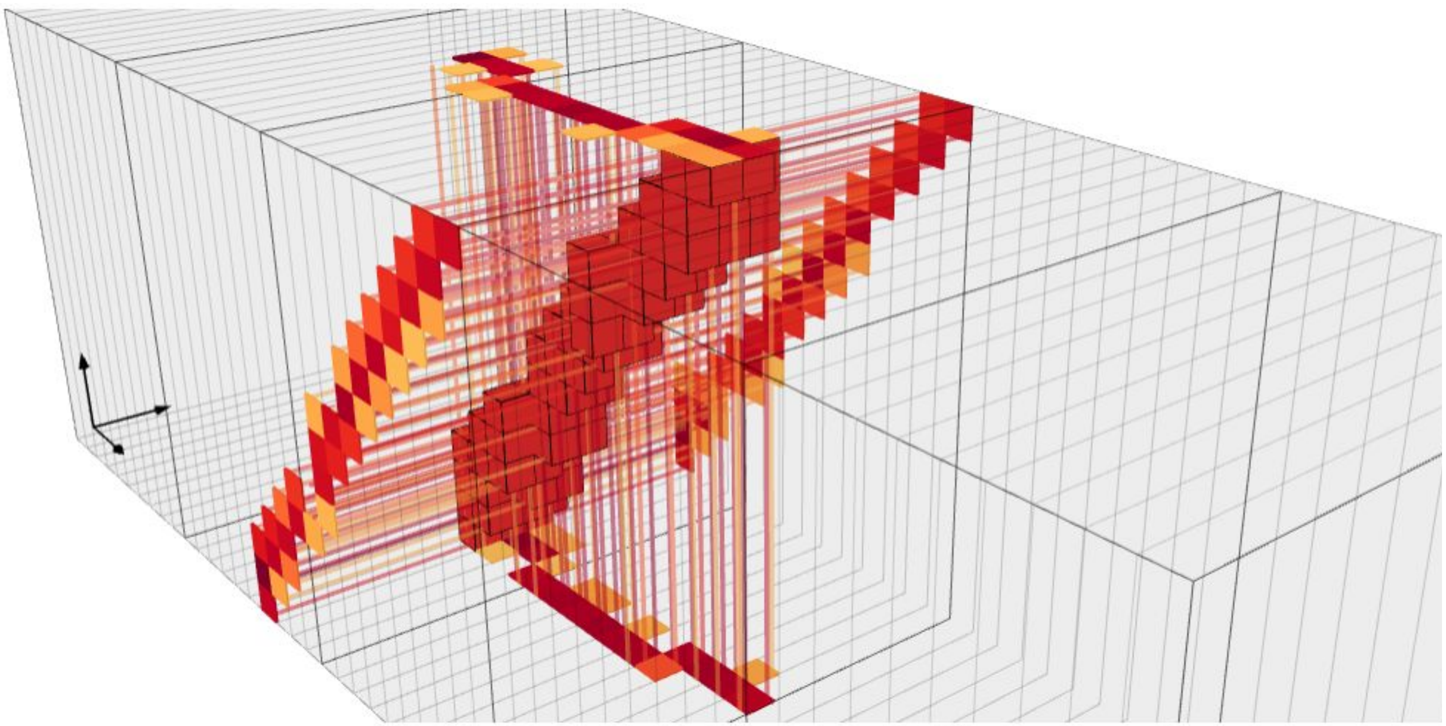
SoLid: Search for neutrino oscillations using a Lithium-6 detector at a nuclear reactor

Deployment of the SoLid Experiment

RAL Seminar, 13th Feb 2019, Dan Saunders



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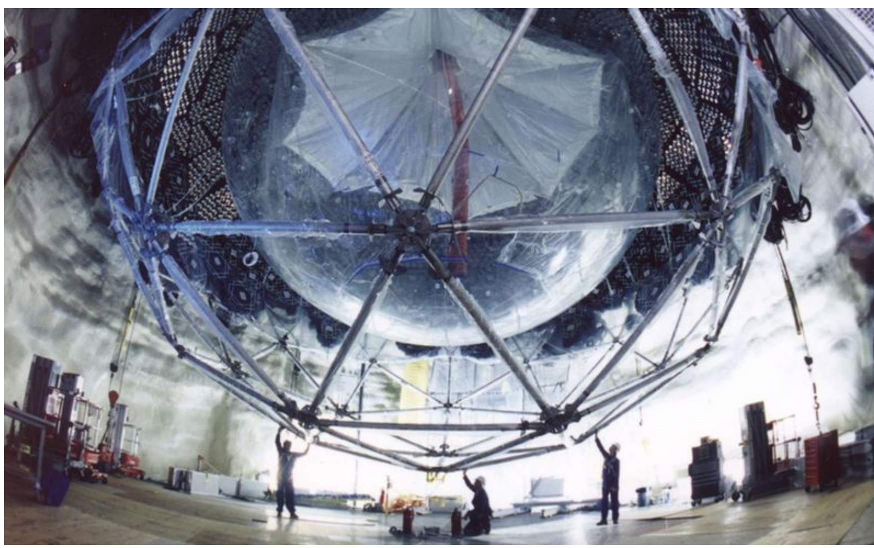
Outline

- Neutrino Oscillations (reminder)
  - Reactor based neutrino experiments (current gen & next gen).
  - Searching for sterile neutrinos.
  - Challenges at very short baselines.
- Detector Research and Development
  - Detection principle.
  - Prototype results.
- Phase I Deployment
  - QA Campaign.
  - Detector commissioning.
- Outlook

Neutrino Oscillations (reminder)

- Neutrino oscillations (3-flavour) well established:
    - Solar oscillations observed first by both SNO + SuperK.
    - Flux measurements of solar electron and muon neutrinos.
    - Solves solar neutrino problem.
    - Requires neutrino’s have mass.



SNO Observatory

Super K

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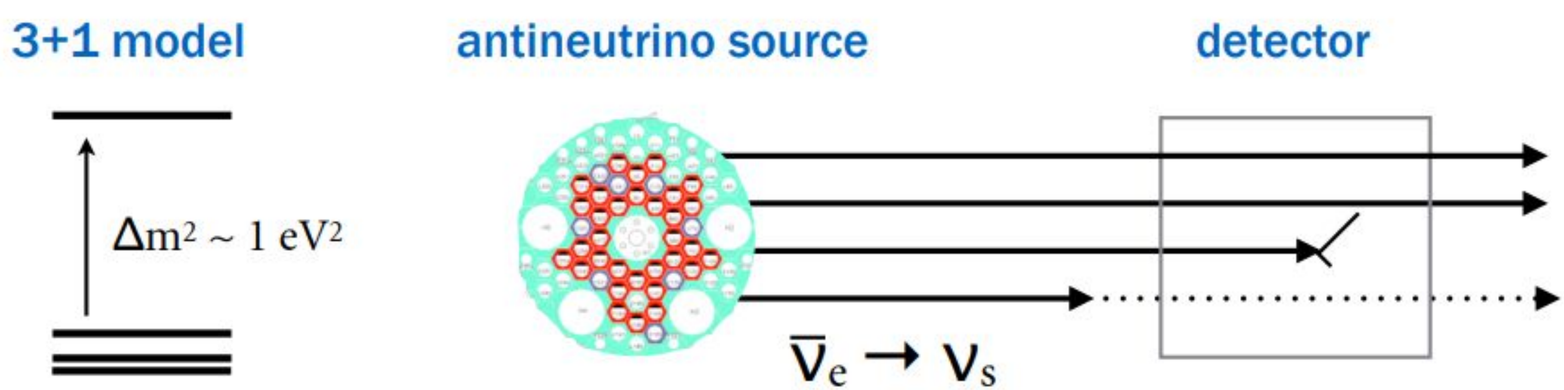
- Oscillations parameterised by PNMS mixing matrix:
  - Many of the 6 free parameters accurately measured:
    - Δm_{12}, θ_{12} → solar experiments + Kamland.
    - Δm_{23}, θ_{23} → beam experiments.
    - θ_{31} → short baseline reactor and beam experiments.
    - δ → beam experiments.

→ **The complete picture?**

Sterile Neutrinos

- Three-flavour case can be expanded to include new 'sterile' state:
  - Flavour interactions forbidden - limits from LEP.
  - Introduces two new oscillation parameters: $\boldsymbol{\Delta m_{14}}$, $\boldsymbol{\theta_{14}}$
  - Current global fits suggest oscillation would be at scale: L/E ~ 1m/MeV
- One of the simplest solutions to several anomalies found by radioactive sources and reactor experiments.

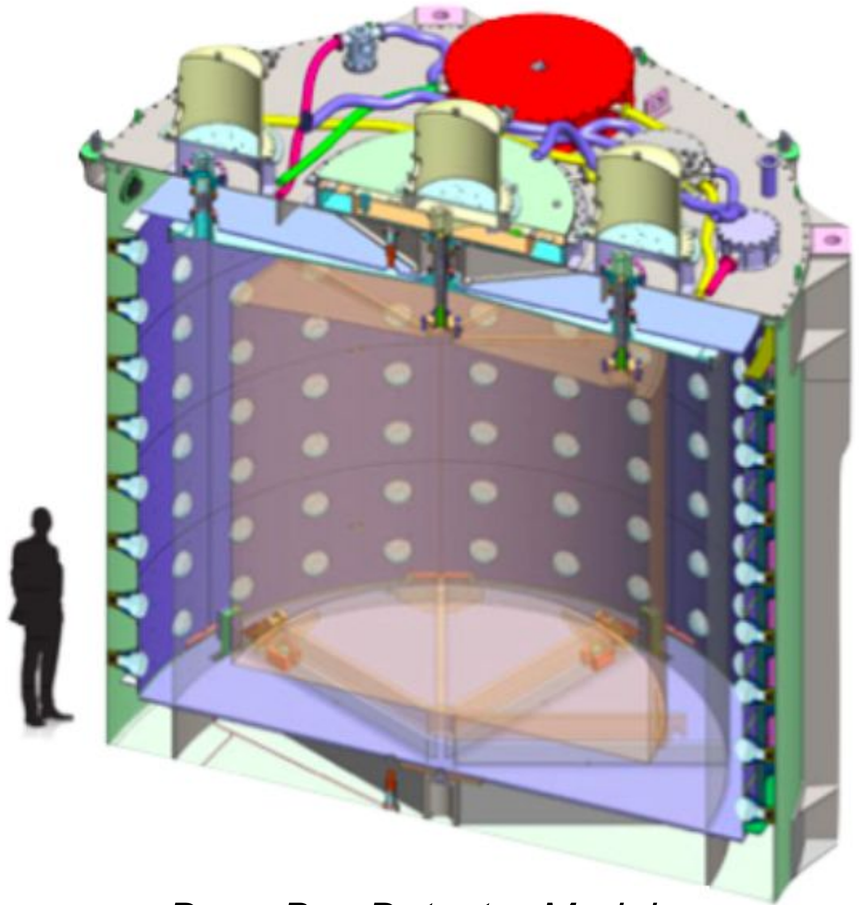
$$P_{ee} \sim 1 - \sin^2(2\theta_{14})\sin(1.267\Delta m_{14}^2 L[m]/E[MeV])$$



Short Baseline Experiments

- Reactor neutrino experiments well established:
  - First successfully attempted 1956 at Savannah River.
  - Multiple experiments since, with varying mass and distances from reactors.

- Take advantage of the large ν flux from reactors:
  - E.g. Daya Bay event rate: ~10 neutrinos per hour.
  - Principally beta decay of Barium and Krypton for U235 reactors.



Daya-Bay Detector Module

Current Generation

- Current experiments searching for oscillations at short baselines:
  - ~100m to ~1km:
  - Daya Bay, RENO, Double-Chooz.

- Very successful physics campaigns:
  - Largely dedicated to measuring antineutrino electron disappearance.
    - First confirmed observation in 2012.
    - Precision measurement of θ_{13}.
  - Use near and far detector to remove systematic errors in flux calculations.

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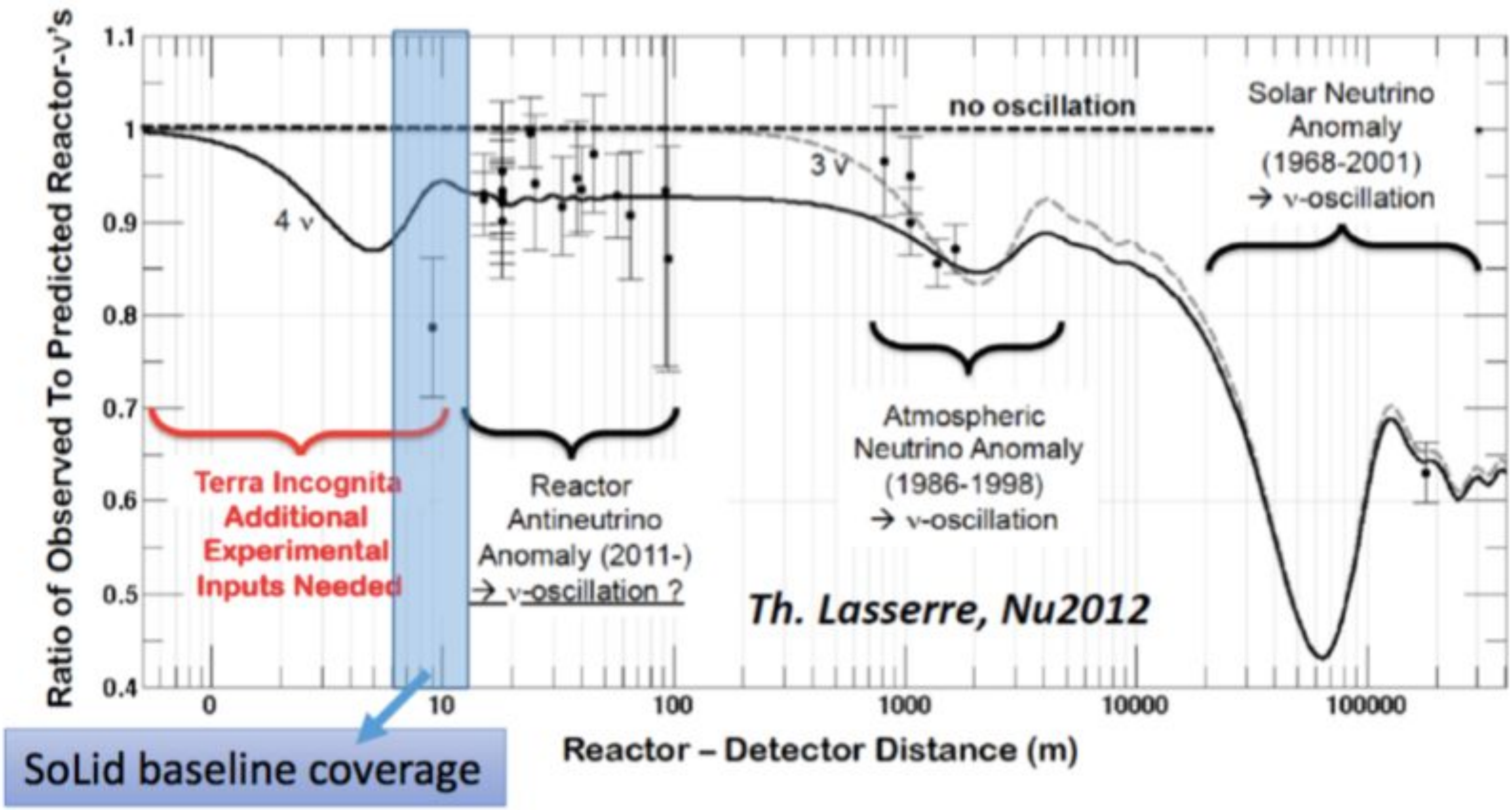
- Common characteristics:
  - Underground lab → reduced background.
  - Liquid scintillator → sometimes flammable.
  - Large external shielding → non-compact.

    → *Difficult to use very short baselines.*

Some anomalies…

Reactor Anomaly

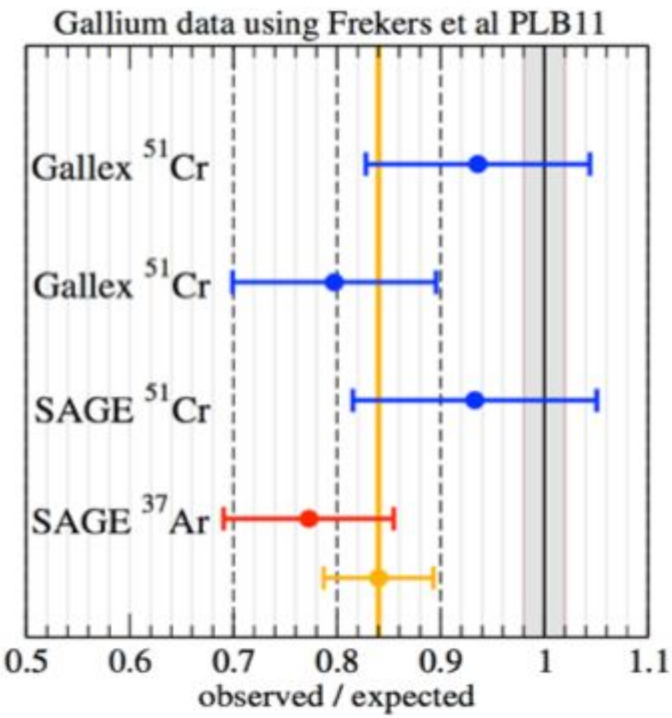
- Re-evaluation of reactor flux increased predicted rate - 2.7σ deficit.
- Analogous to logic used for solar and atmospheric deficits.



