Results of the STEREO experiment

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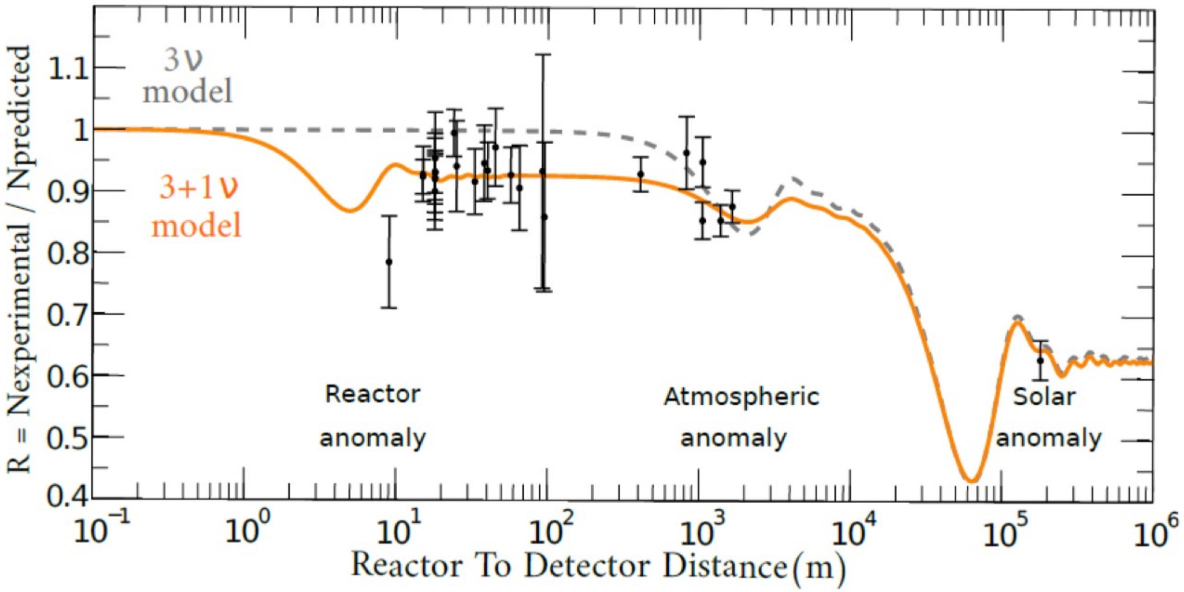
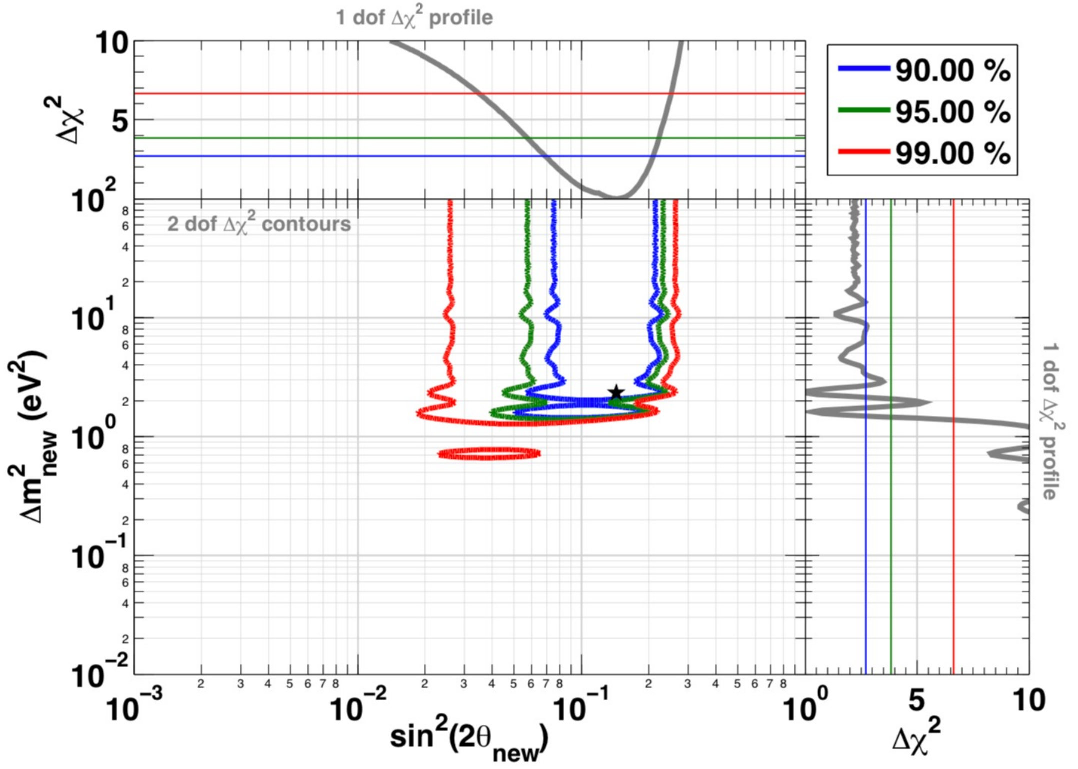
on behalf of the STEREO collaboration

Motivation – Flux anomaly

Improved reactor antineutrino spectrum predictions – *PRC 83:054615 (2011)*

Observed ~**6.5% deficit** in measured fluxes at short-baseline, so-called **Reactor Antineutrino Anomaly (RAA)** – *PRD 83:073006 (2011)*





★: RAA oscillation best fit

$\Delta m^2_{new} = 2.3\ \mathrm{eV}^2$ / $\sin{(2\theta_{new})}^2 = 0.14$

Signature of the oscillation to a sterile state ?

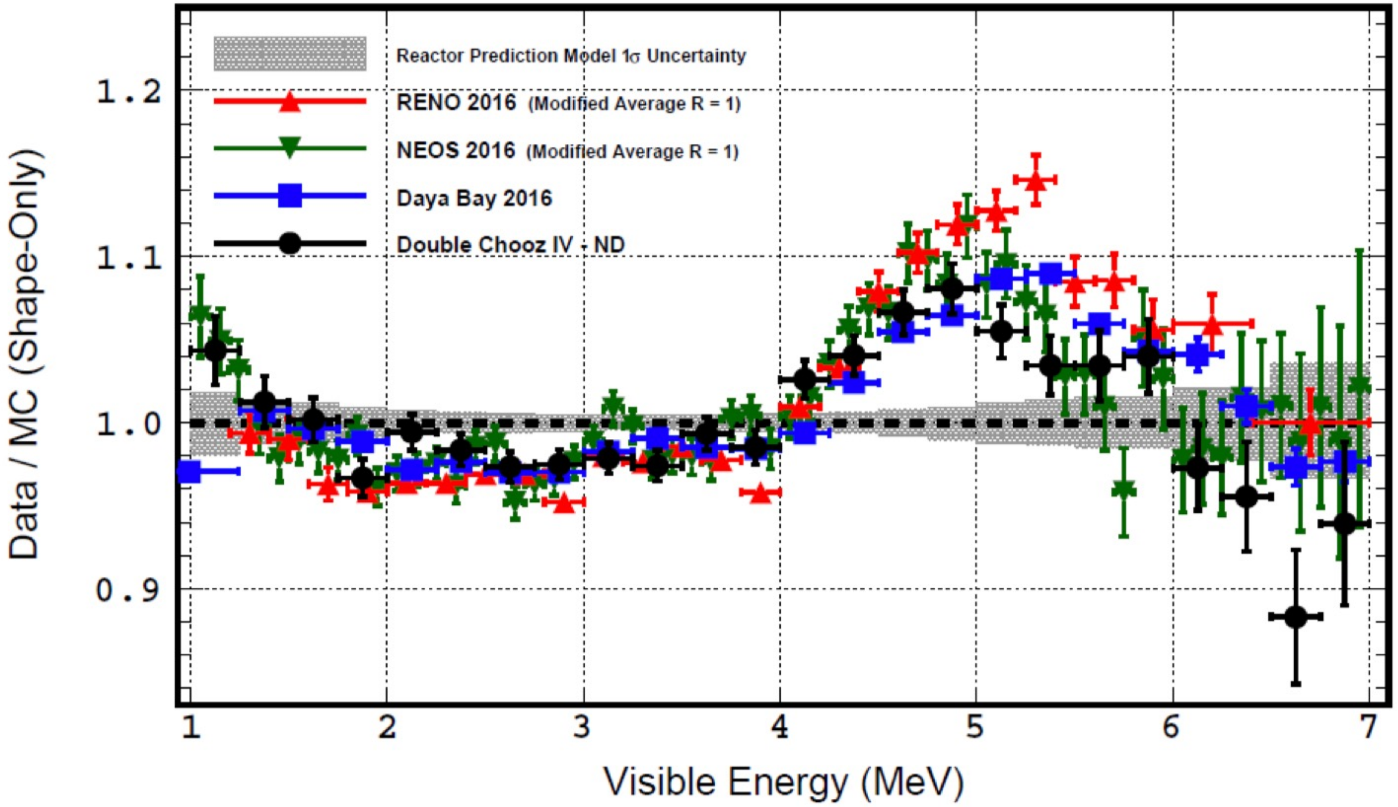
Motivation – Shape anomaly

$\sim 10\%$ local events excess observed by several lowly enriched in ^{235}U (LEU) experiments around 5 MeV wrt. Huber predicted shape.

