THE STEREO EXPERIMENT

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ON BEHALF OF THE STEREO COLLABORATION

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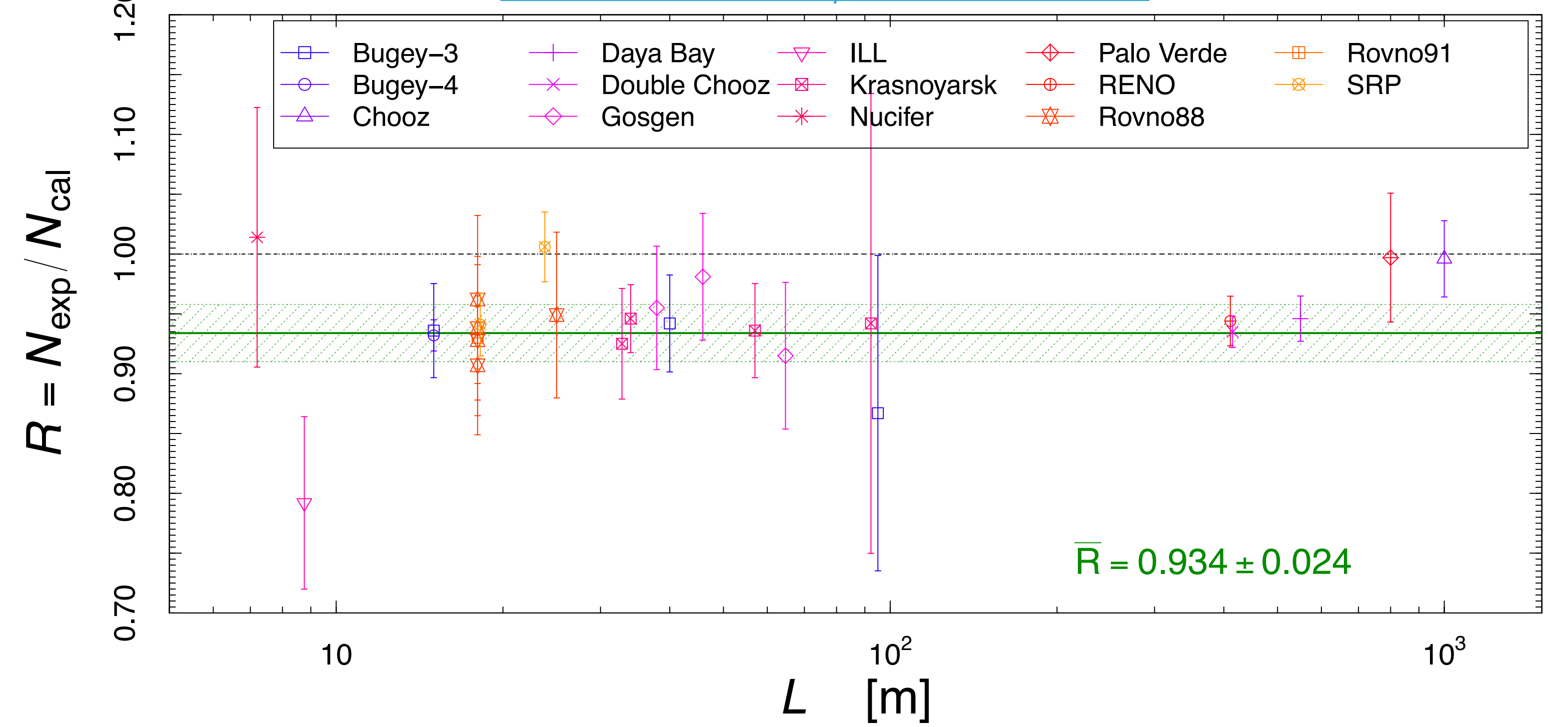
HEIDELBERG

REACTOR ANTINEUTRINO ANOMALY

[arXiv: 1703.00860, S. Gariazzo et al.](https://arxiv.org/abs/1703.00860)



RAA:

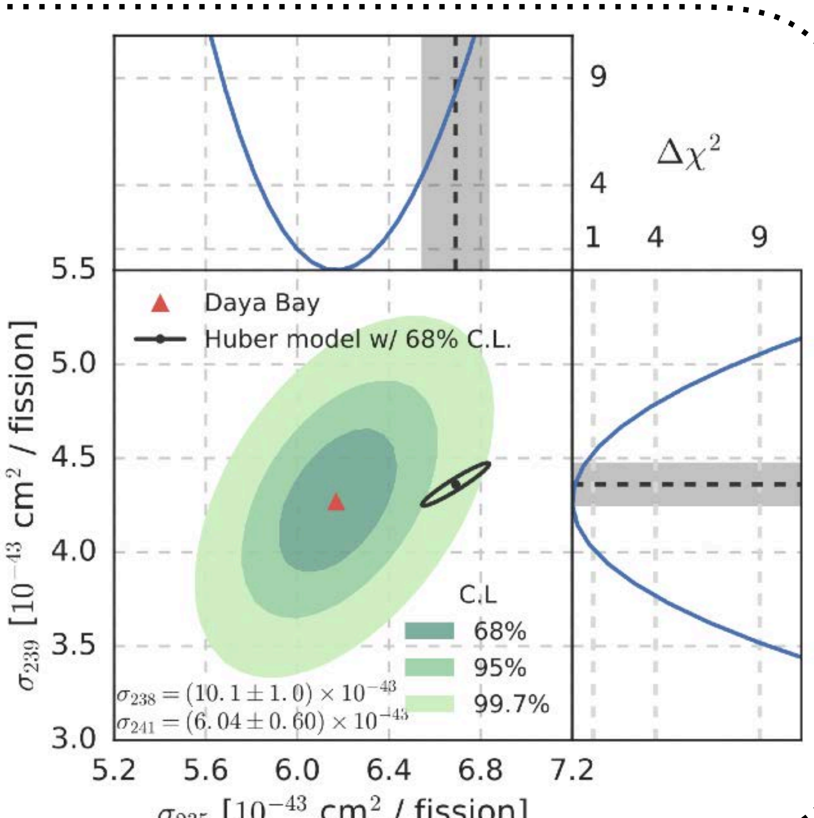
- **deficit** at 2.8σ in $\bar{\nu}_e$ flux measured by several experiments at different distancies from reactors

Possible explanations

→ **wrong prediction?**

Discrepancy between observed and predicted IBD yields from ^{235}U by Daya Bay. Suggests **^{235}U could be** the primary contributor of the RAA

[arXiv: 1704.01082, Daya Bay Collaboration](https://arxiv.org/abs/1704.01082)



→ **sterile neutrino hypothesis?**

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

~ **1 eV sterile neutrino**

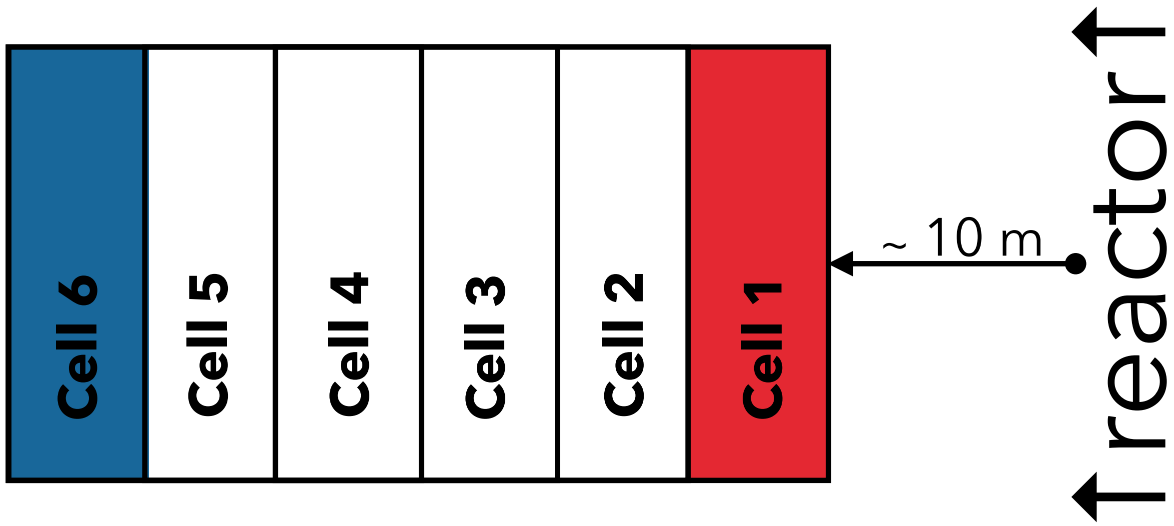
new oscillation angle

and mass splitting

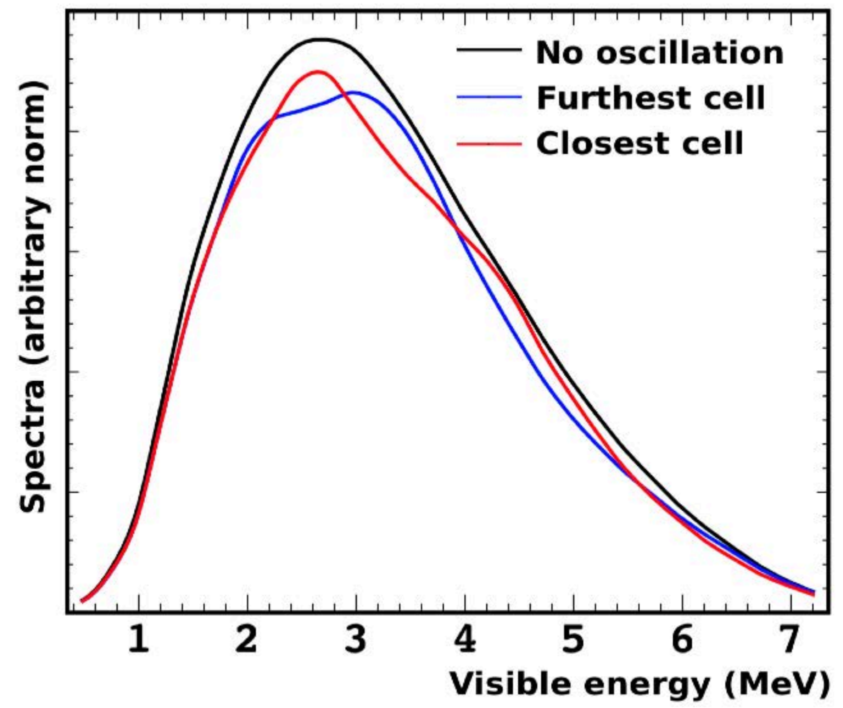
need dedicated measurement at short distances

STEREO EXPERIMENT

segmented detector (6 cells)

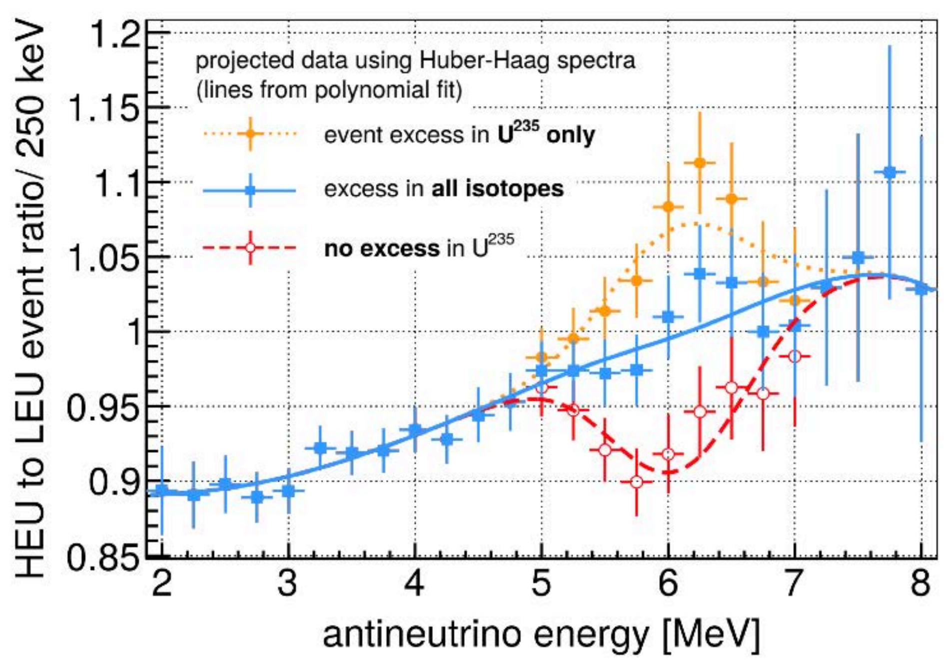


→ **sterile neutrino hypothesis**
to probe the RAA region by measuring relative distortions of the $\bar{\nu}_e$ energy spectrum as a function of the distance [9-11m]



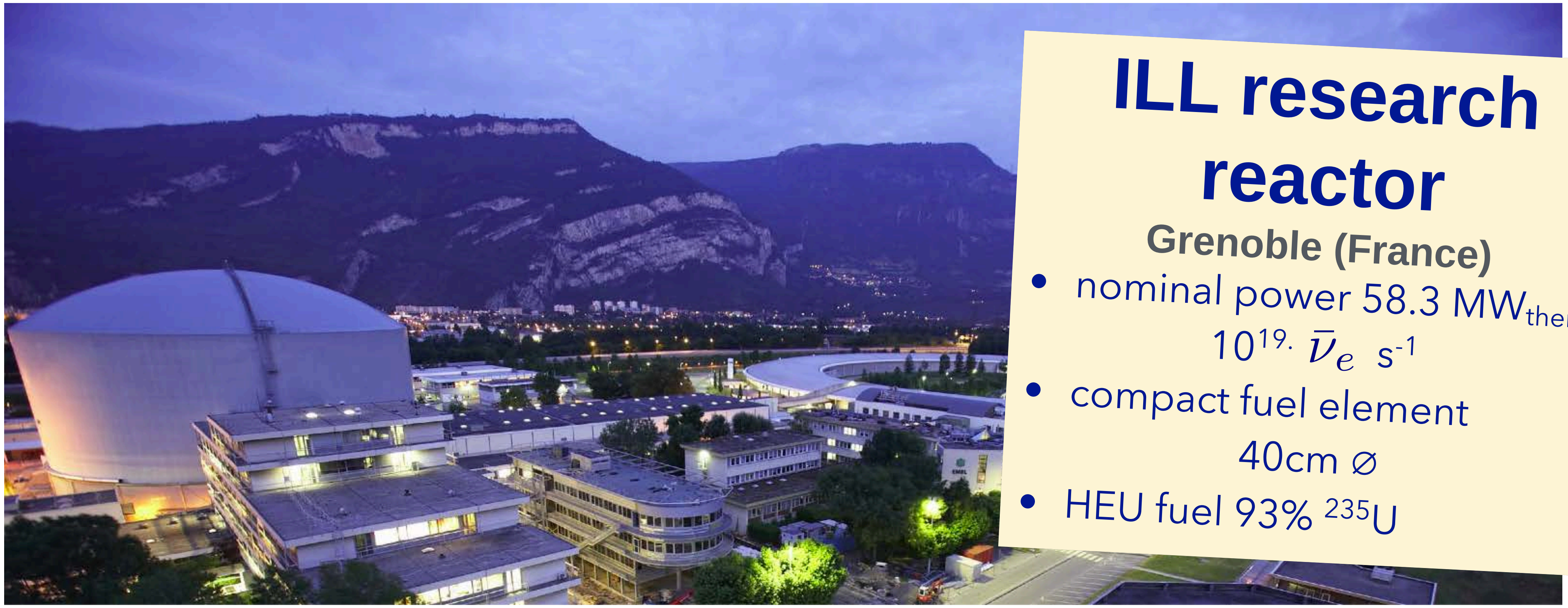
Independent from predicted energy spectrum

→ **spectral shape studies**
Measurement of a pure ^{235}U $\bar{\nu}_e$ energy spectrum
→ Help to understand Daya Bay results



arXiv: 1512.06656, C. Buck et al.

