The STEREO experiment : a search for sterile neutrino ∼1eV at ILL

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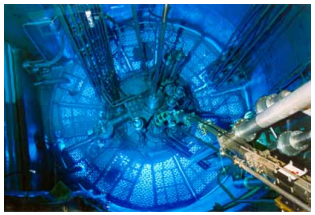
on behalf of the Stereo collaboration

supported by

Motivation : $\bar{\nu}_e$ disappearance

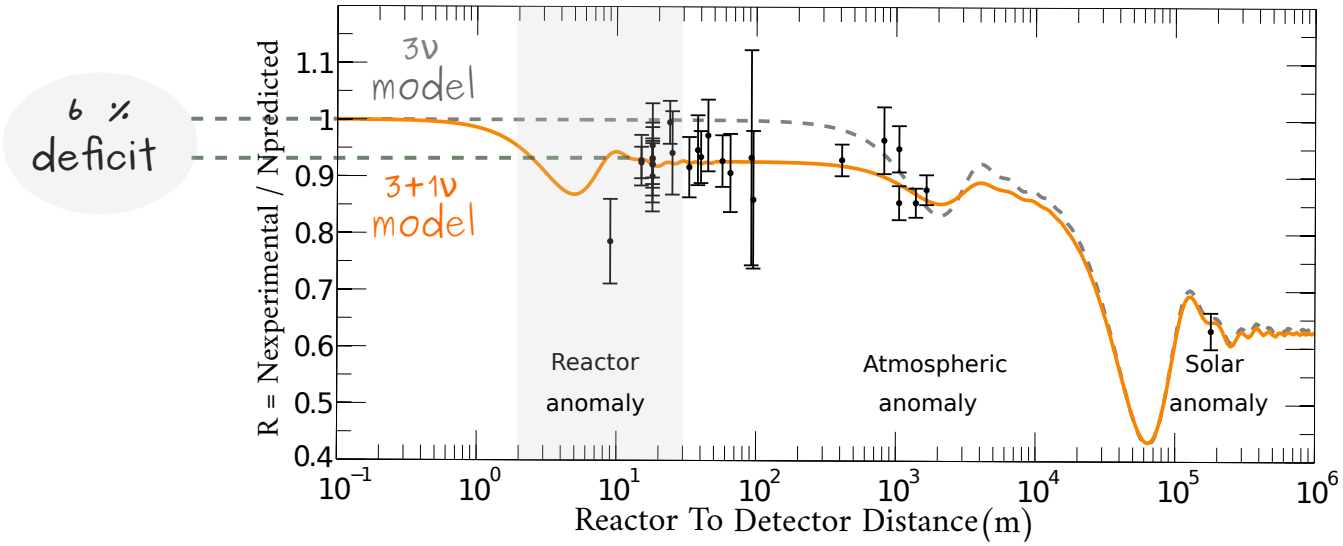
Phys.Rev.D83:073006 (2011)



2011: reevaluation of the $\bar{\nu}_e$ reactor flux prediction

→ **Reactor Antineutrino Anomaly :** All reactor short-baseline experiments are observing a deficit (very accurate measurements : Daya Bay, RENO & Double Chooz)

- Wrong prediction ?
- Sterile neutrino ?



$$P_{\bar{\nu}_e \to \bar{\nu}_e}(E_{\bar{\nu}_e}, L) = 1 - \sin^2(2\theta_{new}) \sin^2\left(1.27 \frac{\Delta m^2_{new}[eV^2] L[km]}{E_{\bar{\nu}_e}[MeV]}\right)$$

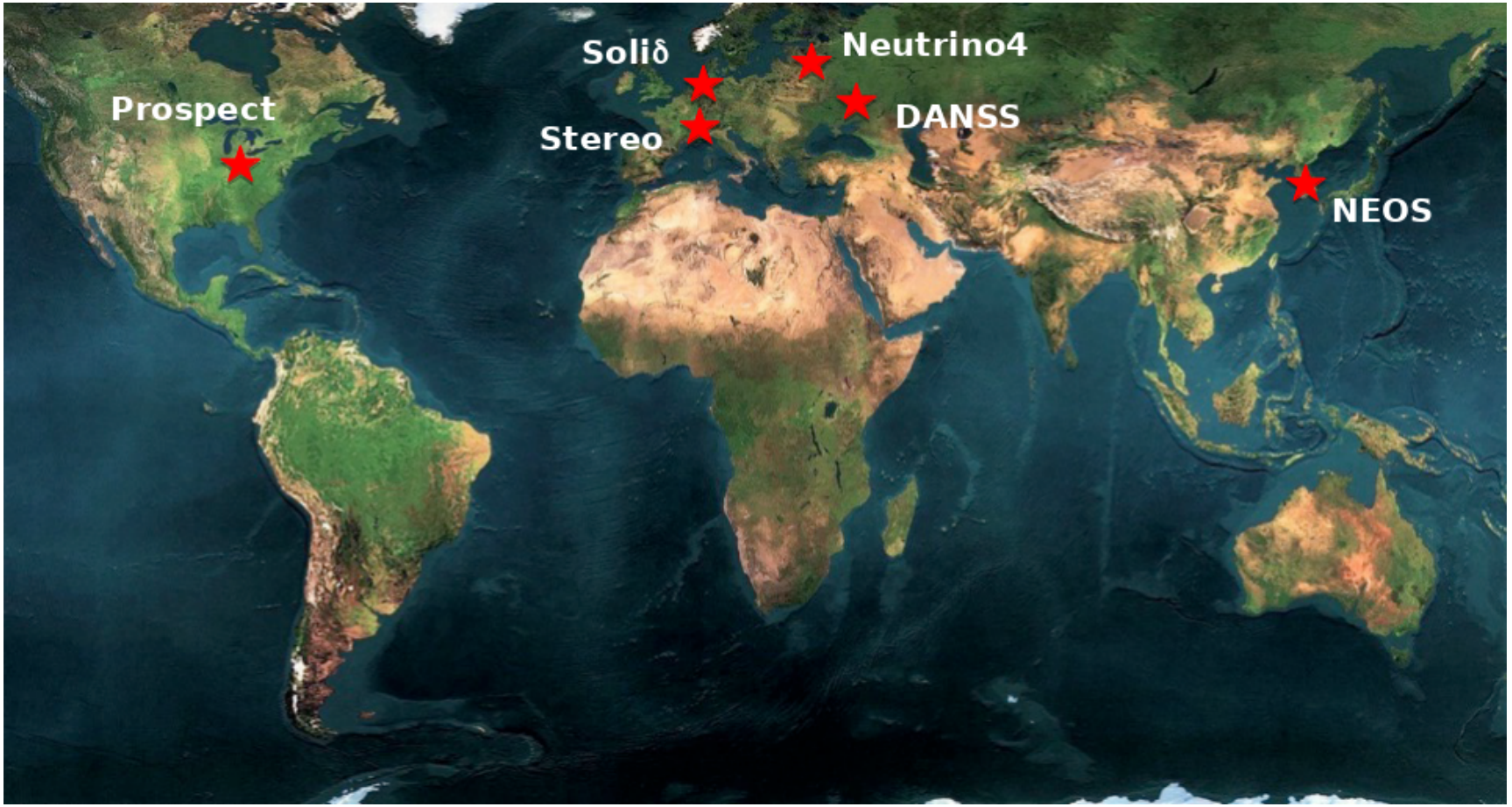
$\sim$ 1eV sterile neutrino

→ **Need dedicated measurements**

A quest for a sterile neutrino in the eV range

More exactly, we need ...

- Non-ambiguous measurements to sign the existence -or not- of a light sterile neutrino
- Accurate energy measurements to constrain antineutrinos spectra



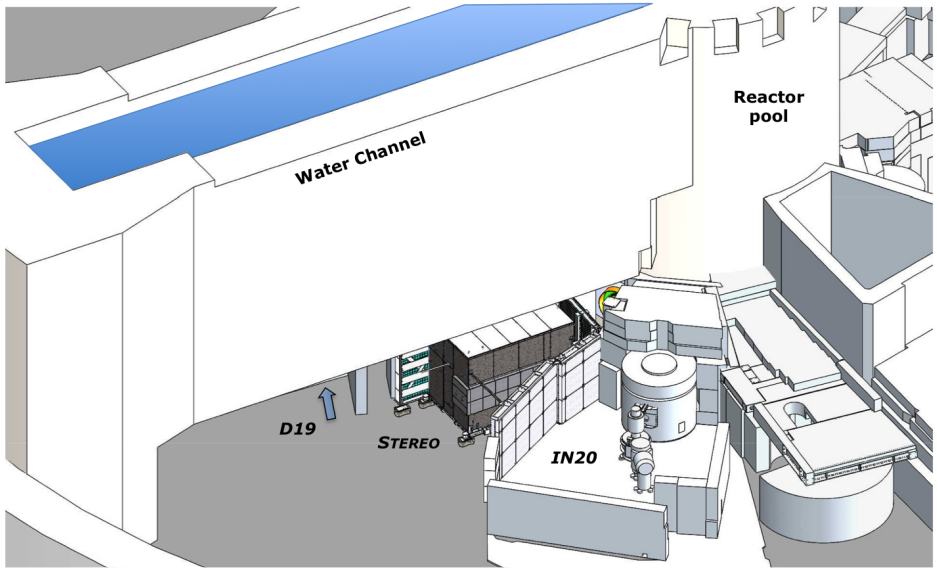
Experimental site
ILL research facility, Grenoble, France

