Status of the SoLid experiment

Search for Oscillation with Lithium-6 Detector

Benoît GUILLON

guillon@in2p3.fr

for the SoLid Collaboration

*Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, **LPC Caen**, 14000 Caen, France*

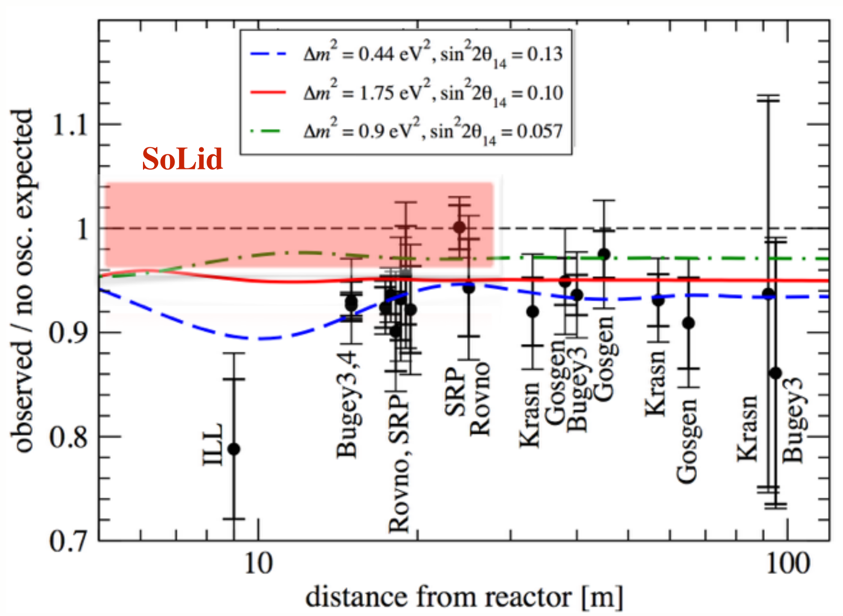
Rencontres du Vietnam

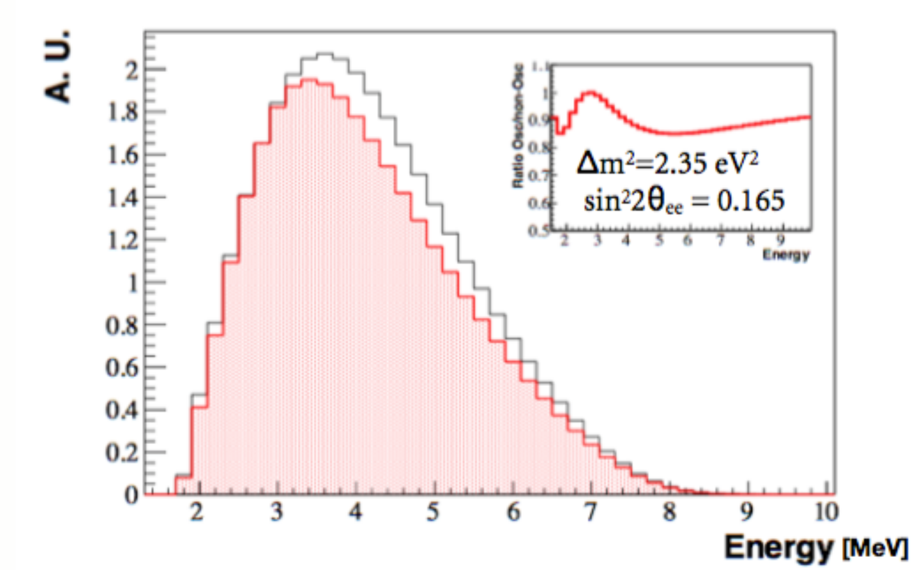
High sensitivity experiments beyond the SM

Physics Motivations

- Search for Short-Baseline Oscillation **(RAA)** ⇢ Light sterile neutrino ($\Delta m^2 \sim eV^2$)

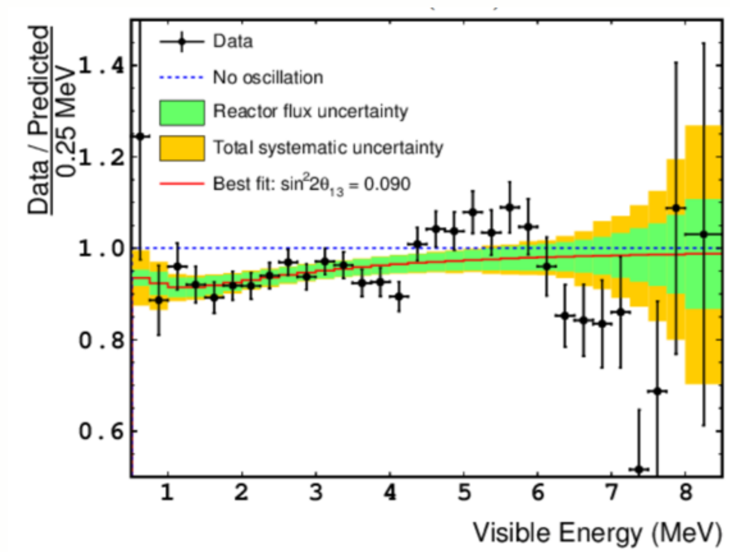
J. Kopp et al., JHEP 1305:050 (2013)



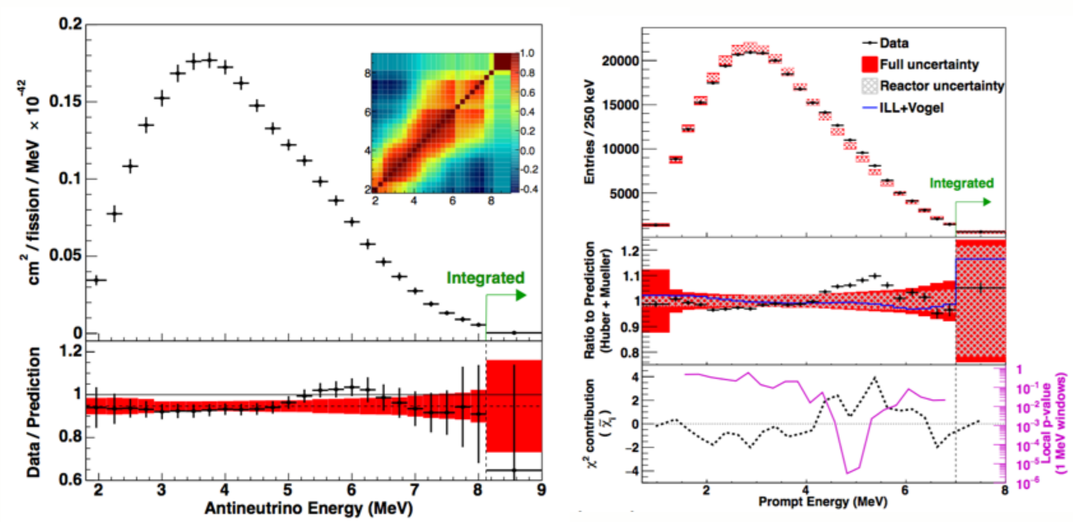


- ^{235}U $\overline{\nu}_{e-}$ spectrum measurement ⇢ Insight for predictions & reactor model

Y. Abe et al., JHEP 10, 086 (2014)



F. P. An et al., Phys. Rev. Lett. 116, 061801 (2016)



All 3 θ_{13} reactor experiments observes an excess ('bump') between 4 and 6 MeV

- New Segmented Solid neutrino detector … Neutron detection, non-proliferation

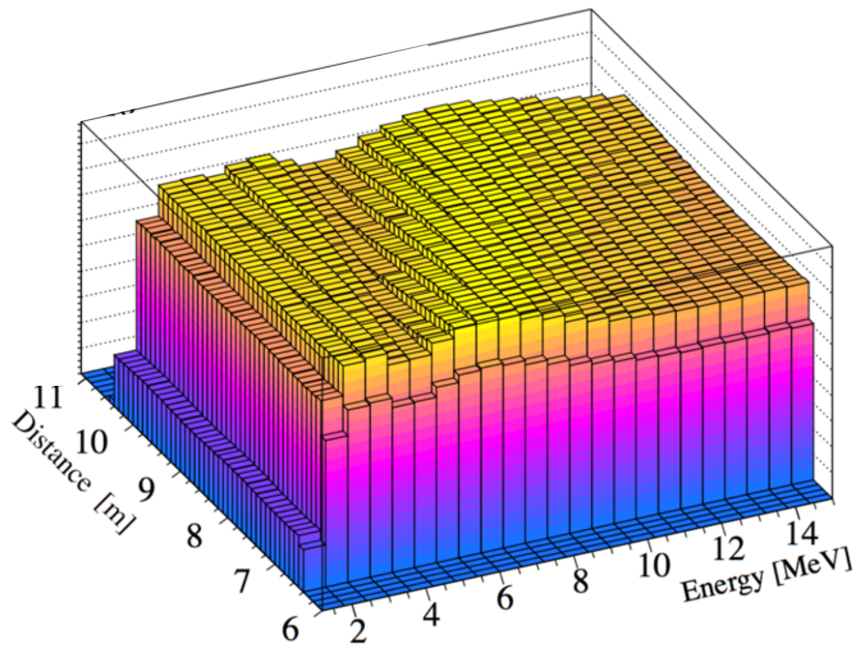
Search for relative shape distortion in identical detector at different baselines

Detector

- High resolution

  Energy (Large statistics, low systematics)

  Spatial (Good vertex reconstruction)



- Effective background rejection

  Low overburden (almost on surface)

  Reactor radiation (neutron, γ)

Reactor

- Compact core
- Understanding of the fuel composition
- Access as close as possible
- Security implications (e.g data rates, access rights, safety issue….)

SoLid overview

- Detector : 1.6 → 3 t fiducial

  Composite solid scintillators (PVT / ^{6}LiF:ZnS)

  Highly Segmented (8 000 voxels/m^3)

- BR2 @ SCK-CEN (Mol, Belgium)

  HEU(^{235}U) : P_{th} = 50 - 80 MW

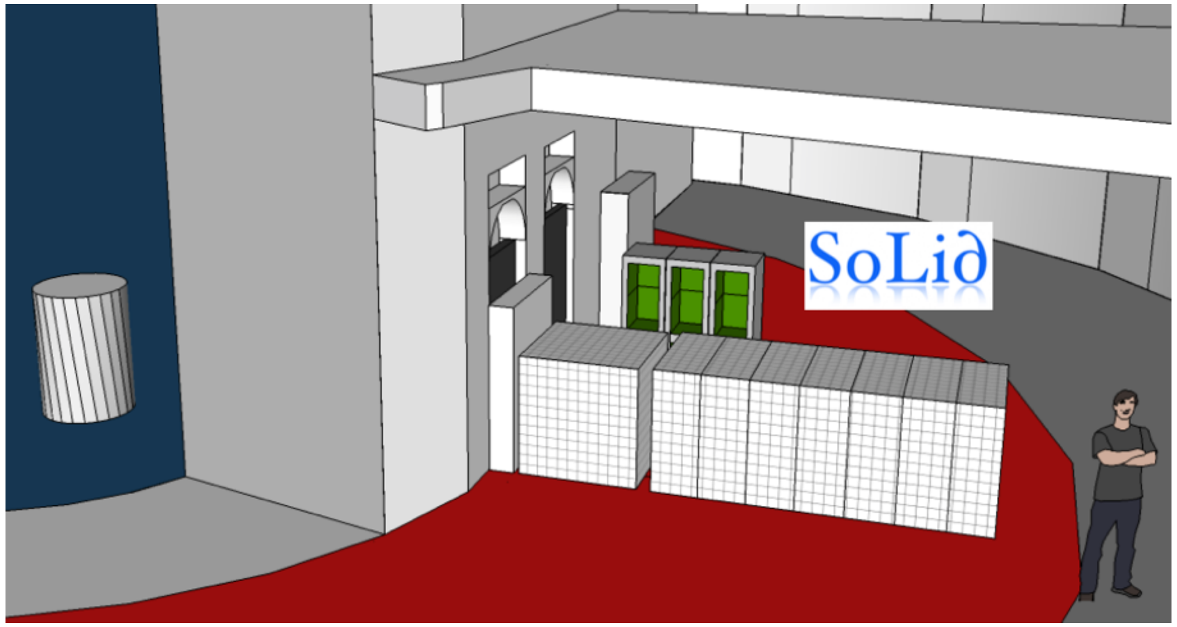
  SoLid @ 5.5 → 12 m

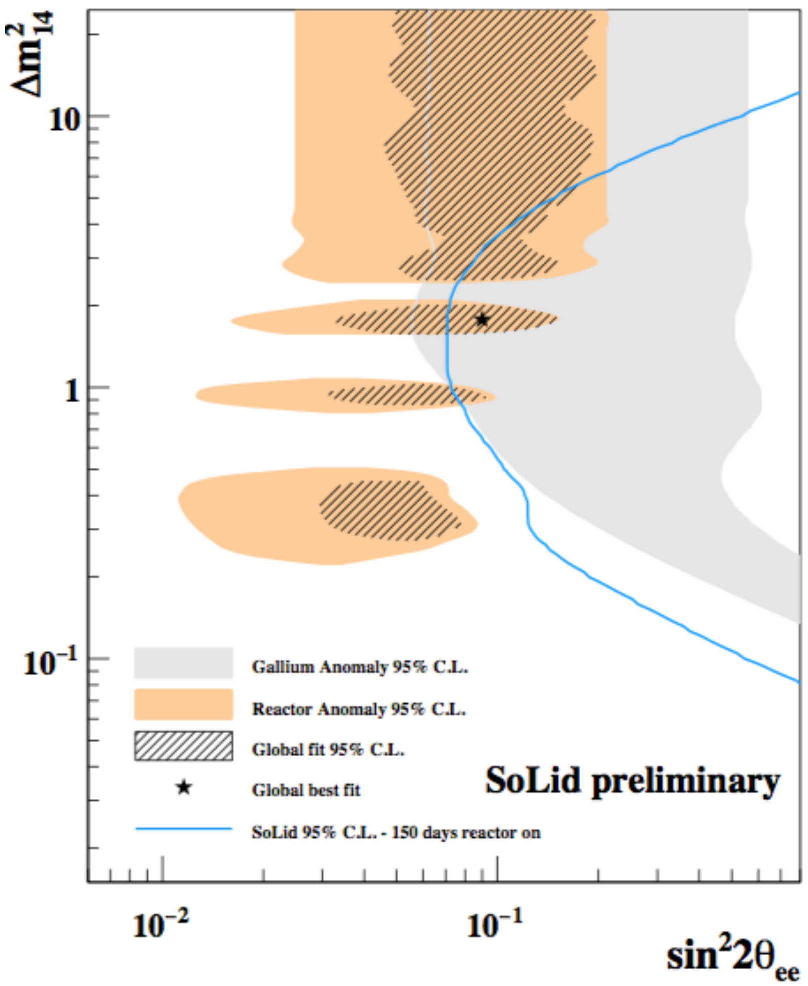
  Low background (neutron, γ)

  Compact : Φ_{eff} = 50 cm, h = 90 cm

- Physics run scheduled to begin end 2016

Parameters	Objectives
Total mass	1.6 t
IBD efficiency	30 %
Threshold	200 - 500 keV
Anti-neutrinos	~1000 d^{-1}
Signal/Background	~3
Energy resolution	14 % à 1 MeV
Systematic uncertainty	2.5 - 4.5 %



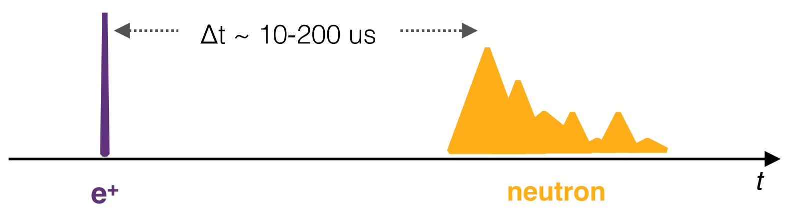


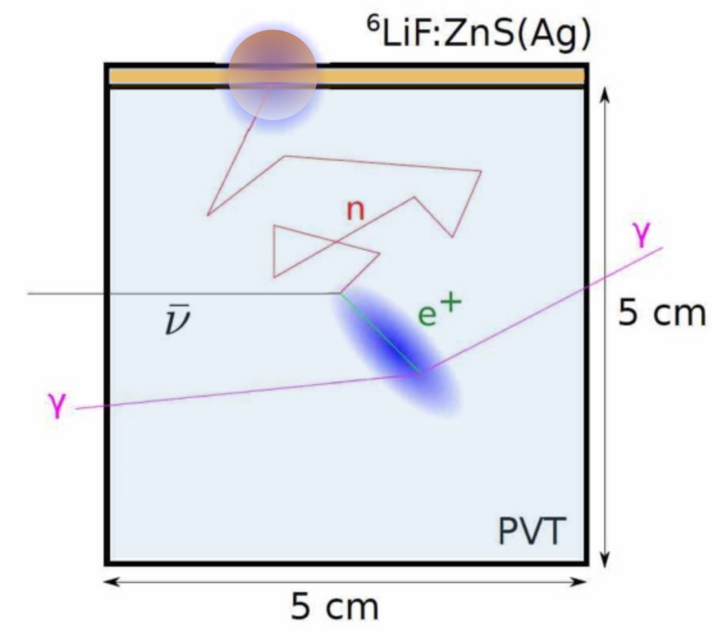
SoLid collaboration

Oxford University	*A. Weber, S. Ihantola, N. Ryder*
Bristol University	*D.Newbold, D.Cussans, K.Petridis, G.Pommery, J.Rademacker, D.Saunders*
Imperial College	***A. Vacheret*** *(new group being formed)…*
SCK-CEN	*B. Coupé, S. Kalcheva, E. Koonen, L. Ghyrs*
Antwerp University	*N van Remortel****,*** *Y. Abreu, A. De Roeck, X. Janssen, I. Piñera,*
Vrije University Bruxel	*J. D'Hondt, P. Van Mulders, S. Vercaemer, L. Kalousis*
Gent University	*M. Labare, C. Moortgat, D. Ryckbosch, I. Michiels*
LPC Caen	*G. Ban, D. Durand, B. Guillon, G. Lehaut*
Subatech Nantes	*F. Yermia, M. Fallot, L. Giot, B. Viaud*
LAL Orsay	*M. Bongrand, L. Simard, M-H Schune, Y. Amhis, D. Boursette*
Virginia-Tech	*J. Link, P. Huber, C. Mariani, J. Park*