Related to fuel composition ? Do U and Pu contribute to the same extent ?

→ Highly-enriched in ^{235}U (HEU) experiments such as STEREO shed a light on the contribution of the pure ^{235}U and are complementary to LEU experiments.

Nature Physics 16, 558-564 (2020)



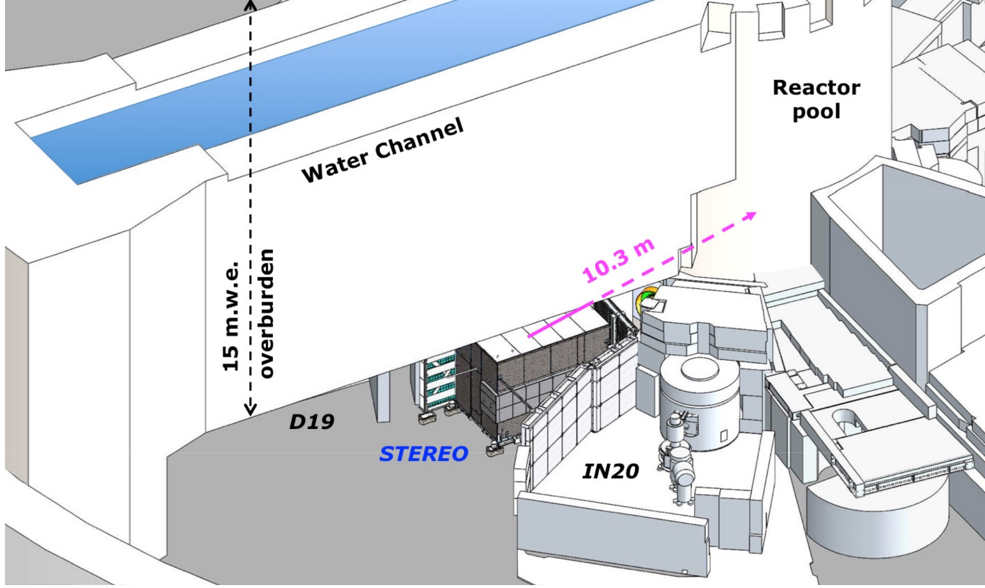
The STEREO experiment [JINST 13 (2019) 07, P07009]

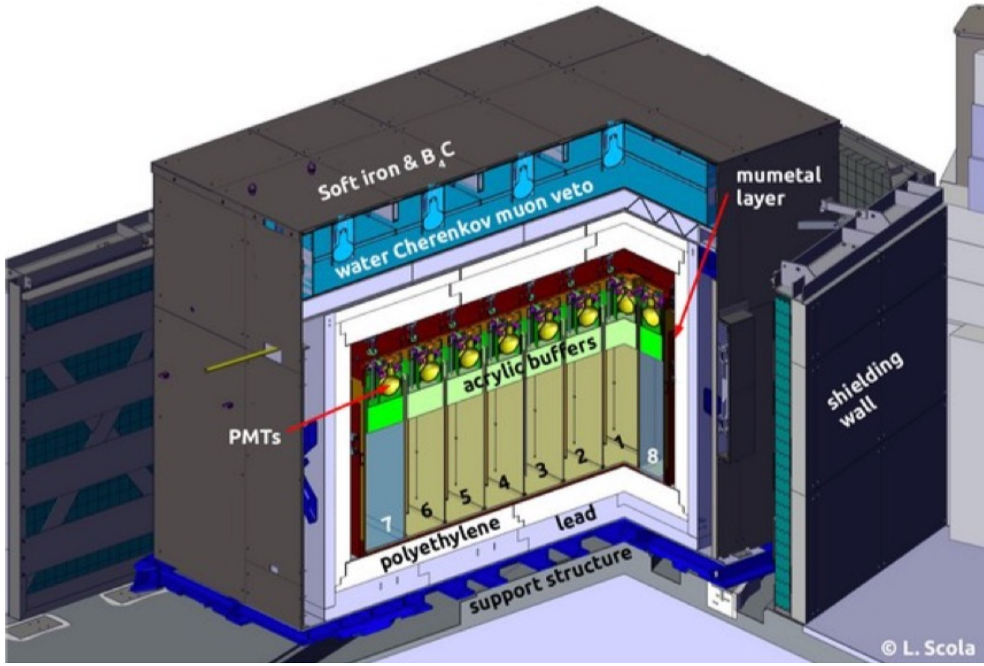
Experimental Site (ILL Grenoble, France):

- Ground-level experiment.
- Compact core (Ø 40cm x 80 cm) and short-baseline (~10m) experiment to probe the RAA.
- 58MW$_{th}$ nominal power / HEU fuel (93% ^{235}U)
  → *99% of $\bar{\nu}$ flux from ^{235}U fissions*.

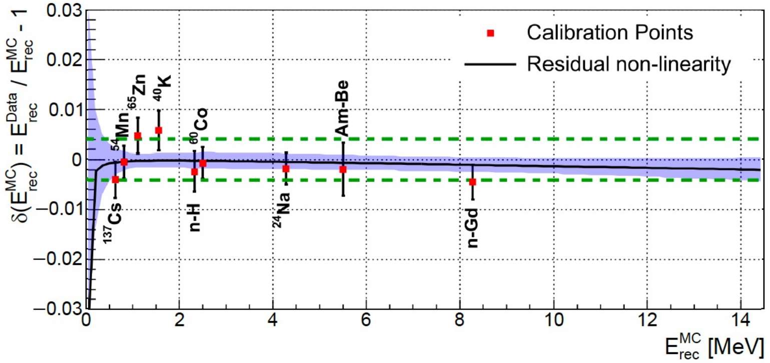
Detector Design:

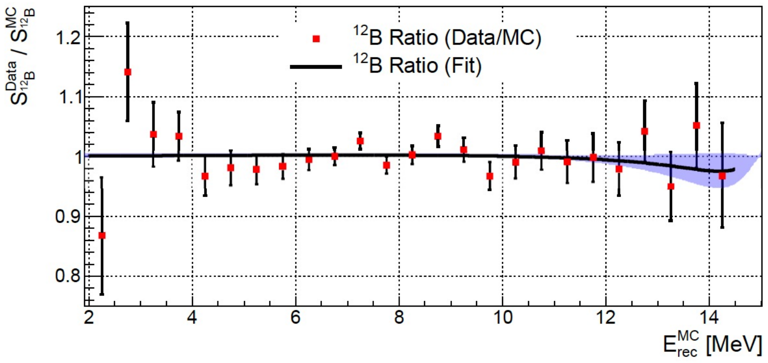
- Segmented design for oscillation analysis: 6 cells (target volume) surrounded by 4 gamma catchers.
- Pb, polyethylene, B_4C shielding + water Cherenkov muon veto + Pulse Shape Discrimination for background mitigation and rejection (achieved S:B of 0.8:1).

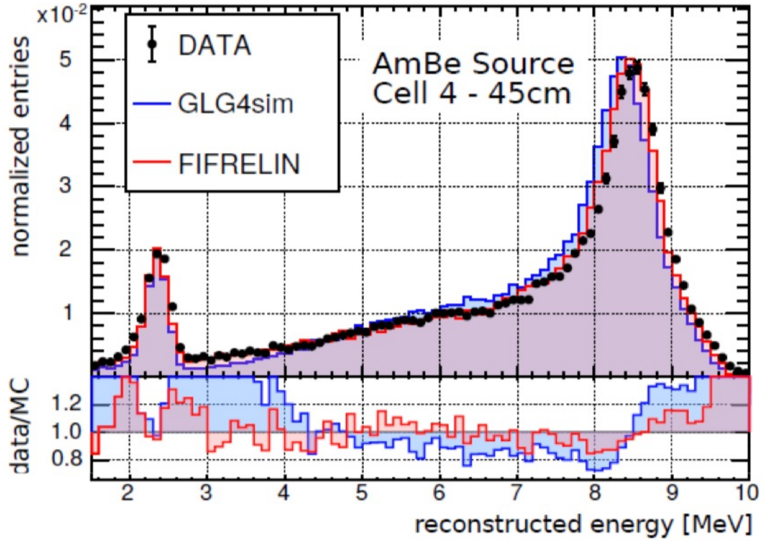




Detector calibration and response [PRD 102,052002 (2020)]







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.

