The STEREO Experiment

Loris Scola

Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications

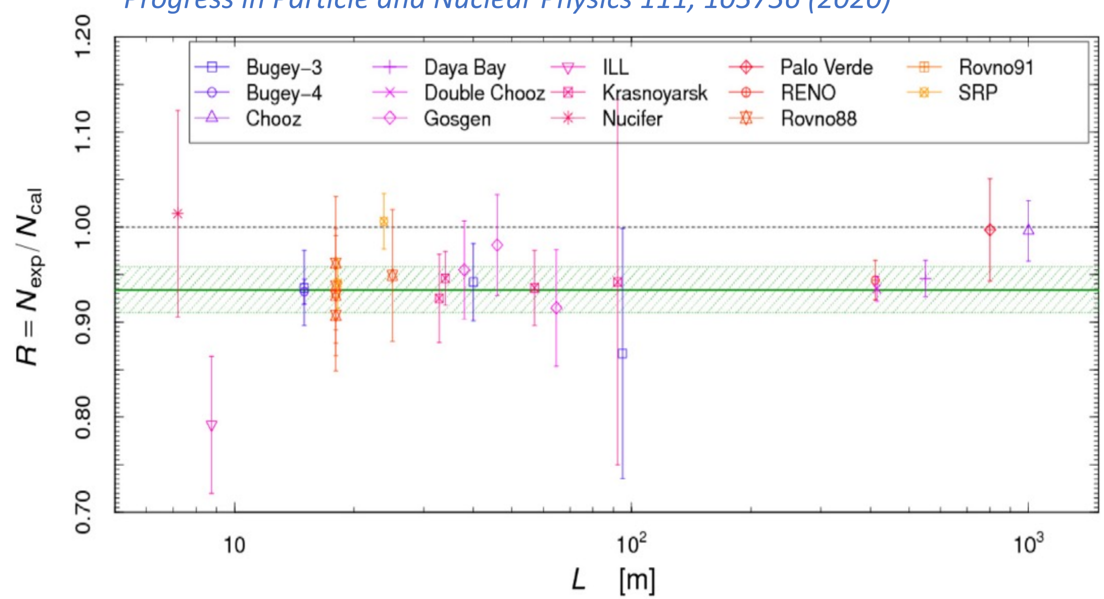
David Lhuillier

Vienna, Jan 2023

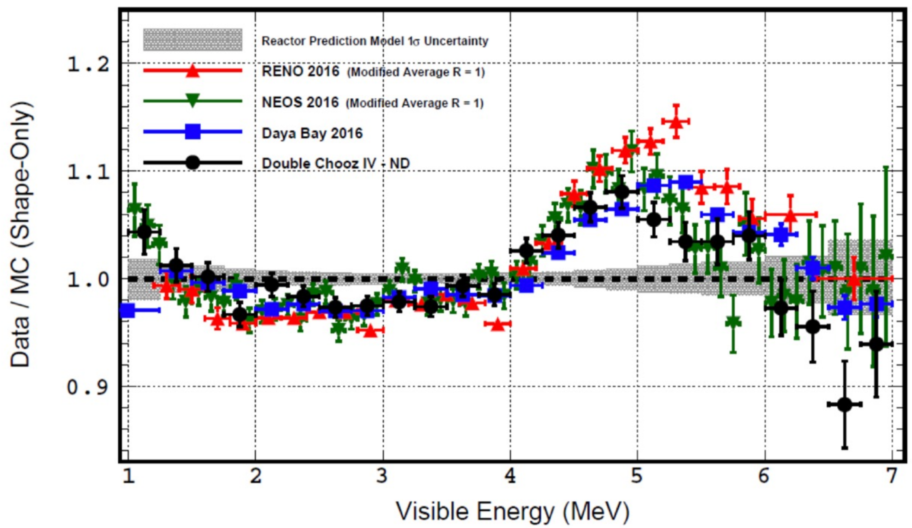
Reactor Antineutrino Anomalies

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)



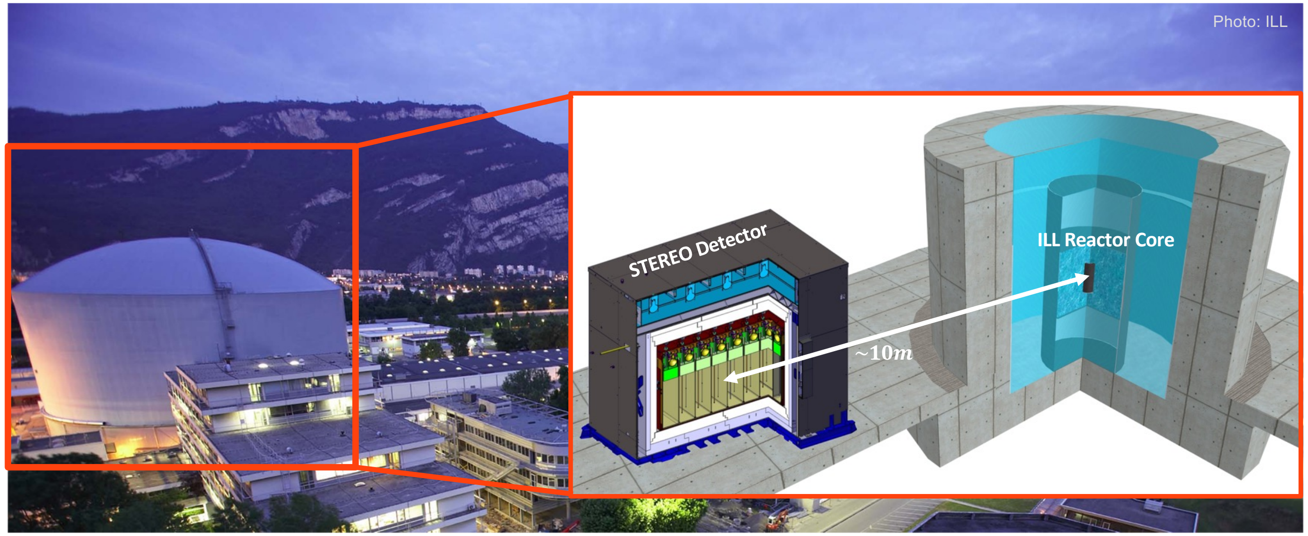
Nature Physics 16, pp. 558–564 (2020)



``5 MeV Bump''
~10% spectral disortion w.r.t. Huber-Mueller prediction.

New physics or prediction bias?

STEREO main goals



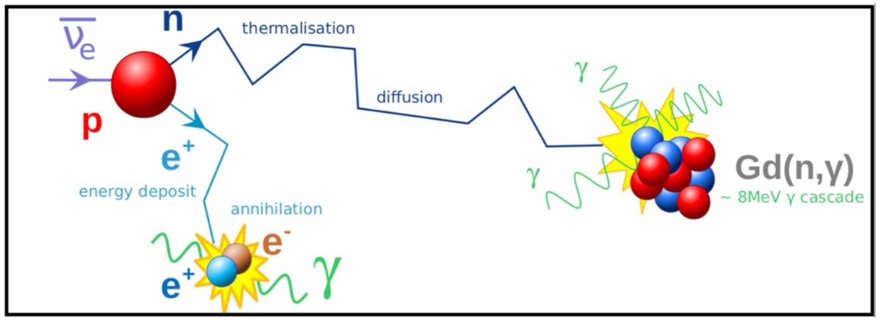
- ❑ **Pure** contribution of ^{235}**U** to the reactor anomalies.
- ❑ **Test of sterile hypothesis**, with a **model-independent** oscillation analysis.
- ❑ **Reference neutrino spectrum of the ^{235}U fission**
  - Precise absolute rate.
  - Precise spectrum shape.

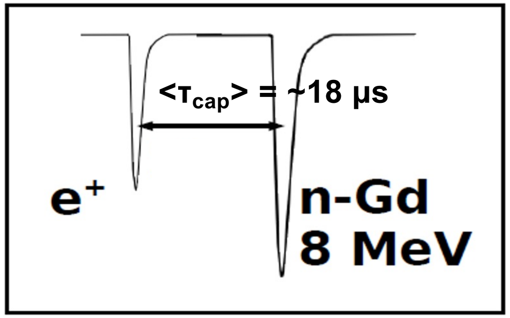
➢ Antineutrino source : research reactor of Institut Laue-Langevin (ILL), Grenoble –France:
- **HEU** fuel (93% enriched)
- **Compact** core (≤1 m)
- P_{th} = 58 MW_{th}

➢ Detector:
- **Very short-baseline** (9-11m)
- Segmented with **6 identical cells**.
- **% level control** of the **detector response**.

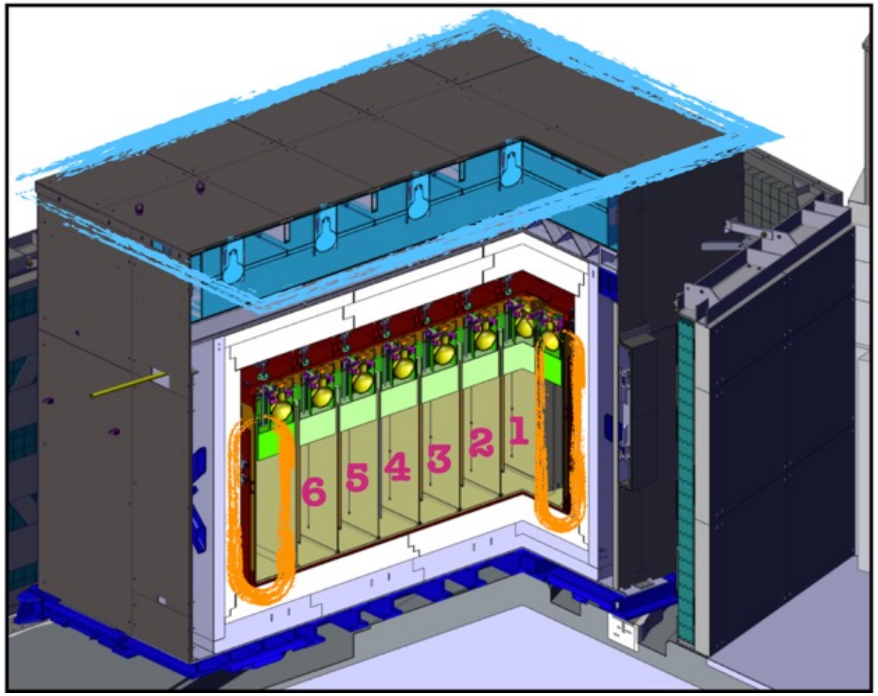
Neutrino detection

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





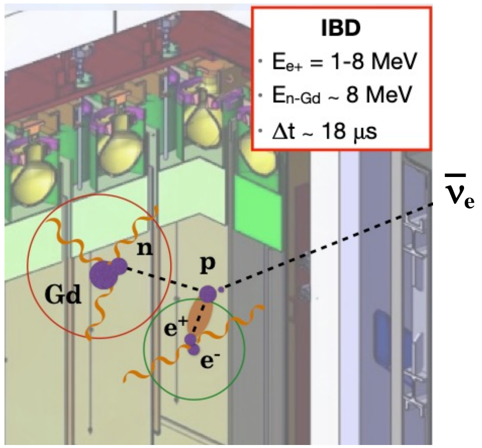
$E_{\bar{\nu}_e} = E_{e^+} - 0.782$ [MeV]

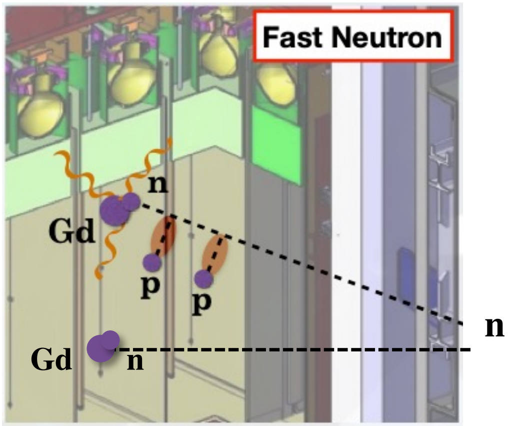


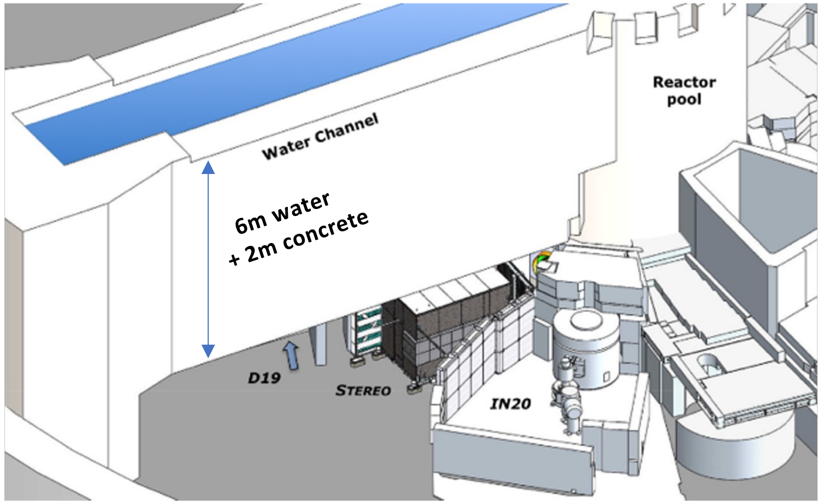
- **6 identical Target cells**, surrounded by a crown of **"γ-catcher"** cells, all filled with Gd-loaded liquid scintillator.
- Heavy passive shielding (Pb, PE, B_4C) mitigate external gamma and neutron background.
- Active **water Cherenkov muon veto**.