Detection Principle

- Inverse Beta Decay **(PVT)** : $\bar{\nu}_e + p \rightarrow e^+ + n$
- Delayed neutron capture **(^{6}LiF:ZnS)** : $n + {}^6Li \rightarrow {}^3H + \alpha$ (4.8 MeV)
  - PSD and $\triangle$T coincidence windows





- Highly-segmented (8 000 voxels/m^3)

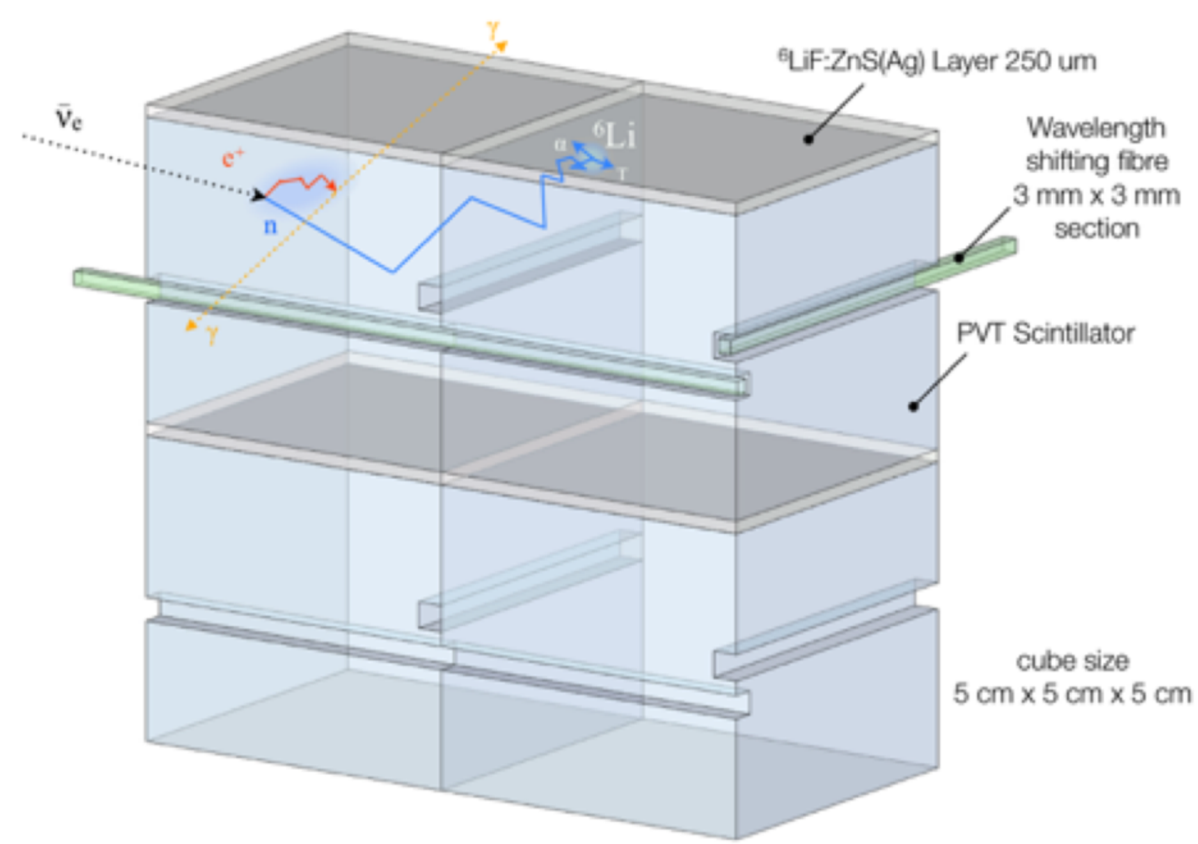
  Cube detection elements (5x5x5cm^3)

  Light collection by (2 →4) WLS (3x3 mm^3)

  Read-out by (2 →4) MPPC (Hamamatsu S12572-050P)

  16x16 cubes lattice / plane (80x80 x5 cm^3)

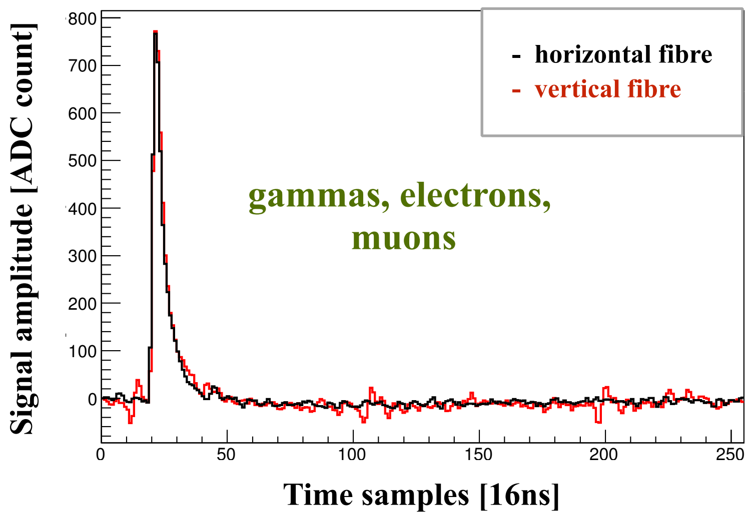
  Optically isolated by Tyvek wrapping

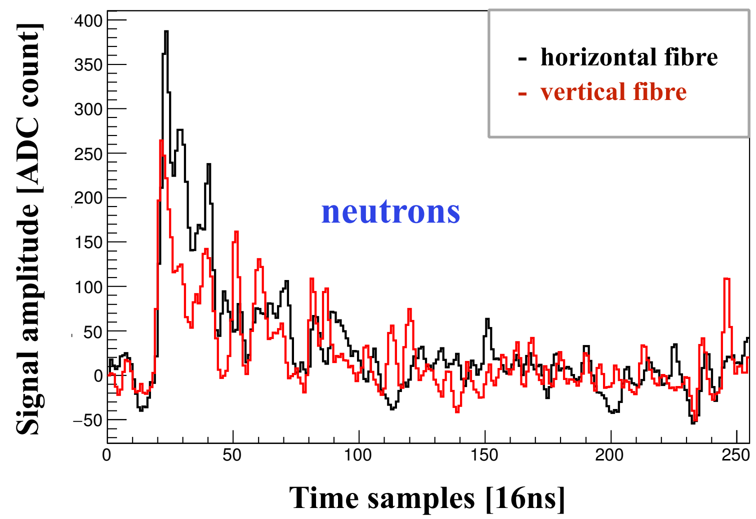


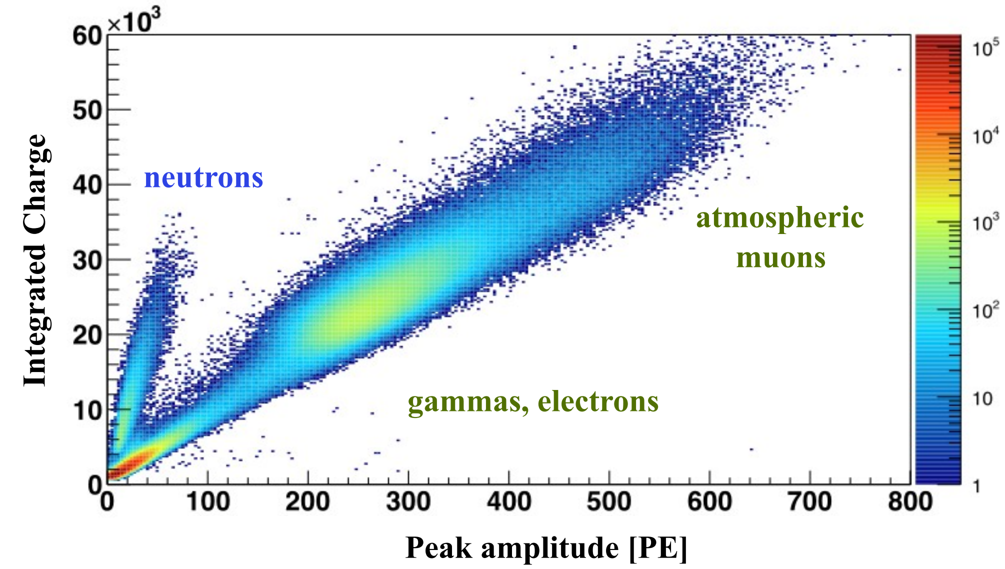
- Good light yield : δE / √E ~ 20 → 14 %

SoLid features

- Pulse Shape Analysis ⇢ Neutron Tag (trigger) !

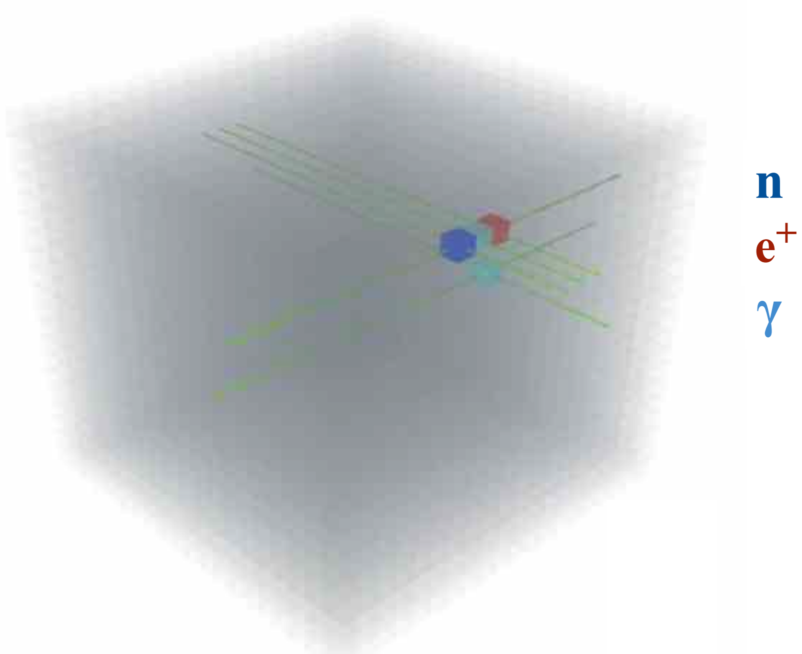




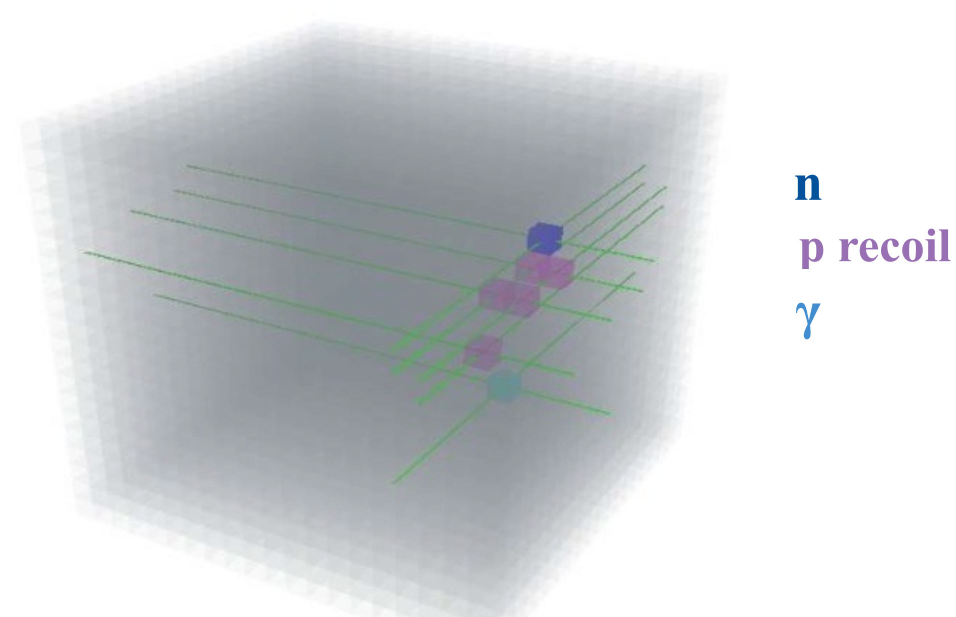


- 3D topology reconstruction ⇢ Background identification/rejection !

Inverse Beta Decay event



Fast neutron event



High granularity allows for signal localization and thus enhances significantly background rejection

- Major MTR-type reactors

  Material testing/Isotopes production…

  No others project in fondamental/particle physics

  Non-proliferation : statutory tasks

- SCK-CEN collaboration

  Support, funding (shielding, source,…)

  Reactor calculation expertise

  Large working area & No time limitation

- Neutrino parameters

  Operating power : $P_{th} \sim 65\ (125)\ MW_{th}$

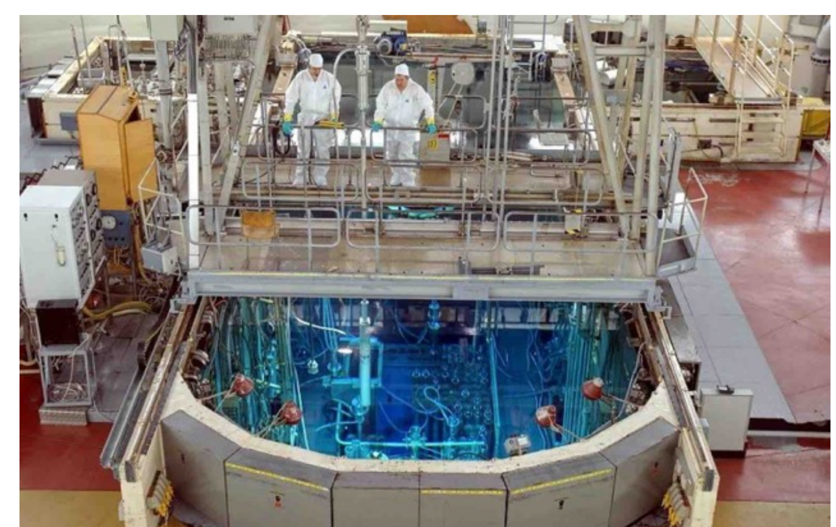
  Highly Enriched Uranium : 93% ^{235}U

  Neutrino flux : $\sim 10^{19}\ \nu_e/s$

  Compact : $\Phi_{eff} = 50$ cm, h = 90 cm

  Duty cycle : 150 days/year

Critical after 1.5 year refurbishment (1/06/2016)
Power operation resumed in July 2016



