Interpreting reactor anomalies with STEREO

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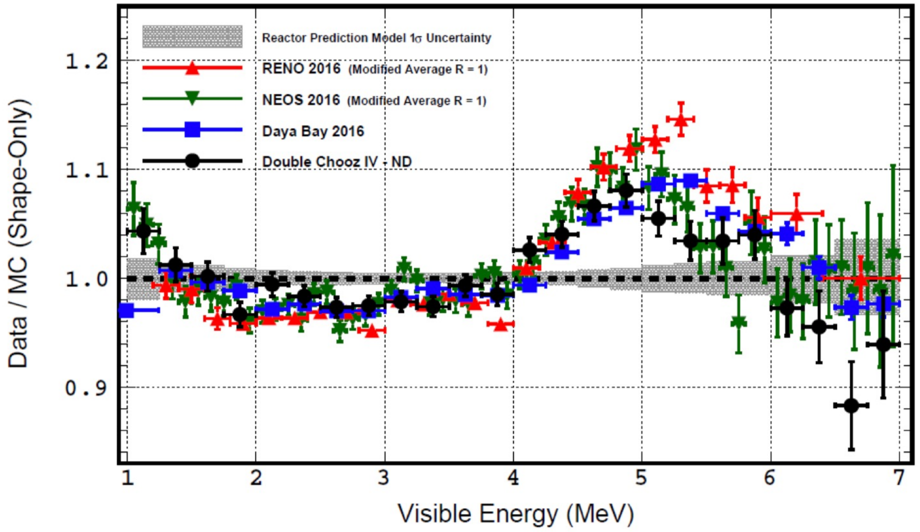
Reactor (anti)neutrinos anomalies

In nuclear reactors, $\bar{\nu}_e$ emitted from the β decay of fission fragments

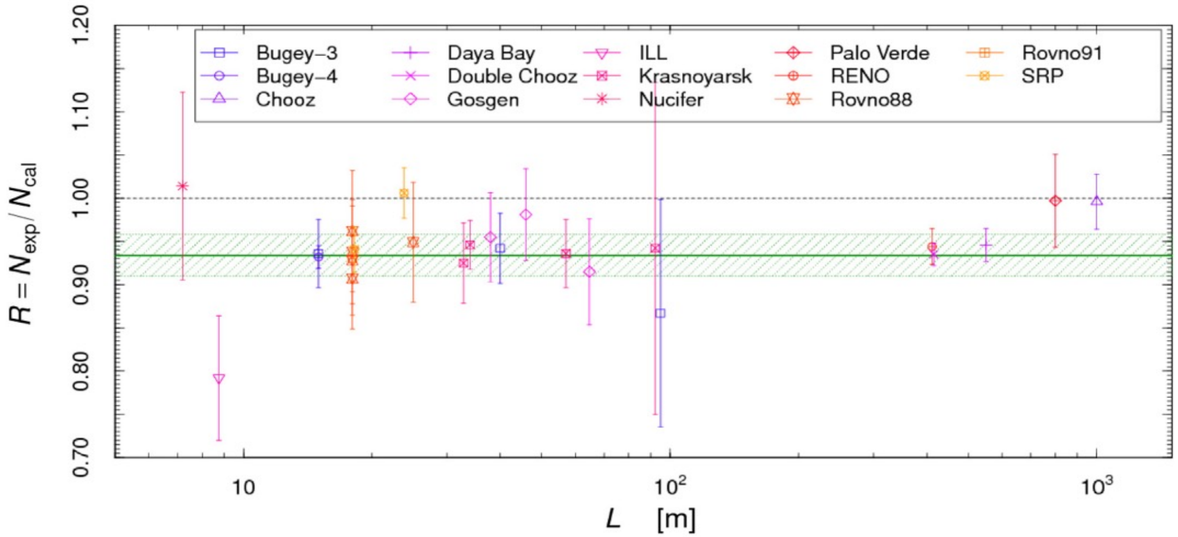
- Research reactors **H**ighly **E**nriched in **U**ranium (**HEU**) : **pure ^{235}U** fuel
- Commercial reactors **L**owly **E**nriched in **U**ranium (**LEU**) : **mixed** ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fuel



``5 MeV Bump''

~10% spectral disortion w.r.t. Huber-Mueller prediction.

Nature Physics 16, pp. 558–564 (2020)



Reactor Antineutrino Anomaly (RAA)

~6% global rate deficit at short-baseline w.r.t. Huber-Mueller prediction.

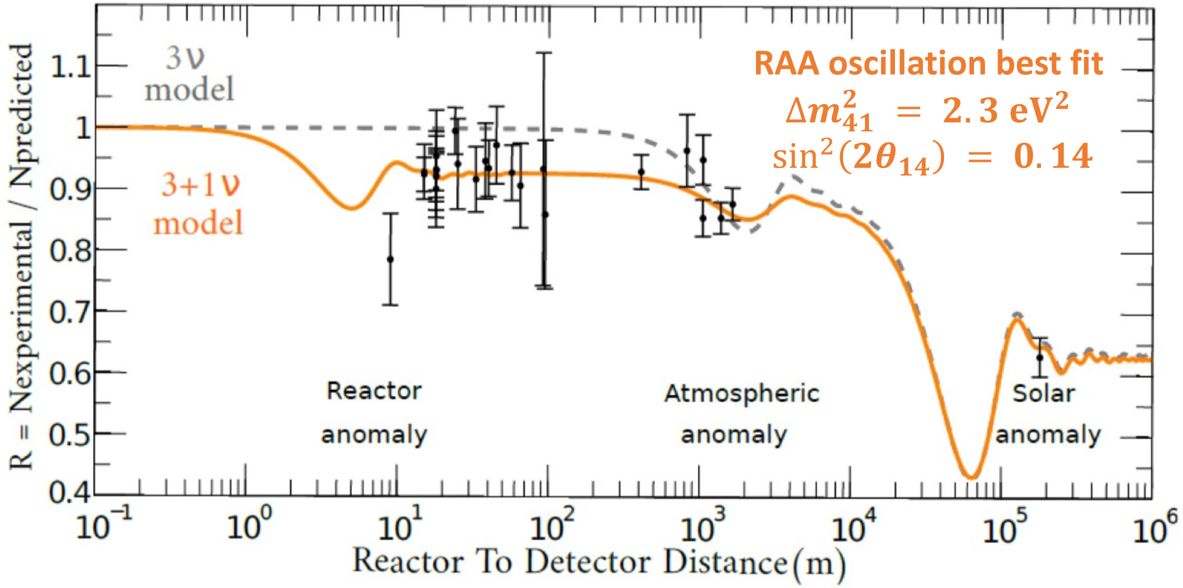
Progress in Particle and Nuclear Physics 111, 103736 (2020)

Biased prediction or new physics ?

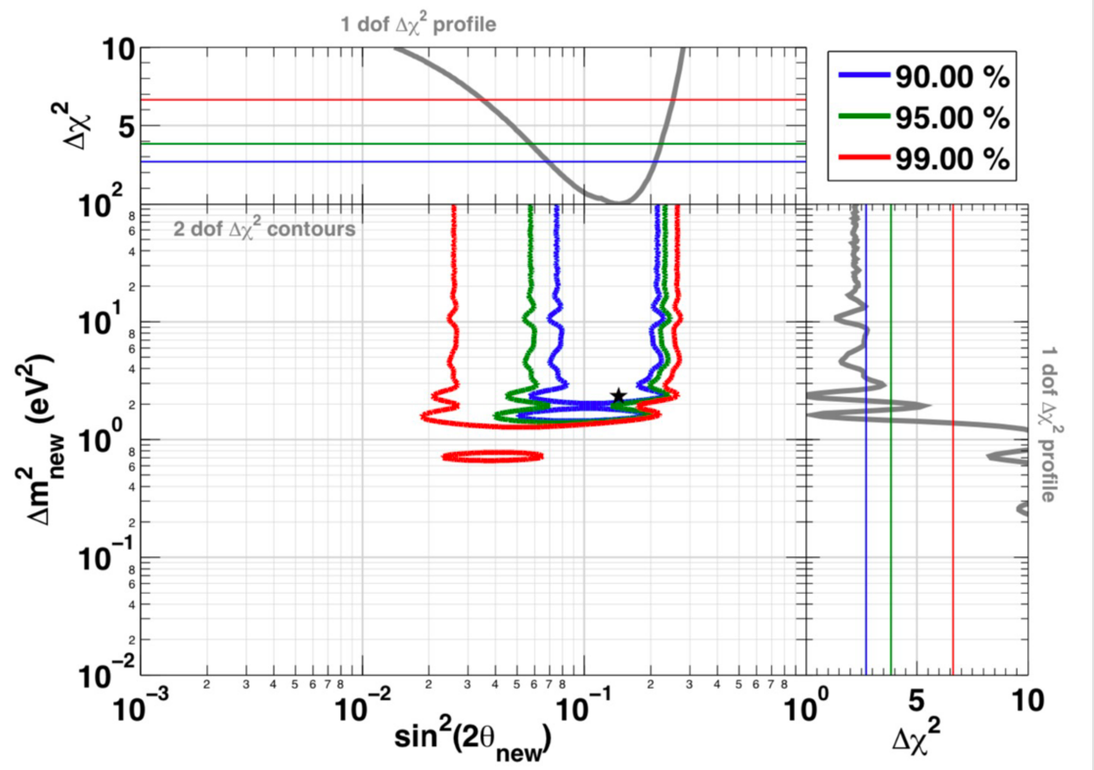
Rate anomaly and sterile neutrino

Short-baseline deficit ↔ Signature of a new oscillation ?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U^{3+1}_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

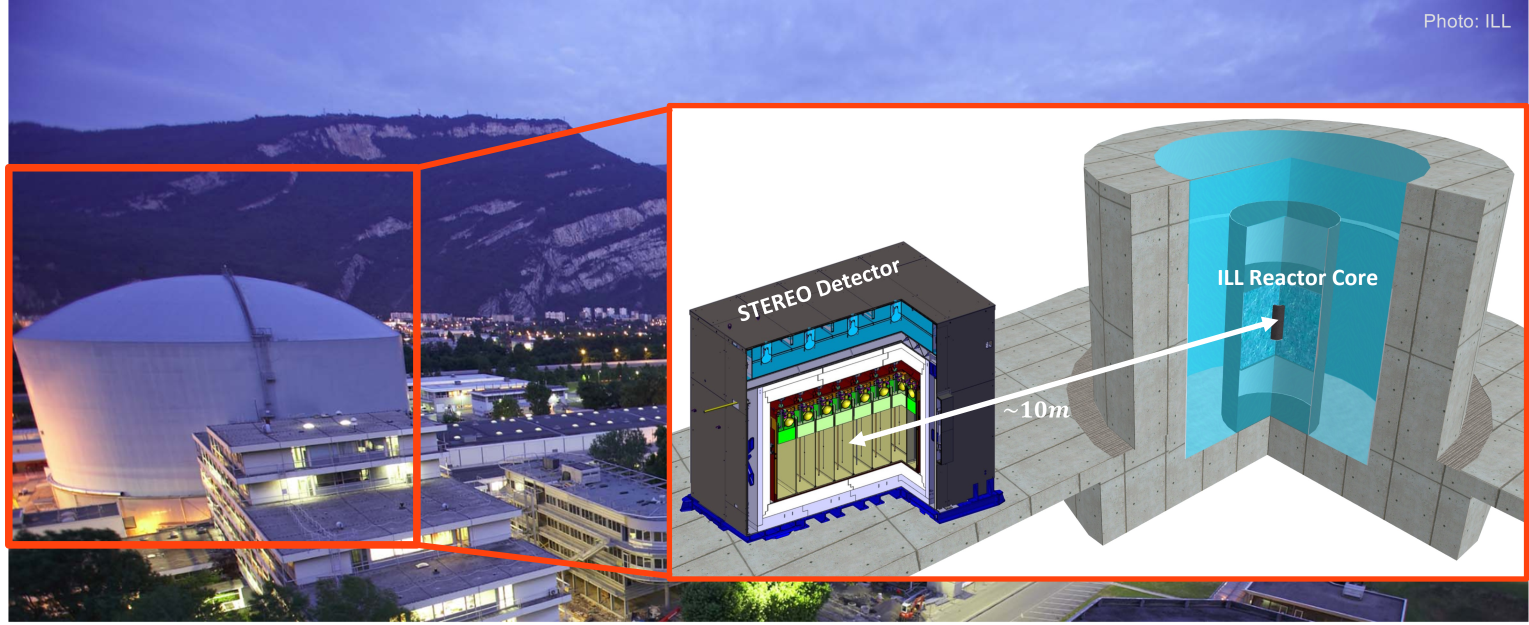


PRD 83, 073006 (2011)



STEREO provides a complete study of all anomalies for a pure ^{235}U antineutrino spectrum (HEU experiment).

