Max-Planck-Institut für Kernphysik

Accurate Measurement of Electron Antineutrinos of U-235 Fissions from the STEREO Experiment

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on behalf of the STEREO collaboration

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Neutrons for Society

Laboratoire d'Annecy de Physique des Particules

LPSC Grenoble | Modane

cea Paris-Saclay

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cnrs IN2P3 Les deux infinis

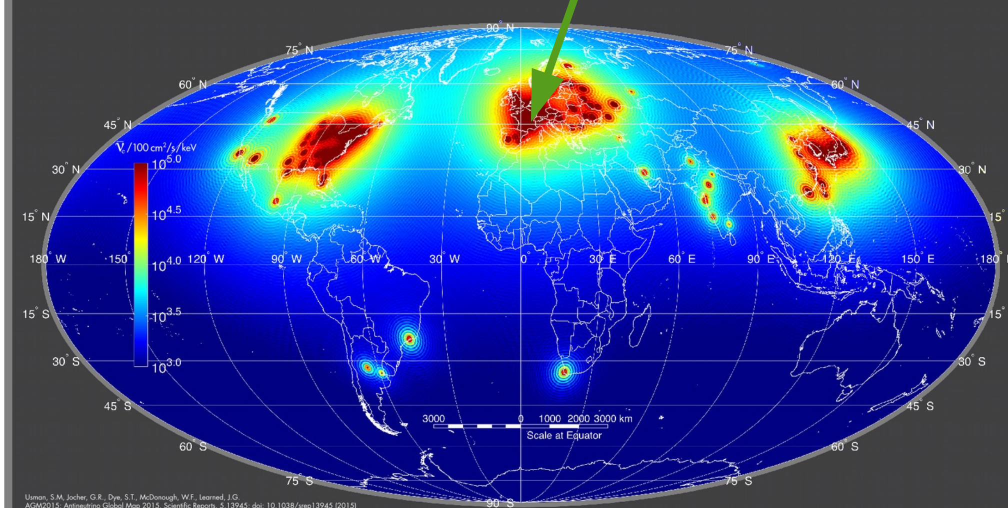
Enigmass

P2IO Physique des 2 Infinis et des Origines

Outline

- Experimental Setup
  JINST 13, P07009 / arXiv:1804.09052
- Oscillation Analysis
  arXiv:1912.06582 / HEPdata.92323
- Absolute Rate Analysis
  arXiv:2004.04075
- Spectral Shape Analysis
- Summary/Outlook

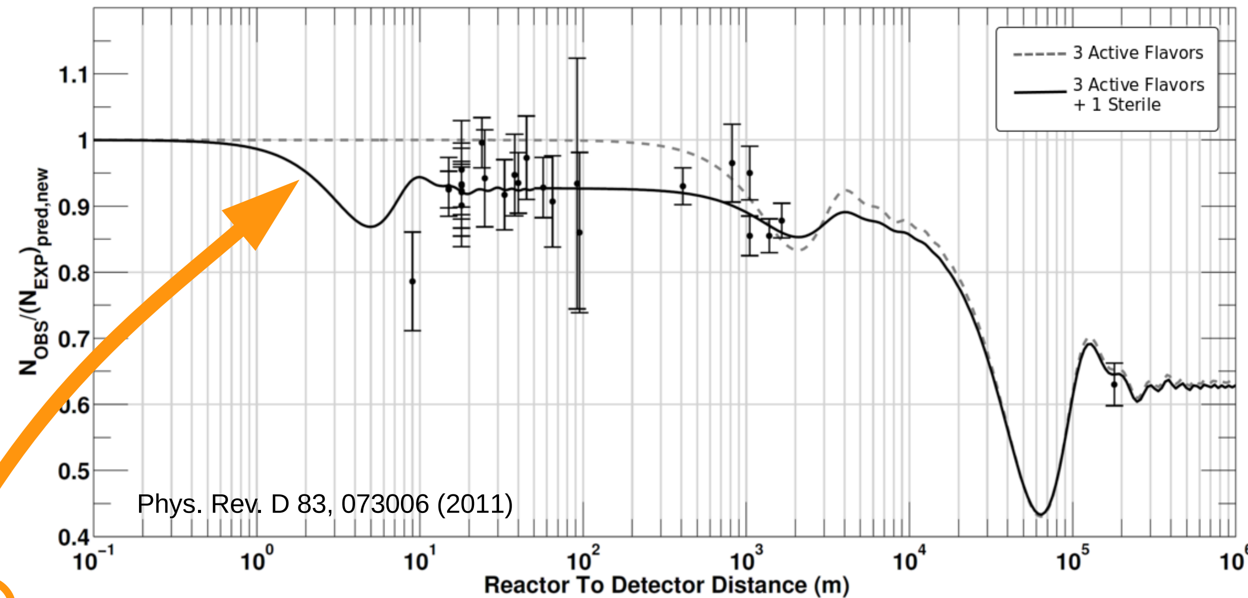
3 MeV reactor antineutrino flux worldwide:



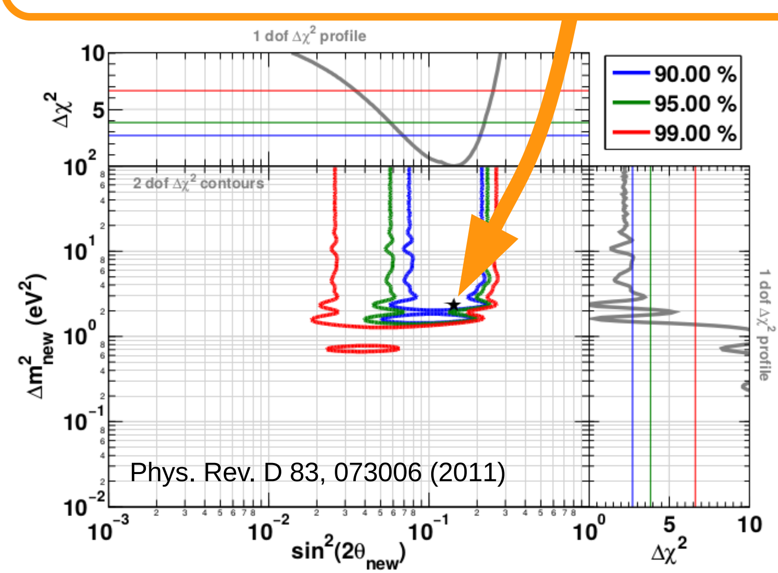
Antineutrino Global Map 2015, Sci.Rep. 5 (2015) 13945

Motivation

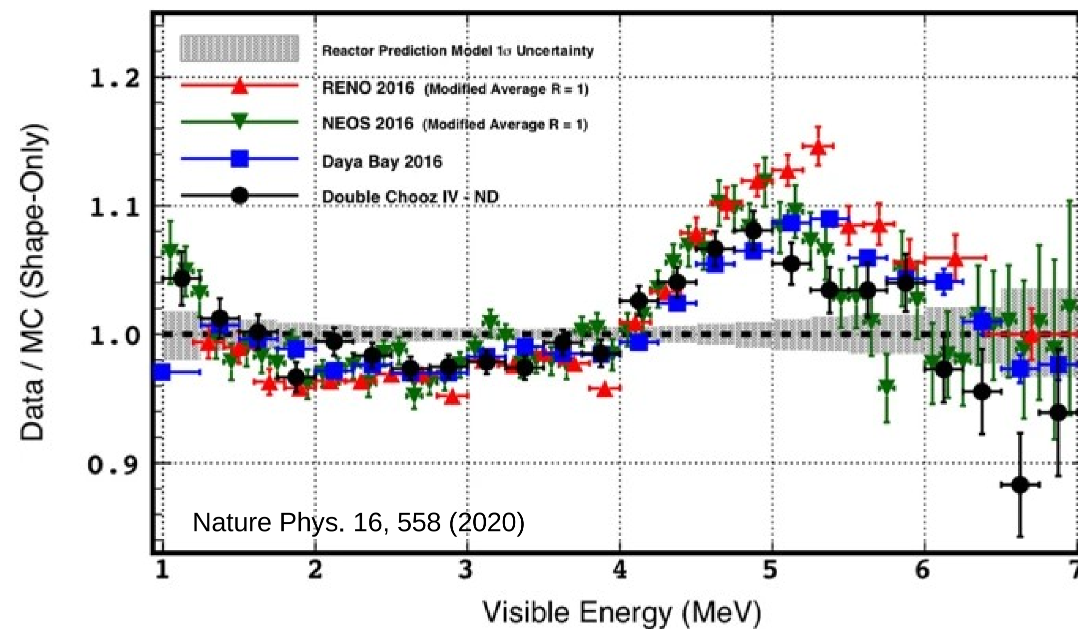
- Improved reactor neutrino flux predictions:
  → deficit in measured fluxes
- One possible explanation:
  → light sterile neutrinos
- Sterile neutrinos:
  → new oscillation channel visible at small L/E



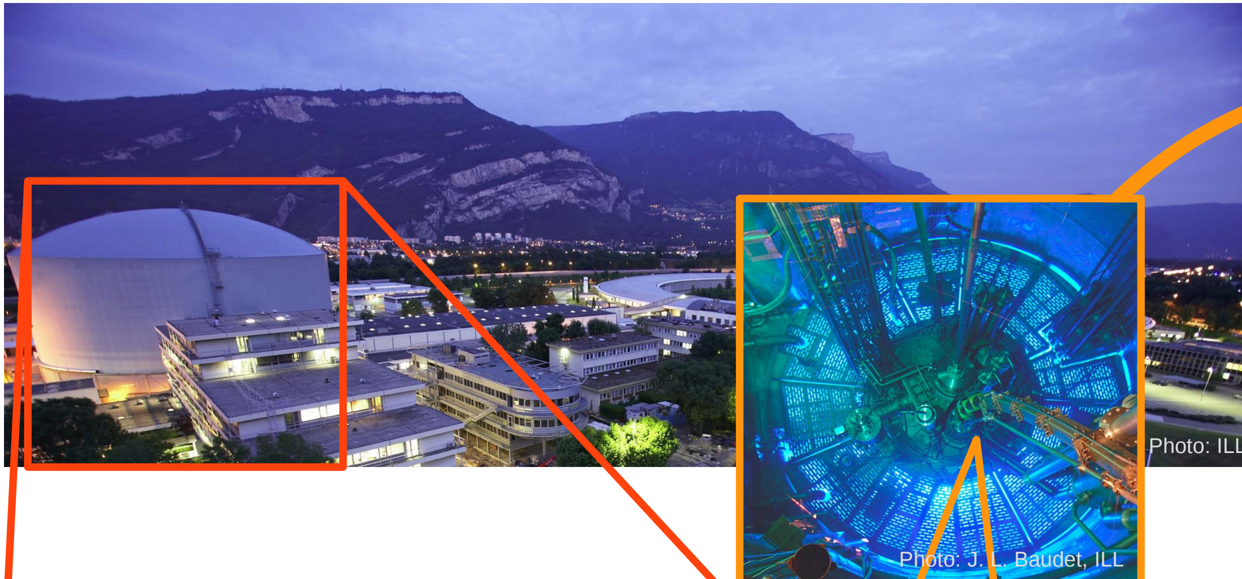
Reactor Antineutrino Anomaly (RAA)
$\sin^2(2\theta_{new})=0.14$, $\Delta m^2_{new}=2.4eV^2$