Improvement of the MC gamma cascade after a n-capture in Gd with the FIFRELIN code.
Eur.Phys.J.A 55 (2019) 10, 183

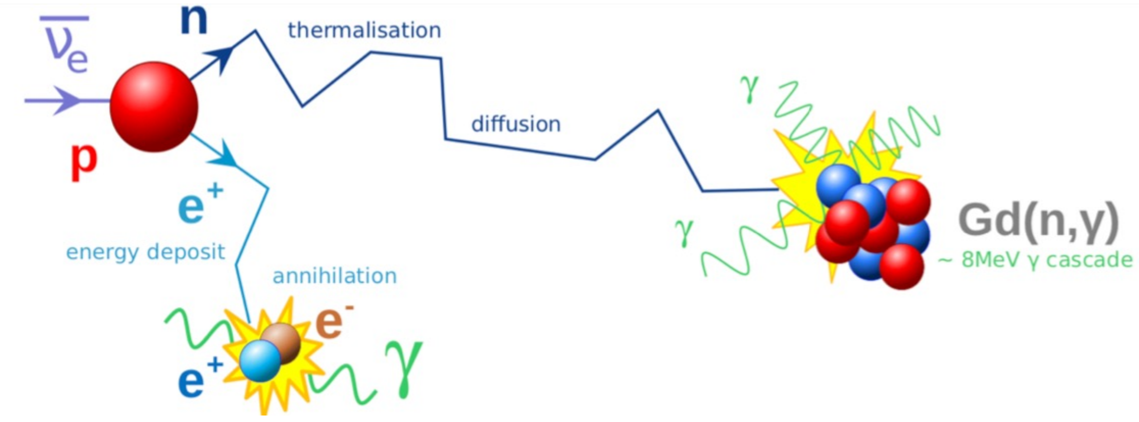
Neutrino detection principle

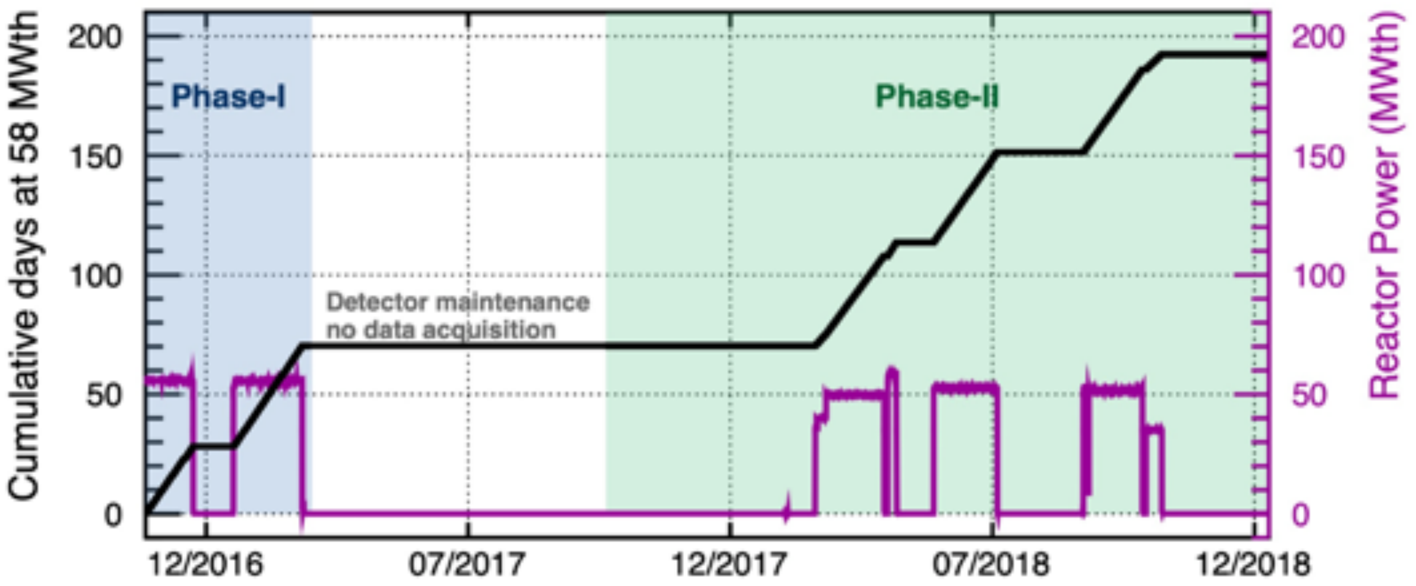
- **Inverse beta decay** (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$

  - **Prompt signal** (positron): $E_{e+} \approx E_{\bar{\nu}_e} - 0.782\text{MeV}$

