Short BaseLine neutrino oscillation experiments

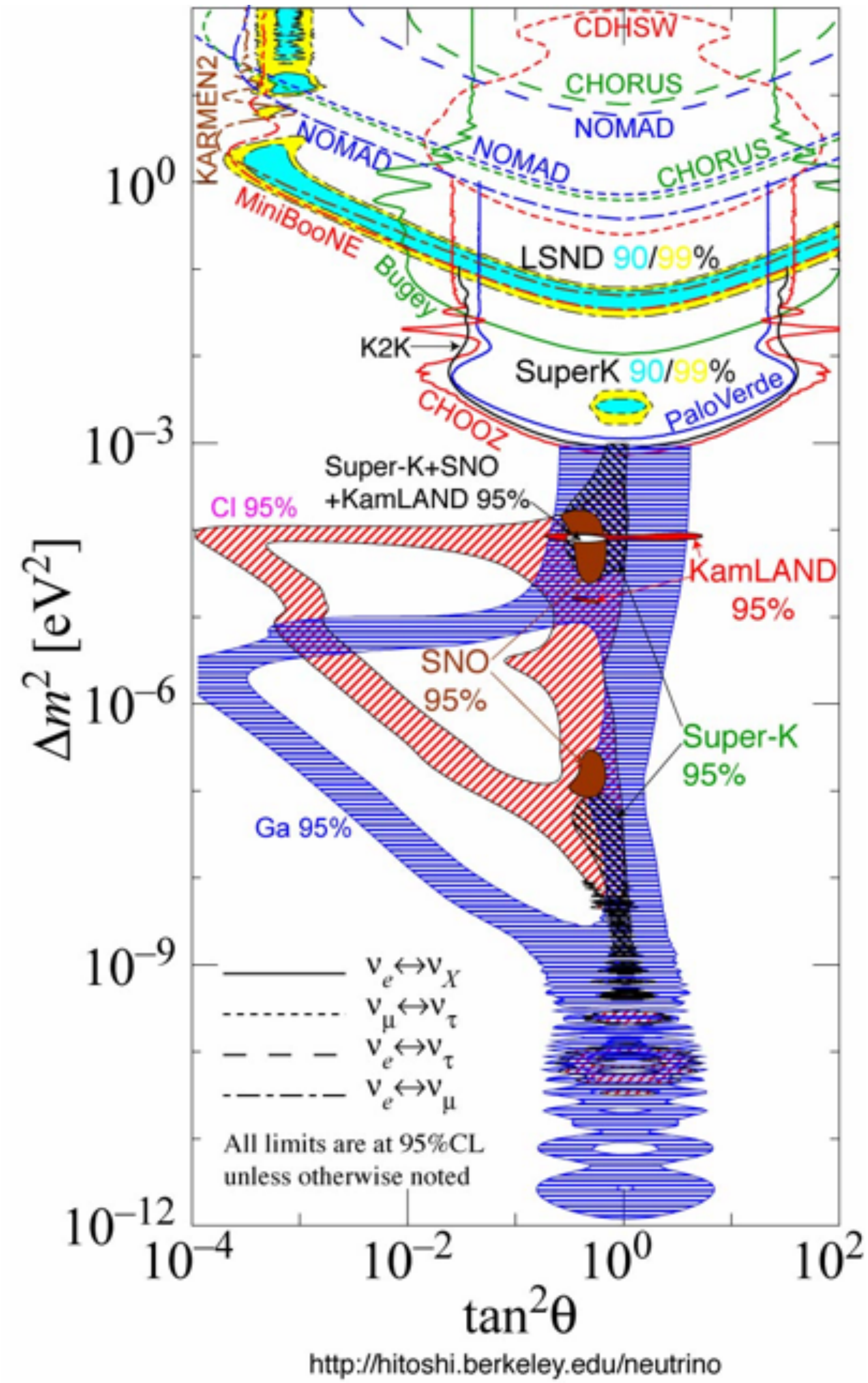
Antonin Vacheret

PPAP community meeting 2016
University of Birmingham

Imperial College London

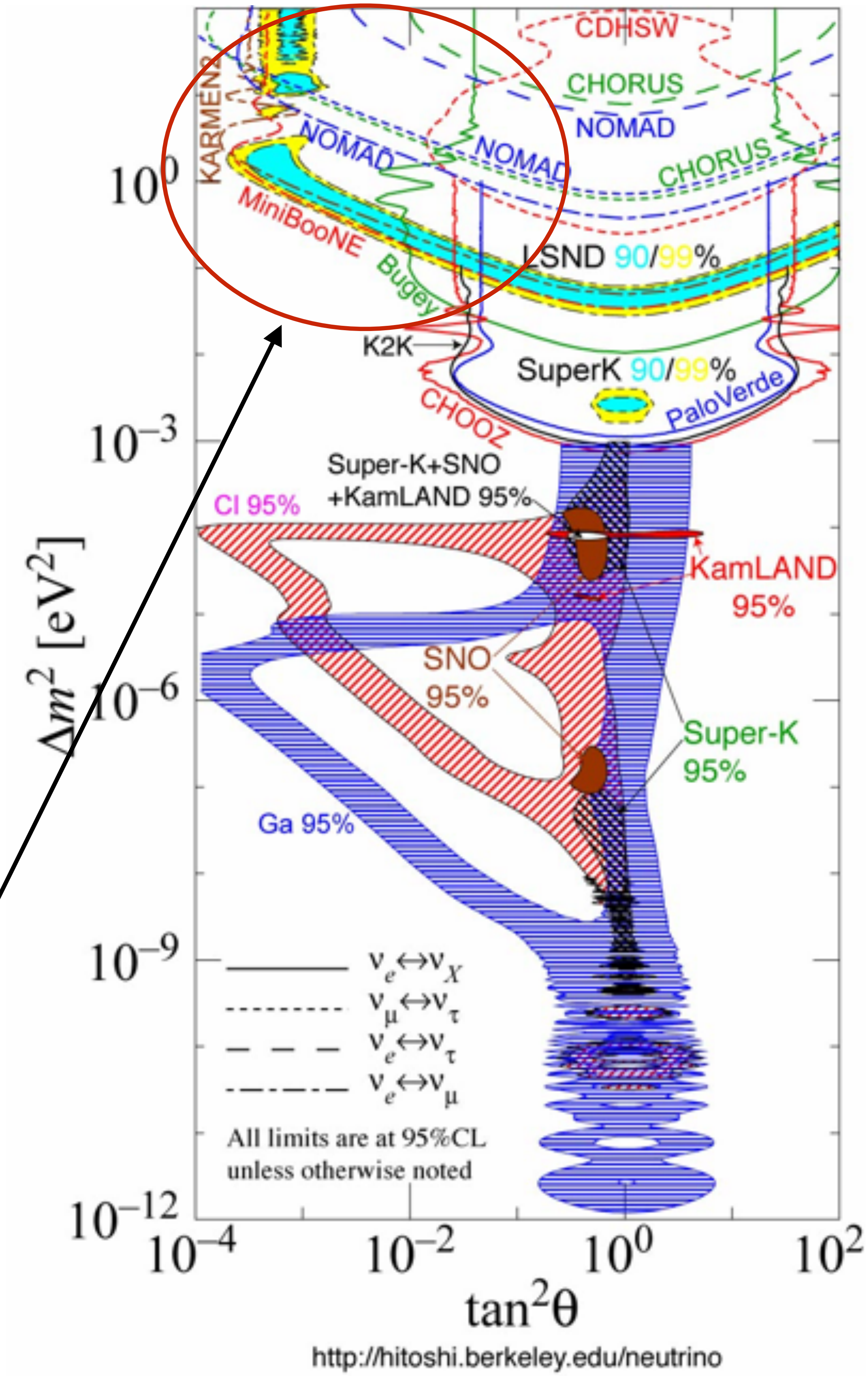
The 1 eV^2 region

- A reminder about the scale of the problem we had once in neutrino physics
- A large number of experiment were needed to establish a coherent picture

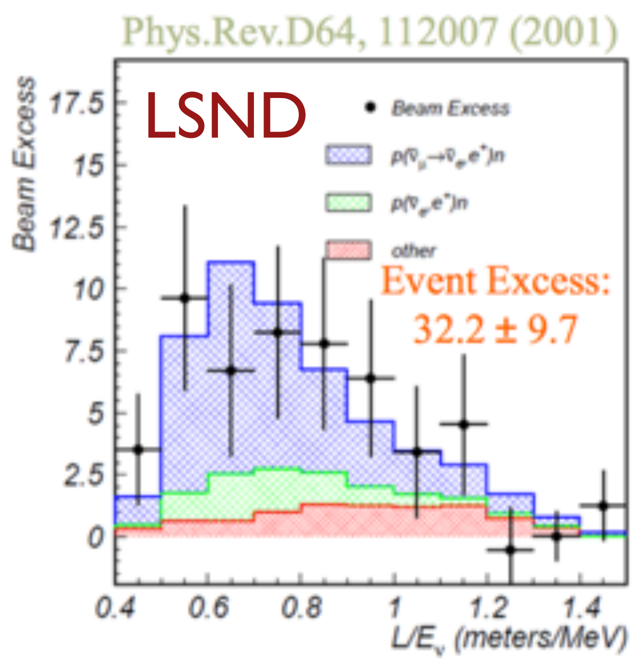


The 1 eV^2 region

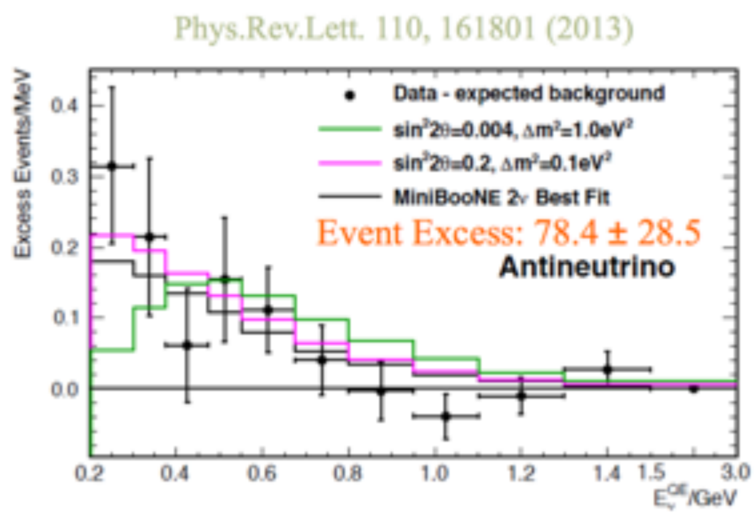
- A reminder about the scale of the problem once in neutrino physics
- A large number of experiment were needed to establish a coherent picture
- The short baseline program is mainly interested is probing further this area *there*



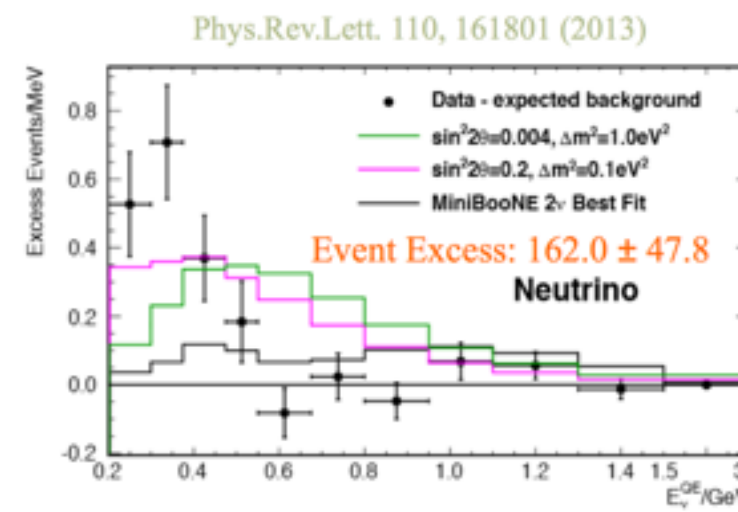
The unorthodox data sets

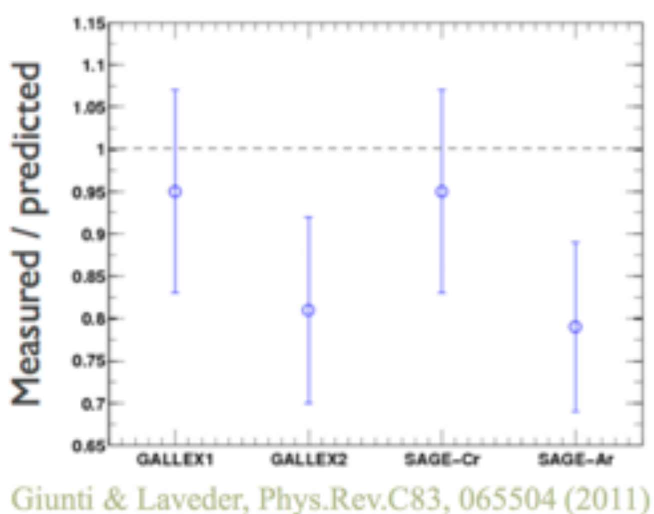


MiniBooNE

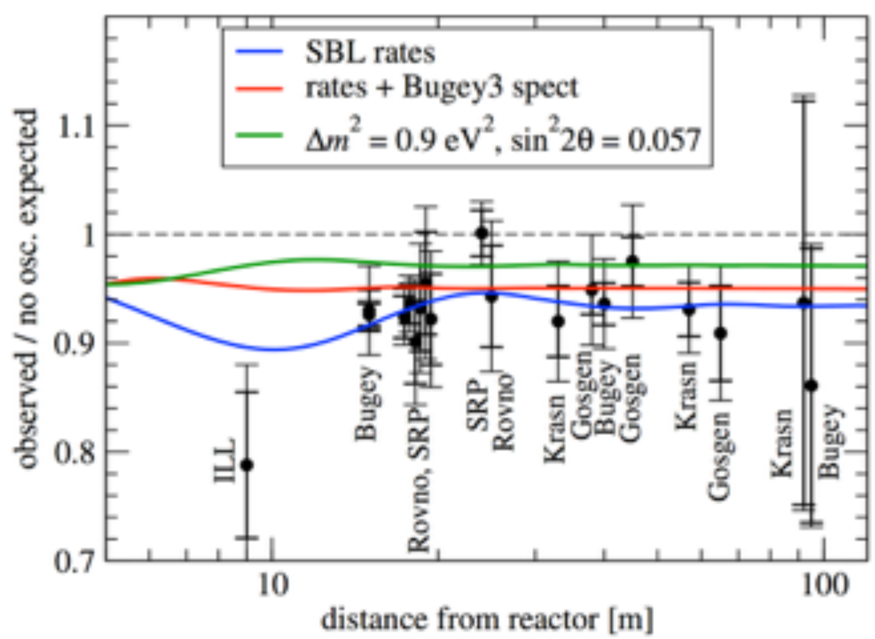


MiniBooNE

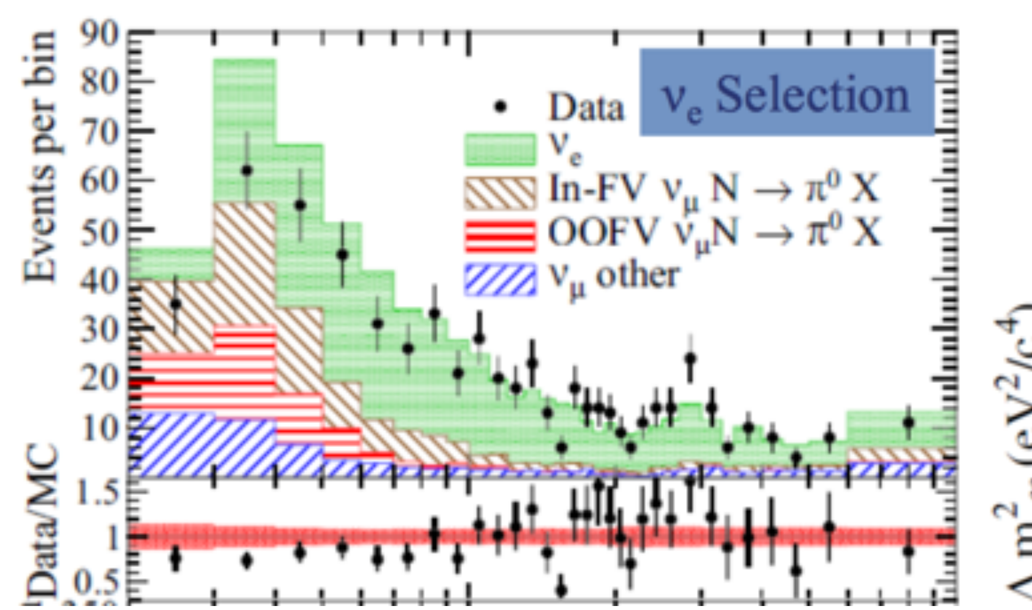




Gallium Anomaly



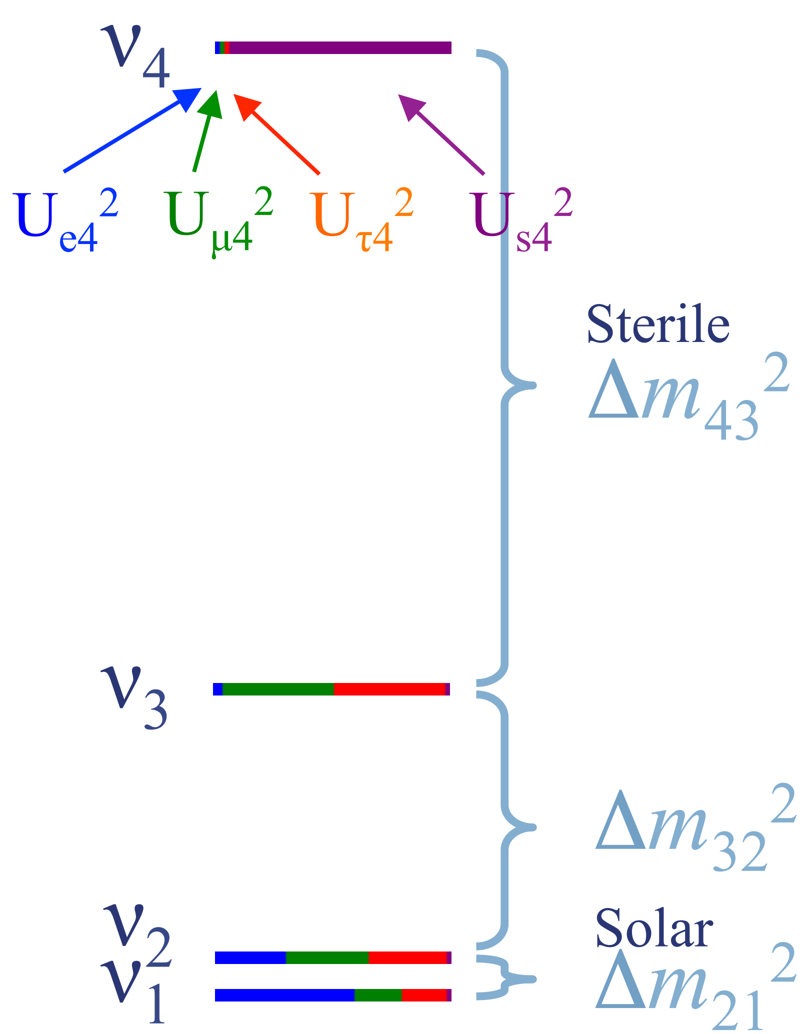
Reactor anomaly



T2K near detector nue deficit

Sterile neutrino(s) ?

3+1 model



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

- muon to electron neutrino appearance

$$P_{\mu e} = 4U_{e4}^2 U_{\mu4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

- electron neutrino disappearance

$$P_{e\not{e}} \approx P_{es} = 4U_{e4}^2 U_{s4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

- muon neutrino disappearance

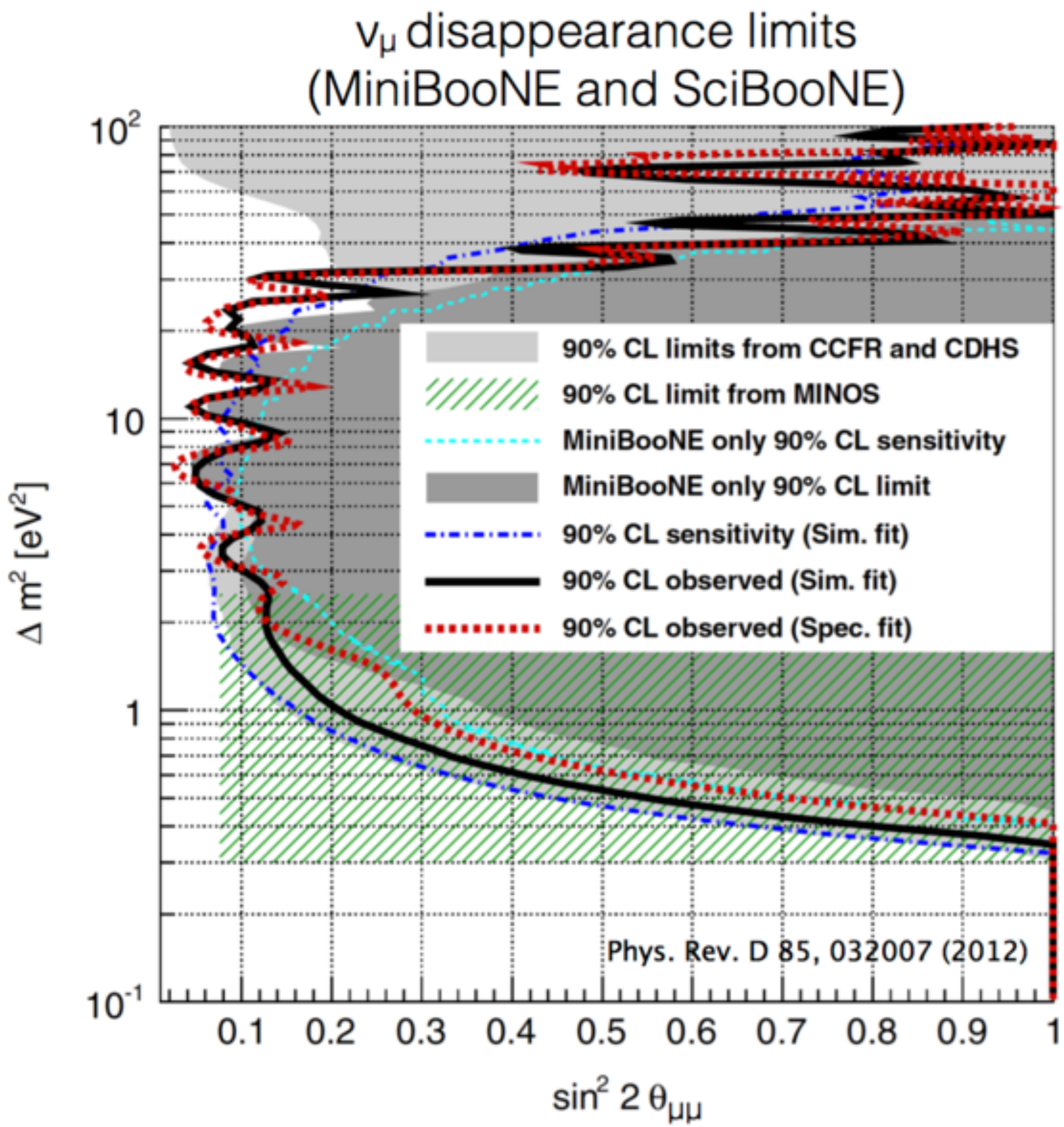
$$P_{\mu\mu} \approx 4U_{\mu4}^2 U_{s4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

need to cover as many channels as possible
for a “definite” answer

J. Link TAUP 2015

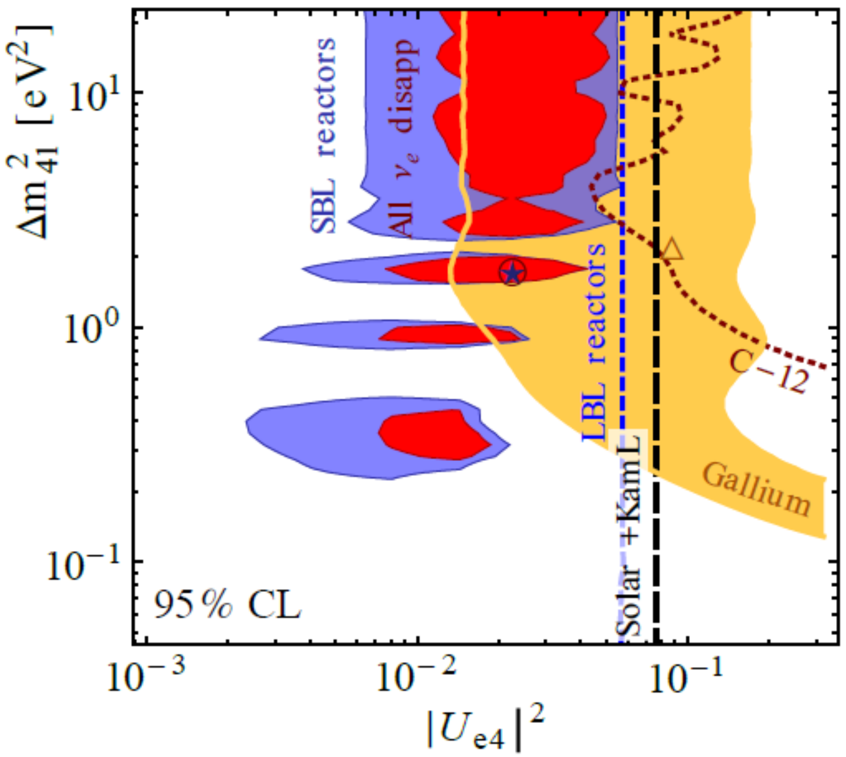
Disappearance limit

- We have also limits on numu disappearance
- they causes issues when trying to interpret results in terms of sterile neutrinos
- need stronger limits ?

