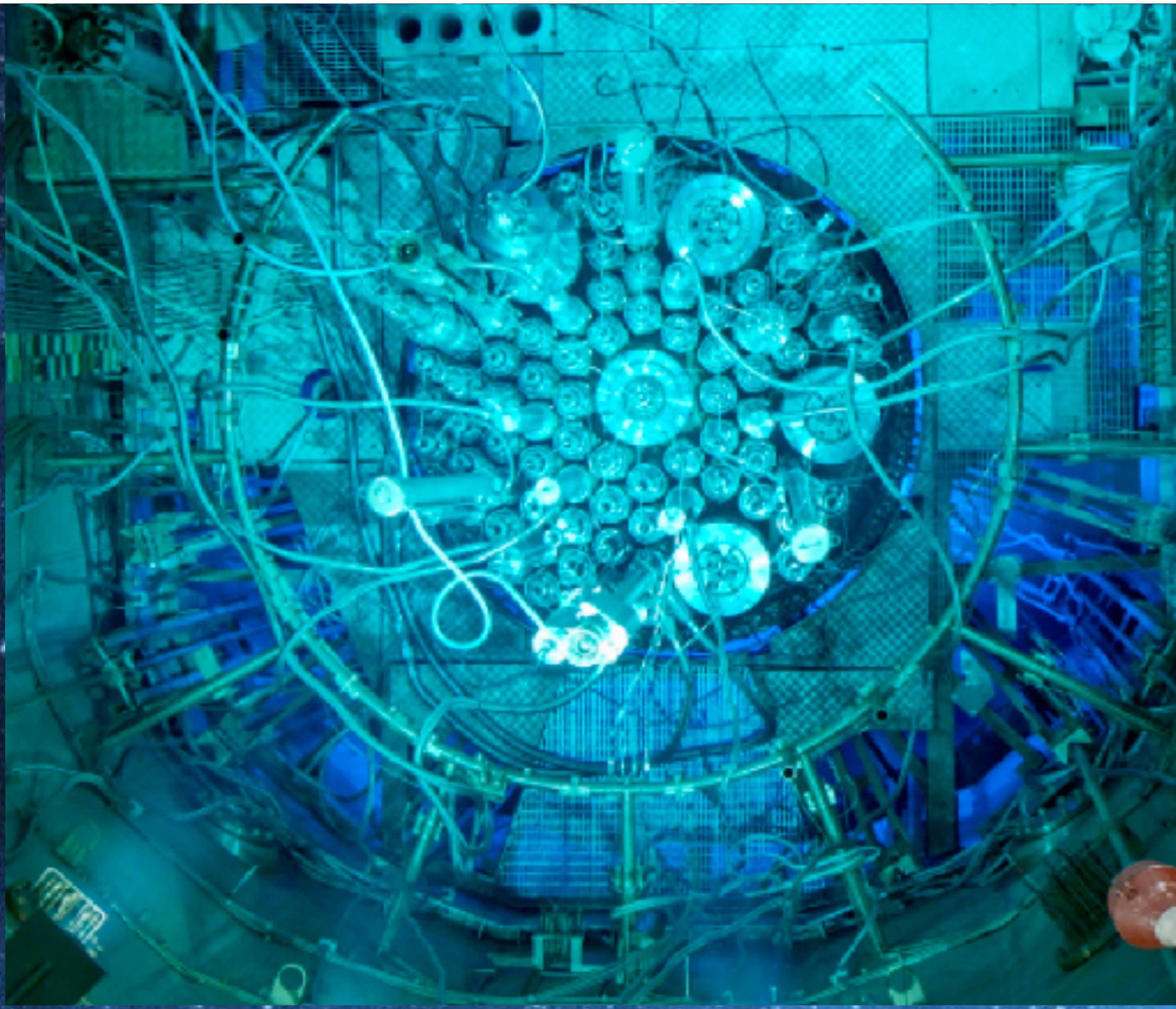
Imperial College London

Sterile Neutrino Search at Reactors

Antonin Vacheret

Neutrino Telescope 2017
17th March 2017,
Venice, Italy

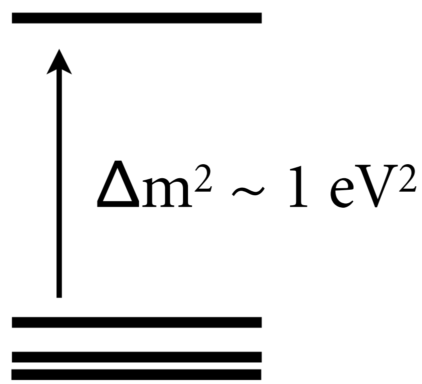


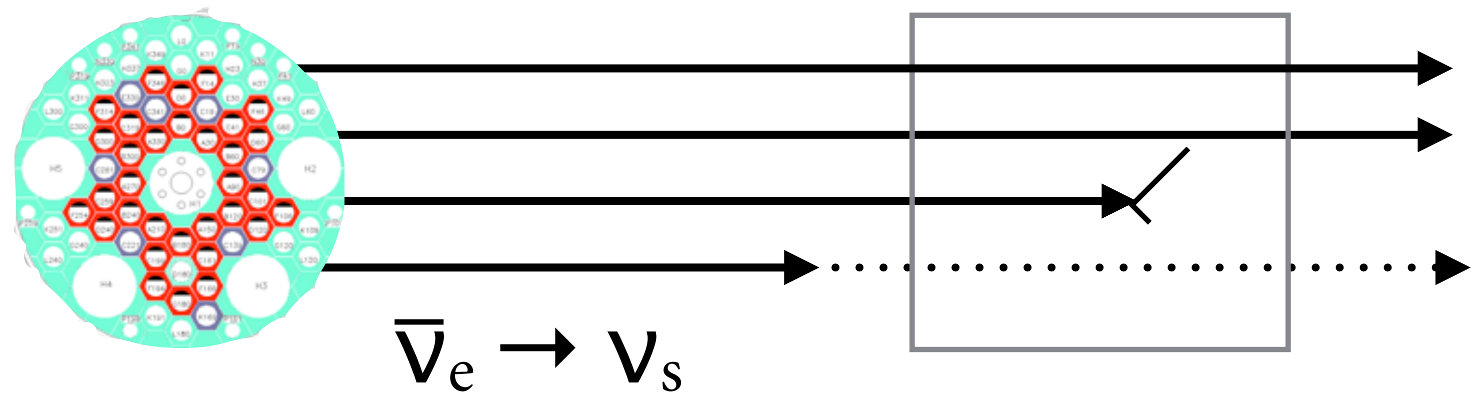
Outline

- Sterile neutrino oscillation
- Antineutrino spectrum measurements and recent limits
- Very short baseline experiments

The sterile neutrino hypothesis

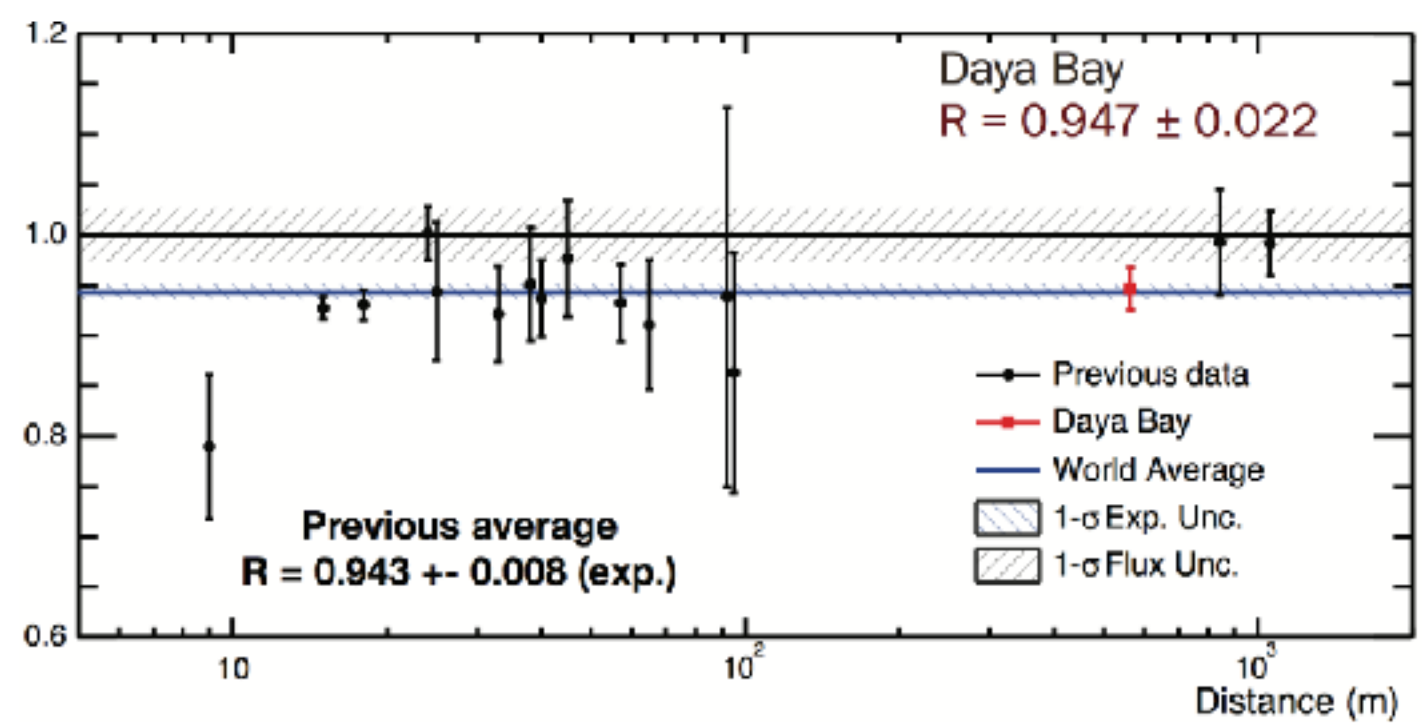
3+1 model | **antineutrino source** | **detector**





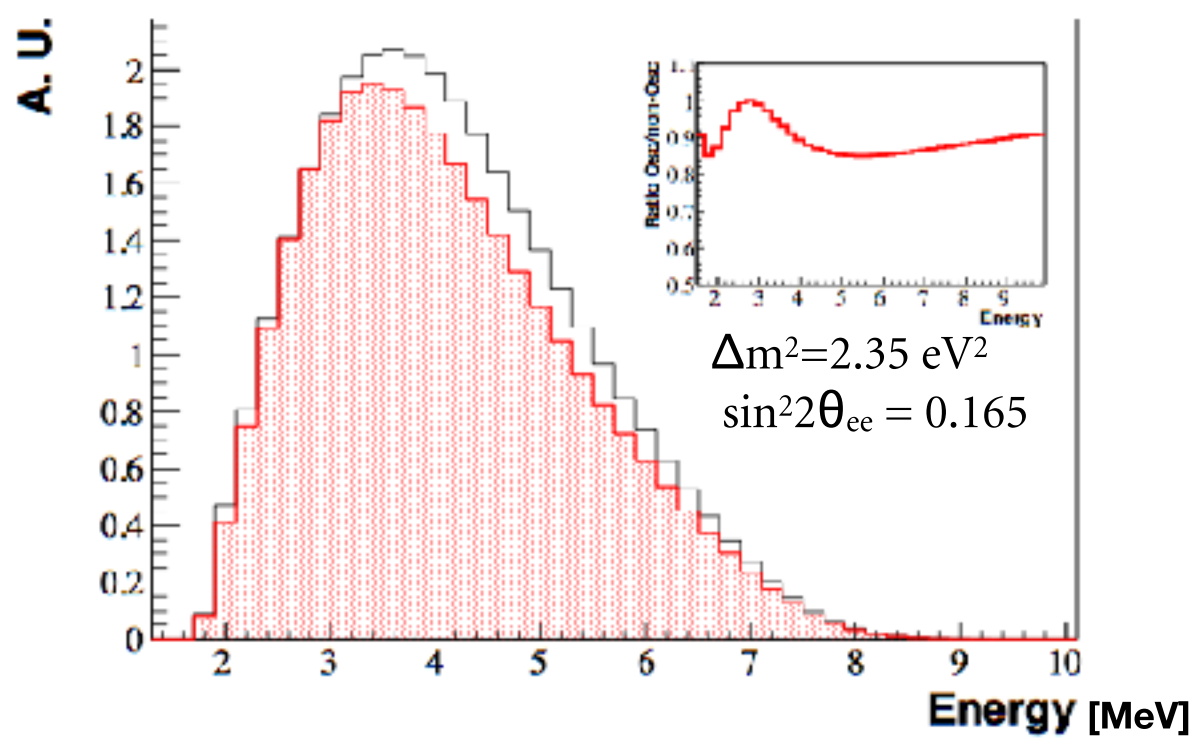
- Additionnal mass state participating to mixing give simple explanation of reactor antineutrino and Gallium anomalies
- not detectable through weak interaction, only indirect measurement possible via oscillation
- small correction from 3 x 3 neutrino mixing to explain active neutrino oscillation data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

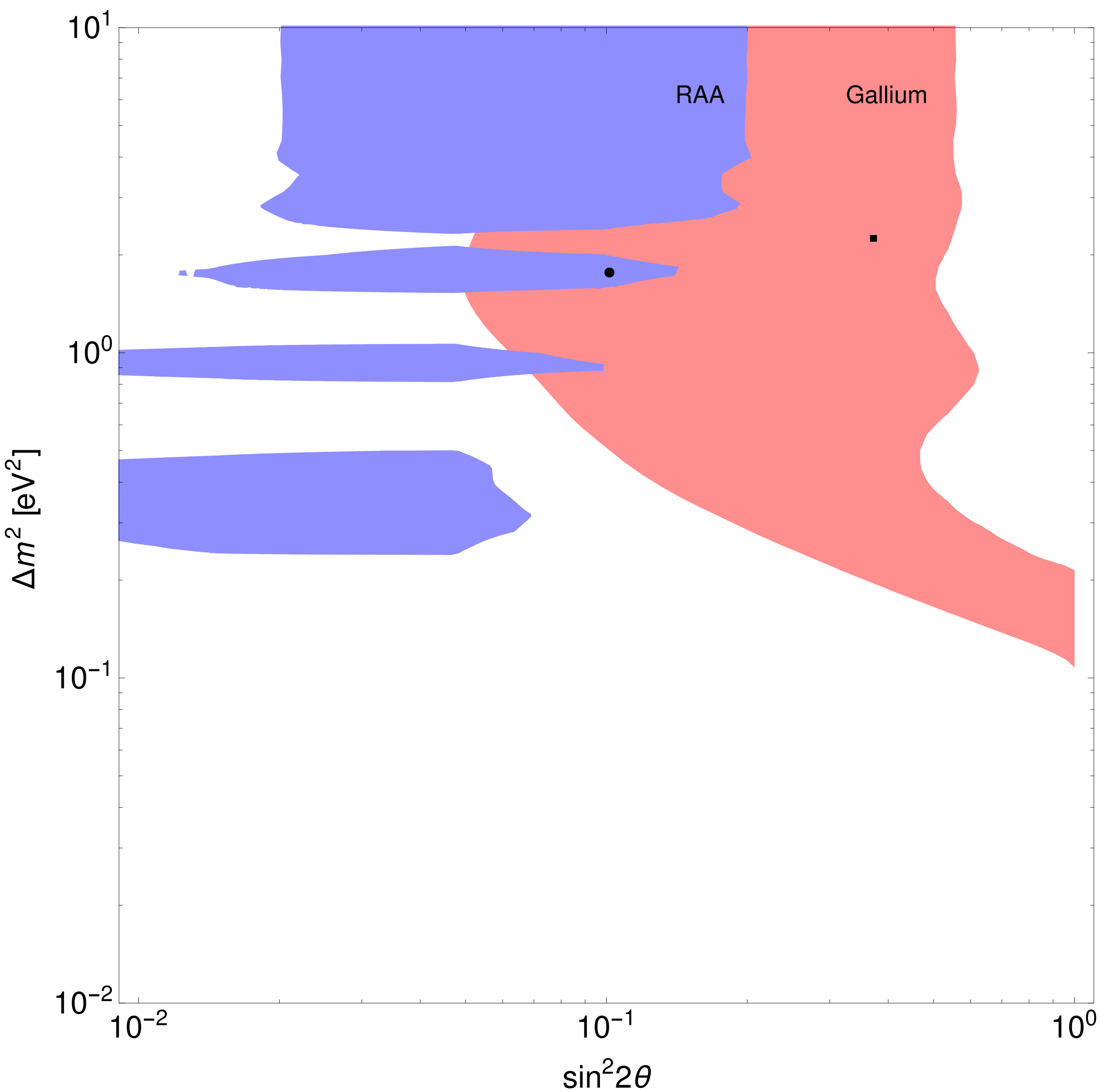
$$P_{ee} \sim 1 - \sin^2(2\theta_{14})\sin\left(1.267\Delta m_{14}^2\, L[m]/E[MeV]\right)$$



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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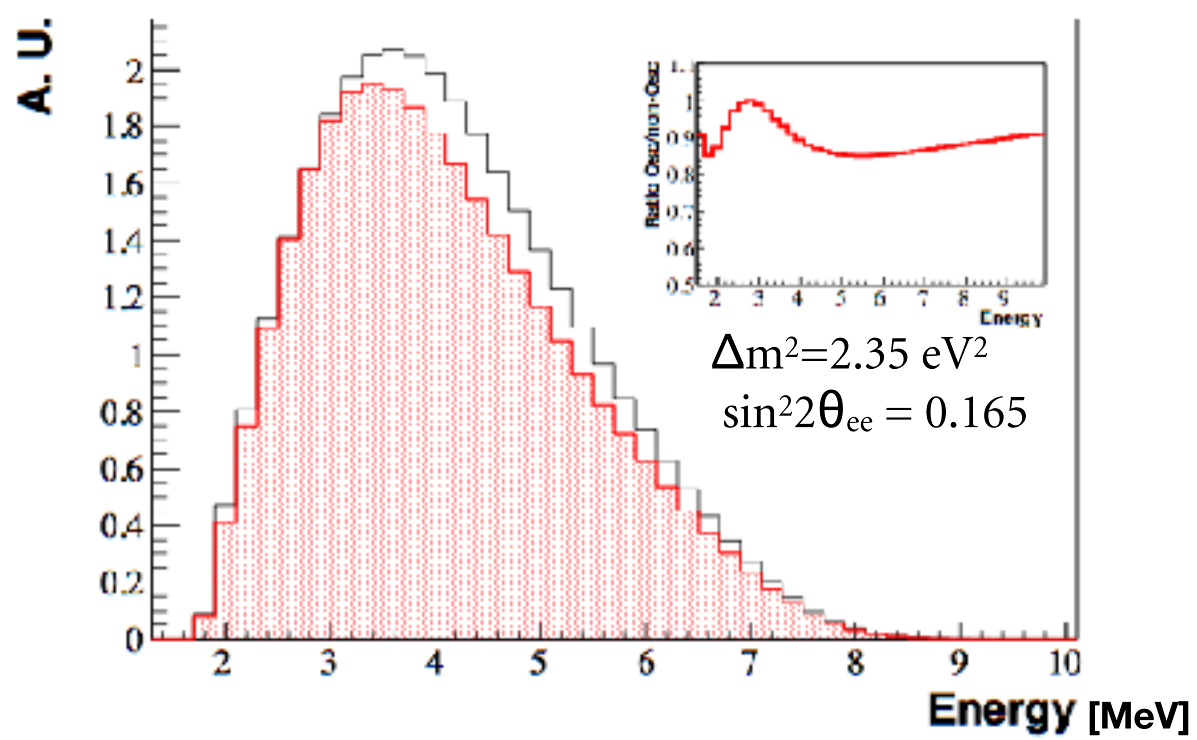
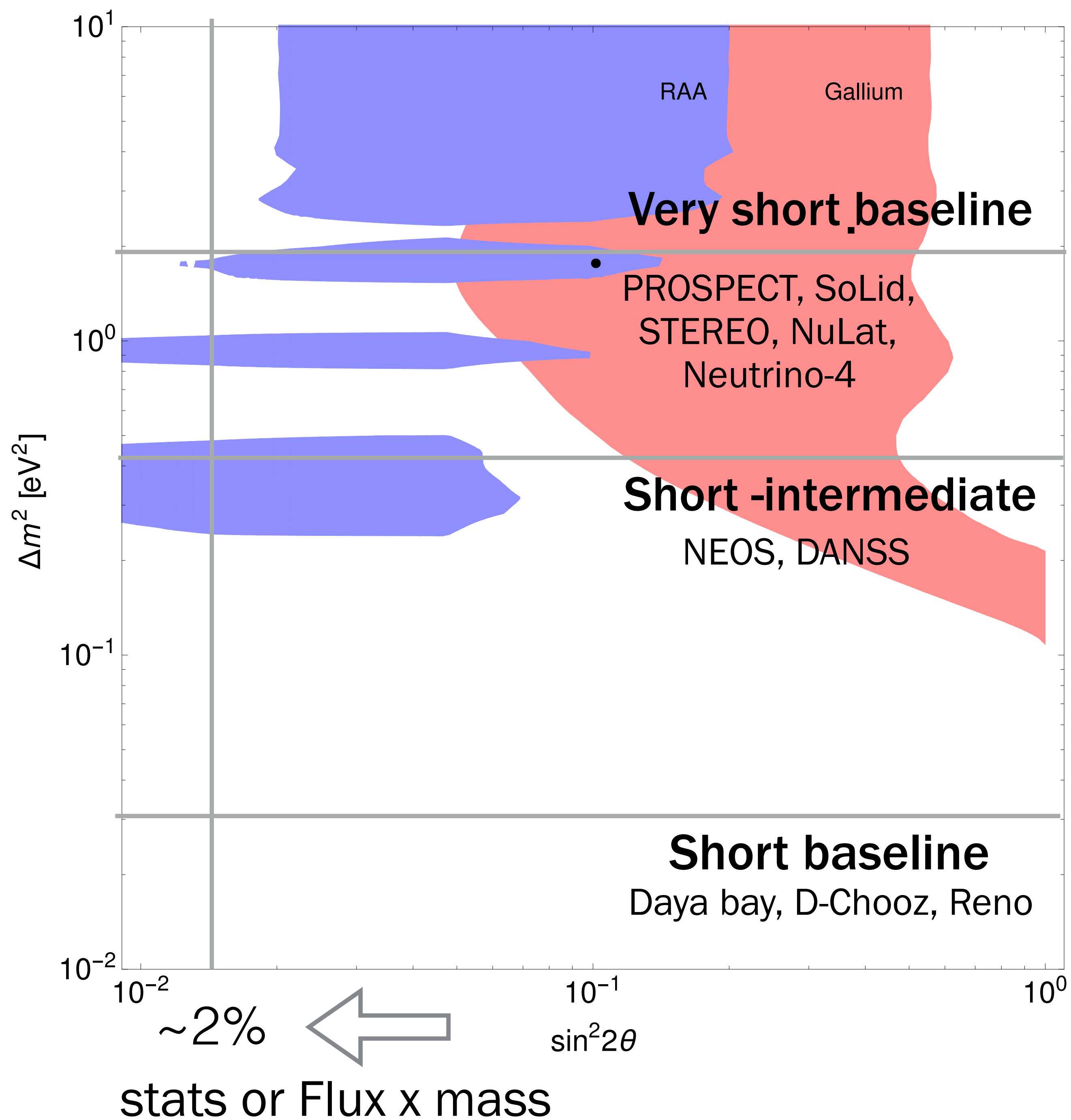
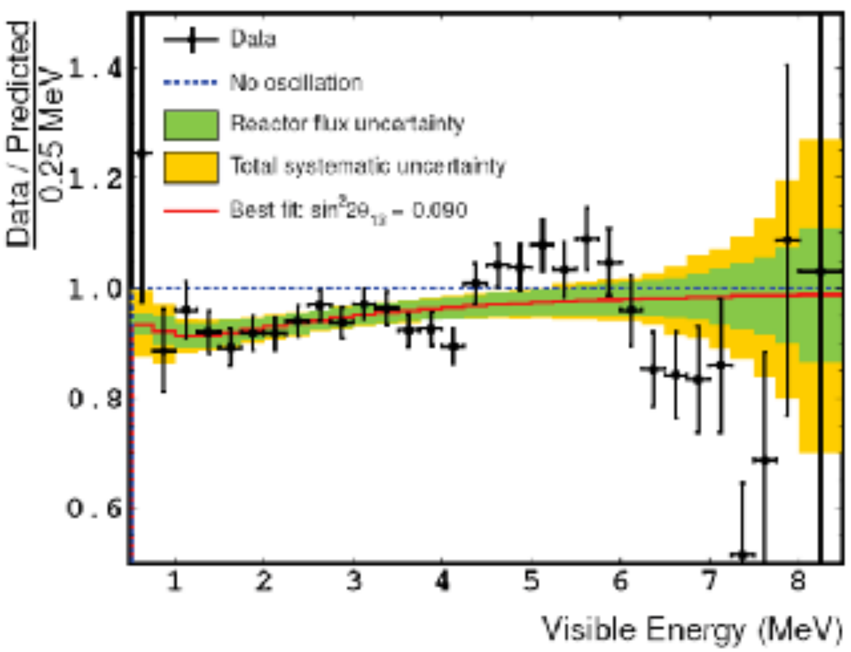




