SoLid and reactor experiments

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CrossTalk workshop: The fate of the Sterile Neutrino
18th January 2017
VUB, Brussels

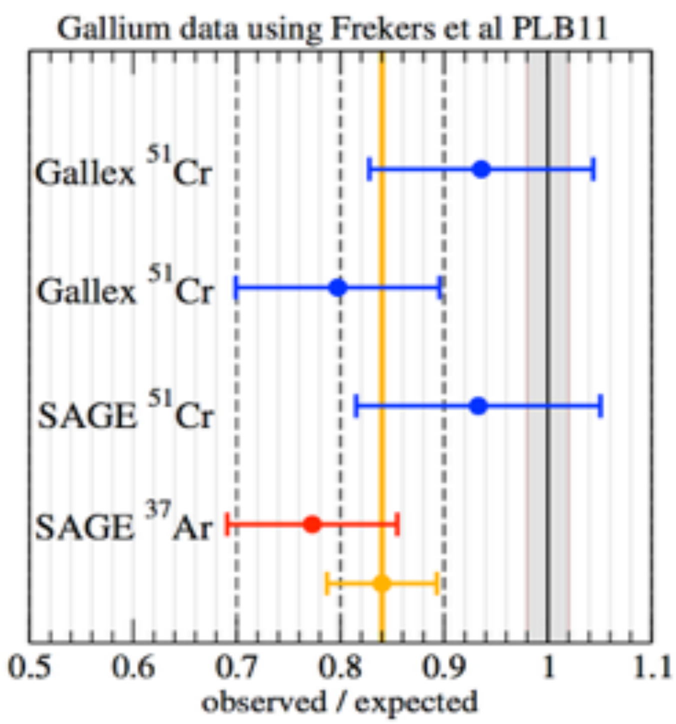
Outline

- Reactor anomalies
- Recent reactor measurements
- SoLid: a dedicated experiment at very short baseline
- Summary

Anomalies 2011

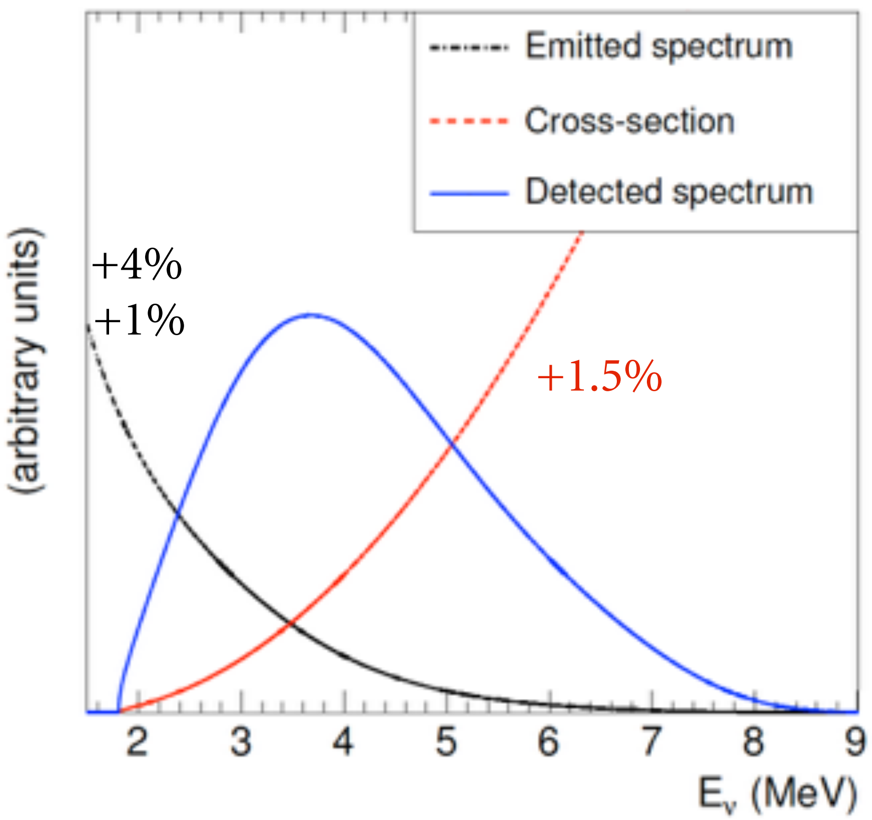
$$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$$

$$\bar{\nu}_e + p \to e^+ + n$$



Giunti Laveder 1006.3244
J. Kopp et al., hep/ph:1303.3011

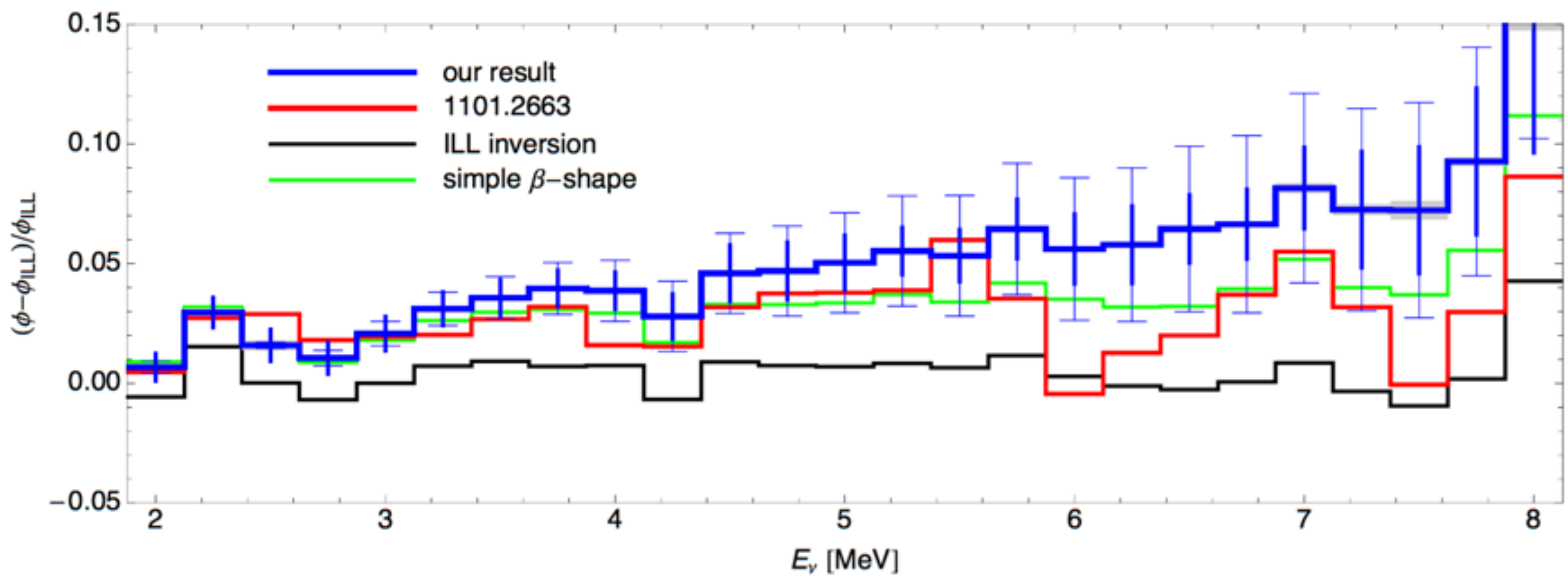
- re-analysis of calibration source data
  - (L/E ~1m/0.1MeV)
- rate deficit of 14 ± 6 %
  - *Gallium anomaly*



- 2011 re-evalatation of reactor antineutrino flux and update on cross-section parameters
  - 3.5% new conversion of ILL beta spectra
  - 1.5% off-equilibrium
  - 1.5% neutron lifetime τ_n
- rate deficit 6.5 %
  - *Reactor anomaly*

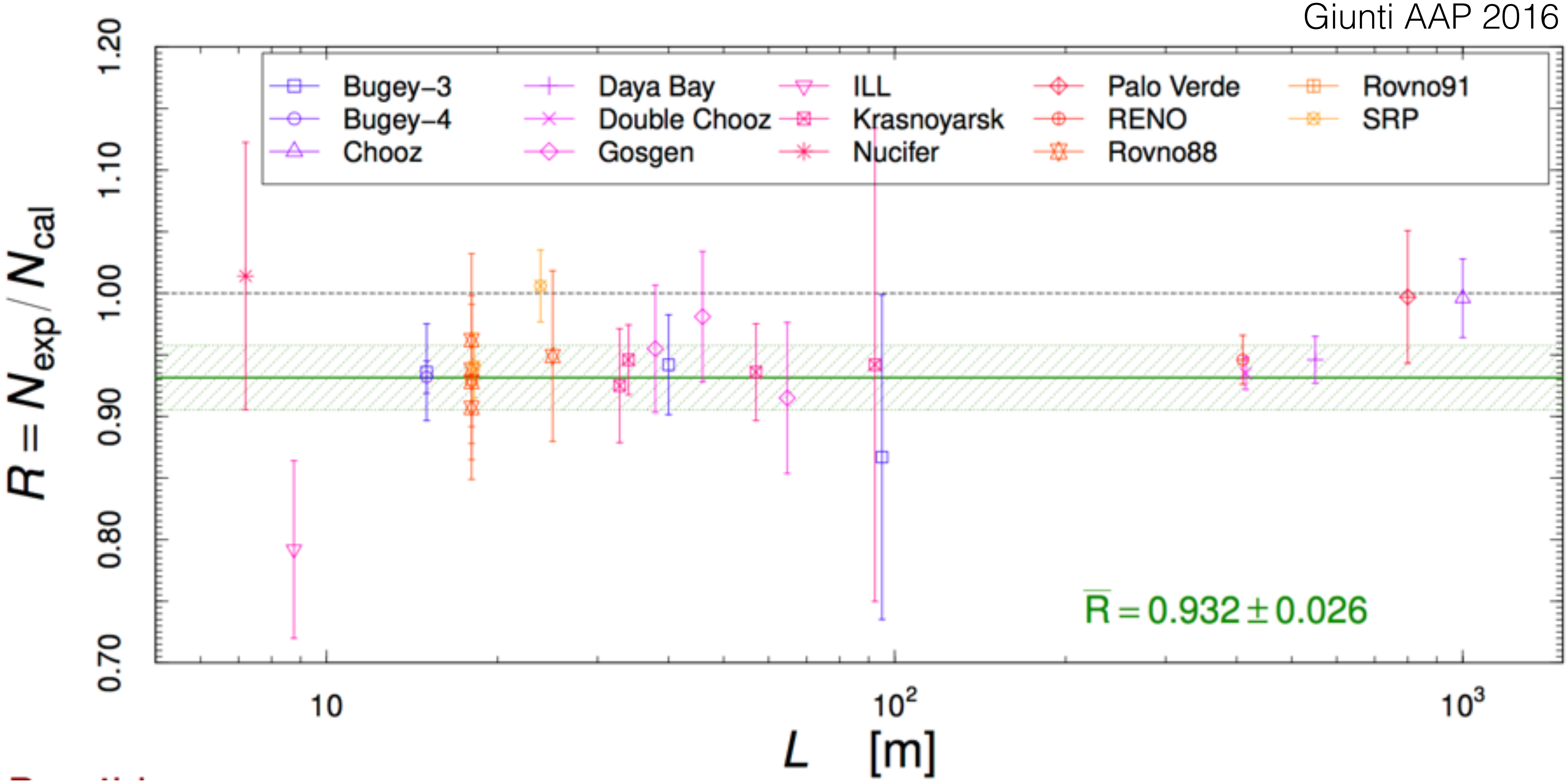
Flux calculations

- Method to calculate flux based on conversion of electron beta spectra to antineutrinos
- Electron beta measurements made at ILL in the 1980s by Schrekenbach et al. used as reference spectra for antineutrino flux calculations. Prediction to ~ 5% level
- Shift upward with respet to ILL beta-shape measurements was also found by P. Huber confirming the anomaly



Size of the rate anomaly

Giunti AAP 2016

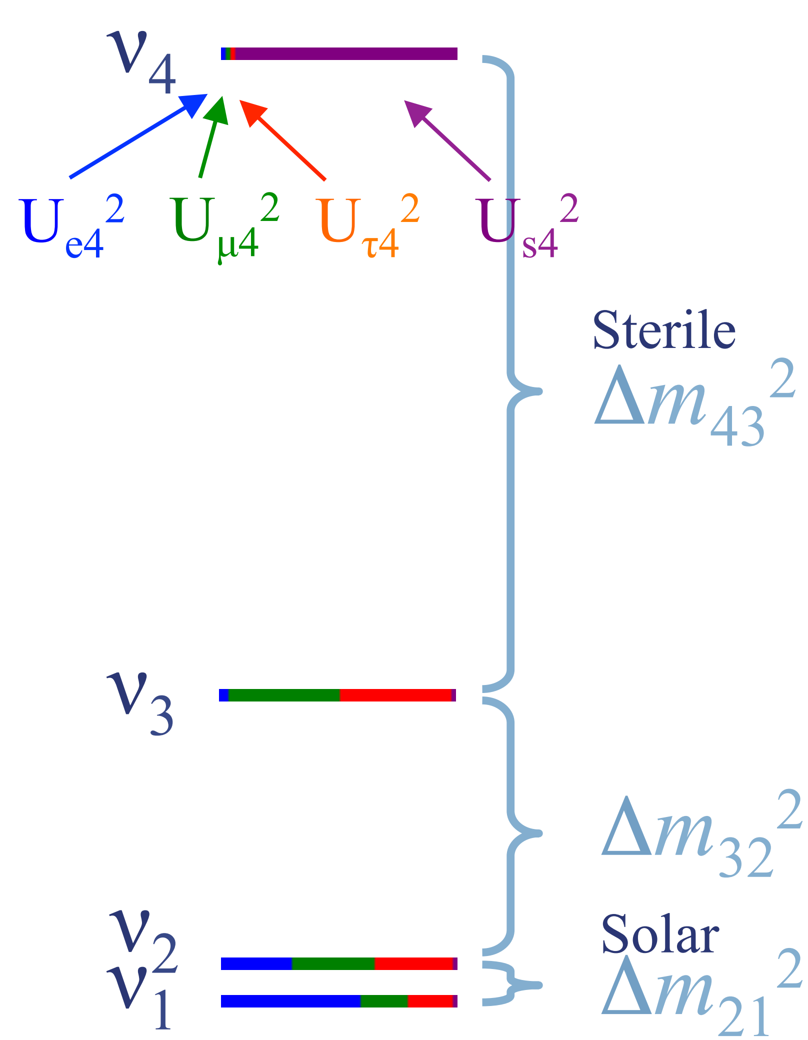


- Current precision experiment at short baseline (km) consistent with previous measurements < 100 m

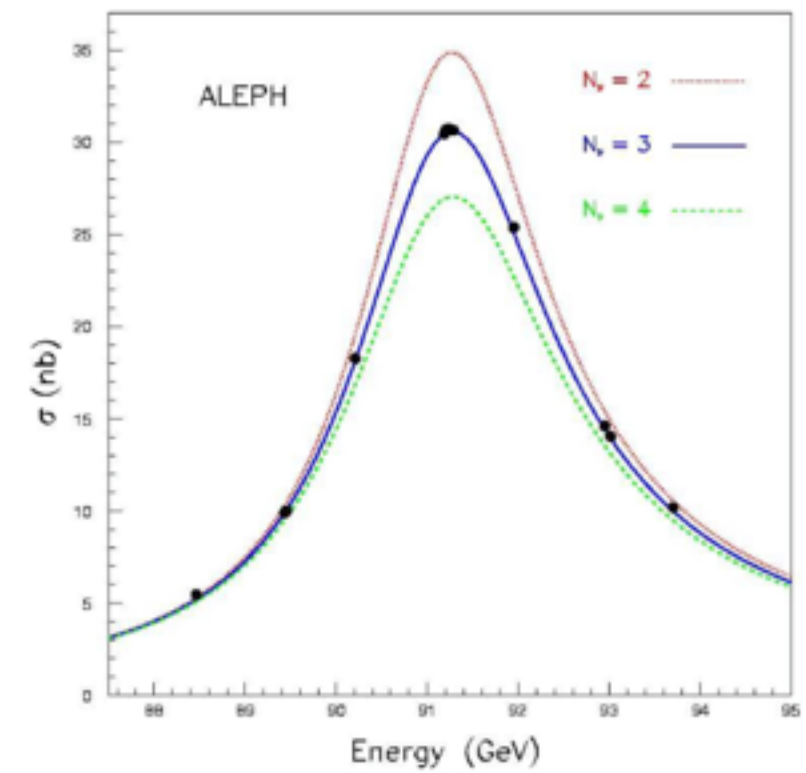
- rate deficit or theoritical excess ?

A possible explanation

3+1 model



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



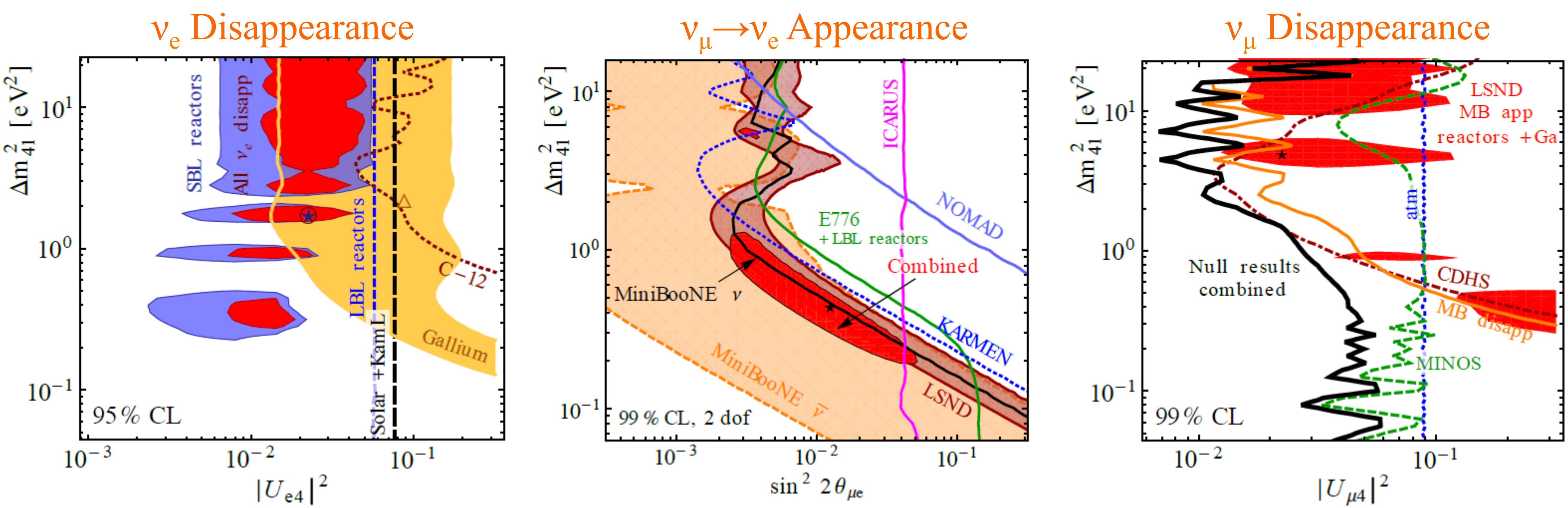
- Light sterile neutrino with mass around 1 eV $\bar{\nu}_e \rightarrow \nu_s$
- electron neutrino disappearance

$$P_{ee} \approx P_{es} = 4U_{e4}^2 U_{s4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

- Oscillation of ~m scale for MeV neutrinos

J. Link TAUP 2015

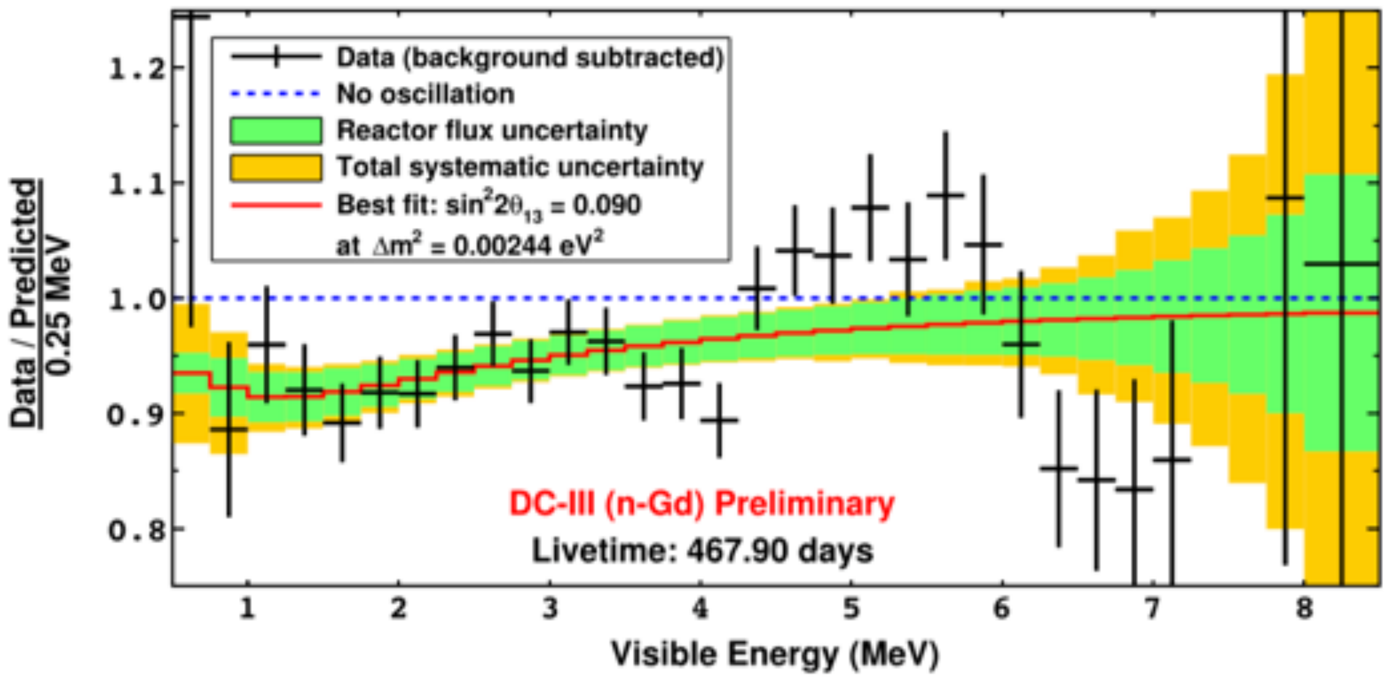
Global fits 3+1 as of 2013



Global fit from Kopp *et al.* JHEP 1305, 050 (2013)

2014: a surprising result

- At neutrino 2014, Double Chooz showed this :



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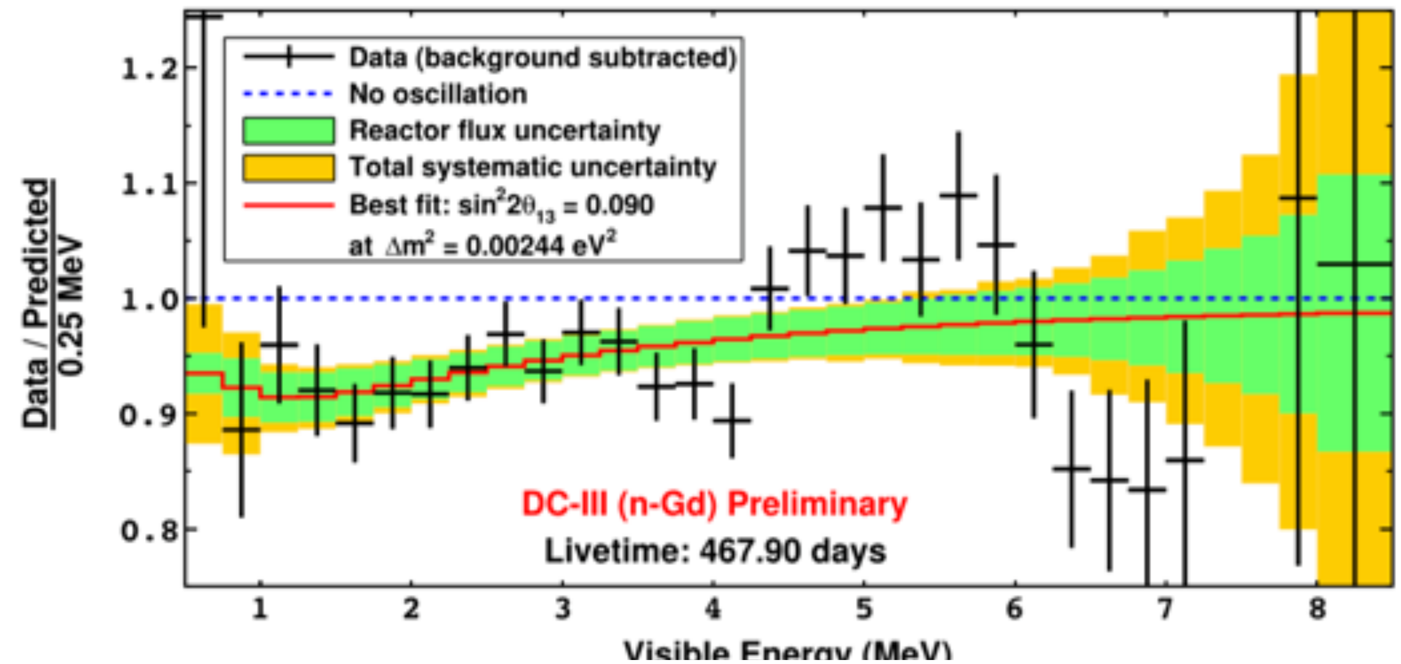
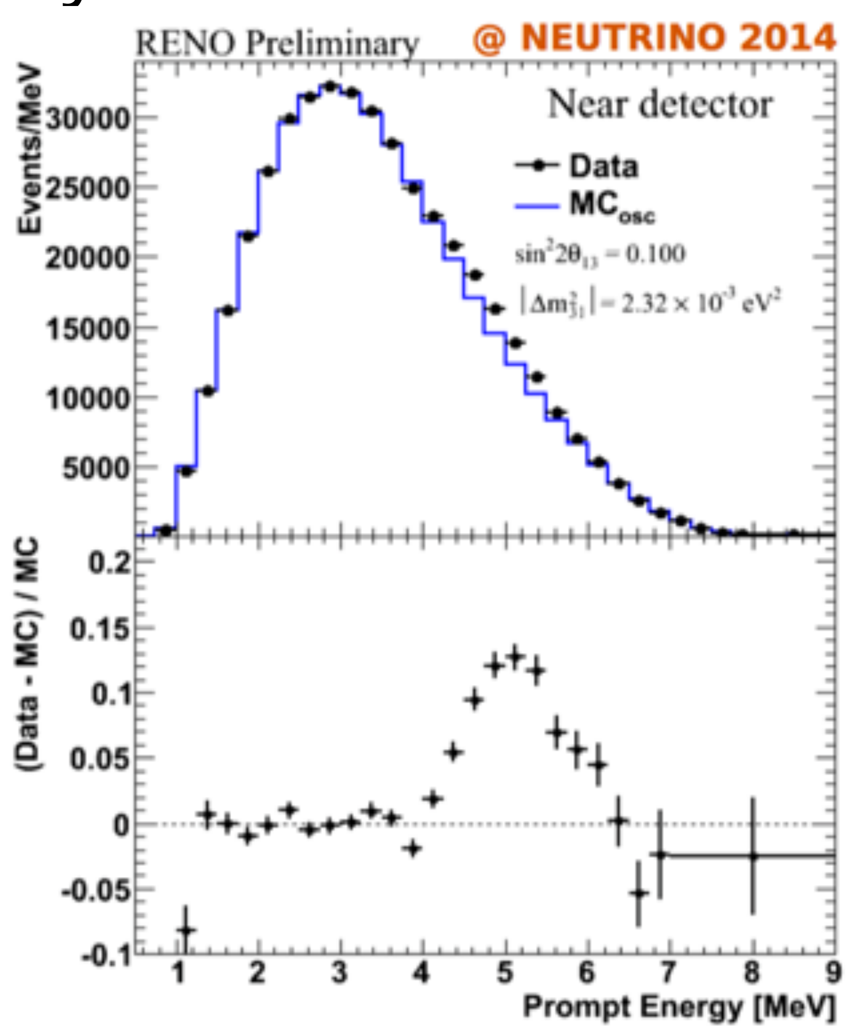
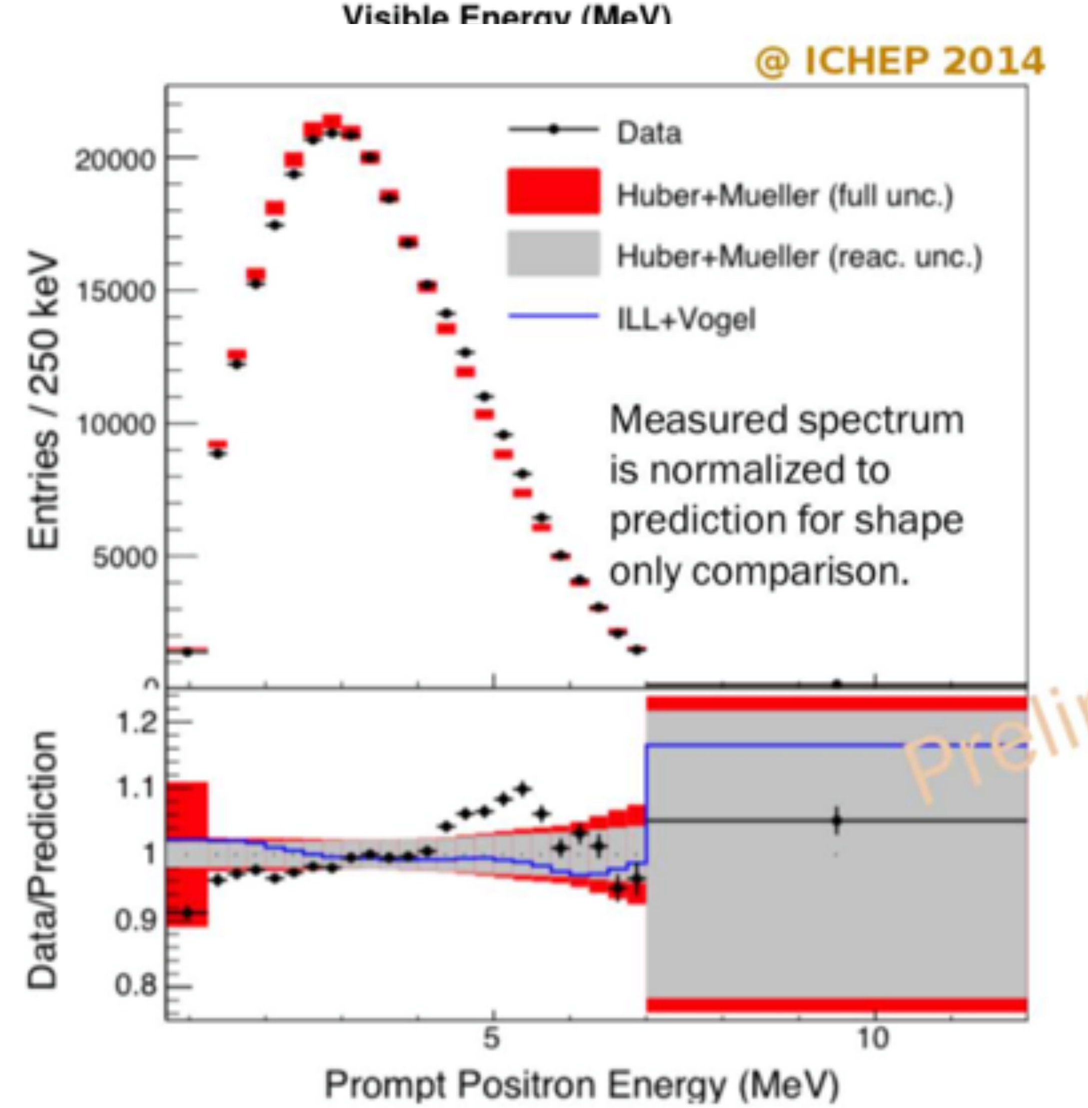


