Accurate neutrino measurements at short distances from reactors

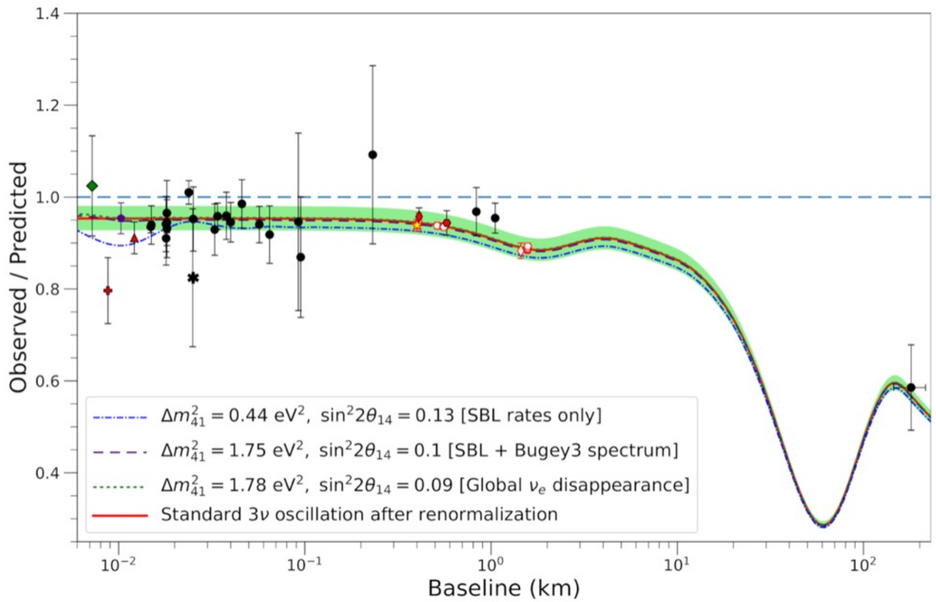
David Lhuillier

cea irfu

Neutrino 2024, Milano

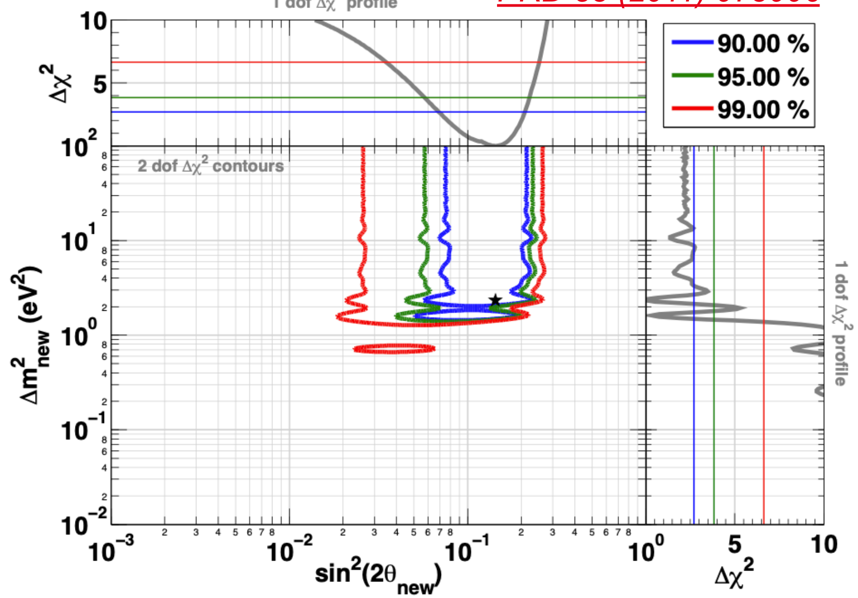
RAA : Reactor Antineutrino Anomaly

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



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

PRD 83 (2011) 073006

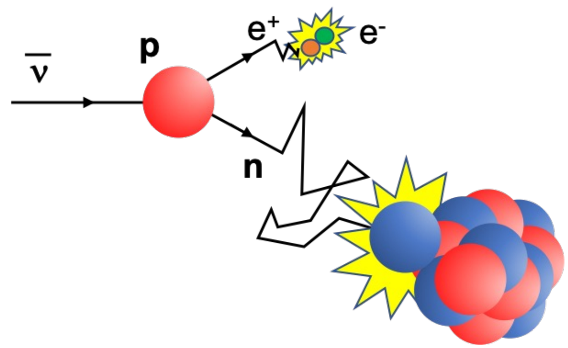


- **Need complementary data to disentangle sterile neutrino and prediction bias hypotheses**
- **Search for unambiguous oscillation signal with few meters wavelength**

Experimental challenges

- **Close to surface** – very exposed to cosmic rays
  - Shielding and/or discrimination against fast & multi neutrons
  - Lower S/B implies reactor OFF measurements and accurate control of the detector response over time
- **Small target volume**
  - Statistically limited
  - Control of edge effects
- **Model independent oscillation analysis**
  - Suppress sensitivity to any reactor spectrum prediction
  - Relative measurement between several detector cells and/or positions
- **Provide new fission neutrino spectra for a complete study of the RAA**
  - Norm and shape, U-Pu separation
  - → Feedback on nuclear data

Inverse Beta Decay



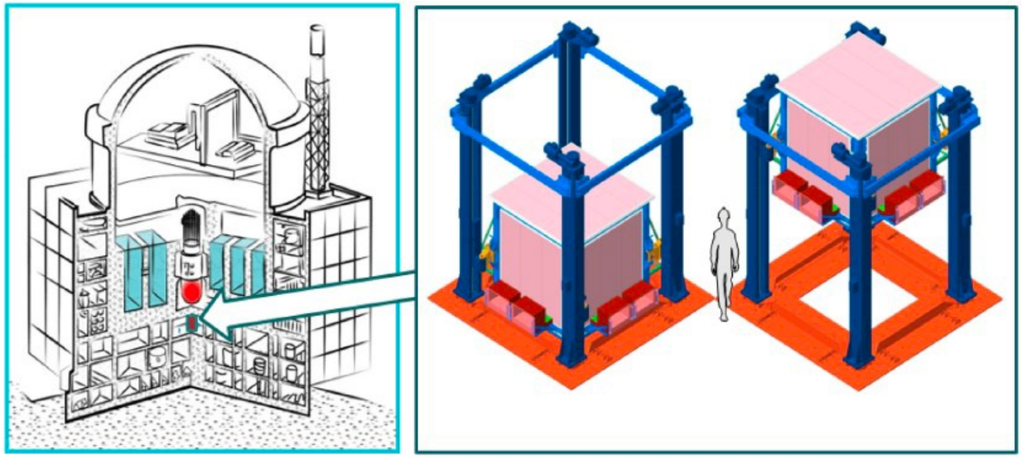
Worldwide Very Short Baseline Experiments

- Commercial reactors
  - High stat
  - Extended core
  - Mixed ^{235}U - ^{239}Pu

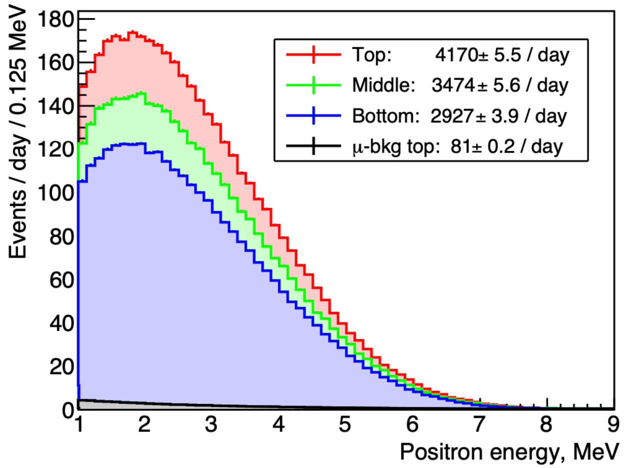
- Research reactors
  - Low stat
  - Compact core
  - Pure ^{235}U

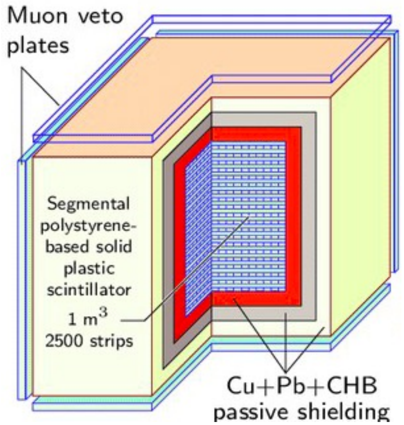
DANSS

Kalininskaya NPP - Russia

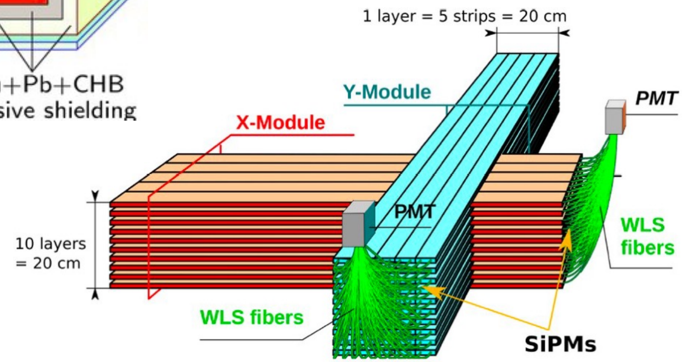


- 3 GW_{th} extended core
- 8 M detected $\overline{\nu}_e$
- ~2% background only !
- Movable detector (10-12 m baseline)





- Highly segmented



Detector upgrade with

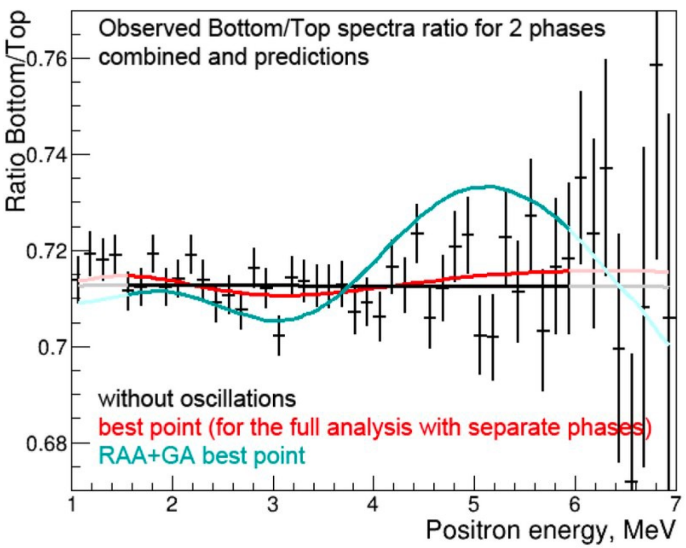
- Improved E resolution 33→12%/$\sqrt{E}$
- Larger target volume

See M. Danilov's talk on Friday

DANSS

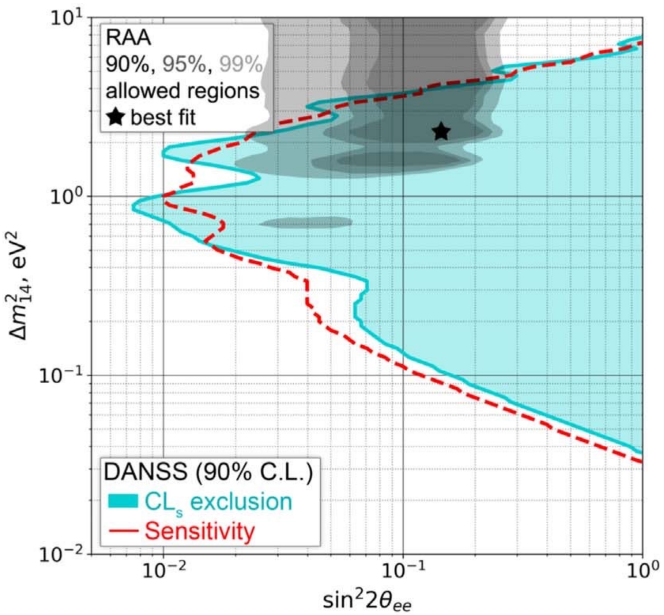
[hep-ex] 2211.01208

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

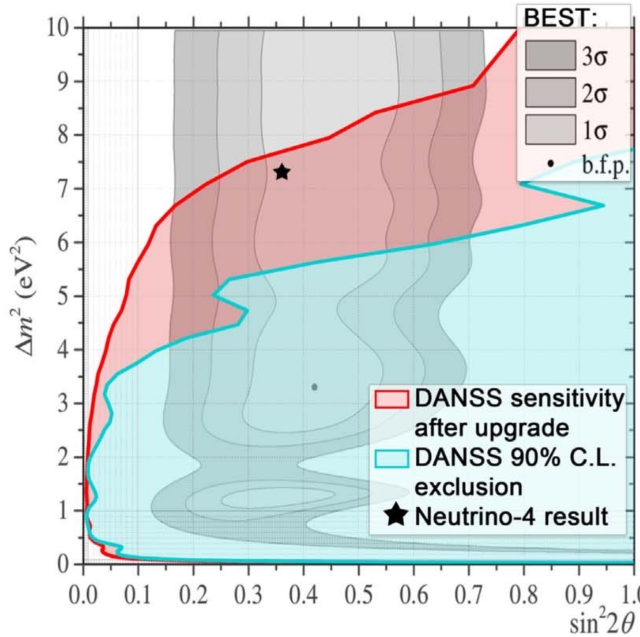


- No oscillation signal
- Best fit point of the initial RAA+Gallium anomaly rejected at >5 σ

N. Skrobova: Poster#234



- Significant gain in sensitivity at higher Δm2 after detector upgrade
- Test of Neutrino-4 best fit



Worldwide Very Short Baseline Experiments

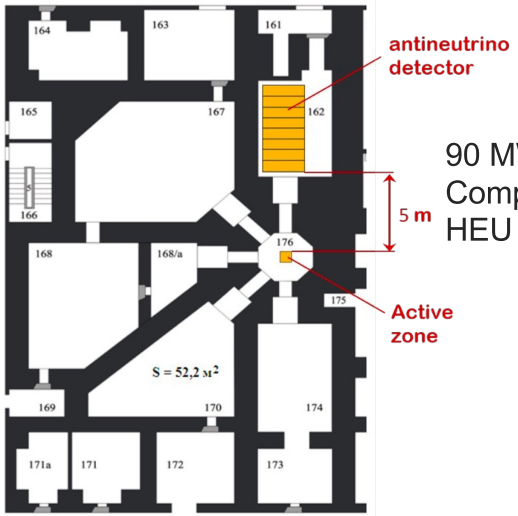
Commercial reactors
- High stat
- Extended core
- Mixed ^{235}U - ^{239}Pu

