Investigation of reactor antineutrino anomalies with STEREO

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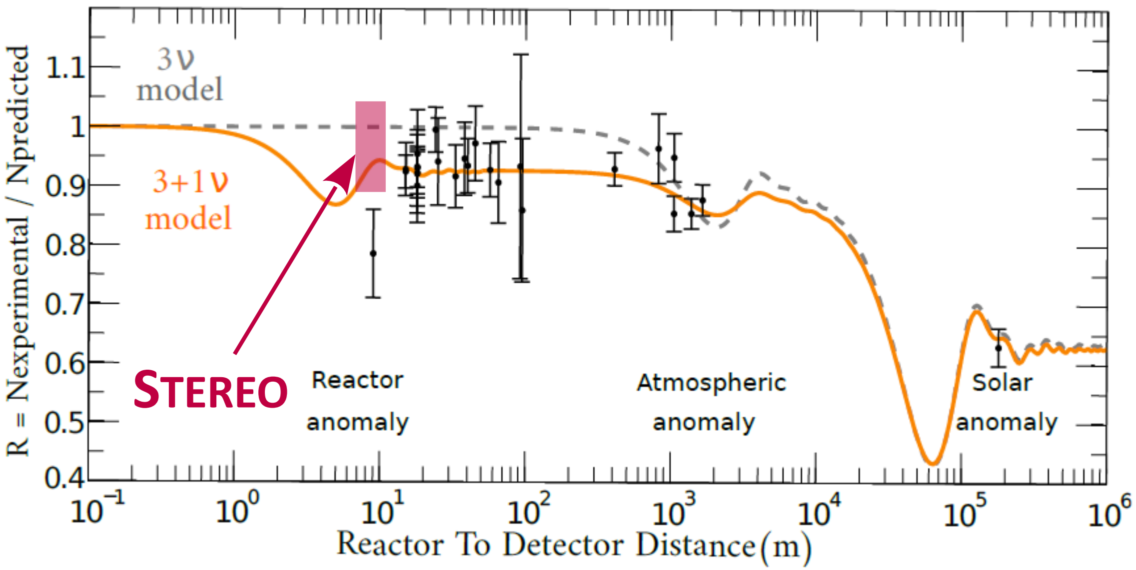
On behalf of the STEREO collaboration

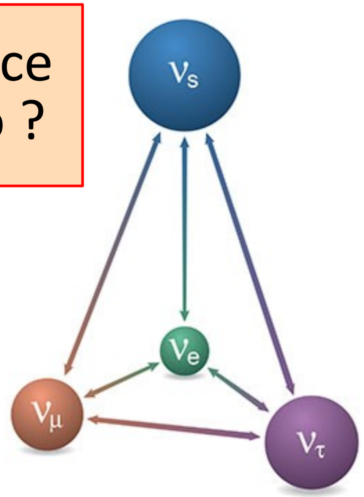
Anomalies in reactor antineutrino spectra

>1. Rate anomaly ("Reactor Antineutrino Anomaly")

- 2011 : revision of predicted neutrino fluxes for U/Pu (+3%) PRC 83:054615 (2011)
- Appearance of a deficit for very short baselines PRD 83:073006 (2011)



Extra disappearance
→ sterile neutrino ?



$$\Delta m^2_{\rm new} \sim 2\ {\rm eV}^2$$

E ≈ 2-8 MeV
→ L_{osc} ≈ 2-10 meters

- Distance detector-source → see oscillations develop
- Size of detector → observe, compare several baselines

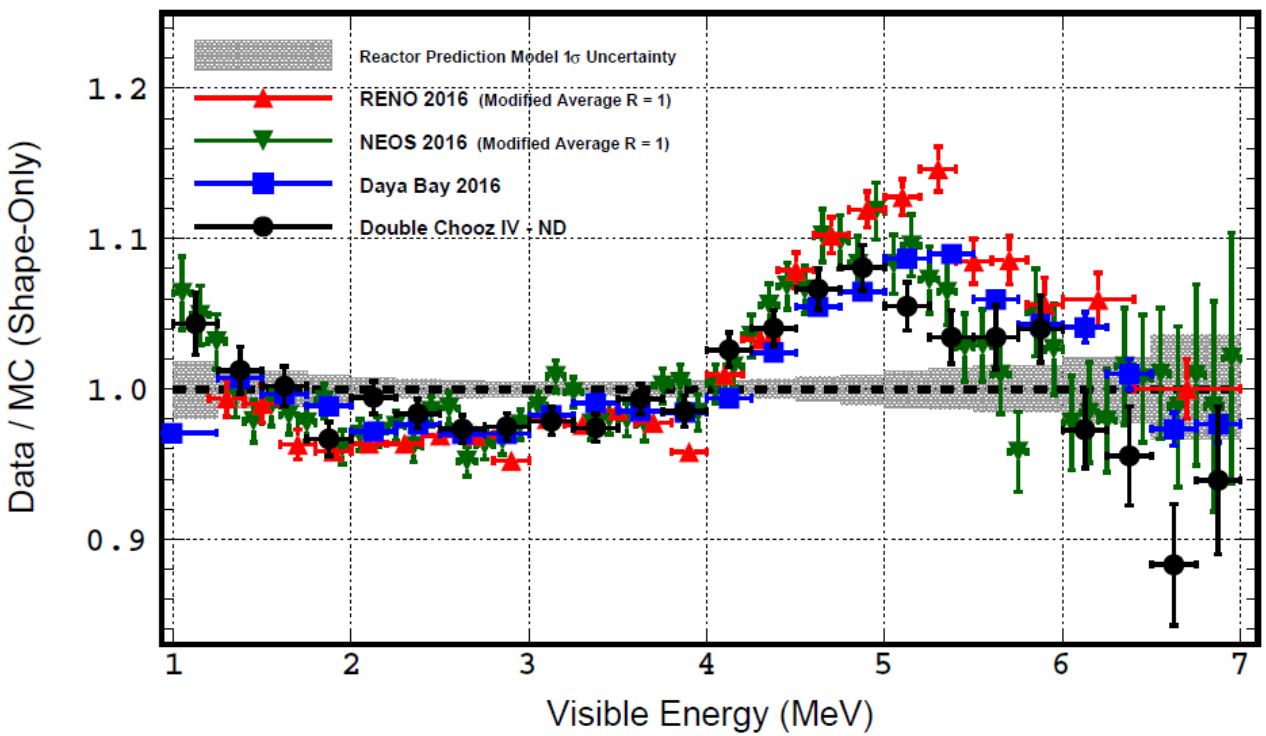
Anomalies in reactor antineutrino spectra

>1. Rate anomaly (“Reactor Antineutrino Anomaly”)

>2. Shape anomaly (“5-MeV bump”)

- Excess of events (≈10%) around 5 MeV
- Observed by recent experiments @ commercial reactors (mixed U-Pu fuel)

Nature Physics 16, 558-564 (2020)



Origin ?
Relation to fuel isotopes ?

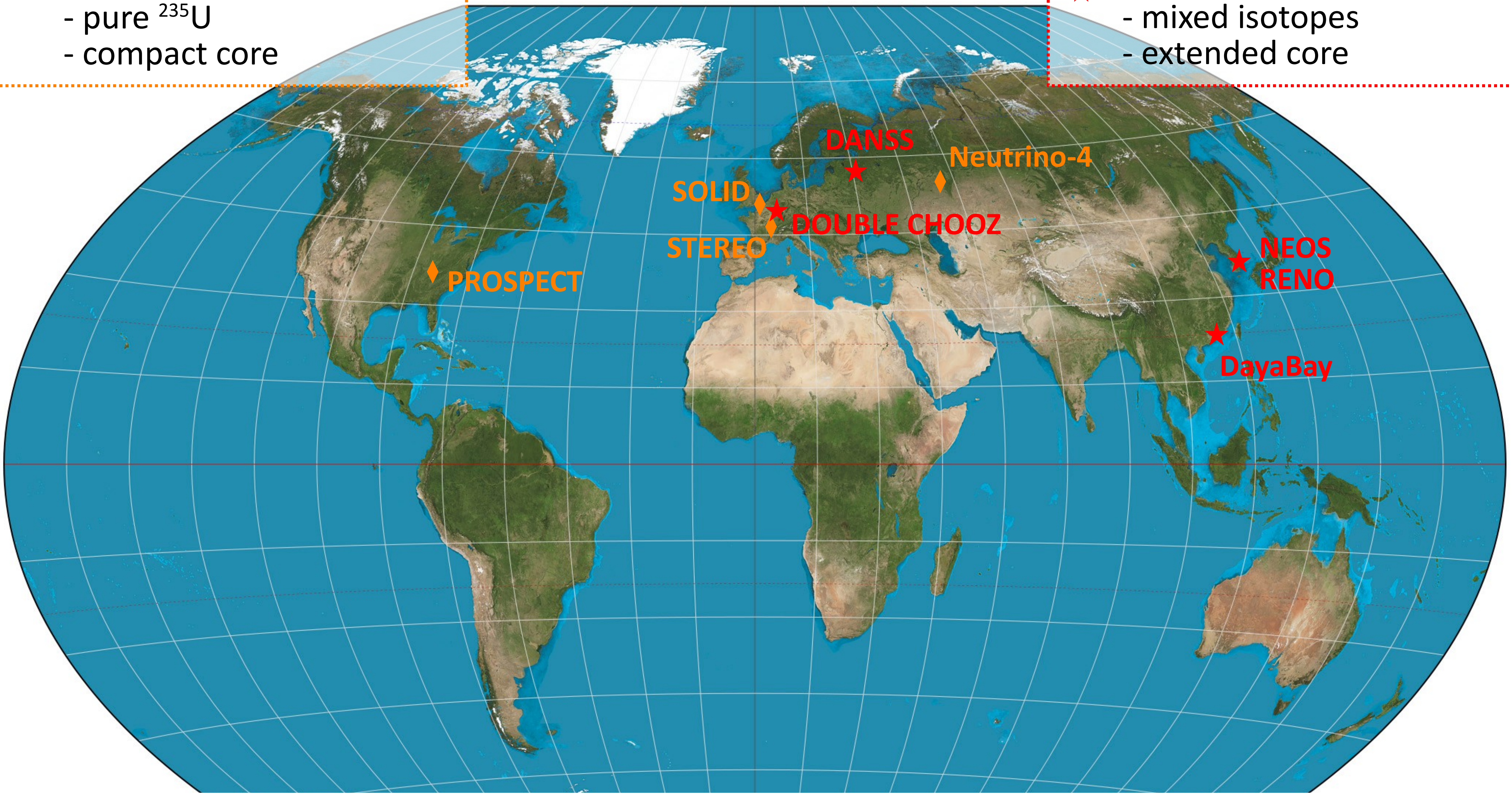
- Pure ^{235}U flux

→ disentangle isotopic contributions

A worldwide effort

♦ Research reactors (HEU)
- lower power, lower stat
- pure ^{235}U
- compact core

