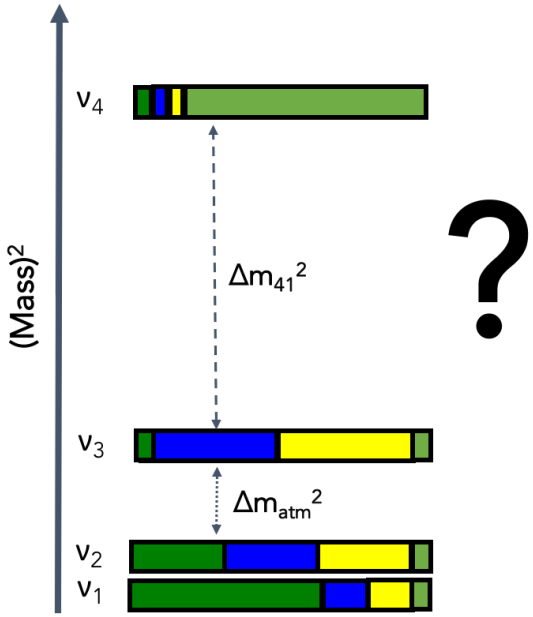
eV scale sterile neutrino searches at reactor



European Neutrino Town meeting
CERN - 23/10/2018

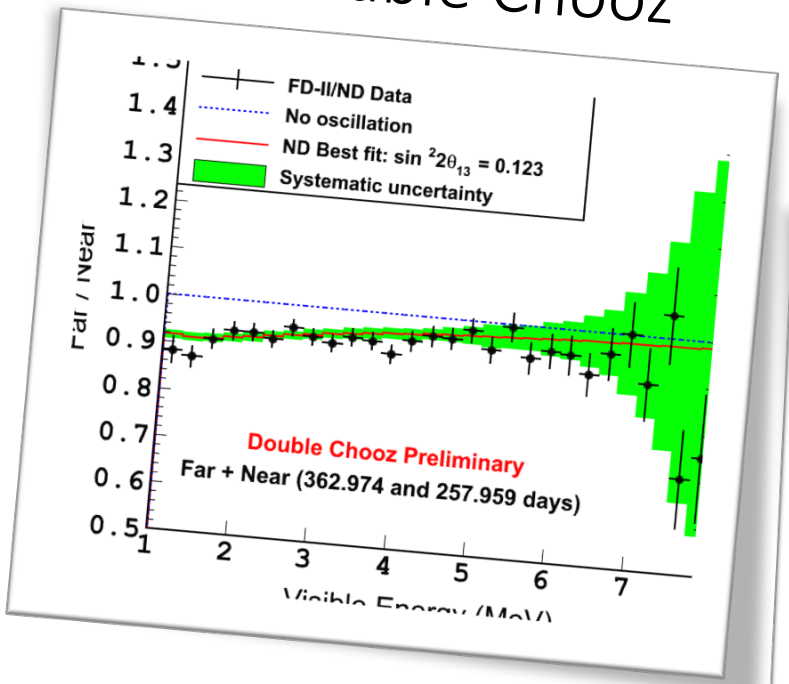
Thierry Lasserre
CEA-Saclay – APC – TUM

Reactor experiments provide the most precise θ_{13} value

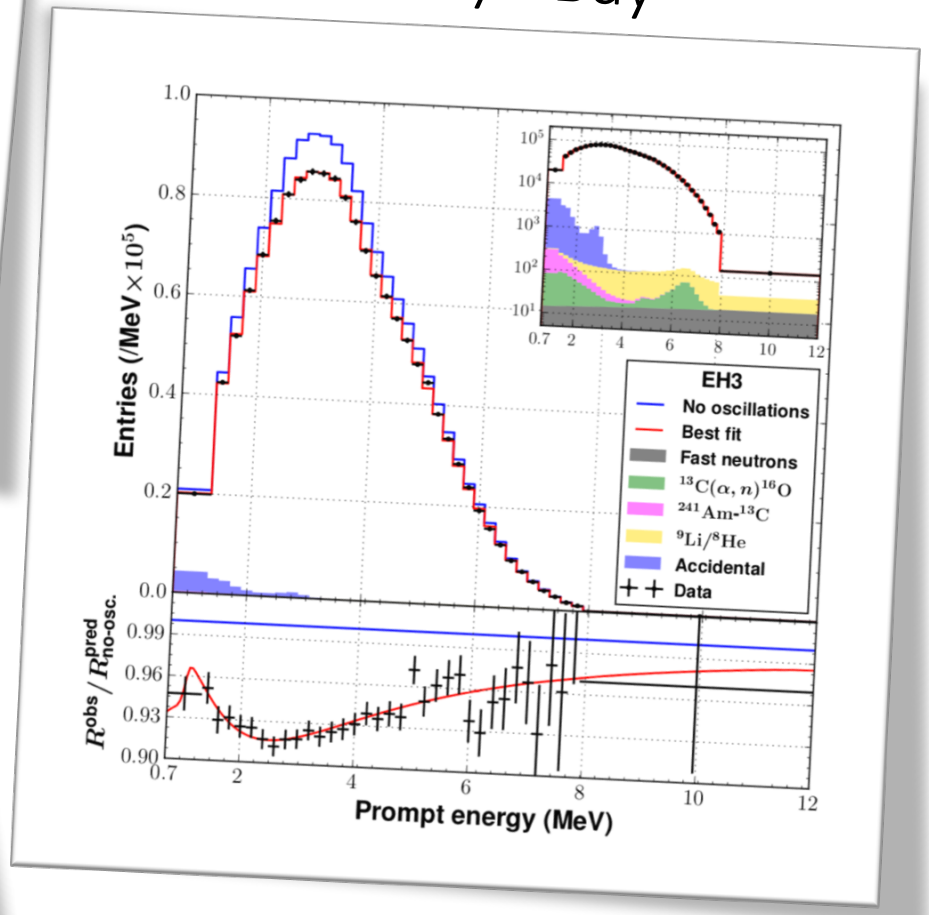
Δm^2	1.4 %
δm^2	2.2 %
$\sin^2\theta_{13}$	3.8 %
$\sin^2\theta_{12}$	4.4 %
$\sin^2\theta_{23}$	~ 5 %

(1 σ uncertainty)

