Chasing the light sterile neutrino with the STEREO experiment

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on behalf of the STEREO collaboration

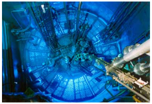
supported by

25th anniversary of the Rencontres du Vietnam - 7th of august 2018

Motivation

The Reactor Antineutrino Anomaly (RAA)

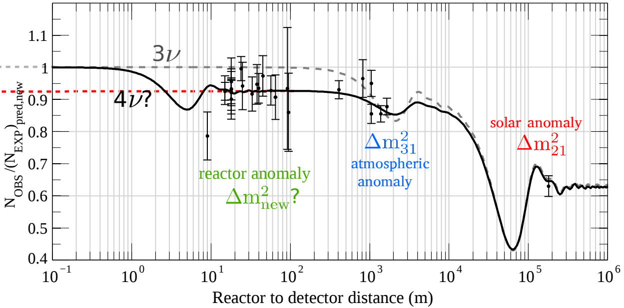
Phys.Rev.D83:073006 (2011)



2011: reevaluation of the $\bar{\nu}_e$ reactor flux prediction
→ **Reactor Antineutrino Anomaly**

~ 6 % deficit

- **Sterile neutrino ?**
- Wrong prediction ?



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

~ 1eV sterile neutrino
→ **Need dedicated measurements**

Experimental site

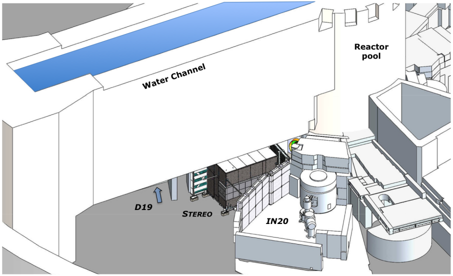
ILL research facility, Grenoble, France

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

✓ **Compact** core (40cm ∅)

✓ **Highly ^{235}U** enriched

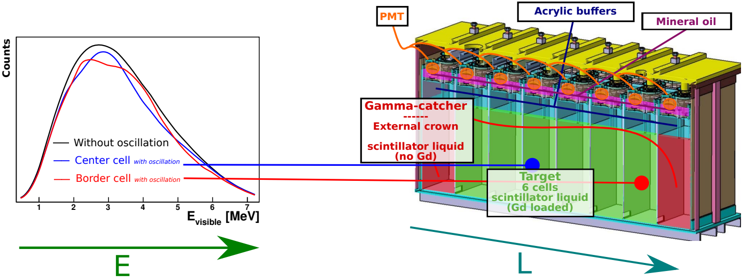
✓ **Short baseline** measurement:
$8.9m < L_{core} < 11.1m$



- **Surface-level** experiment
- γ **and neutron background** from neighboring experiments

The STEREO experiment

Designed to probe the Reactor Antineutrino Anomaly region



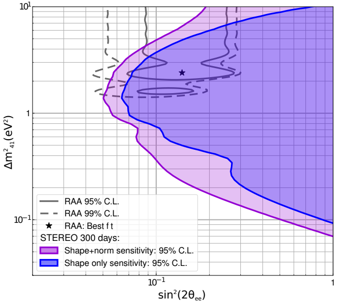
- ✓ **Segmented** target filled with Gd-doped liquid scintillator
- ✓ **Gamma-catcher** as active shielding

- ✓ Oscillation hypothesis test: measuring **relative distortions** of the $\bar{\nu}_e$ energy spectrum

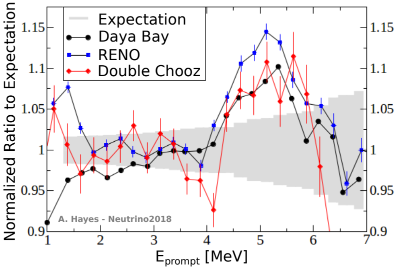
The STEREO experiment

Designed to probe the Reactor Antineutrino Anomaly region

- Designed to probe the RAA region → approach **independent from predicted energy spectrum**

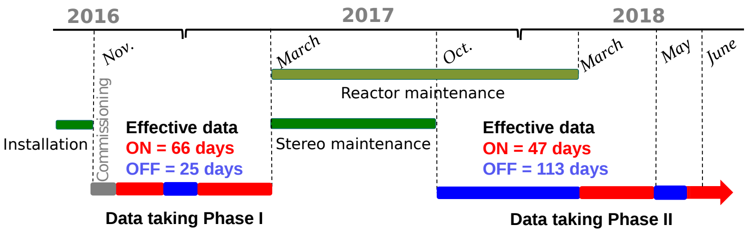


- Measurement of a **pure ^{235}U $\bar{\nu}_e$ energy spectrum** → complementary information to commercial reactor $\bar{\nu}_e$ measurements:
  Origin of the *5 MeV bump* ?
  Bias in the normalisation of one isotope ?



