Latest results from the STEREO experiment : a search for sterile neutrino ∼1eV at ILL

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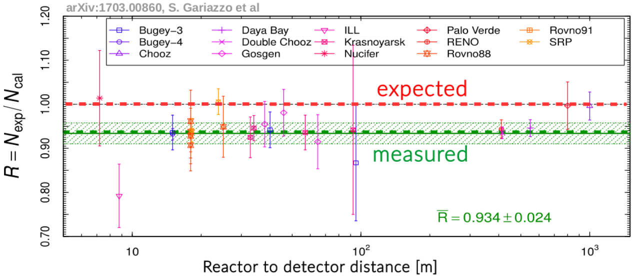
on behalf of the Stereo collaboration

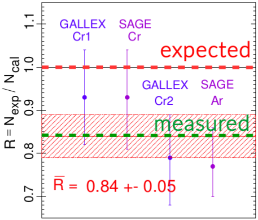
supported by

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

Reactors



Sources



Two compatible anomalies:

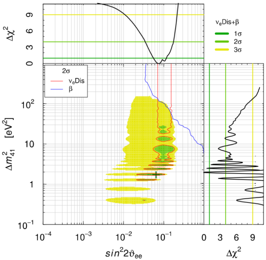
- **Reactor Antineutrino Anomaly**
  All reactor short-baseline experiments are observing a deficit
  $\rightarrow$ confirmed by recent accurate measurements from Daya Bay, RENO & Double Chooz)
- **Sources Anomaly**
  β-emitters sources used for solar experiments calibration in Gallex & Sage experiments show deficit

Motivations: sterile neutrino hypothesis

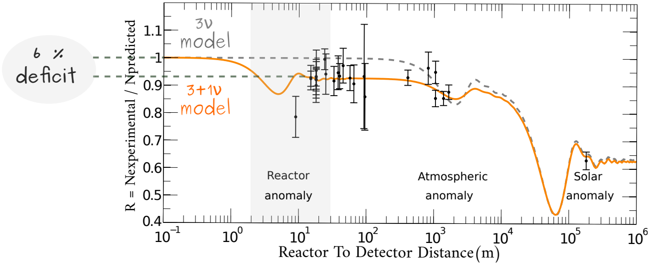
Phys.Rev.D83:073006 (2011)

Suggested oscillation parameter space

arXiv:1703.00860v3



3+1 scenario fits better the experimental data points



Latest best fit
$\sim$1 eV, $sin^2(2\theta) \sim 0.065$

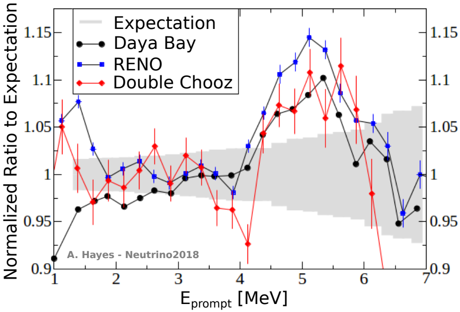
$$P_{\overline{\nu}_e \to \overline{\nu}_e}(E_{\overline{\nu}_e}, L) = 1 - \sin^2(2\theta_{new}) \sin^2\left(1.27 \frac{\Delta m^2_{new}[eV^2] L[km]}{E_{\overline{\nu}_e}[MeV]}\right)$$

→ First oscillation occuring at very short baseline (<10 m)

Motivations: spectral distortions

Several experiments revealed a "bump" around 5 MeV w.r.t prediction spectra

- Could be linked to underestimation of certain isotopes of Uranium/Plutonium
- Can not explain the total deficit



In conclusion:

- Global flux deficit (sterile ν hypothesis)
- Spectral distortions
- ... other recent issues

