Status of the Search for Light Sterile Neutrinos at Short Baselines

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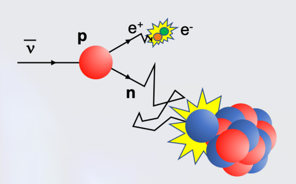
The Reactor Antineutrino Anomaly (RAA)

Mueller (^{238}U)-Huber (^{235}U, Pu) calculations of reactor antineutrino energy spectra for θ_{13}-aimed experiments (2011) indicated a ~6% excess in the inverse beta decay (IBD) rate compared to short baseline measures

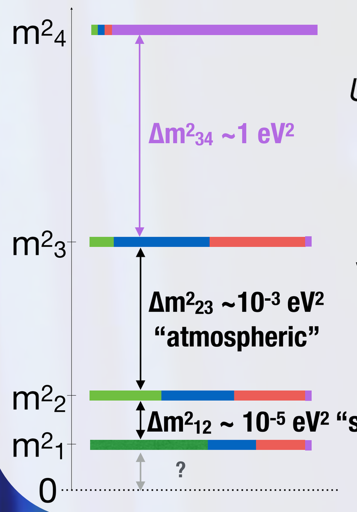
$$N_{IBD}(E_{\bar{\nu}_e}, t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle (t)} \times \langle \sigma_f \rangle (E_{\bar{\nu}_e}, t)$$

Mueller et al., Phys. Rev. C **83.5** (2011): 054615
Huber P., Phys. Rev. C **84.2** (2011): 024617
Mention et al., Phys. Rev. D **83.7** (2011): 073006



Adding a new neutrino particle (m_4 ~ 1 eV) consisting almost exclusively of an extra sterile flavour can account for the observed deficit

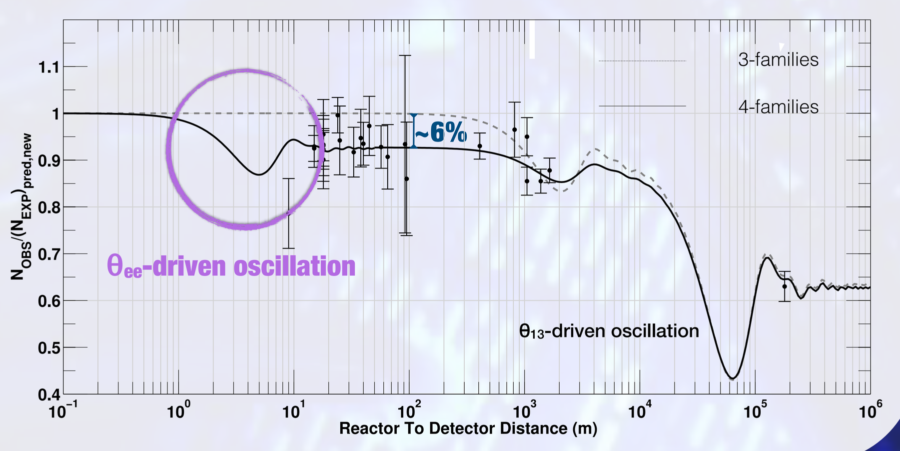
Sterile neutrinos, in fact, do not interact weakly but **mix with the standard 3 neutrino flavours**, originating the disappearance at short baseline via **neutrino oscillation**