STEREO experiment goals



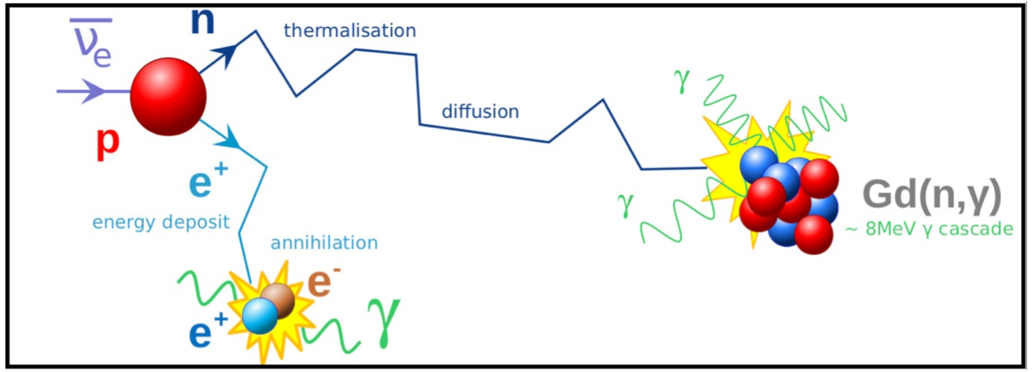
- Insights on the pure **contribution of ^{235}U to the reactor anomalies**.
- **Test of sterile hypothesis**, with a model-independent oscillation analysis.
- Precision measurement of the **absolute antineutrino rate**.
- Precision measurement of the **antineutrino spectrum shape**.

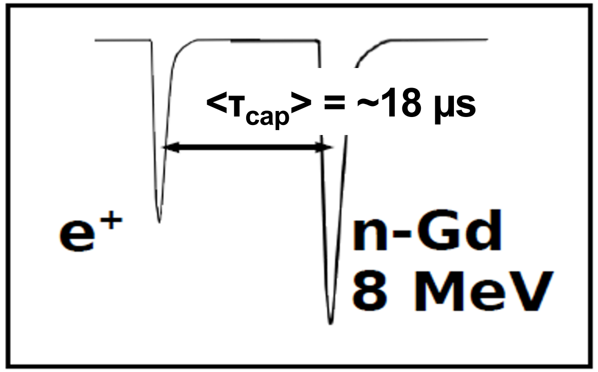
- Antineutrino source : **HEU** research reactor of Institut Laue-Langevin (Grenoble, France).
- **Very short-baseline** (9-11m) & **Compact core** + Segmented detector, with **6 identical cells**.
- P_{th} = 58 MW_{th} known with **1.4% accuracy**.
- **Accurate** determination of the **detector response**.

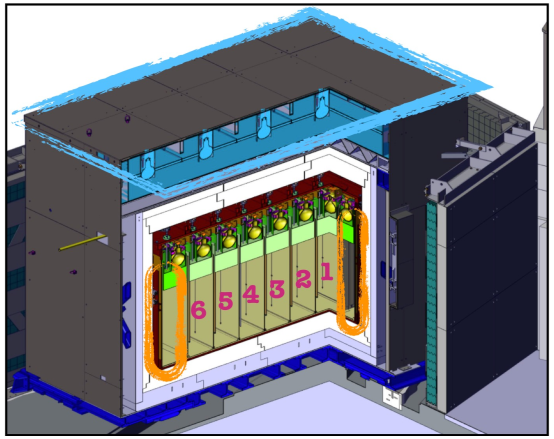
STEREO detector

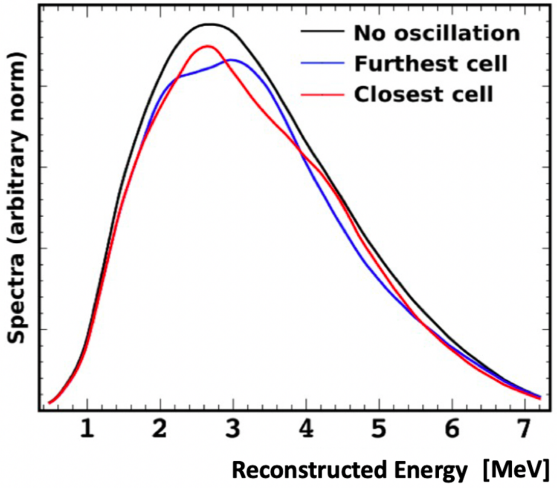
Detection Principle : Inverse beta-decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad E_{\bar{\nu}_e} = E_{e^+} - 0.782[\text{MeV}]$$





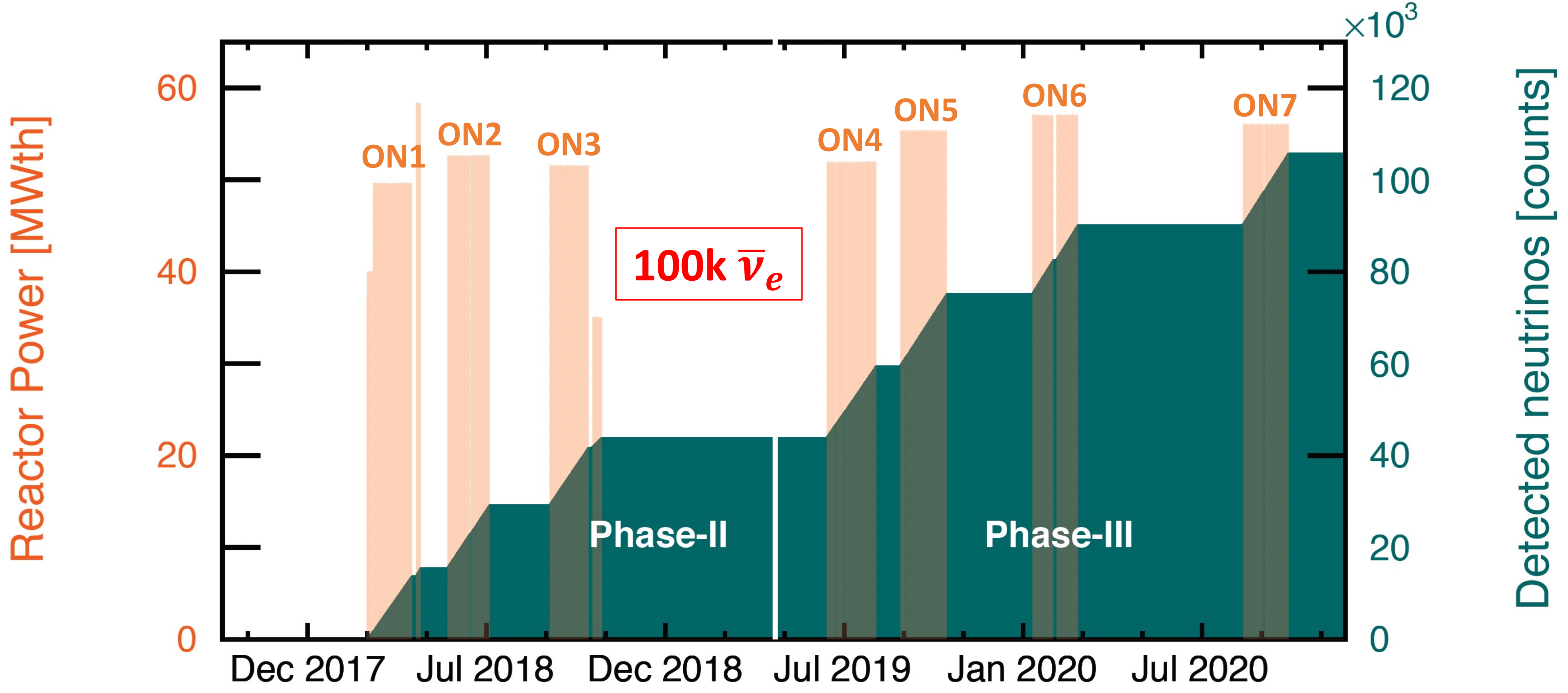




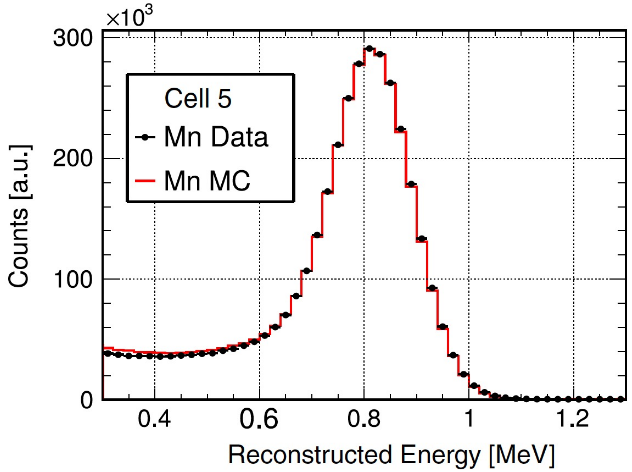
Detector design :

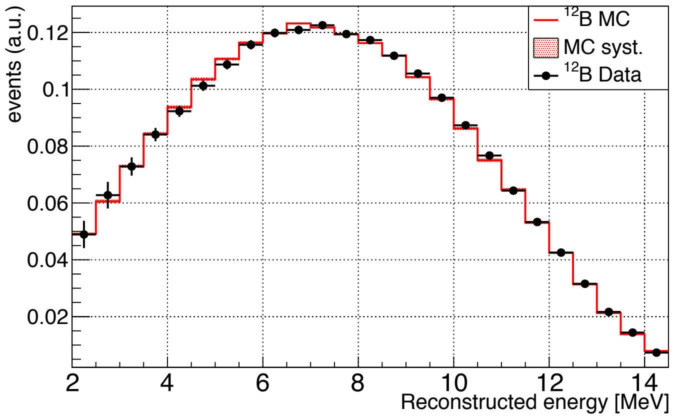
- **6 identical Target cells**, filled with Gd-loaded liquid scintillator (GdLS).
- Heavy passive shielding (Pb, PE, **B_4C**) + active **water Cherenkov muon veto**.
- **Pulse Shape Discrimination** (PSD).