Research reactors
- Low stat
- Compact core
- Pure ^{235}U

Neutrino 4

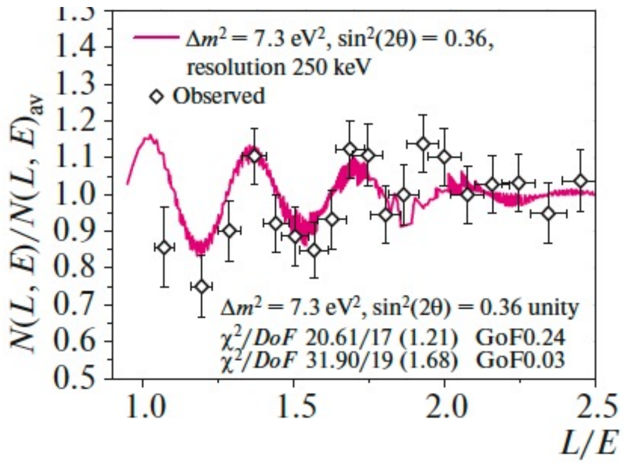
[JETP 137 (2023) 1, 55-70](#)

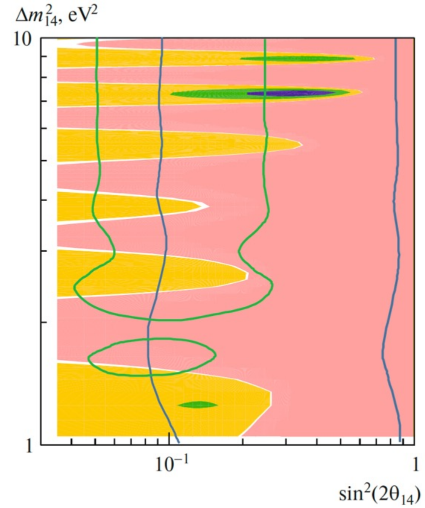
Reactor SM-3 Dimitrovgrad, Russia



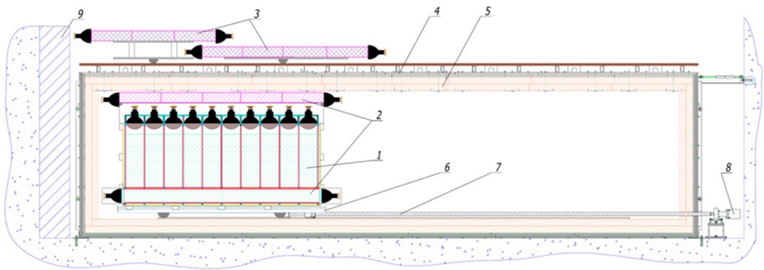
90 MW
Compact core
HEU ^{235}U fuel

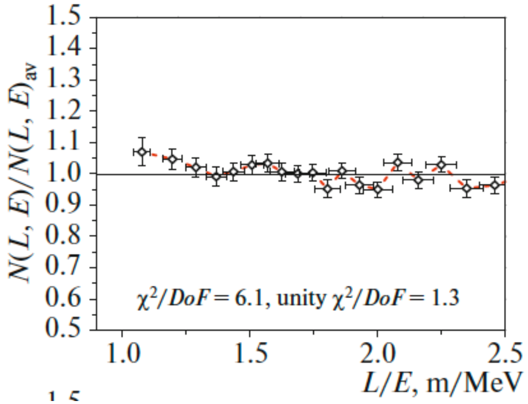
Positive oscillation signal with 2.7σ significance (FC)
Best fit parameters: $\sin^2(2\theta_{14}) \approx 0.36$, $\Delta m_{14} \approx 7.3$ eV





Movable segmented detector filled with Gd-loaded LS
L ≈ 6.4 – 11.9m with 23 cm steps (24 positions)

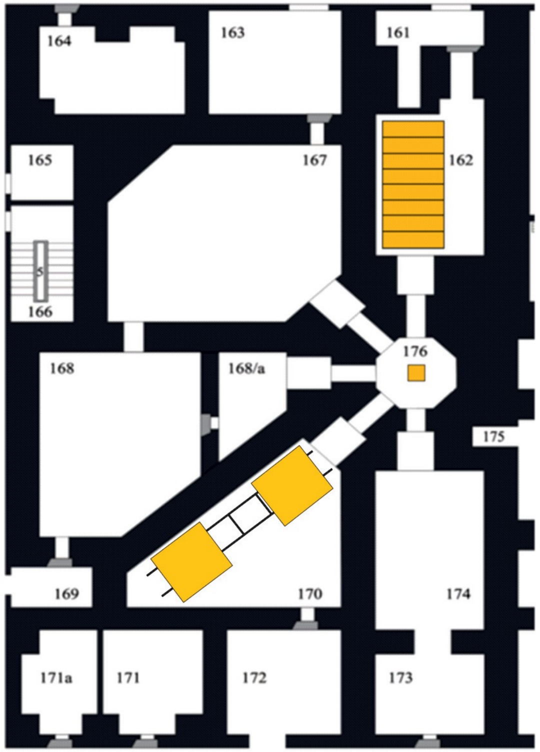




No PSD
S/B = 0.54

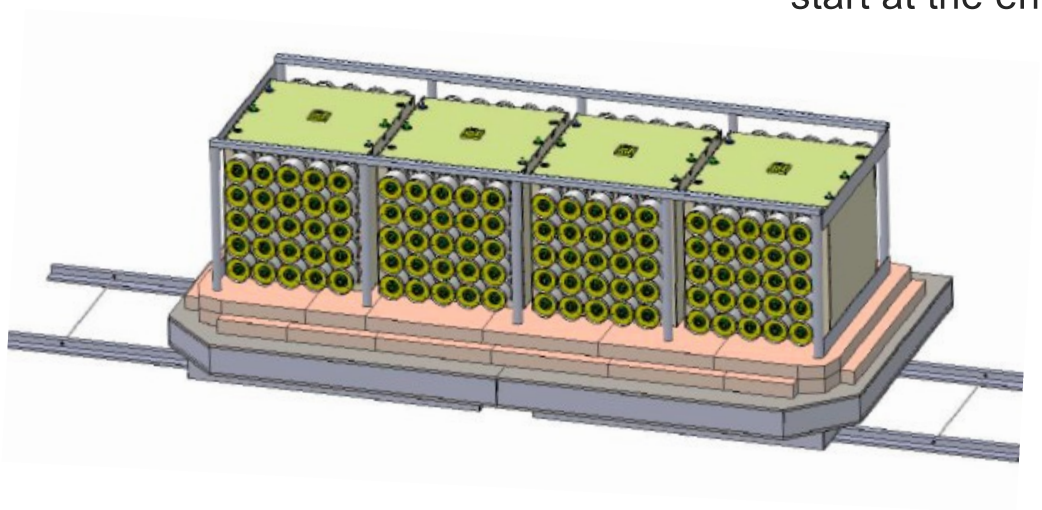
Neutrino 4+

Tech. Phys. 60 (2015) 12, 1863-1871

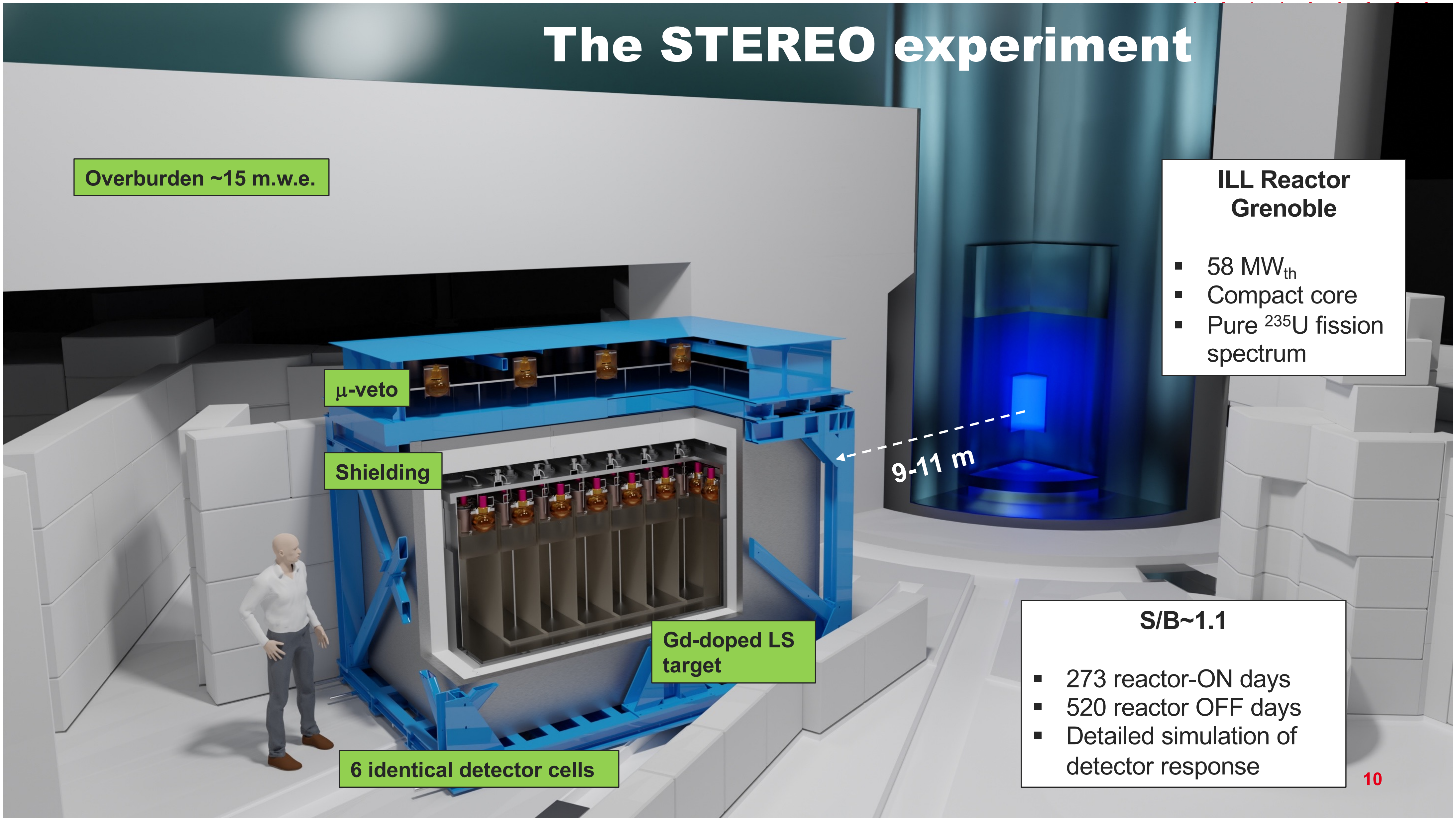


Major detector upgrade with
- Larger volume
- Improved background rejection from active and passive shielding and PSD capability
- Improved resolution from 2-sided readout of detector cells

Data collection is expected to start at the end of this year

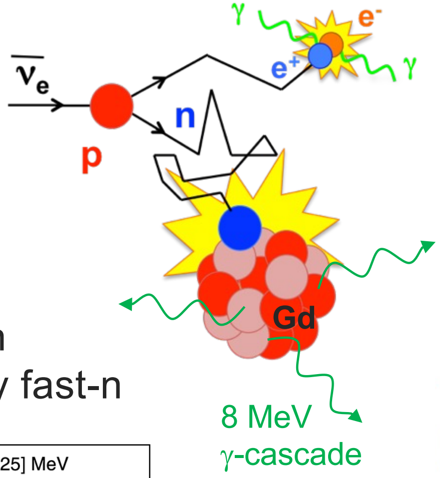


The STEREO experiment



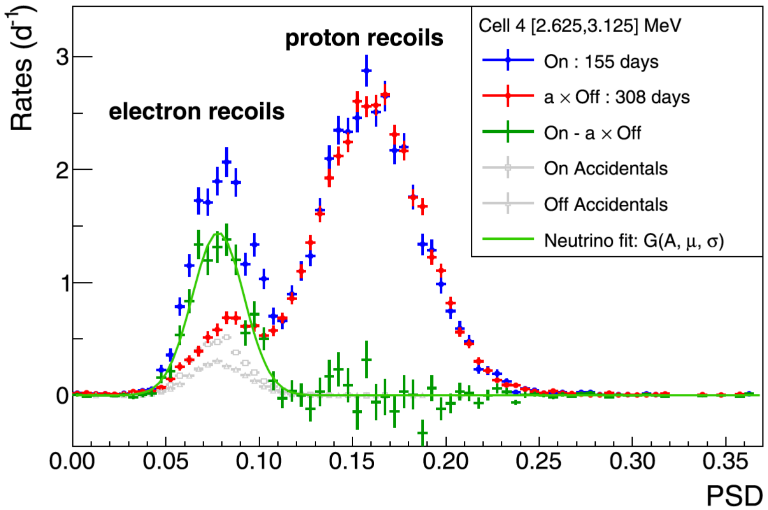
The good old Gd way

- Mature LS technology from the θ_{13} experiments

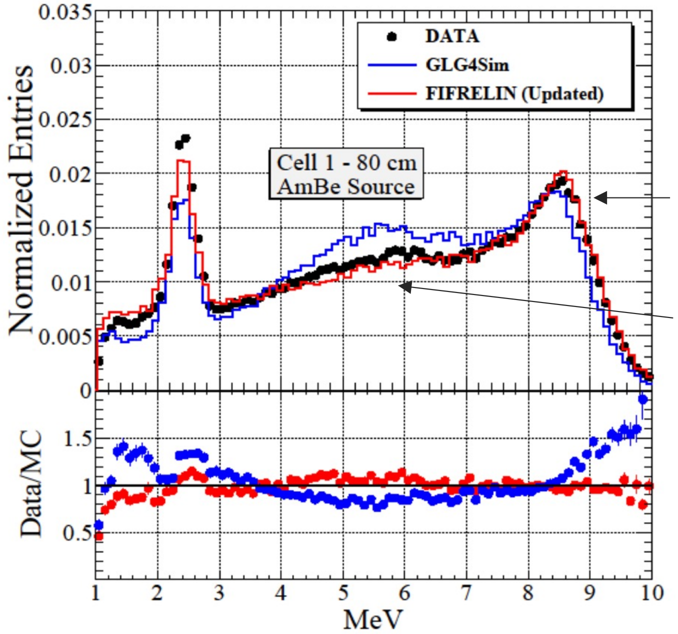


- Unprecedented description of Gd γ-cascades
  - FIFRELIN simulations available on zenodo
  - % level control of the detector response