$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

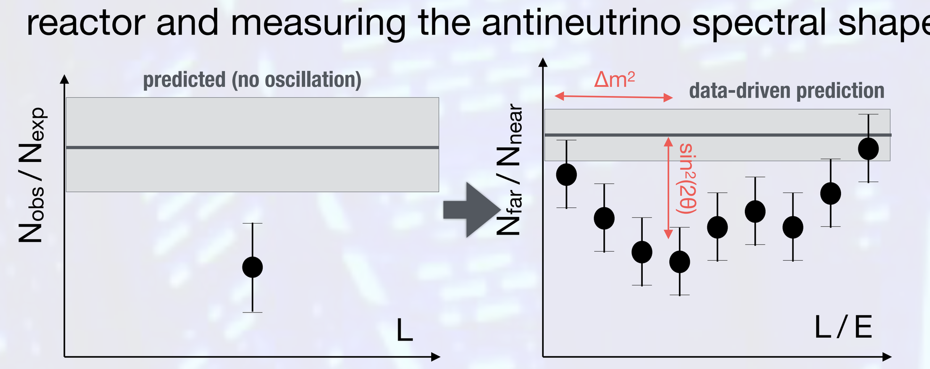
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L \lesssim 10m) \simeq 1 - \sin^2(\theta_{ee}) \sim^2 (1.27 \Delta m^2_{14} L/E)$$

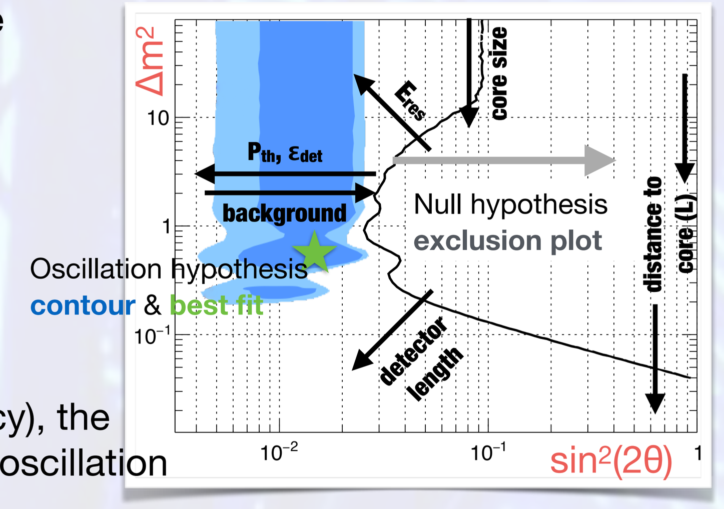
Existing measurements were rate only & could not test the oscillation



Search for the Light Sterile Neutrinos @ Short Baseilne

Difficulties in predicting neutrino rate limit the sensitivity of past rate-only measurements: we need to disentangle the oscillating signature from the absolute rate by getting closer to the reactor and measuring the antineutrino spectral shape

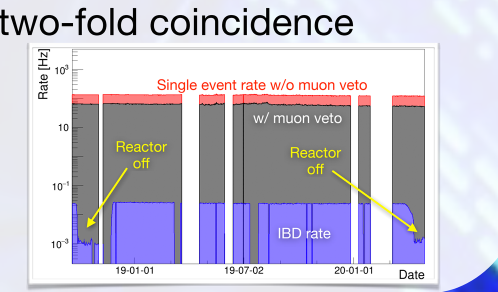




The better statistics (reactor power, detection efficiency), the larger the exclusion, but the core size washes out the oscillation

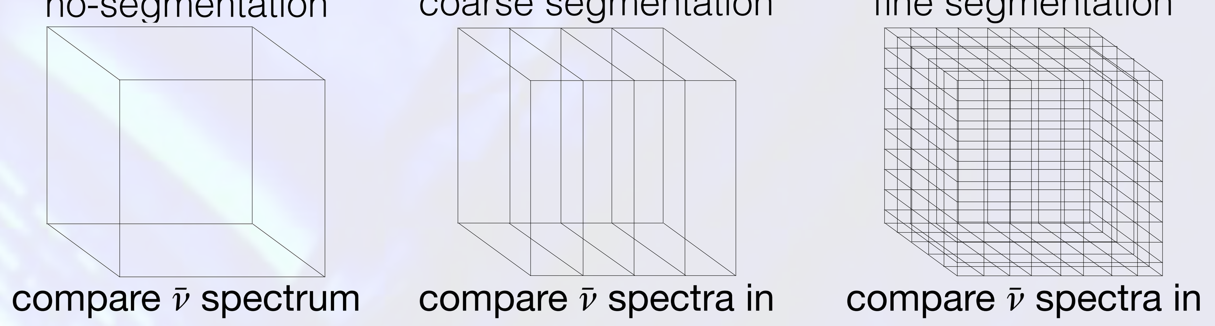
The **main challenge** of the very short baseline is the **background from cosmics** (surface level) **and neutrons from the reactor facility**, that can mimic an IBD e⁺-n two-fold coincidence

