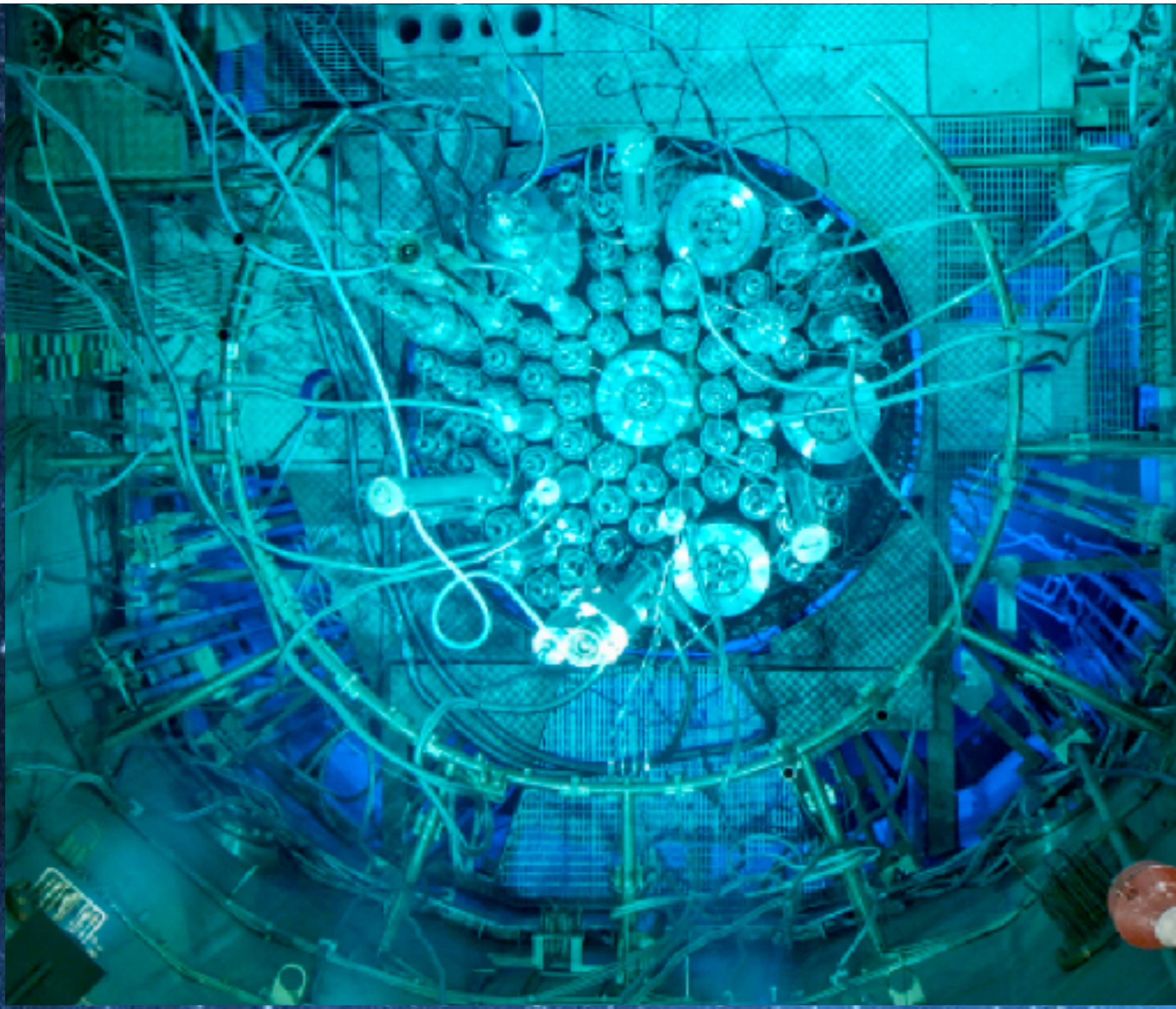
Sterile Neutrino Search at Reactors

Antonin Vacheret

Neutrino workhsop 2019
24-25 October 2019,
Prague, CR

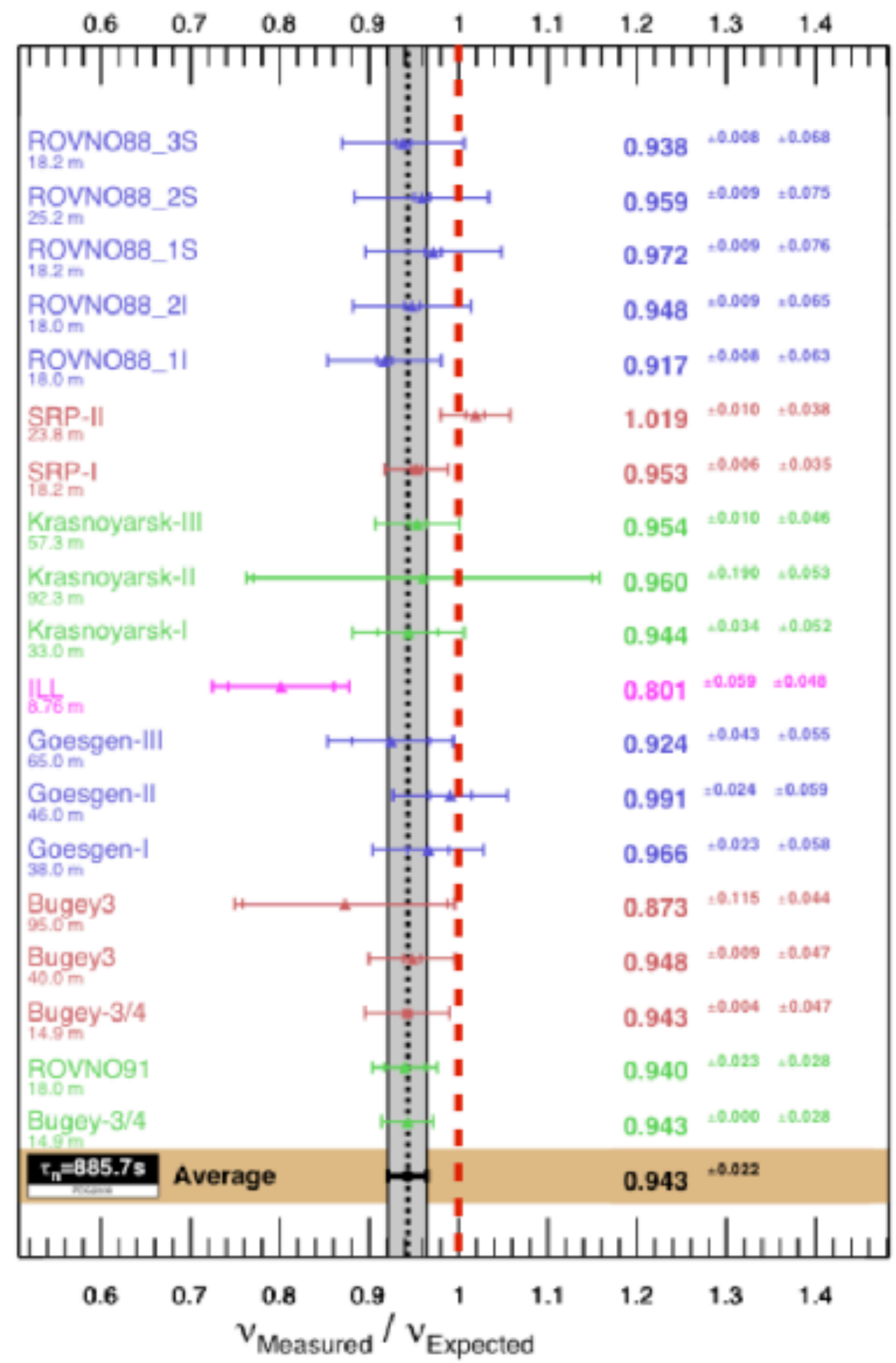


Outline

- Review of reactor anomalies and
- Recent results and review of Very short baseline experiments
- Summary

Reactor Anomaly

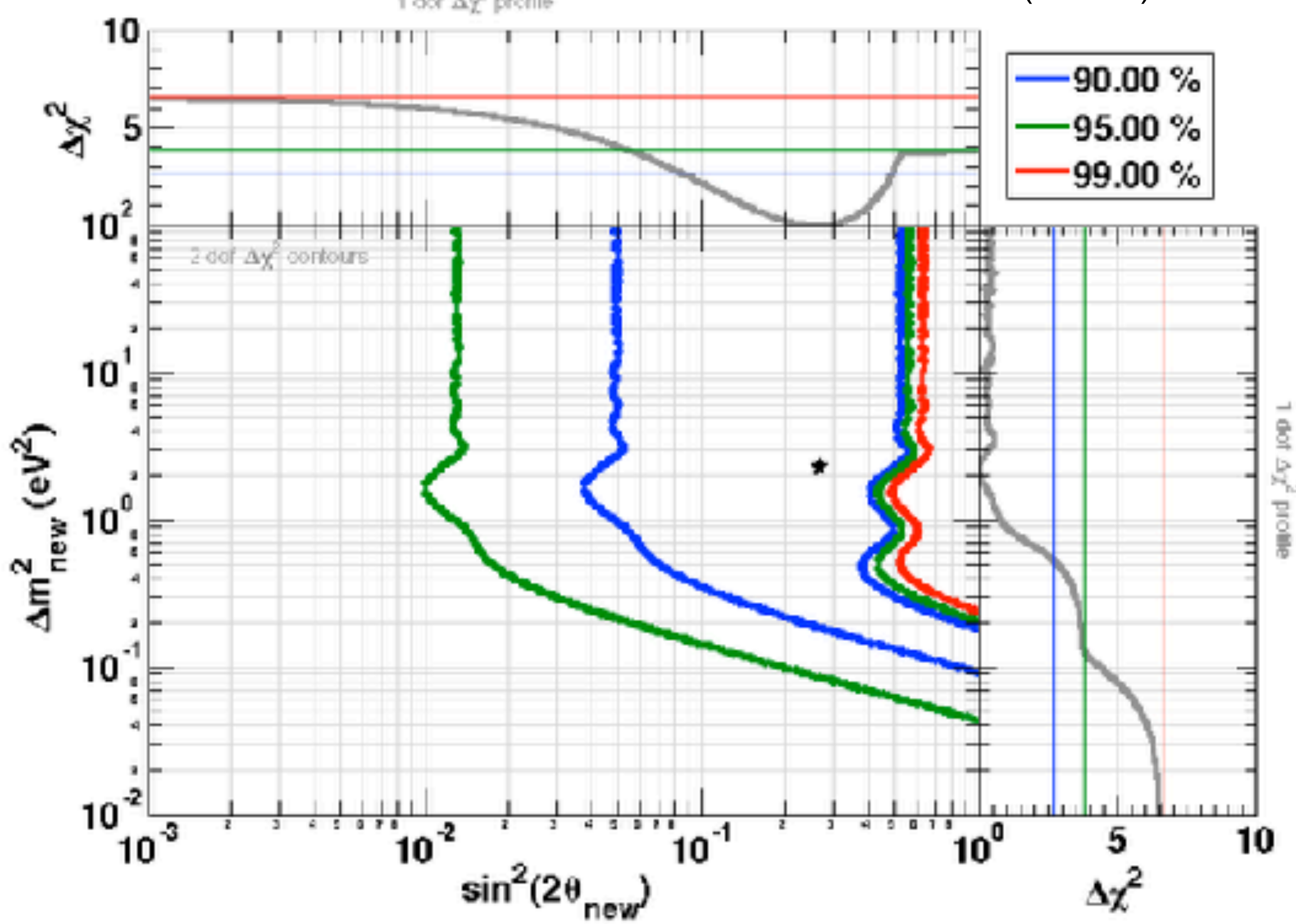
G. Mention et al., PRD 83 (2011) 073006



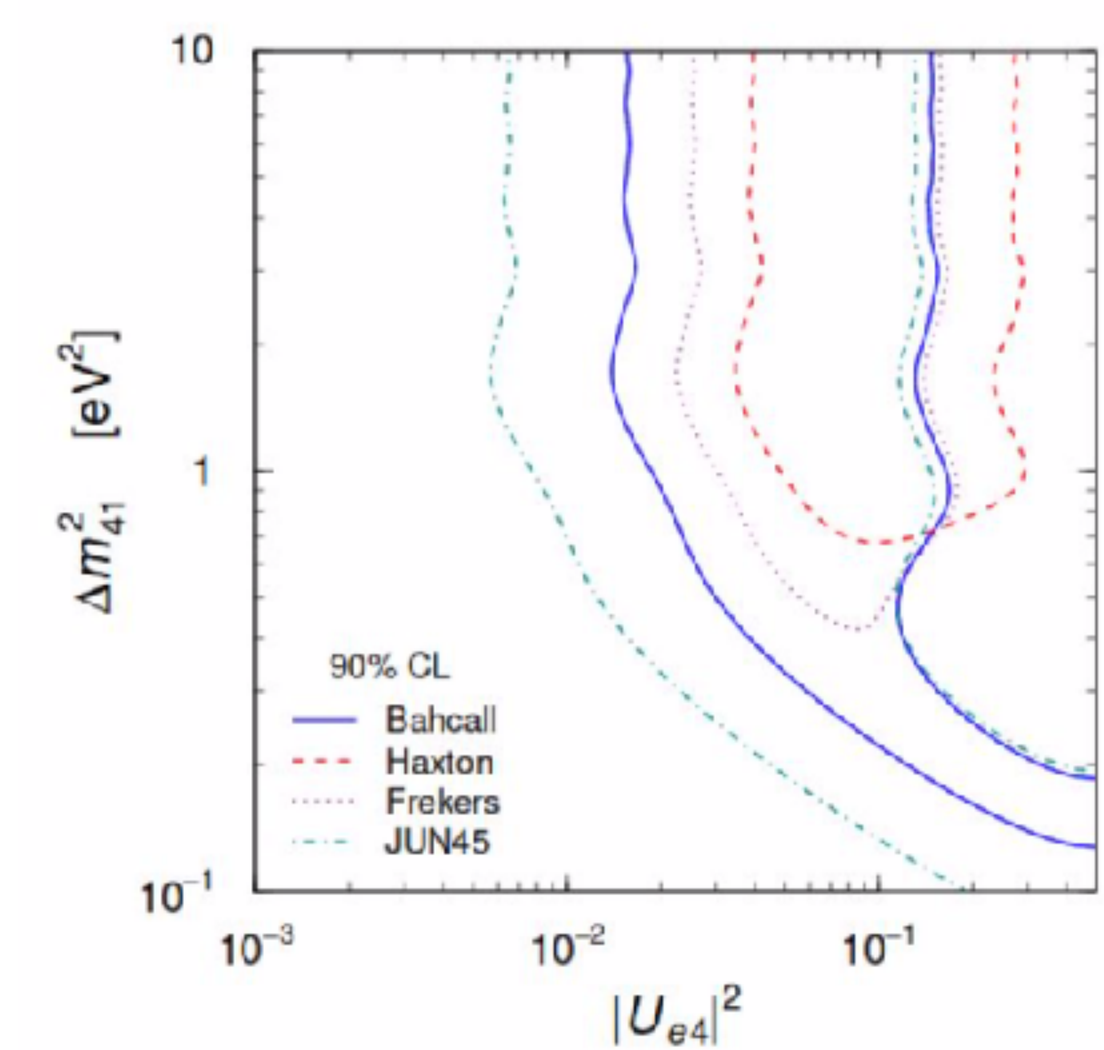
- 2011 reactor anomaly
  - +1.5% from update on neutron lifetime
  - +3.5% from revised conversion
- Moves all data down creating an anomaly at 2-3 sigma

Gallium Anomaly update

C. Giunti & M. Laveder in PRD82 053005 (2010)



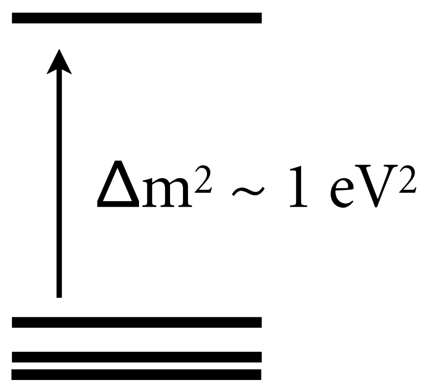
Kostensalo et al., 1906.10980



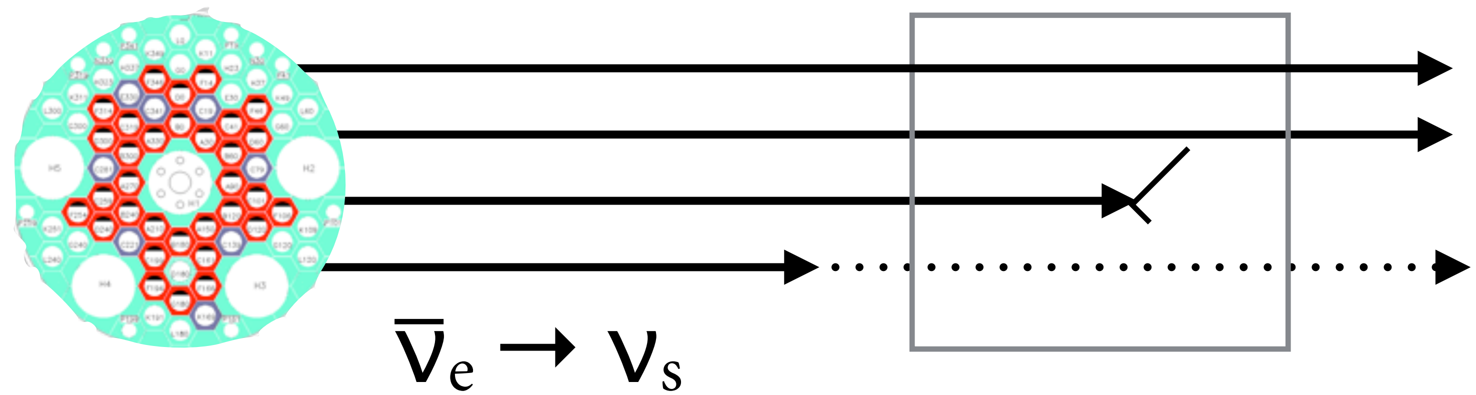
- Review of cross section calculations has pushed the value down
- Comes closer to the RAA opened region but significance goes from 3 to 2 sigma
  - Electron neutrino disappearance anomaly smaller and more consistent

