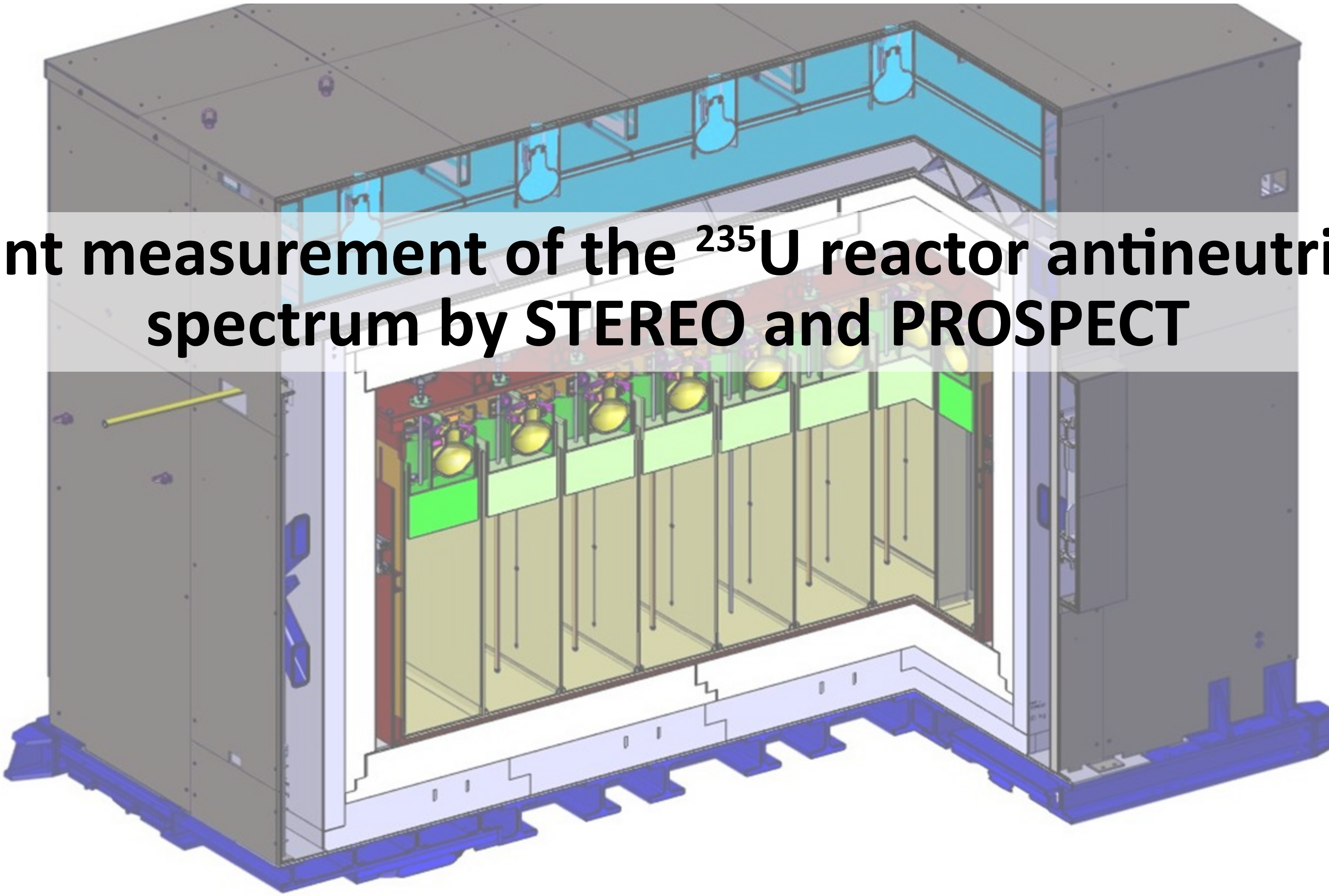
Joint measurement of the ^{235}U reactor antineutrino spectrum by STEREO and PROSPECT

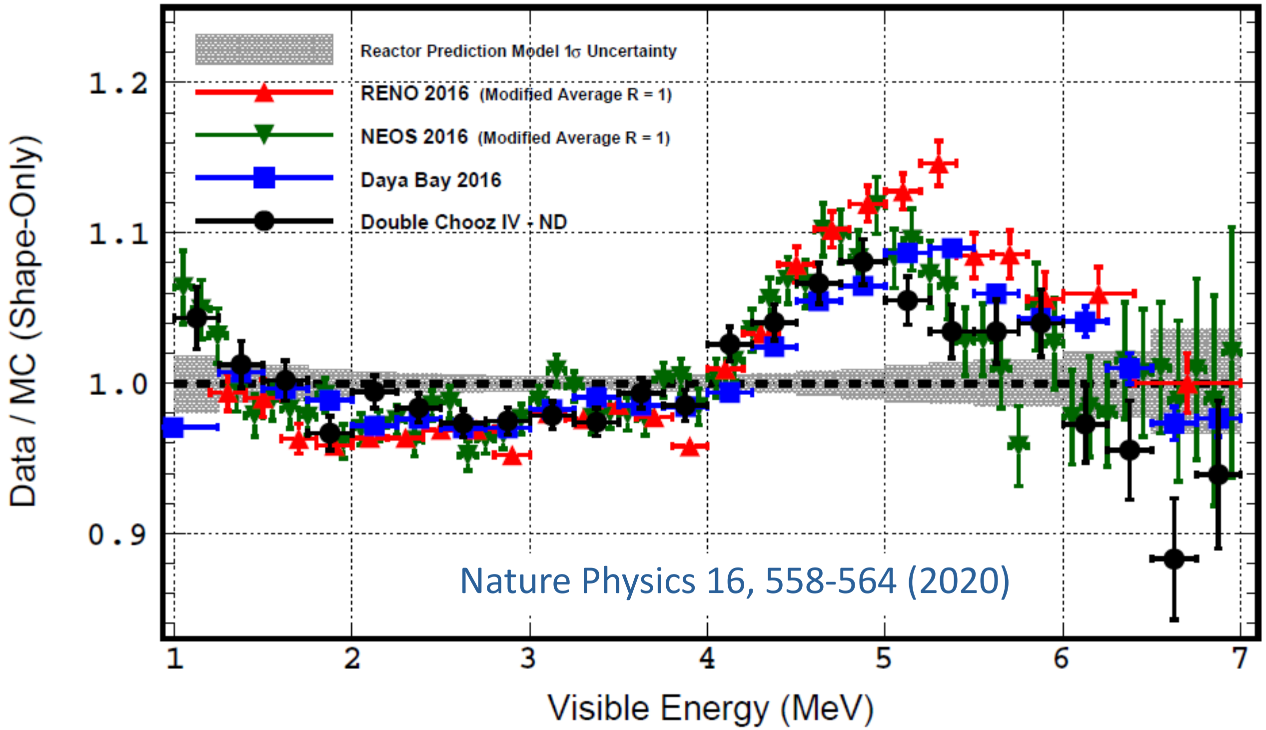


Matthieu Licciardi
On behalf of the STEREO and PROSPECT collaborations

The “5-MeV bump”

