THE SEARCH FOR EV STERILE NEUTRINOS WITH THE STEREO EXPERIMENT

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ON BEHALF OF THE STEREO COLLABORATION

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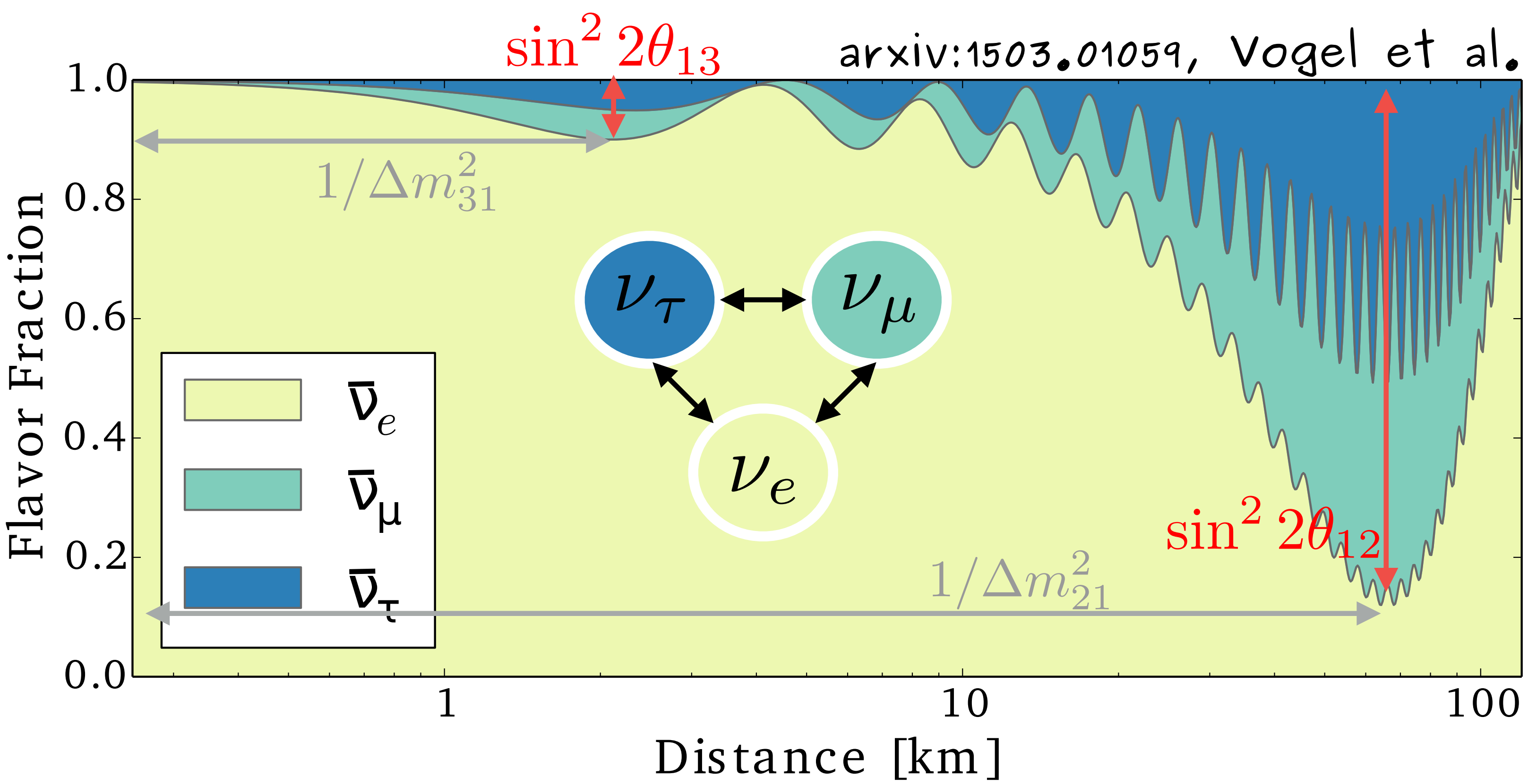
NEUTRINO OSCILLATIONS

Produced: ν_e, ν_μ, ν_τ

Propagation: ν_1, ν_2, ν_3

Detected: ν_e, ν_μ, ν_τ

$$|\nu_\alpha(t)\rangle = e^{-it\mathcal{H}} |\nu_\alpha(0)\rangle = \sum_j e^{-itE_j} \,\mathcal{U}_{\alpha j} \,|\nu_j\rangle$$



$\Delta m^2_{13}, \Delta m^2_{23}, \Delta m^2_{12}$

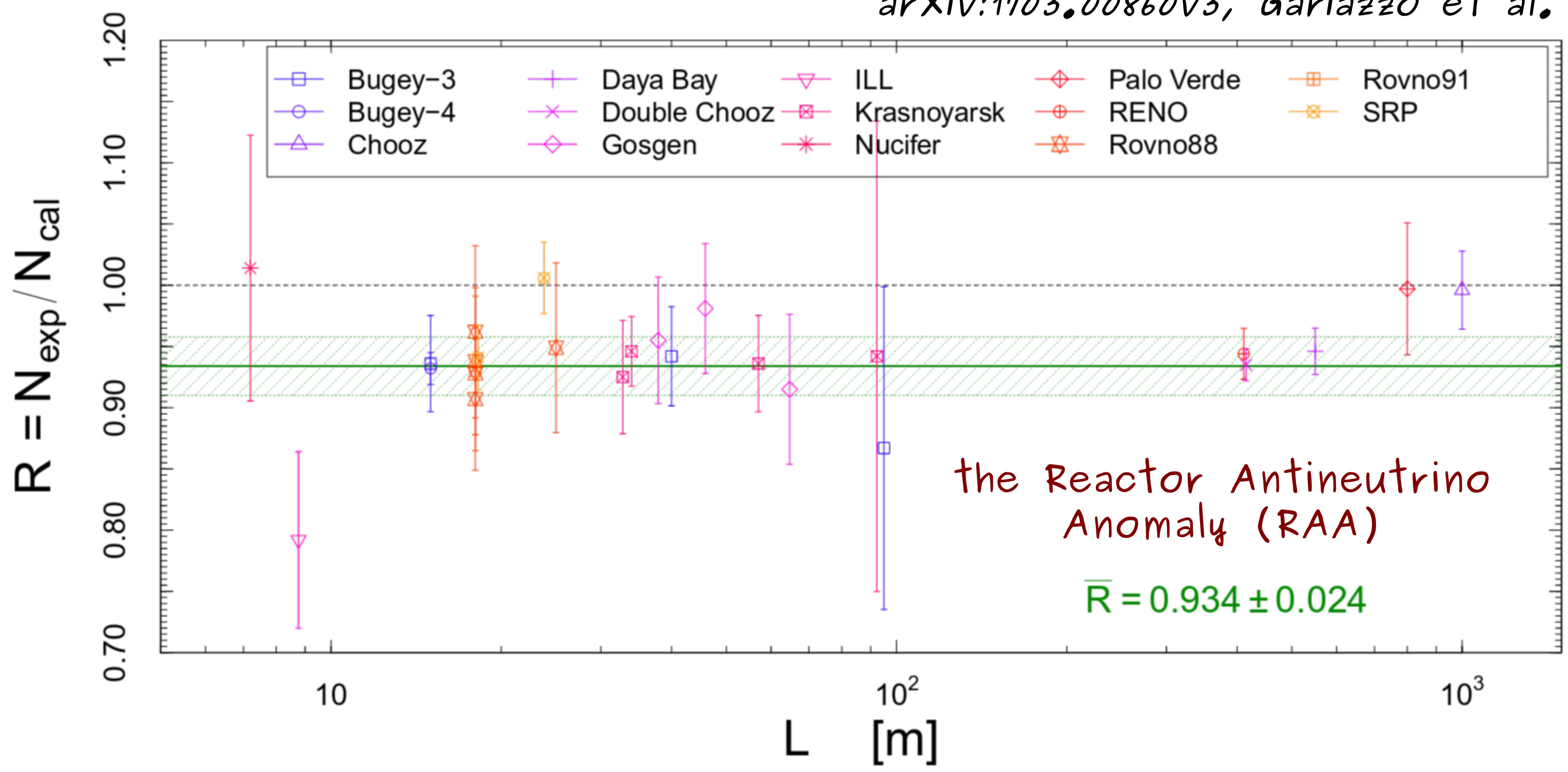
$\mathcal{U} \equiv$ PMNS Matrix

$\theta_{13}, \theta_{23}, \theta_{12}, \delta$

REACTOR ANTINEUTRINO ANOMALY

arXiv:1703.00860v3, Gariazzo et al.

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



→ **wrong prediction?**

inaccuracies in the beta-converted/*ab initio* $\bar{\nu}_e$ flux model of **^{235}U, ^{239}Pu, ^{241}Pu / ^{238}U**

→ **sterile neutrino hypothesis?**

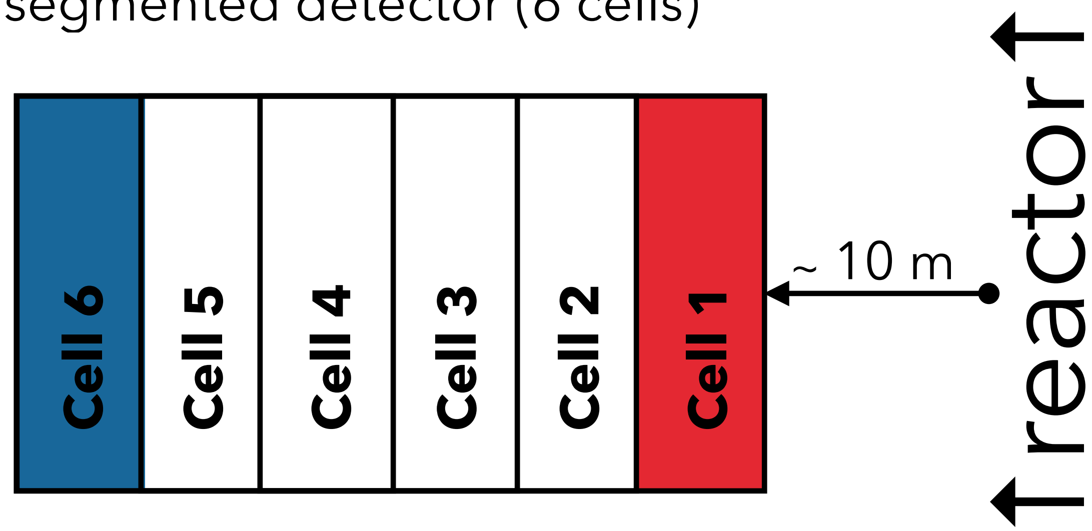
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(E_{\bar{\nu}_e}, L) = 1 - sin^2(2\theta_{new})sin^2\left(1.27\frac{\Delta m^2_{new}[eV^2]L[km]}{E_{\bar{\nu}_e}[MeV]}\right)$$

~ **1 eV sterile neutrino**

new **oscillation angle** and **mass splitting**

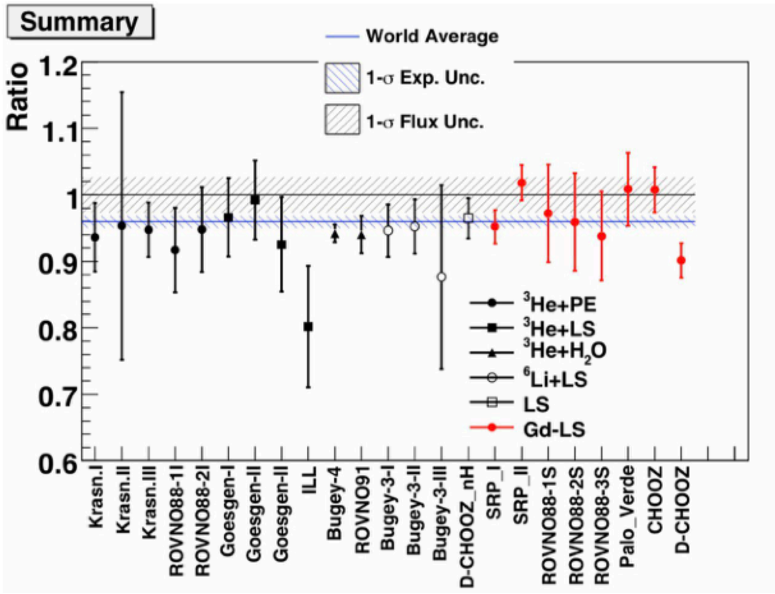
MOTIVATION OF STEREO EXPERIMENT

segmented detector (6 cells)



flux absolute normalization studies

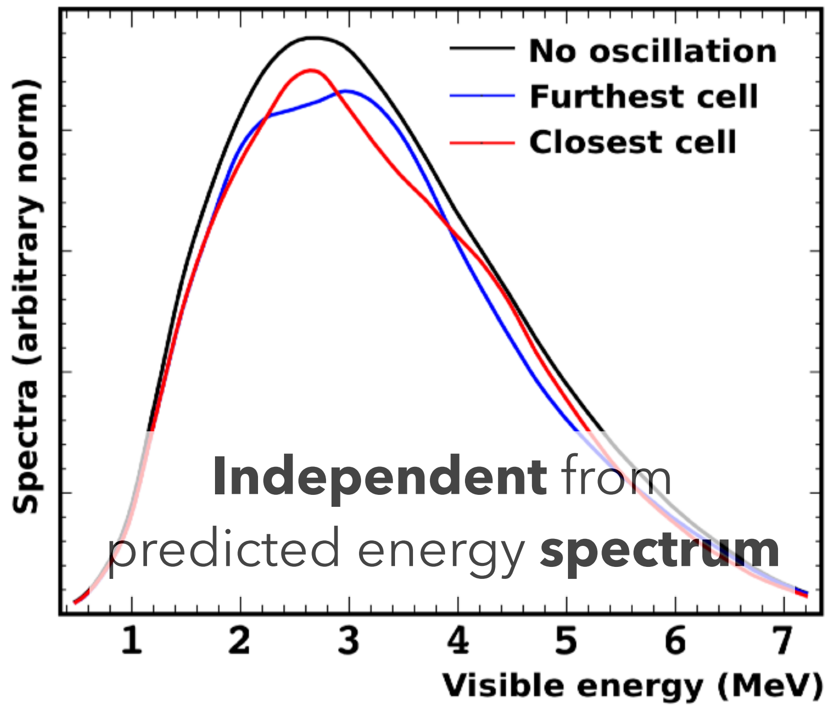
Measurement of abs. rate of. $\bar{\nu}_e$ from HEU reactors



10.1103/PhysRevD.87.073018

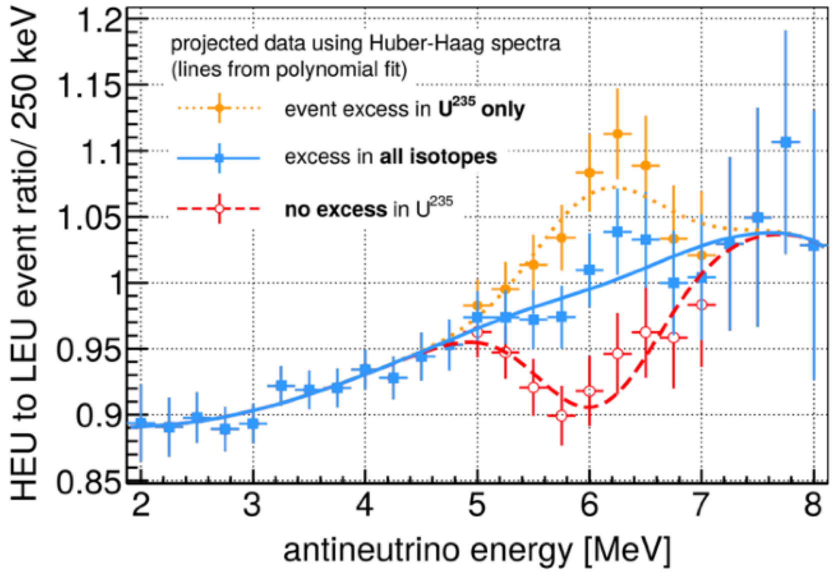
sterile neutrino hypothesis

relative **distortions** of the $\bar{\nu}_e$ energy spectrum as a function of the distance [9-11m]



additional spectral shape studies

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



arXiv: 1512.06656, C. Buck et al.