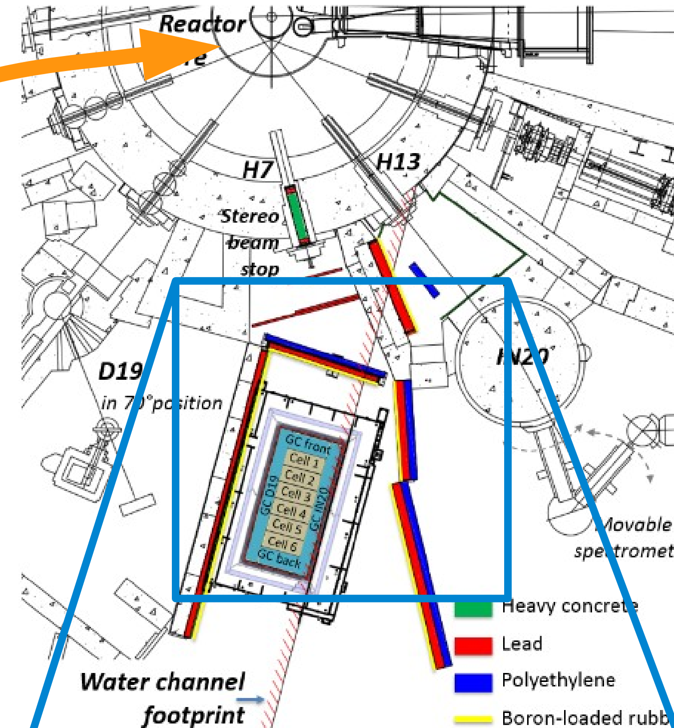


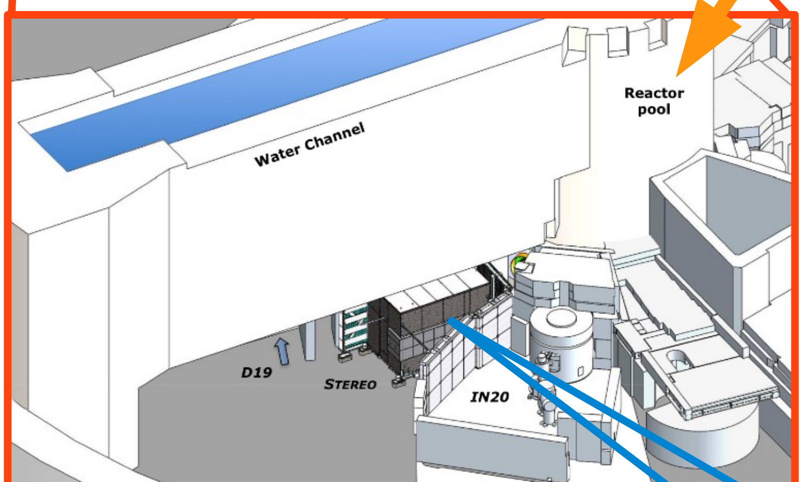
- Energy spectral distortion w.r.t. model
  → up to ~10% between 4 and 6 MeV



Experiment Site

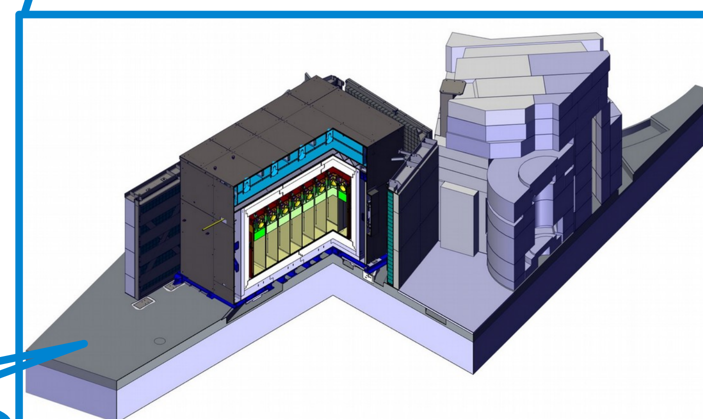






Neutrino source:

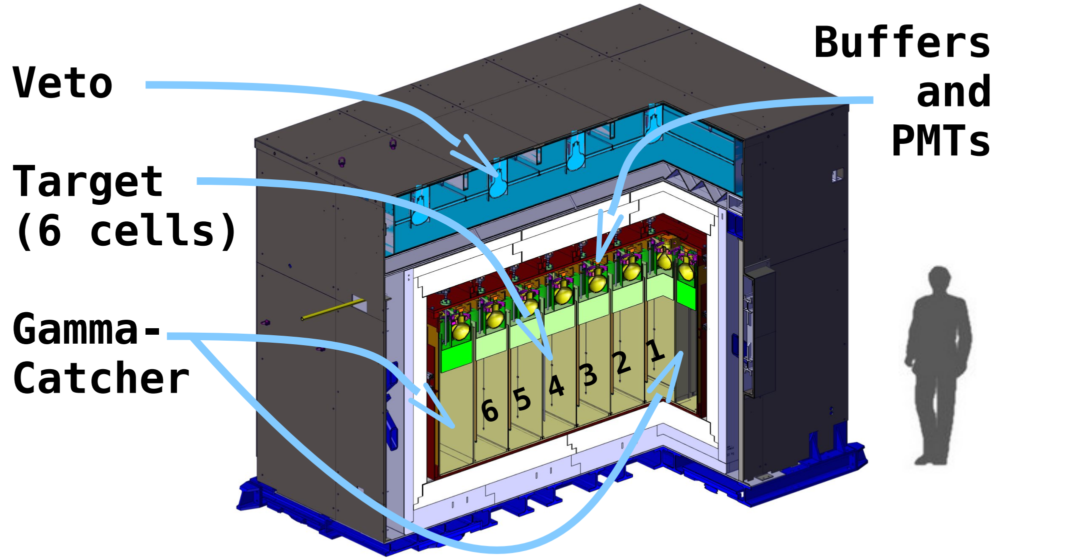
- reactor at ILL Grenoble
- $P_{thermal}$ = 58.3 MW
- Height: 80cm
- Diameter: 40cm
- **Highly enriched in ^{235}U** (99.3% of fissions)



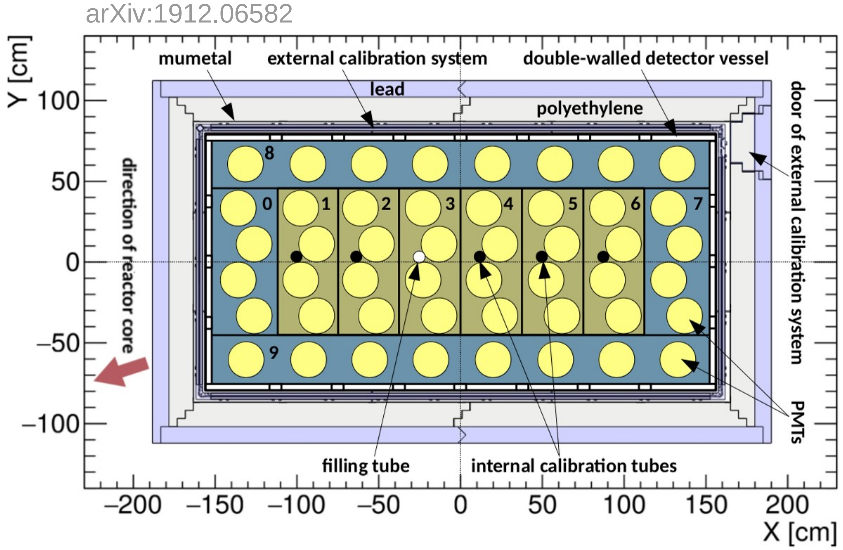
Baseline: 9 – 11 m
Overburden: ~15 m.w.e.

Detector / Measurement Principle

- Target **segmented in 6 cells**
  → 1800 l of Gd-loaded liquid scintillator
- Surrounding Gamma-Catcher to convert escaping gammas
- 48 PMTs of 8 inch diameter
- Layers of acrylic and oil as buffer
- Water Cherenkov veto on top
- About 90 tons of shielding material
  → lead, polyethylene, B_4C, iron

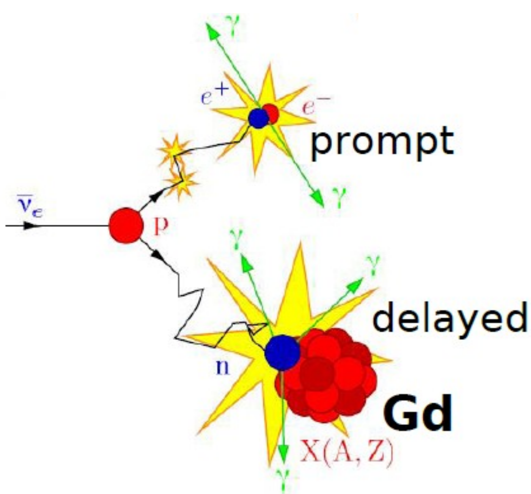


arXiv:1912.06582



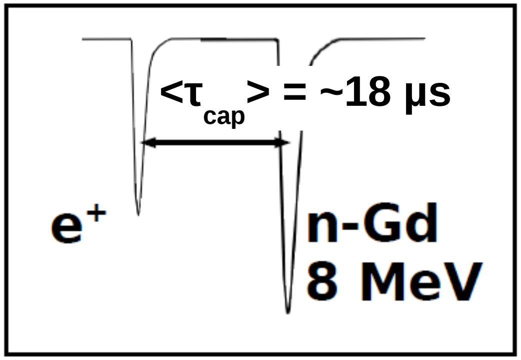
Inverse beta-decay (IBD):

$$\bar{\nu}_e + p^+ \rightarrow e^+ + n$$



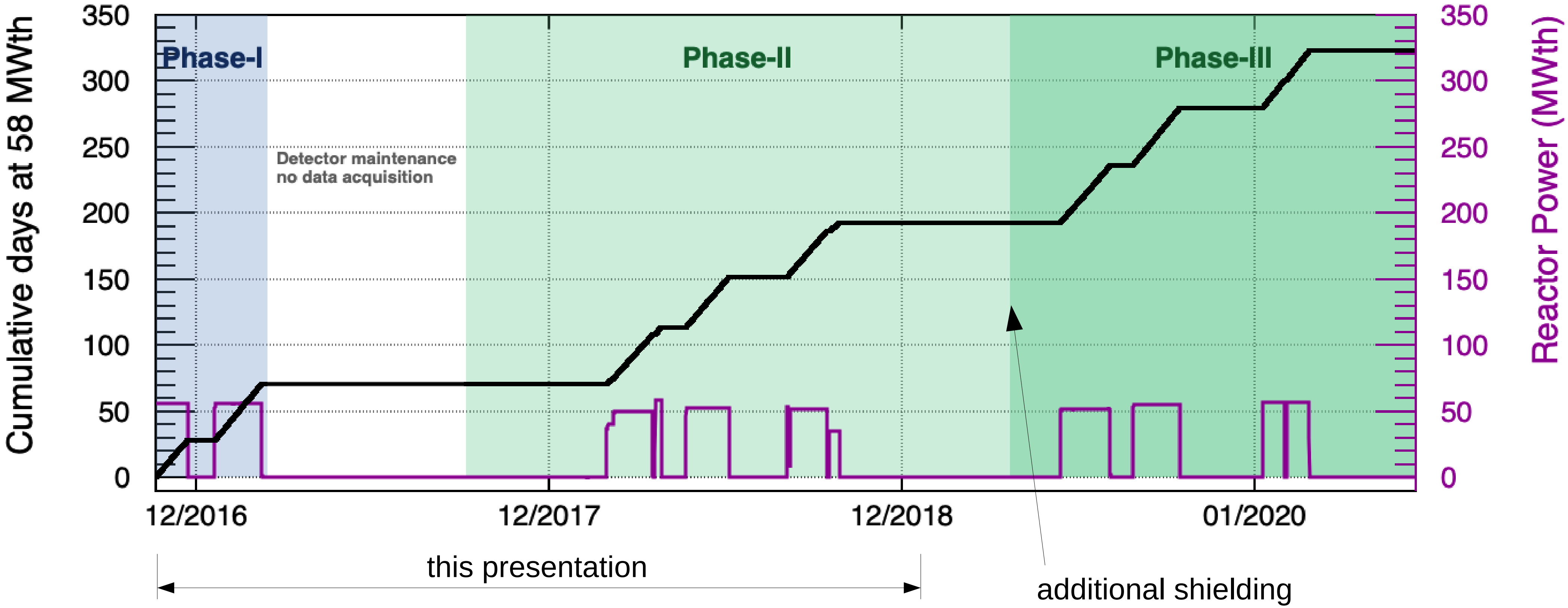
G. Mention, PhD thesis (2005)
Université Lyon 1

