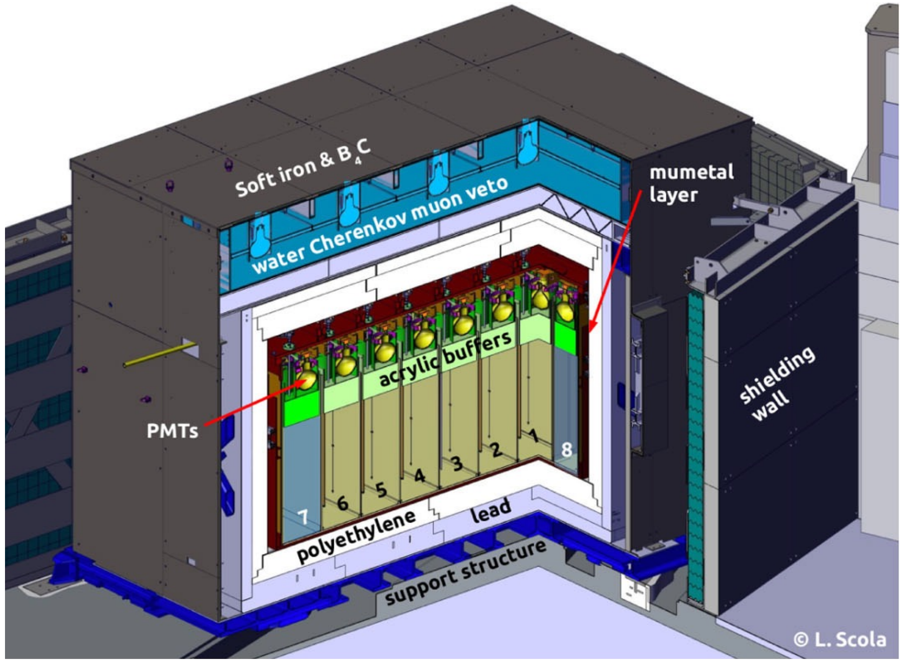
STEREO final results

September 7th 2022

Pablo DEL AMO SANCHEZ

on behalf of the STEREO collaboration



LAPP
CNRS IN2P3 Les deux infinis
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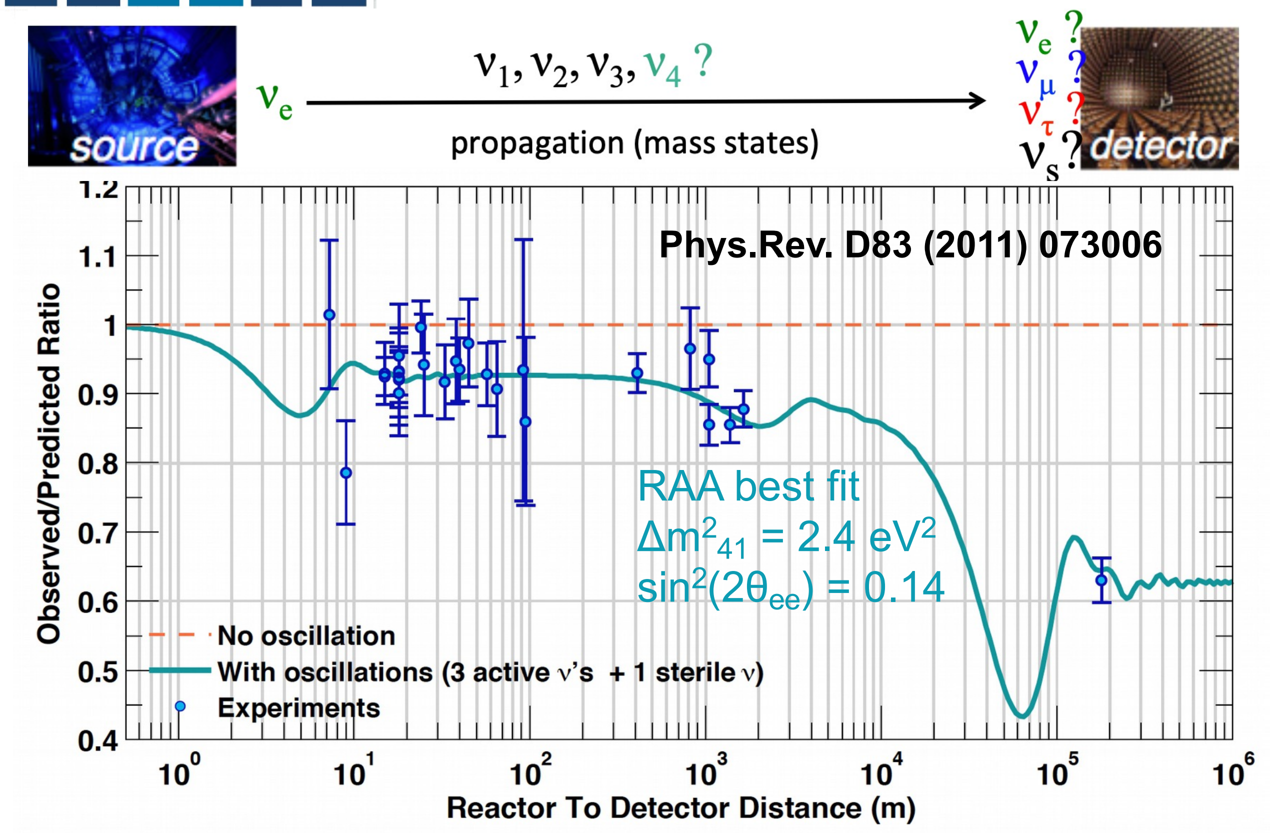
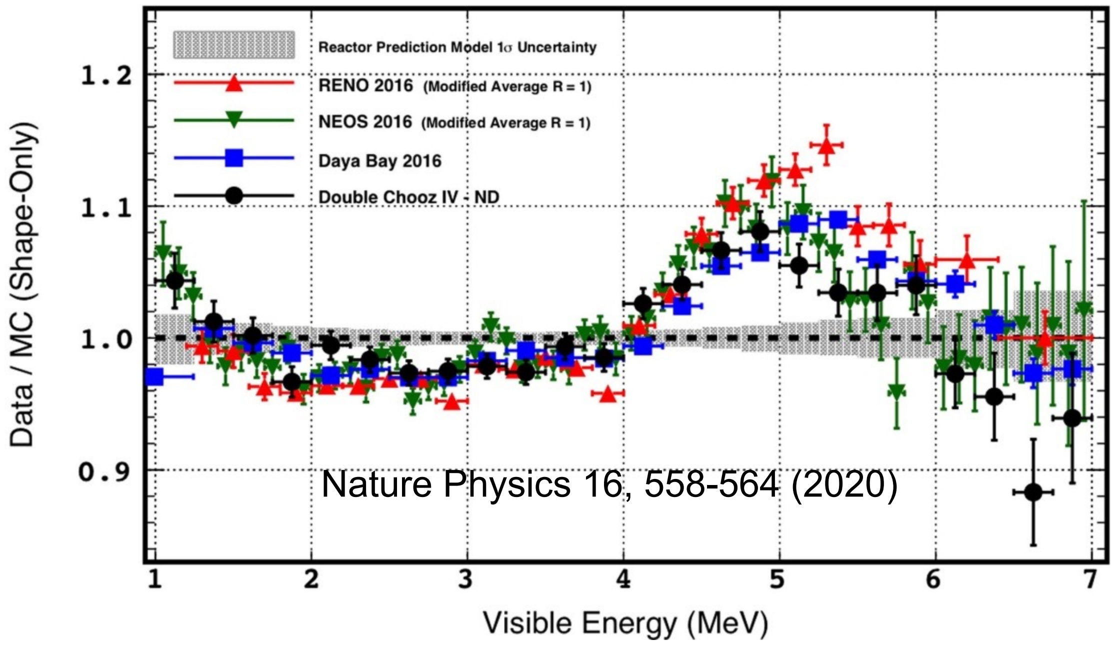
Reactor Antineutrino Anomaly(ies)

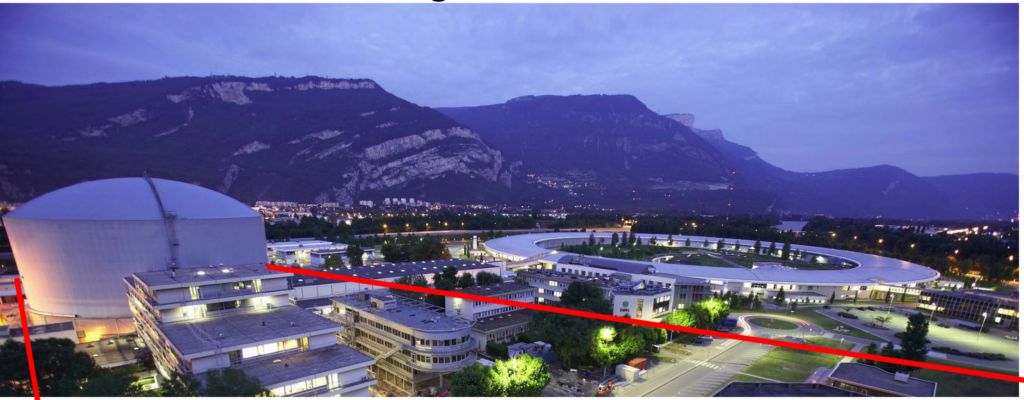


Reactor Antineutrino Anomaly (2011): ~6% deficit observed in measured reactor antineutrino fluxes when compared with latest predictions. Sterile neutrino with $\sin^2(2\theta_{ee})$~0.17 , Δm^2_{41}~2.3 eV^2 would explain RAA and Gallium anomalies



Daya Bay, RENO, Double Chooz (2014): unexpected excess around 5 MeV wrt spectrum predictions ("5 MeV bump")