Strategies to deal with residual background include passive shielding (polyethylene, B, Fe, water), active vetoes, pulse shape discrimination (PSD), and statistical subtraction of accidental coincidences & cosmogenic background using reactor-off data



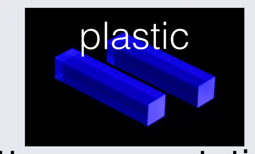
Different Reactors and Technologies

Detector segmentation



no-segmentation	coarse segmentation	fine segmentation
compare $\bar{\nu}$ spectrum with prediction, easier to calibrate	compare $\bar{\nu}$ spectra in different segments (model independent)	compare $\bar{\nu}$ spectra in sections + background rejection w/ topology

Scintillator

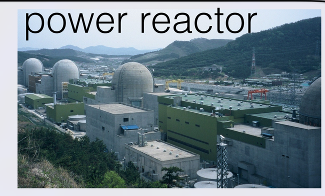


better segmentation & detection efficiency

allows larger volumes

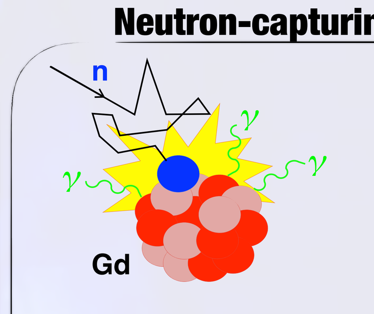
Reactor

Short baseline & compact core, no fuel evolution
$\mathcal{O}10^2$ MW_{th}, limited space, background from facility

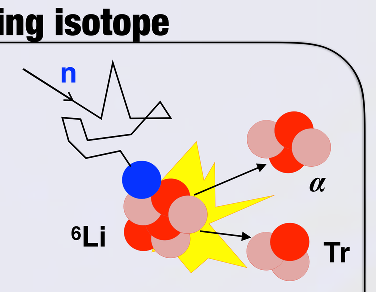


$\mathcal{O}GW_{th}$, some overburden possible
Lower sensitivity at low energy, fuel burnup

Neutron-capturing isotope



Well-established, high E_{dep} and $\sigma_{capture}$



Localised E_{dep}: quenched but can select via PSD

The DANSS Experiment

~1 m³ **highly-segmented** ν spectrometer: 2500 Gd-coated plastic scintillator strips arranged in 50 modules with single & combined readout