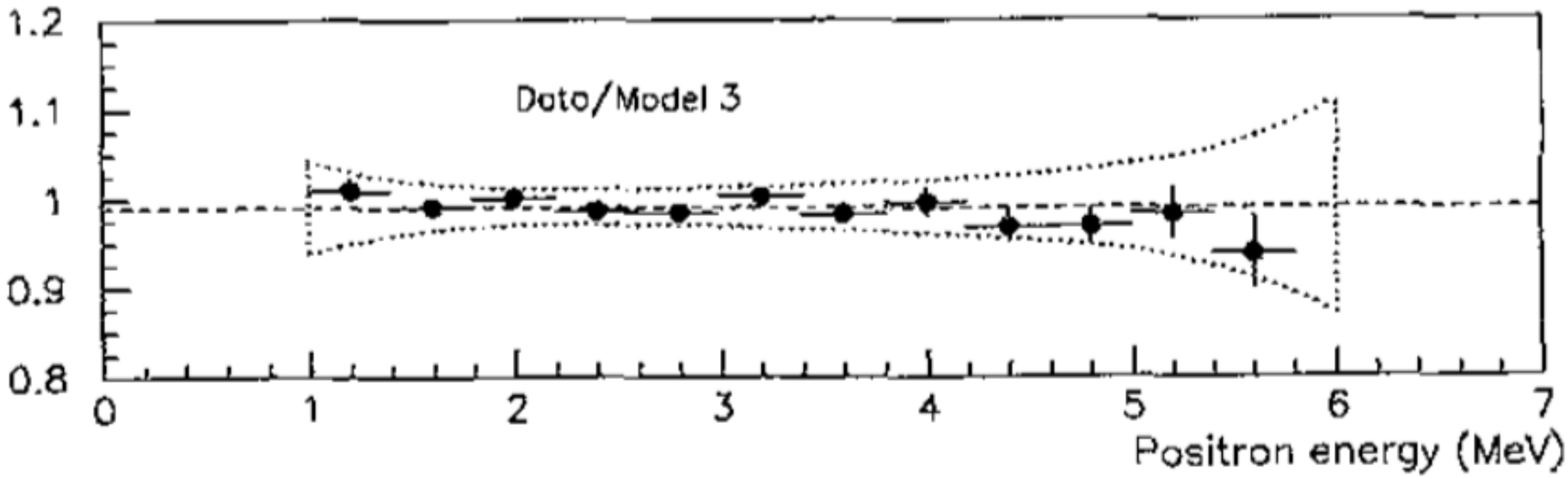
- followed by :





Expected spectrum shape

- Conversion method and other calculations tested at Bugey-3

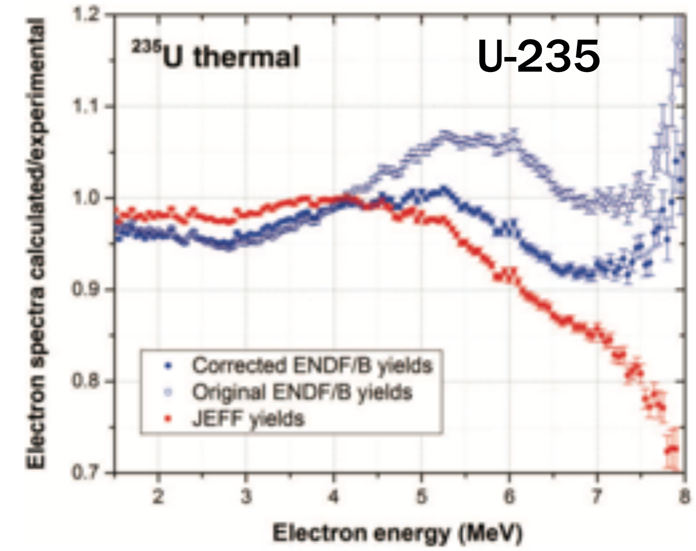


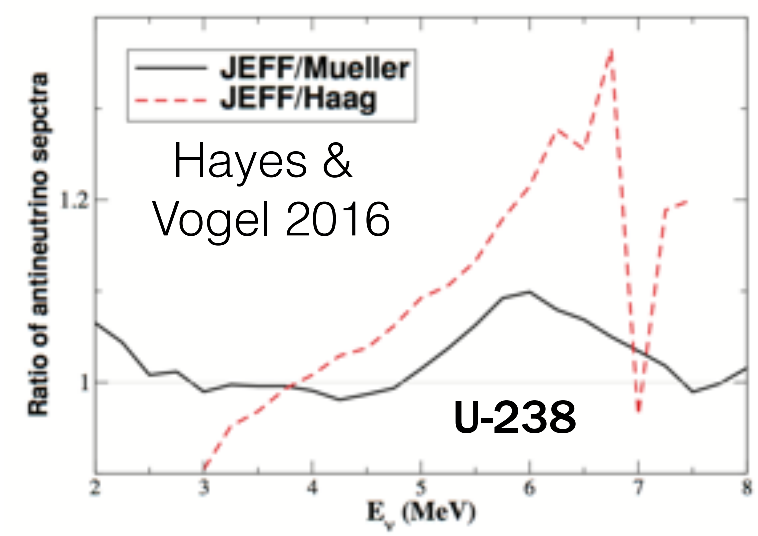
- why bump not seen at Bugey-3 like other experiment at PWR ?

Origin of the bump

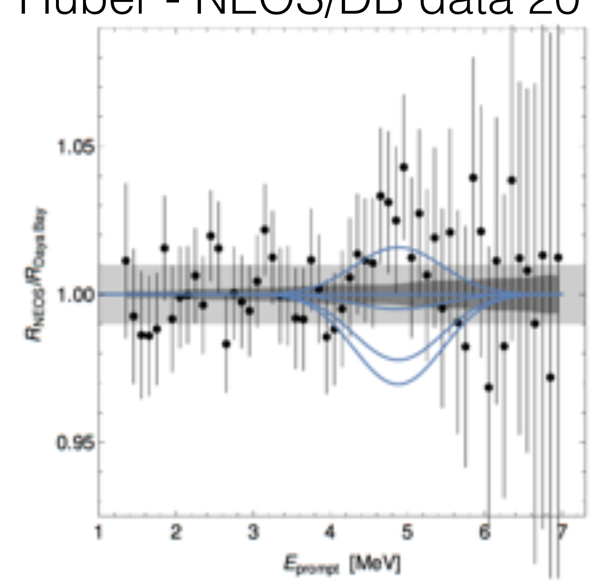
- Size of the bump found to be correlated with reactor power
  - confirmed by cancellation between near and far detector measurements
  - many crosschecks by all 3 reactor experiments
- Existence of a bump points towards issue with flux calculations
  - difficult to disentangle in PWR spectra (combination of isotopes)
  - many hypotheses put forward to explain it
  - Some can be tested with HEU reactor: pure U-235 antineutrino spectrum
    - origin in U-238 or U-235
- Is this linked to the reactor anomaly ?
  - would not explain all of it so other explanations not yet ruled out
- More data needed !

Sonzogni et al. 2016

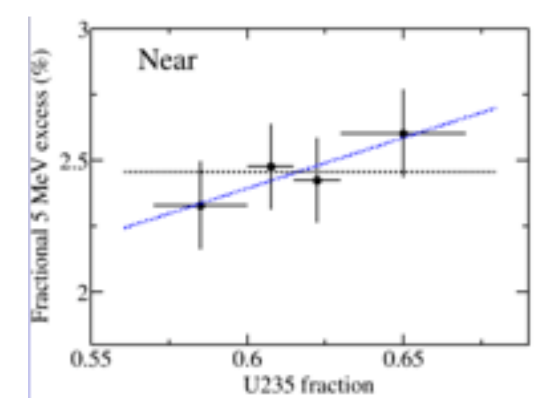




P Huber - NEOS/DB data 2016



RENO 2016

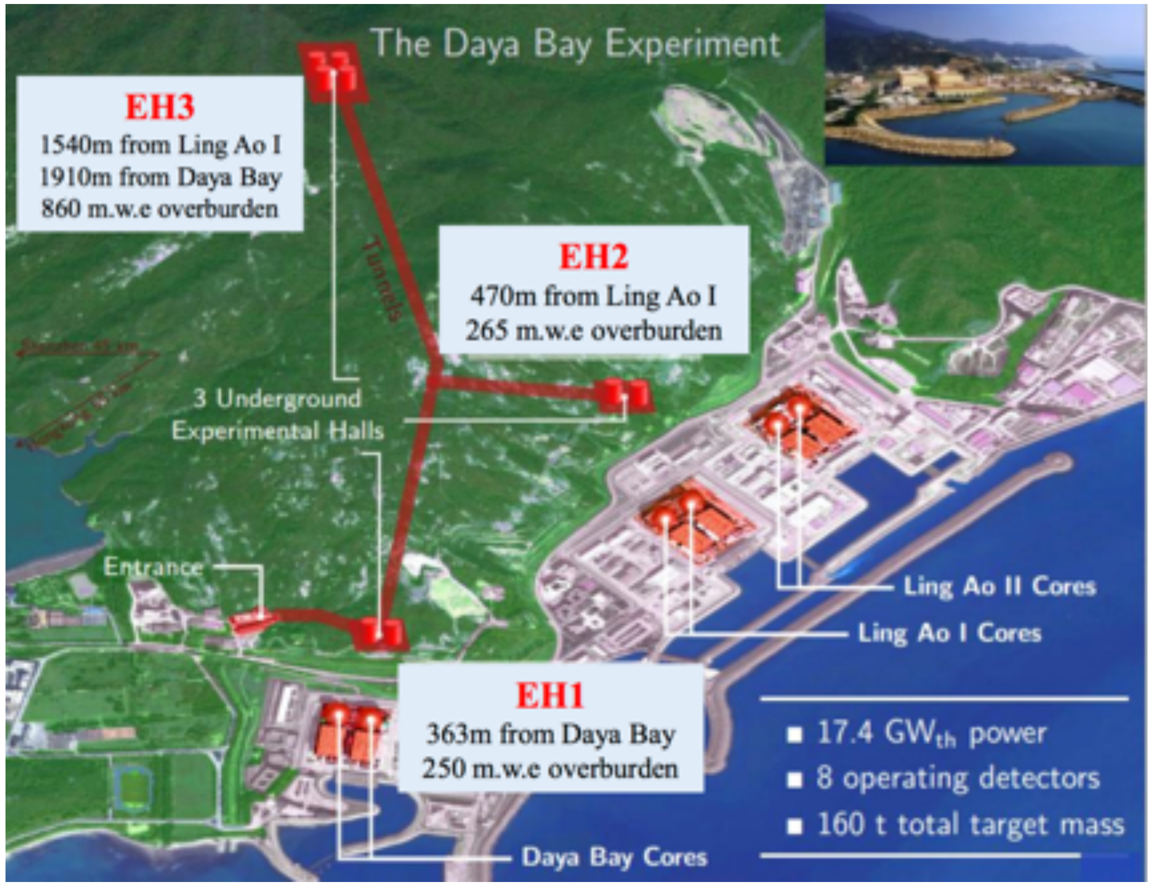


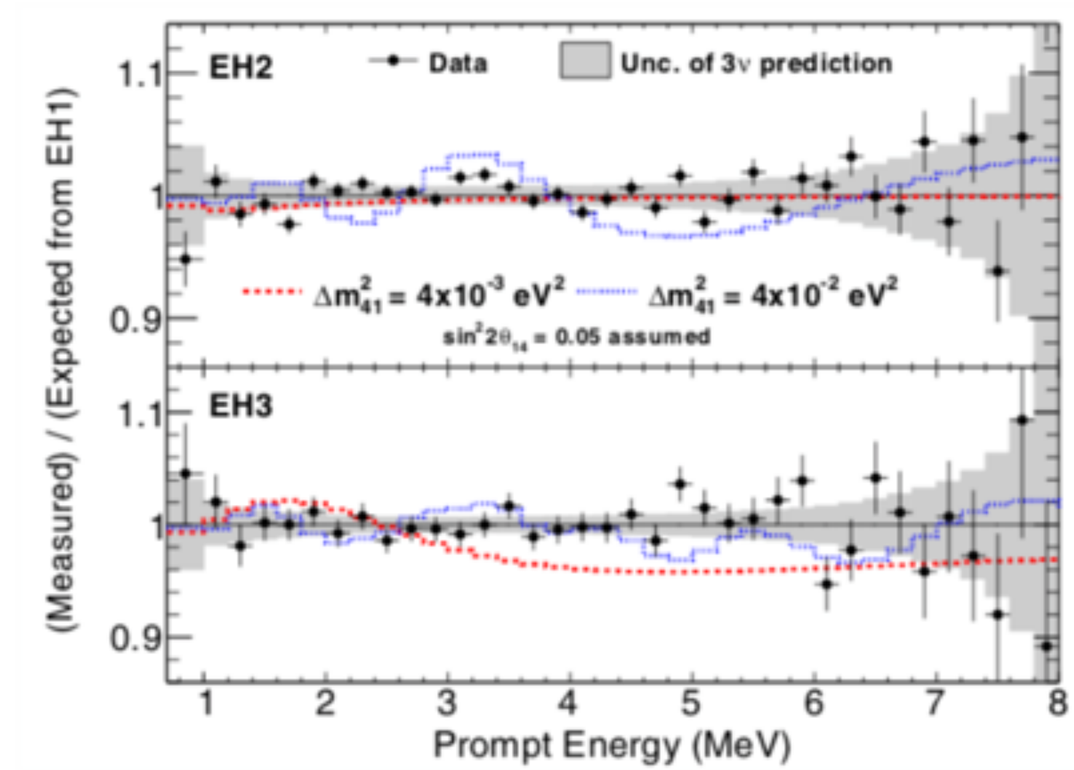
U-235

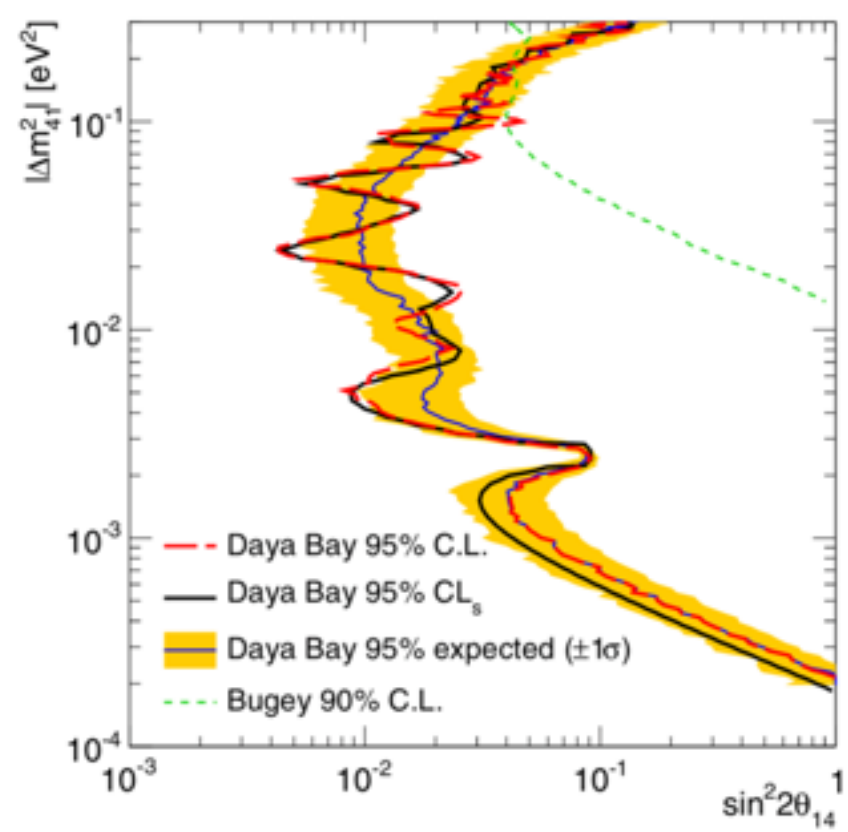
Recent limits

Daya Bay

arXiv:1607.01174







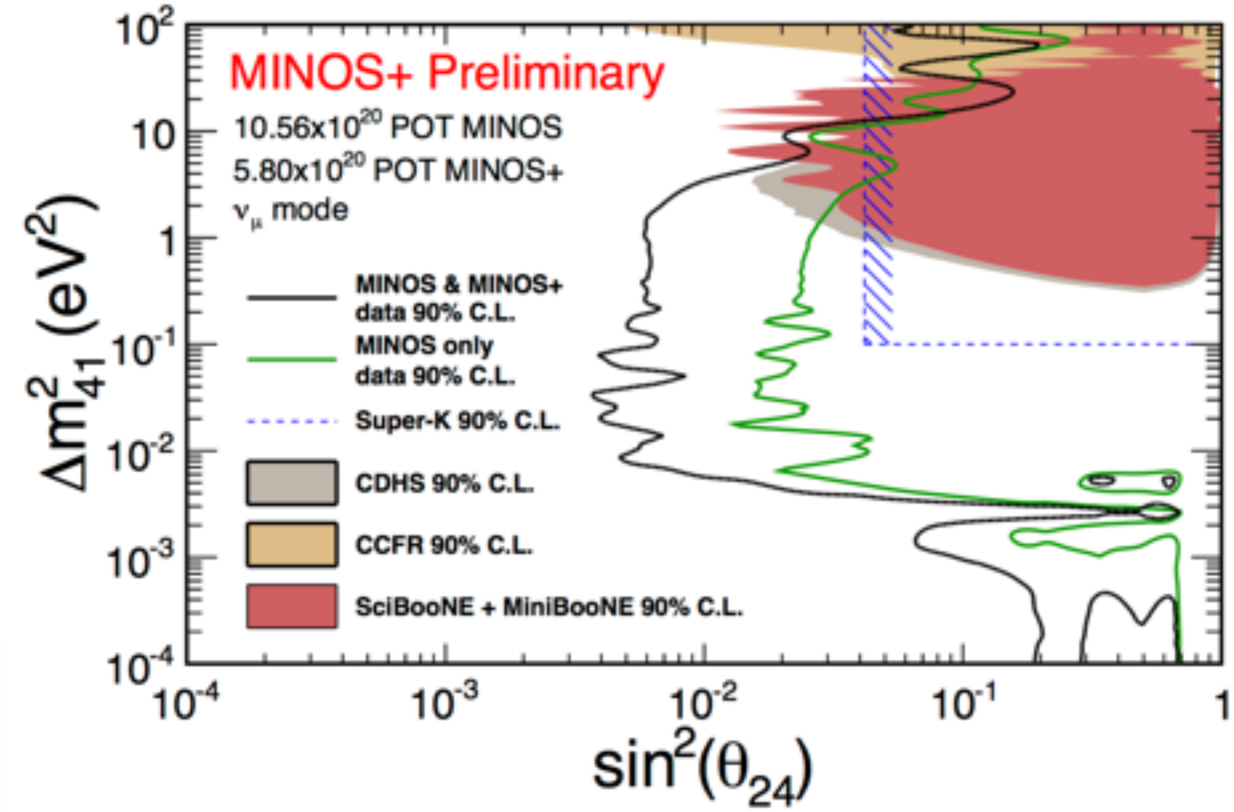
- Relative comparison of spectra at three detector sites
- Sensitivity at <0.1eV^2 region improved by 2x with respect to Phys. Rev. Lett. 113, 141802

