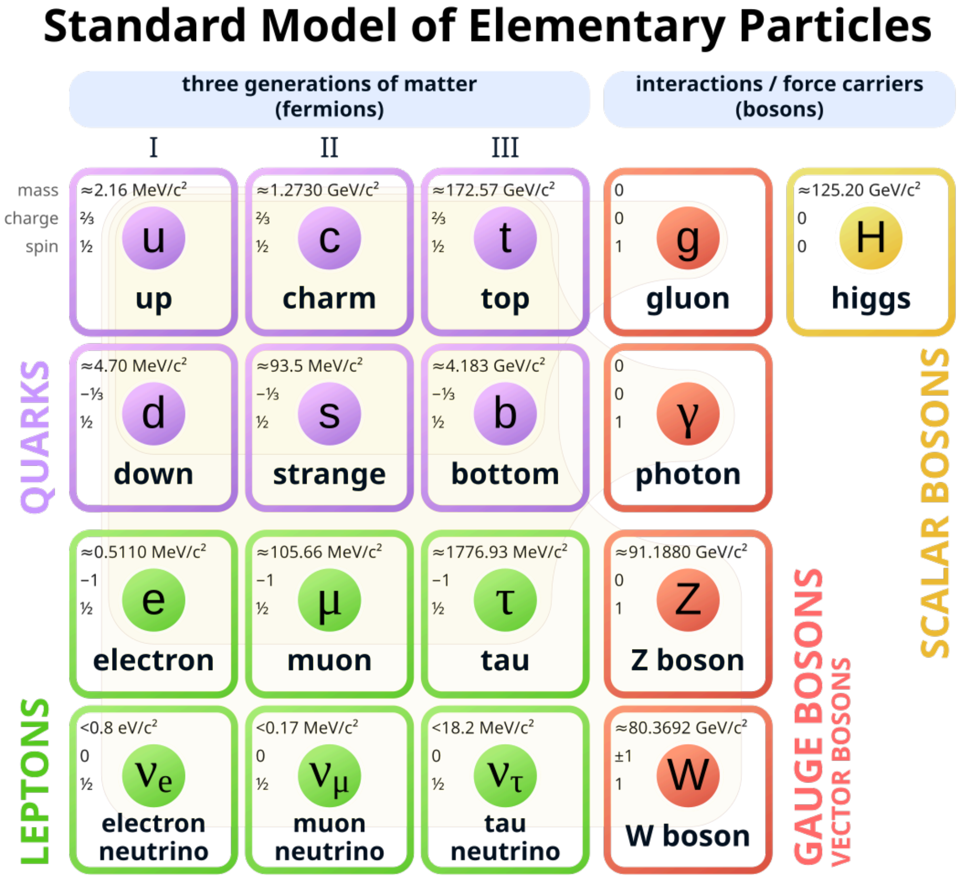
Refining Sterile Neutrino Exclusion through Joint Analysis: Revisiting STEREO Phase 2 and Analytical Response Modeling.

JRJC 2024, friday 29 november 2024.

Yann Querlioz

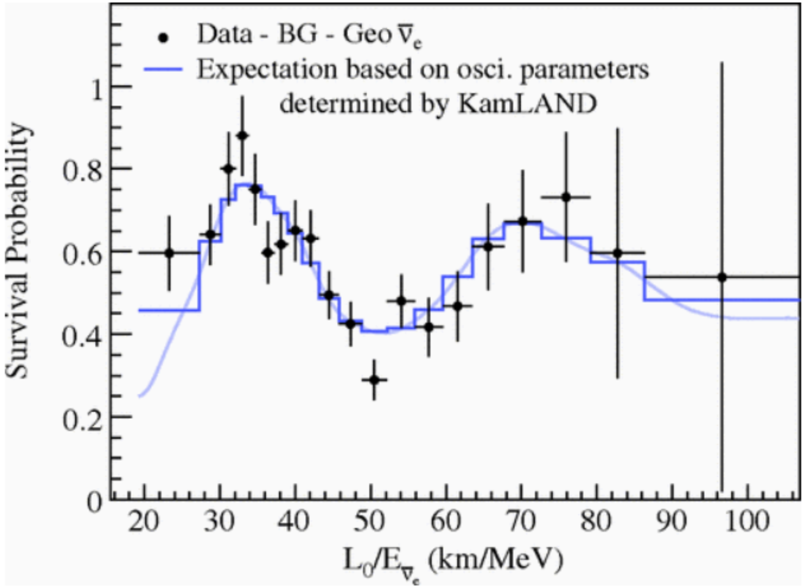
Supervisor: Pablo Del Amo Sanchez

Neutrino, an elementary particle



- Neutral lepton
- Only interact through weak interaction
- Pair-produced with one of the three charged lepton
- A quantum number called "flavor" is associated to the produced neutrino
- Fundamental neutrino property, the neutrino oscillations

Neutrino oscillations

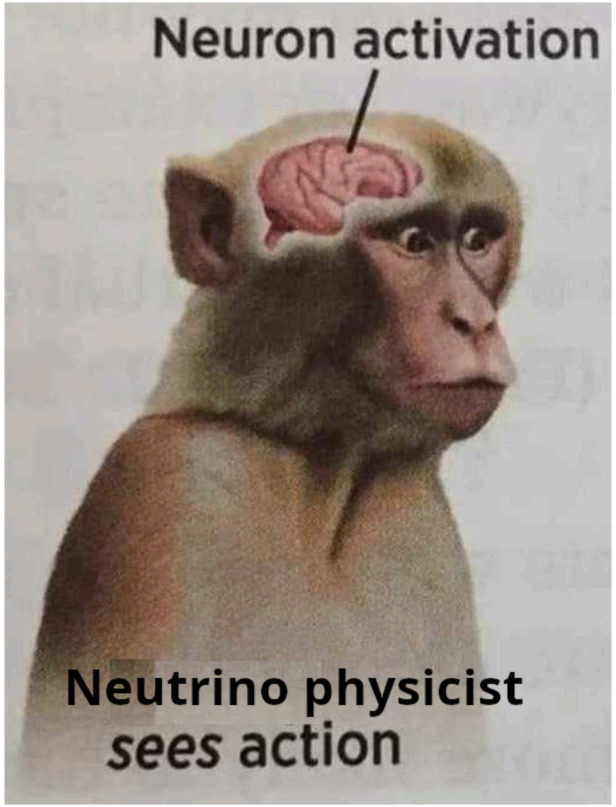


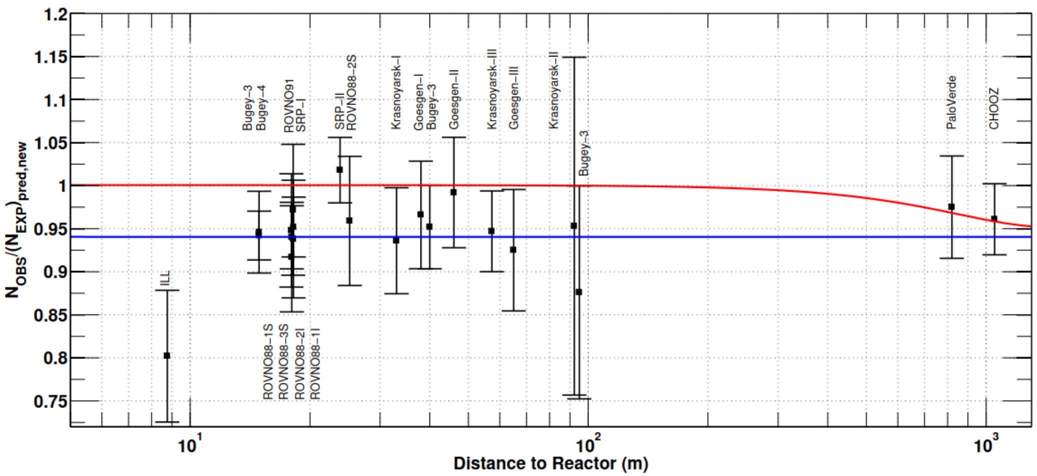
KamLAND Collaboration, **Precision Measurement of Neutrino Oscillation Parameters with KamLAND**, *PhysRevLett.100.221803*

$$\mathcal{P}_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \sin^2(2\theta_{12})\sin^2\left(\Delta m^2_{12}\frac{L}{E_\nu}\right)$$

