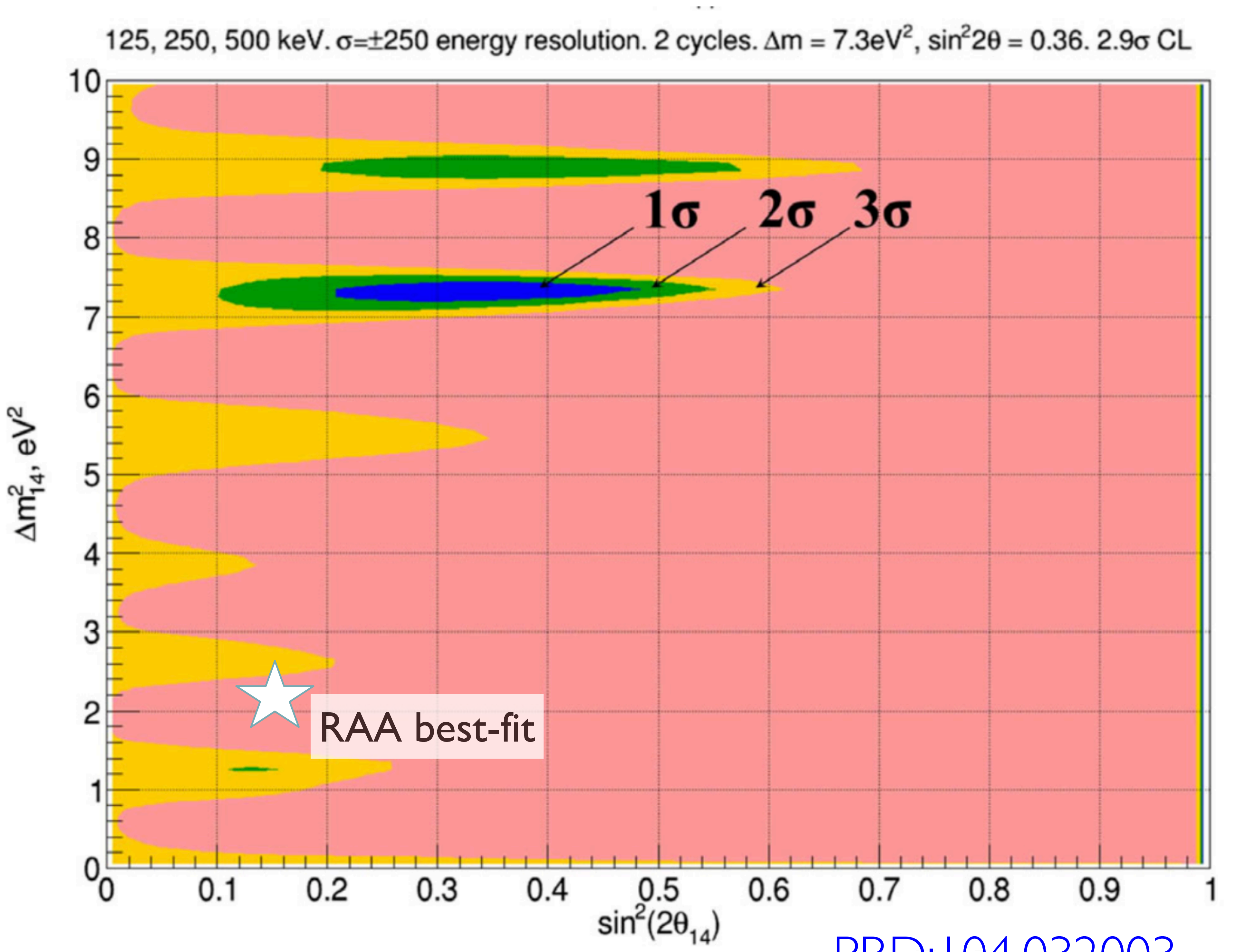


Neutrino-4 Experiment: Claim

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

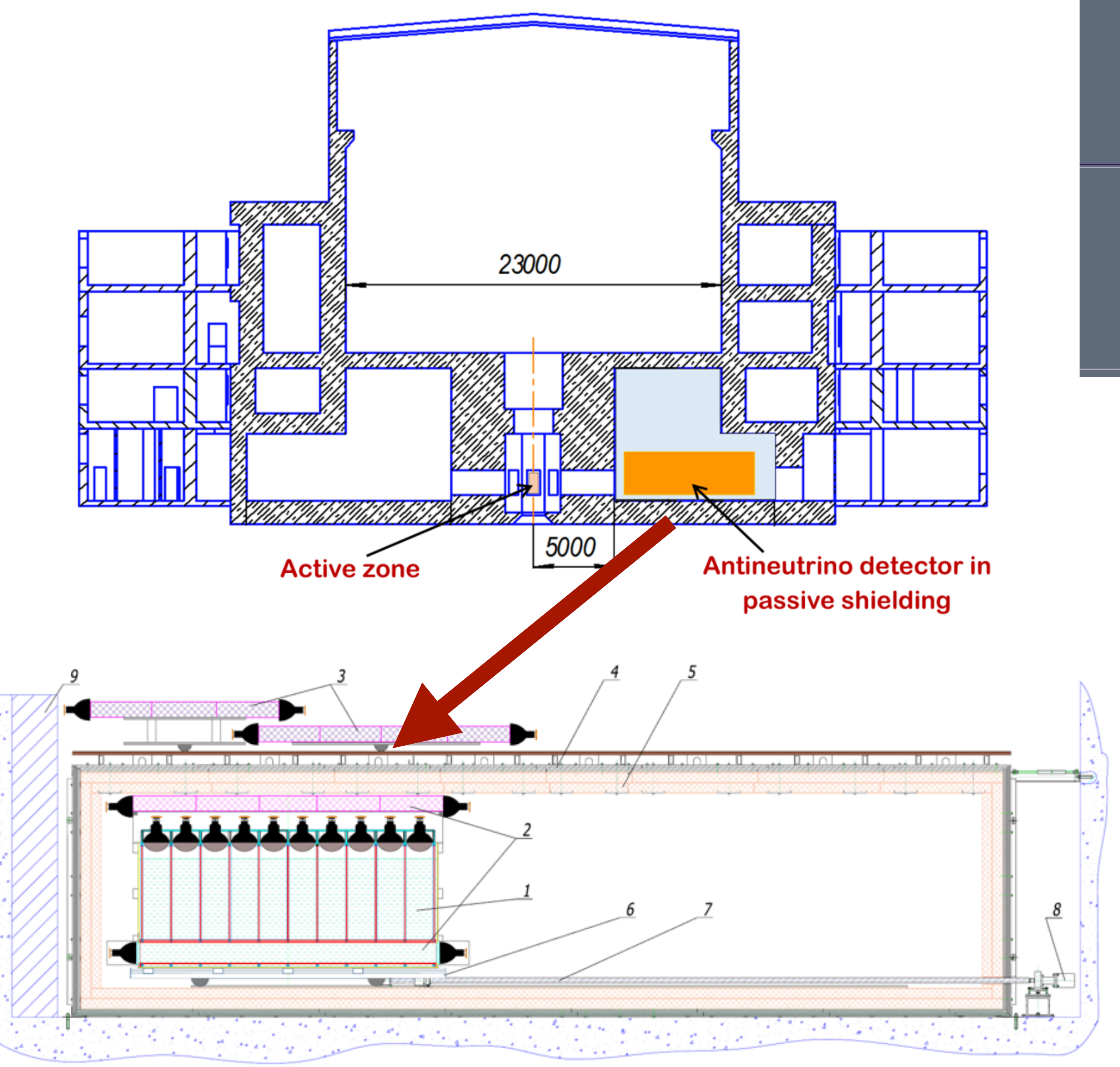


- 5 years of data
- Oscillation search using movable detector
- Claim oscillation:
  - ($\Delta m2$ = 7.3, $\sin 22\theta$ = 0.36) @ 2.9σ
- Detector upgrade underway



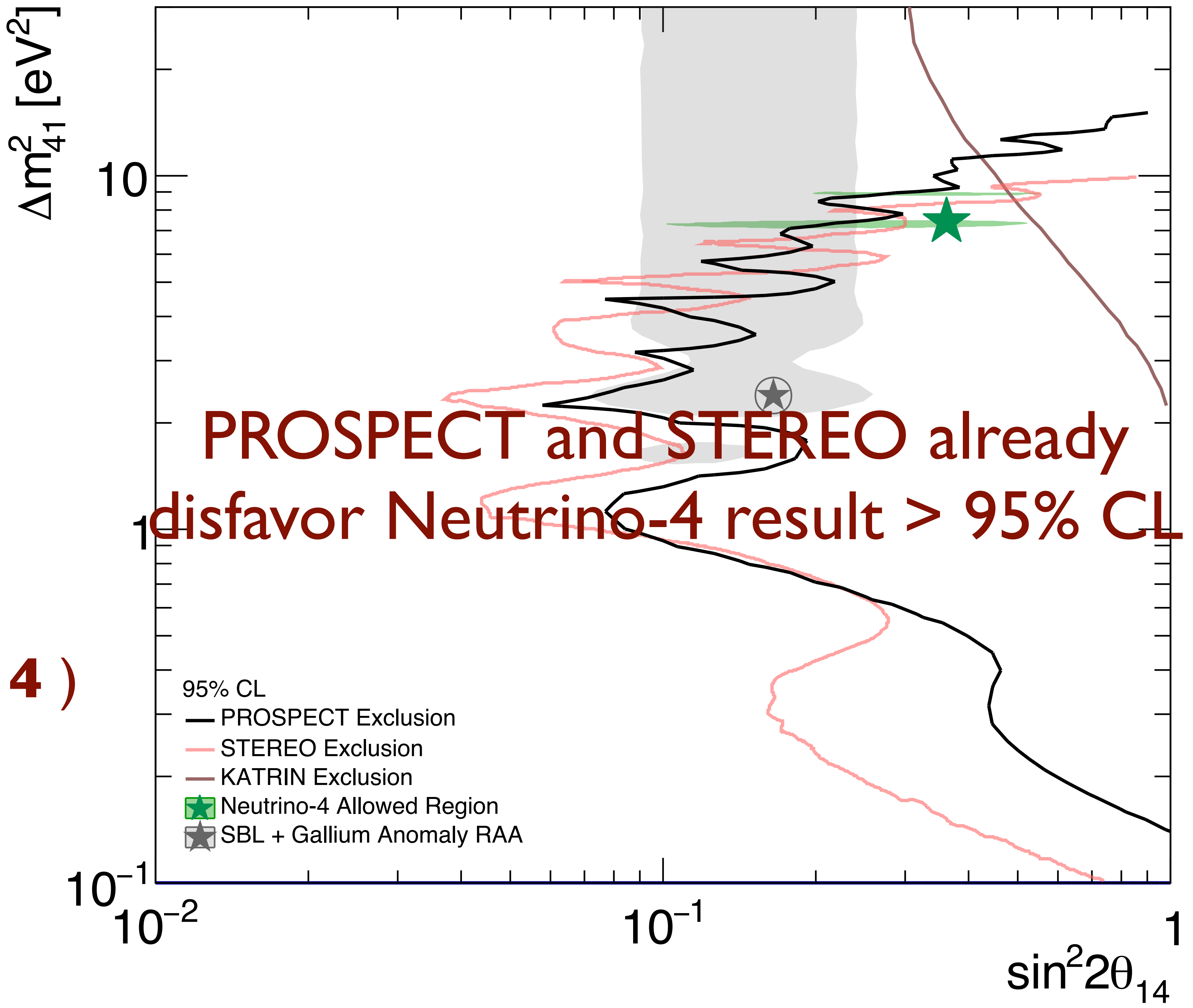
PRD:104.032003

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 m^3	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