EXPERIMENTAL SITE - ILL



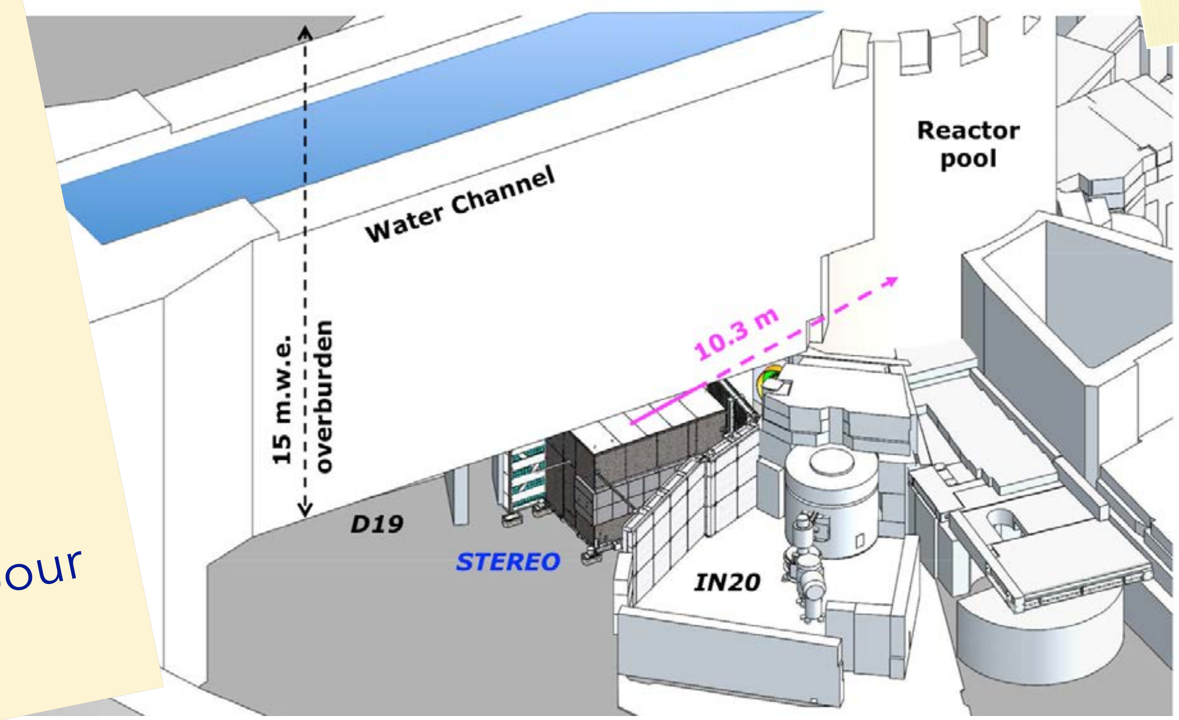
ILL research reactor

Grenoble (France)

- nominal power 58.3 MW_{therm}
  $10^{19} \cdot \bar{\nu}_e \ s^{-1}$
- compact fuel element
  40cm ∅
- HEU fuel 93% ^{235}U

Experimental site

- short baseline experiment
  $8.9m < L_{core} < 11.1m$
- ground-level experiment
- gamma and neutron background from neighbour experiments



STEREO DETECTOR

Neutrino Target

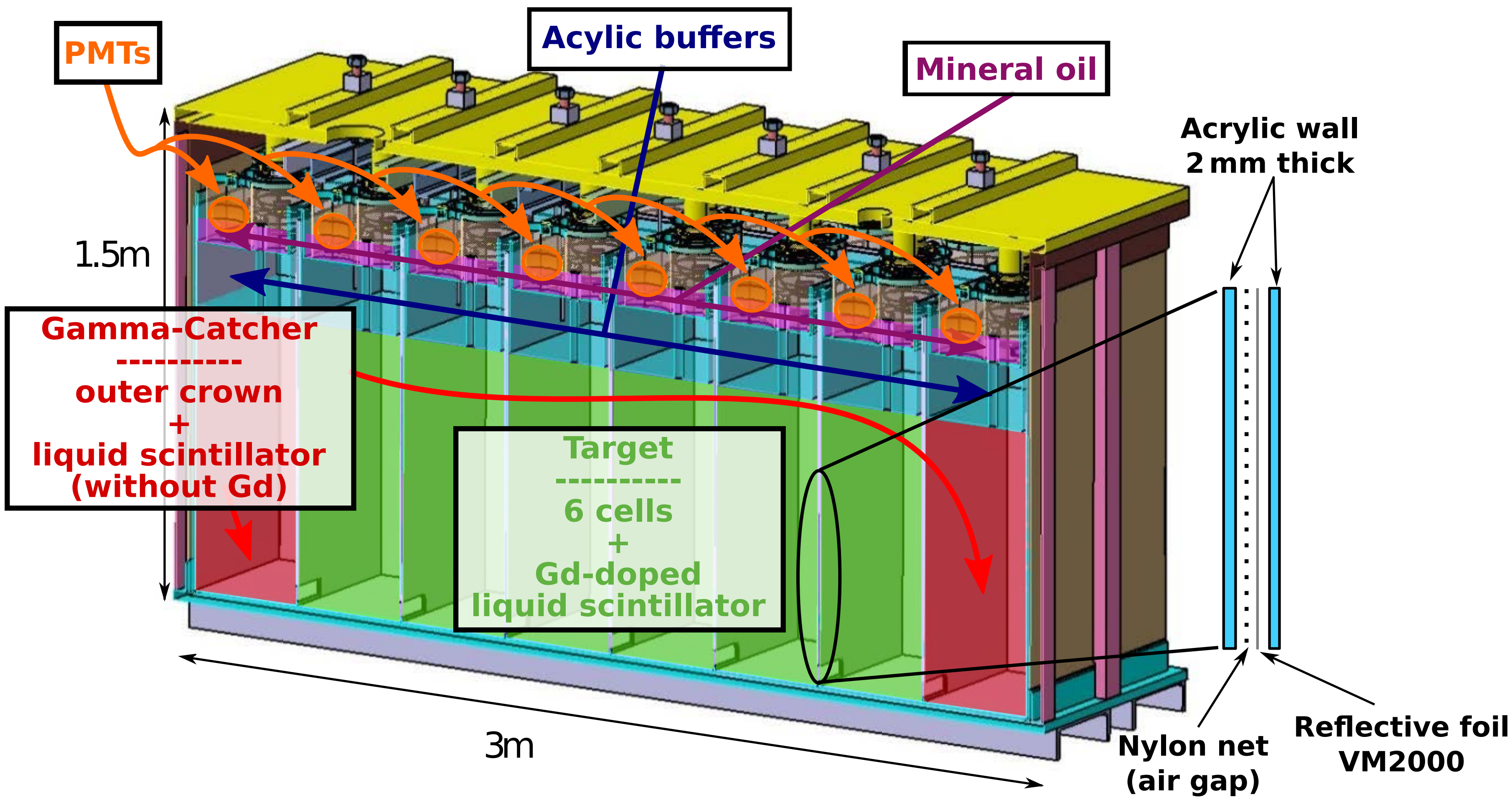
- 2.2 x 1.5 x 0.9 m^3
- Gd-β-diketonate liquid scintillator → good response

Gamma catcher

- Outer crown volume
- filled Gd-free liquid scintillator

Buffer

- 48 **PMTs** (8inch)
- **acrylic buffers**
- **mineral oil** (optical coupling)

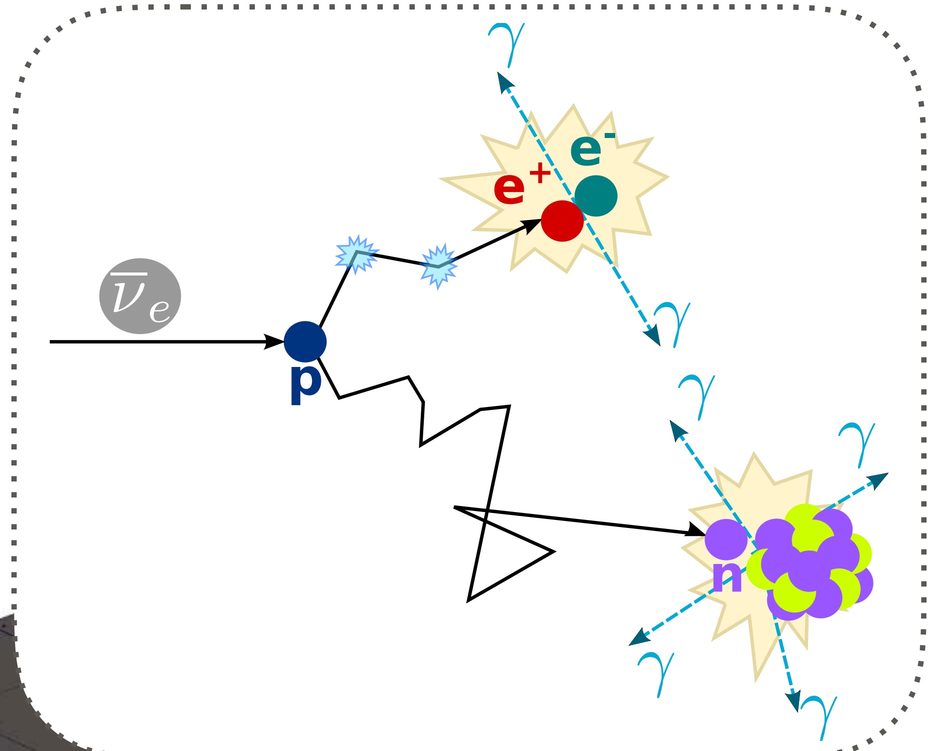


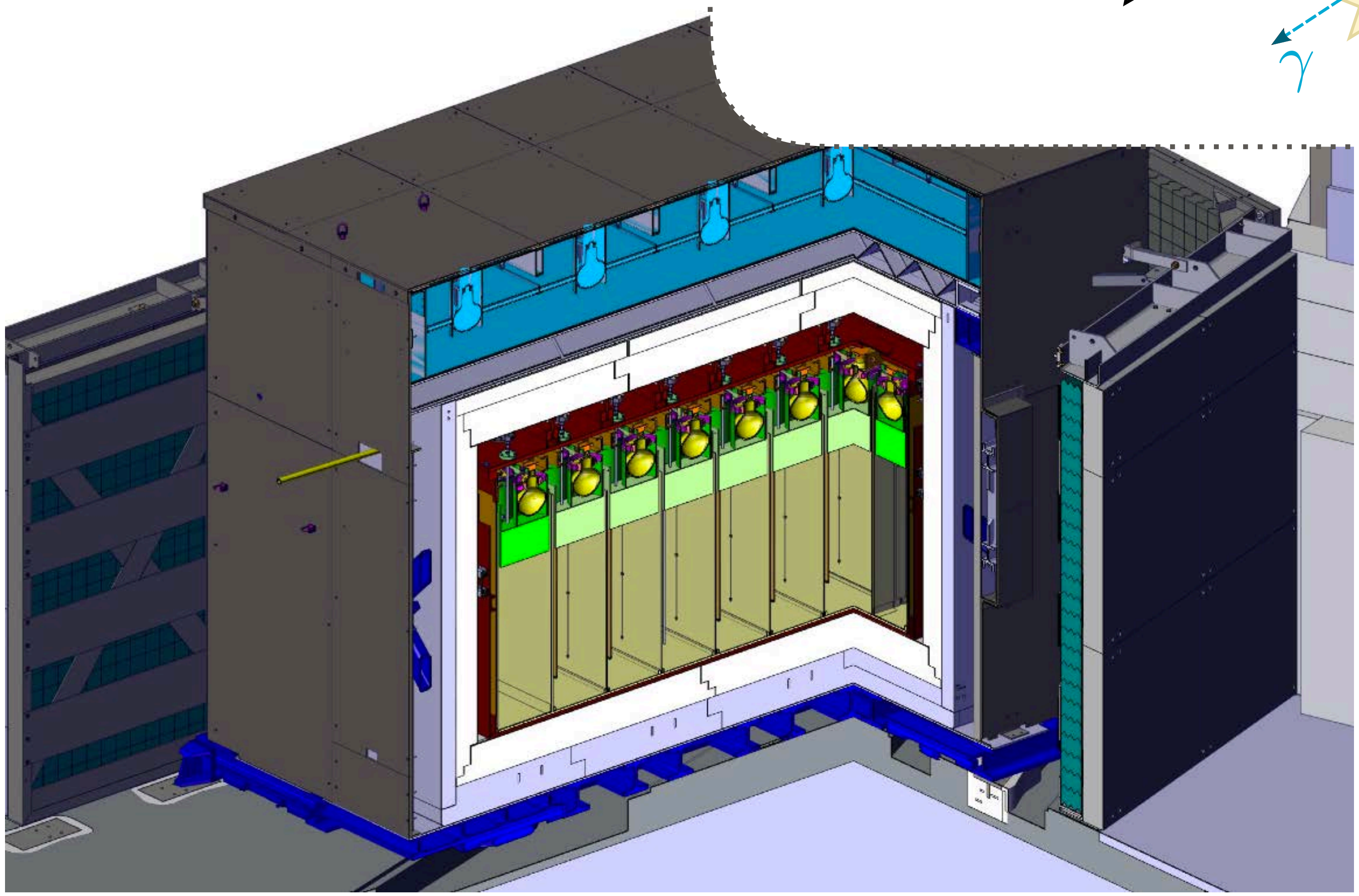
STEREO detector

DETECTION PRINCIPLE

Interaction via
Inverse Beta Decay **IBD**

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



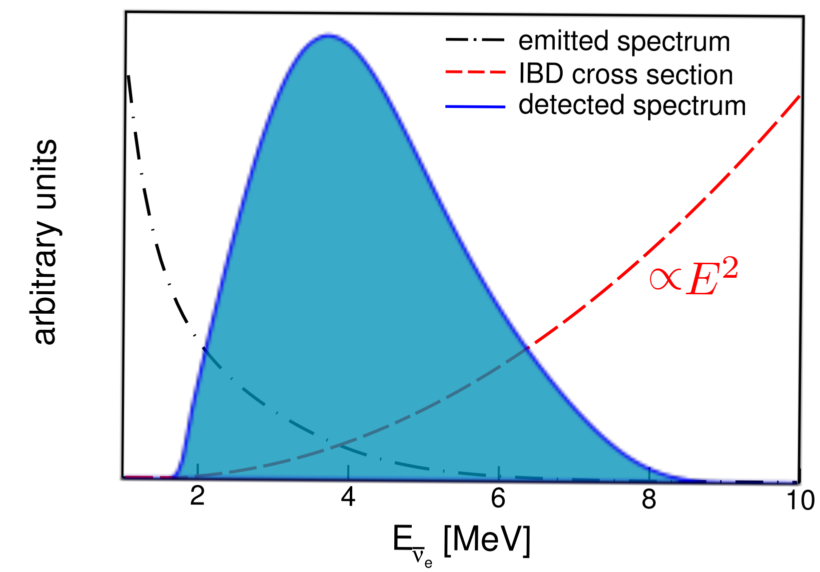


STEREO detector with shielding

1. Prompt Event

positron annihilation

$$E_{vis,e^+} \simeq E_{\overline{\nu}_e} - 0.8MeV$$



2. Delayed Event

neutron capture

- Gd nuclei
  $$\sum_i E_{\gamma,i} \sim 8MeV$$
- H nuclei
  $$E_\gamma \sim 2.2MeV$$

DATA TAKING – TIME LINE

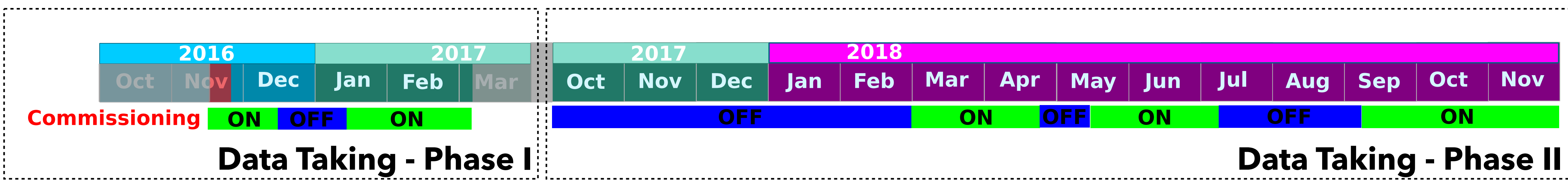
Phase I:

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

→ **repaired during summer 2017**

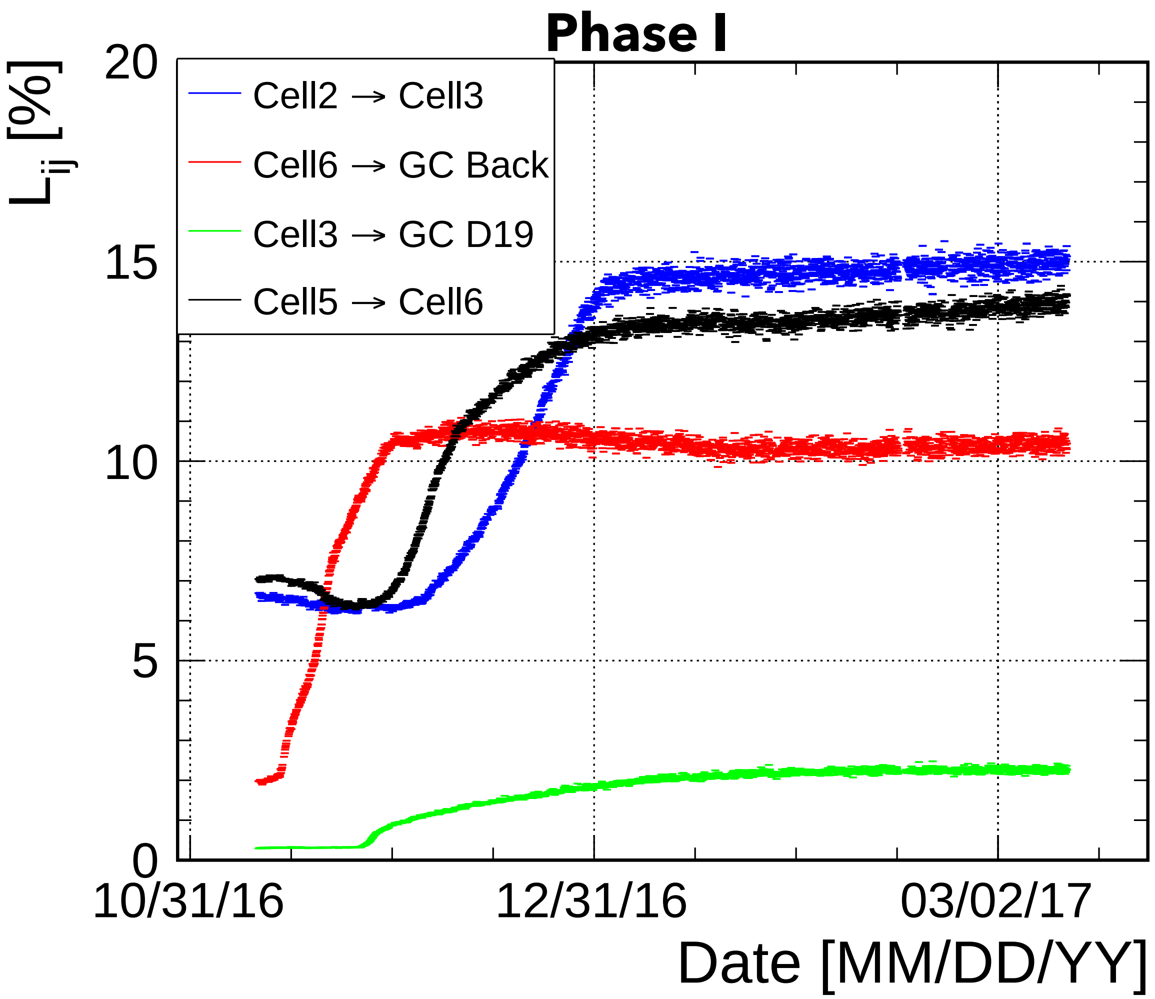
Phase II:

- Stable conditions ~ **95% of data taking time**

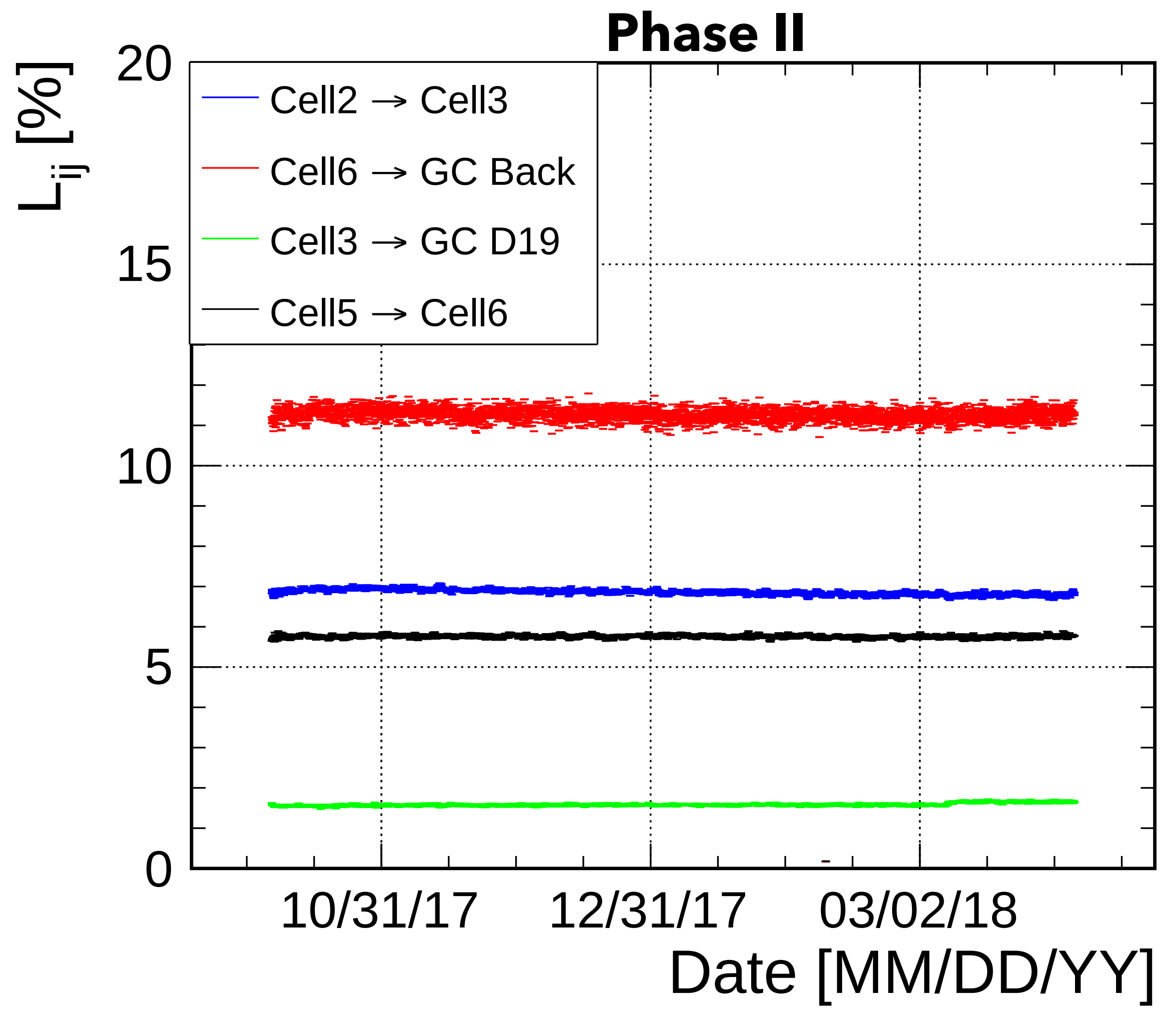


DETECTOR RESPONSE: LIGHT CROSS-TALKS

Evolution of the light cross-talk between cells
estimated by muon events in neutrino runs



liquid slowly infiltrating into acrylic walls

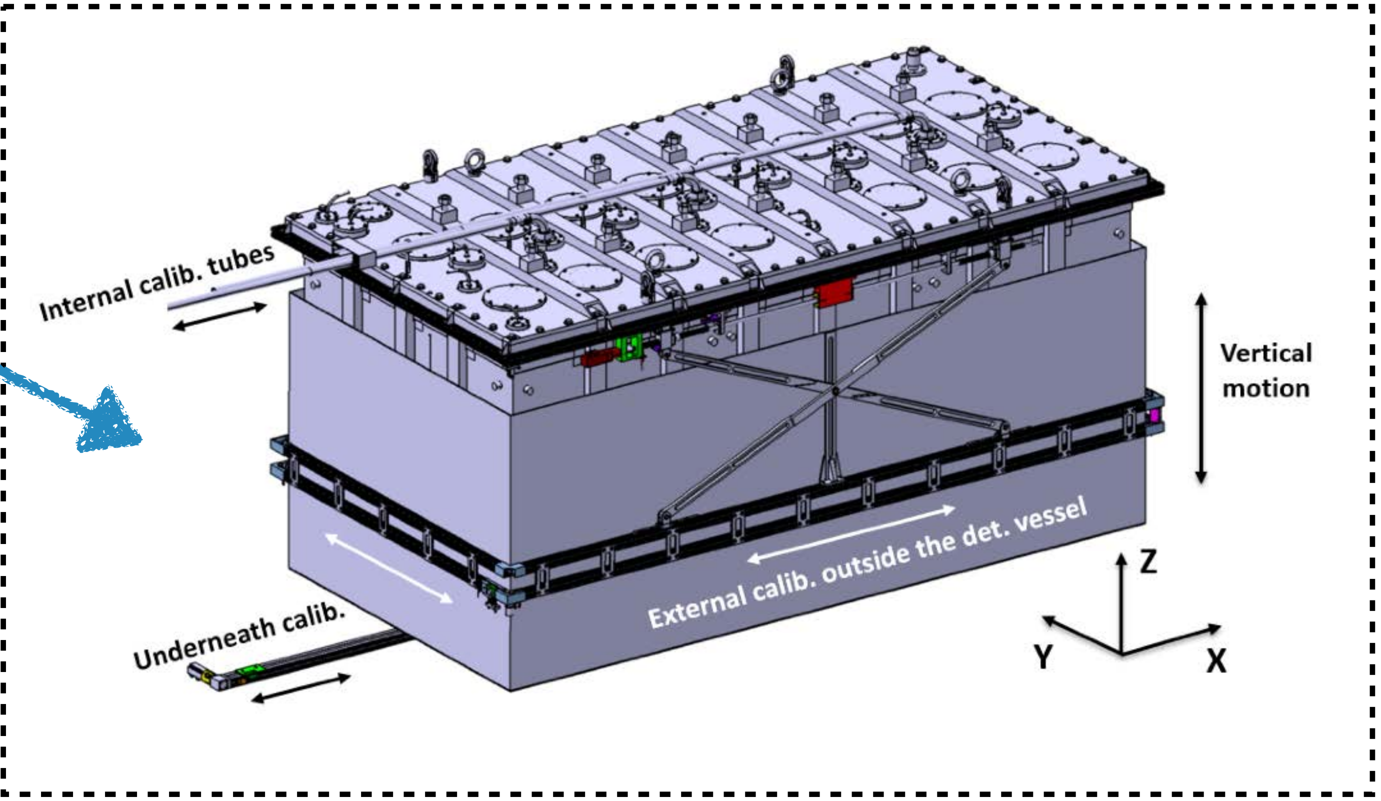


detector stability after walls reparation

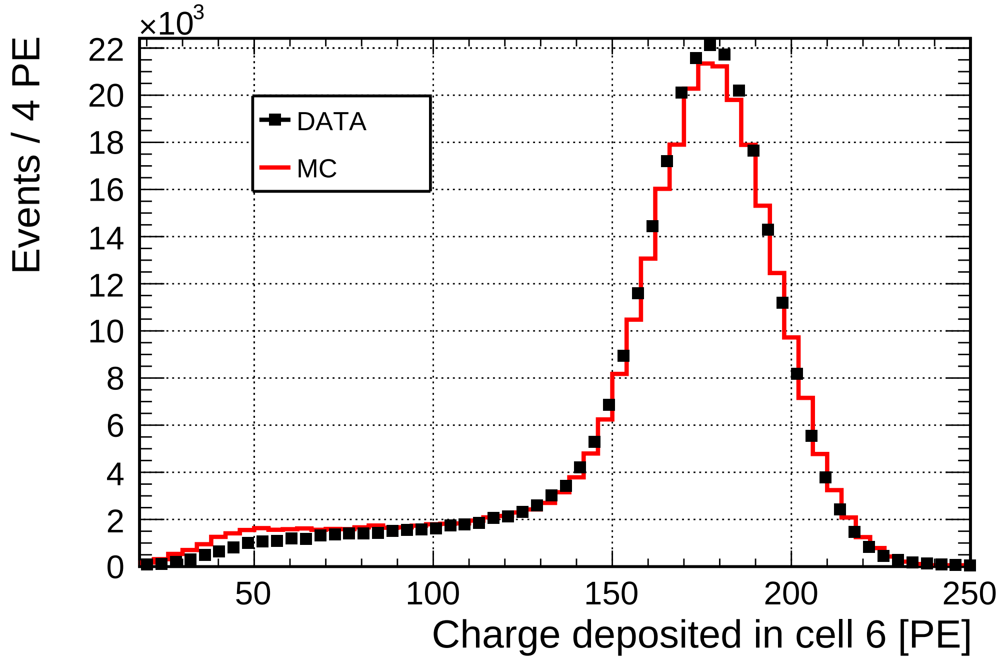
arXiv: 1804.09052, N. Allemandou et al.

DETECTOR RESPONSE: CALIBRATION

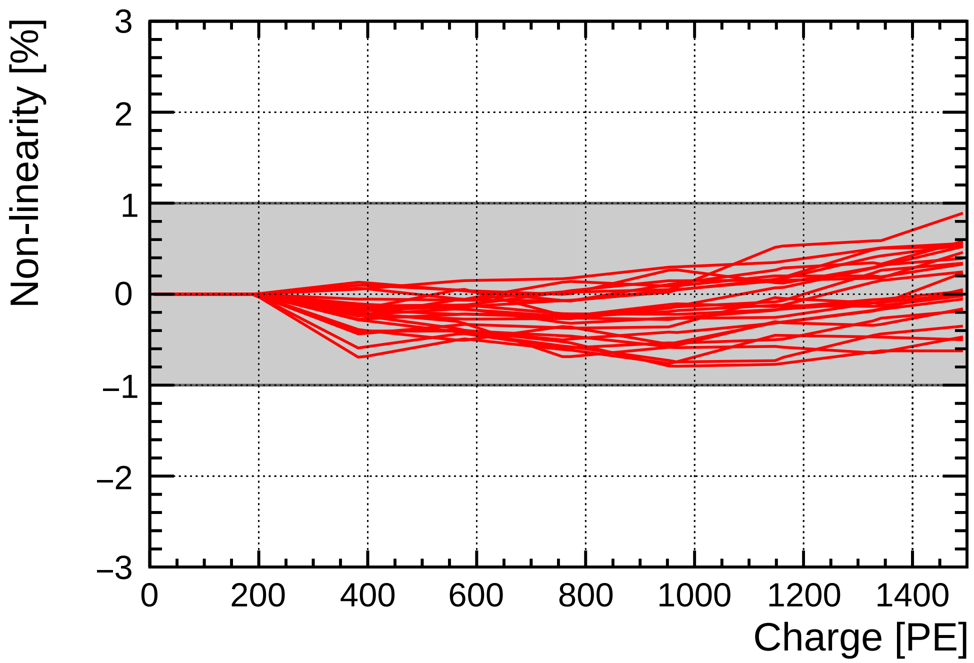
extensive circulation of **radioactive sources** Ge^{68} , Sb^{124} , Cs^{137} , Mn^{54} , Zn^{65} , Na^{24} , AmBe along 3 different *calibration systems*



LED system, used to study the single photoelectron and the PMT-DAQ linearity in the detector target



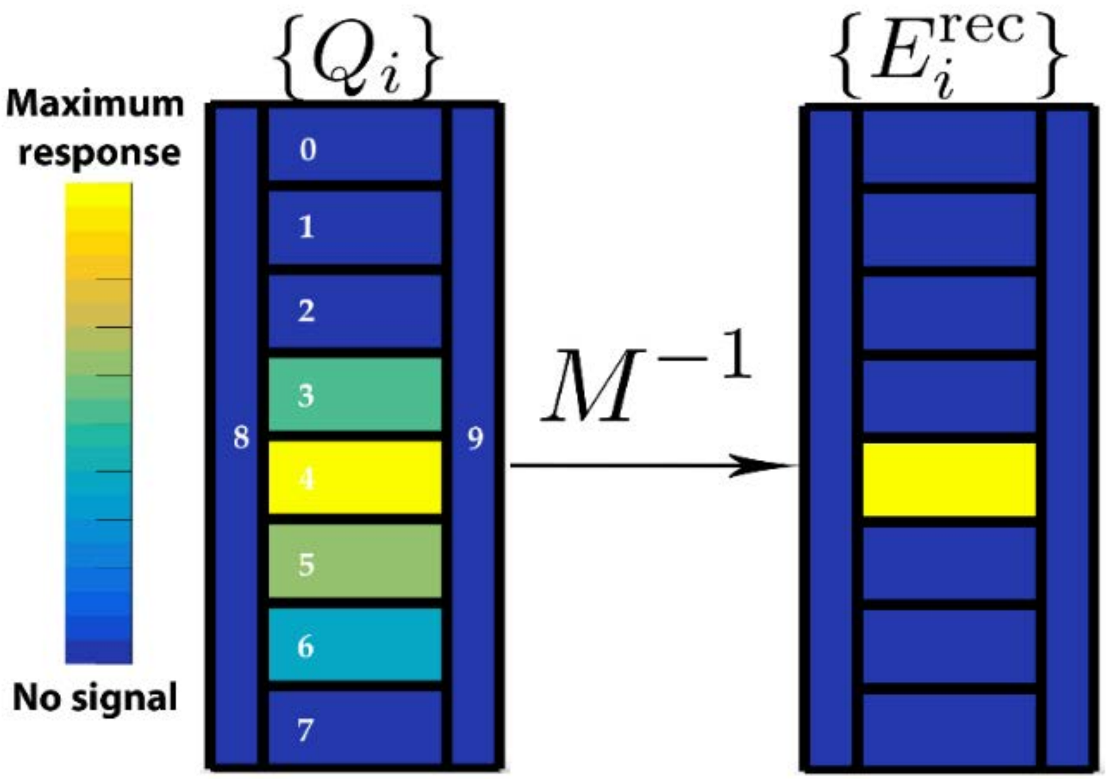
Cell response for Mn source internal deployment in Cell 6



Deviation from linearity for all the Target PMTs

arXiv: 1804.09052, N. Allemandou et al.

DETECTOR RESPONSE: ENERGY RECONSTRUCTION



Charge and energy connection by inverse M matrix

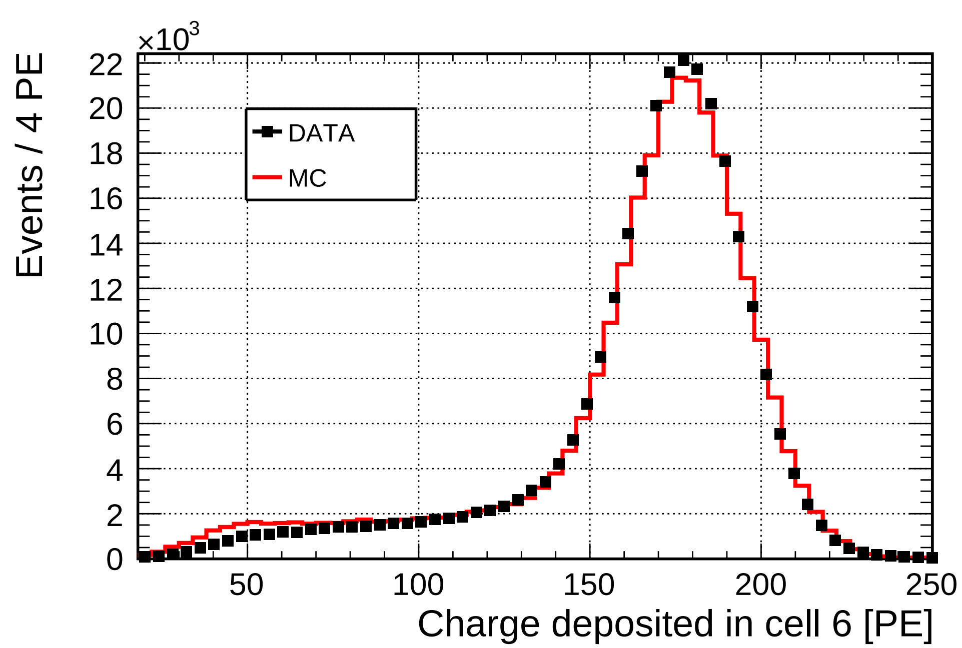
$$\vec{E}_{reco} = M^{-1} \cdot \vec{Q}$$