- PSD capability to reject proton recoils background induced by fast-n



EPJA 59 (2023) 4, 75

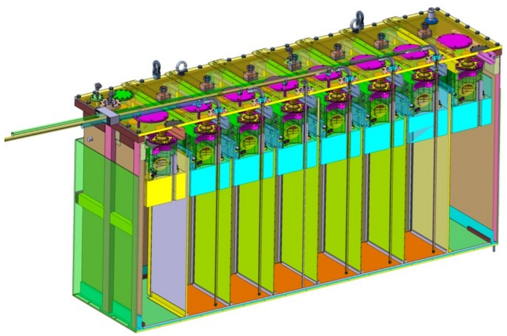


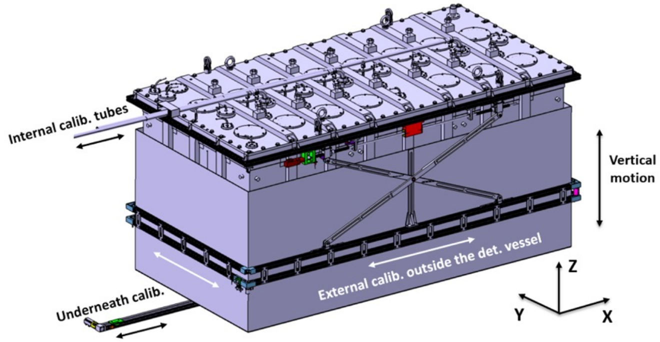
Gd full energy peak

Large leakage of the γ-cascade in the corner of the detector

STEREO – detector response

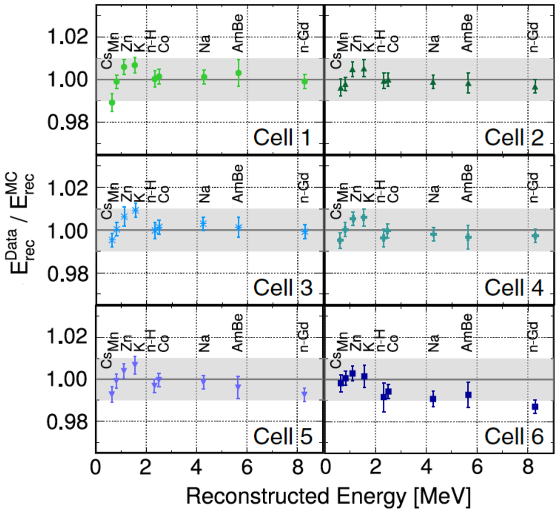
- Fine tuned MC through weekly calibrations



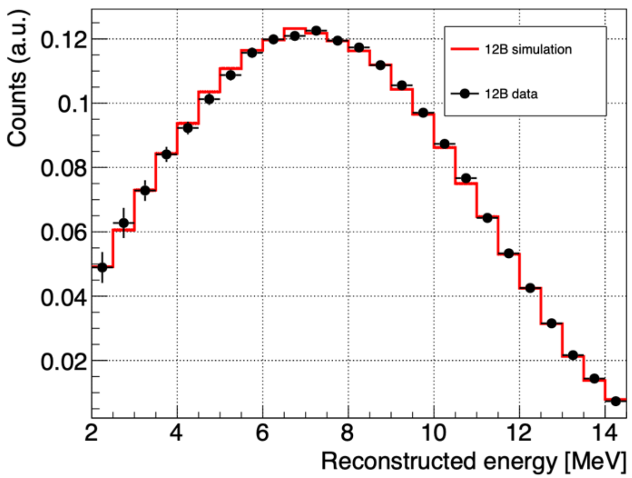


- % level description of energy reconstruction and neutron detection efficiency

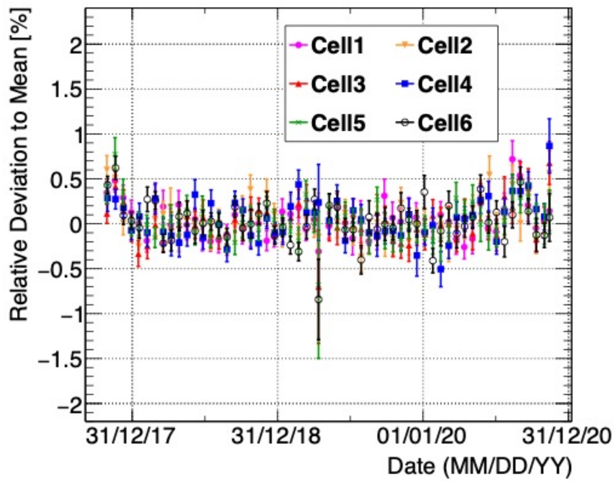
Data/MC calibration residuals



^{12}B β-decay spectrum



Stability of the 2.2 MeV n-H peak

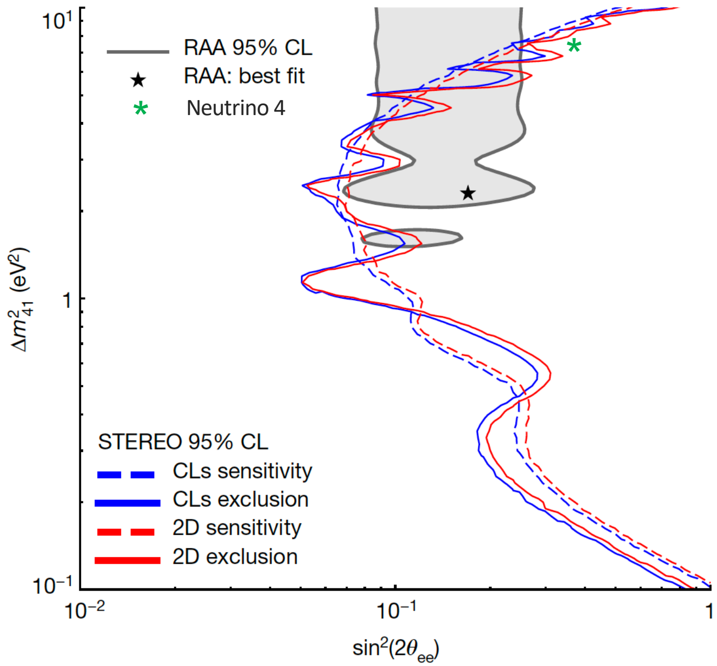


STEREO - results

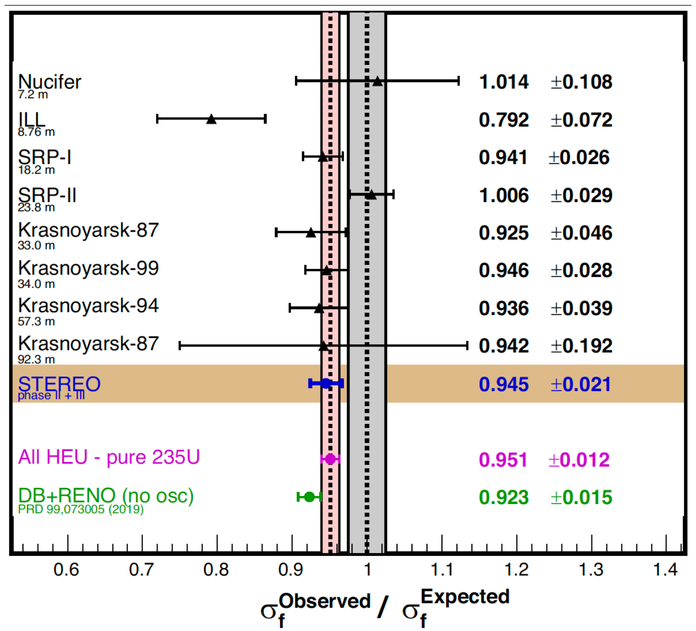
Nature 613 (2023) 7943, 257-261

- Data compatible with no-oscillation
- RAA best fit is rejected at >4 σ level, Neutrino-4 at 3.3 σ
- Model-independent analysis: a free average spectrum "ϕ_i" is fitted to the 6 detection cells

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

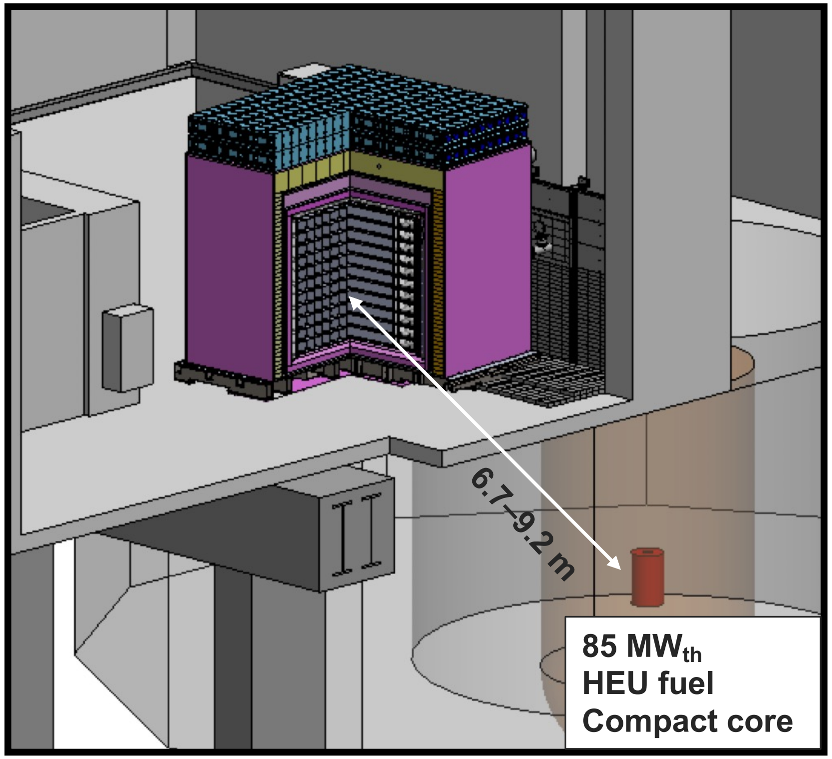


- Best absolute normalization among pure ^{235}U measurements
- The ^{235}U deficit alone can explain the RAA

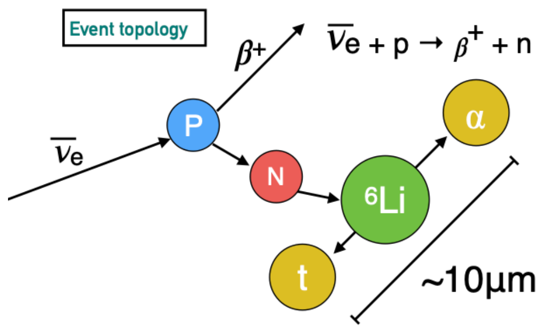


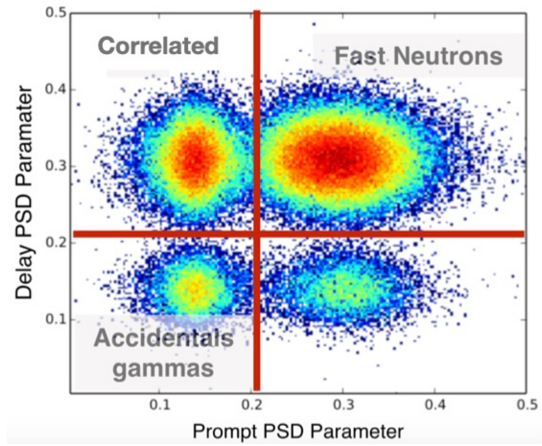
PROSPECT – the Lithium way

High Flux Isotope Reactor – Oak Ridge



4-ton ^{6}Li-doped segmented liquid scintillator detector

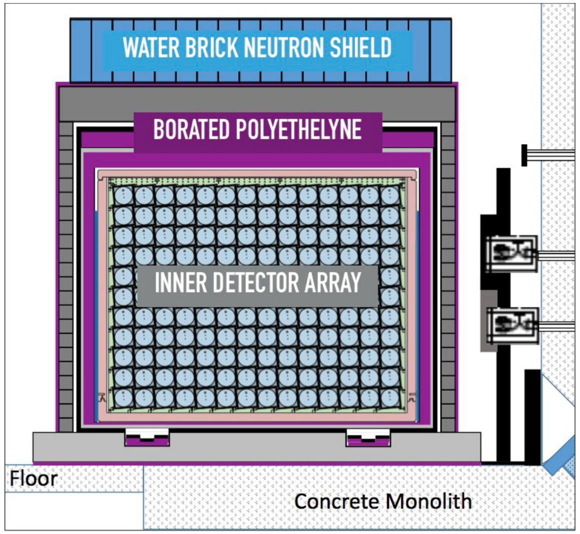




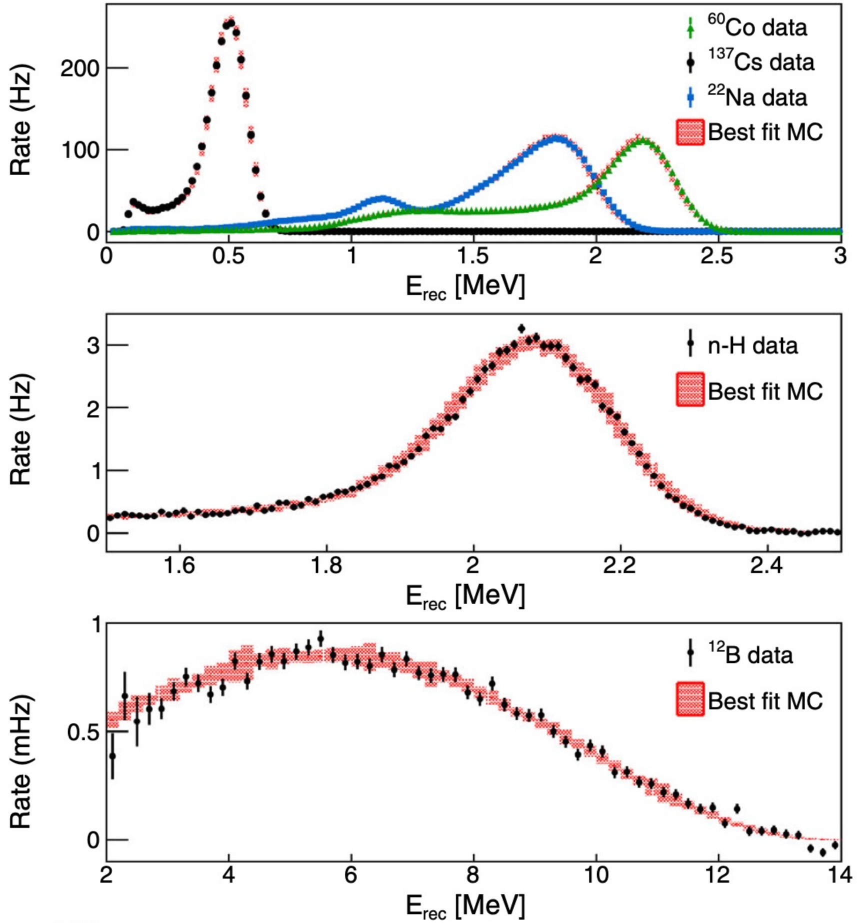
Breakthrough in background rejection by combining high PSD capability in prompt & delayed signals