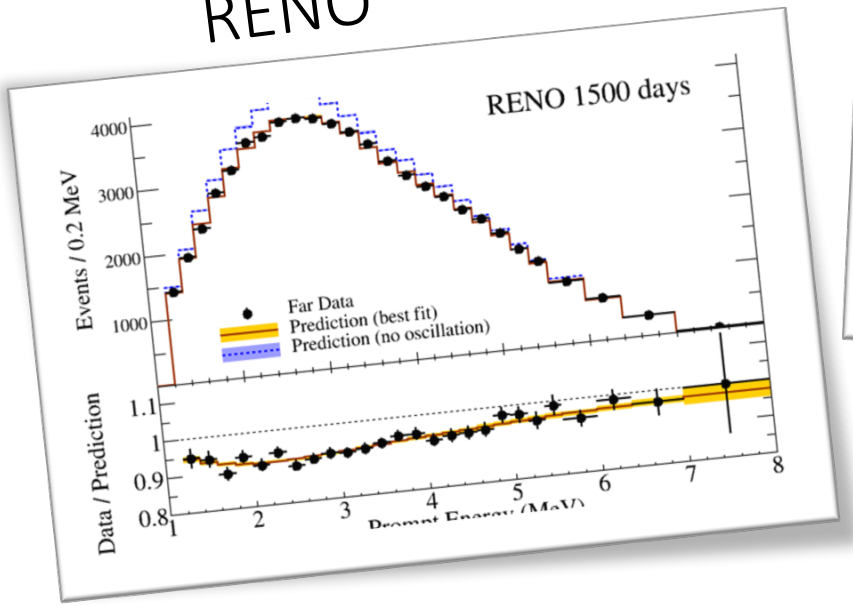
Double Chooz



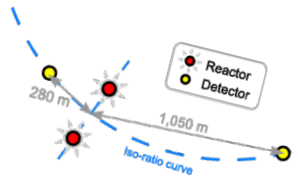
Daya Bay



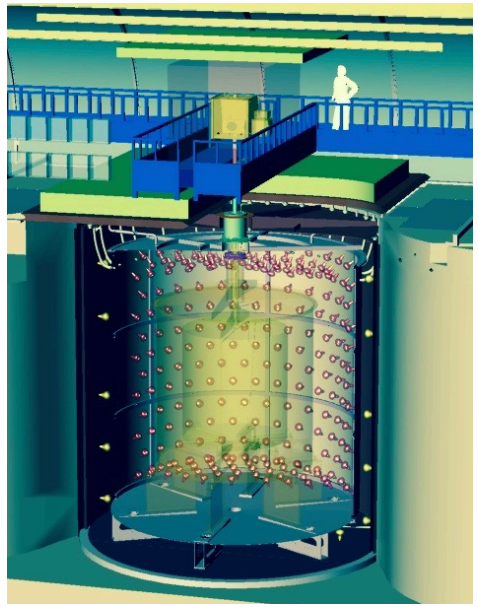
RENO



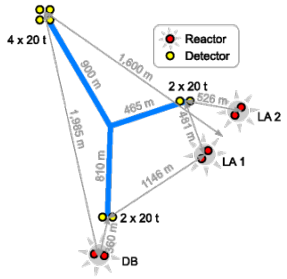
Double Chooz



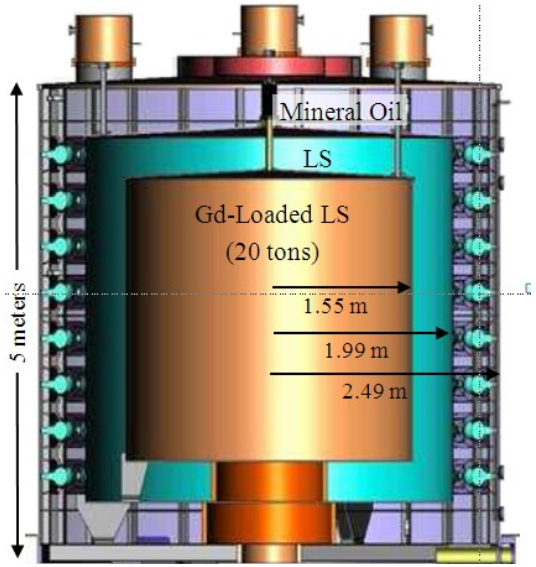
2 detectors Gd-volume: 20 m^3



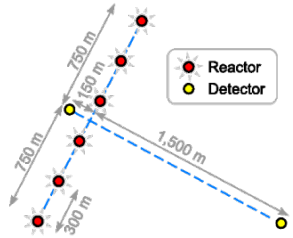
Daya Bay



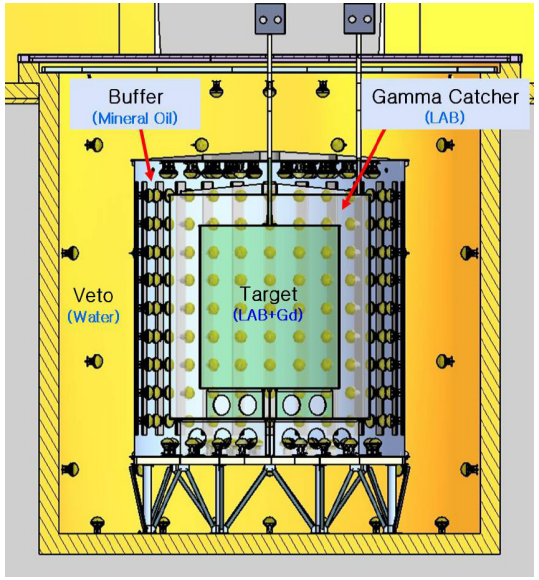
8 detectors Gd-volume: 200 m^3



Reno



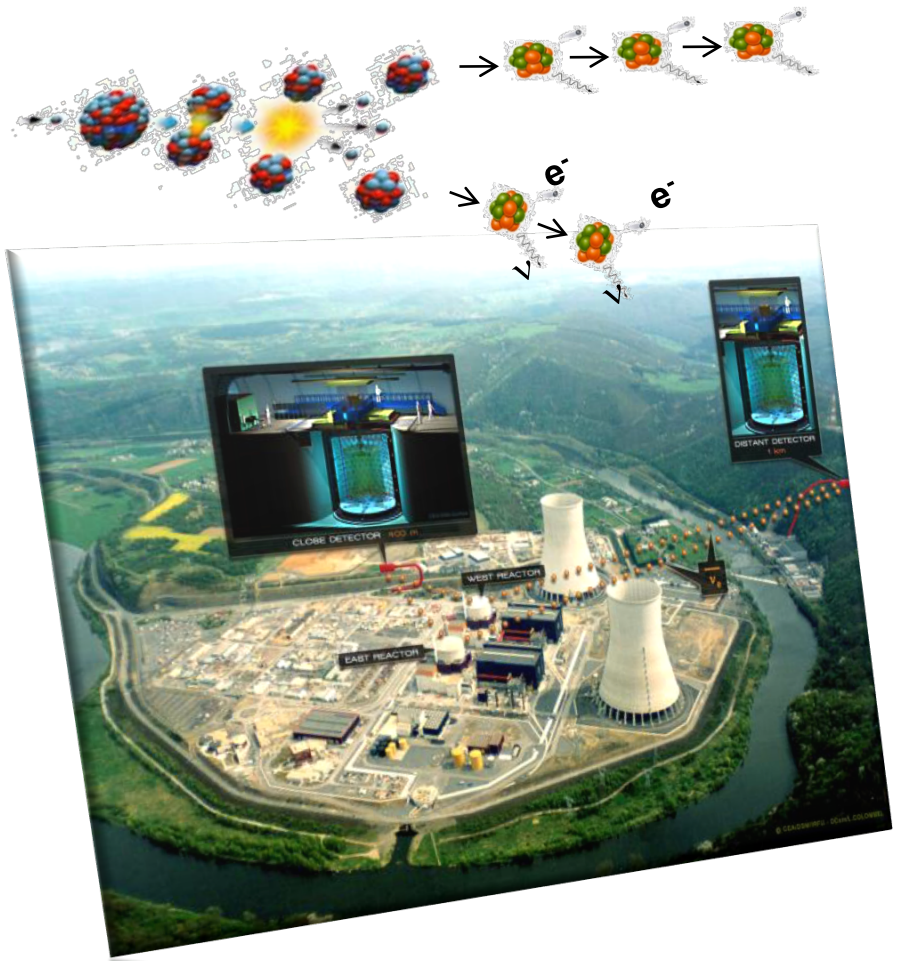
2 detectors, Gd-volume: 40 m^3



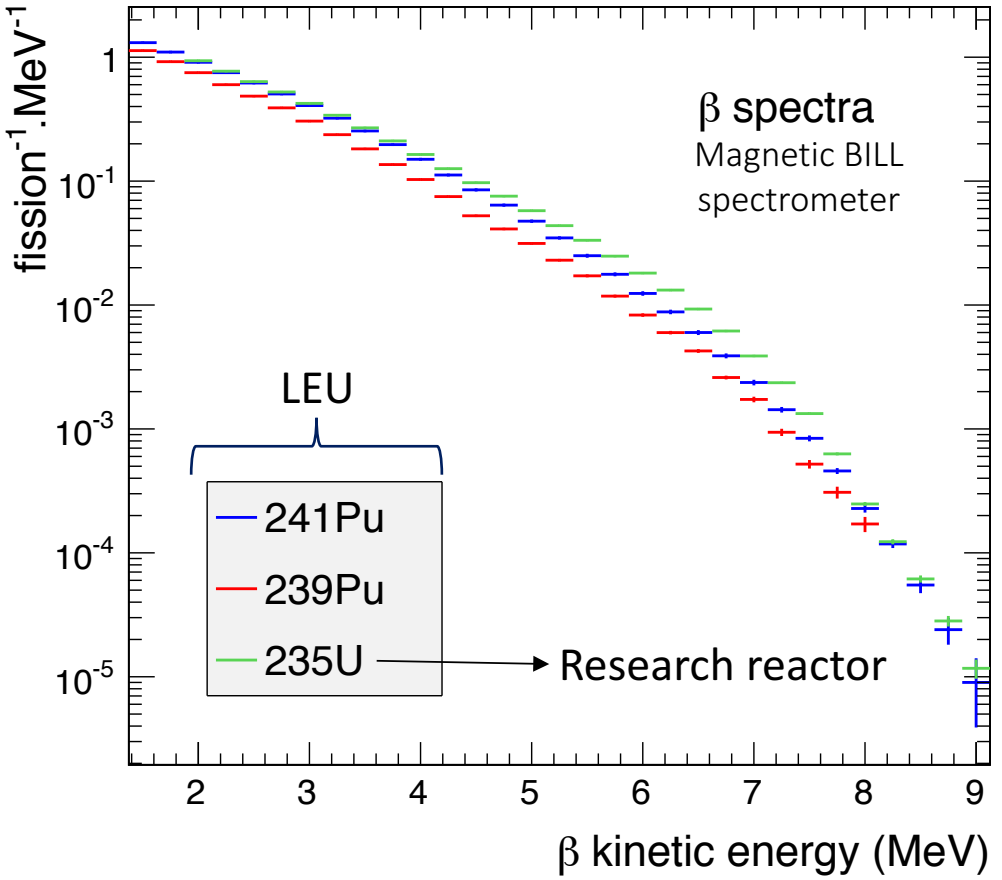
S/B>100 – Fully contained events (calorimeters) – ultra-low systematics: <O(1%)

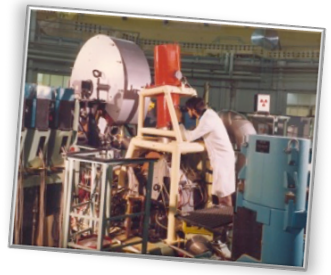
→ High-resolution reactor neutrino spectroscopy with high statistics

Reactor Neutrino Flux and Spectra



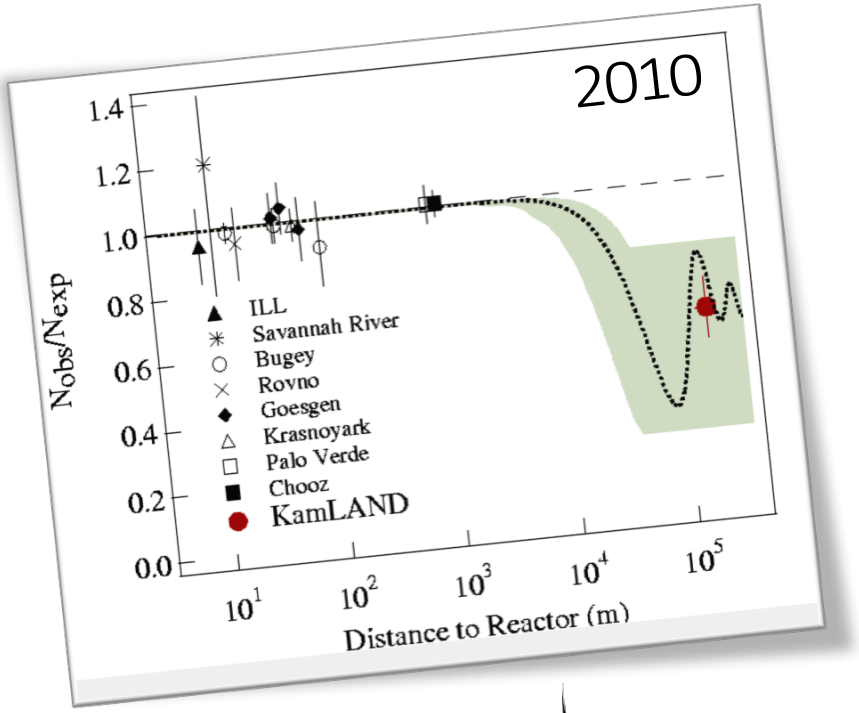
Phys Rev C 83, 054615 (2011)
Phys Rev C 84, 024617 (2011)



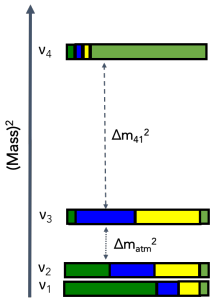


2011: Reevaluation of the $e - \nu$ conversion procedure – Flux reevaluated at + 3.5%! – 3% systematics

Reactor Antineutrino Anomaly - 2011

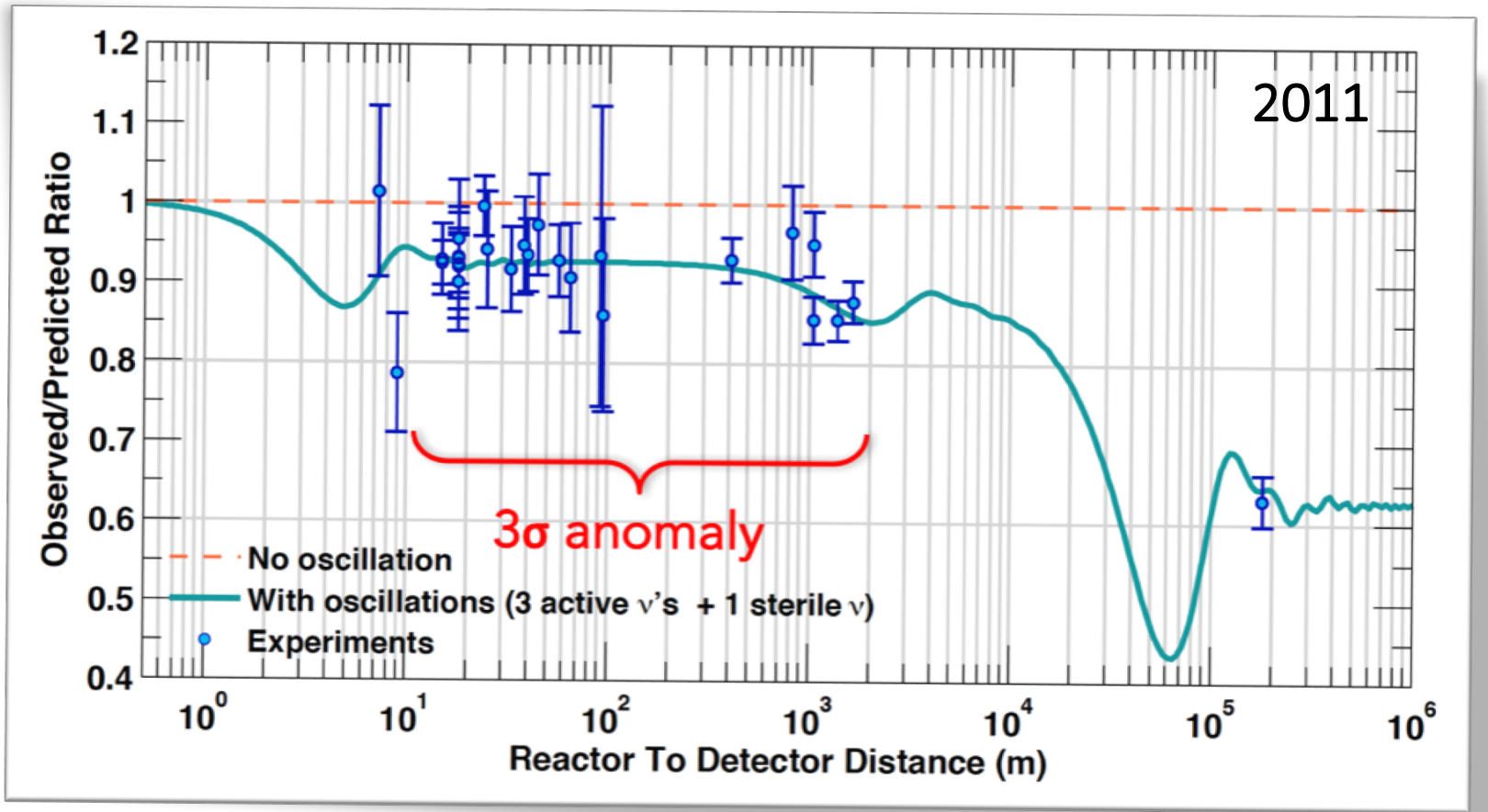


$$\frac{L}{E} \sim 1 \frac{m}{MeV}$$

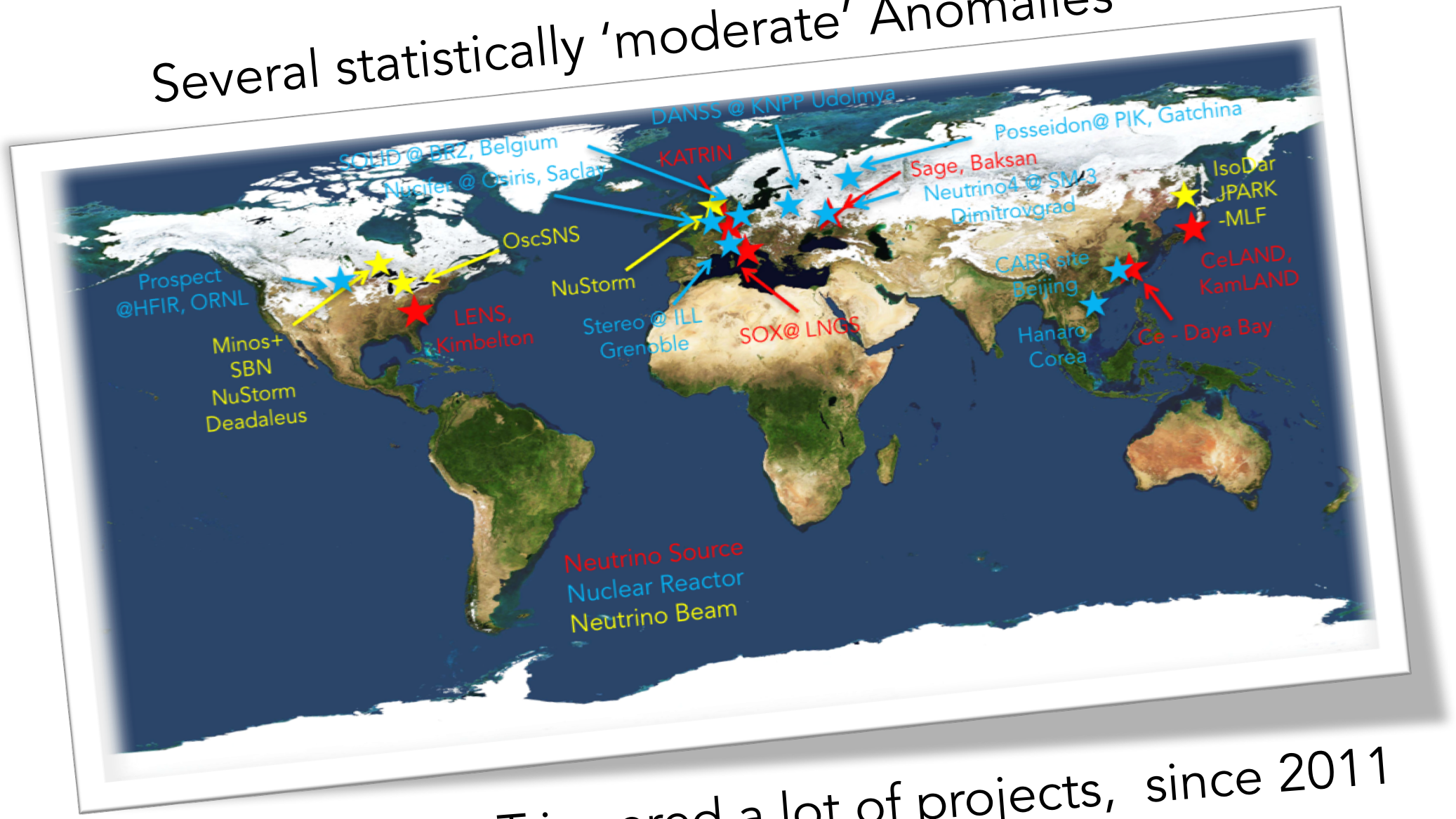


?