EXPERIMENTAL SITE - ILL

ILL research reactor

Grenoble (France)

- nominal power 58.3 MW_{therm}

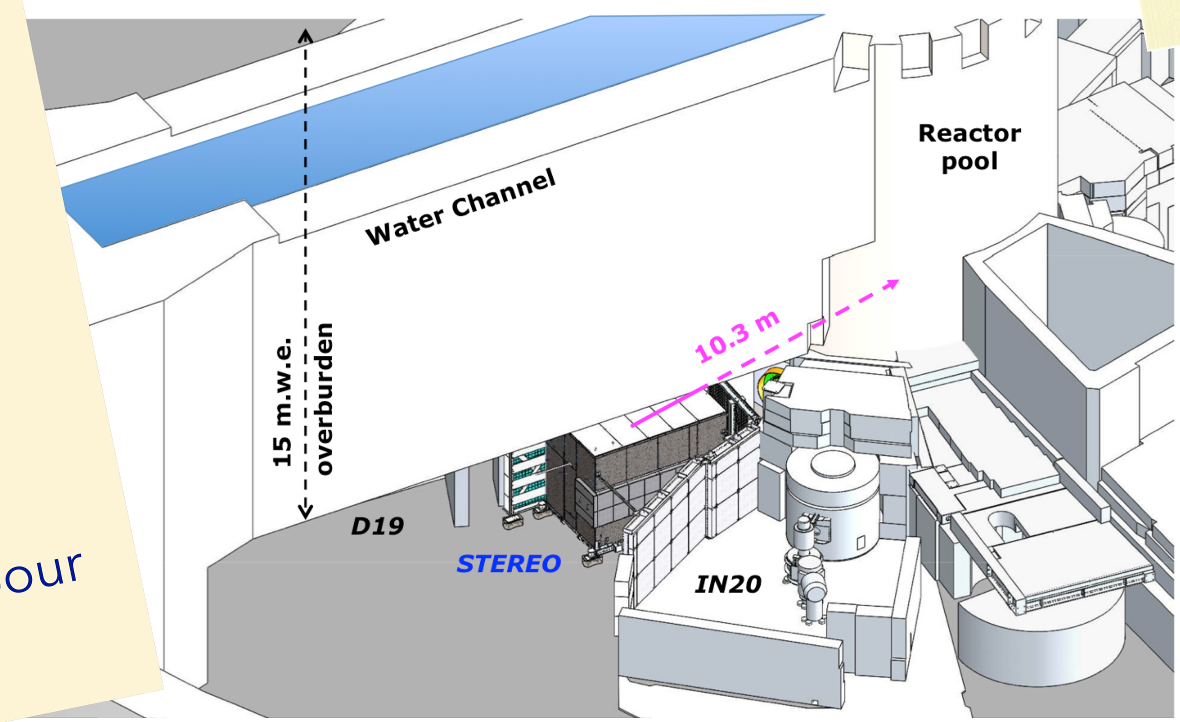
  $10^{19} \cdot \bar{\nu}_e \ s^{-1}$
- compact fuel element

  40cm ∅
- HEU fuel 93% ^{235}U

Experimental site

- short baseline experiment

  8.9m < L < 11.1m
- ground-level experiment
- gamma and neutron background from neighbour experiments



STEREO DETECTOR

Neutrino Target

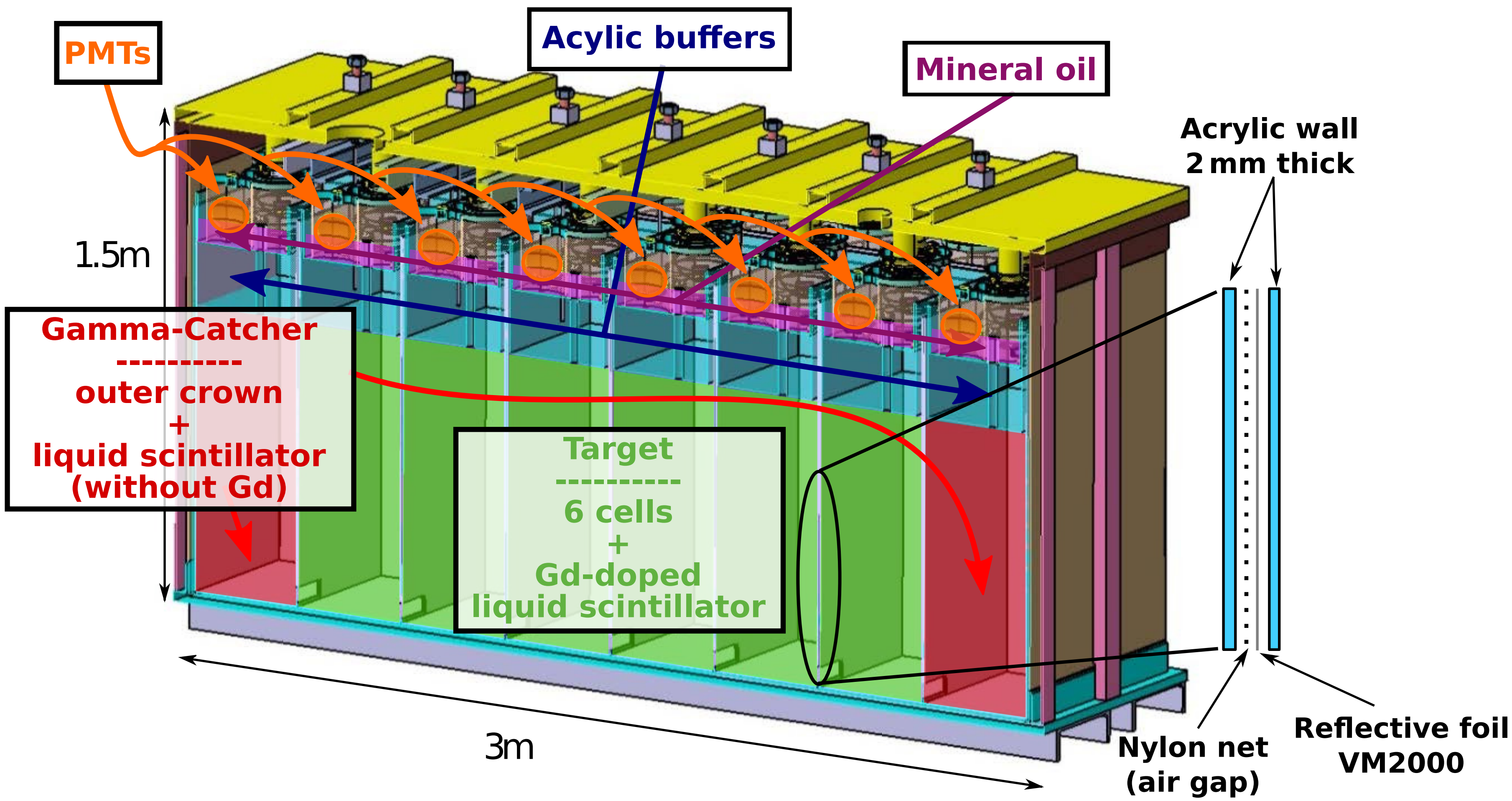
- 2.2 x 1.5 x 0.9 m^3
- Gd-β-diketonate liquid scintillator → good response

Gamma catcher

- Outer crown volume
- filled Gd-free liquid scintillator

Buffer

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



STEREO detector

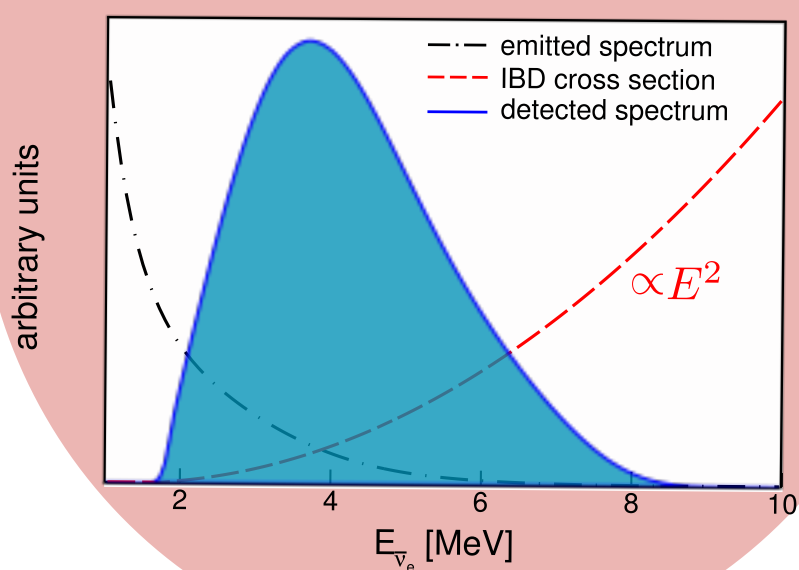
DETECTION PRINCIPLE

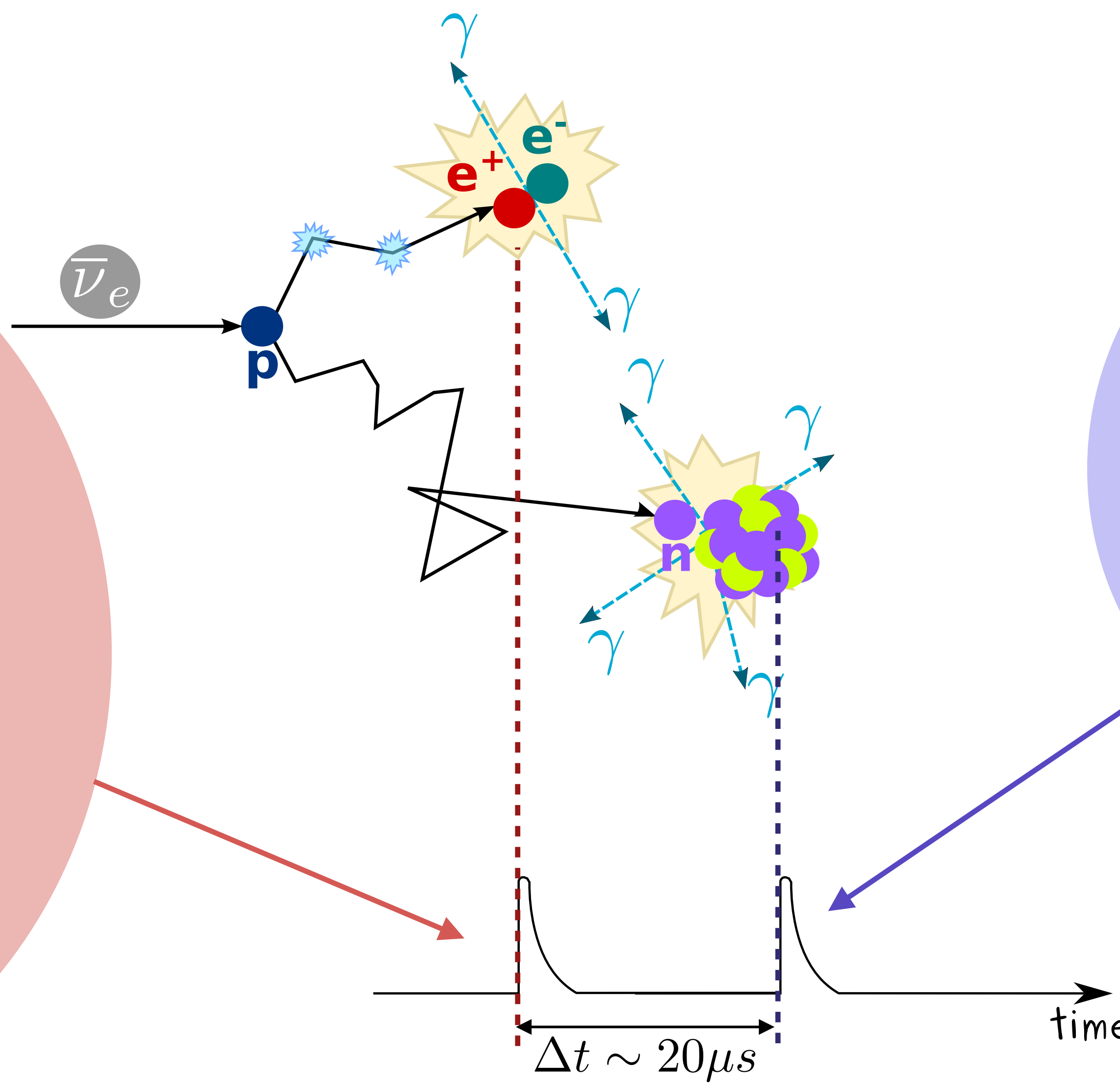
Interaction via
Inverse Beta Decay **IBD** $\overline{\nu}_e + p \rightarrow e^+ + n$

1. Prompt Event

positron annihilation

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



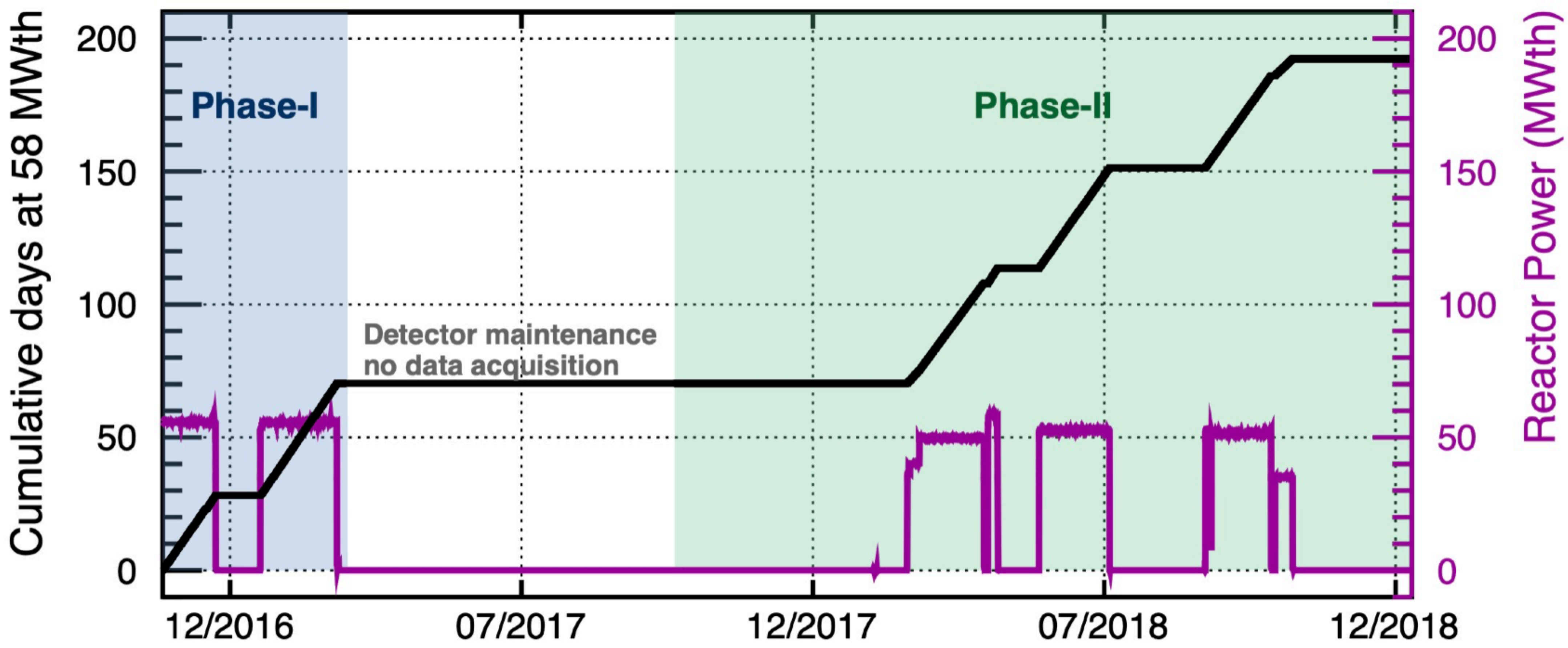


2. Delayed Event

neutron capture

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

DATA TAKING – TIME LINE



Phase I:

66 ON - 22 OFF

- Loss of optical coupling between PMTs and two different cells
- Evolving light cross-talks between cells

→ **repaired during summer 2017**

Phase II:

119 ON - 211 OFF

- Stable conditions ~ **98.5% of data taking time**

DETECTOR RESPONSE: ENERGY RECONSTRUCTION

Charge and energy connection by inverse M matrix

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

weekly ^{54}Mn calibration used to build the matrix

described by

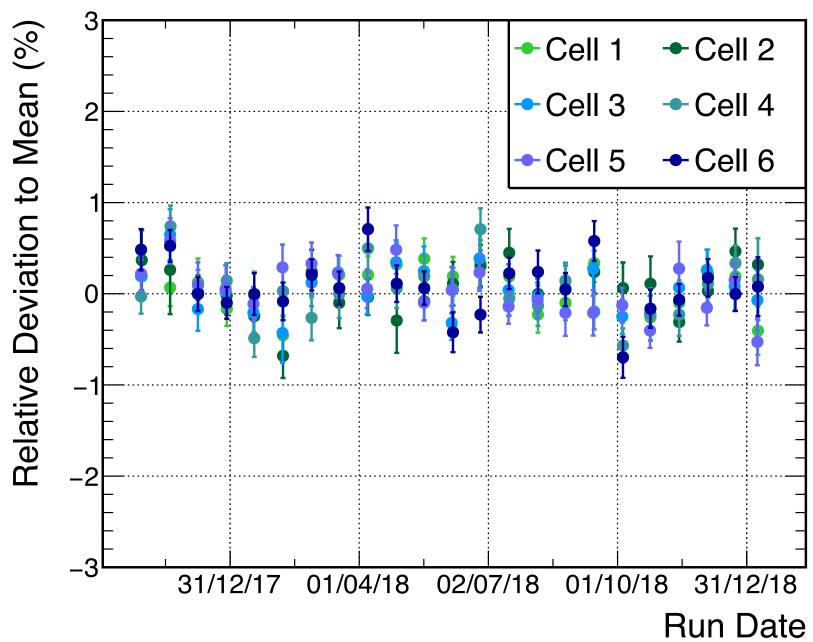
$$M_{ij} = C_j L_{ji}$$

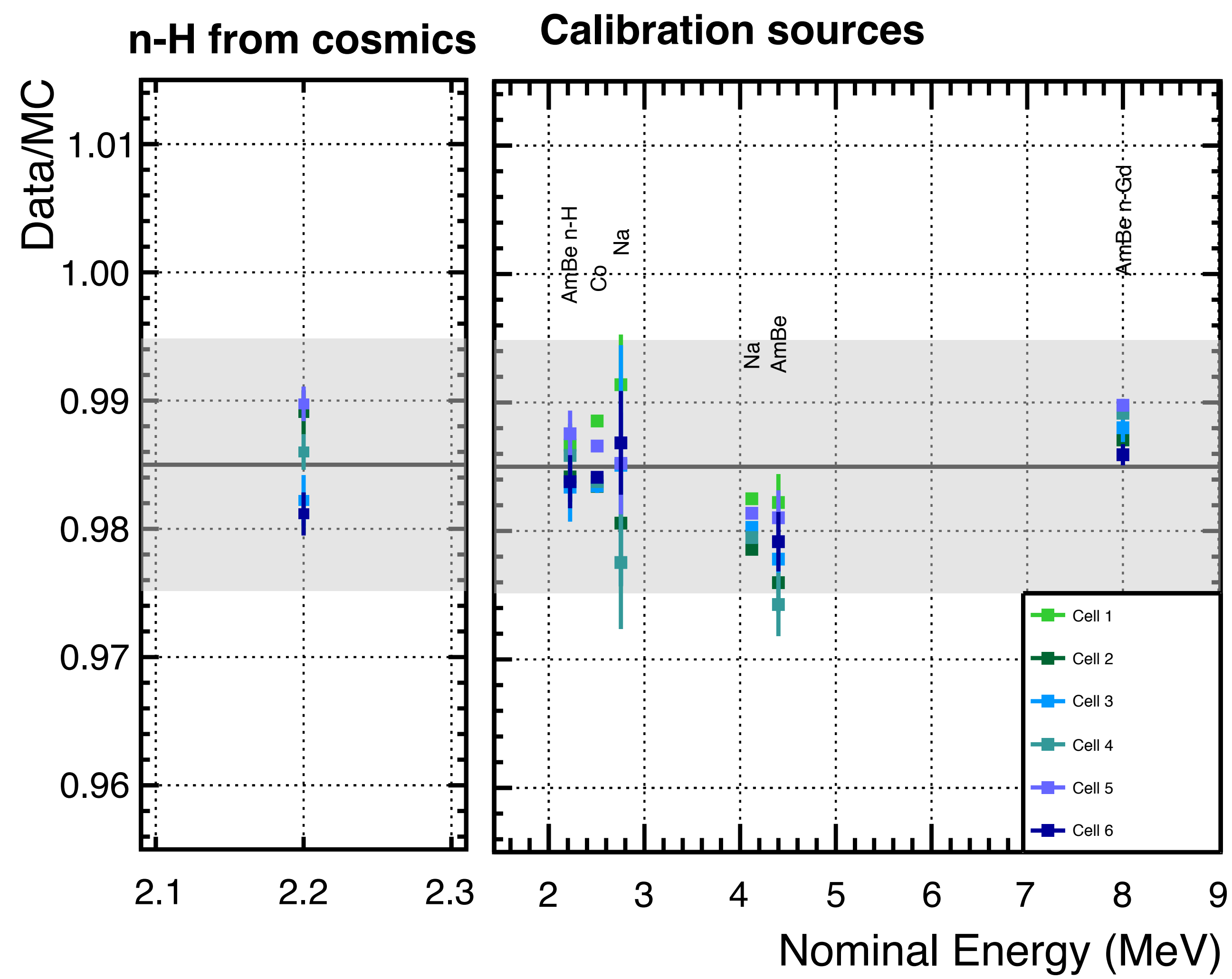
collected photons/MeV from calibration runs in cell i

cross-talk cells j->i measured online

Stability of the reconstructed n-H peak probing whole target volume

Time Stability

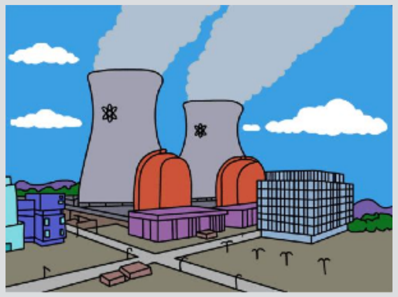




Use n-H peak + set of gammas and neutron sources to rescale MC from residual 1.5% discrepancy

BACKGROUND IN STEREO

Reactor Induced

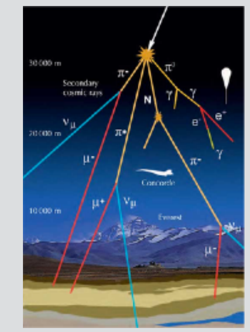


- neutrons
- gamma radiation from n-capture

Environmental Radioactivity

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

Muon induced



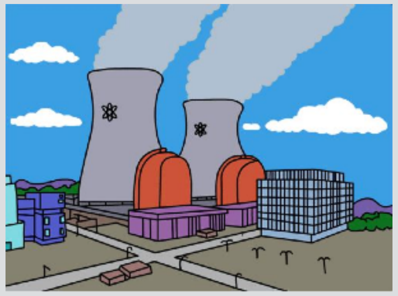
- spallation neutrons (in shielding)
- stopping muons

Reactor OFF

Reactor ON

SHIELDING IN STEREO

Reactor Induced



- neutrons
- gamma radiation from n-capture

Environmental Radioactivity

- Thorium/Uranium (concrete)
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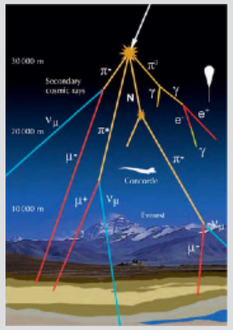
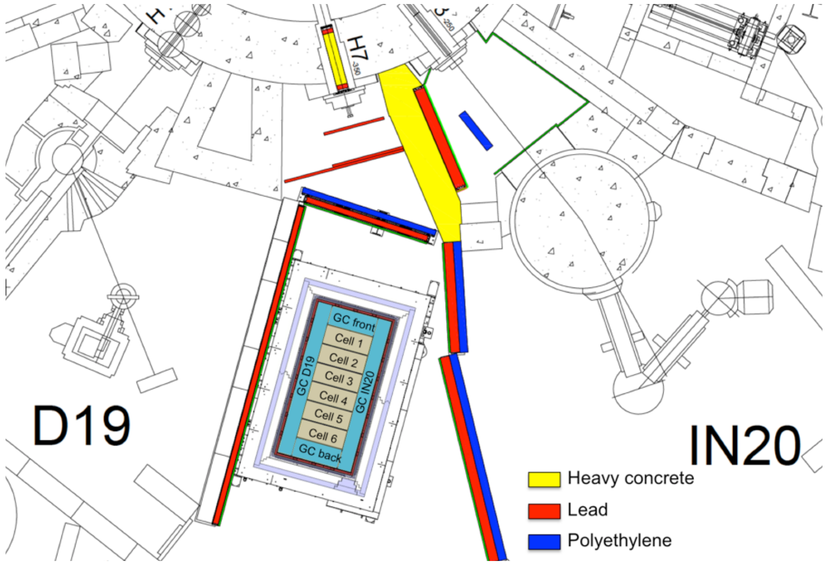
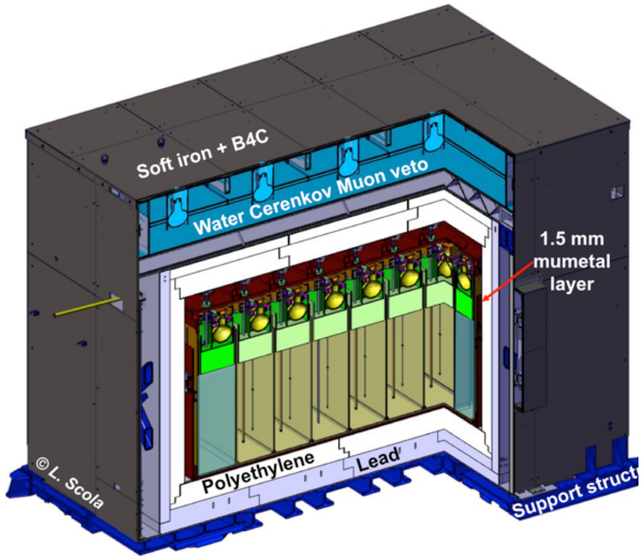
Muon induced

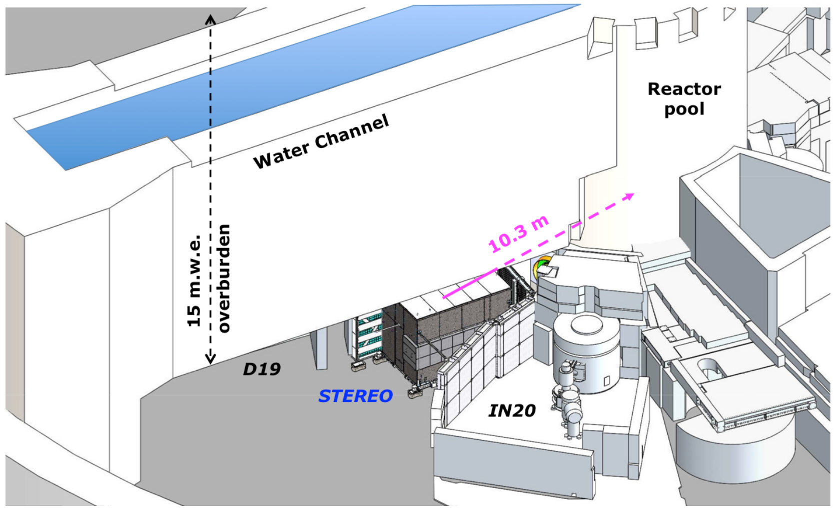


- spallation neutrons (in shielding)
- stopping muons

passive shielding, active veto and water pool

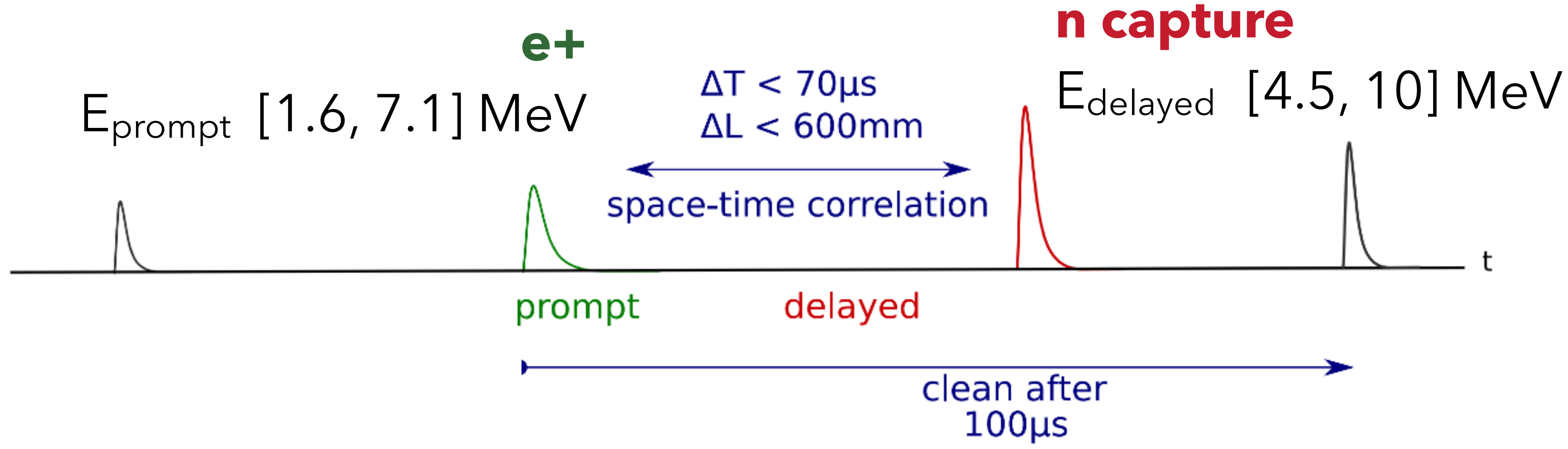






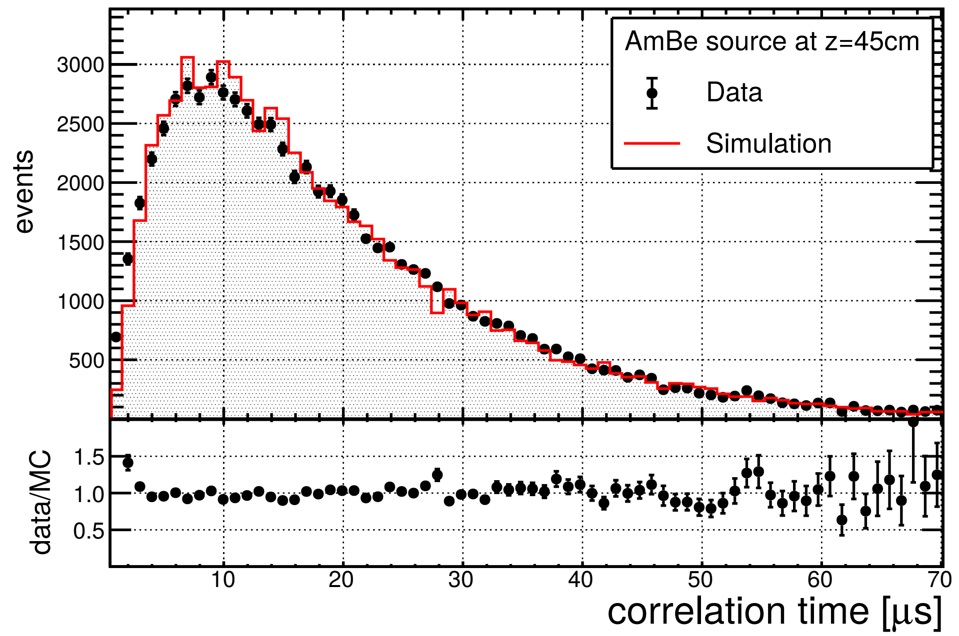
ANTINEUTRINO SELECTION AND EFFICIENCY STUDIES

