Results of the STEREO Experiment

PANIC 2021

09-2021

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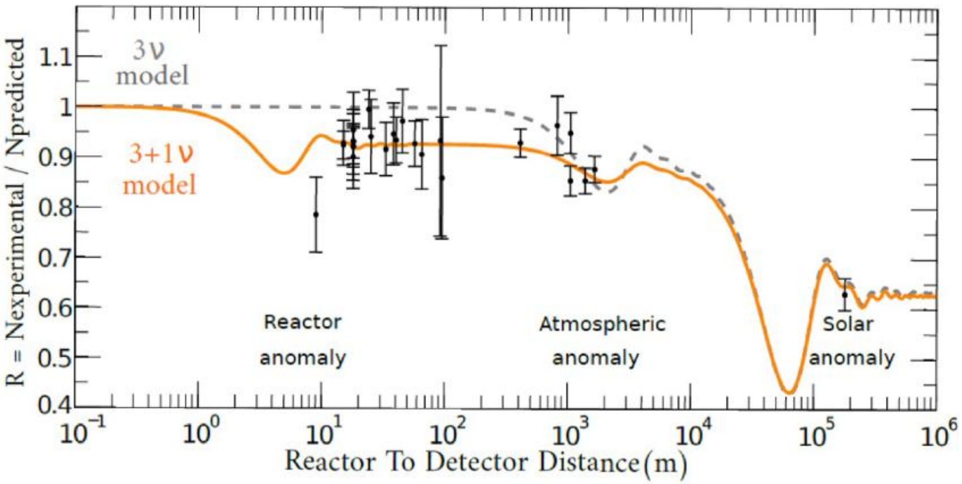
On behalf of the STEREO collaboration

The Reactor Antineutrino Anomaly (RAA)

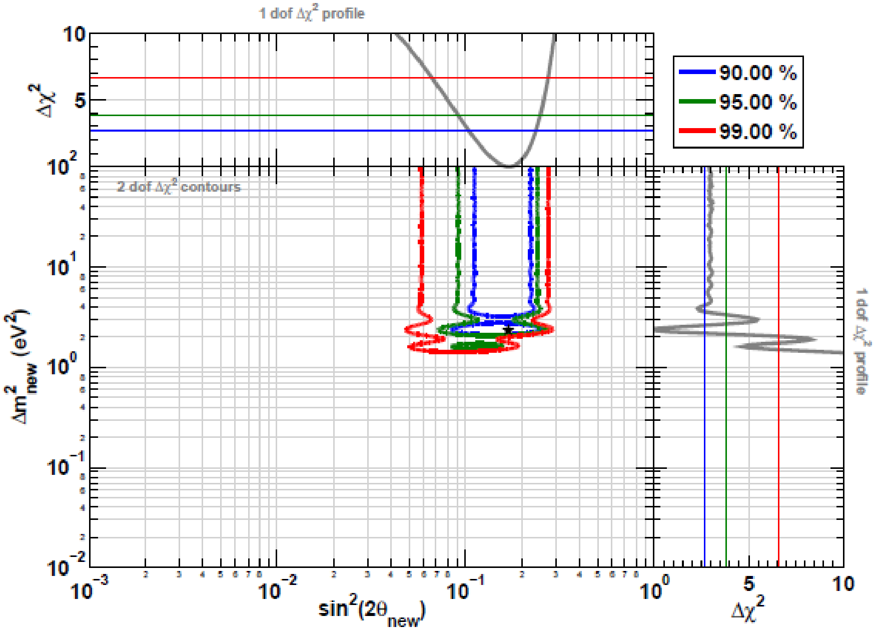
2011: **Re-evaluation of the predicted flux of antineutrinos coming from a reactor (PRC 83:054615)**

→ ~6% deficit measured compared to the prediction: **Reactor Antineutrino Anomaly** (RAA) (PRD 83:073006)



⋆ RAA best fit point:

Δm^2_{new} = 2.3 eV²; $\sin^2(2\theta_{new})$ =0.17



Unpredicted disappearance at short distance -> New sterile neutrino?

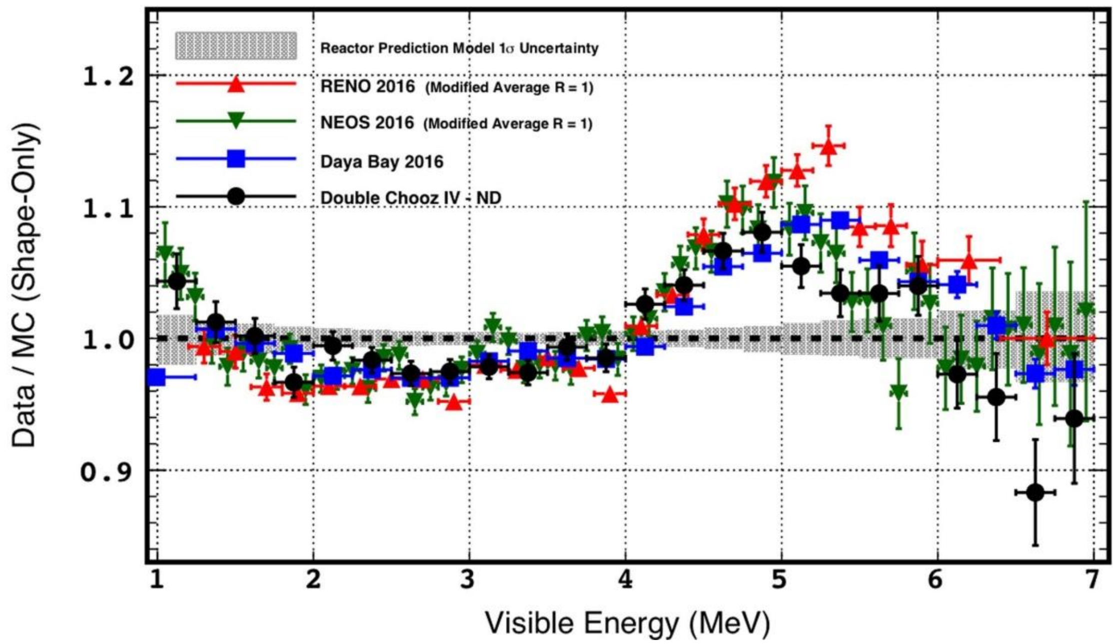
arXiv:1204.5379

Spectral distortion

[Nature Physics 16, 558-564 (2020)]

« Bump » around 5 MeV compared to prediction observed by several LEU experiments

- ≈ 10% amplitude distortion
- Can not explain the total deficit
- Linked to the fuel composition ?