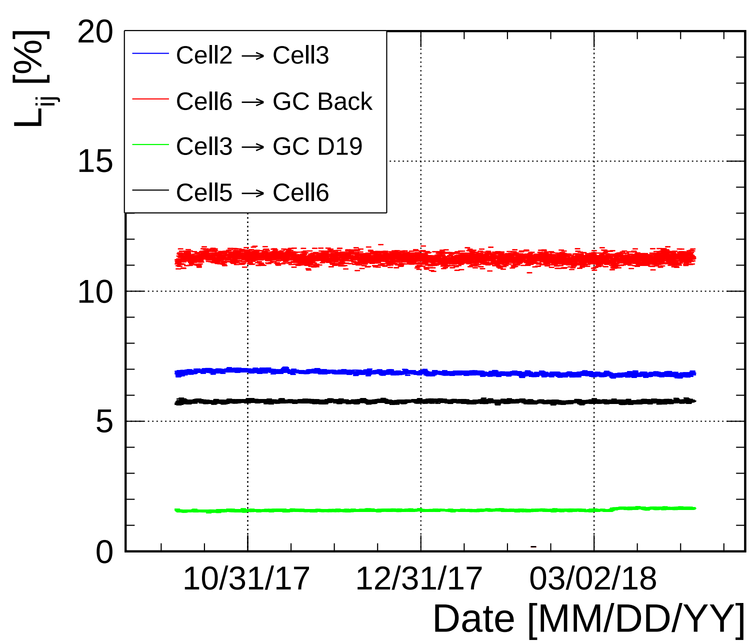
described by

$$M_{ij} = C_j L_{ji}$$

collected photons/MeV from calibration runs in cell i

cross-talk cells j->i measured online





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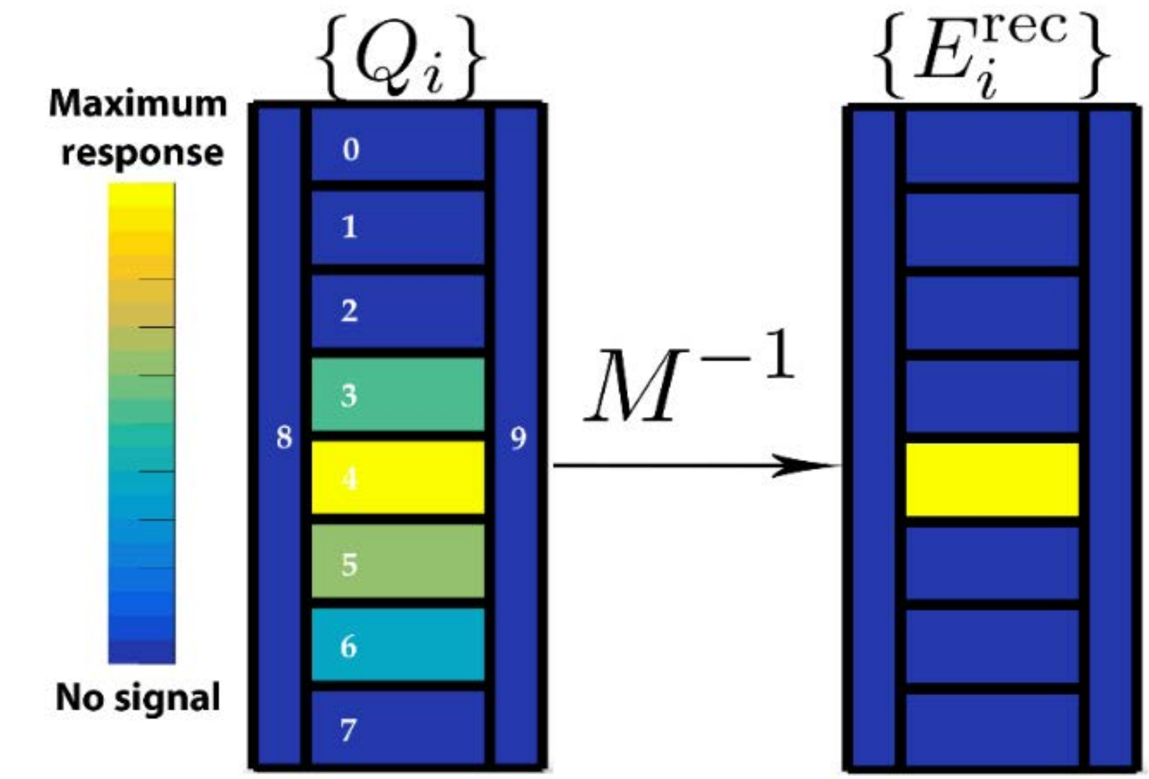
DETECTOR RESPONSE: ENERGY RECONSTRUCTION



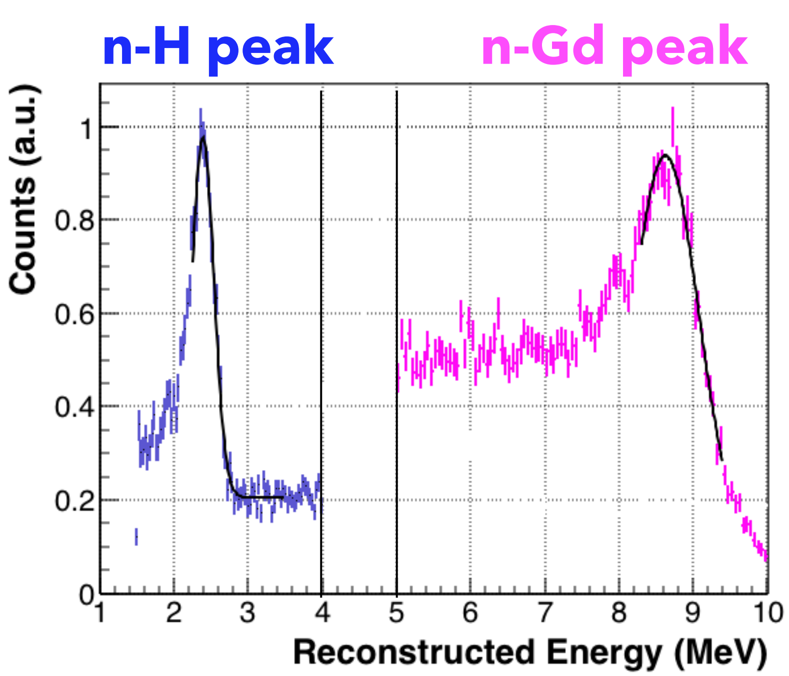
Charge and energy connection by inverse M matrix

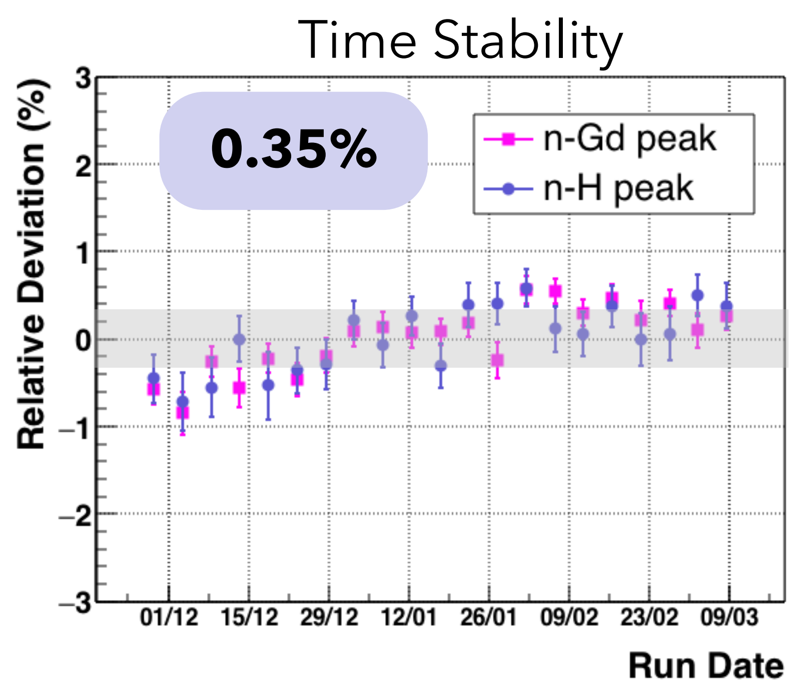
$$\vec{E}_{reco} = M^{-1} \cdot \vec{Q}$$

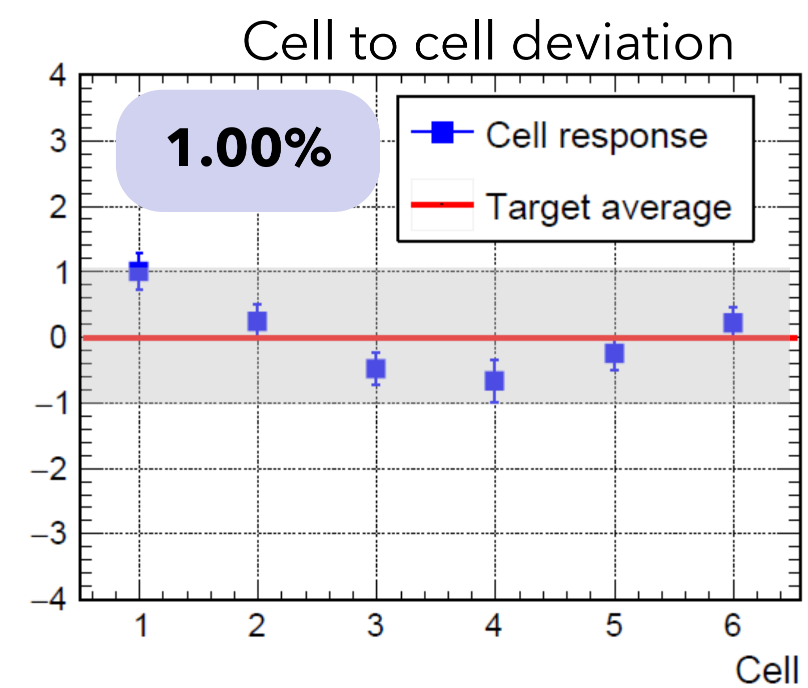
described by

$$M_{ij} = C_j L_{ji}$$

Stability of the reconstructed n-H & n-Gd peaks - probing whole target volume



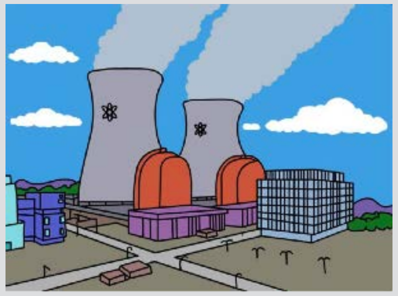




arXiv: 1804.09052, N. Allemandou et al.

BACKGROUND IN STEREO

Reactor Induced

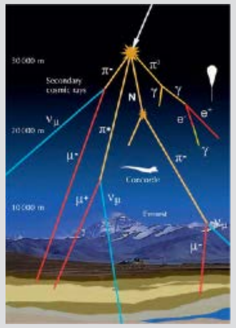


- neutrons
- gamma radiation from n-capture

Environmental Radioactivity

- Thorium/Uranium (concrete)
- Radon/Argon (air)

Muon induced



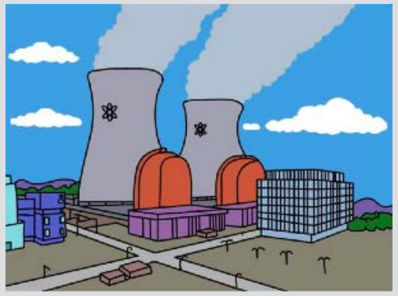
- spallation neutrons (in shielding)
- stopping muons

Reactor OFF

Reactor ON

SHIELDING IN STEREO

Reactor Induced

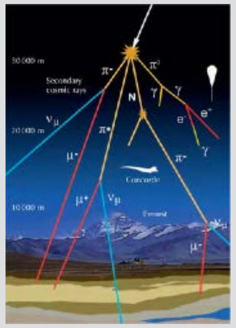


- neutrons
- **gamma radiation from n-capture**

Environmental Radioactivity

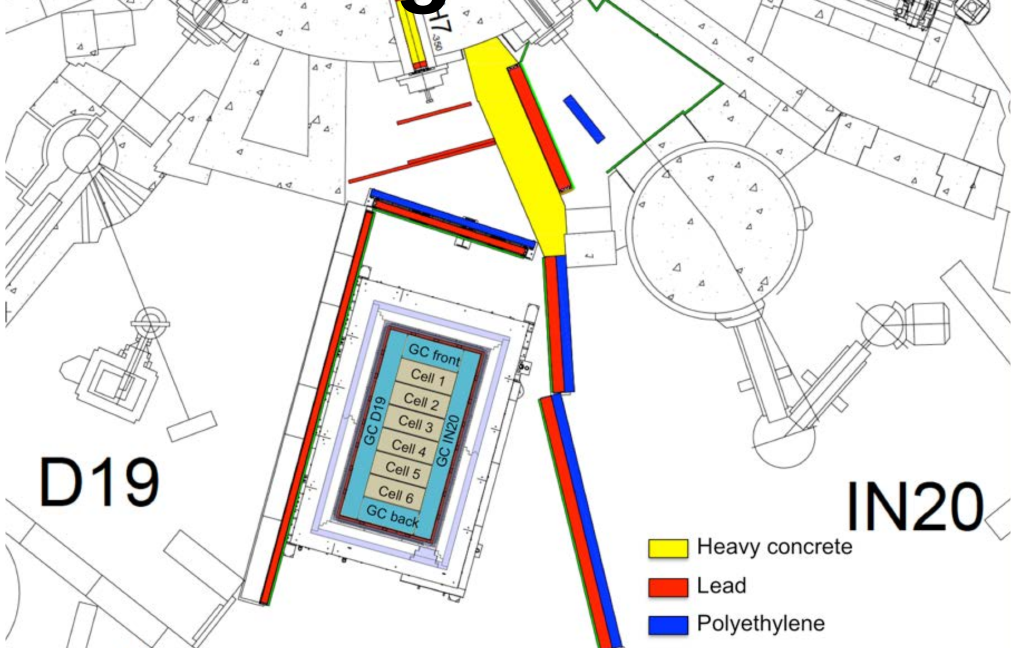
- **Thorium/Uranium (concrete)**
- **Radon/Argon (air)**

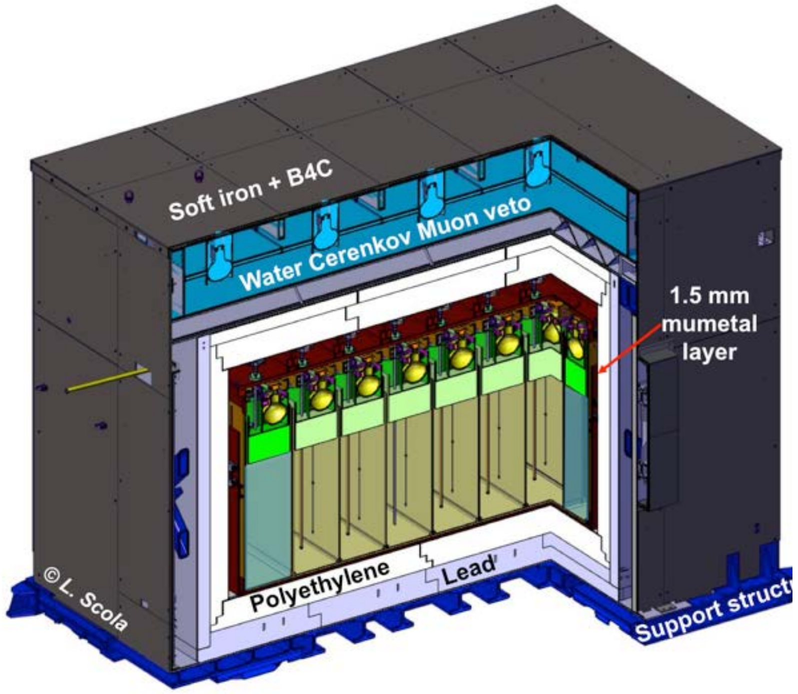
Muon induced



- spallation neutrons (in shielding)
- stopping muons

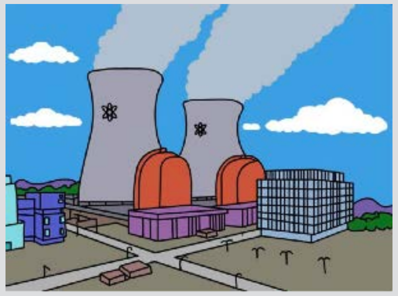
passive shielding





SHIELDING IN STEREO

Reactor Induced

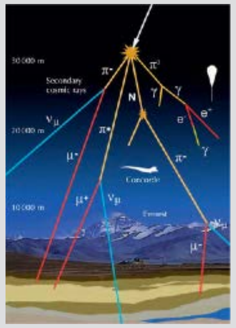


- neutrons
- gamma radiation from n-capture

Environmental Radioactivity

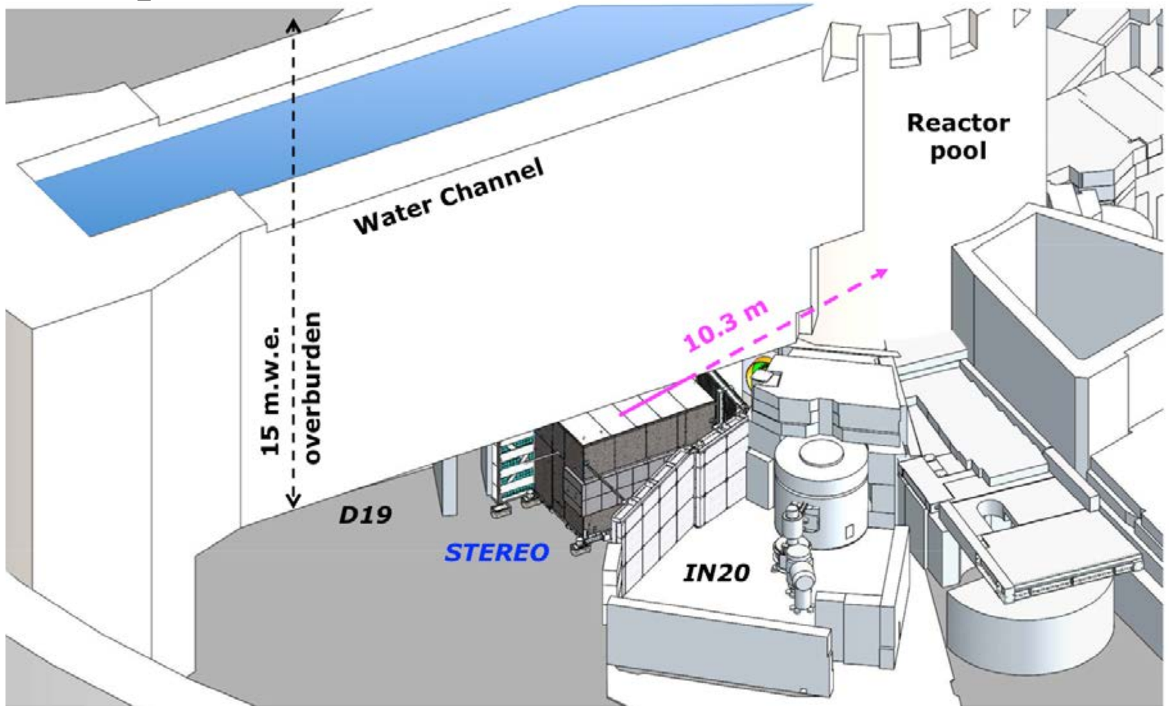
- Thorium/Uranium (concrete)
- Radon/Argon (air)