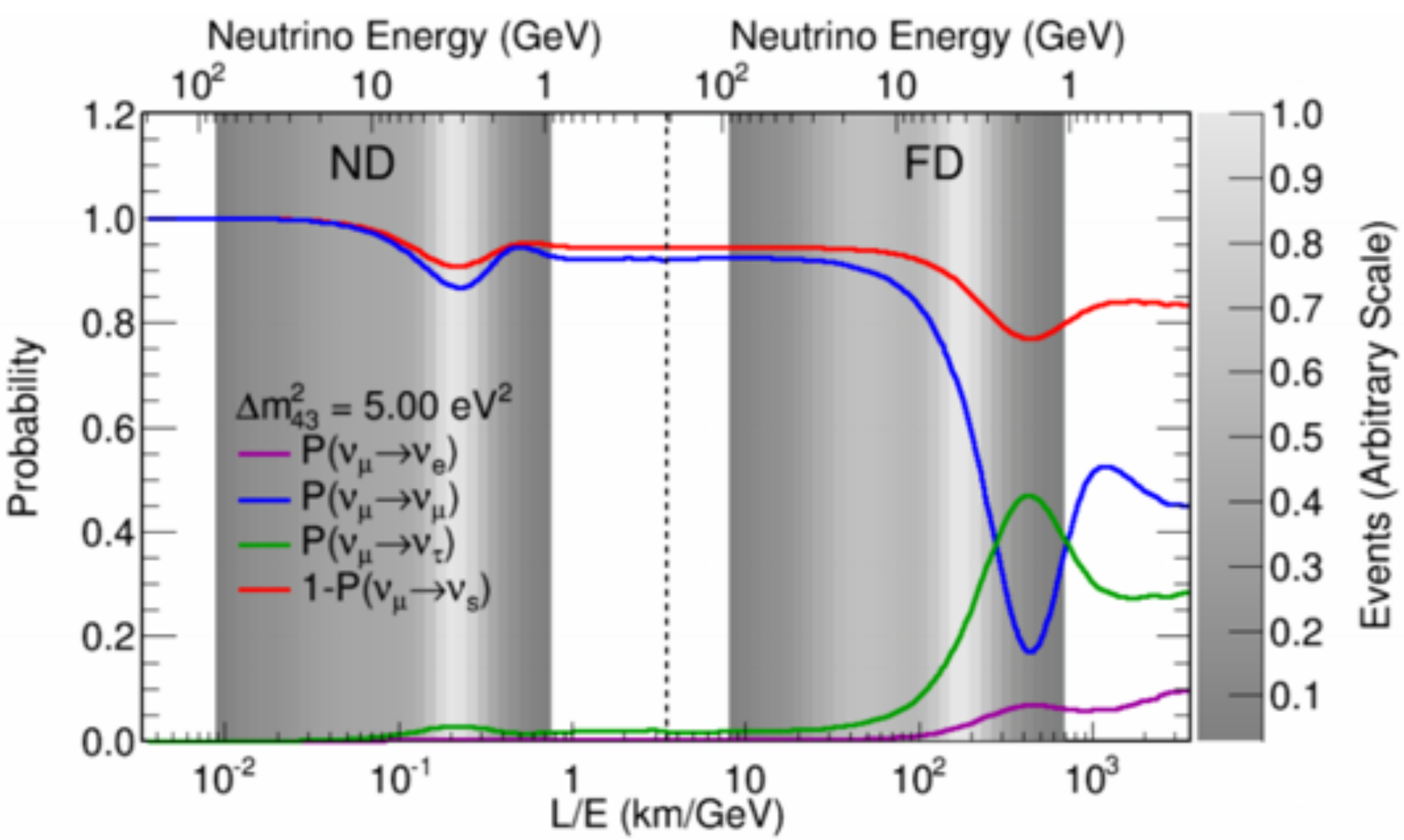
MINOS+

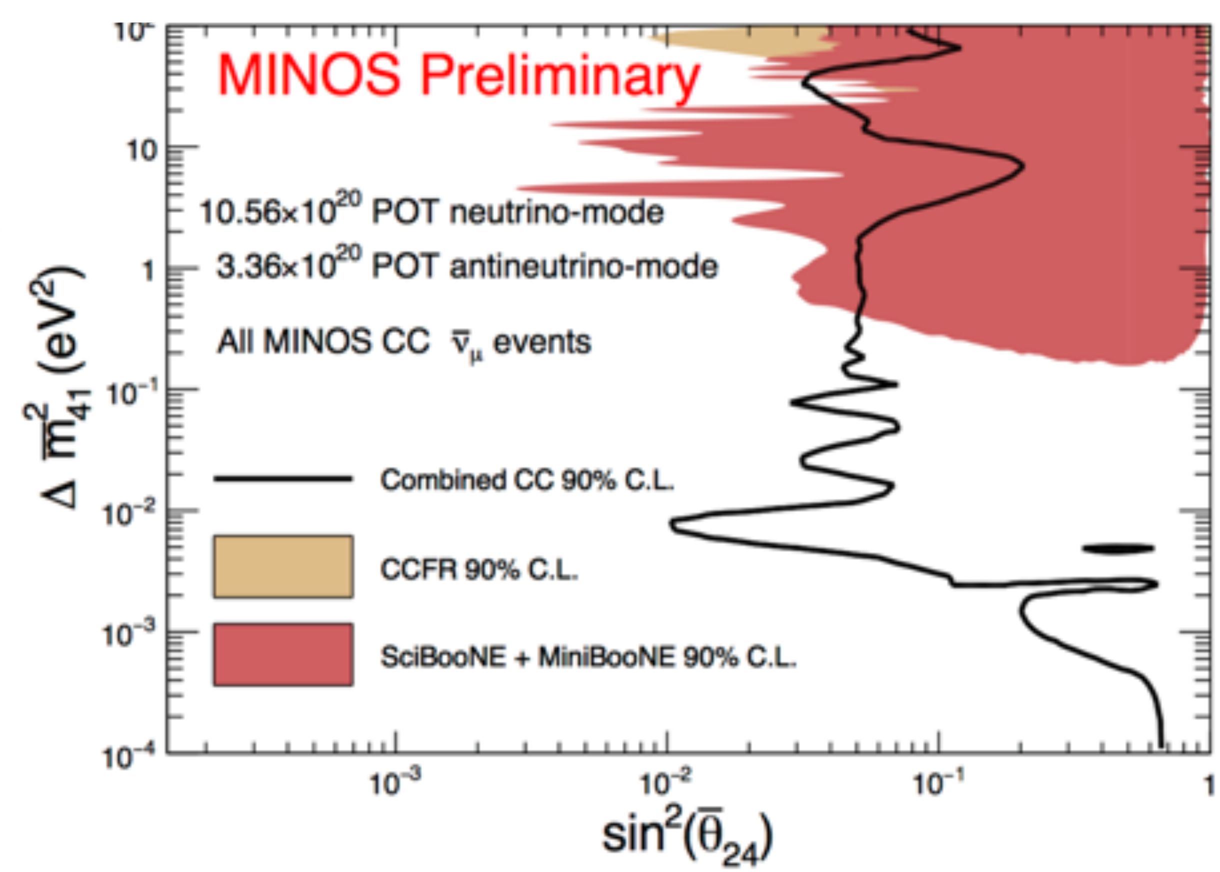
arXiv:1605.04544

Disappearance on top of that from standard oscillations

- at both the Near and Far Detectors
- seen in both NC and CC νμ events



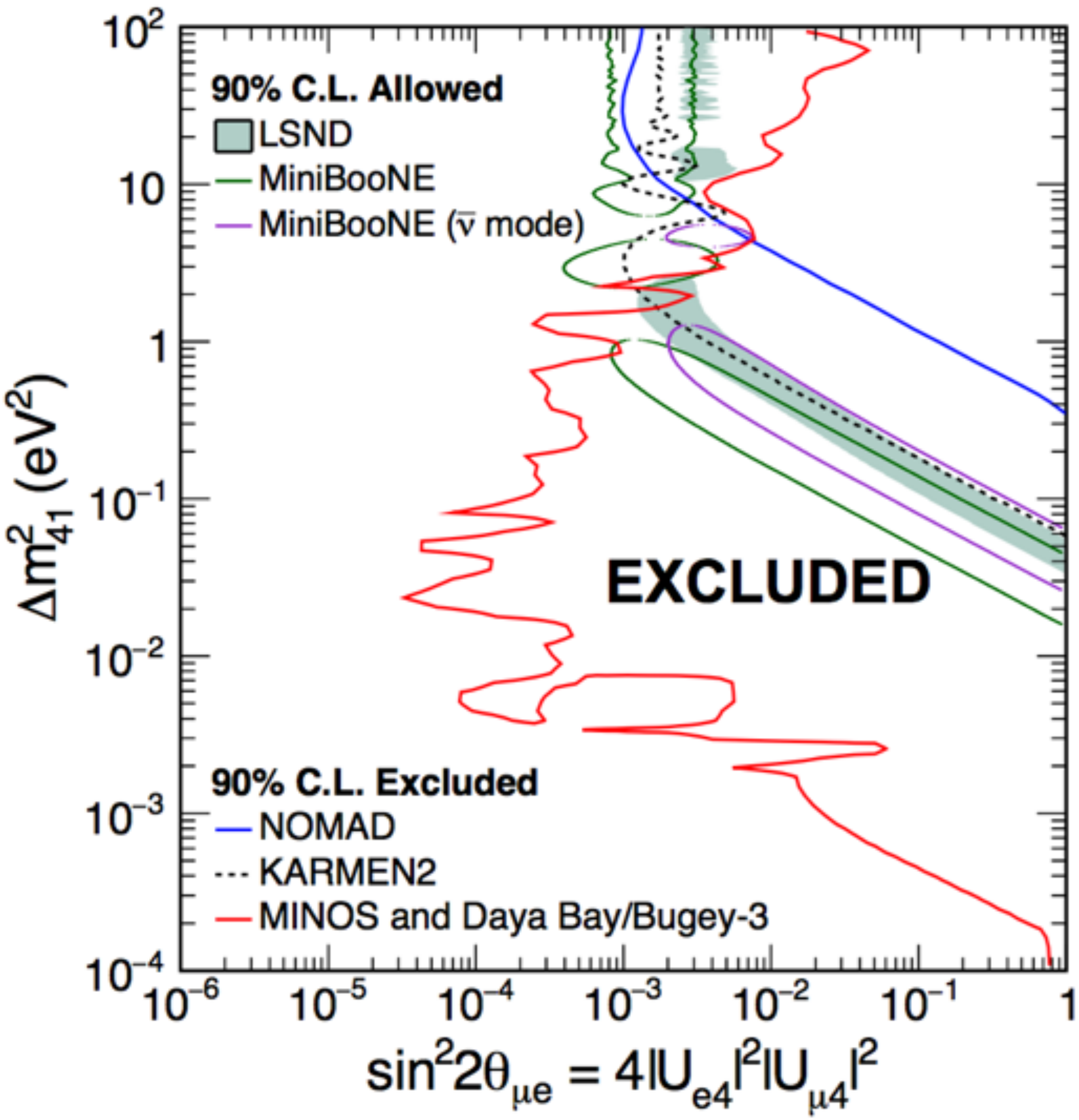




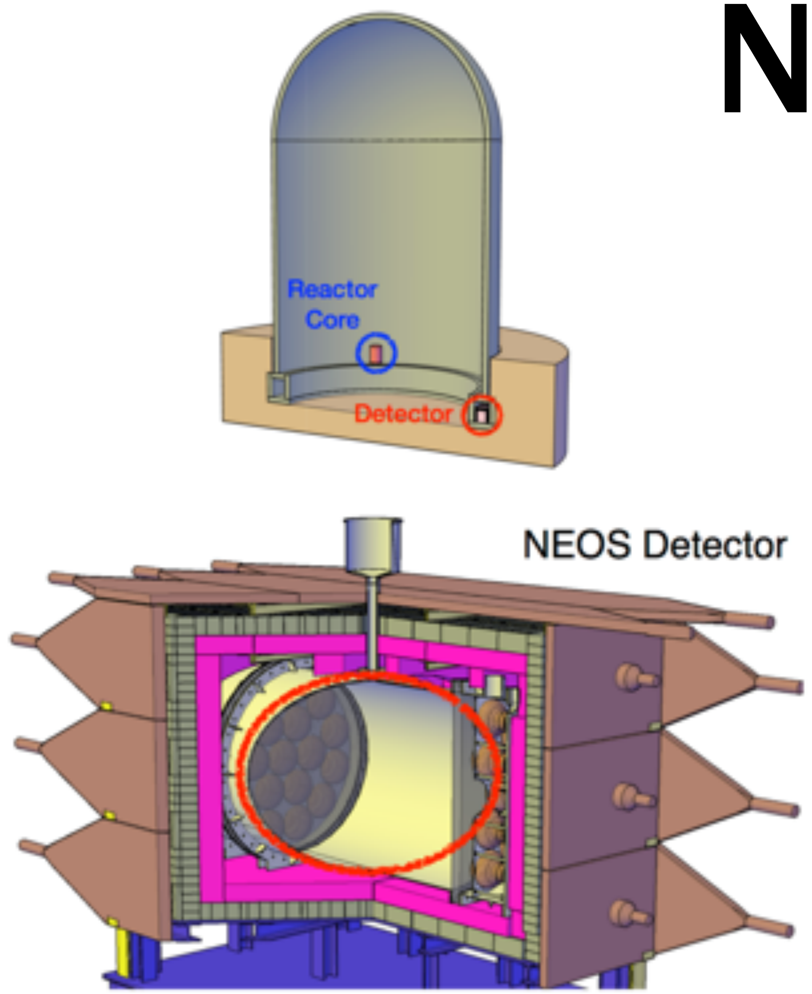
neutrino 2016

Combined results: nue appearance

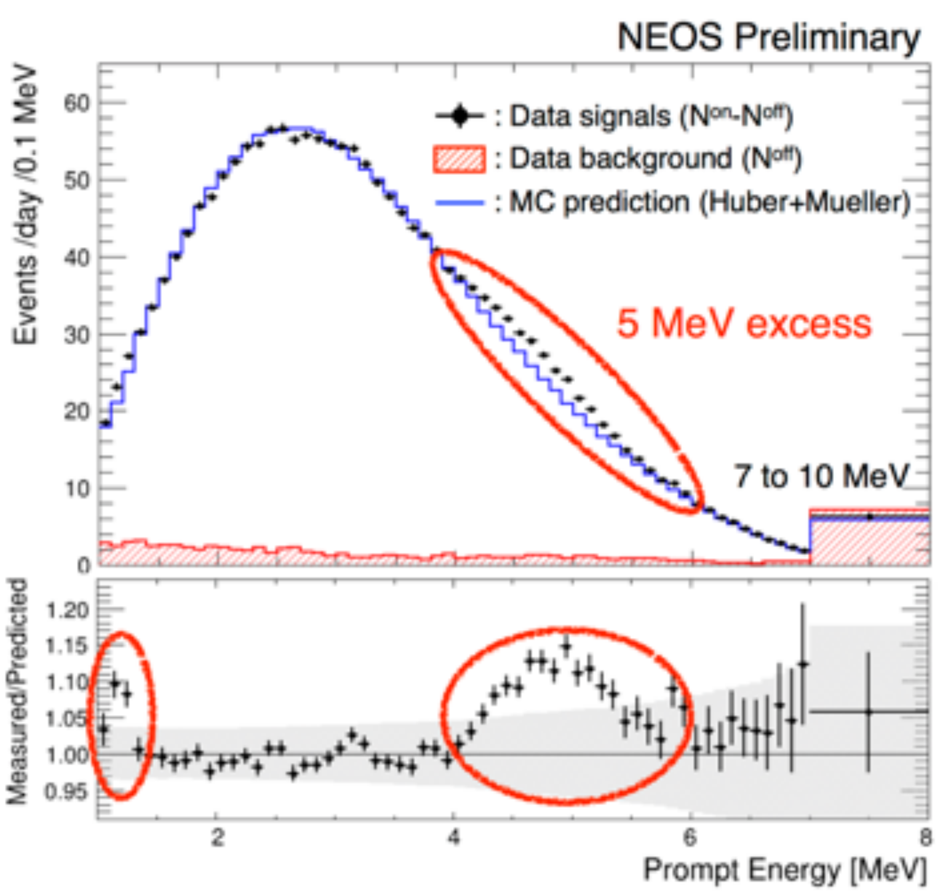
Bugey-3, Daya-Bay, MINOS+

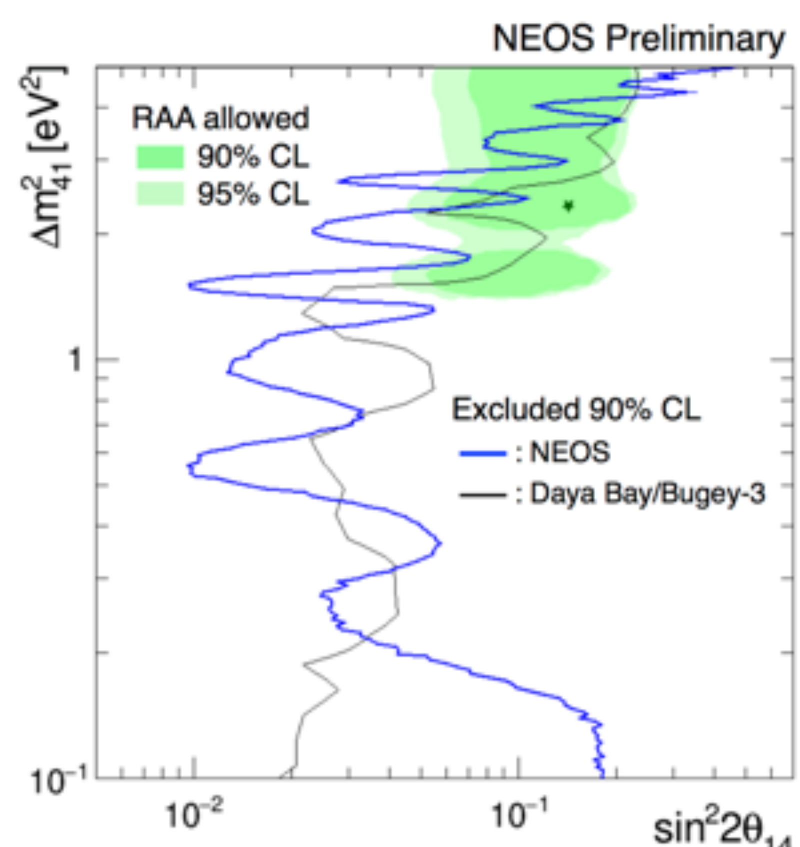


NEOS 2016



- Hanbit nuclear power plant 2.8 GWth, Korea
- baseline 24 m and 20 m.w.e overburden
- Detector in Tendon Gallery
- Homogeneous target detector, LS +Gd technology
- S:B of 20
- Sees two shapes distortions
- Exclusion contour at 90% CL entering region around 1 eV^2

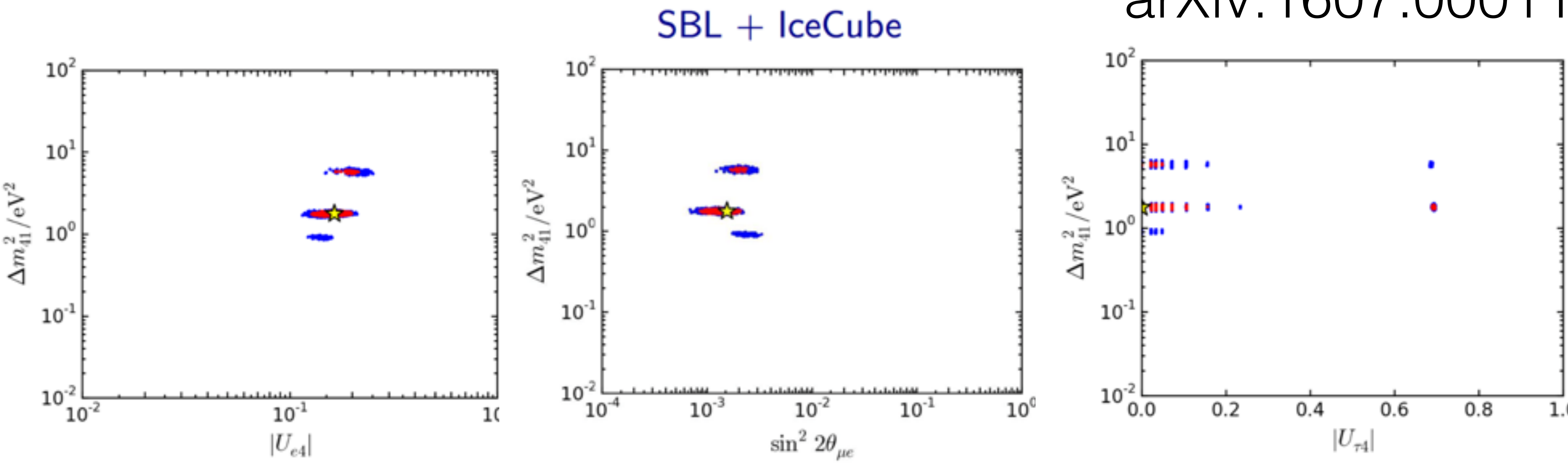




• Raster scan with χ^2 distribution

Global fit 3+1 as of 2016

arXiv:1607.00011



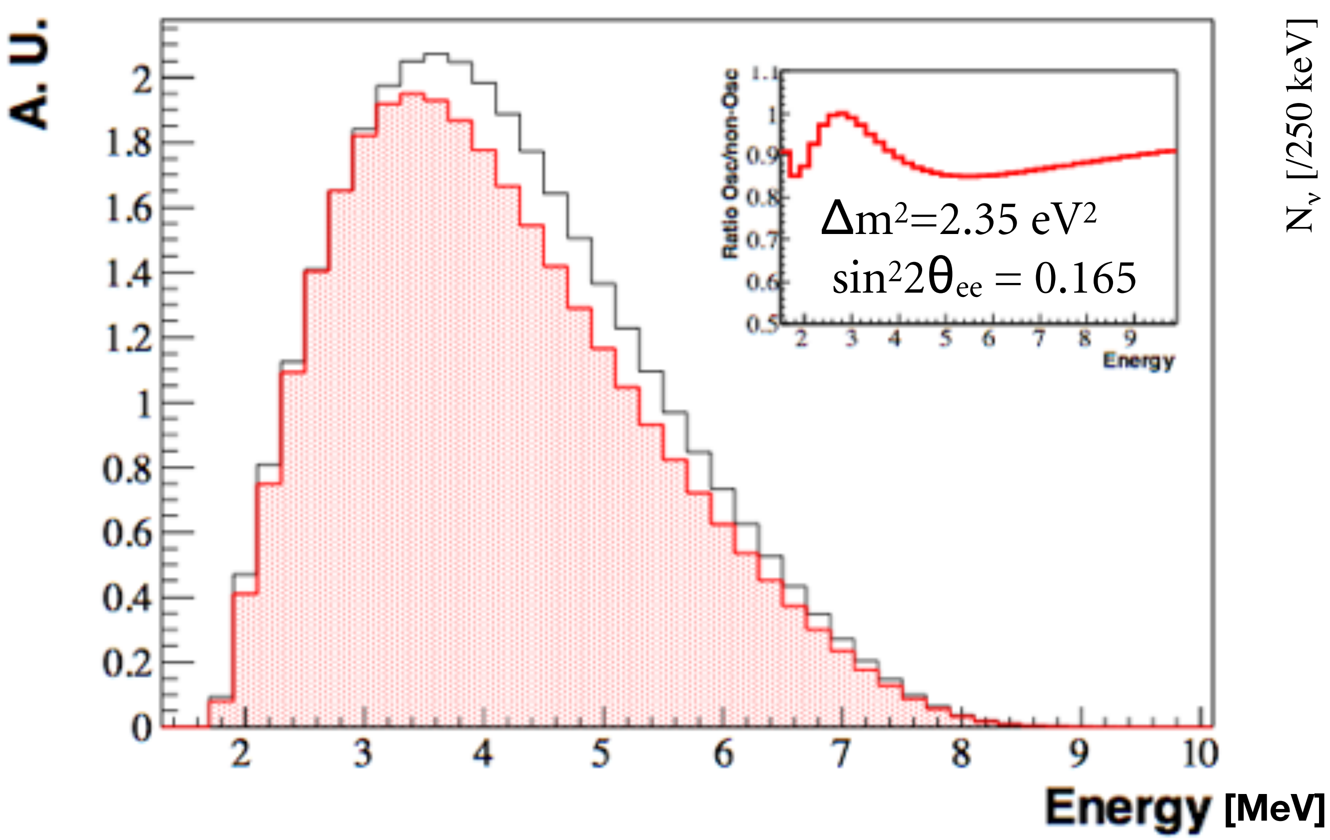
- IceCube and other recent results have restricted significantly the phase space for a 3+1 appearance hypothesis
  - doesn't give strong constraint on disappearance of electron neutrinos
- region around 1 eV^2 remains to be explored

Dedicated experiments

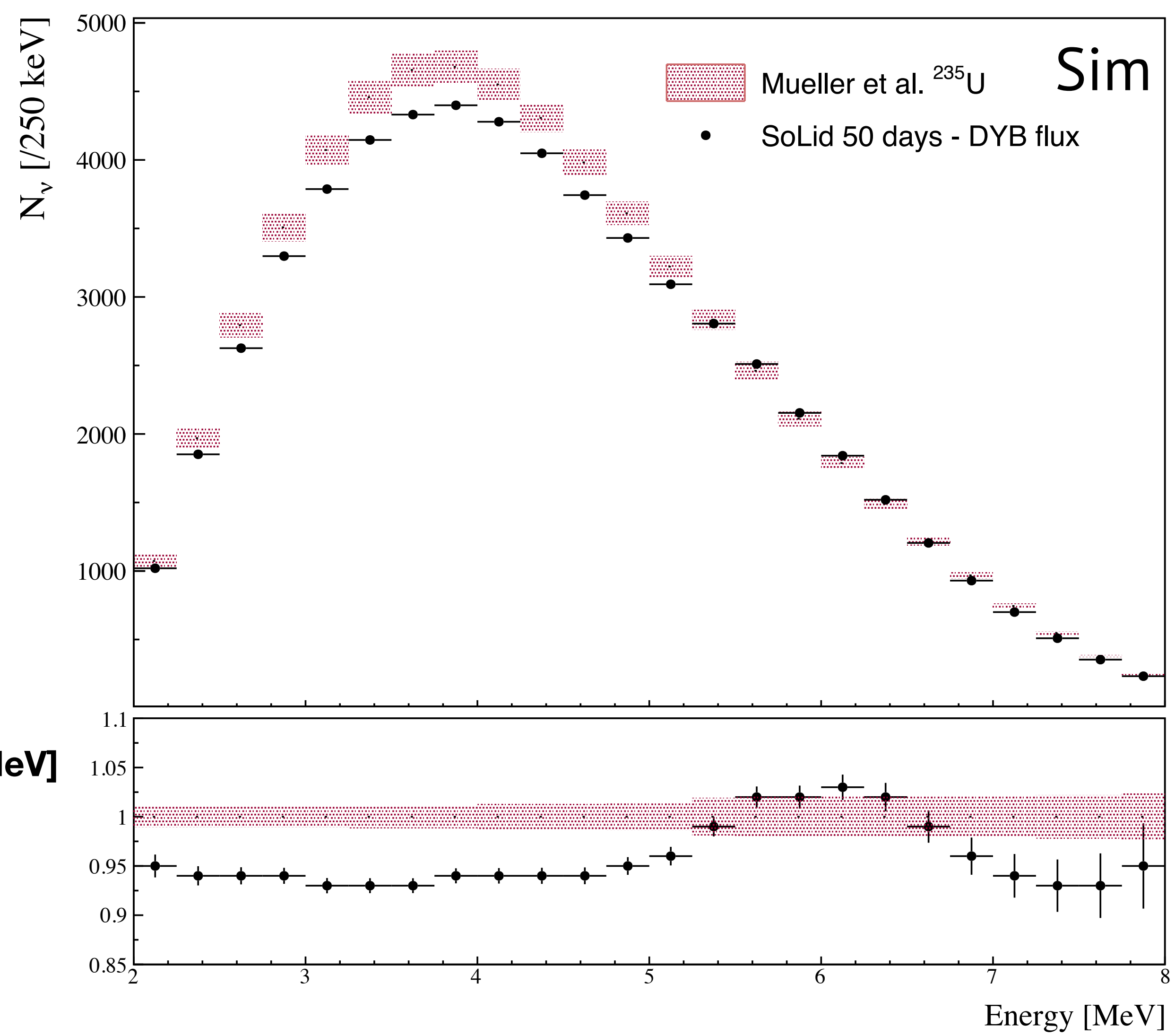
Very short baseline reactor experiment

- dedicated new experiments require **percent level precision** in antineutrino spectrum measurement

Oscillation search

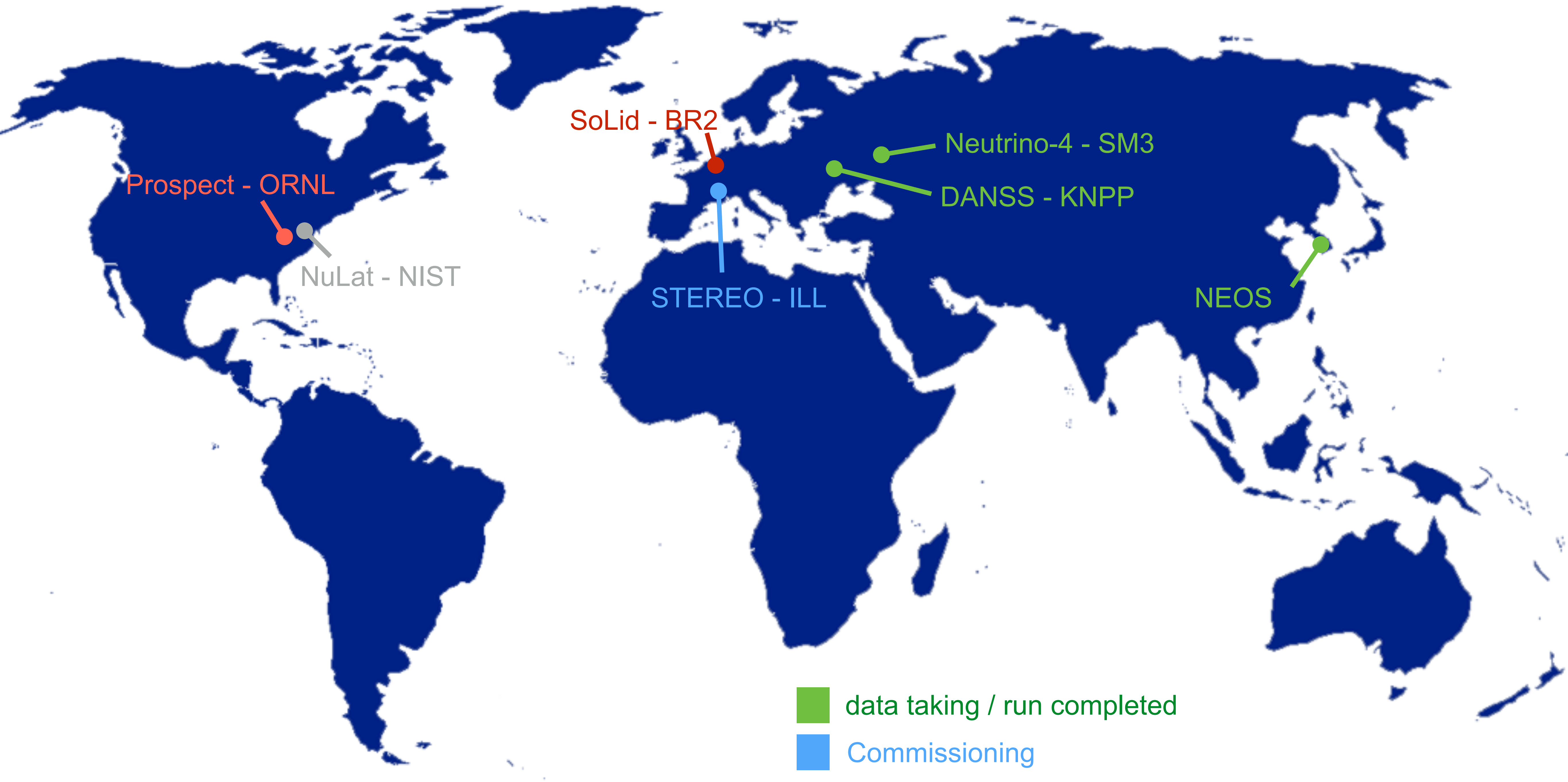


Spectrum shape



- detector located close to reactor core
- operating on the surface

New reactor experiments

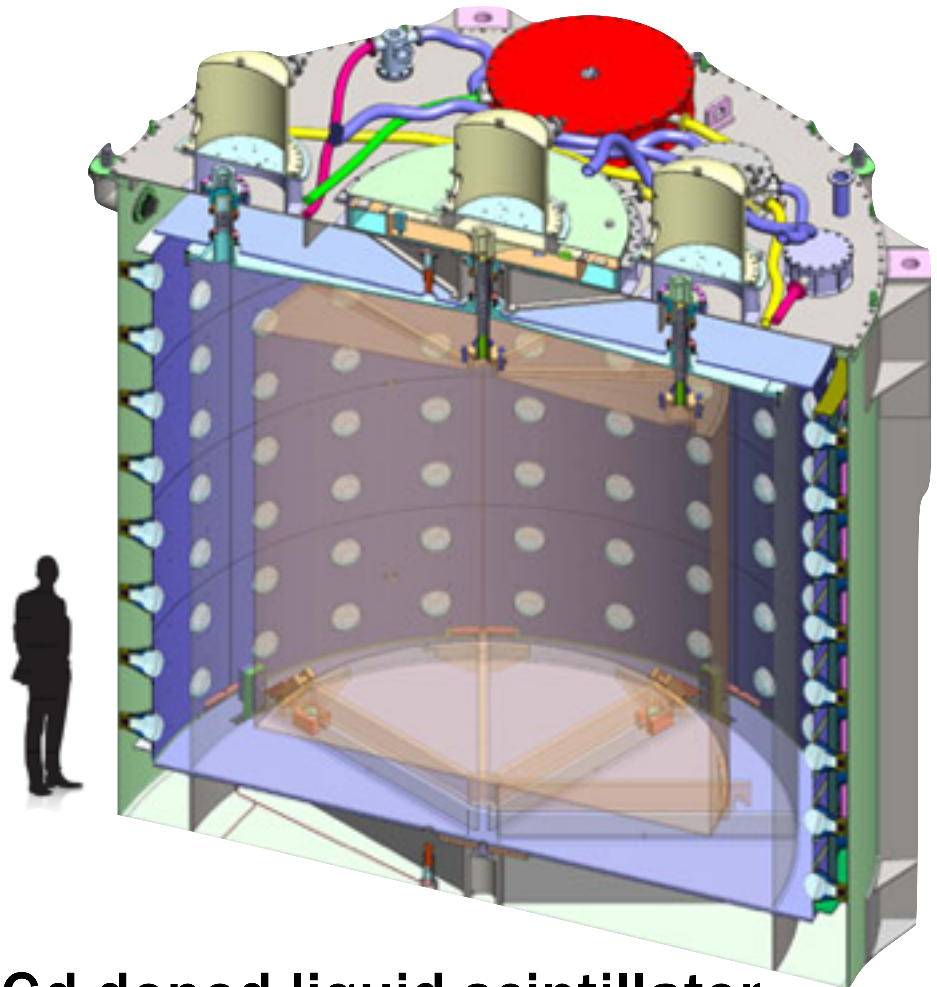


New reactor experiments

	Tech	Reactor	P [MW]	L (m)	M (tonnes)
STEREO (Fr/Ger)	LS+Gd	ILL-HFR	57	8.8-11.2	2
Neutrino-4 (Ru)	LS+Gd	SM3	100	6-12	1.5
PROSPECT (US)	LS + ^{6}Li	ORNL HFIR	85	7-18	2
SoLid (UK/B/Fr)	PVT + ^{6}LiF:ZnS	SCK•CEN BR2	45-80	5.5-11	2
DANSS (Ru)	PS + Gd	KNPP	3000	9.7-12.2	0.9