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

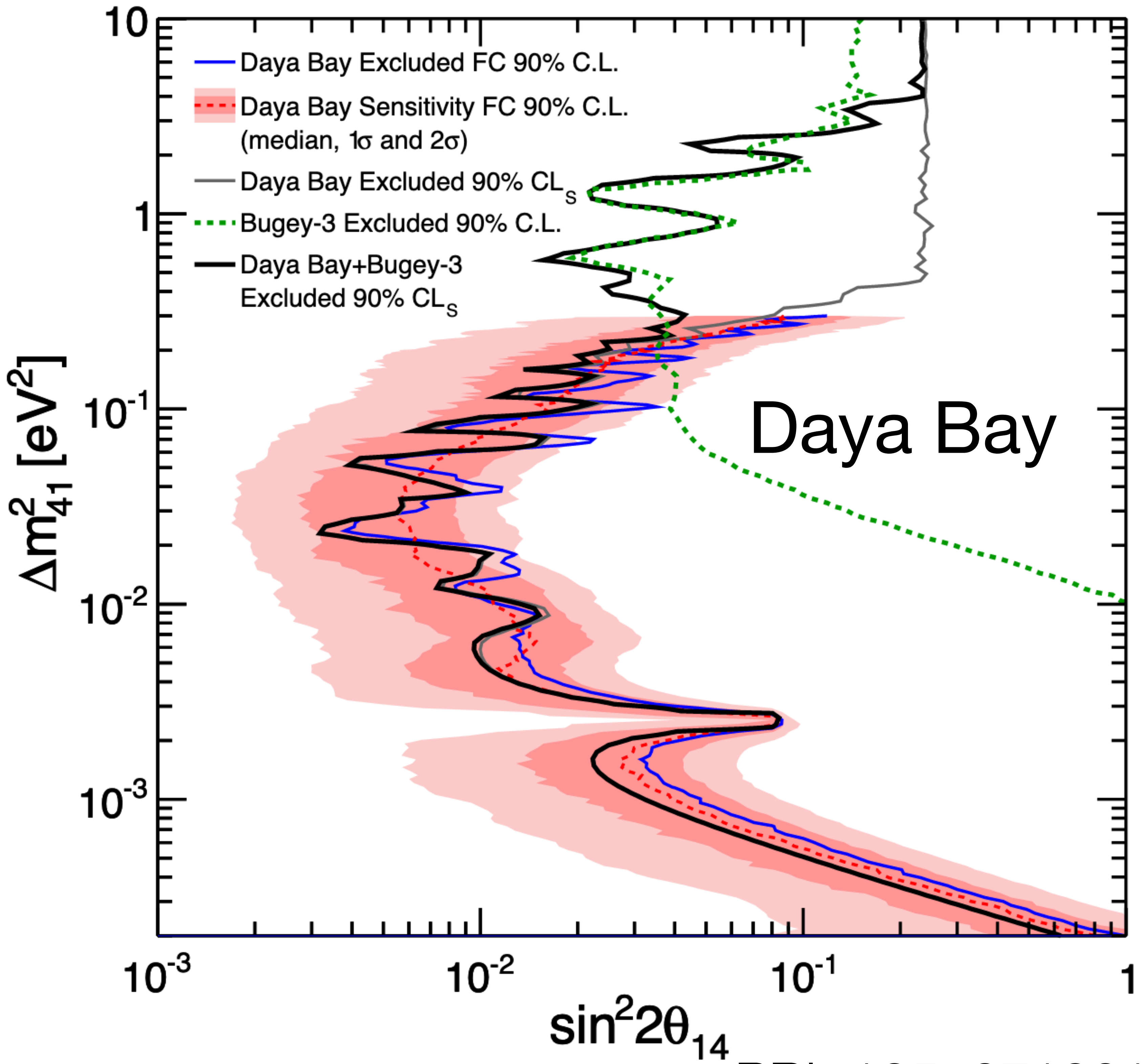
! Several questions raised:

* 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)

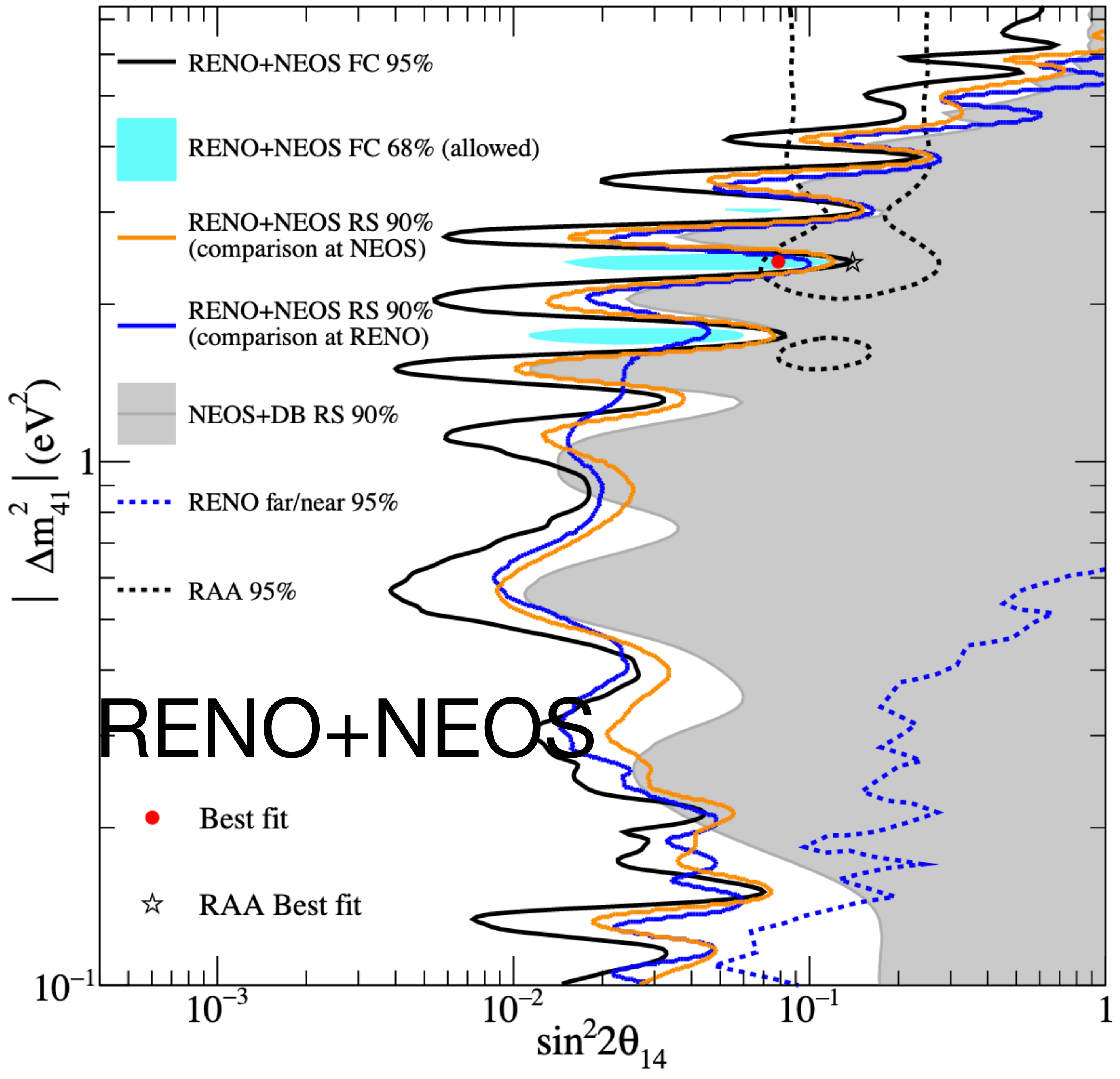
Other Reactor Expts

- Experiments designed to measure θ_{13} also searched for sterile neutrinos
- Sensitivity at low Δm^2 values
- Exclude portions of suggested parameter space