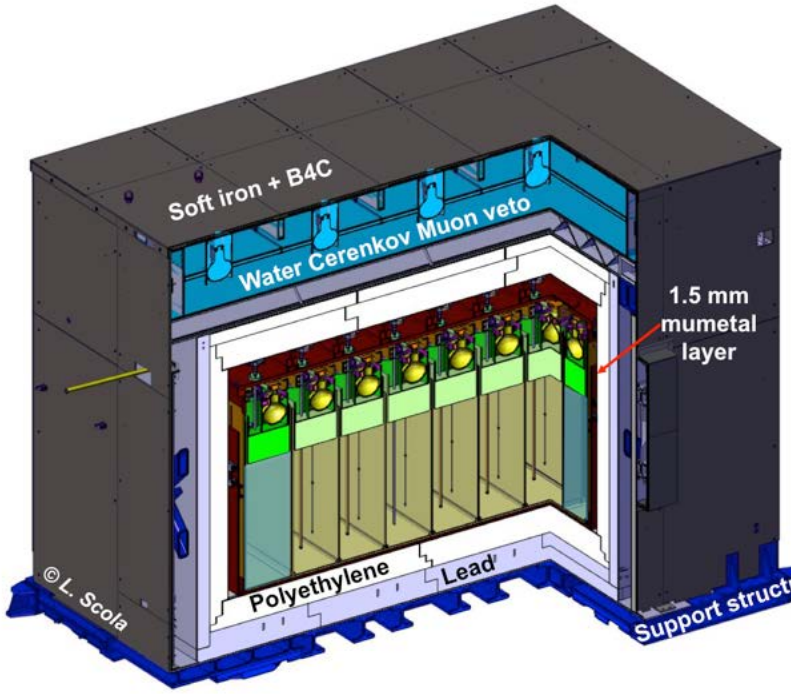
Muon induced



- spallation neutrons (in shielding)
- **stopping muons**

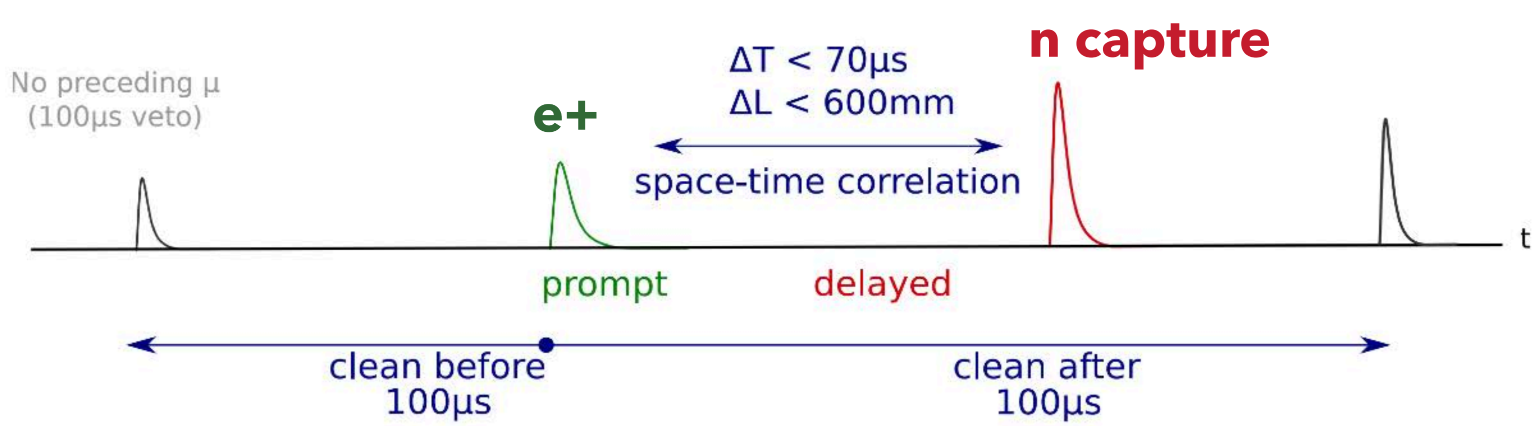
water pool, active veto





ANTINEUTRINO SELECTION AND CORRELATED BACKGROUND

IBD coincidence selection $$\overline{\nu}_e + p \rightarrow e^+ + n$$



Prompt:

- $1.6 < E_{prompt} < 7.1$ MeV
- Prompt contained in a target cell and its 4 neighboring cells

Delayed:

- $4.5 < E_{delayed} < 10$ MeV

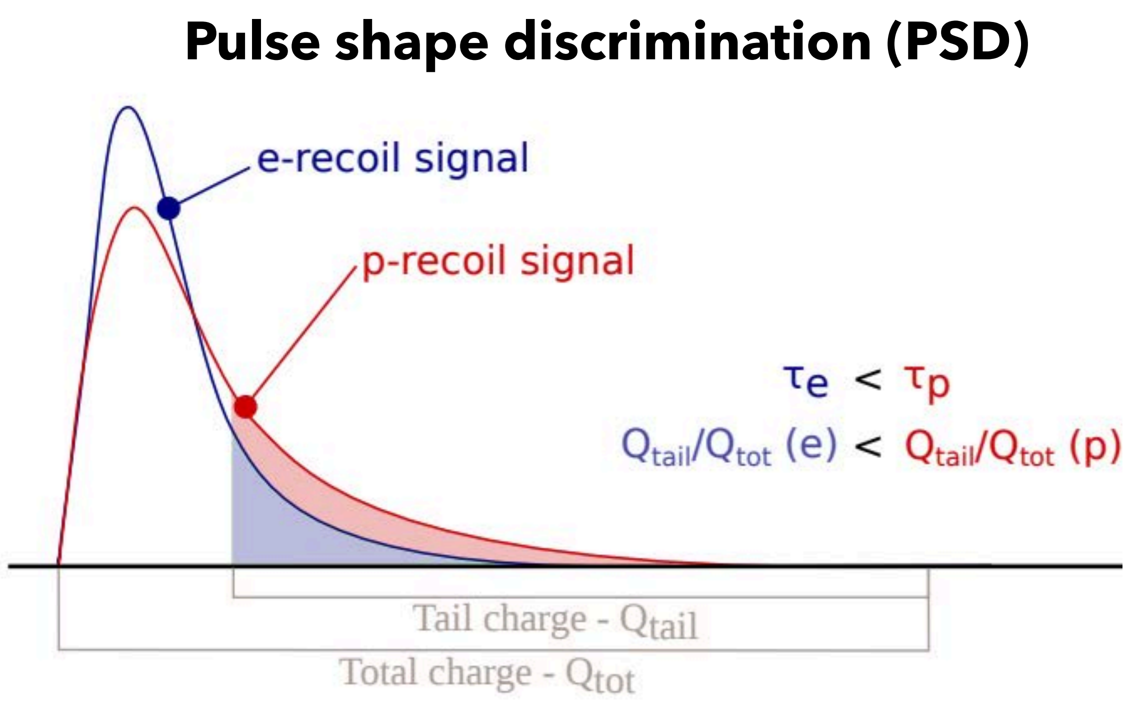
Cosmic rejection:

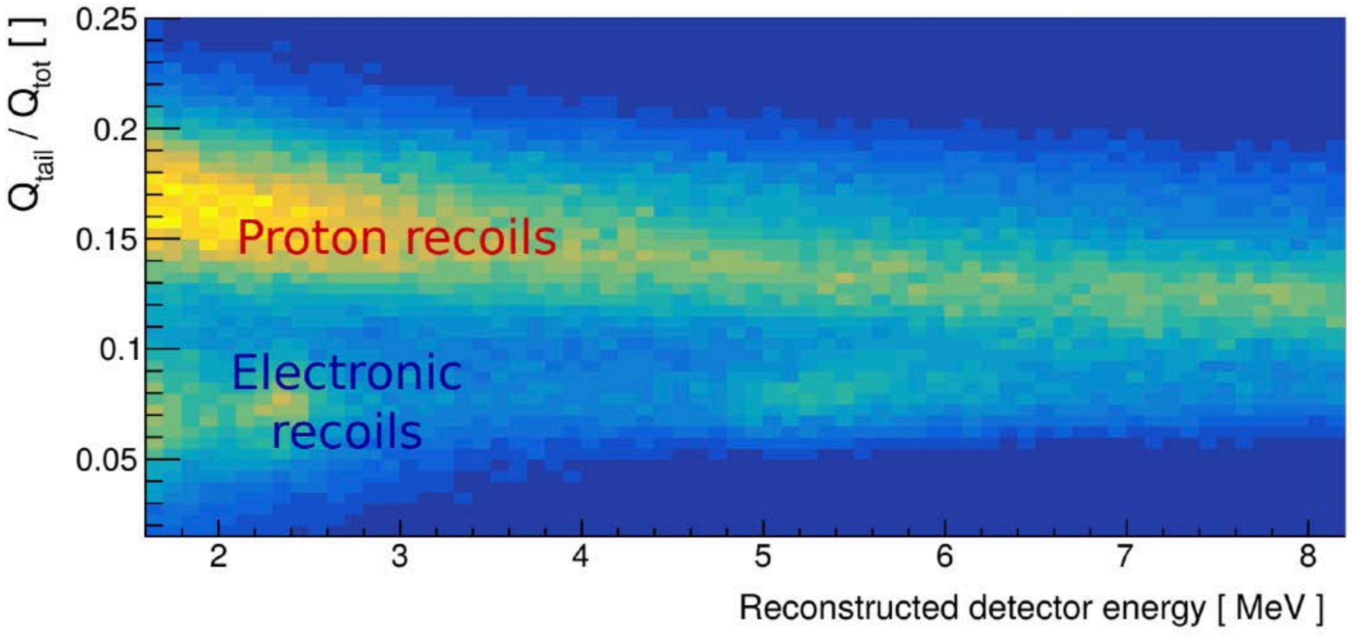
- **Muons**: Veto 100µs after each detected muon
- **Fast neutrons/multiple neutron captures:** Isolation cut of 100µs after and before prompt
- **Stopping muons**: Cut high asymmetry of the light collection in the vertex cell

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

Pulse shape discrimination for prompt signal: background estimation for neutron induced reactions

PULSE SHAPE DISCRIMINATION

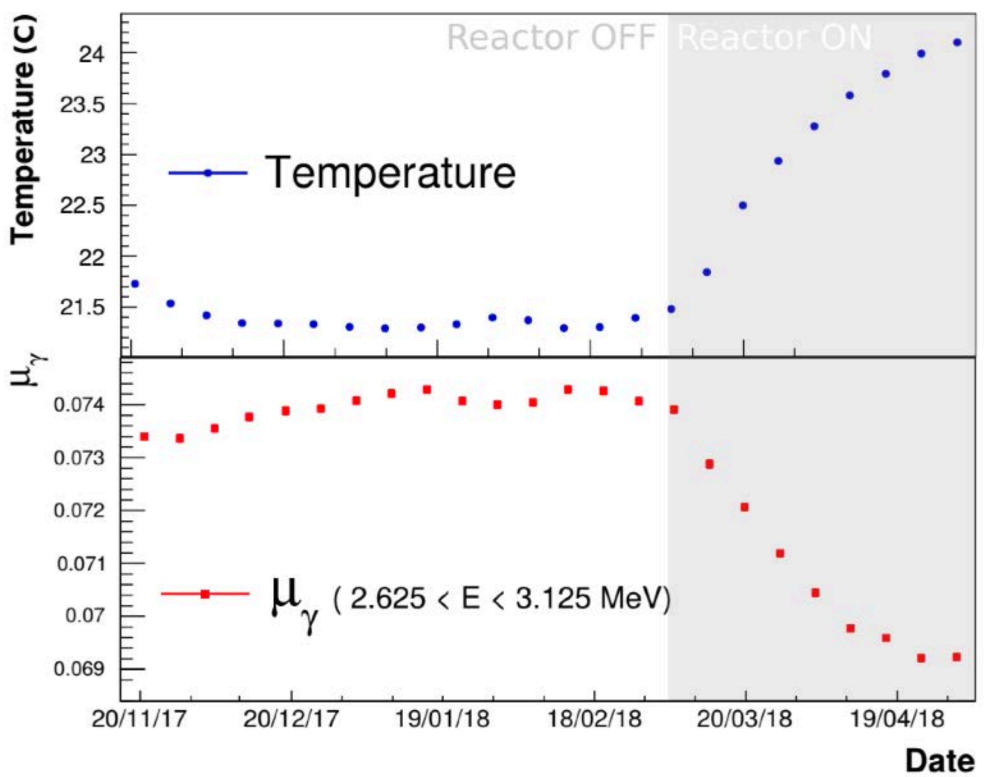




allow us to distinguish background events (neutron induced reactions) with real positron interactions

But PSD follows **temperature changes**

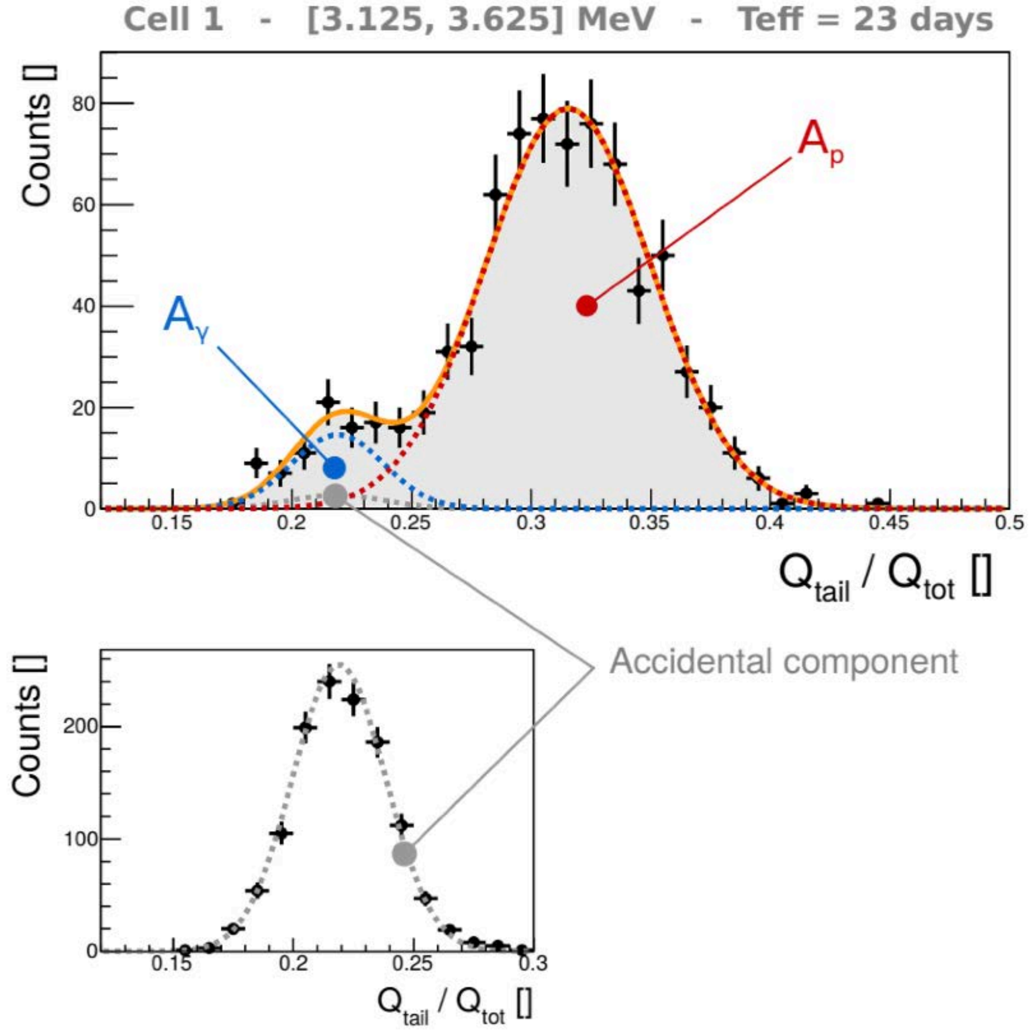
- *seasons* and when *reactor going on or off* (lasting for several weeks)
- A PSD cut does not permit to have at the same time: a constant neutrino acceptance and a constant background rejection



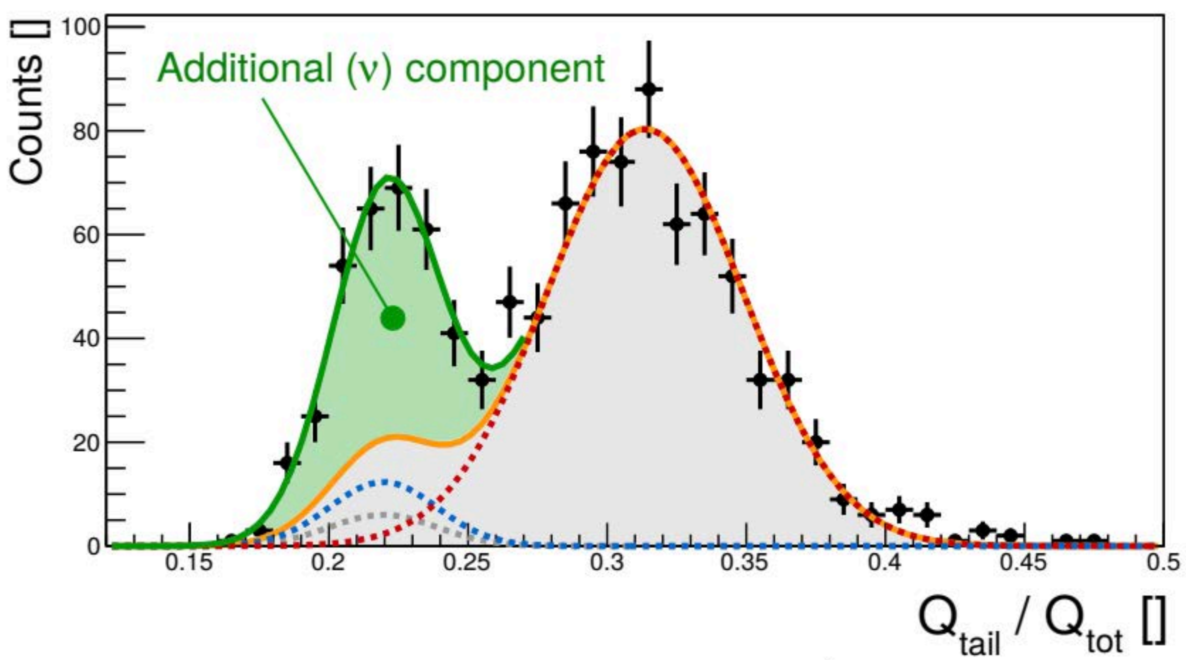
ANTINEUTRINO SIGNAL EXTRACTION: FROM PSD DISTRIBUTION