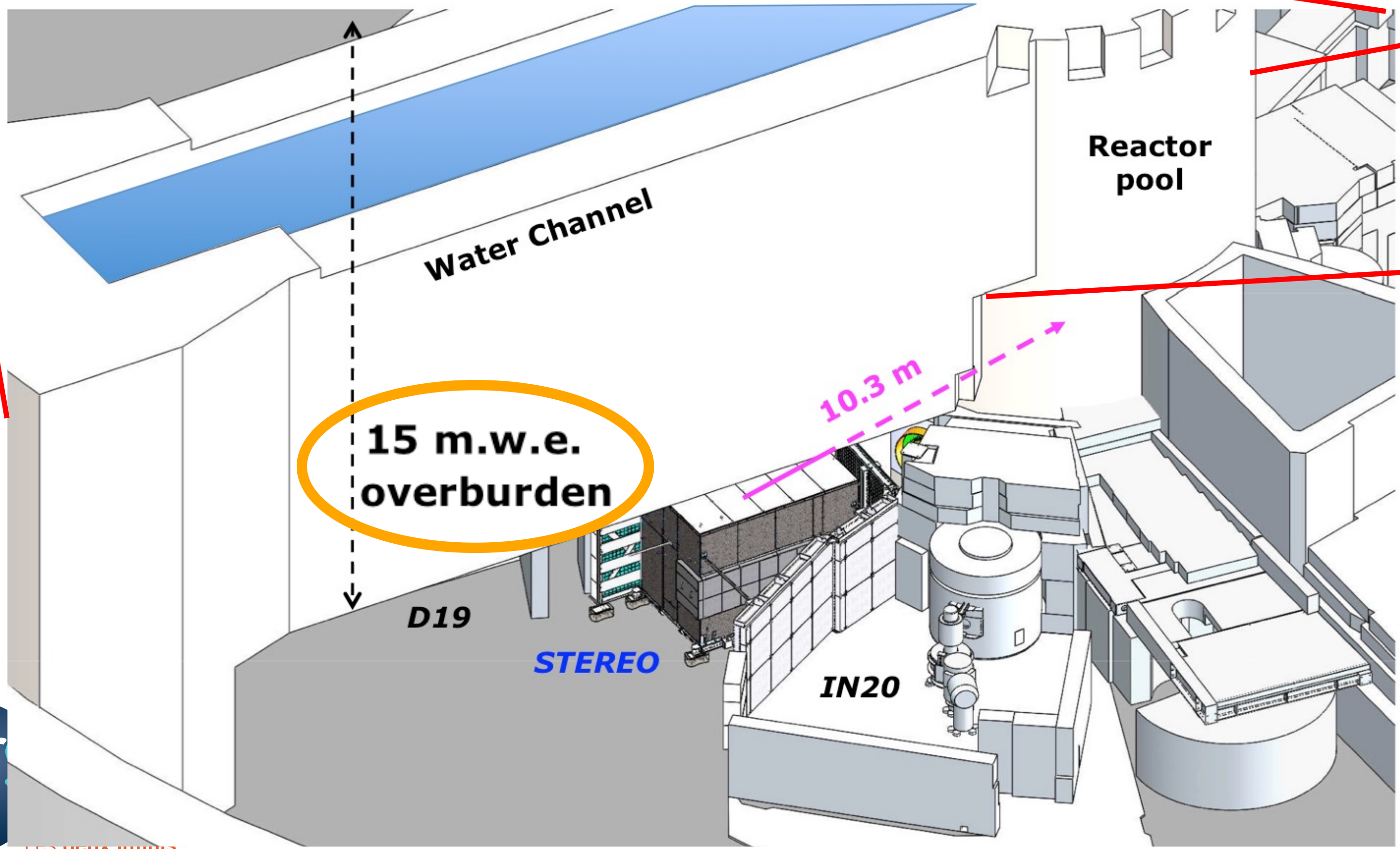
Institut Laue-Langevin, Grenoble, France

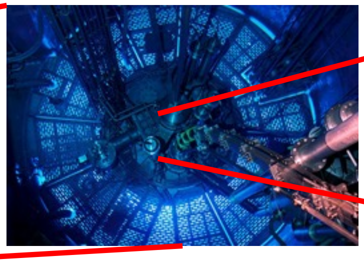


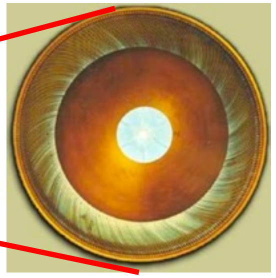
The ILL site

- 58.3 $MW_{thermal}$
- Ø40 cm × 80 cm
- Highly enriched: 93% ^{235}U (fissions > 99% ^{235}U)
- 3-4 cycles/yr x 50 days/cycle
- 10^{19} s^{-1} pure $\overline{\nu}_e$ flux

Challenging backgrounds induced by:
- Cosmic rays
- Neighbouring experiments







Compact core

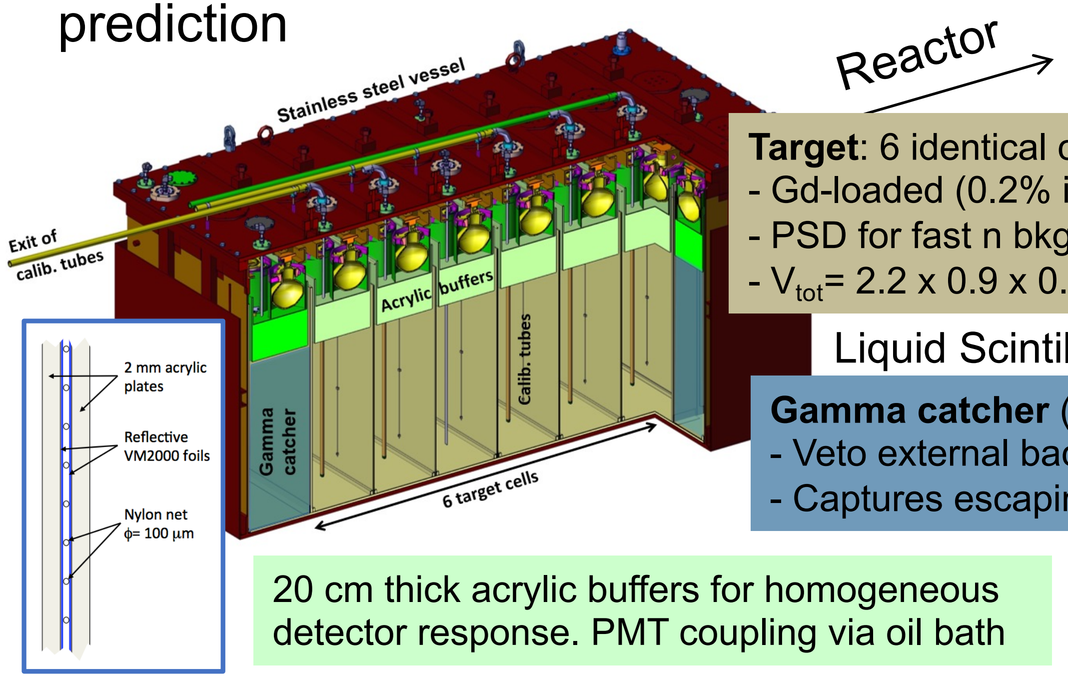
Heavy passive shielding added around detector and on front and side walls:
- > 100 tons Pb
- > 9 tons Borated PE
- B_4C rubber
- (soft iron)

The STEREO detector

JINST 13, 07 (2018): P07009

Compare of 6 target cells looking for oscillation-like distortions in E_ν spectra

⇒Reduce dependence on spectrum prediction

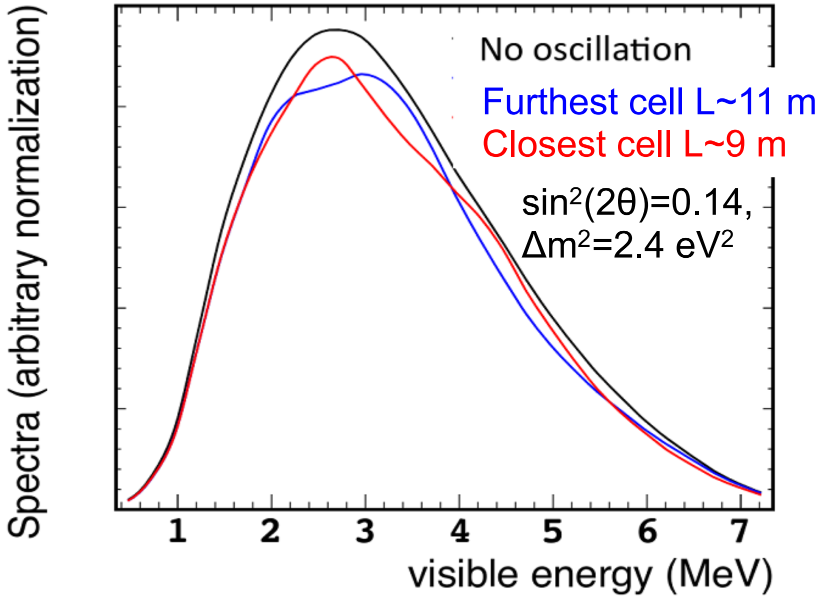


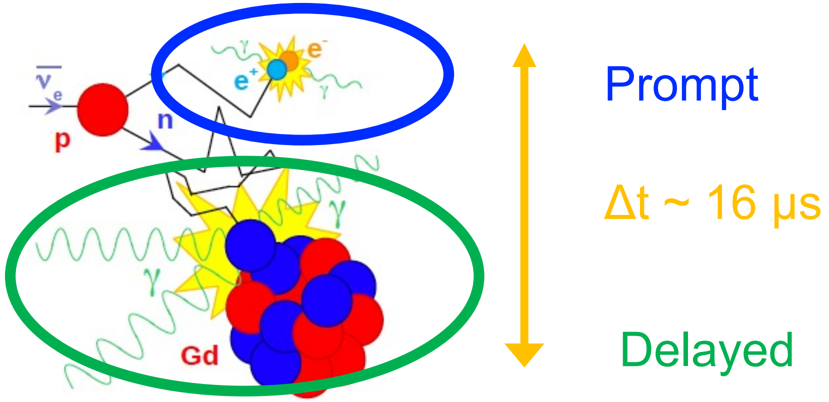
Target: 6 identical cells
- Gd-loaded (0.2% in mass)
- PSD for fast n bkg discrimination
- V_{tot}= 2.2 x 0.9 x 0.9 m^3

Liquid Scintillator

Gamma catcher (no Gd):
- Veto external background
- Captures escaping γ's

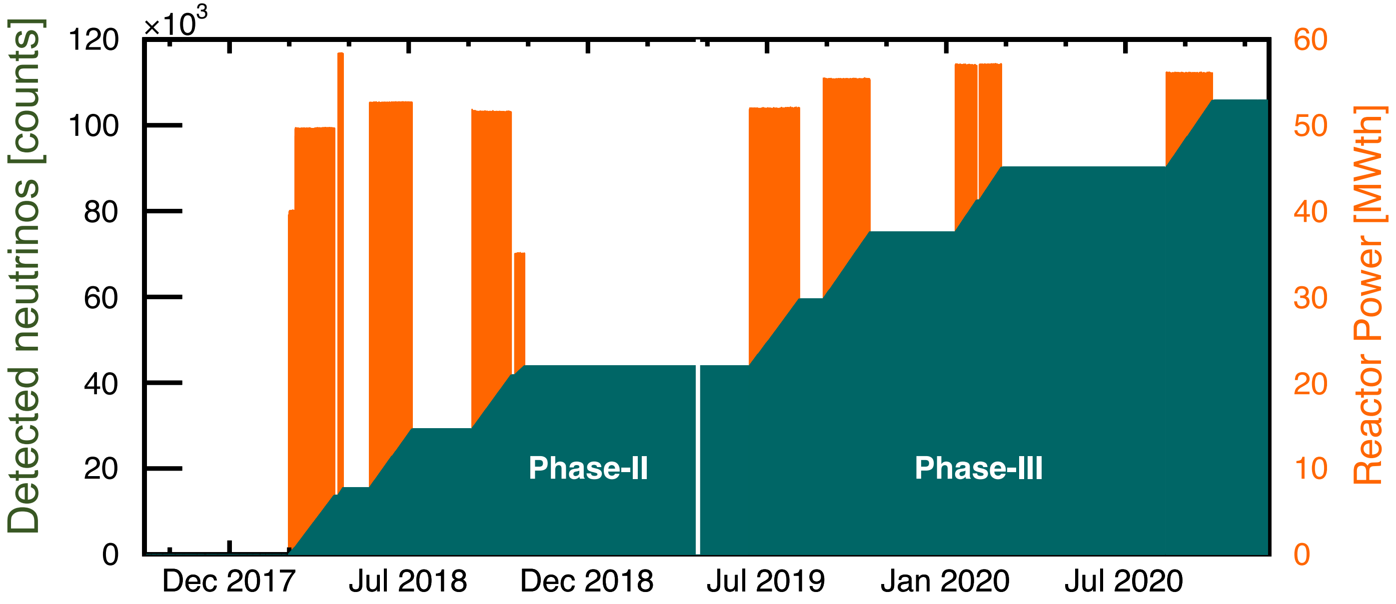
20 cm thick acrylic buffers for homogeneous detector response. PMT coupling via oil bath