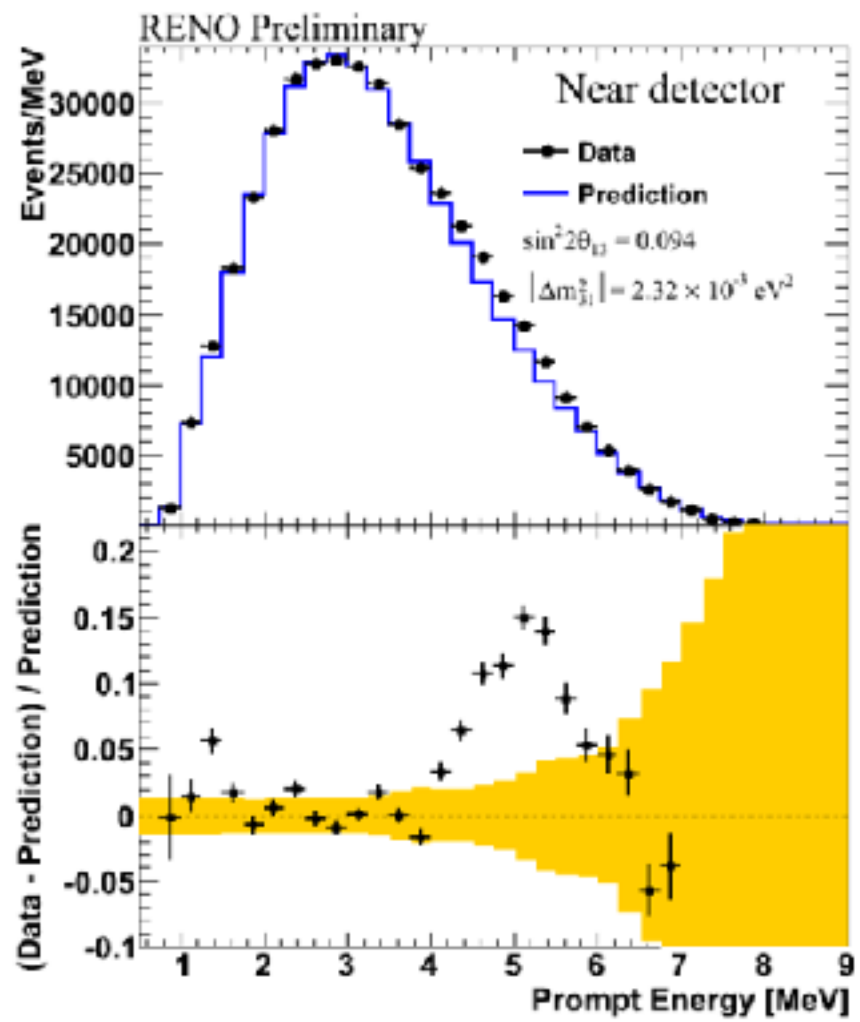
2014: Reactor spectrum distortions

D-CHOOZ

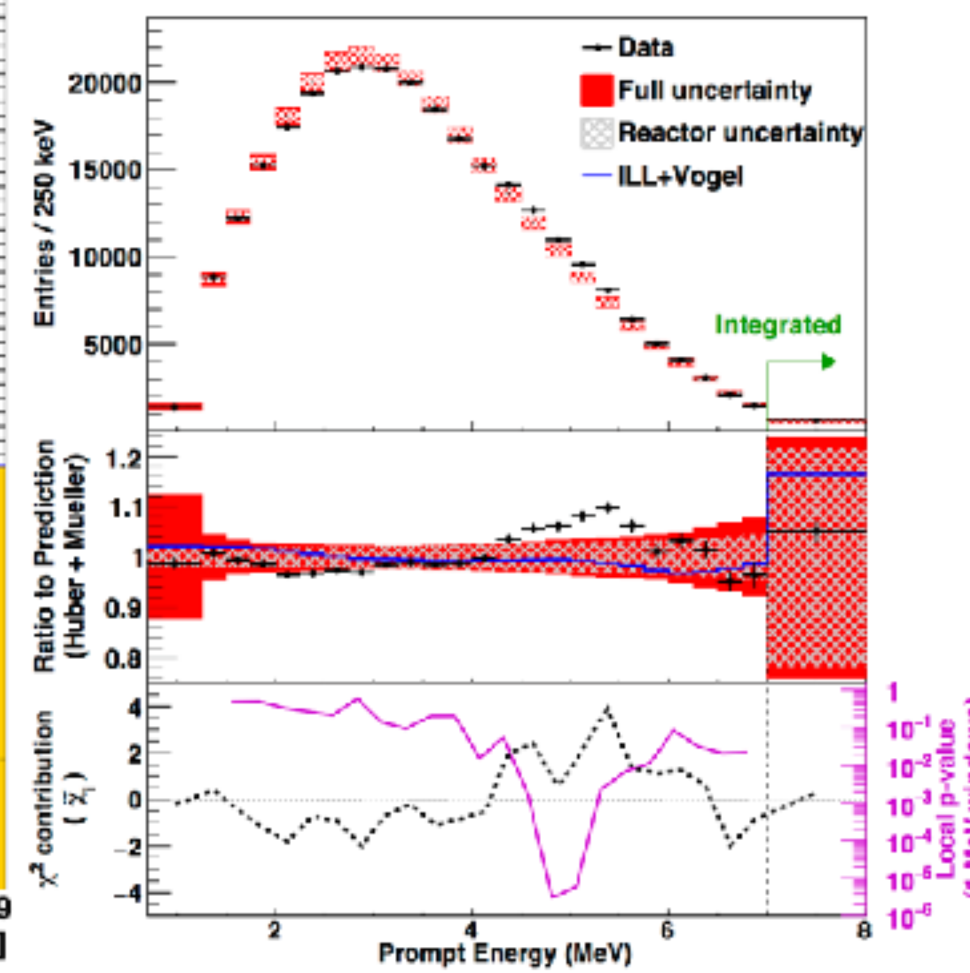
$$E_\nu \simeq E_{e^+} + m_n - m_p$$



RENO



DAYA BAY



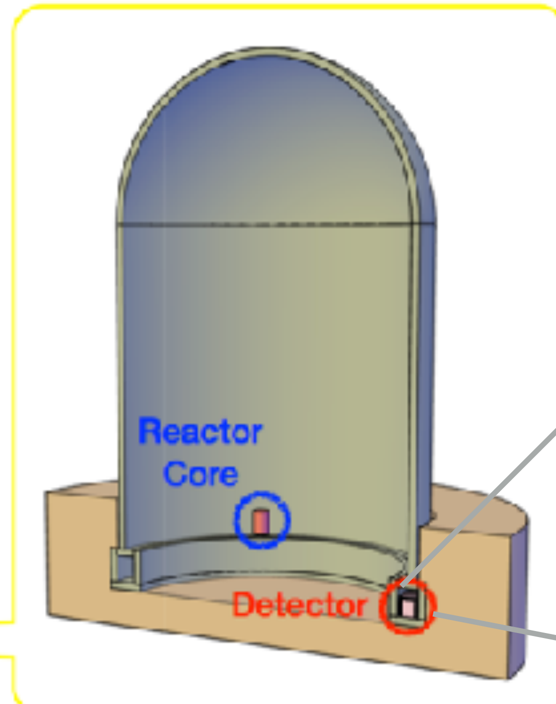
- Energy spectrum distortion seen by all three reactor experiments with high significance (dubbed “the bump”)
- Amplitude of effect correlated with reactor power
- Cancels in near-far ratio

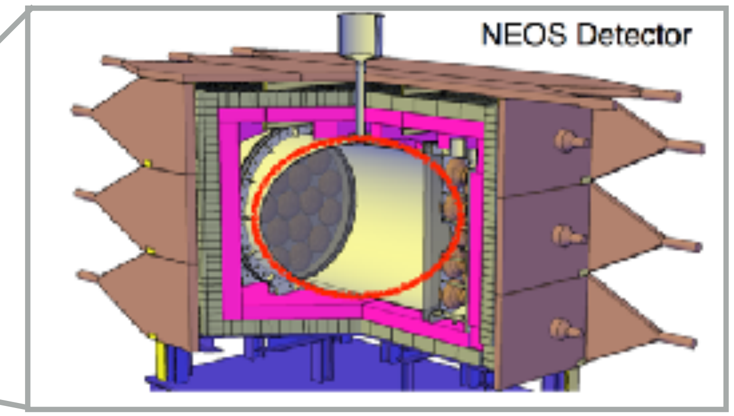
NEOS

- 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

Reactor building





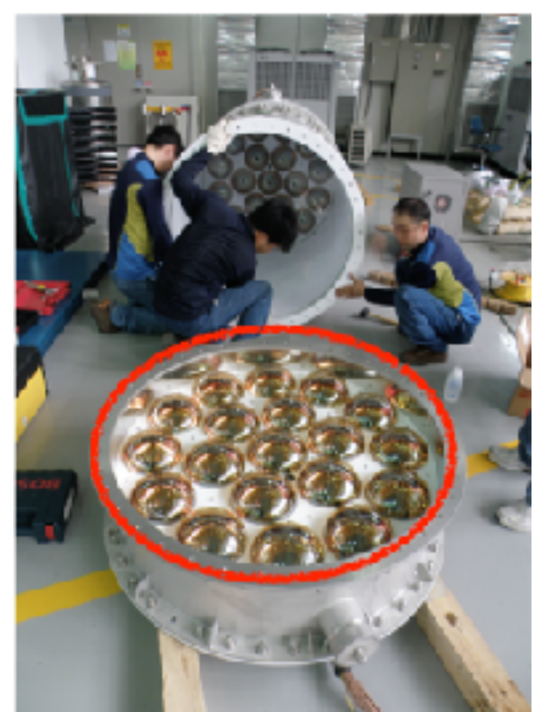
2.8 GW$_{th}$ commercial reactor

- 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 result

Data taking: Aug 2015 - May 2016

- Reactor-on period: 180 days

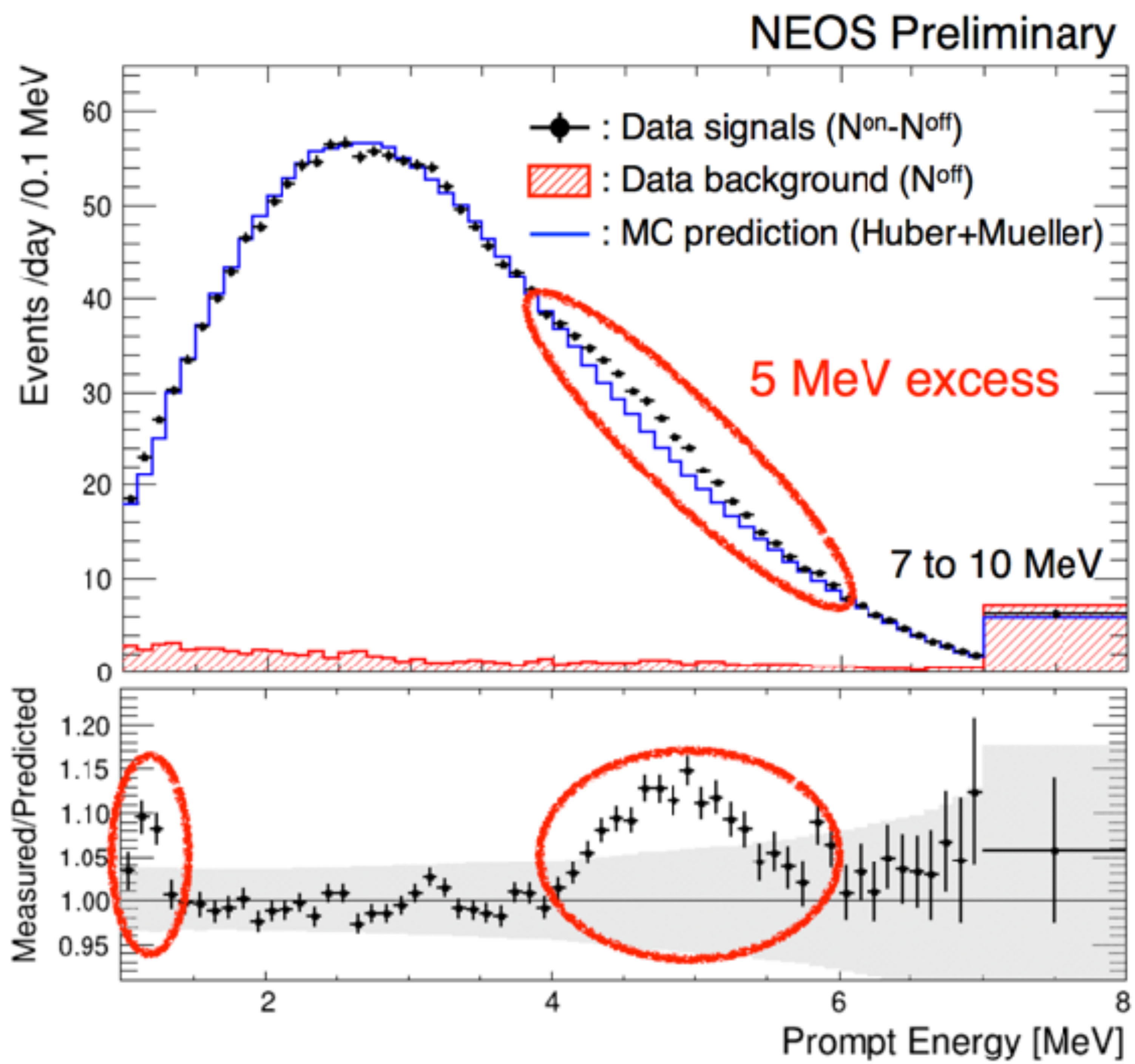
- Reactor-off period: 46 days

- **S:B ~ 23**

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

Comparison with Huber and Mueller's flux model

- 5 MeV excess is clear
- Disagreement around 1 MeV



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- Reactor-on period: 180 days