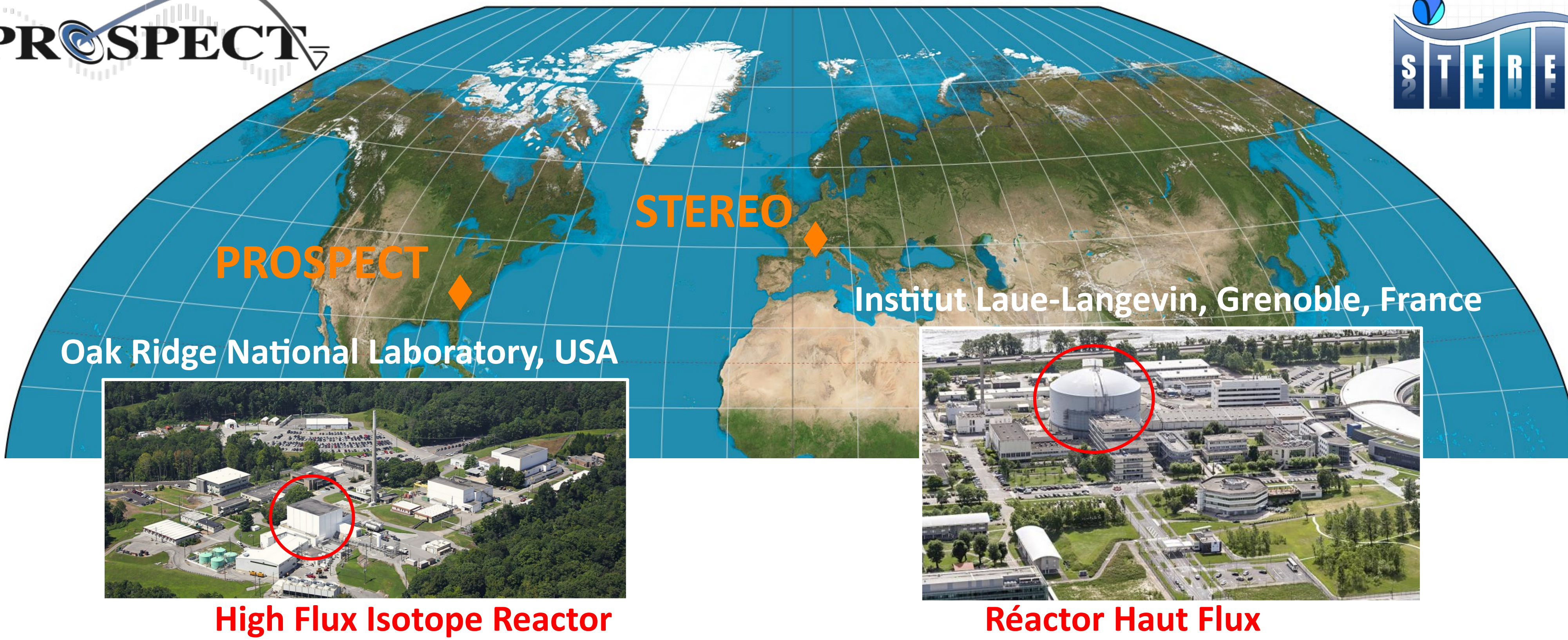
Shape distortion in reactor antineutrino spectra

- Excess of events (≈10%) around 5 MeV w.r.t. reference model (Huber-Mueller)
- First observation in 2016, now seen by all experiments @ commercial reactors
- Unknown origin. New physics ? Energy calibration ? Incomplete models ?
- Fuel is **L**owly **E**nriched in ^{235}**U** (LEU) → $\bar{\nu}_e$ from several isotopes ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



- What is the contribution of ^{235}U to the 5-MeV bump ?

STEREO and PROSPECT experiments



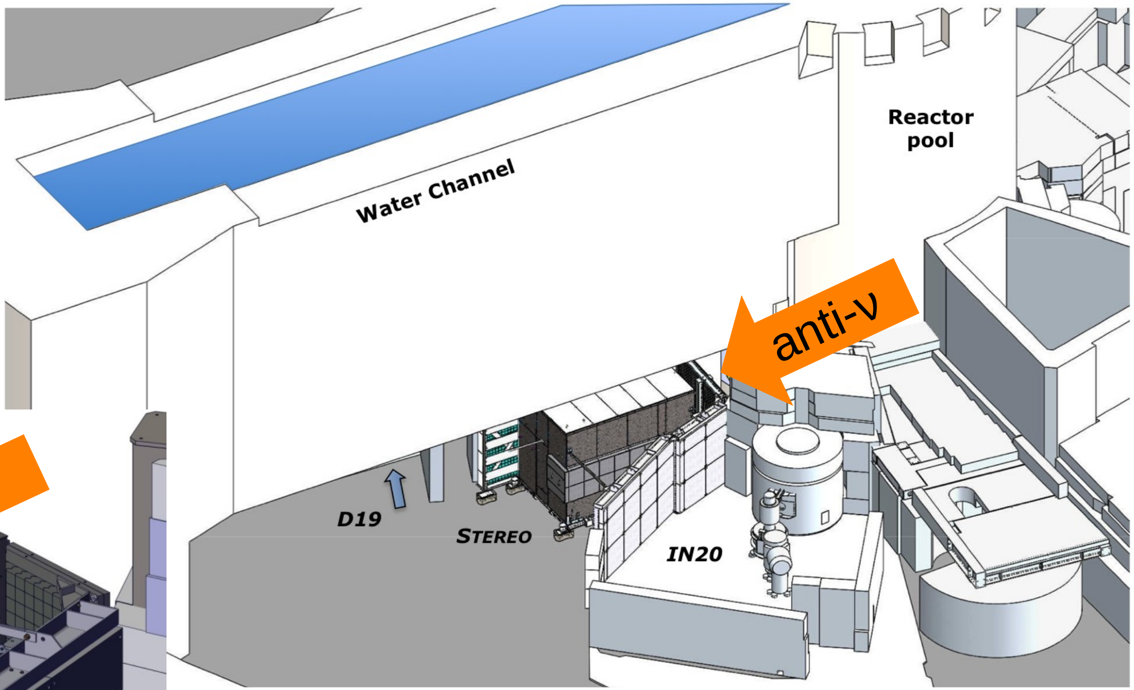
- Leading experiments at research reactors :
  - Fuel is **H**ighly **E**nriched in ^{235}**U** (HEU) : pure ^{235}U neutrino flux (>99%)

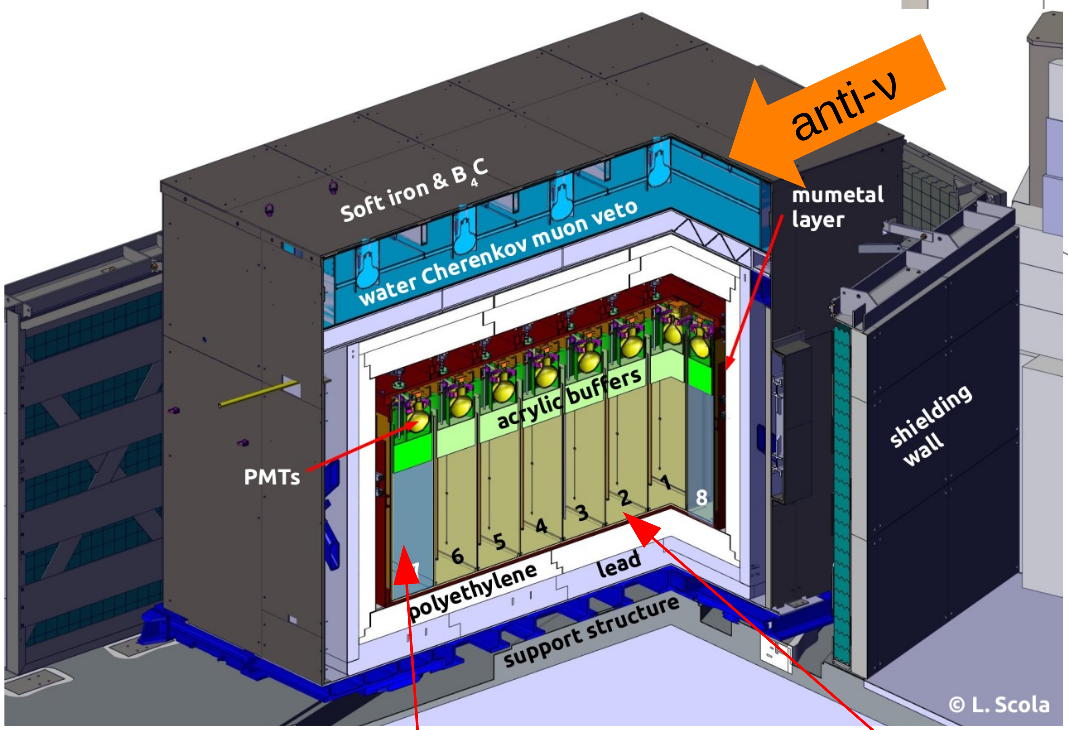
    → disentangle isotope contributions
  - Less statistics (by a factor 10^{-1}–10^{-2}) → interest for a combined measurement

The STEREO detector

JINST 13 (2019) 07, P07009
www.stereo-experiment.org

Experimental site (RHF, ILL):
- Partial 15 m.w.e. overburden
- Backgrounds: ambient neutrons, cosmic rays





Detector design:
- ≈ 10m to reactor core
- Liquid Scintillator + Gd
- Pulse shape discrimination
- ≈ 360 ν/day