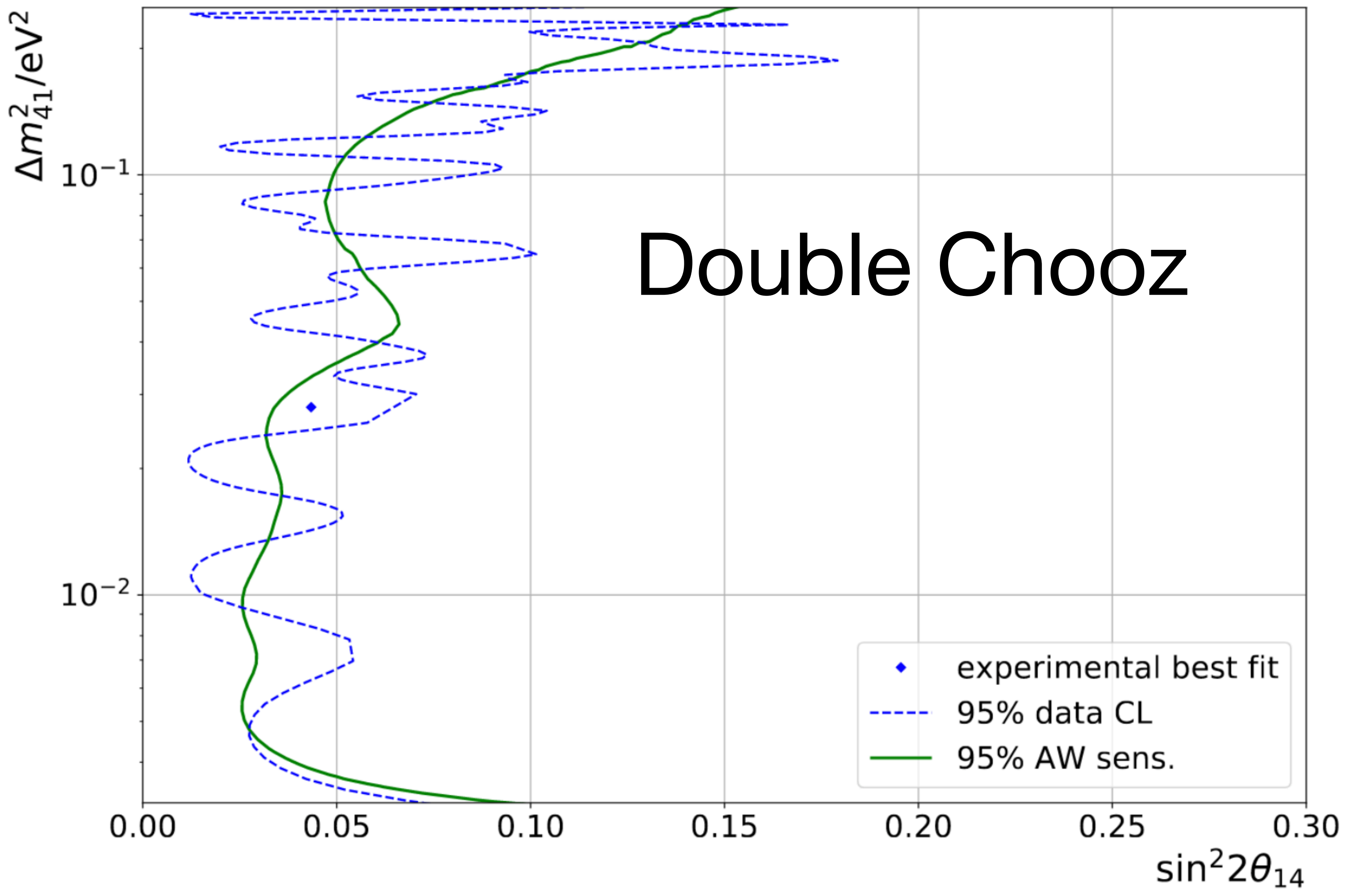
Details in P. Soldin's talk



PRL:125, 071801



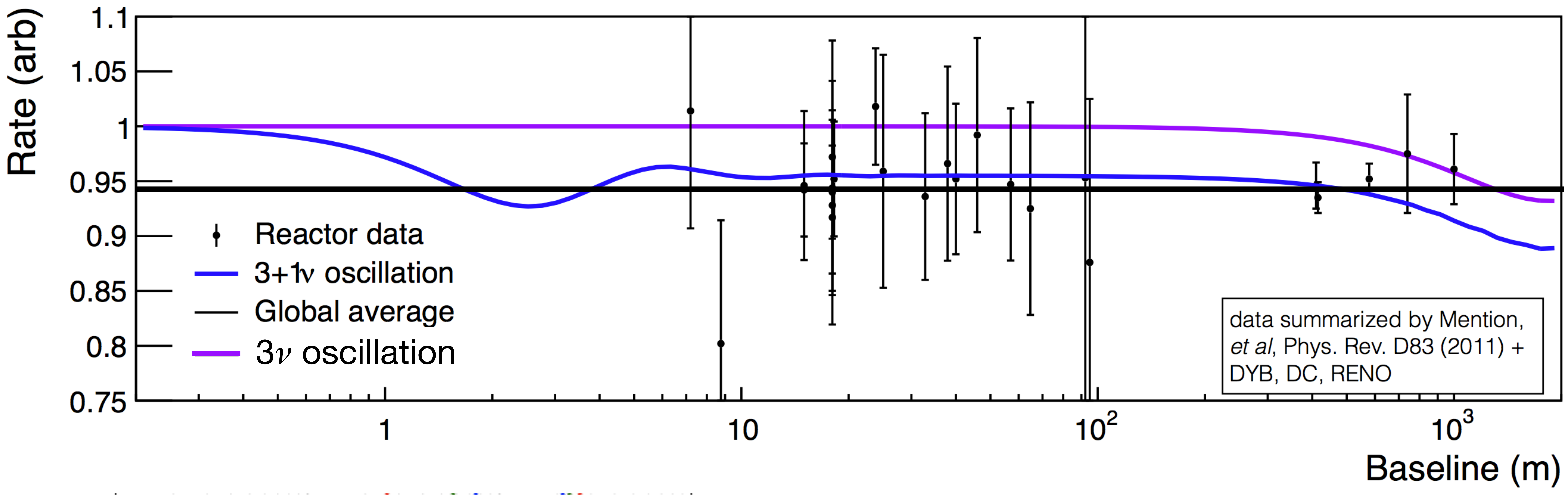
arXiv:2011.00896



EPJC 81-775

More Reactor Neutrino Context

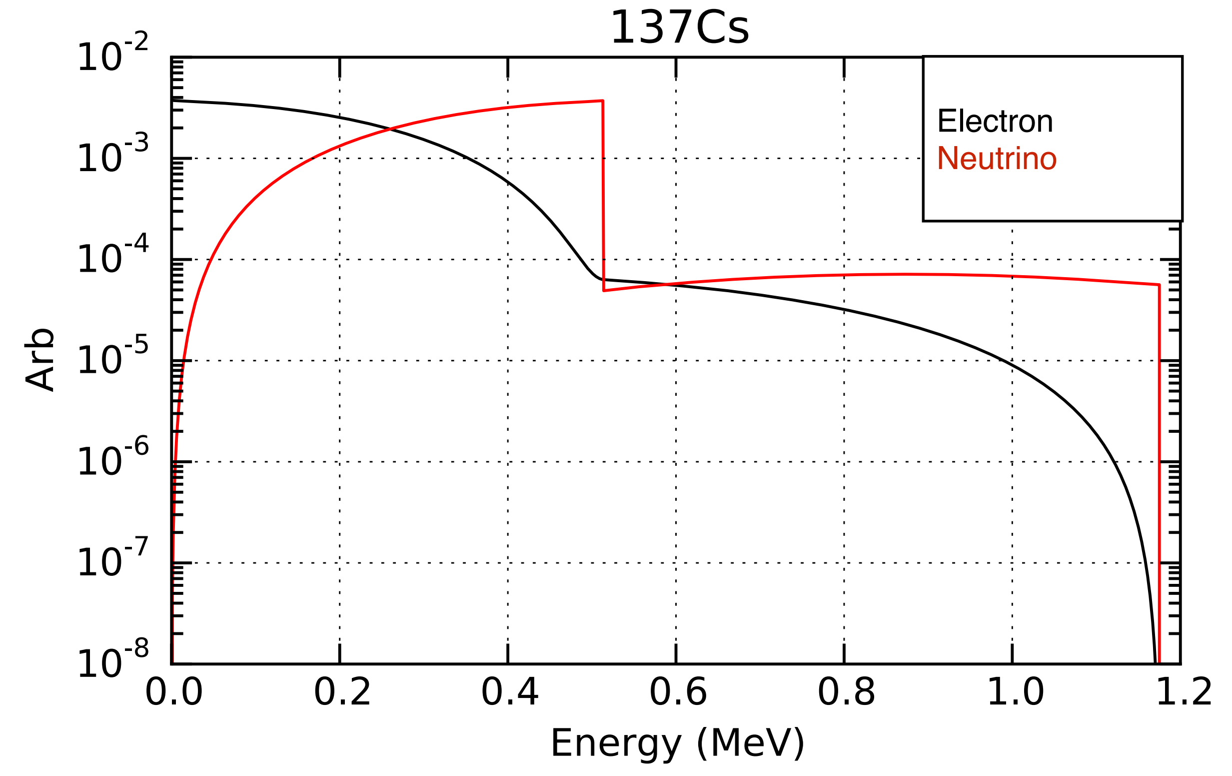
- Reactor Antineutrino Anomaly: Flux predictions disagree with measurements
- Could the flux predictions be wrong ?