SoLid @ BR2

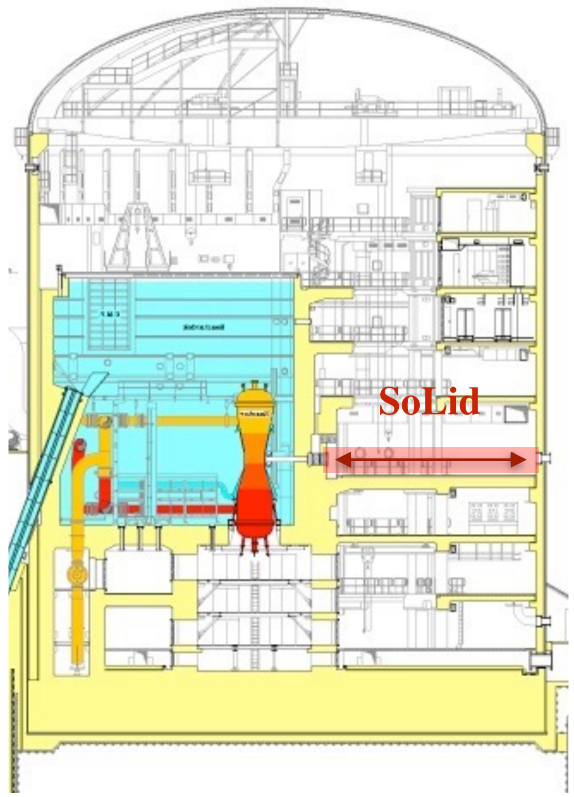
- Adjustable Base-Line

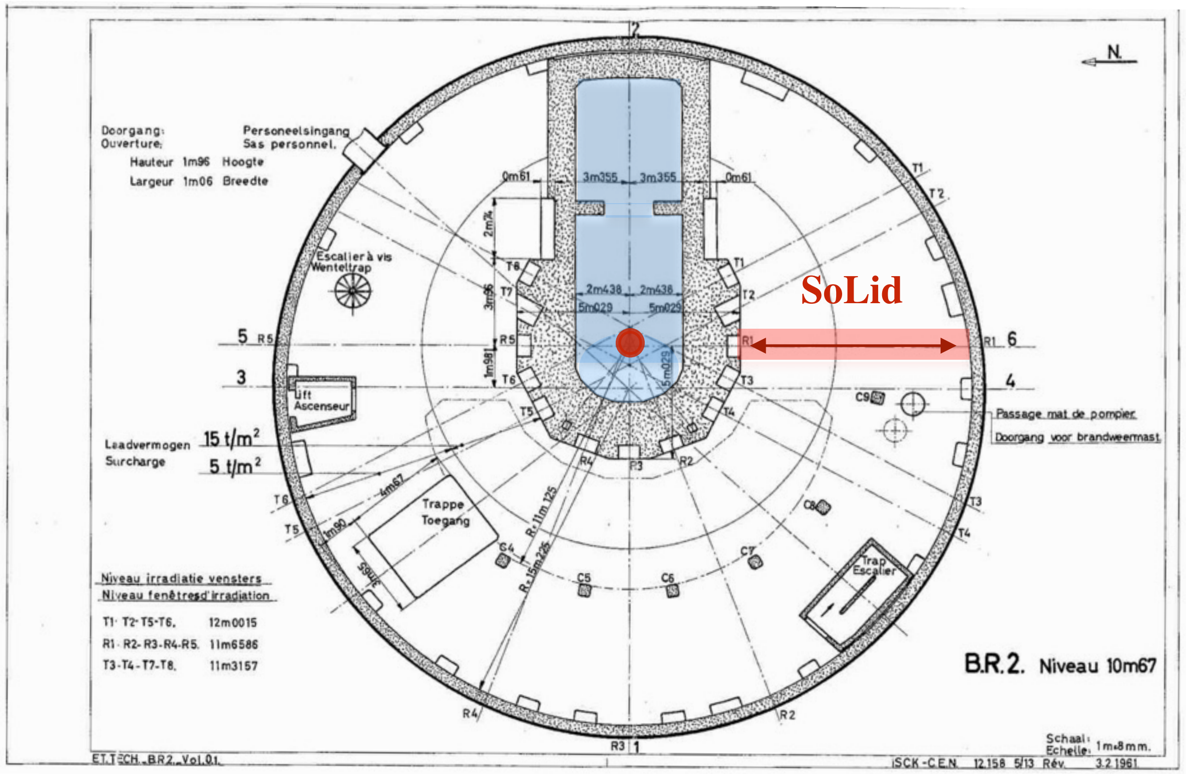
  SoLid @ 5.5 → 12 m

- Reactor On-Axis

- Low vertical overburden

  < 10 m WE





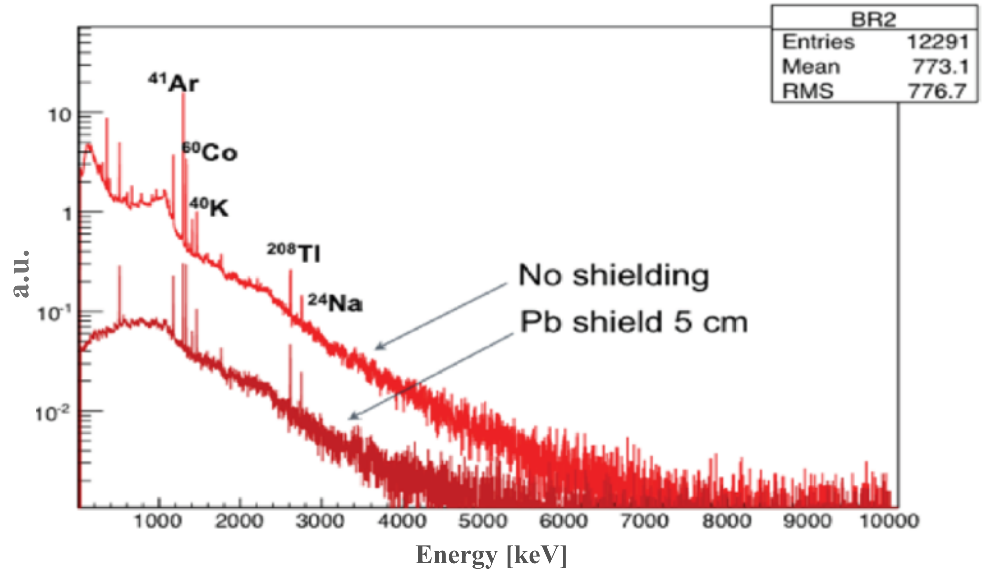
- Low level of Reactor core background (no beam-pipe (bio-shielded), concrete)

  Background measurement campaign … confirmed by NEMENIX and SM1 results

BR2 HPGe detector

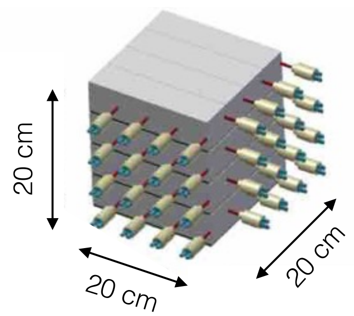
BR2 neutron detector

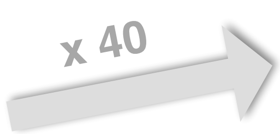
Oxford neutron detector (MARS)



NEMENIX

8kg - 64 voxels
32 channels





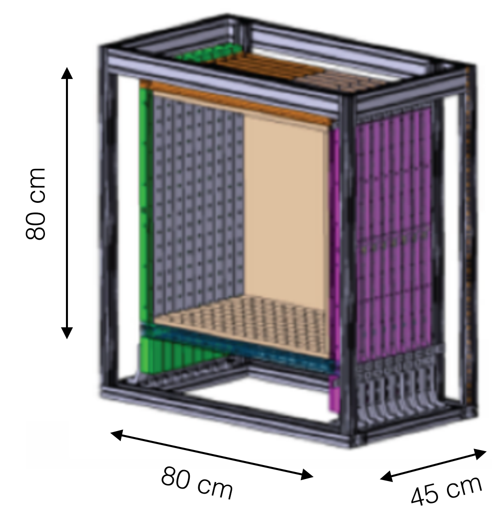
Proof of Concept

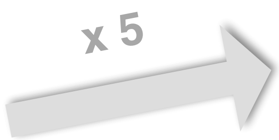
1. Demonstrate neutron PID
2. Measure Backgrounds
3. Measure Coincidence Rate

2013

SM1

288kg - 9 planes
2304 voxels - 288 channels





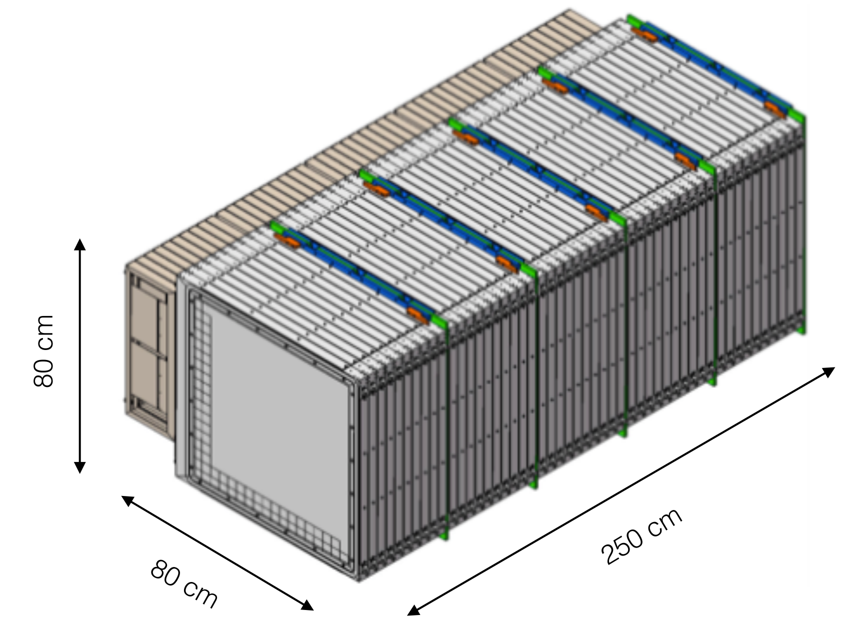
Real Scale Systems

1. Demonstrate scalability
2. Production/Assembly test
3. Demonstrate segmentation capabilities
4. Physics and Background studies

2014-2015

SoLid

1.6 t - 50 planes (2 t)
12 800 voxels - 3200 channels



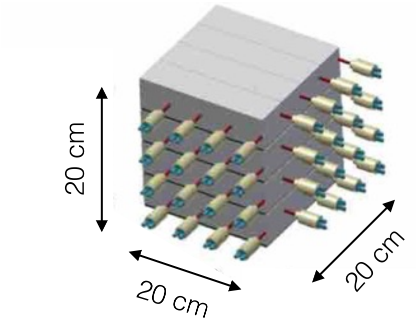
Physics Scale Detector

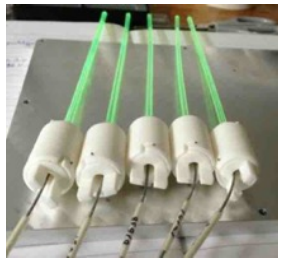
1. Optimize Performance
2. Implement Neutron Trigger
3. Spectrum measurements
4. Oscillation Search

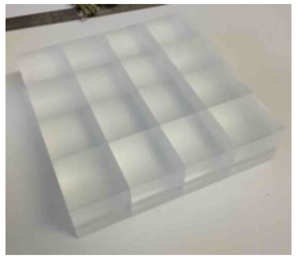
end 2016 …

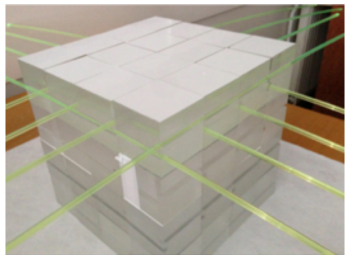
NEMENIX prototype

8kg
64 voxels
32 channels

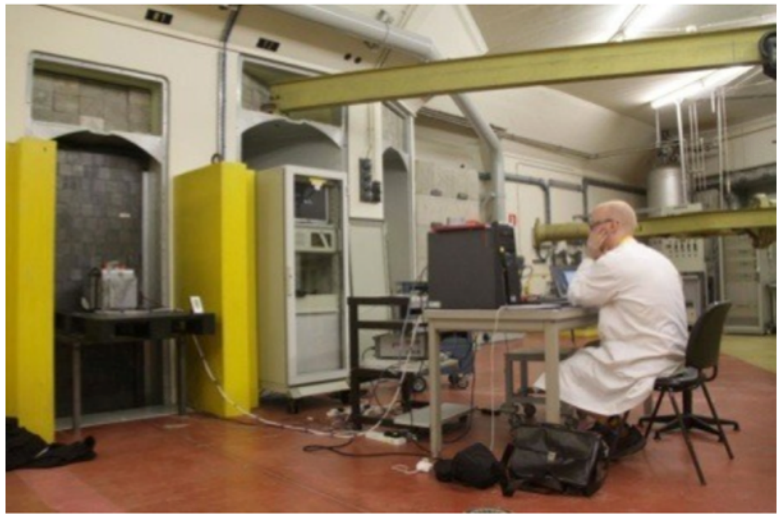




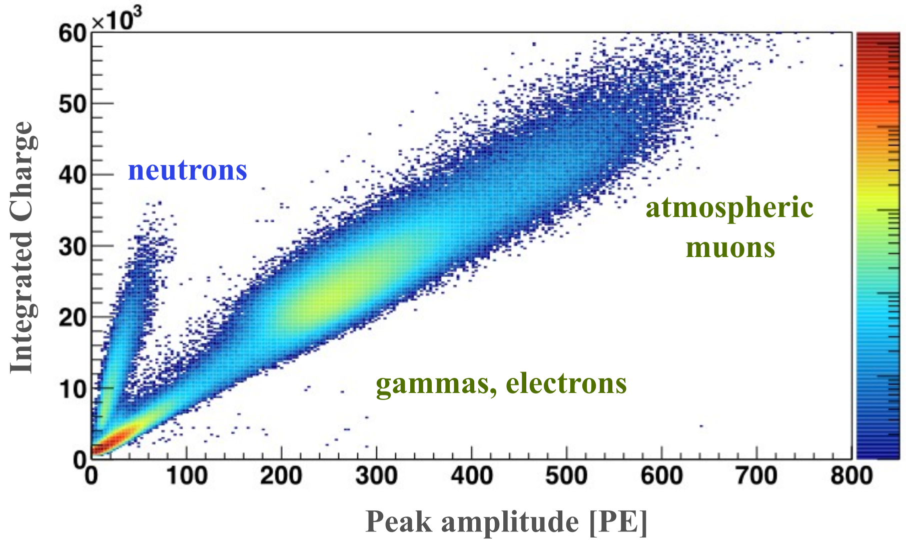


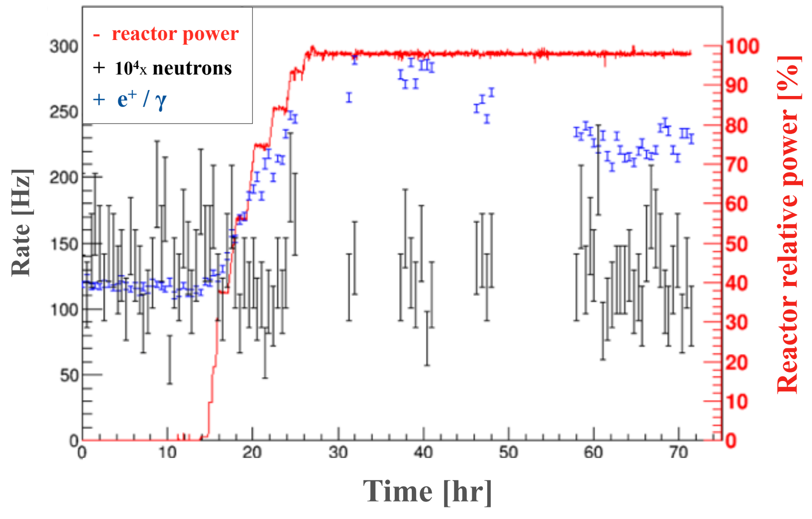


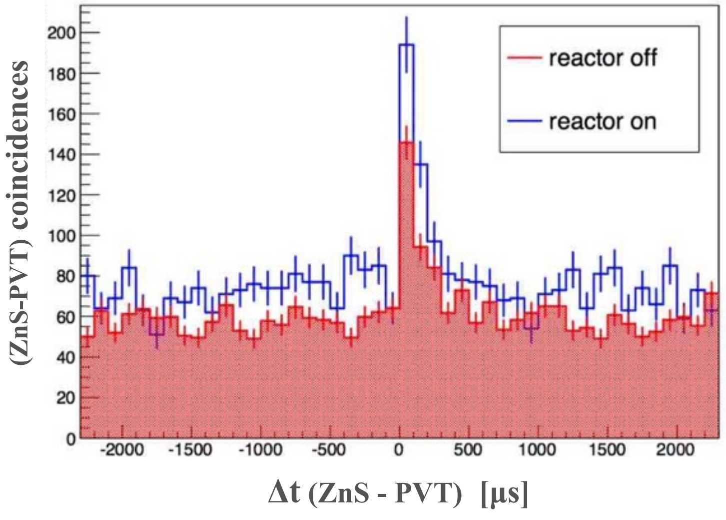
- Moved @ 5.5 m from BR2 [08/2013]
  - ⇢ **30 (19) days reactor ON (OFF)**
- Neutron Calibration @ NPL [2015]
- BiPo measurements @ Boulby [2016]