The sterile neutrino hypothesis

3+1 model

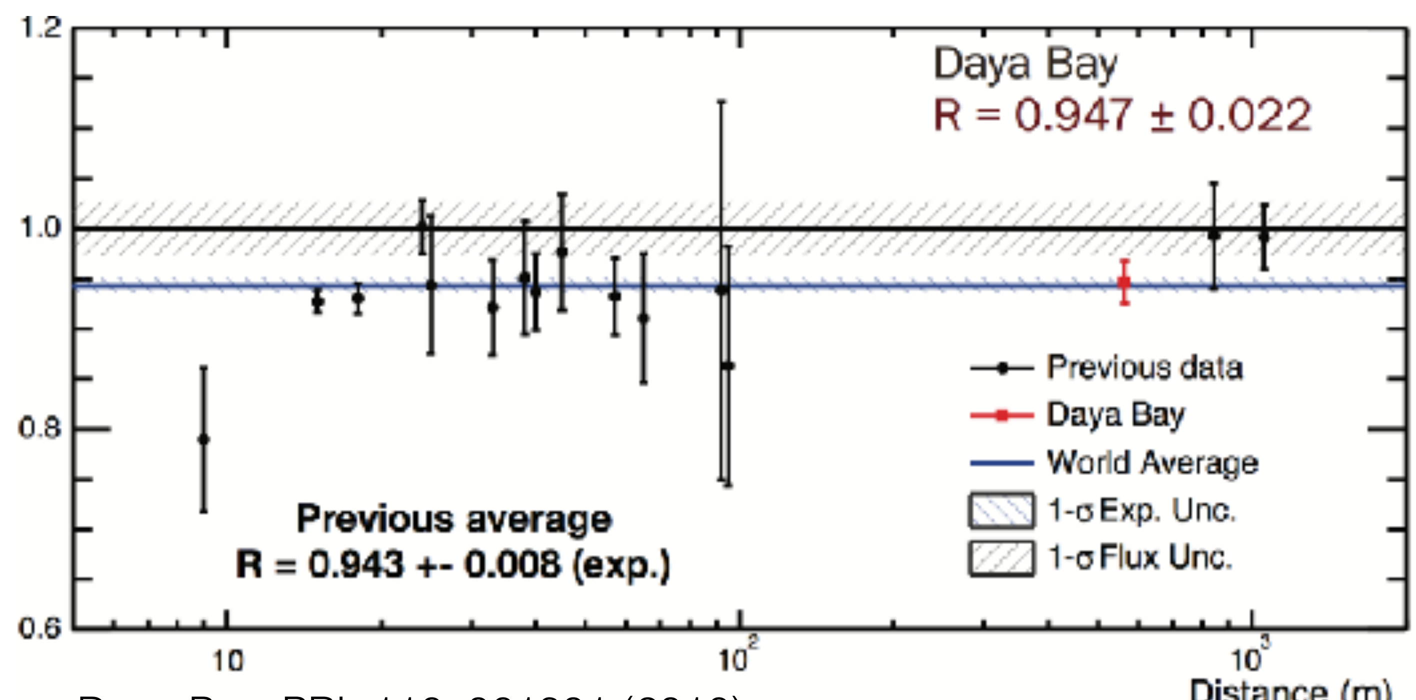


antineutrino source **detector**



- Additionnal mass state participating to mixing give simple explanation of reactor antineutrino and Gallium anomalies
- not detectable through weak interaction, only indirect measurement possible via oscillation
- small correction from 3 x 3 neutrino mixing to explain active neutrino oscillation data
- First best fit gave **Δm^2 ~ 1.73 eV^2** and $\sin^2(2\theta)$ ~ 0.1
- 3+1 model simplest
  - additional sterile neutrino allowed

$$P_{ee} \sim 1 - \sin^2(2\theta_{14})\sin(1.267\Delta m_{14}^2\, L[m]/E[MeV])$$

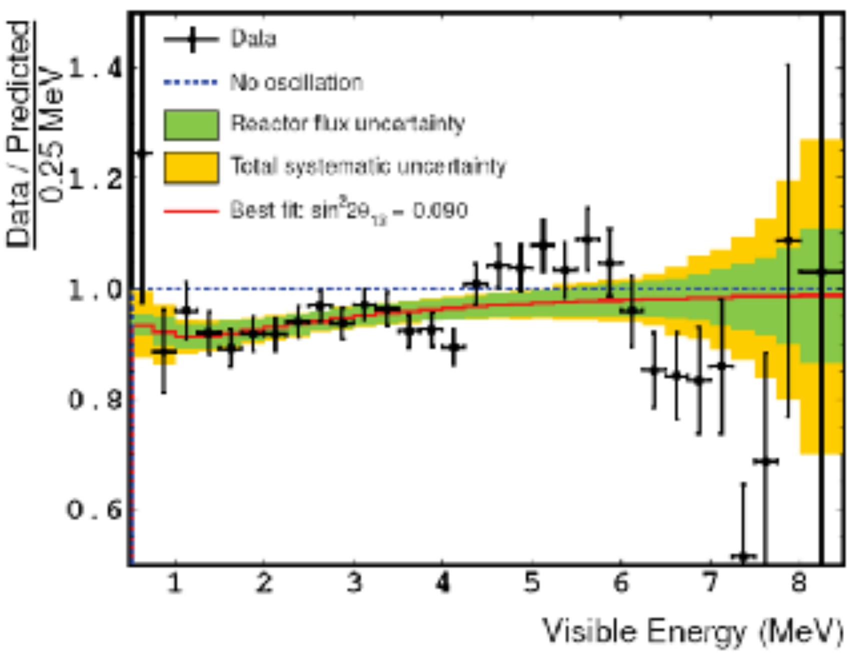


Daya Bay, PRL 116, 061801 (2016)