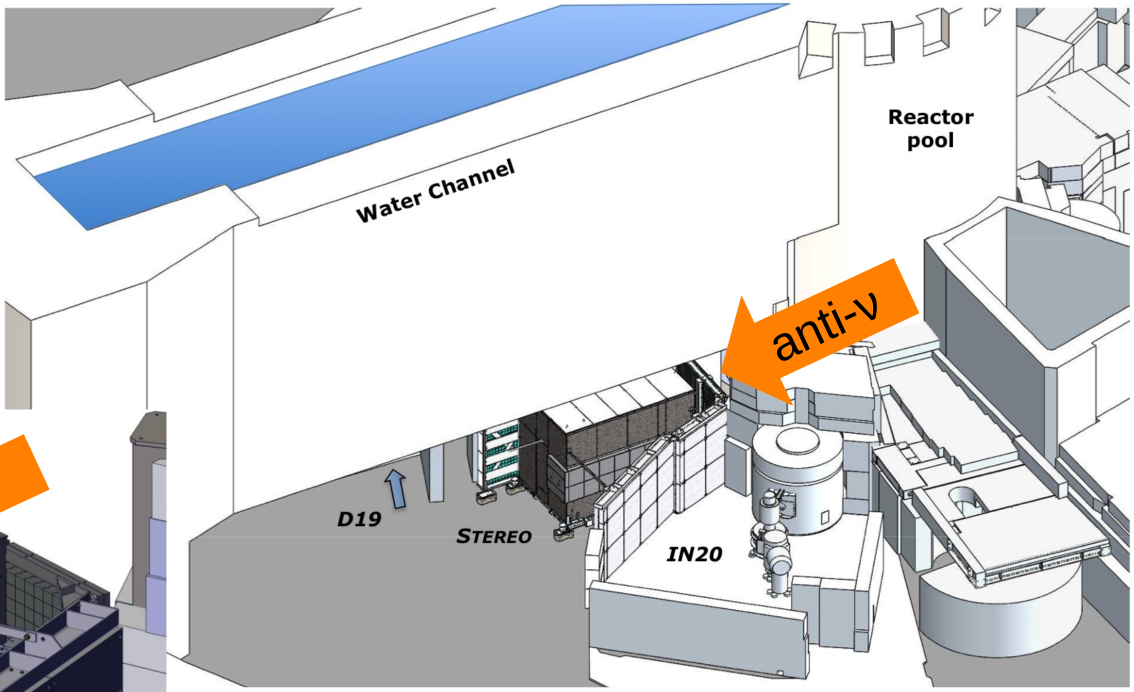
★ Commercial reactors (LEU)
- high power, high stat
- mixed isotopes
- extended core

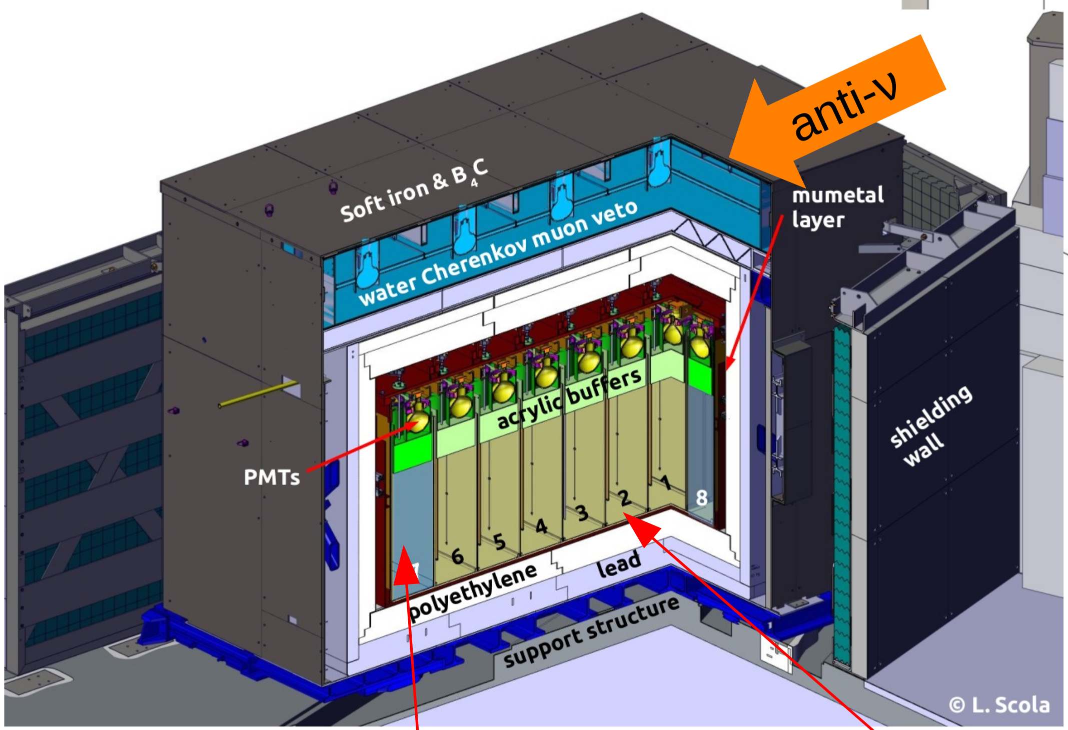


The STEREO detector

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

- Experimental site (RHF, ILL):
  - 58 MW HEU reactor
  - Compact core Ø 40cm, h=80cm
  - >99% of flux from ^{235}U fissions
  - Partial 15 m.w.e. overburden





- Detector design:
  - 6 cells: L in 9.4 – 11.2 m
  - Liquid Scintillator + Gd
  - Pulse Shape Discrimination
  - ≈ 360 ν/day, S/B = 0.8

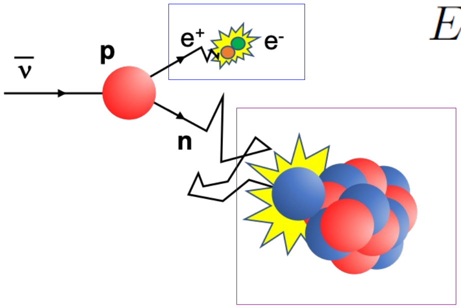
Gamma-Catcher: unloaded liquid scintillator **Target**: Gd-loaded liquid scintillator

Analysis principle

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

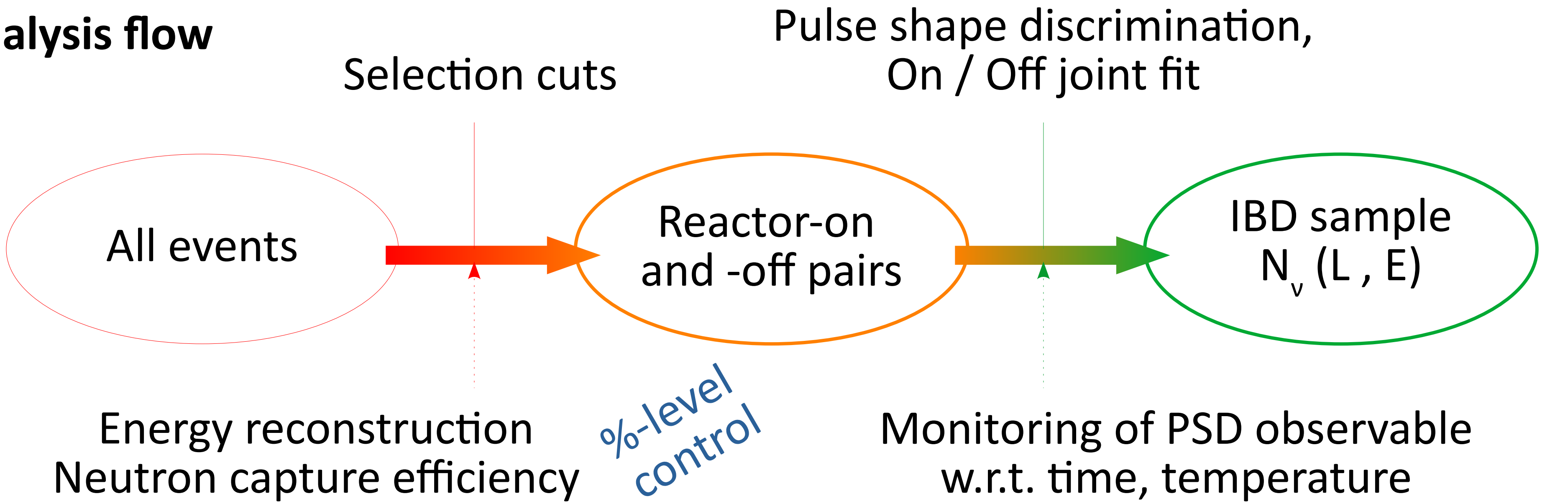
1. Prompt signal: e+ annihilation

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



2. Delayed signal: neutron capture on Gd nucleus

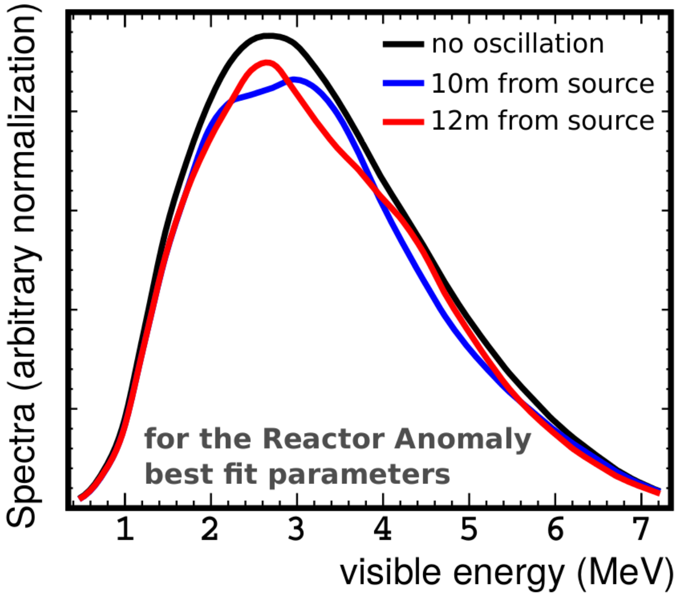
Analysis flow



Search for sterile neutrinos (2020)

Model-free sterile neutrino search

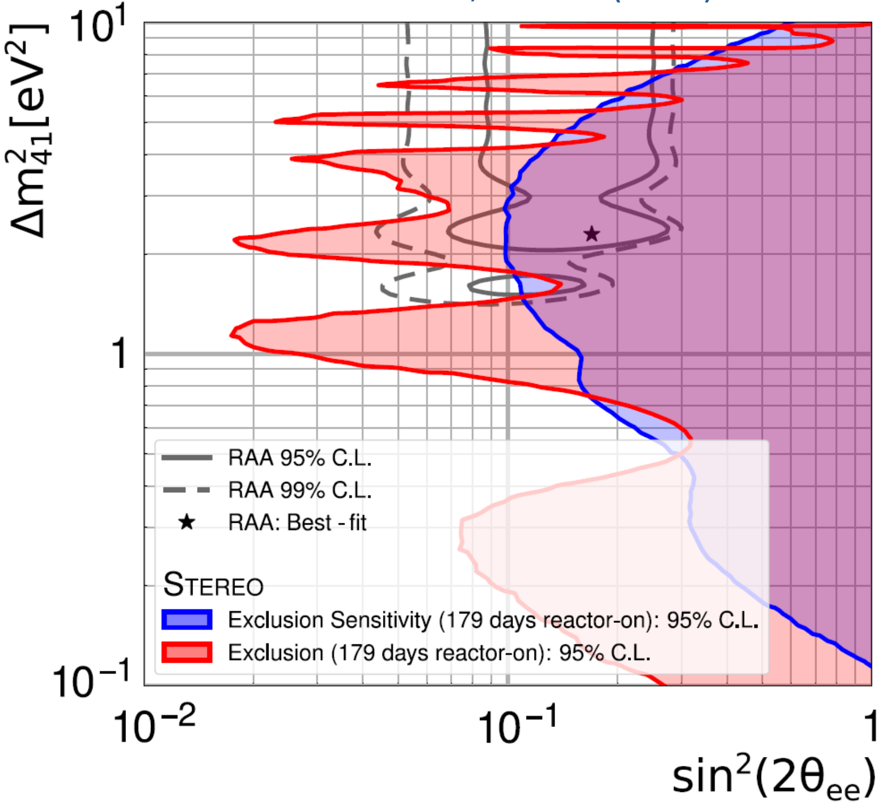
- Thanks to a segmented detector



Free model parameters φi in χ^2 to absorb distortions common to all cells
→ only cell-to-cell dependence remains
→ remove model dependence

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

PRD 102,052002 (2020)