- Detection principle approved *... technical paper in preparation*

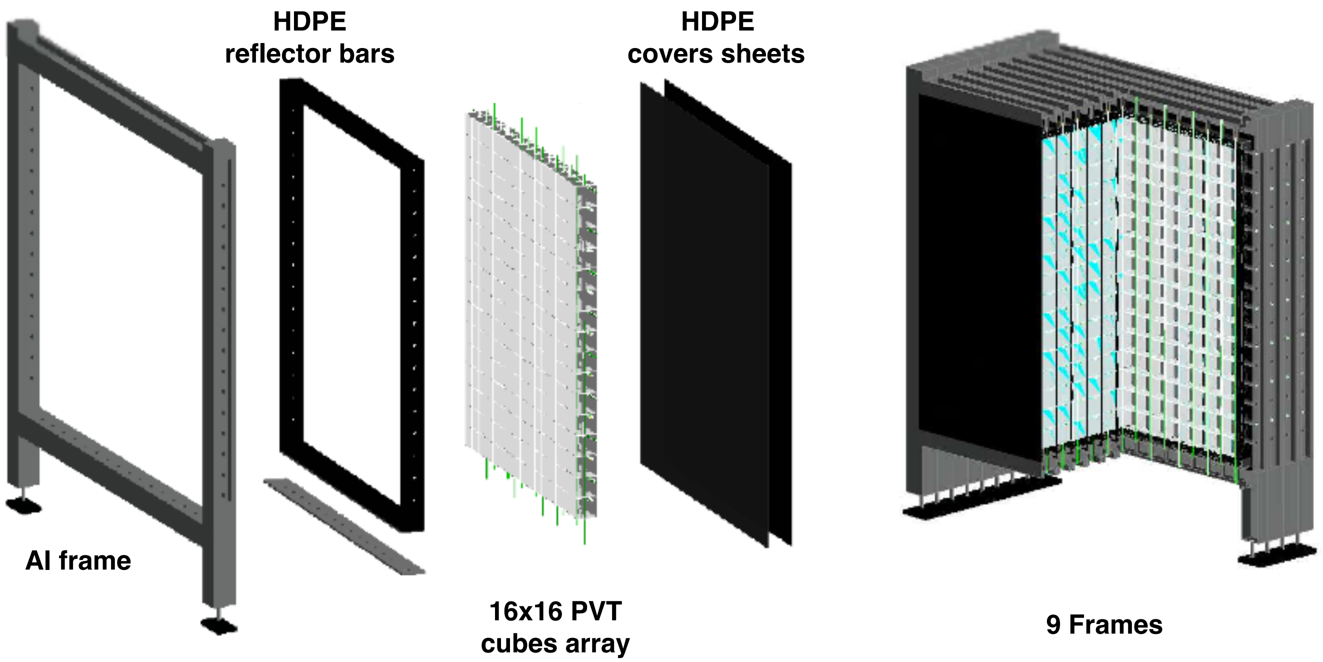




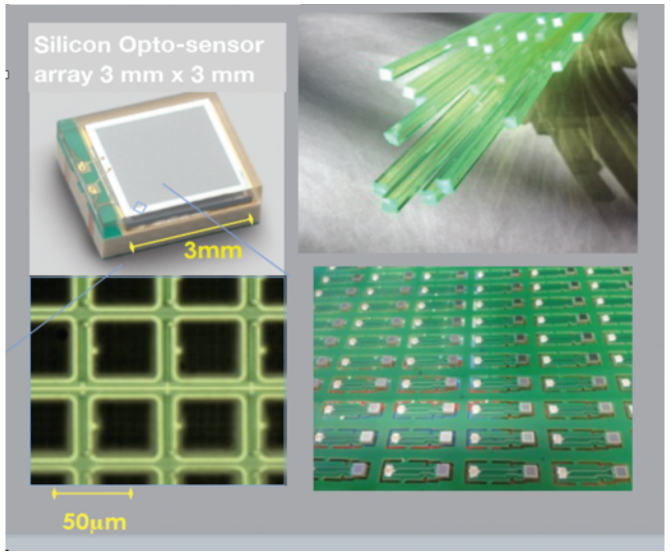


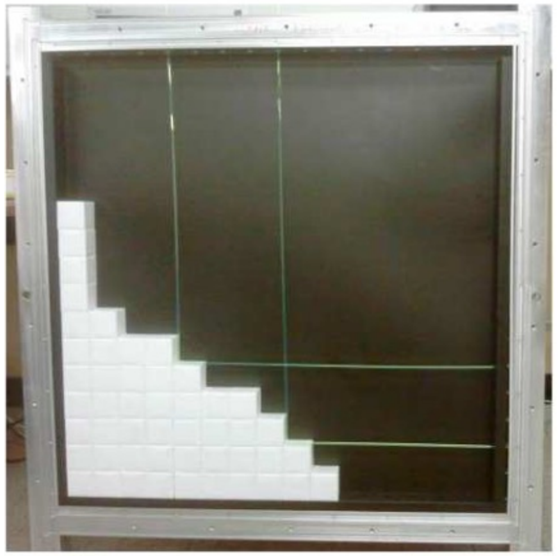
SM1 detector

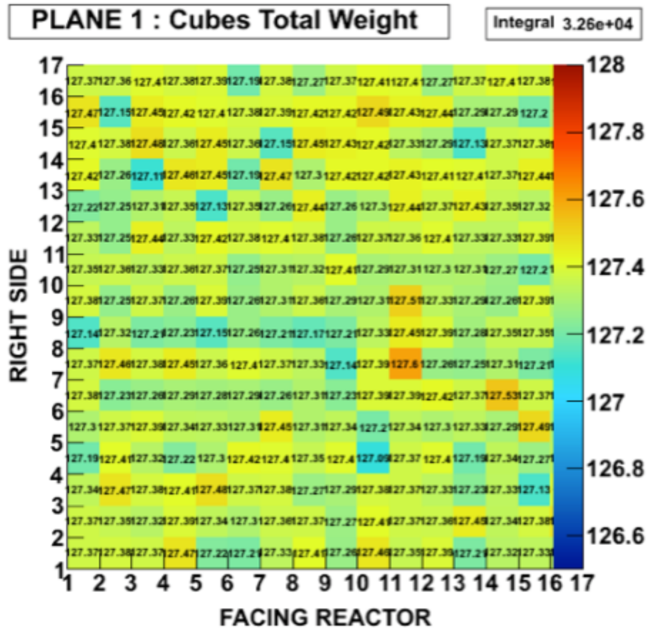
- Full scale 'prototype'
  - 288kg
  - 9 planes (16x16 lattice)
  - 2304 voxels / 288 readout channels
  - Aluminium frame structure
  - HPDE neutron reflector



- Assembly and Built @ Gent/Antwerp (~ 6 months)
  - 2300 cubes machined, assembled, wrapped with Tyvek
  - Carefully weighted : # of protons determined with better than 1 % accuracy







SM1 detector

- Deployement @ BR2 [12/2014]

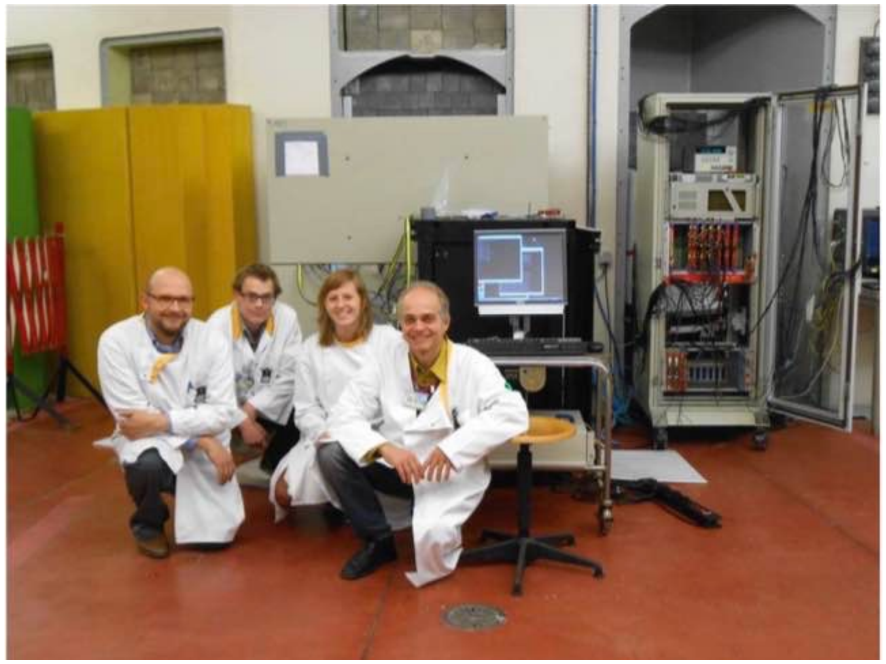
  ADC : 62.5MHz rate (16 ns sample)

  Light yield : 25 PA/MeV (X+Y)

  Energy resolution : δE / √E ~ 20%

  50 ns (XY) coincidence window

  600 keV threshold

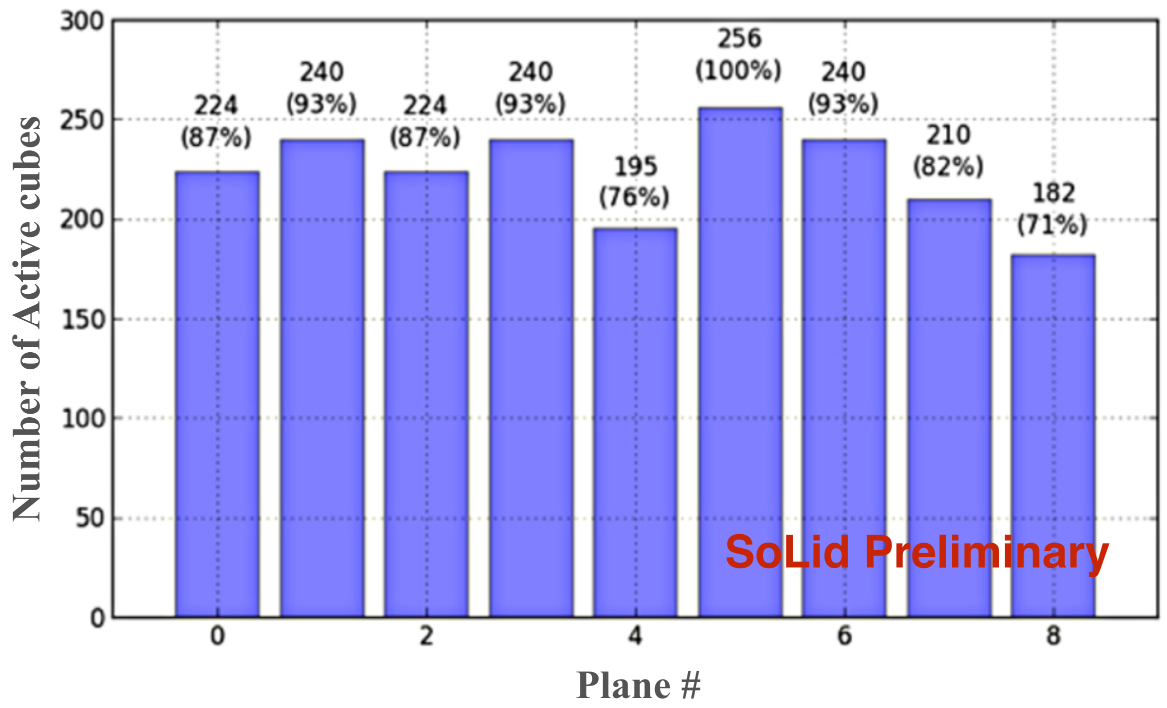


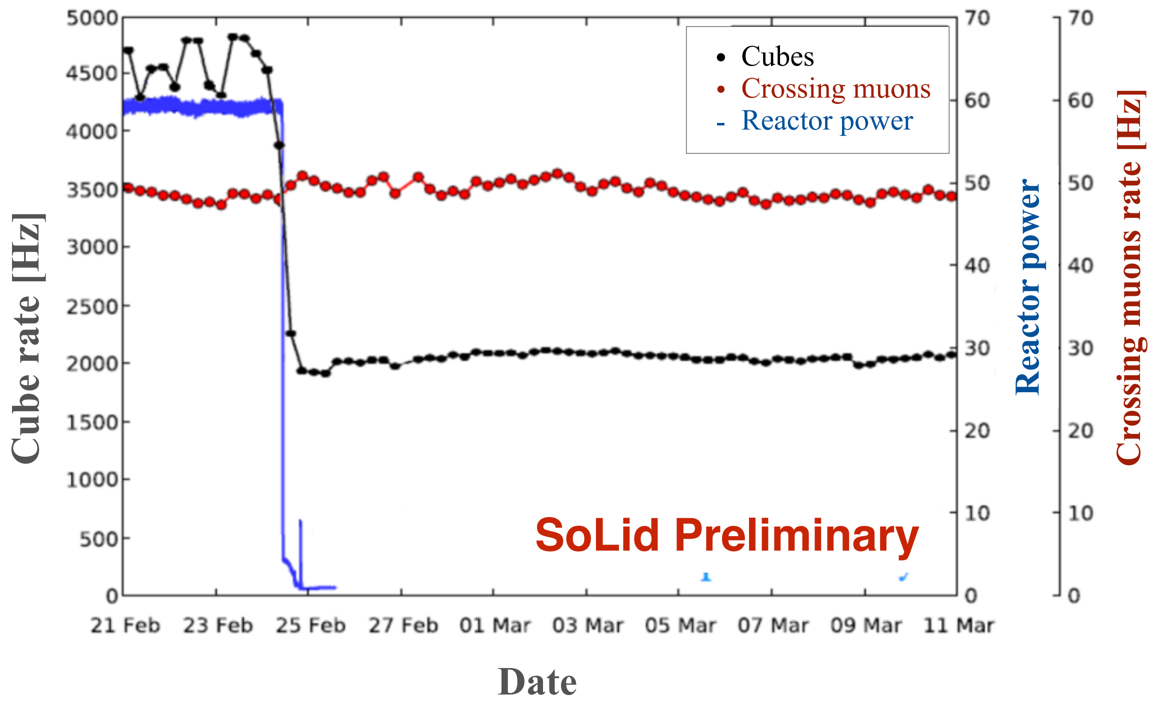
- Improvised trigger and no passive shielding !!

SM1 data taking

- Data from February to April 2015 : ~ 2 days reactor ON / ~ 1 month reactor OFF

Period	Dates	Exposure Time (h)
Reactor ON	00:00 21st Feb to 08:00 24th Feb	50.91
Reactor OFF	00:00 27th Feb to 00:00 13th Mar, and 00:00 27th Mar to 00:00 11th Apr	525.51
	Exposure time ratio (ON/OFF)	0.0969