Precise measurements at reactor

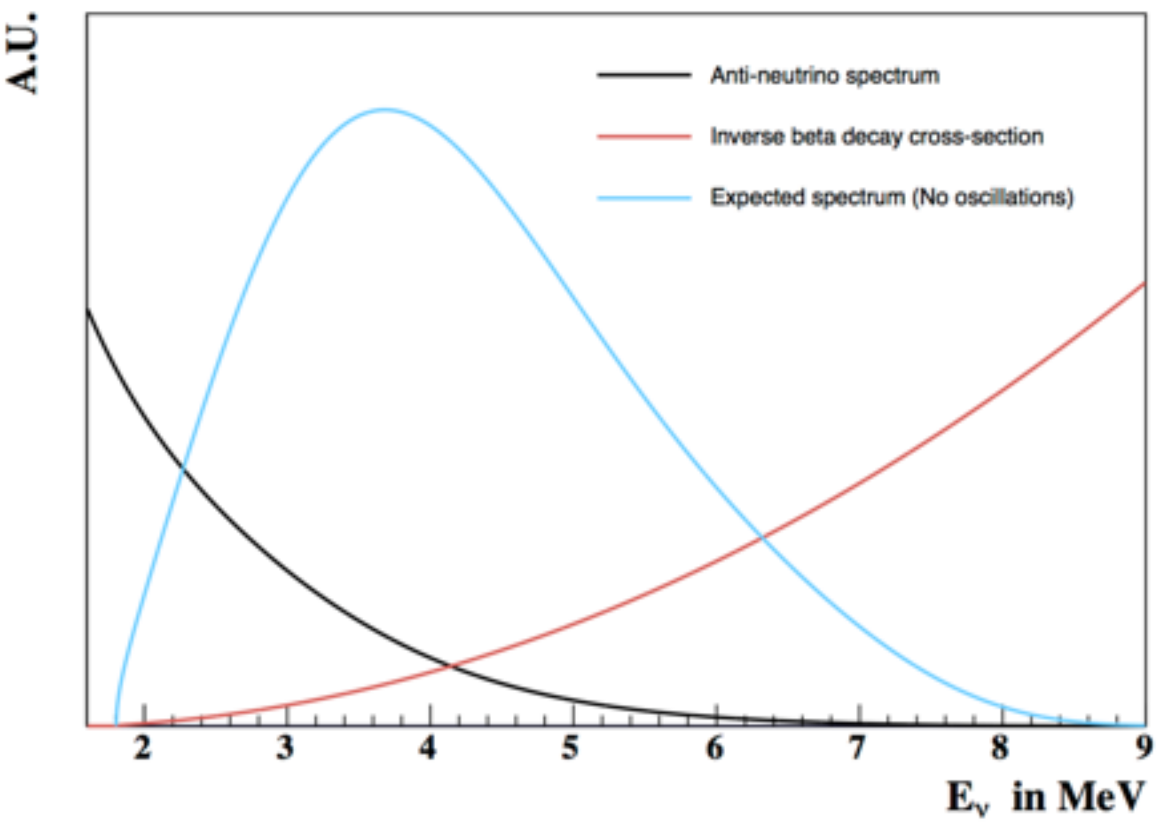
~ 100 m - 1 km baseline



Gd-doped liquid scintillator technology

- underground laboratory
- large external shielding
- homogenous, well contained energy
- achieve percent level antineutrino flux measurement at PWR

$$\bar{\nu}_e + p \to e^+ + n$$



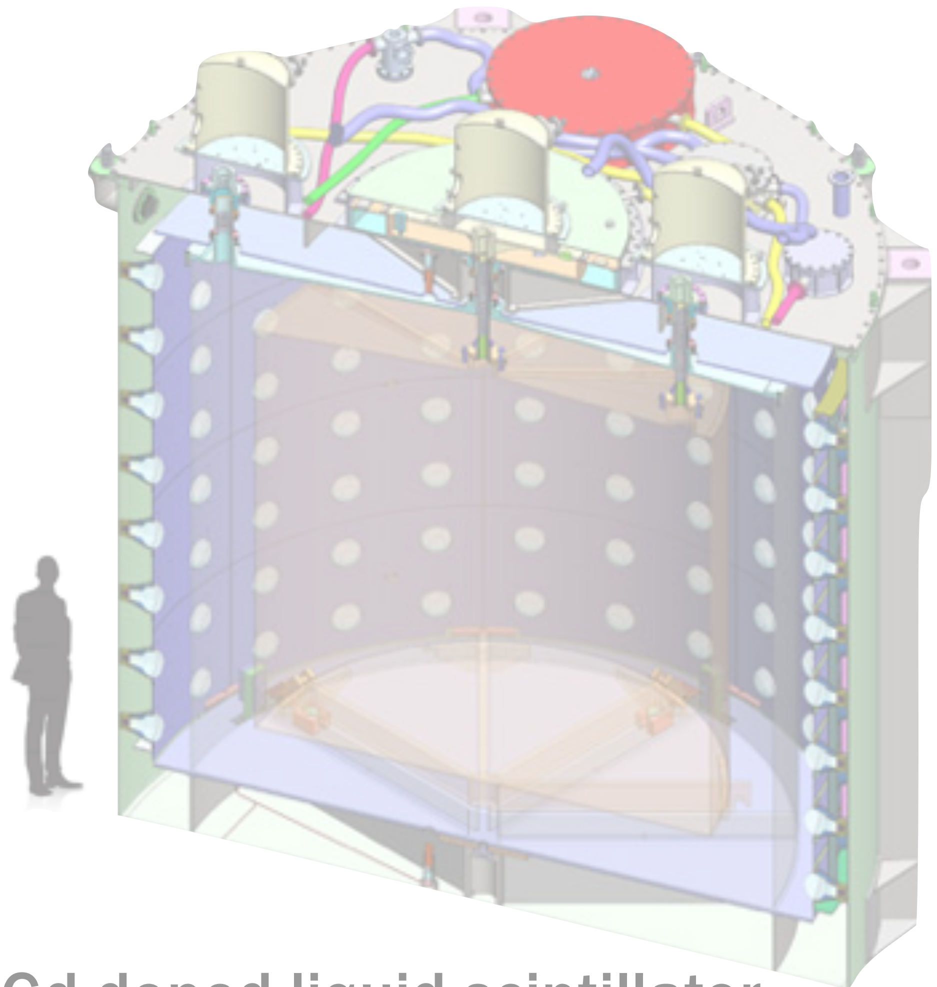
- detection using IBD reaction

$$E_{vis} = E_{\bar{\nu}_e} - 0.782 \text{ MeV}$$

$$E_{vis} = T_{e^+} + 2\gamma \ (511 \text{ keV})$$

Precise measurements at reactor

~ 100 m - 1 km baseline



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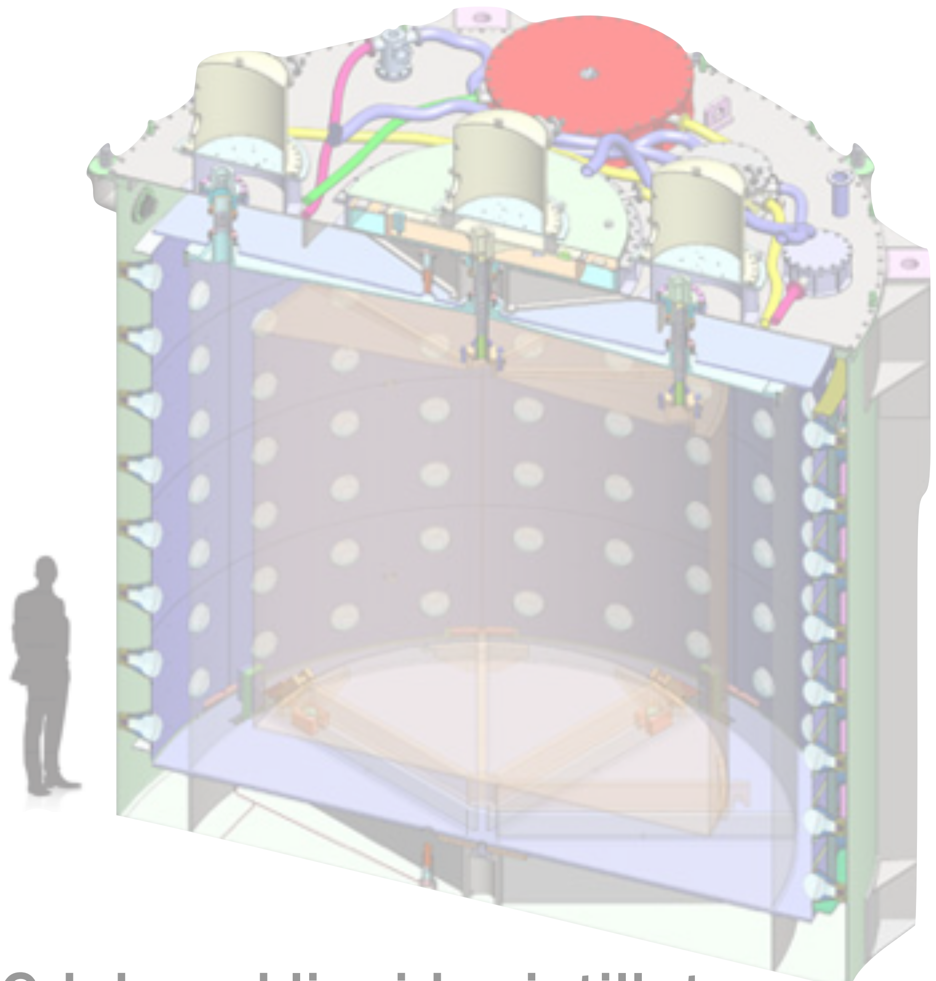
~ 10 m baseline

Challenges:

- sensitivity **in E and L** for oscillation search
- rejection of background
- security and safety constraint on site

Precise measurements at reactor

~ 100 m - 1 km baseline



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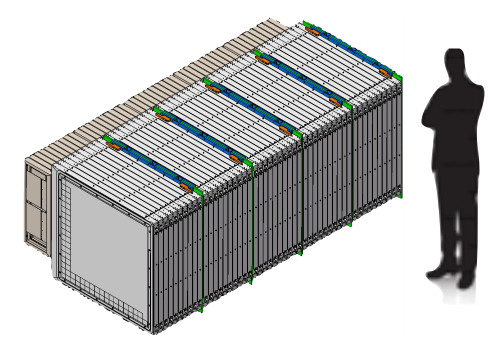
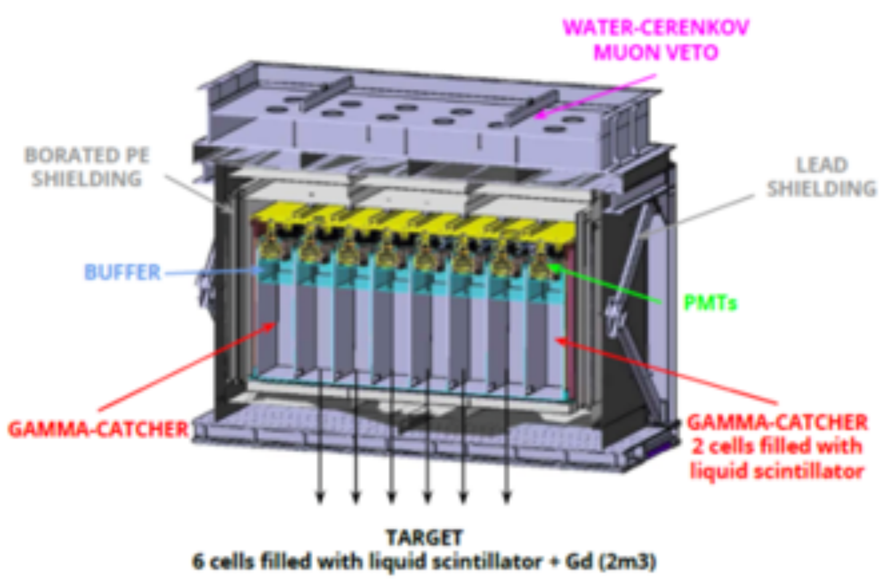


Highly segmented detector

sufficiently compact to deploy meters away from core

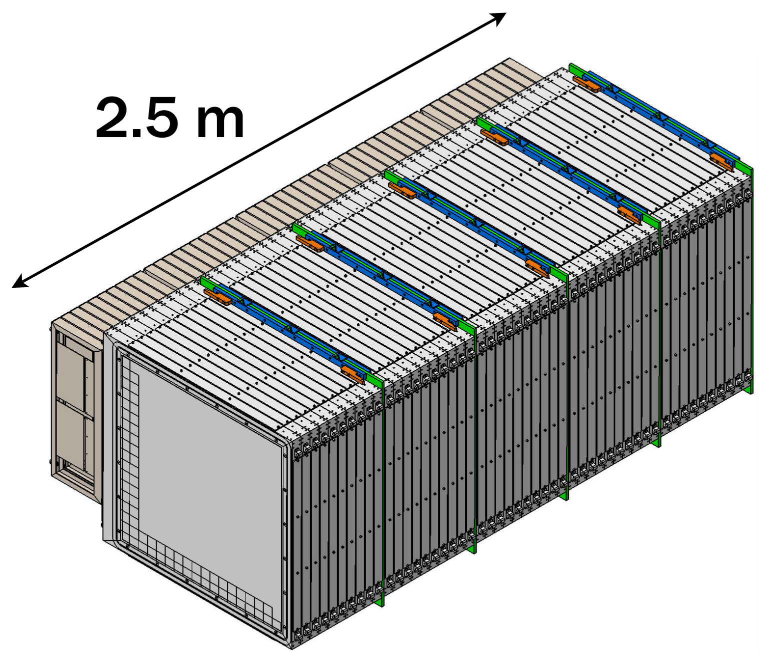
Oscillometric measurement based on segmentation

- Measurement as a function of L and E with extended detector geometries
- Adress challenging background conditions close to reactor core and surface.



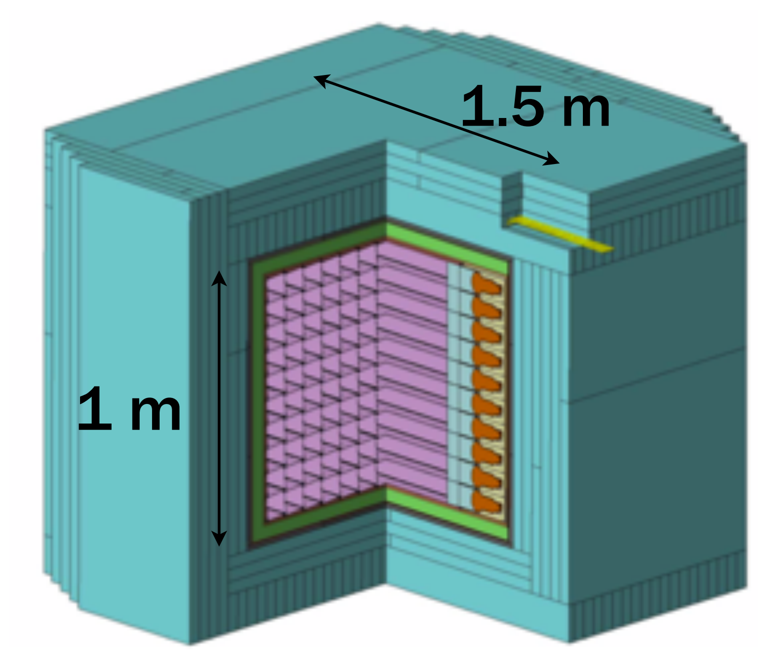
STEREO

~ 6 target cells
Gamma-ray catcher volume



SoLid

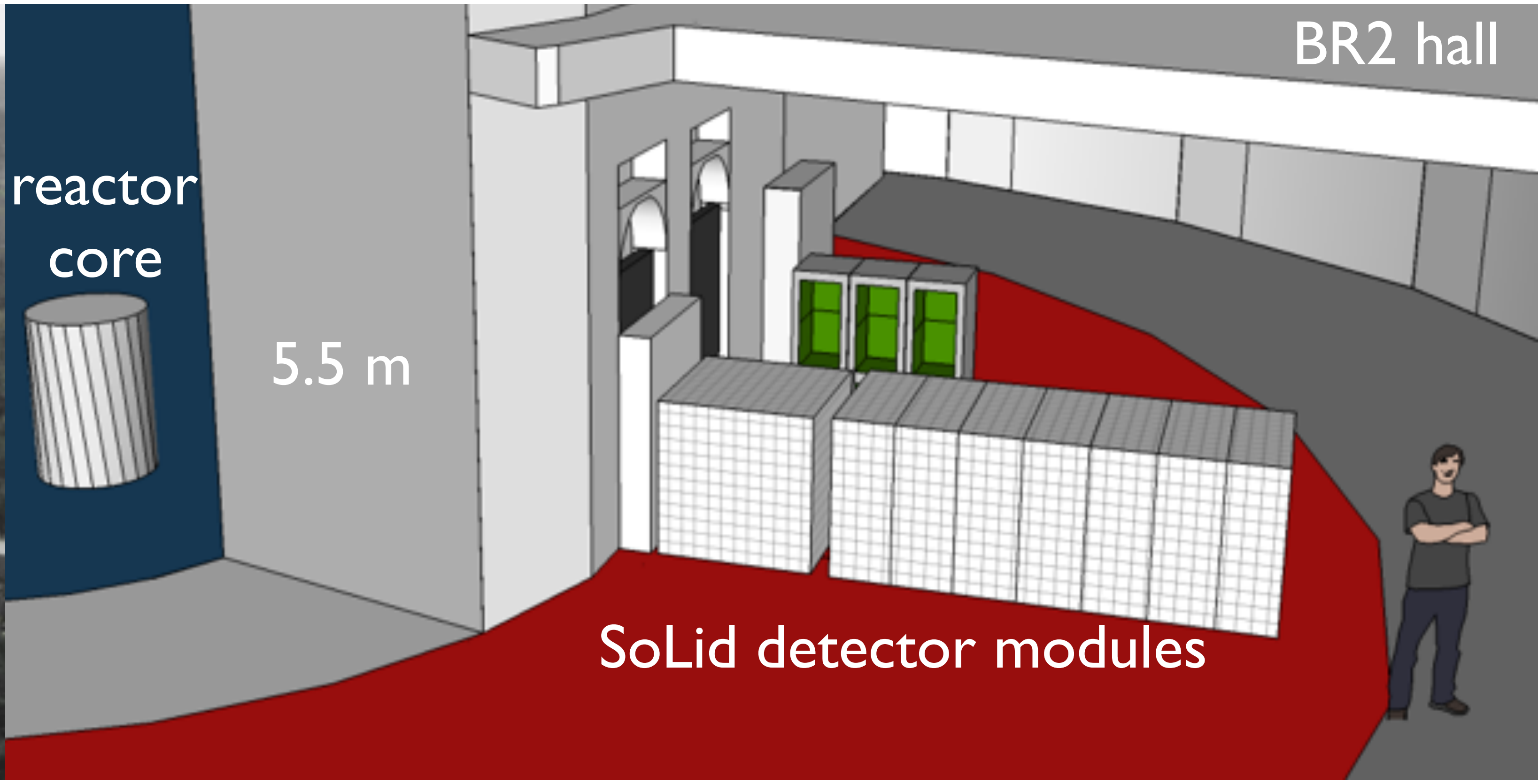
5-6 modules
each of 10 planes
13 000 voxels
3200 read out channels



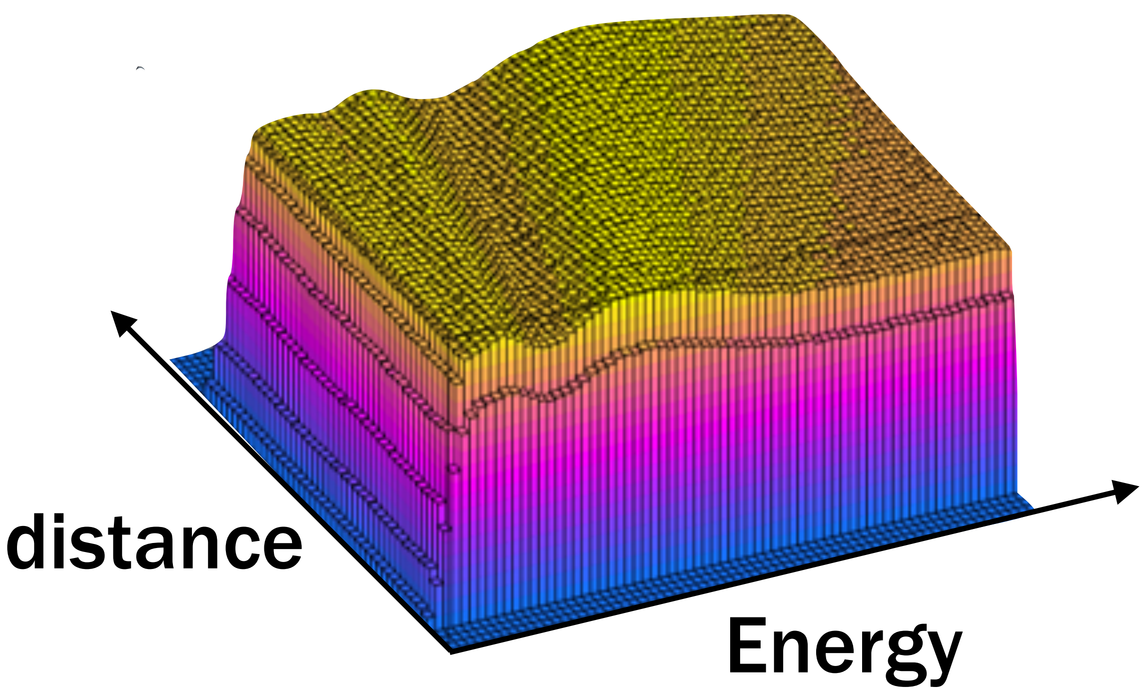
Prospect

Bugey-3 like detector
~100 long cells
read out channels

SoLid



- Search for oscillation with high precision in energy and position
  - only way to demonstrate new oscillation
- HEU core gives pure U-235 spectrum
  - addresses the 5 MeV bump
- New detector technology



SoLid collaboration

- 4 countries, 11 institutes, ~ 50 people

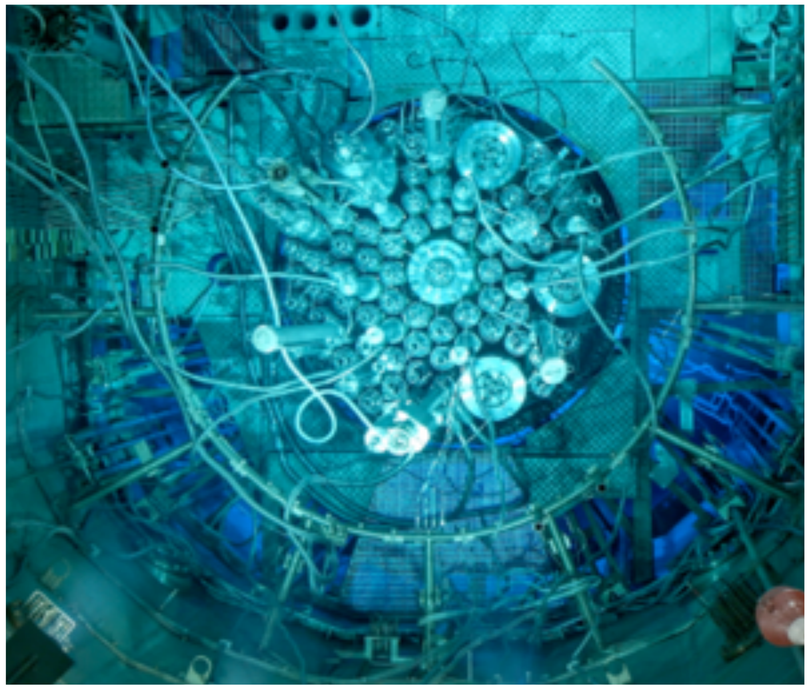
SCK•CEN
Universiteit Antwerpen
Vrije Universiteit Brussel
Universiteit Gent

LAL Laboratoire de l'Accélérateur Linéaire
LPC Caen
Subatech

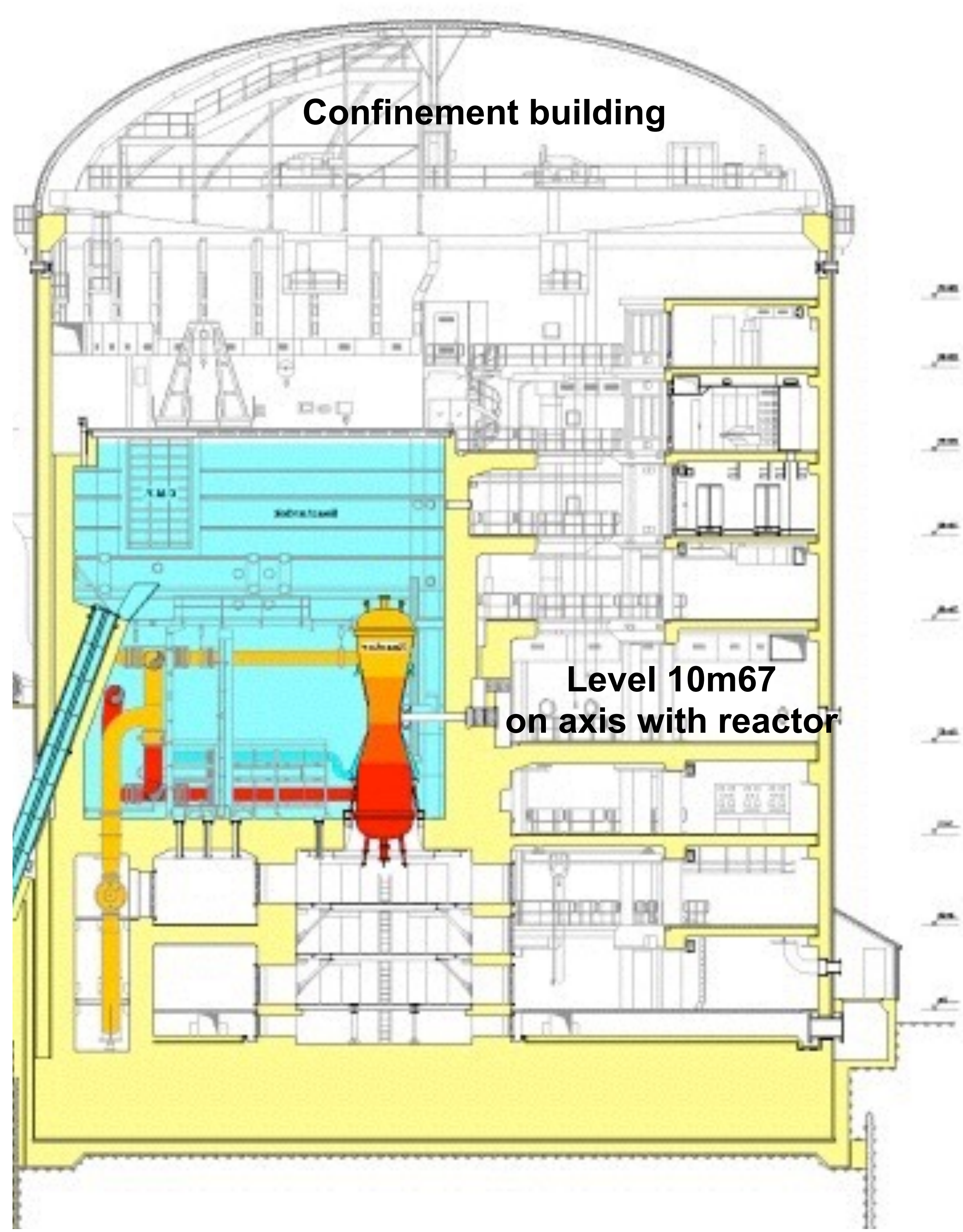
Imperial College London
University of Bristol
University of Oxford

Virginia Tech Invent the Future

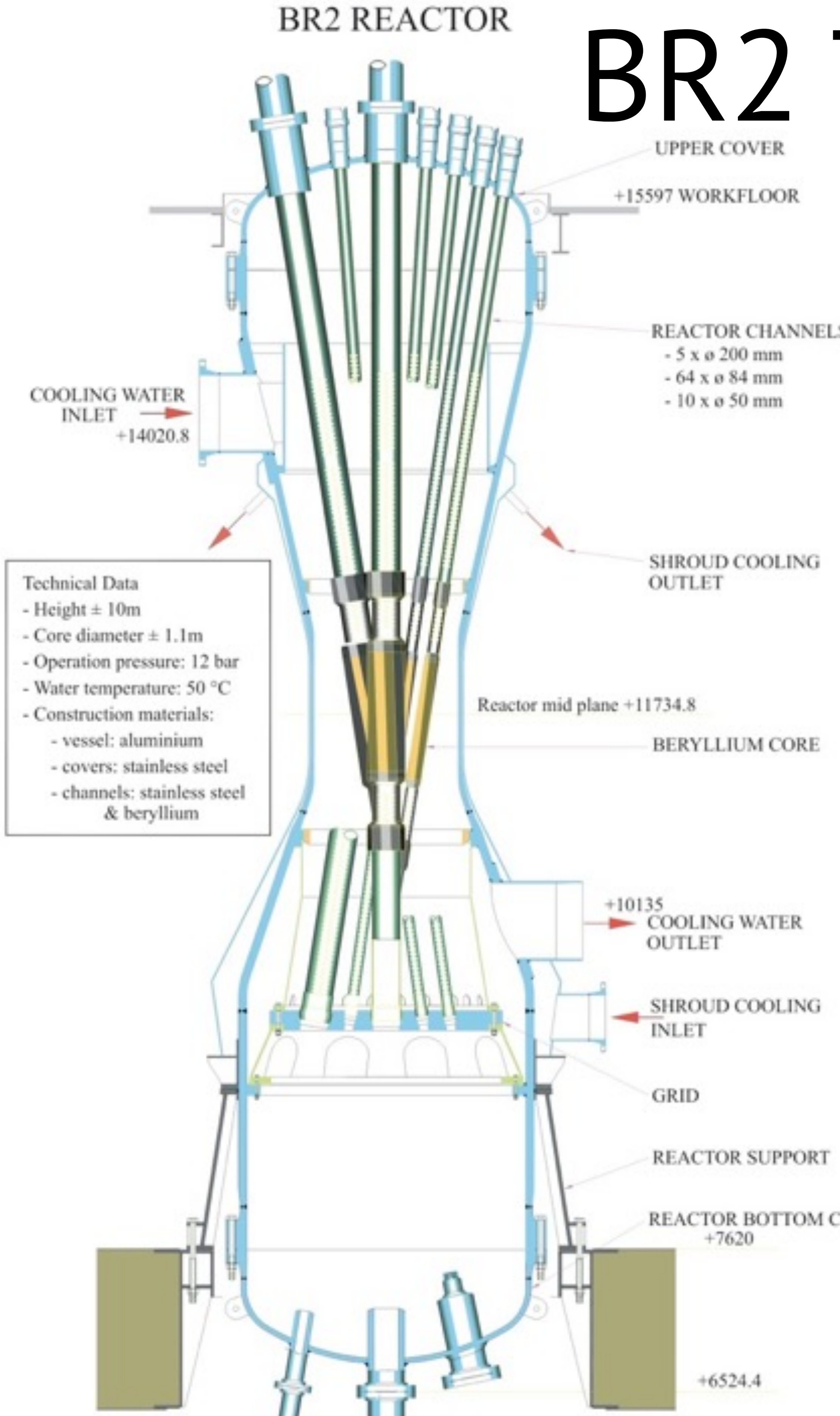
SCK•CEN BR2 reactor



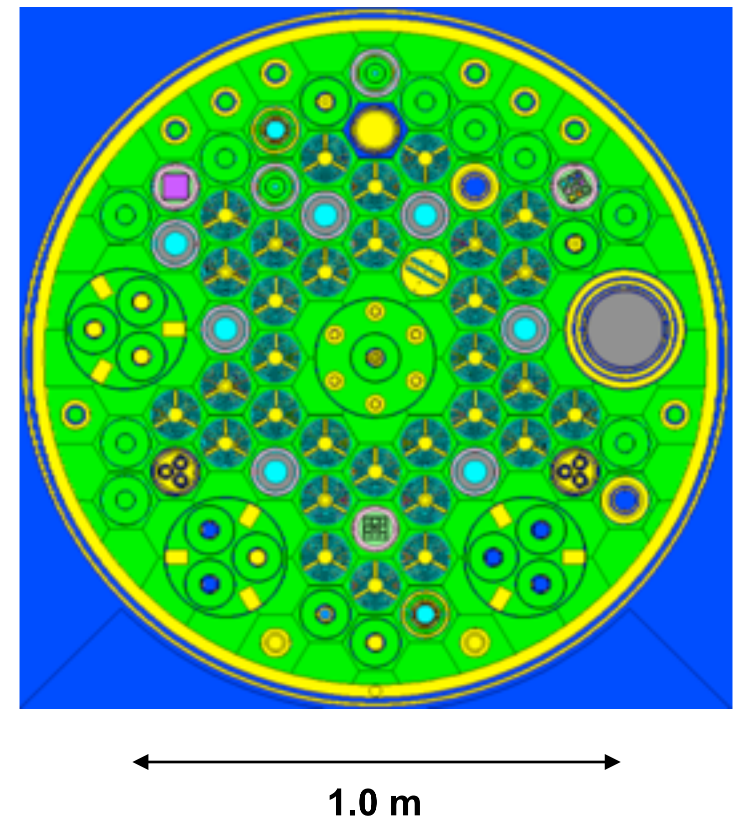
- Tank in Pool MTR research reactor
- Licensed to run at power up to 100 MW
  - variable operating power (45-80 MW)
  - 6 cycles per year
  - Beam ports not in use
    - ideal for low background measurement



