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Sterile Neutrino Searches at Nuclear Reactors

La Thuile
12 mars 2019

On behalf of the Stereo Collaboration

OUTLINE

- Reactor Anomalies
- Experiments at Short baseline
- sterile neutrino dedicated experiments
- Actual situation

Reactor anti neutrino flux

- In the 1980s two flux predictions became the standards for the field:
  - Schreckenbach et al. measured fission β-spectra for ^{235}U, ^{239}Pu and ^{241}Pu and converted them into antineutrino spectra
  - Vogel et al. used the nuclear databases to predict the spectrum for ^{238}U

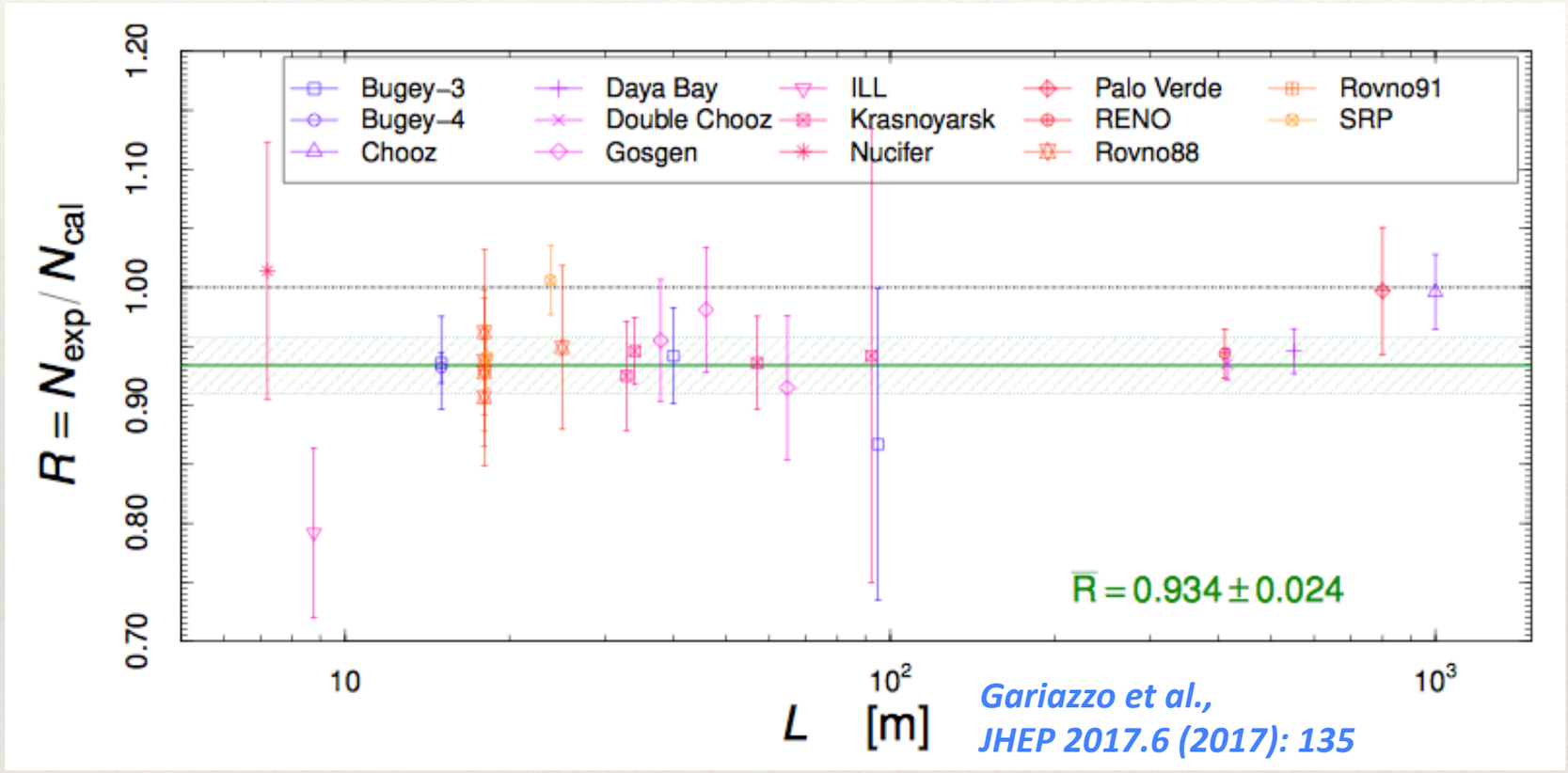
- In 2011 both Mueller et al. and Huber improved the description of the spectra and predicted an expected number of antineutrinos increased by 3%.

The consequence was :

- An increase in the Schreckenbach predicted antineutrino flux for ^{235}U, ^{239}Pu and ^{241}Pu.
- An overall increase in the ^{238}U antineutrino flux due to enhanced nuclear databases over 25 years.

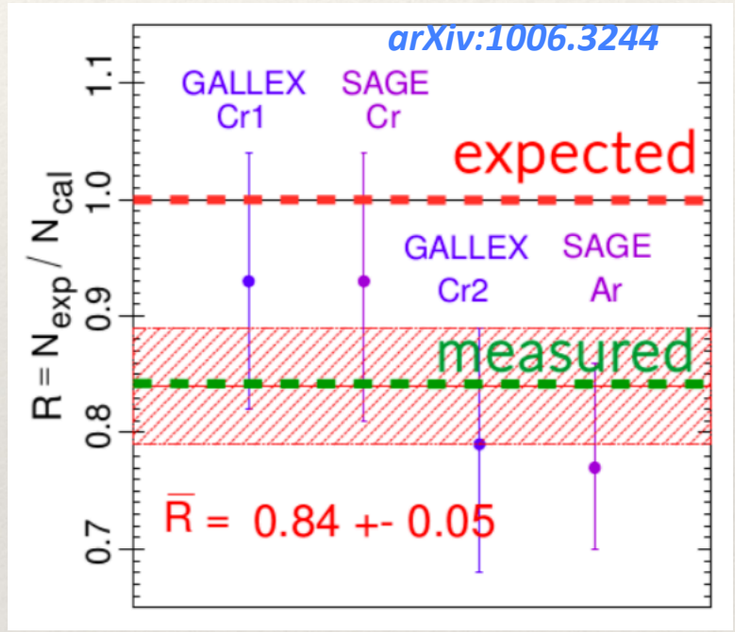
Reactor Anti neutrino Anomaly (RAA)

Detected Neutrino Rates at Reactor



Gariazzo et al., JHEP 2017.6 (2017): 135

Sources



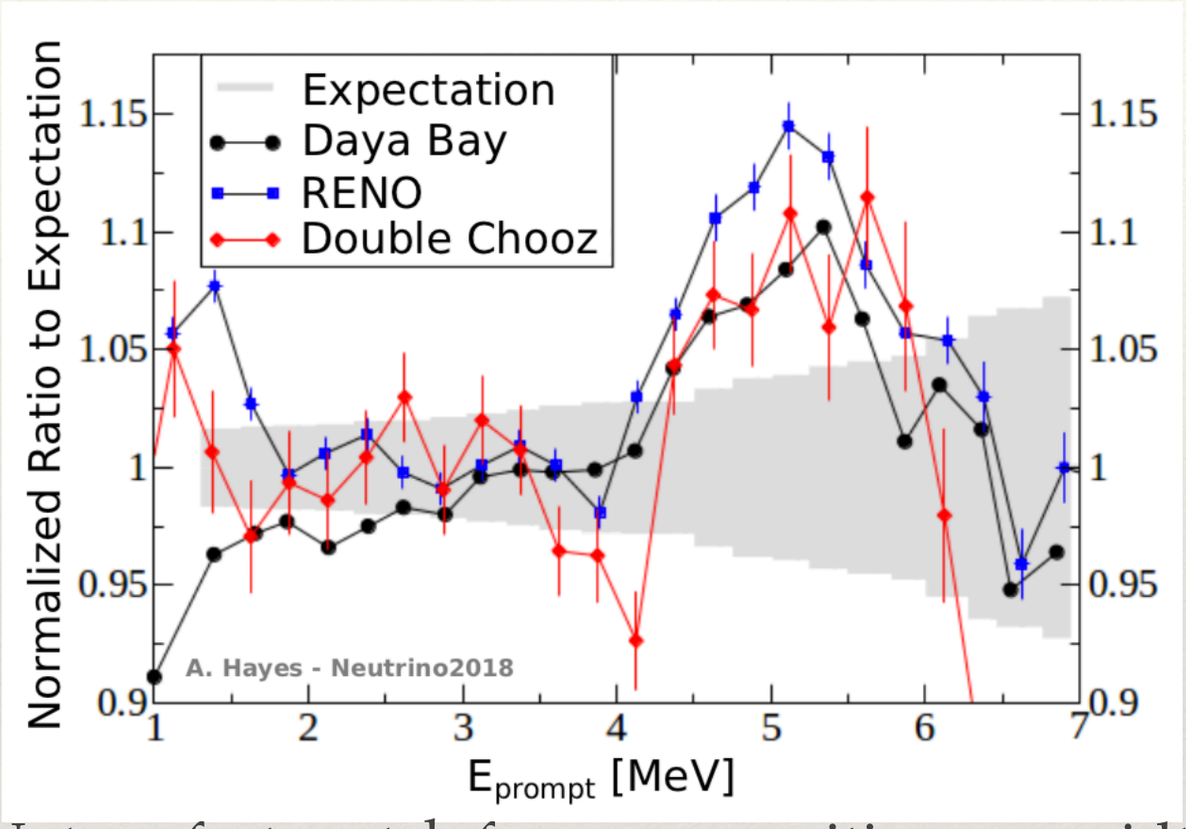
The very accurate measurements of the total flux confirm the deficit:

Daya Bay, RENO and Double Chooz

The issue then becomes ones of:

- Confirming/re-examining the predicted flux
- Confirming/denying the existence of 1eV sterile neutrinos

Reactor shape anomaly



Bump between 4 and 6 MeV
common to all recent precise experiments:
Daya Bay, RENO and Double Chooz
Seen in several other experiment (all using commercial reactor) :