Reactor Neutrino Predictions

Predicted Spectrum — Decay Rate — Spectrum — Branching Fraction

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

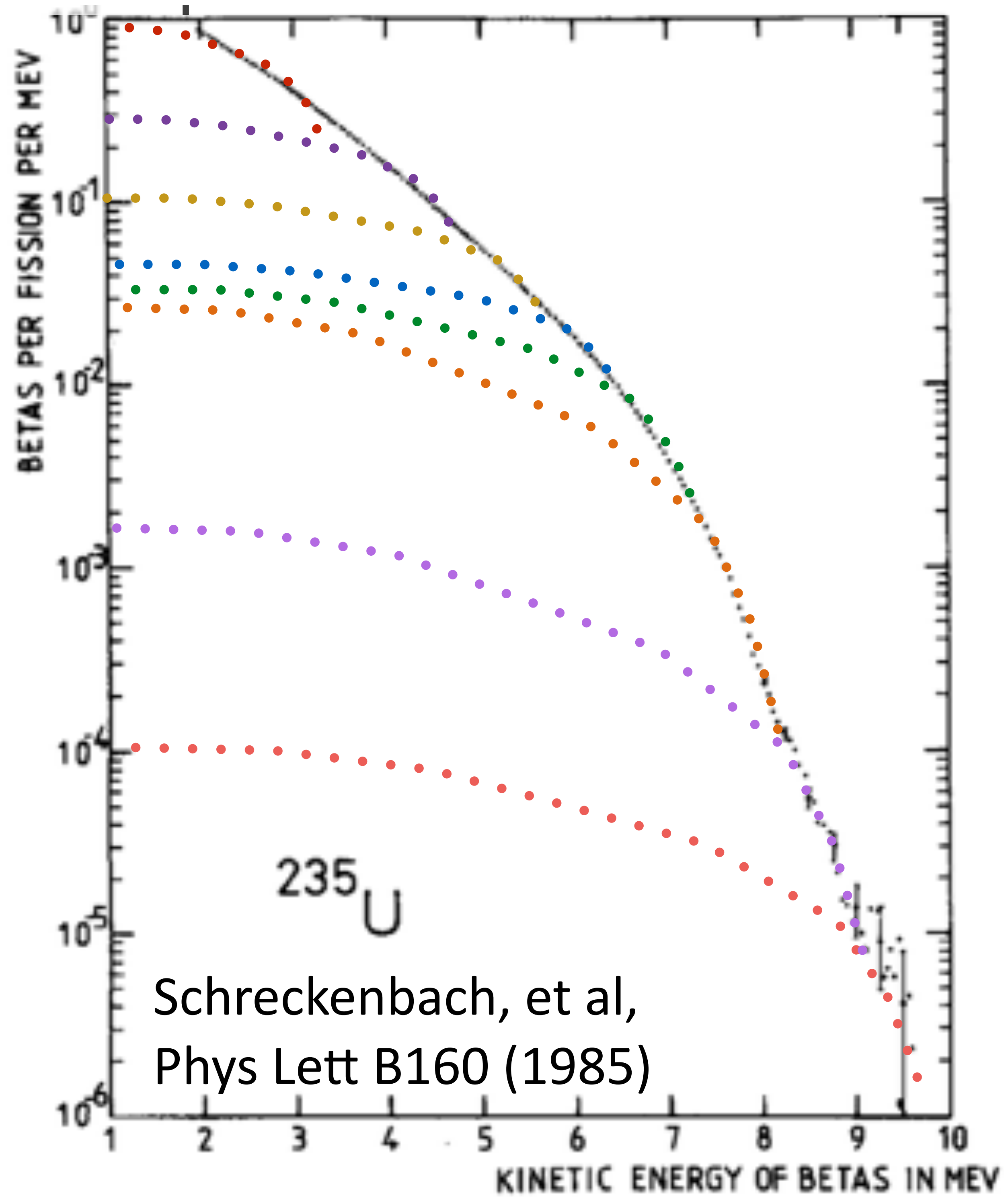


***ab initio* approach**

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

Conversion method

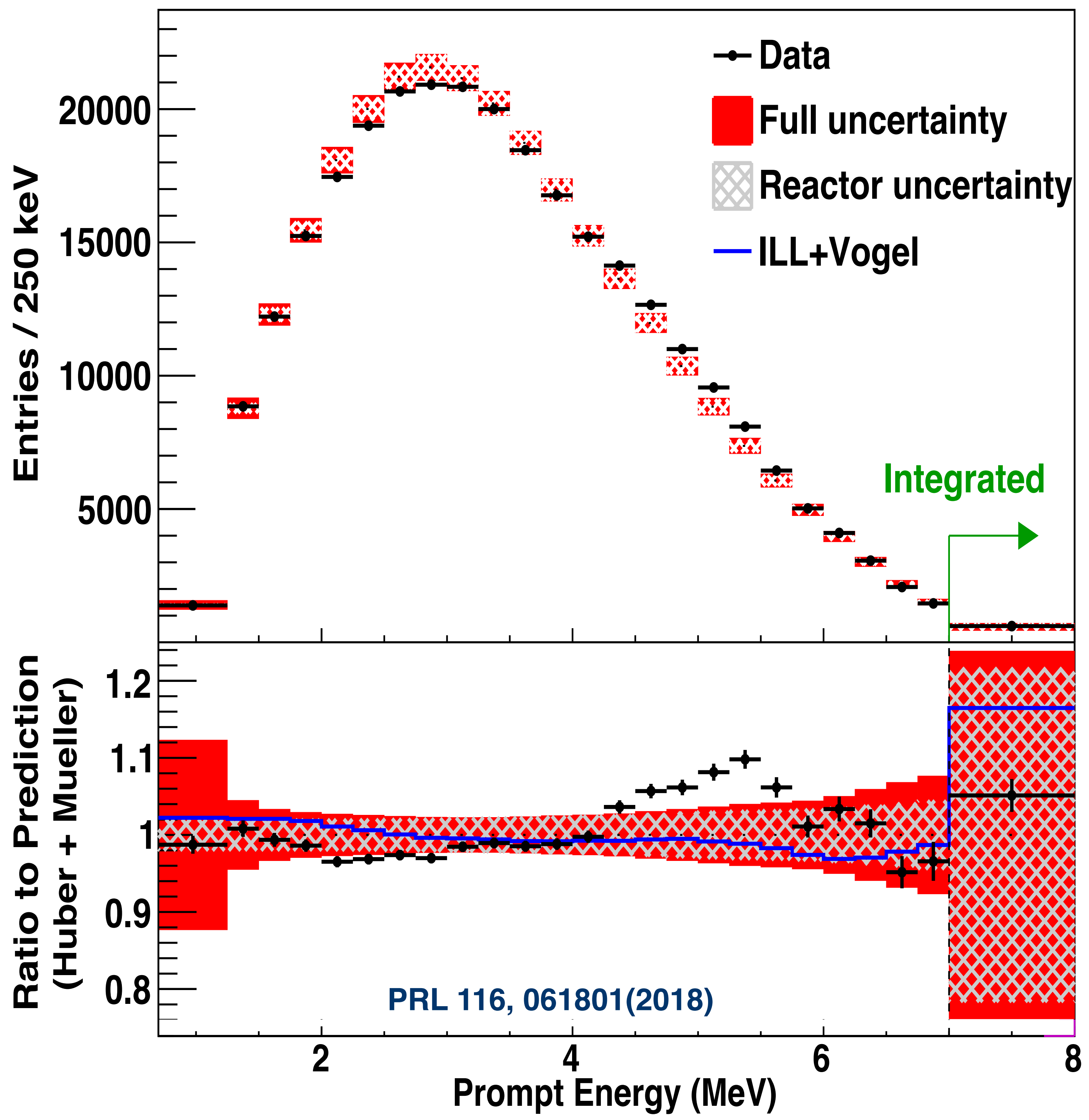
- Measure beta spectrum and fit it to virtual branches to convert to neutrino spectrum
- *Is all relevant physics captured by virtual beta branches*

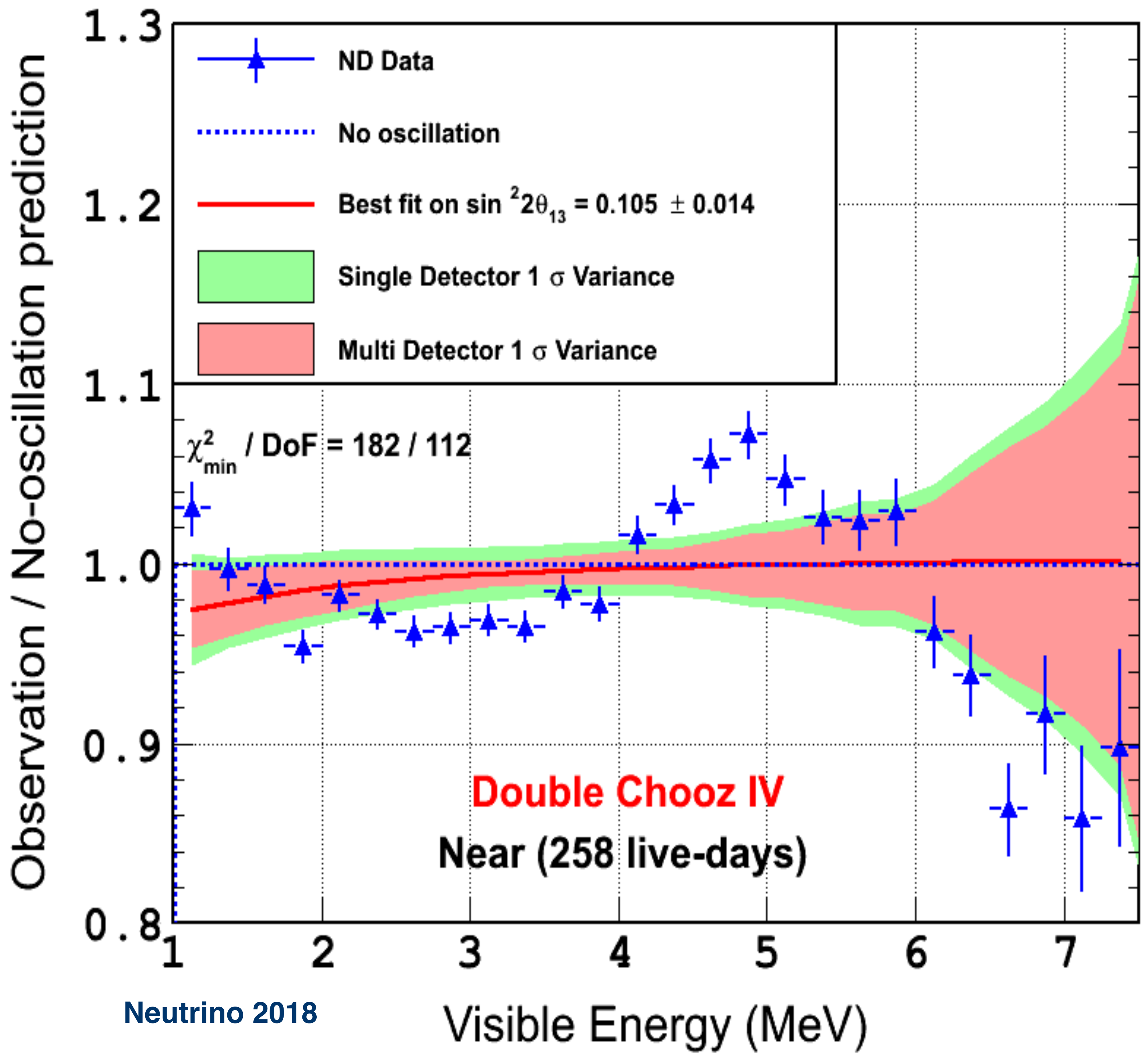


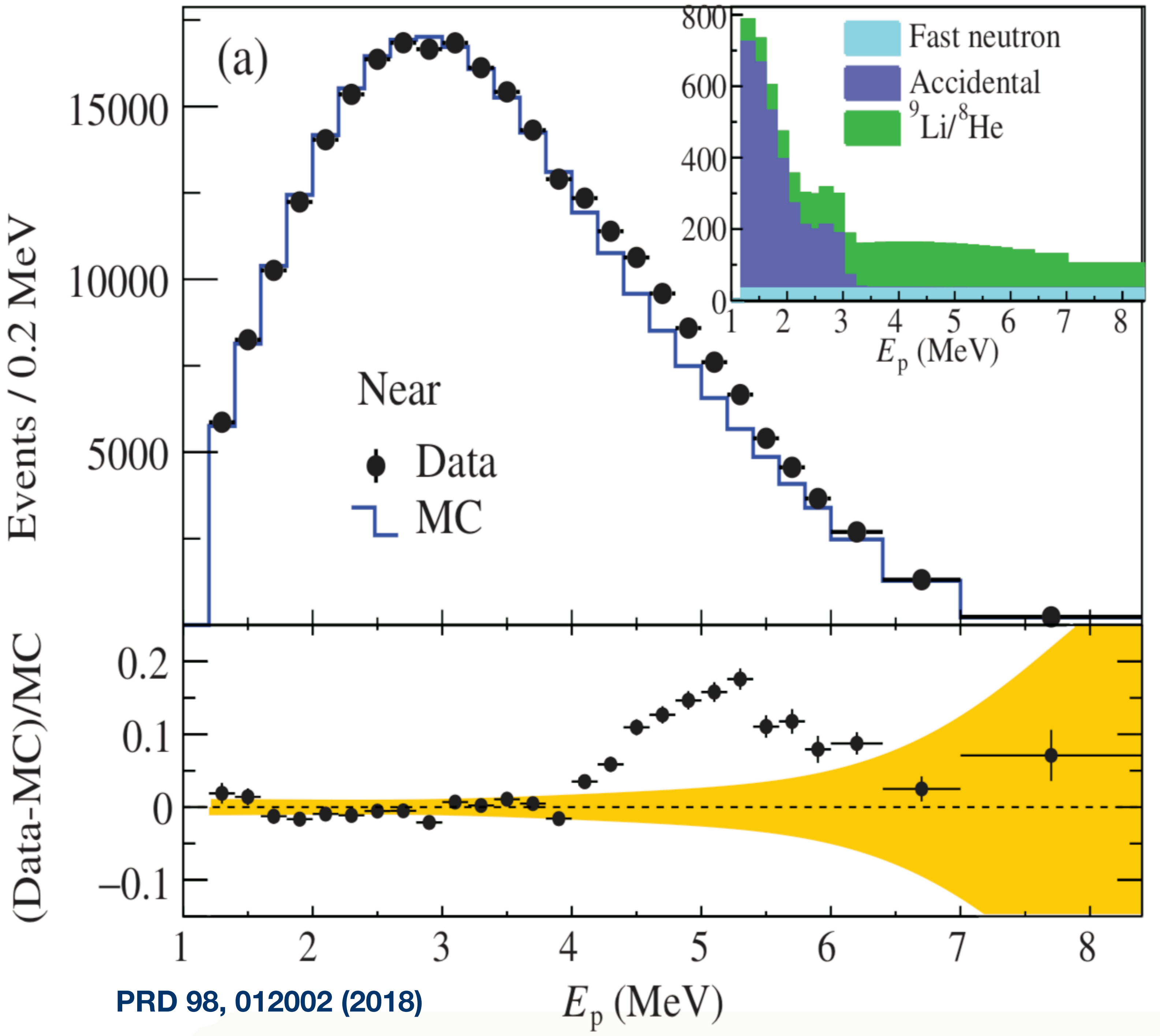
Schreckenbach, et al, Phys Lett B160 (1985)

