Status of the Search for Light Sterile Neutrinos at Short Baselines

Alessandro Minotti (INFN - Università di Milano Bicocca)
alessandro.minotti@unimib.it

20th Lomonosov Conference on Elementary Particle Physics
20/08/2021

Outline

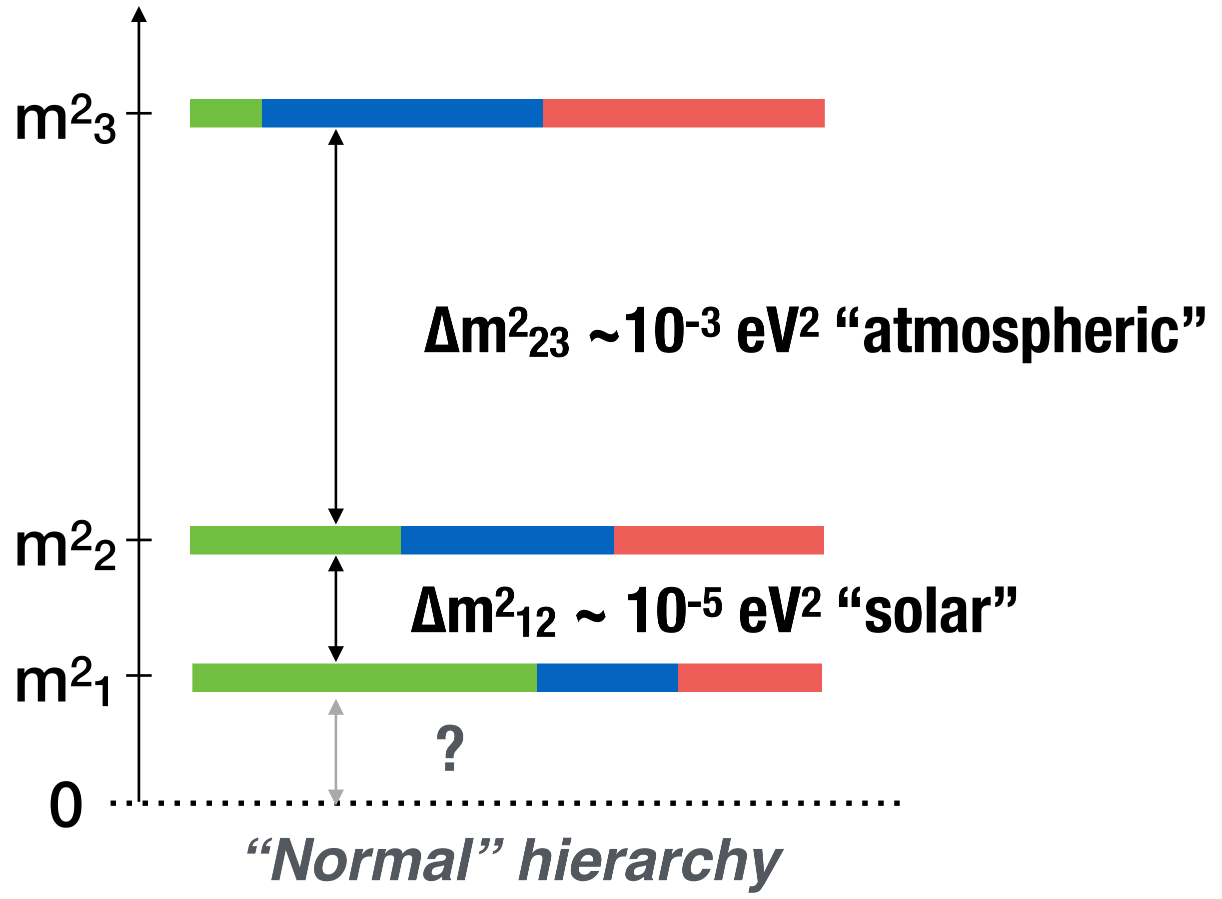
- The Reactor Antineutrino Anomaly and Light Sterile Neutrinos
- Detection Techniques & Challenges
- A worldwide Hunt
- Global Results and Perspectives

- The Reactor Antineutrino Anomaly and Light Sterile Neutrinos
- Detection Techniques & Challenges
- A worldwide Hunt
- Global Results and Perspectives

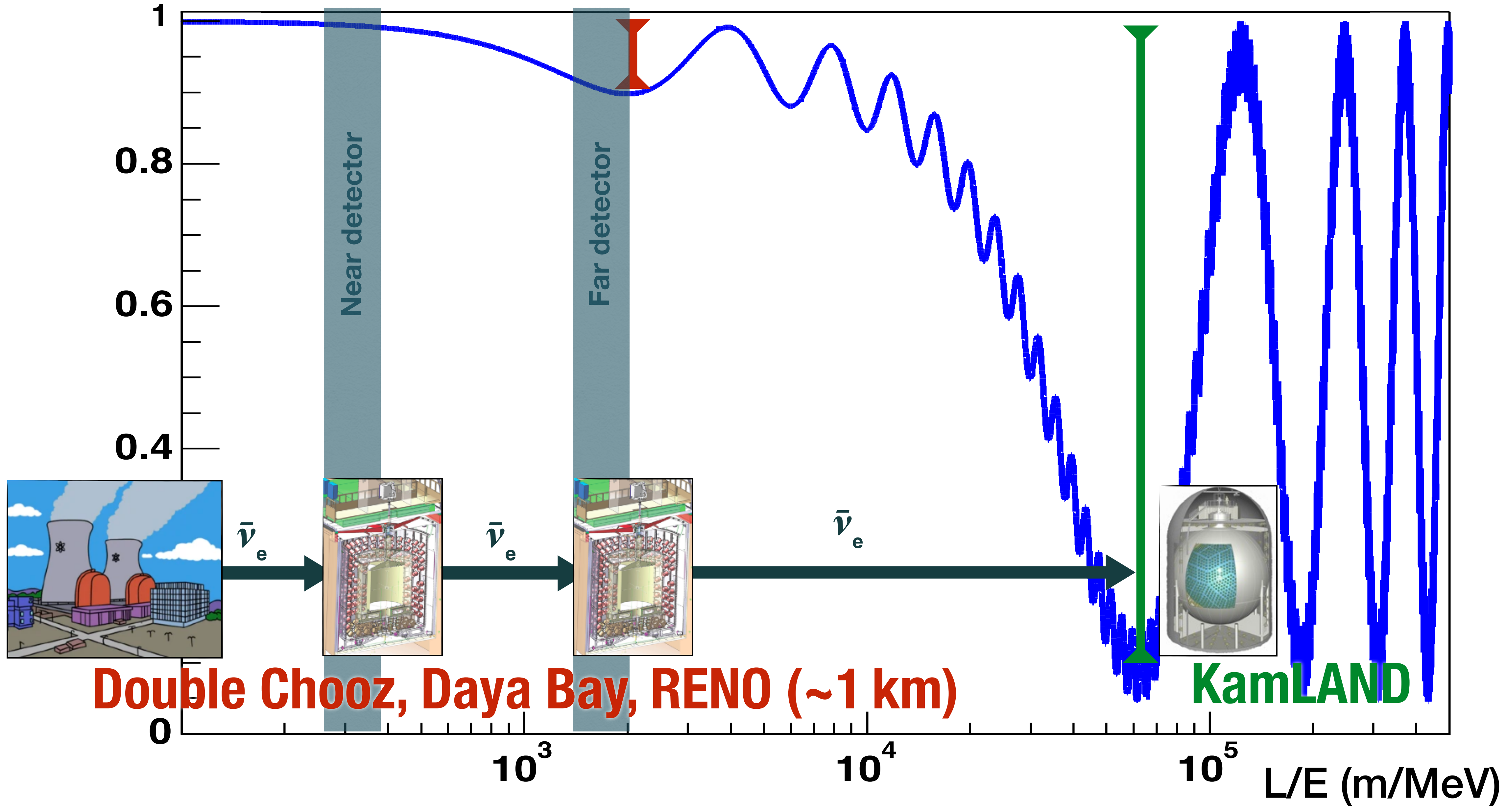
Reactor Antineutrino Experiments

- Reactor antineutrino oscillation is sensitive to **two mixing angles** (θ_{13}, θ_{12}) of the U_{PMNS} matrix, and **both squared-mass splittings**

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - sin^2(2\theta_{13}) sin^2(\Delta m^2_{23} L/4E) - cos^4(\theta_{13}) sin^2(2\theta_{12}) sin^2(\Delta m^2_{12} L/4E)$$



- In the 2000s we built **three experiments to measure** the yet unknown **θ_{13}**, which is the nowadays most precisely measured

- Basic idea: compare spectra in near-far detector(s)

Reactor Antineutrino Anomaly (RAA)

- Mueller (^{238}U)-Huber (^{235}U, Pu) calculated new precise IBD spectra, that could be used before a near detector was operational

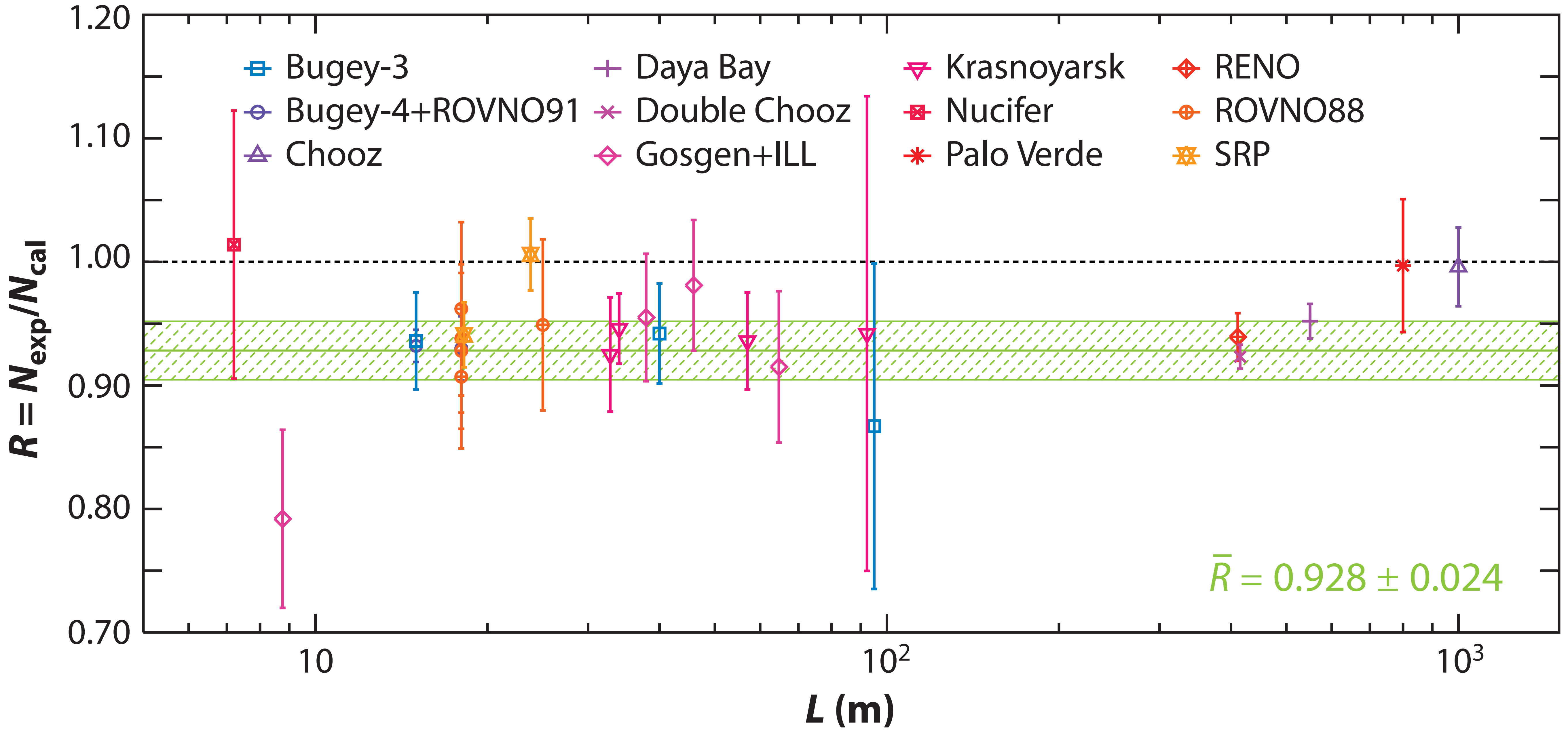
  Mueller et al., Phys. Rev. C **83.5** (2011): 054615

  Huber P., Phys. Rev. C **84.2** (2011): 024617

- **Rate excess of ~6% in the model** compared to previous short baseline measures

  Mention et al., Phys. Rev. D **83.7** (2011): 073006

- Discrepancy confirmed by Double Chooz, Daya Bay and RENO near detectors



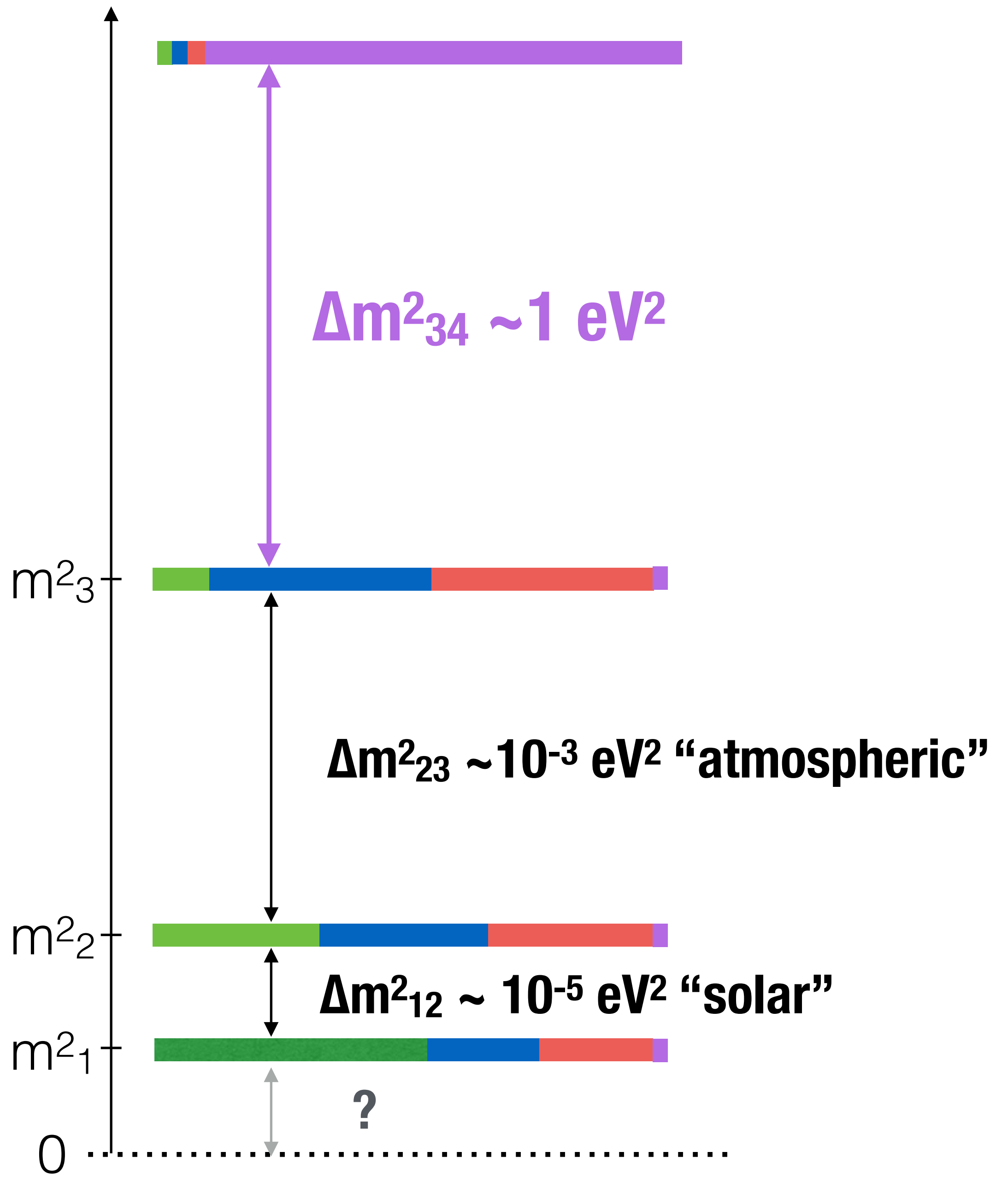
The Light Sterile Neutrino

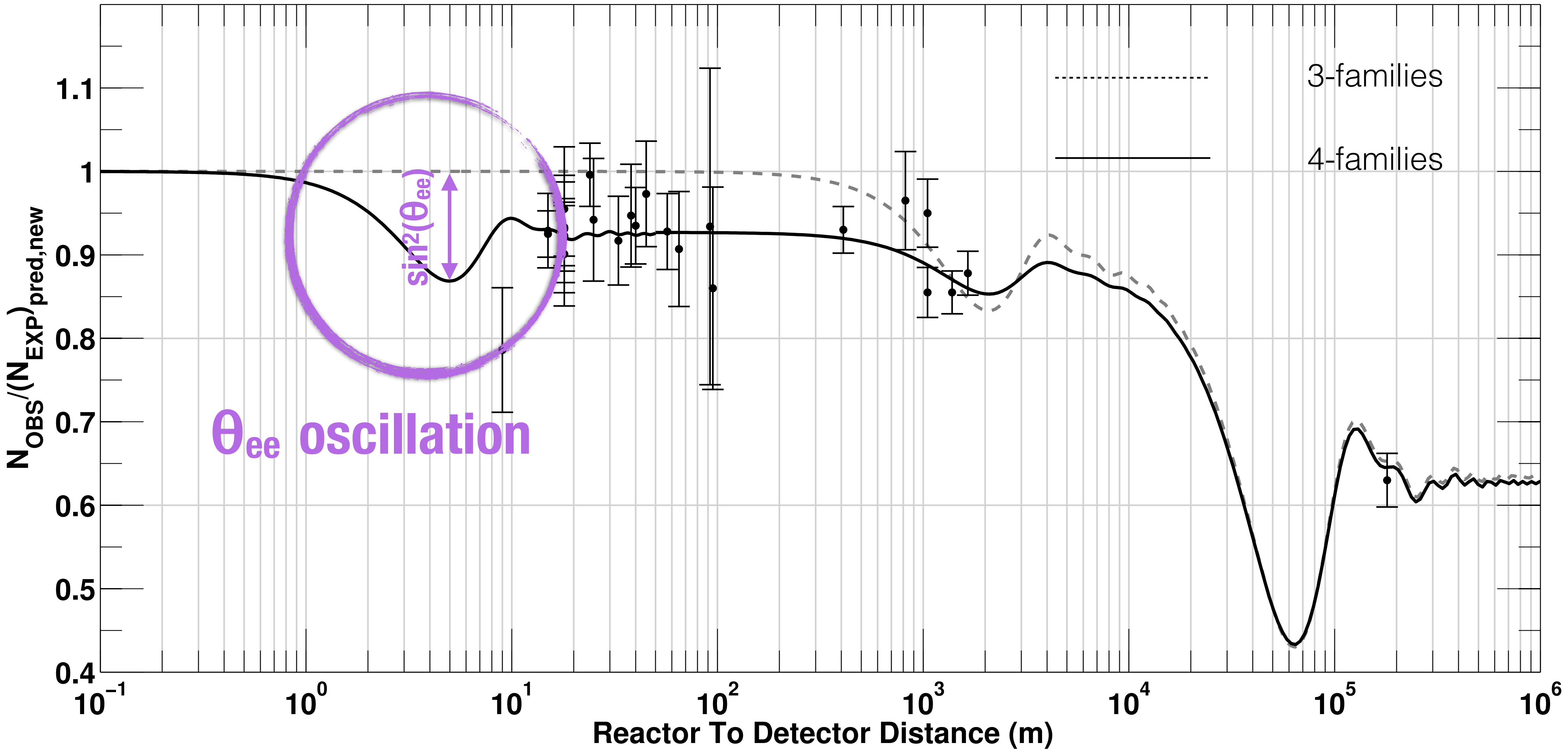
- Adding a **new neutrino** (0.1-1 eV mass) consisting almost exclusively of an **extra sterile flavour** can account for the observed deficit

