Latest results of the STEREO experiment

ICHEP 2020
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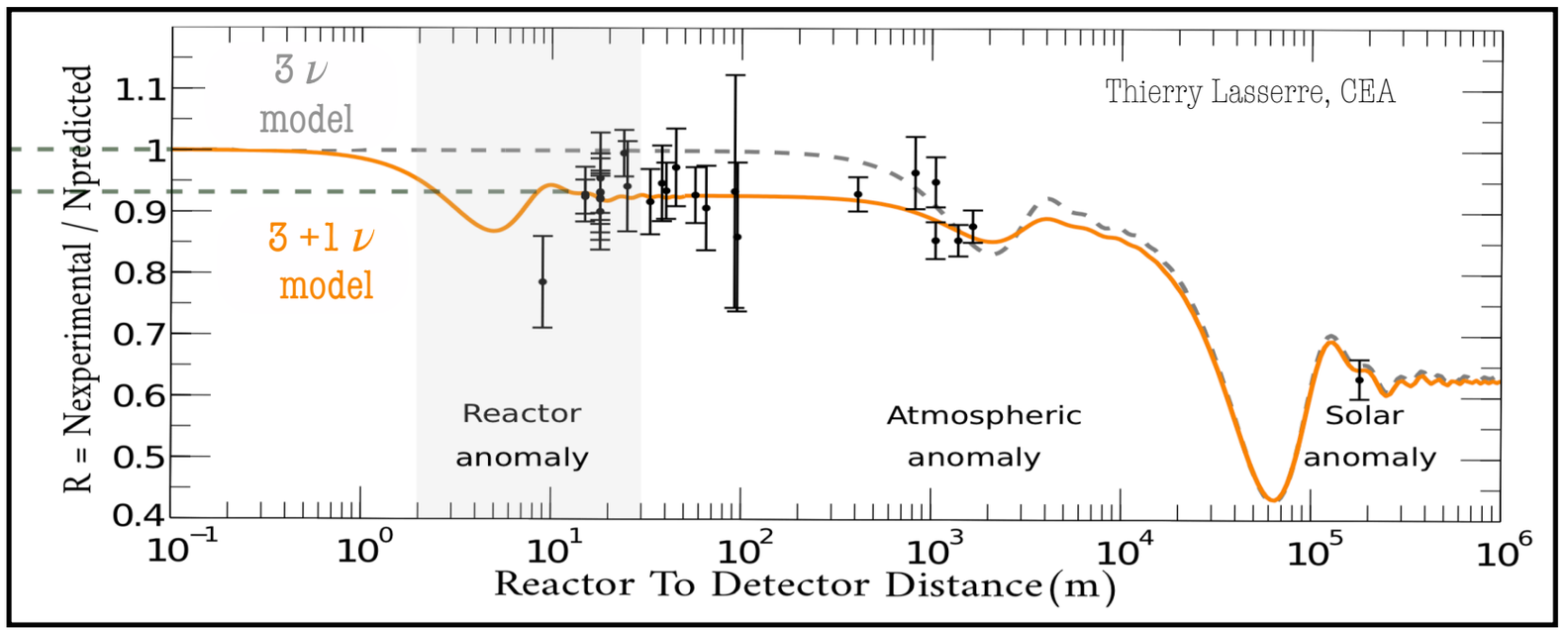
Loïc Labit
on behalf of the STEREO collaboration

Motivation

- Reactor antineutrino flux reappraisal (2011)
  Huber et al, Phys.Rev. C84 (2011) 024617
  & Mueller et al, Phys.Rev. C83 (2011) 054615

  → 6% deficit in measured flux (Reactor Antineutrino Anomaly) G. Mention et al, Phys. Rev., D83 :073006, 2011.

  → Compatible with oscillation toward light sterile neutrino with parameters $\sin^2(2\theta_{new}) = 0.17$ and $\Delta m^2_{new} = 2.2$ eV² arXiv:1204.5379

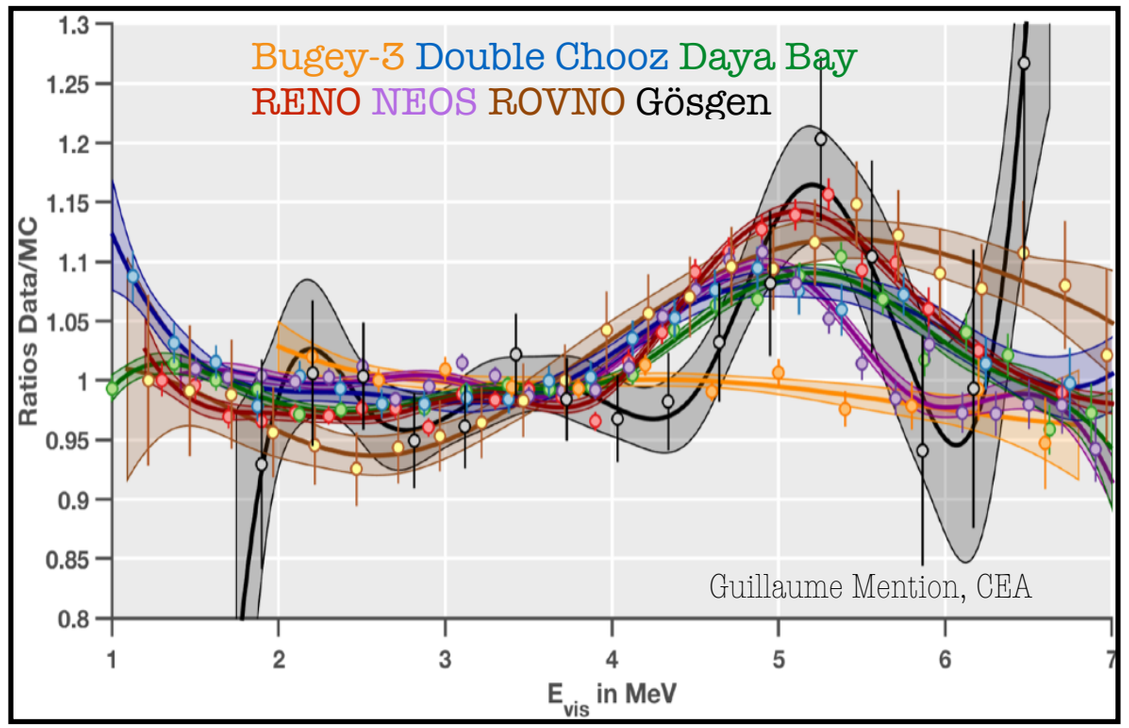


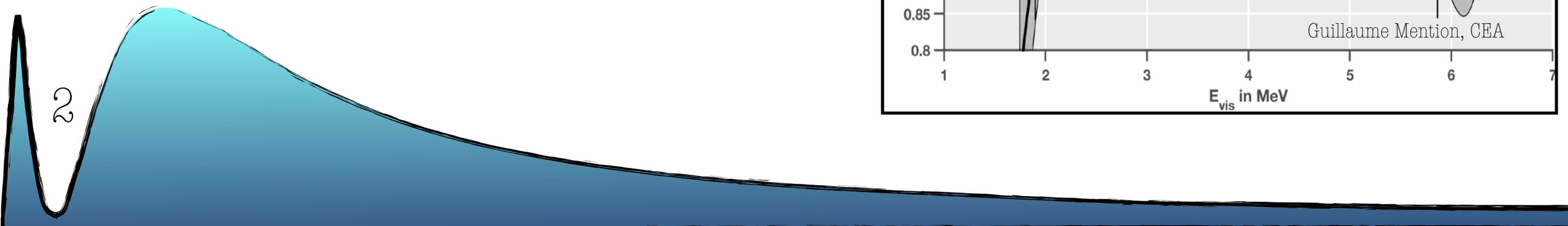
- ~10% Energy spectrum distortion around 5 MeV

  → underestimation of some isotopes contribution ?

  → prediction systematics ?

  → detector effects ?