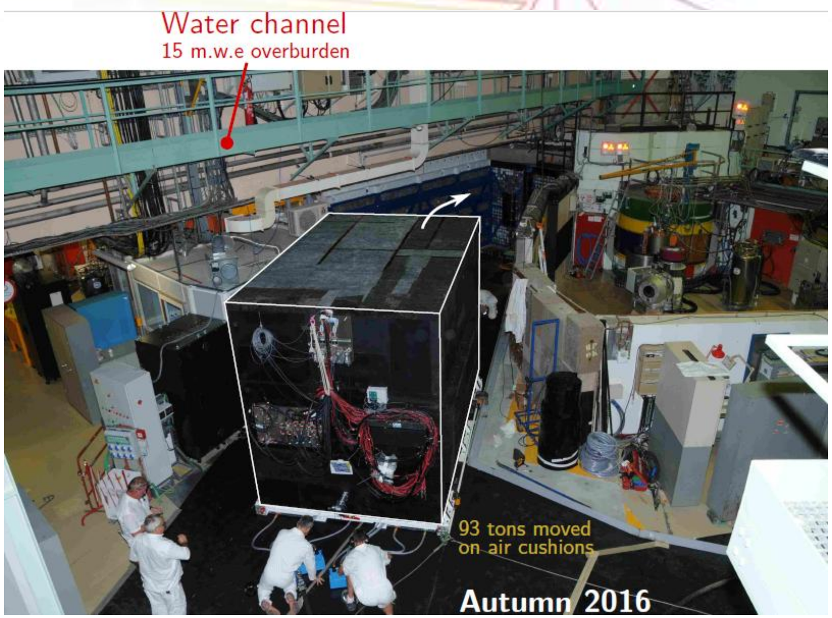
How to test the 2 anomalies:

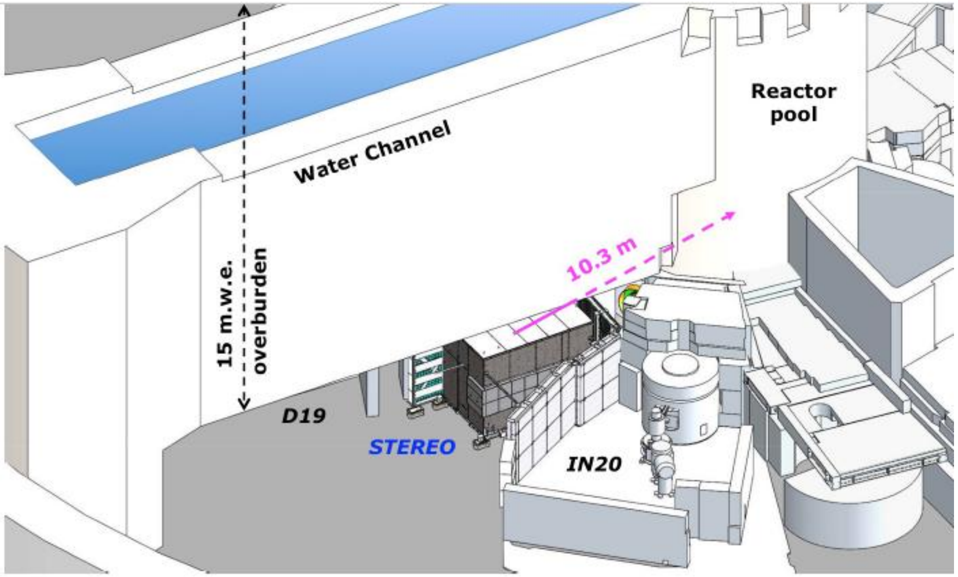
1. **Sterile neutrino hypothesis**
   - Prediction-independent comparison of neutrino spectra measured at different distances from the reactor core
2. **Spectral distortion**
   - Accurate neutrino spectrum measurement from a reactor highly enriched in ^{235}U

Experimental site

Experimental site (France, Grenoble, ILL):

- Research Reactor highly enriched in ^{235}U (99.7% of neutrinos flux)
- Nominal power ~58 MW_{th}
- Compact core (Ø40 x 80 cm)
- Short baseline ~10 m





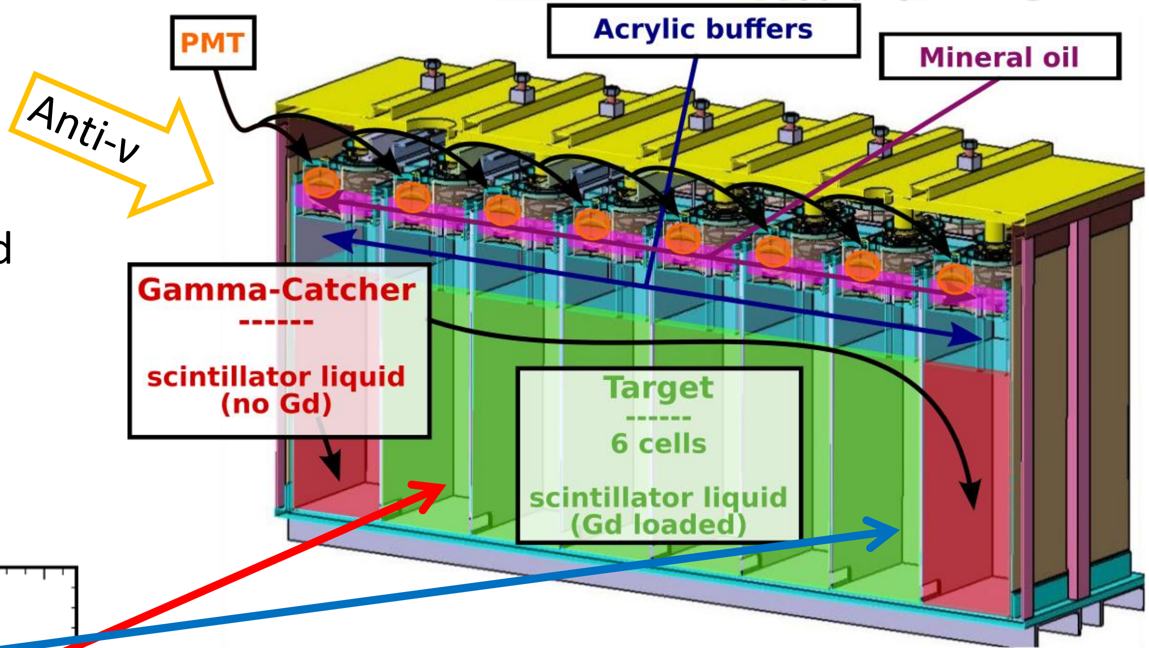
Background sources:

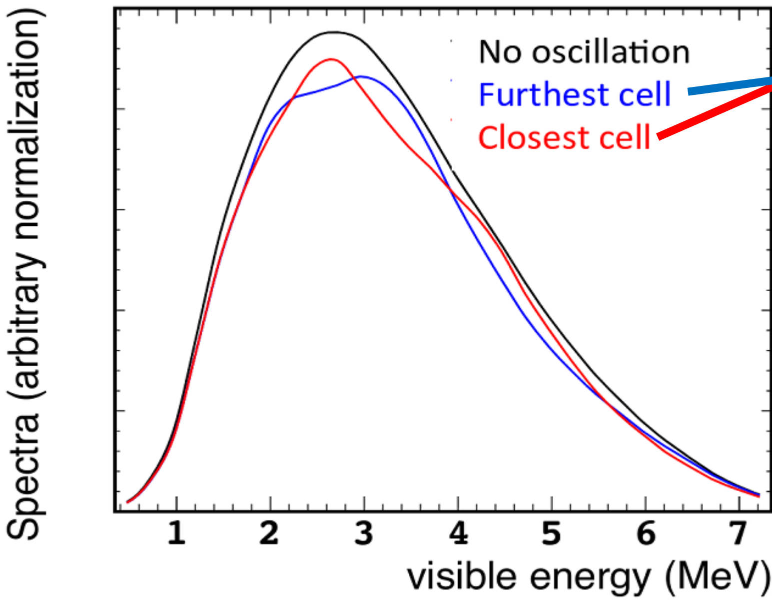
- γ and neutrons coming from neighboring experiments
- Surface level experiment exposed to cosmic rays

The STEREO detector

Detector design:

- Target volume (6 cells)
- Gamma catcher (4 cells around target)
- ≈400 antineutrinos per day
- S/B ≈1





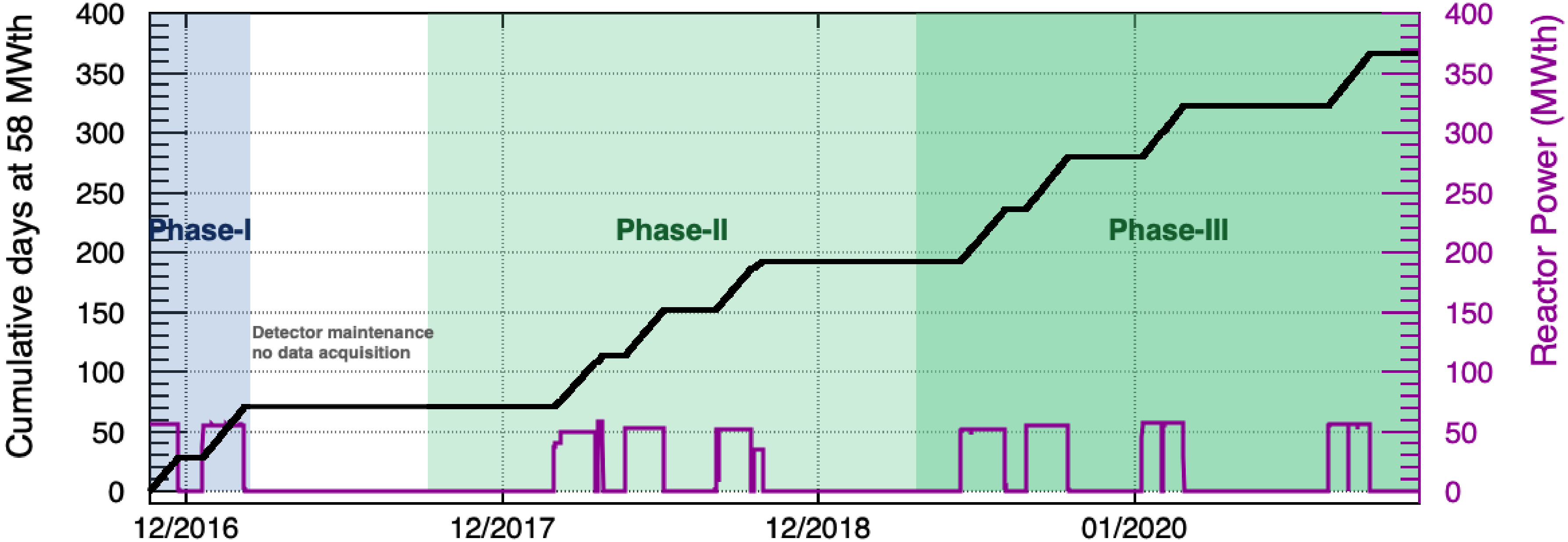
1. **Sterile neutrino research**
   Comparison of spectra measured in each cell
   → Prediction free
2. **Shape analysis**
   Spectrum summed over the 6 Target cells