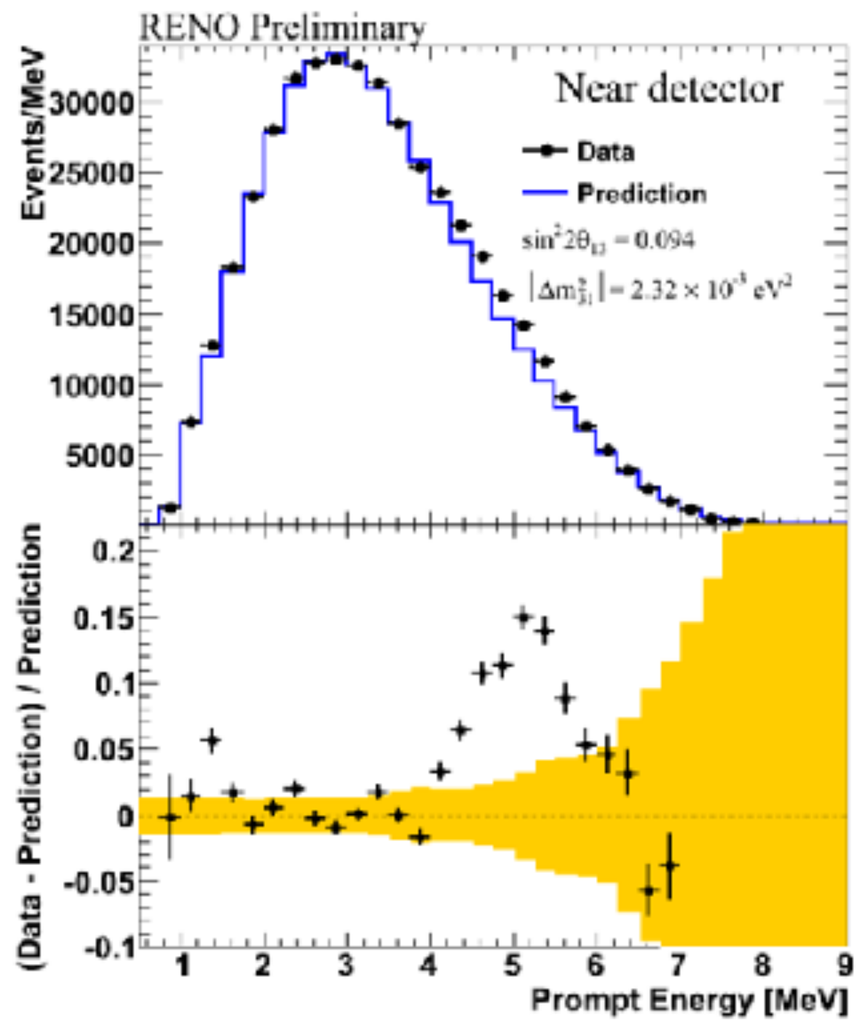
2014: Reactor spectrum distortions

D-CHOOZ

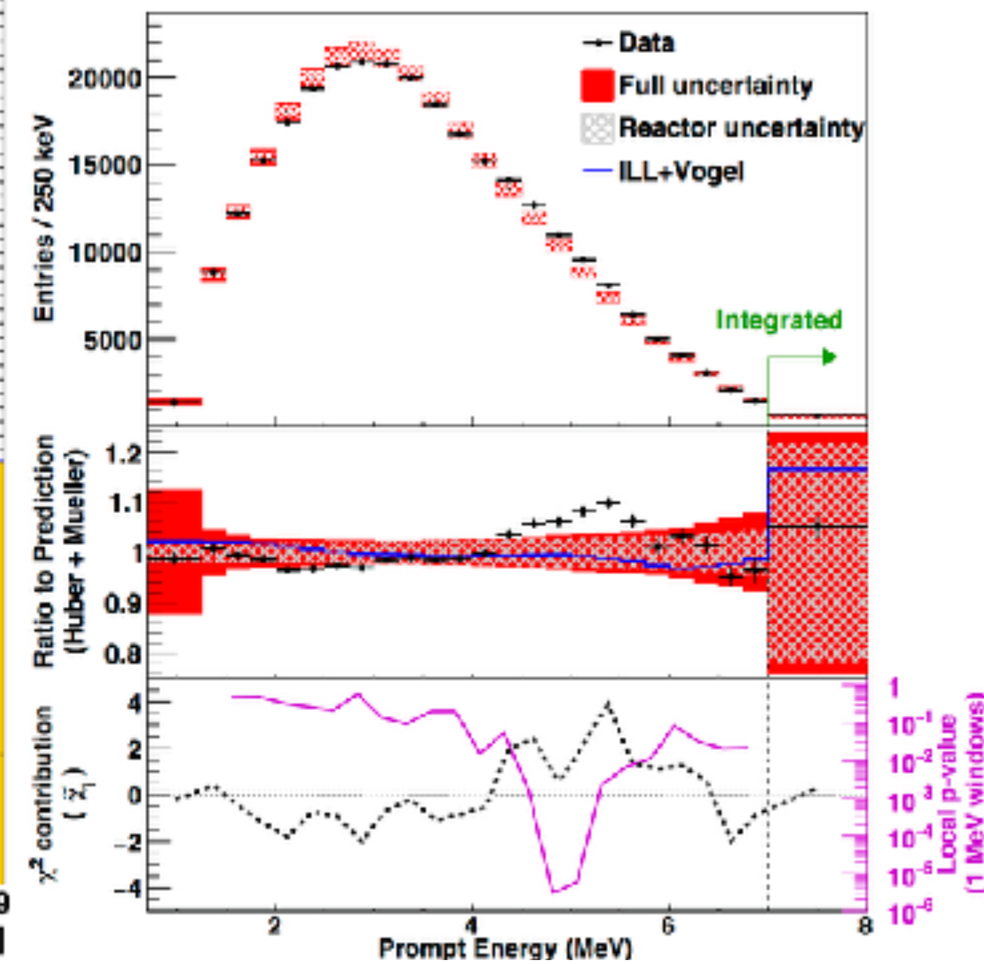
$$E_\nu \simeq E_{e^+} + m_n - m_p$$



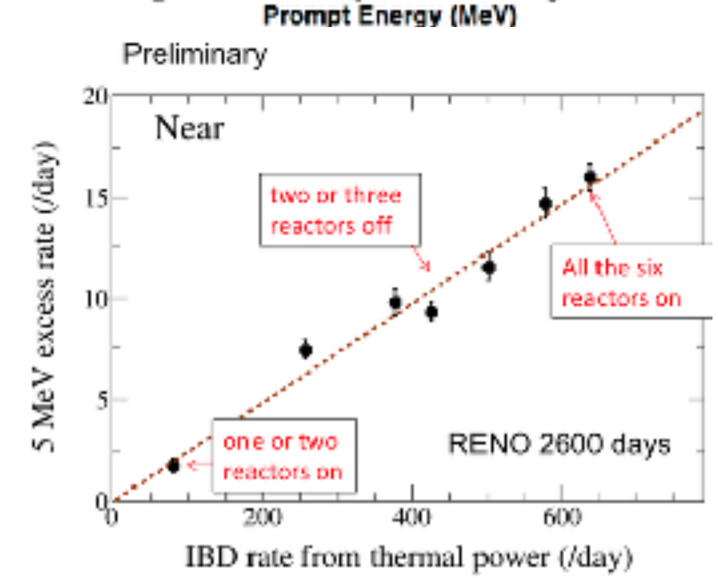
RENO



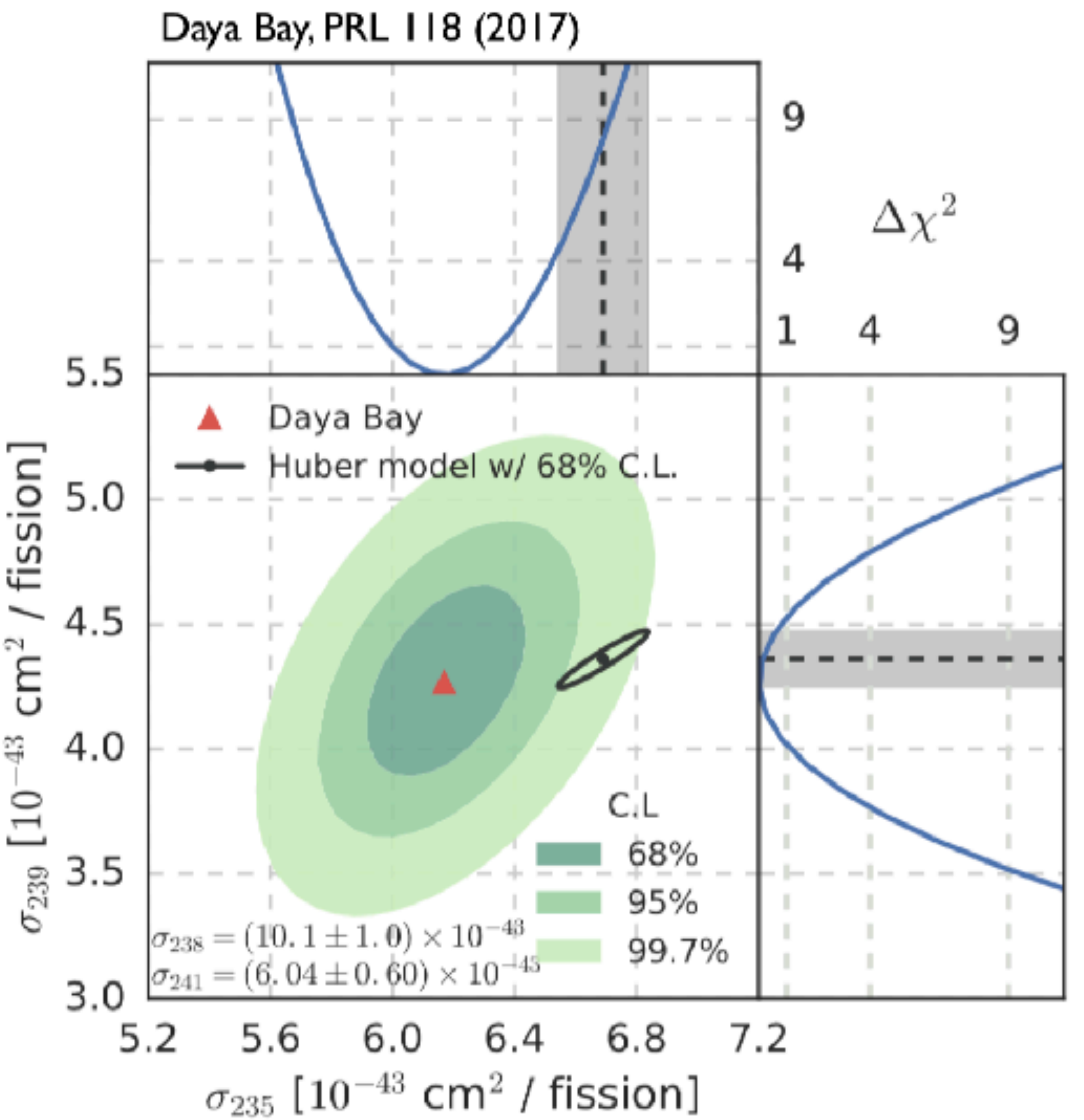
DAYA BAY

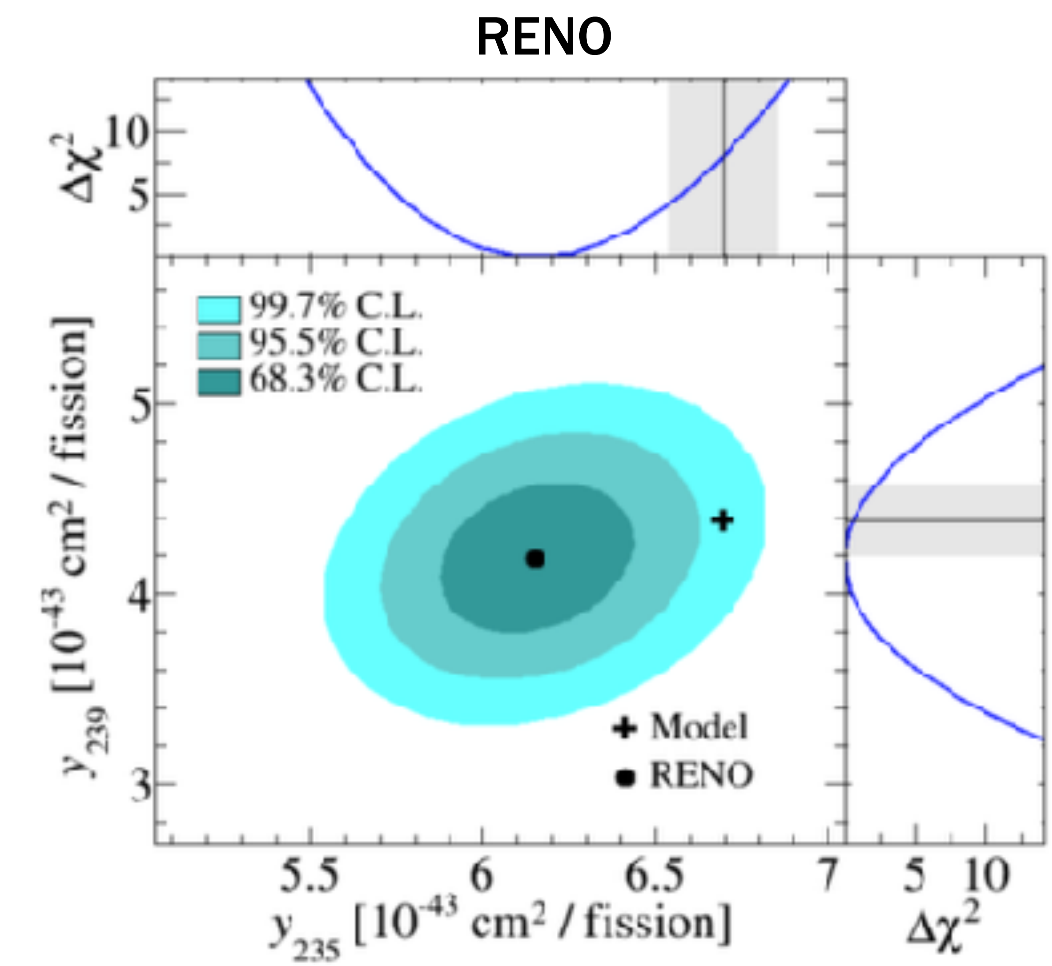


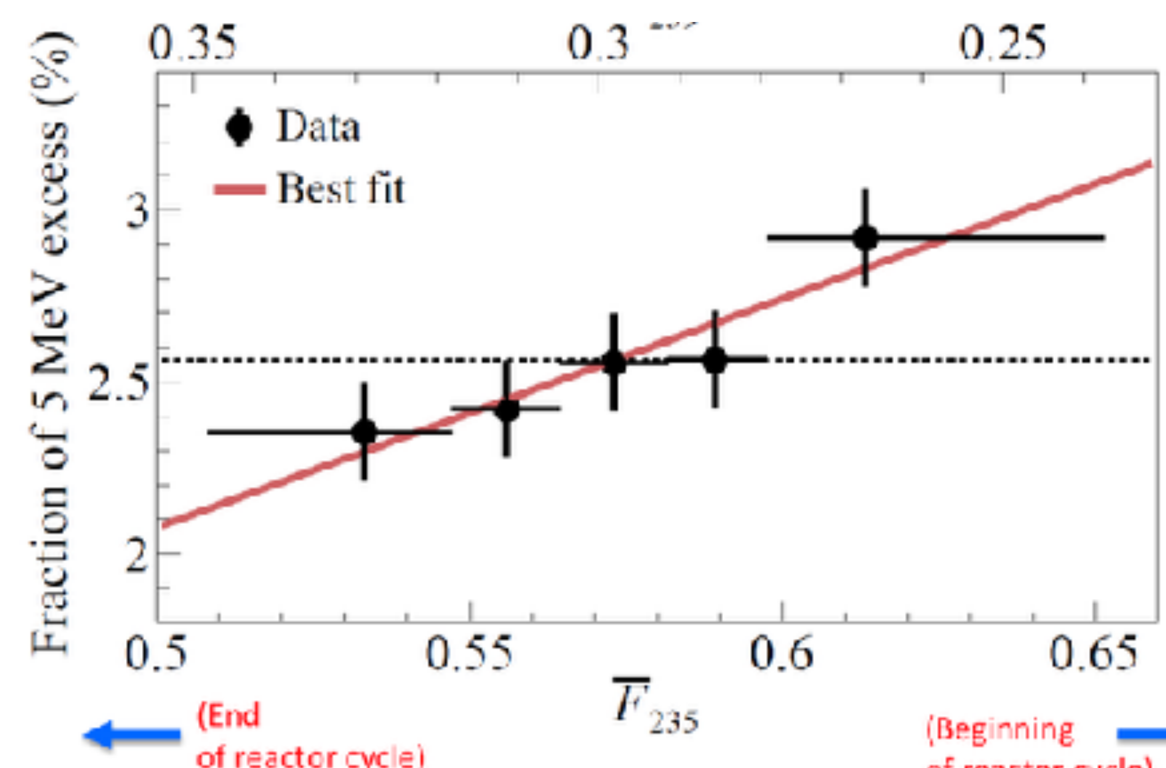
- Energy spectrum distortion seen by all three reactor experiments with high significance (dubbed “the bump”)
- Amplitude of effect correlated with reactor power
- Cancels in near-far ratio
- Not observed by previous Bugey 3 experiment



Study of yield per fission







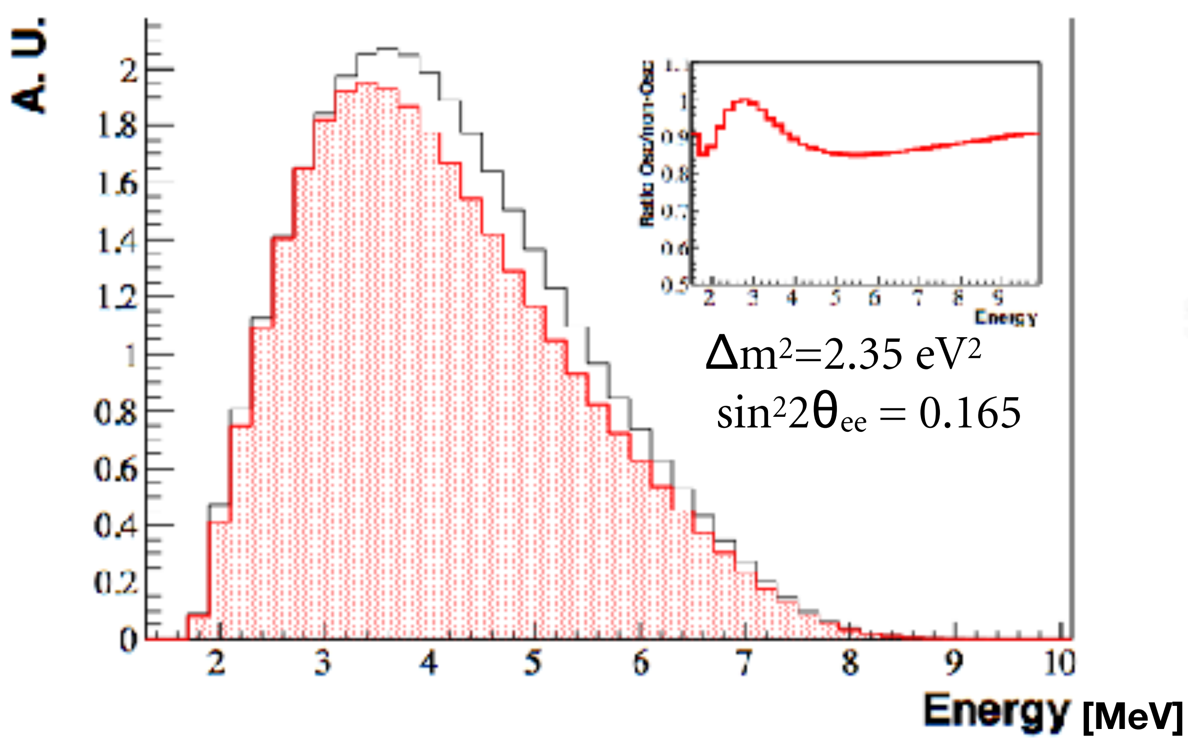
- Points to a issue with U-235 yield mostly

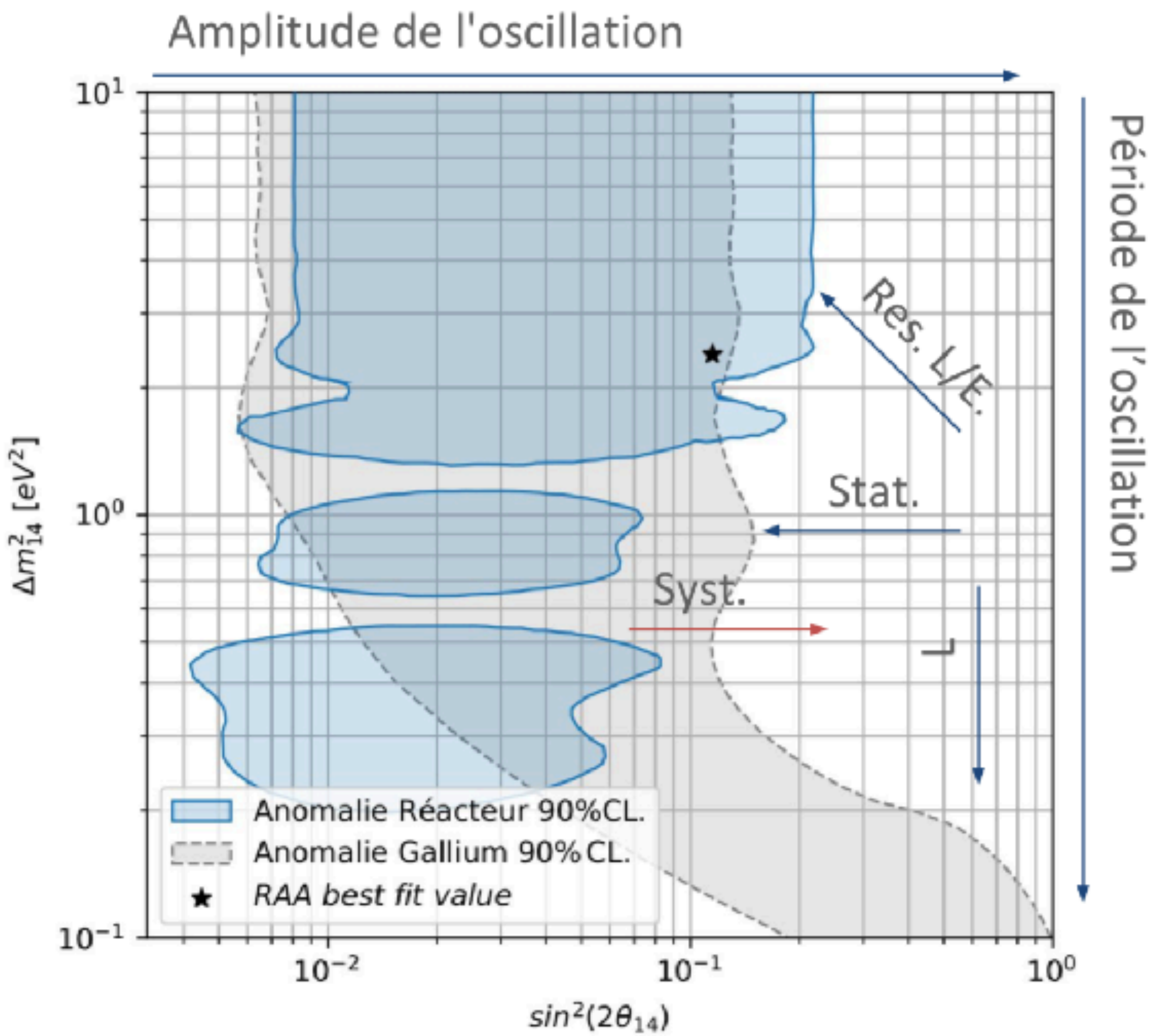
Anomalies: what are the fundamental issues here ?

- Theoritical
  - Reactor flux models : complex calculations relying on knowledge of thousands of beta branches, beta decay
  - Although not as complex as for higher energy neutrino interactions, IBD cross-section.
- Experimental
  - Absolute normalisation: comparing rates requires to understand all normalisation errors. Percent level is extremely challeging ! requires detector systematics
  - Spectrum shape: intrinsically related to how you reconstruct the energy hence the detector technology, reconstruction and calibration strategy. Energy scale biases can create distortions
  - Reference-free measurement: rely on very good uniformity of response in E and L

Sensitivity to a new neutral state

- Sterile neutrino oscillation in L and E
- Sensitivity strongly depends on stats and S:B
- large coverage in L/E possible with good energy resolution
- A strong test depends on the experimental strategy
  - optimum baseline
  - near-far ratio to cancel normalisation errors
  - control of normalisation allows for better limit but harder to achieve





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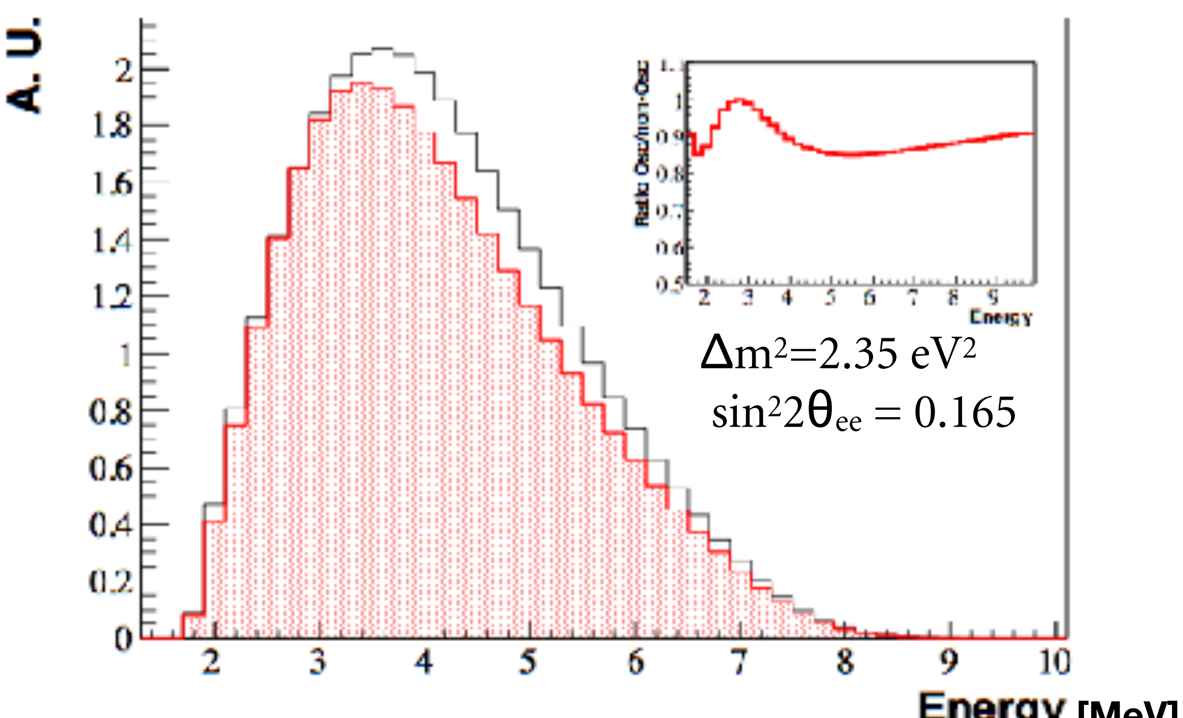
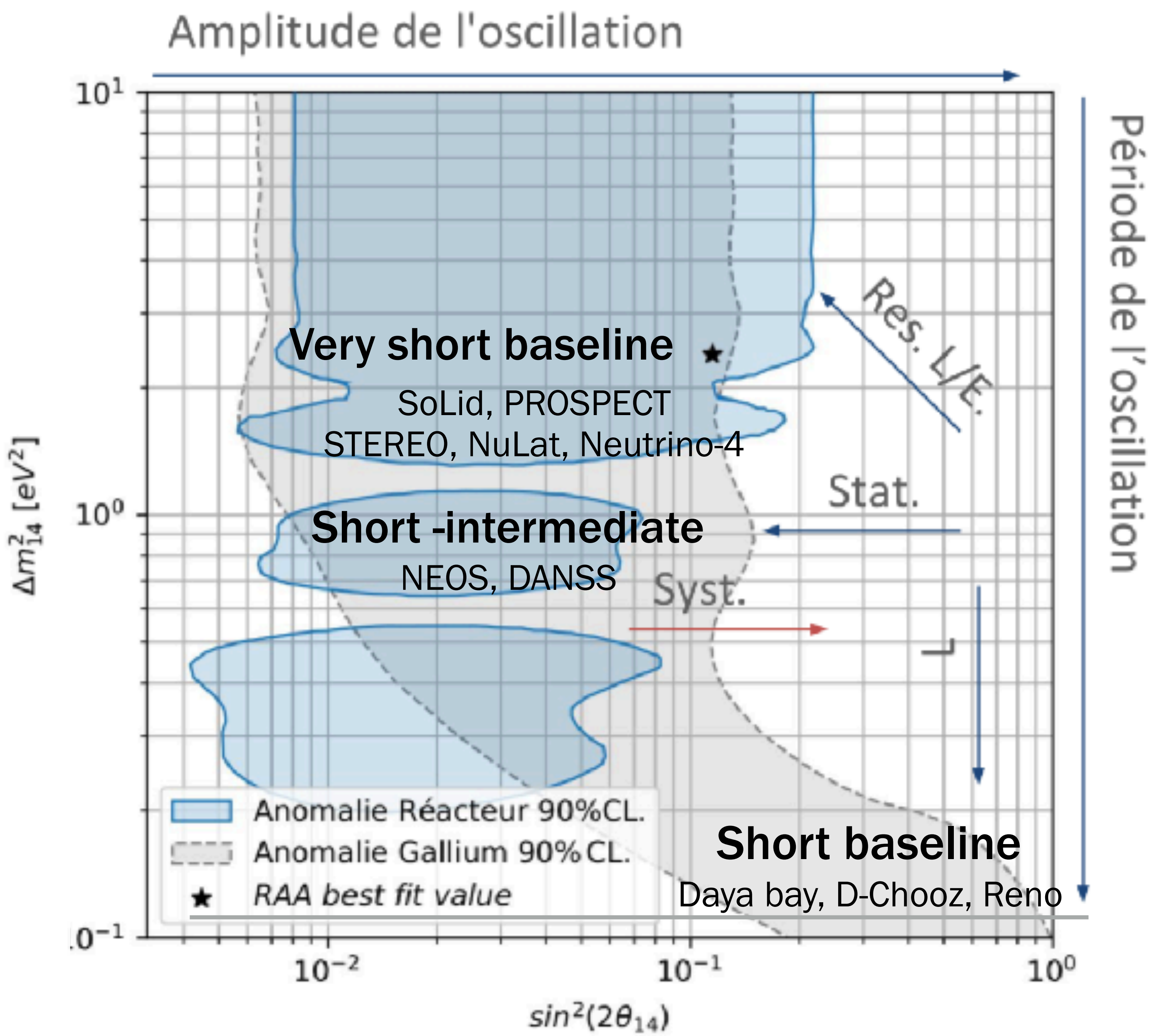