- The probability of measuring a given neutrino flavor is a function of the L/E ratio
- Explain the experimental deficit measured in the solar neutrino flux

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

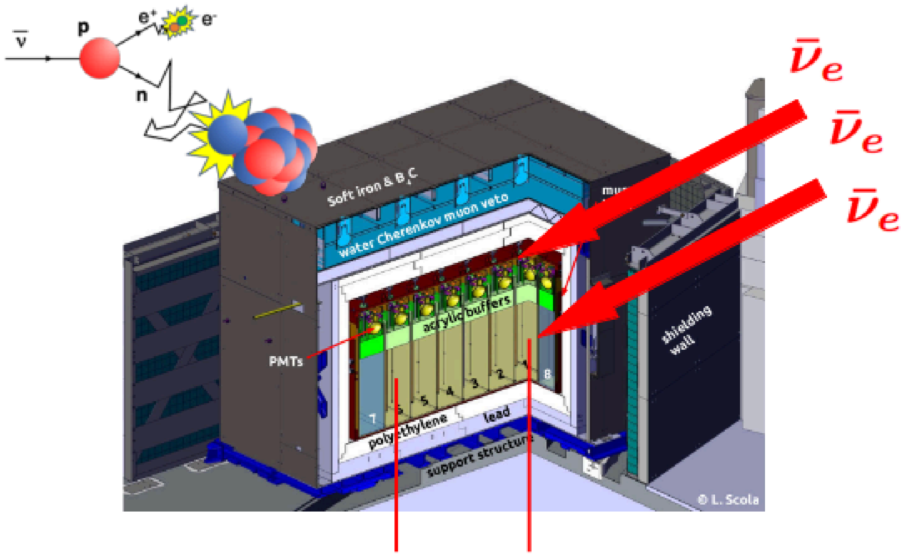


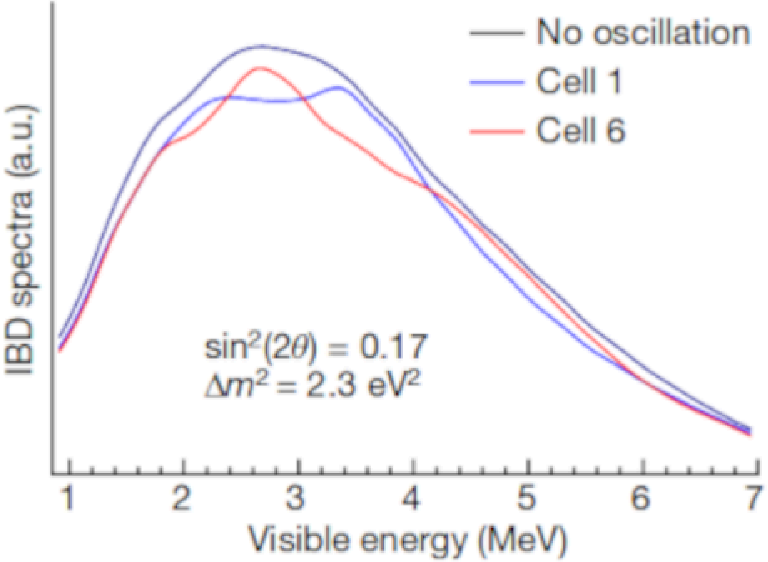


G. Mention and all, **The Reactor Antineutrino Anomaly**, *J. Phys.: Conf. Ser. 408 012025*

RAA illustration plot.
(red) 3 flavors total flux prediction.
(blue) 4 flavors total flux prediction.

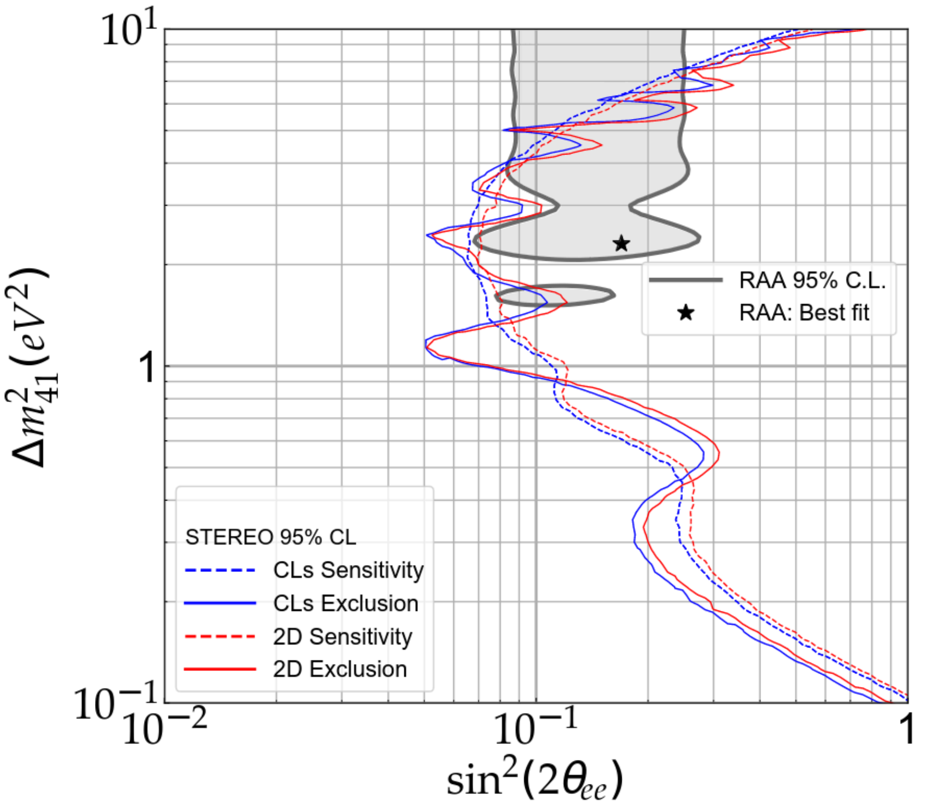
Detection principle, STEREO experiment

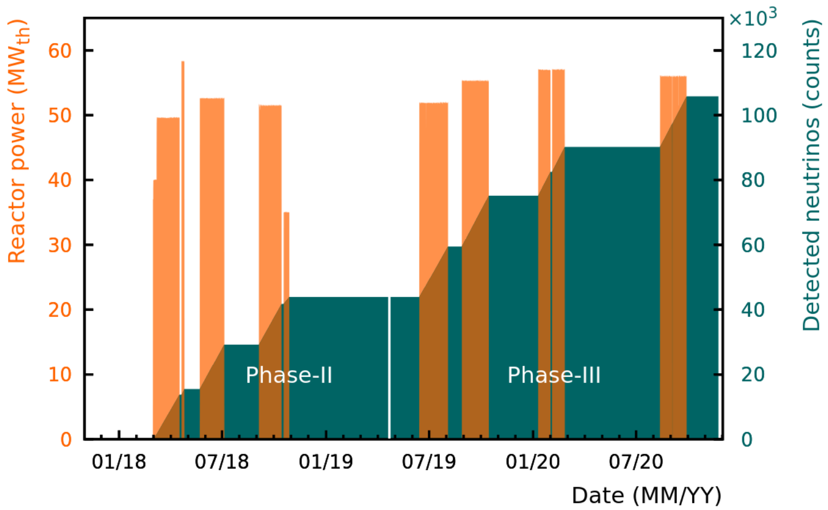




- Inprint of oscillations on $\bar{\nu}_e$ spectrum as function of L
- Inverse beta decay: $\bar{\nu}_e$ + p -> e^+ + n
- Gadolinium-doped liquid scintillator
- Measurement of photons by PMT