  - **Delayed signal** (n-capture on Gd): $\sum_i E_{\gamma,i} \sim 8\text{MeV}$

- **Pulse shape discrimination to extract neutrino signal.**



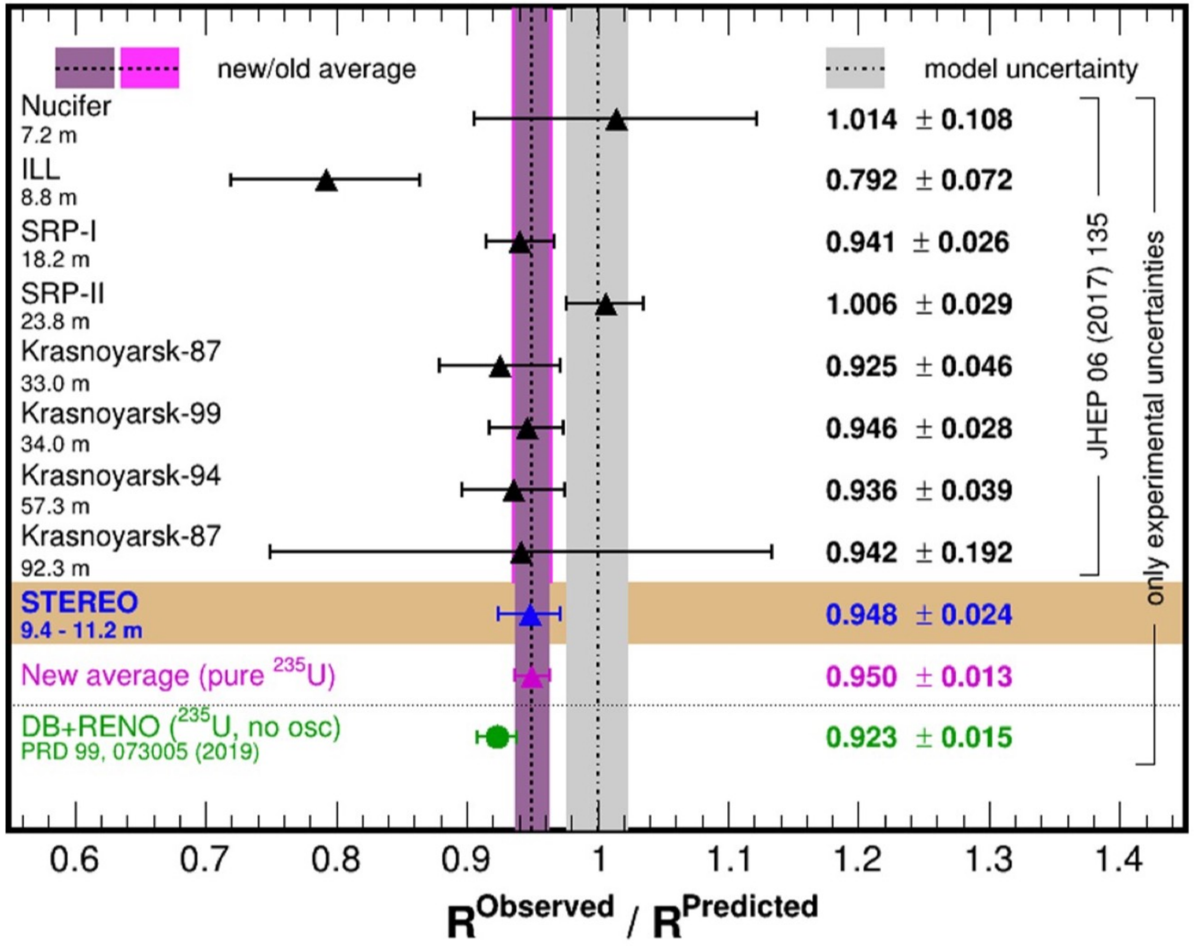


Data taking

- ***Oscillation analysis*** → Phase I+II: 179 days ON / 235 days OFF

- ***Absolute rate and shape analysis*** → Phase II: 119 days ON / 211 days OFF

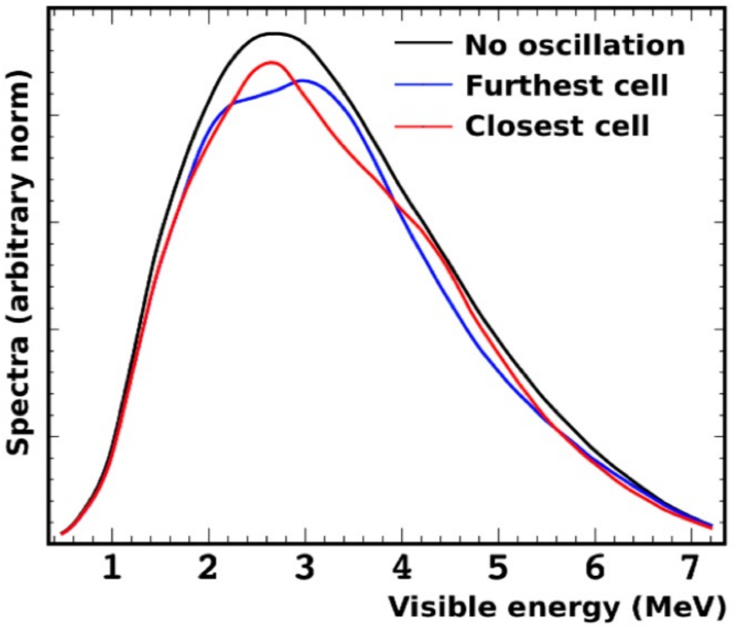
STEREO absolute $\bar{\nu}$ rate PRL 125,201801 (2020)



- Reported deficit wrt. Huber predicted neutrino rate:

$$0.948 \pm 0.008[\text{stat}] \pm 0.023[\text{syst}] \pm 0.023[\text{model}]$$

- **Most accurate measurement** of the **pure ^{235}U antineutrino flux**.
- In **agreement** with **world average**.



STEREO oscillation analysis – Principle

- **Shape-only and prediction-free analysis.**
- **Systematic uncertainties parametrized by nuisance parameters $\vec{\alpha}$.**

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

$$\sum_{l}^{N_{cells}} \sum_{i}^{N_{Ebins}} \left(\frac{D_{l,i} - \phi_i M_{l,i}(\sin(2\theta_{ee})^2, \Delta m_{41}^2, \sigma, \vec{\alpha})}{\sigma_{l,i}} \right)^2 + \sum_{l}^{N_{cells}} \left(\frac{\alpha_l^{NormU}}{\sigma_l^{NormU}} \right)^2 + \left(\frac{\alpha_l^{EscaleU}}{\sigma_l^{EscaleU}} \right)^2 + \left(\frac{\alpha_l^{EscaleC}}{\sigma_l^{EscaleC}} \right)^2$$

Measured spectrum in each cell.

Free-floating parameters, **common to every cell** (absorb model dependence).

Simulated spectrum

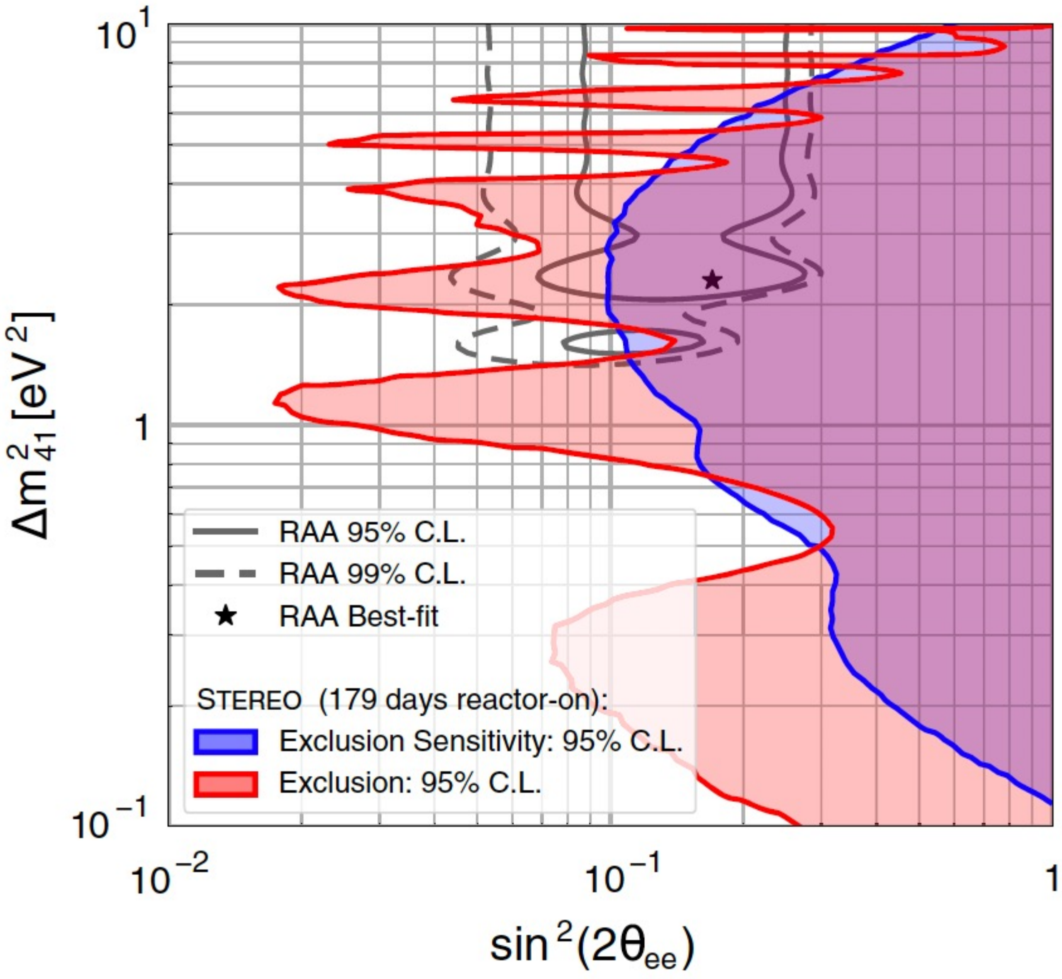
STEREO oscillation analysis – Results PRD 102,052002 (2020)

2D approach.

Non-standard $\Delta\chi^2$ distributions from MC pseudo-experiments.

No-oscillation hypothesis not rejected (p-value = 0.09).

Best-fit point of RAA rejected at more than 99% C.L.



★: RAA oscillation best fit

$$\Delta m^2_{RAA} = 2.3 \text{ eV}^2 \ / \ \sin(2\theta_{RAA})^2 = 0.14$$

STEREO shape analysis – Principle

Goal: Provide ^{235}U antineutrino spectrum free of detector effects, to be used for comparisons with other measured antineutrino spectra (e.g. LEU spectra) or predicted spectra (e.g. Huber model).

Method: Unfold the measured energy spectrum D in antineutrino energy spectrum Φ through the detector response matrix R.

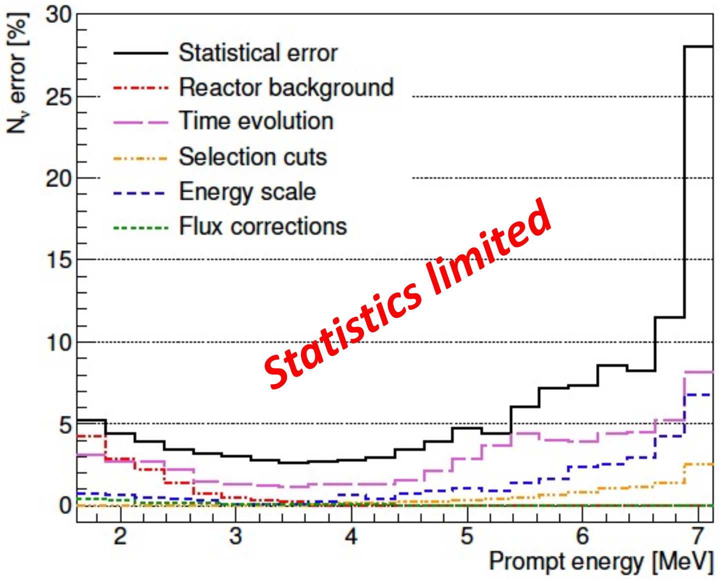
Caveat: Regularized unfolding technic needed to mitigate the effects of the deconvolution of the noise in the antineutrino spectrum shape → Potential bias is controlled by the study of 1000's of unfolded toy spectra. **Mean biases checked to be at the sub-% level** for spectral distortion like the 5 MeV bump.