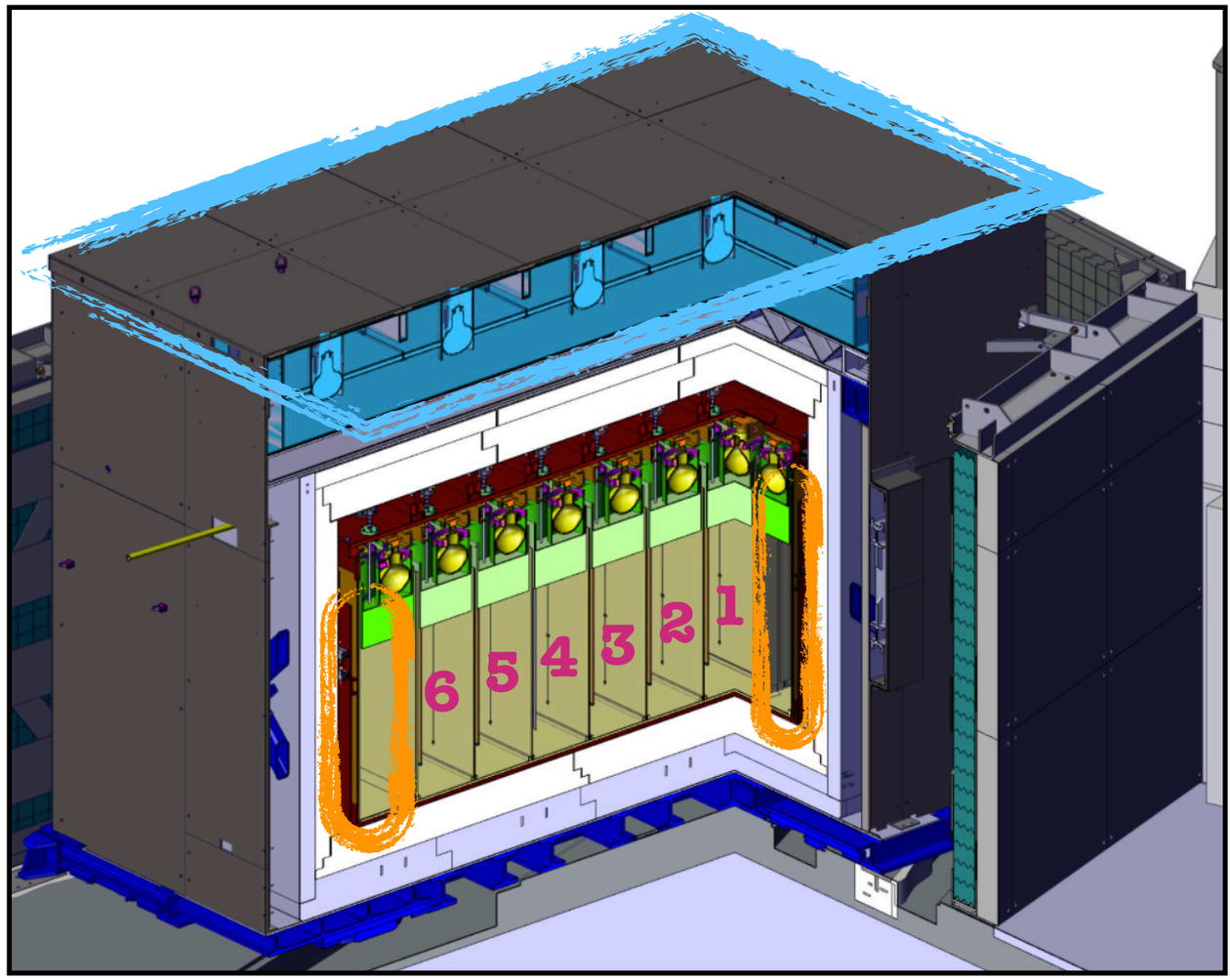


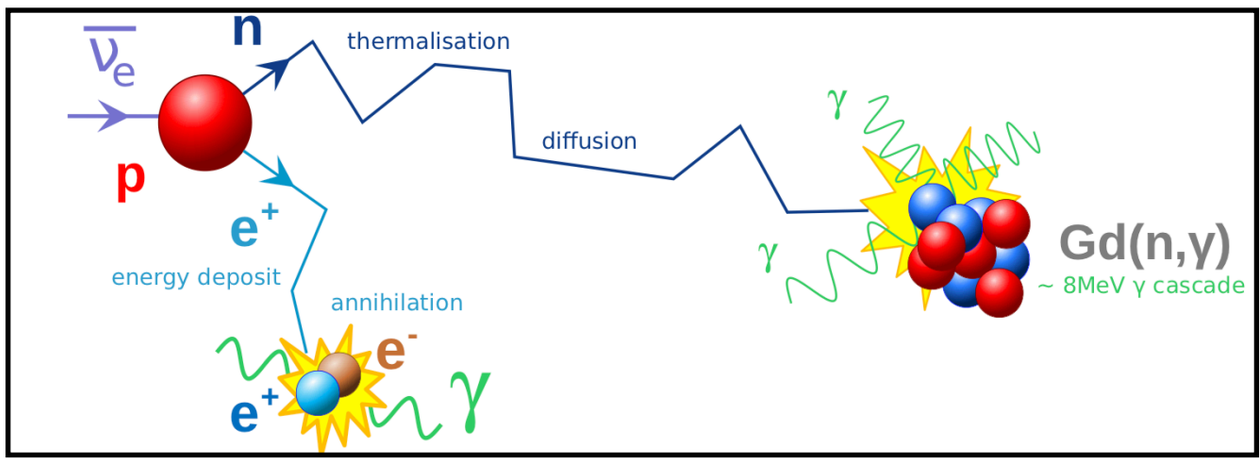
Measurement principle

- Detector design:
  - ~2 tons Gd-doped liquid scintillator Target segmented in 6 identical cells
  - Surrounded by Gamma-catcher (Gd-free liquid scintillator)
  - Surmounted by water Cerenkov muon veto
  - >100 tons of shielding (Pb, polyethylene, B_4C)

- Inverse beta decay (IBD):
  $\bar{\nu}_e + p \rightarrow e^+ + n$
  - prompt: e^+ ionisation and annihilation
  - delayed: n capture on Gd (after ~18 μs) gives γ cascade with total energy ~ 8 MeV

- Fast neutron can mimic IBD signal





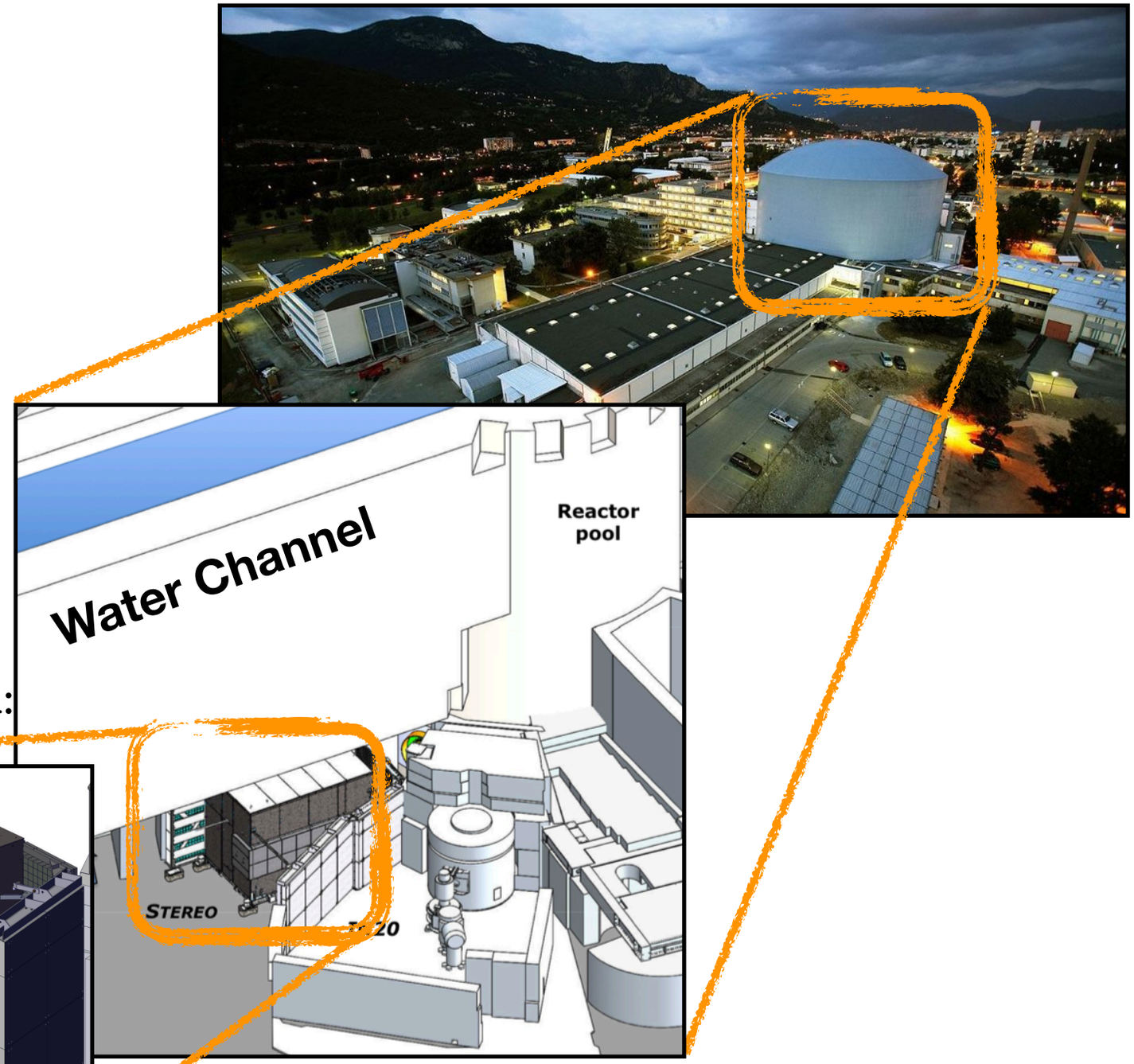
Experiment site

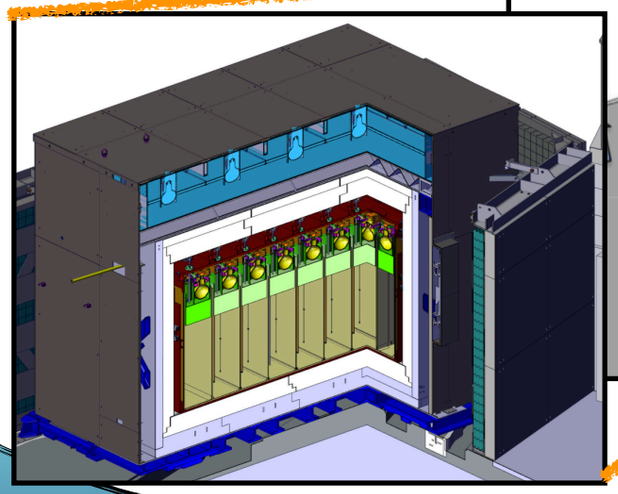
- Institut Laue-Langevin in France (Grenoble)