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

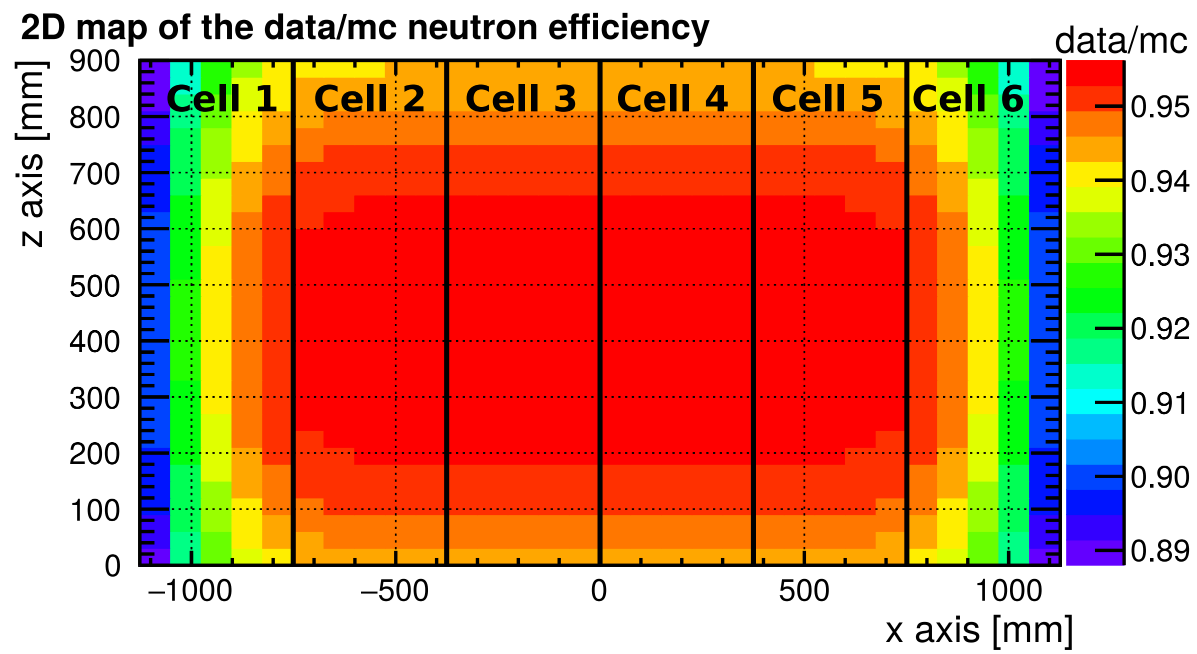


- **Energy and cell dependent cut efficiency included in oscillation analysis**
- **Mean cut efficiency (61.4 ± 0.9)%**
- **Neutron efficiency is dominant uncertainty**

Good agreement in **thermalization** time



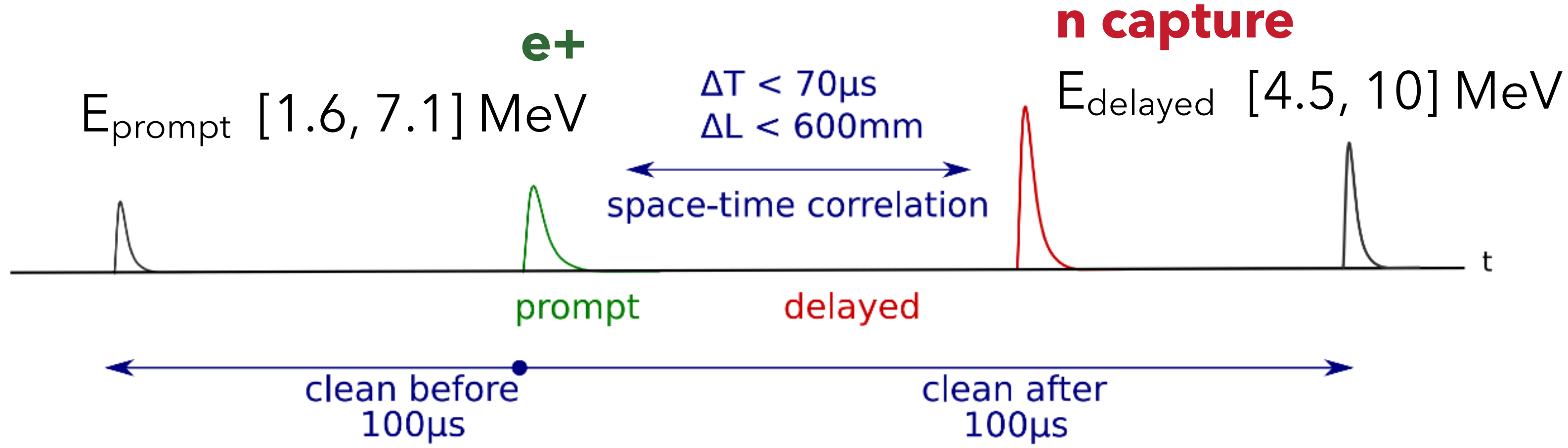
Discrepancy between data and MC corrected by a **3D model**



ANTINEUTRINO SELECTION AND CORRELATED BACKGROUND

IBD coincidence selection

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

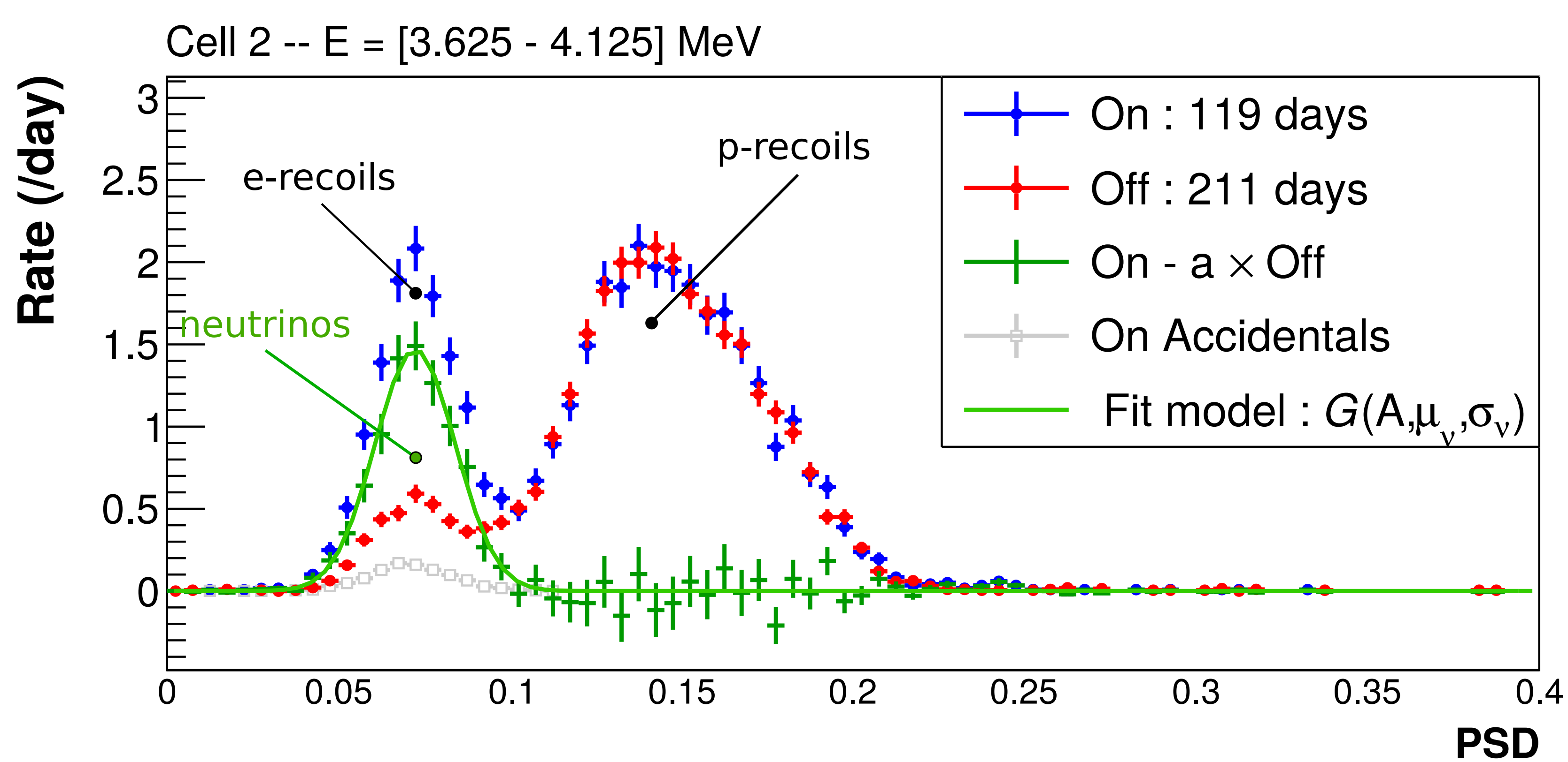


Background rejection:

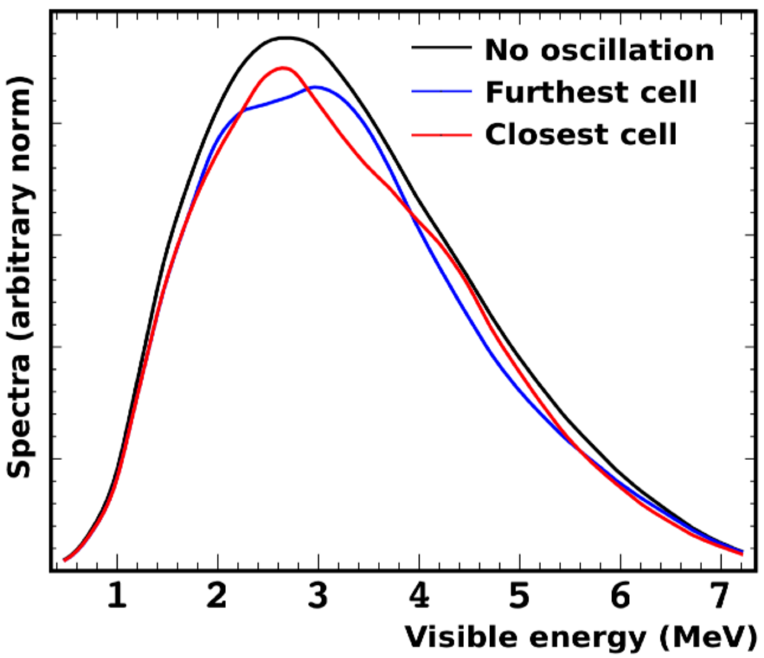
- **Extra isolation cuts**
- **Accidental pair search with time window method**
- **Pulse shape discrimination for prompt signal:** background estimation for neutron induced reactions

Self-consistent method to estimate **neutrino** and **background** events at the same time

- **Background model** measured from reactor off data
- **Neutrino rates** extracted per **cell** and **energy bin**
- Use normal distribution to ***fit neutrino spectrum***



OSCILLATION ANALYSIS



Prediction independent method that **studies distortions** of the electron antineutrino energy spectra

measured spectra in each cell

simulated spectra in each cell

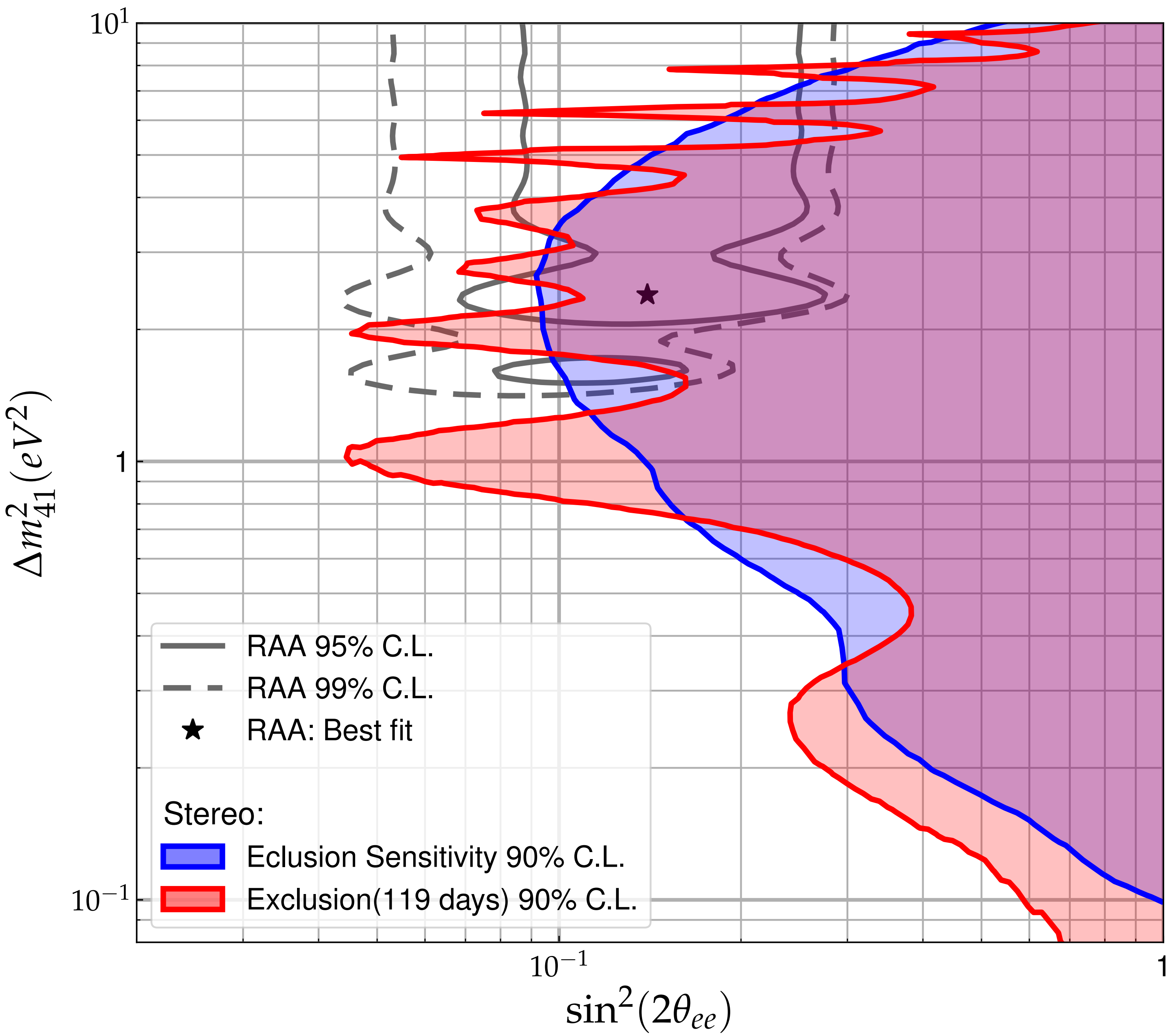
$$\chi^2 = \sum_l^{N_{Cells}} \sum_i^{N_{Ebins}} \left(\frac{D_{l,i} - \phi_i M_{l,i}(\mu, \sigma, \vec{\alpha})}{\sigma_{l,i}} \right) + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{NormU}}{\sigma_l^{NormU}} \right)^2 + \left(\frac{\alpha_l^{EscaleC}}{\sigma_l^{EscaleC}} \right)^2 + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{EscaleU}}{\sigma_l^{EscaleU}}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