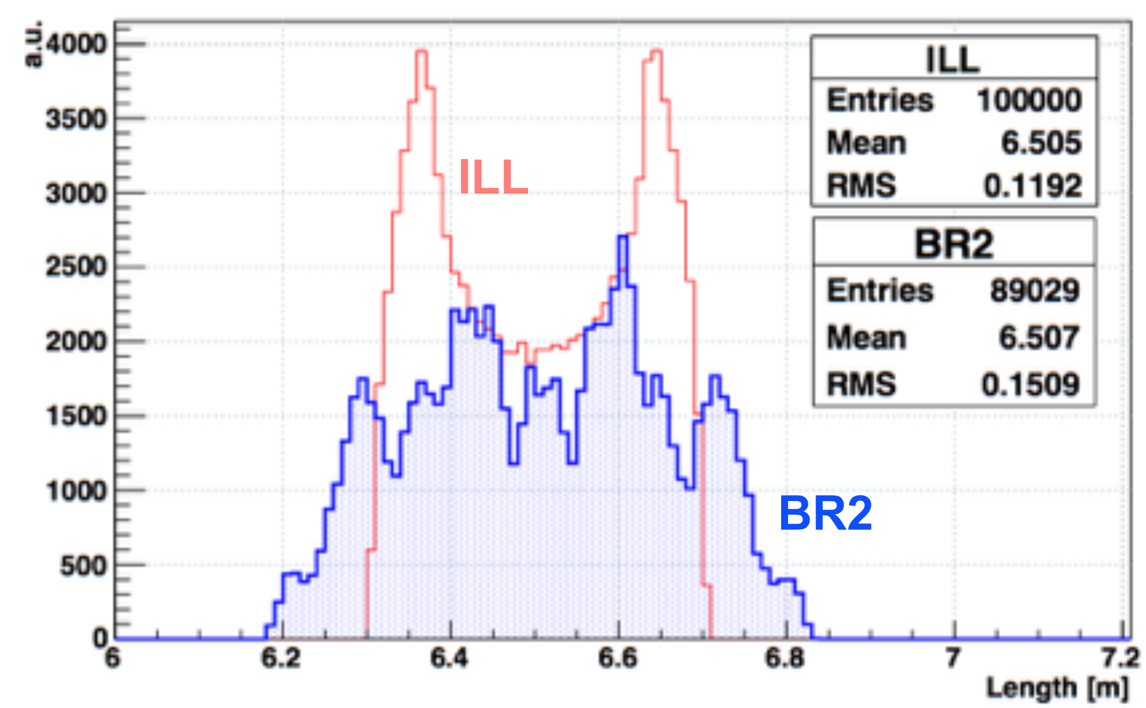
BR2 Twisted core



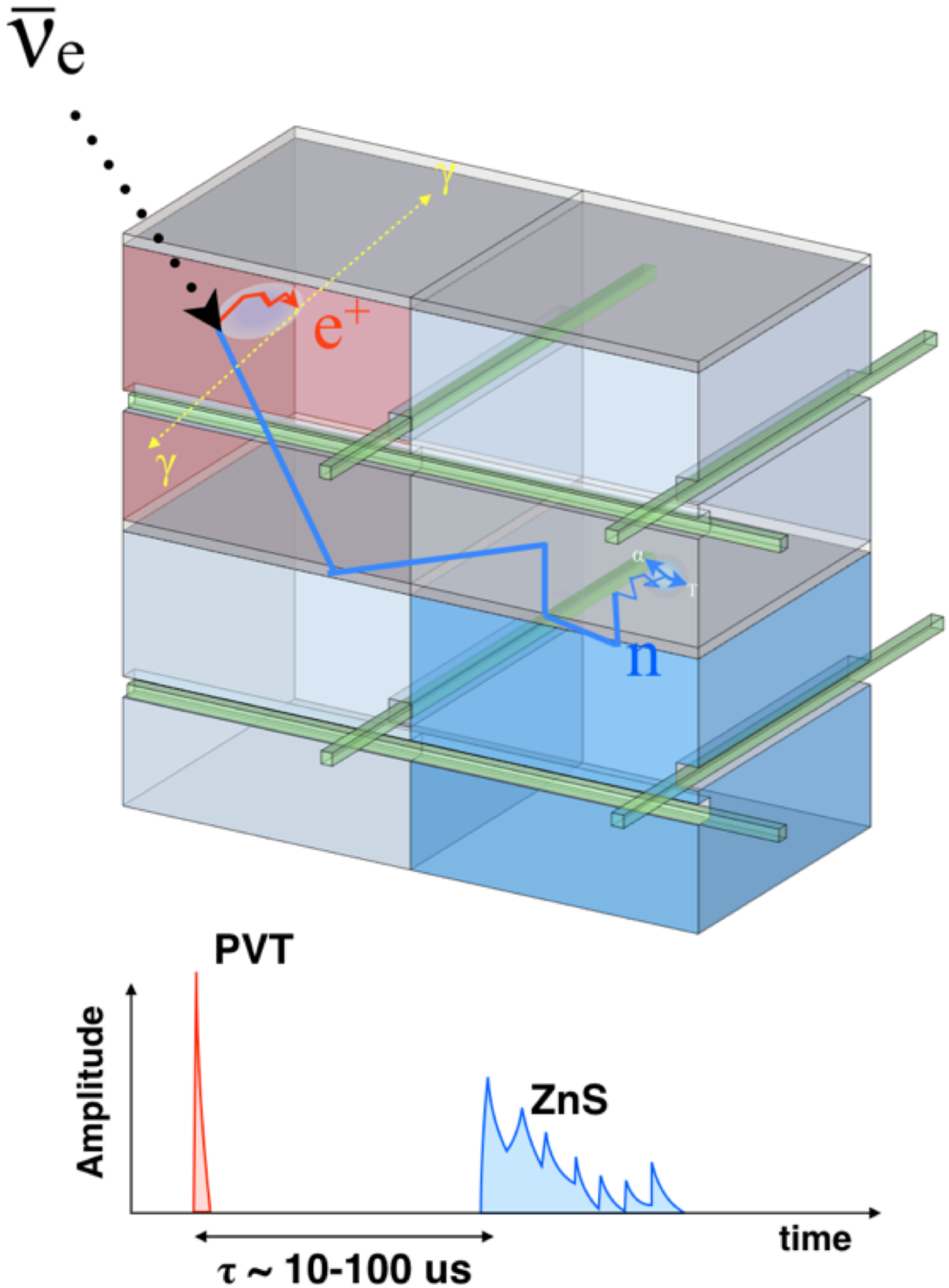
Aluminum pressure Vessel



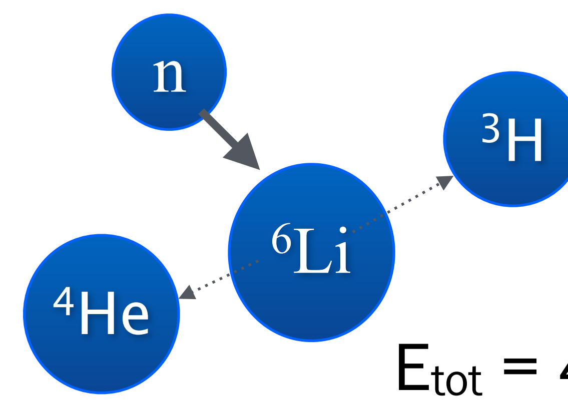
Beryllium matrix and assemblies



3D segmented composite detector



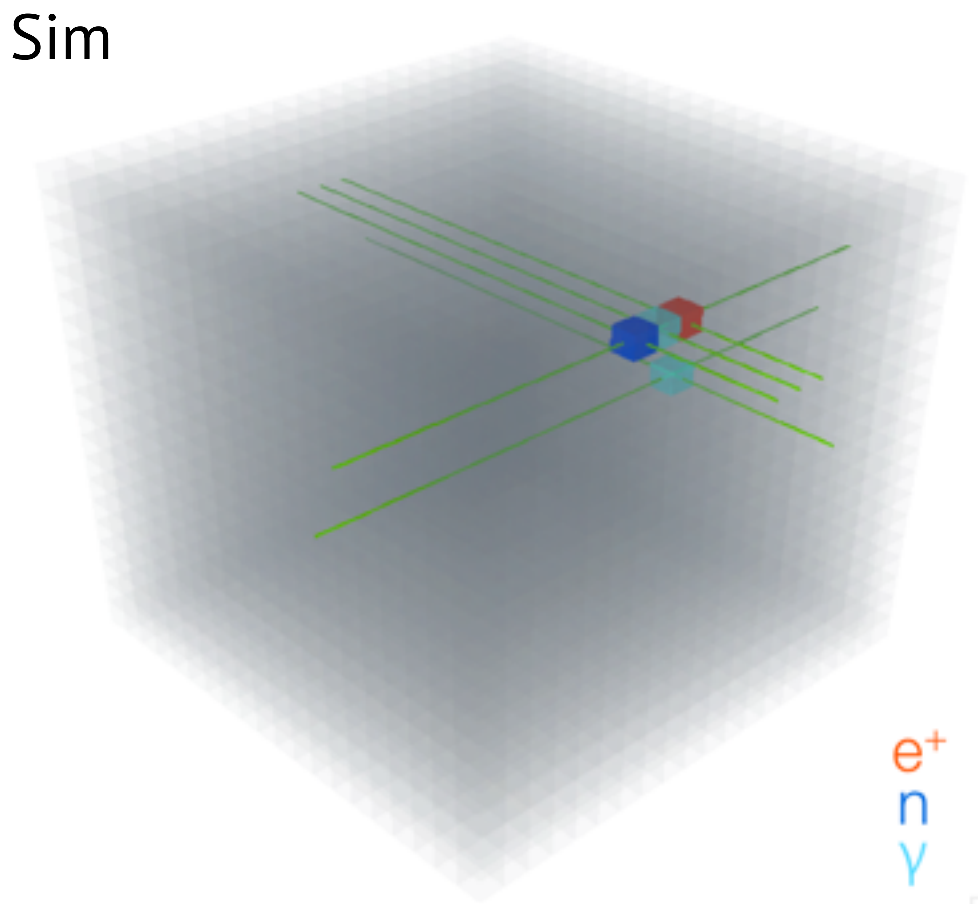
- composite /dual scintillator detector element :
  - 5 cm x 5 cm x 5 cm PVT cube segmentation to contain positron energy and localise interaction
  - Layer of LiF:ZnS(Ag) for neutron detection close to interaction

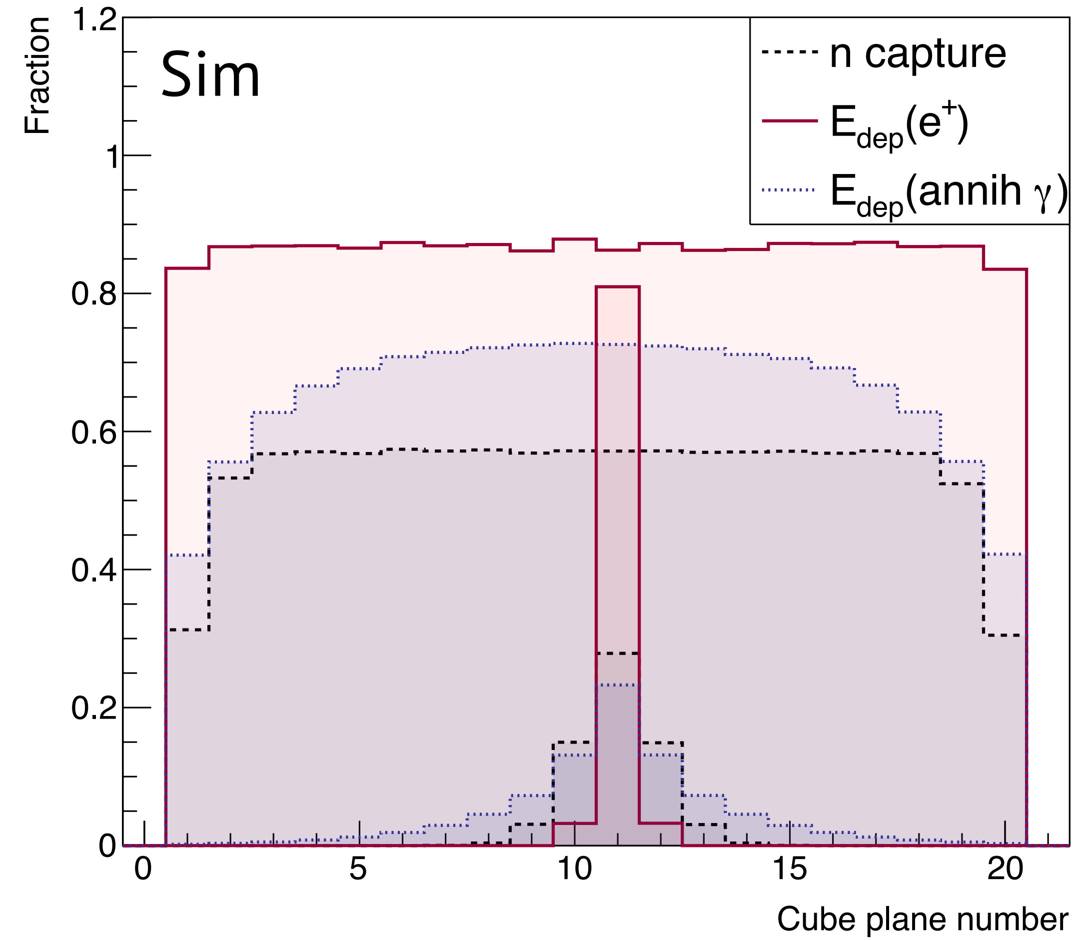


E_{tot} = 4.78 MeV

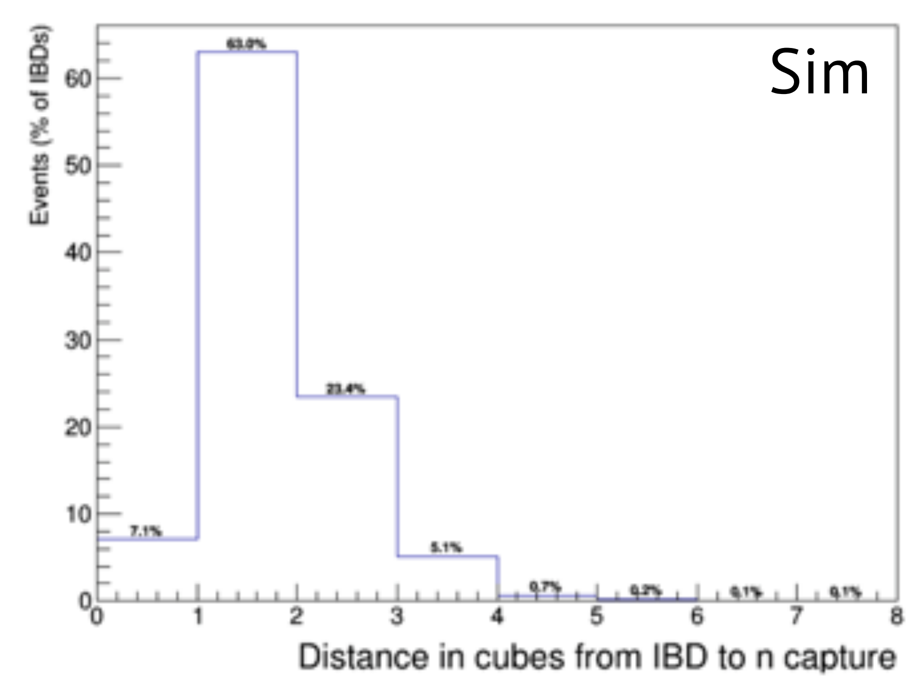
- WLS fibre to collect both scintillation light in X and Y direction
- each cube voxel optically separated from each other by reflective coating
- SiPM to read out fibre signal

Signal localisation

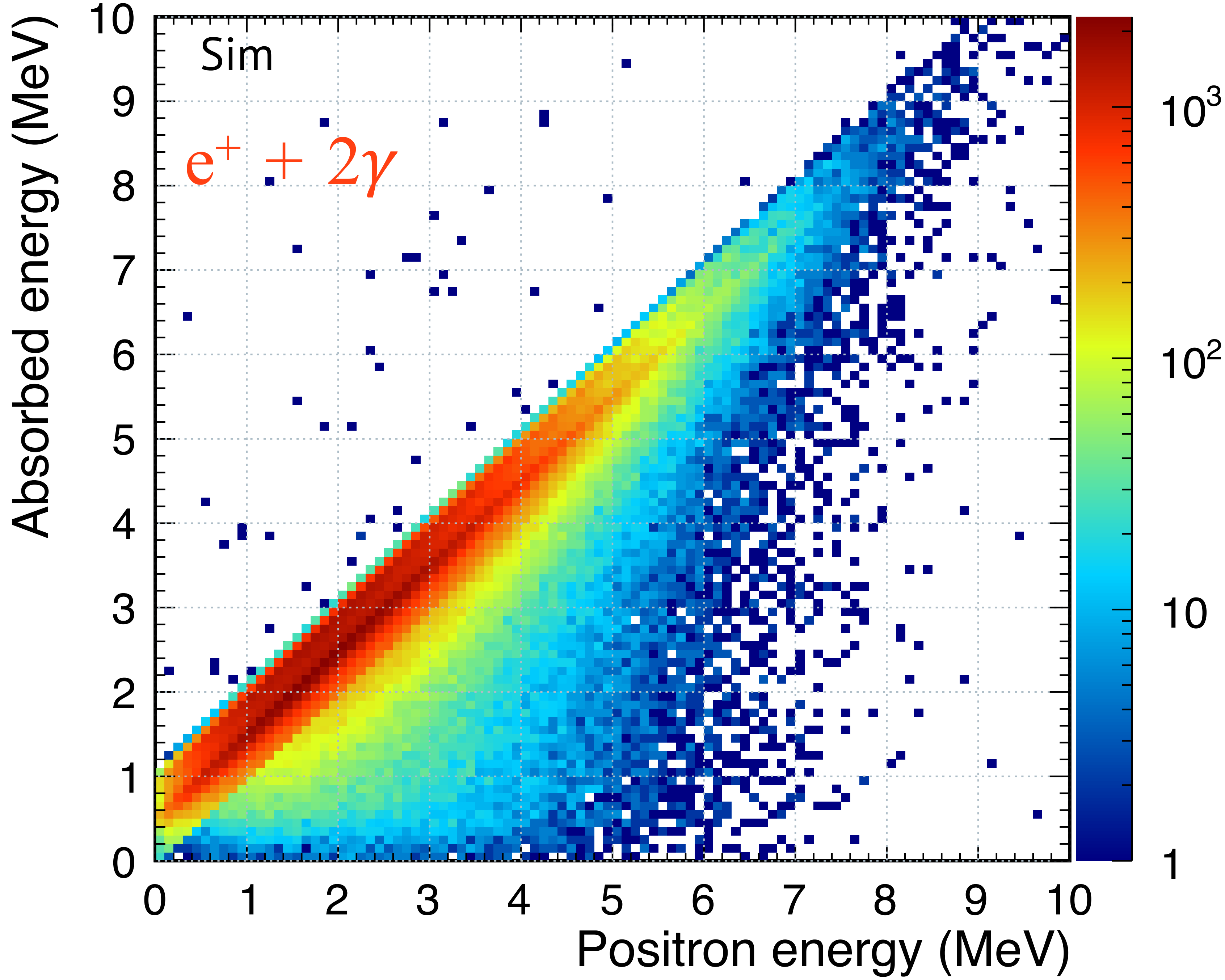




- Positron energy contained in cube voxel
- Neutron capture efficiency uniform up to the edge of the detector
- Neutron capture one cube away from interaction gives directional sensitivity

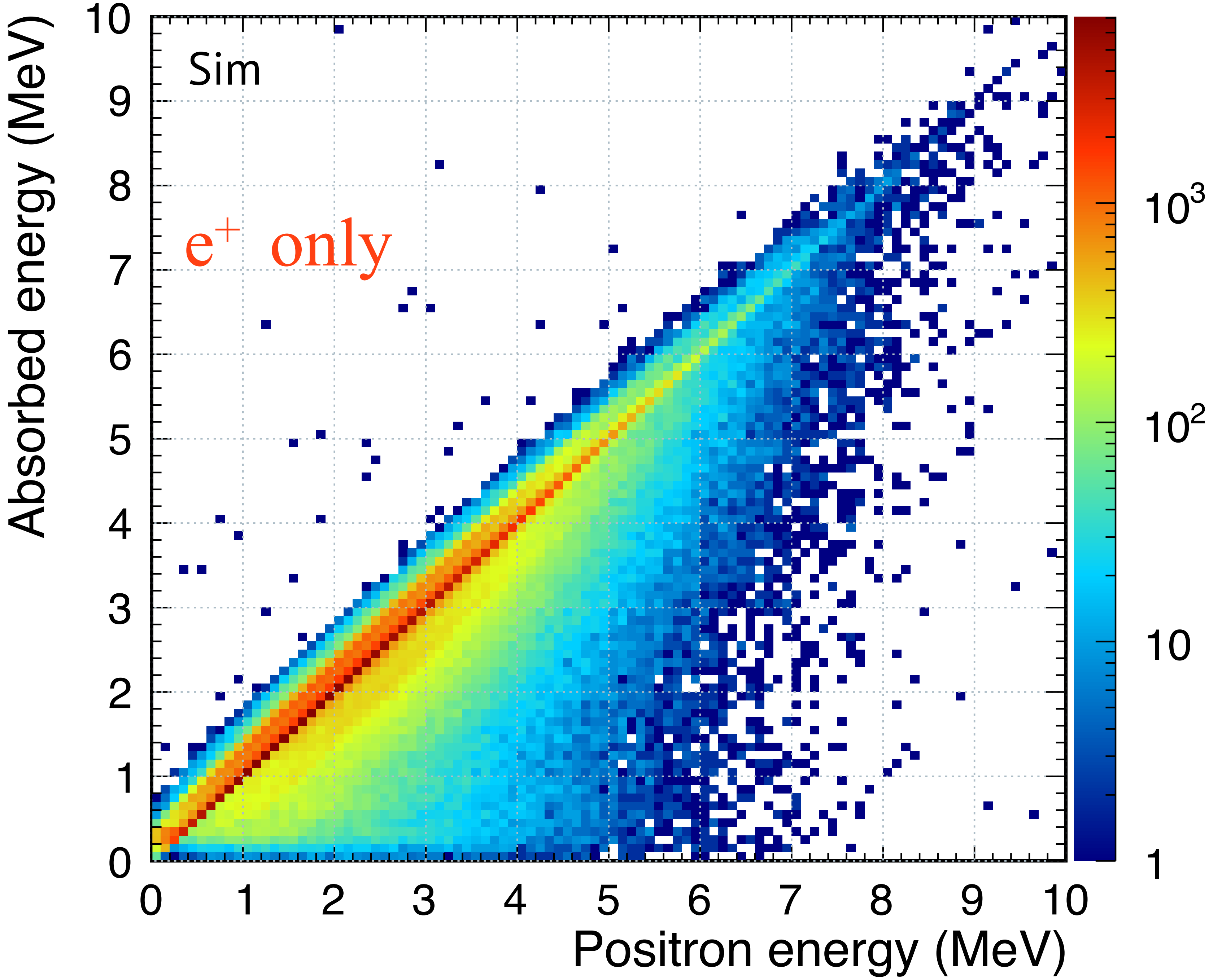


Visible energy reconstruction



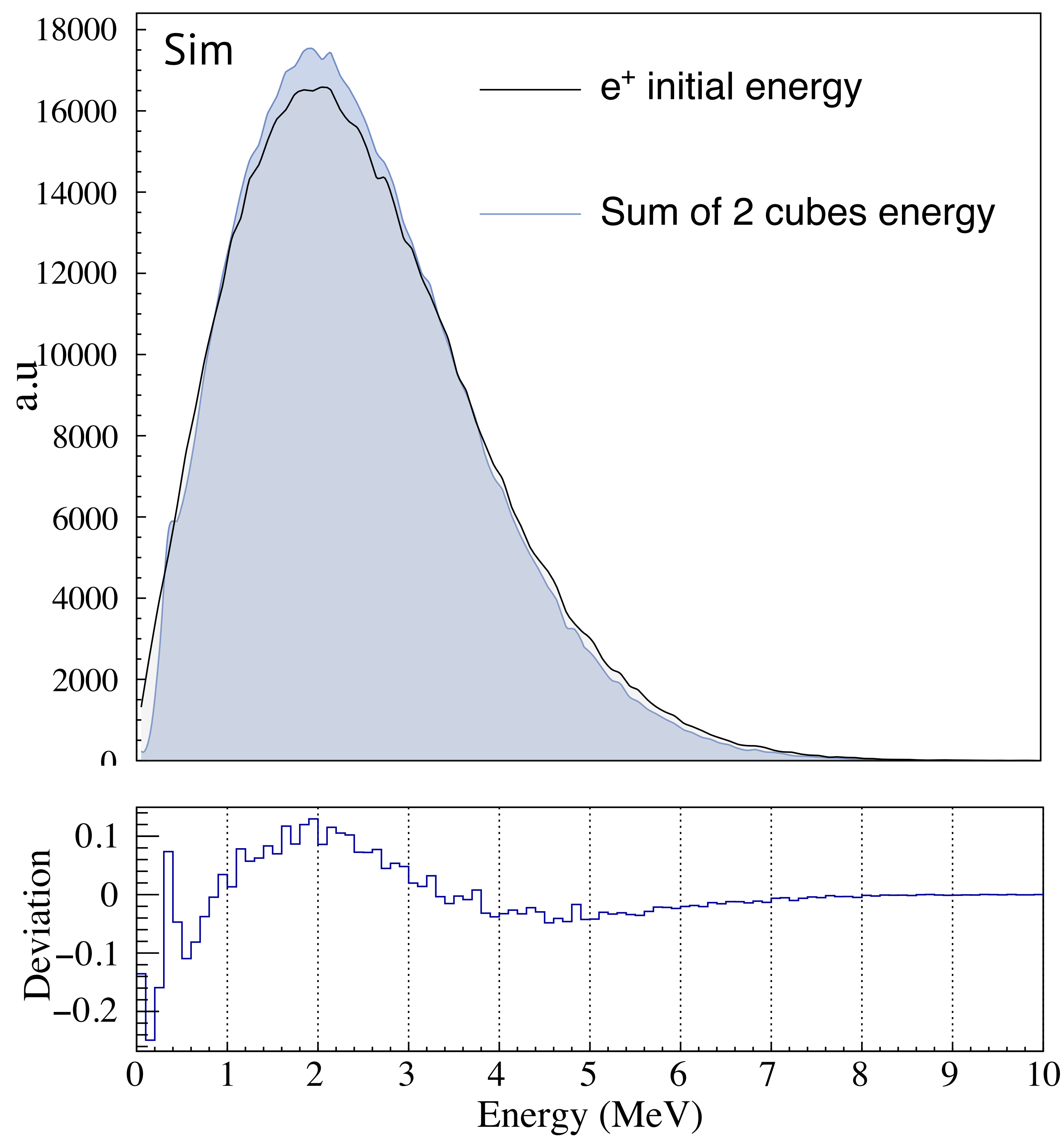
- Summing all energy visible in 1 m^3 detector
- gamma-ray leakage affects energy reconstruction

Visible energy reconstruction



- Energy estimation recovered by selecting two highest energy cube

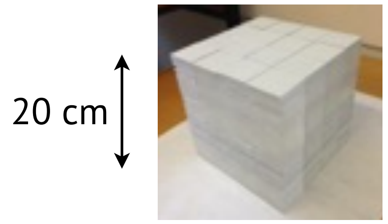
Energy reconstruction



Real scale system SM1

2010- 2013

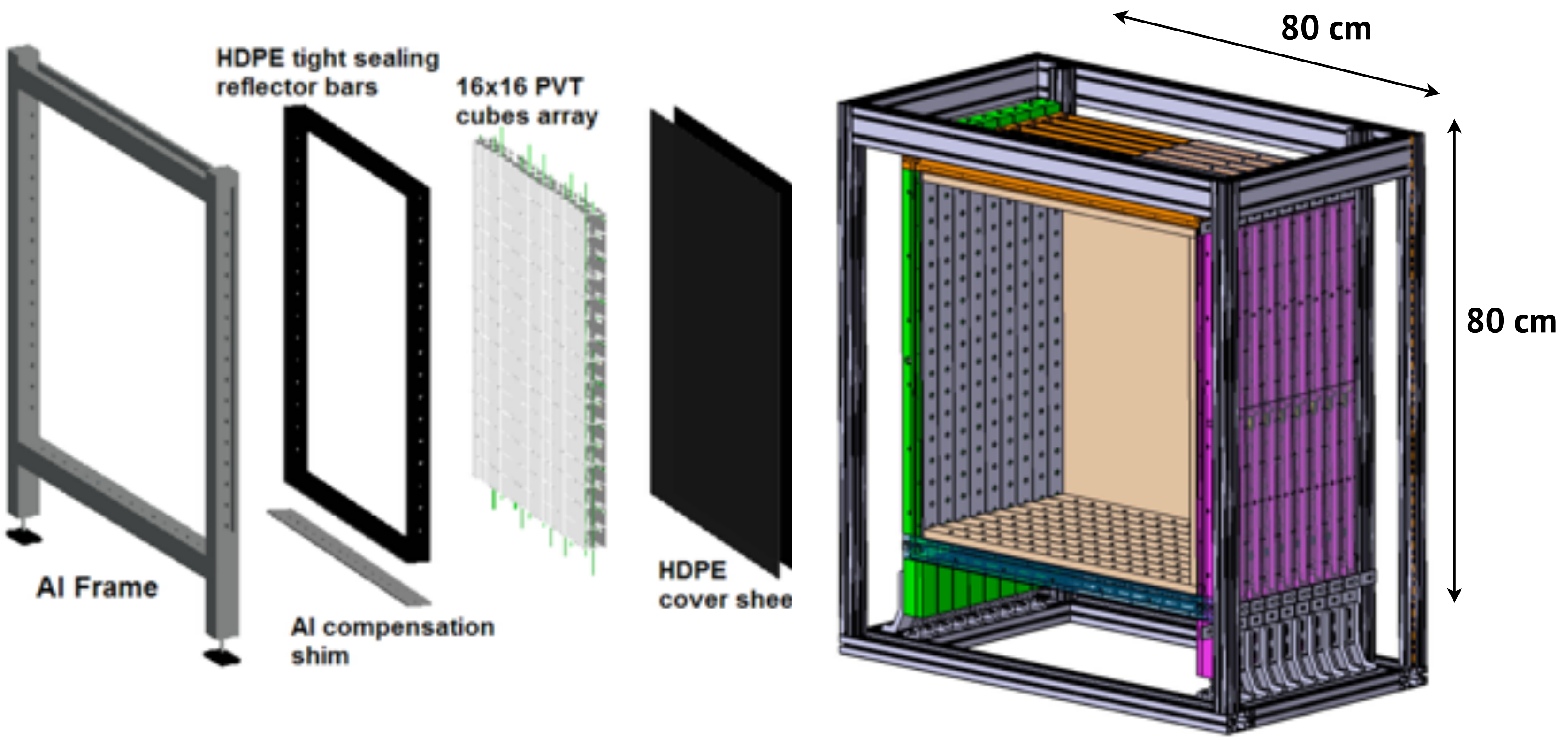
Proof of concept
and small prototype



36x

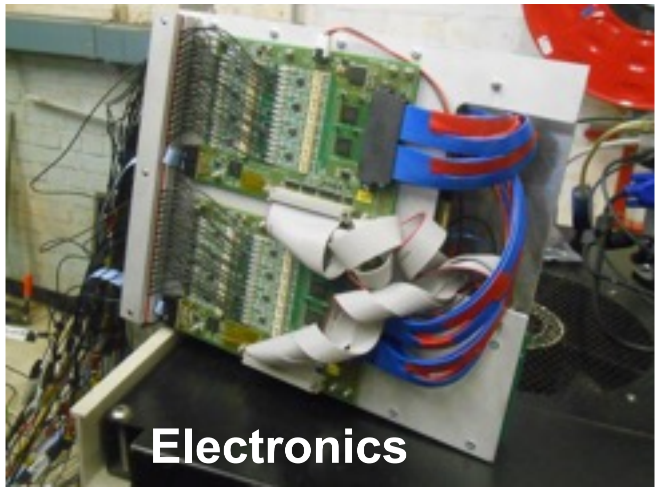
- NEMENIX **8kg**
64 voxels, 32 chan.