STEREO publication



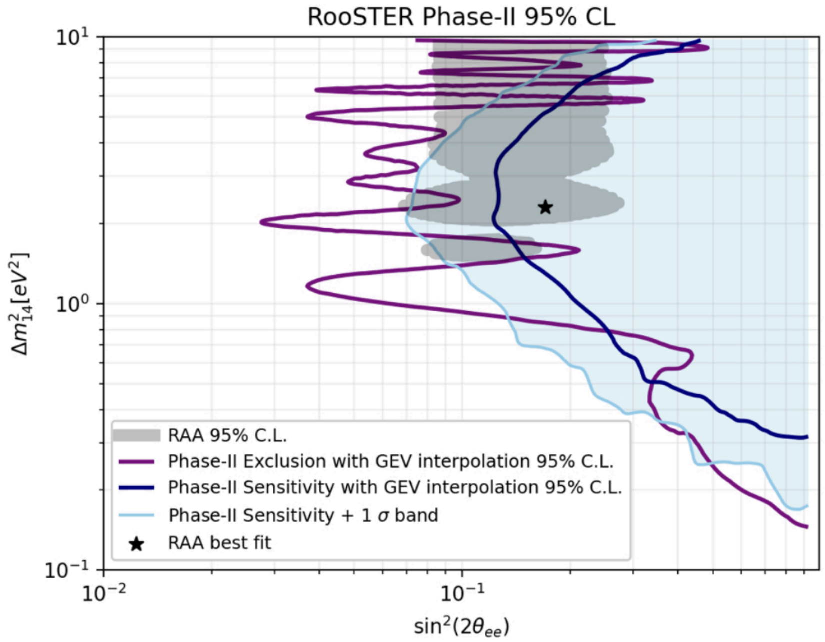


Exclusion of sterile neutrino hypothesis with more than 4σ CL for RAA best fit

STEREO collaboration, **STEREO neutrino spectrum of ^{235}U fission rejects sterile neutrino hypothesis,** *Nature 613 (2023) 7943, 257-261*

STEREO LAPP analysis

- Alternative analysis for phase 2
- Shape only fit
- No Phase 3 due to lack of person-power



Loïc Labit, **Very short baseline neutrino oscillations study with the STEREO detector at ILL.**, *Insp: 2049443*

Rewriting the initial framework

Old framework computation time issue

- Computation time of 24 hours per fit for phase 2
- For ≈ 4M fits
- + Addition of phase 3, Prospect (5 periods), Daya-Bay...

⇒ Computation time way too long

New framework

- Reduction in the number of nuisance parameters of the analytical response model
- Moving from RooFit to libraries allowing finer control of computation steps (Jax et numpy)
- Code compiled on the fly on CPU (or GPU)
- Performance comparison of different algorithms and optimization methods

⇒ **Objective:** validation of the new framework with the old one

⇒ Decrease fit time to ≈ 10 min

Shape only fit

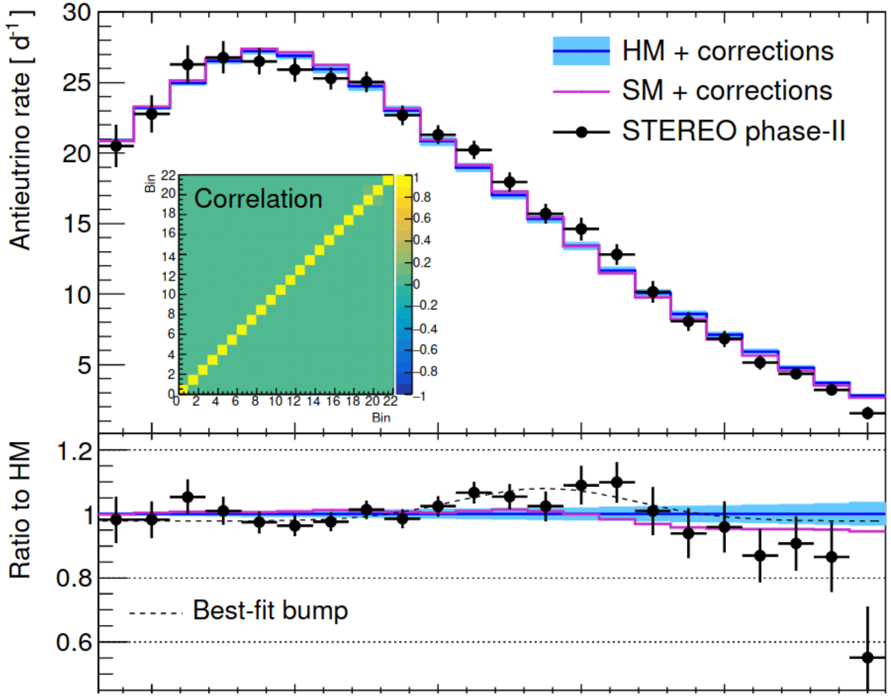
Standard χ^2 with penality "pull-terms" to constrain response nuisances parameters

$$\chi^2(\mathbf{\Omega}, \vec{\kappa}, \pi_{cp} \mid D) = \sum_{i,c=1..6} \left(\frac{N_c \varphi_{\text{ci}}(\mathbf{\Omega}, \vec{\kappa}, \pi_{cp}) - D_{\text{ci}}}{\sigma_{\text{ci}}} \right)^2 + \sum_{c=1..6} \left(\frac{\pi_{cp}}{\sigma_{cp}} \right)^2$$

- Sterile neutrino oscillation parameters $\mathbf{\Omega} = (\sin^2(2\theta_{\text{ee}}), \Delta m^2_{14})$
- Reactor neutrino spectrum nuisances parameters $\vec{\kappa}$
- Response model nuisances parameters π_{cp}
- Shape only fit, prediction φ_{ci} normalised to data D_{ci} for each cell (c)

Reactor antineutrino spectrum prediction

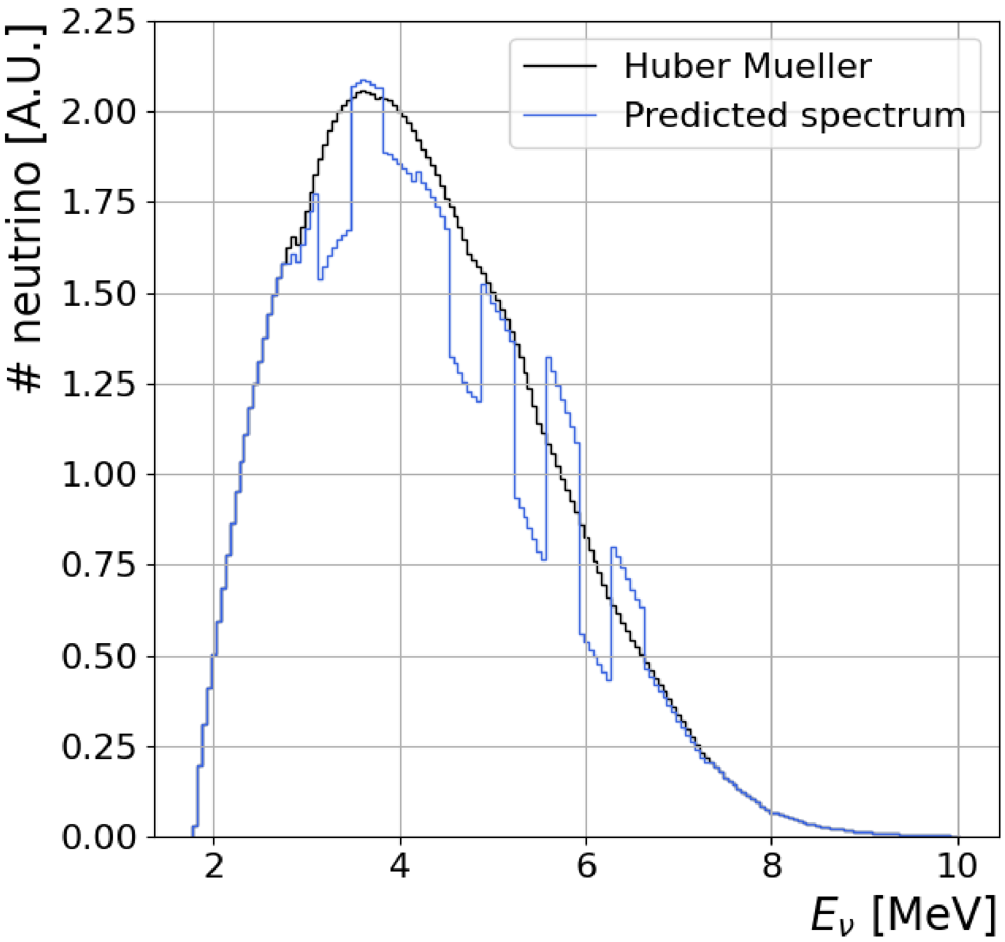
- Huber Mueller, standard in reactor neutrino physics. From measurements on isotope layers
- ⇒ It has been shown that the spectrum is the main systematic