Reactor antineutrino predictions are very complicated

More Reactor Neutrino Context





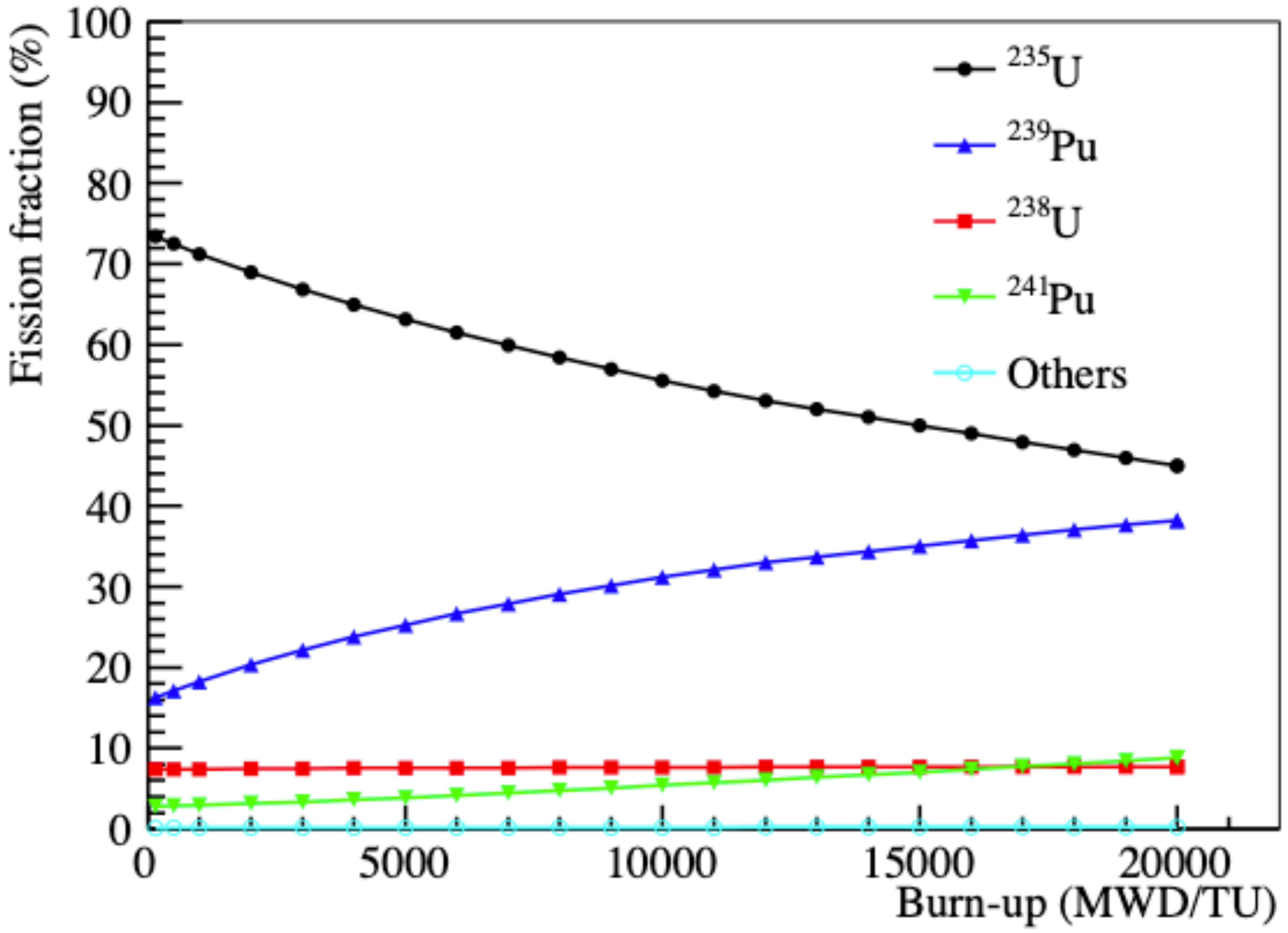


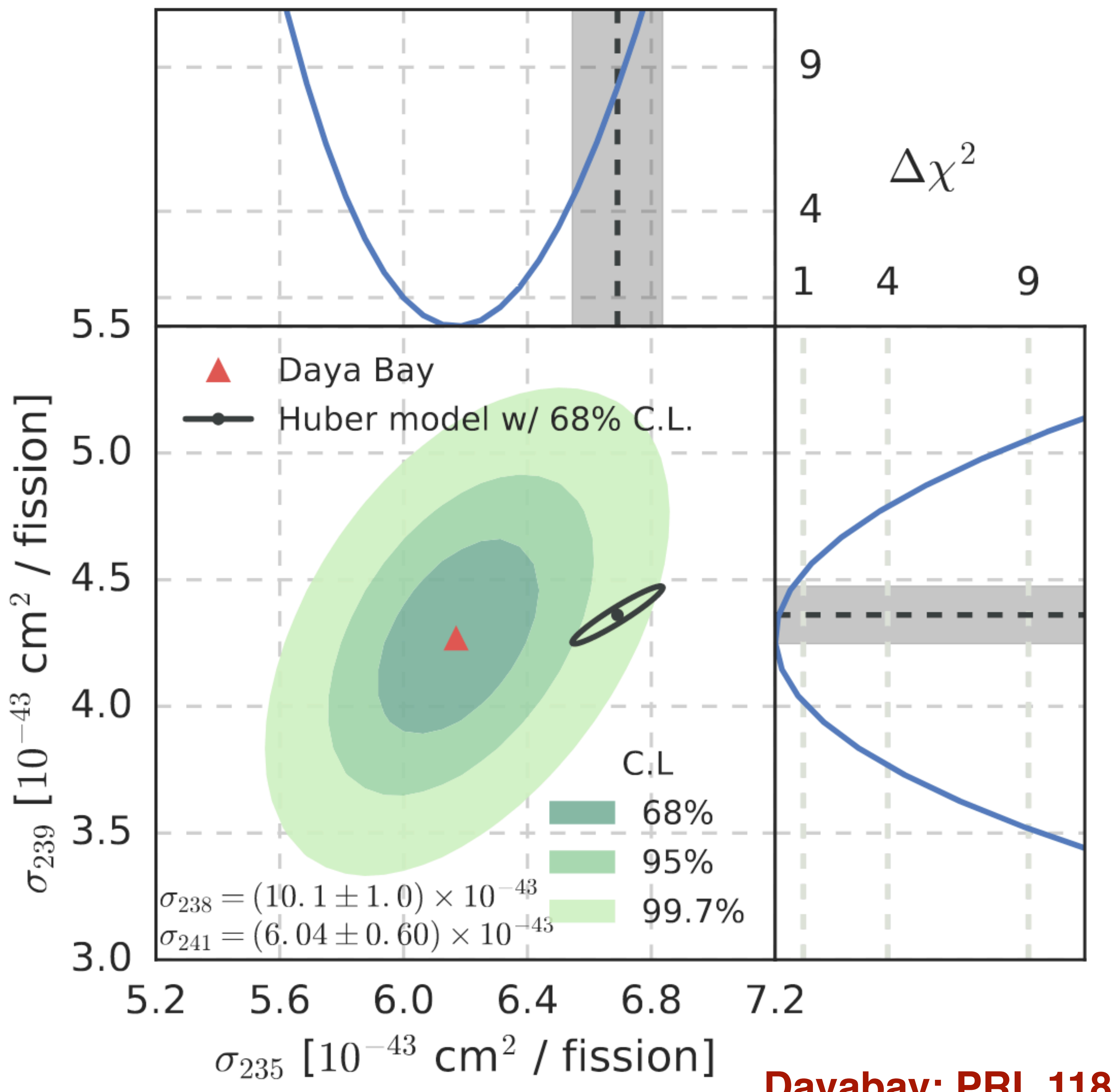
- Spectra shapes measured by θ_{13} experiments at LEU reactors disagree with state-of-the art models
- Sterile neutrinos cannot explain this anomaly
- **Points towards reactor models being wrong**

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

Even More Reactor Neutrino Context

- Daya Bay measures neutrino flux 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
- Measured ^{235}U disagrees but ^{239}Pu agrees well with the predictions
- Similar results from RENO
- **^{235}U seems like the problematic isotope**

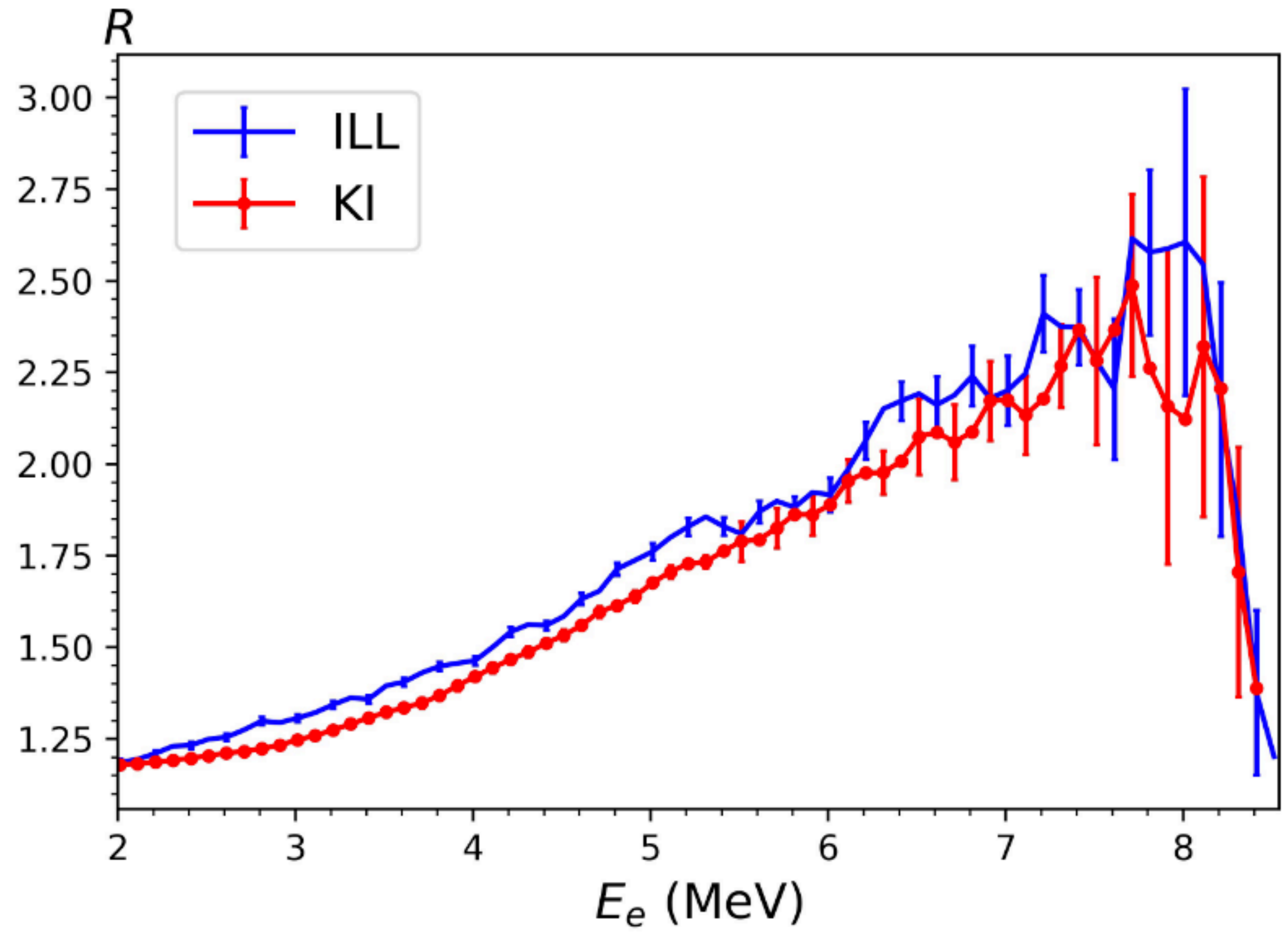




Dayabay: PRL 118 (2017)