Φ is a free parameter for each energy bin but common for all the cells

Systematic effects parametrized by **a nuisance parameters**

$$M_{l,i}(\mu, \sigma, \vec{\alpha}) = M_{l,i}(\mu, \sigma) \times (1 + \alpha_l^{NormU} + (\alpha^{EscaleC} + \alpha^{EscaleU}) \times S_{l,i}^{Escale}(\mu))$$

EXCLUSION CONTOURS



★: RAA oscillation best fit

Δm^2_{RAA} = 2.3 eV² - $\sin^2(2\theta_{RAA})$ = 0.14

- Phase-II only analysis
- Raster scan approach ($\Delta\chi^2$ law simulated in each Δm^2 bin)
- $\Delta\chi^2$ distributions estimated by MC pseudo experiments
- Statistical fluctuations well distributed around the expected sensitivity contour
- Best-fit value of the **RAA rejected at 99% C.L.**
- Additional island of RAA contour at lower Δm^2 still allowed

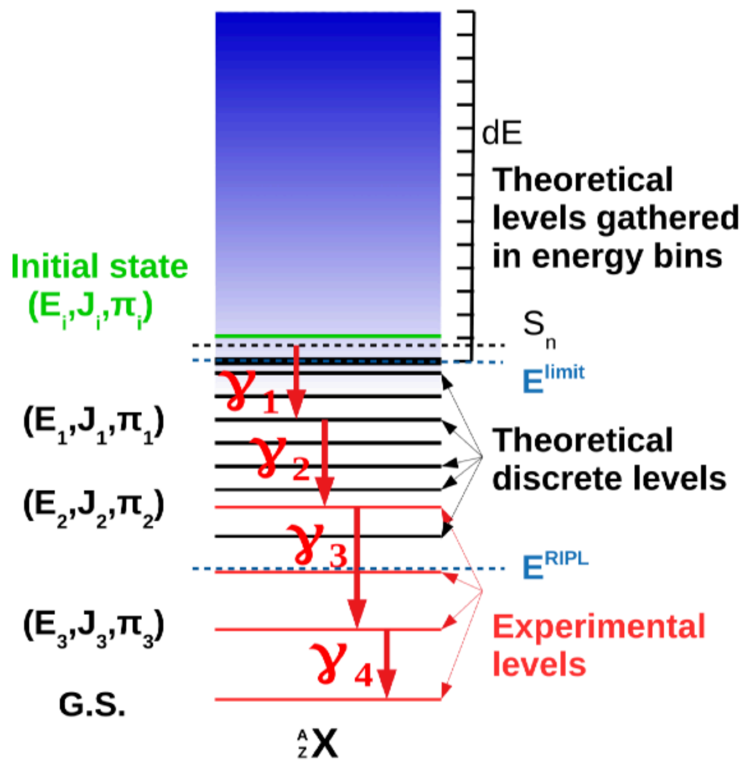
Combination with Phase-I and acquisition of more statistics will probe this region

details at arXiv:1905.11967

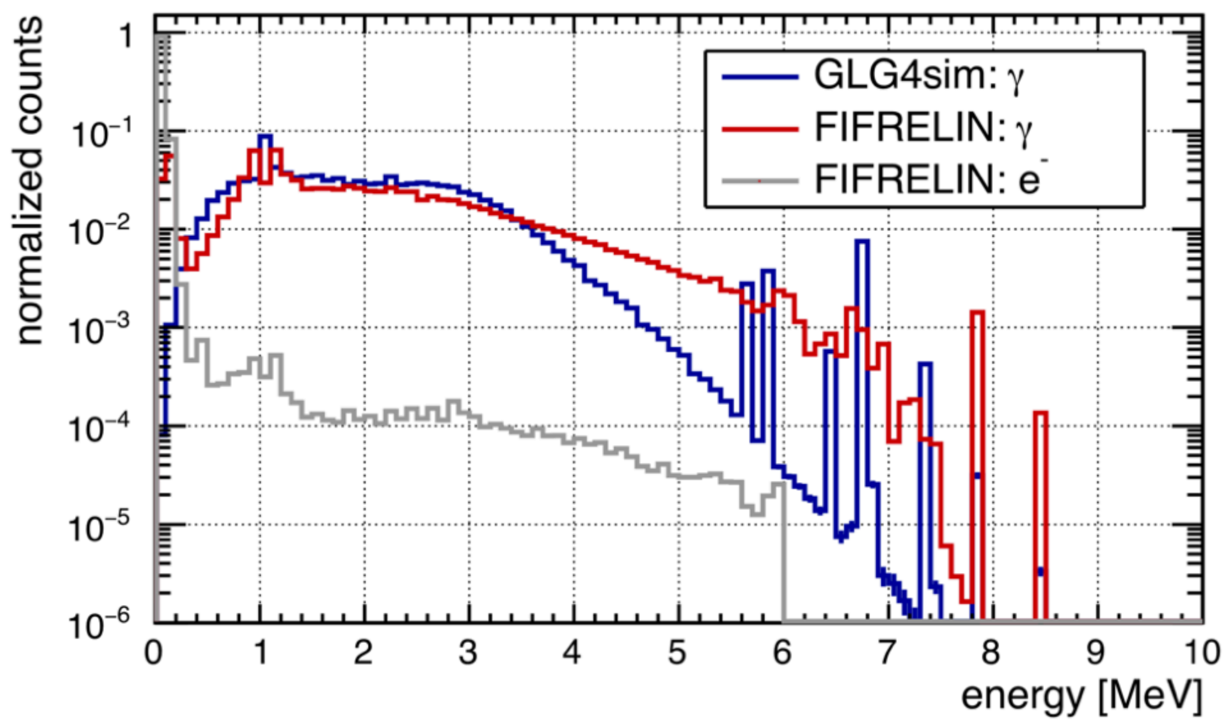
Gamma cascade of neutron captures on Gd nuclei

special importance in small detectors with low gamma containment

Improved **model** using dedicated **nuclear simulation tool FIFRELIN**



FIFRELIN
models deexcitation of Gd-nuclei using all available experimental data + nuclear models



FIFRELIN
yields **gammas** of **higher energy** compared to Geant4-based GLG4sim simulation
(also including conversion electrons)

OUTLOOK - IMPROVED GD GAMMA CASCADE

details at arXiv:1905.11967

Improvement of the neutron capture spectra

Target central position

- >5σ discrepancy with **GLG4sim**
- **1.6σ agreement** with **FIFRELIN**
- no indication for remaining systematic effect

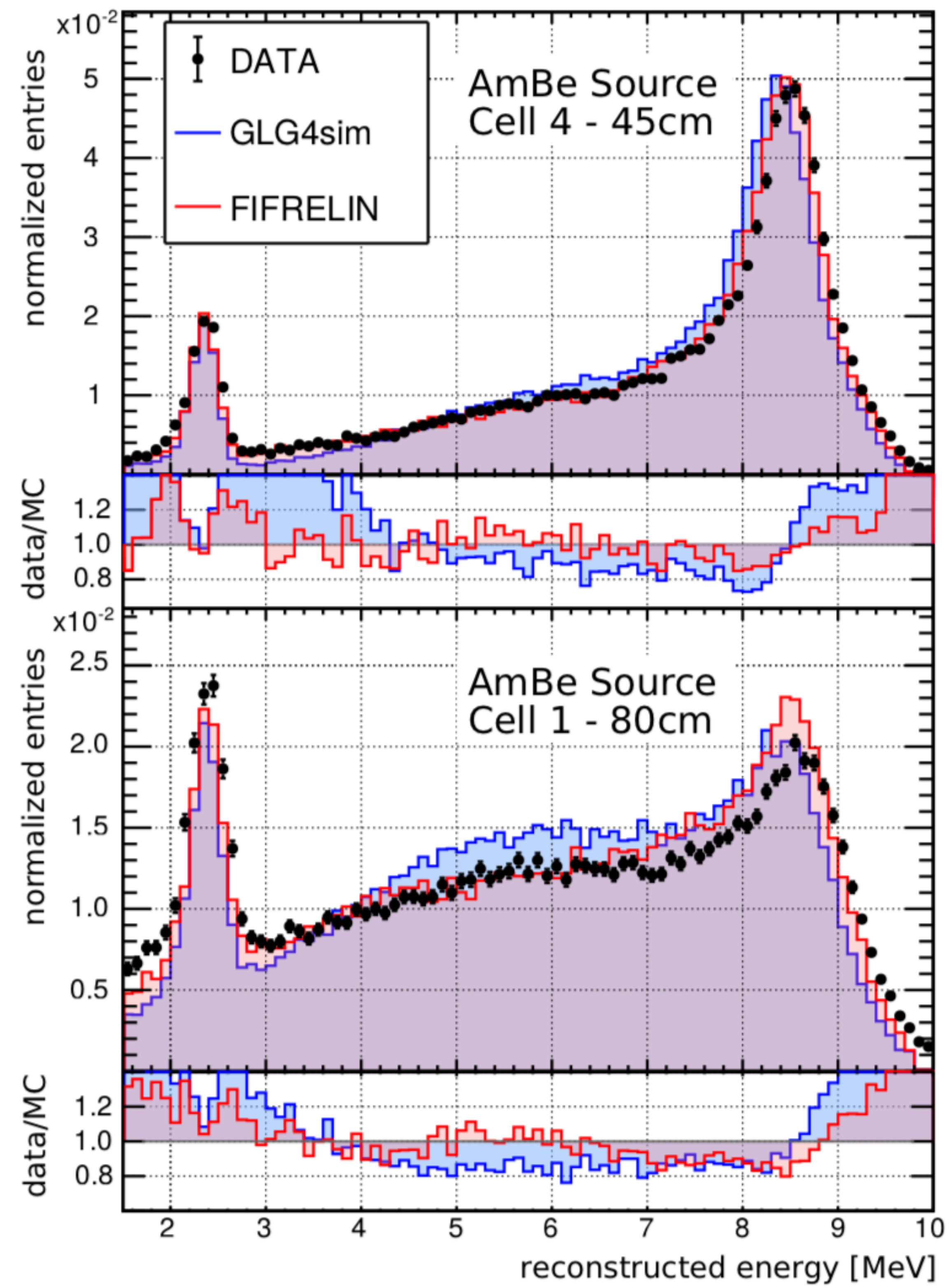
Target top corner position

- remaining effect due to **neutron mobility**
- corrected by modelisation

Improvement of the neutron efficiency

		Central position	Top corner position
$\varepsilon_{Gd}^{data}/\varepsilon_{Gd}^{MC}$	GLG4sim	0.9744 ± 0.0003	0.9436 ± 0.0013
	FIFRELIN	0.9918 ± 0.0003	0.9682 ± 0.0013
$\varepsilon_{IBD}^{data}/\varepsilon_{IBD}^{MC}$	GLG4sim	0.9814 ± 0.0004	0.9957 ± 0.0018
	FIFRELIN	1.0035 ± 0.0005	1.0091 ± 0.0019
$\varepsilon_{tot}^{data}/\varepsilon_{tot}^{MC}$	GLG4sim	0.9562 ± 0.0005	0.9396 ± 0.0025
	FIFRELIN	0.9953 ± 0.0006	0.9770 ± 0.0022

2*10⁷ MC events available!!



SUMMARY

- Stereo is now running under **stable** conditions. 43.4k neutrinos detected in *Phase II* (up to 65.5k in total)
- The **correlated background understanding** improves using reactor-OFF periods
- Improved description of the Gd neutron capture gamma cascade with FIFRELIN arXiv: 1905.11967
- Exclusion contour obtained using the robust ratio method, **rejects** the original **RAA best fit value** is at **99% CL**.
- Publication of current oscillation result under preparation
- Additional results on flux and spectral shape measurements under preparation

Stay tuned!

thanks for your attention

THE STEREO COLLABORATION

STEREO

Irfu
DE LA RECHERCHE À L'INDUSTRIE
cea

NEUTRONS FOR SOCIETY

LAPP
Laboratoire d'Annecy de Physique des Particules

LPSC Grenoble

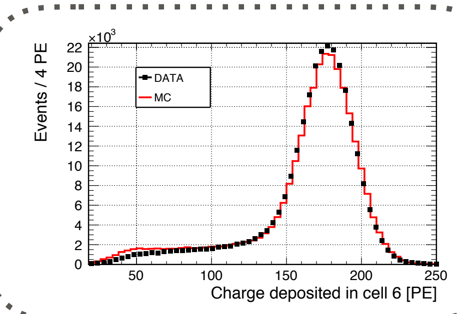
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