STEREO shape analysis – Method [JPG 48:075107 (2021)]

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

$$\chi^2(\Phi) = (R\Phi - D)^T V_D^{-1} (R\Phi - D) + r \cdot \mathcal{R}_1(\Phi)$$

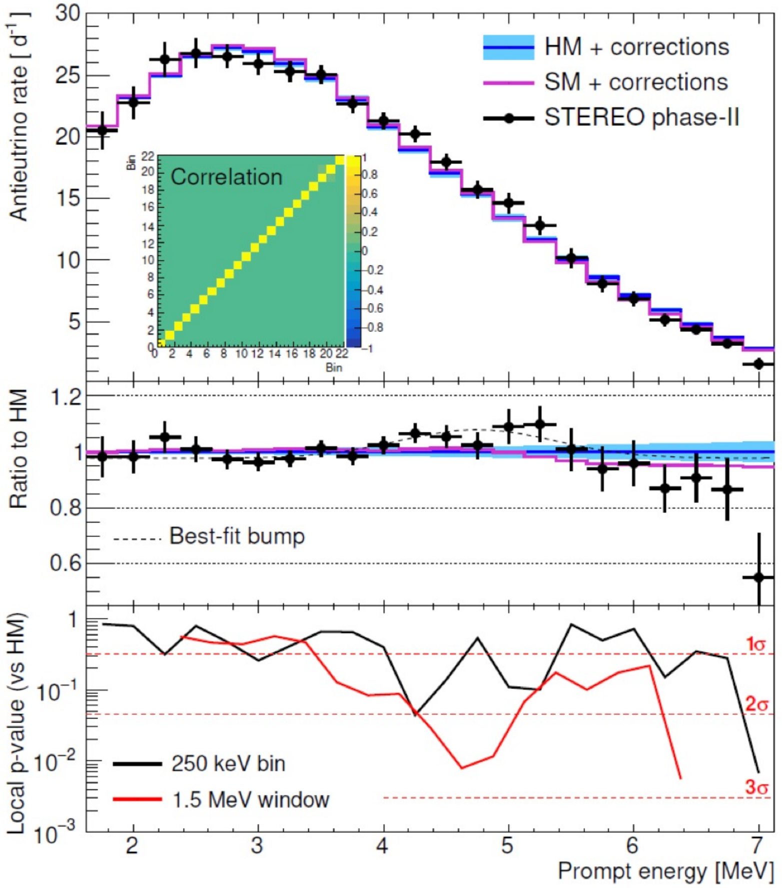
Experimental Covariance matrix

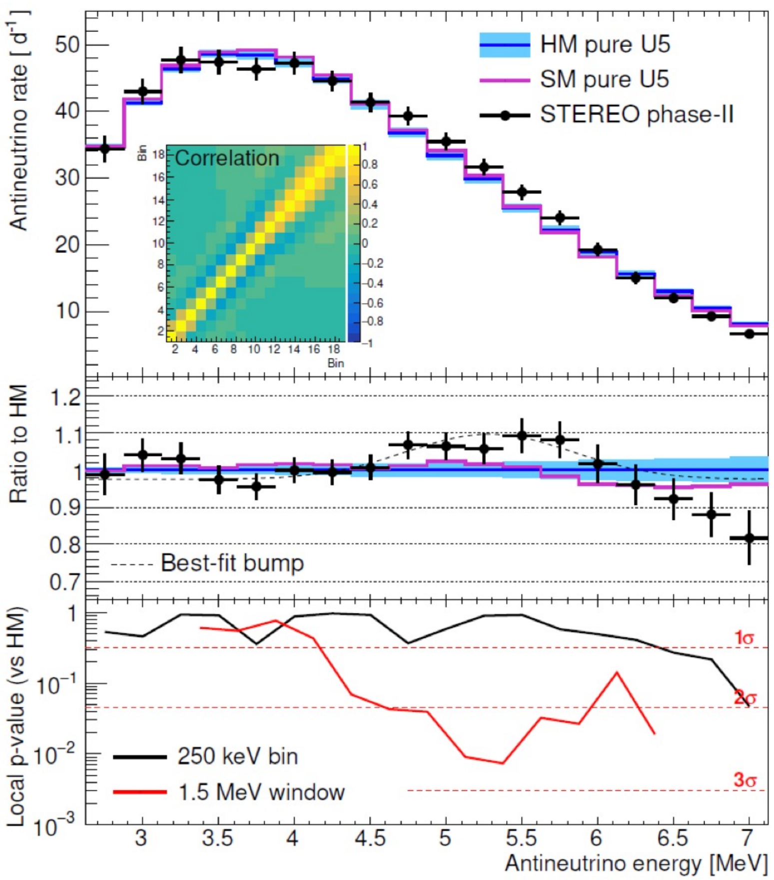


Regularization term:

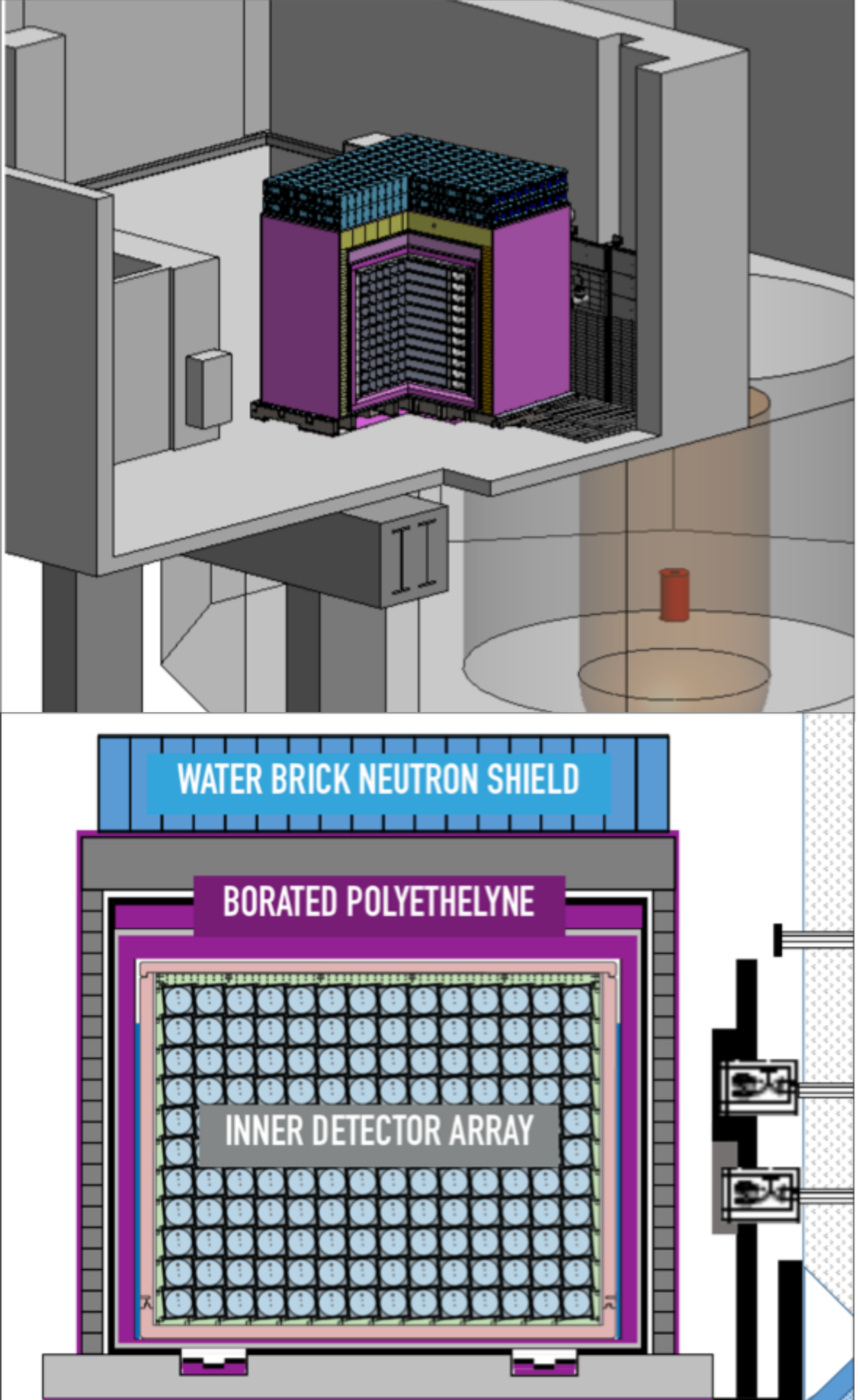
- Tunable r.
- $\mathcal{R}_1(\Phi) = \sum_i \left(\frac{\Phi_{i+1}}{\Phi^0_{i+1}} - \frac{\Phi_i}{\Phi^0_i}\right)^2$, with Φ^0 a prior shape (Huber), is a penalty term on the bin-to-bin fluctuations.