→ RAA best-fit rejected at > 99% CL

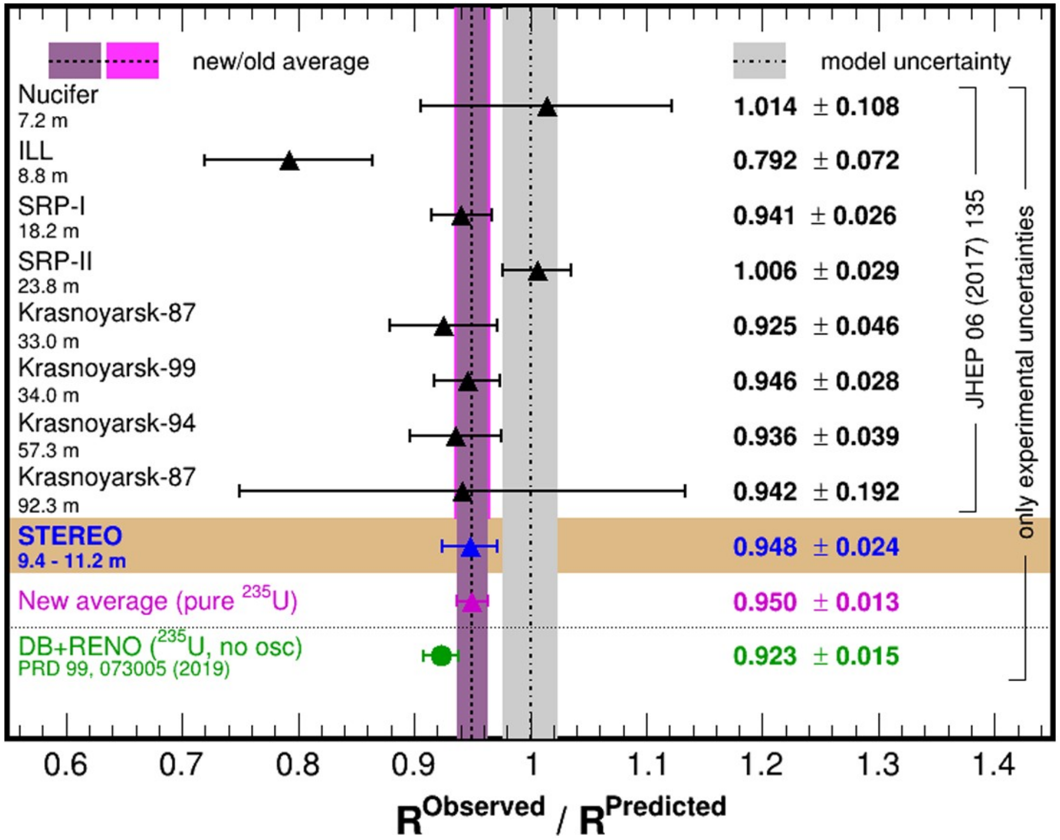
Rate deficit measurement (2020)

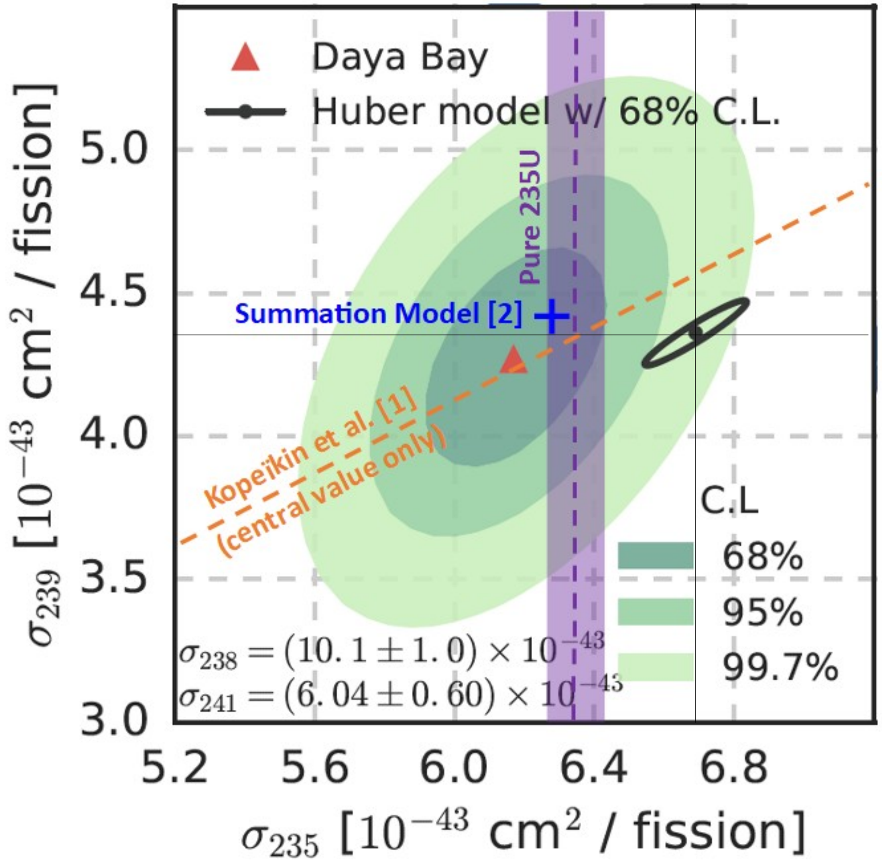
[1] arXiv:2103.01684
[2] PRL 123, 022502 (2019)

Absolute normalization of pure ^{235}U spectrum

- Measured ^{235}U deficit $(5.2 \pm 0.8[\text{stat}] \pm 2.3[\text{sys}] \pm 2.3[\text{model}])\%$

PRL 125,201801 (2020)





→ Global picture: Huber normalization for ^{235}U ≈ 5-6% too high, ^{239}Pu ≈ OK

Spectral analysis (2021)

J.Phys.G 48, 075107 (2021)

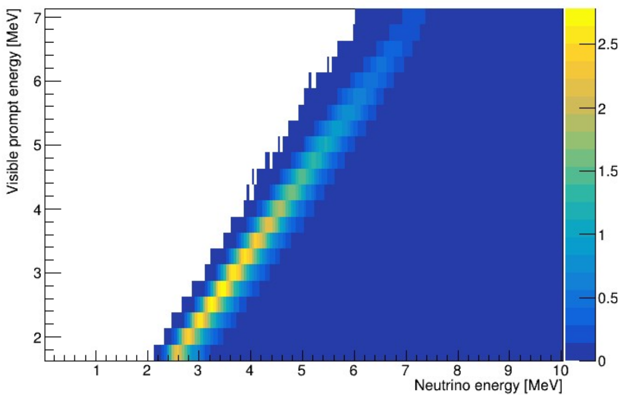
Investigation of the shape anomaly

→ Goal: provide a reference ^{235}U spectrum in E_ν (not E_{meas}) to the community

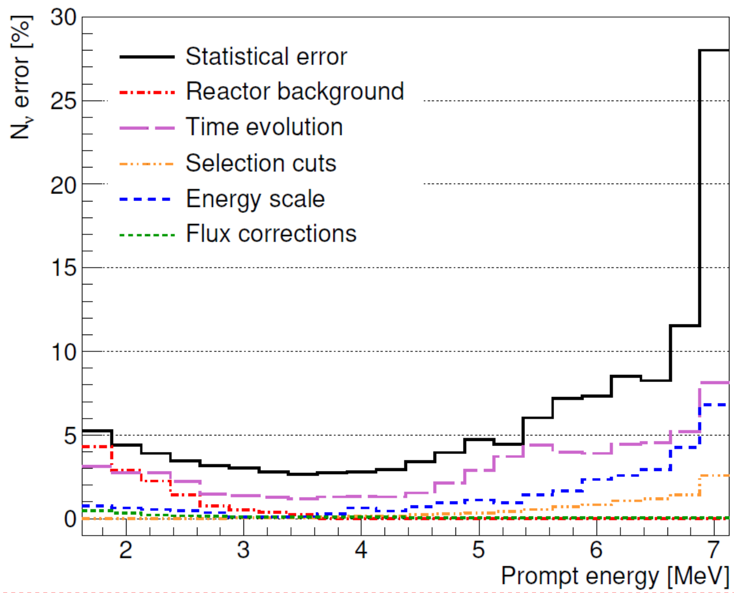
Allows: - model comparisons free of detector effects
- comparison/combination between experiments

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

Response matrix
transitions E_{pr} → E_ν



Uncertainty summary
→ statistically limited



Regularization term
controls sensitivity to noise in unfolding process

$$\mathcal{R}_1(\Phi) = \sum_i \left(\frac{\Phi}{\Phi^0}\Big|_i - \frac{\Phi}{\Phi^0}\Big|_{i+1} \right)^2$$

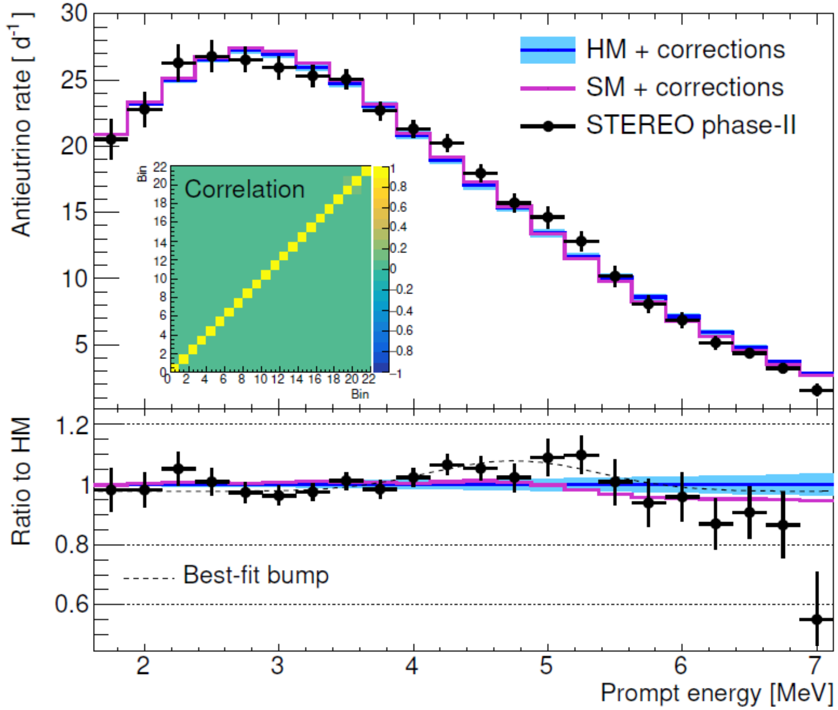
+ tunable *r*
Φ^0: prior (Huber)

Filter matrix (encoding smoothing effects) to be provided
JINST, 12, P10002 (2017)
arXiv:2102.04614

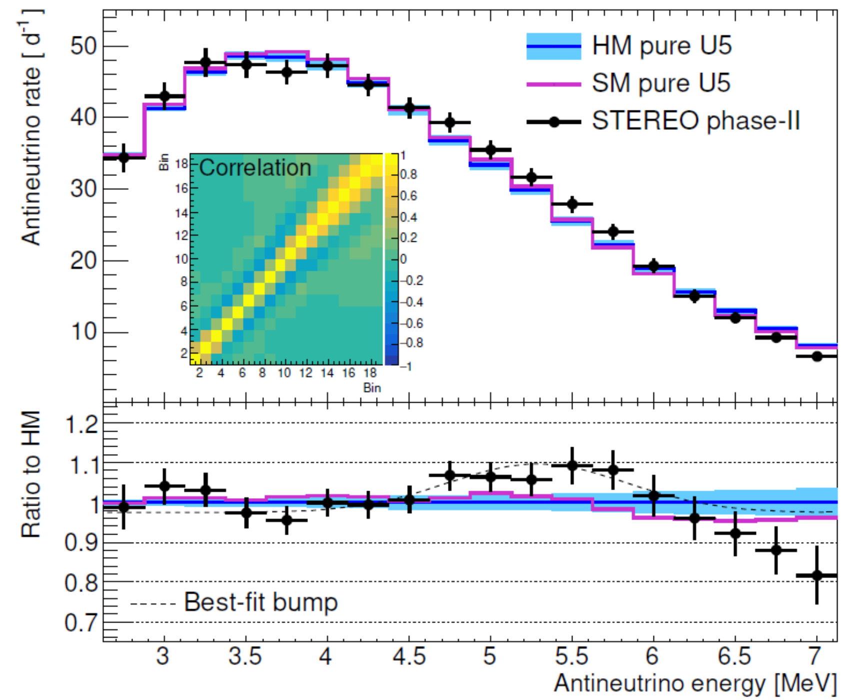
Spectral analysis (2021)