- forbidden transition in beta decay
- nuclear databases for ^{238}U

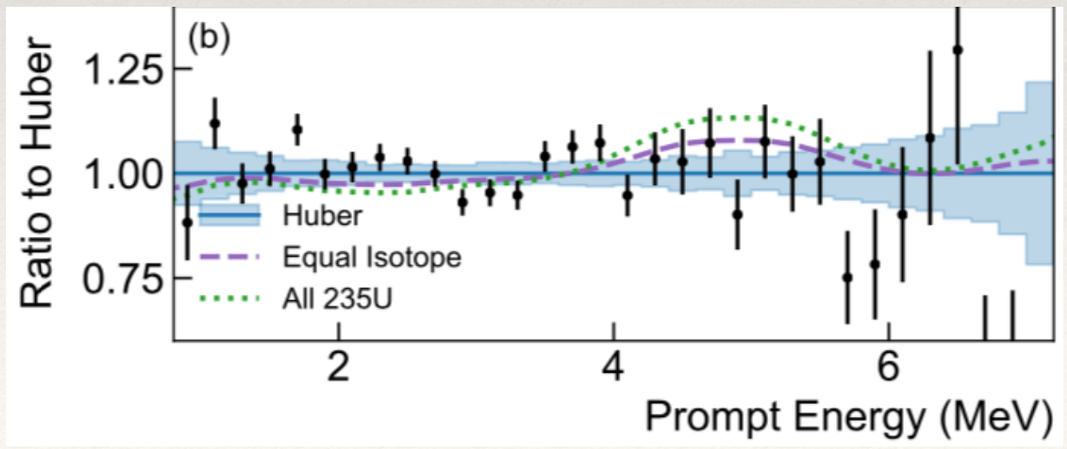
nuclear physics related

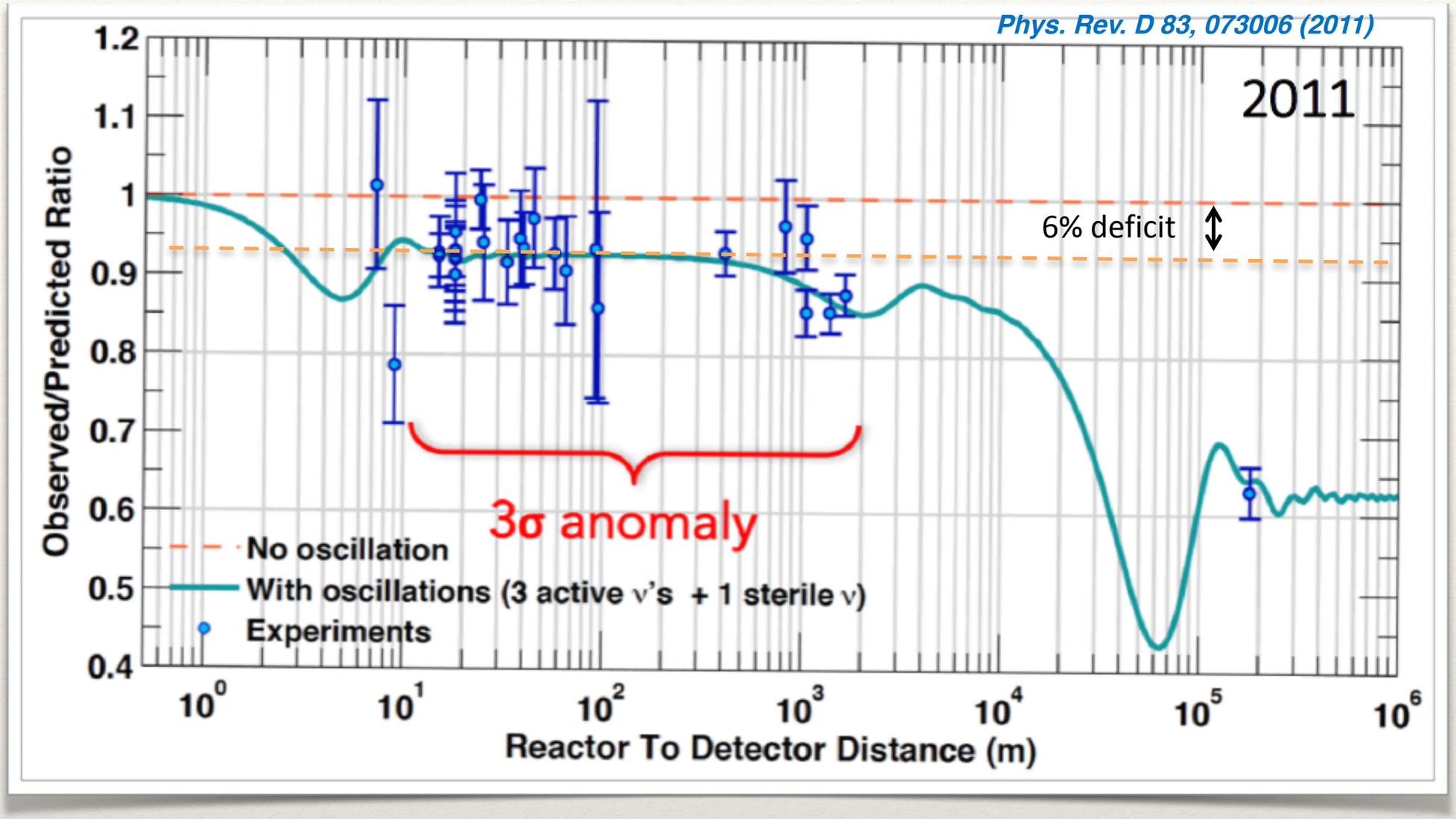
Not perfect match for mean position nor width

First release of pur ^{235}U from prospect:
disfavors at ~3σ C.L ^{235}U as the sole source.

Problem of using predicted spectrum for oscillation analysis

arXiV:1812.10877





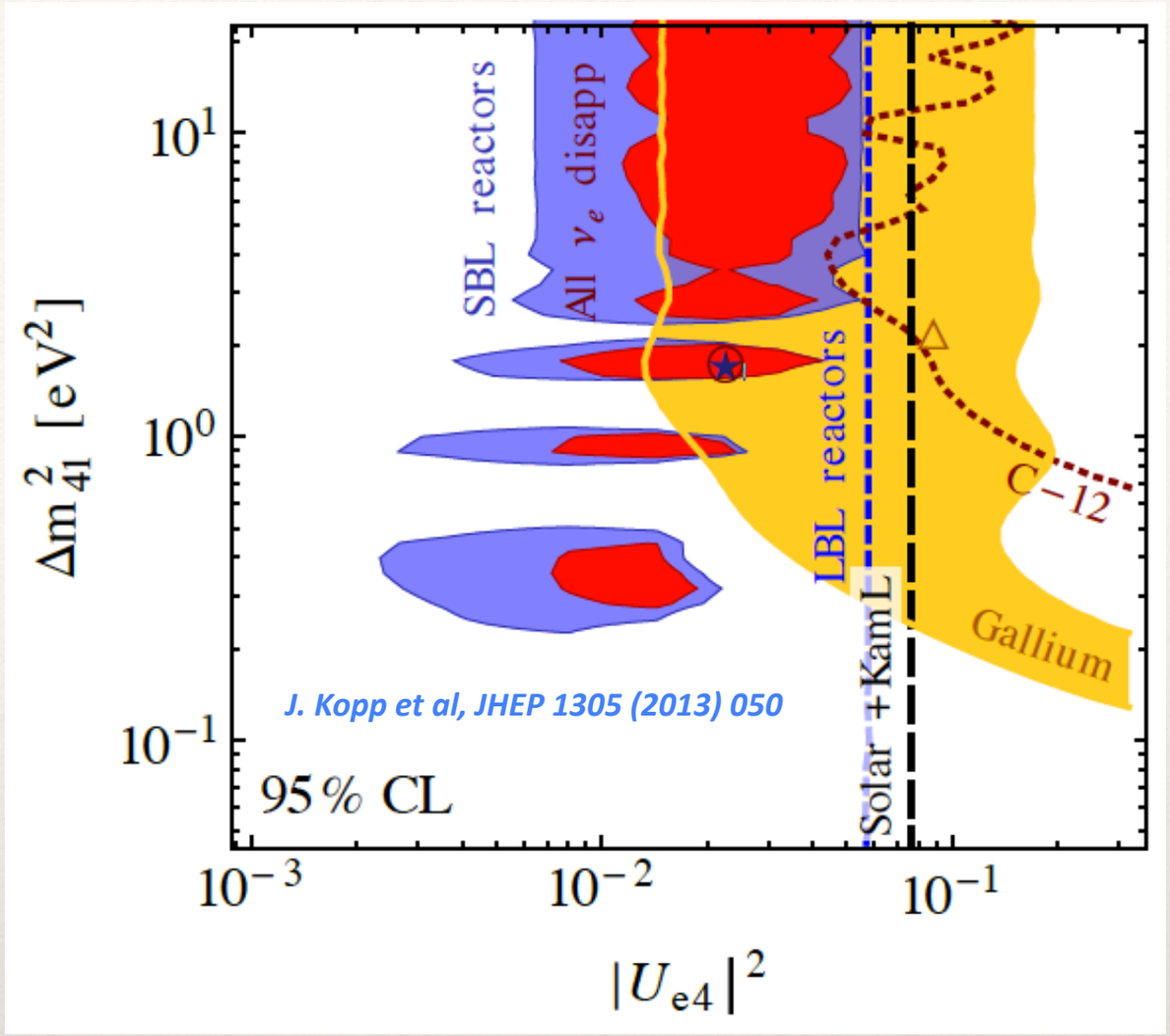
Survival Probability : $P_{\overline{\nu_e}\to\overline{\nu_e}} = 1 - \sin^2(2\theta_{14})\sin^2\left(1.27\Delta m^2_{14}\frac{L}{E_\nu}\right)$

Sterile neutrino

Δm^2 in the 1 eV^2 range
$\sin^2 \sim 0.1$
L_{osc} = 1-10 m range

Need of new precise experiments

- Short distance
- from compact ν source
- Segmentation or moving detector
  to look for an oscillation pattern
- near surface (cosmogenic background)