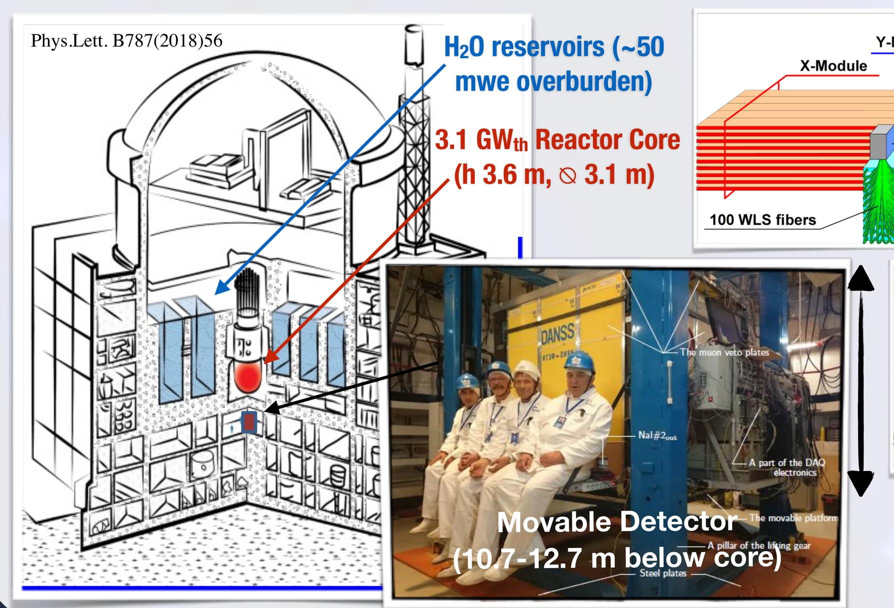
Almost 5 years of data (Apr 2016 - Apr 2021) with ~5000 IBDs/day and excellent S/B (~60)

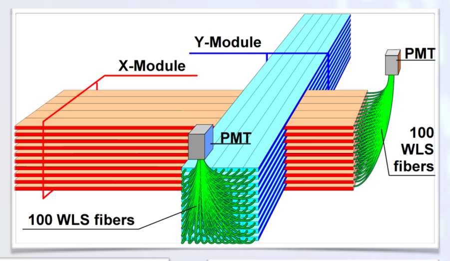
Overburden from the reactor itself

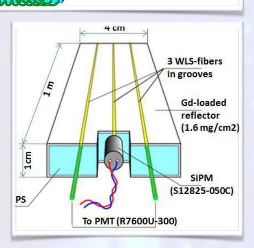
Oscillation hypotheses tested by comparing up/down e⁺ spectra with 4.5 · 10⁶ IBDs → **large portion of RAA excluded and best fit excluded with >5 σ**

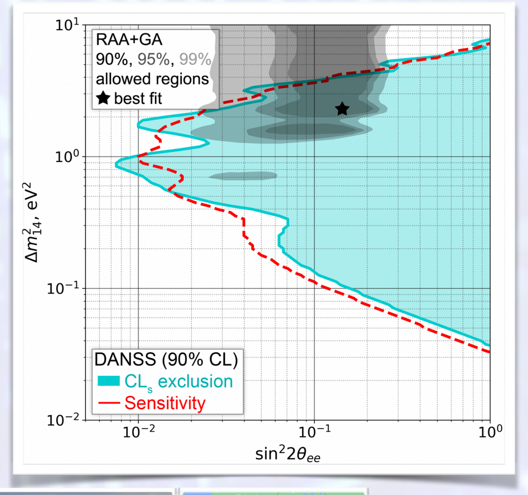
Observed a **clear antineutrino spectrum** and **rate dependence on fuel composition**; rate from ^{239}Pu (26-38 %) in agreement with models

Measured reactor power with 1.5% precision









The NEOS Experiment

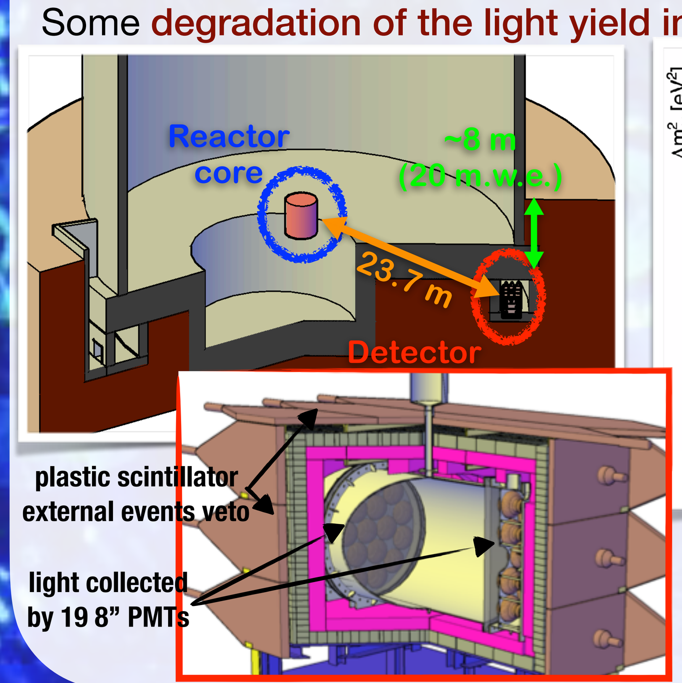
Simple design: 1008 L Gd-loaded (0.48%) liquid scintillator tank, antineutrino spectrum compared with the Data Bay near detector one