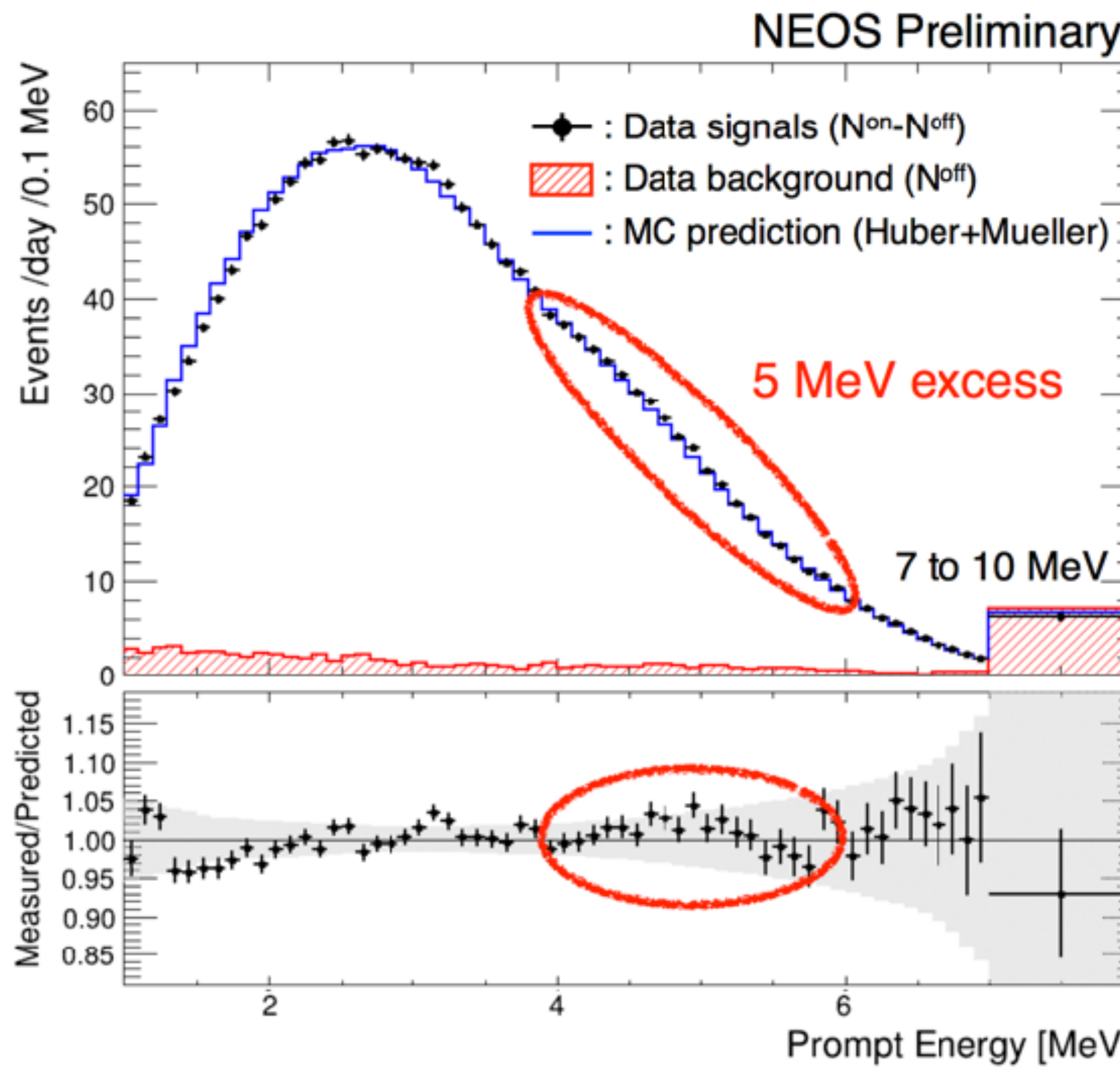
- Reactor-off period: 46 days

- **S:B ~ 23**

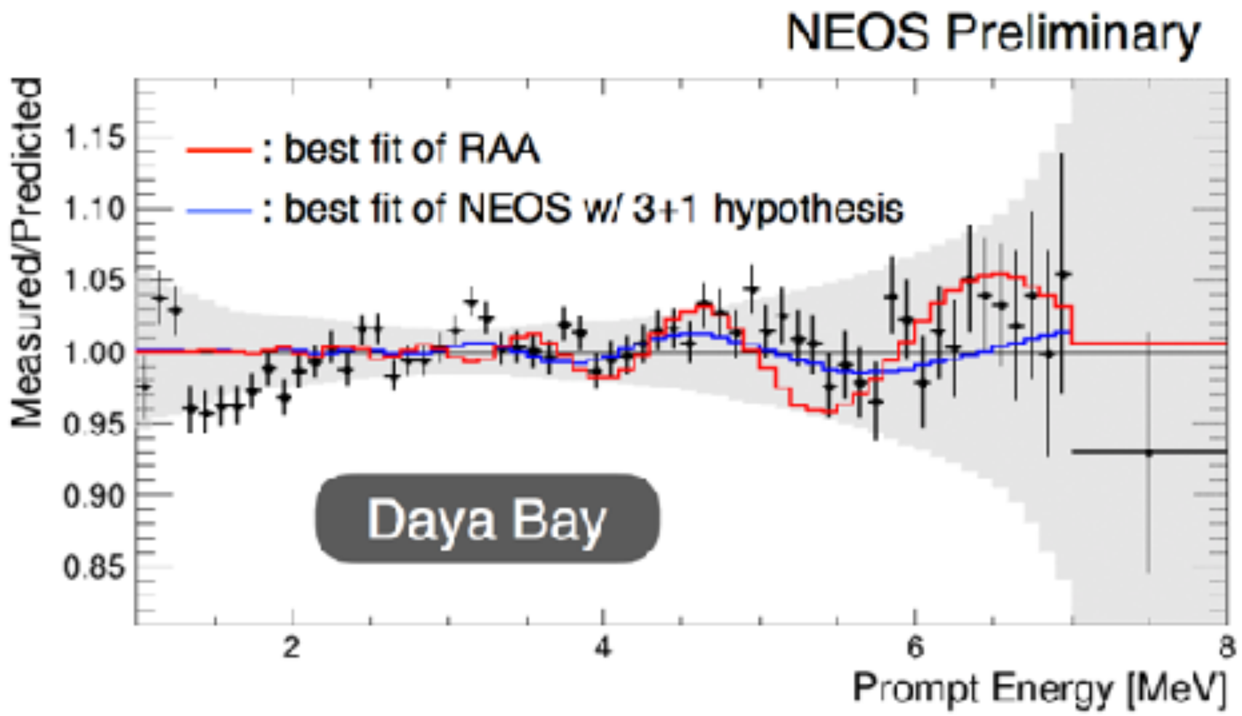
- **5% energy resolution** at 1 MeV

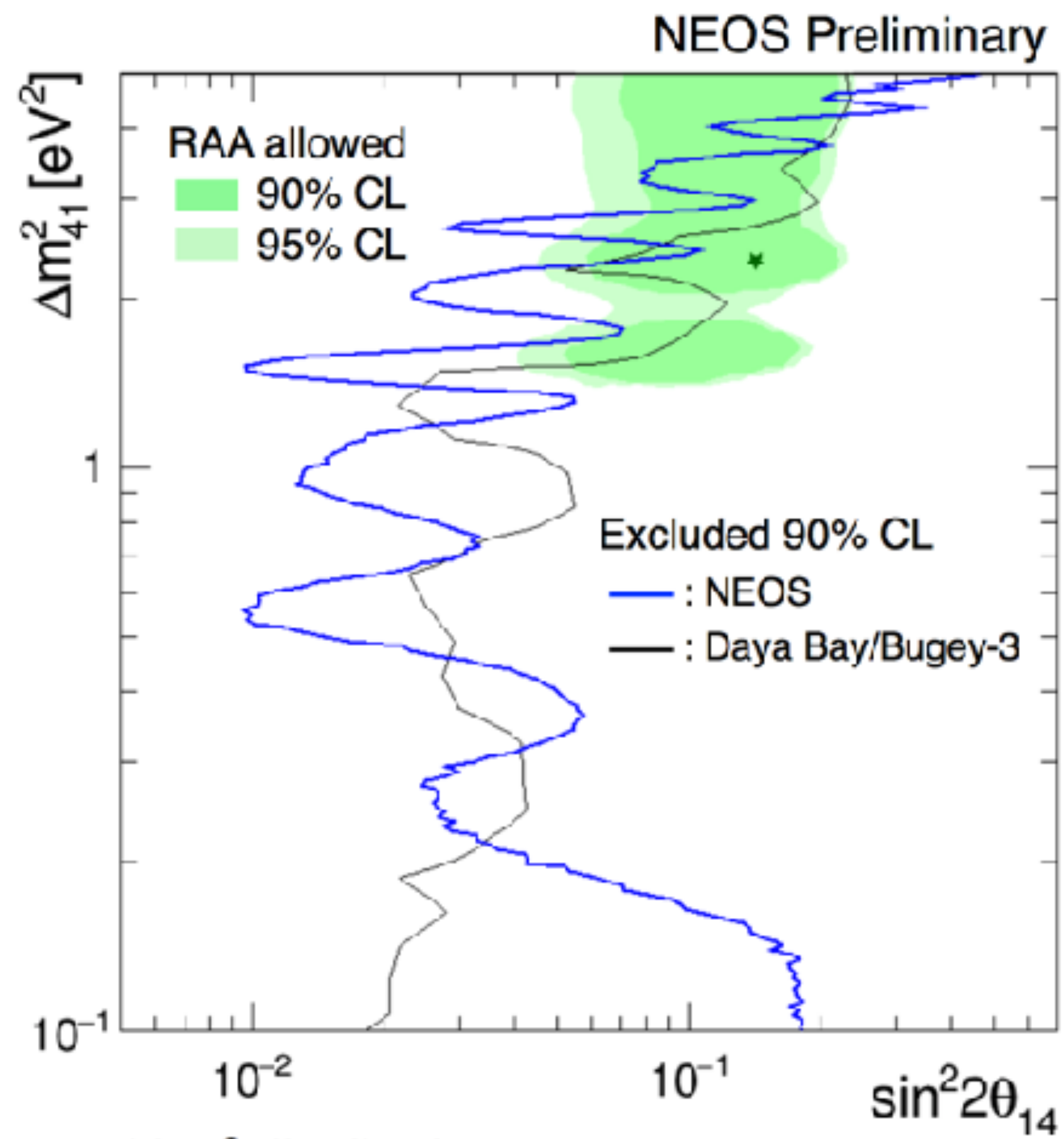
Comparison with Huber and Mueller's flux model

- Better agreement with Daya Bay spectrum



NEOS Sterile Analysis

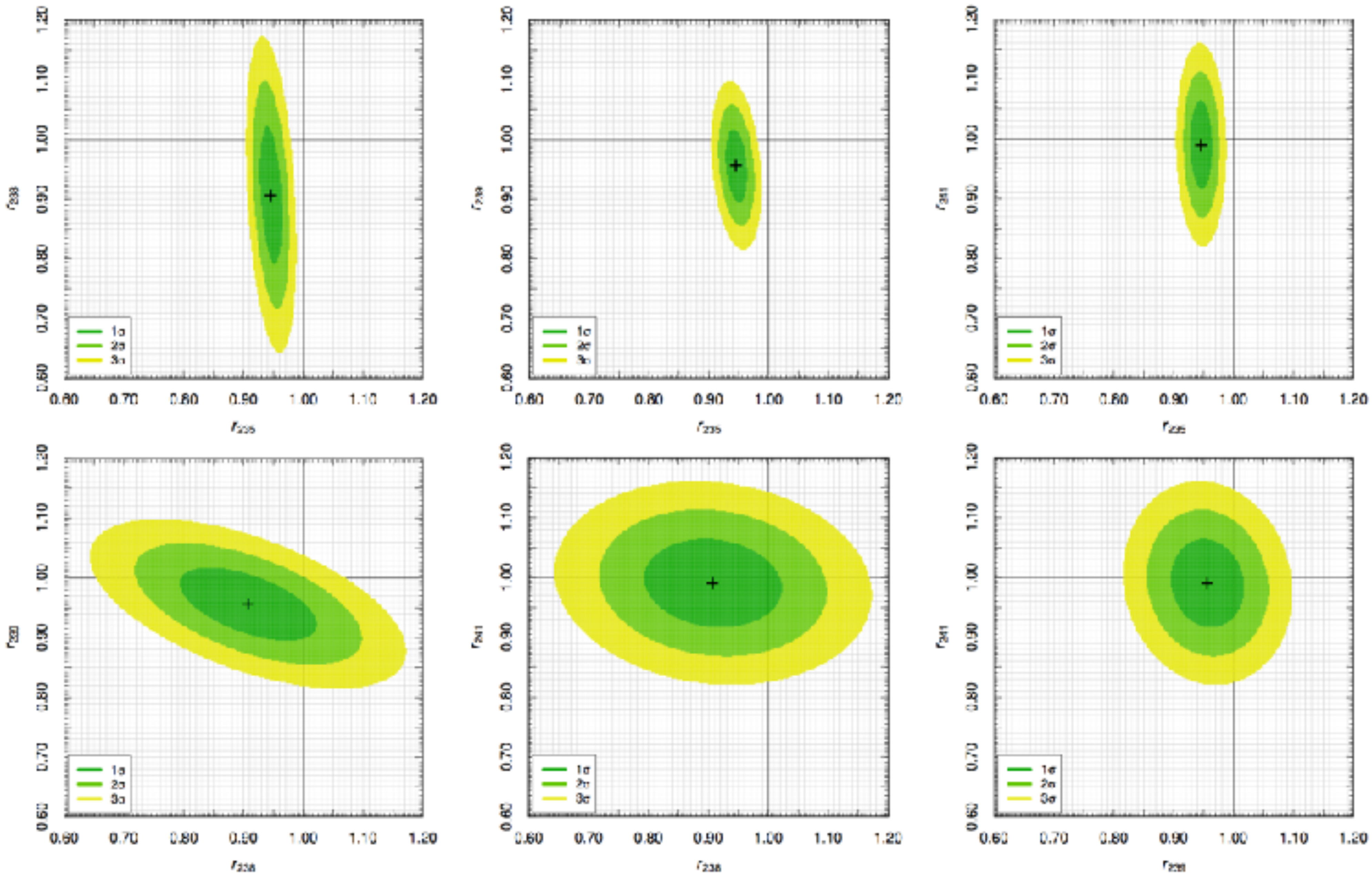




Hypothesis	χ^2/N_{dof}	$(\sin^2 2\theta_{14}, \Delta m^2_{41})$
H_{3v}	66.8/61	(0, 0)
H_{4v}	59.6/59	(0.037, 1.73 eV^2)
RAA	78.0/59	(0.142, 2.32 eV^2)

- 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 ?

Isotopic composition study all data



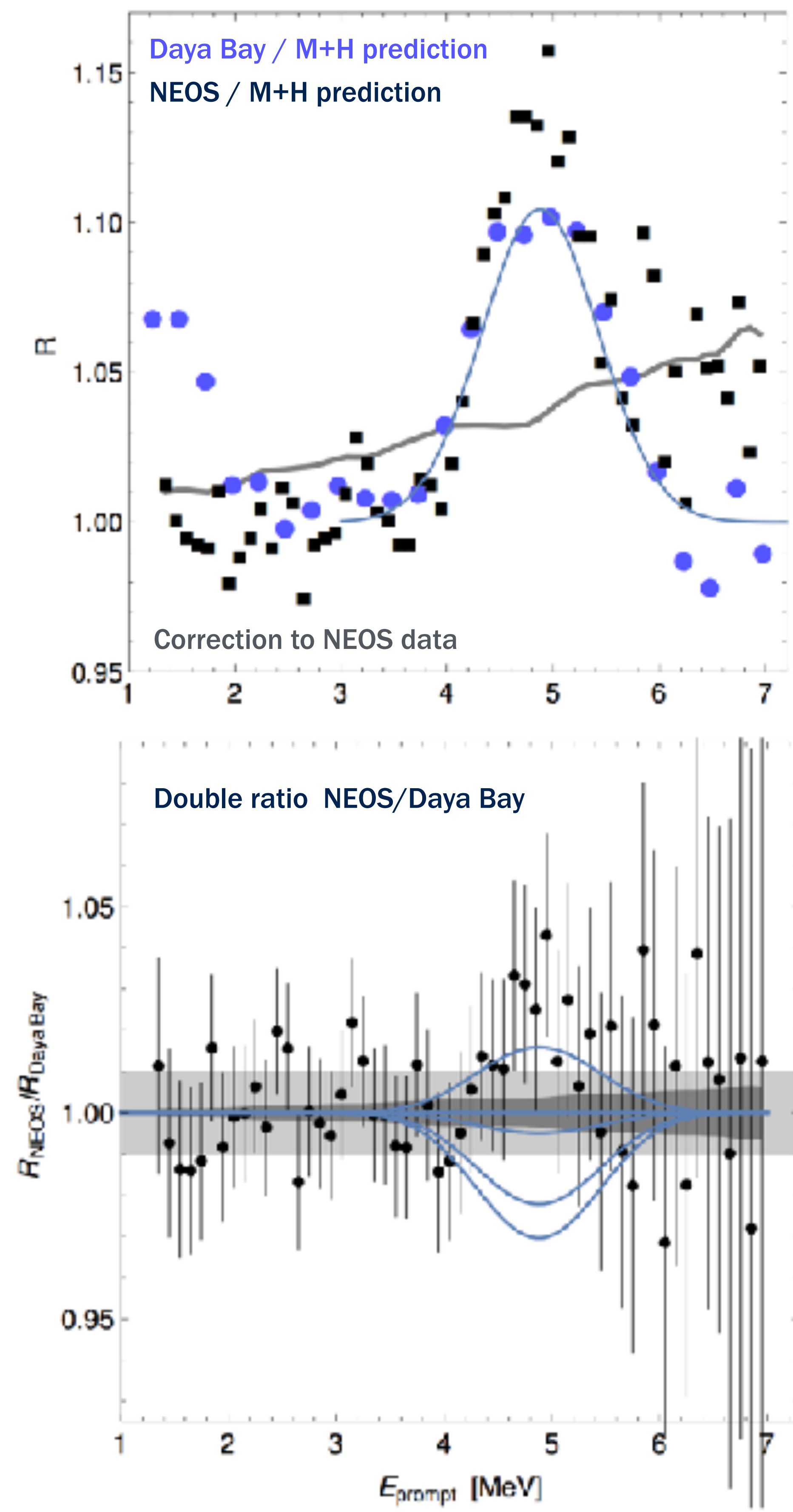
- Look at previous data to infer which isotope could be causing the reactor anomaly if due to miscalculation of flux
- Deviations in cross section per fission for ^{235}U at 2.2 sigma
- Not much sensitivity on other isotopes

C. Giunti, 1608.04096

NEOS-Daya Bay isotopic composition study

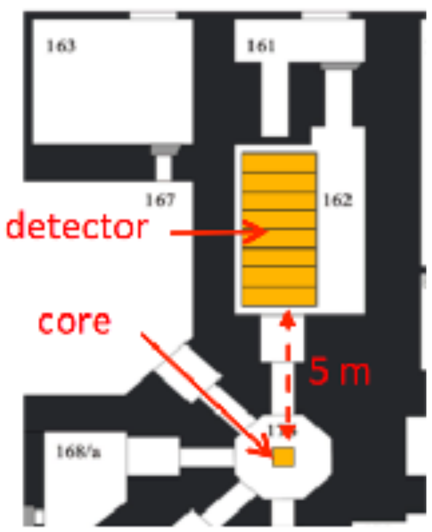
P. Huber 1609.03910

- Combined analysis of NEOS and DAYA BAY spectrum data
- based on double ration to cancel flux shape related uncertainty
- Able to reject Pu isotopes to be sole responsible for the bump at 99% confidence level

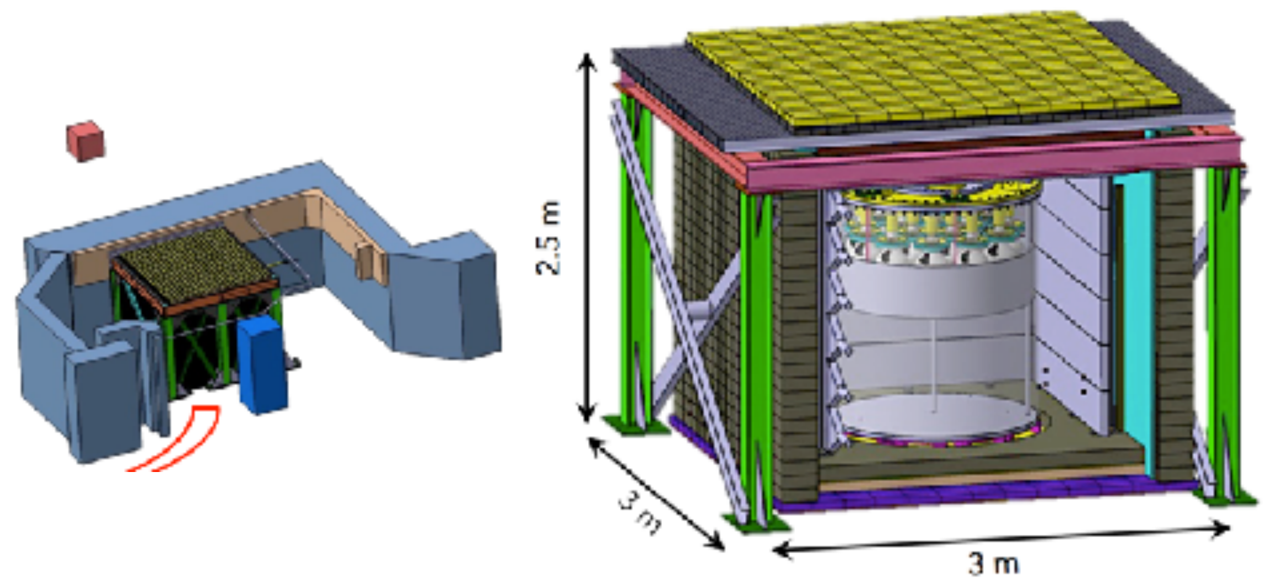


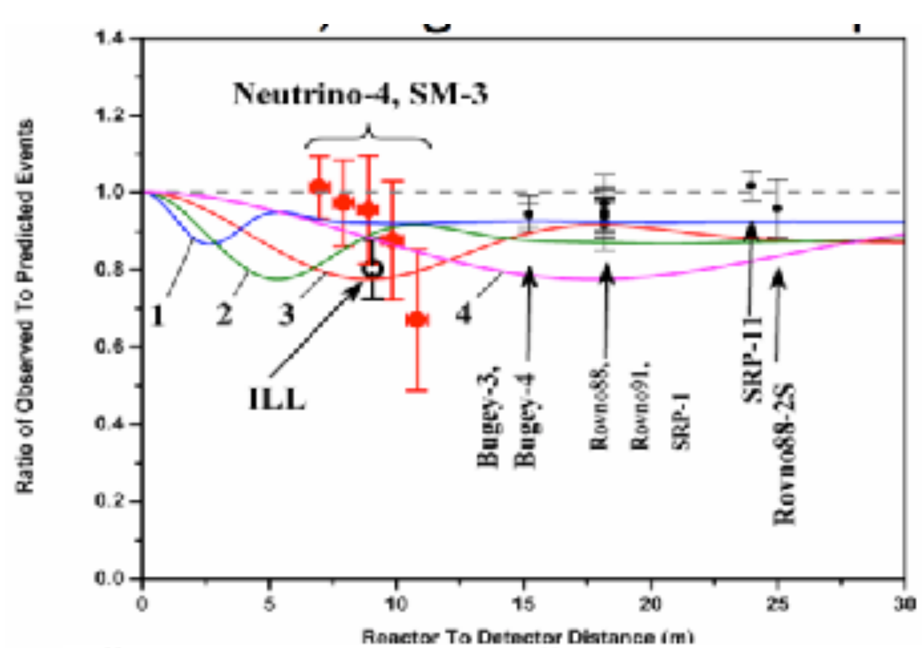
Recent rate measurements

Neutrino-4 @ SM3

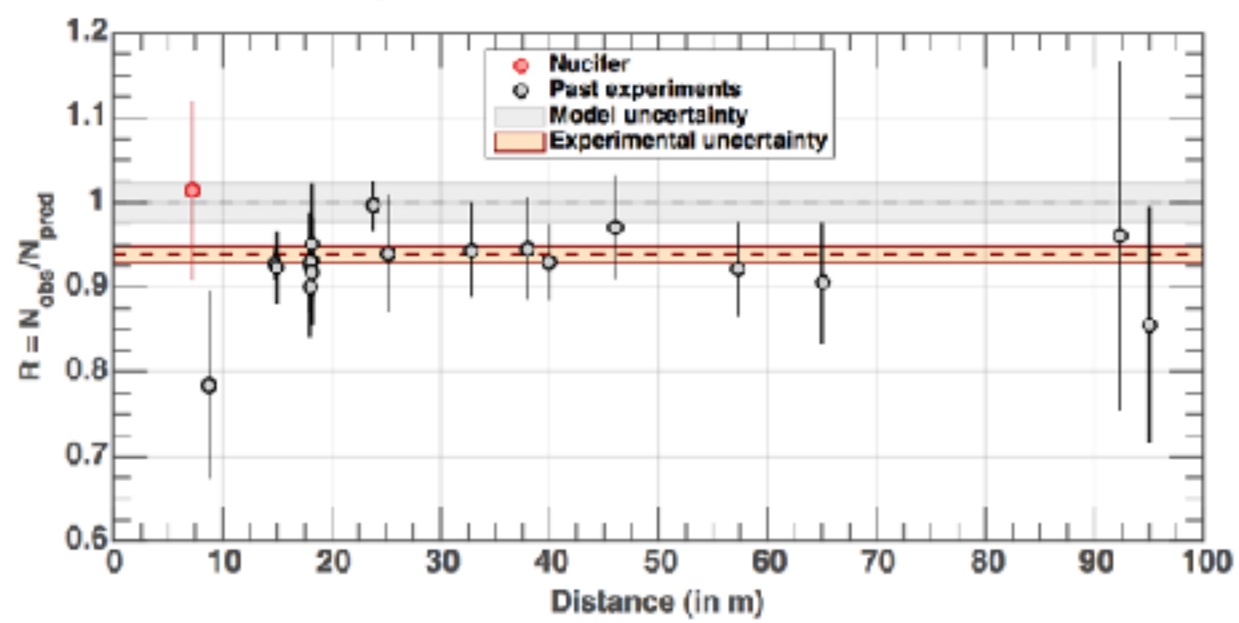


NUCIFER @ OSIRIS





$$R_{\nu}^{obs}/R_{\nu}^{pred} = 1.014 \pm 0.108$$



- Precision of results impacted by adverse conditions and show difficulty of measuring close to reactors
- Neutrino-4 currently taking more data and working on systematics

Very Short Baseline (VSBL) experiments

- Latest data sets are not yet conclusive about the (non-)existence of light sterile neutrino but **the phase space is closing fast**
  - **only experiments at ~ 10 m from reactor can really put strong constraints in the above 1 eV^2 region**
- Since the 2011 reactor anomaly more concerns about the flux model have emerged with the identification of distortion
  - Is the ^{235}U spectrum the culprit ?
  - **motivates even more the need for measurement at research reactors using highly enriched ^{235}U fuel**
    - Older data is patchy and not very precise
    - key ingredient for predicting antineutrino flux

Very Short Baseline (VSBL) vs SBL

Quantities	SBL @ PWR	VSBL @ RR
L/E (m/MeV)	100-1000	1-10
Fiducial Mass	7	1-2
Rates (nu/day)	1-100	1000
S:B	20-50:1	3-1:1
Overburden	50-850	5-20
Thermal Power uncertainty	0.5%	2-5%
Core composition	^{235}U,^{238}U, ^{239}PU,^{241}PU	^{235}U

Compact experiment

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Challenging background environment

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Normalisation precision limited