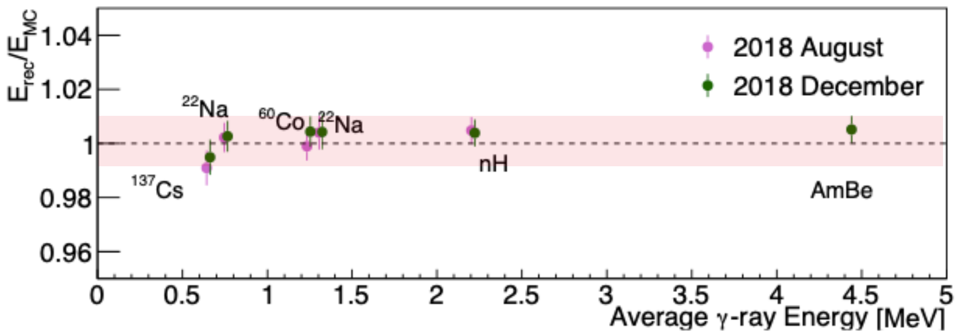
PROSPECT

PRD 103 (2021) 3, 032001



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





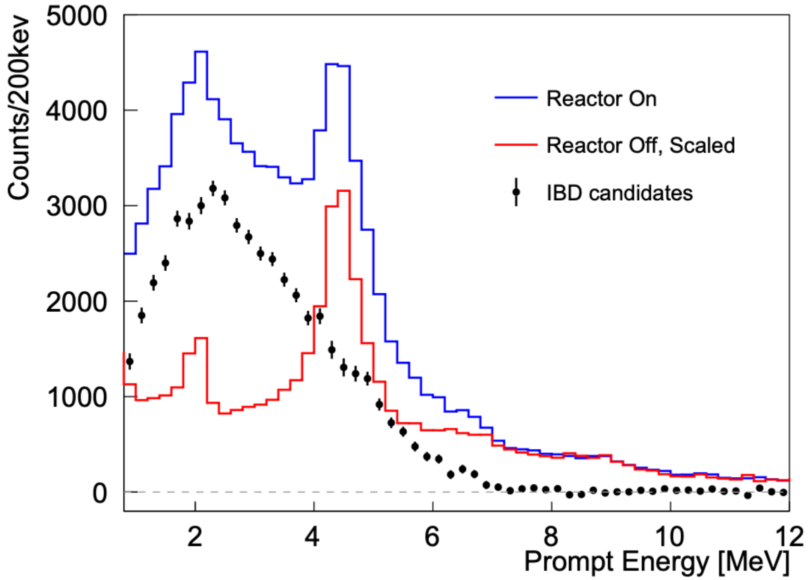
PROPECT - IBD selection

[C. Roca: Poster #470]

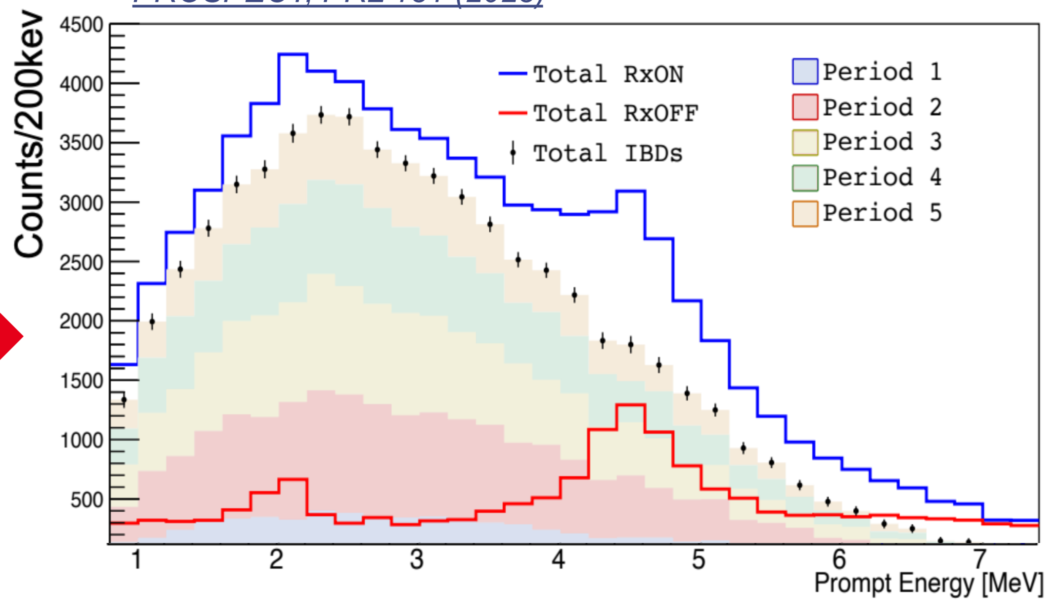
Improved IBD selection in light of gradual PMT failures (62 of 398 PMTs)

- 5 periods: 1 reactor cycle per period.
- Used segments with 1 functioning PMT to veto cosmic neutron backgrounds
- **Ratio of signal to cosmic background increases from 1.4 to 3.9, and IBD counts increase by 20%. Total statistical power is more than doubled.**

PROSPECT, PRD 103 (2021)



PROSPECT, PRL 131 (2023)

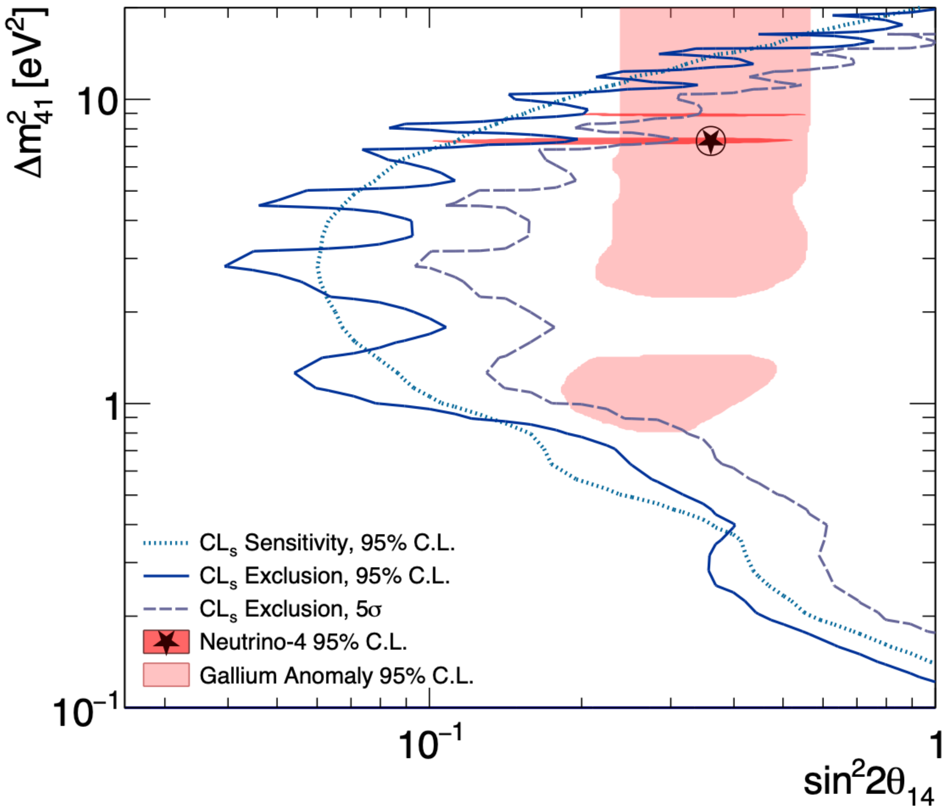


PROSPECT – Oscillation analysis

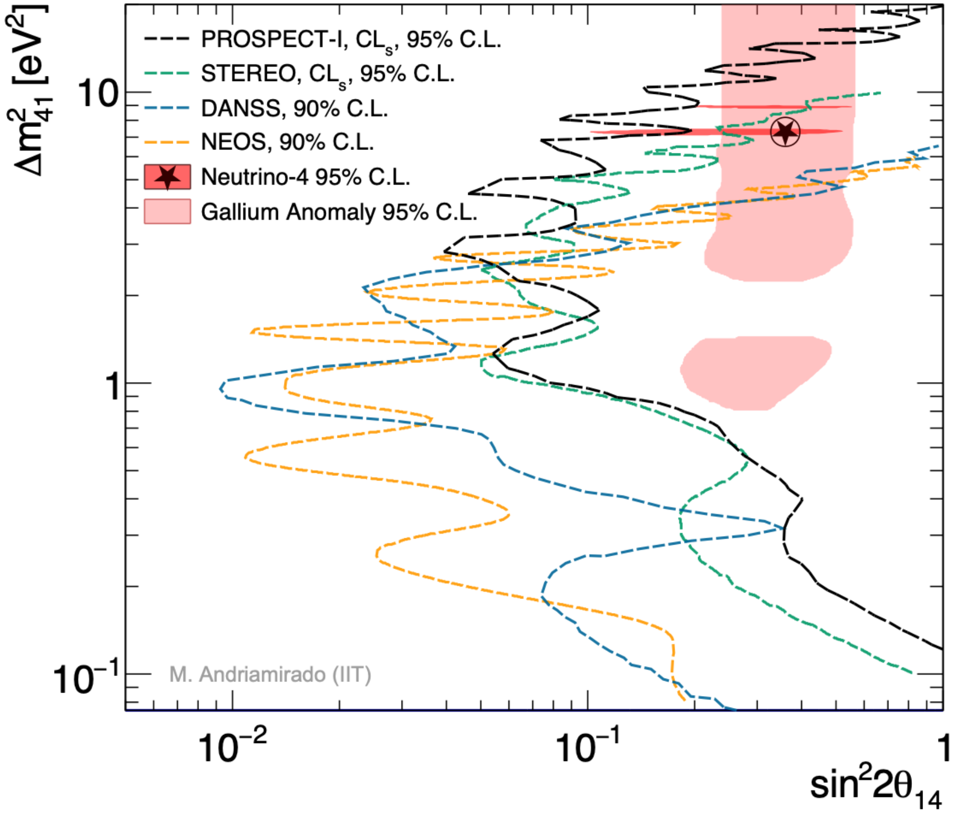
D. Venegas-Vargas: Poster #383

➢ New world-leading limits on sterile neutrino oscillations

- Data are compatible with the null-oscillation prediction
- Excludes space below 10 eV^2 suggested by BEST at >95% CL
- Neutrino-4 best-fit is ruled out at >5σ CL



Short Baselines - Global Context



- Success of the short baseline experimental program.
- Strong limits set on θ_{14} from complementary measurements. The sterile neutrino hypothesis is rejected over most of the RAA phase space.
- Strong tension with the BEST contour. See D. Gorbunov's talk on Friday.

→ Joint analysis of reactor data is of great interest.

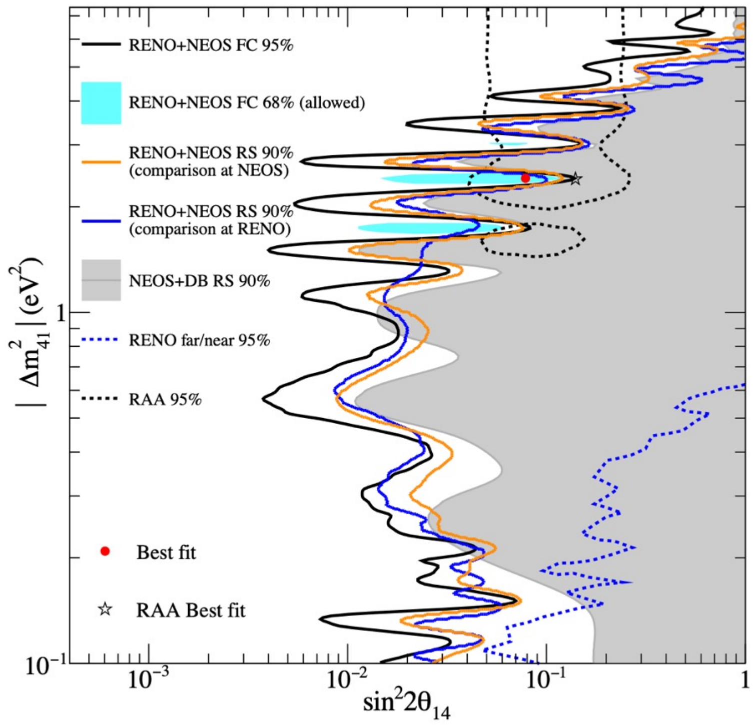
Joint analyses - Oscillation

A combination of complementary datasets offers new benefits for sterile oscillation searches:

- ➢ Increased statistical power
- ➢ Accurate treatment of all experimental effects using the detector response matrices and the covariance matrices of uncertainties.
- ➢ Additional sterile sensitivity unlocked by comparison of long (comercial reactors) and short (research reactors) baseline energy spectra

RENO-NEOS joint analysis

PRD 105, L111101 (2022)



