Performance of the SoLid Reactor Neutrino Detector

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On behalf of the SoLid collaboration

GDR Neutrino

APC – Paris 2018

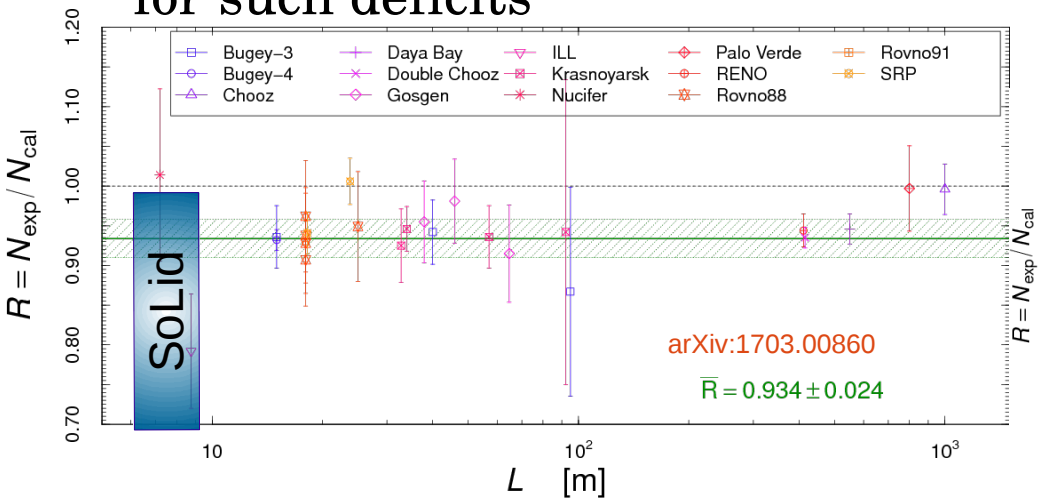
Outlook

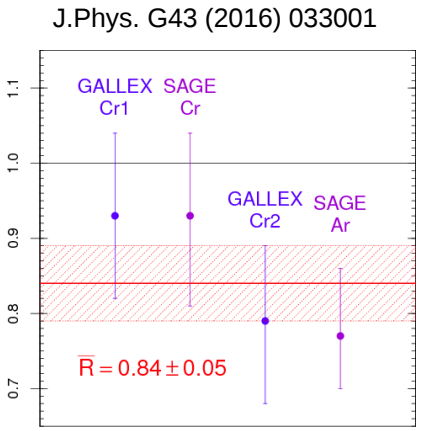
- Physics motivation
- The SoLid experiment
- Construction and QA
- Commissioning and calibration
- Summary

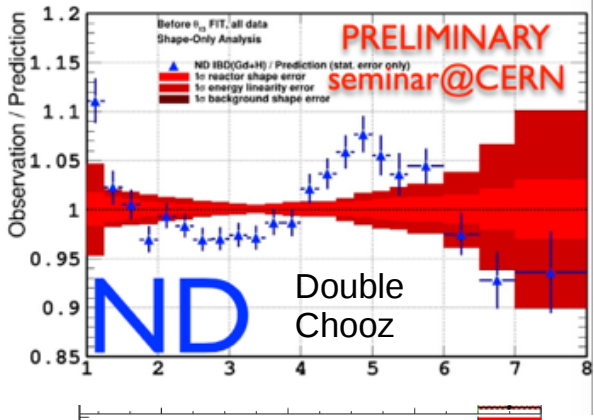
- ***Physics motivation***

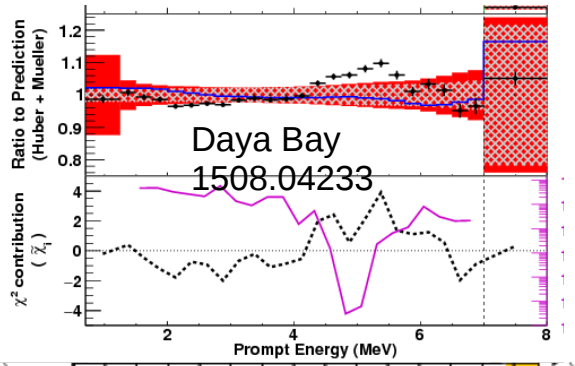
Physics Motivations

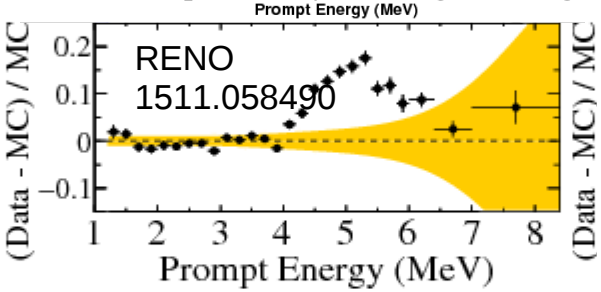
- **Anomalies:** The **reactor antineutrino anomaly** and **gallium anomaly** both show discrepancies wrt expectations at ~3σ level
  - Oscillations into a **light sterile neutrino state** ($\Delta m^2 \sim 1\ eV^2$) could account for such deficits











- **Distortion** observed around **5 MeV** ("bump") in the reactor **antineutrino** energy **spectrum**
  - Hints point to ^{235}U (1609.03910, 1608.04096, 1512.06656)
- **SoLid goals:**
  - RAA: Search for an **energy distortion** pattern at short baselines
  - 5 MeV "bump": Provide a **new** measurement of ^{235}U fuel **antineutrino spectrum** with a different detection technology

- ***The SoLid experiment***

SoLid goals

SoLid goals:

- Using a **different detection technology**
  - RAA: Search for an **energy and space oscillation** pattern at short baselines ([6-9] m)
  - 5 MeV "bump": Provide a **new** measurement of ^{235}**U** fuel **antineutrino spectrum**

SoLid collaboration

The SoLid Collaboration

4 countries **12 institutes** **~50 people**

Universiteit Antwerpen

lpc caen

VUB VRIJE UNIVERSITEIT BRUSSEL

LPC Particules pLasmas Univers applicationS Laboratoire de Physique de Clermont

UNIVERSITEIT GENT

LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

SCK•CEN STUDIECENTRUM VOOR KERNENERGIE CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

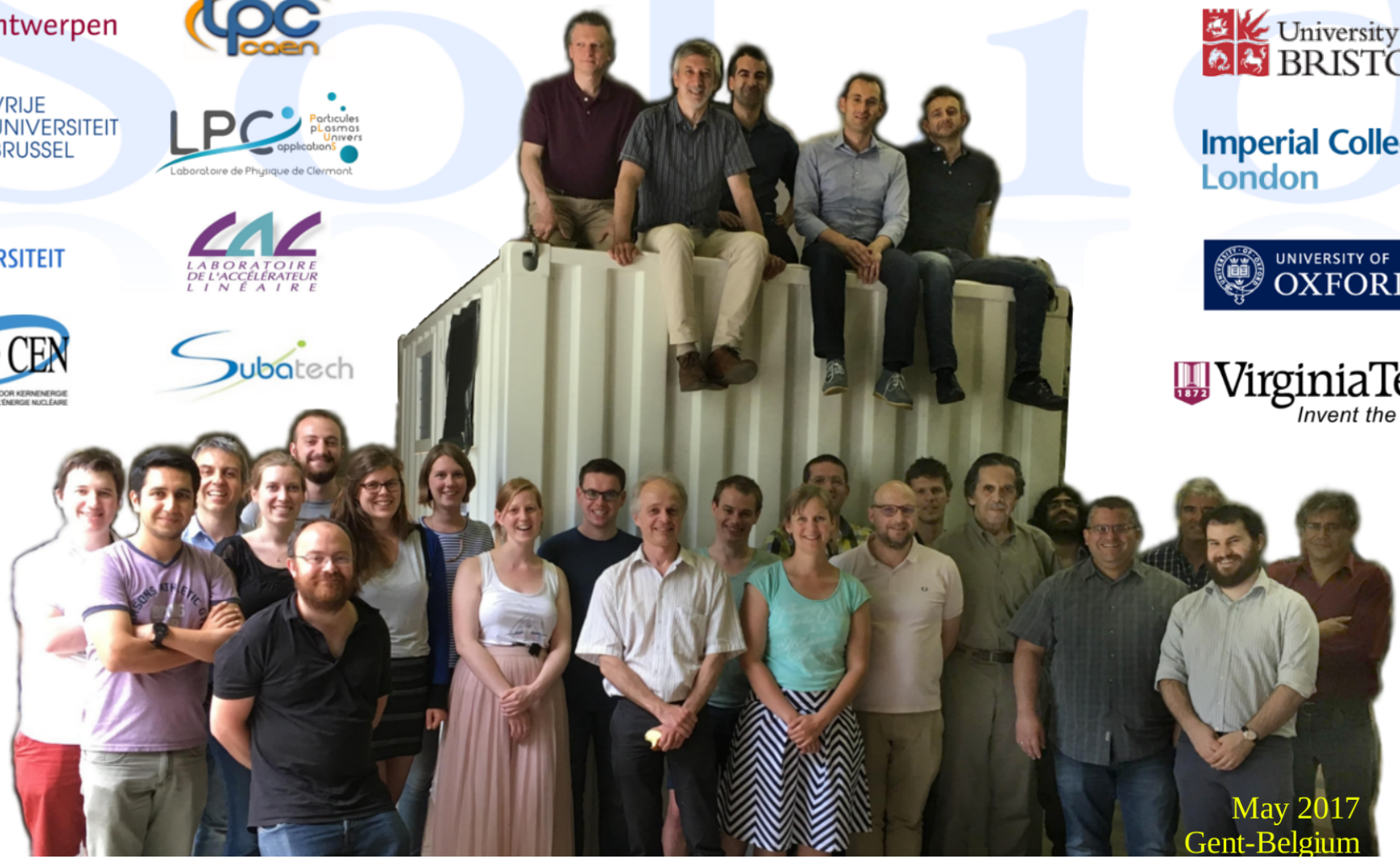
Subatech

University of BRISTOL

Imperial College London

UNIVERSITY OF OXFORD

VirginiaTech Invent the Future

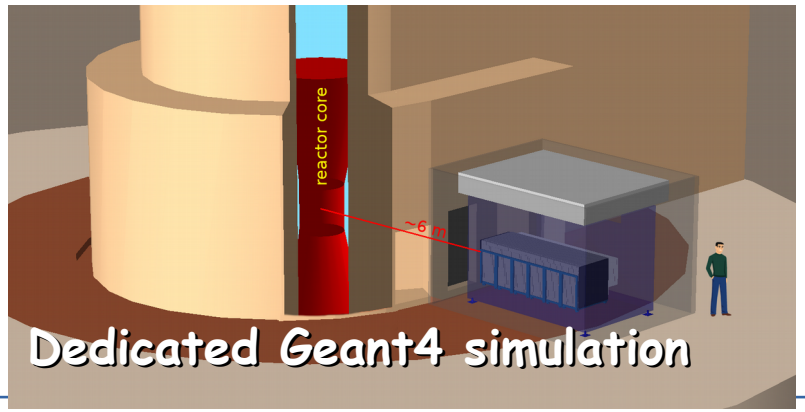


May 2017
Gent-Belgium

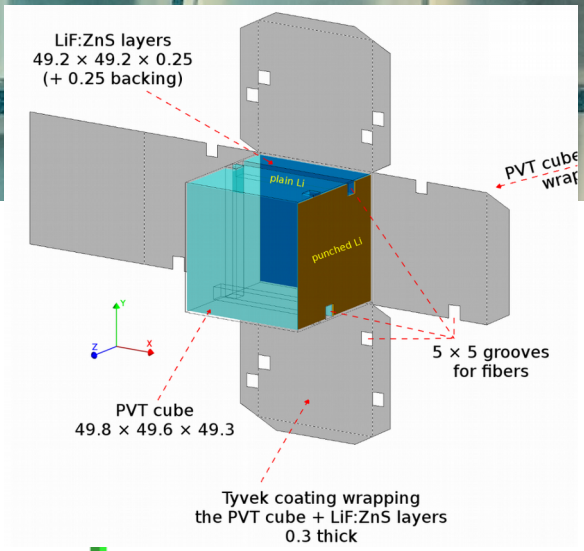
The BR2 site and reactor

Best fit RAA → Oscillation length of 3-4 m for 3 MeV ν's ⇒ **Compact source**

- **Compact** reactor **core** $\Phi < 50$ cm, h = 90 cm
  - Baselines : 6 → 9 m
- Thermal power: 45-80 MW
- Highly ^{235}**U enriched** (up to 93.5 %)
- 150 days per year duty cycle
  - Reactor off data for background estimation and subtraction
- **No nearby experiments**
- Overburden of ~10 mwe
- **Low background** (neutron, γ)
- **Excellent** collaboration with SCK•CEN



