Search for a light sterile neutrino with the STEREO experiment

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On the behalf of the STEREO collaboration

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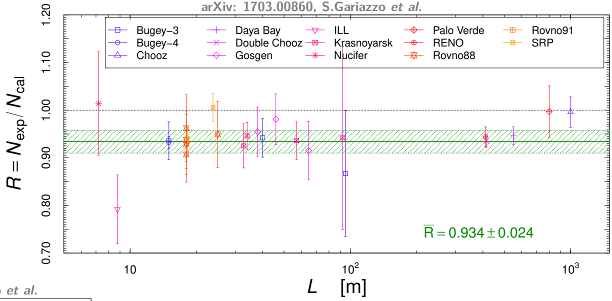
STEREO motivations: short distance anomalies

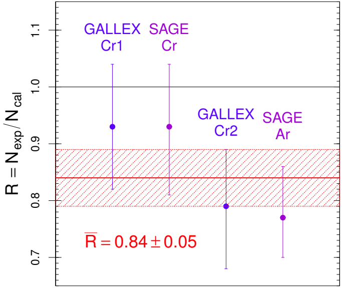
Reactor antineutrino anomaly (RAA) :

deficit at $2.8\,\sigma$ in $\bar{\nu}_e$ flux measured by several experiments at different distances from reactors

arXiv: 1703.00860, S.Gariazzo *et al.*



arXiv: 1507.08204, S.Gariazzo *et al.*



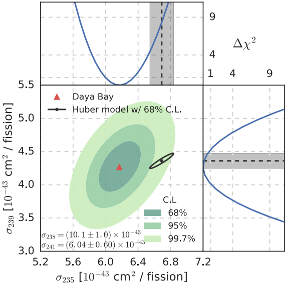
"Gallium" anomaly : ν_e deficit at $2.9\,\sigma$

in ν_e counting with calibration sources inside the SAGE and GALLEX solar neutrino detectors

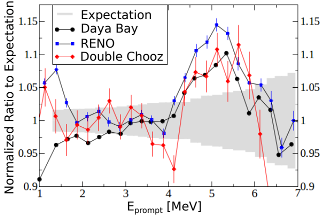
Bias in the prediction of reactor antineutrino spectrum

Possible explanation of the RAA Anomaly: bias in the predicted norm of the antineutrino flux

arXiv:1704.01082, Daya Bay Collaboration



A.Hayes, Neutrino 2018



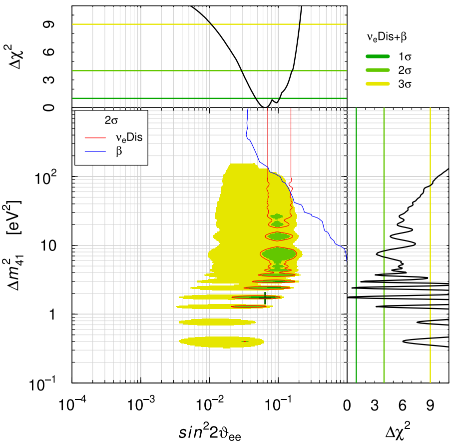
- Discrepancy between observed and predicted IBD yields from ^{235}U by Daya Bay suggests ^{235}U **could be** the primary contributor of the RAA
- Excess in the reactor antineutrino spectra observed between 4 MeV and 6 MeV by Double Chooz, RENO, Daya Bay and NEOS

Need to improve reactor antineutrino spectrum prediction with new measurements.

Light sterile neutrino oscillation ?

A **sterile neutrino** could explained deficits of Gallium and RAA anomalies : $P_{ee} = 1 - \sin^2(2\theta_{ee}) \sin^2\left(1.27 \frac{\Delta m^2_{41}\,[\text{eV}^2] \cdot L\,[\text{m}]}{E\,[\text{MeV}]}\right)$

arXiv: 1703.00860, S.Gariazzo *et al.*

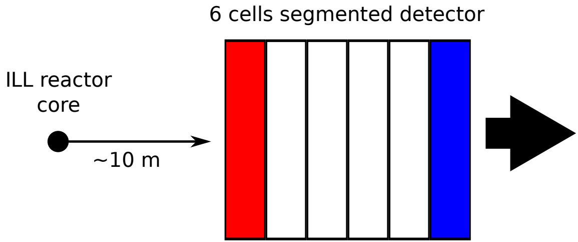


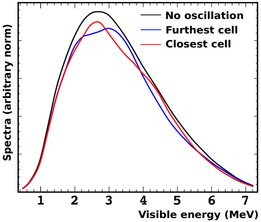
- Combined analysis of data :
  - reactor and gallium anomalies
  - Troisk and Mainz experiment, constrains on the absolute neutrino mass
- Best fit :