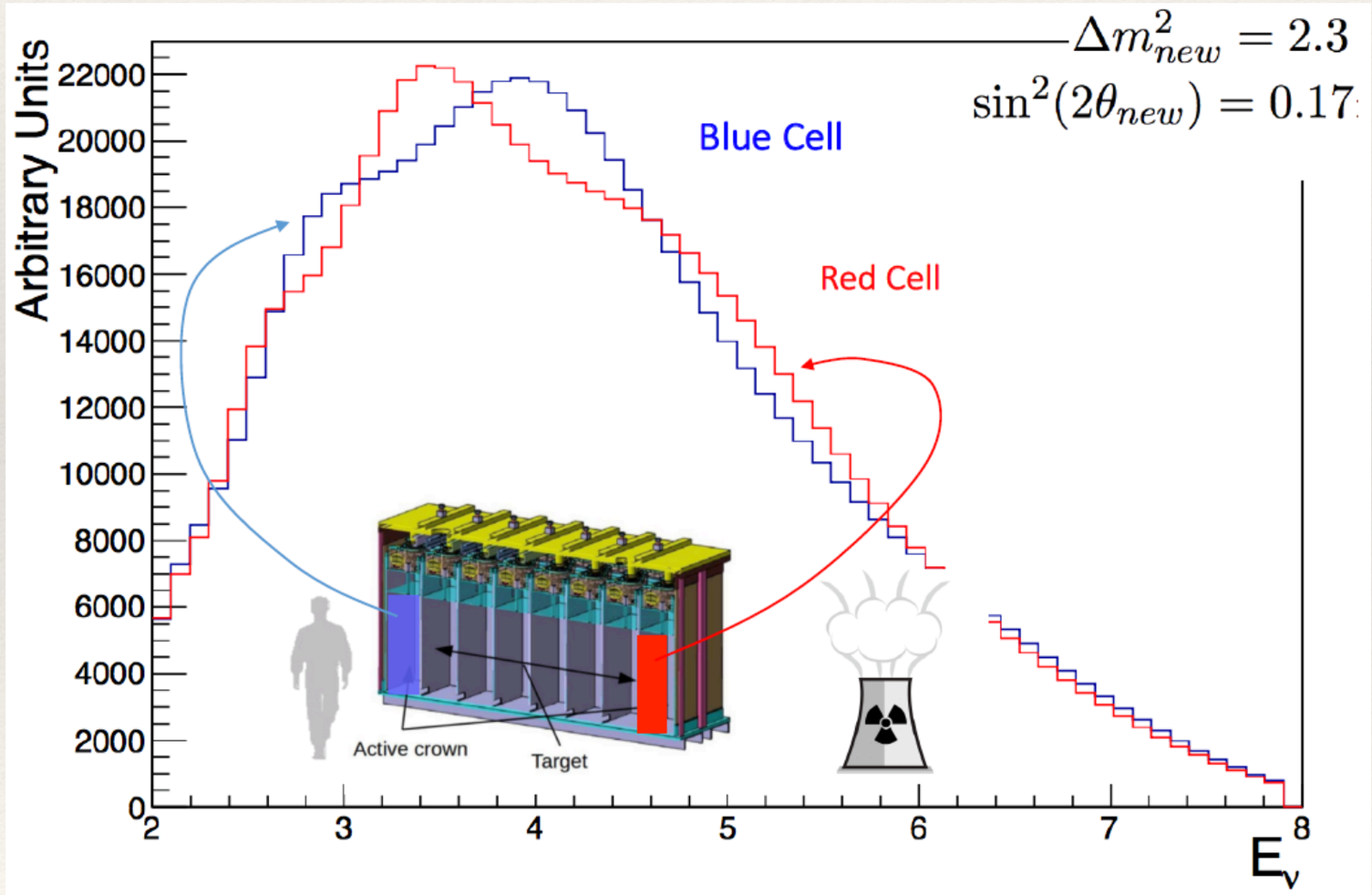


$\sin^2 2\theta_{ee} = 4\,|U_{e4}|^2\,(1 - |U_{e4}|^2)$

Sterile neutrino

Principle

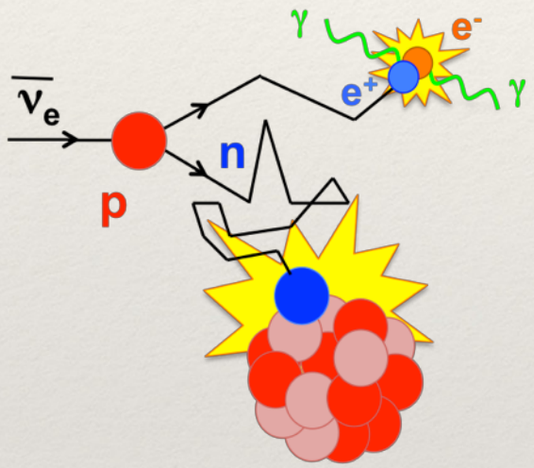
Relative spectrum distortions between identical detector segment, few m apart.
Large E range ([2,7] MeV) combined with baseline allow to cover a factor ~4 in E/L.



Backgrounds rejection

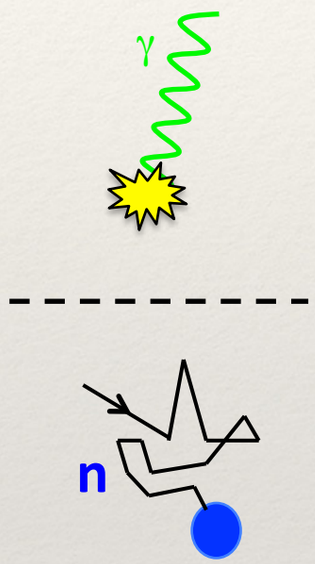
Signal
Inverse Beta Decay

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



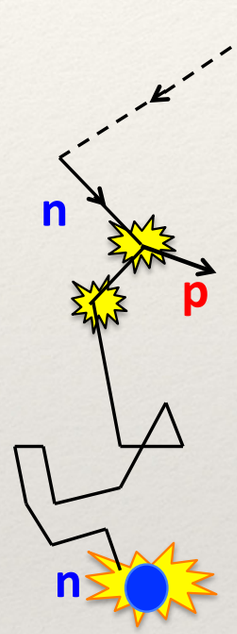
$E_{e+} \rightarrow E_\nu$
Neutron captured by Gd or ^{6}Li
Unambiguous prompt delay correlation

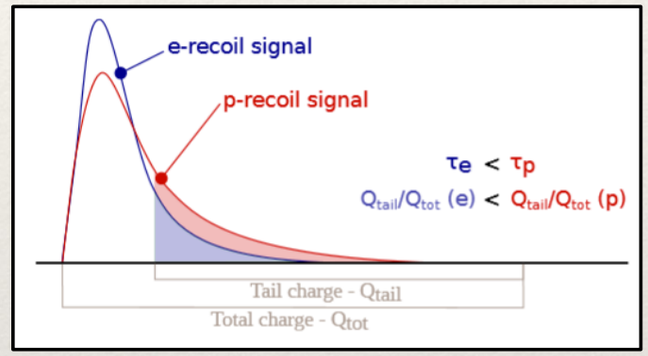
Accidental



Reactor activity
natural radioactivity
shielding & radiopurity

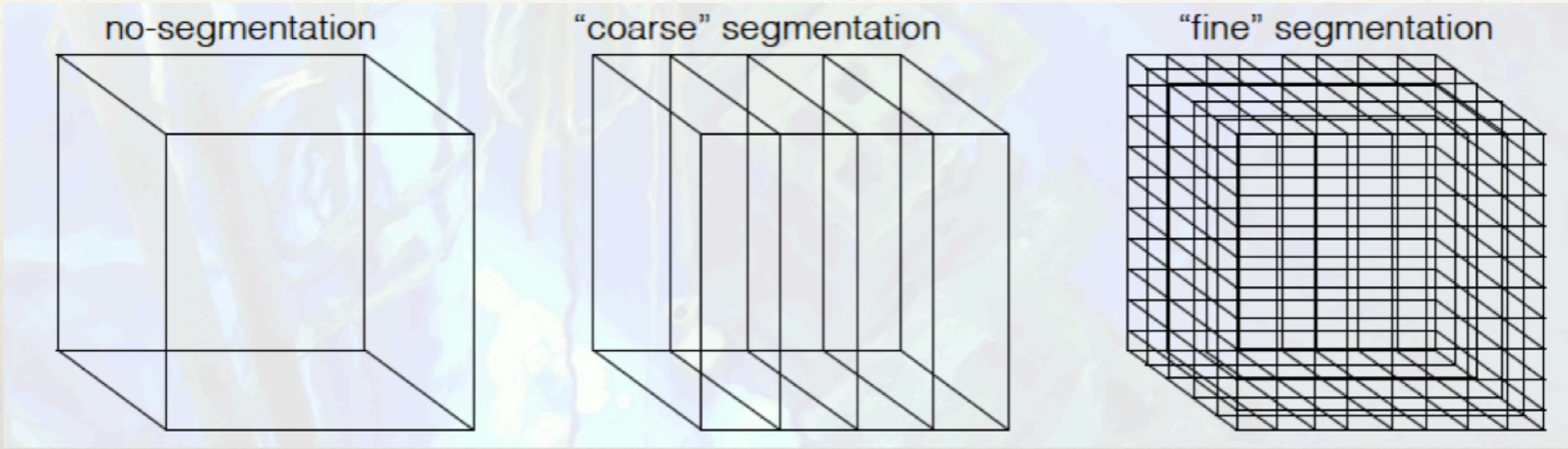
Correlated cosmogenic





Cosmic rays dominant close to surface
Active shielding& Particle Discrimination in liquid scintillators (PSD)

Detectors

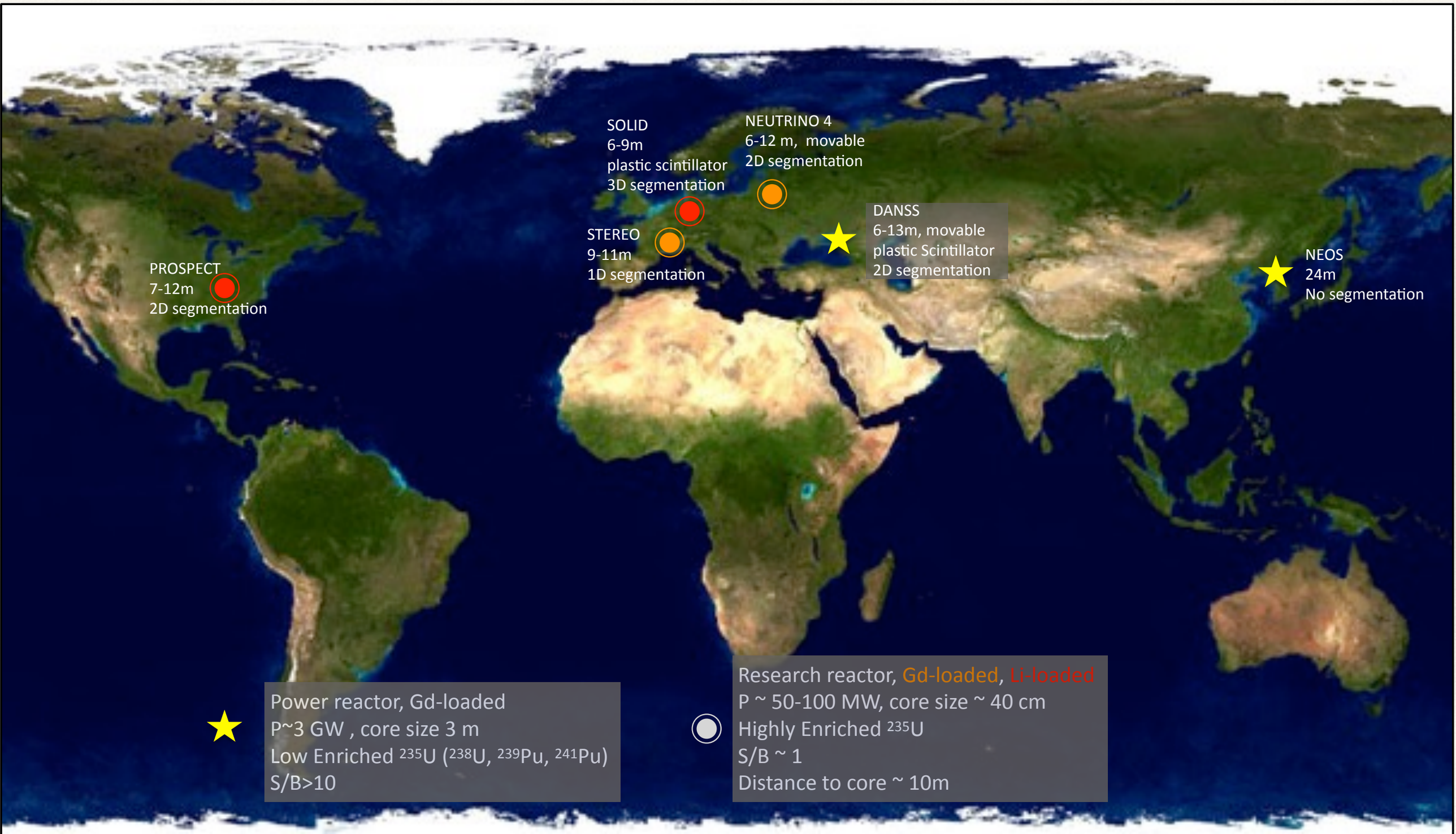


- compare ν spectrum with prediction

- compare spectra in different segments

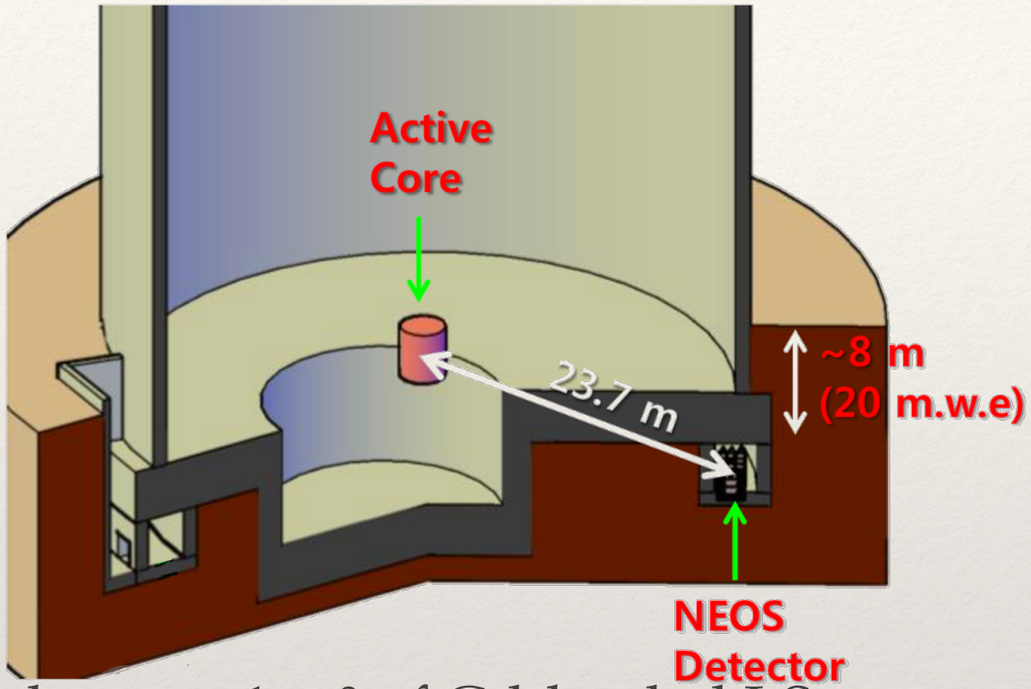
- Background rejection using topology
- Ultimate size limited by dead matter / inter calibration