STEREO collaboration, **First antineutrino energy spectrum from U235 fissions with the STEREO detector at ILL.**, *Phys. G: Nucl. Part. Phys. 48 075107*

Spectrum nuisance parameters

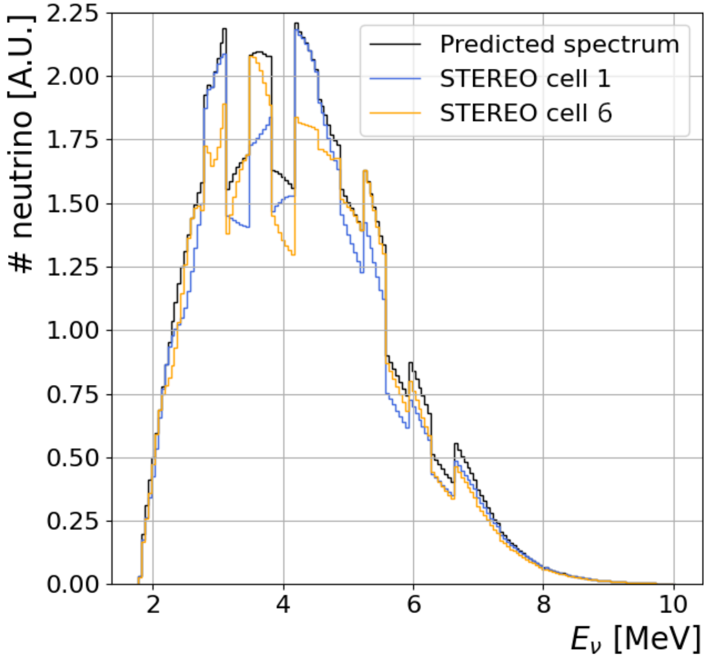
- Fitted reactor antineutrino spectrum on a toy (bleu)
- Defined for each neutrino "true" energy bins "j"; $\Phi(\vec{\kappa})_j$
- $\vec{\kappa}$ allow spectrum variations by 350 keV slices
- Common to all cells ⇒ cannot mimic oscillations



Baseline dependent oscillation

$$\mathcal{P}_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - \sin^2(2\theta_{\text{ee}}) \sin^2\left(\Delta m^2_{14} \frac{L}{E_\nu}\right)$$

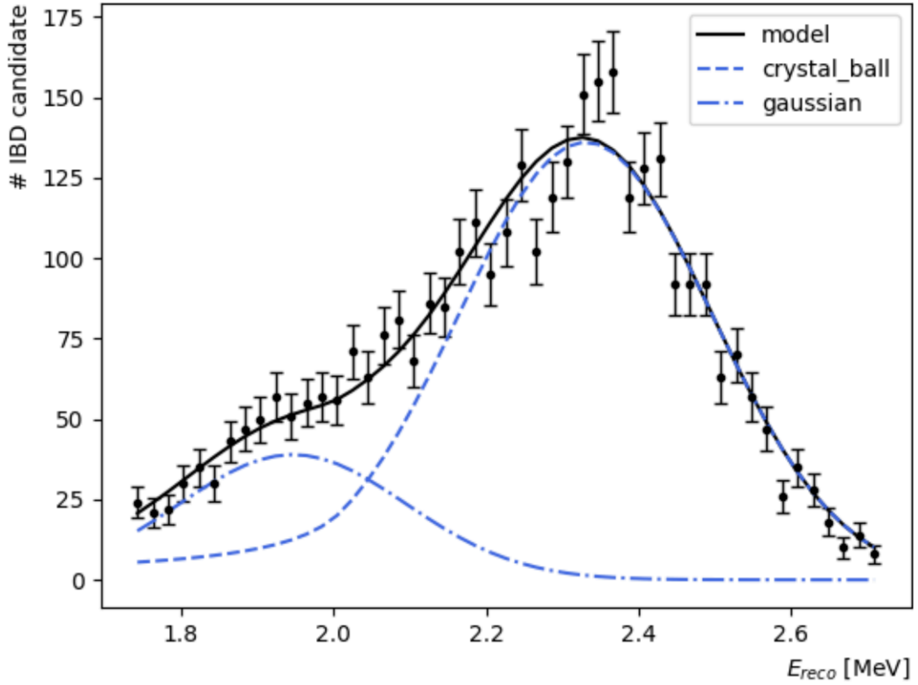
- Fitted reactor antineutrino spectrum (black)
- Fitted antineutrino spectrum with oscillations for nearest cell (blue) and furthest cell (orange)
- Function of L ⇒ Unique to each cell



Analytical response model

- Models the conversion between true neutrino energy to reconstructed energy
- One PDF model, defined per cell (c) and neutrino energy bins (j)
- 2 component PDF over reconstructed energy ($E_{\text{reco;i}}$);
  - A normal distribution for cell contained events
  - A normal + power law for lossy events
- Depend on a set of nuissance parameters ${p_{\text{cp}}}' = p_{\text{cp}}\left(1 + \pi_{\text{cp}}\right)$ constrained by pull terms

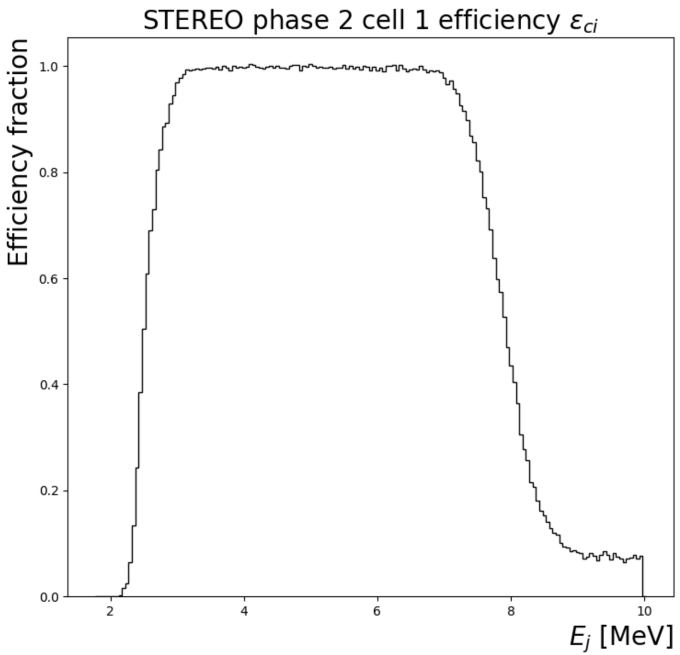
$$R(E_{\text{reco}}, E_{\nu} = 3\ \text{MeV})$$