BACK-UP

DETECTOR RESPONSE: ENERGY RECONSTRUCTION

Charge and energy connection by inverse M matrix

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

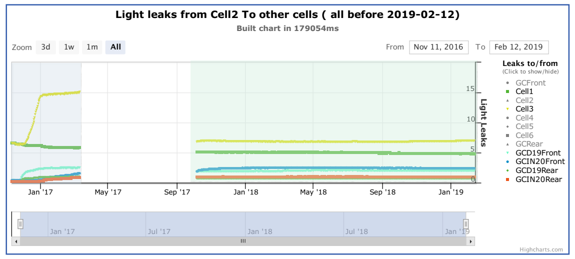


described by

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

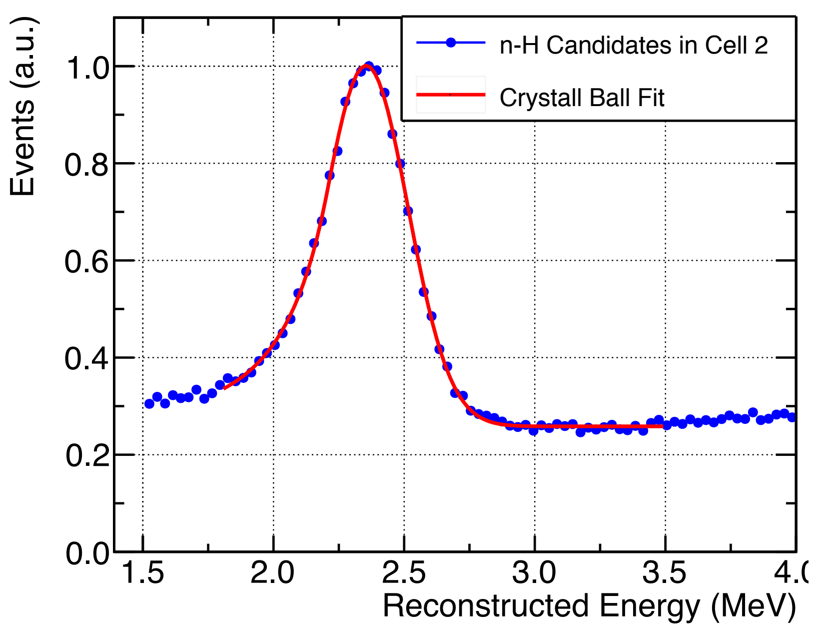
collected photons/MeV from calibration runs in cell i

cross-talk cells j->i measured online

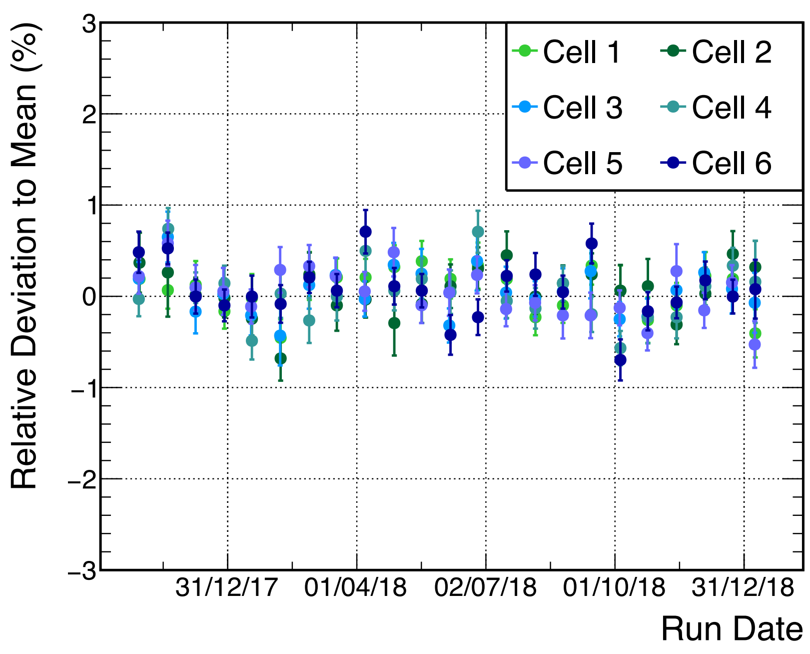


Stability of the reconstructed n-H pea - probing whole target volume

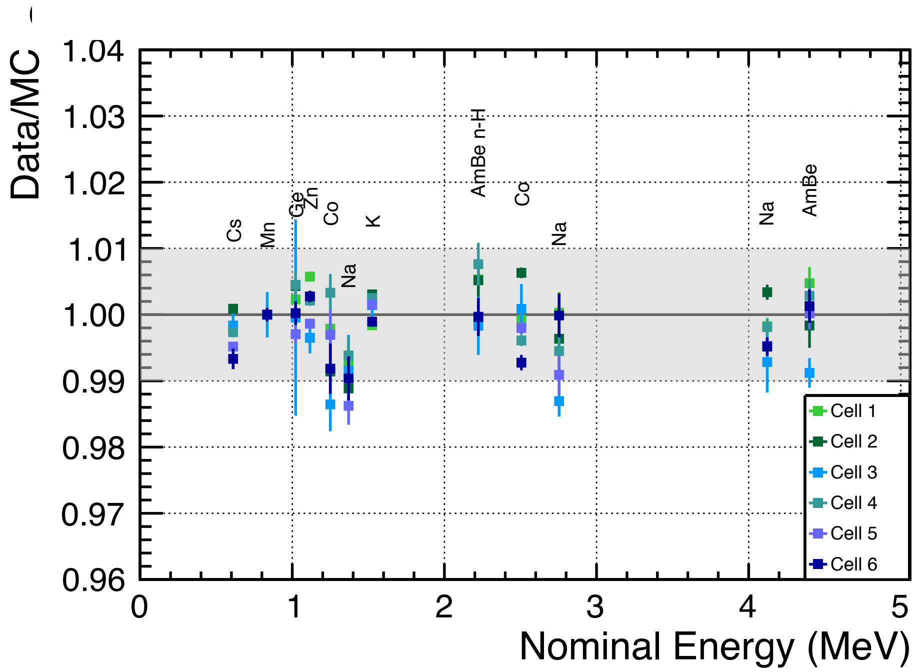
n-H peak



Time Stability



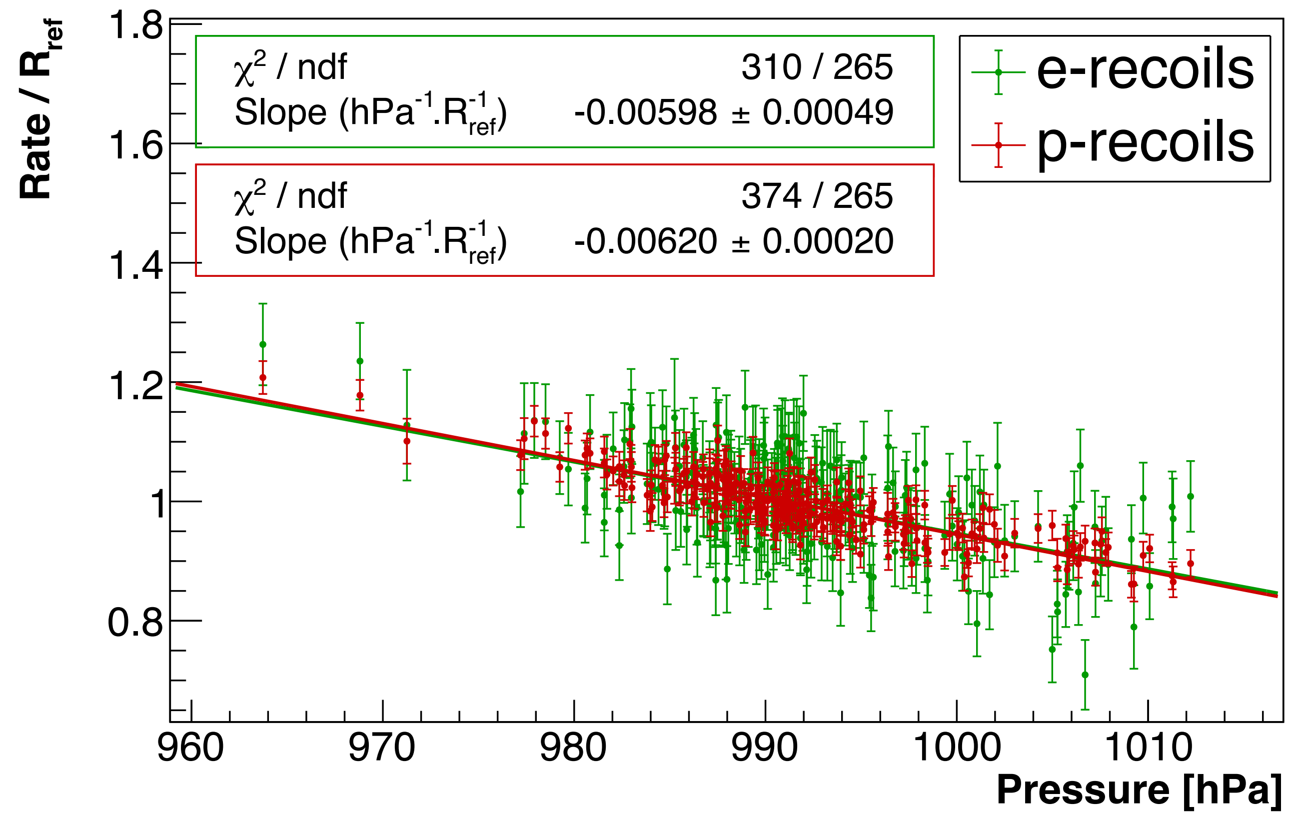
Data vs MC Energy reconstruction



PULSE SHAPE DISCRIMINATION

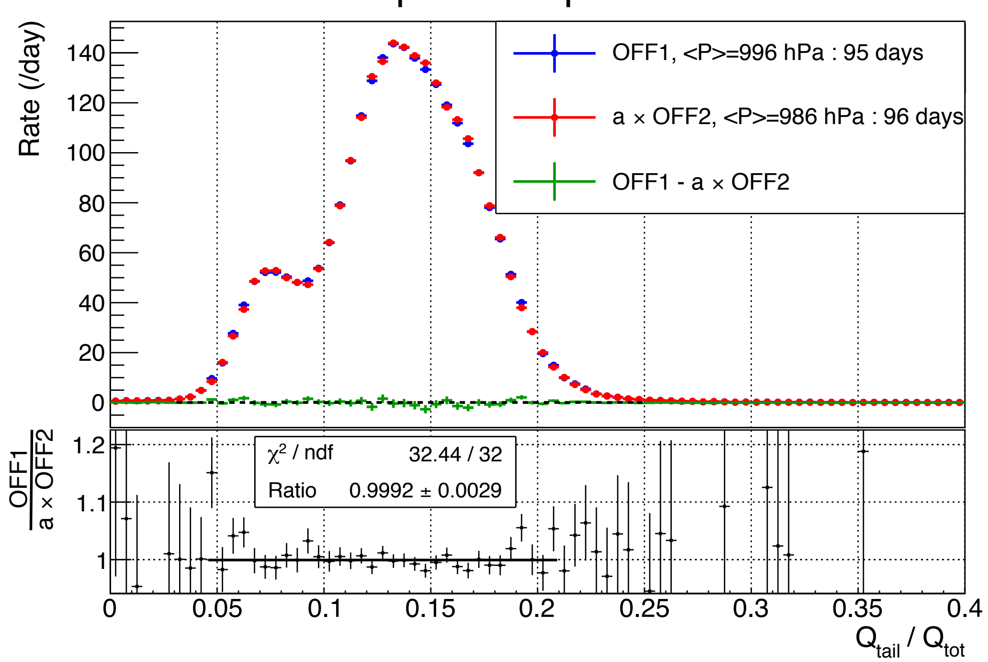
Rate of background events corrected from evolution of

- temperature
- atmospheric pressure
- optical scintillator properties
- bias of fitting procedure

