Neutrino oscillation from reactor experiments, neutrino reactor anomaly and sterile neutrinos

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La Thuile 2022 - Les Rencontres de Physique de la Vallée d'Aoste

08/03/2022

Outline

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

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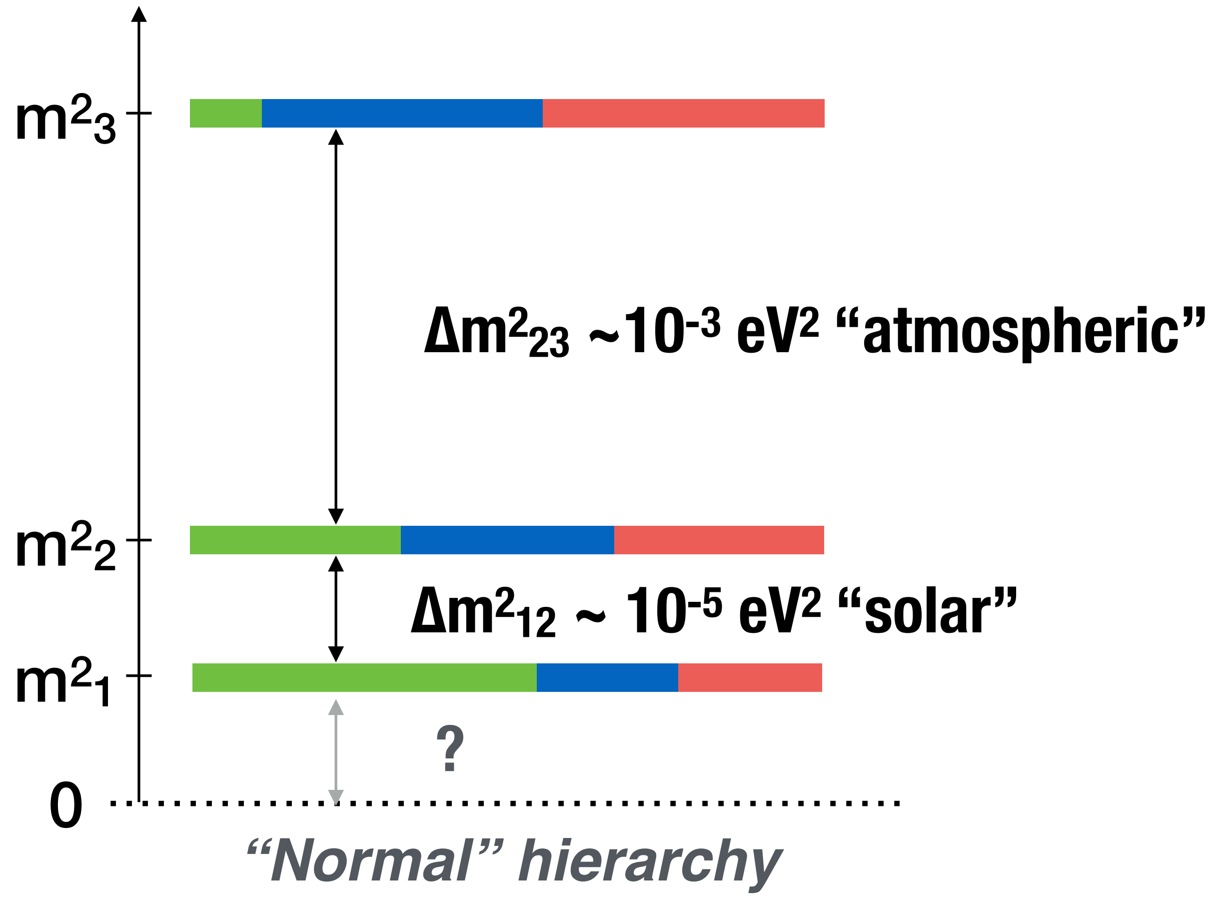
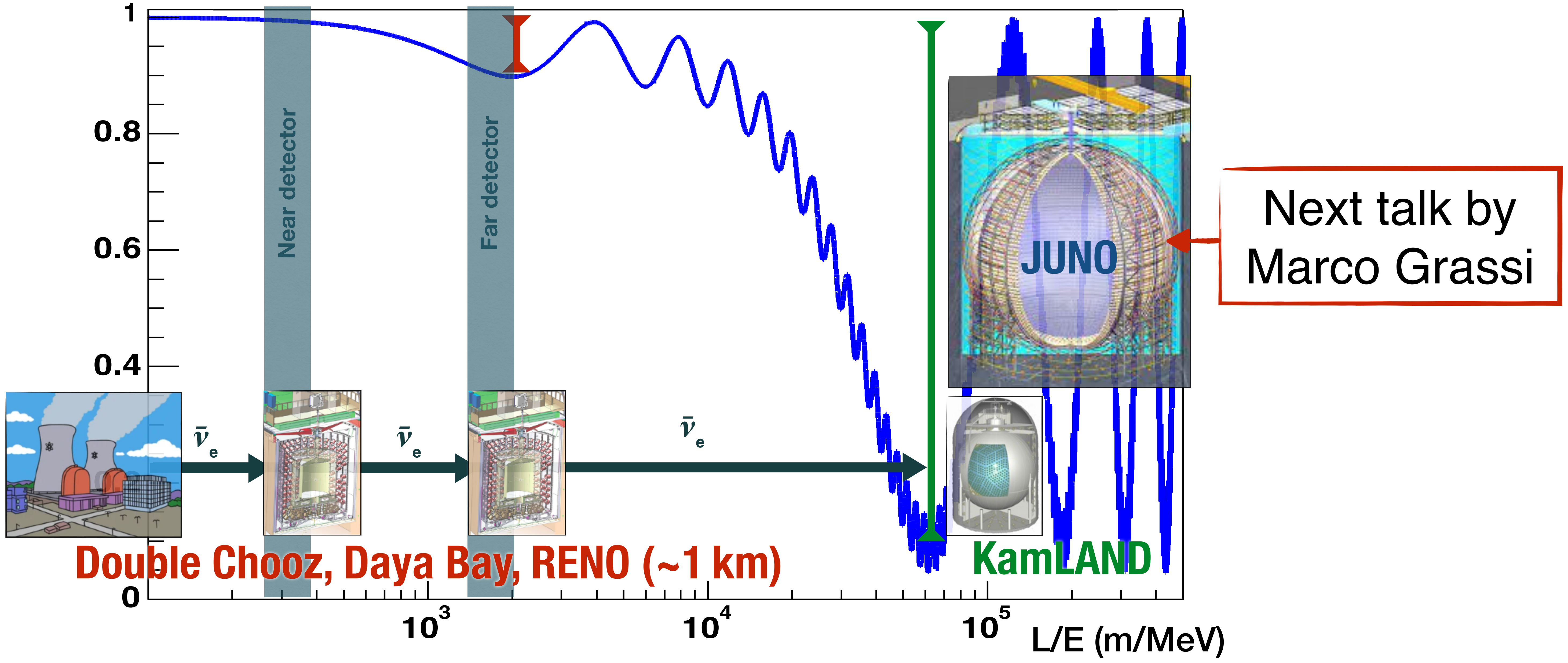
Reactor Neutrino Oscillation Experiments

- Reactor antineutrino oscillation is sensitive to **two mixing angles** (θ_{13}, θ_{12}) of the U_{PMNS} matrix, and **both squared-mass splittings**, including, if energy resolution is good enough, the **sign of Δm^2_{23}**

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

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





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

. D. Adey, F. An, A. Balantekin, H. Band, M. Bishai, S. Blyth et al., *Measurement of the electron antineutrino oscillation with 1958 days of operation at daya bay*, Physical review letters **121** (2018) 241805.
. H. de Kerret and T.D.C. Collaboration, *Double chooz θ_{13} measurement via total neutron capture detection*, Nature Physics **16** (2020) 558.
. C. Shin, Z. Atif, G. Bak, J. Choi, H. Jang, J. Jang et al., *Observation of reactor antineutrino disappearance using delayed neutron capture on hydrogen at reno*, Journal of High Energy Physics **2020** (2020) 1.

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

Reactor Antineutrino Anomaly (RAA)

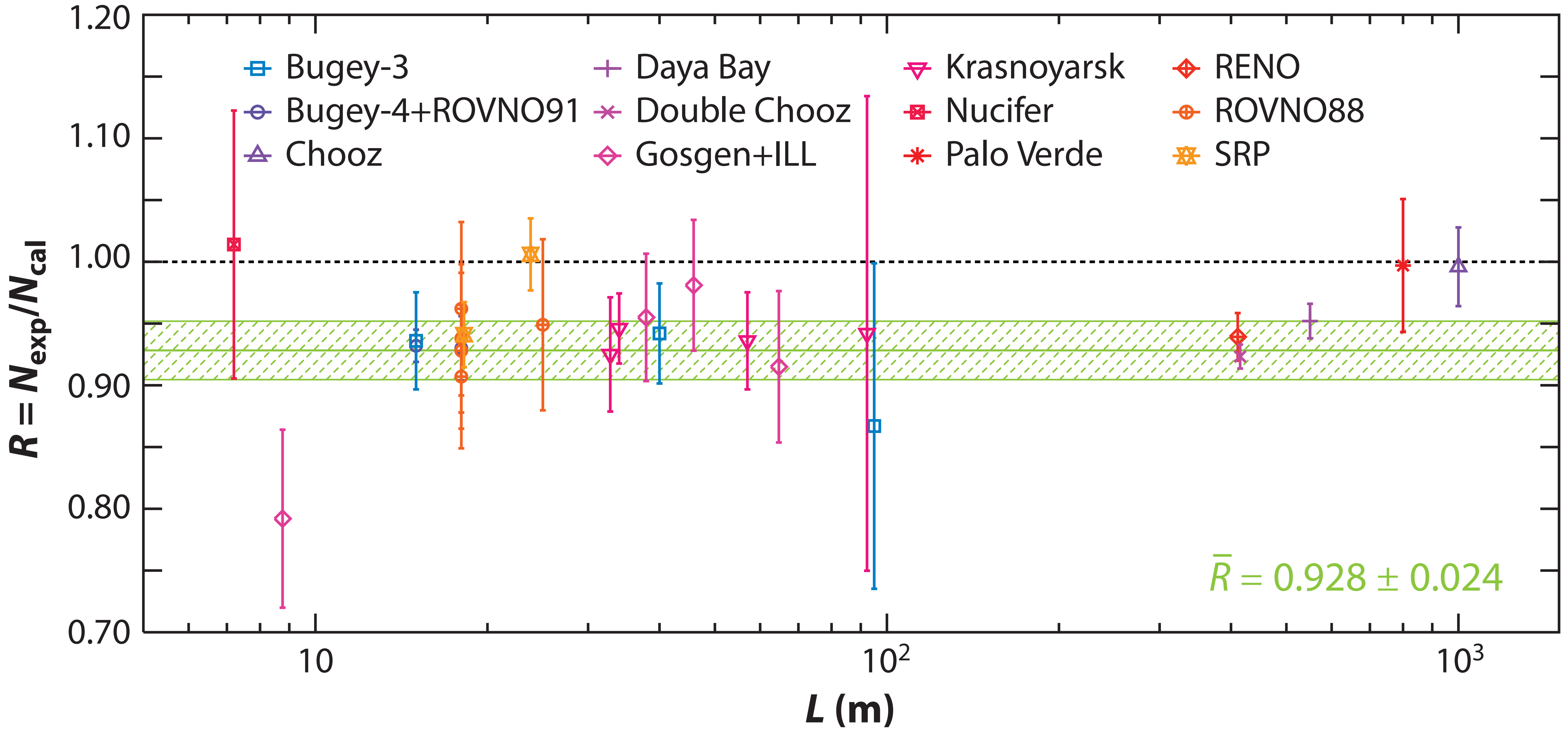
- Mueller (^{238}U)-Huber (^{235}U, Pu) calculated new precise IBD spectra, that could be used before a near detector was operational

- [4] T.A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner et al., *Improved predictions of reactor antineutrino spectra*, *Physical Review C* **83** (2011) 054615.
- [5] P. Huber, *Determination of antineutrino spectra from nuclear reactors*, *Physical Review C* **84** (2011) 024617.

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

- [6] G. Mention, M. Fechner, T. Lasserre, T.A. Mueller, D. Lhuillier, M. Cribier et al., *Reactor antineutrino anomaly*, *Physical Review D* **83** (2011) 073006.

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



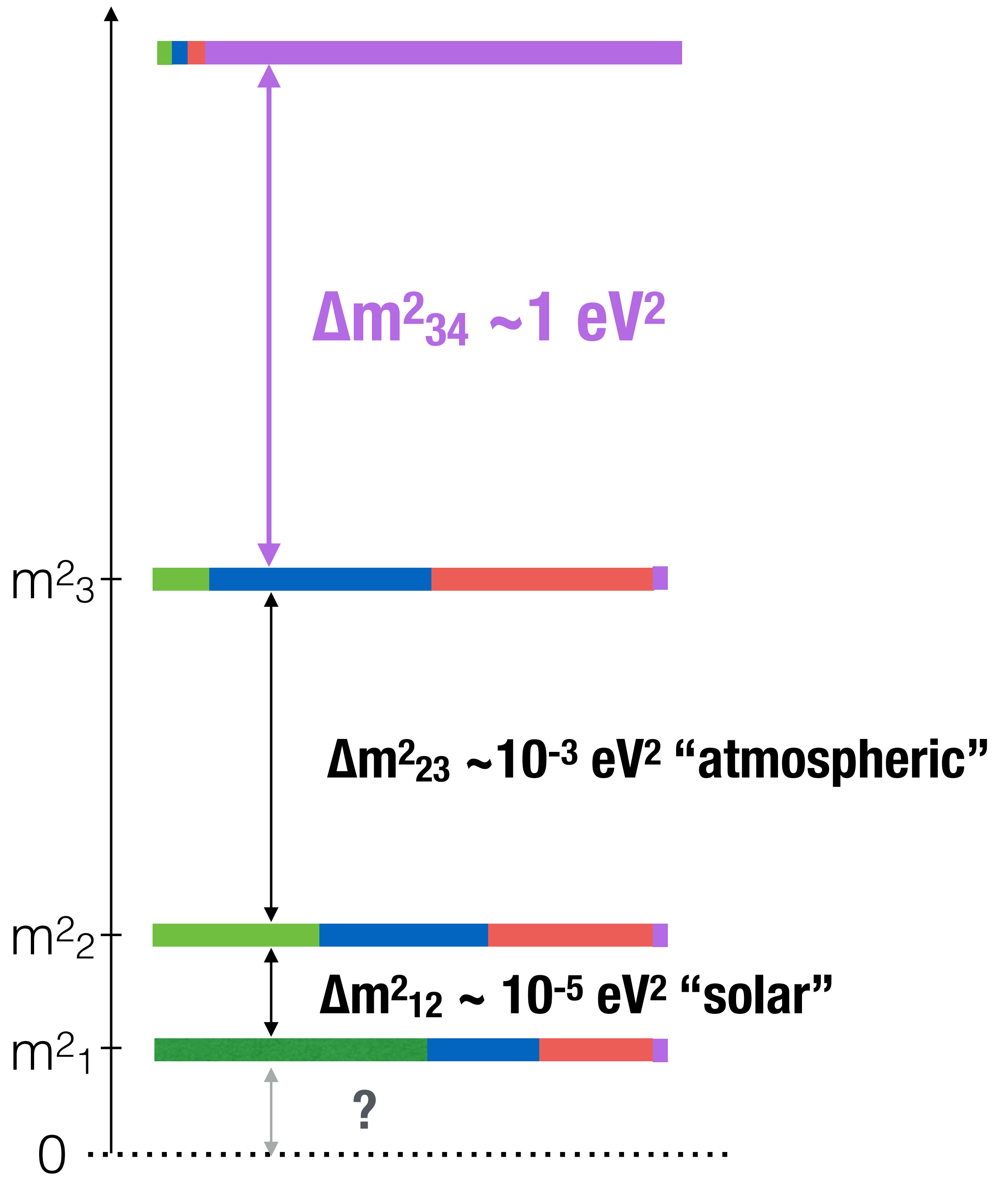
The Light Sterile Neutrino

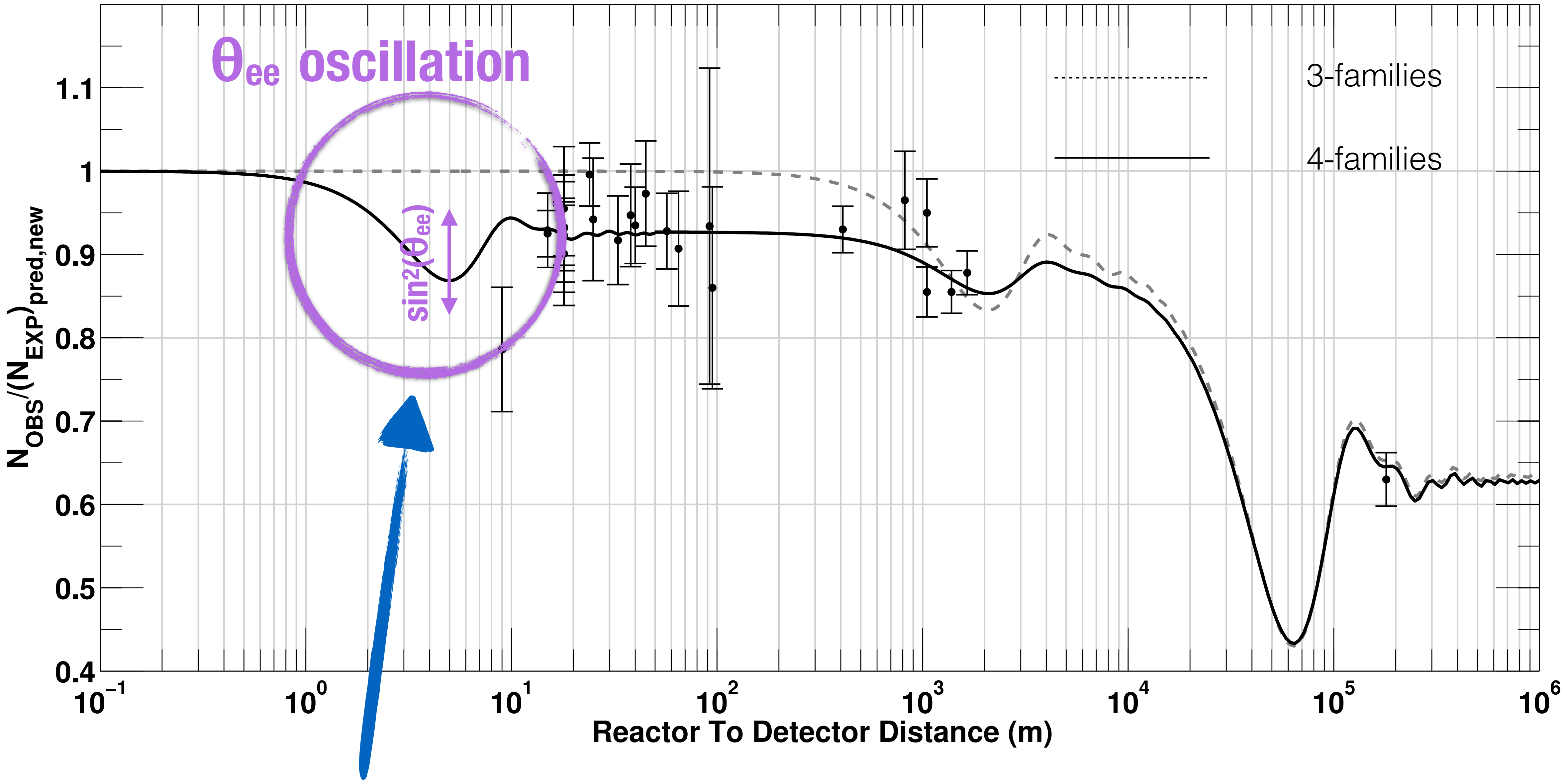
- Adding a **new neutrino** (0.1-1 eV mass) consisting almost exclusively of an **extra sterile flavour** can account for the observed deficit

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

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

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



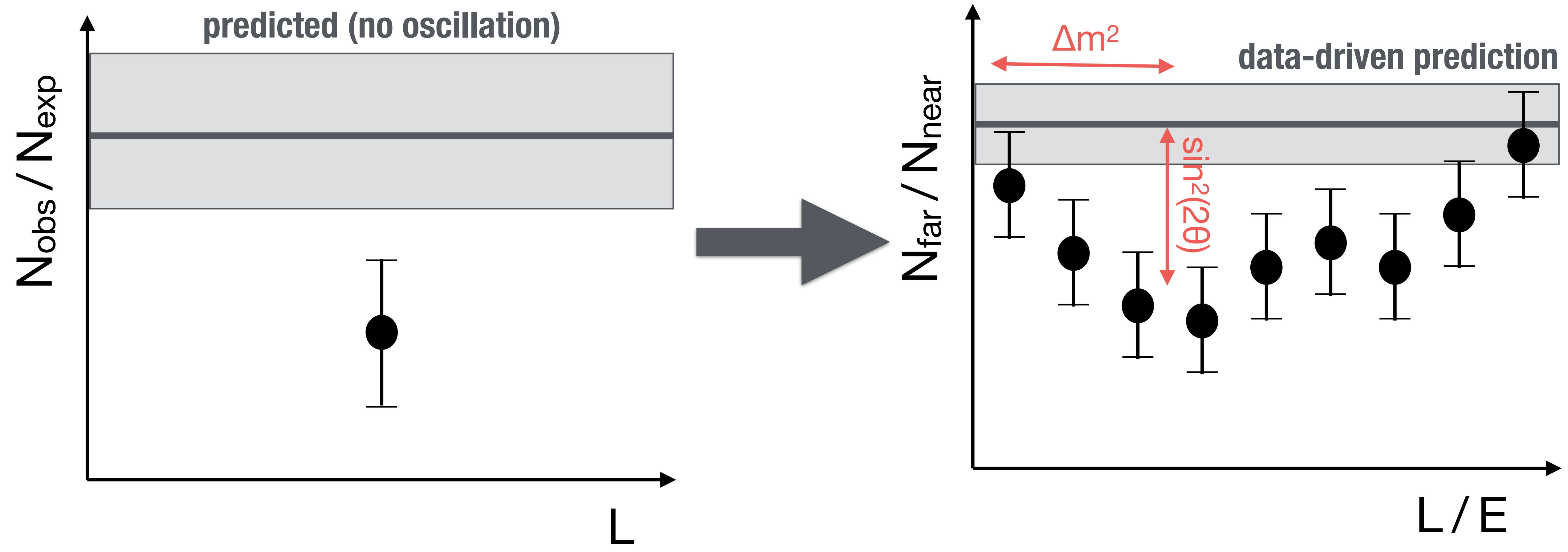


- To see this oscillation we need to **go look at very short (~10m) baselines**

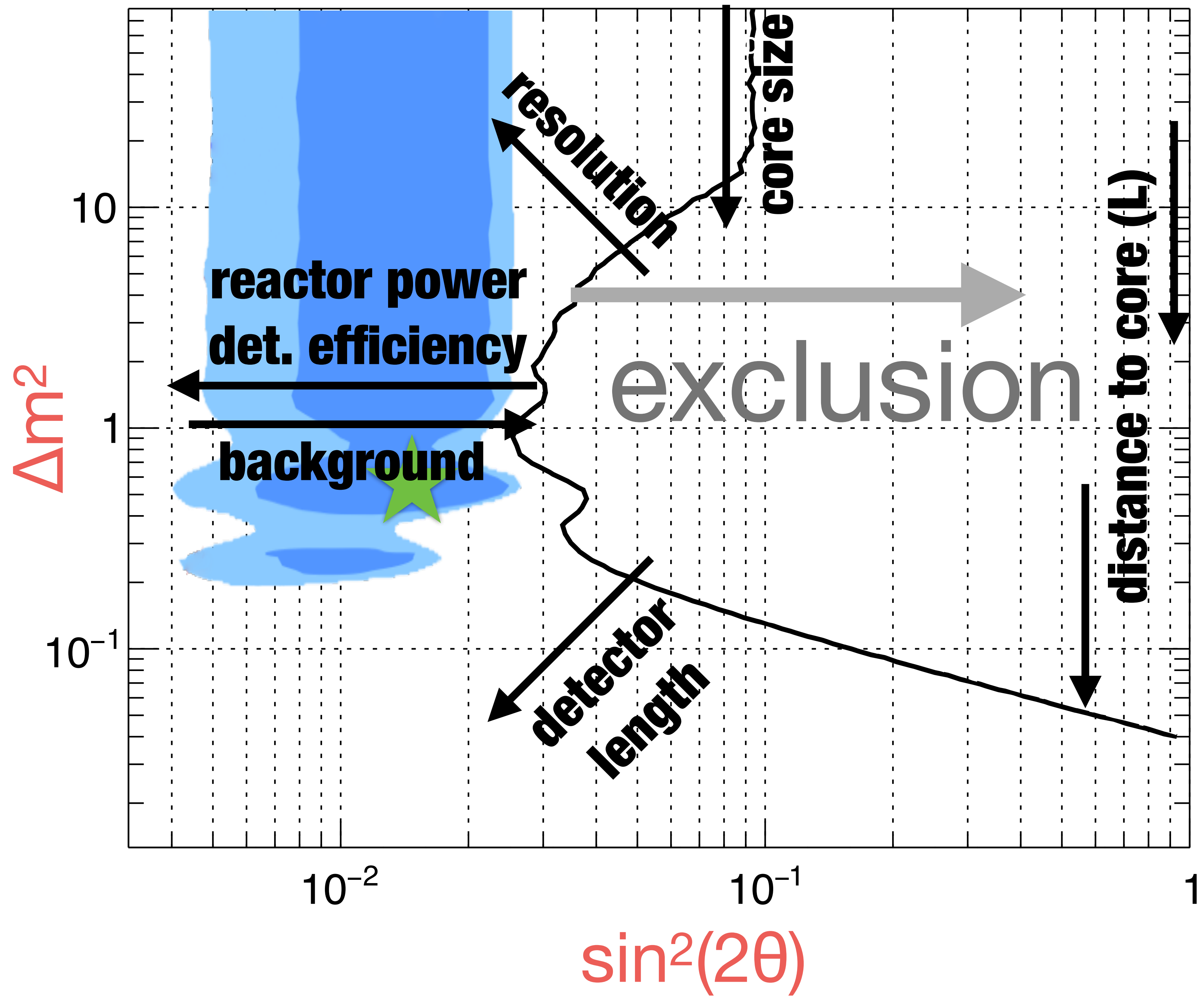
- The Reactor Antineutrino Anomaly and Light Sterile Neutrinos
- **Detection Techniques & Challenges**
- A worldwide Hunt
- Globa Results and Perspectives

