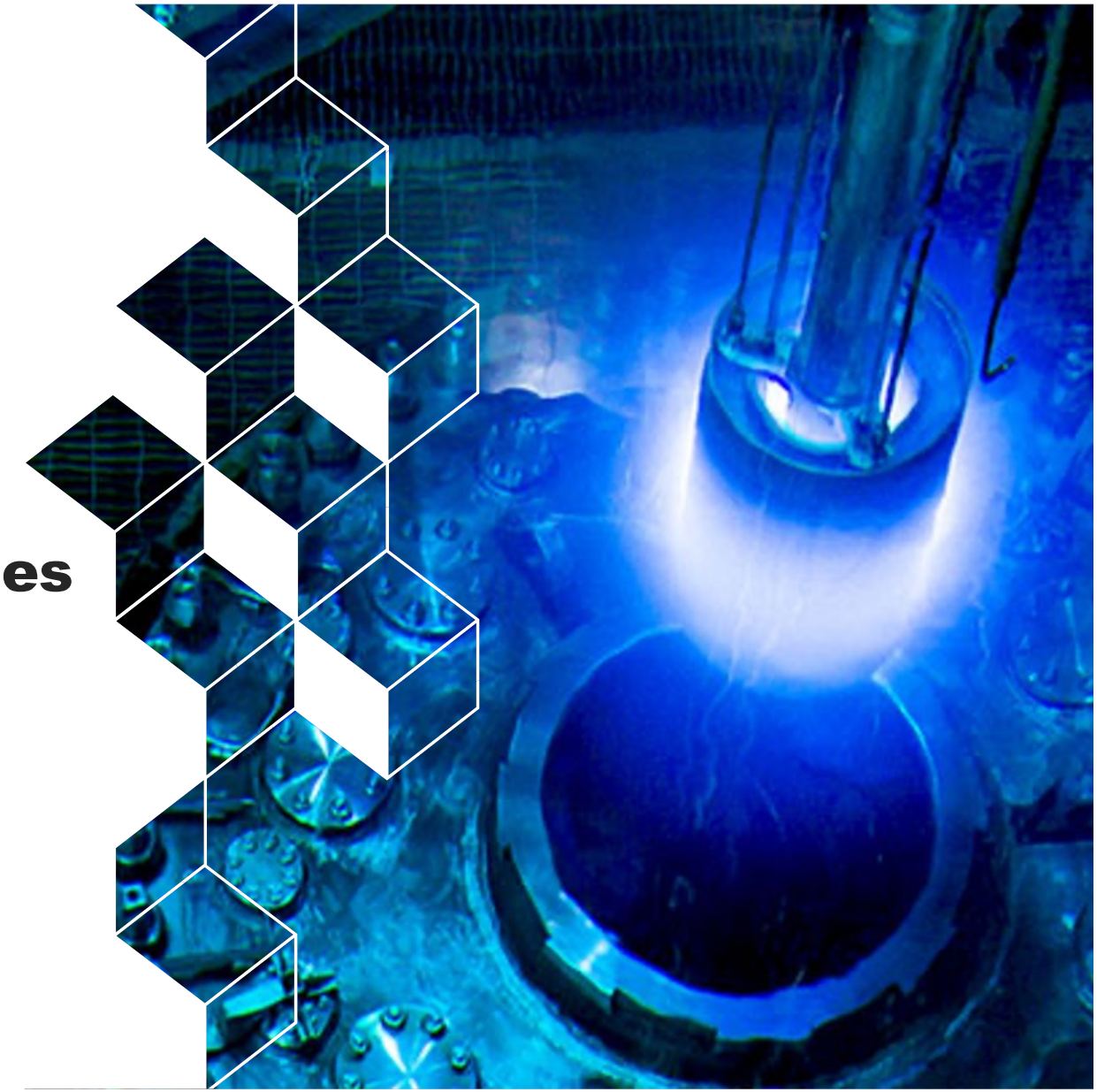
Sterile Neutrino Searches at Reactors

David Lhuillier

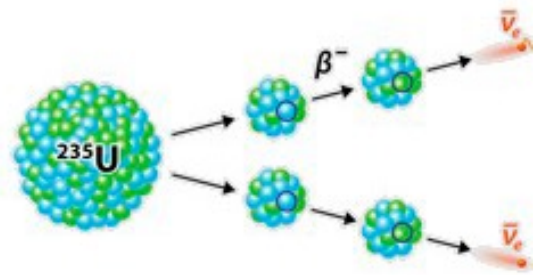
cea irfu

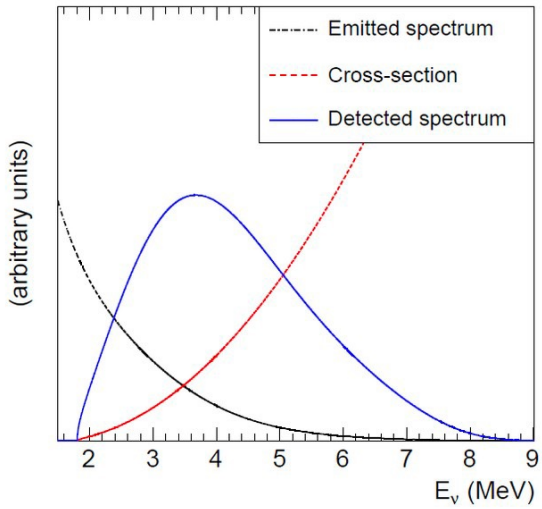
Neutrino Telescopes 2023, Venice



Neutrinos @ Reactors

Fission of heavy, neutron rich, nuclei leads to unstable fission products de-exciting by β^- decay

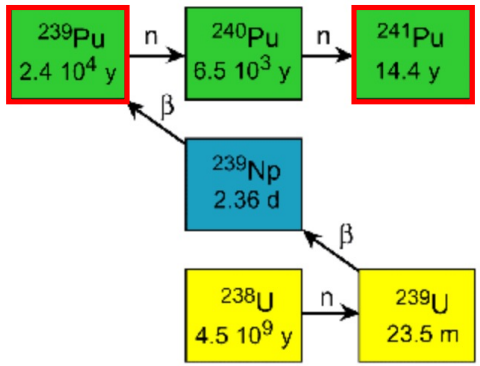




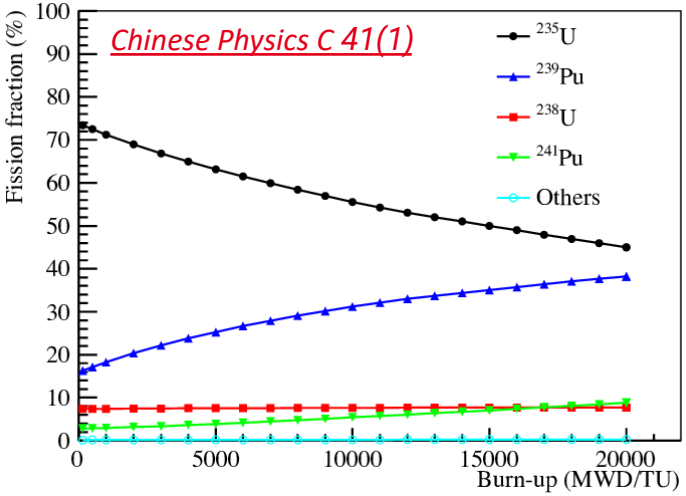
- Pure $\bar{\nu}_e$ source
- 0-10 MeV energy range
- About 2.10^{20} $\bar{\nu}_e$ / GW_{th}

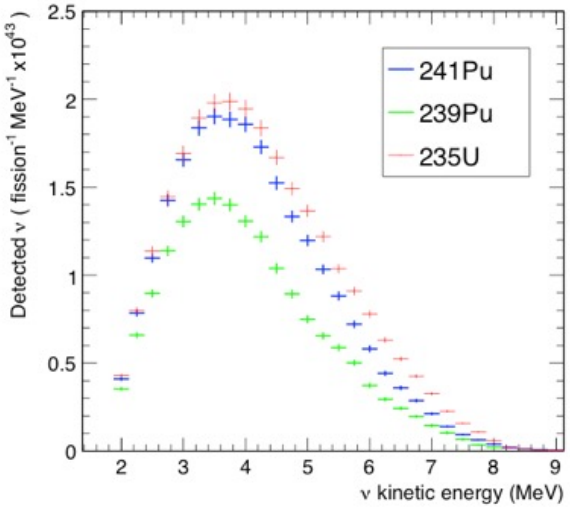
- Most intense man-controlled source of neutrinos.
- IBD detection process: $\bar{\nu_e} + p \rightarrow e^+ + n$

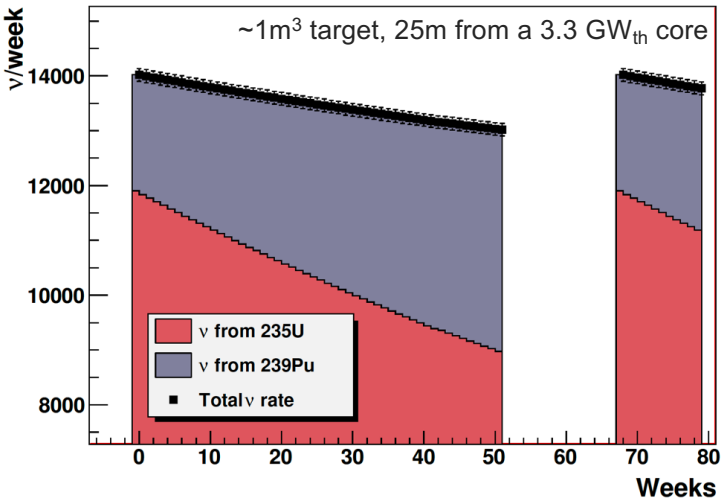
Reactor Fuel Evolution



- Production of the $^{239\text{-}41}$Pu fissile isotopes by n-capture on ^{238}U.
- Time evolution of low-enriched cores (commercial reactors, 4% ^{235}U), inducing a ~10% decrease of detected ν flux over 1 reactor cycle.
- Highly enriched cores (research reactors, 20-90% ^{235}U) give access to the pure ^{235}U fission spectrum.



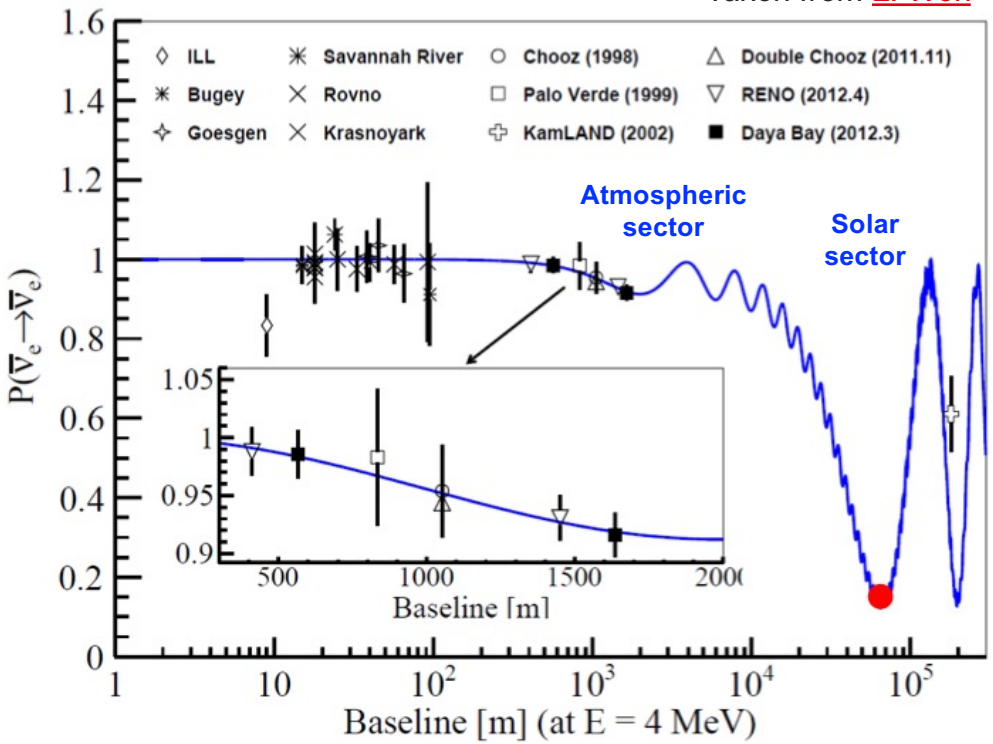




Sterile Neutrino Signal

No interaction with matter by definition
→ search for an oscillation pattern induced by the mixing with the active flavors

Taken from L. Wen



- Atmospheric and solar oscillation sectors accurately probed by reactor neutrinos.
- Pure ν_e source and pure ν_e IBD detection process → **disappearance measurements**.
- Control of the **absolute normalization** is challenging.
- Look for spectrum shape distortions: development of **relative, model independent, measurements** between identical detectors or detector segments.