- Compact research reactor core:
  - 40 cm ⌀ × 80 cm
  - P_{th}= 58.3 MW
  - highly enriched in ^{235}U
  (99% of fission events)

- short baseline ~9-11 m

- Surface level experiment:
  Additional shielding against cosmics provided by water channel:
  ~15 m.w.e





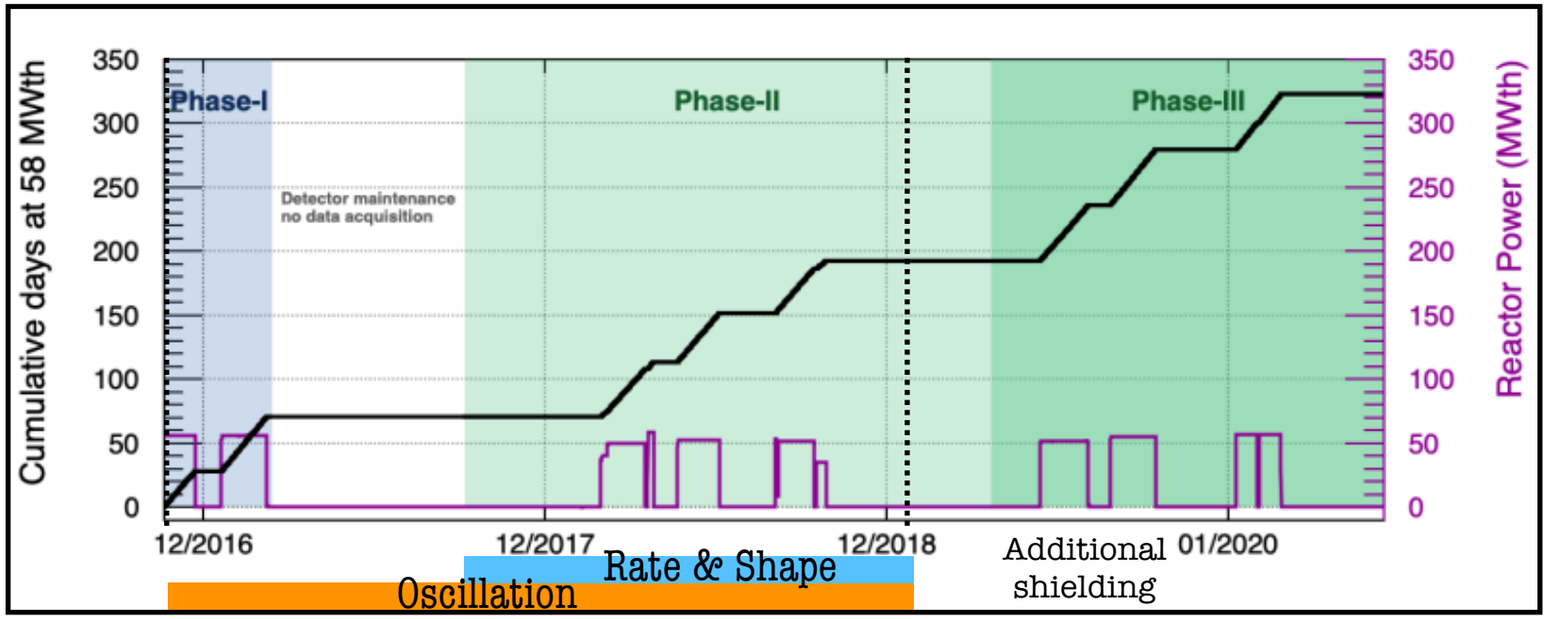
Data taking

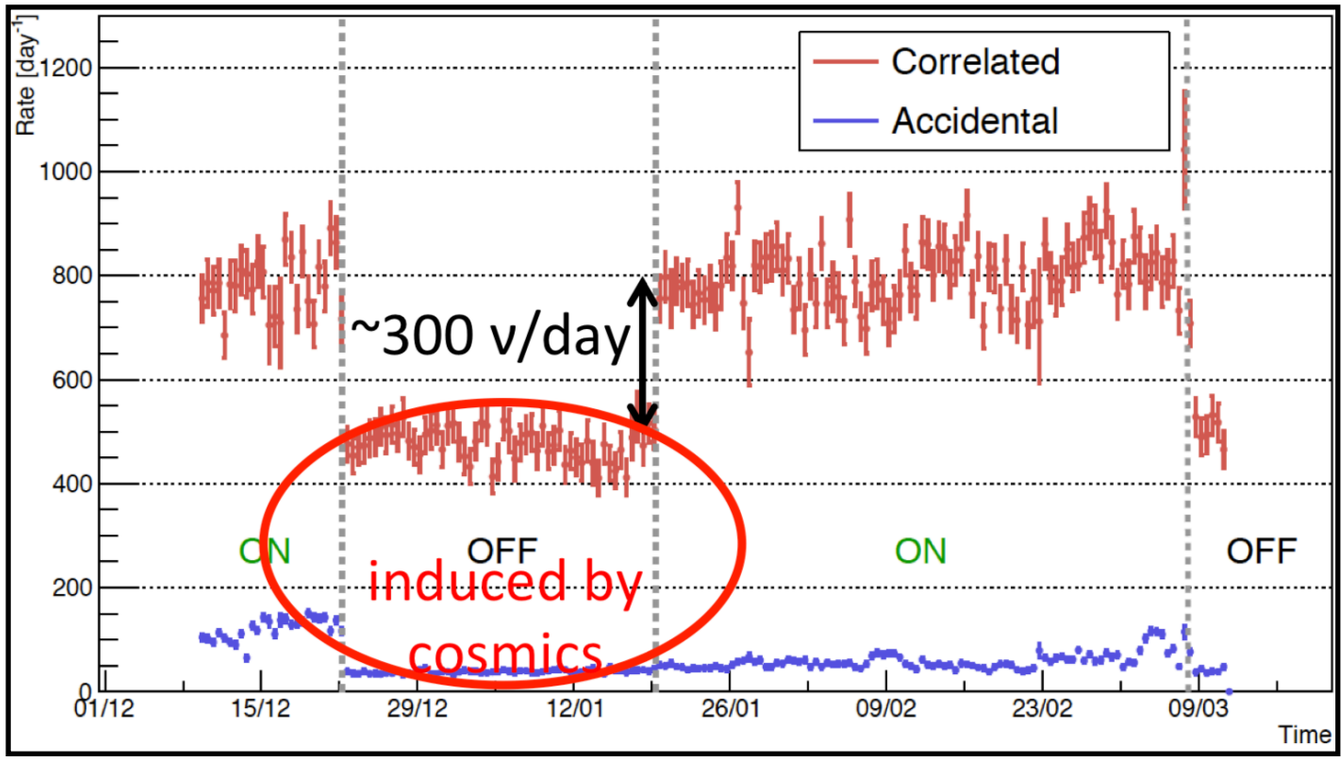
- Data taking started in Nov 2016:
  - Phase I + II :
  179 days reactor-on
  235 days reactor-off

- This talk:
  →Phase II data
  (Rate & Shape analysis)
  →Phase I + II
  (Oscillation analysis)

- Reactor-off data critical for background subtraction

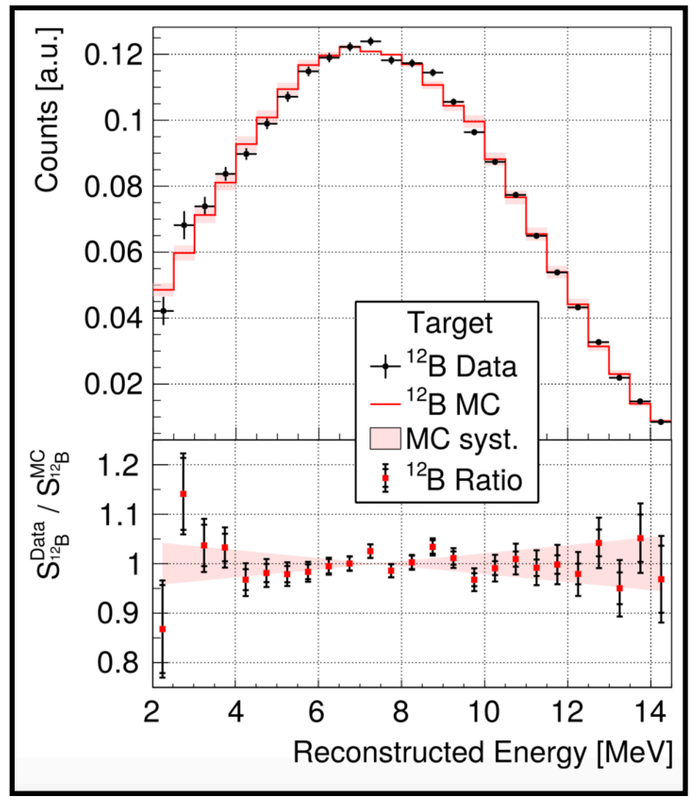
- Data acquisition expected to continue until end of 2020