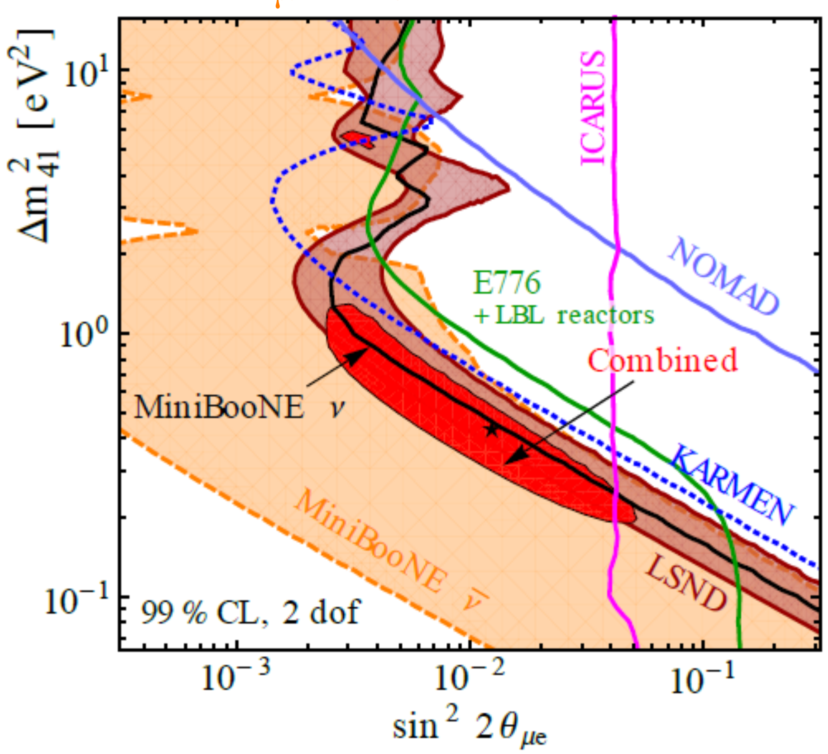


Global fits

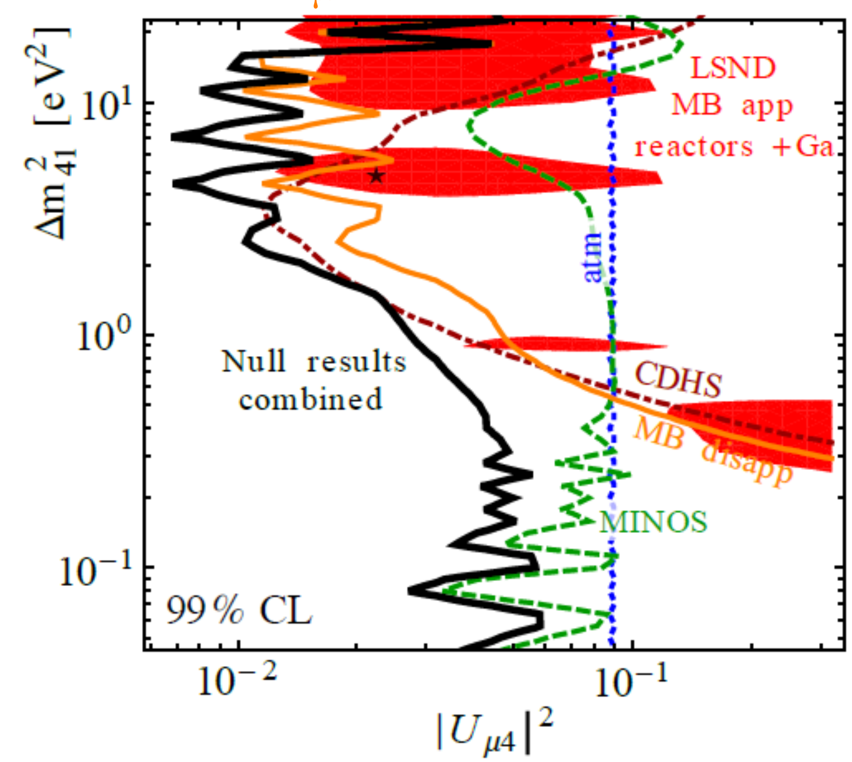
ν_e Disappearance



$\nu_\mu \rightarrow \nu_e$ Appearance



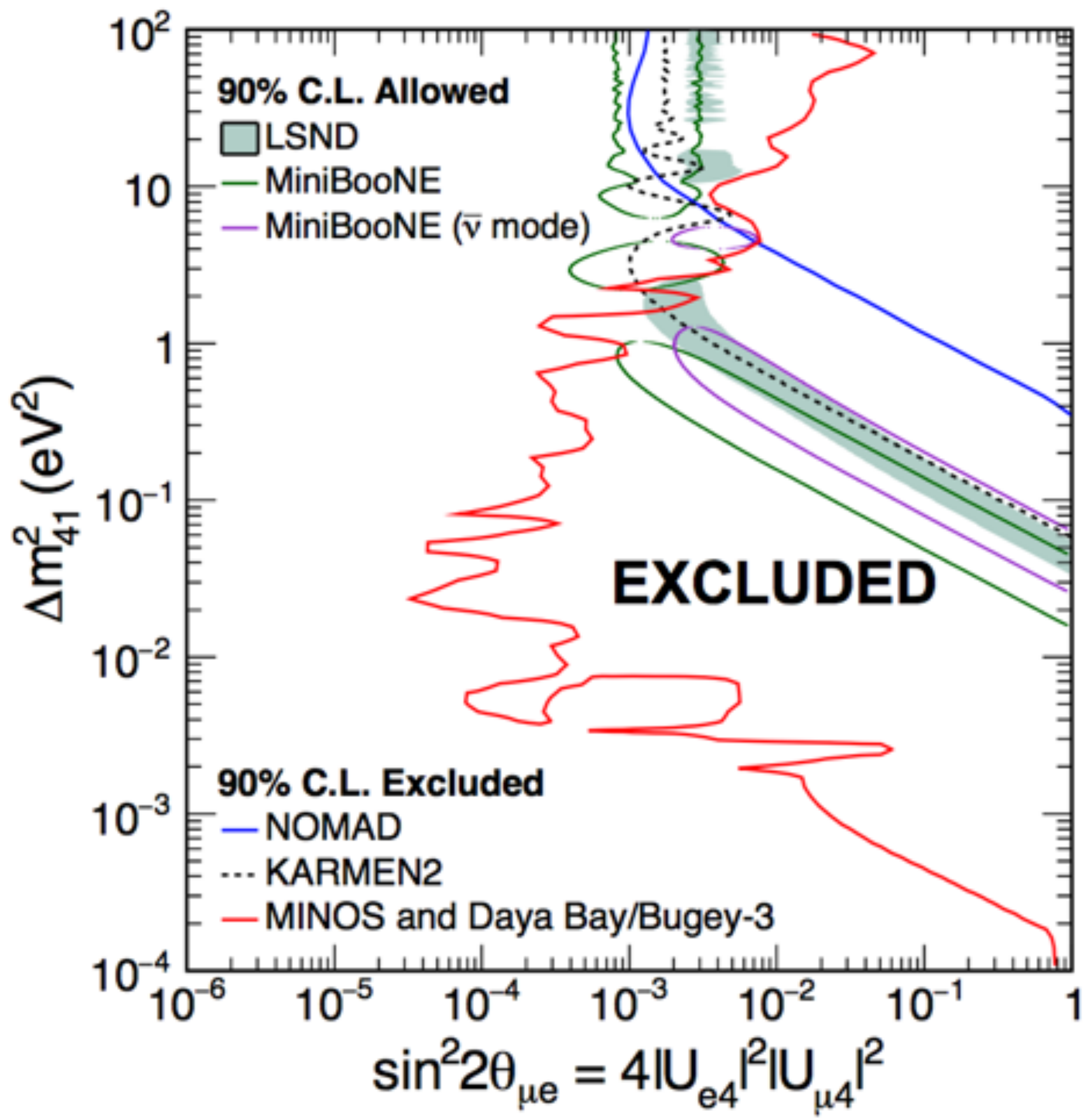
ν_μ Disappearance



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

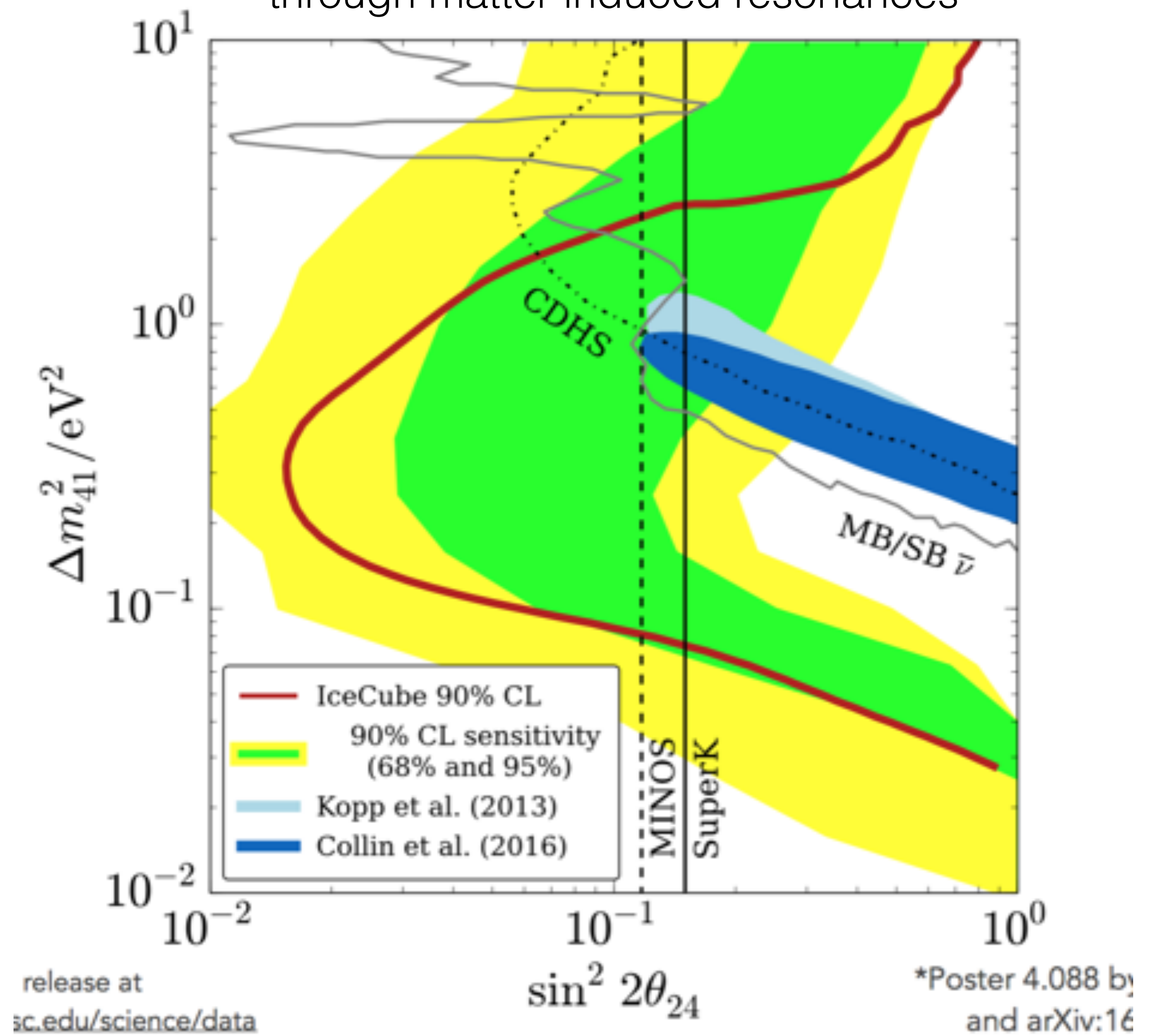
Recent results, not SBL yet

Bugey-3, Daya-Bay, MINOS+



IceCube

through matter induced resonances



On-going and future SBL program

- **Accelerator Decay-in-flight**
  - **FERMILAB SBL (SBND, microBooNE, ICARUS)**
  - **T2K near detector**
- **Accelerator decay at rest**
  - muDAR (JSNS^2), IsoDAR, kDAR, kPIPE
- **Reactor experiments**
  - DANSS, NEOS
  - STEREO, **SoLid**
  - PROSPECT, NULat
- **Radioactive neutrino sources**
  - SOX, RICCOCHET

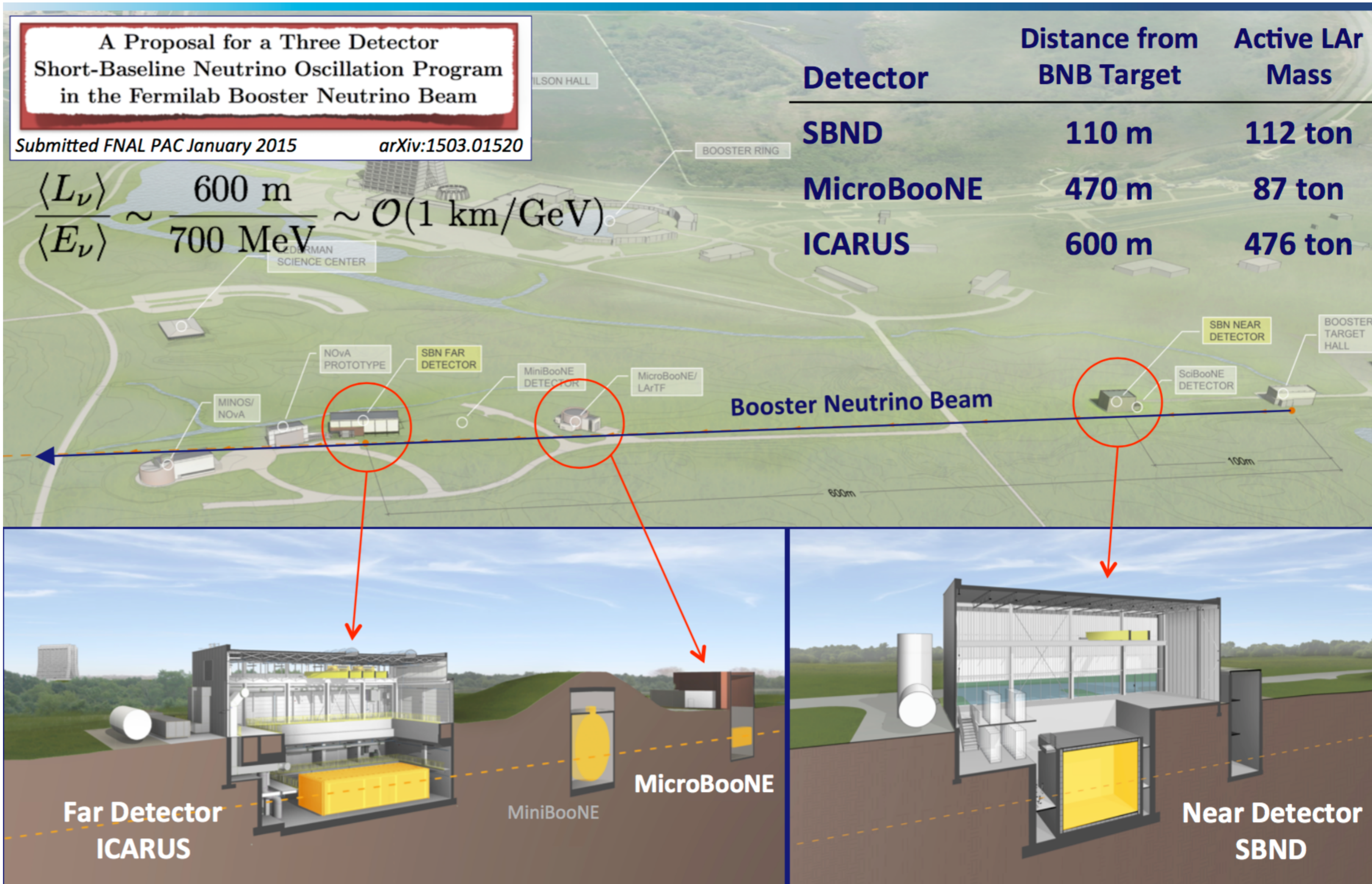
The three LArTPC SBN Programme at FNAL

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

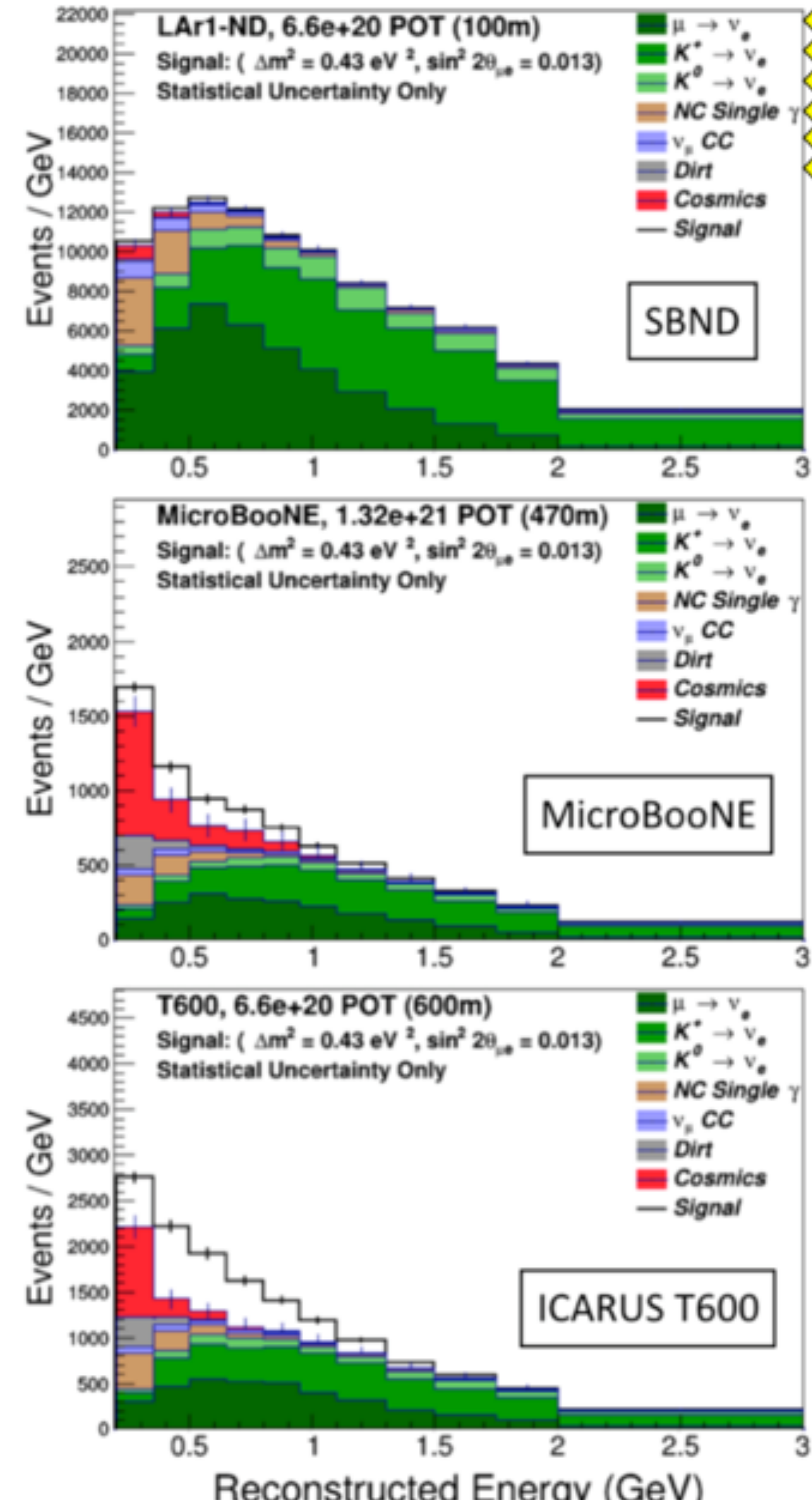
Submitted FNAL PAC January 2015 *arXiv:1503.01520*

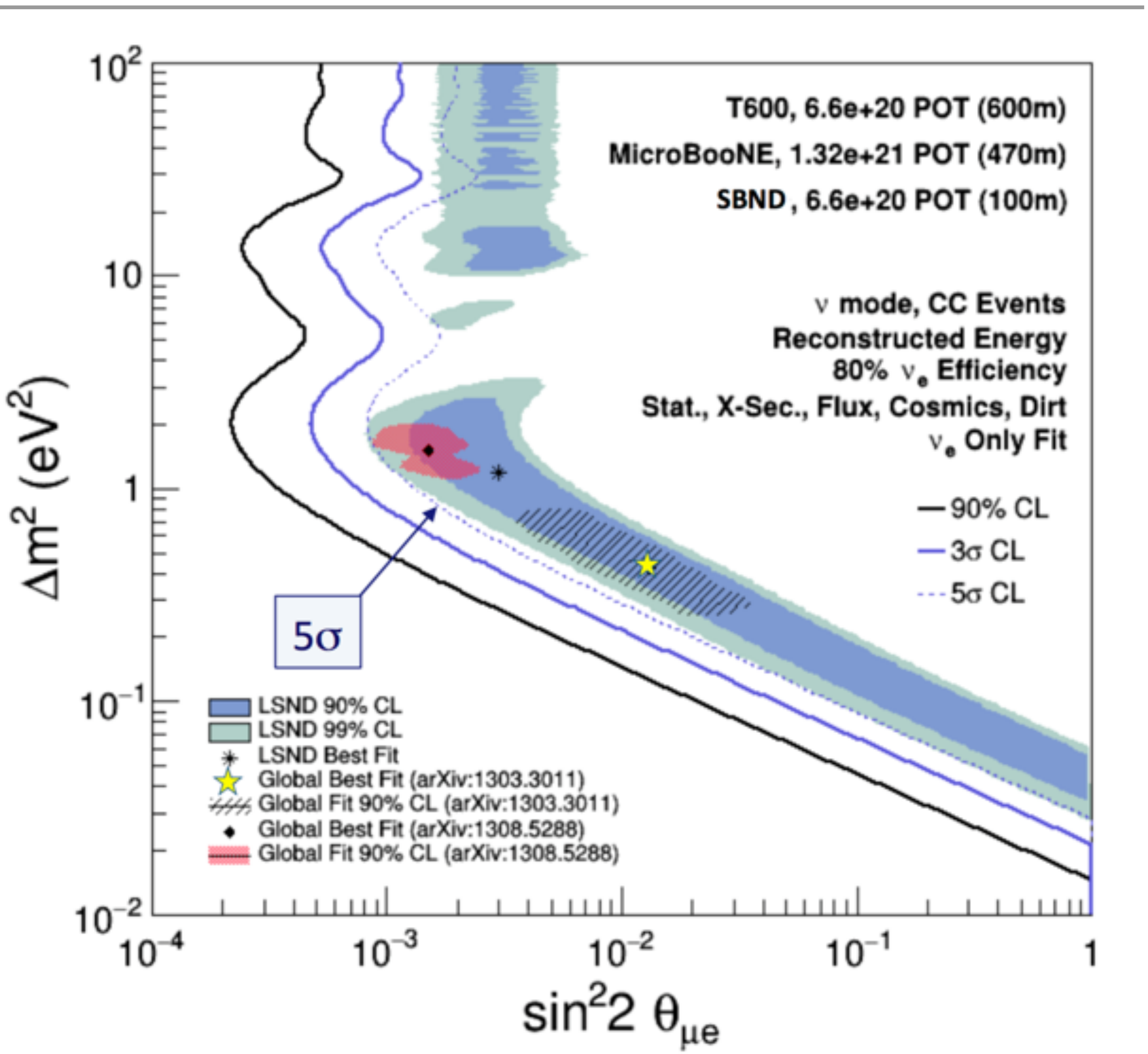
$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



The SBN Programme Physics Goal



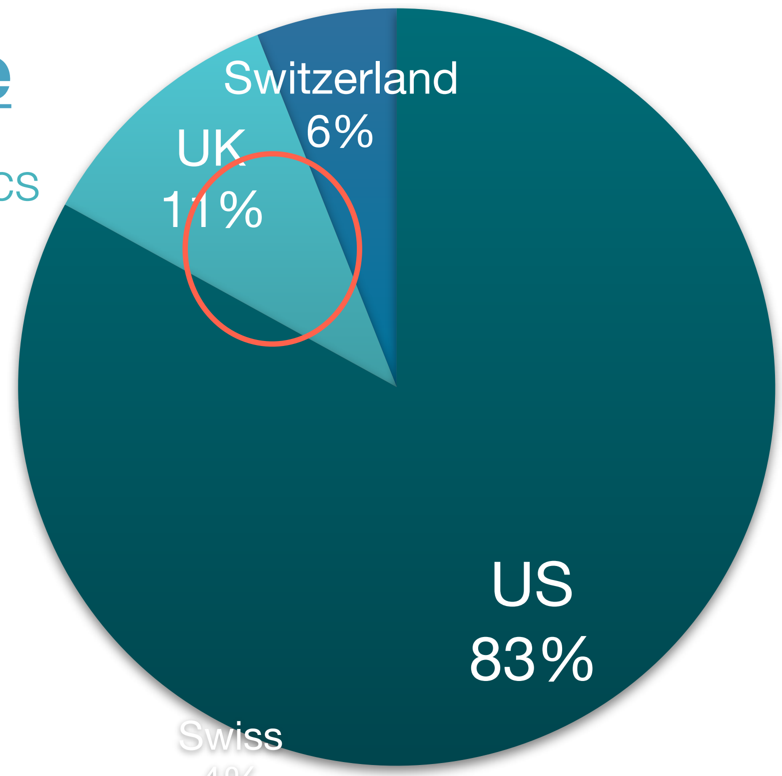


SBN proposal arxiv:1503.01520

MicroBooNE in the UK

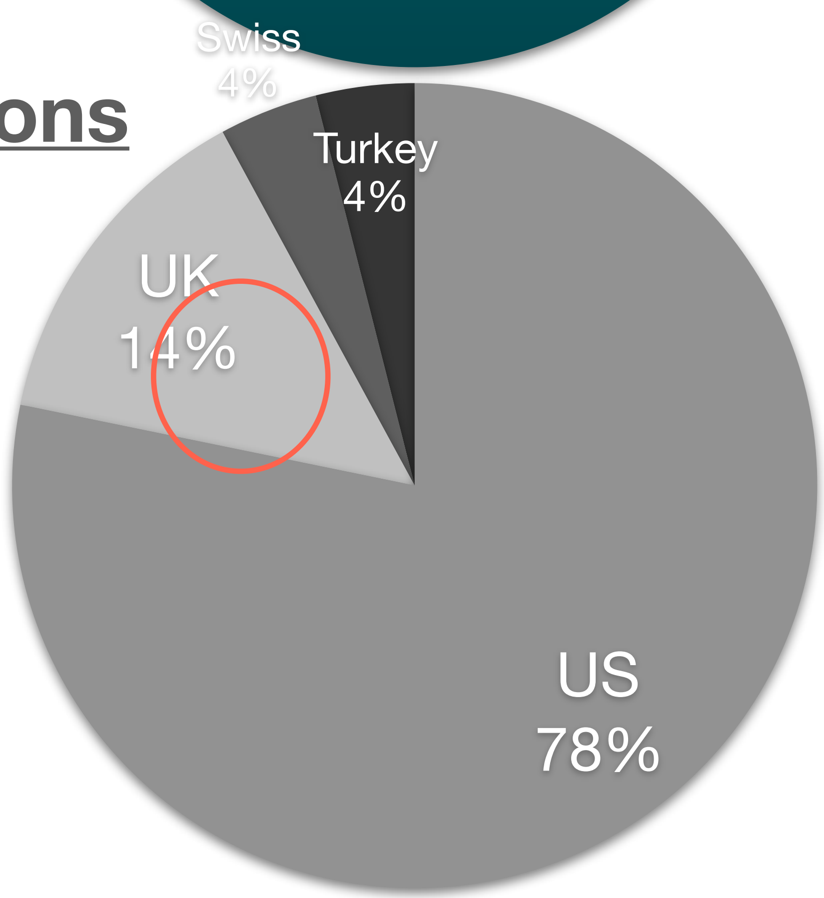
People

8 Academics
3 PDRAs
11 PhDs

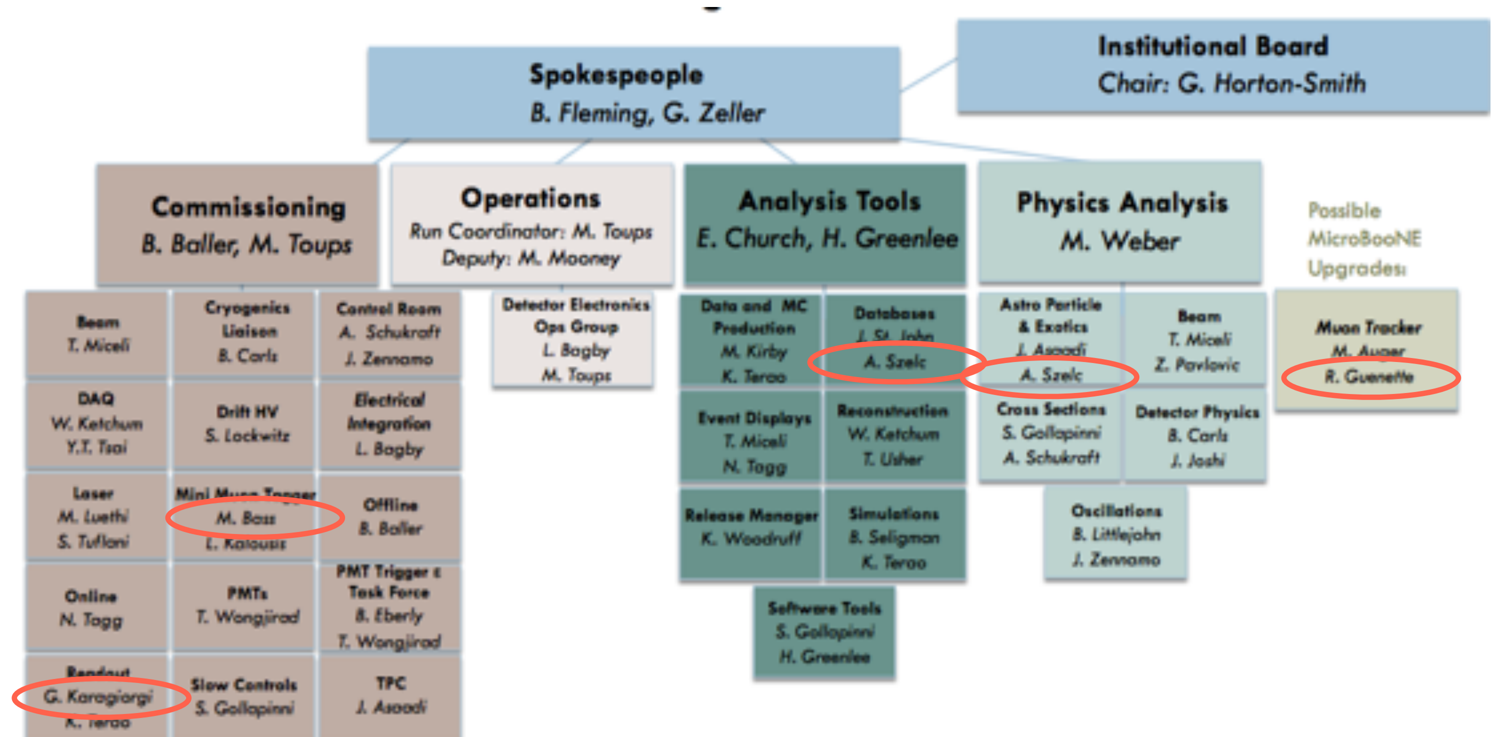


Institutions

Cambridge
Manchester
Lancaster
Oxford



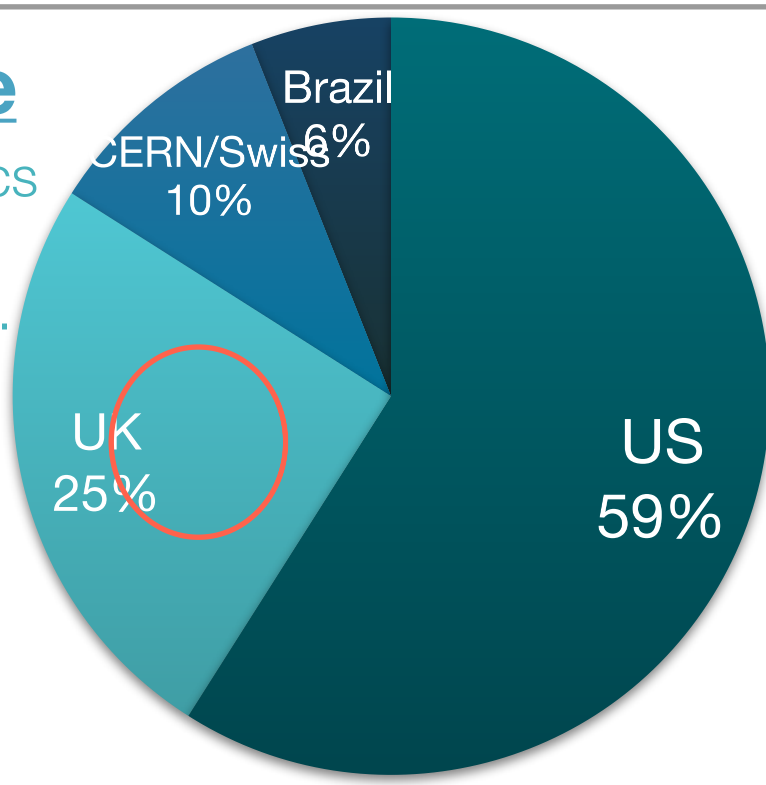
- Biggest non-US contribution
- Many leadership roles
- Significant impact on science
- Knowledge transfer for future LArTPCs