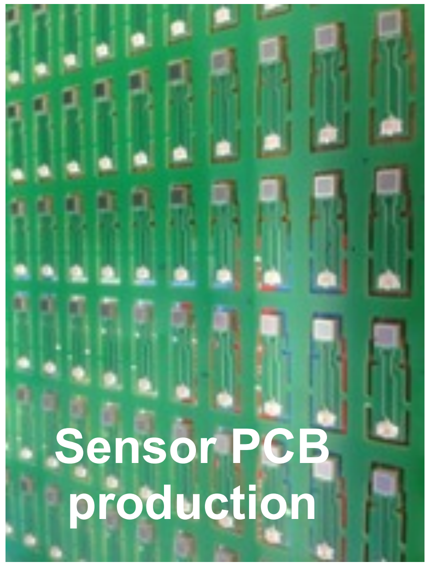
2014-2015

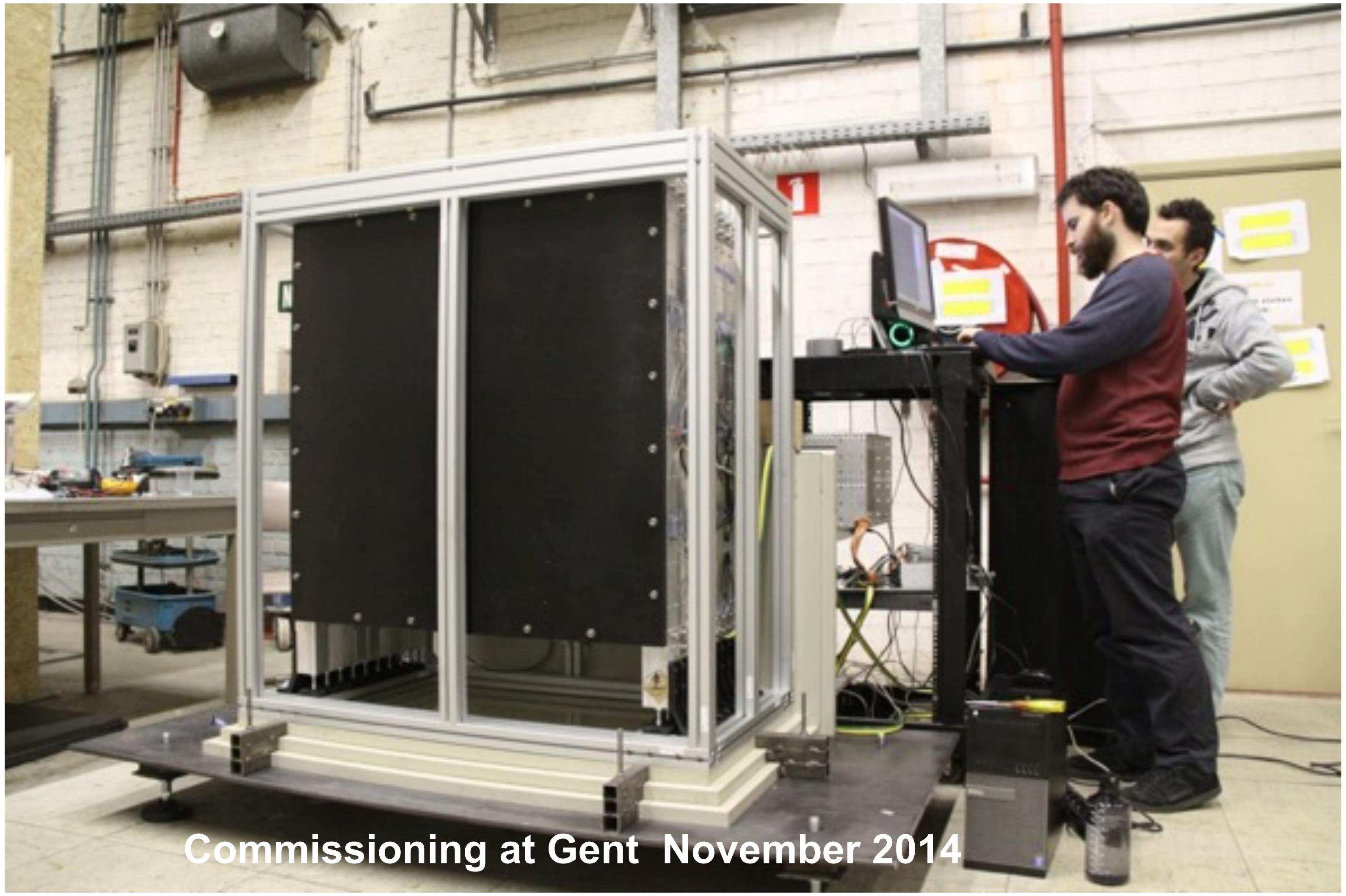


- SoLid Module 1 (SM1)
288kg
2 304 voxels, 288 chan.
9 detector planes

Learning how to build it

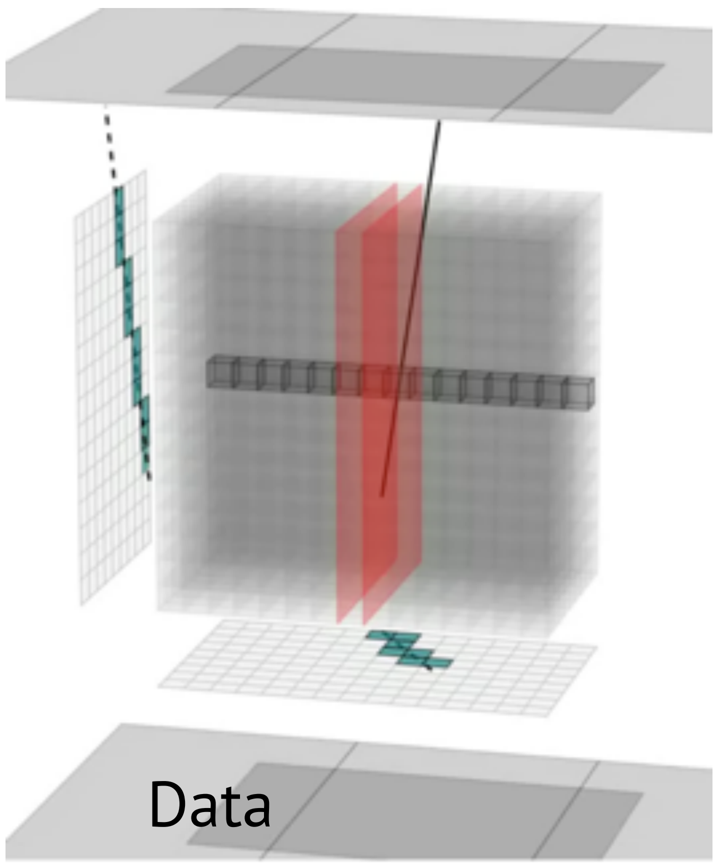


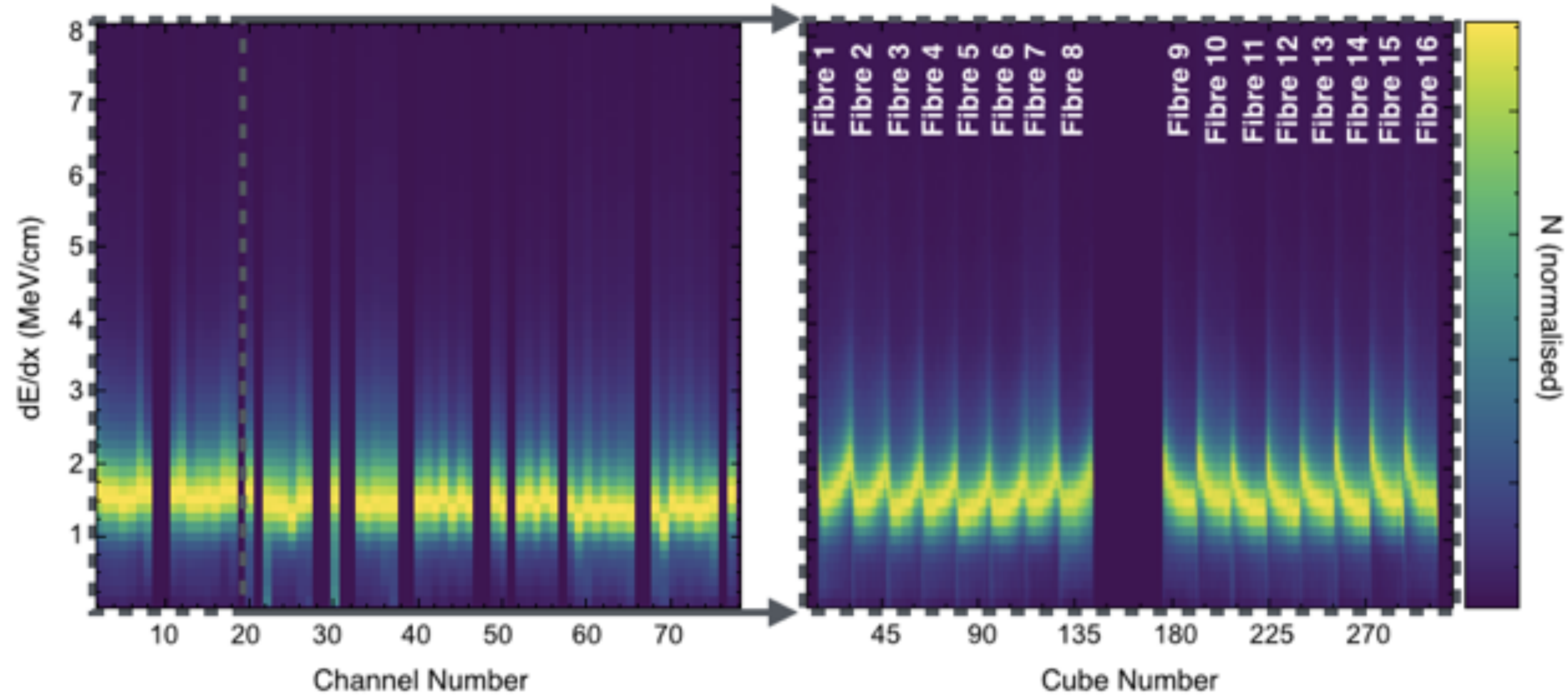


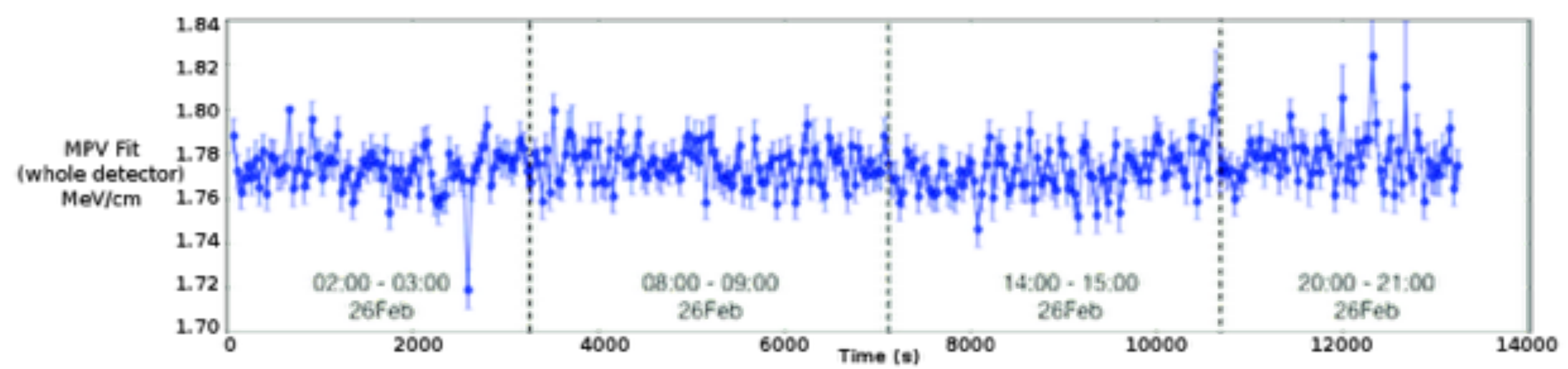


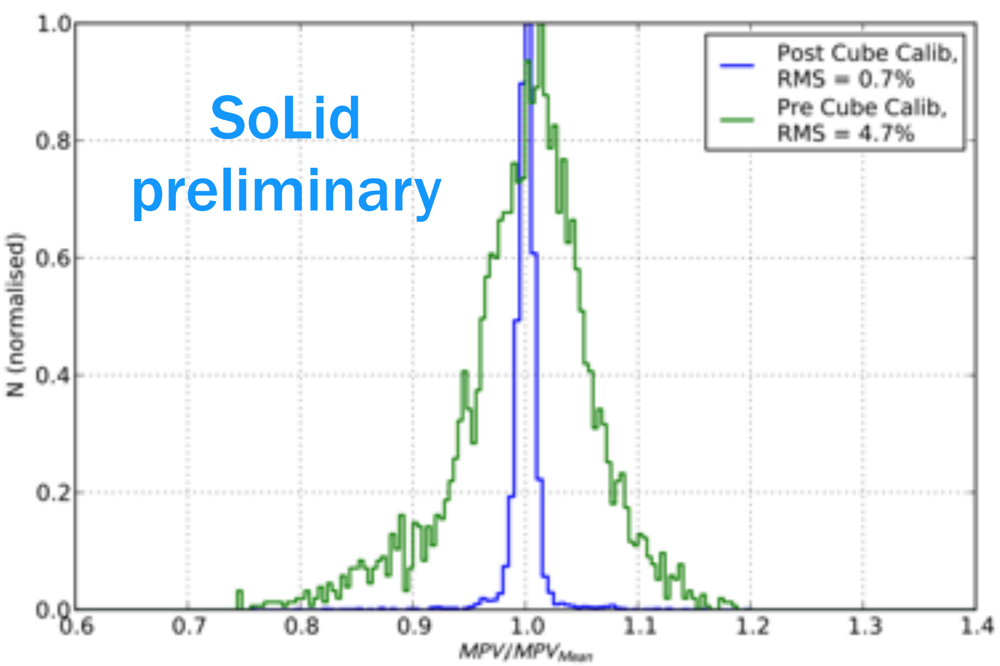
Deployment at BR2

Energy response calibration



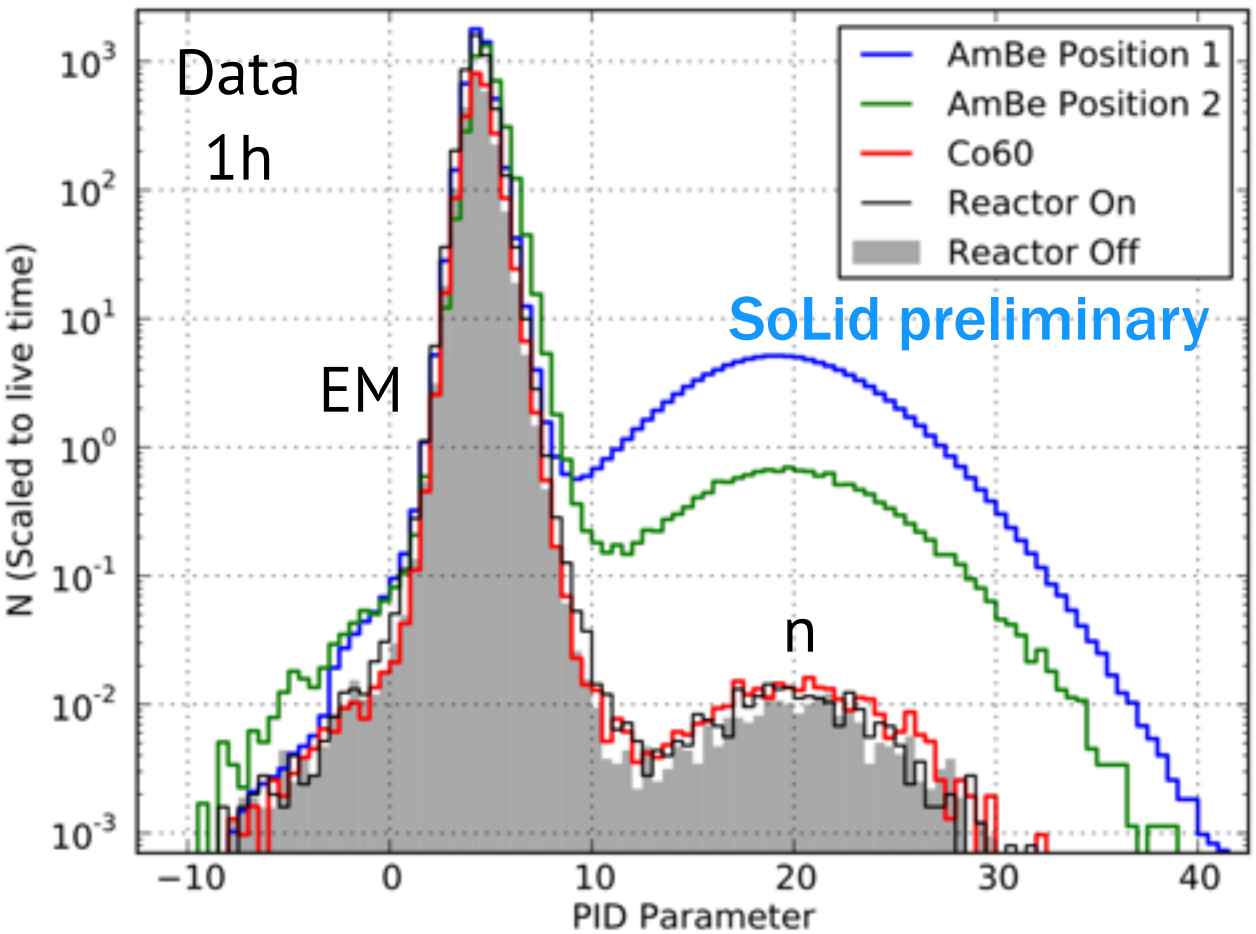


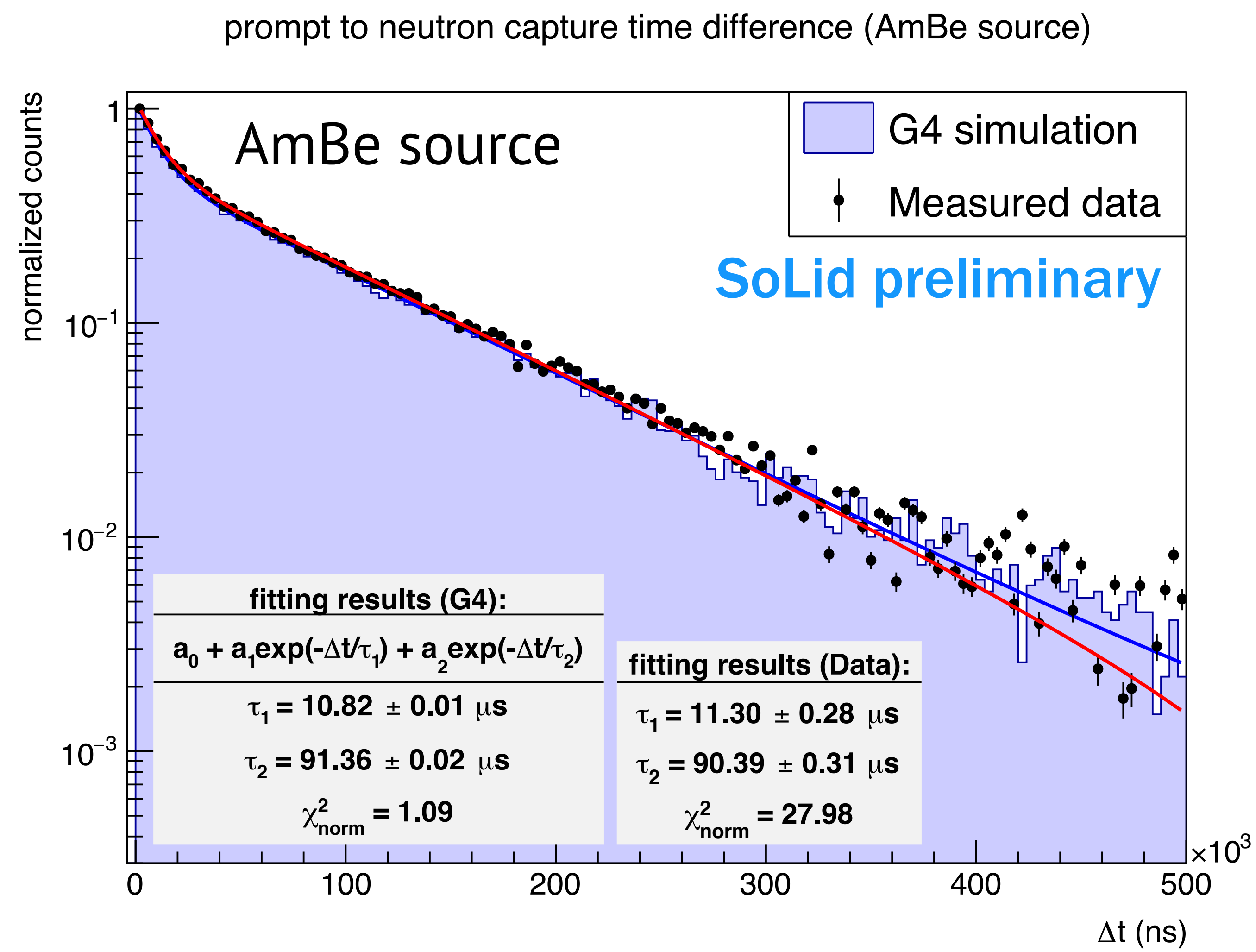




- PVT response intercalibrated using muons
- cube response equalised to better than 1% for majority of channels
- stability over time of energy scale ~ 1%

Neutron ID and capture time

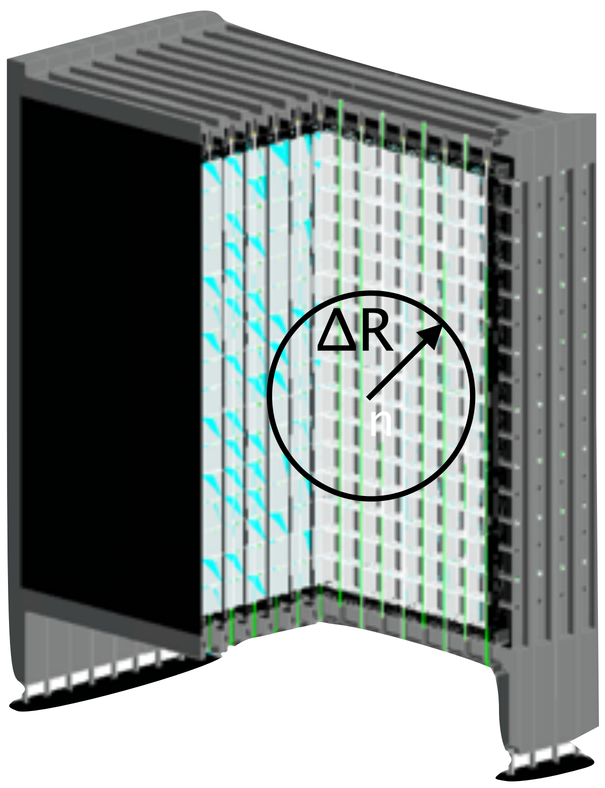


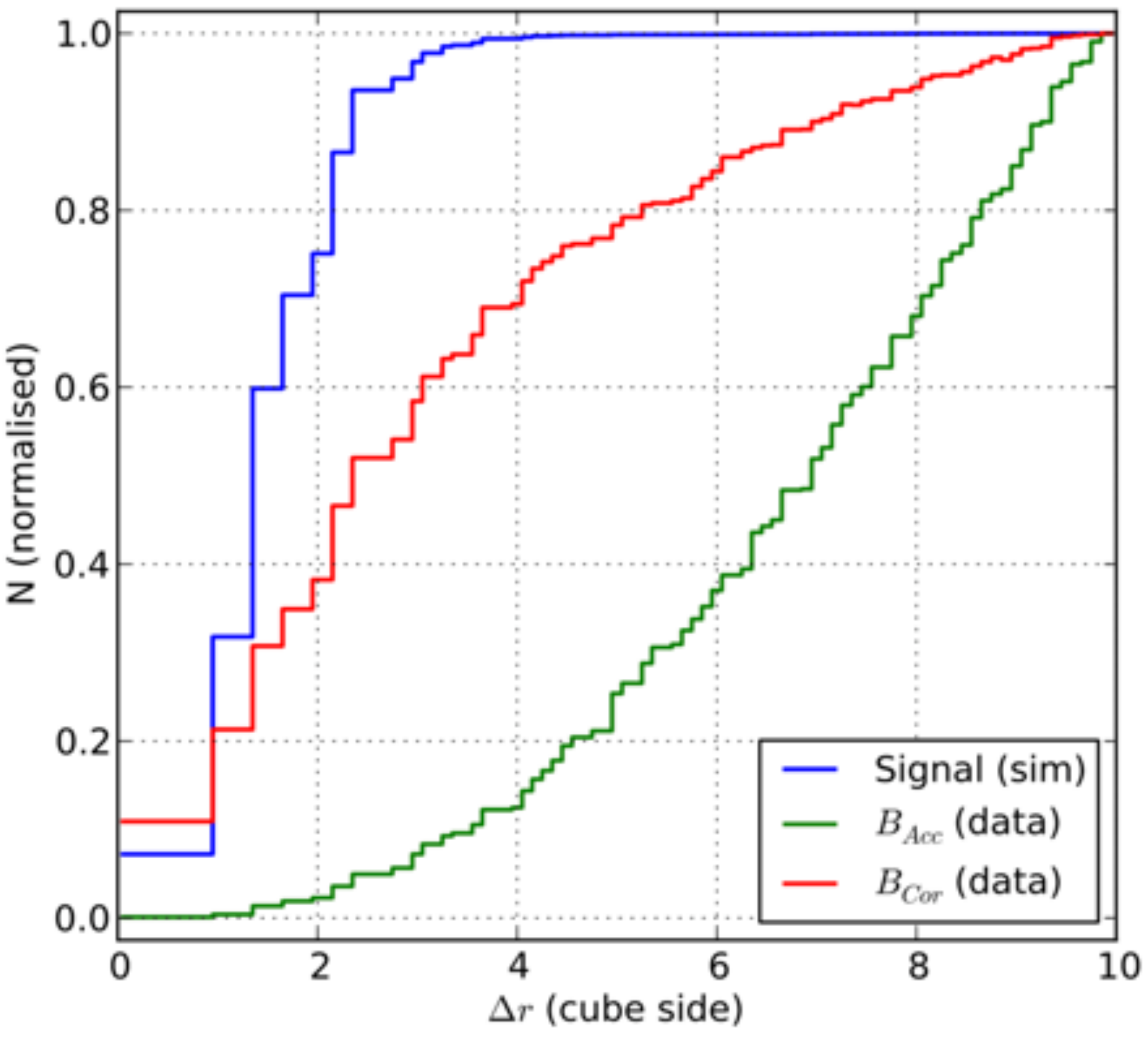


- Validated PID, neutron tranport simulation (MCNP & G4) and Li capture efficiency

