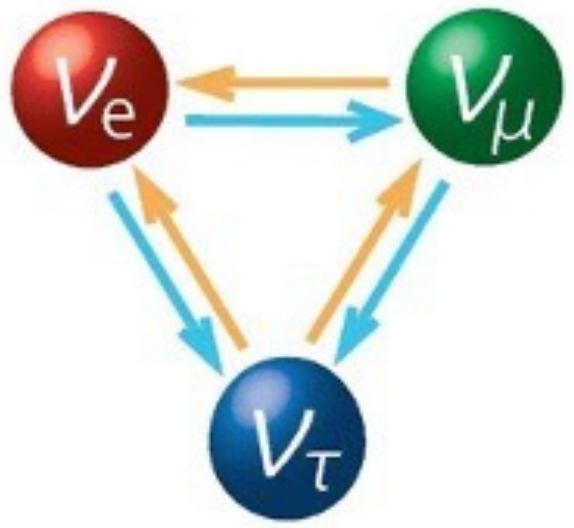
Joint measurement of the reactor antineutrino spectrum and investigation of the light sterile neutrino sector with STEREO, PROSPECT and Daya Bay

Rudolph Rogly - Laboratoire Leprince-Ringuet (CNRS/École Polytechnique)

EPS-HEP Conference — *July 07-11, 2025*

3-flavor neutrino oscillation mechanism



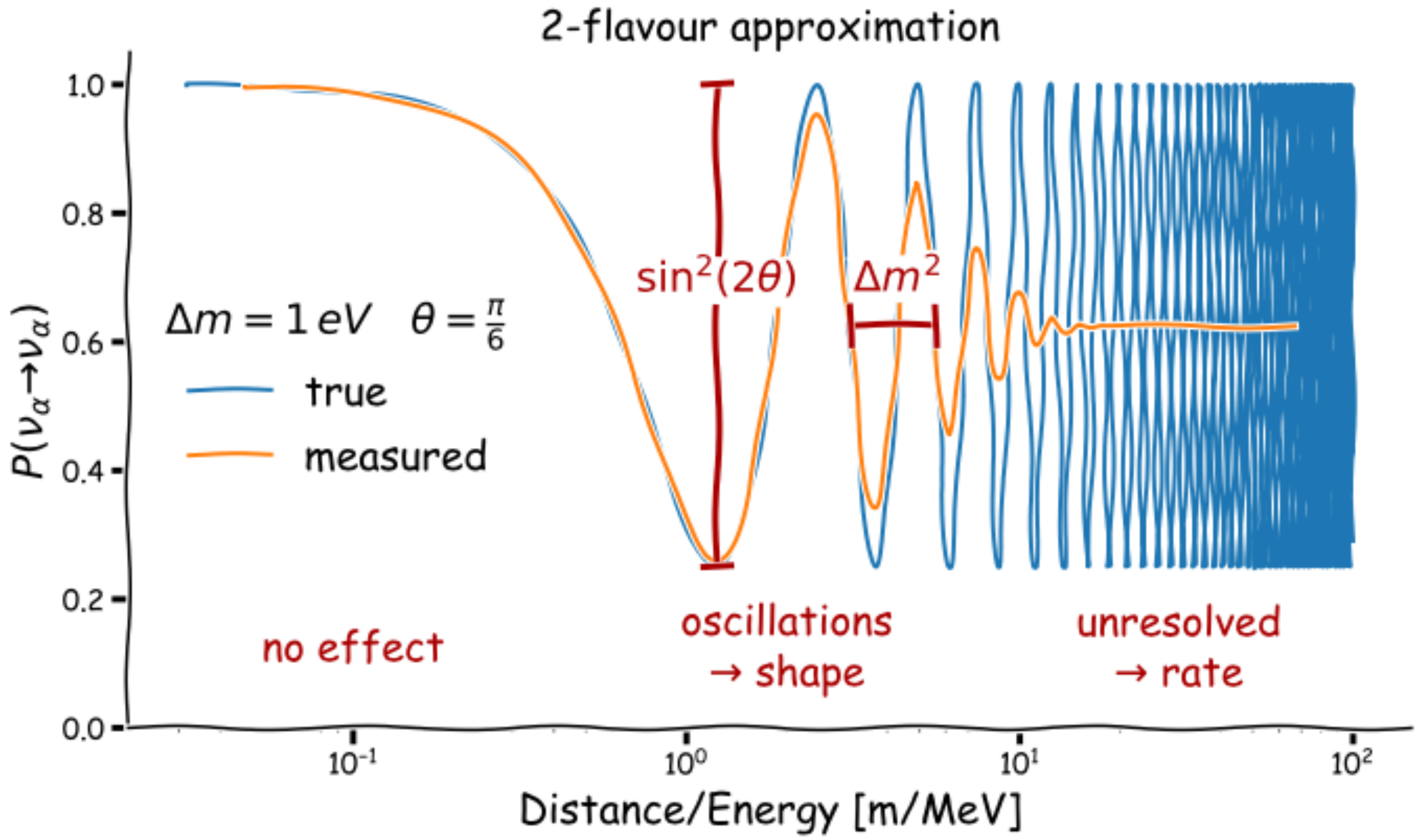
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates

Mass eigenstates $(m_1,\ m_2,\ m_3)$

Parametrized by $(\theta_{13},\ \theta_{23},\ \theta_{12},\ \delta_{CP})$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\ \sin^2\left(1.27 \frac{\Delta m^2\,[eV^2] \cdot L[km]}{E[MeV]}\right)$$



Mixing angles and mass-squared splitting parameters almost all measured:

Δm^2_{21} [eV²]	$\lvert\Delta m^2_{31}\rvert$ [eV²]
$7.4 \cdot 10^{-5}$	$2.5 \cdot 10^{-3}$

$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
~ 0.3	~ 0.4	~ 0.02

3-flavor neutrino oscillation mechanism

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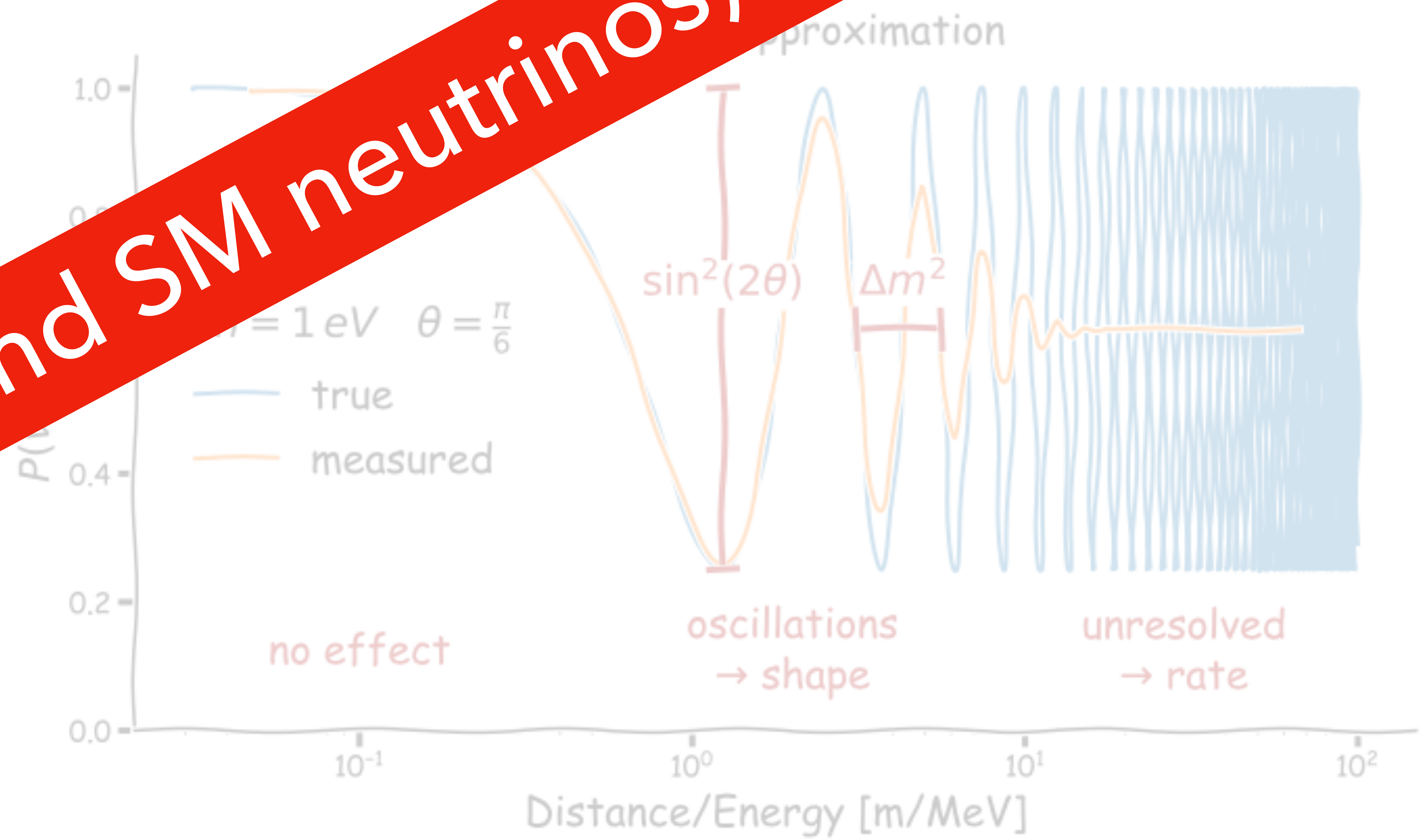


Mixing angles and mass-square spl… …ters

almost all me…

Δm^2…	$\lvert\Delta m^2_{31}\rvert$ [eV²]
[illegible]	$2.5\cdot 10^{-3}$

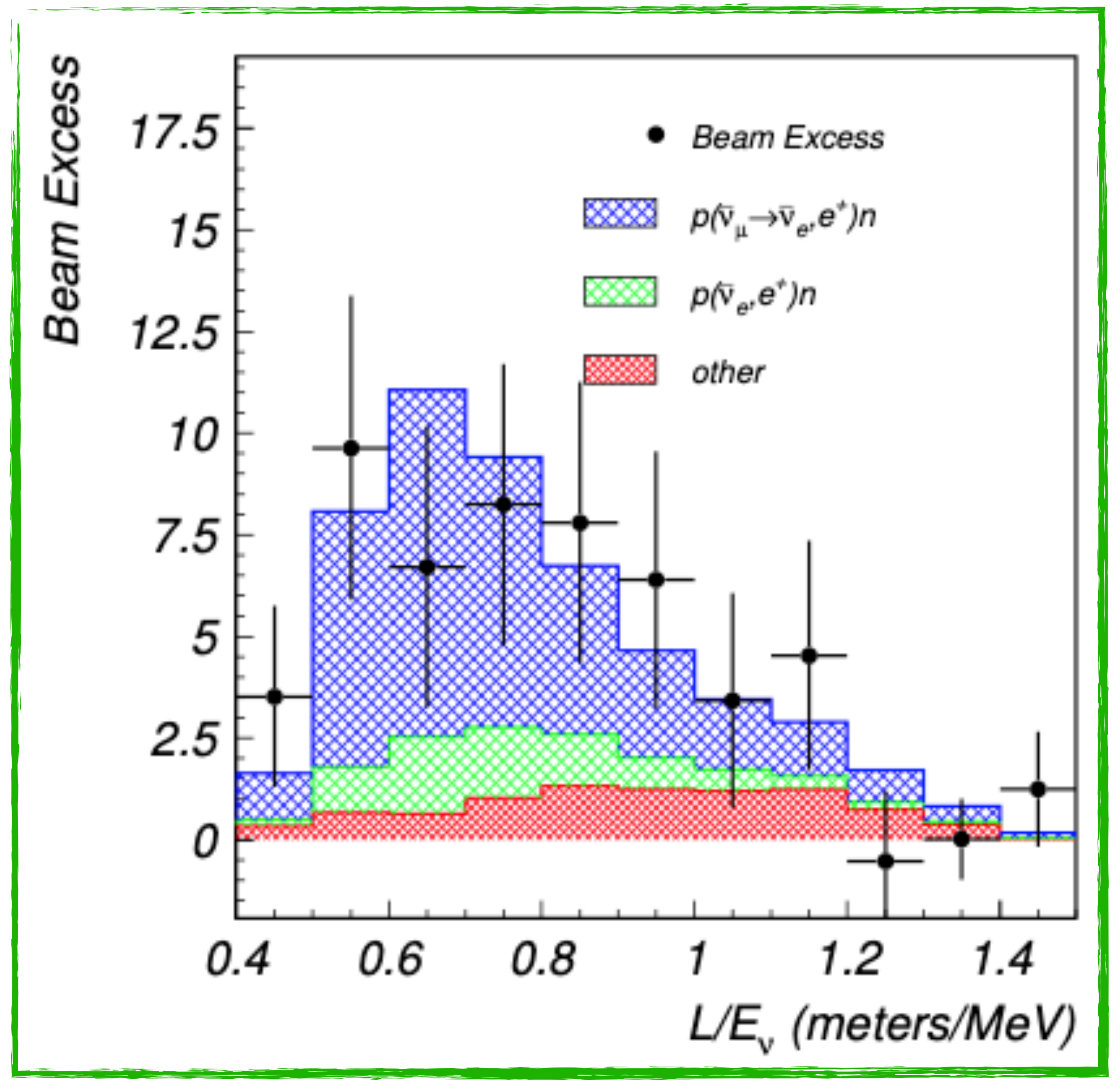
$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
~ 0.3	~ 0.4	~ 0.02

Is there anything else (beyond SM neutrinos) ?

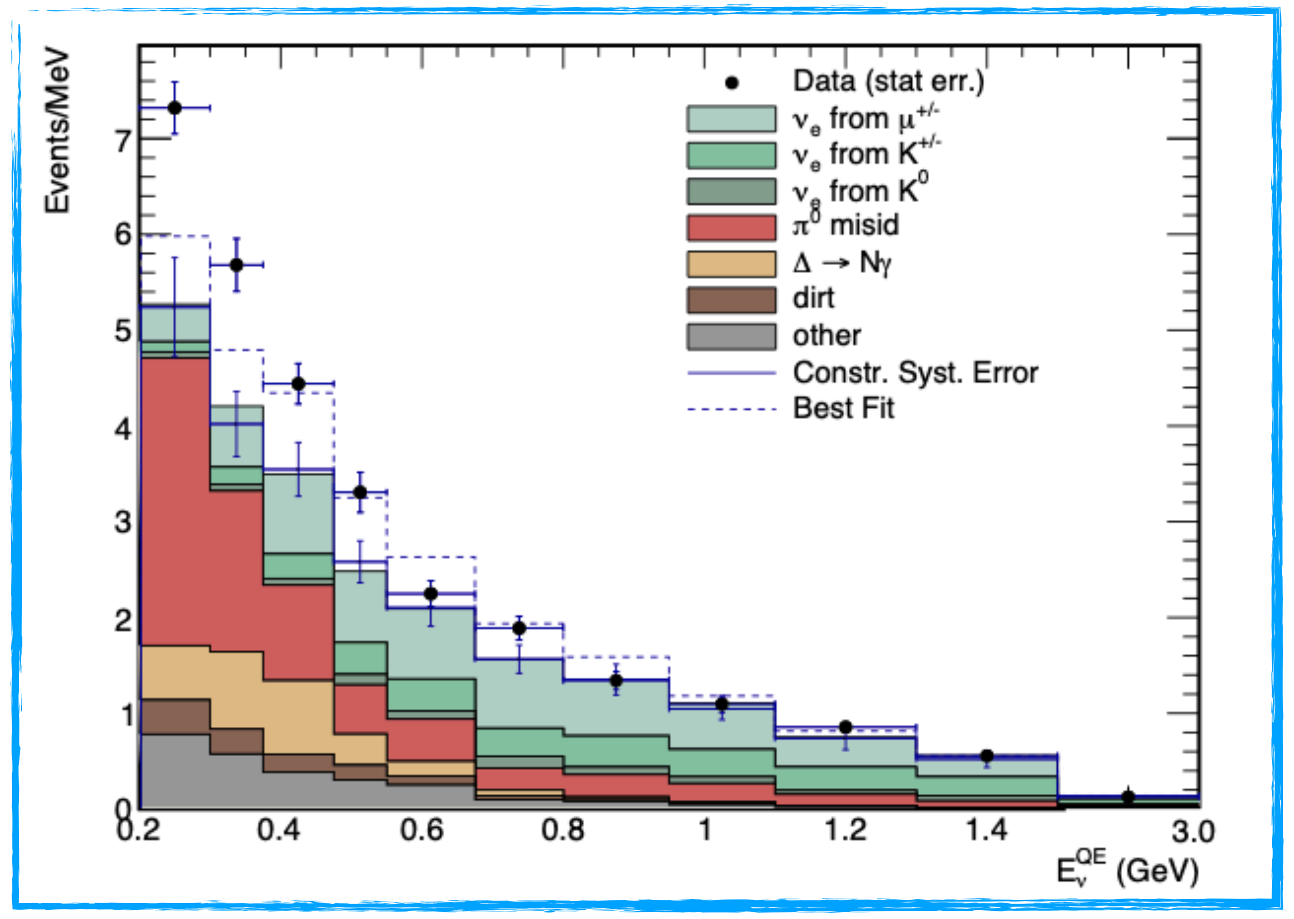
Short-baseline anomalies in neutrino physics

$\bar{\nu}_e$ / ν_e appearance channel

- The **LSND** anomaly: **excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam**.
- The **MiniBooNE** anomaly: **excess of ν_e events in a ν_μ beam**.



Phys. Rev. D ***64****, 112007 (2001)*



Phys. Rev. D ***103****, 052002 (2021)*

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- The **MiniBooNE** anomaly: **excess of ν_e events in a ν_μ beam.**
- Combined significance of **LSND** + **MiniBooNe** is 6.1σ, with a baseline $L/E \sim 1\ (m/MeV)$ → compatible with $\Delta m^2_{41} \gtrsim 10^{-1}\ eV^2$.

Δm^2_{21} [eV²]	$\lvert\Delta m^2_{31}\rvert$ [eV²]
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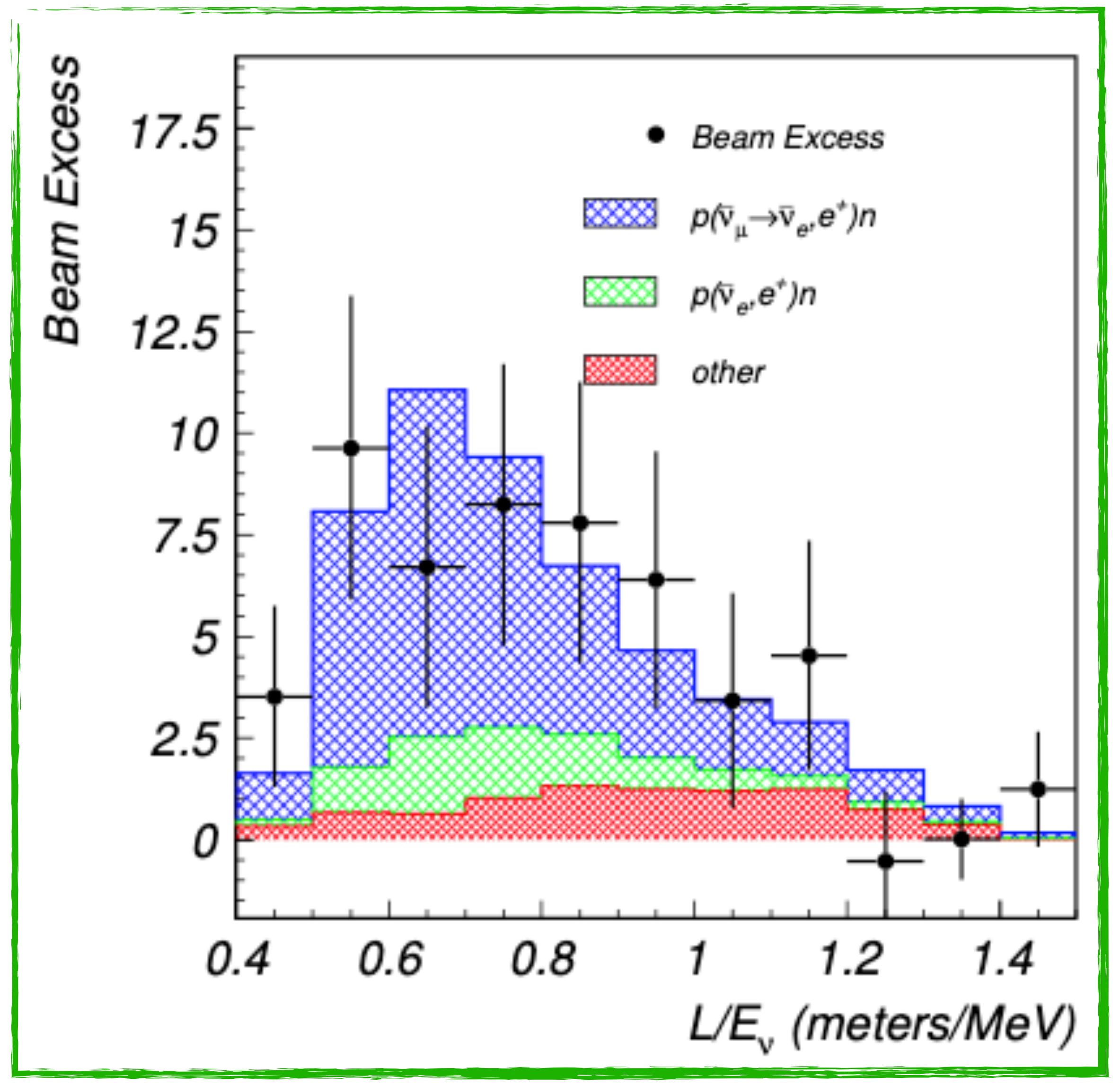
Sub-eV sterile neutrino state ?