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

✓ **Compact** core (40cm ∅)

✓ **Highly enriched** ^{235}**U**

✓ **Short baseline** measurement:
$8.9\mathrm{m} < \mathrm{L}_{core} < 11.1\mathrm{m}$

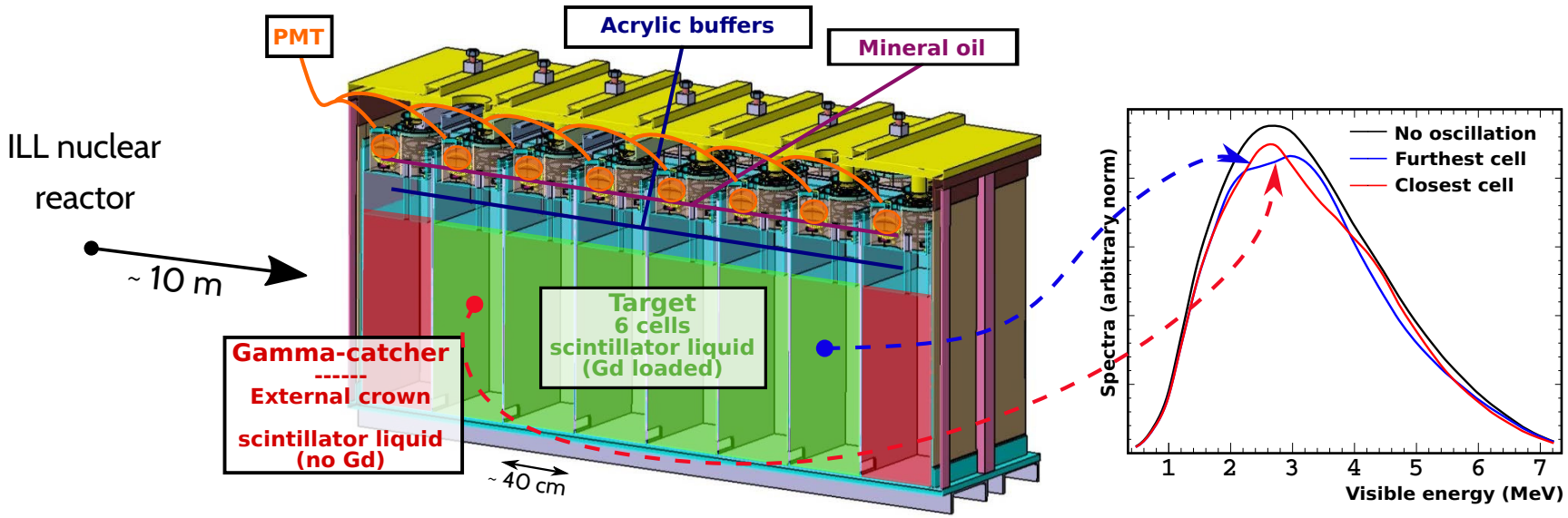


× **Surface-level** experiment (BUT 15 m.w.e only thanks to water channel)

× γ **and neutron background** from neighboring experiments

The STEREO experiment

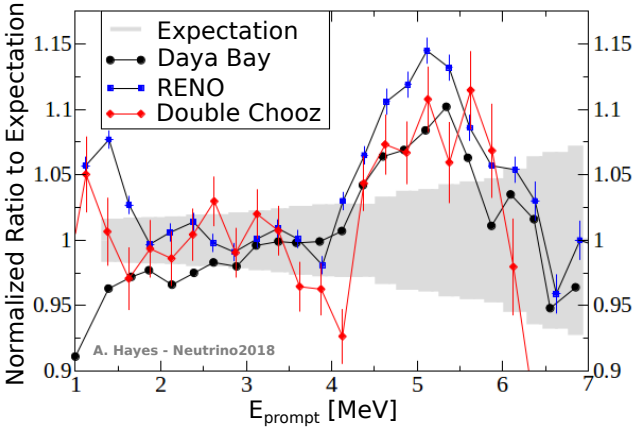
arXiv:1804.09052 (2018)



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]

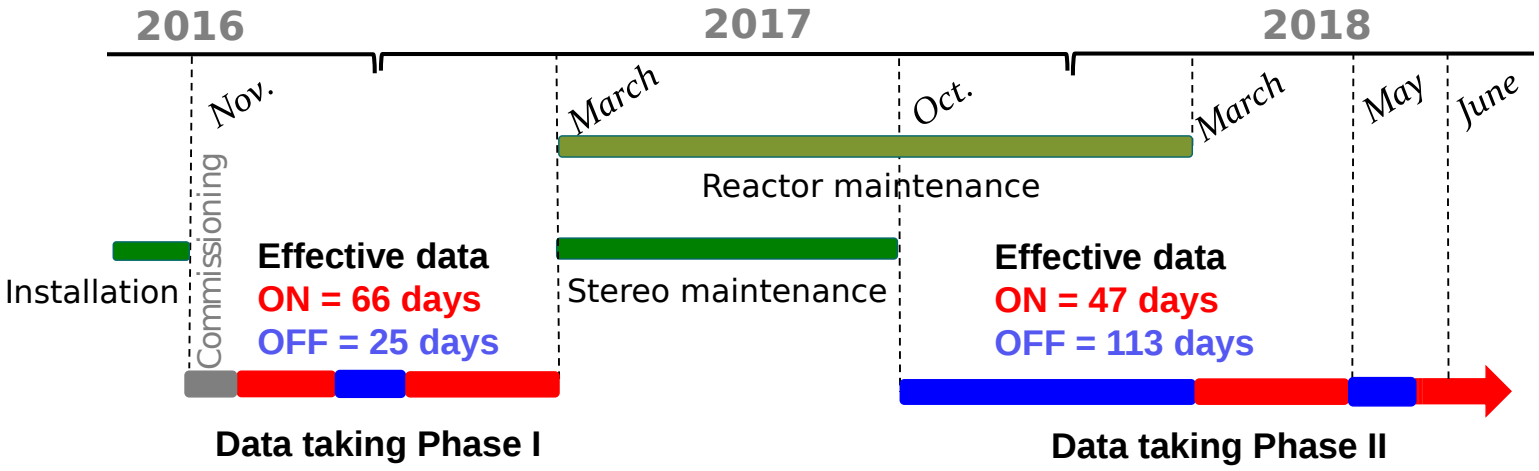
✓ **Independent from predicted energy spectrum** (norm. + shape)

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



Data taking

STEREO is running since Nov. 2016



Phase-I:

- Loss of optical coupling between PMTs and target for one target and on GC cell
- Evolving light cross-talks between cells

  $\rightarrow$ repaired during summer 2017

Phase-II:

- Stable conditions

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

Detector response

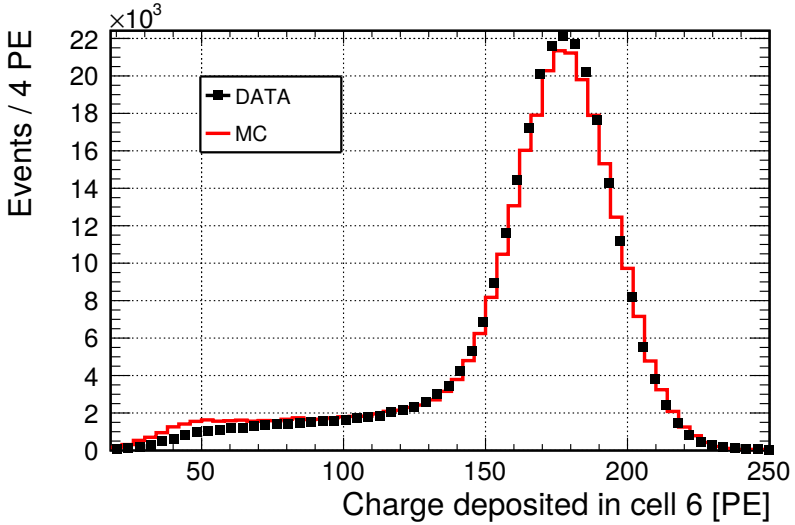
arXiv:1804.09052 (2018)

- **Monitoring of liquids/electronics:**
  Automatic daily **LED measurement**: PMT gain, liquid stability, electronics linearity

- **Monitoring of the energy response:**
  On a weekly basis: 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:**
  Using dedicated AmBe source