  $\Delta m^2_{41} = 1.7$ eV^2 et $\sin^2(2\theta_{ee}) = 0.066$

The STEREO experiment

arXiv:1804.09052, STEREO Collaboration





1- Designed to probe the RAA region by measuring **relative distortions** of the $\bar{\nu}_e$ energy spectrum as a function of the distance [9-11m]

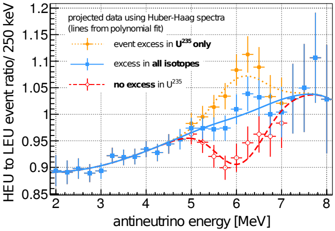
✓ **Independent from predicted energy spectrum**

2- Measurement of a **pure ^{235}U $\bar{\nu}_e$ energy spectrum**

→ Help to understand Daya Bay results

→ Could indicate if the bump is related to ^{235}U

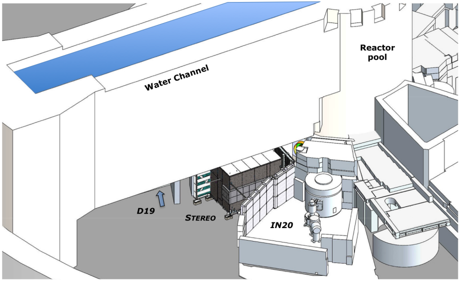
arXiv:1512.06656, C. Buck et al



Experimental site ILL research facility, Grenoble, France

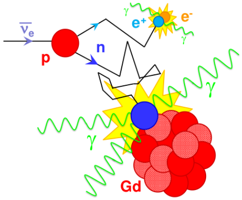
Research reactor core $\sim 58\,\text{MW}_{th}$
$\rightarrow 10^{19}\ \bar{\nu}_e\ s^{-1}$

- ✓ **Compact** core (40cm ∅)
- ✓ **Highly enriched ^{235}U**
- ✓ **Short baseline** measurement: $8.9\text{m} < \text{L}_{core} < 11.1\text{m}$



- × **Surface-level** experiment (15 m.w.e. only thanks to water channel)
- × **γ and neutron background** from neighboring experiments

Detection principle and detector design



ν detection via IBD in liquid scintillator : $\bar{\nu}_e + p \rightarrow e^+ + n$

Prompt signal - e^+ thermalization + annihilation

$$\Rightarrow E_{vis}^{\text{Prompt}} = E_\nu - 0.782\,\text{MeV}$$

Delayed signal - n-capture on gadolinium (Gd)

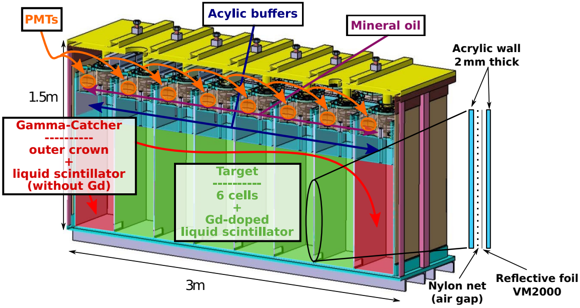
- $\sim 3\,\gamma$ emission for a total of 8 MeV
- neutron lifetime: $[0 - 100]\mu$s

Two sub-volumes : filled with liquid scintillator

- **Target** (for IBD) segmented in 6 identical cells
- **Gamma-catcher** to collect escaping gamma, improve efficiency and energy resolution

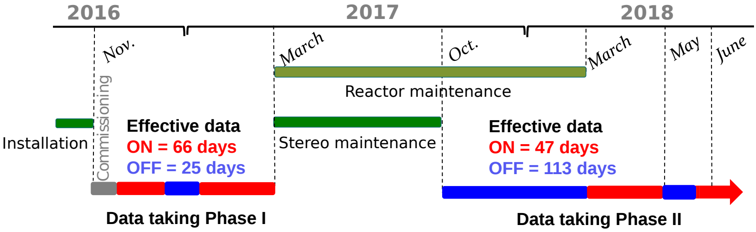
48 PMTs:

- 4 PMTs per Target cell
- 4 or 8 PMTs per Gamma-catcher cell



Data taking

STEREO is running since Nov. 2016



Physics runs: **$\sim$95% of data taking time**

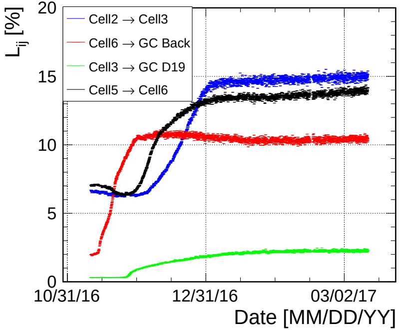
Phase-I:

- Buffer leaks: loss of optical coupling between PMTs and liquid, for one Target cell and one Gamma-Catcher cell
- Acrylic wall cracks: loss of total reflection of cell walls

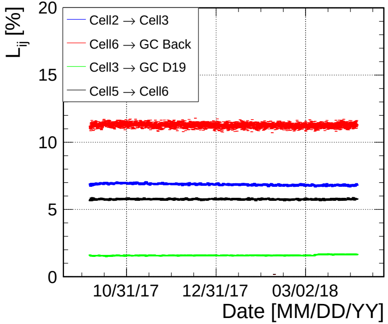
$\rightarrow$ **repaired during summer 2017**

Detector response: light cross-talk evolution

Phase I:



Phase II:



- Evolution of light cross-talk between cells

  ⇒ liquid slowly infiltrating into acrylic walls

- Stable conditions

  ⇒ detector repaired

Detector response: calibration

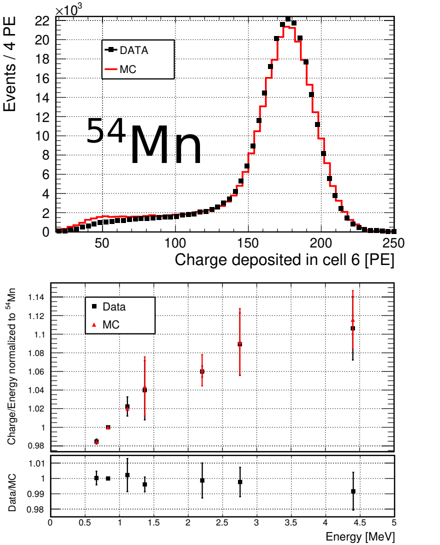
- **Monitoring of liquids/electronics:** **LED measurement**: PMT gain, liquid stability, electronics linearity (non-linearity $< 1\%$)

- **Monitoring of the energy response:** Internal and external calibrations using **radioactive sources** $\mathrm{Ge}^{68}, \mathrm{Sb}^{124}, \mathrm{Cs}^{137}, \mathrm{Mn}^{54}, \mathrm{Zn}^{65}, \mathrm{Na}^{24}, \mathrm{H}^{1}(n,\gamma)$

- **Monitoring of the neutron capture efficiency:** Using dedicated AmBe source

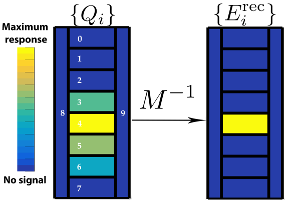
→Tuning of the MC simulation of the detector: Light collection, liquid properties, non linearity (k_b)

Good agreement MC/data



Energy reconstruction

- **Energy reconstruction** takes into account:
  - Light cross-talk
  - Evolving properties along time: light collection and cross-talk



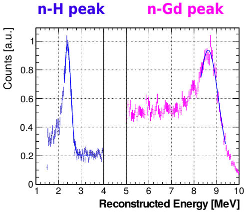
$$\begin{pmatrix} E_0 \\ E_1 \\ \vdots \\ E_9 \end{pmatrix} = M^{-1} \begin{pmatrix} Q_0 \\ Q_1 \\ \vdots \\ Q_9 \end{pmatrix}$$

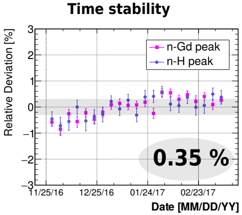
Light cross-talk coefficient

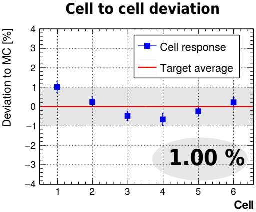
$$M_{ij} = C_i L_{ij}$$

Calibration coefficient (photoelectrons/MeV)