Phys. Rev. D 83, 073006 (2011)



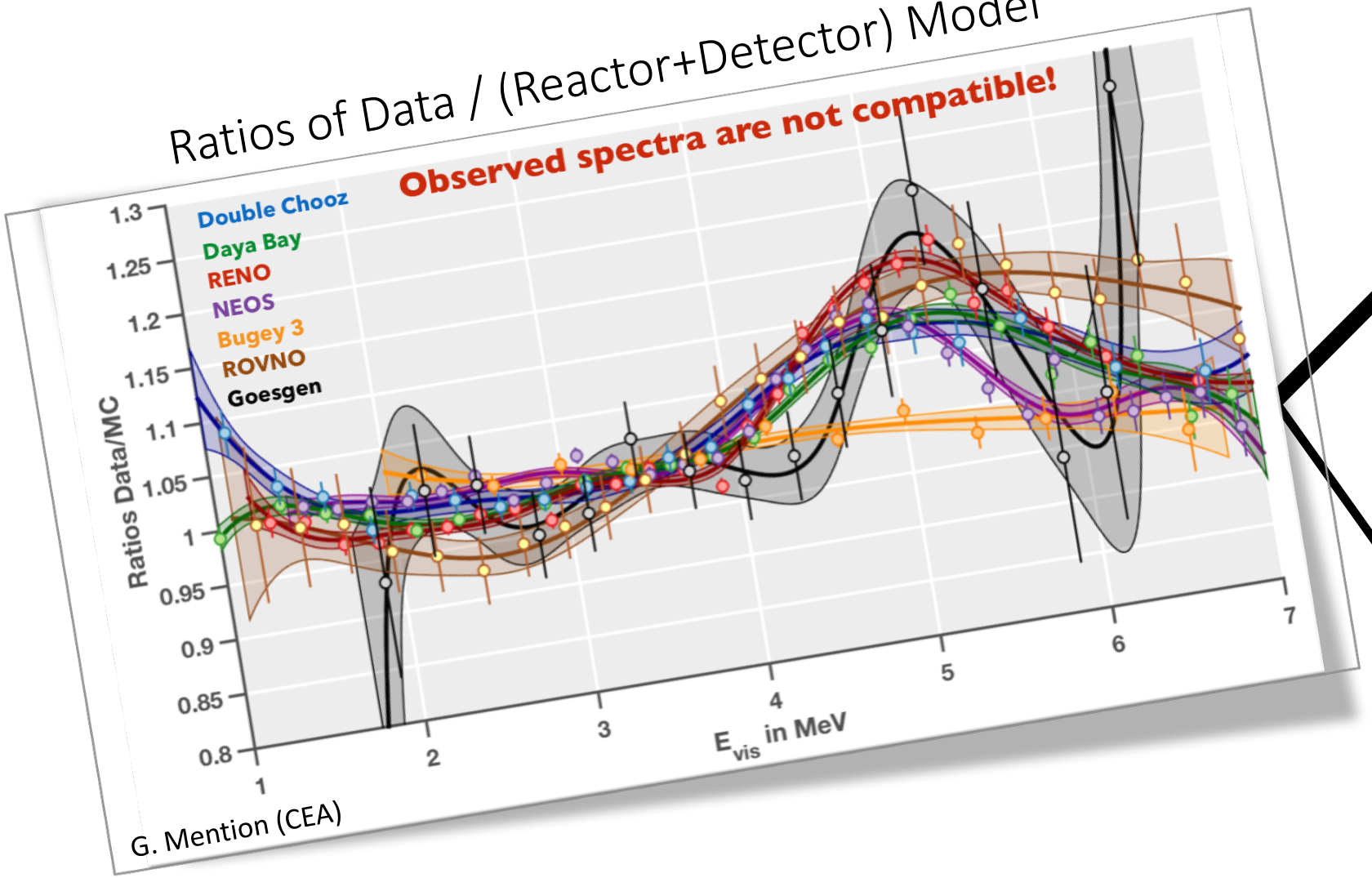
Several statistically ‘moderate’ Anomalies



Triggered a lot of projects, since 2011

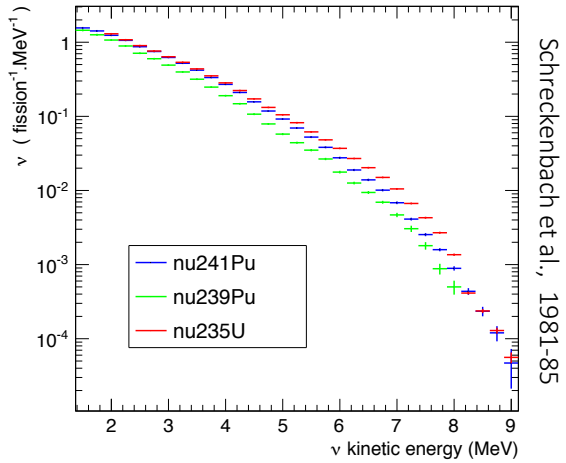
2014: 4-6 MeV spectral distorsion still unexplained…

Ratios of Data / (Reactor+Detector) Model



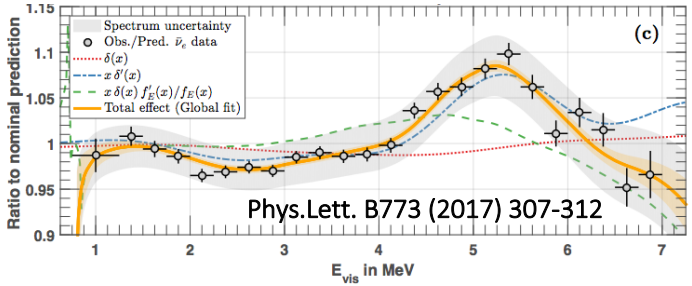
Reactor ν-spectra?

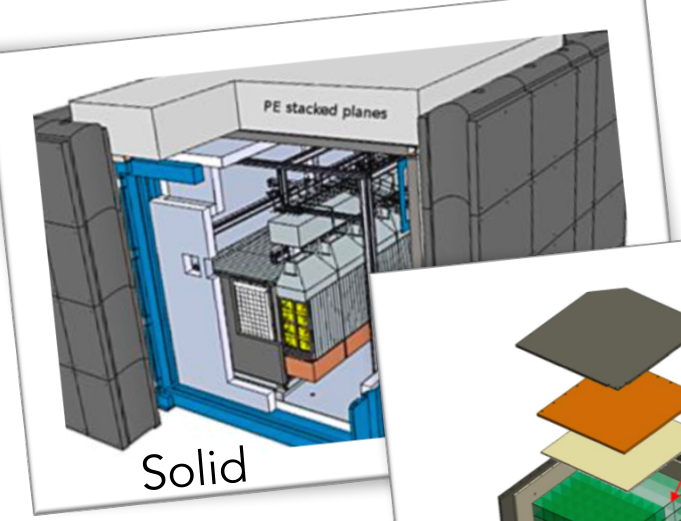
Bias? Underestimated systematics?

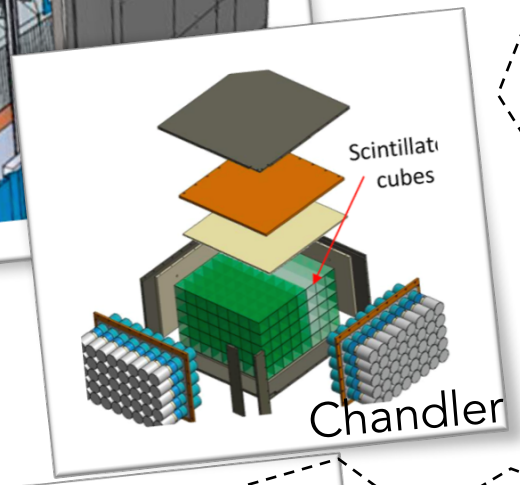


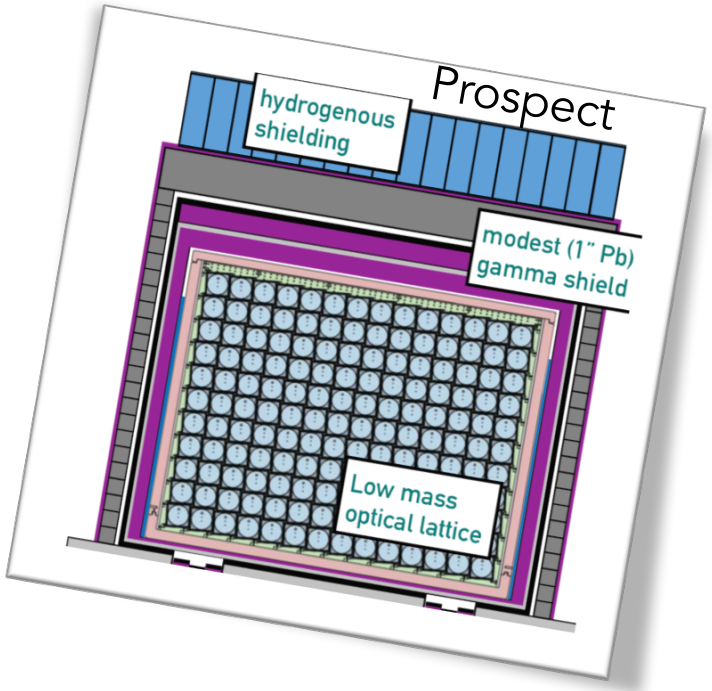
Detector response?

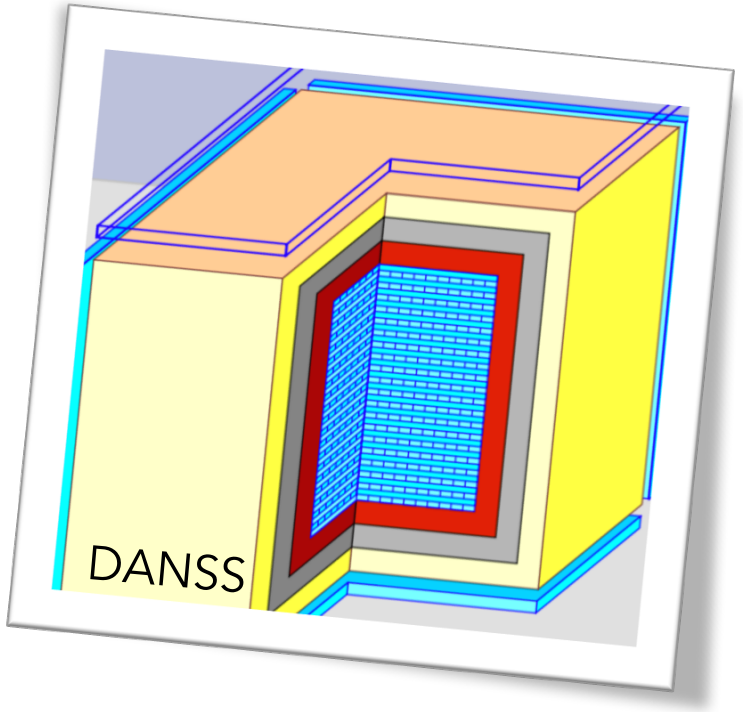
E-scale non-linarity?