SBND in the UK

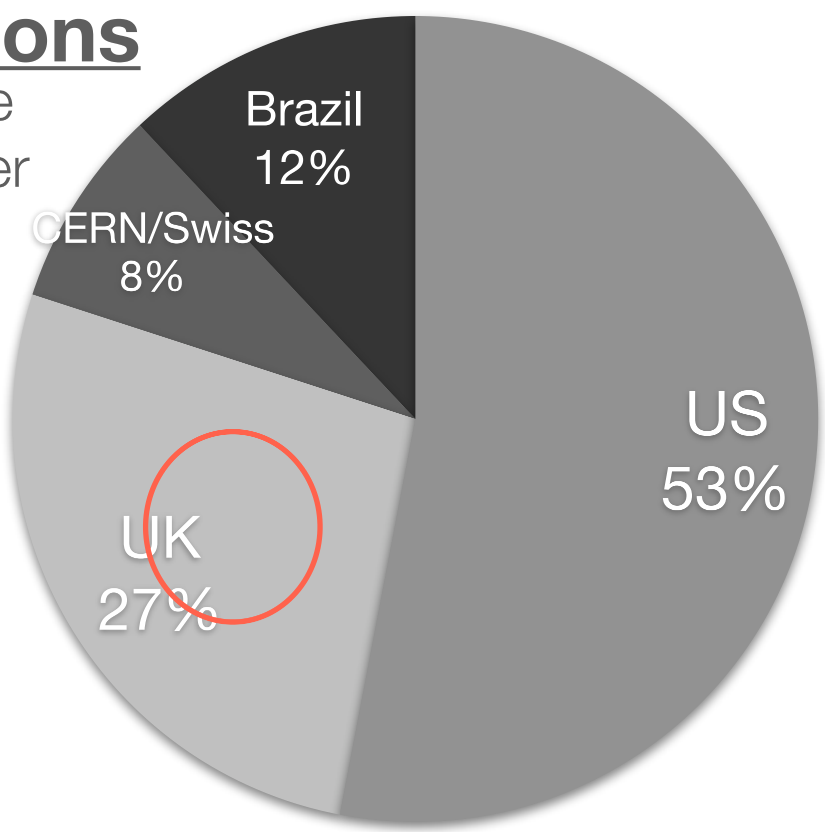
People

13 Academics
8 PDRAs
6 Eng./Tech.
6 PhDs



Institutions

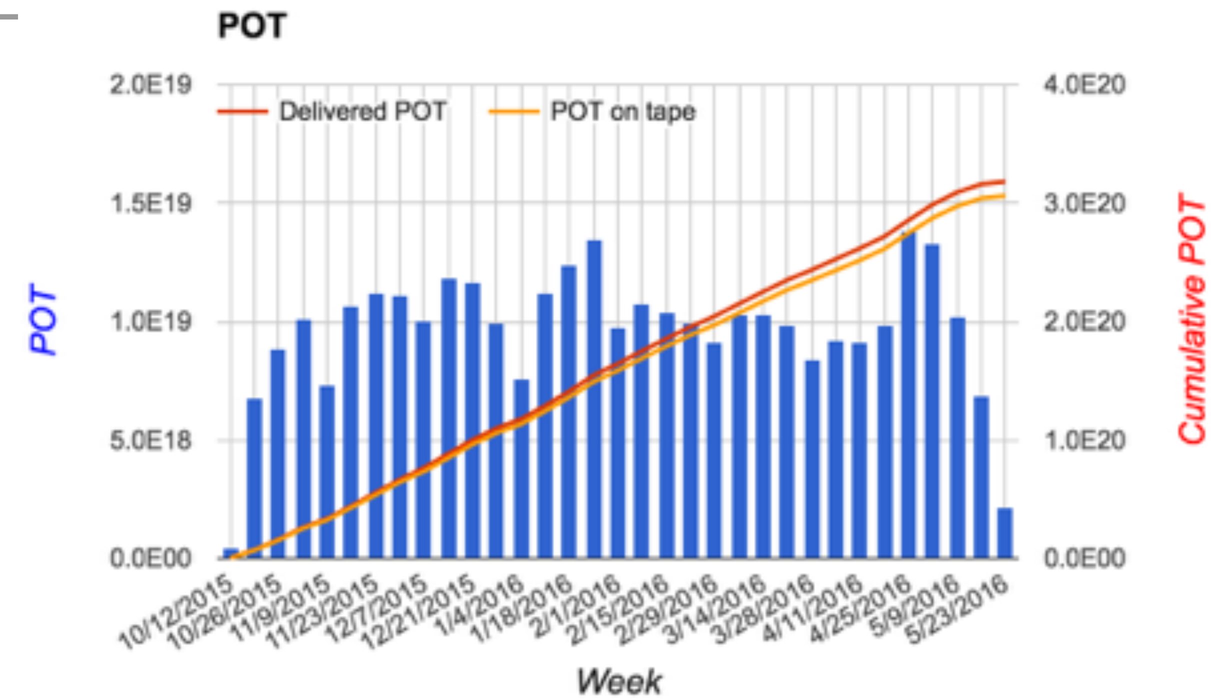
Cambridge
Manchester
Lancaster
Liverpool
Oxford
Sheffield
UCL

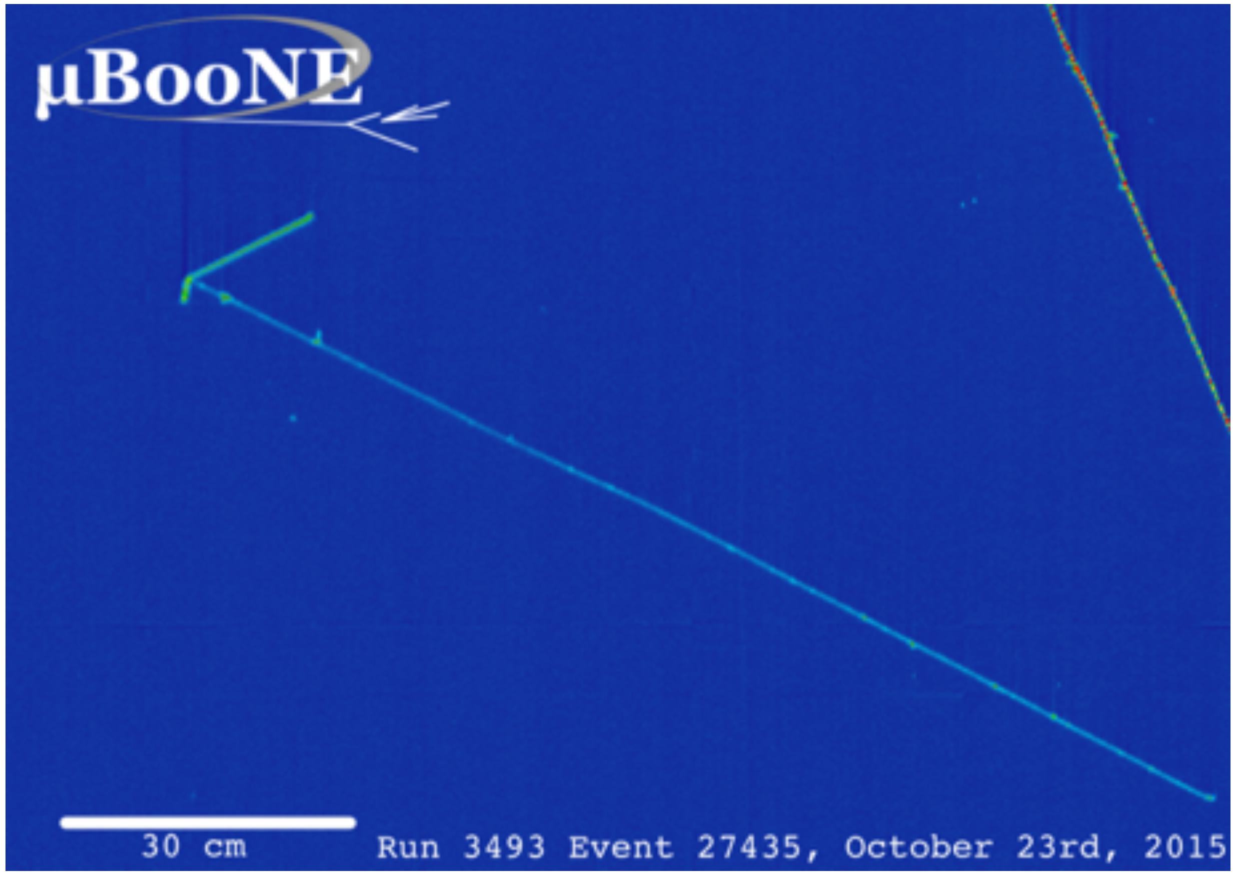


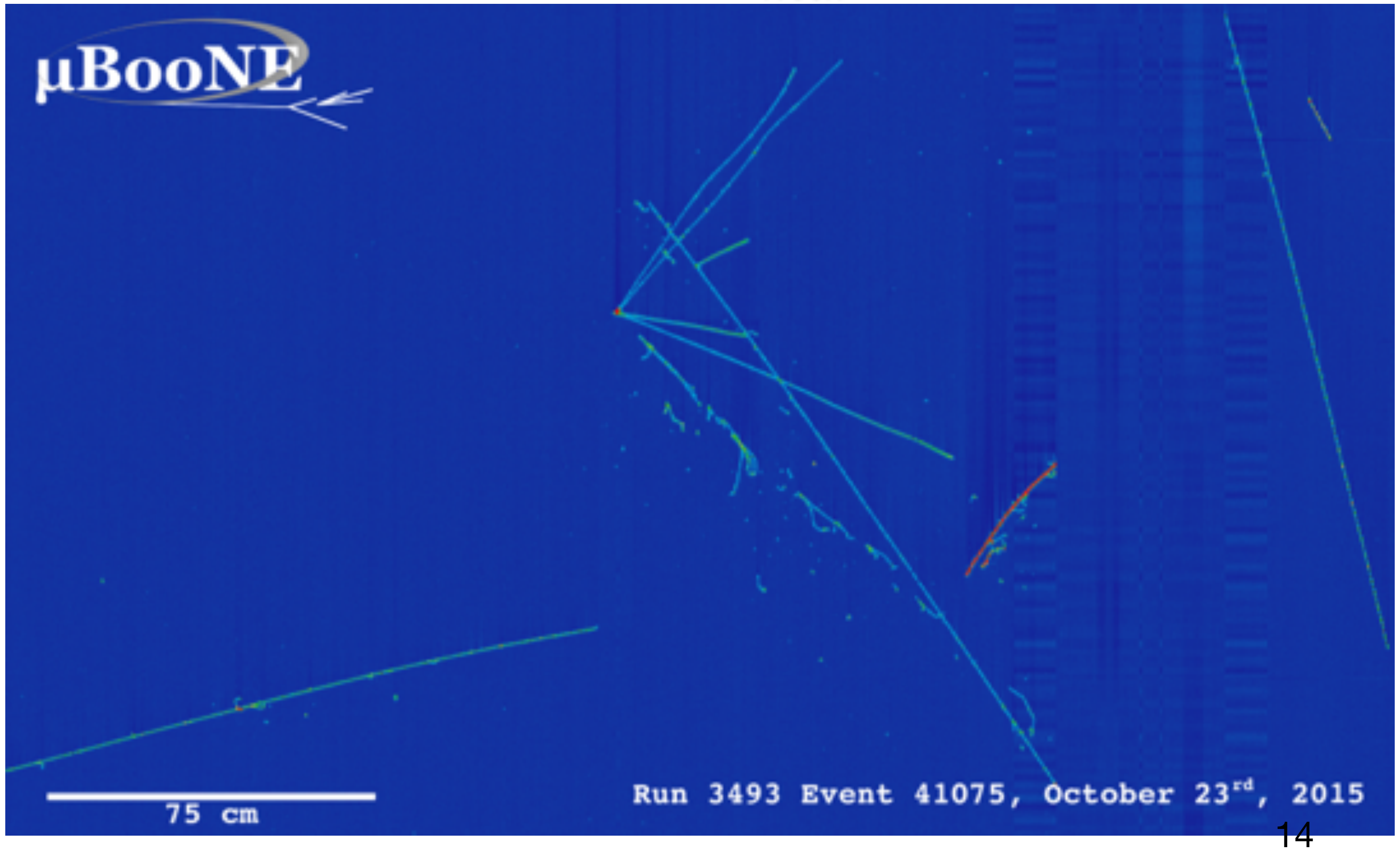
- Biggest International contribution
- Many leadership roles (L2-manager for TPC, Conveners of Simulation & Software Group, Speaker Committee Leader)
- Significant impact on science and DUNE roadmap
- Knowledge transfer for DUNE:
  - APA construction
  - APA wire winding
  - HV feedthrough
  - light collection systems
  - installation and integration of TPC
  - Event Reconstruction Software

Data taking started 10/2015

- > 3 x 10^{20} POT recorded (~1/2 data set)

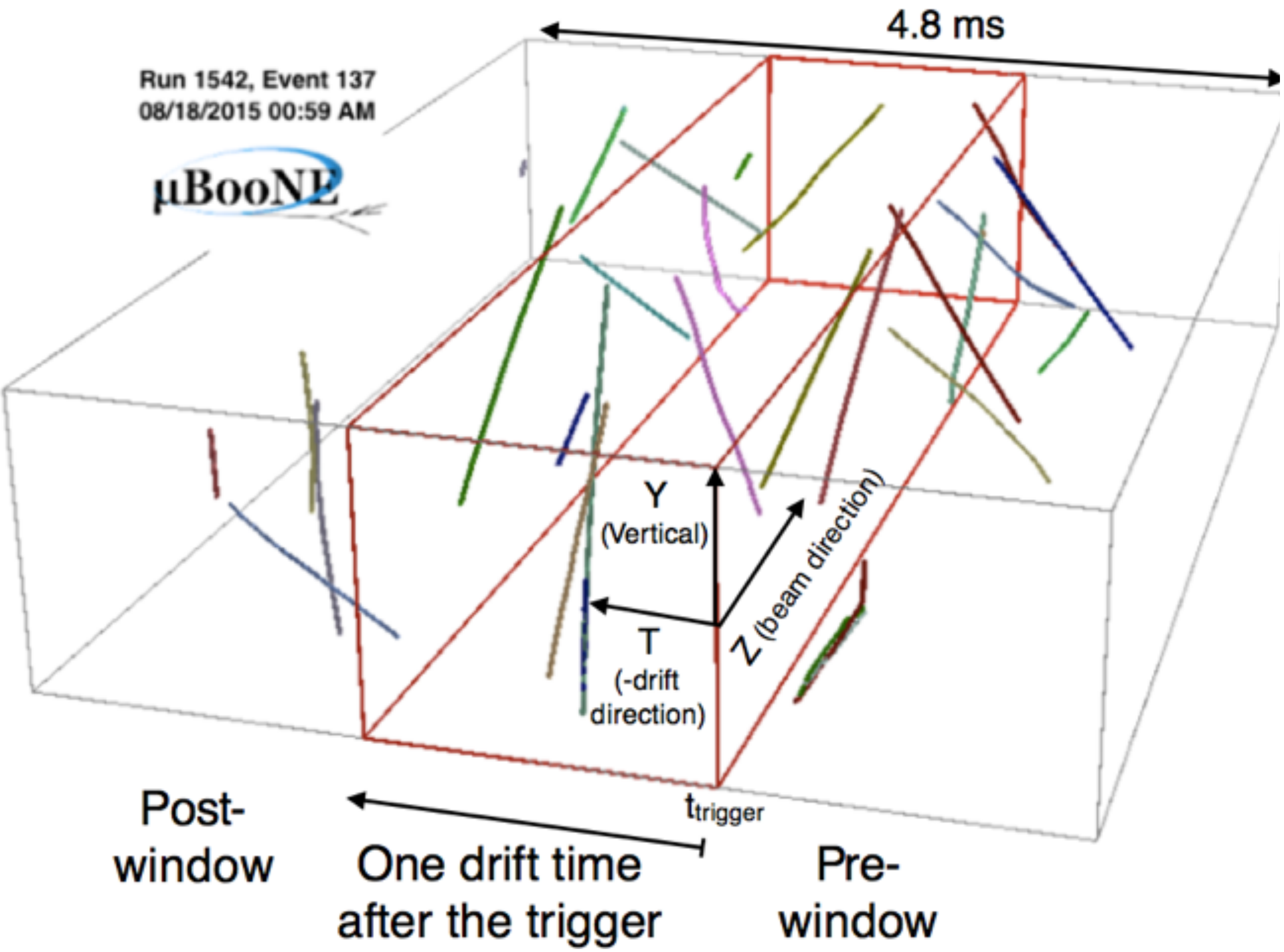


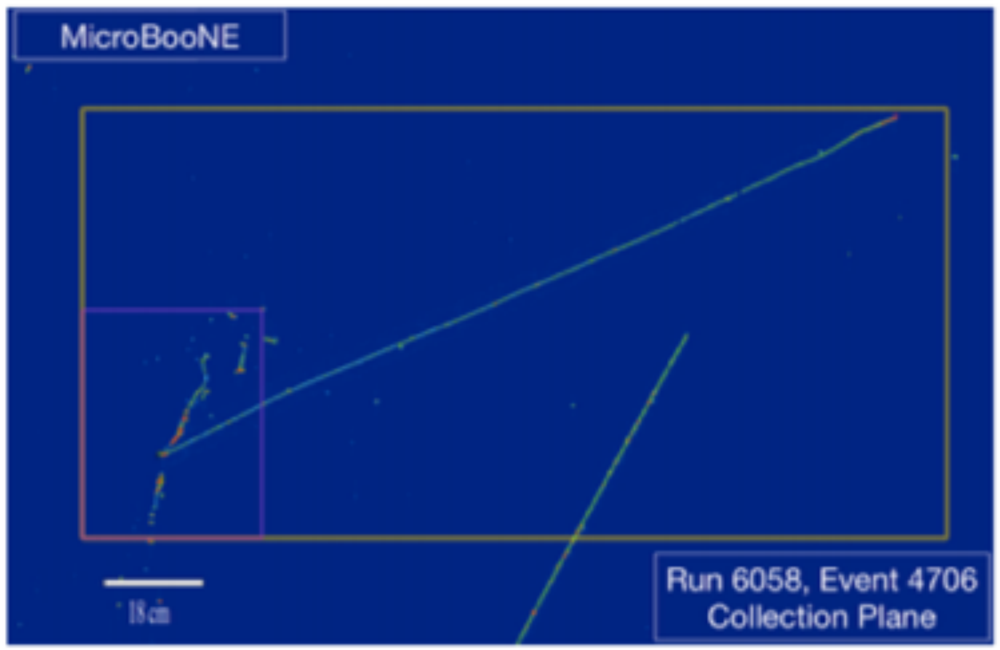


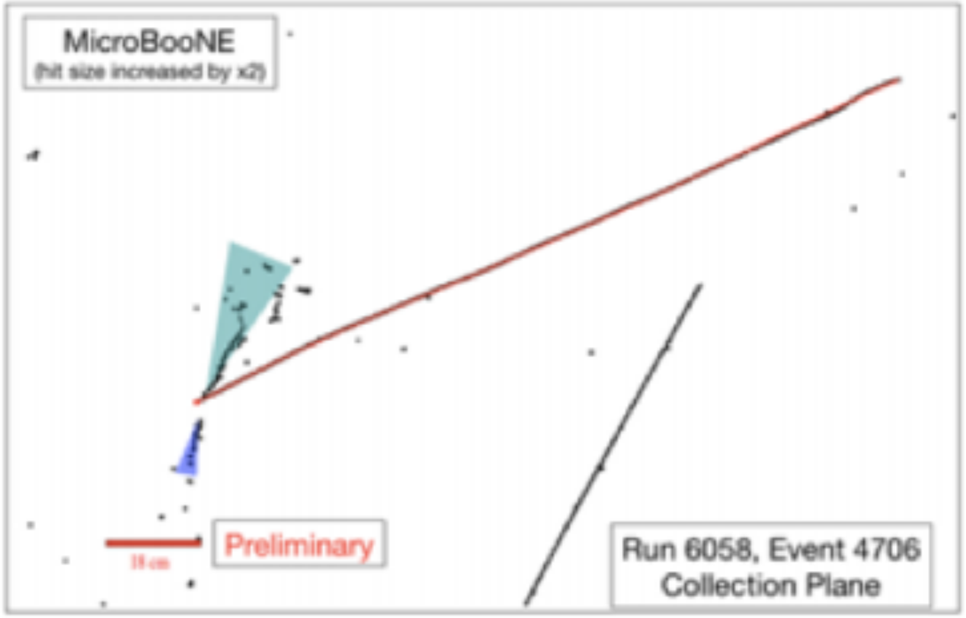


MicroBooNE automated reconstruction

Reconstructed cosmic tracks in MicroBooNE data
(assuming $t_0 = t_{trigger}$)