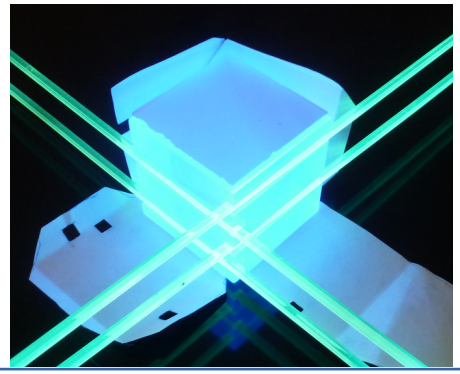
The SoLid technology

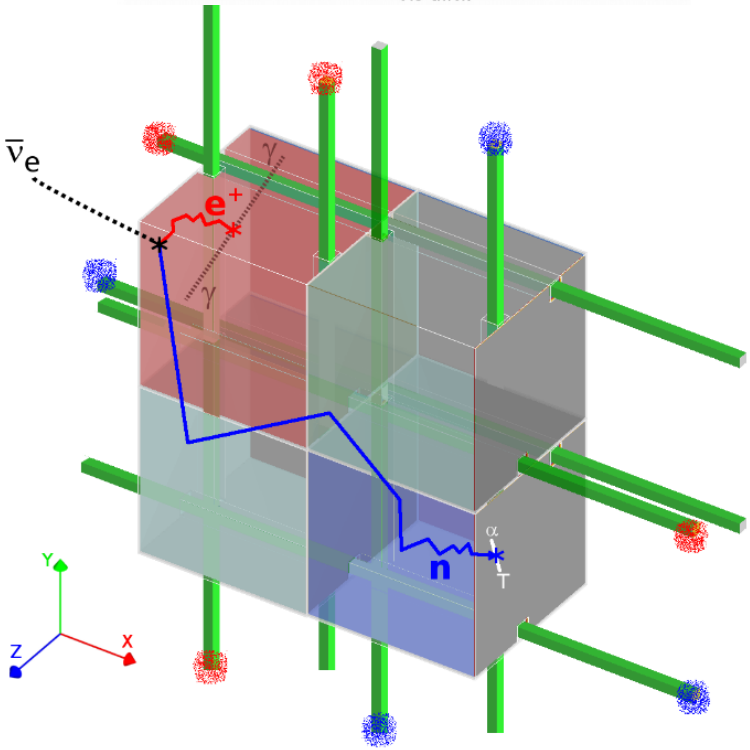


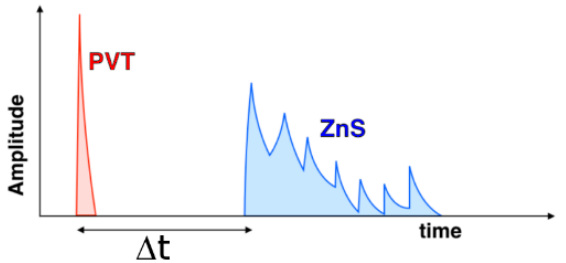
- Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
- 3D highly **segmented composite detector**
  - 5 cm x 5 cm x 5 cm **PVT** cubes
    - $\bar{\nu}_e$ interaction
  - 2 layers / cube of **LiF:ZnS**(Ag) for neutron detection
    - Neutron capture on Li in ZnS layer :

      $n + {}^6Li \rightarrow {}^3H + \alpha + 4.78\ MeV$
  - Nuclear signals (NS) and electronic signals (ES) very different
    - → Waveform shape discrimination ("~PSD") + neutron trigger
- Cubes optically separated (Tyvek)
- WLS fibers + SiPM to read out signals

JINST, Vol. 12, 2017, arXiv:1703.01683

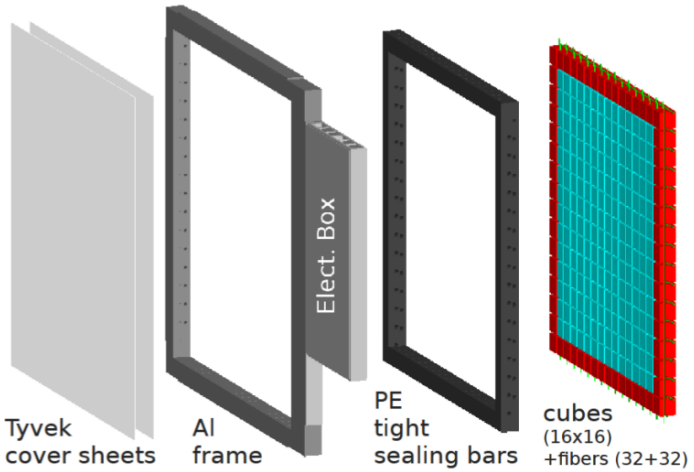


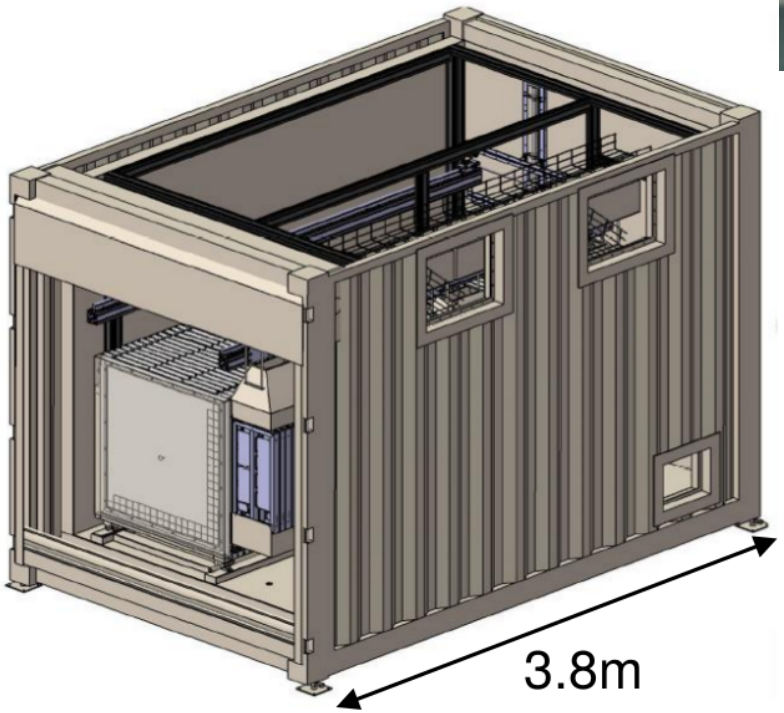


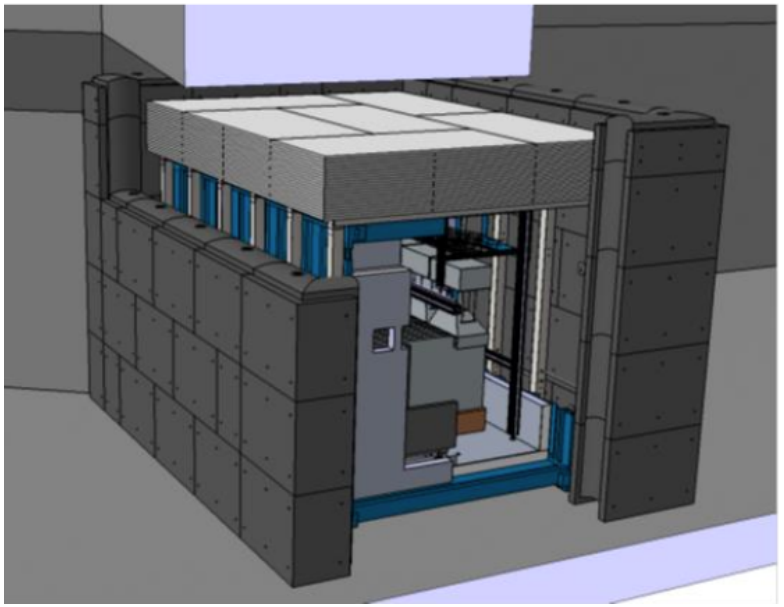


The SoLid (1600 kg) detector

- **5 Modules** of 10 planes
  - Planes of 16x16 cubes
- 4 x (fiber + SiPM + Mirror) per cube
- Automated calibration system
- Container (2.4x2.6x3.8 m) for **cooling at 5 °C**
  - Reduction of dark count rate
- **Shielding:**
  - Water wall: 50 cm thick, 3.4 m high, 28000 kg
  - Polyethylene ceiling: 50 cm thick, 6000 kg



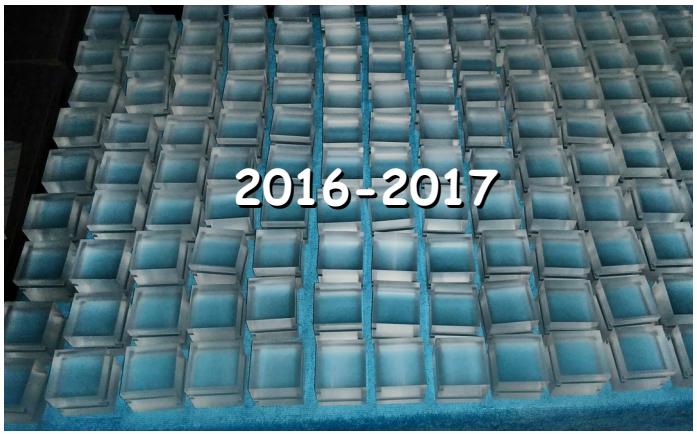


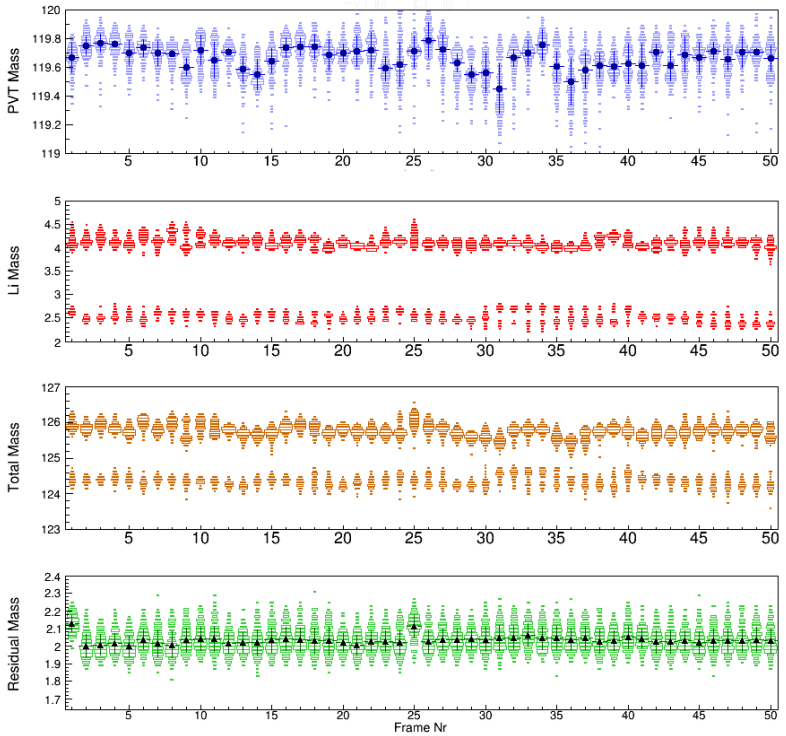


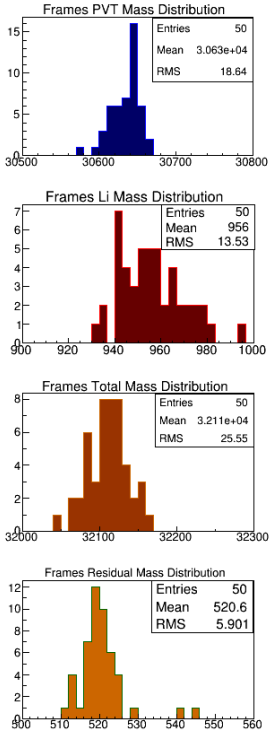
- ***Construction and QA***

Plane construction

- ~13 000 cubes manually washed, weighted, wrapped, stacked, …
- All cube components product information stored in database





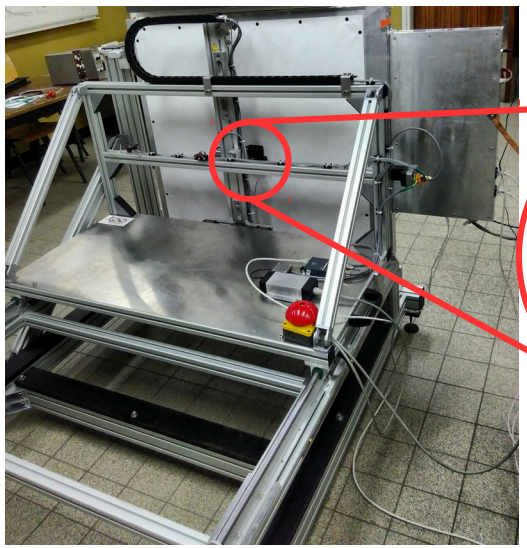


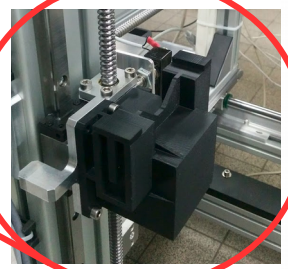
Plane qualification with CALIPSO

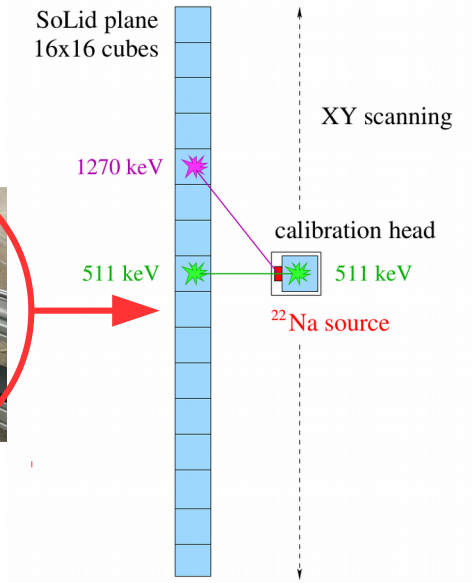
- **Automated** system to place radioactive sources in front of **each cube**
  - Gamma and neutron mode
- Check **quality** and **uniformity** of the SoLid planes
  - → **Early identification of defective components**
- Gave a good **knowledge** of the detector response **before installation** at BR2
- Allowed calibration of 1 plane / day