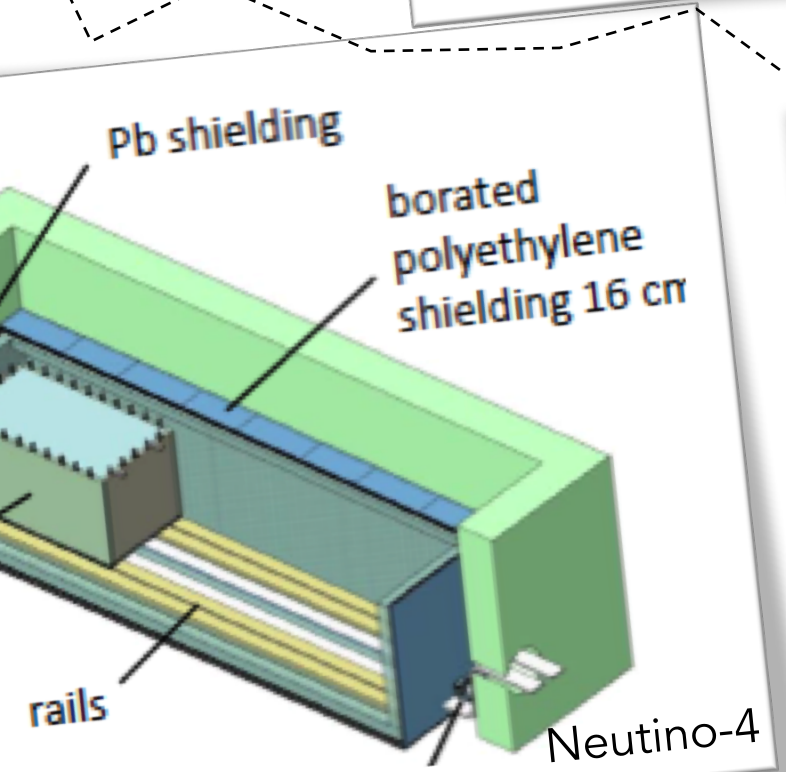


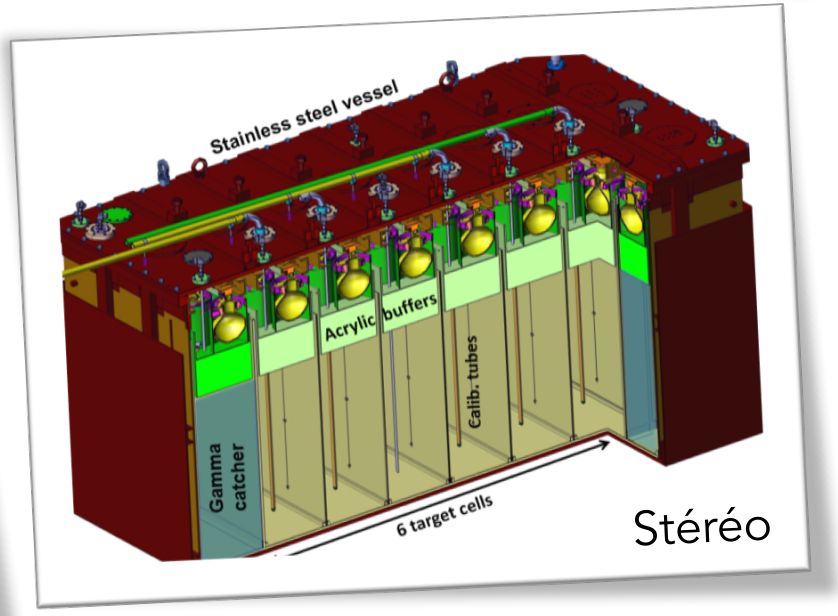

PE stacked planes
Solid

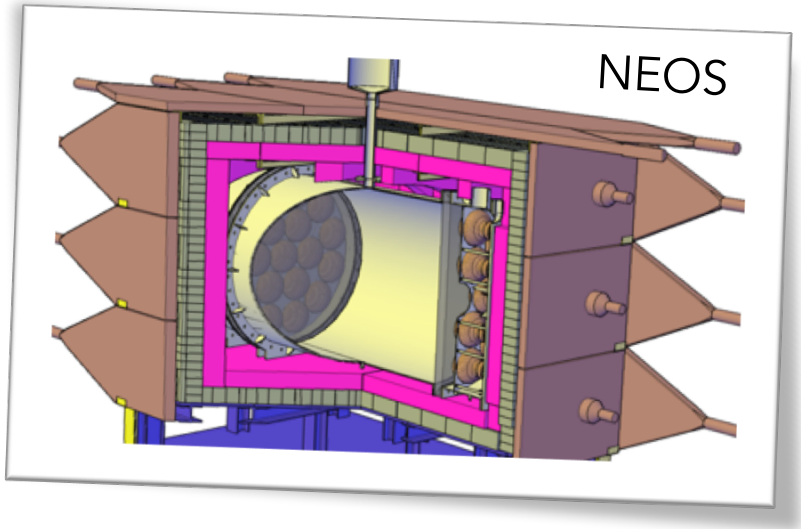

Scintillat
cubes
Chandler


Prospect
hydrogenous shielding
modest (1" Pb) gamma shield
Low mass optical lattice

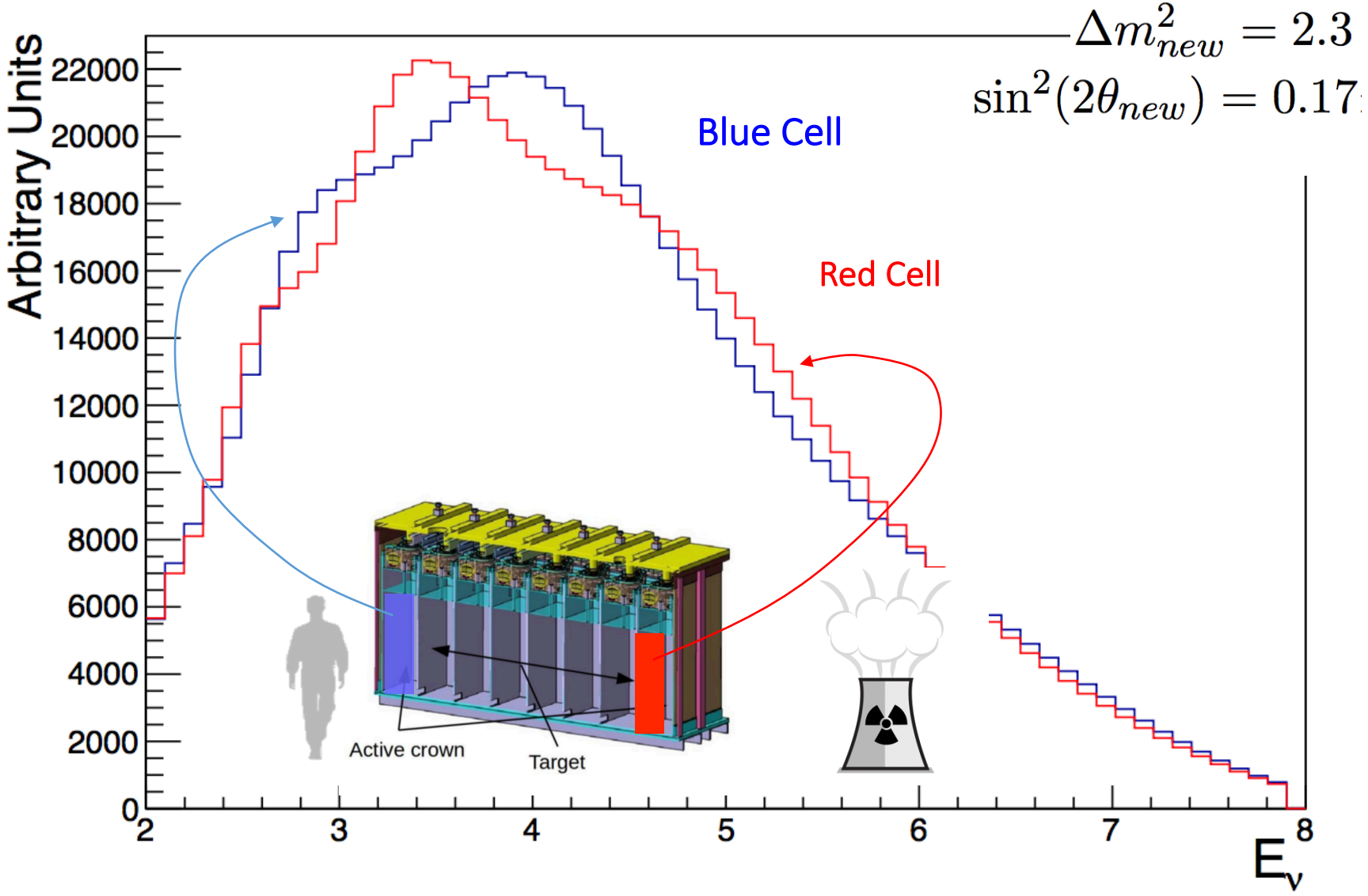

DANSS


Pb shielding
borated
polyethylene
shielding 16 cm
rails
Neutino-4

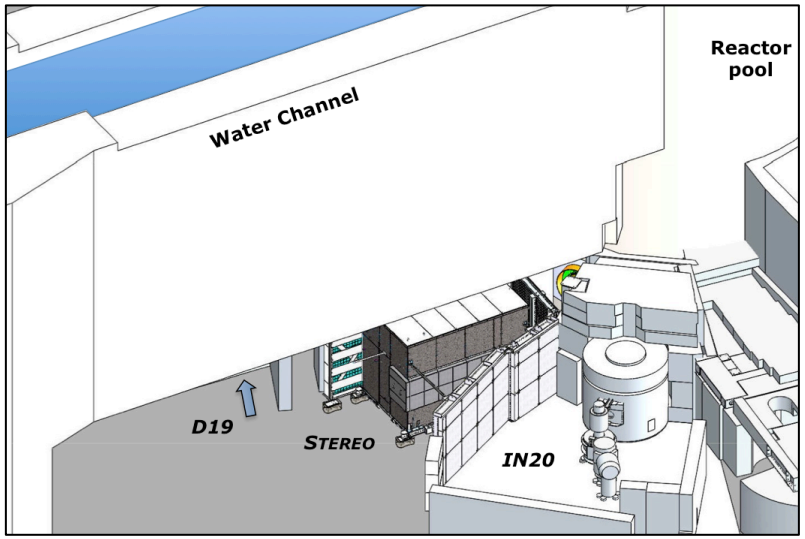

Stainless steel vessel
Acrylic buffers
Calib. tubes
Gamma catcher
6 target cells
Stéréo

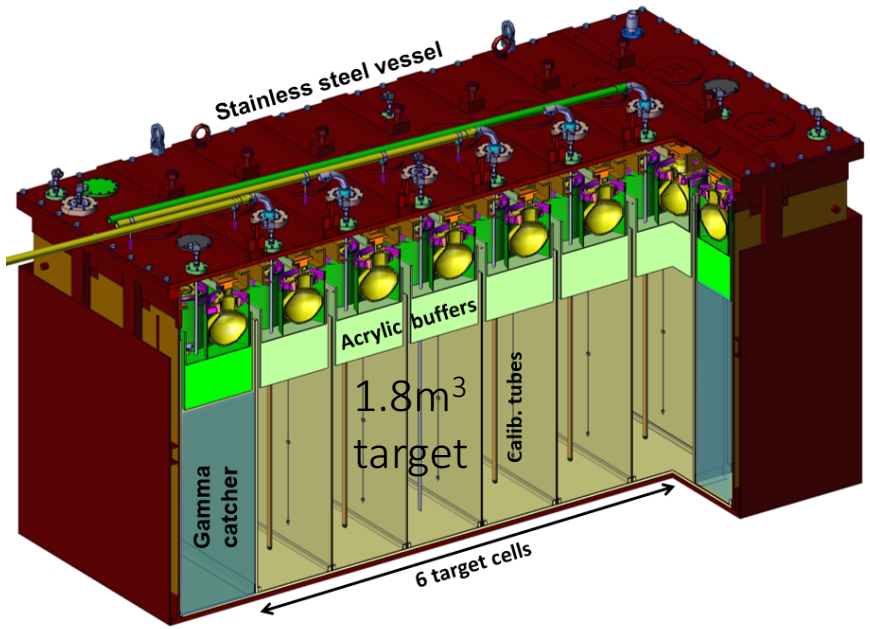

NEOS

Concept: relative measurement, not relying on reactor neutrino spectra



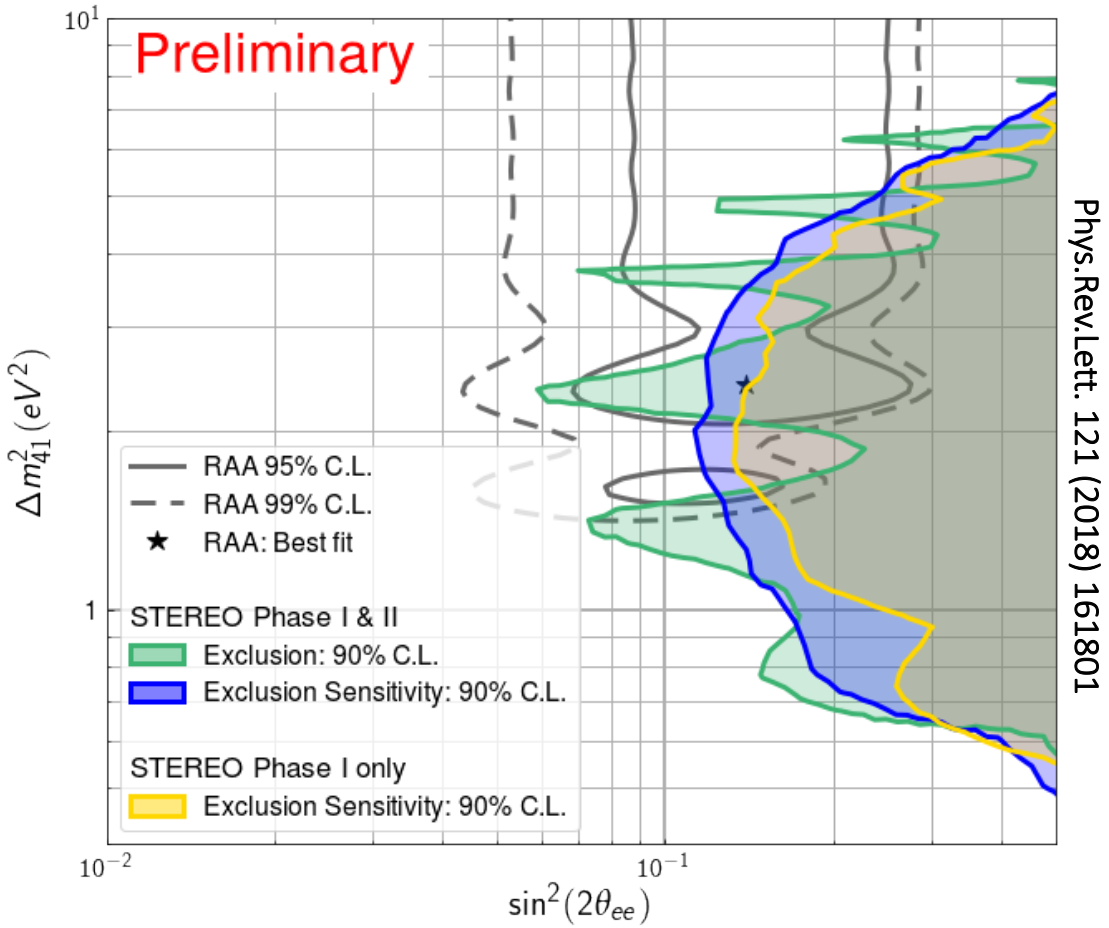
Stéréo – 50 MW ILL compact core – France