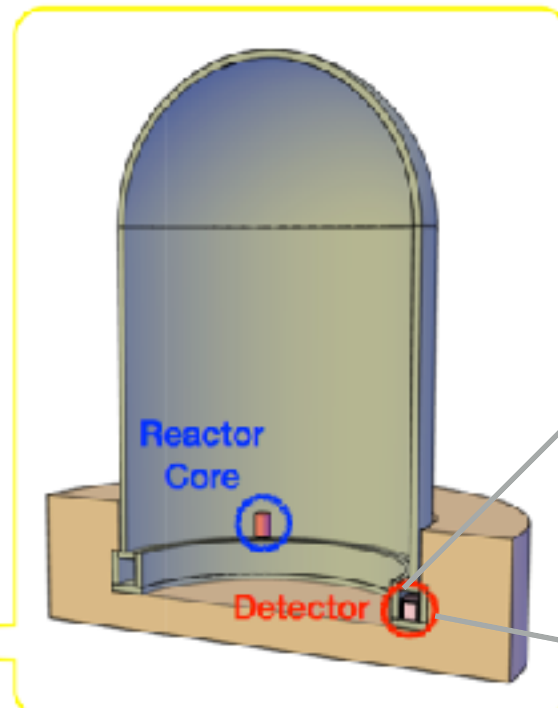
Very Short baseline experiment

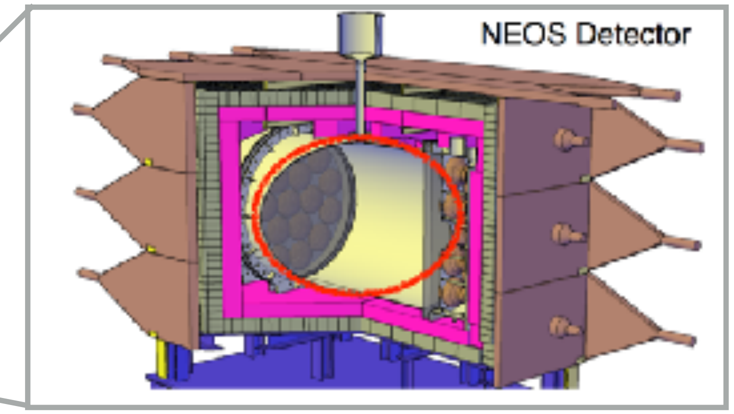
Experiment	Tech	Reactor	Power/ Fuel	P [MW]	L (m)	M (tonnes)
STEREO (Fr/ Ger)	LS+Gd	ILL-HFR	^{235}U	57	9-11	2
Neutrino-4 (Ru)	LS+Gd	SM3	^{235}U	100	6-12	1.5
PROSPECT (US)	LS + ^{6}Li	ORNL HFIR	^{235}U	85	7-18	2
SoLid (UK/B/Fr)	PVT & $^{6}LiF:ZnS$	SCK • CEN BR2	^{235}U	45-80	6-9	2
DANSS (Ru)	PS + Gd	KNPP	^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu	3000	9.7-12.2	0.9
NEOS (Kr)	LS+Gd	Hanbit	^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu	2800	24	1

NEOS

- Active target (Liquid Scintillator, LS)
- Homogeneous, 1000 L volume
- 0.5% Gd-loaded LS
- LAB- and DIN-based LS (9:1): improved PSD
- 38x R5912 8" PMTs
- Muon veto planes

Reactor Unit 5, Hanbit NPP
in Younggwang, Korea





2.8 GW_{th} commercial reactor

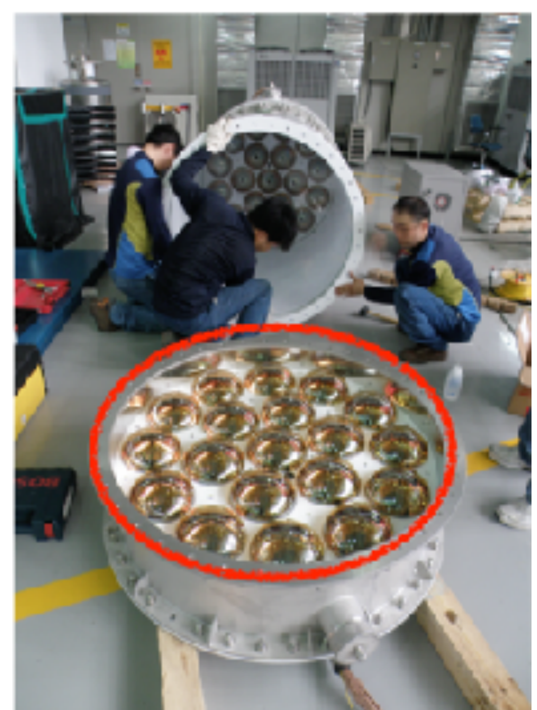
- Core size: 3.1 m diameter and 3.8 m height

- Low enriched uranium fuel (4.6% ^{235}U)

Detector in Tendon Gallery

- **~24 m baseline and ~20 m.w.e**

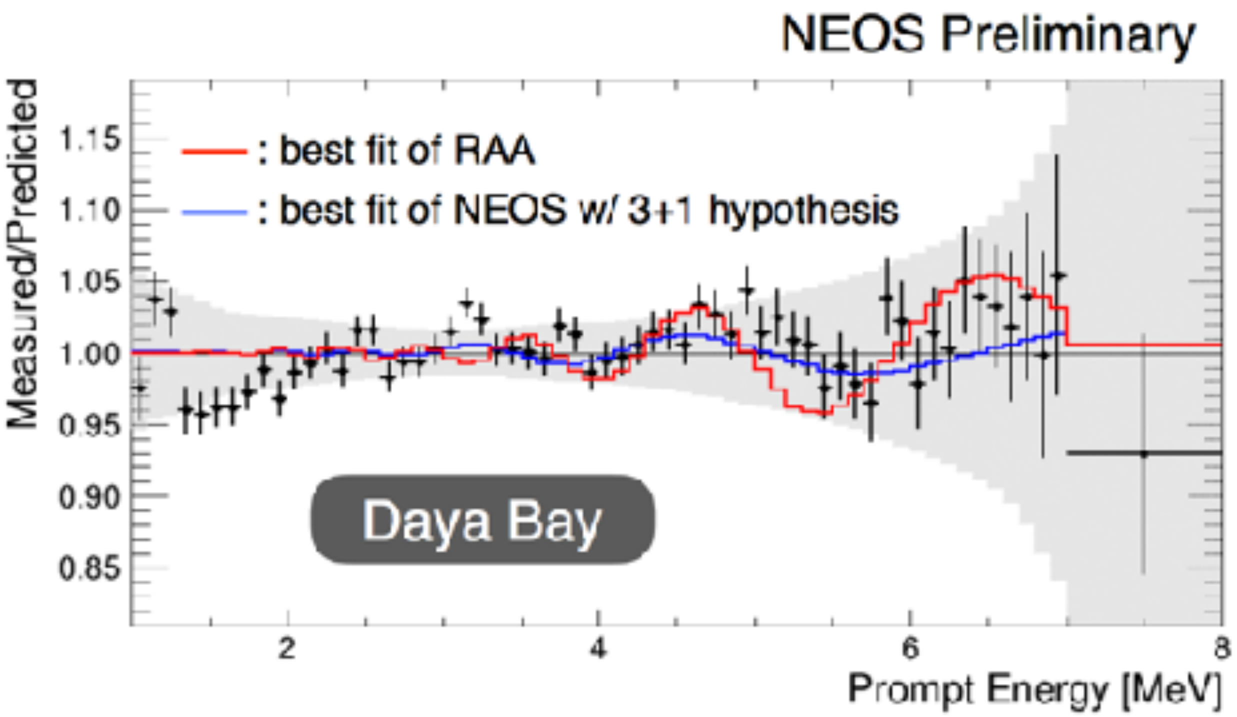
overburden



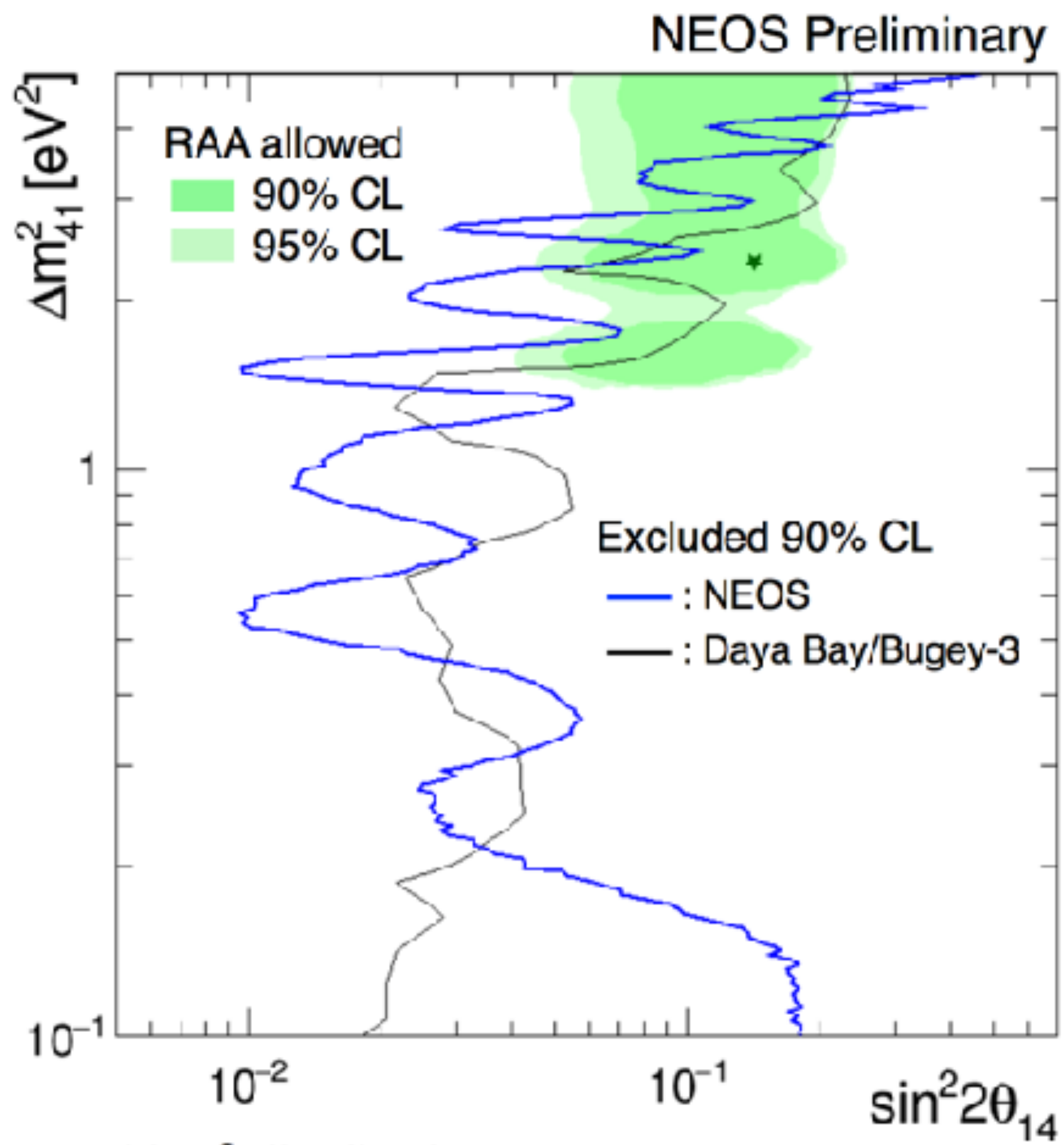
- Cylindrical stainless steel tank with PTFE reflector
-

Detector in Tendon Gallery

NEOS Sterile Analysis

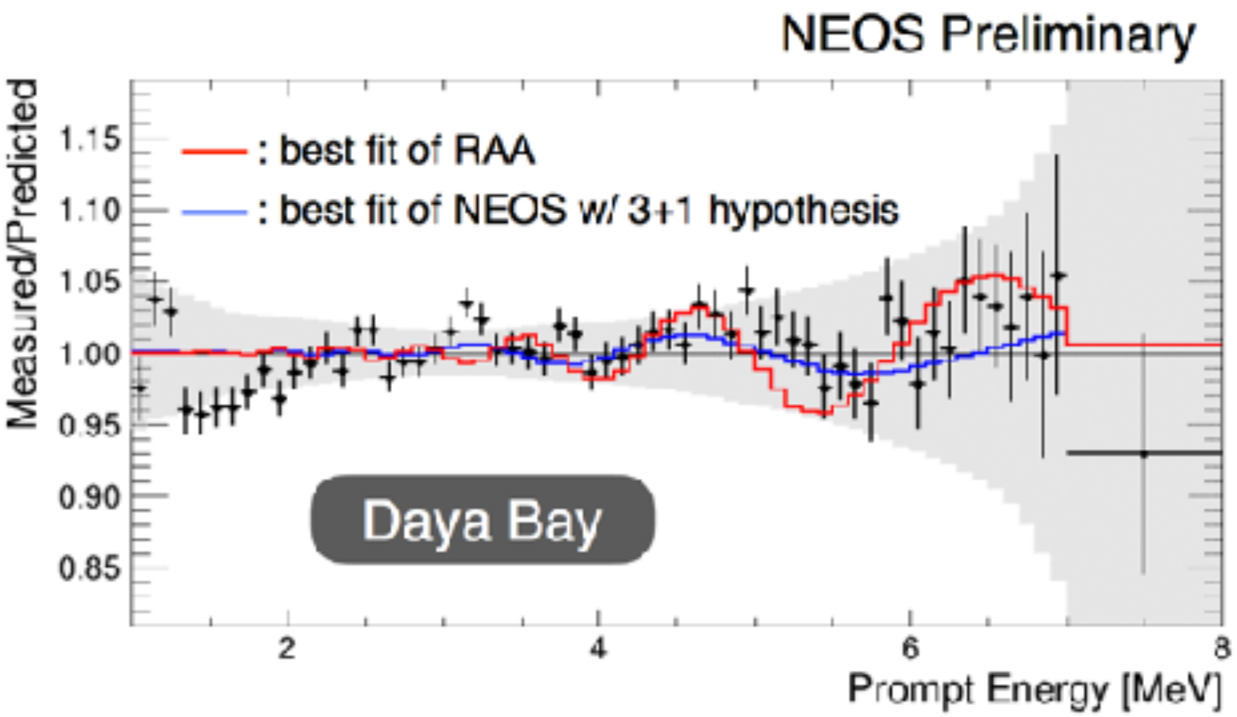


Hypothesis	χ^2/N_{dof}	$(\sin^2 2\theta_{14}, \Delta m_{41}^2)$
$H_{3\nu}$	66.8/61	(0, 0)
$H_{4\nu}$	59.6/59	(0.037, 1.73 eV^2)
RAA	78.0/59	(0.142, 2.32 eV^2)



- Use Daya Bay spectrum to subtract flux distortions
- No significant effect found, RAA found to not fit well current data either
- Can significance be improved with subtraction from RENO data ?