Delay due to:
thermalisation of neutron before capture
+
time constant of the capture process



Event Selection and Systematics

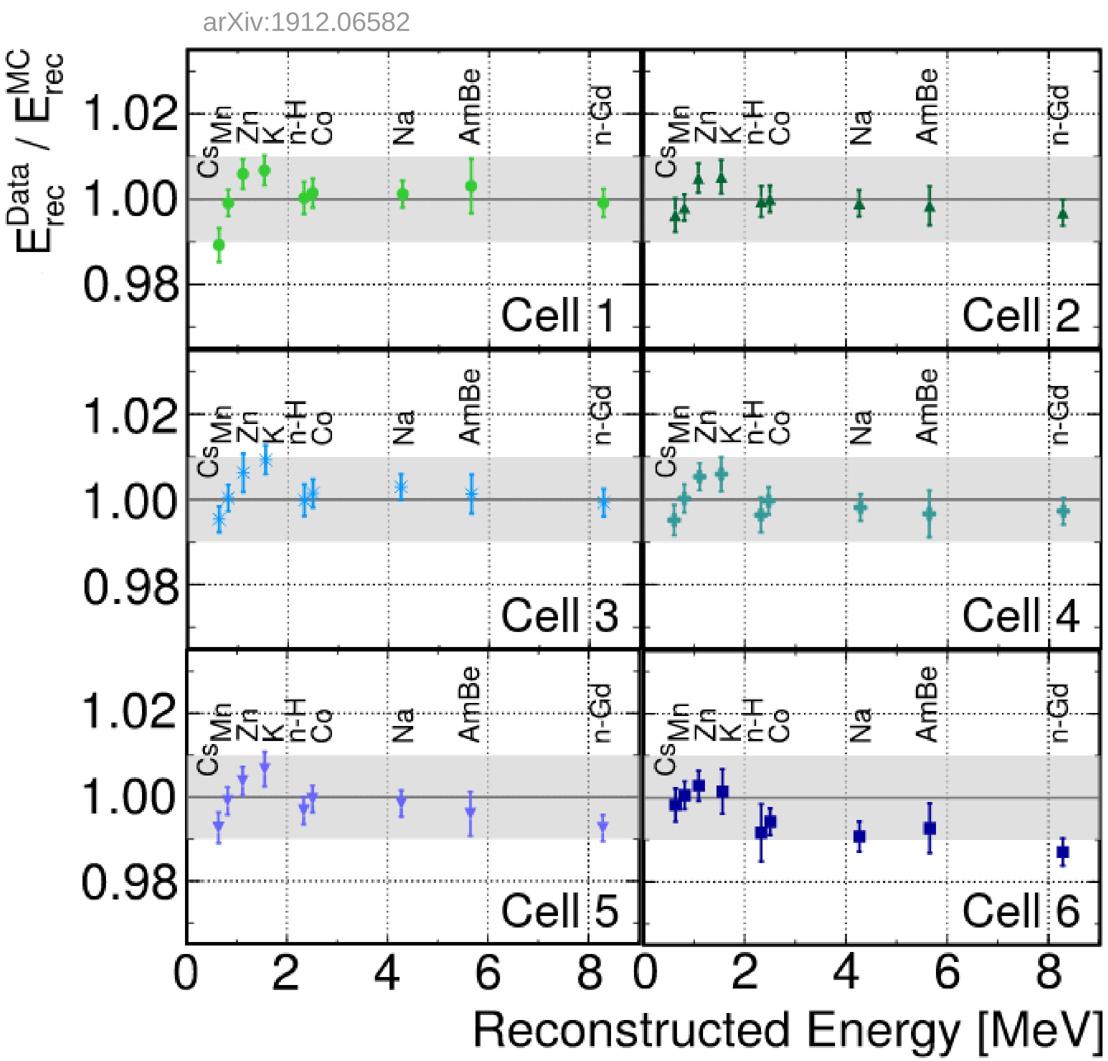
Dataset

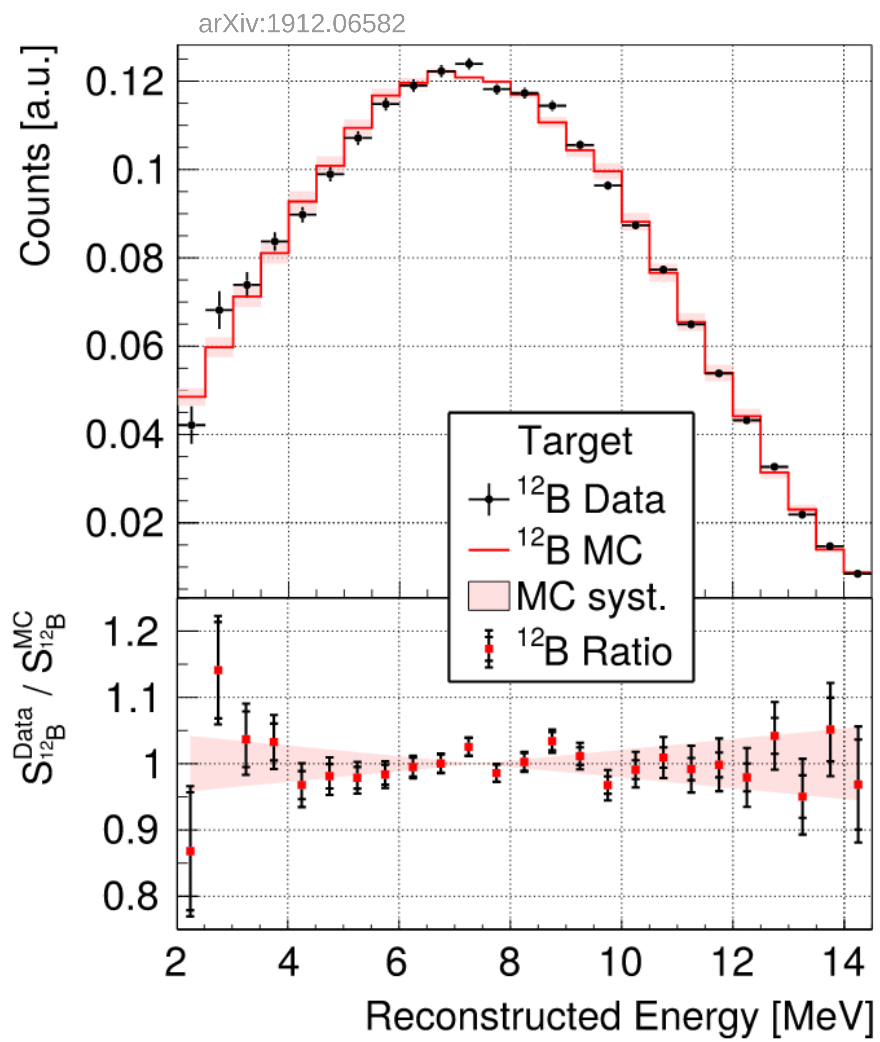


- Factor 2.9 increase in reactor-on dataset since Neutrino2018
- Data acquisition continuing further
- Better background understanding due to increased reactor-off dataset
- Cell-to-cell relative oscillation analysis:
  → phase-I+II (179 days reactor-on / 235 days reactor-off)
- Absolute rate and spectral shape analysis:
  → phase-II (119 days reactor-on / 211 days reactor-off)
  → more stable dataset

Energy Calibration

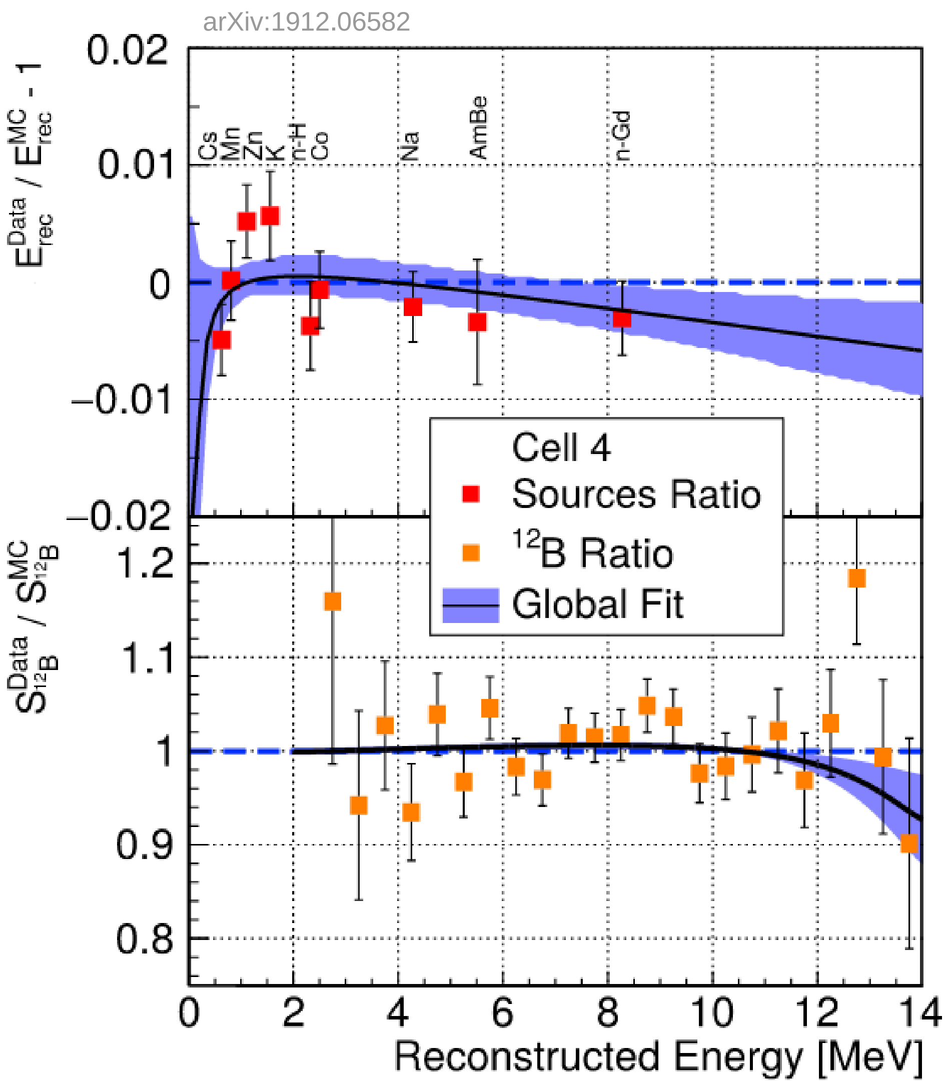
- weekly calibrations with Mn-54
- regular data from various other isotopes and cosmic-induced neutron captures
- continuous spectrum from B-12