Good agreement MC/data (Mn^{54})



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

Energy reconstruction

arXiv:1804.09052 (2018)

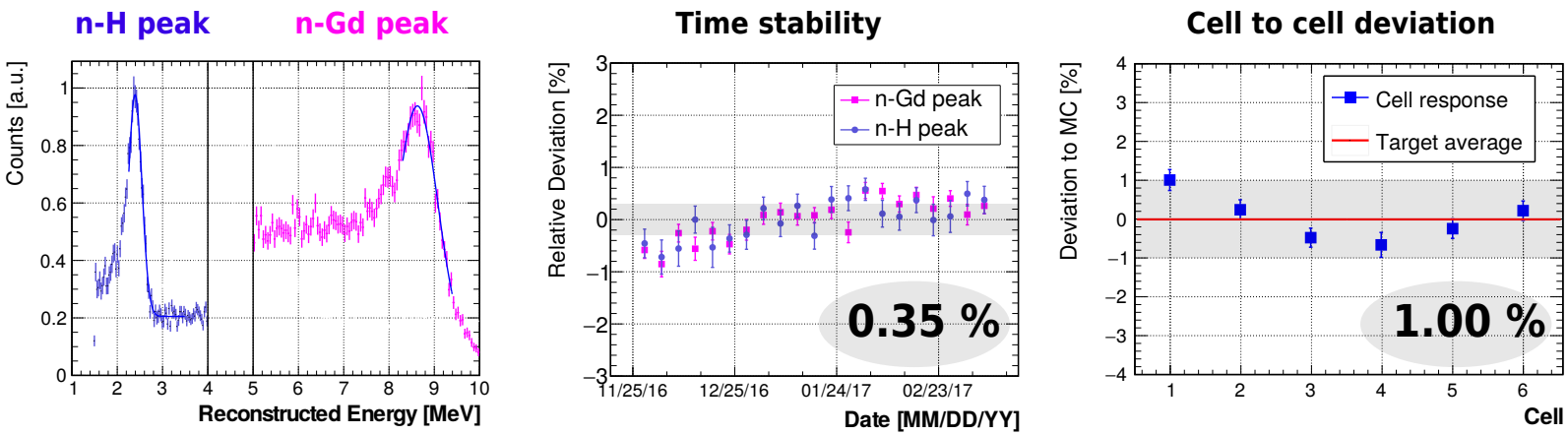
- **Tool developped** to take into account:
  - Light collection loss
  - Evolving light leaks along time

$$Q_i = \sum_{j=cells} E_j C_j L_{ji}$$

Collected photons/MeV from calib runs

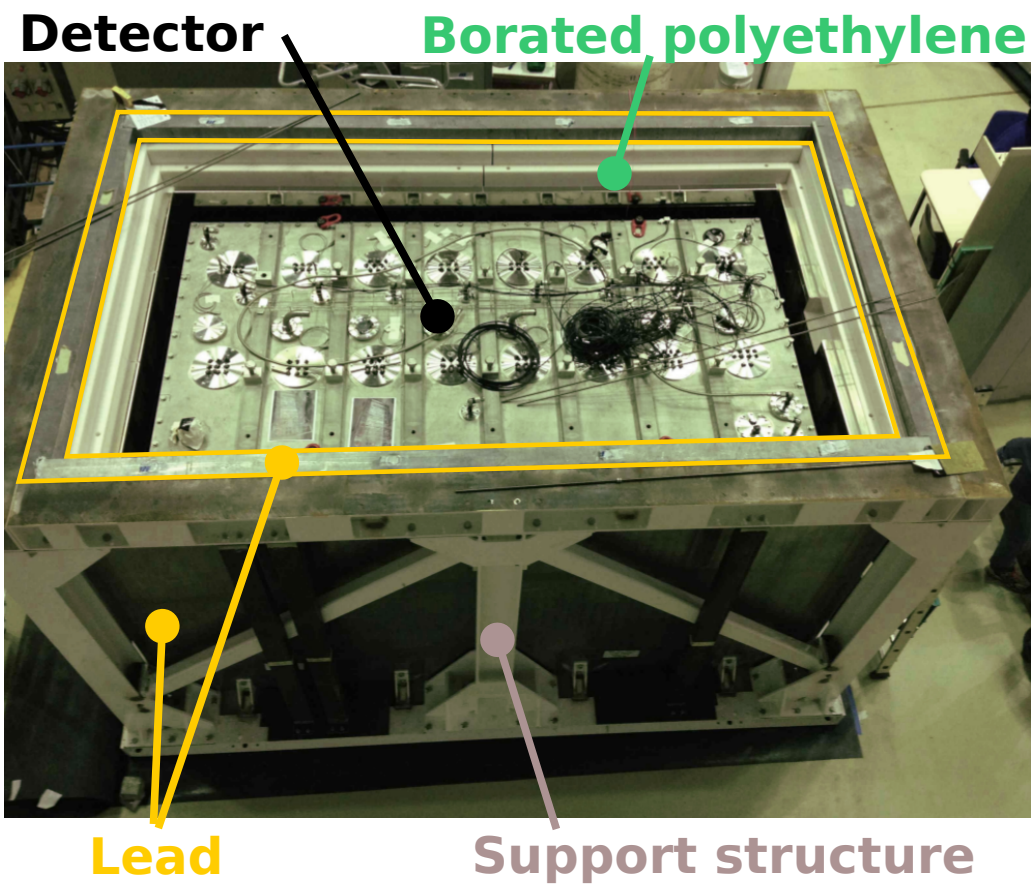
Light cross-talk between cells Measured online + calib

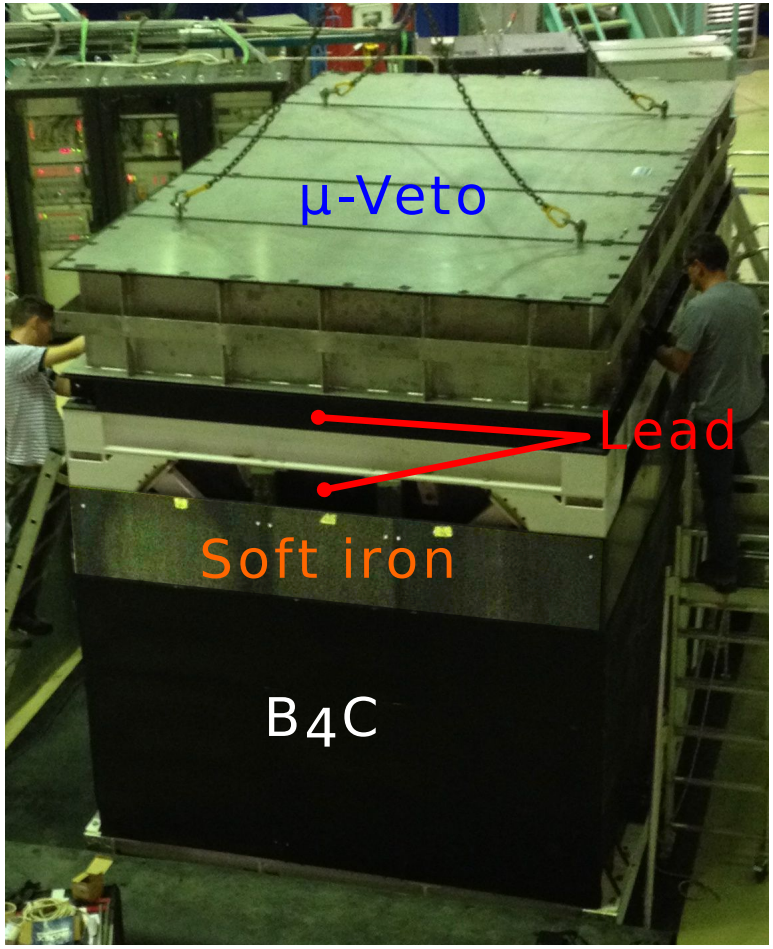
- **Stability of the reconstructed n-H & n-Gd peaks** (whole target volume) and **deviation to MC**



Shielding against background

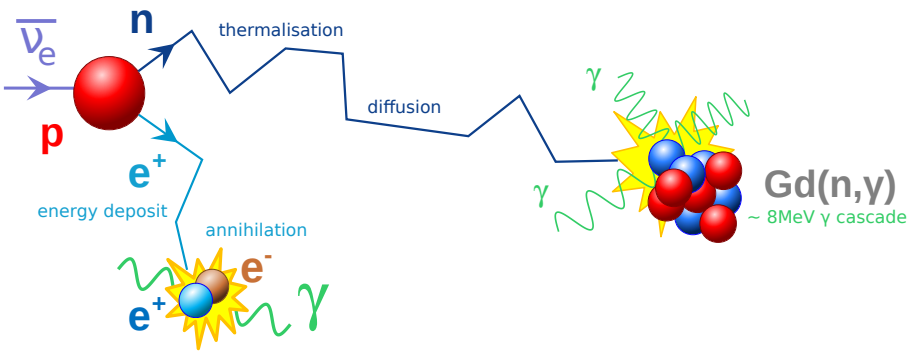
Passive and active shieldings against gamma, neutron and muon induced background