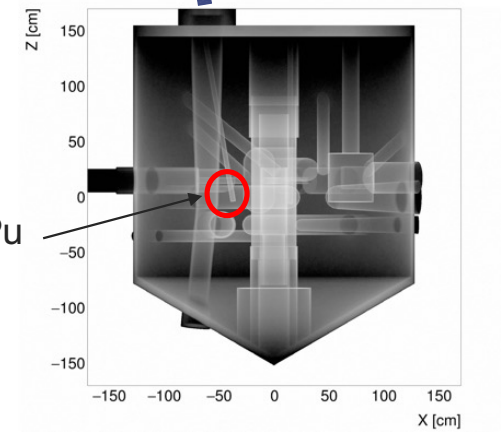
Predicted Fission Neutrino Spectra

K. Schreckenbach et al.

Magnetic spectrometer

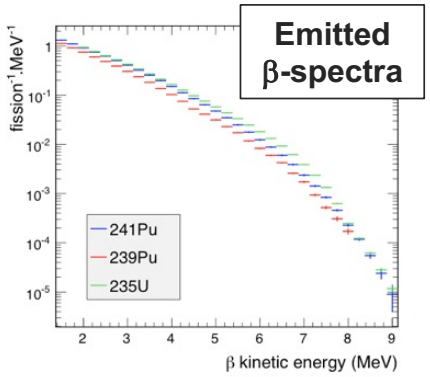
e^- from fission products' β-decay

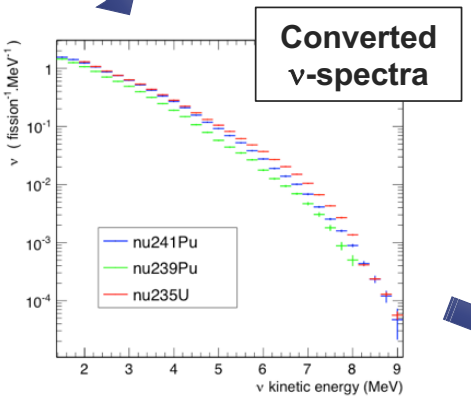
e^-



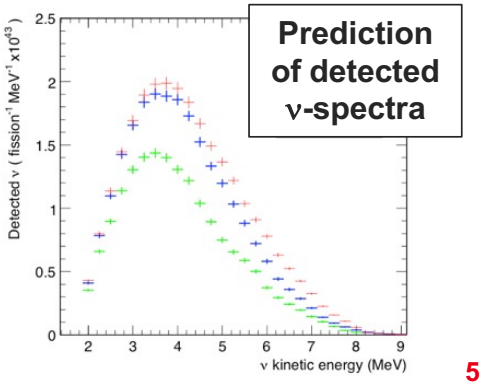
Target foils (^{235}U , ^{239}Pu and ^{241}Pu) exposed to an intense flux of thermal neutrons

Cut view of ILL core
(courtesy of A. Onillon)



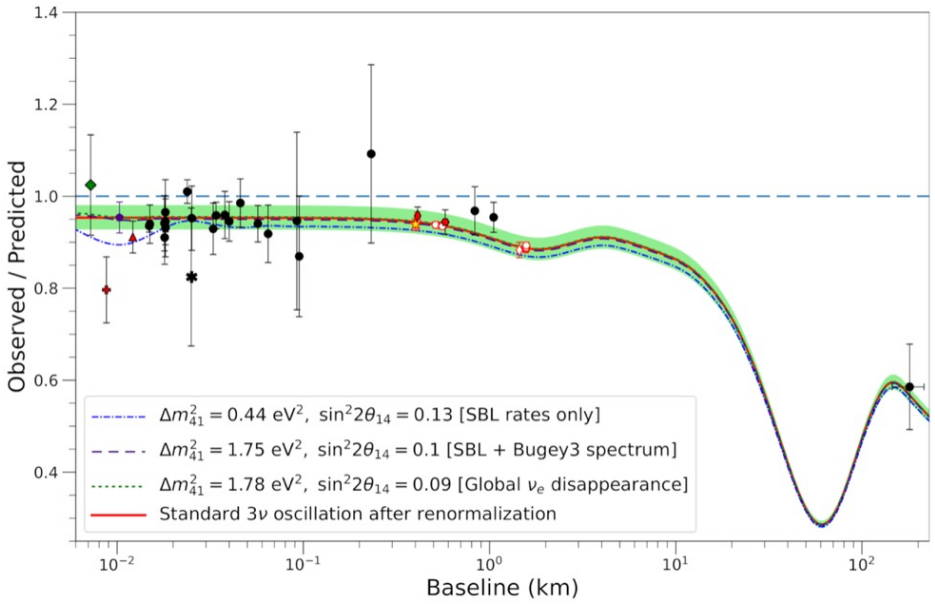


- Total fission β-spectra measured in the 80's
- Numerical procedure for β to ν conversion. Breakthrough in the accuracy of predicted spectra.
- Revisited in 2011 (PRC83, PRC84)

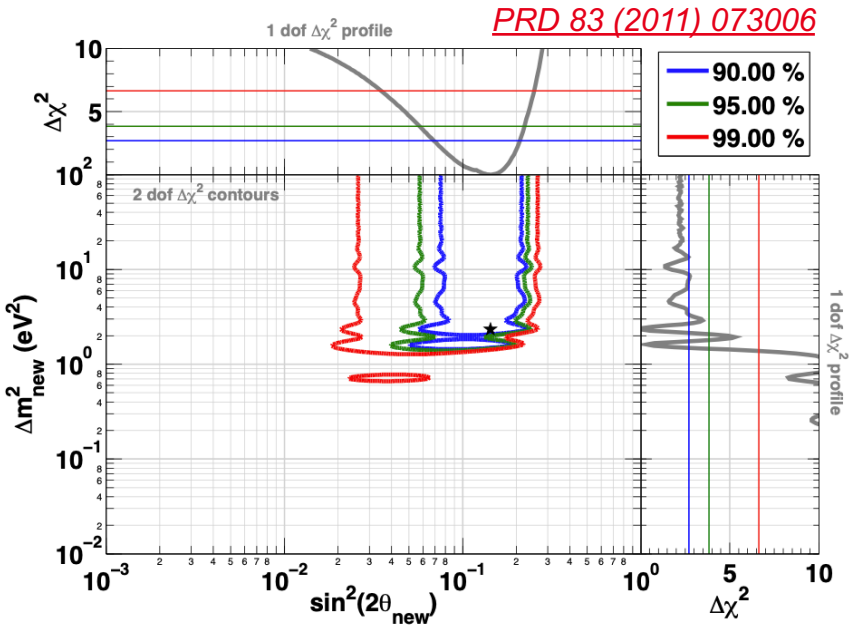


RAA : Reactor Antineutrino Anomaly

Global deficit of observed ν's w.r.t. prediction



Combined RAA and Gallium anomalies strengthen the sterile ν hypothesis (99.7% C.L.)

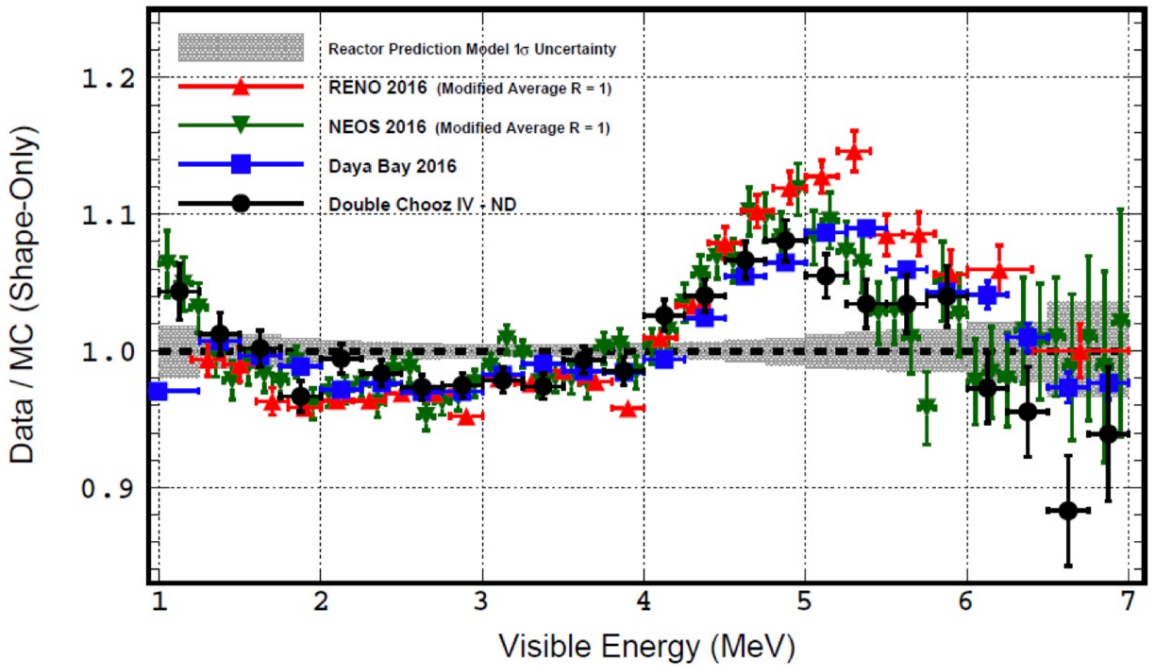


Need complementary data to disentangle sterile neutrino and prediction bias hypotheses

→ **Search for unambiguous oscillation signal with few meters wavelength**

Spectrum Shape “Anomaly”

Nature Physics 558–564 (2020)

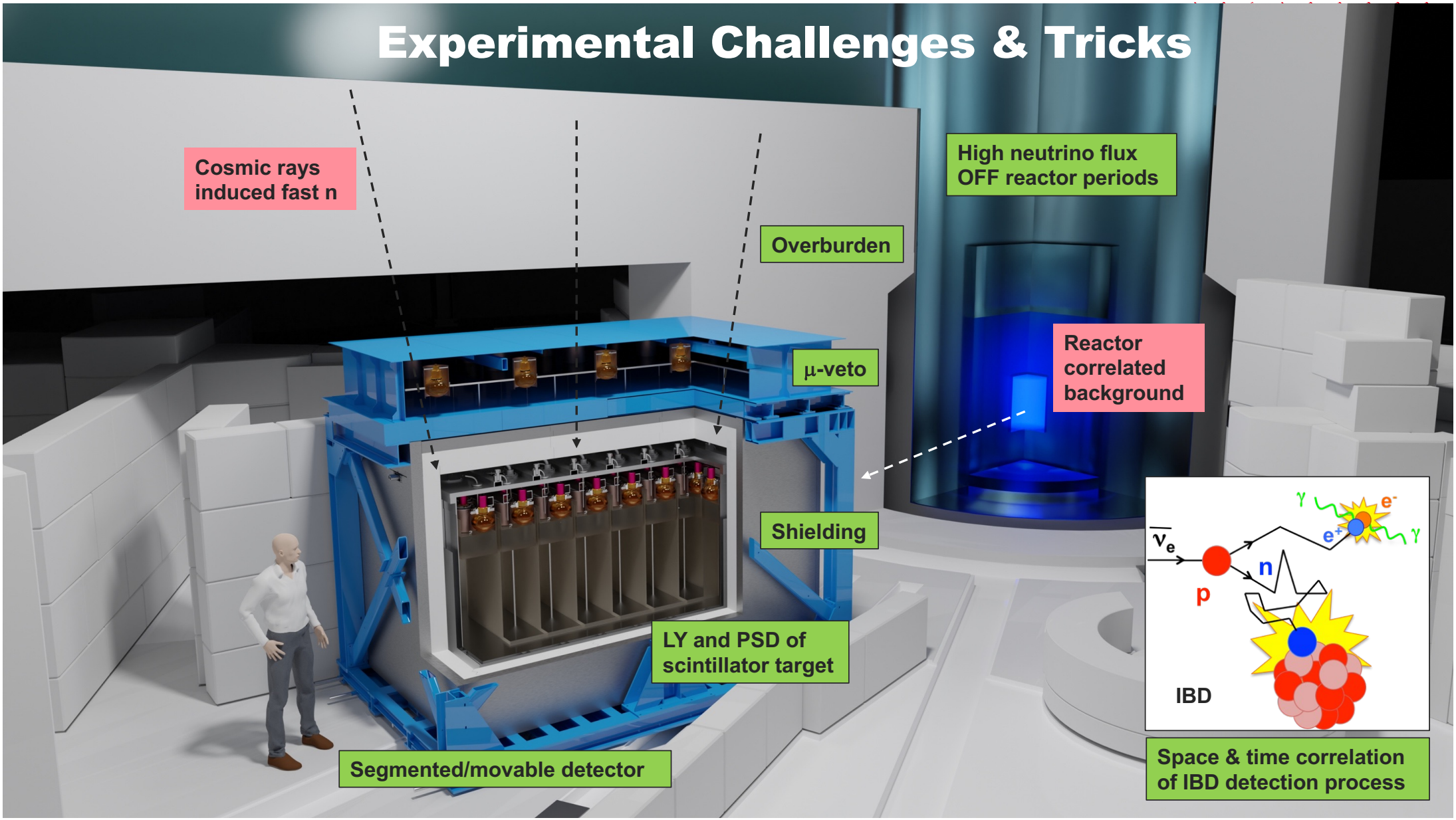


- Accurate spectra measured **few 100 m** from commercial reactors by the Double Chooz, Daya Bay and Reno experiments
- **Unexplained local shape distortion**, the “5 MeV bump”, on top of the global deficit
- Contribution of this bump to the global deficit is sub-%