Detector control

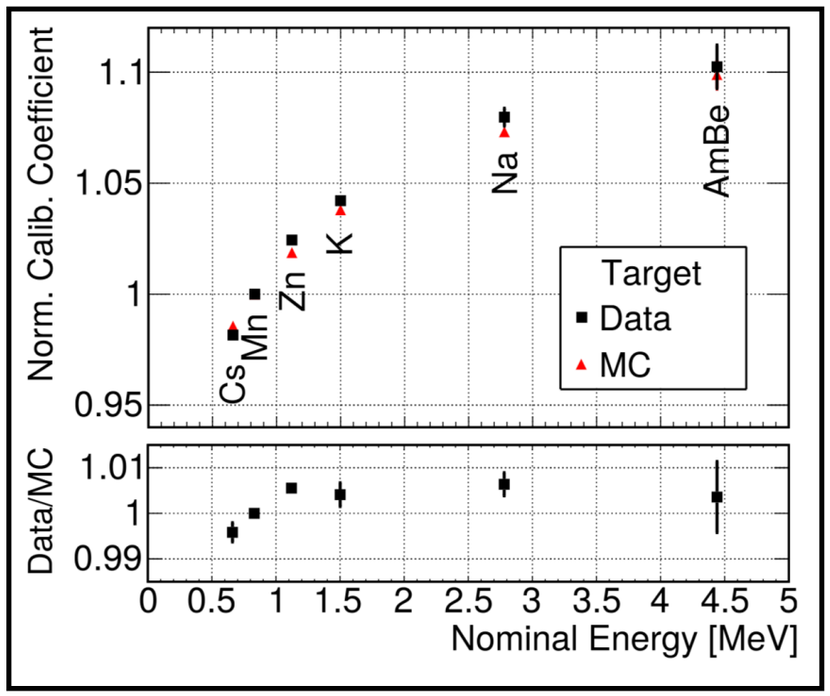
- Energy calibration:
  - weekly ^{54}Mn (γ~0.83MeV), monthly AmBe calibrations
  - Other γ sources: 0.5 - 4.4 MeV
  - cosmogenic ^{12}B spectrum

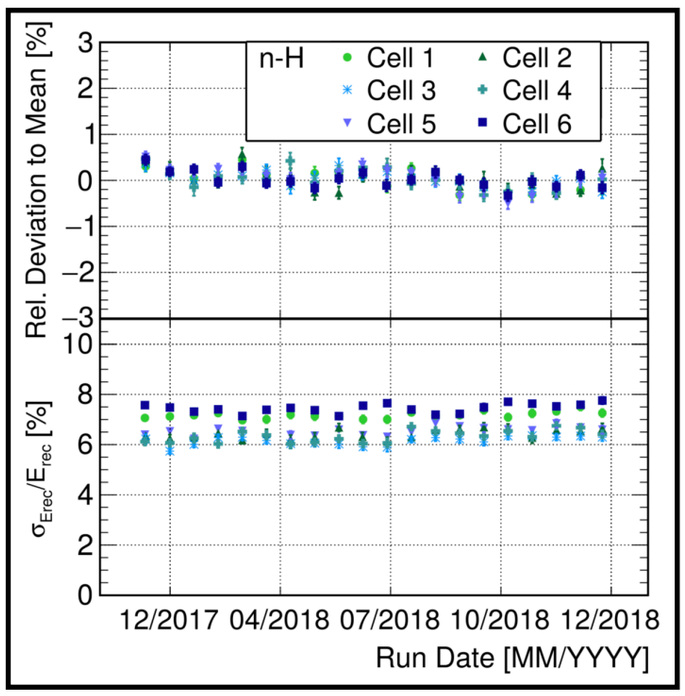


- Time stability monitored with n-H capture:
  - mean energy stable at 0.3% level

arXiv:1912.06582

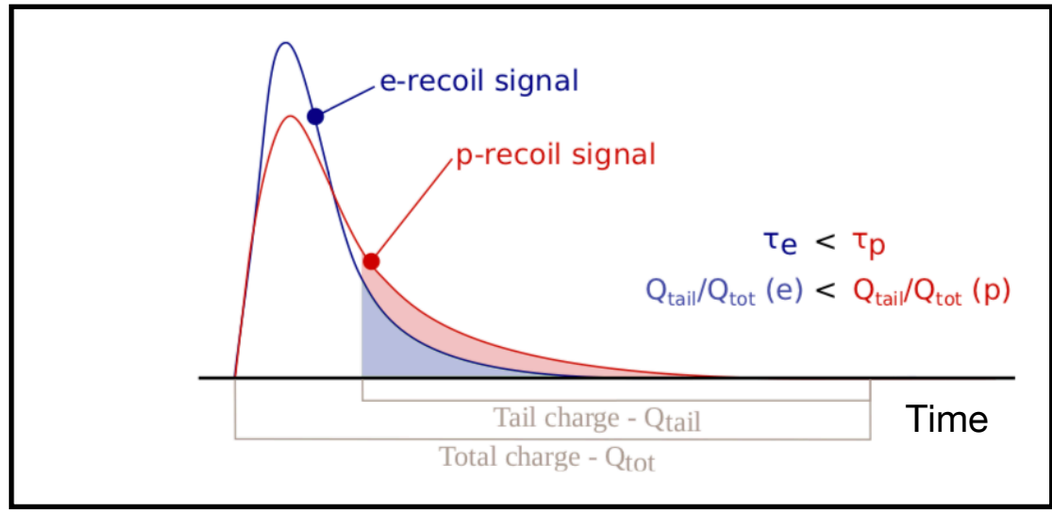
- Non-linearity:
  - Mn anchor of energy scale
  - Data/MC agreement better than 1%





Neutrino signal extraction

- Pulse Shape Discrimination (PSD):
  - Q_{tail}/Q_{tot}
  - electronic recoils have low Q_{tail}/Q_{tot}
  - proton recoils have large Q_{tail}/Q_{tot}

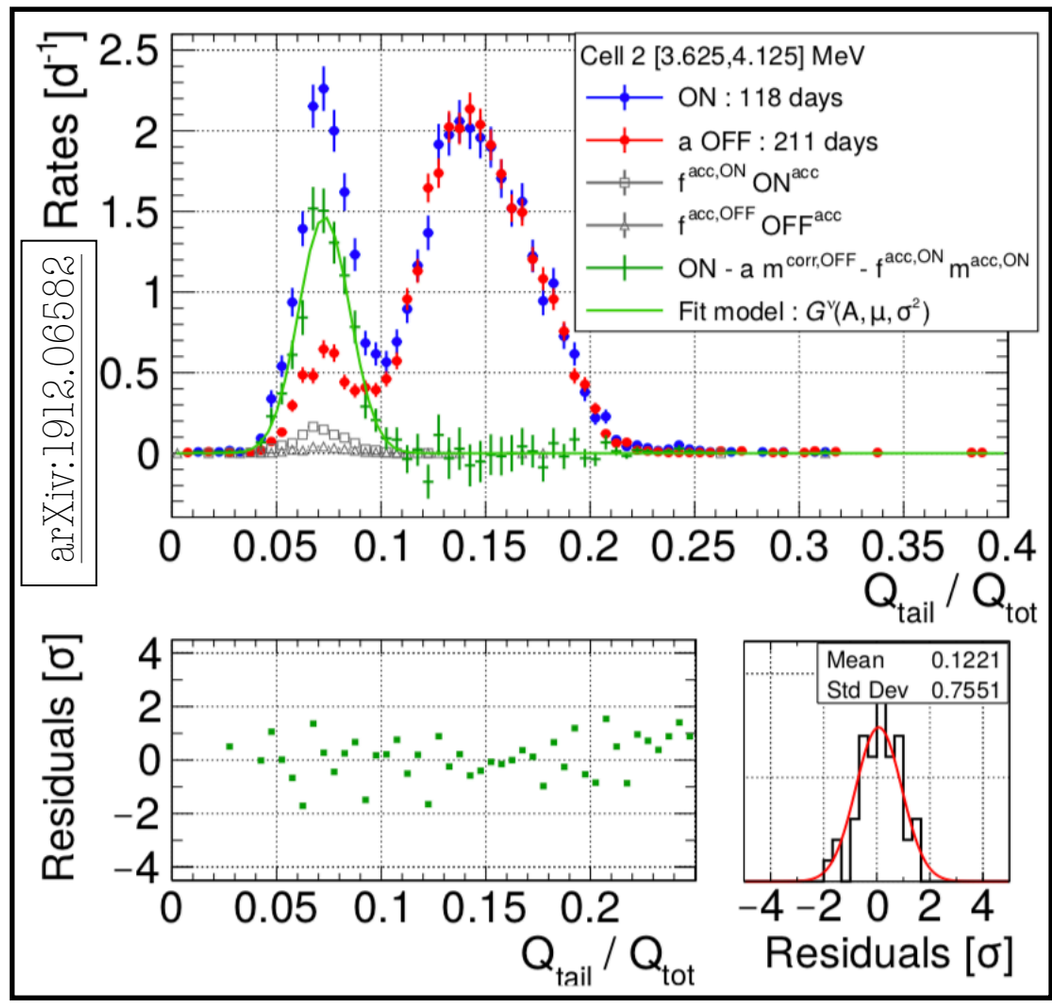


- PSD model:

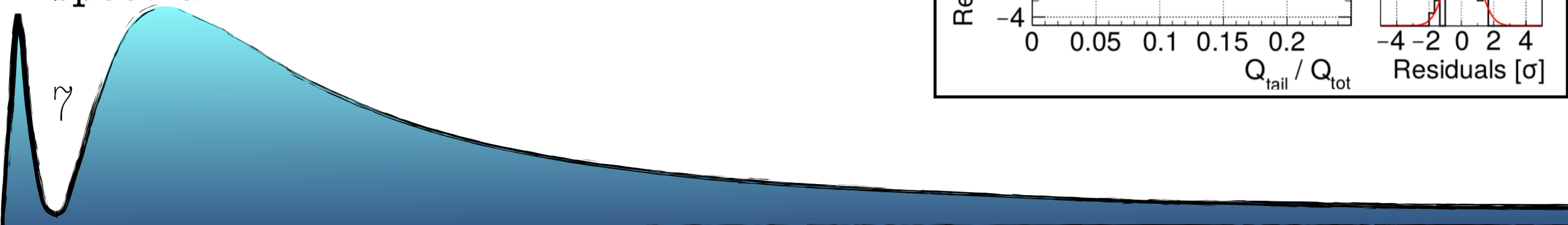
$$ON_{l,i,p} = a_{l,i} \times m^{corr,OFF}_{l,i,p} + f^{acc,ON} \times m^{acc,ON}_{l,i,p} + G^{\nu}_{p}(A_{l,i}, \mu_{l,i}, \sigma^2_{l,i})$$

$$OFF_{l,i,p} = m^{corr,OFF}_{l,i,p} + f^{acc,OFF} \times m^{acc,OFF}_{l,i,p}$$

  - $a_{l,i}$ normalisation param. between ON and OFF for cell l and energy bin i
  - accidentals measured with high stat. from shifted time windows
  - neutrino: gaussian function



- Simultaneous fit of OFF and ON PSD spectra



Oscillation analysis

- Spectrum shape only analysis,
  no information from absolute rate

- Comparison between cells and
  energy bins independent from prediction:

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

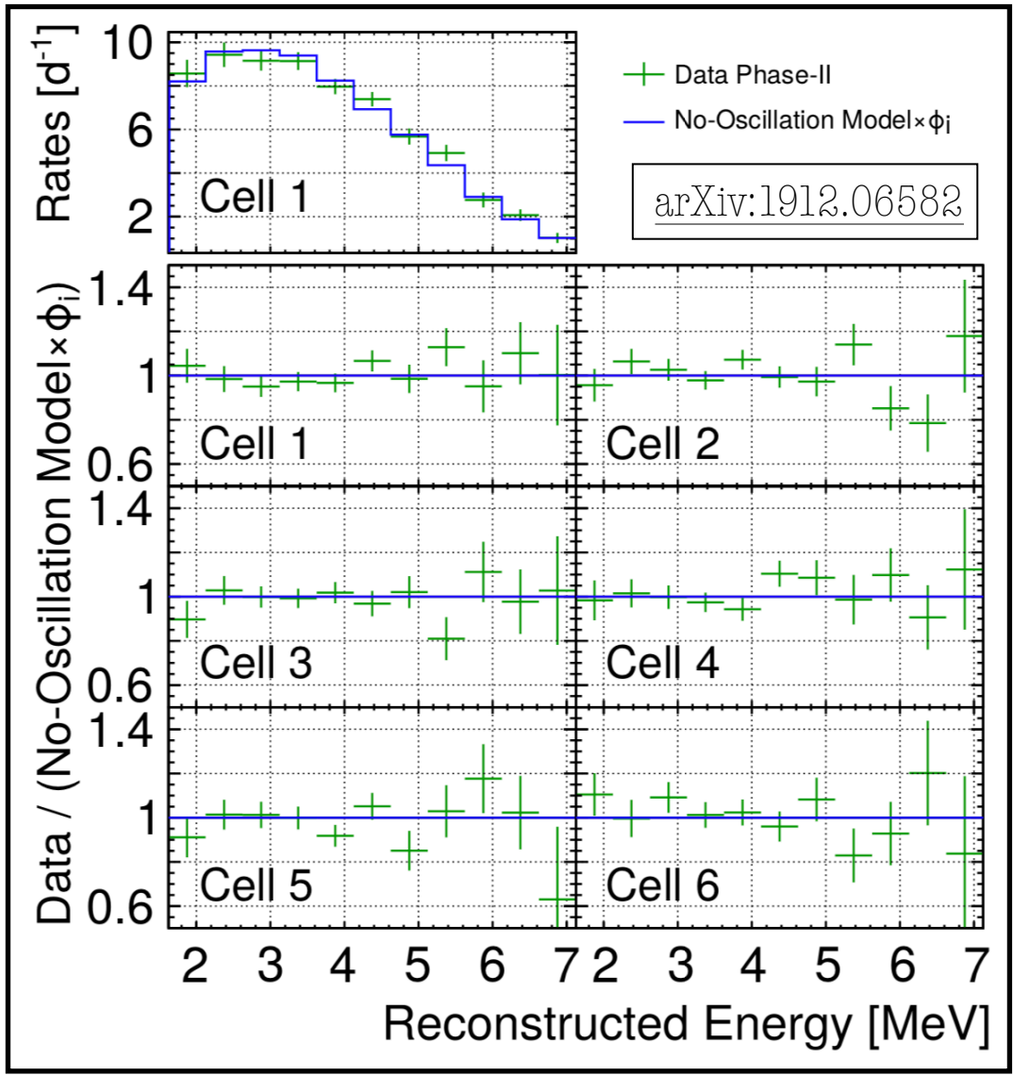
$$+ \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{NormU}}{\sigma_l^{NormU}} \right)^2 + \left(\frac{\alpha_l^{EScaleC}}{\sigma_l^{EScaleC}} \right)^2 + \left(\frac{\alpha_l^{EScaleU}}{\sigma_l^{EScaleU}} \right)^2$$

- Each energy bin normalised by param. ϕ_i common to all cells:

  → analysis independent from absolute rate

  → analysis independent from predicted spectrum

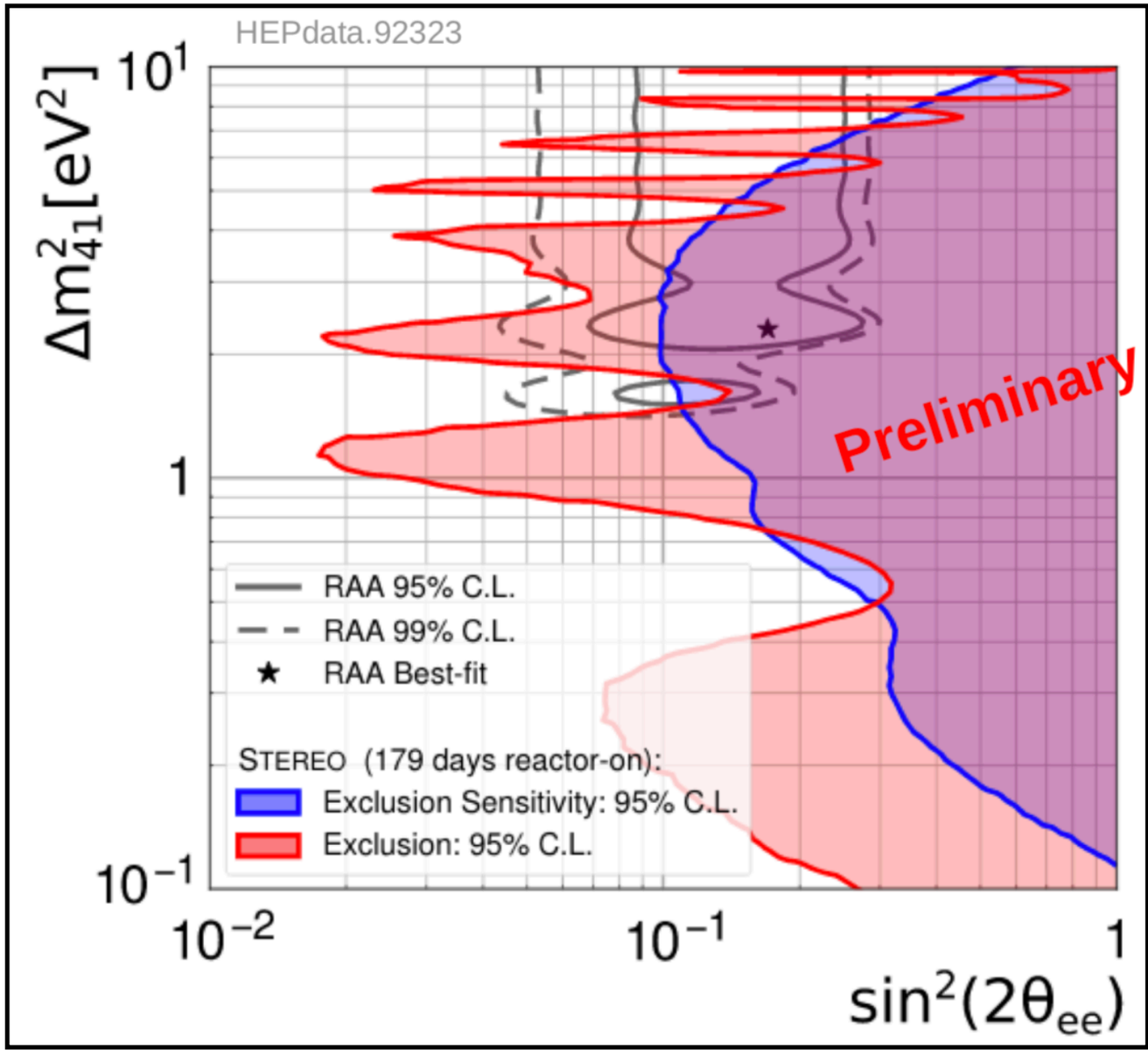
- Systematic uncertainties parameterised by nuisance parameters $\vec{\alpha}$