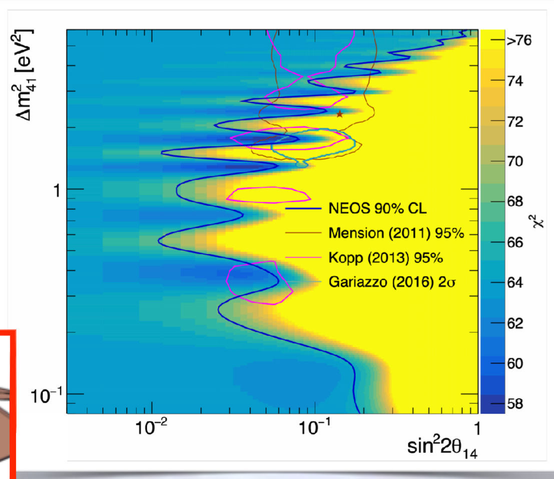
Very high statistics (~2000 ν/day) thanks to the 2.8 GW Yeonggwang Nuclear Power Plant

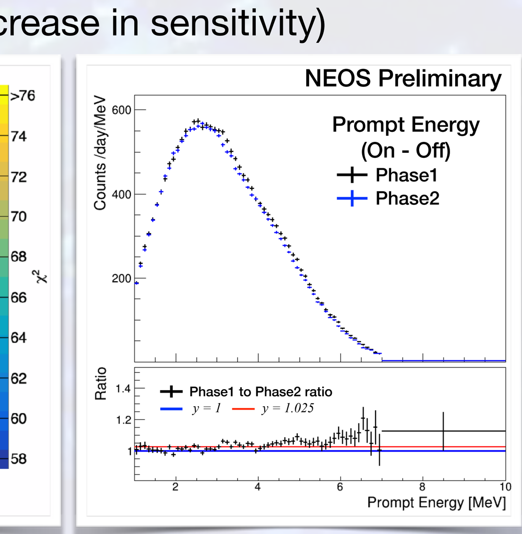
Some degradation of the light yield in time

Phase I (46 days reactor OFF + 180 days ON): oscillation analysis with RAA best fit excluded @ 90% CL

Phase I+II: antineutrino energy spectrum unfolded, oscillation analysis ongoing (expected X2 increase in sensitivity)







The STEREO Experiment

Segmented design: 6 optically separated cells filled with Gd-loaded liquid scintillator → **cell-to-cell relative oscillation analysis**

ILL compact highly enriched uranium (58 MW) reactor & short baseline (9-11 m from core) → little damping of the oscillation