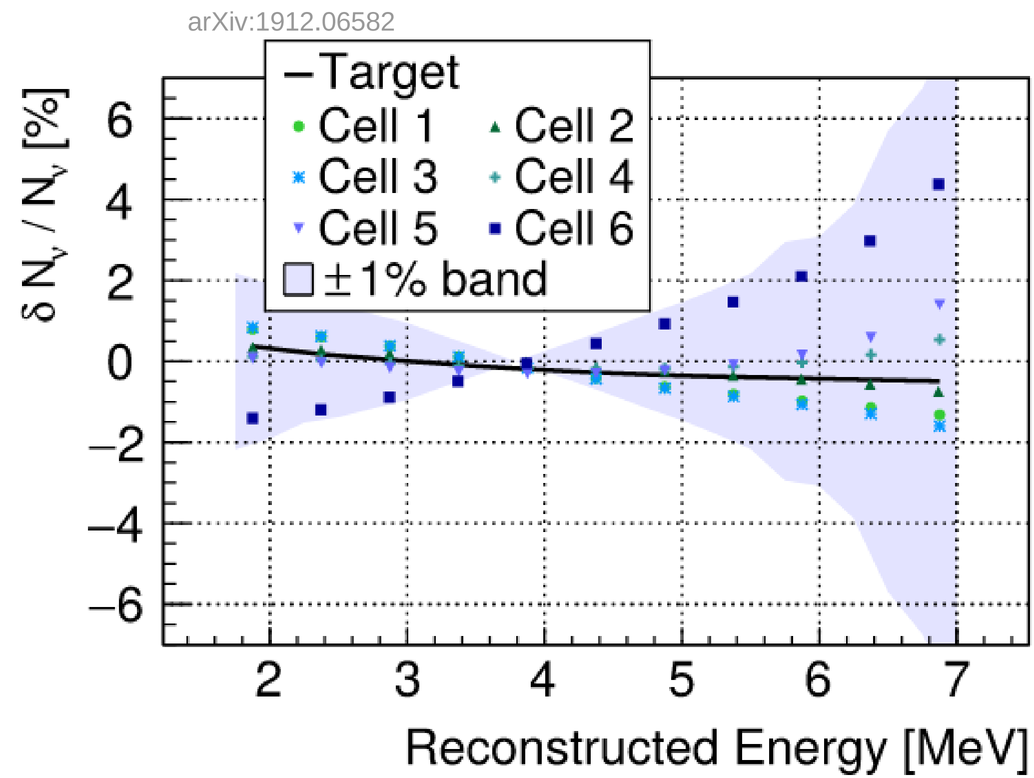




Energy Scale Model

Poster #142
Session #3





- polynomials at different degrees as well as general KDE approach with Gaussian kernel fitted to all data
- following formalism of Phys. Lett. B 773, 307 (2017) / arXiv:1705.09434

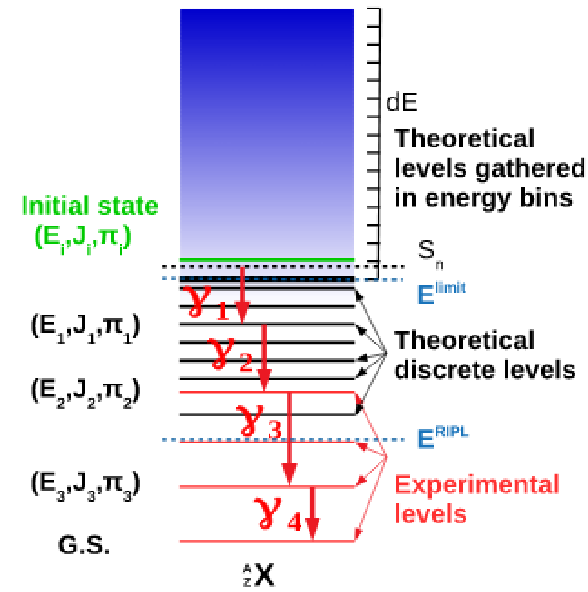
- cell-to-cell uncorrelated deviations always contained within a **1% deviation** of a simple linear energy scale model

- reduced **uncertainty at Target level** enters **spectral shape analysis**

Improved Gd Gamma-Cascade

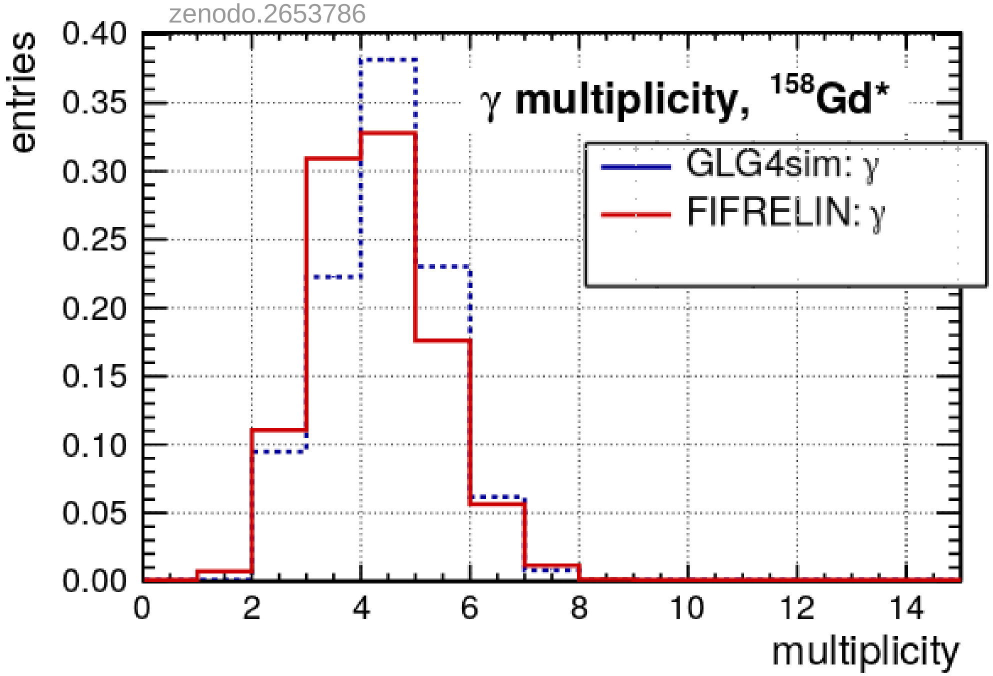
Poster #142
Session #3

- Improved model of gamma cascade after neutron capture by Gd via dedicated **nuclear simulation tool FIFRELIN**
- Useful especially for **smaller detectors** with less containment of gammas and **Cherenkov detectors**
- FIFRELIN tool models deexcitation of Gd-nuclei using all available experimental data plus nuclear models (RIPL-3, CGCM, CTM, FGM)
- FIFRELIN yields gammas of higher energy compared to Geant4-based GLG4sim simulation
  → also including conversion electrons