NEOS Sterile Analysis



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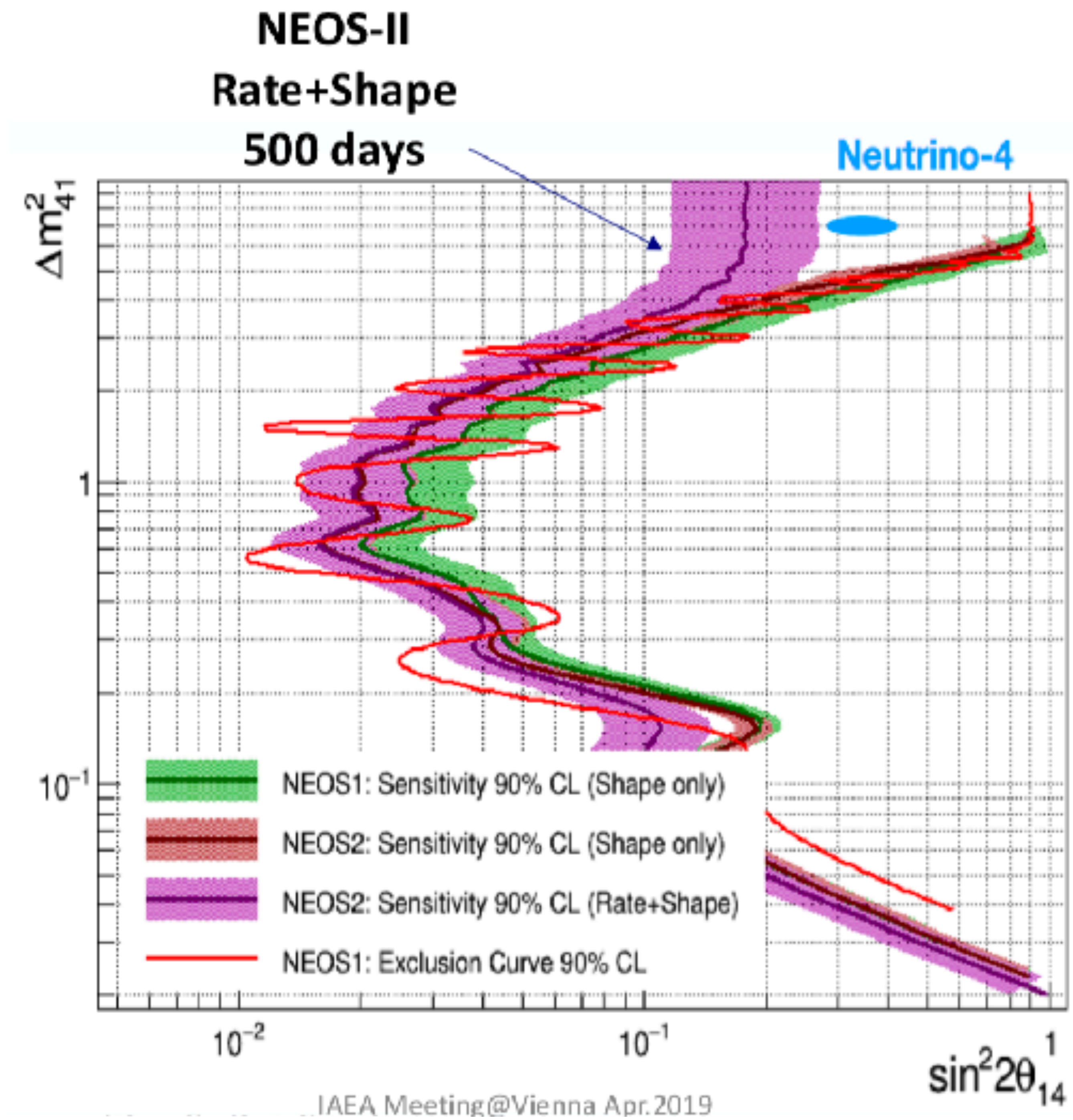

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NEOS-I result

Data taking: Aug 2015 - May 2016

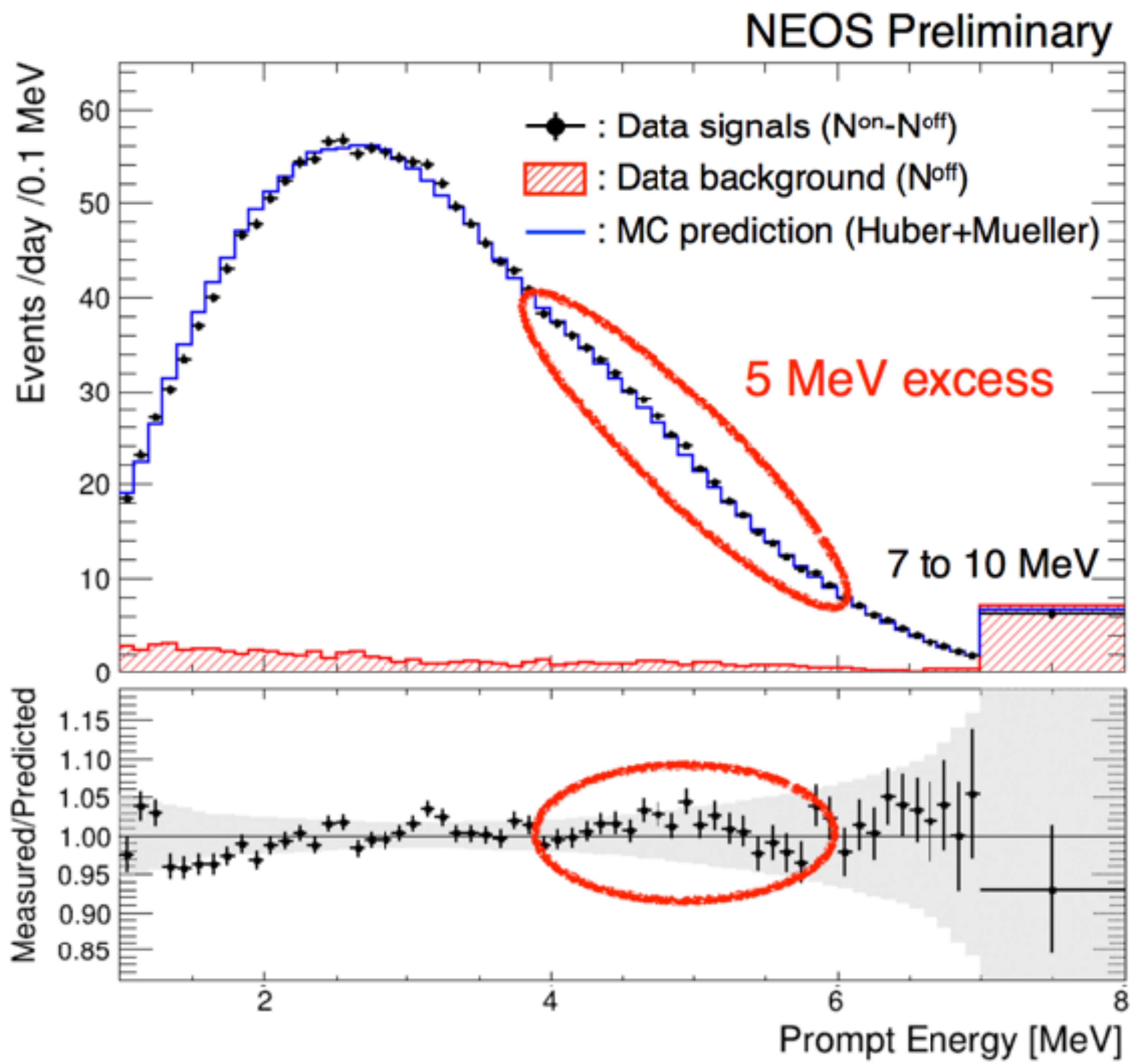
- Reactor-on period: 180 days
- Reactor-off period: 46 days

- **S:B ~ 23**

- **5% energy resolution** at 1 MeV

Comparison with Huber and Mueller's flux model

- Better agreement with Daya Bay spectrum

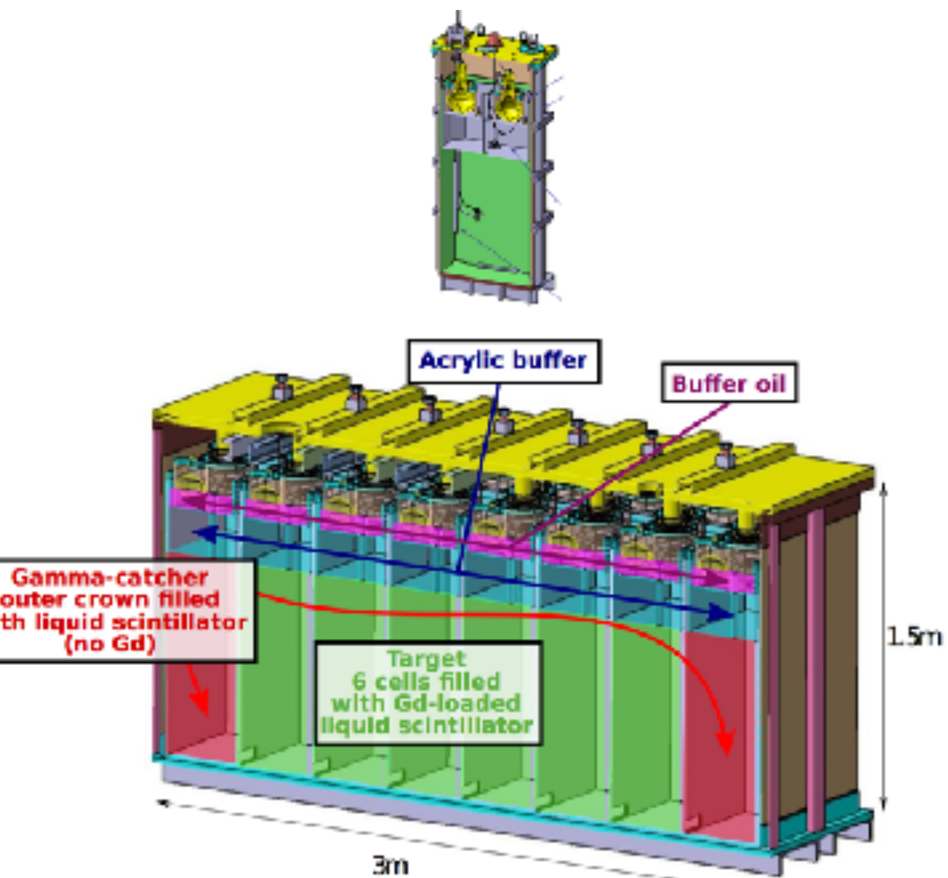


Research reactors experiments

Segmentation, segmentation, segmentation…

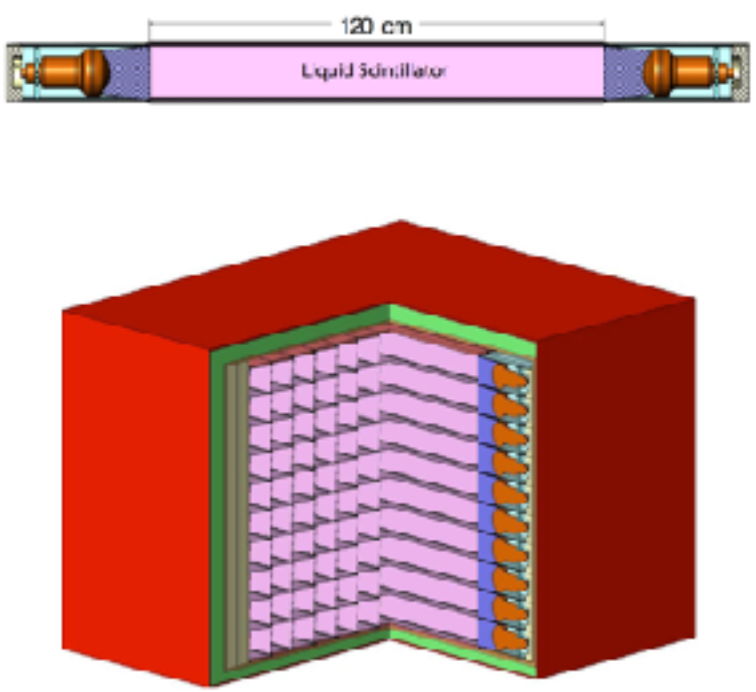
- Detector segmentation provides relative measurement along oscillation length
  - **combined with energy measurement is only way to demonstrate oscillation !**
- Finer segmentation provides additional capability to reject background and select positron energy

STEREO



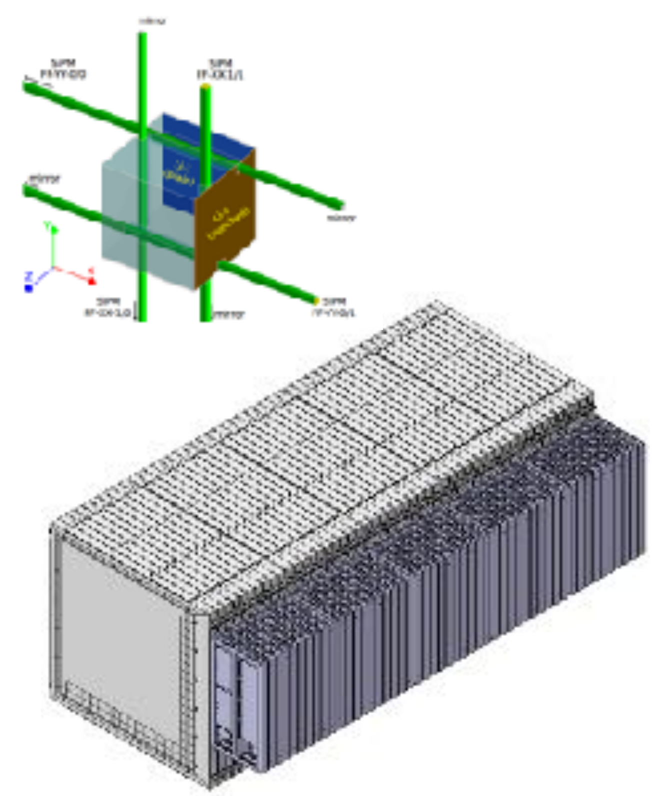
6x inner 1D cells 90 x 90 x 35 cm3
buffer cells around the target
2000 L of Gd loaded LS