JINST 13 (2019) 07, P07009

STEREO data taking

- **November 2016 to November 2020**

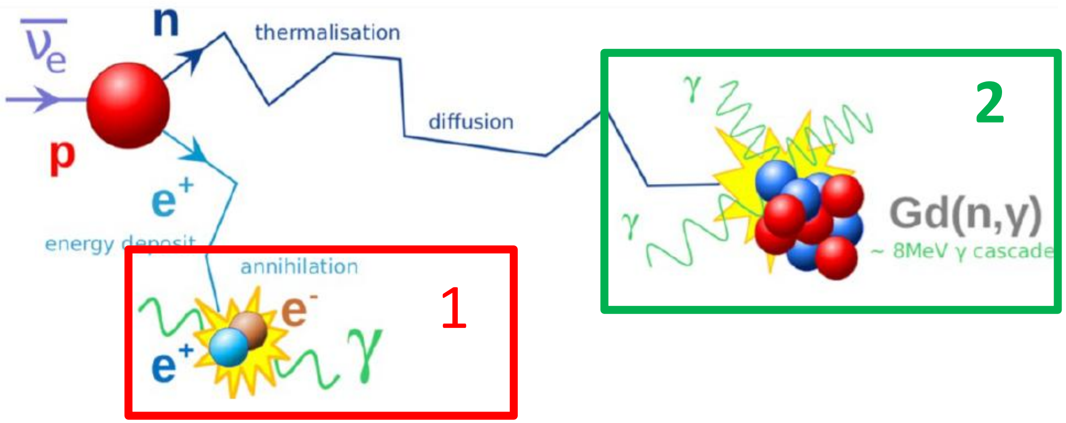
Phase-I	Phase-II	Phase-III
ON = 61 days	ON = 118 days	ON = 155 days
OFF = 21 days	OFF = 211 days	OFF = 311 days



- **ON and OFF** data taking ⇒ control of the cosmogenic background
  - Oscillation analysis: entire dataset (Phase-I+II+III) with 334(543) days ON (OFF)
  - Shape analysis: Phase-II and III data with 273(519) days ON(OFF)

IBD events selection

- **Detection by Inverse Beta Decay (IBD) process**



Type of cuts	Cut
Energy	1.625 MeV < E(prompt) < 8.125 MeV 4.5 MeV < E(delayed) < 10.0 MeV
Coïncidence	2µs < ΔT < 70µs ΔX < 600 mm
Topology	E(neighbour cells) < 1 MeV (1.1 in Phase-III) E(other cells) < 0.4 MeV E(delayed) at least 1 MeV in target
Muon rejection	Asymetry of light at PMTs of vertex cell < 0.5 No muon in veto 100µs before prompt No muon in detector 200µs before prompt No events with E>1.5MeV 100µs before prompt and after delayed

1. **Prompt signal:** $E_e \approx E_\nu - 0.782$ MeV
2. **Delayed signal:** $\sum E_\gamma \approx 8$ MeV

Cuts used to select IBD events and optimize signal/background at low systematics

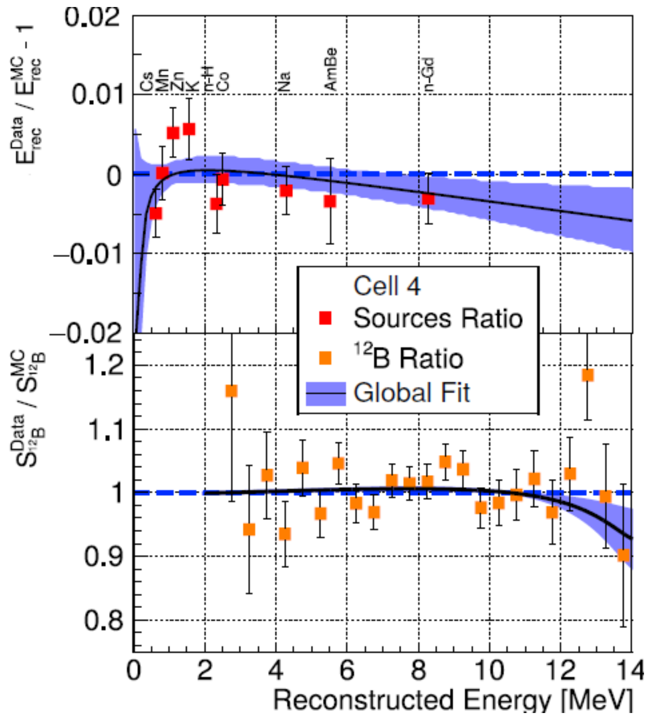
Reconstructed energy

Precise energy reconstruction is necessary for oscillation and spectrum shape analysis

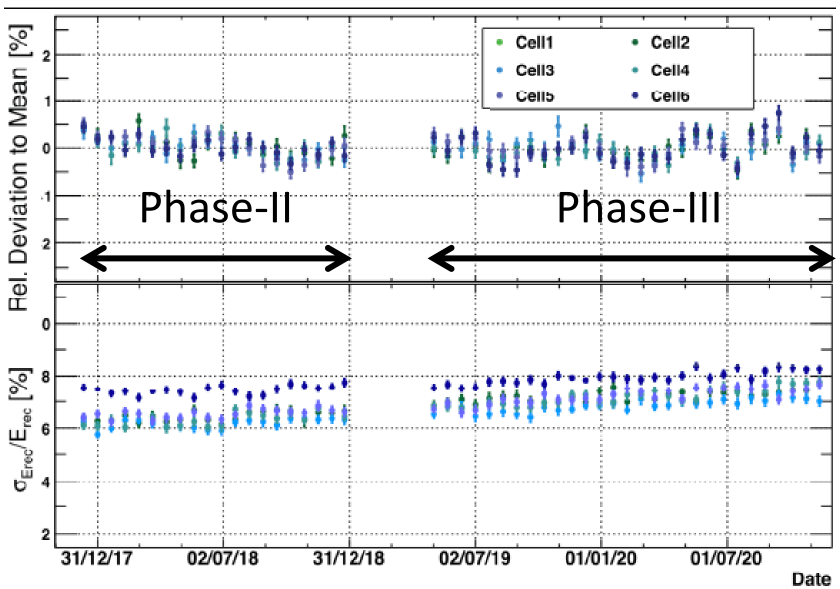
➢ Energy scale accuracy tested with a global fit of:

1. **Calibration sources** at different positions in the detector
2. **^{12}B spectrum** with Q_β = 13.4 MeV