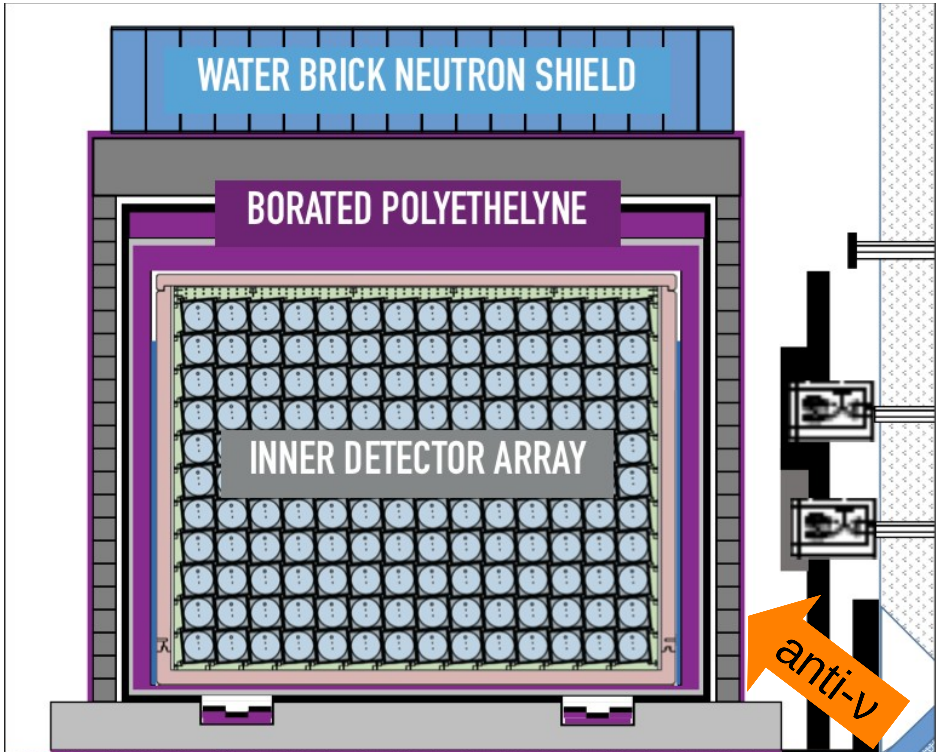
Gamma-Catcher: unloaded liquid scintillator **Target**: Gd-loaded liquid scintillator

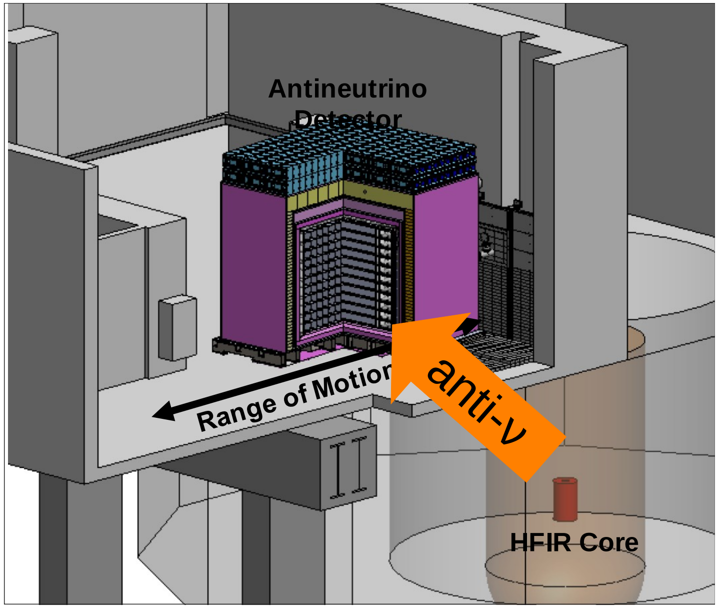
The PROSPECT detector

NIM A922 (2019) 287-309
https://prospect.yale.edu

Experimental site (HFIR, ORNL):

- No overburden
- Backgrounds: ambient neutrons, cosmic rays





Detector design:

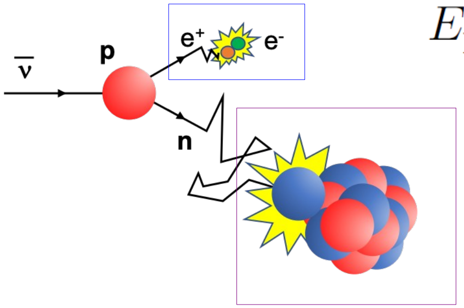
- ≈ 10m to reactor core
- Liquid Scintillator + ^{6}Li
- Pulse shape discrimination
- ≈ 500 ν/day

Analysis principle

Detection = inverse beta decay (IBD) → time and space coincidence

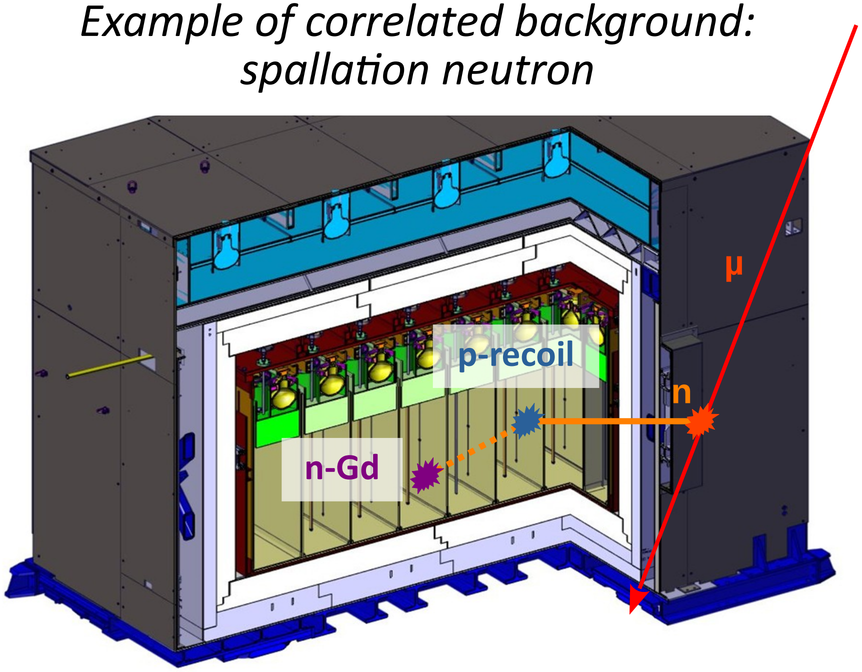
1. Prompt signal: e^+ annihilation

$$E_{\rm pr} \simeq E_\nu - \Delta M + m_e = E_\nu - 0.782 \text{ MeV}$$

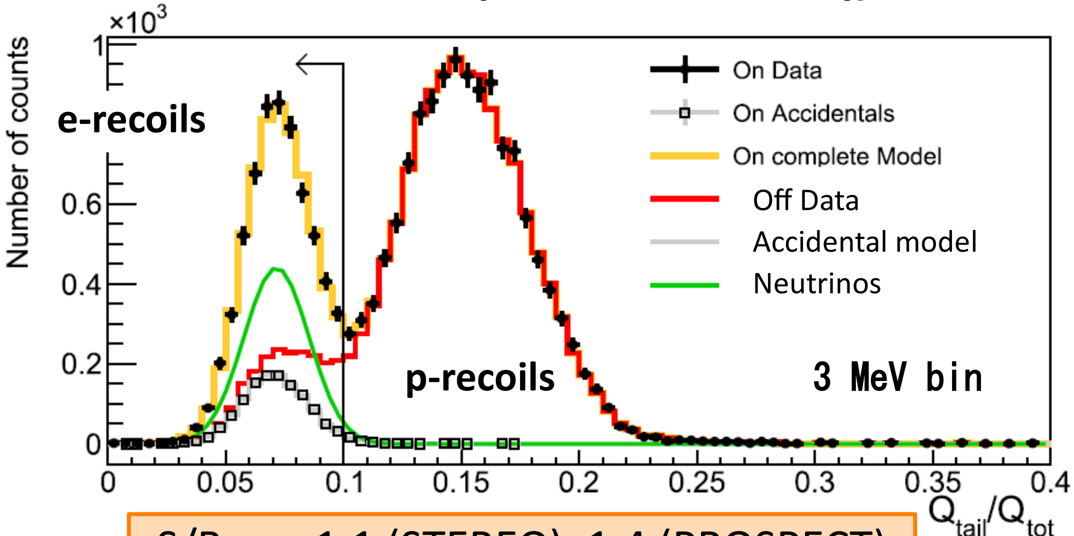


2. Delayed signal: neutron capture on Gd/Li nucleus

Example of correlated background: spallation neutron



Pulse Shape Discrimination on prompt signals + combination of reactor-on and -off data



S/B_{corr} = 1.1 (STEREO), 1.4 (PROSPECT)

Energy reconstruction : example of STEREO

Crucial for spectral measurement !

Is E_{rec}^{MC} consistent with E_{rec}^{Data}?