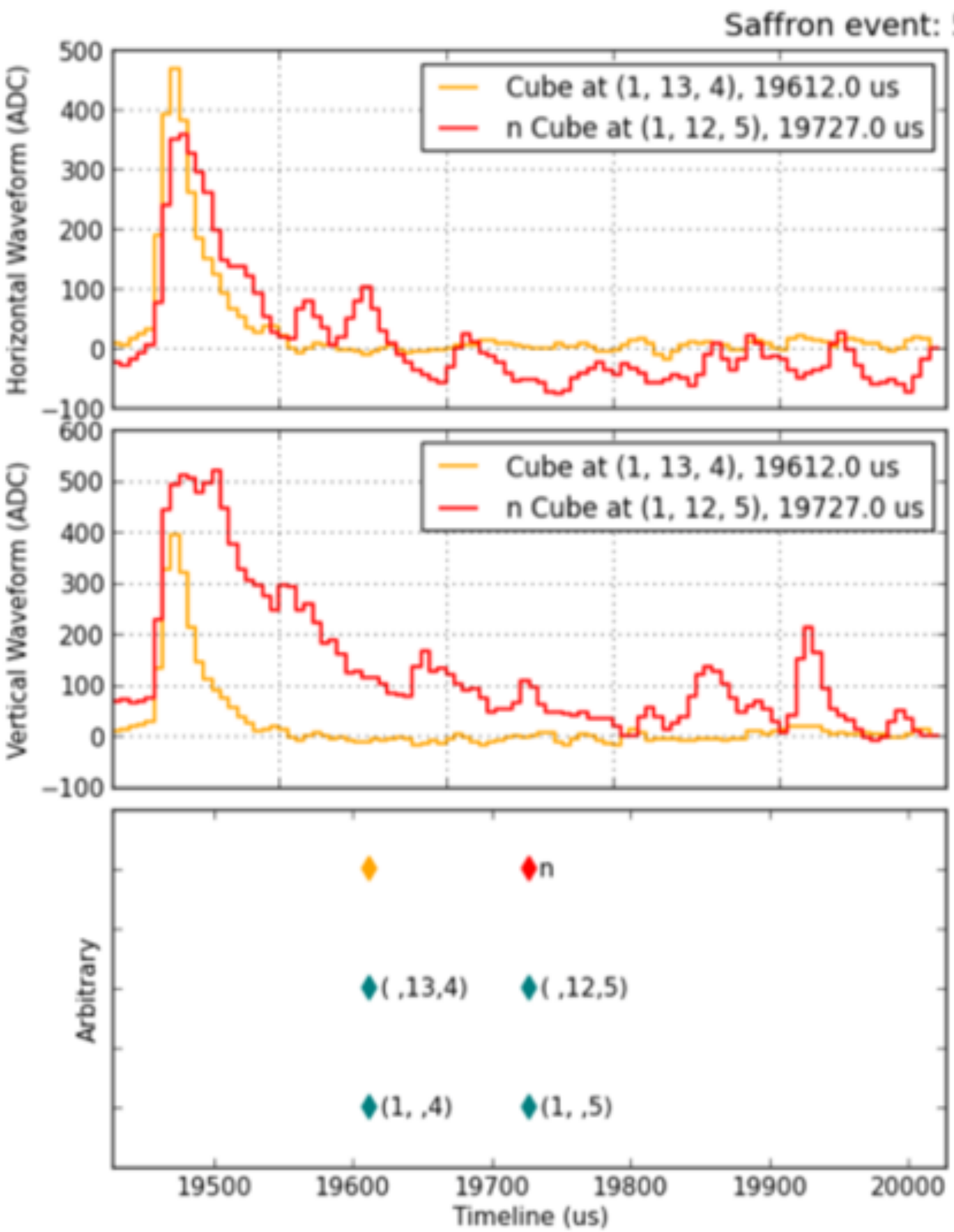
Signal analysis

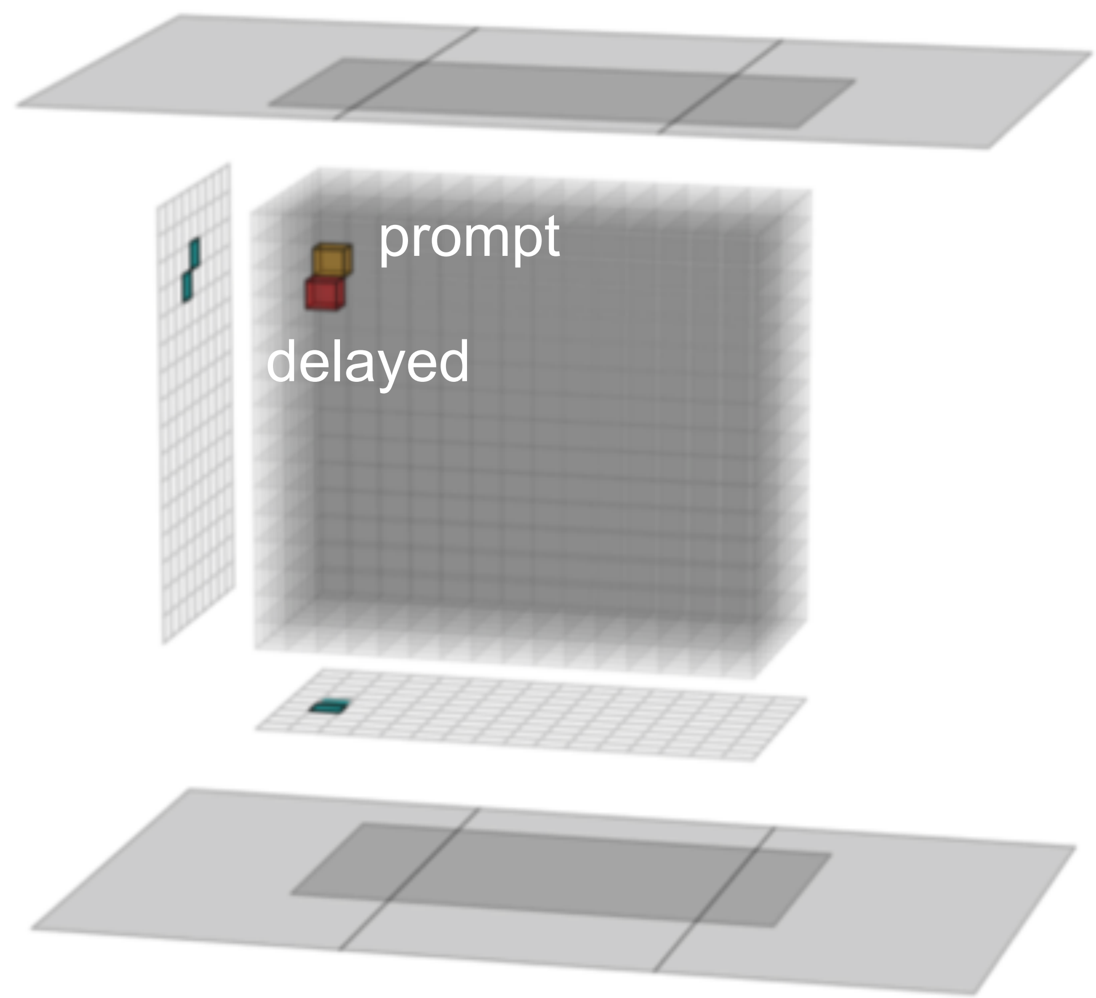
- Demonstrated power of segmentation on background rejection





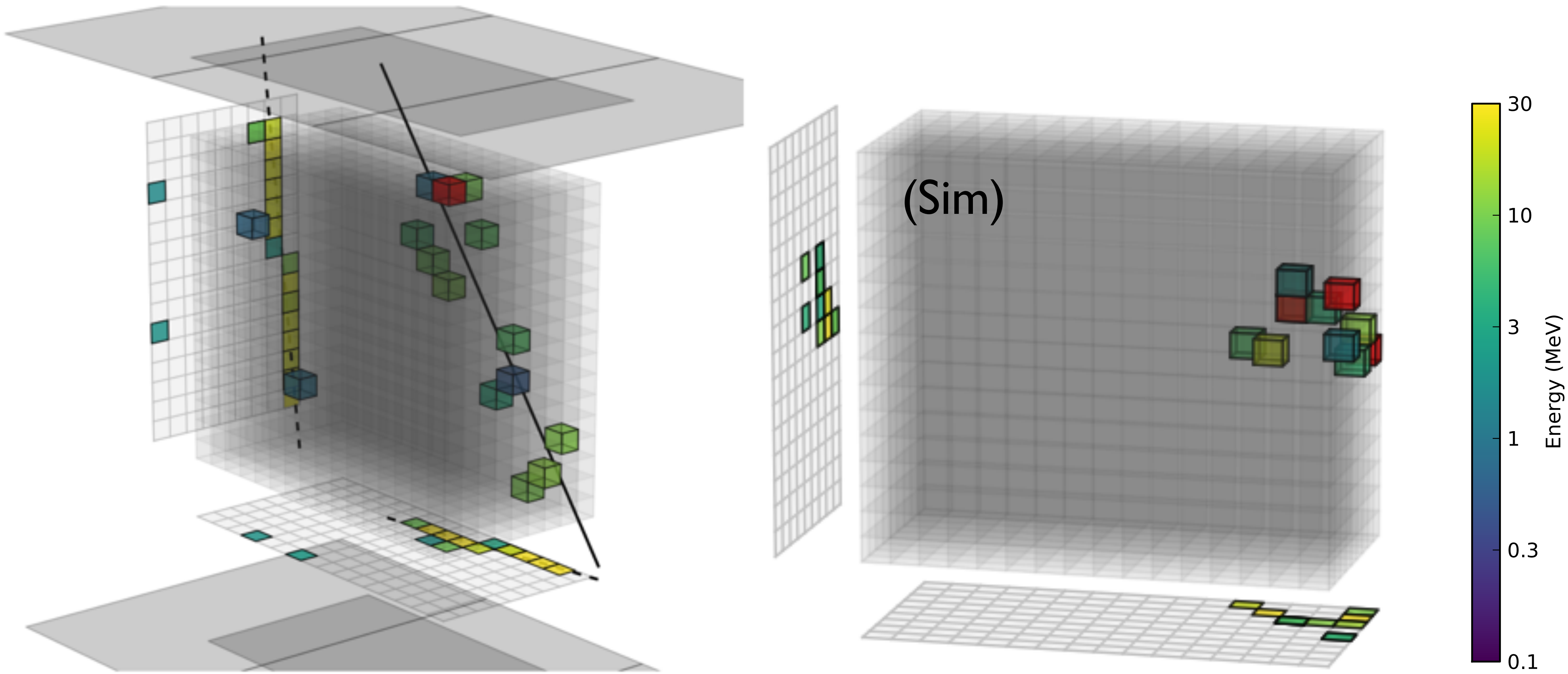
IBD candidate





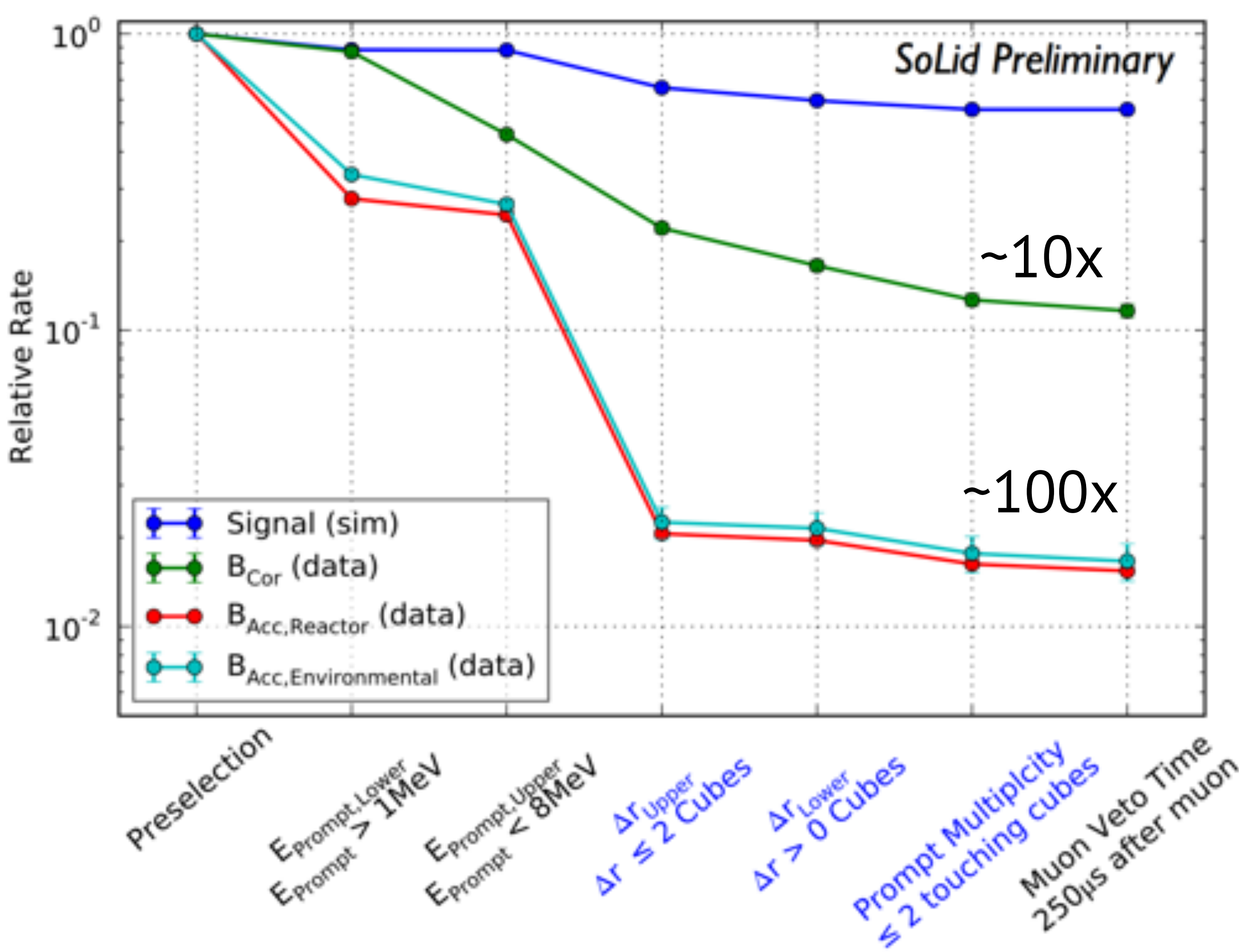
Data

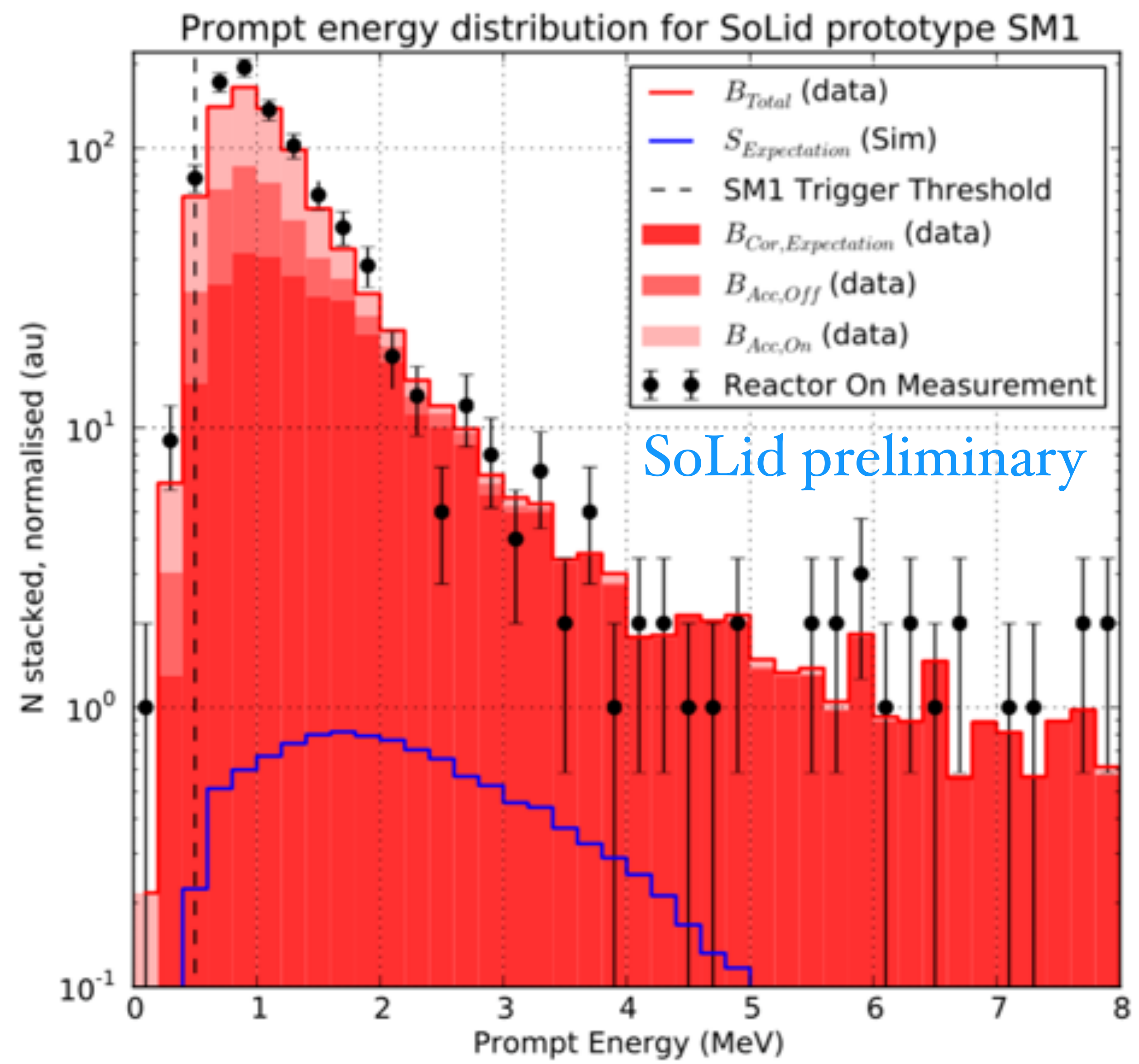
Background events



Signal analysis

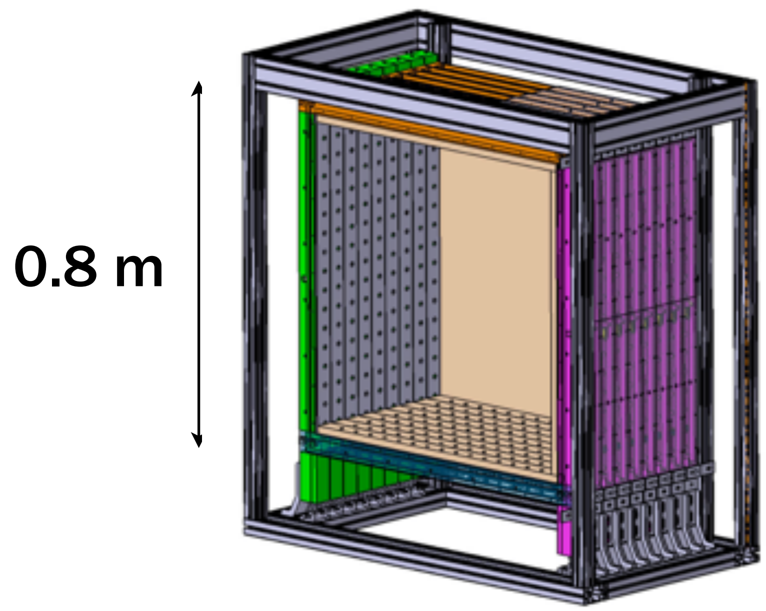
- Demonstrated power of segmentation on background rejection
- but SM1 had limited shielding and lower absolute neutron efficiency of ~ 2.5% due to high data rate





Scaling up to full mass

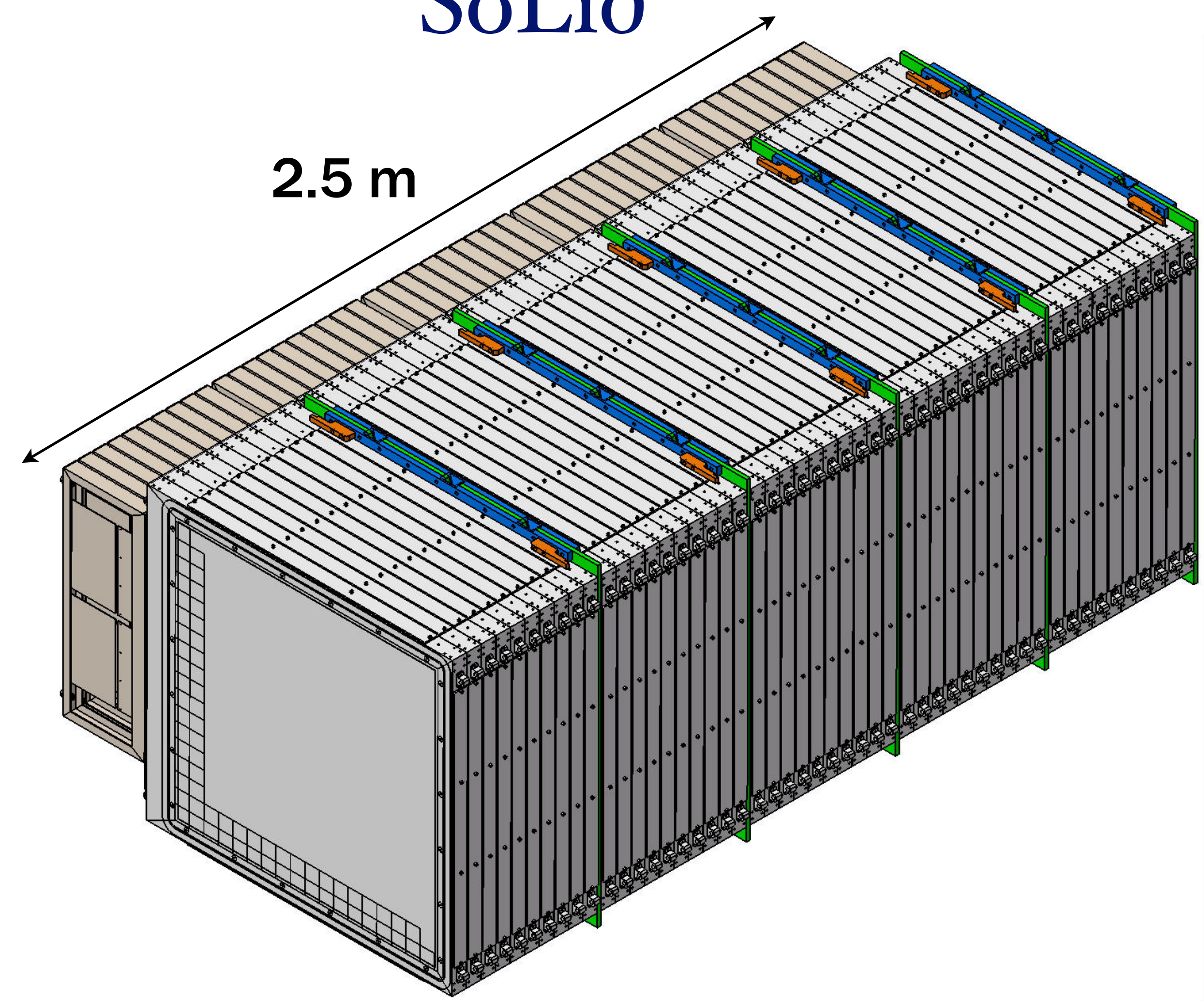
2014-2015



5x

Phase-I 2016-2017

SoLid



- SoLid Module 1 (SM1)
  288kg
  2 304 voxels, 288 chan.
  9 Detector planes
  limited performance
  data rate 0.45 TB/day

- 5-6x modules **1.6-2 tonnes**
  12 000 voxels,
  3 200 read out channels
  high performance
  data rate max 0.5 TB/day

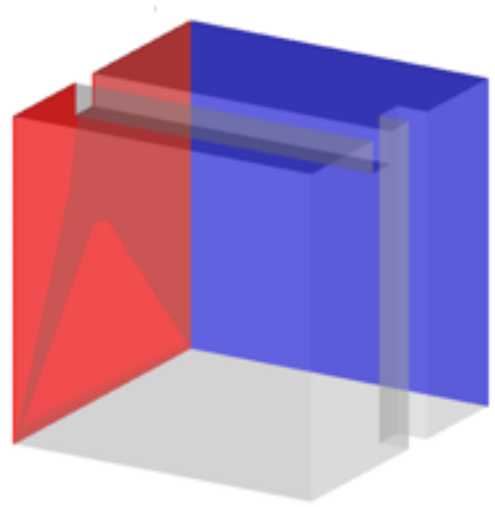
Improvements for SoLid

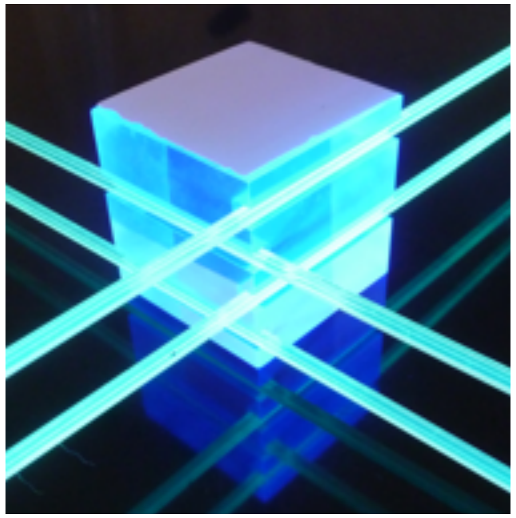
Neutron capture efficiency

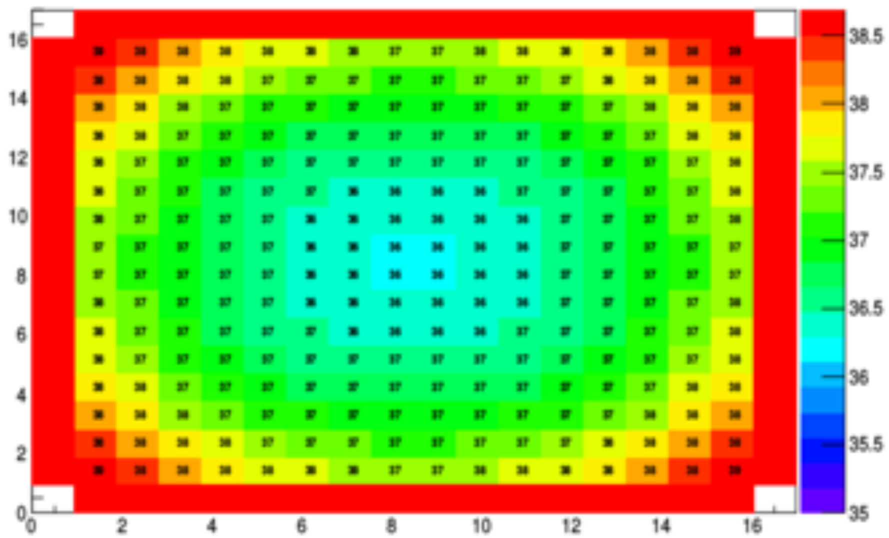
- Additional LiF:ZnS sheets
  - ^{6}**Li** capture efficiency 0.55 to 0.7 **+30%**
  - Reduced capture time **105 to 66** us
- new screens with **improved transparency**

Light yield and uniformity of response

- 4 fibre read out
  - 37 PA/cube/MeV **+66%** increase in light yield from SM1
  - on target for **14%/sqrt(E)** resolution
- **7%** total variation of light yield across detector planes