Worldwide Experimental Program



NEOS @ Hanbit-5 Reactor, Korea

Neutrino Experiment for Oscillation at Short baseline



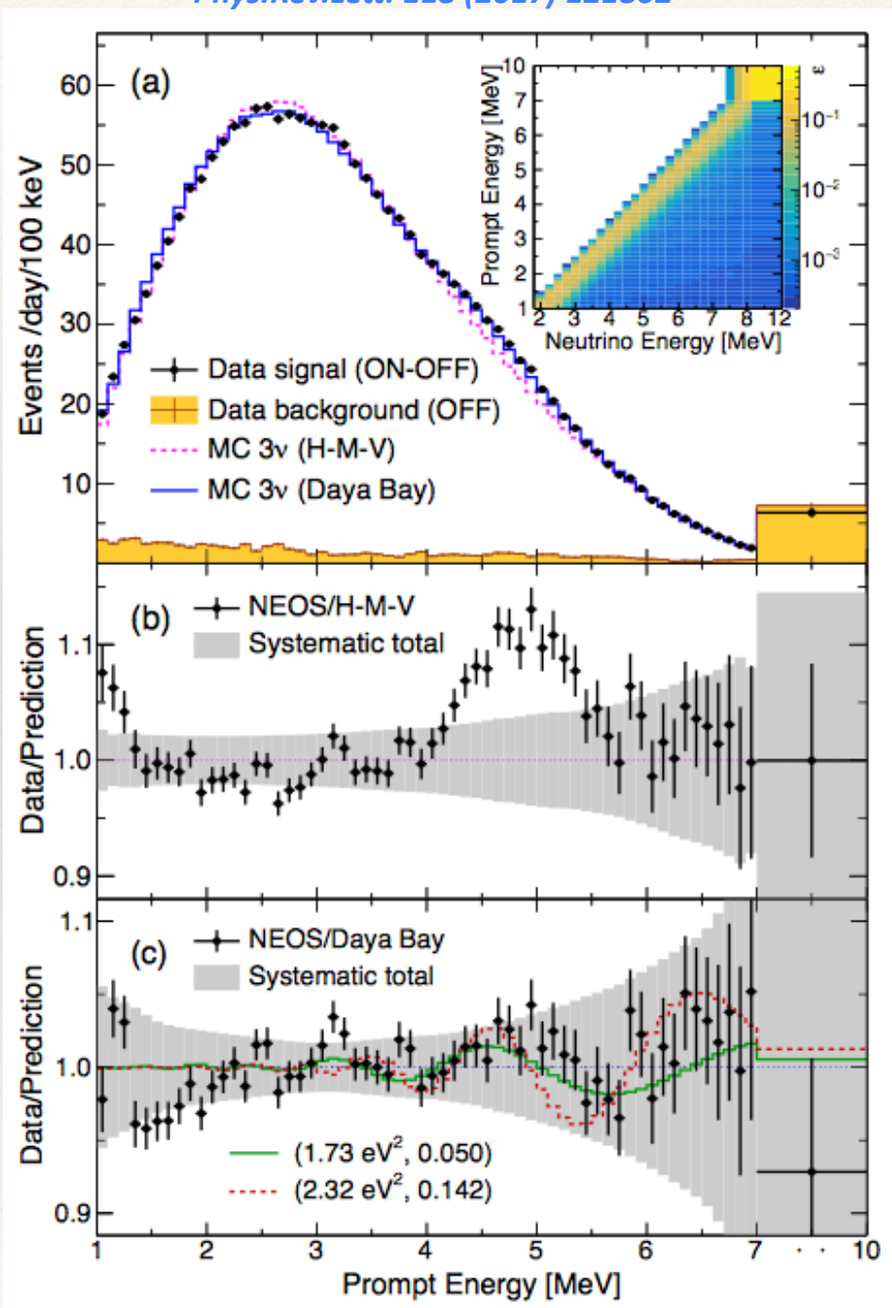
- 1 single fixed detector 1 m³ of Gd-loaded LS
- 24 m from a 2.8 GW core
- Large size of the core (3.1 m) damps down the oscillation signal at low E
  - Phase-I: Aug 2015~May 2016
  - Phase-II: Sep 2018~Now running

Oscillation analysis :

relies on the comparison with an external prediction.

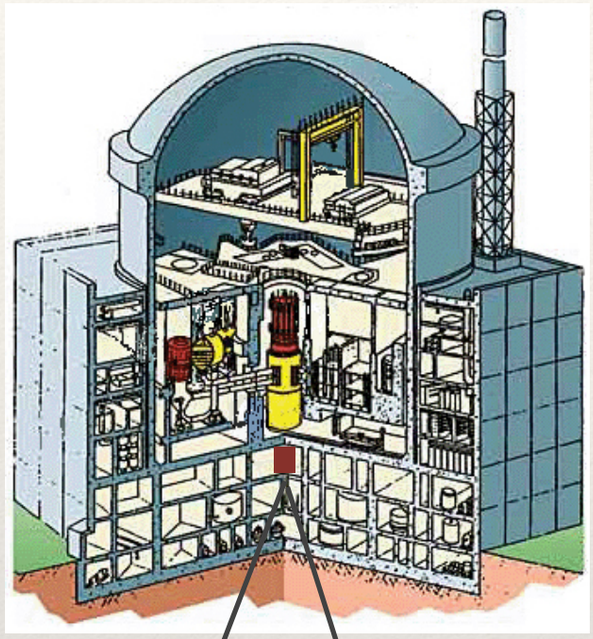
Daya Bay spectrum is used as a non-oscillated reference.

Phys.Rev.Lett. 118 (2017) 121802



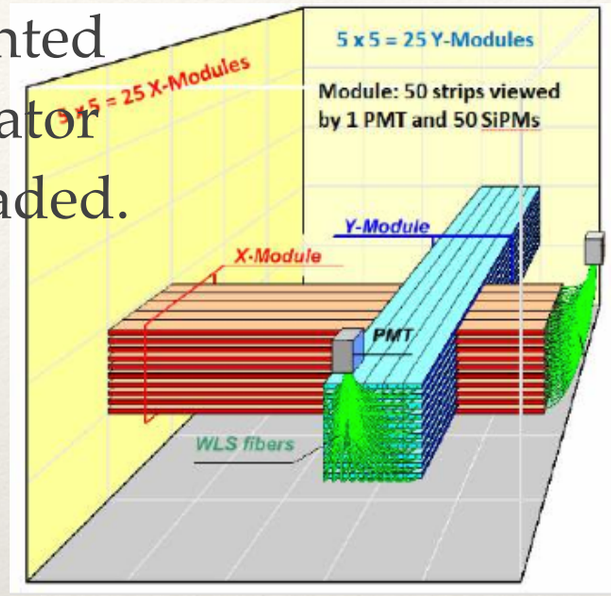
DANSS

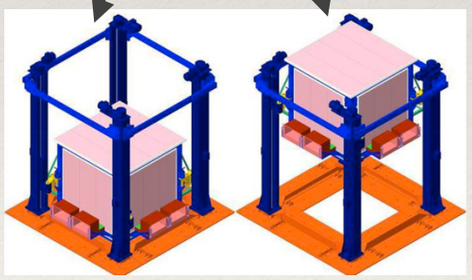
Detector of the reactor AntiNeutrino based on Solid-state Scintillator



Huge statistics of ~5000/day compensate for the damping of ν signal due to core size (3.6 m) & E resolution.

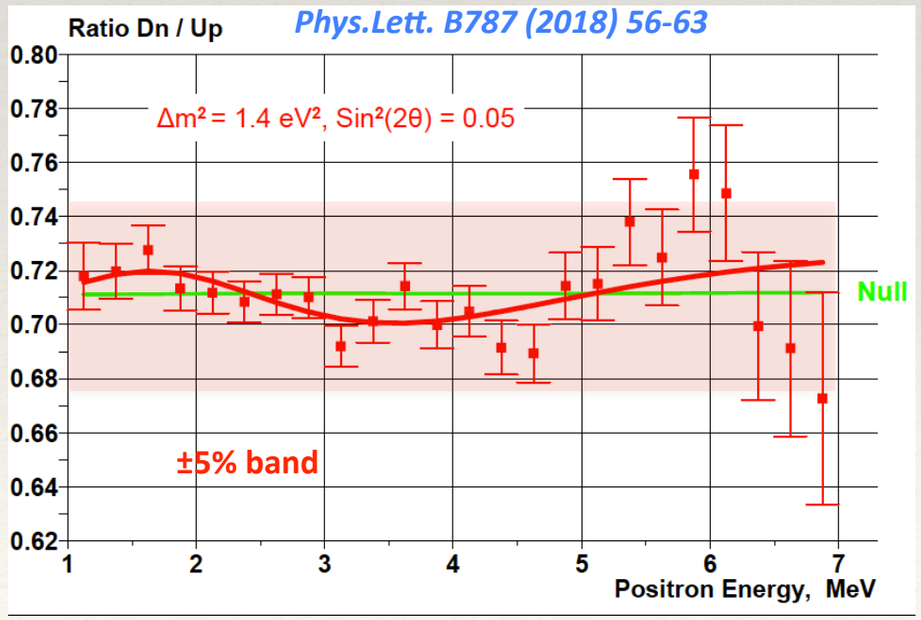
Highly segmented Plastic Scintillator detector, Gd-loaded.



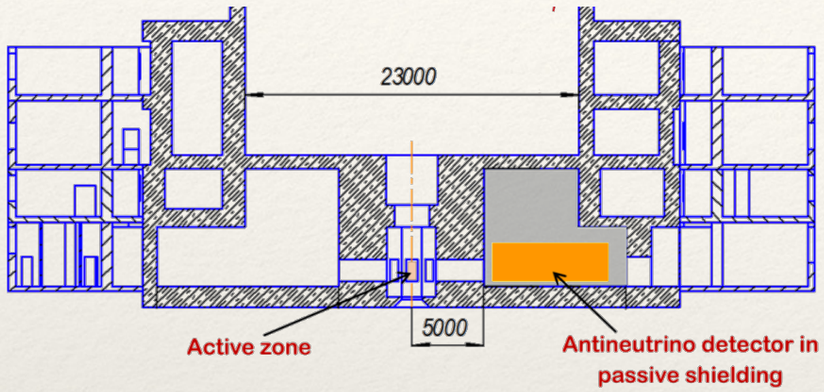


Movable detector with 10.7-12.7 m baseline, underneath the core.