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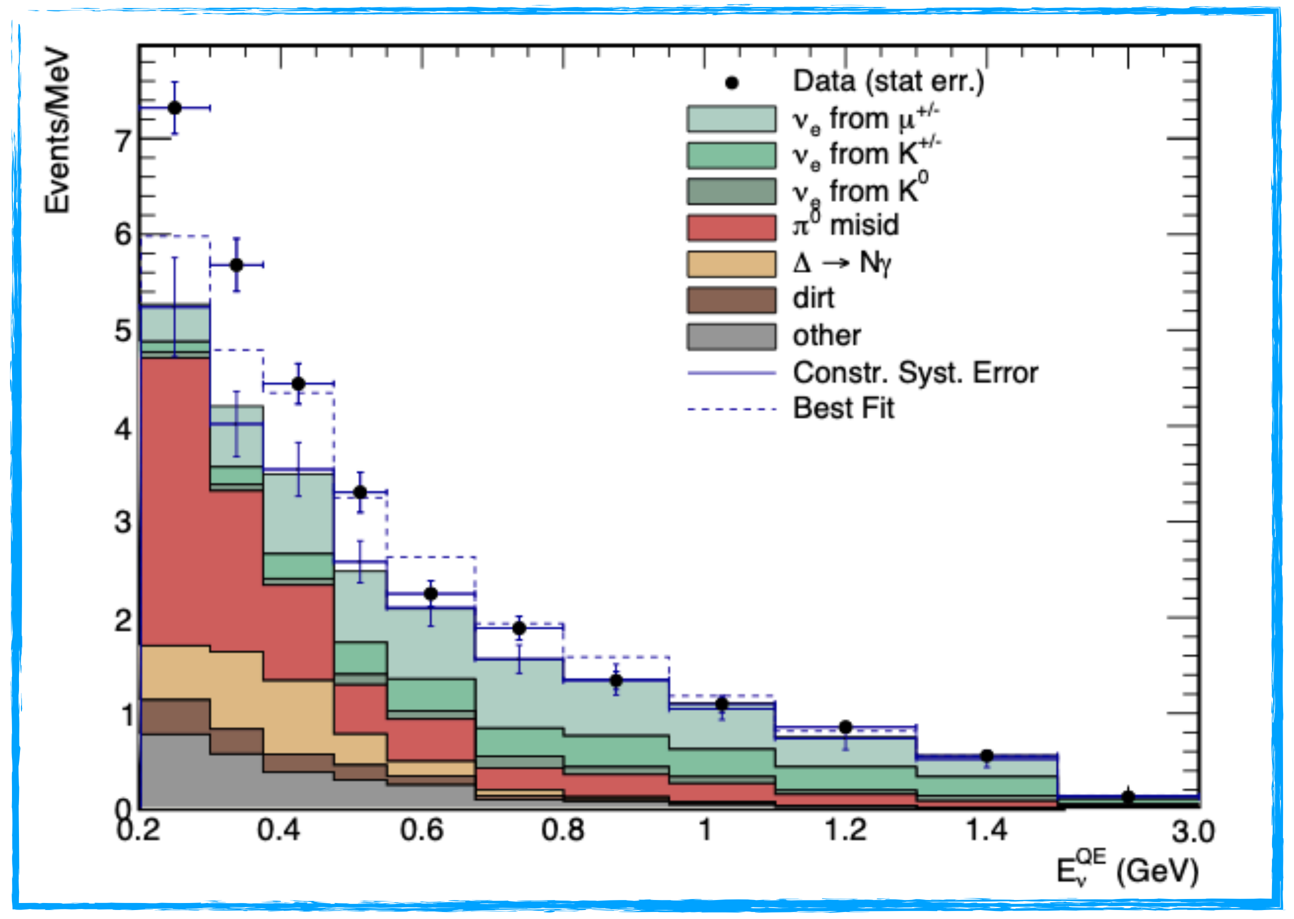
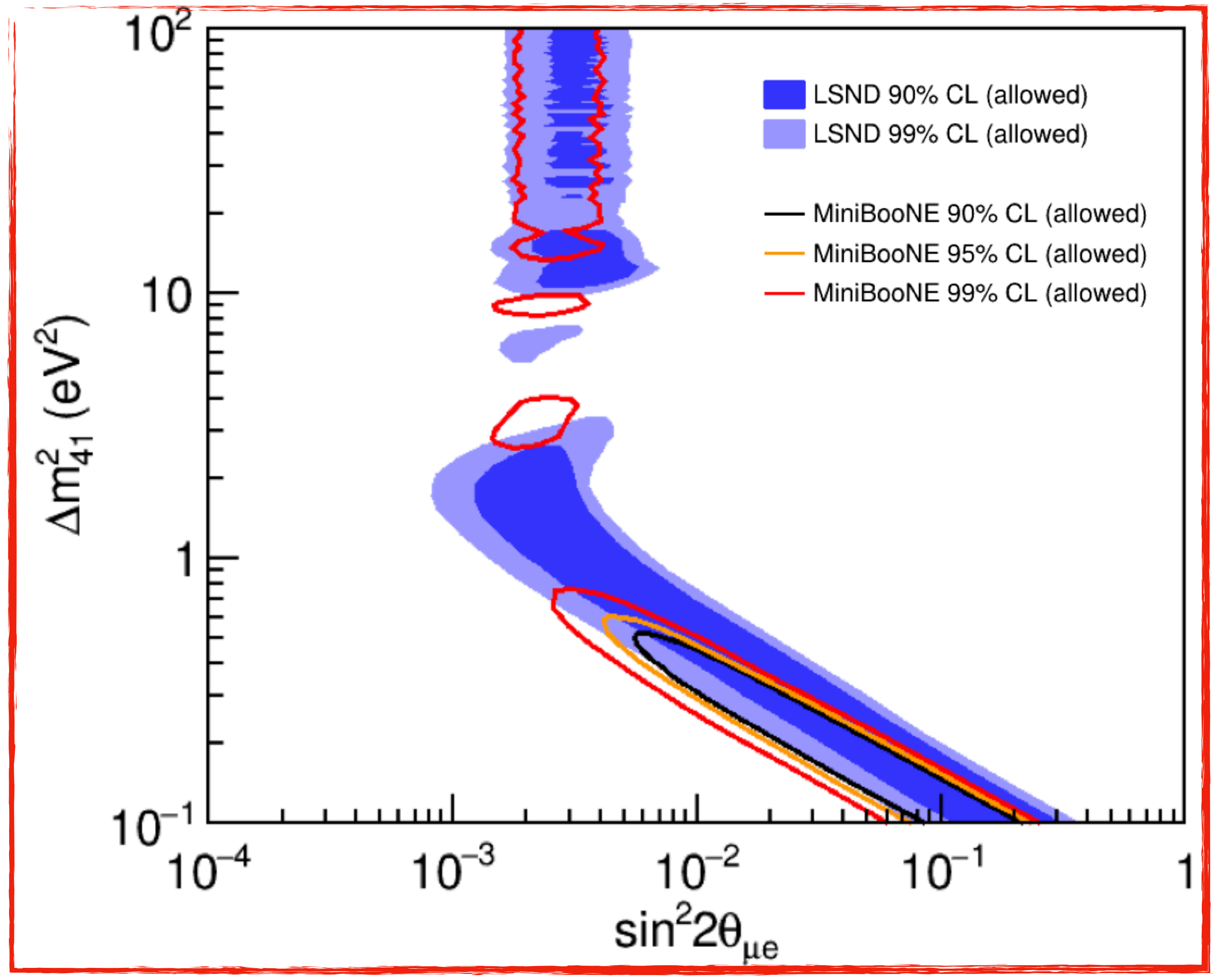


Phys. Rev. D **103**, 052002 (2021)

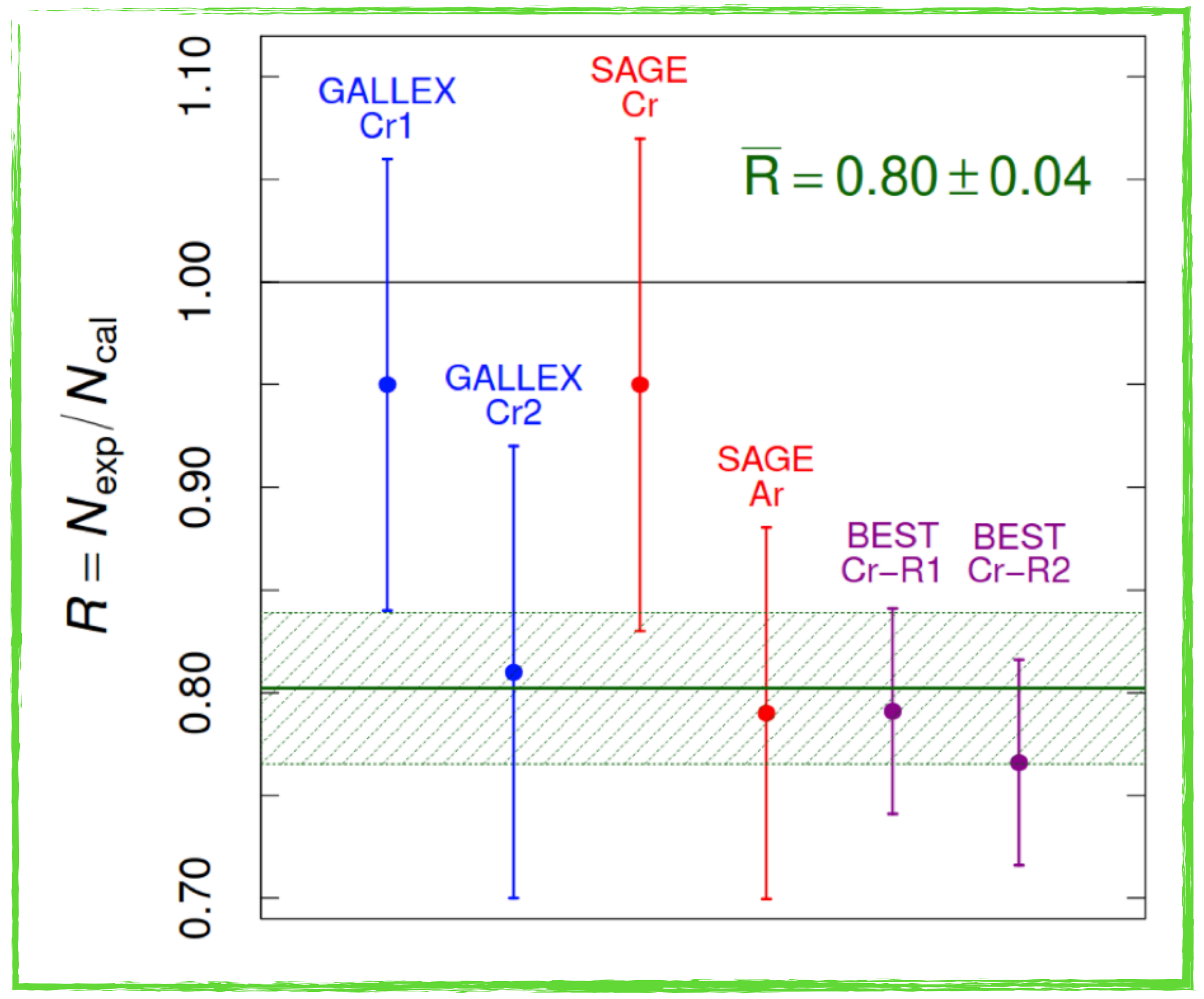


Allowed contours for the LSND and MiniBooNe anomalies.

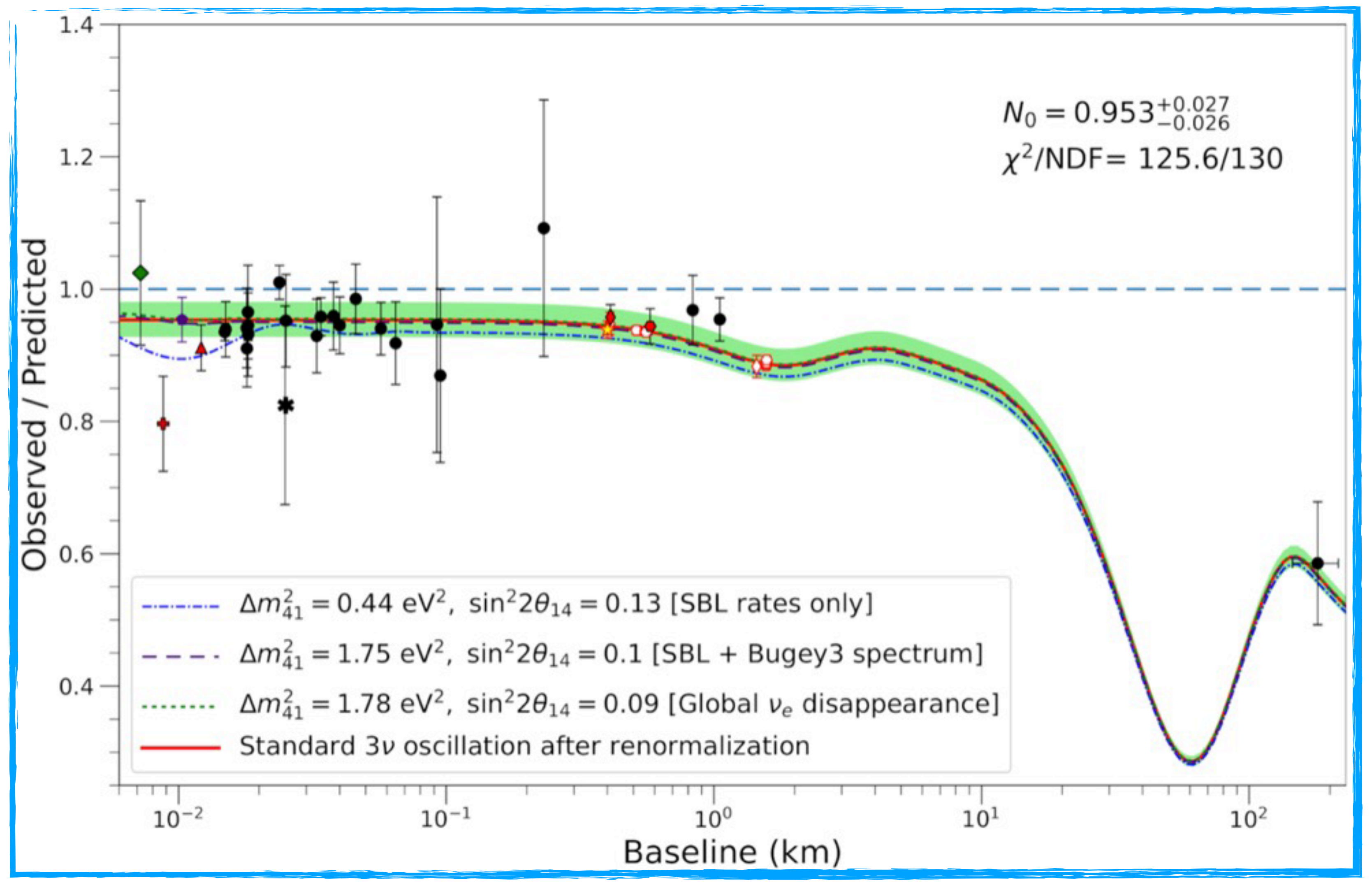
Short-baseline anomalies in neutrino physics

$\bar{\nu}_e$ / ν_e disappearance channel

- The **Gallium** anomaly: **deficit of ν_e capture events** on ^{71}Ga from radioactive sources (SAGE, GALLEX, BEST) → **~5 σ** significance.
- The **Reactor** antineutrino anomaly: **deficit of $\bar{\nu}_e$** at short baseline from nuclear reactors → **~2-3 σ** significance.



C. A. Ternes, IRN Neutrino Meeting 2022



Phys. Rev. D **83**, 073006 (2011)

Short-baseline anomalies in neutrino physics

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- With a baseline $L/E \sim 1\ (m/MeV)$, compatible with $\Delta m^2_{41} \gtrsim 1\ eV^2$.

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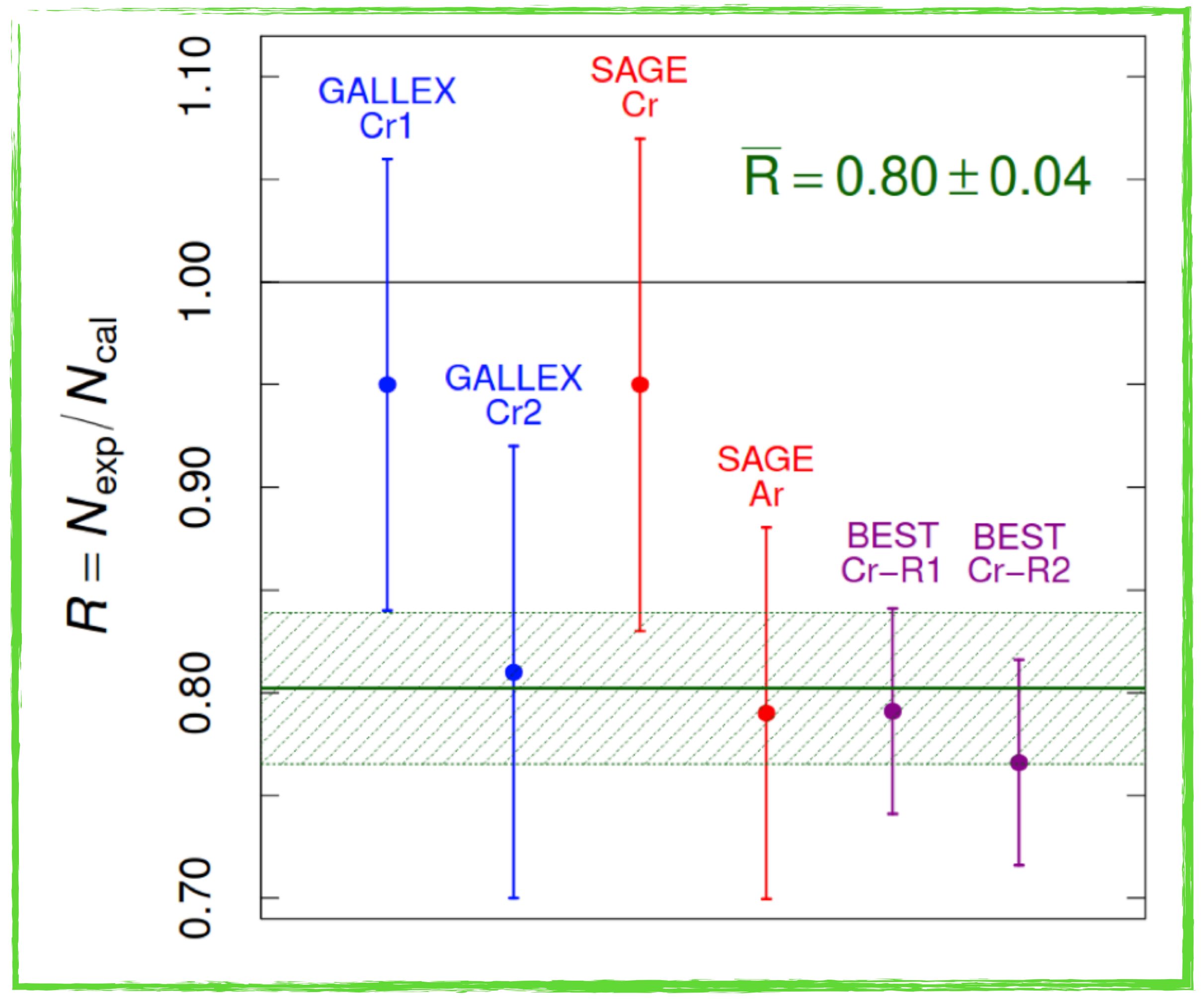

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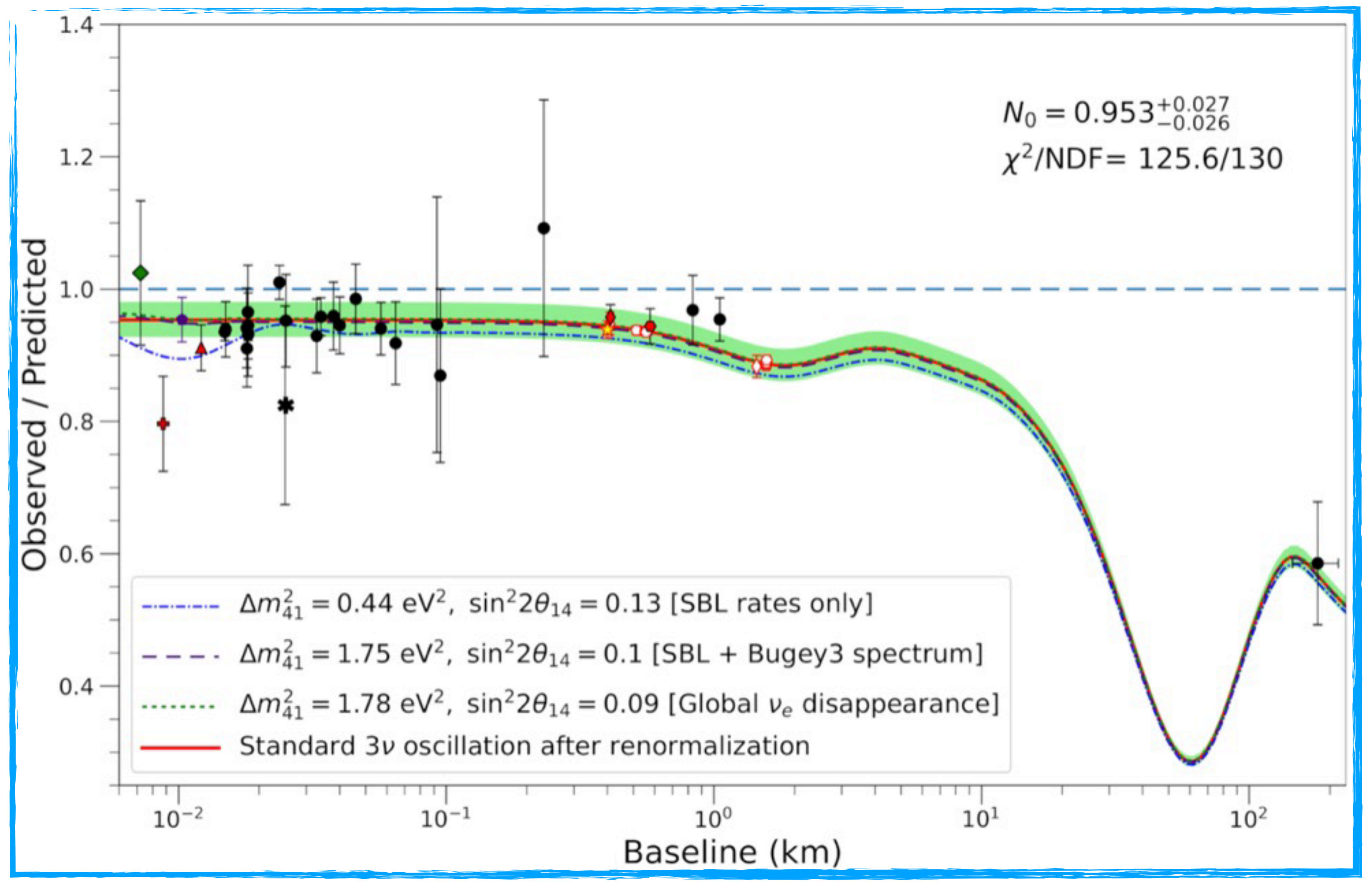