Gallium Anomaly

- Gallex and SAGE solar experiments tested with intense radioactive sources at short baselines:
  - Rate deficit of 14 ± 6 %.
  - 2.8σ
- Could be explained by sterile oscillation.

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

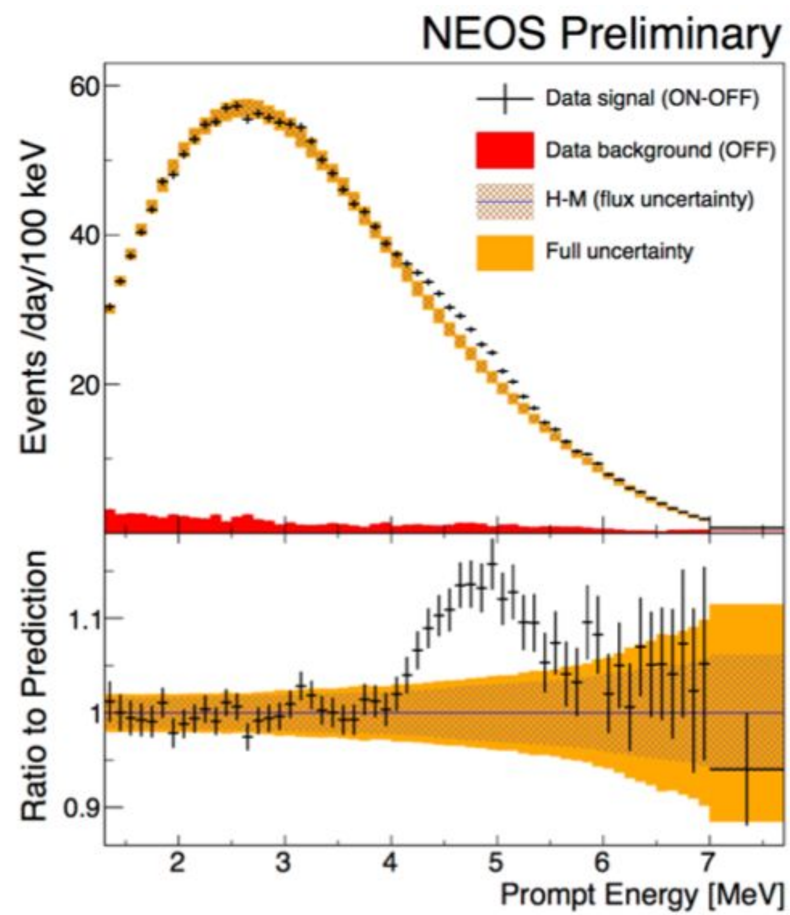


Giunti Laveder 1006.3244
J. Kopp et al., hep/ph:1303.3011

5 MeV Distortion

- All experiments observe distortion around 5 MeV. Some possibilities:
  - Errors in neutrino flux calculations from less understood isotopes.
  - Uncertainties in non-linear energy calibrations.
    - *Cannot in itself explain current anomalies.*

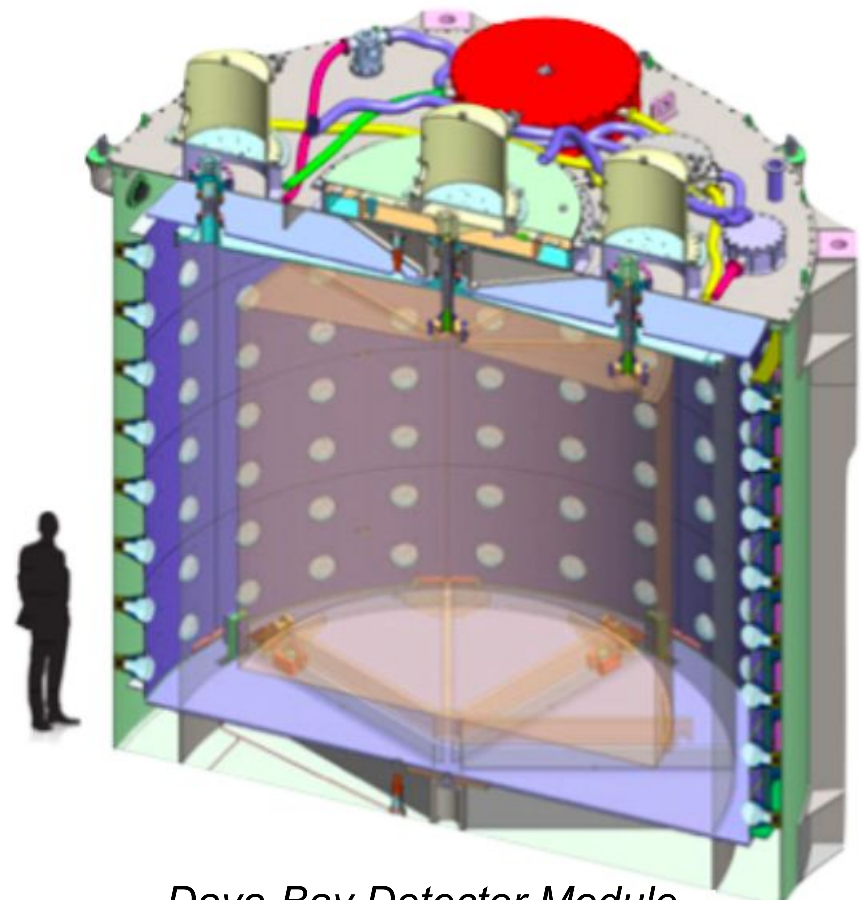
→ Motivation to measure spectra from reactors with different energy spectra (e.g pure ^{235}U) using different technology.



NEOS neutrino energy spectrum

Very Short Baseline (VSBL) Experiments

- Next generation of reactor neutrino experiments study ***very short*** baseline (<10m):
  - Increased sensitivity for oscillation search.
  - Require compactness to be placed near reactor.



Daya-Bay Detector Module

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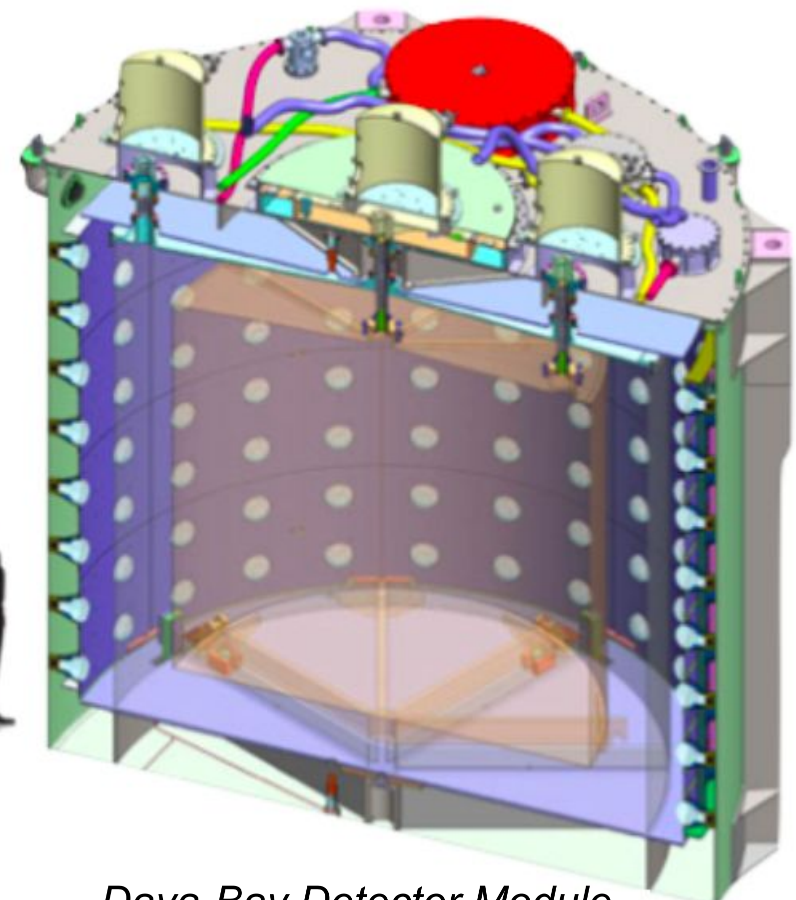
SoLid Phase 1



Daya-Bay Detector Module

Challenges at VSBL

Detector

- Key resolutions for sterile search:
  - Spatial.
  - Energy.
- Effective background rejection:
  - Low overburden.
  - Reactor radiation.

Reactor

- Compact core:
  - Understood fuel composition.
  - Access as close as possible.
- Security implications:
  - Reduce flammable liquids.

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SoLid Solutions

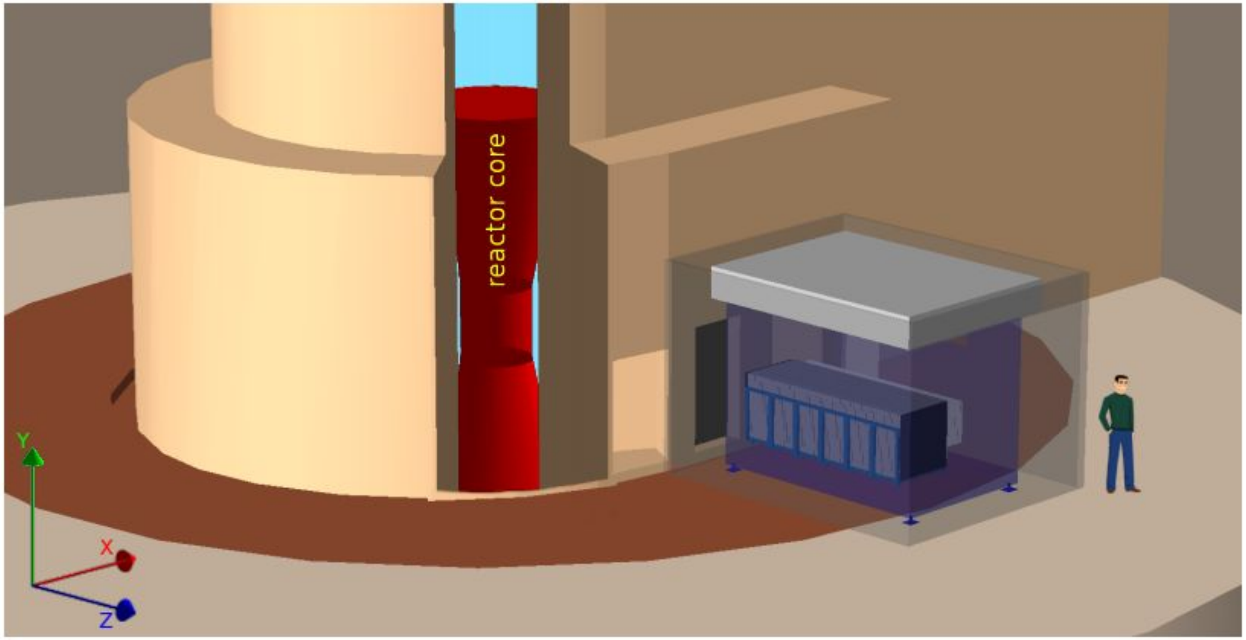
- Highly segmented detector:
  - Localisation of events.
  - (Quasi) 3D topological information.
- Scintillator with high lightyield → PVT (see later).
- Active and passive shielding.

- Research reactor:
  - Belgian Reactor 2 (BR2) at SCK-CEN.
  - Core diameter 0.5m.
- 95% Enriched 235U, 60MW.
- Access ports for experiments.


The SoLid Collaboration
4 countries
12 institutes
~50 people
Universiteit Antwerpen
VUB VRIJE UNIVERSITEIT BRUSSEL
UNIVERSITEIT GENT
SCK•CEN
lpc caen
LPC Laboratoire de Physique de Clermont
LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
Subatech
University of BRISTOL
Imperial College London
UNIVERSITY OF OXFORD
VirginiaTech Invent the Future
May 2017
Gent-Belgium

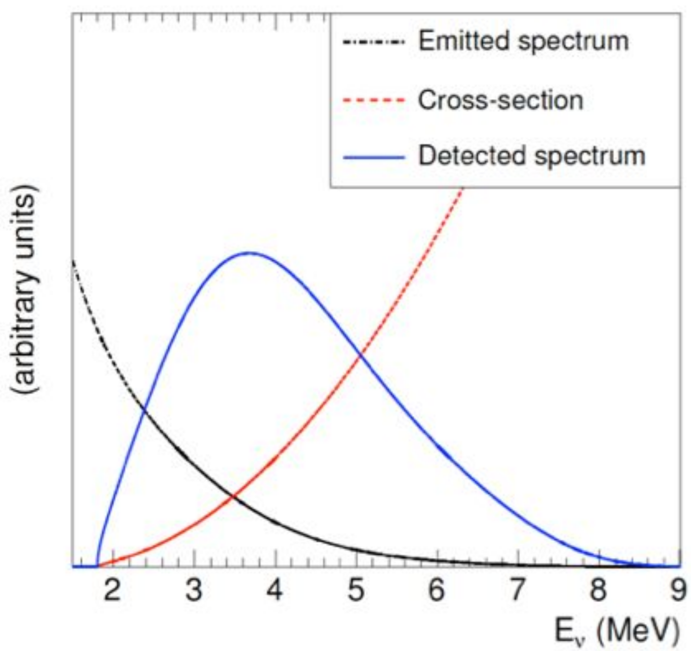
BR2 Reactor @ SCK CEN

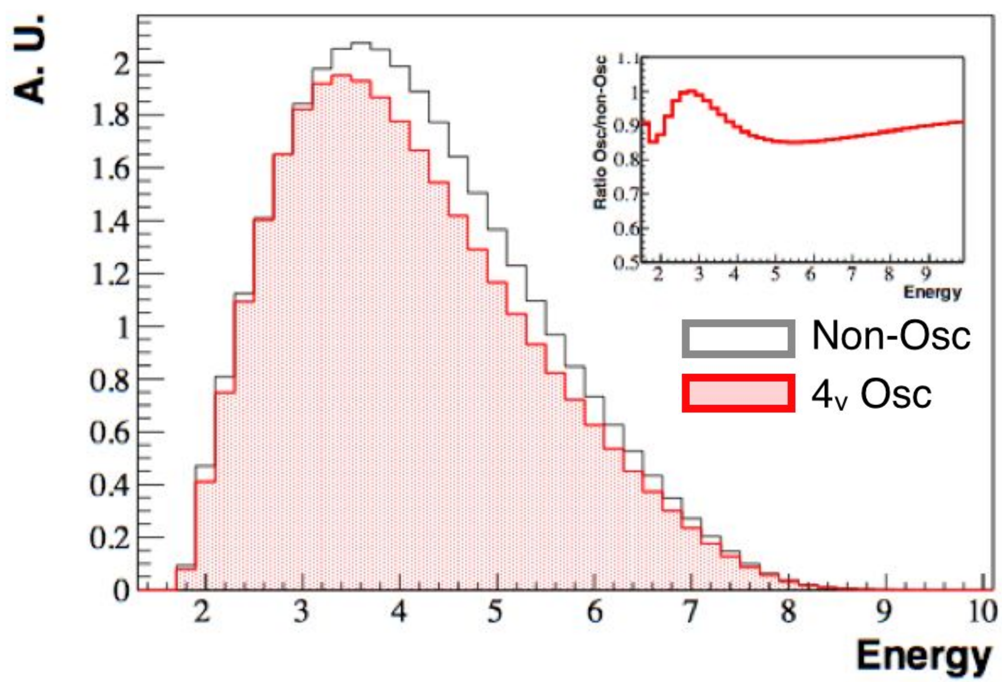
- Suitable reactor core:
  - >95% 235U, 0.5m.
  - Reactor uptime ~50% in ~1 month durations - high fraction of background data.
- Low vertical overburden (<10m WE).
- (Comparatively) low environmental background.