Cosmic rays induced correlated background

Prompt-delayed correlated background induced by spallation neutron(s)

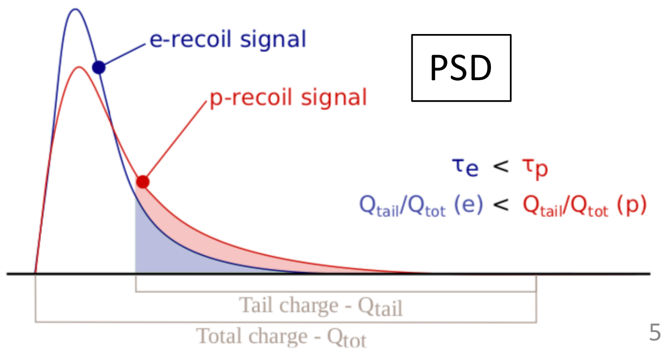






- Key extra background reduction :
  - Attenuation of the flux of cosmic rays by the water channel
  - Pulse Shape Discrimination (PSD) of the delayed signal

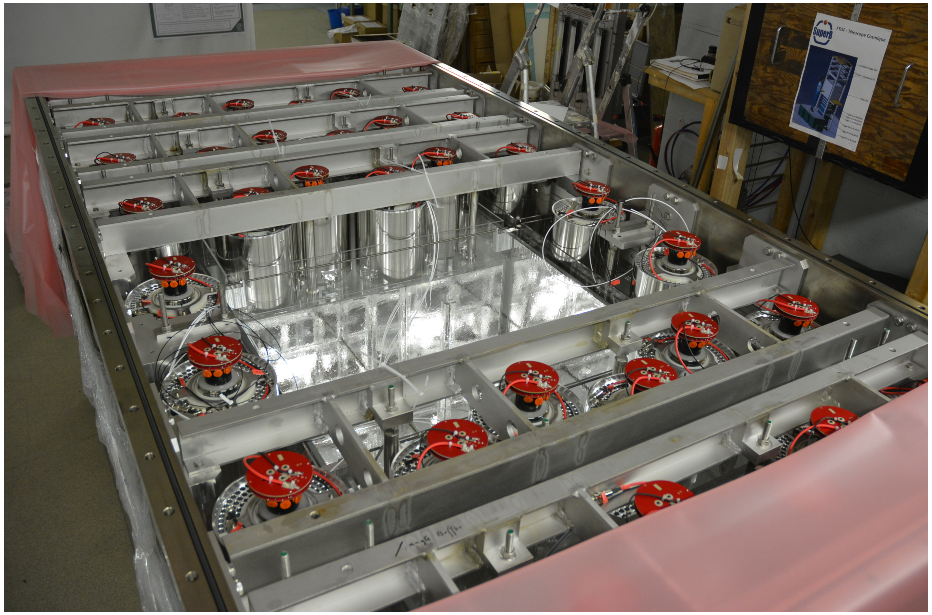
- Valuable heritage from Double Chooz and Nucifer experiment for the chemistry of liquid scintillators and background rejection techniques.

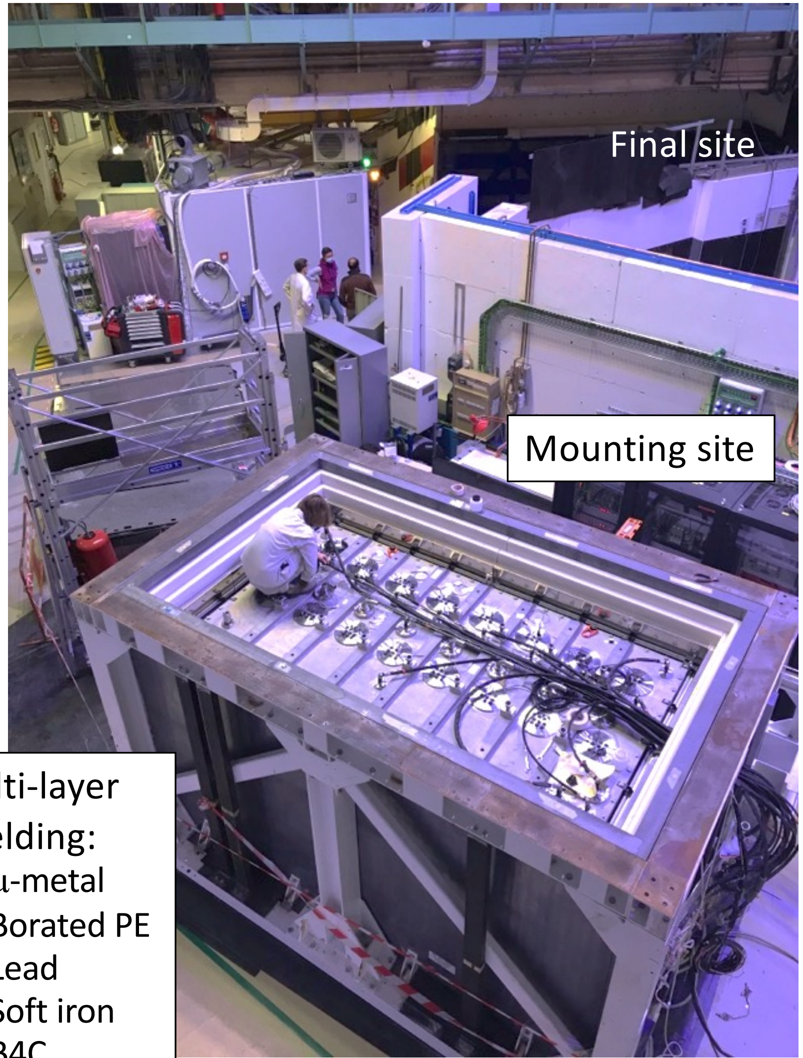


Onsite installation

Stereo detector

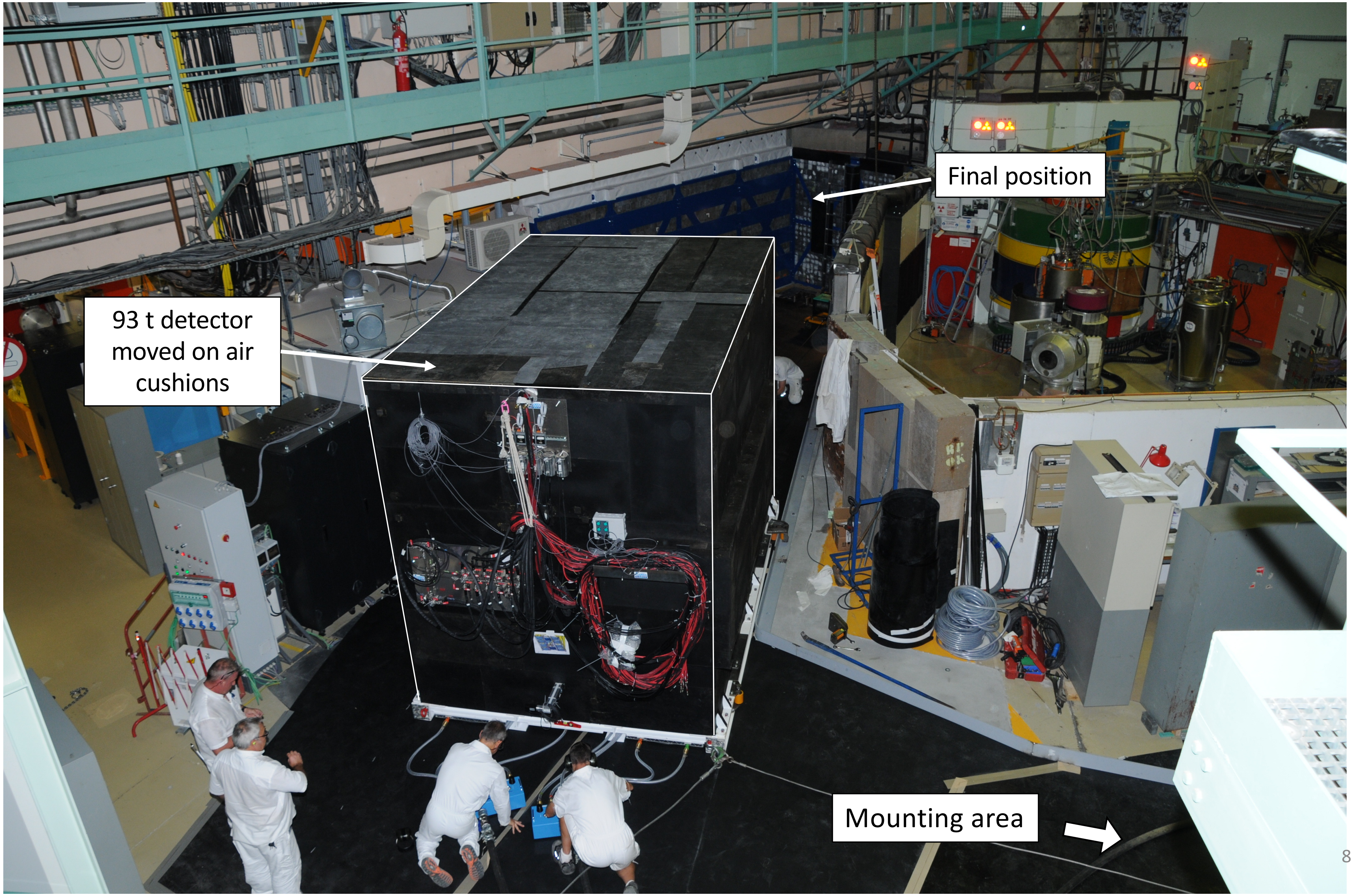
Inner detector being equipped with its photomultipliers



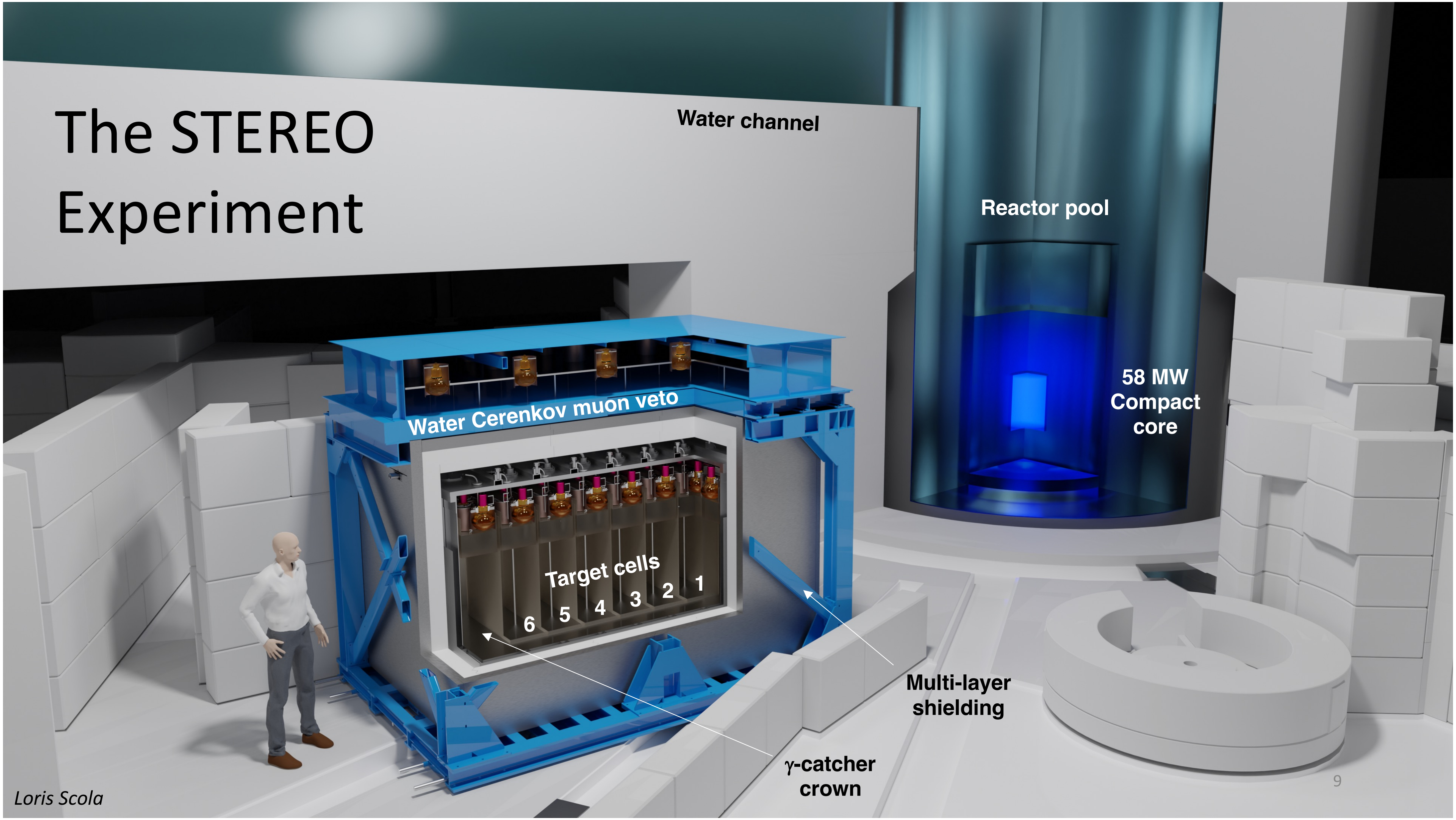


Multi-layer shielding:

- μ-metal
- Borated PE
- Lead
- Soft iron
- B4C


Final position
93 t detector moved on air cushions
Mounting area

The STEREO Experiment



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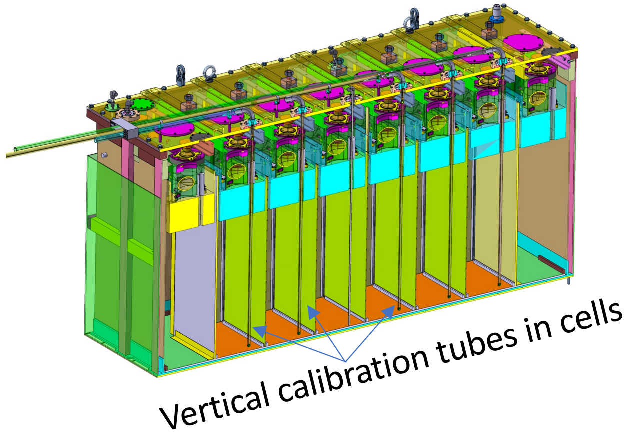
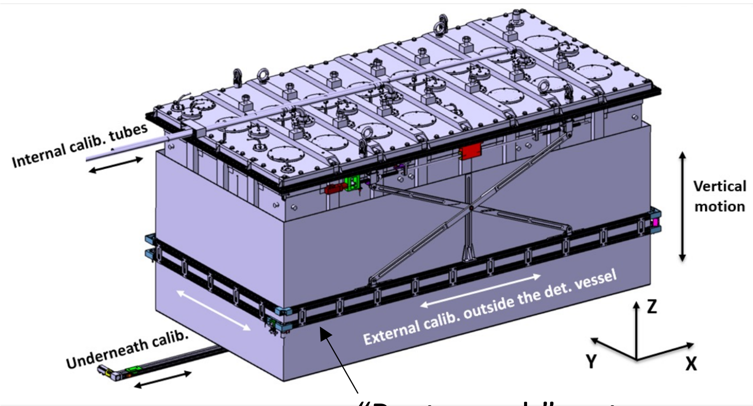
Detector response

Stereo long paper: Phys. Rev. D 102 (2020) 5, 052002

Calibration – radioactive sources

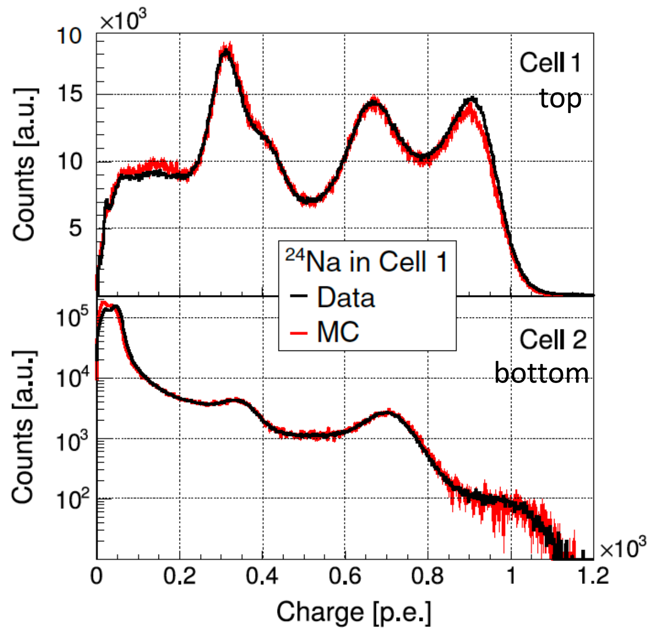
γ-ray and neutron sources regularly deployed inside and around the target volume: ^{68}Ge, ^{137}Cs, ^{54}Mn, ^{65}Zn, ^{60}Co, ^{42}K, ^{24}Na, ^{241}Am-^{9}Be



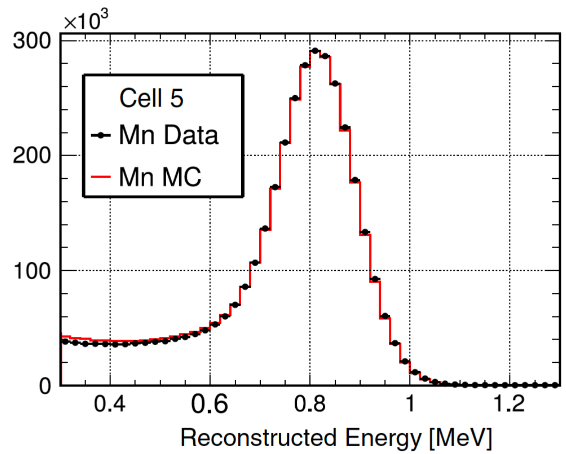


"Pantograph" system around the detector

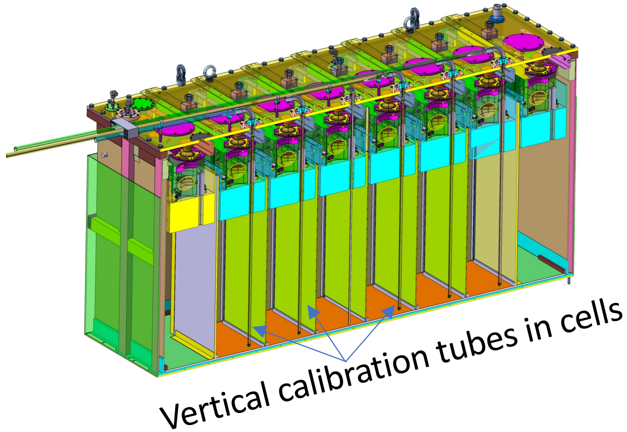
Fine tuning of optical model

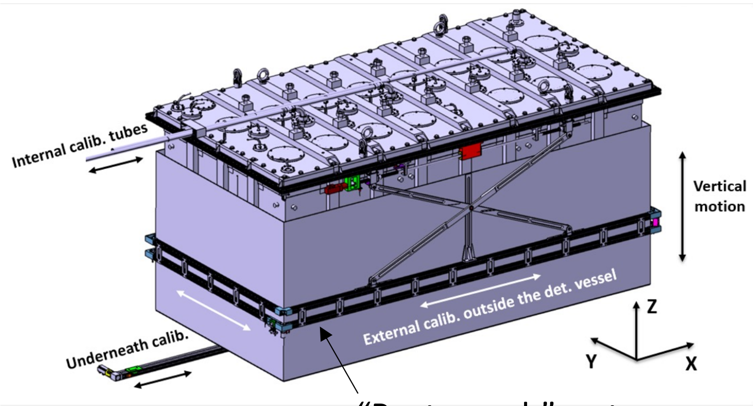


Anchor point of calibration coefficients



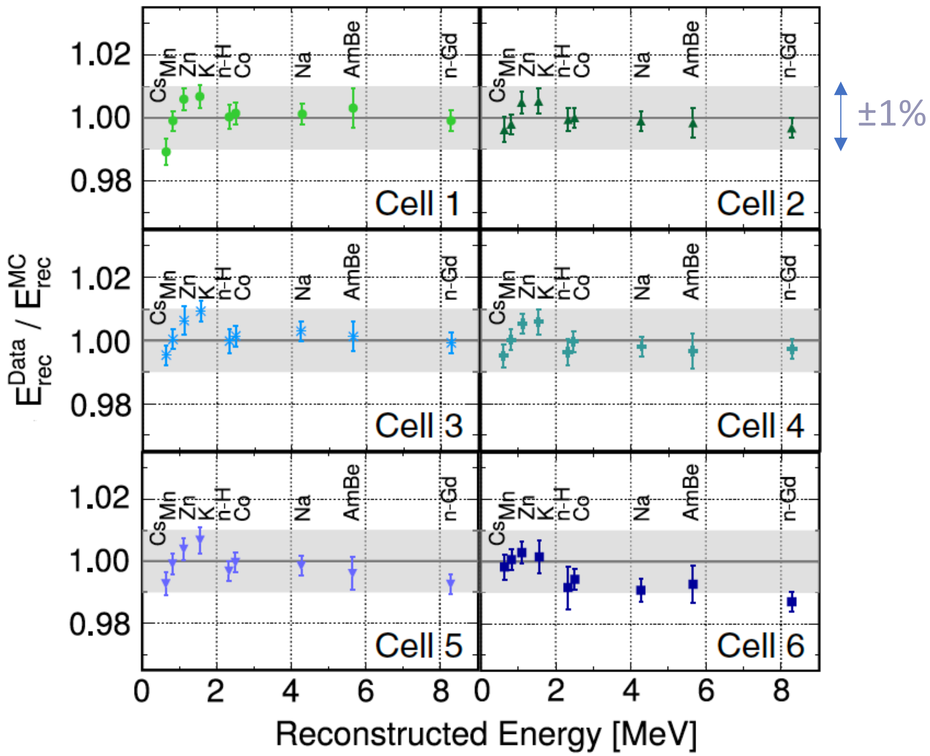
Calibration – radioactive sources





"Pantograph" system around the detector

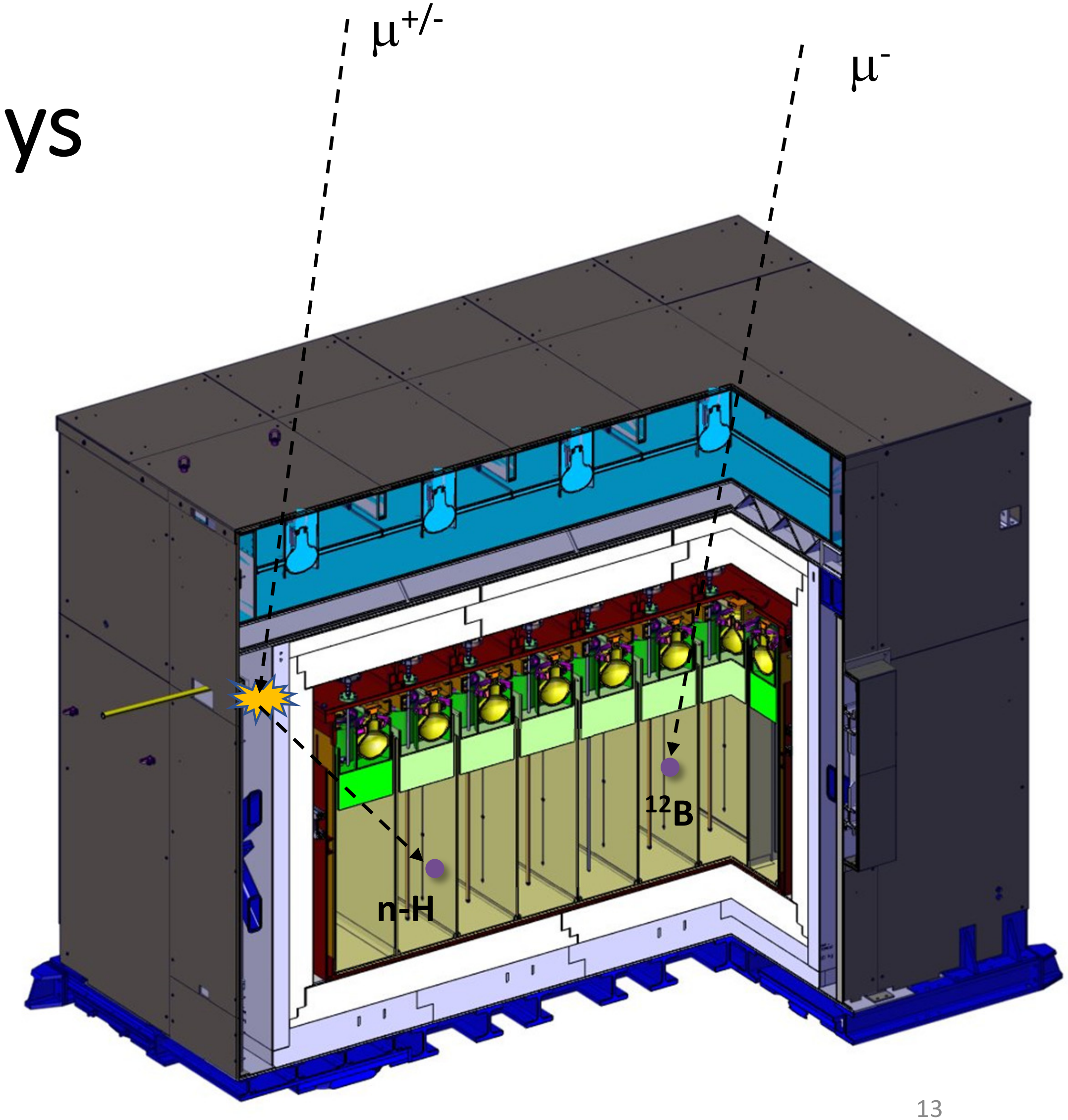
Sub-% data-simulation agreement in all cells and across the whole energy range



Calibration - Cosmic rays

Known signals induced quasi-uniformly in the whole detector volume:

- Capture of stopping μ^- on ^{12}C nuclei in the LS produces unstable ^{12}B
  → **continuous β^- spectrum** with 13.37 MeV end-point.
- Spallation neutrons can be captured on H atoms of the liquid scintillator, producing **2.2 MeV γ-ray**.