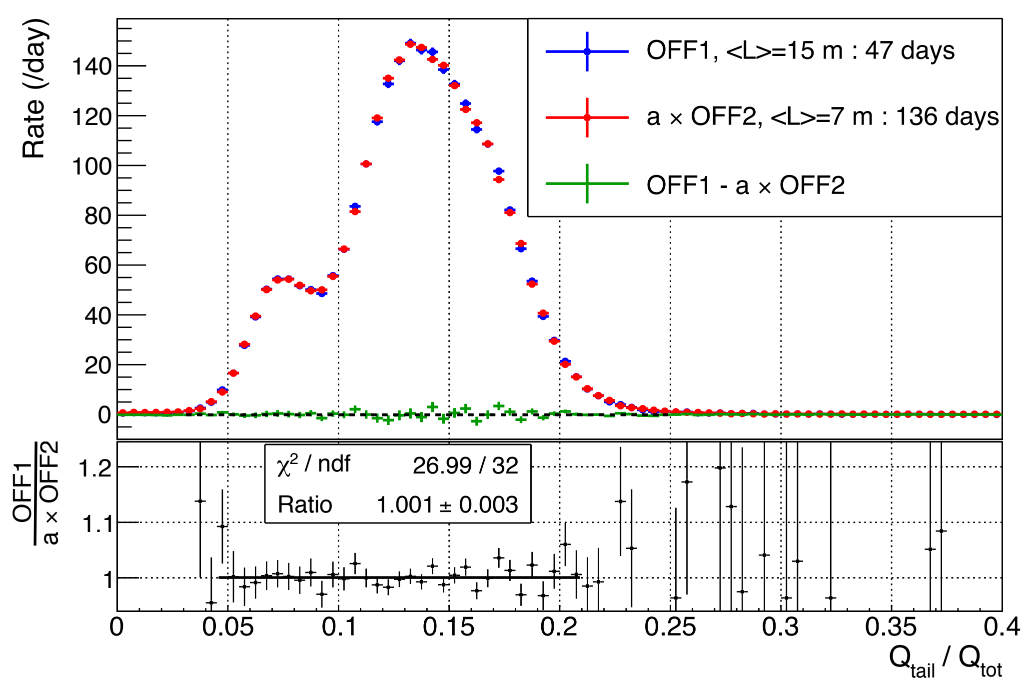


PSD distributions show identical shape with respect to

Atmospheric pressure

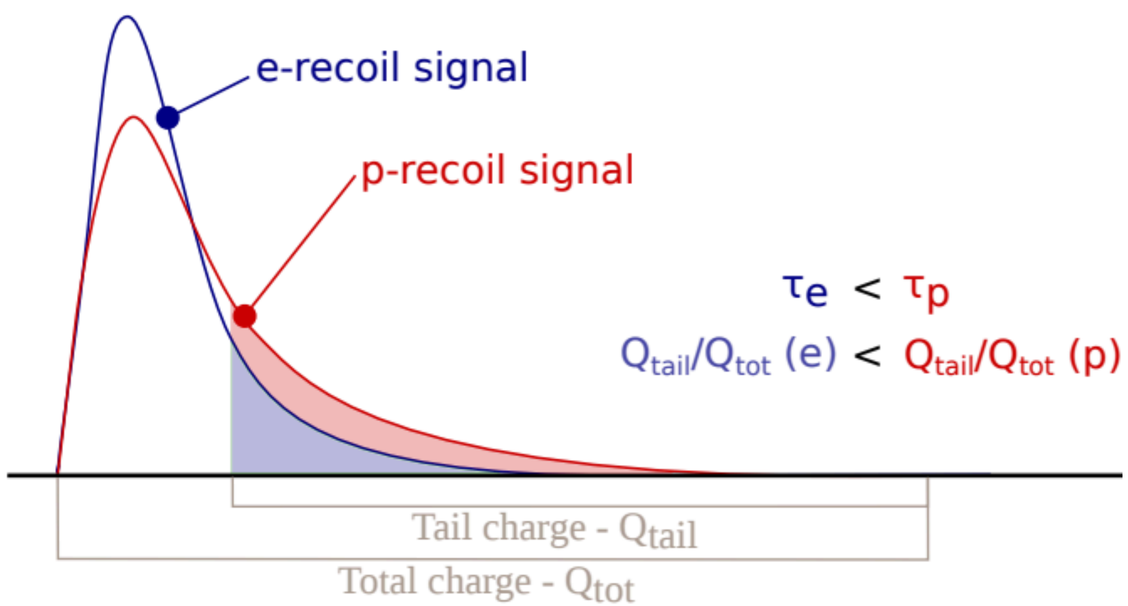


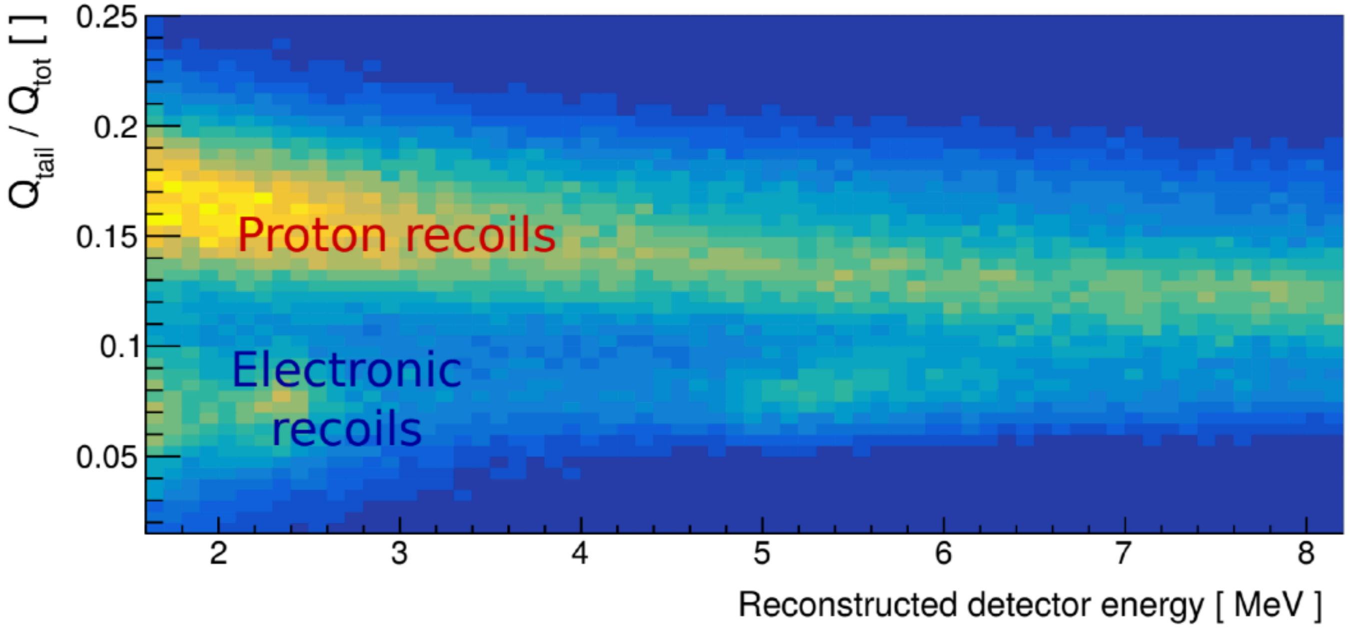
Water level L



PULSE SHAPE DISCRIMINATION

Pulse shape discrimination (PSD)

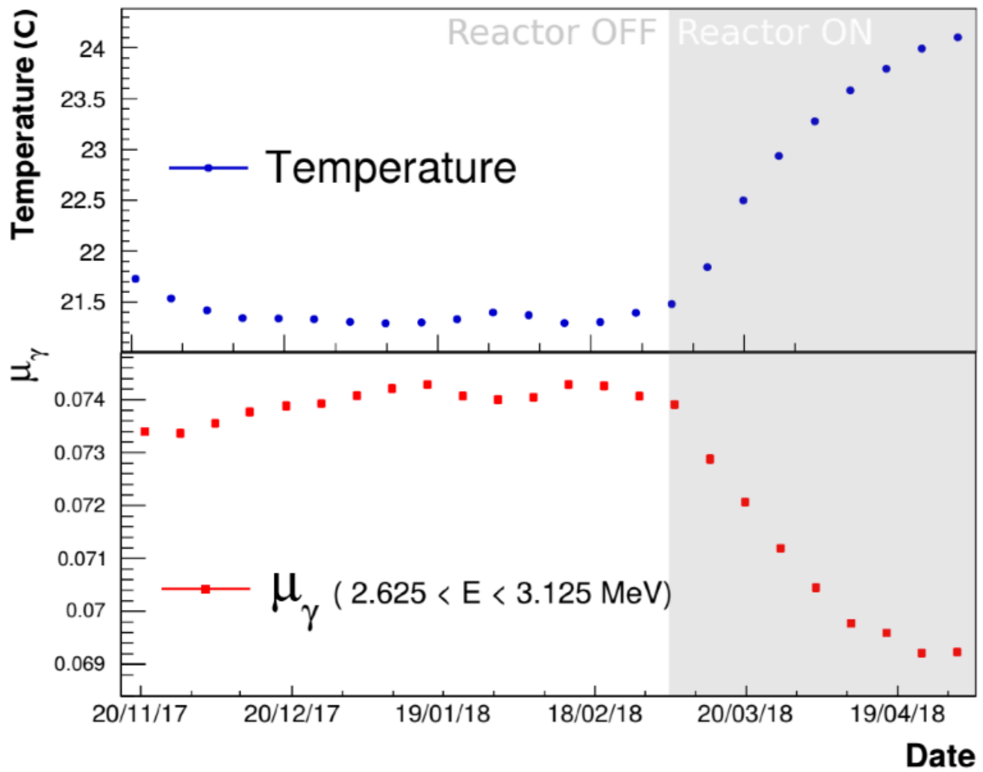




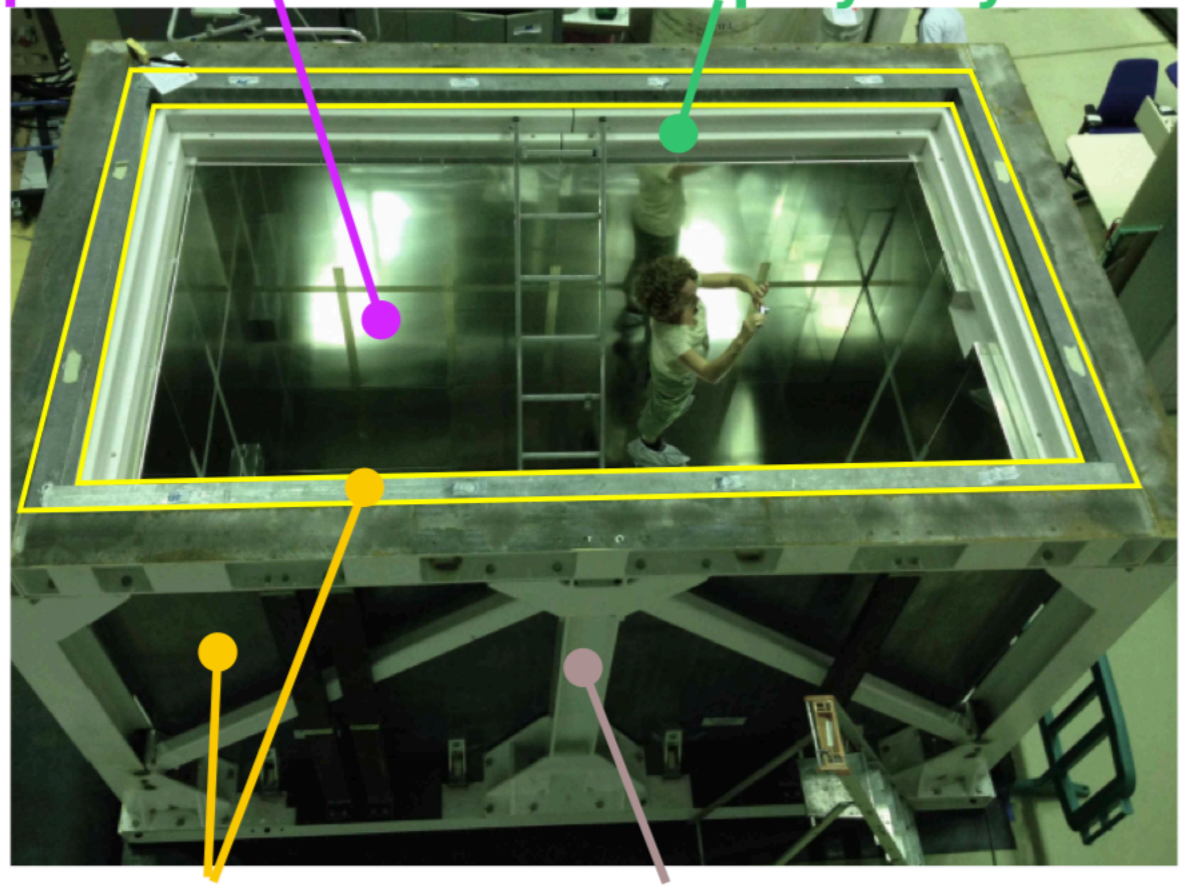
allow us to distinguish background events (neutron induced reactions) with real positron interactions