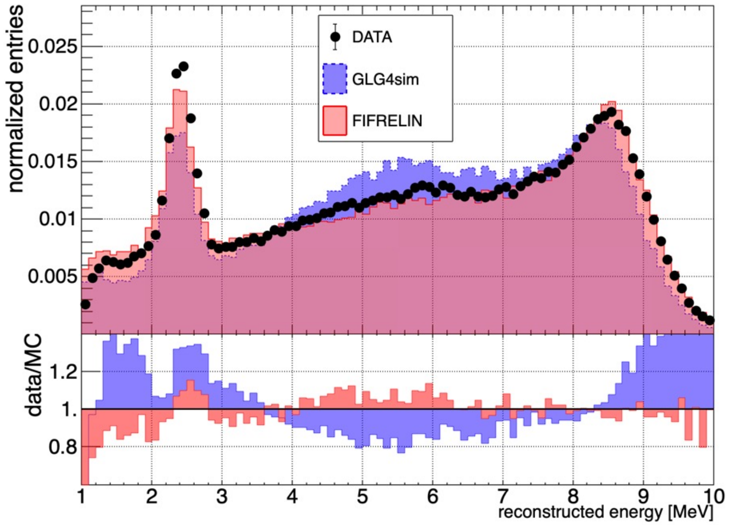
3 years of STEREO Data taking



$< S:B > \sim 1 \leftrightarrow$ 274 days-ON and 520 days-OFF for background subtraction.







Detector calibration and response

Energy scale derived from a **global fit of** :

- ❑ Calibration data taken with point-like radioactive sources in each cell, at different heights.
- ❑ Cosmogenic ^{12}B beta spectrum ($Q_\beta = 13.4$ MeV).

Data-MC residuals contained within a ±1% band for all cells.

Phys. Rev. D, 102:052002, 2020

Improvement of the MC gamma cascade after a n-capture in Gd with the FIFRELIN code.

Cf. Achment Chalil's talk this afternoon

Sterile neutrino search

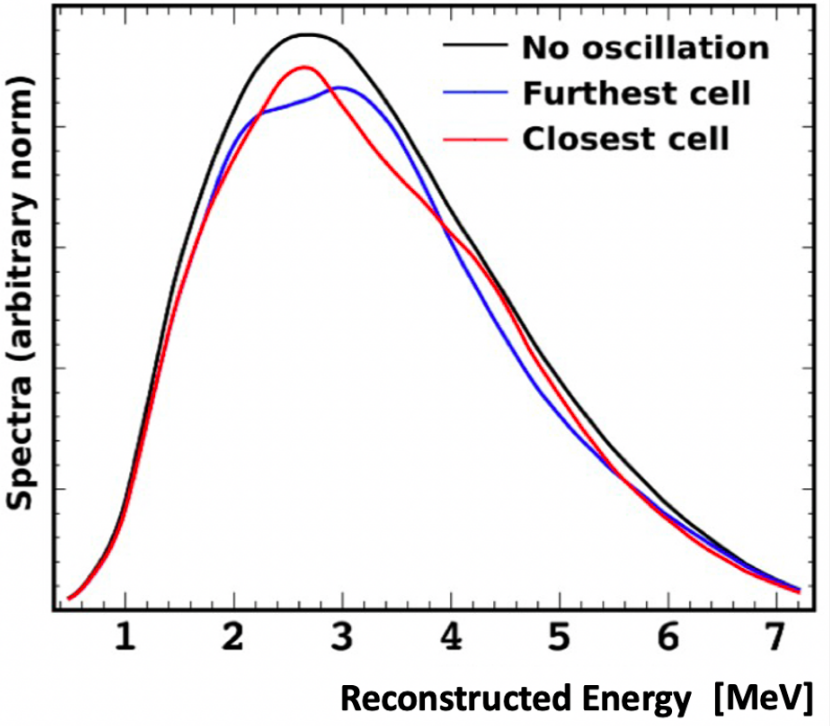
STEREO oscillation analysis

$$\chi^2(\phi, \vec{\alpha}, \sin^2(2\theta_{ee}), \Delta m^2_{41}) =$$

$$\sum_{p}^{N_{phases}} \sum_{c}^{N_{cells}} \sum_{i}^{N_{Ebins}} \left(\frac{Data_{p,c,i} - \phi_i Model_{p,c,i}(\sin^2(2\theta_{ee}), \Delta m^2_{41}, \vec{\alpha})}{\sigma_{c,i}} \right)^2 + pull\ terms$$

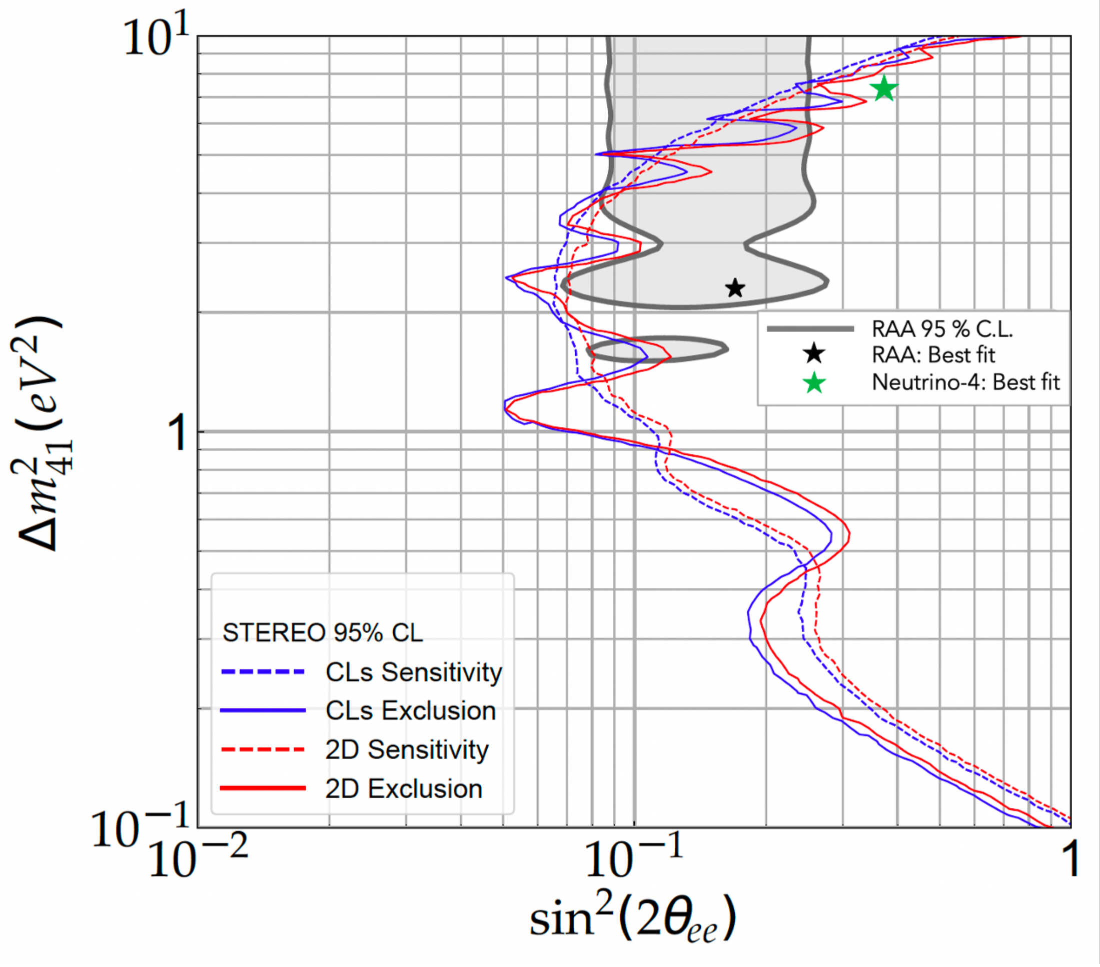
Non-oscillated model, common to all cells, let free in the fit

Prediction-free analysis



STEREO oscillation analysis

- Non-standard $\Delta\chi^2$ distributions from MC pseudo-experiments.
- 2D Feldman-Cousins and CLs approaches yield compatible results.
- No-oscillation hypothesis not rejected (p-value = 0.52).
- RAA best fit point excluded at about 4σ level / Neutrino-4 best fit point excluded at about 3.3σ level.



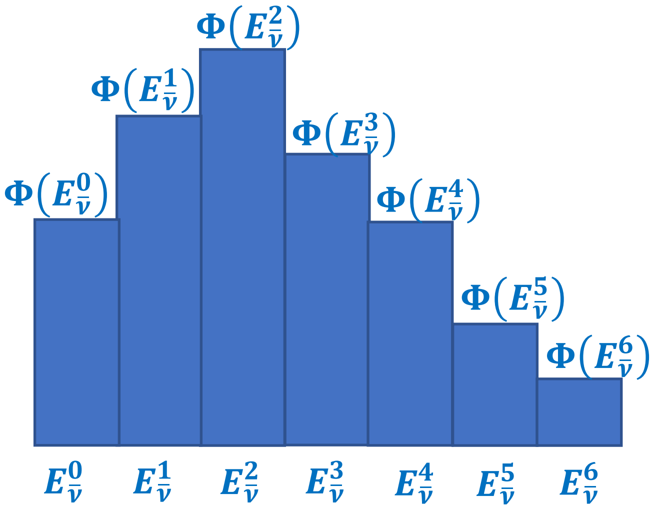
Sterile neutrino hypothesis disfavored with high confidence level.

arXiv:2210.07664

Reference ^{235}*U* $\bar{\nu}_e$ *spectrum*

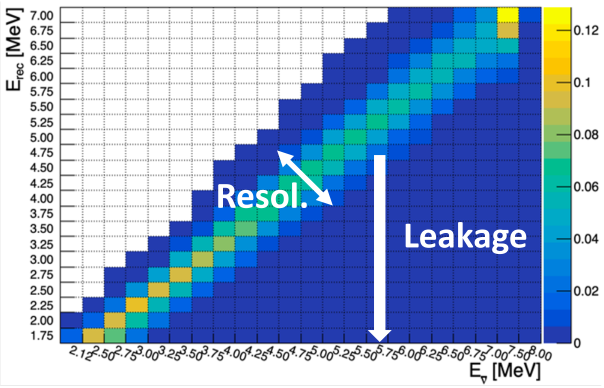
STEREO ^{235}U spectrum – Unfolding procedure

True neutrino energy

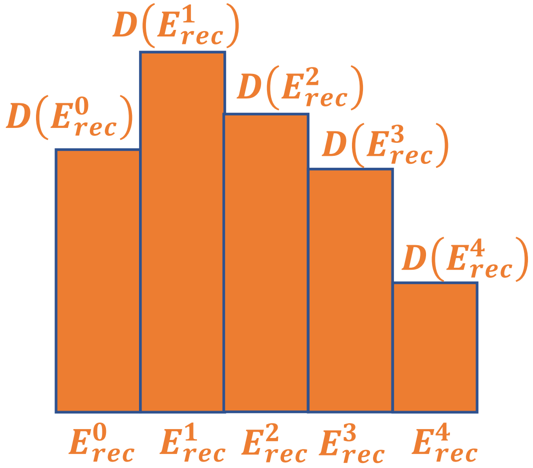


$$\boldsymbol{\Phi} = \begin{pmatrix} \Phi(E_{\bar{\nu}}^0) \\ \Phi(E_{\bar{\nu}}^1) \\ \Phi(E_{\bar{\nu}}^2) \\ \Phi(E_{\bar{\nu}}^3) \\ \Phi(E_{\bar{\nu}}^4) \\ \Phi(E_{\bar{\nu}}^5) \\ \Phi(E_{\bar{\nu}}^6) \end{pmatrix}$$