Searching for Oscillations

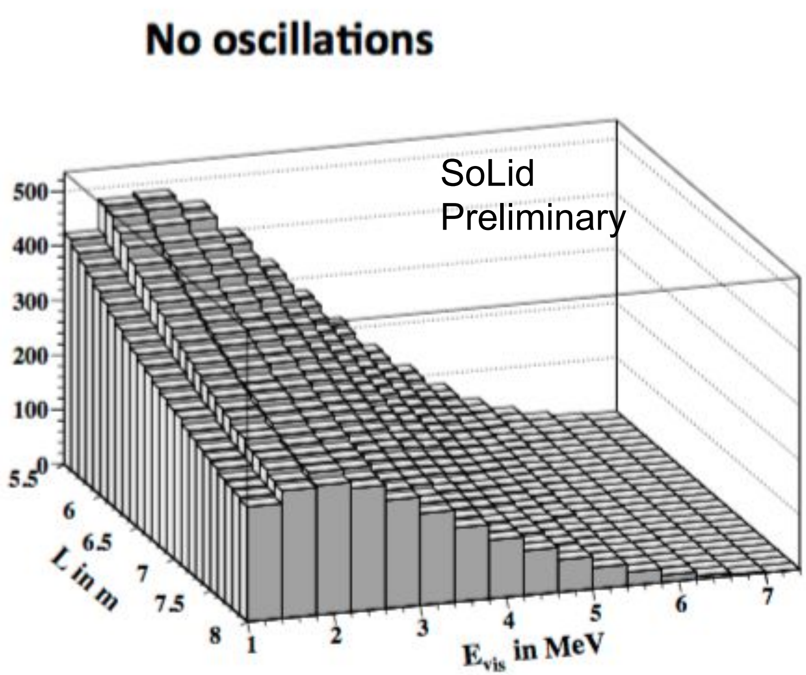
- Probability ν_e disappearance proportional to E_ν/L (L=dist from reactor).
  - Just like other oscillations.
- Distorts E_ν spectrum:

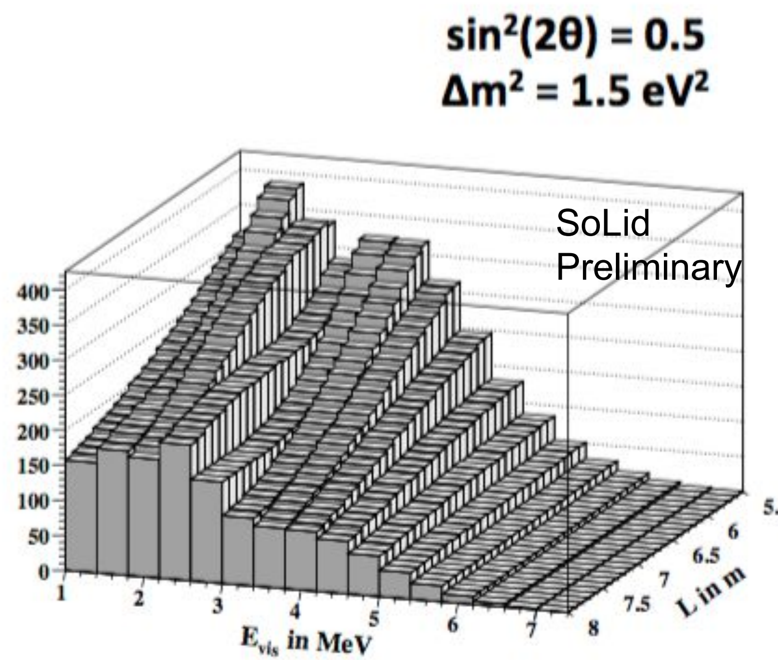




Searching for Oscillations

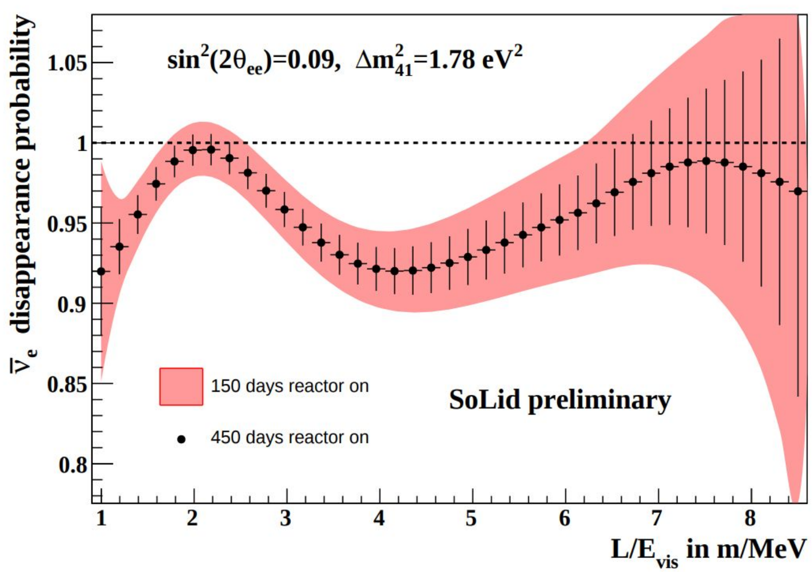
- Probability ν_e disappearance proportional to E_ν/L (L=dist from reactor).
  - Just like other oscillations.
- Distorts E_ν spectrum:
  - 2D shape fit to distribution of E_ν vs L (analogous to using near and far detector).





Searching for Oscillations - Sensitivity

- After 1 year (i.e 150 days reactor on):
  - Best fit can be ruled out to 95% cf.
  - Scan fraction of Gallium anomaly space.
- After 3 years:
  - 3 sigma sensitivity to global best fit.
  - Scan large fraction of reactor anomaly.



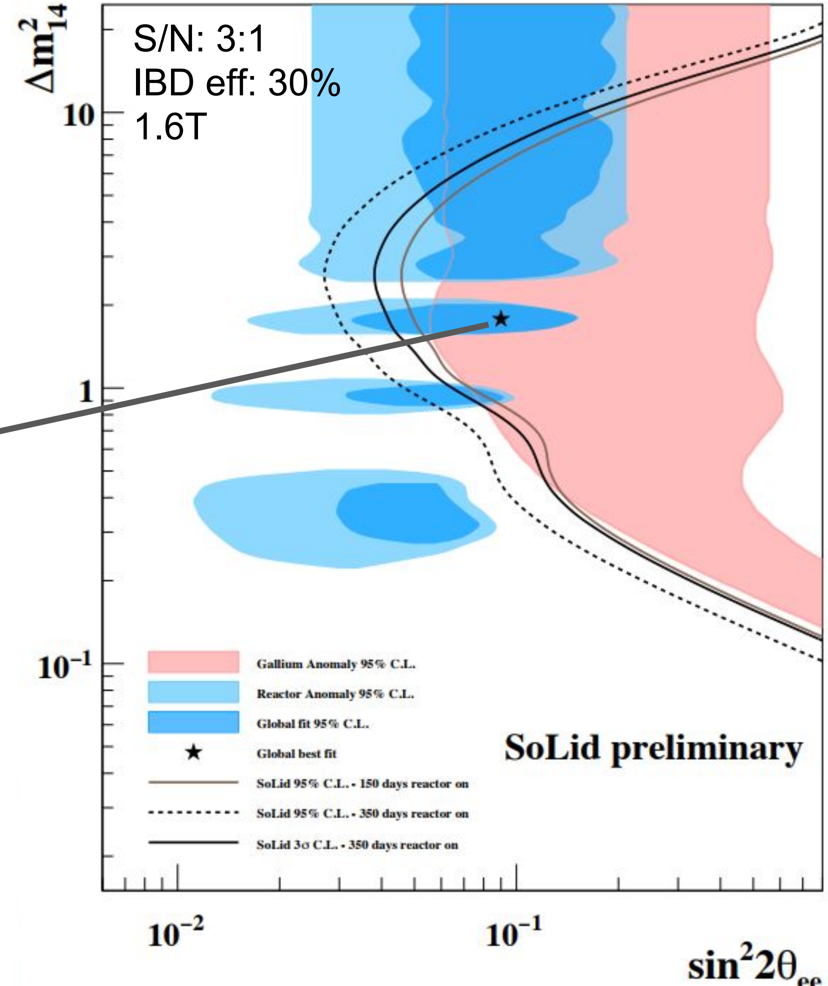


Fig: SoLid 3-year sensitivity.

Competition

Experiment	Tech	Reactor	Fuel	Power (MW)	L (m)	M (tonnes)
DANSS (Ru)	PS+Gd	KNPP	235U, 238U, 239Pu, 241Pu	3k	10-12	0.9
NuLat (US)	6Li doped PS	NIST	235U	25	6-10	1
Neutrino-4 (Ru)	LS + Gd	SM3	235U	100	6-12	1.5
SoLid (UK/B/Fr)	PVT & 6LiF:ZnS	SCK CEN BR2	235U	45-80	6-9	2
Stereo (Fr/Ger)	LS+Gd	ILL-HFR	235U	57	9-11	2
PROSPECT (US)	LS+6Li	ORNL HFIR	235U	*5	7-18	2

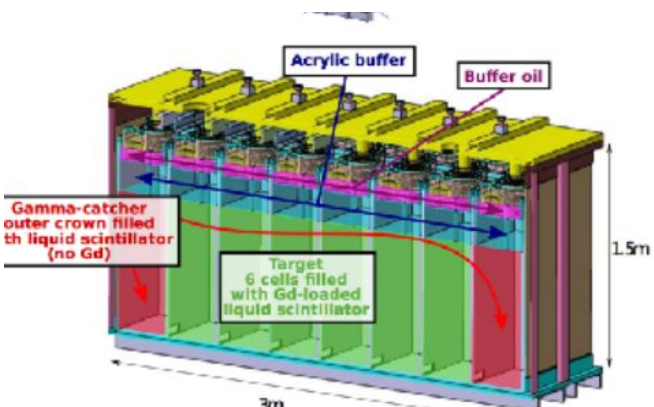
Non-direct competitor (different E, M and/or L)

Direct Competitor

Competition

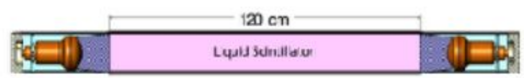
- Main competitors have similar E/L & rector - varies in technology:
  - Level of segmentation, level of passive shielding, and methods to tag background.

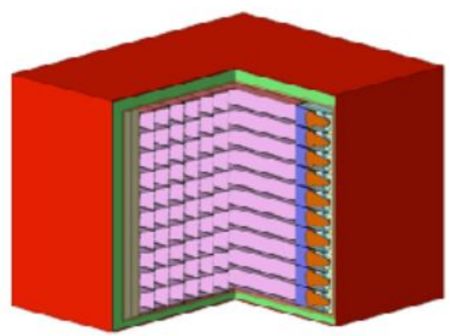
STEREO



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

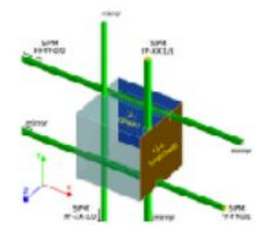
PROSPECT

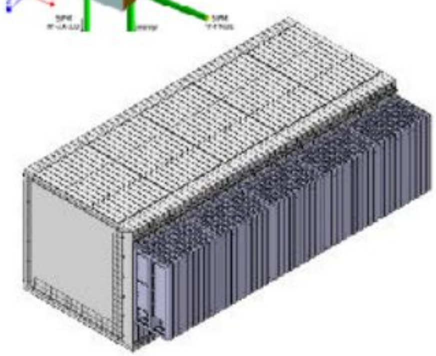




120x 2D LS unit segment
dimension 15 x 15 x 120 cm3
3000 L of Li6 loaded LS

SoLid



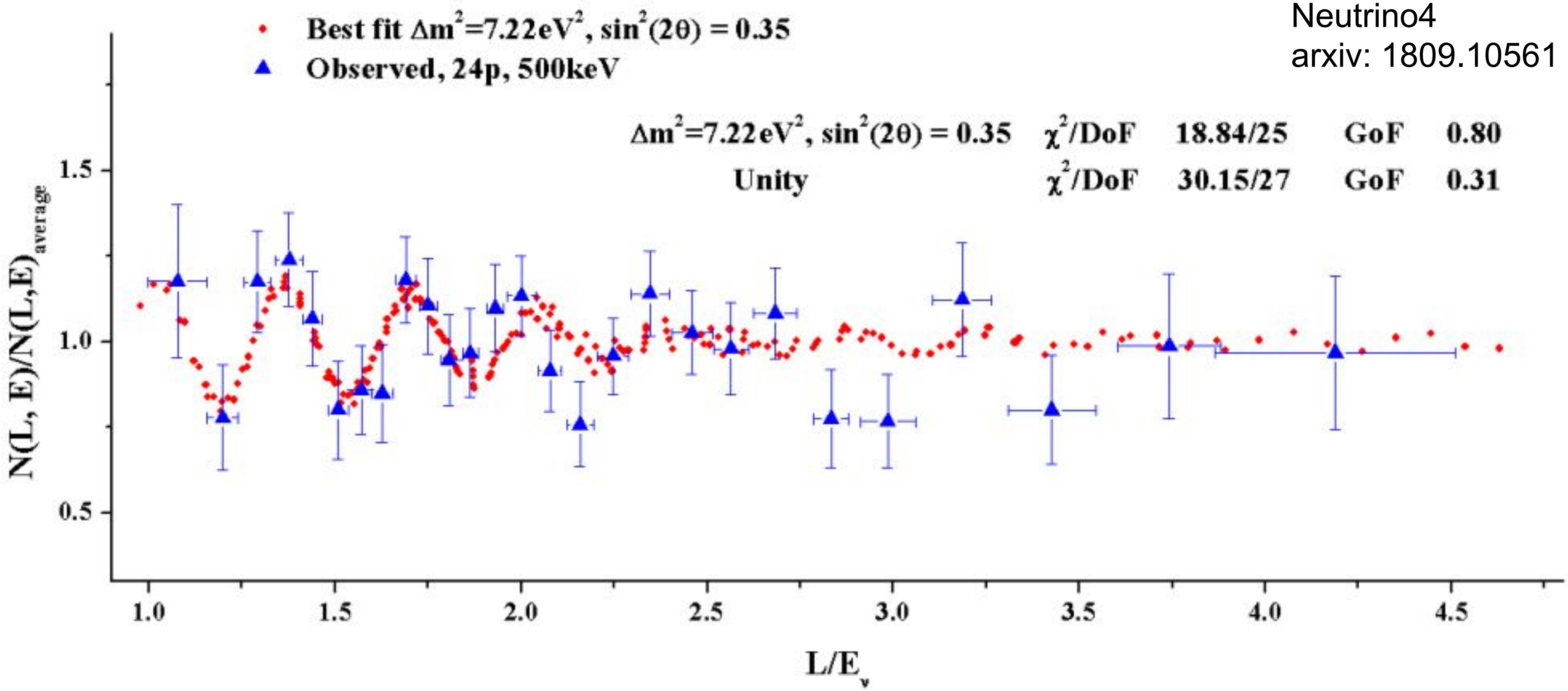


5-6x modules 2560 cubes
dimension 5 x 5 x 5 cm3
1.6-2 tons PVT+LiF:ZnS

Recent Results

- DANNS & Neutrino4 both claim (different) 3σ oscillation signals from 2015-2018 datasets. Tensions with other experiments.

Neutrino4
arxiv: 1809.10561



Detector
Research & Development

Neutrino Channel

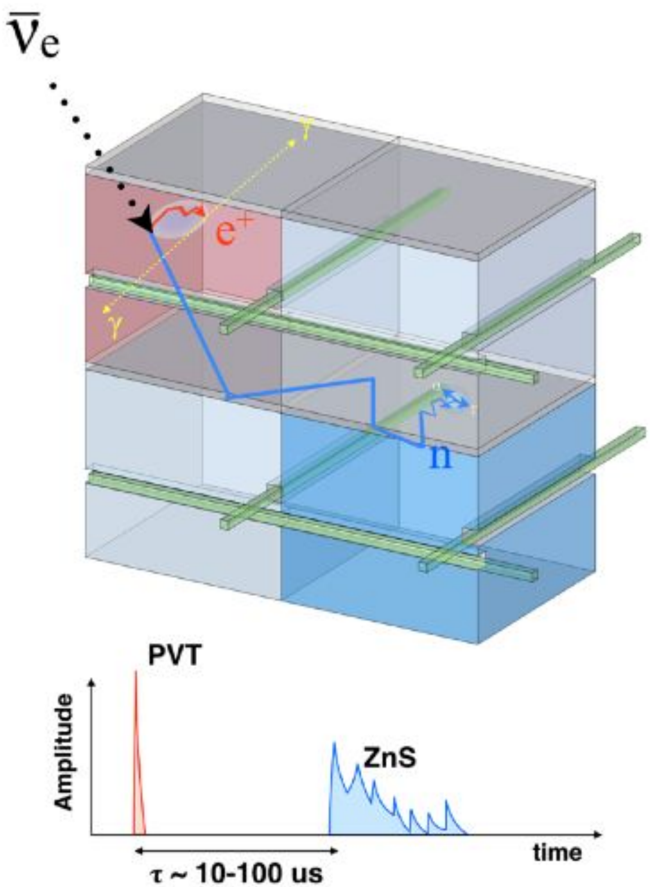
- Inverse beta decay (IBD) interactions: $\bar{\nu}_e + p \rightarrow e^+ + n$

- Proton from (hydrogen rich) detector volume.
- Positron briefly travels through detector before annihilating to two annihilation γ:
  - Energy in the range of 1-8 MeV - highly correlated with ν_e energy.
  - γs typically travel ~20cm away before absorption - separated from positron.

- Neutron needs to thermalise before capture:
  - Initially spatially near the positron (unlike background).