STEREO shape analysis – Results *JPG 48:075107 (2021)*





- **3.5σ local events excess** observed wrt. Huber around 5.3 MeV in antineutrino energy: $A = 12.1 \pm 3.4\%$.
- Cannot distinguish yet between the « U5-only » $(A \approx 16\%)$ and « equally shared » $(A \approx 9\%)$ scenarios.



The PROSPECT experiment [NIM A922 (2019) 287-309]

Experimental Site (HFIR, ORNL):

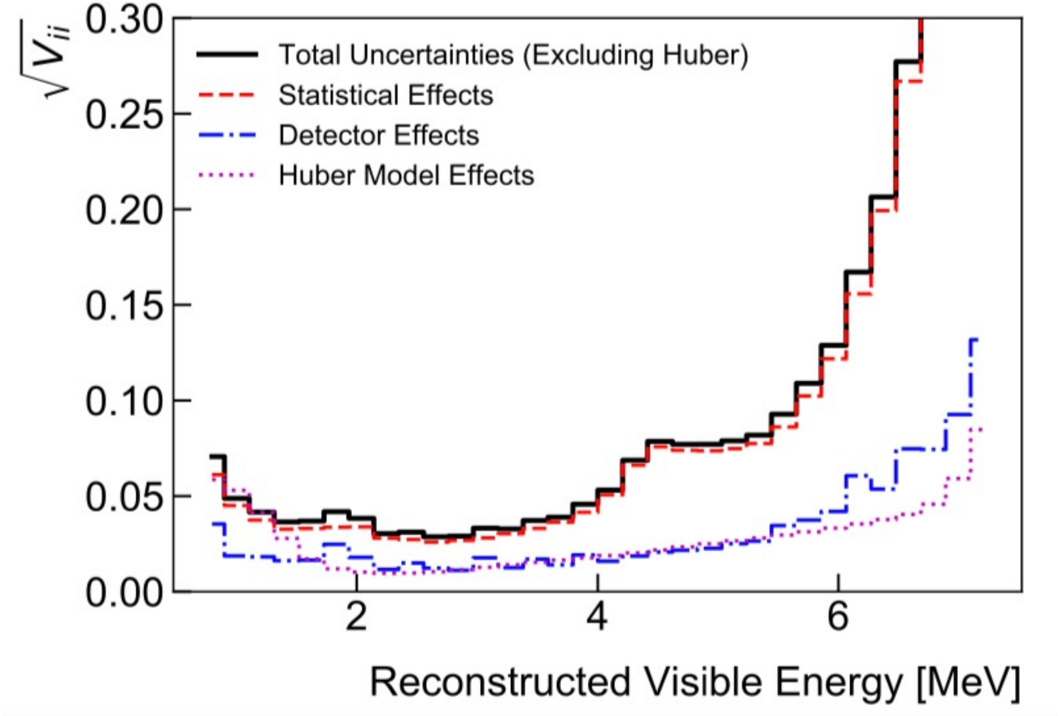
- 85 MW HEU reactor core with 46% duty cycle.
- 99% of $\bar{\nu}$ flux from ^{235}U fissions.

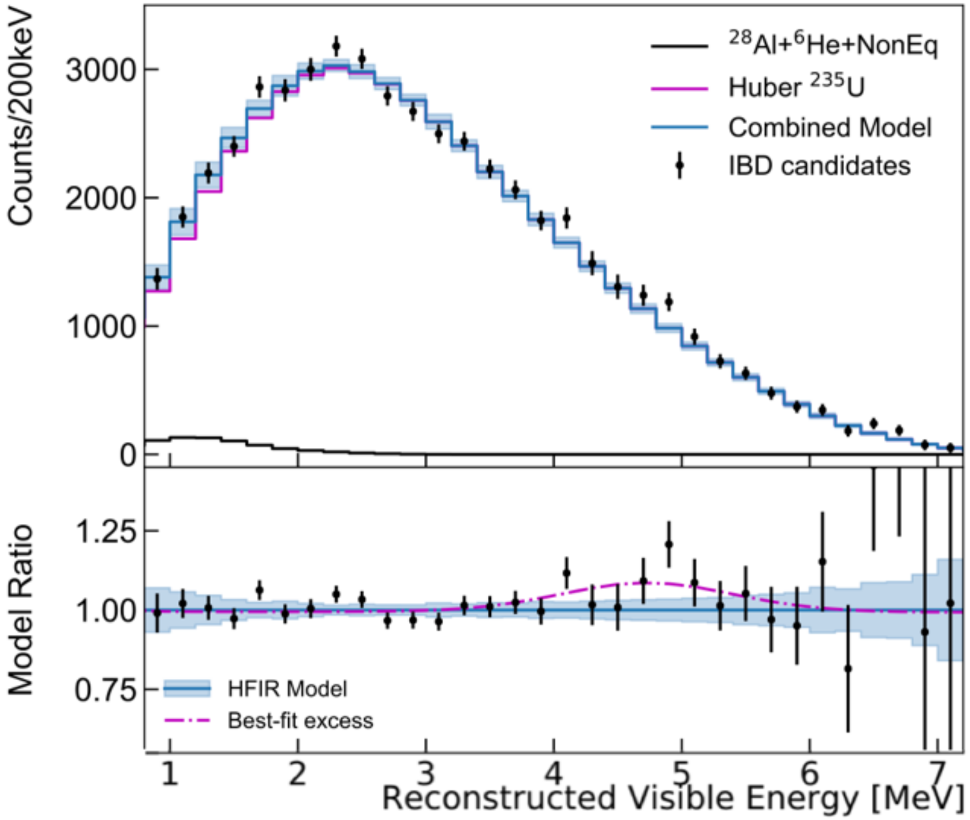
Detector Design:

- Segmented design for calibration access.
- Optimized for background suppression (achieved S:B of 1.4:1).
- PSD for Particle identification.

PROSPECT measured ^{235}U spectrum [PRD 103:032001 (2021)]

- 50560 ± 406 IBD signal events.
- S:B of 1.4:1 in signal energy range (0.8-7.2 MeV).
- Best fit bump size relative to Daya Bay: 84% ± 39%.
- Still statistics limited.