>1 Radioactive sources

- in each cell, at 5 different heights

>2 ^{12}B spectrum

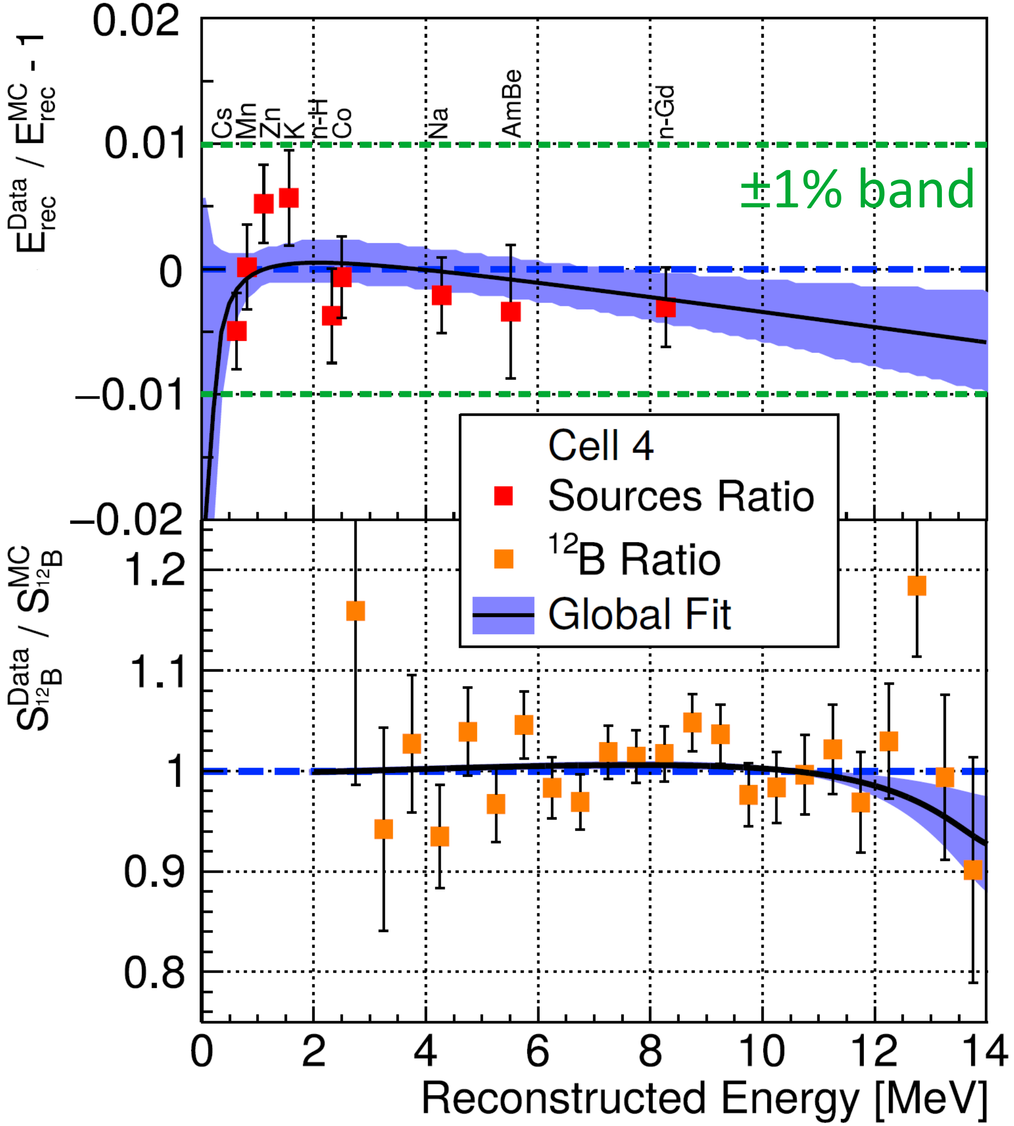
- Continuous spectrum, Q_β = 13.4 MeV

>3 Global fit

- Tested models:
  - polynomial (order 2-5)
  - Kernel density estimation

→ Data/MC agree with 1% accuracy

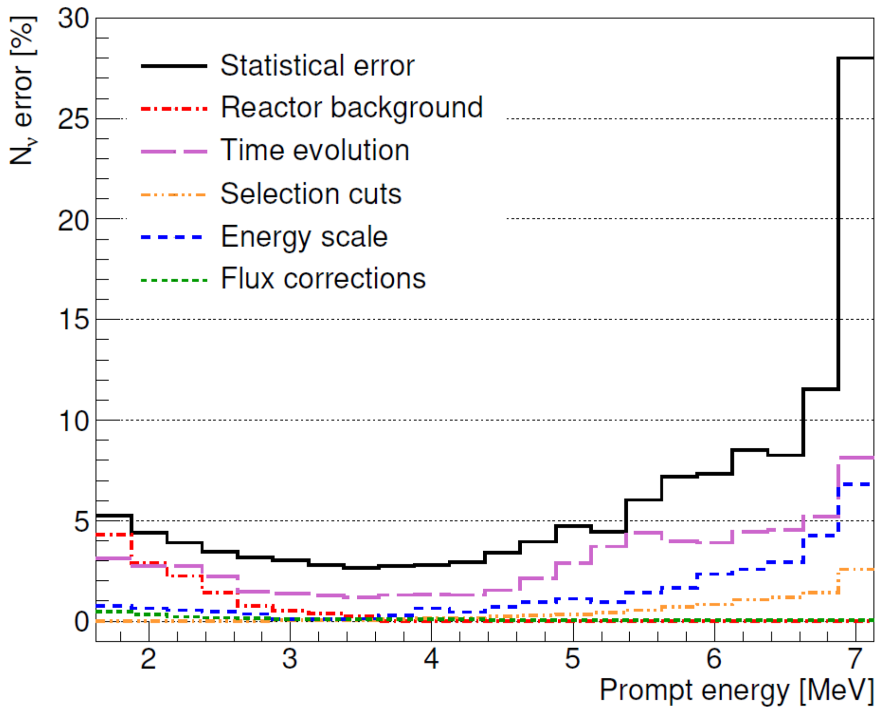
PRD 102,052002 (2020)



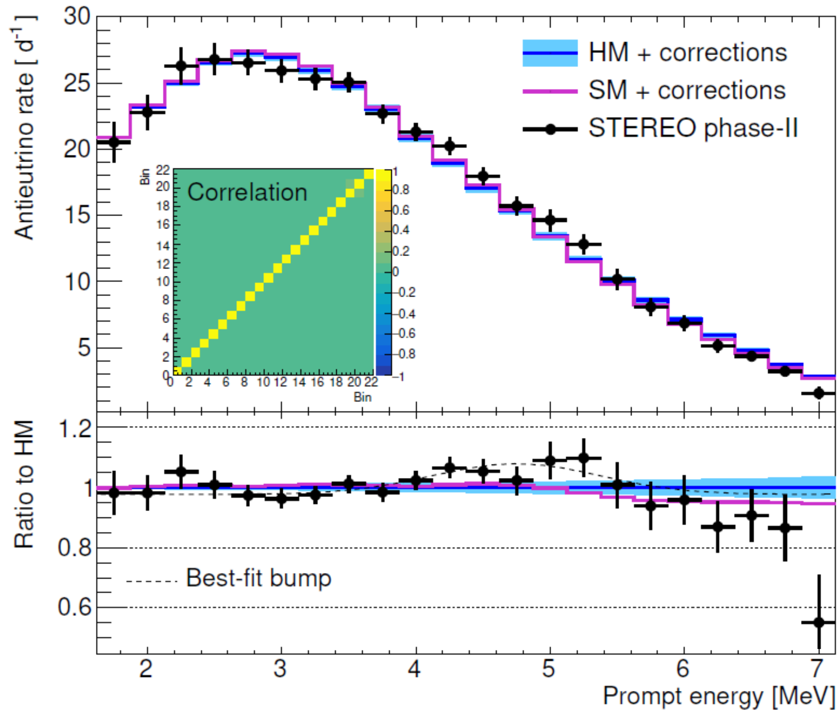
STEREO prompt energy measurement

J.Phys.G 48, 075107 (2021)