- Ratio of spectra Dn/Up
- mitigates the detector systematics
- Model independent analysis

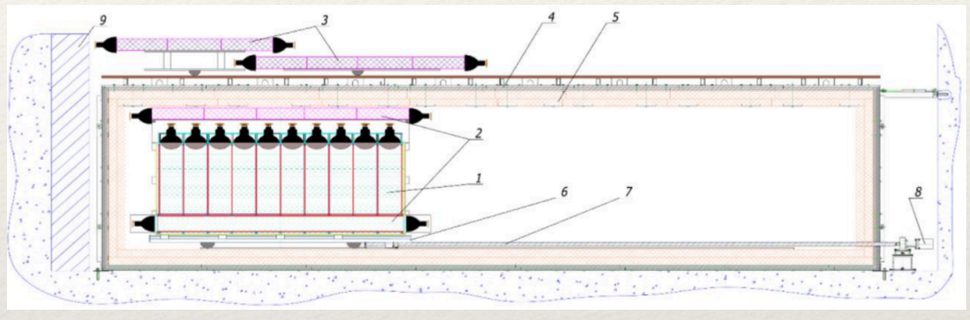


Neutrino 4

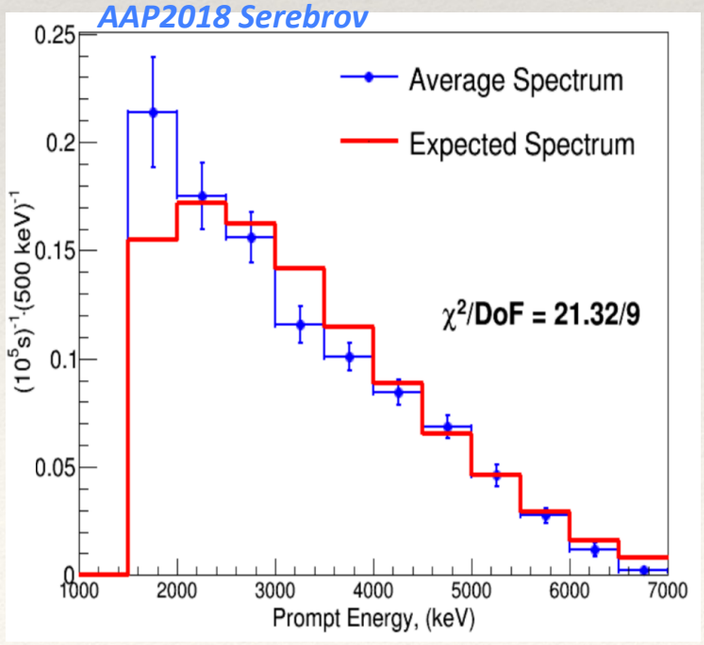


42 X 35 cm
Higly enriched in ^{235}U
Pth = 100 MW
10 days cycles (5 days OFF)

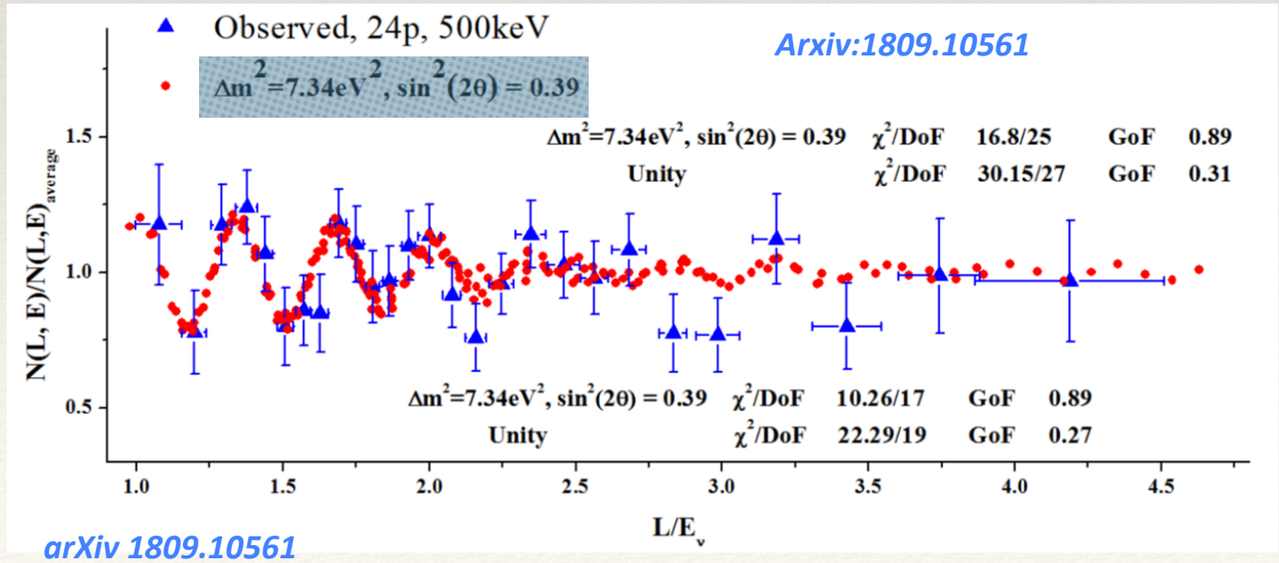
Segmented 5x10 cells
Liquid Scintillator Gd-loaded
movable 6-12 m



Data taking: from June 2016



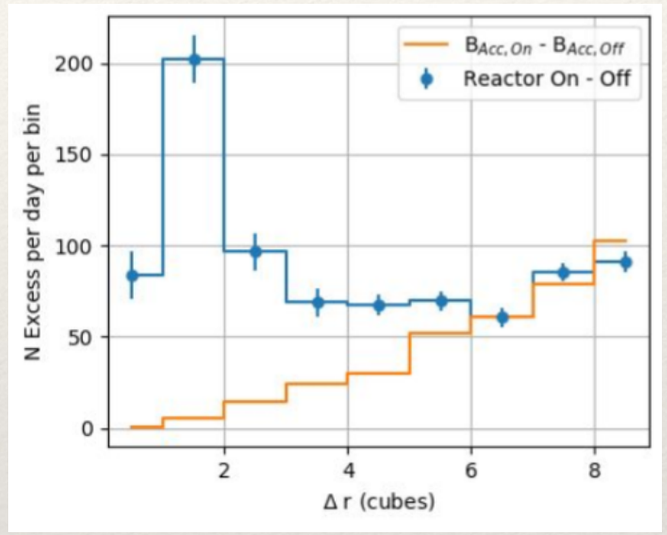
Found Oscillation at very large Δm^2 and large mixing



SoLid

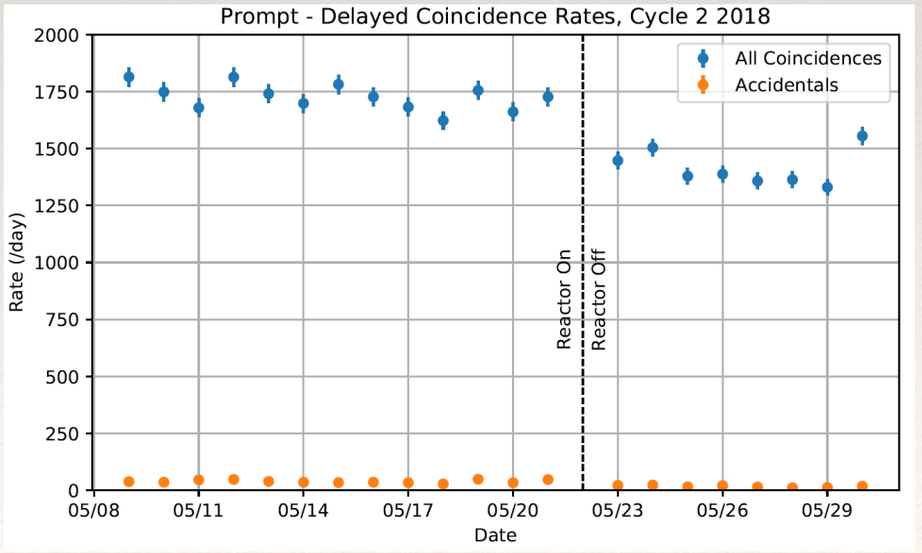
BR2 Mol, Belgium
Φ = 50 cm, H = 90 cm
93.5% 235U
Pth = 50-80 MW
1 month cycles
(150 days/year)
Baseline 6-9 m

PVT cubes of 5x5x5 cm3
with 2 ^{6}Li neutron screens

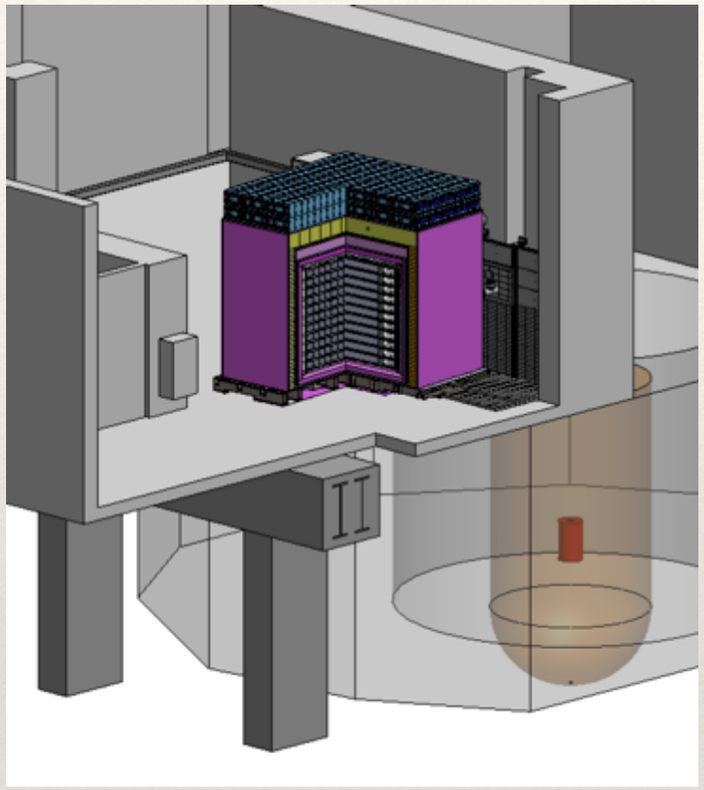


AAP2018 Maja

- Accidentals rejected by topological cuts
- Correlated background to be reduced further using more refined cuts
- Data taking from 2018.
- Analysis in development