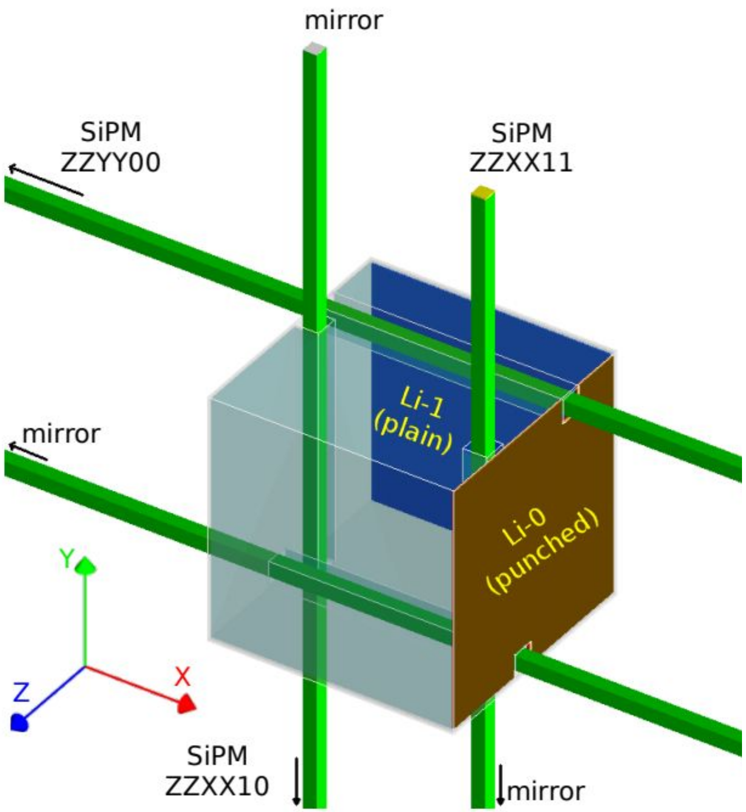
Neutrino Signal
Positron and neutron correlated in space and time.

Detector Technology



- Cubes are stacked to form detector.
- PVT acts as neutron moderator:
  - Positron and neutron typically separated by less than two cubes: ***Topologically different to background***
  - Average time separation ~60μs.
- Each cube (PVT + Li) is wrapped in Tyvek for light tightness:
  - Positron and neutron signals localised to specific cubes → high spatial resolution.

Detector Technology



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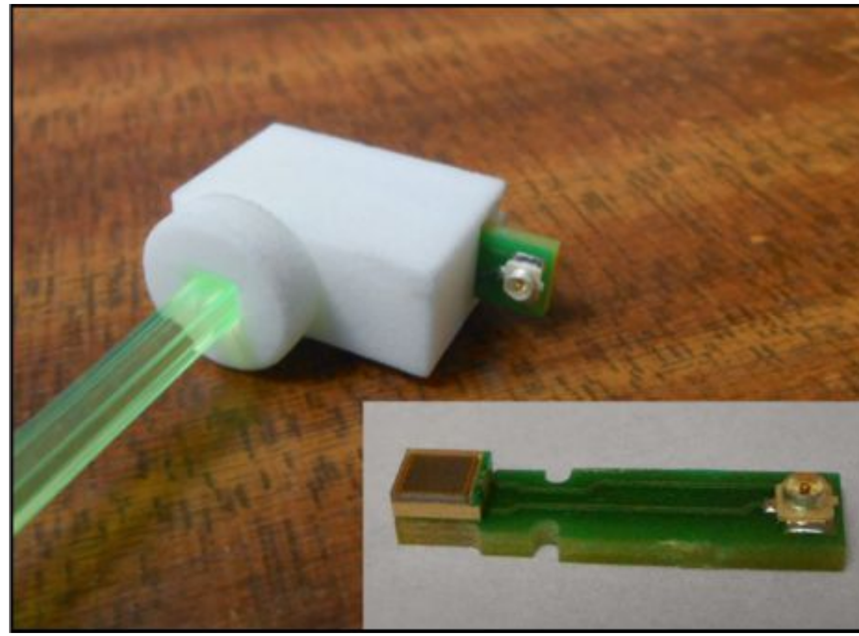
Readout

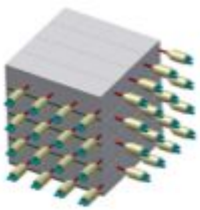
- Cubes readout using a 2D array of wavelength shifting fibres:
  - 3mm^2 square fibres in 5mm^2 grooves.
- Each end of a fibre coupled to a silicon photomultiplier.
- SiPMs readout by custom electronics:
  - Typically 14bit ADC range.
  - Sample period of 25ns - fast enough to show neutron shape.
  - Waveforms saved for offline analysis.



Light Fibre with SIPM and Connector

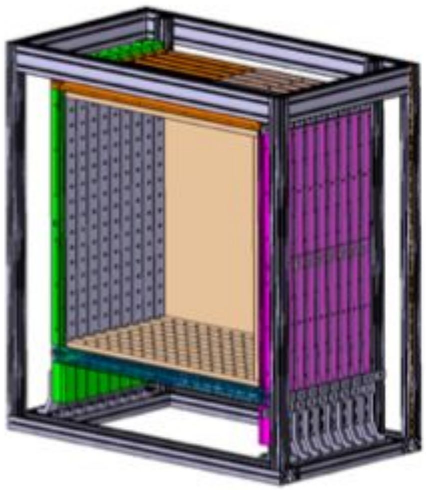
SoLid Prototypes

2013



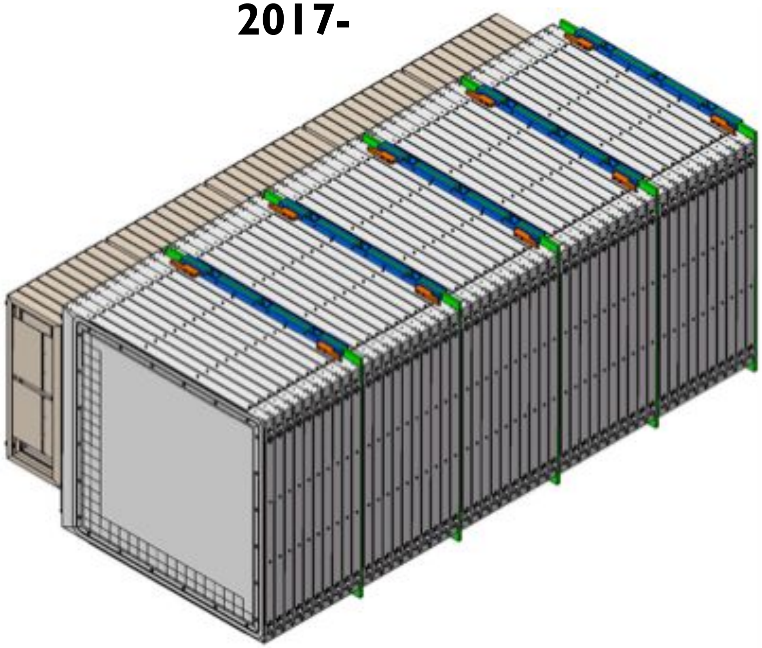
Nemenix (8kg)
Proof of concept.
Demonstrate PID.

2014-15



Module 1 Prototype (288kg)
Test scalability and production.
Show power of segmentation.

2017-



SoLid Phase I (1.6 T)
12k cubes with 3.2k channels,
~300 events/day.
Perform oscillation search.

Prototype SoLid Module I

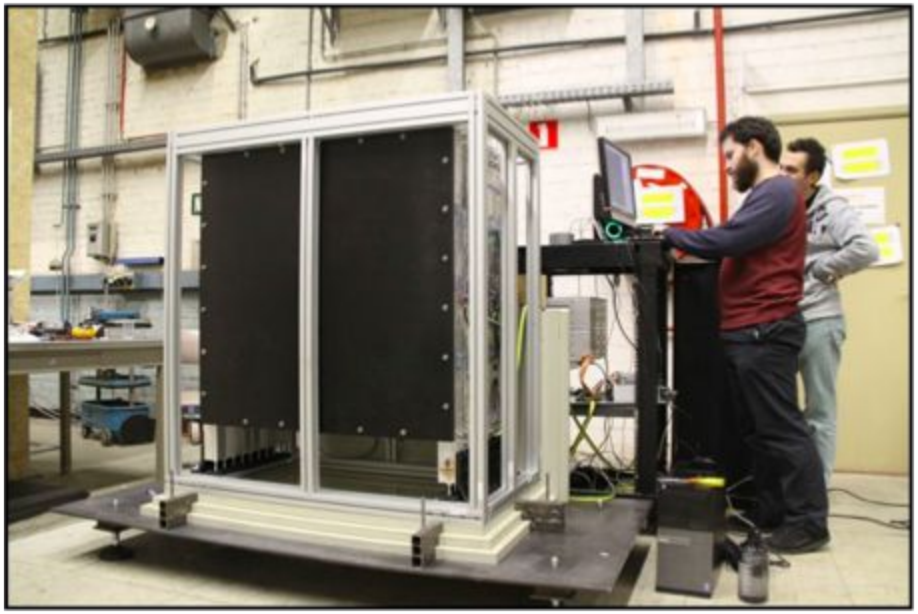
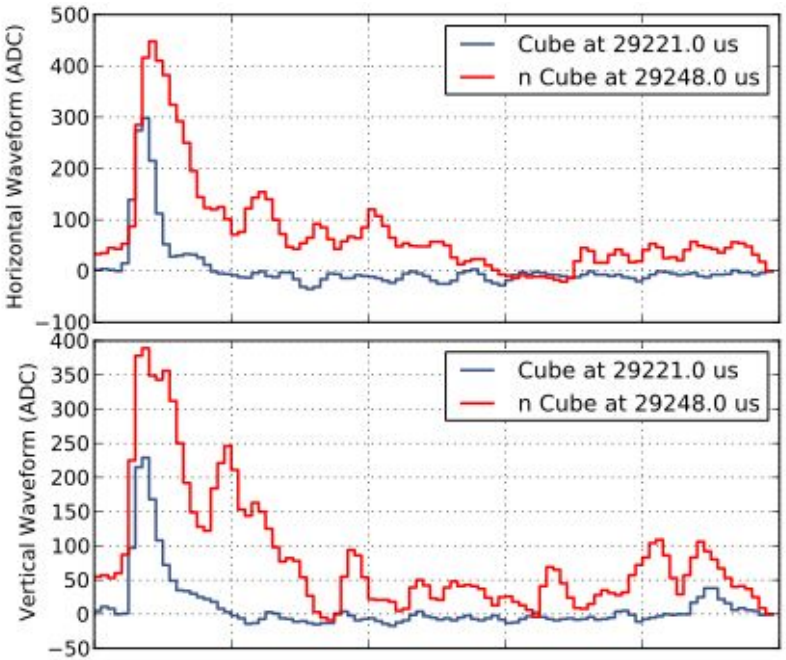


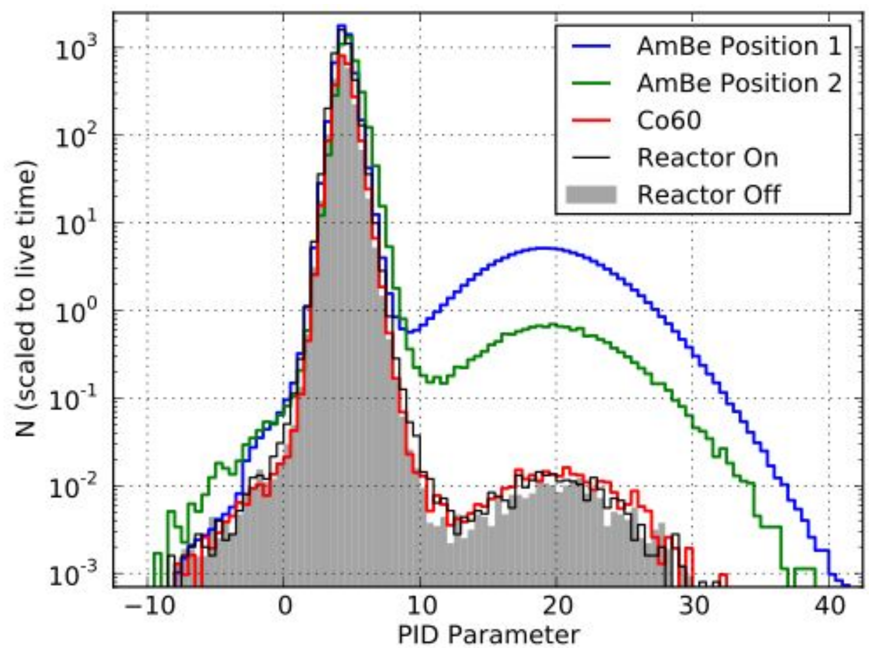
Fig: Commissioning at Gent, Nov 2014

Fig: Deployment at BR2, Dec 2014

- 50hr reactor on run. Long reactor off and source calibration runs.
- Simple amplitude based trigger for all signals.
- No passive shielding: statistically limited to see ν_e signal.

Prototype SoLid Module I - Neutron ID





- Pulse shape discrimination algorithms developed (e.g. ratio of integral to amplitude)
    - Source runs demonstrate good population separation, despite large background environments.
- Neutrons well separated despite enormous EM background.

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Prototype SoLid Module I - Correlated Events

- Example prompt-delayed coincidences from prototype data:

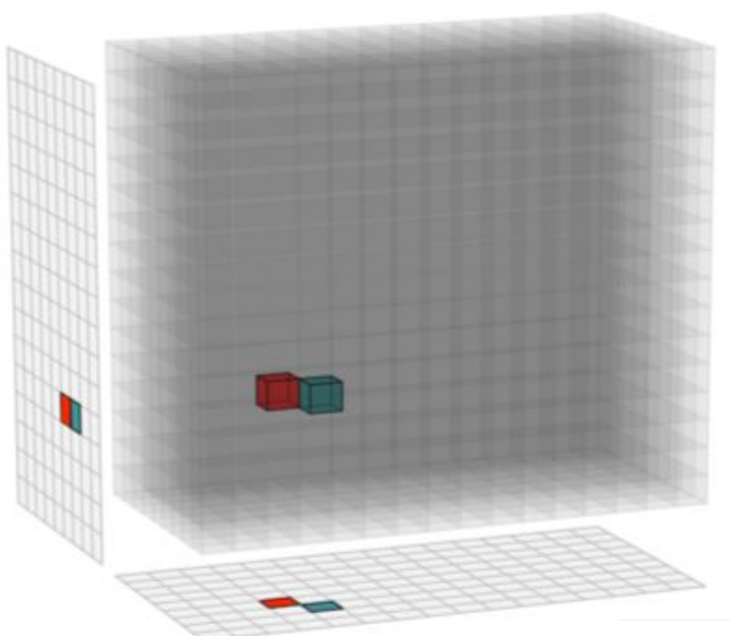


Fig: Prototype IBD Candidate

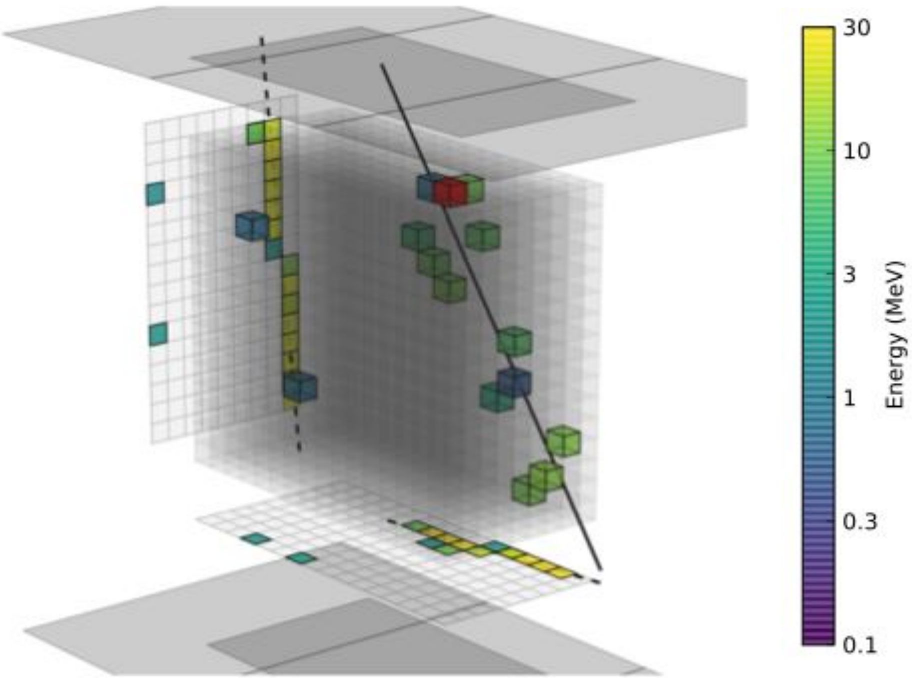
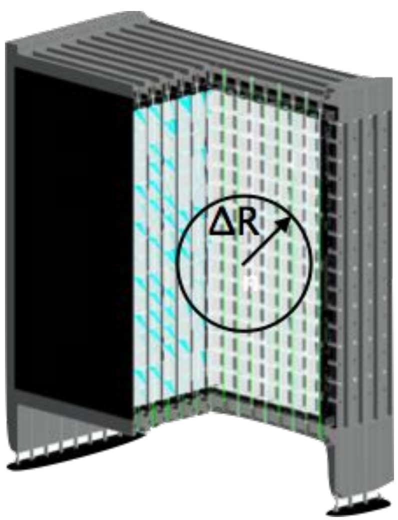


Fig: Prototype Muon Spallation Candidate

Prototype SoLid Module I - Segmentation

- Segmentation demonstrated to clearly reduce background:
  - Particularly accidentals.