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 %

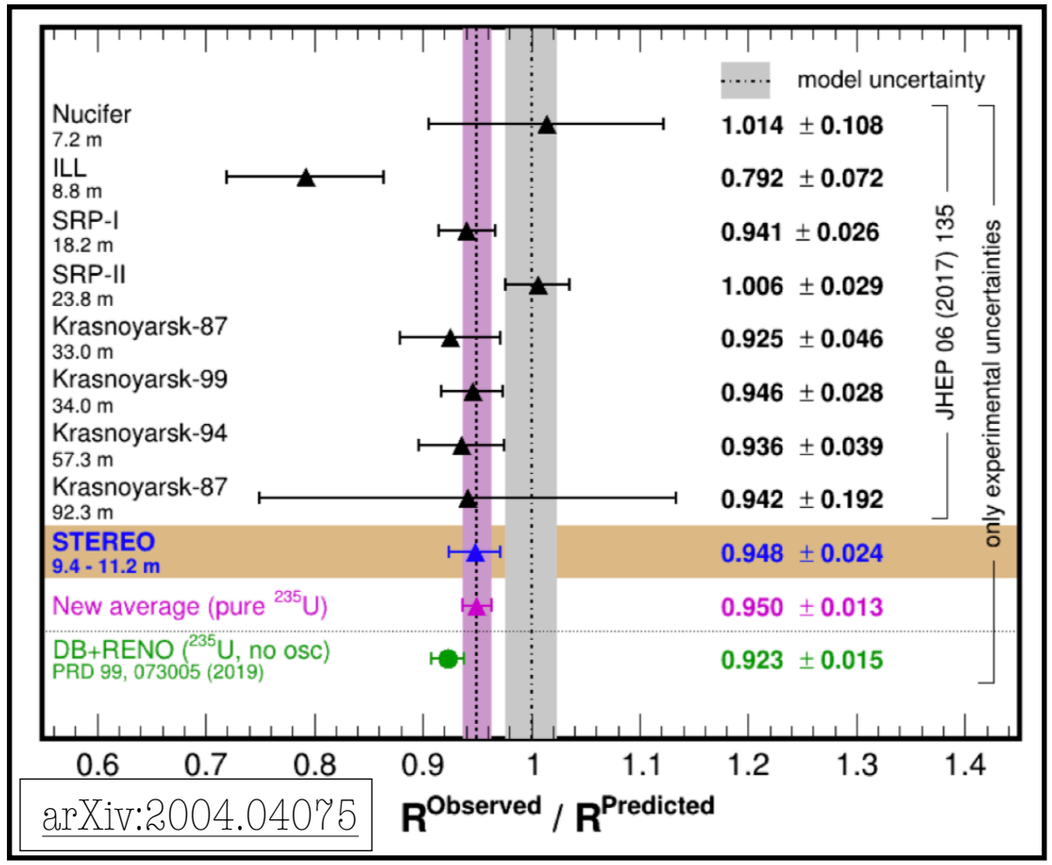
Oscillation analysis results

- $\Delta\chi^2$ distributions obtained from MC pseudo-experiments
- Contour obtained from 2-dimensional $\Delta\chi^2$ map
- No-oscillation hypothesis not rejected (p-value = 0.09)
- RAA best fit point excluded at more than 99.9% C.L.



Absolute rate measurement

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



- Observed neutrino rate: 364 ± 3 stat. ± 4 syst. $\rightarrow \frac{R_{obs}}{R_{pred}} = 0.948 \pm 0.024$

  - in agreement with current world average

- Main uncertainties are thermal power, proton number & neutron efficiency

- Among the most precise measurement for pure ^{235}U fuel

Spectrum shape unfolding

- Prompt energy spectrum D_i unfolded in antineutrino energy spectrum ϕ_j thanks to response matrix R_{ij} :

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

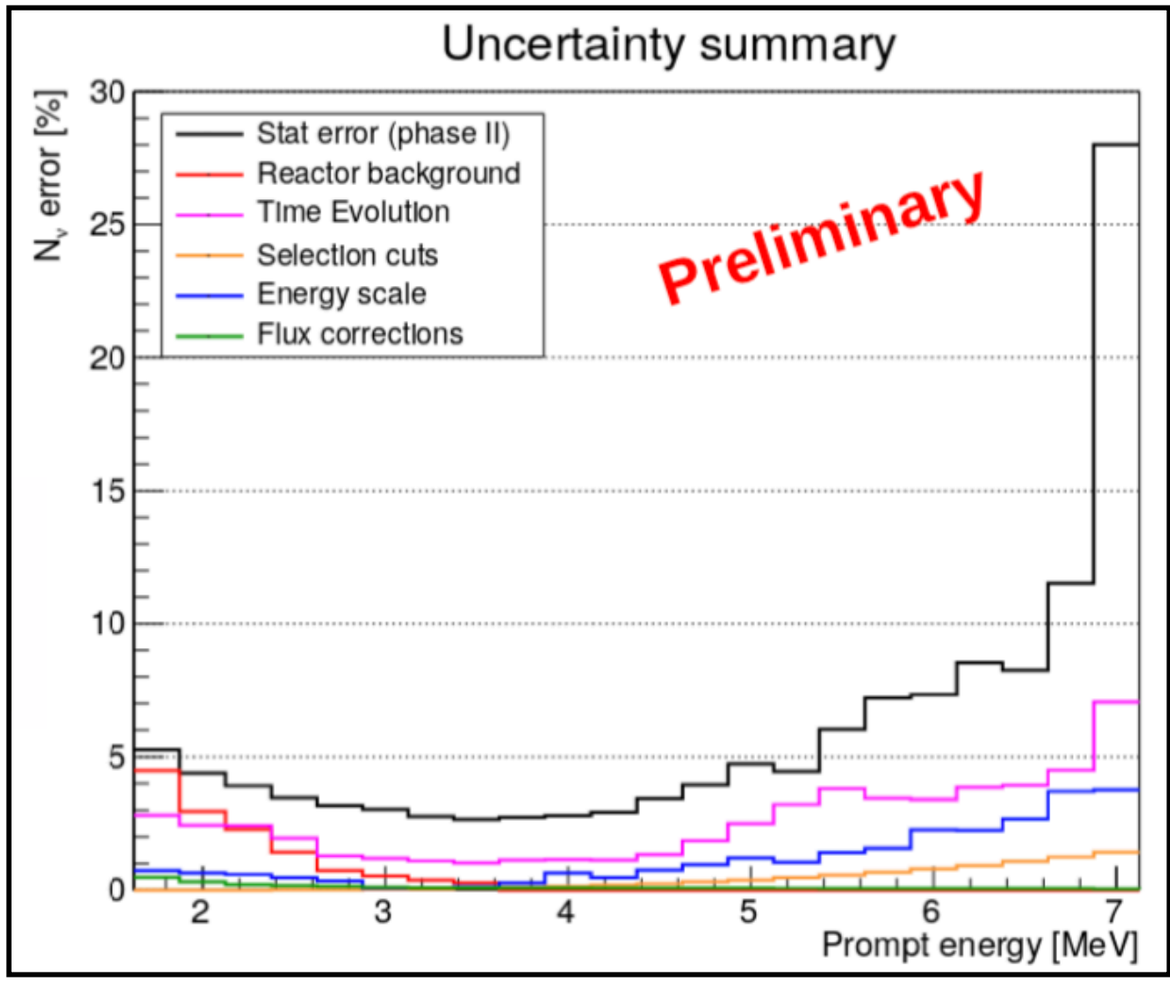
- Main uncertainty is statistic

- Regularisation term to smooth unfolding of statistical fluctuations:

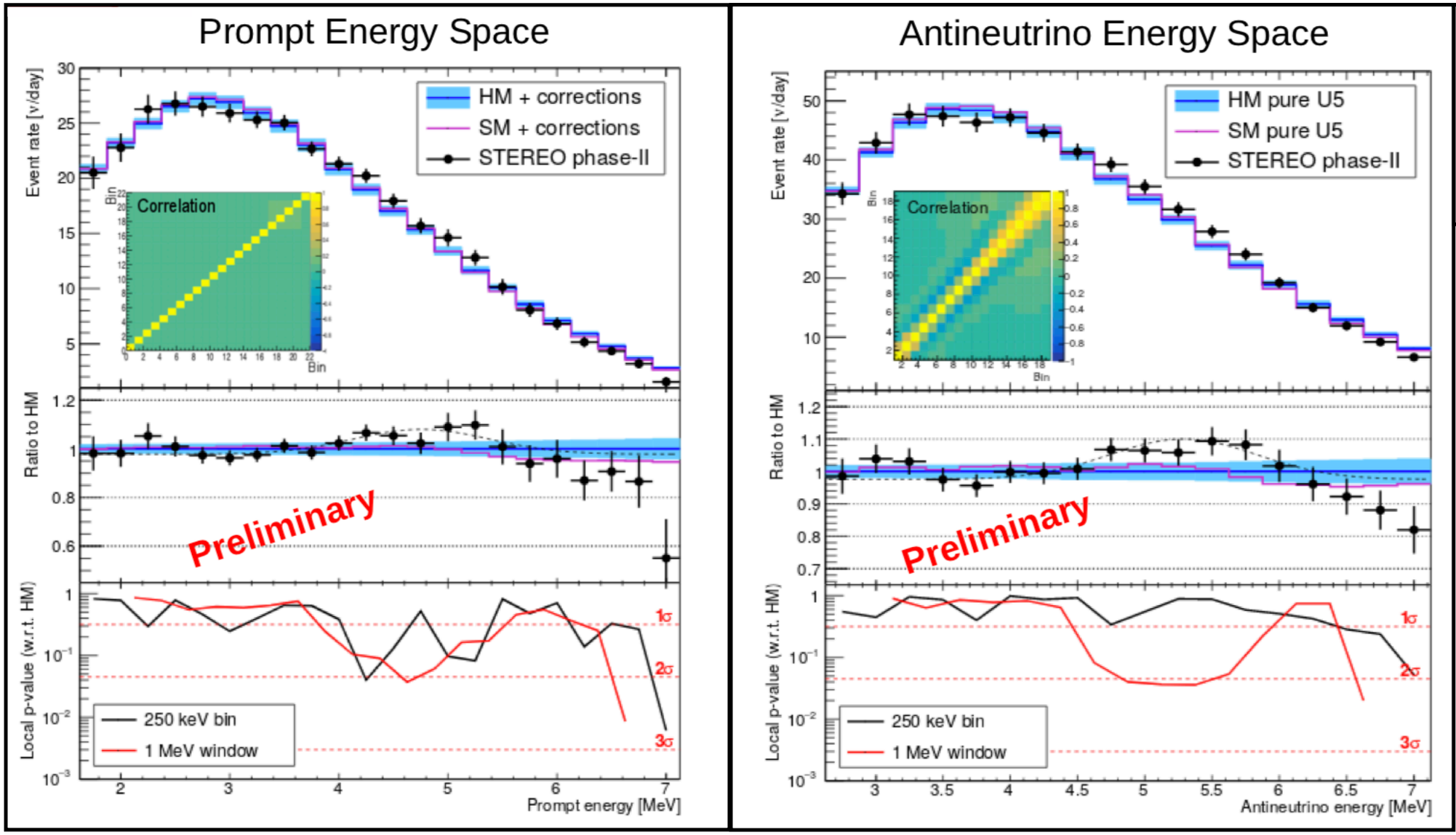
$$\Lambda(\vec{\phi}) = \left(\sum_i \frac{\phi_{i+1}}{\phi^0_{i+1}} - \frac{\phi_i}{\phi^0_i} \right)^2$$

$\vec{\phi^0}$ prior spectrum: Huber's ^{235}U spectrum

- Regularisation strength r chosen to minimise dependence to prior spectrum



Unfolding results



HM: Huber Model
PRC 84, 024617 (2011)

SM: Summation Model
PRL 123, 022502 (2019)

- Hint of a spectral distortion, fit with a free gaussian:

  → Amplitude = 10.1± 2.9% Mean = 4.8±0.2 MeV in prompt space

Preliminary

Conclusion & Outlook

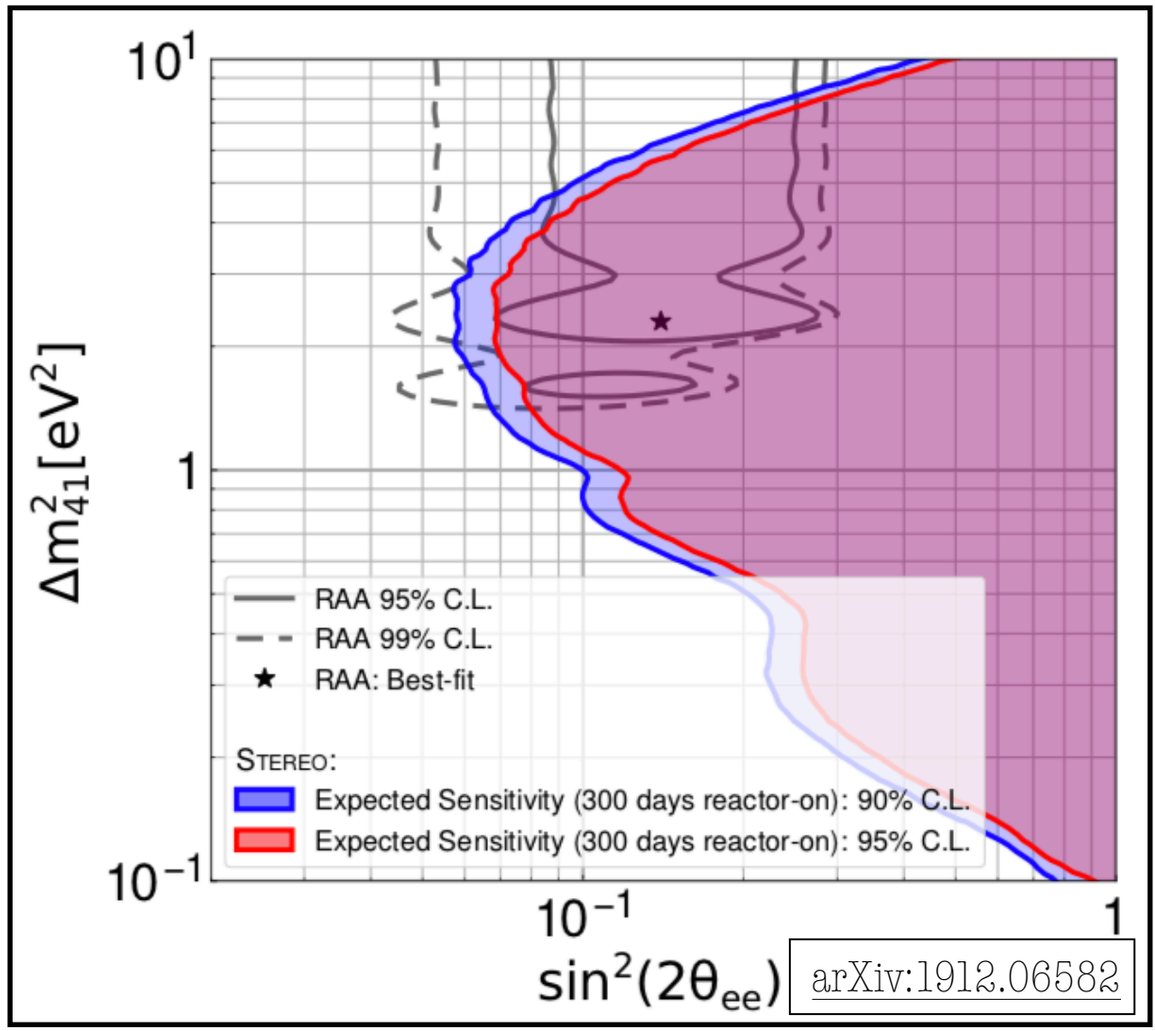
- Large portion of the RAA parameter space excluded, in particular RAA best fit point excluded at more than 99.9% C.L.

- Absolute rate measurement for pure ^{235}U among world-wide leading measurements, consistent with the RAA deficit

- Spectral shape in neutrino energy space:
  - Hint of a ~10% spectral distortion at ~5 MeV in prompt space with respect to Huber-Mueller predicted spectrum

- Further data taking until the end of the year:
  → expected more than 300 days reactor ON
  → 2× more statistics

- Stay tuned for PROSPECT and STEREO joint spectrum analysis !



Recent STEREO papers :
- Oscillation: arXiv:1912.06582
- Absolute Rate: arXiv:2004.04075
- Gd improved cascade: Eur.Phys.J.A 55 (2019) 10, 183

The STEREO collaboration

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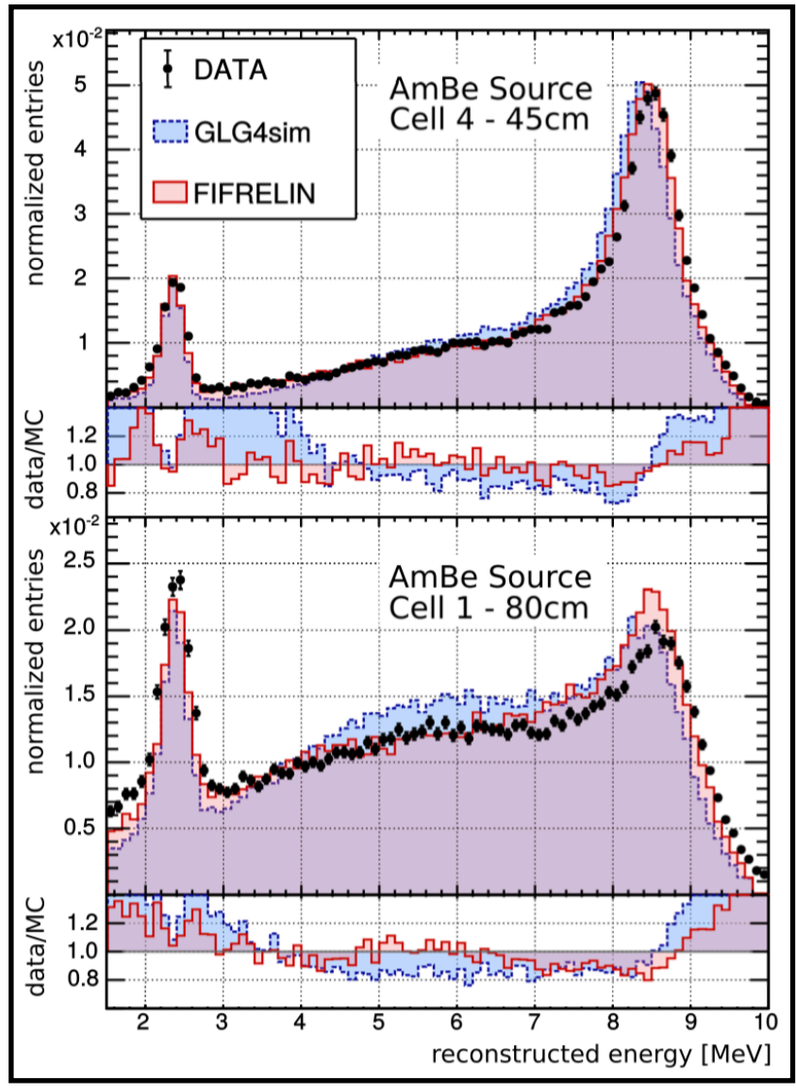
www.stereo-experiment.org

Thank you for your attention !