Data/MC residuals inferior to ±1%



Uncertainty due to time stability ≈0.3%



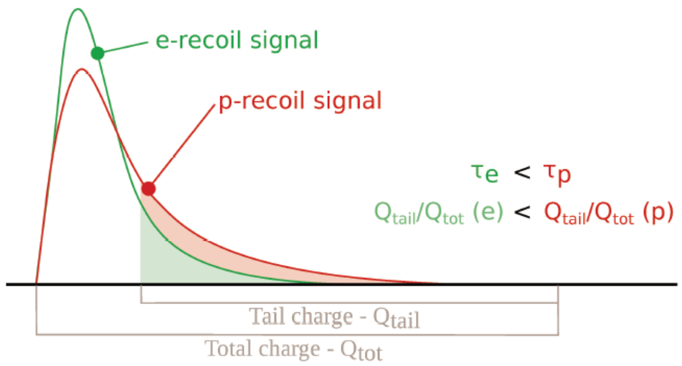
➢ **Two different versions** of calibration and Monte Carlo used for Phase-II and Phase-III

➢ Time stability of energy from **variations of the n-H peak position**

Signal extraction from PSD distribution

Discriminate neutrino signal from background using the Pulse Shape Discrimination (PSD)

- PSD = Q_{tail} / Q_{tot}
  - **Lower PSD for electron than for proton recoils**

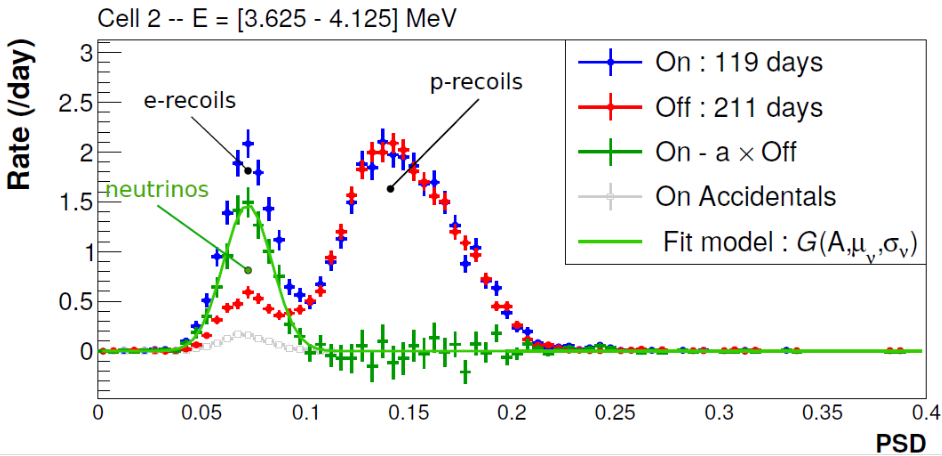


- Background PSD model from **reactor OFF data**

- **Simultaneous fit** of ON and OFF data performed for each energy bin and cell

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

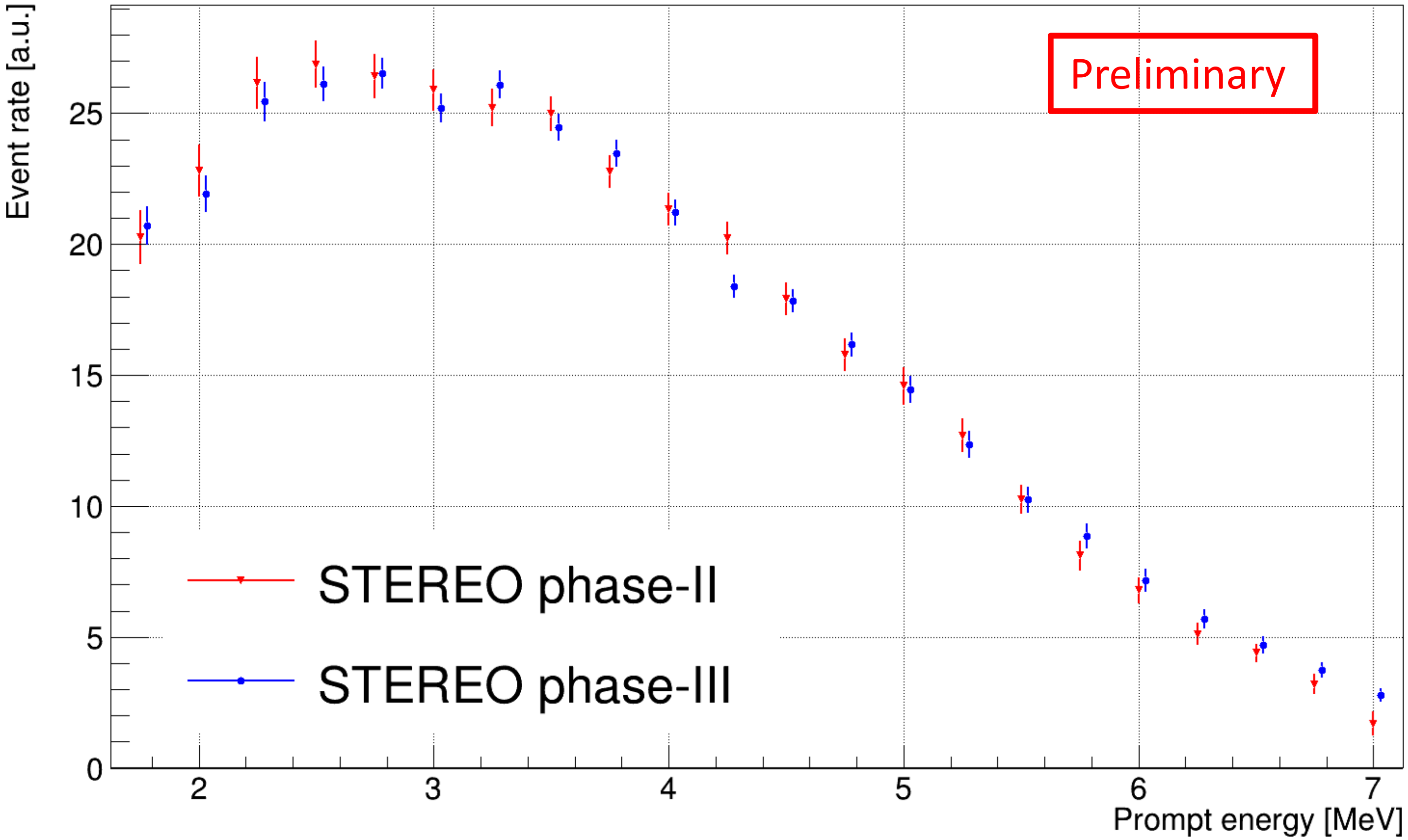
$$OFF_{l,i,p} = m^{corr,OFF}_{l,i,p} + f^{acc,OFF} m^{acc,OFF}_{l,i,p}$$