- 87% good/stable cube
- Data over time

+ dedicated calibration runs : ^{60}Co, ^{137}Cs, AmBe, ^{252}Cf

SM1 Neutron ID

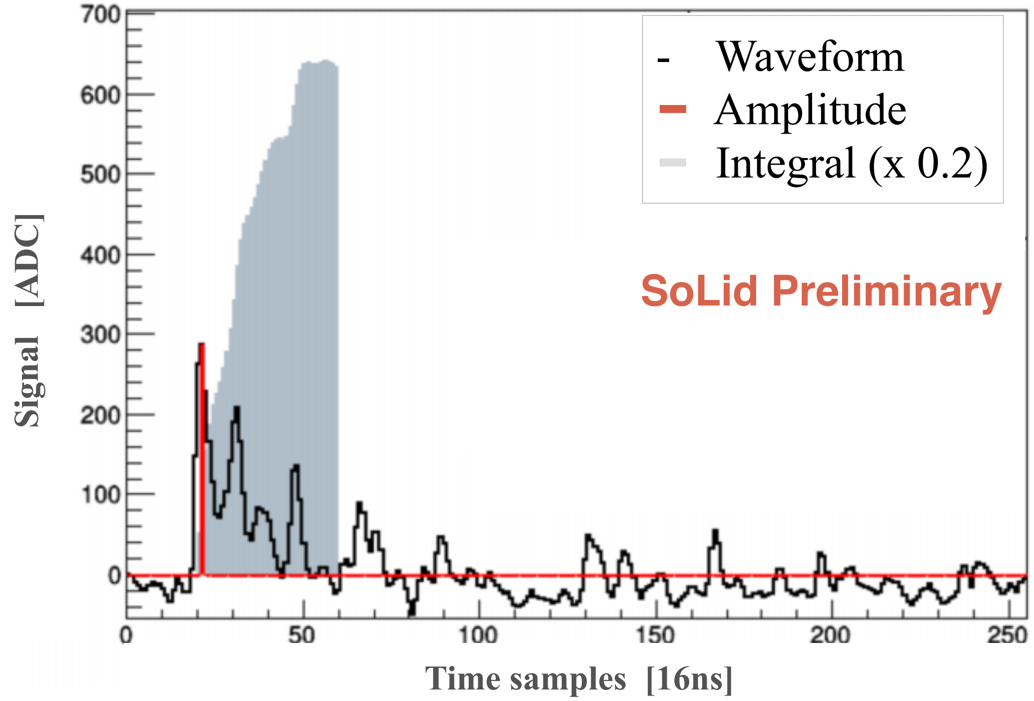
- IBD neutron capture efficiency : 55%

  MCNP/Geant4 benchmark

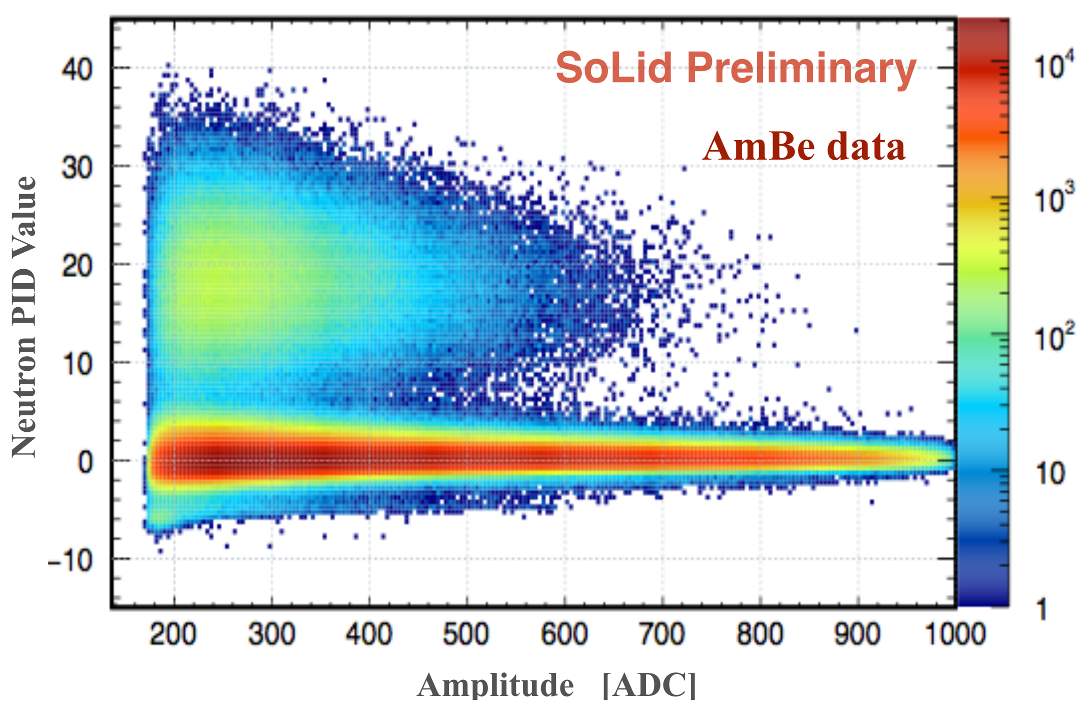
- Pulse shape analysis to tag neutrons

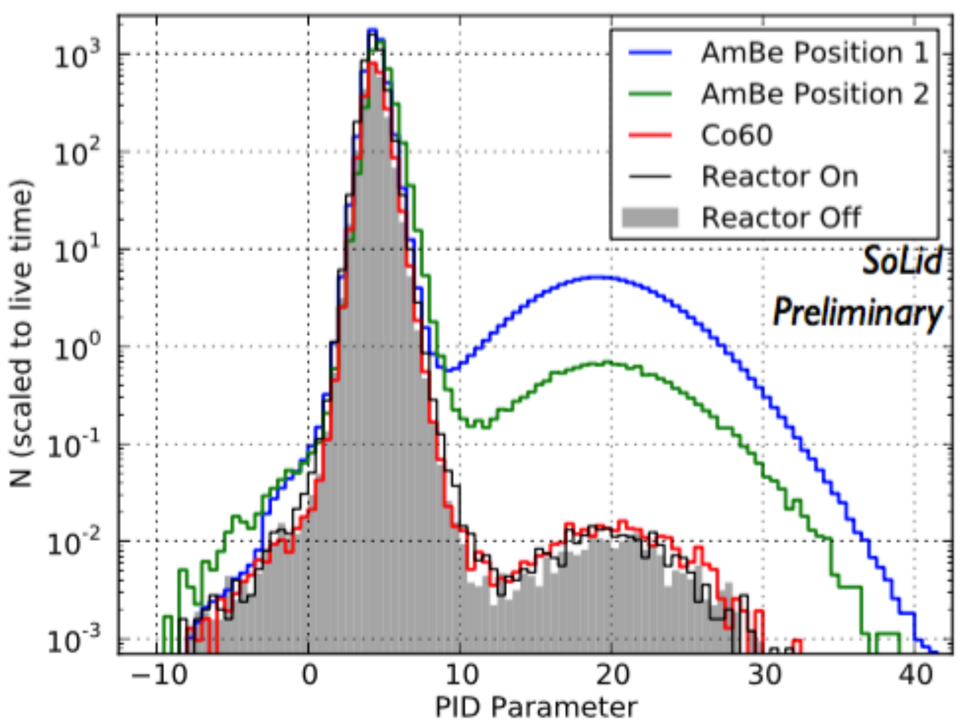
  PID = Integrale/Amplitude ± Cor_{chan}

  Coincidence X/Y



- PID cuts validated by ^{60}Co and AmBe data

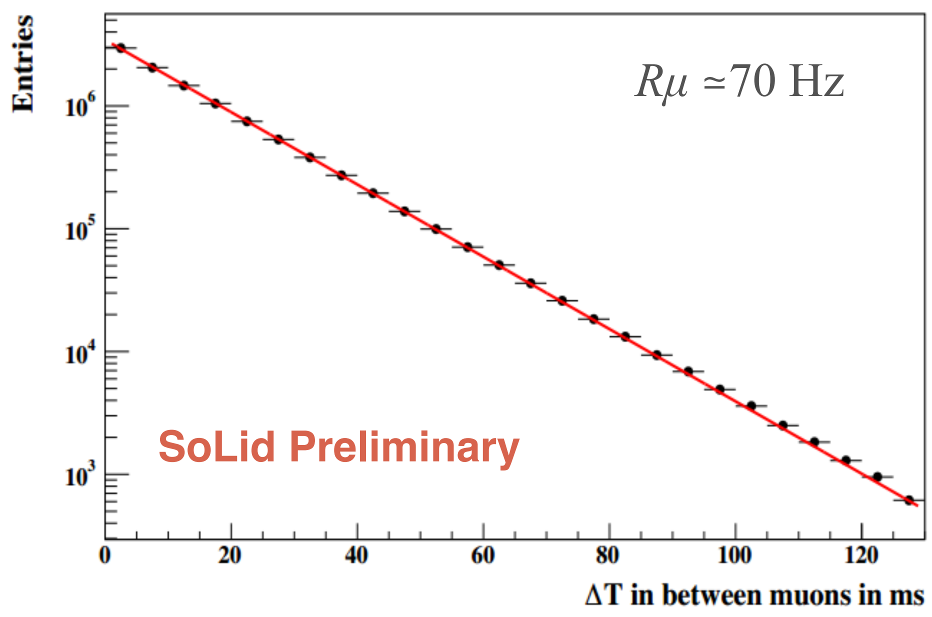


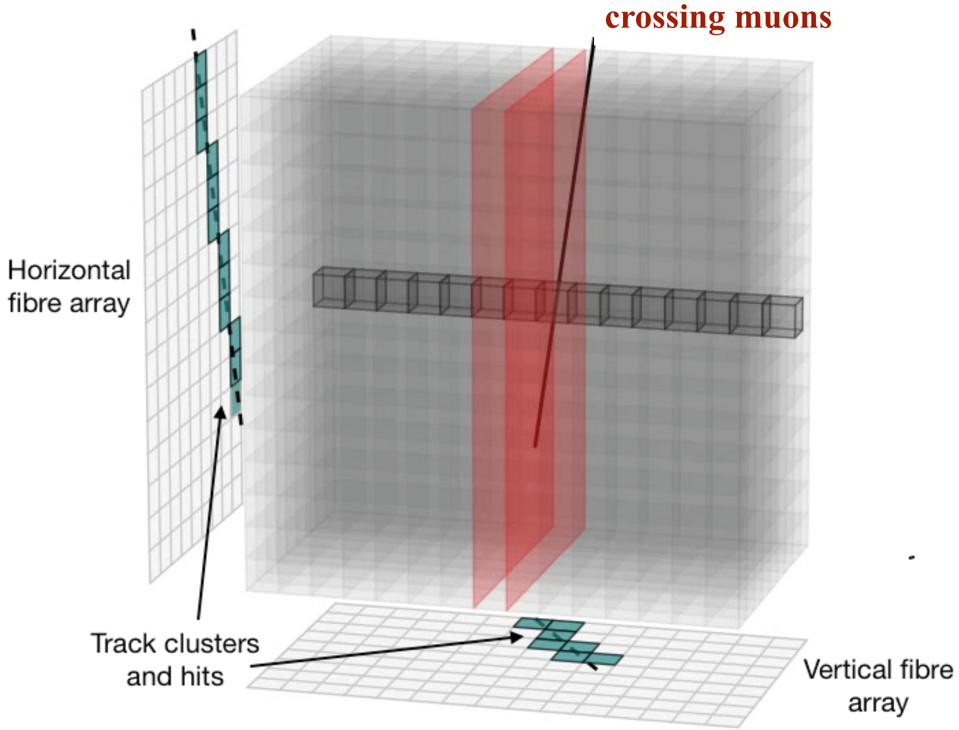


- Can distinguish a neutron in 10 millions events !

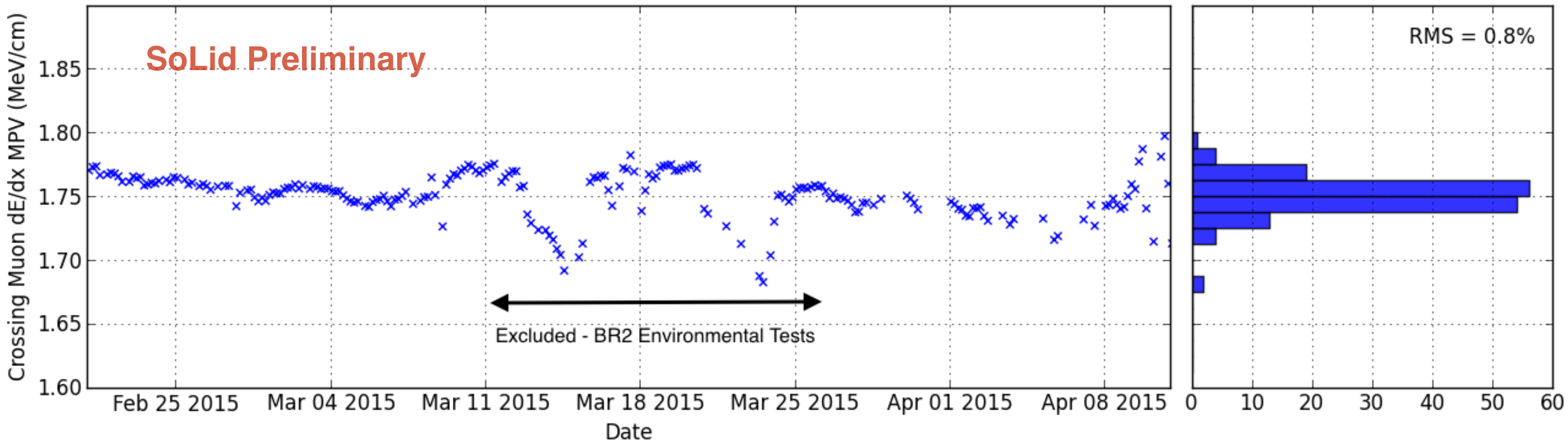
- Excellent muons tracker (>95% efficiency)

PSD, deposit energy, topology, timing





- Monitor detector stability over time (@ % level)



Energy-scale and resolution

- Cube inter-calibration (fibre attenuation) to better than 1% for majority of channels

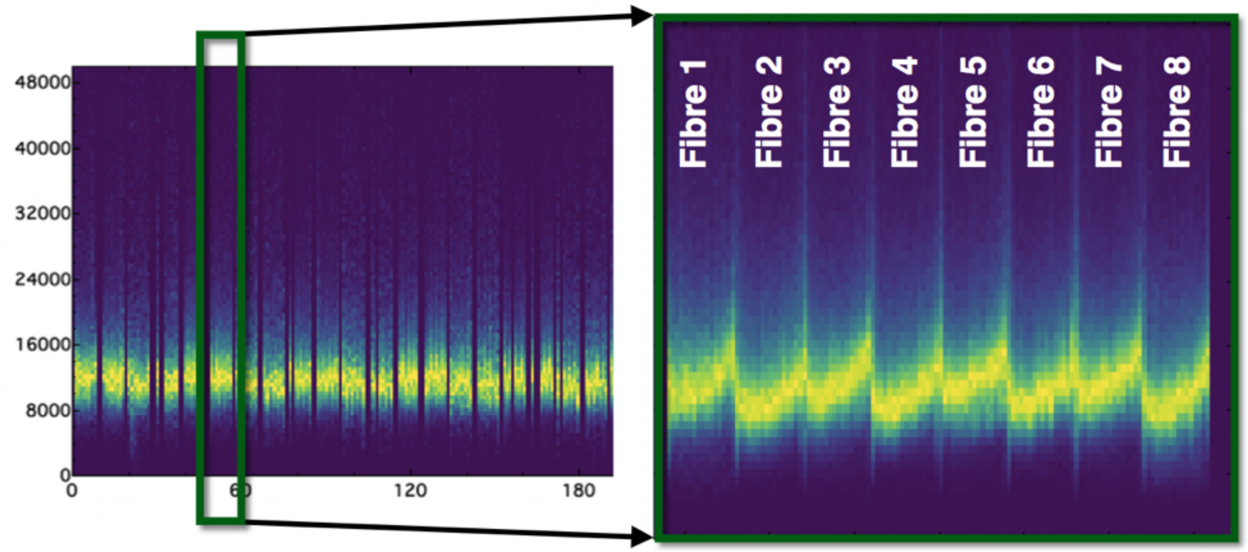
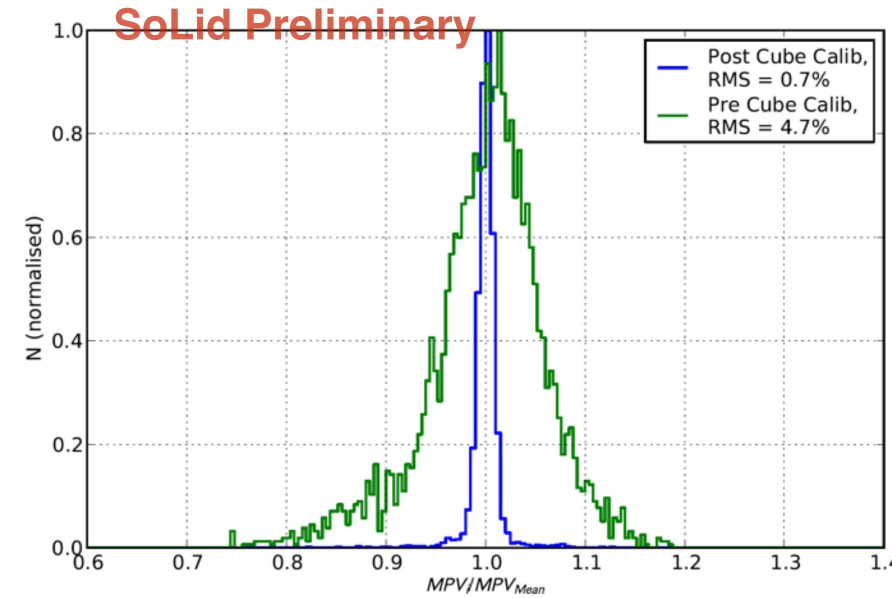
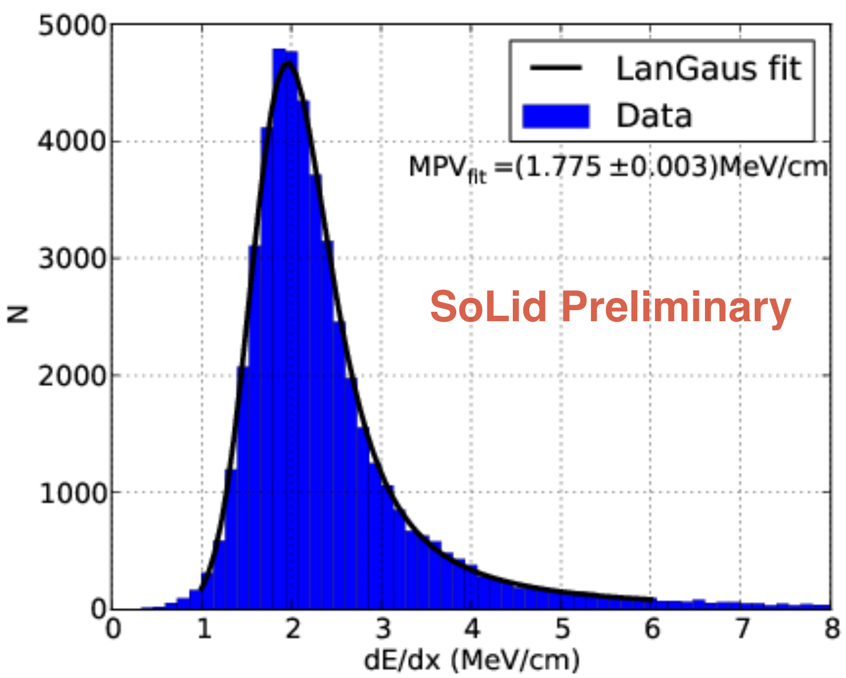


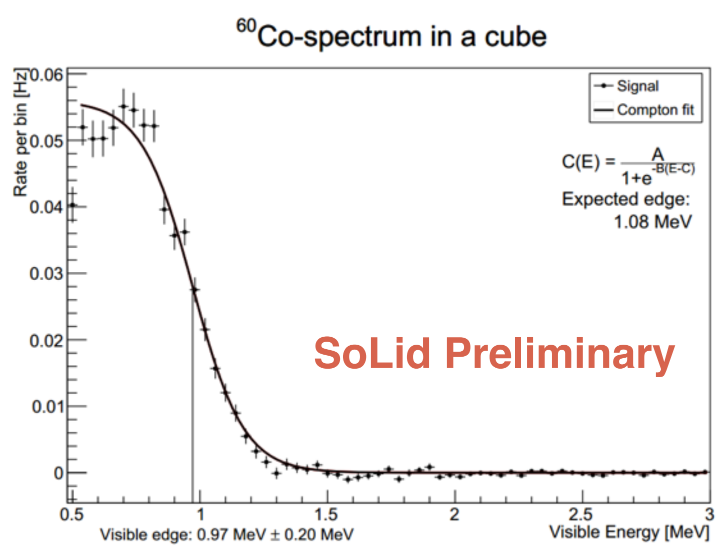
Fig: dEdx distribution across cubes.