J.Phys.G 48, 075107 (2021)

Measured spectrum



Unfolded spectrum



- Significant bump is observed on the ^{235}U spectrum $A = 12.1 \pm 3.4\%$
- Bump at LEUs would lead to :
  - A ≈ 9% if equally shared by all isotopes
  - A ≈ 16% if due to pure ^{235}U

→ no strong preference

- Unfolded spectrum available for reference on HEPData

STEREO/PROSPECT joint spectral analysis (coming soon)

Goal: increase the physics reach of both experiments by combining data sets

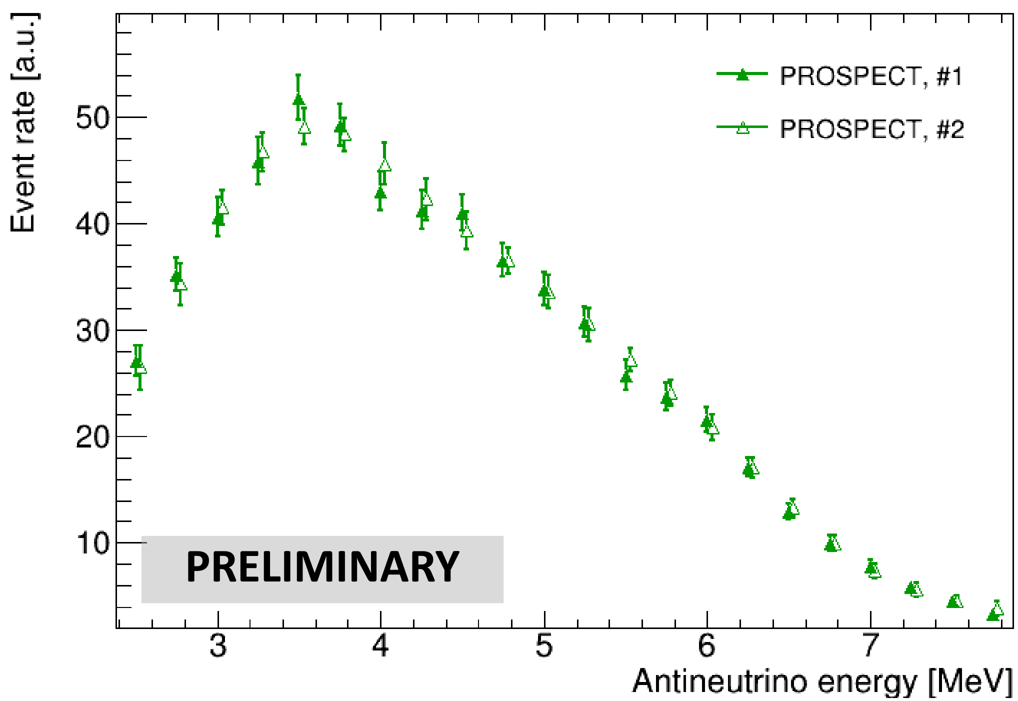
→ **Joint collaboration**

>1 Validation of frameworks

- #1: STEREO's method with covariance matrix
- #2: PROSPECT's method: Wiener-SVD unfolding (regularization optimized wrt S/B JINST, 12, P10002 (2017))

→ Consistent results

Unfolding of PROSPECT data with several methods →



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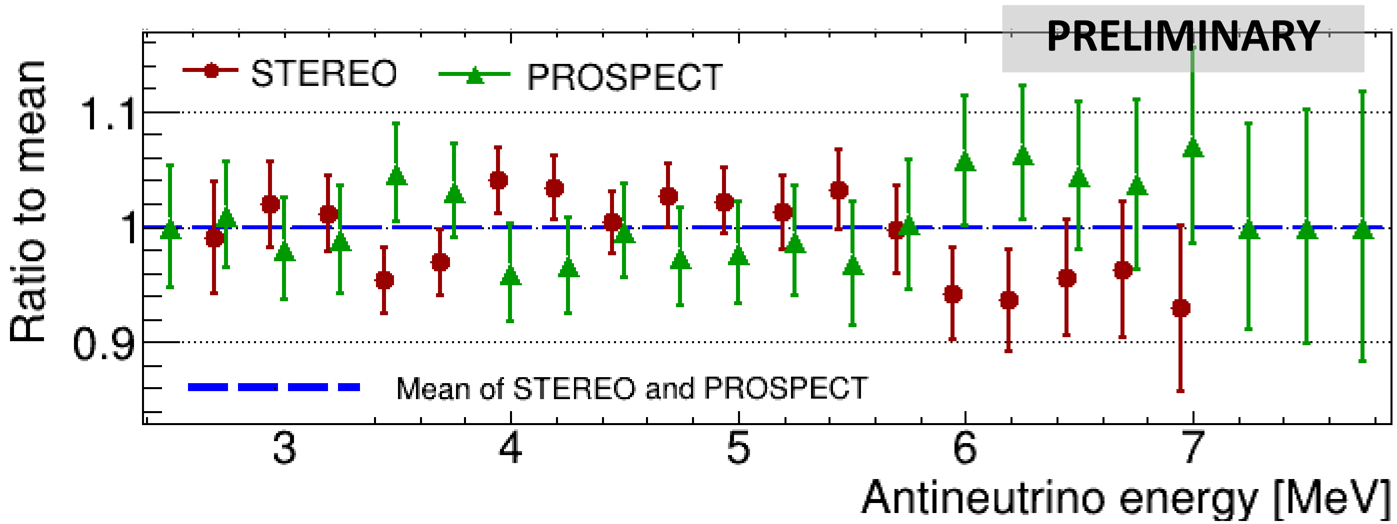
>2 Compatibility of spectral measurements

→ χ^2 = 22.3/17 (p-value: 0.17)

→ Statistically compatible



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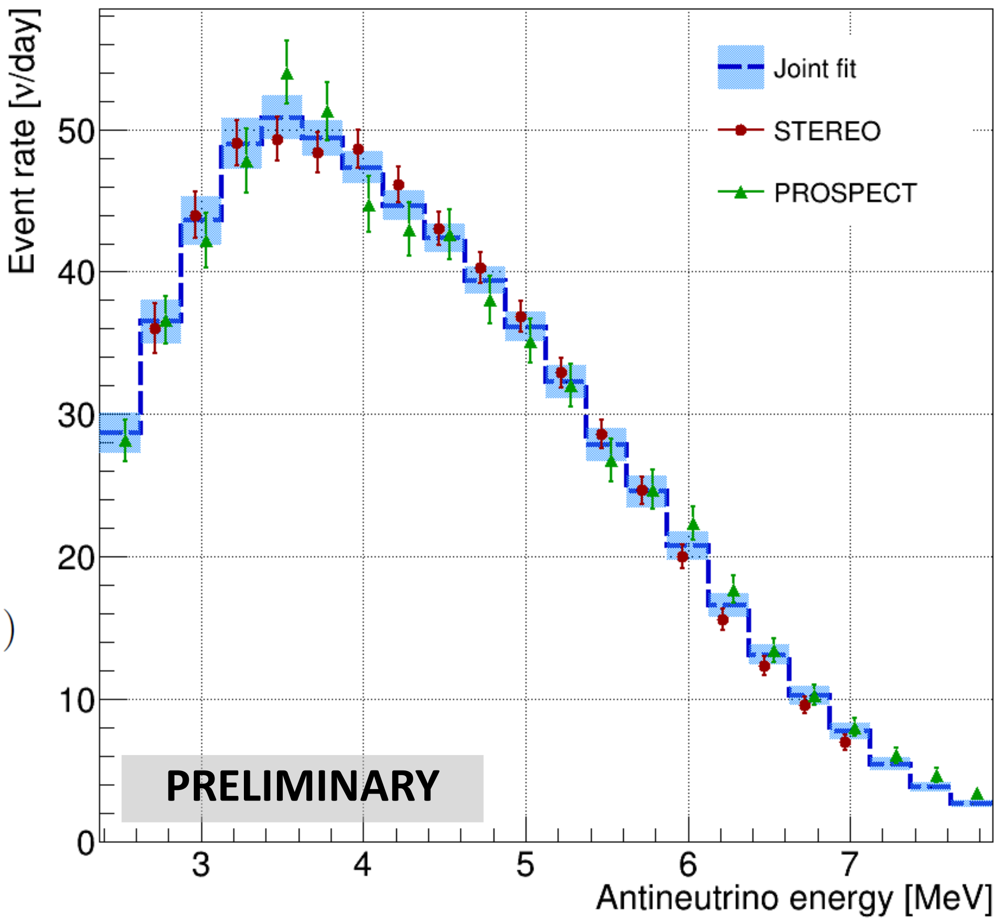
>3 Extension to a joint fit

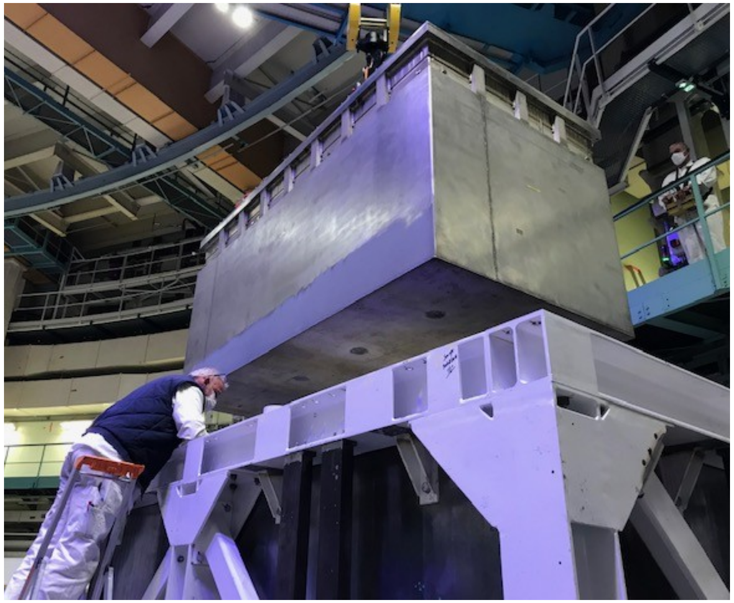
$$\chi^2(\Phi) = \left(R_{\mathrm{ST}}\Phi - D_{\mathrm{ST}}\right)^T V_{\mathrm{ST}}^{-1}\left(R_{\mathrm{ST}}\Phi - D_{\mathrm{ST}}\right) + \left(R_{\mathrm{PR}}\Phi - D_{\mathrm{PR}}\right)^T V_{\mathrm{PR}}^{-1}\left(R_{\mathrm{PR}}\Phi - D_{\mathrm{PR}}\right) + r \cdot \mathcal{R}_1(\Phi)$$