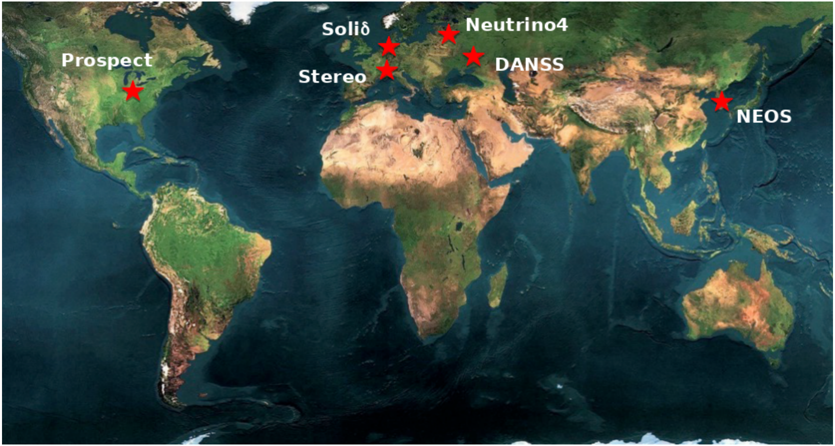
Need dedicated measurements to:

- Confirm or rule out sterile ν hypothesis
- Constrain the $\bar{\nu_e}$ energy spectra

A quest for a sterile neutrino in the eV range

Several experiments with different sources and detection methods...

- Segmented or movable (**Independant from predicted spectra**)
- HEU (High Enriched Uranium 235) = experimental cores
- LEU (Low Enriched Uranium 235) = commercial cores



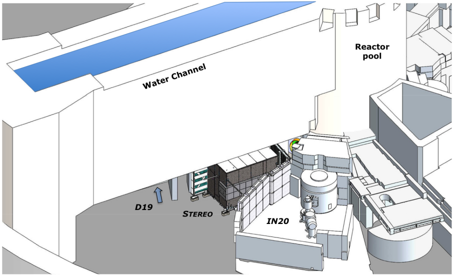
Experimental site
ILL research facility, Grenoble, France

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

✓ **Compact** core (40cm ∅)

✓ **Highly enriched ^{235}U**

✓ **Short baseline** measurement:
$8.9\text{m} < L_{core} < 11.1\text{m}$

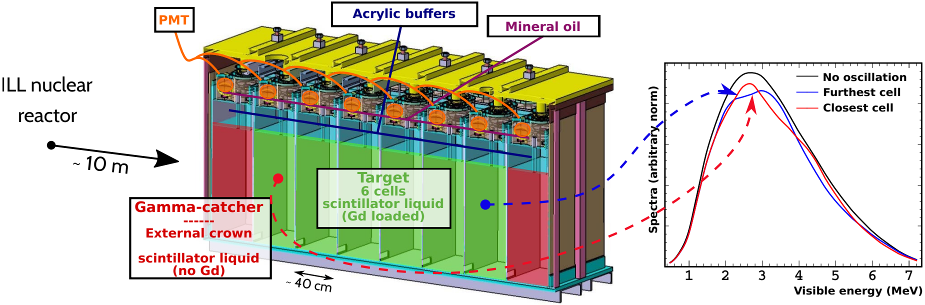


× **Surface-level** experiment (BUT 15 m.w.e only thanks to water channel)

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

The STEREO experiment

arXiv:1804.09052 (2018)



Designed to:

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

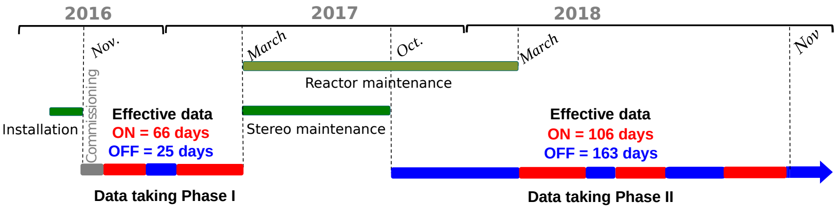
✓ **Independent from predicted energy spectrum** (norm. + shape)