Error budget



IBD spectrum

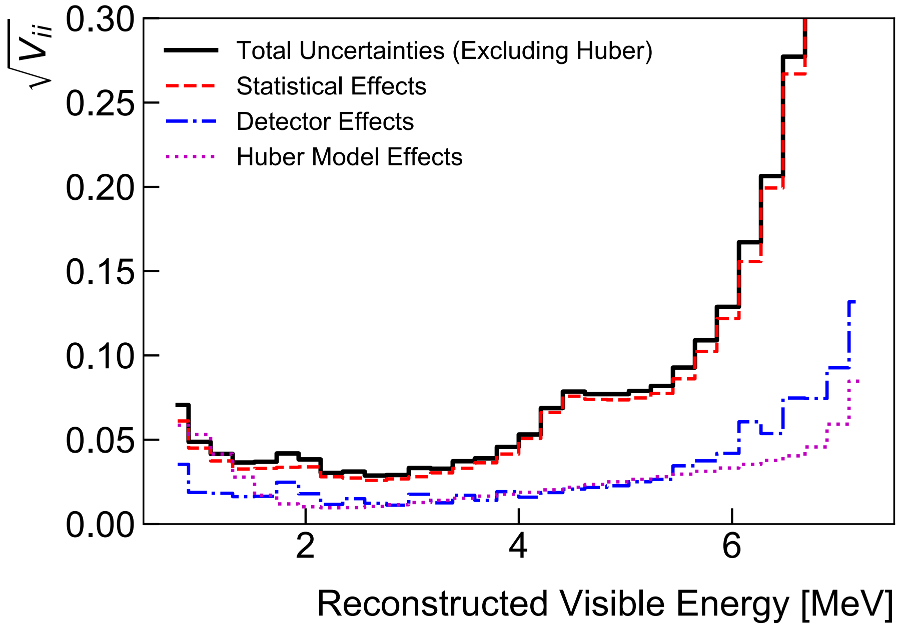


- Significant bump is observed on the ^{235}U spectrum:
  - free Gaussian fit gives A = 10.1 ± 2.9 %, compatible with LEU observations
- Measurement is statistically limited
- Unfolded spectrum available for reference on HEPData doi.org/10.17182/hepdata.99805

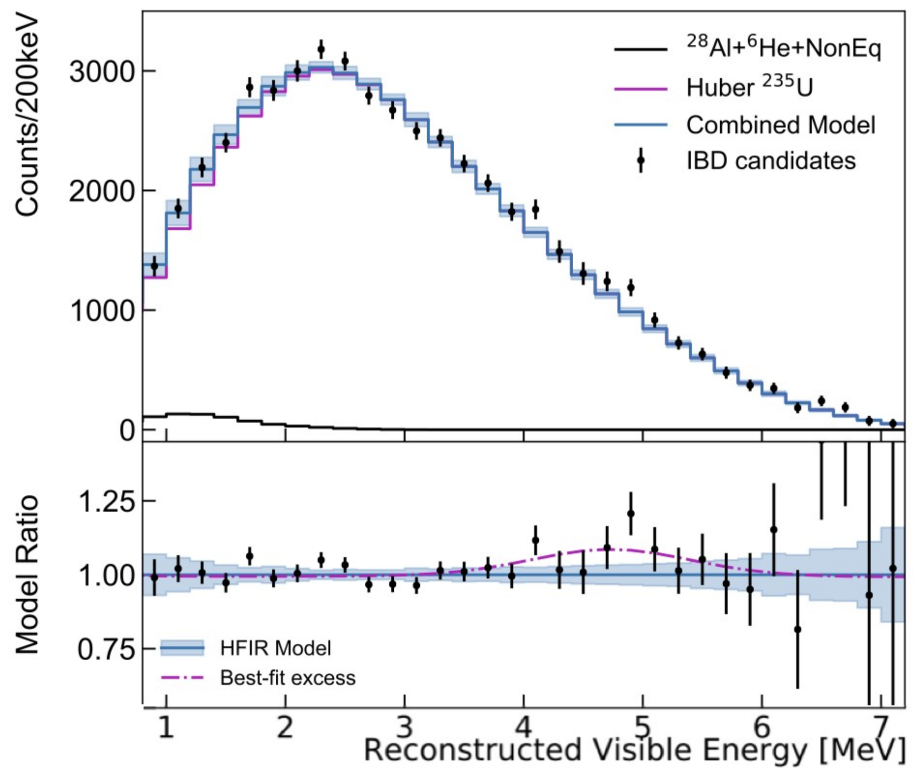
PROSPECT prompt energy measurement

PRD 103:032001 (2021)

Error budget



IBD spectrum



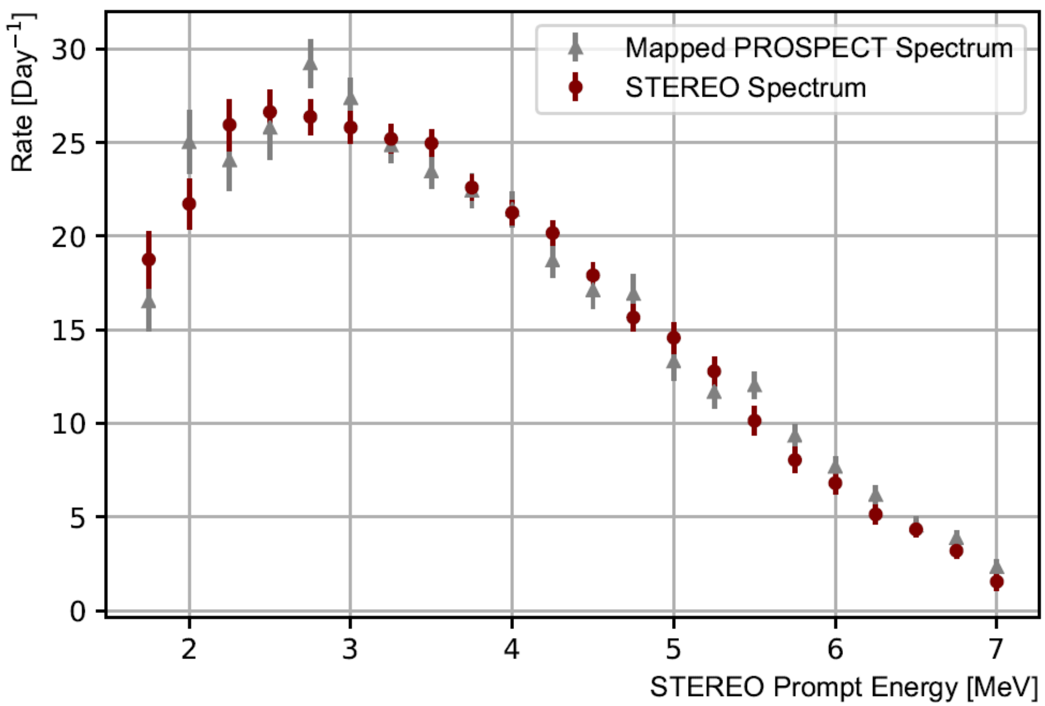
- Significant bump is observed on the ^{235}U spectrum:
  - Amplitude relative to Daya-Bay measurement is $A/A_{DB} = 0.84 \pm 0.39$
- Measurement is statistically limited

STEREO/PROSPECT compatibility

arXiv: 2107.03371

Must be compared in the same energy space

- PROSPECT mapped into STEREO space: $R_{\mathrm{map}} = R_{\mathrm{ST}} \cdot R_{\mathrm{PR}}^{-1}$
- Comparison free of unfolding biases



$\chi^2/\mathrm{ndf} = 24.1/21$ (p-value : 0.29)
→ compatible experiments

(free normalization fitted)

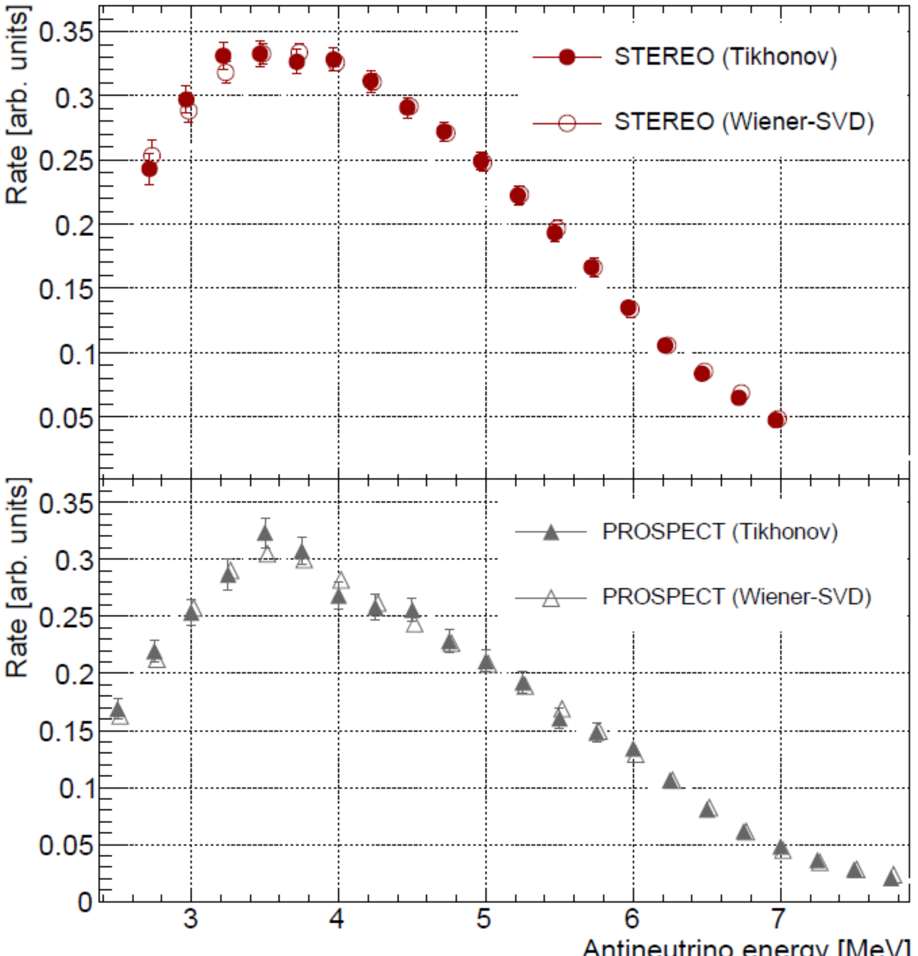
Unfolding frameworks

arXiv: 2107.03371

Joint unfolding:

- Deconvolve experimental effects to provide a reference spectrum vs E_ν
- Recovery of lost information requires regularized techniques
- Two independent methods used
  - Tikhonov regularization
  - Wiener-SVD

→ validated frameworks giving consistent results



- Filter matrices encoding unfolding biases are provided

Joint unfolded ^{235}U spectrum

arXiv: 2107.03371

- Combined antineutrino spectrum
- Model comparisons use filter matrix A_C

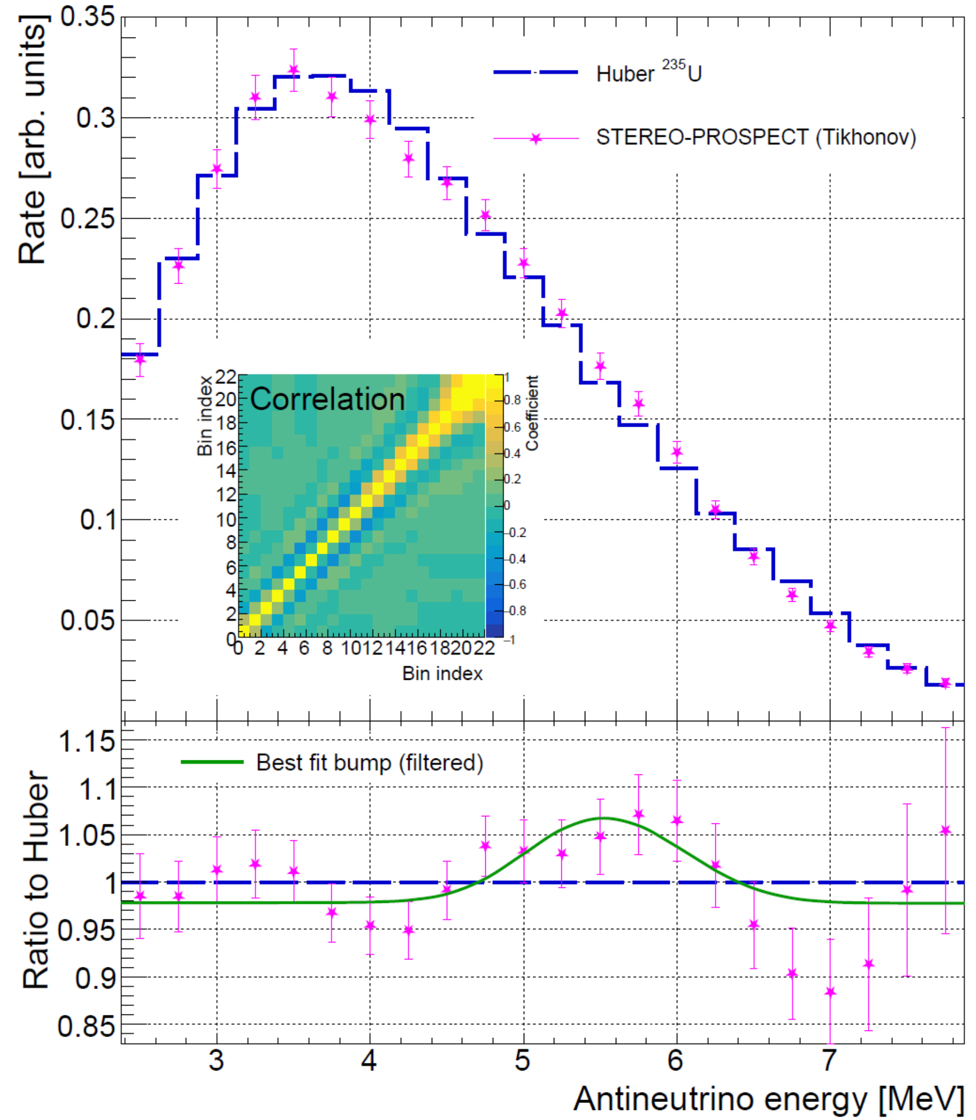
$$\chi^2 = (A_C \cdot M - \Phi^{U5})^T V_\Phi^{-1} (A_C \cdot M - \Phi^{U5})$$

→ vs Huber model :
$\chi^2 = 30.8/21$ (p-value : 0.07)

- Event excess around 5-6 MeV:
  - 2.4σ significance
  - free Gaussian fit → A = 9.9 ± 3.3 %

→ Bump in ^{235}U independent of other LEU isotopes

- Compatible with Daya-Bay ^{235}U spectrum
  Chin.Phys.C 45 (2021) 073001 ($\chi^2 = 21.0/21$)



Summary

“5 MeV bump” is still mysterious, but contribution of ^{235}U has been investigated by STEREO and PROSPECT **→ arXiv: 2107.03371 ←**

- STEREO and PROSPECT datasets are statistically **compatible**
- Antineutrino spectra have been successfully combined and unfolded, providing a **robust ^{235}U spectrum** to the community
- Filter matrix allows comparisons with ^{235}U models free of unfolding biases
- **Excess is observed for ^{235}U** in 5-6 MeV region (2.4σ) without information on any other fuel isotope
  - ^{235}U amplitude ≈10 % → can’t explain 5-MeV bump on its own, other isotopes involved

More data is being analyzed, stay tuned !

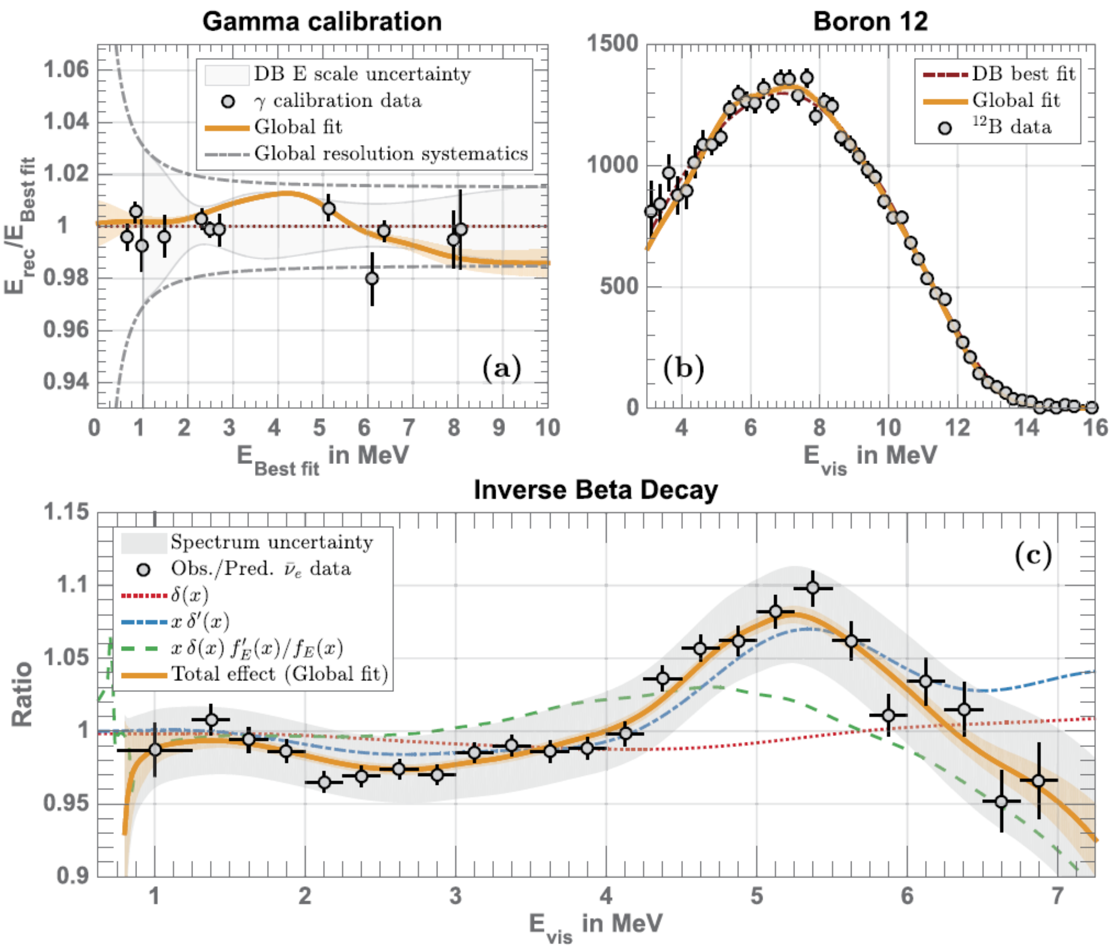
Thank you for your attention !