Worldwide Very Short Baseline Experiments

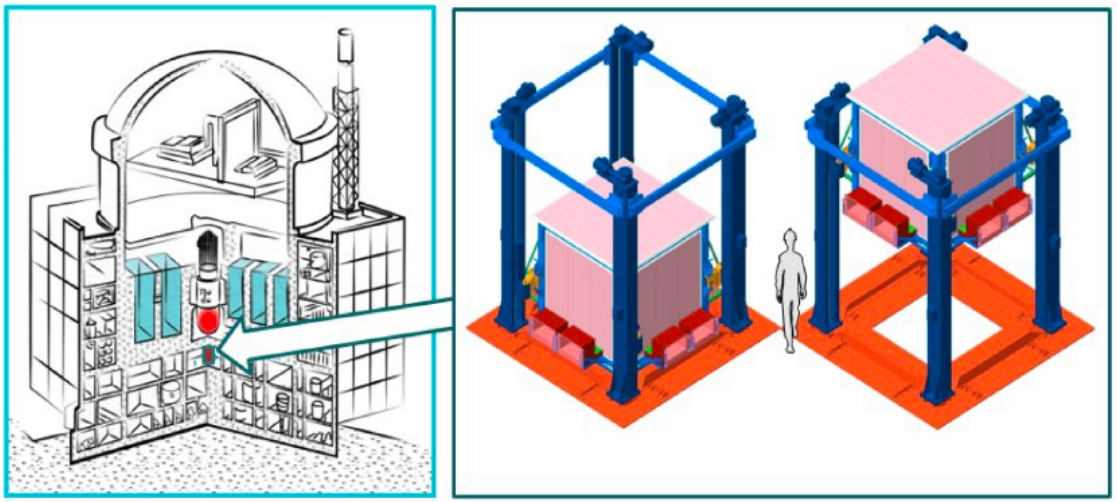
- Research reactors
  - Low stat
  - Compact core
  - Pure ^{235}U
- Commercial reactors
  - High stat
  - Extended core
  - Mixed ^{235}U - ^{239}Pu

Experimental Challenges & Tricks



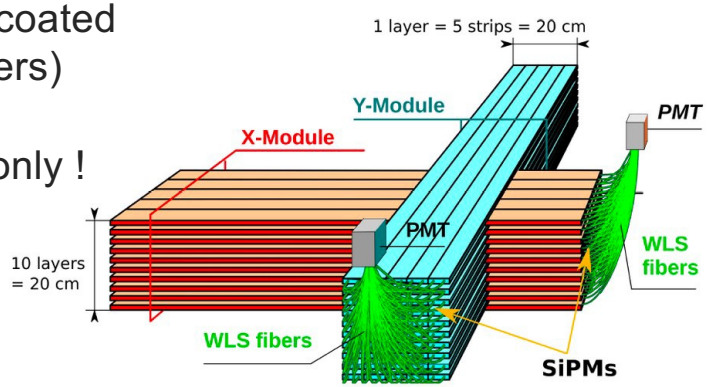
DANSS

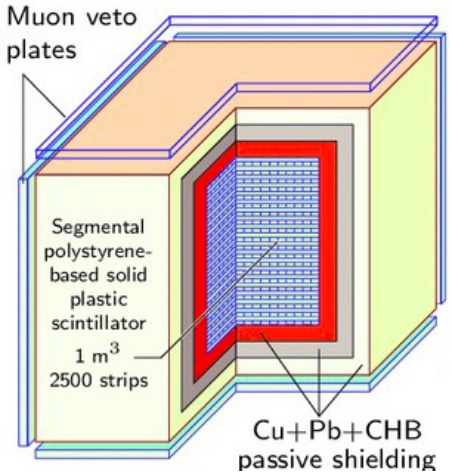
Kalininskaya NPP - Russia



- 3 GW_{th} extended core
- Movable detector (10-12 m baseline)
- Energy scale constrained by radioactive sources and ^{12}B β-spectrum (2% systematics). $E_{resolution}$ = 34% / √E

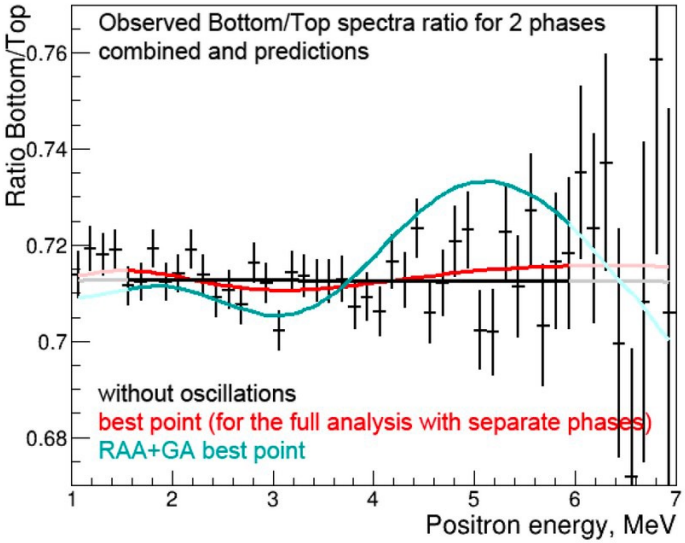
- Highly segmented detector (Gd-coated plastic bars read out by WLS fibers)
- 5000 $\overline{\nu}_e$ / day, ~2% background only !



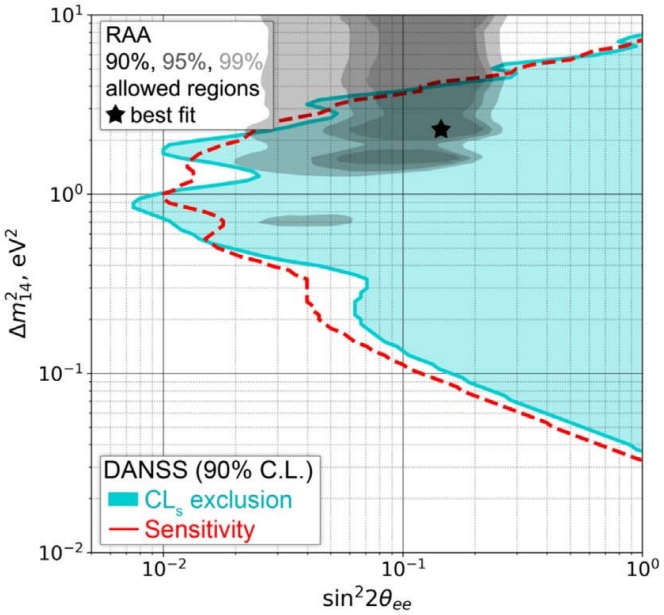


DANSS

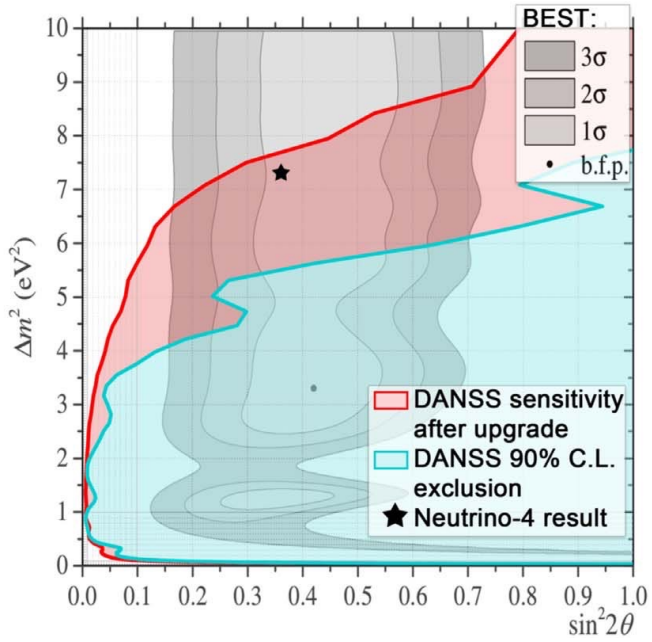
- High statistics, low background and robust analysis of spectra ratios at ≠ detector positions compensate the damping of oscillations induced by the core size.



- No oscillation signal from 5M detected neutrinos
- Best fit point of the initial RAA+Gallium anomaly rejected at >5 σ



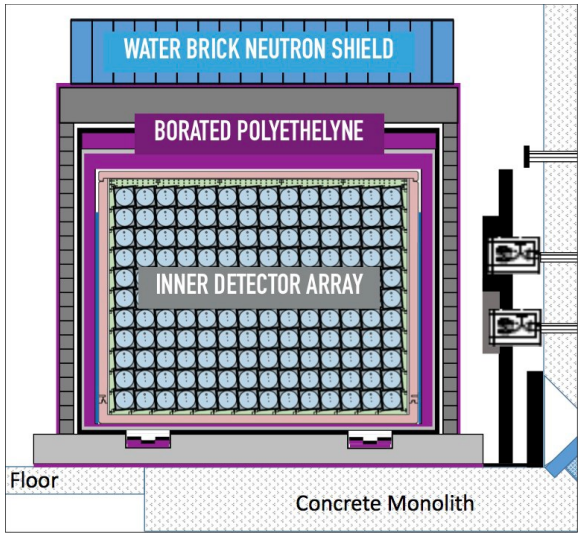
- Upgrade plan with large target volume and better resolution.
- Significant gain in sensitivity at higher Δm2



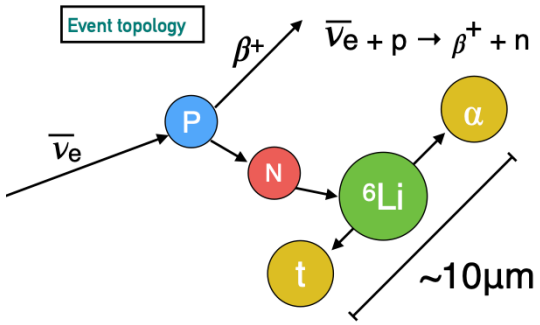
See M. Danilov's talk on Wednesday

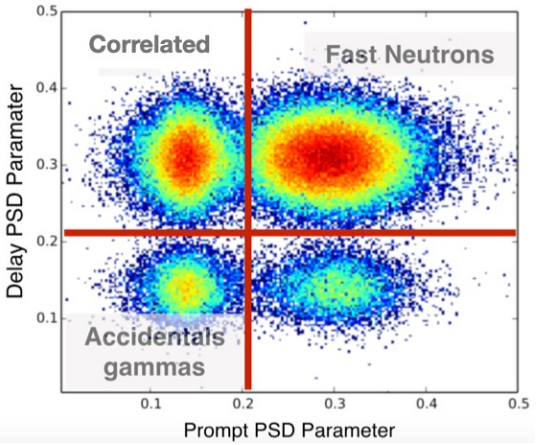
PROSPECT

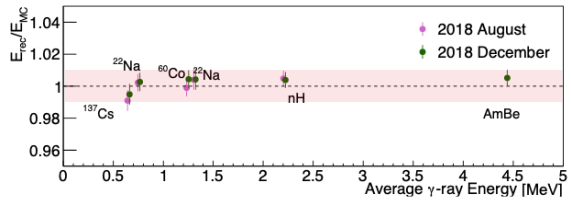
- High Flux Isotope Reactor – Oak Ridge
- 85 MW_{th} very compact core (ϕ 44 cm)
- HEU fuel → pure ^{235}U fission spectrum