- Neutrinos represented by a gaussian function
- $a_{l,i}$: normalisation parameter between ON and OFF distributions

[Phys. Rev. D 102, 052002 (2020)]

Phase-II and III compatibility



- **Phase-II and III neutrino spectra are compatible** within the error bars:

Only stat: **χ^2/ndf = 18.5 / 21**

Stat + syst: **χ^2/ndf = 17.9 / 21**

STEREO shape analysis: methods

Provide a reference ^{235}U spectrum in antineutrino energy to be compared with other experiments and predictions

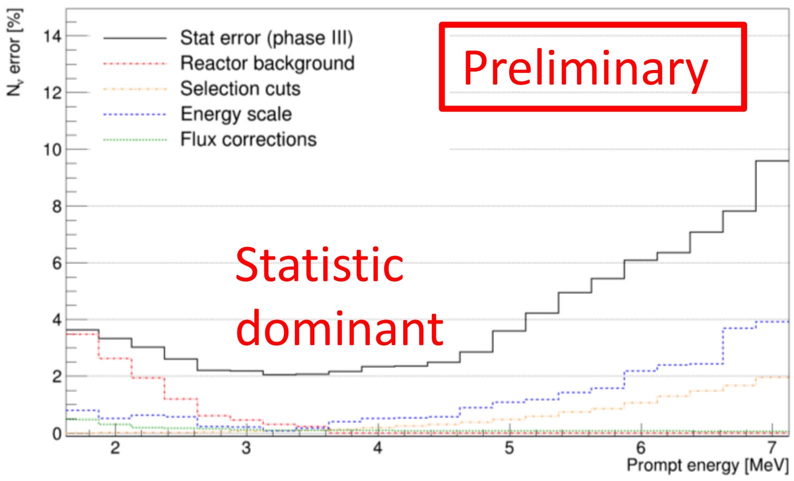
Method: Unfold the measured energy spectrum D in antineutrino energy spectrum Φ through the detector response R

$$\chi^2(\Phi) = (R(\boldsymbol{\alpha})\Phi - D)^T V_{stat}^{-1} (R(\boldsymbol{\alpha})\Phi - D) + |\boldsymbol{\alpha}| + r \cdot \Lambda(\Phi)$$

- $\boldsymbol{\alpha}$ parameterizes the systematic uncertainties
- $r \cdot \Lambda(\Phi)$: regularization term to avoid too high bin-to-bin fluctuations

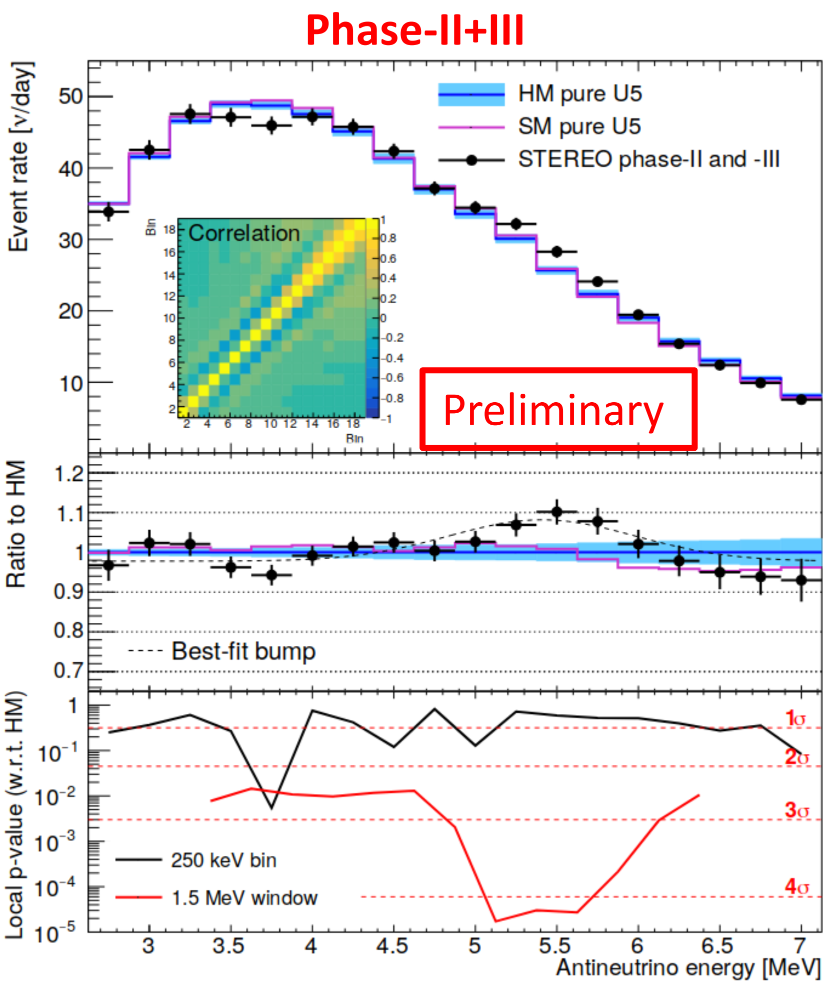
  - $\Lambda(\Phi) = \sum_i \left(\frac{\Phi_{i+1}}{\Phi_{i+1}^0} - \frac{\Phi_i}{\Phi_i^0} \right)^2$

    with Φ_0 the prior shape (Huber model)
  - r tuned to limit prior dependence



STEREO shape analysis: results

Spectrum of the two phases jointly unfolded:



Models: HM: PRC 84, 024617 (2011)
SM: PRL 123, 022502 (2019)

Comparison with Huber (norm free):

$$\chi^2/\text{ndf} = 40.5/17$$

Best fit bump:

$$\chi^2/\text{ndf} = 11.6/14$$

$$A = 0.107 \pm 0.021$$

$$\mu = 5.39 \pm 0.13 \text{ MeV}$$

$$\sigma = 0.585 \pm 0.157 \text{ MeV}$$

Confirms the events excess in the 5-6 MeV range for a pure ^{235}U spectrum

Oscillation analysis: Method

Test the hypothesis of a new sterile neutrino causing the RAA

Method: Analyse relative variations of the spectrum shape between cells, to be **independent from the prediction shape and rate**