Gamma mode

^{22}Na source with **external trigger**

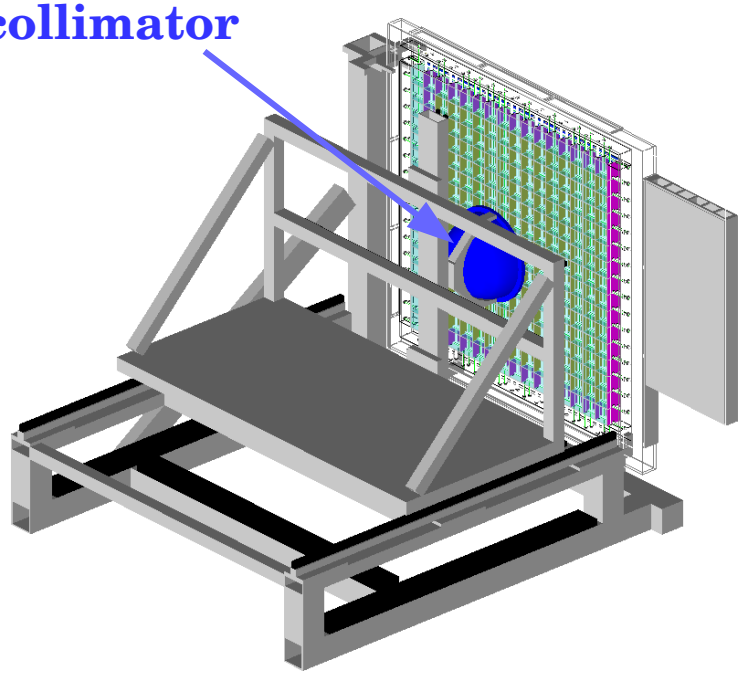






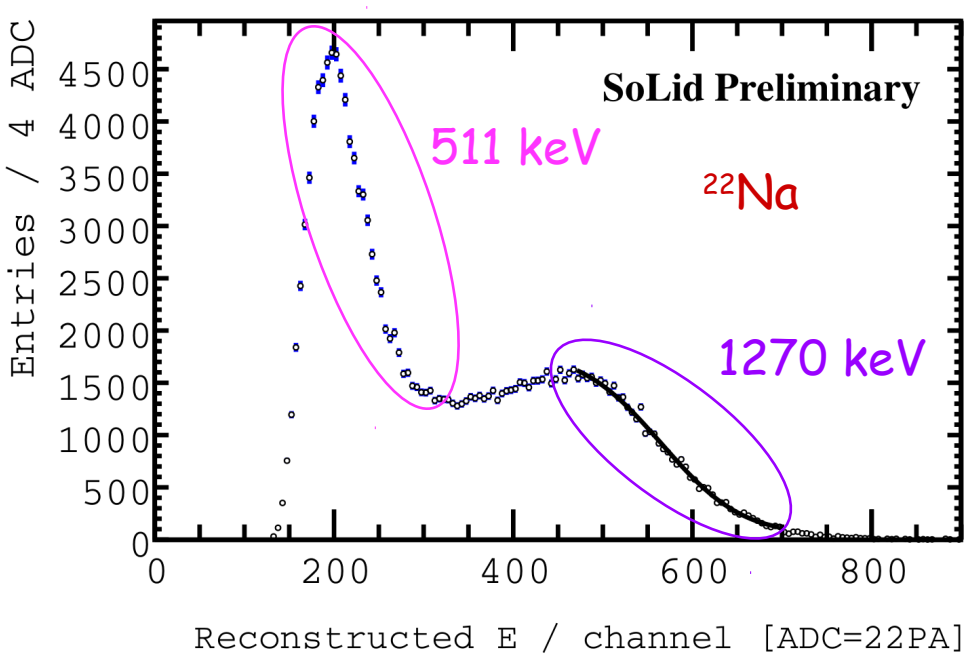
Neutron mode

^{252}Cf source with **polyethylene collimator**

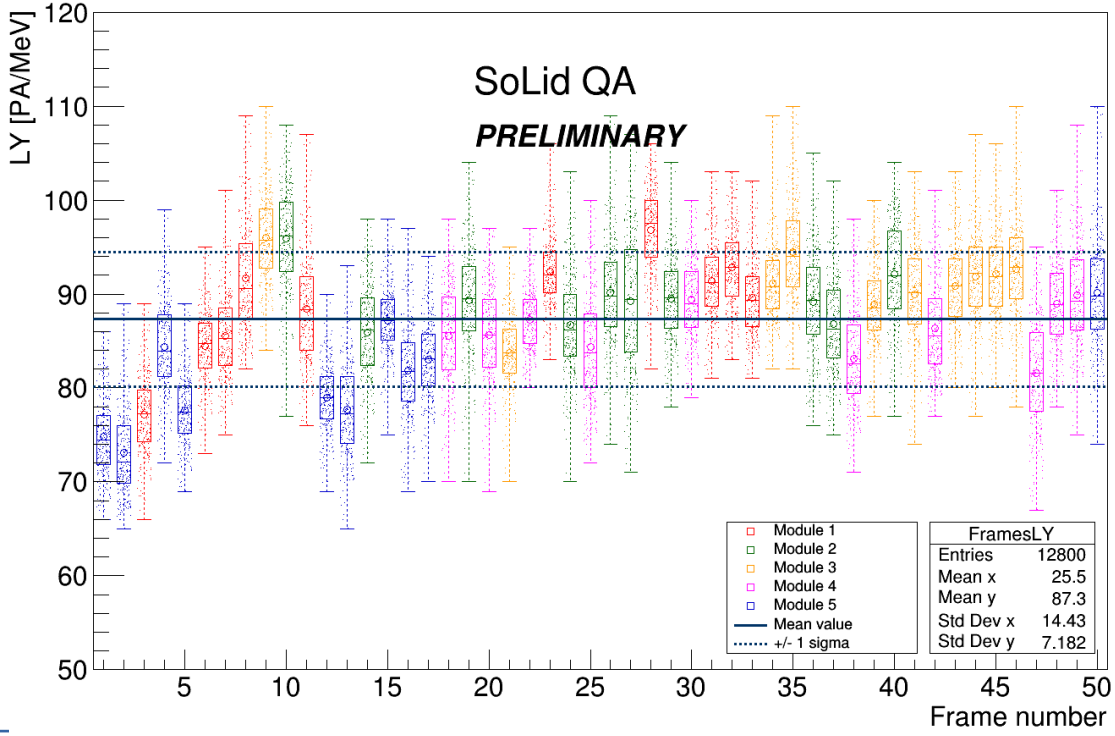


CALIPSO LY results

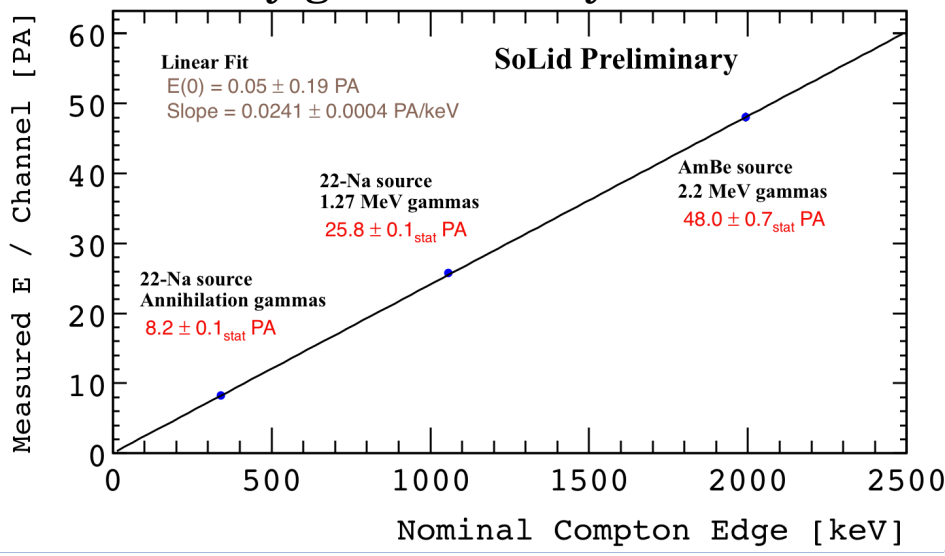
- Preliminary estimation of **LY** in all 12800 cubes
  - **Exceeds** SoLid **requirements**
    (40 PA/MeV → >60PA/MeV !)
- **Homogeneous** response
  - Can be improved with correction from attenuation length
- Minor construction **problems identified and fixed**



Light yield QA

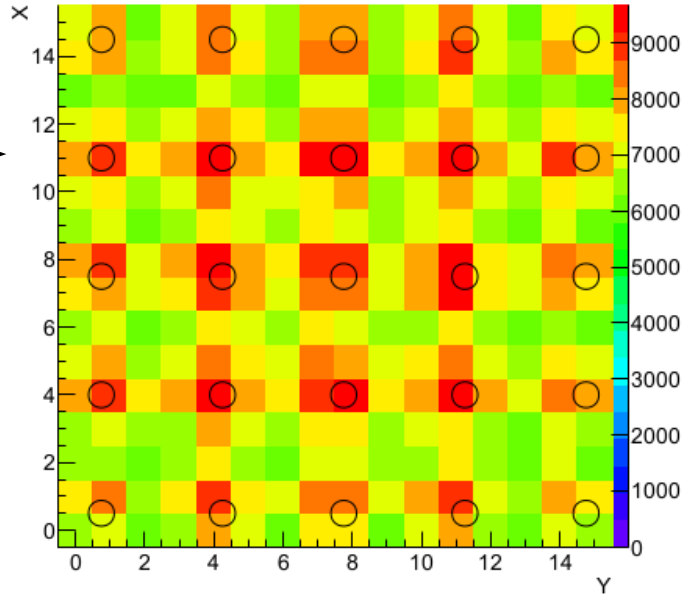


Very good linearity



CALIPSO neutron results

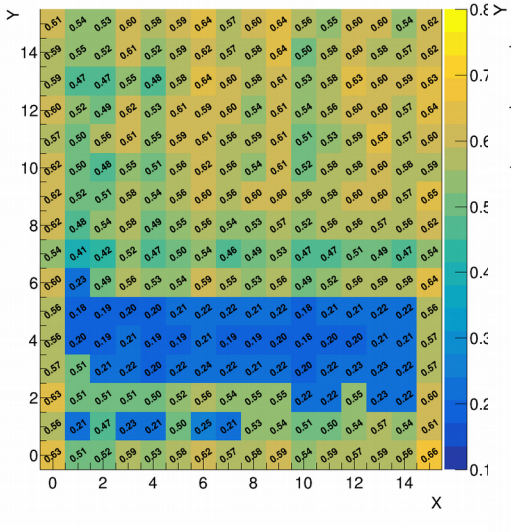
- ^{252}Cf calibration with PE collimator on 25 positions per plane in 3 h
  - Compared to Geant4/MCNPX prediction
  - Neutron **capture time** reduced to **τ ~ 65 µs** with 2 Li screens / cube and capture efficiency ~66 %