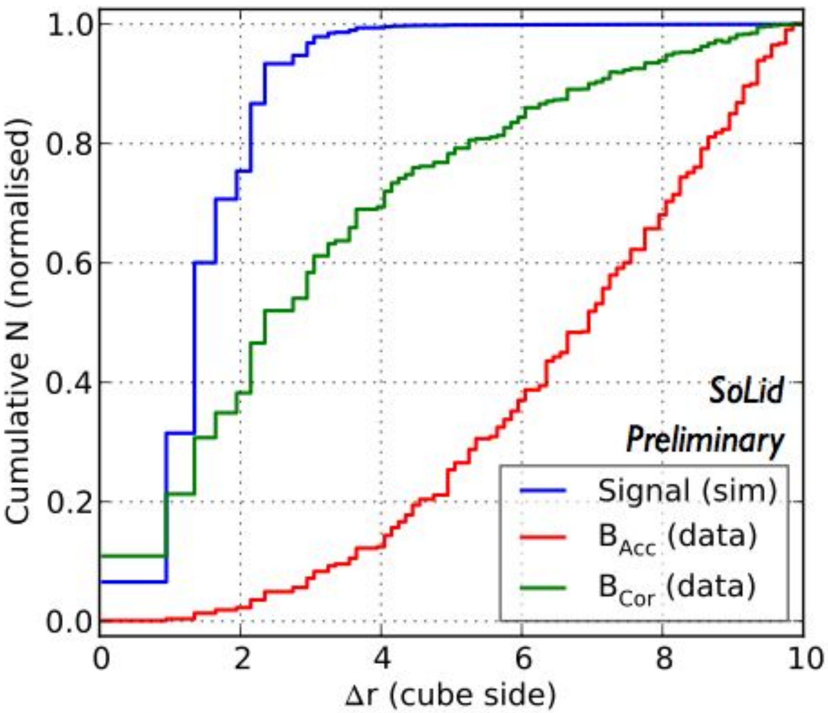


Fig: Radial separation between prompt and delayed event for signal (sim) and background IBD candidates.

Phase I Design

- Construction of Phase I began early 2017:
  - 12,800 cubes, split into 50x 16x16 detector planes.
  - Readout in 4 directions.
  - 3.2k detector channels.
    - *Massive quality assurance (QA) campaign.*

- Detector built inside insulated container:
  - Designed by IC, Bristol & RAL.
  - Allows cooling to 10 degrees C to stabilise SiPMs and reduce dark count rate.

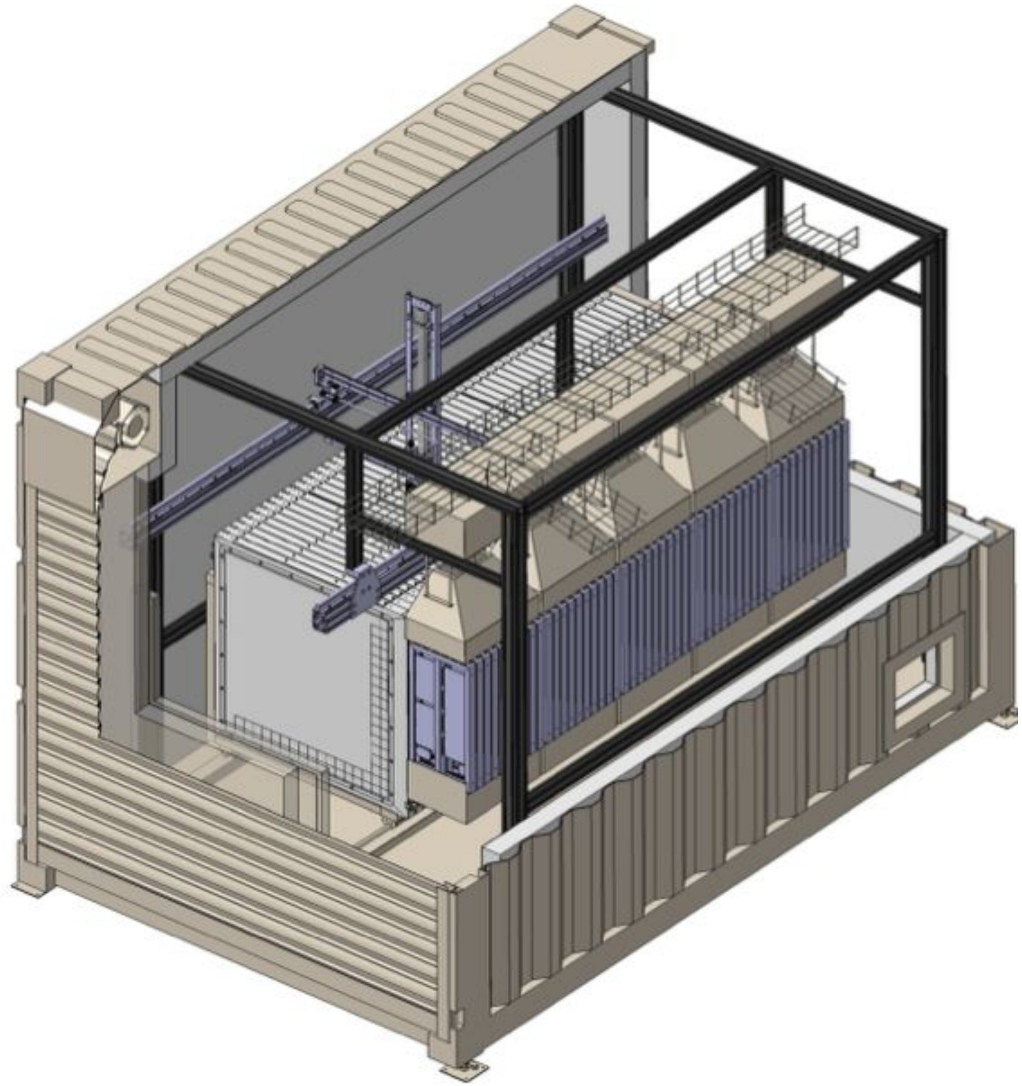


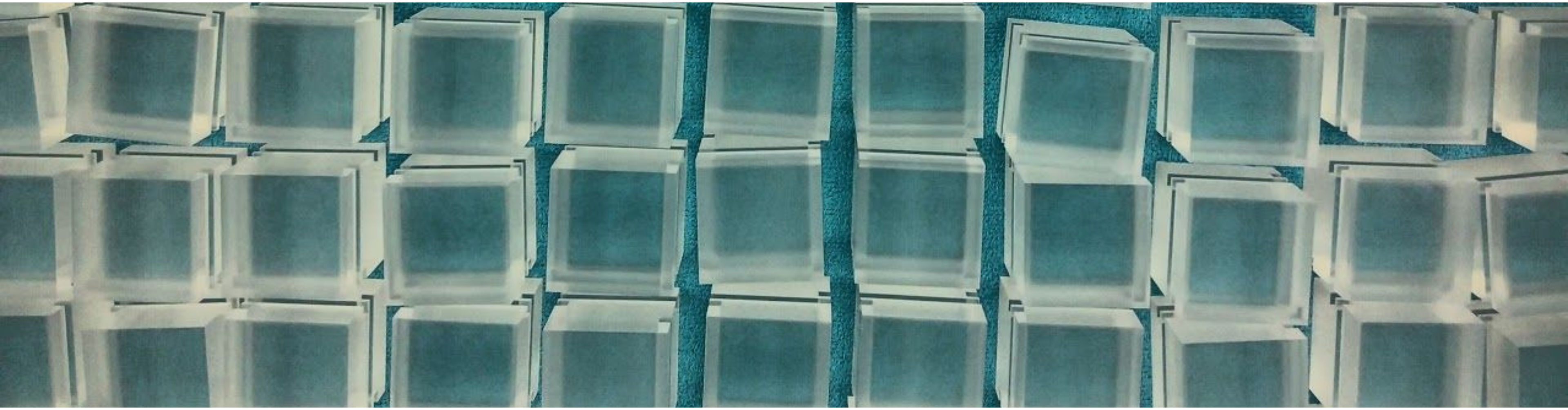
Fig: Schematic of SoLid container with detector.

Quality Assurance Campaign

Cubes Quality

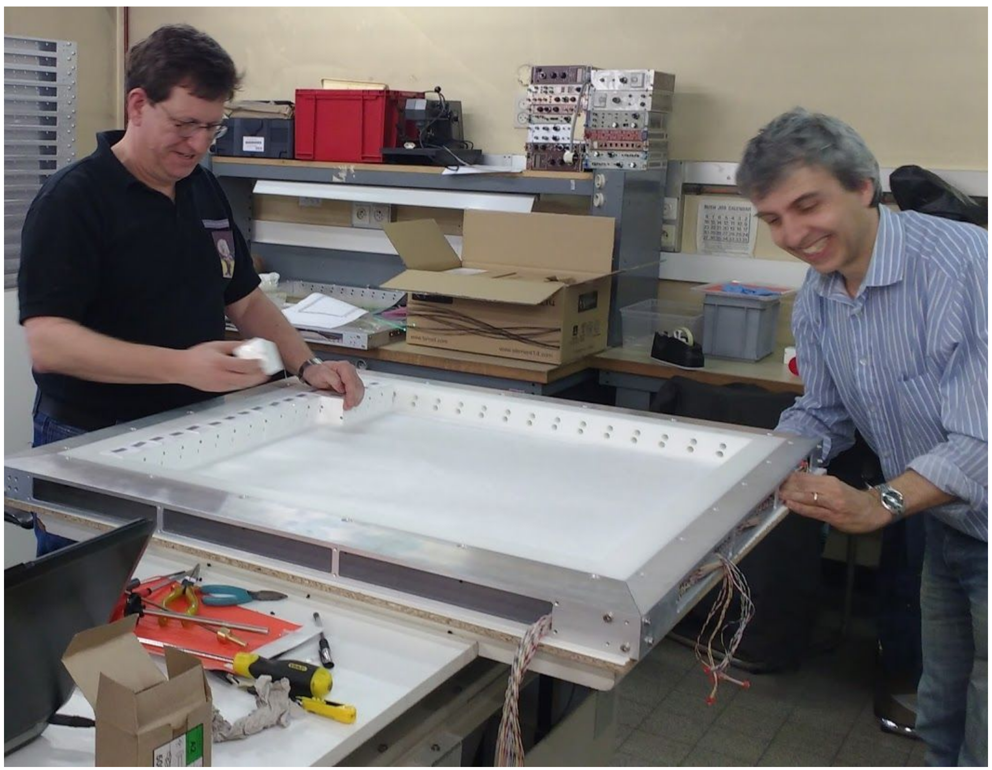
- Cubes began to arrive Jan 2017:
  - Each cleaned, size checked.
  - Wrapped in tyvek by hand.

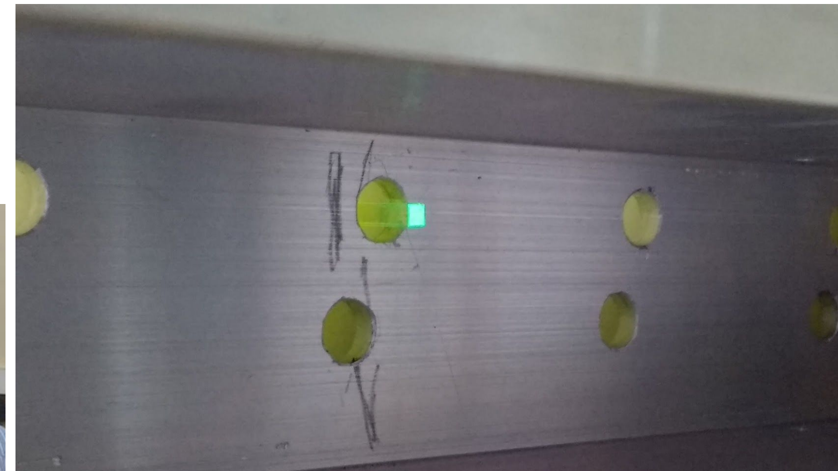
→ … shifts started early.

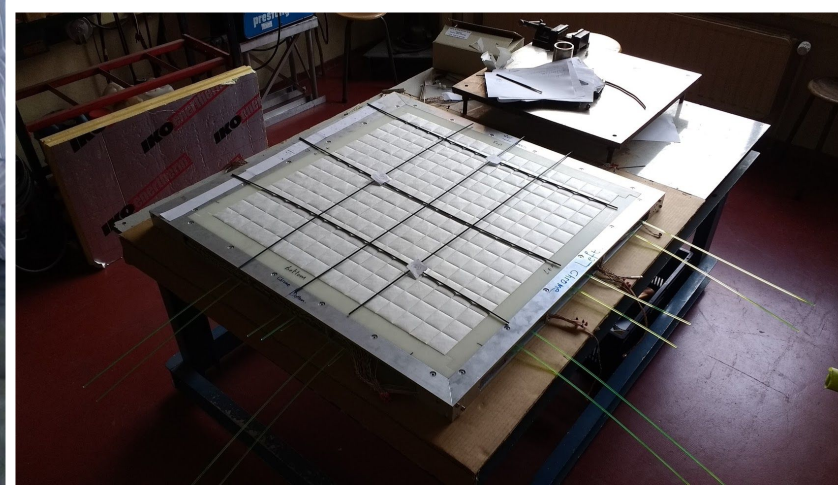


Plane Construction

- Cubes stacked in 16x16 planes with vertical & horizontal fibres.
- 64 SiPMs per plane around edge.







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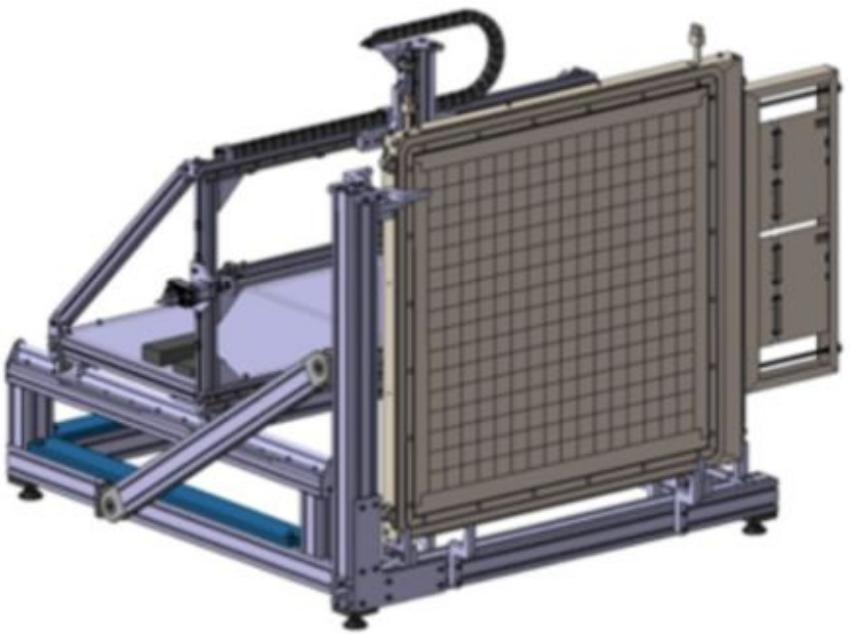
Cubes Quality - Source Tests

- Dedicated calibration robot built to scan detector planes: ‘Calipso’.
- Uses prototype electronics boards & DAQ → run like full detector.



Cubes Quality - Source Tests

- Each cube scanned with at least two sources:
  - Gamma source - test cube & channel light yield.
  - Neutron source - test cube neutron efficiency.