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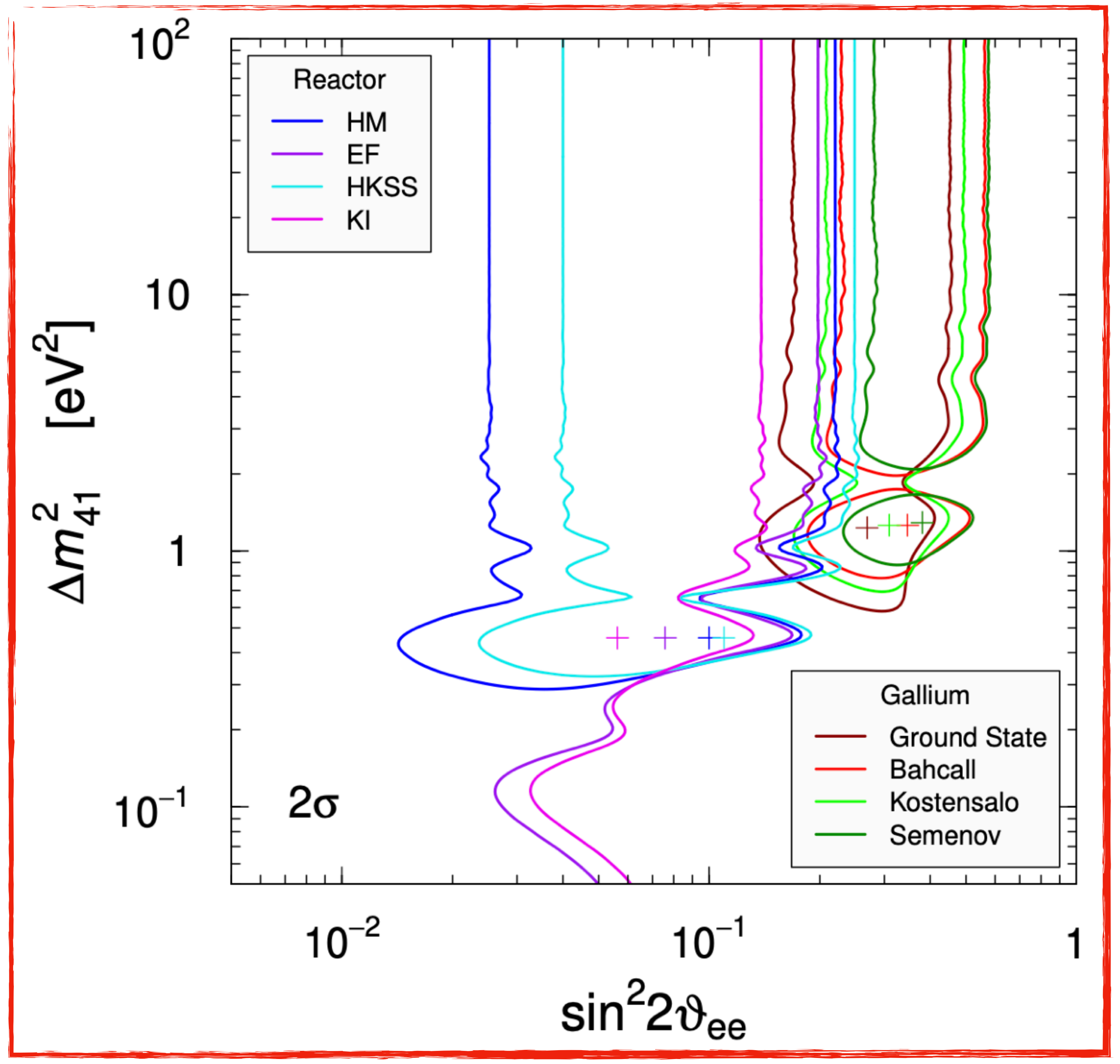
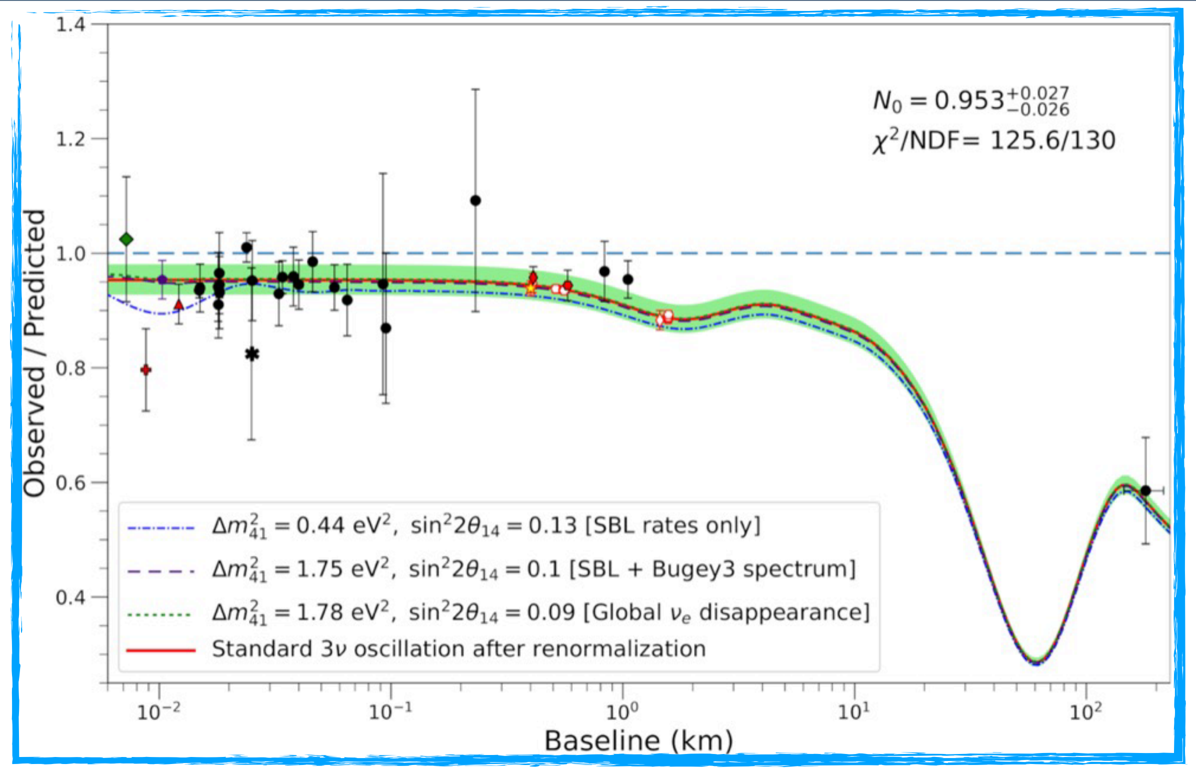


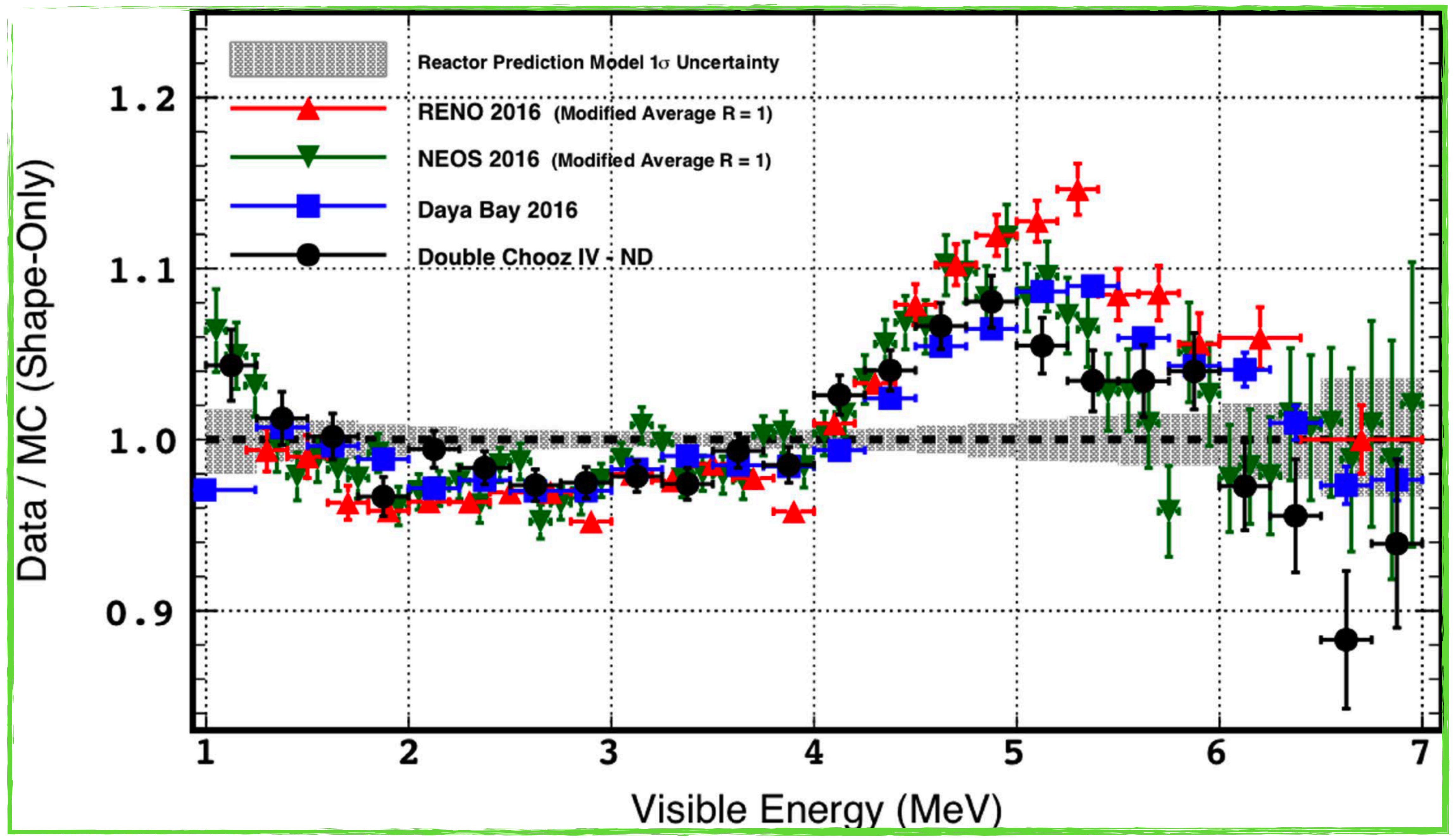
Allowed contours for the Gallium and Reactor anomalies.
JHEP 10 (2022) 164

Focus on reactor antineutrino anomalies

The « 5 MeV bump »

- On top of the **reactor antineutrino flux anomaly** → **Shape anomaly**, with a local excess in the antineutrino spectrum around 5 MeV.
- Excess independent of baseline → unrelated to neutrino oscillation mechanism.
- **Points towards inaccuracies in the reactor antineutrino flux predictions.**





Nature Physics 16, pp. 558–564 (2020)

Nuclear physics rather than BSM particle physics explanation ?

Reactor antineutrino flux predictions

Conversion vs. Summation method

- In nuclear reactors, $\bar{\nu}_e$ stem from the β^- decay of fission fragments from:
  - ❖ **^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu** in case of **LEU** commercial reactors, e.g. **Daya Bay** experiment.
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Reactor Antineutrino Flux

β^- decay of fission fragments from:
- ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu (**LEU**)
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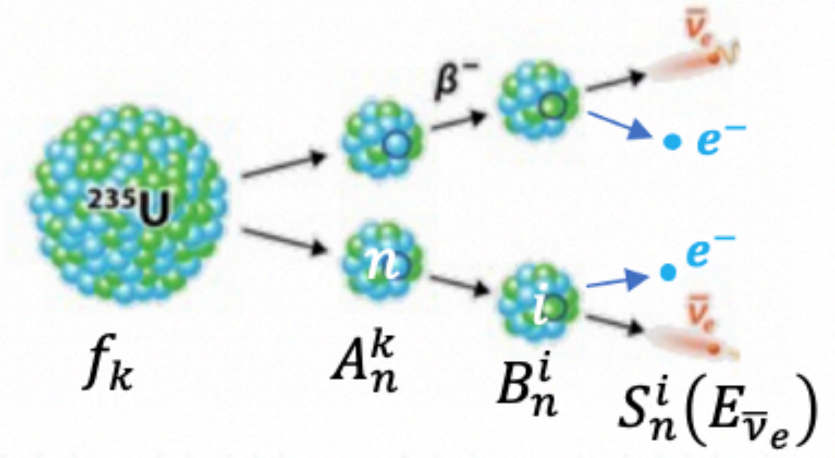

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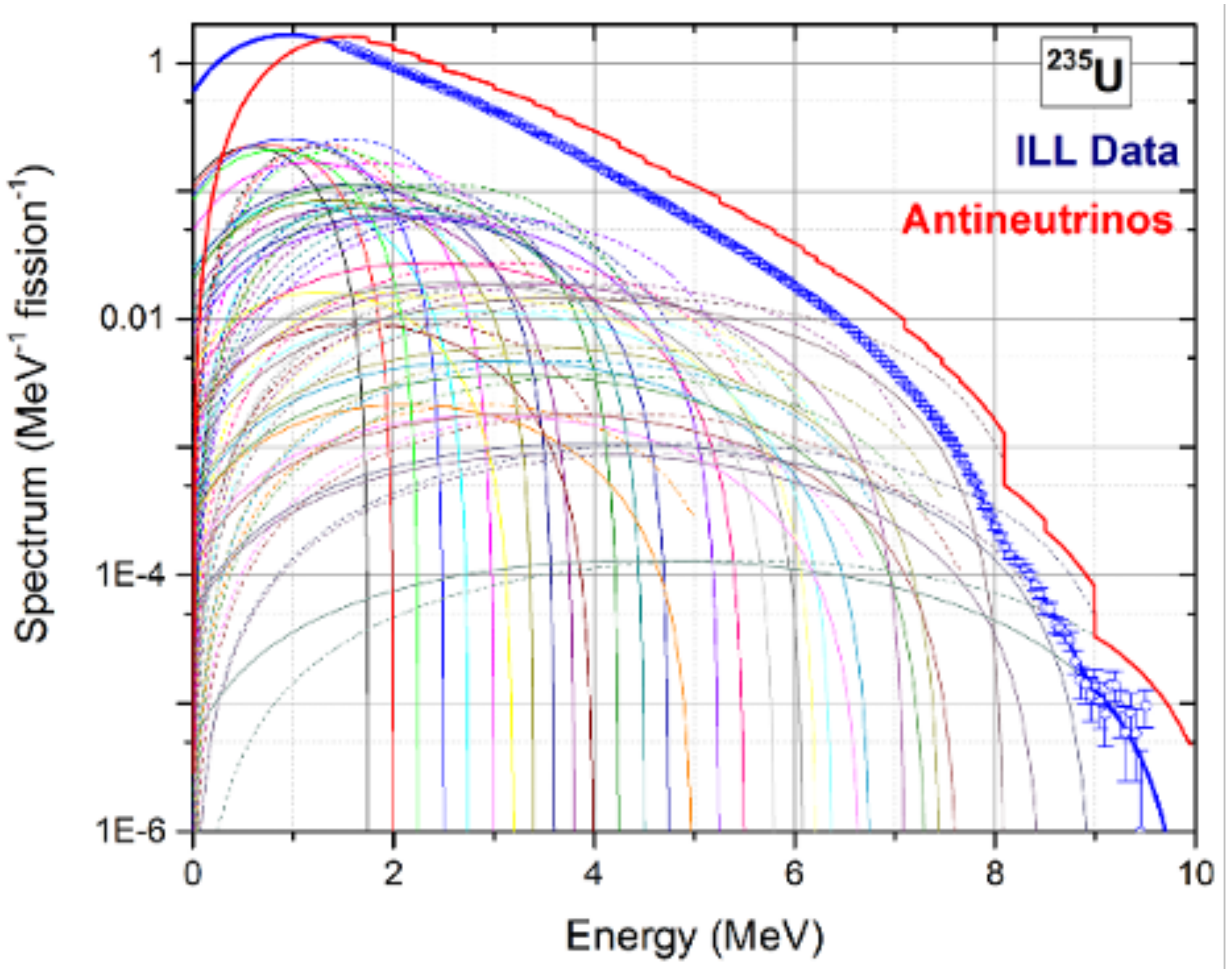
- Conversion Method
  - ❖ Prediction used by claims of Reactor Antineutrino Flux Anomaly.
  - ❖ Effective method to convert measured β spectra of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu to $\bar{\nu}_e$ spectrum → so-called ***Huber-Mueller*** (***HM***) prediction.



Huber-Mueller (HM) prediction for ^{235}U
PRC 84, 024617 (2011) / PRC 83, 054615 (2011)

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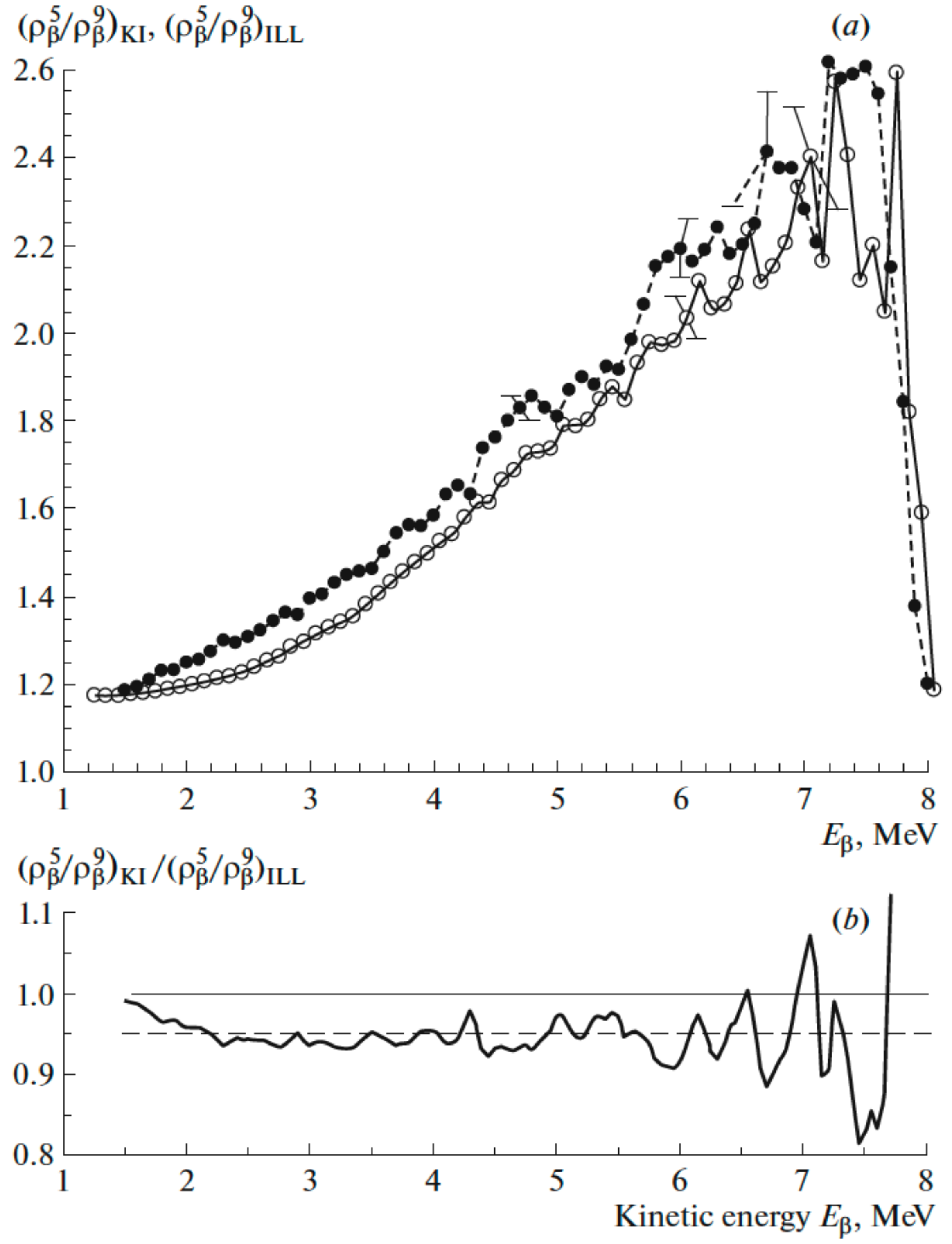
  - Suffers from **potential bias of the β spectra measurement**. HM prediction **corrected from such effect** in recent re-evaluation → *Kurchatov Institute* (*KI*) renormalized prediction.



Kurchatov Institute (KI) measurement of ^{235}U to ^{239}Pu ratio
*Phys. Rev. D **104**, L071301 (2021)*

With this flux correction:
- flux anomaly ↓~1σ
- 5 MeV bump stands !

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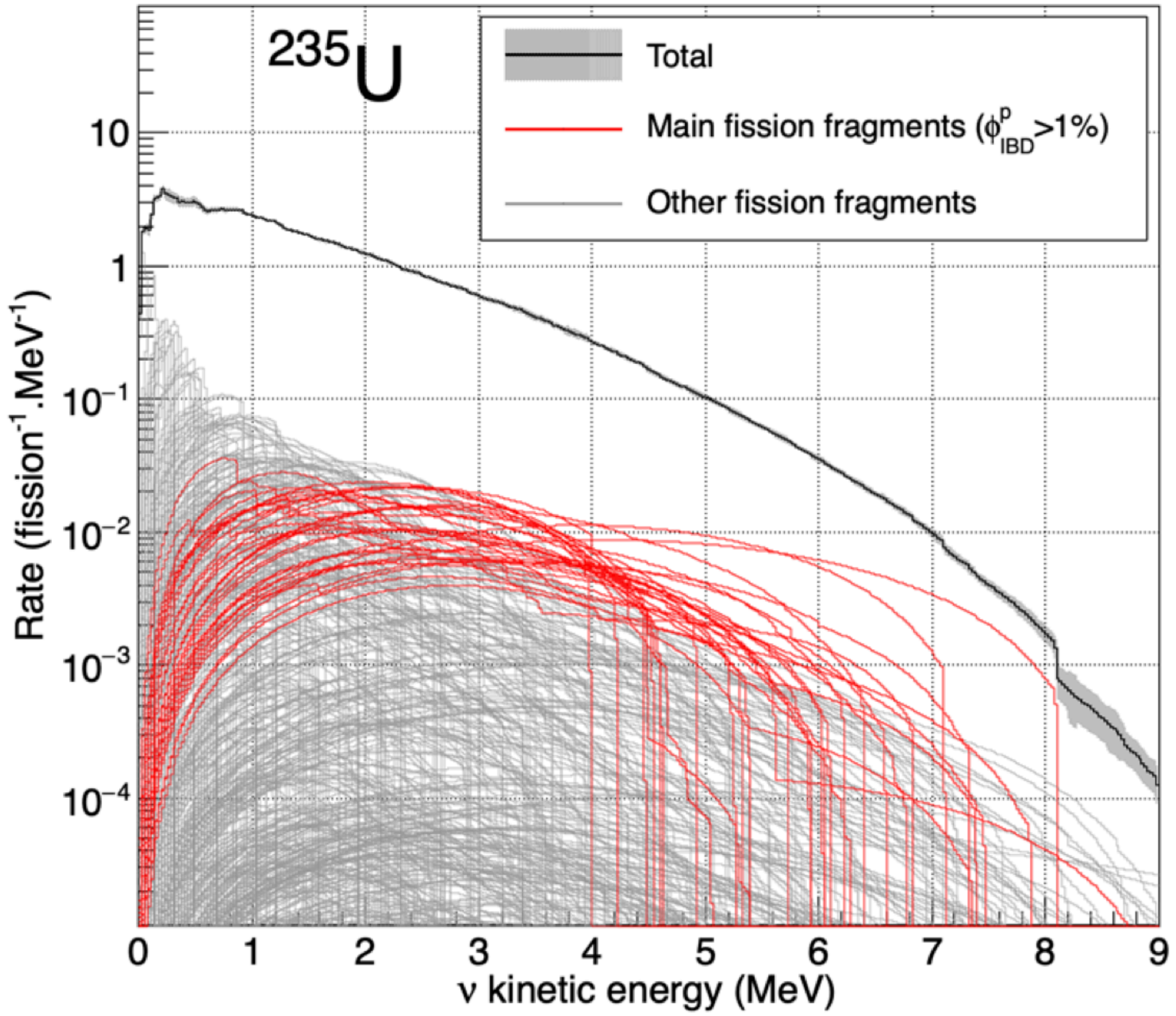
- Summation Method
  - Sum up the $\bar{\nu}_e$ spectrum of all (~10 000) β decay branches of all fission fragments, tabulated in **nuclear data bases**.