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 (Δm², θ) are tested against data
  - Oscillation hypothesis ⇒ **contour plot (CL)** + **best fit**
  - Null hypothesis ⇒ **exclusion plot**



★ $\Delta m^2 > 10$ eV² $L_{osc} < E_{res}$

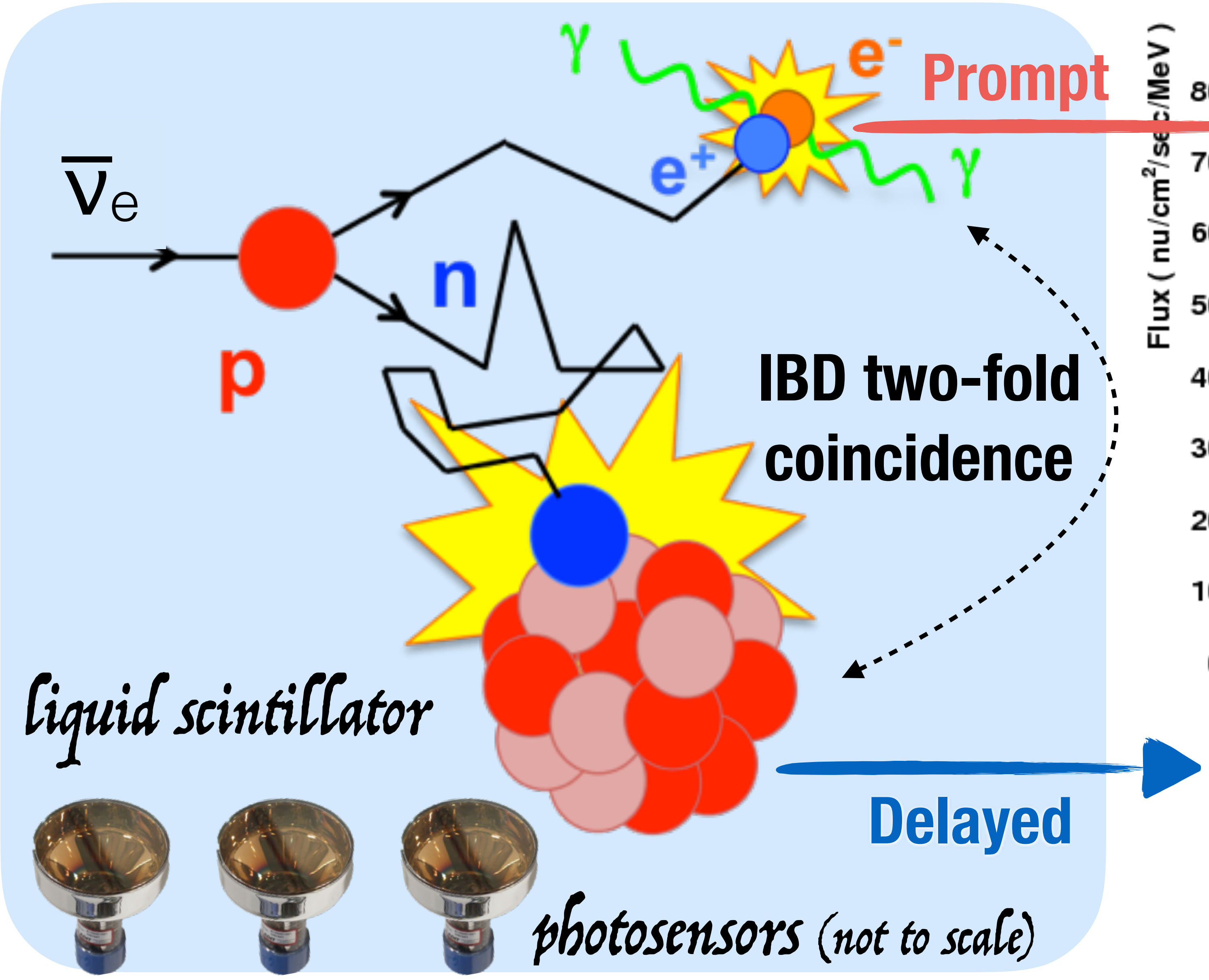
★ **Δm^2 ~ 1 eV² Can resolve oscillation**

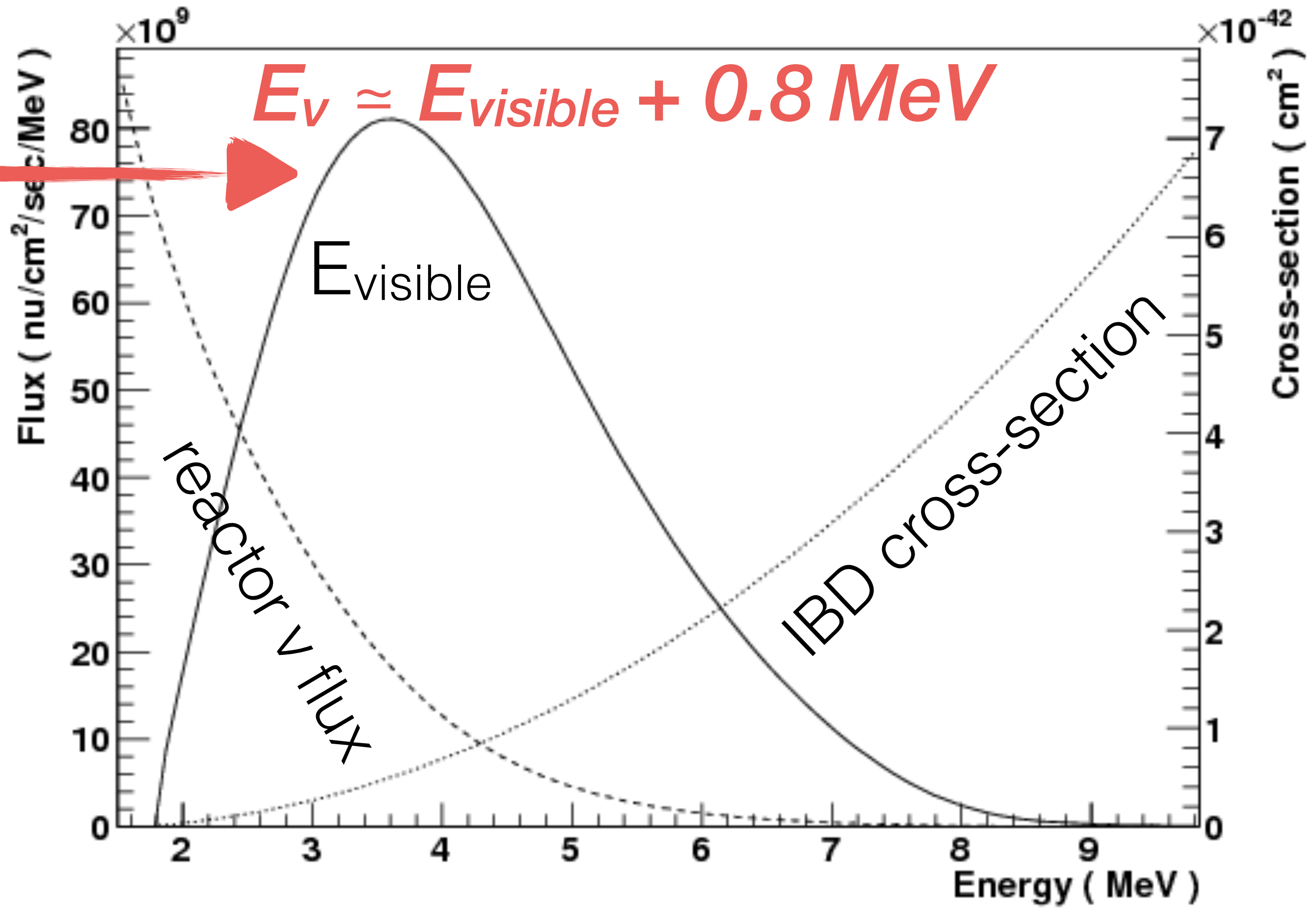
★ $\Delta m^2 < 0.1$ eV² $L_{osc} > L_{detector}$

- 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



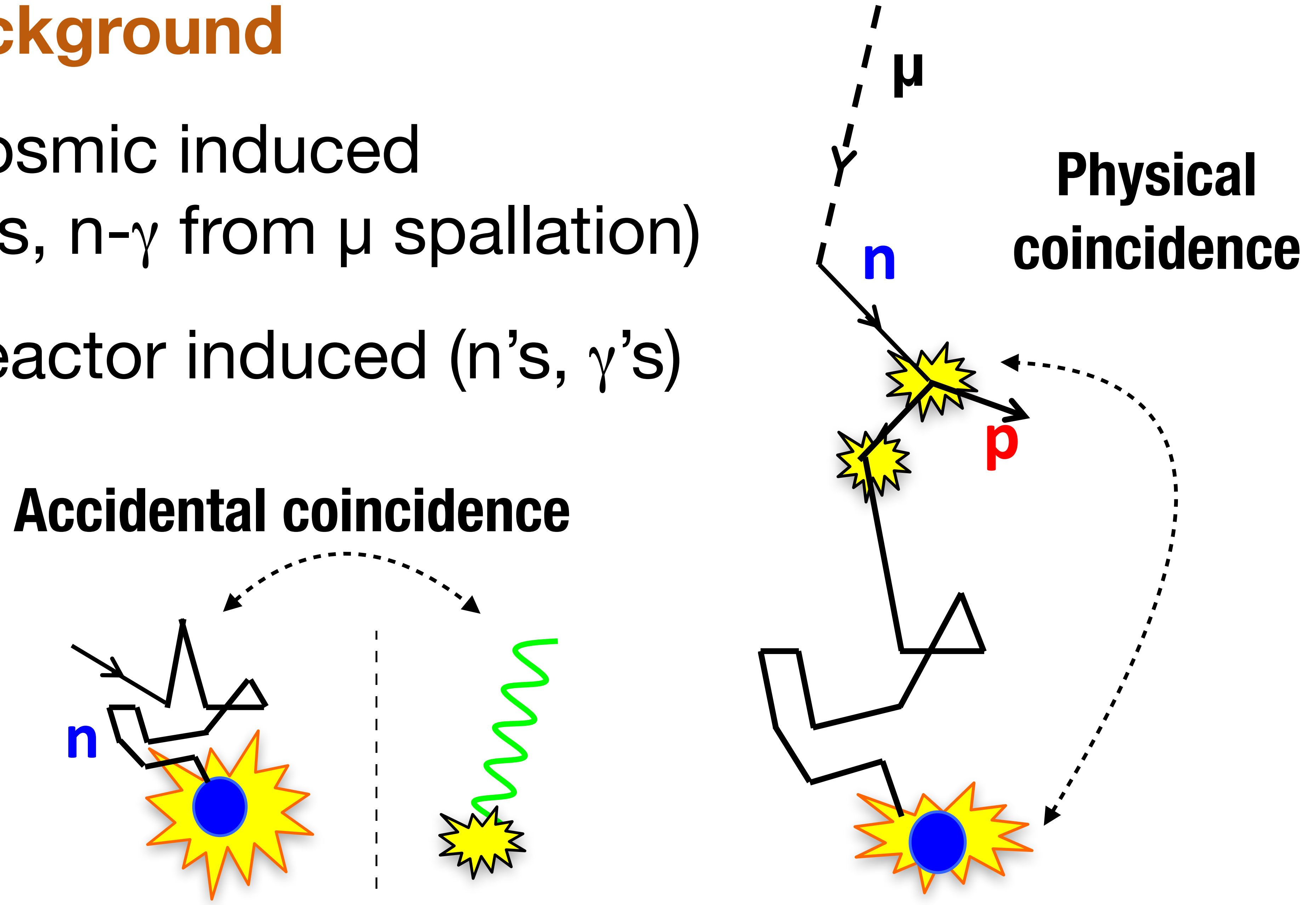


$n + H \rightarrow D + \gamma$ (2.2 MeV)

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

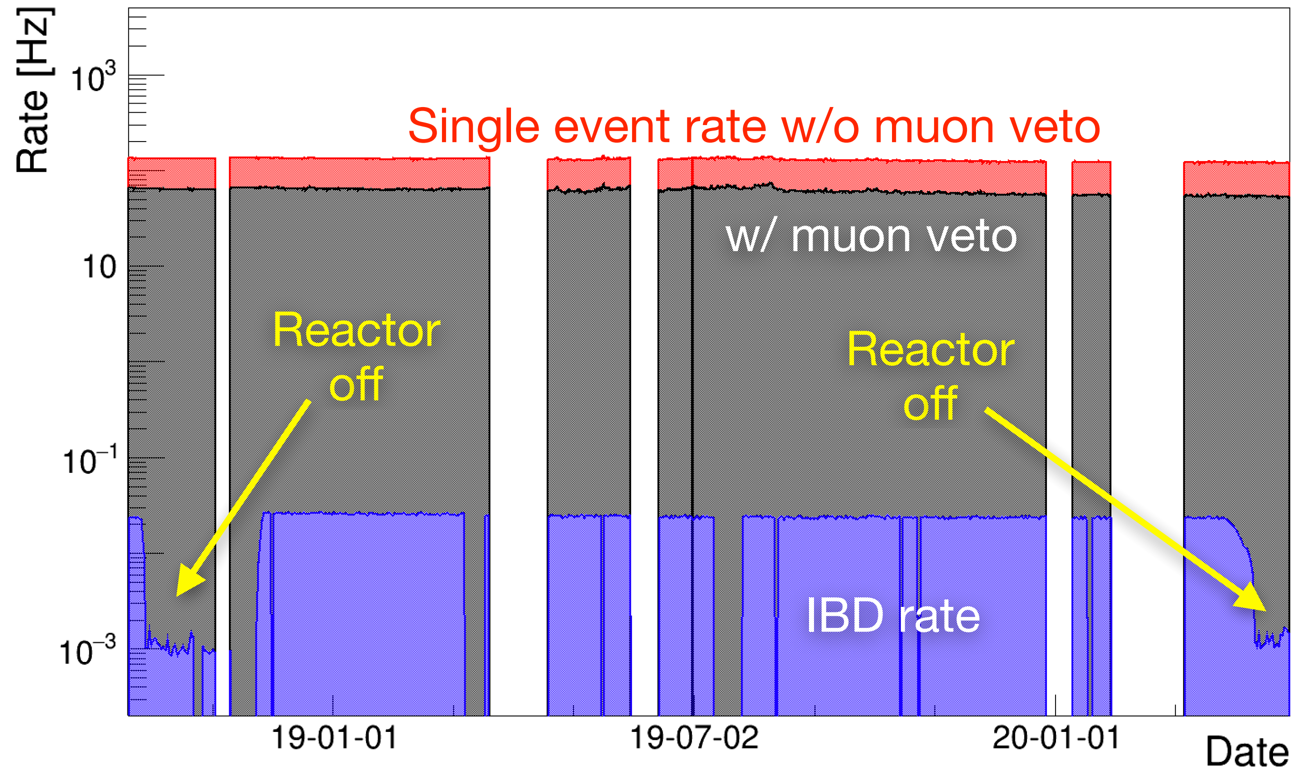
$n + {}^6Li \rightarrow \alpha + {}^3H$ (4.78MeV)

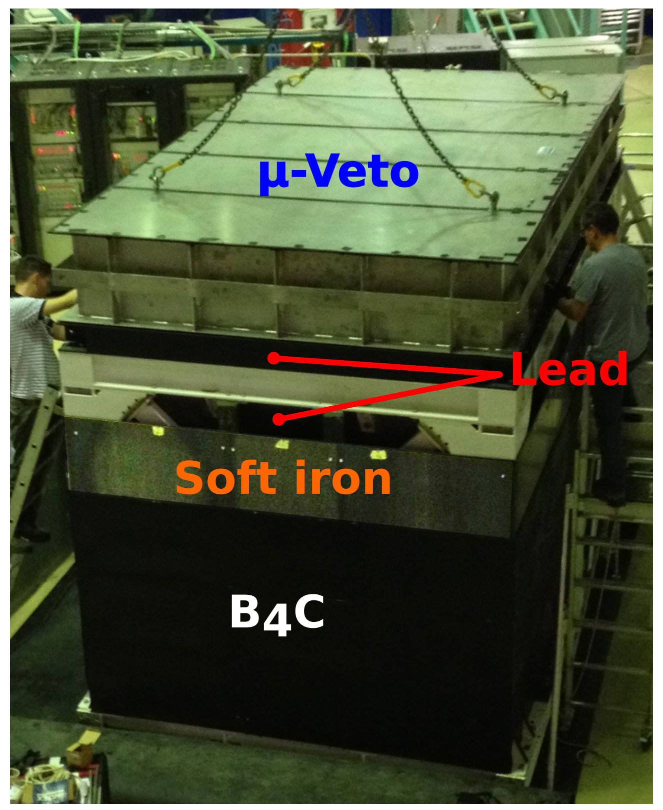
- **Background**
  - Cosmic induced (μ's, n-γ from μ spallation)
  - Reactor induced (n's, γ's)



- 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)

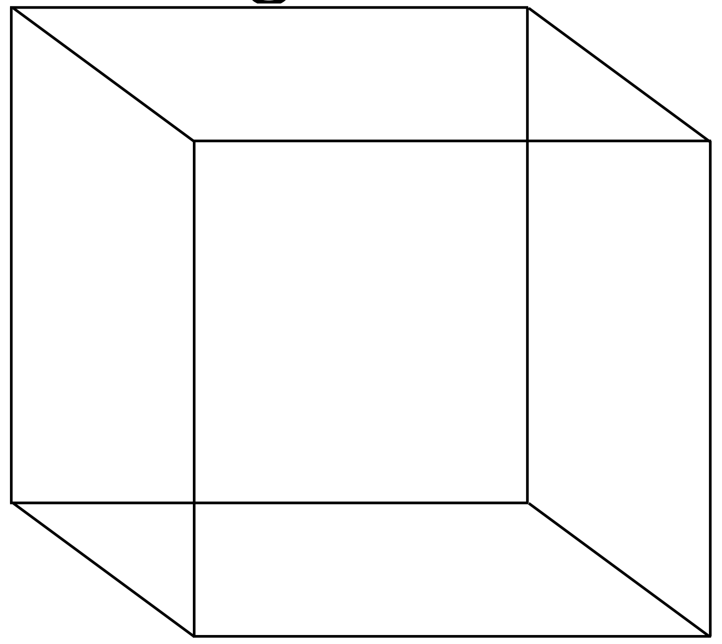




Different Reactors and Technologies

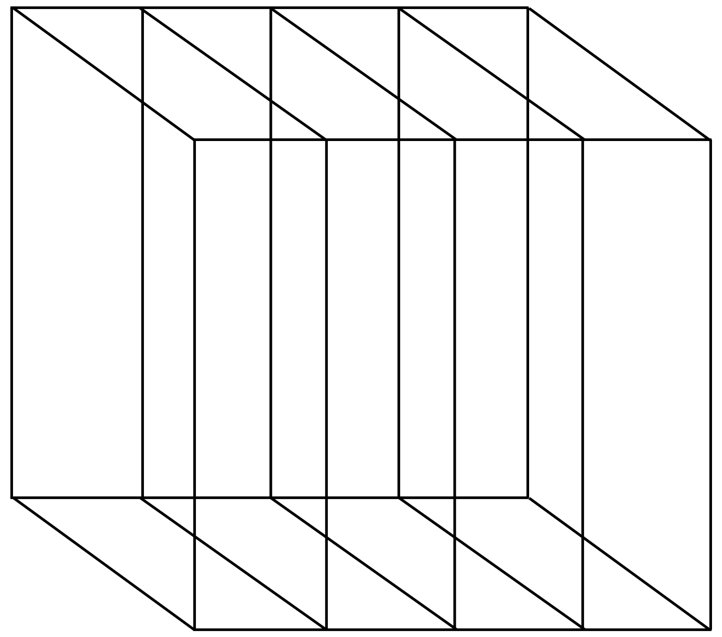
Detector segmentation

no-segmentation



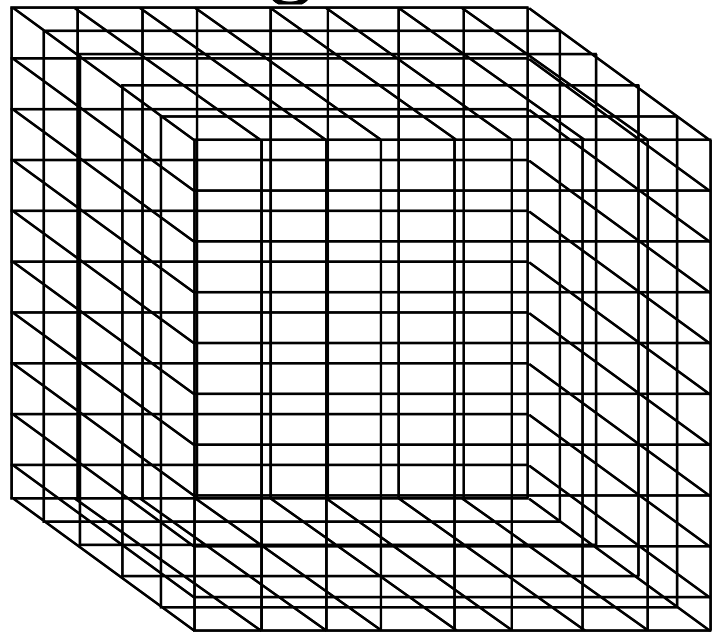
compare $\bar{\nu}$ spectrum with predictions

coarse segmentation



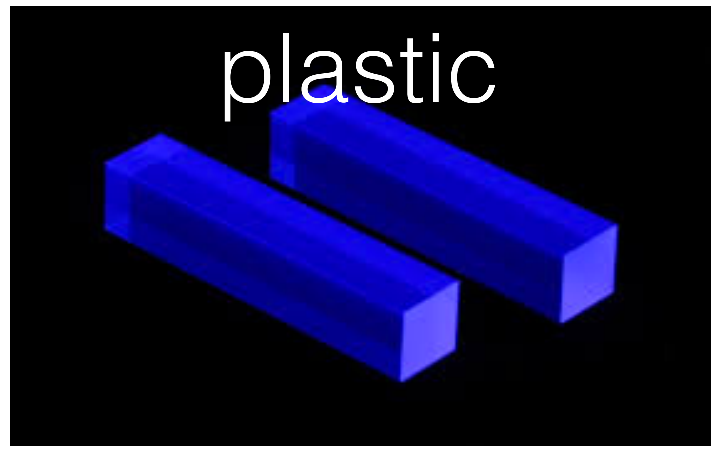
compare $\bar{\nu}$ spectra in different segments (model free)