Fig: Calipso with source head

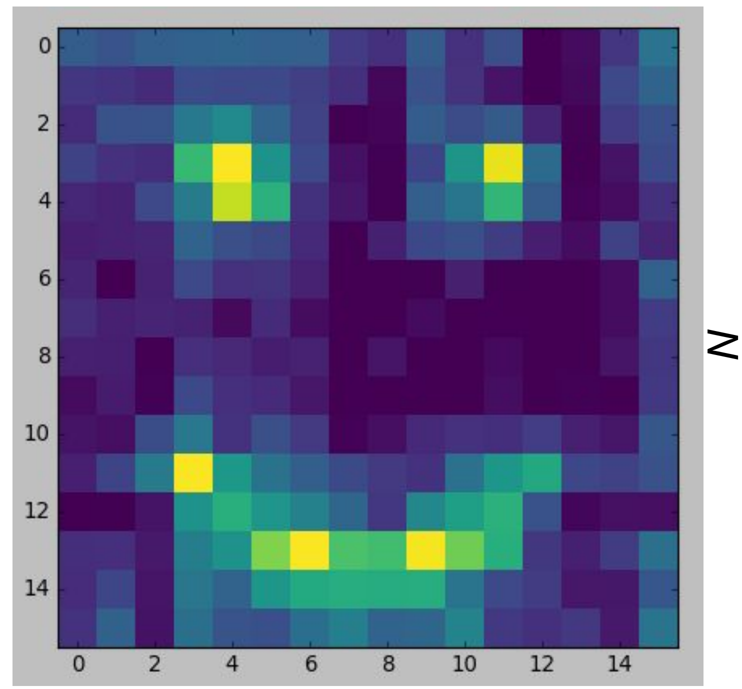
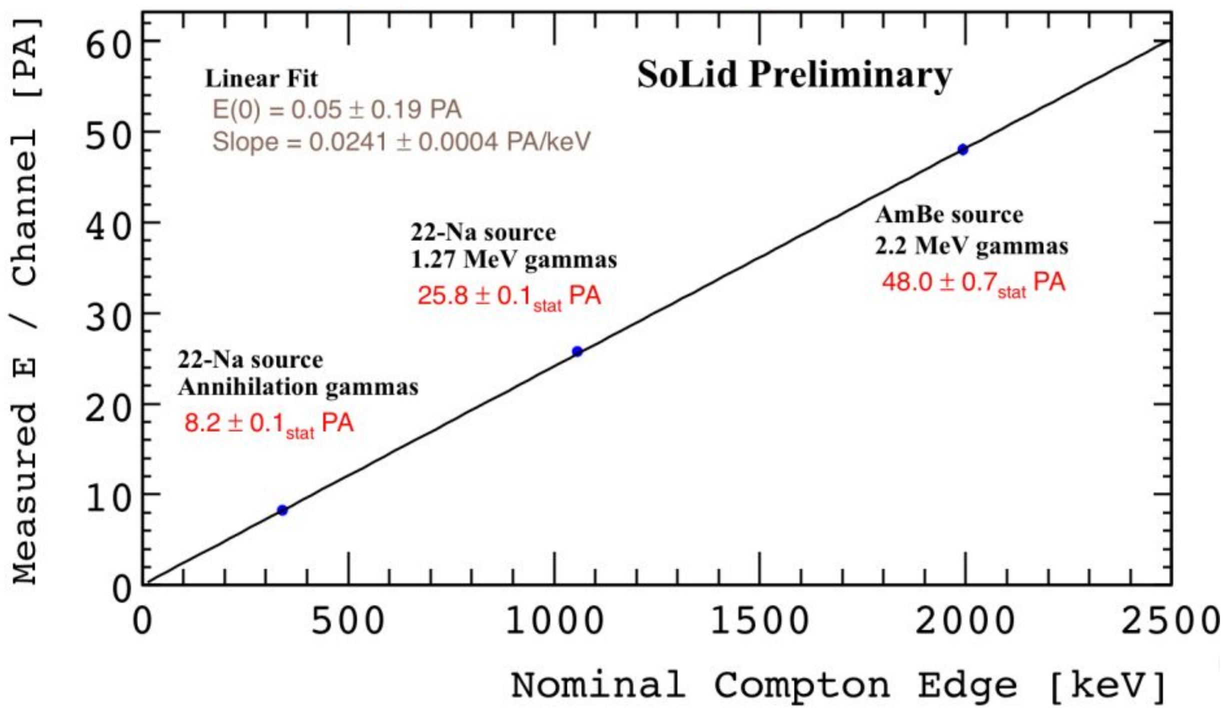


Fig: First Na22 Scan

Cubes Quality - Source Tests

- Gamma sources demonstrate high linearity:
  - Reduced systematic uncertainty compared to liquid scintillator.
- Light yield ~30% higher than expectations!

High linearity combined with 235U = strong handle on 5 MeV distortion.



Cubes Quality - Source Tests

SoLid Preliminary

- Neutron sources identified some interesting cases:
  - 1/12800 cubes where Li mis-placed.
  - One batch of Li with reduced ZnS concentration (resulting in reduced n eff).

- Efficiency at room temperature exceeds expectations.
  - New expected absolute n efficiency in the cold: ~50%
    - *cf 40% expectation.*
    - *Loss dominated by capture eff (66%).*

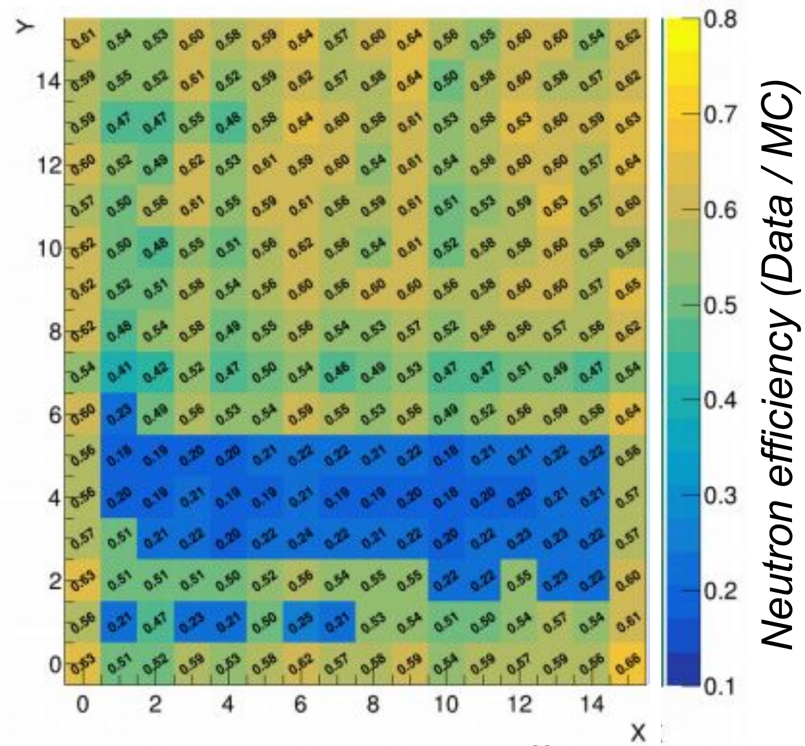


Fig: Example neutron eff hitmap.

Cubes Quality - Source Tests

- Neutron sources identified some interesting cases:
  - 1/12800 cubes where Li mis-placed.
  - One batch of Li with reduced ZnS concentration (resulting in reduced n eff).
  - Once corrected, high uniformity observed.

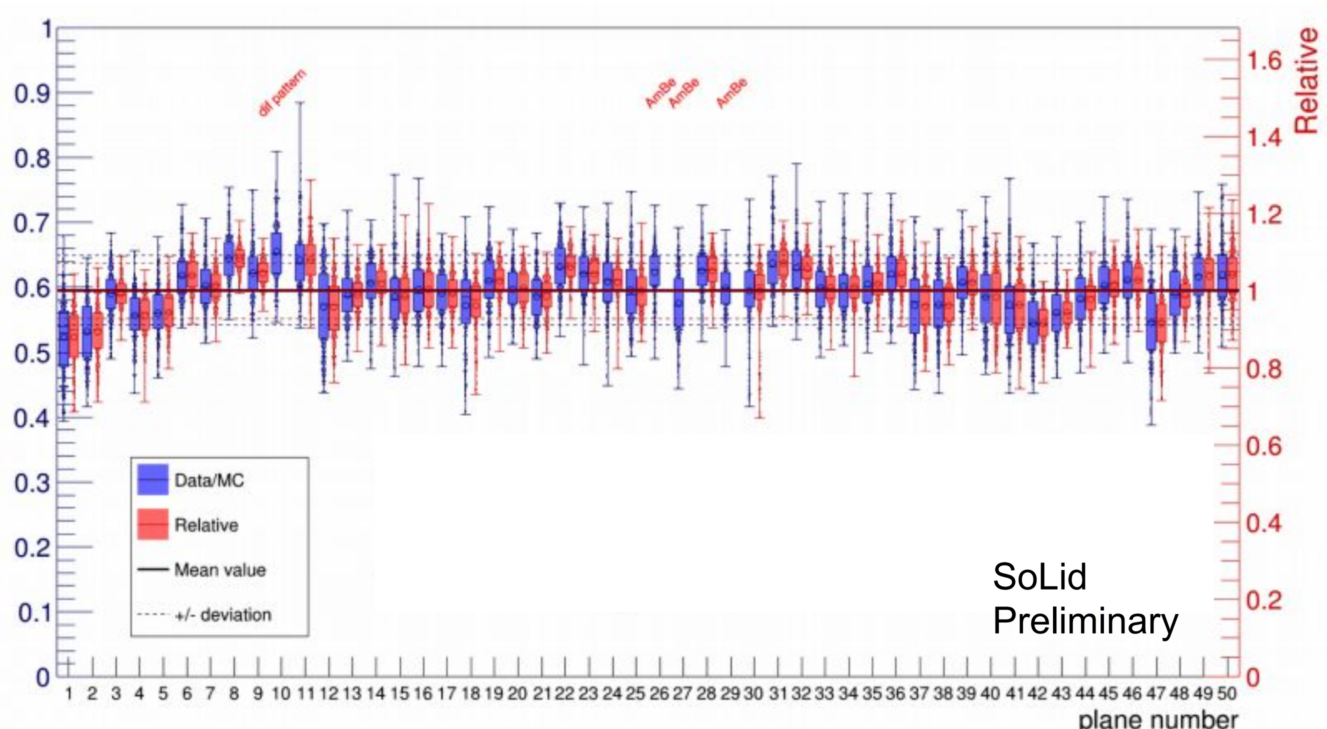


Fig: Neutron efficiency for cubes and planes - room temperature.

Electronics Testing

- One electronics enclosure per detector plane:
  - 64 Channels.
  - Shielded from outside pickup.
    - *Enclosures, small boards and power cables made at IC.*

- Custom electronics designed at Bristol:
  - Analogue amplification and gain calibration.
  - 8x8 ADCs to digitise SiPM output into 14bit 25ns waveforms.
  - On-board FPGA for hardware triggering (see later).

Fig: Electronics Enclosure.

Phase I Commissioning

Detector Shipping

- Shipping container modified at RAL:
  - Design by IC & Bristol.
  - Rails for detector planes.
  - Slow control services.
  - Insulation & cooling.
- Container first shipped to Univ Gent:
  - Integration with detector planes.
  - Test cooling & first detector runs.
- Detector shipped to the reactor in November 2017.

Fig: Lads in the container at RAL.

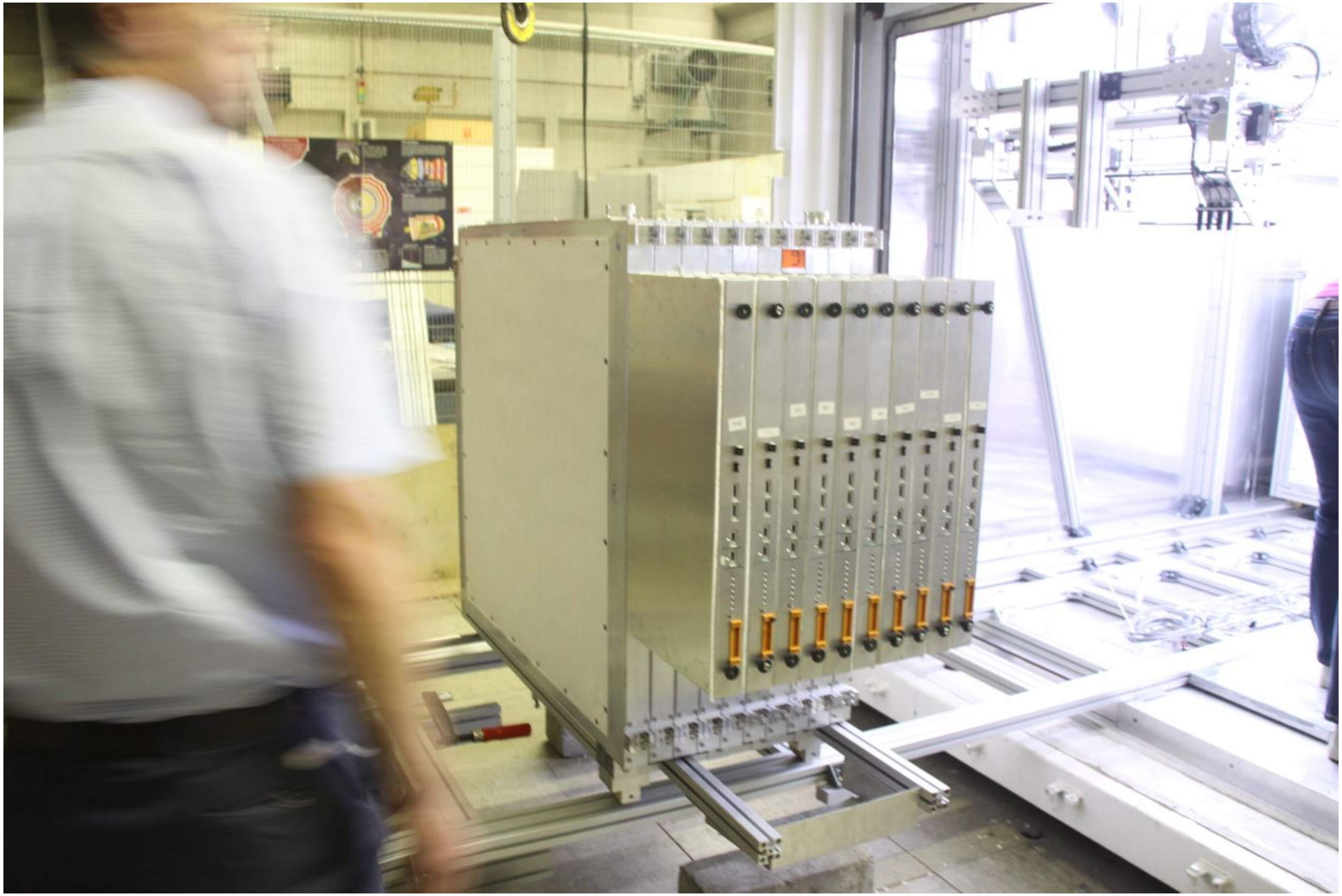


Fig: Example detector module of ten planes.


Laser
www.laserint.co.uk

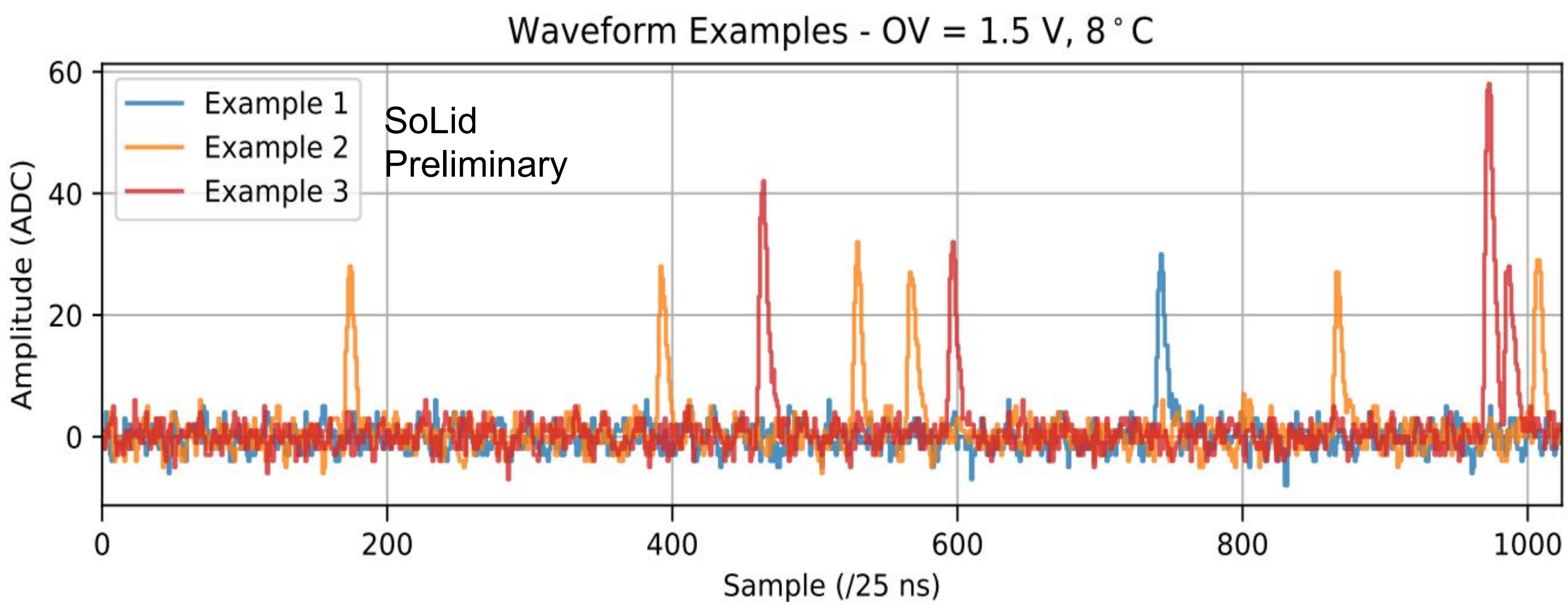
Installation at the Reactor

- Container surrounded by passive shielding:
    - 50 cm HDPE roof.
    - 50cm wide water bricks.
    - Significantly decreases neutrons from cosmic origins - dominant prototype background.
- Chiller cools container interior to 10 C:
    - Reduce and stabilize SiPM dark count rate.
-

Fig: Container at Reactor with Shielding

Turning it on...

- First runs dedicated to electronics performance:
  - Noise checks for data quality - many channels to manage.
  - Small number (<1%) of detector channels masked.
  - SiPM gain equalisation - challenging due to large spread in breakdown voltage.