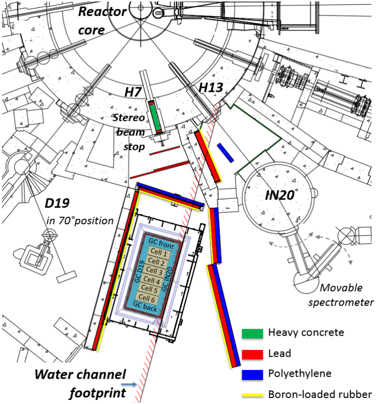
- **Stability of the reconstructed n-H & n-Gd peaks** (whole target volume) and **deviation to MC**





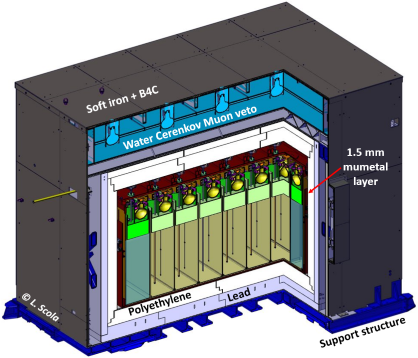


Shielding against background



Cosmic background:

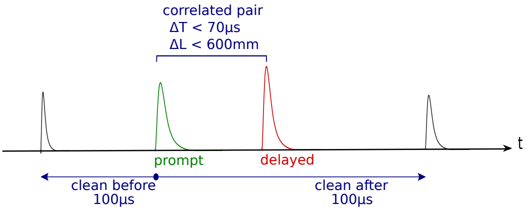
- Detector under the water channel: 15 m.w.e.
- Muon veto: water Cherenkov detector



Gammas and neutrons:

- heavy concrete
- lead
- boron (B4C)
- (borated-)polyethylene

Neutrino selection and correlated background



IBD events:

- $1.6\,\mathrm{MeV} < \mathrm{E}_{\mathrm{prompt}} < 7.1\,\mathrm{MeV}$
  Prompt contained in a target cell and its 4 neighbouring cells
- $4.5\,\mathrm{MeV} < \mathrm{E}_{\mathrm{delayed}} < 10\,\mathrm{MeV}$

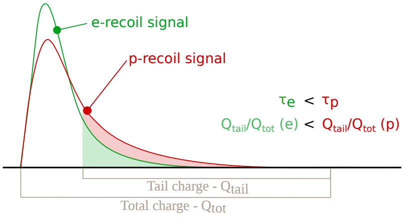
Cosmic background rejection:

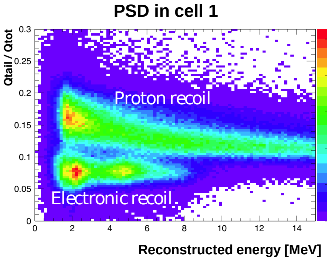
- **Muons:**
  Veto of 100μs after each detected muon
- **Fast neutrons / multiple neutron captures:**
  Isolation cut of 100μs after and before prompt
- **Stopping muons:** at the top of the detector
  Cut high asymmetry of the light collection in the vertex cell

Accidental pairs: estimated with shifted time windows for the delayed search

Pulse shape discrimination (PSD)

Pulse Shape Discrimination for prompt signal

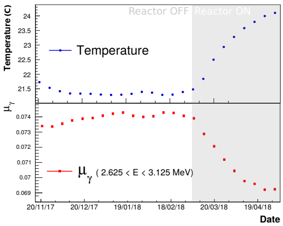




PSD follows temperature changes

- Temperature changes and with seasons and when reactor going on or off (lasting for several weeks)

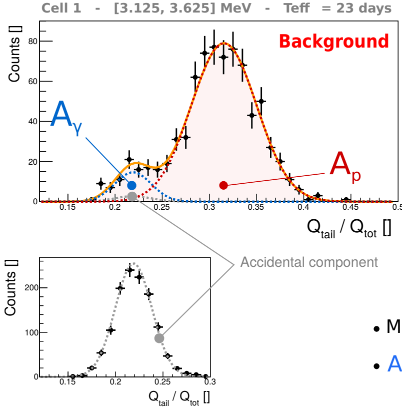
- A PSD cut does not permit to have at the same time:
  - a constant neutrino acceptance
  - a constant background rejection