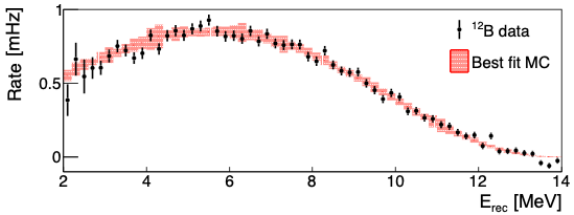


Breakthrough in the rejection of background using a Li-doped LS









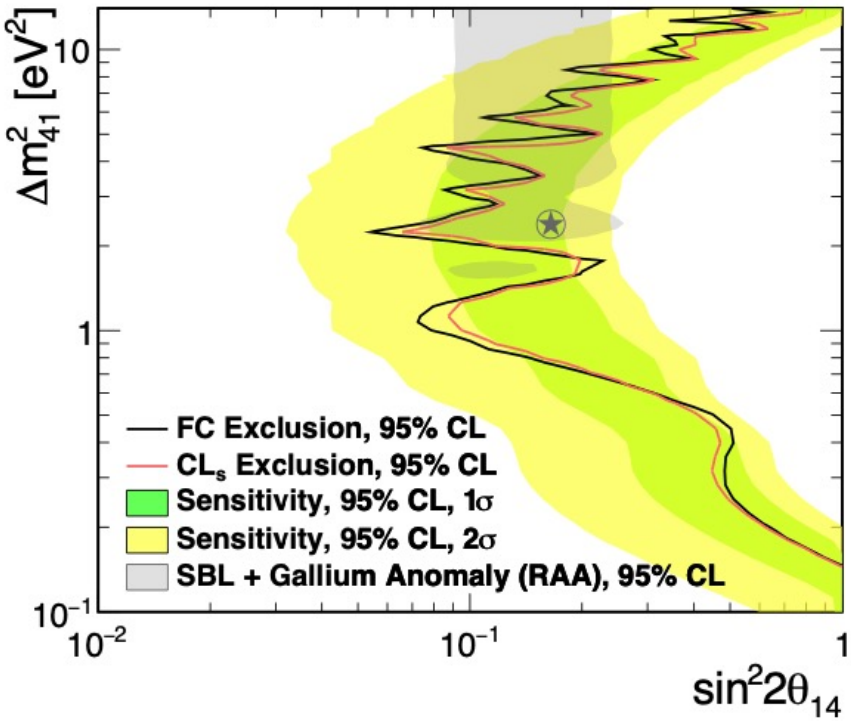
- Refined control of the detector response
- 5% resolution @ 1 MeV

Model independent oscillation analysis by searching for relative spectrum distortions between groups of detector cells at different baselines (L=6.7–9.2 m)

PROSPECT

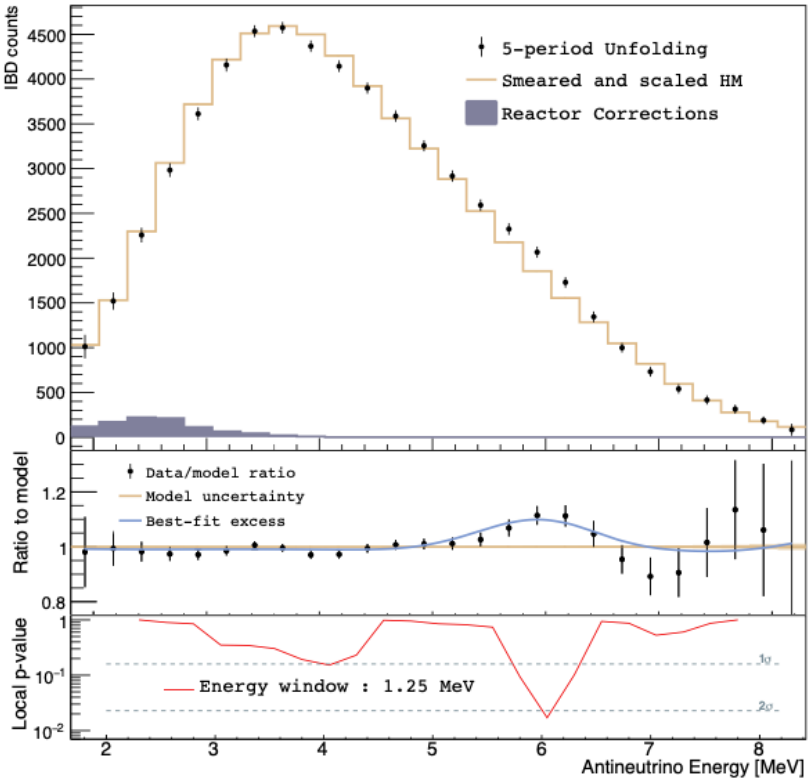
- Data compatible with no-oscillation
- RAA+Gallium best fit rejected at 2.5 σ level

PRD 103 (2021) 032001



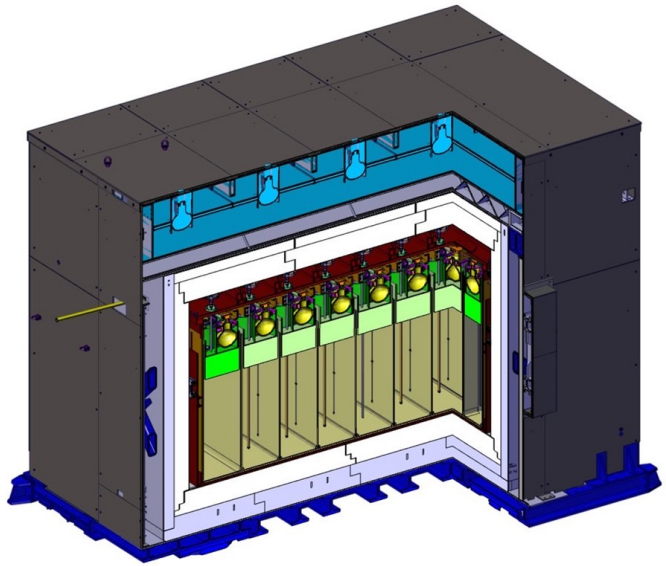
- Updated analysis provides a reference ^{235}U neutrino spectrum
- S/B=1.6 → 4.1

PRL 131 (2023) 2, 021802



STEREO

- ILL Reactor – Grenoble
- 58 MW_{th} very compact core (ϕ 40 cm)
- HEU fuel → pure ^{235}U fission spectrum
- S/B~1.1, compensated by long OFF periods and detector stability



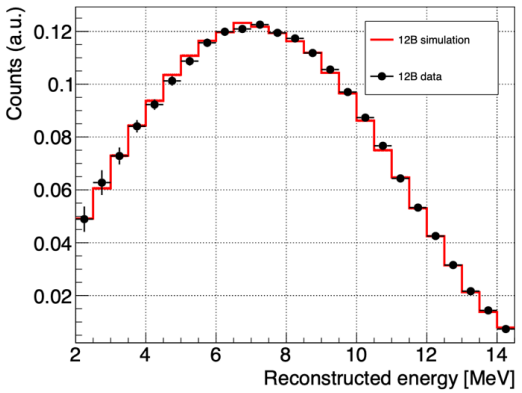
6 cells filled with Gd-loaded LS

- Model-independent analysis: a free average spectrum "ϕ_i" is fitted to the 6 detection cells

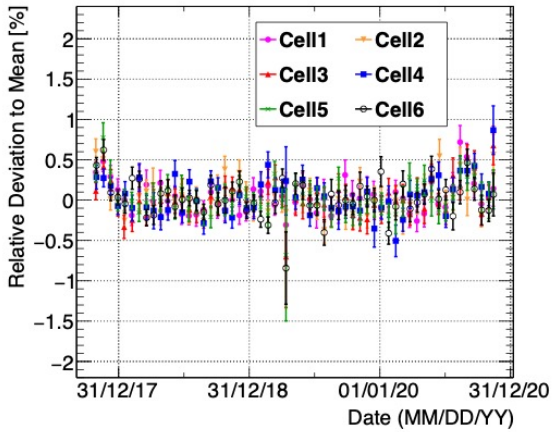
$$\chi^2 = \sum_{l=1}^{N_{\text{cells}}} \sum_{i=1}^{N_{\text{Ebins}}} \left(\frac{A_{l,i} - \phi_i M_{l,i}}{\sigma_{l,i}} \right)^2$$

- Fine tuned MC reaching % level description of energy reconstruction and neutron detection efficiency

^{12}B β-decay spectrum



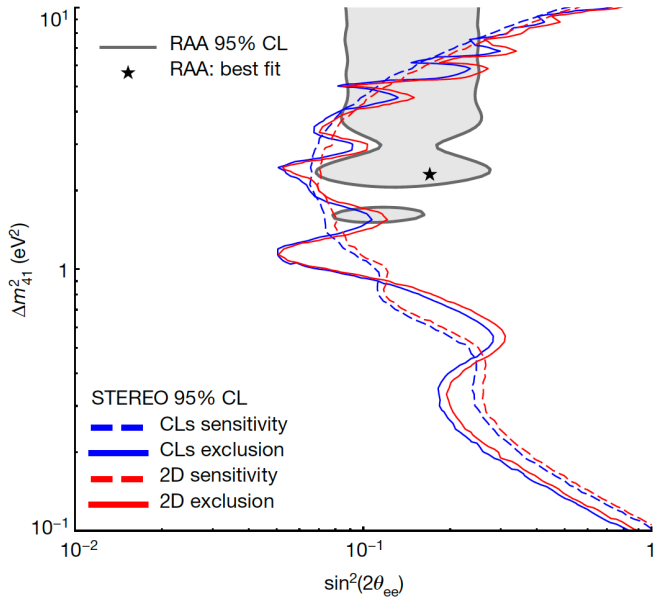
Stability of the 2.2 MeV n-H peak



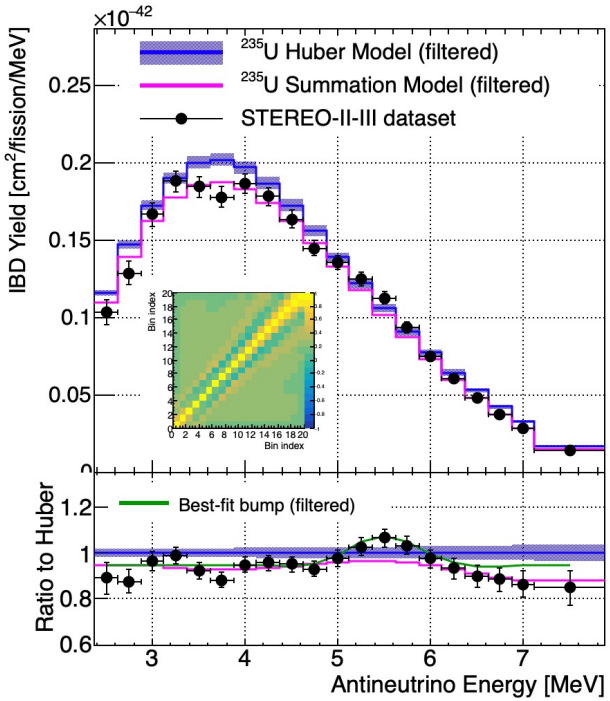
STEREO

Nature 613 (2023) 7943, 257-261

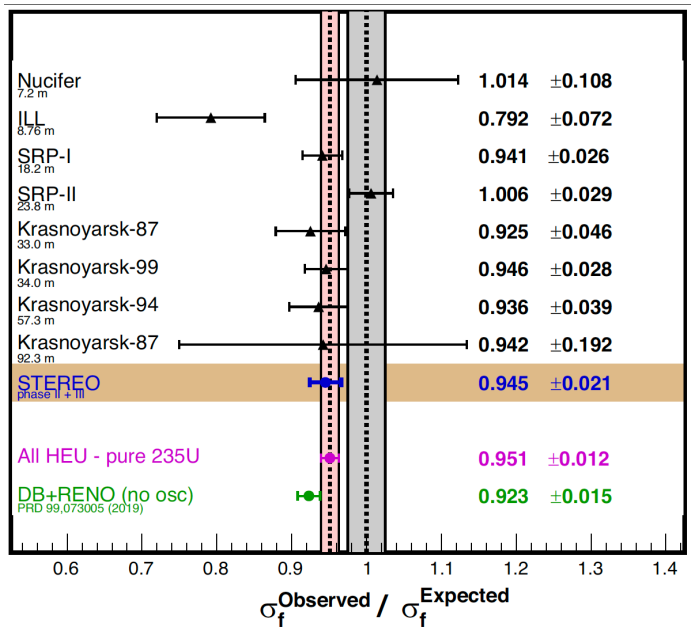
- Data compatible with no-oscillation
- RAA+Gallium best fit is rejected at >4 σ level