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- **Sterile neutrinos** do not interact weakly but **mix with standard neutrinos**, originating the disappearance at short baseline

$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L \lesssim 10m) \simeq 1-\sin^2(\theta_{ee}) \sim^2 (1.27\Delta m^2_{14} L/E)$$

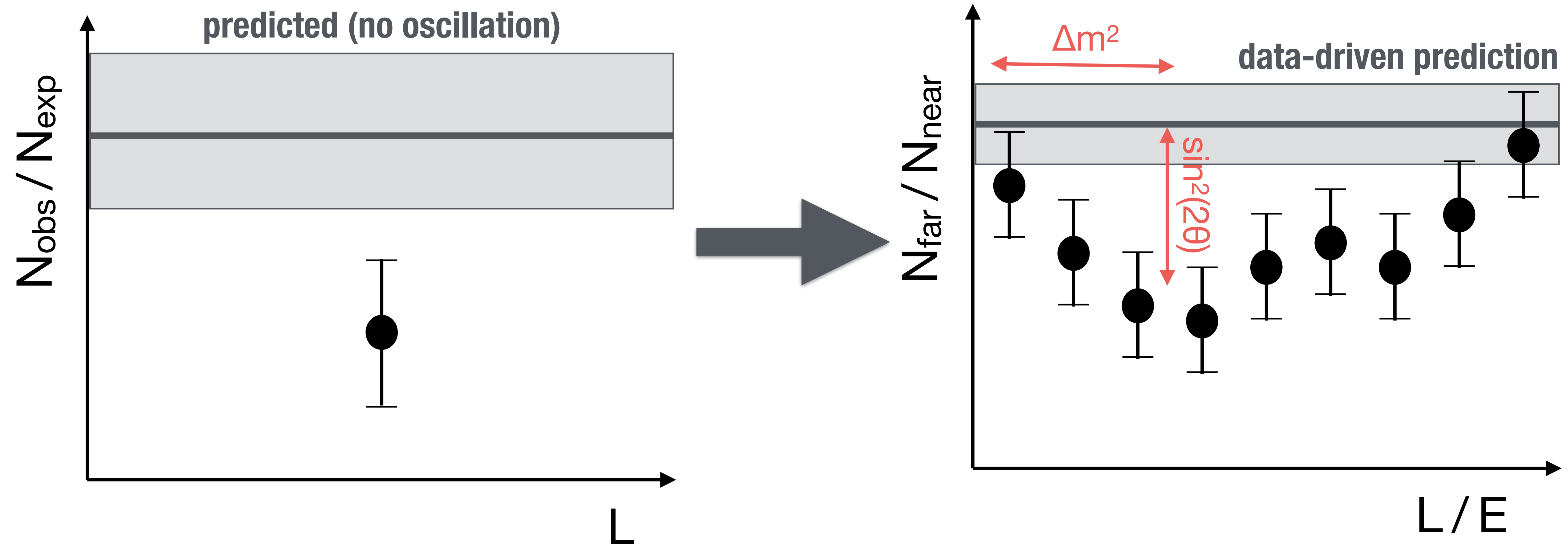




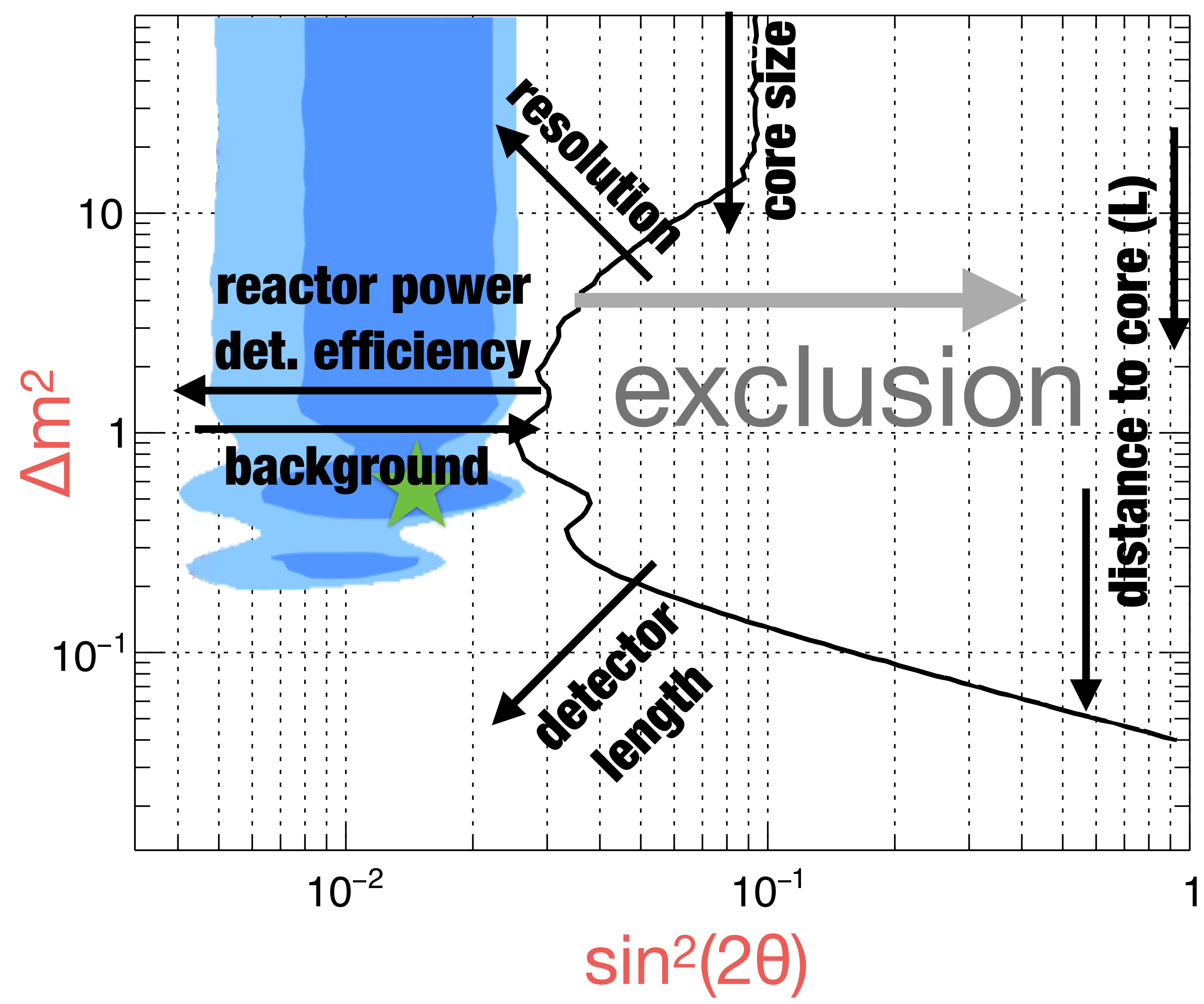
- The Reactor Antineutrino Anomaly and Light Sterile Neutrinos
- **Detection Techniques & Challenges**
- A worldwide Hunt
- Globa Results and Perspectives

Search for the Light Sterile Neutrino

- Difficulty in predicting the neutrino rate limits the sensitivity of past measurements → need to **disentangle the oscillating signature from the absolute rate**



- Oscillation parameters (Δm^2, θ) are tested against data
  - Oscillation hypothesis ⇒ **contour plot (CL)** + **best fit**
  - Null hypothesis ⇒ **exclusion plot**



★ $\Delta m^2 > 10$ eV^2 $L_{osc} < E_{res}$

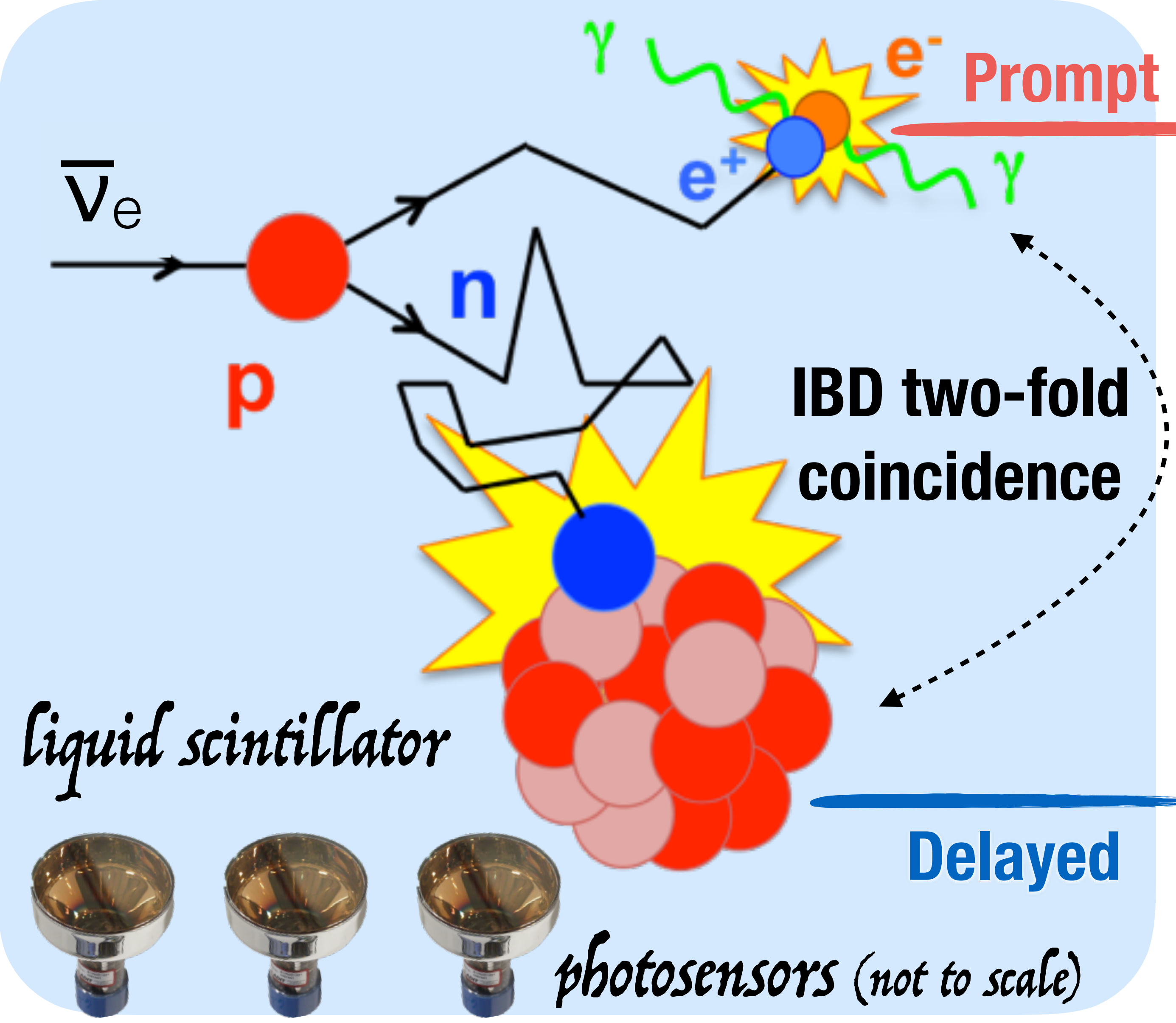
★ **Δm^2 ~ 1 eV^2 Can resolve oscillation**

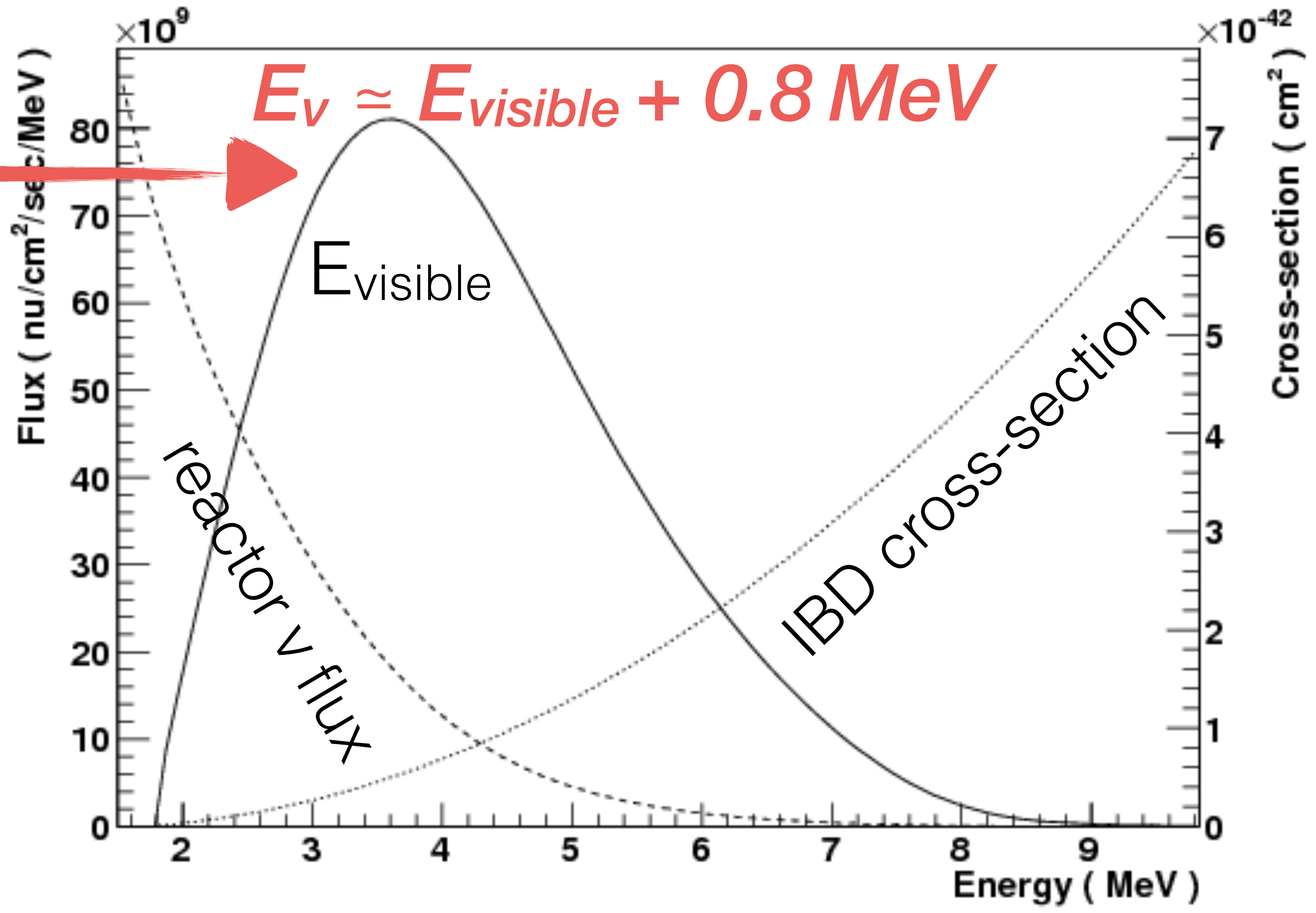
★ $\Delta m^2 < 0.1$ eV^2 $L_{osc} > L_{detector}$

- The better statistics (reactor power, detection efficiency), the larger the exclusion, but the core core size washes out the oscillation, and distance from core send us far from the RAA zone

Reactor Antineutrino Detection

- **Signal**: **I**nverse **B**eta **D**ecay in scintillator target



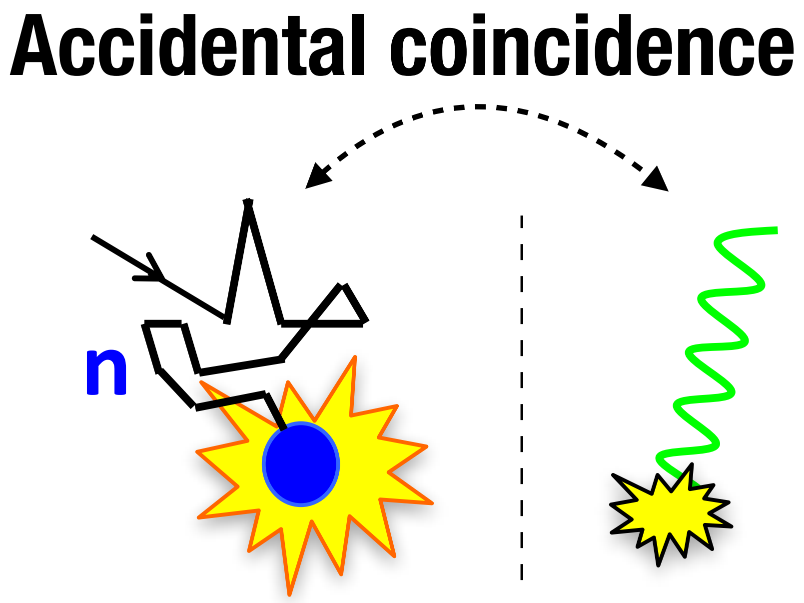


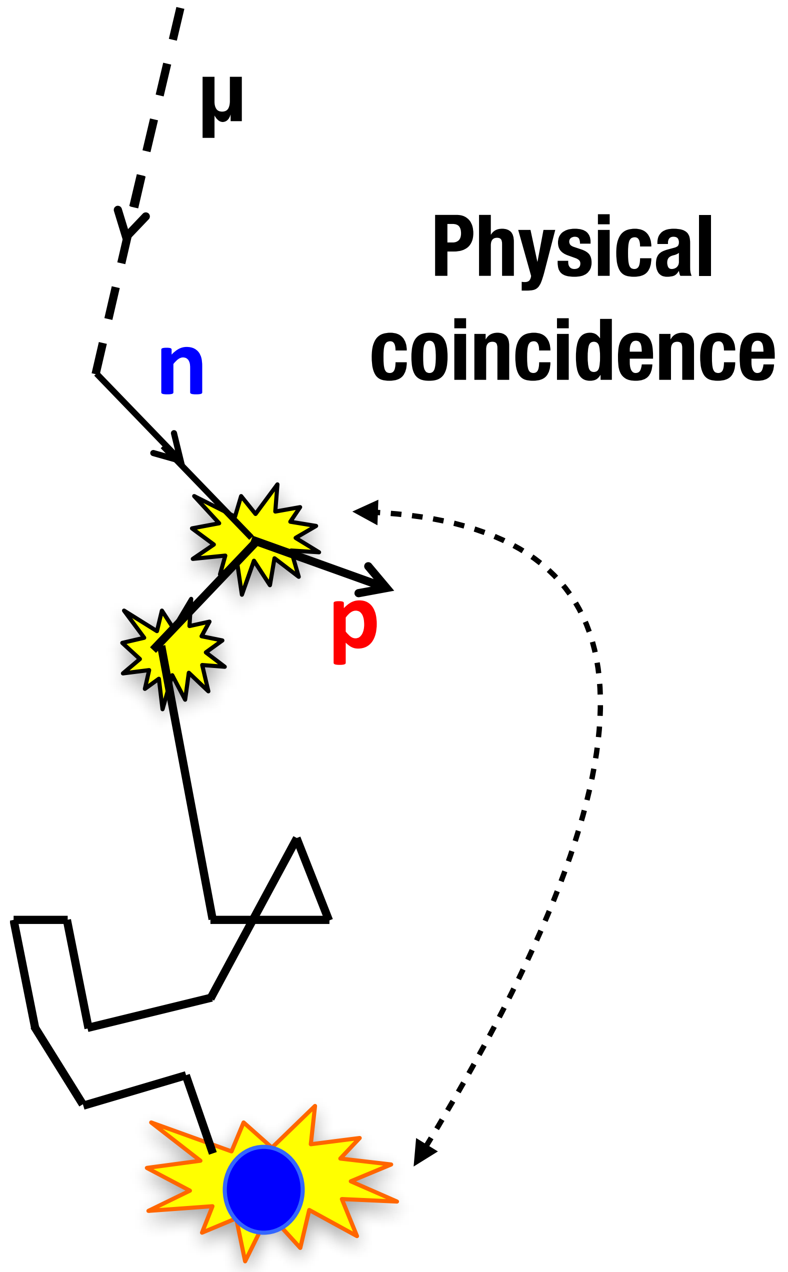
$n + H \rightarrow D + \gamma$ (2.2 MeV)