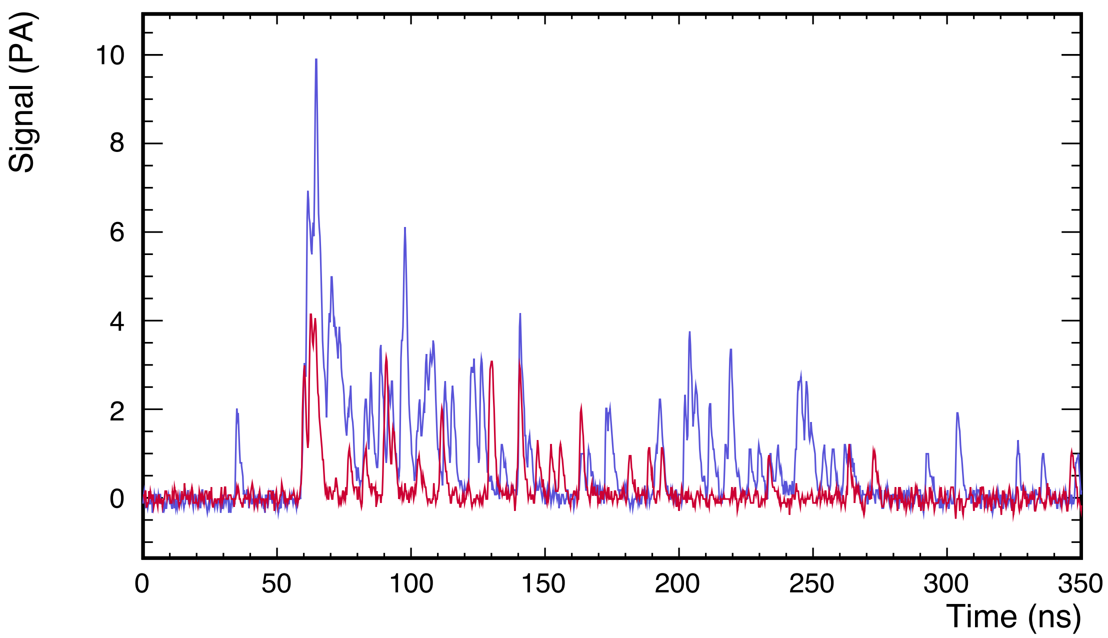


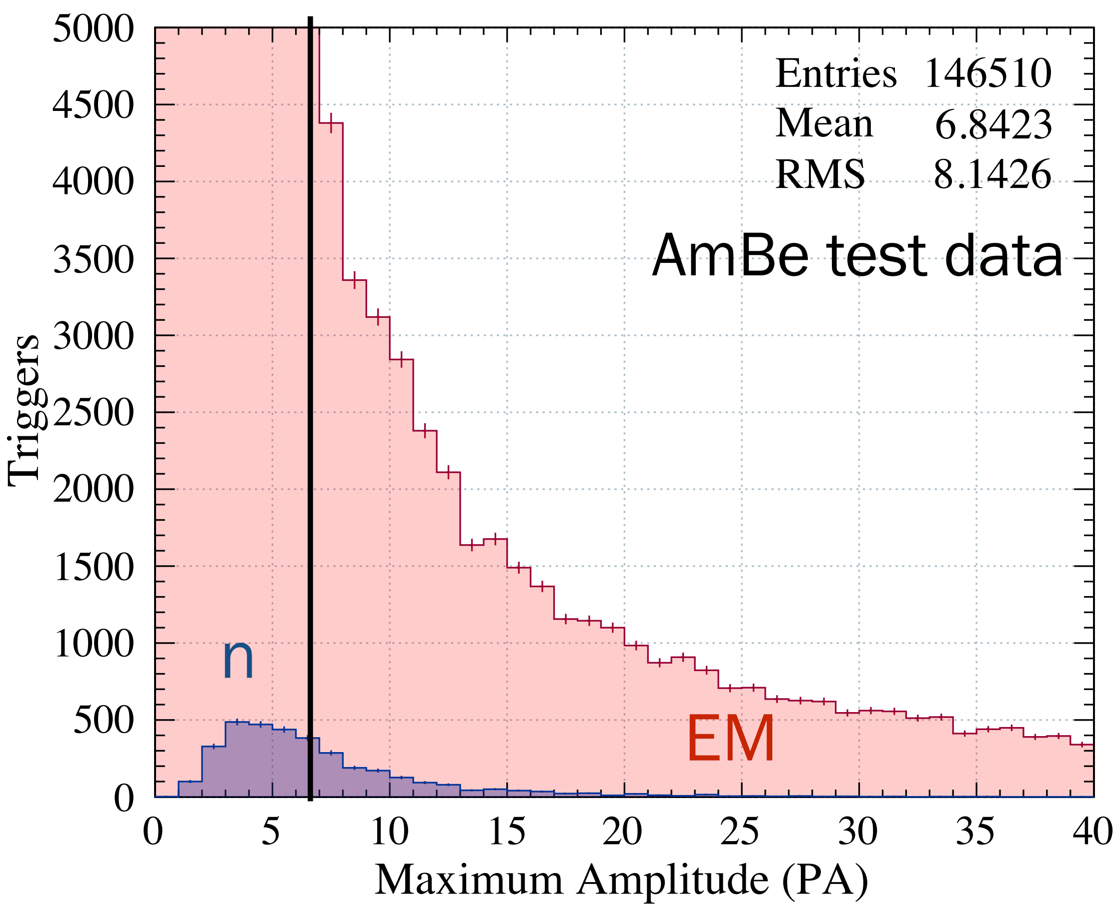




Average PA/cube = 37.2

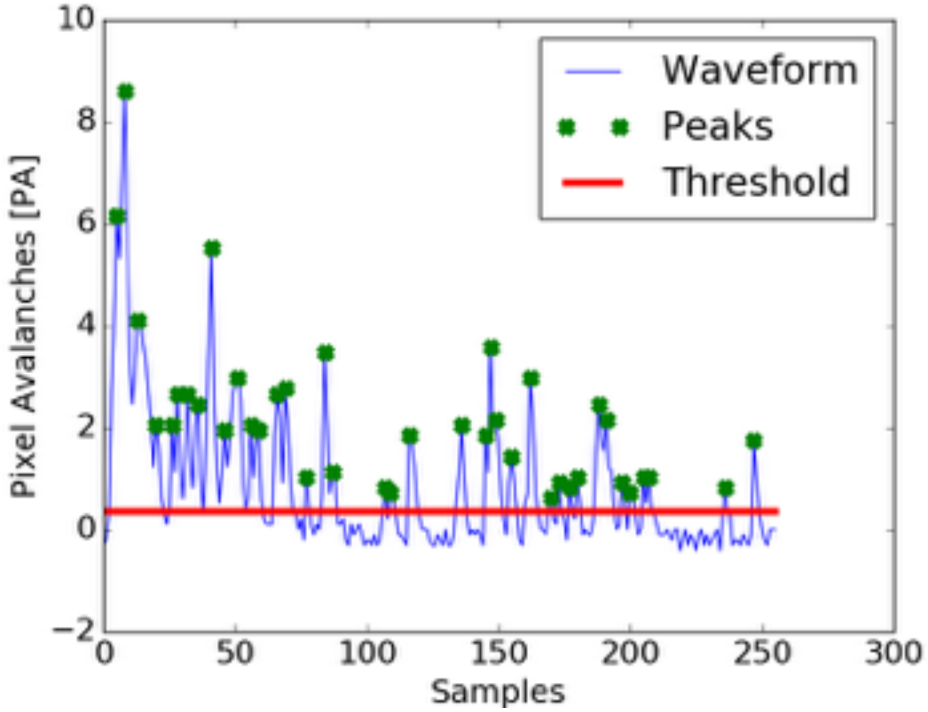
Trigger and efficiency

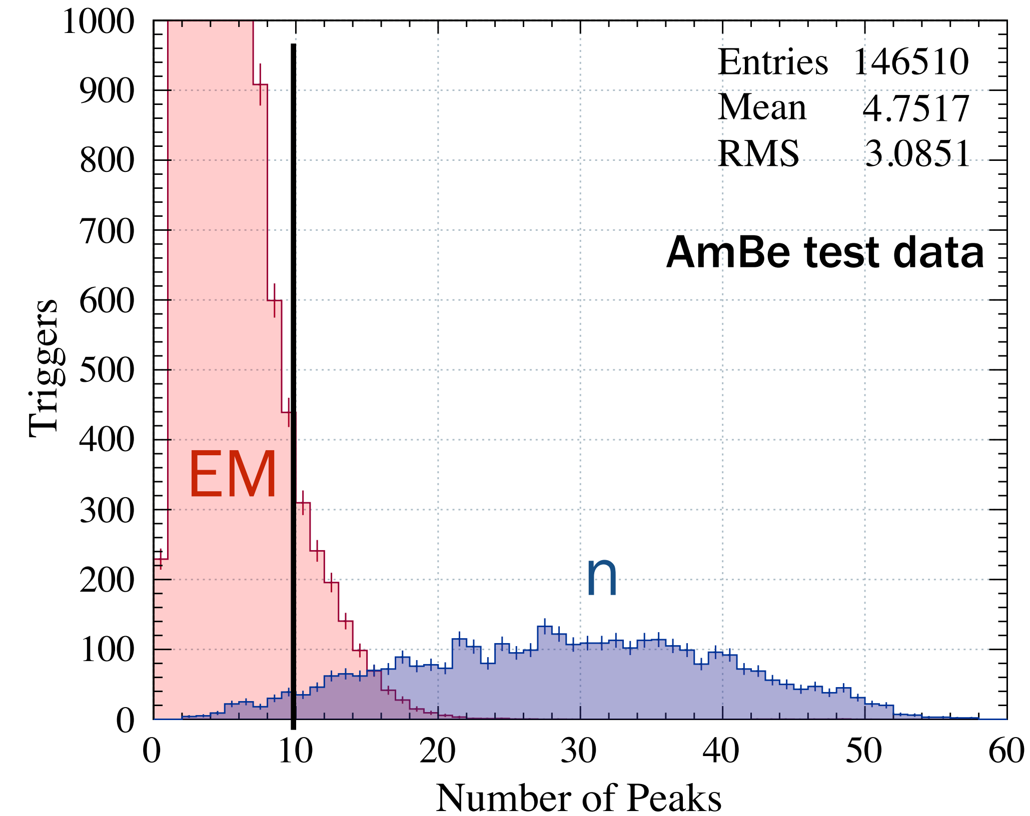




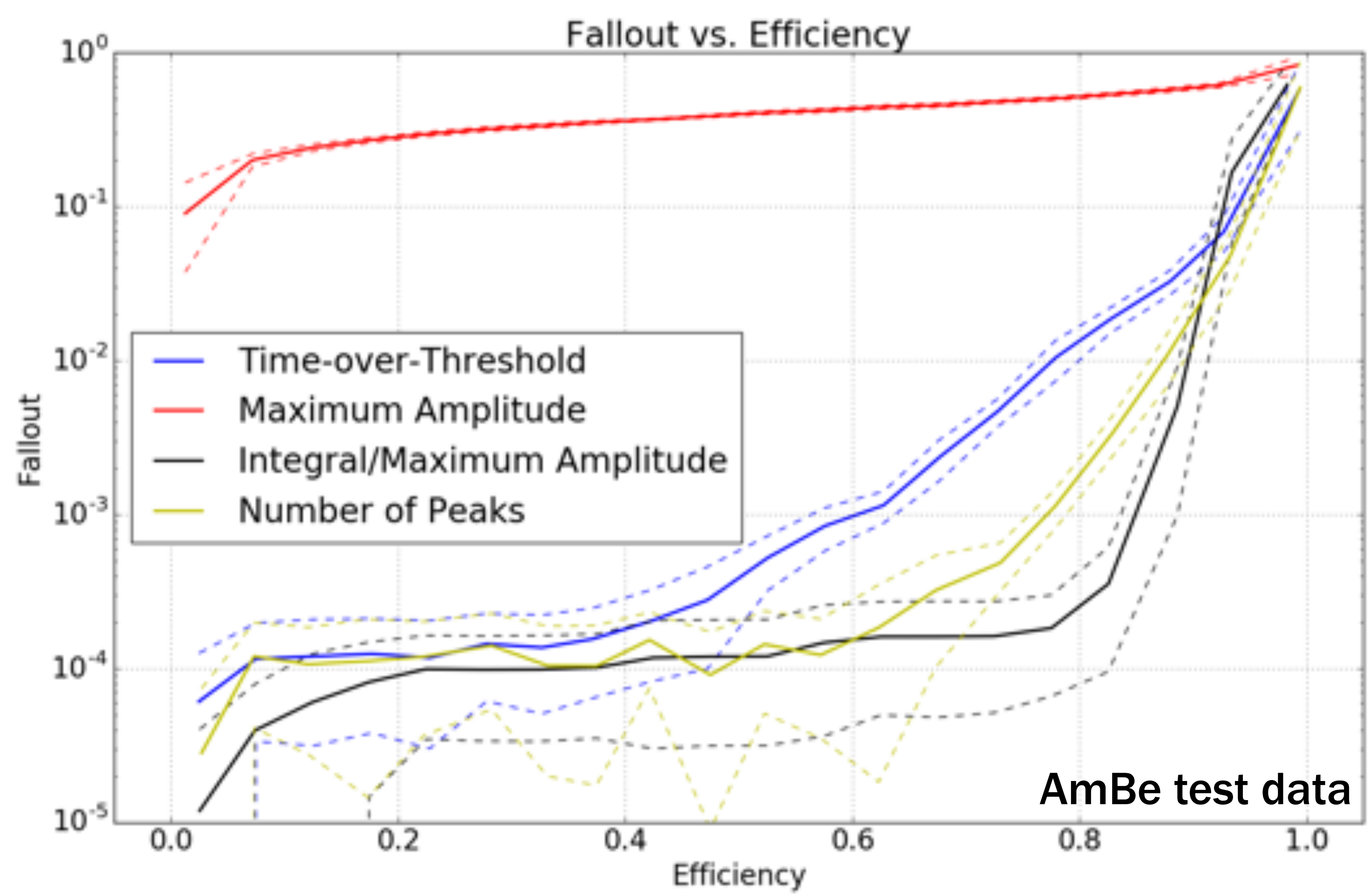
- Neutron signal : large number of photons but distributed in time and large range of light output
  - in SM1 direct threshold had to be set to 6.5 PA to limit data rate and required two channel in coincidence
  - **reduced neutron detection efficiency to 5%**
- Neutron trigger implementation
  - limit reactor ON/OFF data sizes and rate
  - maximise neutron and IBD efficiency
  - reduce rate dependence to threshold

Neutron trigger and data size

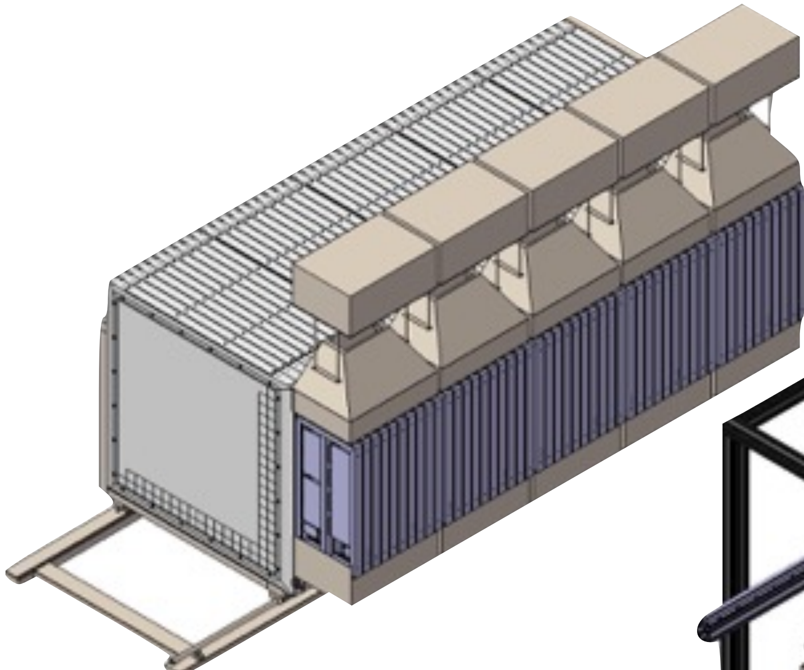




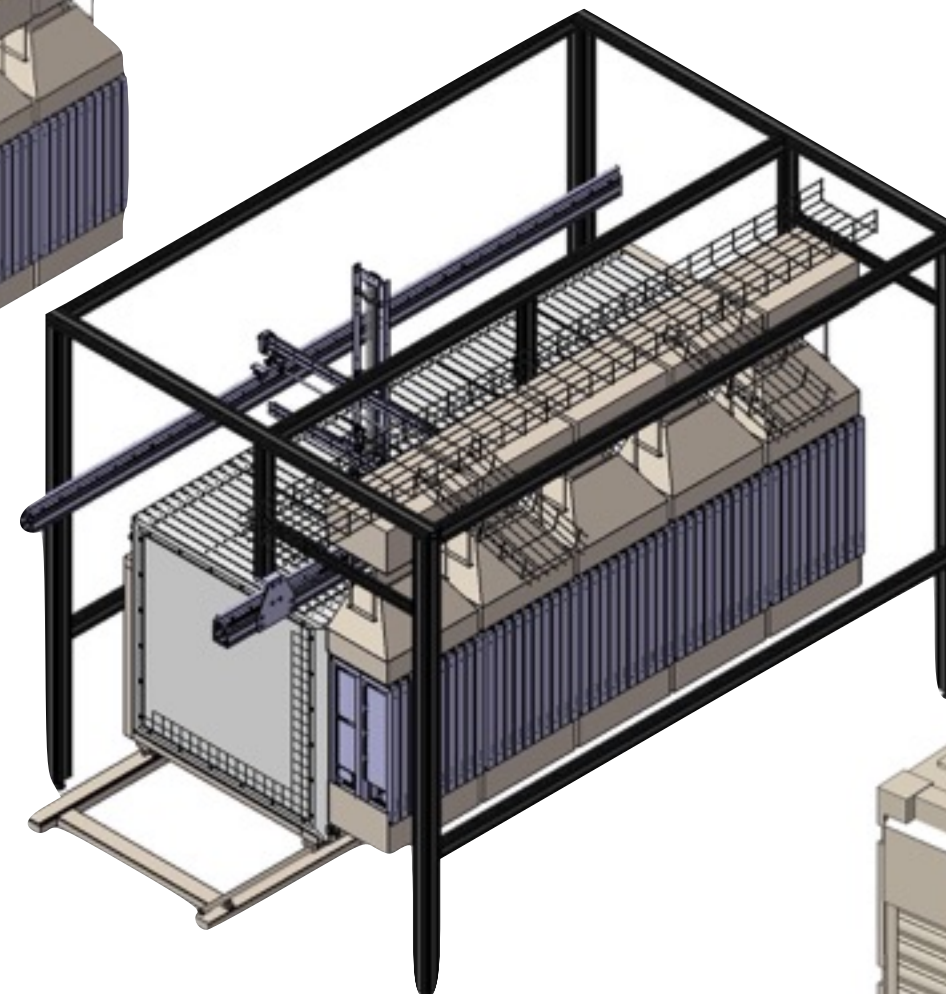
- **Neutron pattern recognition in firmware**
  - neutron rate is low: Rn ~ 7 Hz
- Buffer time ±500 us and ±2 planes around neutron
  - **can recover neutron detection efficiency from 5% to 70% !**
- remove inefficiencies of forming coincidence
- **Zero suppression** threshold at 1.5 PA applied to other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



SoLid detector integration

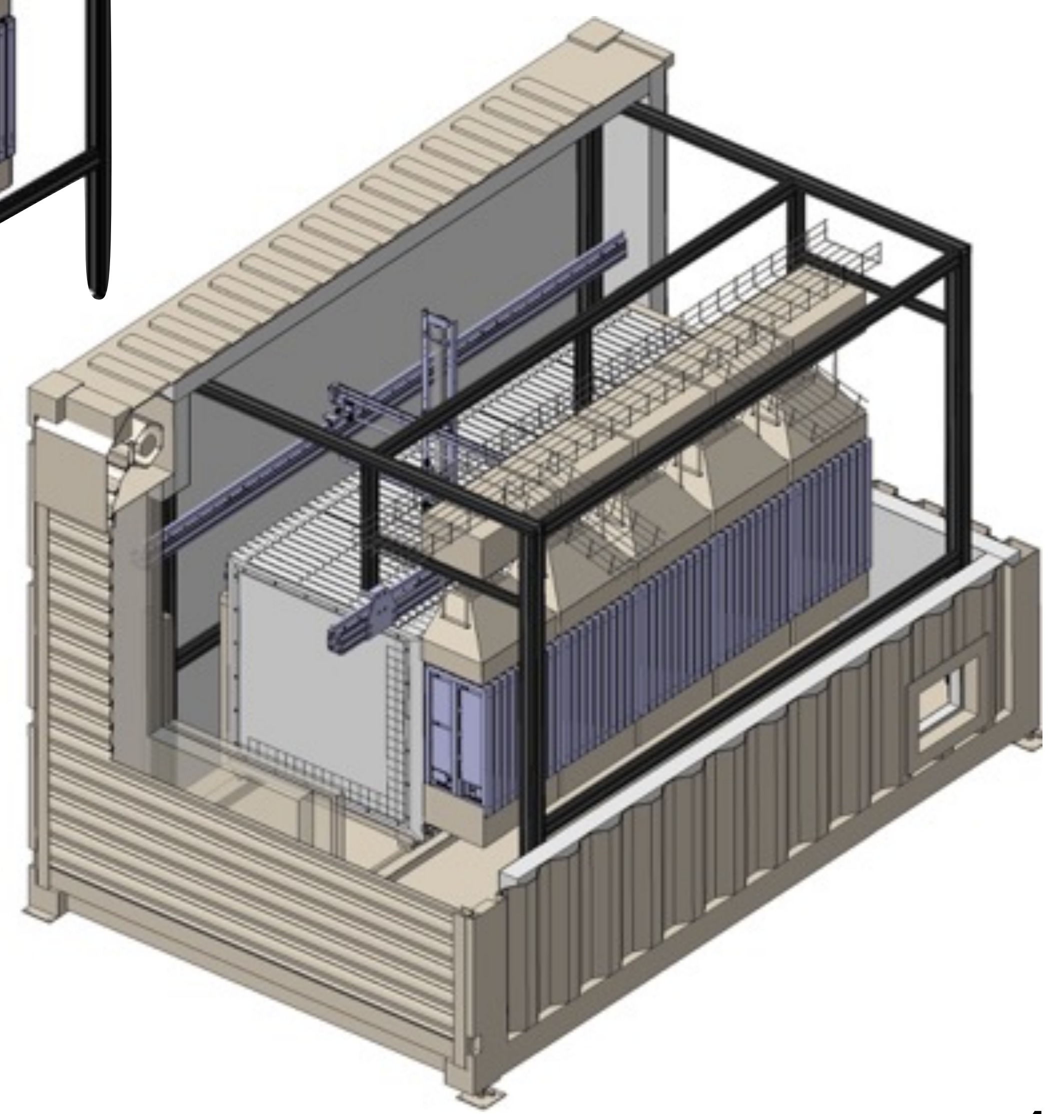


5 modules with
electronics and cooling



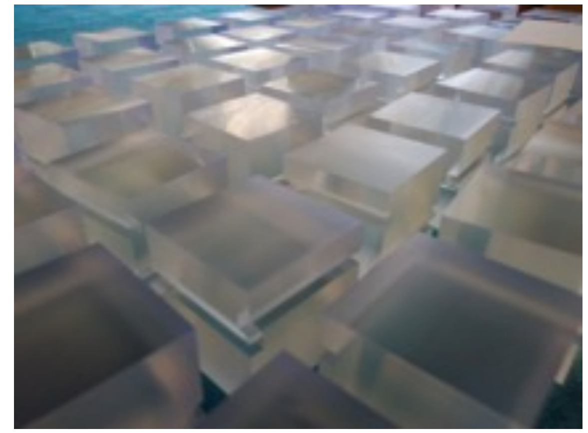
CROSS calibration robot
precision calibration
automated procedure

SoLid detector in cooling
container

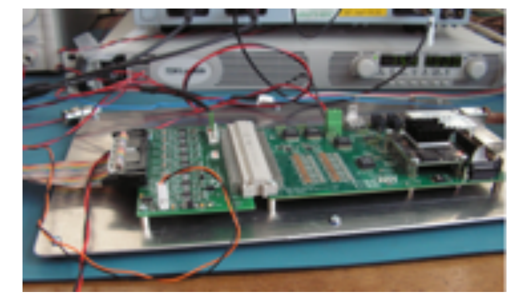
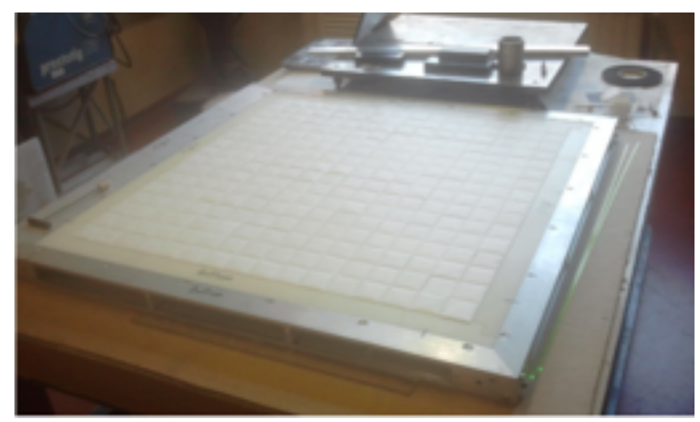
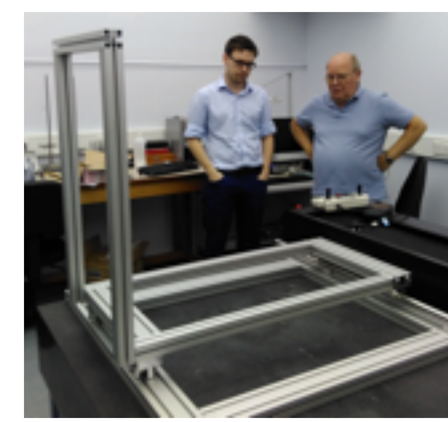
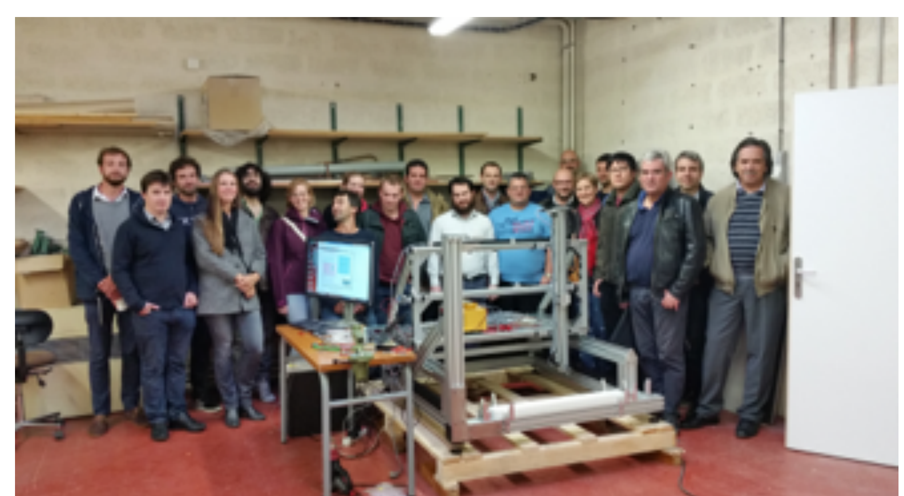


SoLid construction

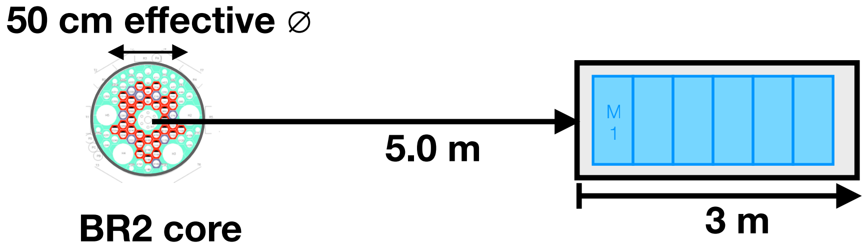
- SoLid detectors are under construction !
- cube production and assembly well underway
- Staged production of electronics
- Trigger implemented and DAQ under development
- Calibration system to be commissionned next month
- Container built and to be delivered this month

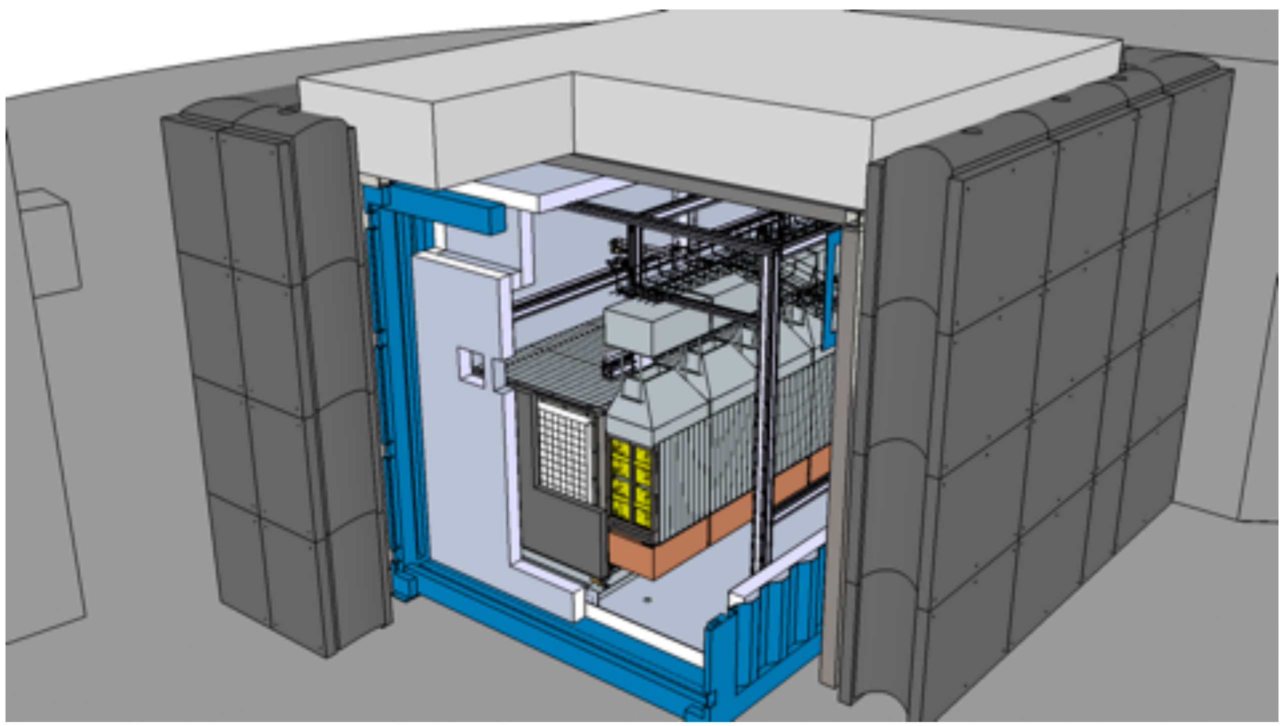




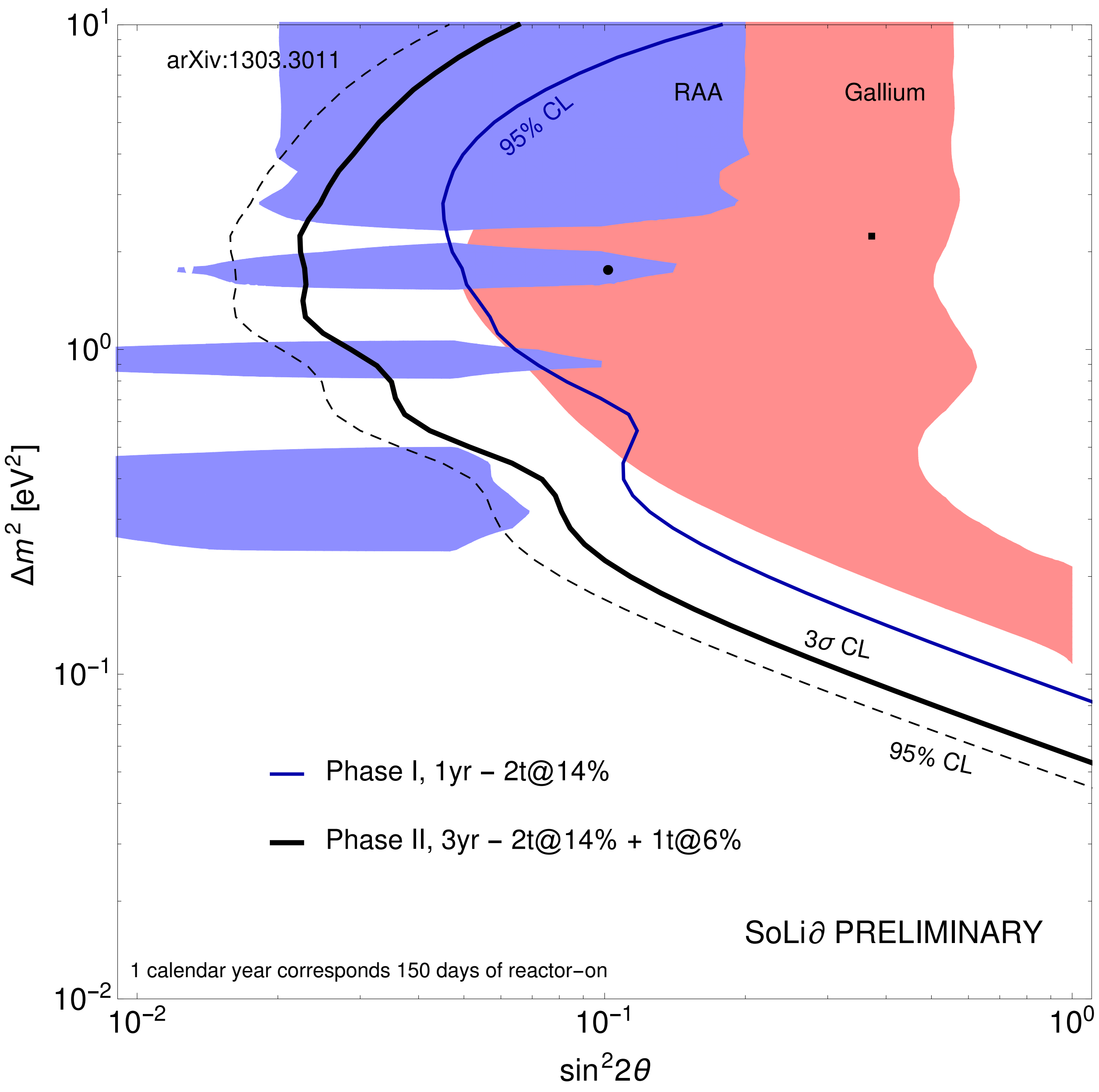






SoLid sensitivity





- 40% IBD efficiency
- S:B ~ 3:1
- Background is combination of $1/E^2$ and flat
- 2% relative energy scale uncertainty
- shape only measurement
- Data taking starting spring 2017



Summary

- Reactor anomalies in the electron antineutrino sector are still not understood
  - in addition to a rate deficit (or theoritical excess), disagreement in the spectrum shape have been measured
    - put current accuracy of conversion model in question
    - origin of deviation not yet understood but new U-235 spectrum measurement will test many hypotheses.
- Currrent experimental sensitivity is now entering the region of interest to look for a sterile neutrino of 1 eV^2
- Dedicated experiments have started or about to start in 2017
- SoLid will use a new technology and the HEU core of BR2 to search for oscillations
- New measurements should address the anomalies before 2020

Back up