Experimental efficiency per cell ε_{ci}

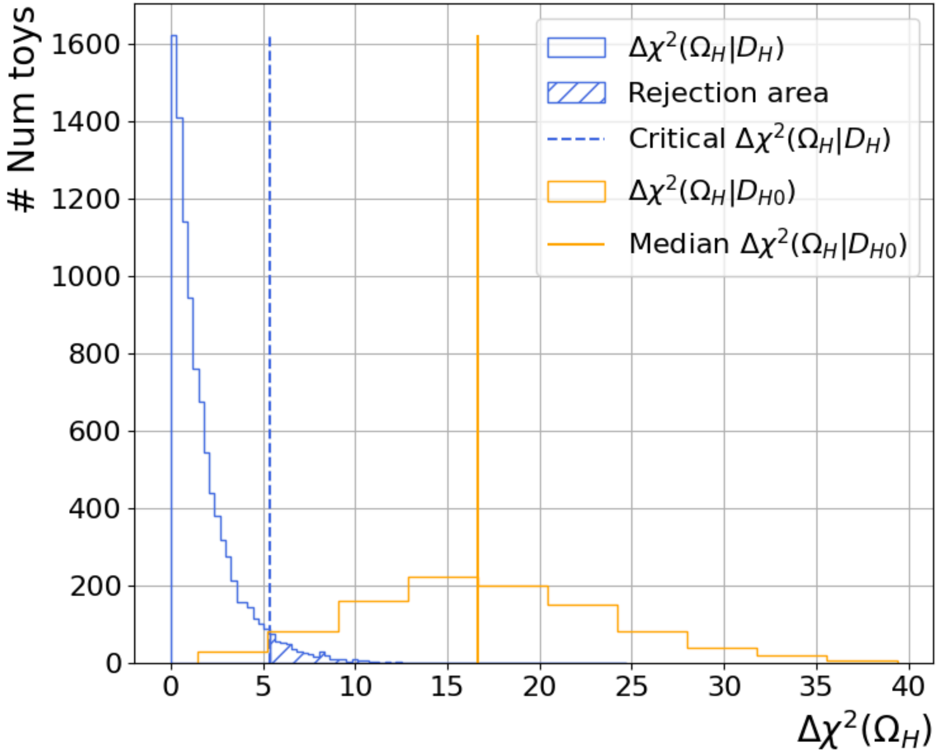
- Extracted from neutrino MC dataset
- Defined for each experiment baselines

$$\varphi_{\text{ci}} = \sum_j R_{\text{cij}}(\pi_{\text{cp}})\mathcal{P}_{\text{cj}}(\boldsymbol{\Omega})\varepsilon_{\text{cj}}\Phi_j(\vec{\kappa})$$



Feldman Cousins sensitivity to RAA best fit

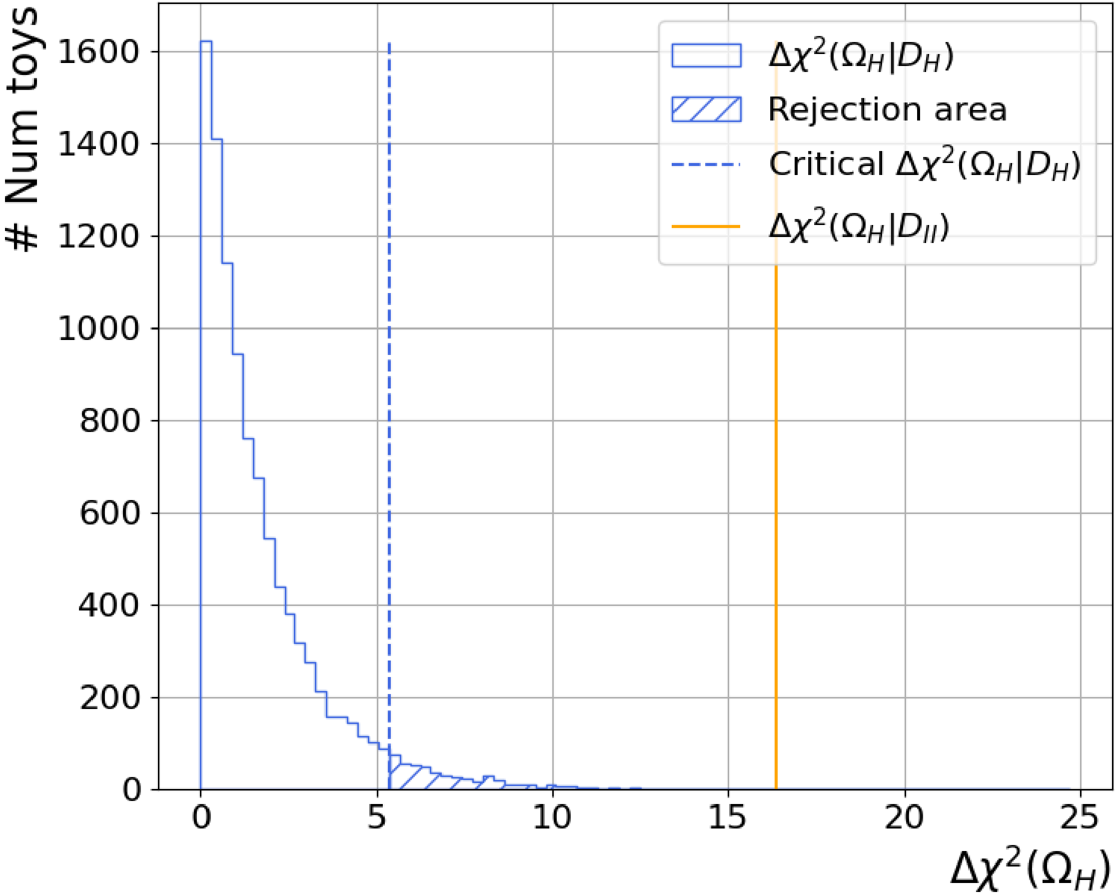
$$\Delta\chi^2(\boldsymbol{\Omega_H} \mid D_H) \stackrel{\text{def}}{=} \chi^2_{\text{min}}\left(\boldsymbol{\Omega}, \vec{\kappa}, \pi_{\text{cp}} \mid D_H\right) - \chi^2_{\text{min}}\left(\boldsymbol{\Omega_H}, \vec{\kappa}, \pi_{\text{cp}} \mid D_H\right)$$



$$\boldsymbol{\Omega}_H = (0.17 \;\; 2.3\text{eV}^2)$$

- χ^2 distribution for the RAA hypothesis ($\boldsymbol{\Omega}_H$) for RAA "toys" (D_H): $\Delta\chi^2(\boldsymbol{\Omega}_H|D_H)$
- Compared to the χ^2 distribution for the RAA hypothesis for null hypothesis "toys" (D_{H0}): $\Delta\chi^2(\boldsymbol{\Omega}_H|D_{\text{H0}})$