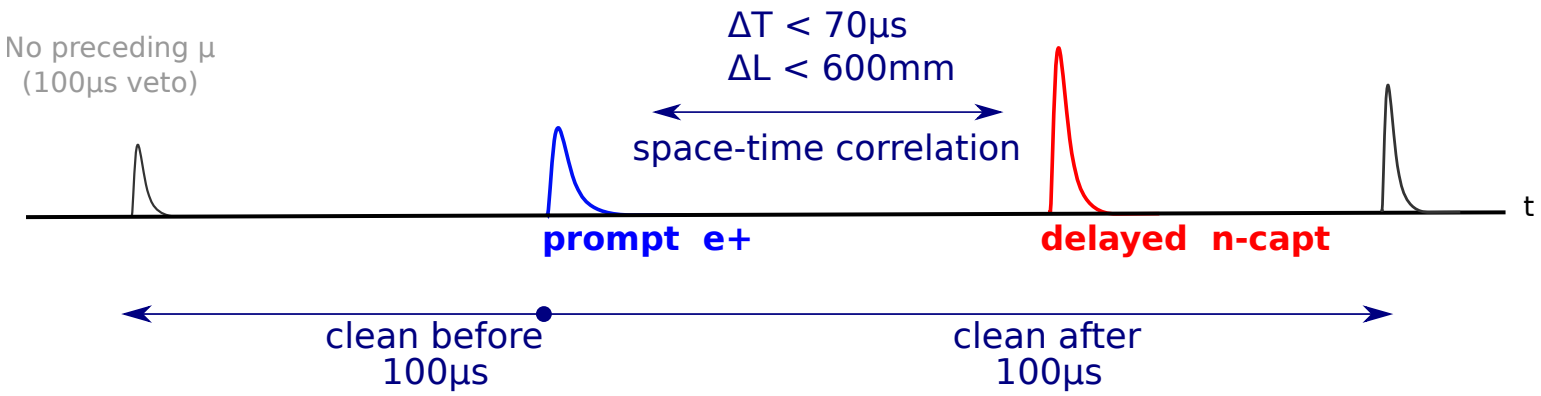




$\bar{\nu}_e$ signal selection

Inverse Beta Decay reaction





$1.6 < E_{prompt} < 7.1\,\text{MeV}$ $\quad$ $4.5 < E_{delayed} < 10\,\text{MeV}$

Prompt contained in vertex cell
and 4 neighbouring cells

Correlated background

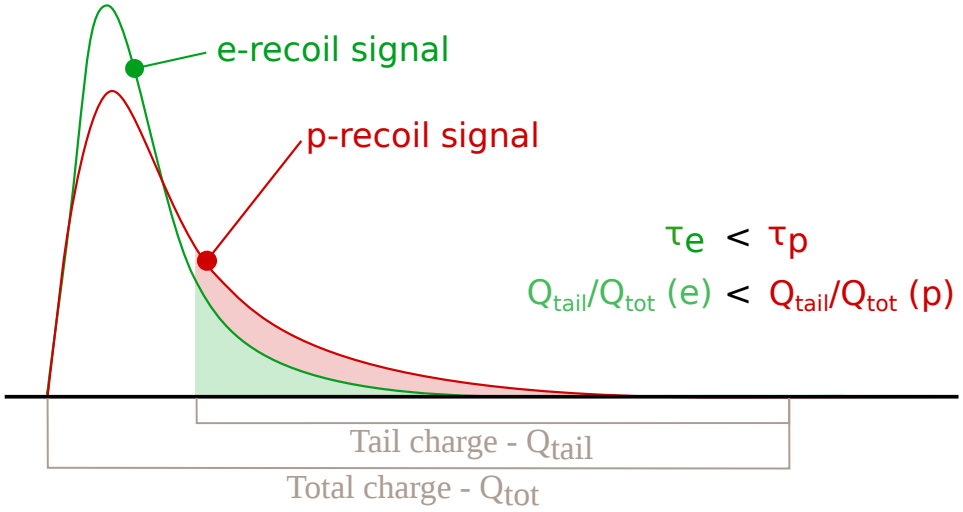
Neutron induced reactions:

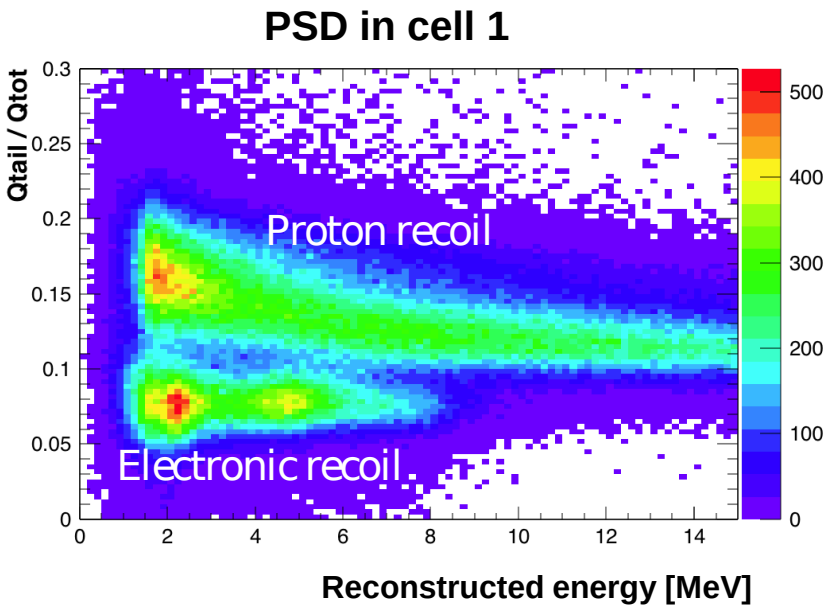
- **Fast neutrons**
  Prompt: proton recoil
- **Multiple neutron captures**
  Prompt: 2.2 MeV γ or a 8 MeV γ cascade from n-capt
- **^{12}C(n,n'γ)^{12}C** reactions
  Prompt: **mixing** between 4.4 MeV γ and proton recoil

Stopping muons:

Prompt: μ stop
Delayed: Michel $e^{+/-}$
✓ Mainly rejected by asymmetry based cut

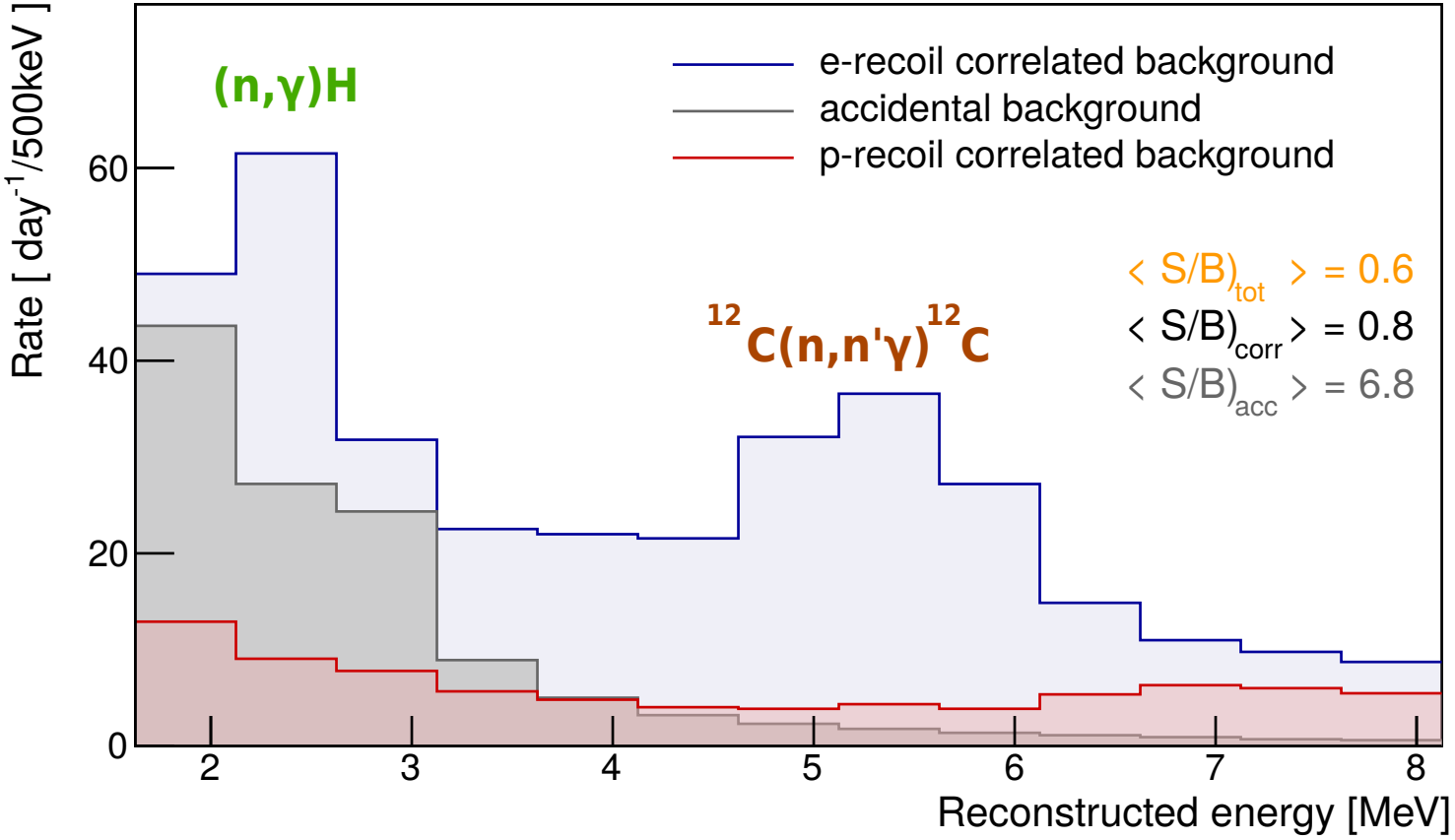
Pulse Shape Discrimination for prompt signal