- Reference neutrino spectrum of ^{235}U fission in $\overline{\nu}_e$ energy



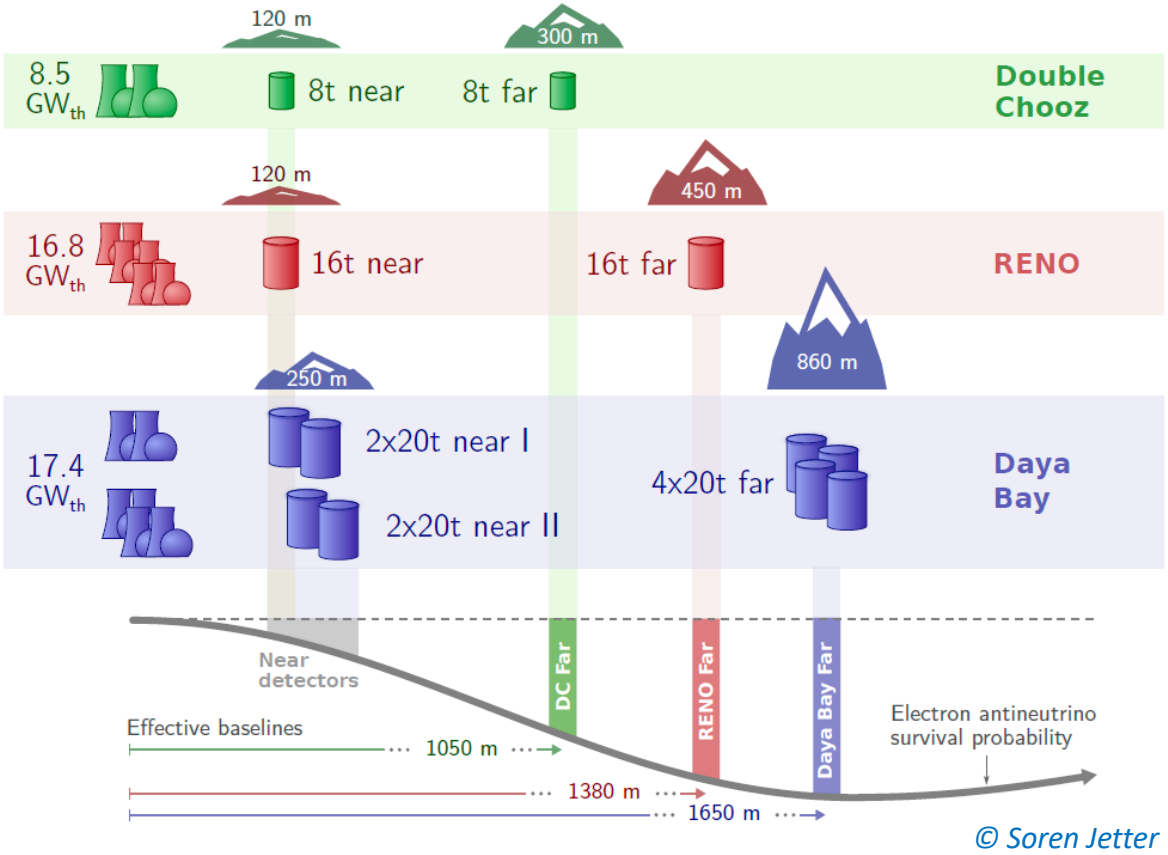
- Best absolute normalization among pure ^{235}U measurements



Worldwide Sterile Neutrino Searches

- Research reactors
  - Low stat
  - Compact core
  - Pure ^{235}U
- Commercial reactors
  - High stat
  - Extended core
  - Mixed ^{235}U - ^{239}Pu
- Θ_{13} measurements at commercial reactors

Θ_{13} Experiments



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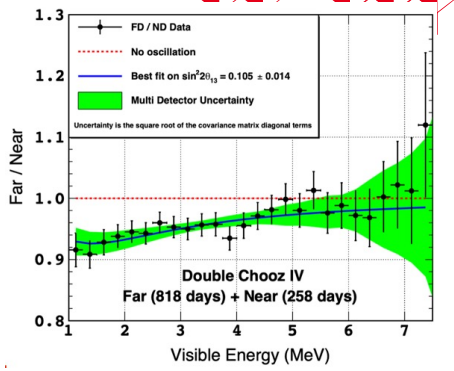
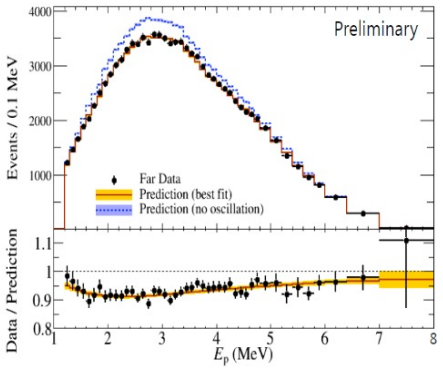
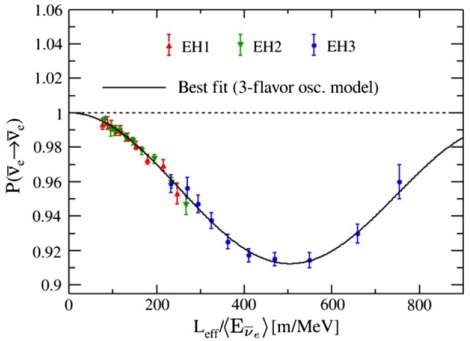




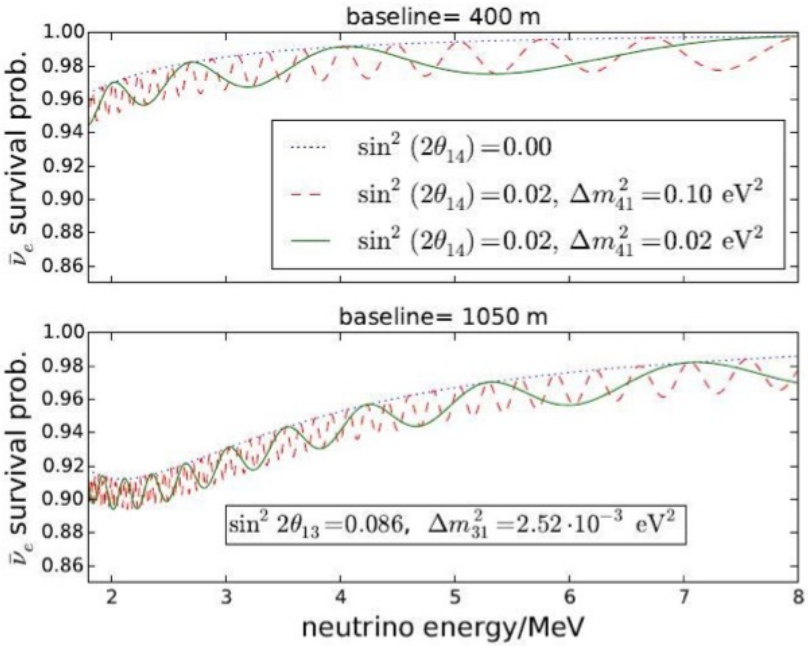


- Impressive accuracy on θ_{13} from ratios of near/far detectors
- Paved the way for VSB experiments

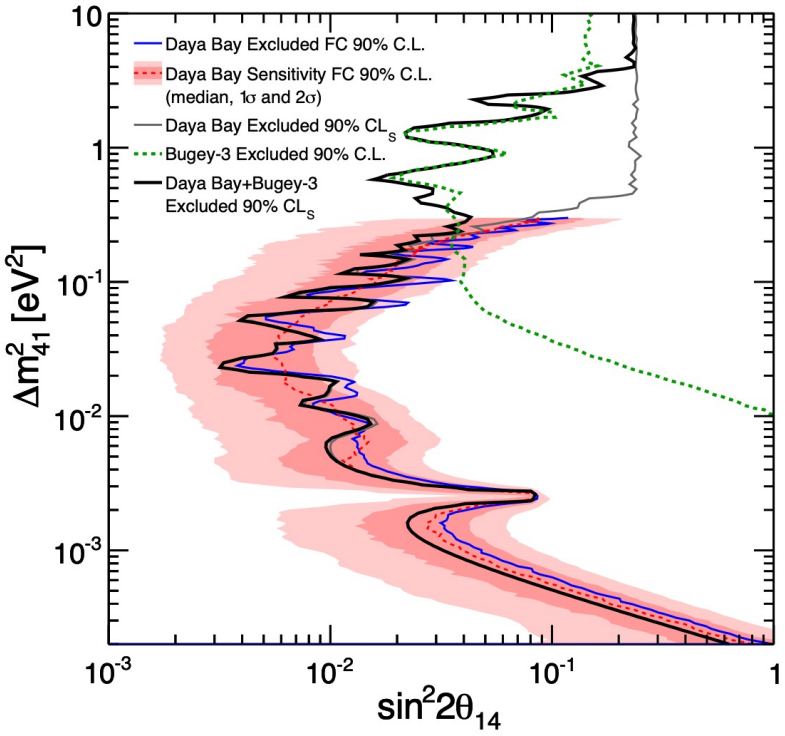
Θ_{13} Experiments

- Model independent analysis searching for an extra oscillation pattern in near and far detectors, on top of the θ_{13} oscillation.

Eur. Phys. J. C 81 (2021)



PRL 125 (2020) 7, 071801

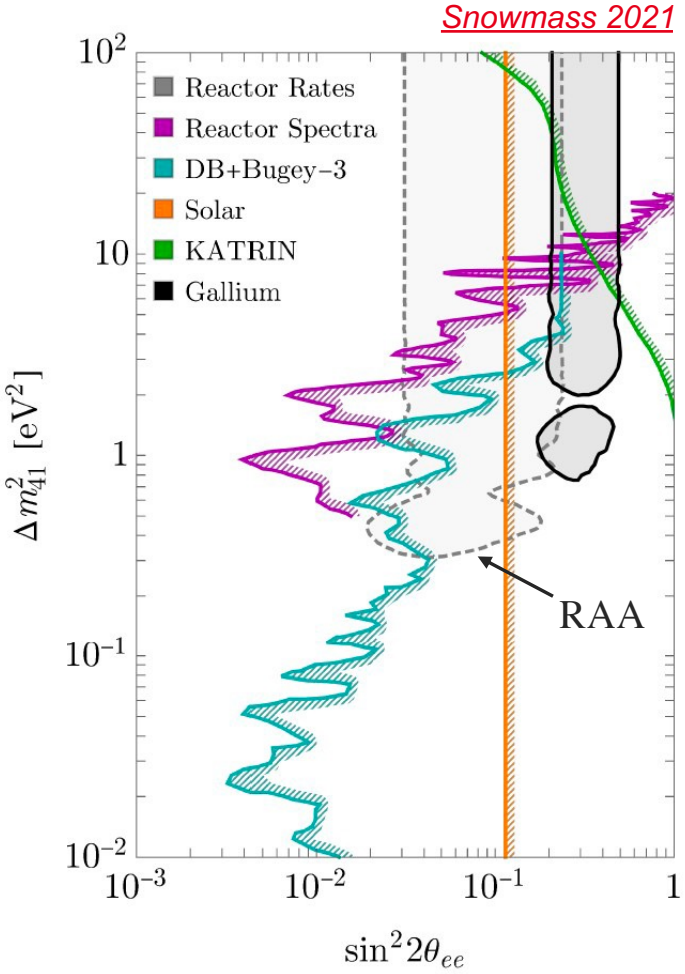


- Near detectors few 100 m from cores

→ Sensitivity in the 0.01-0.1 eV2 range, complementary to VSB.

Combined contours

Snowmass 2021

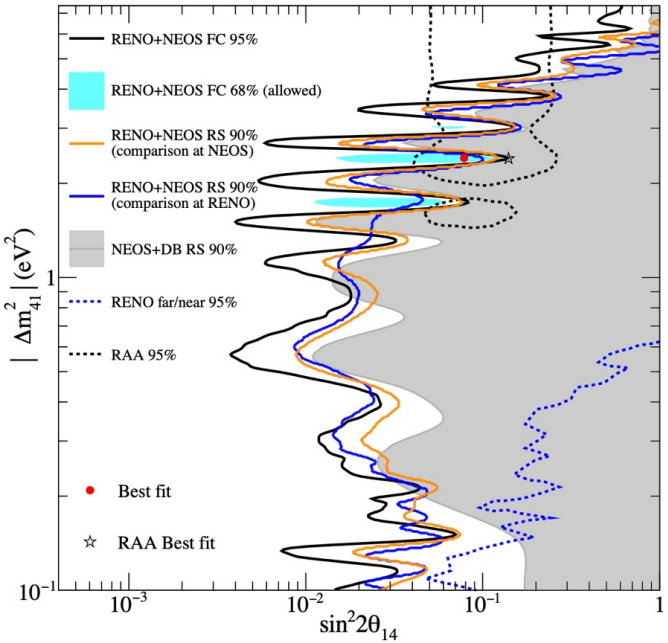


- %-level oscillations sensitivity!
- Rejection contours cover a large fraction of the RAA, missing Δm^2>5-10 eV2.
- Initial region of interest around 1 eV2 is rejected with high C.L.
- Strong tension with the latest gallium result from the BEST collaboration…

Positive Signals (?)