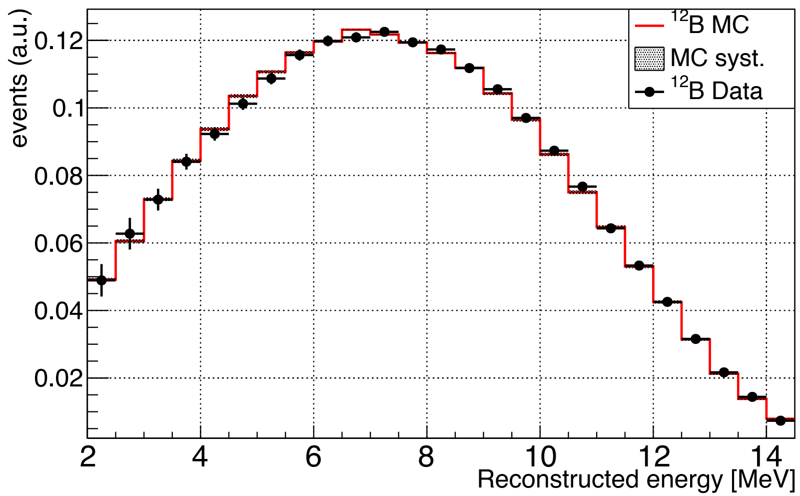
Calibration – ^{12}B β–spectrum

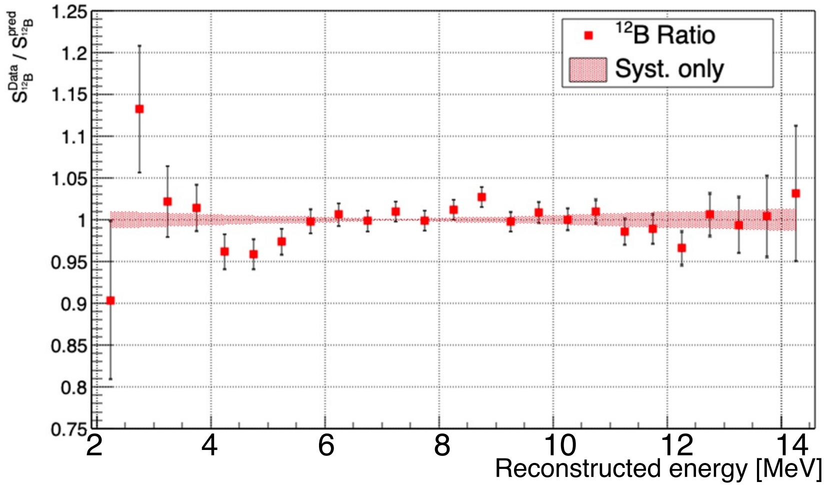
- Produced by the capture of atmospheric muons on carbon nuclei in the liquid scintillator
- Complementary to calibration sources: quasi-homogeneous distribution of vertices & continuous spectrum

$$^{12}C + \mu^- \rightarrow \quad ^{12}B + \nu_\mu$$

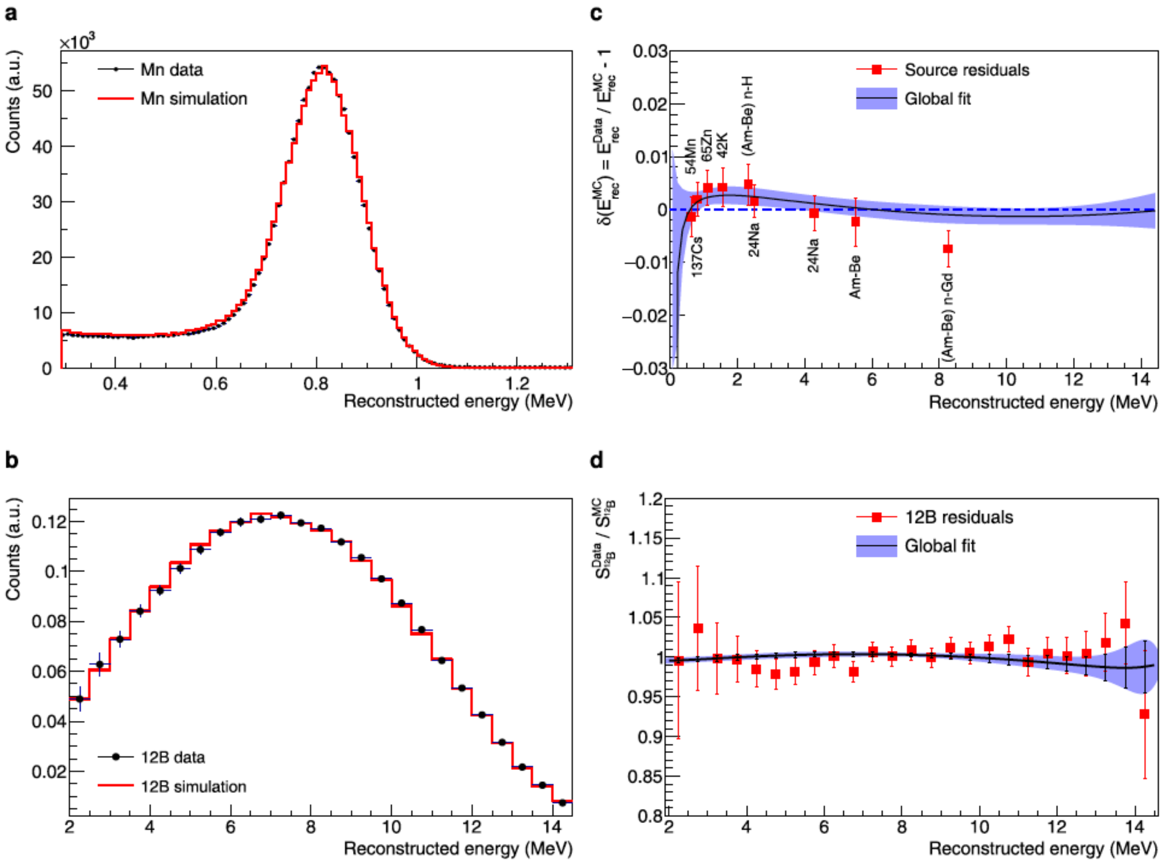
$$^{12}B \rightarrow \quad ^{12}C^{(*)} + e^- + \bar{\nu}_e$$

- 20 ms lifetime
- 13.37 MeV





Simultaneous fit of all residuals



Very general approach, using various polynomial function or Kernel Density Estimation

→ Stringent constraints put on the energy scale:

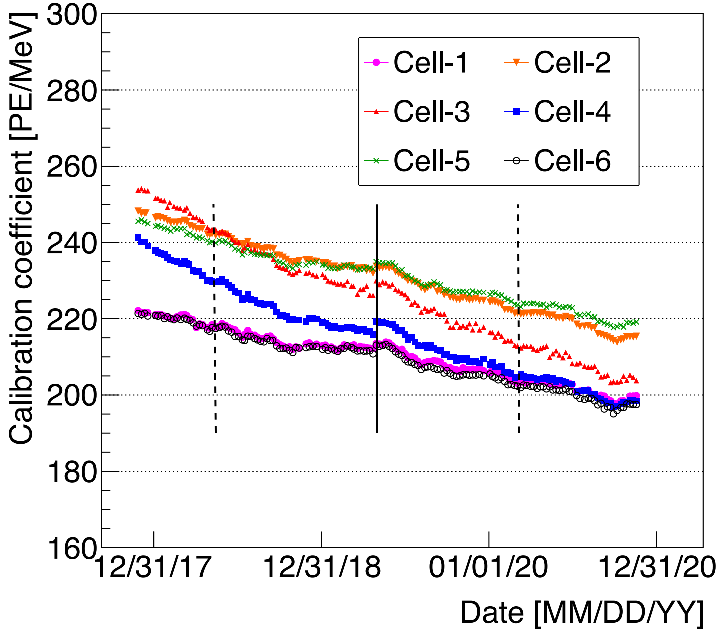
- Contained in a ±1% band at the cell level.
- Contained in a $\pm 1\%/\sqrt{6}$ band at the target level.

The potential systematic distortions induced on the antineutrino spectrum remain subdominant with respect to the statistical fluctuations.

Time stability

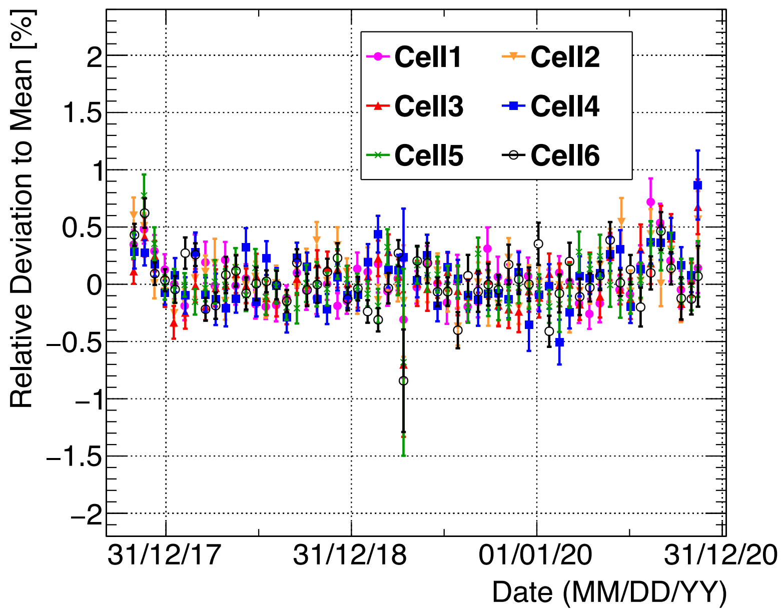
Slow chemical kinetics are unavoidable in the liquid scintillators. Valuable heritage of Double Chooz, which developed Gd-doped liquids stable on a multi-year scale

Calibration coefficients



3% loss in collected light / year

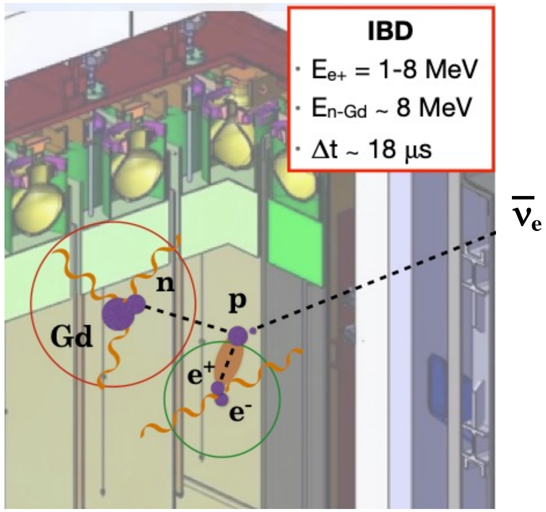
Stability of the n-H reconstructed energy

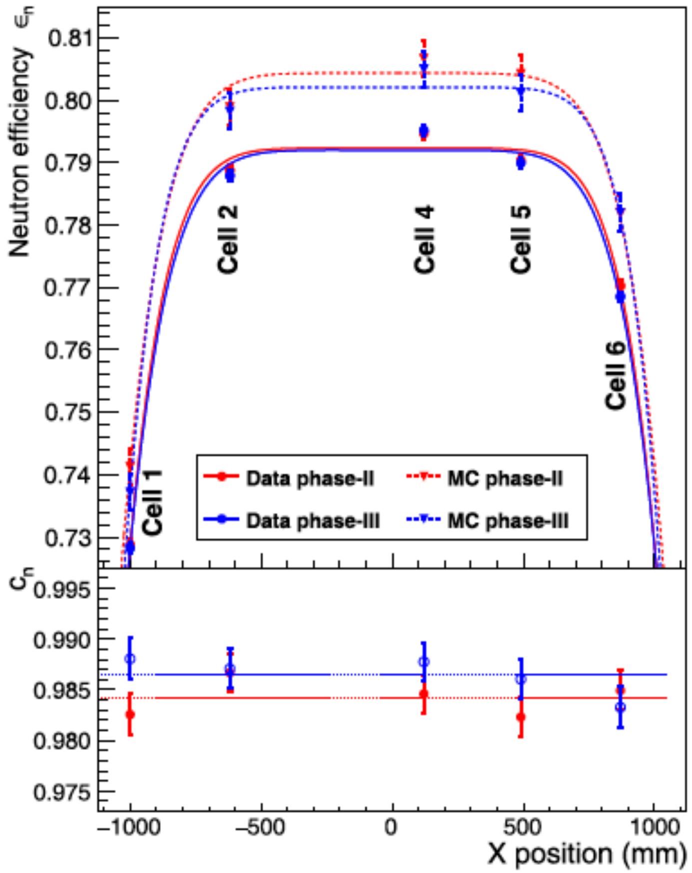


Fully corrected by the regular calibrations

Neutron detection efficiency

The **n-Gd signal** consists in a high energy γ-cascade in a small detector
→ sensitivity to energy leakages and accurate knowledge of the Gd de-excitation.



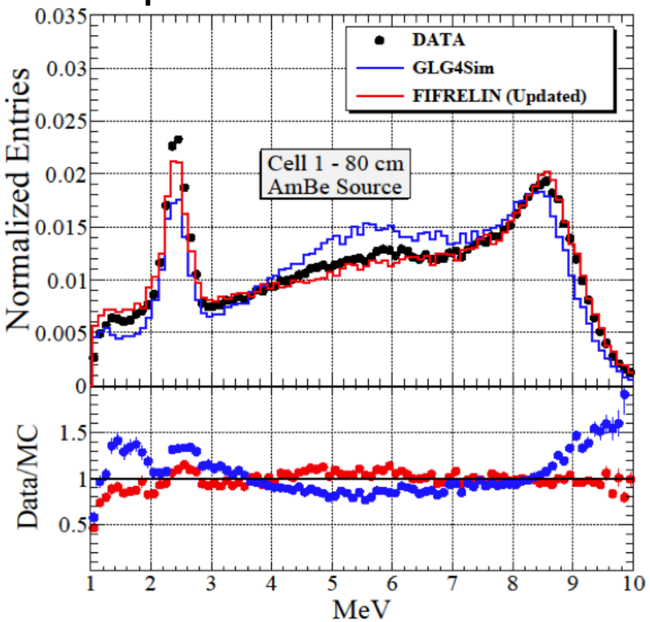


- Extensive studies with an Am-Be neutron source
- Unprecedented data-simulation agreement for such a small detector is achieved.
- 0.7% uncertainty on the n detection efficiency.
- Significant improvement from the FIFRELIN code

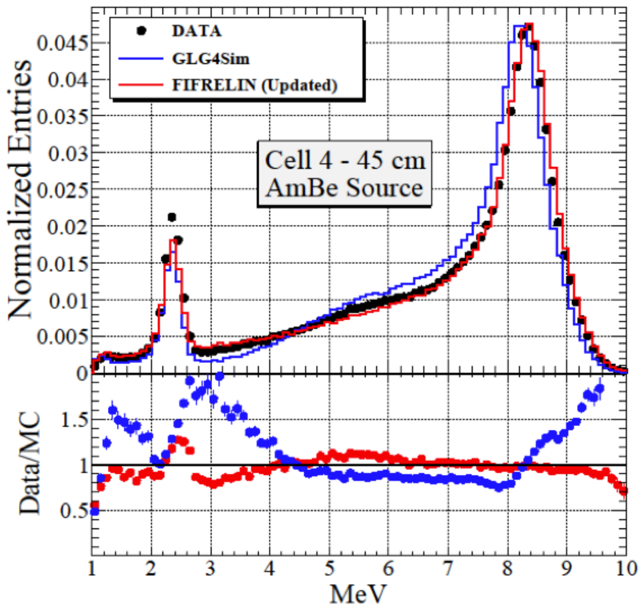
FIFRELIN

- Detailed prediction of the $^{156,158}Gd$ γ-cascades with e-conversion process, γ angular correlations, …
- Significant improvement with respect to previous GEANT4 simulations.
- Unexpected application to the calibration of bolometers, of primary interest for CEνNS measurements (T. Lasserre's talk).