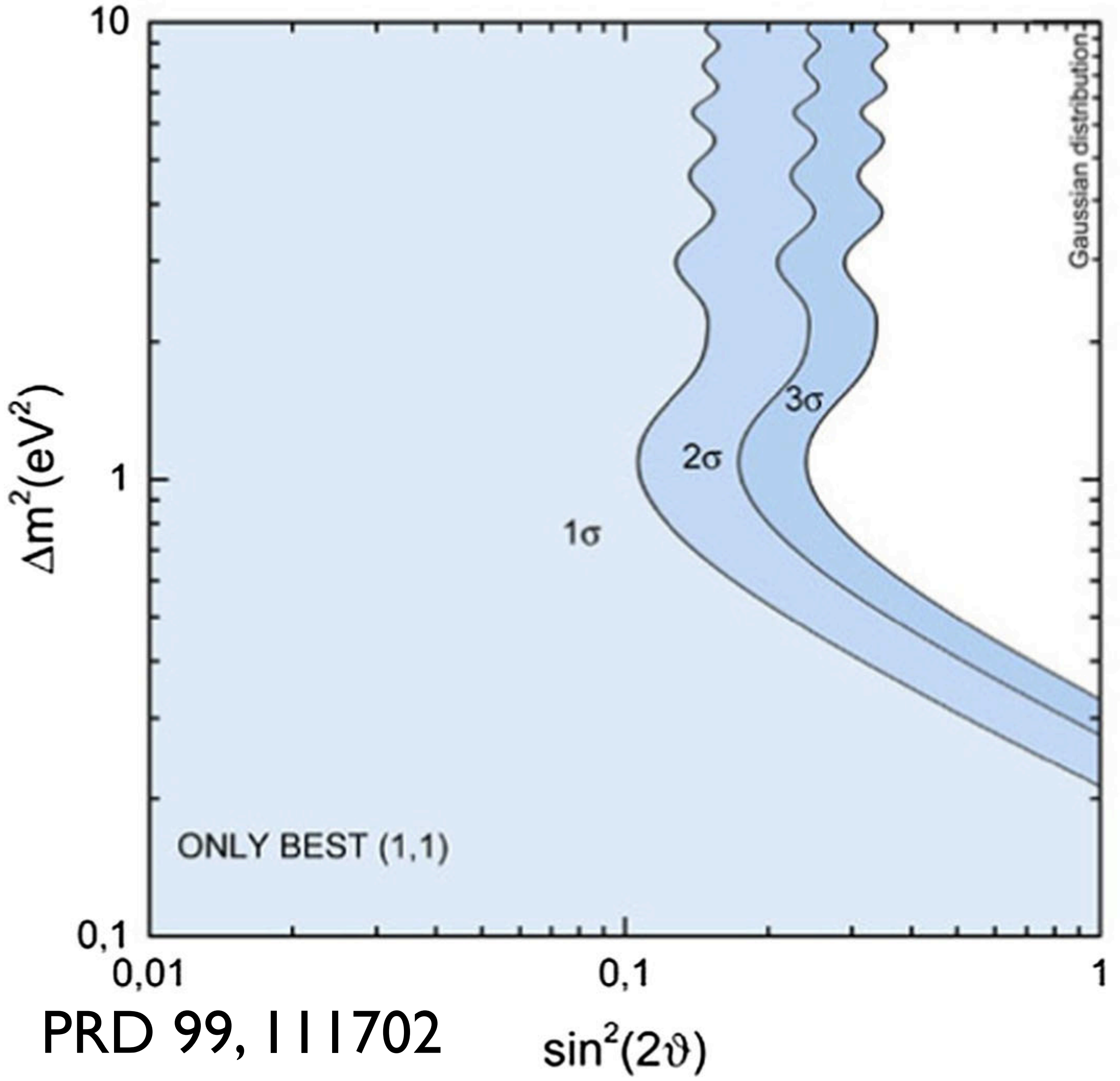
Even More Reactor Neutrino Context

- 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

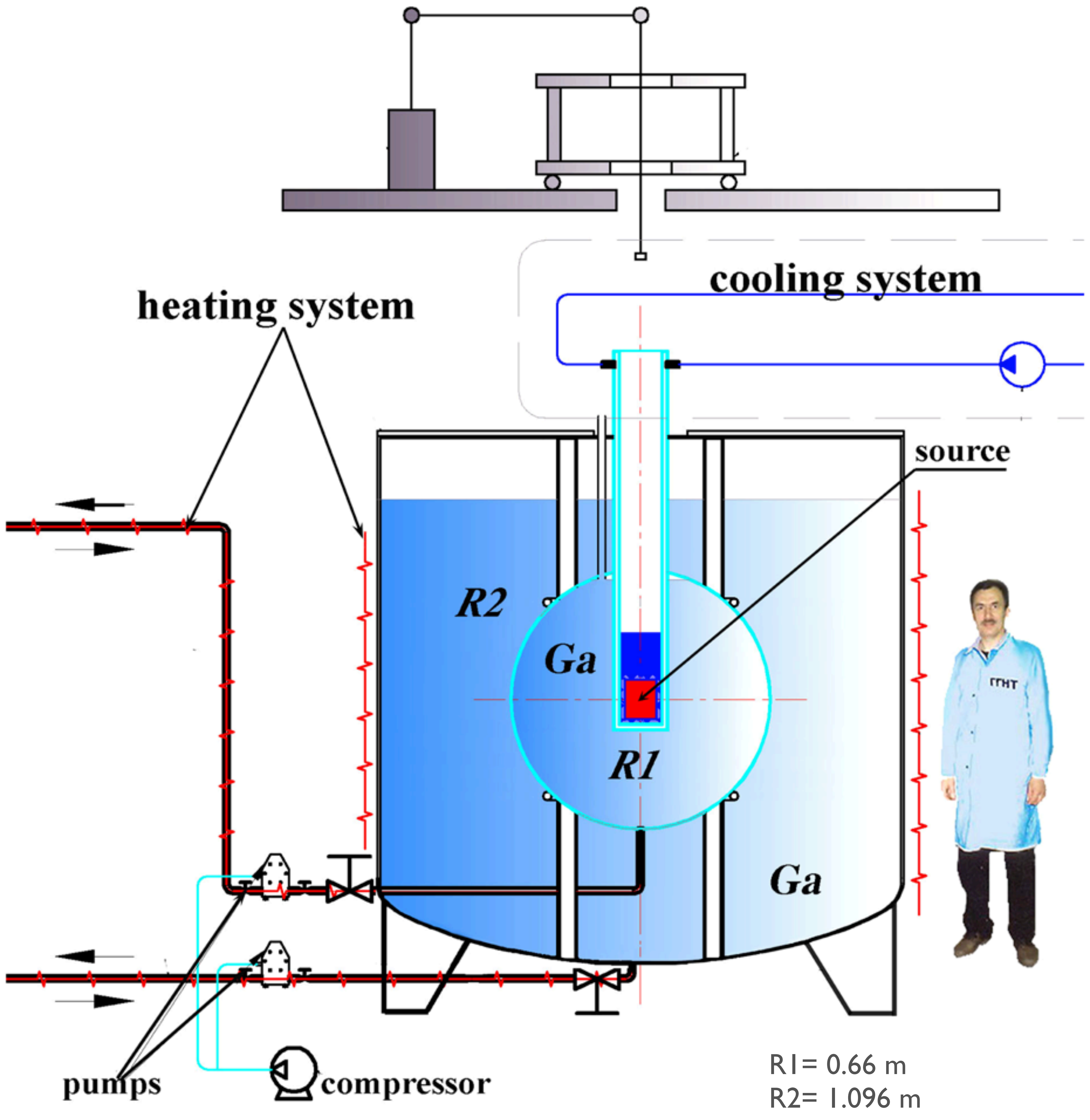


Testing Galium Anomaly: BEST Experiment

- BEST: Gallium source experiment similar to GALLEX and SAGE
- Source: 3 MCi of ^{51}Cr source
- Two zones for flux cross-checks
- Data taking July - Nov 2019; Data processing Dec - Nov 2020
- Results to be out soon