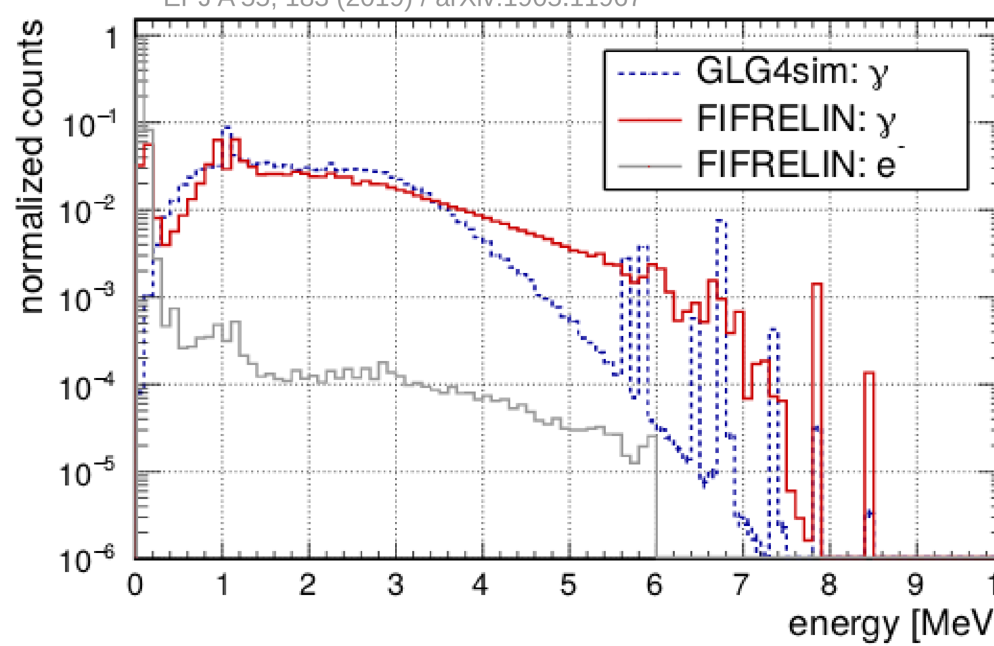


EPJ A 55, 183 (2019) / arXiv:1905.11967

zenodo.2653786



EPJ A 55, 183 (2019) / arXiv:1905.11967



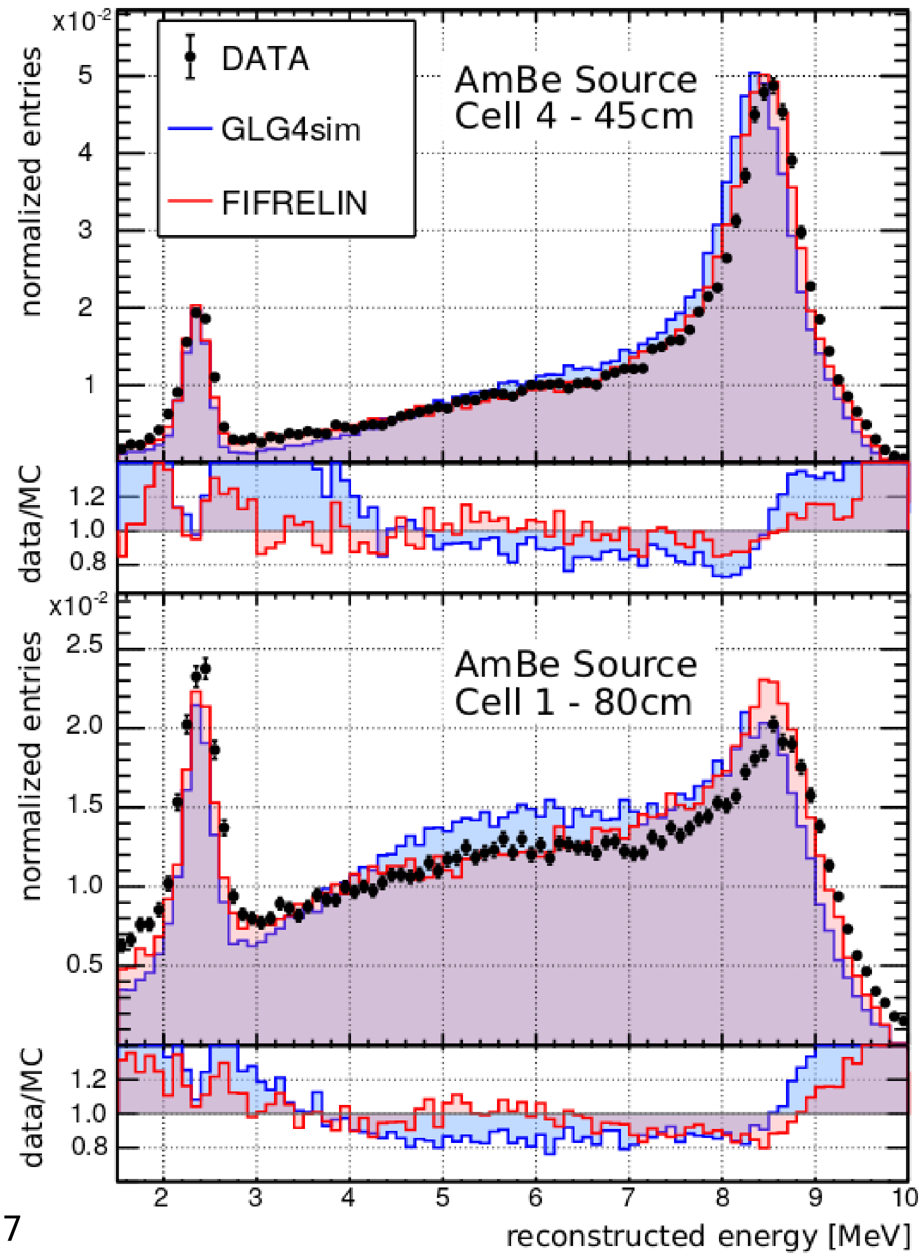
Improved Uncertainty of Neutron Efficiency

- Clear improvement in description of the tail between 3 and 7 MeV
- At centre position (cell 4, 45cm)
  → >5σ discrepancy with GLG4sim
  → 1.6σ agreement with FIFRELIN
  → no indication for remaining systematic effect between data and FIFRELIN
- Also improvement at corner position
  → Remaining effect due to neutron mobility
  → corrected by map
- Improved description of neutron efficiency

Cell	$\sigma_{uncorrelated}$	$\sigma_{correlated}$
1	0.0084	0.0041
2	0.0084	0.0015
3	0.0084	0.0013
4	0.0084	0.0013
5	0.0084	0.0015
6	0.0084	0.0040

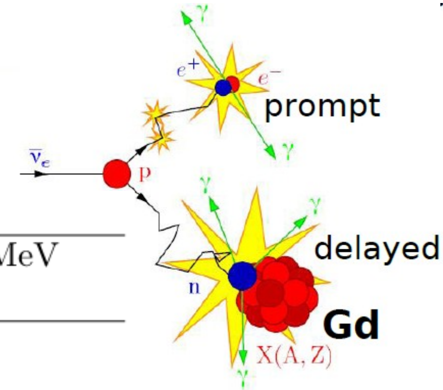
- More information: EPJ A 55, 183 / arXiv:1905.11967

EPJ A 55, 183 (2019) / arXiv:1905.11967

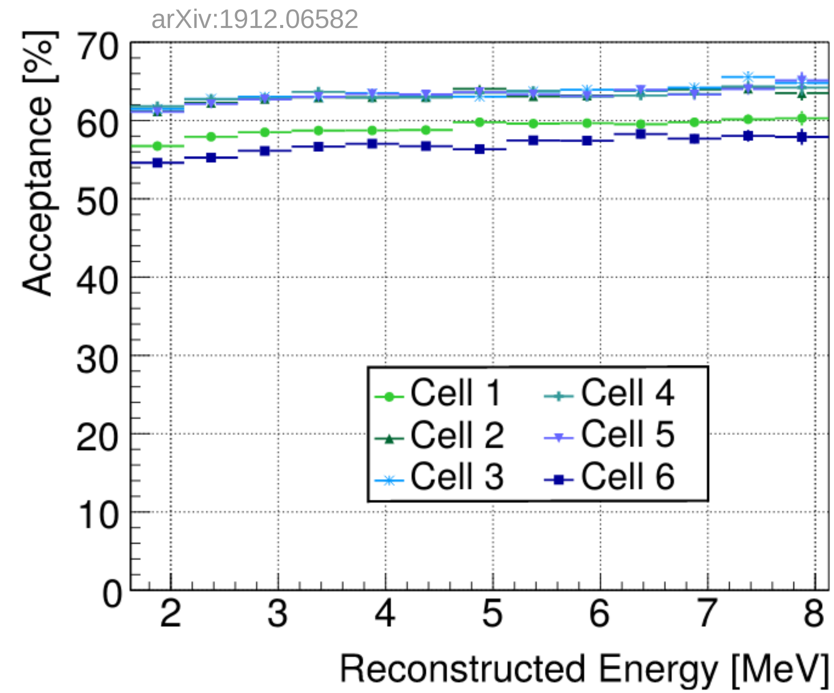


$2*10^7$ MC events (^{156}Gd and ^{158}Gd) available at Zenodo.2653786

Event Selection



Type	#	Requirement for passing cut
Energy	1	$1.625\,\text{MeV} < E^{\text{detector}}_{\text{prompt}} < 7.125\,\text{MeV}$
	2	$4.5\,\text{MeV} < E^{\text{detector}}_{\text{delayed}} < 10\,\text{MeV}$
Coincidence	3	$2\,\mu\text{s} < \Delta T_{\text{prompt-delayed}} < 70\,\mu\text{s}$
	4	$\Delta X_{\text{prompt-delayed}} < 600\,\text{mm}$
Topology	5	$E^{\text{cell}}_{\text{prompt}} < 1\,\text{MeV}$, neighbour cells
	6	$E^{\text{cell}}_{\text{prompt}} < 0.4\,\text{MeV}$, not neighbour cells
	7	$E^{\text{Target}}_{\text{delayed}} > 1\,\text{MeV}$
Rejection of muon-induced background	8	$\Delta T^{\text{veto}}_{\text{muon-prompt}} > 100\,\mu\text{s}$
	9	$\Delta T^{\text{detector}}_{\text{muon-prompt}} > 200\,\mu\text{s}$
	10	$\Delta T_{\text{event-prompt}} > 100\,\mu\text{s}$ and $\Delta T_{\text{delayed-event}} > 100\,\mu\text{s}$ for all events with $E^{\text{detector}}_{\text{event}} > 1.5\,\text{MeV}$
	11	$\frac{Q_{\text{PMT max, prompt}}}{Q_{\text{cell, prompt}}} < 0.5$



- Cut-based approach selecting delayed coincidence (IBD pair search)
- Background rejection by event topology, isolation of IBD, and after-muon rejection
- Mean cut efficiency
  → (61.4 ± 0.9)%
  → small energy dependence
  → edge cells (1 and 6) show only few percent smaller efficiency

Neutrino Rate Extraction by PSD

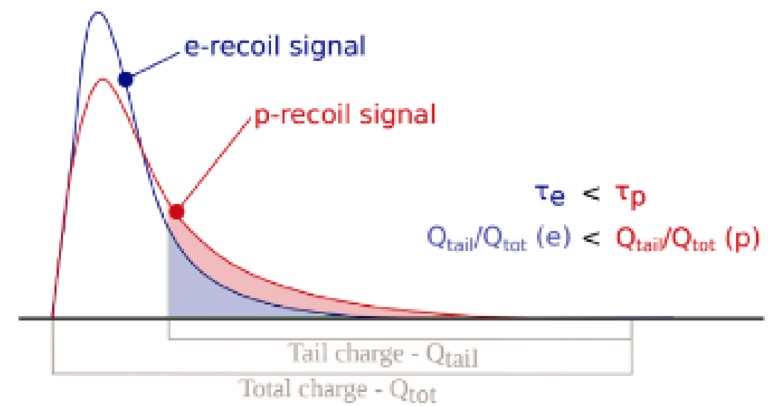
→ Accidental background measured with high statistics by off-time method

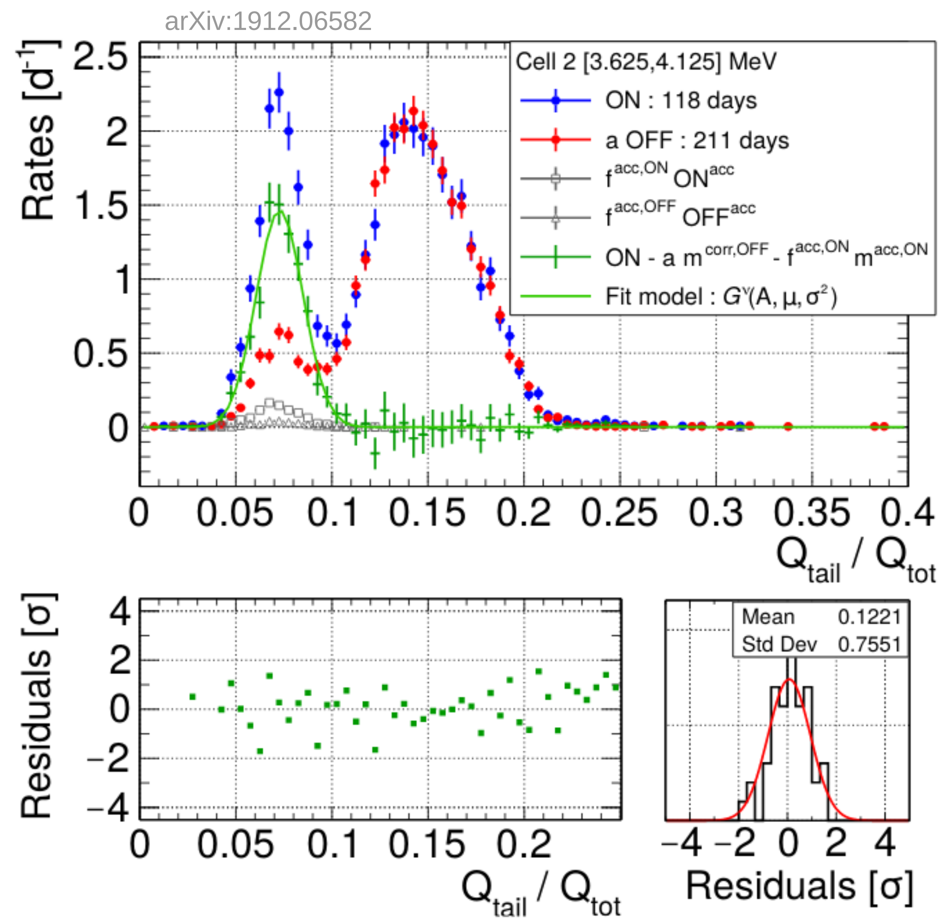
→ Background model measured in-situ from reactor-off data