- To be published with *filter matrix* encoding unfolding effects



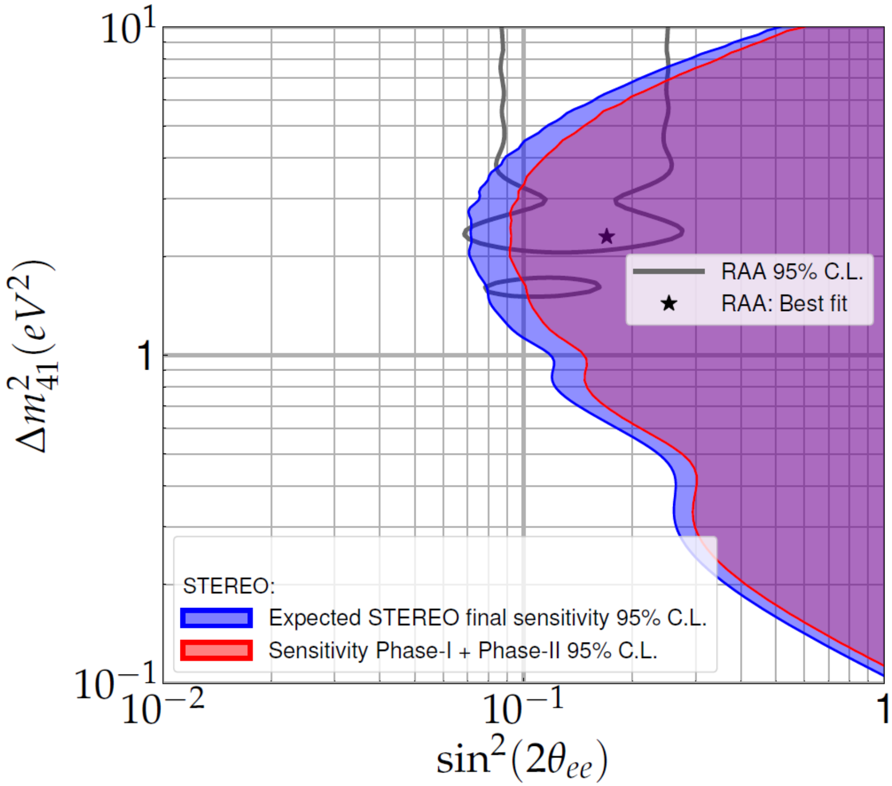
Future of STEREO

- December 2020: dismantling
- Phase-III data currently analyzed (≈ half of total data)
  - Improved sensitivity for sterile search
  - Improved spectral analysis



Detector extracted from shielding

Final STEREO sensitivity with phase-III



Summary

STEREO has successfully run for 5 years, 160k+ antineutrinos detected !

>1. Rate anomaly

- **Sterile hypothesis** (RAA best-fit point) **rejected at >99% CL** by a model-independent analysis
- Most accurate ^{235}U deficit, HEU world-average now at (5.0±1.3)%
- Global picture: ^{239}Pu norm about right, **^{235}U carries most of the deficit**

>2. Shape anomaly

- Confirmation of a *O*(10%) **bump in pure-^{235}U spectrum**
- **Unfolded antineutrino spectrum**:
  - available to the community
  - complementary to ^{235}U spectrum extracted at LEU
- Joint analysis with PROSPECT to be released soon

And twice more data to come!

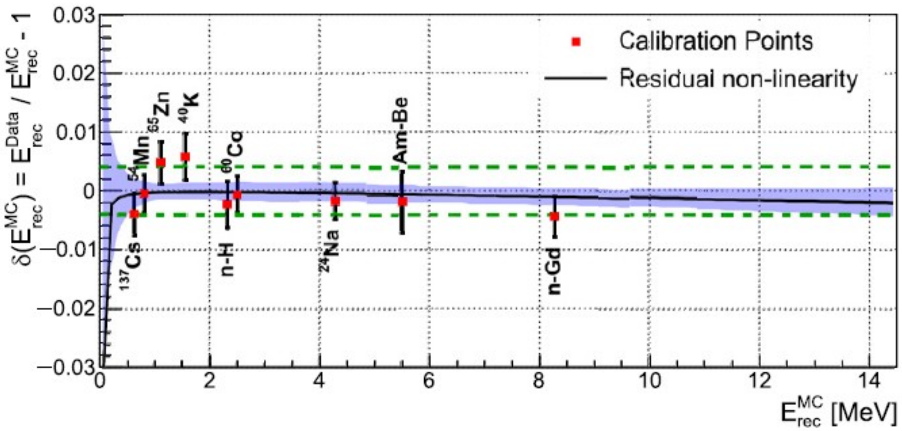
Thank you for your attention !

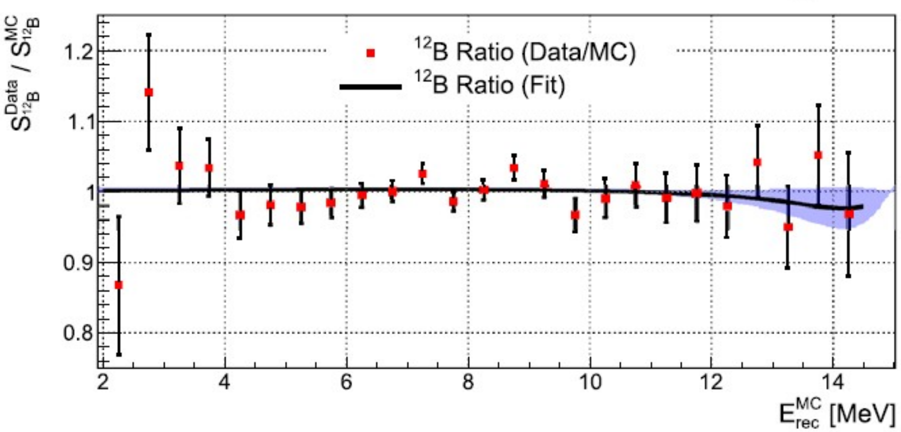
Supplementary slides

Calibration and response

→ Accurate energy reconstruction

- Weekly calibration runs with sources
- Cosmogenic 12B spectrum (continuous)



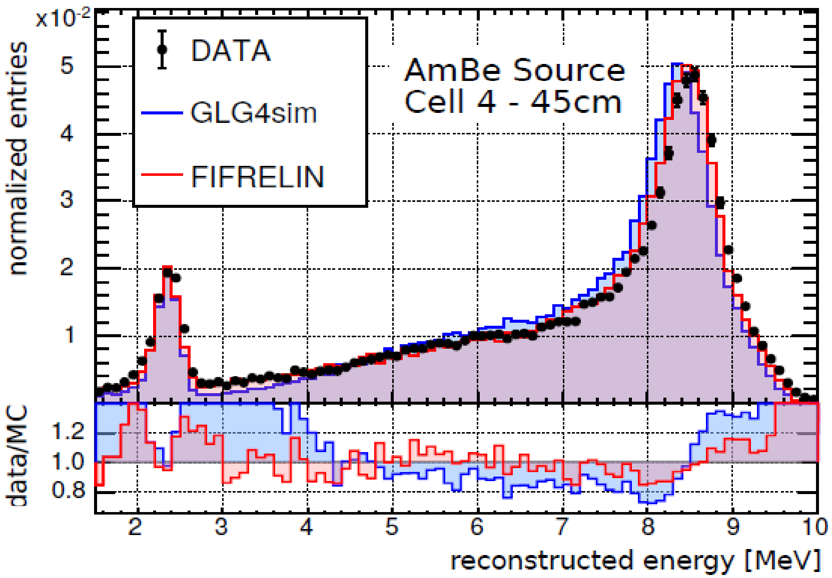


→ Neutron capture efficiency

- Improved cascade modelling

  thanks to the FIFRELIN code

Eur.Phys.J.A 55 (2019) 10, 183



STEREO : energy reconstruction

Accurate energy reconstruction is crucial
- for oscillation analysis (L/**E** term)
- for spectrum analysis

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

>1 Calibration sources

- in each cell, at 5 different heights

>2 ^{12}B spectrum

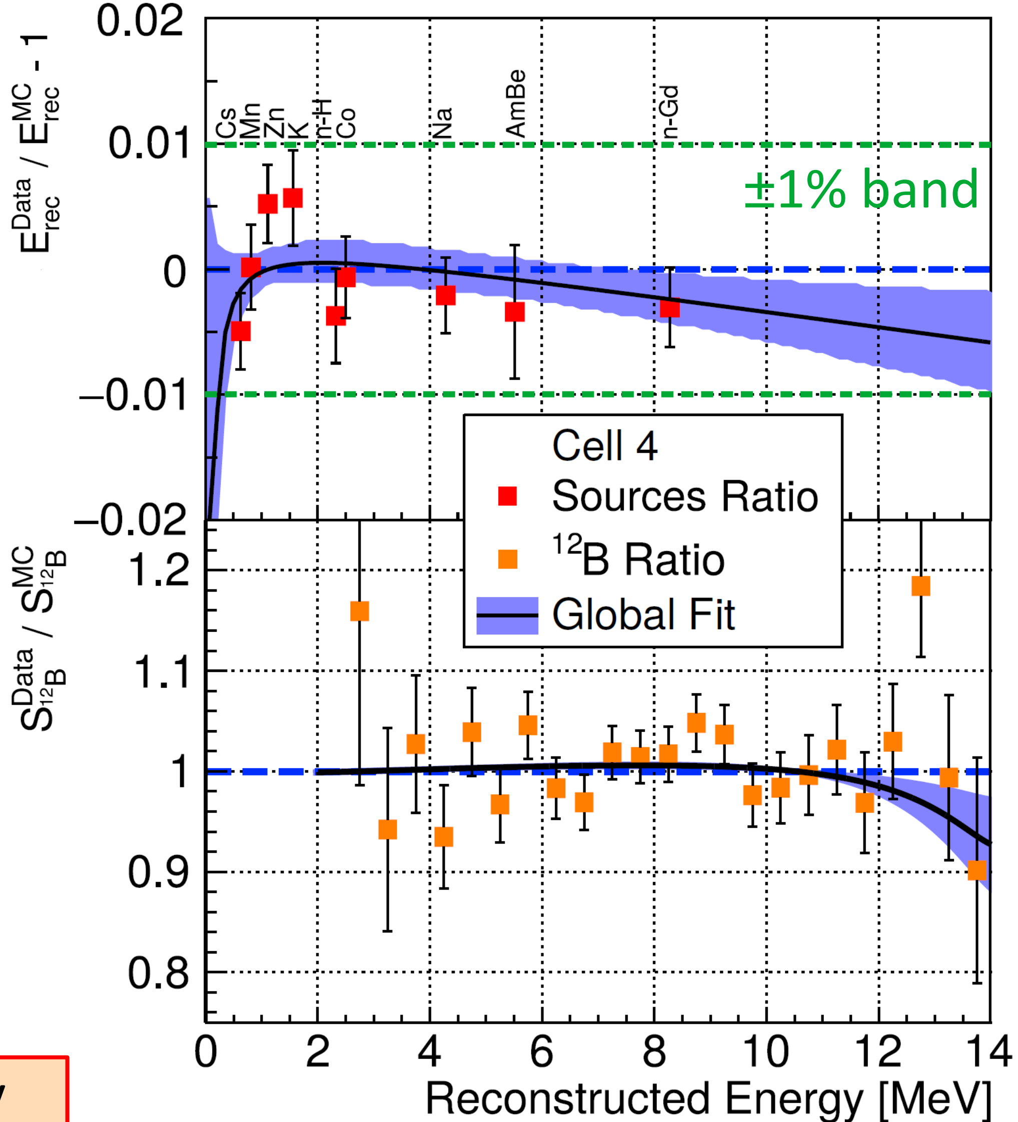
- Continuous spectrum, Q_β = 13.4 MeV

>3 Global fit

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

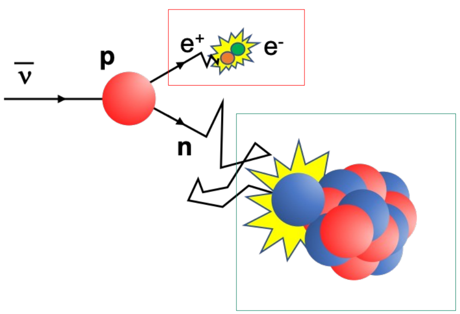
→ Data/MC agree with 1% accuracy

PRD 102,052002 (2020)