$n + Gd \rightarrow Gd^{*} + \gamma$'s (8 MeV)

$n + {}^{6}Li \rightarrow \alpha + {}^{3}H$ (4.78MeV)

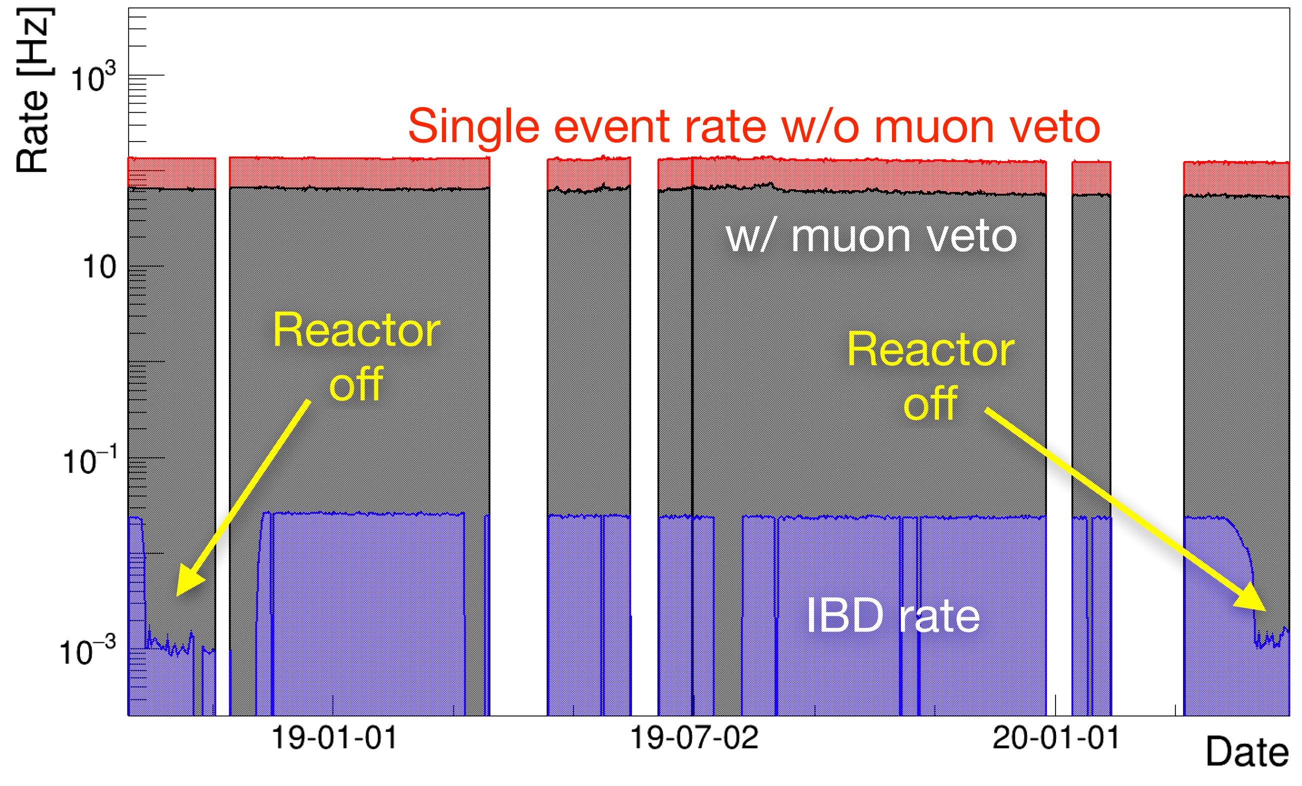
- **Background**
  - Cosmic induced (μ's, n-γ from μ spallation)
  - Reactor induced (n's, γ's)

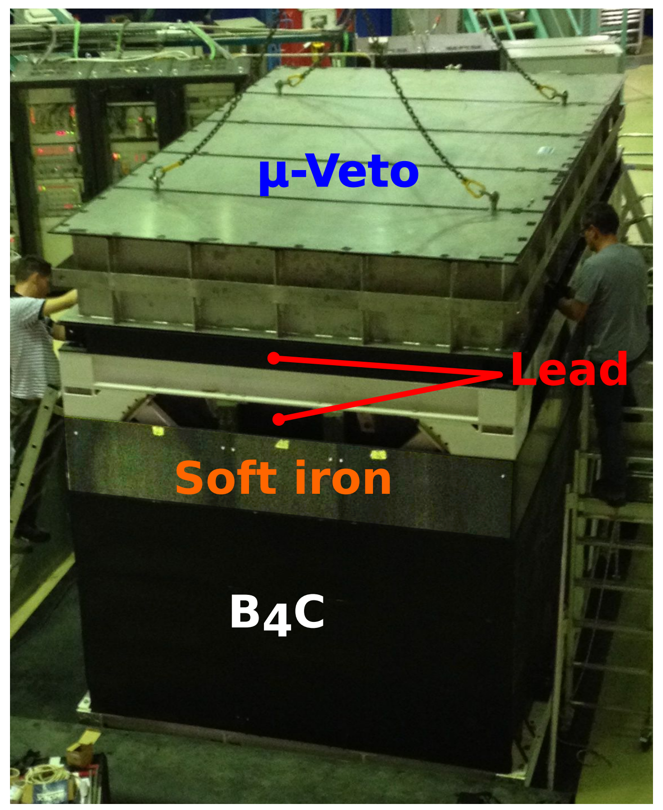




- Event topology (E_{prompt}, $E_{delayed}$, Δt, $\Delta \bar{x}$) allows to isolate IBD signal from the sea of single-events

- Strategies to deal with residual background
  - Passive shielding (PE, B, Fe, H_2O) & active vetoes
  - Pulse shape discrimination (PSD)
  - Statistical subtraction of **accidental coincidences** & **cosmogenic background** (reactor OFF)

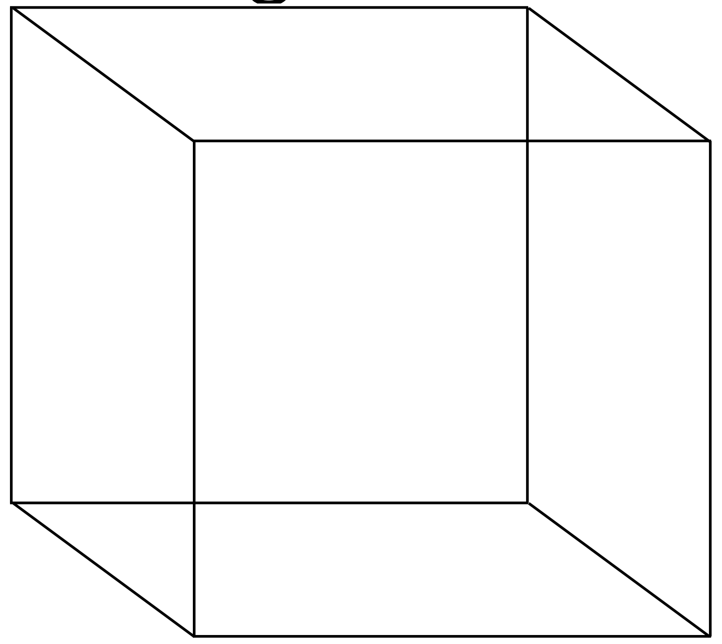




Different Reactors and Technologies

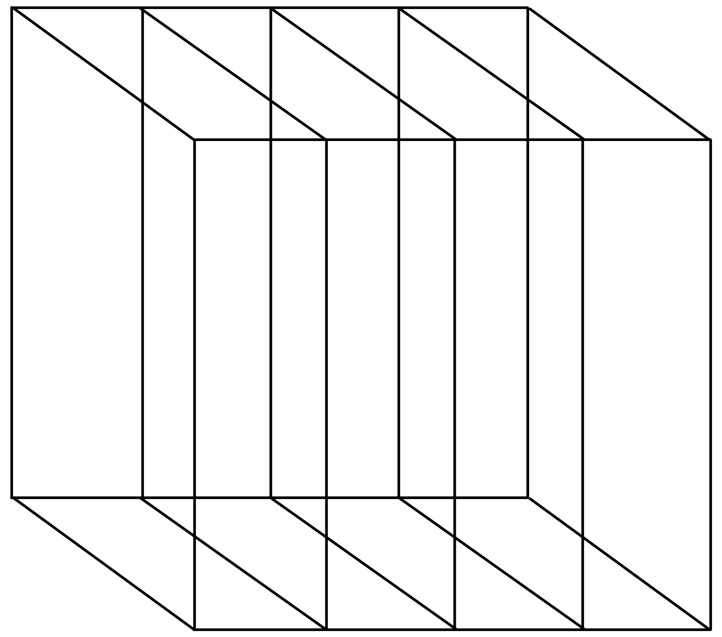
Detector segmentation

no-segmentation



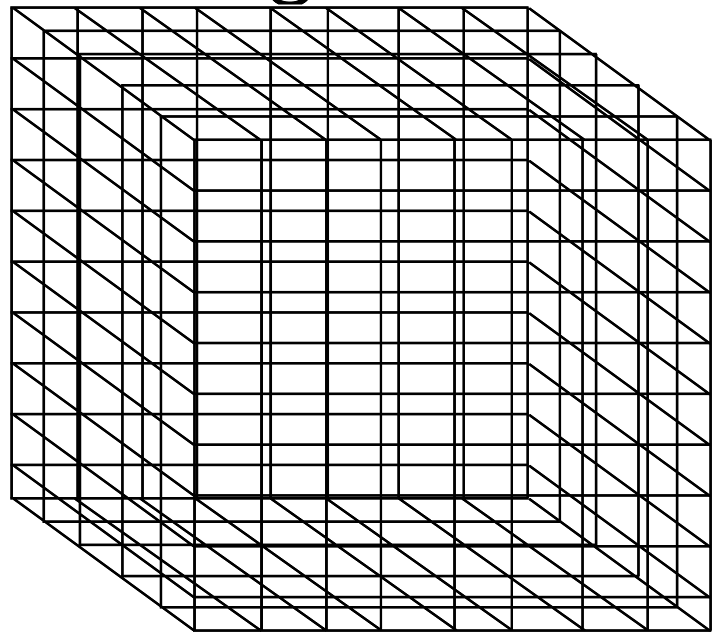
compare $\bar{\nu}$ spectrum with predictions

coarse segmentation



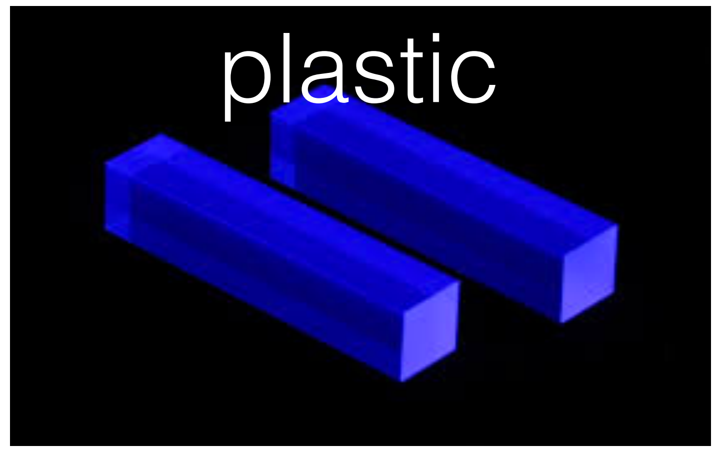
compare $\bar{\nu}$ spectra in different segments (model free)

fine segmentation

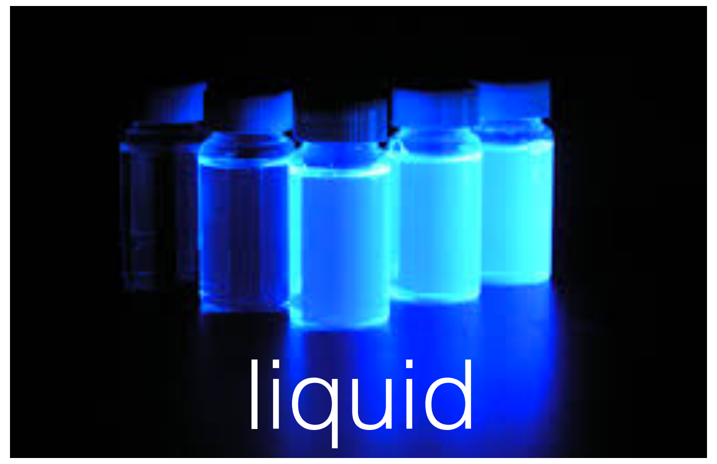


compare $\bar{\nu}$ spectra in sections + background rejection w/ topology

Scintillator

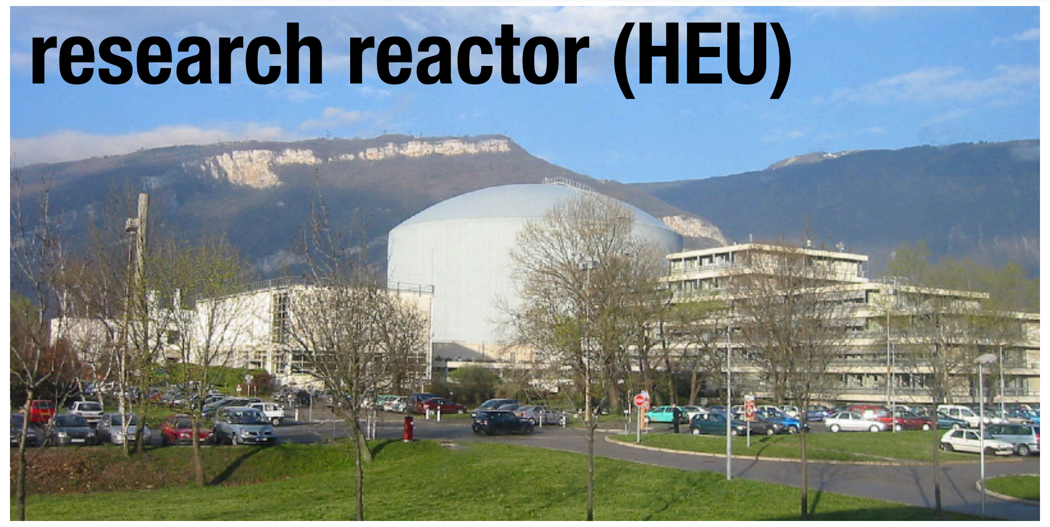


better for segmentation & detection efficiency



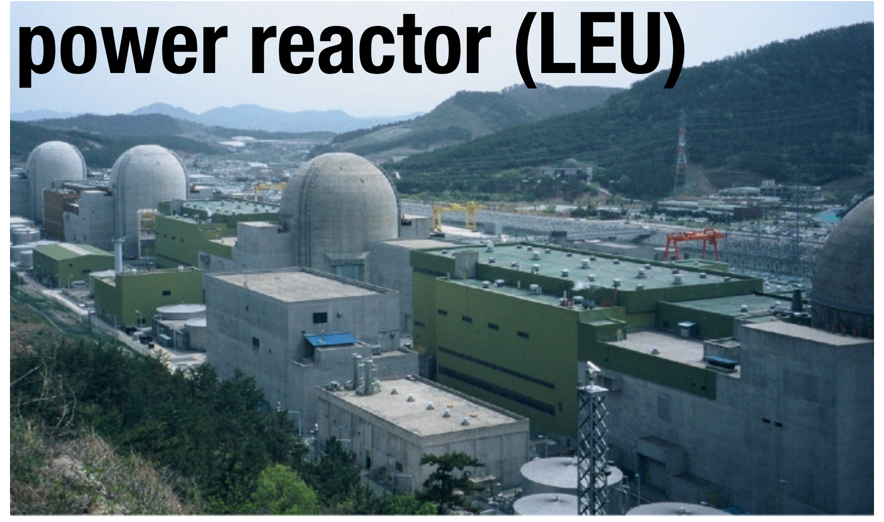
Easier to have large volumes

Reactor



Short baseline & compact core, no fuel evolution

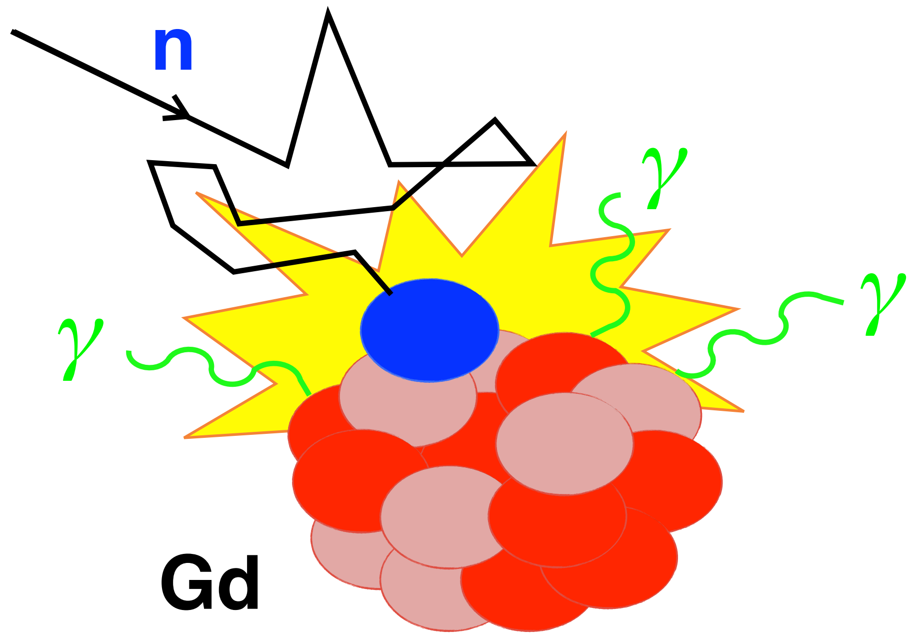
$\mathcal{O}10^2$ MW_{th}, limited space, background from facility