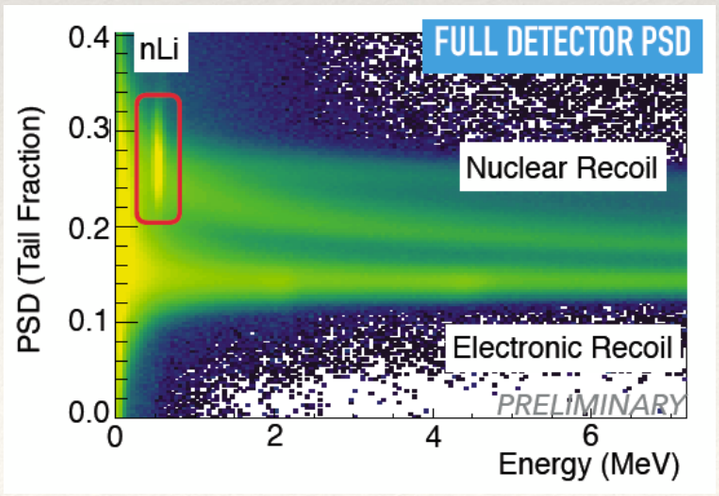


PROSPECT
Precision Reactor Oscillation and Spectrum Experiment

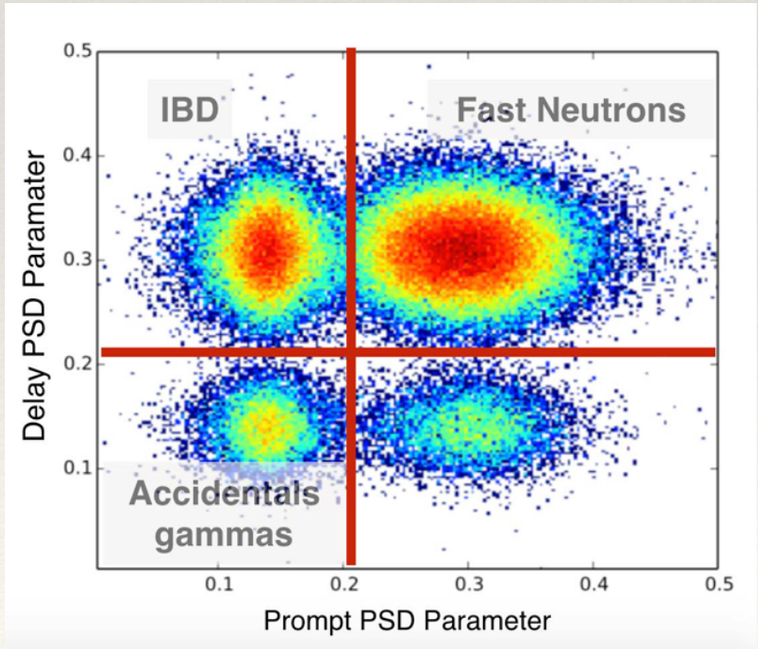


154 cells (118cm x 15cm x 15cm) filled with Li-loaded LS
Baseline 7-9 m

HFIR - Oak Ridge
Φ = 43 cm, H = 40 cm
highly enriched in ^{235}U
Pth = 83 MW
S/B ~ 1.32
Data taking from March 2018

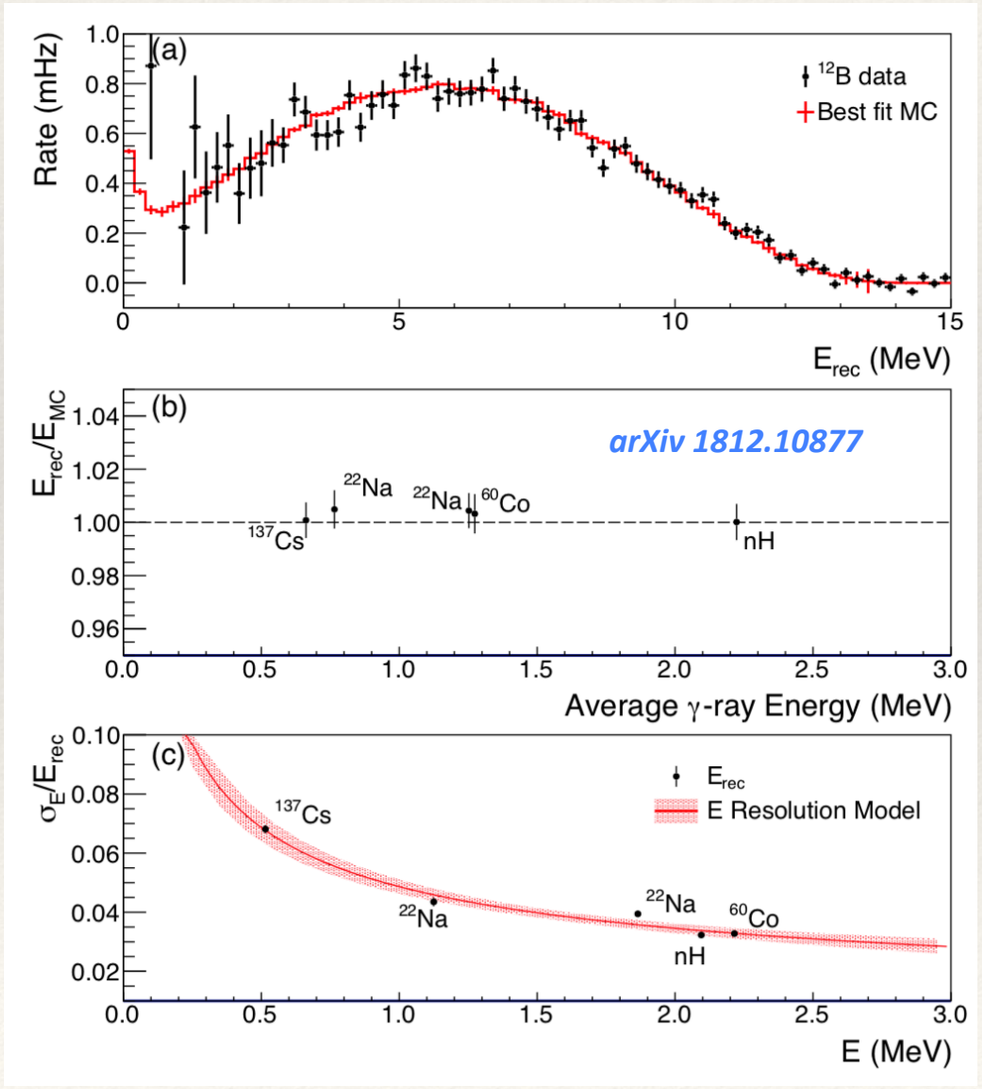


Powerful combination of PSD in the prompt and the delayed signal

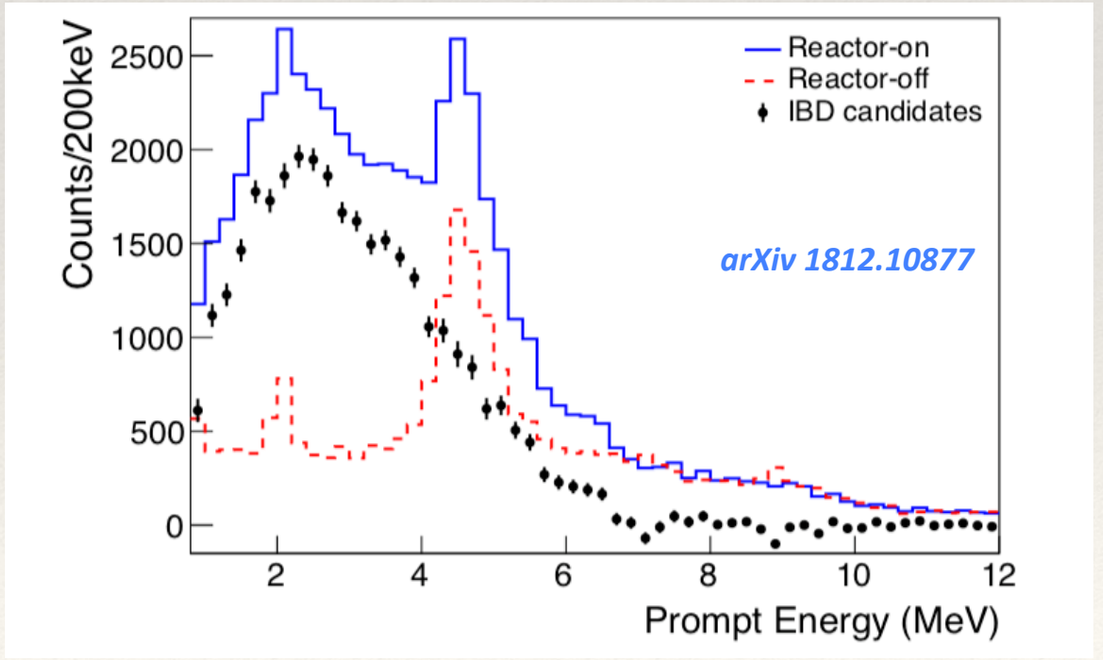


PROSPECT@HFIR - Oak Ridge

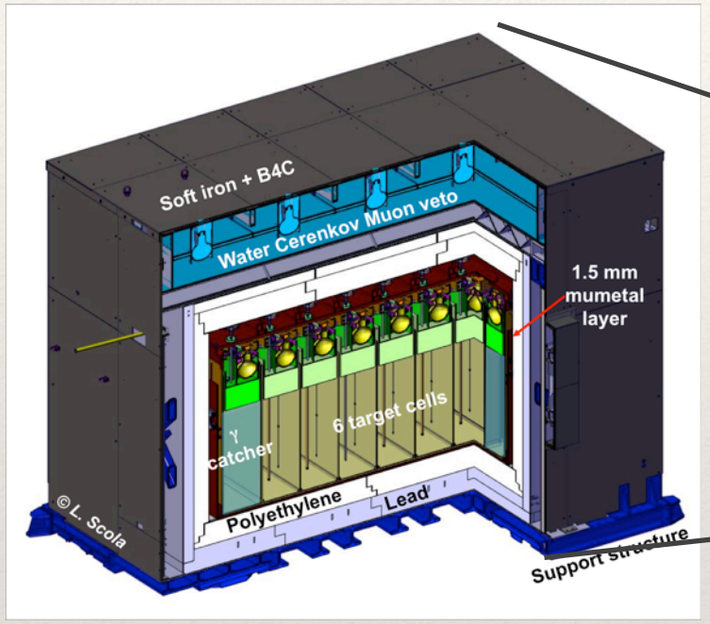
Control of E scale demonstrated at the 1% level

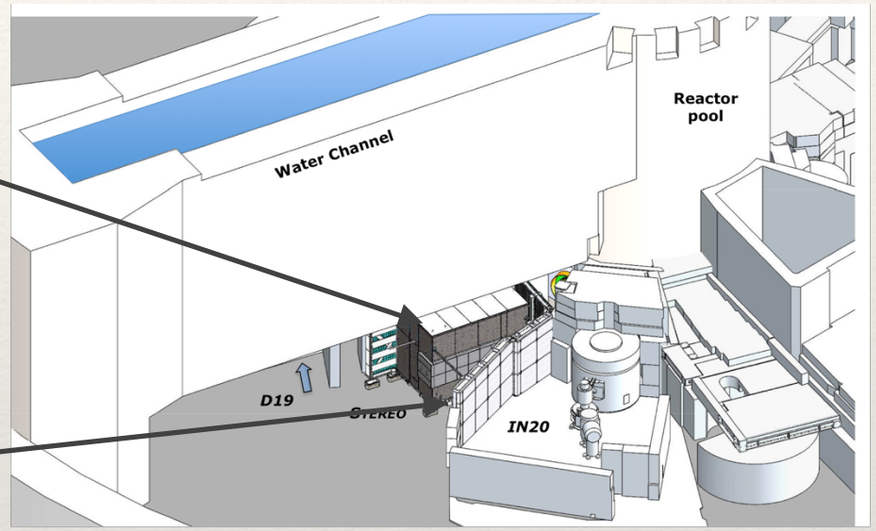


Mean S/B ~ 2 at surface!
(overburden < 1 m.w.e)