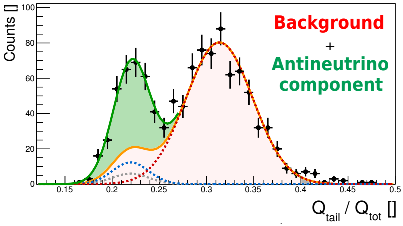
→ Solution: fit PSD distributions to extract neutrino rates

$\bar{\nu}_e$ signal extraction: from PSD distributions

OFF periods → background model



ON periods → neutrino extraction



- Multi-Gaussian fit for each cell / energy / time bin
- A_γ/A_p ratio constrained by the OFF model

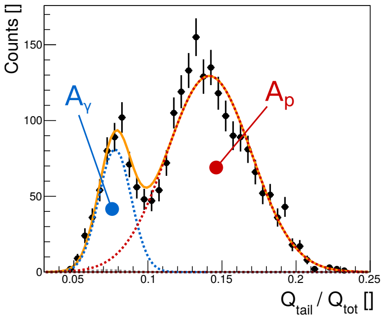
Coherent method to estimate background under $\bar{\nu}_e$ component:

- No assumption on PSD stability (temperature sensitivity)
- No assumption on global norm (pressure sensitivity)

$\bar{\nu}_e$ signal extraction: phase-2

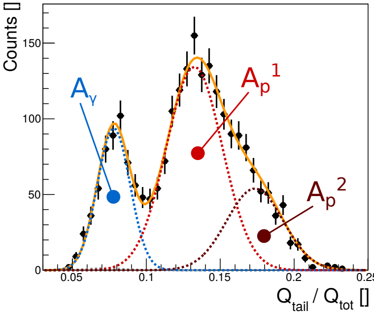
OFF period of phase-II:

- 84 days (t_{eff}) with **more stable** conditions → increased statistics (larger time binning)



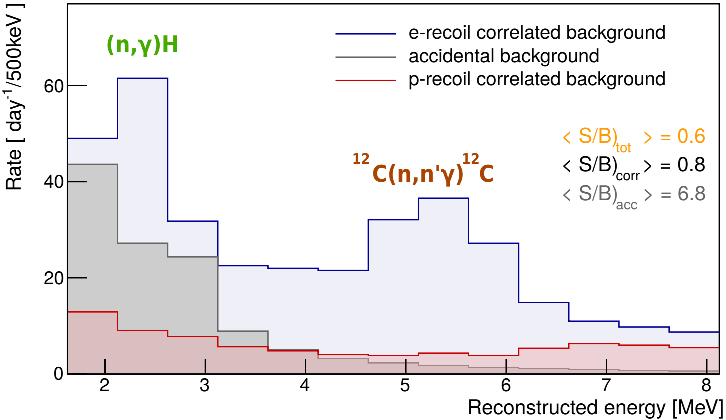
Updated background model

Additionnal gaussian (multiple proton recoils hypothesis (under study))



Background spectrum

Prompt energy spectrum in the region of interest



Relative comparison of ν energy distributions

Compare measured and simulated **ratios of energy distributions** - **cell 1 taken as reference**

- Insensitive to absolute flux normalization
- Insensitive to predicted spectrum shape

$$R_{i,j}^{\text{Data}} = \frac{\text{Data}_{i,j}}{\text{Data}_{i,ref=1}} \quad \text{compared with} \quad R_{i,j}^{\text{MC}} = \frac{\text{MC}_{i,j}}{\text{MC}_{i,ref=1}}$$