→ **simultaneous fit of reactor-on and reactor-off spectra**

→ Neutrino rates extracted per cell and energy bin using Gaussian function to fit neutrino spectrum

$$
\begin{aligned}
ON_{l,i;p} &= a_{l,i}\, m^{\mathrm{corr,OFF}}_{l,i;p} + f^{\mathrm{acc,ON}}\, m^{\mathrm{acc,ON}}_{l,i;p} \\
&\quad + G^{\nu}_{p}(A_{l,i}, \mu_{l,i}, \sigma^{2}_{l,i}), \\
OFF_{l,i;p} &= m^{\mathrm{corr,OFF}}_{l,i;p} + f^{\mathrm{acc,OFF}}\, m^{\mathrm{acc,OFF}}_{l,i;p},
\end{aligned}
$$





→ fit based on pulse shape of scintillator pulses (PSD)

→ electronic recoils have low Q_{tail}/Q_{tot}

→ proton recoils have large Q_{tail}/Q_{tot}

→ **free normalisation parameter $a_{l,i}$** between reactor-on and reactor-off spectra

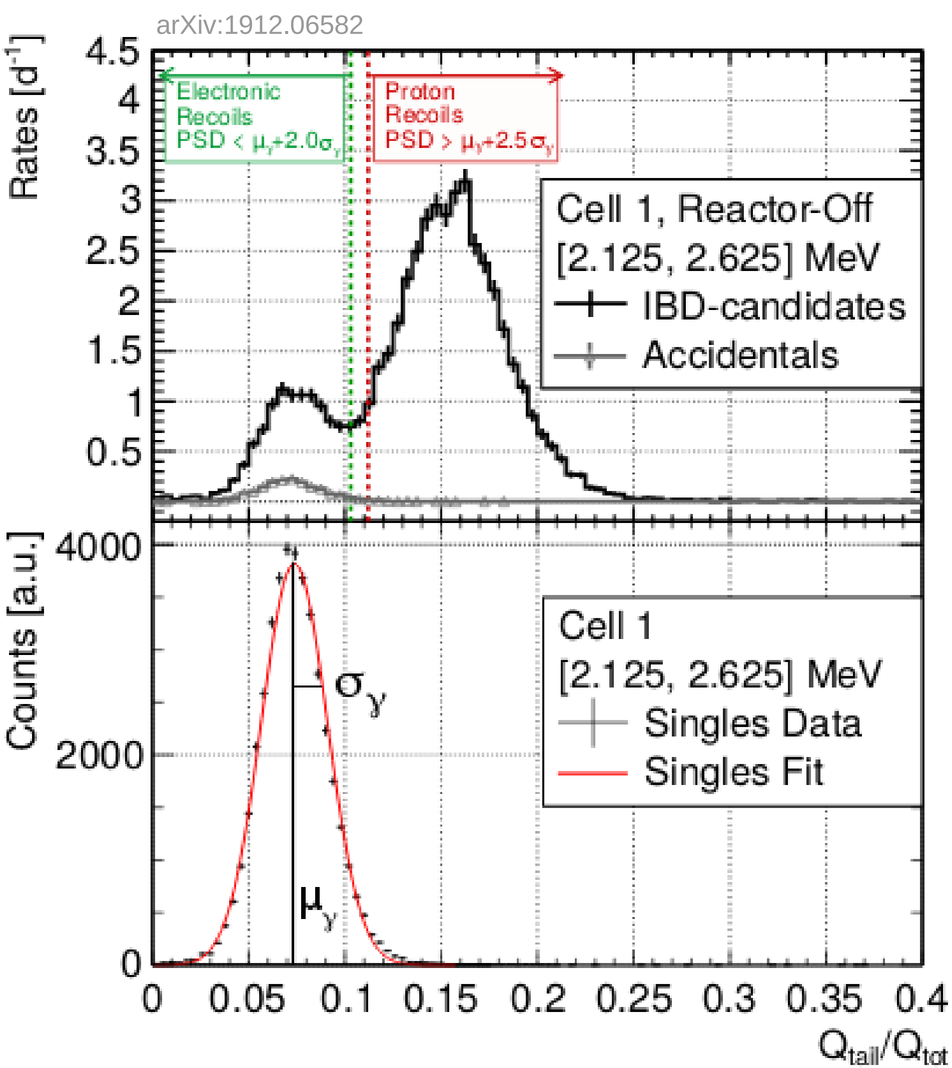
→ mainly driven by proton recoil population

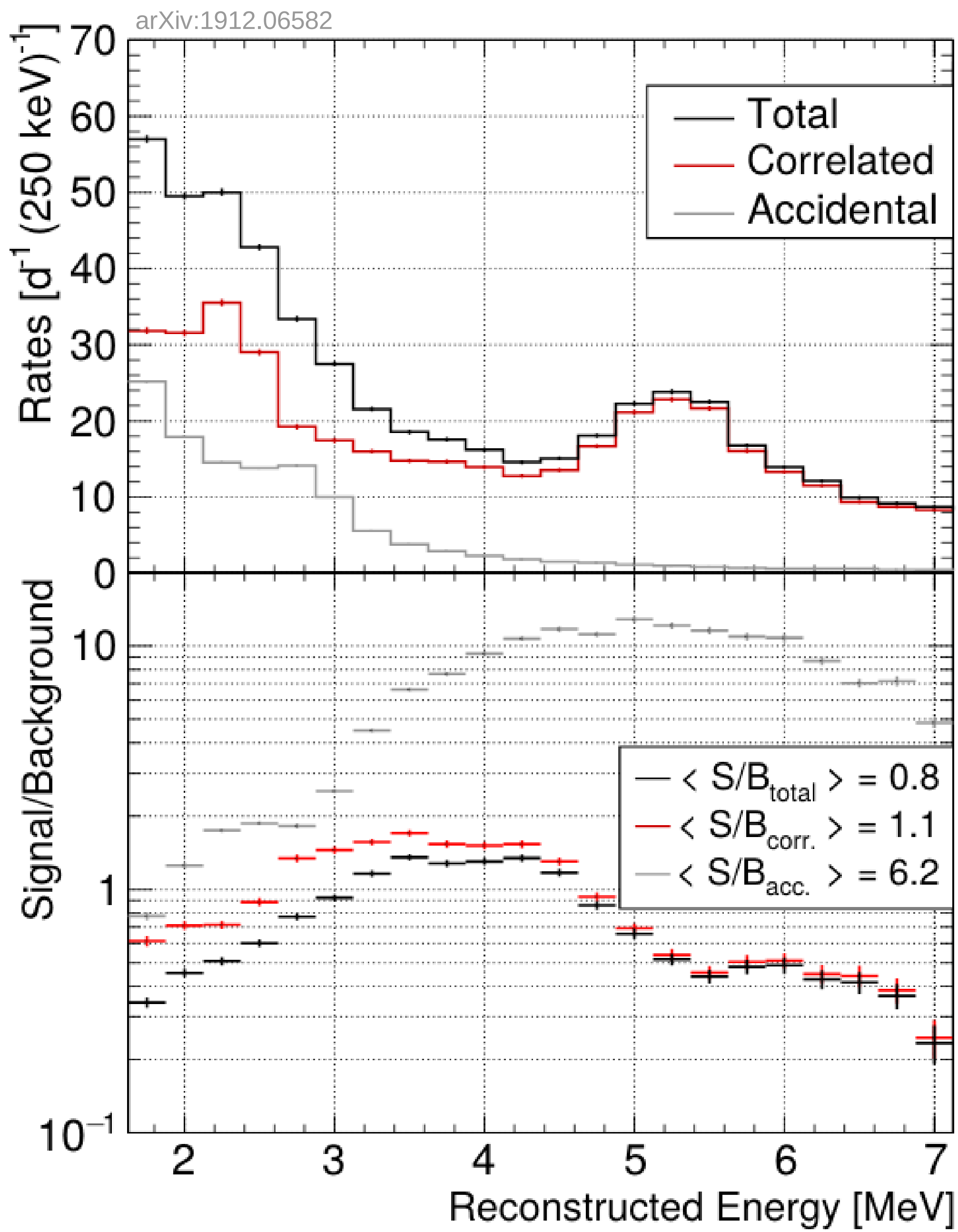
→ also compensates the atmospheric pressure dependency

Signal and Background Rates

→ signal and background rates for the electronic recoil population defined via γ-ray population by $Q_{tail}/Q_{tot} < \mu_\gamma + 2\,\sigma_\gamma$

→ signal over background of ~0.8





Results

Oscillation Analysis – Method

- Prediction independent comparison between cells and energy bins only taking into account spectrum shape, no absolute rate information

- Each energy bin is normalised by a free parameter ϕ_i common to all cells
  → causes analysis to be **independent from the absolute rate** in each energy bin
  → decouples energy bins, comparison only along the six Target cells
  → method is **only sensitive to relative changes** in the expected rates $M_{l,i}(\mu, \sigma, \vec{\alpha})$ which are due to oscillations

$$\chi^2 = \sum_l^{N_{\mathrm{Cells}}} \sum_i^{N_{\mathrm{Ebins}}} \left(\frac{D_{l,i} - \phi_i M_{l,i}(\mu, \sigma, \vec{\alpha})}{\sigma_{l,i}} \right)^2 + \sum_l^{N_{\mathrm{Cells}}} \left(\frac{\alpha_l^{\mathrm{NormU}}}{\sigma_l^{\mathrm{NormU}}} \right)^2 + \left(\frac{\alpha^{\mathrm{EscaleC}}}{\sigma^{\mathrm{EscaleC}}} \right)^2 + \sum_l^{N_{\mathrm{Cells}}} \left(\frac{\alpha_l^{\mathrm{EscaleU}}}{\sigma_l^{\mathrm{EscaleU}}} \right)^2$$

$$M_{l,i}(\mu, \sigma, \vec{\alpha}) = M_{l,i}(\mu, \sigma) \times (1 + \alpha_l^{NormU} + (\alpha^{EscaleC} + \alpha^{EscaleU}) \times S_{l,i}^{Escale}(\mu))$$