ν detection through Inverse Beta Decay (prompt + delayed coincidence)

Dataset

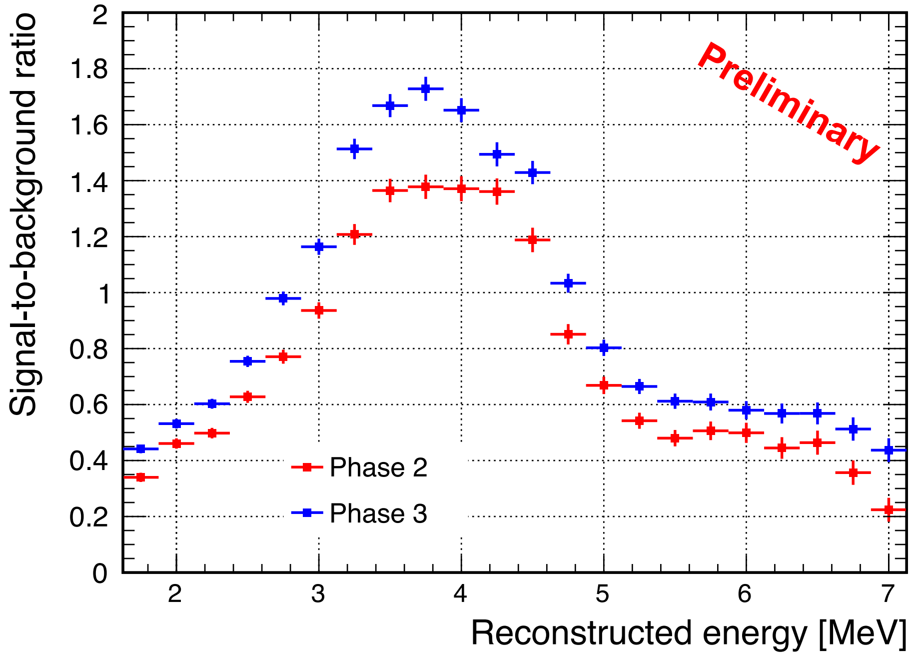


- Data-taking ended Nov 2020
- For better data quality, do not use Phase I
- Phase II + Phase III: 107k nu
  + calibration runs (hourly LEDs, weekly ^{54}Mn, monthly AmBe, bi-annual ^{68}Ge, ^{137}Cs, ^{60}Co, ^{24}Na)
- Reactor OFF data for background subtraction

S/B ~ 1

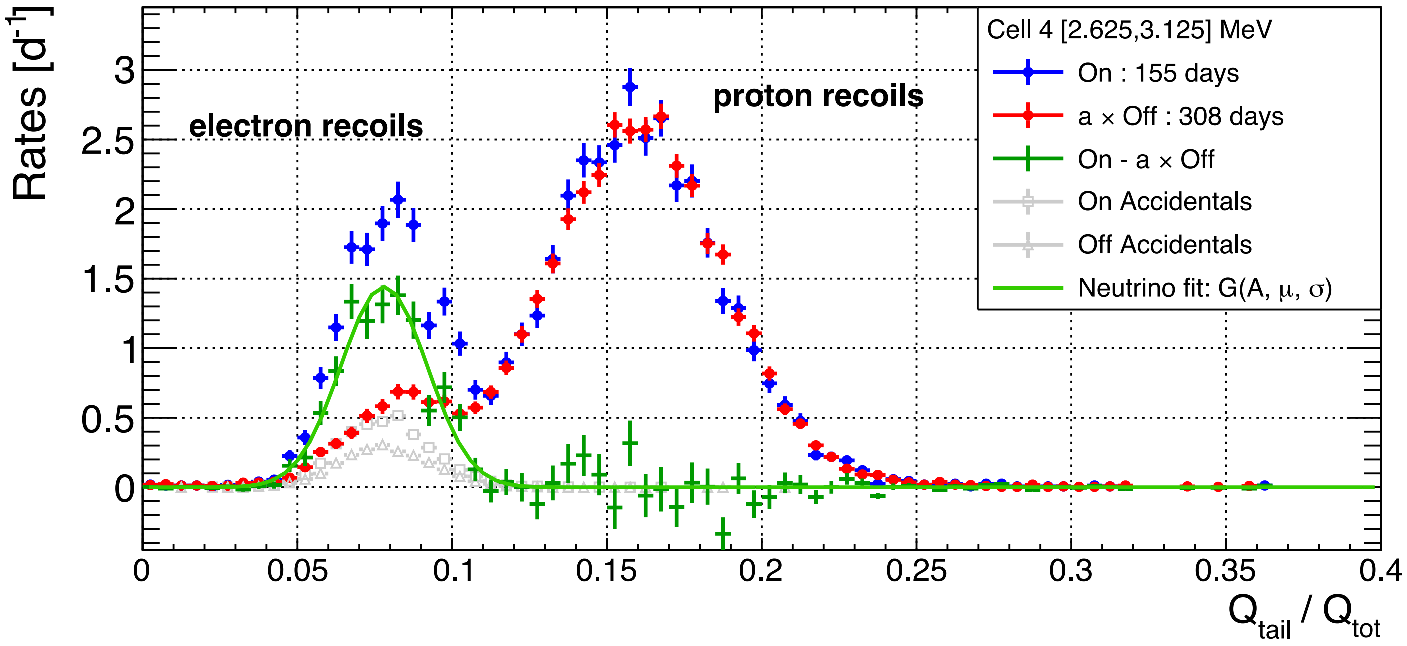
Higher reactor power in Phase III

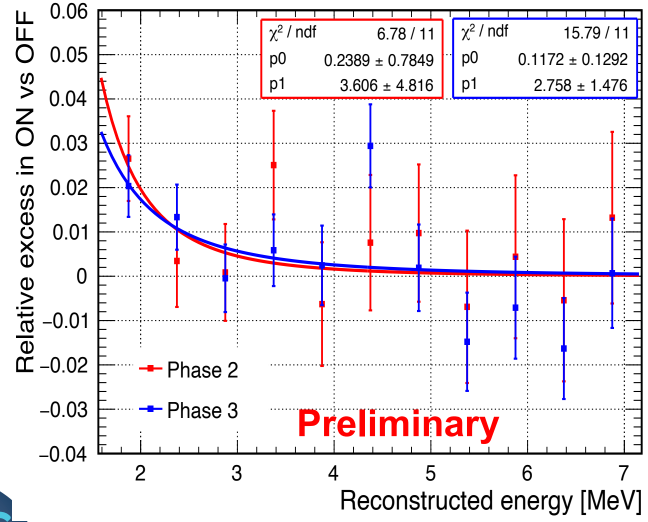
⟹ better S/B



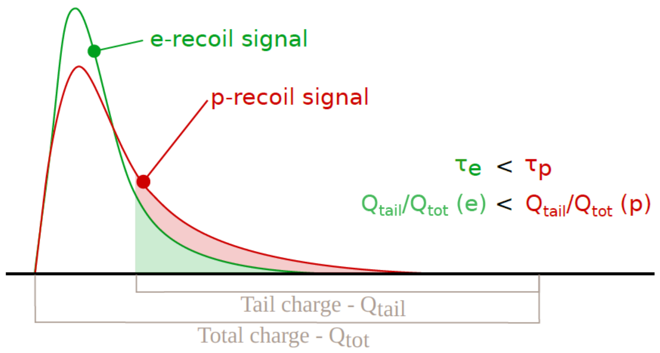
Neutrino extraction

- Fit Pulse Shape Discrimination (PSD) spectra to extract neutrino signal from correlated backgrounds (e.g. fast neutron from spallation by cosmics) in each cell and energy bin
- Background shape from OFF data
- Accidentals from displaced-time window