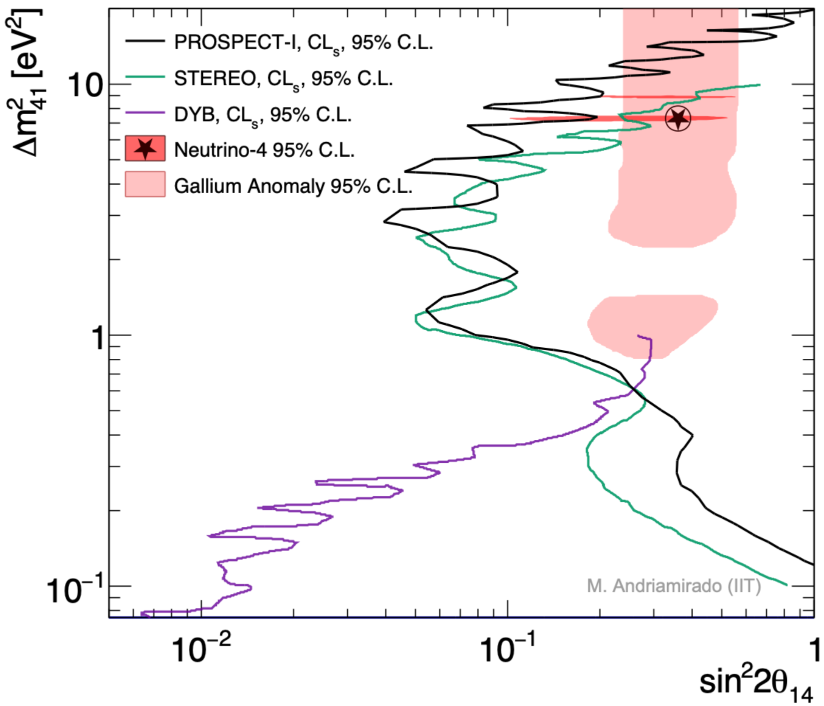
Joint analyses - Oscillation

A combination of complementary datasets offers new benefits for sterile oscillation searches:

- Increased statistical power
- Accurate treatment of all experimental effects using the detector response matrices and the covariance matrices of uncertainties.
- Additional sterile sensitivity unlocked by comparison of long (commercial reactors) and short (research reactors) baseline energy spectra

The combination of all data provides neutrino fission spectra with unprecedented accuracy, challenging the predictions and associated nuclear data.

Joint analysis started late 2023 between DayaBay, Prospect and Stereo

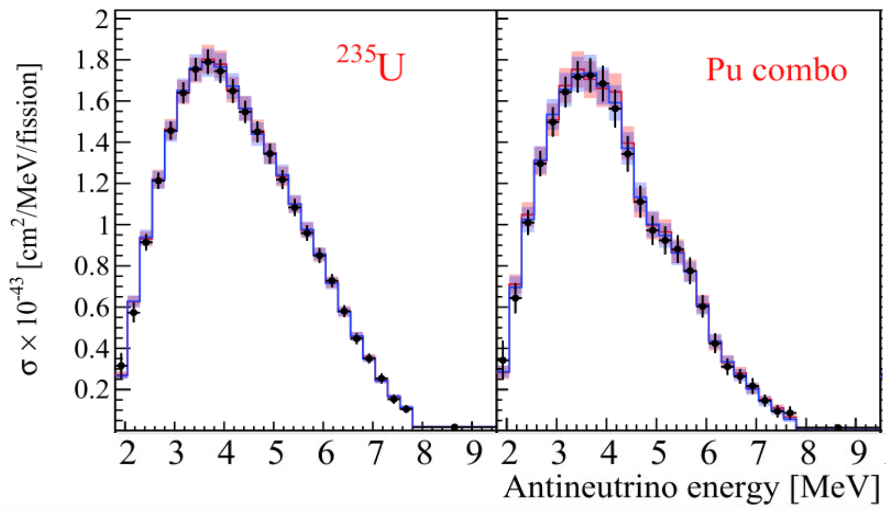


Reference fission spectra

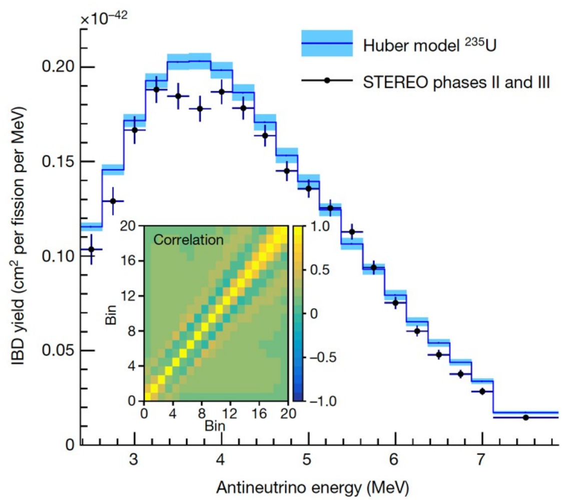
- Commercial reactors: Millions of detected ν's
  + simulation of the fuel evolution
  →U-Pu separation

- Research reactors: Highly Enriched Fuel
  → Pure ^{235}U neutrino spectrum

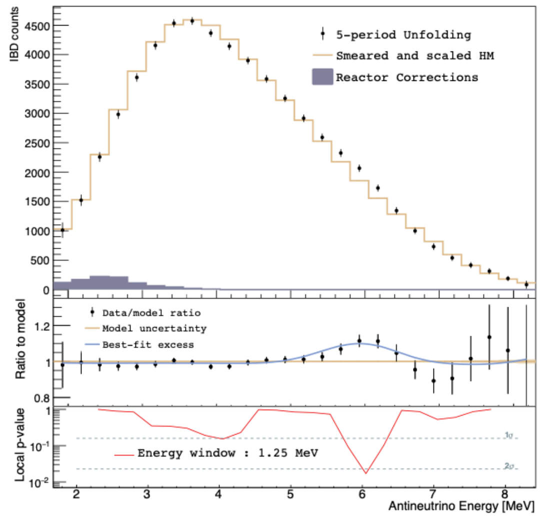
DAYA BAY - Chinese Phys. C 45 (2021) 073001



STEREO - Nature 613 (2023) 7943



PROSPECT - PRL 131 (2023) 2, 021802



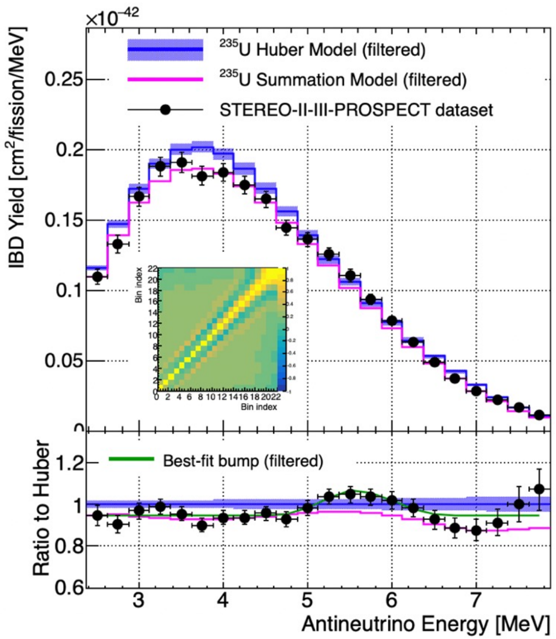
- Unfolded spectra in true E_ν space, corrected for all detection effects

Joint analyses - Spectra

Stereo-Prospect

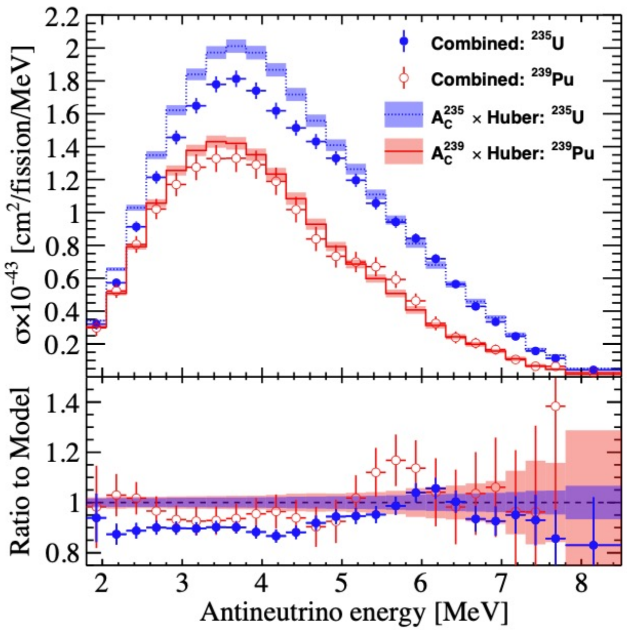
PRL128 (2022)

R. Rogly's PhD thesis



Prospect - DYB

PRL 128 (2022)

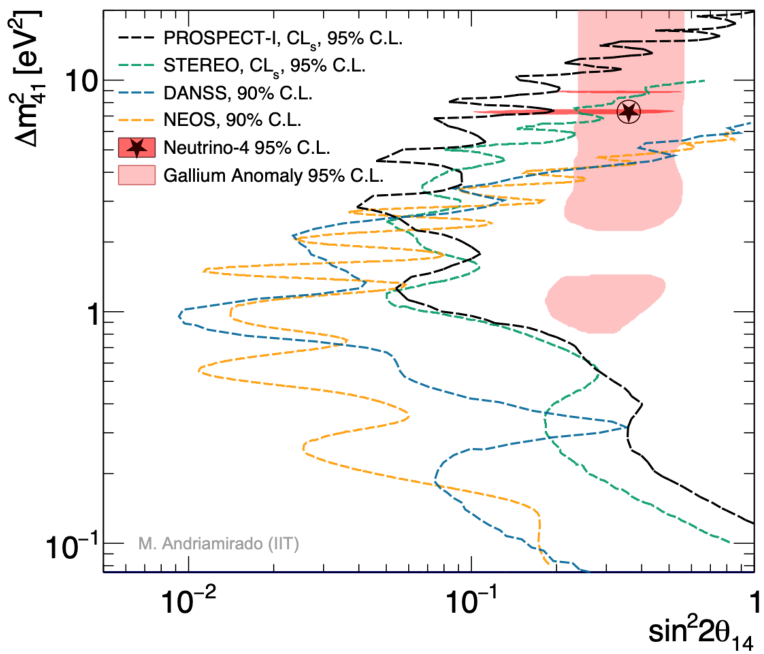


- Most accurate treatment possible of detector response and systematics
- Relevant data available online
- Main deficit carried by ^{235}U
- The "bump" local distortion is confirmed with high significance in all ^{235}U spectra. The hypothesis of a similar bump in the Pu spectrum is favored.

Conclusion

- **Accurate measurements** :
  - Background rejection at Earth surface -breakthrough of the Li-liquid technology.
  - State-of-art simulations demonstrating a % level control of the detector response.
  - Feldman-Cousins statistical analyses.
  - Shared data and joint analyses.

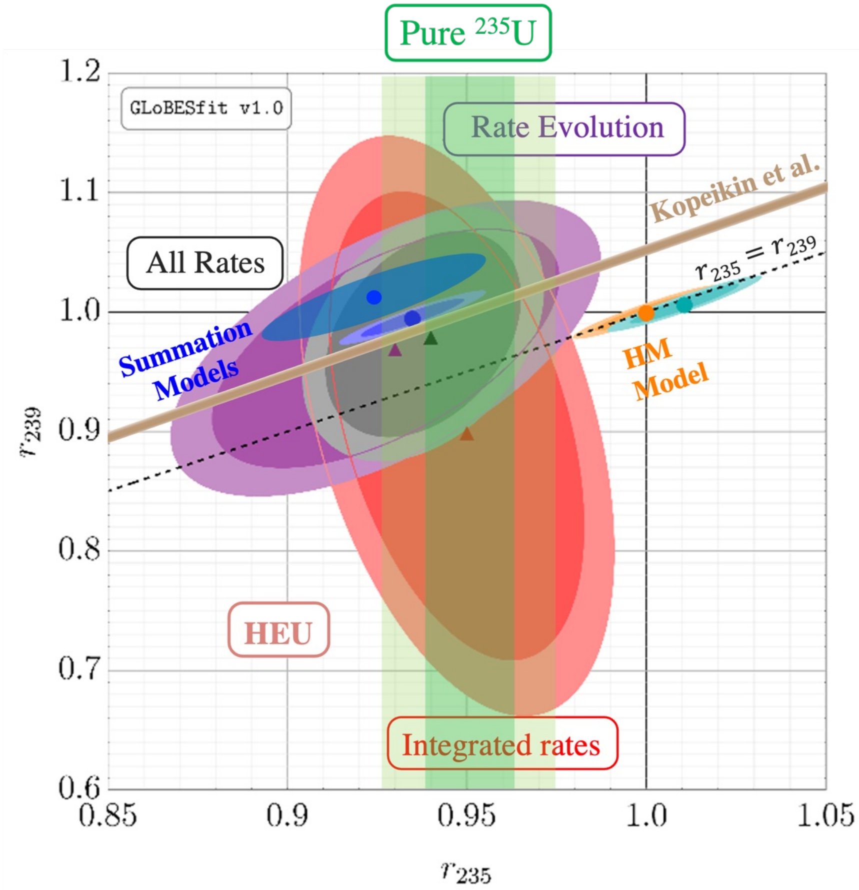
- **Sterile neutrino hypothesis disfavored with high CL**
  - High complementarity of commercial and reactor measurements.
  - Coverage of the RAA contour up to Δm^2= 10 eV^2.
  - The Neutrino-4 best fit is rejected by STEREO and PROSPECT with >5σ CL. Strong tension remains with the Gallium results.