- Overburden: 15 mwe - under water channel
- Baseline: 9-11m
- Pure ^{235}U fission spectrum
- 6 identical cells filled with LS-Gd – 1.5 ton
  Oscillation analysis independent of the prediction
- High external background mitigated by Heavy shielding and PSD capability on delayed IBD
- 400 IBD/day – S/B ~ 1
- 66 days of data analyzed

Stéréo Results – Exclusion of part the RAA domain

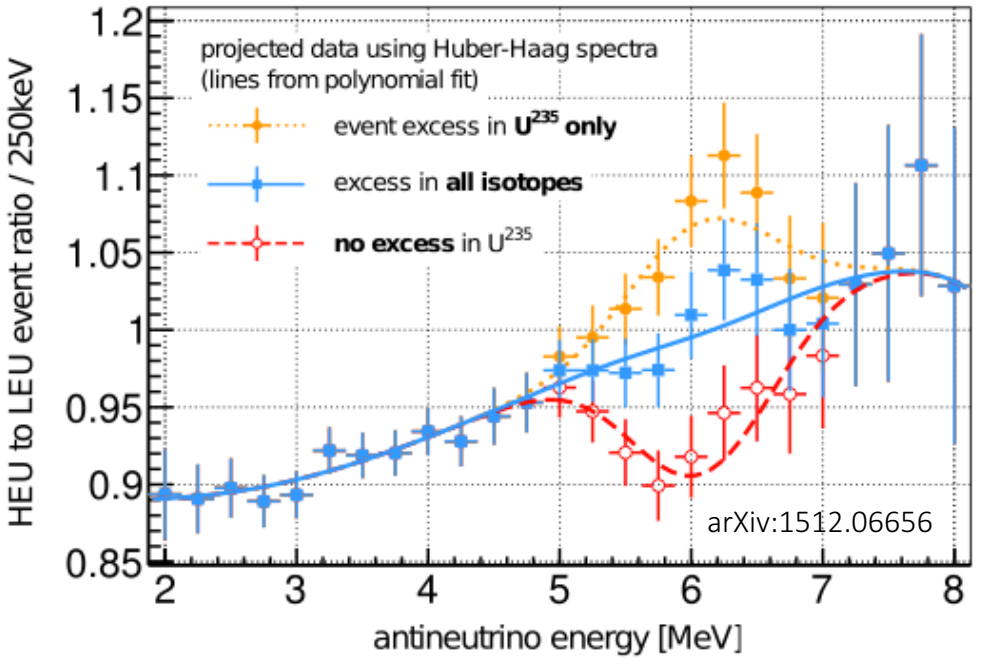


- Robust oscillation analysis based on:
  - Ratios of cell spectra
  - Extensive background characterization (reactor OFF 50% time)

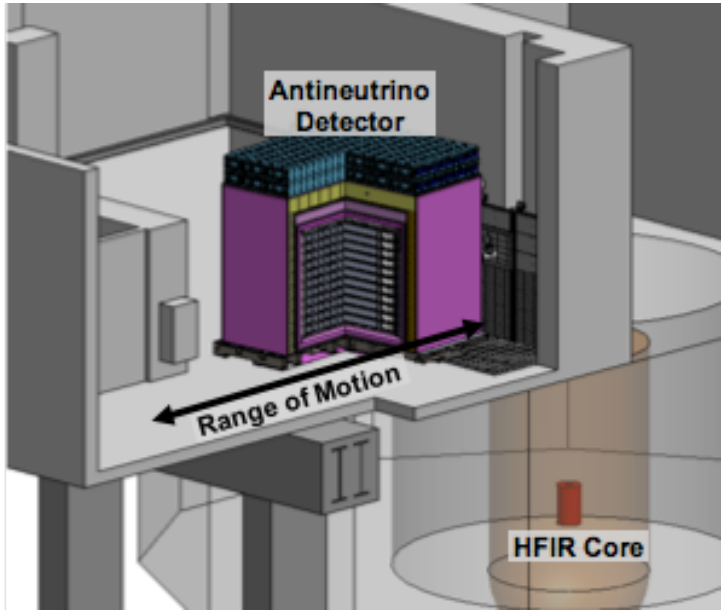
Final sensitivity (2020):

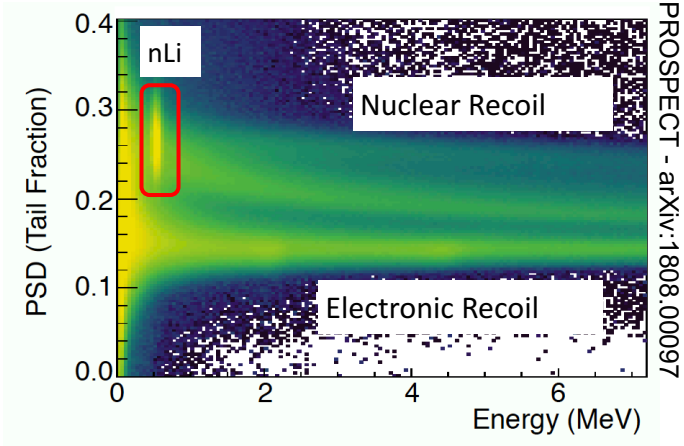
- Covers the whole RAA domain
- Factor 4 variation in L/E
- Test the 5 MeV bump (^{235}U)

Projected sensitivity to ^{235}U spectrum shape



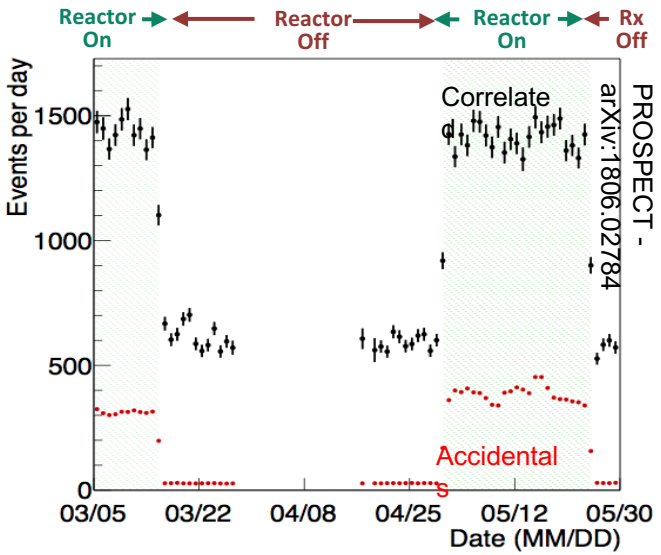
Prospect – 85 MW HFIR compact core - USA

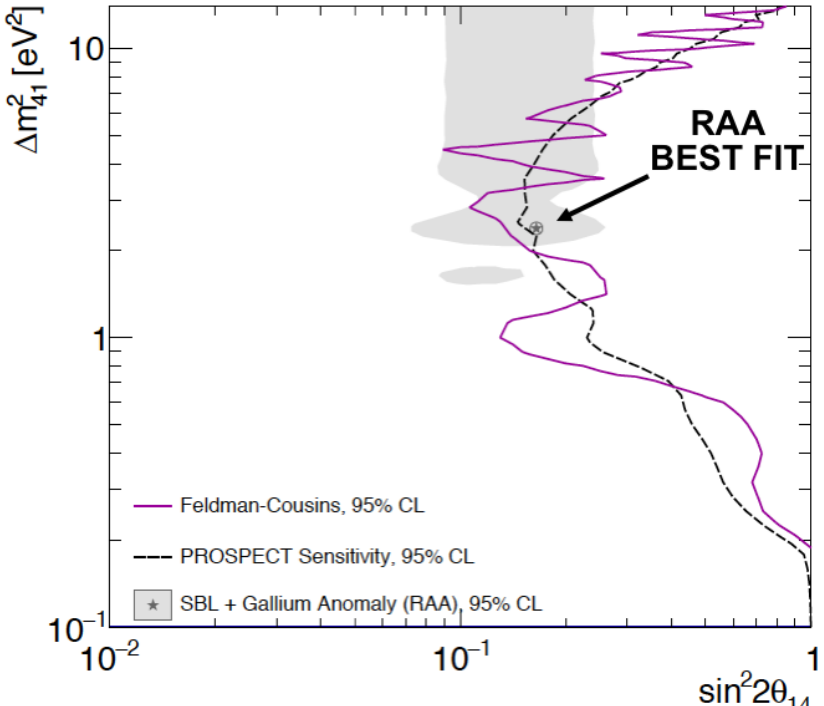




- **At the surface**. Overburden < 1 mwe!
- Baseline: 7 to 12 m
- Pure ^{235}U fission spectrum
- 4t ^{6}Li-doped liquid scintillator segmented detector ~4.5%/√E energy resolution
- High external background mitigated by heavy shielding – Prompt/Delayed IBD PSD capability and event localization
- 750 IBD/day – S/B ~ 1.36
  Best S/B achieved at the surface

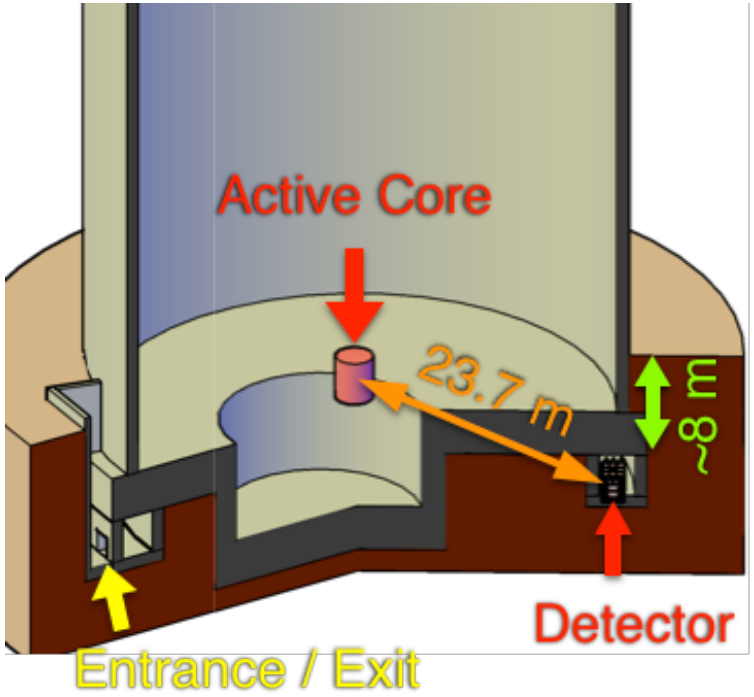
Prospect Results – Exclusion of part the RAA domain

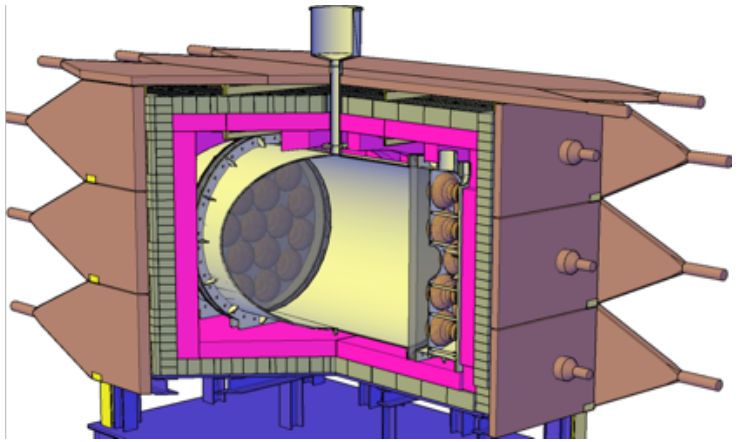




- 5σ neutrino detection achieved in < 2hr
- Oscillation analysis independent of the prediction
- 33 days of data analyzed – Accepted PRL
- RAA best-fit disfavored at > 95%
- Neutrino-4 best-fit disfavored at > 95%
- Next Steps
  - Improved oscillation search with higher statistics
  - ^{235}U reactor neutrino spectrum measurement (test the 5 MeV bump)
  - Detailed modeling of near-surface backgrounds for future experiments

NEOS – 2.8 GW extended core - Korea





- **overburden ≳ 20 m.w.e.**
- Baseline: 24 m
- Homogeneous liquid scintillator detector of 1 ton

  0.5 % Gd loaded, PSD discrimination for n-signal
- Shieldings: 10 cm B-Pe, 10 cm Pb, muon counter
- 2000 IBD evts/day - S/N ~ 22
- Phase 1 - completed: 180 d ON & 46 OFF