Apply the Response Matrix *R*



Energy reconstructed in the detector



$$\boldsymbol{D} = \begin{pmatrix} D(E_{rec}^0) \\ D(E_{rec}^1) \\ D(E_{rec}^2) \\ D(E_{rec}^3) \\ D(E_{rec}^4) \end{pmatrix}$$

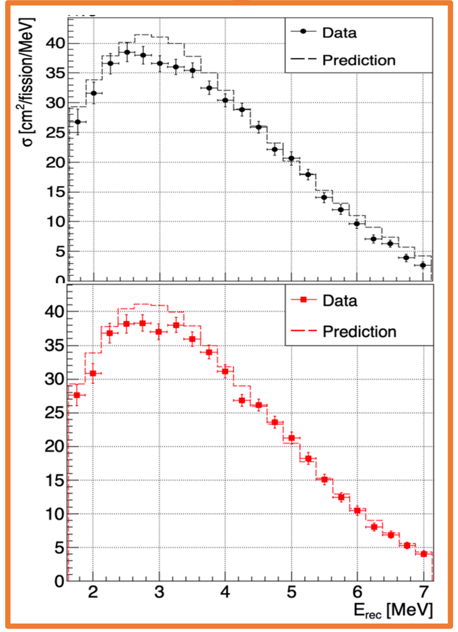
$$||X||_M^2 := X^T M X$$

STEREO ^{235}U spectrum – Unfolding procedure

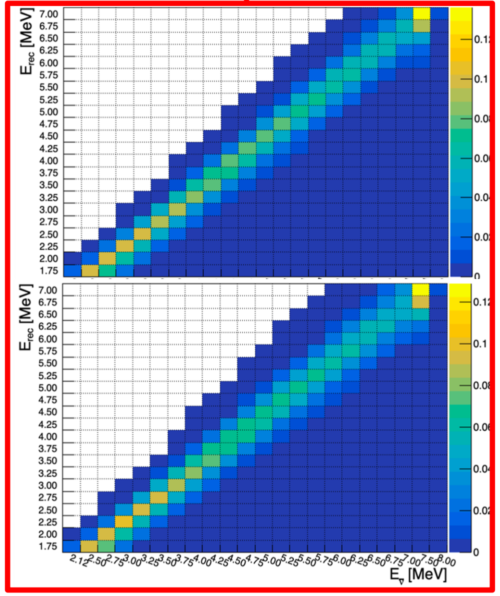
Goal: **Provide a reference ^{235}U antineutrino spectrum in antineutrino energy space, free of detector effects.**

- **Classical approach** (χ^2 minimization):

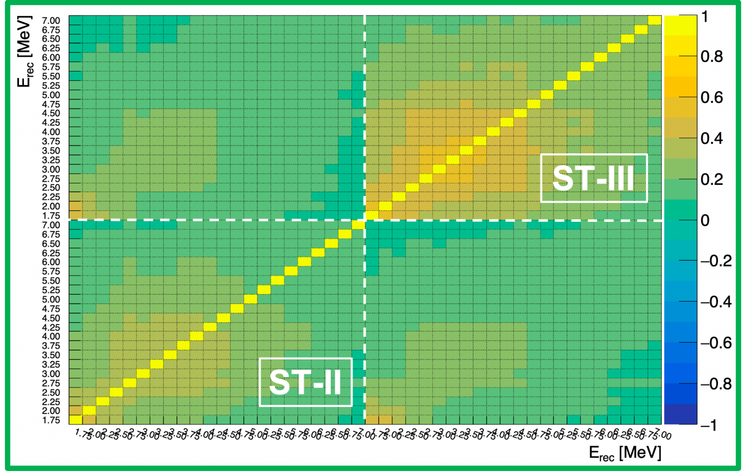
$$\chi^2(\Phi) = \left\| \begin{bmatrix} D_{II} \\ D_{III} \end{bmatrix} - \begin{bmatrix} R_{II} \\ R_{III} \end{bmatrix} \cdot \Phi \right\|^2_{V^{-1}_{II+III}}$$



Data Spectra



Response matrix



Experimental Covariance matrix

$$||X||_M^2 := X^T M X$$

STEREO ^{235}U spectrum – Unfolding procedure

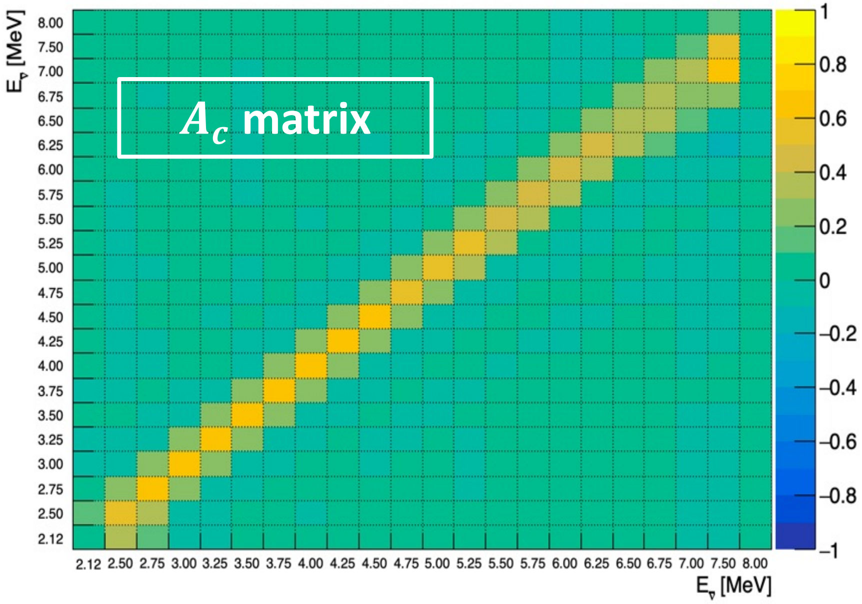
***Goal*: Provide a reference ^{235}U antineutrino spectrum in antineutrino energy space, free of detector effects.**

- **Tikhonov-like approach** (minimization of a regularized χ^2):

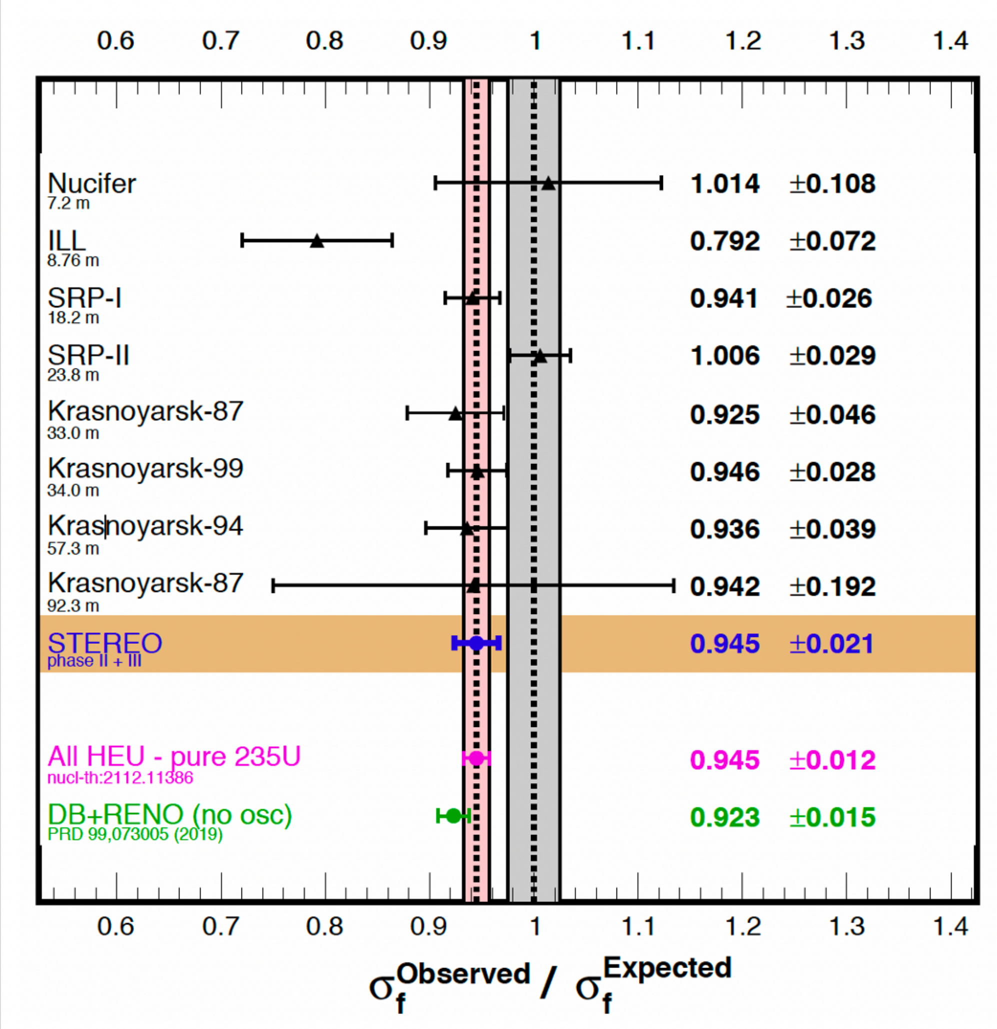
$$\chi^2(\Phi) = \left\|\begin{bmatrix} D_{II} \\ D_{III} \end{bmatrix} - \begin{bmatrix} R_{II} \\ R_{III} \end{bmatrix} \cdot \Phi \right\|^2_{V^{-1}_{II+III}} + \boldsymbol{\lambda} * ||\Phi||^2_{\boldsymbol{M_{HM}}}$$

Regularization term

- $\sum_i \left(\frac{\Phi_{i+1}}{\Phi_{i+1}^{HM}} - \frac{\Phi_i}{\Phi_i^{HM}}\right)^2$: penalty term on the bin-to-bin fluctuations, with Φ^{HM} a **prior shape (Huber ^{235}U spectrum)**.
- λ tuned with Generalized Cross-Validation criterion – *Technometrics Vol. 21 N°2, May 1979*
- Inherent smoothing effects encoded in the ``filter matrix'' A_c of the regularized unfolding – *JINST 12, P10002 (2017)*