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

✓ **Confirm origin of 5 MeV bump w.r.t ^{235}U**

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

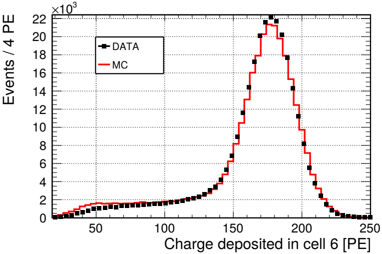
arXiv:1804.09052 (2018)

- **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)

- **Charge in a given cell** - Tool developped to take into account:
  - Light collection loss
  - Evolving light leaks along time

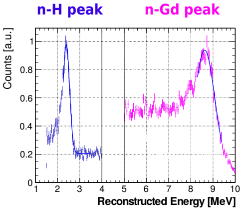
$$Q_i = \sum_{j=cells} E_j C_j L_{ji}$$

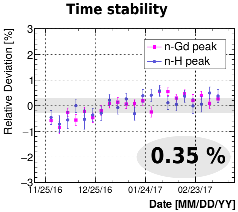
Collected photons/MeV from calib runs

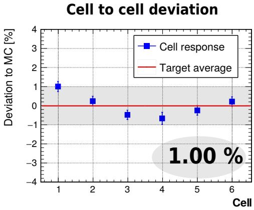
Light cross-talk between cells
Measured online + calib

→ Inversion of Q_i matrix gives E_i matrix

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

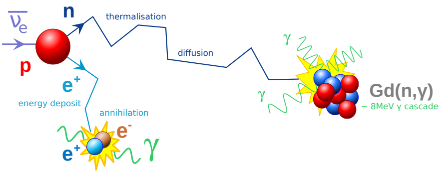


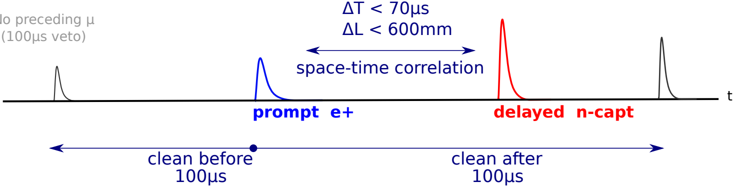




$\bar{\nu}_e$ signal selection

Inverse Beta Decay reaction $\rightarrow$ correlated pair





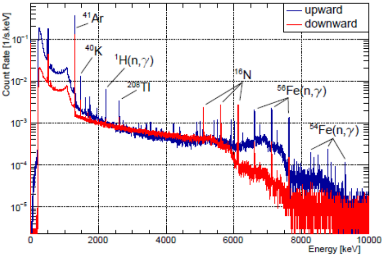
$1.6 < E_{prompt} < 7.1$ MeV

$4.5 < E_{delayed} < 10$ MeV

Prompt contained in vertex cell
and 4 neighbouring cells

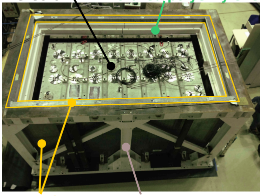
Shielding against background

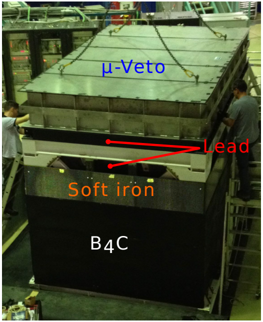
Extensive campaigns of characterization of neutron and γ sources before shielding design:



Two types of backgrounds

- Accidental background:
  ✓ removed by statistical subtraction
- Correlated background:
  ✓ reduced by shielding and $\bar{\nu_e}$ selection
  ✗ **Counterpart of so much shielding:** atmospheric muons spallation producing **fast neutrons**





Correlated background discrimination

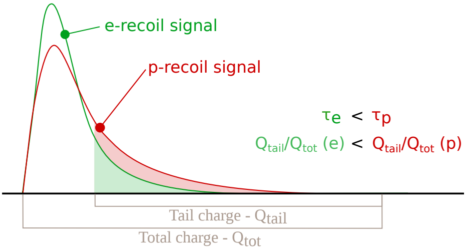
Muons induced background (Prompt + Delayed):