  Phase 2 - starting: Origin of the 5 MeV bump

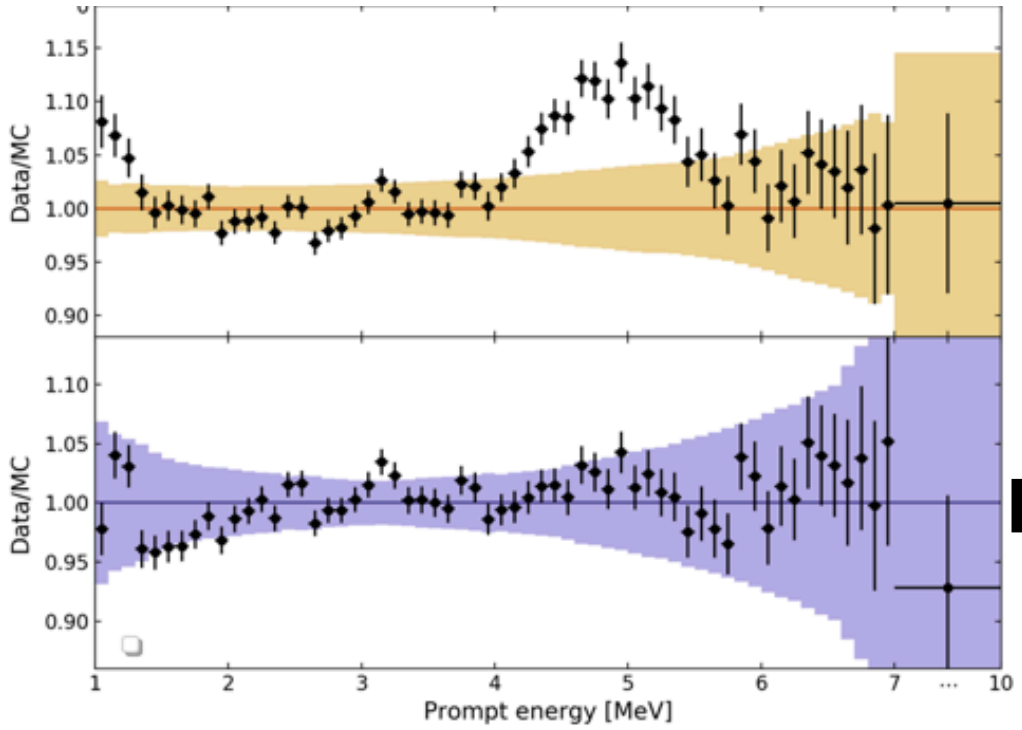
NEOS – Phase I Results

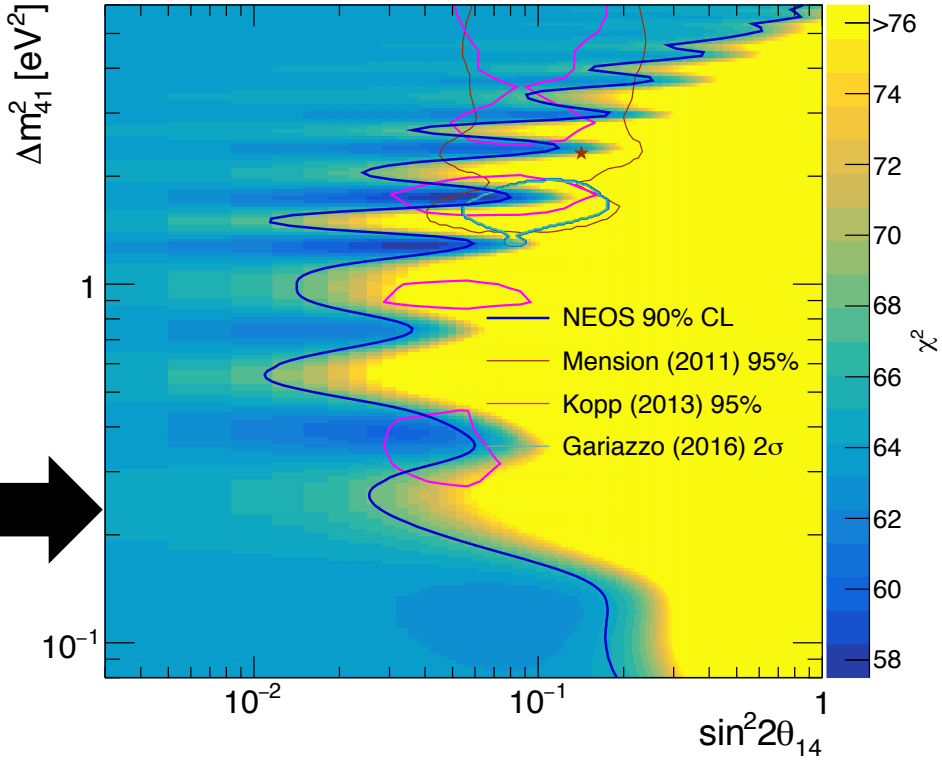
NEOS

Reactor Model

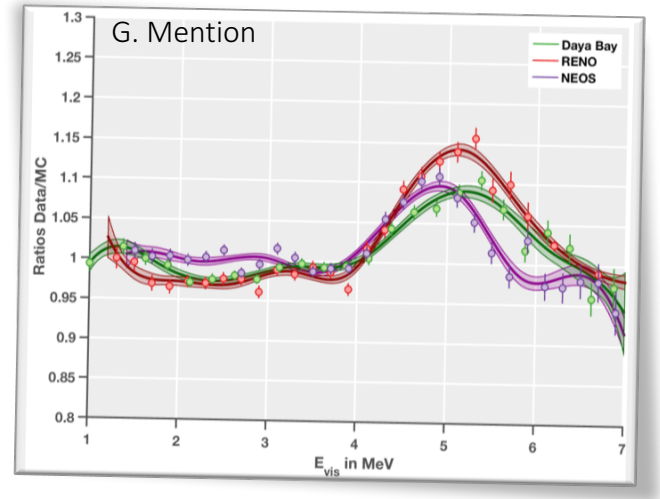
NEOS

Daya Bay Spectrum





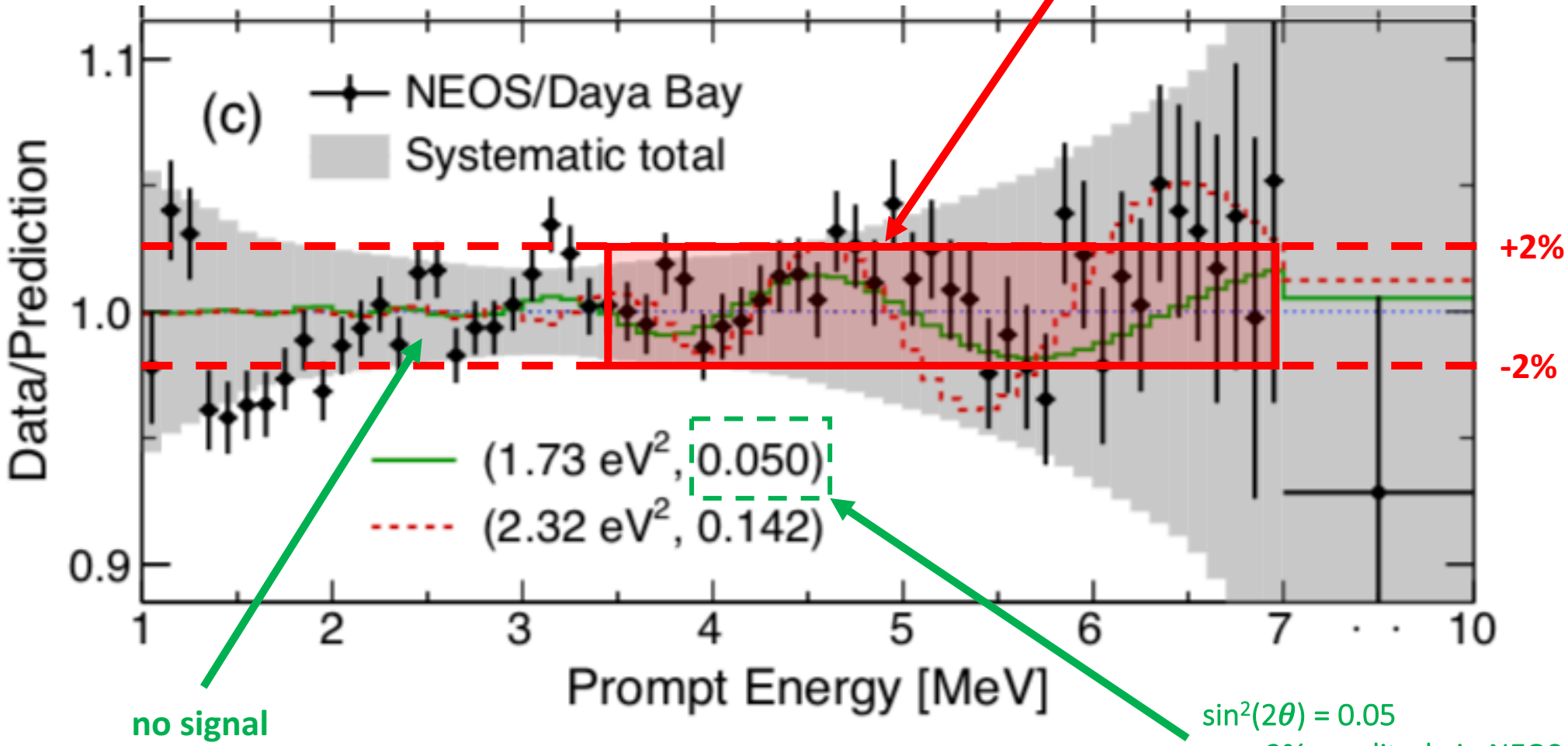
- Exclusion of part of the reactor anomaly region
- Oscillation expected @E>4 MeV: rely on Daya Bay Bump subtraction
- Caveat: RENO/Daya Bay bumps look differents…



Caveat concerning low mixings best-fits – NEOS (2016)

Oscillation signal:
- dominant in the region of the Daya Bay bump subtraction
- washed out since source is extended

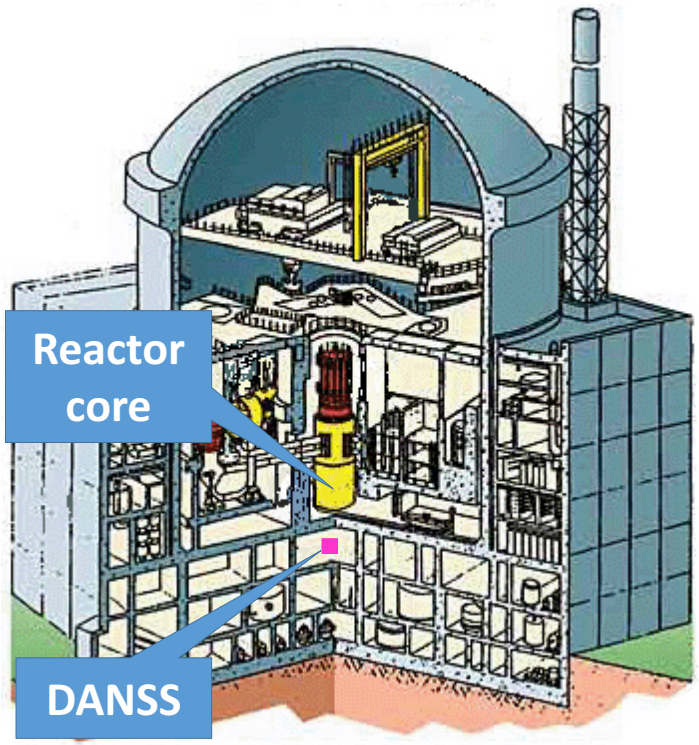
PRL 118 (2017) 12, 121802



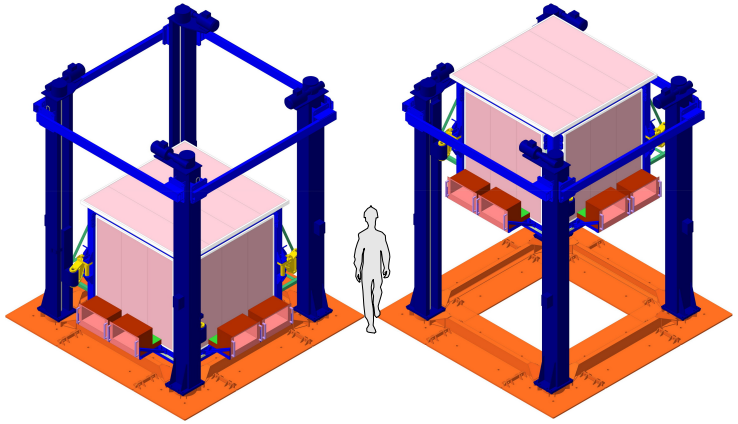
no signal

$\sin^2(2\theta) = 0.05$
- <2% amplitude in NEOS (extended source)
- Embedded by %-ish systematic effects