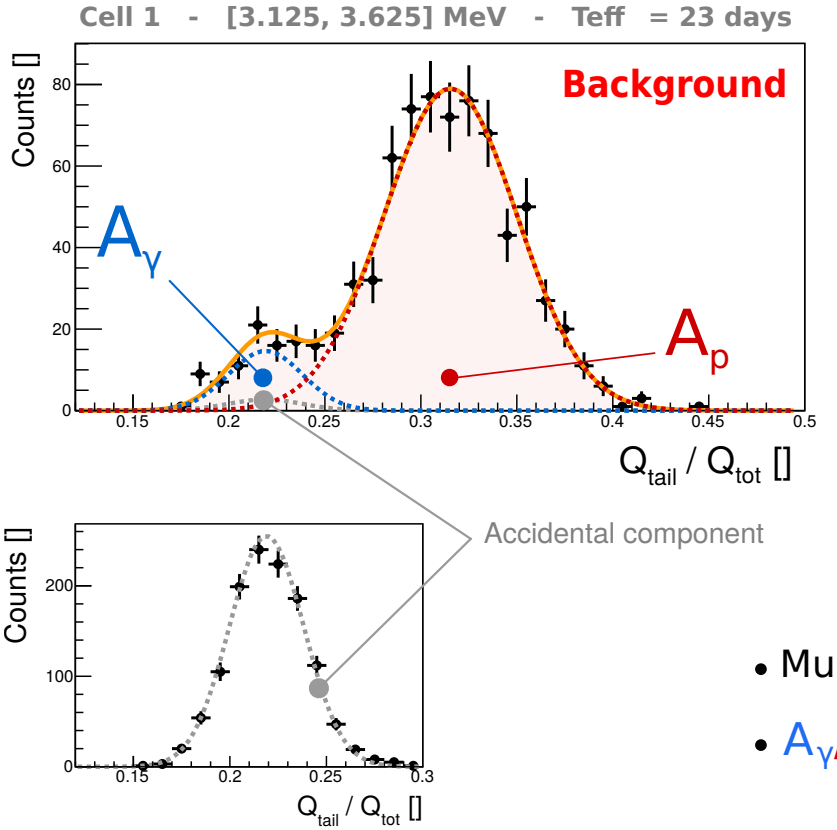
Correlated background

Prompt energy spectrum in the region of interest

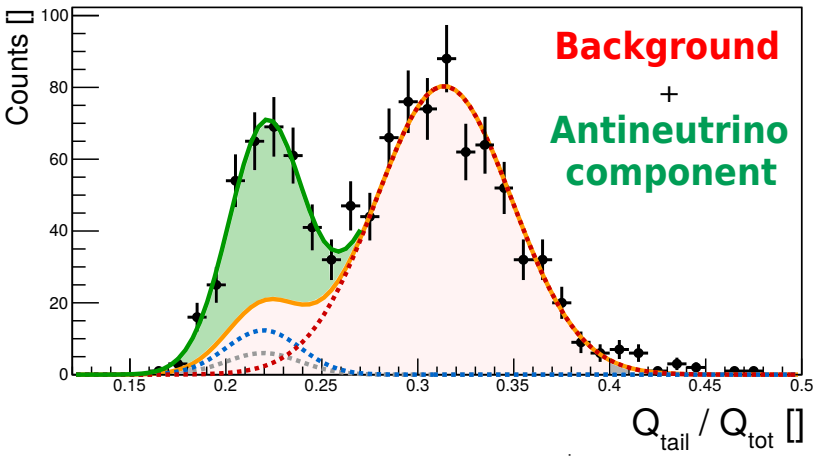


$\bar{\nu}_e$ signal extraction: from PSD distributions

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)

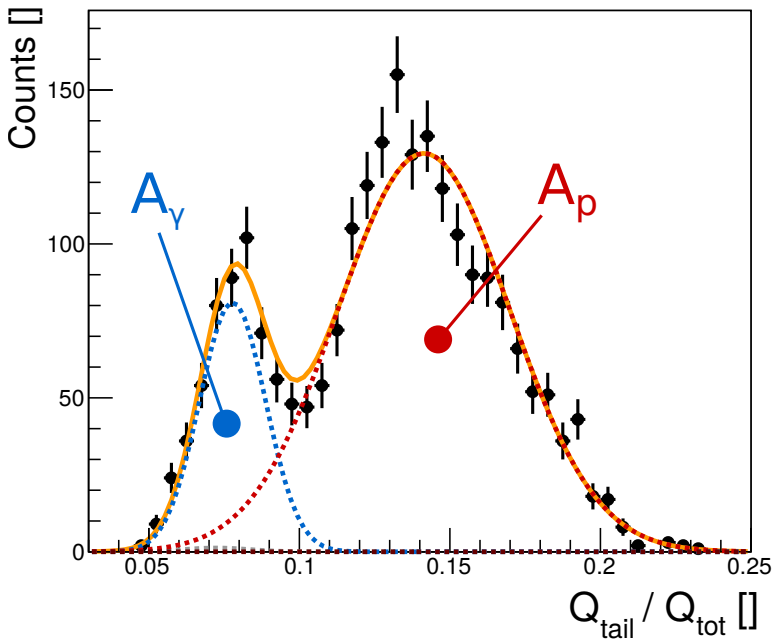
$\bar{\nu}_e$ signal extraction: what's new with phase-2 ?

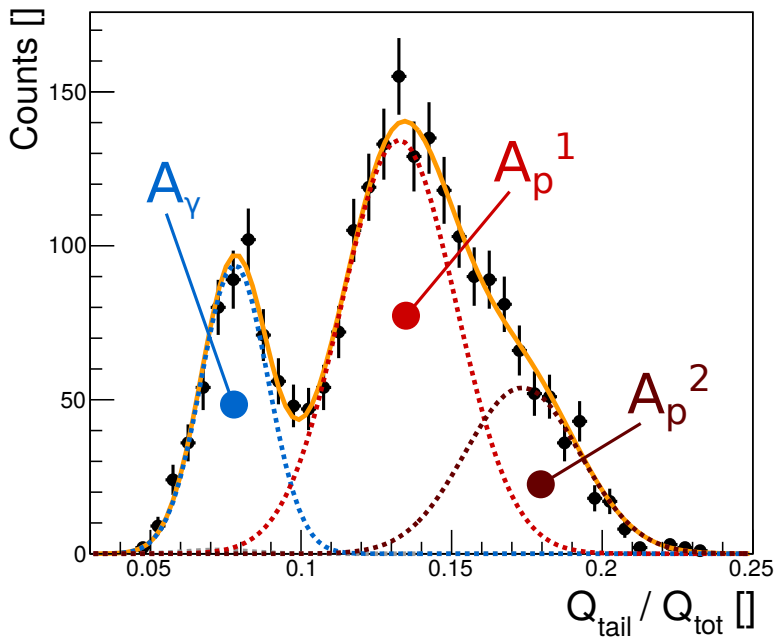
OFF period of phase-II:

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

Updated background model

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





Relative comparison of ν energy distributions: Ratio method

arXiv:1806.02096 (2018)