- Model independent analysis by combining **NEOS & RENO** detectors
- Covers a large range in Δm^2

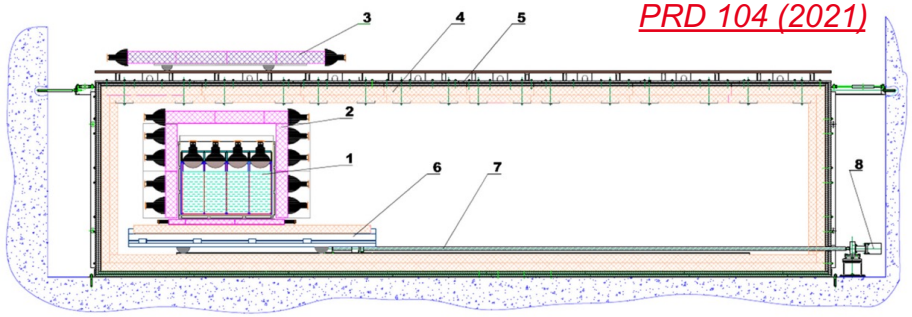
PRD 105 (2022)

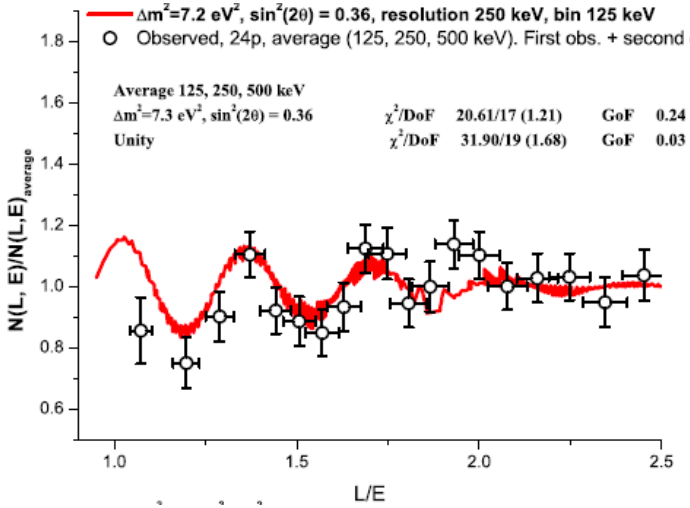


Low significance of the oscillation signal: 1.7 σ

NEUTRINO4

PRD 104 (2021)

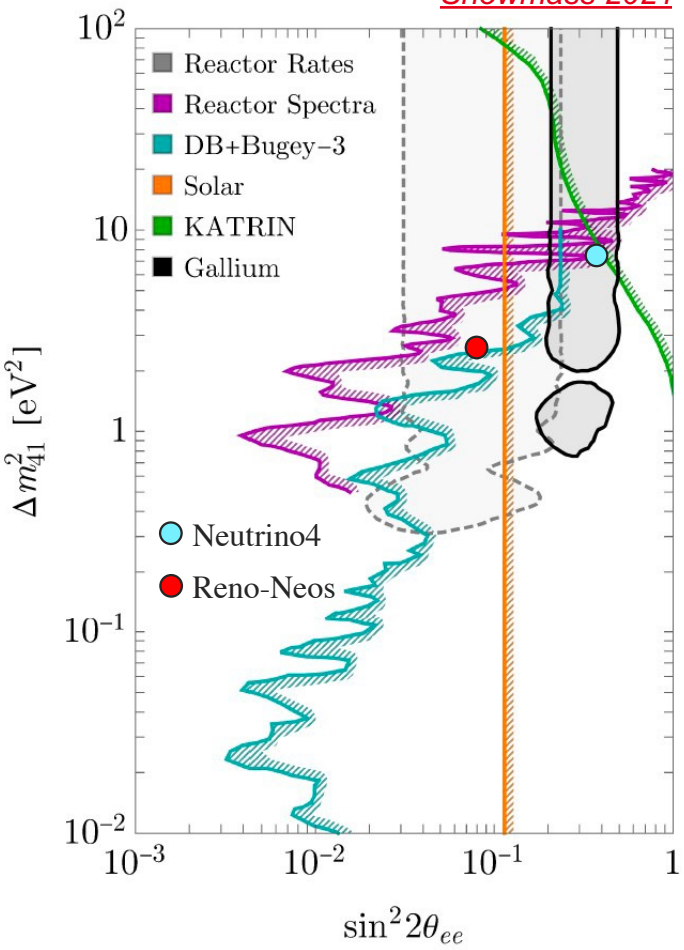




- Discussions on analysis and simulation
- 2.7σ significance of the oscillation signal with FC
- Upgrade with larger volume & PSD capability

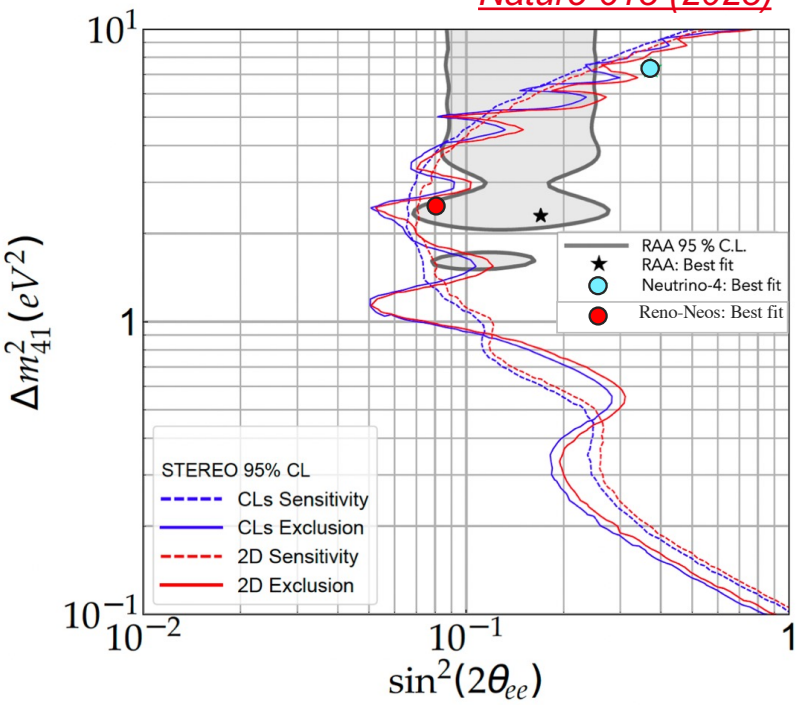
Combined contours

Snowmass 2021



STEREO

Nature 613 (2023)



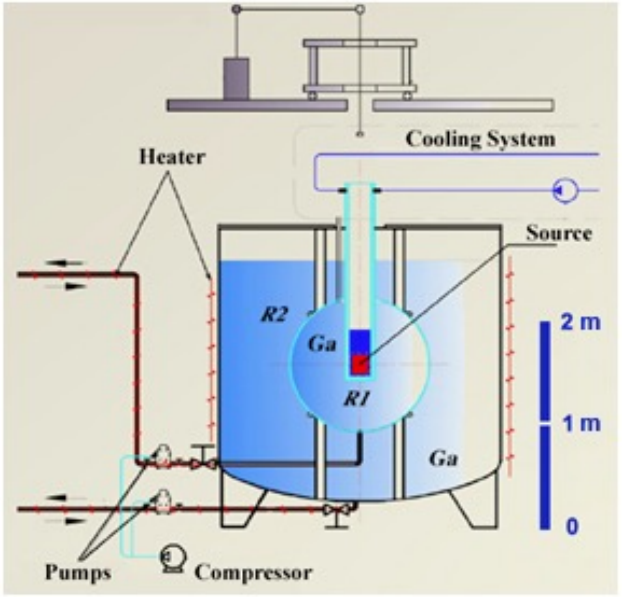
Significance of best fit points rejection:

- Neutrino4: 3.3σ
- Reno-Neos: 2.8σ

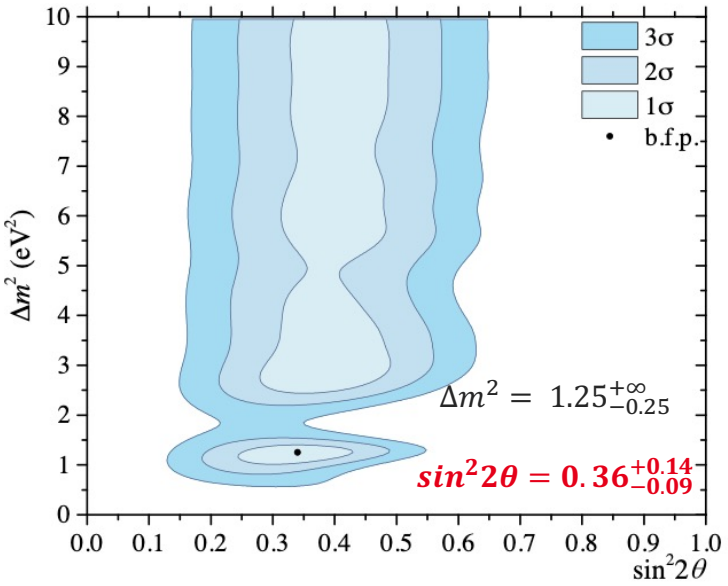
Positive Signals (?) – BEST Experiment

PRC 105 (2022)

3.4 MCi ^{51}Cr source in two concentric volumes of Gallium: ^{71}Ga(ν,e)^{71}Ge



BEST+GALLEX+SAGE contour



- 20% deficit confirming GALLEX and SAGE results with >5σ significance.
- Very large mixing angle.
- Rate only, no oscillation pattern → intensive search for possible normalization biases, so far unfruitful.

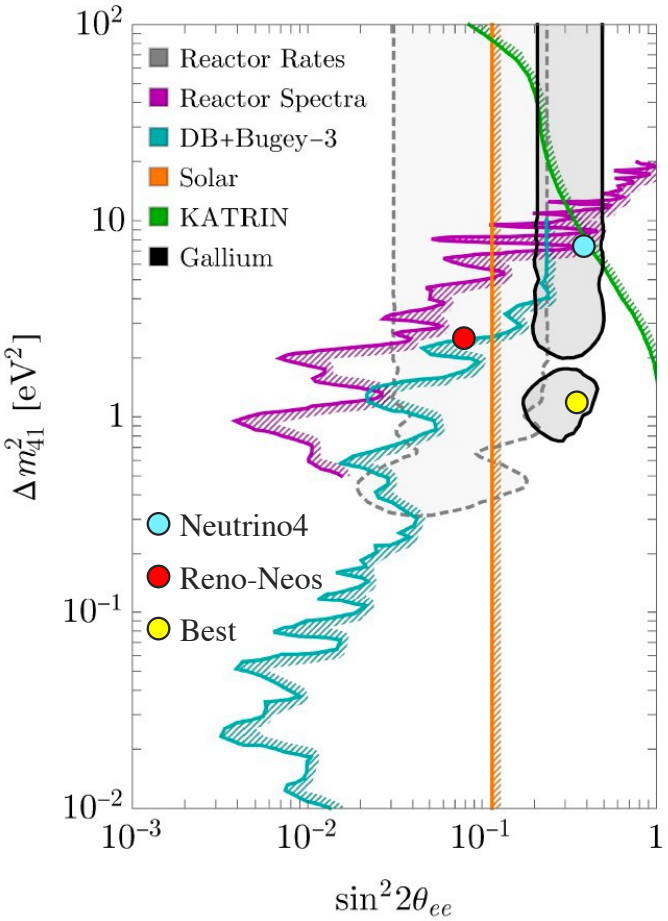
Ratio of observed/measured events:

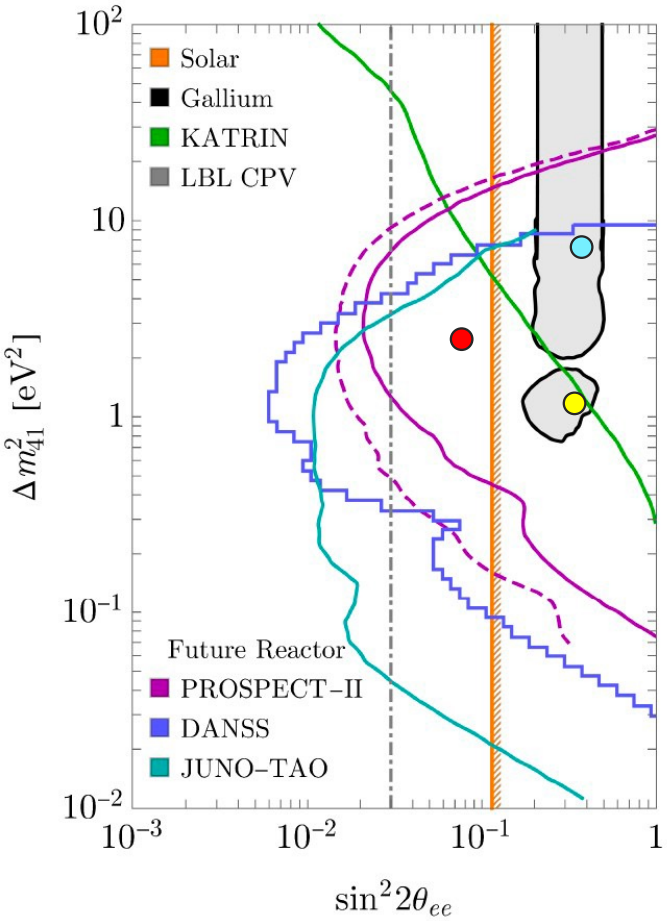
R_{in} = 0.79 ± 0.05
R_{out} = 0.77 ± 0.05

Anchoring of the ν-capture cross section on the ^{71}Ge decay:

W. Hampel, L.P. Remsberg PRC, 31 (1995)

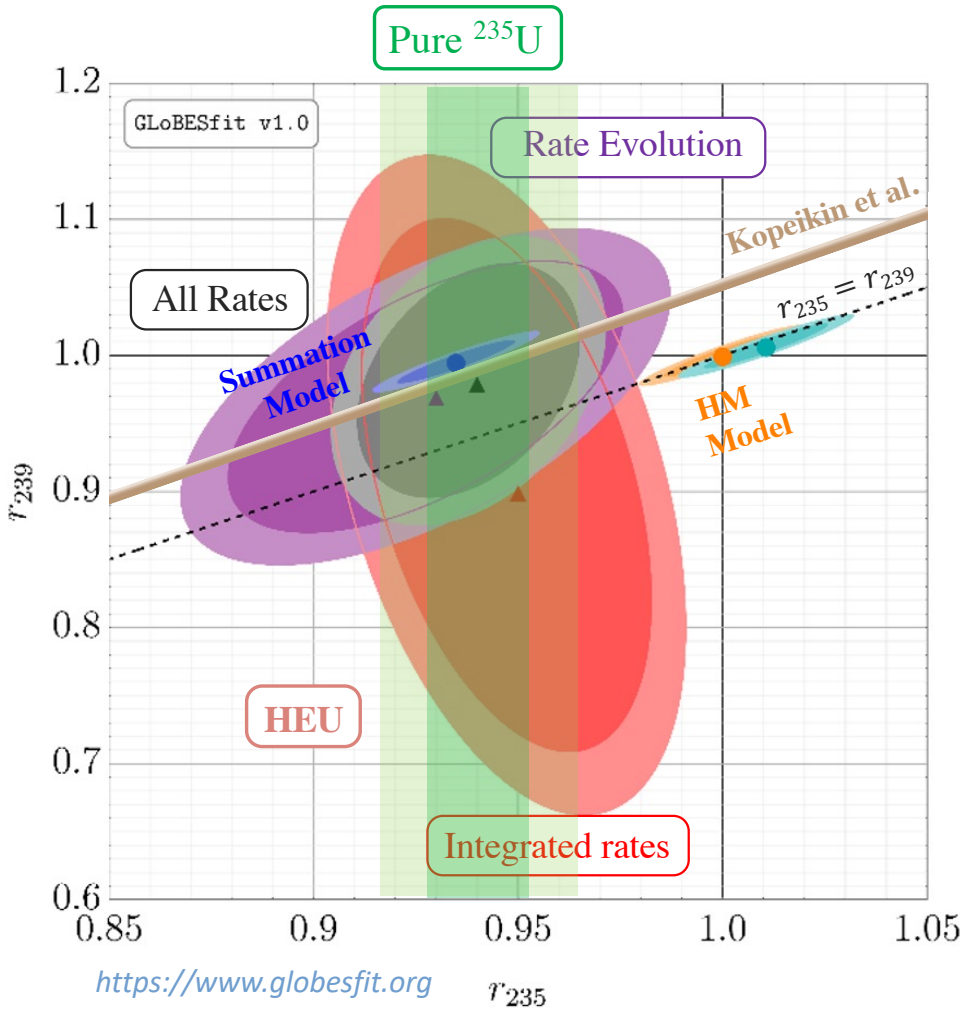
Combined Contours & Perspectives





- Global picture of reactor experiments: rejects the sterile neutrino hypothesis as explanation of the RAA.
- Complementary constraints from Katrin in the high mass range.
- 3σ tension with the Gallium result.
- Full coverage of the BEST and RAA contours by upcoming data from Katrin, Prospect-II, DANSS, JUNO-TAO, …

Origin of the RAA



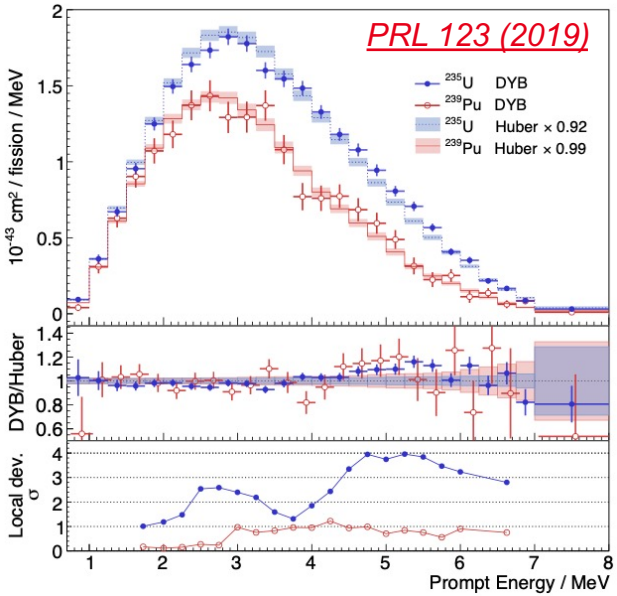
https://www.globesfit.org

- HEU, pure ^{235}U, measurements confirm the global picture of ^{235}U being mainly responsible for the Reactor Antineutrino Anomaly.
- Absolute normalizations of the ^{235}U and ^{239}Pu fission β-spectra, on which is anchored the HM model, were actually independent.
- The rate of e-conversion from ^{197}Au(n,e-)^{198}Au was initially used for both isotopes. Then another ^{235}U run was taken and considered as the reference, normalized with the ^{207}Pb(n, e$^-$)^{208}Pb process…

→ A bias in the ^{207}Pb(n, e$^-$)^{208}Pb cross section is the best candidate – to be proven by a new direct measurement(?)

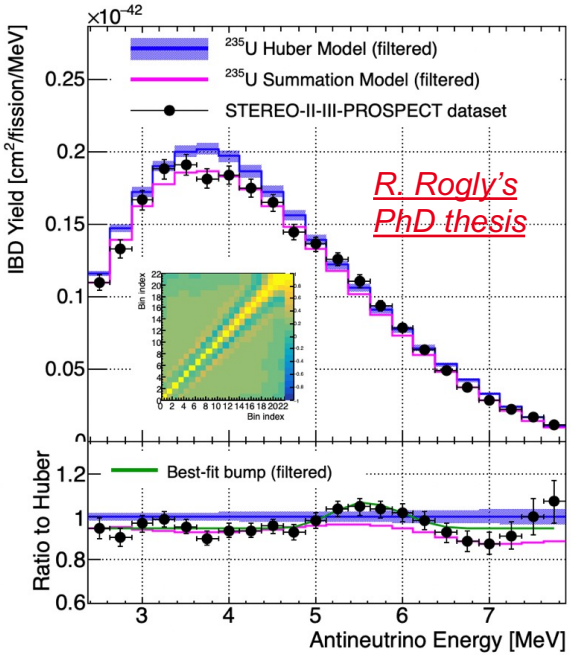
Reference Fission Spectra

- U-Pu separation using high stat and fuel evolution at commercial reactors (DB, Reno, Neos)

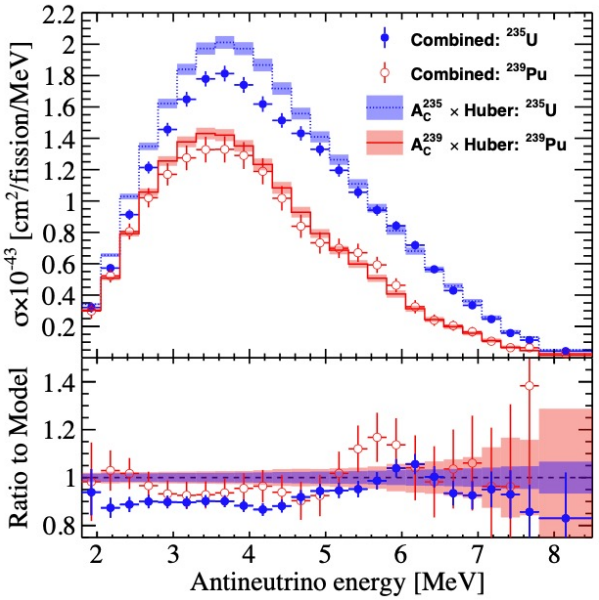


- Complementary pure ^{235}U spectra from research rectors

Updated Stereo-Prospect



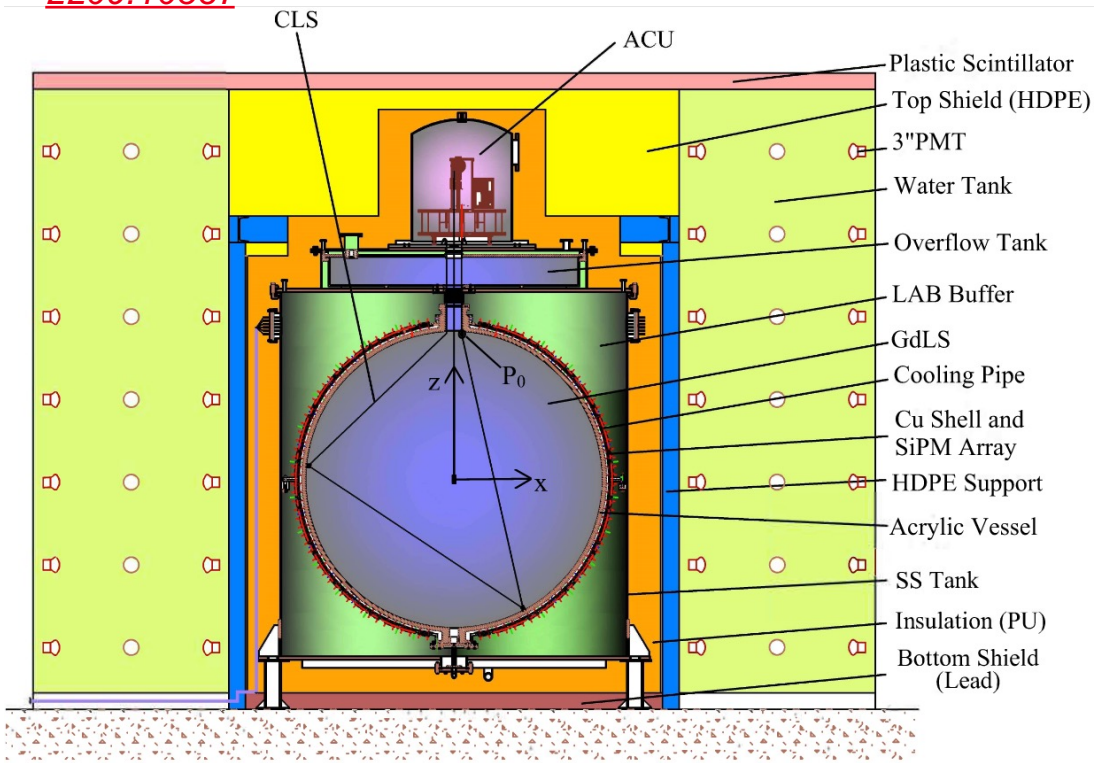
Prospect - DYB *PRL 128 (2022)*



- Spectra corrected for detection effects made available to the community
- Local distortion confirmed with high significance in all spectra – preferred scenario of a similar bump of ~11% amplitude in U and Pu spectra (arXiv:2212.10669)

JUNO-TAO

2209.10387



Ultimate accuracy expected from the Taishan Antineutrino Observatory (TAO):