Top corner



Target center



10 millions Gd-cascades available here: DOI: 10.5281/zenodo.6861341

See also:
Eur. Phys. J. A 55 (2019) 10, 183
and arXiv:2207.10918 [hep-ex]

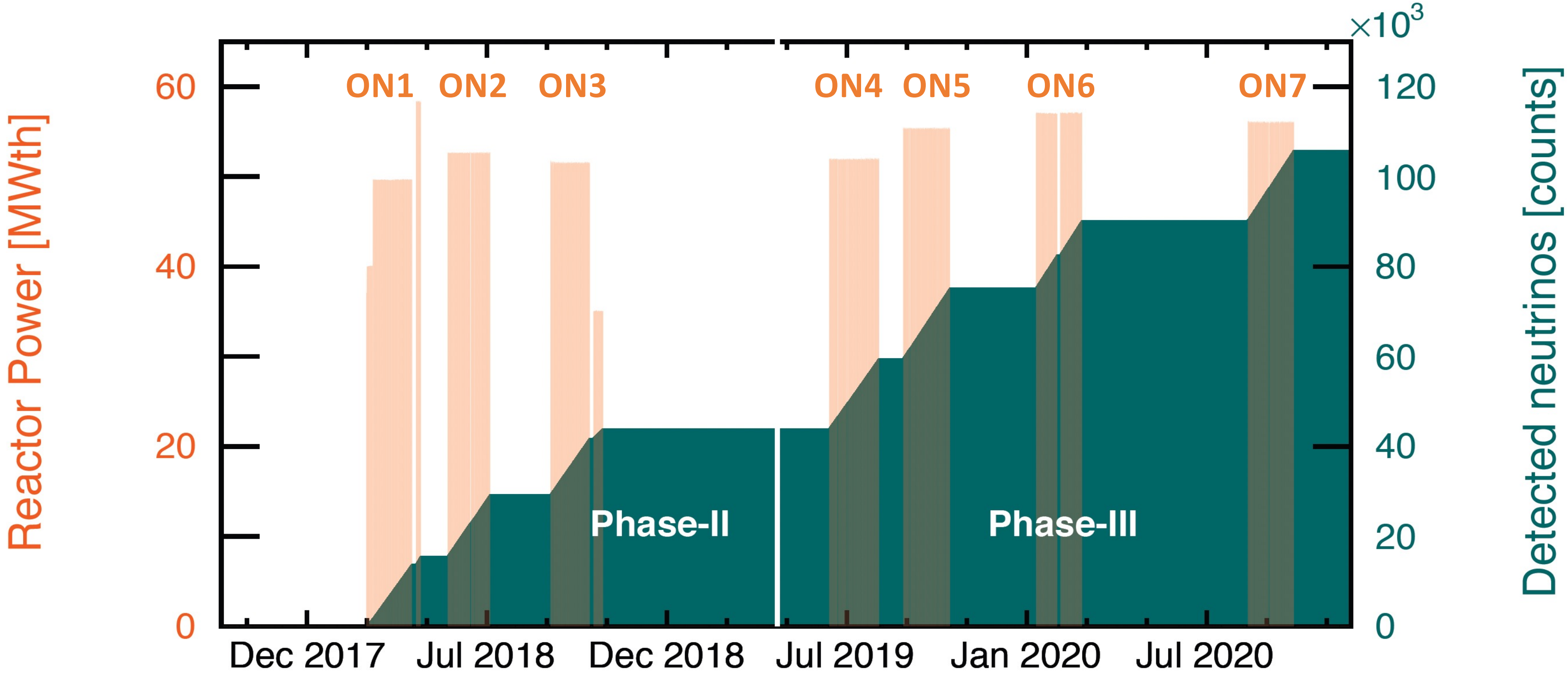
STEREO results

Oscillation analysis: Phys. Rev. D 102 (2020) 5, 052002
Absolute normalization: Phys. Rev. Lett. 125 (2020) 20, 201801
Spectrum shape analysis: J. Phys. G 48 (2021) 7, 075107

Final results: Nature 613 (2023) 7943, 257-261

Public access: https://rdcu.be/c3dsz

2 years of high quality data

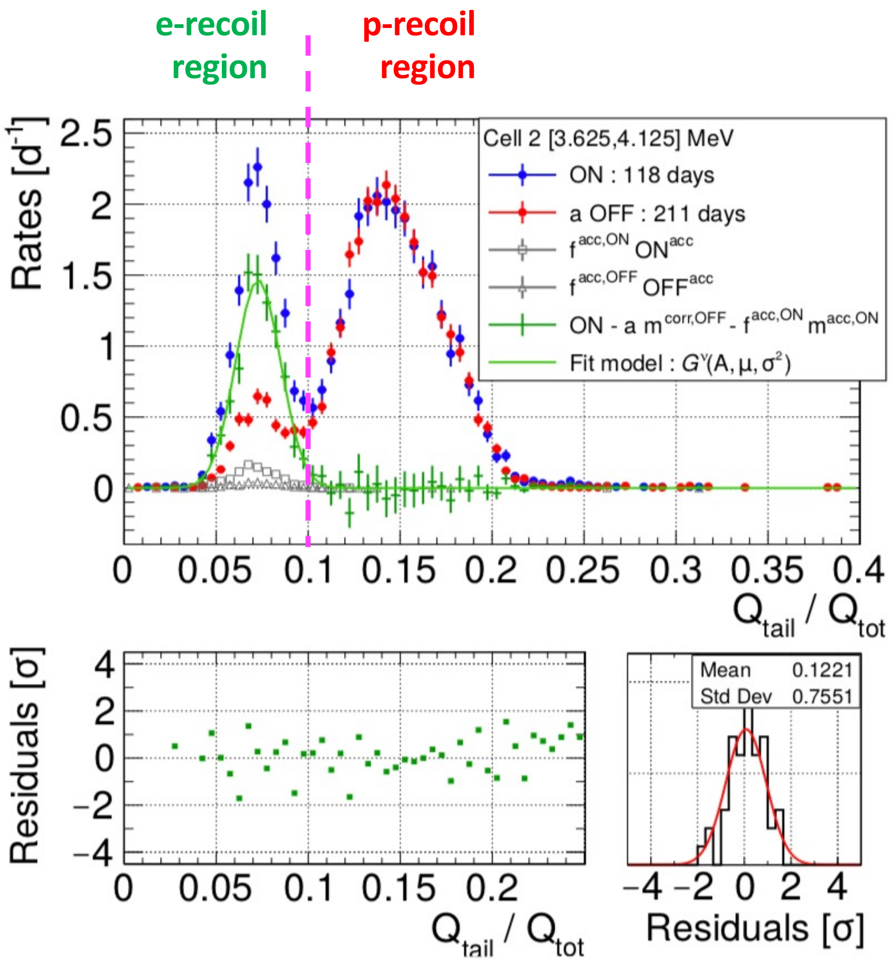


107 558 detected antineutrinos (~400 $\overline{\nu}_e$ /day)

274 days-ON (7 reactor cycles) + 520 days-OFF

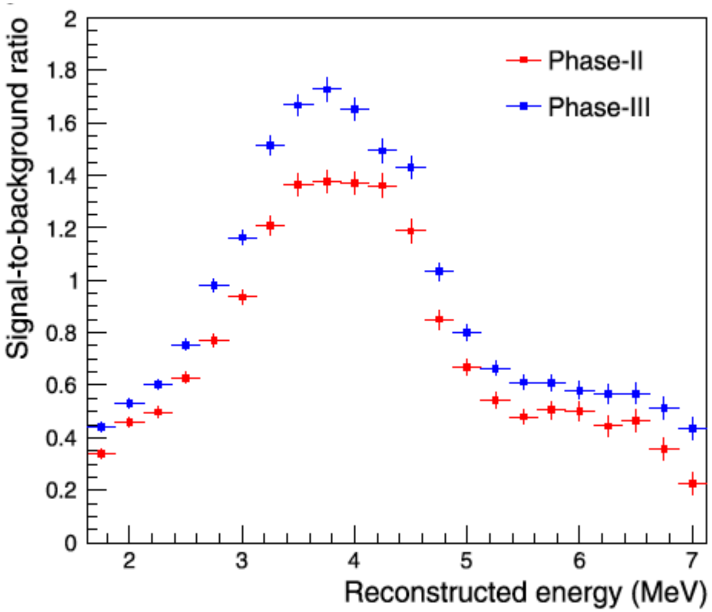
Neutrino Signal Extraction

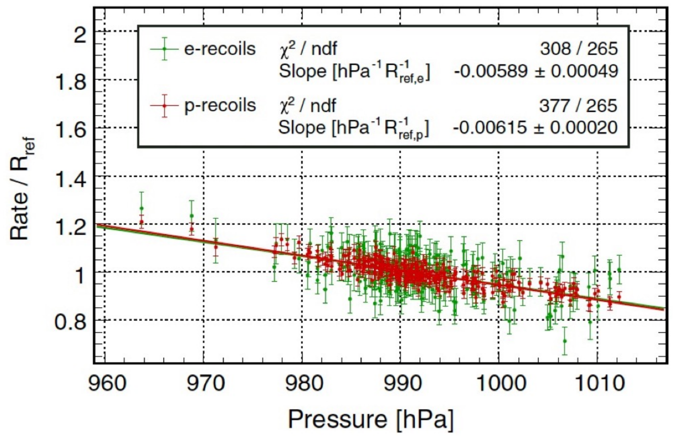
- PSD spectrum of **reactor-ON** and **reactor-OFF** data.
- Accurate model of correlated background during reactor ON periods:
  - Demonstrated high stability of the PSD spectrum shape
  - Dependence on P_{atmos} absorbed by a free normalization parameter “a”
  - Interleaved ON-OFF periods
- Accidental background measured online
- Gaussian fit to extract the **neutrino signal** on top of the background model.



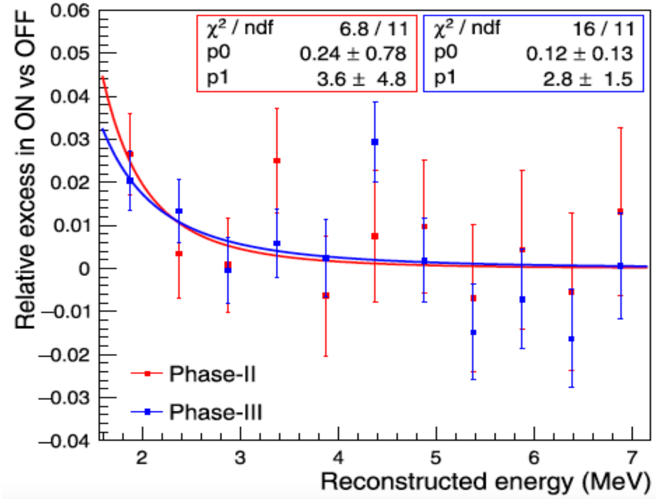
Backgrounds

Signal-to-background ratio of order 1
(±2.5 σ around neutrino peak)





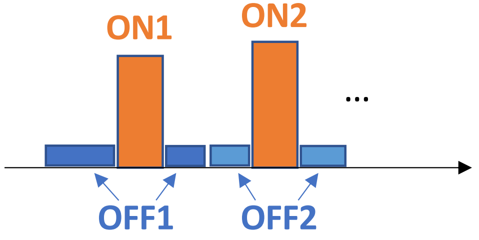
Independent correction of P_{atmos} effect allows to check reactor-induced background



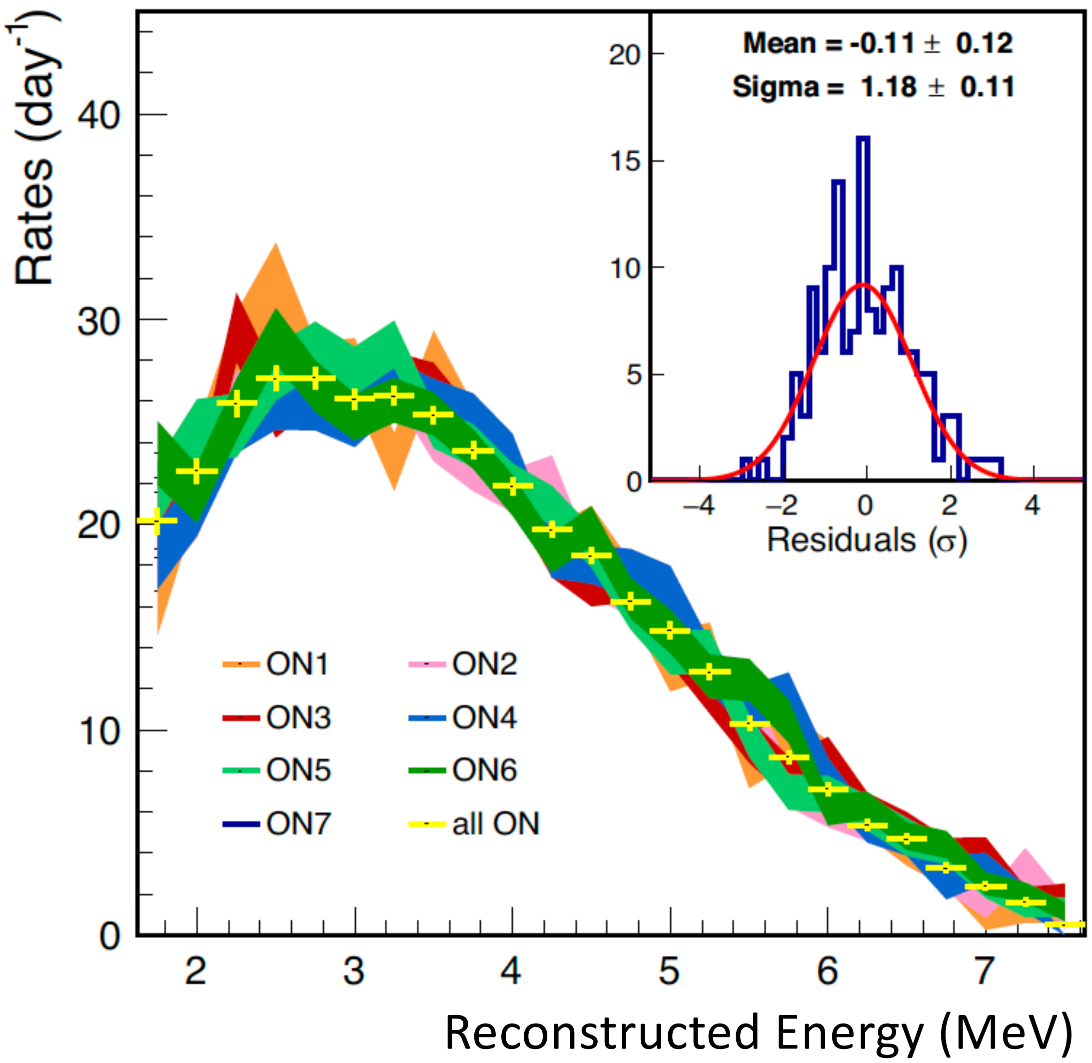
Potential few-% contribution at low energy
→ included as 100% systematic uncertainty

Stability of the detected spectra

- A spectrum is measured for each reactor cycle.
- The background is subtracted using OFF periods contiguous to the cycle.