PROSPECT



120x 2D LS unit segment
dimension 15 x 15 x 120 cm3
3000 L of Li6 loaded LS

SoLid

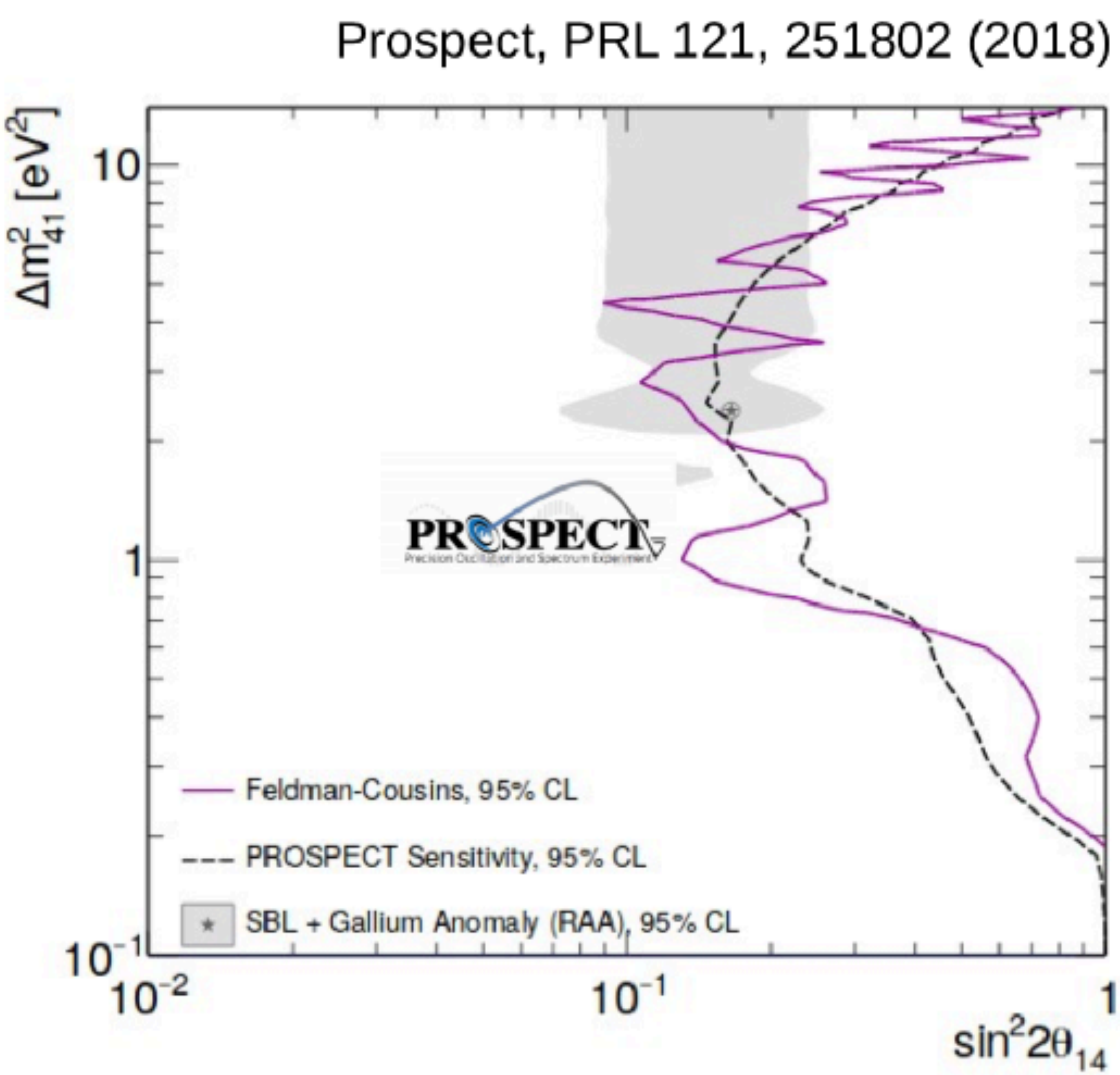


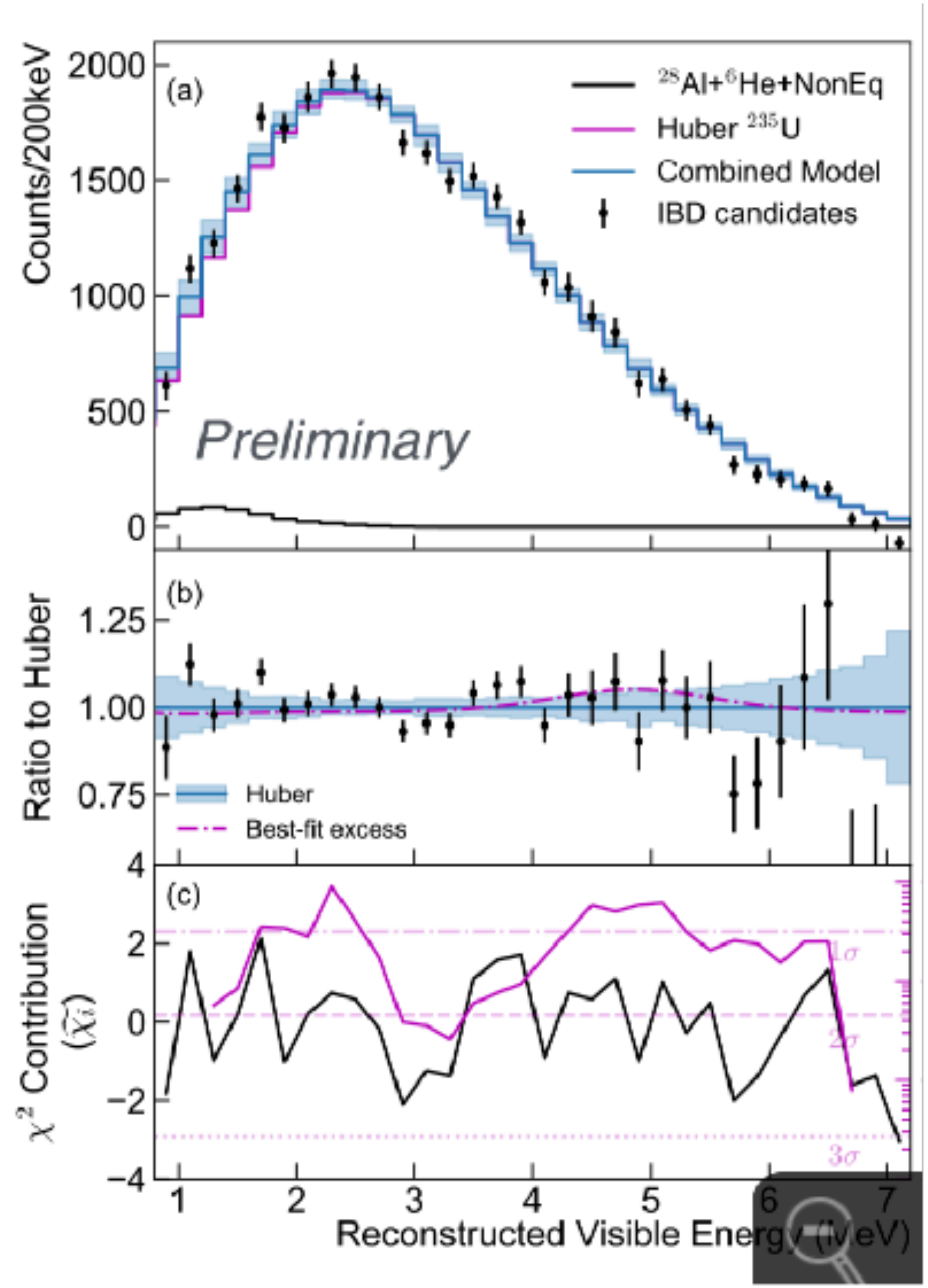
5-6x modules 2560 cubes
dimension 5 x 5 x 5 cm3
1.6-2 tons PVT+LiF:ZnS

Complementarity of measurements

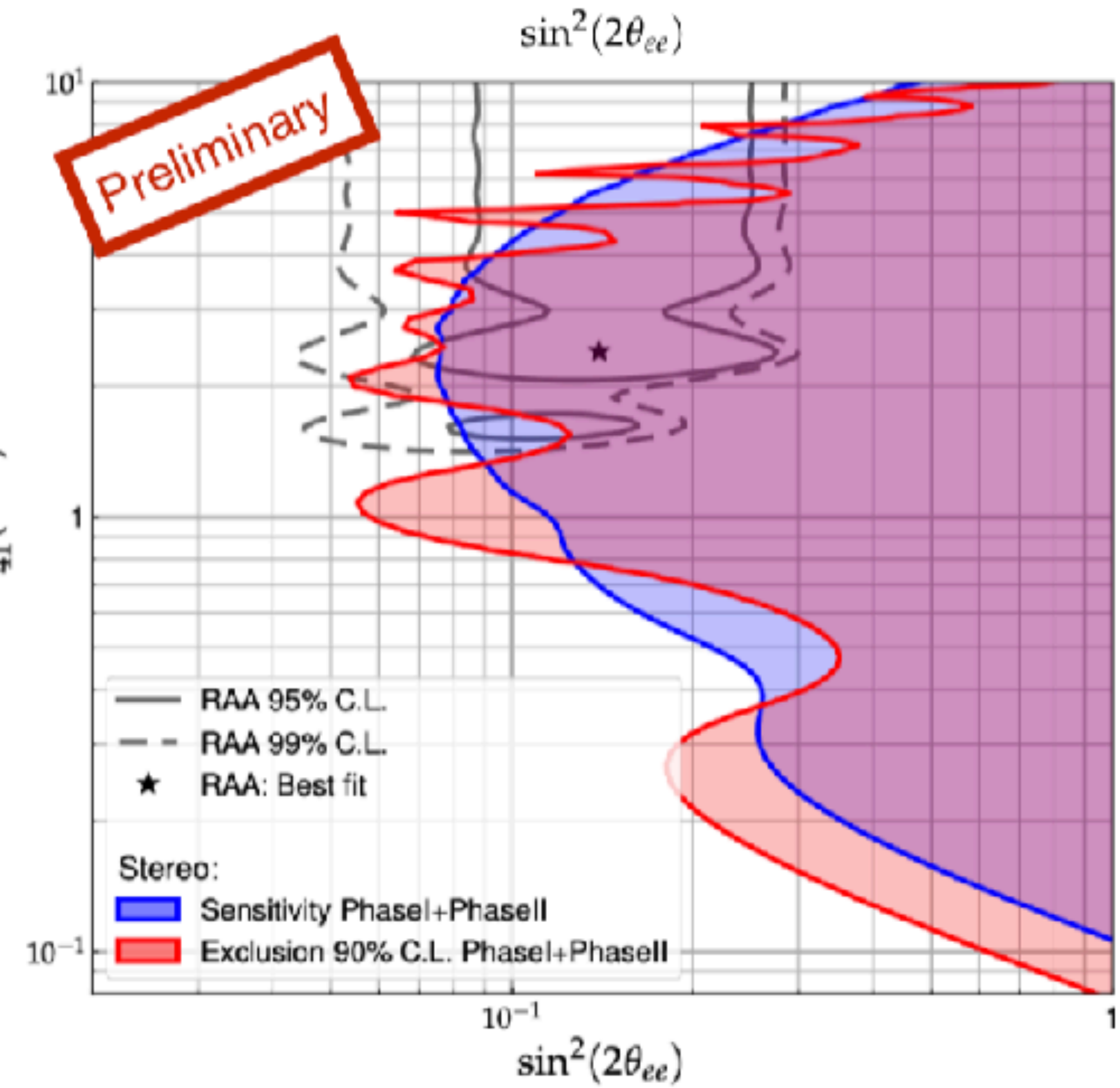
- Lithium vs Gadolinium
  - Localised signature, additional PSD in PROSPECT
  - Alpha-neutron PSD in SoLid
- Coarse vs fine segmentation
  - Provides positron energy in SoLid / DANSS
- Plastic vs liquid scintillators
  - Linear response in energy for Plastic
  - gamma/neutron PSD in liquids

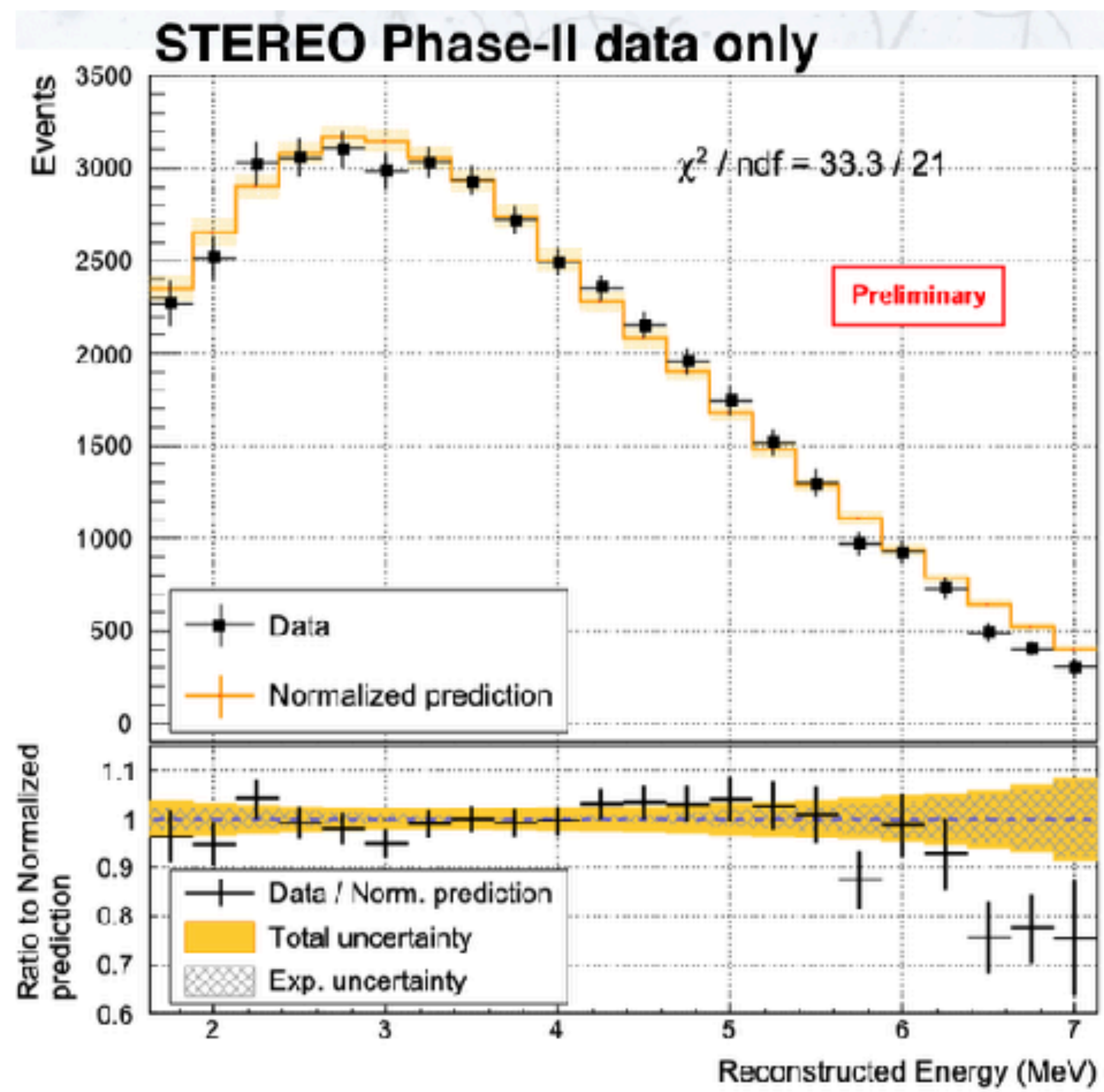
PROSPECT first results 2018





STEREO recent results

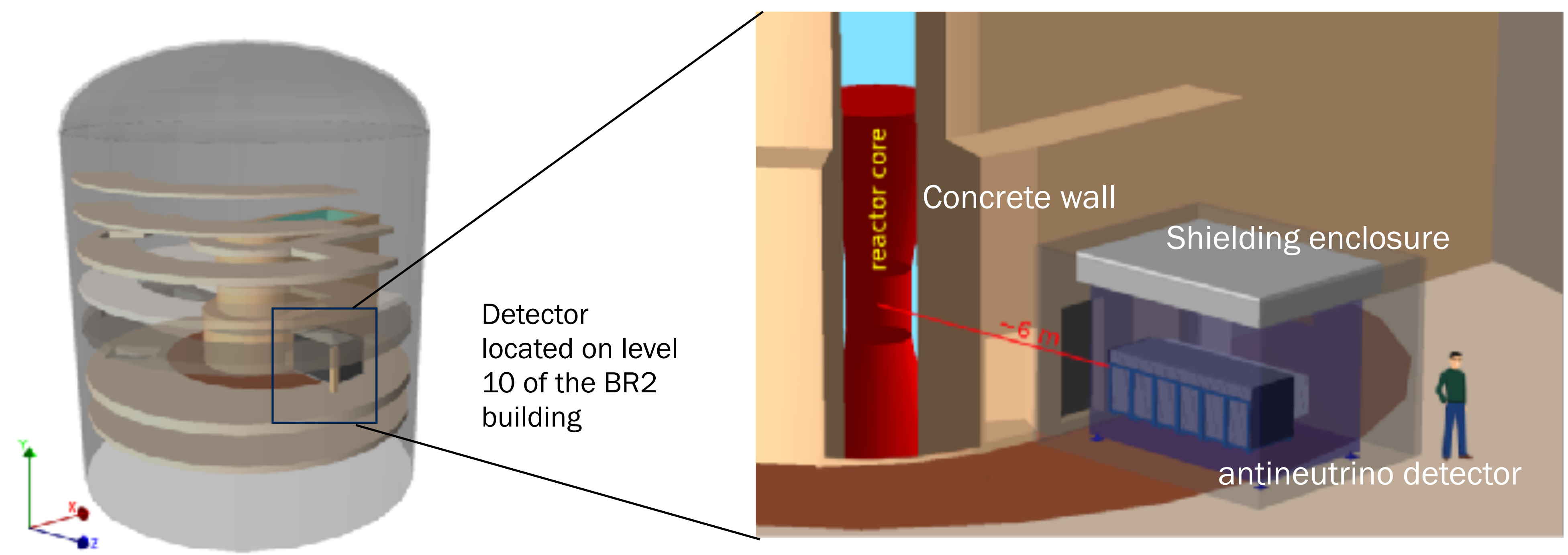




SoLid

The SoLid experiment at BR2 SCK•CEN

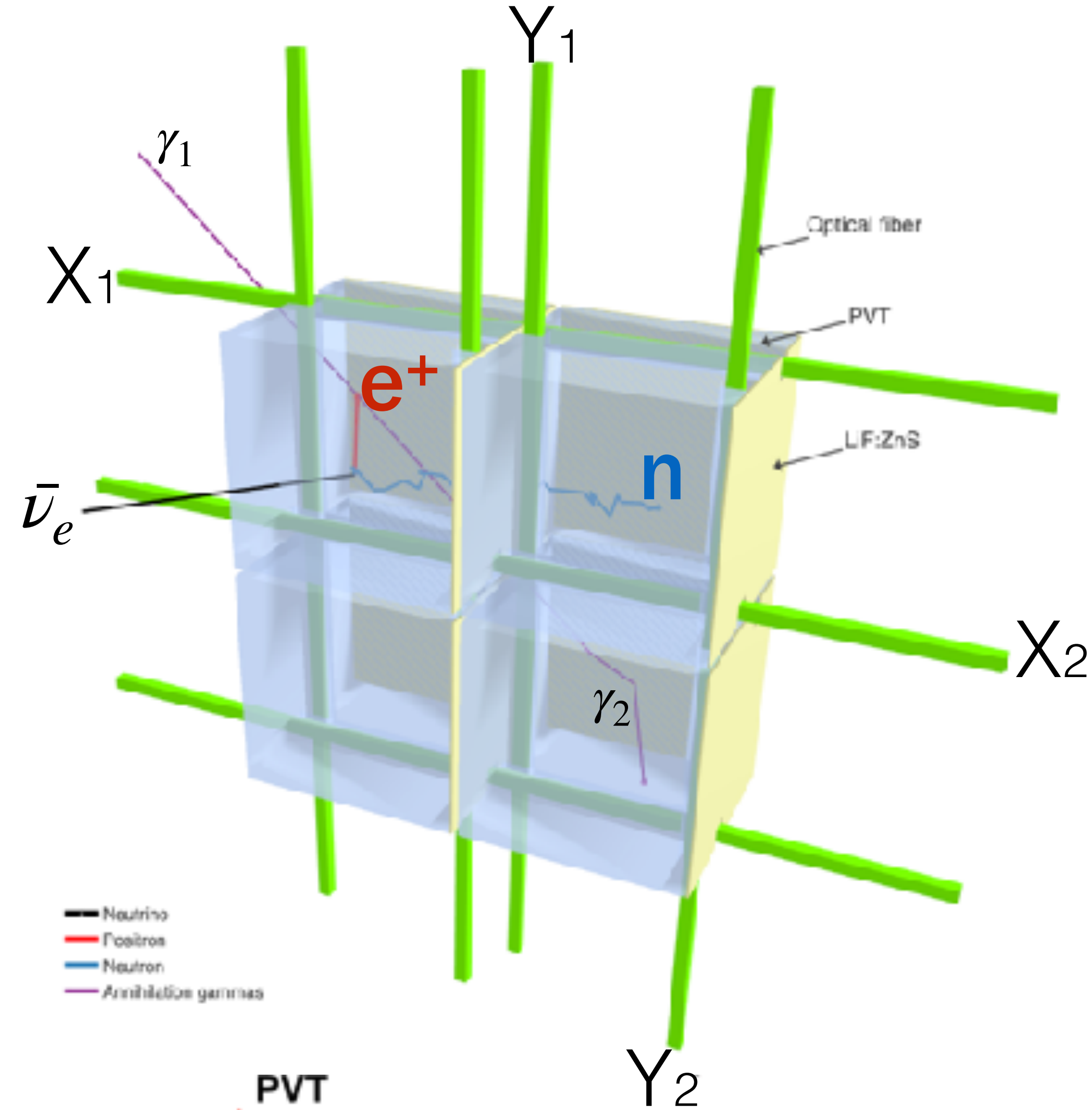
- SoLid baseline : 6-9m from the BR2 MTR reactor at SCK•CEN mol, Belgium - High security area with restricted access
  - 5-6x movable modules on rail system 1.6-2 tonnes fiducial mass
  - Refrigirated container to limit impact of MPPC sensors dark noise
  - Low Z external shielding based on H_2O bricks and PE slabs.
  - High Z gamma-ray shielding in front of beam ports, outside enclosure