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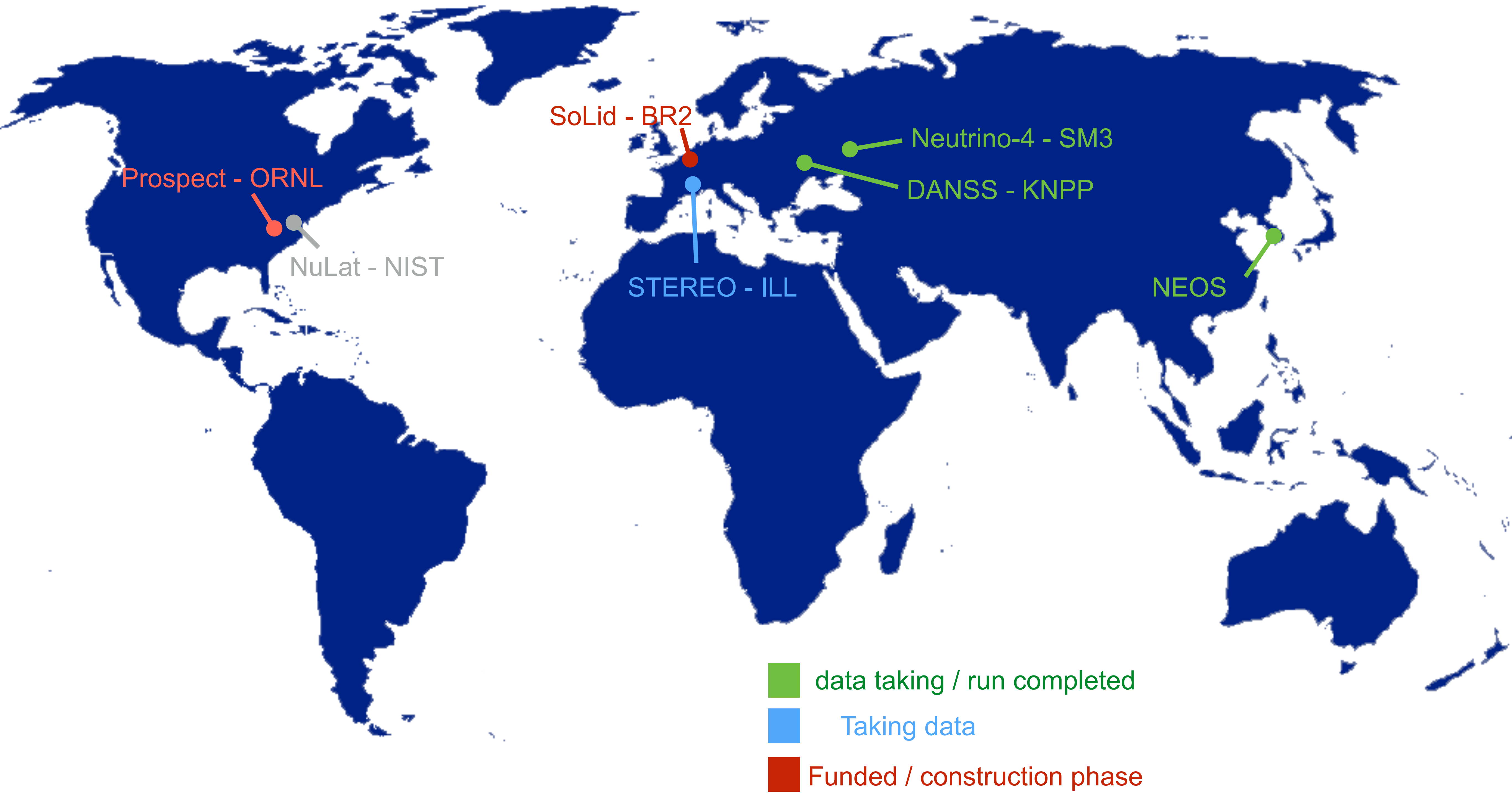
Single isotopic composition

VSBL reactor experiments



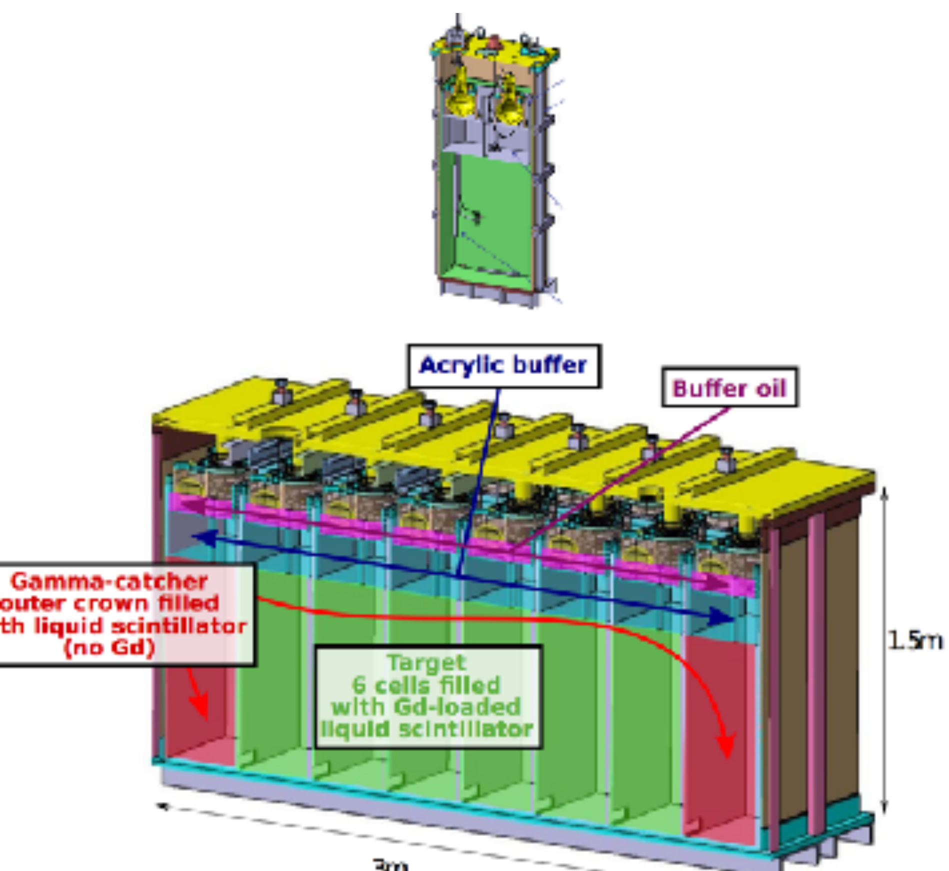
Very Short baseline experiment

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
NuLat (US)	^{6}Li doped PS	NIST	^{235}U	25	6-10	1

Segmentation, segmentation, segmentation...

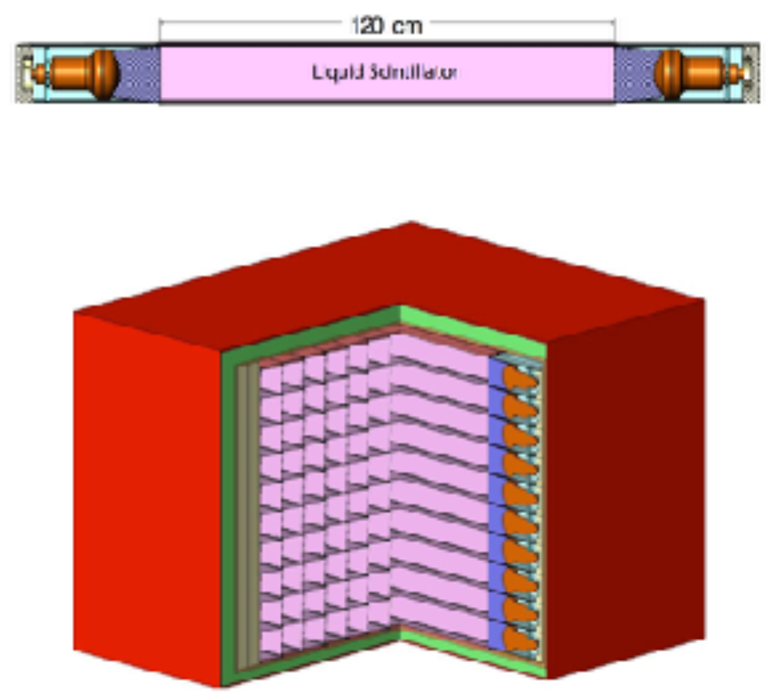
- Detector segmentation provides relative measurement along oscillation length
  - **combined with energy measurement is only way to demonstrate oscillation !**
- Finer segmentation provides additional capability to reject background and select positron energy

STEREO



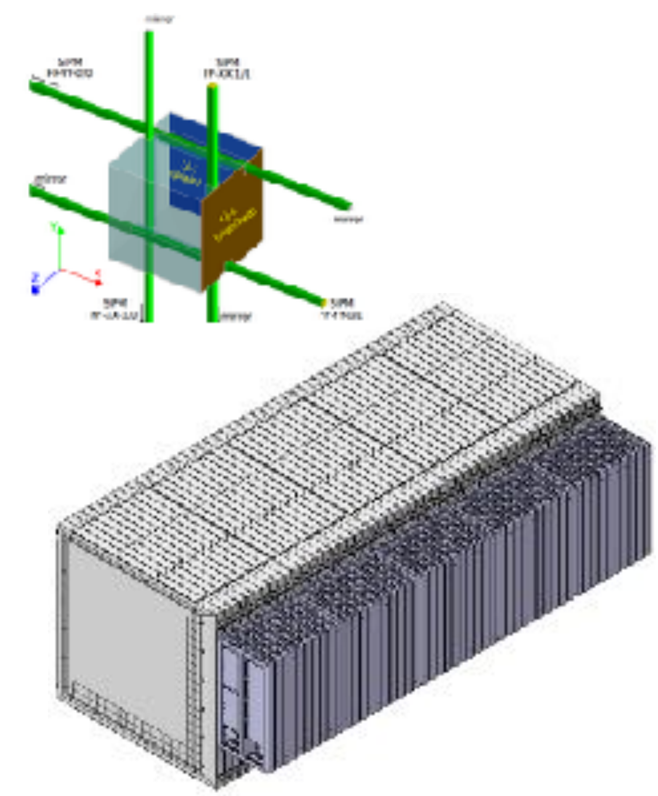
6x inner 1D cells 90 x 90 x 35 cm3
buffer cells around the target
2000 L of Gd loaded LS

PROSPECT



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

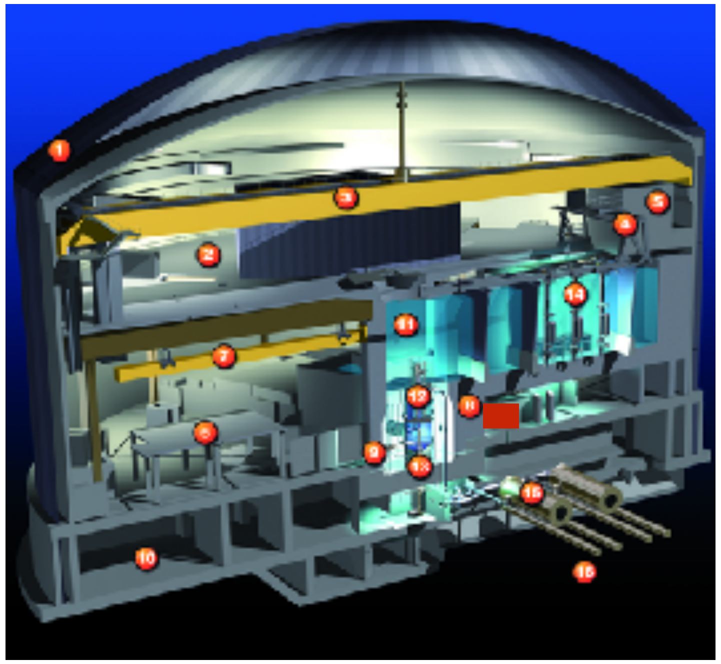
SoLid

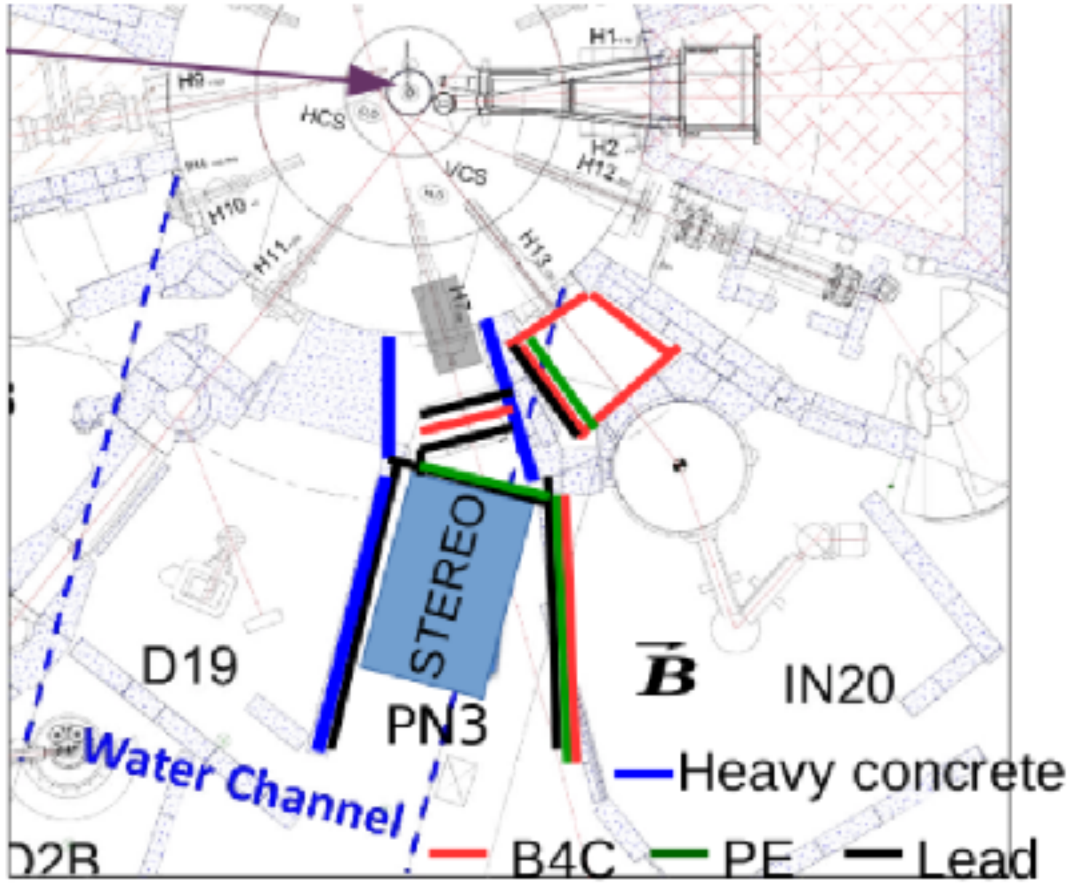


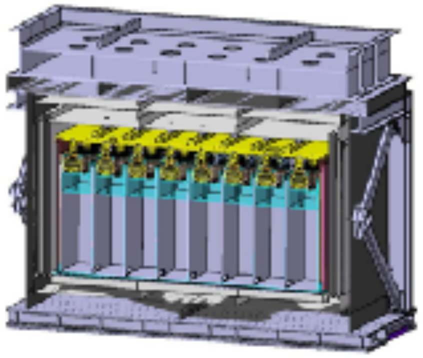
5-6x modules 2560 cubes
dimension 5 x 5 x 5 cm3
1.6-2 tons PVT+LiF:ZnS

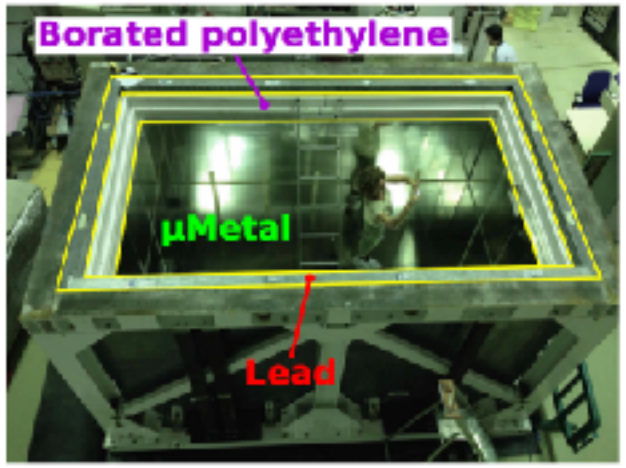
STEREO

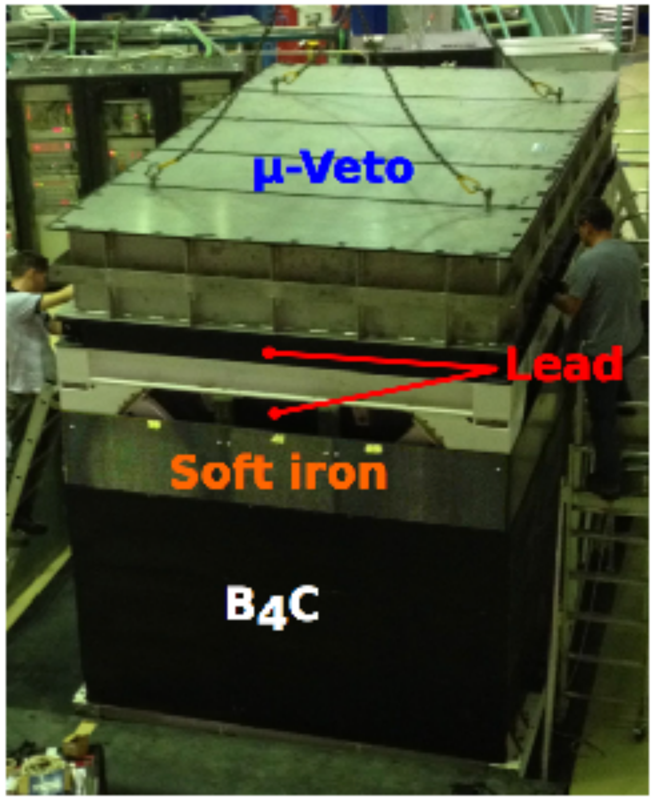
- Detector installed at 8.9-11m of ILL-HFR
- Overburden 15 mwe against muons
- Challenging reactor environment requiring external shielding in front and between other experiments
  - Detector shielding against fast neutrons, gamma-rays and magnetic field
  - Muon veto umbrella detector
- **Installation completed in September 2016**







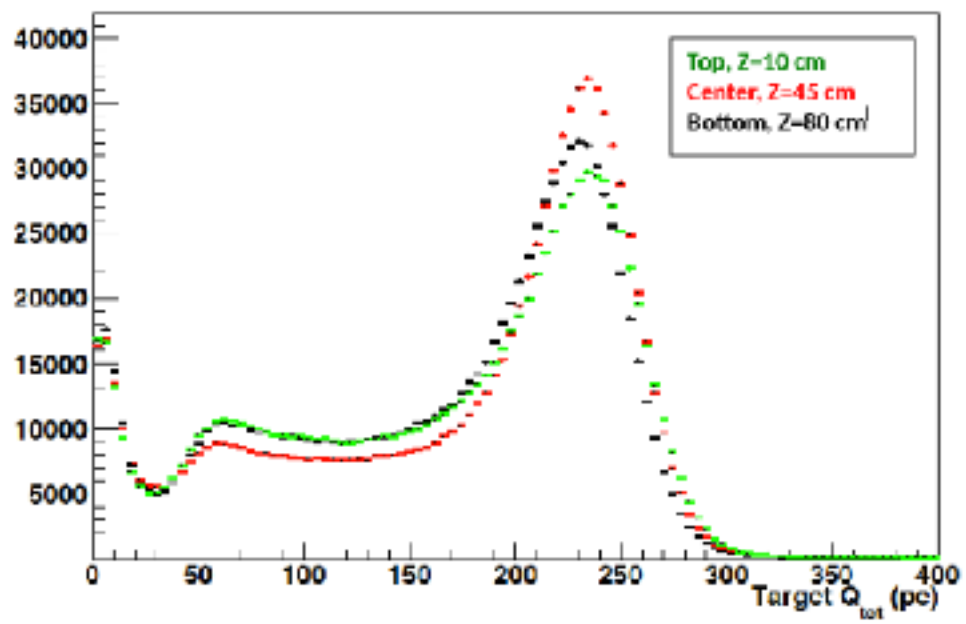




Commissioning

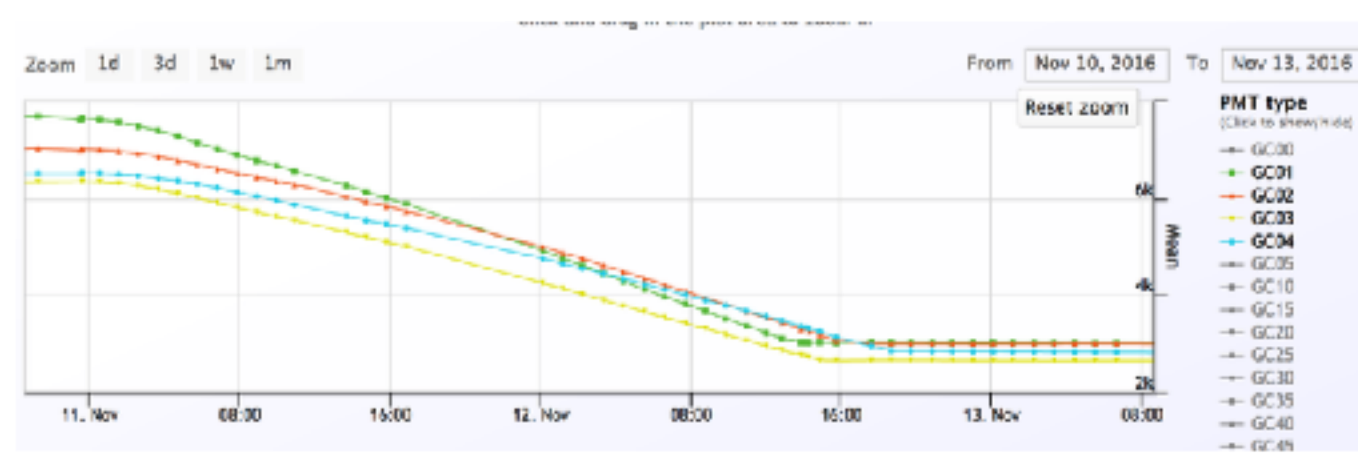
First source calibration done :

- ~280 PEs/MeV in Target cells as expected
- Small top-bottom effect on the detector response : 2% of differences



Buffer leak in cell 4 and one short gamma-catcher cell :

- Decrease by a factor 2.5 of the light collection
- LS and buffer oil chemically compatible