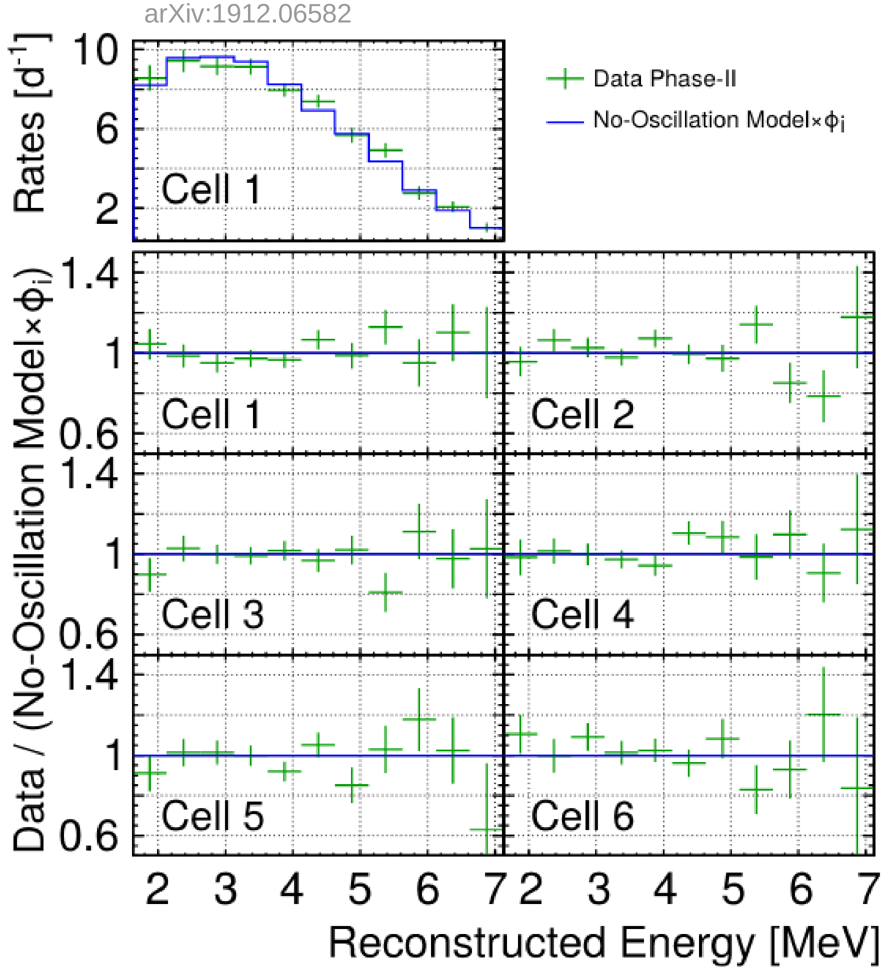
- Systematic effects parameterised by nuisance parameters $\vec{\alpha}$

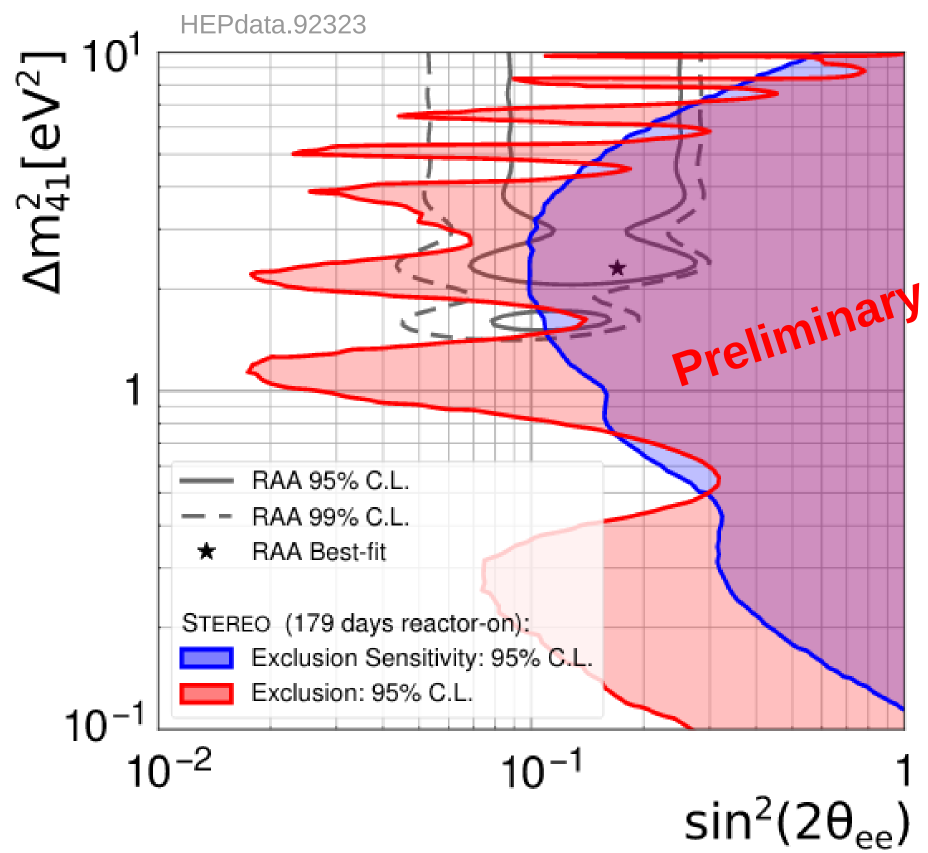
Type	Relat. uncert.
Normalisation (uncorrelated)	
Cell volume	0.83 %
Neutron efficiency correction	0.84 %
Energy scale (uncorrelated)	
Mn anchor point	0.2 %
Cell-to-cell deviations	1.0 %
Energy scale (correlated)	
Time stability	0.3 %

- Complementary analysis by including all systematic effects into global covariance matrix gives consistent results

Oscillation Analysis – Results

Poster #78
Session #3



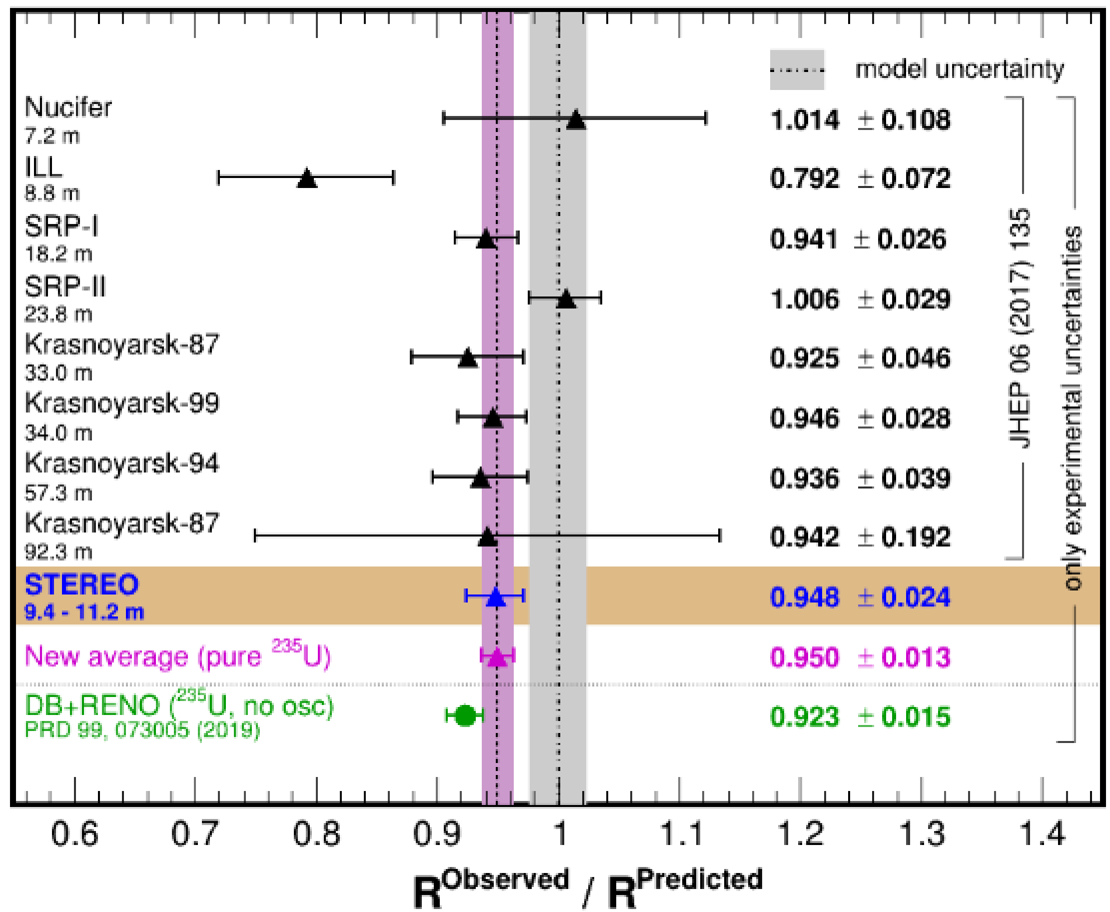


- No-oscillation hypothesis (p-value = 0.09) not rejected
- Pull terms show no tension beyond 1 standard deviation
- Exclusion contour rendered from **two-dimensional method**
- Non-standard $\Delta\chi^2$ distributions from MC pseudo-experiments used
- **Best-fit point of RAA rejected at more than 99.9% C.L.**
- more information: arXiv:1912.06582 / HEPdata.92323

Absolute Rate – Results

Quantity	Symbol	Value	Uncert./%
Number of ν/fission	$N_\nu^{[2,8]\mathrm{MeV}}$	1.846	2.40
Huber prediction		1.722	2.40
Correction factors		1.072	0.10
Number of fissions/day		$1.30 \cdot 10^{23}$	1.44
Thermal power	$\langle P_{\mathrm{th}} \rangle$	49.2 MW	1.44
Energy/fission	$\langle E_f \rangle$	203.4 MeV	0.13
Fract. of interacting ν	τ_{int}	$8.10 \cdot 10^{-21}$	0.56
Solid angle			0.50
IBD cross-section	σ_{IBD}		0.22
MC statistics			0.12
Correc. of p-number	$c_p^{\mathrm{Data/MC}}$	0.983	1.00
Detection efficiency	ϵ_{d}	0.2049	0.54
Selection cuts			0.41
Energy Scale			0.30
MC statistics			0.19
Correc. of delayed effi.	$c_n^{\mathrm{Data/MC}}$	0.9774	0.86
Predicted IBD yield		$383.7\,\mathrm{d}^{-1}$	$2.10 \oplus 2.40$
Observed IBD yield		$363.8\,\mathrm{d}^{-1}$	$0.88 \oplus 1.06$
Statistics			0.88
ν extrac. method			0.65
Reactor-induced bkg.			0.83
Off-time method			0.14

arXiv:2004.04075



- Dedicated study for an accurate rate prediction carried out
- Observed rate of (364 ± 3 [stat.] ± 4 [sys.]) ν/day compared to predicted rate
- Achieved a good control of the uncertainties
  → reactor power, neutron detection efficiency, proton number
- Among the leading measurements of the neutrino flux from pure ^{235}U nuclear fuel
- **In agreement with world average**, improvement from (0.950±0.015) to (0.950±0.013)
- more information: arXiv.2004.04075

New

Spectral Shape – Unfolding Method

Poster #140
Session #1

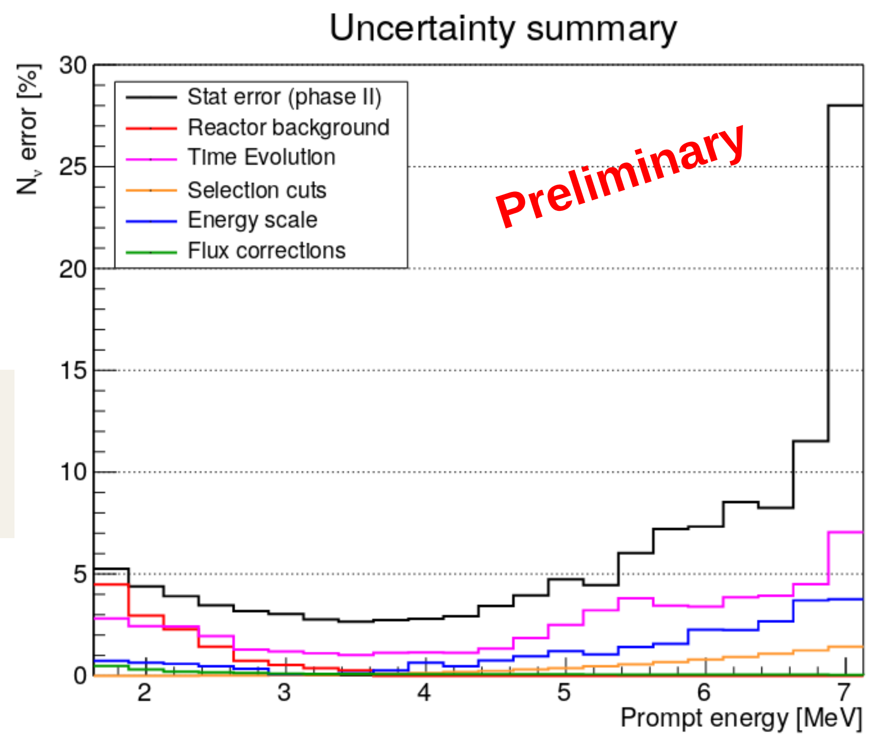
- most relevant source of uncertainty: statistics
- unfolding of data spectrum D_i into neutrino energy spectrum ϕ_j via response matrix R_{ij}