→ **Solution: fit PSD distributions to extract neutrino rates**

Reactor OFF



Reactor ON



Multi-Gaussian fit for each cell / energy / time bin

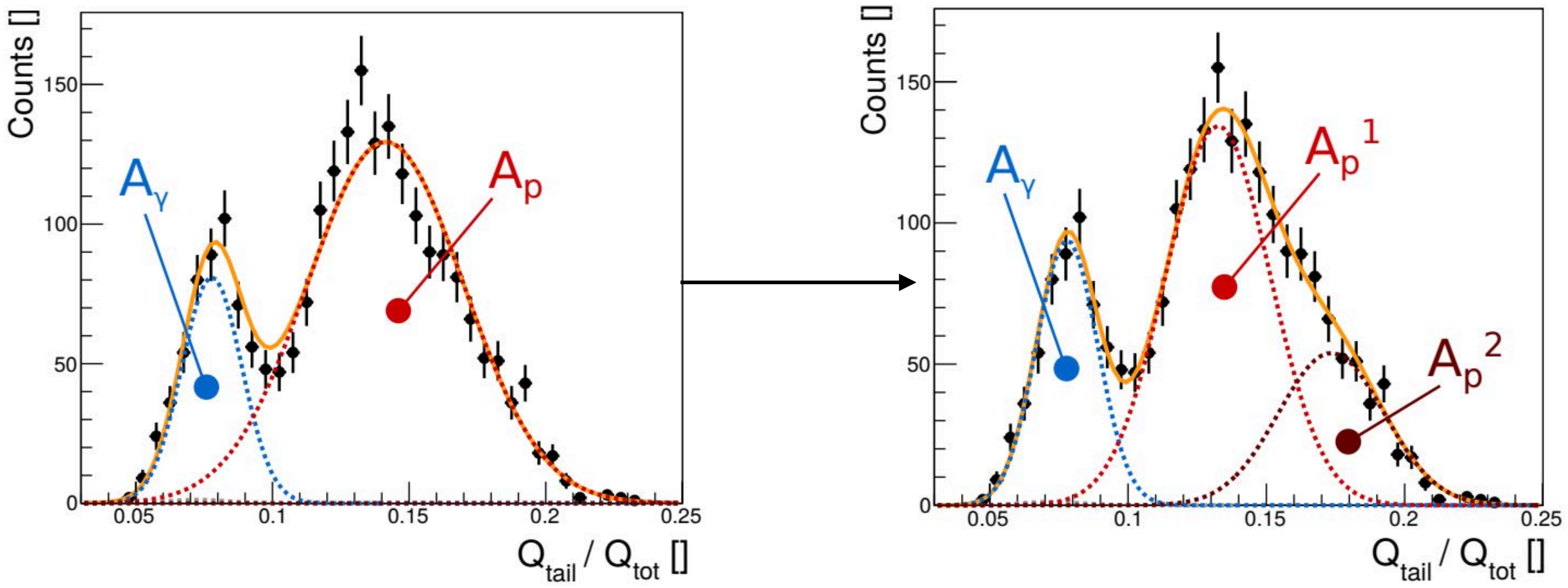
Aγ/**Ap** ratio constrained by the OFF model

Self-consistent method to estimate background under component:

- **Adapt** to **PSD variations** (temperature sensitivity)
- Local rescaling to **global norm** (pressure sensitivity)

ANTINEUTRINO SIGNAL EXTRACTION: FROM PSD DISTRIBUTION

Phase-II: Updated background model with increased statistics (large time binning)



A second component (**Ap**) for p-recoils, anchored relatively to the first one (**Ap**) → Possible physical origin: **multiple proton recoils** (under study)

RELATIVE COMPARISON OF NEUTRINO ENERGY DISTRIBUTION

Oscillation test using **ratio of energy distributions** - **cell 1 taken as reference**

- **Reduced systematics**
- Insensitive to **absolute flux normalization** and **predicted spectrum shape**

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

MC takes into account cells differences, detection efficiencies etc.

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

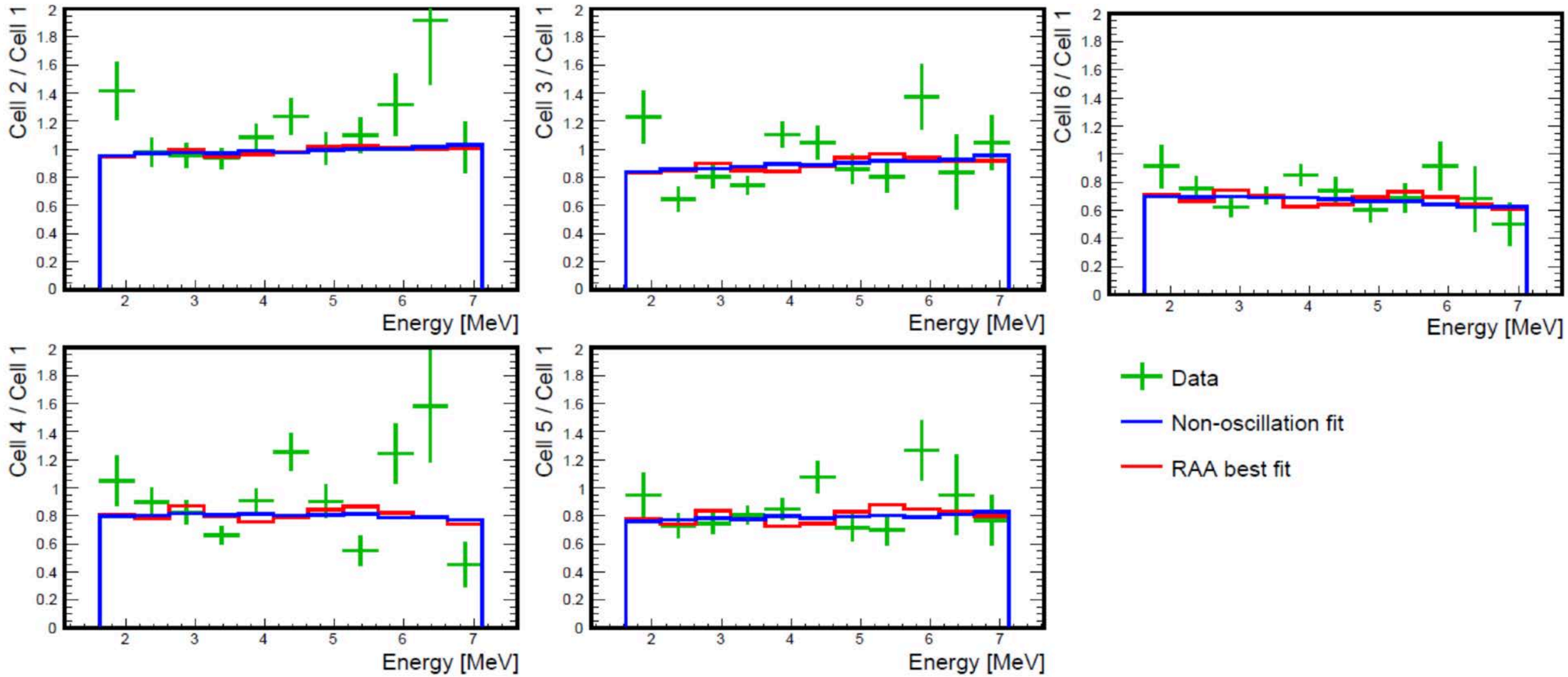
- V_i is the covariance matrix of the 5 ratios (common reference for each cell) for the energy bin i
- **{α}** are nuisance parameters to take into account estimated systematics

Pull terms	Cell-to-cell correlated	Uncorrelated
Energy scale	0.35%	1.00% from energy scale
Normalization	-	1.70% from neutron efficiencies

arXiv:1806.02096, STEREO Collaboration

NO OSCILLATION HYPOTHESIS TEST

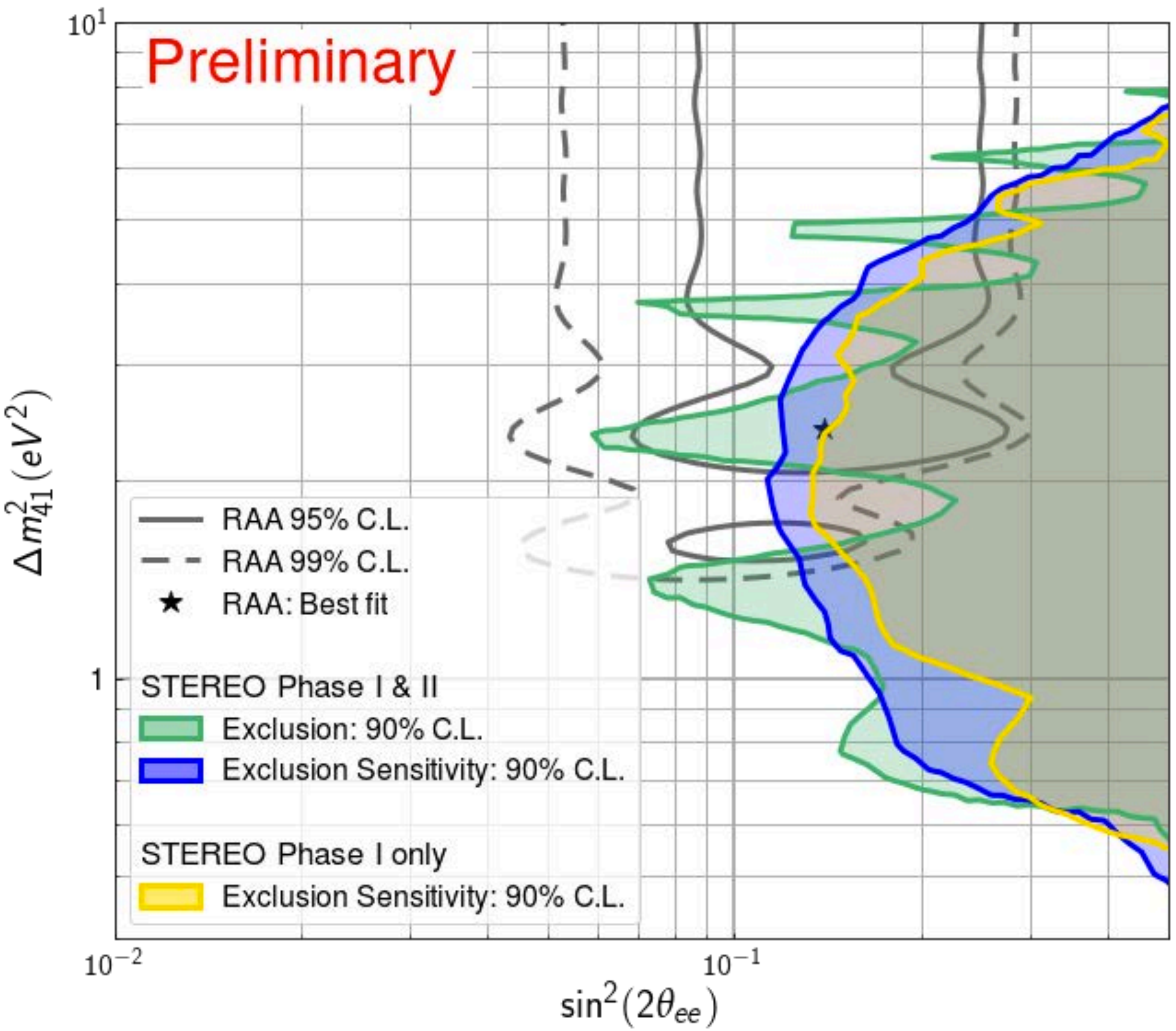
Comparison between cells for data



- Minimized pull terms stay within ± 1 σ
- **Non-oscillation hypothesis (H0) can not be rejected**: **p-value = 34 % for phase-I**

arXiv:1806.02096, STEREO Collaboration

EXCLUSION CONTOURS



- **Phase I and II combined** results **(66 + 47 data days reactor ON)**

Considered as two independent measurements:

$$\chi^2 = \chi^2_I(\vec{\alpha}_I) + \chi^2_{II}(\vec{\alpha}_{II})$$

- Raster scan approach ($\Delta\chi^2$ law simulated in each Δm^2 bin)

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

arXiv:1806.02096, STEREO Collaboration

Talk at Neutrino 2018

★: RAA oscillation best fit
$\Delta m^2_{RAA} = 2.3\ eV^2$ - $\sin^2(2\theta_{RAA}) = 0.14$

CONCLUSION

- Stereo is now running under **stable** conditions
- Data taking will continue **until end 2019**, reaching **300 days of reactor-ON data**
- The **correlated background understanding** improves using reactor-OFF periods
- Exclusion contour obtained using the robust ratio method, **rejects** the original **RAA best fit value** is at **98% CL** using a ratio comparison insensitive to bias in spectra prediction arXiv: 1806.02096, STEREO Collaboration (submitted and accepted at PRL)
- Improved results are coming **soon**, with a **pure ^{235}U spectrum**