Related systematics under studies

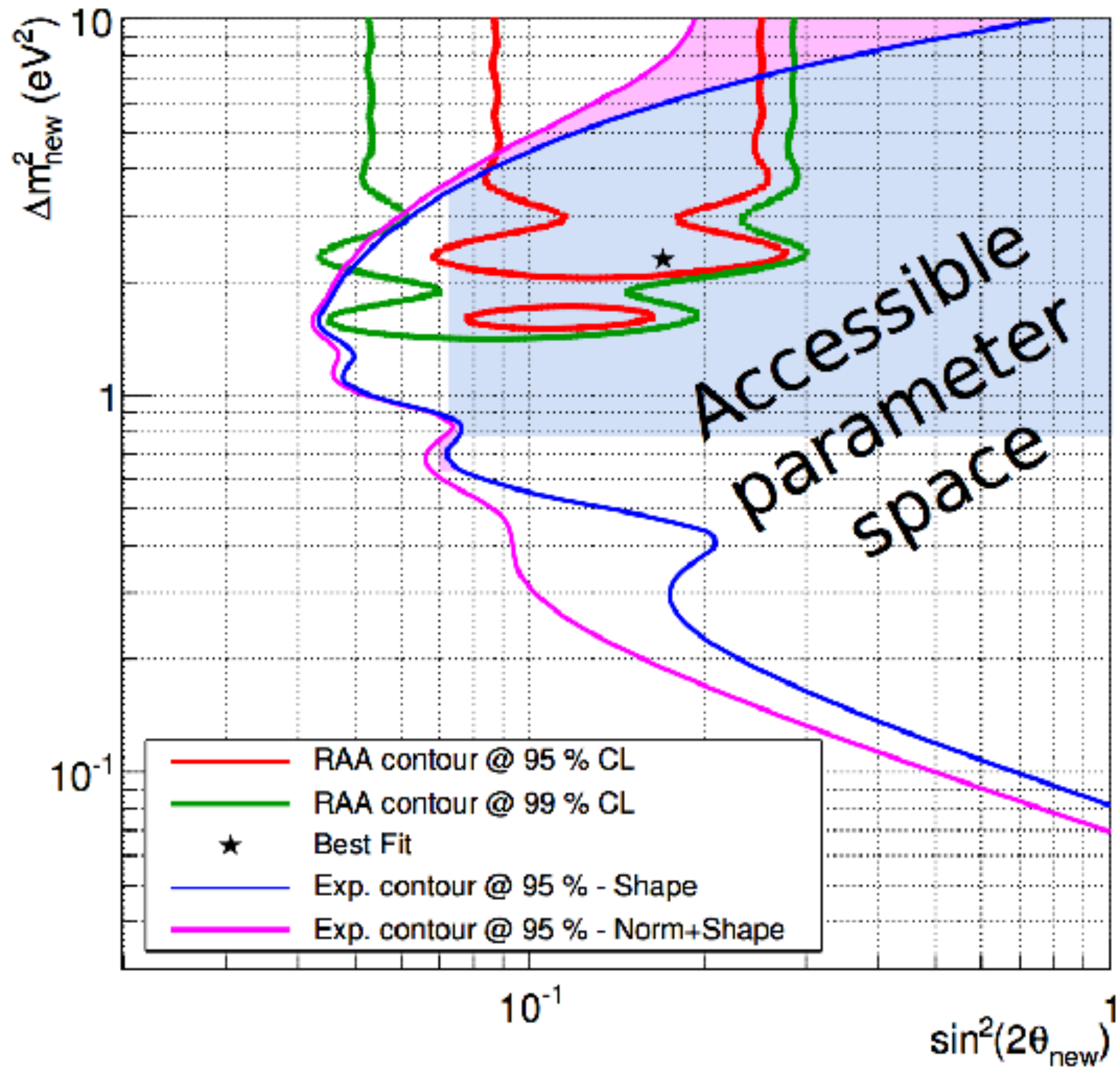
Data taking already started : after 10 days of commissioning

- Acquisition rate of $\sim 3\,\mathrm{kHz}$ with $\sim 1.8\%$ deadtime at ~250 keV threshold
- Single rate in neutrino window $(2\,\mathrm{MeV} < E_{vis} < 8\,\mathrm{MeV})$: ~14 Hz

T. Salagnac, AAP 2016

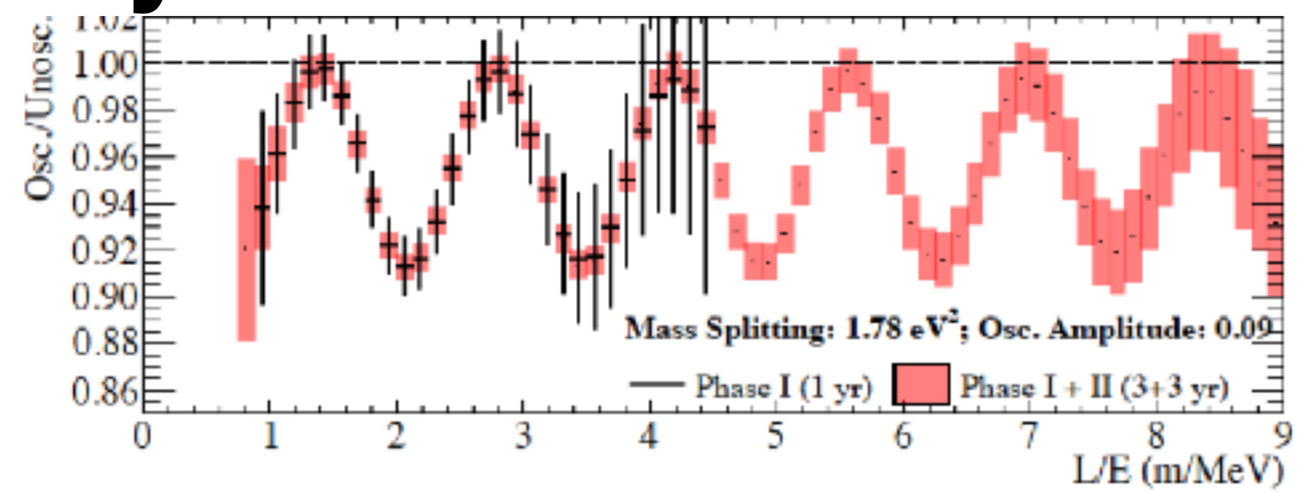
Status and sensitivity

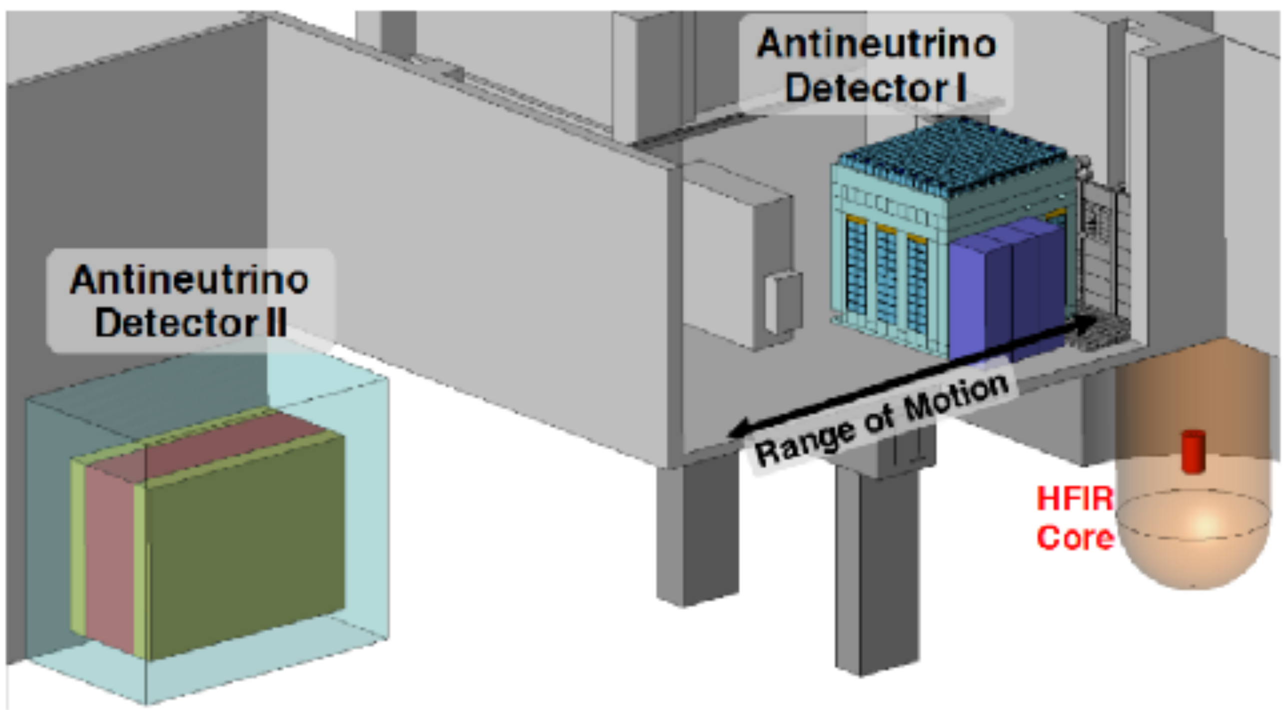
- Detector has been running since November 2016
  - short commissioning phase
- Data taking until March 2017
  - 80 days reactor ON
- Results coming soon



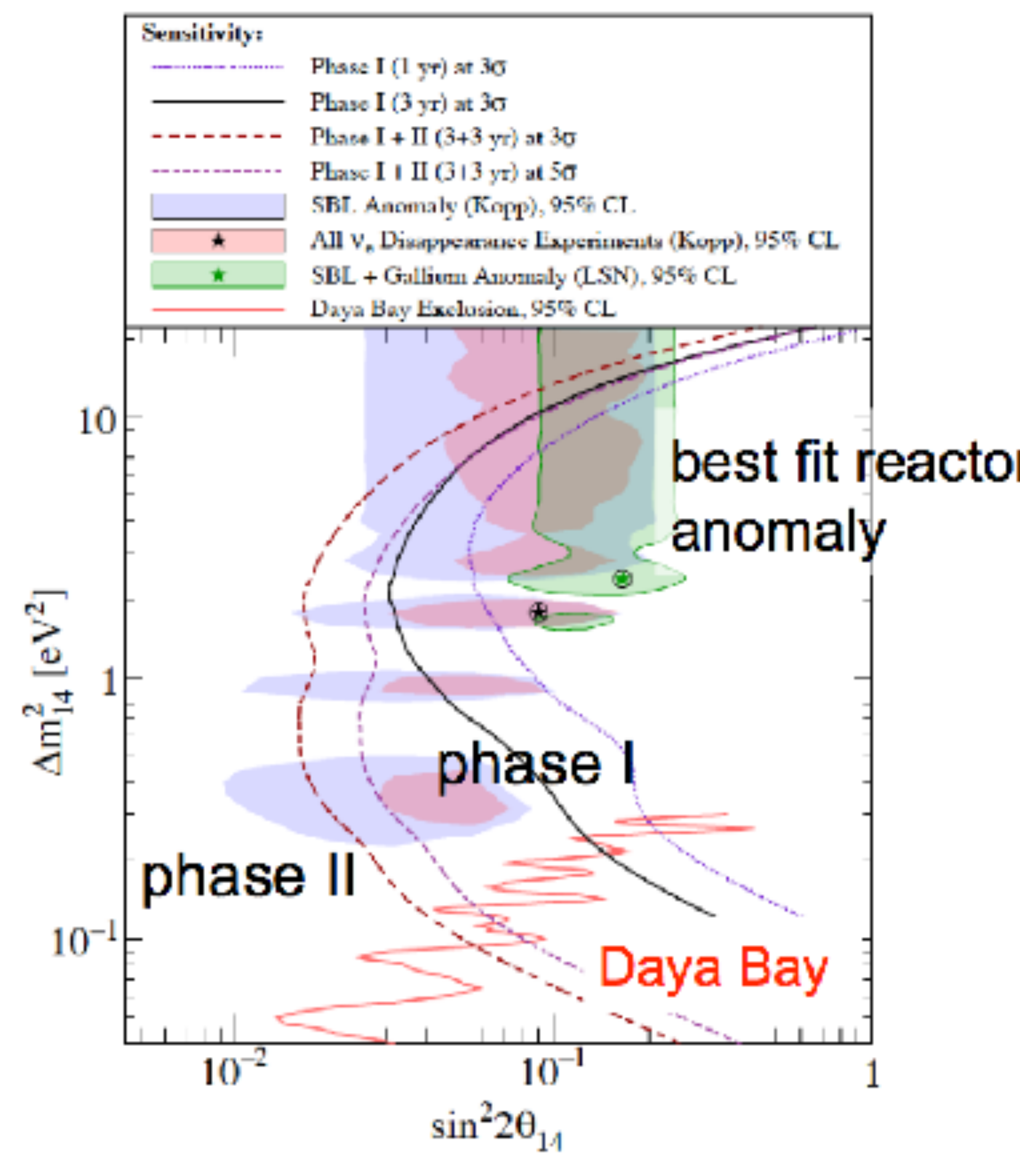
PROSPECT sensitivity to 3+1 model

A model independent experimental approach to test for oscillation of eV-scale neutrinos





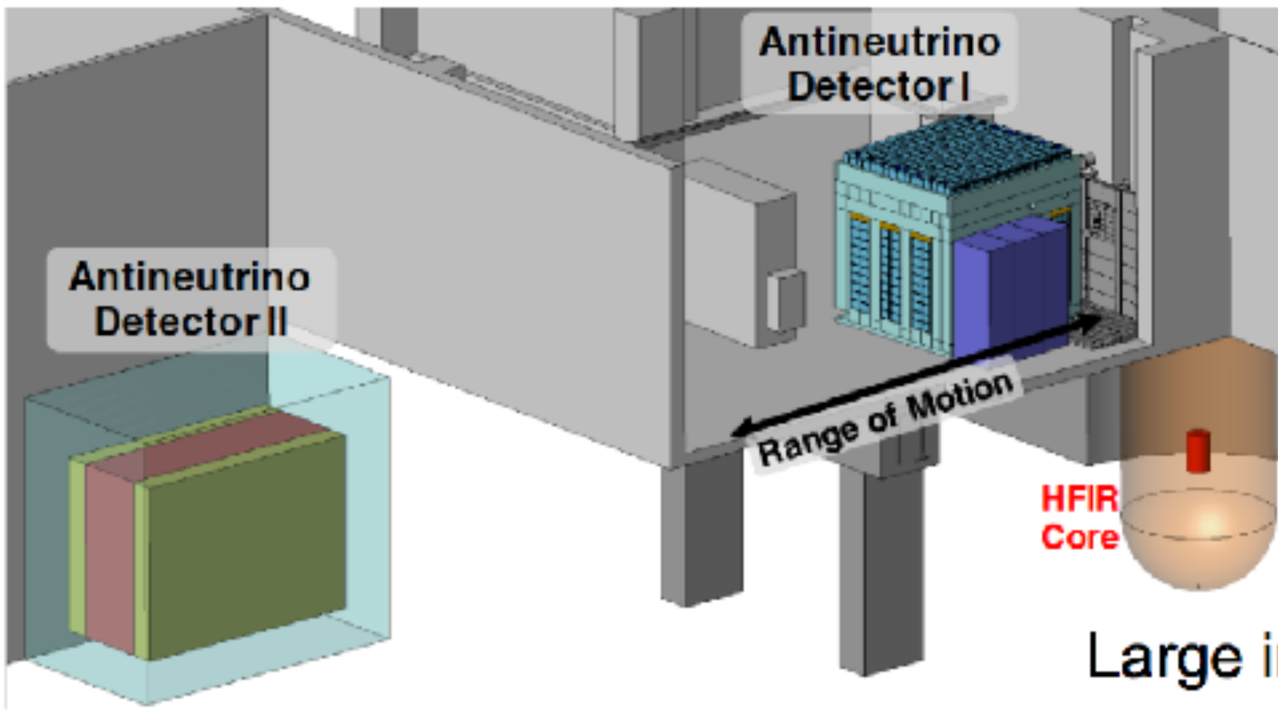
Phase I = AD-I, 3 years
Phase II = AD-I + AD-II, 3+3 years



Objectives
4σ test of best fit after 1 year
>3σ test of favored region after 3 years
5σ test of allowed region after 3+3 years

PROSPECT spectrum measurement

A precision measurement to address spectral unknowns

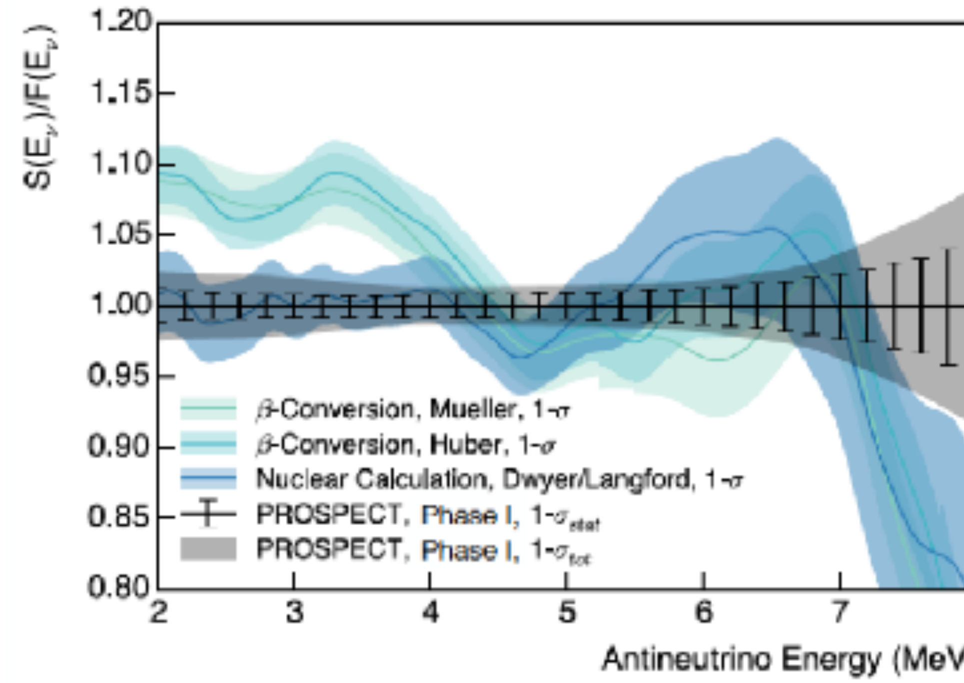


Phase I = AD-I only

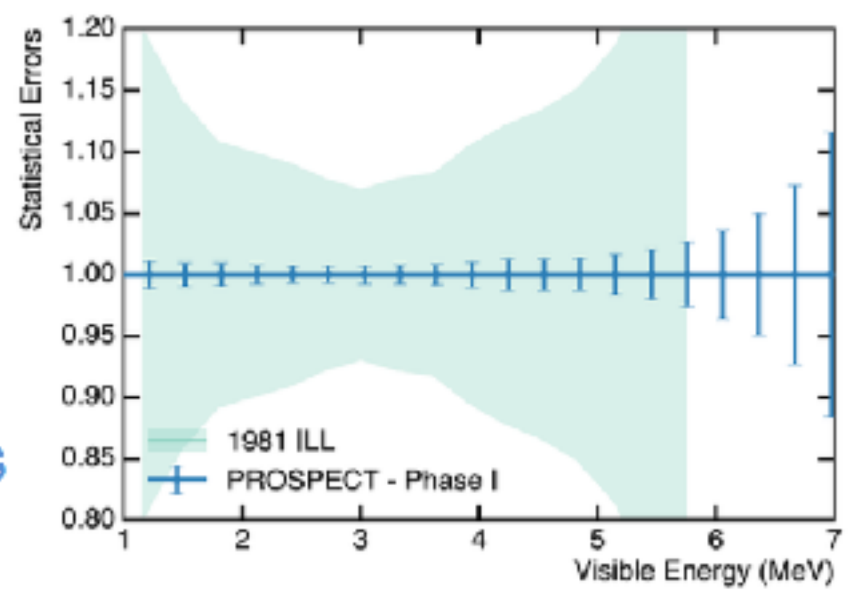
Objectives

Measurement of ^{235}U spectrum
Compare different reactor models
Compare different reactor cores

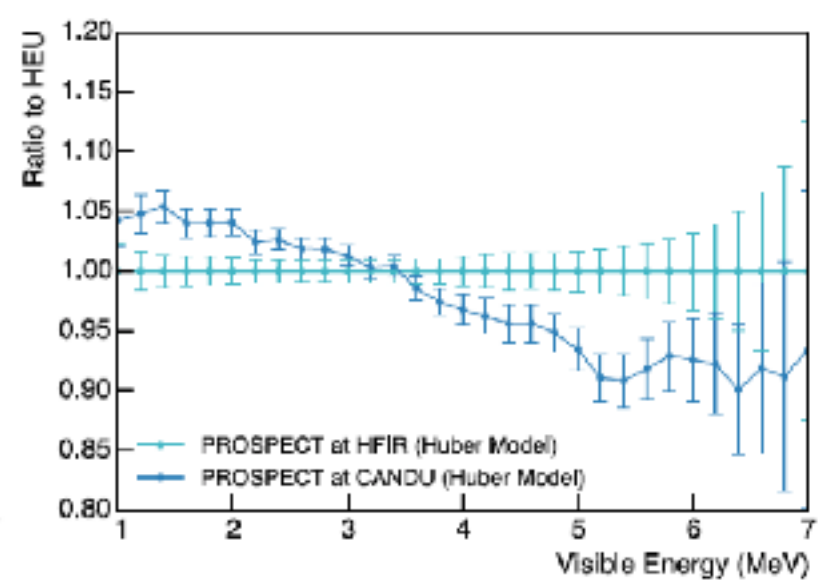
Testing ^{235}U $\overline{\nu}_e$ spectrum models