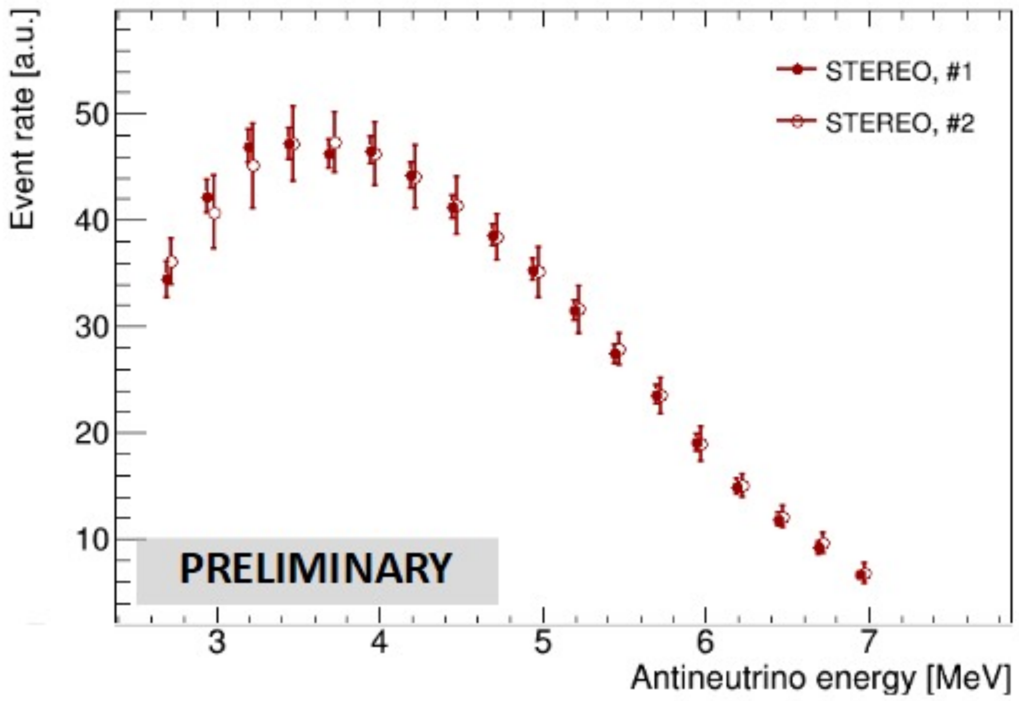


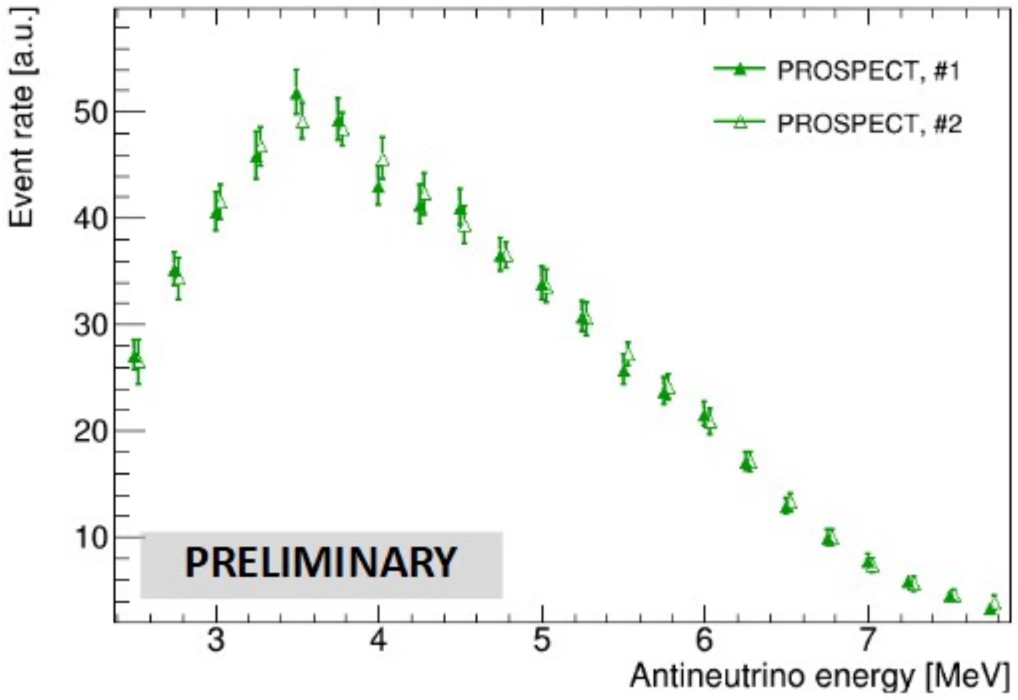
Joint analysis of STEREO/PROSPECT

Framework validation:

- #1: STEREO Tikhonov regularization
- #2: PROSPECT Wiener-SVD filter method
  (optimization wrt. S/B – cf. *JINST, 12, P10002 (2017)*)

Consistent results



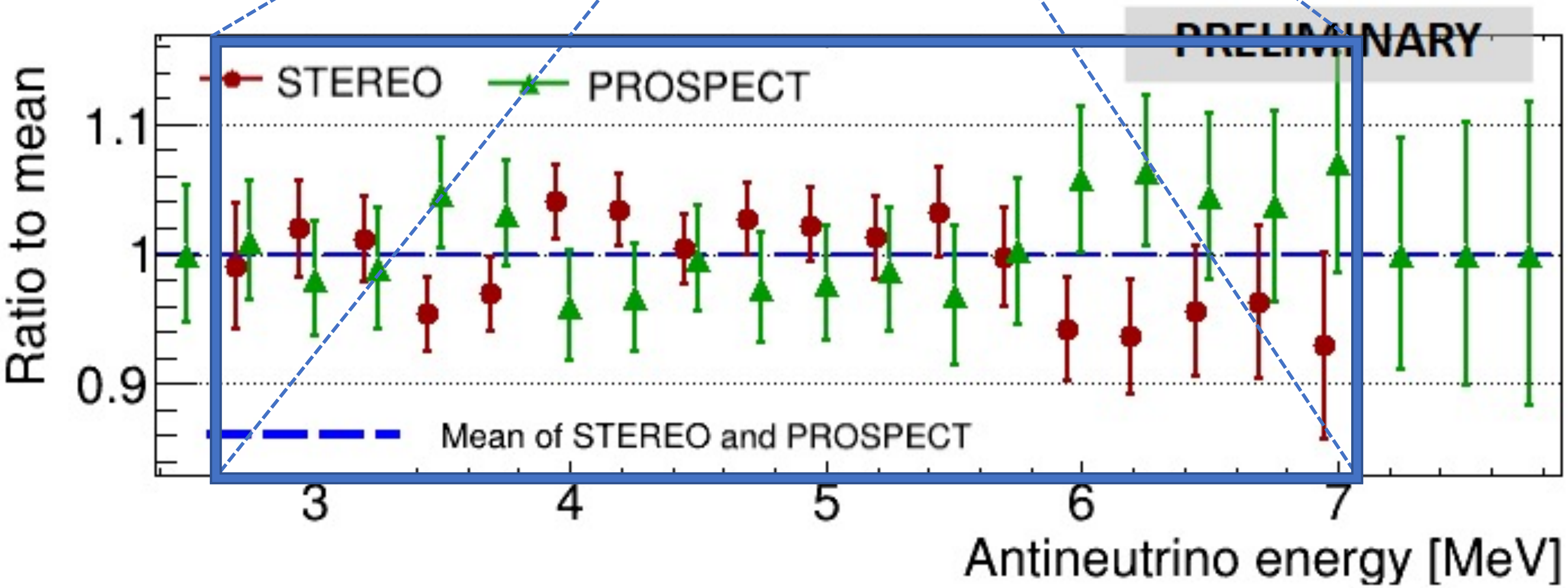


Joint analysis of STEREO/PROSPECT

Compatibility of measurements (Tikhonov approach):

➢ $\chi^2 = 22.3/17$

Compatible spectra

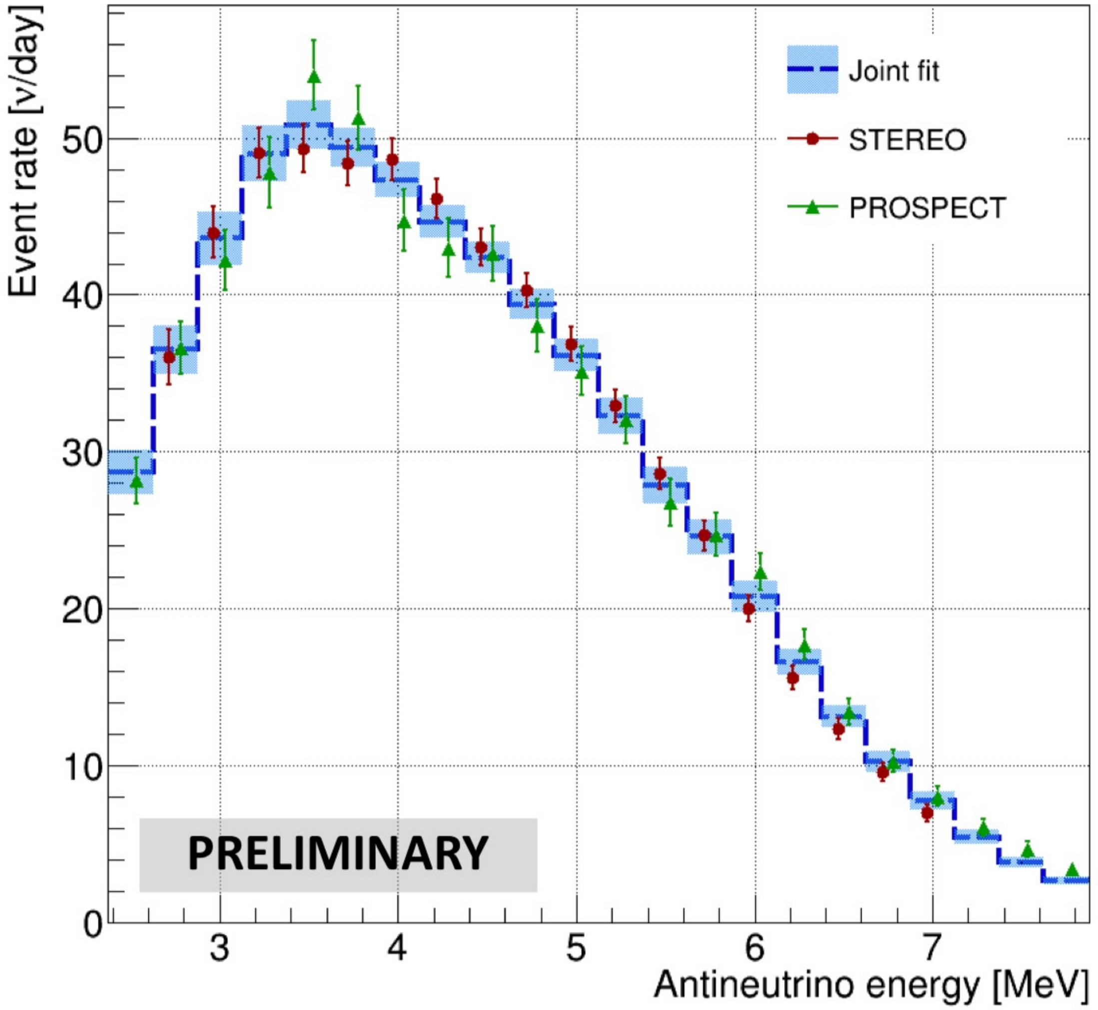


Joint analysis of STEREO/PROSPECT

Extension to a joint unfolding (Tikhonov approach):

$$\chi^2(\Phi) = (R_{ST}\Phi - D_{ST})^T V_{ST}^{-1} (R_{ST}\Phi - D_{ST})$$
$$+ (R_{PR}\Phi - D_{PR})^T V_{PR}^{-1} (R_{PR}\Phi - D_{PR})$$
$$+ r \cdot \mathcal{R}_1(\Phi)$$