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

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

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

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

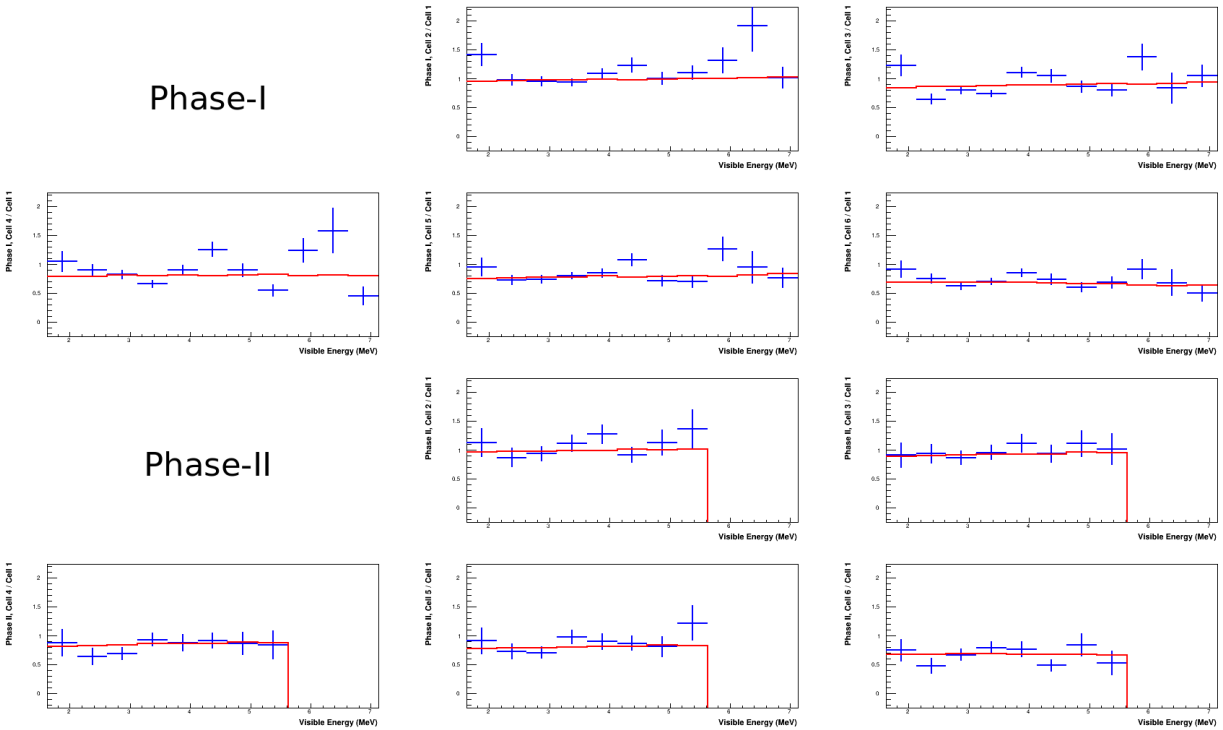
V_i is the **covariance matrix** of the 5 ratios (common reference for each cell) for the energy bin i
$\{\alpha\}$ are nuisance parameters to take into account estimated **systematics**

	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

Ratio method: Results for Phase-I & II

arXiv:1806.02096 (2018)

Ratio method: cell 1 taken as reference



Measured ratios for the cells from 2 to 6 (blue) compared to the null oscillation hypothesis model (red)

- **Measured ratios**
- **Non-oscillation prediction**

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

- **Non-oscillation hypothesis (H_0) can not be rejected:** p-value = 34 % (40 %) for phase-I (phase-I+II)

Exclusion contours Phase-I+II combined

arXiv:1806.02096 (2018)

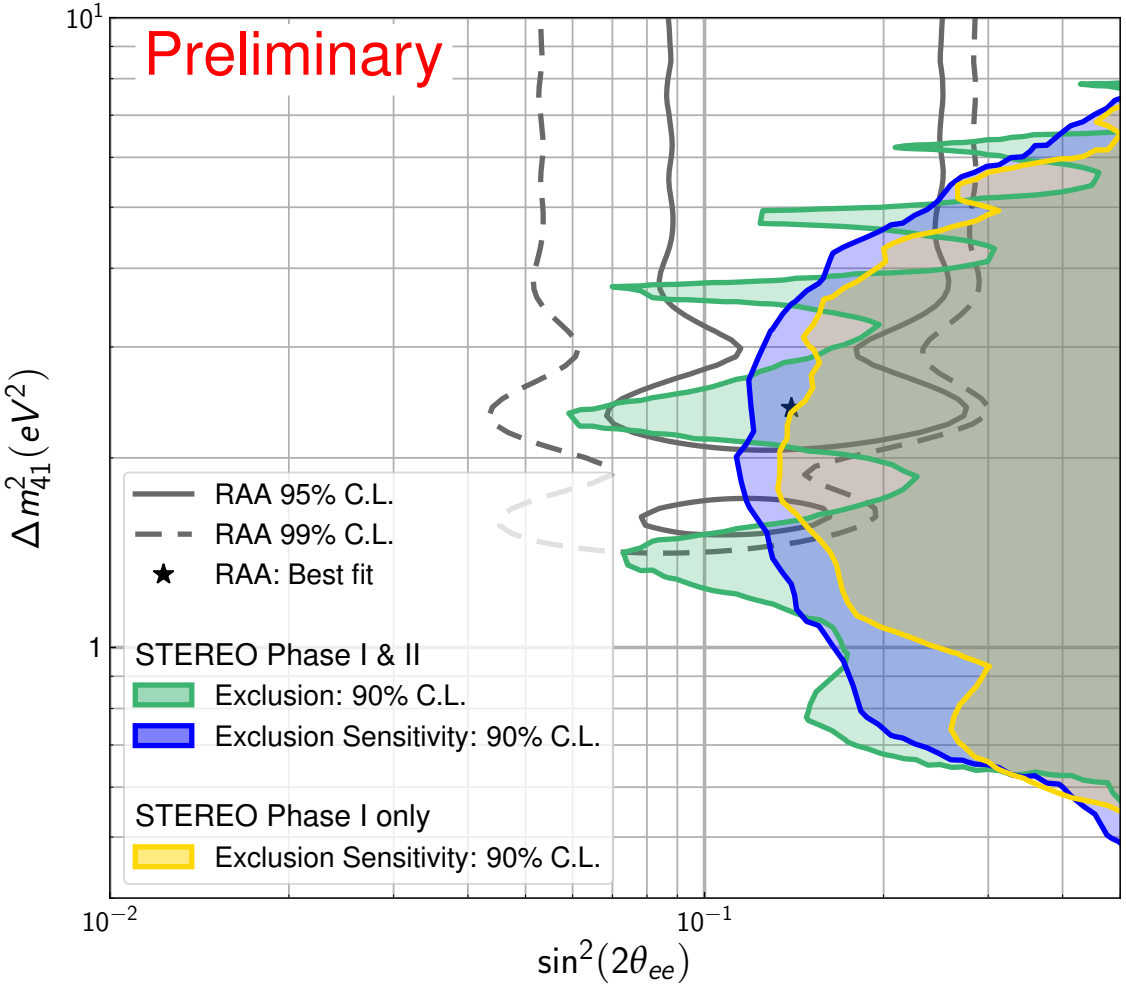
- **Phase-I + Phase-II combined results**
  (66+47) days reactor-ON
  (396 ± 4) $\bar{\nu}_e$ day^{-1}