Summation prediction for ^{235}U
Phys. Rev. C ***108***, *055501*

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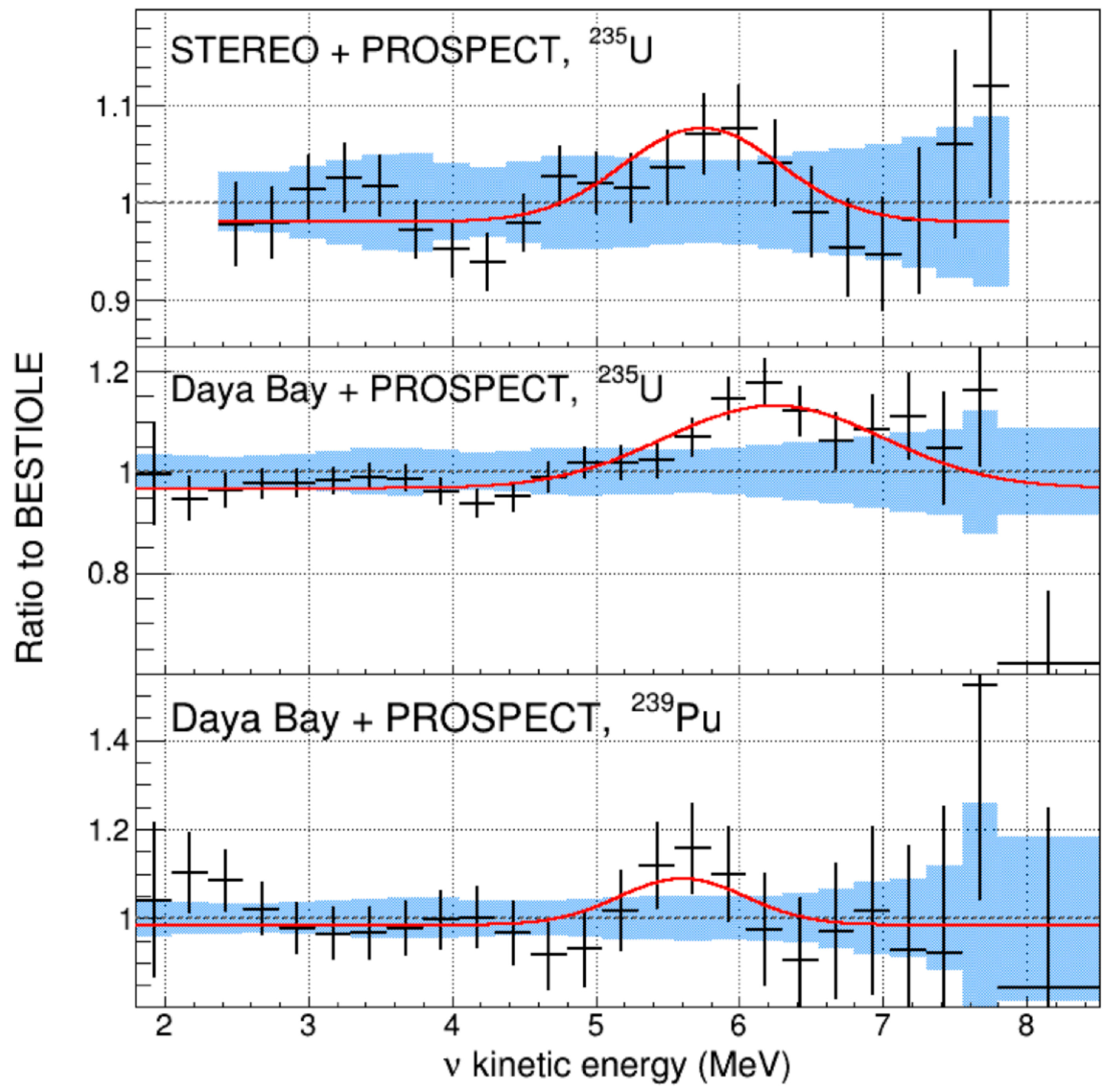

Summation prediction compared to partial neutrino datasets from STEREO, PROSPECT, Daya Bay
Phys. Rev. C ***108***, *055501*

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Reactor antineutrino flux predictions

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Reactor Antineutrino Flux

β^- decay of fission fragments from:
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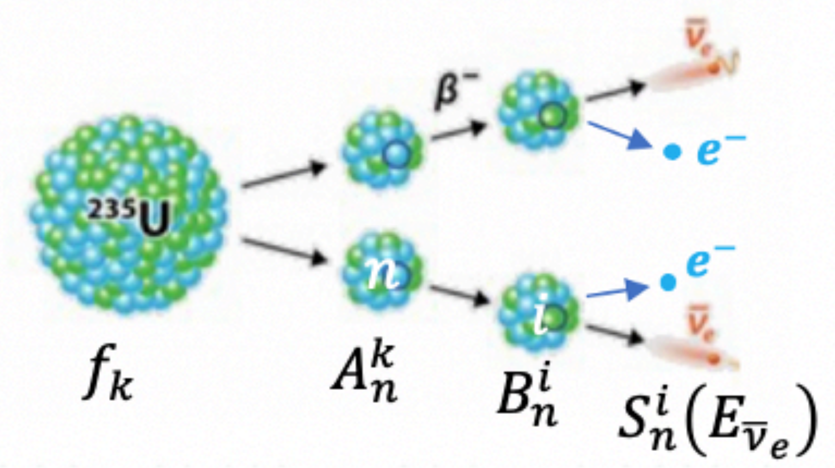
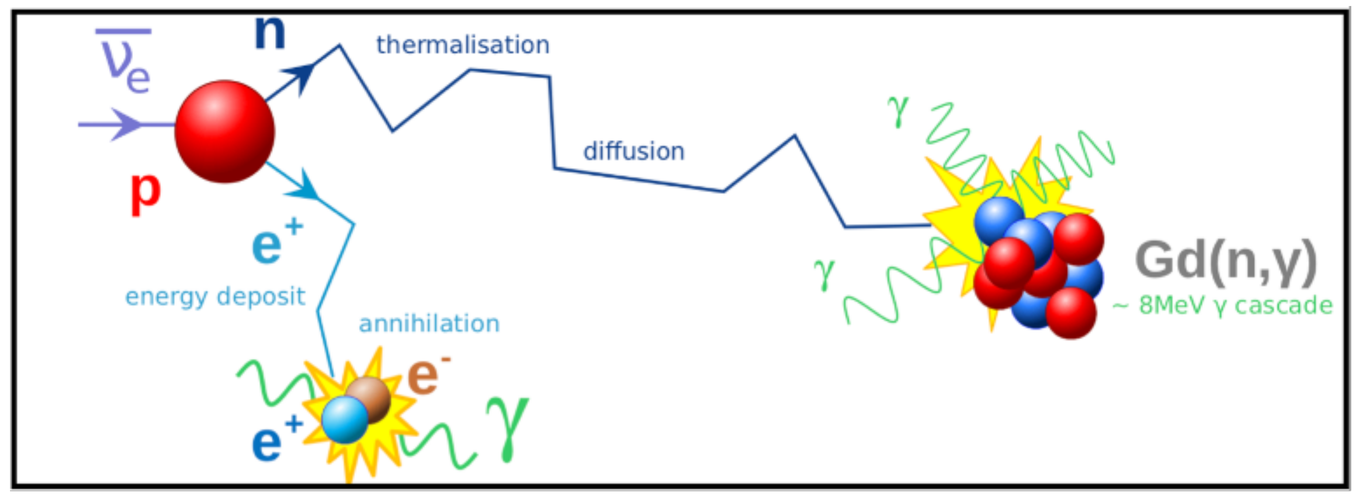
- ^{235}U-only (**HEU**)



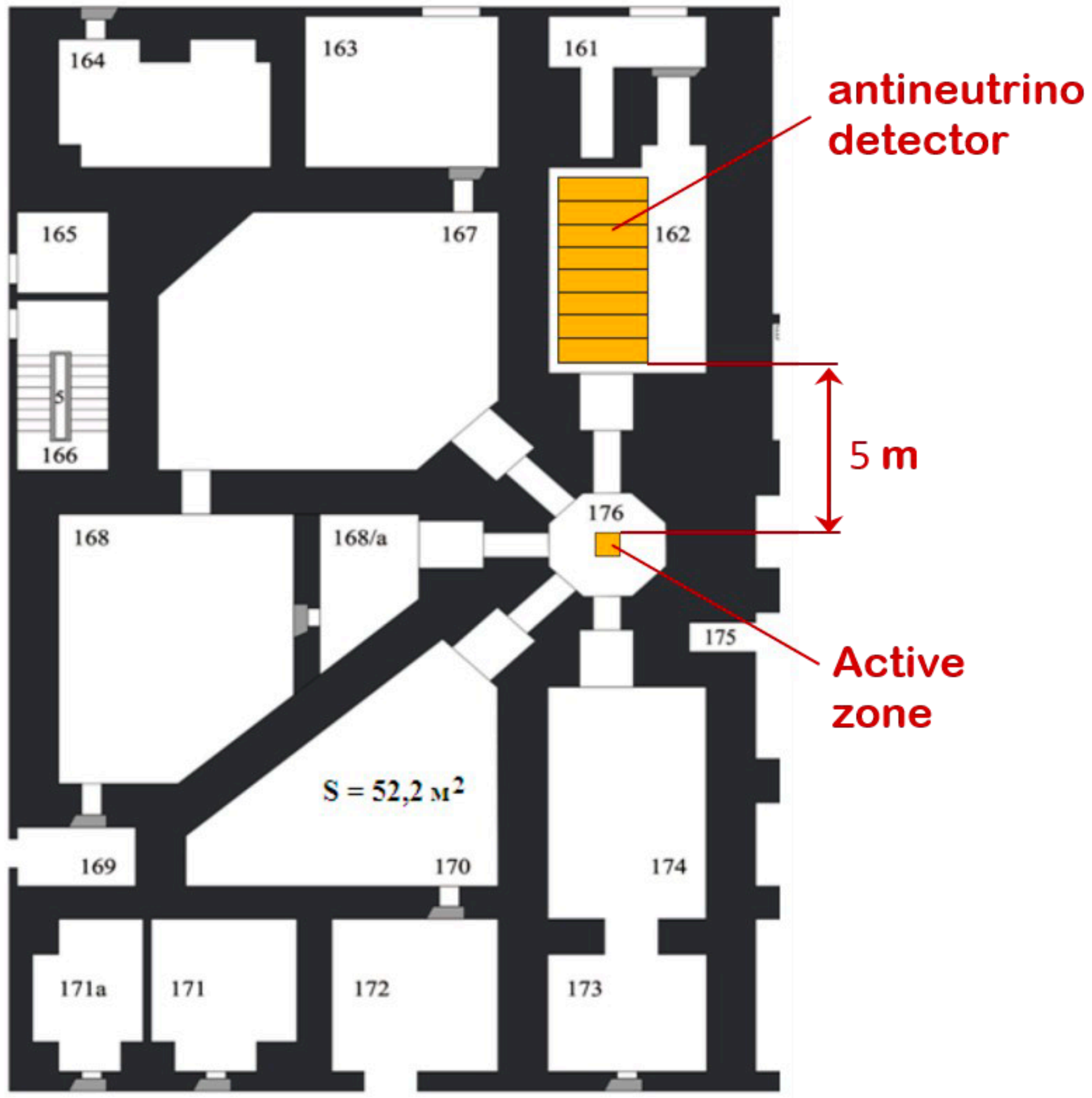
Other predictions (HKSS…) but as of today, none explains both flux & shape anomalies.
Yet, sterile neutrino as explanation of the flux anomaly seems less relevant … IS IT ?

Hints for a sterile neutrino signal from the Neutrino-4 experiment

- The Neutrino-4 experiment in short:
  - ❖ ~200k $\bar{\nu}_e$, with S:B ~ 0.5.
  - ❖ **HEU** experiment, i.e. ^{235}**U-only** induced neutrinos.
  - ❖ **Very-short baseline** experiment with movable detector, spanning a baseline **6.4 - 11.9 m**.



$\bar{\nu}_e$ detection via IBD reaction



Schematic view of the Neutrino-4 experiment

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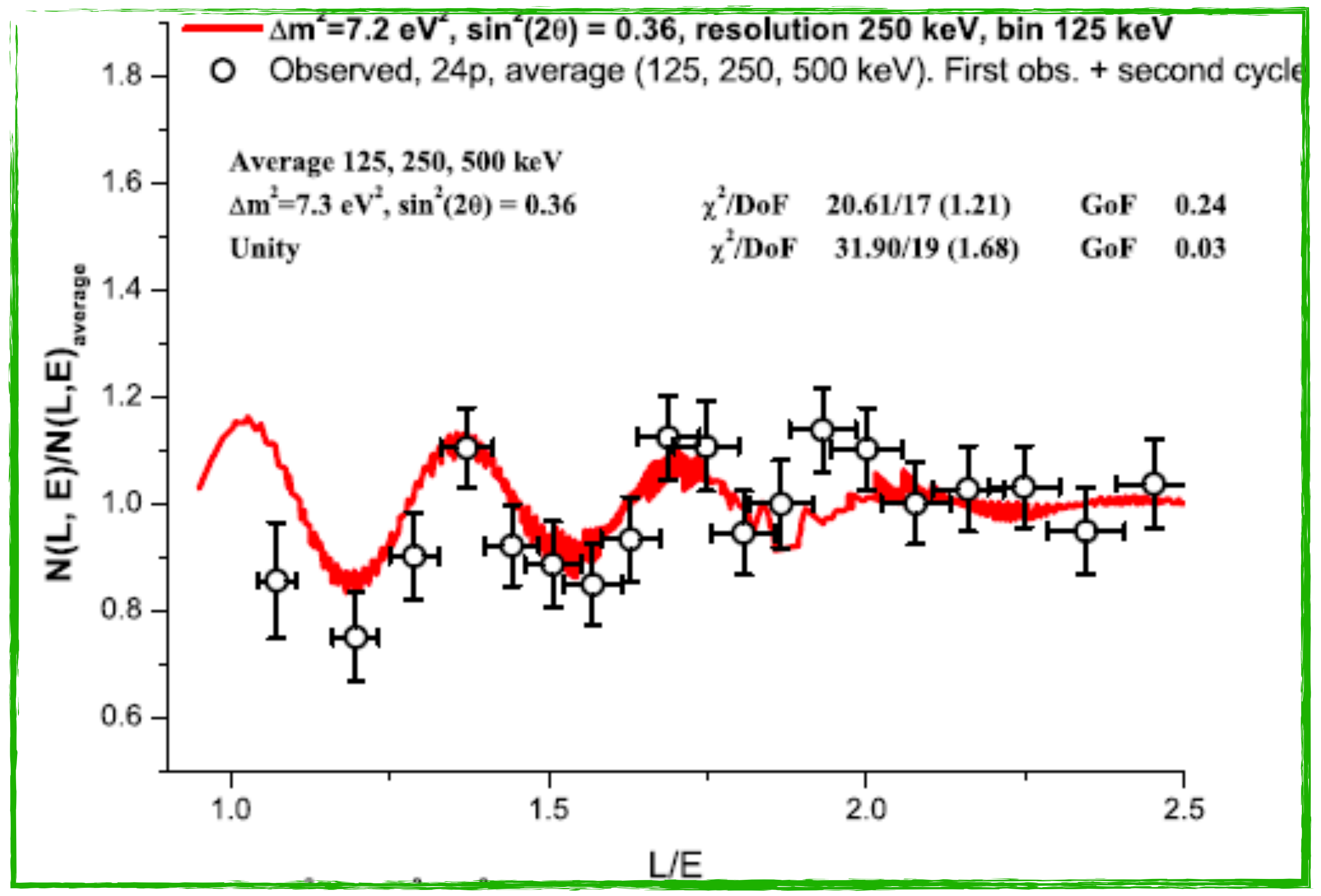
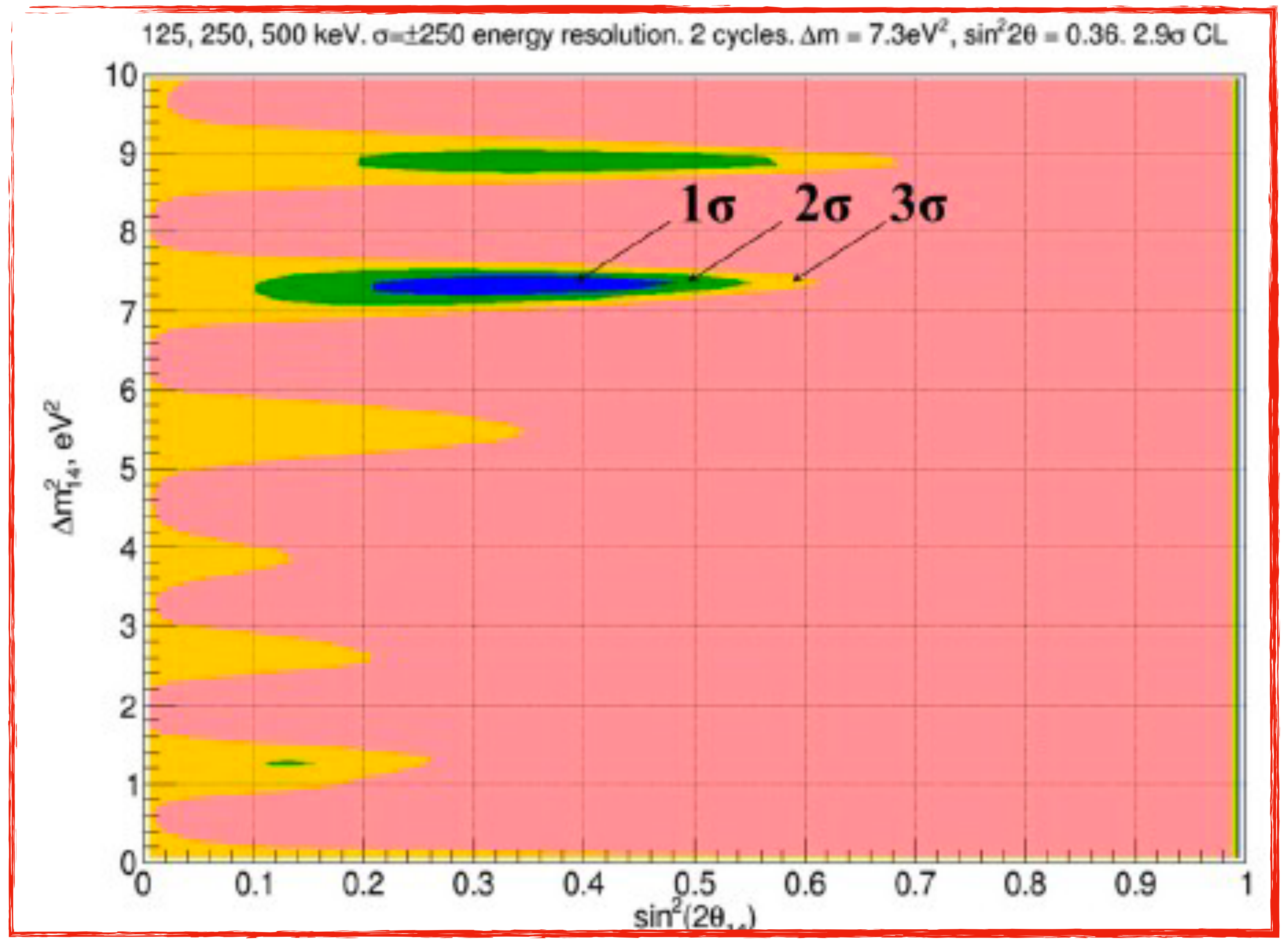


- **Flux model-independent analysis** consisting in measuring the neutrino rate at different L/E baselines, taking as reference the baseline-averaged spectrum:
  - ➡ Sterile neutrino signal at **2.7σ** level, with $\sin^2(2\theta_{14}) \approx 0.36,\ \Delta m^2_{14} \approx 7.3\ eV^2$ — *Phys. Rev. D **104**, 032003*
  - ➡ **Questions were raised** as of e.g. potentially missed oscillation-mimicking systematic effects (*arXiv:2006.13147*), potential mistreatment of energy resolution and approximate statistical analysis (*Phys. Lett. B **816**, 136214*).



Neutrino-4 experiment allowed contour

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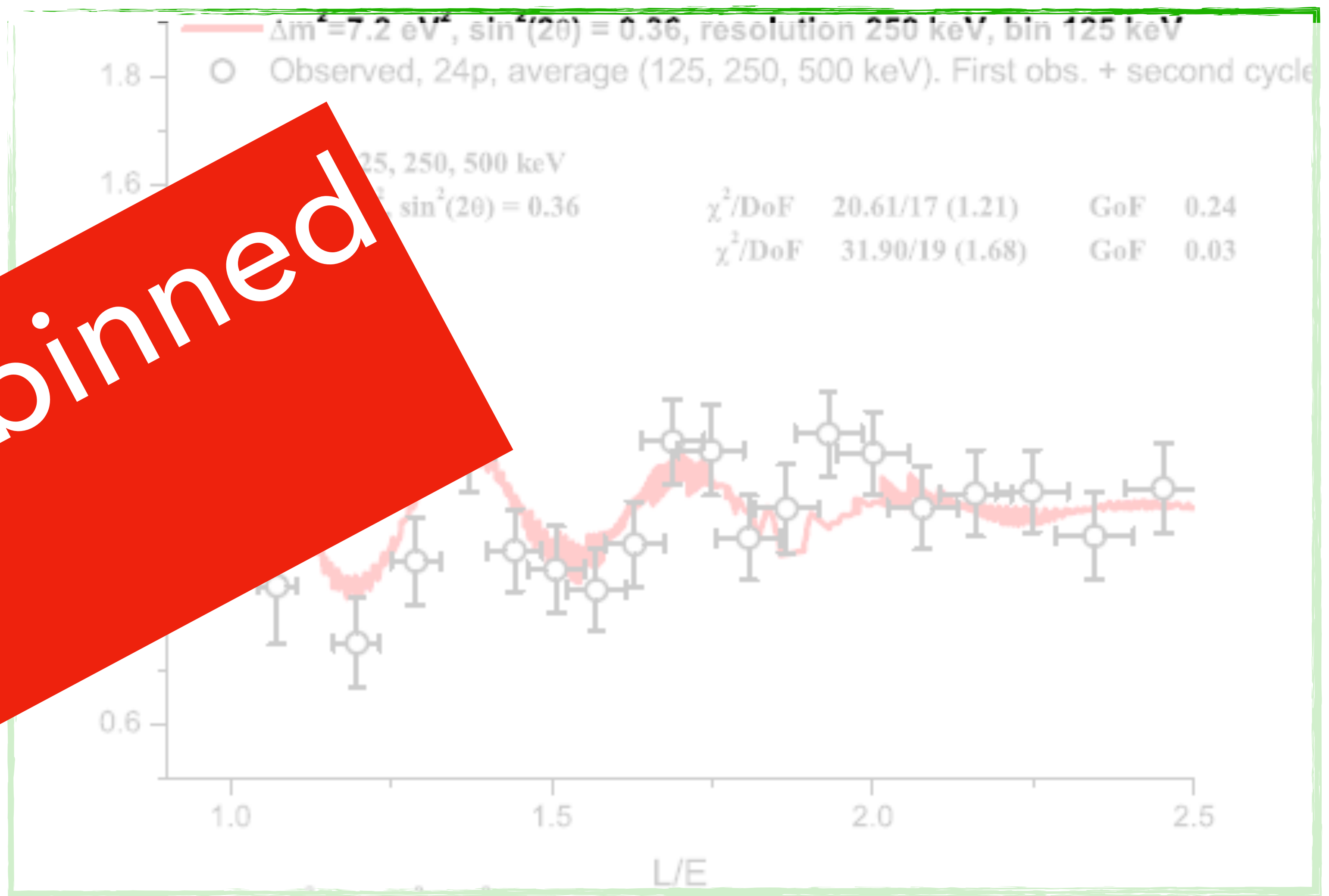
Need more data on absolute and baseline-binned spectrum measurements



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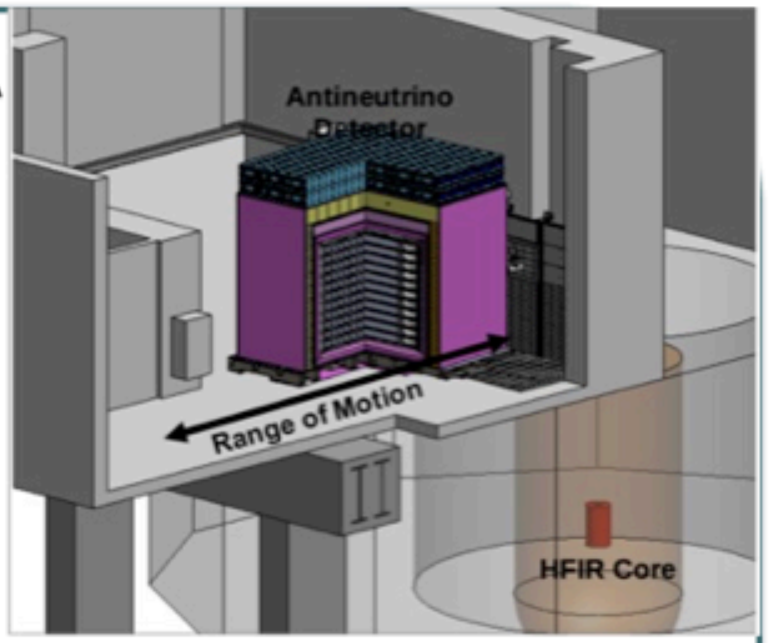
STEREO, PROSPECT & Daya Bay as reactor antineutrino experiments