Large improvement on ILL



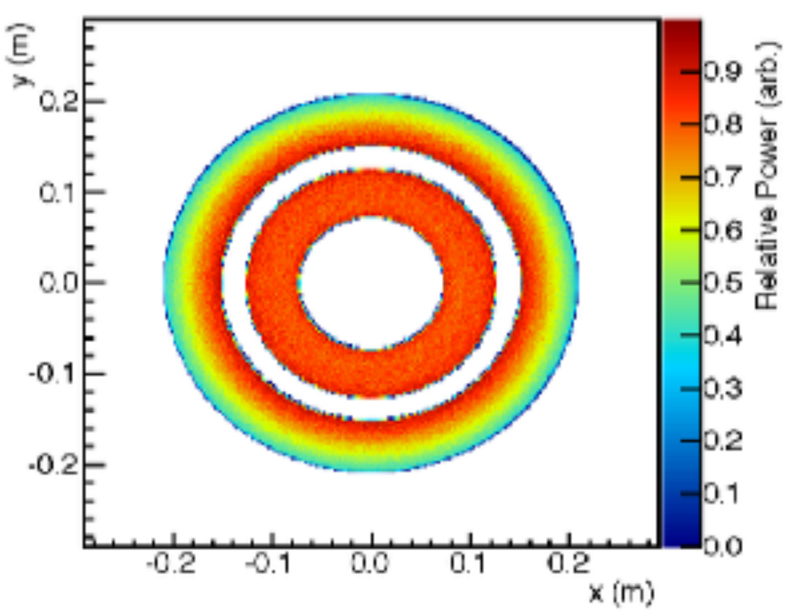
Different reactor cores



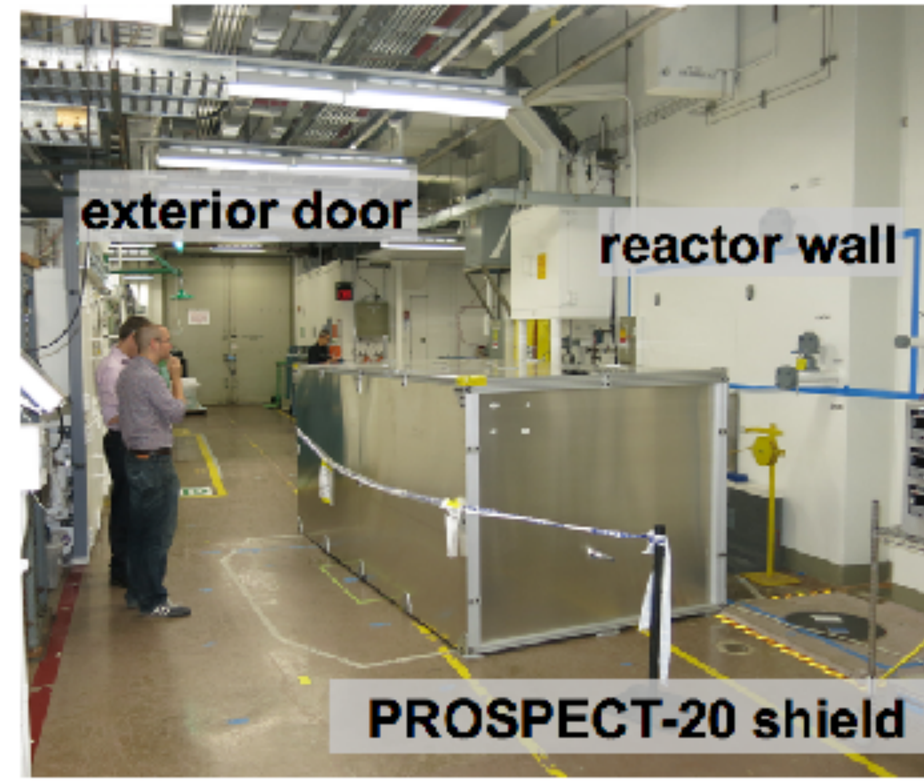
HFIR Reactor at ORNL

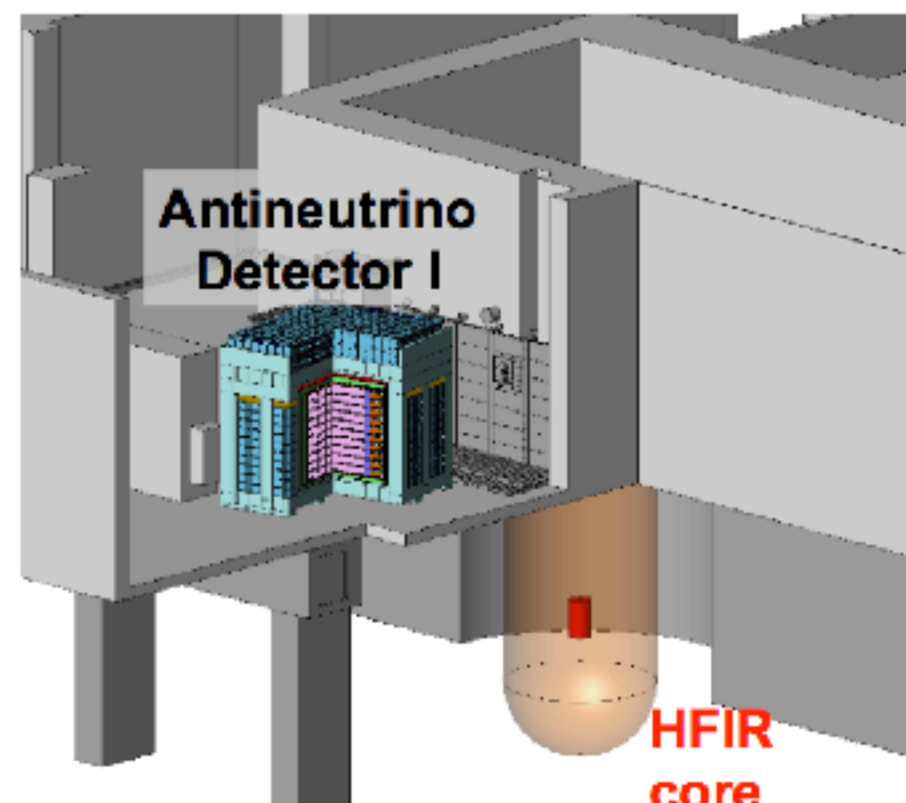
Compact Reactor Core

Power: 85 MW
Fuel: HEU (^{235}U)
Core shape: cylindrical
Size: h=0.5m r=0.2m
Duty-cycle: 41%



- Established on-site operation
- User facility, easy 24/7 access
- Exterior access at grade
- Full utility access, incl. internet





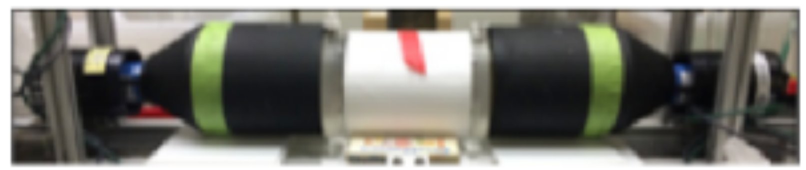
PROSPECT R&D

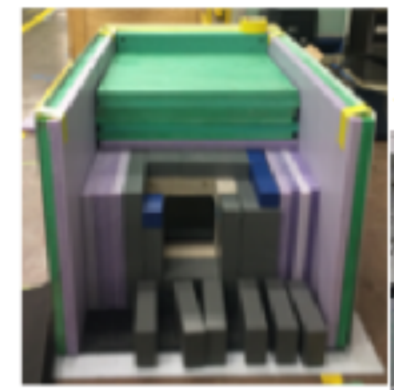
PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

5cm length
0.1 liters
LS, ^{6}LiLS

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 length
1.7 liters
^{6}LiLS

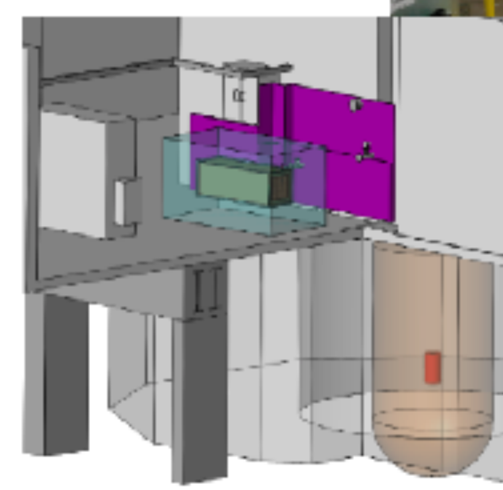




multi-layer
shielding

PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

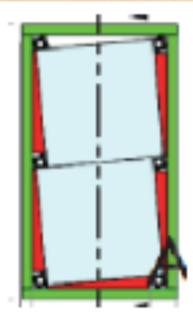
1m length
23 liters
LS, ^{6}LiLS



local reactor
shielding

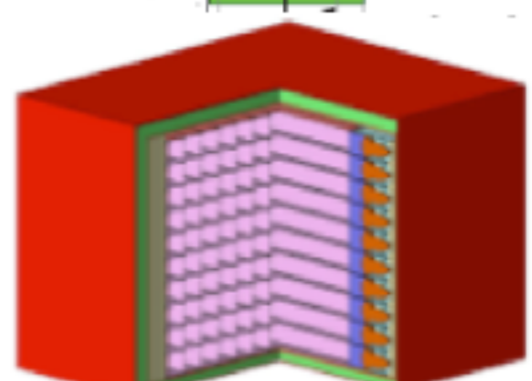
PROSPECT-50
Baseline design prototype
Spring 2016

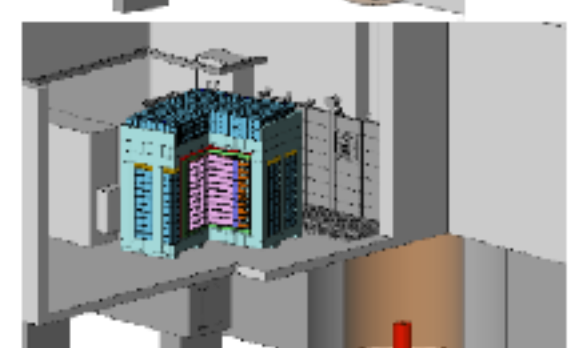
1x2 segments
1.2m length
50 liters
^{6}LiLS



PROSPECT AD-I
Physics measurement
2017

10x12 segments
1.2m length
~3 tons
^{6}LiLS



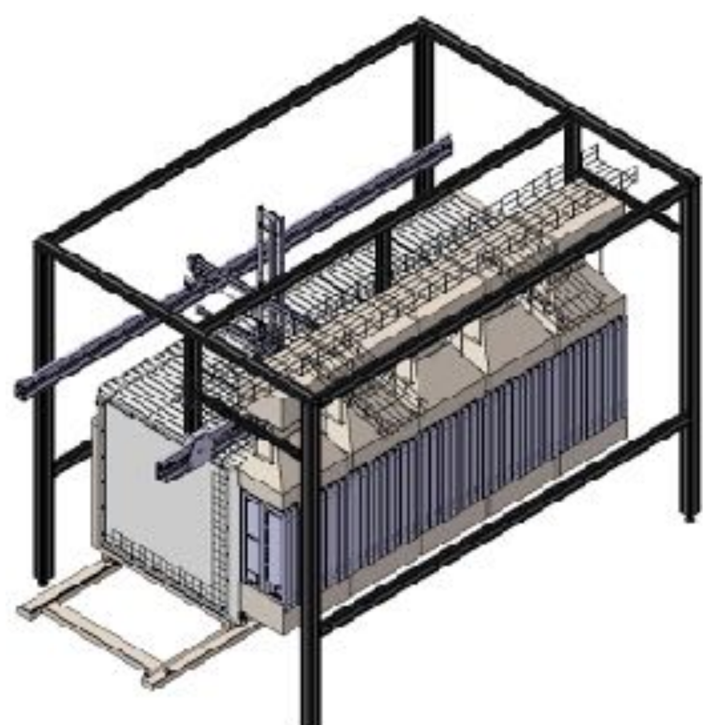


SoLid

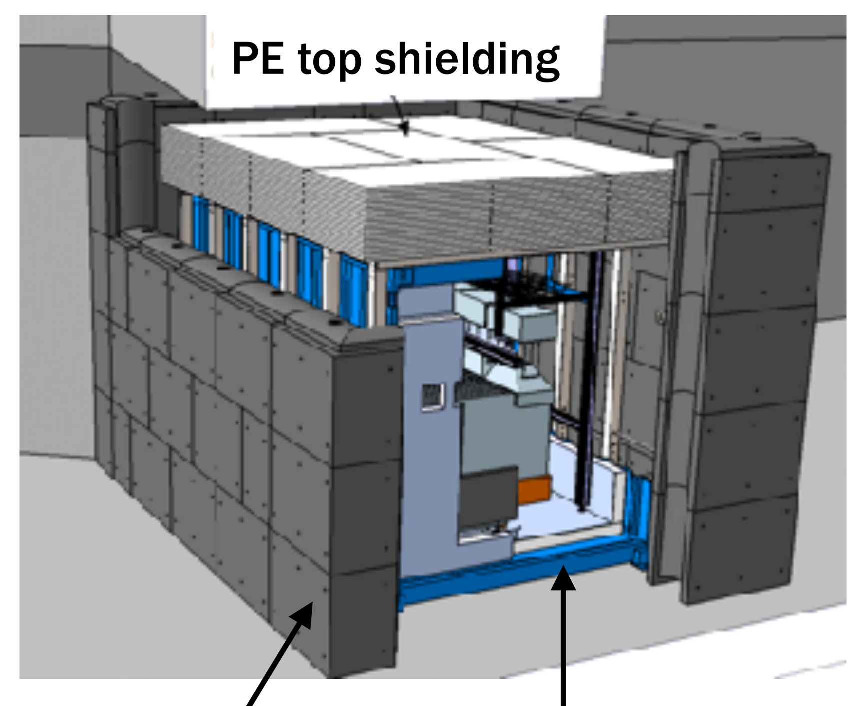
ArXiv:1703.01683

- SoLid baseline : 6-9m from the BR2 MTR reactor at SCK•CEN mol, Belgium
  - 5-6x movable modules on rail system 1.6-2 tonnes fiducial mass
  - Refrigirated container to limit impact of MPPC sensors dark noise
  - CROSS calibration robot for absolute efficiency and energy scale calibration at % level (207Bi, 60Co, 22Na, AmBe, 252Cf)
  - Low Z external shielding based on H_20 bricks and PE slabs.
  - High Z gamma-ray shielding in front of beam ports, outside enclosure

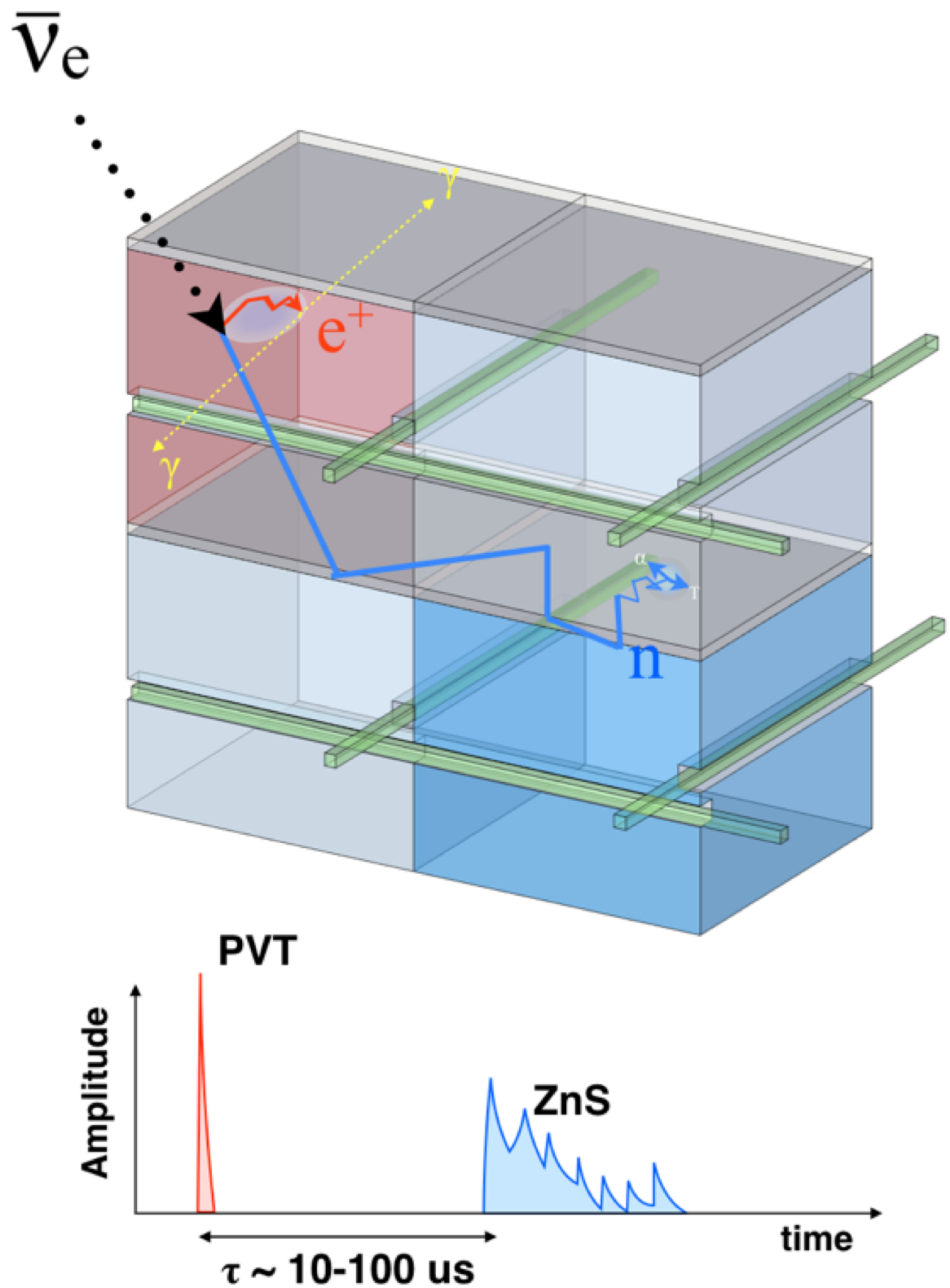
Geant4 model of SoLid at BR2



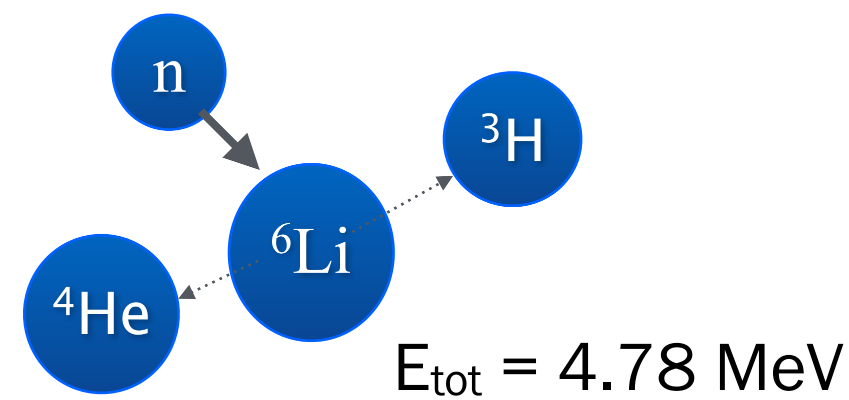
Detector Modules and rail
CROSS source calibration robot



3D segmented composite detector

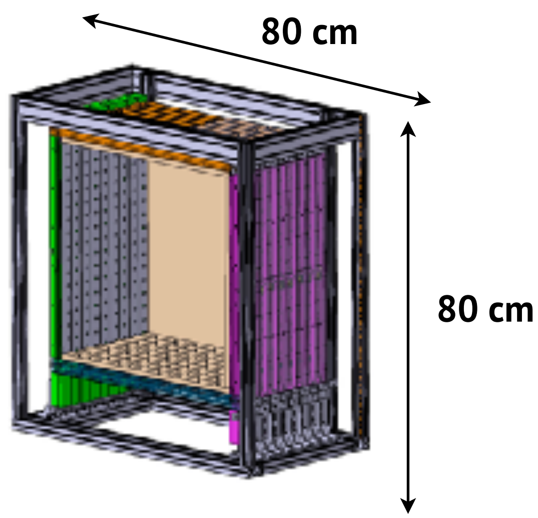


- composite /dual scintillator detector element :
  - 5 cm x 5 cm x 5 cm PVT cube segmentation to contain positron energy and localise interaction
  - Layer of LiF:ZnS(Ag) for neutron detection close to interaction



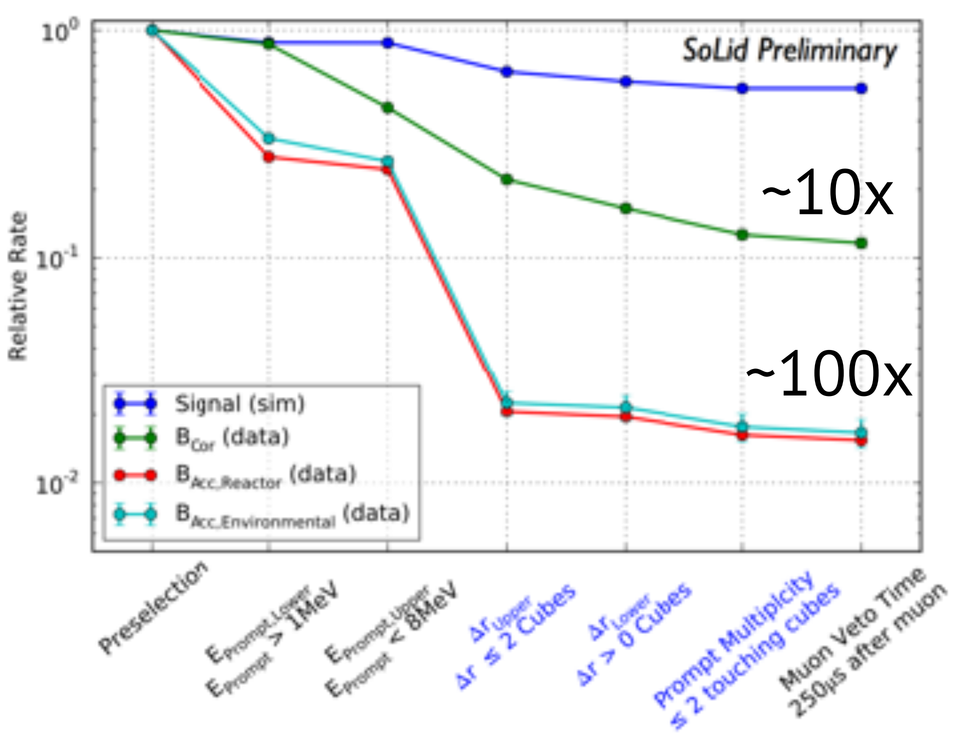
- WLS fibre to collect both scintillation light in X and Y direction
- each cube voxel optically separated from each other by reflective coating
- SiPM to read out fibre signal