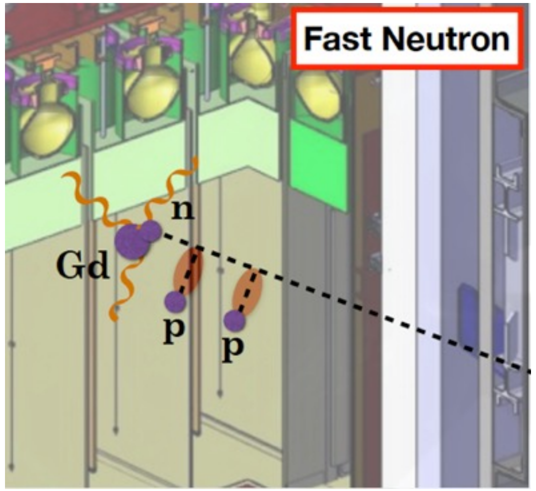




Look for reactor prompt background in proton recoils

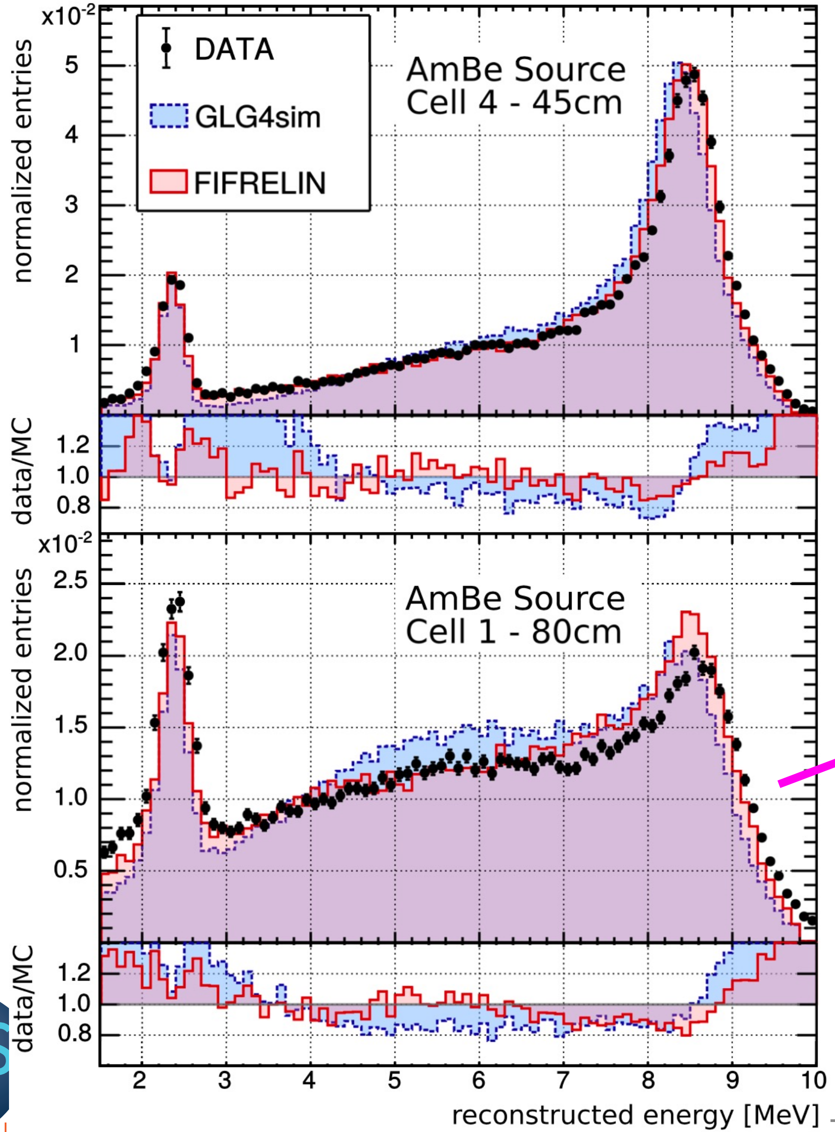


PSD = Q_{tail} / Q_{tot}

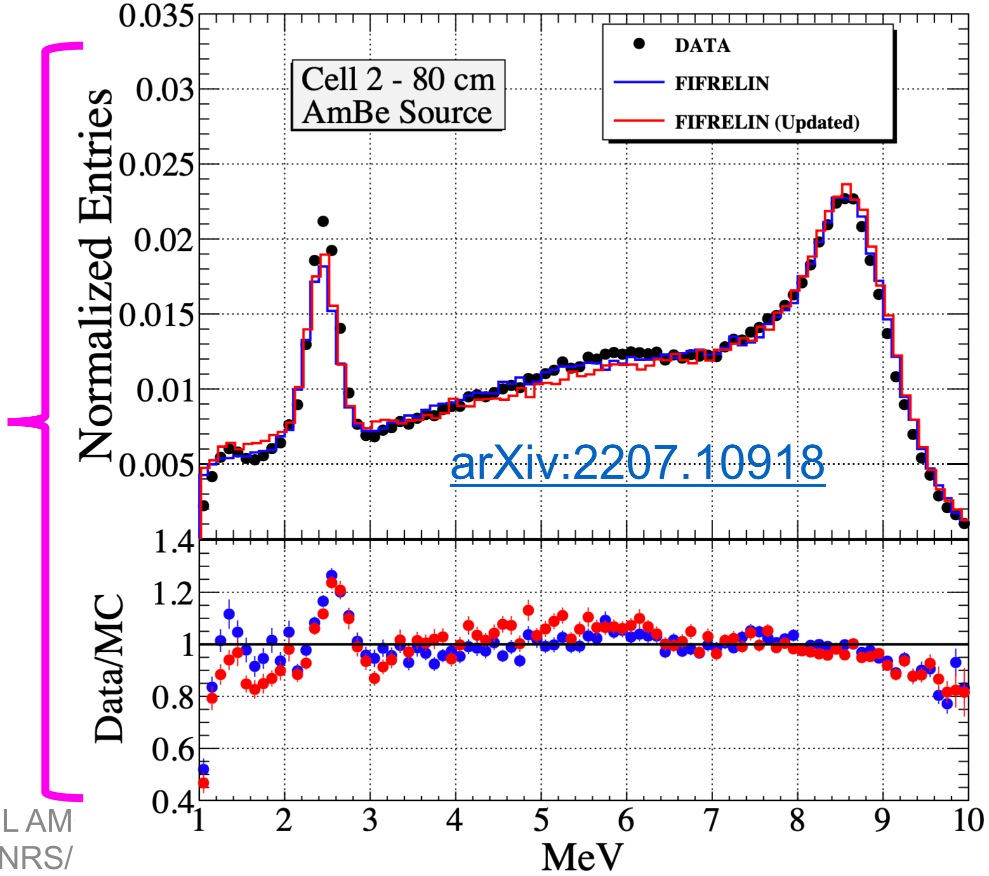


New n-Gd γ-cascade model

O. Litaize et al., Eur. Phys. J. A (2015) 51: 177



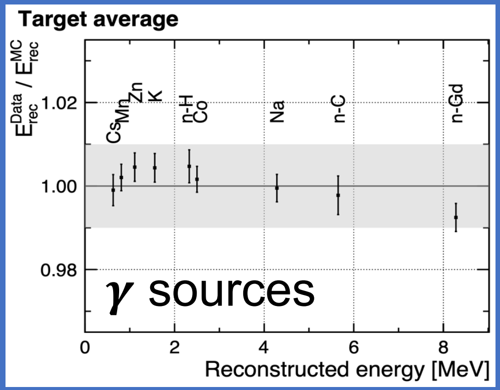
- Especially important for small detectors, where high energy gamma more likely to escape
- NEW: FIFRELIN code improved: EGAF exp data, angular correlations, better conversion electrons arXiv:2207.10918