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

- **Regularisation term mitigates unfolding of statistical fluctuations**

$$\Lambda(\vec{\Phi}) = \sum_i \left(\frac{\Phi_{i+1}}{\Phi^0_{i+1}} - \frac{\Phi_i}{\Phi^0_i}\right)^2$$

- Using Huber's ^{235}U spectrum as prior ϕ^0
- Regularisation strength *r* chosen a-priori by requiring negligible prior-dependence
- Independent validation by covariance matrix approach yields same results and regularisation strength

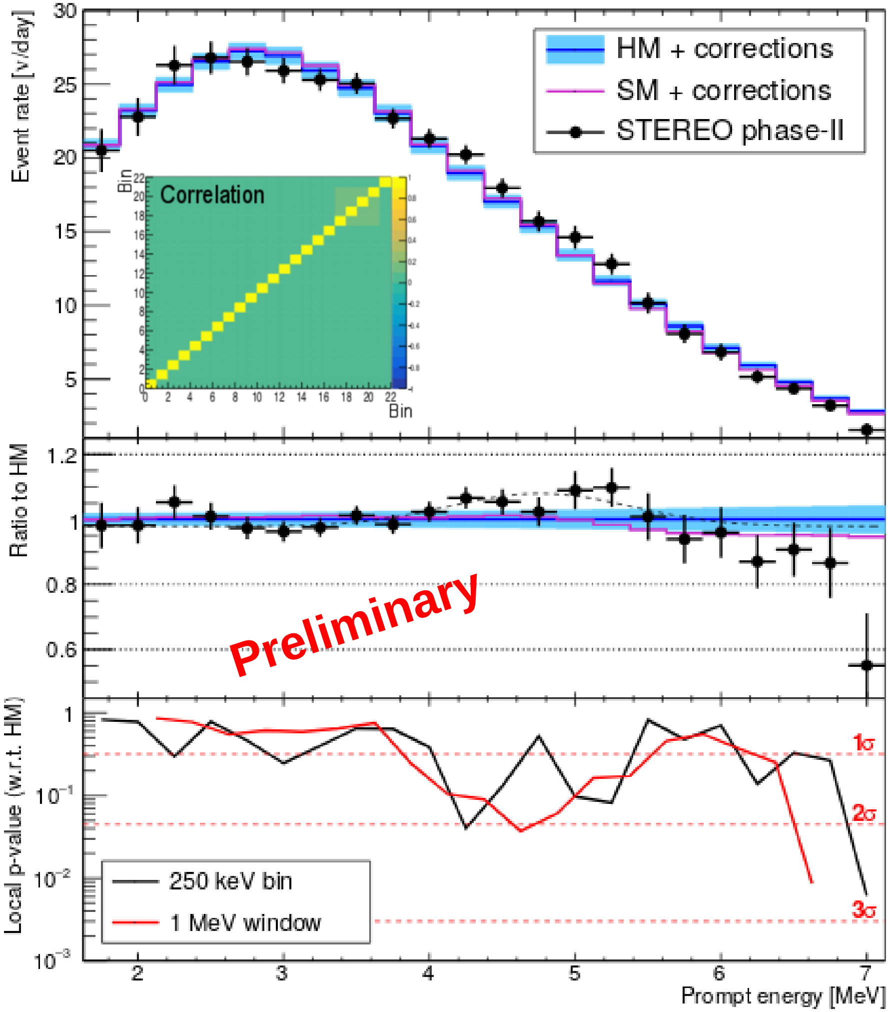


New

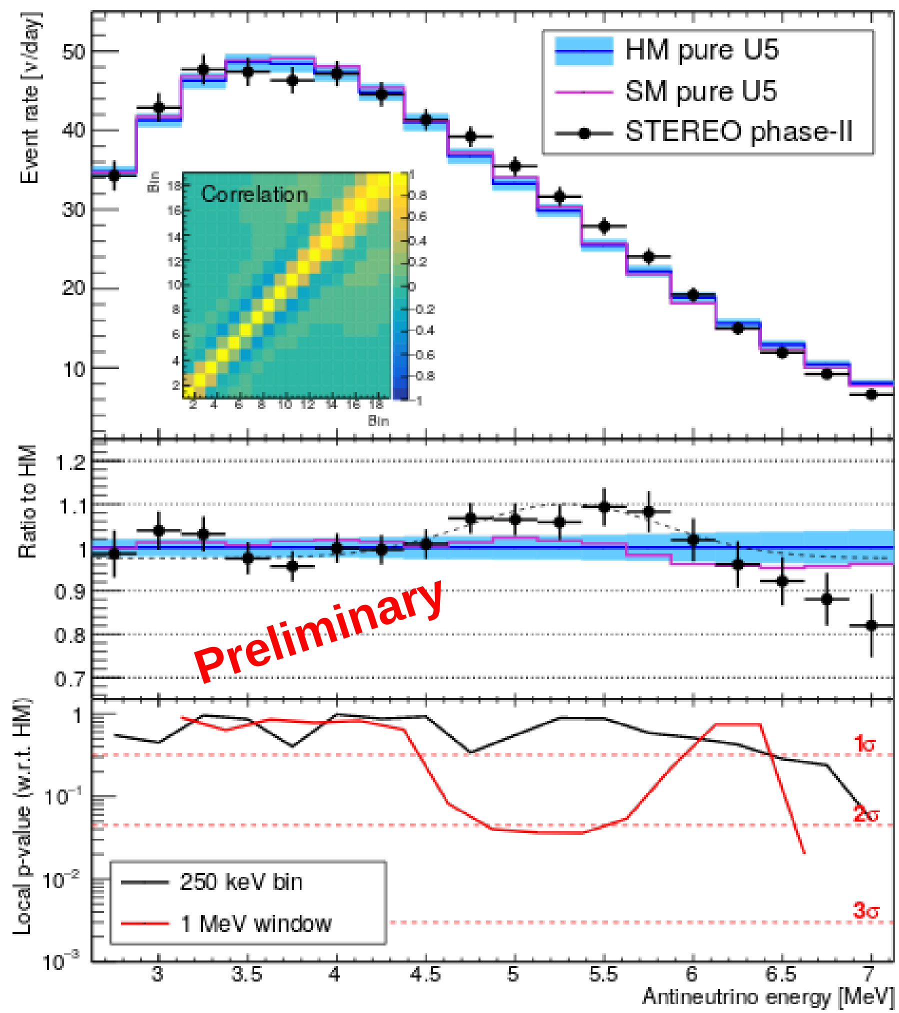
Spectral Shape – Result

Poster #140
Session #1

Prompt Energy Space



Antineutrino Energy Space



→ first spectrum in unfolded energy space achieved

→ **indication for spectral distortion** by fitting a free Gaussian function (including a free normalisation factor for the entire spectrum)

Amplitude: (10.1±2.9)% } prompt space
Mean: (4.8±0.2)MeV

HM – Huber Model: PRC 84, 024617 (2011)
SM – Summation Model: PRL 123, 022502 (2019)

Summary/Outlook

Summary/Outlook

→ data taking phase-I+II completed (65k neutrinos)

→ improved background description by in-situ measurements during reactor-off periods and pulse shape discrimination

→ improved description of gamma-cascade after neutron capture by gadolinium
  → EPJA 55, 183 / arXiv:1905.11967 / Zenodo.2653786

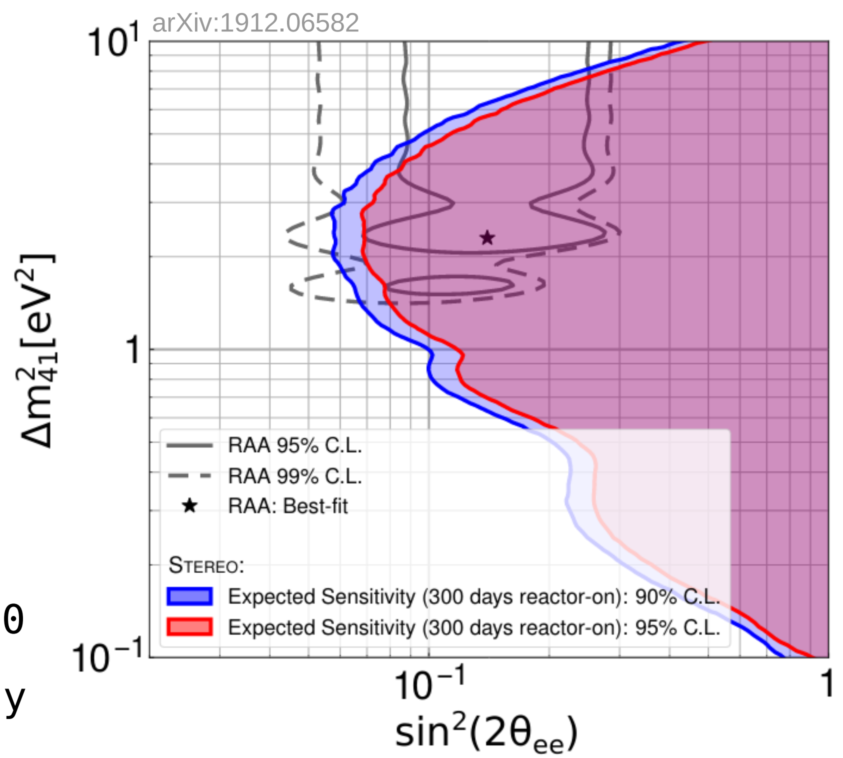
→ large fraction of RAA parameter-space excluded
→ **RAA best-fit point rejected at >99.9% C.L.**
  → arXiv:1912.06582 / HEPdata.92323

→ **rate deficit consistent with RAA found**
→ result among the world leading measurements for pure ^{235}U reactors
  → arXiv:2004.04075

→ first spectral shape in unfolded energy space achieved
→ **spectral distortion of ~10% between 4.0 and 5.5 MeV (prompt space) found**
→ publication under preparation

→ further data taking until end of 2020:
  → final dataset of >300 days expected
  → **factor ~2 increase** with respect to Neutrino2020

→ joint analysis with PROSPECT and Daya Bay underway (poster #556)



STEREO

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Laboratoire d'Annecy de Physique des Particules

LPSC
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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Photo: S. Schoppmann

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www.stereo-experiment.org

Photo: ILL