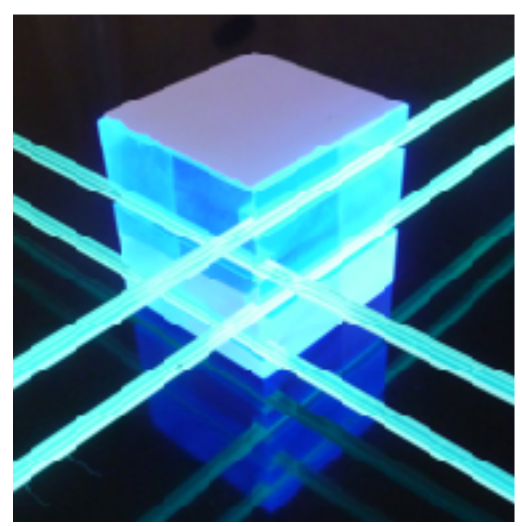
SoLid R&D 2015-16

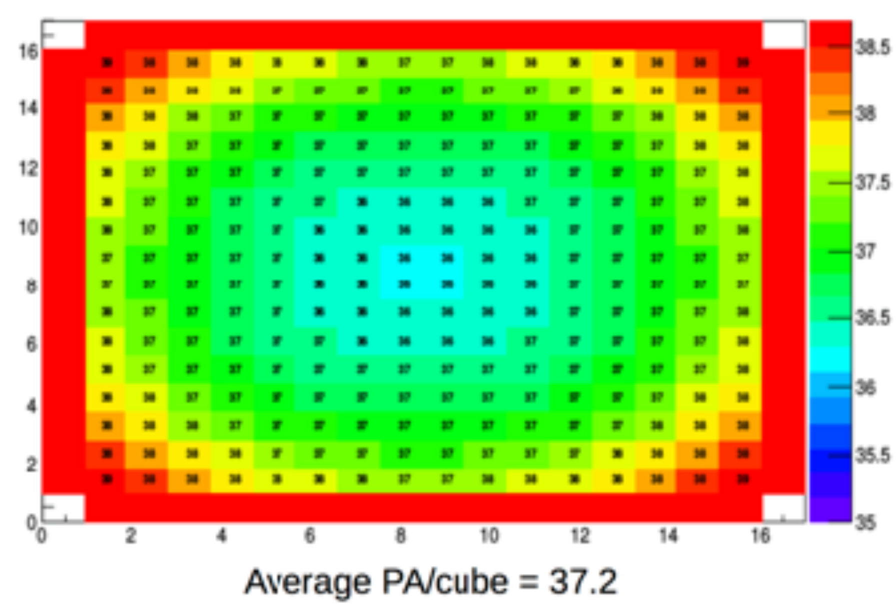


- SoLid Module 1 (SM1)
  288kg
  2 304 voxels, 288 chan.
  9 detector planes

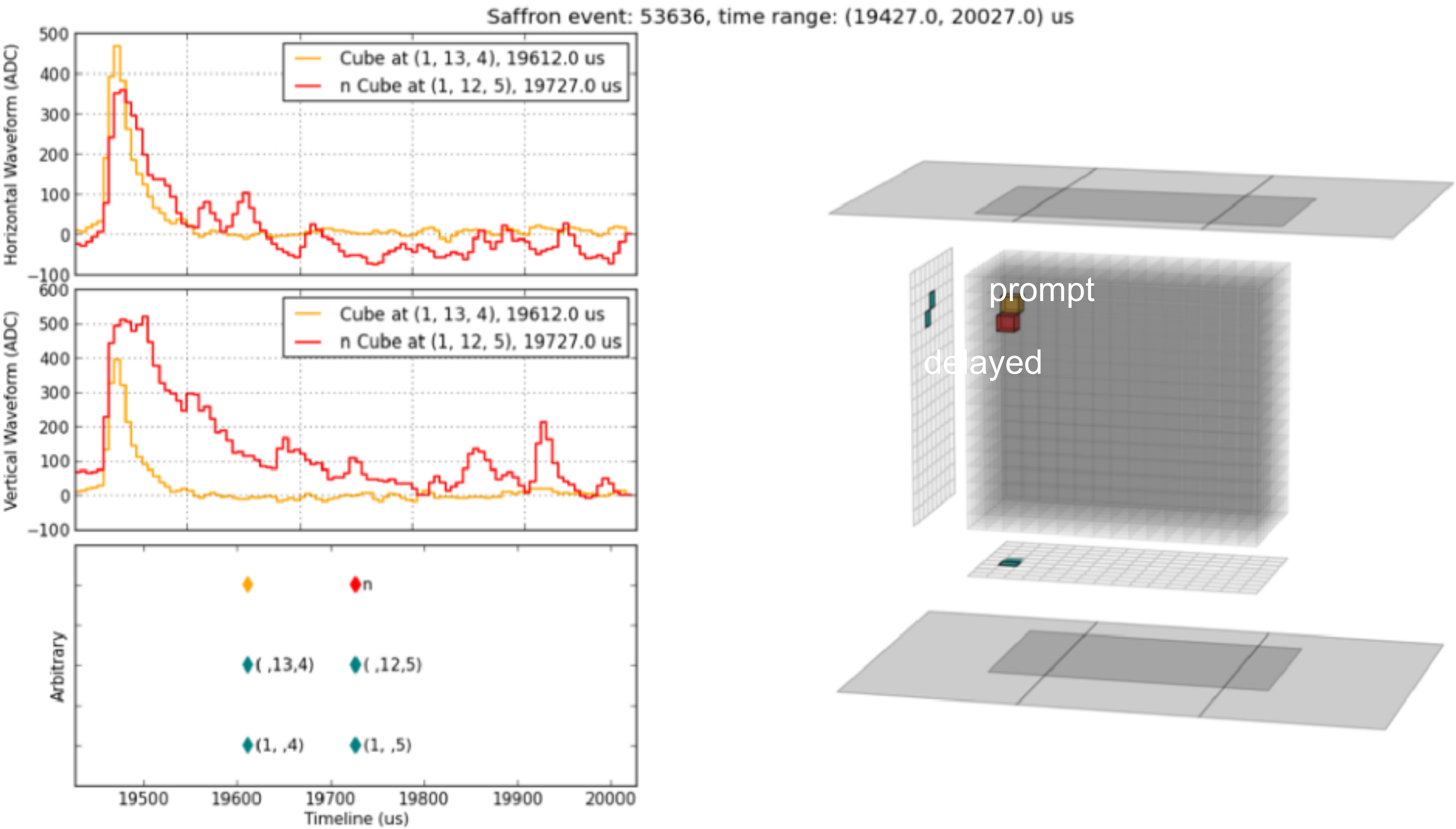
- **Prototype SM1 system deployed to validate technology**
  - 3 days Reactor ON, 1.5 month OFF
  - mechanical design
  - neutron PID
  - target mass estimation dNp < 1%
  - uniformity of cube energy response < 1%
  - Stability at 1% level
  - measurement of IBD background





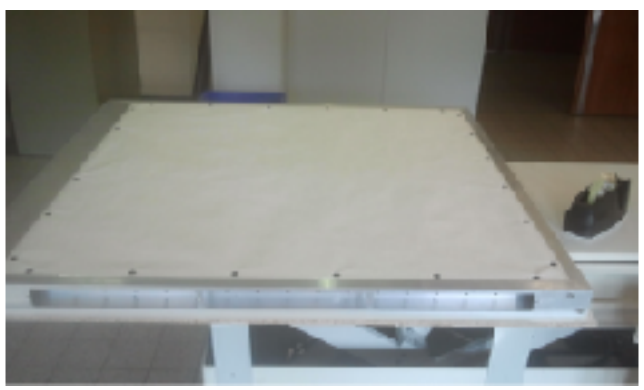
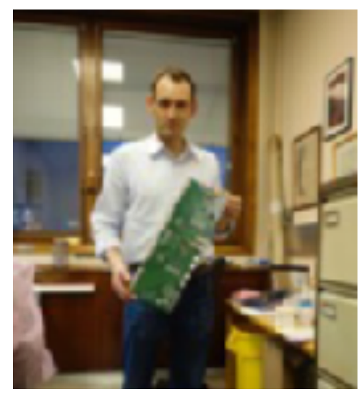


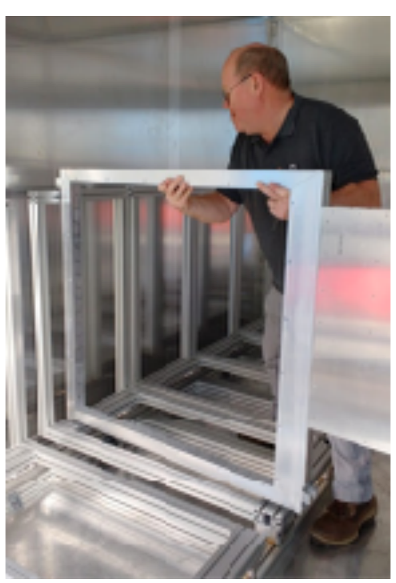
Imaging IBD events

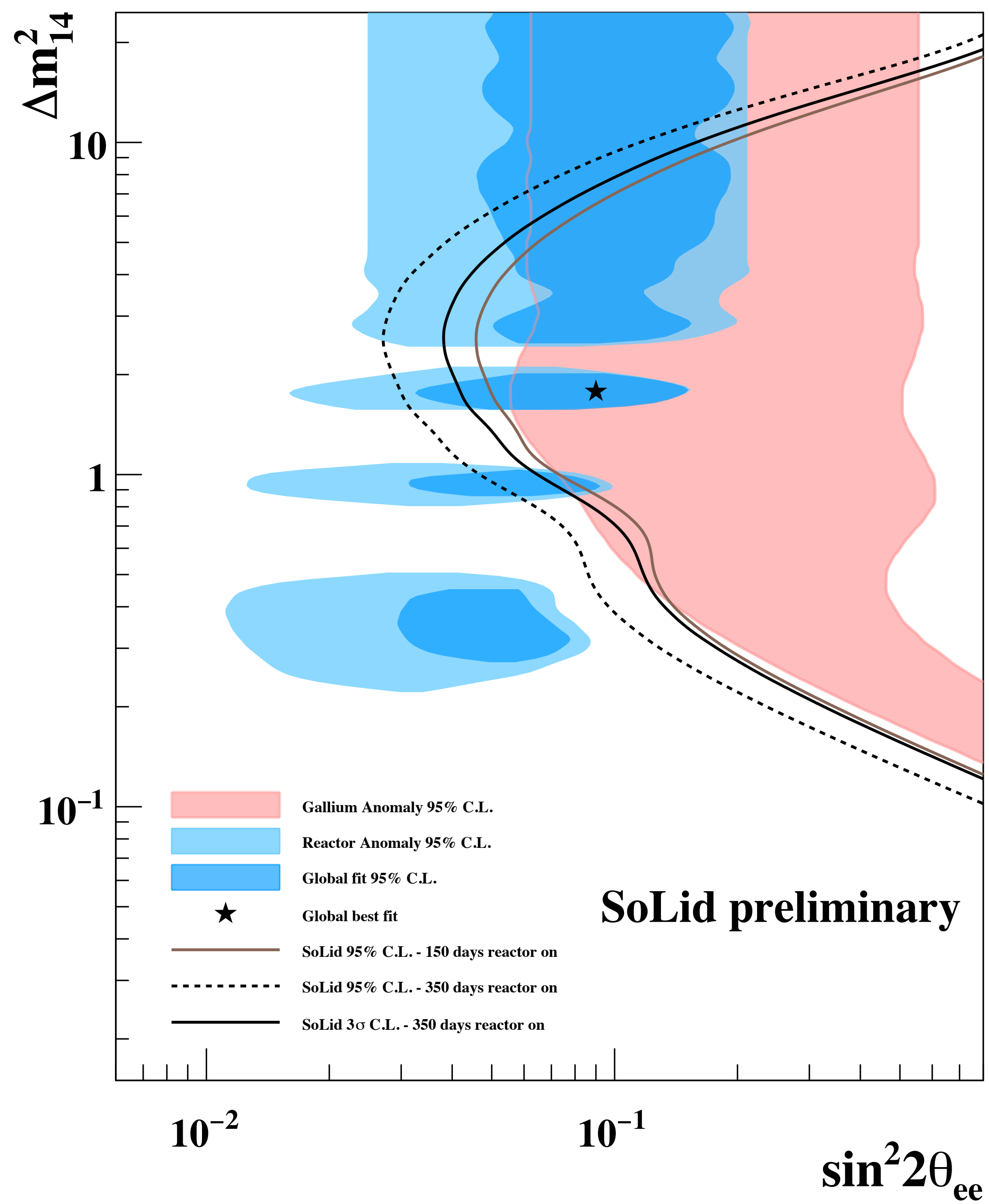


SoLid status

- Entered construction phase in Octover 2016
    - all parts ordered and received
- Electronics and trigger developments
- QA and calibration of planes starting this month
- Data taking expected this summer



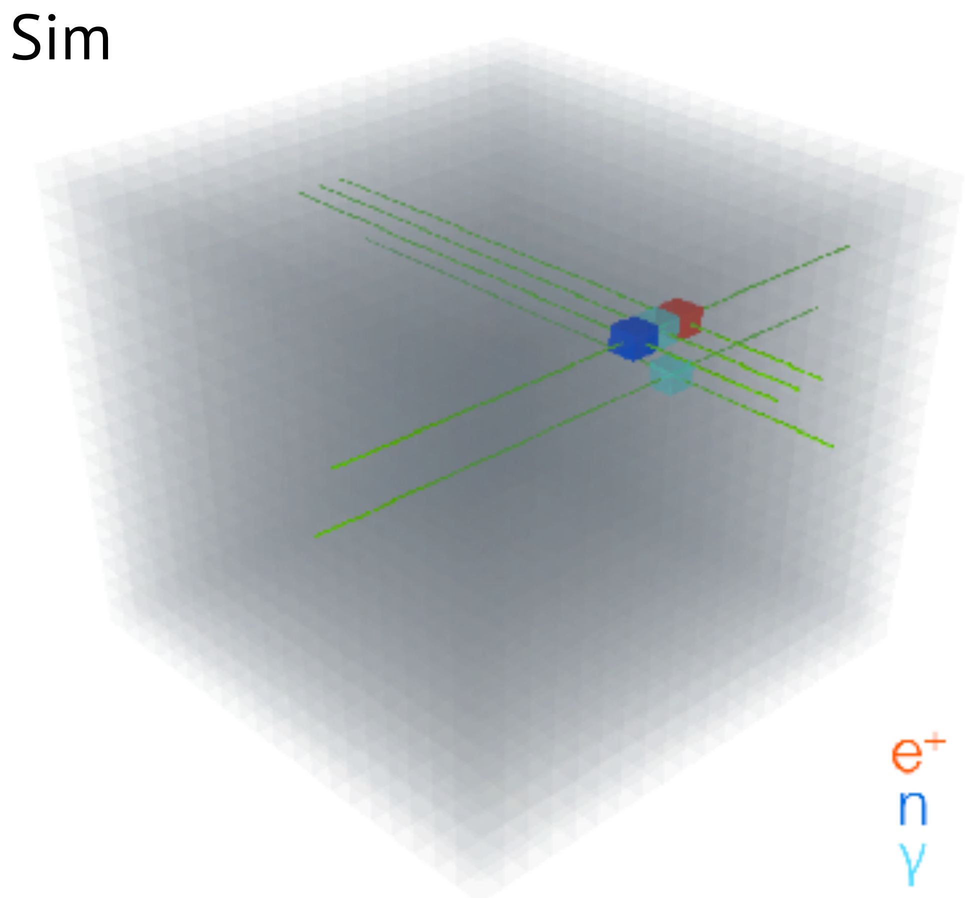


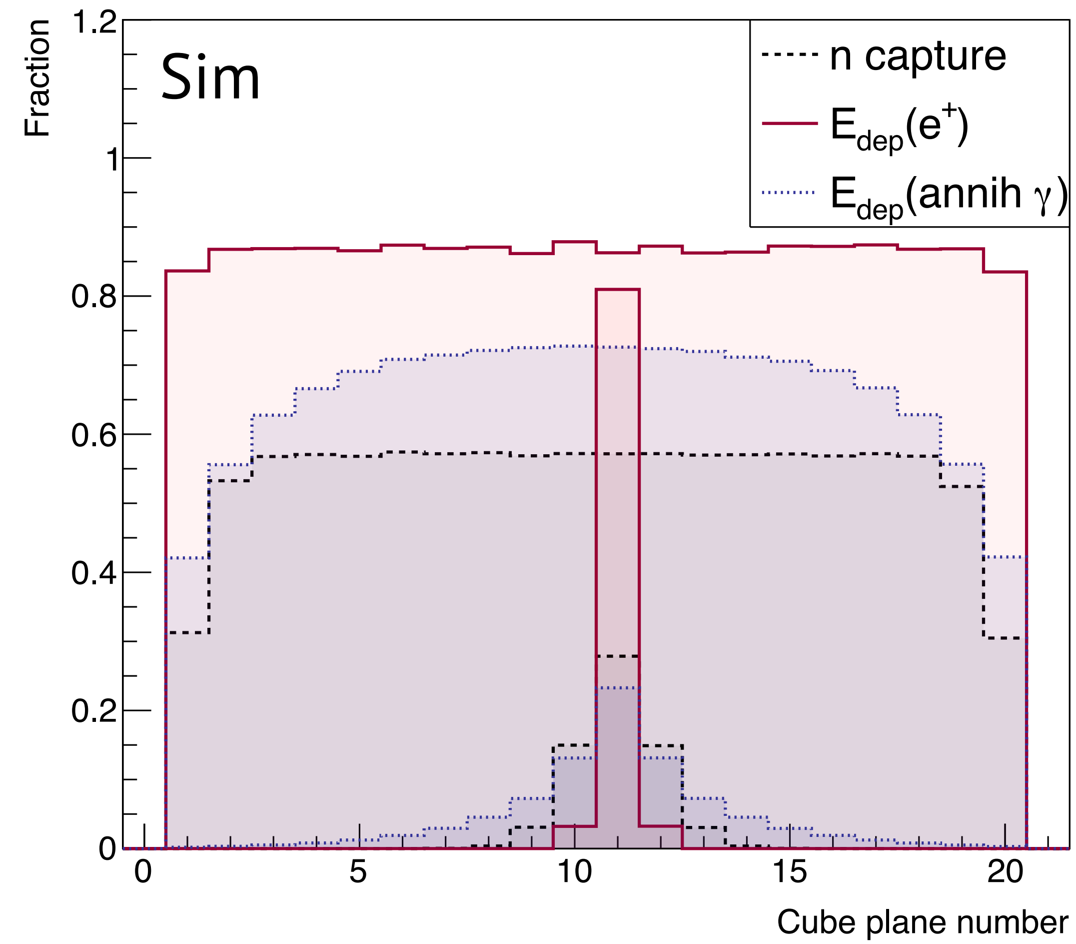
Summary

- **The search for sterile neutrino with mass ~ 1 eV has began at research reactors**
- new dedicated experiments have started taking data or are about to come online this year
  - 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 many more questions about the spectrum have surfaced**
  - high statistical samples of antineutrino spectra from 235U core will be available soon !
  - fix the lack of data for this crucial flux ingredient
  - measurements at different reactor will give welcome 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**