STEREO @ ILL

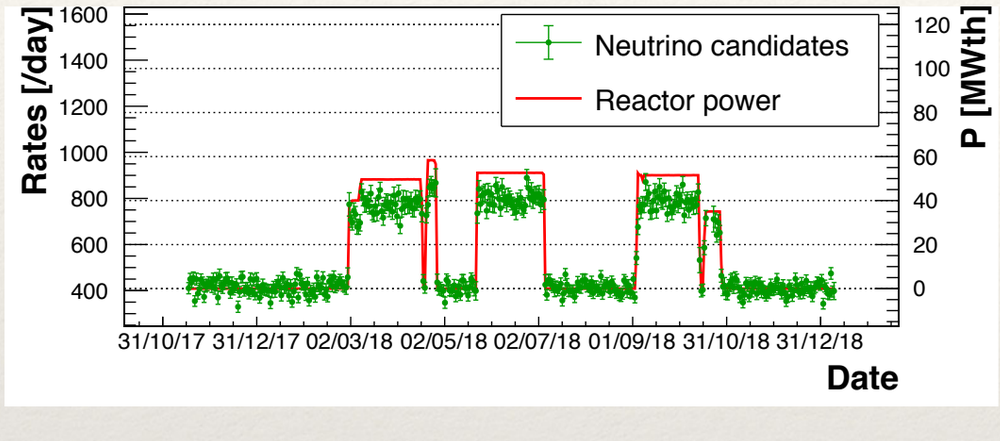




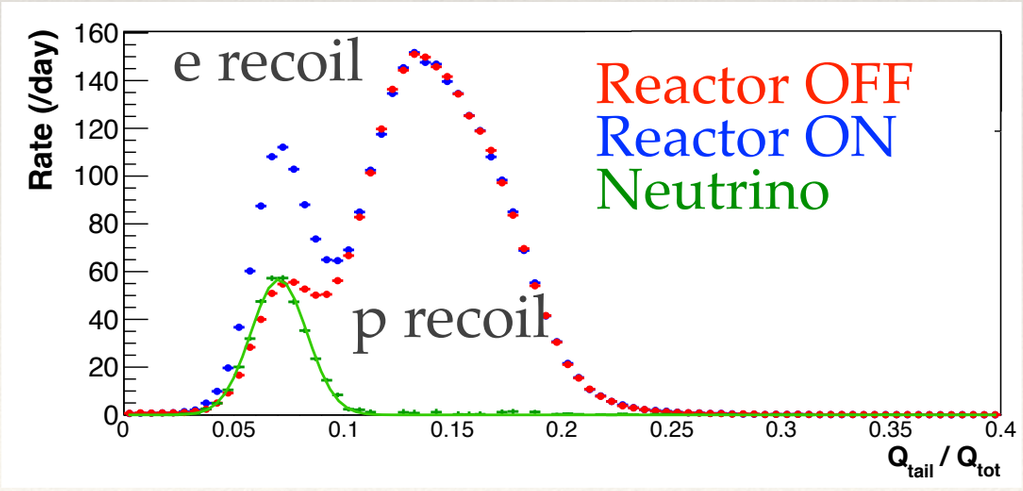
58 MW research reactor.
Pure ^{235}U fission spectrum.
9-11 m from compact core (Φ=40 cm).
Challenging background mitigation, S/B~1 achieved so far.
Relative measurement in 6 identical cells.

- Phase-I: Nov 2016~March 2017
- Phase-II: Oct 2017~ 2020

STEREO @ ILL

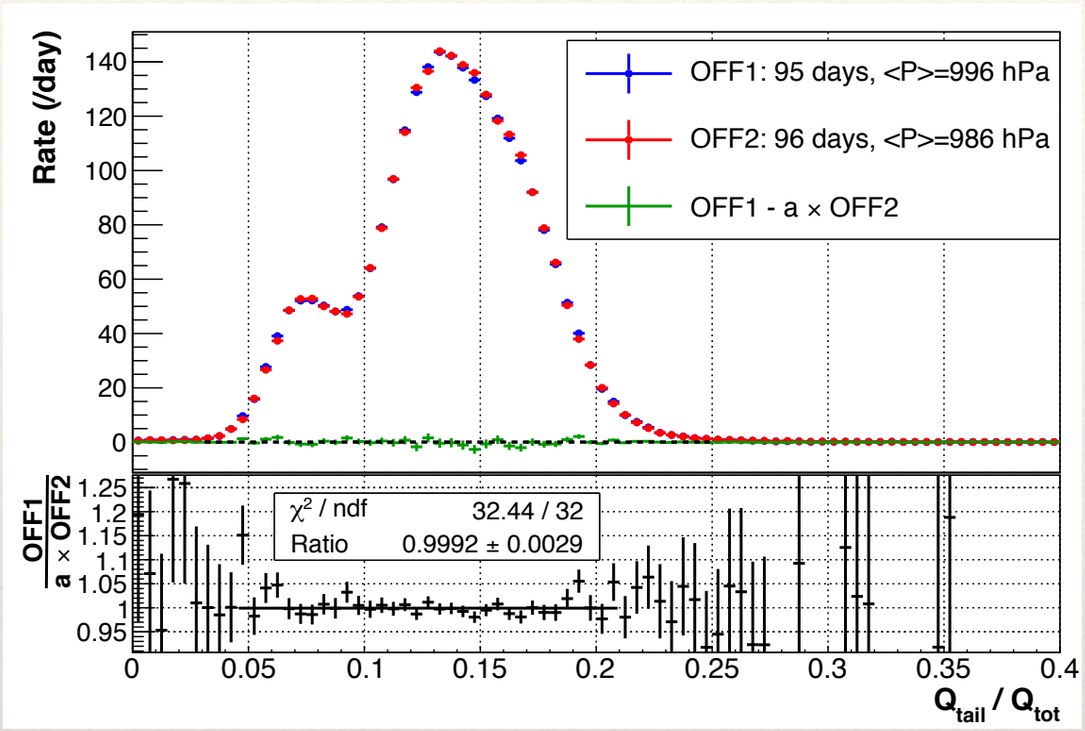


Accidental background due to the reactor activity mitigated by the large detector shielding



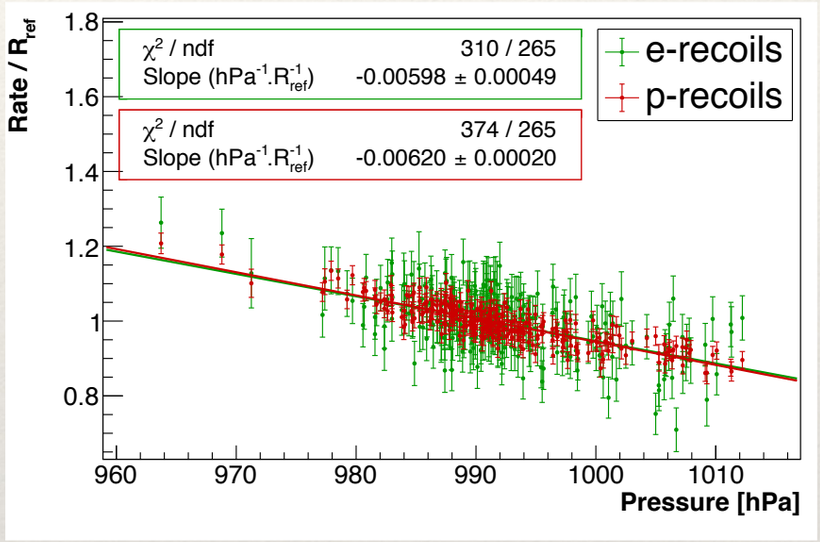
The dominant background is induced by cosmic-rays. The main contribution is a p-recoil in the prompt signal, followed by a n-capture coming from the same cosmic shower
efficiently rejected by the Pulse Shape discrimination PSD

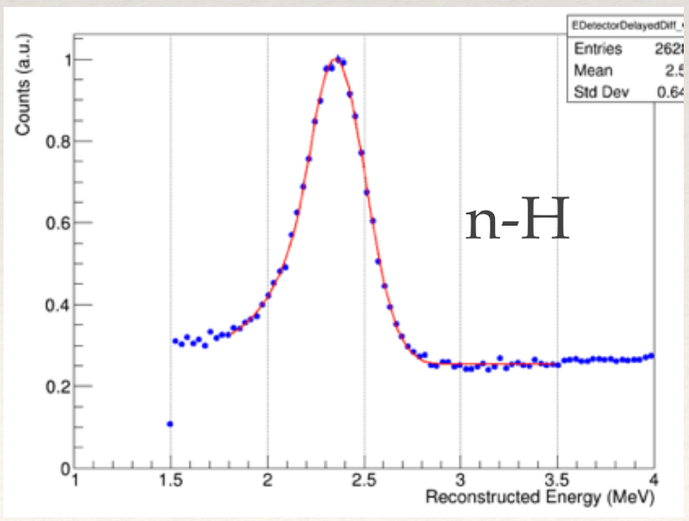
STEREO stability



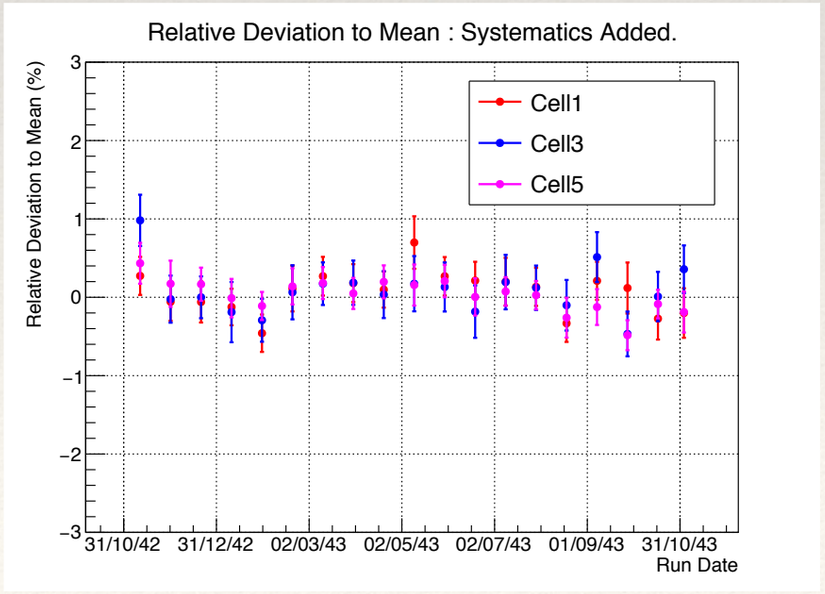
Identical background shape after temperature correction for the high & low P_{atmos} periods

Rescaling factor 93.3±0.3% compatible with pressure correction expected from independent fit: 93.8±0.3 %