  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

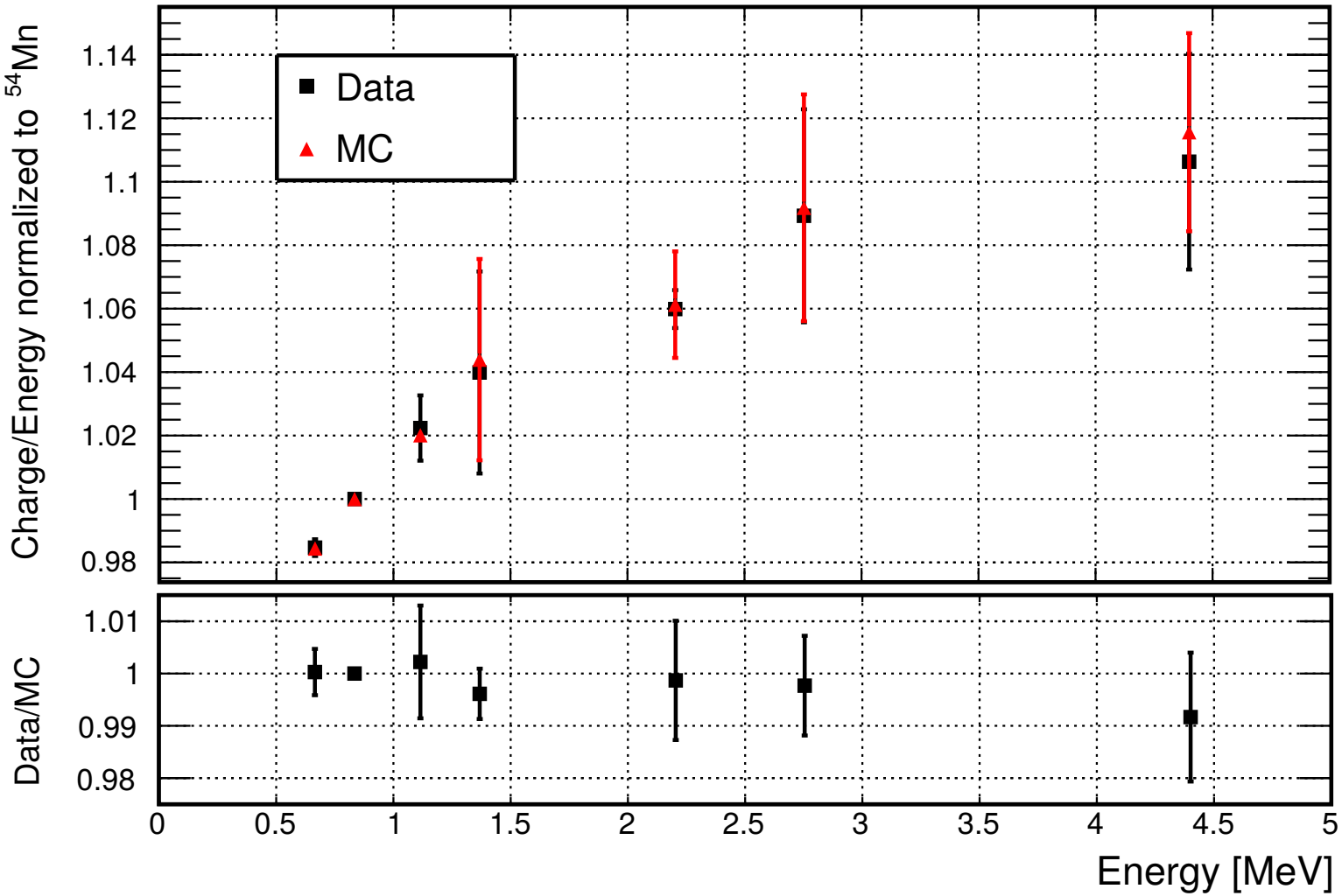
- STEREO is now running under **very stable conditions**
- The **correlated background understanding improves** using reactor-OFF periods
- First exclusion contour obtained, original RAA is rejected at 98%CL using the **robust ratio method**. Data taking will continue until end 2019, reaching **300 days of reactor-ON data**
  arXiv:1806.02096 (2018)
- Improved results are coming soon, with a **pure ^{235}U spectrum**

$\sim$ Thanks for your attention ! $\sim$

BACKUP

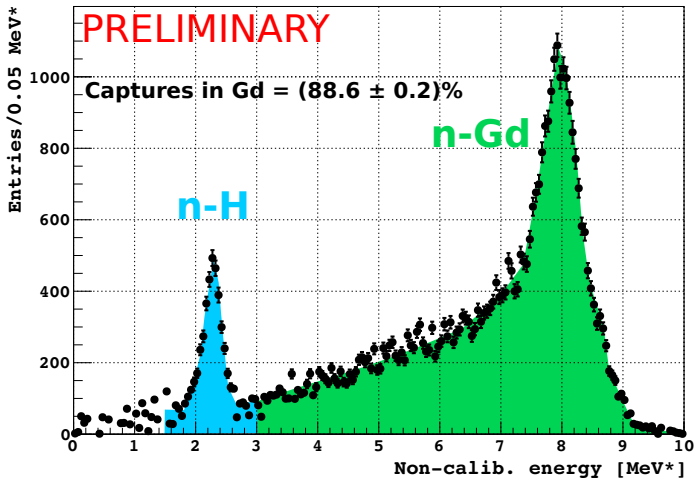
Quenching curve

Non-linear light production in the large dE/dx regime (low E – Bragg peak)

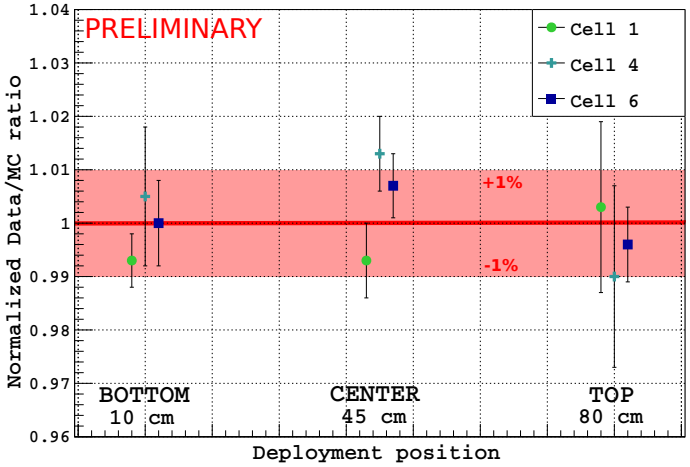


Am-Be neutron source in target cells :