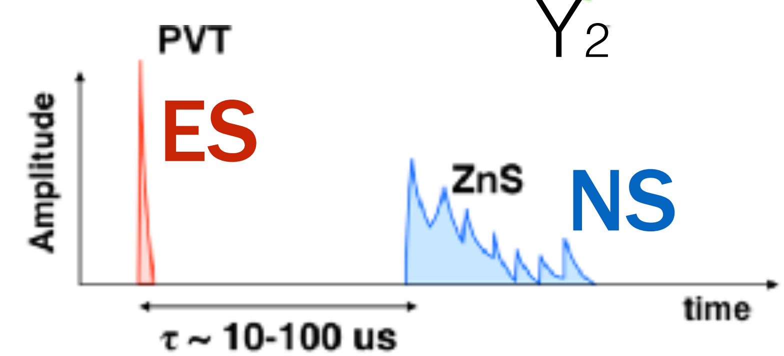


SoLi∂

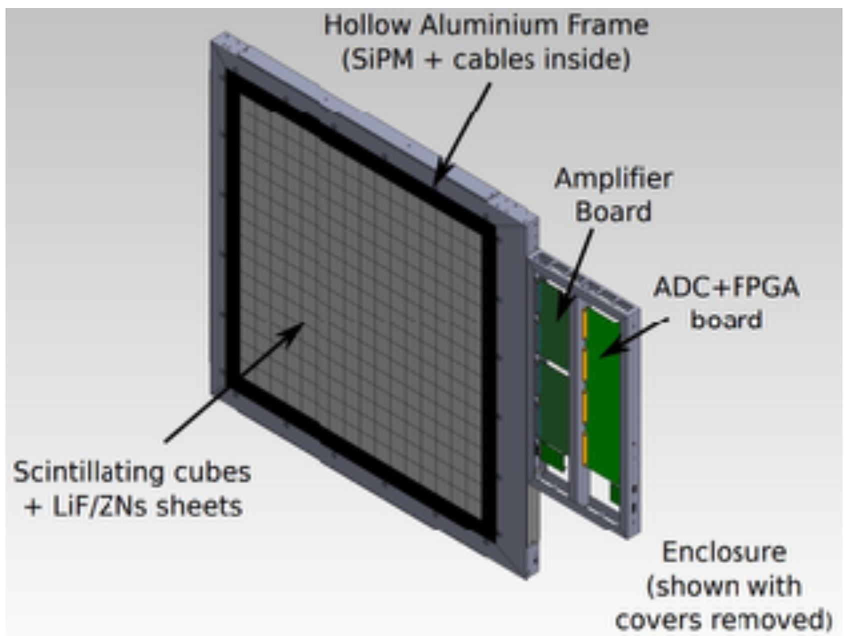
Detector concept

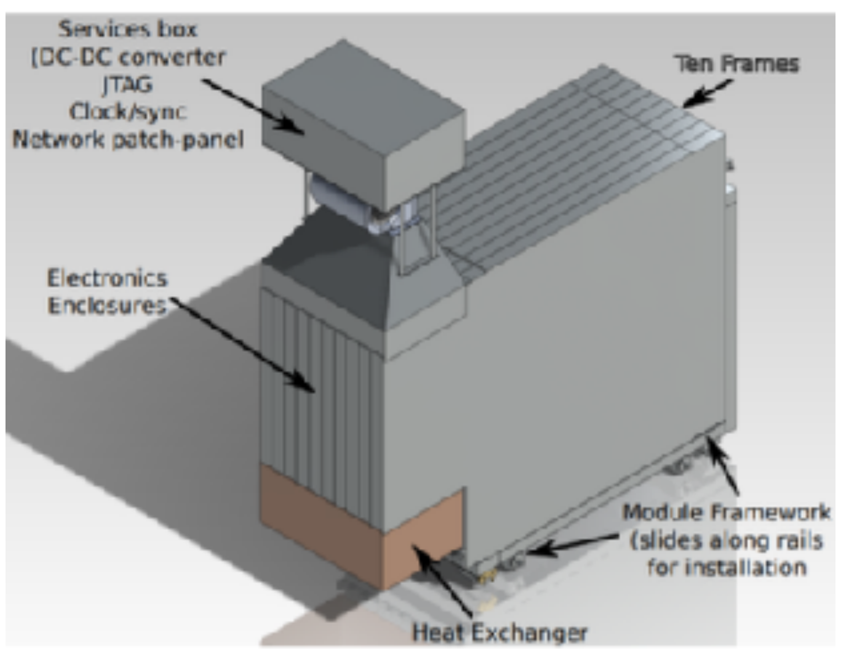
- Stack of 5 x 5 x 5 cm cubes
- Covered with two LiF:ZnS(Ag) sheets
- Wrapped in reflective material (Tyvek)
- Four Wavelength shifting fibres crosses each cube ($X_{1,2}$ and $Y_{1,2}$)
- Electron Signals (**ES**) are fast signals in PVT/ZnS
- Nuclear Signals (**NS**) defines ZnS slow scintillation
- Time and spatial signature of event



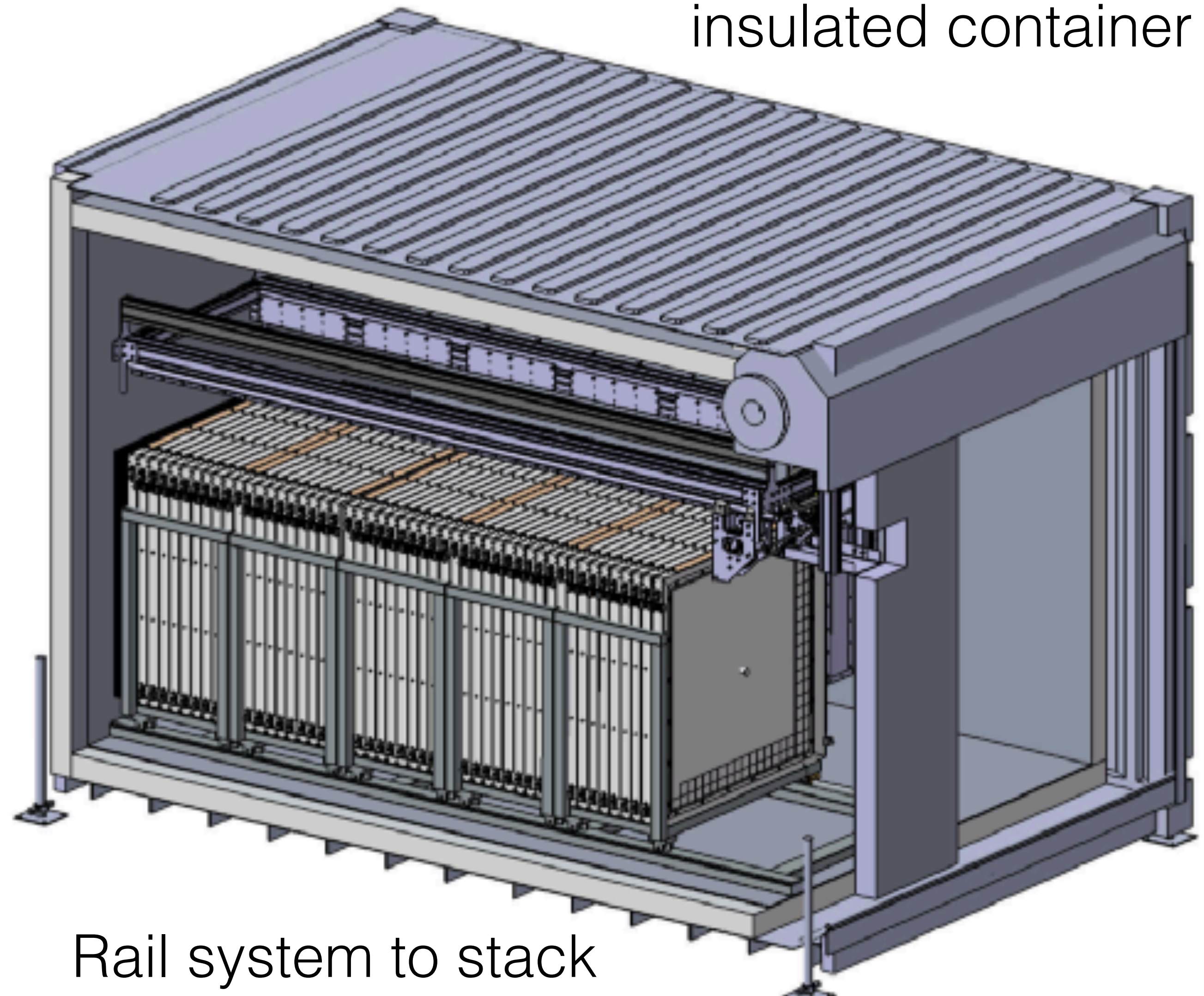


SoLid detector design





Customised insulated container



Rail system to stack modules

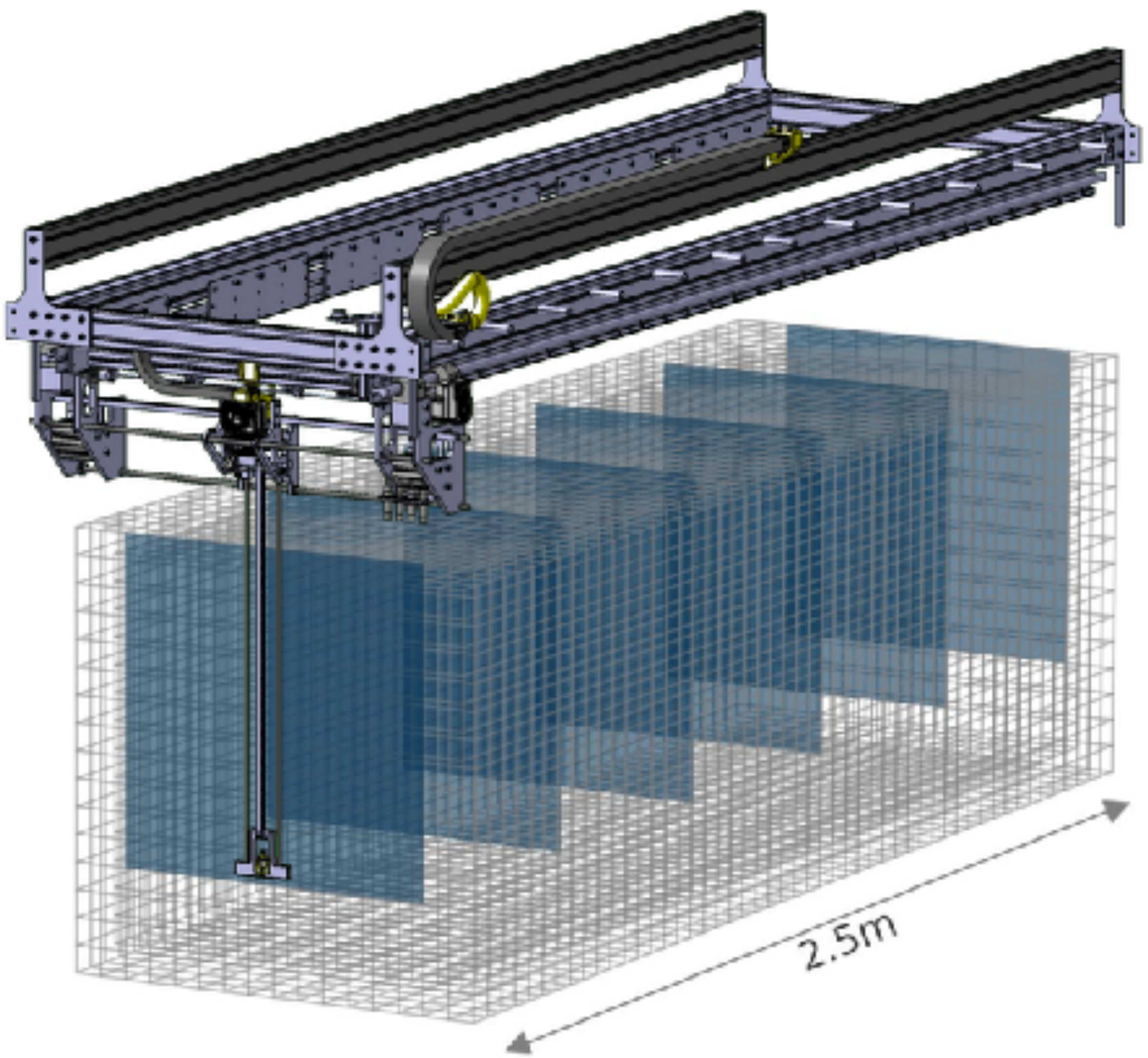
SoLid

Deployment at BR2

SoLið

Experiment footprint

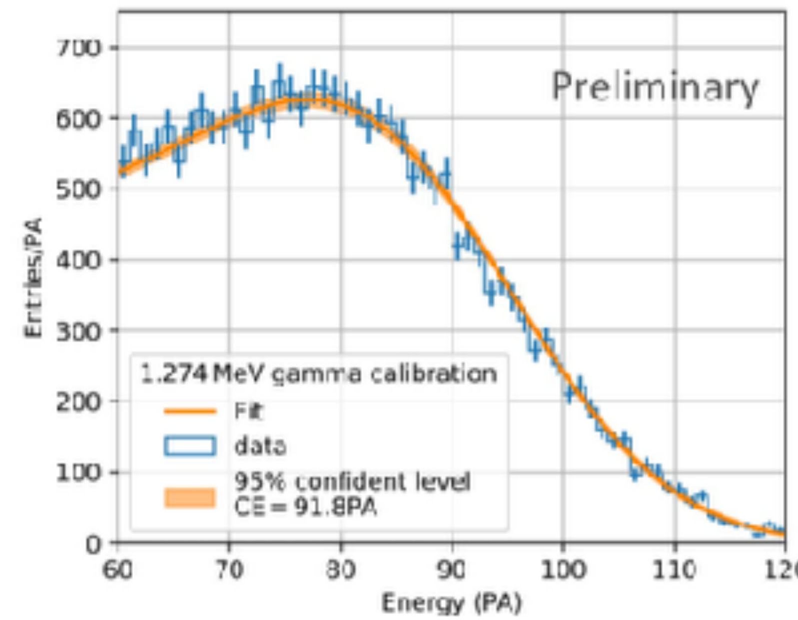
SoLid CROSS calibration robot

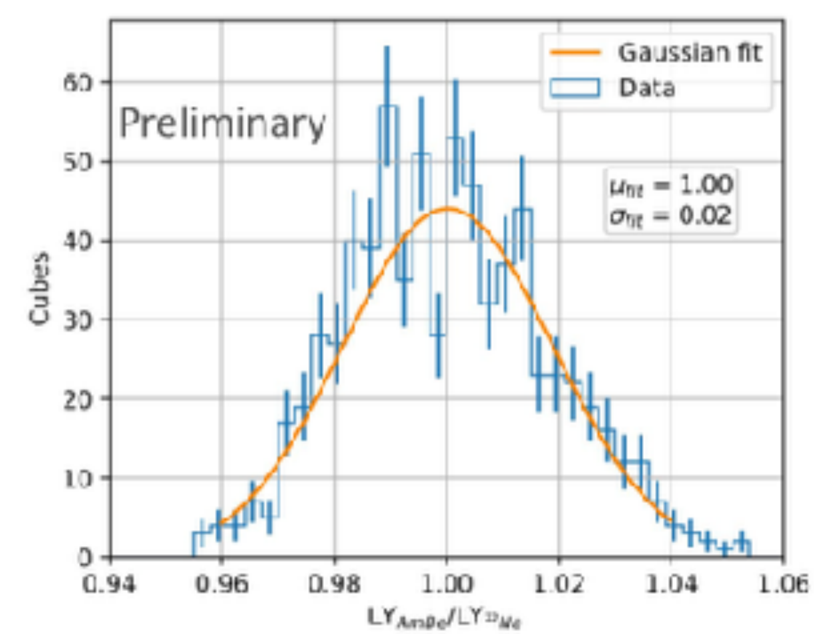


- Automated X-Y source scan of 6 gaps within detector
- Measure absolute efficiency and energy scale calibration at % level
  - Gamma-ray: ^{207}Bi, ^{60}Co, ^{22}Na
  - Neutrons: AmBe, ^{252}Cf