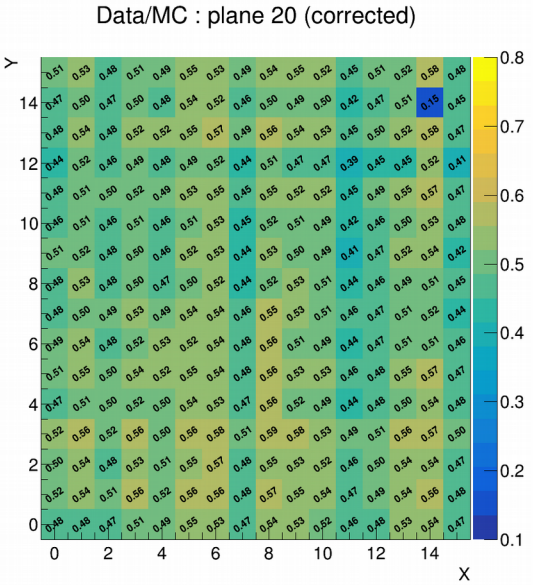


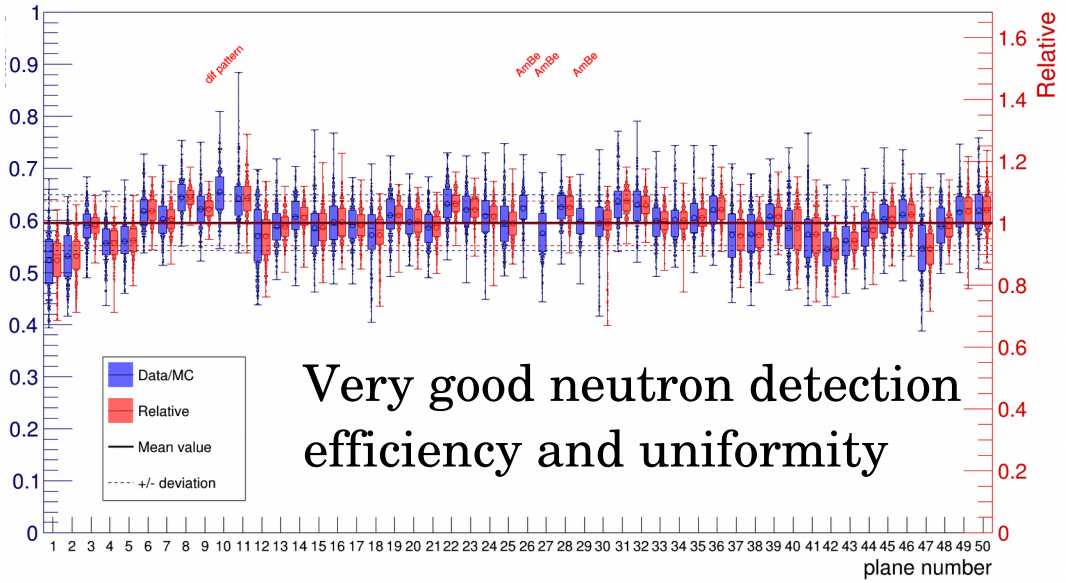
Cube efficiency distribution

One **bad** ^{6}LiF:ZnS **batch identified** and replaced

Only 1/12800 cubes where 1 Li **screen** was missing → has been replaced





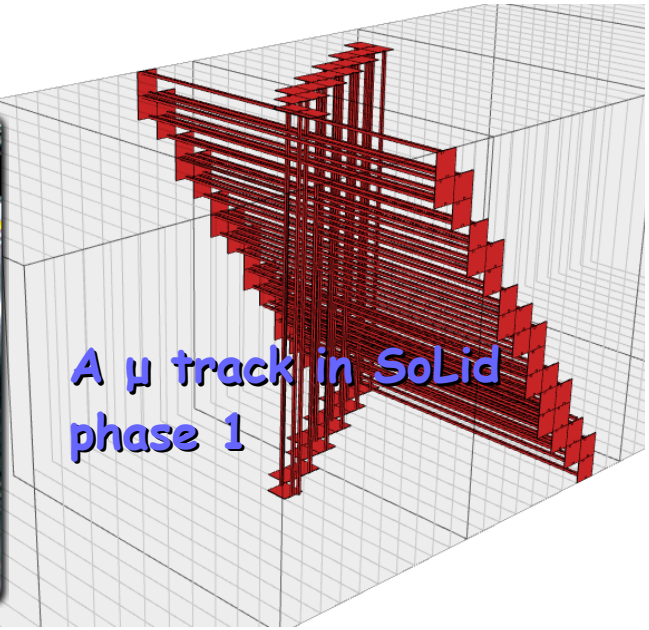


Very good neutron detection efficiency and uniformity

- ***Commissioning and calibration at BR2***

Commissioning at BR2

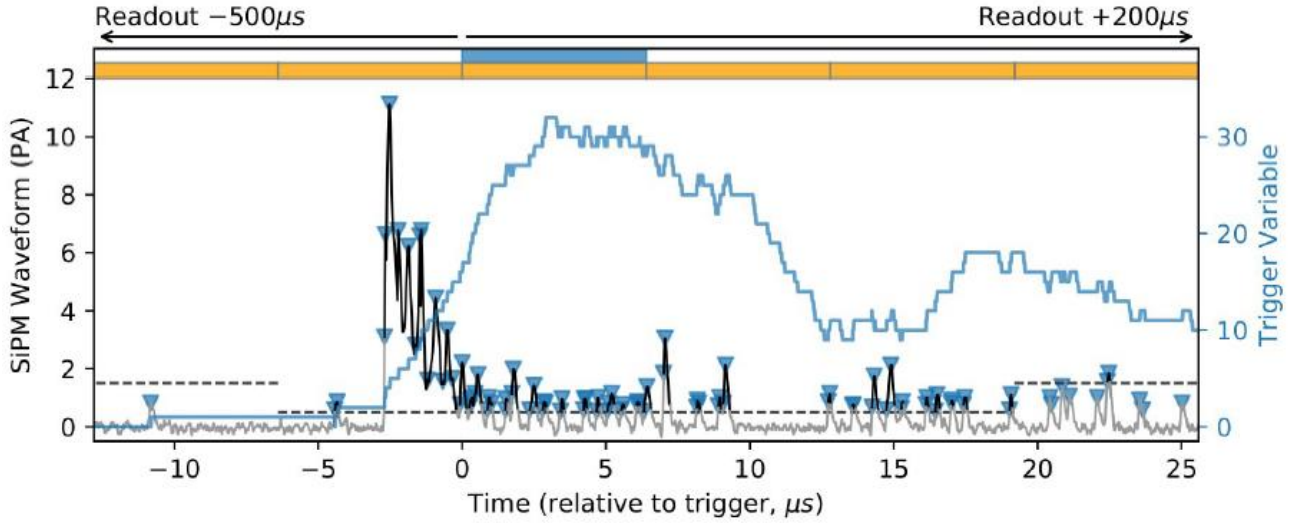
- **First modules deployed** at BR2 last November
- **Commissioning** of the full detector **completed** beginning of February 2018
- Expected ~150 days of reactor ON data in 2018



DAQ and triggers

- **Random:** Full detector readout at 1 Hz
  - Non zero-suppressed waveforms for SiPMs monitoring
- **Threshold:** XY coincidence > 2 MeV
  - Muon and high electromagnetic event tagger
- **Neutrino:** "PSD" algorithm for neutrons
  - Past time buffer (500 µs) & multiplane readout (+/- 3 planes)
  - → Unbiased prompt detection

- Neutron trigger implemented in FPGA
  - Based on **peak counting**.
  - Read out long time buffer around NS: [-500 µs, +200µs]

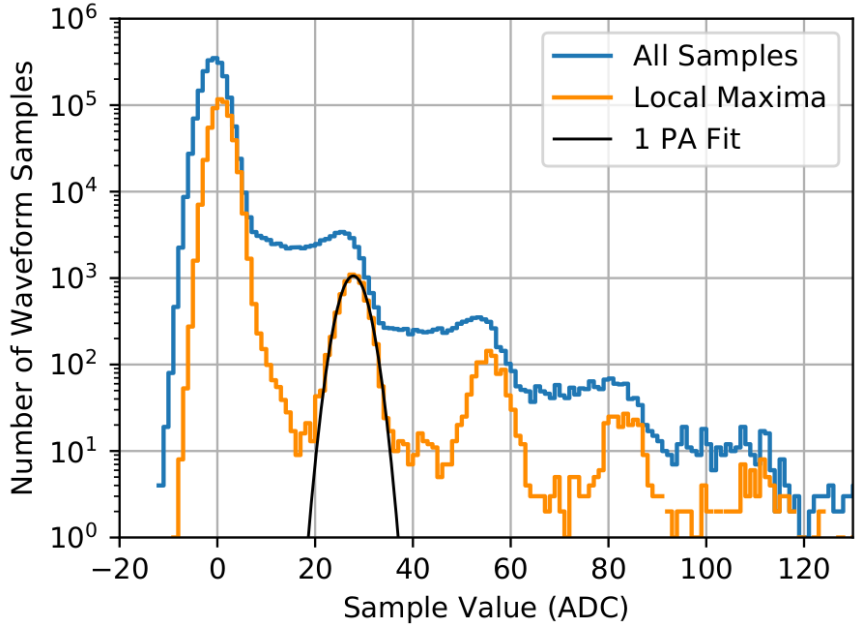


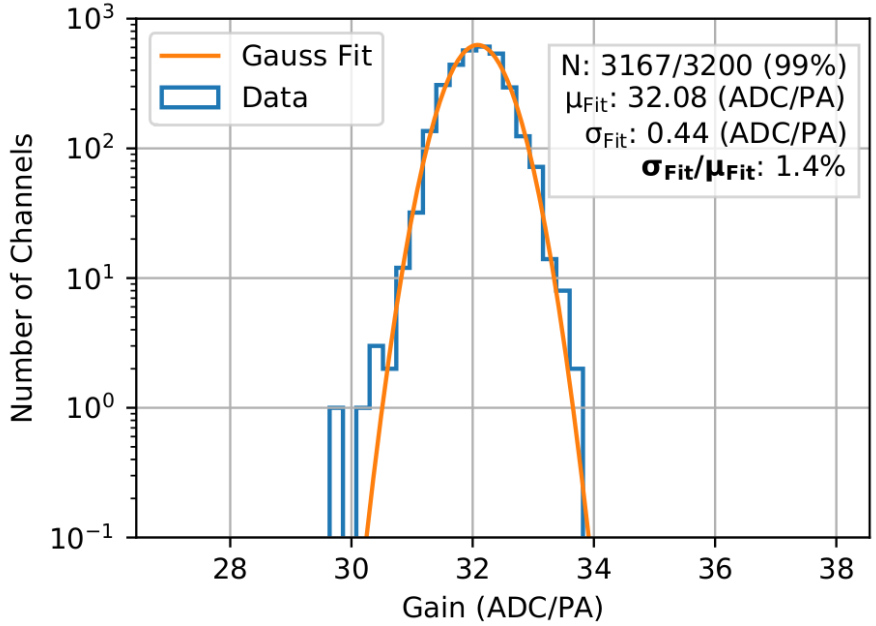
SoLid calibration goals

- Gains + crosstalk better than 1 % per channel
  - 3200 channels
- **12800 SoLid units**
  - Energy scale at 2% level
  - Neutron capture efficiency per cube at 3 % level
- Neutron capture time at the 1% level

MPPC equalization

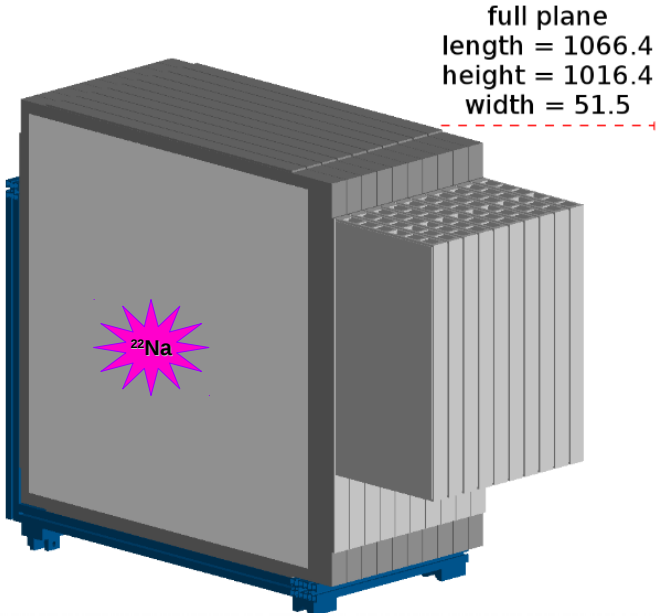
- 99% channels operational
- Amplitude response calibrated to high quality, spread ~1%
- Voltage scans used to calibrate individual MPPC breakdown voltages and amplification responses
- Equalize for gain response (i.e 1 PA amplitude) of 32.0 ADC/PA - equivalent to 1.8 V over-voltage



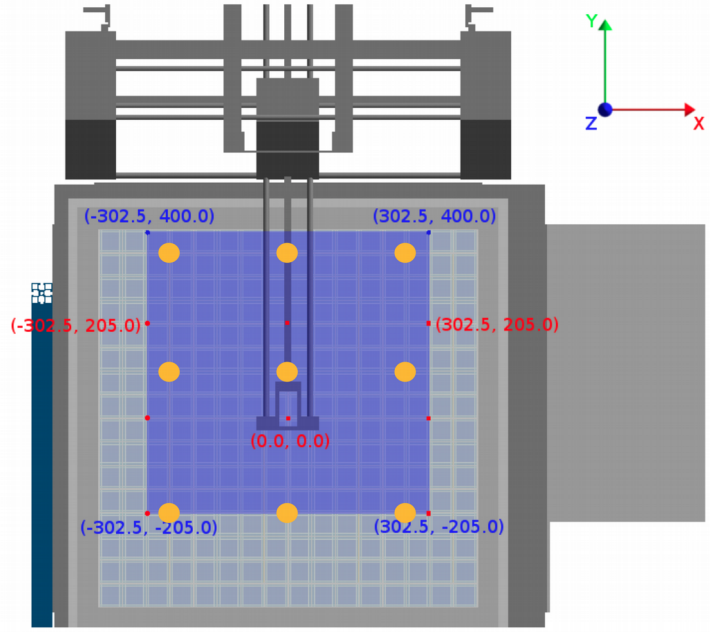


Calibrating with CROSS system

- **In situ** calibration
- Sits above detector planes
- Mechanically open gap between sets of ten planes (Module)
  - Source free to move in gap
  - 9 positions per gap used
  - 6 gaps in total → modules irradiated from two sides

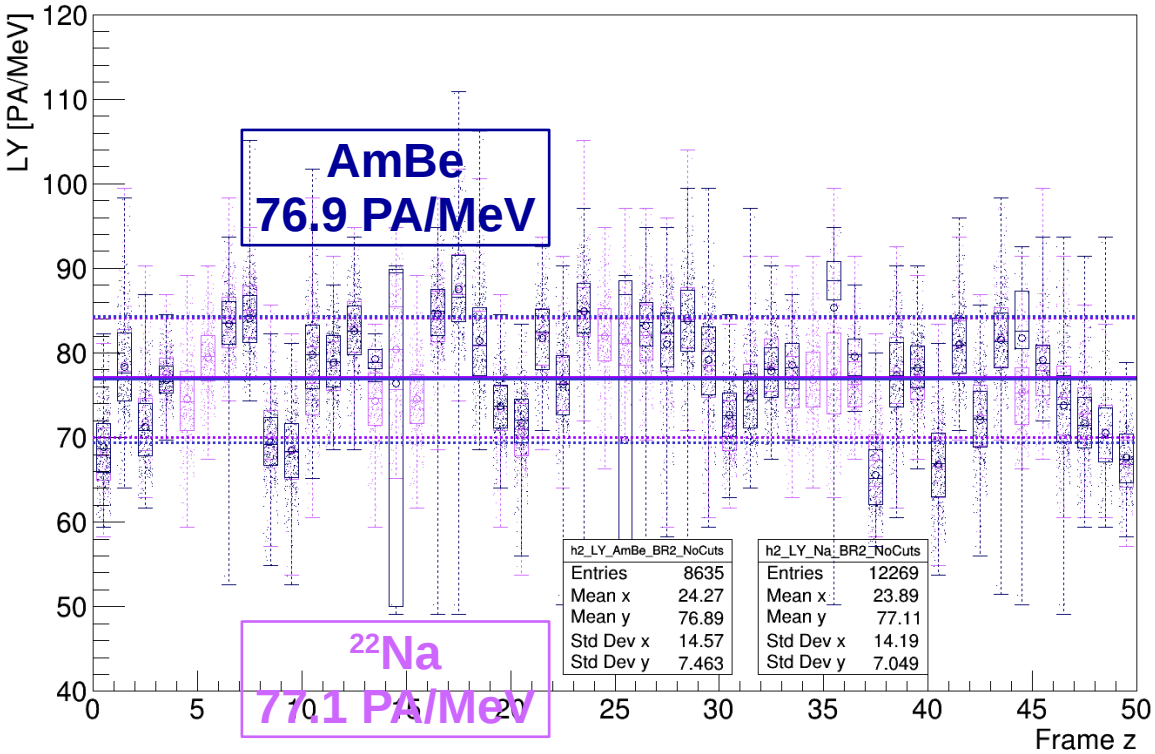


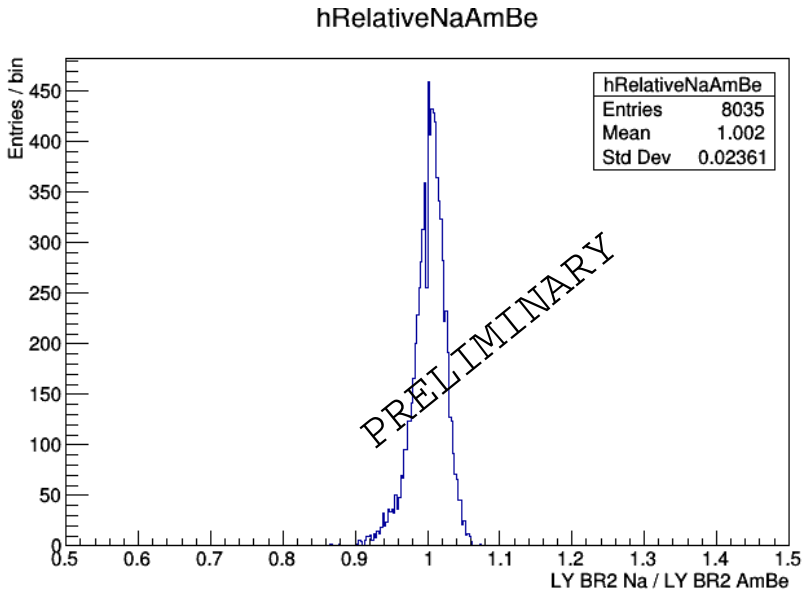
Rails to move modules



CROSS calibration - gamma

- First calibration campaign results with ^{22}Na and AmBe
  - **100% of cubes** (w/ 4 ch) have been **calibrated** with 94 hours of data taking
  - Average of 77 PA/MeV w/o crosstalk subtraction (~13%) for OV of 1.5
  - Currently running at OV of 1.8 → **LY should increase** of ~15% (x-talk too)