fine segmentation

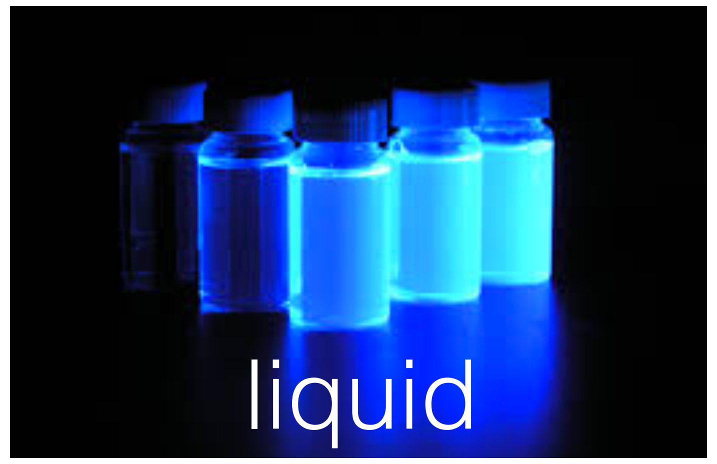


compare $\bar{\nu}$ spectra in sections + background rejection w/ topology

Scintillator

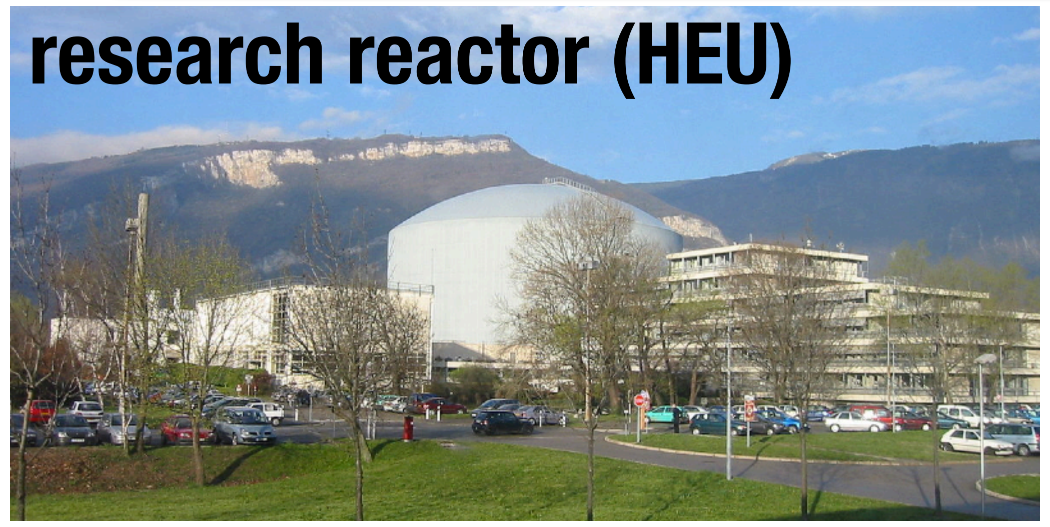


better for segmentation & detection efficiency



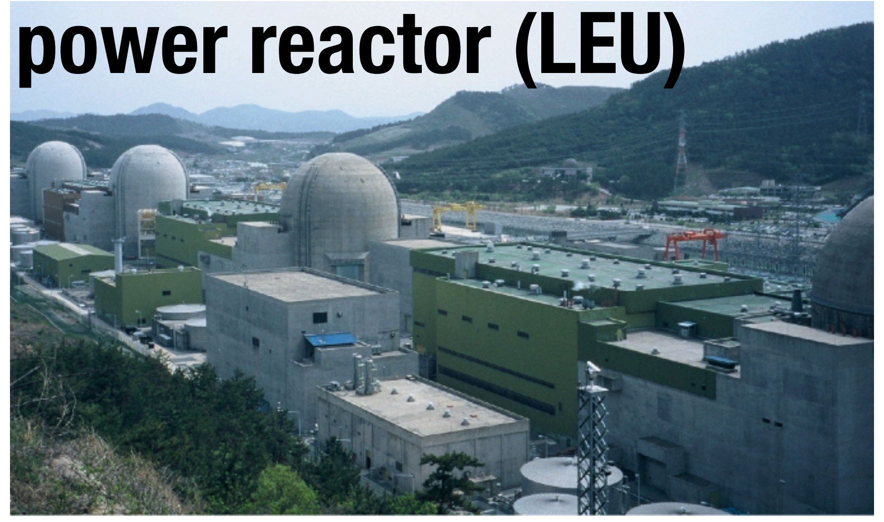
Easier to have large volumes

Reactor



Short baseline & compact core, no fuel evolution

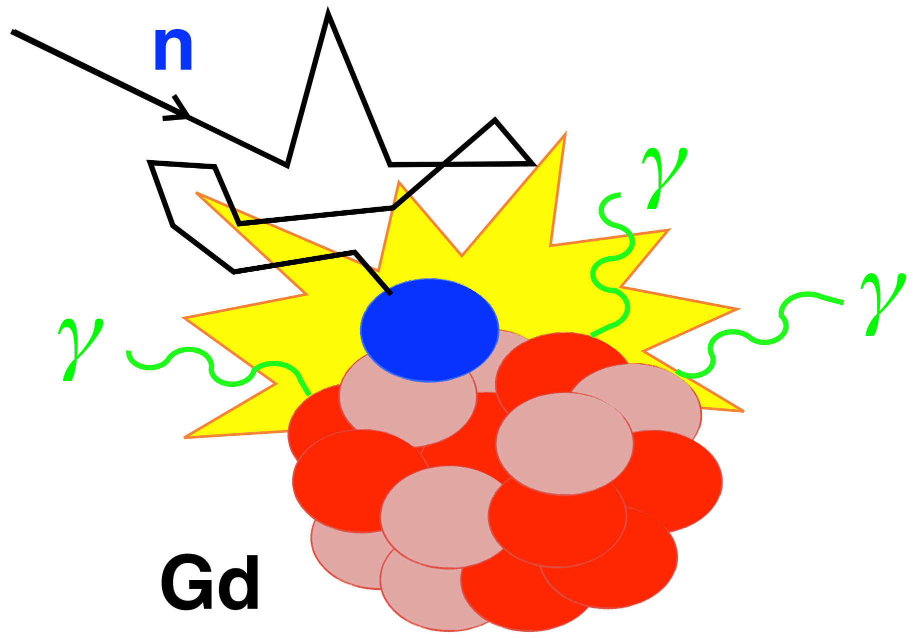
$\mathcal{O}10^2$ MW_{th}, limited space, background from facility



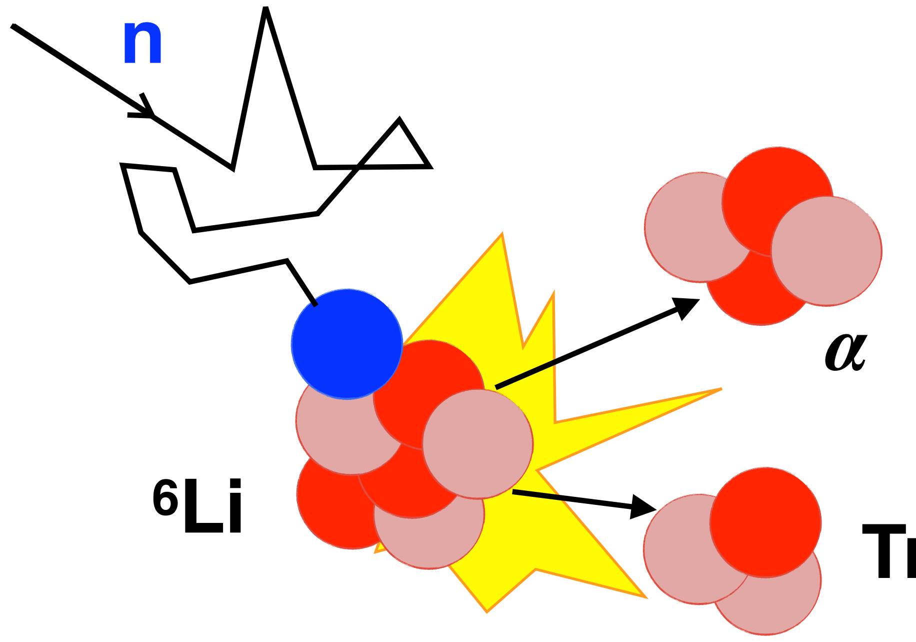
$\mathcal{O}$ GW_{th}, some overburden possible

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

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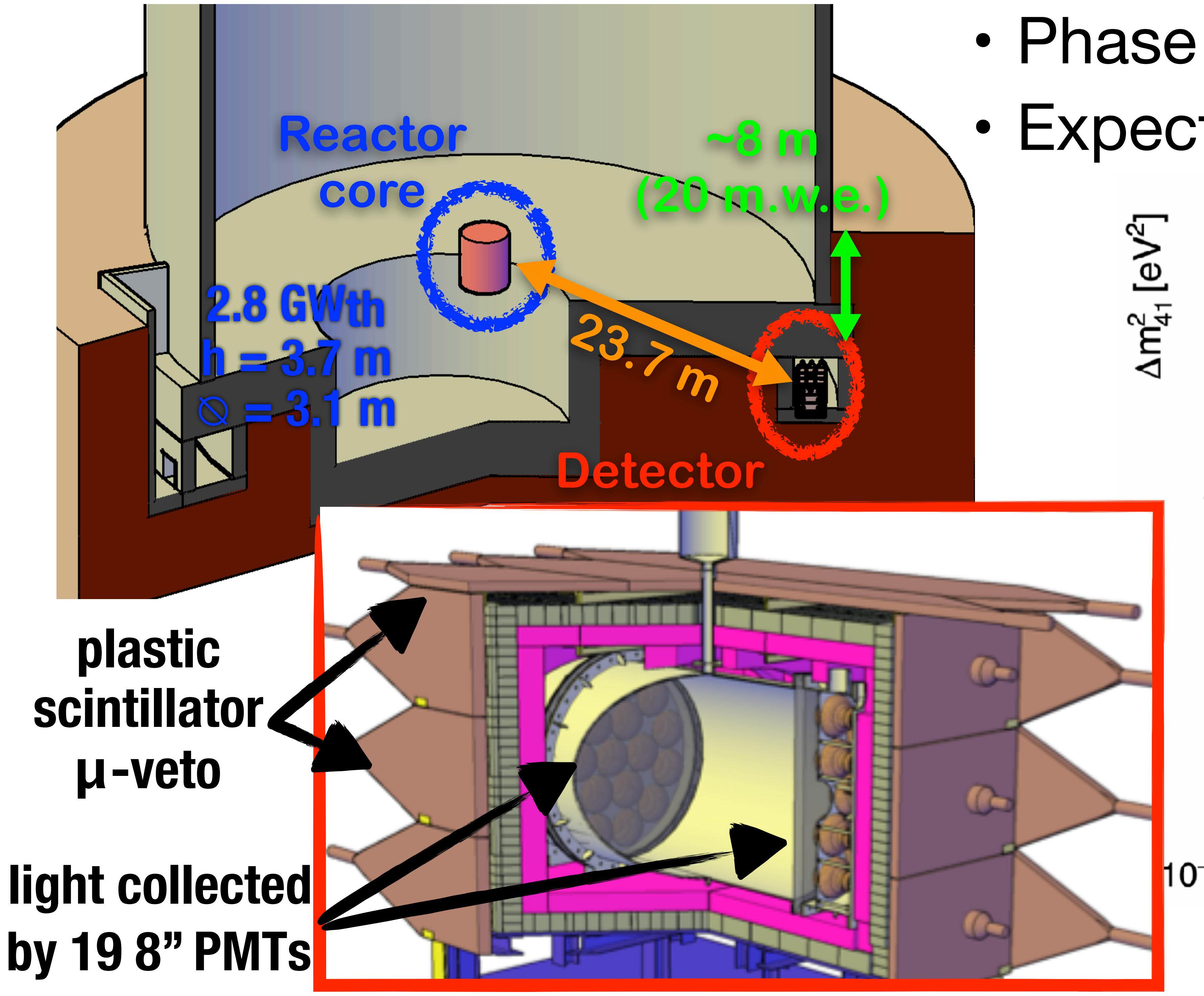
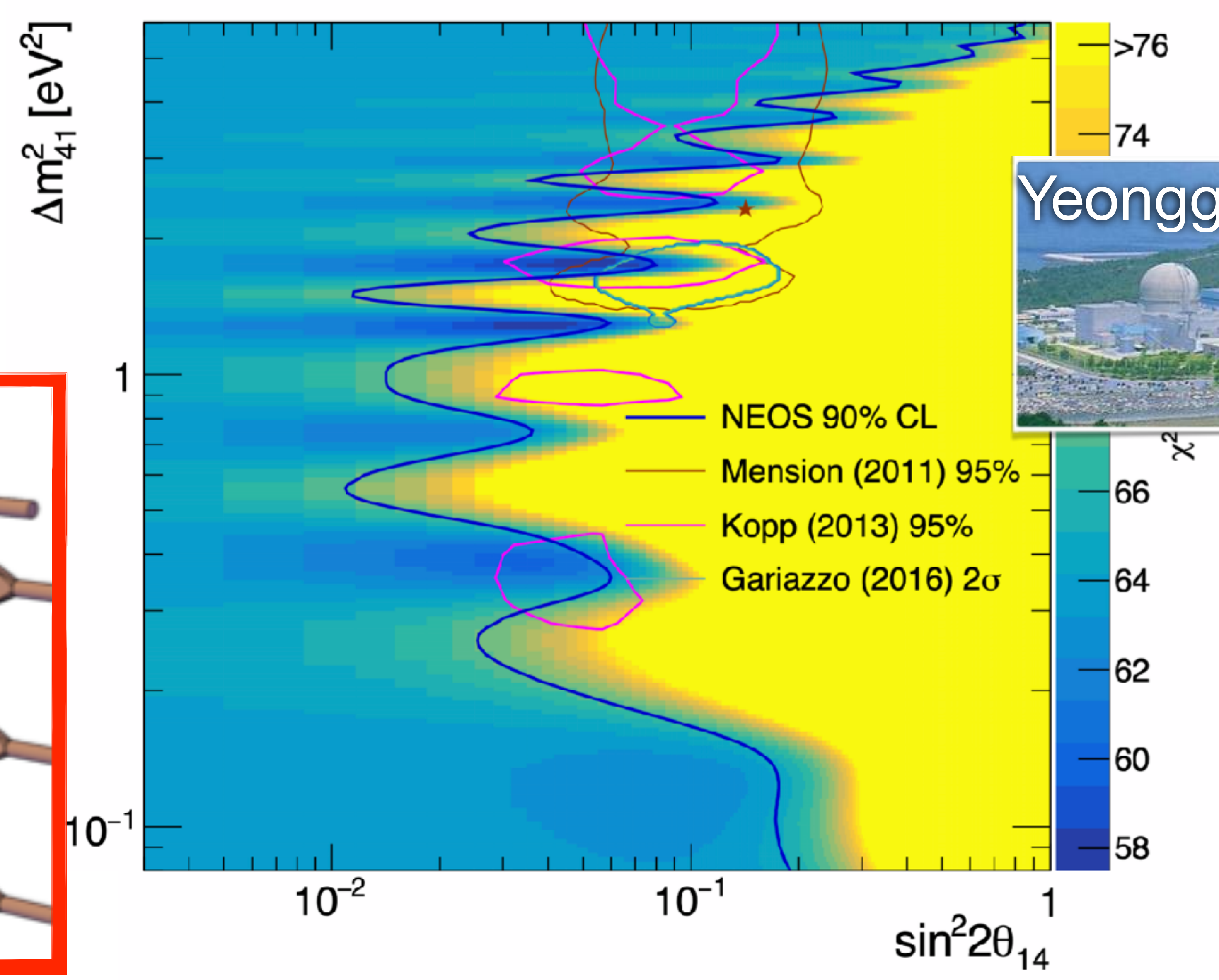
Neutrino4
SoLiδ
DANSS
Prospect
Stereo
NEOS
Power reactors, Gd-loaded
Research reactors, Gd-loaded
Research reactors, Li-loaded

- **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 powerful (2.8 GW) commercial reactor
- **Degradation of light yield in time**

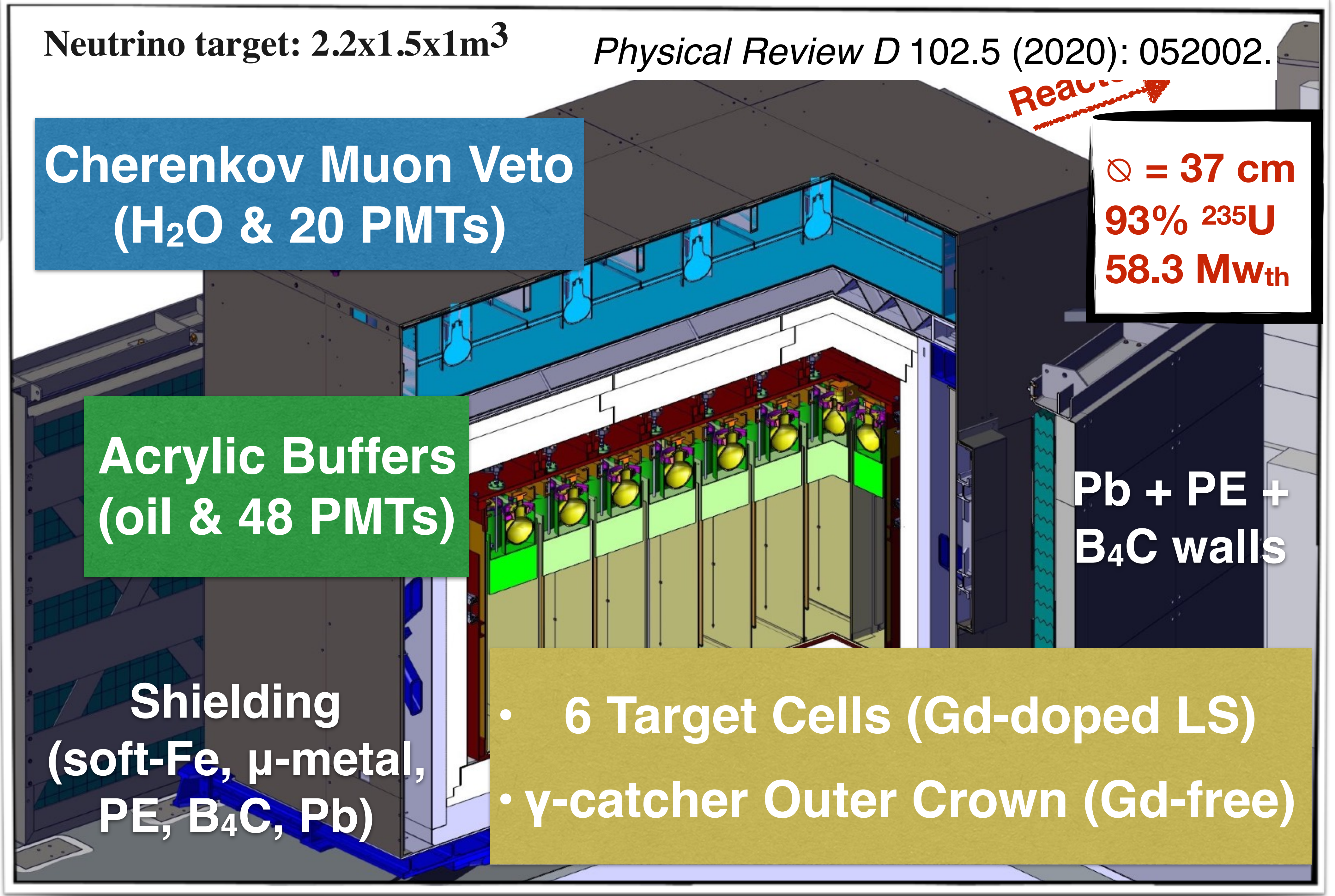


- Phase I (46 day OFF + 180 ON)
- Expected X2 sensitivity w/ phase I+II

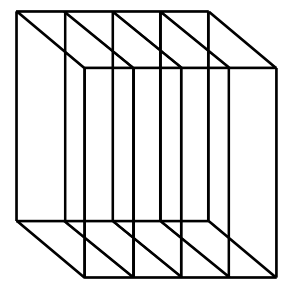


NEOS

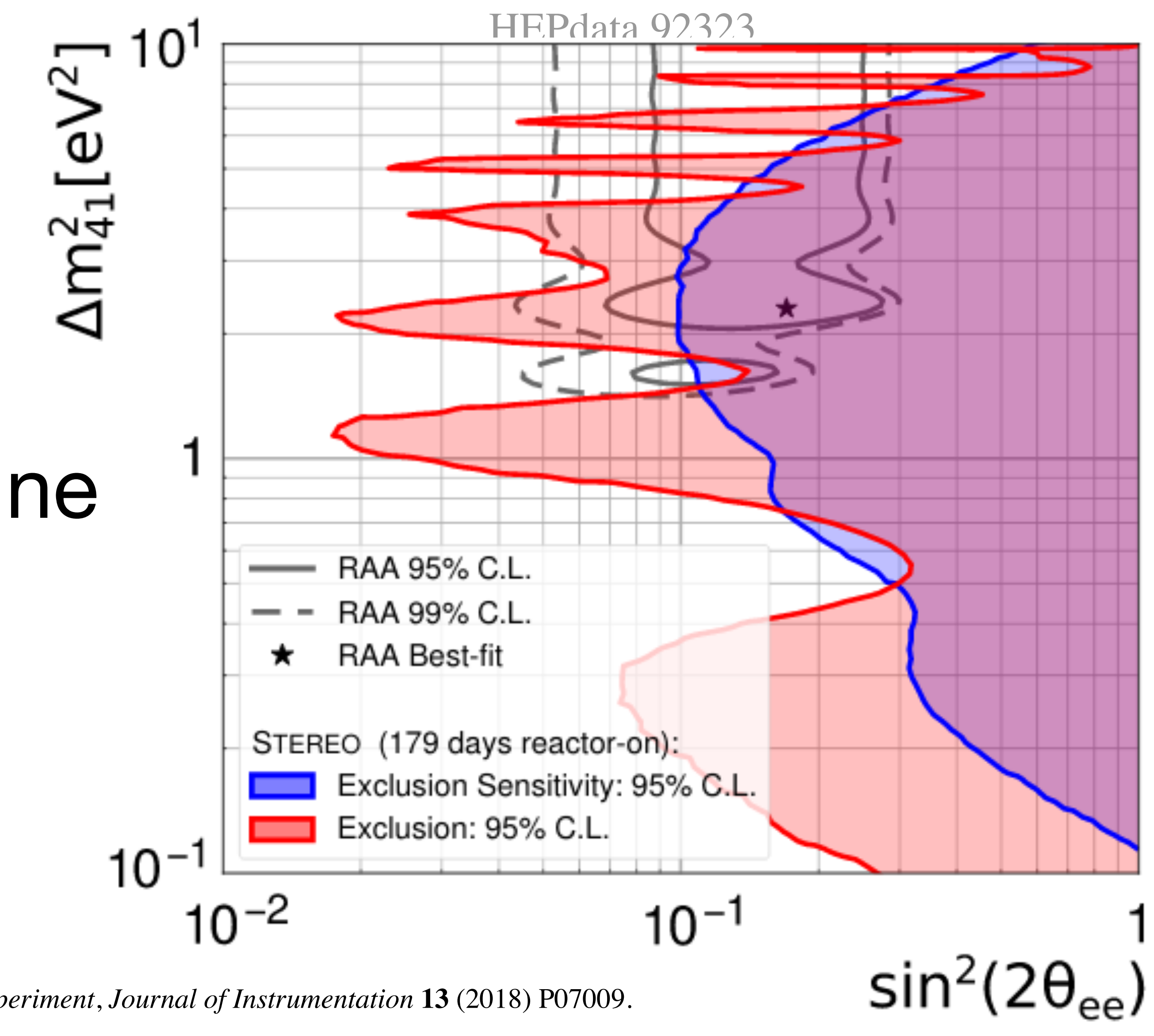
Y. Ko, B. Kim, J. Kim, B. Han, C. Jang, E.J. Jeon et al., *Sterile neutrino search at the neos experiment*, Physical review letters **118** (2017) 121802.



- Phase I+II (65k IBDs, 179 day ON + 235 OFF)
- Expected X2 sensitivity with full dataset

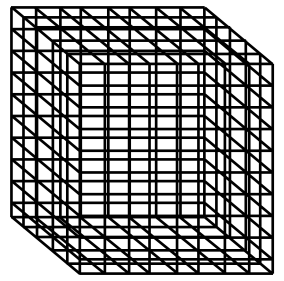


- Segmented design → cell-to-cell relative oscillation analysis
- Compact HEU core & short baseline → **little damping of oscillation**
- **Little overburden** & **noise from reactor facility** → S/B~1

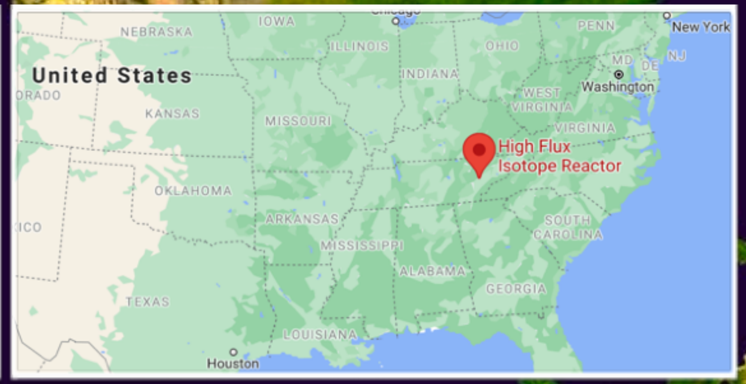


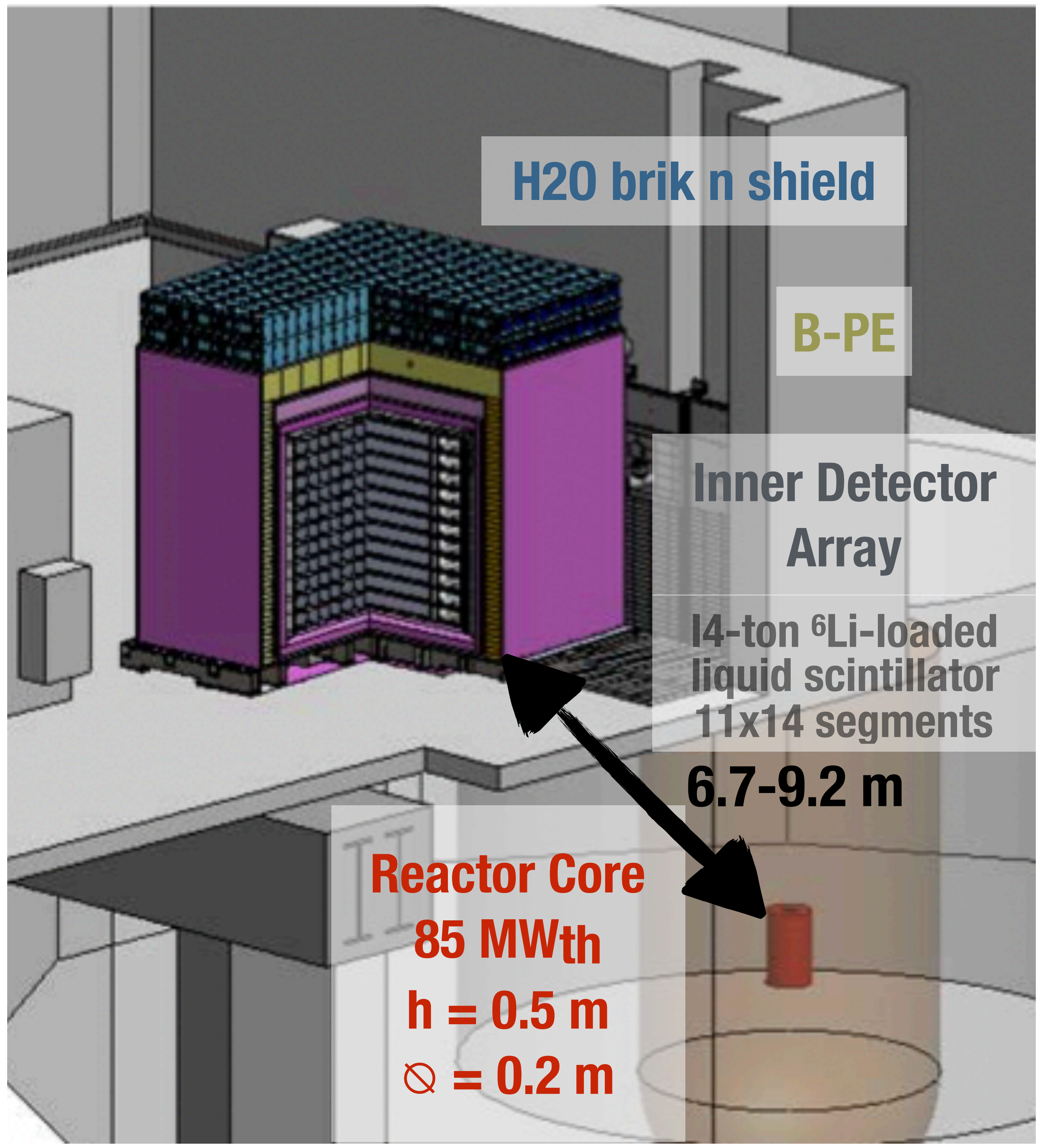
N. Allemandou, H. Almazán, P. del Amo Sanchez, L. Bernard, C. Bernard, A. Blanchet et al., *The stereo experiment*, *Journal of Instrumentation* **13** (2018) P07009.