- **To be published with filter matrix.**
- **Can be compared to other measurements or ^{235}U predictions.**



Summary and outlook

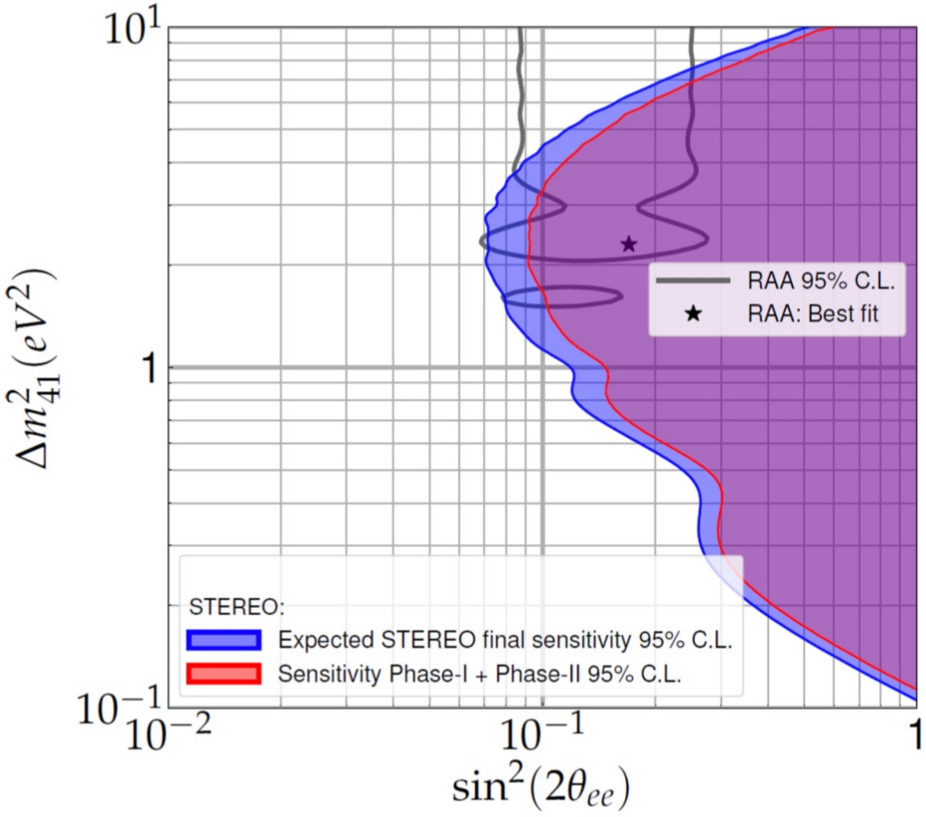
Thanks for your attention !

STEREO results provide a complete study of the reactor anomaly, with:

- ✓ The **most accurate measurement of the ^{235}U antineutrino flux** to date. **Consistent with the world average** of all other ^{235}U measurements.
- ✓ The exclusion of the **RAA best-fit point** at **more than 99% C.L.**
- ✓ A **3.5σ local events excess wrt. the Huber prediction**, similar to the events excess reported by several LEU experiments.

New results to come, stay tuned!

- ❑ The phase-III data will **double the statistics** !
- ❑ Ongoing STEREO/PROSPECT **joint analysis** to produce a reference ^{235}U antineutrino spectrum.



STEREO sensitivity with phase III

The STEREO collaboration

supported by

Spokesperson:
David Lhuillier (CEA)

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david.lhuillier@cea.fr

Back-up

STEREO shape analysis – Validation *JPG 48:075107 (2021)*

2 complementary implementations of the Tikhonov approach have been independently developed:

- Covariance matrix:

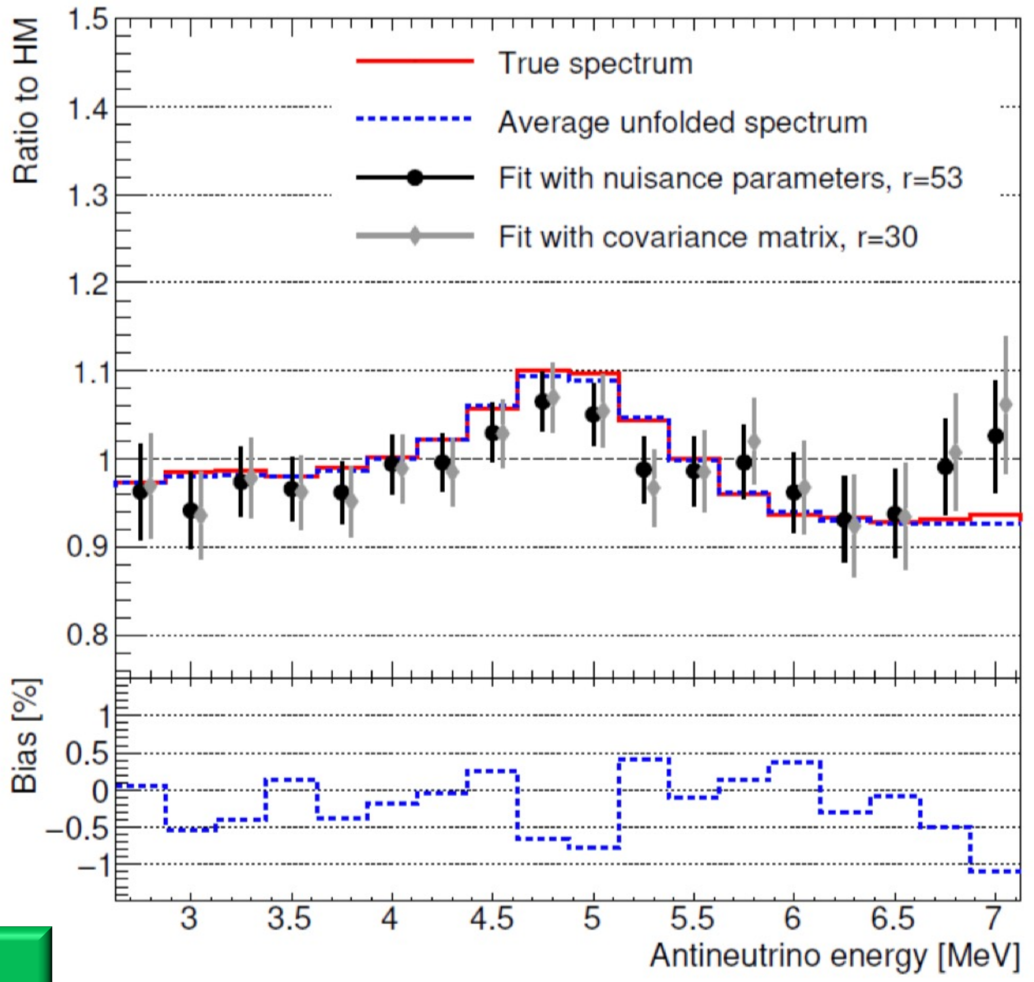
$$\chi^2(\Phi) = (R\Phi - D)^T V_D^{-1}(R\Phi - D) + r' \cdot \mathcal{R}_1(\Phi)$$

Tuned with GCV prescription – Wahba et al, Technometrics 21, n°2, 1979

Tuned to achieve negligible prior-dependence

- Nuisance parameters:

$$\chi^2(\Phi, \vec{\alpha}) = \sum_i \left(\frac{\sum_j R_{ij}(\vec{\alpha})\Phi_j(\vec{\alpha}) - D_i}{\sigma_i^{stat}} \right)^2 + \sum_{s \in syst} \left(\frac{\alpha_s}{\sigma_s} \right)^2 + r \cdot \mathcal{R}_1(\Phi)$$



Yield to consistent results and negligible bias on toy spectra

Filter matrix A_c

- A_c encodes the bias and smoothing induced by the regularized unfolding method.

- On this example, we compare a bump model to a filtered bump model. The smoothing induced by the regularization tends to flatten the bump, at the 1%-level residuals.

- The filter matrix enables to account for those effects in the model comparison, so that one should compare the measured unfolded spectrum to the filtered model instead of the nominal model.