DANSS – Kalinin 3 GW extended core – Russia

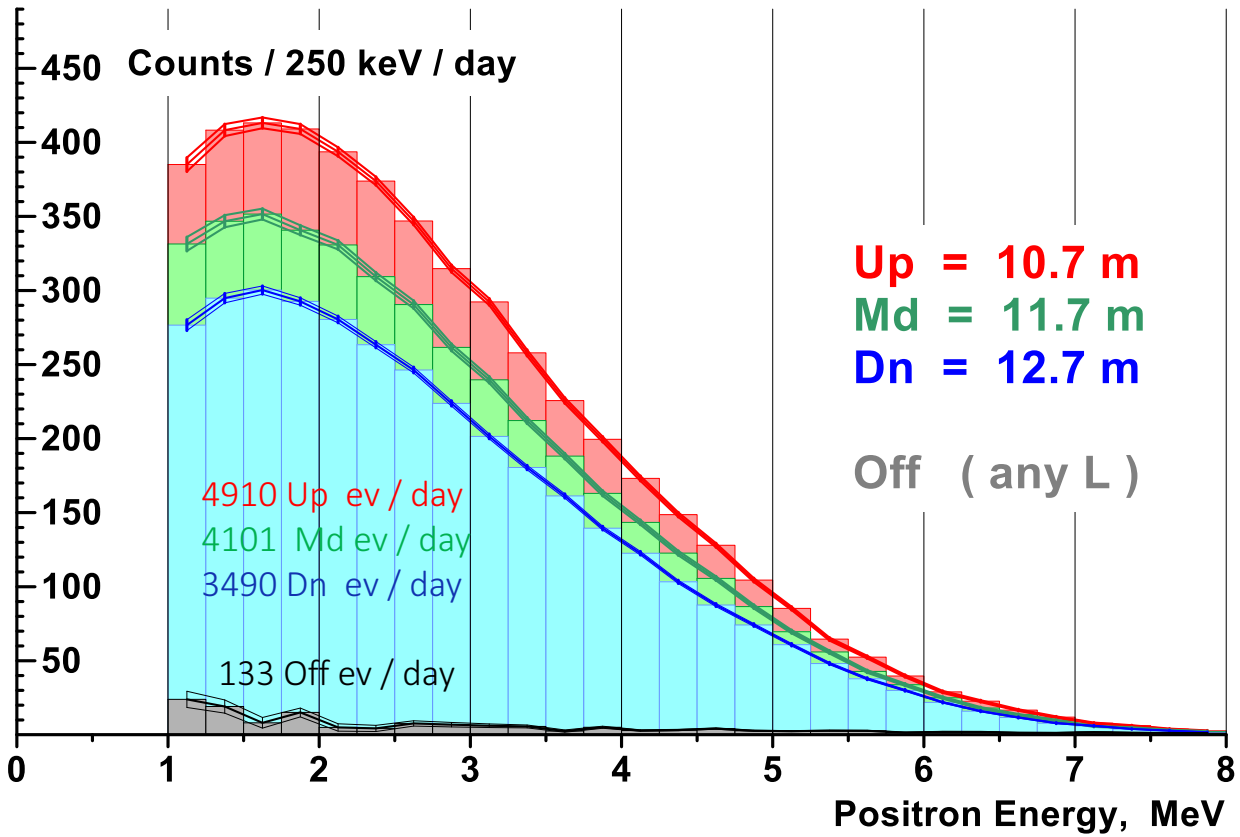


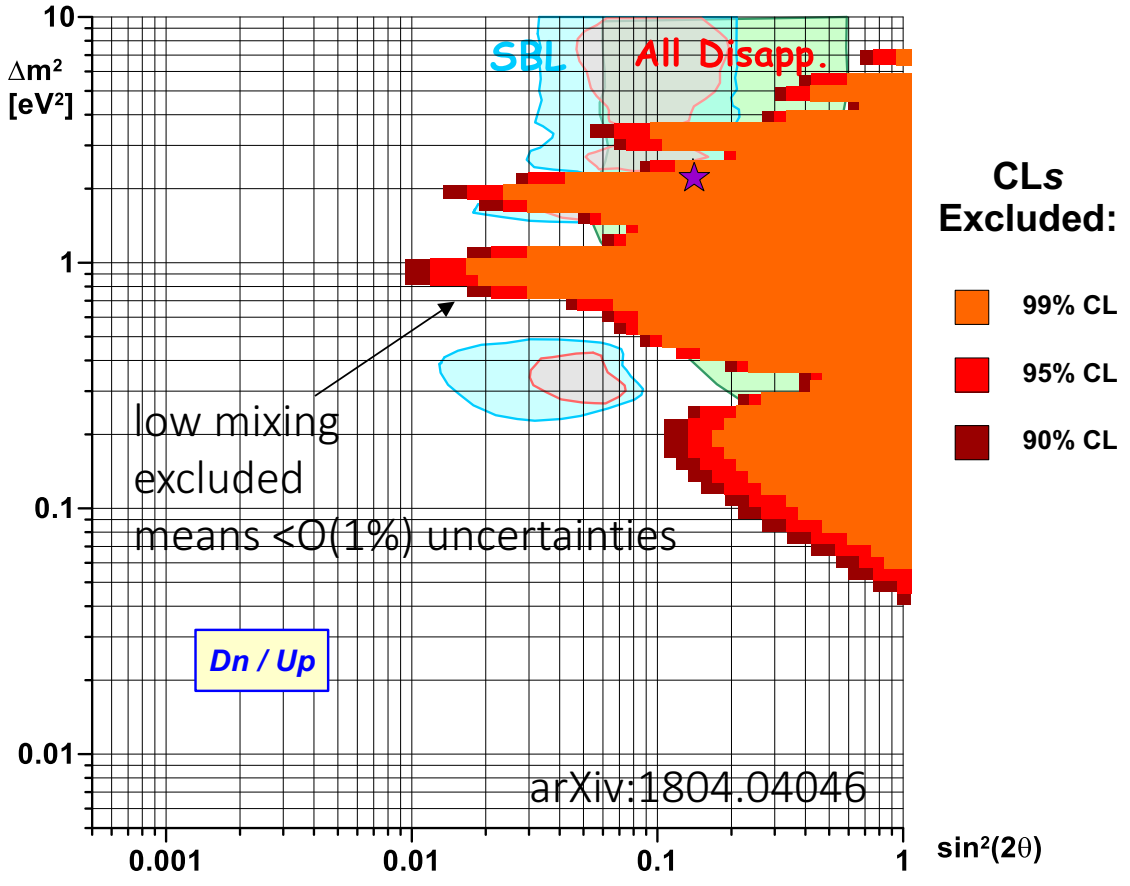
JINST 11 (2016) no.11, P11011



- Overburden ~ 50 m w.e.
- L ≈ 10.7-12.7 m – Evolution of the neutrino flux and spectrum with distance via lifting platform (top/middle/down every 2.5 days)
- Segmented plastic scintillator - 3D-information about each event
- IBD count rate 4000 IBD / day
  High signal / background ~ 40
- Status: 2 y data taking – ½ data analyzed

DANSS – The strongest RAA exclusion

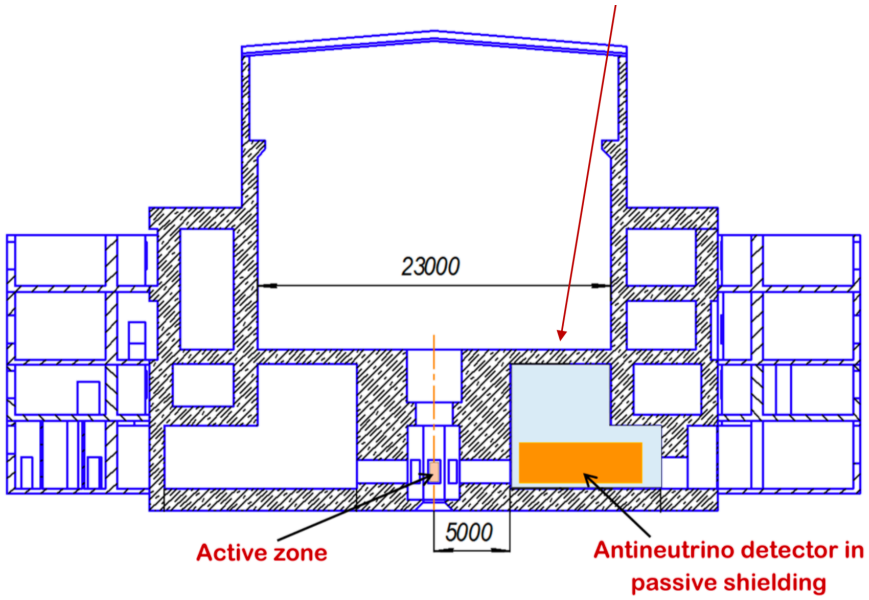


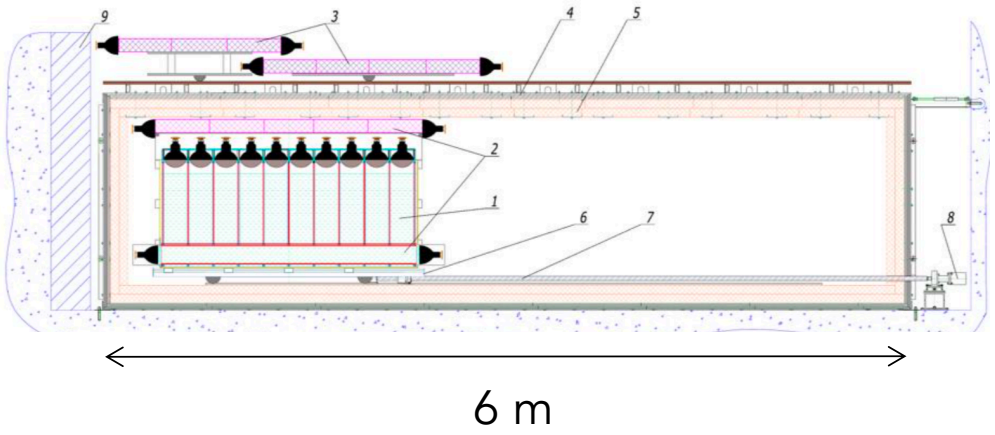


- Reactor modeling independent analysis based on spectral ratio (down /up) → robust
- Exclude most the reactor antineutrino anomaly region – systematics treatment?

$$\chi^2 = \sum_{i=1}^{N} (R_i^{obs} - k \times R_i^{pre})^2 / \sigma_i^2$$

Neutrino-4 – 100 MW SM-3 compact core –Russia



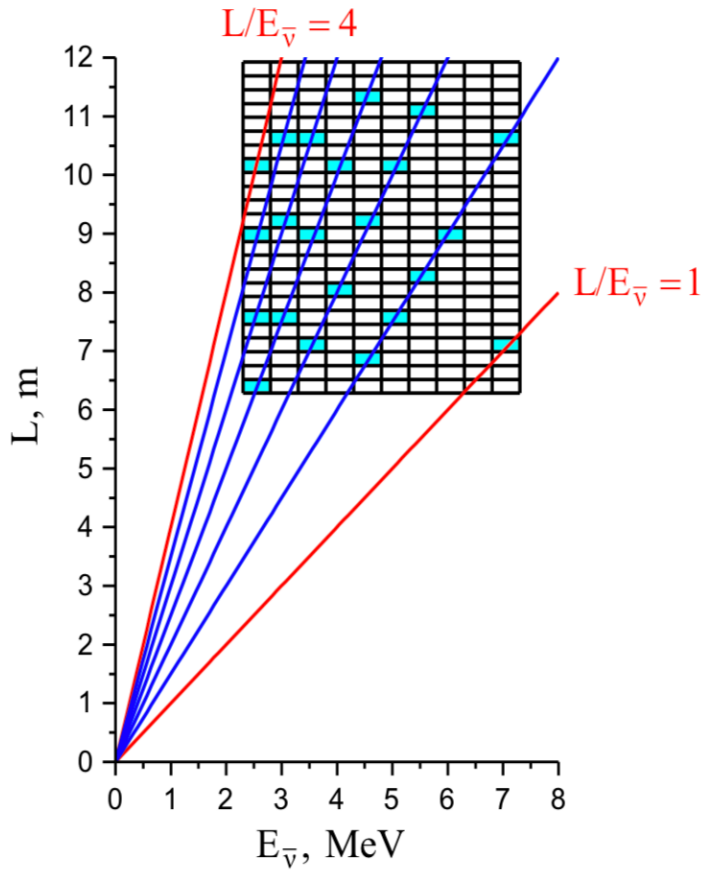


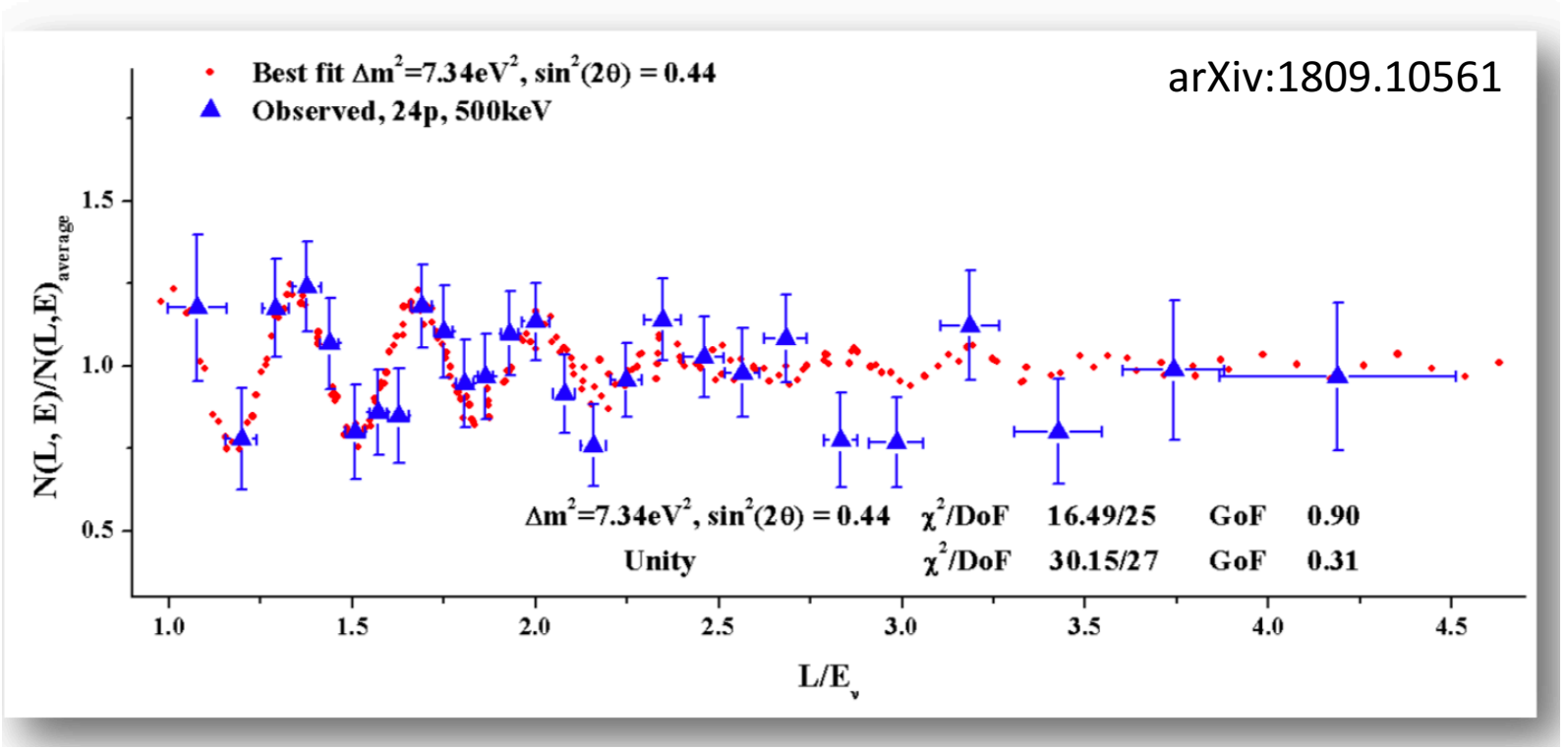
- Overburden: 3-5 mwe
- Baseline: 6-12m
- Pure ^{235}U fission spectrum
- 5x10 identical cells filled with LS-Gd
  Oscillation analysis independent of the prediction
- High external background mitigated by
  - Heavy shielding - PSD capability
- 200 IBD/day – S/B ~ 0.5
- 480 days of data analyzed