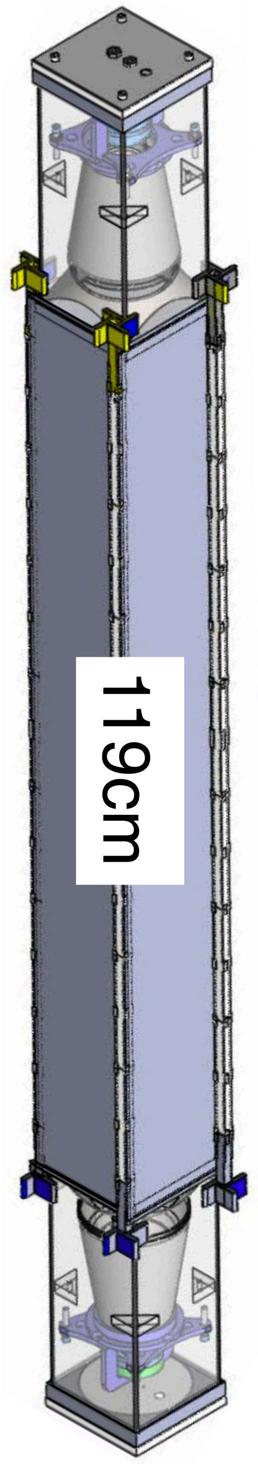
- Highly segmented design → **good E_{res}, 2D reconstruction**



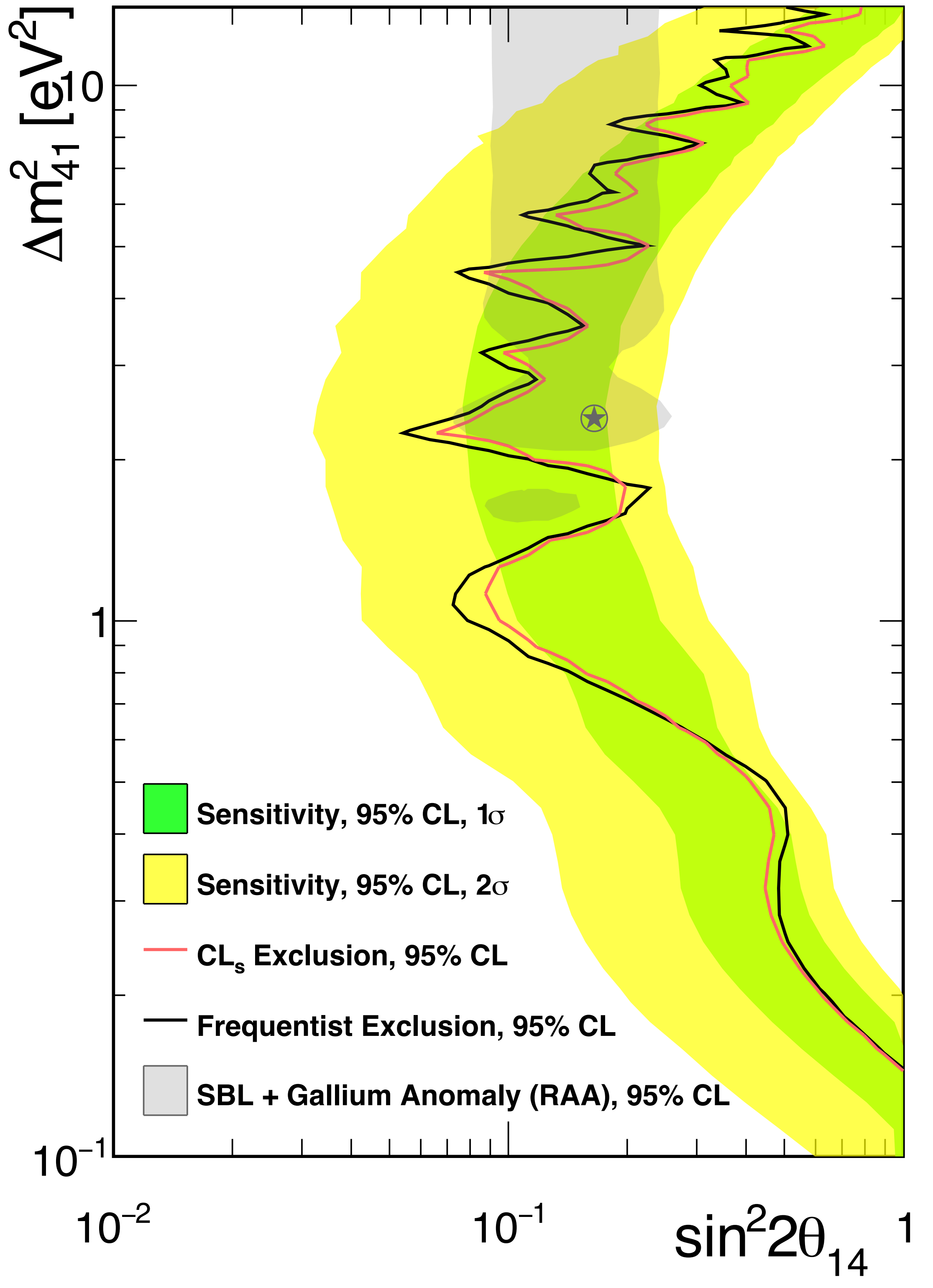
- Relatively high stat (530 IBD/day) and S/B (>1) for a HEU
- **Results from 2018 dataset**; improved analysis using dead cells (+50%) ongoing



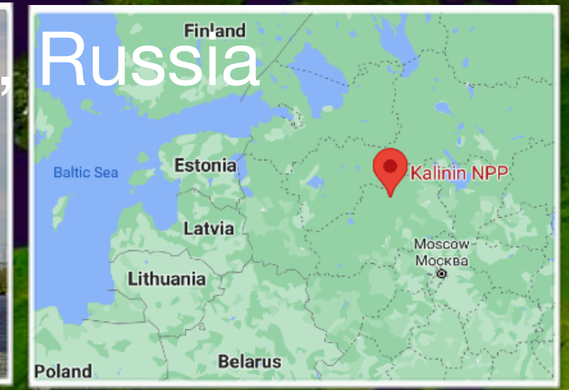




- 50k IBDs (105 days ON + 78 OFF)

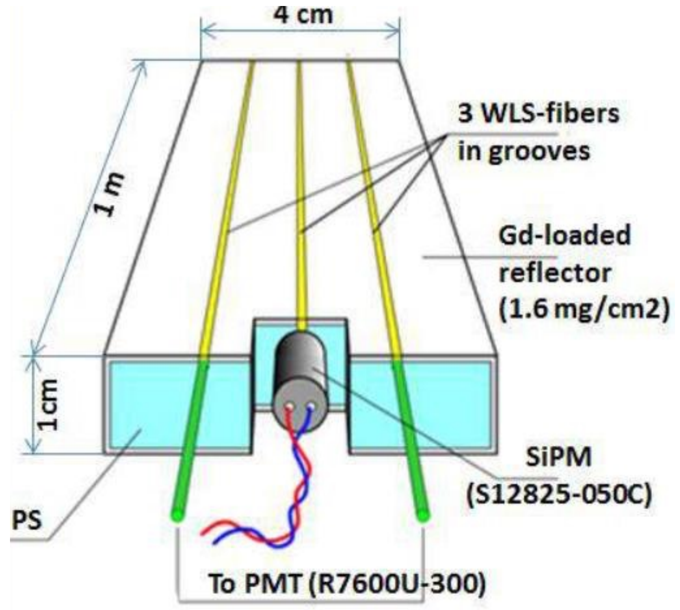


. J. Ashenfelter, A. Balantekin, H. Band, G. Barclay, C. Bass, D. Berish et al., *The prospect physics program*, *Journal of Physics G: Nuclear and Particle Physics* **43** (2016) 113001.

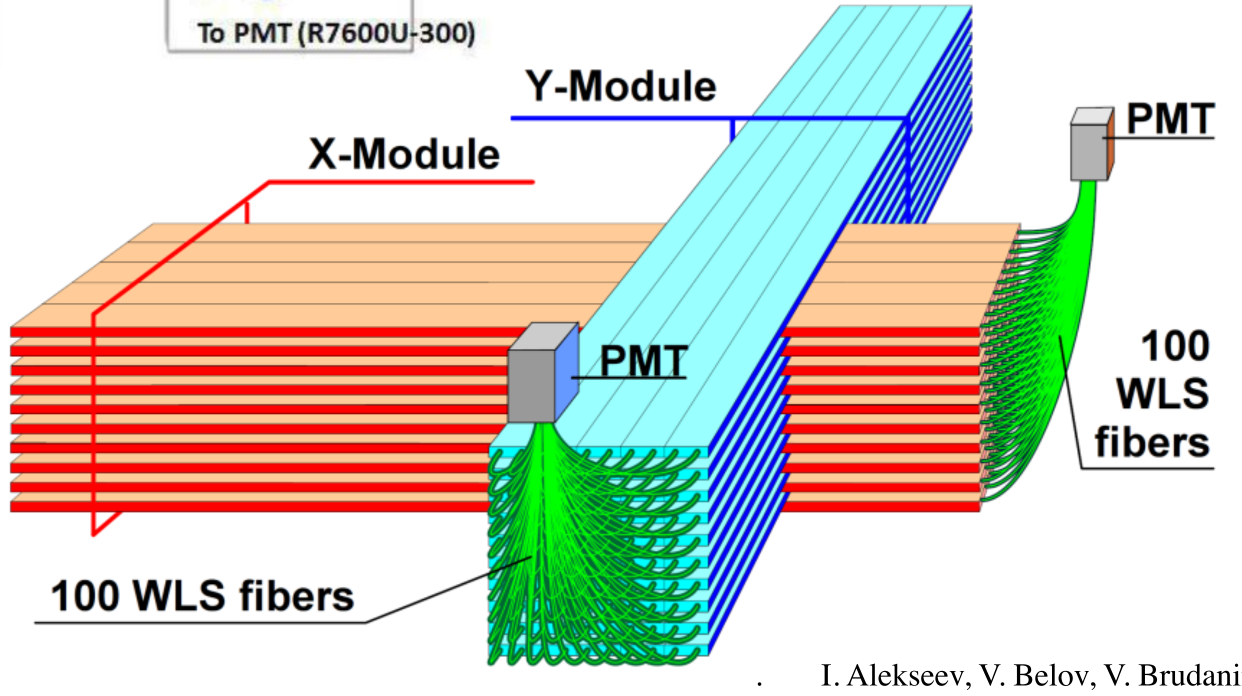


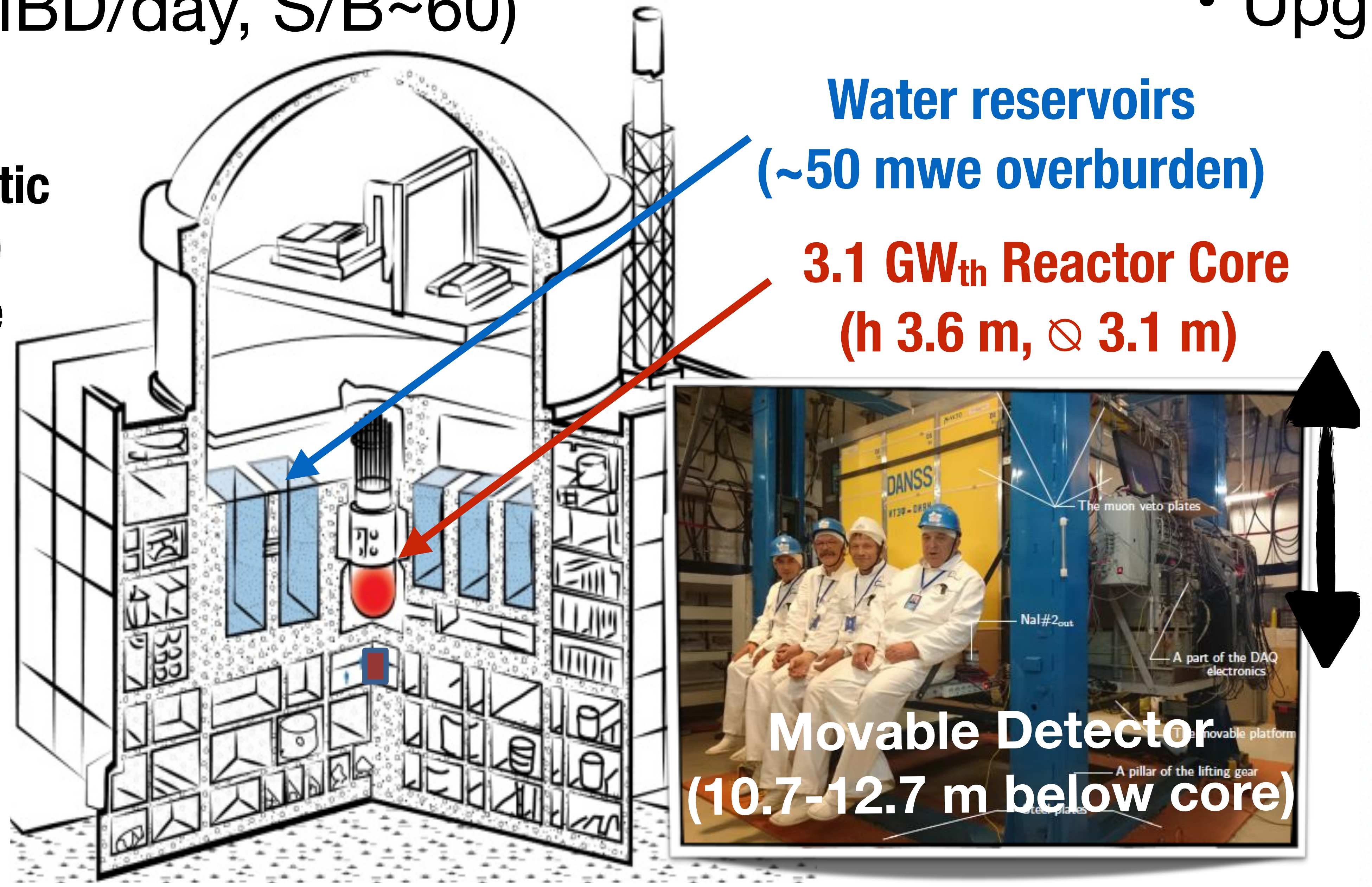
★DANSS

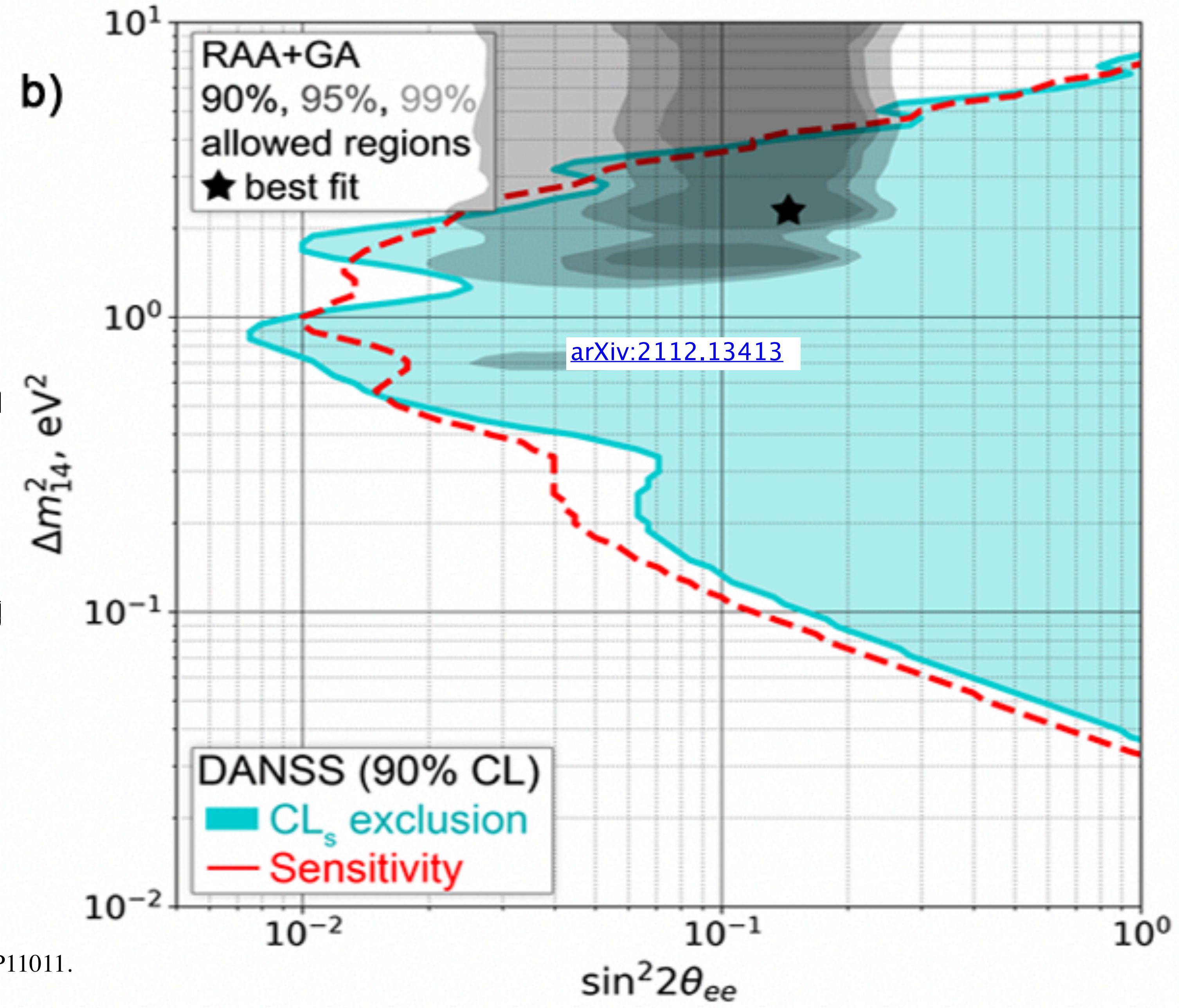
- Highly-segmented ν spectrometer → **quasi-3D reconstruction**
- **Excellent statistics** (~5000 IBD/day, S/B~60)
- Phase-I (5.5 M IBD in 5 years)
- Upgrade ongoing → halve E_{res} increase V_{det}



2500 Gd-coated plastic scintillator strips (50 modules) with single & combined readout







I. Alekseev, V. Belov, V. Brudanin, M. Danilov, V. Egorov, D. Filosofov et al., *Danss: Detector of the reactor antineutrino based on solid scintillator*, Journal of Instrumentation **11** (2016) P11011.

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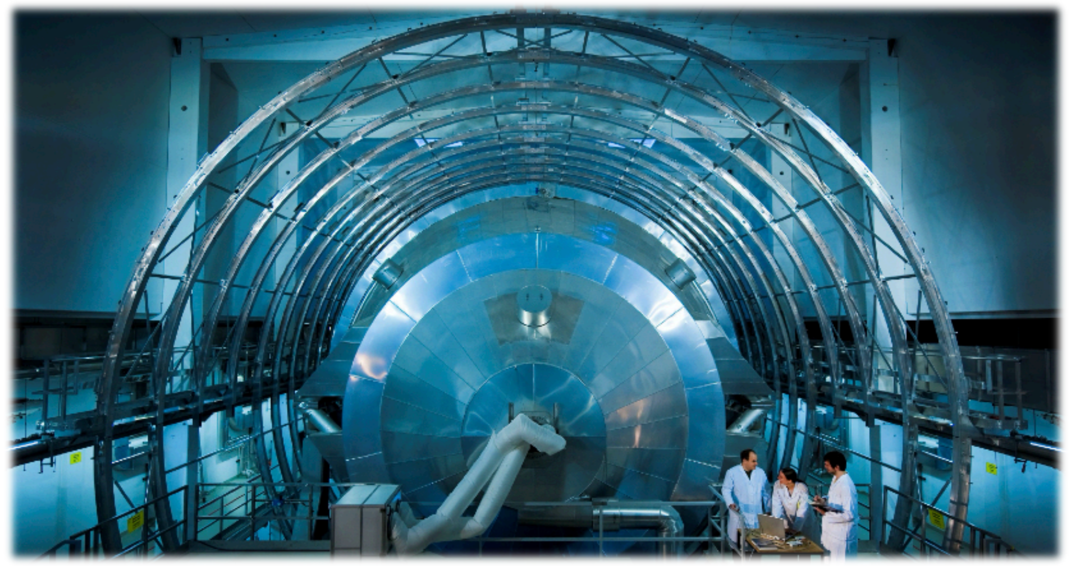
https://www.symmetrymagazine.org/article/game-changing-neutrino-experiments

Reactor Anomaly and Recent Results: the Global Picture

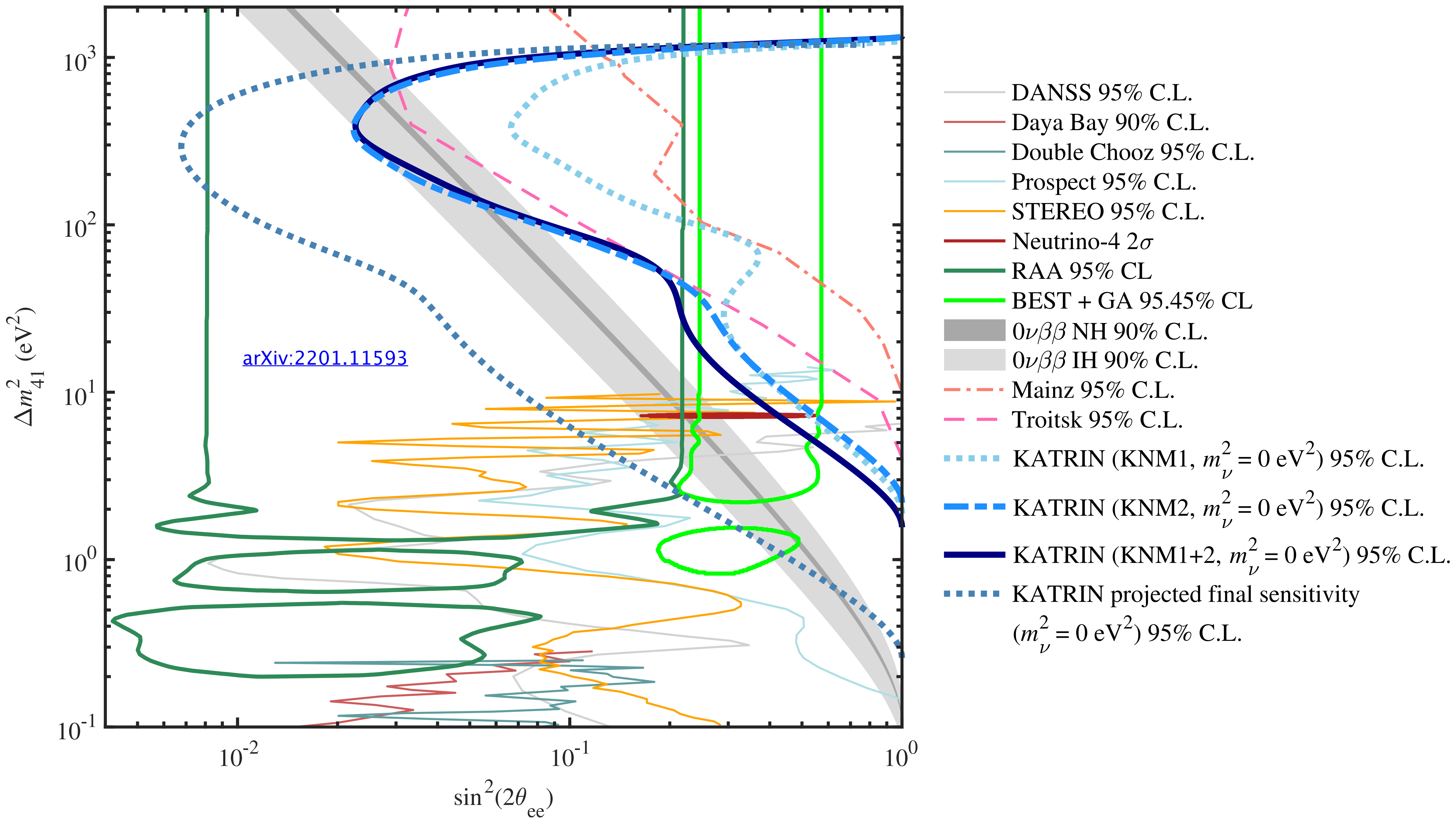
- Each of the 4 experiments: **DANSS, NEOS, STEREO, PROSPECT** **excluded large portions of the RAA** region **& the best fit value** (> 90% CL), while **Neutrino-4** claims a **2.8 σ CL observation** of a $\Delta m^2 \sim 7.3\,eV^2$ oscillation

M. Danilov and N. Skrobova, *New results from the danss experiment*, *arXiv preprint arXiv:2112.13413* (2021) .
Y. Ko, B.-Y. Han, C.-H. Jang, E.-J. Jeon, K.-K. Joo, B.-R. Kim et al., *Neos experiment*, in *Journal of Physics: Conference Series*, vol. 1216, p. 012004, IOP Publishing, 2019.
H. Almazán, L. Bernard, A. Blanchet, A. Bonhomme, C. Buck, P. del Amo Sanchez et al., *Improved sterile neutrino constraints from the stereo experiment with 179 days of reactor-on data*, *Physical Review D* **102** (2020) 052002.
M. Andriamirado, A. Balantekin, H. Band, C. Bass, D. Bergeron, D. Berish et al., *Improved short-baseline neutrino oscillation search and energy spectrum measurement with the prospect experiment at hfir*, *Physical Review D* **103** (2021) 032001.
A.P. Serebrov, V.G. Ivochkin, R.M. Samoilov, A.K. Fomin, A.O. Polyushkin, V. Zinoviev et al., *First observation of the oscillation effect in the neutrino-4 experiment on the search for the sterile neutrino*, *JETP Letters* **109** (2019) 213.