thanks for your attention

THE STEREO COLLABORATION

STEREO

DE LA RECHERCHE À L'INDUSTRIE

Irfu

cea

NEUTRONS FOR SOCIETY

LAPP

Laboratoire d'Annecy-le-Vieux de Physique des Particules

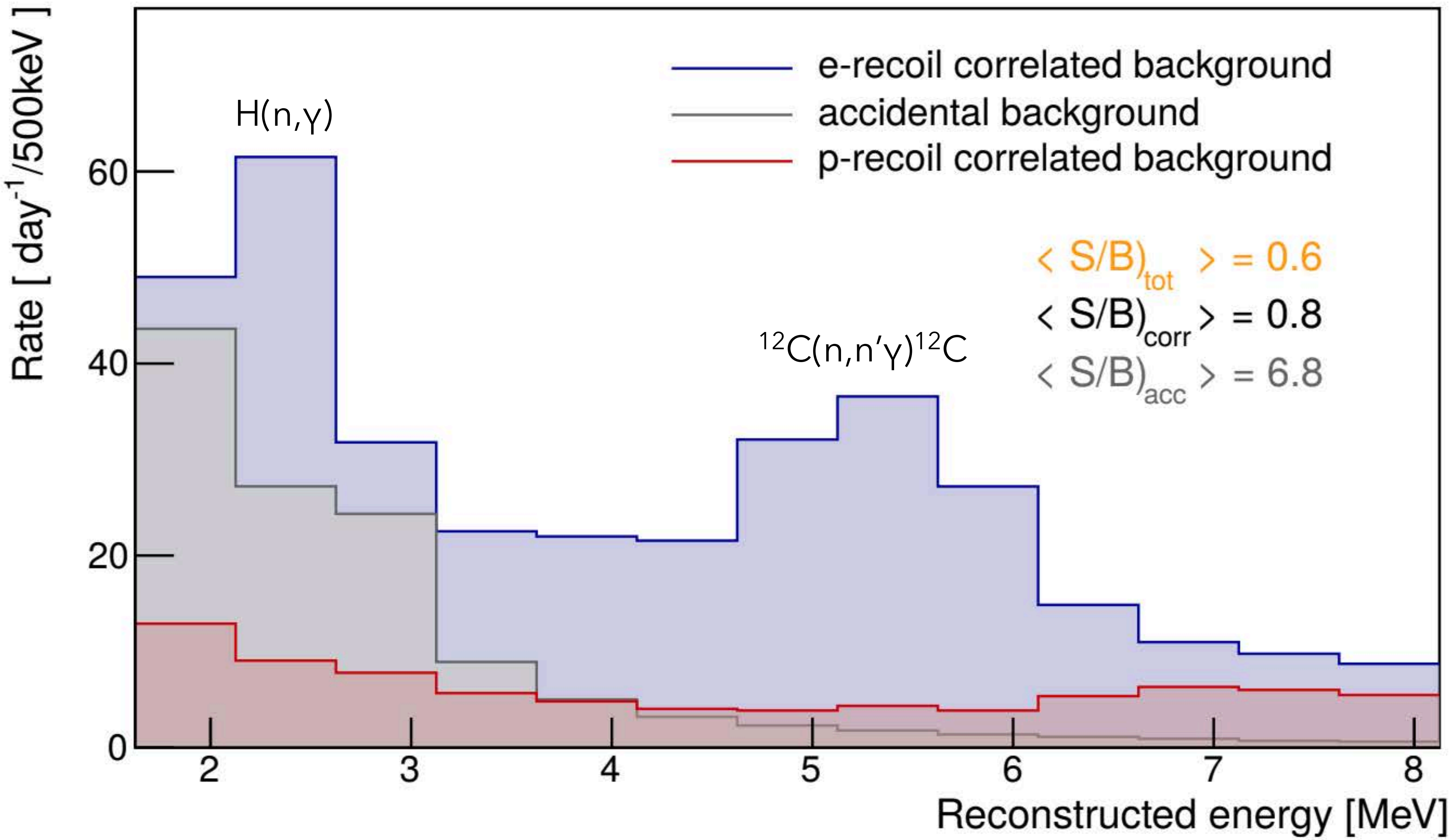
LPSC Grenoble

Max-Planck-Institut für Kernphysik Heidelberg

BACK-UP

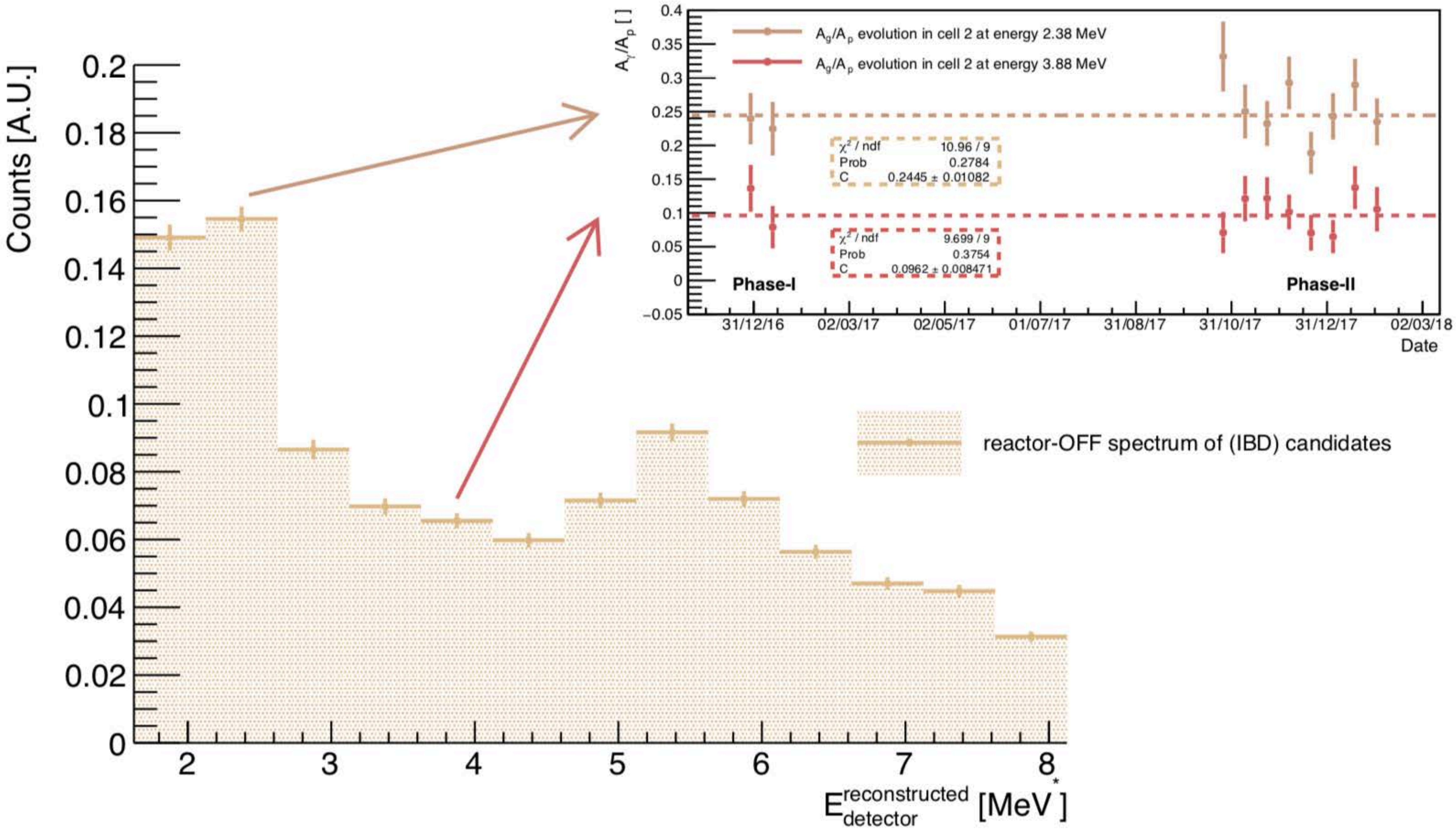
BACKGROUND SPECTRUM

Reactor OFF prompt energy spectrum

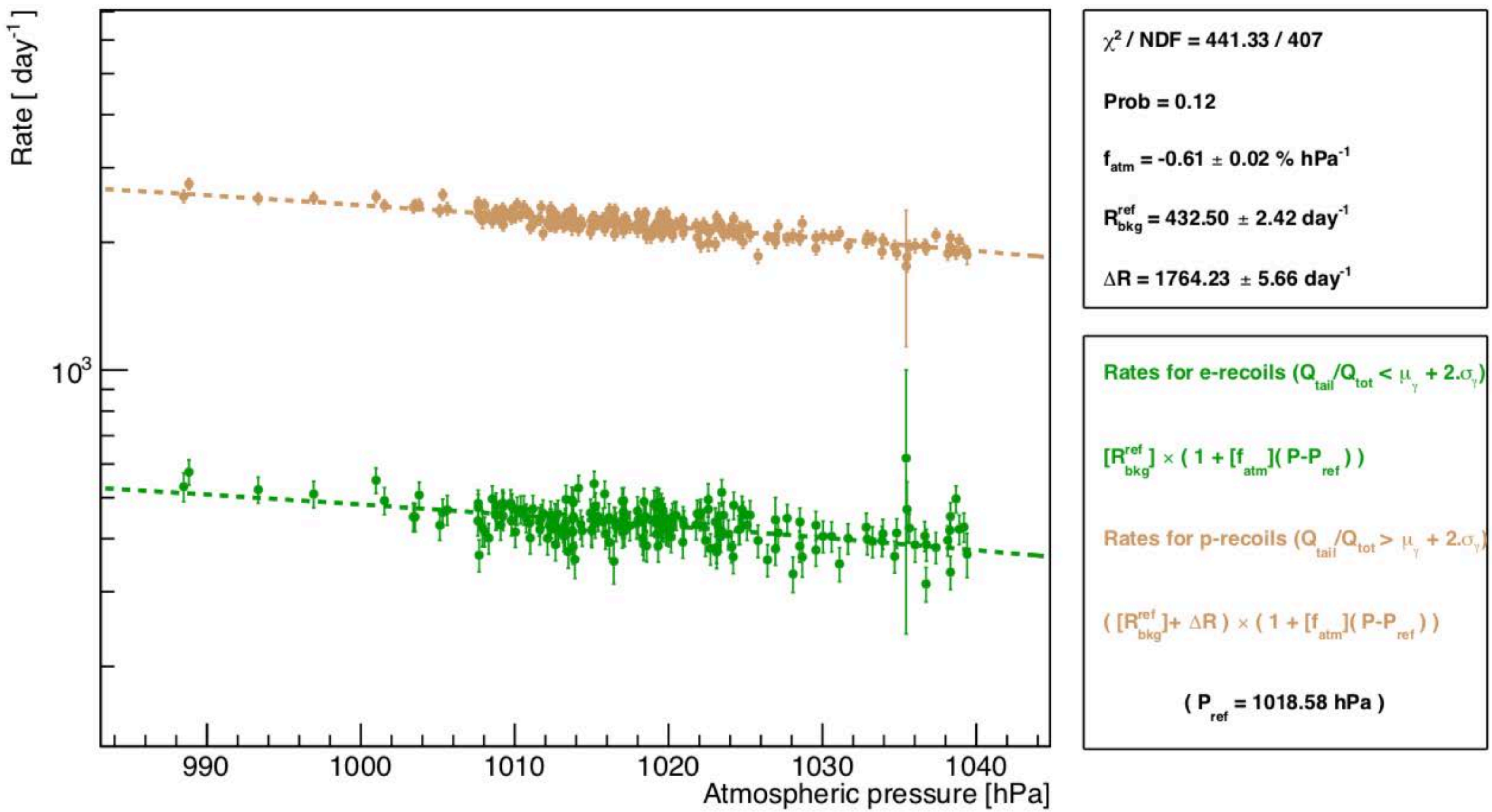


both prompt and delayed are **neutron captures**

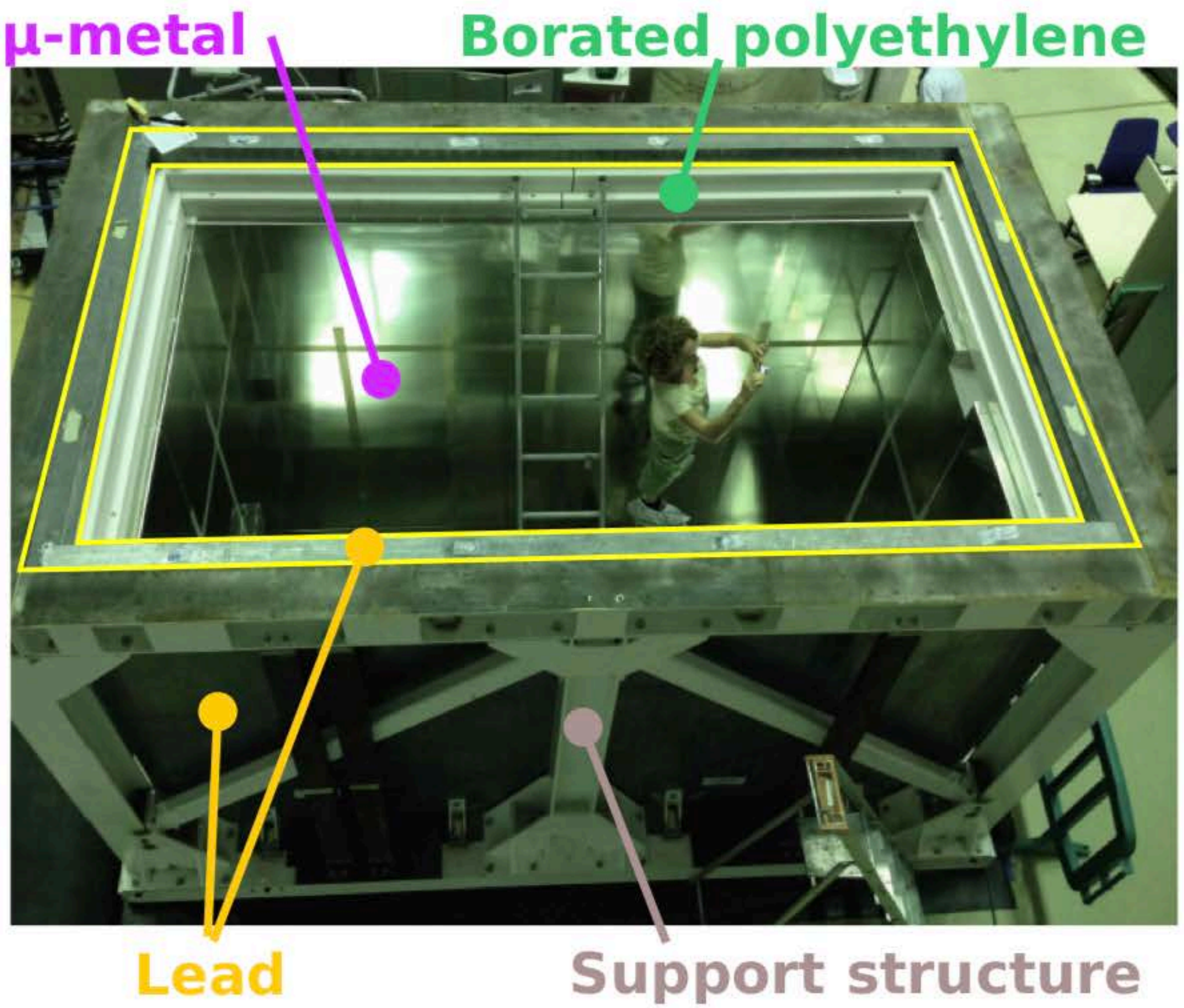
BACKGROUND SPECTRUM



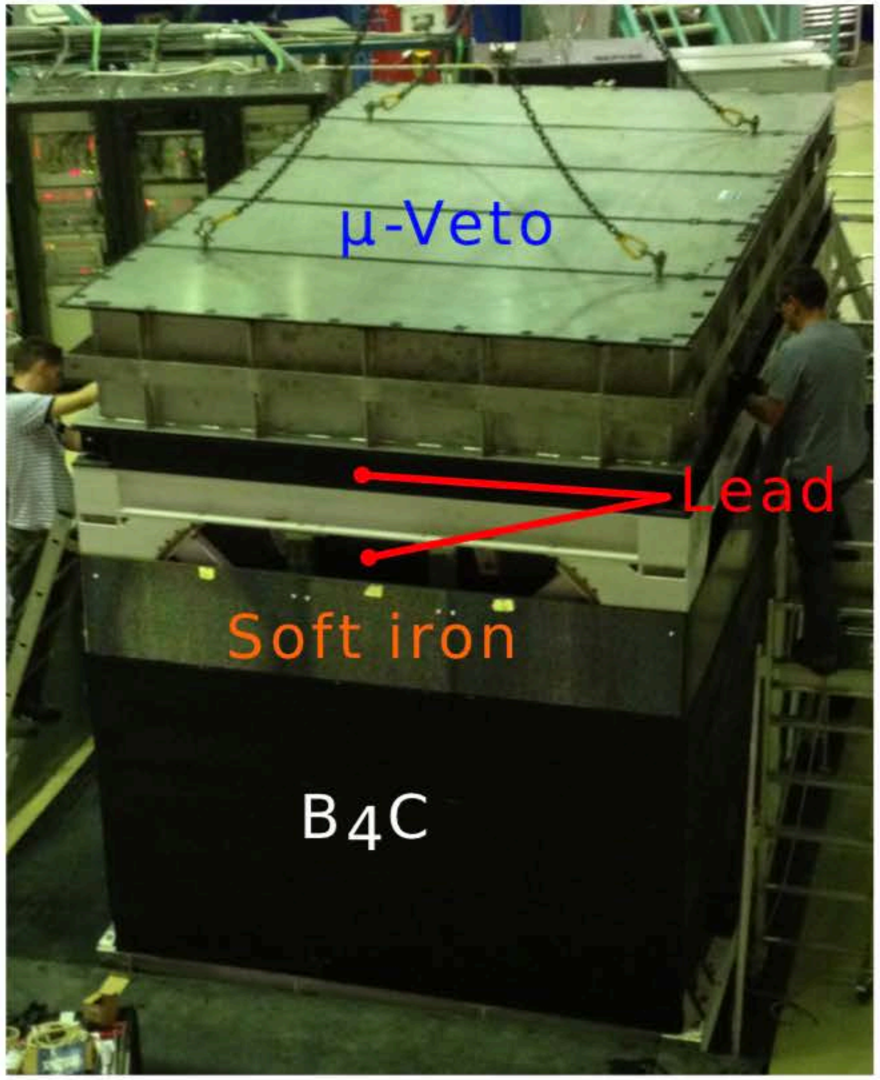
BACKGROUND SPECTRUM



SHIELDING

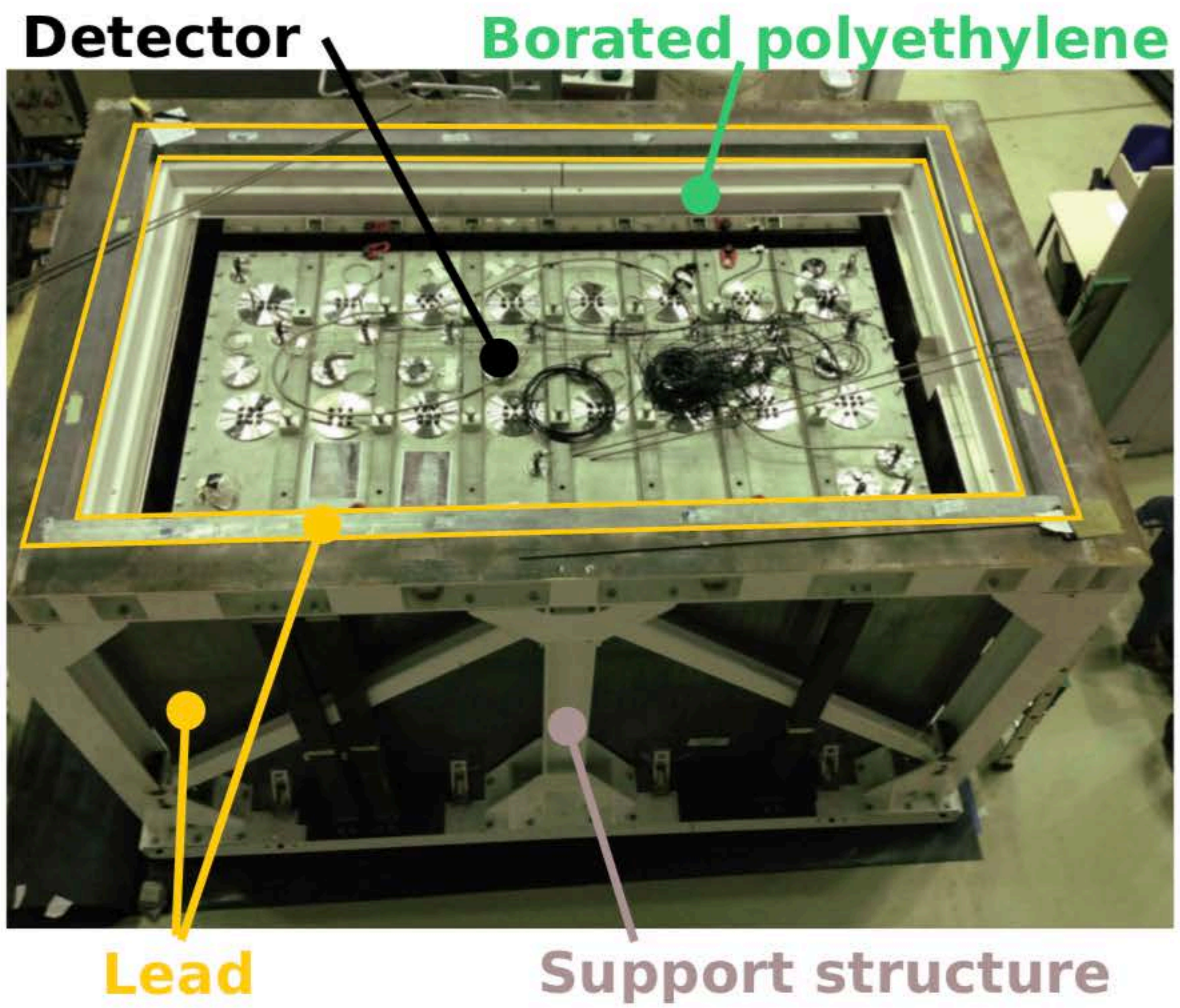


μ-metal
Borated polyethylene
Lead
Support structure

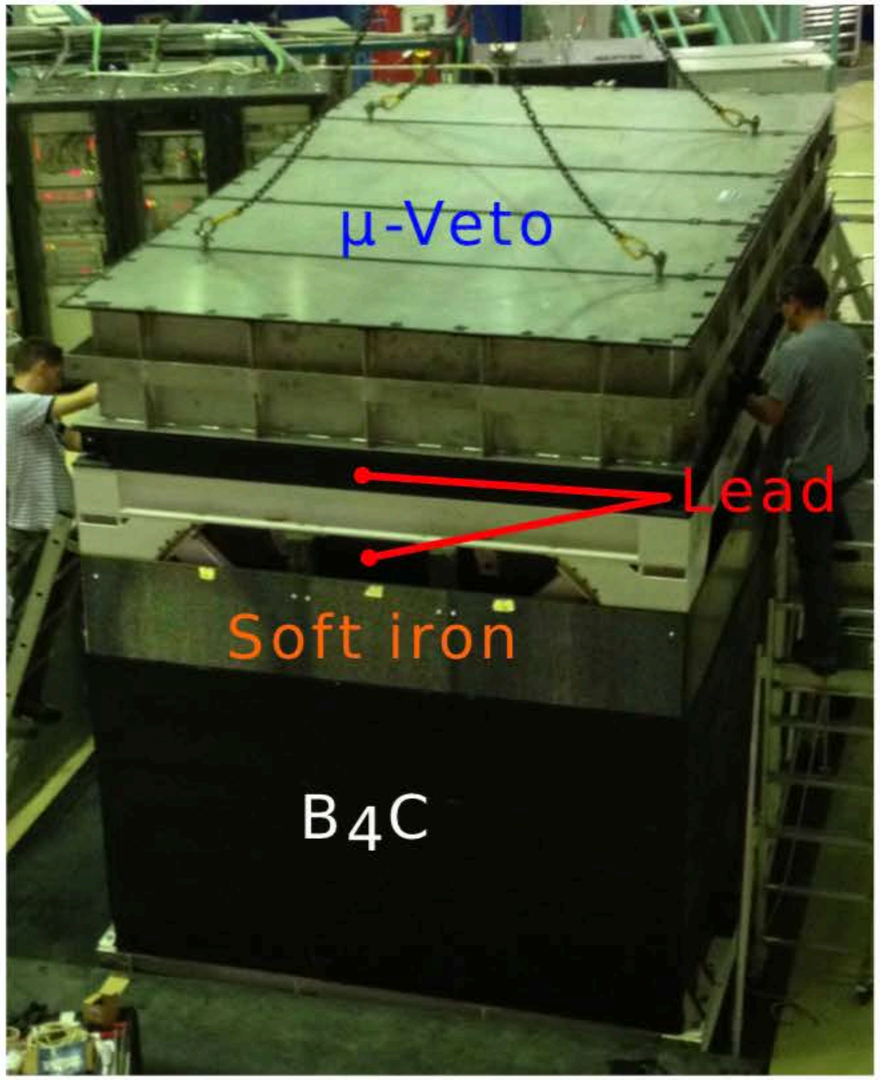


μ-Veto
Lead
Soft iron
B4C

SHIELDING