- **All spectra are found statistically compatible with each other.**



No sterile neutrino signal

Oscillation analysis

Comparison between the 6 identical cells

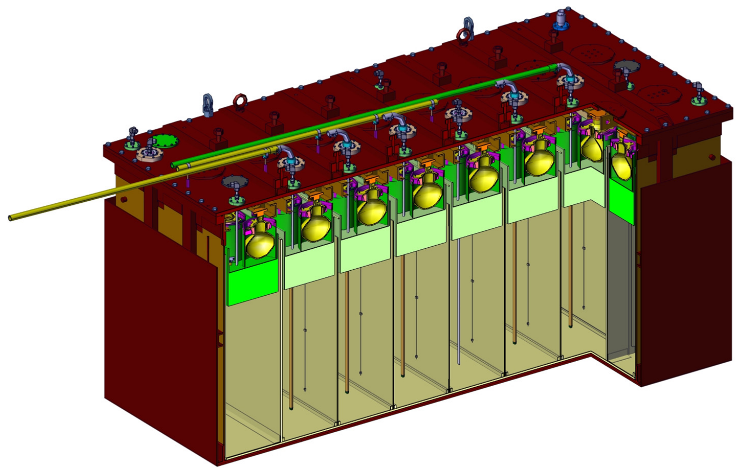
$$\chi^2(\phi, \vec{\alpha}, \sin^2(2\theta_{ee}), \Delta m^2_{41}) =$$

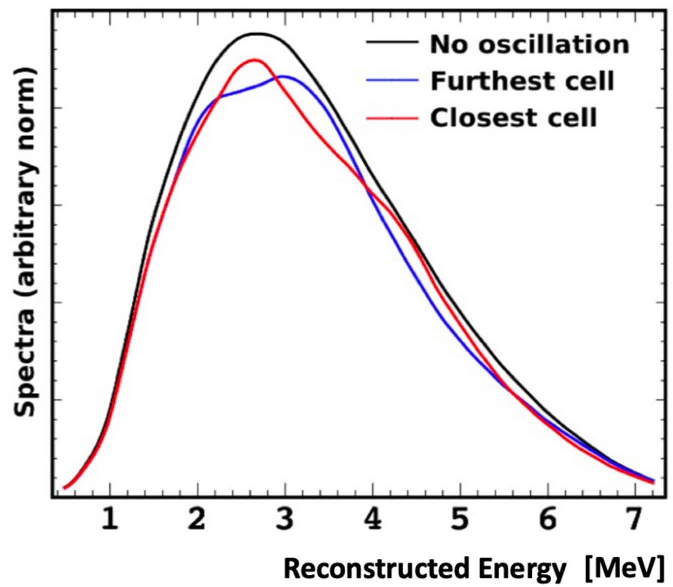
$$\sum_p^{N_{phases}} \sum_c^{N_{cells}} \sum_i^{N_{Ebins}} \left(\frac{D_{p,c,i} - \phi_i M_{p,c,i}(\sin^2(2\theta_{ee}), \Delta m^2_{41}, \vec{\alpha})}{\sigma_{c,i}} \right)^2 + pull\ terms$$

Data

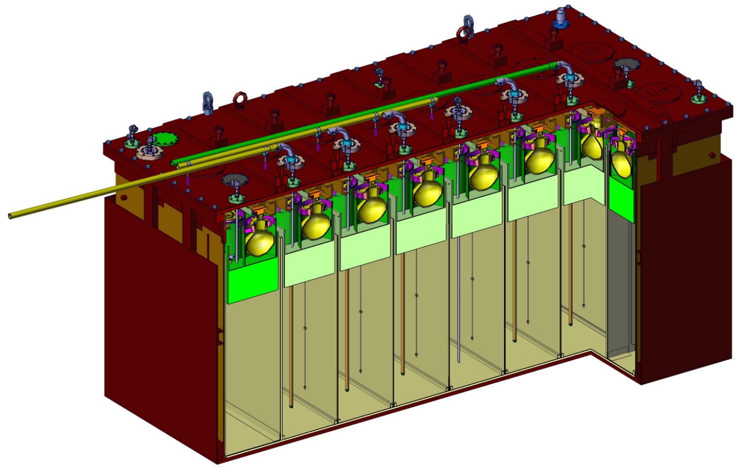
Non-oscillated model

Simulated impact of the oscillation parameters (θ_{ee}, Δm^2) and all detection effects (α's)





Oscillation analysis



Prediction-free

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

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

Data

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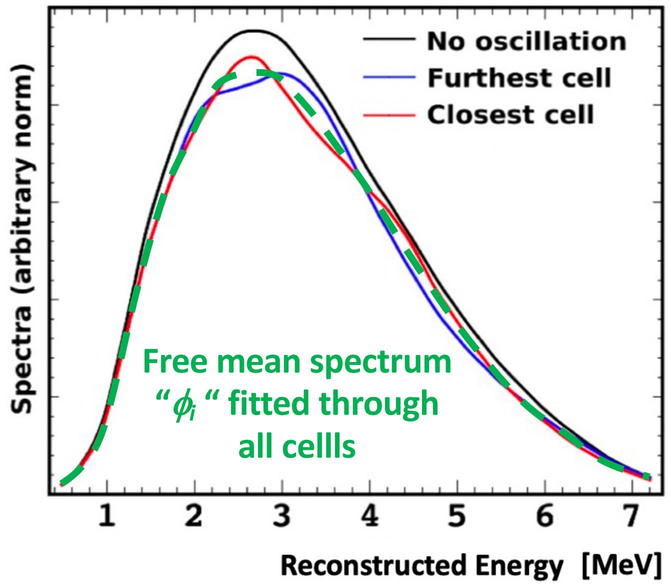
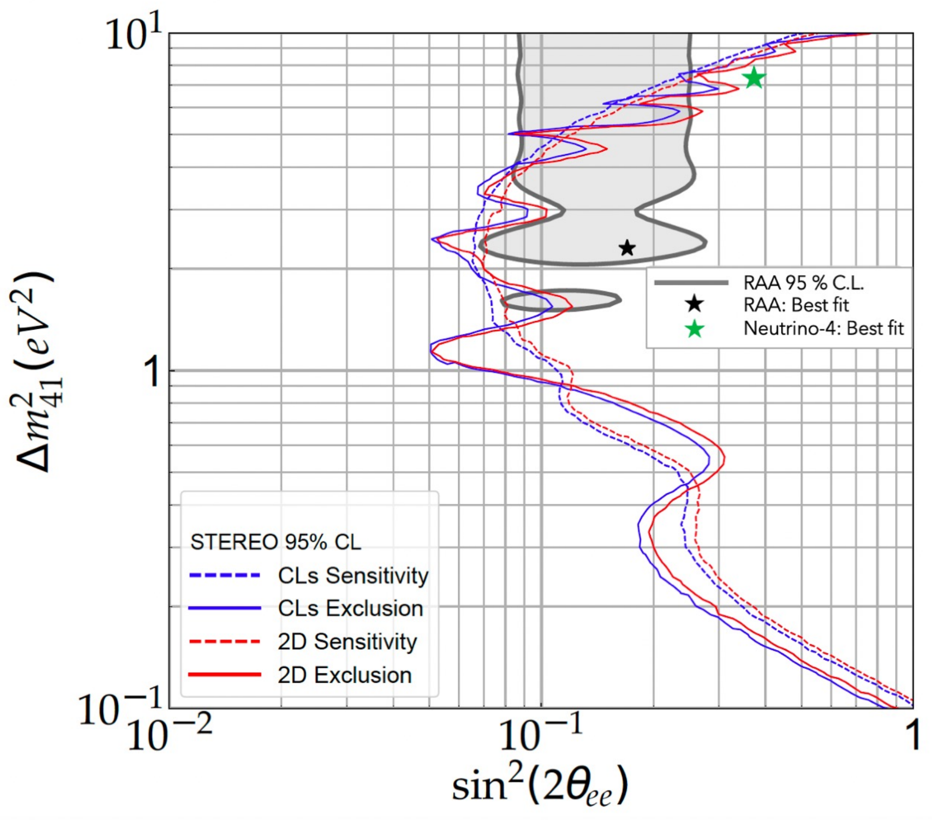


Rejection of the sterile neutrino hypothesis

- 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 ~4σ level / Neutrino-4 best fit point excluded at ~3.3σ level.

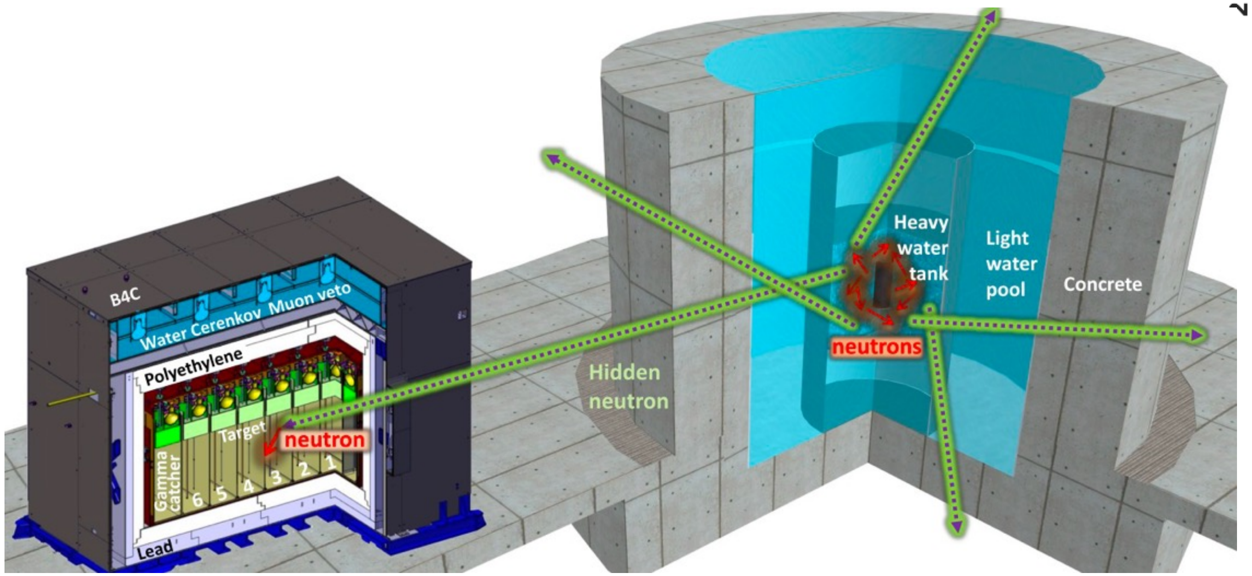
Sterile neutrino hypothesis disfavored with high confidence level.

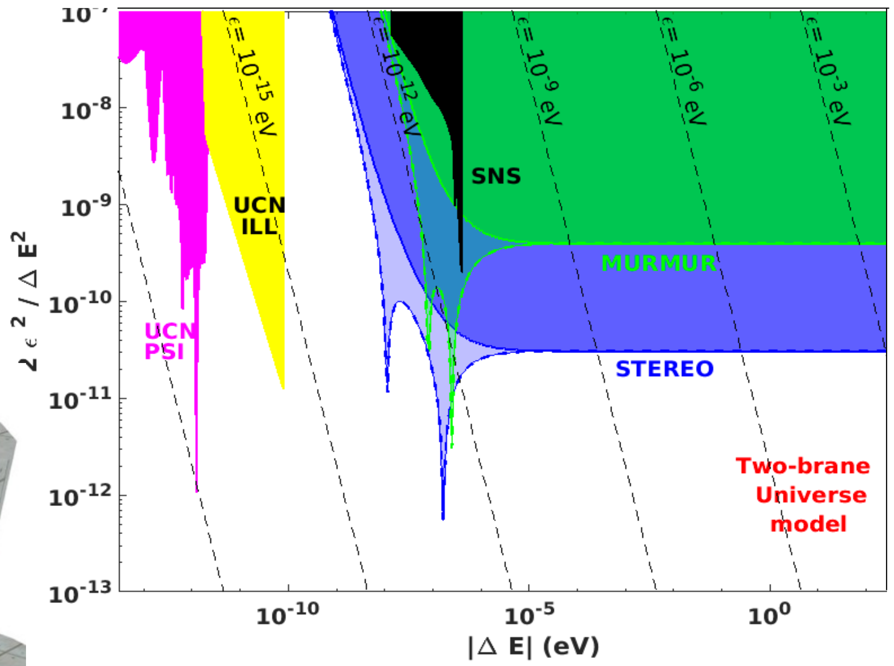
All relevant data available on HEPData.