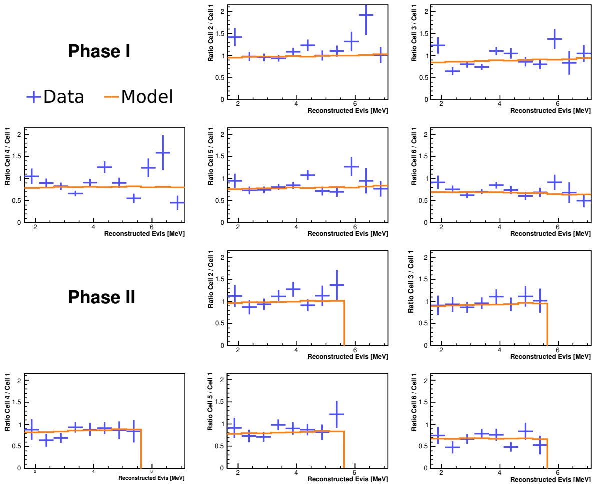
$$\chi^2 = \sum_{i=1}^{N_{\text{Ebins}}} \left(\overrightarrow{R_i^{\text{Data}}} - \overrightarrow{R_i^{\text{MC}}}(\alpha) \right)^t V_i^{-1} \left(\overrightarrow{R_i^{\text{Data}}} - \overrightarrow{R_i^{\text{MC}}}(\alpha) \right) + \sum_{j=1}^{N_{\text{Cells}}} \left(\frac{\alpha_j^{\text{Norm}}}{\sigma_j^{\text{Norm}}} \right)^2 + \sum_{j=0}^{N_{\text{Cells}}} \left(\frac{\alpha_j^{\text{Escale}}}{\sigma_j^{\text{Escale}}} \right)^2$$

V_i is the **covariance matrix** of the 5 ratios (common reference for each cell) for the energy bin i
$\{\alpha\}$ are nuisance parameters to take into account estimated **systematics**

	Cell-to-cell correlated	Uncorrelated	
Energy scale σ_j^{Escale}	0.35 %	1.00 %	from energy scale
Normalization σ_j^{Norm}	-	1.70 %	from neutrino efficiencies

Non oscillation hypothesis test

Ratio method: cell 1 taken as reference



- Minimized pull terms stay within $\pm 1\,\sigma$

- **Non-oscillation hypothesis (H_0) can not be rejected:**

  p-value = 40 % for phase-I+II

Exclusion contours Phase-I+II combined

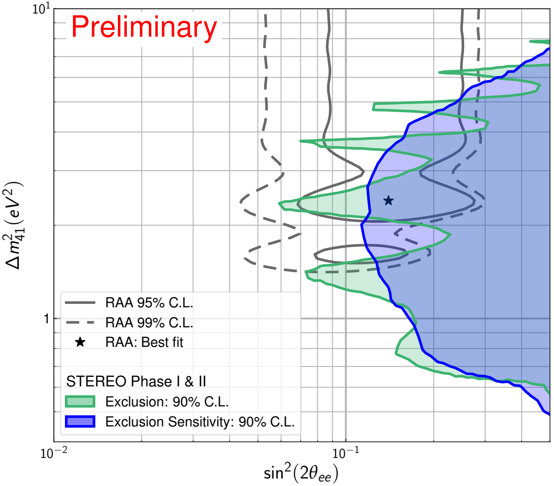
- **Phase-I + Phase-II combined results**
  (66+47) days reactor-ON
  (396 ± 4) $\bar{\nu}_e$ day^{-1}

  Considered as two **independent measurements**:
  $\chi^2 = \chi^2_I(\overrightarrow{\alpha_I}) + \chi^2_{II}(\overrightarrow{\alpha_{II}})$
  $\overrightarrow{\alpha_I} \neq \overrightarrow{\alpha_{II}}$

- **Raster-scan** approach (Δ^2_m slices)

- $\Delta\chi^2$ distributions estimated by MC pseudo experiments

- Best-fit value of the **RAA rejected at 98 % C.L.**



Conclusions and perspectives

- STEREO is now running under **very stable conditions**
- The **correlated background understanding improves** using reactor-OFF periods
- Exclusion contour obtained, original RAA best fit value is rejected at 98% CL using a **ratio comparison** insensitive to bias in spectra prediction **(arXiv:1806.02096)**
- Next step: extract a **pure ^{235}U spectrum**
- Data taking will continue until end 2019, reaching **300 days of reactor-ON data**

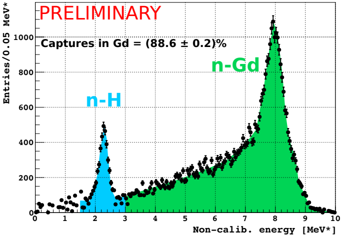
∼ Thanks for your attention ! ∼

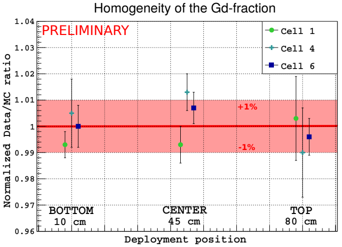
Backup

Neutron detection efficiency

Am-Be neutron source in target cells :