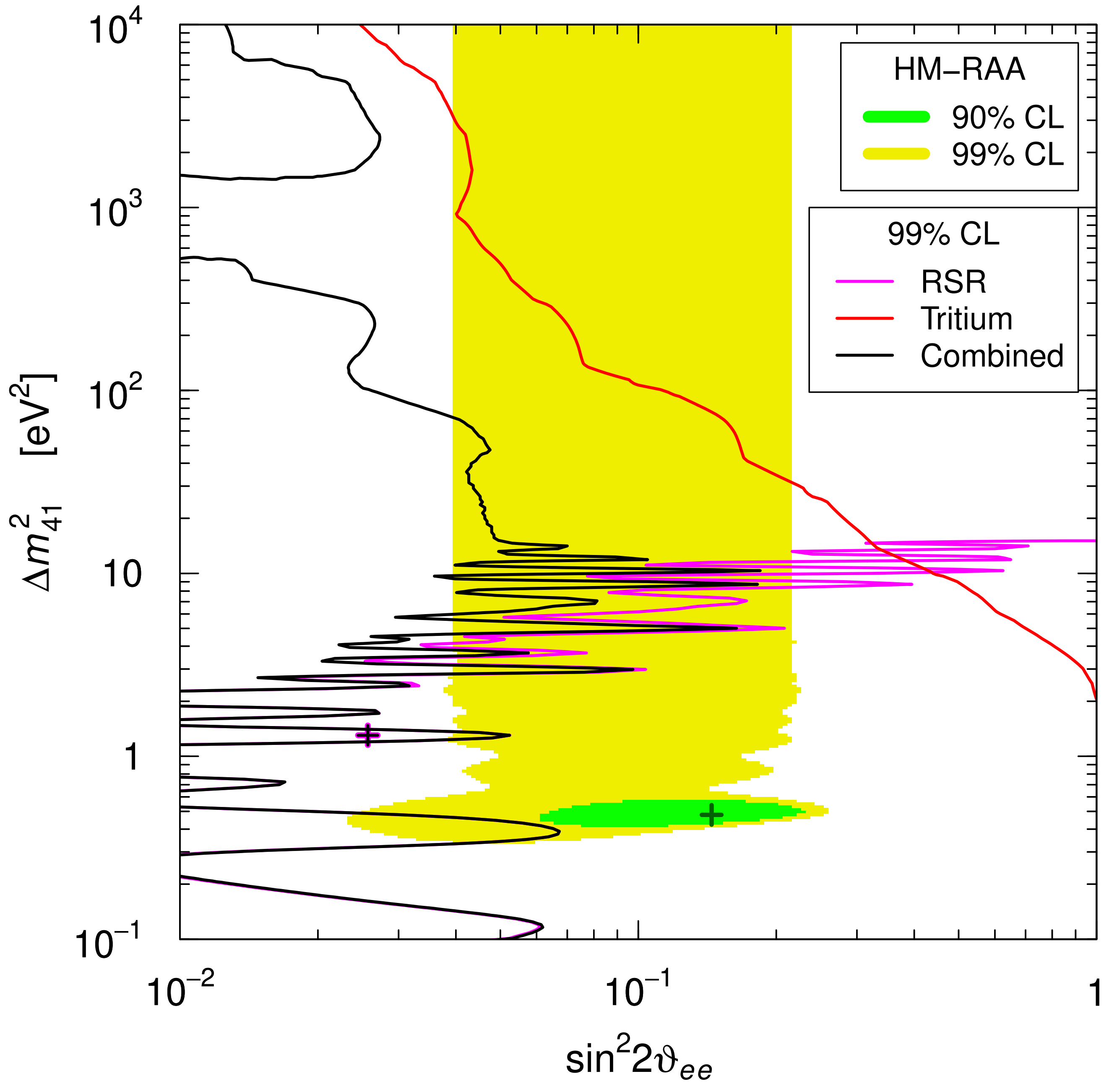
- STEREO, PROSPECT, DANSS are releasing their χ2 tables and data to help combined fits
- **KATRIN**, a 200t spectrometer for the measurement of the ν_e mass, has also published results on sterile → **exclusion of RAA region with strong synergy with the short-baseline reactor searches**



M. Aker et. al. Improved eV-scale Sterile-Neutrino Constraints from the Second KATRIN Measurement Campaign arXiv:2201.11593



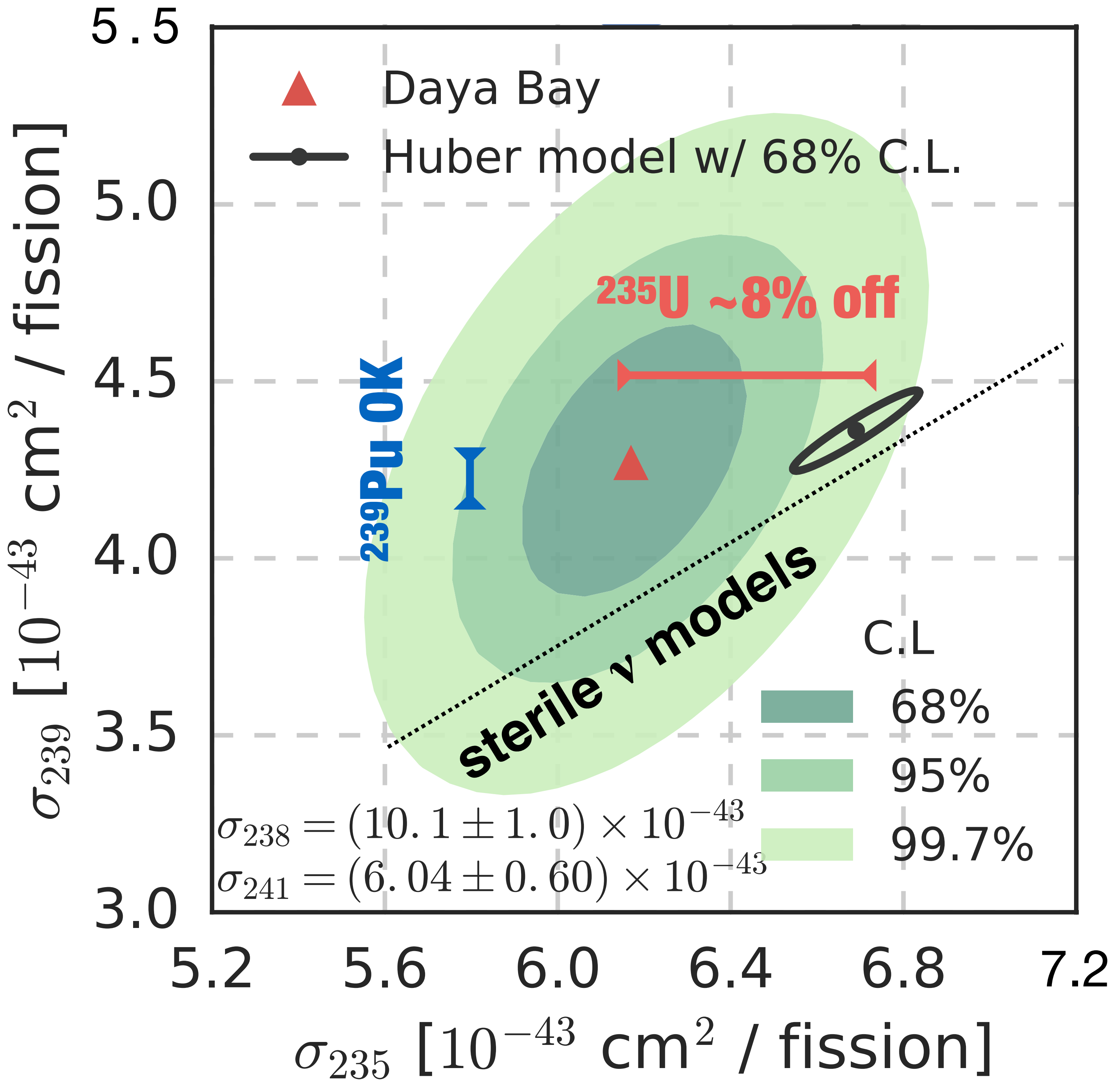
Giunti, C., Li, Y. & Zhang, Y. KATRIN bound on 3+1 active-sterile neutrino mixing and the reactor antineutrino anomaly. *J. High Energ. Phys.* **2020,** 61 (2020).



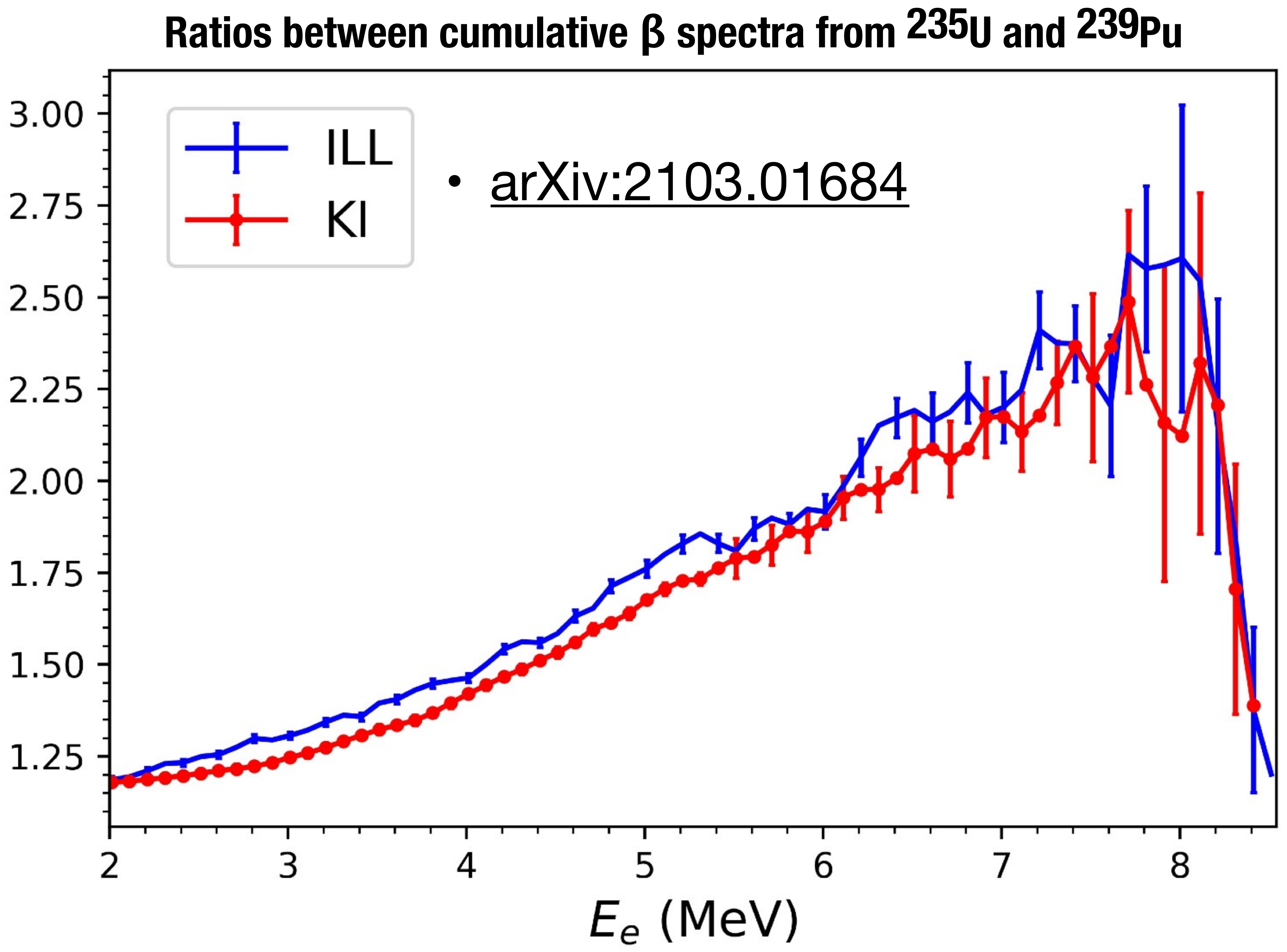
On Isotopes and Antineutrino Flux & Spectrum

- Daya Bay and RENO can separate ^{235}U and ^{239}Pu contribution to $\bar{\nu}_e$ flux → **RAA rate deficit mainly from ^{235}U**
- Estimation of antineutrino spectra based on global β spectra measured at ILL; recent re-evaluation in Kurchatov Institute suggest a ~5% excess in ^{235}U to ^{239}Pu ratio for ILL (compatible with the RAA excess)

F. An, A. Balantekin, H. Band, M. Bishai, S. Blyth, D. Cao et al., *Evolution of the reactor antineutrino flux and spectrum at daya bay*, Physical review letters **118** (2017) 251801.



V. Kopeikin, M. Skorokhvatov, O. Titov Reevaluating reactor antineutrino spectra with new measurements of the ratio between 235U and 239Pu β spectra arXiv:2103.01684



On Isotopes and Antineutrino Flux & Spectrum

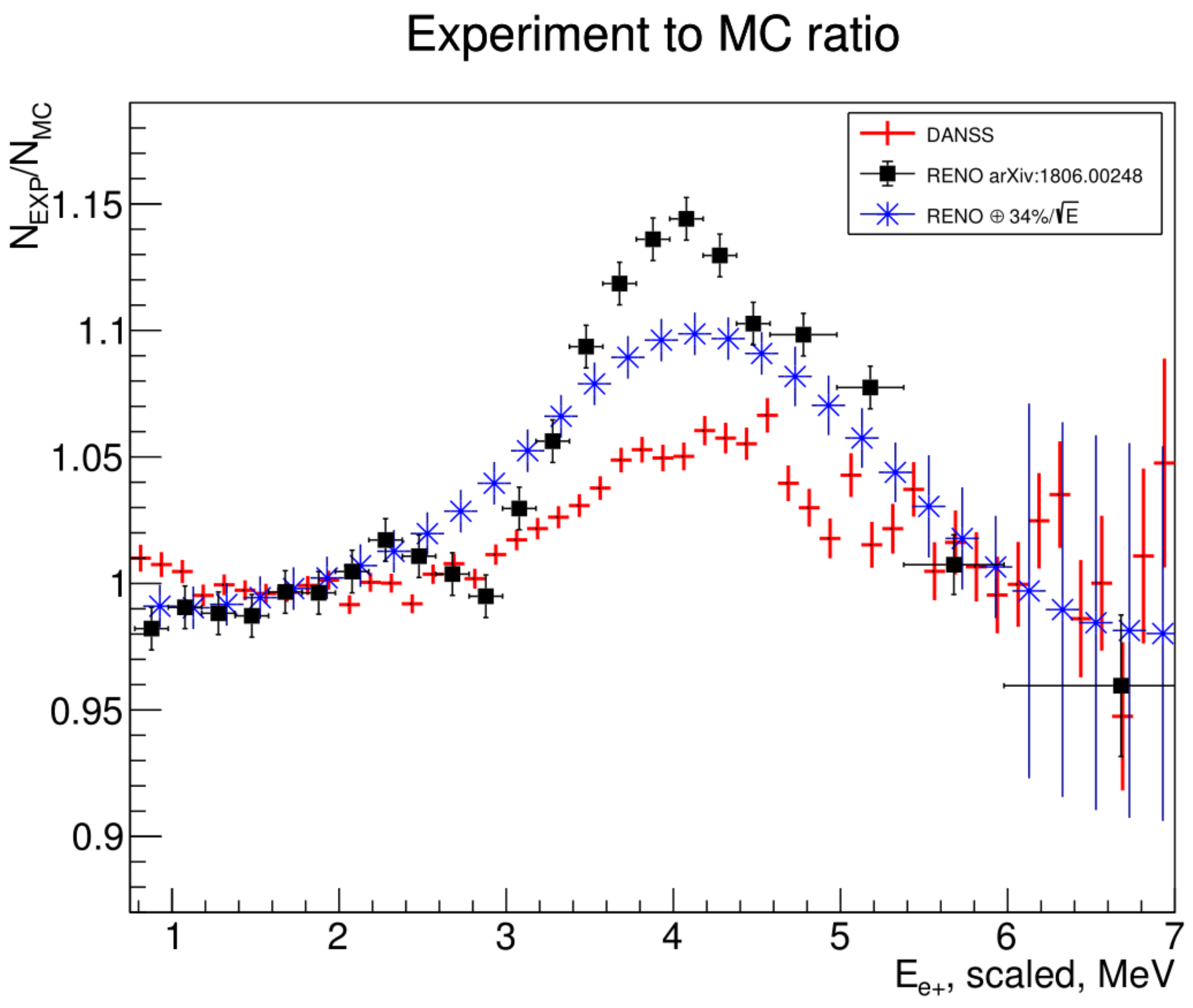
- A spectral distortion @ E_ν ~ 6 MeV was observed in θ_{13}-aimed neutrino experiments in 2014
- **STEREO & PROSPECT** released a **combine spectral analysis** confirming the distortion w/ **2.4 σ significance** and **A = 9.9 ± 3.3 % for pure ^{235}U → distortion independent of other isotopes**

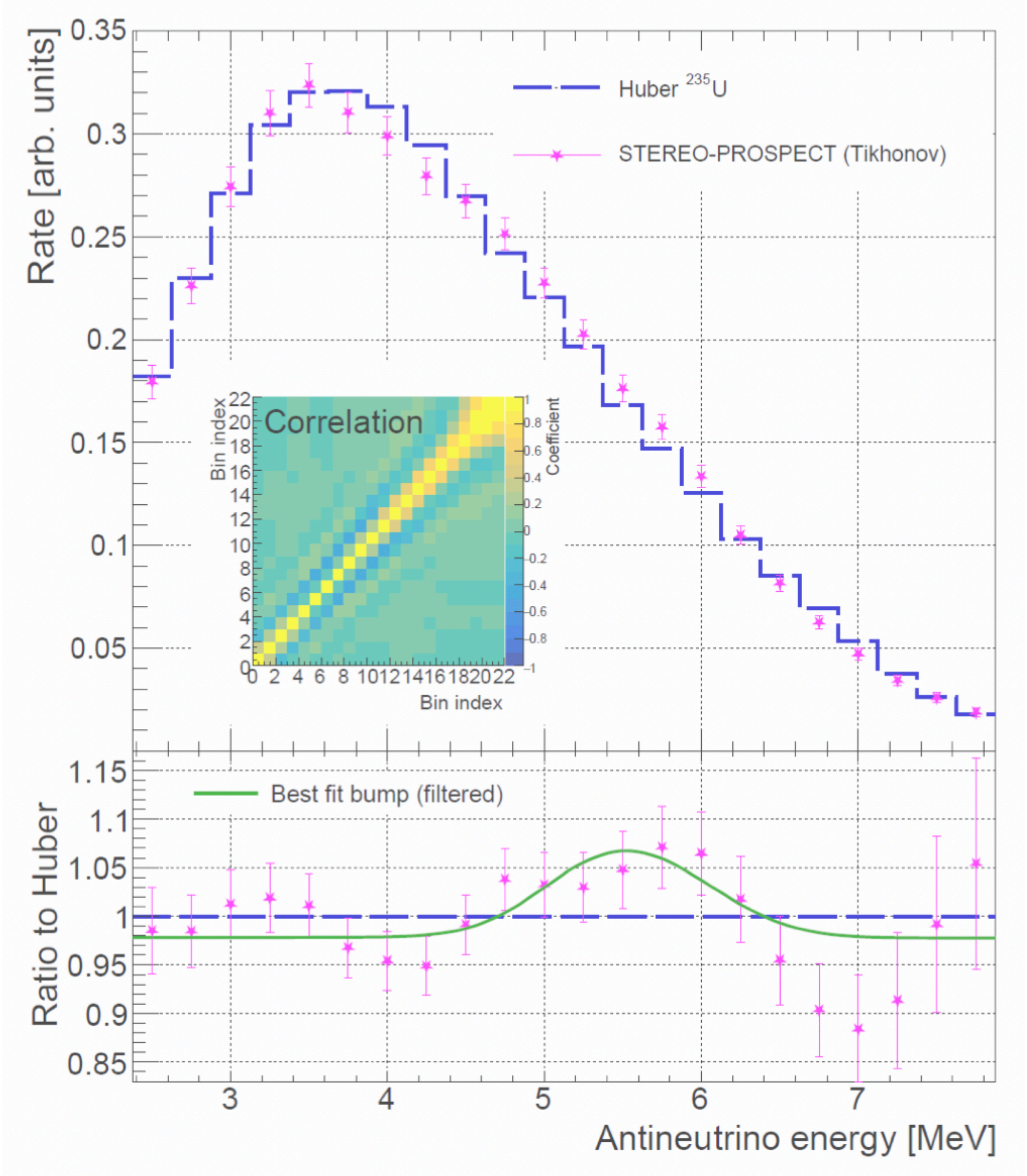
. H. Almazán, M. Andriamirado, A. Balantekin, H. Band, C. Bass, D. Bergeron et al., *Joint measurement of the ^{235}U antineutrino spectrum by prospect and stereo*, *arXiv preprint* arXiv:2107.03371 (2021) .

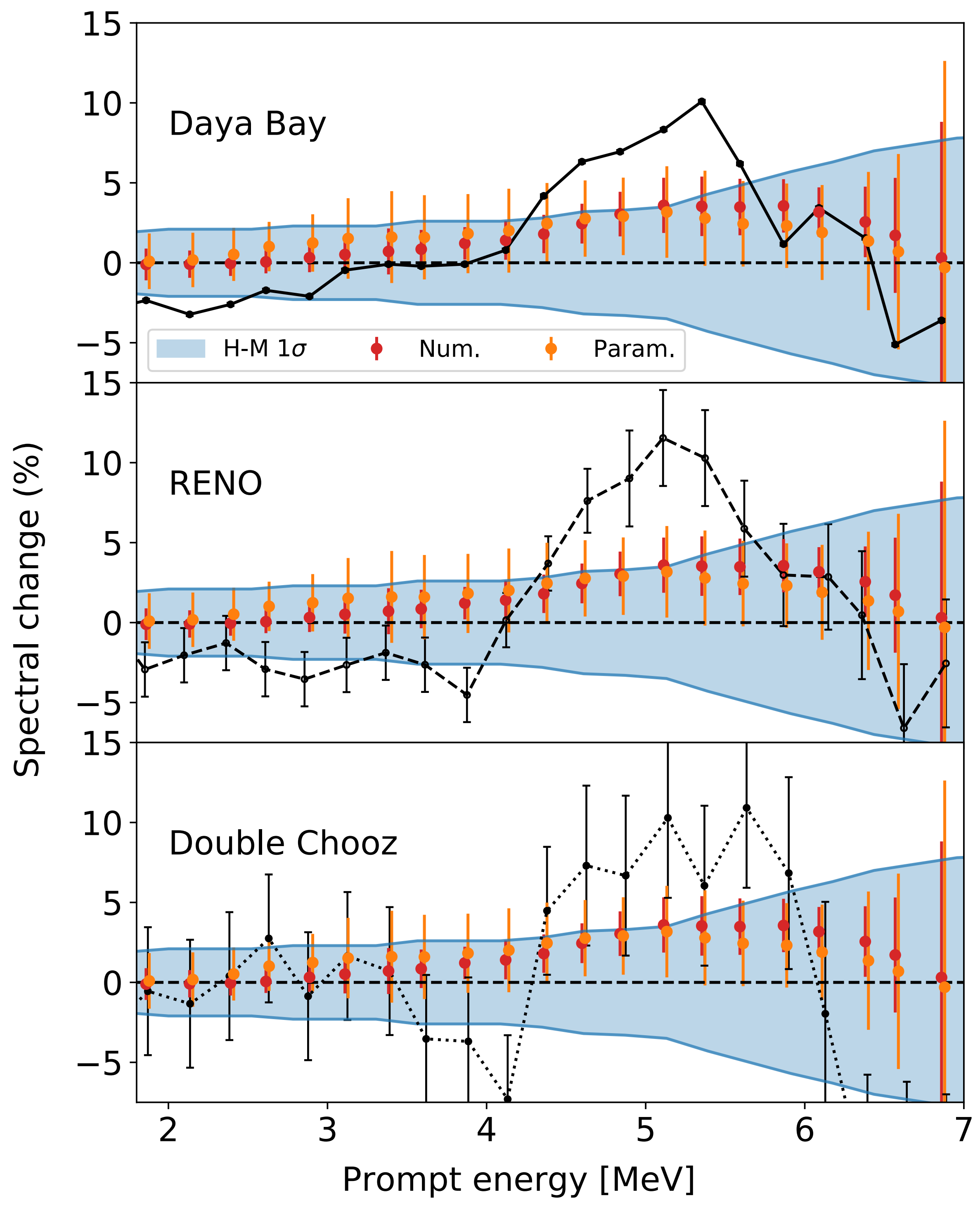
- Meanwhile, limits of current spectrum models are emerging, and the **treatment of forbidden decays could change both normalisation and spectral shape**

. A. Hayes, J. Friar, G. Garvey, D. Ibeling, G. Jungman, T. Kawano et al., *Possible origins and implications of the shoulder in reactor neutrino spectra*, *Physical Review D* **92** (2015) 033015.