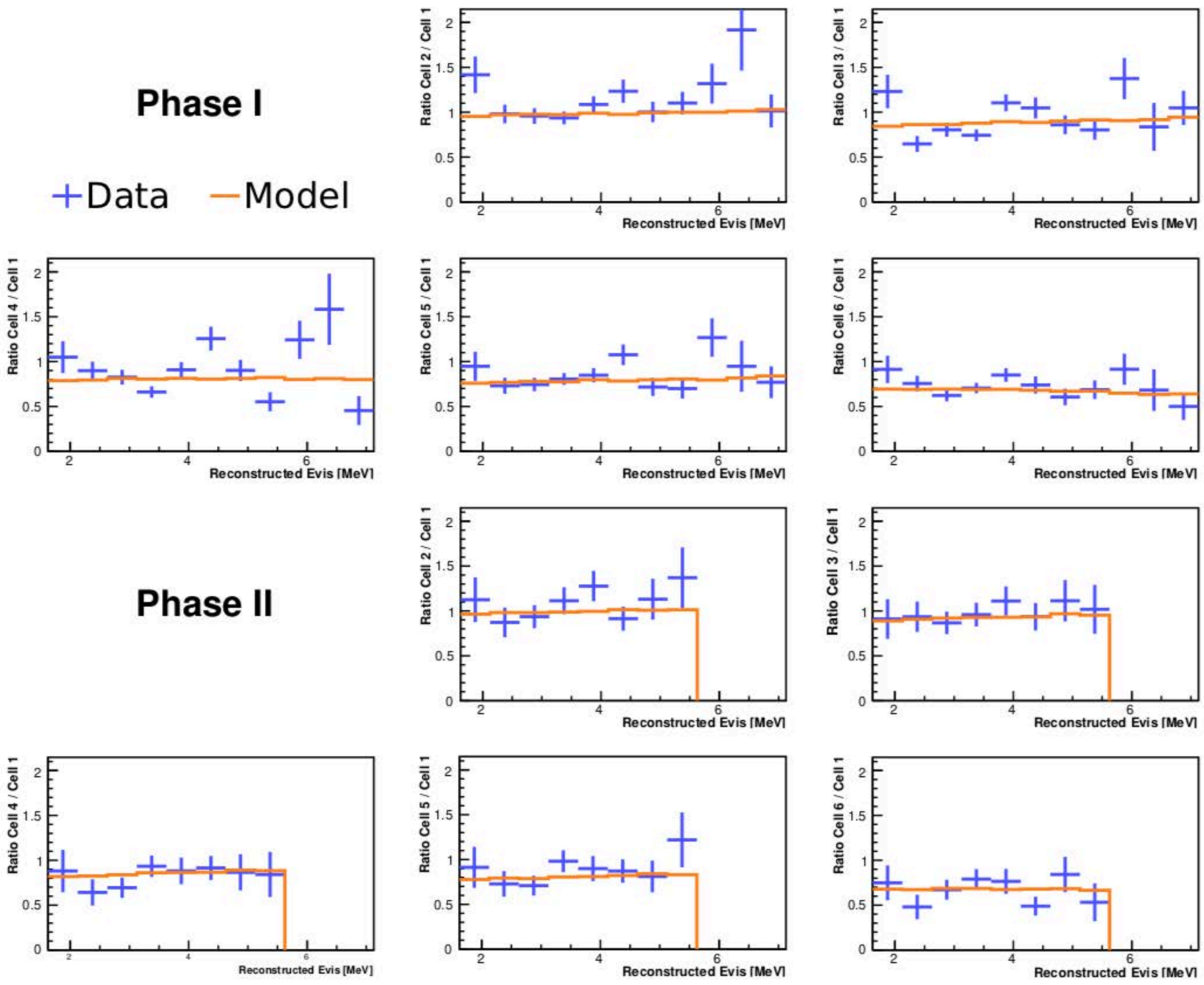


Detector
Borated polyethylene
Lead
Support structure



μ-Veto
Lead
Soft iron
B4C

FIT



Phase I
Data
Model
Phase II
Ratio Cell 2 / Cell 1
Ratio Cell 3 / Cell 1
Ratio Cell 4 / Cell 1
Ratio Cell 5 / Cell 1
Ratio Cell 6 / Cell 1
Reconstructed Evis [MeV]

SENSITIVITY CONTOUR

complete detector response simulated

included systematics:

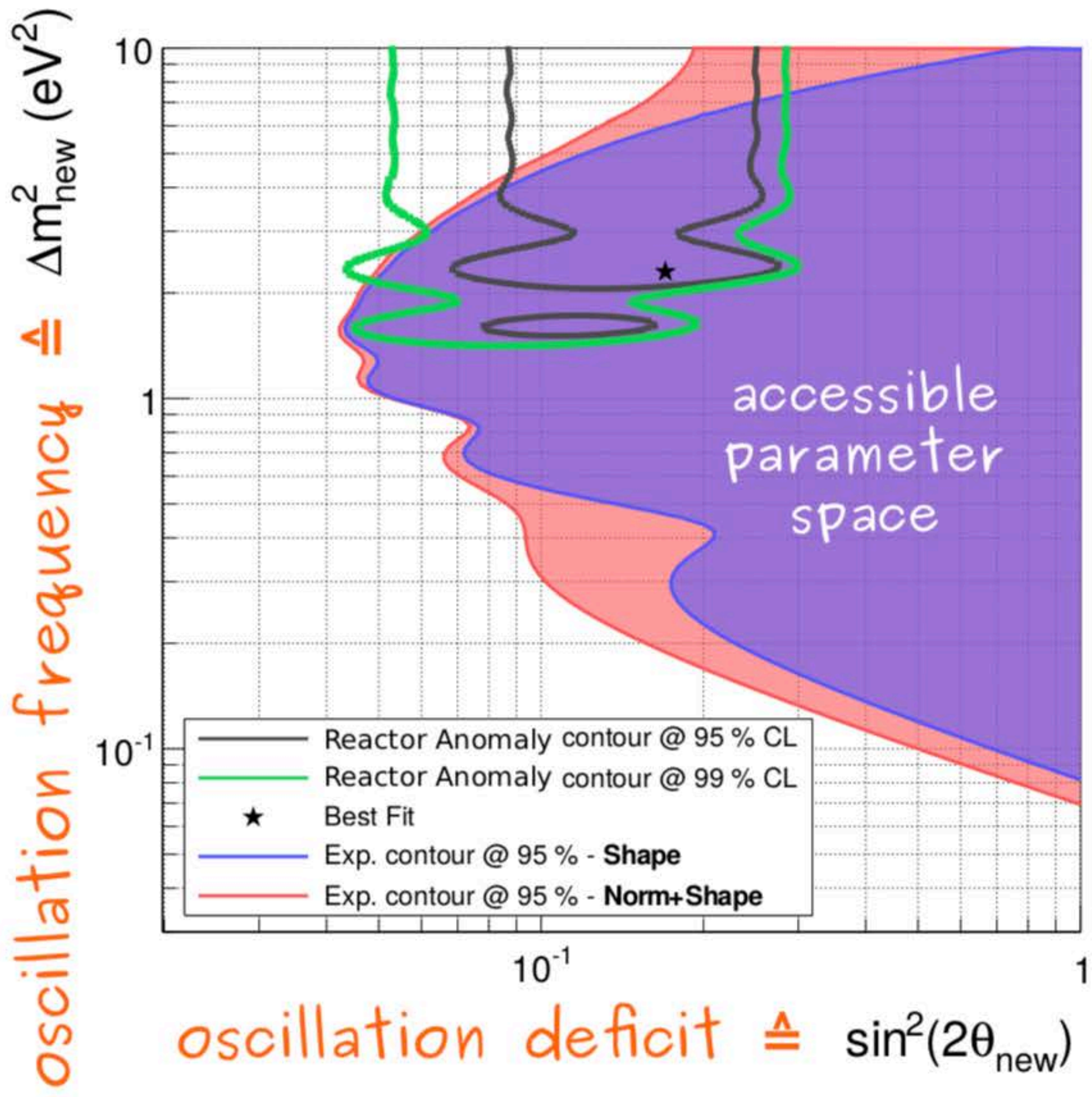
neutrino spectra, detection & reconstruction

prompt signal: E > 2 MeV

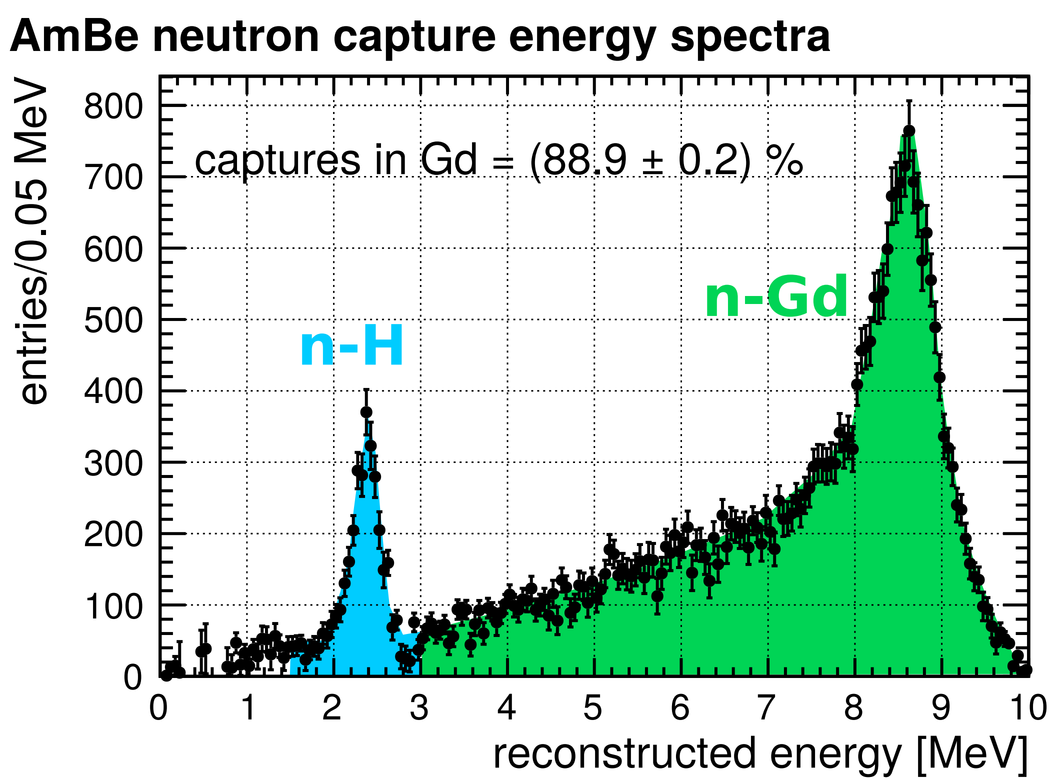
delayed signal: E > 5 MeV

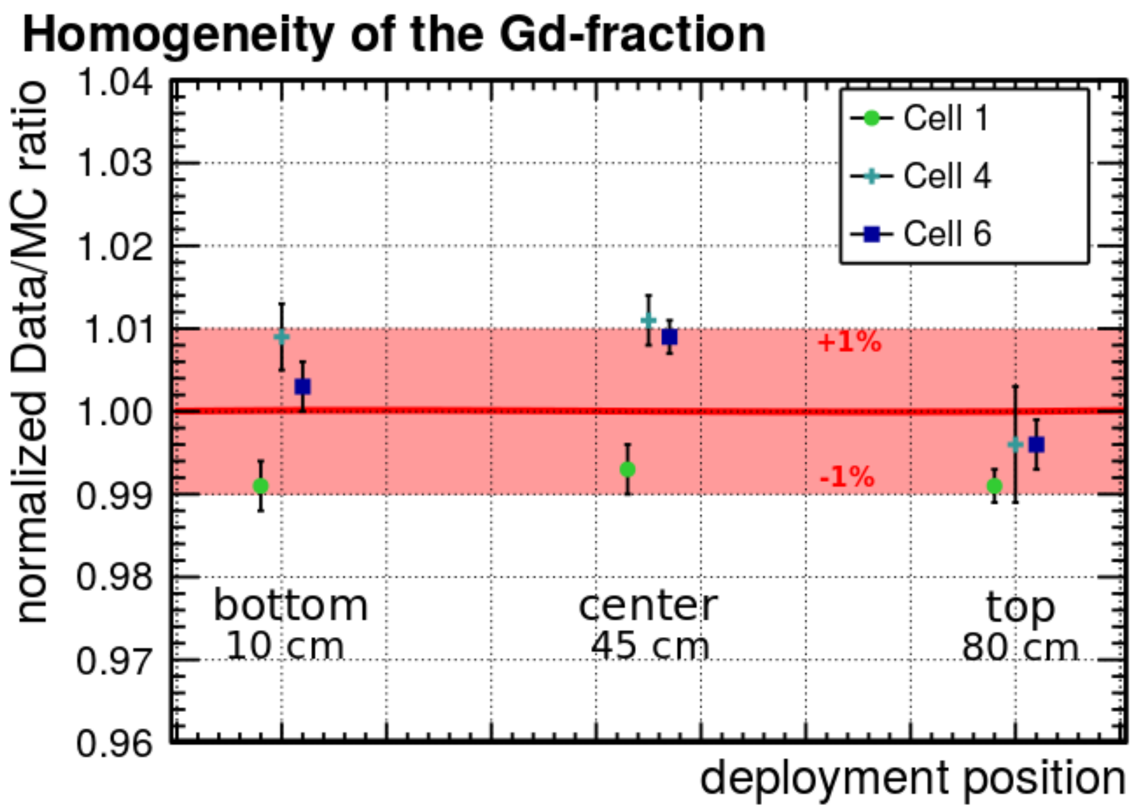
S/B = 1.5

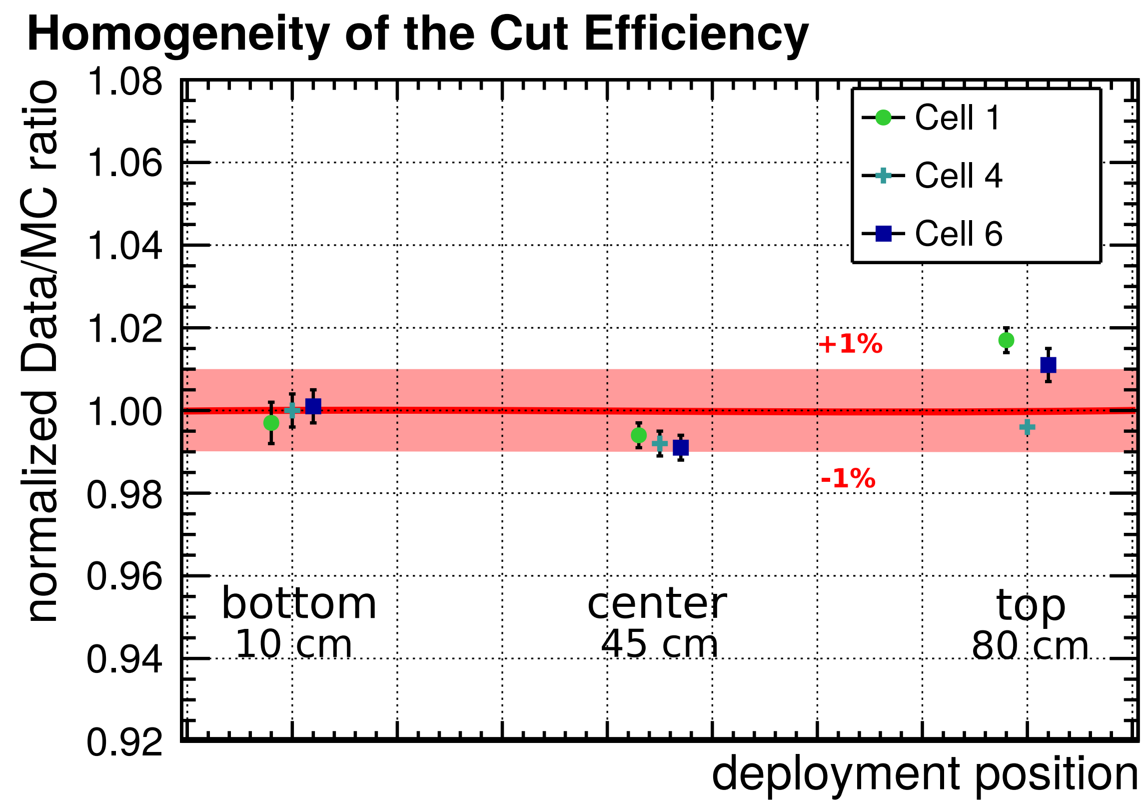
300 live-days
(6 reactor cycles)



NEUTRON EFFICIENCY STUDIES







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-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 %