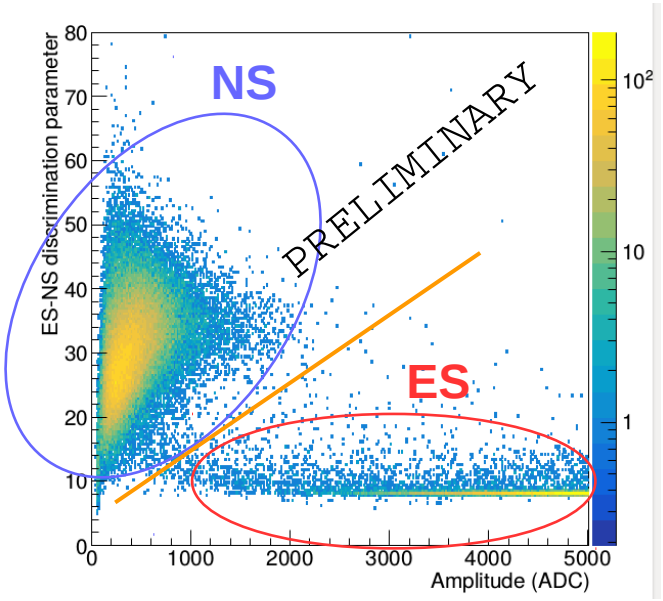


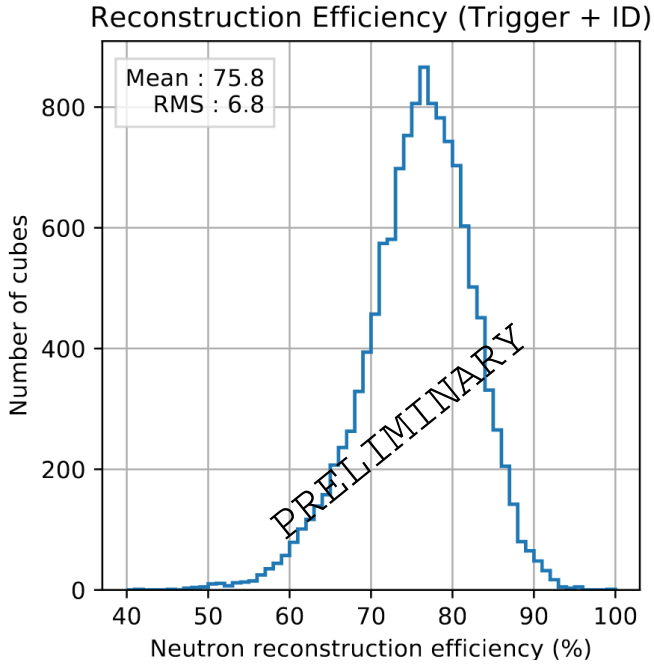


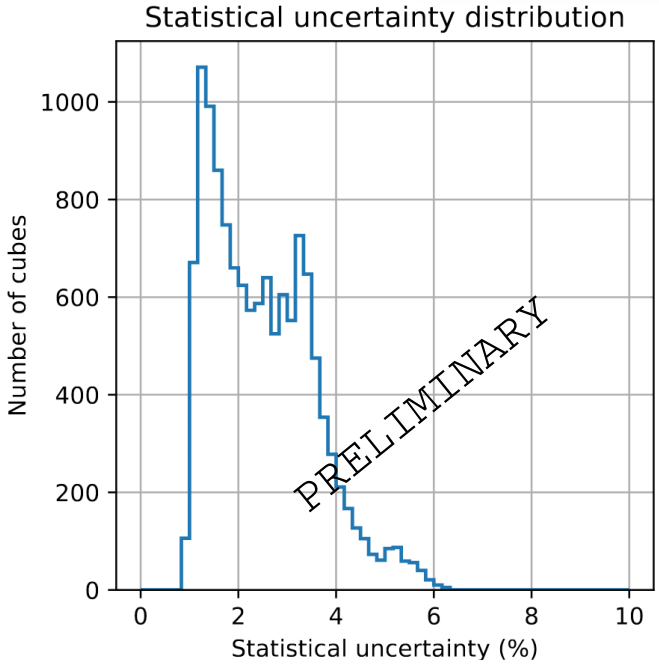
- Excellent **agreement between ^{22}Na and AmBe**
  - **Confirms PVT energy linearity**
- ^{137}Cs, ^{60}Co, ^{207}Bi will be deployed in the next weeks for linearity studies + μ's at high energy

CROSS calibration - neutron

- Calibration with AmBe (~4 MeV) and ^{252}Cf (~2 MeV)
  - Able to calibrate **n efficiency per cube** with both sources!
  - **Agreement at the ~3% level**
- Neutron reconstruction efficiency > 75%!
- Statistical error ~2.5%
  - Dominated by cubes far from the source
  - Will decrease with next calibration campaigns

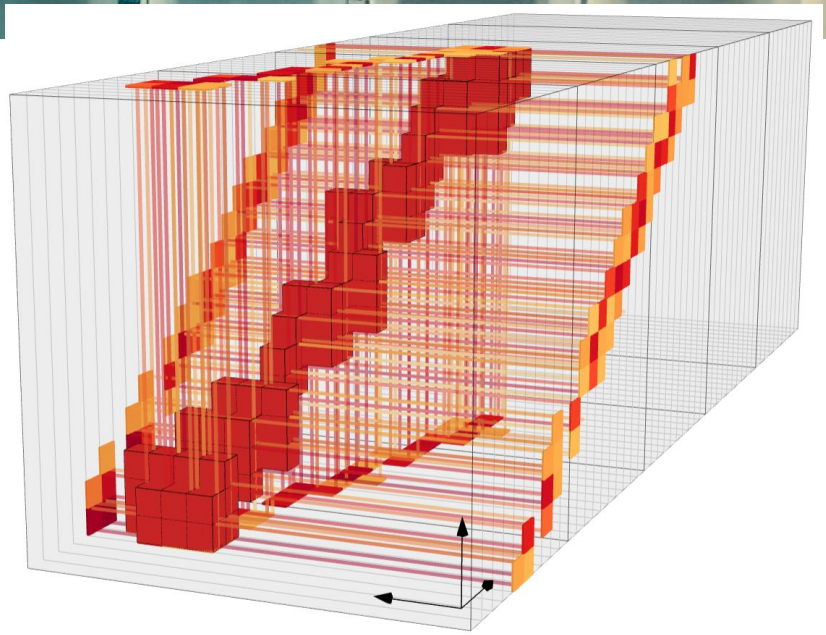


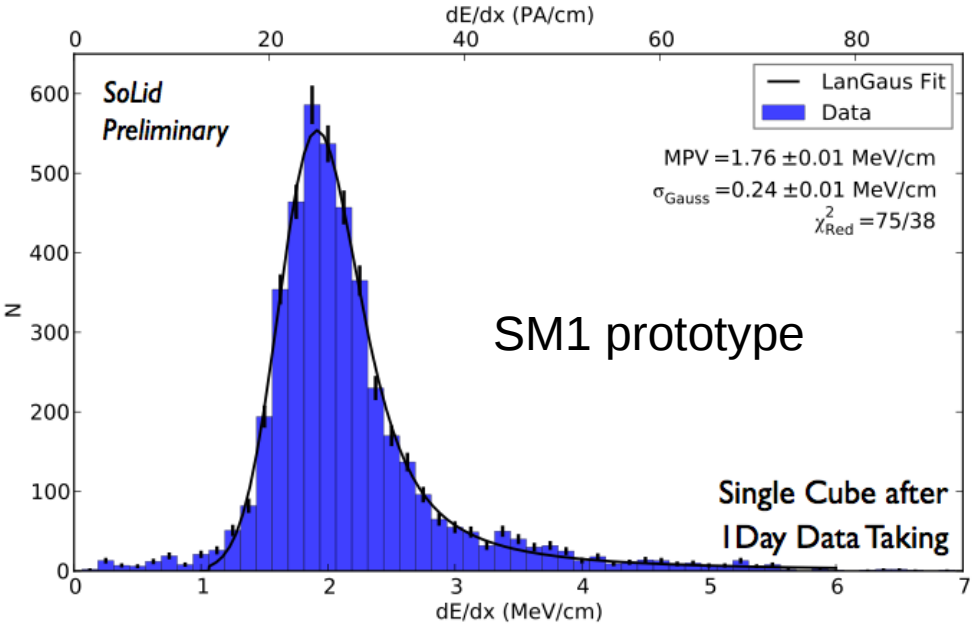


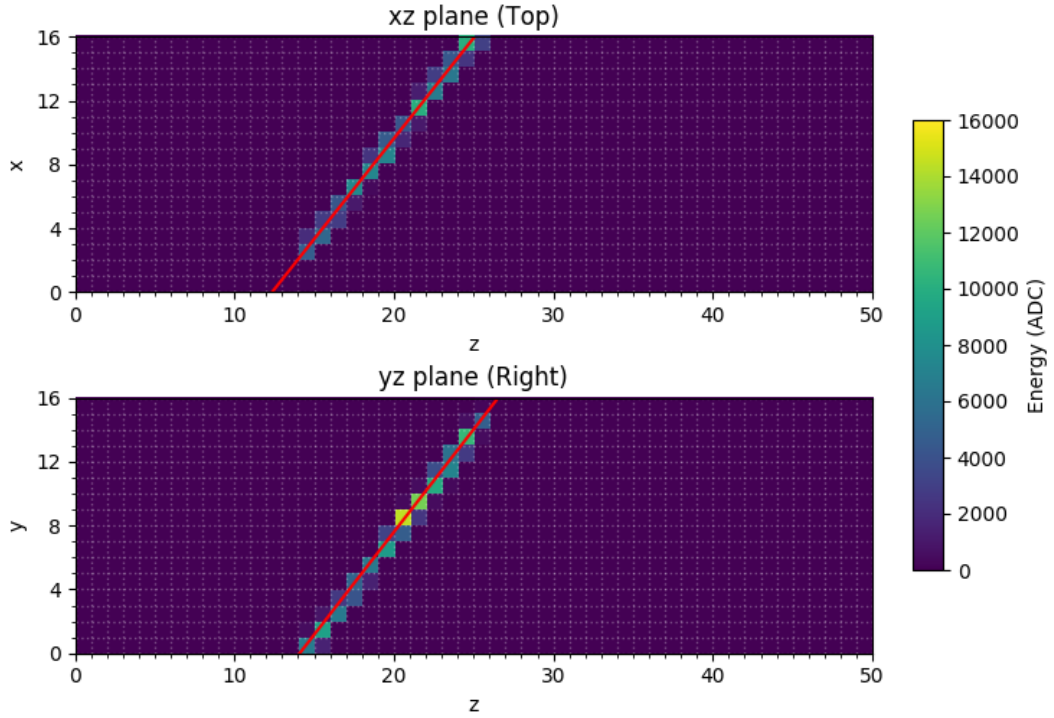


Muon calibration

- Reconstruct muon tracks
  - → Edep / cube using well known dE/dx
  - Monitoring detector stability
  - Linearity at high energy