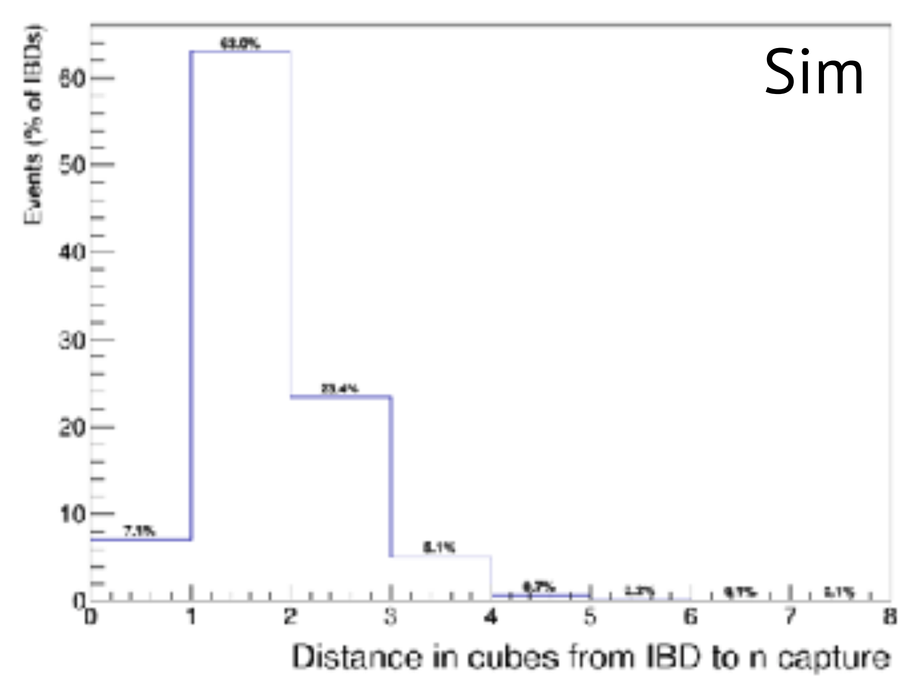
Back up

Signal localisation

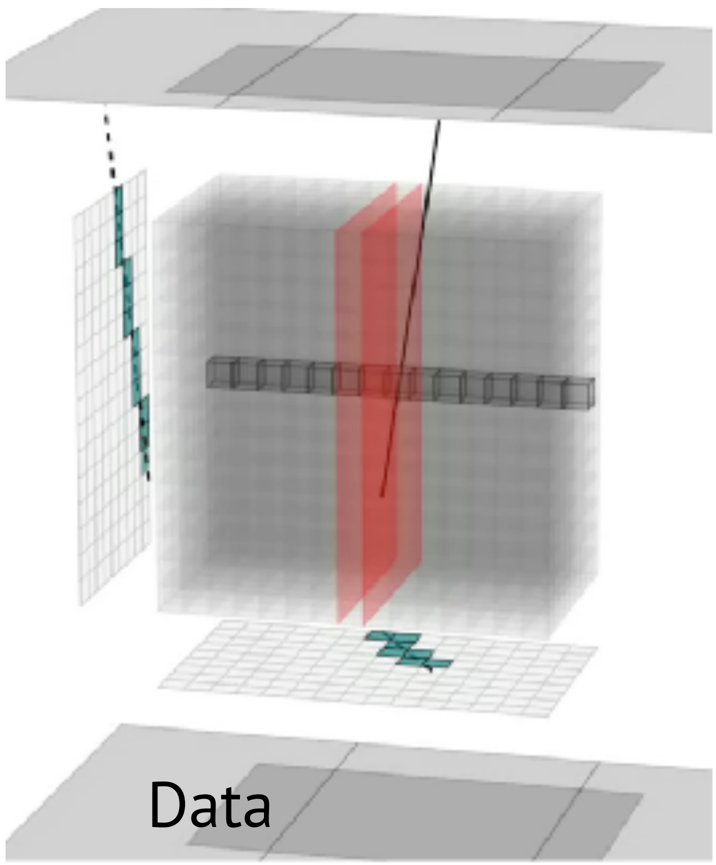


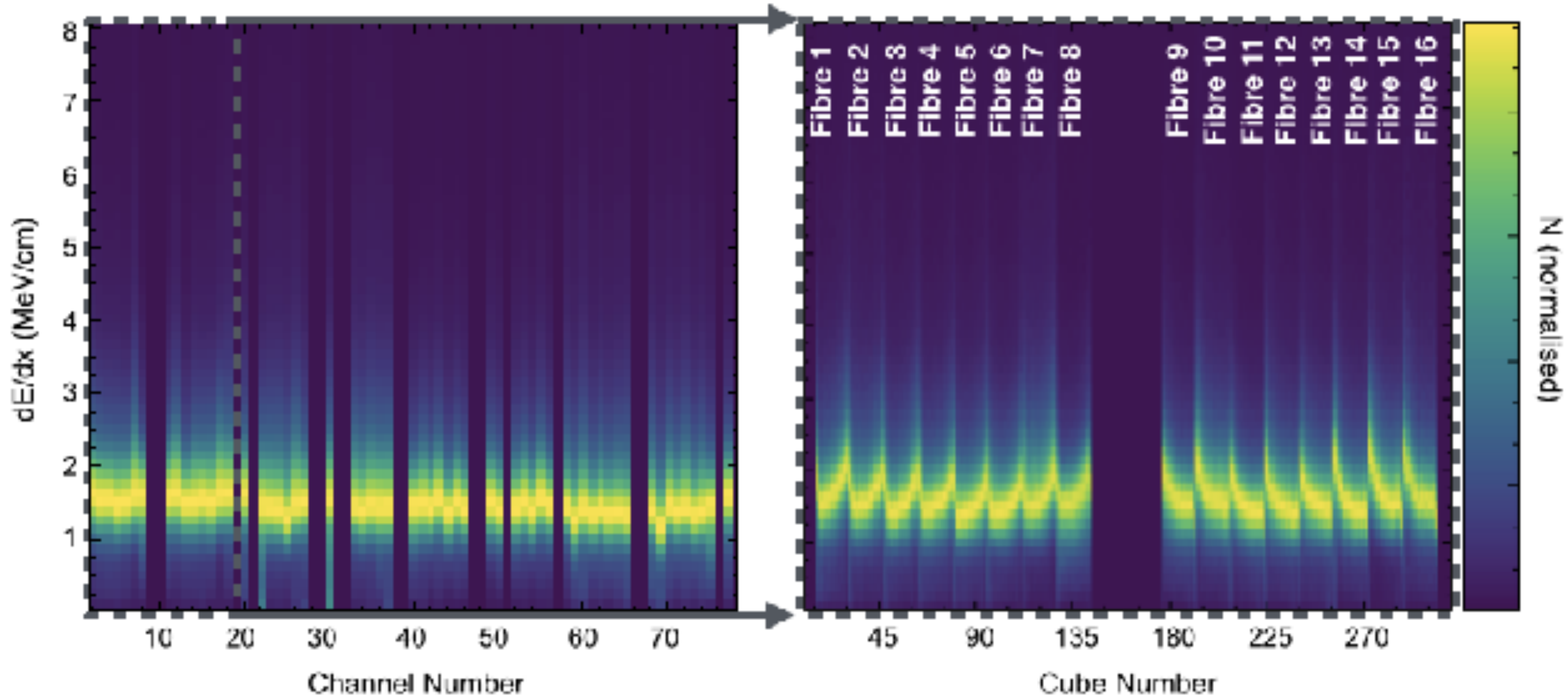


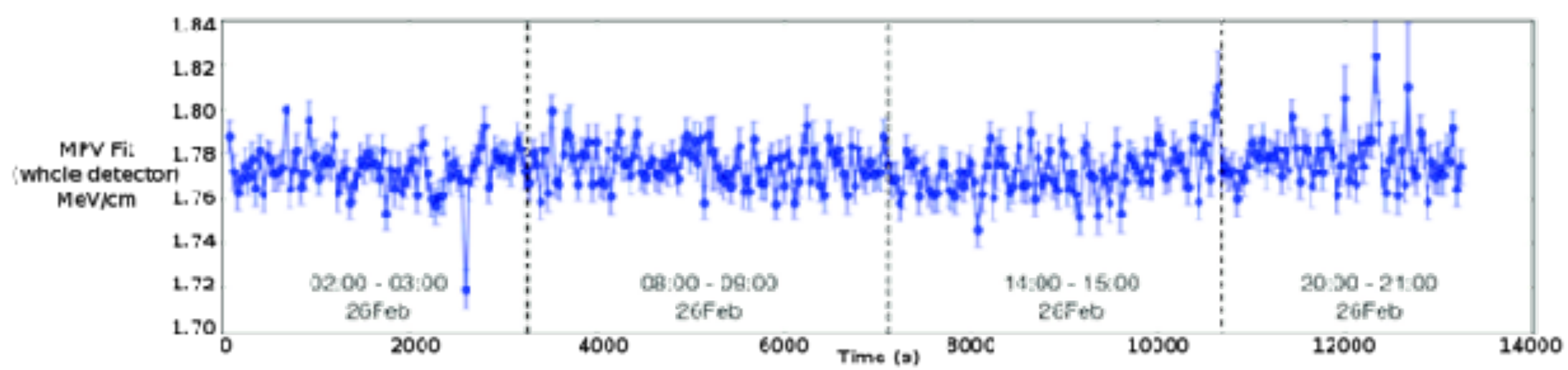
- Positron energy contained in cube voxel
- Neutron capture efficiency uniform up to the edge of the detector
- Neutron capture one cube away from interaction gives directional sensitivity

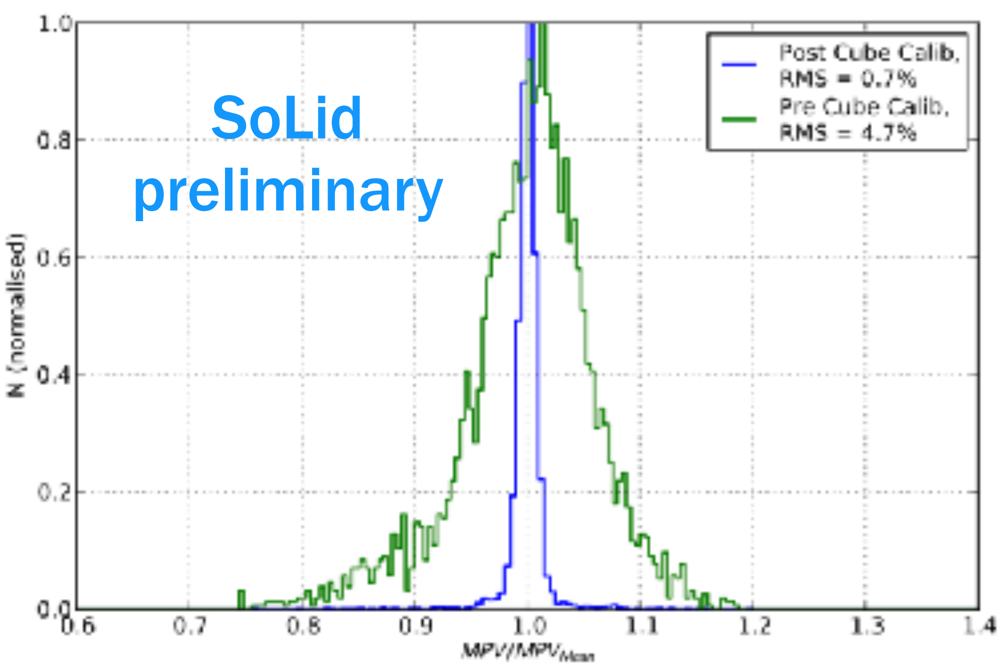


SoLi∂ Energy response calibration



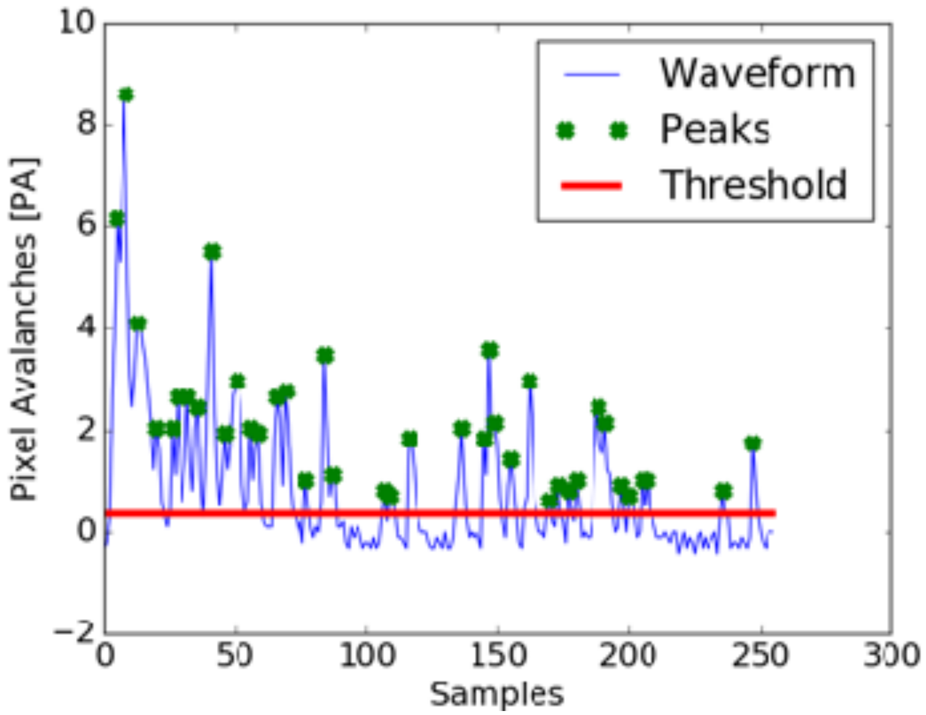


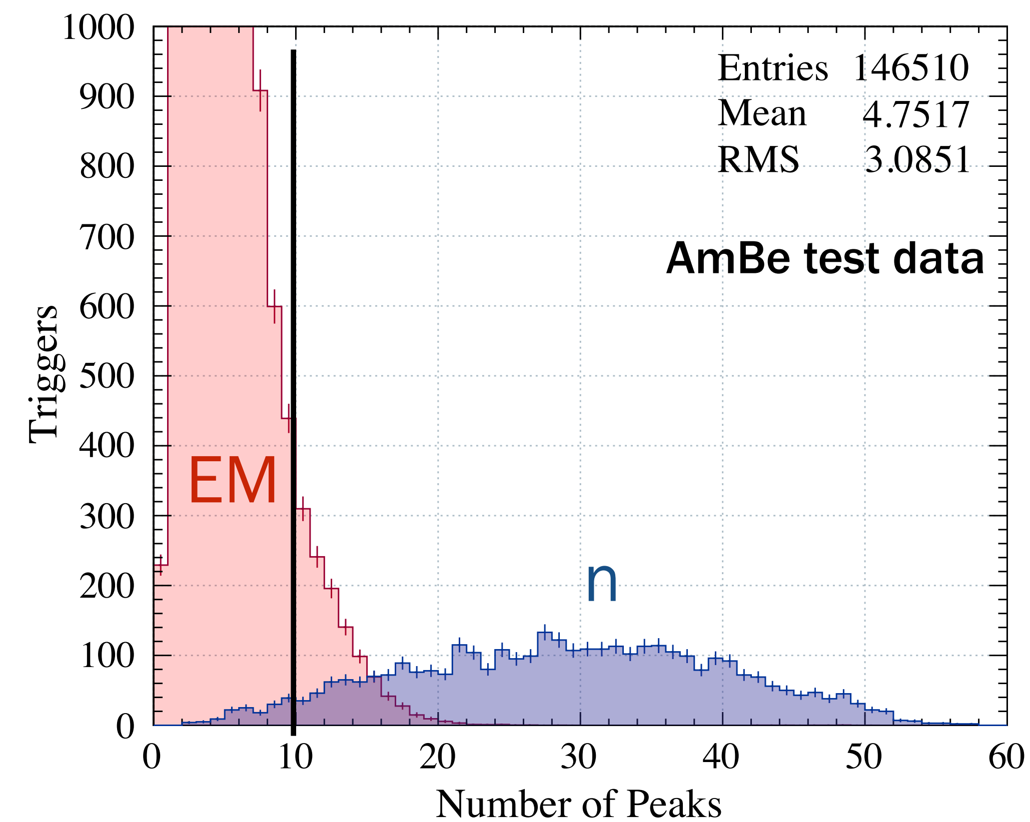




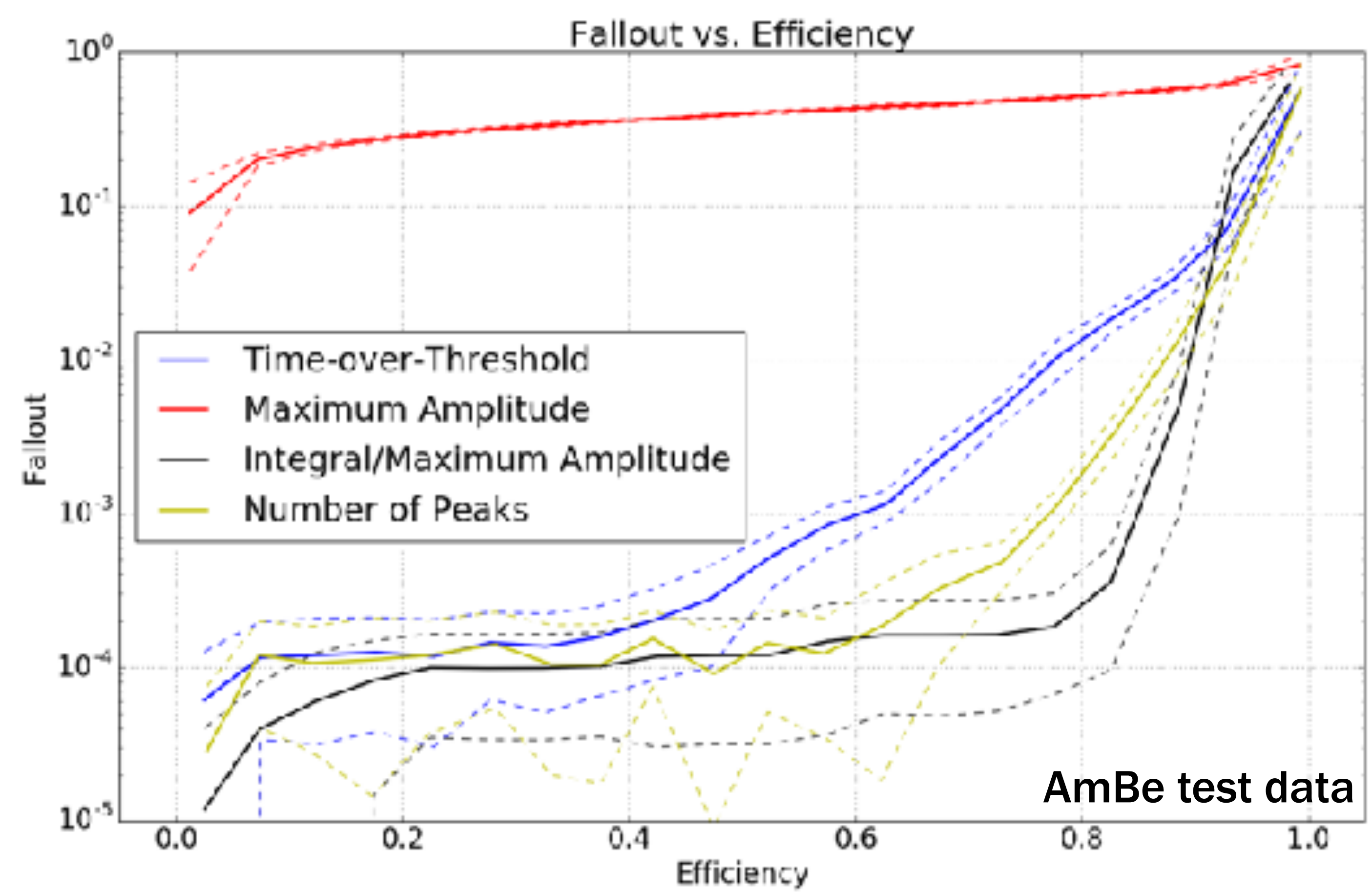
- PVT response intercalibrated using muons
- cube response equalised to better than 1% for majority of channels
- stability over time of energy scale ~ 1%

SoLi∂ Neutron trigger and data size

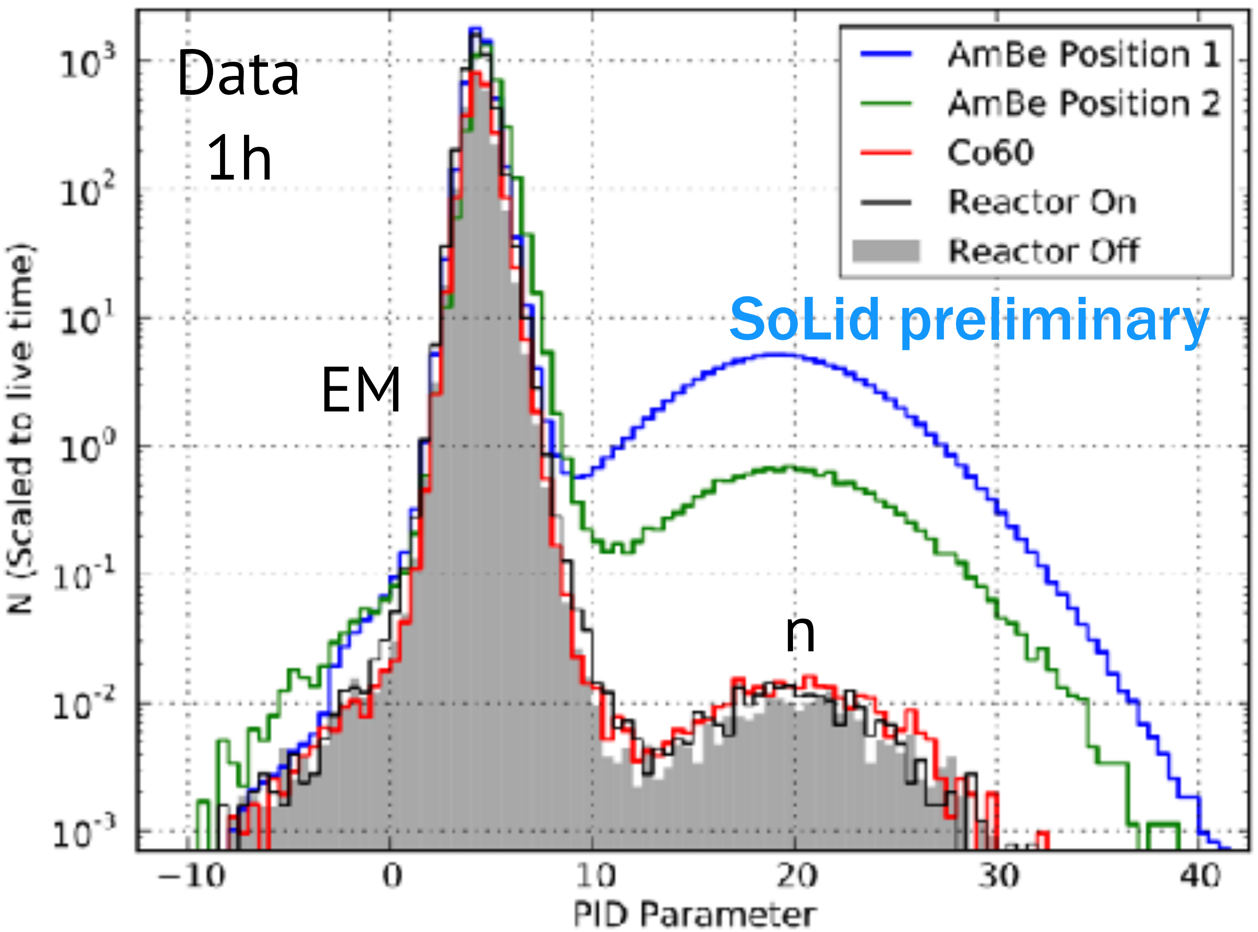


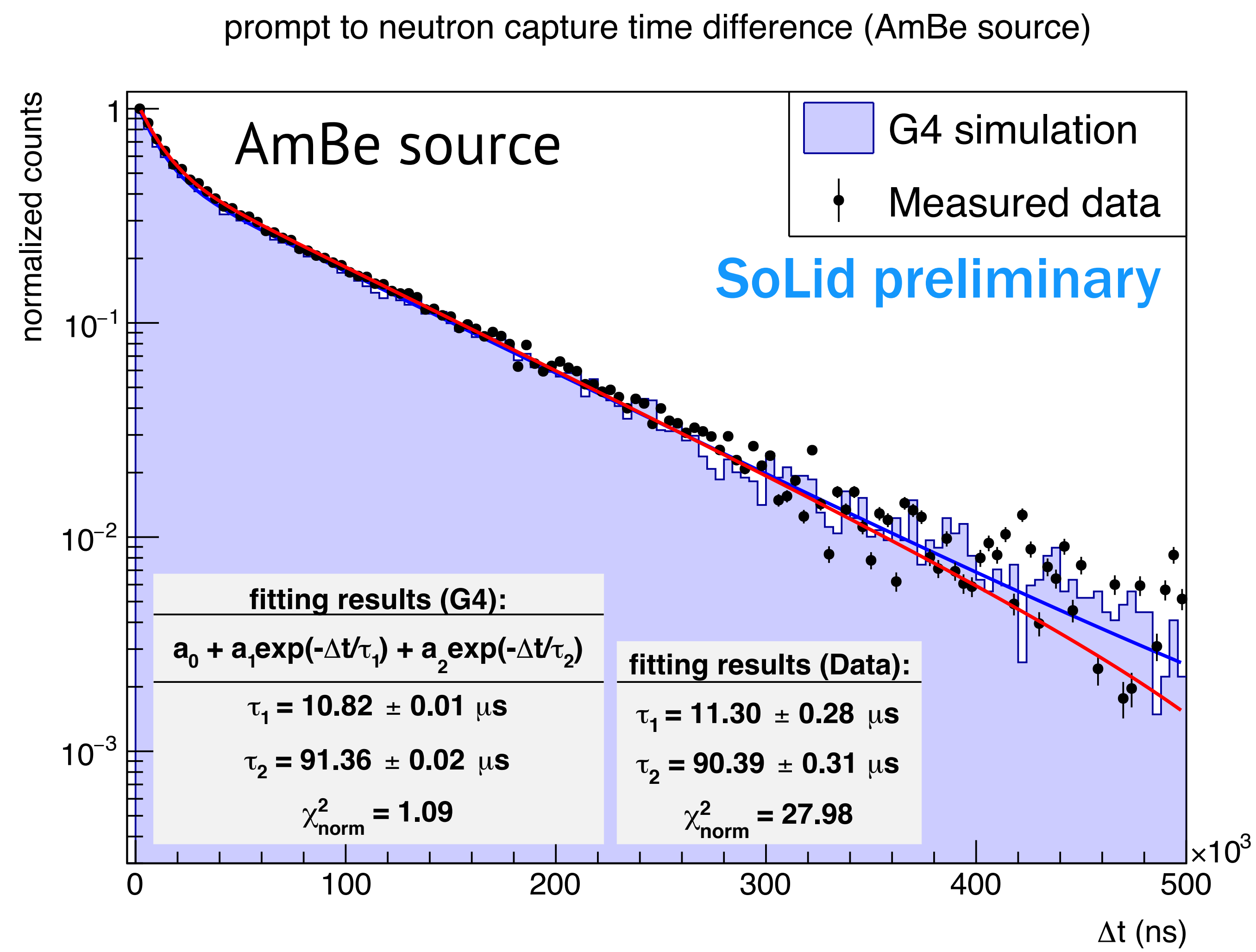


- **Neutron pattern recognition in firmware**
  - neutron rate is low: Rn ~ 7 Hz
- Buffer time ±500 us and ±2 planes around neutron
  - **expect high detection efficiency above 70%**
- **Zero suppression** threshold at 1.5 PA applied to other signals
  - limit data size and storage
  - **Detector cooling to 5 deg to reduce dark counts**



SoLi∂ Neutron ID and capture time





- Validated PID, neutron tranport simulation (MCNP & G4) and Li capture efficiency