Conclusion

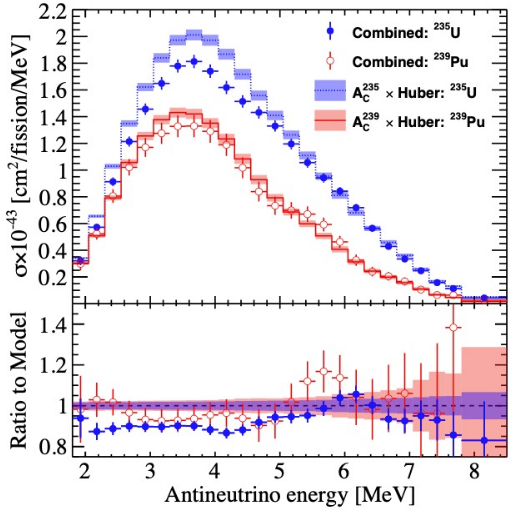
➢ **Reference fission neutrino spectra**

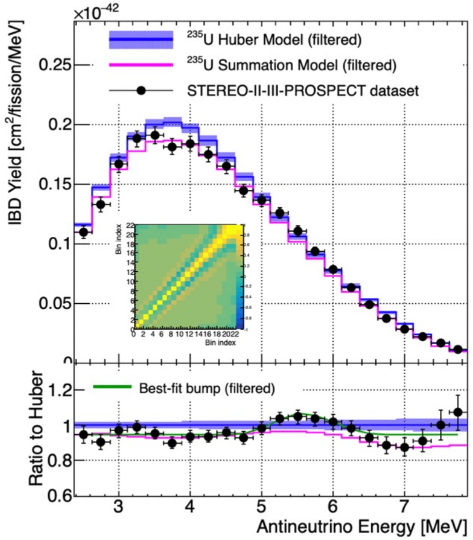
- Coherent set of experimental spectra from commercial (U-Pu) and research reactors (pure ^{235}U contribution).
- Spectra corrected for detection effects available online.
- **Normalization**: RAA deficit is confirmed. Combining all data points to a normalization issue of the reference ^{235}U beta spectra used by the predictions.



Conclusion

- **Reference fission neutrino spectra**
  - Coherent set of experimental spectra and pure ^{235}U contribution from research
  - Spectra corrected for detection effects available online.
  - **Normalization**: RAA deficit is confirmed. Combining all data points to a normalization issue of the reference ^{235}U beta spectra used by the predictions.
  - **Shape:** the bump is confirm with high significance.
- Published and ongoing **joint analyses**
- **Benchmark for future neutrino experiments and for nuclear data.**





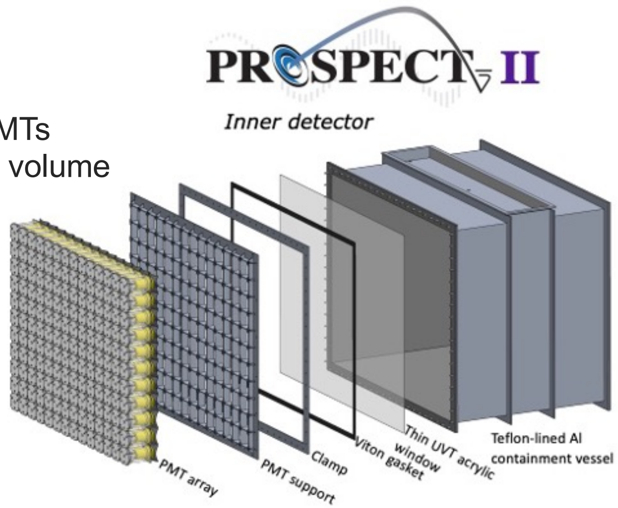
Perspectives

Statistically limited measurements → a significant gain in precision is achievable in the 1 eV range

Several next generation experiments in preparation

Neutrino4, DANSS, *M. Danilov's talk*
NEOS-II, *K. Syeon's talk*

Remove PMTs
from active volume

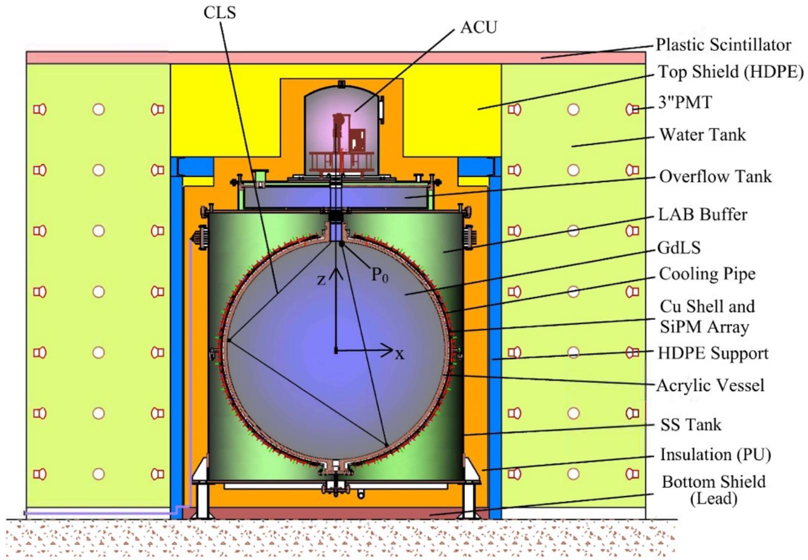


O. Benevides Rodrigues Poster#421

Enable emptying/refilling for multiple sites measurements

Juno-TAO

D. Chiesa Poster#369
L. Zhan Poster#308



Impressive 2% resolution expected @ 1 MeV
First data end of this year

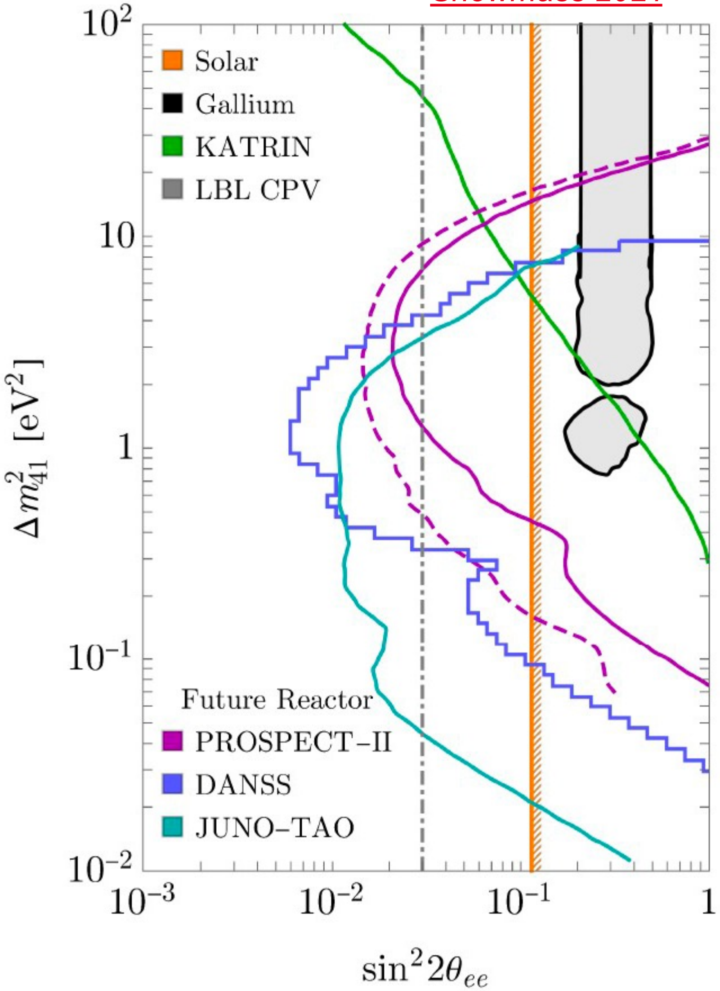
Perspectives

- Full coverage of the BEST and RAA contours, filling the gap between the expected final sensitivity of Katrin at high Δm^2 and the coverage at low Δm^2 by the commercial reactors.

- Combination of several independent and accurate neutrino fission spectra, superseding the accuracy of the predictions!

  - Ultimate background rejection from anti-matter signature of neutrinos…?

Snowmass 2021



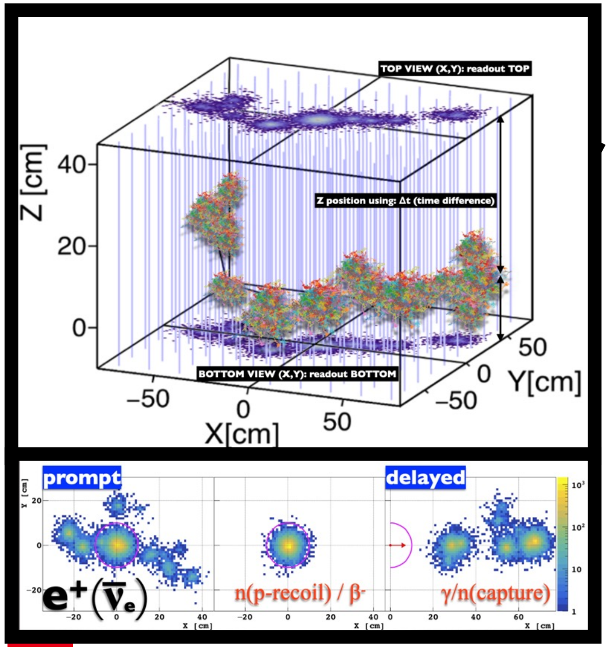
CLOUD: Chooz Liquido Ultranear Detector

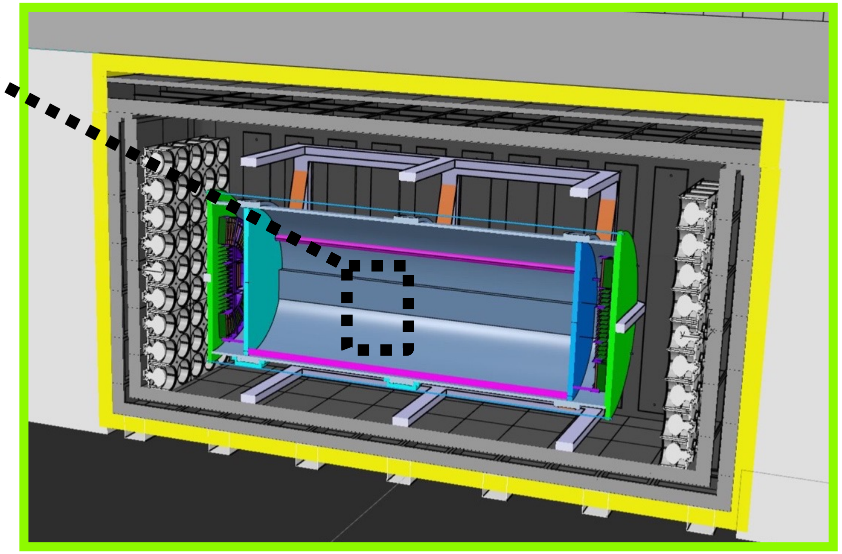
[DOI 10.5281/zenodo.10049845](https://doi.org/10.5281/zenodo.10049845)

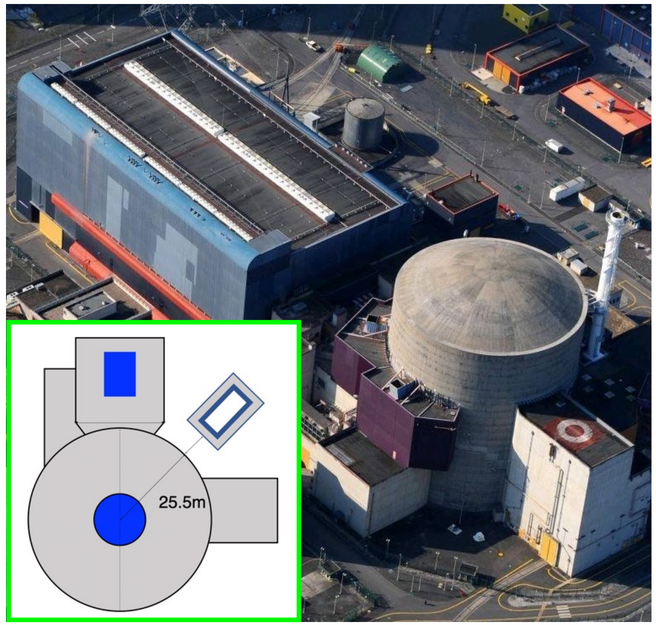
D. Navas Poster#328
G. Wendel Poster#612

Novel Liquido technology, e+ PID
→ S/B>100 @ 3 mwe

High Statistics 10k IDB/day
Sub-% accuracy expected on the rate&shape of fission neutrino spectrum
New prediction, reactor monitoring, search for new physics, …

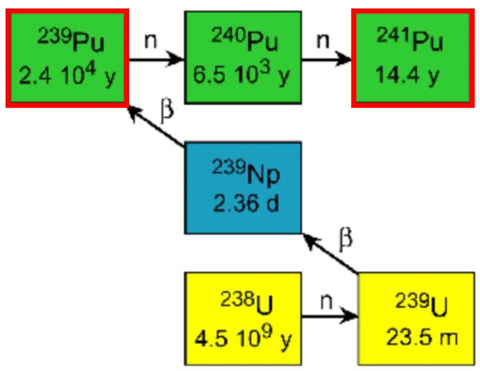




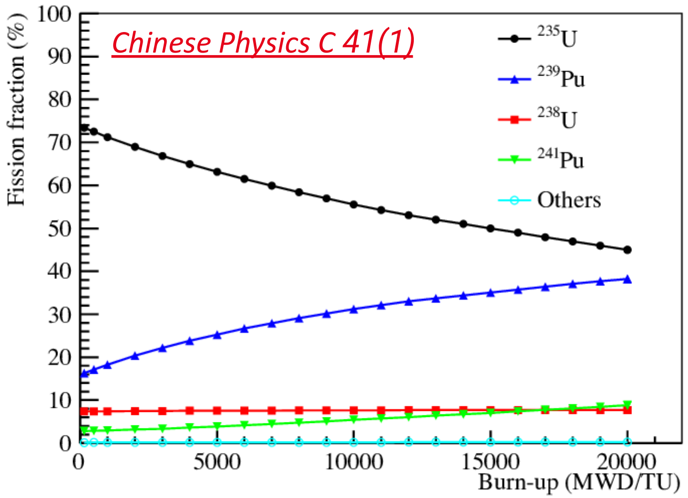


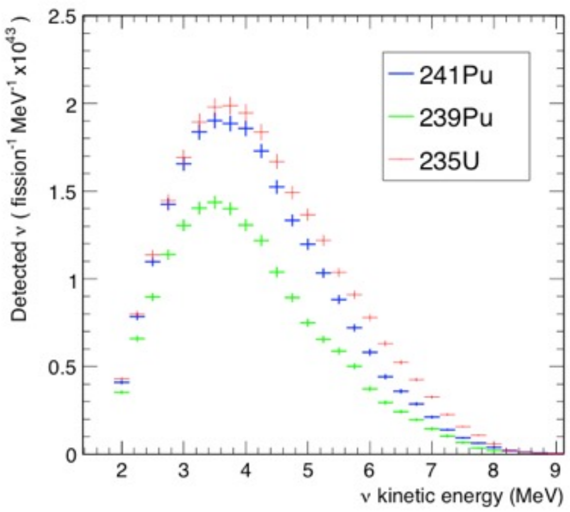
Thank you

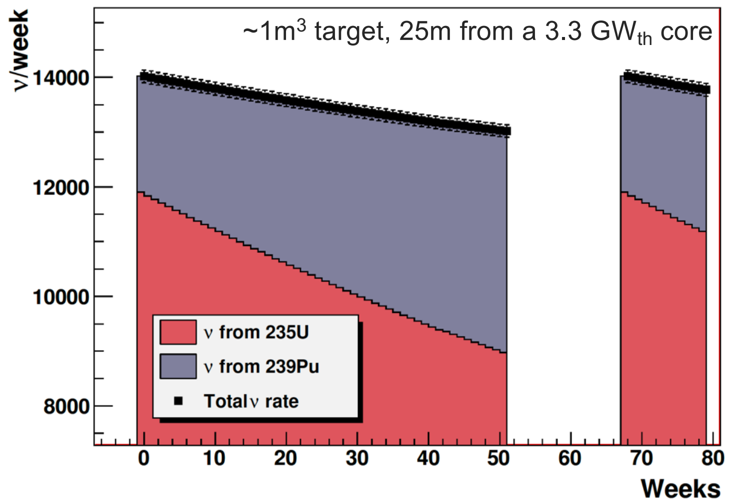
Reactor Fuel Evolution



- Production of the $^{239-41}Pu$ 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.