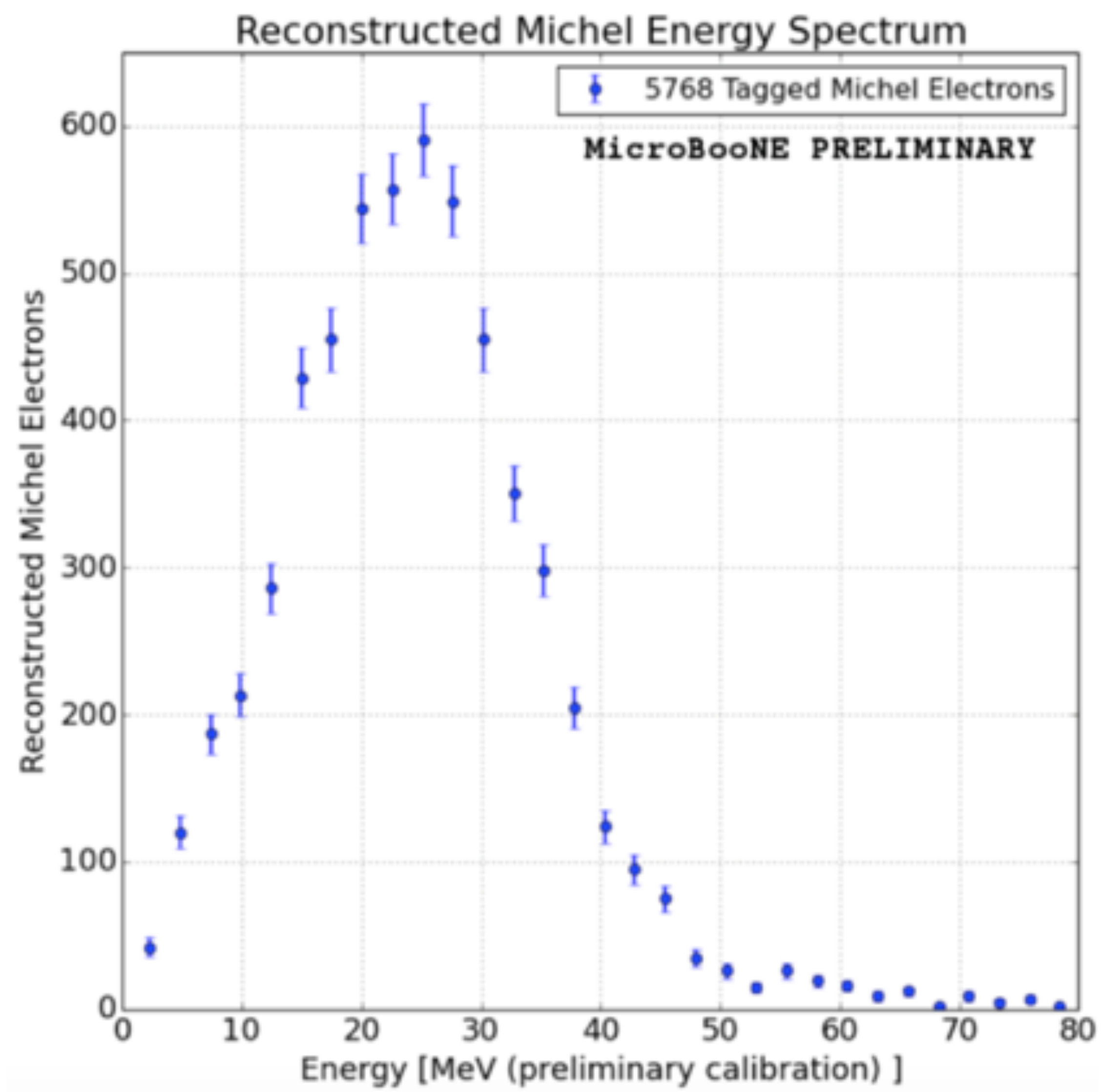


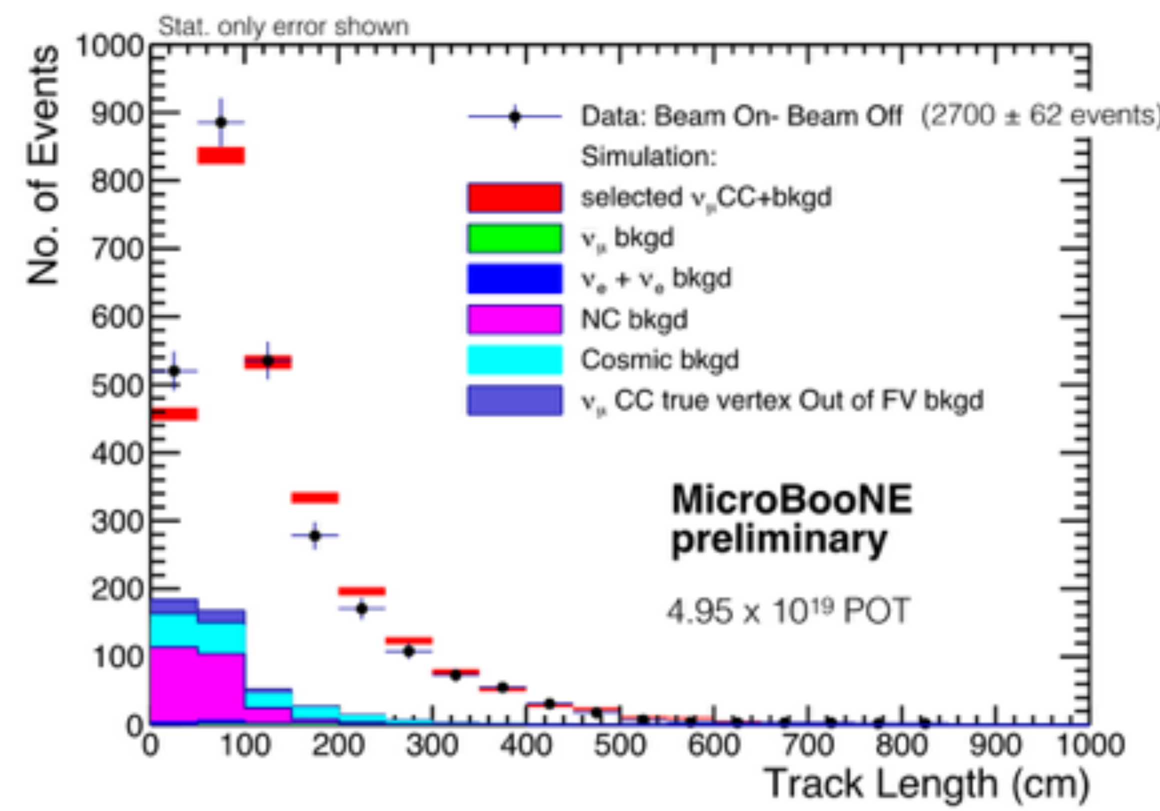


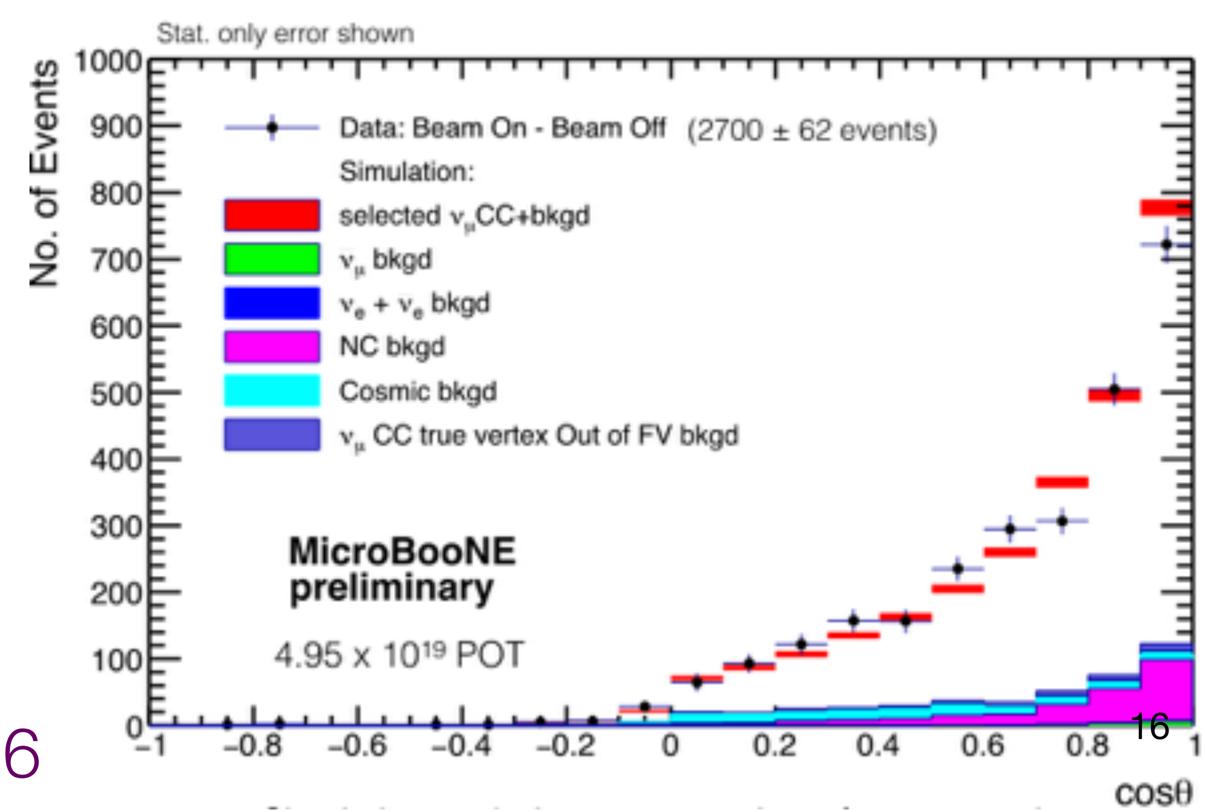


Recent results

- Michel e- spectrum
- ν_μ CC distributions







Presented at Neutrino 2016

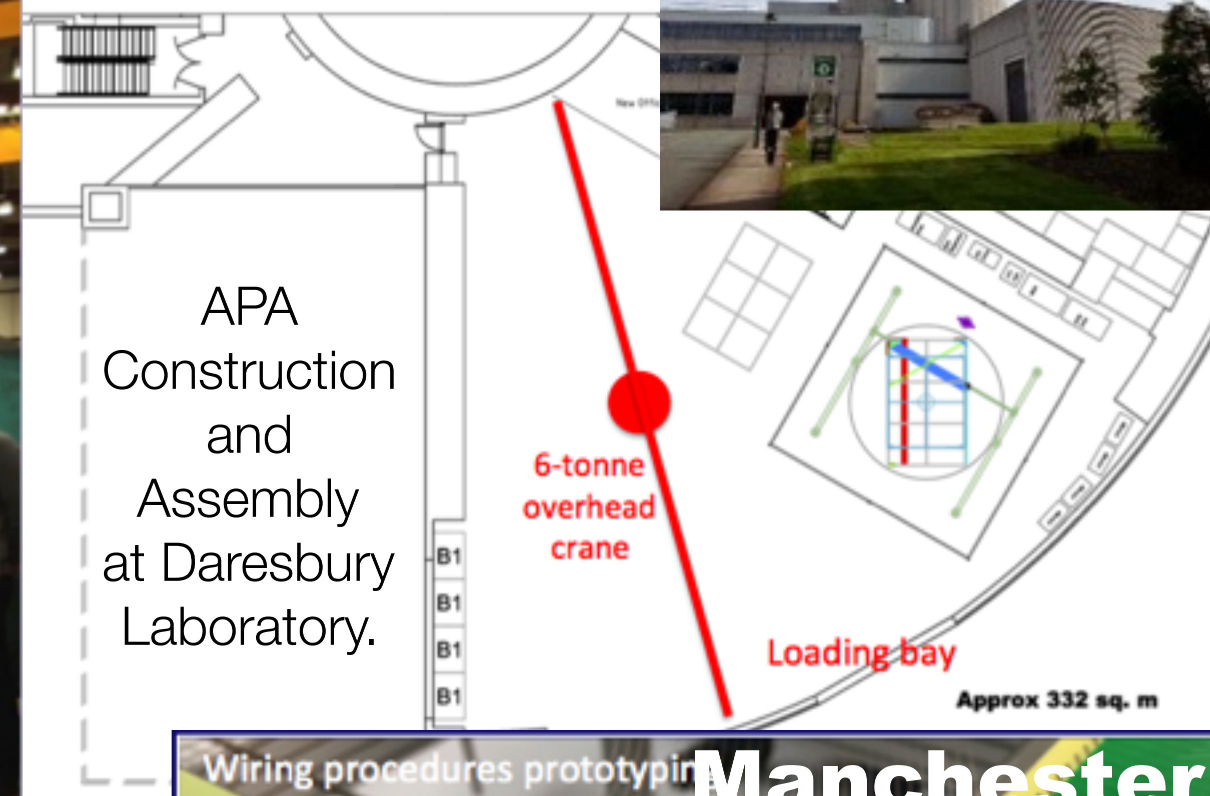
Recent progress (building construction)

SBND

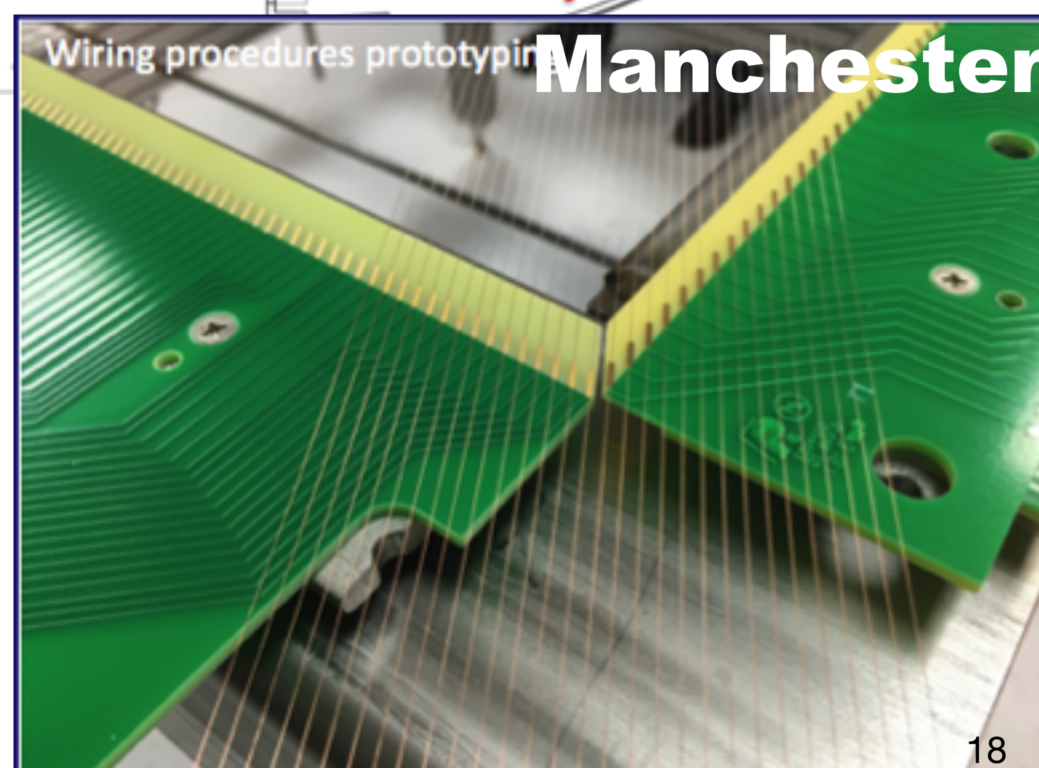
ICARUS

Recent progress (detector construction)

Wire plane frames in produc9on

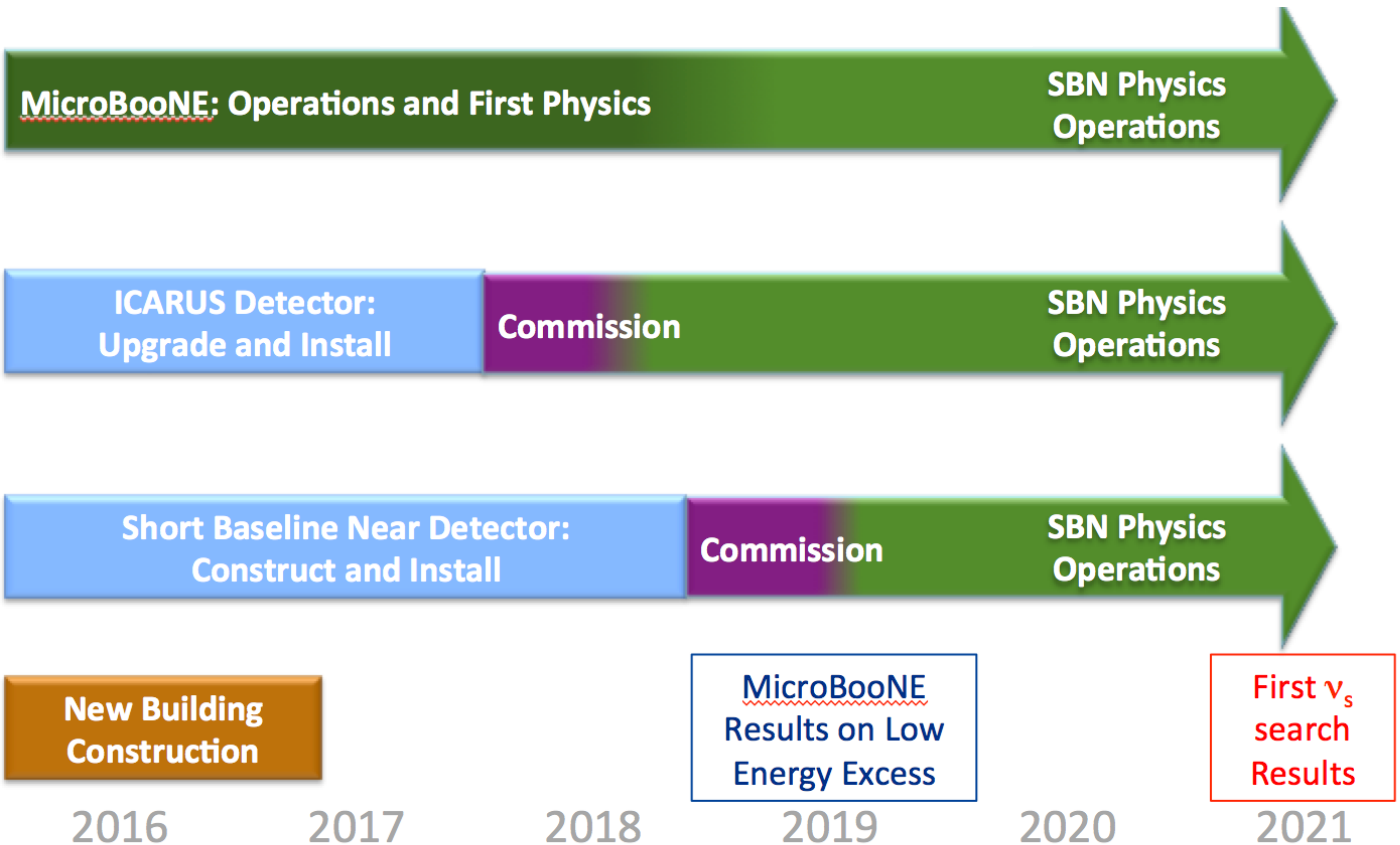


HV feed-through prototype



Wiring procedures prototypin

Timeline to Physics for SBN Programme

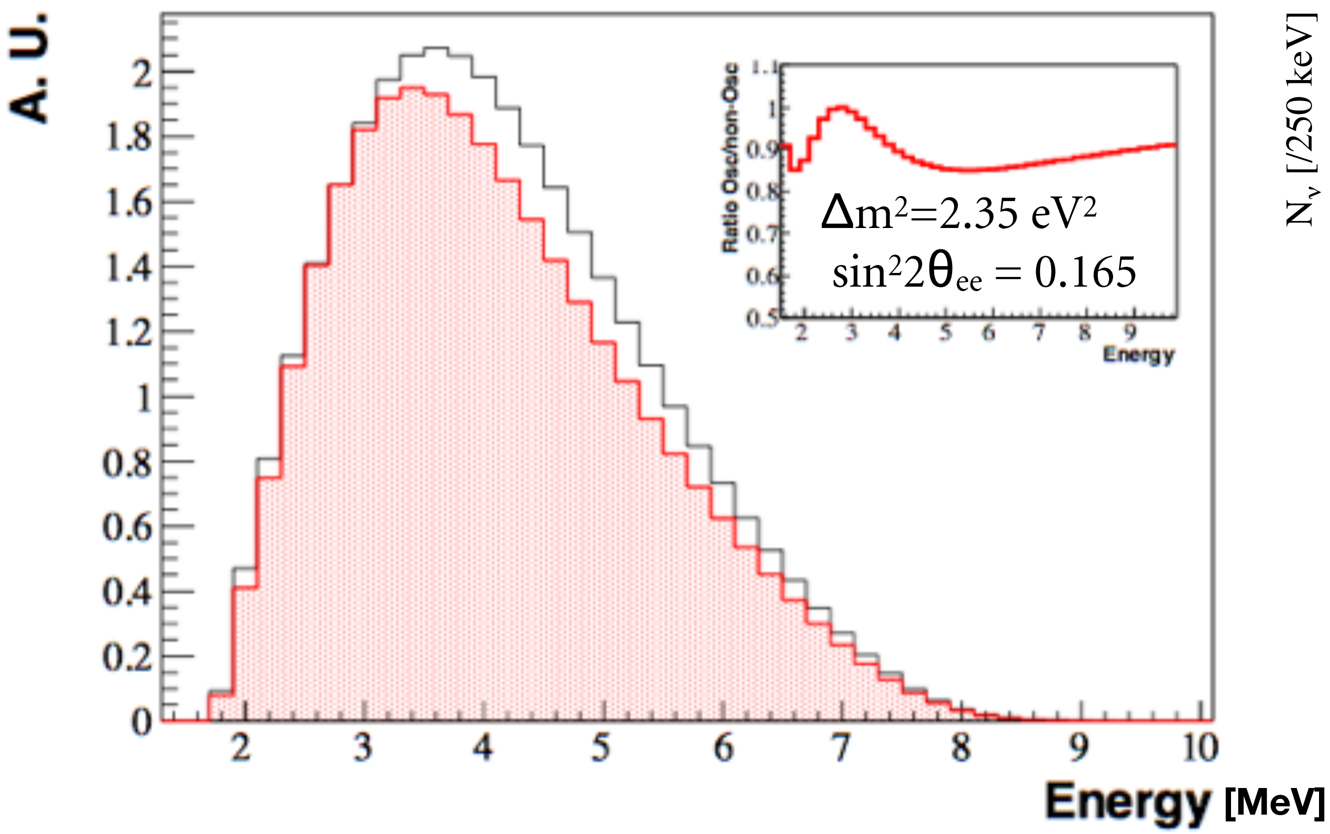


P. Wilson, April 22, 2016 12

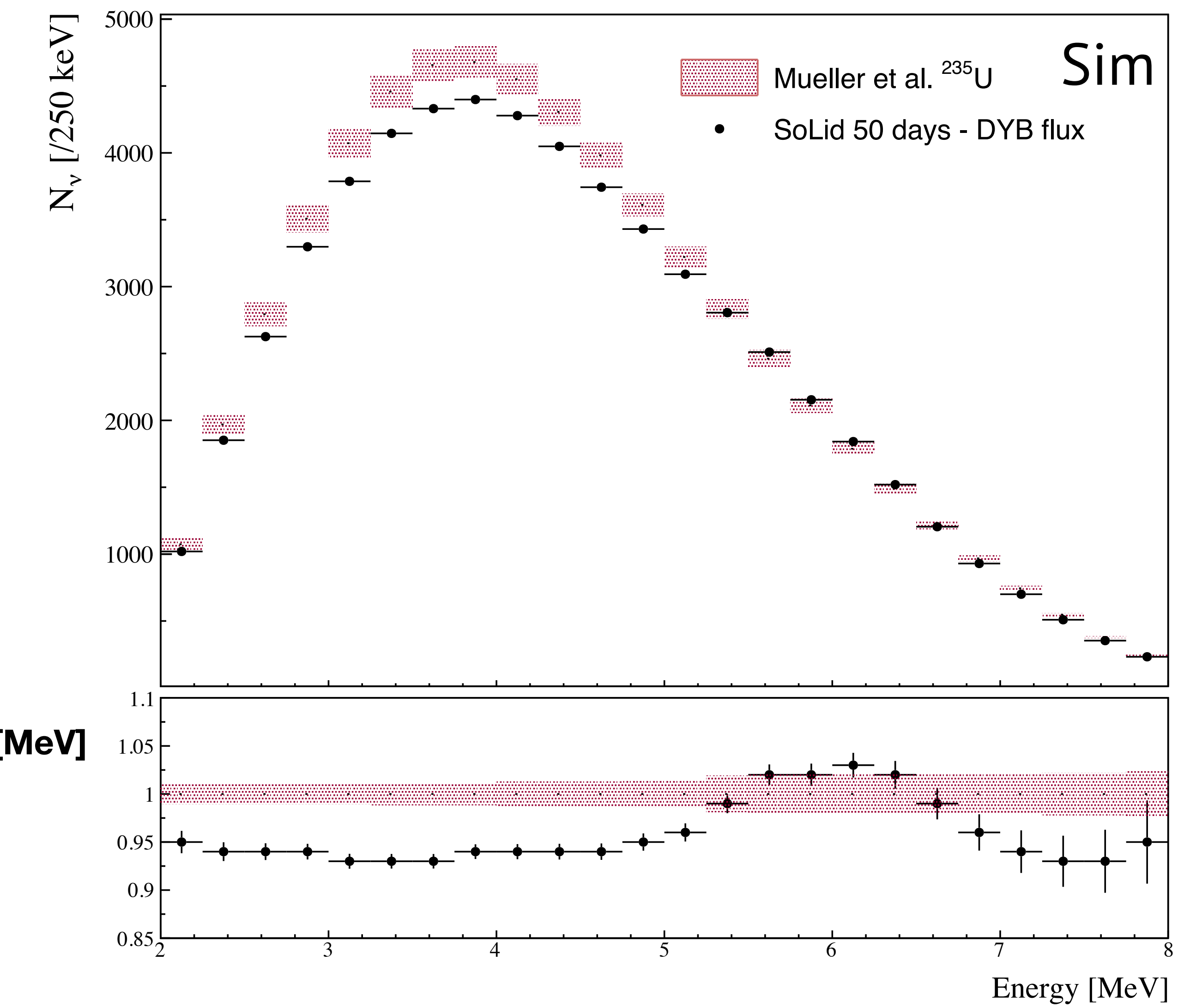
Very short baseline reactor experiment

- Upcoming experiments require **percent level precision** in antineutrino spectrum measurement

Oscillation search

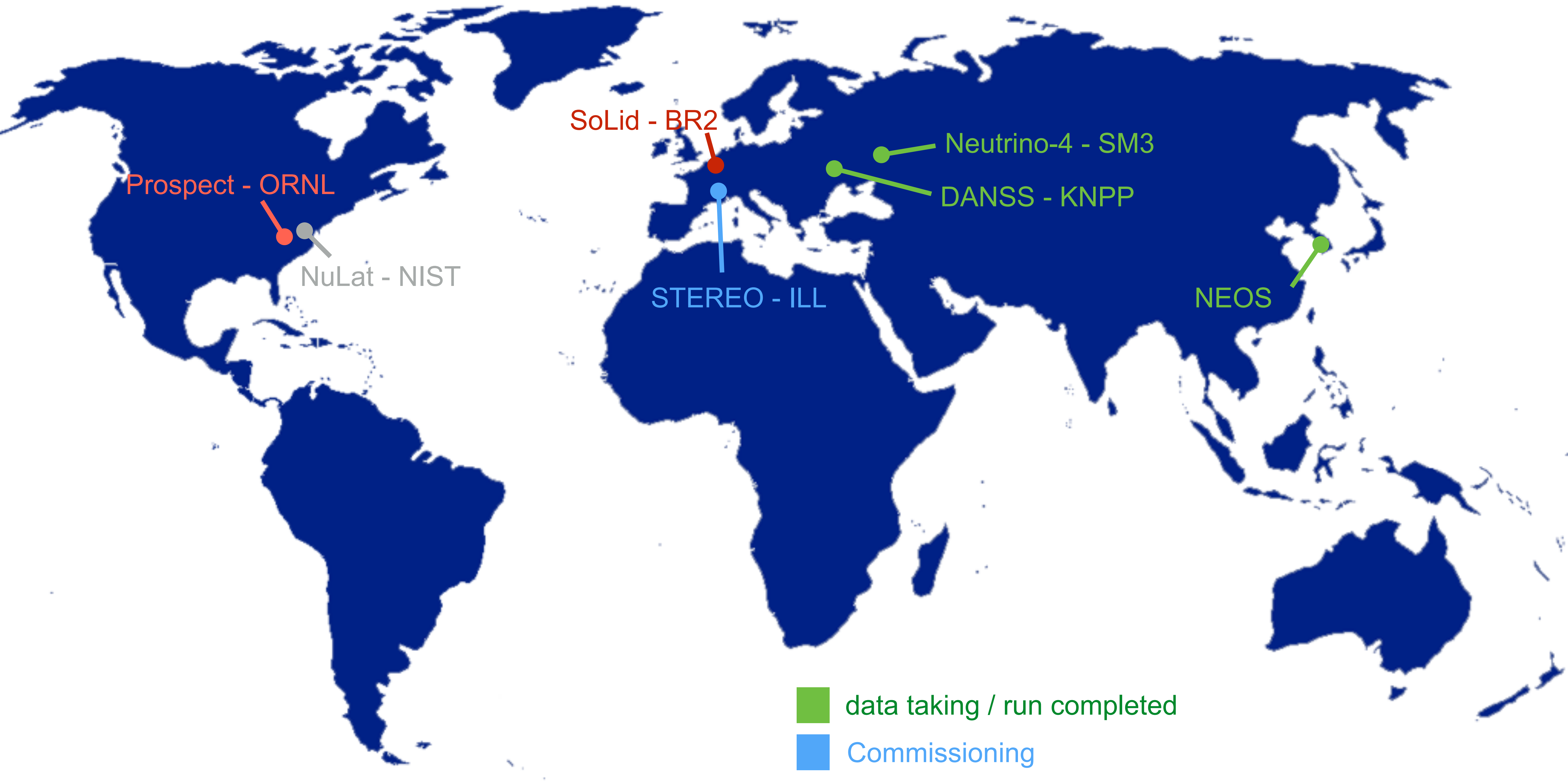


Spectrum shape



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

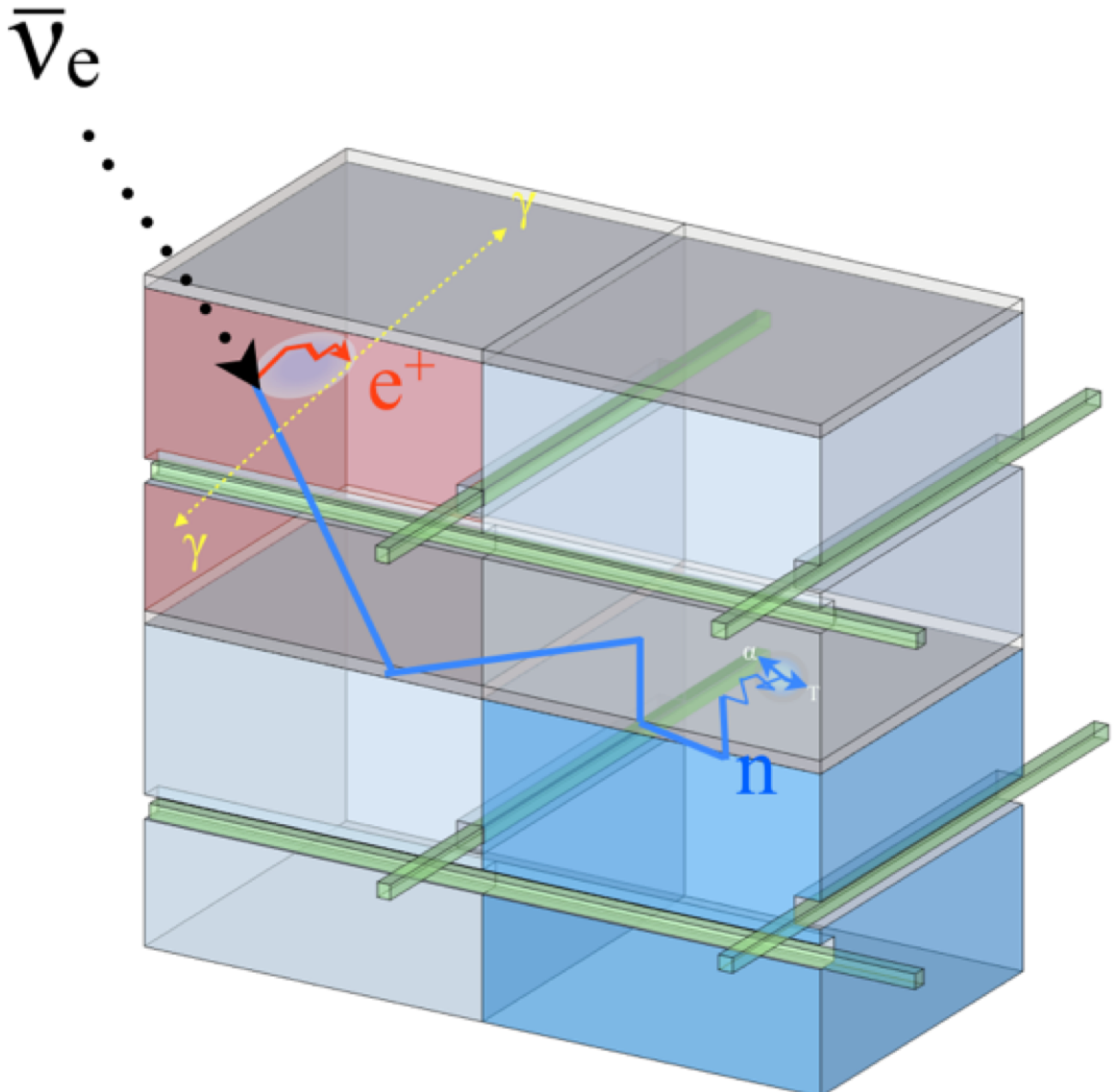
New reactor experiments

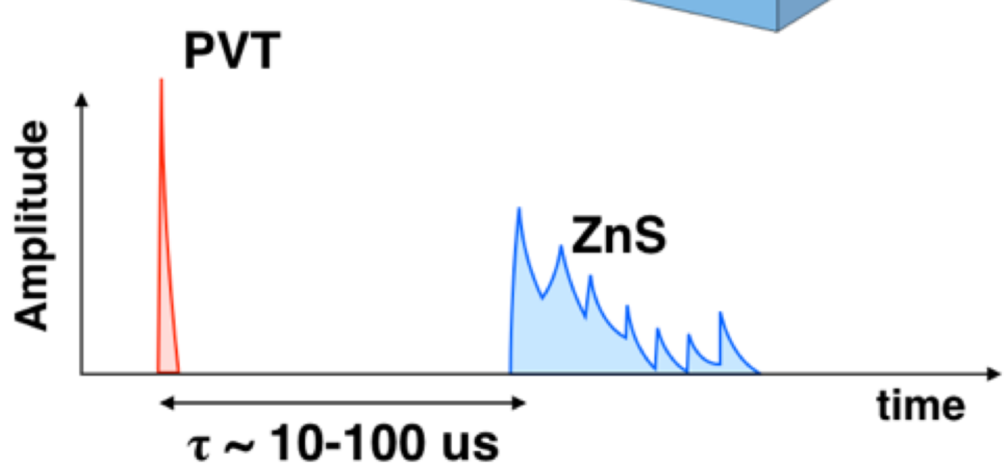


New reactor experiments

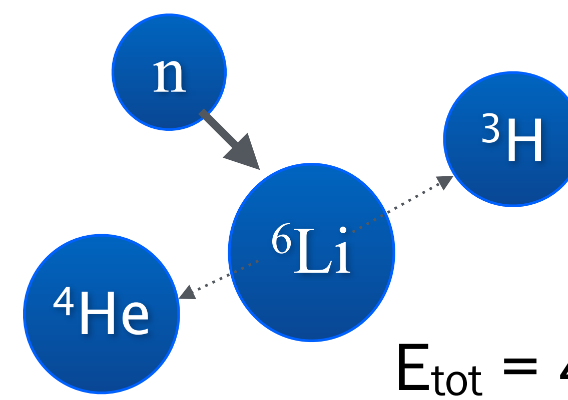
	Tech	Reactor	P [MW]	L (m)	M (tonnes)
STEREO (Fr/Ger)	LS+Gd	ILL-HFR	57	8.8-11.2	2
Neutrino-4 (Ru)	LS+Gd	SM3	100	6-12	1.5
PROSPECT (US)	LS + ^{6}Li	ORNL HFIR	85	7-18	2
SoLid (UK/B/Fr)	**PVT + ^{6}LiF:ZnS**	**SCK • CEN BR2**	**45-80**	**5.5-11**	**2**
DANSS (Ru)	PS + Gd	KNPP	3000	9.7-12.2	0.9
NEOS (KO)	PS + Gd	Younggwang	2800	25	~1