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

  → repaired during summer 2017

Phase-II:

- Stable conditions

Physics runs: ~**95% of data taking time**

Detector response

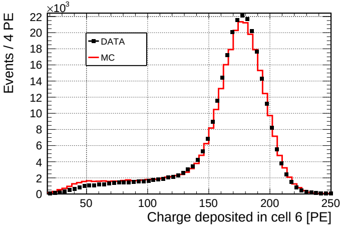
Calibration

JINST, Vol. 13, 2018 (arXiv:1804.09052)

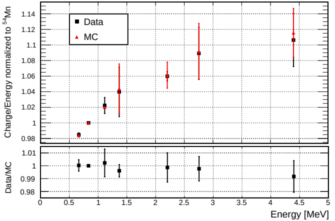
- **Monitoring of liquids/electronics:** Automatic daily **LED measurement**: PMT gain, liquid stability, electronics linearity
- **Monitoring of the energy response:** On a weekly basis: internal and external calibrations using **radioactive sources**
- **Monitoring of the neutron capture:** Using dedicated AmBe source

→ Tuning of the MC simulation of the detector: optical surfaces, liquid properties...

(a) ^{54} source deployed in cell 6



(b) Quenching of the liquids



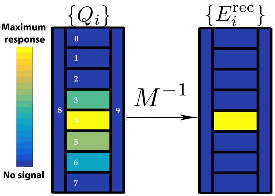
Detector response

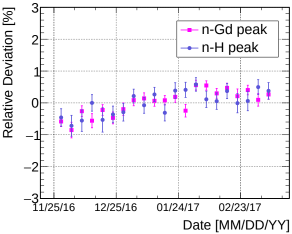
JINST, Vol. 13, 2018 (arXiv:1804.09052)

Energy reconstruction

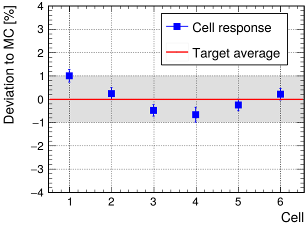
Energy reconstruction takes into account evolving
- Light collection (Calibration coefficients C_i [pe/MeV])
- Light cross-talks between cells (L_{ij} coefficients)

$$\begin{pmatrix} E_0^{\mathrm{rec}} \\ E_1^{\mathrm{rec}} \\ \vdots \\ E_9^{\mathrm{rec}} \end{pmatrix} = M^{-1} \begin{pmatrix} Q_0 \\ Q_1 \\ \vdots \\ Q_9 \end{pmatrix} \quad \text{with } M_{ij} = C_i L_{ij}$$





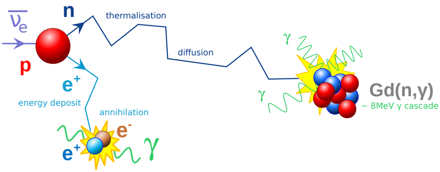
(a) Time stability

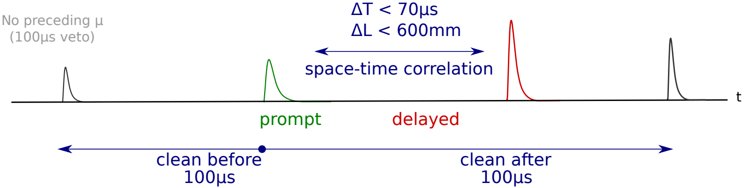


(b) Cell to cell deviations

$\bar{\nu}_e$ signal selection

Inverse Bêta Decay reaction





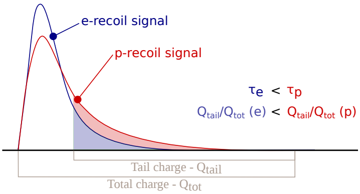
$1.6 < E_{prompt} < 7.1\,\text{MeV}$ $\quad$ $4.5 < E_{delayed} < 10\,\text{MeV}$

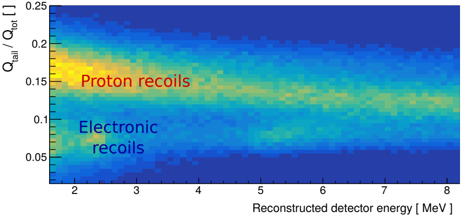
Prompt contained in one cell

Correlated background

Pulse Shape Discrimination

Pulse Shape Discrimination for prompt signal





Neutron induced reactions:

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

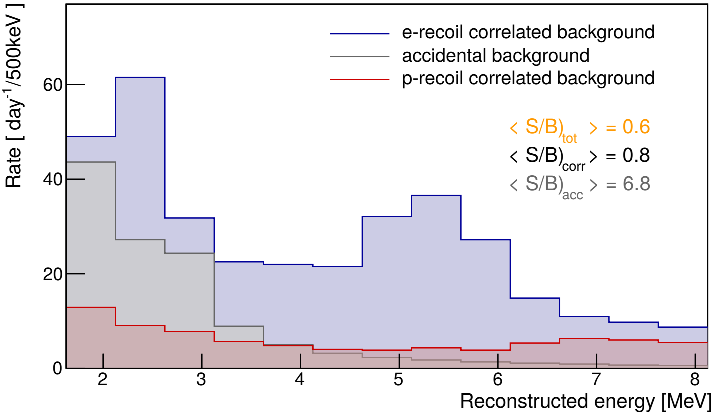
(Delayed are Gd capture)

Stopping muons:
Prompt: μ stop
Delayed: Michel $e^{+/-}$
Asymmetry based rejection

Correlated background

Reactor-OFF prompt energy spectrum

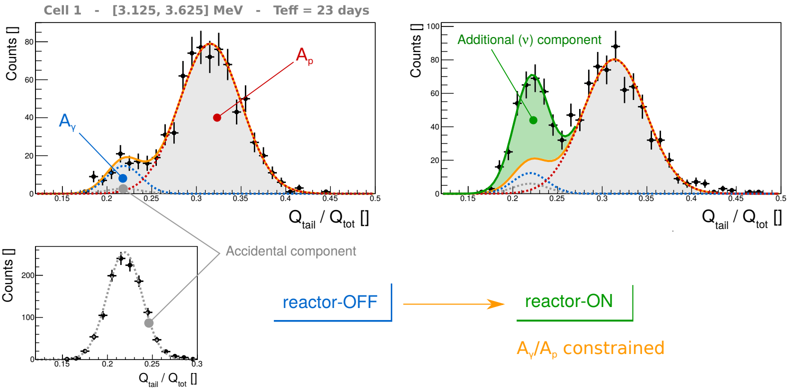
Reactor-OFF prompt energy spectrum in the region of interest



$\bar{\nu}_e$ signal selection

Extraction of the $\bar{\nu}_e$ rates from PSD distributions

Multi-Gaussian background model for each cell/energy/time bin PSD:



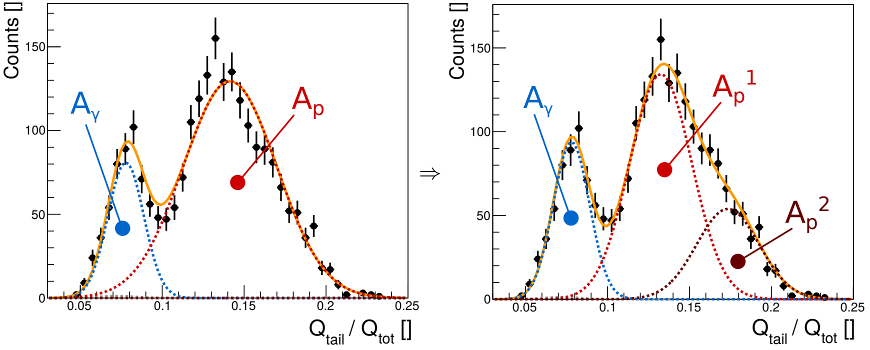
Self-consistent method to estimate background under $\bar{\nu}_e$ component:

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

$\bar{\nu}_e$ signal selection

Extraction of the $\bar{\nu}_e$ rates from PSD distributions

Phase-II: 84 days (effective time) with **stable** conditions
→ Updated background model with increased statistics



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

Ratio method

arXiv:1806.02096 (2018)

Relative comparison of energy distributions

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

- Reduced systematics
- Insensitive to absolute flux normalization
- Insensitive to spectrum shape

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

MC takes into account cell differences, detection efficiencies etc.