Supplementary slides

Possible origins of the shape anomaly

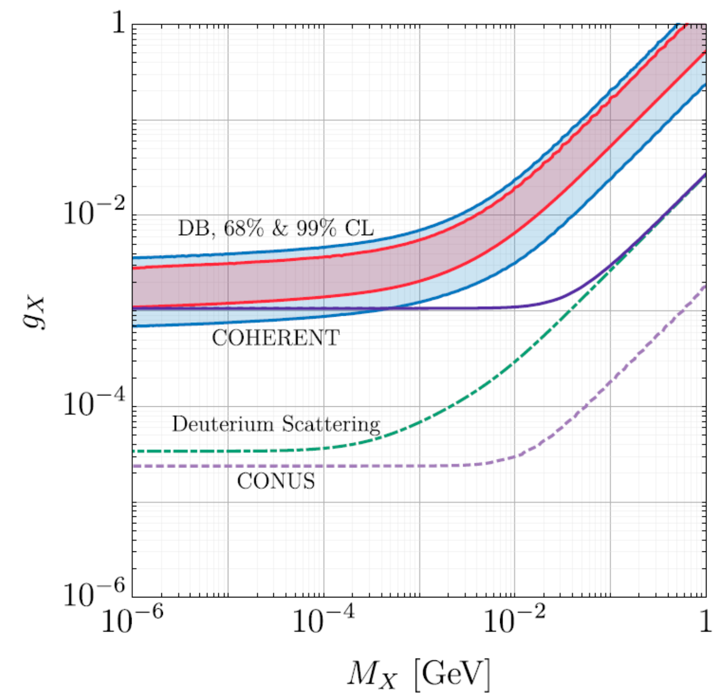
- Non linearity in E reconstruction

[Mention et al, PhysLettB 773:307-312 (2017)]



- New physics process?

$^{13}\mathrm{C}(\overline{\nu},\overline{\nu}'n)^{12}\mathrm{C}^*$ via a new vector boson X



[Berryman et al, PRD 99, 055045 (2019)]

Possible origins of the shape anomaly

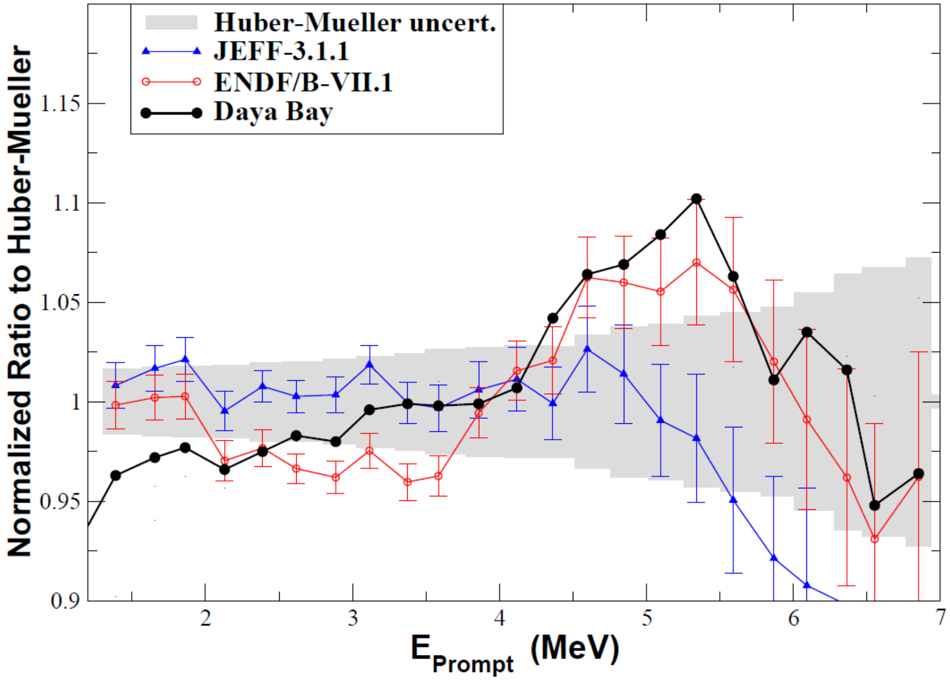
- Non linearity in E reconstruction

- Issue in nuclear models

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i (f_i/F) S_i(E_\nu)$$

Relies on nuclear databases for fission fractions f_i

[Hayes et al, PRD 92, 033015 (2015)]



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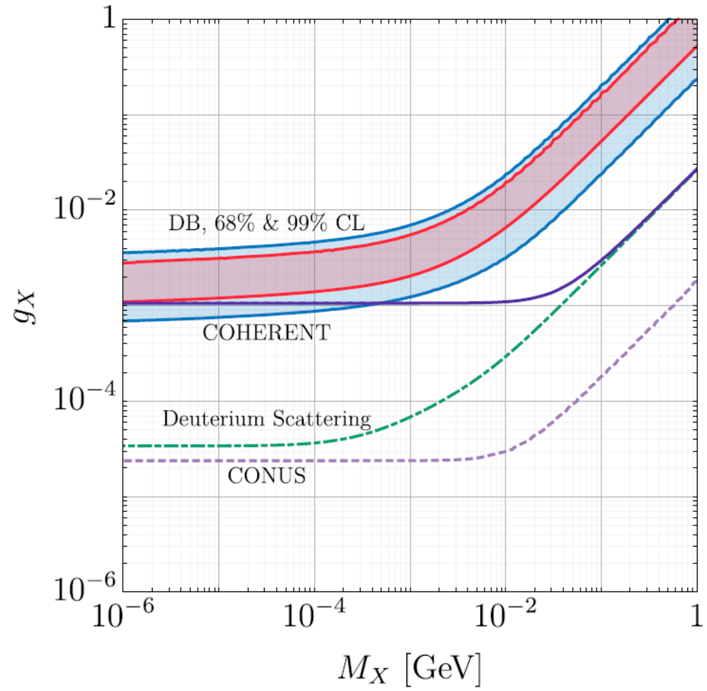


[Berryman et al, PRD 99, 055045 (2019)]

Wiener SVD unfolding

JINST, 12, P10002 (2017)

Adaptation of **S**ingular **V**alue **D**ecomposition (SVD) method

- SVD decomposition of the response matrix $R = U \cdot D \cdot V^T$
- Standard unfolding $\hat{s} = \left(R^T R\right)^{-1} \cdot R^T \cdot M$ becomes $\hat{s} = V \cdot D^{-1} \cdot U^T \cdot M$
- Insertion of a filter to cancel small values of D being inverted $F_{ii} = \frac{d_i^2}{d_i^2 + \tau}$
  (τ : arbitrary tunable parameter)

Wiener filter:

- F is replaced by the following filter

$$W_{ik} = \frac{d_i^2 \cdot \left(\sum_j V_{ij}^T \cdot \bar{s}_j\right)^2}{d_i^2 \cdot \underbrace{\boxed{\left(\sum_j V_{ij}^T \cdot \bar{s}_j\right)^2}}_{\text{signal}} + \underbrace{\boxed{1}}_{\text{noise (pre-whitened)}}} \cdot \delta_{ik}$$