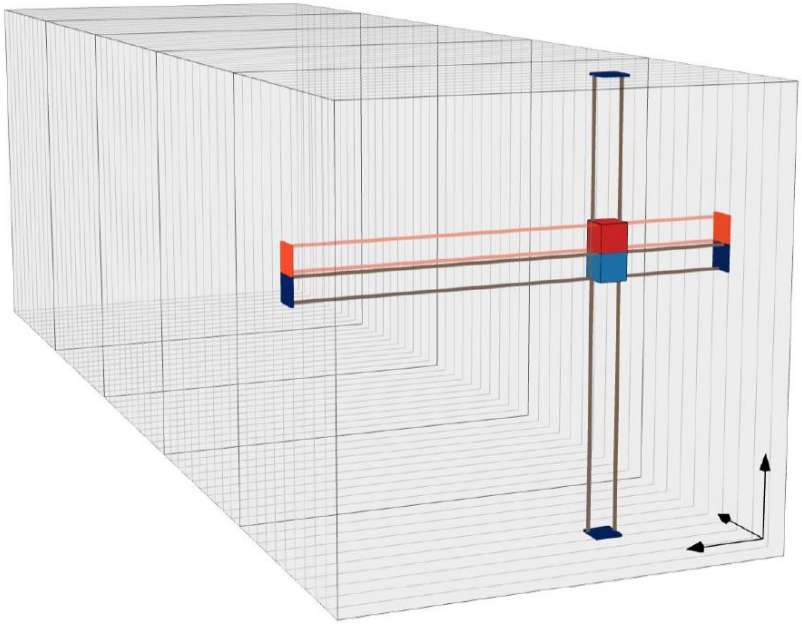




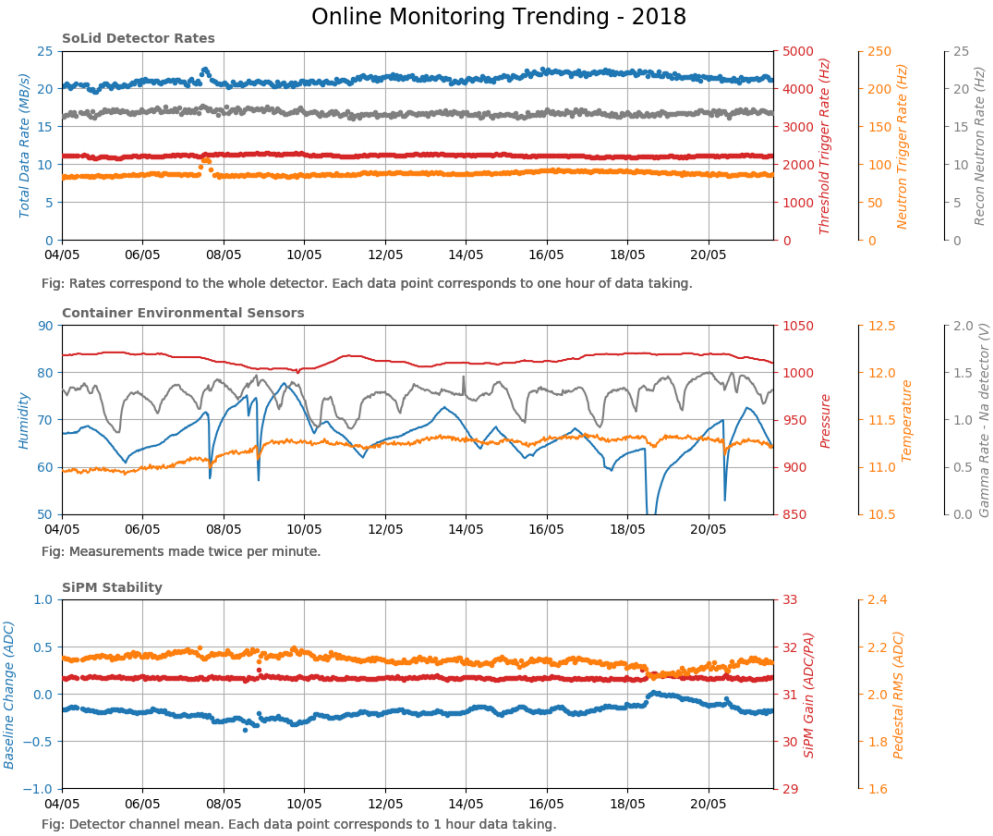


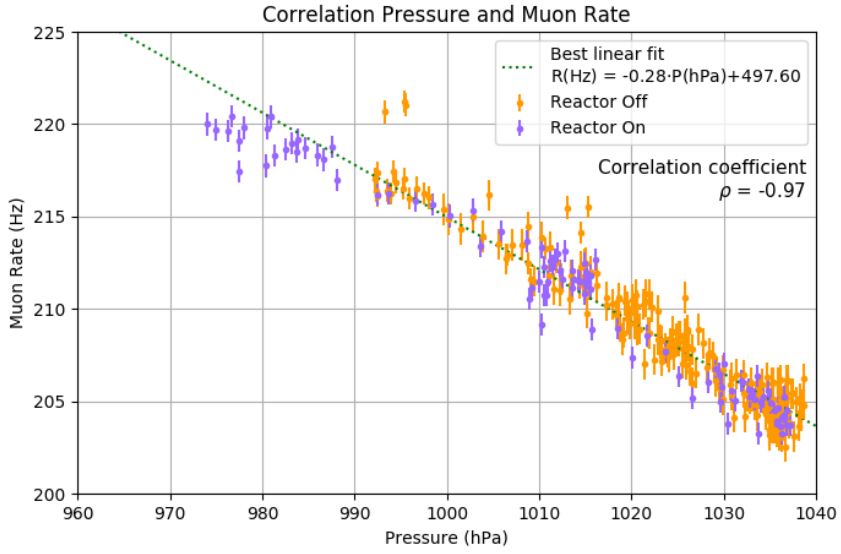
Data taking and stability

- **Stable** data taking since February → Highly stable for both reactor on and off
- **Online**, live, remote **detector monitoring**
- Online event reconstruction for subsample of data
- **Physics variables available online**



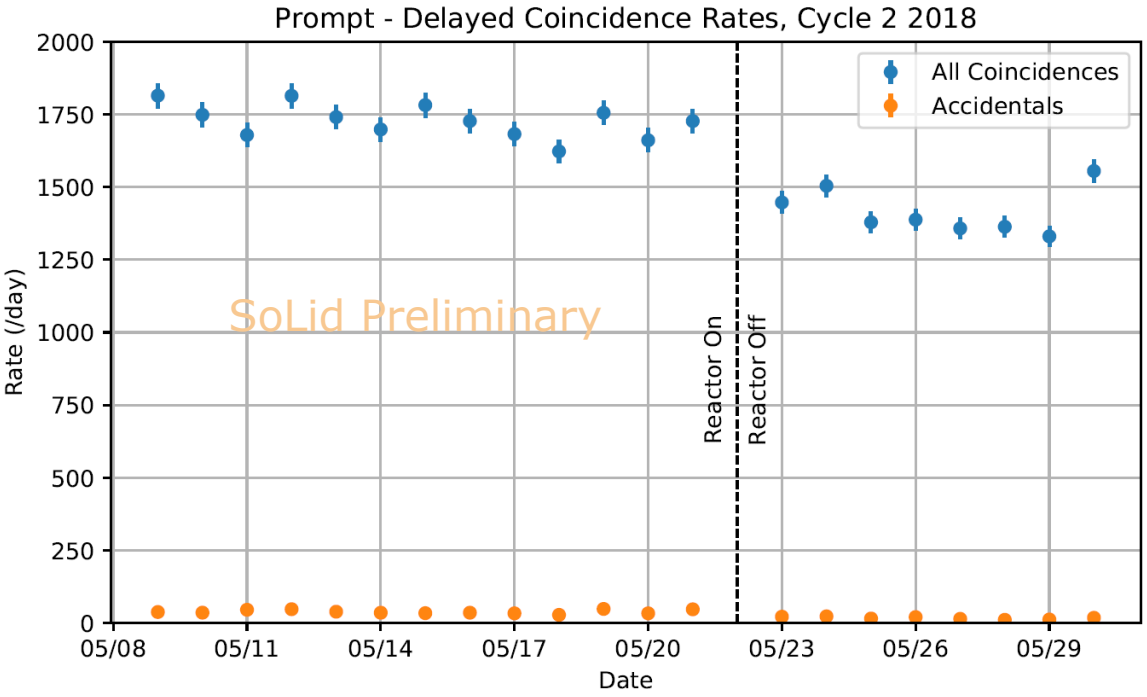
Prompt-Delayed Coincidence Candidate - 2017/12/05, 00:07:26

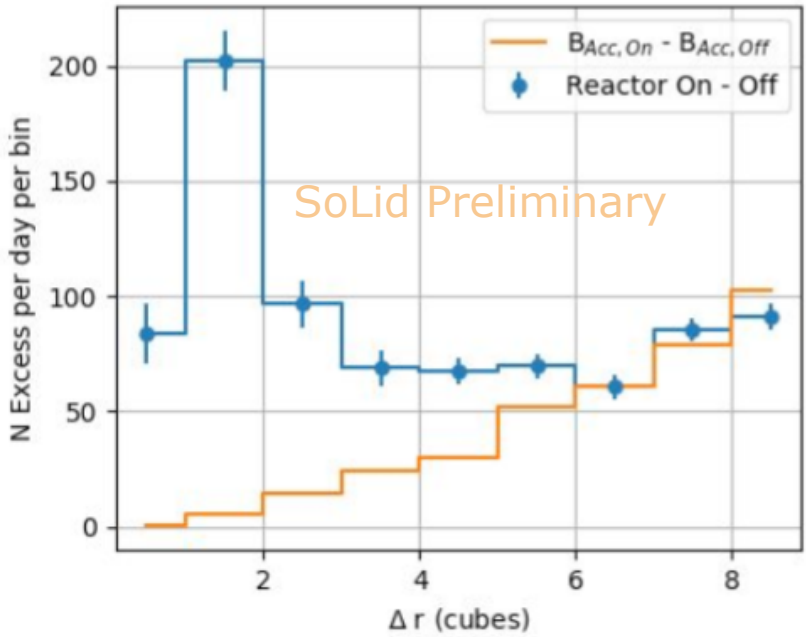


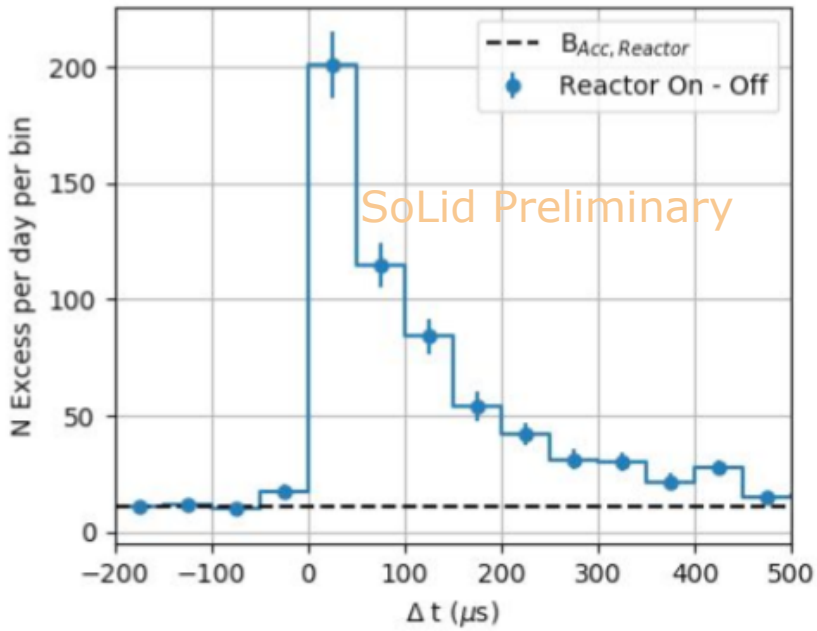


First IBD like events

- Preliminary rate monitoring based on minimal cuts:
  - Timing, topology, μ veto, energy
- Significant IBD-like rate during reactor ON period
- Behaves according to what is expected
  - Spatially confined
  - Time difference consistent with thermalized n capture



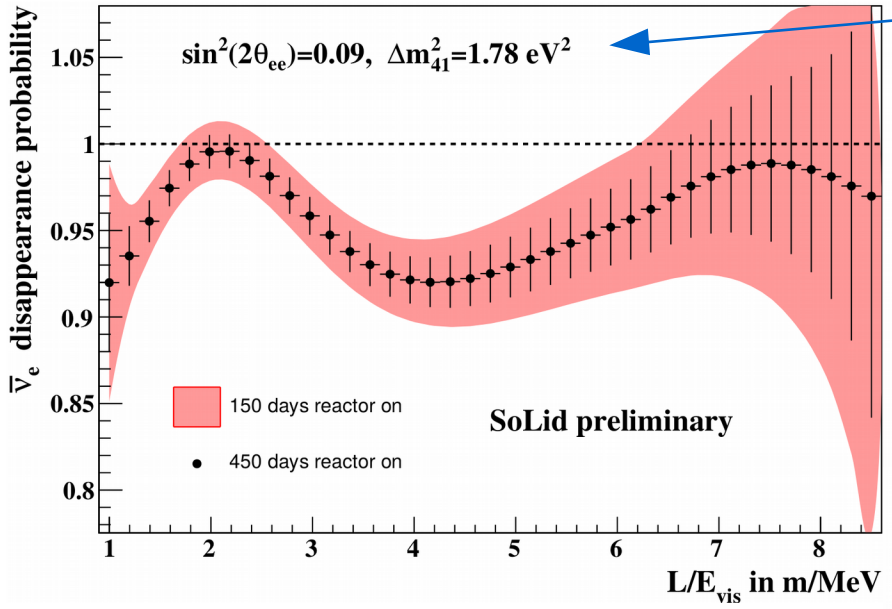


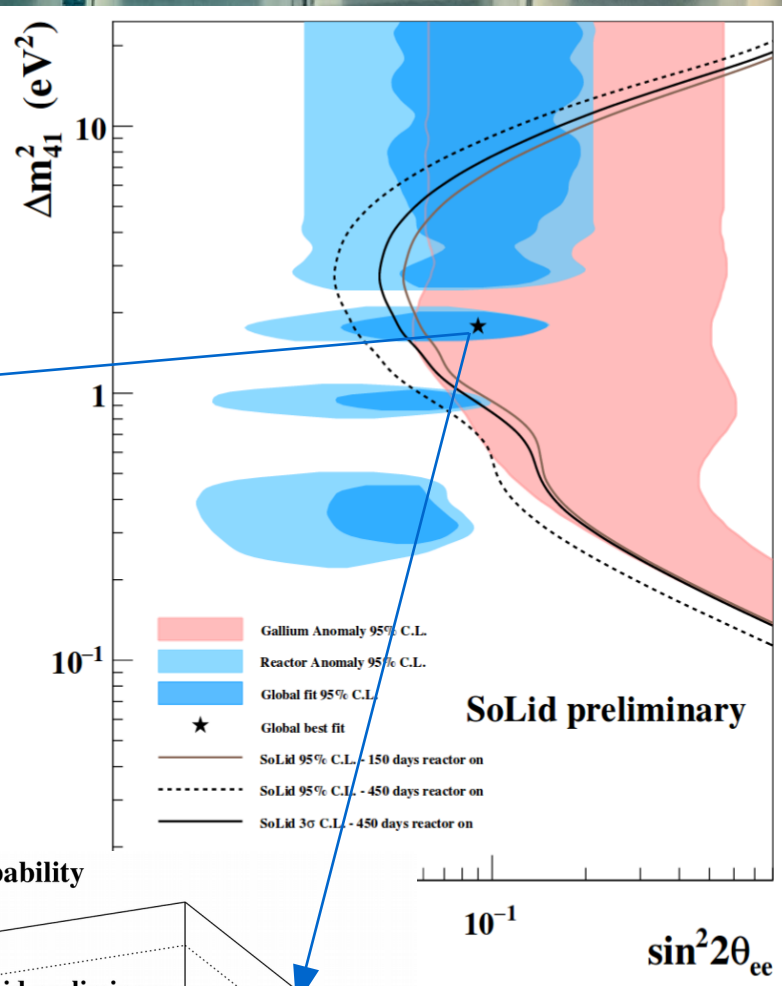


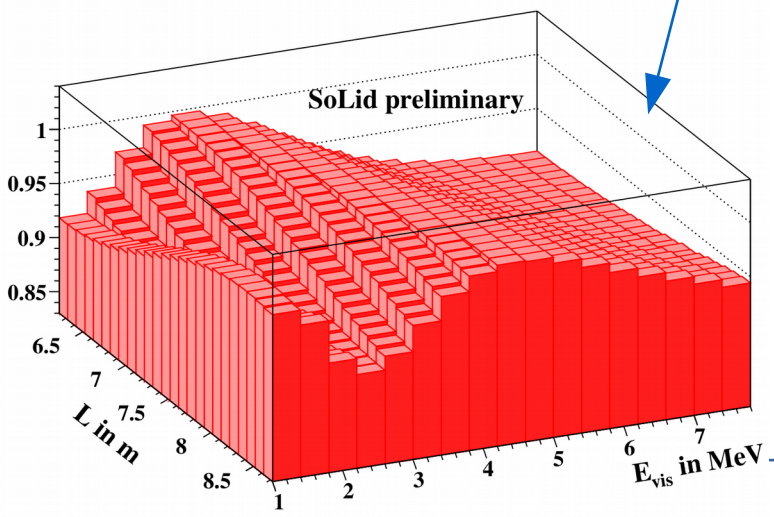
- ***Expected physics results***

Expected physics results

- Baselines: 6 – 9 m
- Energy resolution 14% / √E
- IBD eff: 30%
- Thermal power: 60 MW
- S:B of 3:1 5 Modules
- 450 days of reactor ON