Feldman Cousins exclusion of RAA best fit

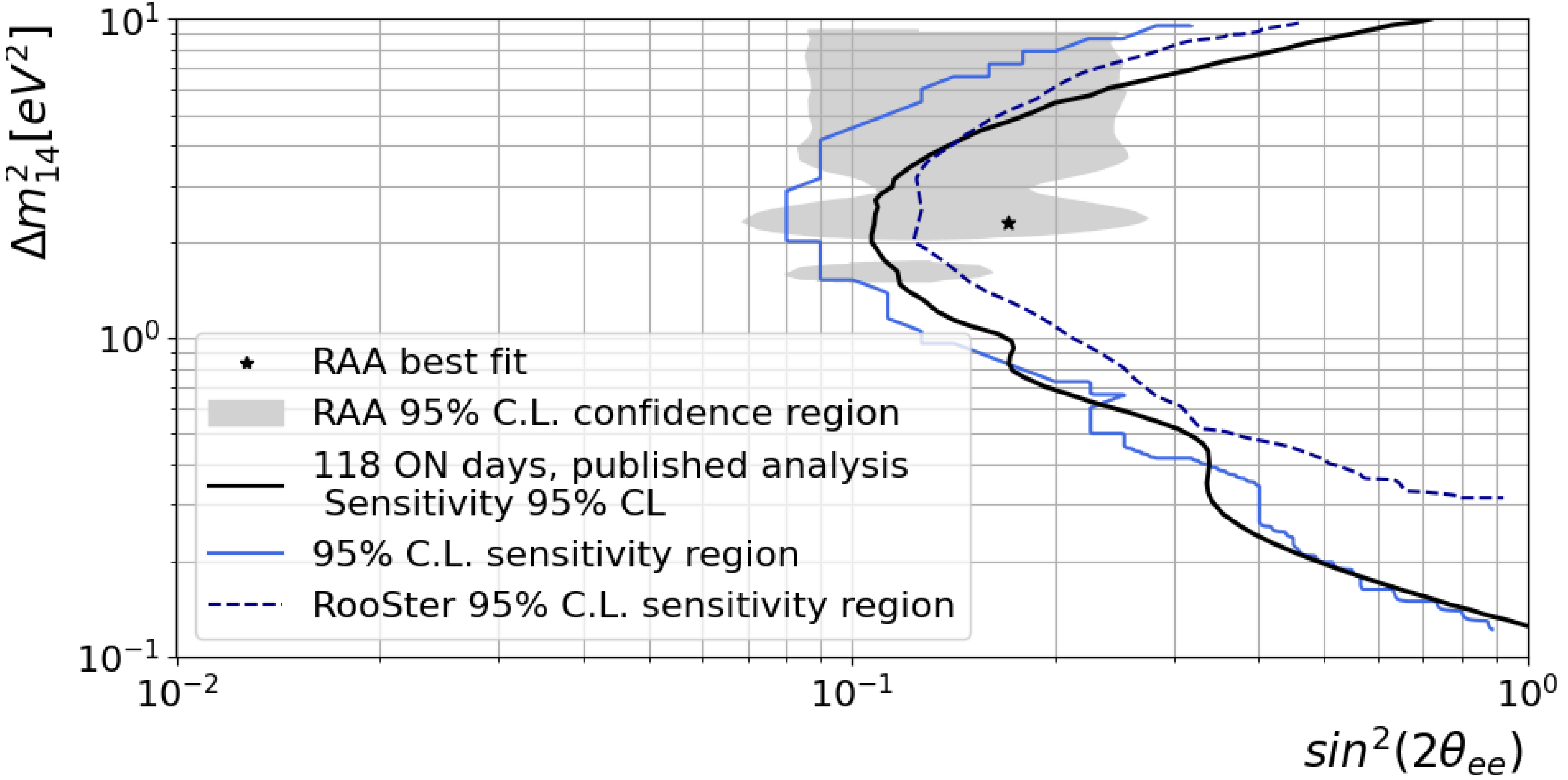


$$\Omega_H = (0.17 \;\; 2.3\text{eV}^2)$$

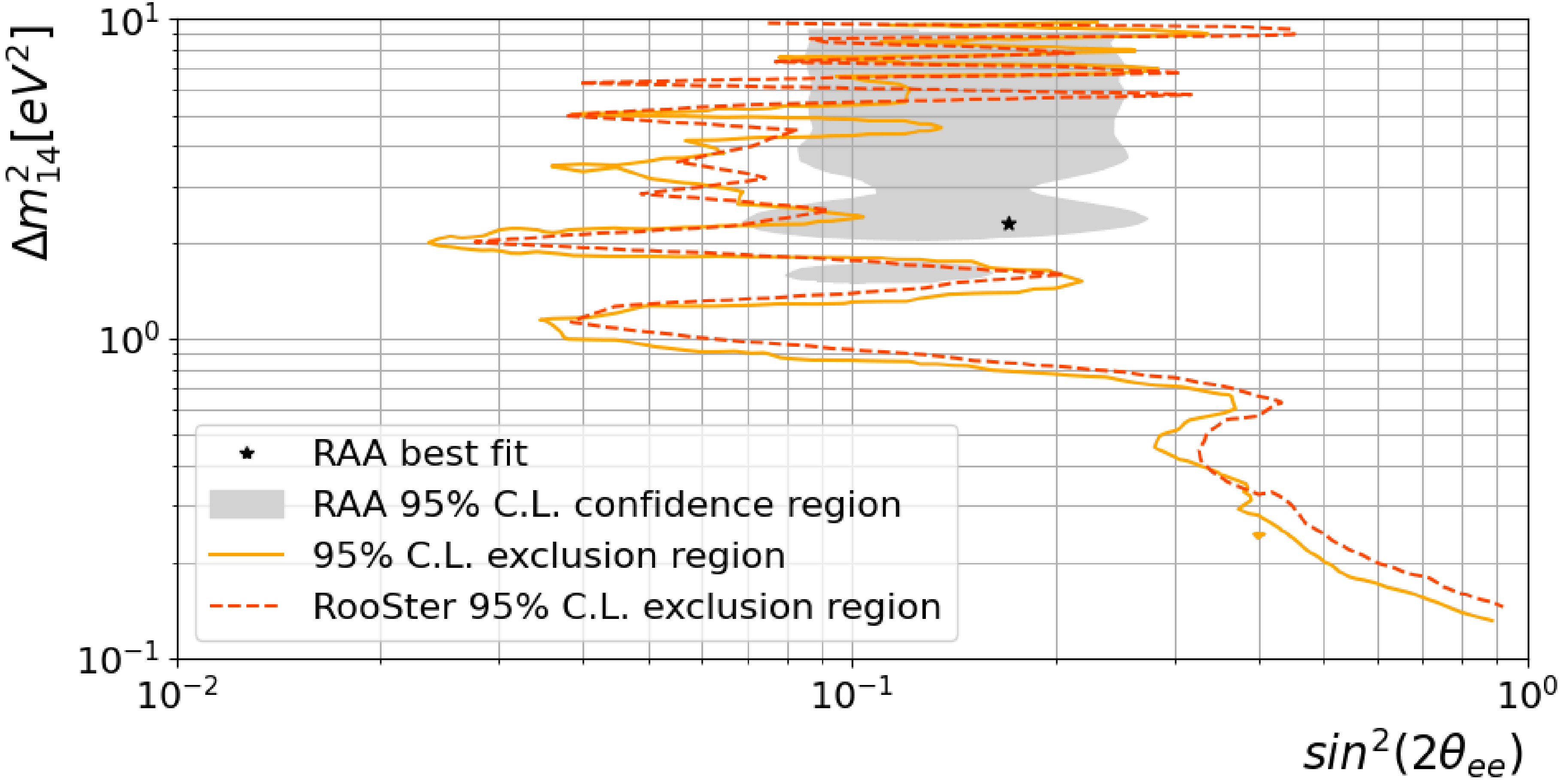
Comparing the likelihood distribution $\Delta\chi^2(\Omega_H|D_H)$ with the likelihood of the data $\Delta\chi^2(\Omega_H|D_{\text{II}})$ rather than the median of the toys D_{H0}