PROSPECT

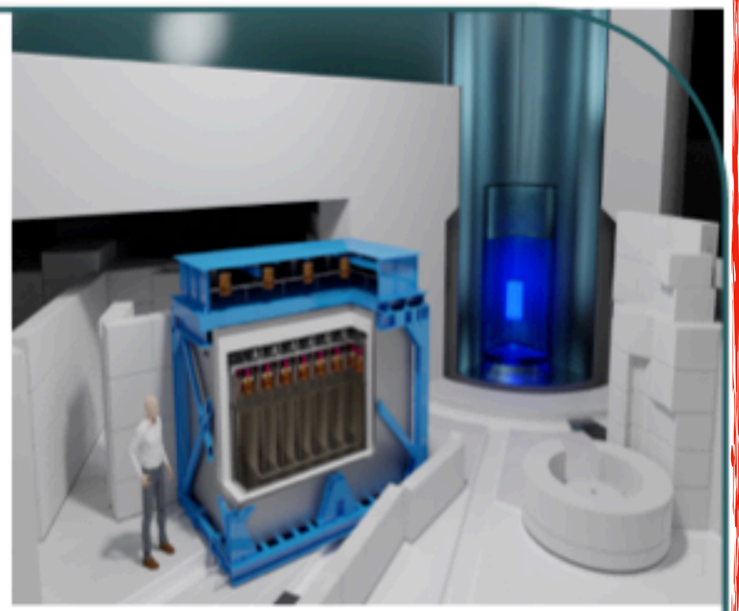


Experimental Site (HFIR, USA):
- 85 MWth HEU reactor
- Compact core Ø 40cm, h=50cm
- >99% of flux from ^{235}U fissions

Detector design:
- Segmented detector, 154 segments
- Baseline coverage [6.9,8.9] m
- Li-doped LS, PSD

Physics Results Highlights:
- 60k IBD counts
- Spectral shape analysis
- Oscillation analysis
- S:B ~ 4

STEREO

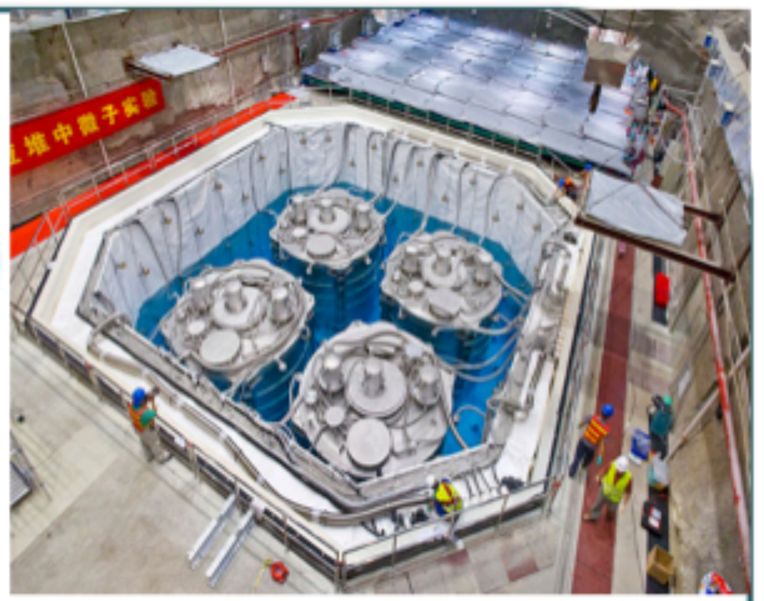


Experimental Site (ILL, France):
- 58 MWth HEU reactor
- Compact core Ø 40cm, h=80cm
- >99% of flux from ^{235}U fissions

Detector design:
- Segmented detector, 6 cells
- Baseline coverage [9.4,11.2] m
- Gd-doped LS, PSD

Physics Results Highlights:
- 107k IBD counts
- Absolute flux measurement
- Spectral shape analysis
- Oscillation analysis
- S:B ~ 1

Daya Bay θ13



Experimental Site (Daya Bay, China):
- 6-2.9 GWth LEU reactors
- Flux from evolving fuel mixture

Detector design:
- 8 antineutrino detectors
- Baseline coverage: [360,1900] m
- Gd-doped LS

Physics Results Highlights:
- 5.55 x 10^6 IBD counts
- Absolute flux measurement
- Oscillation analysis
- Spectral shape analysis
- background/signal <2%

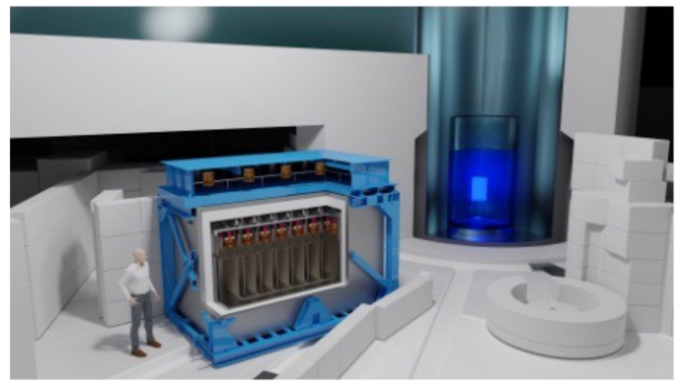
- **HEU → ^{235}U spectrum absolute meas.**
- **Very short baselines coverage: ~1-10m**

  → eV scale sensitivity for sterile

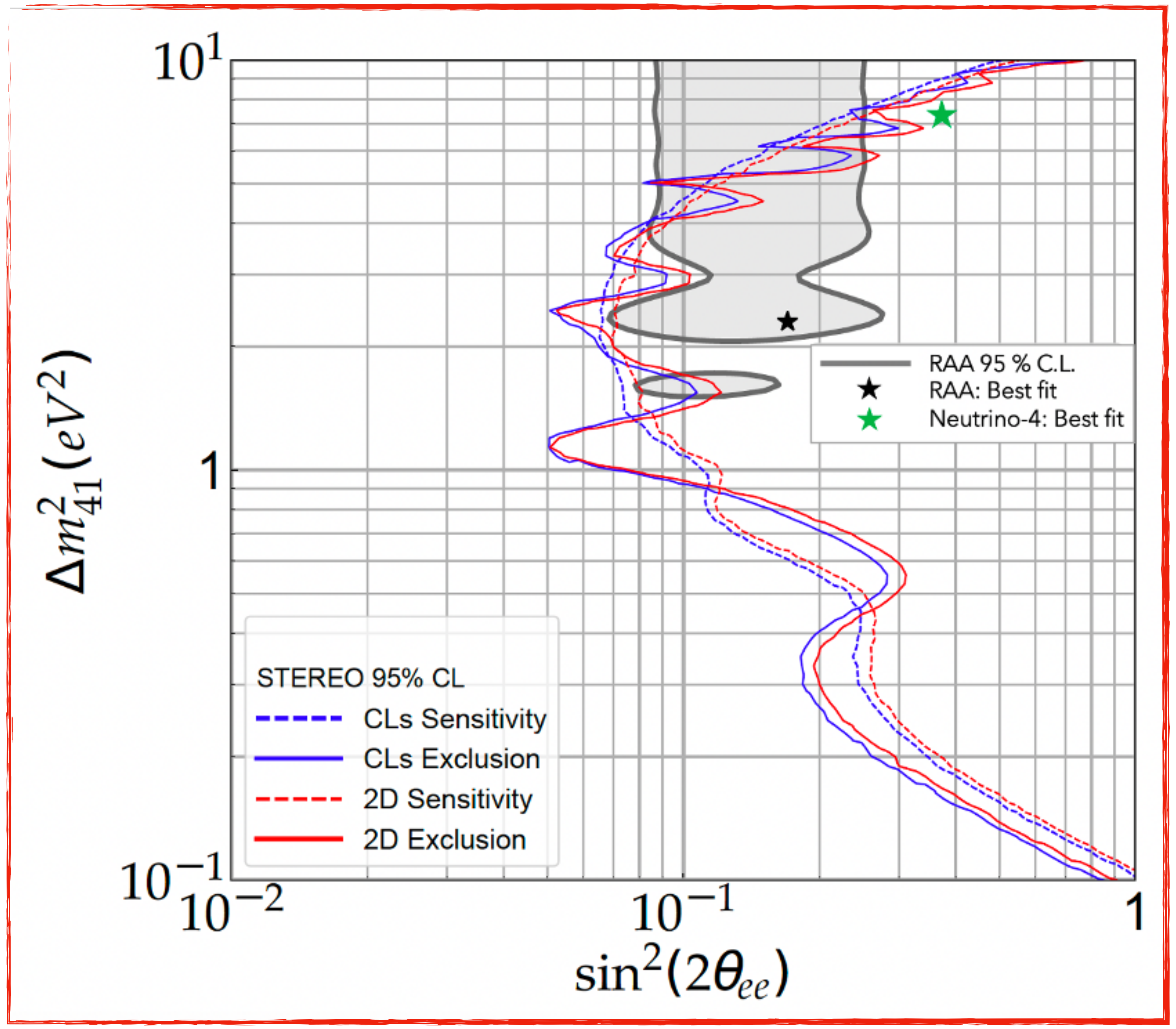
- **LEU → ^{235}U, ^{239}Pu spectrum extraction**
- **Short baselines coverage: ~100-1000m**

  → sub-eV scale sensitivity for sterile

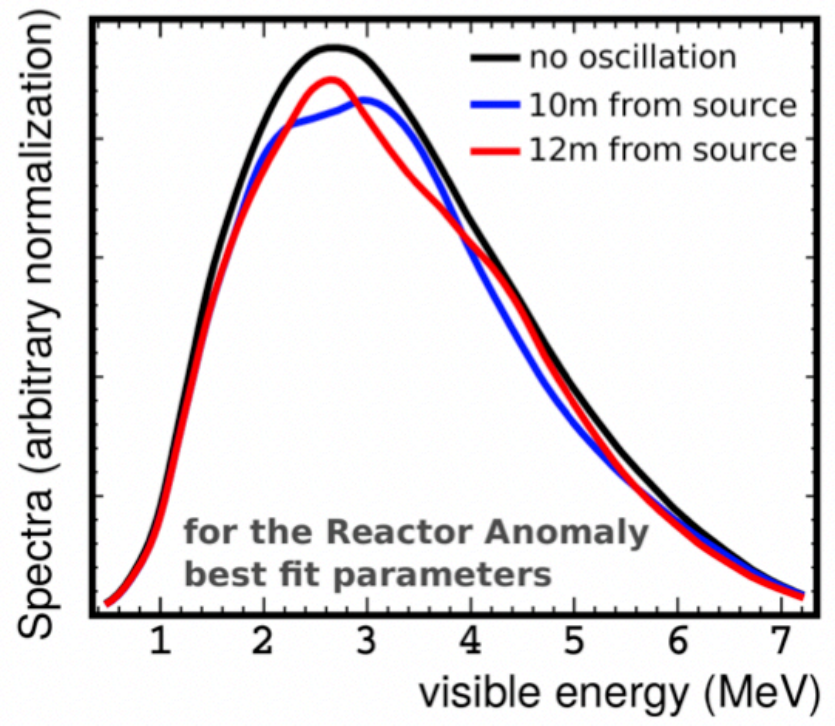
STEREO highlights — 2018-2020 final dataset



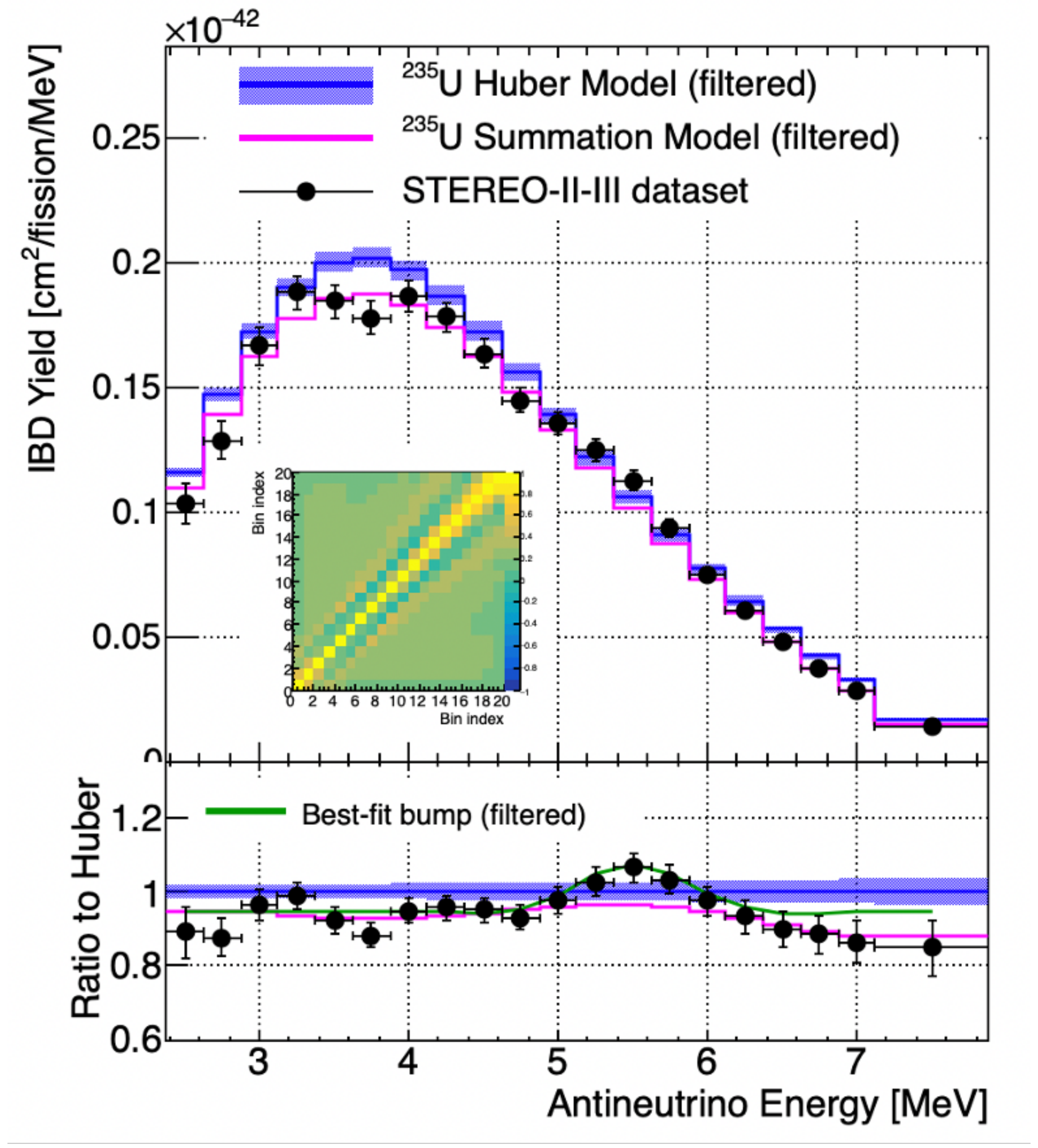
- **Flux model-independent analysis,** with a fitted average spectrum across the 6 baseline cells.
- ^{235}U baseline-binned data **compatible with no-oscillation hypothesis** (p-value ~ 0.52).
- Best-fit point of ***model-dependent* Reactor Antineutrino Flux Anomaly signal excluded at ~4σ**.
- Best-fit point of ***model-independent* Neutrino-4 signal excluded at ~3.3σ**.



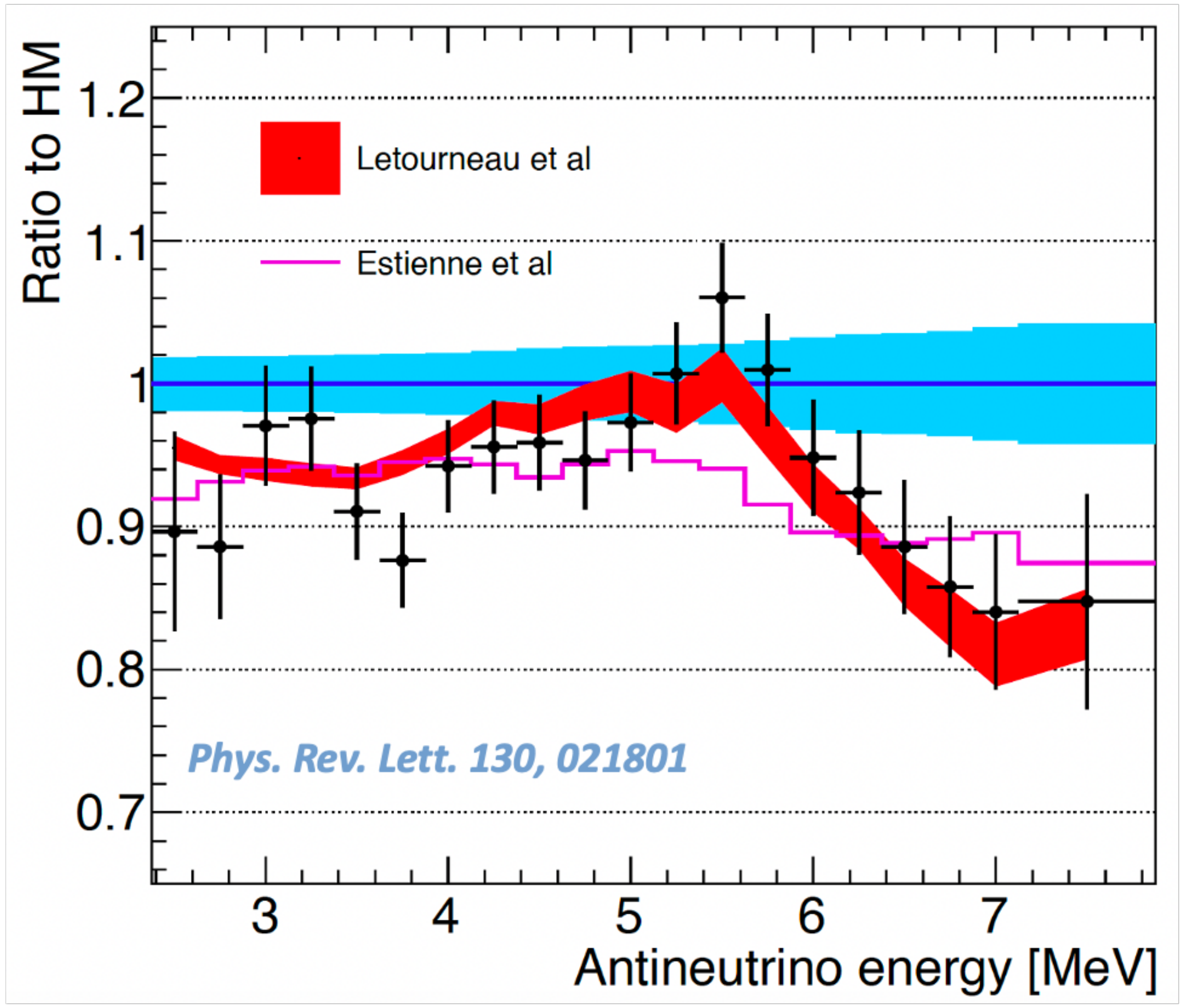
STEREO exclusion contour
Nature, 613:257–261, 2023

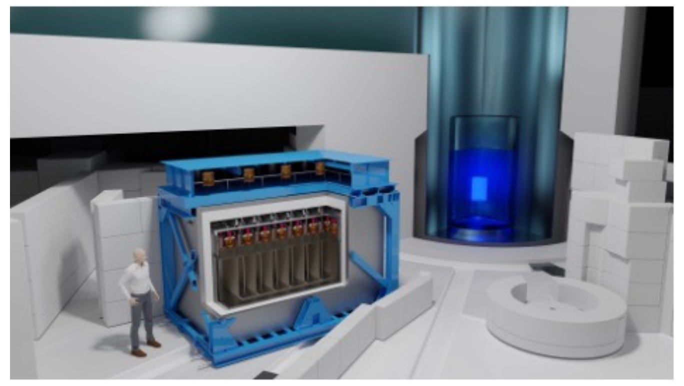


STEREO highlights — 2018-2020 final dataset



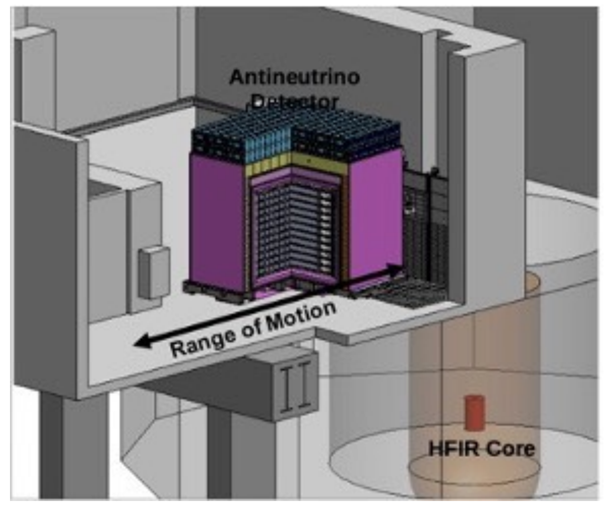
STEREO measured ^{235}U spectrum
Nature, 613:257–261, 2023





- Precision of direct measurement of ^{235}U-induced neutrino spectrum **starts to constrain the nuclear observables** → Tentative effective correction of known bias of the summation method yielded unprecedented agreement with STEREO ^{235}U spectrum.

PROSPECT recent highlights — 2018 full dataset



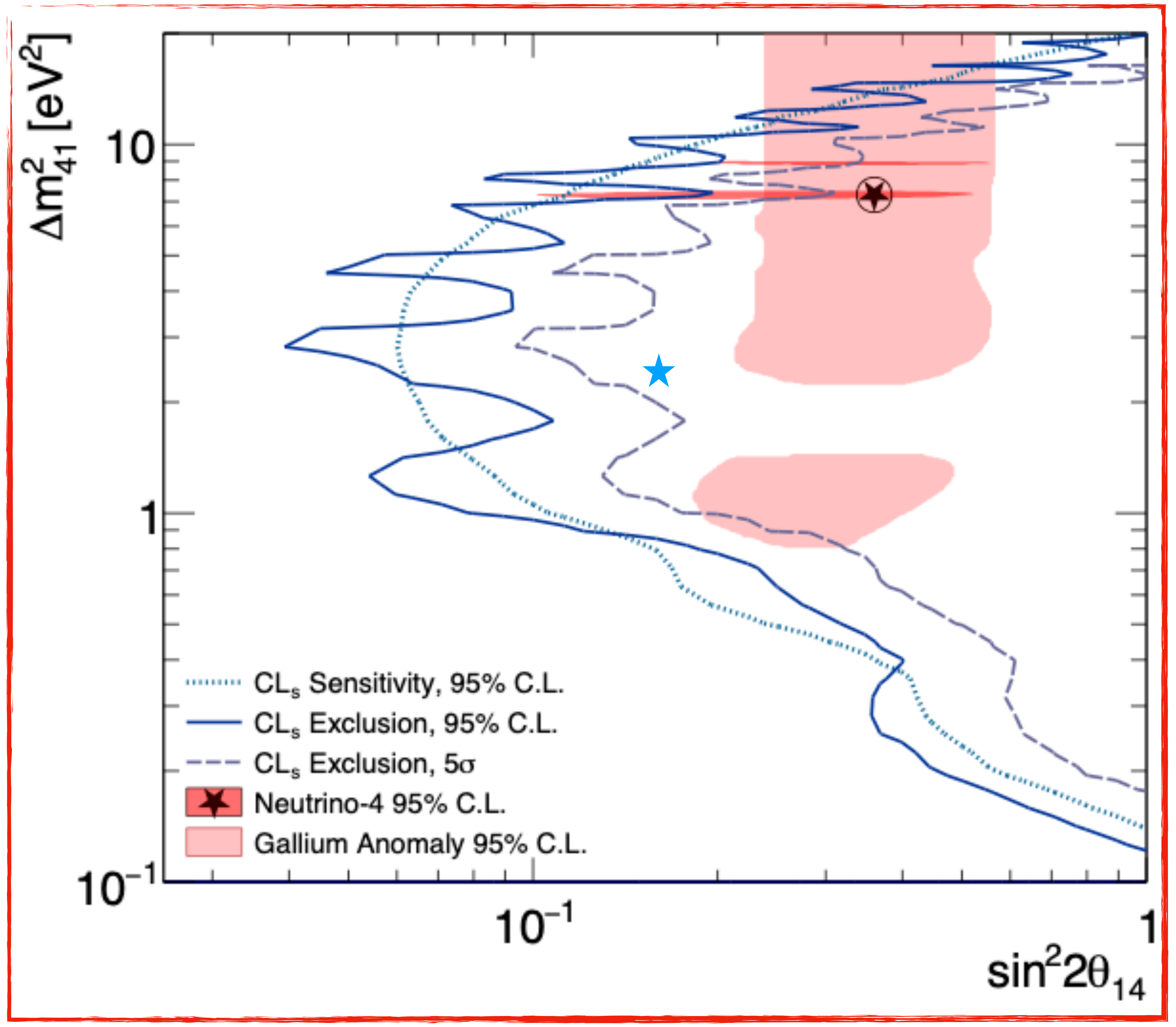
- Recent improvement of IBD selection improved the signal to background ratio from 1.4 to ~4 → **Double the statistical power of the experiment**.