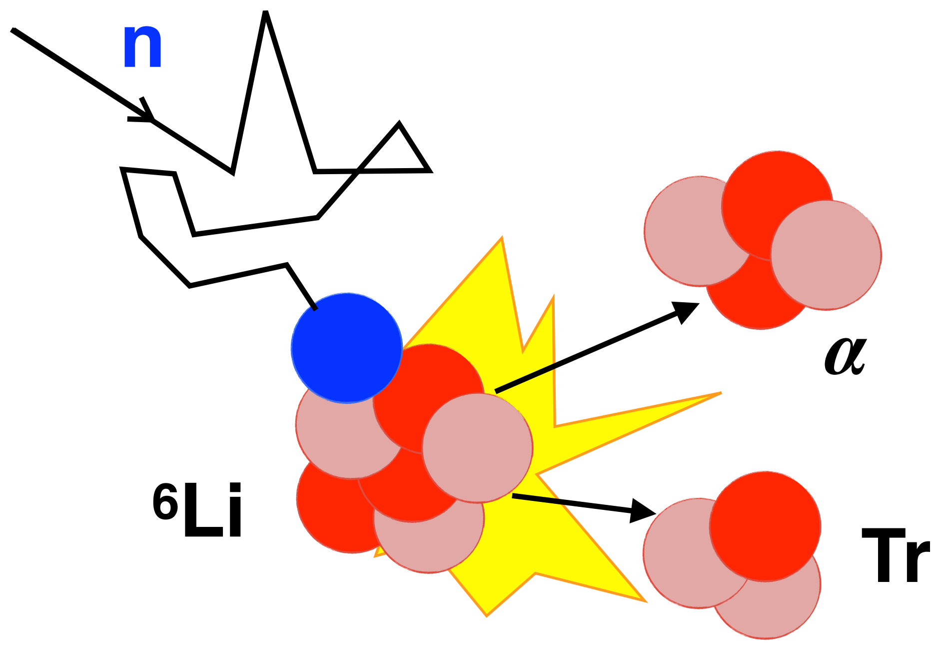
$\mathcal{O}GW_{th}$, some overburden possible

Lower sensitivity at low energy, fuel burnup

Neutron-capturing isotope



Well-established, high E_{dep} & $\sigma_{capture}$



Localised E_{dep}: quenched but can select via PSD

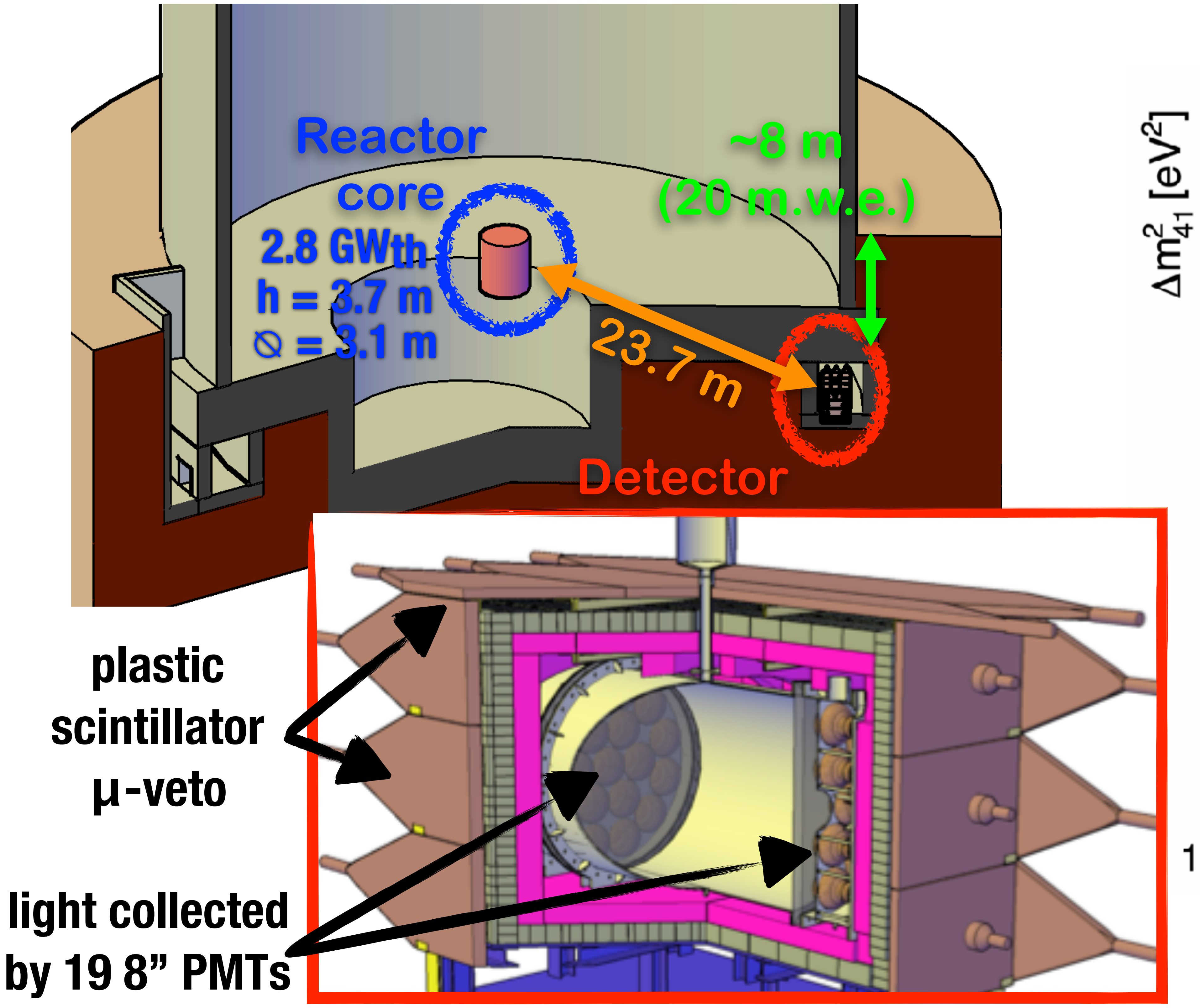
- The Reactor Antineutrino Anomaly and Light Sterile Neutrinos
- Detection Techniques & Challenges
- **A worldwide Hunt**
- Global Results and Perspectives

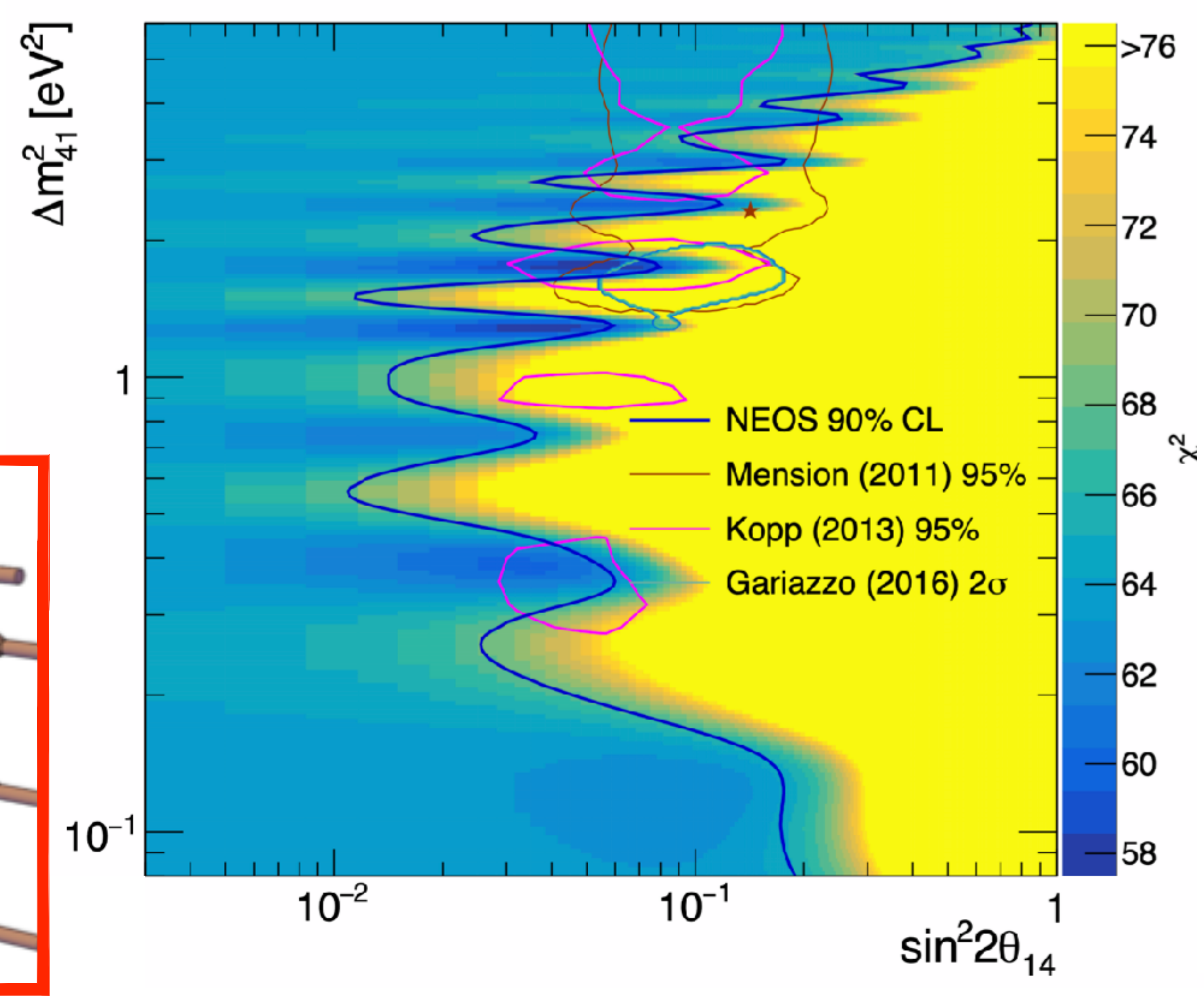

Neutrino4
SoLiδ
DANSS
Prospect
Stereo
NEOS
Power reactors, Gd-loaded
Research reactors, Gd-loaded
Research reactors, Li-loaded

The NEOS Experiment

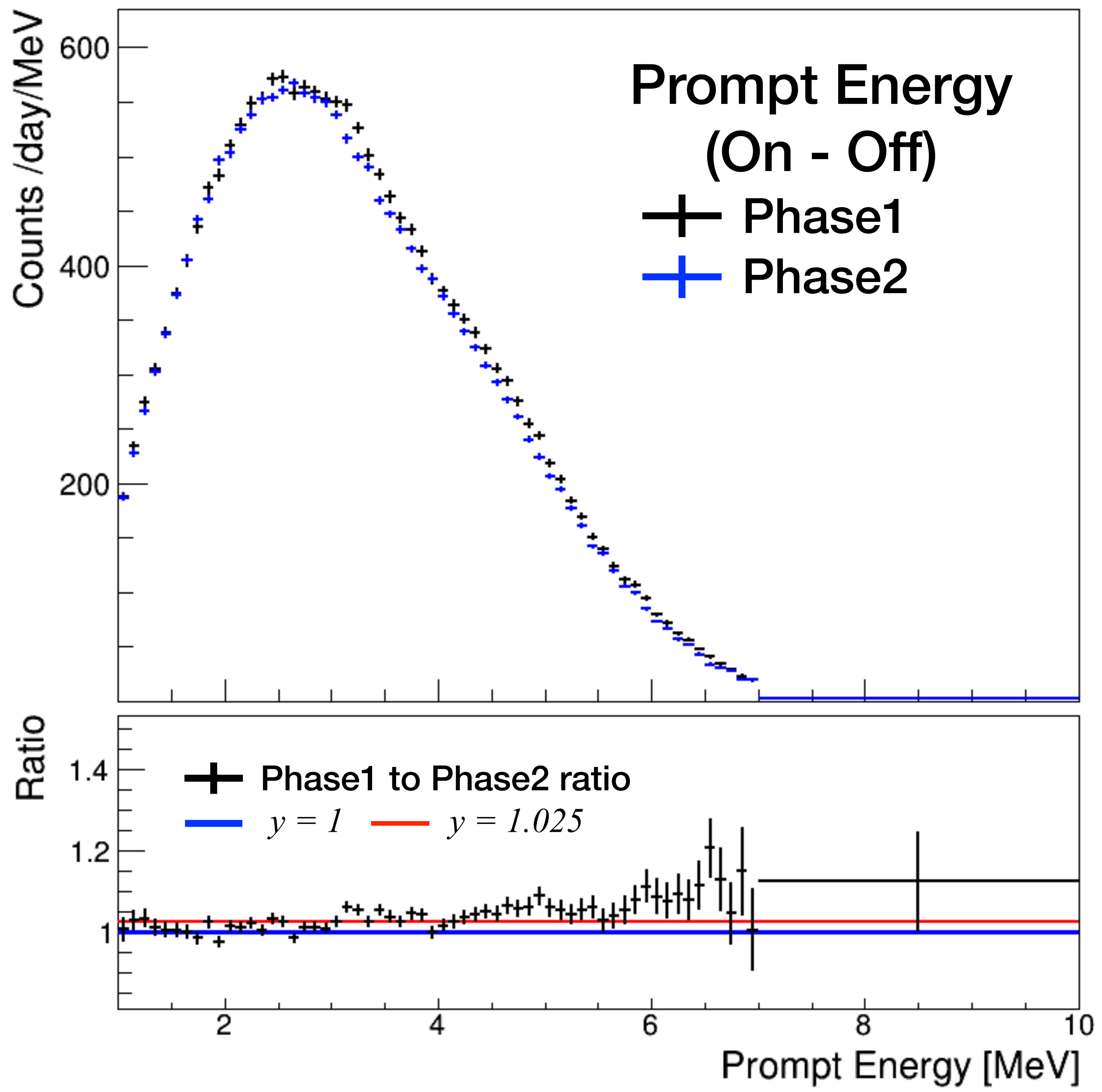
- **Simple design**: 1008 L Gd-loaded (0.48%) liquid scintillator tank, spectrum compared with Data Bay
- **Very high statistics** (~2000 ν/day) thanks to the 2.8 GW commercial reactor
- **Degradation of light yield in time**

- Phase I (46 days OFF + 180 days ON)
- Oscillation analysis with RAA best fit excluded @90%CL
- Phase I+II
- Energy spectrum released
- Oscillation analysis ongoing (expected X2 sensitivity)