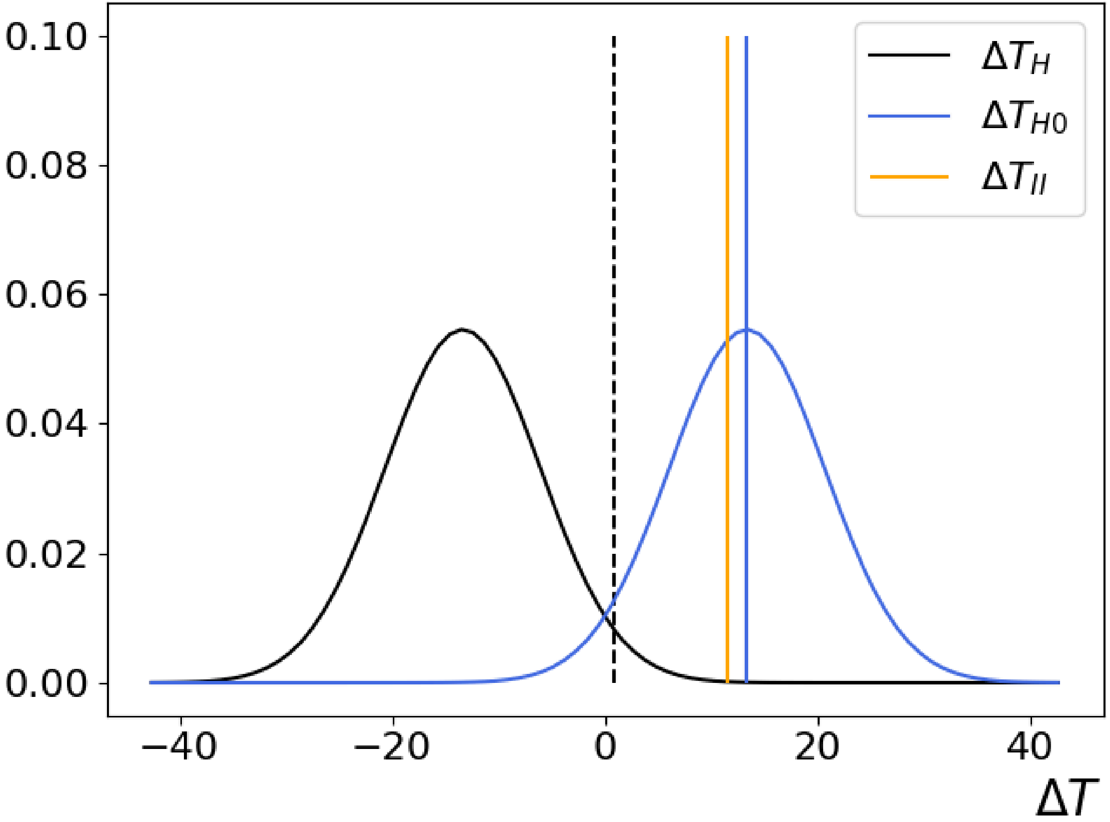
$\Rightarrow$ RAA is excluded at more than 4σ

FC sensitivity contour



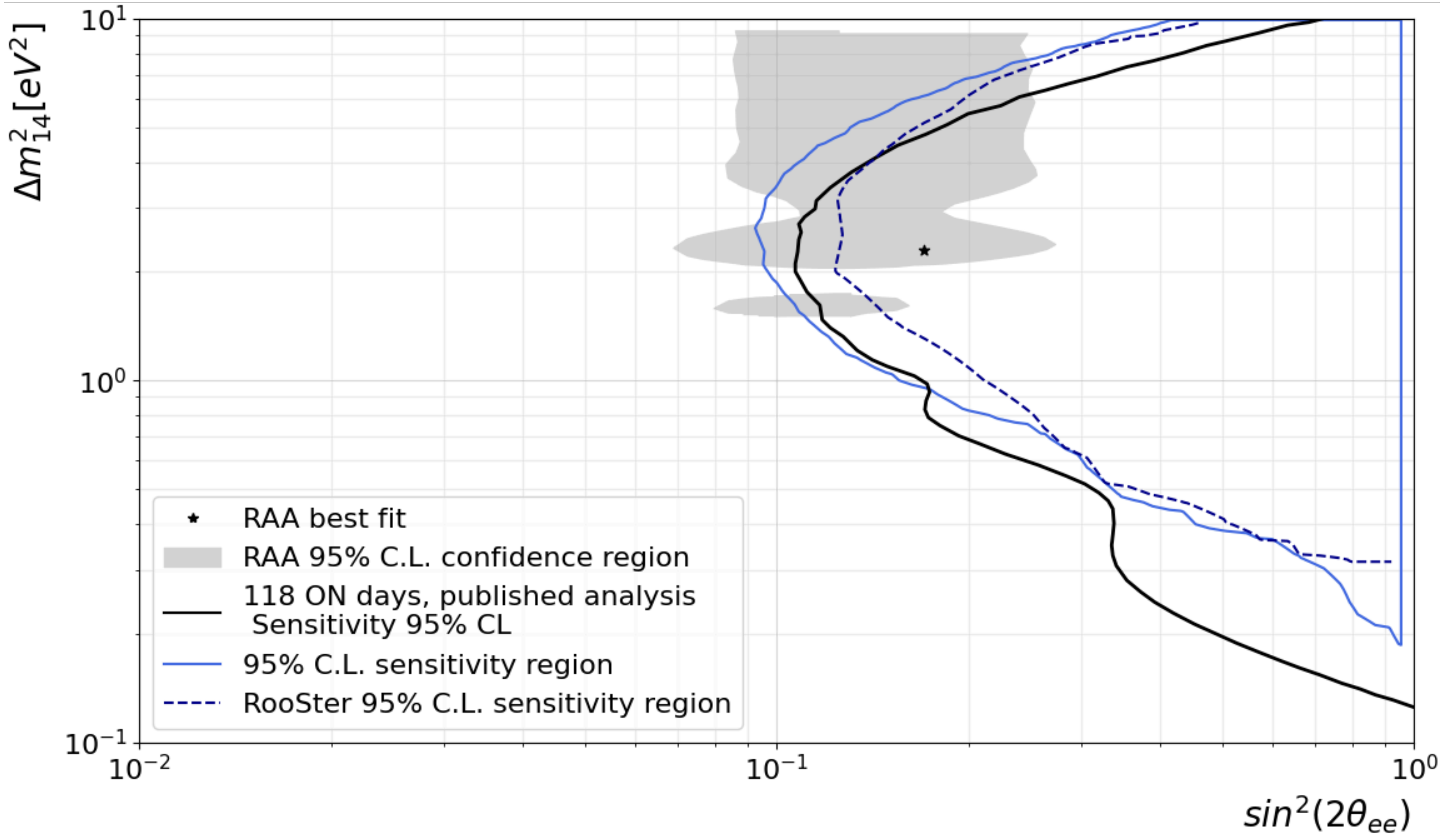
FC exclusion contour



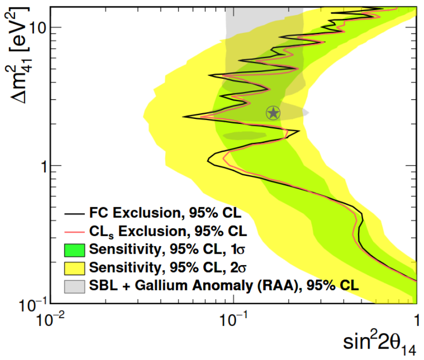


Replacing $\Delta\chi^2$ distributions by hypothesys likelihood test on asimov dataset

CLs sensitivity and exclusion



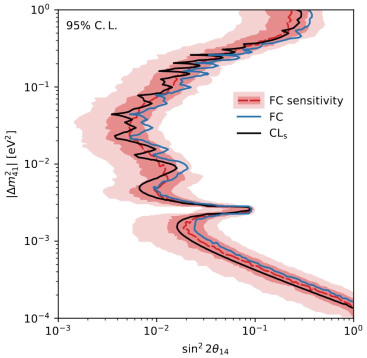
Joint analysis Daya-Bay - Prospect - STEREO



Prospect:

- Short baseline, high segmentation
- Best S/B ratio, less IBD candidates
- Almost identical reactor spectrum as STEREO

Prospect collaboration, **Final Search for Short-Baseline Neutrino Oscillations with the PROSPECT-I Detector at HFIR,** *arXiv:2406.10408*



Daya Bay:

- Designed for precise measurement of $\sin^2(\theta_{13})$
- Nuclear power reactor core

Daya Bay collaboration, **Search for a sub-eV sterile neutrino using Daya Bay's full dataset,** *arXiv:2404.01687*

Conclusion & Outlook

Conclusion:

- Present motivations and details of a sterile oscillation analysis
- Sensitivity issue currently being studied