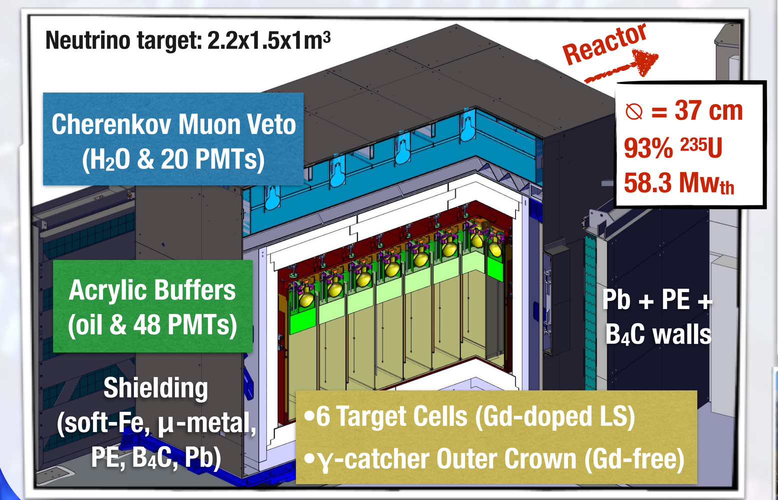
Little overburden & noise from reactor facility

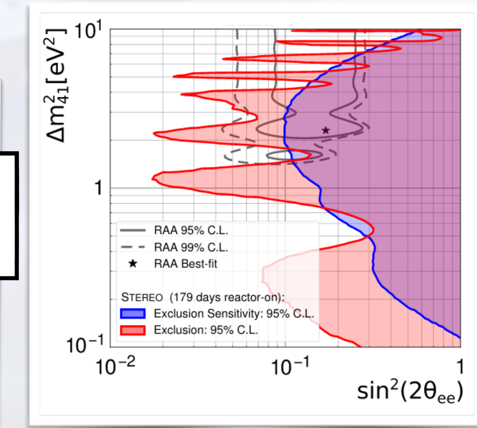
Phase-I & -II combined data (65k IBDs, 179 days reactor ON + 235 OFF) with S/B ~ 1: **RAA best-fit rejected at > 99% CL**

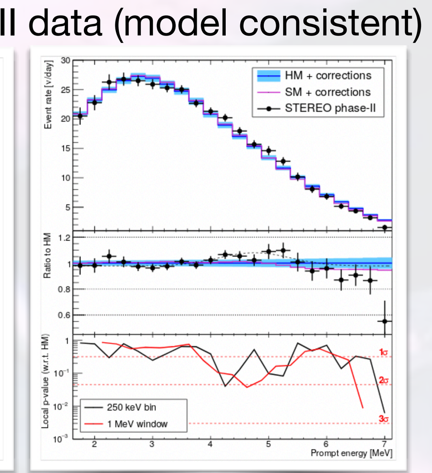
Expected X2 increase in sensitivity with full dataset, analysis ongoing

Absolute ^{235}U rate and spectral shape unfolded with phase-II data (model consistent)

H. Almazán et al. (STEREO), arXiv:1905:11967
Physical Review D 102.5 (2020): 052002.







The PROSPECT Experiment

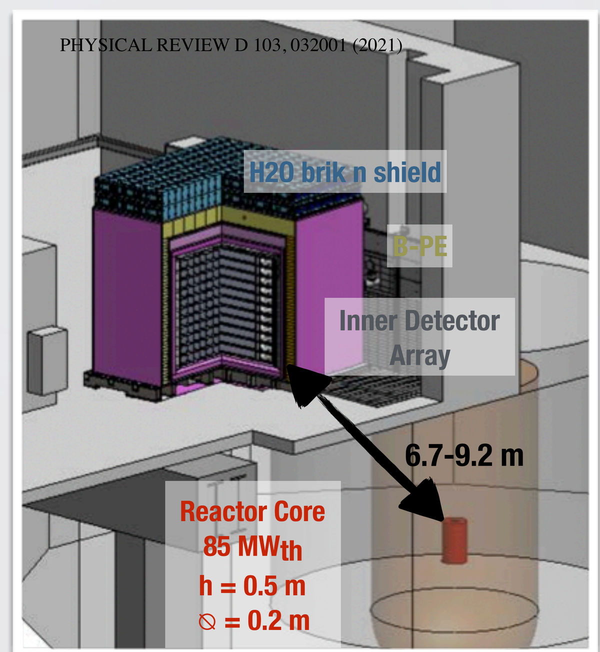
Highly segmented design: 4-ton ⁶Li-loaded liquid scintillator in 11x14 optically separated segments → good E_{res} and 3D reconstruction