3D segmented composite detector





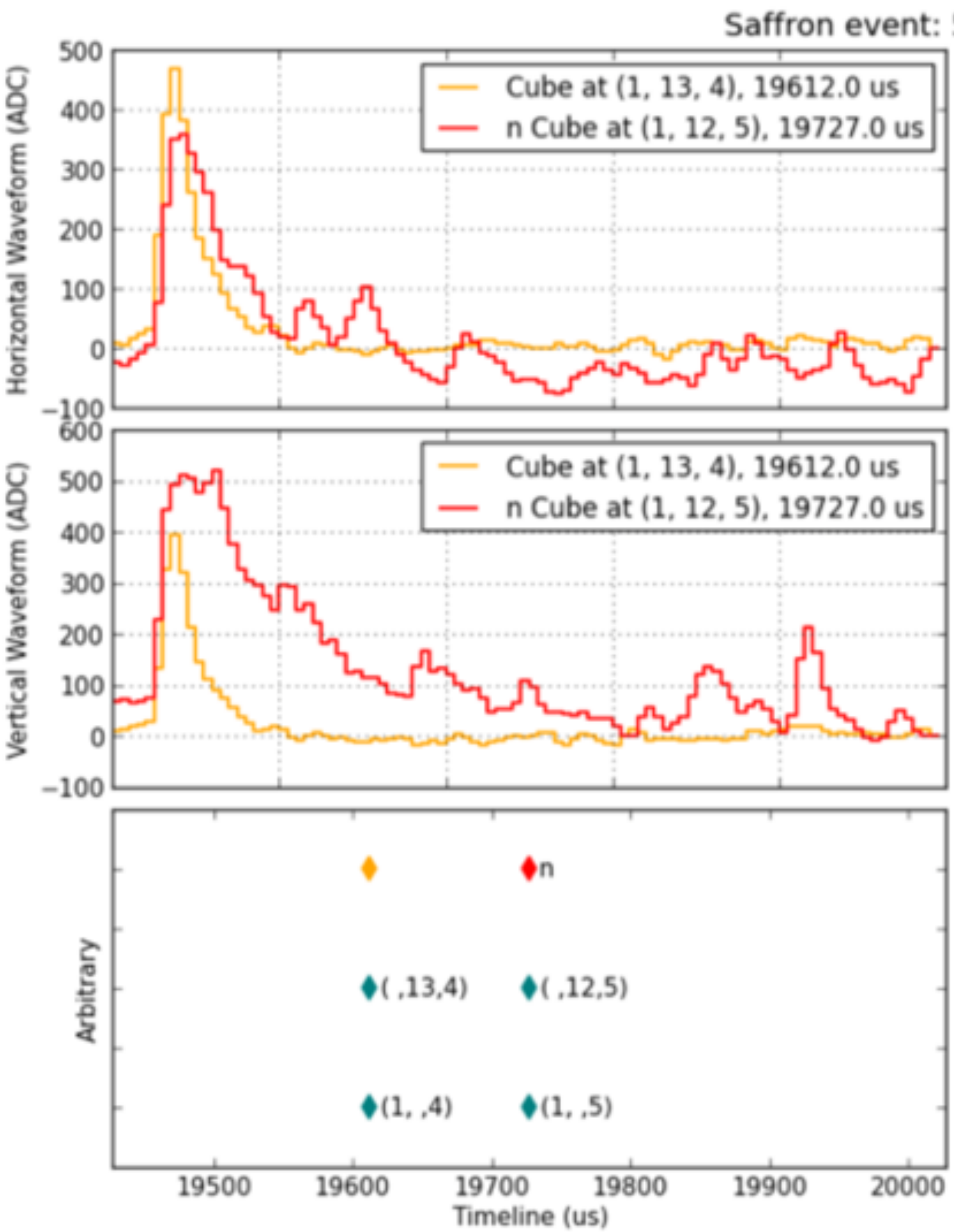
- composite /dual scintillator detector element :
  - 5 cm x 5 cm x 5 cm PVT cube segmentation to contain positron energy and localise interaction
  - Layer of LiF:ZnS(Ag) for neutron detection close to interaction

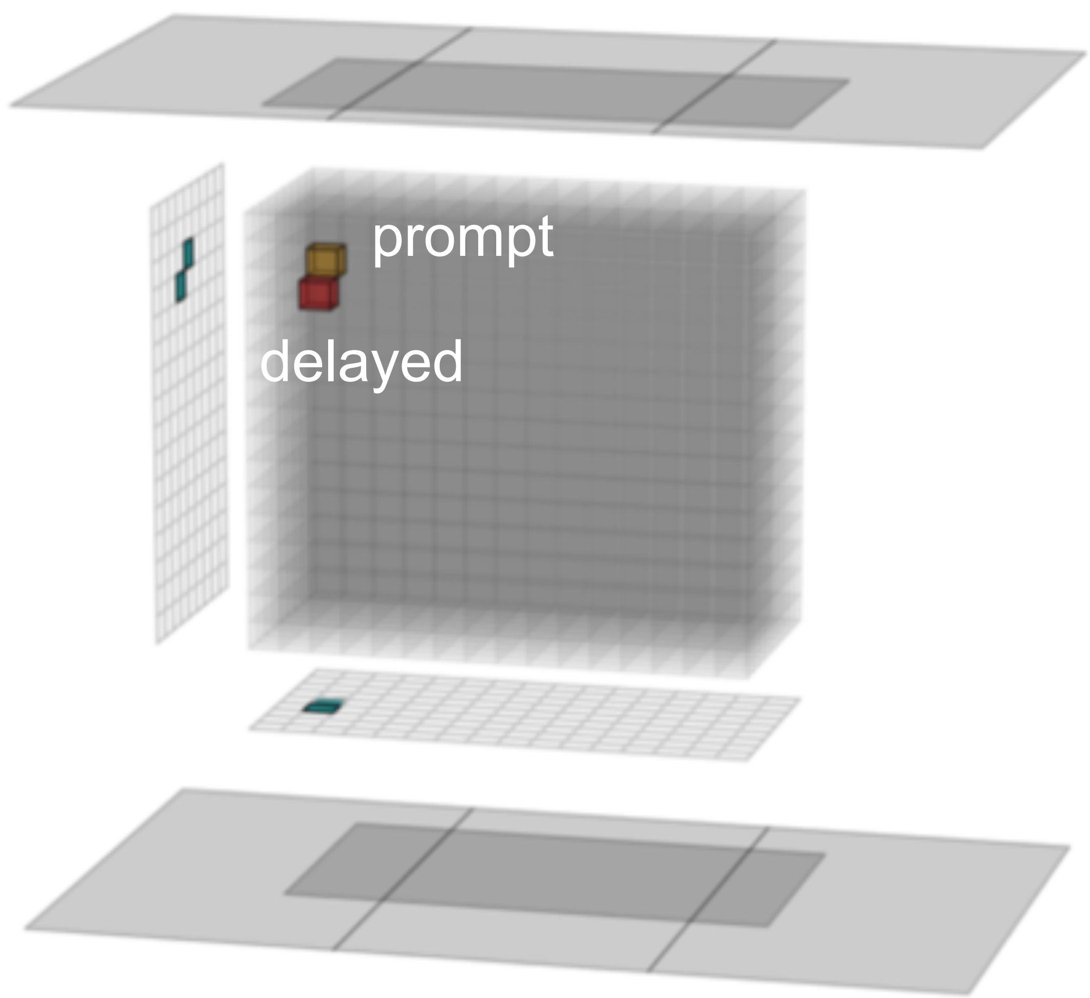


E_{tot} = 4.78 MeV

- 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

IBD candidate

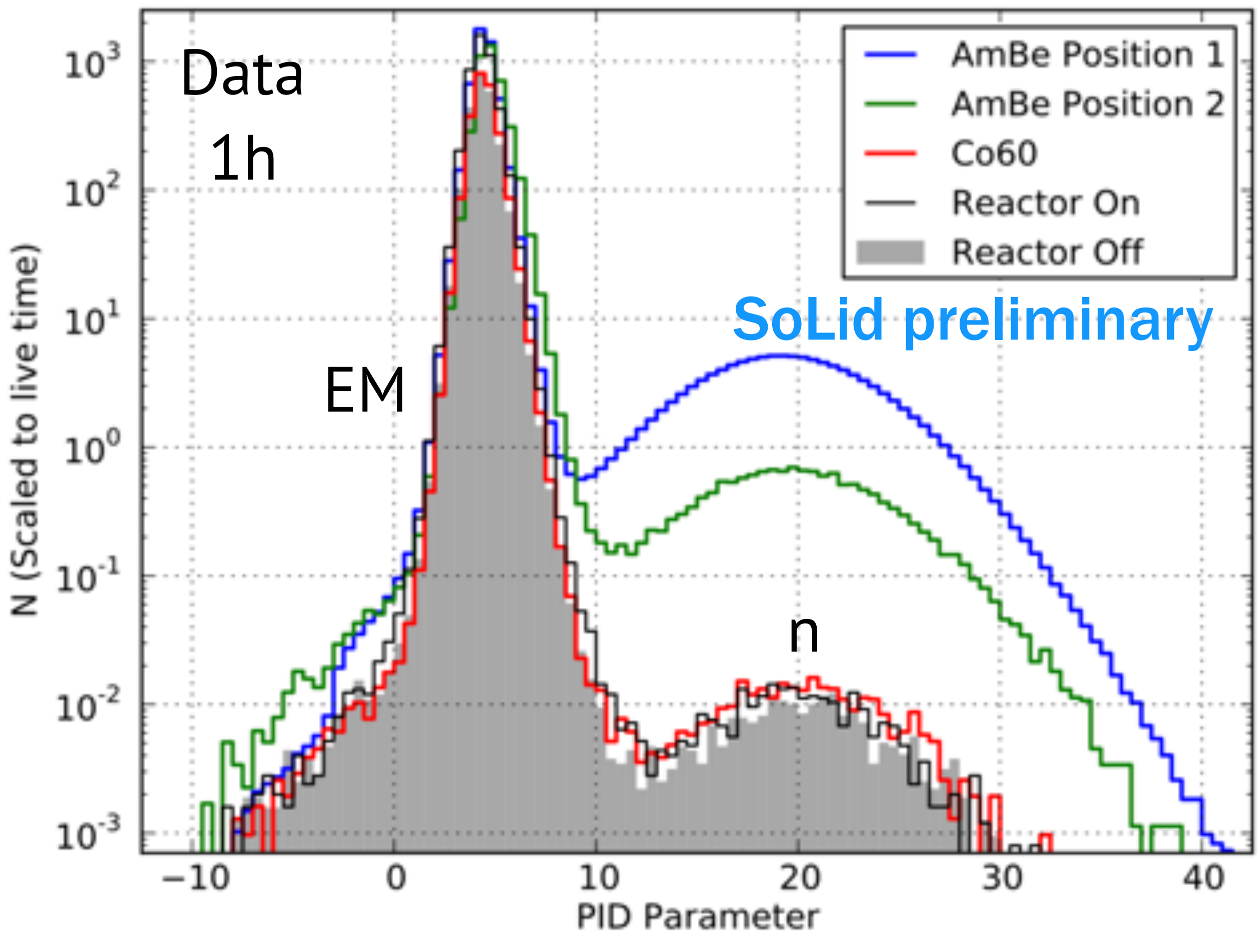


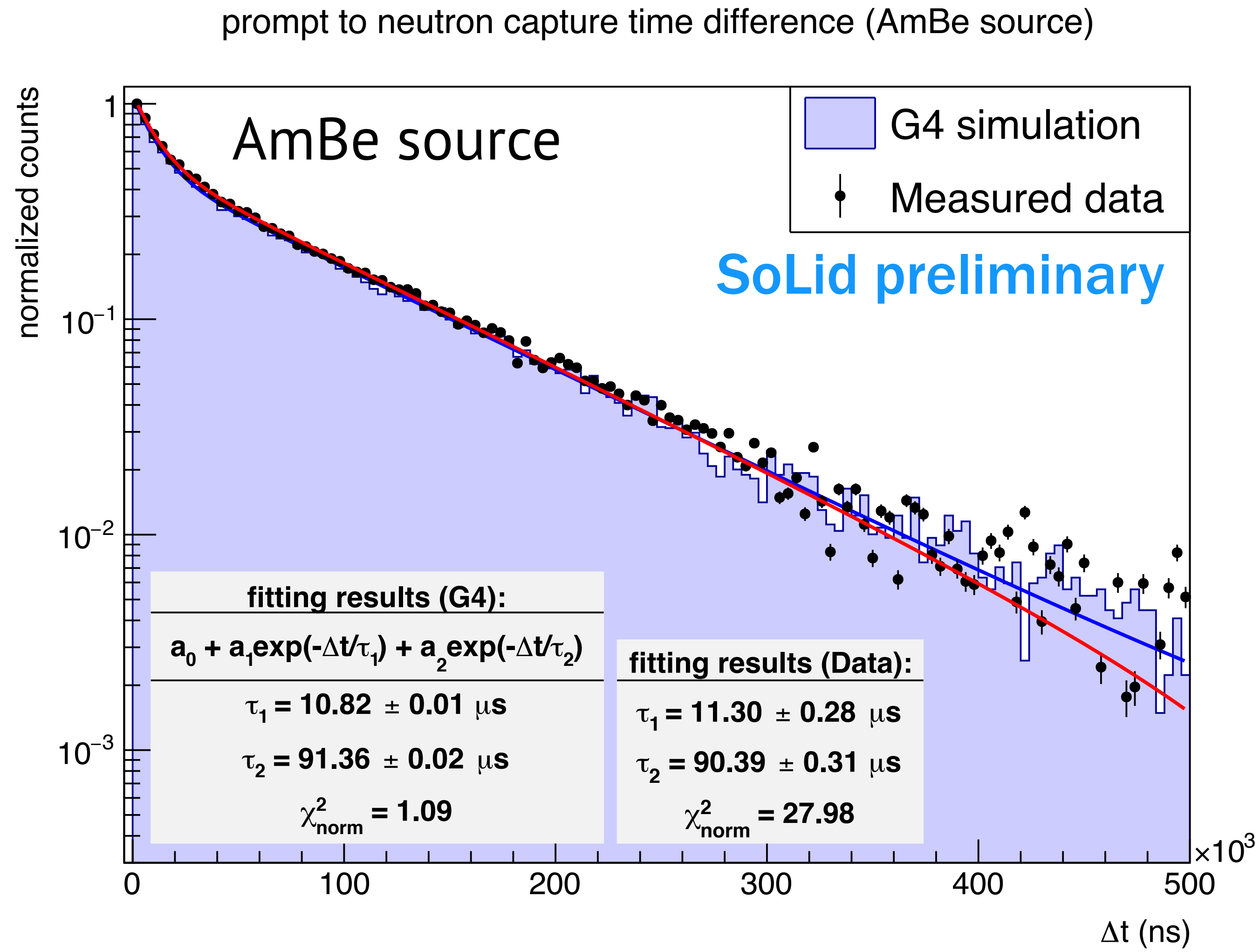


Data

Deployment at BR2

Neutron ID and capture time

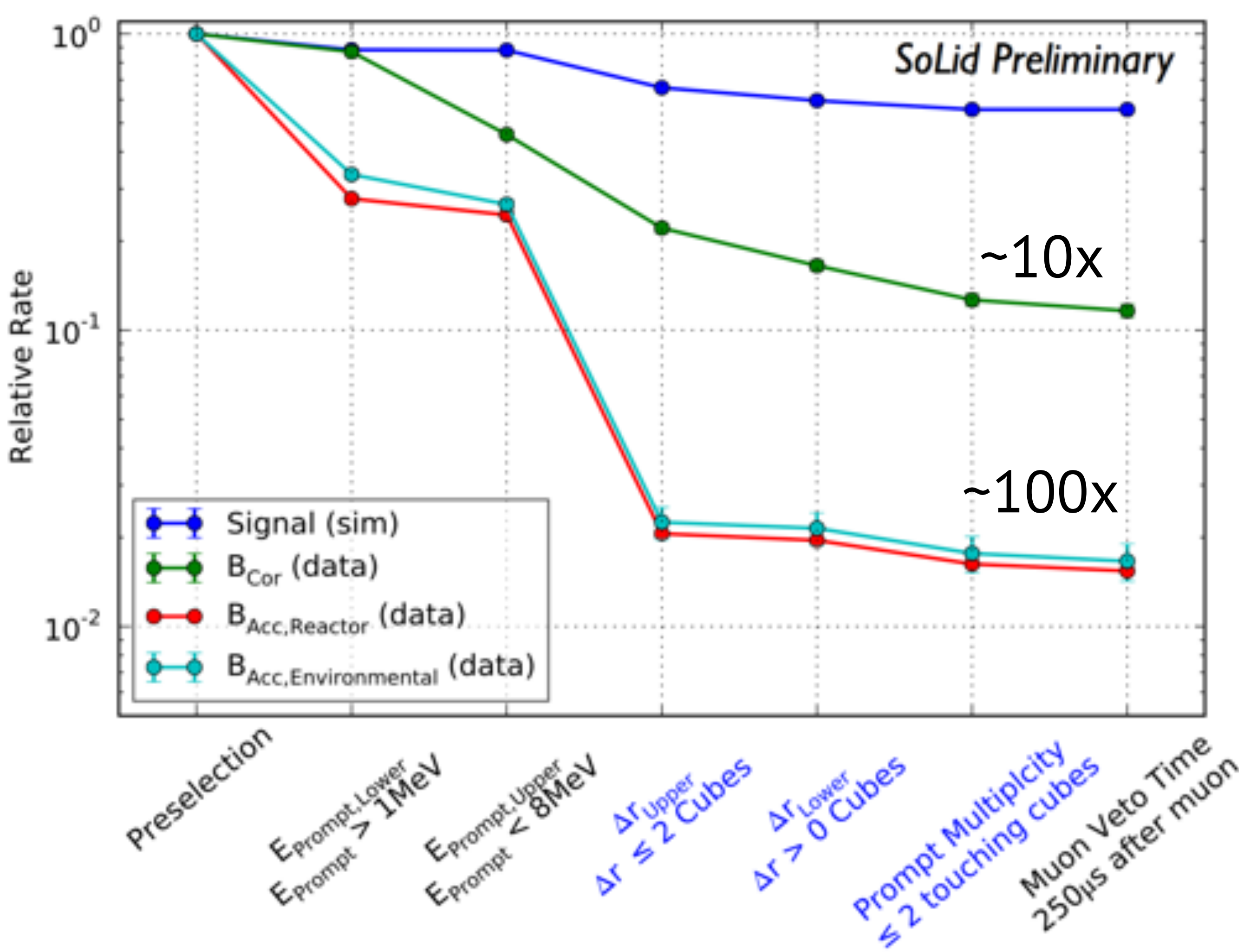


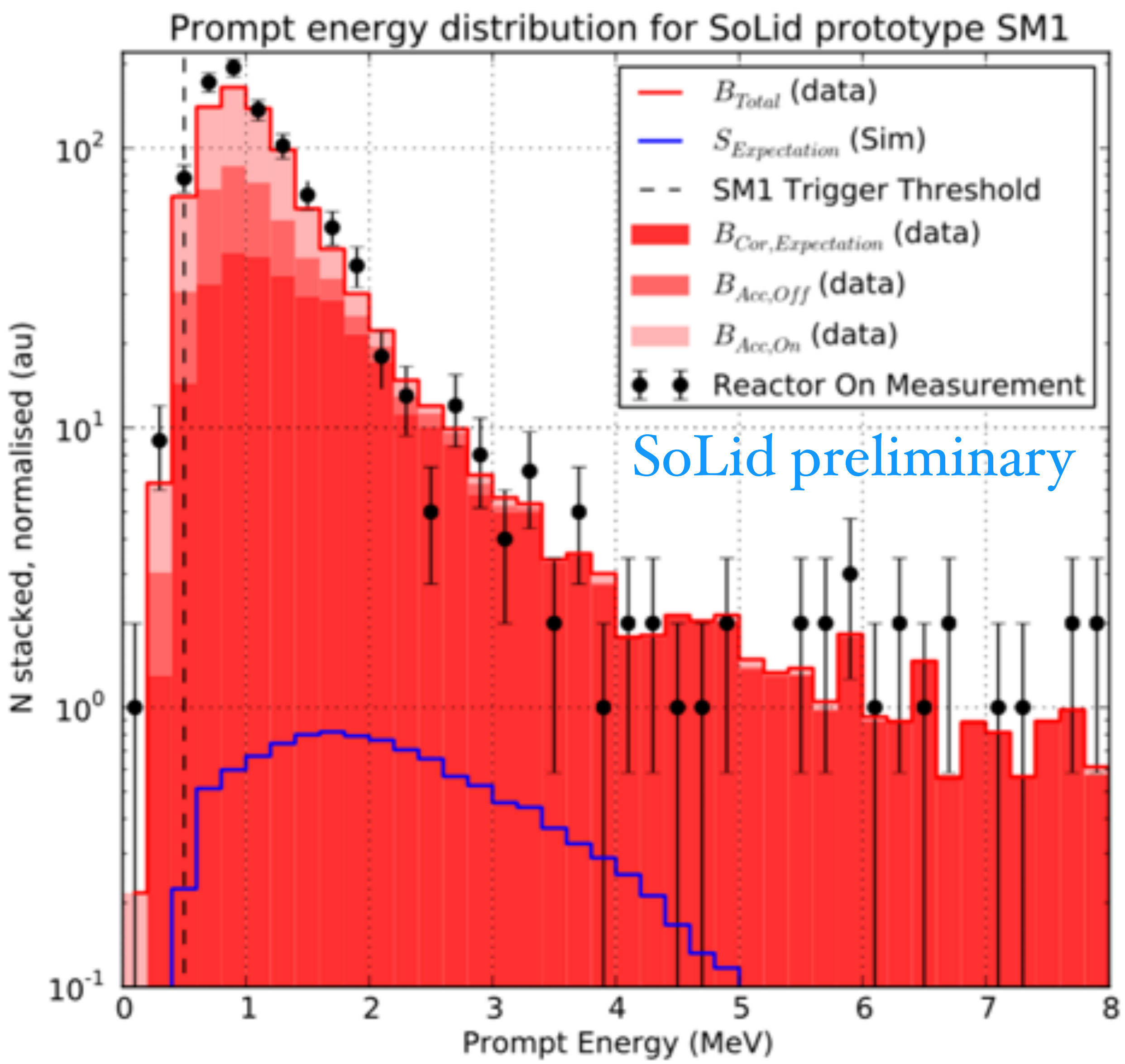


- Validated PID, neutron tranport simulation (MCNP & G4) and Li capture efficiency

Signal analysis

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



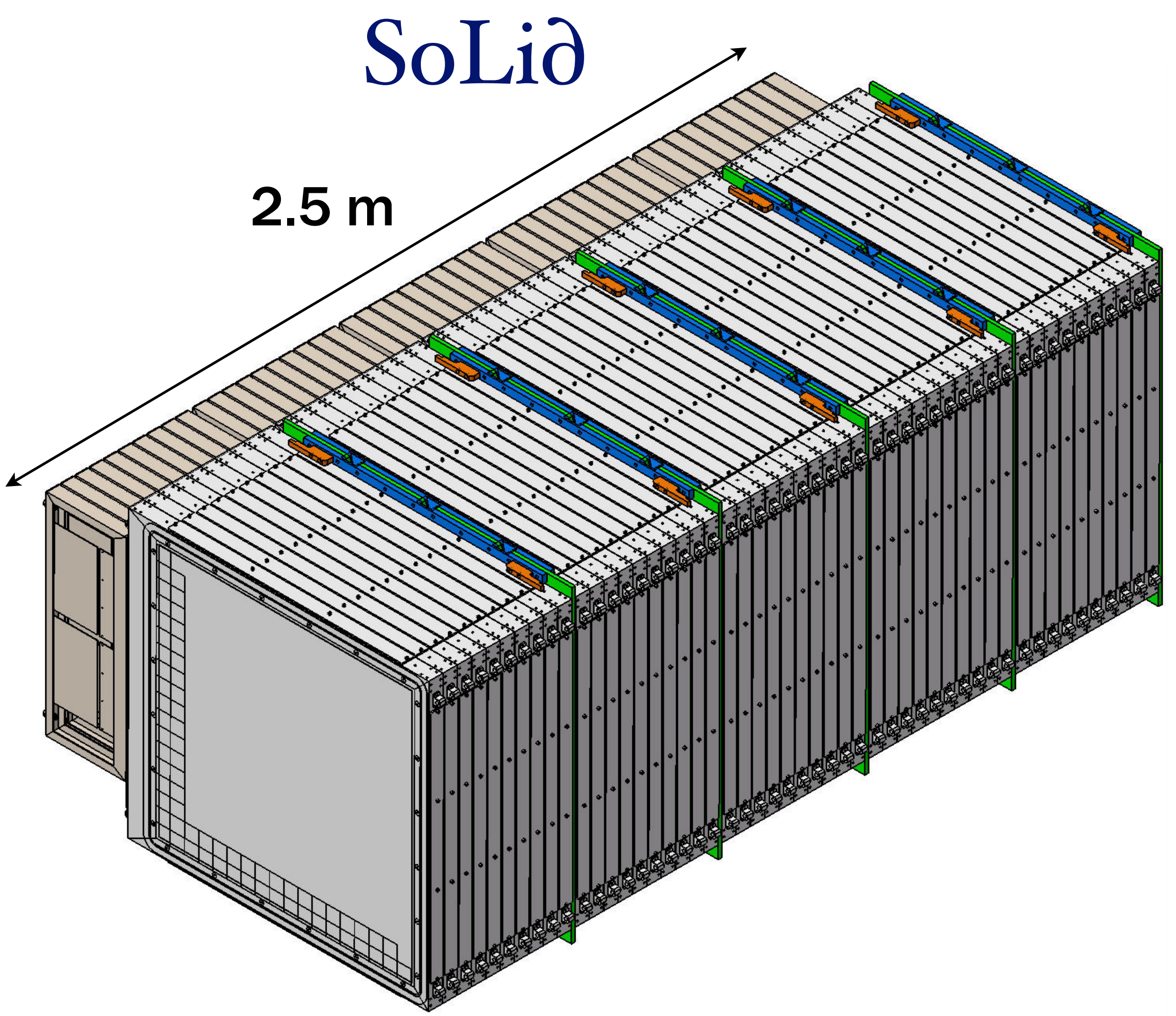


SoLid in the UK

- **SoLid is a UK led experiment based on UK technology**
  - responsible for 1/3 of total fiducial mass
  - key deliverables in electronics
  - KE in neutron detection and antineutrino monitoring
- **Imperial**
  - **UK PI** and current **spokesperson**
  - Module design and construction
  - Background and shielding
- **Oxford**
  - Analog design, test and delivery of customised electronics
  - DAQ
- **Bristol**
  - Digital board design and delivery
  - neutron trigger
  - integration

- UK leadership in the project was paramount to succesfull deployment of SM1 prototype and data taking and analysis (Led by Bristol student)
- H2020 funded in Dec 2015 secured phase-I program for period

Phase-I 2016-2017



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

breaking news:
1 additional module funded by French ANR !