New measurement of **ν spectrum** of ^{235}U

On track for first physics result around the end of the year, beginning of next year

Summary

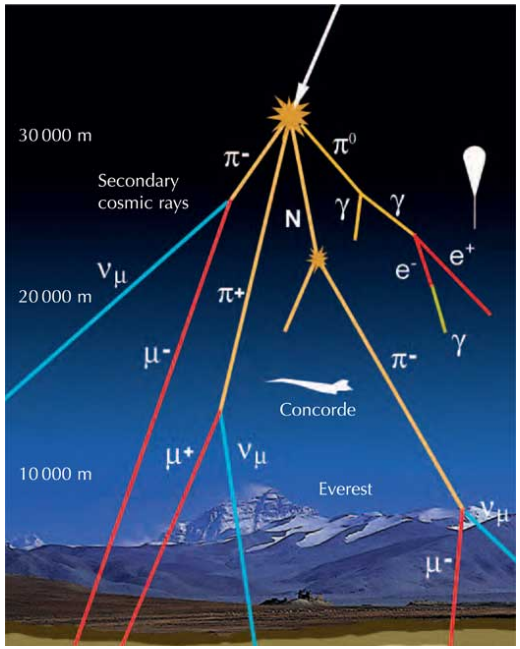
- **Construction of phase 1 (1600 kg) completed**
- **Commissioning at BR2 research reactor finished in February 2018**
- **First calibration results indicate good detector performance**
  - SiPMs equalized at the 1% level
  - LY > 60 PA/ MeV
  - Neutron trigger efficiency > 70 %
- **Data taking** in physics mode ongoing
  - ~ aiming for 150 days of reactor ON using 2018 dataset
  - + data in 2019 -2020
- SoLid observes IBD-like events
- First **physics results** expected by the end of **2018, beginning of 2019**

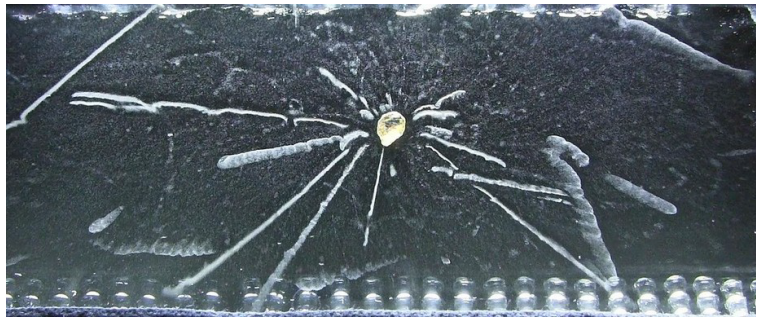
Thanks for your attention

Stay tuned !

BACK UP

Backgrounds





Muon induced

- Fast neutrons from spallation
- Stopping μ's (with Michel e^-)
- Cosmogenic isotopes (e.g. ^{9}Li, ^{8}He)

Countermeasures:

- ✔ Shielding/underground lab
- ✔ Active veto
- ✔ Pulse Shape Discrimination (PSD)

Reactor induced

- Neutrons (fast & slow)
- γ's from n captures

Countermeasures:

- ✔ Shielding
- ✔ PSD
- ✔ **Topology**

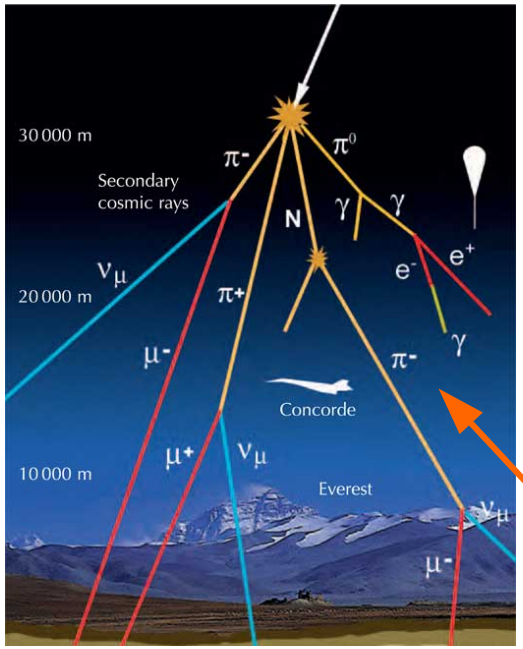
Radioactivity

- Thorium/Uranium
- Radon/Argon
- Potassium

Countermeasures:

- ✔ Material radiopurity
- ✔ **Topology**

Backgrounds



Muon induced

- Fast neutrons from spallation
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Countermeasures:

- ✓ Shielding/underground lab
- ✓ Active veto
- ✓ Pulse Shape Discrimination (PSD)

MEASURED DURING REACTOR OFF PERIODS

Radioactivity

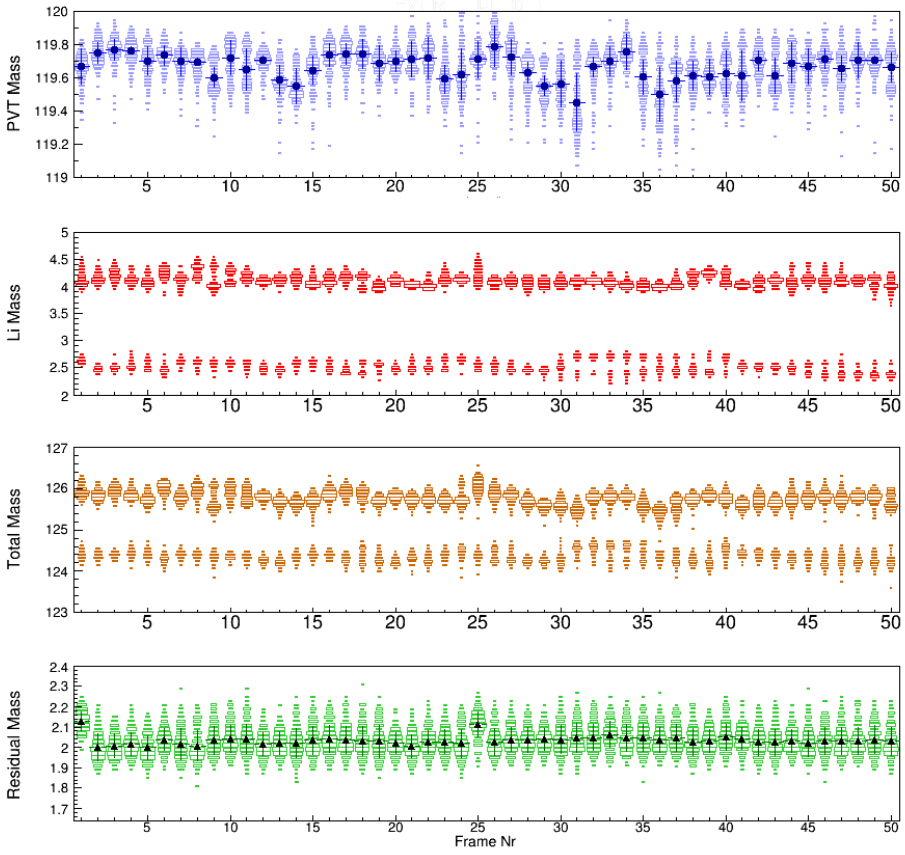
- Thorium/Uranium
- Radon/Argon
- Potassium

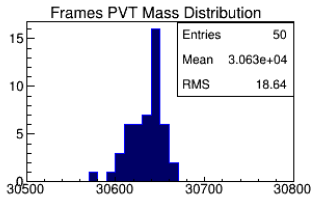
Countermeasures:

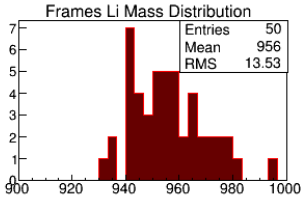
- ✓ Material radiopurity
- ✓ **Topology**

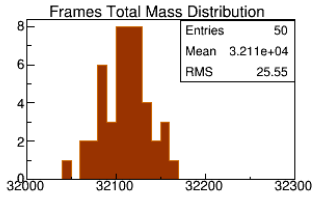
Quality assurance

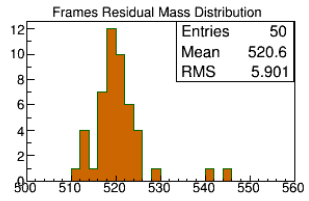
- How to guarantee a good and homogeneous response of more than 12000 cubes?
  - → Quality assurance procedure











Preparation of cubes

Control and documentation of materials of each cube

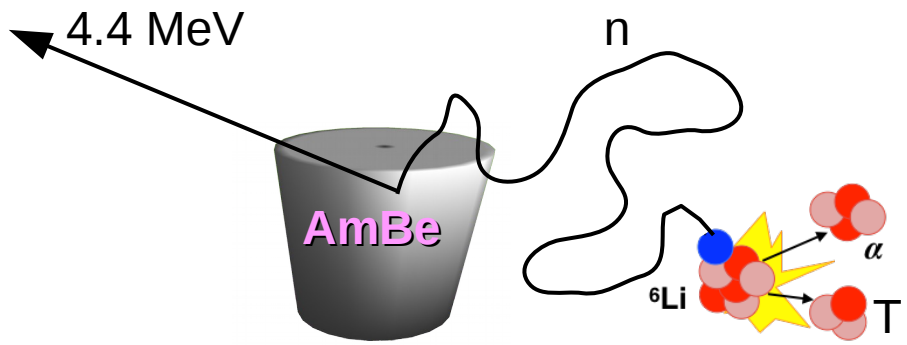
Frame construction

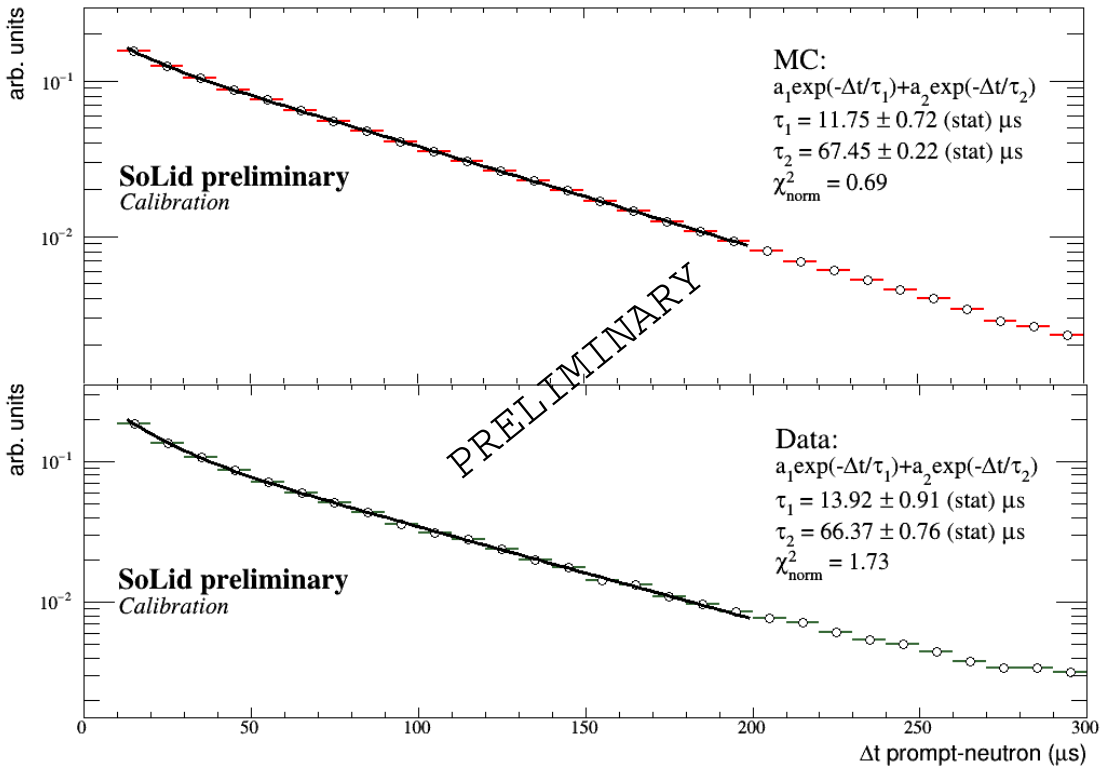
Validation of response with a first calibration

Frames assembled into modules

Neutron capture time

- Using AmBe source
- ~57% of neutrons emitted always with a 4.4 MeV γ
- Use 4.4 MeV γ to tag neutrons
- Look for a n capture on ZnS after the γ
  - Precise measurement of n capture time
  - → Comparison with MC
  - → Excellent agreement
- Validated with muon induced neutrons





Resources for calibration

- Neutron sources: AmBe (~4 MeV) +^{252}Cf (~2MeV)
  - Neutron rate **calibrated at the 1% level** at the National Physical Laboratory (UK)
- Gamma sources:

Source	^{22}Na	^{137}Cs	^{207}Bi	^{60}Co	n-H (AmBe/Cf)	AmBe
Energy [MeV]	2x0.511 1.27	0.667	0.57 1.064 1.77	1.17 1.33	2.2	4.44