A smart measurement for a ”no brane” result

- Could dark matter be hiding in a parallel brane?
- Stereo improves previous limits by a factor 13!



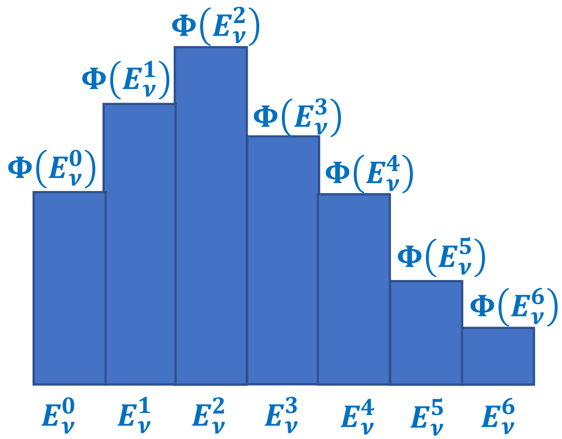


Phys. Rev. Lett. 128 (2022) 6, 061801

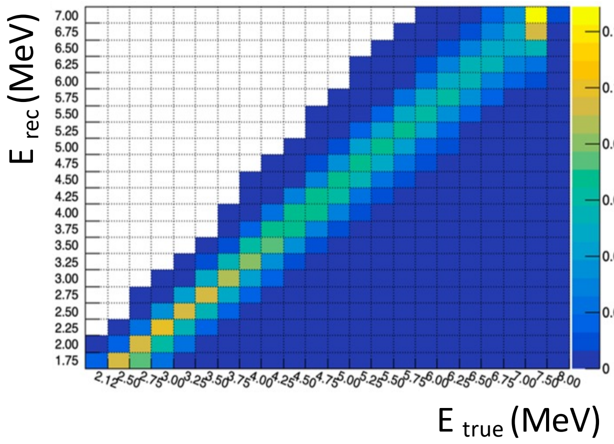
Reference neutrino spectrum of ^{235}U fission

Correcting all detection effects

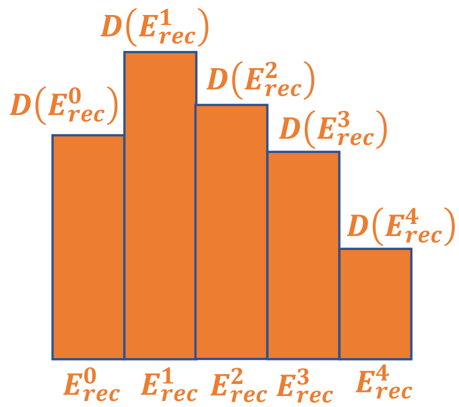
Fit of the spectrum $\Phi(E_\nu)$ in true energy space



… through the response matrix of the detector …



… to the data in reconstructed energy space



Tikhonov-like approach

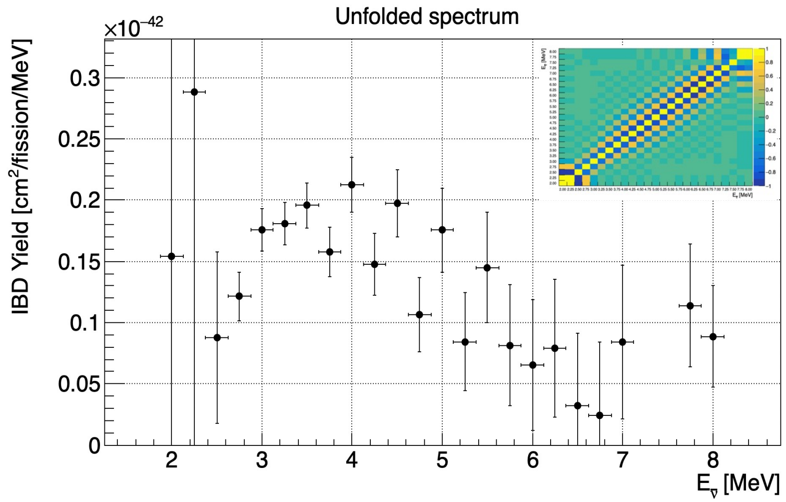
Minimization of a regularized χ^2:

$$\chi^2(\Phi) = (\vec{D} - [R]\cdot\vec{\Phi})\, V_\Phi^{-1}\, (\vec{D} - [R]\cdot\vec{\Phi}) \;+\; \lambda * \left|\left|\Phi\right|\right|^2_{M_{HM}}$$

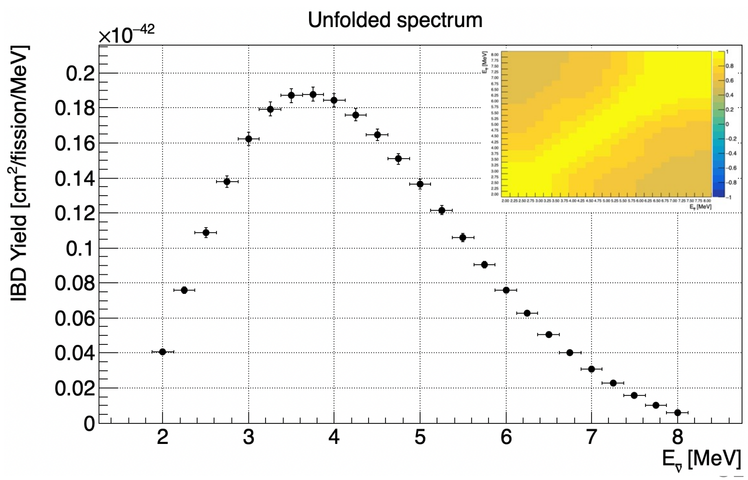
Regularization term

$\sum_i \left(\frac{\Phi_{i+1}}{\Phi_{i+1}^{HM}} - \frac{\Phi_i}{\Phi_i^{HM}}\right)^2$: penalty term on the bin-to-bin fluctuations, with Φ^{HM} a **prior shape** (here Huber ^{235}U prediction).

λ ``small'': unphysical large fluctuations, no correlations

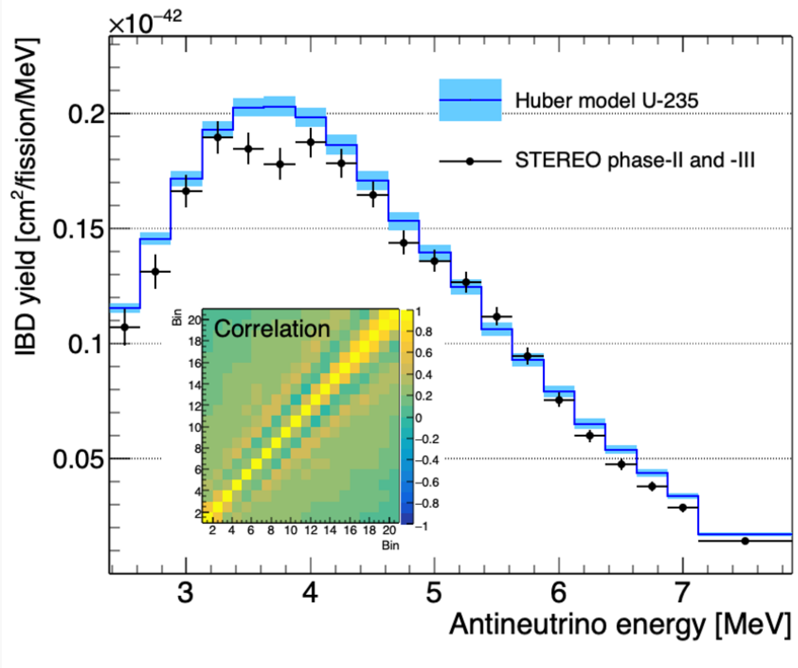


λ ``high'' : very smooth, hig correlations

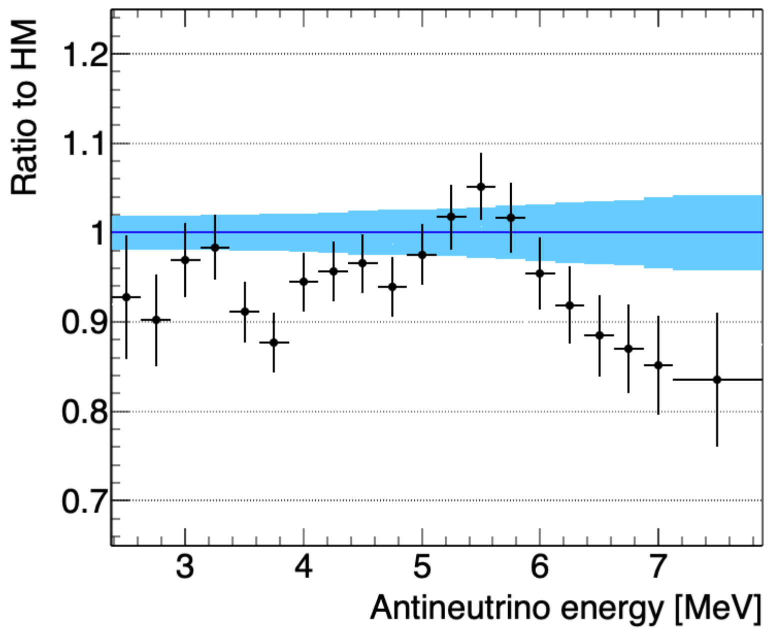


Reference ^{235}U antineutrino spectrum

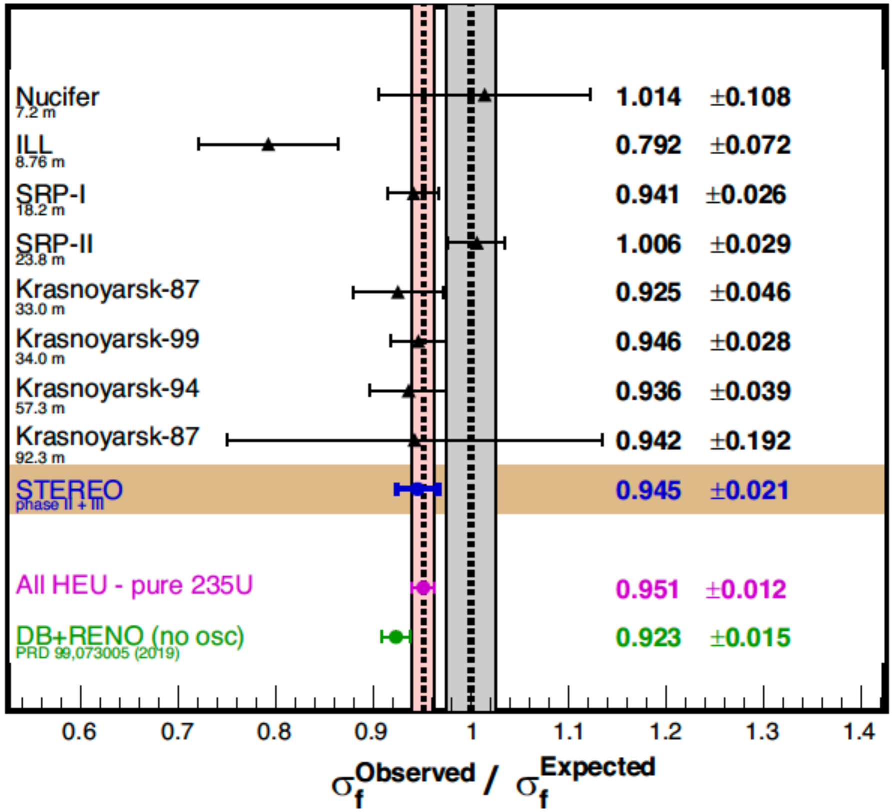
- All relevant data available for the community on HEPData:
  - Spectrum in E_{true} space Φ
  - Covariance matrix V_{Φ}^{-1}
  - Filter matrix A_C (unbiased comparison with a model)



Ratio to Huber-Mueller prediction
confirms deficit & shape distorsion for pure ^{235}U



Confirming rate deficit of ^{235}U neutrino rate



- Reported deficit wrt. Huber predicted neutrino rate [2.375MeV, 7.875MeV]:

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

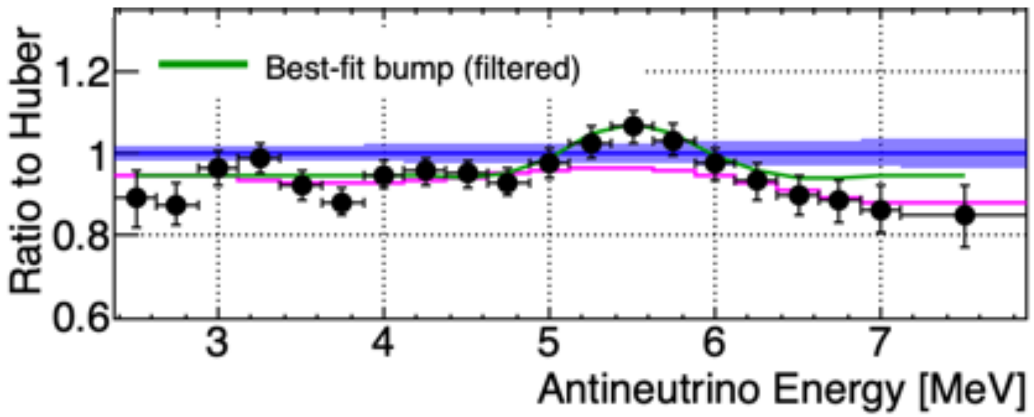
- **Most accurate measurement** of ^{235}U fission yield.

- In agreement with world average $(\mathbf{4.9 \pm 1.2\ [stat + syst]})\%$

- ^{235}U deficit deduced from power reactors measurements is slightly larger, but within uncertainties.

- ^{235}U is a main contributor to the Reactor Anomaly.