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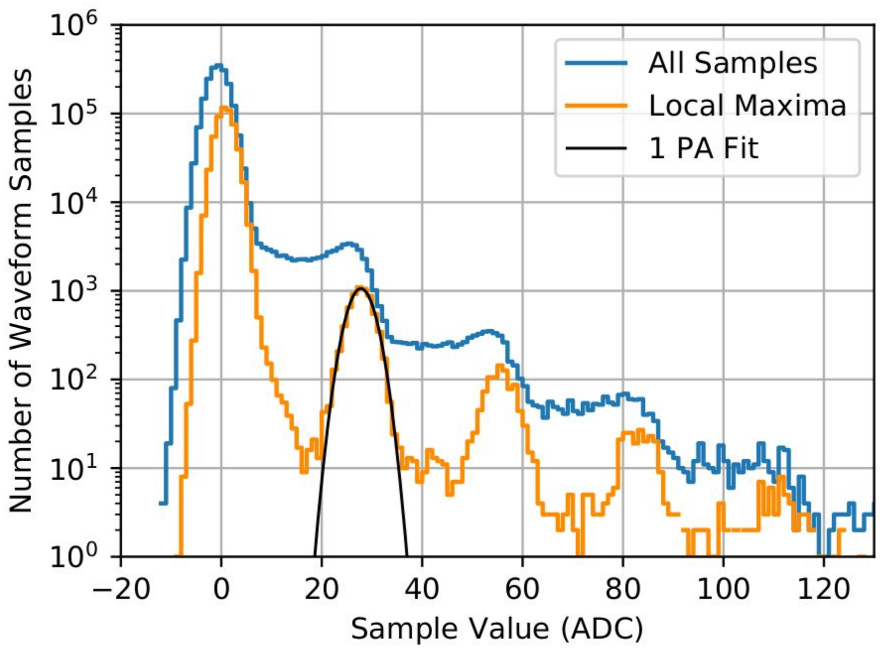

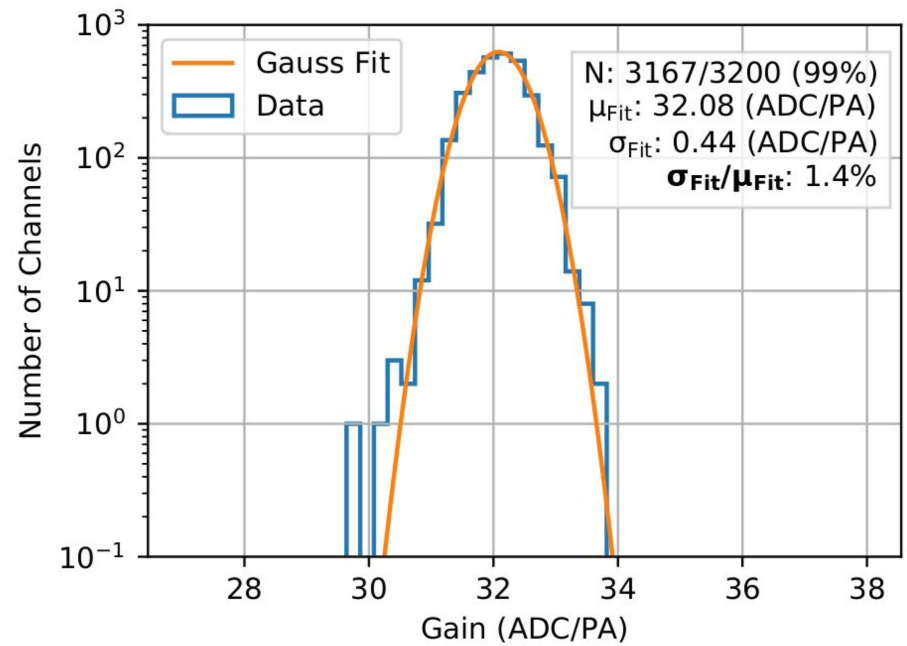

Readout System

- Data-rate of digitised SiPMs ~3 Tb/s total:
  - Comparable with the ATLAS tracker!
- Online data reduction & triggers required to handle data rate:
  - Dedicated PSD algorithm developed for neutron signals:

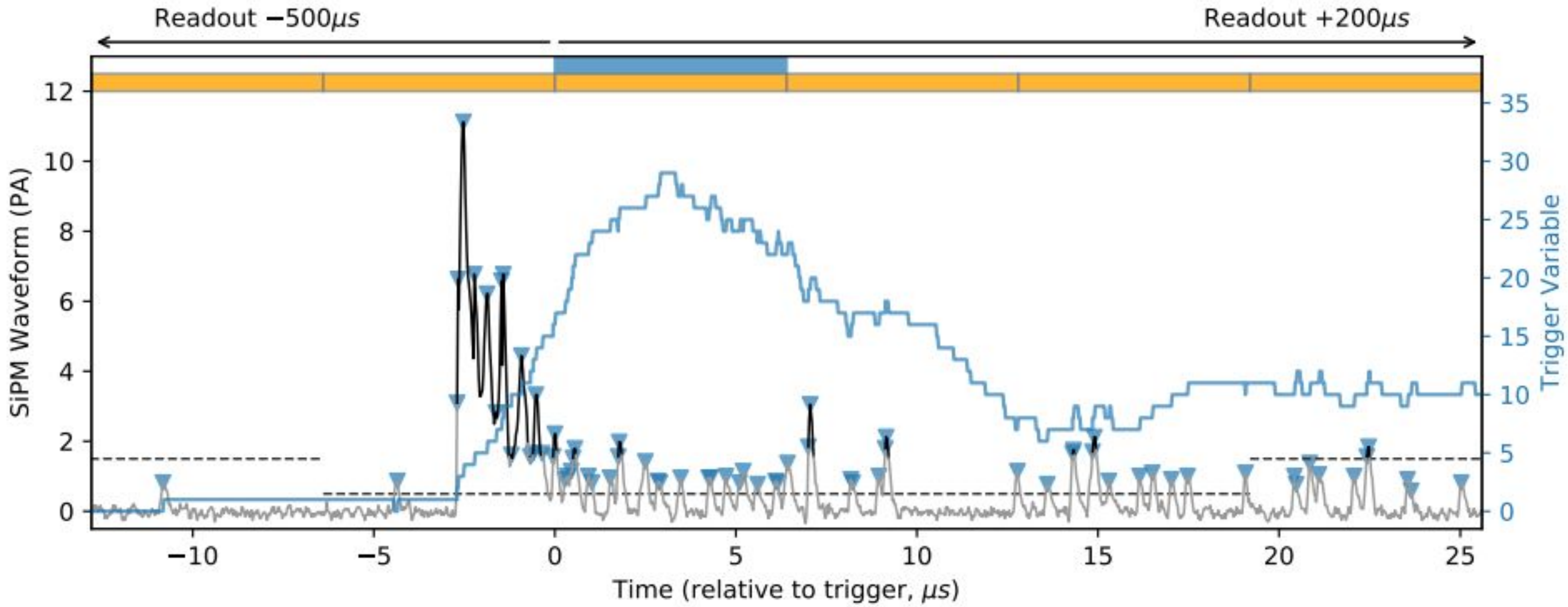

Fig: Neutron triggered waveform with trigger variable.
Trigger counts waveform local maxima in rolling time window.

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Readout System

- Data-rate of digitised SiPMs ~3 Tb/s total:
  - Comparable with the ATLAS tracker!
- Online data reduction & triggers required to handle data rate:
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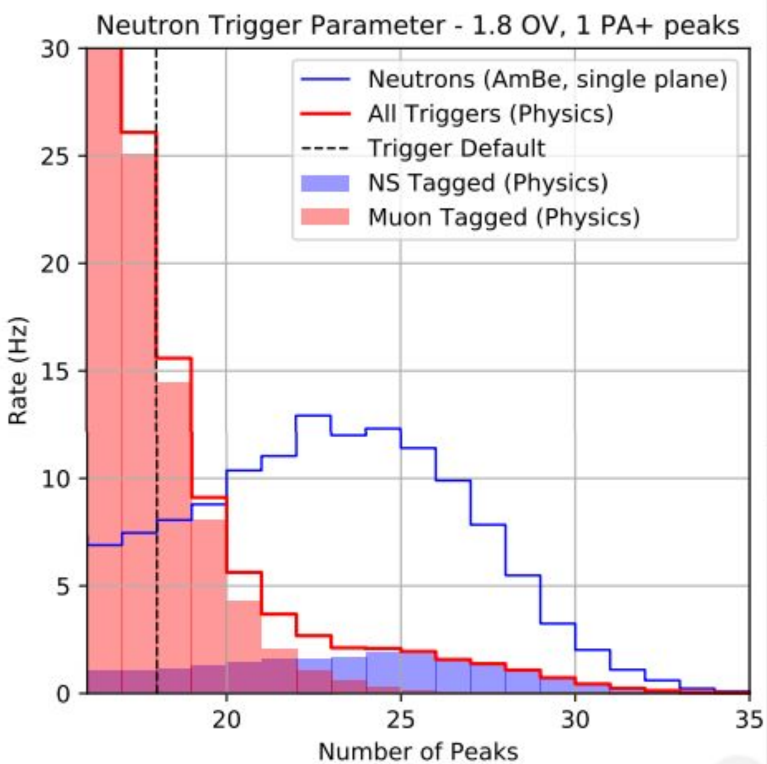


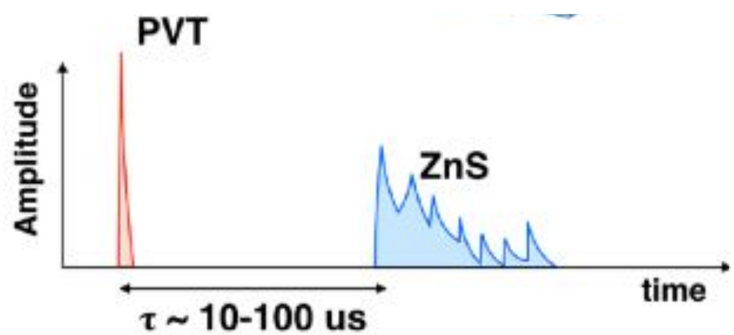
Readout System

- Data-rate of digitised SiPMs ~3 Tb/s total:
  - Comparable with the ATLAS tracker!
- Online data reduction & triggers required to handle data rate:
  - Dedicated PSD algorithm developed for neutron signals: ~80% efficient.
- Combined with large time buffer 'history' to readout prompt:
  - Prompt not required to self trigger.
  - Multiple detector planes readout per neutron.
    - *Neutrino trigger!*

Prompt-Delayed Coincidences

- First reactor cycle in Dec 2017.
  - First prompt-delayed candidates.
  - Imperial college press release: http://www.imperial.ac.uk/news/183690/solid-start-quest-elusive-particle/

Fig: Concept paper IBD interaction



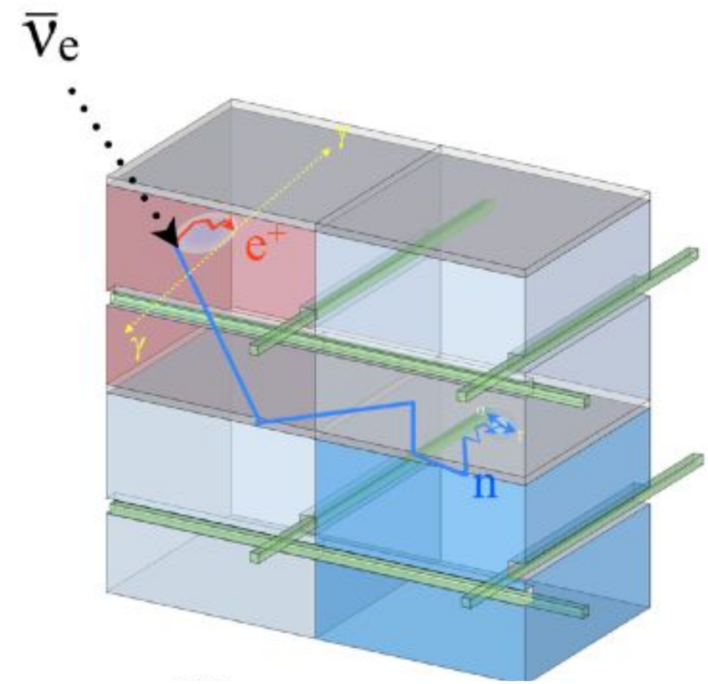


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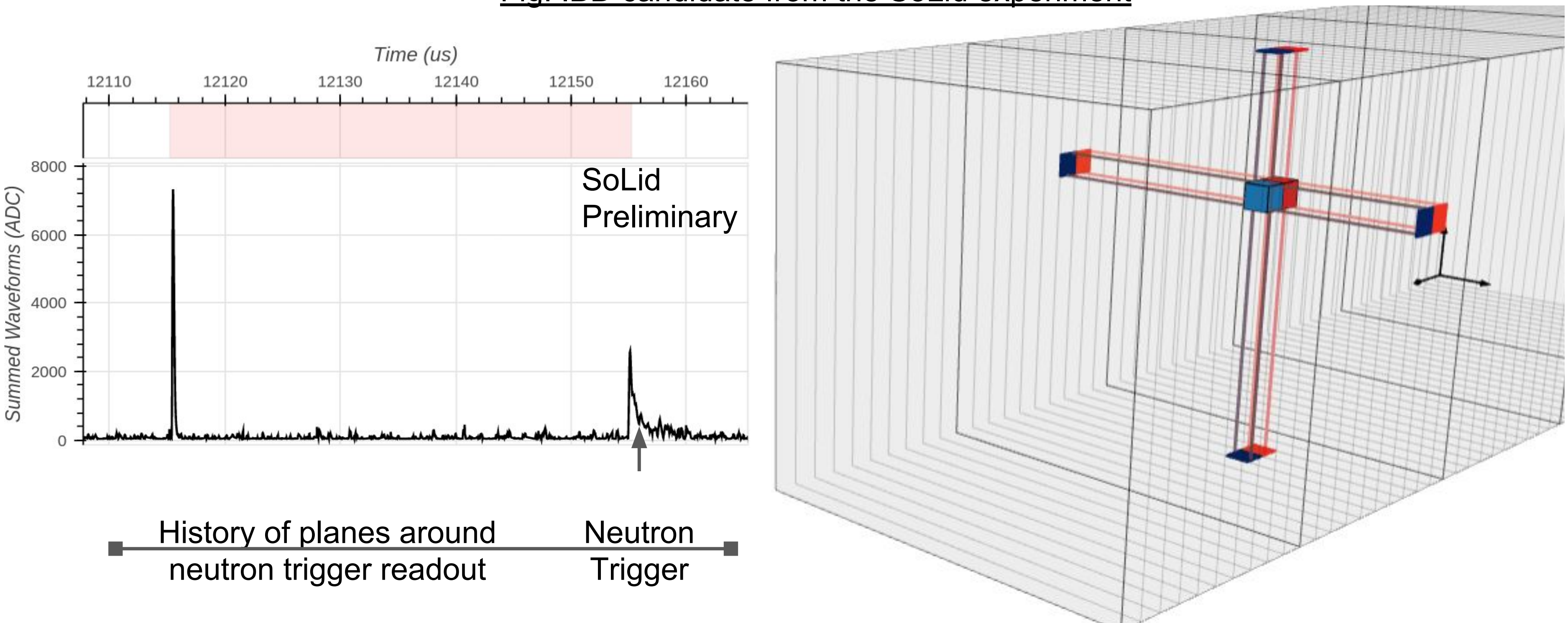
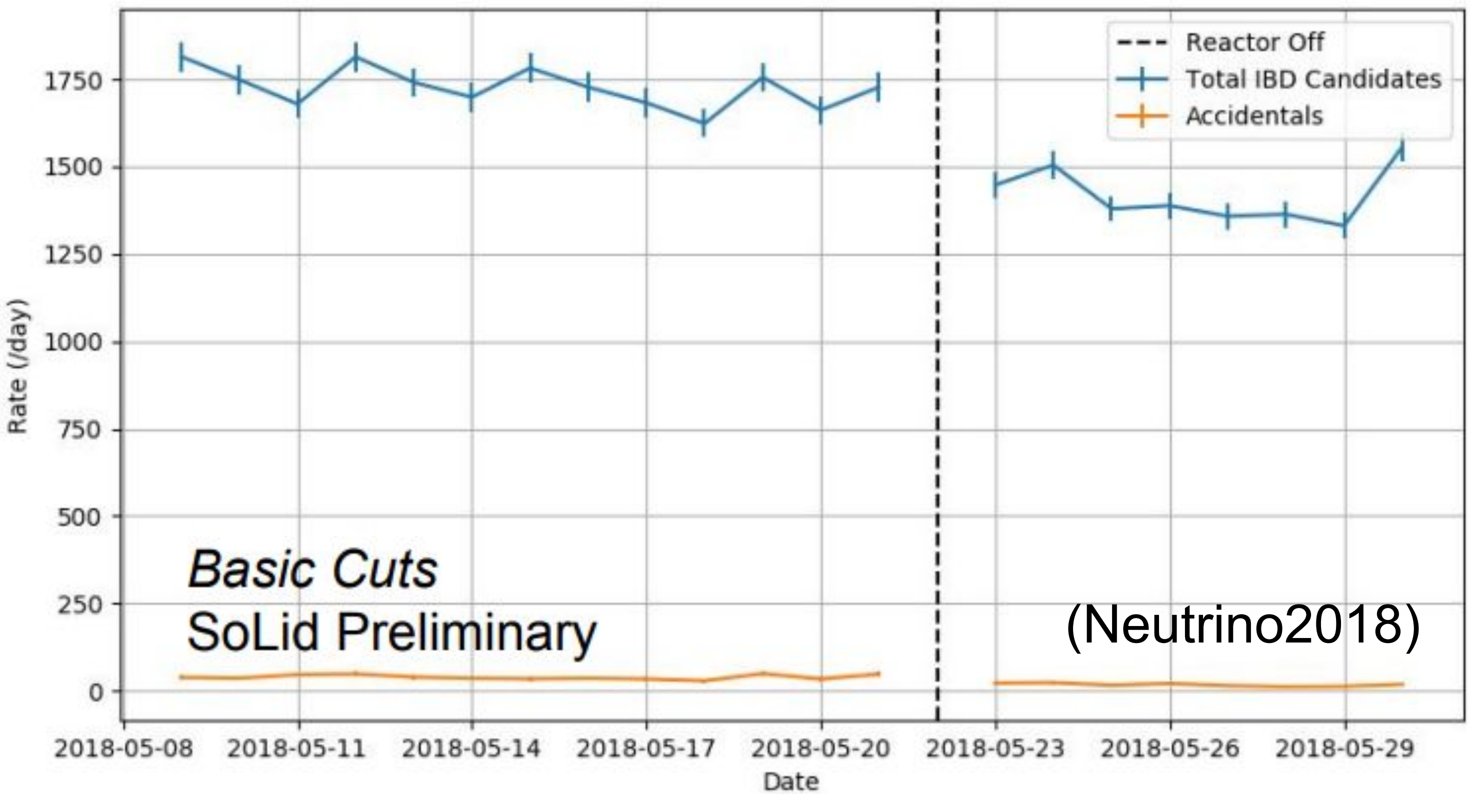
Fig: IBD candidate from the SoLid experiment



Reactor On-Off Transition

- Clear change in neutrino candidate rate with reactor power.
    - Topology consistent with neutrino expectations.