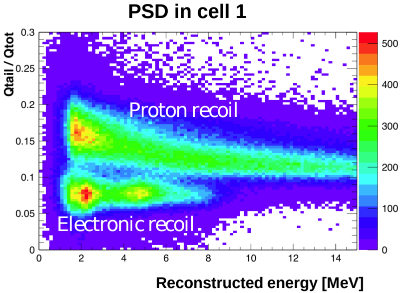
- **Fast neutrons**
  Prompt: proton recoil
- **Multiple neutron captures**
  Prompt: 2.2 MeV γ or a 8 MeV γ cascade from n-capt
- ^{12}**C(n,n'**γ**)**^{12}**C** reactions
  Prompt: **mixing** between 4.4 MeV γ and proton recoil

- **Stopping muons**

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

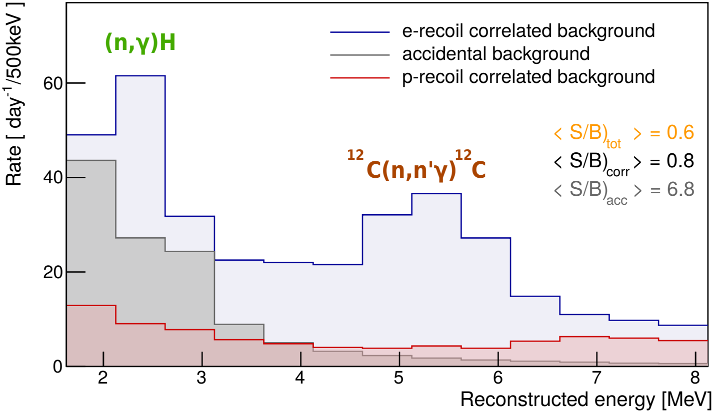
Pulse Shape Discrimination for prompt signal





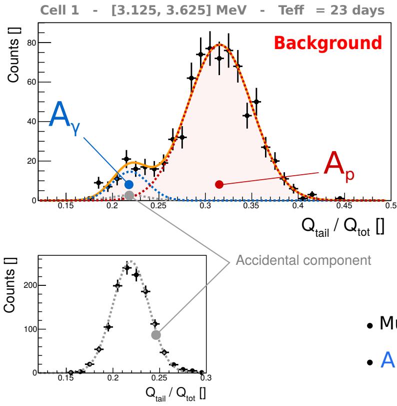
Correlated background identification

Prompt energy spectrum under neutrino component

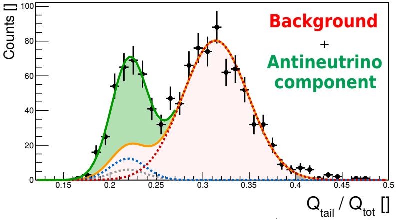


$\bar{\nu}_e$ signal extraction from PSD distributions (OFF & ON)

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

$\bar{\nu}_e$ are extracted per <u>time bin of 2 weeks</u>

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

arXiv:1806.02096 (2018)

Ratio method:

Compare **ratios** of energy distributions - **cell 1 taken as reference** of measured ($R_{i,j}^{\text{Data}}$) and simulated ($R_{i,j}^{\text{MC}}$) spectra.

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

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

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**

Null hypothesis testing ($\Delta\chi^2$):

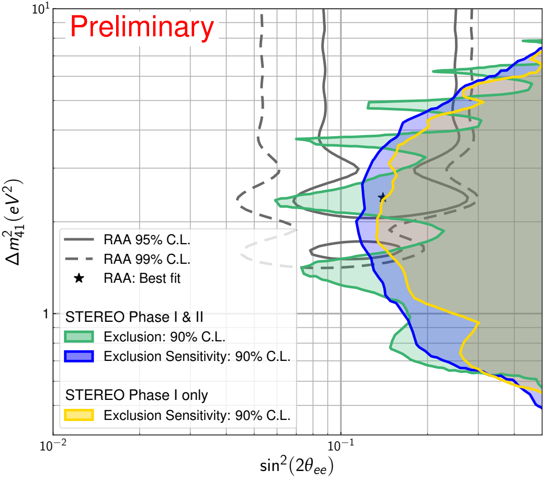
- **Non-oscillation hypothesis (H_0) can not be rejected:**
  p-value = 34 % (40 %) for phase-I (phase-I+II)

arXiv:1806.02096 (2018)