STEREO ^{235}U unfolded spectrum – Rate analysis

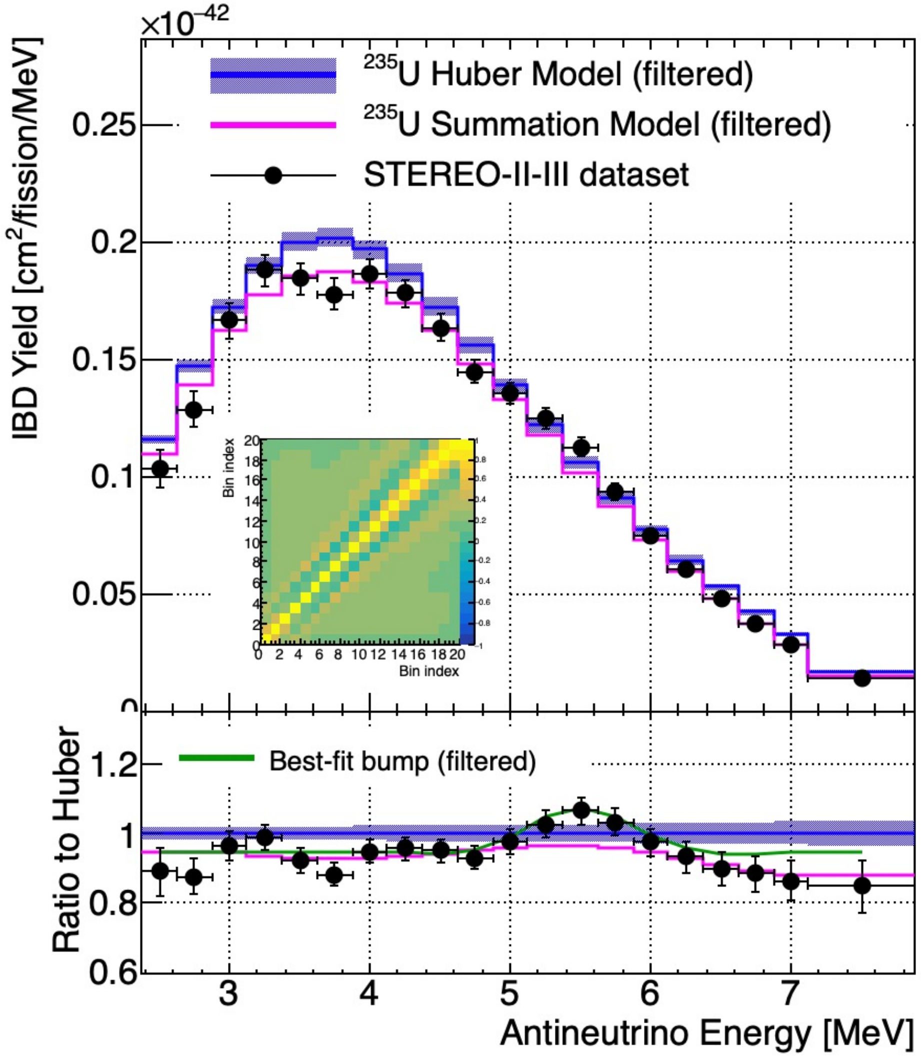


- **Global deficit** wrt. Huber prediction for ^{235}U:

$$(5.5 \pm 2.1\ [\text{stat} + \text{syst}])\%$$

- Update of the result in *Phys.Rev. Lett., 125:201801 (2020)*.
- **Most accurate measurement** of ^{235}U fission yield.
- In agreement with world average.

STEREO ^{235}U unfolded spectrum – Bump analysis



arXiv:2210.07664

$$Pred_{A,\mu,\sigma}(E) = HM(E) \cdot \alpha \left(1 + A \cdot \exp \frac{(E-\mu)^2}{2\sigma^2}\right)$$

- Minimize:

$$\chi^2(A,\mu,\sigma) = \left(\Phi - A_c \cdot Pred_{A,\mu,\sigma}\right)^T V_\Phi^{-1} \left(\Phi - A_c \cdot Pred_{A,\mu,\sigma}\right)$$

- **Local event excess** wrt. Huber around 5.5 MeV for ^{235}U with **4.6 σ** significance.

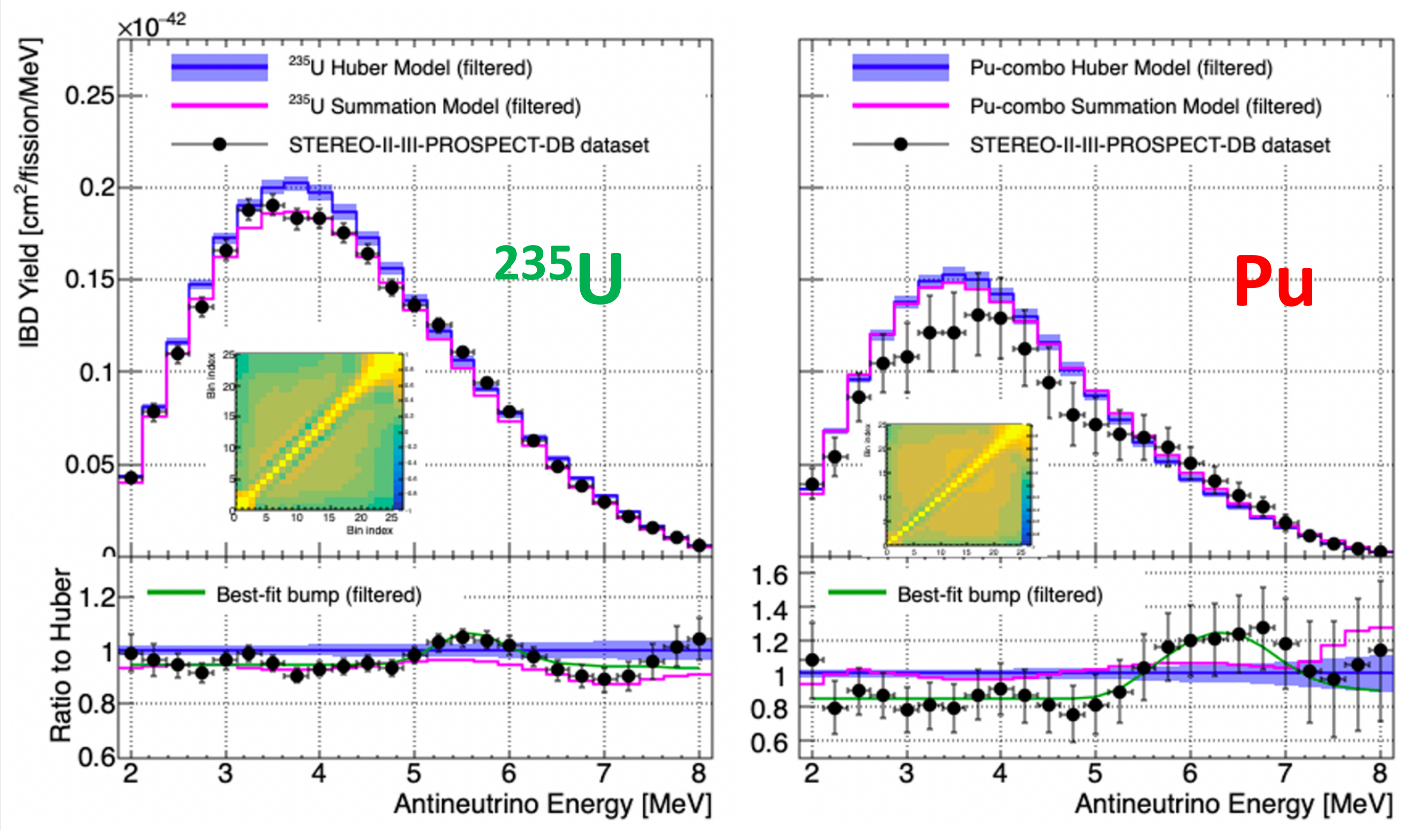
$$A = (15.6 \pm 5.2)\ \%$$
$$\mu = (5.500 \pm 0.092)\ \text{MeV}$$
$$\sigma = (0.308 \pm 0.143)\ \text{MeV}$$

Global Analysis

HEU + LEU Global shape analysis

- Update of joint STEREO-PROSPECT HEU analysis for ^{235}U (*Phys. Rev. Lett., 128:081802, 2022*)

- Extension of the formalism to LEU data, with global Daya Bay spectrum for ^{235}U + Pu (*Chin. Phys. C, 45:073001, 2021*)



- **Simultaneous unfolding of all spectra.**
- **Minimal sensitivity to reactor simulations.**

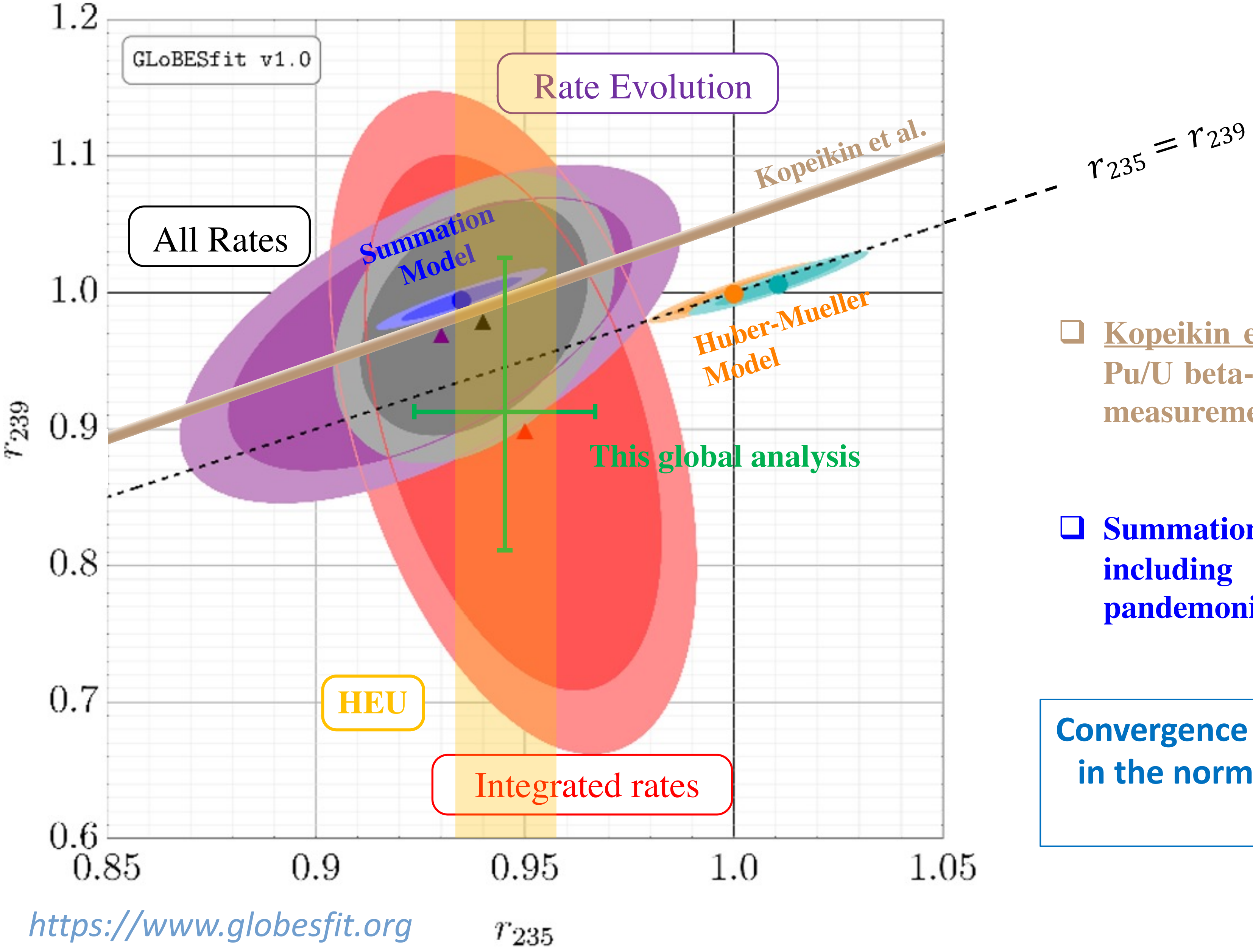
HEU+LEU ^{235}U Best-fit bump parameters (4.7σ):

$$A = (14.4 \pm 3.4)\%$$
$$\mu = (5.593 \pm 0.092)MeV$$
$$\sigma = (0.330 \pm 0.097)MeV$$