$\boldsymbol{\mu}$:[$\sin^2(2\theta_{ee})$;Δm^2_{14}]

Preliminary	**Uncertainty**	
Type	**Phase-II**	**Phase-III**
Uncorrelated normalization • Cell volume • Neutron efficiency correction	 0.83% 1.13%	 0.83% 1.13%
Uncorrelated energy scale • Mn Anchor point • Cell-to-cell deviations	 0.2% 1.0%	 0.3% 1.0%
Correlated energy scale • Time stability	 0.3%	 0.3%

➢ Data fitted with the formula:

$$\chi^2(\boldsymbol{\mu},\boldsymbol{\alpha},\boldsymbol{\varphi}) = \sum_l^{N_{Cells}} \sum_i^{N_{Bins}} \left(\frac{D_{l,i} - \varphi_i M_{l,i}(\boldsymbol{\mu},\boldsymbol{\alpha})}{\sigma_{l,i}}\right)^2 + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{NormU}}{\sigma_l^{NormU}}\right)^2$$

$$+\left(\frac{\alpha^{EscaleC}}{\sigma^{EscaleC}}\right)^2 + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{EscaleU}}{\sigma_l^{EscaleU}}\right)^2 + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{ReacBkg}}{1}\right)^2$$

Where $\boldsymbol{\alpha}$ parameterizes the systematic effects

M_l : Simulated spectra

$$M_{l,i}(\boldsymbol{\mu},\boldsymbol{\alpha}) = T_{l,i}(\boldsymbol{\mu}) * (1 + R_{l,i} * \alpha_l^{ReacBkg} + \alpha_l^{NormU} + S_{l,i}^{Escale}(\boldsymbol{\mu}) * (\alpha^{EscaleC} + \alpha_l^{EscaleU}))$$

D_l: Data spectra

T_l: Huber-Mueller simulated spectra

$\boldsymbol{\varphi}$: Free parameters common to all cells (removes prediction dependence)

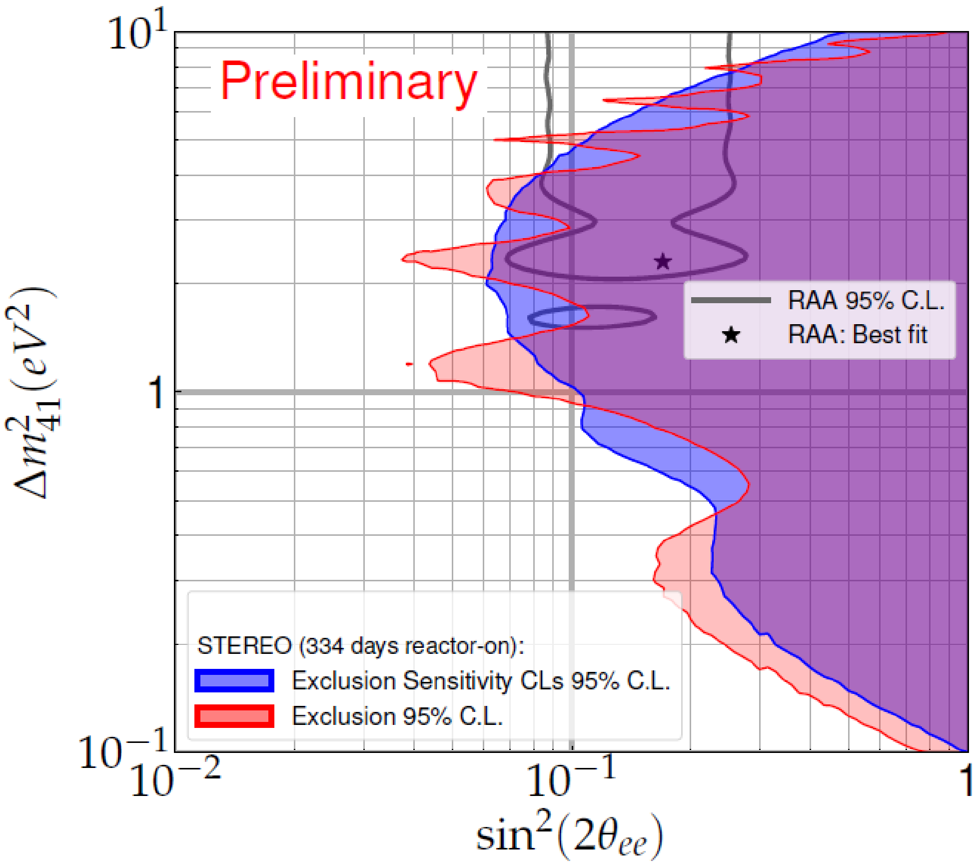
➢ Combination of the 3 phases:

$$\chi^2_{PI+PII+PIII} = \chi^2_{PI}(\boldsymbol{\mu},\boldsymbol{\varphi},\boldsymbol{\alpha_{PI}}) + \chi^2_{PII}(\boldsymbol{\mu},\varphi,\boldsymbol{\alpha_{PII}}) + \chi^2_{PIII}(\boldsymbol{\mu},\varphi,\boldsymbol{\alpha_{PIII}})$$

Oscillation analysis: Results

New Preliminary results obtained with full dataset (Phase-I+II+III)

- CLs method used
- $\Delta\chi^2$ distributions estimated with pseudo-experiments
- No-oscillation hypothesis p-value = 0.17 **(not rejected)**
- RAA best fit rejected at **more than 4σ**



Conclusion and perspectives

STEREO preliminary results including Phase-III:

- Oscillation analysis:
  - Exclusion of a great part of the RAA acceptance area
  - RAA best fit excluded at more than 4σ
- Pure ^{235}U spectrum shape analysis:
  - Confirmation of a significant « Bump » (A≈10%) around 5 MeV, similar to the event excess reported by LEU experiments
  - Joint analysis with PROSPECT experiment (arXiv:2107.03371) could be improved by the addition of Phase-III data