Exclusion contours Phase-I+II combined ($\Delta\chi^2$):

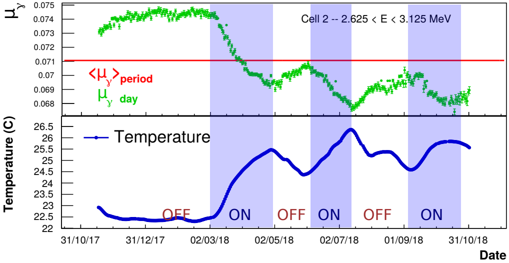
- $\Delta\chi^2$ distributions estimated by MC pseudo experiments
- **Raster-scan** approach (Δ^2_m slices)
- **Phase-I + Phase-II combined results**
  (66+47) days reactor-ON
  (396 ± 4) $\bar{\nu}_e$ day^{-1}

  ✗ Considered as two **independent measurements**:
  $\chi^2 = \chi^2_I(\vec{\alpha_I}) + \chi^2_{II}(\vec{\alpha_{II}})$
  $\vec{\alpha_I} \neq \vec{\alpha_{II}}$
- Best-fit value of the **RAA rejected at 98 % C.L.**



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

- Increased statistics + **More stable** conditions
  → Detailed studies on the PSD revealed **strong correlations** with temperature & light leaks in the detector
  → Need a reference population (singles γ's) able to follow PSD variations per day



- **New complementary & promising method based on an event by event PSD correction**
  → No assumed model of the background + no time bin
  → Stays coherent with first neutrino extraction method
  → On-going tests on LS prototype at MPIK (Heidelberg)

Conclusions and perspectives

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

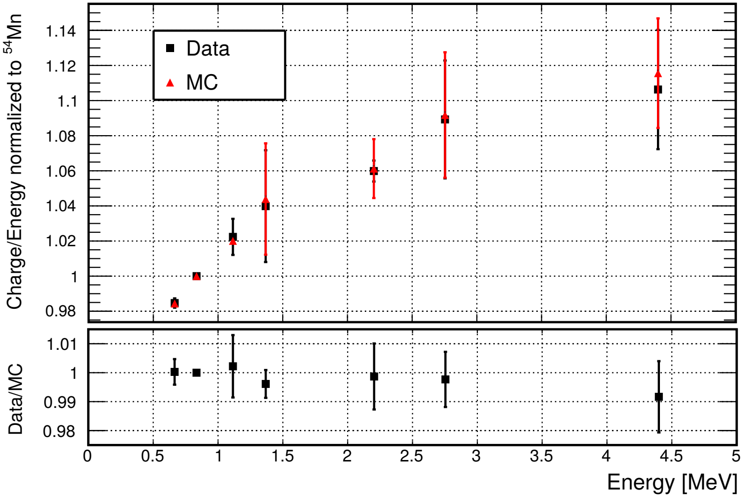
$\sim$ Thanks for your attention ! $\sim$

BACKUP

MC tuning

Quenching curve

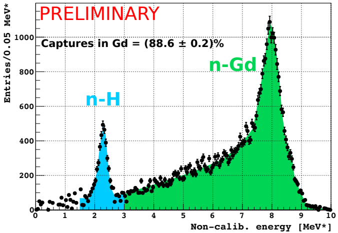
Non-linear light production in the large dE/dx regime (low E – Bragg peak)