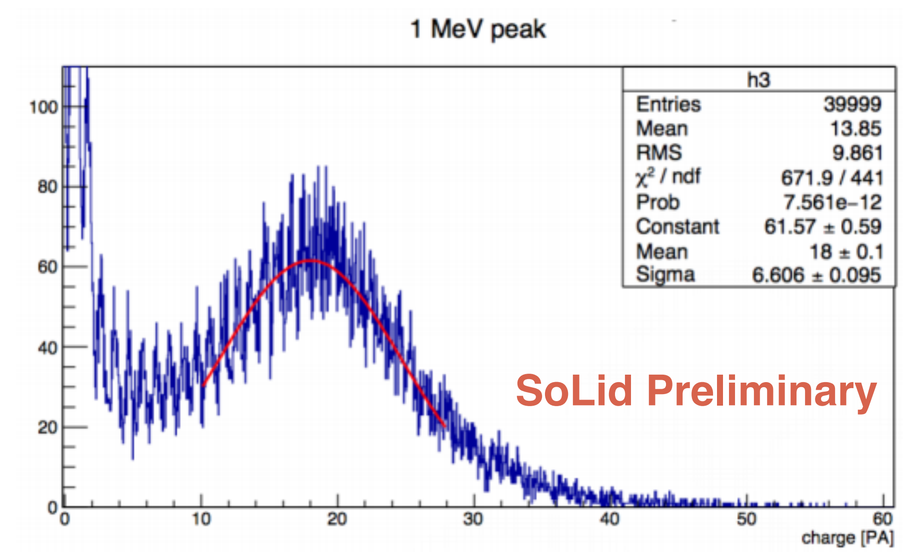


- dE/dx : $\delta E / \sqrt{E} \sim 20$ %



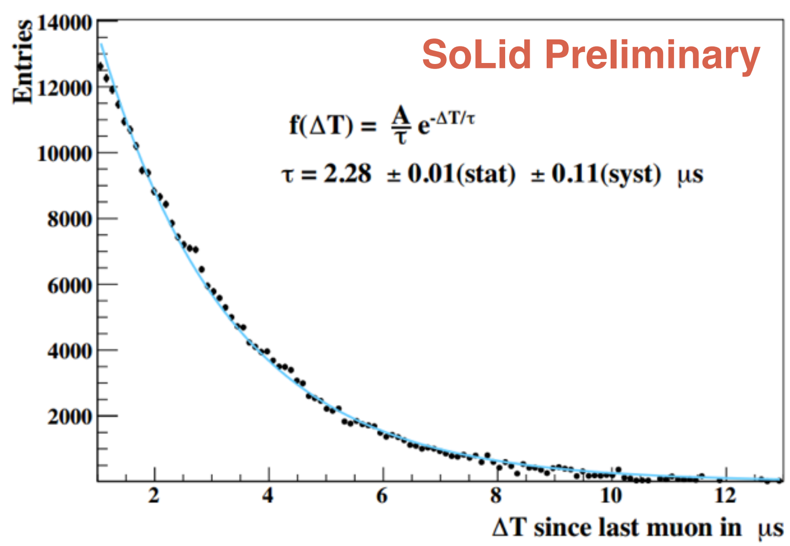
- In agreement with ^{60}Co run, ^{207}Bi test-bench and AmBe data (4.4MeV γ)