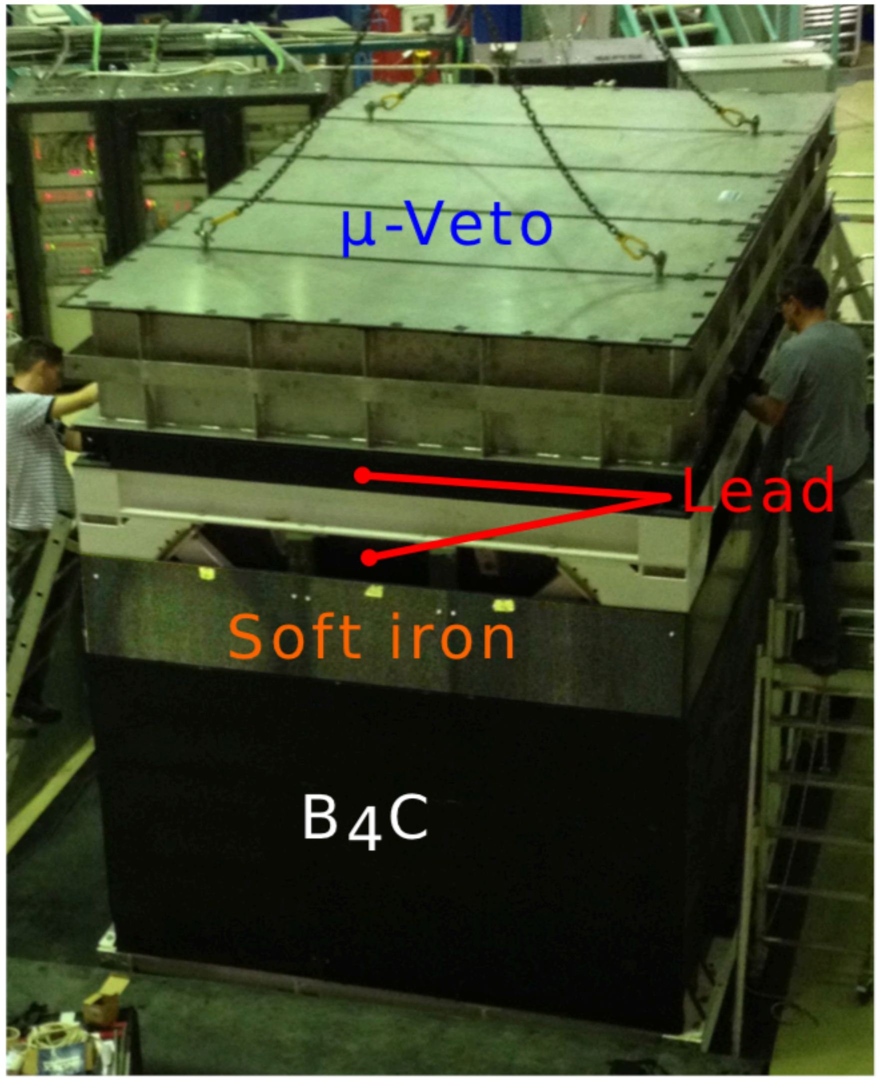
But PSD follows **temperature changes**

- *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

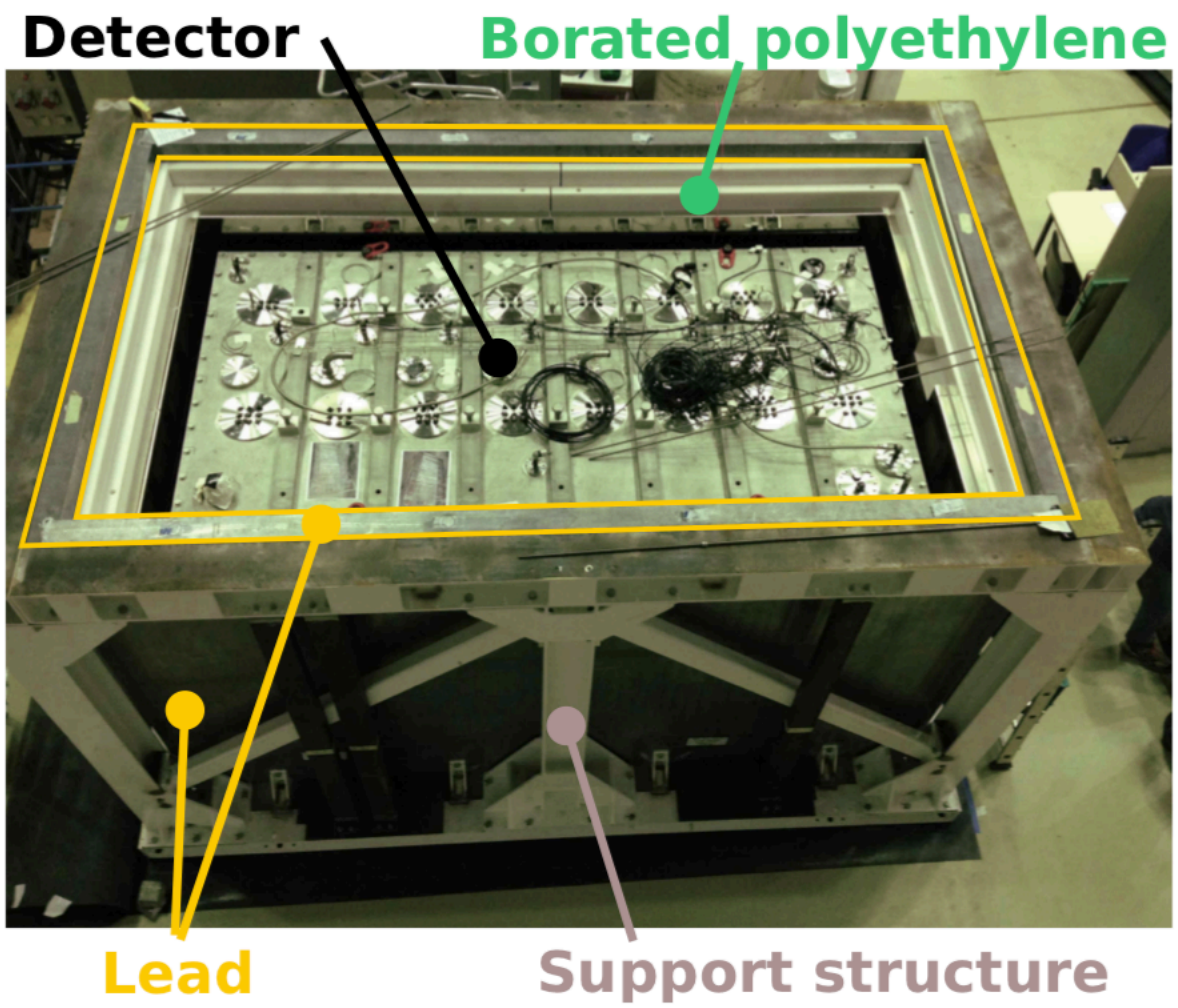


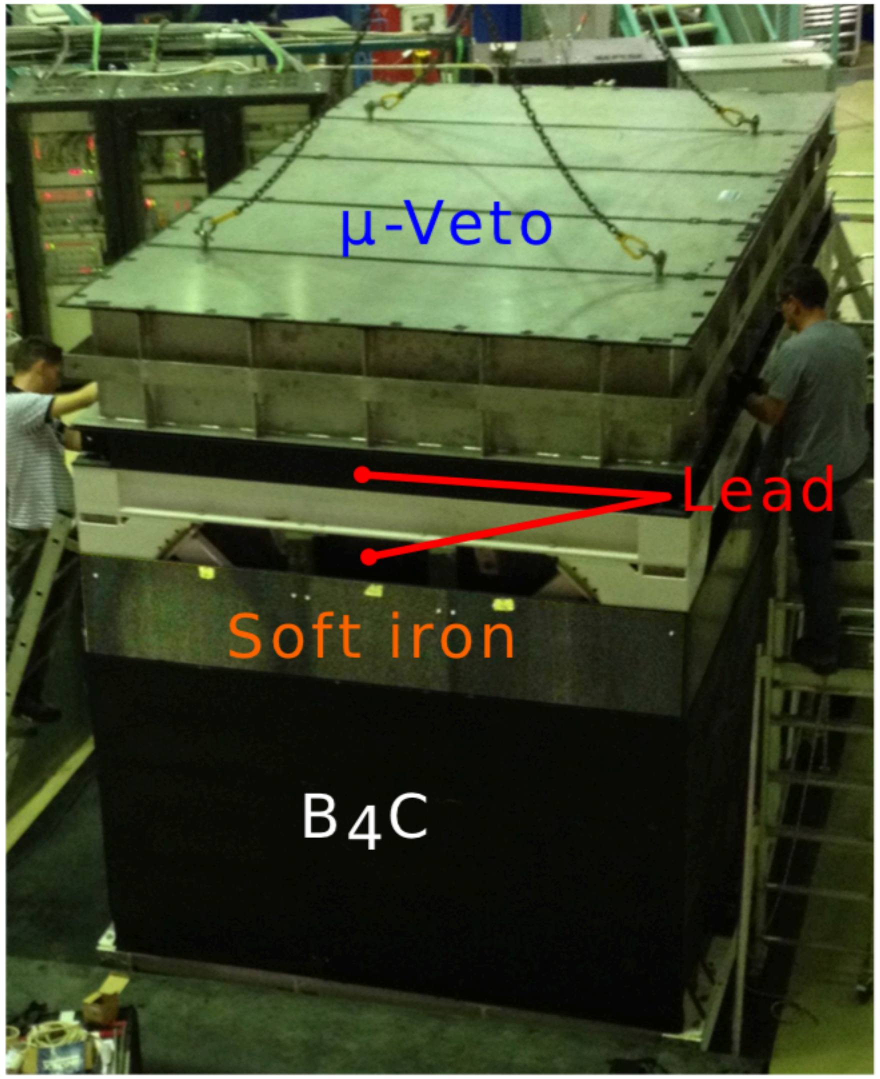
SHIELDING


μ-metal
Borated polyethylene
Lead
Support structure


μ-Veto
Lead
Soft iron
B_4C

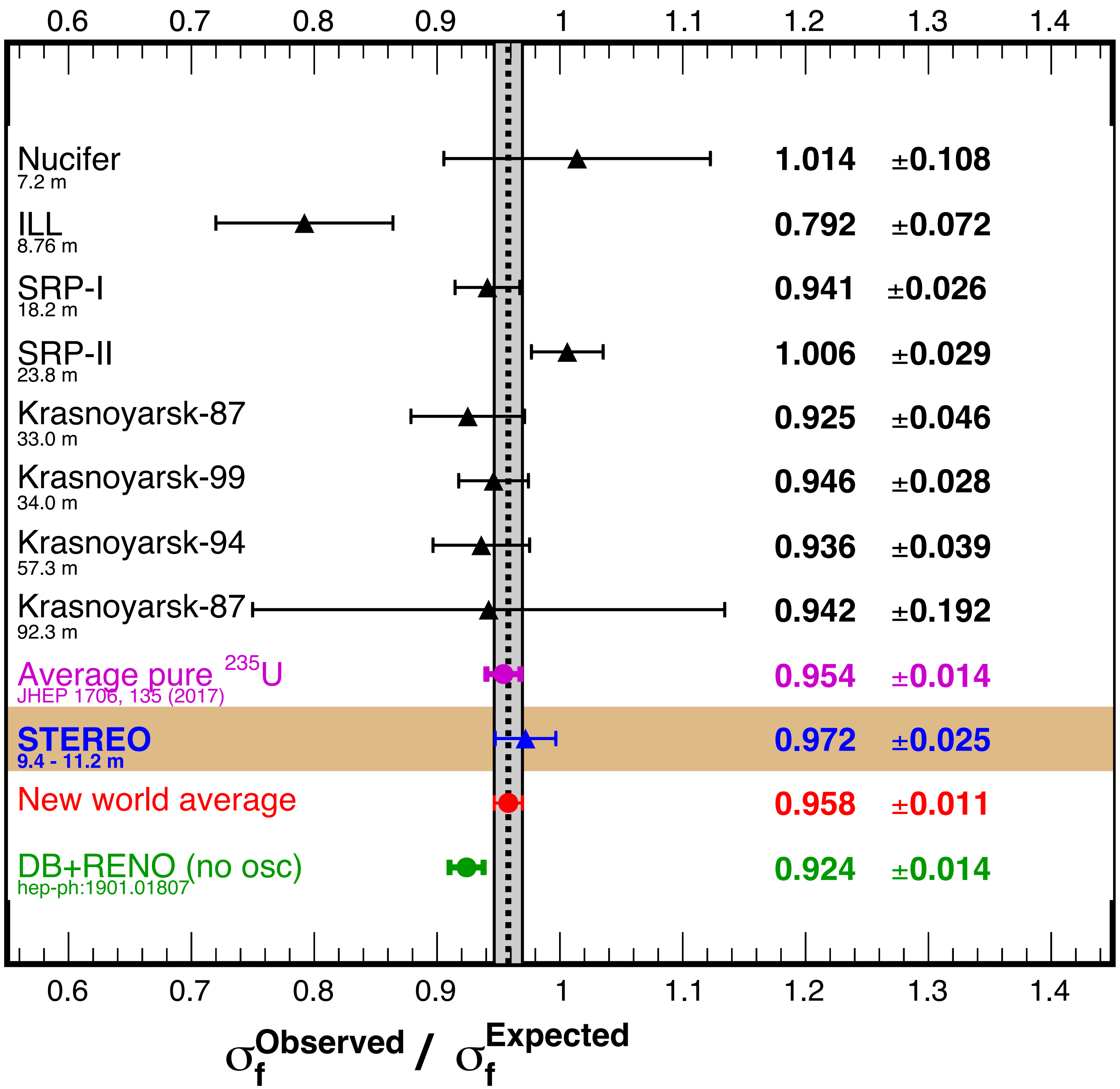
SHIELDING


Detector
Borated polyethylene
Lead
Support structure

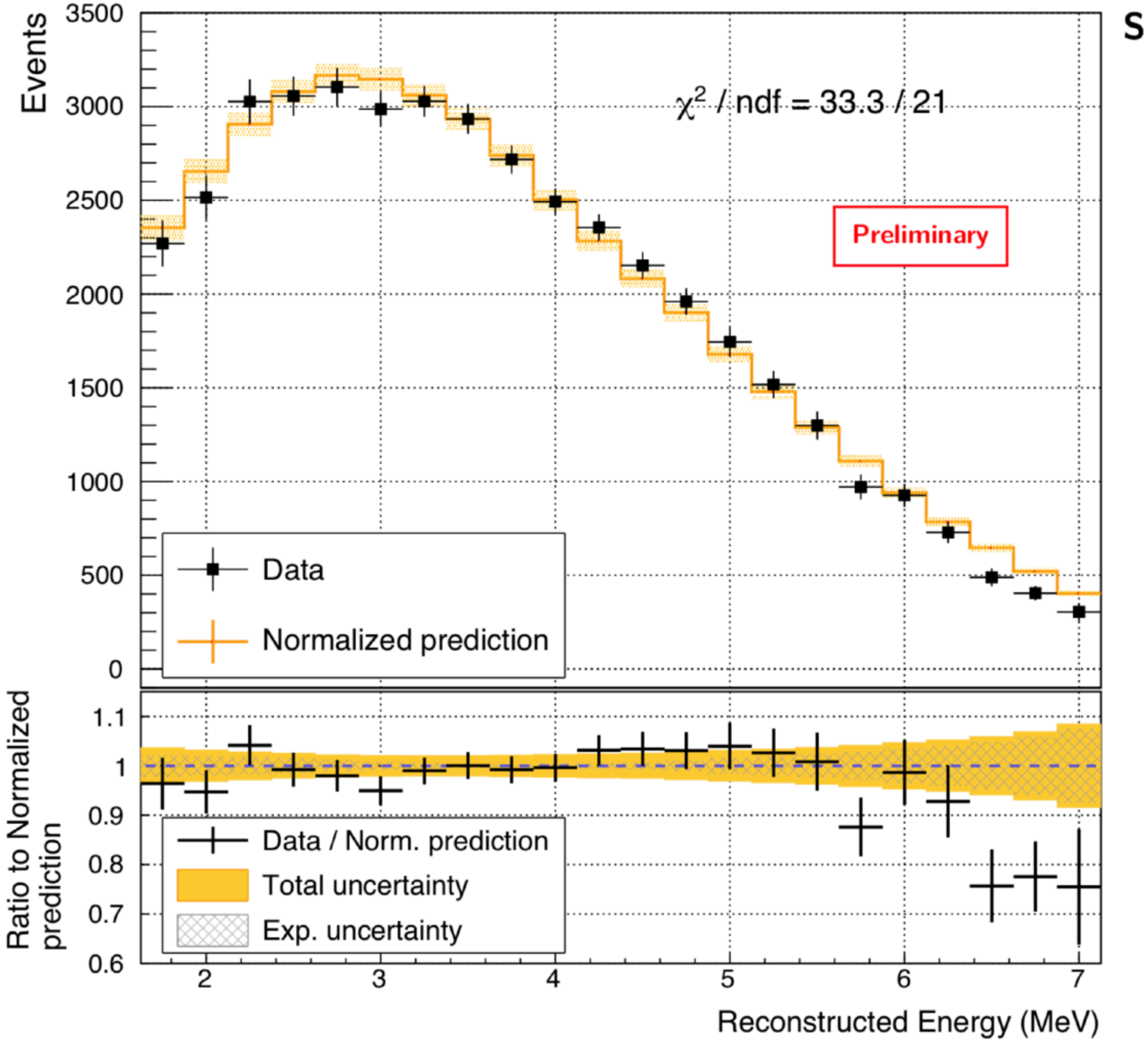

μ-Veto
Lead
Soft iron
B4C

2 RATE ABSOLUTE NORMALIZATION STUDIES

- Total extracted rate of 365.7 ± 3.2 ($\bar{\nu}_e$/day)
- Achieved a **good control** of two key ***uncertainties***
  - Thermal power ± 1.4%
  - Neutrino det. efficiency ± 0.94%
- Among the most **accurate measurement** of the **neutrino flux** from pure **^{235}U** nuclear fuel
- In **good agreement** with **averaged world**



3 SPECTRAL STUDIES



- Predicted spectrum, **Huber ^{235}U**
- **Good agreement with data up to 6.375 MeV** (χ^2=14.9/18)
- **Large deviation observed in the 3 highest energy bins** (χ^2=33.3/21)
- Further constraints from upcoming **higher statistical accuracy** and combination with other pure 235U spectra are **required** to draw pertinent tests of the spectrum shape.

SENSITIVITY CONTOUR

complete detector response simulated

included systematics:

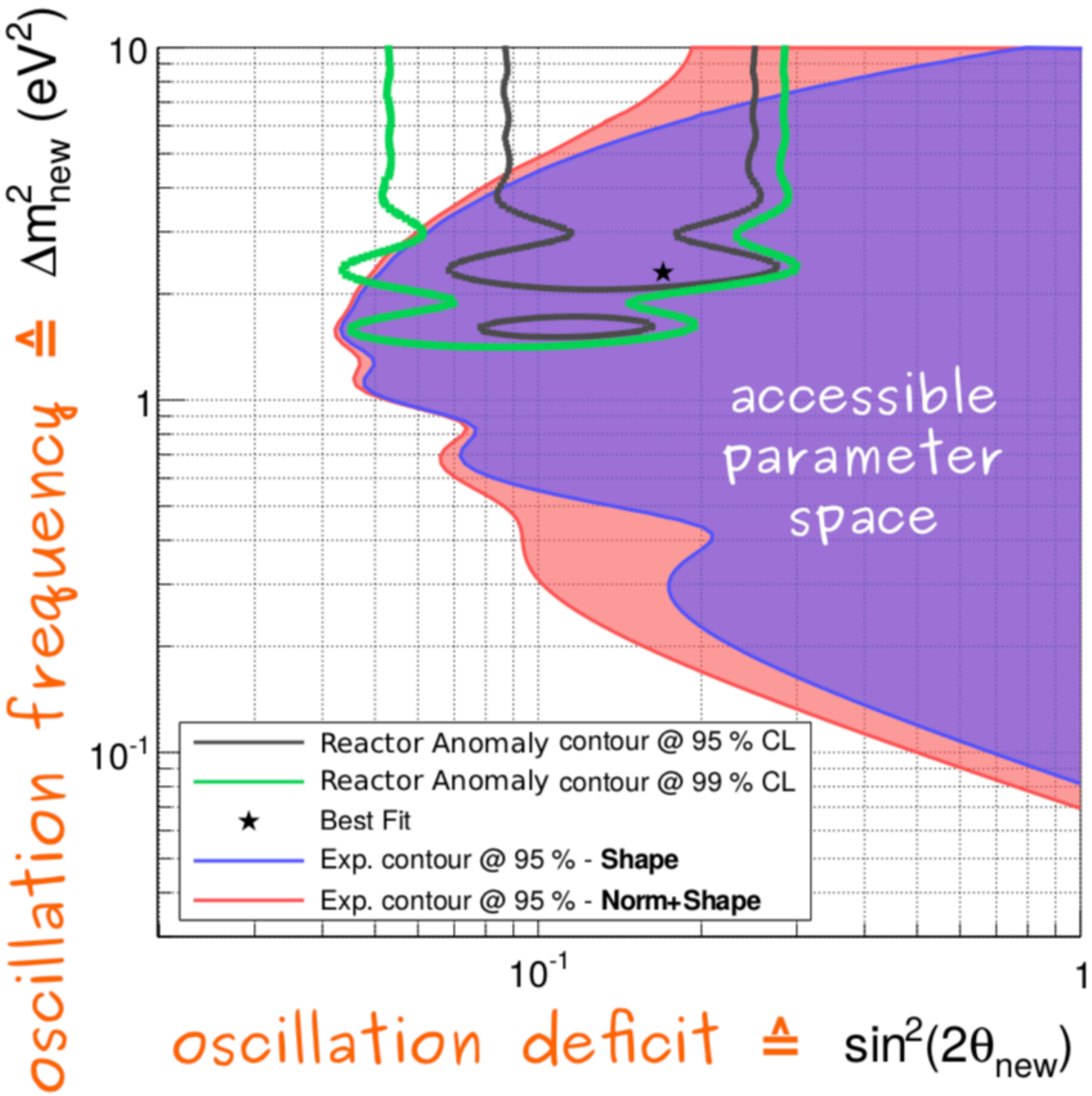
neutrino spectra, detection & reconstruction

prompt signal: E > 2 MeV

delayed signal: E > 5 MeV

S/B = 1.5

300 live-days
(6 reactor cycles)



DETECTOR RESPONSE: ENERGY RECONSTRUCTION

systematic uncertainties

Source	Relat. Uncert. (%)	Cell-to-cell corr.
Time stability	± 0.3	100 %
Anchoring of MC	± 1.0	100 %
n-H cell-to-cell	± 0.5	0 %