- 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



Homogeneity of the Gd-fraction

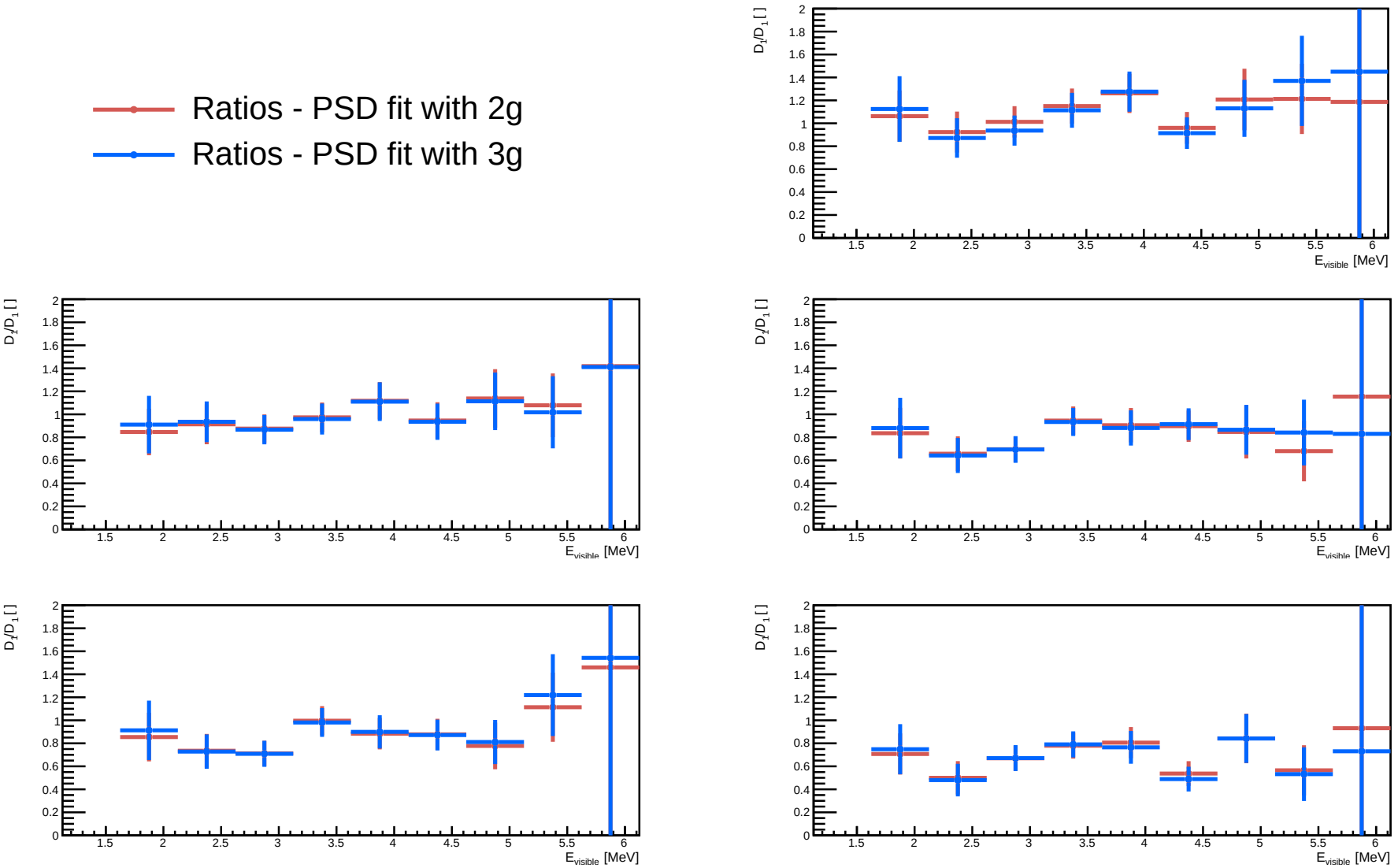


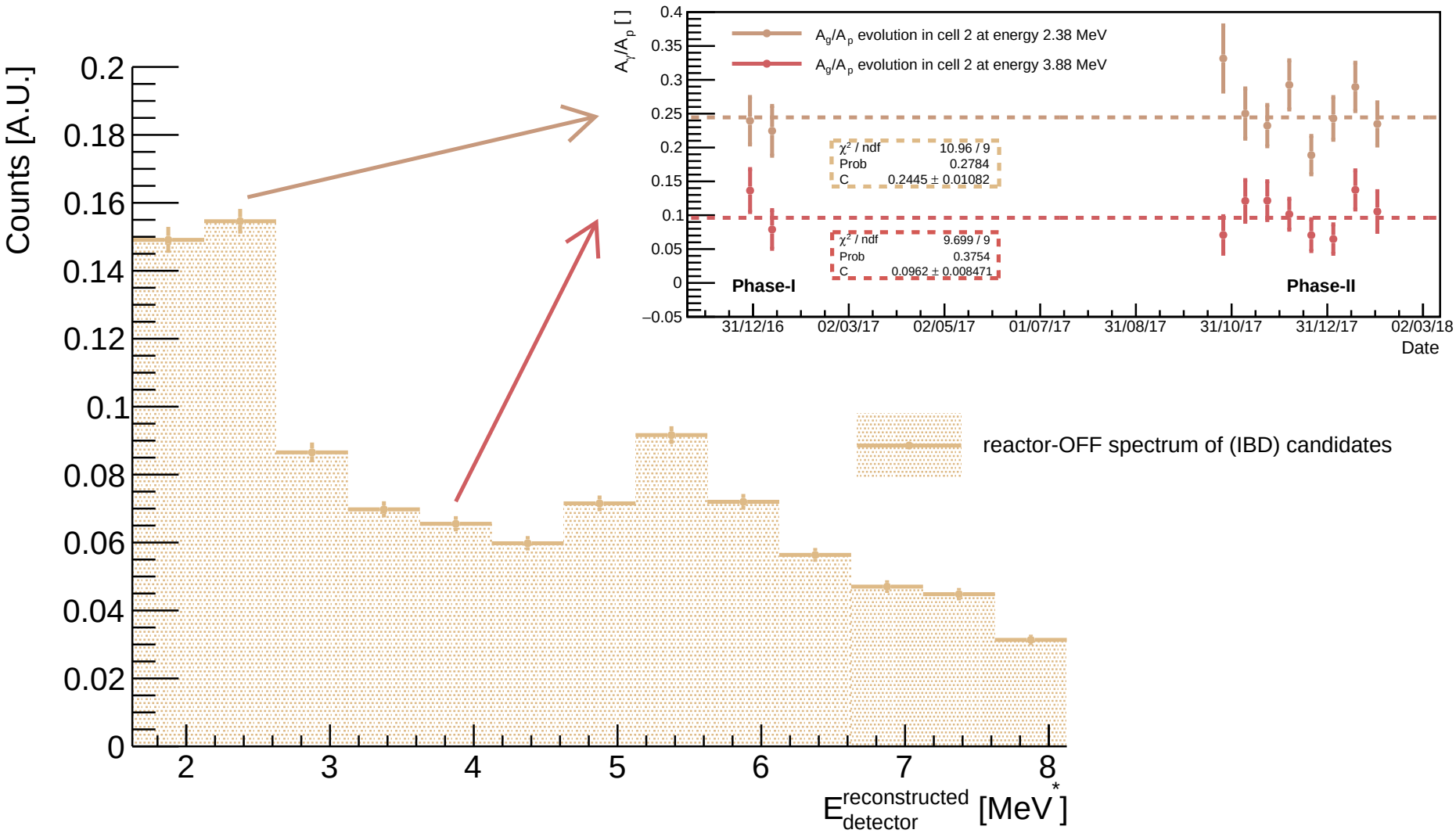
Systematics

Source	**Contrib to $\sigma_{Cell}^{NormUncor}$**
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)**

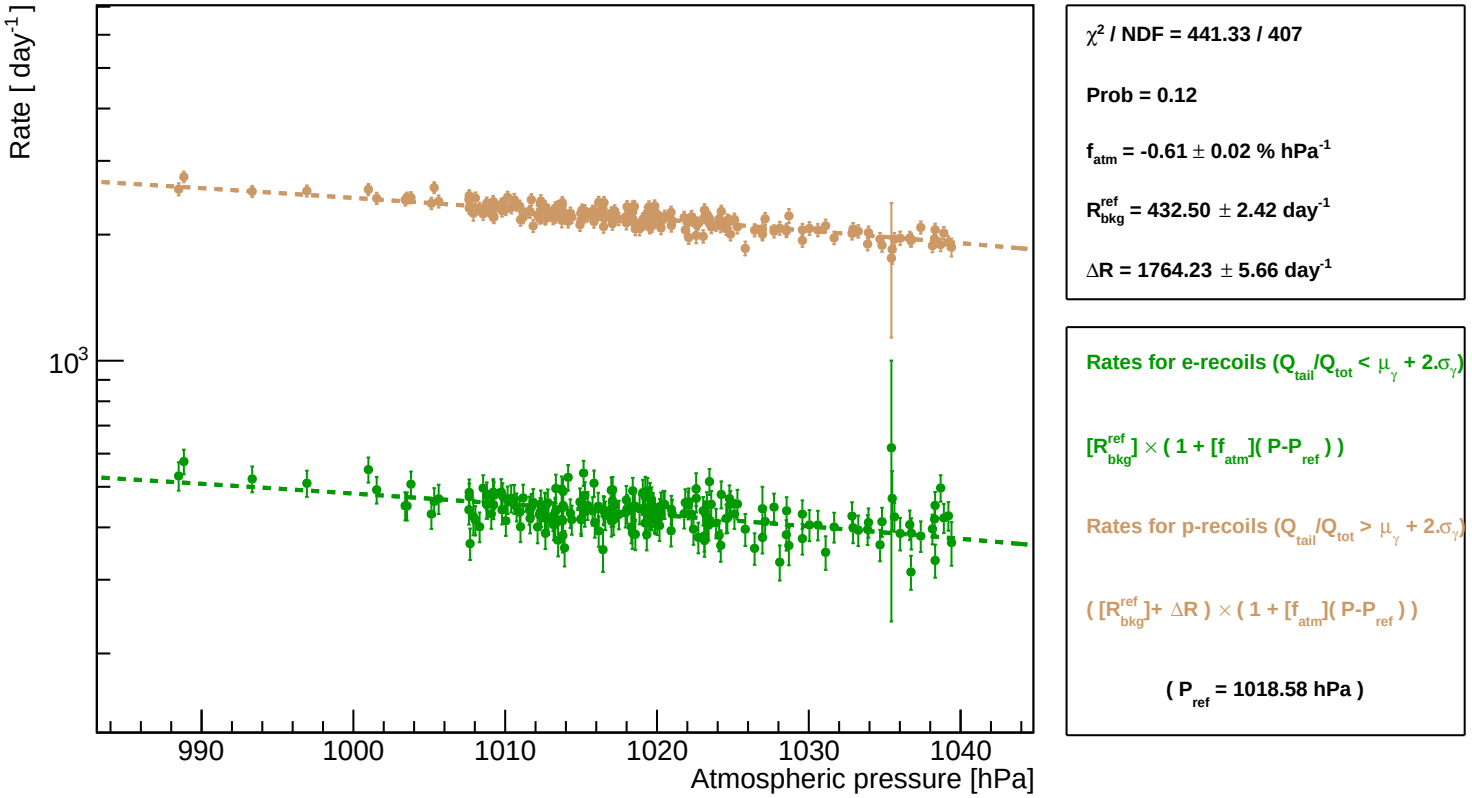
Source	**Contrib to σ^{Escale}**
Escale correlated	0.35 %

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


Ratios - PSD fit with 2g
Ratios - PSD fit with 3g
D_i/D_1 []
$E_{visible}$ [MeV]


Counts [A.U.]
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
2
3
4
5
6
7
8
$E^{reconstructed}_{detector}$ [MeV*]
reactor-OFF spectrum of (IBD) candidates
A_γ/A_p [ ]
A_g/A_p evolution in cell 2 at energy 2.38 MeV
A_g/A_p evolution in cell 2 at energy 3.88 MeV
χ^2 / ndf 10.96 / 9
Prob 0.2784
C 0.2445 ± 0.01082
χ^2 / ndf 9.699 / 9
Prob 0.3754
C 0.0962 ± 0.008471
Phase-I
Phase-II
31/12/16
02/03/17
02/05/17
01/07/17
31/08/17
31/10/17
31/12/17
02/03/18
Date

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



PSD (electronic) correlation with temperature

PSD follows temperature changes

- Temperature changes occur when reactor goes on, or off, and lasts for several weeks
- Linear correlation with slope [-0.015 / -0.020] (PSD unit/Celsius degree)