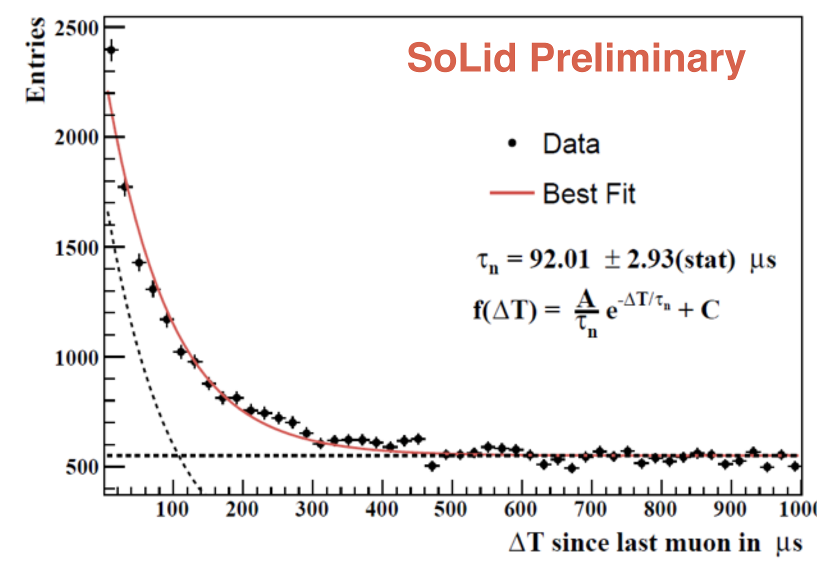




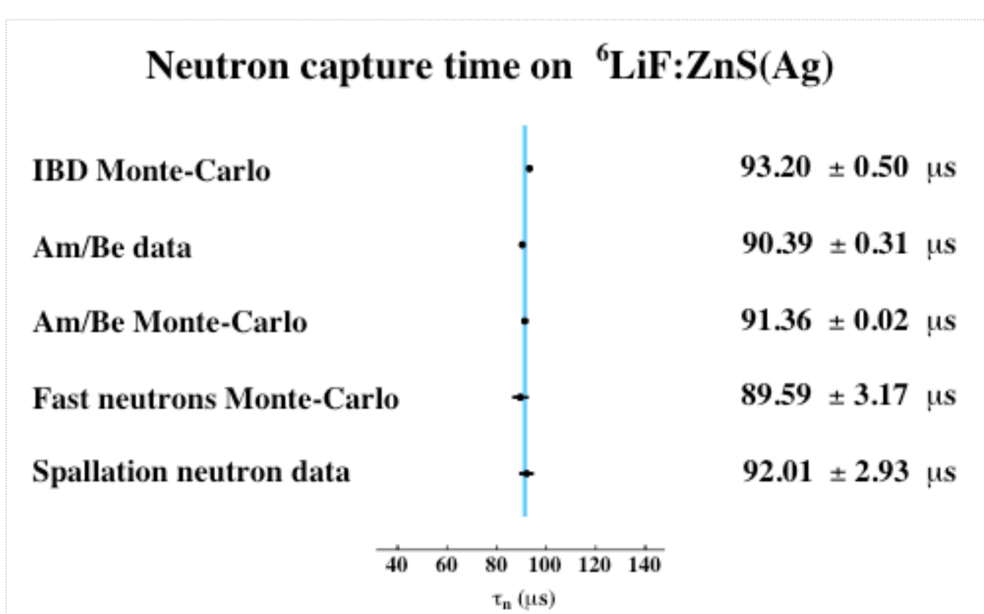
Time-correlated signal

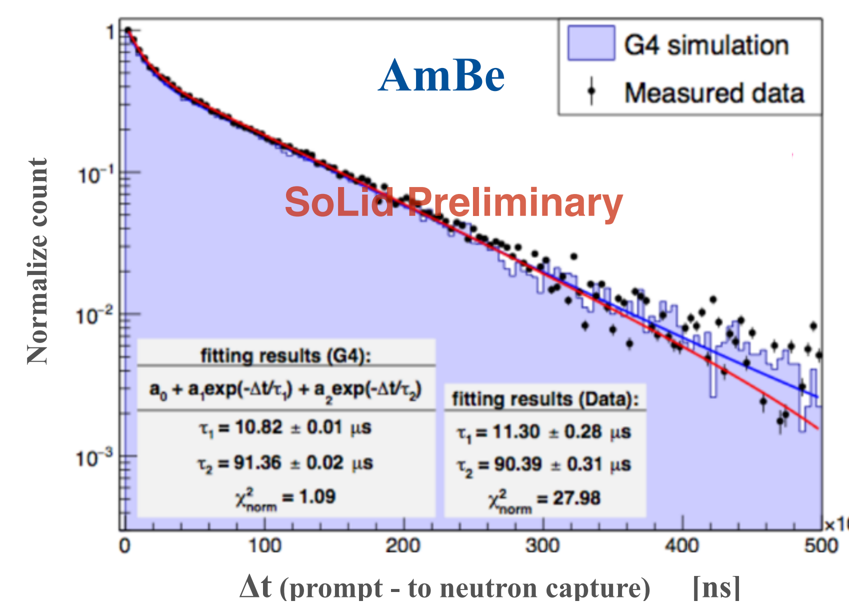
- Muon correlated time signals





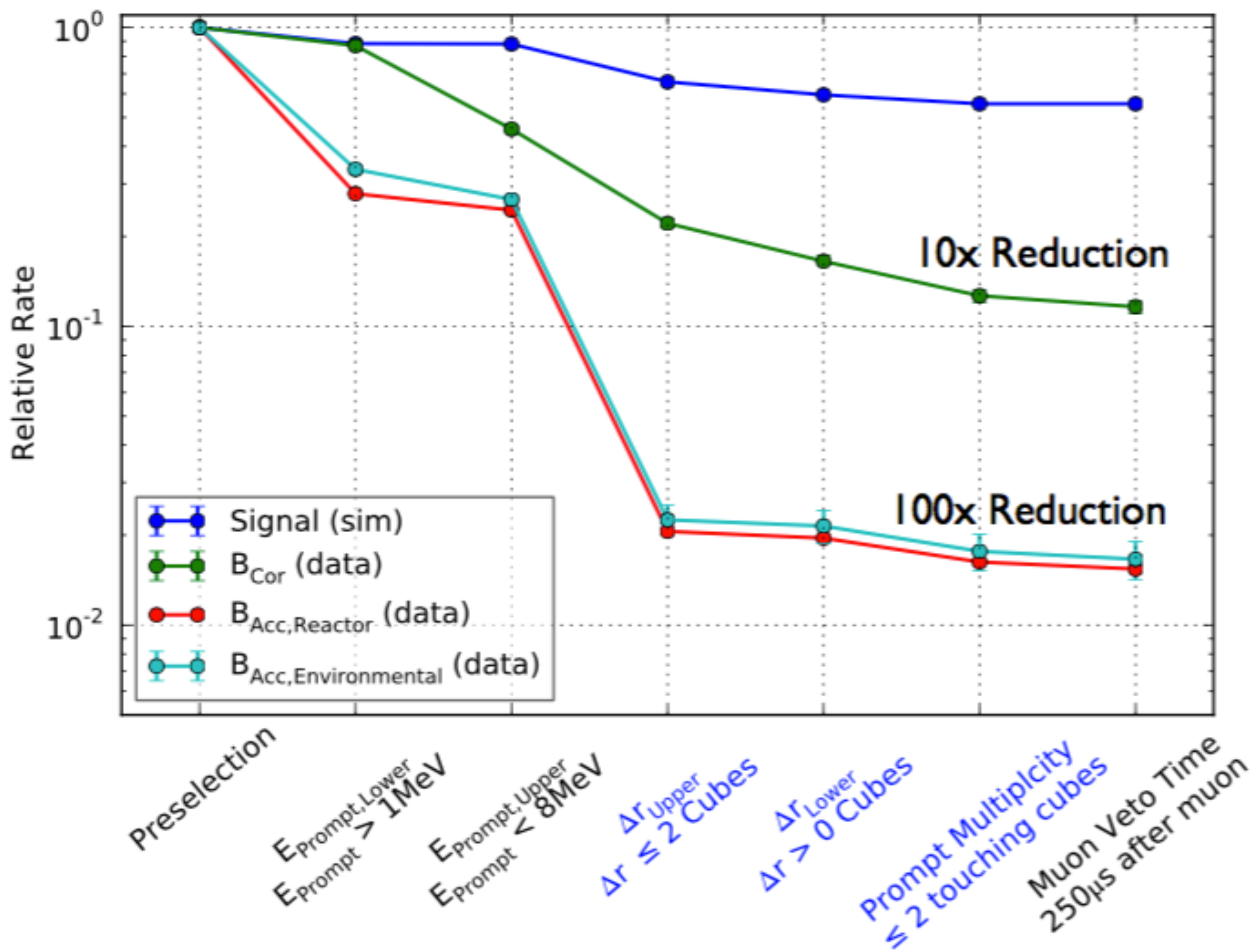
- IBD-like neutron capture time



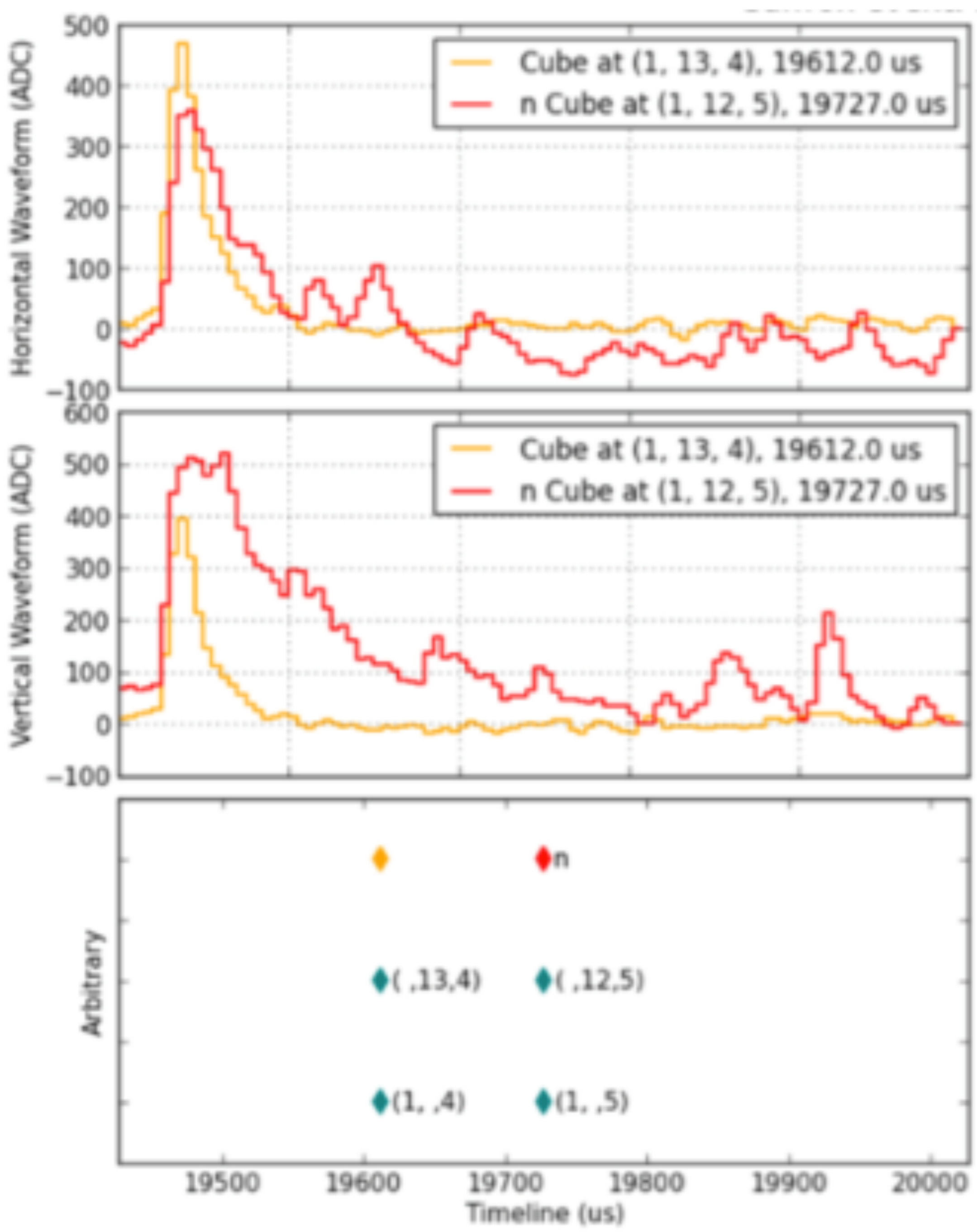


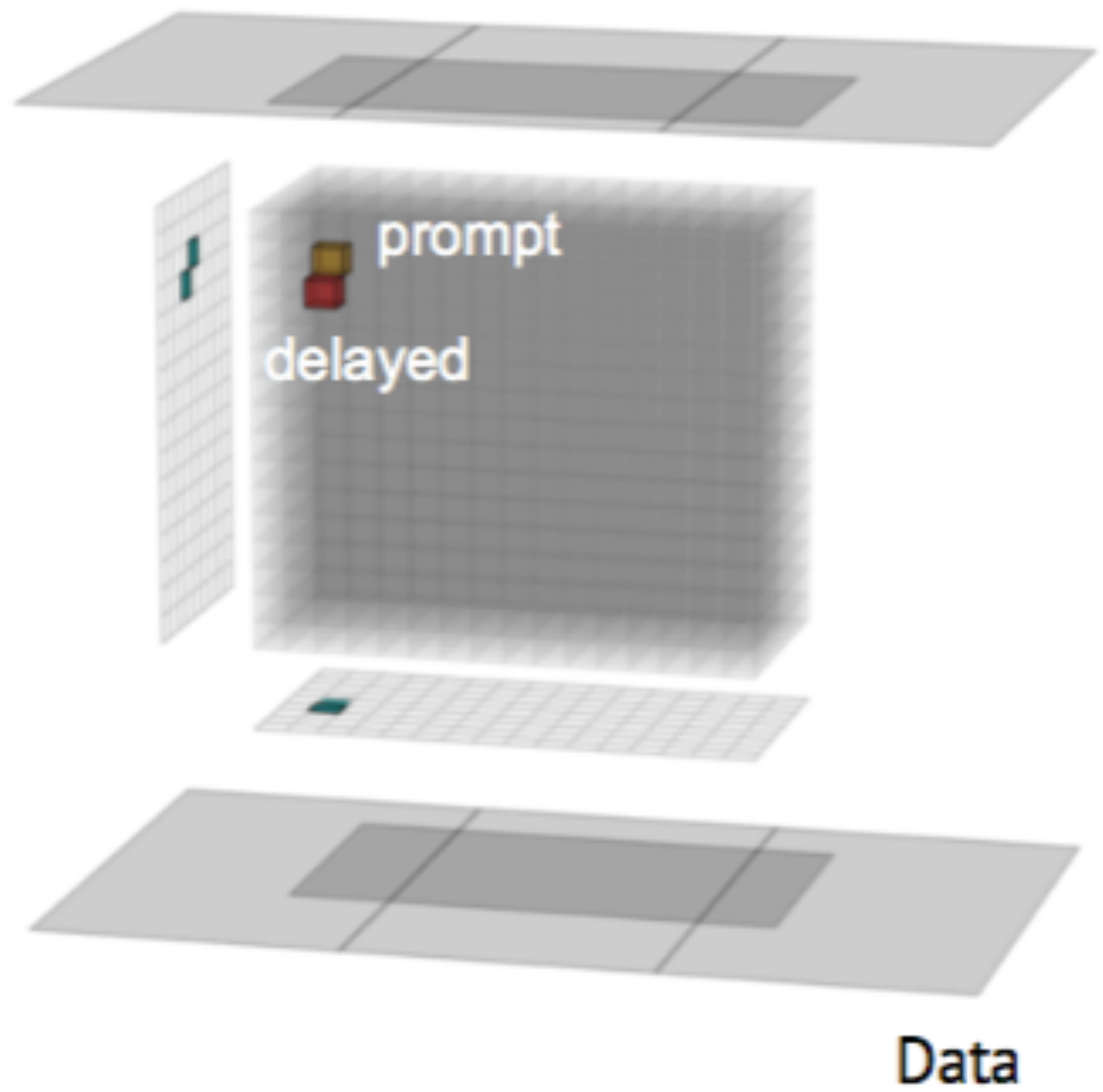
Signal analysis & IBD selection cuts

- Power of segmentation on background rejection ($0.1 < \Delta t\ (\mu s) < 250$)

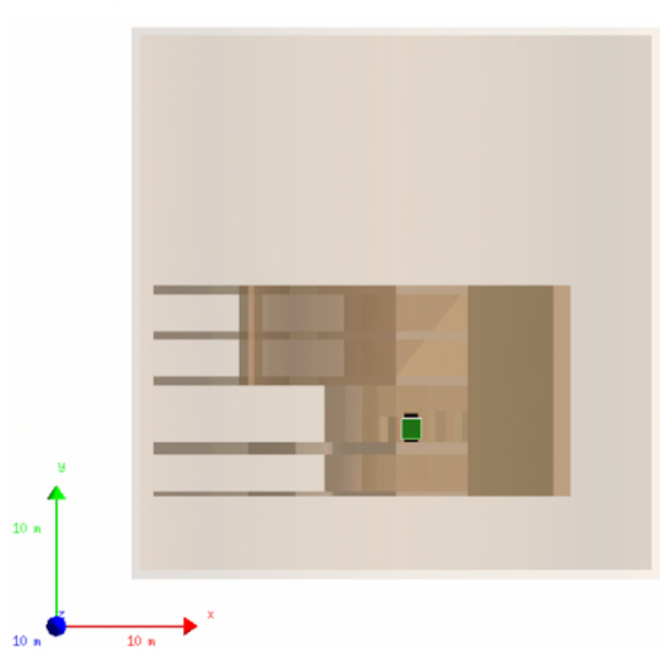


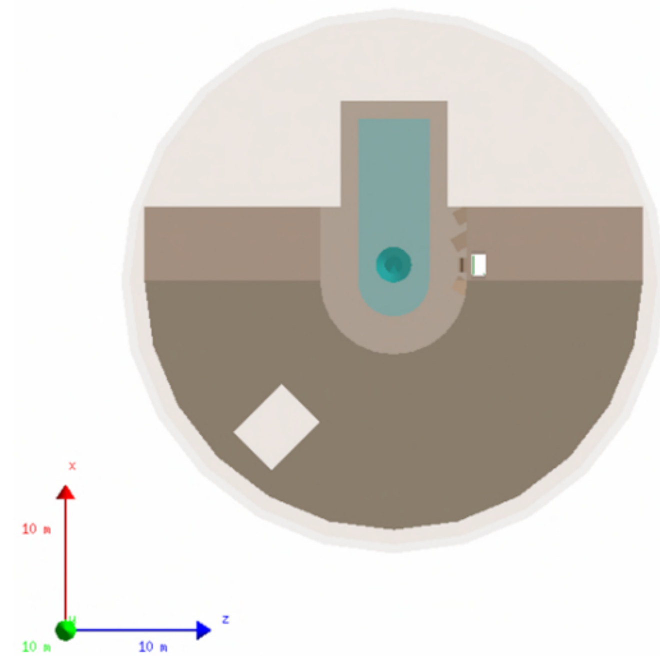
IBD candidate

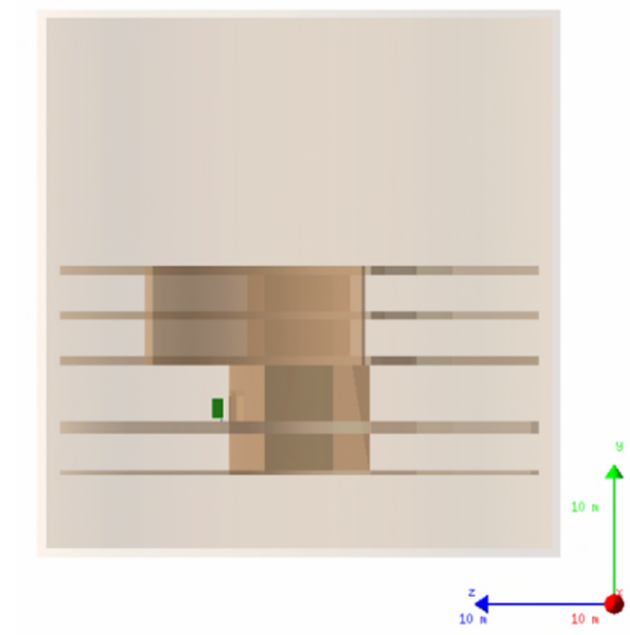




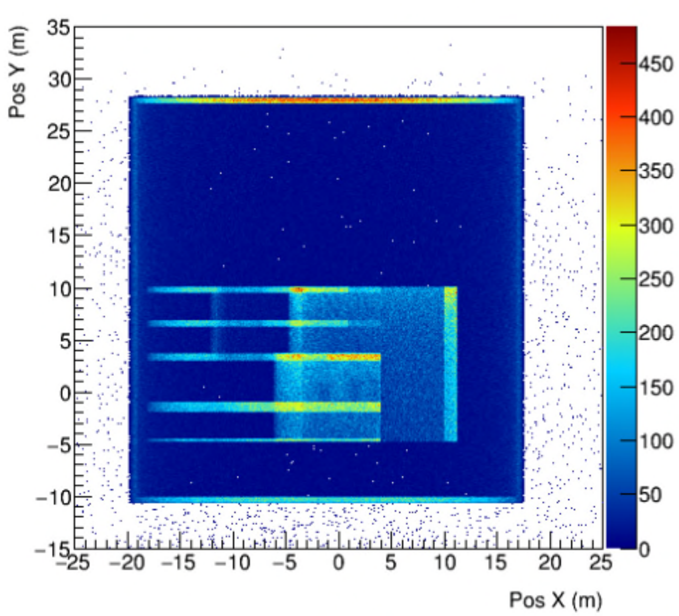
- Full Geant4 BR2 model implemented & 3 independent muons generators (CRY, Reyna, Guang)

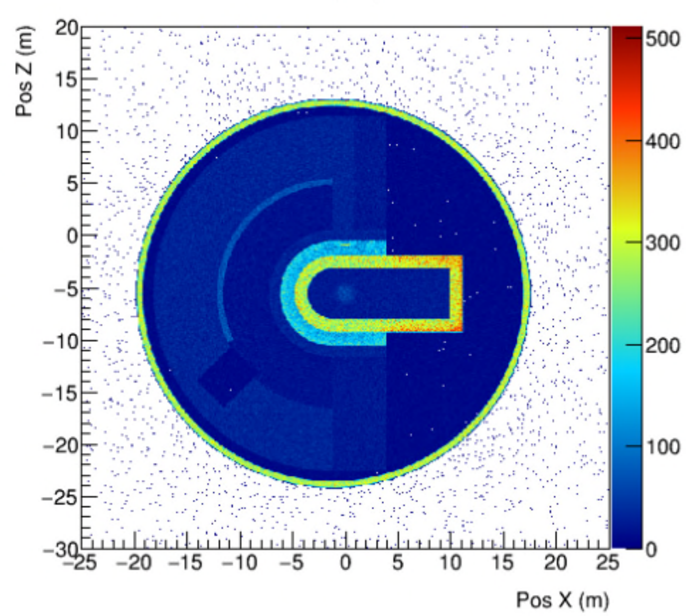


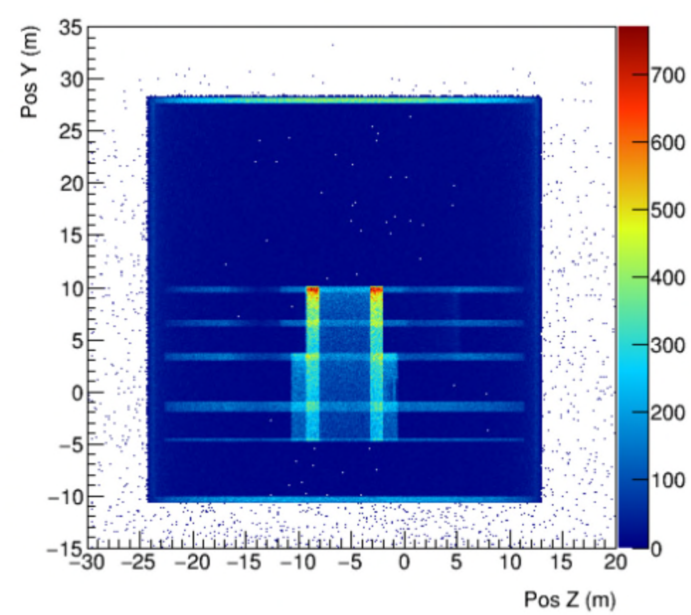




- Spallation Neutrons generation (CRY & Gordon)







Vol name	n generation (%)
other	0.080362
LiFZnS	0.000000
PVT	0.000444
PPL shielding	0.000752
n reflector	0.000051
HDPE in plane	0.000051
Al frame	0.001760
Air	0.254757
NORCAN	0.000376
Iron table	0.002153
Al plate	0.000051
Pb wall	0.059613
Concrete wall	32.877433
Concrete other	64.930263
Reactor core	0.153938
Water pool	1.637994

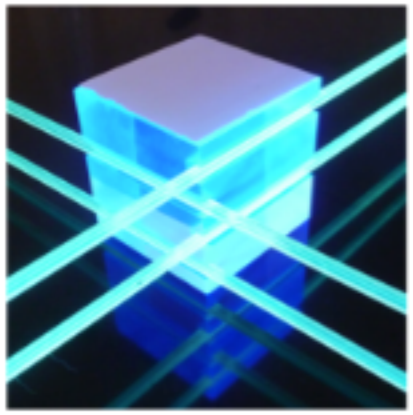
SoLid improvements

- Neutron capture efficiency

  Additional LiF:ZnS sheets

  New screens with improved transparency

  - Li capture efficiency 0.55 to 0.7 : +30%
  - Reduced capture time 105 to 66 μs



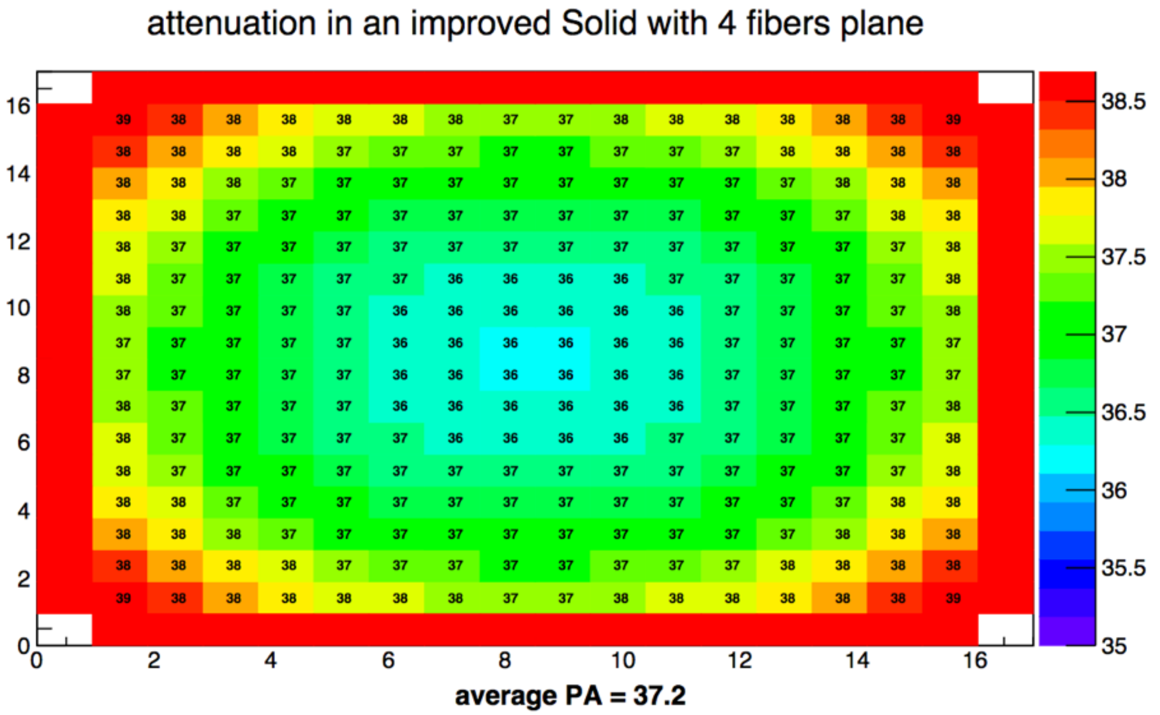
- Light yield and uniformity of response