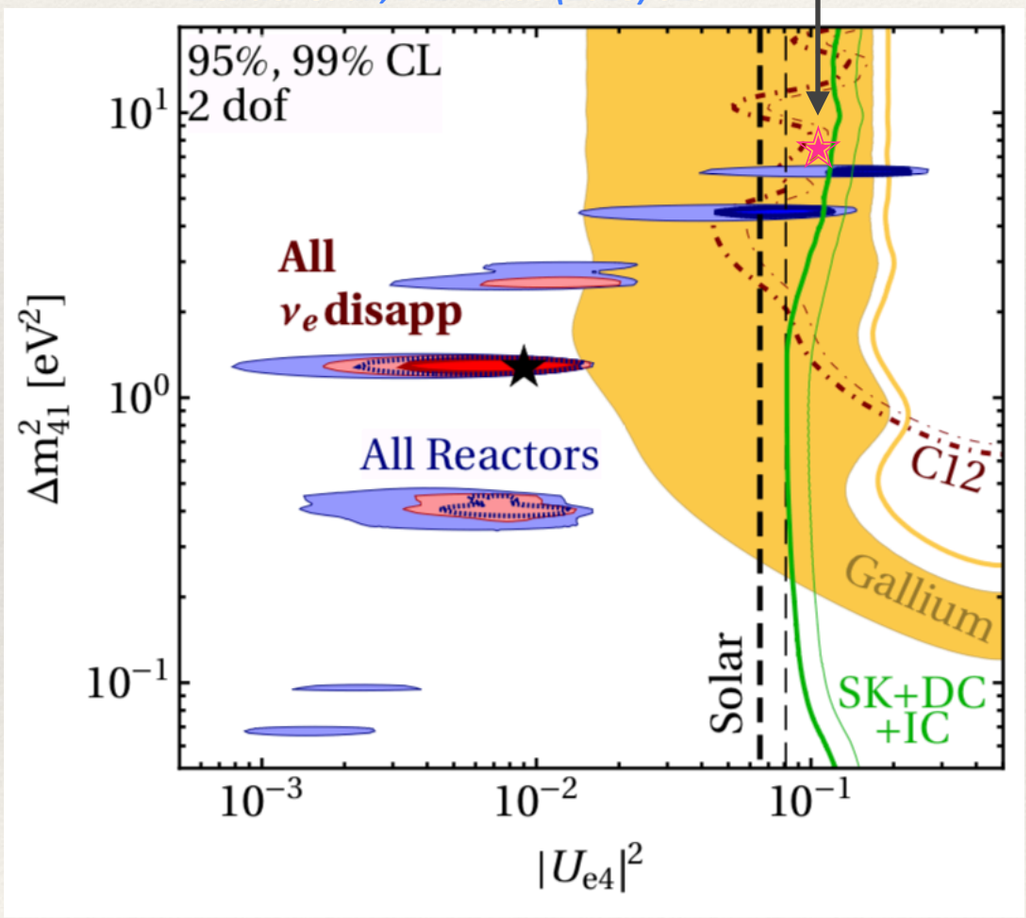
The position of the n-H peak reconstructed from the cosmic background events is stable at the sub-% level



Evidence for sterile υ

Neutrino 4 best fit

Dentler et al., JHEP 1808 (2018) 010



Global fit for all υ_e disappearance disfavor at ~3.3$\boldsymbol{\sigma}$ the no-oscillation

NEOS & DANSS reject scenarios with large mixing angle with high significance.

Taken at face value their oscillation analysis point to the same spot with more than 99% C.L.:

Δm^2=1.29 eV^2
$\sin^2$=0.0096

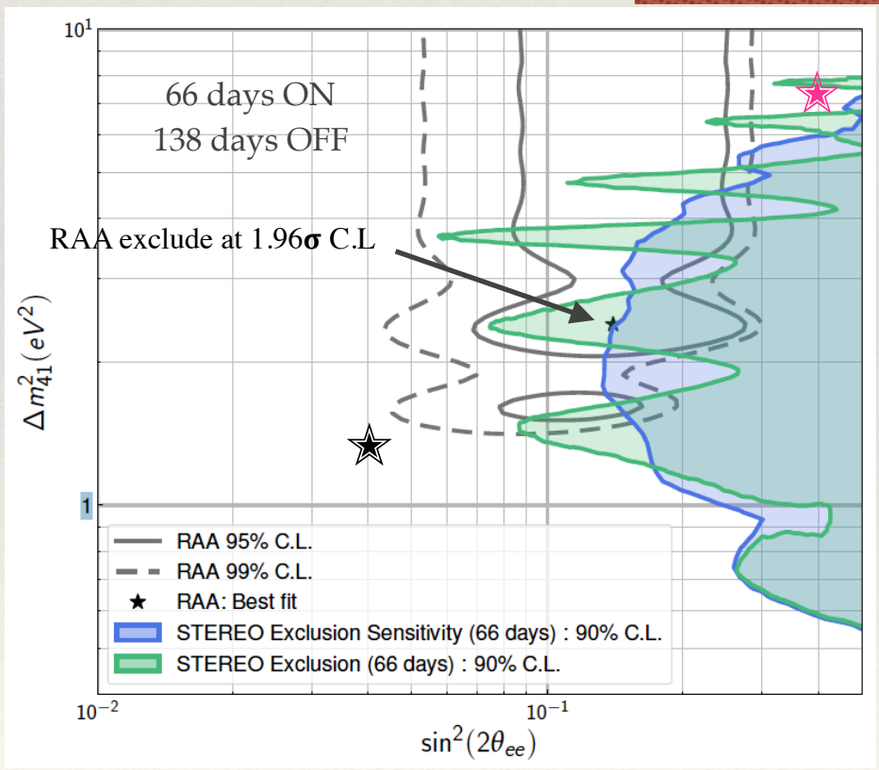
Evidence for sterile υ

★neutrino-4 best fit

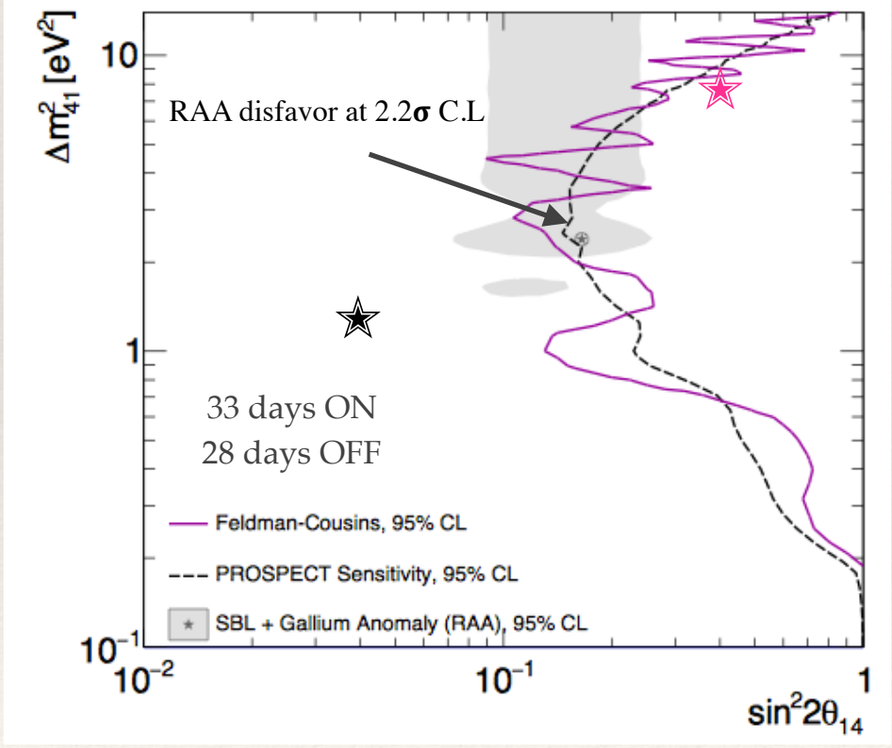
★all υ_e disappearance

Model independent analysis

Phys.Rev.Lett. 121 (2018) no.16, 161801 STEREO



Phys. Rev. Lett. 121 (2018) no.25, 251802 Prospect

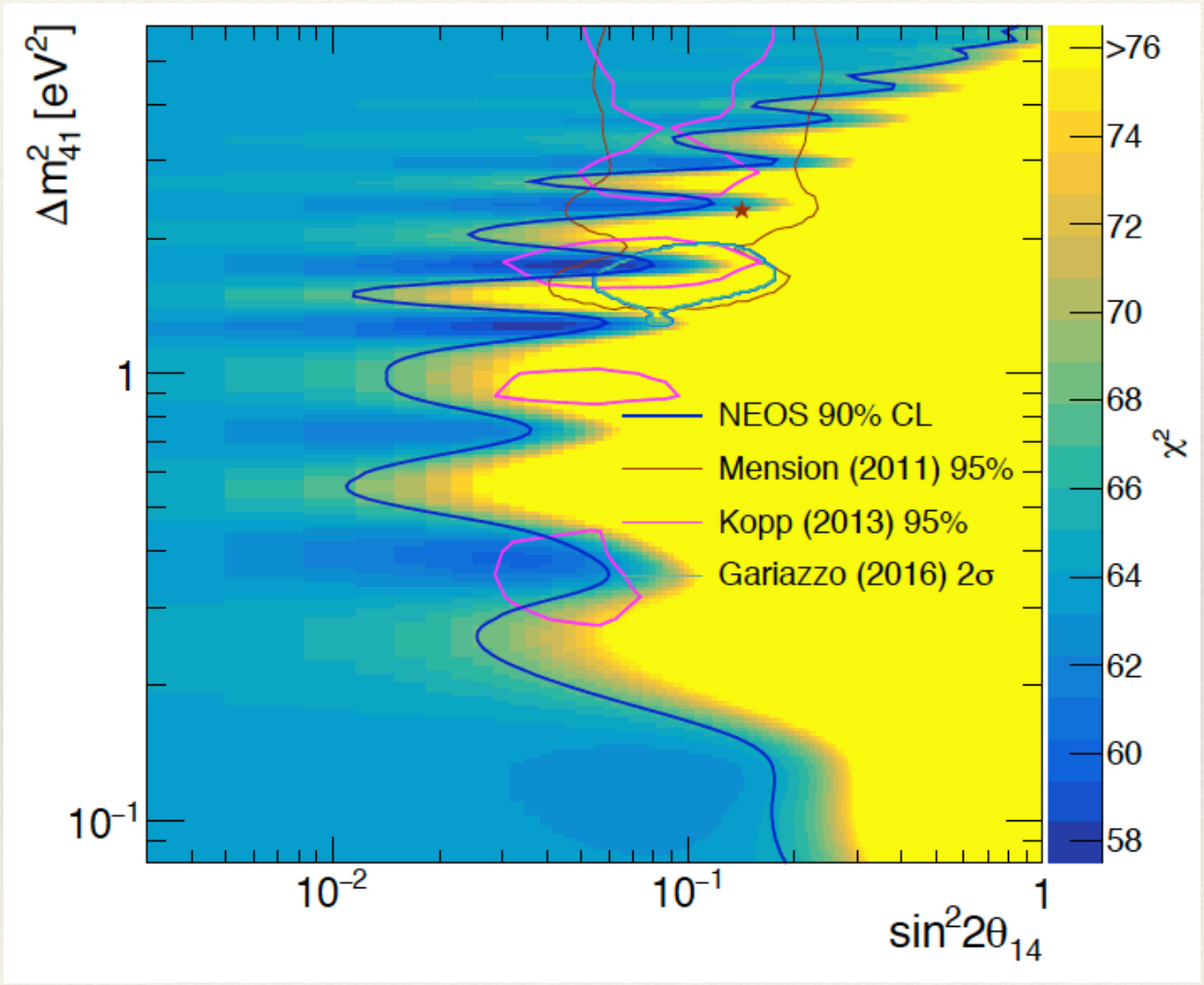


Summary

- Promising combination of ongoing measurements at research reactors:
  - Direct searches of the sterile neutrino covering the relevant area.
  - Accurate measurements can now be performed combining different systematics.
    - Model independent analysis.
    - New experimental rates and shapes of the ^{235}U fission ν spectrum.
- No definitive signature of sterile neutrinos reported.
- Data in the next 2 years will help to probe the parameter space further.

The existence (or not) of the sterile neutrino at eV scale will be addressed in the next 2 years

NEOS Contour



DANSS contour