HEU+LEU Pu combo Best-fit bump parameters (2.3σ):

$$A = (50.4 \pm 15.2)\%$$
$$\mu = (6.325 \pm 0.268)MeV$$
$$\sigma = (0.531 \pm 0.244)MeV$$

HEU + LEU Global rate analysis (HEU = ST)



https://www.globesfit.org

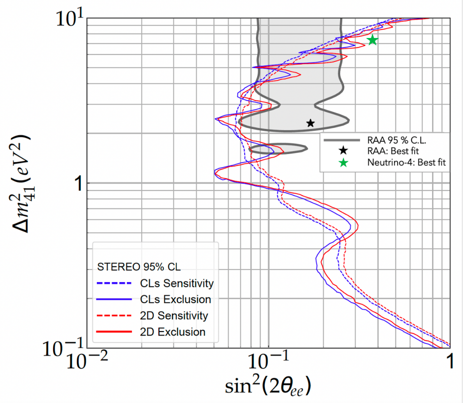
- Kopeikin et al. : new measurement of the ratio of Pu/U beta-spectra → 5% deviation w.r.t. the initial measurement at ILL.
- **Summation Model (Estienne et al.): calculations including the latest TAGS data, correcting the pandemonium effect for relevant nuclei**

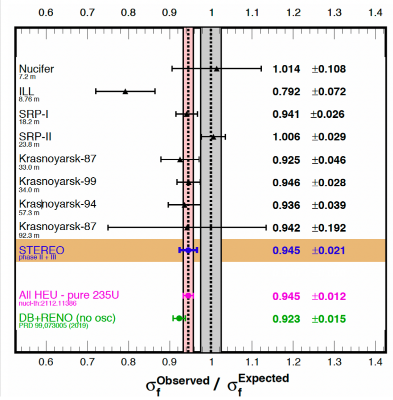
Convergence of experimental hints pointing to a bias in the normalization of predicted ^{235}U as the main explanation of the RAA.

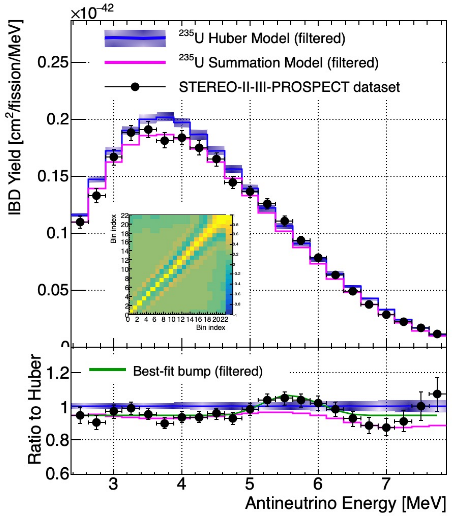
Conclusions

Most accurate measurement of the ^{235}U spectrum to date, providing a **complete study of the reactor anomalies**:

- **Sterile neutrino hypothesis disfavored**.
- (5.5 ± 2.1)% rate deficit observed in ^{235}U pointing to a **biased prediction normalization** as the main origin of the RAA.
- **4.6σ local distortion** around 5.5 MeV.
- Unbiased unfolding procedure, extended to a global analysis including HEU and LEU data with minimal inputs from reactor simulation.





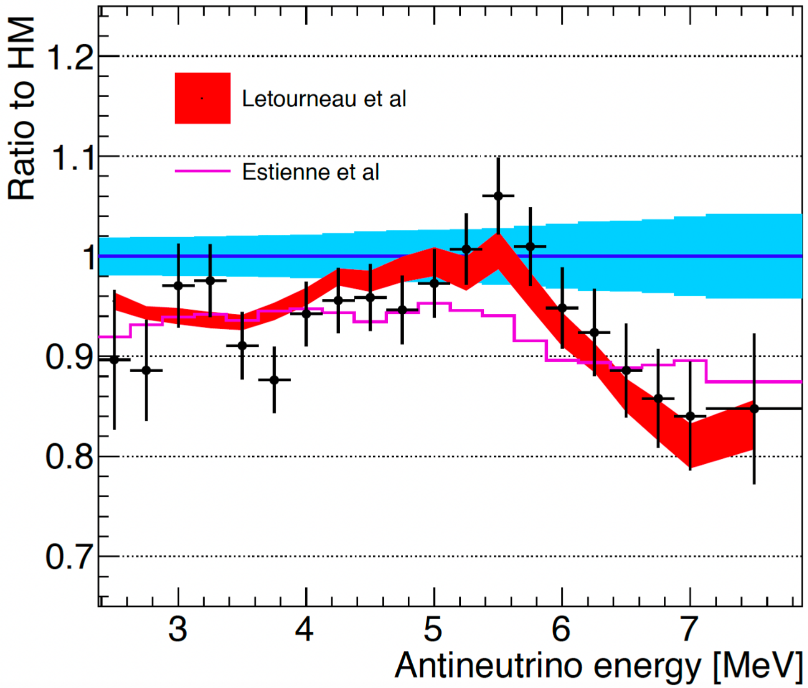


Outlook

Precise reference antineutrino spectrum from the fission of ^{235}U:

- ❑ Spectrum expressed in true antineutrino energy available for the upcoming high precision reactor antineutrino experiments.

- ❑ ***Shift of paradigm***: precision of the direct neutrino measurements constrains the nuclear observables. Latest summation model calculations showed the critical impact of the correction of the pandemonium effect.

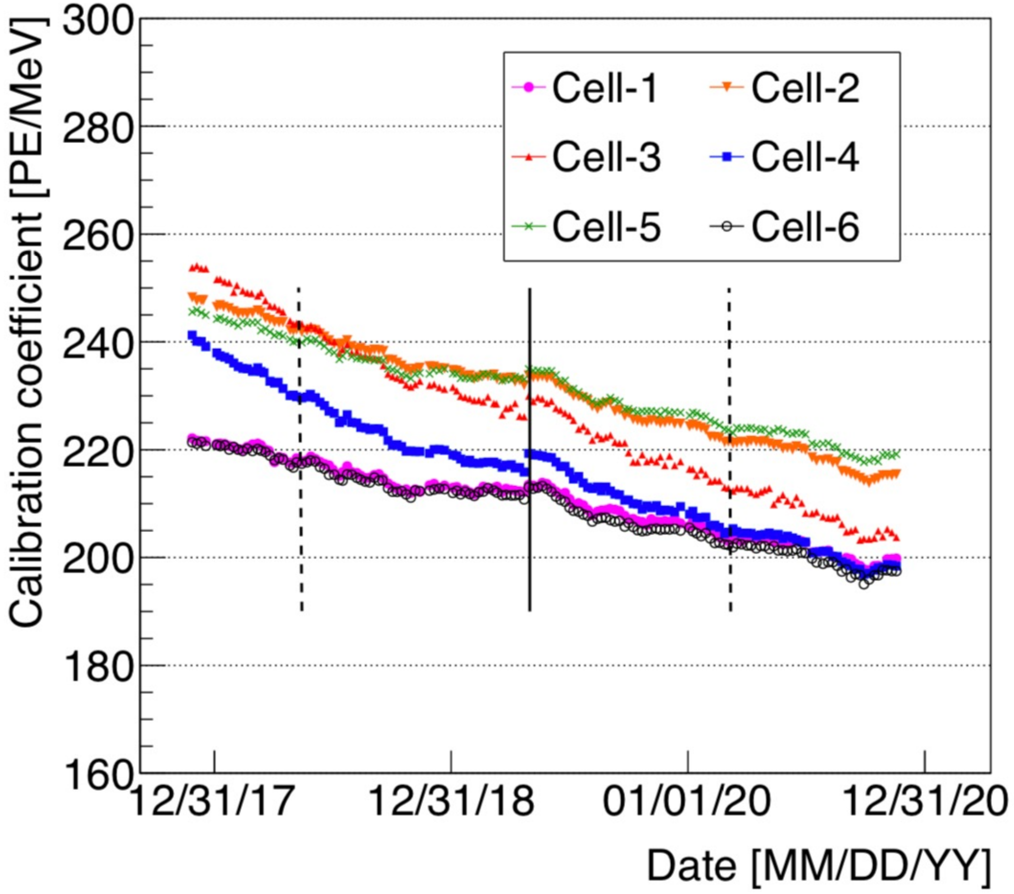


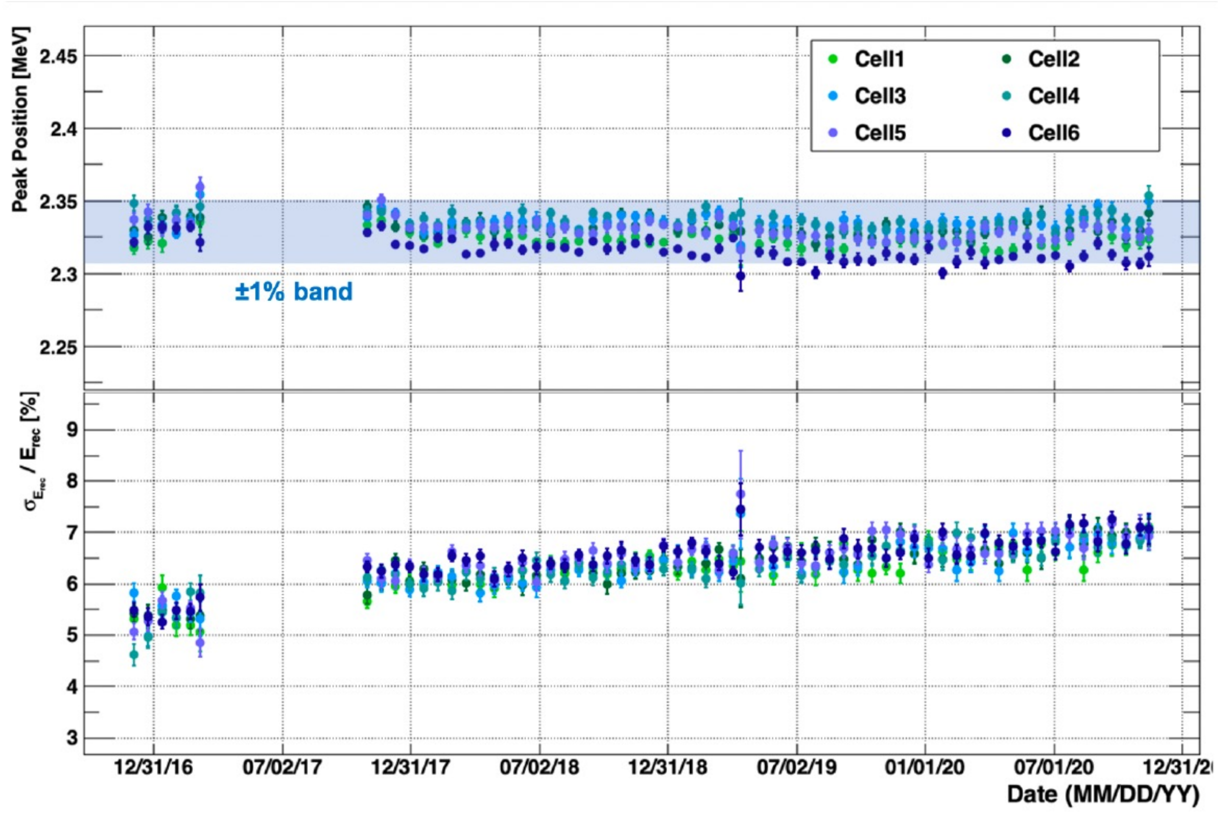
arXiv.2205.14954

Thank you for your attention !