  Double readout : 2 → 4 fibre/MPPC per cube

  Thick Tyvek wrapping

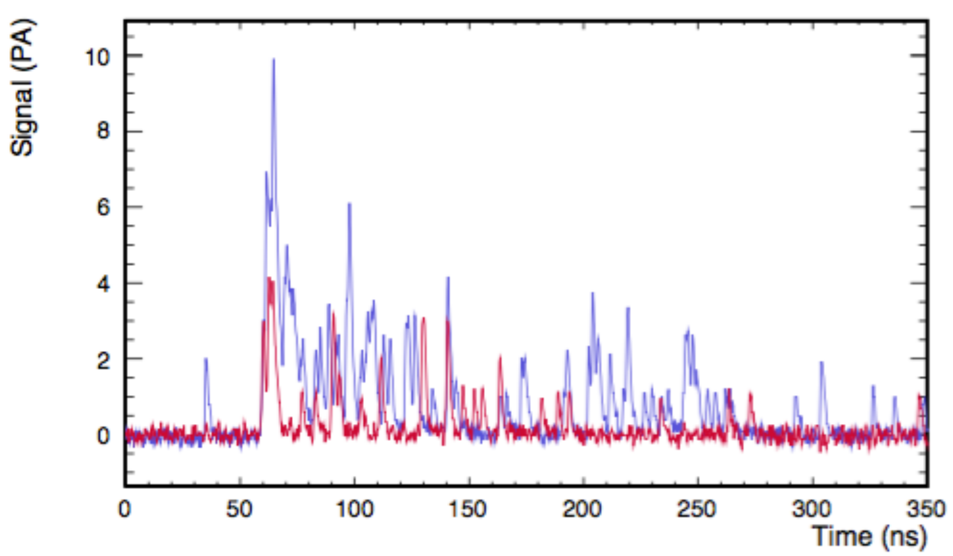
  Cube polishing

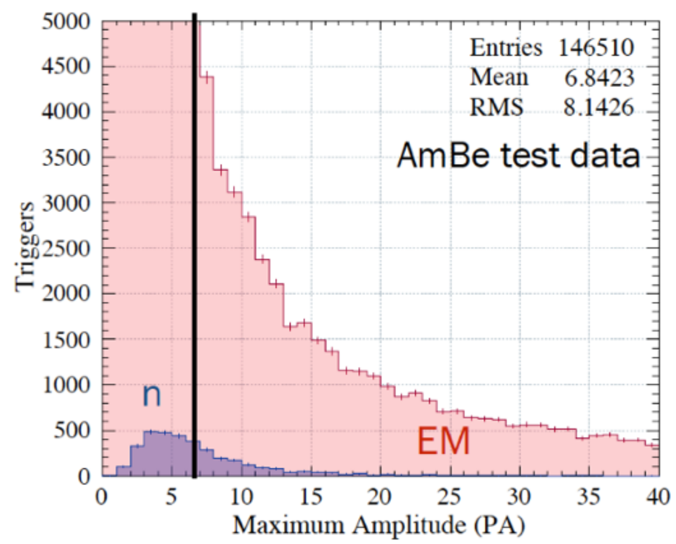
  - 37 PA/cube/MeV : +66%
  - 7% total variation across detector planes
  - On target for 14% /√E resolution



SoLid improvements - Neutron trigger

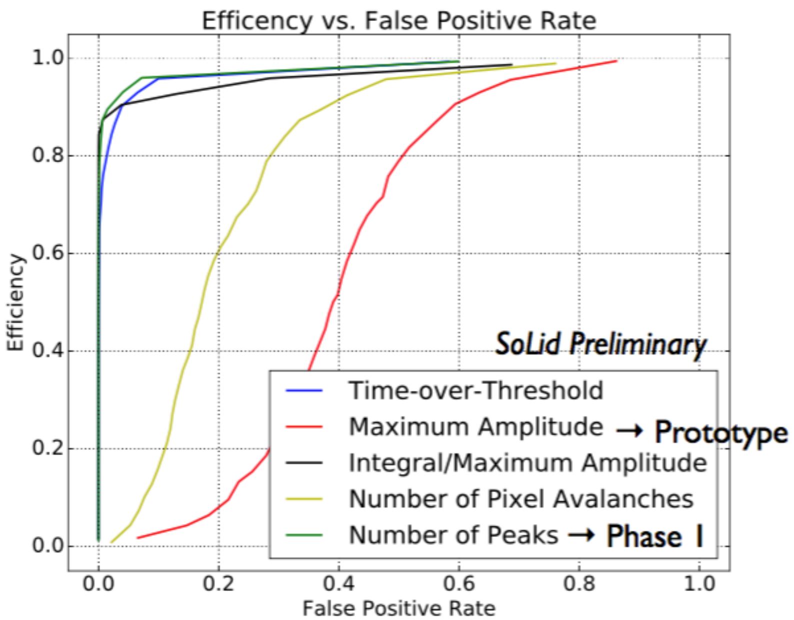
- Neutron signal : large number of photons but distributed in time and large range of light output
- SM1 had a rather low neutron detection efficiency of ~ 5%, due to high trigger threshold (~6.5 PA)

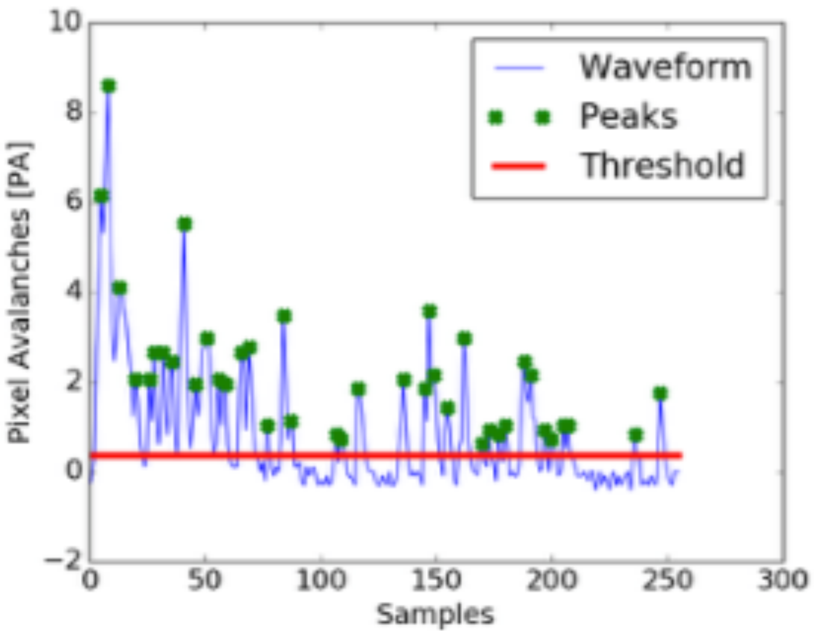


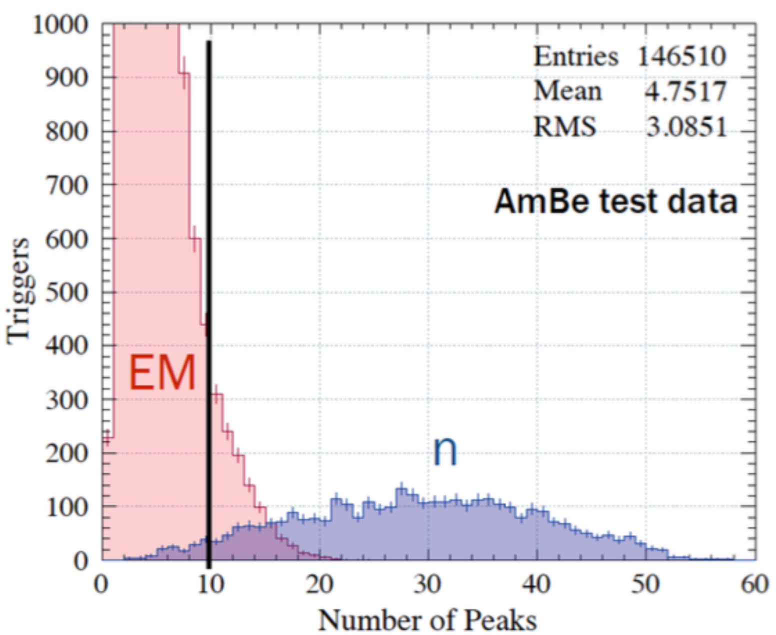


- Neutron trigger implementation (at the firmware level)

Limit data size, rate and dependance to threshold & Maximise neutron and IBD efficiency



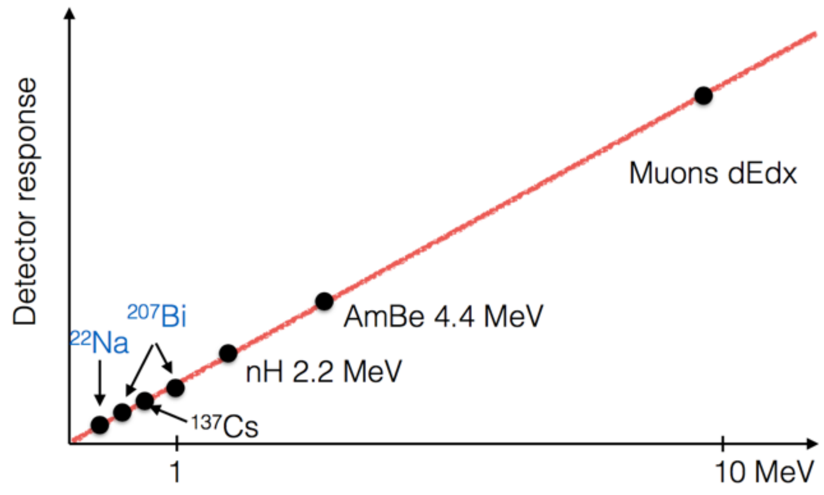




- Can recover neutron detection efficiency from 5% to 70% !

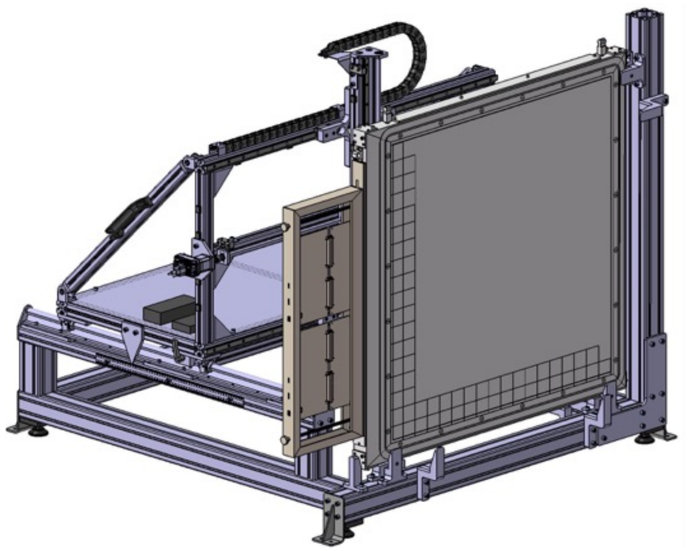
Calibration - neutron efficiency and energy resolution (% level)

- PVT response linear in range [0.1-20] MeV
- Sources : Muons, ^{137}Cs, ^{60}Co, …, AmBe, n(H)
- R&D on dedicated trigger system : ^{207}Bi, ^{22}Na



Off-site calibration system (CALIPSO)

Individual automated X-Y scanning

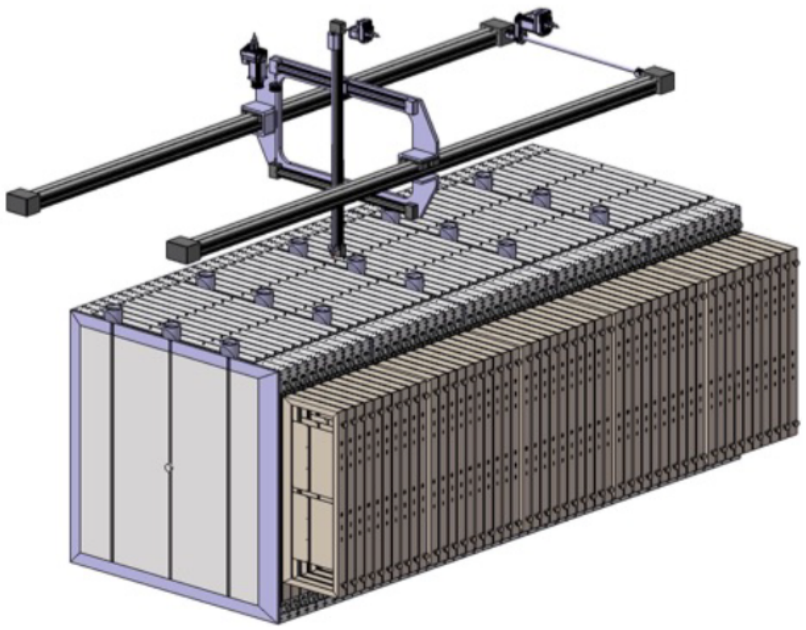


Plane characterization and commissioning

Cube to cube equalization

In-situ calibration system (CROSS)

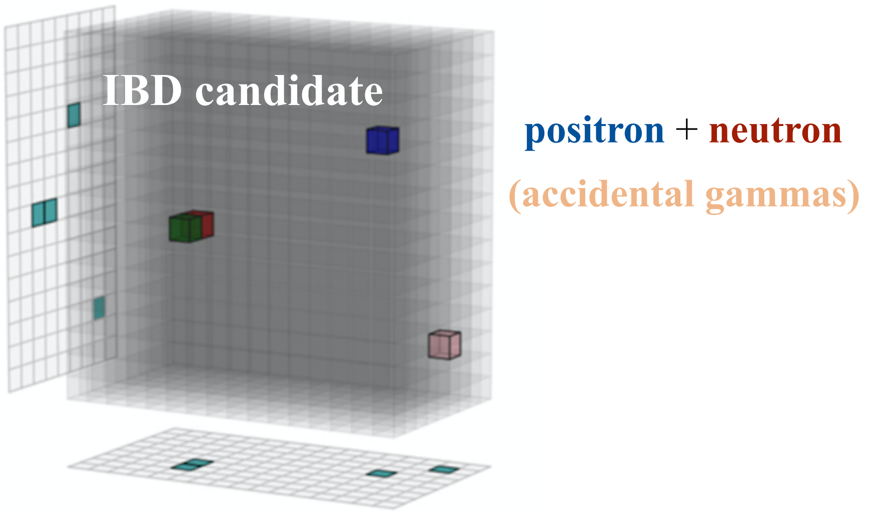
In-situ radioactive sources deployment



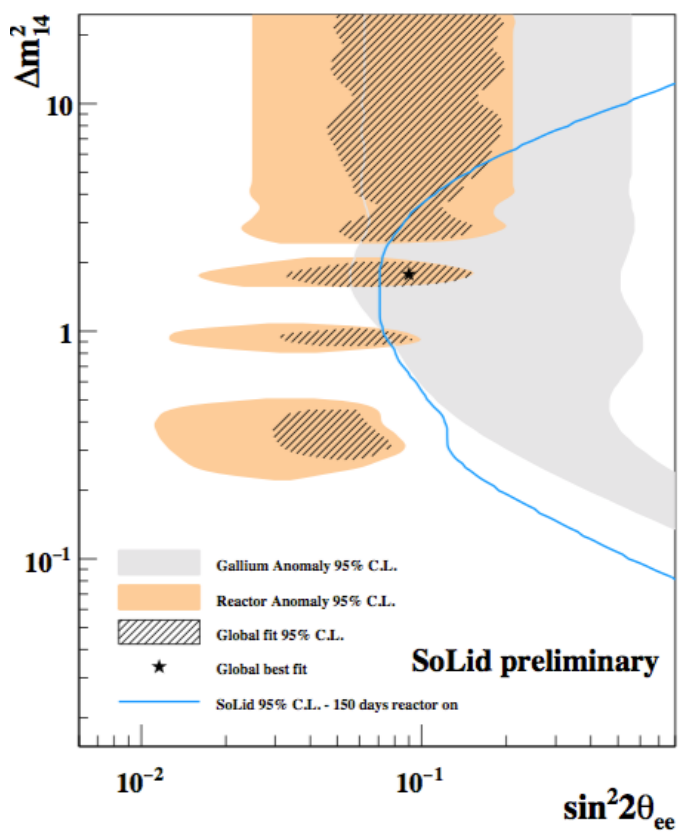
Absolute energy scale and neutron detection efficiency determination at a few %

Summary

- Successful NEMENIX and SM1 runs
  - Excellent neutron/EM identification
  - Muons tracking opportunities
  - Background studies & rejection capabilities
  - IBD analysis ongoing … *2 papers in preparation*



- SoLid Phase I under construction : 1.6 t (2t) / 50 planes modular
  - Funded by ERC (EU), ANR (Fr), and FWO (B)
  - Better light yield/energy resolution
  - Read-out improvements : cooling, DAQ/electronics, triggers
  - In-situ calibration (γ, neutron, e^-)
  - Passive shielding (50 cm borated water)
  - Cosmic veto umbrella (under studies)



- Deploiement for phase I data taking at the end of 2016