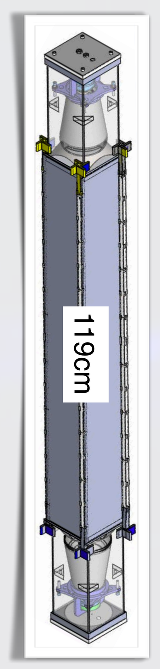
Relatively high statistics (530 IBD/day) & S/B (>1) for a highly enriched uranium reactor

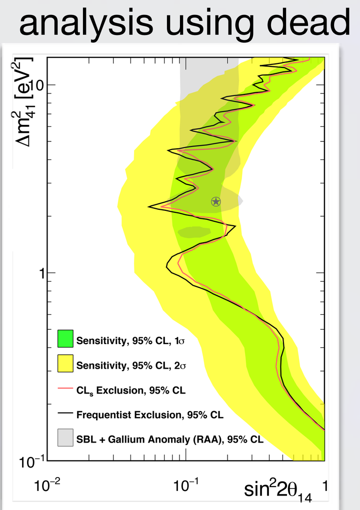
50k IBDs (105 days reactor ON + 78 days OFF) → **RAA best-fit rejected at 98.5% CL**

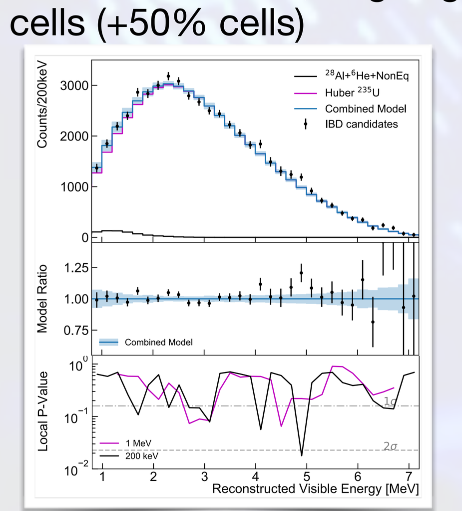
Pure ^{235}U spectrum unfolded, and combined spectral analyses with Data Bay and STEREO

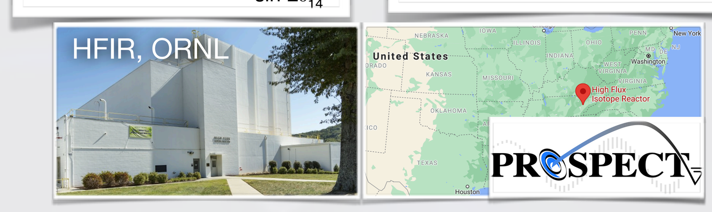
Results based on dataset from 2018; ongoing analysis using dead cells (+50% cells)