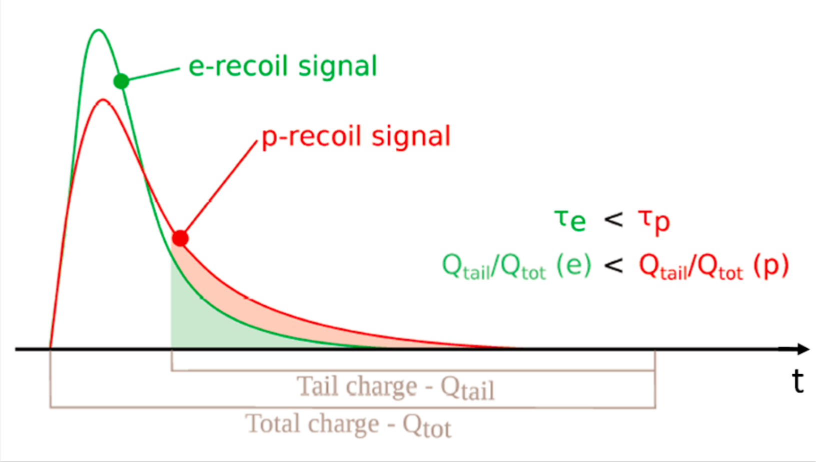
Back-up

STEREO Detector Response

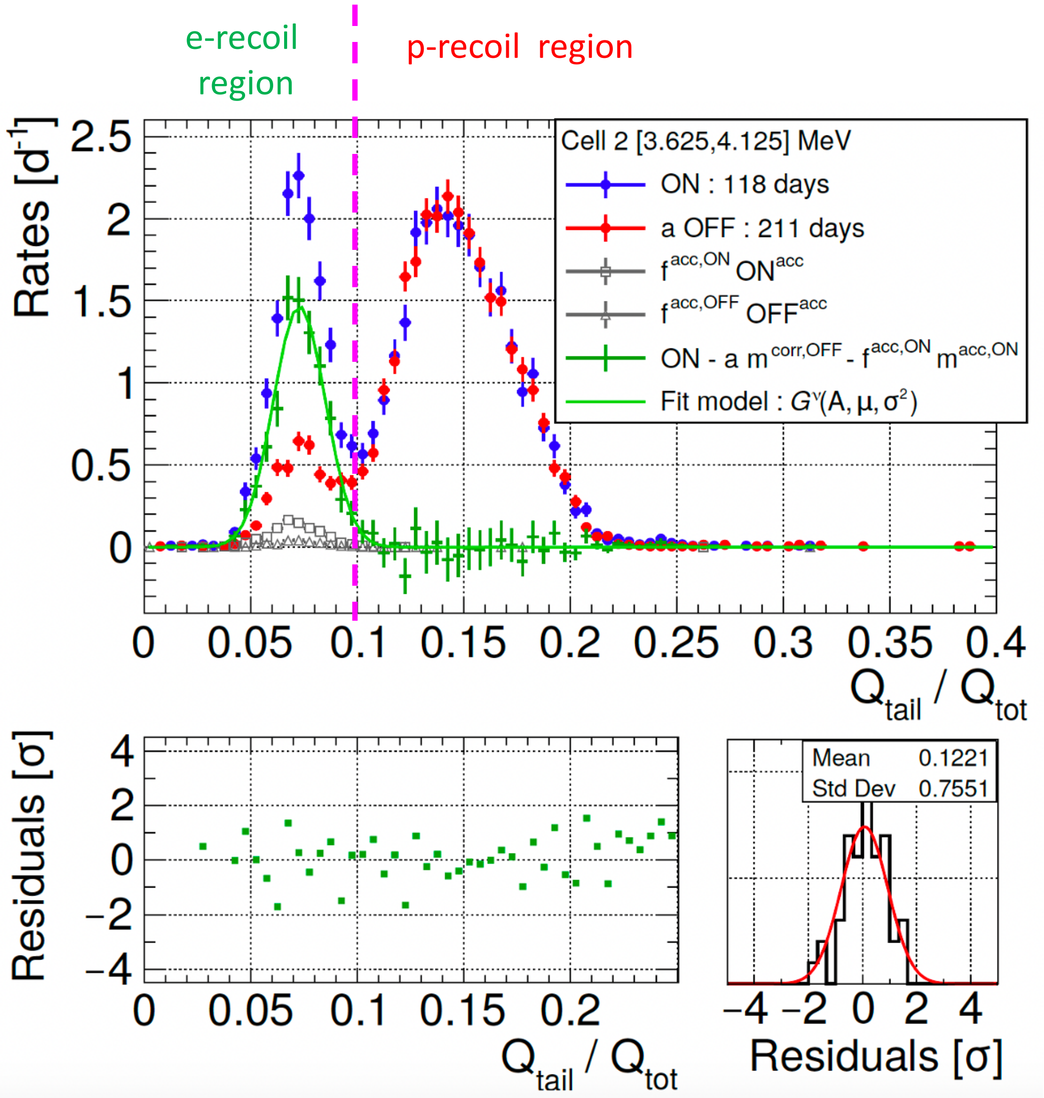




Antineutrino signal extraction

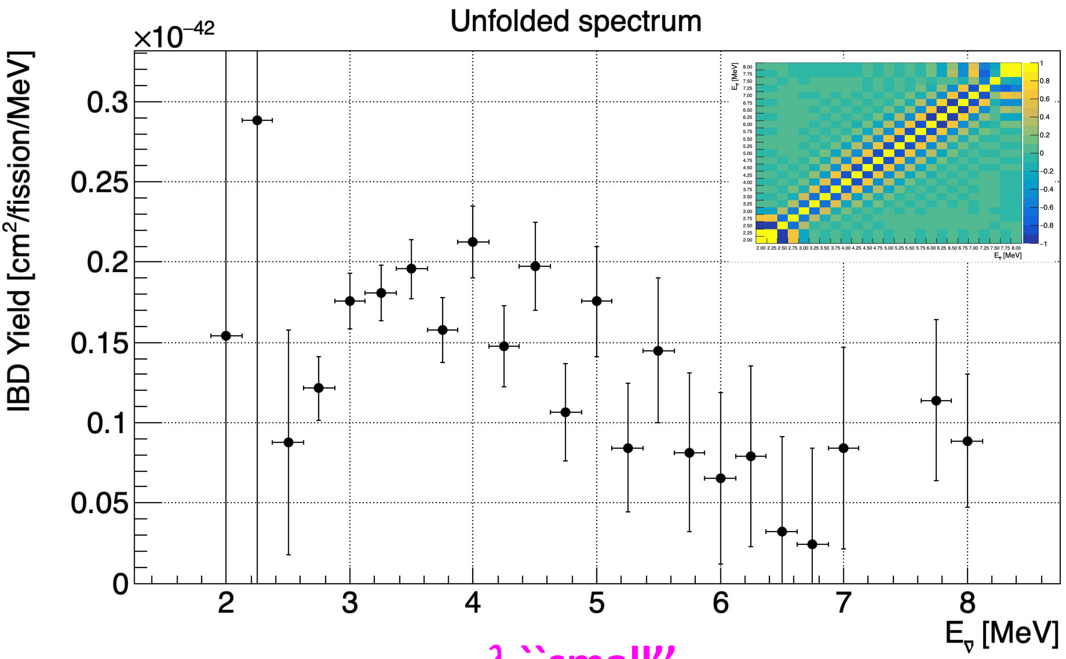


Pulse Shape Discrimination (PSD)

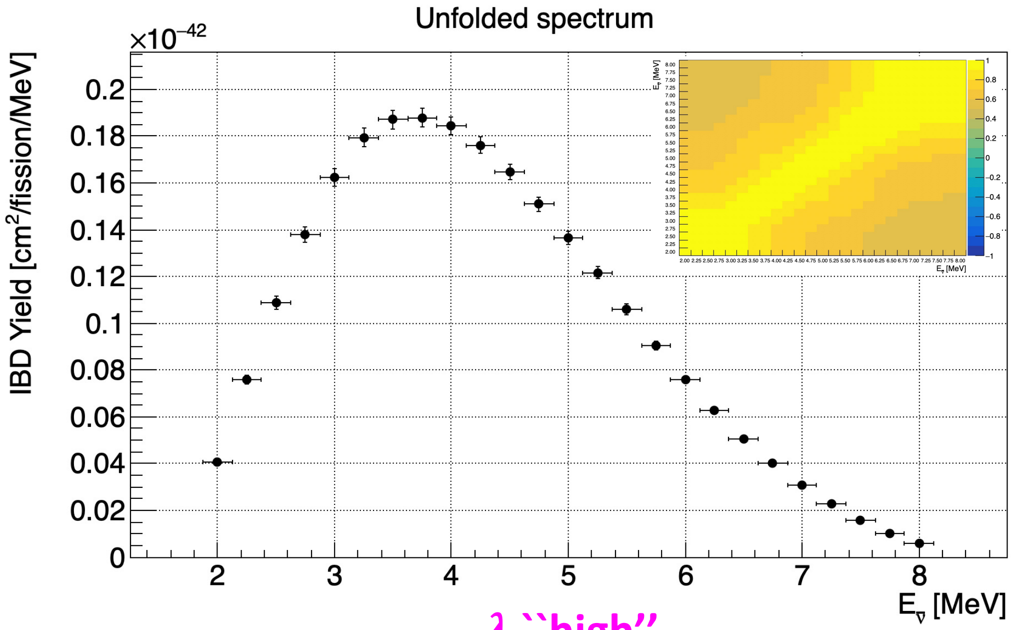


- PSD spectrum of **reactor-ON** and **reactor-OFF** data.
- **Proven to be very stable in shape** and anti-correlation of rate with P_{atm} accounted for by a free normalization parameter a.
- Gaussian fit to extract the **neutrino signal** in the e-recoil region.