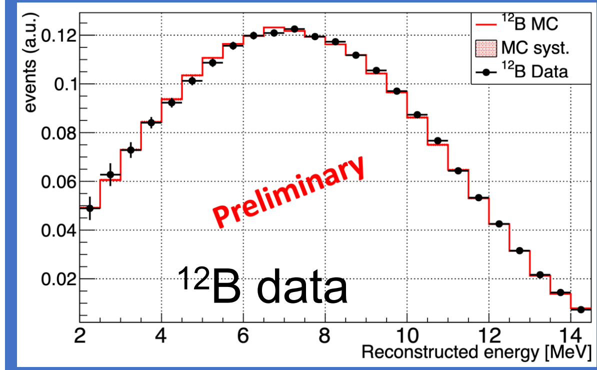


Better n-Gd peak data/MC agreement in borders of detector

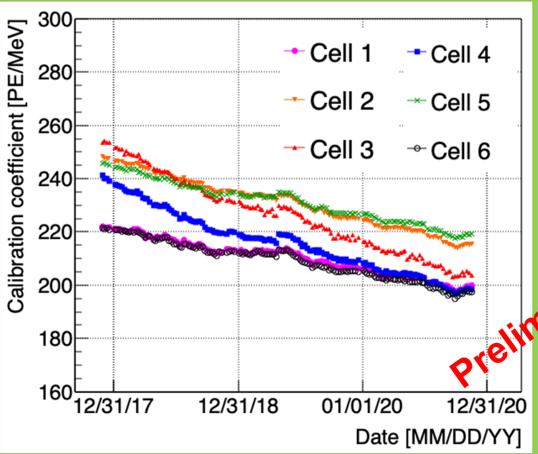
Detector response

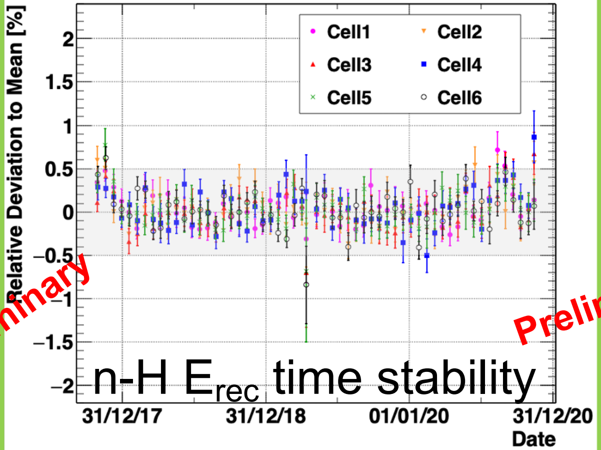
Energy scale

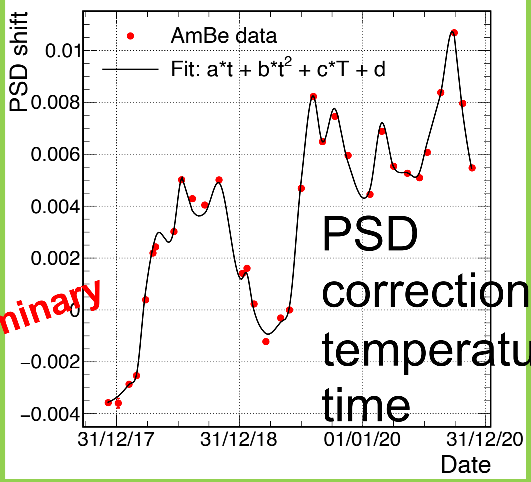




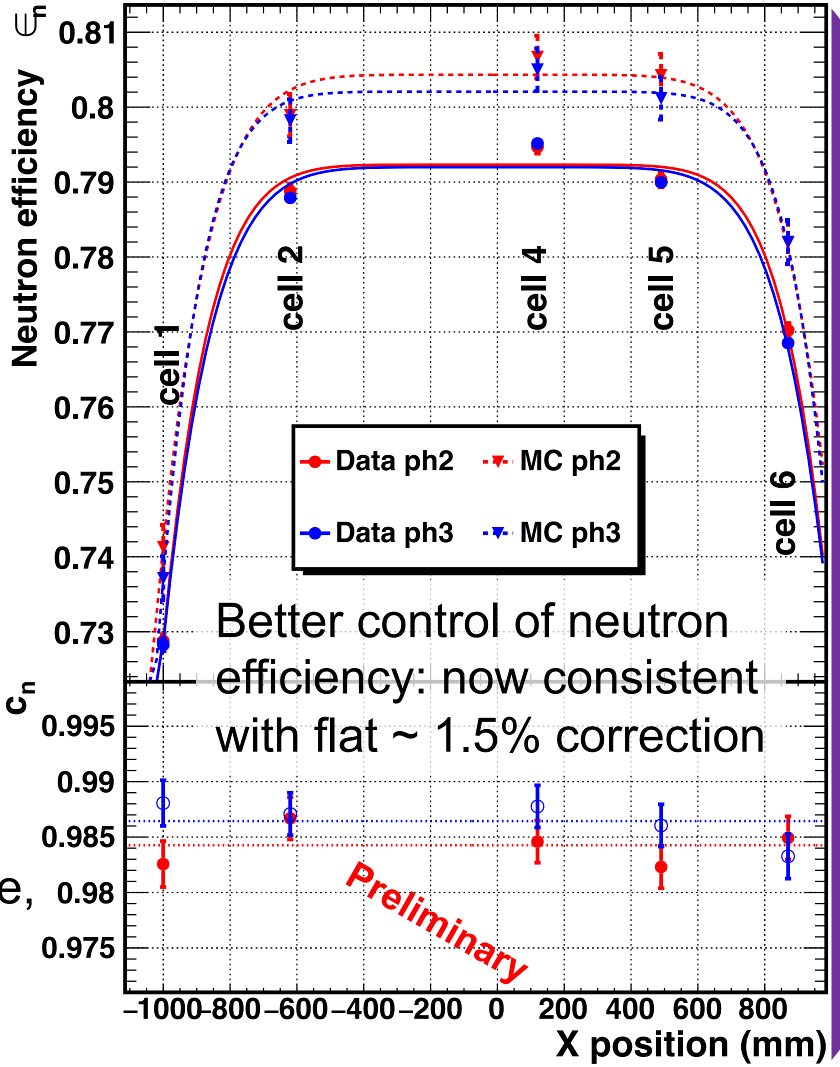
Time stability







Neutron efficiency



Better control of neutron efficiency: now consistent with flat ~ 1.5% correction

Time stability

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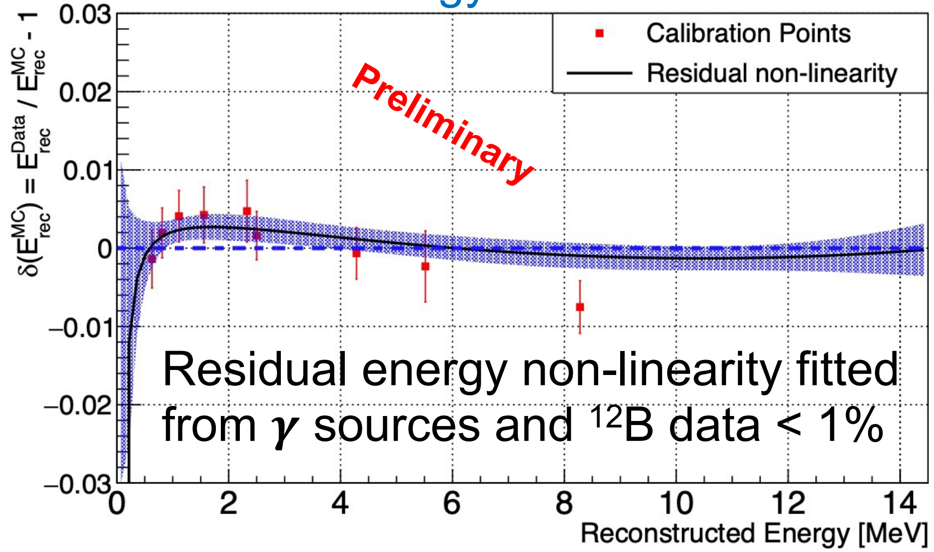
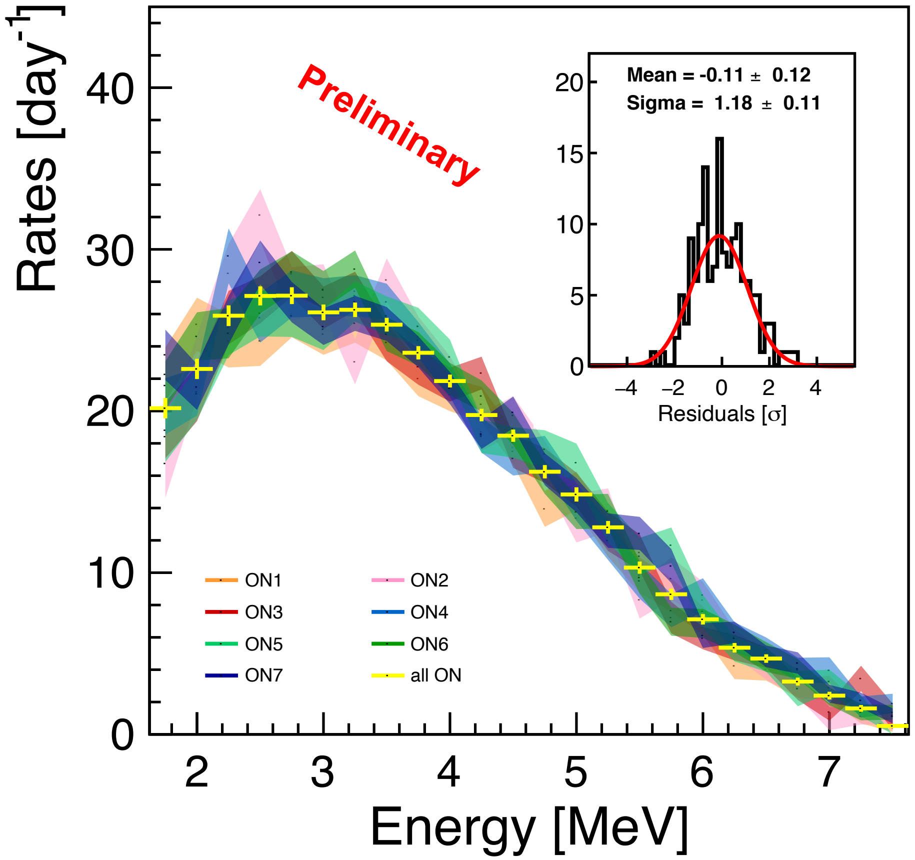
Validation and systematics

Energy scale



Time stability



Stability of correlated background subtraction: comparison of IBD spectra extracted from every ON period using adjacent OFF data. Spectra are compatible with each other within statistical uncertainties.

For final neutrino signal extraction, all ON and OFF runs within same Phase are merged

Oscillation analysis

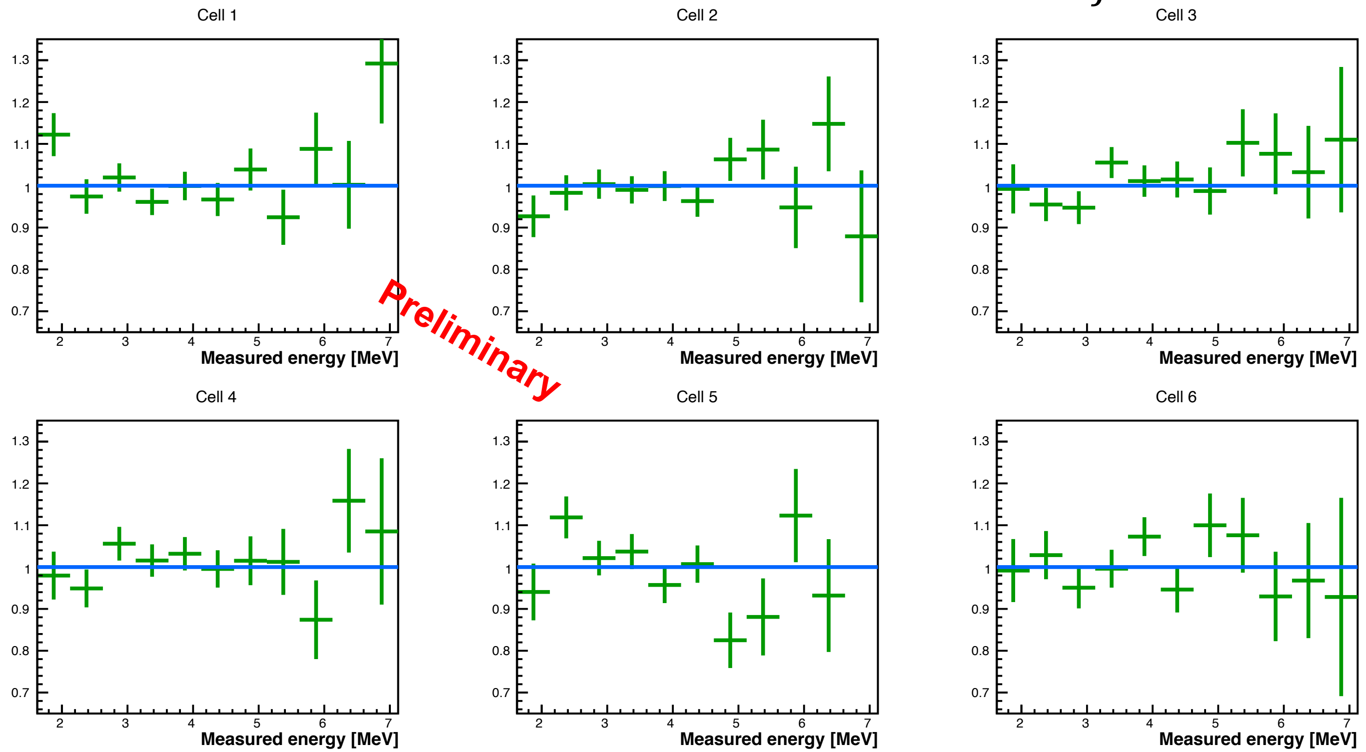
Compare data energy spectra of each cell $D_{l,i}$ to prediction $M_{l,i}$ for oscillation parameter values $\sin^2(2\theta_{ee})$ and Δm^2_{41} (α_j, nuisance parameters):

$$\chi^2(\sin^2(2\theta), \Delta m^2, \phi_i, \alpha_j) = \sum_l^{N_{cells}} \sum_i^{N_{Ebins}} \left(\frac{D_{l,i} - \phi_i \times M_{l,i}(\sin^2(2\theta), \Delta m^2, \alpha_j)}{\sigma_{l,i}} \right)^2 + \sum_j \left(\frac{\alpha_j}{\sigma_j} \right)^2$$

Spectrum prediction-independent (free ϕ_i)

Uncertainty type	Value (relative)
E scale (cell uncorrelated): cell-to-cell deviations	1.0%
E scale (corr): time stability	0.25%
Norm (uncor): cell volume ⊕ n efficiency correction	0.83% ⊕ 0.63%
Reactor background	0.7% (P-II: 118 days) 0.6% (P-III: 156 days)
Norm Phases II VS III ($\sim\sigma(P_{th})$)	1.5%