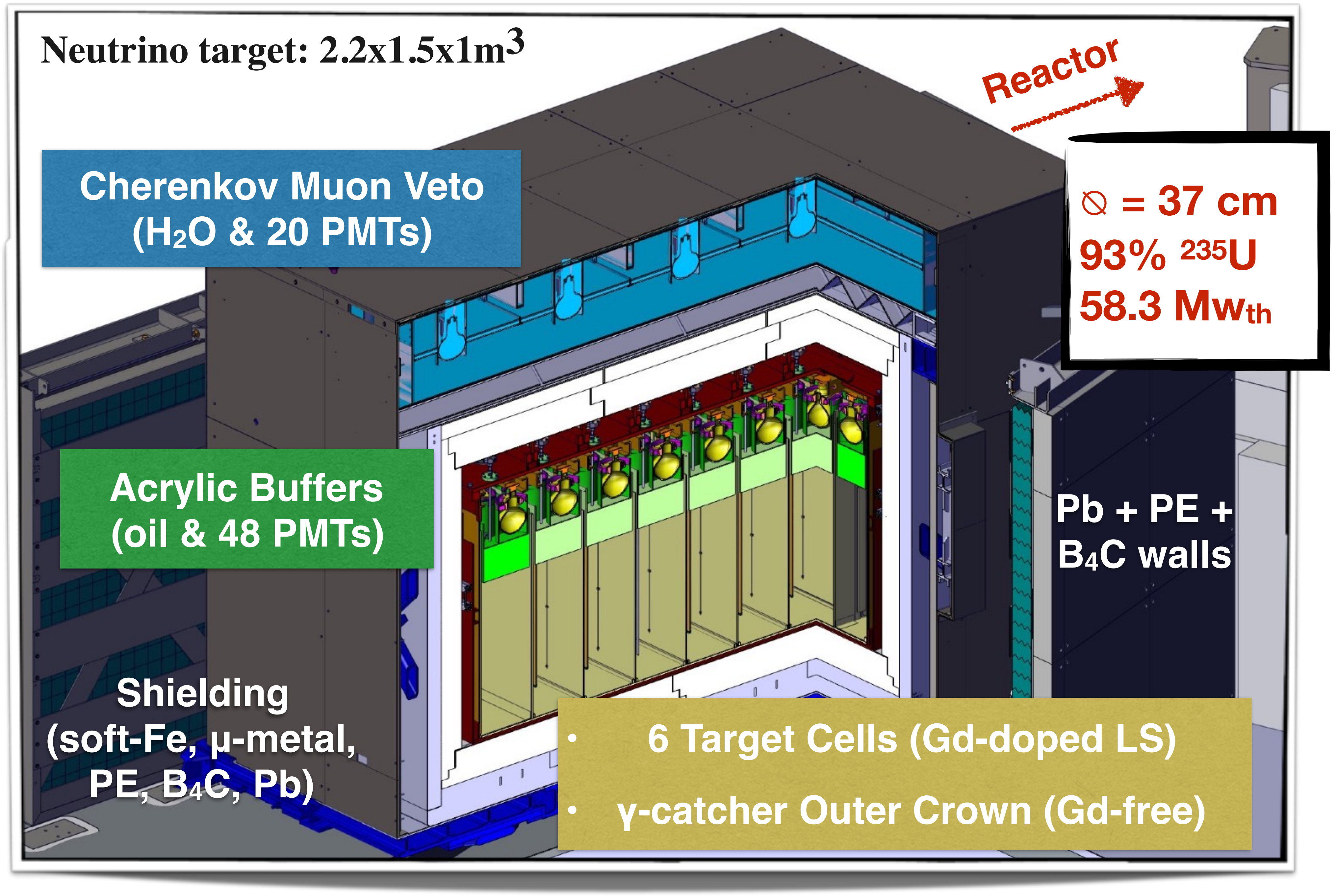
NEOS Preliminary

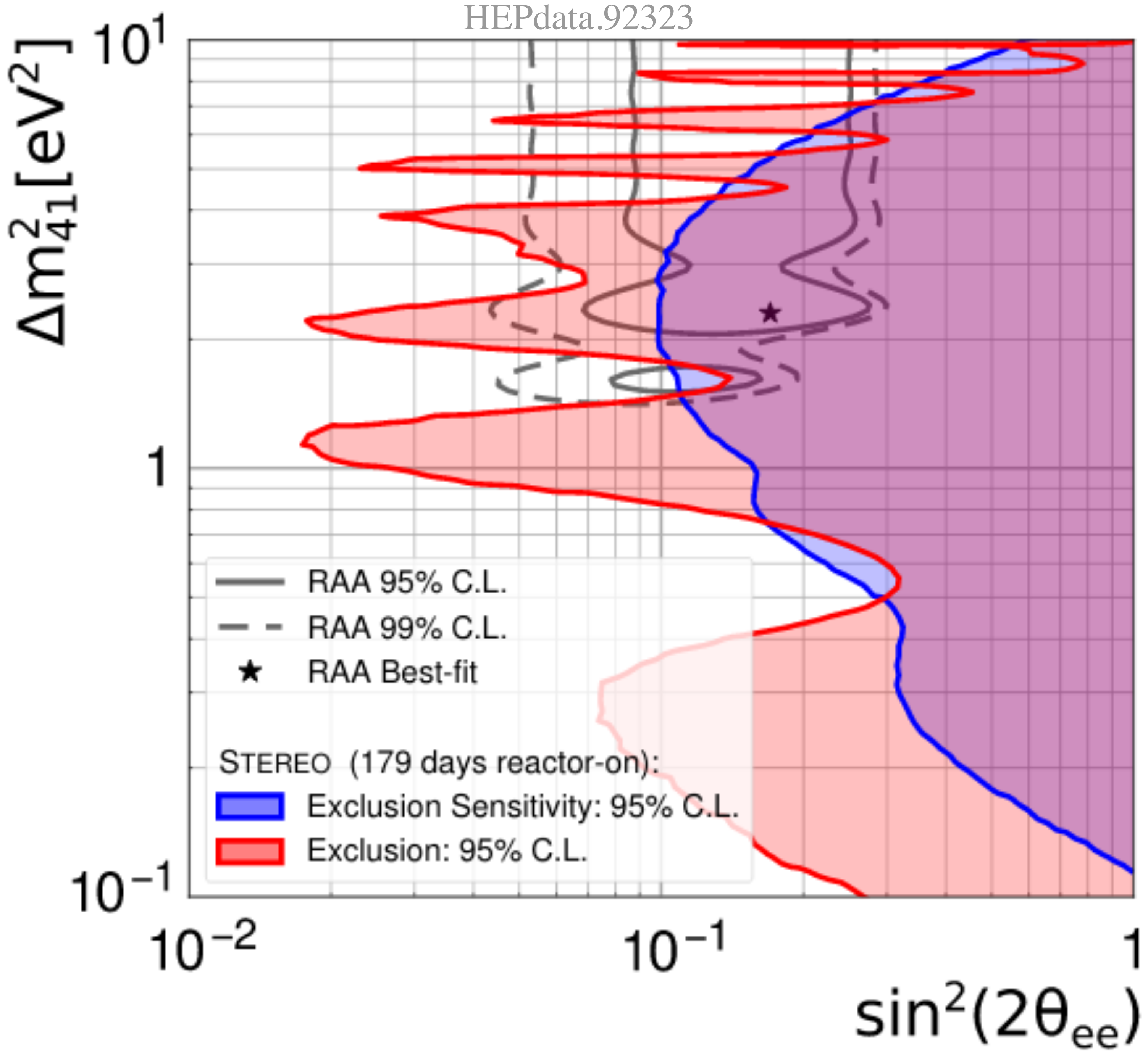


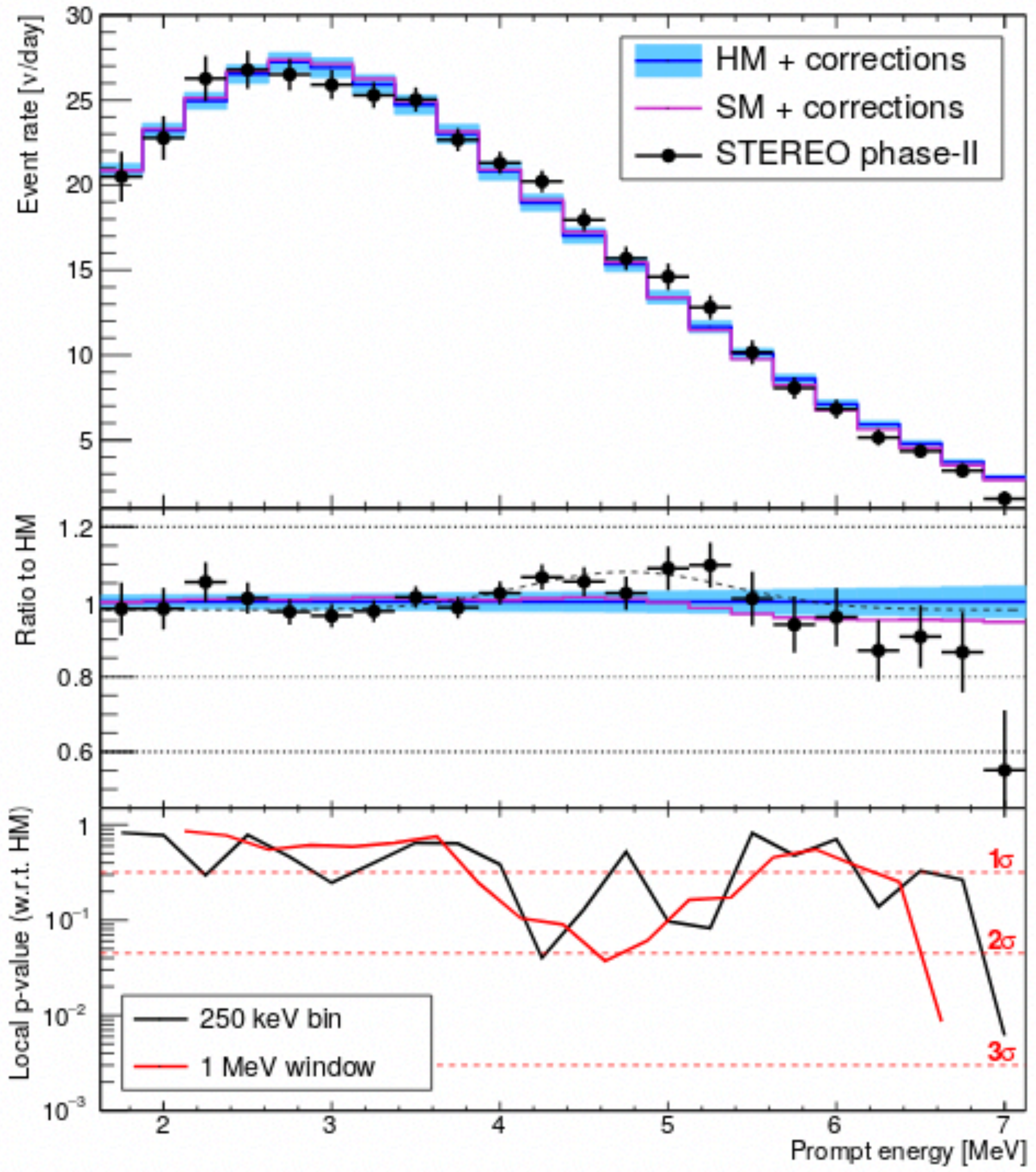
The STEREO Experiment

- Segmented design: 6 cells filled with Gd-loaded liquid scintillator → cell-to-cell relative oscillation analysis
- Compact HEU (58 MW) reactor core & short baseline (9-11 m from core) → **little damping of oscillation**
- **Little overburden** and **noise from reactor facility**

- Phase-I & -II combined data (65k IBDs, 179 days ON + 235 OFF) with S/B ~1 → **RAA best-fit rejected at > 99% CL**
- Expected X2 increase in sensitivity with full dataset
- **Absolute ^{235}U rate and spectral shape** released using phase-II data (consistent with models)



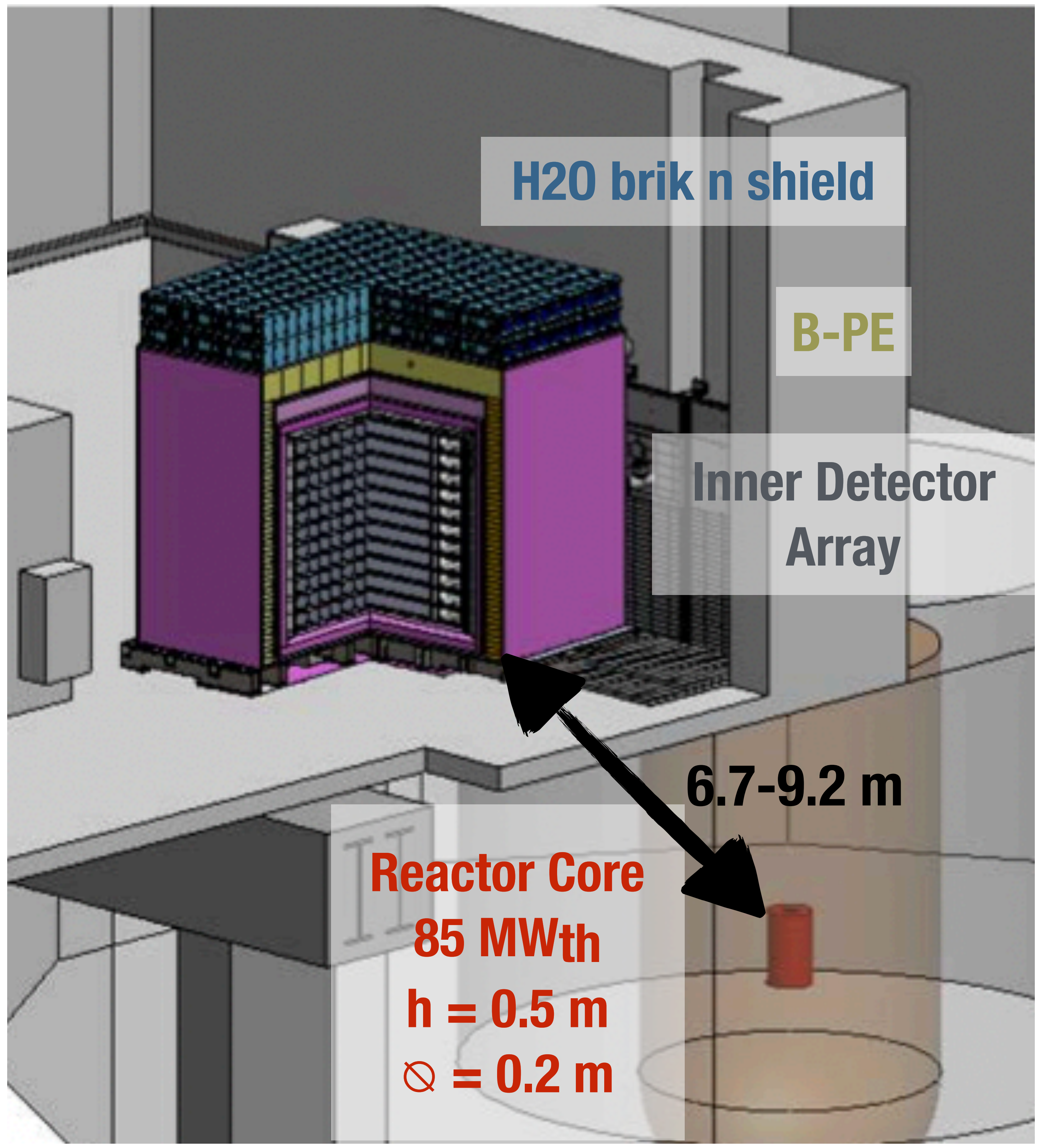


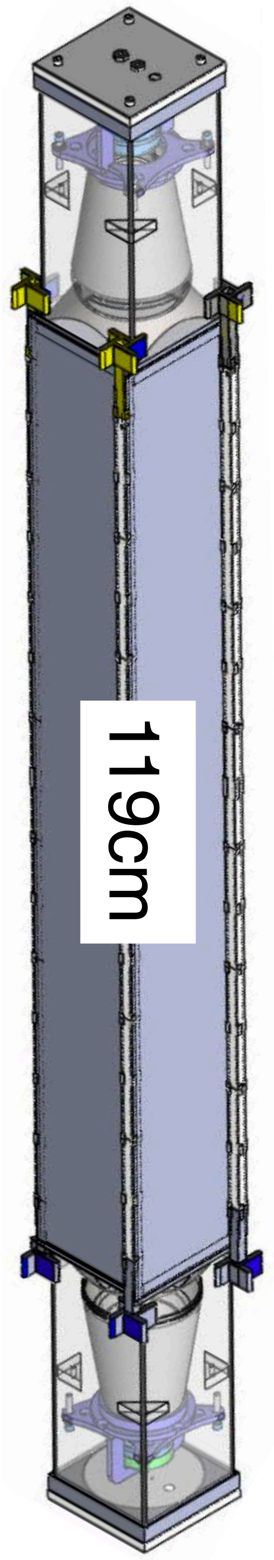


The PROSPECT Experiment

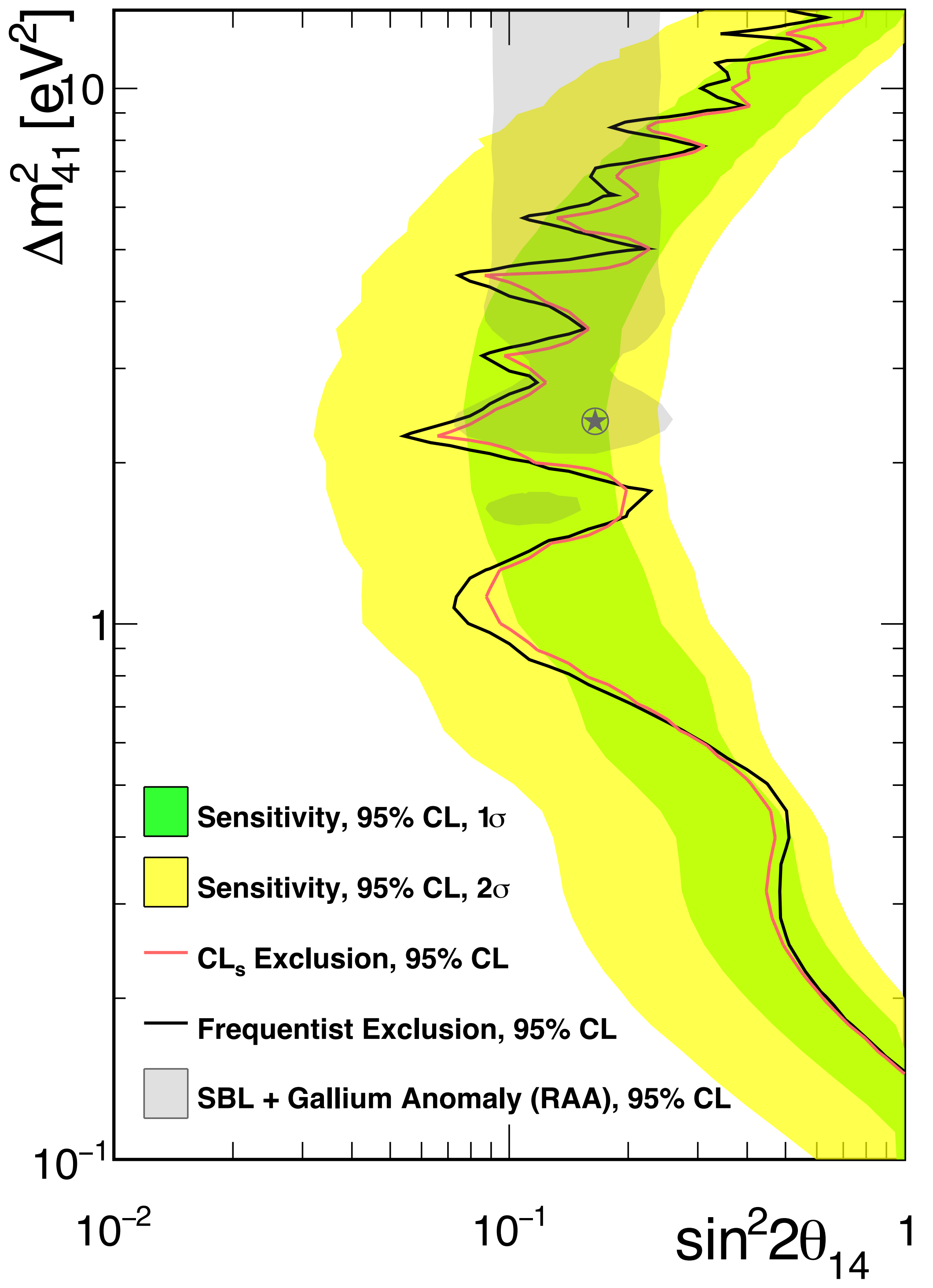
- Highly segmented design: 4-ton ^{6}Li-loaded liquid scintillator in 11x14 optically separated segments → **good E_{res}**, and **3D reconstruction**
- Relatively **high statistics** (530 IBD/day) and S/B (>1) **for a HEU experiment**

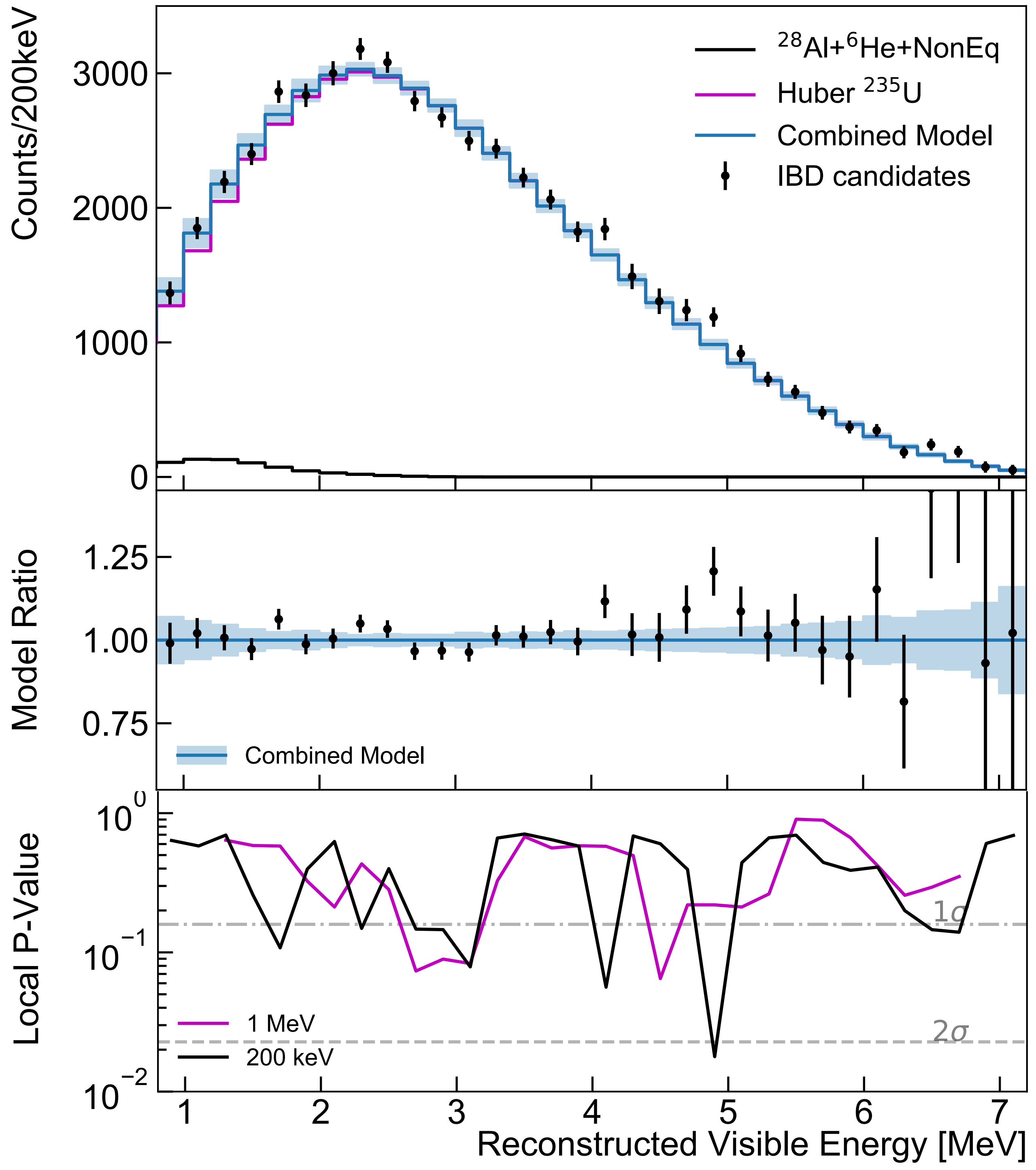
PHYSICAL REVIEW D 103, 032001 (2021)





- Published results with 50k IBDs (105 days ON + 78 days OFF) → **RAA best-fit rejected at 98.5% CL**
- Pure ^{235}U spectrum measured (consistent with models) and combined analyses with Data Bay and STEREO
- **Results based on dataset from 2018**; improved analysis using dead cells (+50%) ongoing

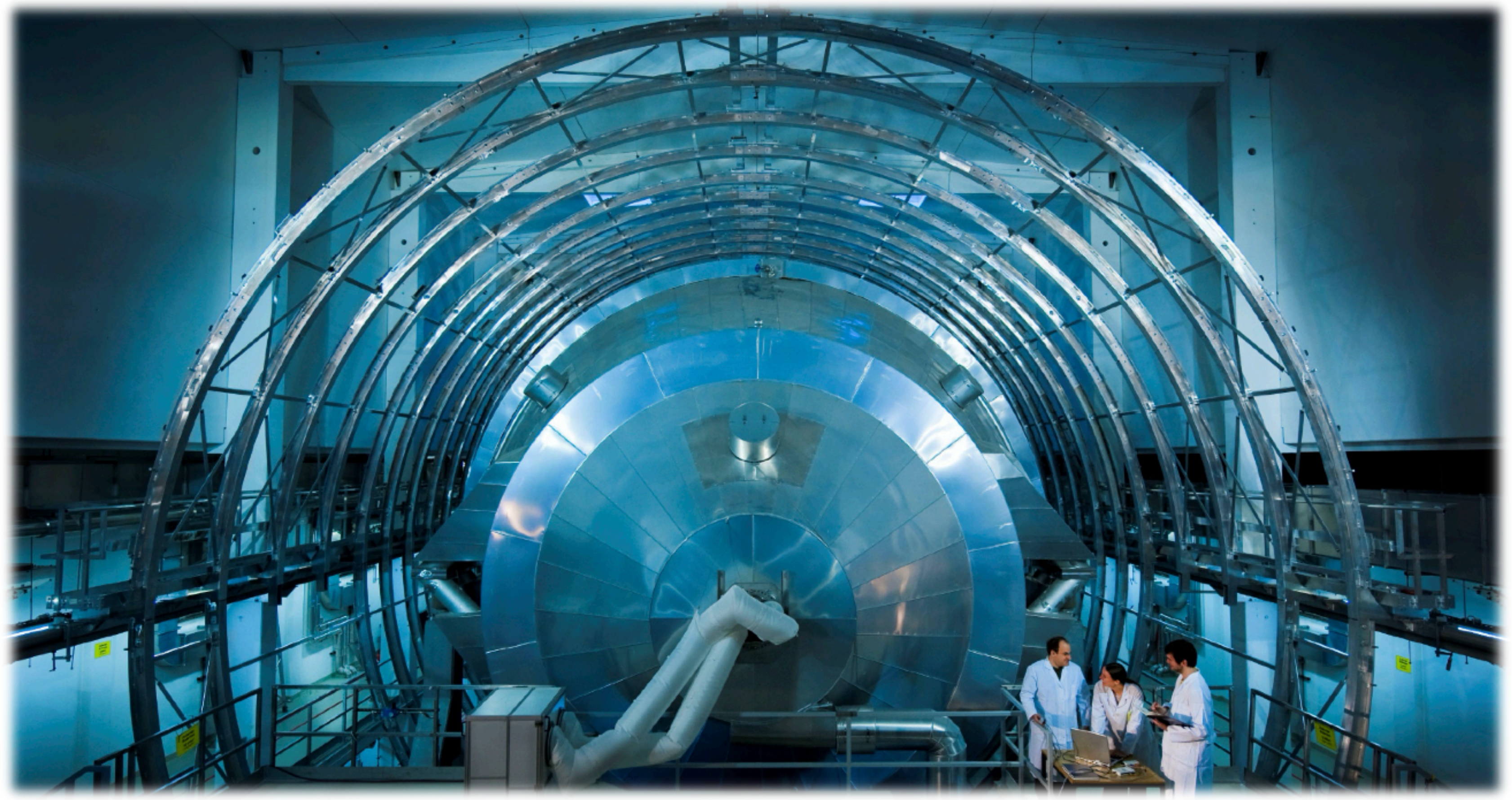


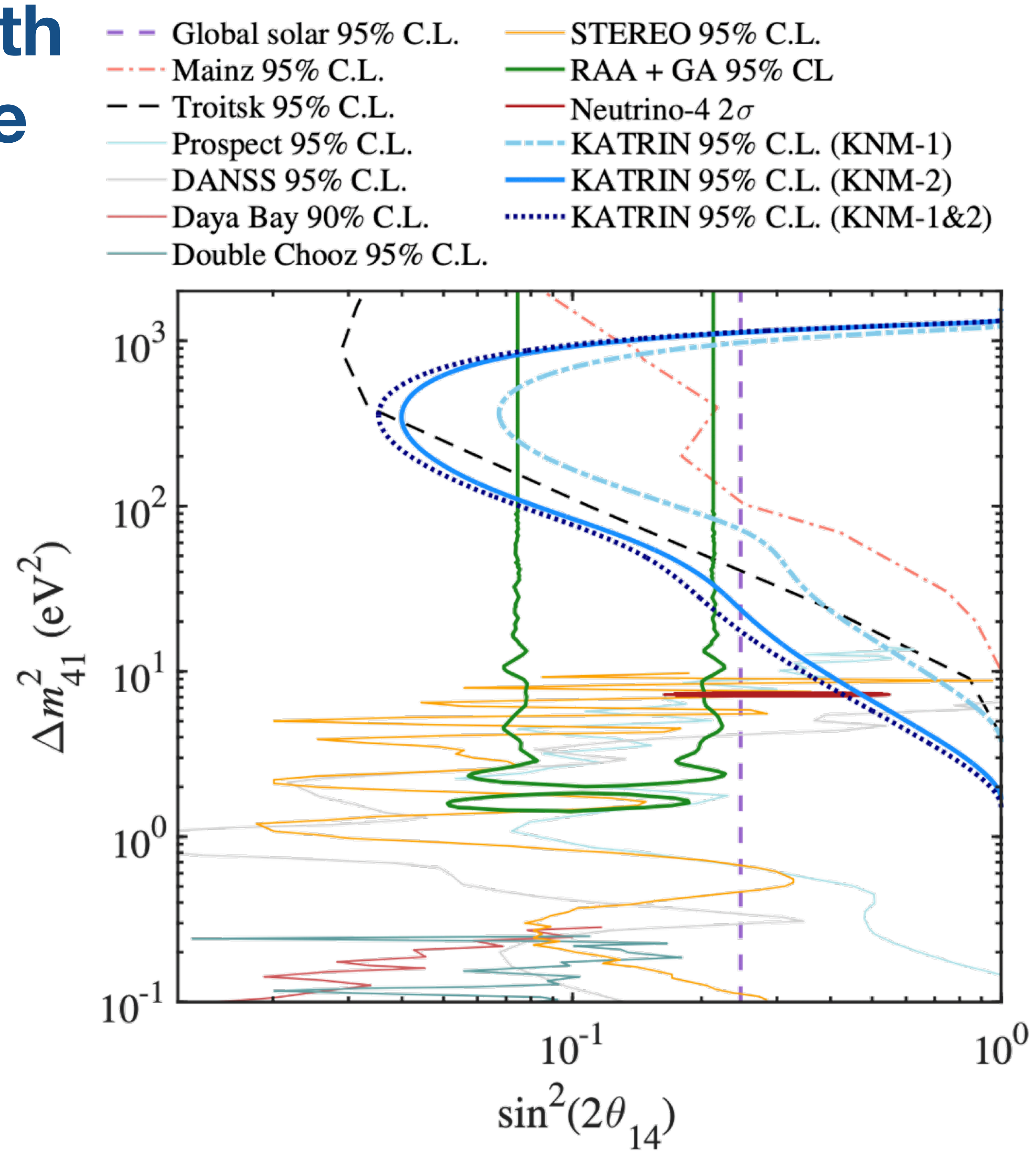


- The Reactor Antineutrino Anomaly and Light Sterile Neutrinos
- Detection Techniques & Challenges
- A worldwide Hunt
- Global Results and Perspectives

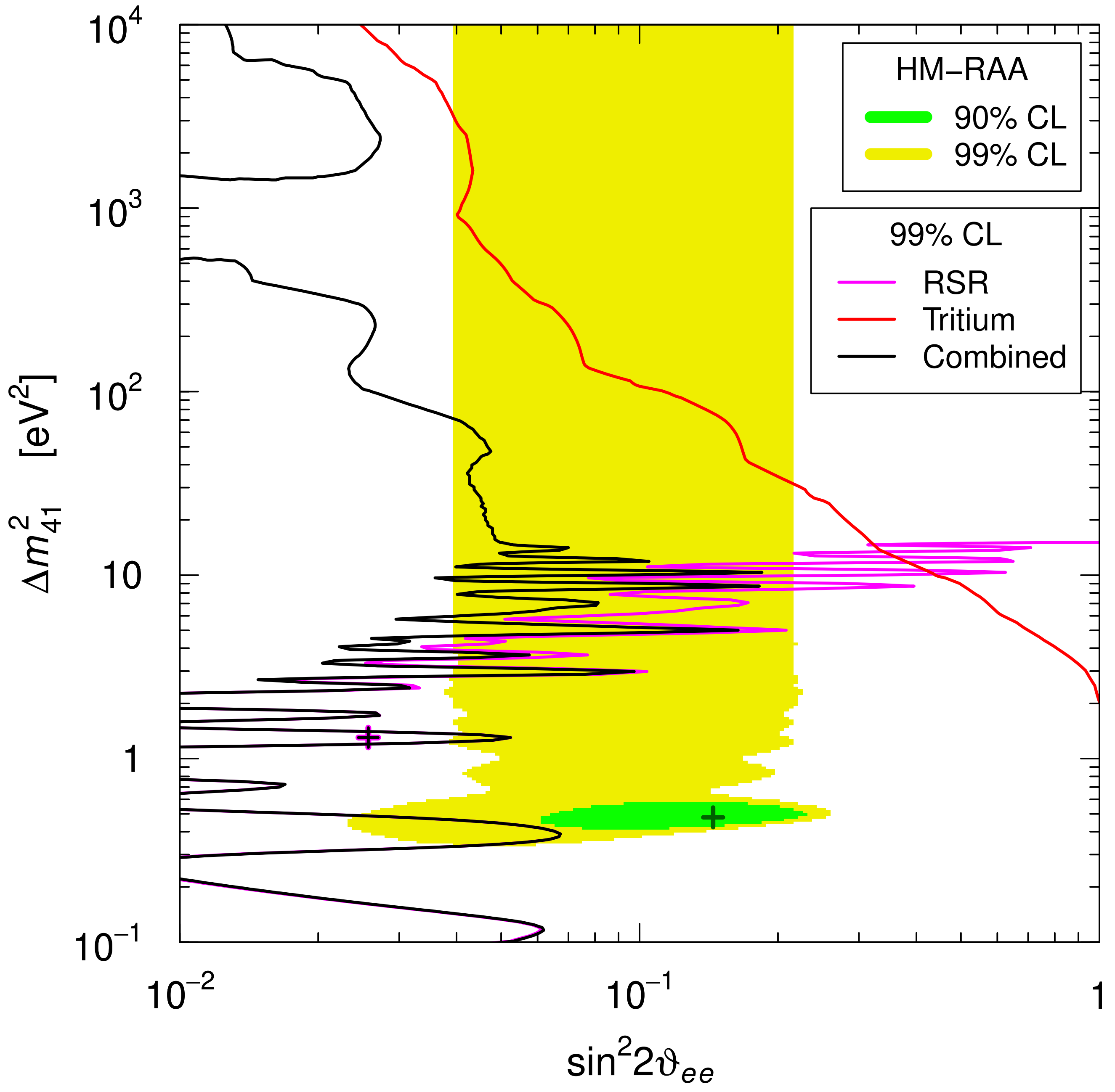
Reactor Anomaly and Recent Results: the Global Picture

- Each of the four experiments: **DANSS, NEOS, STEREO, PROSPECT excluded large portions of the RAA** region **& the best fit value** at > 90% CL, while Neutrinio-4 claims the observation of a $\Delta m^2 \sim 10$ eV oscillation
- Despite the challenges of a combination of these results (different statistical methods, “wiggly” nature of the spectra), growing statistics is helping us **progressing towards a total exclusion of the RAA**
- **KATRIN**, a 200t spectrometer for the measurement of the ν_e mass, has also published results on light sterile → **exclusion plot in the RAA region with strong synergy with the short-baseline searches**



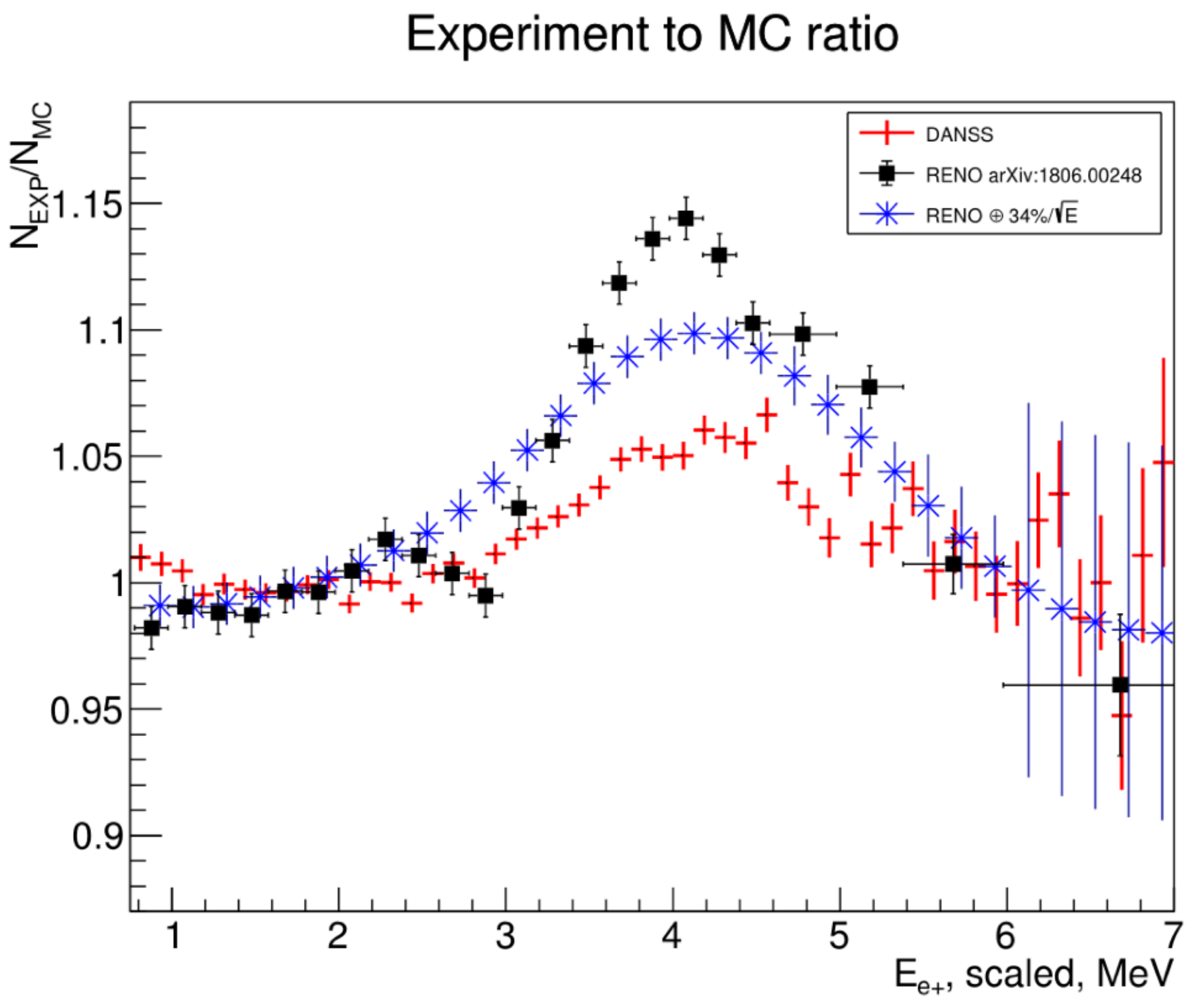


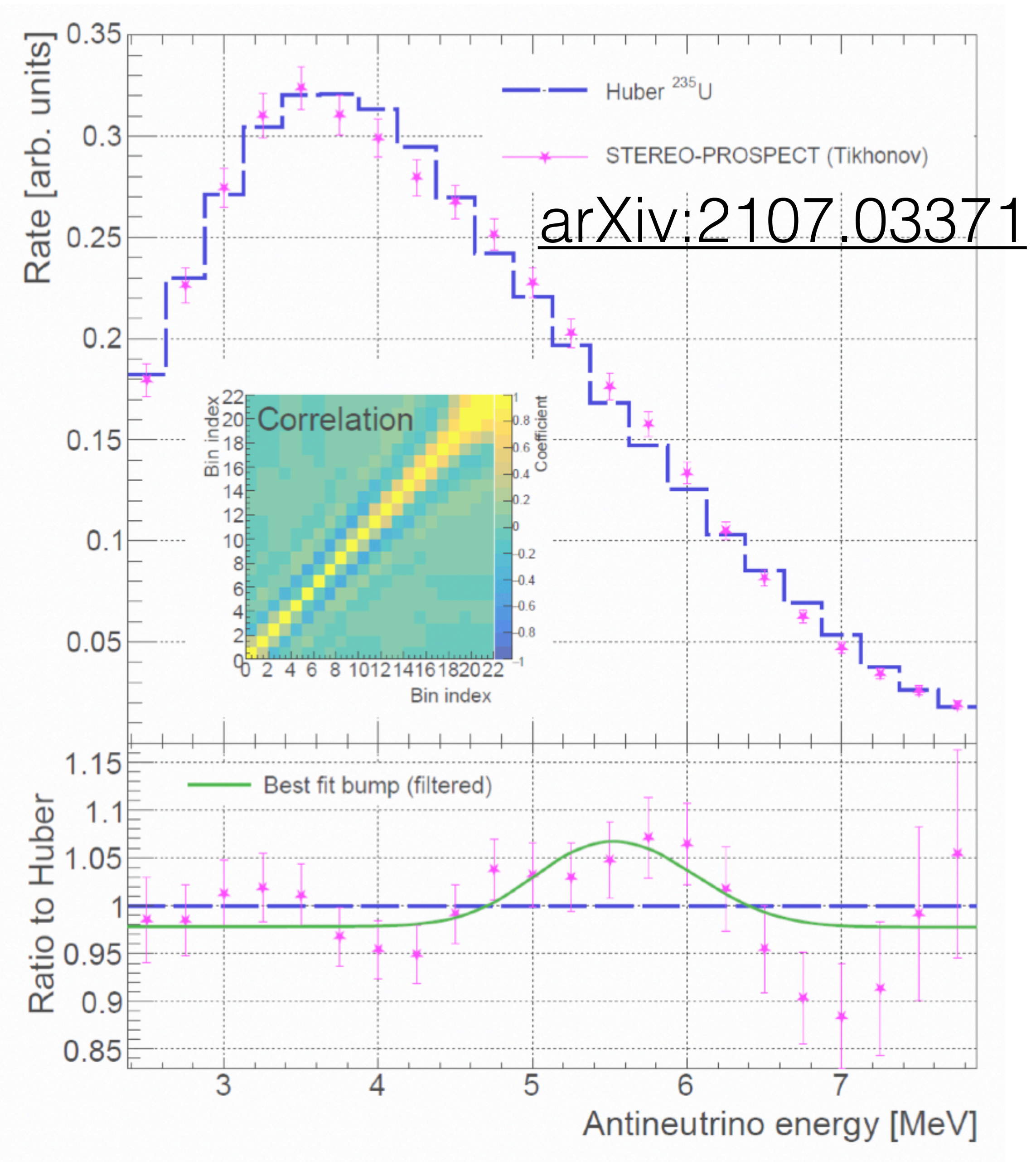
Giunti, C., Li, Y. & Zhang, Y. KATRIN bound on 3+1 active-sterile neutrino mixing and the reactor antineutrino anomaly. *J. High Energ. Phys.* **2020,** 61 (2020).

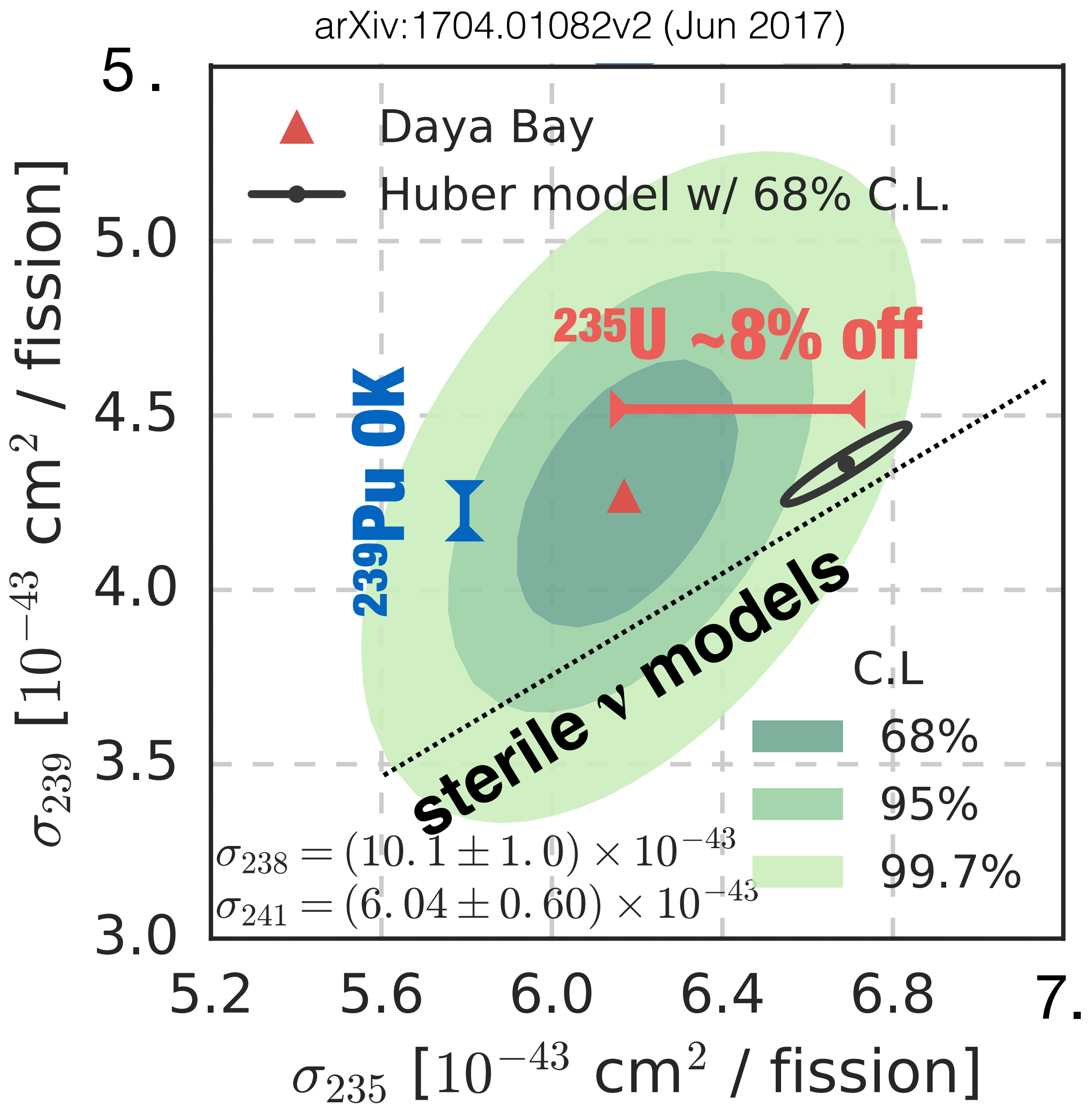


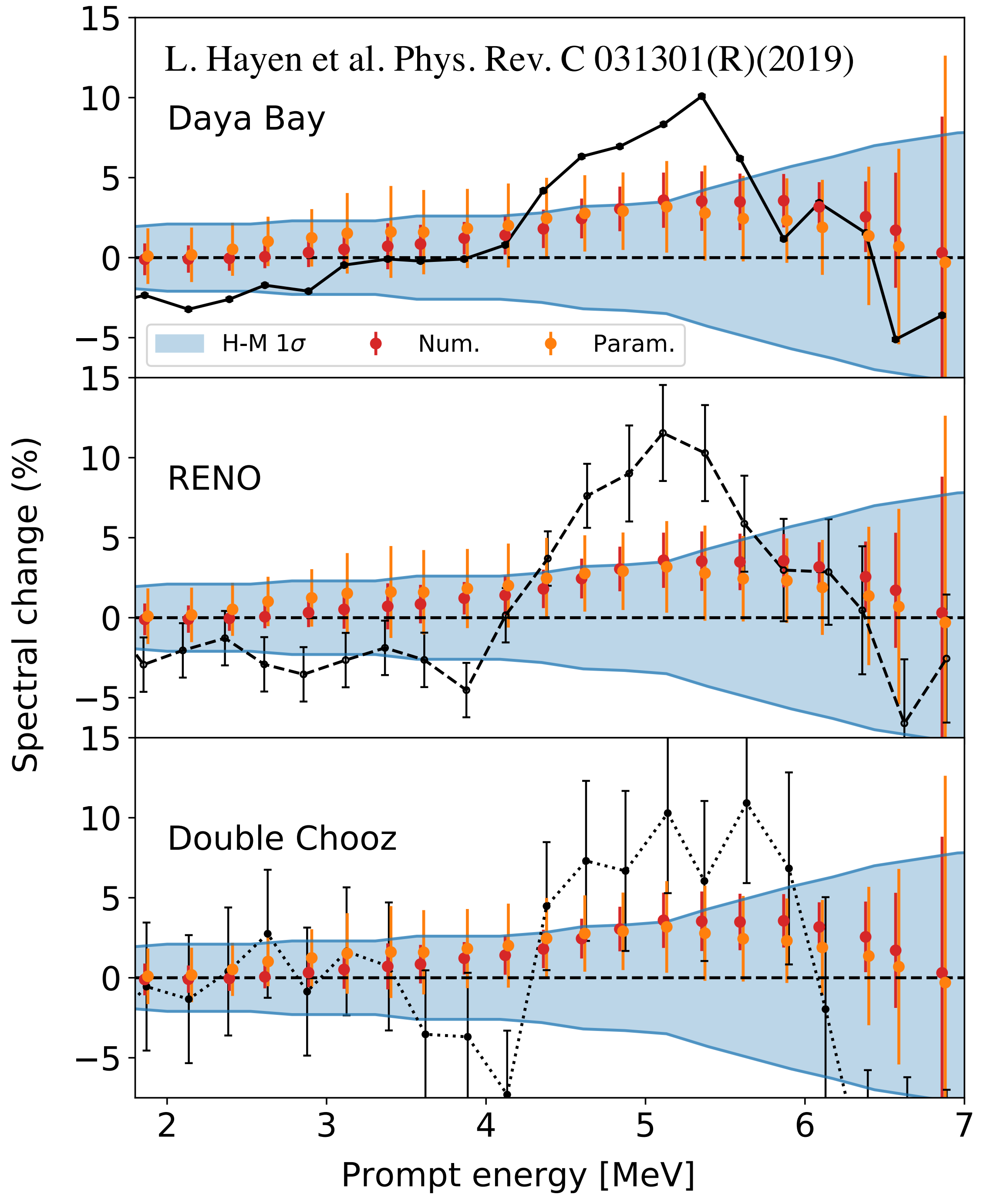
On Isotopes and Antineutrino Flux & Spectrum

- A spectral distortion @ E_ν ~ 6 MeV was observed in θ_{13}-aimed neutrino experiments in 2014, that could be due to **non-linearity** in the energy reconstruction, new **Physics BSM**, or **unknown branches** (isotope related)
  [Mention et al, PhysLettB 773:307-312 (2017)] [Berryman et al, PRD 99, 055045 (2019)] [Hayes et al, PRD 92, 033015 (2015)]
- **STEREO & PROSPECT** released a **combine spectral analysis** confirming the distortion w/ **2.4 σ significance** and **A = 9.9 ± 3.3 % for pure ^{235}U** → **distortion independent of other isotopes**
- Daya Bay and RENO can separate ^{235}U and ^{239}Pu contribution to $\bar{\nu}_e$ flux → **RAA rate deficit mainly from ^{235}U**
- Meanwhile, limits of current spectrum models are emerging, and the treatment of forbidden decays could change both normalisation and spectral shape









Conclusions

- The quest for θ_{13} in the 2010's prompted new models for reactor $\bar{\nu}_e$ spectra, which marked the emergence of the so-called reactor antineutrino anomaly
- Several projects worldwide were designed to study the anomaly and investigate the possible existence of extra sterile neutrino families
- These projects faced new and existing experimental challenges and produced compelling results in term of active-sterile neutrino oscillation analyses, as well as new spectral and rate analyses for reactor antineutrinos
- Meanwhile, the limits of existing models are also being pushed by theoretical advancements, and new measurements can help shed light on unexplained observations
- Overall, the combination of the rapidly-advancing analysis of data from reactor short-baseline experiments and others, and the improvement of models, could allow us to solve the reactor antineutrino anomaly


Thank You For Your Attention!

Extra Slides

Not the Only Anomaly

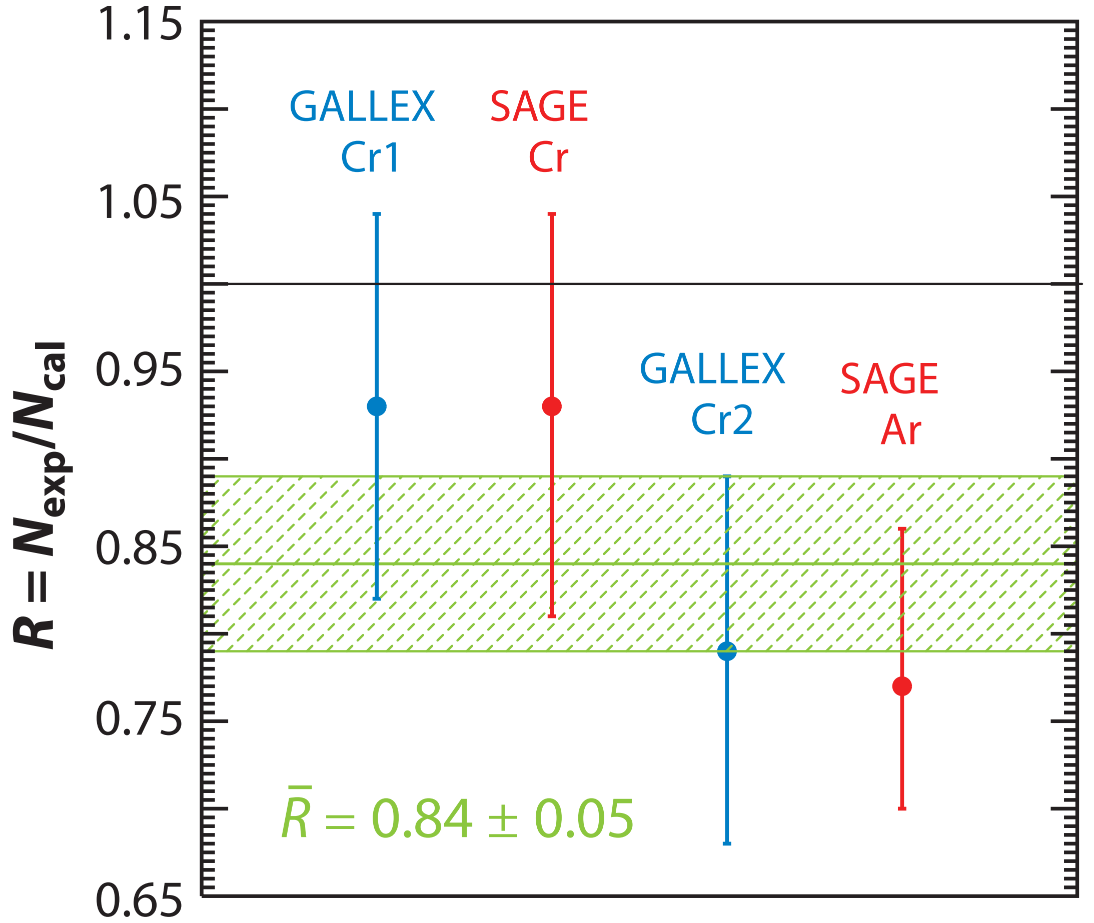
- **Gallium anomaly - disappearance of ν_e** measured with radioactive sources in the solar neutrinos gallium experiments GALLEX and SAGE (rate only)
- **LSND/MiniBooNE anomaly** - energy-dependent event **excess in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel** measured in LSND, consistent with an active-sterile oscillation with **$\Delta m^2 \gtrsim 0.1$ eV^2**; a similar excess was later seen by MiniBooNE
- All these anomalies can be explained by the existence of a light sterile neutrino, but a global simple solution combining them all is not possible
- **LSND/MiniBooNE anomaly** ($\nu_\mu \rightarrow \nu_e$) is **highly disfavoured** by disappearance ($\nu_\mu \rightarrow \nu_\mu$) results, while the **Reactor/Gallium anomalies** remain yet **untested**

$$P_{\nu_e \to \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

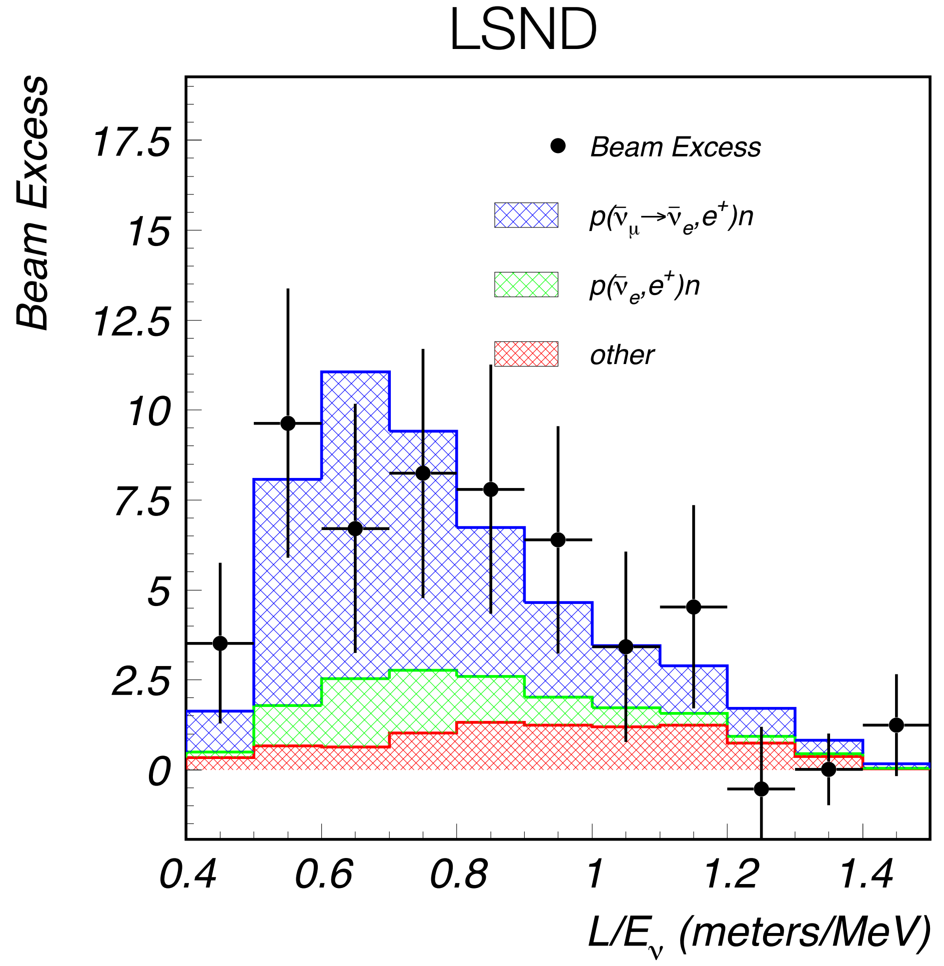
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$