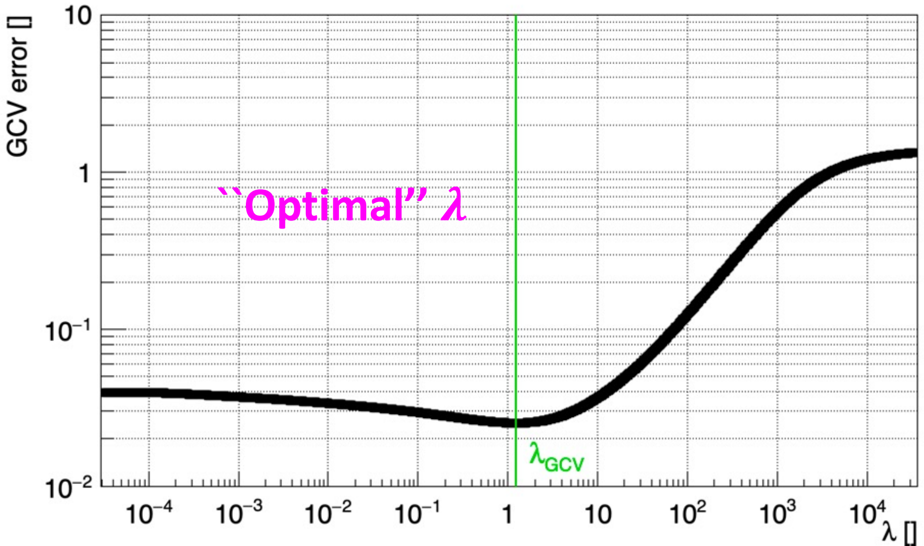
Impact of regularization



λ ``small''

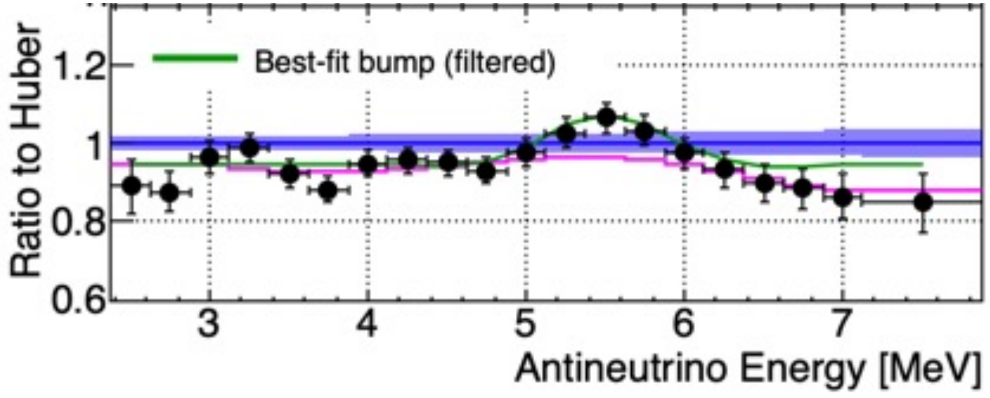


λ ``high''



- **Minimization of the Generalized Cross-Validation (GCV) error.** *Technometrics Vol. 21 N°2, May 1979*

STEREO shape analysis



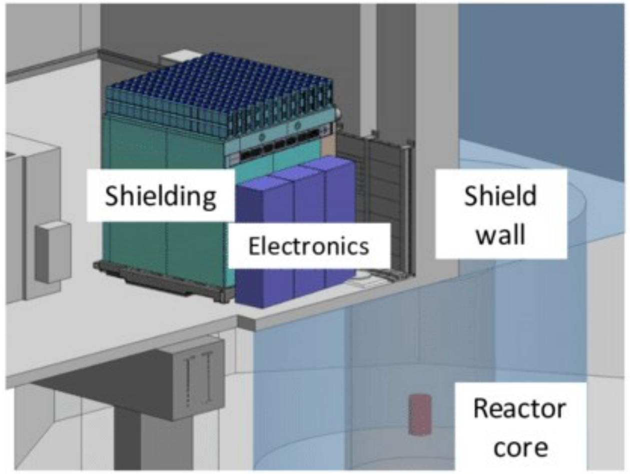
$$Pred(E) = HM(E) \cdot \alpha \left(1 + A \cdot \exp \frac{(E-\mu)^2}{2\sigma^2}\right)$$

ST-II-III Best-fit bump	Antineutrino Energy space		Reconstructed Energy space
	w/o. Filter $\chi^2 = (\Phi - Pred)^T V_\Phi^{-1} (\Phi - Pred)$	**w. Filter** $\chi^2 = (\Phi - A_c \cdot Pred)^T V_\Phi^{-1} (\Phi - A_c \cdot Pred)$	**w. Response** $\chi^2 = (D - R \cdot Pred)^T V^{-1} (D - R \cdot Pred)$
A [%]	14.4 ± 3.6	$\mathbf{15.6 \pm 5.2}$	15.5 ± 5.1
μ [MeV]	5.505 ± 0.089	$\mathbf{5.500 \pm 0.092}$	5.500 ± 0.092
σ [MeV]	0.339 ± 0.112	$\mathbf{0.308 \pm 0.143}$	0.311 ± 0.143
Significance	4.6σ	$\mathbf{4.6\sigma}$	4.6σ

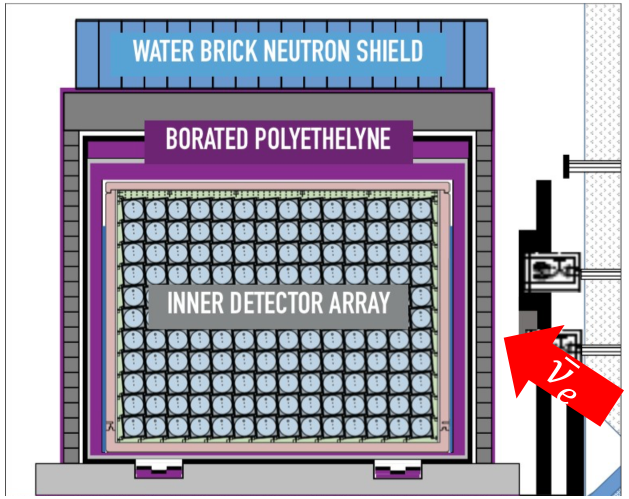
$$(\mathbf{\Phi}, \mathbf{V_\Phi}, \mathbf{A_c}) \leftrightarrow (\boldsymbol{D}, \boldsymbol{V}, \boldsymbol{R})$$

HEU + LEU Global analysis

HEU experiment: PROSPECT



HFIR Experimental site (Oak Ridge, USA)



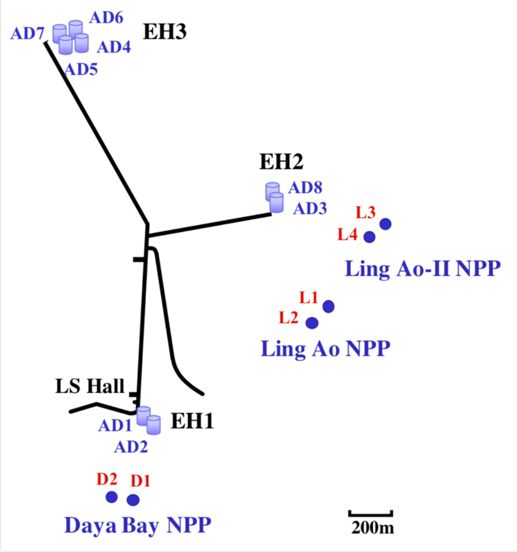
PROSPECT Detector

^{235}U

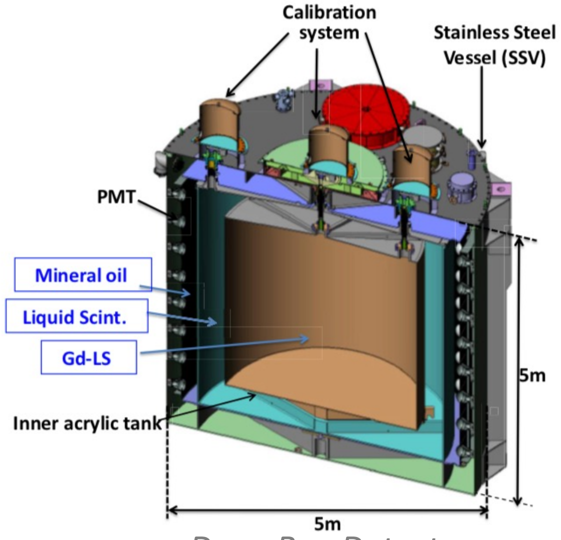
50k $\overline{\nu}_e$

LEU experiment: Daya Bay

^{235}U + Pu + (^{238}U)



Day Bay nuclear power complex (Shenzhen, China)

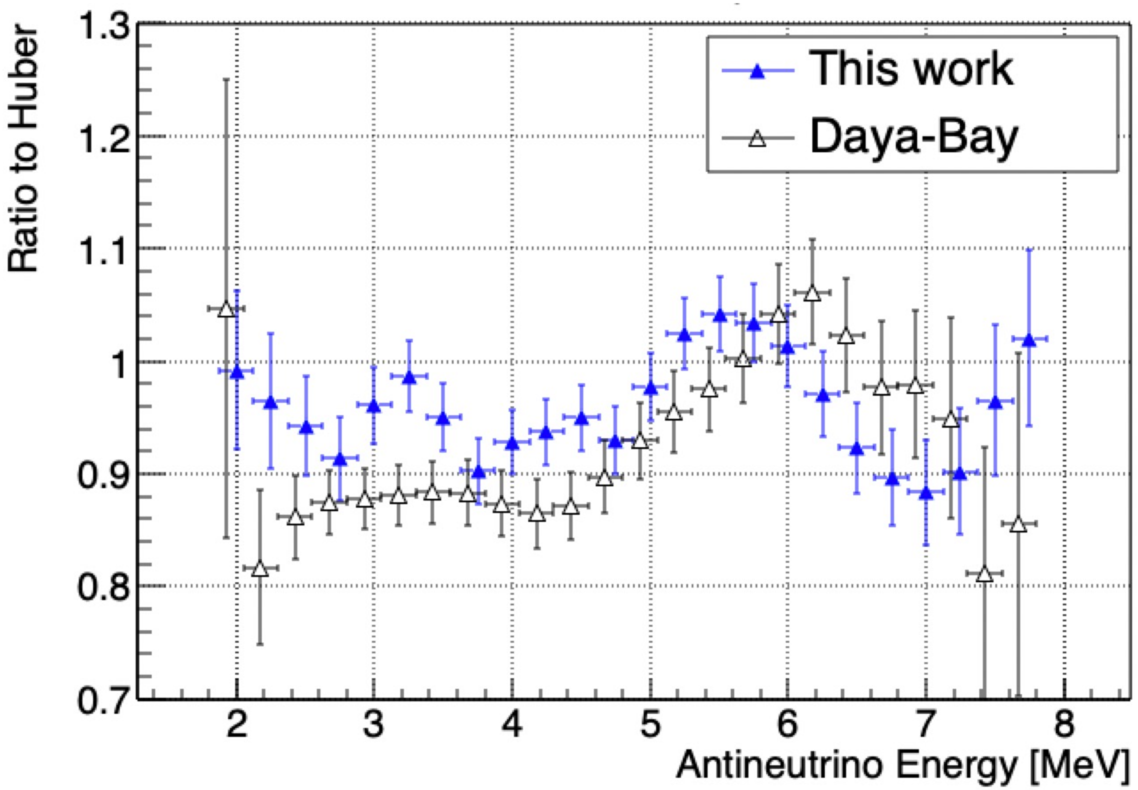


Daya Bay Detector

3500k $\overline{\nu}_e$

Tikhonov (ST-PR-DB) vs DB

^{235}U comparison



Pu Combo comparison