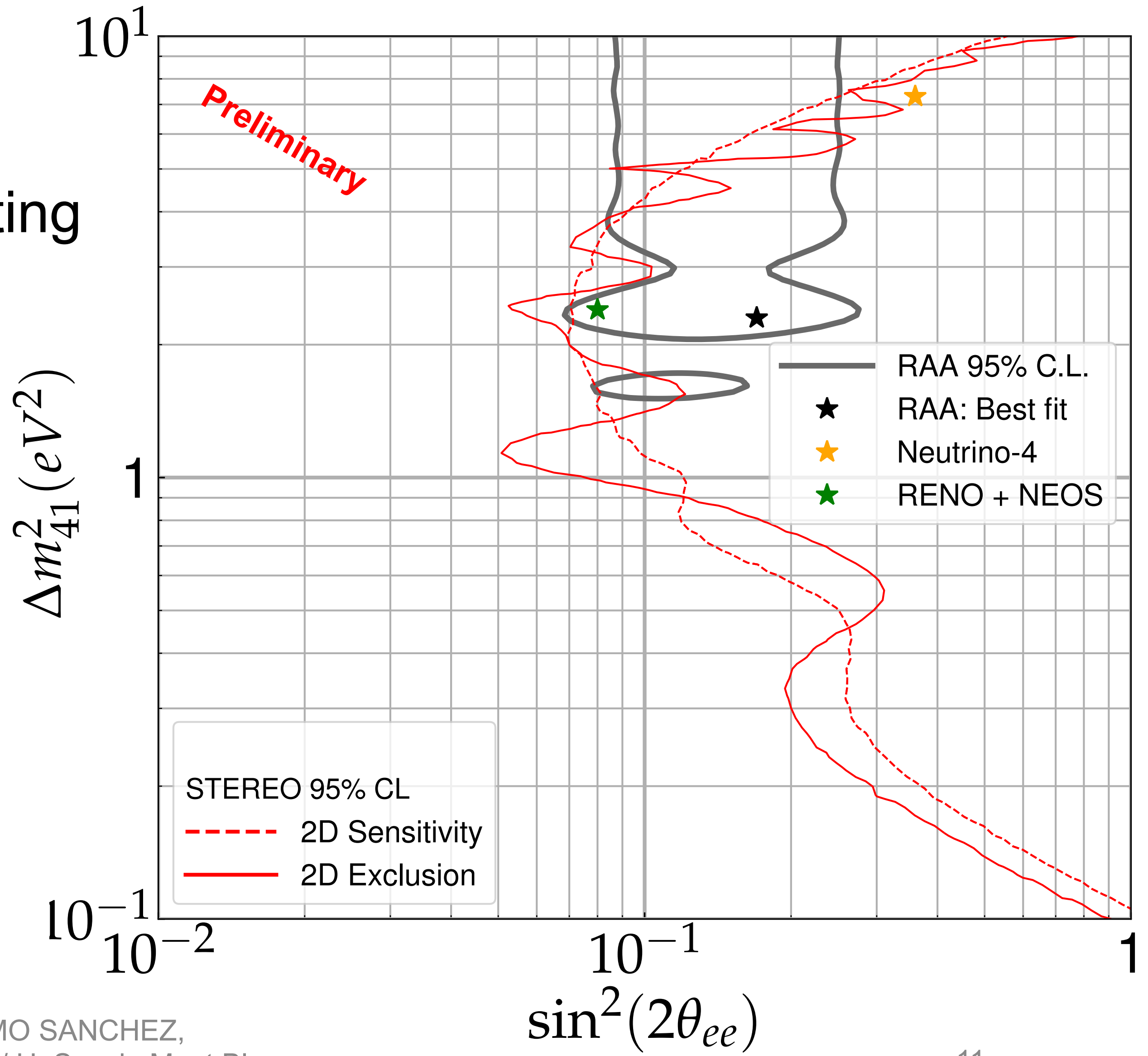
Phase III data/No oscillation prediction (ϕ_i, α_j optimised)



Oscillation results

- Reactor spectrum prediction-independent
- $\Delta\chi^2$ pdf determined at each point in ($\sin^2(2\theta)$, Δm^2) plane by generating and fitting pseudoexperiments ("Feldman-Cousins")

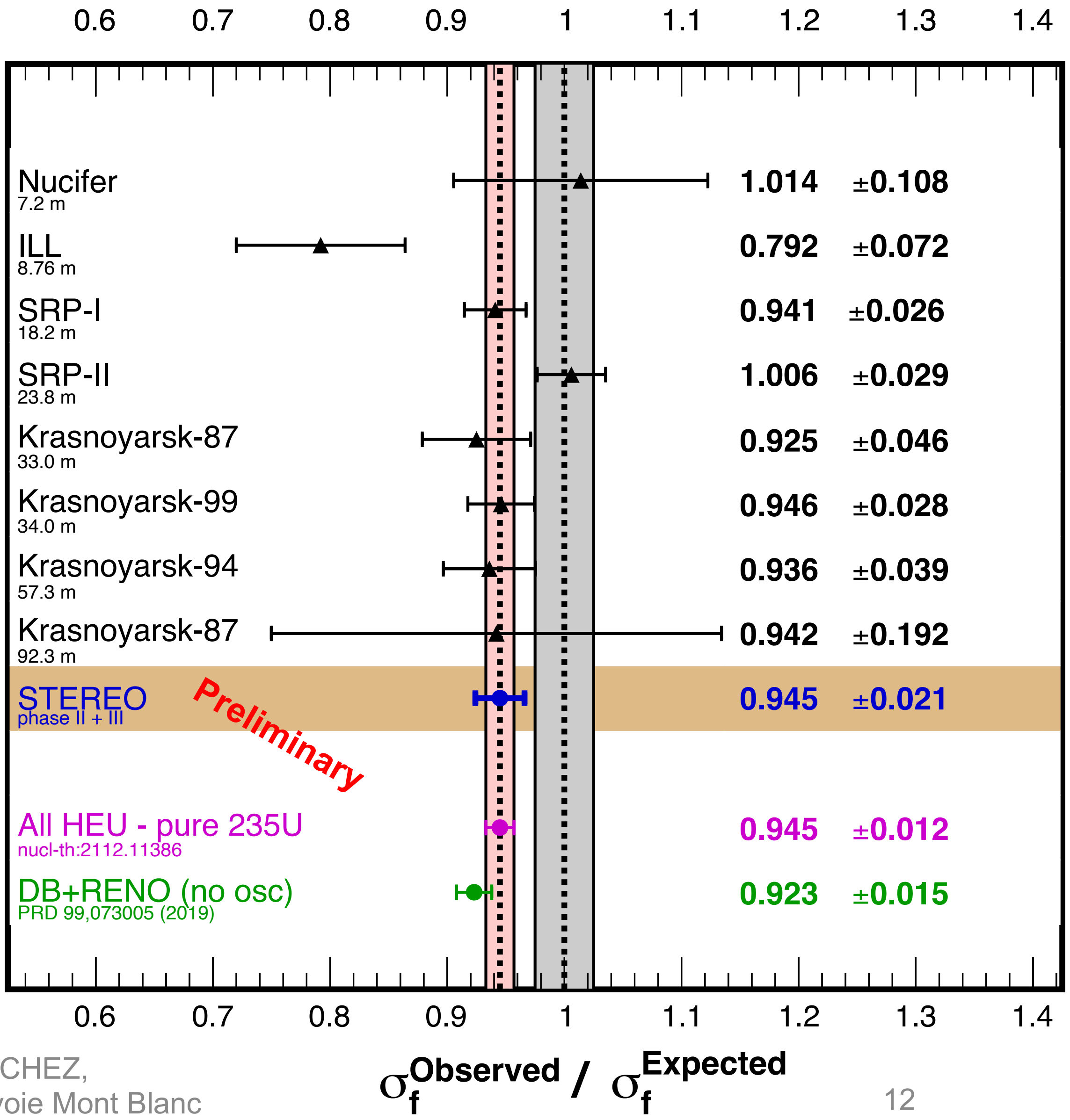
- Exclude most RAA allowed param space at > 95% CL for $\Delta m^2_{41} < 4$ eV^2
  - No oscillation ***not*** excluded (p-value=0.54)
  - RAA best fit excluded at $\gtrsim 4\,\sigma$
  - Neutrino-4 best fit excluded at 3.1 σ
  - Neos-RENO best fit excluded at 2.8 σ
- Higher Δm^2_{41} in strong tension with cosmology, will be probed by KATRIN



Reactor flux

- Better neutron efficiency treatment (0.7% syst)
- Dominant exp error: reactor P_{th} (1.4% syst)
- No aging of diaphragm in primary circuit, as checked by ILL staff ✓

Normalization	Reactor thermal power	1.4%
	Proton number	1.0%
	Neutron efficiency	0.7%
	Neutrino extraction method	0.7%
	Solid angle	0.5%
	Others [5]	0.3%
	→ **Total**	**2.1%**



Overall ~5% deficit confirmed

Most precise ^{235}U flux measurement

Reactor spectrum measurement

- Joint Phases II + III unfolding ($E_{rec} \rightarrow E_\nu$)

$$\chi^2(\lambda_l, \alpha_k) = \sum_p^{phases} \sum_j^{N_{Ebins}} \left(\frac{D_{j,p} - \varphi_p \times R_{ij,p}(\alpha_k) \times \phi_j(\lambda_l)}{\sigma_{j,p}} \right)^2$$

$$+ \sum_k \left(\frac{\alpha_k}{\sigma_k} \right)^2 + \text{corr pull }(\varphi_\text{p}) + r \times \sum_l (\lambda_l - \lambda_{l+1})^2$$