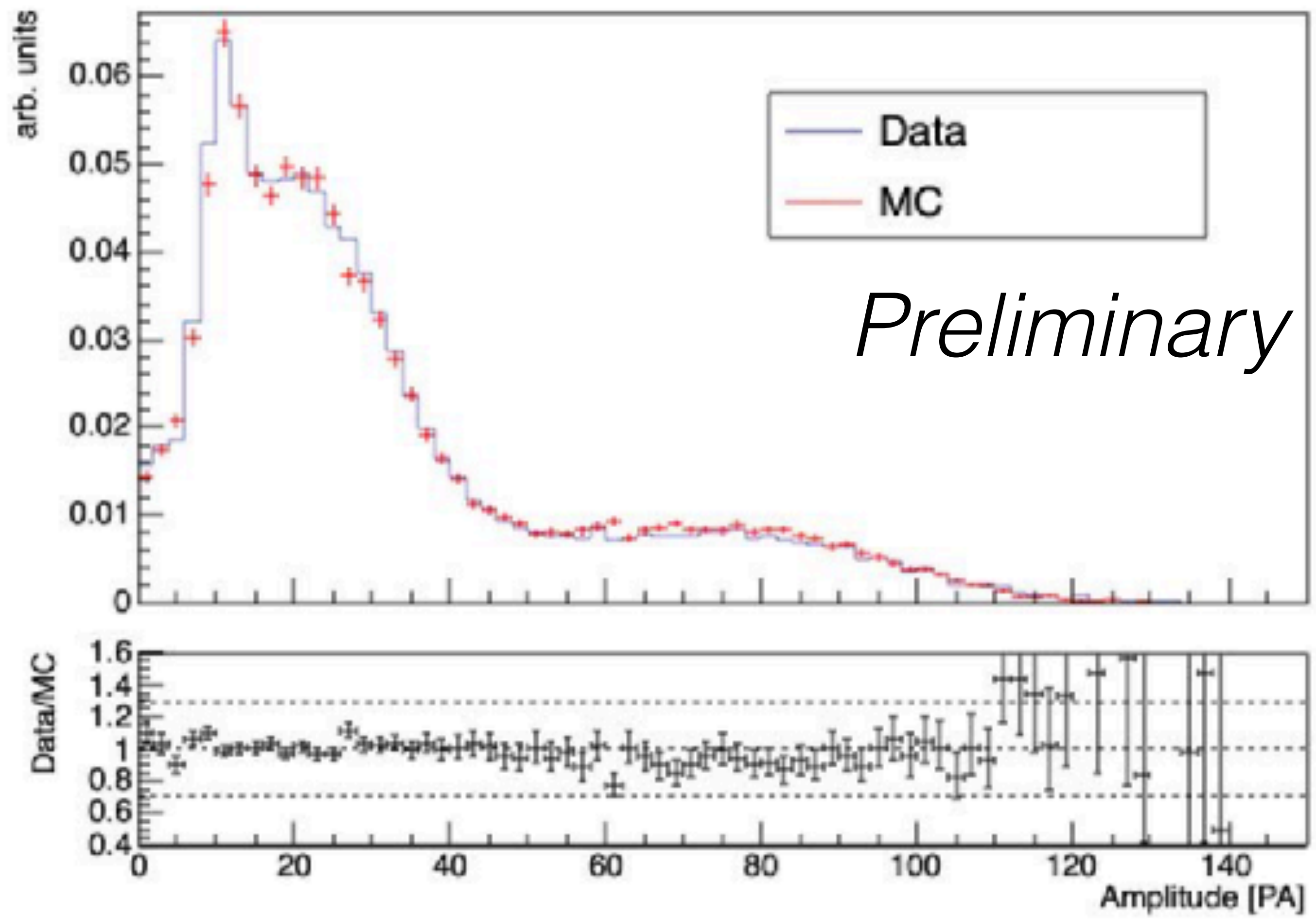
SoLid Energy scale calibration

- Energy scale anchored on Na-22 source calibration using two methods
    - MC-data KS test
    - Analytical fit
- Light yield (LY) = 96 PA/MeV
    - Stochastic term $\sigma_E = 12\,\%$ at 1 MeV
- Linearity of energy response
    - Comparison at different energies gives very good agreement
        - 1.27 MeV and 4.4 MeV
        - Good agreement with measurement made during QA



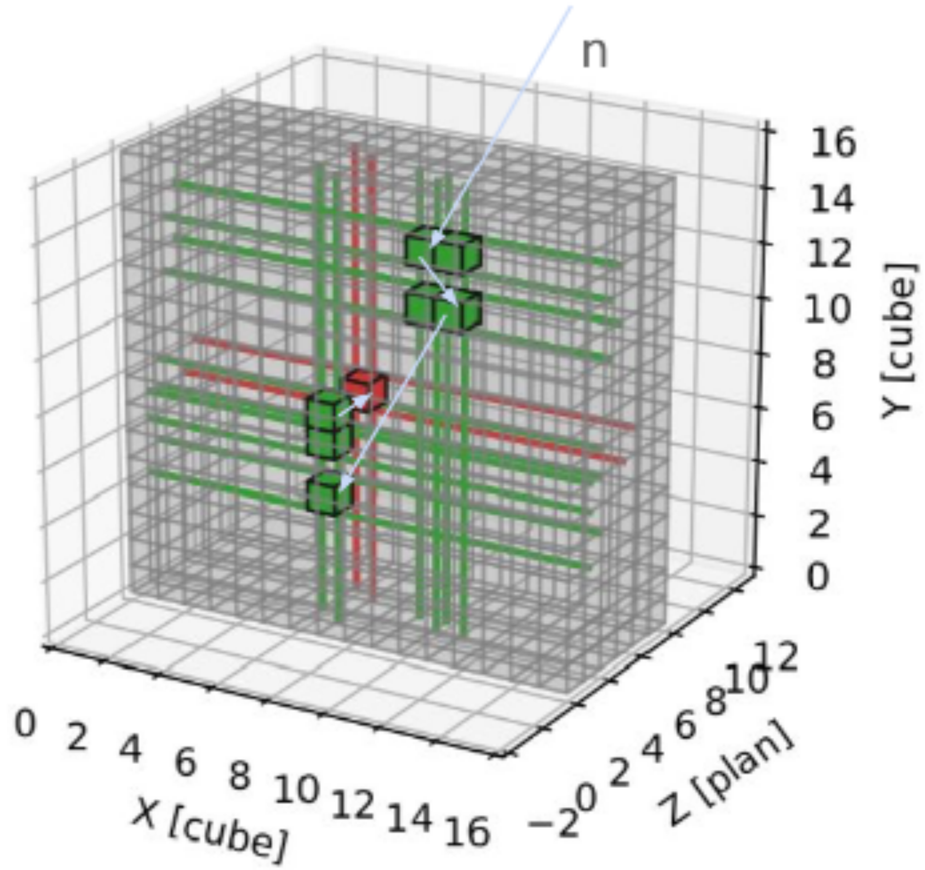


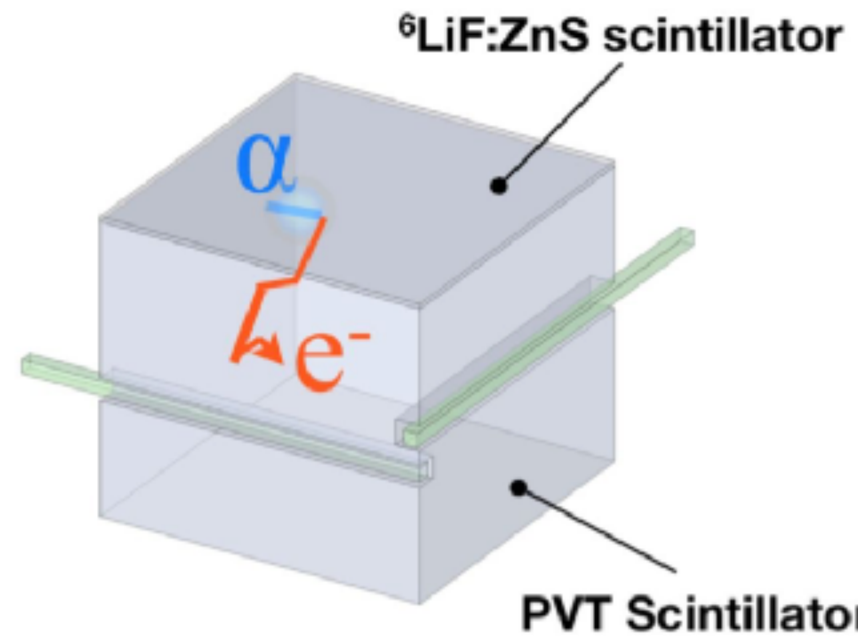
SoLid Detector energy response



- Energy reconstruction and MC simulation validated against calibration runs
- BiPo and B-12 comparison also used to tune the MC

SoLid antineutrino backgrounds

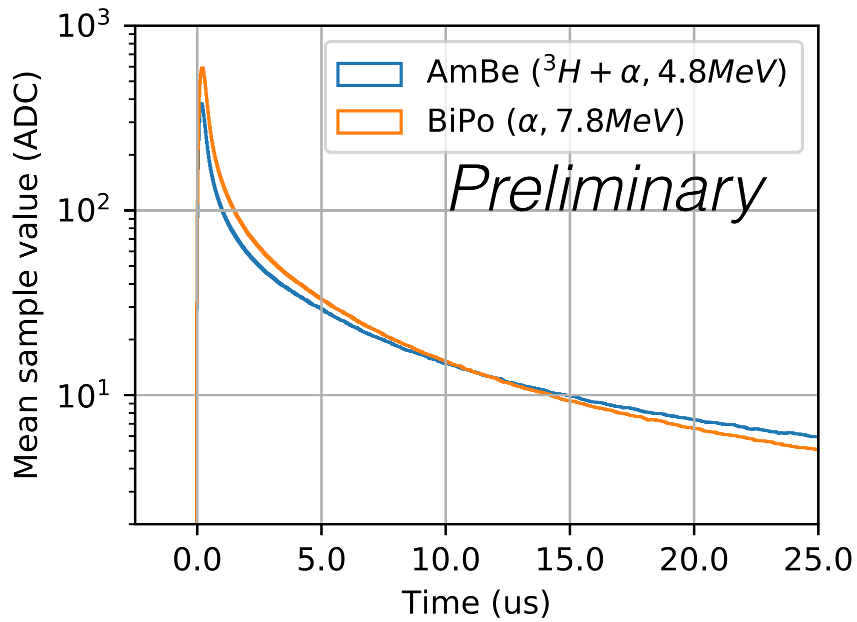


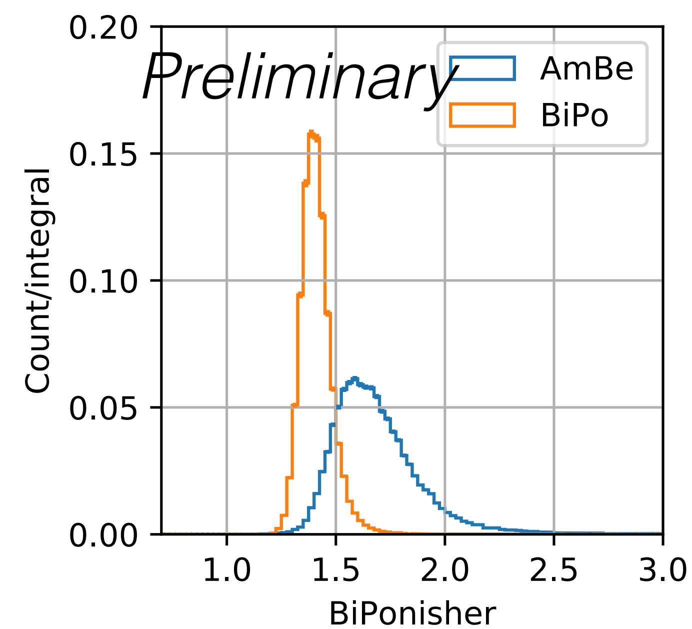


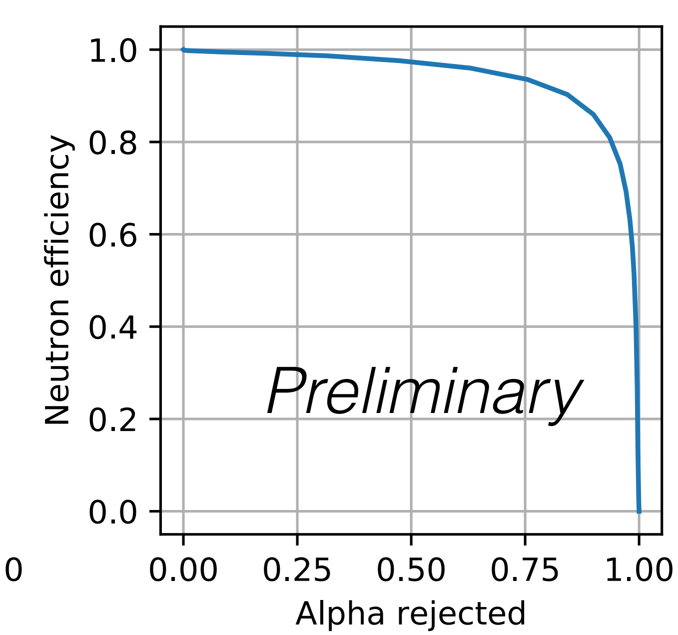
- External
  - Fast neutrons: Atmospheric shower and spallation neutrons
  - Gamma-rays (Ar-41) : reactor accidentals
  - Radon emanation from the building

- Internal background
  - from U-238 / Th progenies mainly in LiF:ZnS(Ag)
    - Bi-Po 214 (264 us decay constant)

Alpha - Neutron discrimination







- Discovered that LiF:ZnS(Ag) has PSD capabilities (ZnS is an inorganic scintillator)
  - neutron / alpha discrimination to reject alphas from Th/U decay chains
- **Used to reduce BiPo-214 contamination**

SoLi∂

Status of analysis

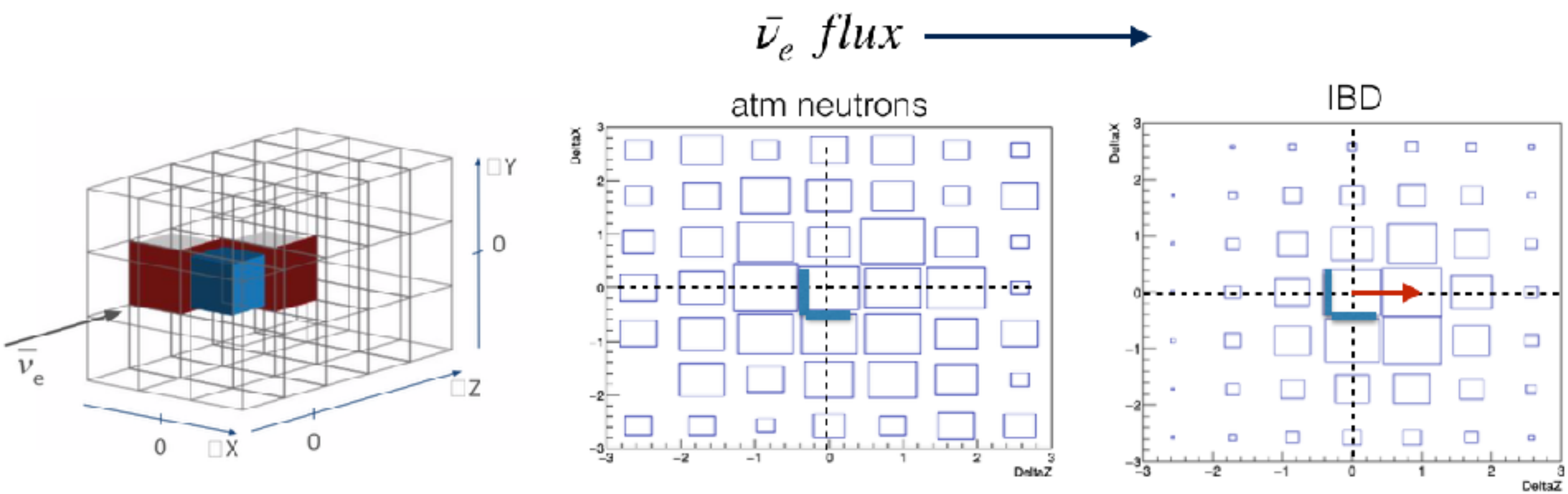
- Data taking since April 2018, Many reactor cycles on tape
- Reconstruction and background rejection techniques have been validated
  - understand background topologies and variations
- Optimising the IBD selection
- Oscillation analysis in preparation

First IBD analysis to be presented at the French GDR next week by V. Pestel

SoLiд

Directionality ?

- Looked at possibility to measure the directionality
  - Feature used in the analysis
- Open some interesting capabilities beyond SoLid



Summary

- **The search for sterile neutrino with mass ~ 1 eV his underway at research reactors**
  - **the allowed region is shrinking fast**
- Dedicated experiments
  - compact segmented detectors provide full coverage of L/E oscillation region
  - probing oscillation lengths not reachable by SBL experiments
- **Since the re-evaluation of the reactor flux in 2011 more questions about the spectrum (and detector response ?) have surfaced**
  - high statistical samples of antineutrino spectra from 235U core will be available in the near future from different technologies
  - measurements at different reactor and different technology will give complementarity for a more robust interpretation of the data
- **can confirm or reject sterile neutrino hypothesis (3+1 model) with unprecendented precision**
- **will provide new constraints to the antineutrino flux model but extensions to current programs may be neded to actually solve anomalies**

Thank you !