Backup

Neutron efficiency

- Neutron efficiency (delayed trigger): dominant uncertainty
- Studied with AmBe γ-n source (mimics IBD)
- Remaining discrepancy at corner position corrected by 3D-model
- Good agreement in capture time



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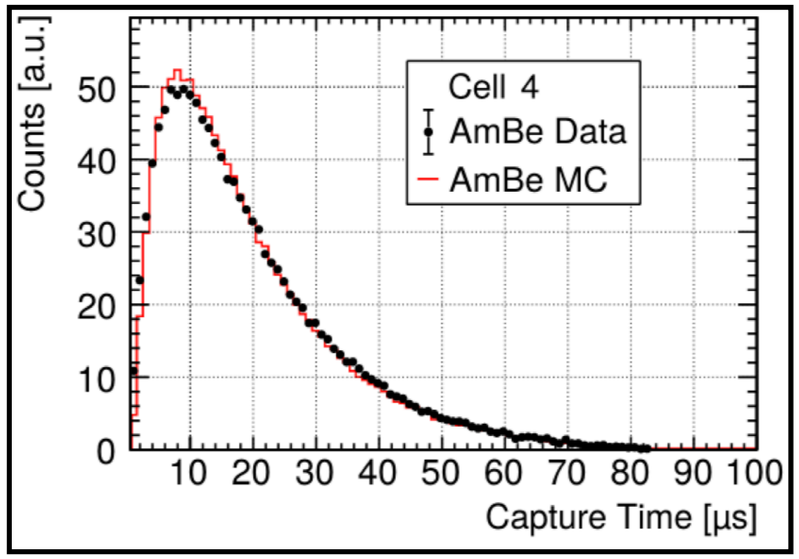
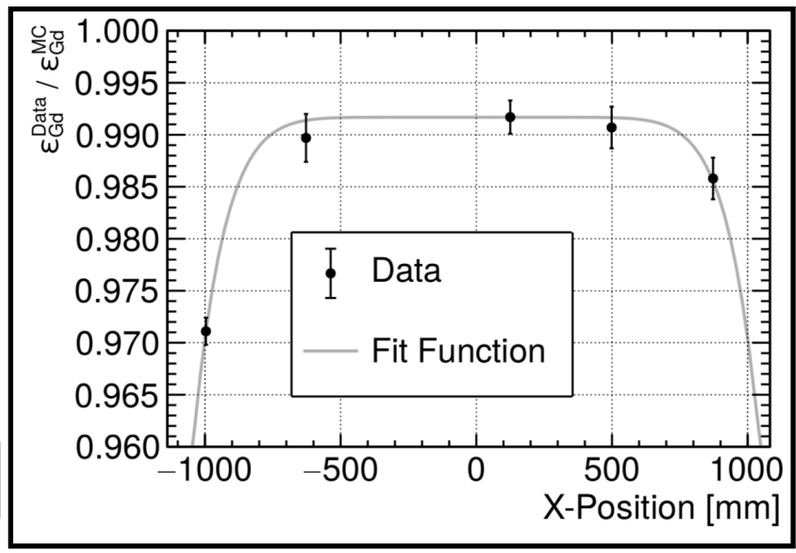


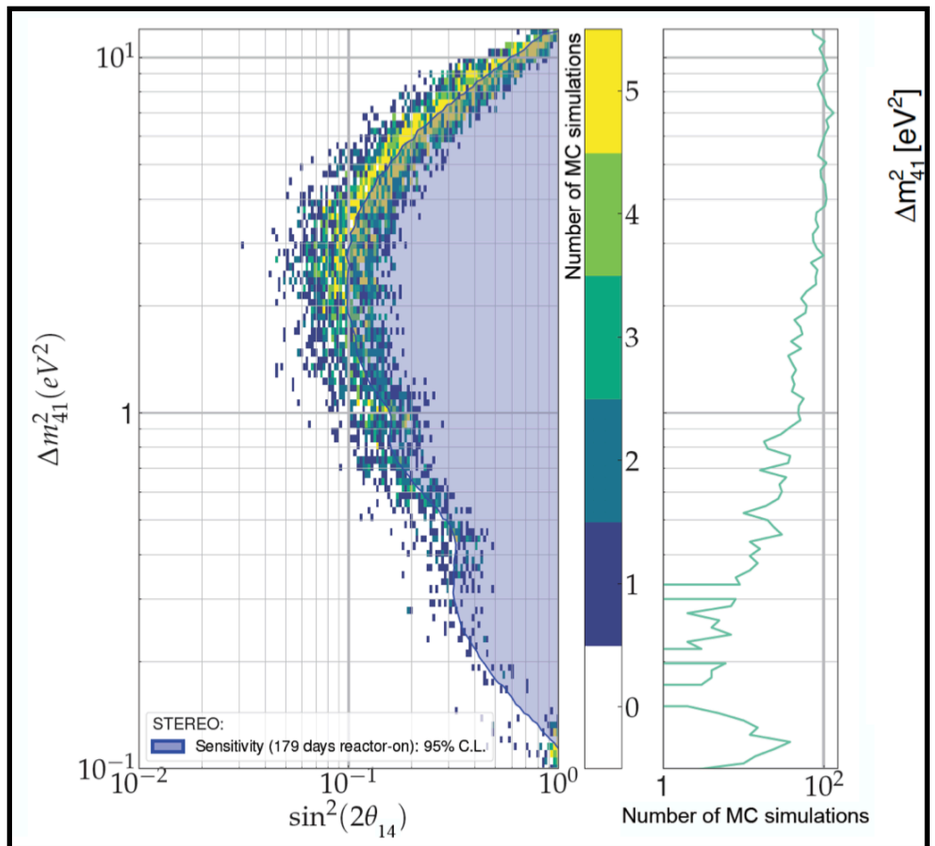
arXiv:1912.06582



Important aspects to consider in oscillation measurement

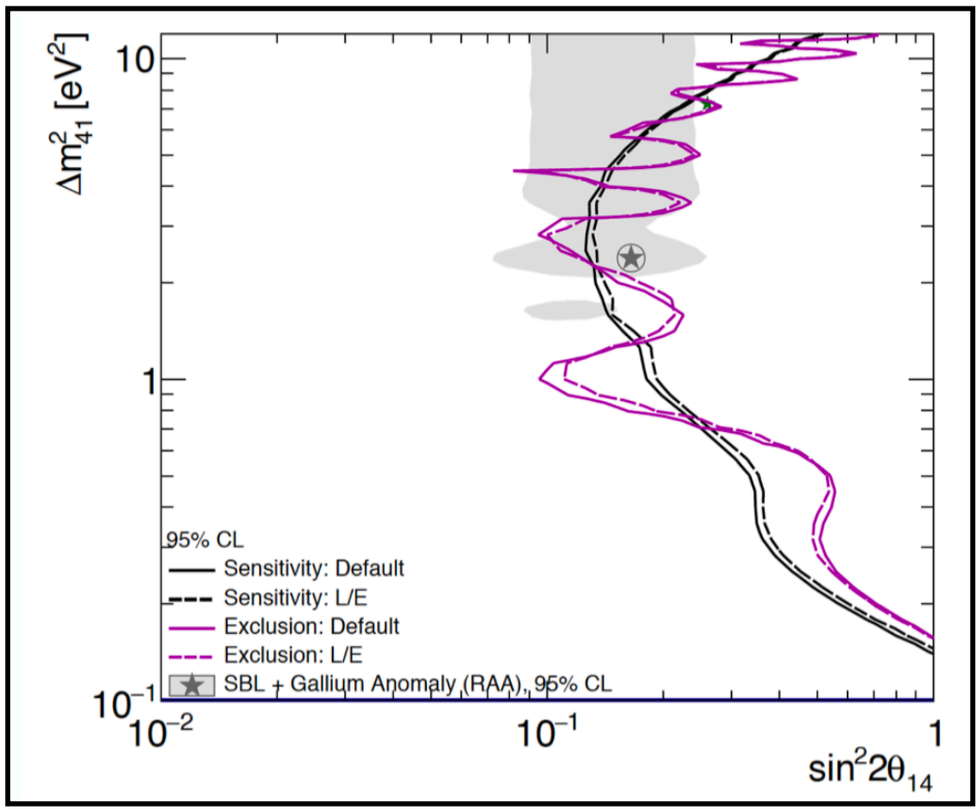
- Statistical method: frequentist test necessary
  → χ^2 of best fit non-zero even for no-oscillation

- Consider position and time dependent variation of energy response



Best fit point of MC toys with no oscillation

PROSPECT & STEREO, arXiv:2006.13147



- Exclusion and sensitivity curves similar for L/E and (E,L) bins