$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu4}|^2$$

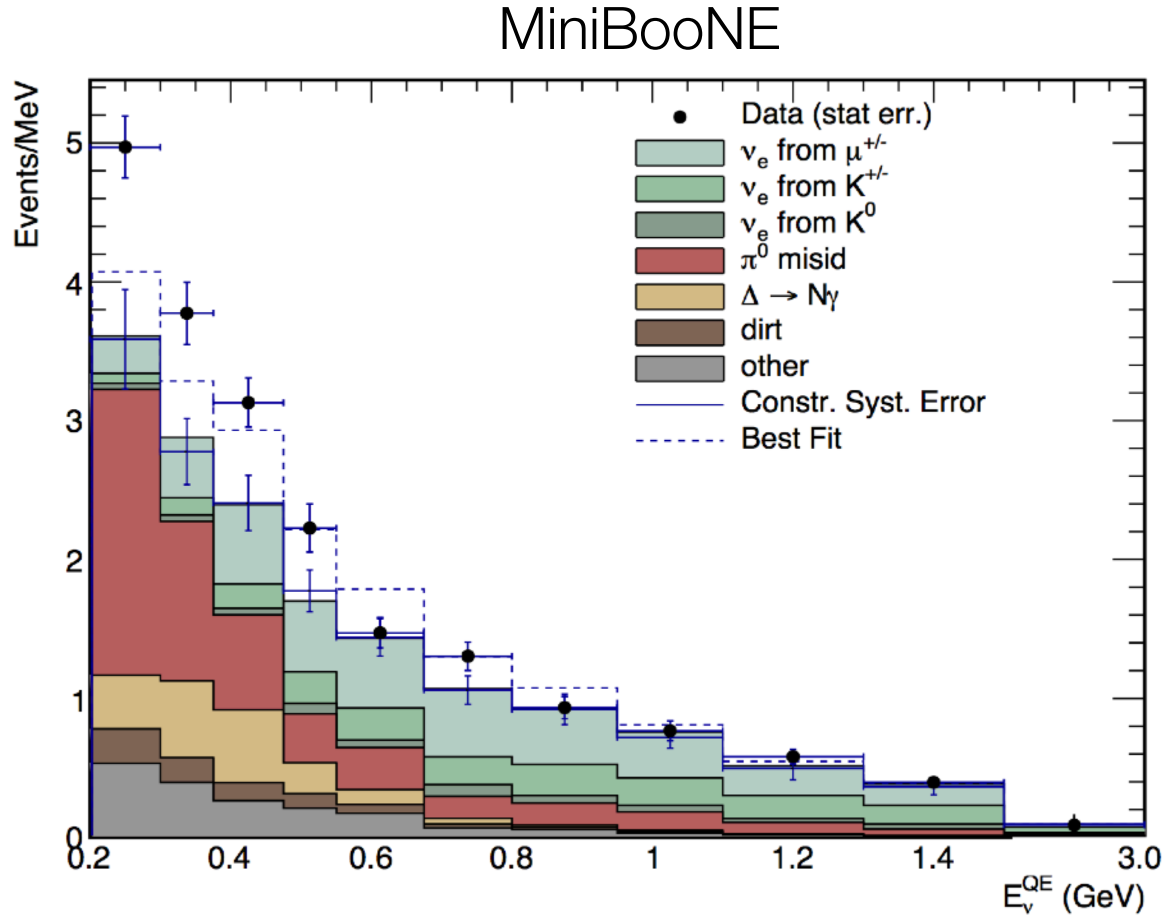
Phys. Lett. B 685:47 (2010)
Phys. Rev. C 73:045805 (2006)

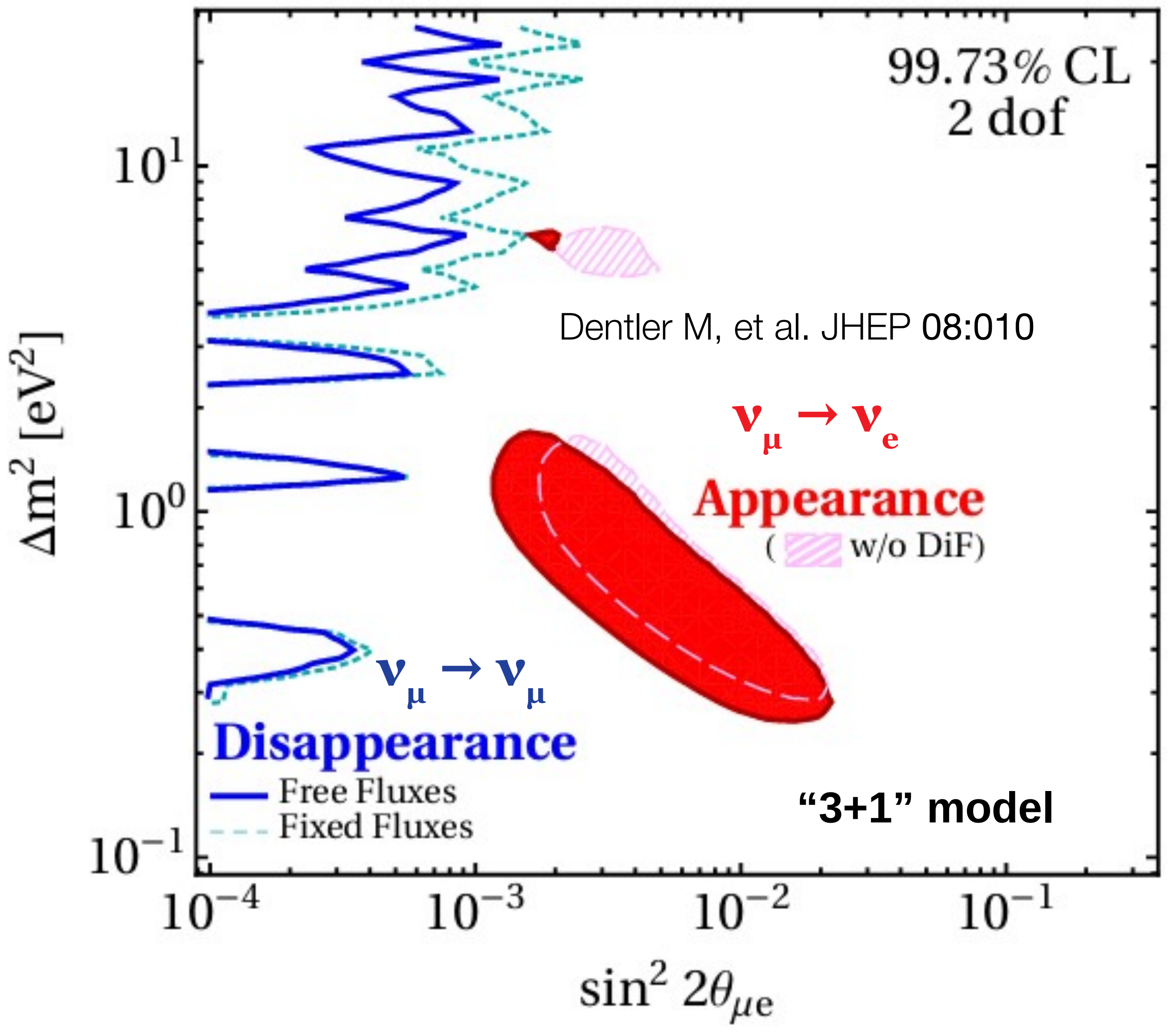


Phys. Rev. D 64:112007 (2001)



Phys. Rev. Lett. 121, 221801 (2018)





Antineutrino Spectrum Estimation

- In low-enriched-uranium (LEU) facilities four isotopes contribute to neutrino spectrum (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu), their fraction $\boldsymbol{\alpha_k}$ evolves with time (burnup)

reactor thermal power

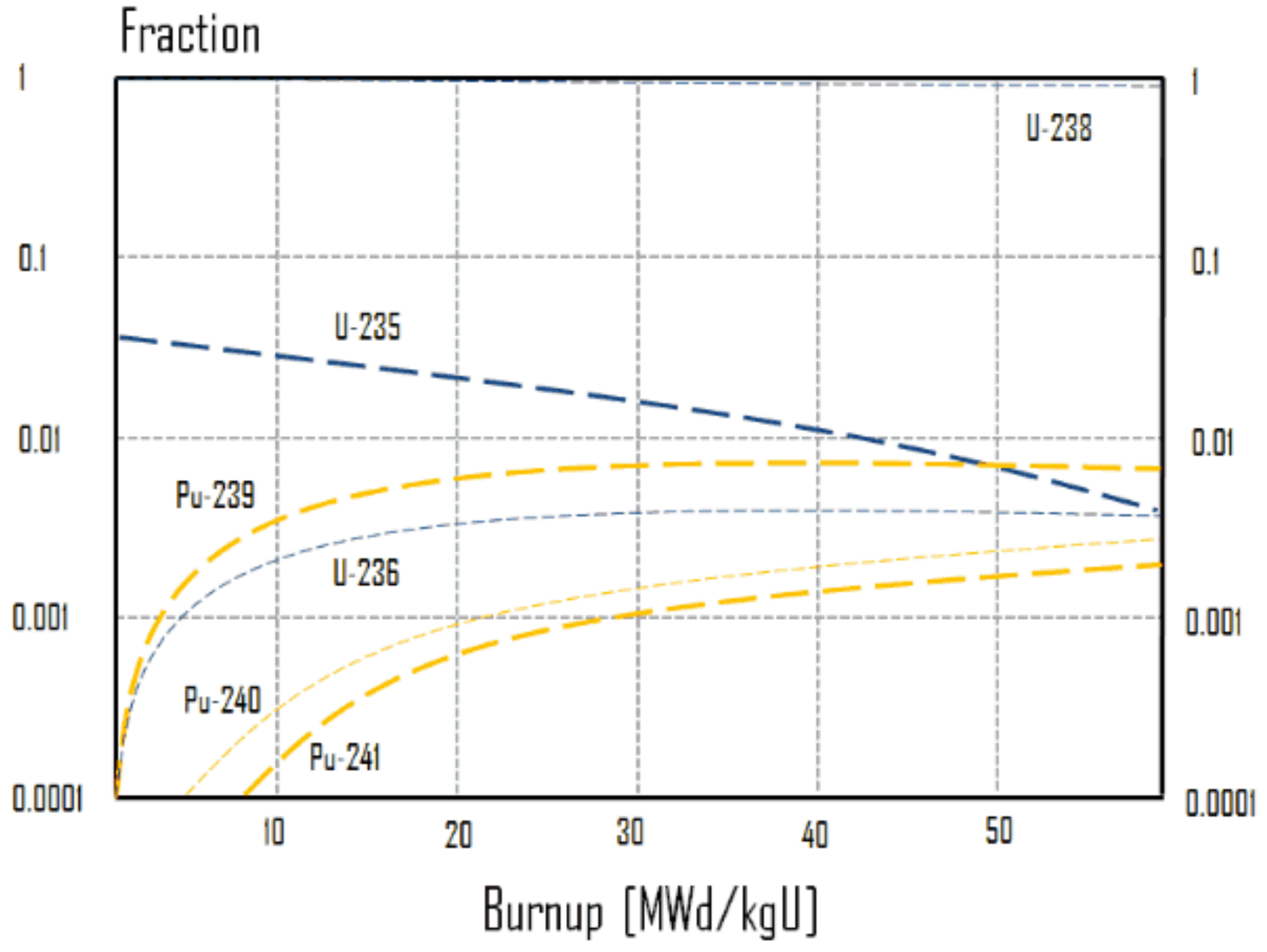
$$N_{IBD}(E_{\bar{\nu}_e}, t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle (t)} \times \langle \sigma_f \rangle (E_{\bar{\nu}_e}, t)$$

average energy released per fission

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_f \rangle_k$$

average IBD cross-section per fission

$$\langle \sigma_f \rangle_k = \int S_k(E)\, \sigma_{IBD}(E) dE$$



- IBD cross-section from theoretical calculations

- **Single $\bar{\nu}$ spectra** $S_k(E)$ unavailable, **obtained from global β spectrum** ($\mathcal{O}10^3$ branches)

  - Start with known branches from nuclear data tables…

  - … and complement with *effective decay branches*

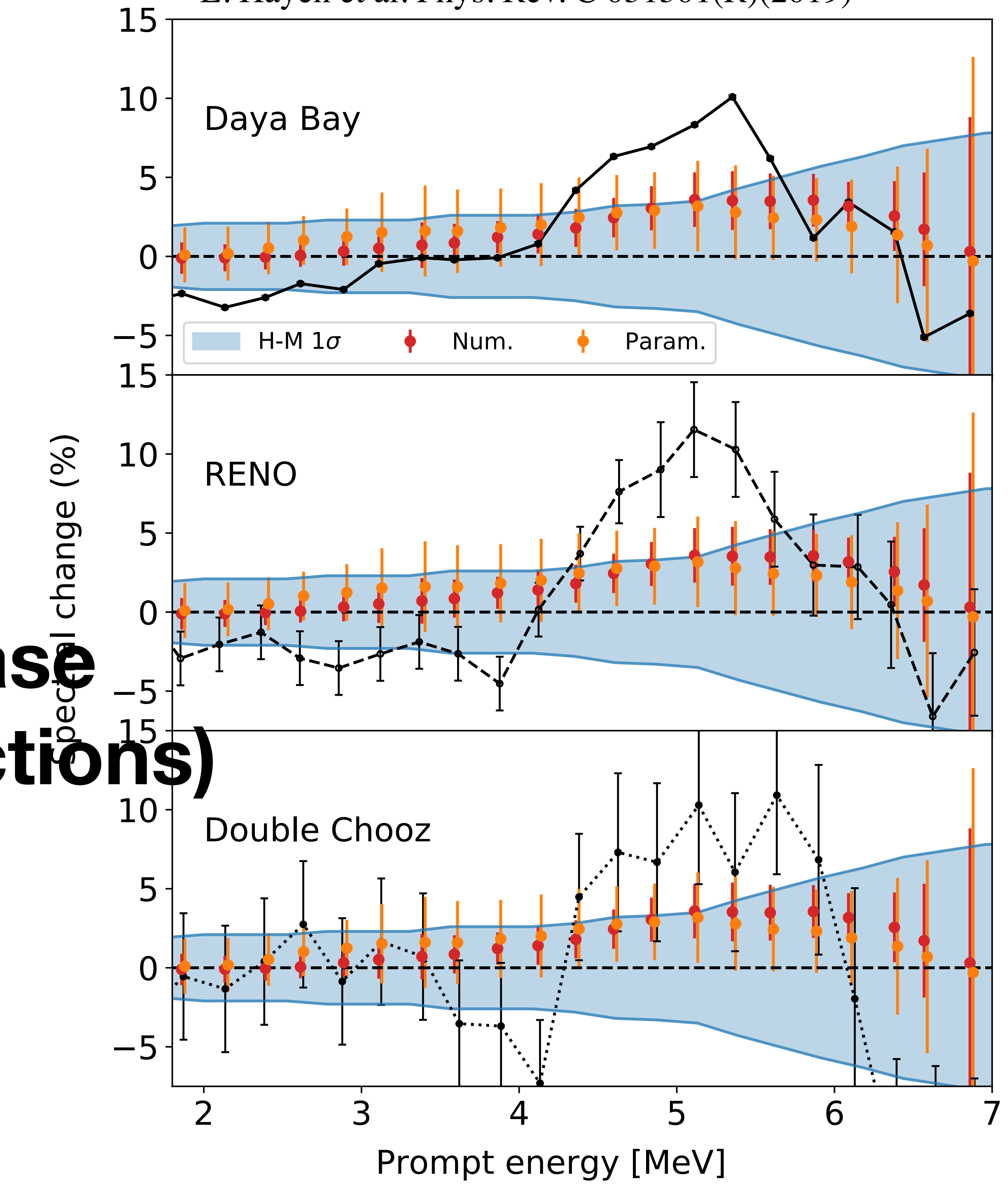
Limits of Current Neutrino Spectrum Models

- Converted spectra method (used for the ^{235}U and Pu contribution:
- Large uncertainty for the weak magnetism term P. Huber PRC84,024617(2011) D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015)
- Underestimated impact on uncertainties of the selection of average effective Z distributions used in the fit of the ILL spectra (up to 5%)
- Treatment of forbidden decays could change both normalisation and spectral shape measurement of the shape factors for the most important forbidden decays is crucial

A . Hayes et al. Phys. Rev. Lett. 112, 202501 (2014)
D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015)
X.B. Wang, J. L. Friar and A. C. Hayes Phys. Rev. C 95 (2017) 064313
L. Hayen et al. Phys. Rev. C 031301(R)(2019) and PRC.100.054323

- Summation method (used for ^{238}U)
- Incomplete or biased nuclear decay schemes
- Pandemonium effect, which can be solved by total absorption γ spectroscopy measurements (data-model discrepancy reduced to < 2%) J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

L. Hayen et al. Phys. Rev. C 031301(R)(2019)



- **To solve the RAA, we must tackle the problem from both experimental (increase statistics, detector upgrades) and theoretical side (new models, better corrections)**

A World-Wide Hunt

	Core P_{Th}	Core Size	Overburden	Segmentation	Baseline	Material
Chandler	72 MW (^{235}U)	⌀ = 50 cm	~10 mwe	6.2 cm (3D)	5.5 m	PS + Li layer
DANSS	3 GW (LEU)	h = 3.6 m ⌀ = 3.1 m	~50 mwe	5 cm (2D)	10.7-12.7 m	Gd-doped PS
NEOS	2.8 GW (LEU)	h = 3.7 m ⌀ = 3.1 m	~20 mwe	-	23.7 m	Gd-doped LS
Neutrino4	90 MW (^{235}U)	35x42x42 cm^3	few mwe	22.5 cm (2D)	6-12 m	Gd-doped LS
NuLat	40/1790 MW (^{235}U/LEU)		few mwe	6.35 cm (3D)	4.7/24 m	Li-doped PS
Prospect	85 MW (^{235}U)	h = 0.5 m ⌀ = 0.2 m	few mwe	15 cm (2D)	7 m	Li-doped LS
SoLiδ	72 MW (^{235}U)	⌀ = 0.5 m	~10 mwe	5 cm (3D)	5.5 m	PS + Li layer
Stereo	58 MW (^{235}U)	⌀ = 37 cm	~15 mwe	25 cm (1D)	8.8-11.2 m	Gd-doped LS

The SoLi∂ Exeperiment

- **Highly-segmented 3D detector design**: 12800 5×5×5cm^3 optically separated PVT cubes, with a ^{6}LiF:ZnS(Ag) layer for neutron identification
- Relatively powerful HEU compact core & very short baseline (6-9 m from the core)
- Very little overburden, but **can use topology to separate IBDs from cosmic background**

- **Challenging background from BiPo coincidences** due to the internal ^{238}U/^{230}Th series isotopes (mainly in LiF:ZnS(Ag))
- Analysis of phase-I data (326 days ON + 87 days OFF) ongoing
- Detector upgrade for Phase-II with new SiPMs