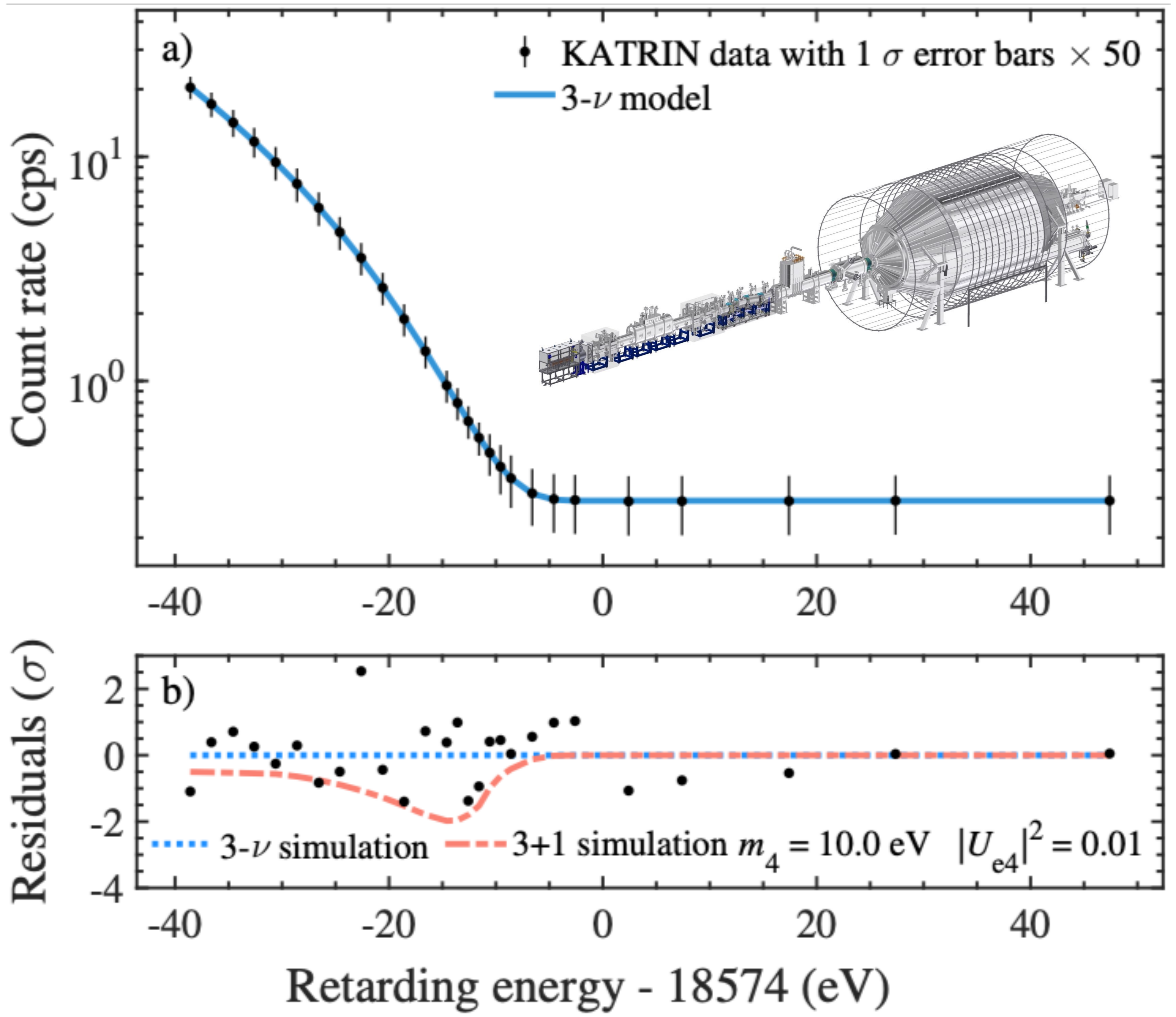


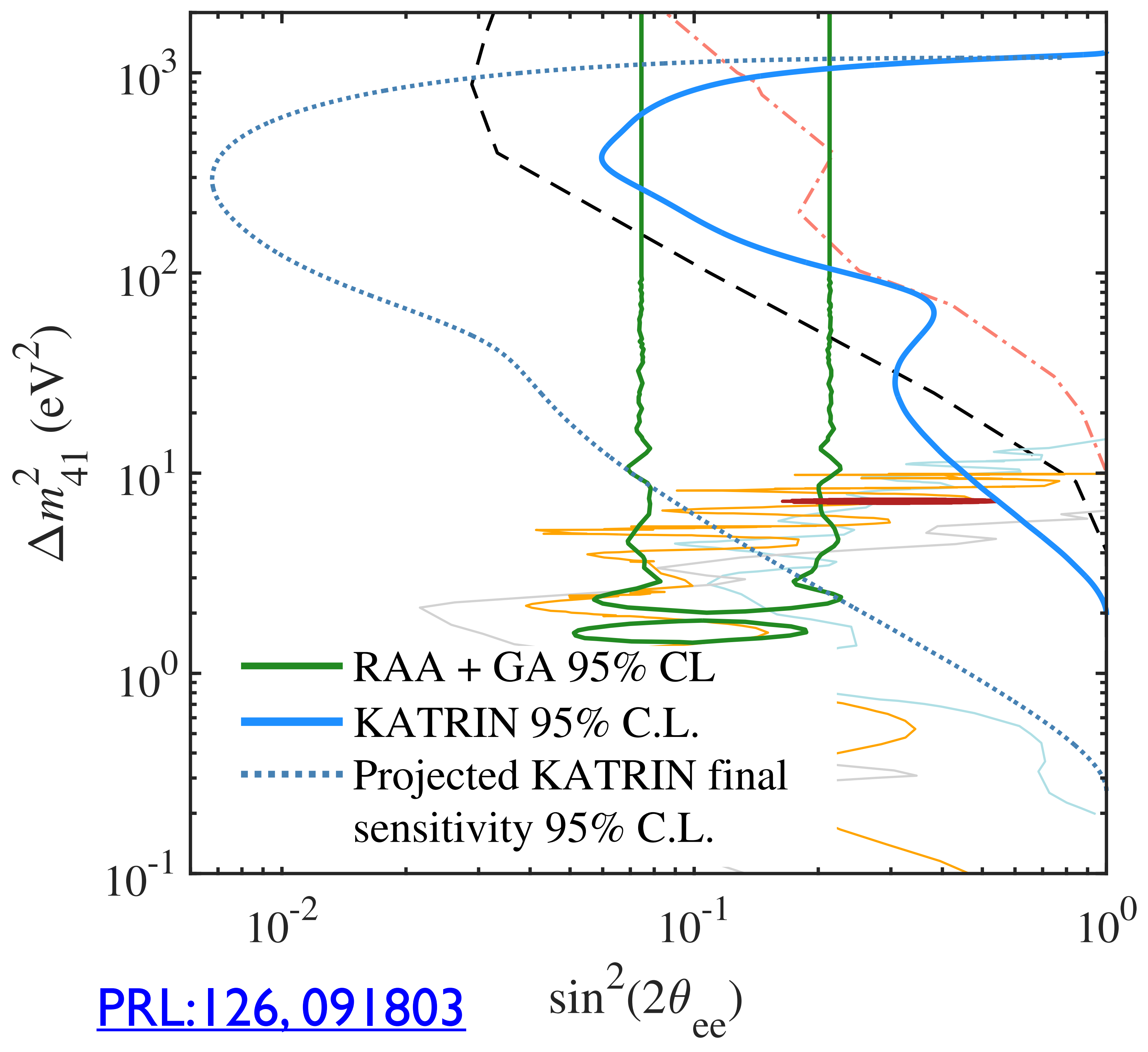
PRD 99, 111702



Other Negative Results : KATRIN

- KATRIN is a direct neutrino mass measurement using beta decay of tritium
- Also sensitive to sterile neutrino oscillations at high Δm^2
- No oscillation signature found
- Projected sensitivity to cover a significant portion of suggested parameter space