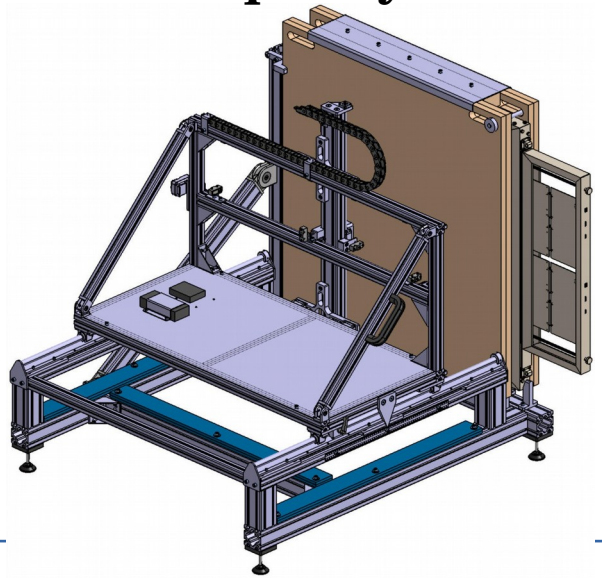
- Muons at high energy

SoLid Calibration systems

Double calibration: **during construction** and **in-situ**

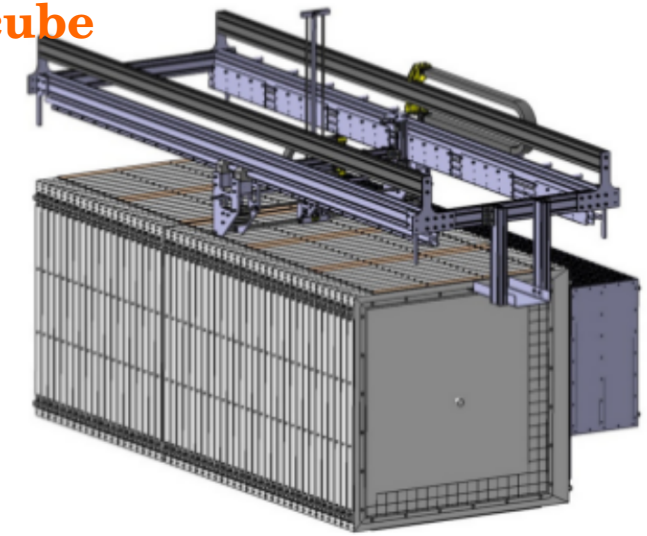
CALIPSO system

- **Individual** plane calibration
- Automated robot to place **radioactive sources in front of each cube**
- Calibration during detector construction
- Preliminary detector performance
- **Used for quality assurance**



CROSS system

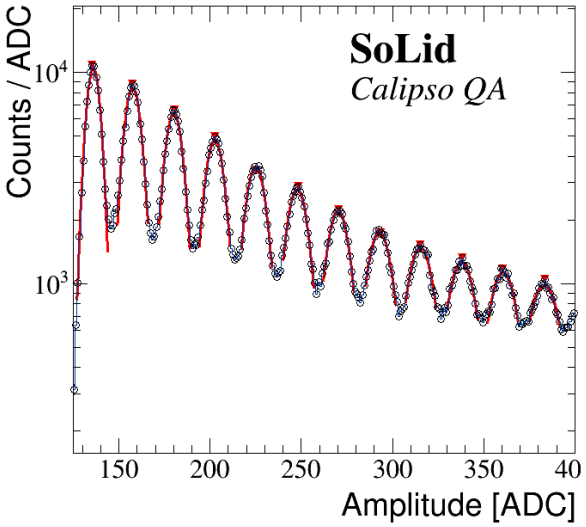
- **Global** detector calibration
- Automated robot to place **radioactive source between modules**
- Calibration during reactor OFF periods
- Detailed detector performance
- **Energy scale + n capture** efficiency **per cube**

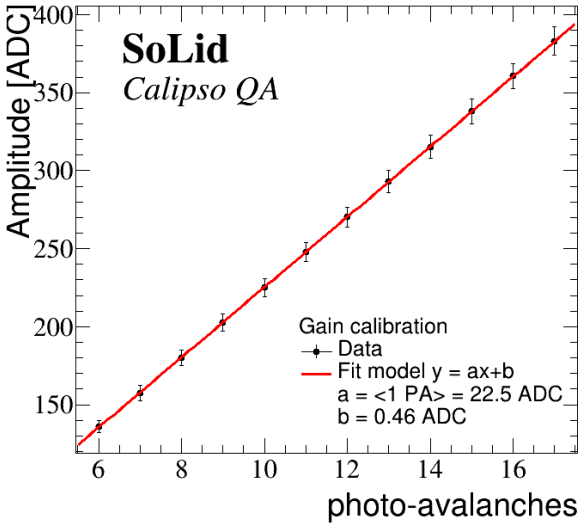


+ Muon calibration

Energy scale with ^{22}Na source

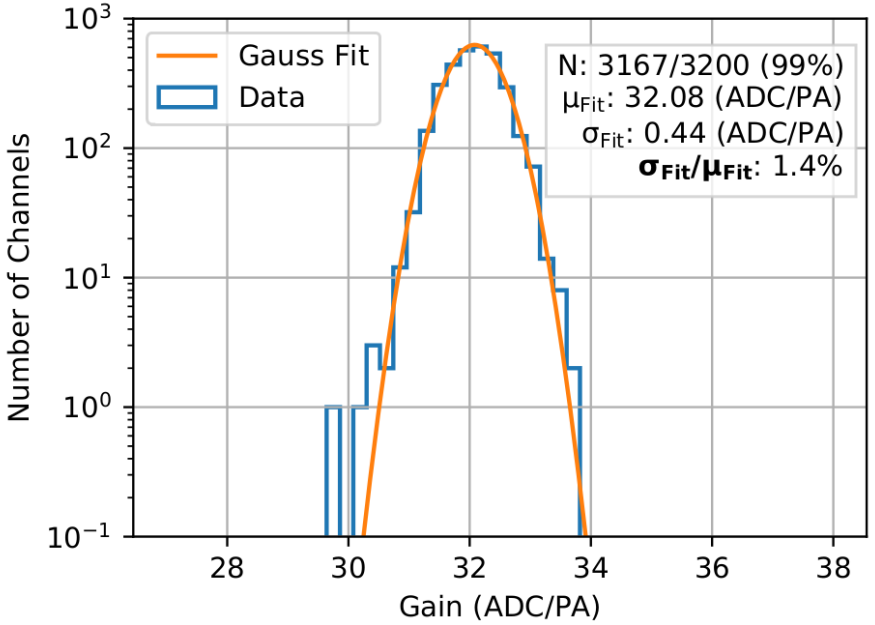
- SiPMs are **equalized** (gains) at **the 1 % level**!
  - Crosscheck with data: ADC → PA





Individual PA arrivals can be identified

SiPM response is very linear!



- The total amplitude per cube (A_{ij}) is found summing the amplitudes of the 4 SiPMs associated to each cube

$$A_{ij} = \frac{A_i^t}{g_i^t} + \frac{A_i^b}{g_i^b} + \frac{A_j^l}{g_j^l} + \frac{A_j^r}{g_j^r}$$

t,b,l,r for the position of the SiPM in the frame

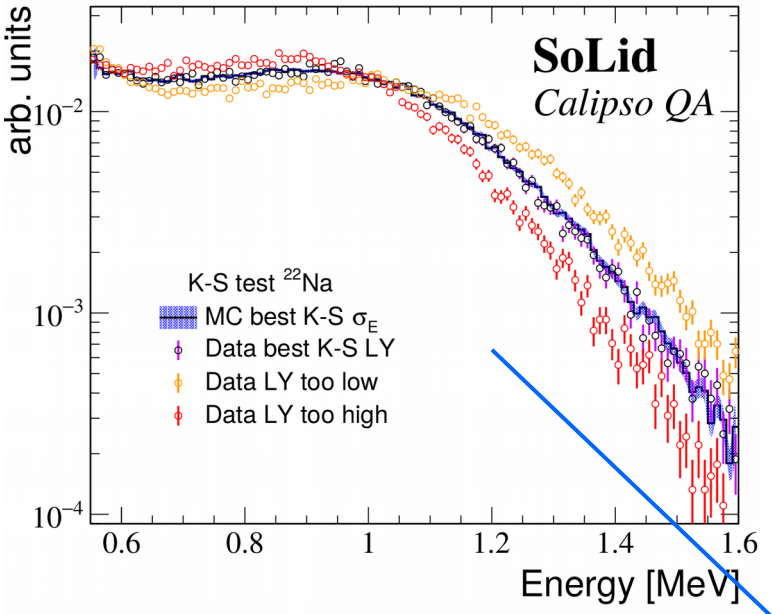
g the gain of each SiPM

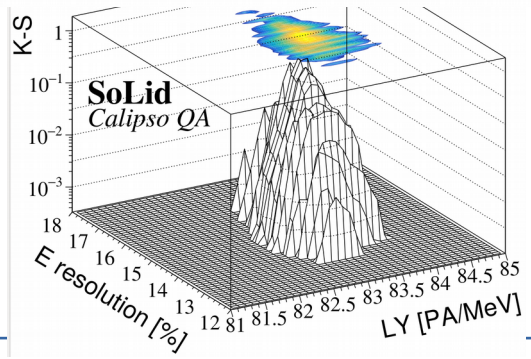
Energy scale with ^{22}Na source

- No photo-peak in PVT cubes → using Compton edge
  - **Two** independent **approaches** to assess the energy scale

Kolmogorov S test (KS)

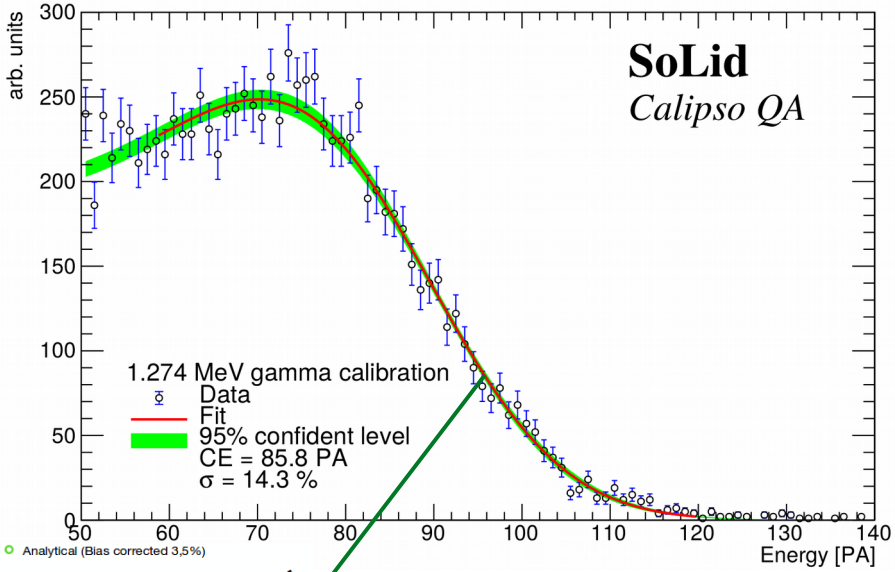
Compare measured sample to a Geant4 MC sample

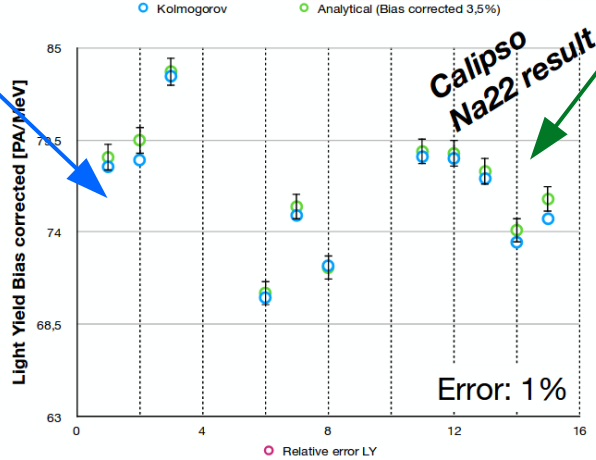




Analytical fit

Use pdf based on Klein-Nishina cross-section





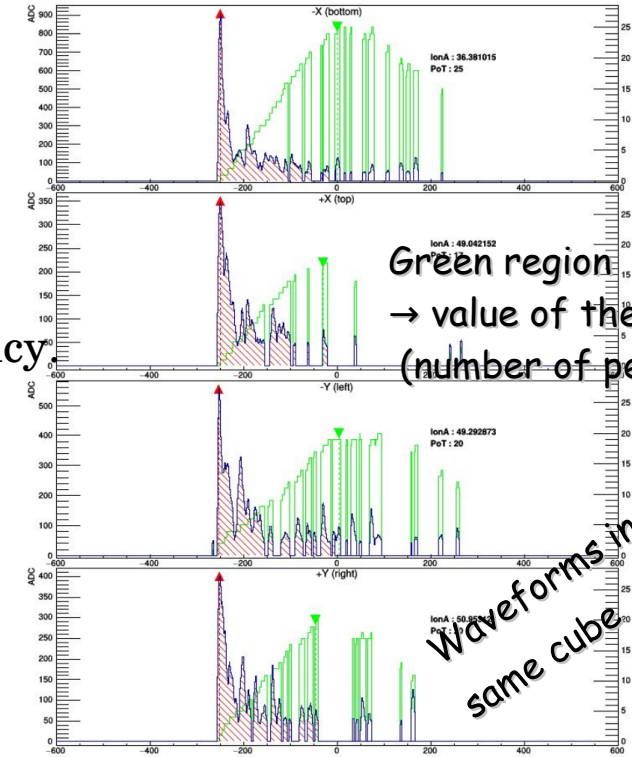
Agreement between both methods at the 1% level!

Neutron trigger deployment

- Dedicated **neutron trigger** for neutrino detection.
  - Based on **peak counting**.
  - Combined with **large buffer** for prompt detection→ high IBD efficiency.
- Deployed with CALIPSO
  - **Fulfills** SoLid **requirements**

  (n trigger eff > 60 %)

A n event using AmBe source



Integral distribution