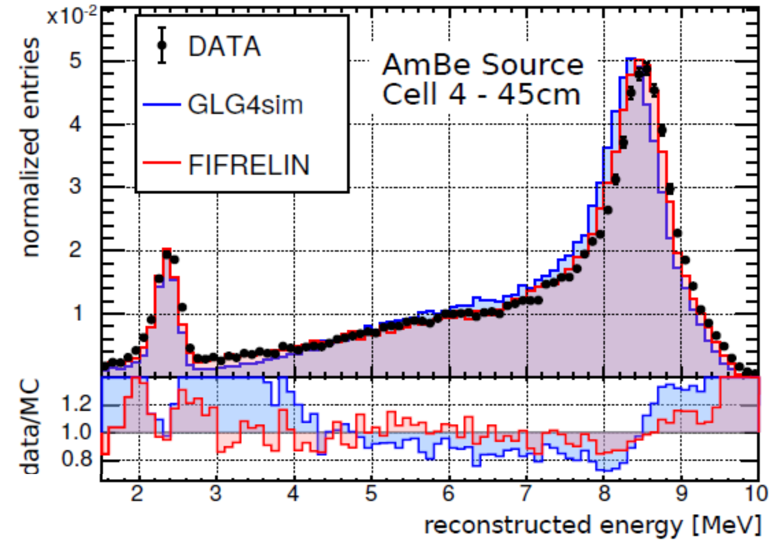


STEREO : capture efficiency

Capture efficiency:
→ Key for absolute rate measurement

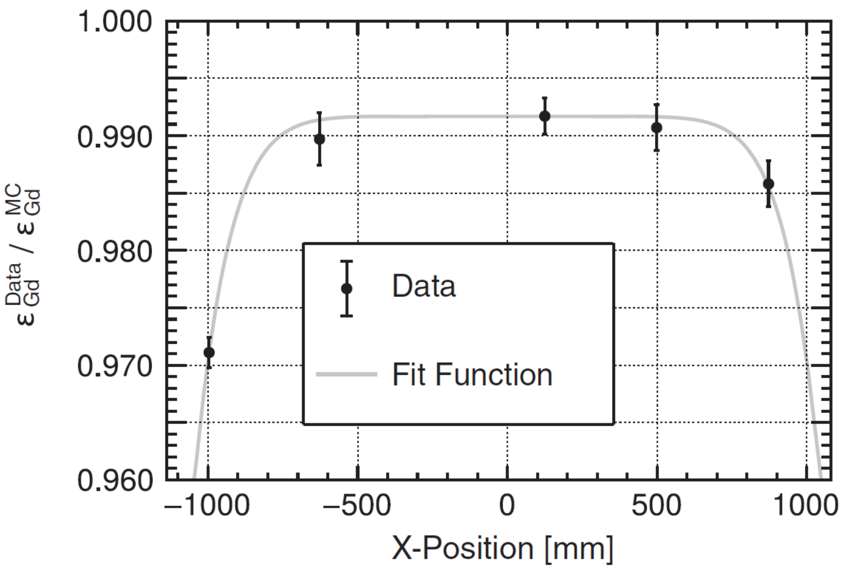


2. Delayed signal: neutron capture on C, H or Gd
→ de-excitation cascade



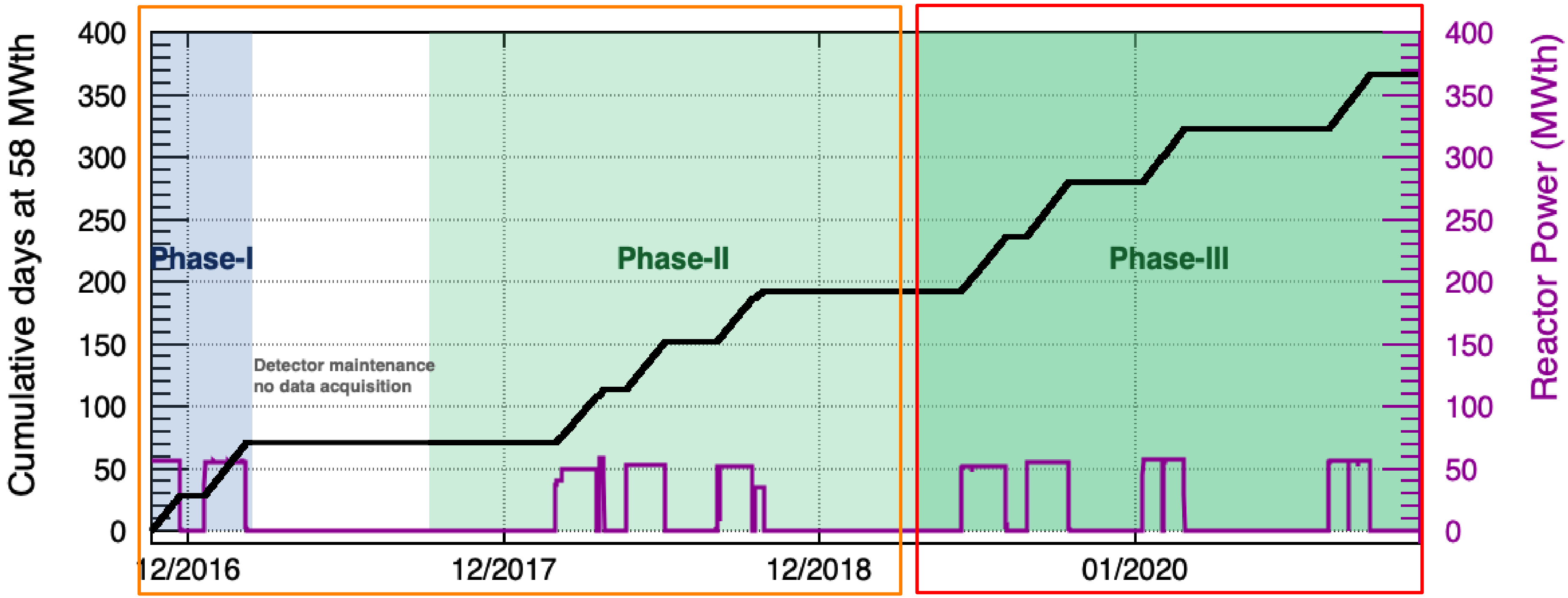
1. Cascade modelling
   → improved predictions by the FIFRELIN code
   → made available to the community
   Eur.Phys.J.A 55 (2019) 10, 183