Confirming shape distortion



Fit of a gaussian distortion through the filter matrix:

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

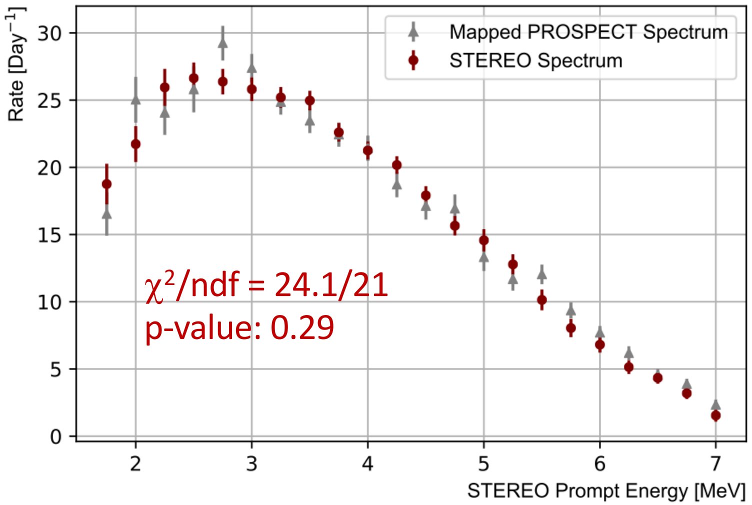
$$\chi^2 = (\Phi - A_c \cdot Pred)^T V_\Phi^{-1} (\Phi - A_c \cdot Pred)$$

Improvement of the agreement with data leading to a **4.6 σ significance** of the existence of a "bump".

Amplitude:	A = 15 ± 5%
Mean:	μ = 5.55 ± 0.09 MeV
Sigma:	σ = 0.31 ± 0.14

Global analysis – STEREO-PROSPECT

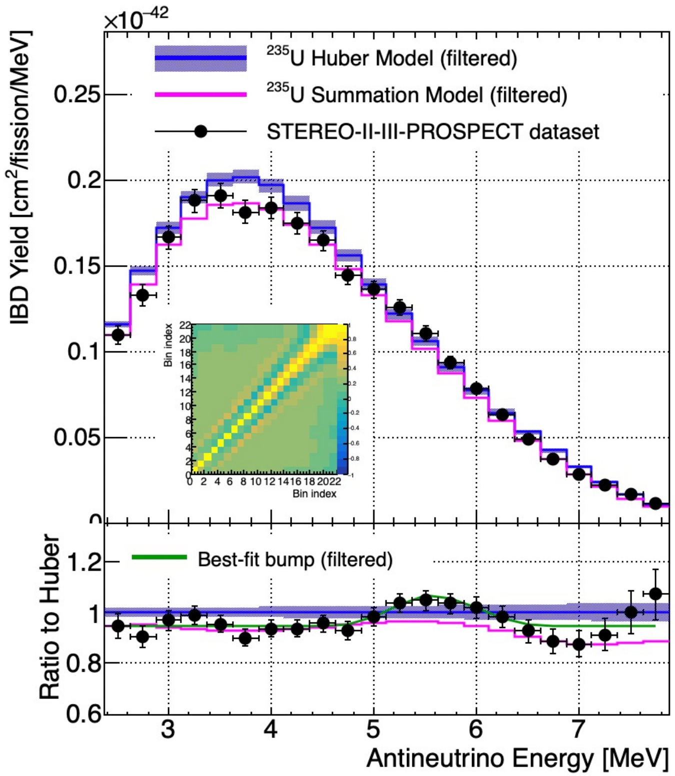
Projected in the same E_{rec} space the two sets of data are fully compatible



Phys. Rev. Lett. 128 (2022) 8, 081802

Updated joint unfolded spectrum with full STEREO data set

R. Rogly's PhD thesis



- **4.7σ bump**, for an overall statistics of **150k antineutrinos** events
- Similar bump parameters:
  $$A = (13.5 \pm 3.3)\%$$
  $$\mu = (5.583 \pm 0.101)\text{MeV}$$
  $$\sigma = (0.369 \pm 0.116)\text{MeV}$$
- **Robust result**, combining two independent HEU experiments.
- STEREO-PROSPECT-DB joint fit to published

Benchmark for nuclear data

Shift of paradigm: model independent and accurate neutrino measurements constrains the nuclear data.

- In the "summation" approach the agreement with the neutrino data is a test of the quality of fission yields and β^- decay spectra of fission products.

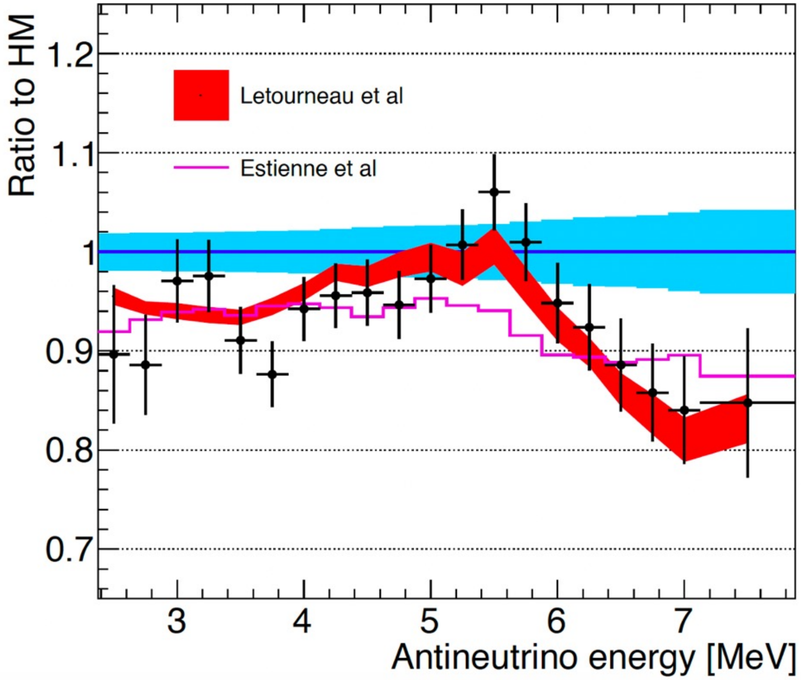
- Convergent hints toward the dominant role of the correction of the Pandemonium effect in β^- spectra:

  - Steady progress of the TAGS measurements makes the prediction converge on the observed deficit.

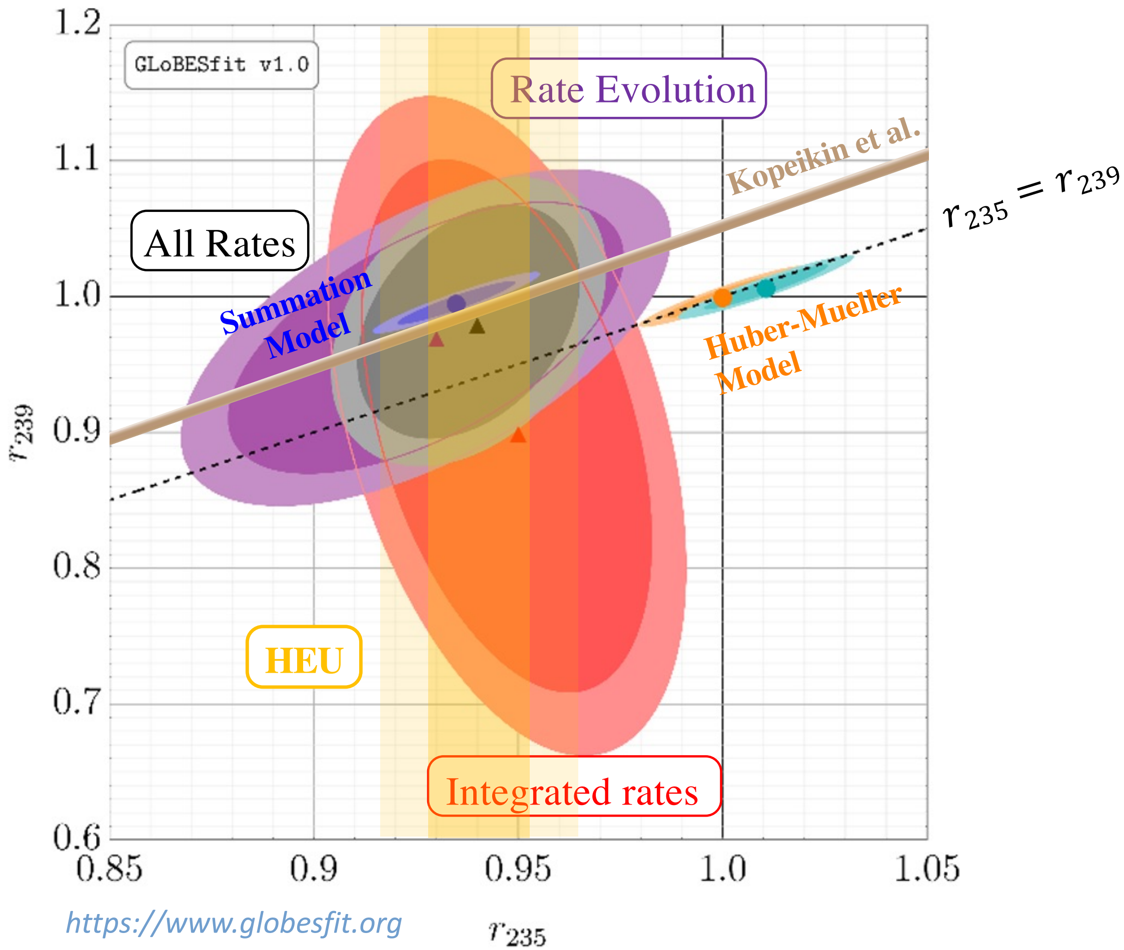
  - Phenomenological, 1 parameter, model of Gamow-Teller decay strength applied to all fission products achieves an unprecedented agreement with measured rate and shape.

Pheno: *Phys. Rev. Lett. 130 (2023) 2, 021801*

TAGS: *Phys. Rev. Lett. 123 (2019) 2, 022502*



Biases of the Huber-Mueller Model - Rate



https://www.globesfit.org

HEU, pure 235U, measurements confirm the global picture of 235U being mainly responsible for the Reactor Antineutrino Anomaly.

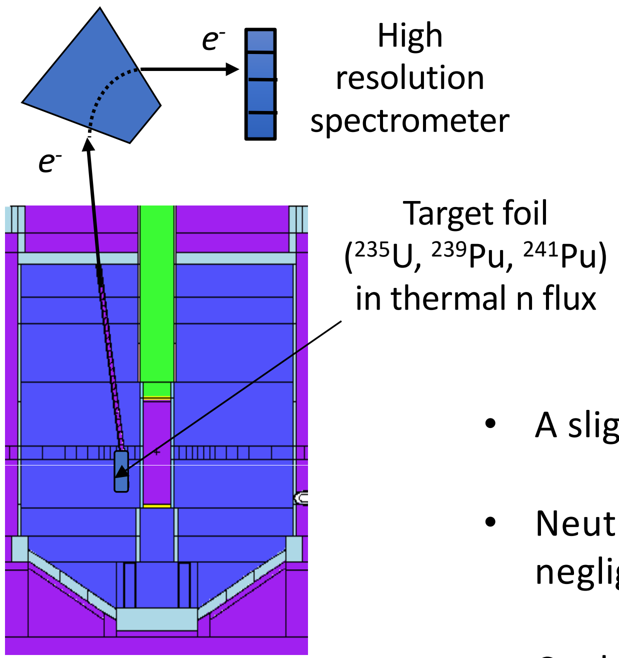
Absolute normalizations of the 235U and 239Pu fission β-spectra, on which is anchored the HM model, were indeed independent.

The rate of e-conversion from ^{197}Au(n,e-)^{198}Au was initially used for both isotopes. Then another 235U run was taken and considered as the reference, normalized with the ^{207}Pb(n, e$^-$)^{208}Pb process…

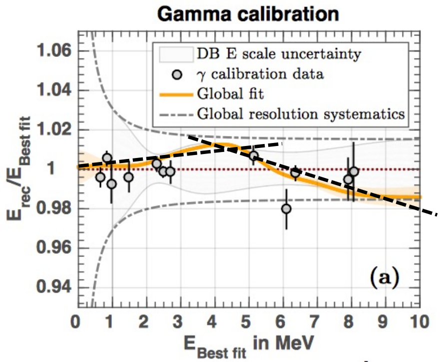
Biases of the Huber-Mueller Model - Shape

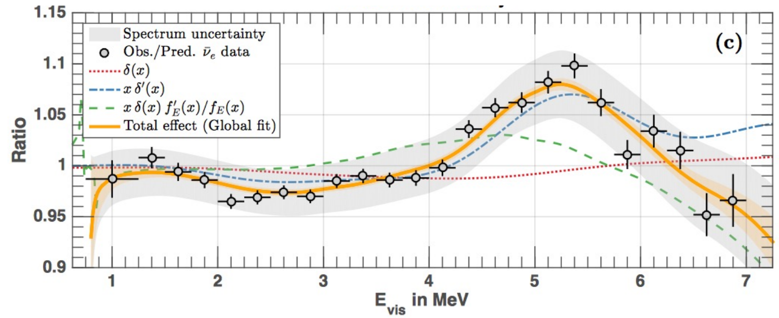
A similar bump in the β-spectra would easily propagate in the converted neutrino spectra

[Phys. Lett. B773 (2017) 307-312]



ILL research reactor
(Grenoble, France)





- A slight kink in the energy scale can induce the observed shape distortion
- Neutrino experiment have worked hard to make this systematic uncertainty negligible.
- Could we have a similar effect in the control of the amplitude of the magnetic field used to analyze the β fission spectra? Magnet power supply, range of Hall probe, …. or fancy nuclear effects ?

Conclusions

STEREO has performed a complete study of the reactor antineutrino anomalies with the pure ^{235}U fission spectrum of the ILL reactor

- **Sterile neutrino hypothesis strongly disfavored**.
- **5.5 ± 2.1 % rate deficit** observed pointing to a **biased normalization** of the ^{235}U fission β-spectrum used by the HM prediction as the main origin of the RAA.
- New **reference spectrum shape**, reinforced by the STEREO-PROSPECT joint analysis. **Local distortion** measured around 5.5 MeV with **4.7*σ*** significance.
- Unbiased unfolding procedure provides a new **benchmark for the quality of nuclear data**.