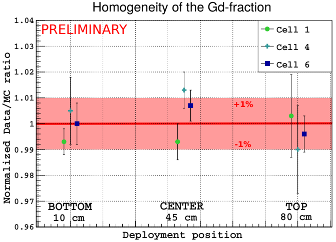


MC tuning

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



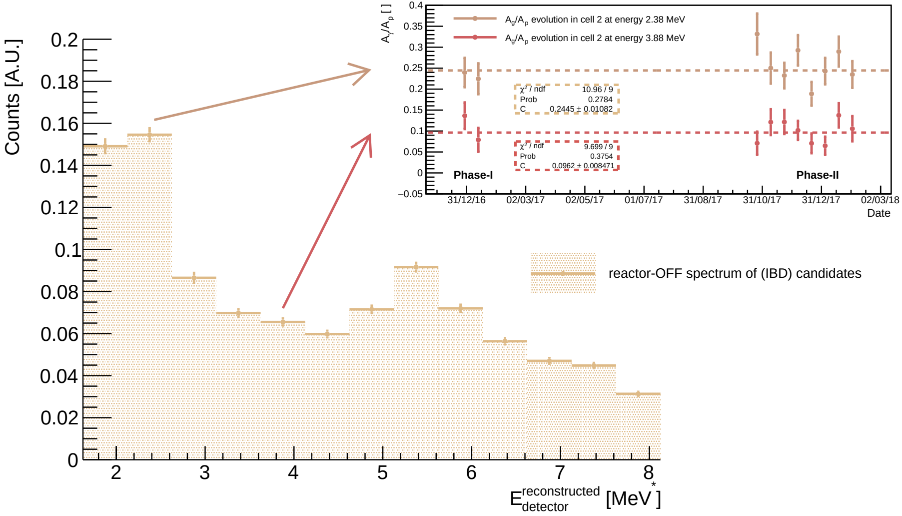


Systematics

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

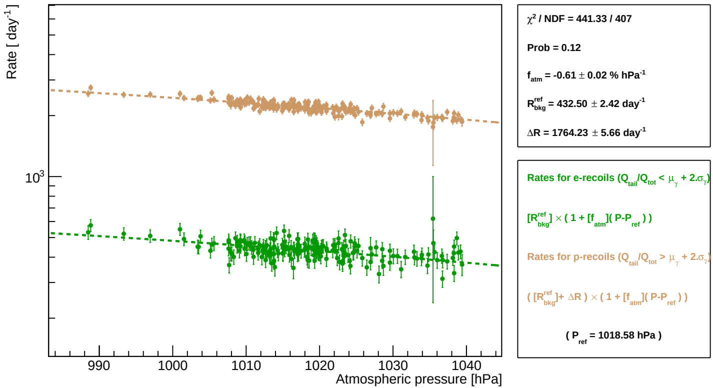
Source	**Contrib to σ^{Escale}**
Escale correlated	0.35 %

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



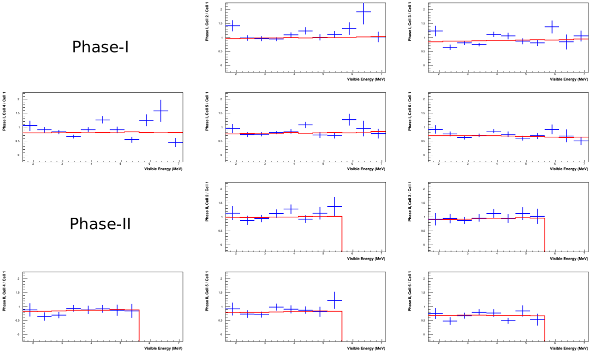
Counts [A.U.]
reactor-OFF spectrum of (IBD) candidates
E reconstructed detector [MeV*]
A_γ/A_p [ ]
A_g/A_p evolution in cell 2 at energy 2.38 MeV
A_g/A_p evolution in cell 2 at energy 3.88 MeV
χ^2 / ndf 10.96 / 9
Prob 0.2784
C 0.2445 ± 0.01082
χ^2 / ndf 9.699 / 9
Prob 0.3754
C 0.0962 ± 0.008471
Phase-I
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**



Ratio method: Results for Phase-I & II

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)