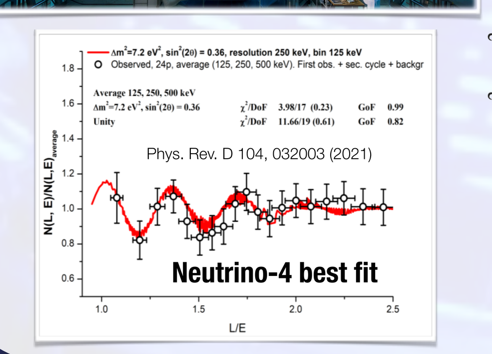


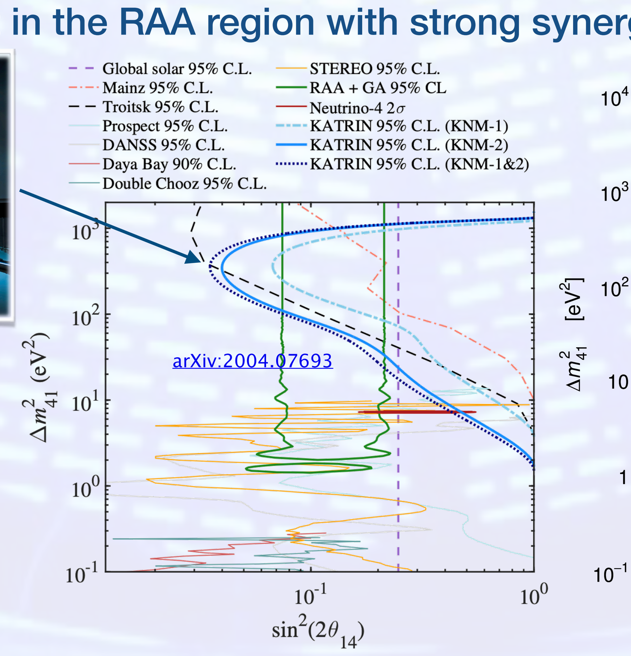
The Global Picture

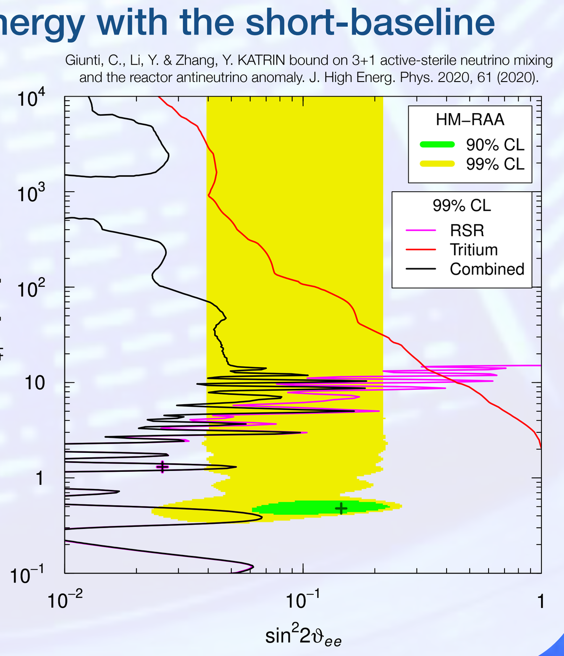
DANSS, NEOS, STEREO, PROSPECT all excluded large portions of the RAA region & best fit (> 90% CL), while the Neutrino-4 experiment claims observation of a Δm² ~ 7.2 eV² oscillation

Despite the challenges of a combined analysis (different statistical methods, "wiggly" nature of the spectra), growing statistics is helping us **progressing towards a total exclusion of the RAA**

KATRIN, a 200t spectrometer for the measurement of the ν_e mass, has also published results on light sterile → exclusion plot in the RAA region with strong synergy with the short-baseline







Other Experimental and Theoretical Challenges to the RAA

The spectral distortion @ E_ν ~ 6 MeV observed in θ_{13}-aimed experiments in 2014 could be due to **non-linearity** in the E reconstruction, new **Physics BSM**, or **unknown branches** (isotope related)

Mention et al, PhysLettB 773:307-312 (2017) Berryman et al, PRD 99, 055045 (2019) Hayes et al, PRD 92, 033015 (2015)

STEREO & PROSPECT released a **combined spectral analysis** confirming the distortion with **2.4 σ significance and A = 9.9 ± 3.3 % for pure ^{235}U → distortion independent of other isotopes**

Daya Bay and RENO **separated ^{235}U and ^{239}Pu contribution to the $\bar{\nu}_e$ flux**, showing that the rate deficit of the RAA comes mainly from ^{235}U, which disfavours the sterile neutrino hypothesis

While limits of current spectrum models are emerging, there is evidence that the **treatment of forbidden decays could change both normalisation & spectral shape**