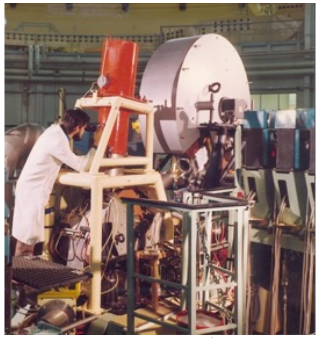


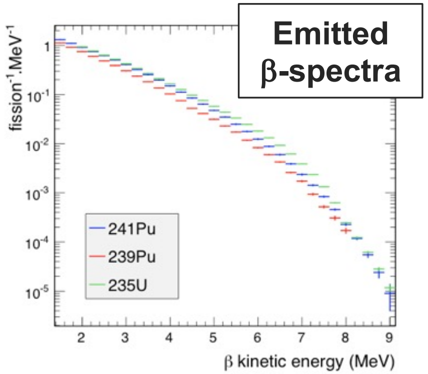


Predicted Fission Neutrino Spectra

K. Schreckenbach et al.

Magnetic spectrometer



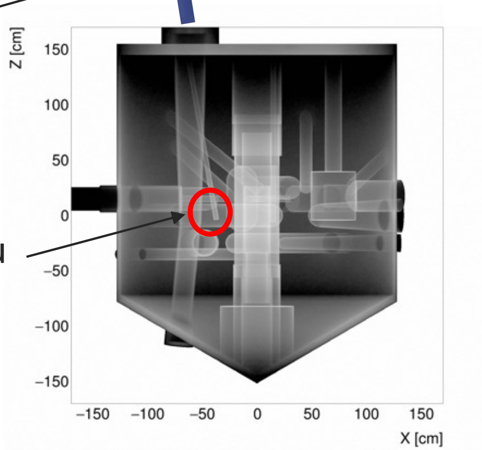


- Total fission β-spectra measured in the 80's

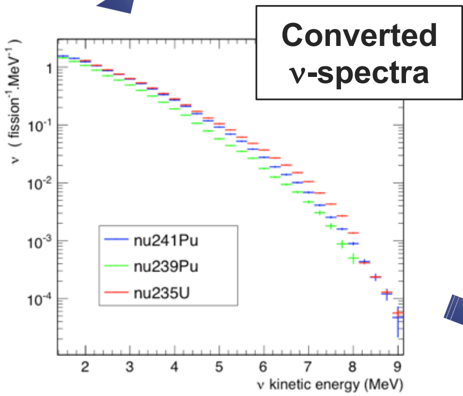
e^- from fission products' β-decay

e^-

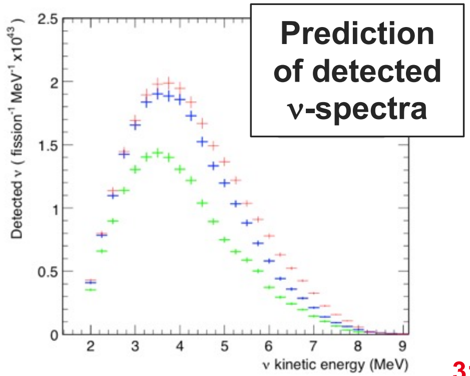
Target foils (^{235}U , ^{239}Pu and ^{241}Pu) exposed to an intense flux of thermal neutrons



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

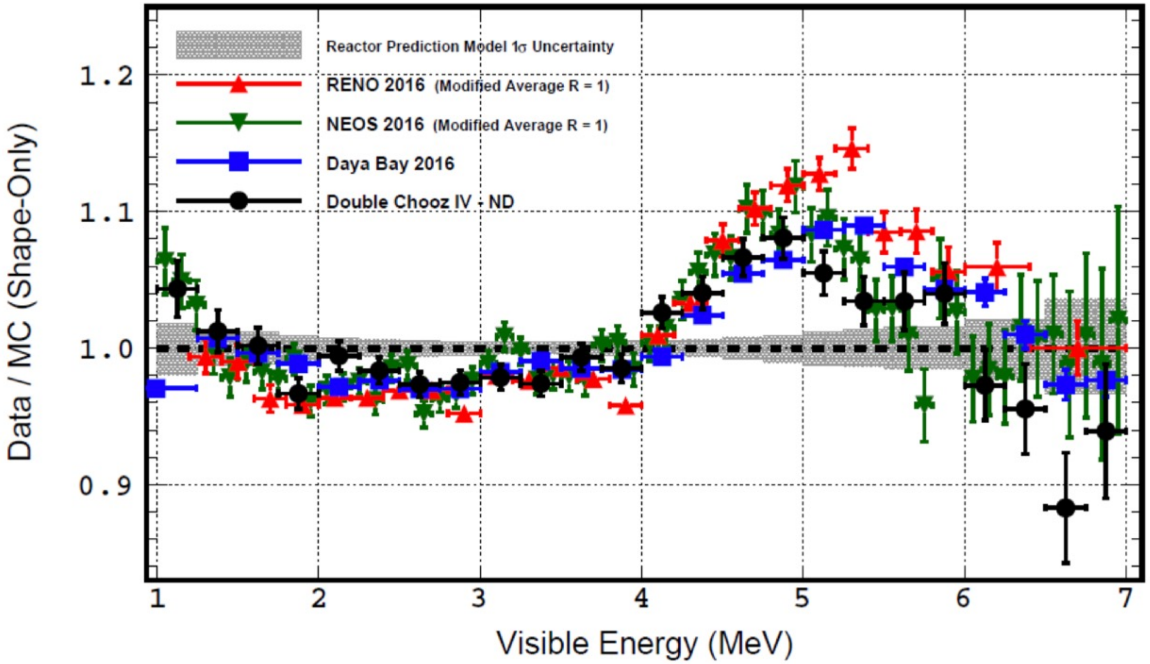


- Numerical procedure for β to ν conversion. Breakthrough in the accuracy of predicted spectra.
- Revisited in 2011 (PRC83, PRC84)



Spectrum Shape "Anomaly"

Nature Physics 558–564 (2020)

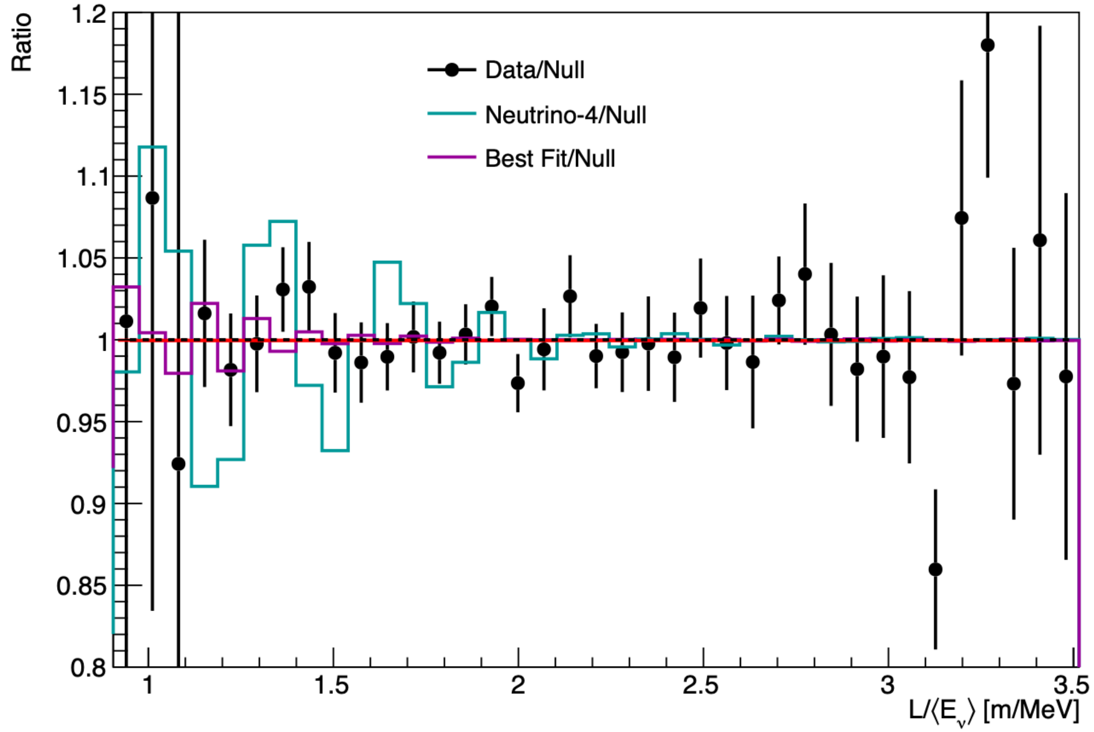


- Accurate spectra measured **few 100 m** from commercial reactors by the Double Chooz, Daya Bay and Reno experiments
- **Unexplained local shape distortion**, the "5 MeV bump", on top of the global deficit
- Contribution of this bump to the global deficit is sub-%

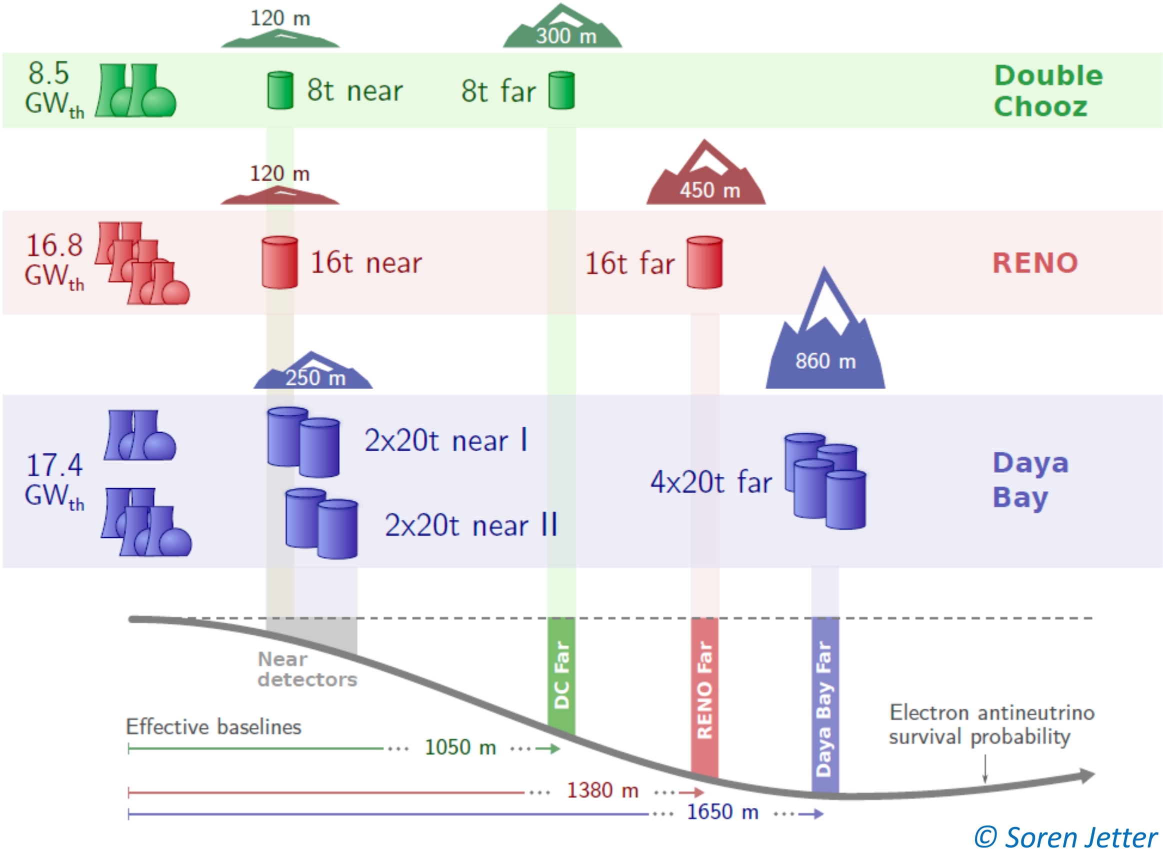
PROSPECT – Oscillation analysis

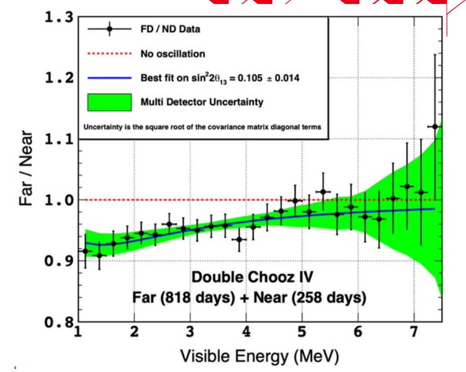
➢ No obvious oscillatory features in the ratio of L/E_ν spectra between data and the null-oscillation prediction