2. Correction for data/MC difference
   → Neutron physics, Gd uniformity...



Data taking

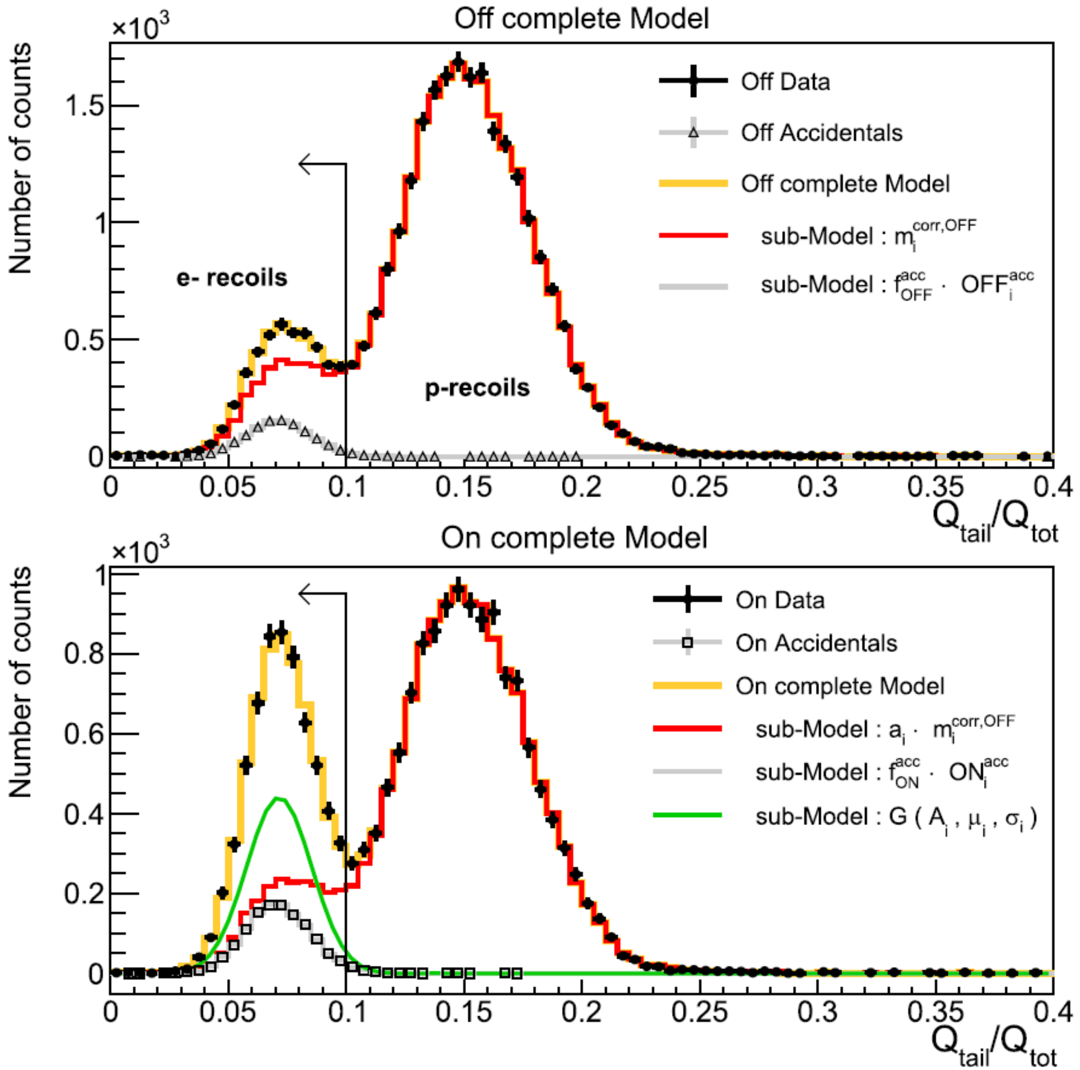
on-off alternation



Published STEREO data

Currently analyzed

PSD fit

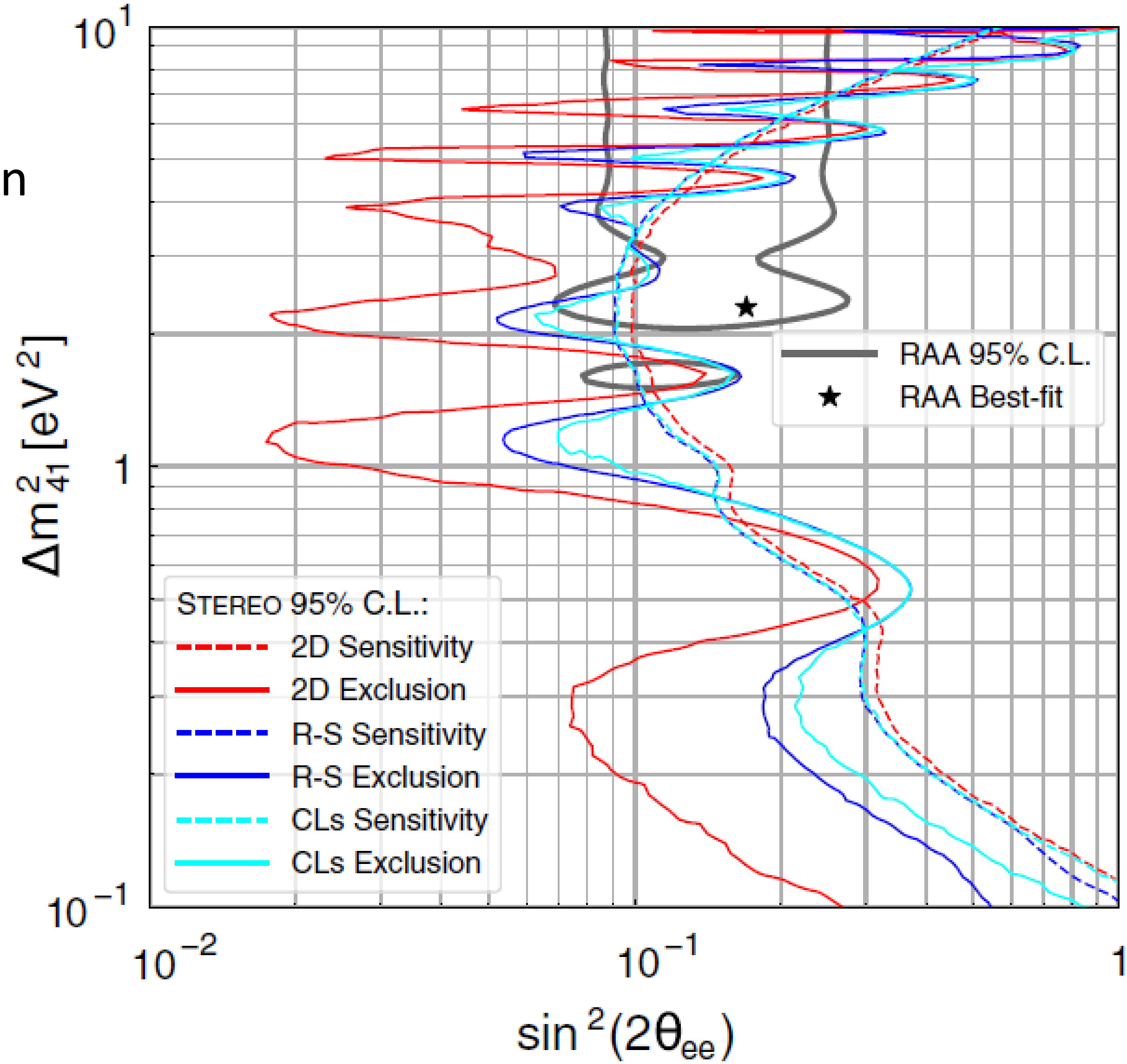


$$\mathrm{ON}_{i,p} = a_i\, m_{i,p}^{\mathrm{corr,OFF}} + f_{\mathrm{ON}}^{\mathrm{acc}}\, \mathrm{ON}_{i,p}^{\mathrm{acc}} + G_\nu(A_i, \mu_i, \sigma_i^2),$$

$$\mathrm{OFF}_{i,p} = m_{i,p}^{\mathrm{corr,OFF}} + f_{\mathrm{OFF}}^{\mathrm{acc}}\, \mathrm{OFF}_{i,p}^{\mathrm{acc}},$$

Oscillation analysis : methods

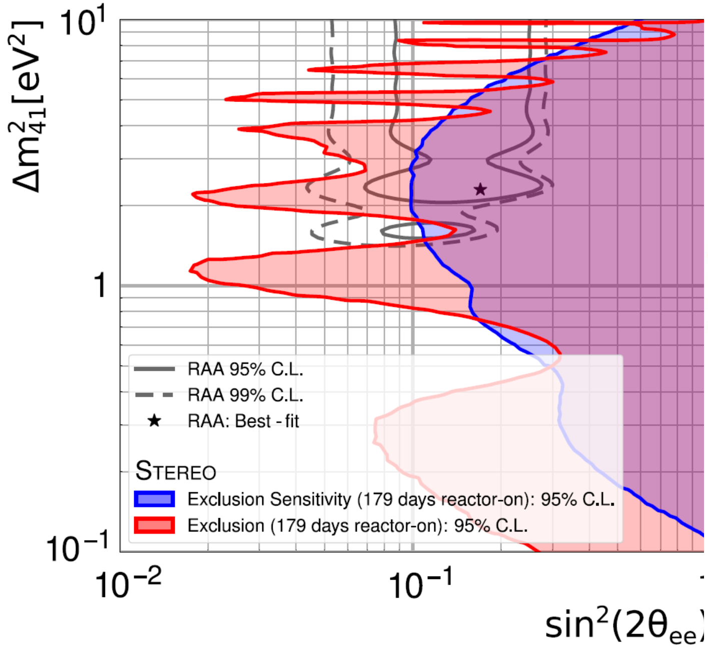
P-value for no-oscillation hypothesis is 9% (2D)



Oscillation analysis : results

STEREO

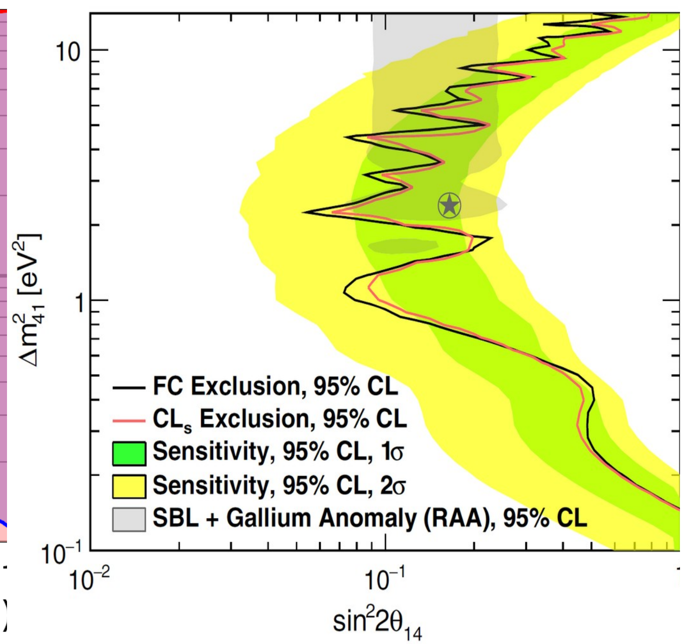
PRD 102,052002 (2020)



RAA excluded > 99% CL

PROSPECT

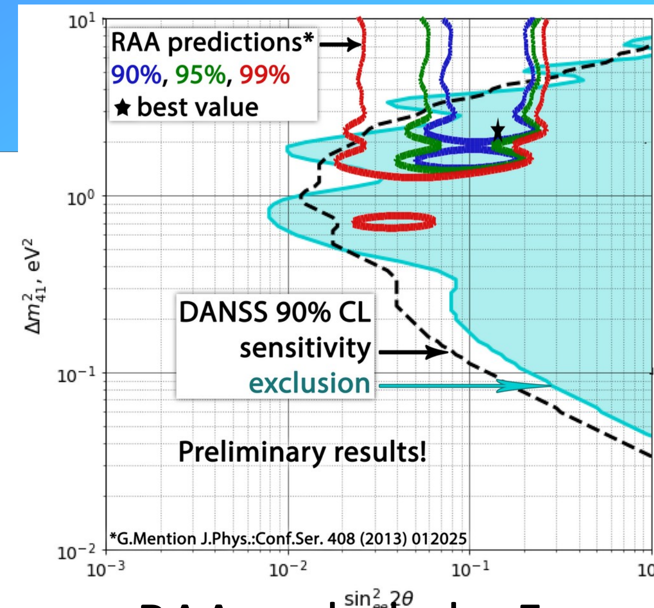
PRD 103:032001 (2021)



RAA excluded > 95% C

DANSS

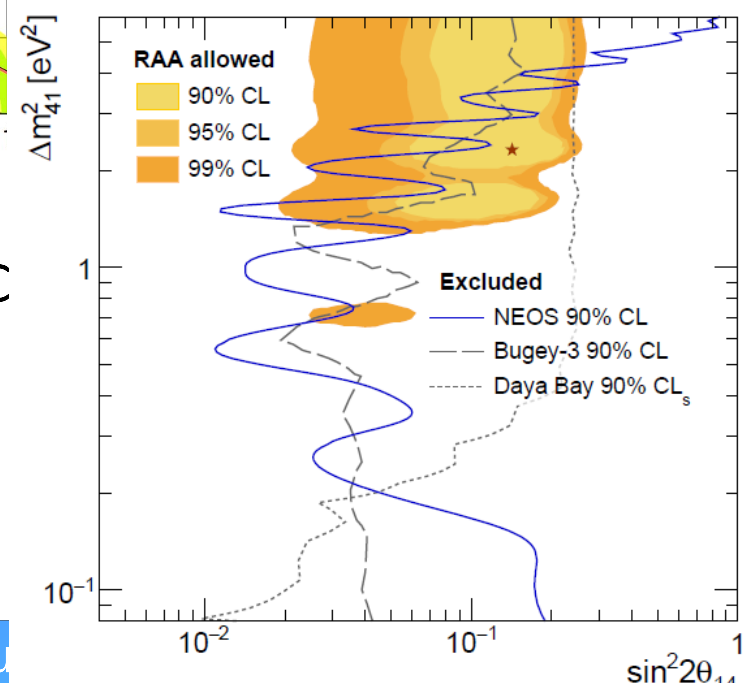
arXiv:2012.10255



RAA excluded > 5σ

NEOS

PRL 118, 121802 (2017)