- **Flux model-independent analysis,** with (L, E) binned data.

- ^{235}U baseline-binned data **compatible with no-oscillation hypothesis** (p-value ~ 0.87).

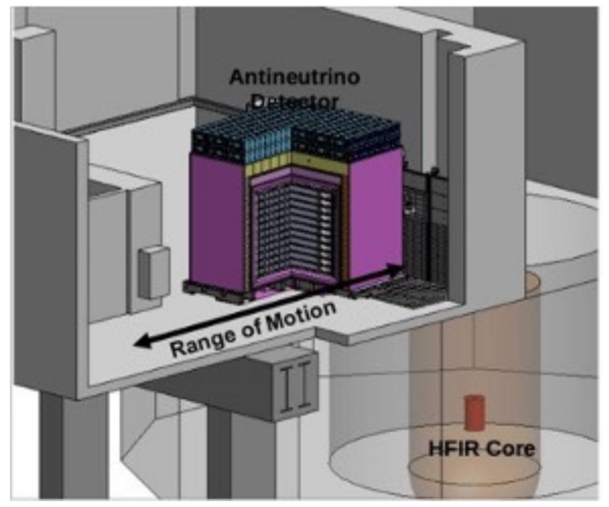
- Best-fit point of ***model-dependent* Reactor Antineutrino Flux Anomaly signal excluded at >5σ**.

- Best-fit point of ***model-independent* Neutrino-4 signal excluded at >5σ**.

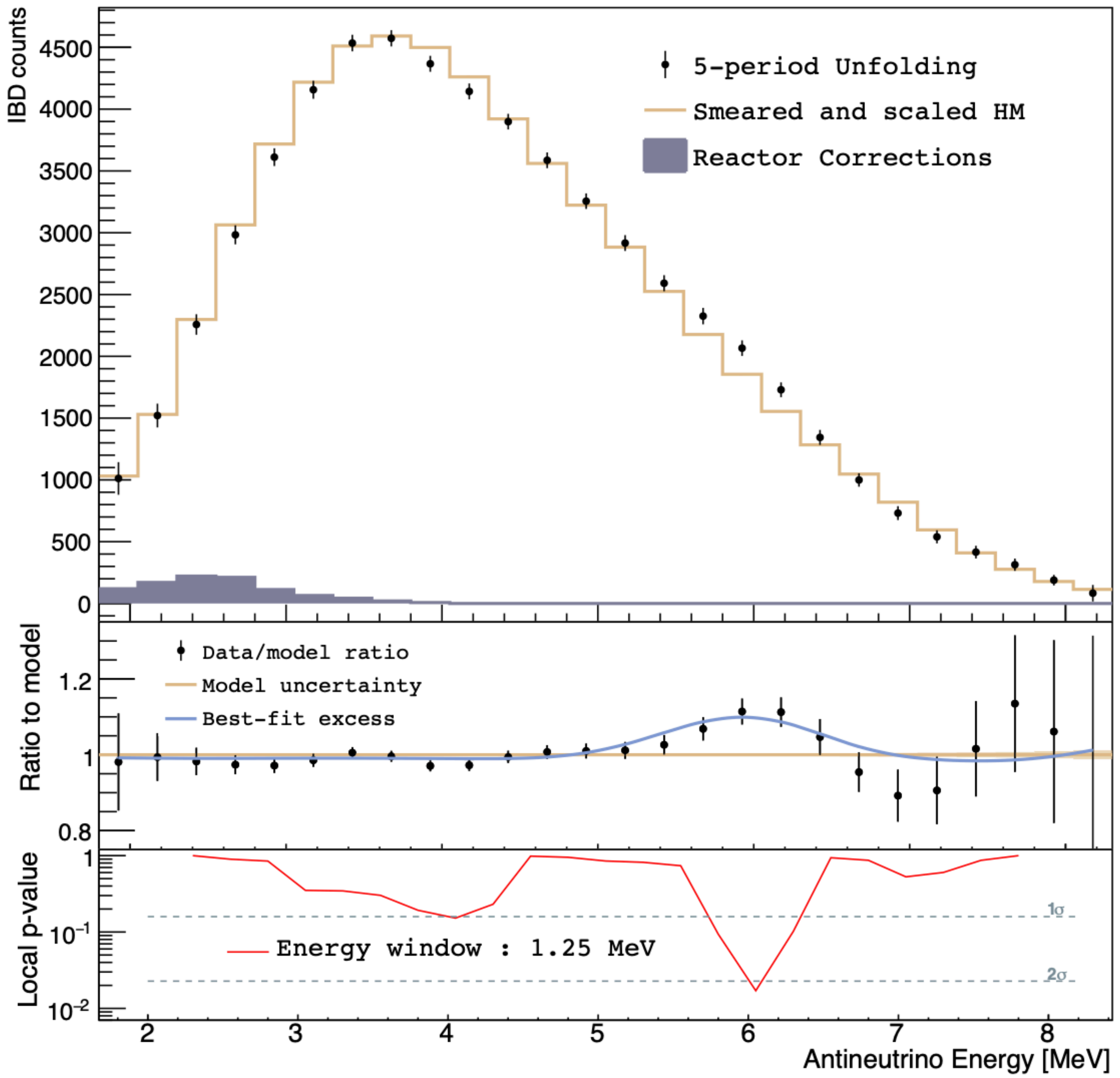


PROSPECT exclusion contour
Phys. Rev. Lett. ***134****, 151802 (2025)*

PROSPECT recent highlights — 2018 full dataset

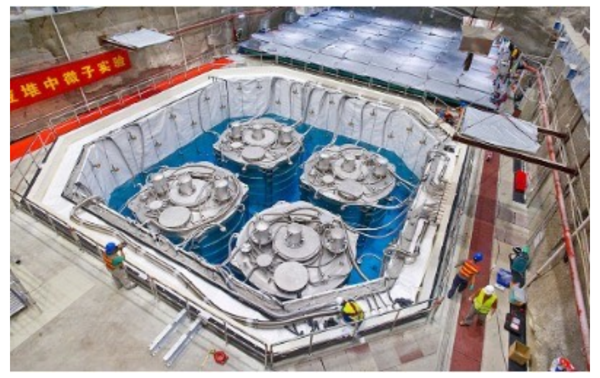


- Precision measurement of ^{235}U spectrum shape.
  - ➡ Shape anomaly confirmed for ^{235}U, akin to STEREO measurement.
  - ➡ Hints towards mixed isotopic origin of shape anomaly.

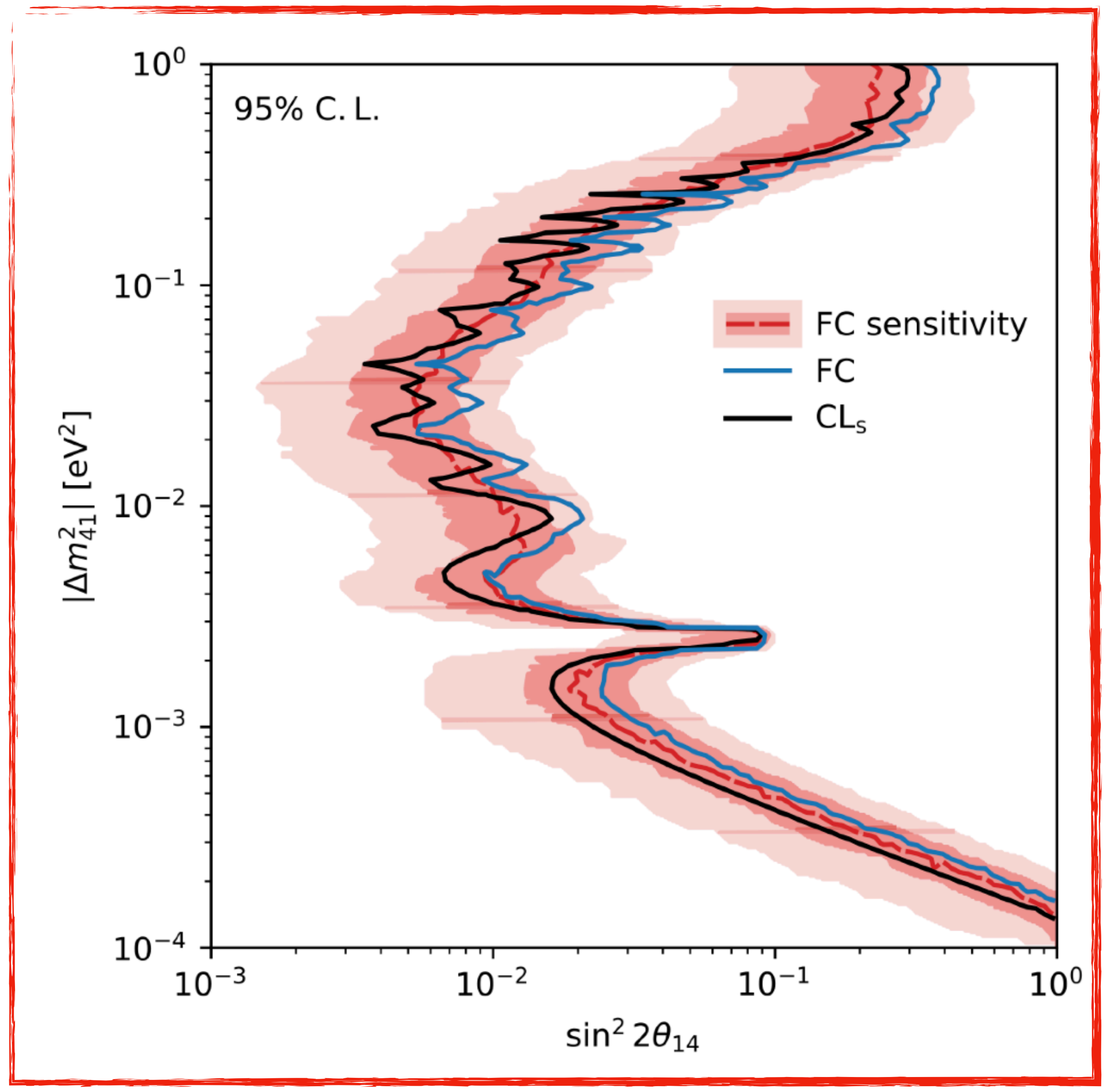


PROSPECT measured ^{235}U spectrum
*Phys. Rev. Lett. **131**, 021802 (2023)*

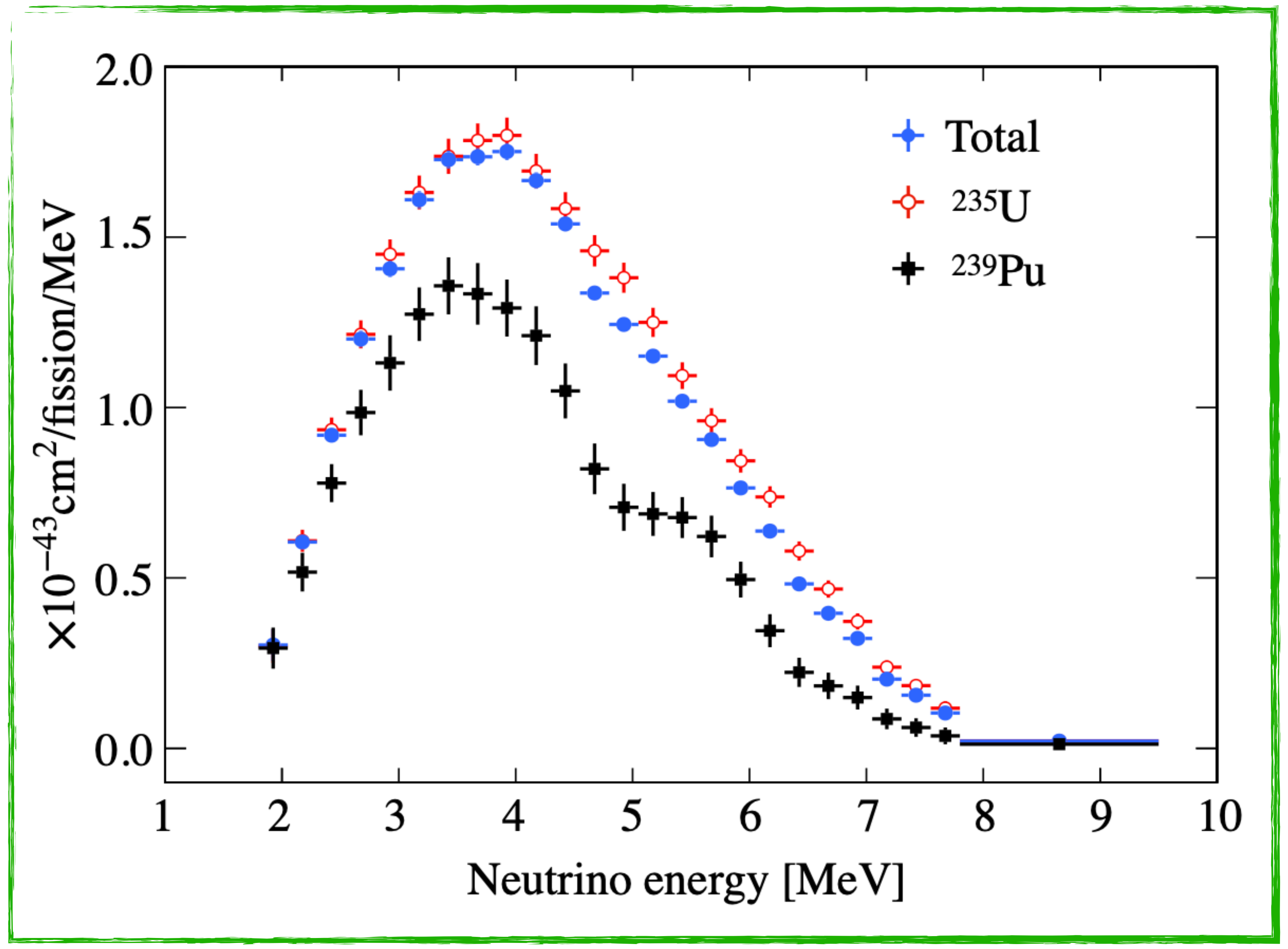
Daya Bay recent highlights — 2011-2020 full dataset



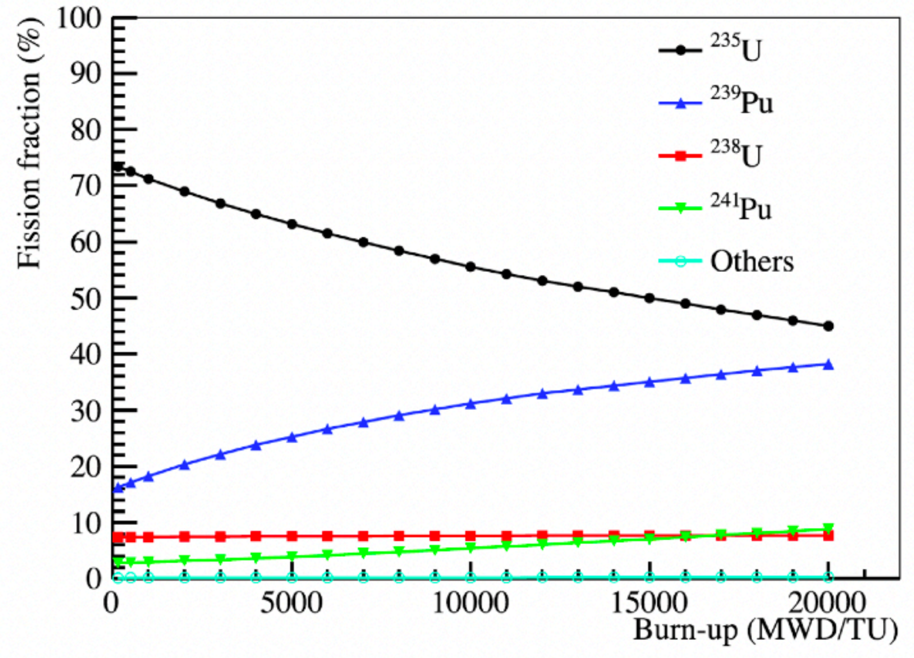
- **Flux model-independent analyses,** with average spectrum fitted or measured at the near detectors.
- Baseline-binned data **compatible with no-oscillation hypothesis** (p-value ~ 0.86).
- Extraction of **^{235}U and ^{239}Pu absolute spectra**, by leveraging reactor fuel content evolution.



Daya Bay exclusion contour
Phys. Rev. Lett. ***133****, 051801 (2024)*



Daya Bay extracted ^{235}U / ^{239}Pu spectra
Phys. Rev. Lett. ***134****, 201802 (2025)*



Statistical compatibility of reactor data ?

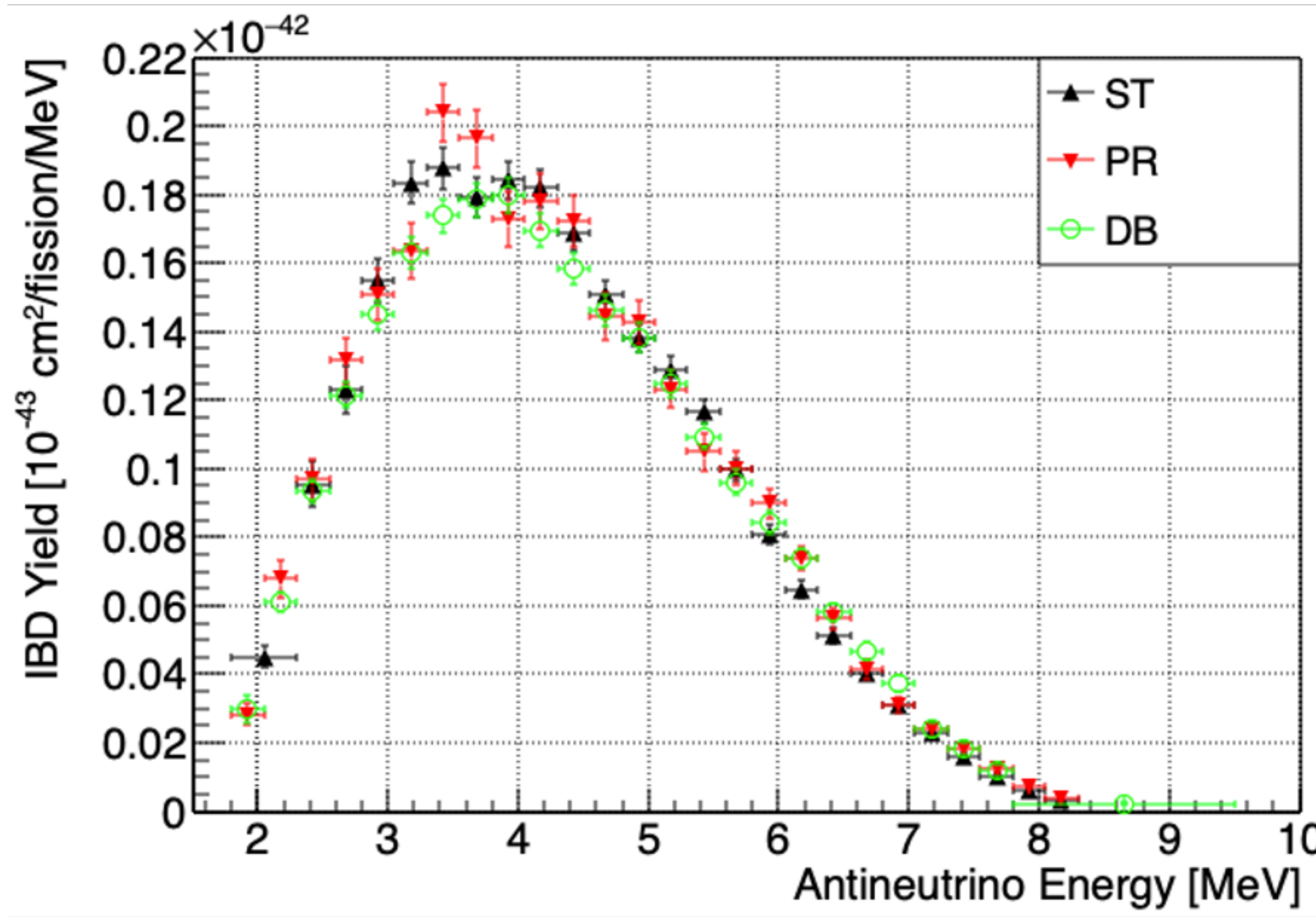
- STEREO, PROSPECT and Daya Bay have all performed model-independent searches for sterile neutrinos & measurements of the ^{235}U antineutrino spectrum. **Are they compatible ?**

- Standard experimental result is a ***doublet***, provided in **antineutrino energy space** (**unfolding**):
  - ➡ ***Unfolded spectrum*** Φ , reported in antineutrino energy from unfolding / deconvolution procedure.
  - ➡ ***Covariance matrix*** $\mathrm{Cov}(\Phi)$ of the unfolded spectrum.

- ***Naive*** comparison of ^{235}U measurements from STEREO, PROSPECT and Daya Bay done by fitting a common spectrum:

$$\chi^2 = \min_{\Phi} \left\{ \left|\left|\Phi_{ST} - \Phi\right|\right|^2_{\mathrm{Cov}(\Phi_{ST})^{-1}} + \left|\left|\Phi_{PR} - \Phi\right|\right|^2_{\mathrm{Cov}(\Phi_{PR})^{-1}} + \left|\left|\Phi_{DB} - \Phi\right|\right|^2_{\mathrm{Cov}(\Phi_{DB})^{-1}} \right\}$$

→ Suffers from biases from unfolding procedure.



STEREO, PROSPECT, Daya Bay final ^{235}U measurements

Statistical compatibility of reactor data ?