Neutrino-4: claim for a 3σ sterile neutrino signal

- Coherent sum of E-spectra from 10 cells at 24xL, binned in L/E
- Model independent analysis

$$R_{i,k}^{\exp} = \frac{N(E_i^{\nu}, L_k)L_k^2}{K^{-1}\sum_k^K N(E_i^{\nu}, L_k)L_k^2} = \frac{[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 L_k / E_i^{\nu})]}{K^{-1}\sum_k^K [1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 L_k / E_i^{\nu})]} = R_{i,k}^{th} \quad (2)$$





arXiv:1809.10561

Neutrino-4: claim for a « 3σ » sterile neutrino signal

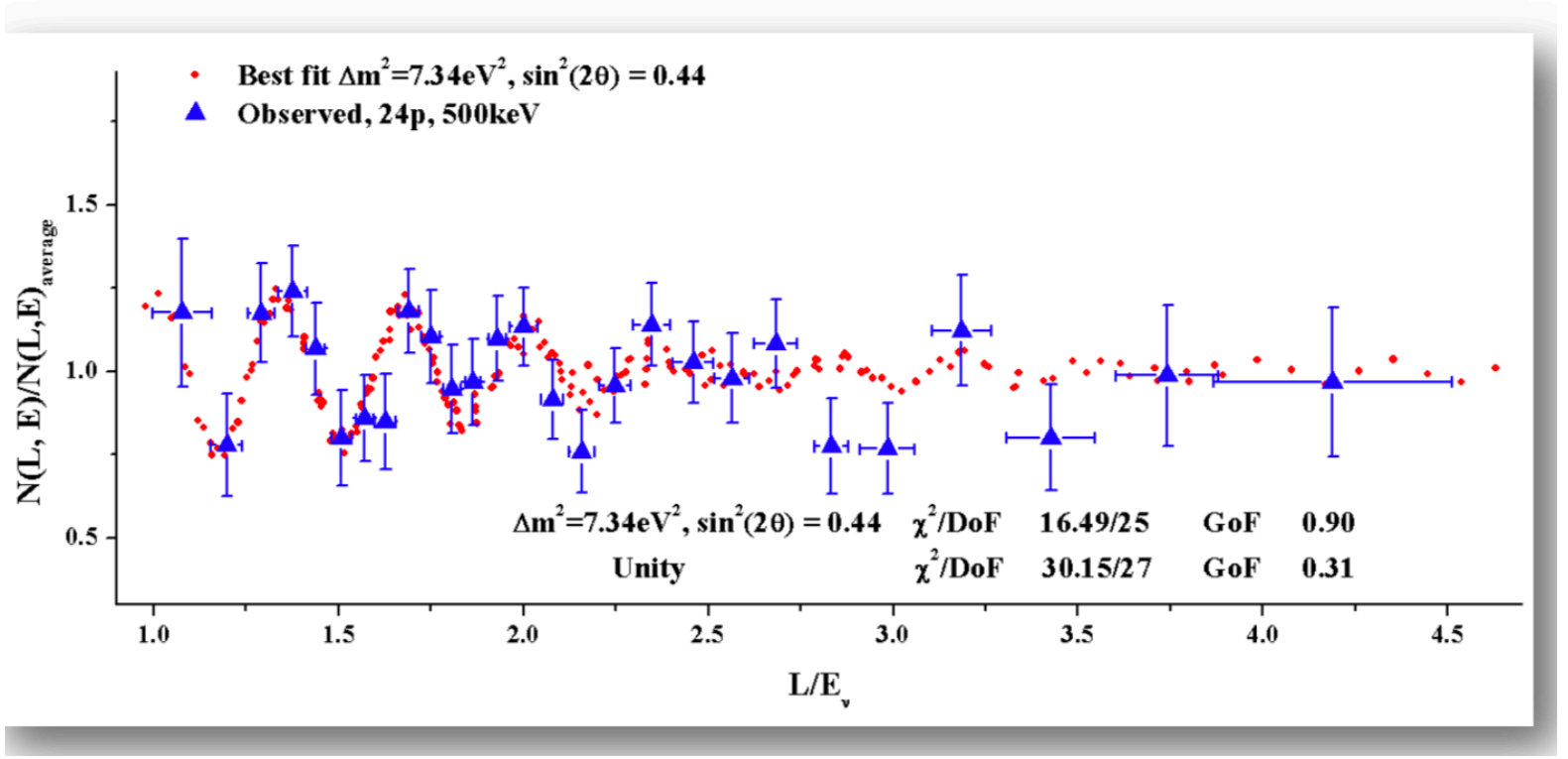
- Analysis
  - Correlations not included (considered small)
  - Systematics considered as negligible

$$R_{i,k}^{\exp} = \frac{N(E_i^{\nu}, L_k)L_k^2}{K^{-1}\sum_k^K N(E_i^{\nu}, L_k)L_k^2} = \frac{[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 L_k / E_i^{\nu})]}{K^{-1}\sum_k^K [1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 L_k / E_i^{\nu})]} = R_{i,k}^{th} \quad (2)$$

- No-oscillation rejected@3σ (see arXiv:1809.10561)

- Best fit
  - $\Delta m^2 = 7.3\ \mathrm{eV}^2$
  - $\sin^2(2\theta) = 0.44$ (17% deficit)

- Large mixing solution!
  - Tension with DC/DB/Reno Stéréo/Prospect/DANSS…



Conclusion and Outlook

- eV-scale sterile neutrinos hypothesis being tested by short baselines reactor expts Chandler, **DANSS, NEOS, Neutrino-4, Prospect, Stéréo**, Solid, …

- 1st Objective achieved: exclusion of part of the RAA Domain. Will improve.

- **2nd Objective: Improve knowledge on reactor neutrino spectra**
  - Understand the 5 MeV Bump (pure ^{235}U ν-spectra) – Not yet completed
  - Reactor Applications

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- Caveat: Oscillation signal(s)
  - $\sin^2 2\theta \geq 0.1$: Neutrino-4 claim for sterile ν (3σ)
    - Not confirmed by others. Background/analysis/systematics to be discussed.
  - $sin^2\, 2\theta \ll 0.1$: NEOS, DANSS best-fits
    - Oscillation signal amplitude comparable to systematics (underestimeted?)
    - Difficult to address at high-significance with current SBL reactor experiments!

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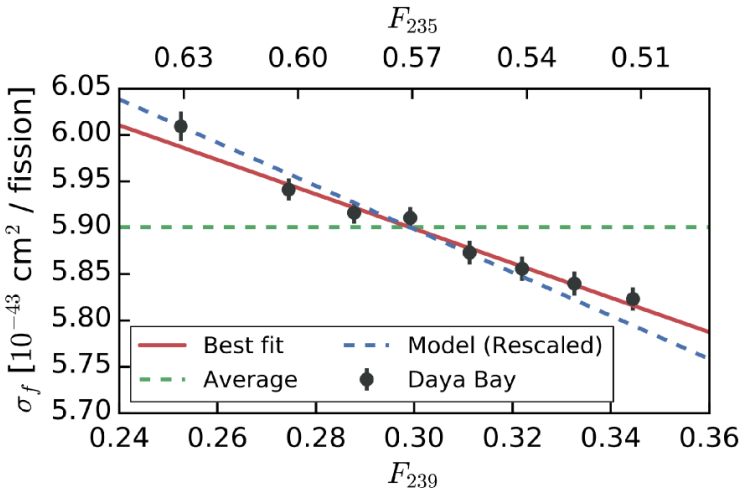
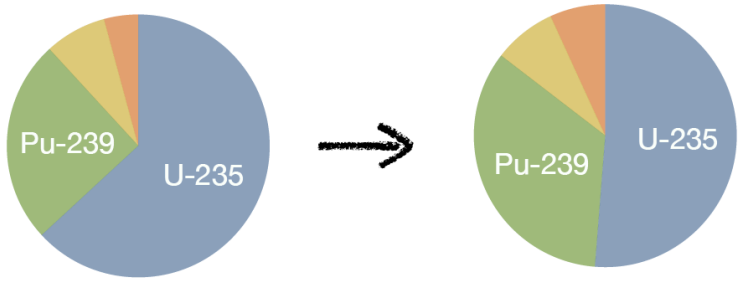
eV-sterile neutrino search results @SBL Reactor Experiments

Expt	Reactor	Over-burden	L (m)	$\sigma_E/\sqrt{E}$	Detector / segmentation	IBD signal	S/N	syst	Results
NEOS	Extended 2800 MW ^{235}U, ^{239}Pu	20 mwe	24	5%	Gd-LS 1 cell PSD: delayed	2000/day	22	few %	Partial exclusion of RAA
Stéréo	Compact 50 MW ^{235}U	15 mwe	9-11		Gd-LS 6 cells PSD: delayed	400/day	1	2.3%	Partial exclusion of RAA
Neutrino-4	Compact 100 MW ^{235}U	surface	6-12		Gd-LS 10 cells	200/day	0.5	few %	Claim for a signal $\Delta m^2 = 7.3\ eV^2$ $sin^2(2\theta) = 0.44$
DANSS	Extended 3000 MW ^{235}U, ^{239}Pu	50 mwe	11-13		PS+WLS 2500 strips	4000/day	40	few %	Largest exclusion of RAA
Prospect	Compact 85 MW ^{235}U	surface	7-12	4.5%	^{6}Li-LS 154 cells PSD: prompt/delayed	750/day	1.4	few %	Partial exclusion of RAA

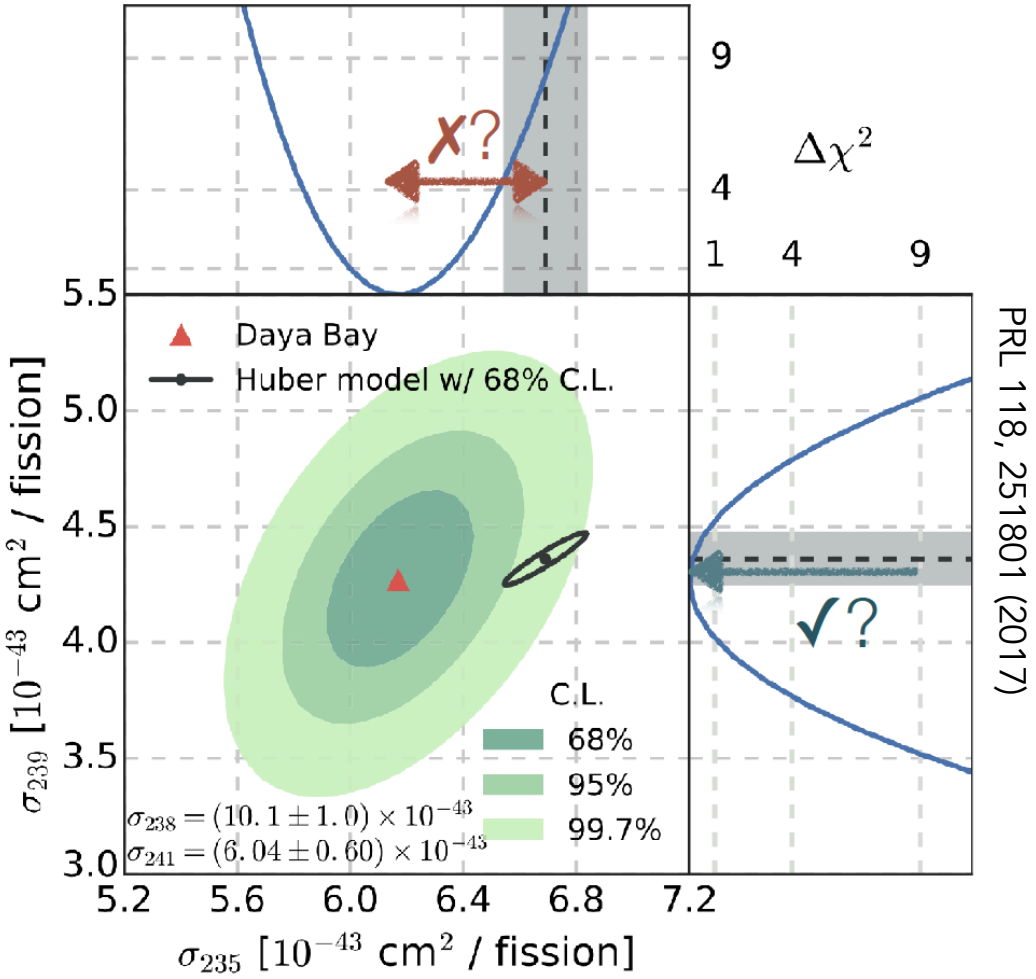
Reactor Neutrino Spectra (Daya Bay)

Claim for a mismatch concerning ^{235}U **ν-flux** in reactor models?





~2.2 10^6 neutrino candidates



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