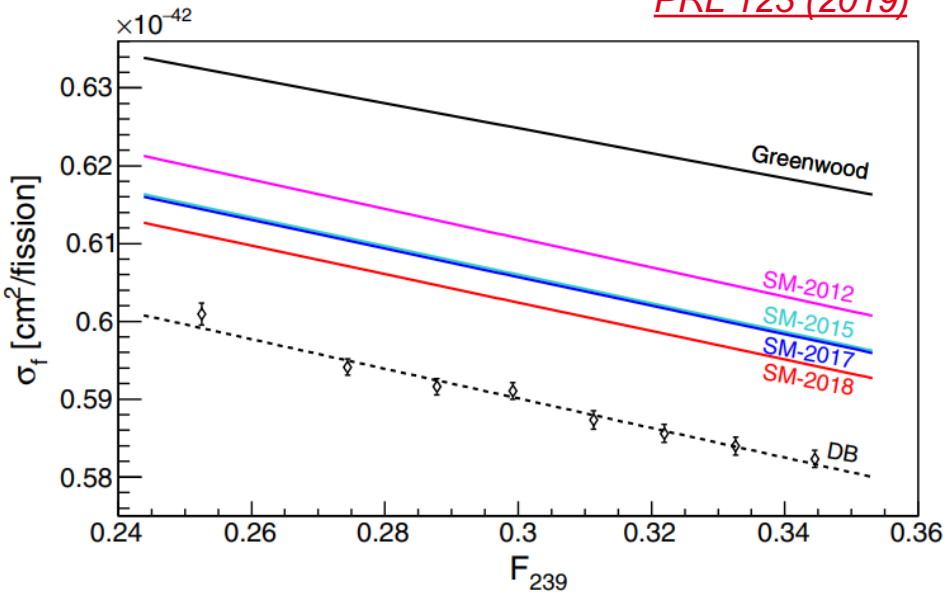
- 2.8 ton Gd-loaded LS detector at 30 m from the 4.6 GW_{th} core, JUNO very near detector
- High resolution: <2% @ 1MeV
- 4500 p.e./MeV obtained with full coverage of the targe volume by SiPMs operated at -50°C
- Data taking to start next year

Benchmark for nuclear data

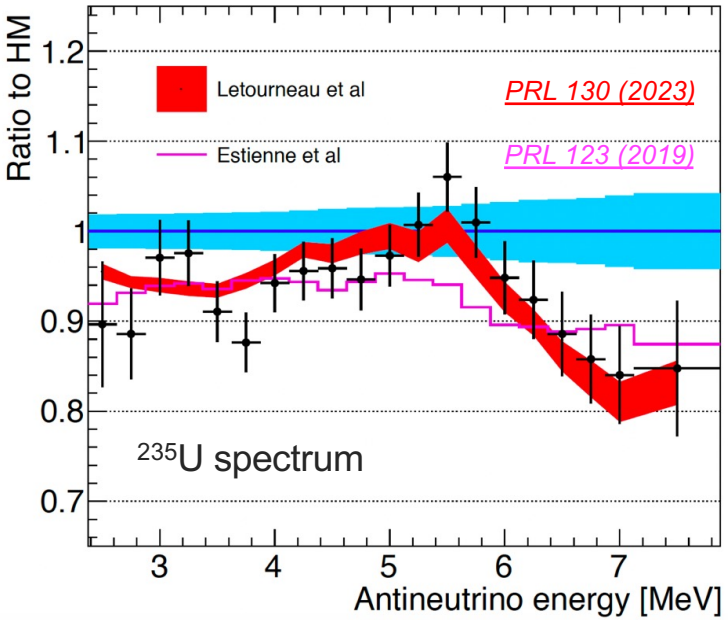
Shift of paradigm: model independent and accurate neutrino measurements constrains the nuclear data.

Steady improvement of the ab-initio predictions with the TAGS measurements

PRL 123 (2019)



Phenomenological model of GT decay-strength applied to all fission products

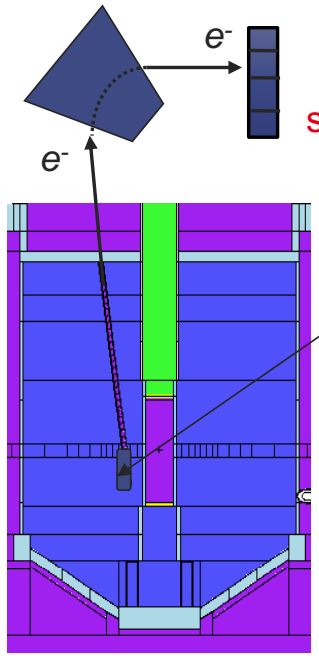


Hints of a dominant role of the correction of the Pandemonium effect in β^- spectra

Another candidate is the impact of shape factors of forbidden transitions

Origin of the 5 MeV Bump (?)

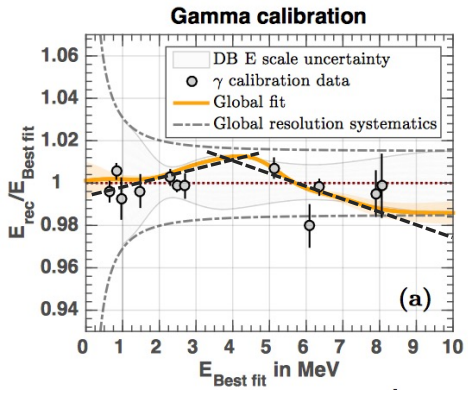
A similar bump in the β-spectra would naturally propagate in the converted neutrino spectra



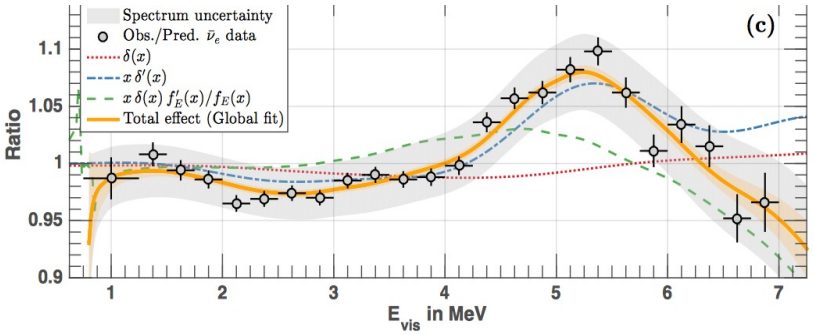
BILL: High resolution spectrometer

Target foil (^{235}U, ^{239}Pu, ^{241}Pu) in thermal n flux

ILL research reactor (Grenoble, France)



Phys. Lett. B773 (2017)

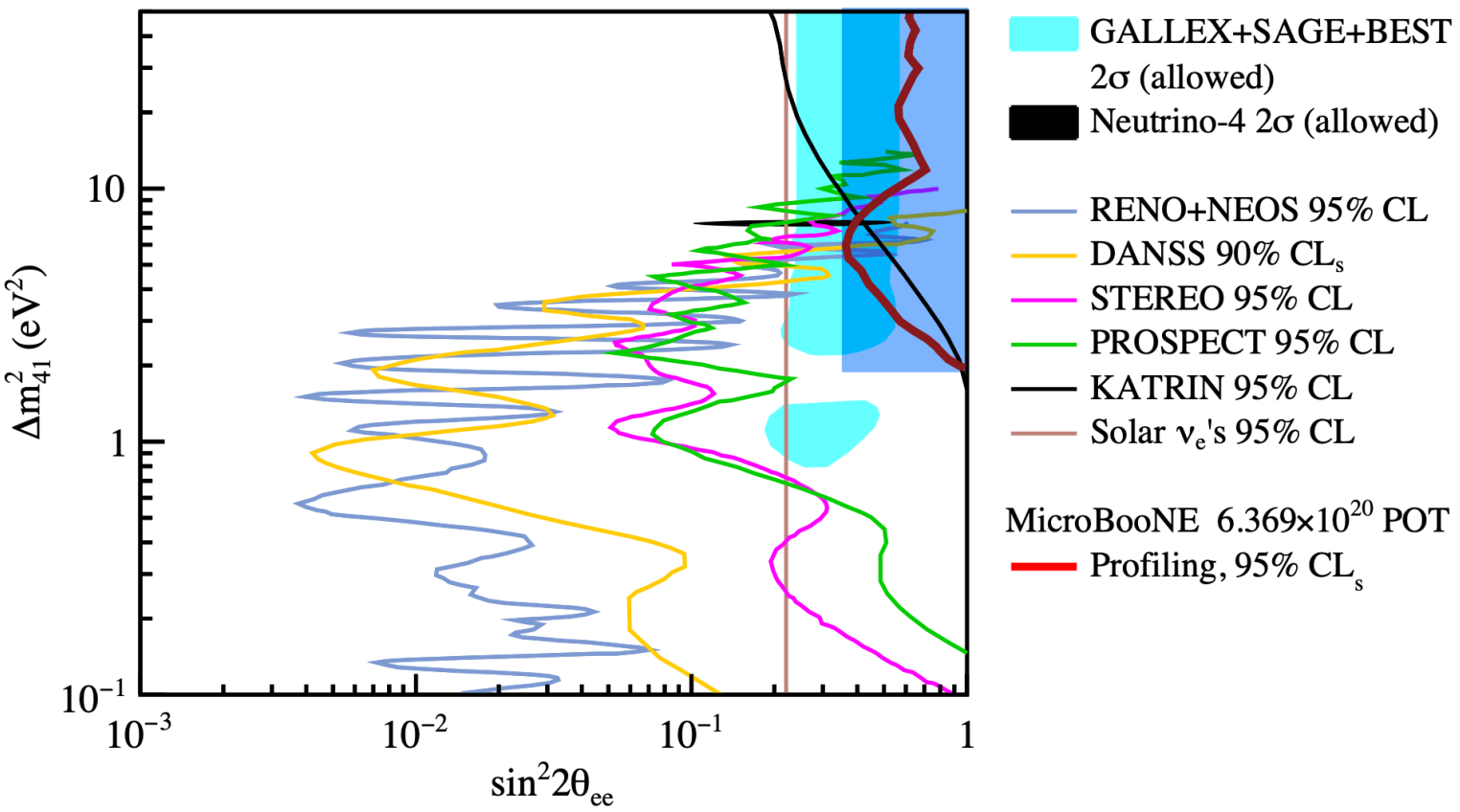


- A slight kink in the energy scale can induce the observed shape distortion
- Such bias in the E scale of all neutrino experiments has ruled out by the many complementary measurements.
- Could we have a similar effect in the control of the amplitude of the magnetic field used to analyze the β fission spectra? Magnet power supply, range of Hall probe, ….

Conclusion

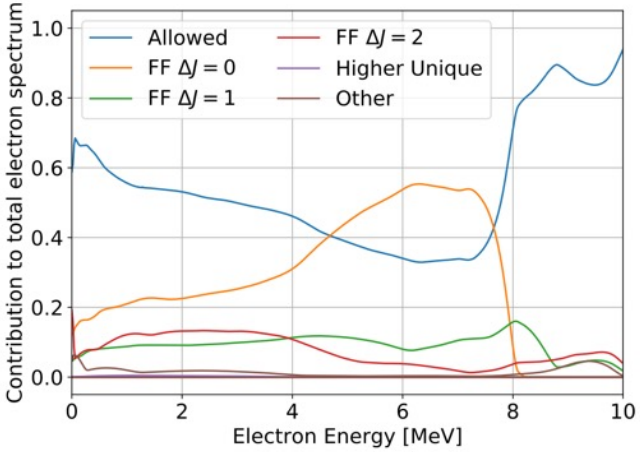
- High precision experiments at reactors. Coherent measurements of neutrino fluxes confirming the deficit of the RAA.
- No oscillation to sterile neutrino observed with high significance. The Sterile neutrinos hypothesis is unlikely to explain the RAA.
- Combination of all reactor measurements with Katrin covers most of the RAA contour with high C.L. Full coverage of the large Δm^2 range expected with the upcoming data from Danss, Neutrino4, Prospect-II, Katrin,...
- Reference fission neutrino spectra, corrected for detection effects are provided. Benchmark for future neutrino experiment and for nuclear data. Increased accuracy expected from the TAO detector.

Contours


10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
Δm^2_{41} (eV^2)
$\sin^2 2\theta_{ee}$
GALLEX+SAGE+BEST 2σ (allowed)
Neutrino-4 2σ (allowed)
RENO+NEOS 95% CL
DANSS 90% CL$_s$
STEREO 95% CL
PROSPECT 95% CL
KATRIN 95% CL
Solar ν_e's 95% CL
MicroBooNE 6.369×10^{20} POT
Profiling, 95% CL$_s$

Forbidden transitions

Dominant contribution of forbidden β-decays above ~4 MeV



- Shell-model calculation of the shape of forbidden β-decays, included in the conversion method.
- Combination of this correction with the correction of the pandemonium effect could reach a good agreement with the experimental neutrino spectrum shapes.

L. Hayen et al. arXiv:1908.08302