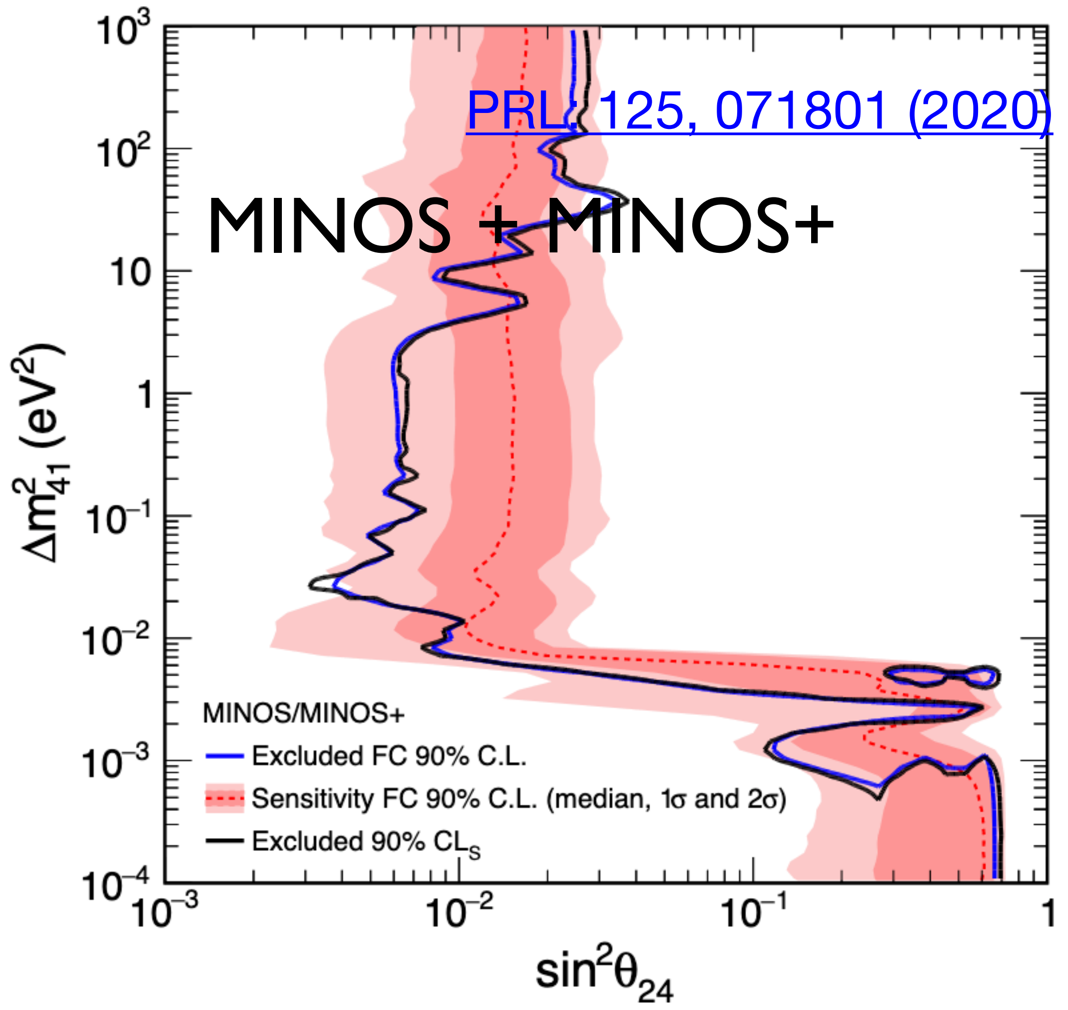




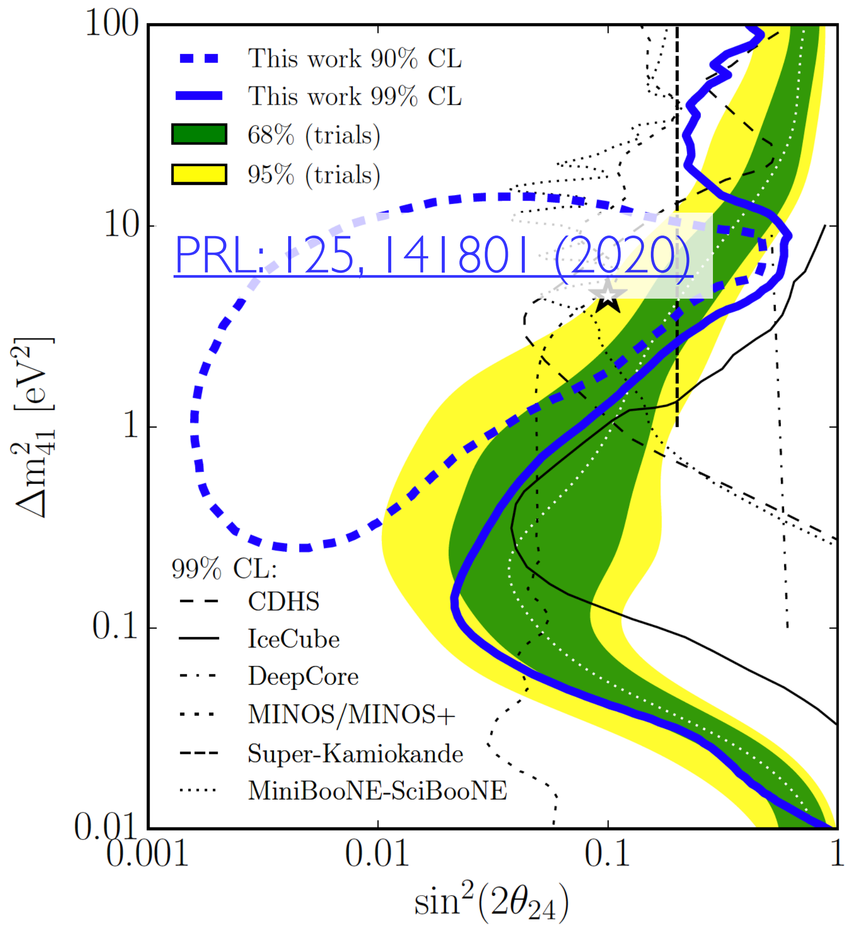
PRL:126, 091803

Other Negative Results : ν_μ Disappearance

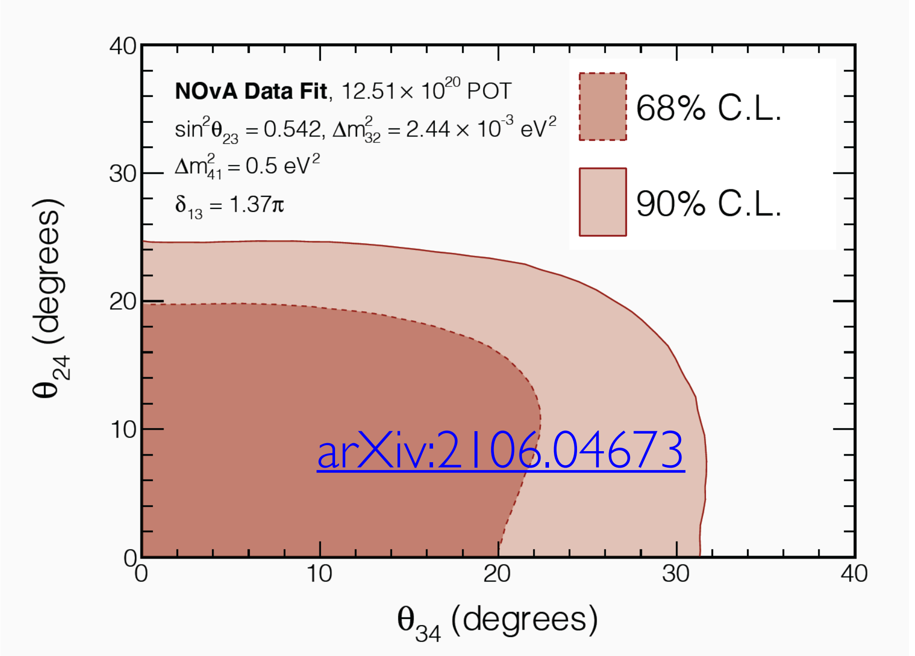
- Several disappearance searches don't find any evidence of sterile neutrino oscillations
- Rules out most of the 3+1 suggested parameter space by LSND and MiniBooNE anomalies

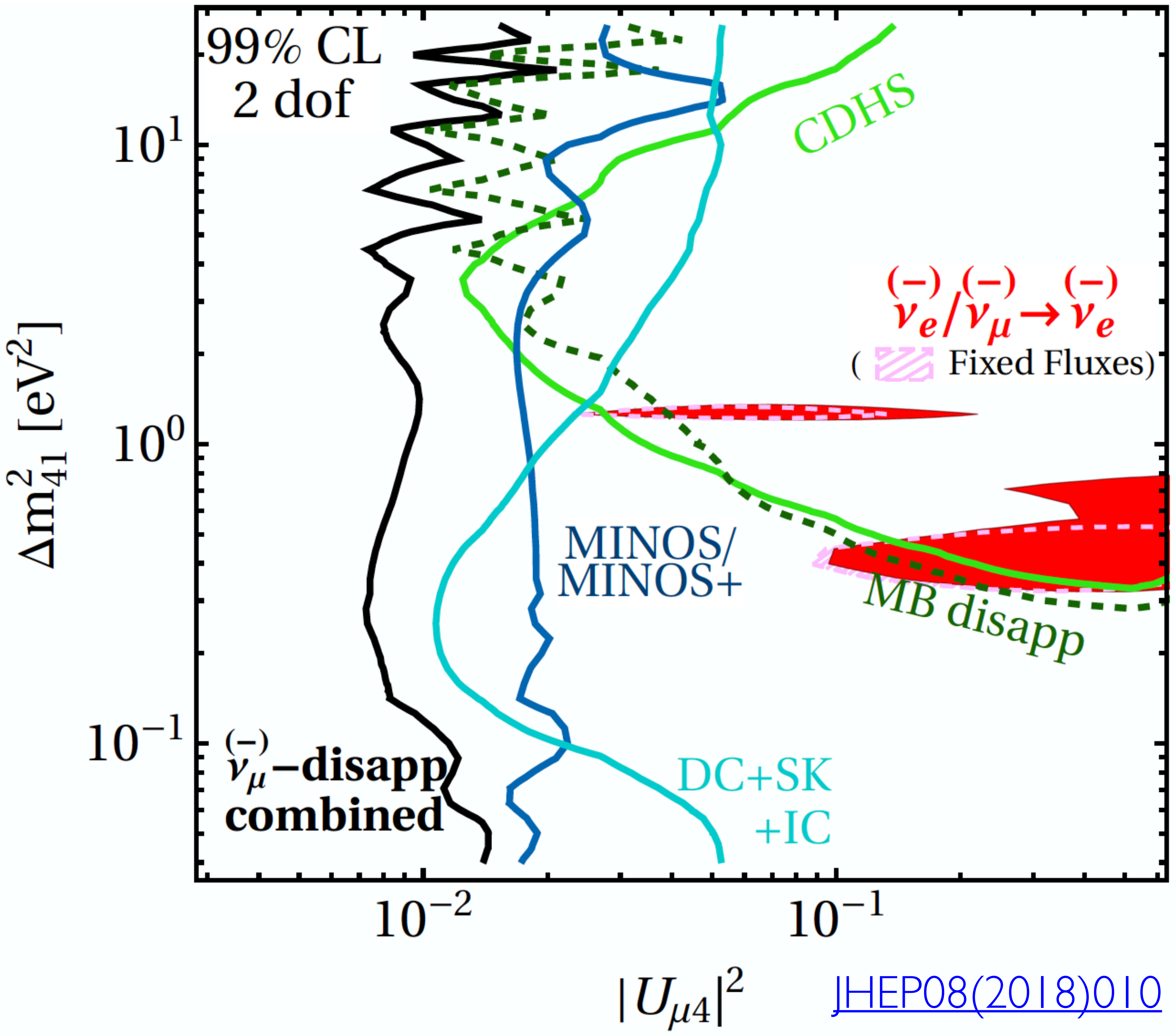


IceCube Experiment



NOvA Experiment

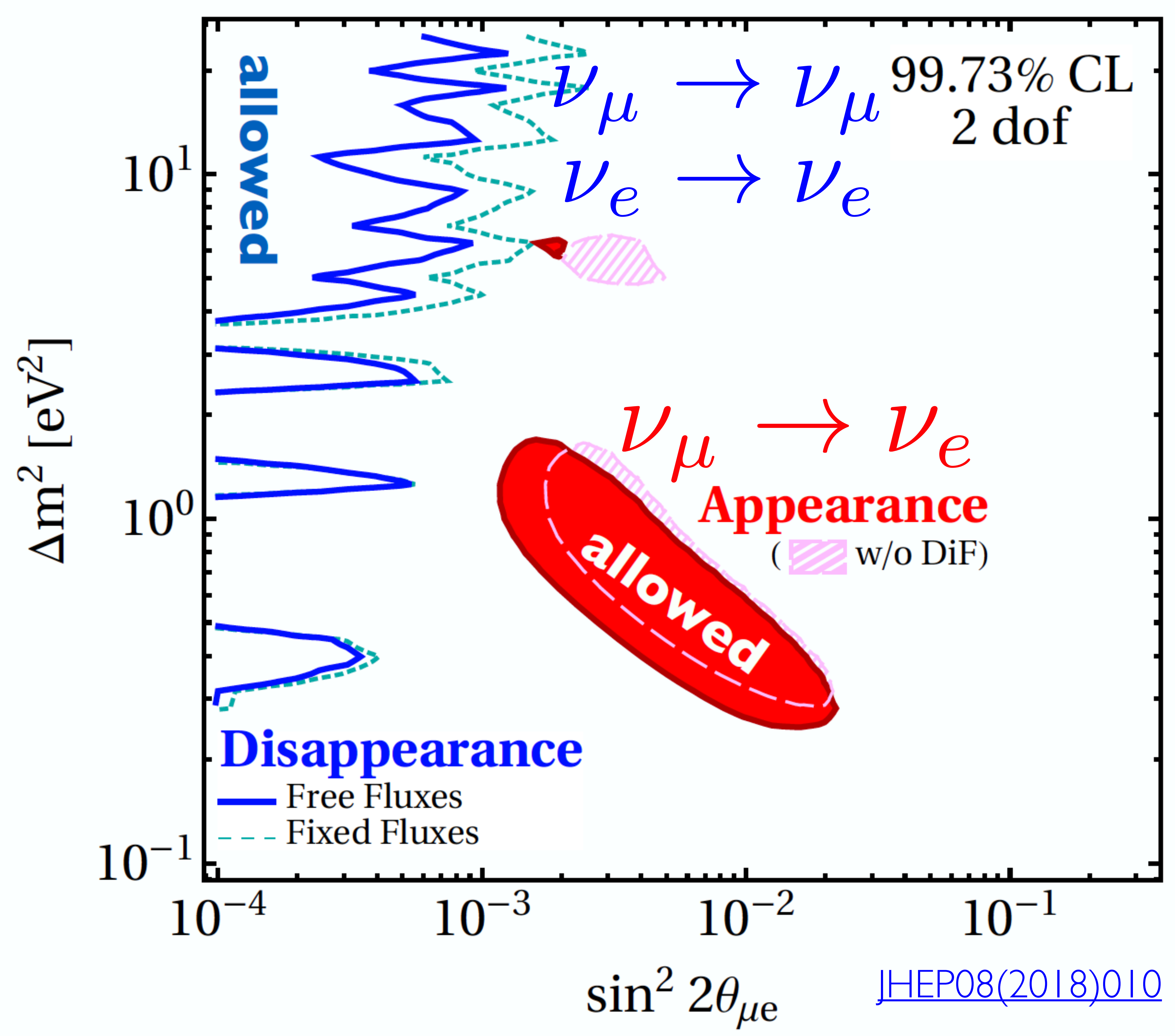




JHEP08(2018)010

Global Context

- Suggested parameter space under eV-scale sterile interpretation appearance and disappearance experiments disagree
- **4.7 σ tension** between the data sets
- All the existing anomalies can't simply be explained by eV-scale sterile neutrinos
- Other non-minimal BSMs may need to be invoked



JHEP08(2018)010

*Some new data since, but the qualitative picture remains

Conclusion

- Several appearance and disappearance experiments observed anomalous results
- eV-scale sterile neutrinos invoked as a solution to the anomalies
- Experiments very diverse; different sources and detector technologies
- Several experiments already exclude regions of parameters space
- Awaiting more results and experiments
- Need to invoke more complicated models if anomalies persist

Oscillation channel	Source	Anomalies	Status
$\nu_\mu \rightarrow \nu_e$	Accelerator	LSND (3.8 σ) MiniBooNE (4.8 σ)	Unresolved; awaiting results
$\nu_\mu \rightarrow \nu_\mu$	Accelerator, atmospheric	No anomalies	N/A
$\nu_e \rightarrow \nu_e$	Reactor, source	Reactor (~3σ) Source (~3σ)	Significant parameter space covered; awaiting more experiments and results

Conclusion

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Thanks for your attention

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