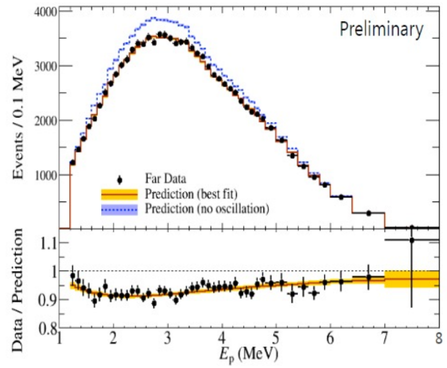
PROSPECT, Neutrino 2024, arXiv[2406.TBD]

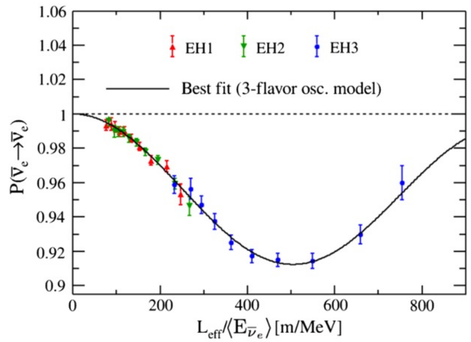


Θ_{13} Experiments







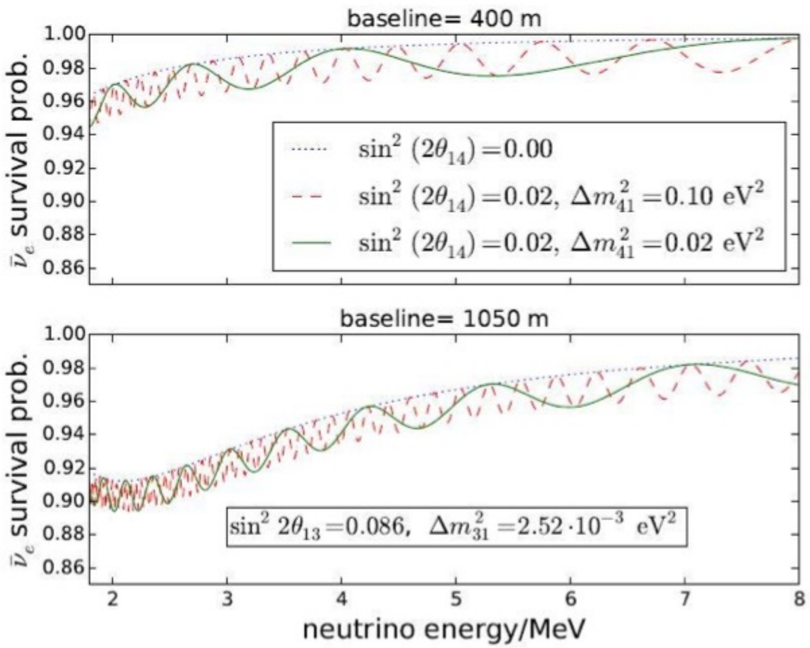


- Impressive accuracy on θ_{13} from ratios of near/far detectors
- Paved the way for VSB experiments

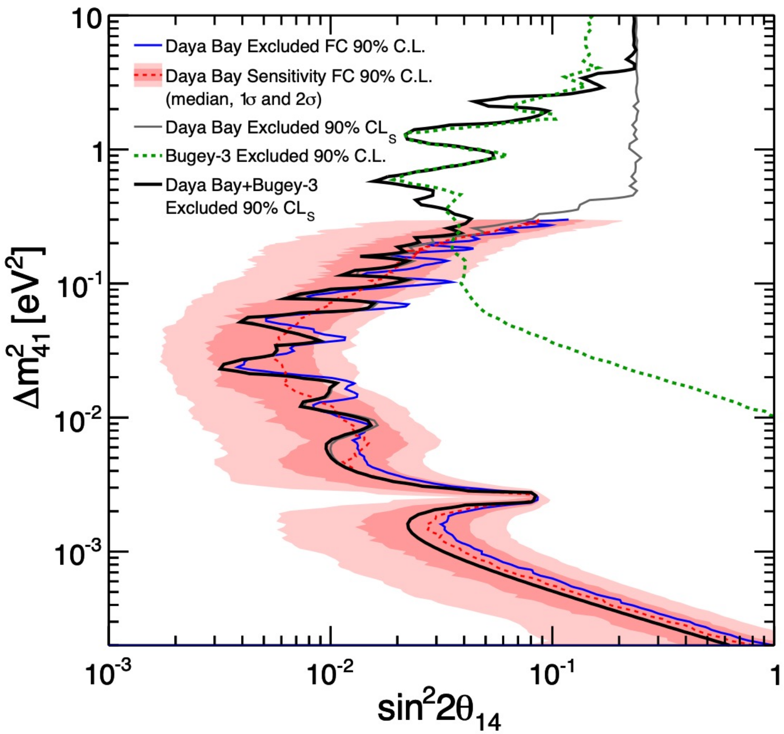
Θ_{13} Experiments

- 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

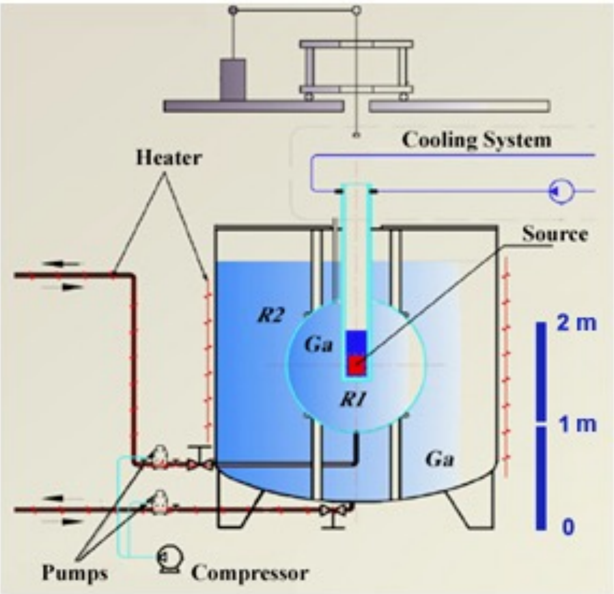


- Near detectors few 100 m from cores → Sensitivity in the 0.01-0.1 eV2 range, complementary to VSB.

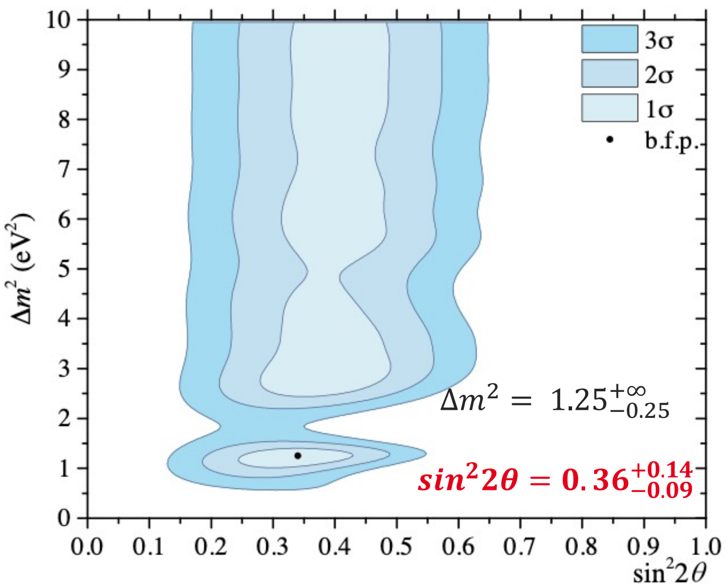
Positive Signals (?) – BEST Experiment

PRC 105 (2022)

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



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:

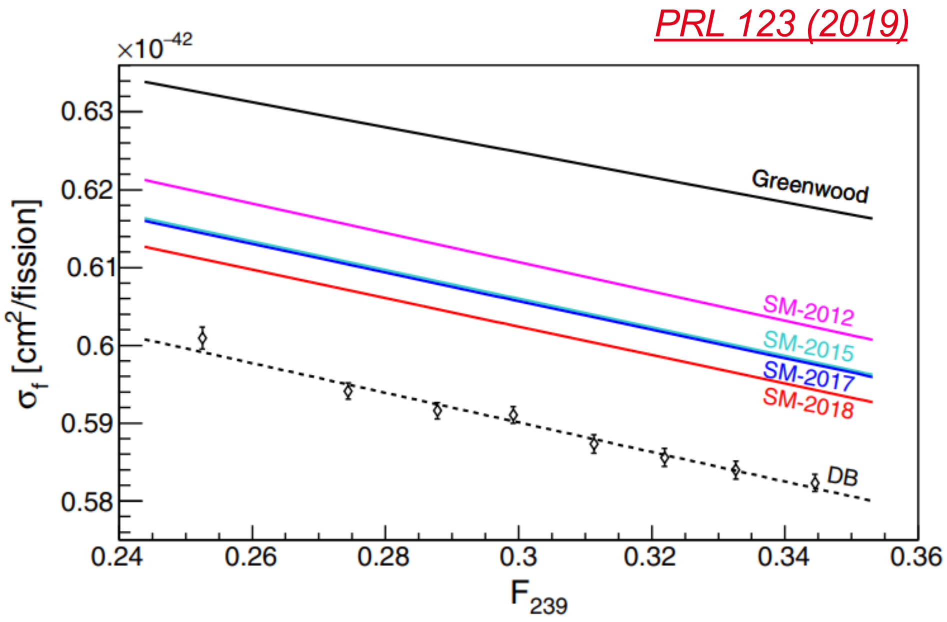
W. Hampel, L.P. Remsberg PRC, 31 (1995)

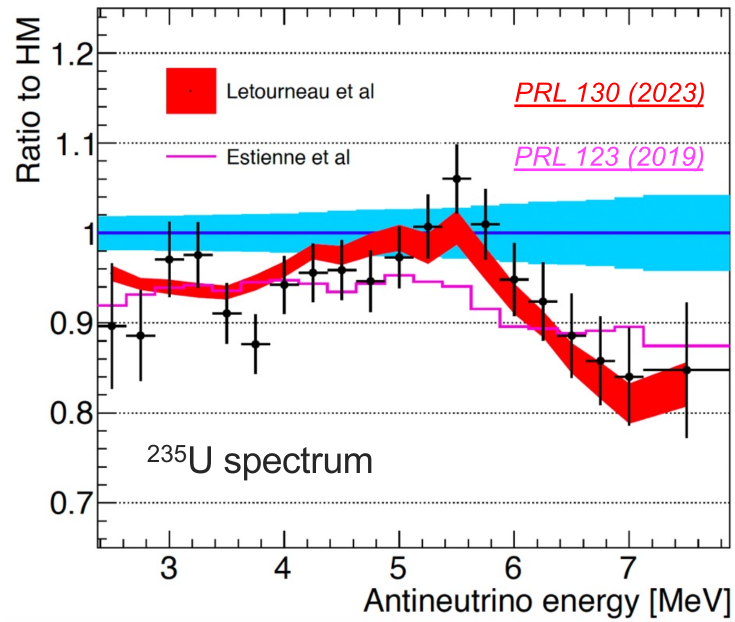
Benchmark for nuclear data

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

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

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



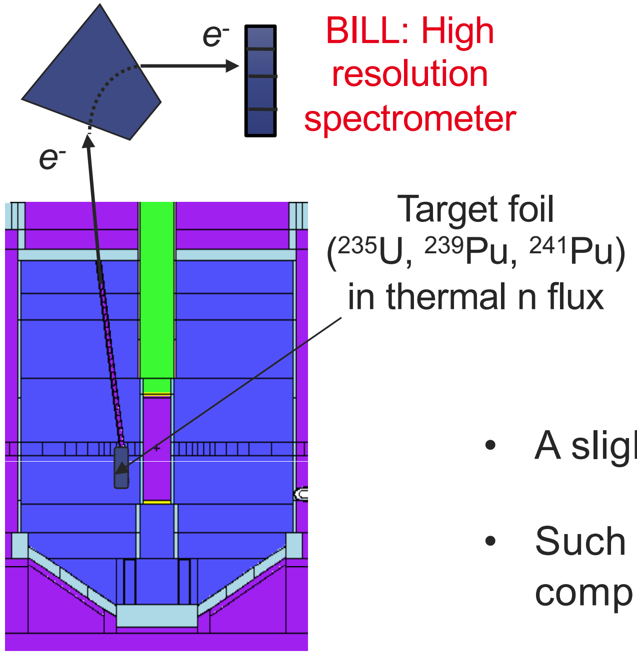


Hints of a dominant role of the correction of the Pandemonium effect in β^- spectra

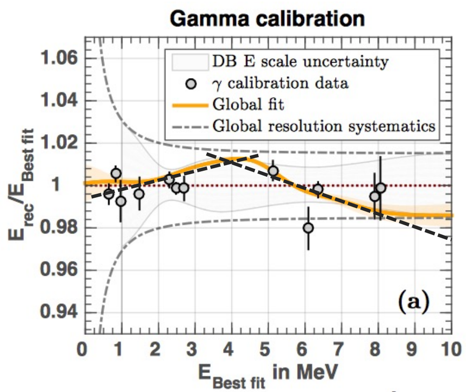
Another candidate is the impact of shape factors of forbidden transitions

Origin of the 5 MeV Bump (?)

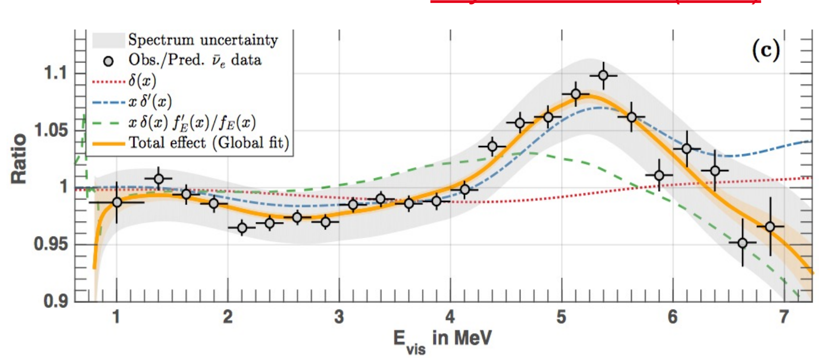
A similar bump in the β-spectra would naturally propagate in the converted neutrino spectra



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, ….