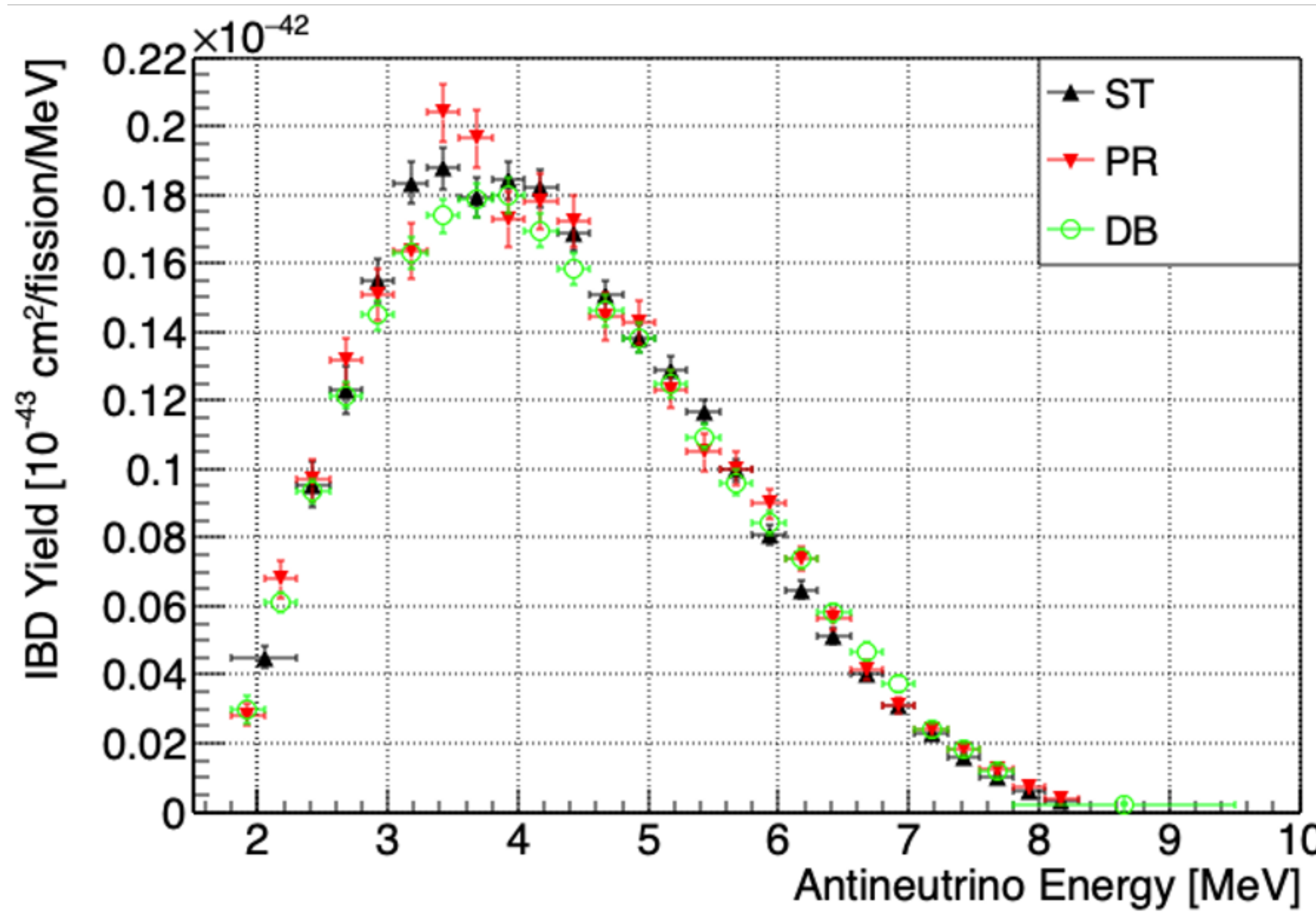
- STEREO, PROSPECT and Daya Bay have all performed model-independent searches for sterile neutrinos & measurements of the ^{235}U antineutrino spectrum. **Are they compatible ?**

- Now experimental result is a ***triplet***, provided in **antineutrino energy space** (**unfolding**):
  - ➡ ***Unfolded spectrum*** Φ, reported in antineutrino energy from unfolding / deconvolution procedure.
  - ➡ ***Covariance matrix*** $\mathrm{Cov}(\Phi)$ of the unfolded spectrum.
  - ➡ ***Filter matrix*** A, to correct from the unfolding intrinsic bias in the comparison — *2017 JINST 12 P10002, Phys. Rev. Lett.* ***128****, 081802 (2022)*.

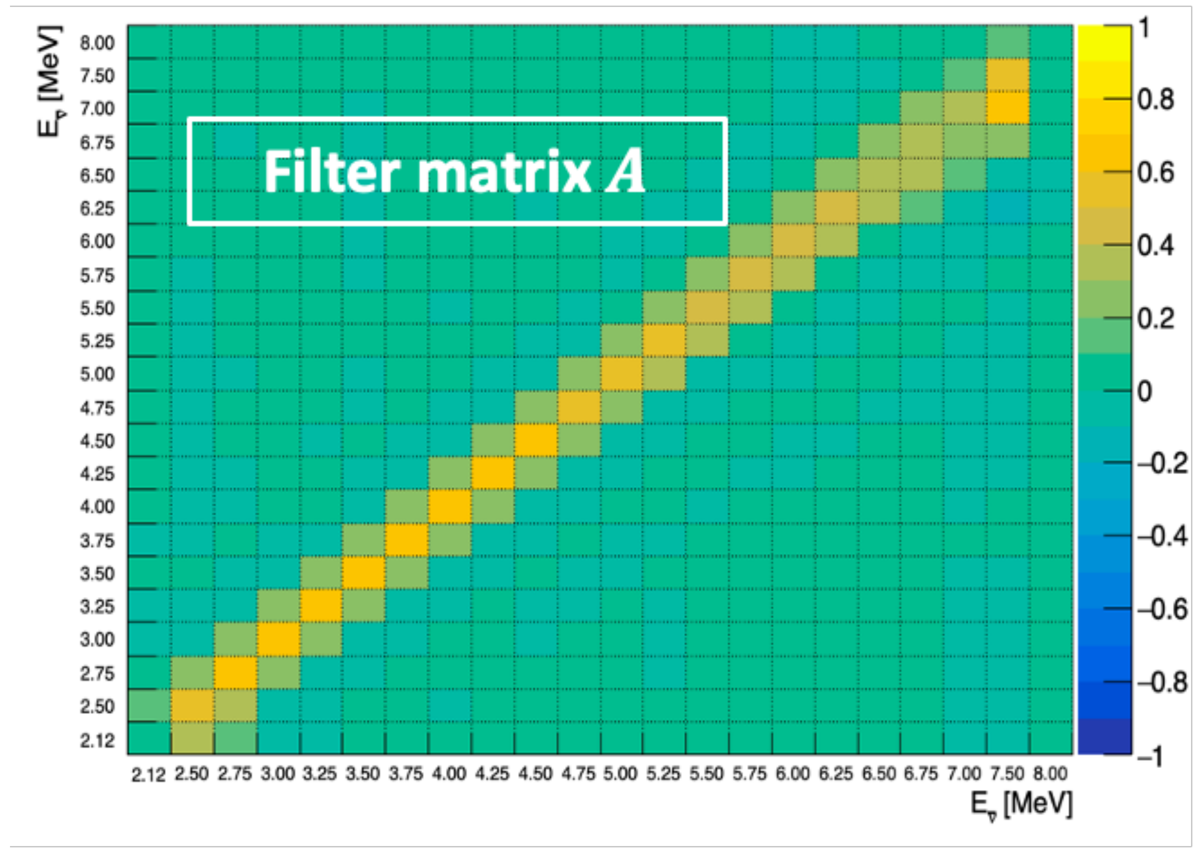
- ***Accurate*** comparison of ^{235}U measurements from STEREO, PROSPECT and Daya Bay done by fitting a common spectrum *through the filter matrices*:

$$\chi^2 = \min_{\Phi} \left\{ \left|\left|\Phi_{ST} - A_{ST}\cdot\Phi\right|\right|^2_{\mathrm{Cov}(\Phi_{ST})^{-1}} + \left|\left|\Phi_{PR} - A_{PR}\cdot\Phi\right|\right|^2_{\mathrm{Cov}(\Phi_{PR})^{-1}} + \left|\left|\Phi_{DB} - A_{DB}\cdot\Phi\right|\right|^2_{\mathrm{Cov}(\Phi_{DB})^{-1}} \right\}$$

Analysis highlight→ Corrected from unfolding biases.



STEREO, PROSPECT, Daya Bay final ^{235}U measurements



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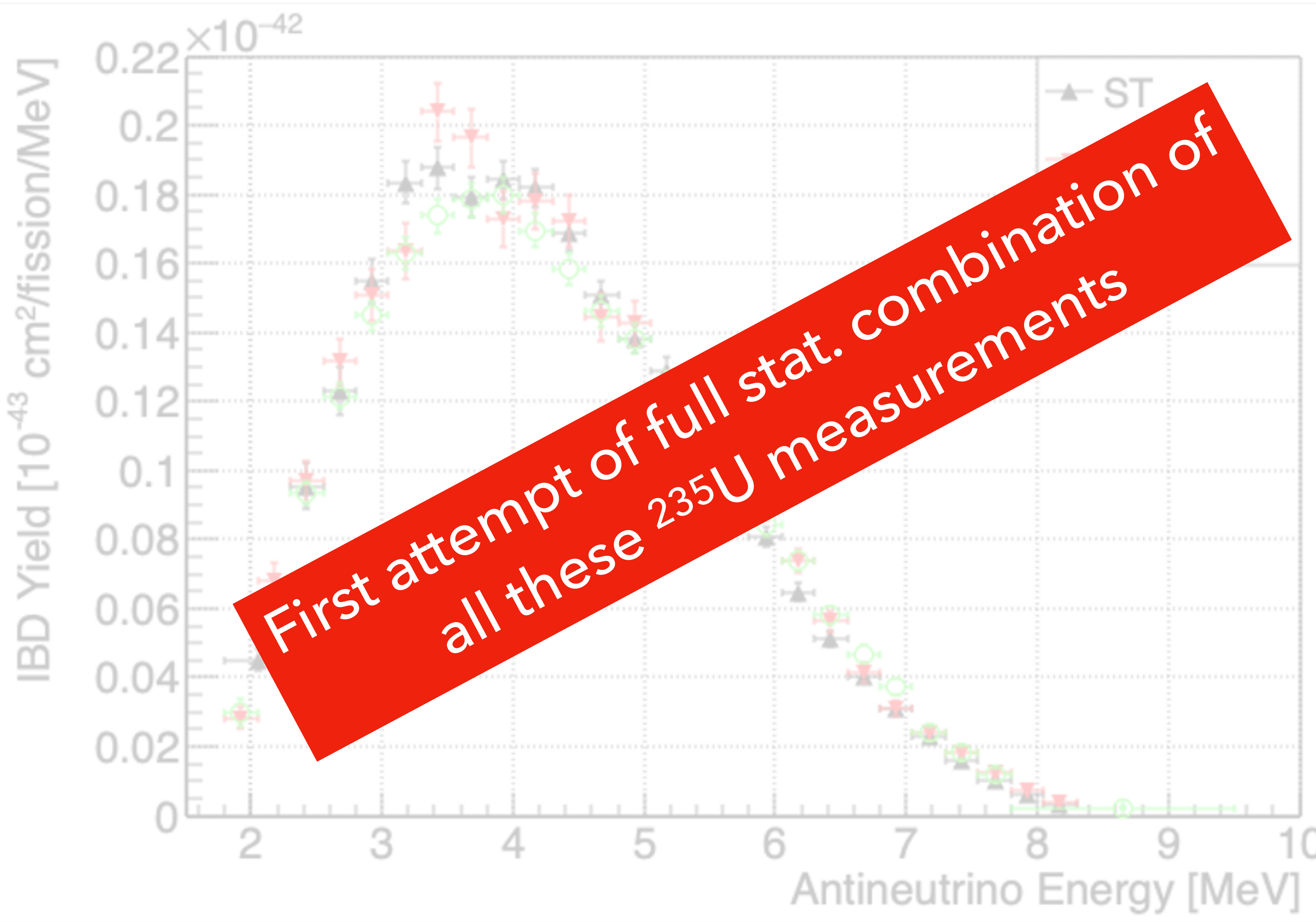
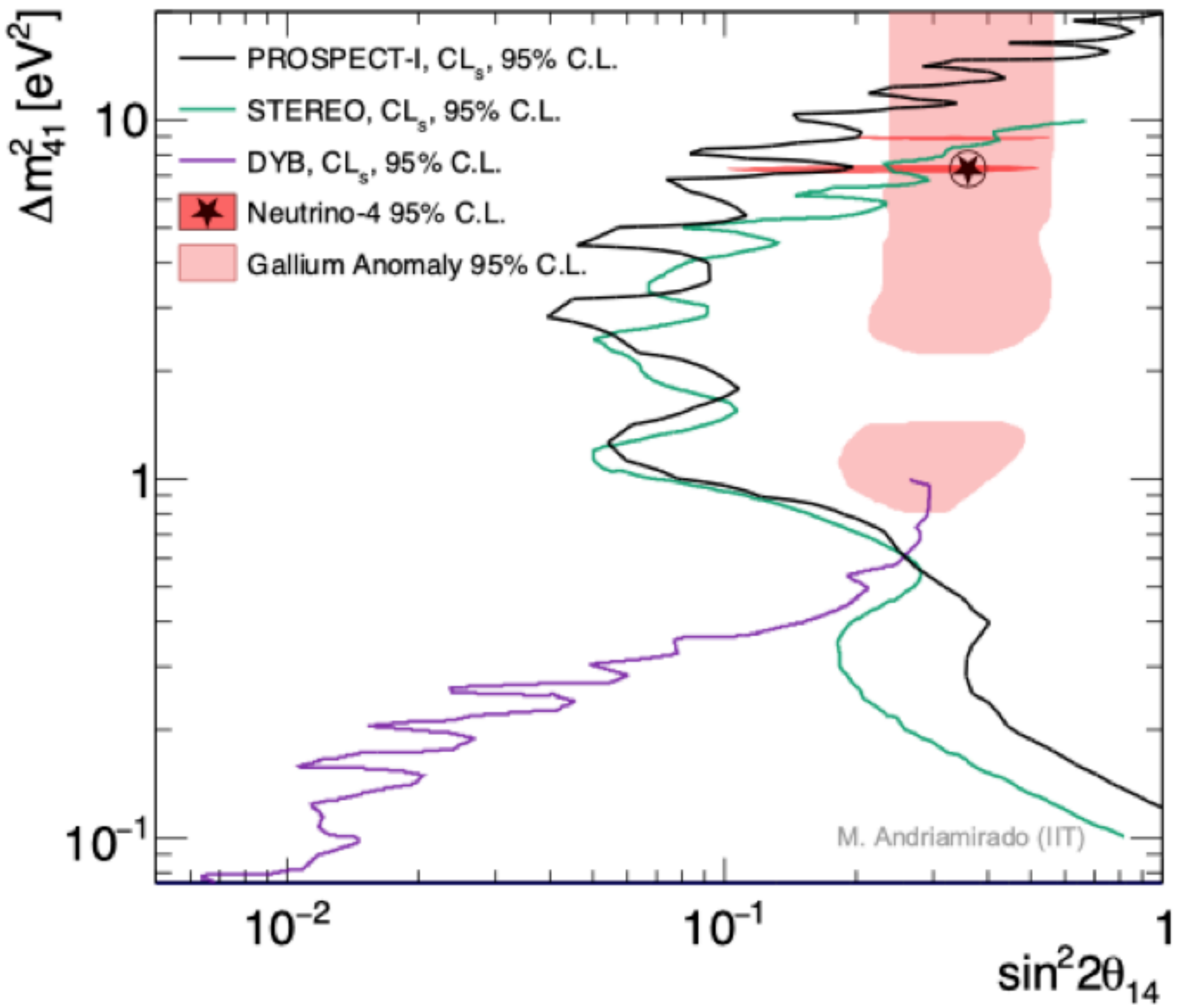


STEREO, PROSPECT, Daya Bay final ^{235}U measurements

Unfolded ^{235}U spectra from STEREO, PROSPECT and Daya Bay are consistent at ~1 sigma level (**preliminary**).

Joint analysis motivation

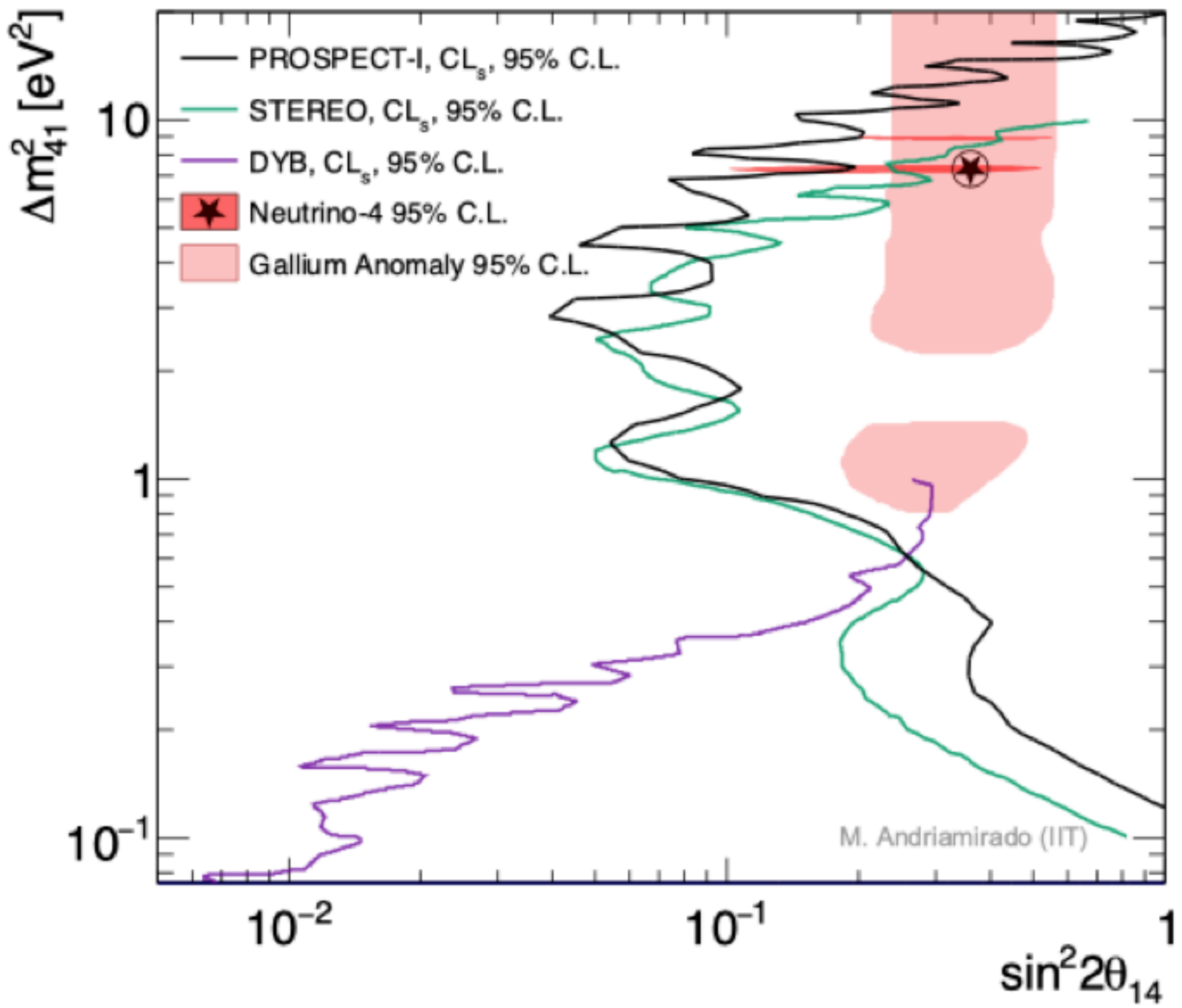
- STEREO, PROSPECT and Daya Bay have all performed model-independent searches for sterile neutrinos, consistent with the no-oscillation hypothesis.



Joint analysis motivation

- STEREO, PROSPECT and Daya Bay have all performed model-independent searches for sterile neutrinos, consistent with the no-oscillation hypothesis.

- (1) There is room to boost the sensitivity at high Δm^2_{14} & enhance the rejection power of the 2σ allowed contour of Neutrino-4:
  - ➡ Combine STEREO + PROSPECT ^{235}U baseline-binned data.
  - ➡ Switch to a **model-dependent analysis, by introducing Daya Bay extracted ^{235}U spectrum *shape* as a reference model**.



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- Method1:

$$\chi^2_{rel} = \Delta^T V^{-1}_{rel} \Delta$$

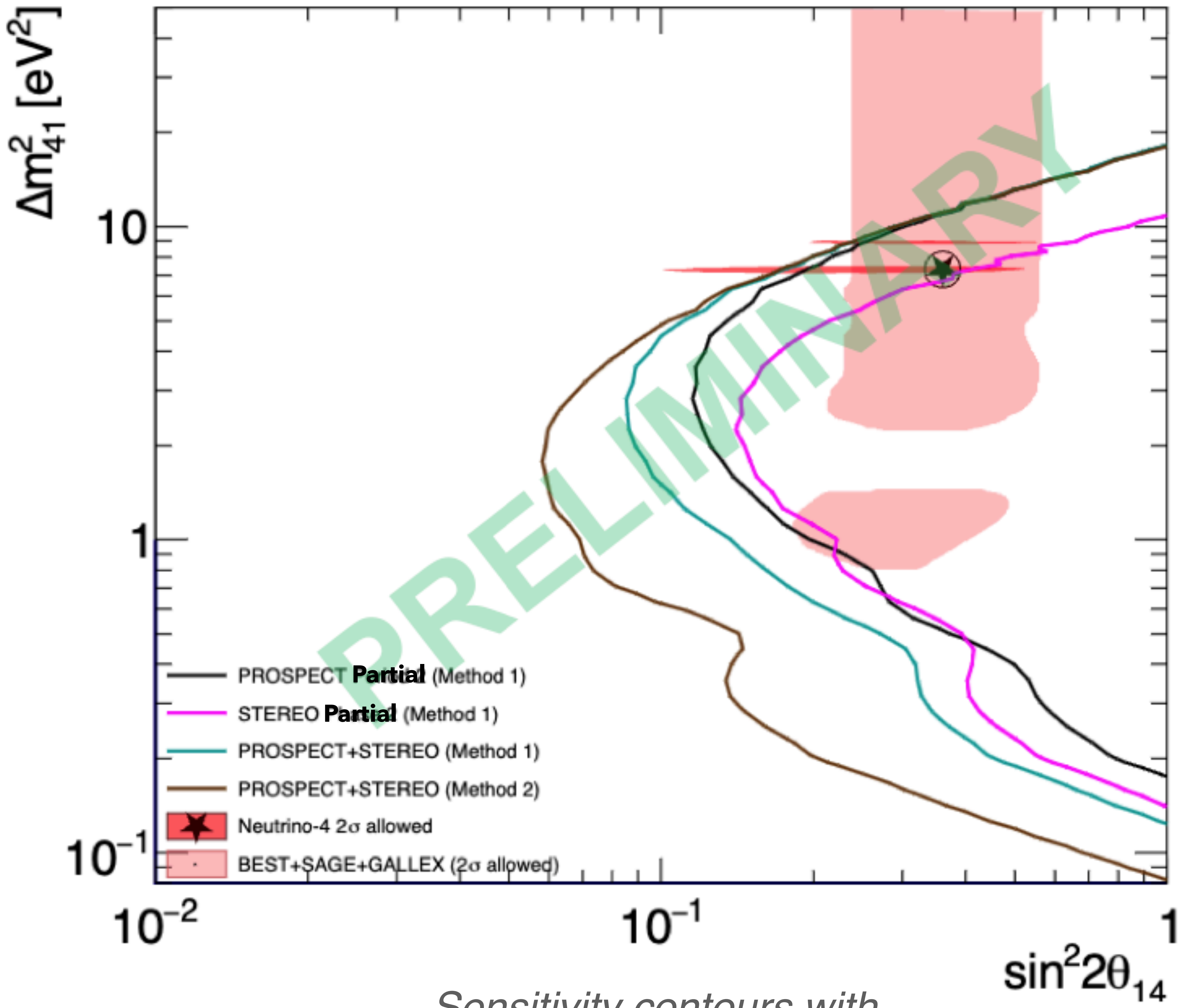
$$\Delta_{l,e} = M_{l,e} - P_{l,e} \frac{M_e}{P_e}$$

- Method2:

$$\chi^2_{abs} = \delta^T V^{-1}_{abs} \delta$$

$$\delta_{l,e} = M_{l,e} - \boxed{P_{l,e}}$$

Using DYB unfolded spectra



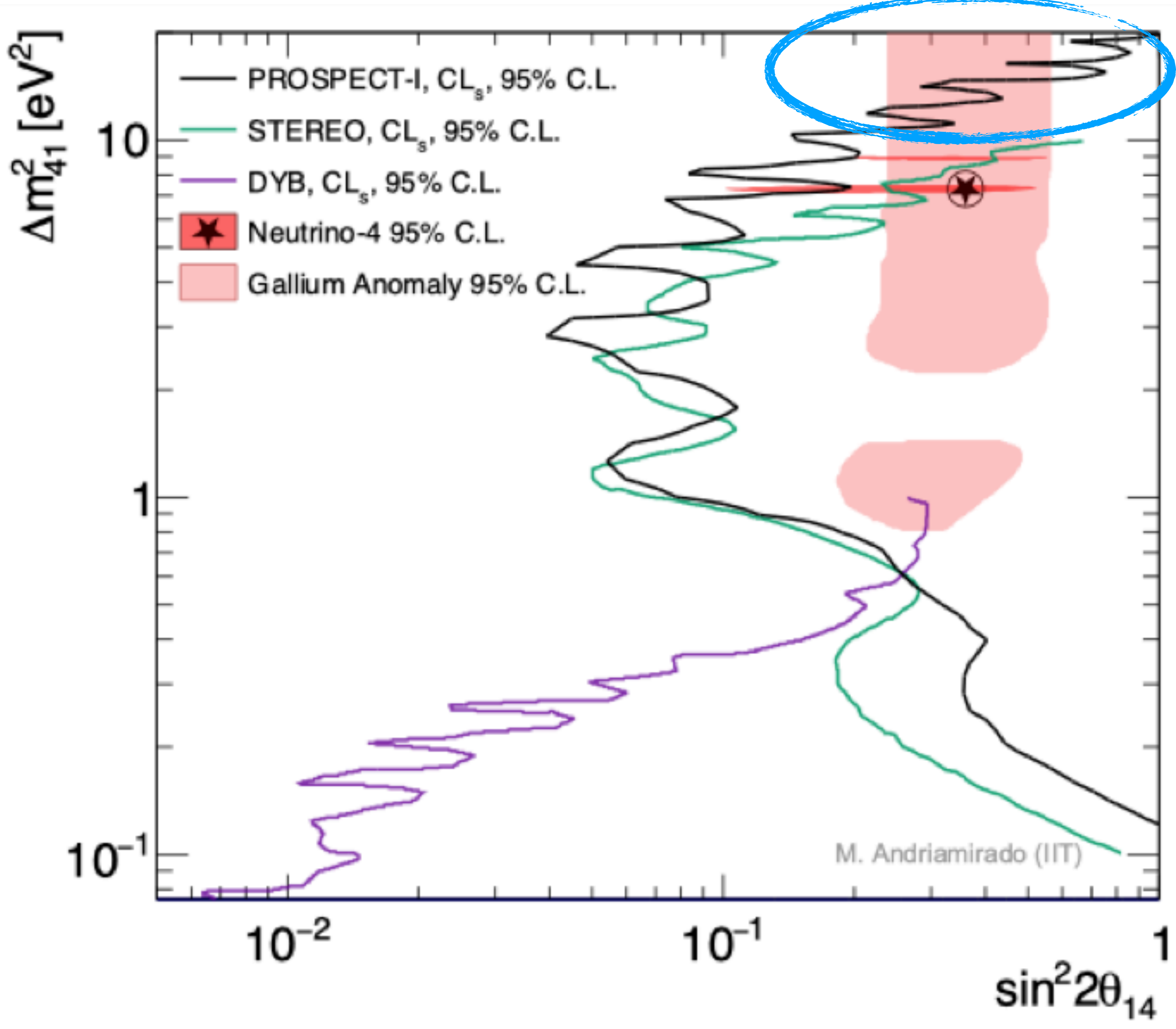
Sensitivity contours with partial datasets of STEREO & PROSPECT in the model-independent (Method 1) and Daya Bay model-dependent (Method 2) approaches

Joint analysis motivation

- STEREO, PROSPECT and Daya Bay have all performed model-independent searches for sterile neutrinos, consistent with the no-oscillation hypothesis.