. L. Hayen, J. Kostensalo, N. Severijns and J. Suhonen, *First-forbidden transitions in reactor antineutrino spectra*, *Physical Review C* **99** (2019) 031301.







Conclusions

- The quest for θ_{13} in the 2010's prompted **new models for reactor $\bar{\nu}_e$ spectra** & a **~6% discrepancy with measured $\bar{\nu}_e$ rates** was found (reactor antineutrino anomaly)

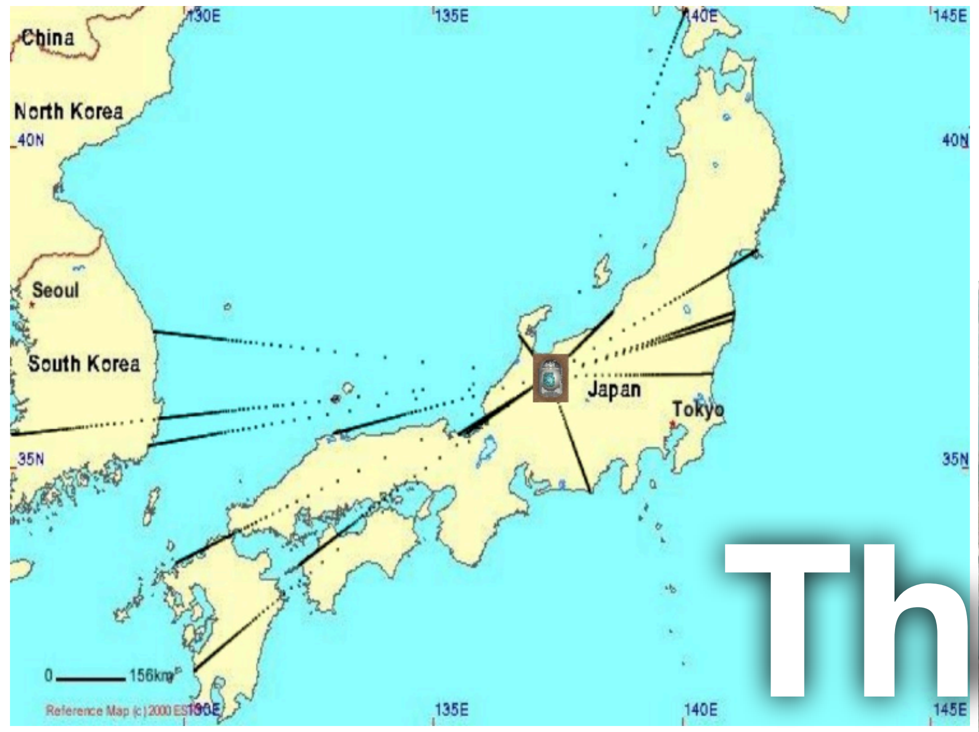
- **Several projects worldwide** were launched to study the anomaly and test the sterile neutrino hypothesis by **looking for neutrino oscillations at very short baseline**, and produced compelling results

- Overall, the **sterile neutrino hypothesis** as a solution of the RAA is **under increasing pressure** by experimental results and advancements in theoretical models

- Thanks to the these different contributions, we are starting to **better understand our antineutrino rates & spectra**, as well as our detectors; an important effort in view of the future of reactor neutrino physics

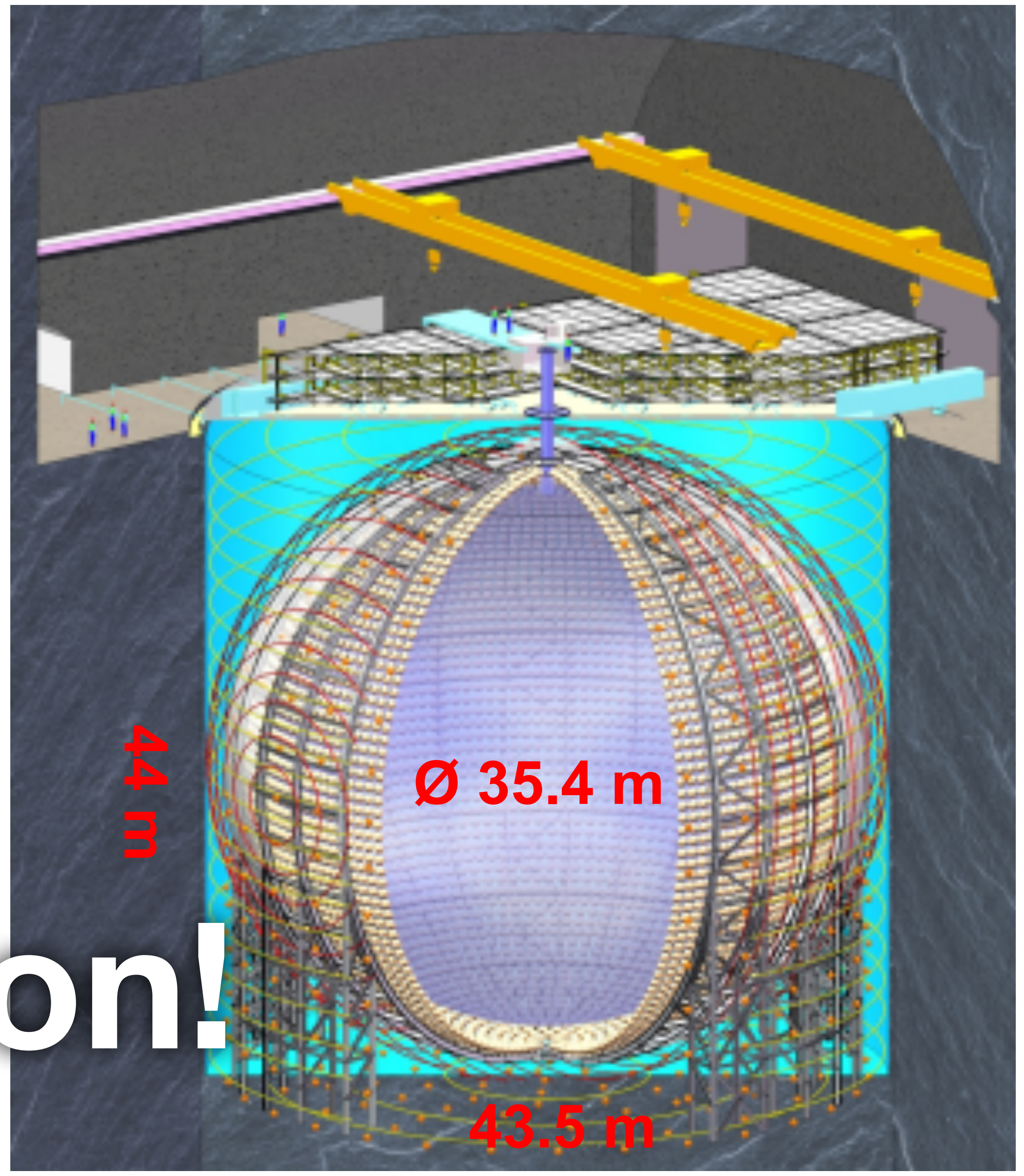
…I'll Leave You With This

- kt mass
- 50 km baseline
- **Measure θ_{12}**



- 10-100 t mass
- ~ km baseline
- **Measure θ_{13}**

- ~ t mass
- ~10m baseline
- **Search for ν_s**



- 20 kt
- 50 km baseline
- **Precision measurements of U_{PMNS} mixing angles & neutrino mass ordering**

Thank You For Your Attention!

Mass/Baseline

2000 2005 2010 2015 2020 2025 Time

Extra Slides

Not the Only Anomaly

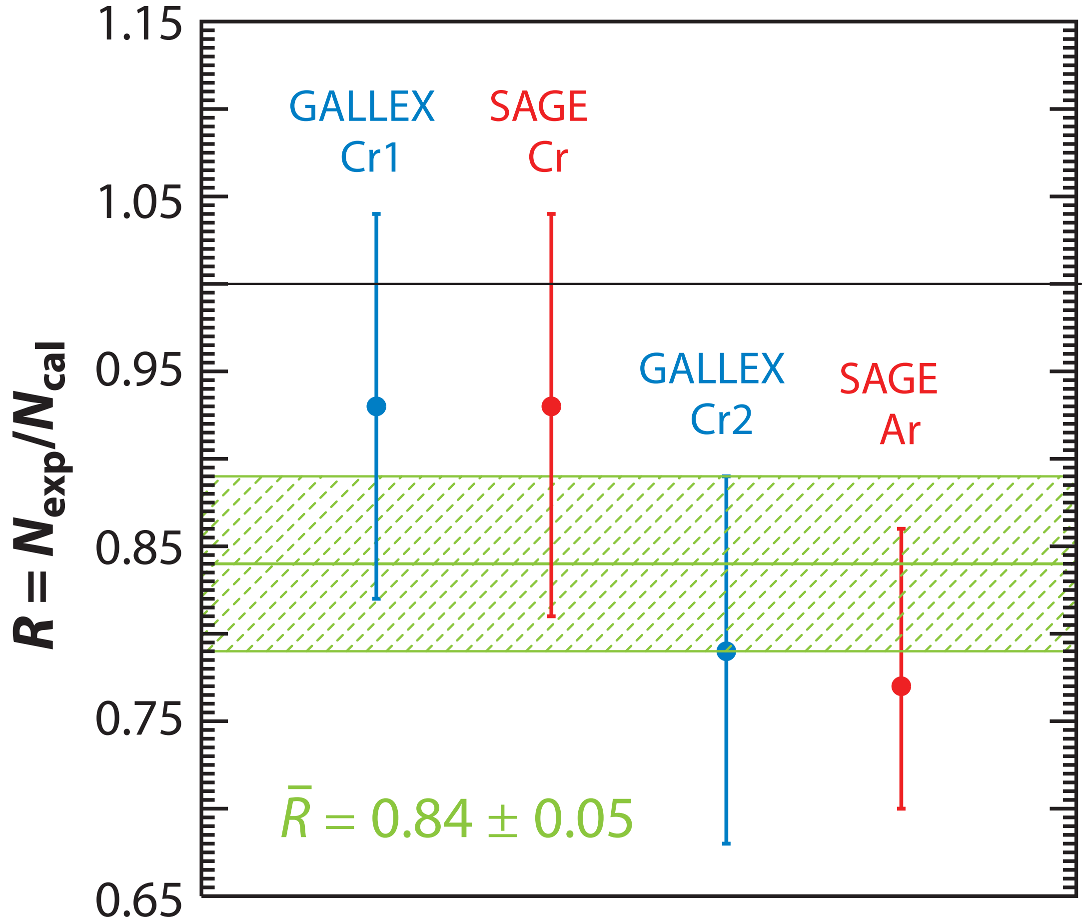
- **Gallium anomaly - disappearance of ν_e** measured with radioactive sources in the solar neutrinos gallium experiments GALLEX and SAGE (rate only)
- **LSND/MiniBooNE anomaly** - energy-dependent event **excess in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel** measured in LSND, consistent with an active-sterile oscillation with **$\Delta m^2 \gtrsim 0.1$ eV²**; 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**

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

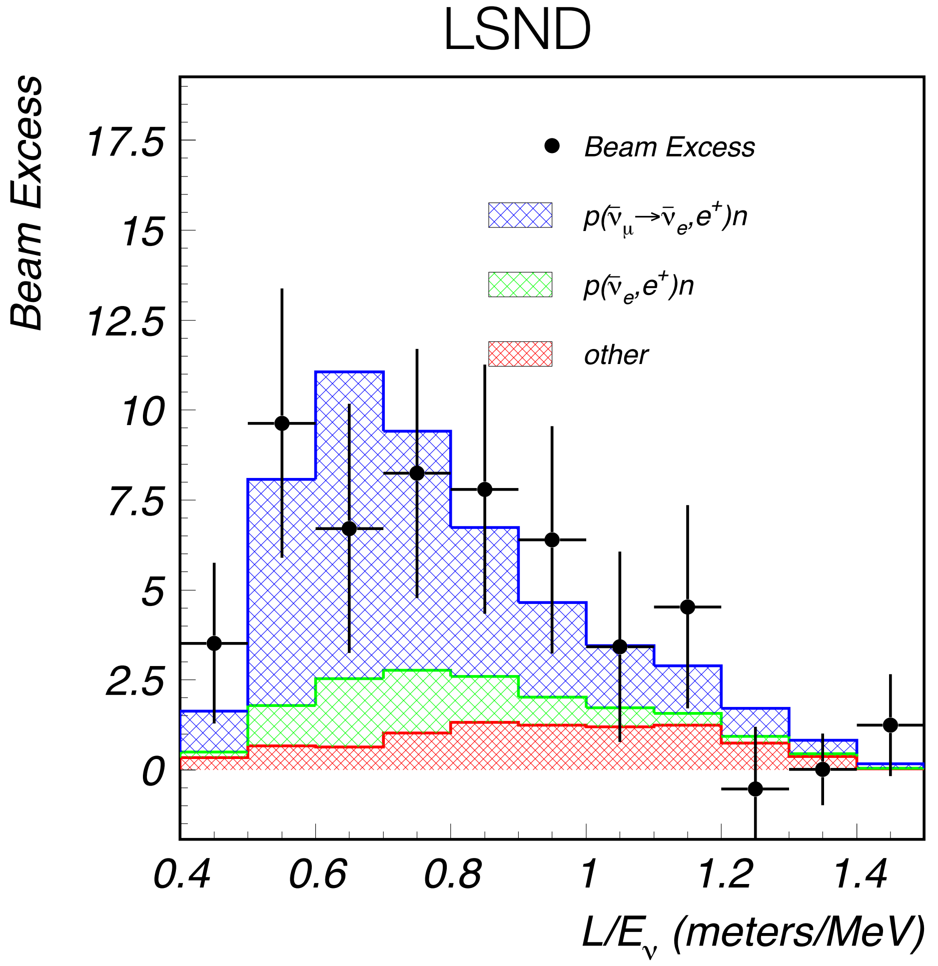
$$P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$

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

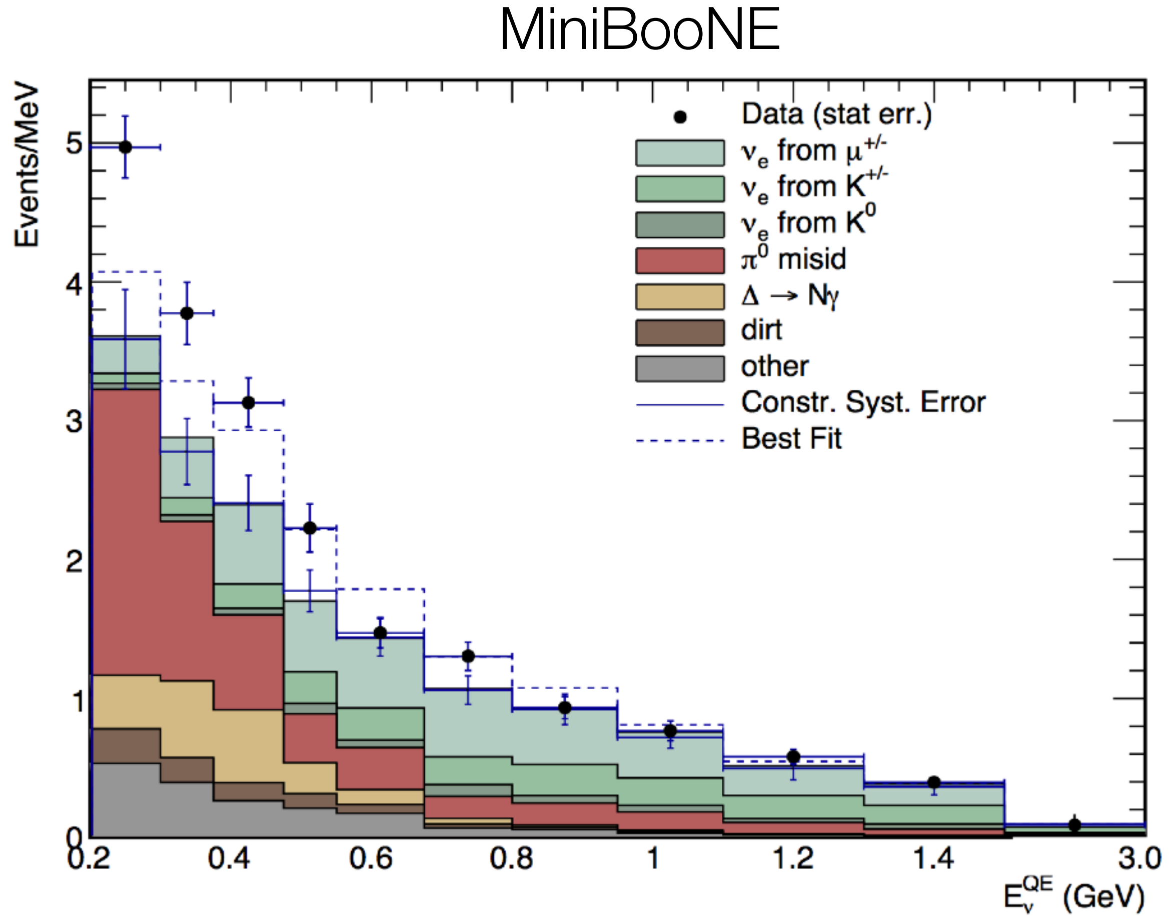
Phys. Lett. B 685:47 (2010)
Phys. Rev. C 73:045805 (2006)

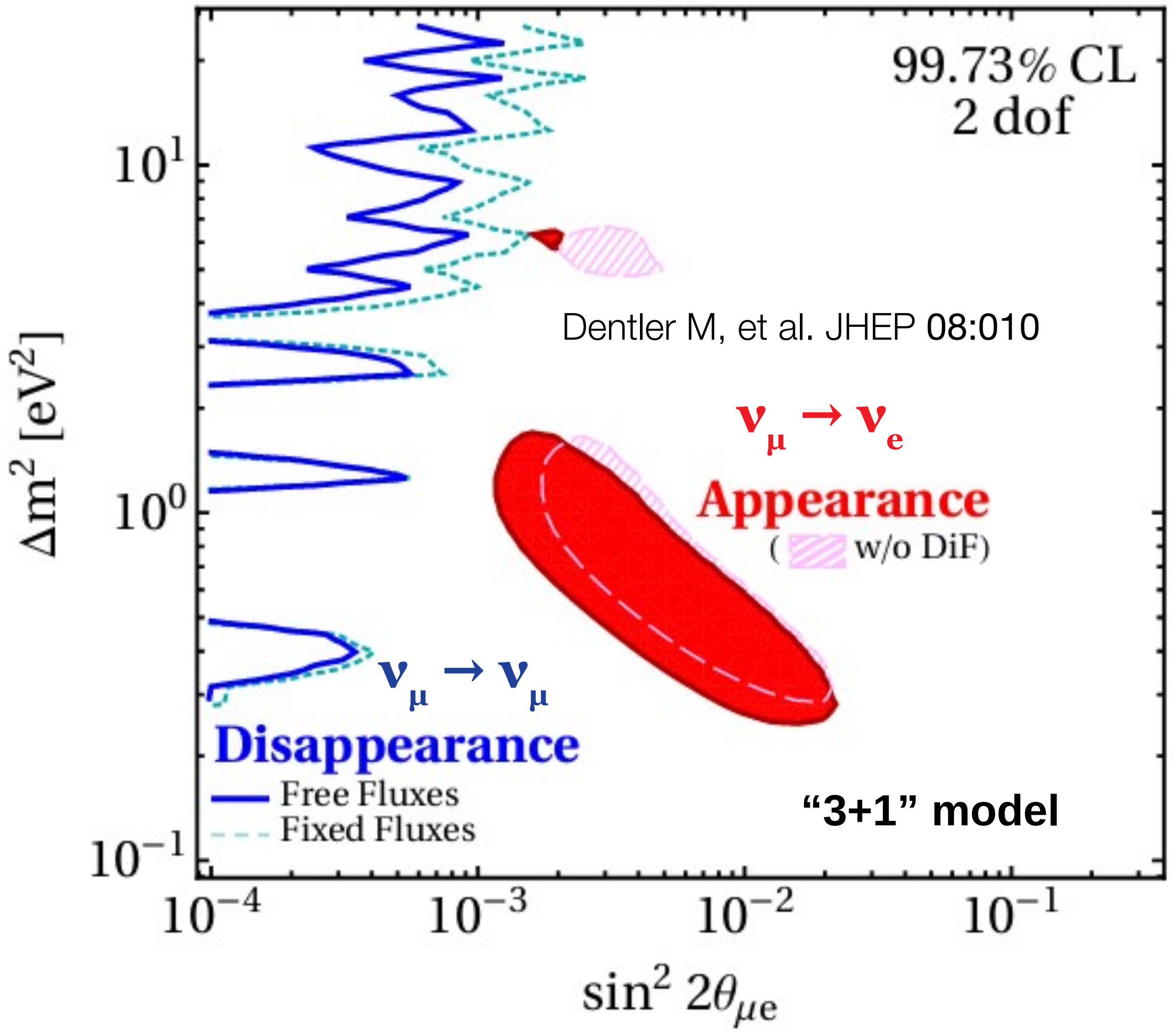


Phys. Rev. D 64:112007 (2001)



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

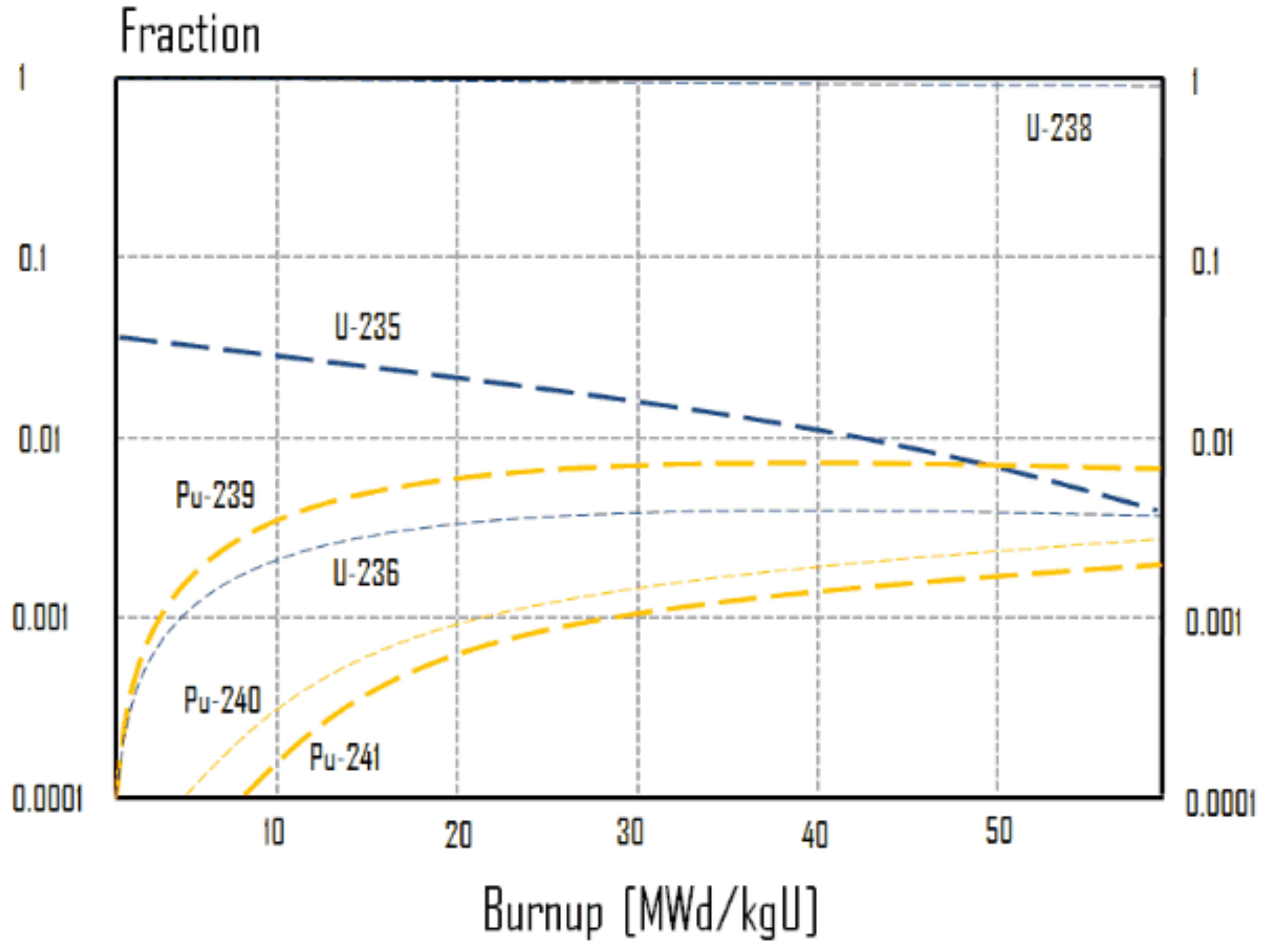
$$N_{IBD}(E_{\bar{\nu}_e}, t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle (t)} \times \langle \sigma_f \rangle (E_{\bar{\nu}_e}, t)$$