The STEREO Collaboration

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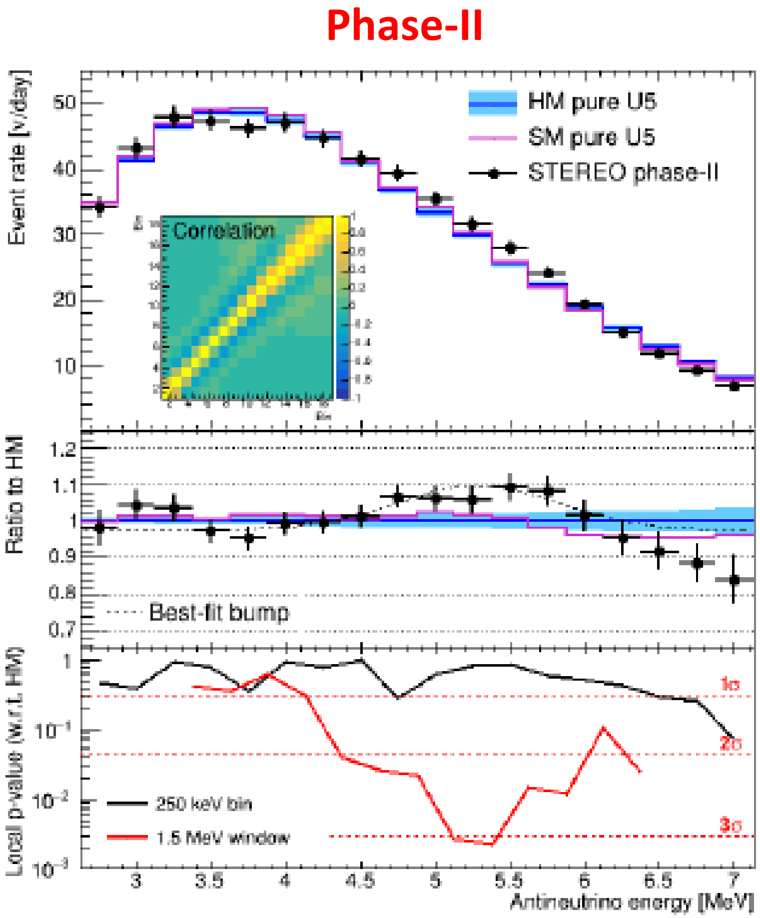
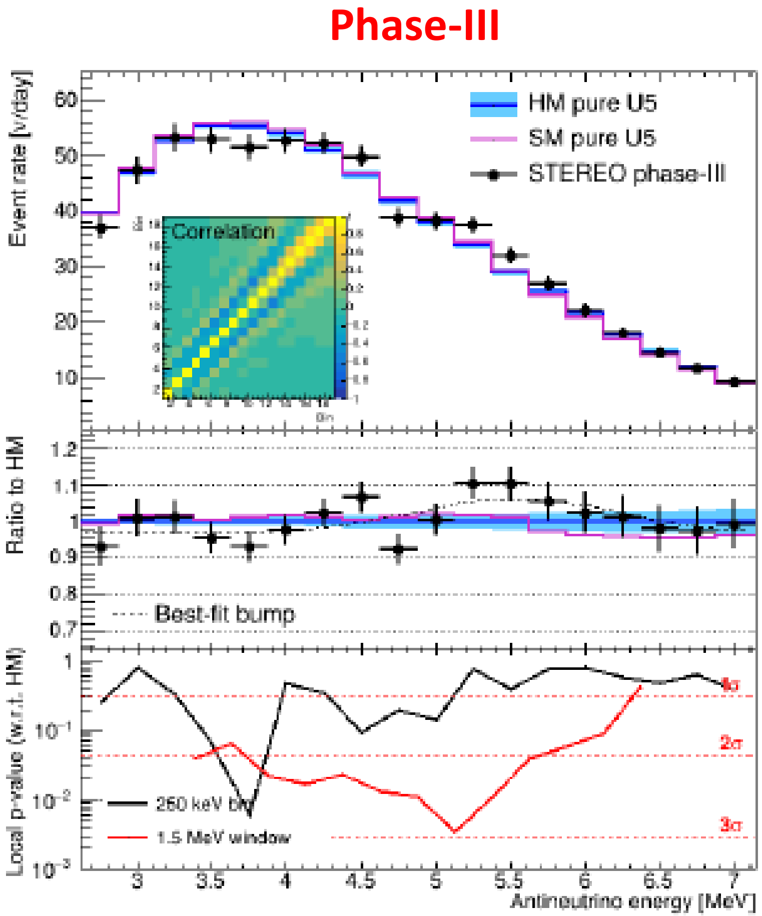
Back-up

STEREO shape analysis: separated phases

Unfolded spectra of the two phases separately:





- **Significant excess** of events observed around 5.4 MeV w.r.t Huber for the two phases
- Observed excesses are compatible

Oscillation analysis: norm difference

- Possible systematic **difference of normalisation** between phases:
  - Phase-I: no precise information on the norm ⇒ **completely free** term A added to the formula to adjust the normalisation difference w.r.t Phase-III
  - Phase-II: normalisation precisely determined ⇒ **constrained term** B added as a systematic error
- Fit formula:

$$\chi^2(\boldsymbol{\mu},\boldsymbol{\alpha},\boldsymbol{\varphi}) = \sum_{l}^{N_{Cells}} \sum_{i}^{N_{Bins}} \left(\frac{D_{l,i} - A\varphi_i M_{l,i}(\boldsymbol{\mu},\boldsymbol{\alpha})}{\sigma_{l,i}}\right)^2 + \sum_{l}^{N_{Cells}} \left(\frac{\alpha_l^{NormU}}{\sigma_l^{NormU}}\right)^2$$

$$+\left(\frac{\alpha^{EscaleC}}{\sigma^{EscaleC}}\right)^2 + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{EscaleU}}{\sigma_l^{EscaleU}}\right)^2 + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{ReacBkg}}{1}\right)^2 + \left(\frac{B}{\sigma_B}\right)^2$$

- Simulated spectra formula:

$$M_{l,i}(\boldsymbol{\mu},\boldsymbol{\alpha}) = T_{l,i}(\boldsymbol{\mu}) * (1 + R_{l,i} * \alpha_l^{ReacBkg} + \alpha_l^{NormU} + S_{l,i}^{Escale}(\boldsymbol{\mu}) * (\alpha^{EscaleC} + \alpha_l^{EscaleU}) + B)$$