- Generalization: use 1st/2nd discrete derivative of signal instead (using C_k matrices)

$$C_1 = \begin{bmatrix} -1 & 1 & 0 \dots & 0 & 0 \\ 0 & -1 & 1 \dots & 0 & 0 \\ \vdots & \vdots & \vdots \ddots & \vdots & \vdots \\ 0 & 0 & 0 \dots & -1 & 1 \\ 0 & 0 & 0 \dots & 0 & -1 \end{bmatrix} \quad C_2 = \begin{bmatrix} -1+\epsilon & 1 & 0 \dots 0 & 0 & 0 \\ 1 & -2+\epsilon & 1 \dots 0 & 0 & 0 \\ \vdots & \vdots & \vdots \ddots \vdots & \vdots & \vdots \\ 0 & 0 & 0 \dots 1 & -2+\epsilon & 1 \\ 0 & 0 & 0 \dots 0 & 1 & -1+\epsilon \end{bmatrix}$$

Tikhonov unfolding

Find the solution of the following χ^2

$$\chi^2\left(\beta,\Phi^{\mathrm{U5}}\right)=\boldsymbol{\Delta}\left(\beta,\Phi^{\mathrm{U5}}\right)^T\boxed{V^{-1}}\boldsymbol{\Delta}\left(\beta,\Phi^{\mathrm{U5}}\right)+\boxed{\mathcal{R}_1\left(\Phi^{\mathrm{U5}}\right)}$$

$$\boldsymbol{\Delta}(\beta,\Phi^{\mathrm{U5}})=D^{\mathrm{JNT}}-R_\beta\Phi^{\mathrm{U5}}$$

Joint data

$$D^{\mathrm{JNT}}=\begin{pmatrix}D^{\mathrm{PR}}\\D^{\mathrm{ST}}\end{pmatrix}$$

Response matrix
(free relative norm)

$$R_\beta=\begin{pmatrix}\beta\cdot R^{\mathrm{PR}}\\R^{\mathrm{ST}}\end{pmatrix}$$

Experimental covariance

$$V=\begin{pmatrix}V^{\mathrm{PR}}&0\\0&V^{\mathrm{ST}}\end{pmatrix}$$

Regularization term
controls sensitivity to noise in unfolding process

$$\mathcal{R}_1\left(\Phi^{\mathrm{U5}}\right)=r\sum_i\left(\frac{\Phi^{\mathrm{U5}}_{i+1}}{\Phi^{\mathrm{H}}_{i+1}}-\frac{\Phi^{\mathrm{U5}}_{i}}{\Phi^{\mathrm{H}}_{i}}\right)^2$$

+ tunable *r*
Φ^{H}: prior (Huber)

Matrix form:

$$\mathcal{R}_1(\Phi^{\mathrm{U5}})\equiv r\cdot(\Phi^{\mathrm{U5}})^T\cdot C_T\cdot(\Phi^{\mathrm{U5}})$$

Analytical solution : $\Phi^{\mathrm{U5}}=H_{r,\beta}\cdot D^{\mathrm{JNT}}$

$$H_{r,\beta}=\left[1+r(R_\beta^TV^{-1}R_\beta)^{-1}C_T\right]^{-1}\left(R_\beta^TV^{-1}R_\beta\right)^{-1}R_\beta^TV^{-1}$$

Filter matrix

Unfolding matrix (depends on regularization parameter λ if any) $\hat{s} = \boxed{H(\lambda)} \cdot D$

The unfolding matrix may be factorized as
→ **all reg. effects contained in filter matrix**

$$H(\lambda) = \underbrace{\boxed{A_C(\lambda)}}_{\text{Filter matrix}} \cdot \underbrace{\boxed{H(0)}}_{\text{Un-regularized unfolding}}$$

How to use?
Comparison of unfolded spectrum ŝ with model $\bar{s}$
→ pass model through filter matrix (A_c) before comparison

$$\chi^2 = \underbrace{\Big(\underbrace{\boxed{A_C\bar{s}}}_{\text{Filtered model}} - \underbrace{\boxed{\hat{s}}}_{\text{Unfolded spectrum (filtered)}}\Big)^T V_{\hat{s}}^{-1} \left(A_C\bar{s} - \hat{s}\right)}_{\text{Comparison in “filtered space”}} = \underbrace{\left(\bar{s} - \hat{s}_{\text{unfilt}}\right)^T V_{\hat{s}_{\text{unfilt}}}^{-1} \left(\bar{s} - \hat{s}_{\text{unfilt}}\right)}_{\text{Comparison in “unfiltered space”}}$$

Hypothetical unfolded spectrum with no regularisation

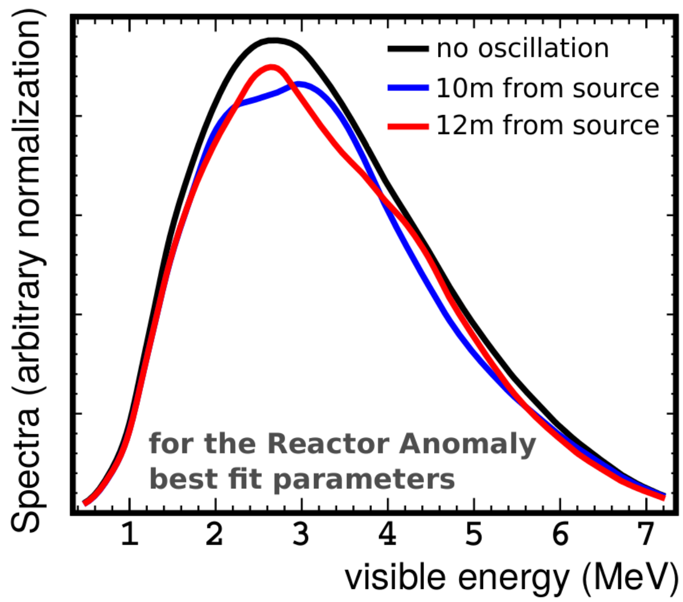
Its covariance

→ comparison **as if** there was no regularisation

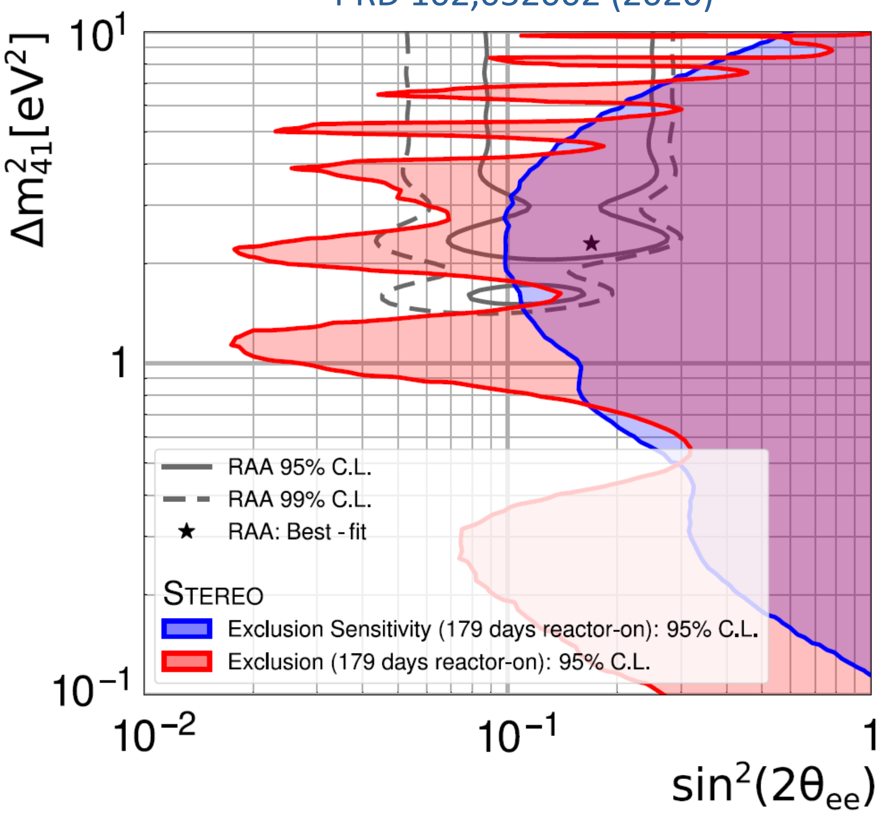
Search for sterile neutrinos with STEREO

Model-free sterile neutrino search

- Thanks to a segmented detector



PRD 102,052002 (2020)



Free model parameters ϕi in χ^2 to absorb distortions common to all cells

→ only cell-to-cell dependence remains

→ remove model dependence

$$\chi^2 = \sum_{l=1}^{N_{\mathrm{cells}}} \sum_{i=1}^{N_{\mathrm{Ebins}}} \left(\frac{A_{l,i} - \phi_i M_{l,i}}{\sigma_{l,i}} \right)^2$$ + pull terms

→ RAA best-fit rejected at > 99% CL