SoLid in the UK

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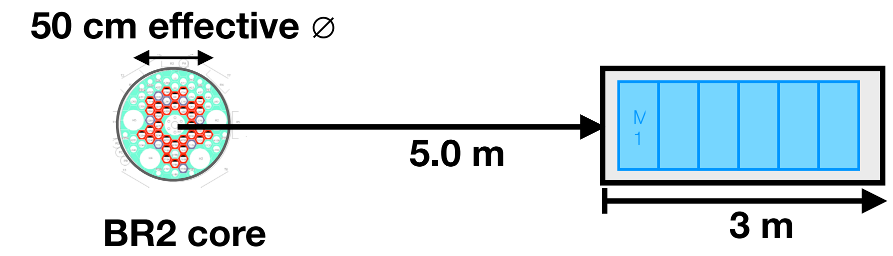
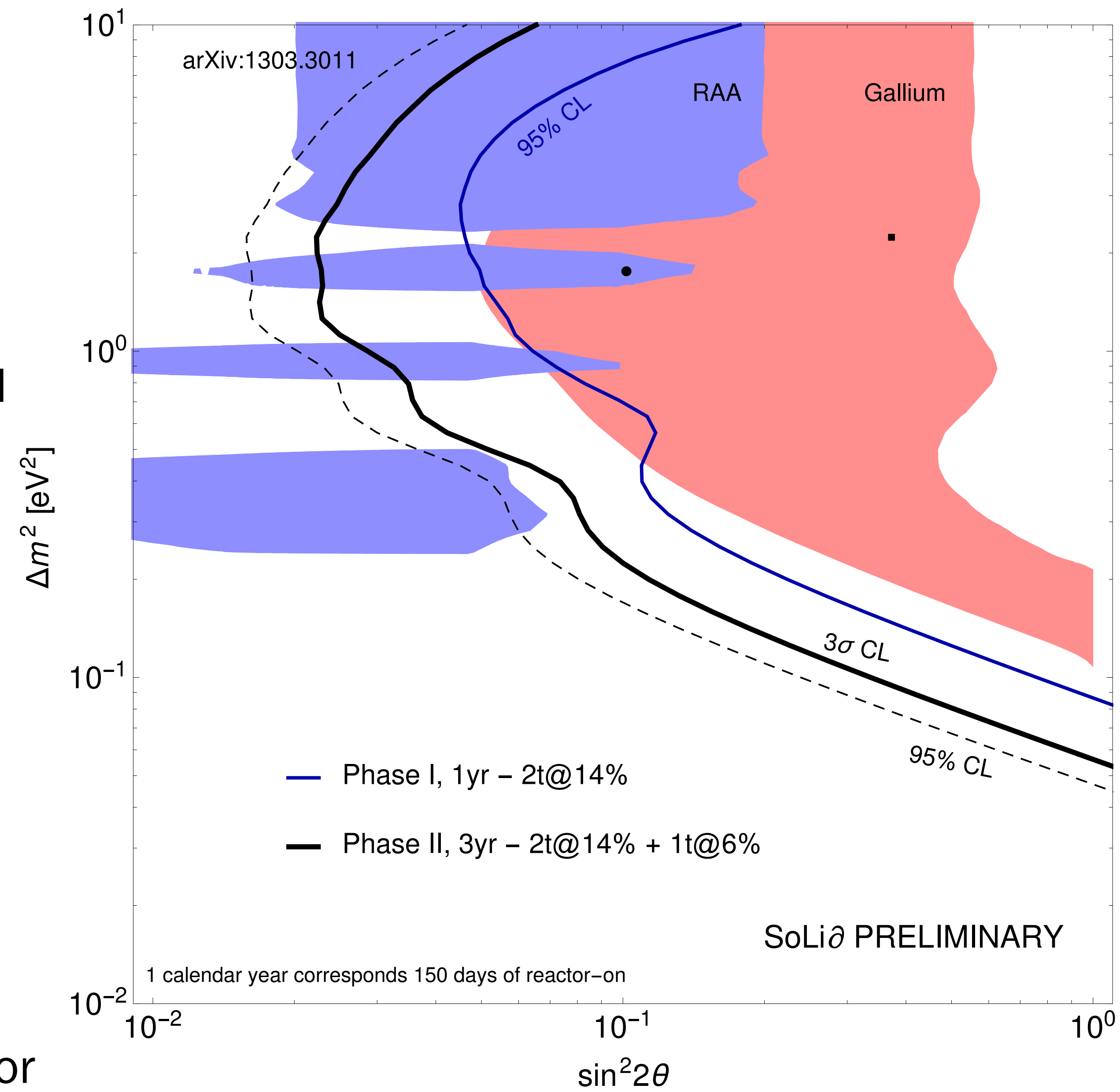
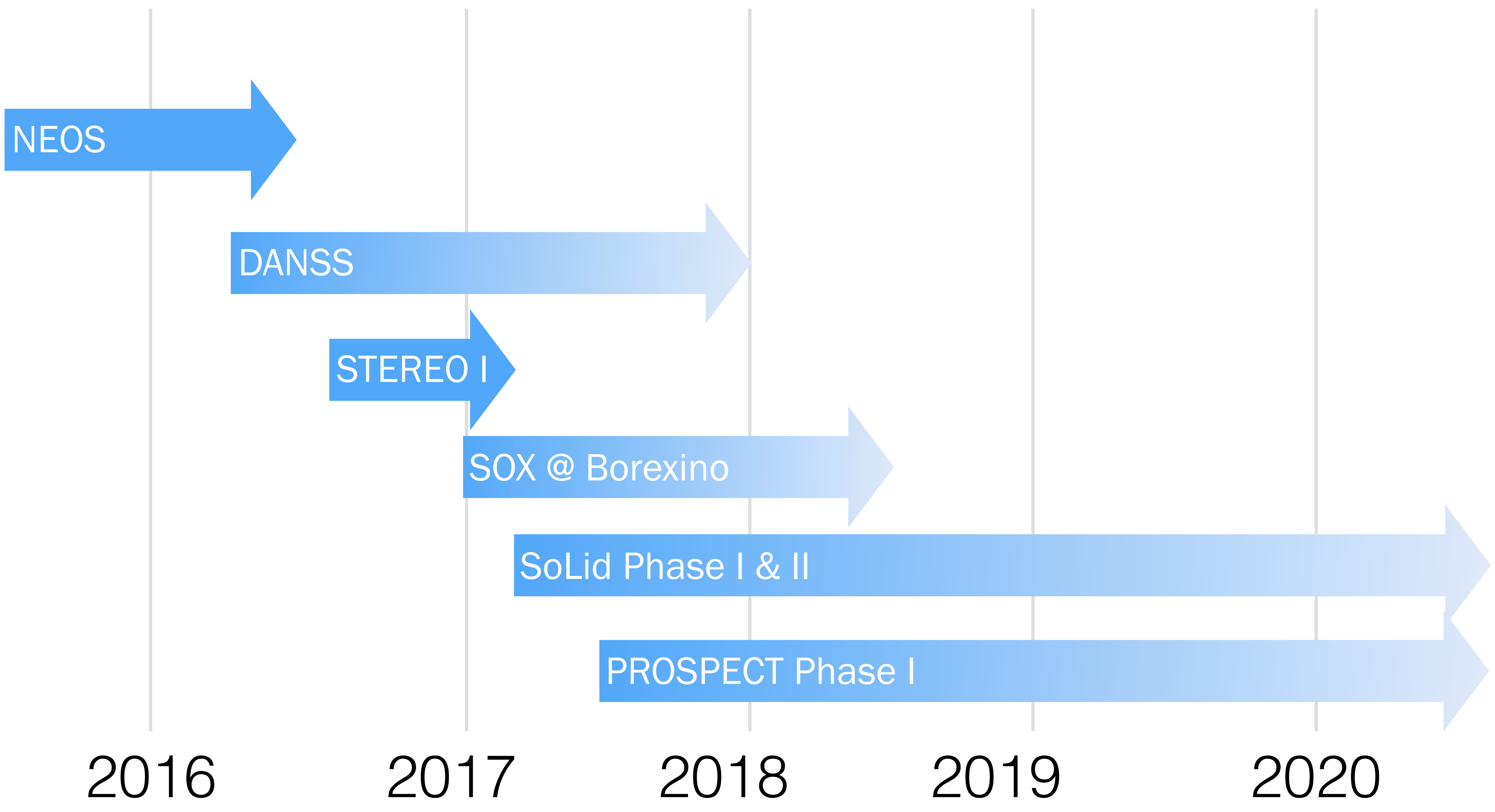




- UK leadership in the project was paramount to succesfull deployment of SM1 prototype and data taking and analysis (Led by Bristol student)
- ERC funding Dec 2015 secured phase-I program for period

Timeline for reactor/source experiments



Summary

- Short baseline program well covered in the UK for a definite answer on existance of 1 eV^2 sterile neutrino by 2020-2021
  - a few projects with specific timeline and physics reach
  - very good opportunity for younger generation to gain responsibilities at international stage
  - **UK driving many areas** of the SBN program at FERMILAB
    - **largest non-US collaboration** with active role in LAr reconstruction and analysis of microBooNE
    - **microBooNE** only LAr detector online with very encouraging first results
    - **SBND** adds wide physics program and R&D inline with DUNE
    - goal to adress MiniBooNE excess and LSND anomaly
- UK also leading very short baseline reactor experiment
  - SoLid to start running early next year with first strong limit expected after 150 days of reactor
  - develop new technology for applications in radiation detection, non-proliferation, material engineering etc…
- **First results only a few years away !**

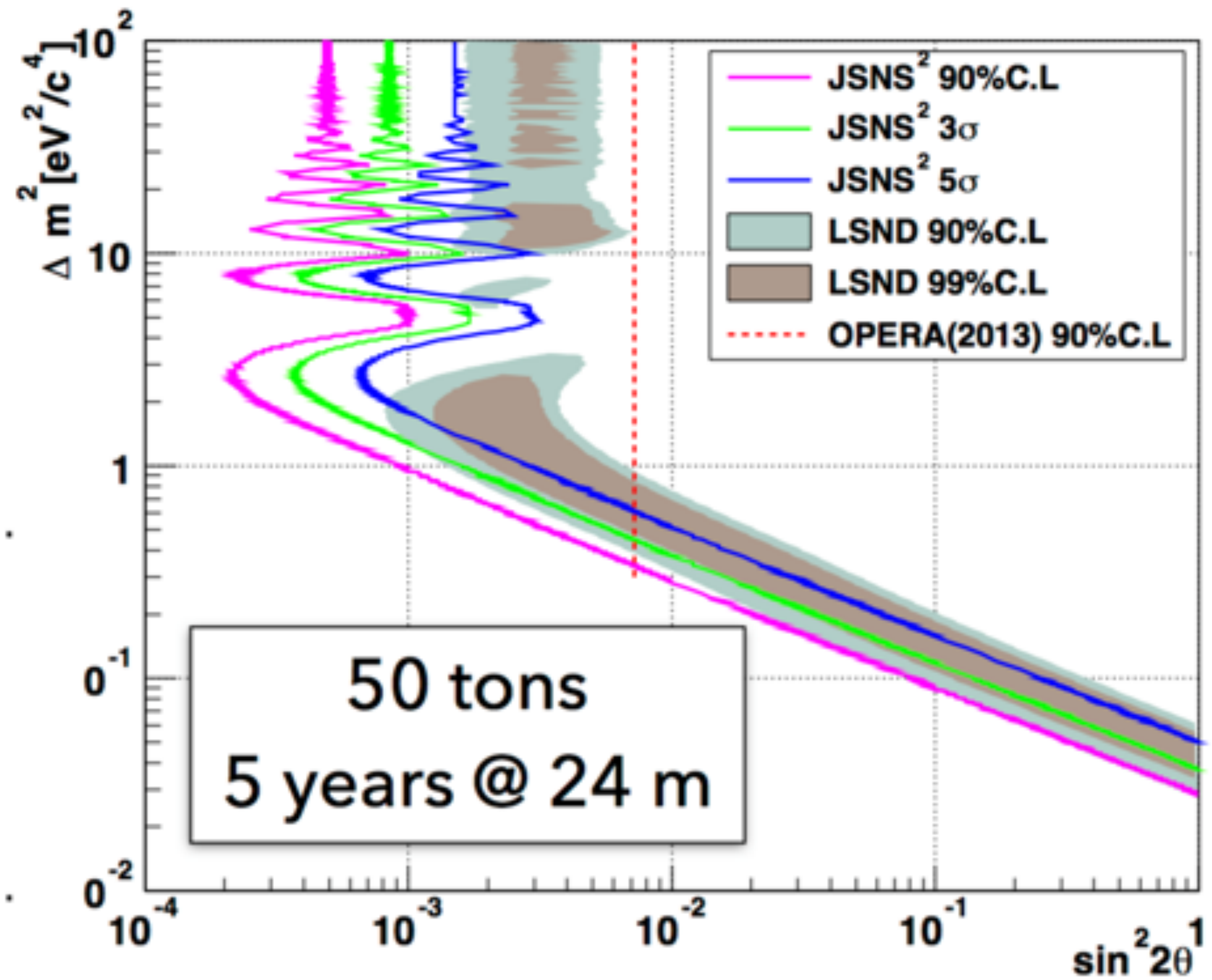
Other projects JSNS^2

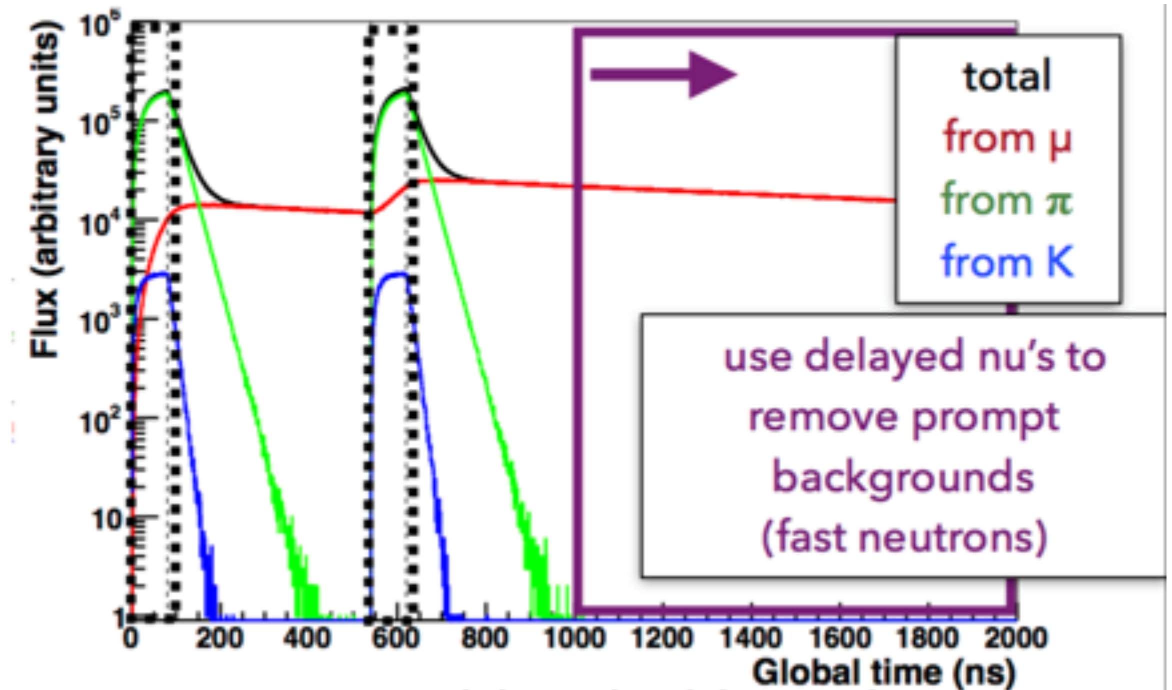
Sterile neutrino search with:

$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu \ ; \ \overline{\nu}_\mu \rightarrow \overline{\nu}_e \ (\text{osc.}) \ ; \ \text{IBD}$$

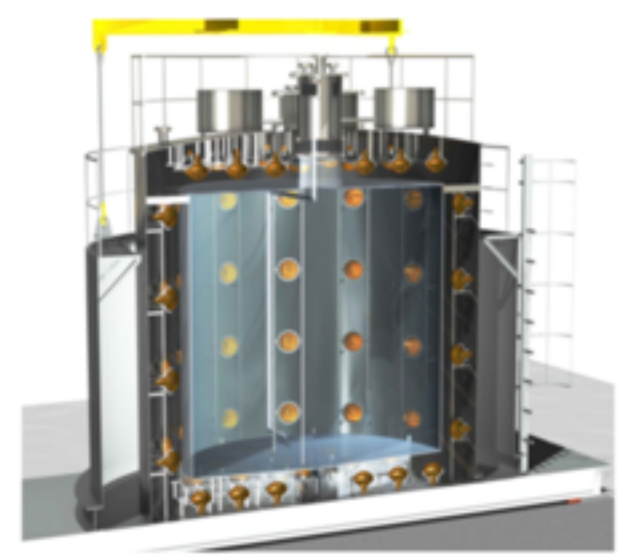
w/ timing selection, excellent purity, high energy resolution

A direct test of LSND





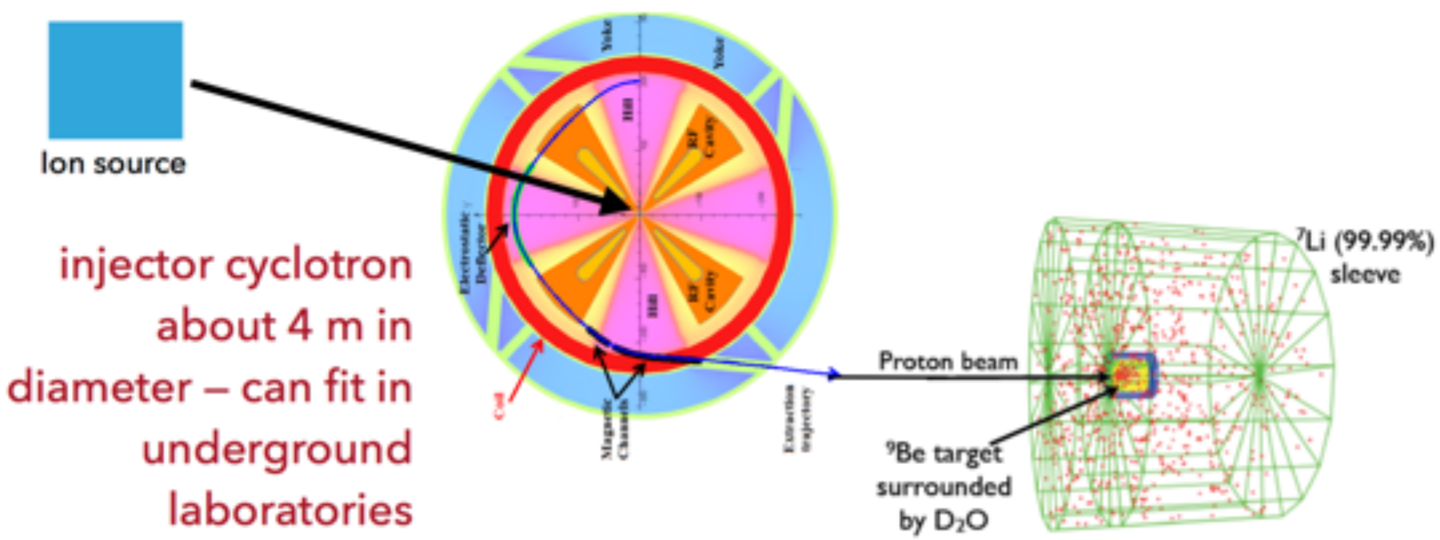
- 2 25-ton Gd-loaded liquid scintillator detectors, located at the *J-PARC MLF*: 1 MW, 3 GeV spallation neutron source

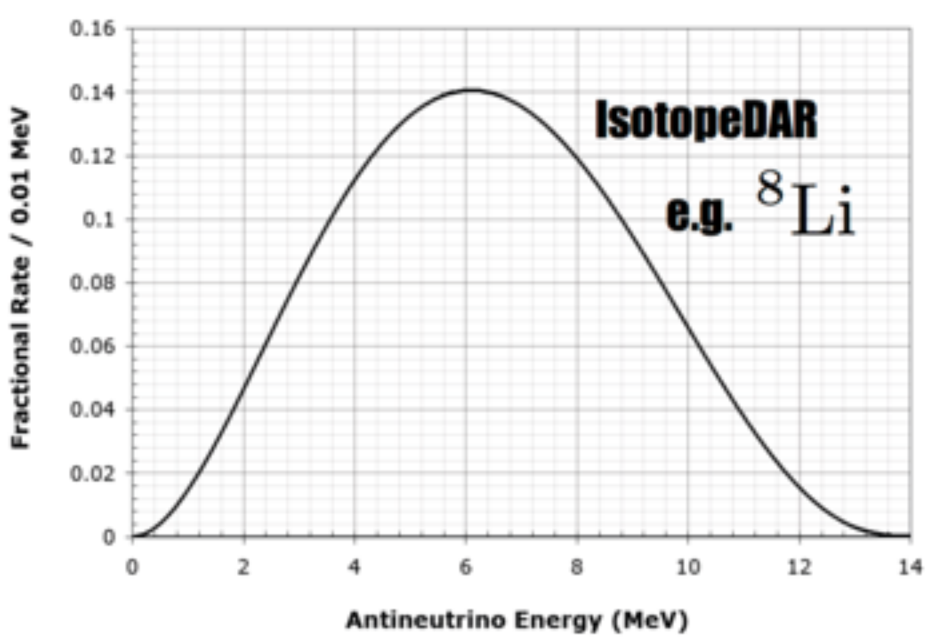


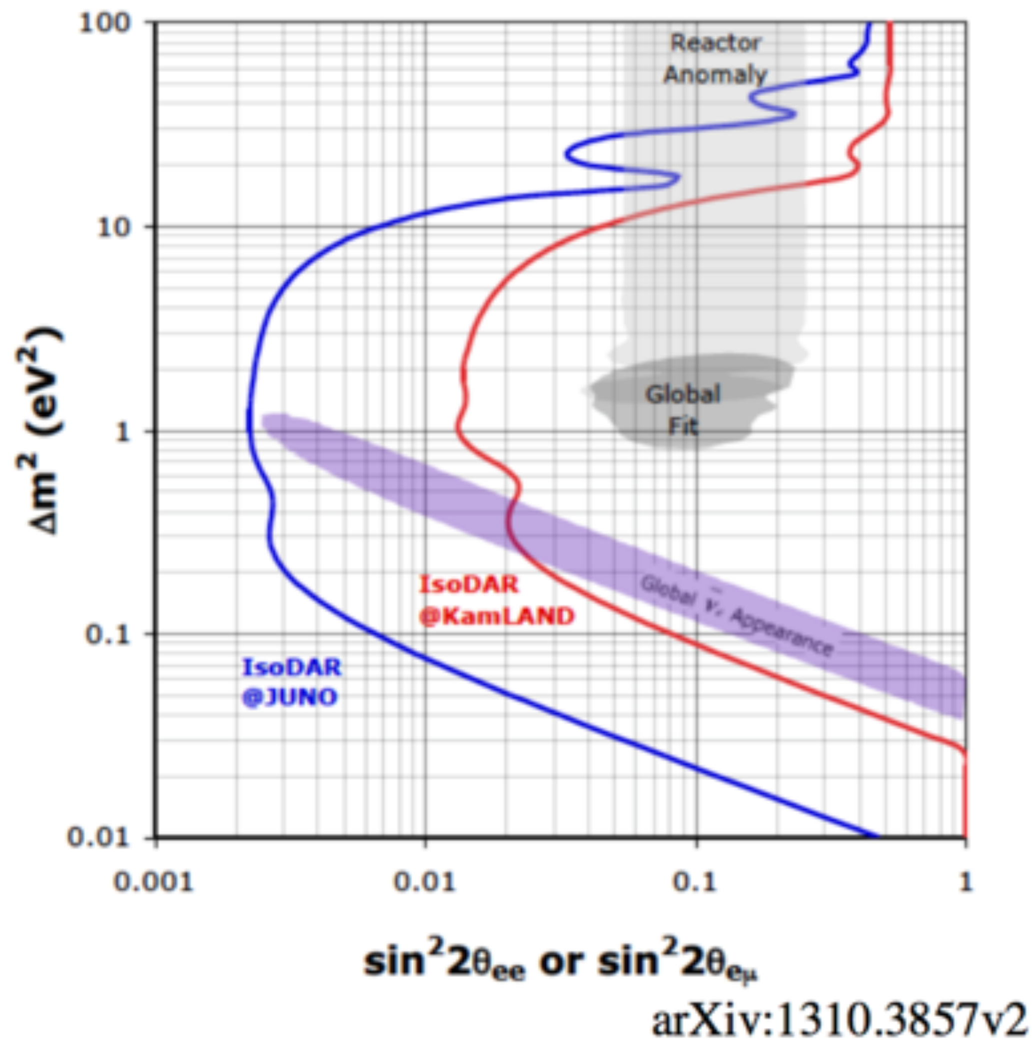
- Signals are nue-bar IBD events

Other projects ISODAR

Received NSF MRI for state-of-art injection (can reduce cyclotron intensity reqs). system for IsoDAR





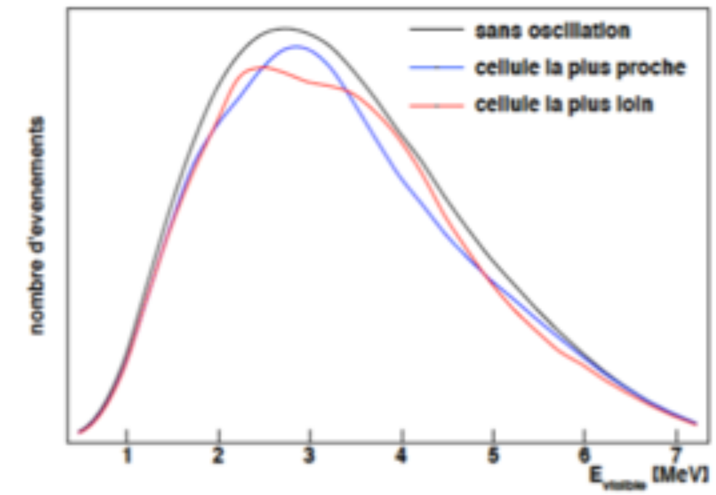


- do these projects represent an opportunity for developping future PP technology as well as offering the platform to increase UK researcher diversity of profiles and initiatives ?