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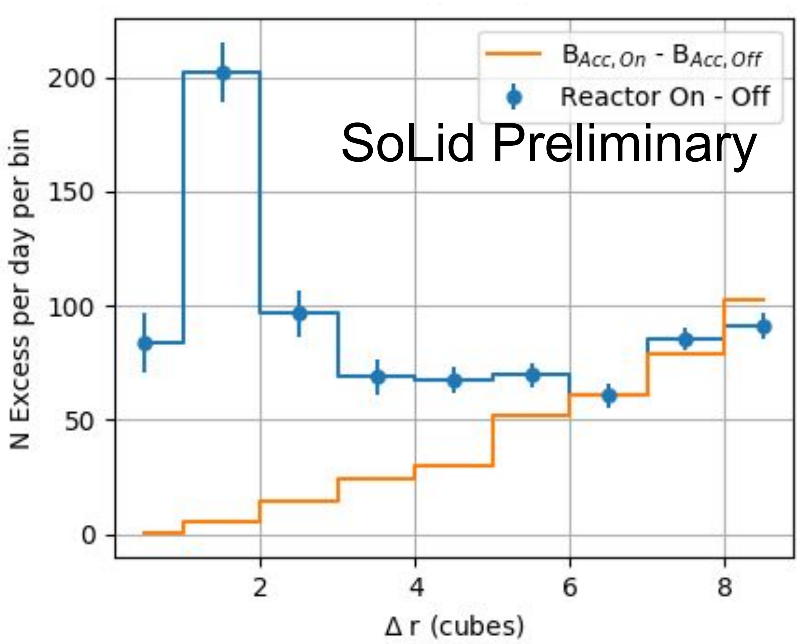
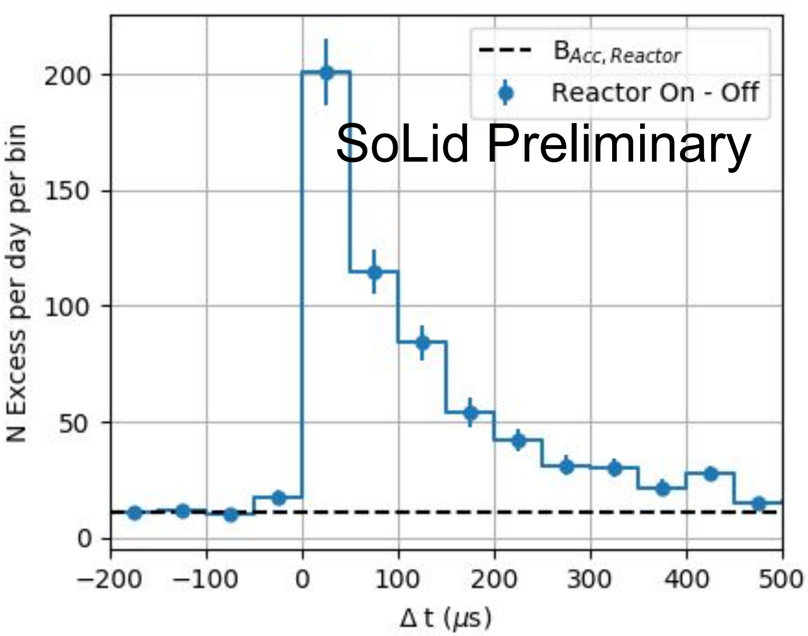




Threshold Trigger

- Threshold trigger also included for high energy signals:
  - Muon tagger - can be also used for calibration.

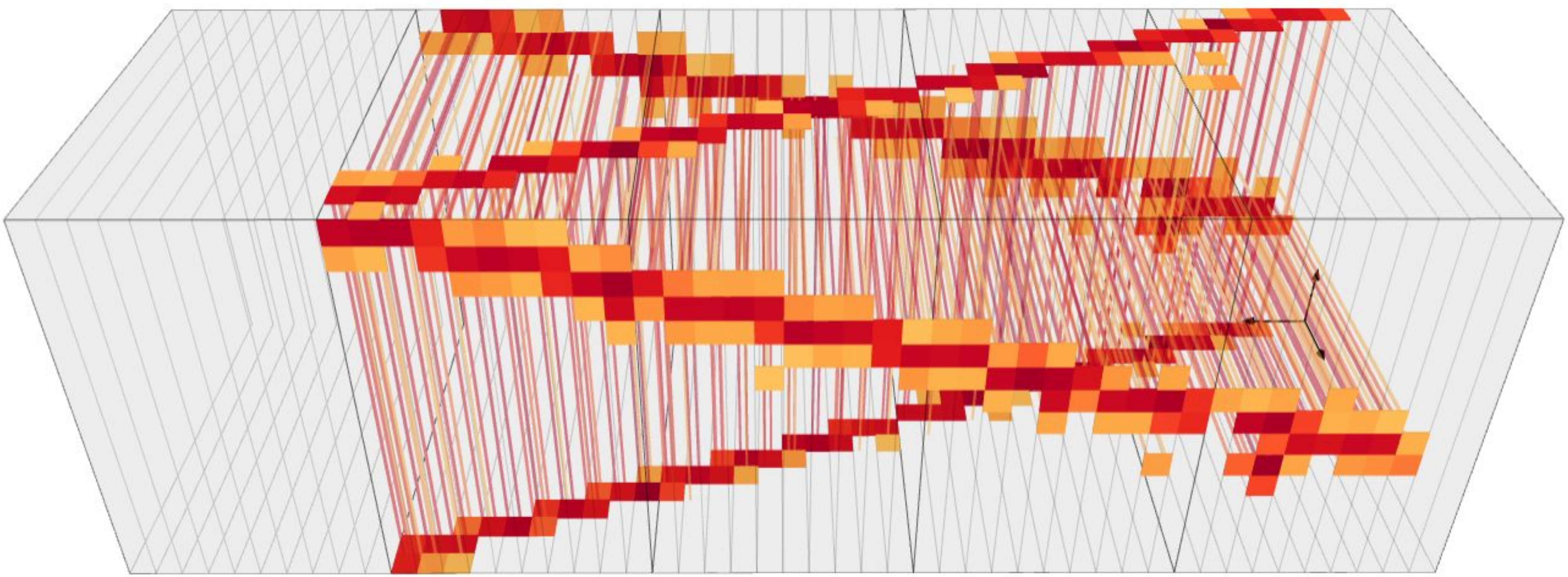
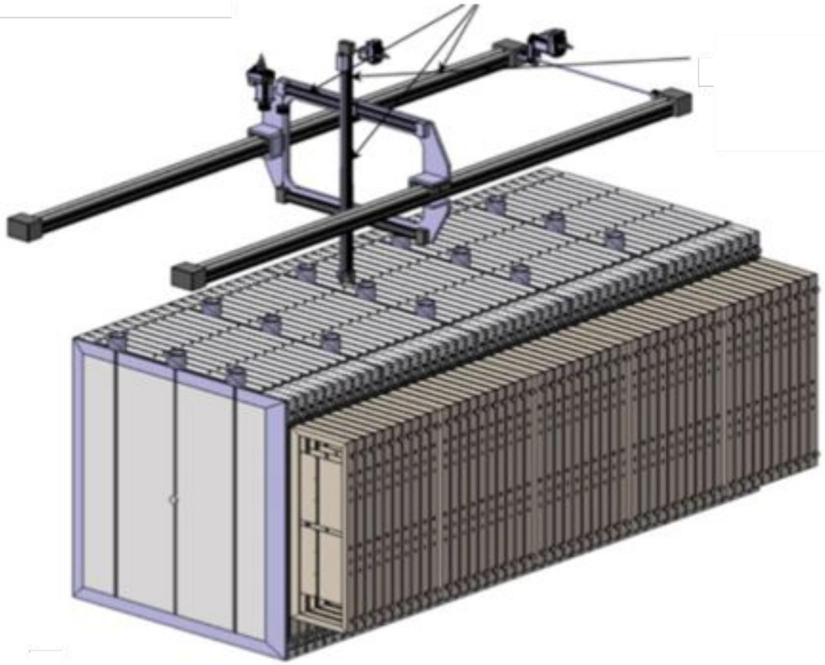


Fig: Example muon candidate, crossing all four modules. 50ns time window.

Calibration

- Second calibration robot in situ: CROSS
- Sits above detector planes.
- Mechanically open gap between sets of ten planes.
  - Source free to move in gap between planes in 2D.
- Muon tracking gives addition handle.



Software

DAQ

- Novel DAQ written in google 'Go':
  - Take advantage of built in multithreading handling.

Simulation & Reconstruction

- GridPP used for bulk of simulations.
- Dedicated software developed for data reconstruction & quality monitoring.

Online Monitoring

- Web-based run-control and data quality monitoring.
- Detector ran remotely with daily shifters & automated alarms.

Outlook

- 2017 saw successful construction and deployment of the 1.6 T SoLid detector:
  - Robust n/e-gamma discrimination.
  - High segmentation to tag background.
  - Many upgrades based on experience:
    - *Increased passive shielding.*
    - *Optimised light yield.*
    - *Dedicated PSD for trigger efficiency.*

  Performance exceeding expectations.

- Data taking in 2018 continuing stably:
  - ~ 150 days reactor on.
  - First Physics results expected early 2019.

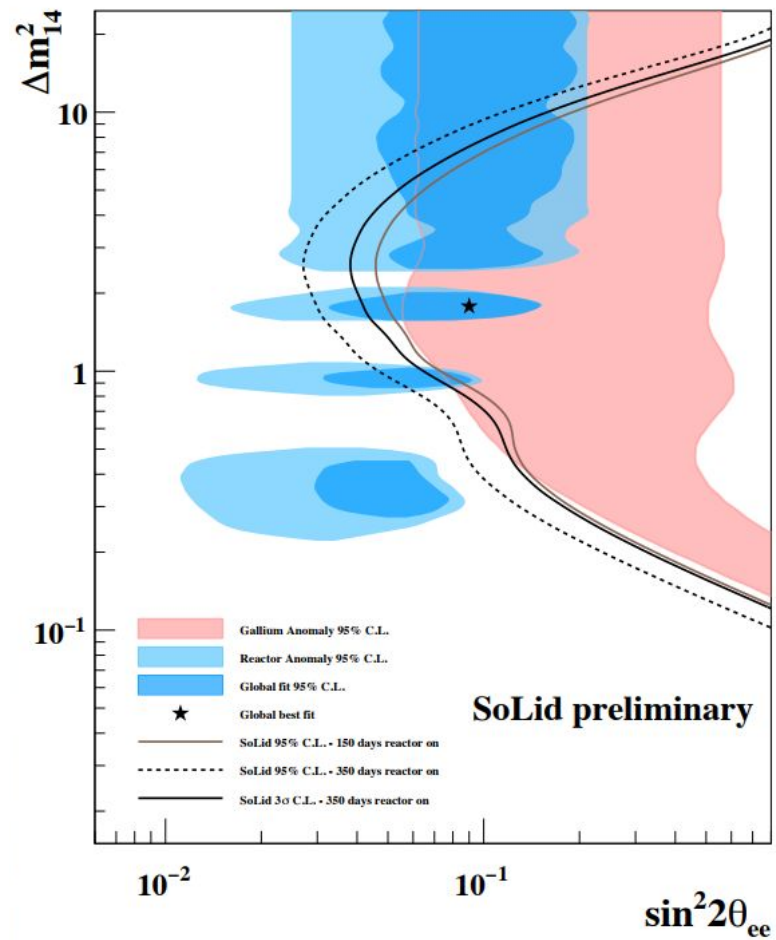


Fig: SoLid 3-year sensitivity

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Backup

Detector Technology

- Prompt energy reconstructed independently of annihilation gammas:
  - Gamma leakage not a problem.

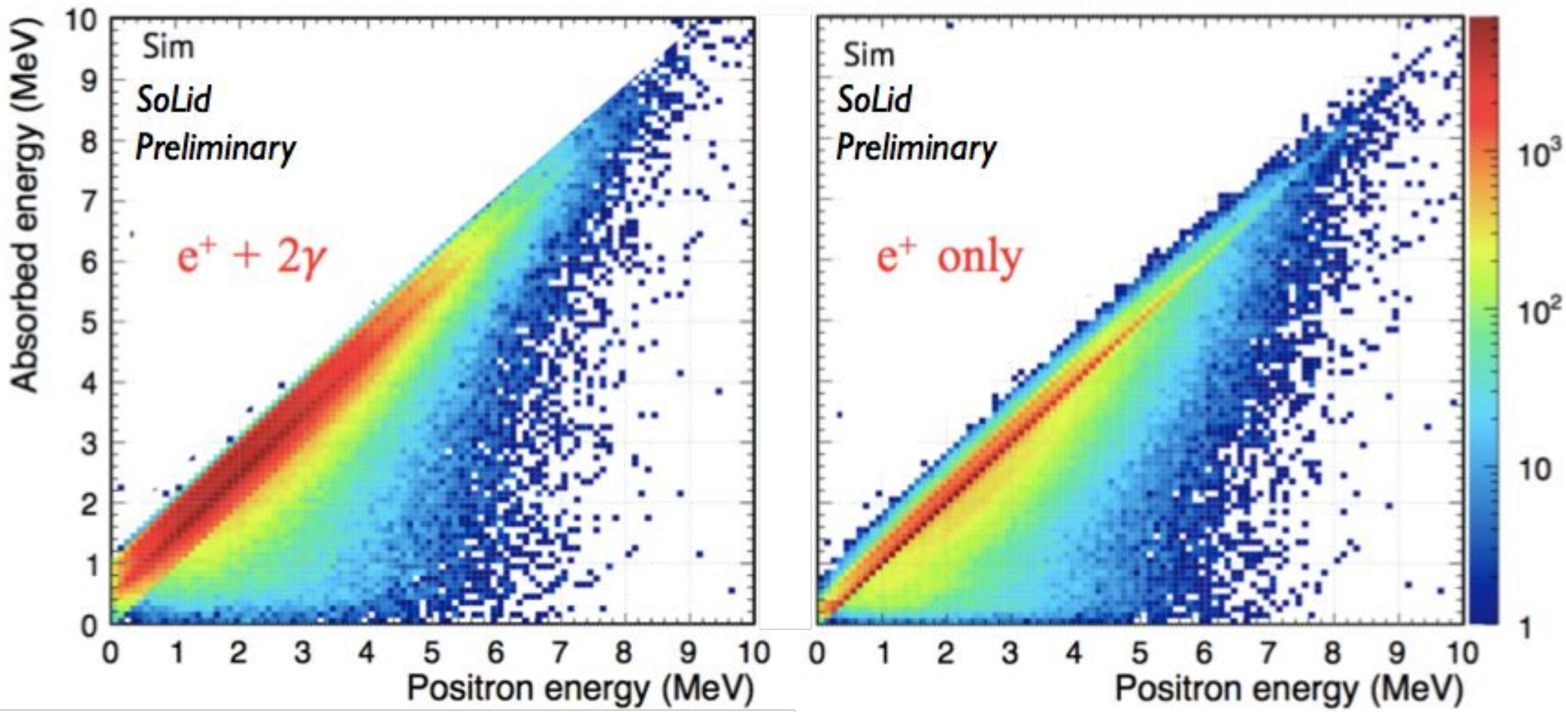

Fig: Positron energy reconstruction.
Left: including gamma energy. Right: only cubes near the positron.
RO effects not included.

Muon Calibration