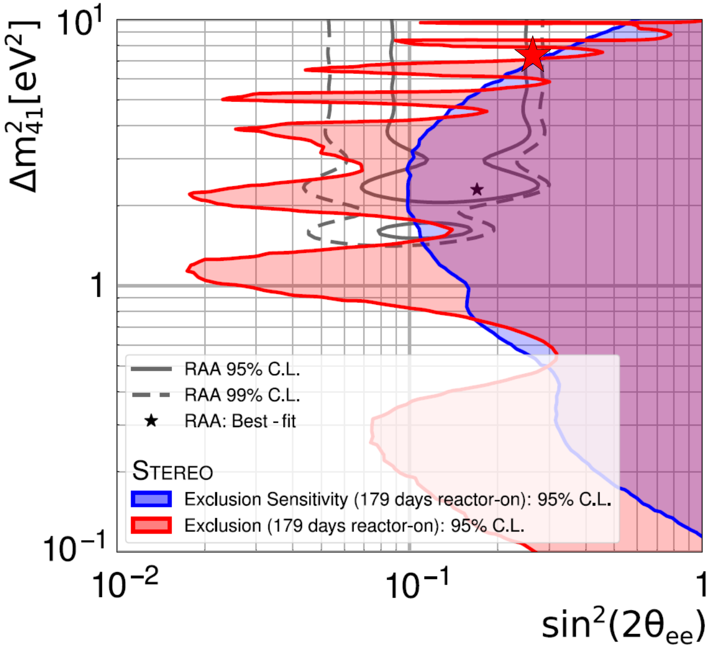


→ Strong experimental rejection of the RAA sterile hypothesis

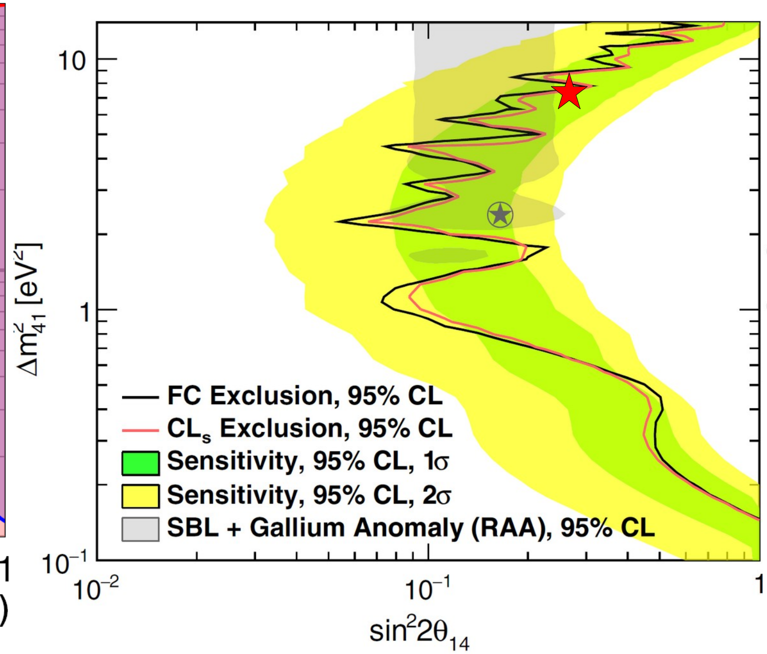
Neutrino-4 best-fit point

arXiv:2005.05301
JETP Lett 112 (2020) 4

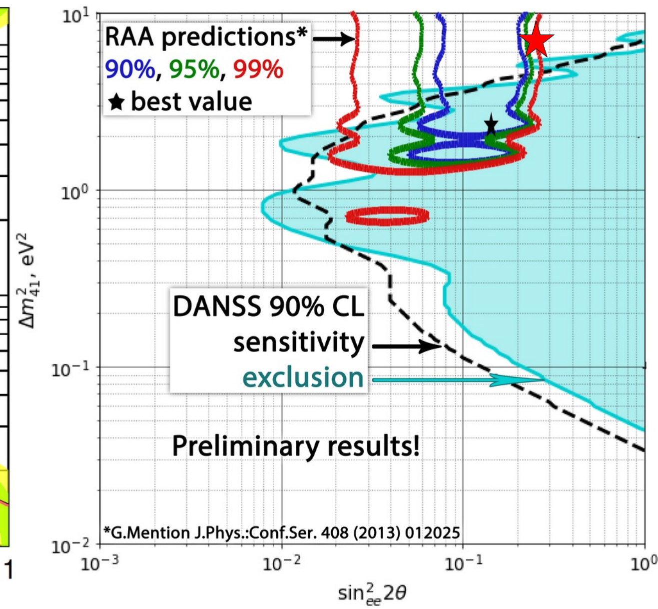
STEREO

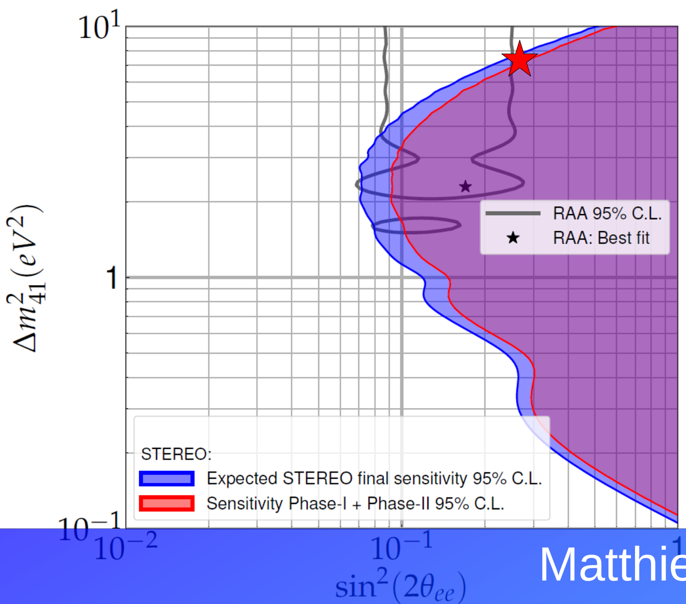


PROSPECT



DANSS





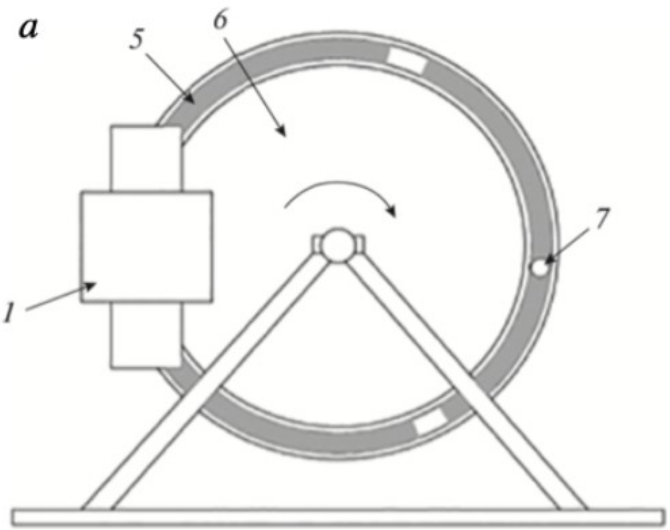
★ Neutrino-4 best-fit point
$\Delta m^2_{14} = 7.2\ eV^2$, $\sin^2 \Theta_{14} = 0.26$

Kopeikin et al.

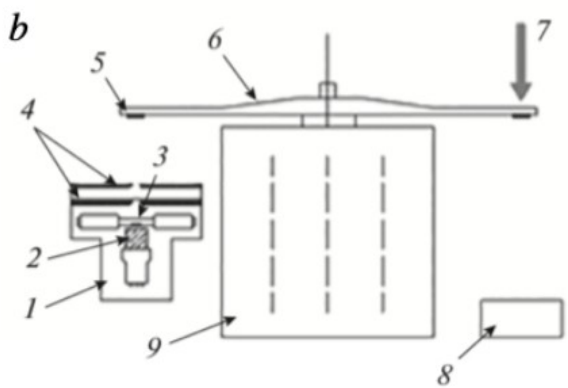
arXiv:2103.01684
Physics of Atomic Nuclei 84, 3 (2021)

Measurement of the β-spectrum ratio $\rho_\beta^5/\rho_\beta^9$

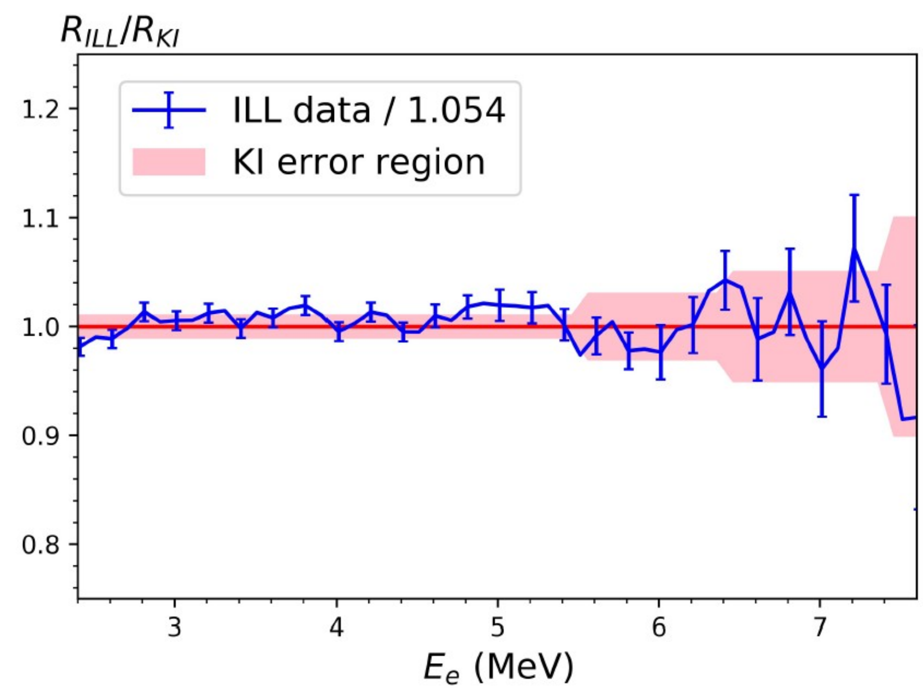
Back view



Top view



1: spectrometer 5: $^{235}U/^{239}Pu$/empty foils
6: spinning wheel (10rot/min) 7: n beam



New inputs for the conversion method (Huber, Mueller)

ν spectrum ratio $^{235}U/^{239}Pu$ reduced by -5.4% ?

Shape analysis : methods & validation

2 independent & complementary frameworks

>1 Covariance matrix

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

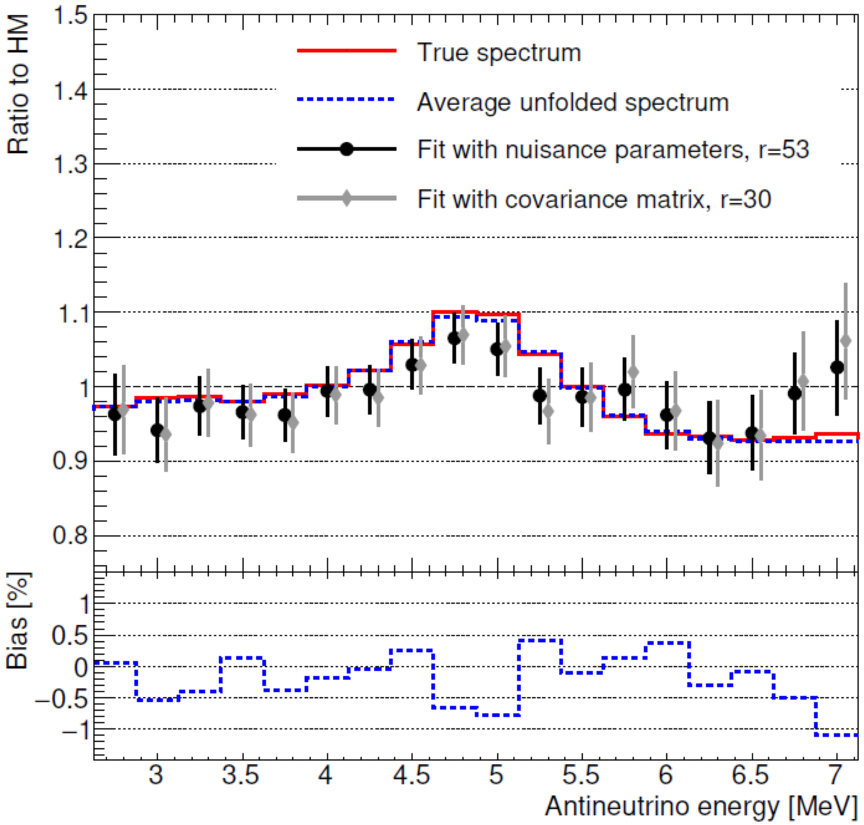
r tuned with General Cross Validation (information theory)
Wahba et al, Technometrics 21, n°2, 1979

>2 Nuisance parameters

$$\chi^2(\Phi) = (R(\vec{\alpha})\Phi - D)^T V_{\text{stat}}^{-1} (R(\vec{\alpha})\Phi - D) + |\vec{\alpha}|^2 + r \cdot \mathcal{R}_1(\Phi)$$

r tuned to limit prior dependence

Validation with bumped toy models: →
1- comparison of the two frameworks on a single pseudo-data set
2- average bias <1%



Well controlled unfolding process

Shape analysis : best-fit bump

Parameter	Antineutrino energy		Prompt energy	
	HM + bump	SM + bump	HM + bump	SM + bump
Amplitude A (%)	12.1 ± 3.4	11.8 ± 3.6	10.1 ± 2.9	10.1 ± 3.1
Mean energy μ (MeV)	5.29 ± 0.18	5.47 ± 0.21	4.75 ± 0.21	4.94 ± 0.25
Width σ (MeV)	0.55 ± 0.17	0.60 ± 0.20	0.63 ± 0.17	0.69 ± 0.19
Goodness of fit χ^2/nbins	12.3/18	9.1/18	15.6/22	12.5/22

Daya Bay (2017): μ ≈ 5.7 MeV, σ ≈ 0.6 MeV
Daya Bay (2021): μ ≈ 6.0 MeV, σ ≈ 0.6 MeV

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**

$$H(\lambda) = \boxed{A_M(\lambda)} \cdot \boxed{H(0)}$$

Filter matrix — Un-regularized unfolding

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

$$\chi^2 = \left(\boxed{A_C \overline{s}} - \boxed{\hat{s}}\right)^T V_{\hat{s}}^{-1} \left(A_C \overline{s} - \hat{s}\right) = \left(\overline{s} - \hat{s}_{\text{unfilt}}\right)^T V_{\hat{s}_{\text{unfilt}}}^{-1} \left(\overline{s} - \hat{s}_{\text{unfilt}}\right)$$

Filtered model — Unfolded spectrum (filtered)

Hypothetical unfolded spectrum with no regularisation

Its covariance

Comparison in "filtered space" — Comparison in "unfiltered space"

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