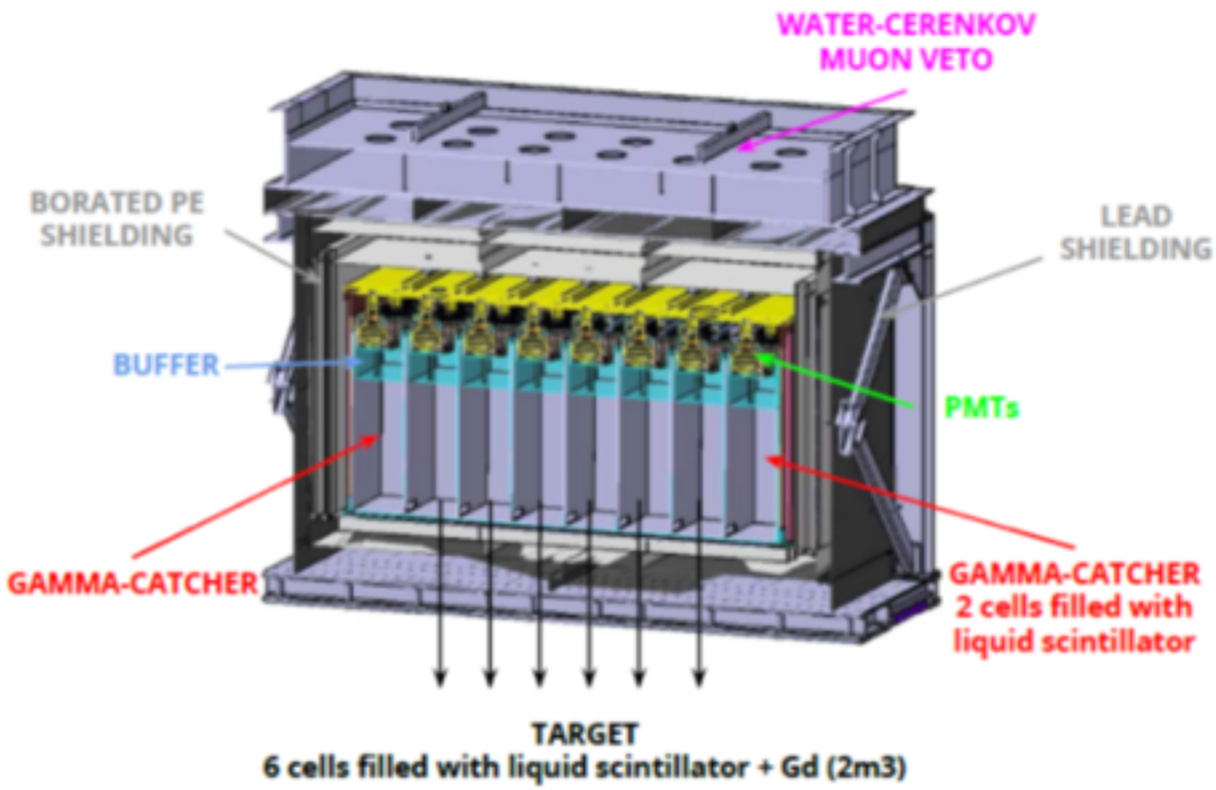
Back up

Supported by ANR

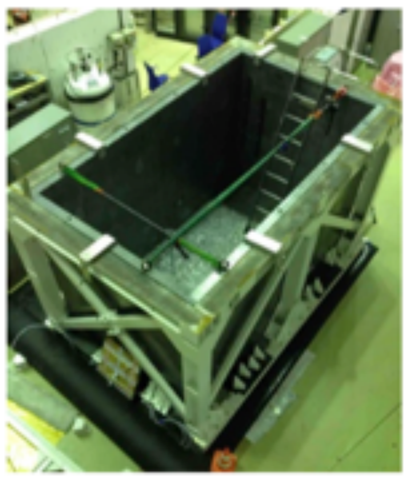
- ILL site : 58MW, compact core <1 m, highly enriched ^{235}U
- [8.9-11.1] m from core
- 15 mwe overburden
- Relative energy shape distortions in 6 identical cells



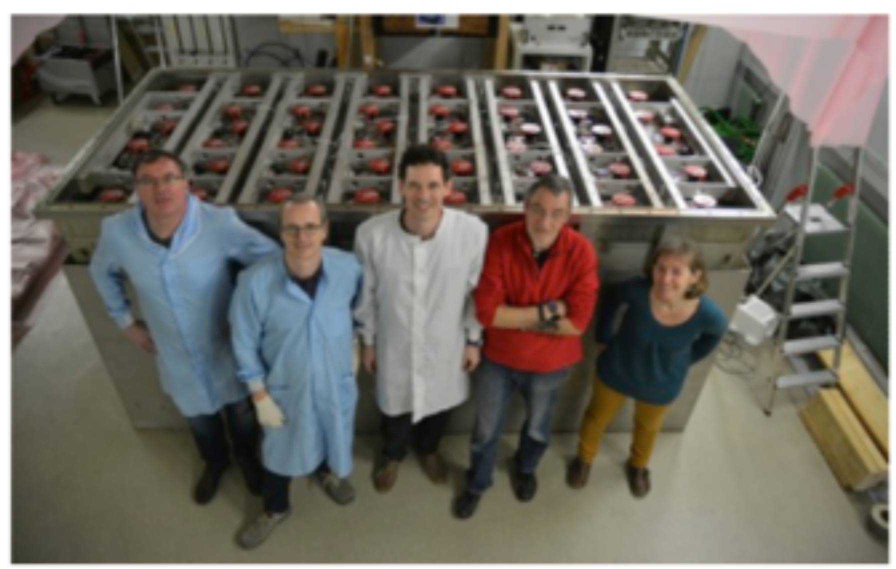
Goal : *Observe a new oscillation by comparing ν spectra in identical cells*

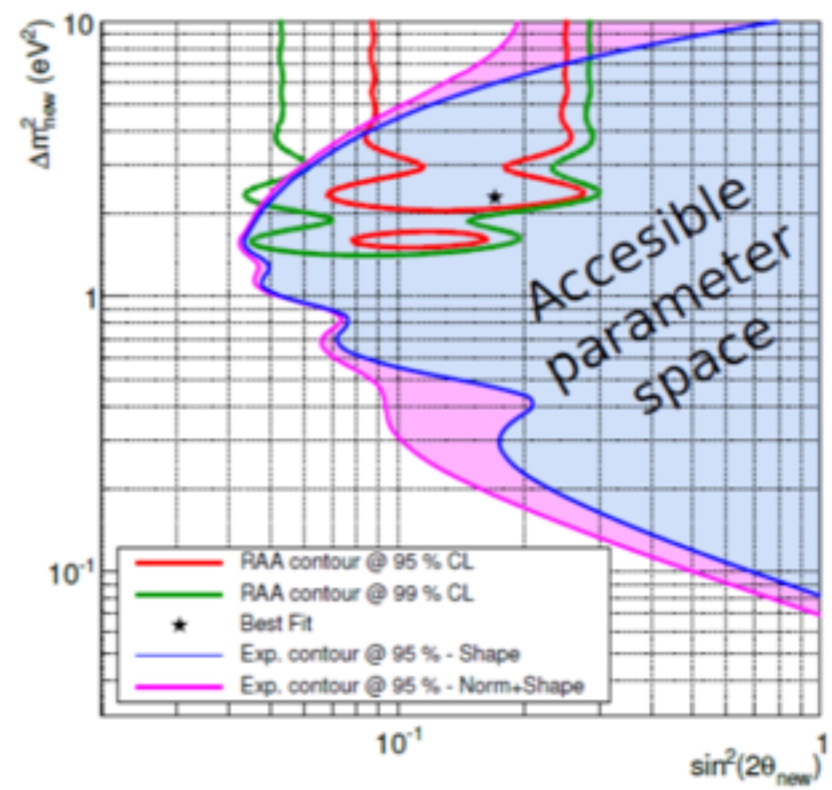


First data expected on **September 2016**



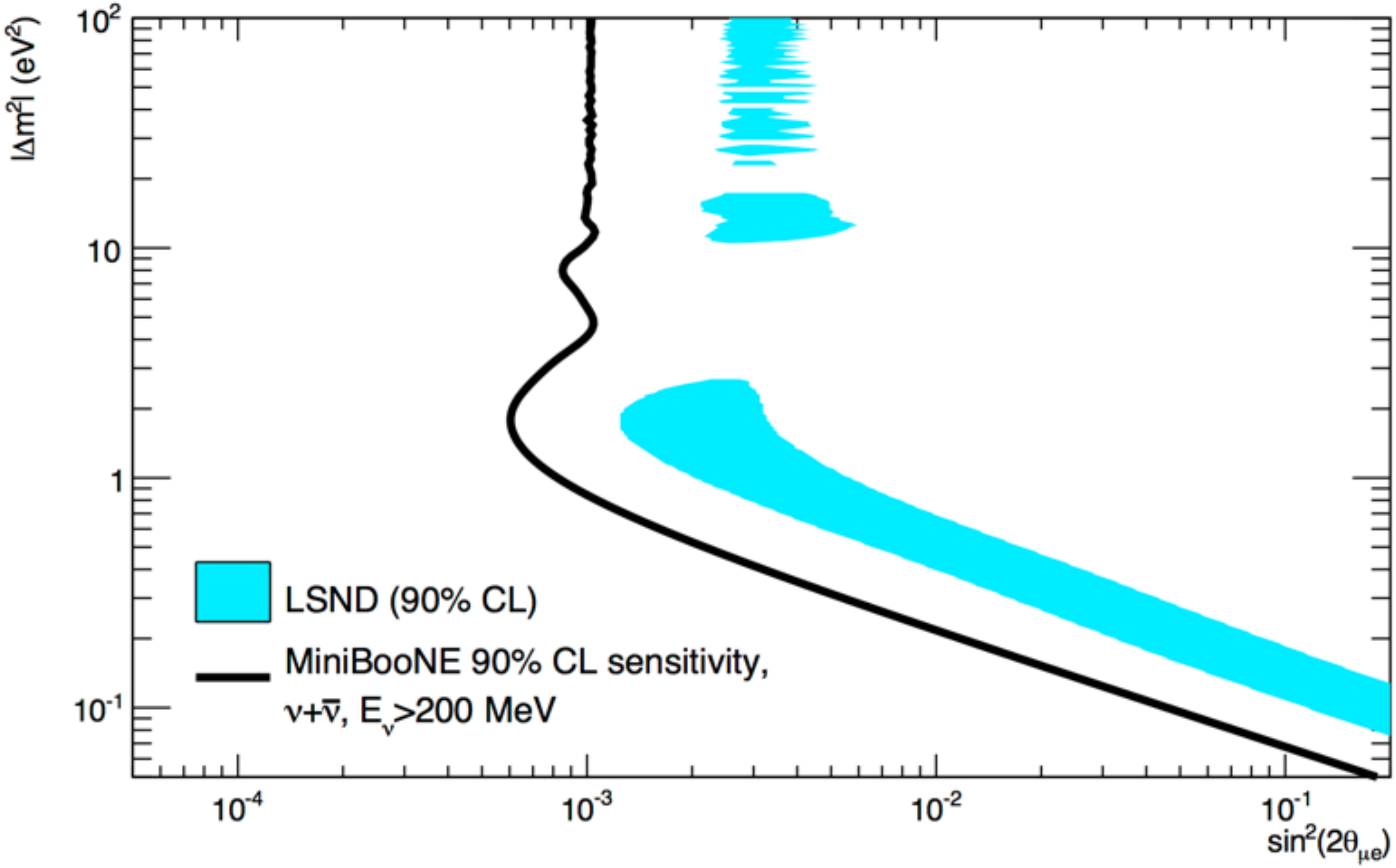
- Detector response validated with prototype cell
- Detector and active muon veto components fully integrated
- Passive shielding installation in progress
- STEREO site reinforced with lead and PEHD





What was MiniBooNE's sensitivity*?

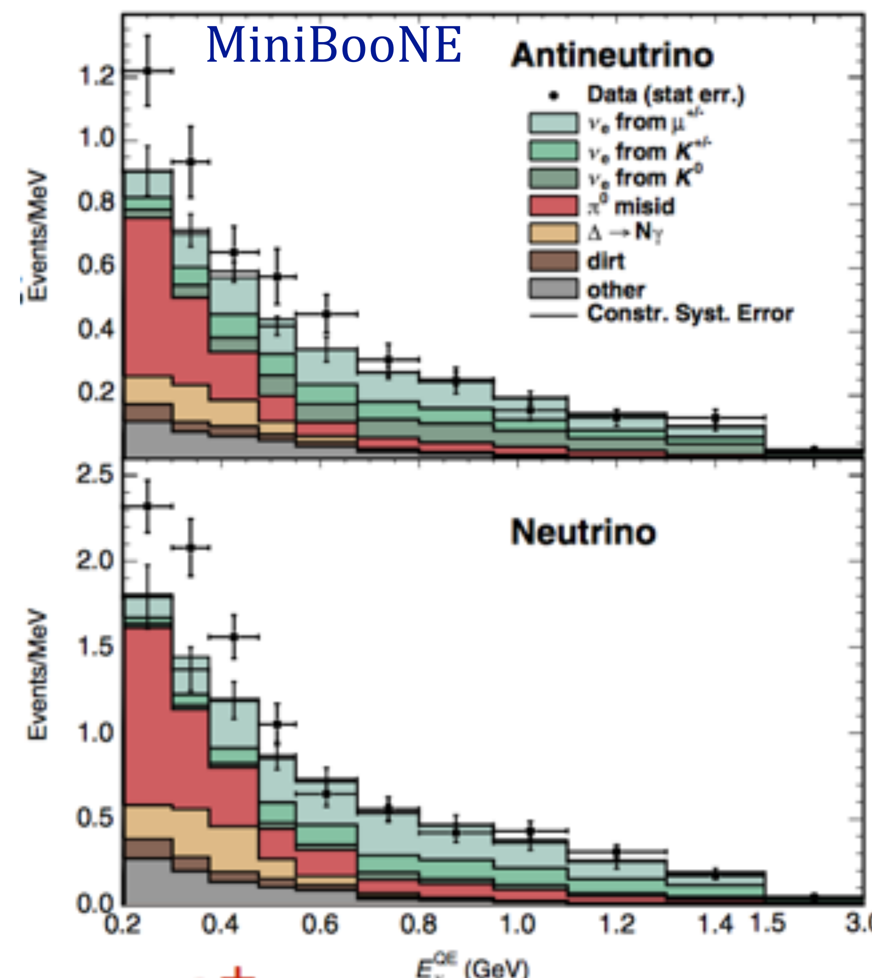
*The *actual* experimental sensitivity achieved
(not from the proposal)



From MiniBooNE data release:
http://www-boone.fnal.gov/for_physicists/data_release/nue_nuebar_2012/

MicroBooNE

- Address the MiniBooNE low-energy excess
  - Look for excess
  - Identify signal (γ or e^- ?)
- Oscillation physics study (appearance/ disappearance)
- Cross-section measurements
- Astroparticle and Exotic physics

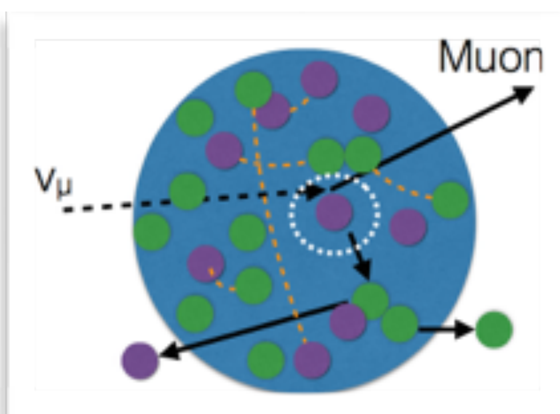


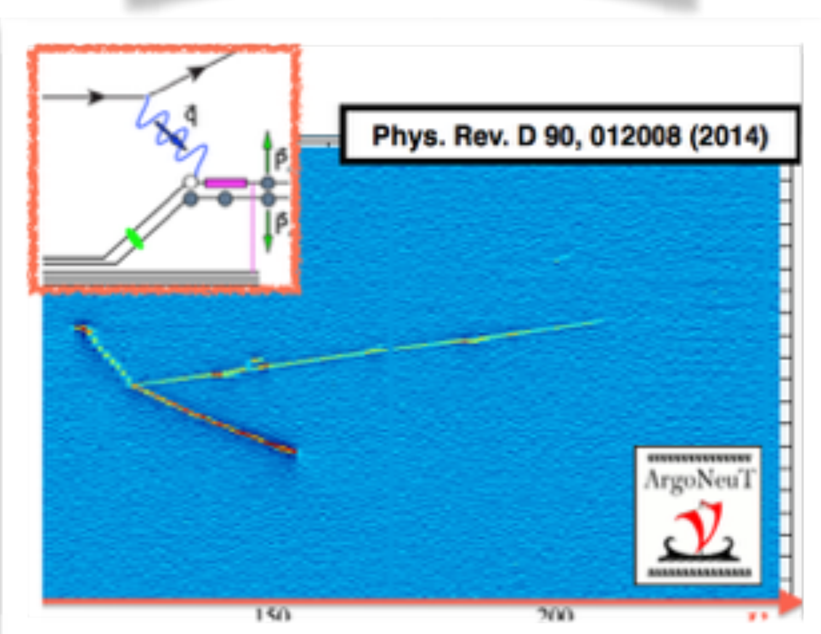
Phys. Rev. Lett. 110, 2013

courtesy of T. Miceli

SBND Physics

- Crucial to identify the source of potential excess in MicroBooNE
- Essential to understand beam contamination (ν_e, $\bar{\nu}_e$)
- Cross-sections measurements



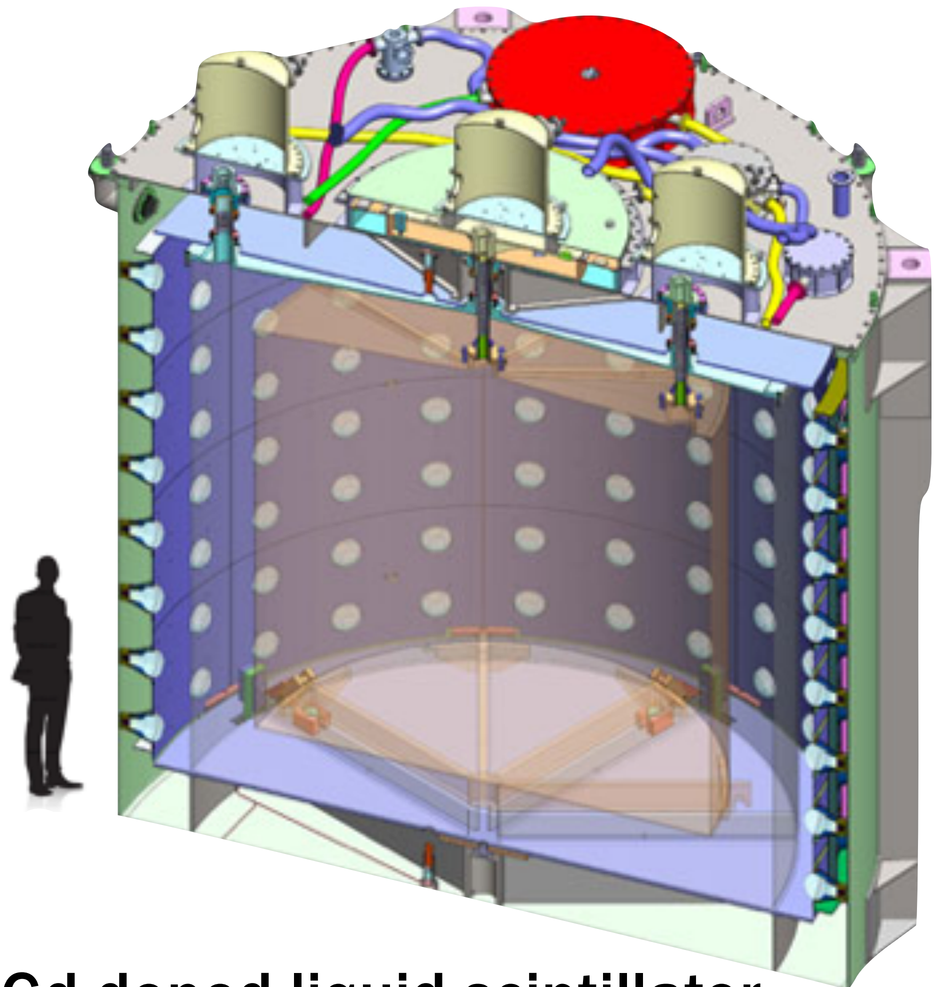


Process		No. Events	Events/ ton	Stat. Uncert.
	ν_μ Events (By Final State Topology)			
CC Inclusive		5,212,690	46,542	0.04%
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830	31,713	0.05%
	· $\nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	· $\nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	· $\nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	· $\nu_\mu N \to \mu + \geq 3p$	371,347	3,316	0.16%
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924	2,330	0.20%
NC $\geq 2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ \geq 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to$ nucleons $+ \geq 1\pi^0$	358,443	3,200	0.17%
	ν_e Events			
CC Inclusive		36798	329	0.52%
NC Inclusive		14351	128	0.83%
Total ν_μ and ν_e Events		7,251,948	64,750	
	ν_μ Events (By Physical Process)			
CC QE	$\nu_\mu n \to \mu^- p$	3,122,600	27,880	
CC RES	$\nu_\mu N \to \mu^- \pi N$	1,450,410	12,950	
CC DIS	$\nu_\mu N \to \mu^- X$	542,516	4,844	
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	18,881	169	

Millions of events!

Precise measurements at reactor

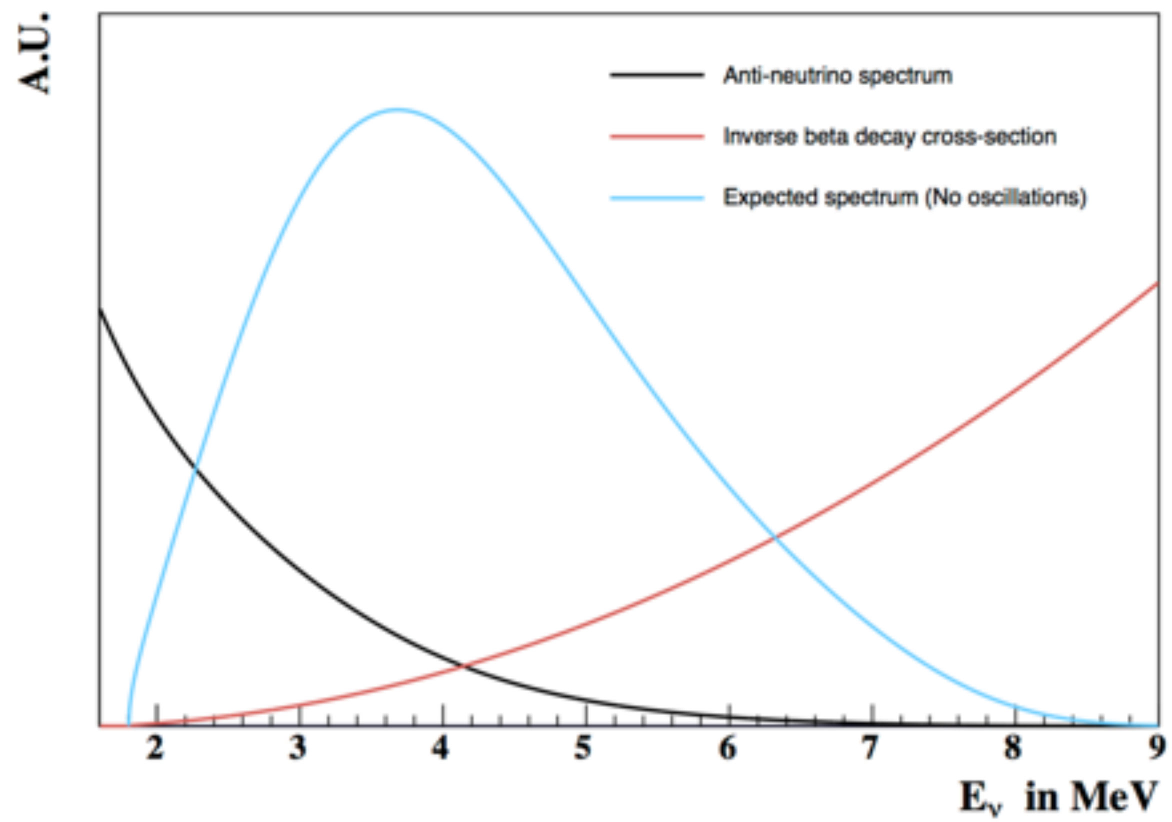
~ 100 m - 1 km baseline



Gd-doped liquid scintillator technology

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

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



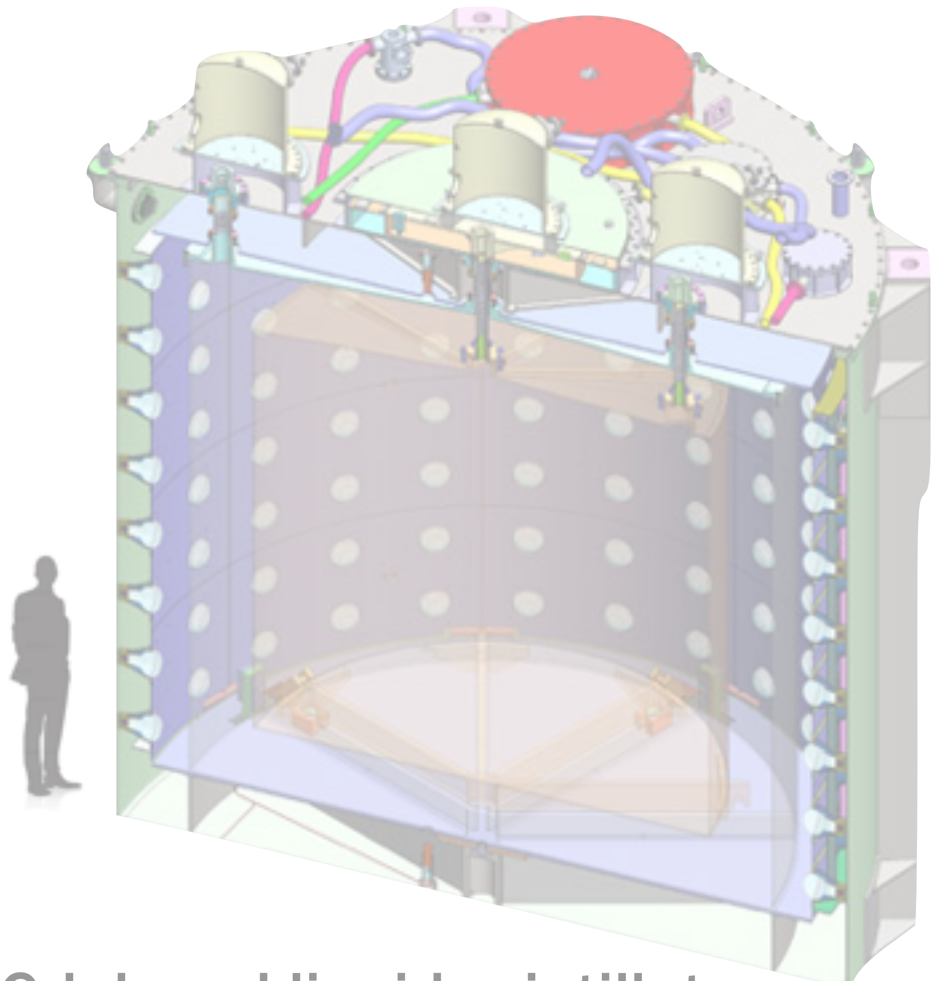
- detection using IBD reaction

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

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

Precise measurements at reactor

~ 100 m - 1 km baseline



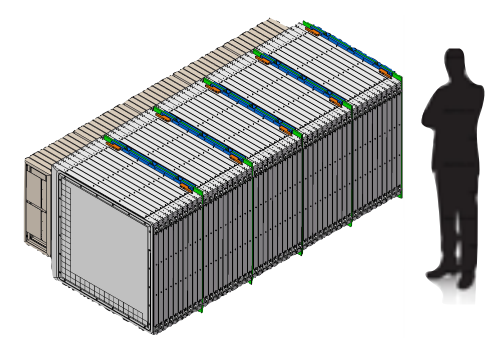
Gd-doped liquid scintillator technology

- Underground laboratory
- Large external shielding
- Well contained energy
- achieve percent level antineutrino flux measurement at PWR

~ 10 m baseline

Challenges:

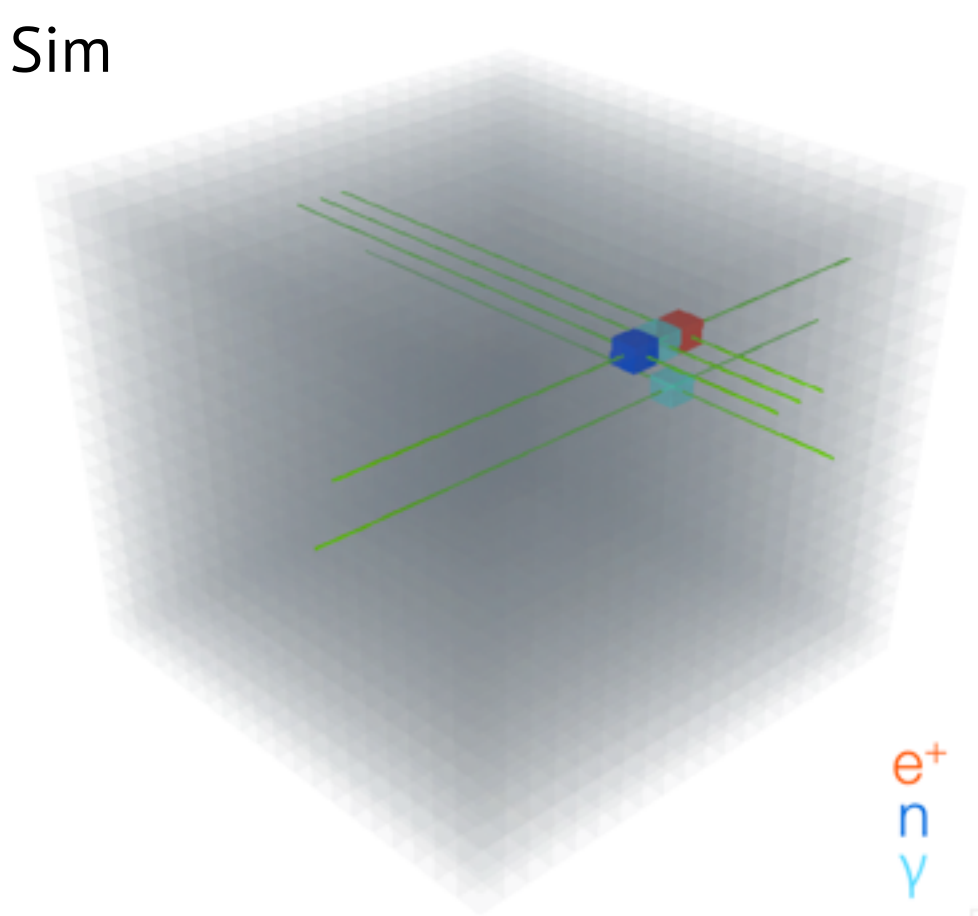
- sensitivity **in E and L** for oscillation search
- rejection of background
- security and safety constraint on site