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

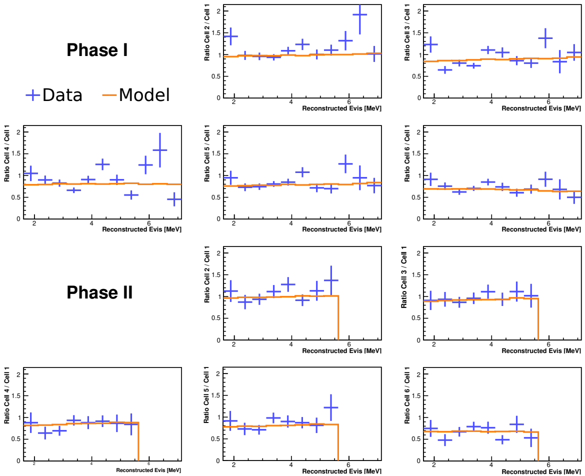
V_i is the **covariance matrix** of the 5 ratios (common reference for each cell) for the energy bin i
$\{\alpha\}$ are pull-terms to take into account estimated **systematics**

Ratio method

Non-oscillation hypothesis

arXiv:1806.02096 (2018)

Ratio method: cell 1 taken as reference



– **Measured ratios**

– **Non-oscillation prediction**

- Minimized pull terms stay within $\pm 1\,\sigma$
- **Non-oscillation hypothesis (H_0) not rejected:** p-value = 34 % (40 %) for phase-I (phase-I+II)

Ratio method

arXiv:1806.02096 (2018)

Exclusion contours - Phase I

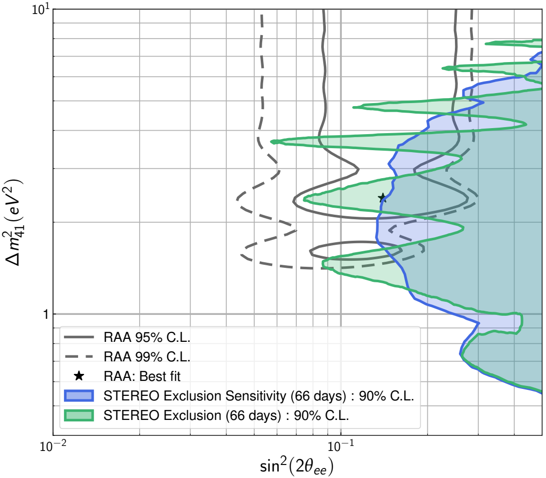
- **Phase-I results**
  66 days reactor(ON)
  $396 \pm 4\ \bar{\nu}_e\ \mathrm{day}^{-1}$

- **Raster-scan** method
  $\Delta\chi^2$ distributions estimated by MC pseudo experiments

- Best-fit value of the **RAA*** **rejected at 97.5 % C.L.**

  * RAA(2011) parameters:

$$\begin{cases} \Delta m^2_{\mathrm{RAA}} = 2.3\,\mathrm{eV}^2 \\ \sin^2(2\theta_{\mathrm{RAA}}) = 0.14 \end{cases}$$



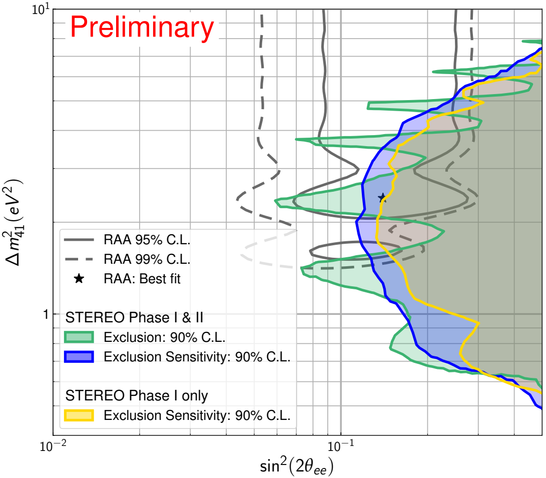
Ratio method

Exclusion contours - Phase I+II combined

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

  * RAA(2011) parameters:

  $$\begin{cases} \Delta m^2_{\text{RAA}} = 2.3\,\text{eV}^2 \\ \sin^2(2\theta_{\text{RAA}}) = 0.14 \end{cases}$$



Conclusions and perspectives

- STEREO is now running under **very 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**
  arXiv:1806.02096 (2018)
- Improved results are coming soon, with a **pure ^{235}U spectrum**

Thanks for your attention !

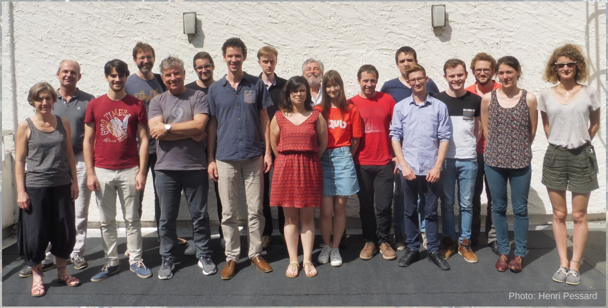


Photo: Henri Pessard

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