- n-capt time from AM-Be in agreement with IBD candidates
- Relative variations of n efficiency in agreement between MC and data
- Absolute fraction of Gd-capture fine-tuned in MC : determination of the glocal n-capture efficiency





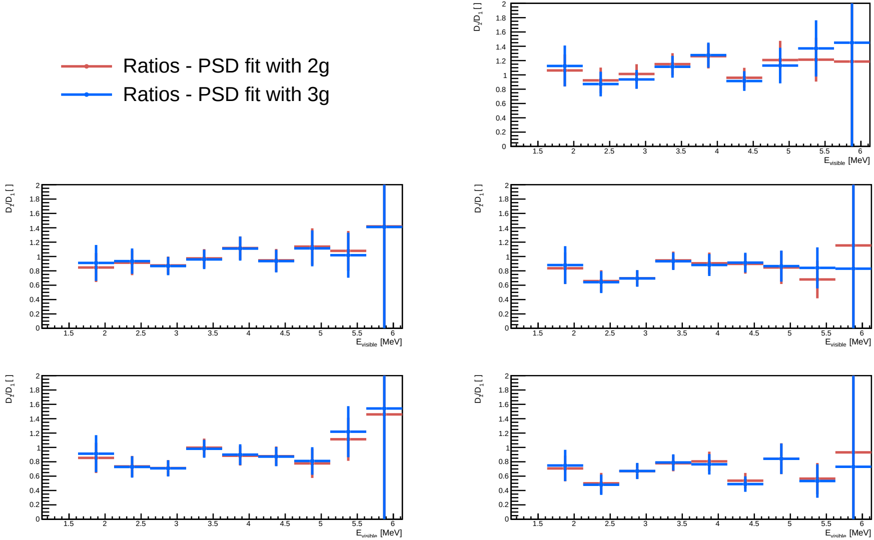
Systematics

Source	**Contrib to $\sigma^{NormUncor}_{Cell}$**
Cell volume	0.85 %
n-capture efficiency	1.20 %
Asym cut efficiency	0.50 % (3% cell4)
$D_{p\text{-}d}$ cut efficiency	0.50 %
Annihilation cut efficiency ($E_{j\neq vertex}$<0.8 MeV)	0.50 %
TOTAL	**1.7 % (3.4 % cell4)**

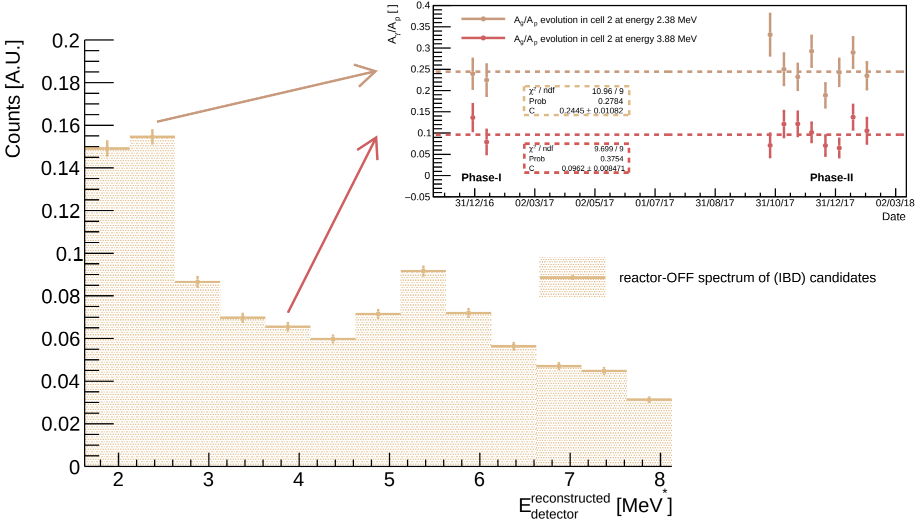
Source	**Contrib to σ^{Escale}**
Escale correlated	0.35 %

Source	**Contrib to σ^{Escale}_{Cell}**
Escale uncorrelated	1.50 %

PSD extraction: 2 gaussians model vs 3 gaussians model



Stability of the A_p/A_γ ratio



Evolution of A_p and A_γ with atmospheric pressure

- $\mathcal{A}_\gamma/\mathcal{A}_p$ **compatible with a constant** in all cell/energy bin
- Same correlation with atmospheric pressure for **e-recoils rates** and **p-recoils rates**