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

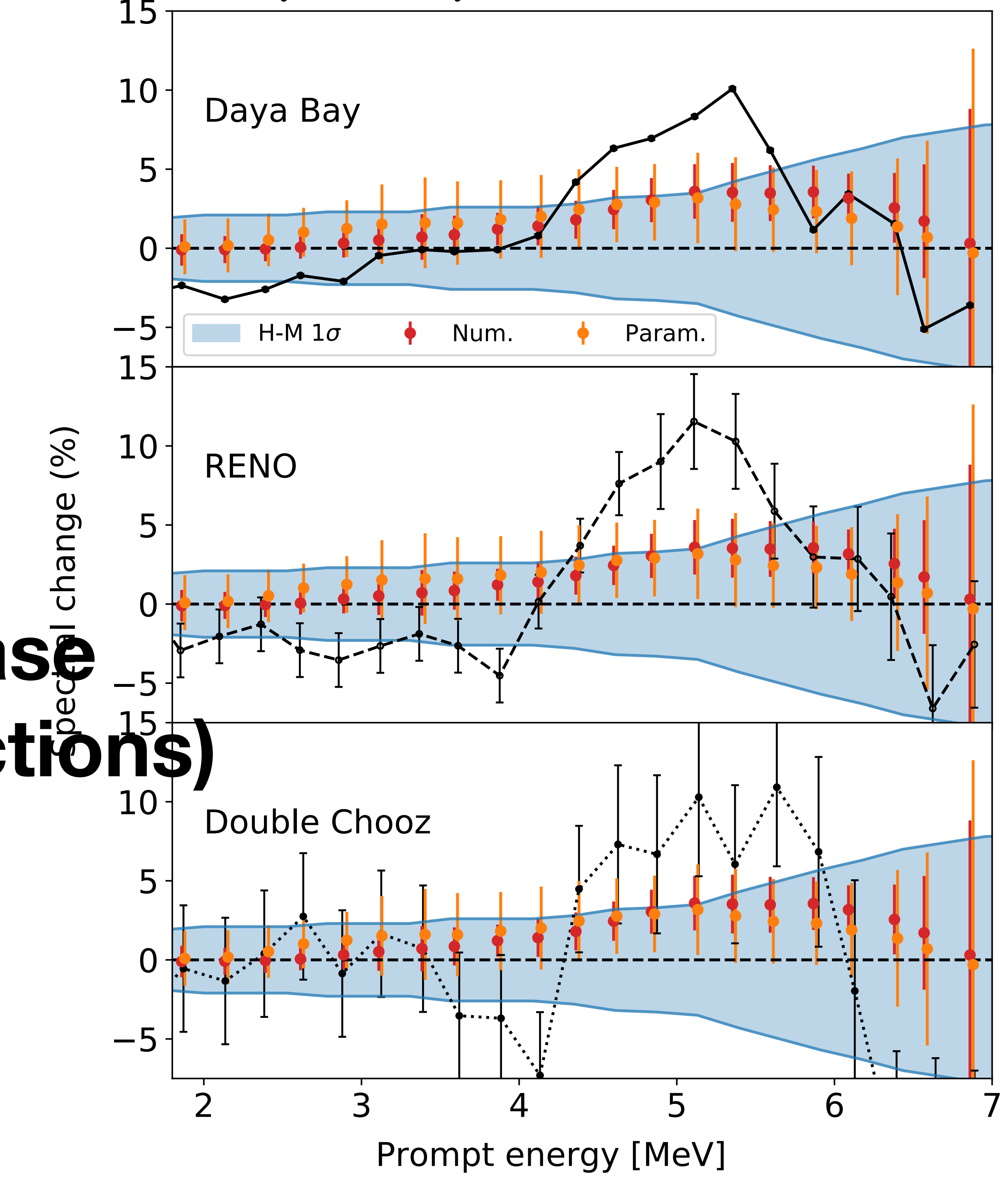
- **Single $\bar{\nu}$ spectra** $S_k(E)$ unavailable, **obtained from global β spectrum** ($\mathcal{O}\,10^3$ branches)
  - Start with known branches from nuclear data tables…
  - … and complement with *effective decay branches*

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

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



- 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)

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

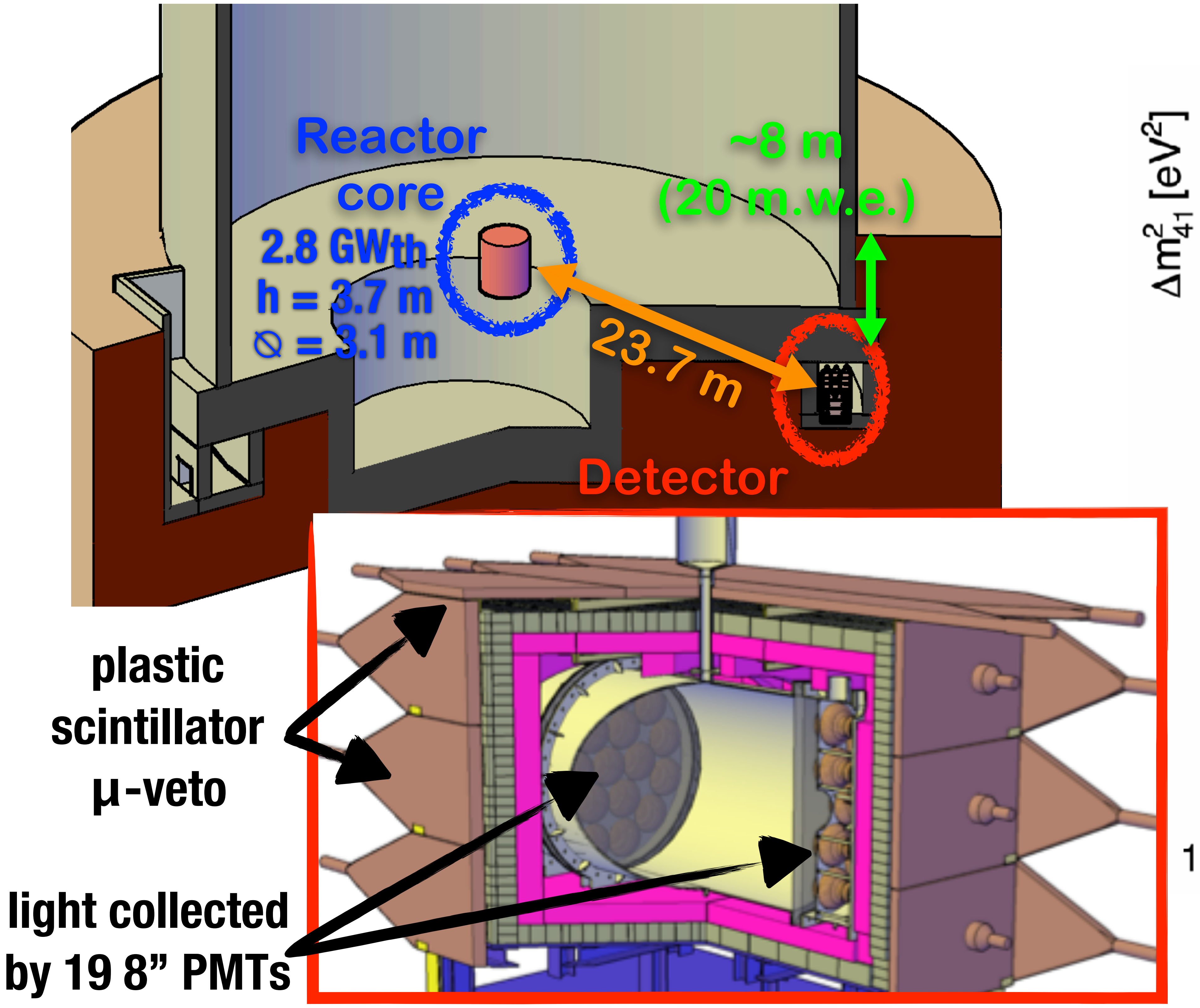
A World-Wide Hunt

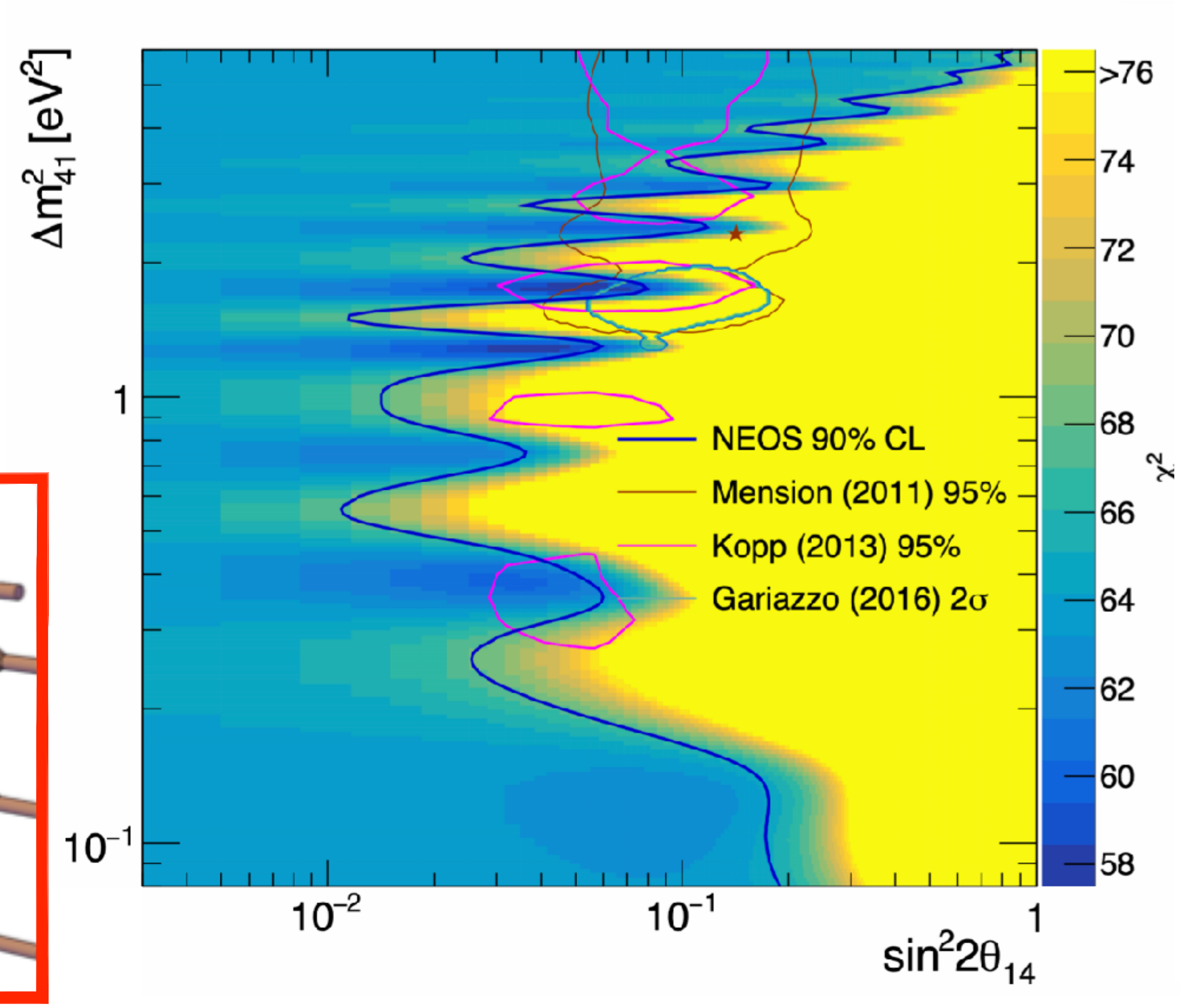
	Core P_{Th}	Core Size	Overburden	Segmentation	Baseline	Material
Chandler	72 MW (^{235}U)	⌀ = 50 cm	~10 mwe	6.2 cm (3D)	5.5 m	PS + Li layer
DANSS	3 GW (LEU)	h = 3.6 m ⌀ = 3.1 m	~50 mwe	5 cm (2D)	10.7-12.7 m	Gd-doped PS
NEOS	2.8 GW (LEU)	h = 3.7 m ⌀ = 3.1 m	~20 mwe	-	23.7 m	Gd-doped LS
Neutrino4	90 MW (^{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

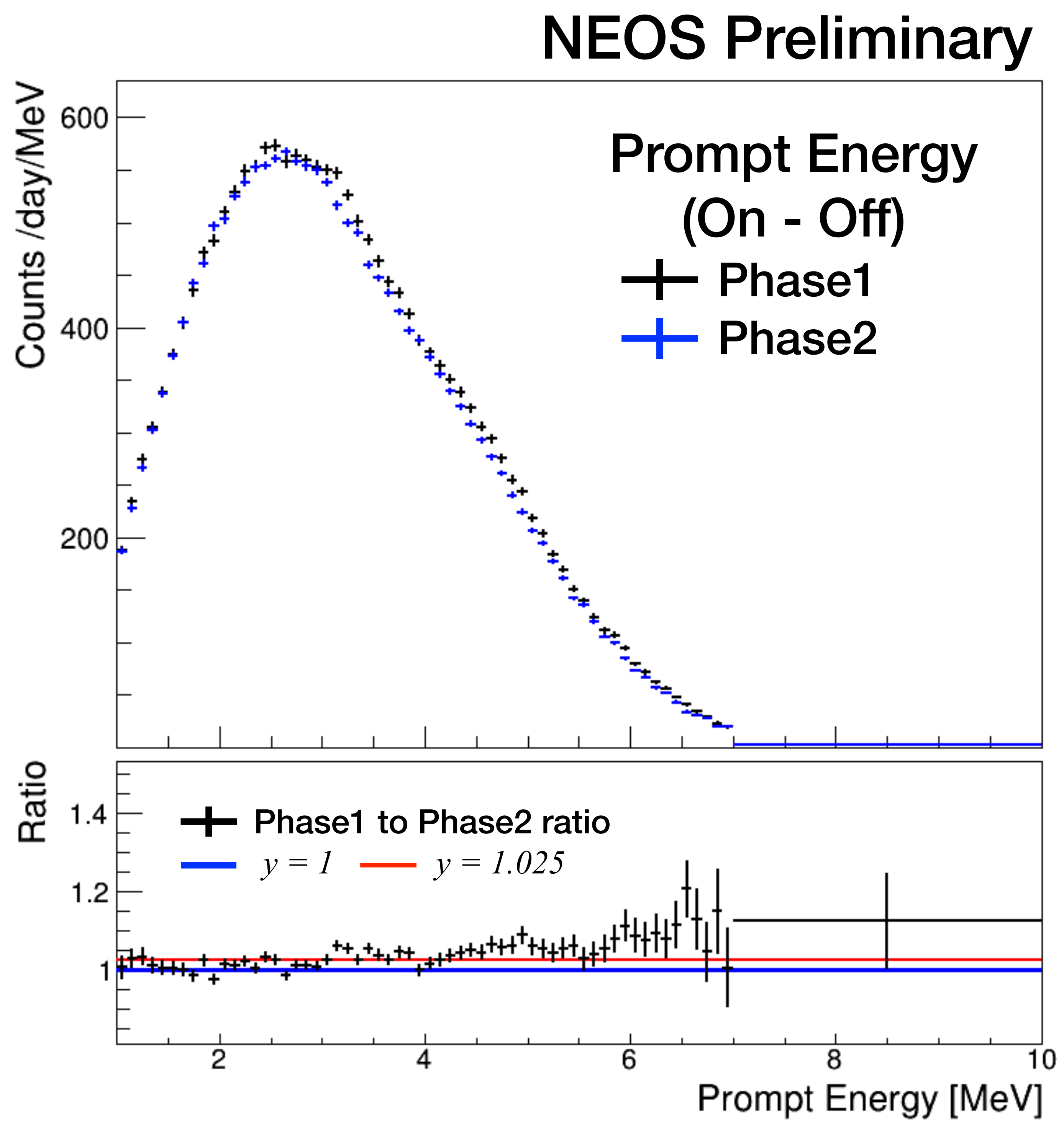
The NEOS Experiment

- **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)



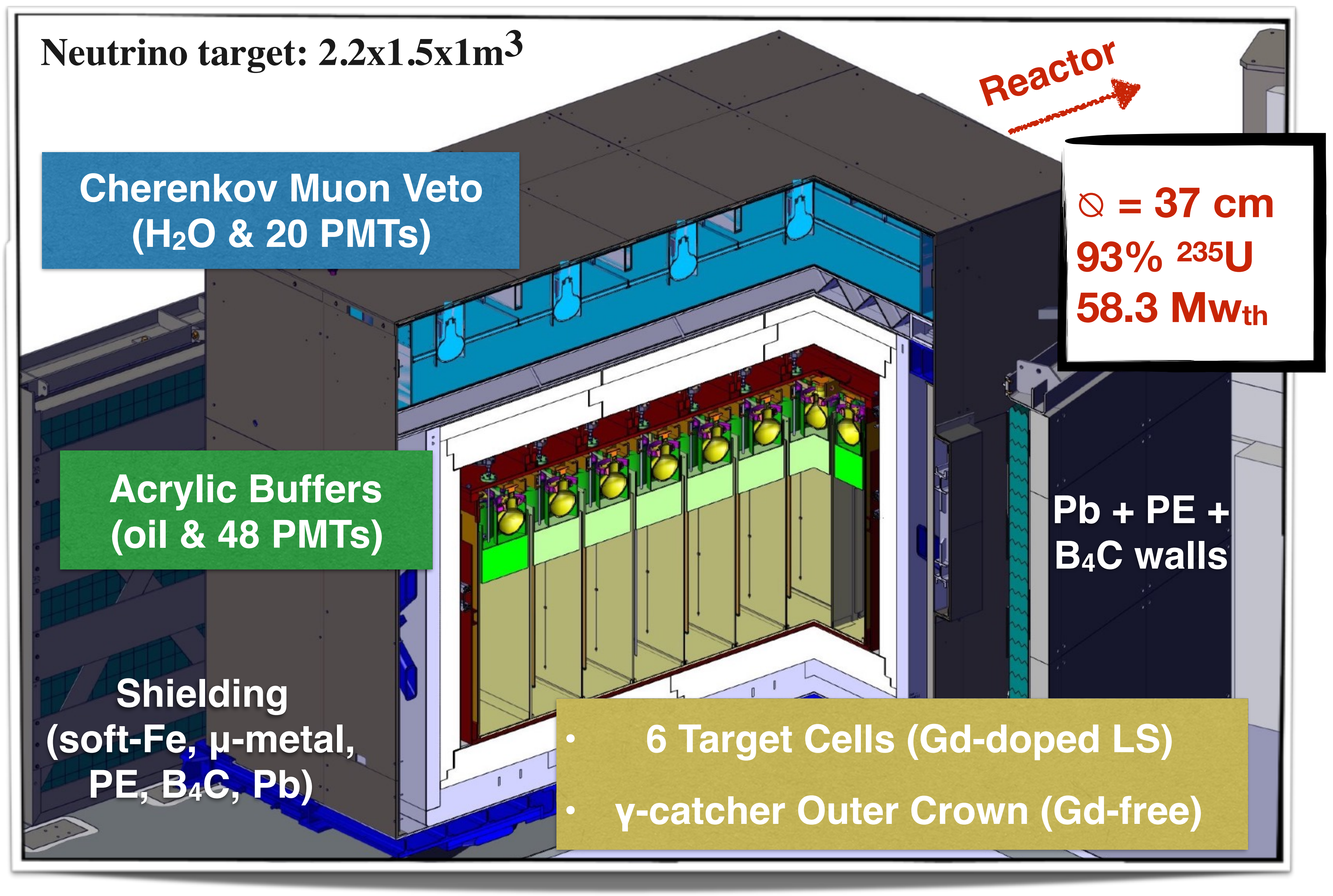


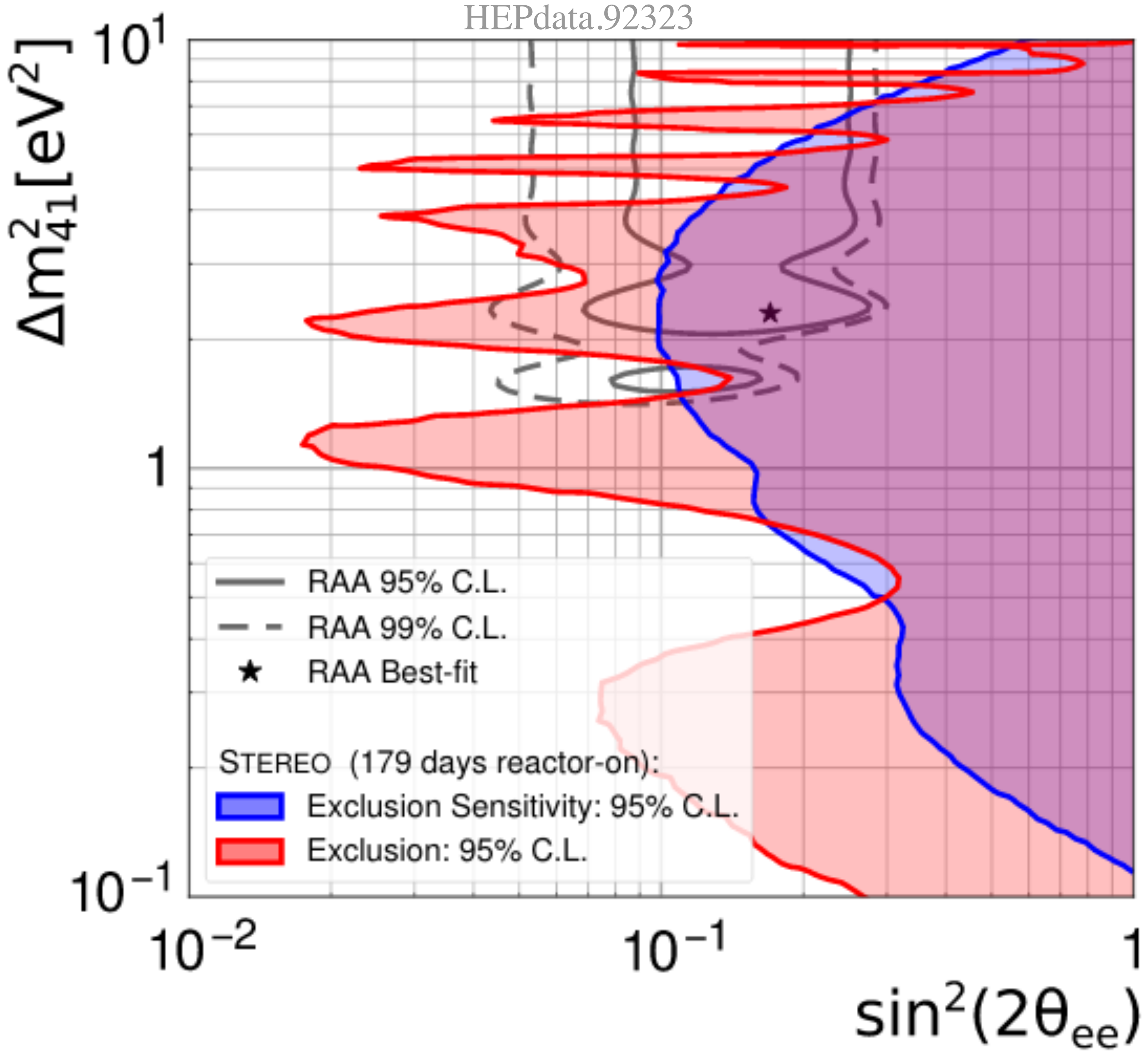


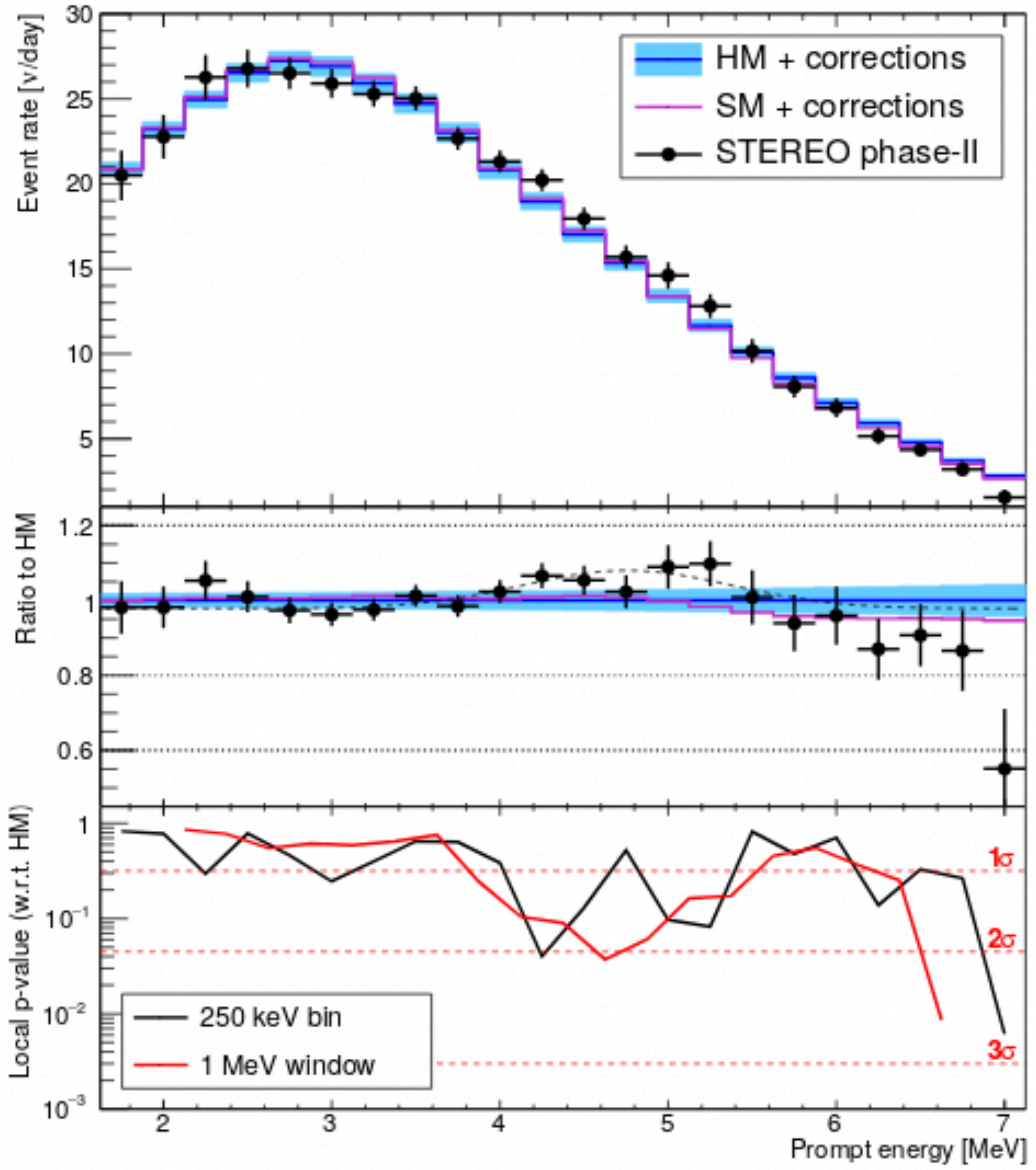
The STEREO Experiment

- 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)

Physical Review D 102.5 (2020): 052002.