- (1) There is room to boost the sensitivity at high Δm^2_{14} & enhance the rejection power of the 2σ allowed contour of Neutrino-4:
  - ➡ Combine STEREO + PROSPECT ^{235}U baseline-binned data.
  - ➡ Switch to a **model-dependent analysis, by introducing Daya Bay extracted ^{235}U spectrum *shape* as a reference model**.

- (2) There is room to boost even further the sensitivity at high Δm^2_{14} & **provide a unified contour from sub-eV scale to eV scale**:
  - ➡ Combine STEREO + PROSPECT ^{235}U baseline-binned data and Daya Bay U+Pu baseline-binned data.
  - ➡ Will provide **additional *normalization* constraint in the very-high Δm^2_{14} region** to further enhance the rejection power of the 2σ allowed contour of the Gallium anomaly.
  - ➡ Capability to extract ^{235}U & ^{239}Pu absolute spectra, out of STEREO + PROSPECT + Daya Bay measurements.



Take-away

- Over the last decades, several short-baseline anomalies in neutrino experiments pointed towards the existence of sub-eV to eV scale sterile neutrino.

- Reactor antineutrino experiments **probe most of the relevant phase space of the oscillation parameters**.
  - ➡ STEREO, PROSPECT and Daya Bay proved to be leaders in the field and found no evidence for light sterile neutrino state. In particular, Neutrino-4 best-fit sterile signal has been rejected to a high confidence level.
  - ➡ To further enhance the sensitivity to oscillation scenarios, **joint oscillation analyses between the 3 experiments are underway** → potential to tackle most of the 2σ allowed contour of Neutrino-4 signal and Gallium anomaly with high significance level.

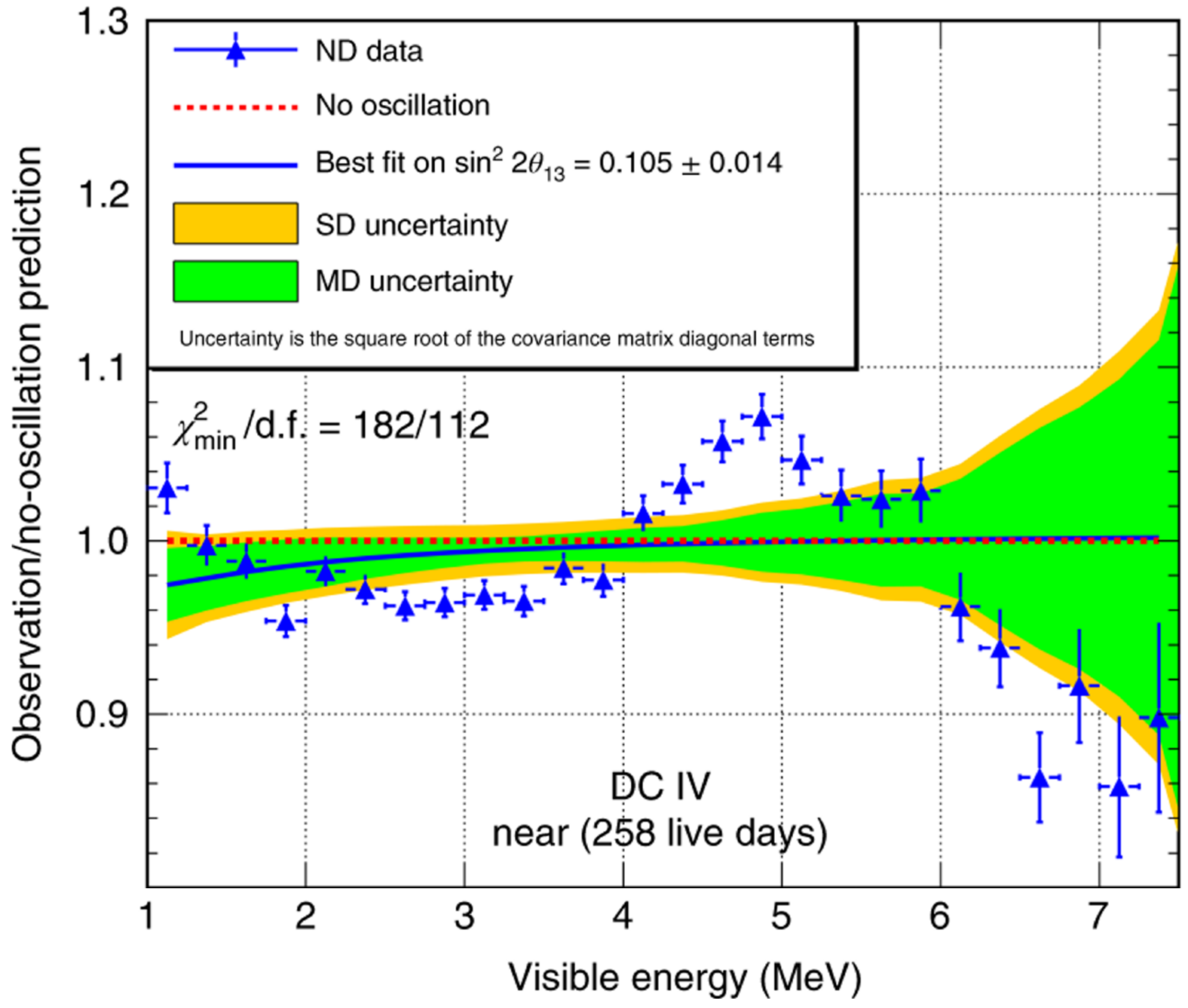
- Measurements from reactor antineutrino experiments are now **precise enough to be considered as nuclear data** on their own.
  - ➡ Joint measurement of STEREO, PROSPECT and Daya Bay of ^{235}U and ^{239}Pu spectra will allow to constrain further the nuclear data bases.

Stay tuned !

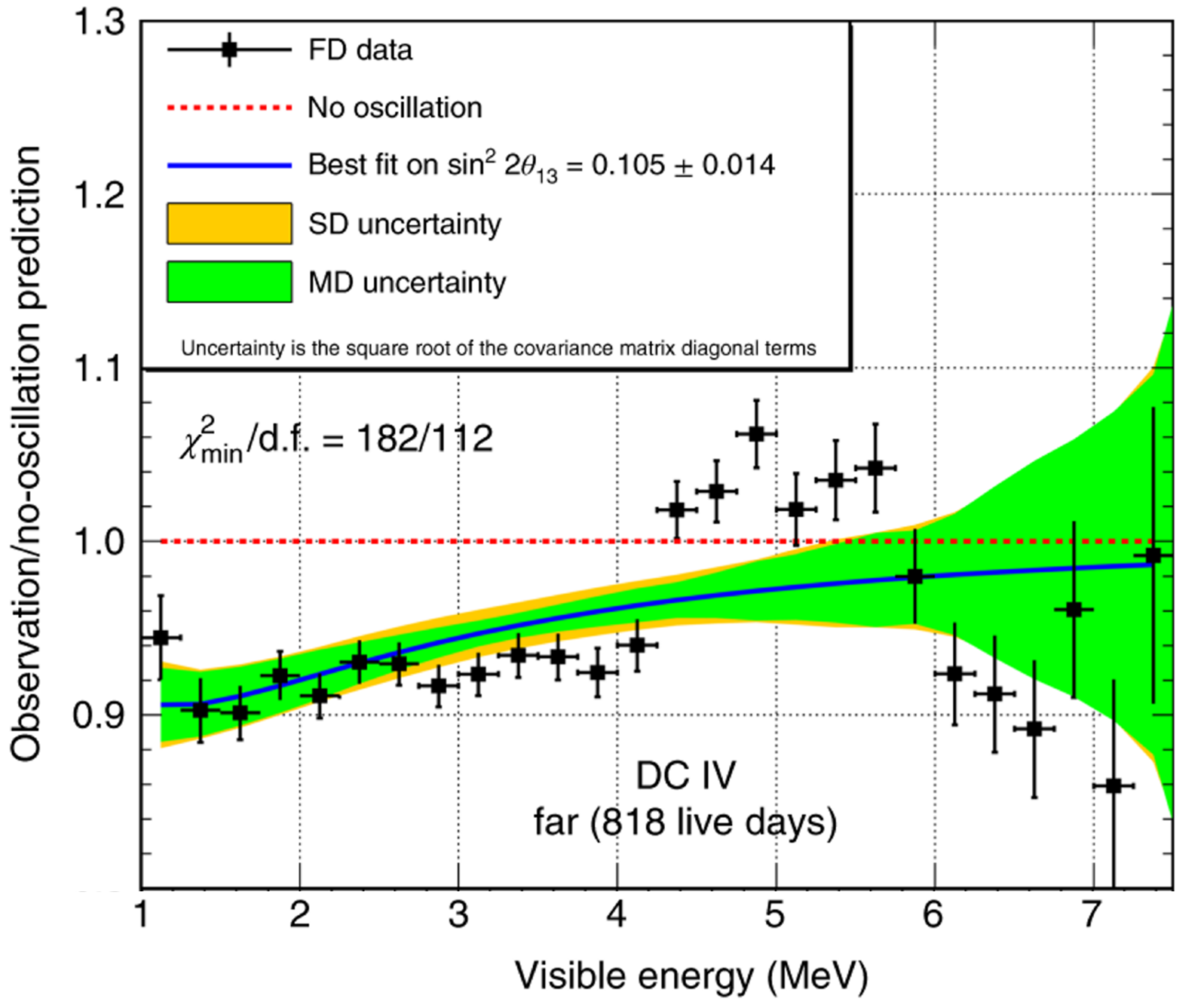
Back-up

5 MeV bump and baselines

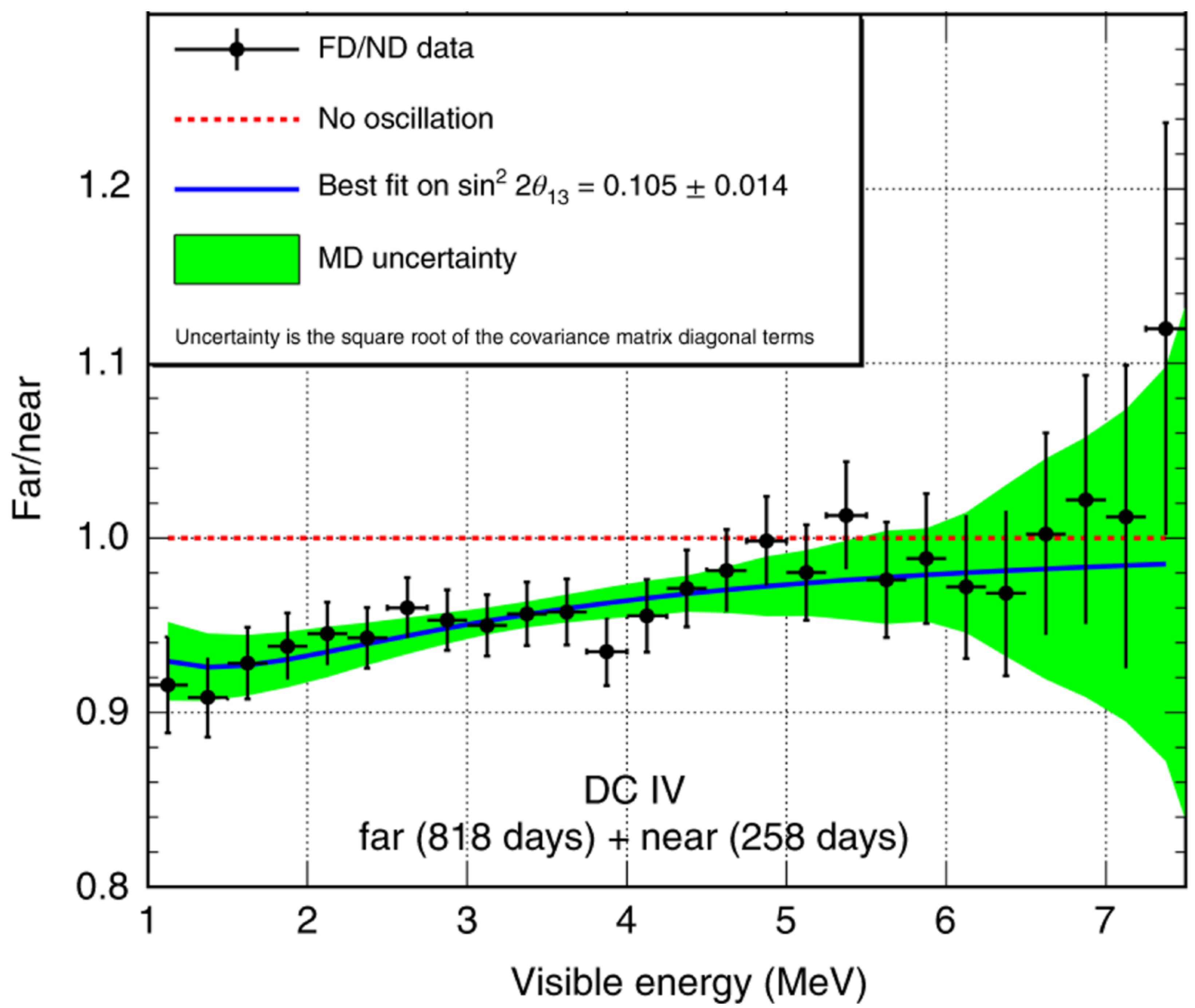
The Double Chooz Experiment — *Nature Physics* **16**, pp. 558–564 (2020)



Near Detector — L ~ 400 m



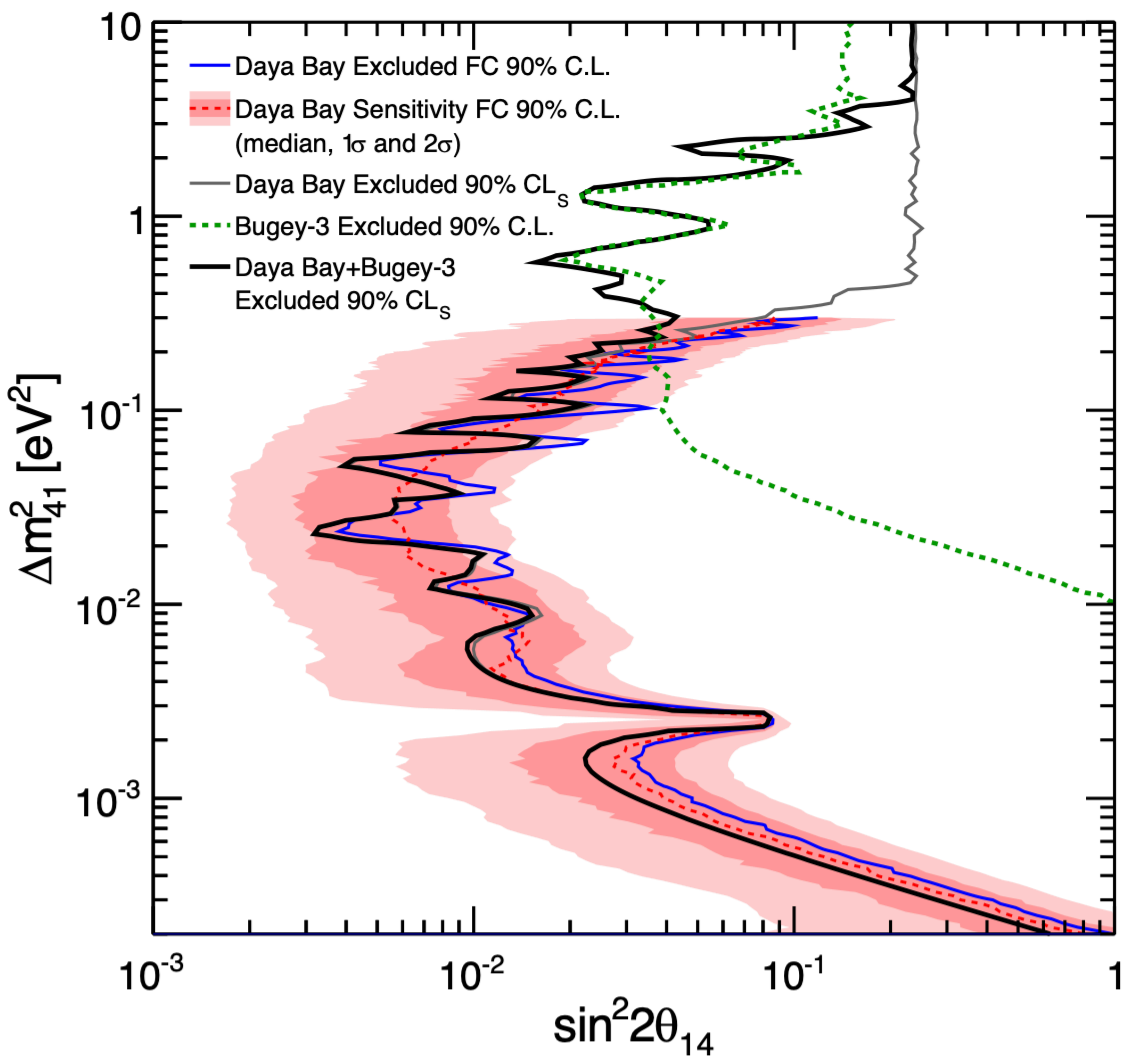
Far Detector — L ~ 1050 m



Far Detector / Near Detector

Daya Bay 2011-2015 dataset and LSND+MiniBooNe anomaly

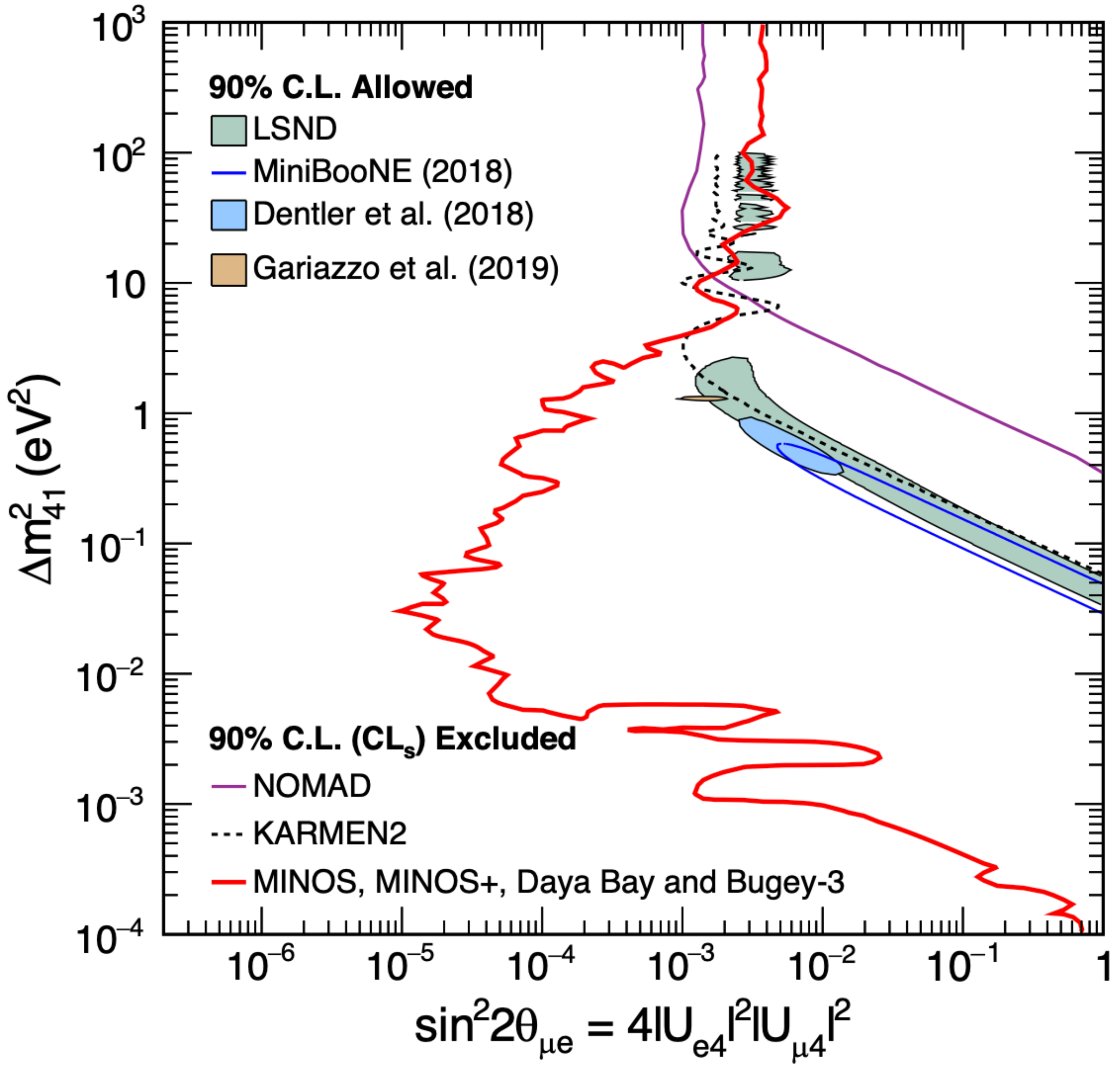
Sterile neutrino search — *Phys. Rev. Lett.* ***125****, 071801* (2020)



Exclusion contour in the $\bar{\nu}_e$ disappearance channel

$$|U_{e4}|^2 = \sin^2\theta_{14},$$
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}.$$

$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$$



Exclusion contour in the $\bar{\nu}_e$ appearance channel