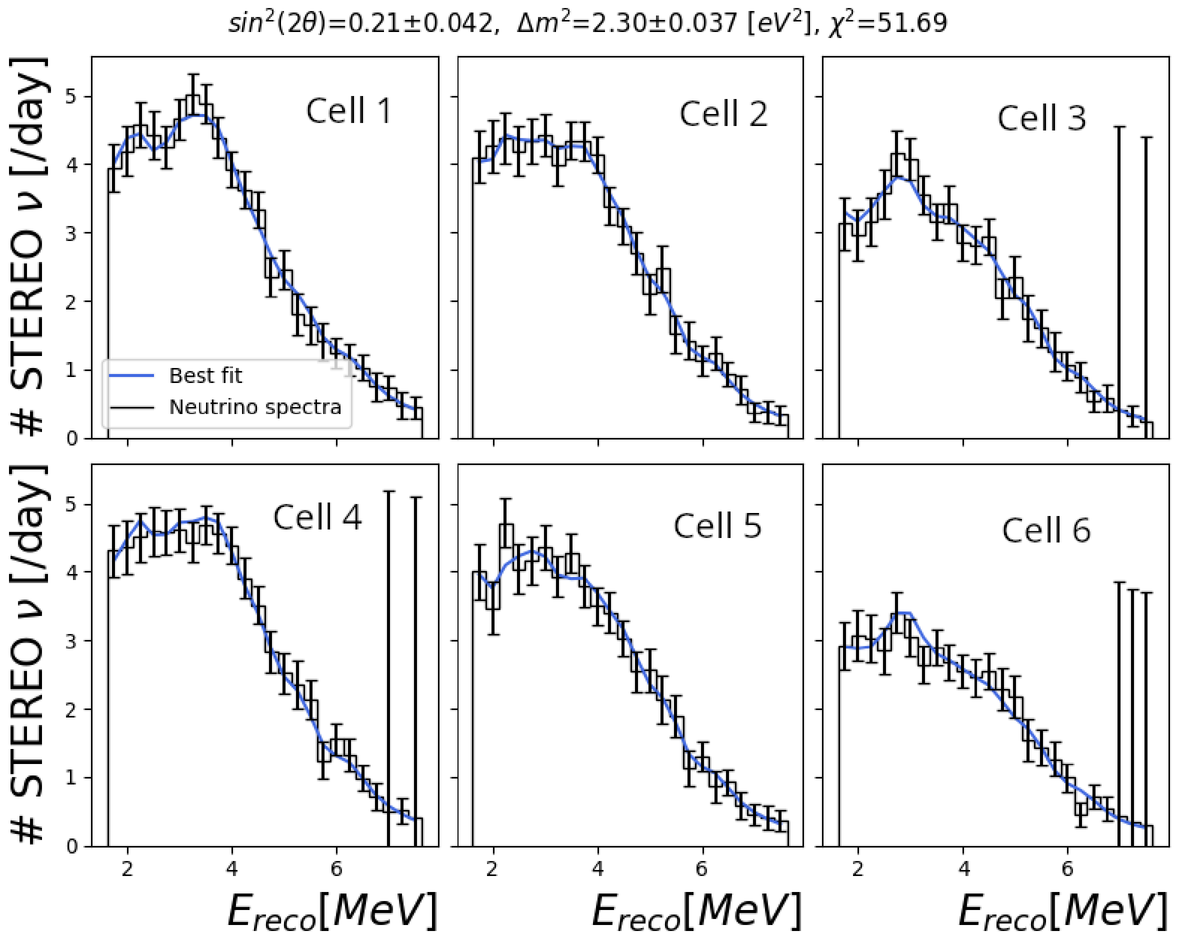
Outlook:

- Continue to investigate the reasons for over-sensitivity
- Work in progress on the Prospect analytical response model to be completed
- Extend analysis to phase III data and Prospect + Daya Bay experiments

Merci !

Backup…

Exemple d'ajustement



- Spectre en neutrino "mesuré" (noir)
- En bleu le spectre ajusté avec tous les paramètres libres
- Observation de schémas d'oscillations différentes dans chaques cellules
- On retrouve des valeurs ajustées proches de l'hypothèse de génération

Statistical treatment

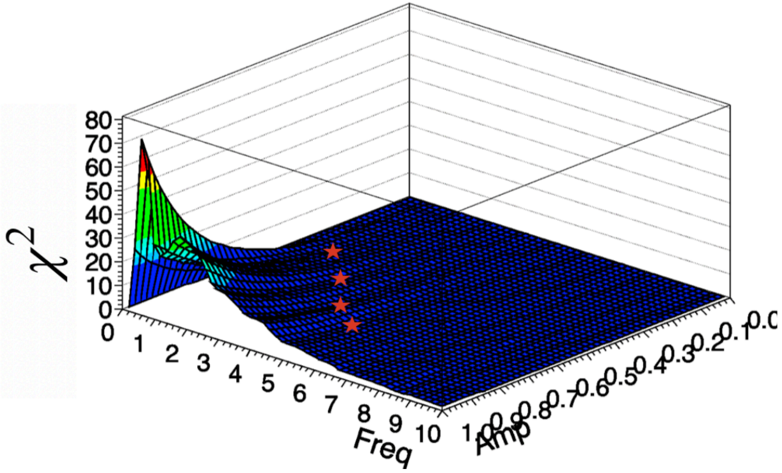
$$\Delta\chi^2(\theta_{\text{fixed}}) = -\ln(\mathcal{LR}(\theta_{\text{fixed}})) =$$
$$\min_{\vec{\pi}_{\vec{p}},\Phi}\left\{\chi^2\left(\theta_{\text{fixed}}, \vec{\pi}_{\vec{p}}, \Phi \,\middle|\, D_{\text{ci}}\right)\right\} - \min_{\theta_{\text{free}},\vec{\pi}_{\vec{p}},\Phi}\left\{\chi^2\left(\theta_{\text{free}}, \vec{\pi}_{\vec{p}}, \Phi \,\middle|\, D_{\text{ci}}\right)\right\}$$

- $\theta \doteq (\sin^2(2\theta_{14}), \Delta m^2_{14})$ physical parameters of interest.

"Feldman Cousins", i.e.:

- Likelihood ratio test for each point in the sterile neutrino phase space plan.
  - $\Delta\chi^2(\theta_{\text{fixed}})$ distribution from fitting toys
  - Compare with data's $\Delta\chi^2(\theta_{\text{fixed}})$ and compute p-value.

Periodict behavior of χ^2 along Δm^2.



Le comportement sinusoïdale des oscillations selon la fréquence, avec le choix du binning du spectre observé, induit une succession de minima locaux à explorer.

- Minuit2, gradient descend based algorithm.
- Minuit2 has trouble crossing between valleys in chi2.
- $\Rightarrow$ 30 minimization using different initial values for frequency.

Loïc Labit, **Very short baseline neutrino oscillations study with the STEREO detector at ILL.**, *Insp: 2049443*

Frequentist approach, Gaussian CLs

$$\Delta T(\boldsymbol{\Omega_H} \mid x) \stackrel{\text{def}}{=} \min_{\boldsymbol{\eta}}[T(\boldsymbol{\Omega_H}, \boldsymbol{\eta} \mid x)] - \min_{\boldsymbol{\eta}}[T(\boldsymbol{\Omega_{\mathrm{H0}}}, \boldsymbol{\eta} \mid x)]$$

Replace the computation of $\Delta\chi^2$ distributions by likelihood tests on Asimov datasets

- Helps avoid potential errors due to random generation unlike FC methods
- Allows for quicker iterations due to infinitely lower numerical complexity

Potential issue reasons

- Toy experiments generation ⇒ **should not appear with CLs**
- Wrong uncertainty on measured spectra

  ⇒ **Only problematic at high** $\boldsymbol{\sin^2(2\theta_{ee})}$
- Reactor spectrum systematics not correctly handled

  ⇒ **Low frequency problem**
- Response model systematics not correctly handled
  - Too strong constraints on response model