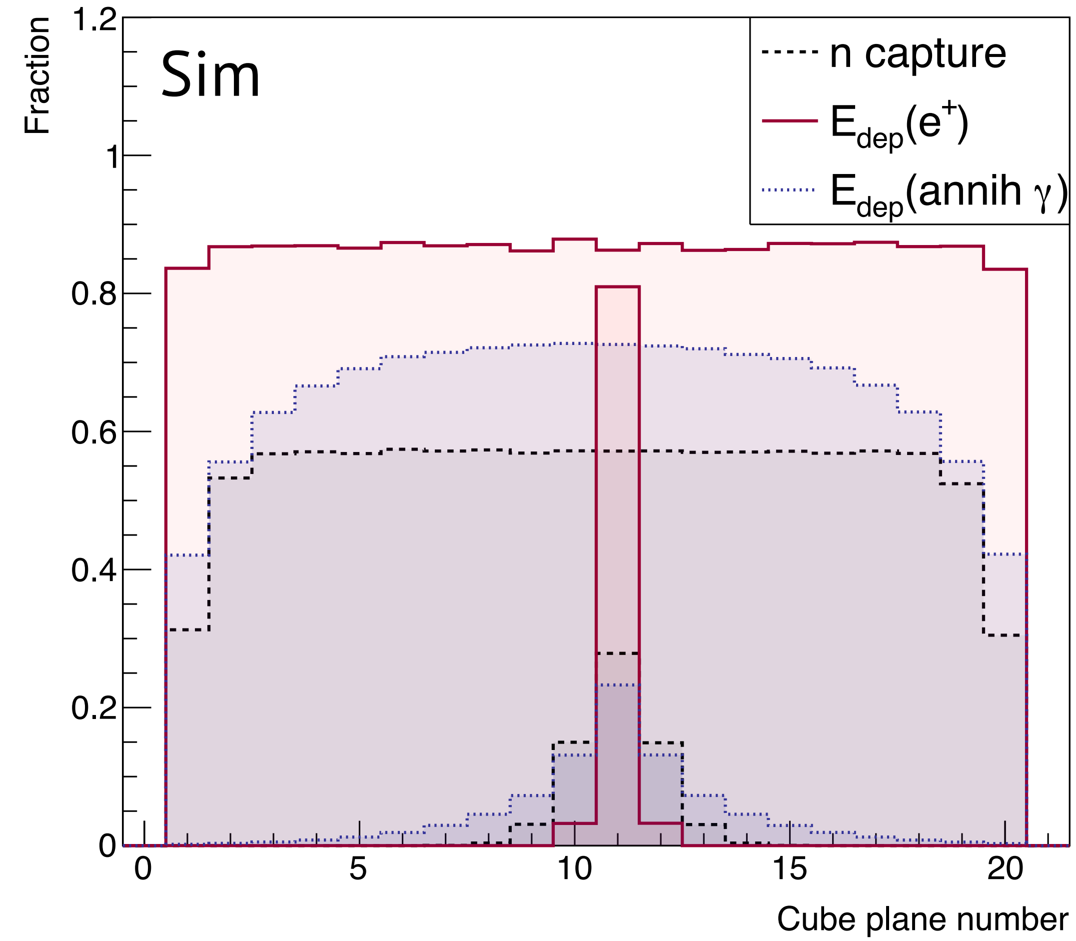


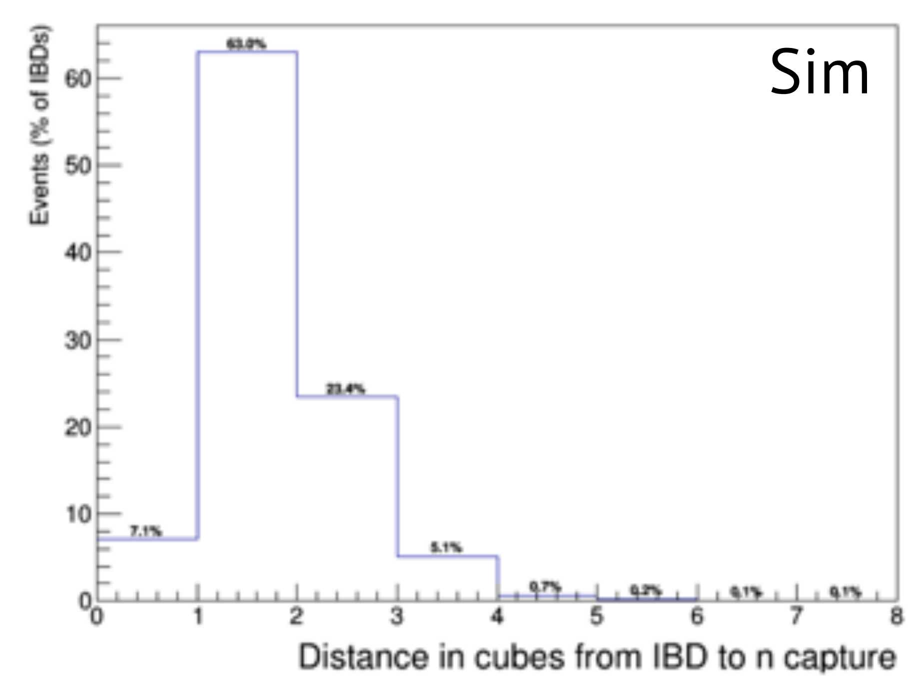
Highly segmented detector

sufficiently compact to deploy meters away from core

Signal localisation

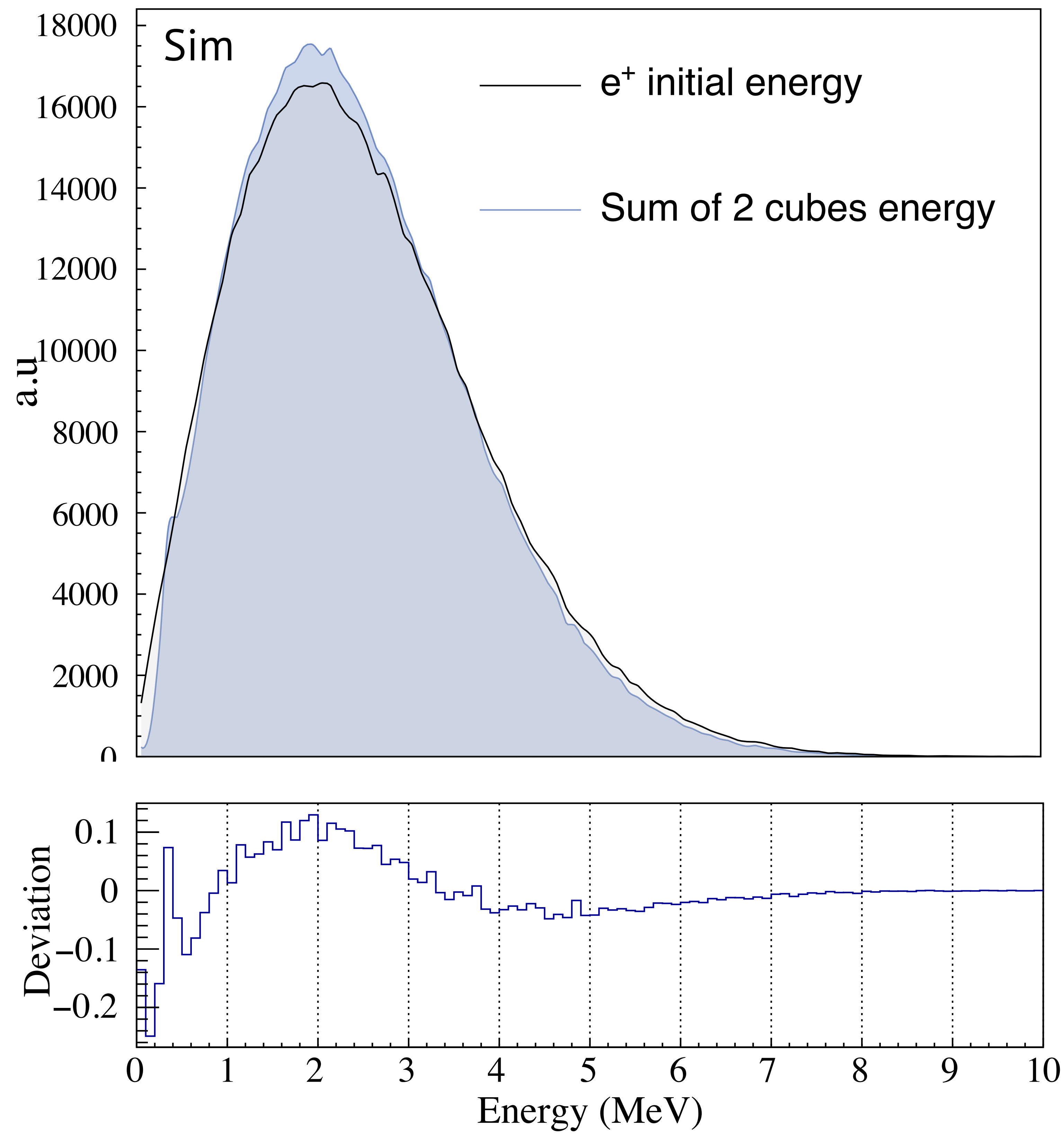




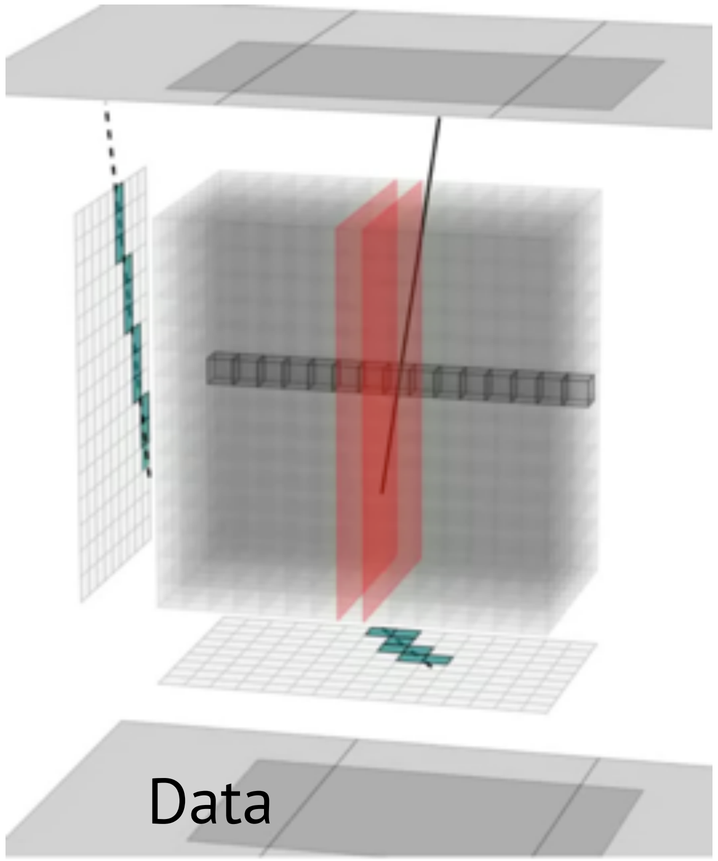


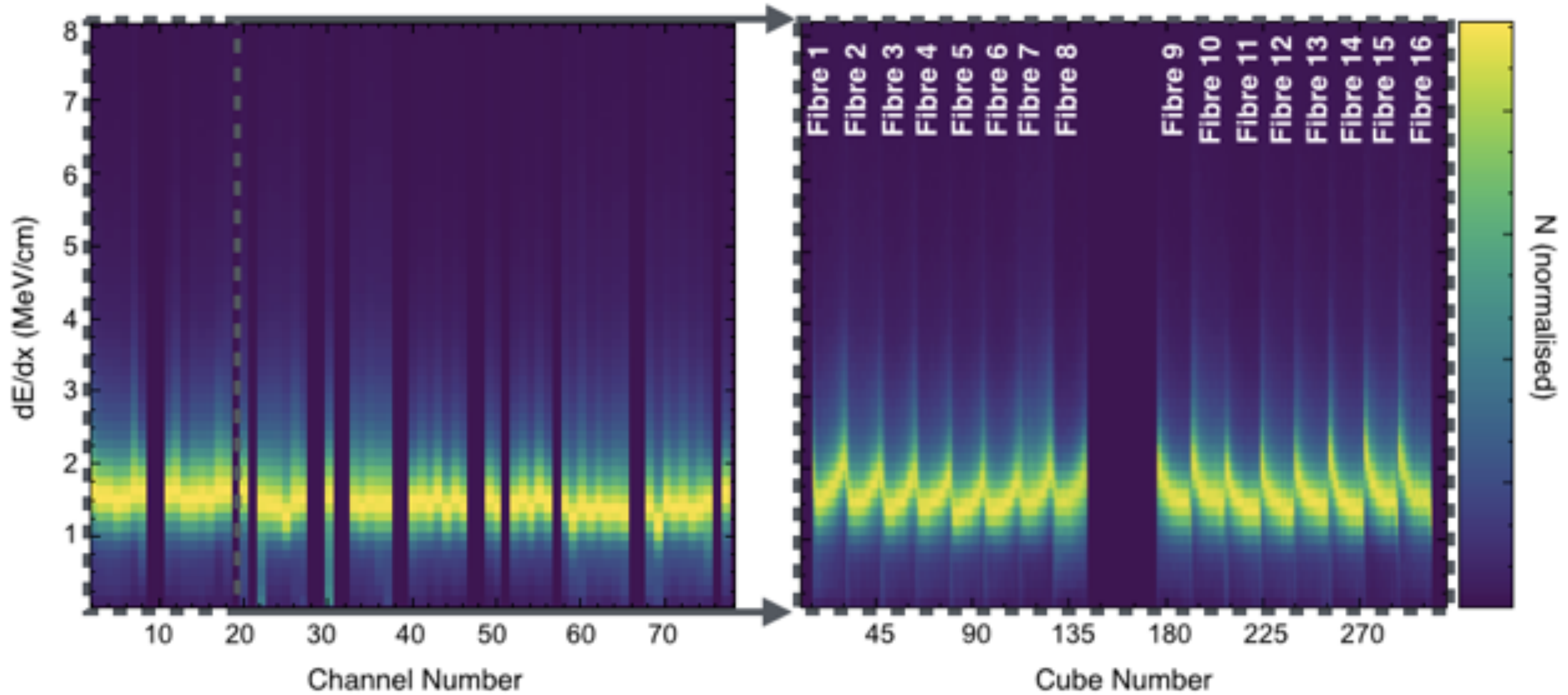
- Positron energy contained in cube voxel
- Neutron capture efficiency uniform up to the edge of the detector
- Neutron capture one cube away from interaction gives directional sensitivity

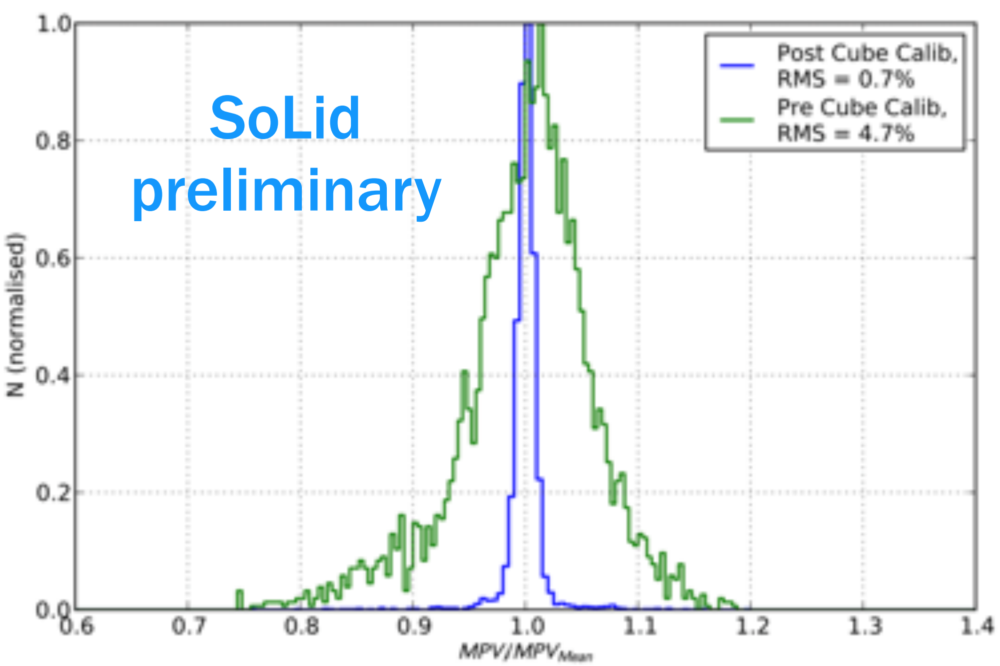
Energy reconstruction

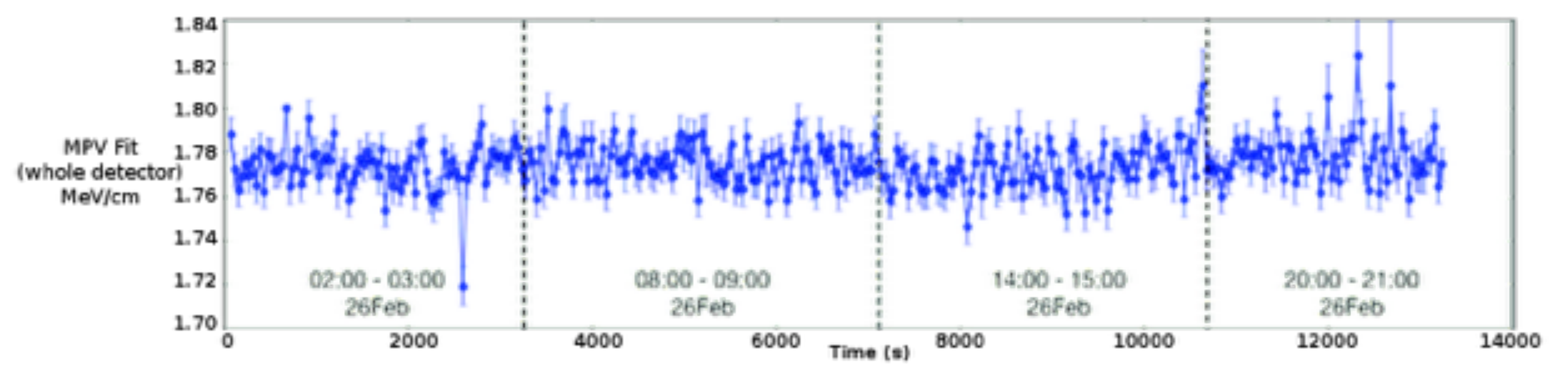


Energy response calibration





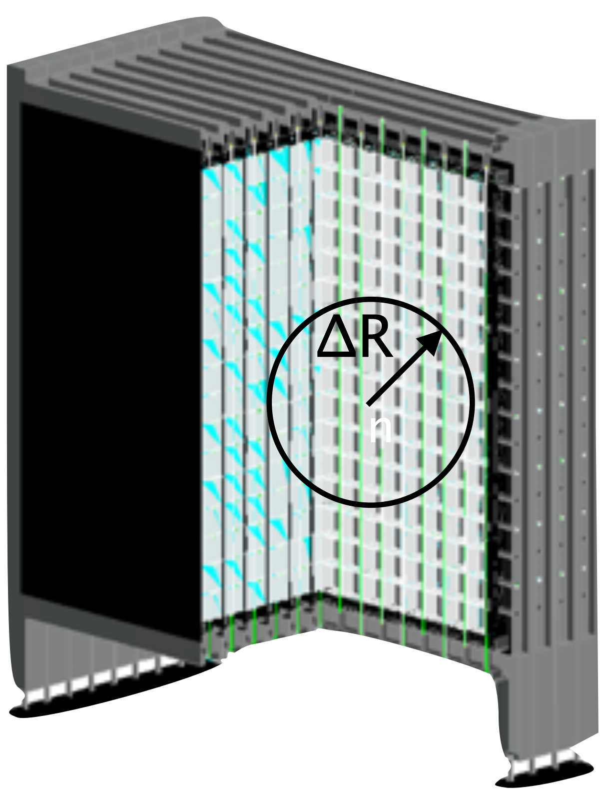


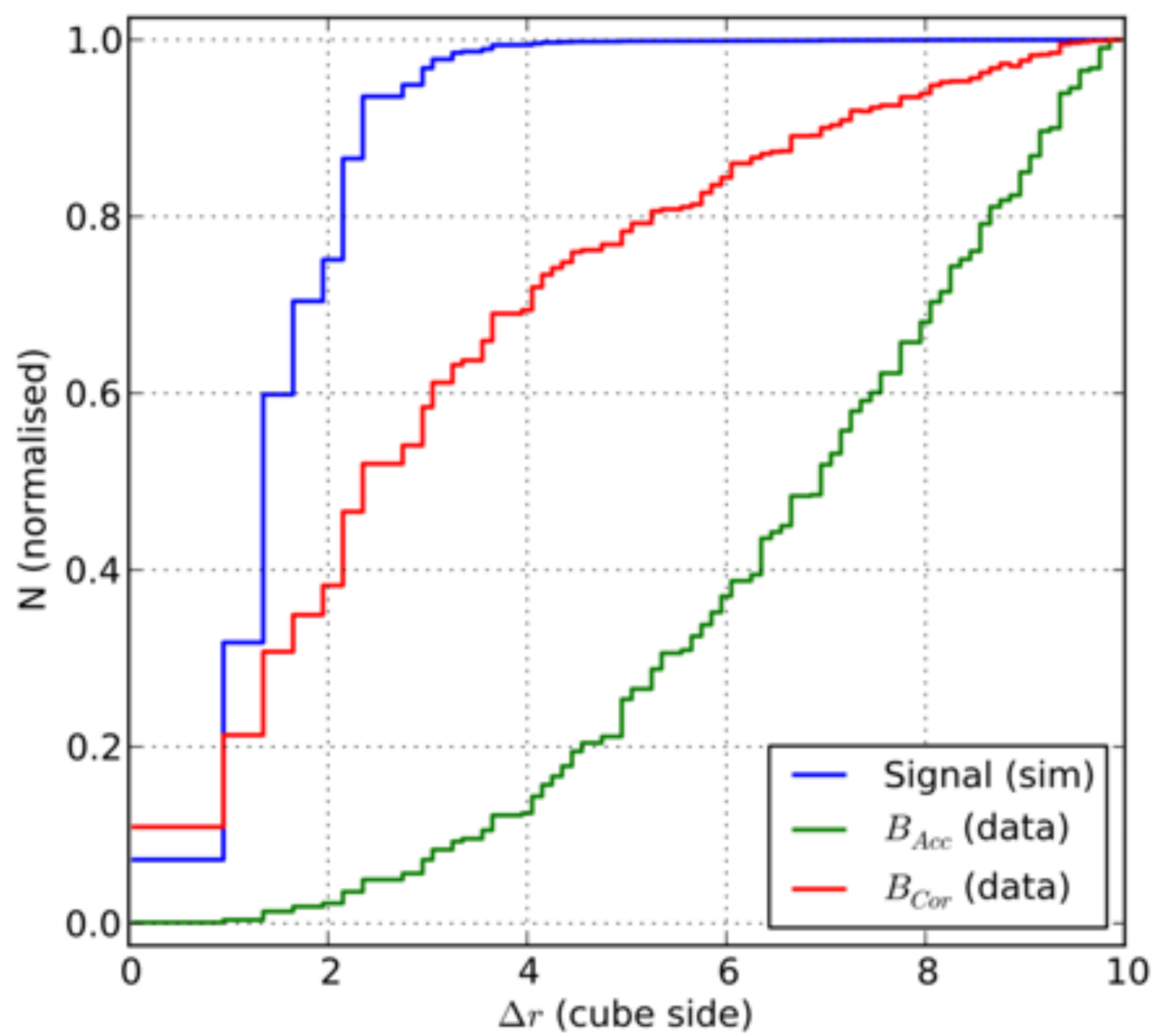


- PVT response intercalibrated using muons
- cube response equalised to better than 1% for majority of channels
- stability over time of energy scale ~ 1%

Signal analysis

- Demonstrated power of segmentation on background rejection





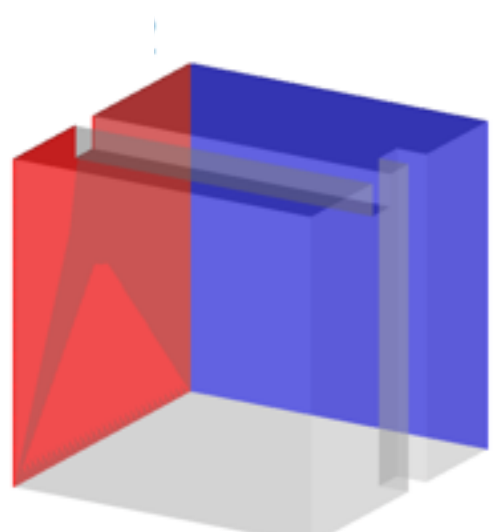
Improvements for SoLi∂

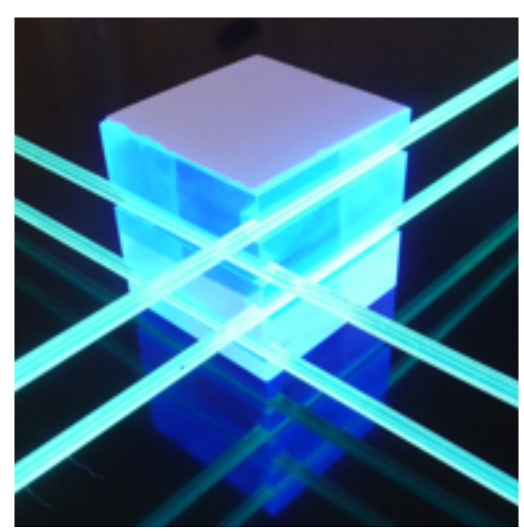
Neutron capture efficiency

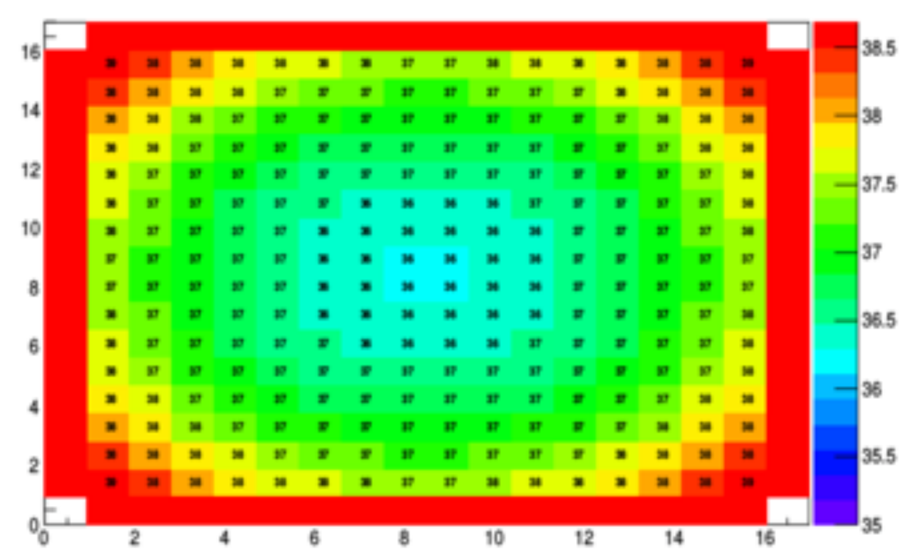
- Additional LiF:ZnS sheets
  - ^{6}**Li** capture efficiency 0.55 to 0.7 **+30%**
  - Reduced capture time **105 to 66** us
- new screens with **improved transparency**

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