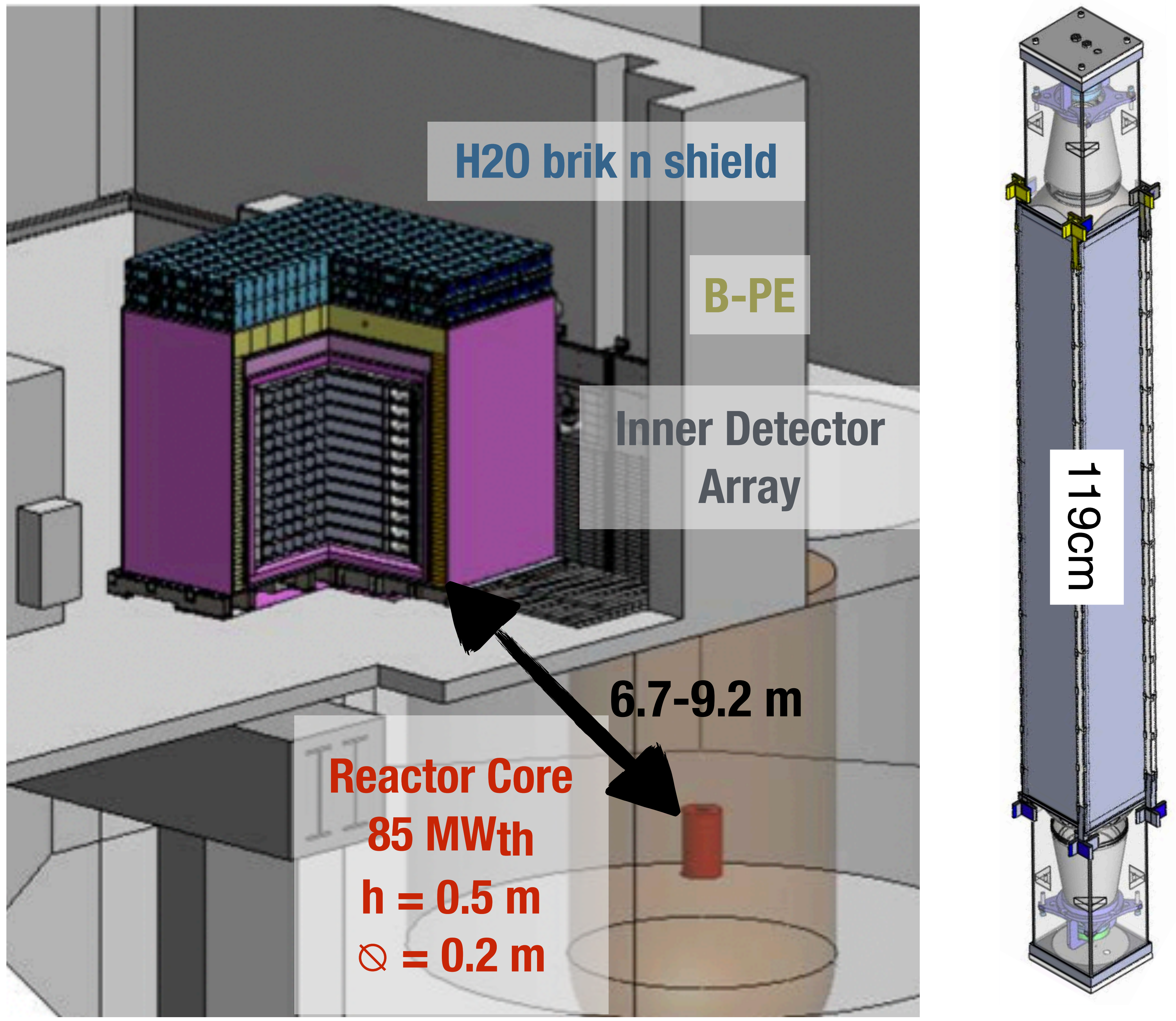


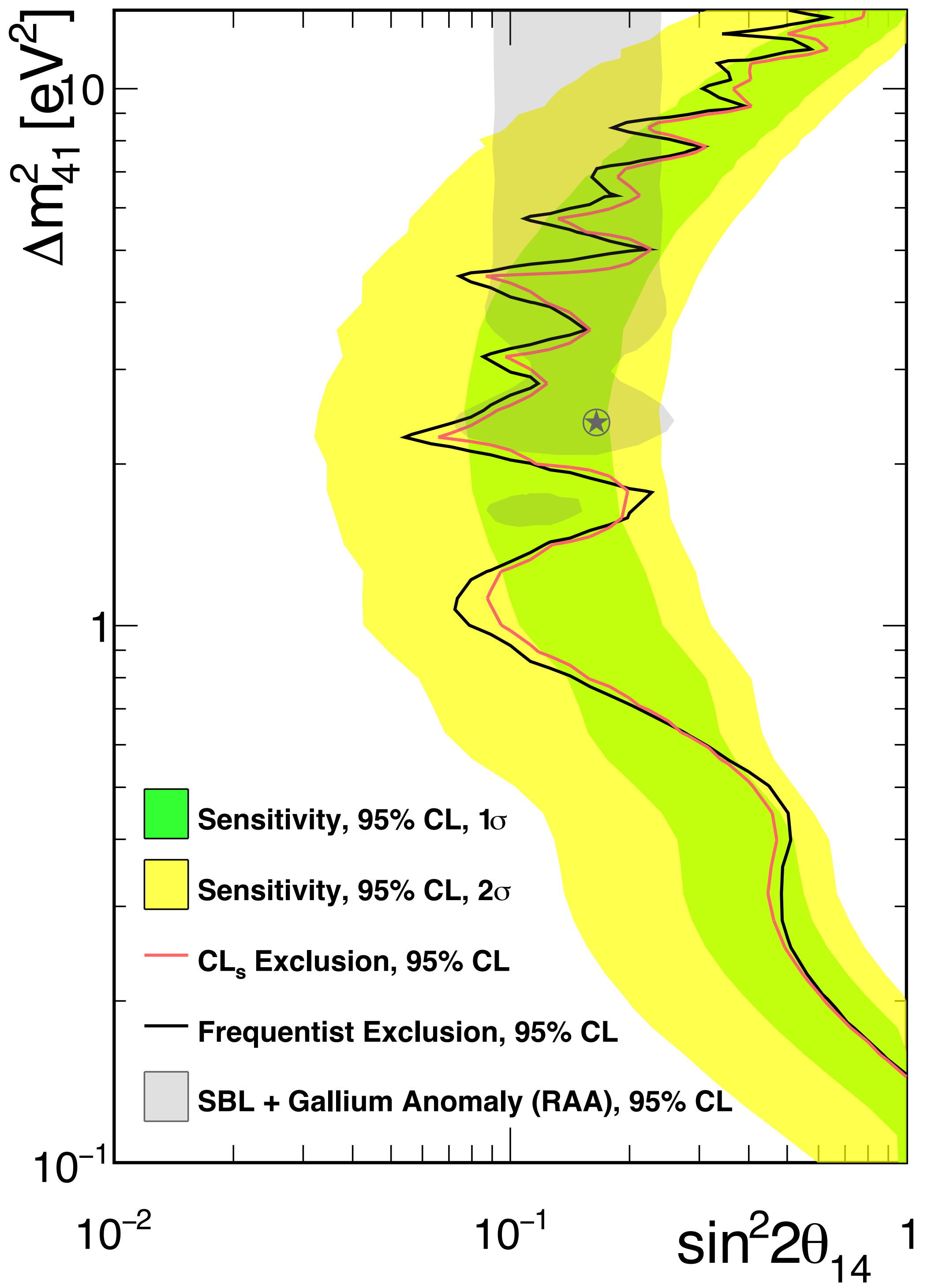
The PROSPECT Experiment

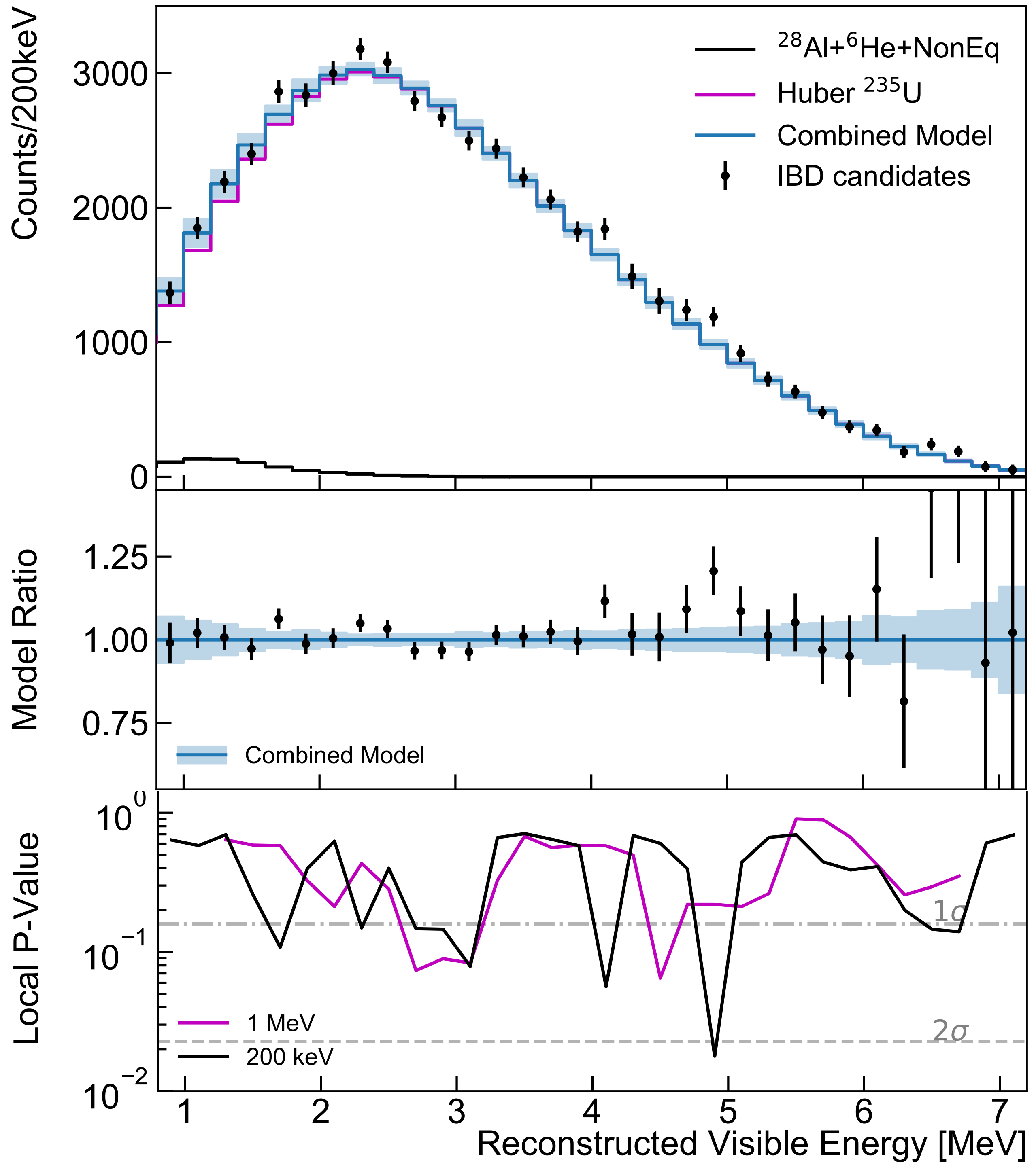
- Highly segmented design: 4-ton ^{6}Li-loaded liquid scintillator in 11x14 optically separated segments → **good E_{res}**, and **3D reconstruction**
- Relatively **high statistics** (530 IBD/day) and S/B (>1) **for a HEU experiment**

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



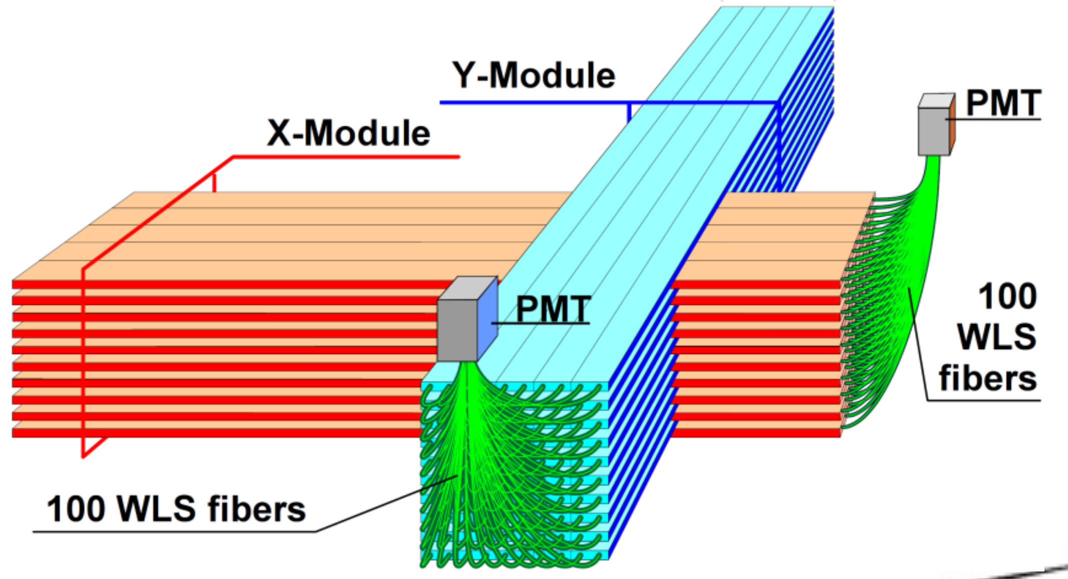


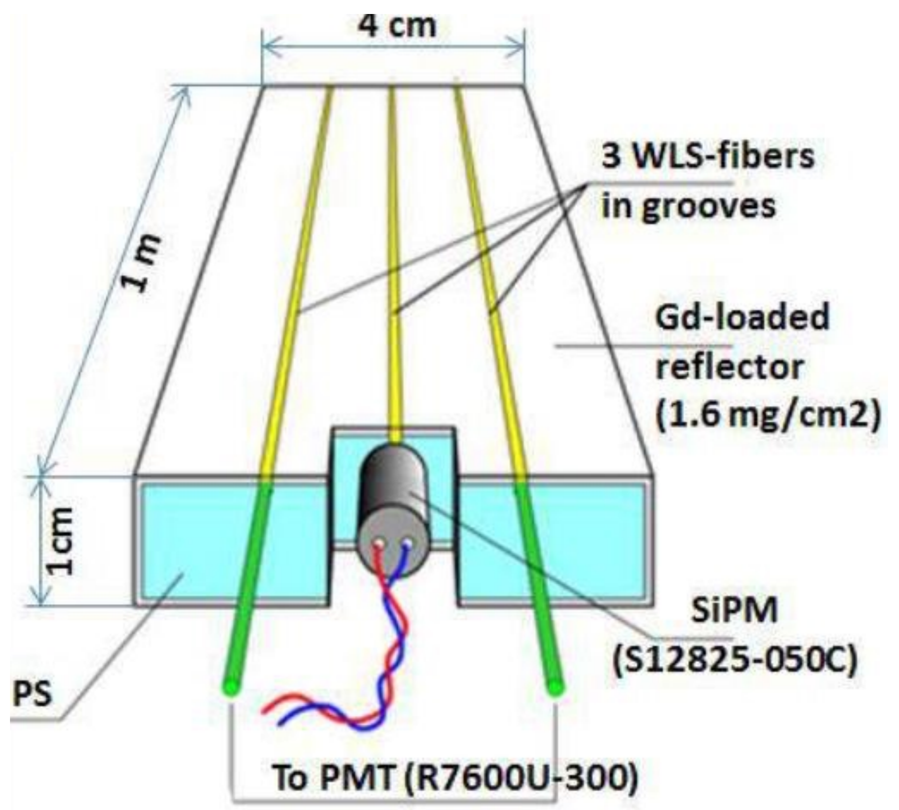


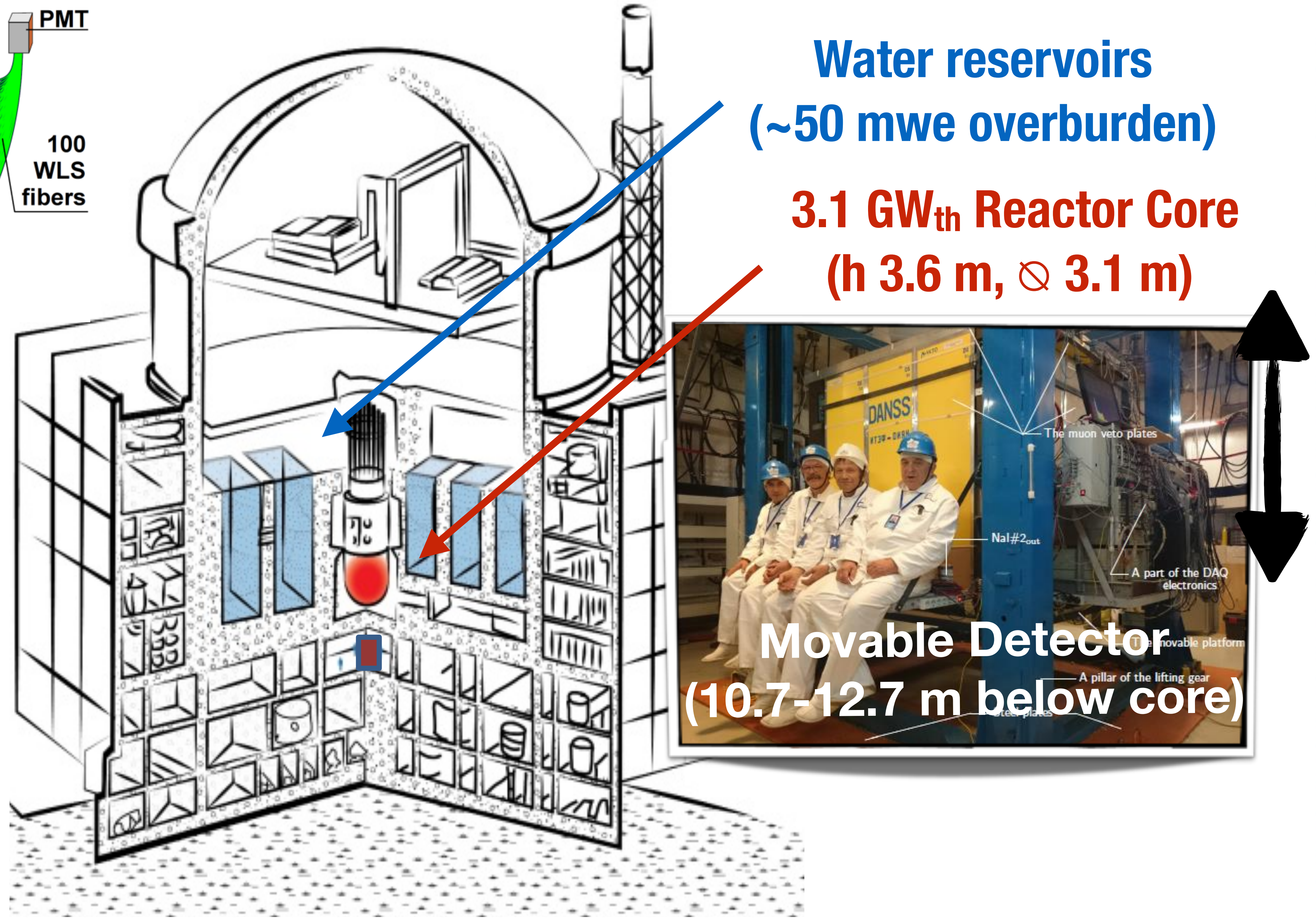
The DANSS Experiment

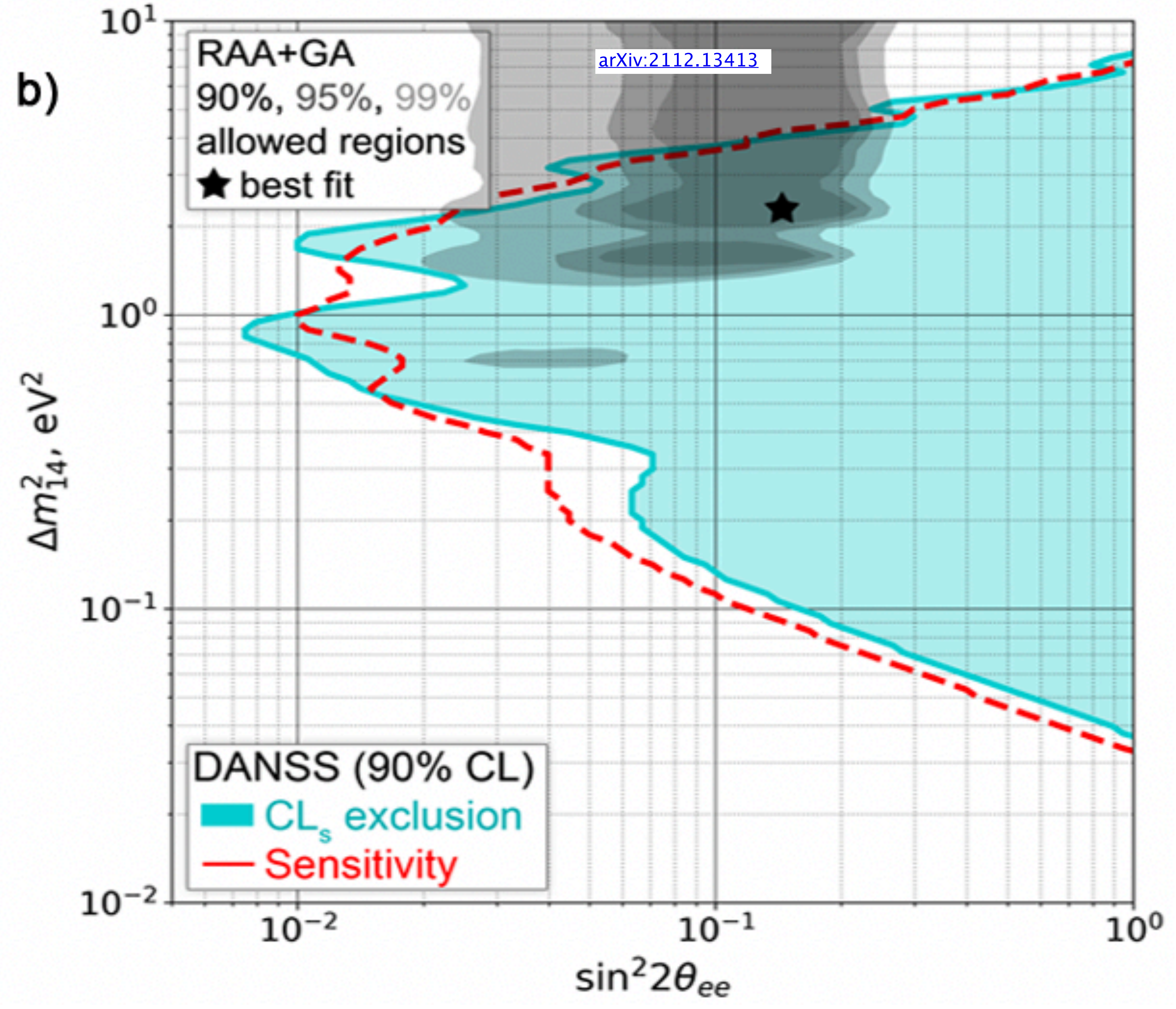
- Highly-segmented ν spectrometer: 2500 Gd-coated plastic scintillator strips in 50 modules → **quasi-3D reconstruction**
- **Excellent statistics** (~5000 IBD/day, S/B~60)
- Movable detector under the reactor (suppression of systematic + overburden)

- Phase-I results (5.5 M IBD in 5 years) **exclude a large portion of the RAA** allowed region and its best fit
- Phase-II upgrade ongoing → goal is to halve energy resolution and increase detector volume (new strips)









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