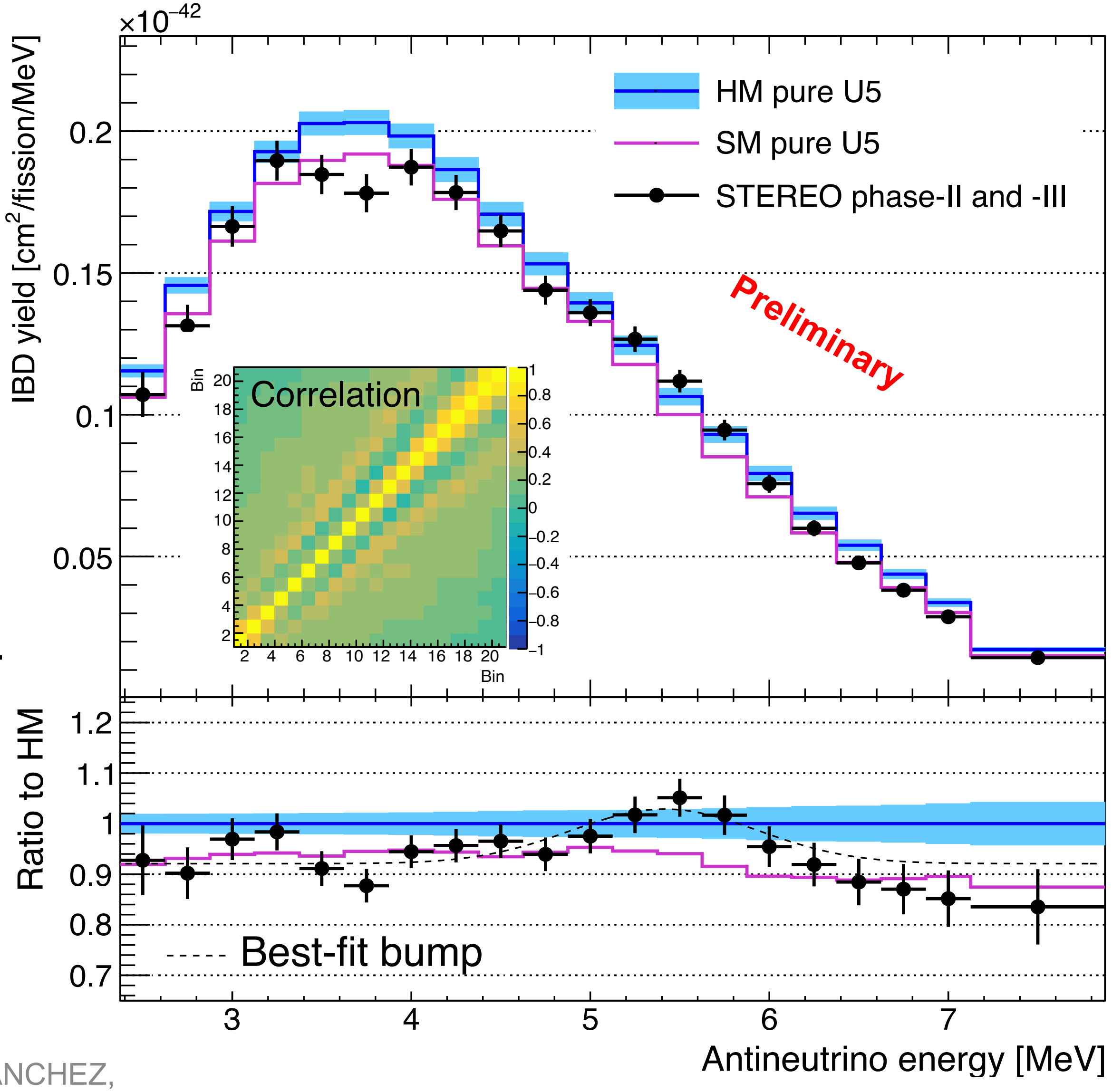
regularisation term

where: D_j = data energy spectrum bin

λ_l = ratio of spectrum to ref spectrum (p.ex. HM)

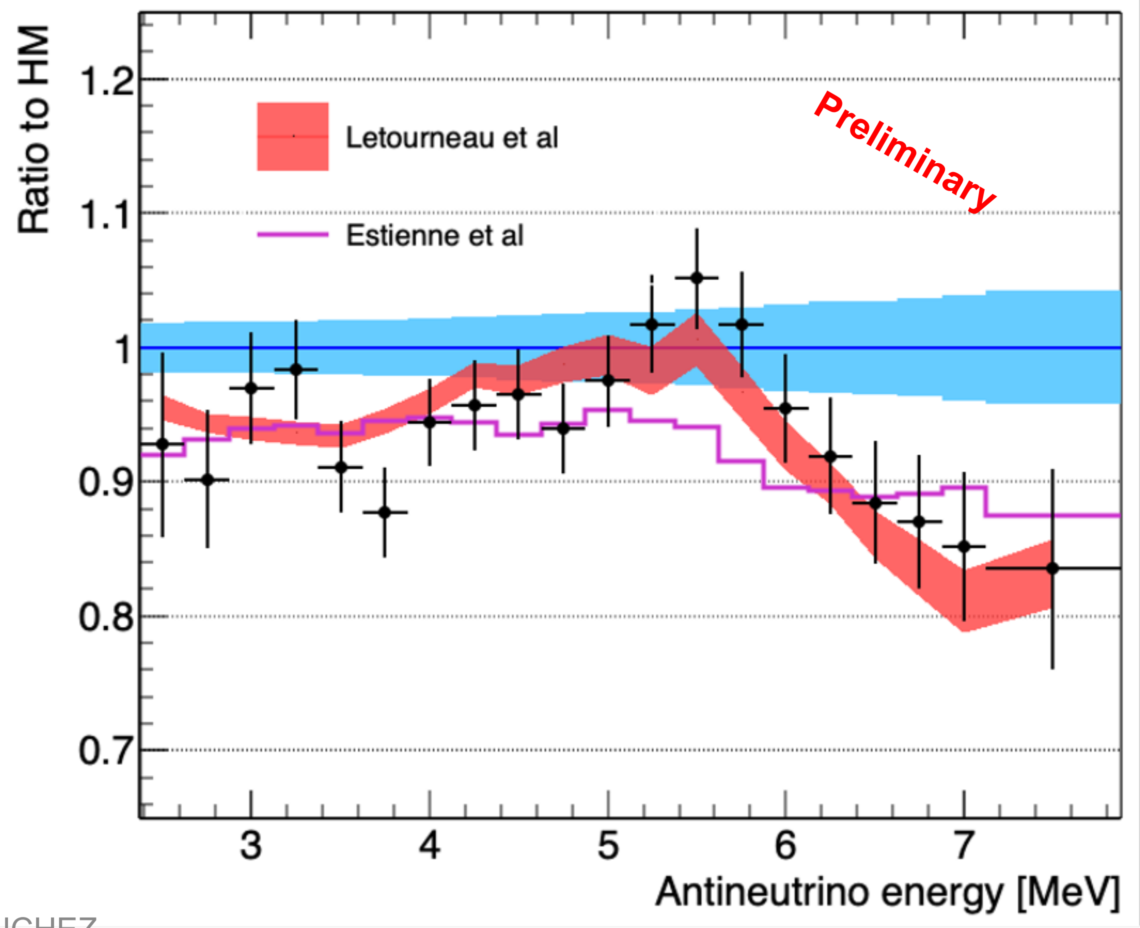
R_{ij} = detector response matrix

- Tikhonov regularisation, strength *r* tuned with pseudo-experiments to minimise prior dependence. Covariance-matrix formalism gives ~identical results
- Bump observed (4.6 σ) at ~5.5 MeV
- Reference ^{235}U ν spectrum will be provided to community

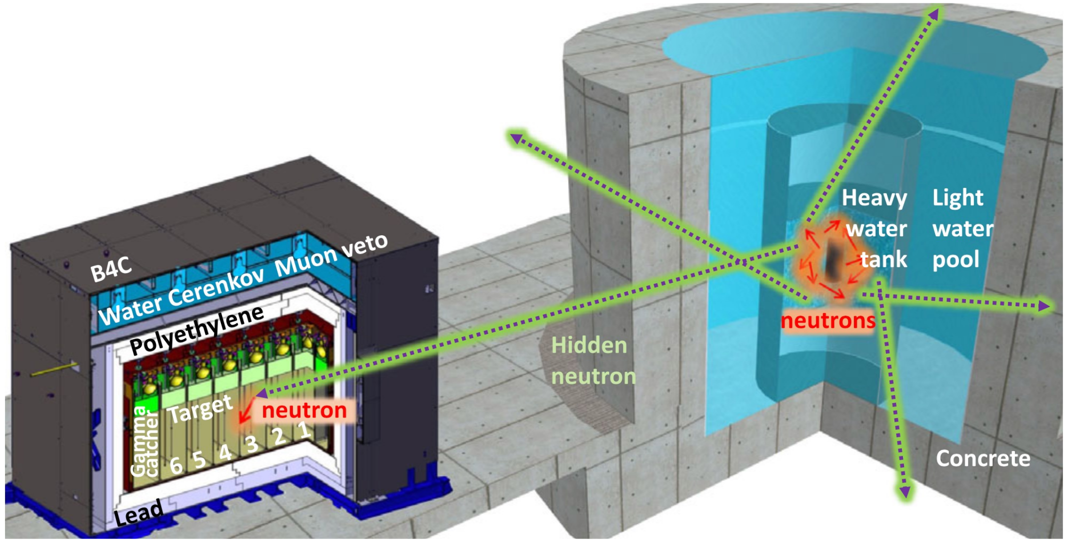


Reactor neutrino spectra: tool for nuclear data validation

- RAA: if not a sterile neutrino, a nuclear data problem?
- Test nuclear data with reactor neutrinos!
- A. Letourneau *et al* (arXiv:2205.14594, sub. to PRL):
  - Observe bias when comparing ENSDF nuclear database data with isotopes measured with TAGS
  - Model of bias
  - Correct all isotopes (not TAGS measured) for modelled bias
  - Predict spectrum
  - Test predicted spectrum against STEREO's measured reactor spectrum
  - Good qualitative agreement!
- Towards reactor neutrino data as reference nuclear data?

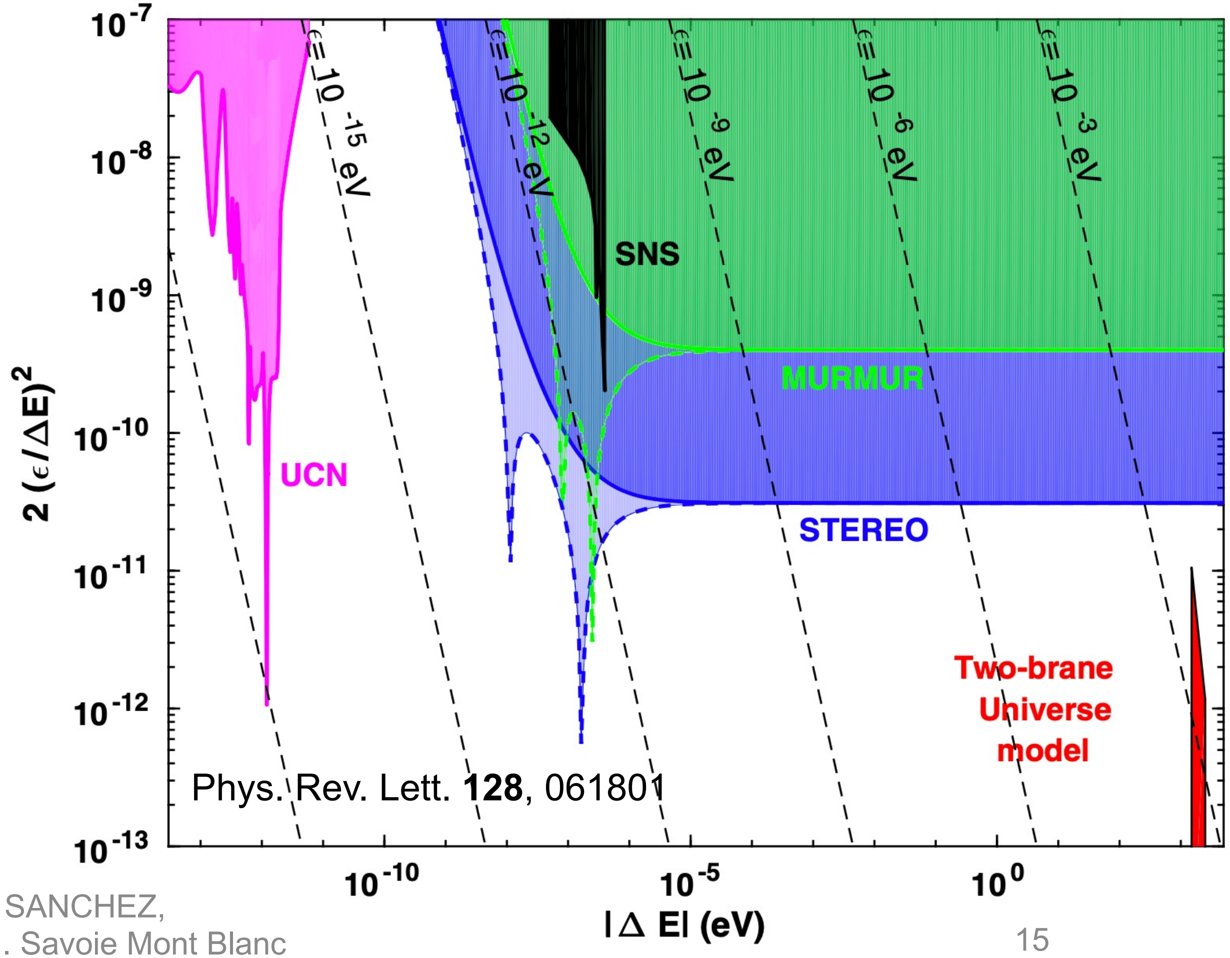


BONUS: neutrons and hidden branes



ϵ, coupling between hidden and visible states

ΔE, energy difference between hidden and visible states



In some models:

- Neutron collision has ≠0 prob of sending neutron to hidden brane and viceversa
- Hidden neutrons can escape reactor and reappear in STEREO

→ constrain swapping probability parameters ϵ and ΔE

Summary & outlook

- We present here the analysis of STEREO's final dataset
- STEREO confirms ~5% deficit in reactor antineutrino flux
- Exclude most of the RAA allowed parameter space at low masses (below ~4 eV^2)
- Provide most precise measurement of pure ^{235}U reactor $\bar{\nu}$ spectrum

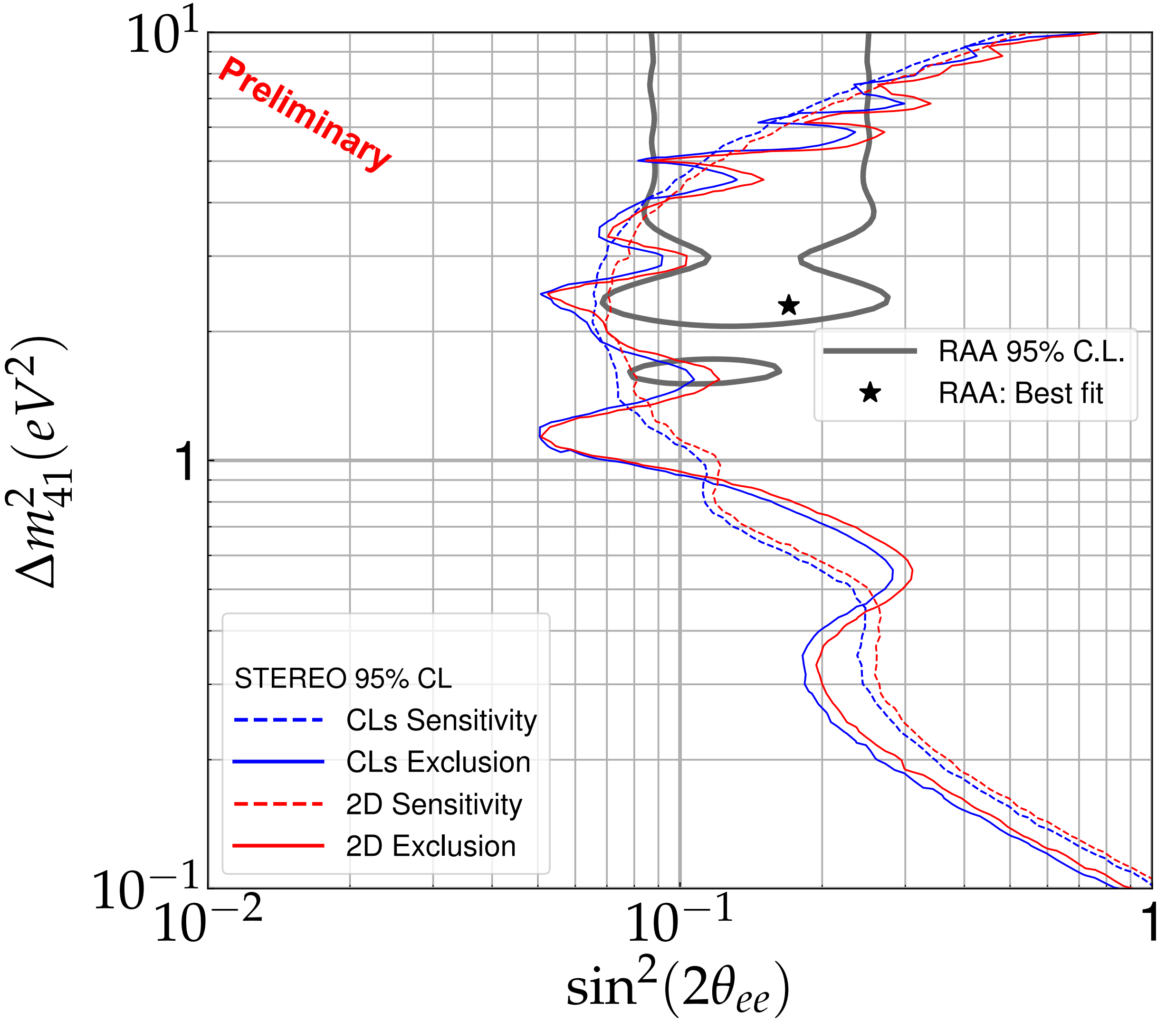
→ Towards reactor neutrino data as reference nuclear data?

- Ongoing reactor $\bar{\nu}$ spectrum joint unfolding with other experiments' data

The STEREO Collaboration

BACK UP SLIDES

Statistics crosscheck: CLs VS 2D

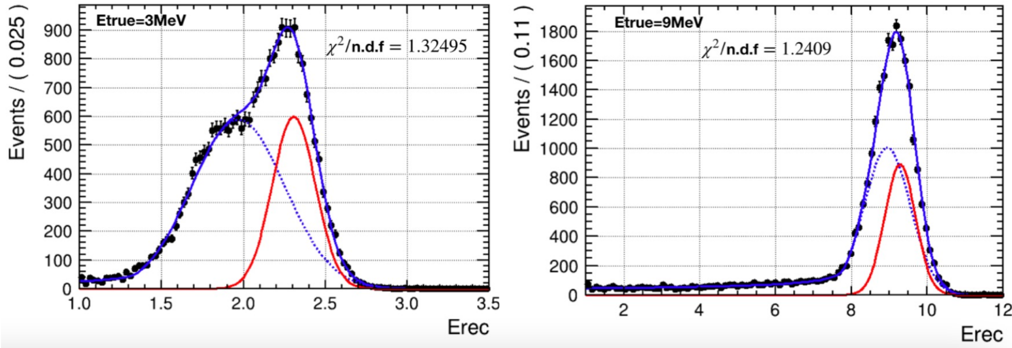


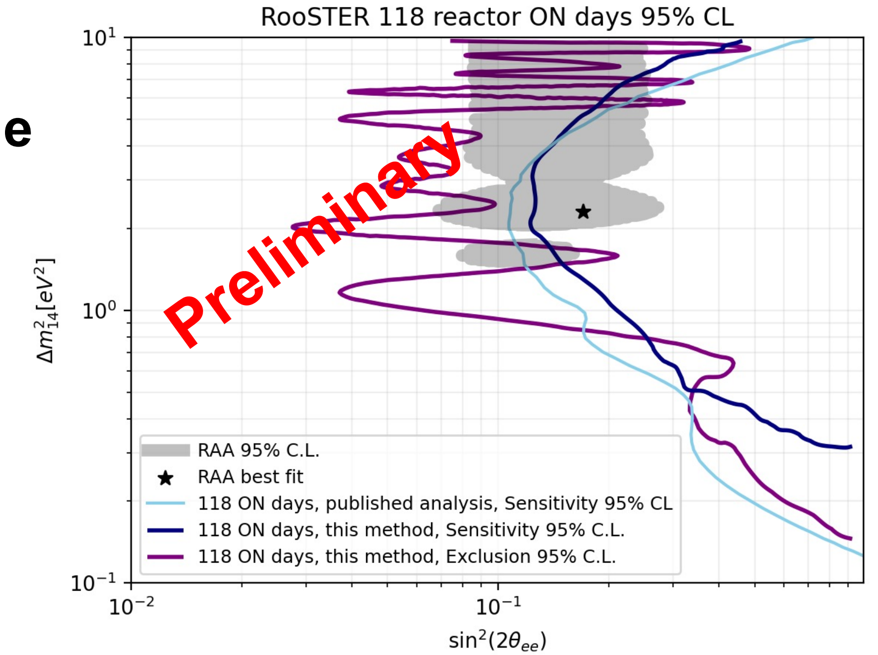
Gaussian CLs method:
Qian *et al*,
Nucl.Instrum.Meth.A
827 (2016) 63-78

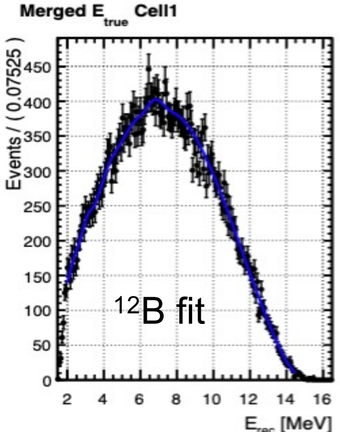
Oscillation analysis crosscheck

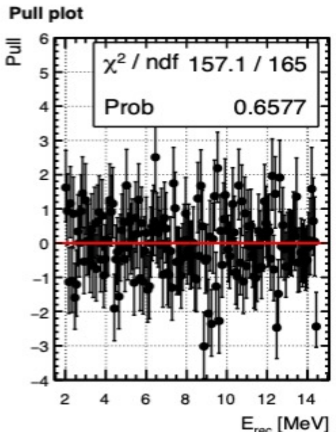
Approach: instead of fixed response model $M_{l,i}$ from Geant4 MC with allowed linear variation on each cell's energy and norm, use analytical parameterisation in order to leave free in fit ~all response model params.

- Parametrise and fit analytical response model: 15 params/cell (3 for $E_{rec}=E_{rec}(E_{true})$, 3 for $\sigma = \sigma(E_{rec})$, rest for shoulder and non-gaussian tail)
- PDF in E_{rec} = convolution of E_{true} PDF (free spectrum x acceptance x oscillation probability) with analytical response model
- Derive systematics from fit to ^{12}B data
- Finer binning (250 keV VS 500 keV), only 118 reactor ON days
- **Independent, radically different oscillation search compatible with published results** (*Phys.Rev.D* 102 (2020) 5, 052002)









Data VS no oscillation model after nuisance params fit: