Status of the SoLid experiment

Search for Oscillations with Lithium-6 detector at the SCK-CEN BR2 reactor

Conseil Scientifique IN2P3

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for the SoLid Collaboration

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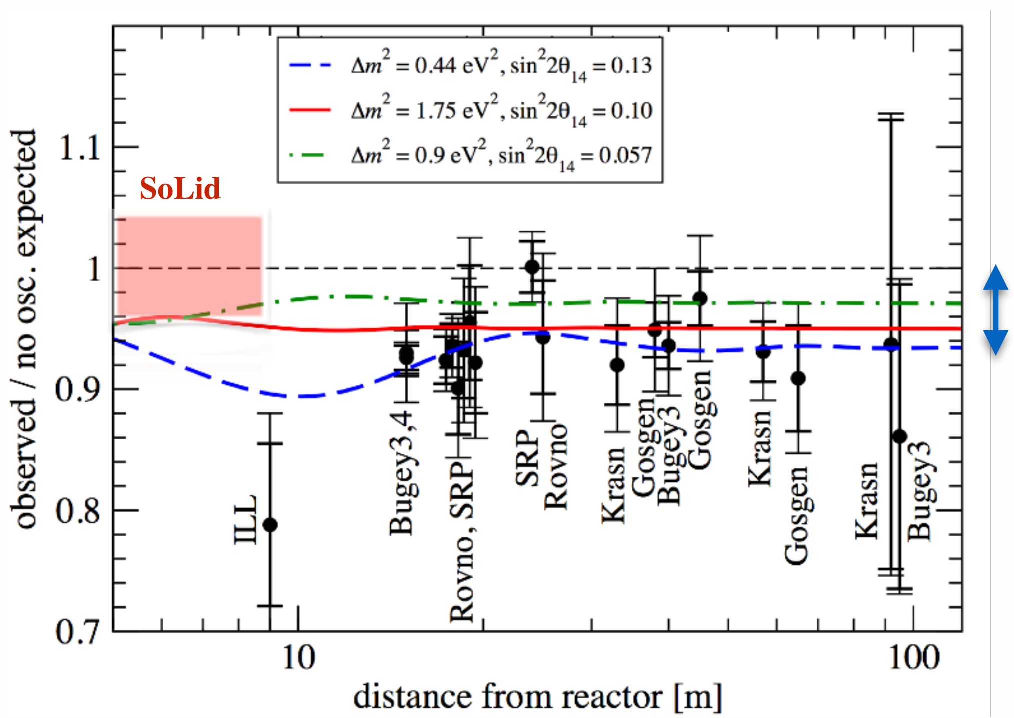
Physics Motivations

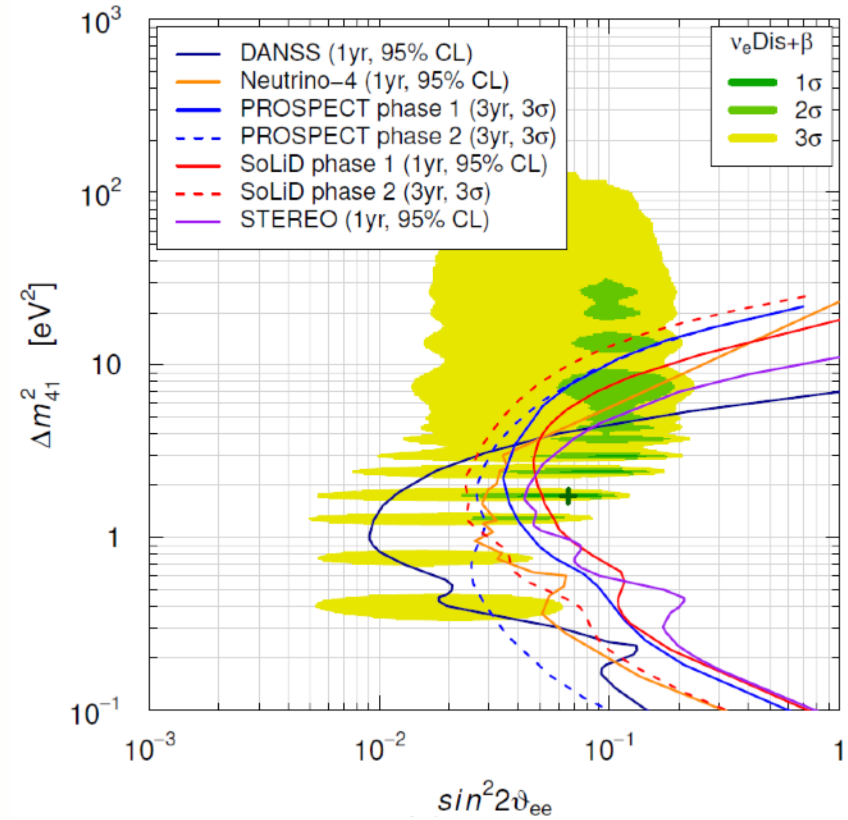
- Reactor Antineutrino Anomaly (RAA) ➔ Sterile Neutrino search at eV-scale

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



6% deficit
2.7 σ

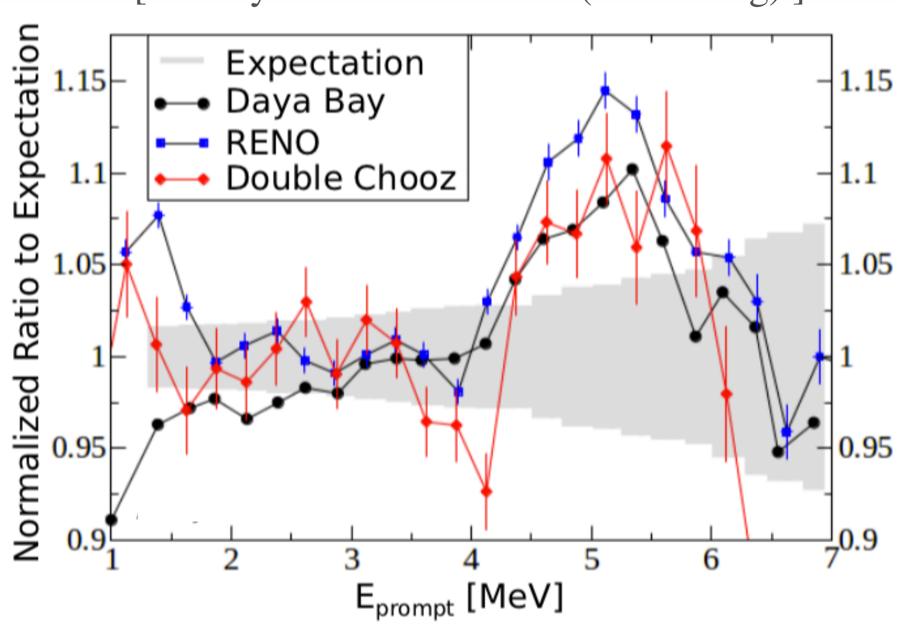
[Gariazzo et al., JHEP06 135 (2017)]



(3+1) model allow to reproduce both Reactor and Gallium Anomaly

- Antineutrino energy spectrum deviation (4-6 MeV), observed by all θ_{13} experiments

[A. Hayes - Neutrino 2018 (Heidelberg)]



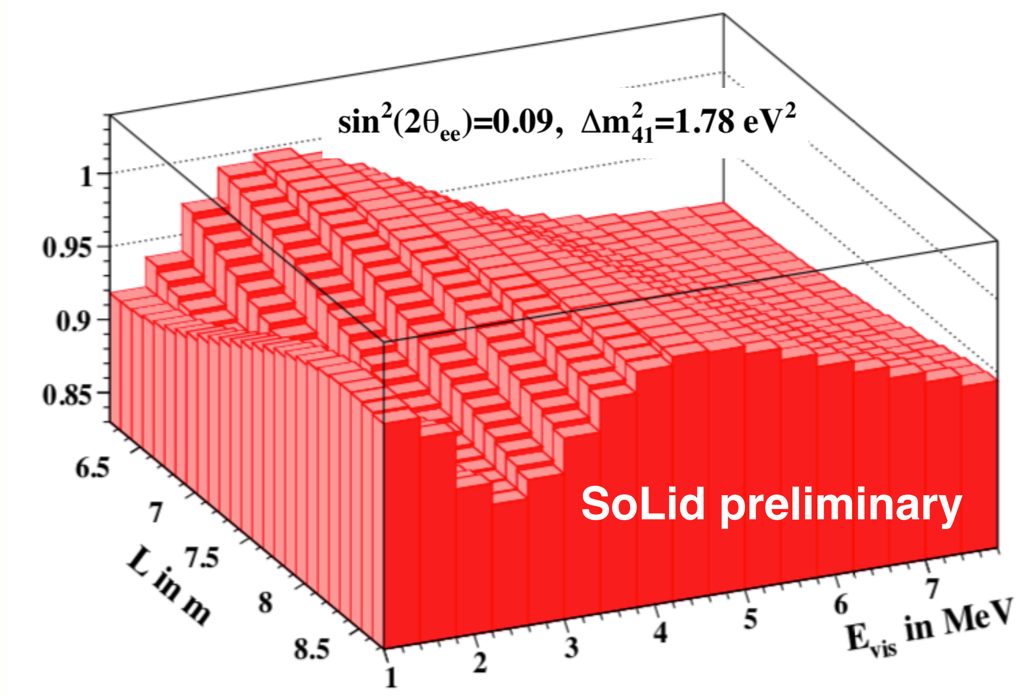
- Flux prediction (fission yields, beta spectrum shape …) and detector energy response linearity scrutinized
- SoLiD will procure direct ^{235}U antineutrino spectrum

Experimental Chalenges

2D Neutrino Oscillometry

Search for Absolute/Relative Energy Spectrum & Rate distortion with distance

Using identical detectors at different baselines



- **Detector(s)**
  - High Energy resolution: Large statistics, low systematics
  - High Spatial resolution: Good vertex reconstruction
  - Homogenous / well inter-calibrated
  - Effective background rejection: Low overburden (on surface), Reactor radiation (neutron, γ)
- **Reactor**
  - Compact core
  - Access as close as possible
  - Security implications (access rights, safety issue, data transfert, ….)

Very Short Baseline Experiments (~10 m)

	Tech	Segmentation	Fuel	P_{th} [MW]	L (m)
STEREO	Gd-doped LS	1D (25 cm)	HEU	57	8.8 - 11.2
Neutrino-4	Gd-doped LS	2D (10 cm)	HEU	100	6 - 12
PROSPECT	Li-doped LS	2D (15 cm)	HEU	85	7 - 10
NEOS	Gd-doped LS	-	LEU	2800	23.7
SoLid	**Li screens - PS**	**3D (5 cm)**	**HEU**	**60**	**6.2 - 9.2**
DANSS	Gd-doped PS	2D (5cm)	LEU	3000	10.7 - 12.7

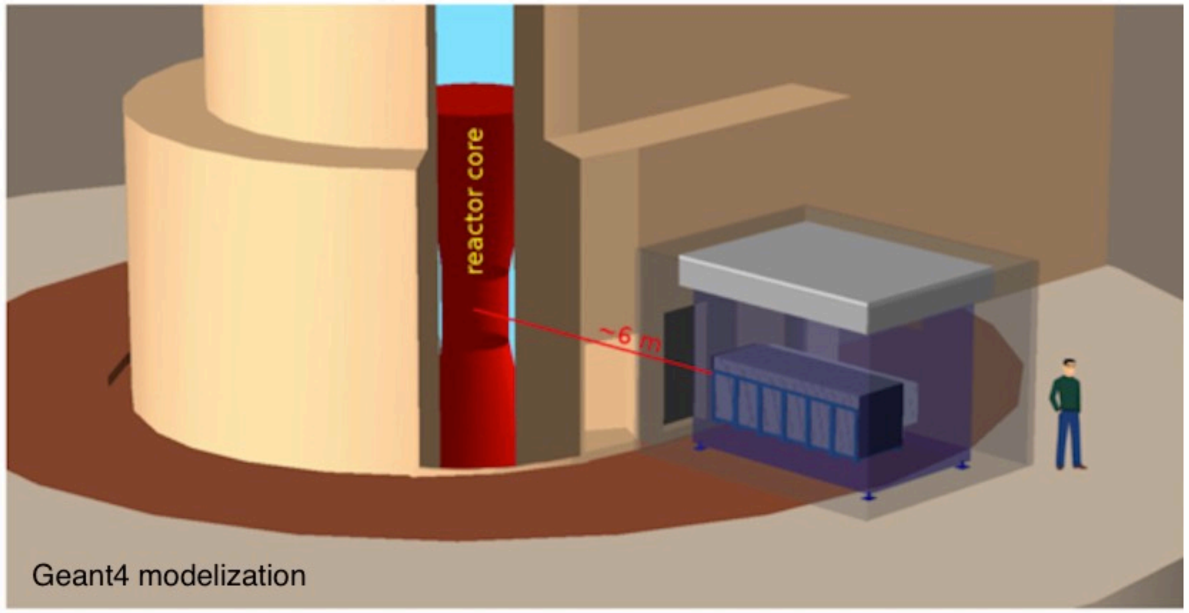
SoLid overview

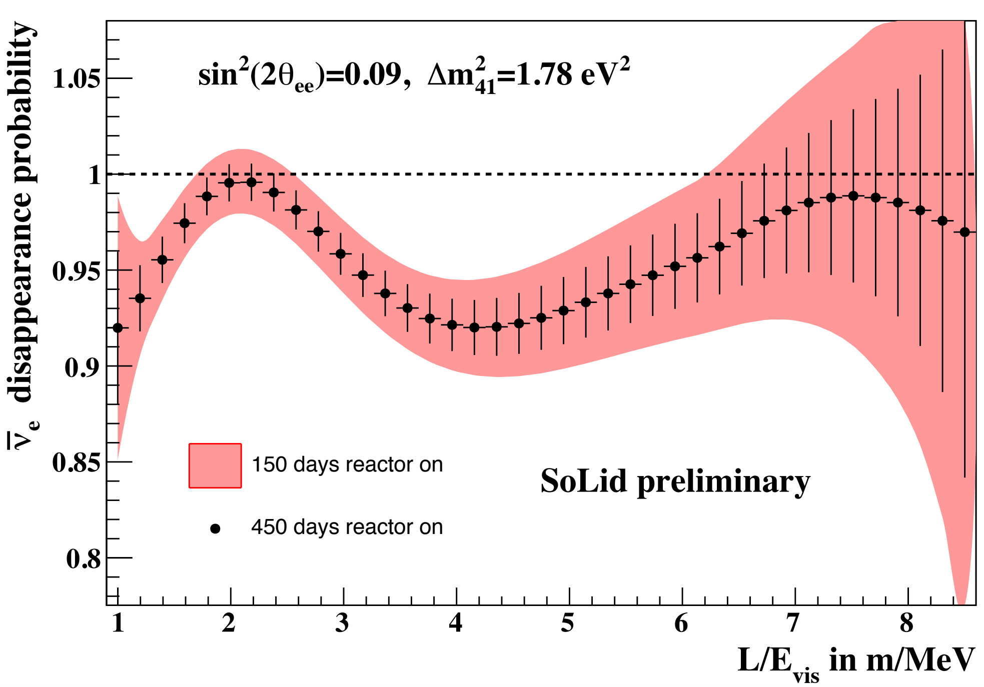
- Composite solid scintillator**s** (PVT/LiF:ZnS)

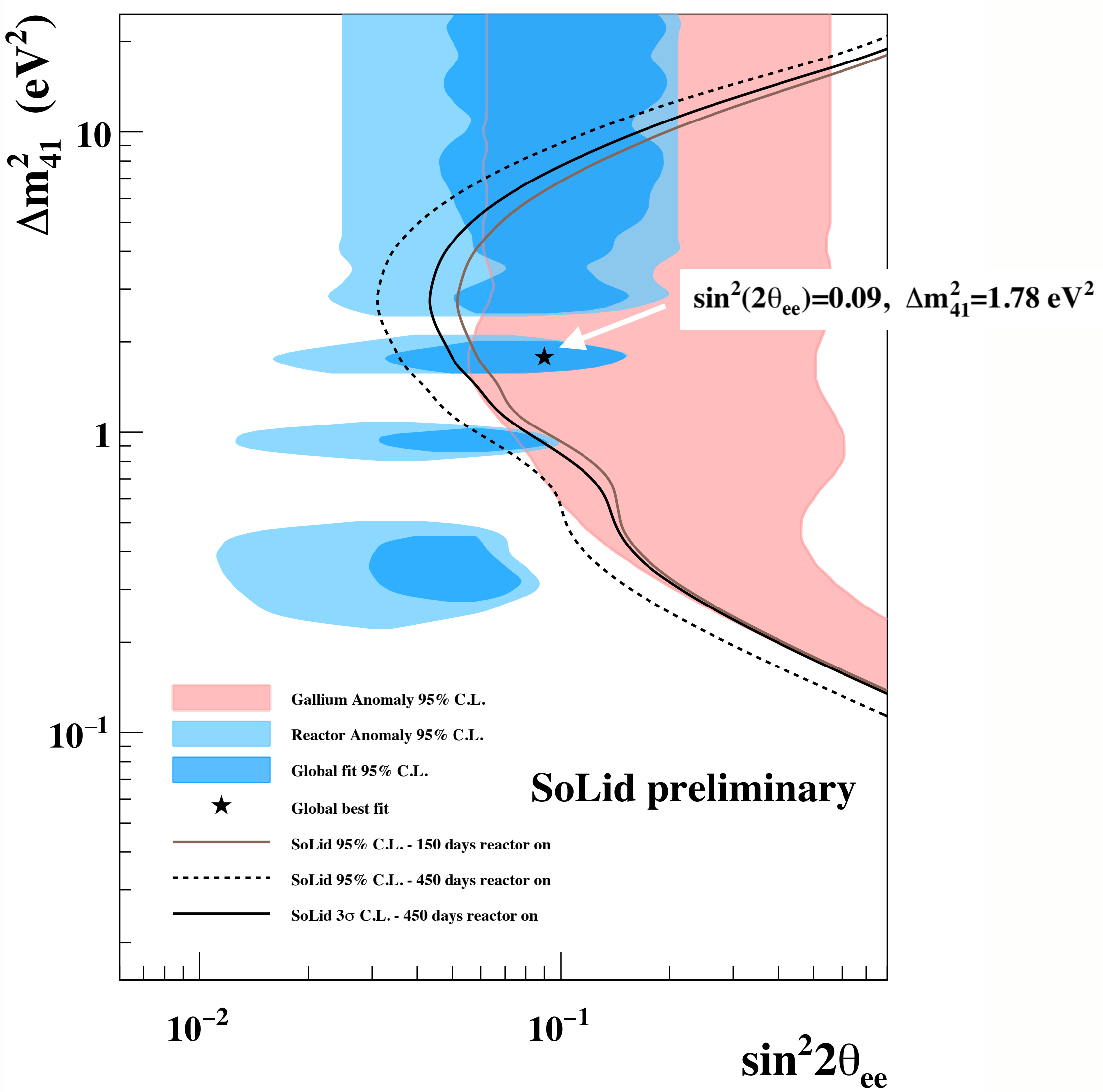
  1.6 t fiducial mass (highly segmented)

- BR2 reactor @ SCK-CEN (Mol, Belgium)

Parameters	**Objectives**
Baseline	6.2 - 9.2 m
Anti-neutrinos	~1200 int.d^{-1}
IBD efficiency	> 30 %
Threshold	200 - 500 keV
Signal/Background	~3
Energy resolution	< 14 % à 1 MeV
Systematic uncertainty	2.5 - 4.5 %





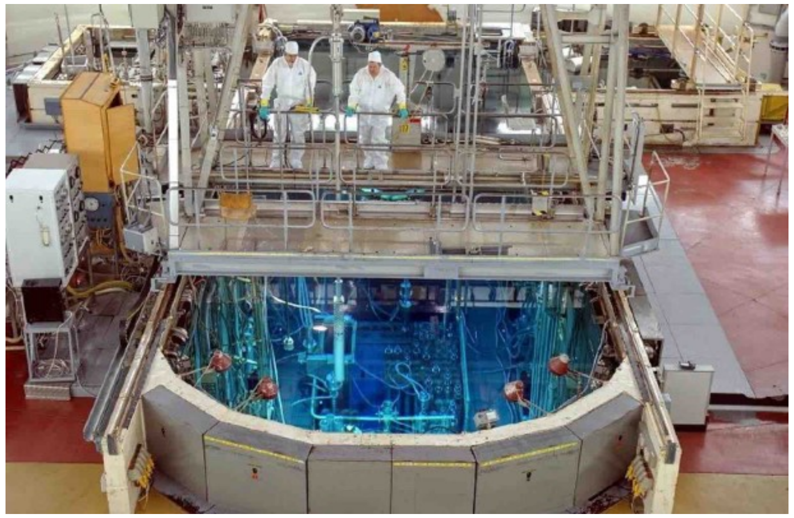


Belgian Reactor 2 @ SCK-CEN

- Major MTR-type reactors
  - Material testing/Isotopes production…
  - No others project in fondamental/particle physics
  - Non-proliferation : statutory tasks

- SCK-CEN collaboration
  - Technical support, funding (shielding, source, maointenance…)
  - Reactor calculation expertise
  - No time limitation

- Neutrino parameters
  - Compact Core : Φ_{eff} = 50 cm, h = 90 cm
  - Operating power : $P_{th} \sim 65$ (125) MW_{th}
  - Highly Enriched Uranium : 93% ^{235}U
  - Neutrino flux : $\sim 10^{19}\ \overline{\nu_e}/s$
  - Duty cycle : 150 days/year
  - Low overburden (10 mw.e) / Low reactor neutron and gamma fluxes

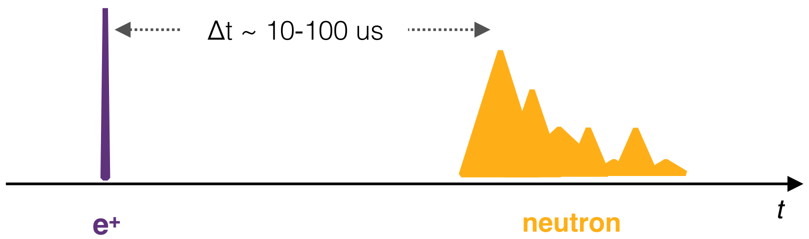


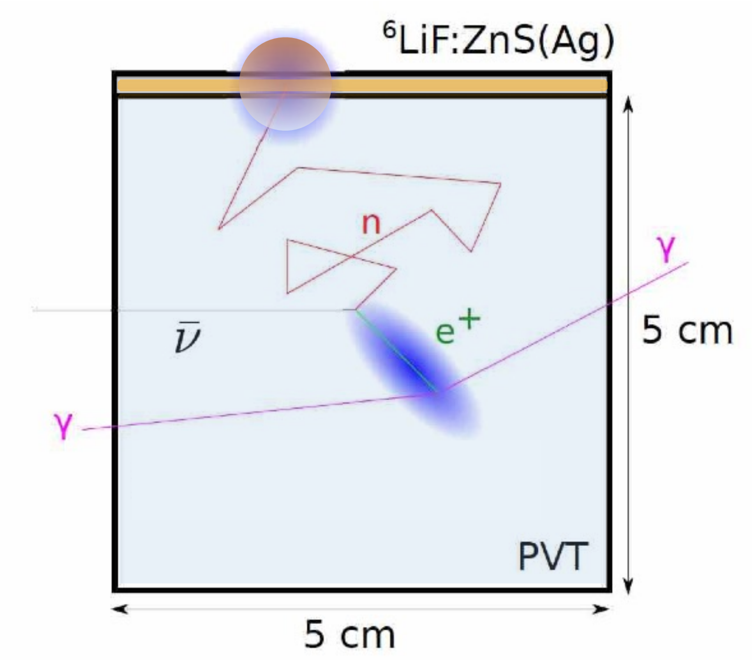
→ Critical after 1.5 year refurbishment (1/06/2016)
Power operation resumed in July 2016

Detection Principle : Composite scintillators

- Inverse Beta Decay (IBD) : $\bar{\nu}_e + p \rightarrow e^+ + n$

Reaction products detection within ΔT windows



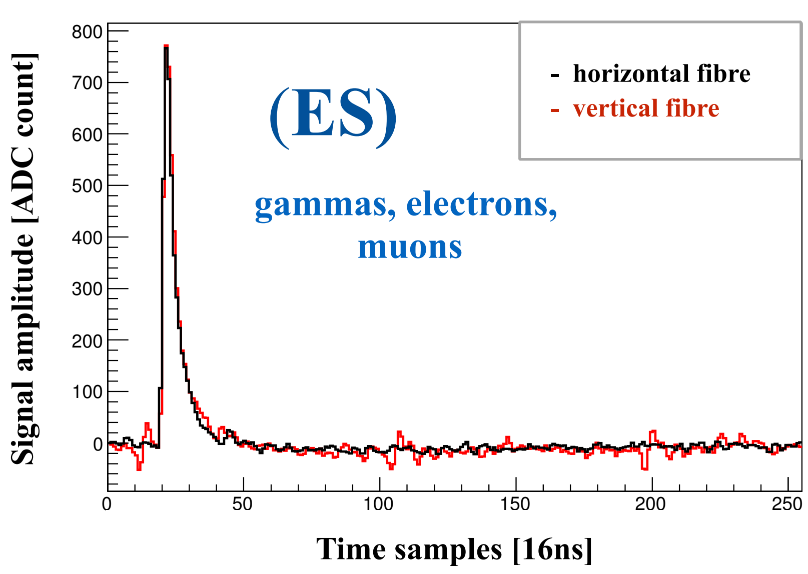


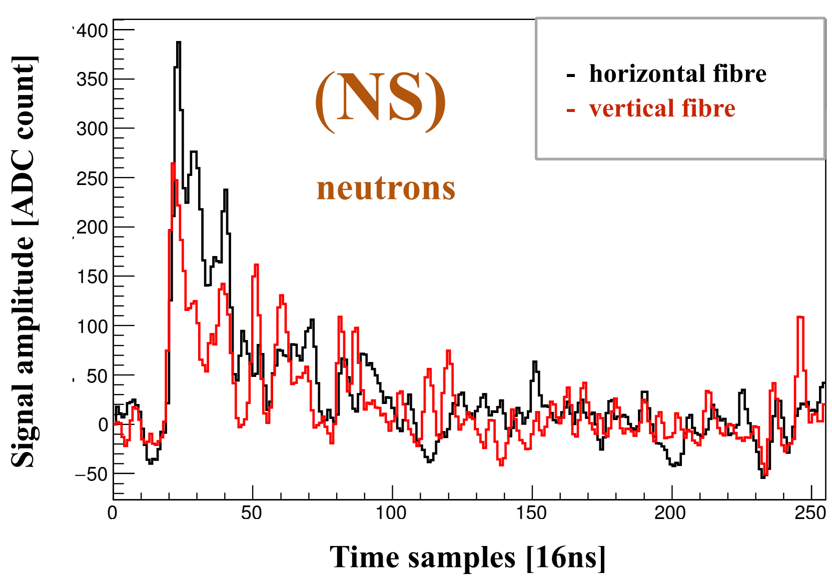
- Prompt positron signal in Polyvinyltoluene (PVT) $\rightarrow$ **ES**
- Delayed neutron capture in ^{6}LiF:ZnS screens $\rightarrow$ **NS**

$$n + {}^6Li \rightarrow {}^3H + \alpha \quad (4.8 \text{ MeV})$$

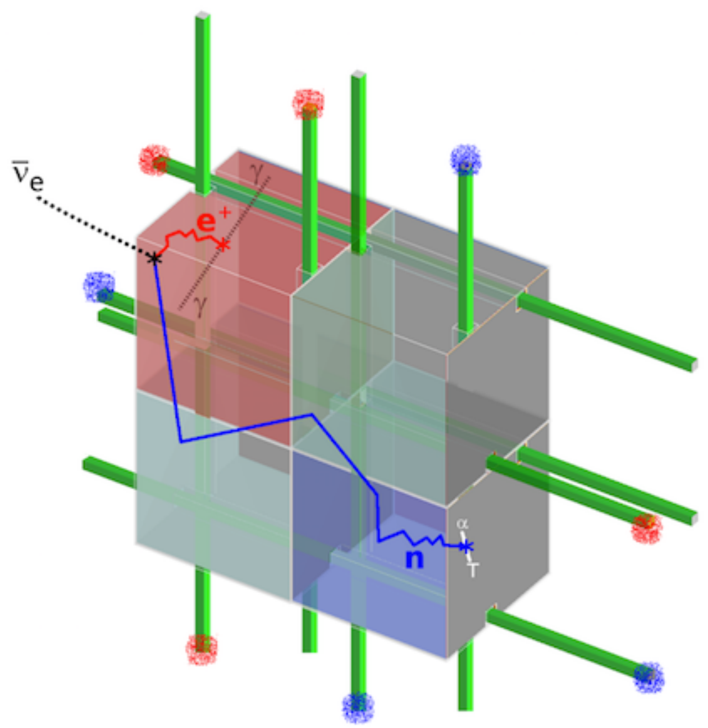
- Pulse Shape Analysis

⇢ Neutron Tag (trigger) !



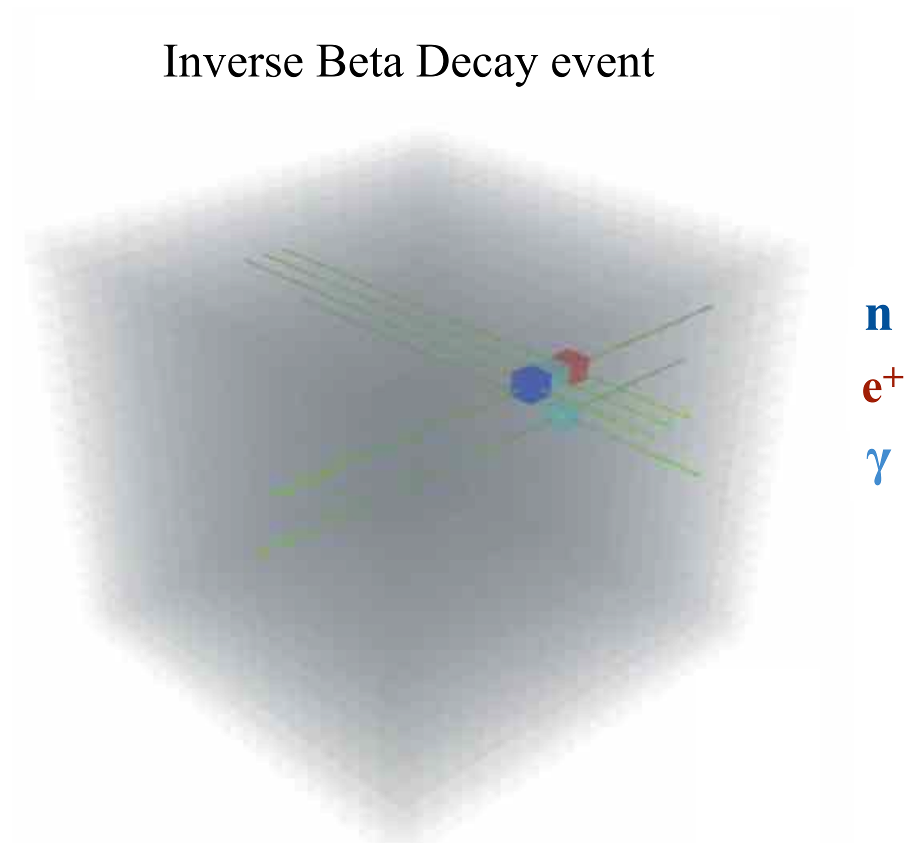


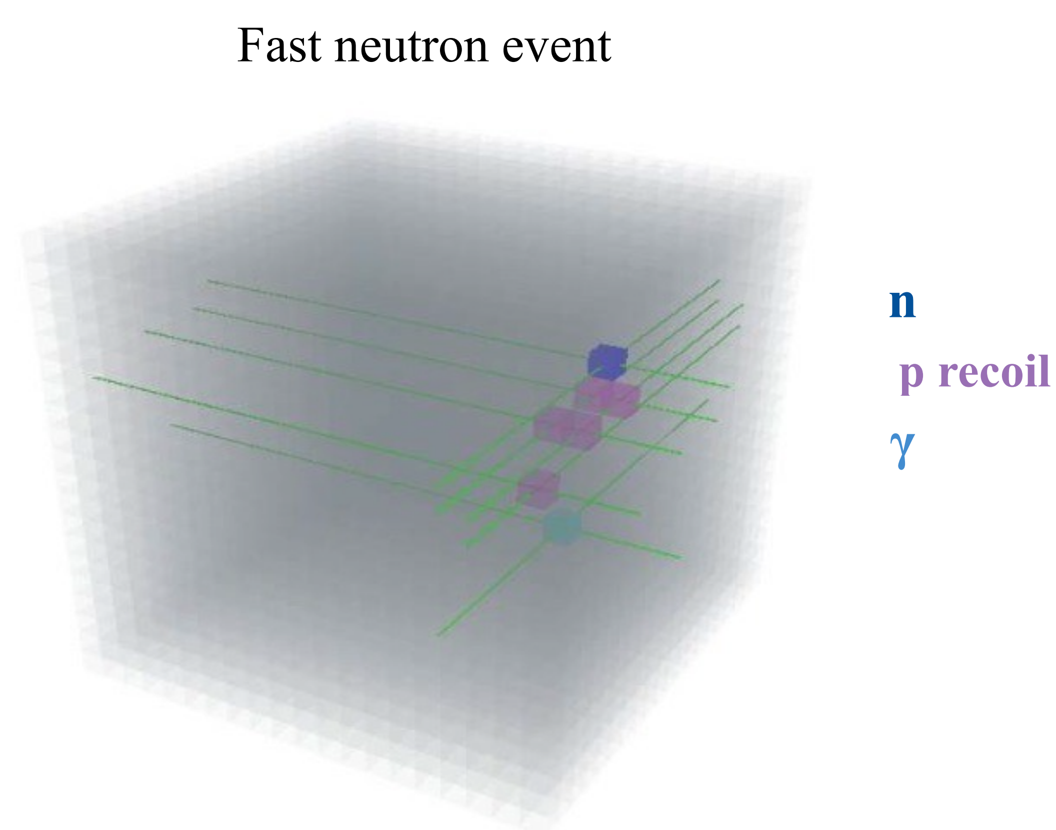
Detection Principle - High granularity (8 000 voxels/m³)



- Elementary cells [5x5x5 cm³] : PVT + ^{6}LiF:ZnS(Ag) layers
- Optically isolated with Tyvek wrapping
- Light collection by Wavelength Shifting Fibers [3x3 mm²]
- Read-out by Silicon PMs [Hamamatsu S12572-050]

- 3D topology reconstruction ⇢ Background identification/rejection !

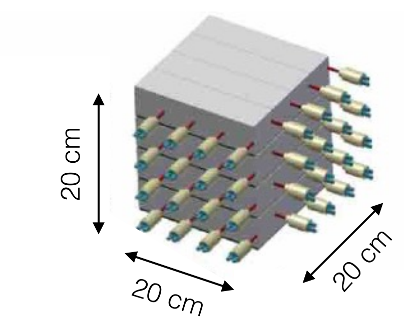




Project Timeline

NEMENIX

Proof of Concept

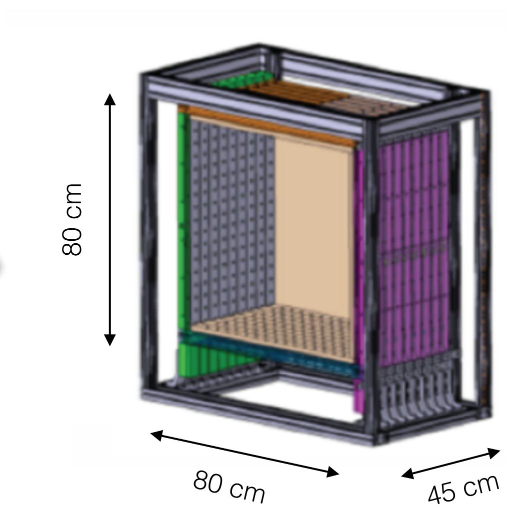


x 40

8kg - 64 voxels
32 channels

SM1

Real Scale System

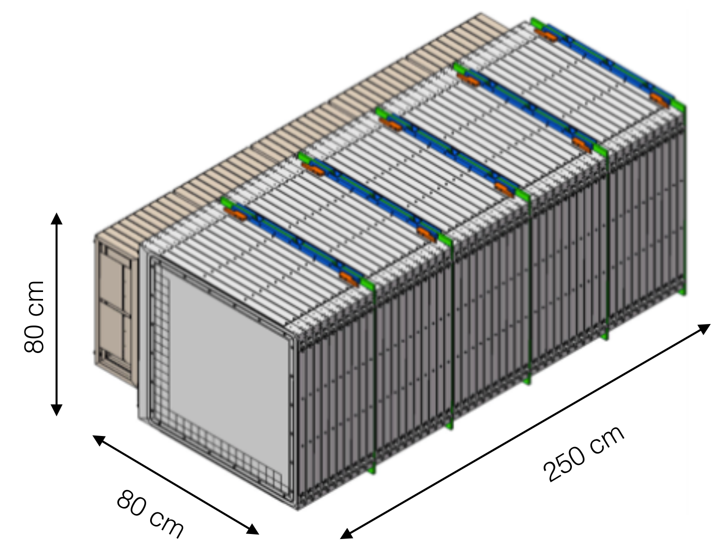


x 6

288kg - 2304 voxels
288 channels

SoLid

Physics Scale Detector



1.6 t - 12 800 voxels
3200 readout channels

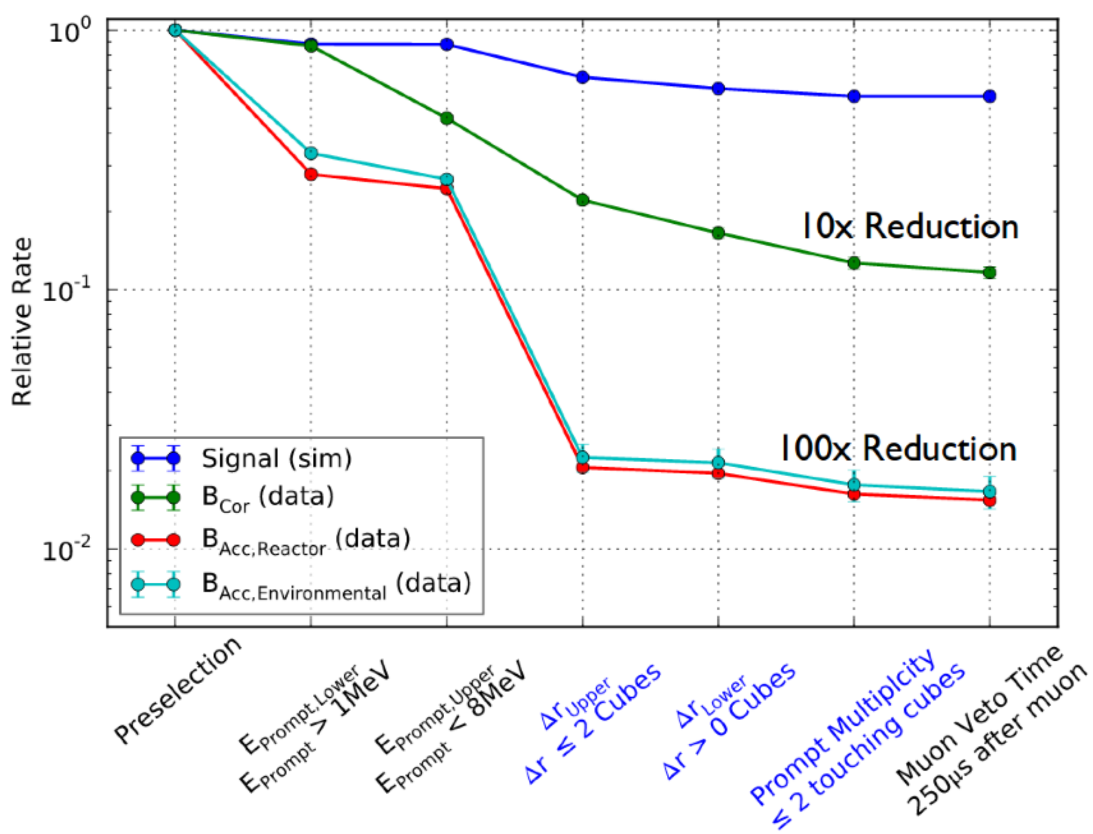
2013 **2014** **2015** **2016** **2017** **2018** **2021**

Physics Run

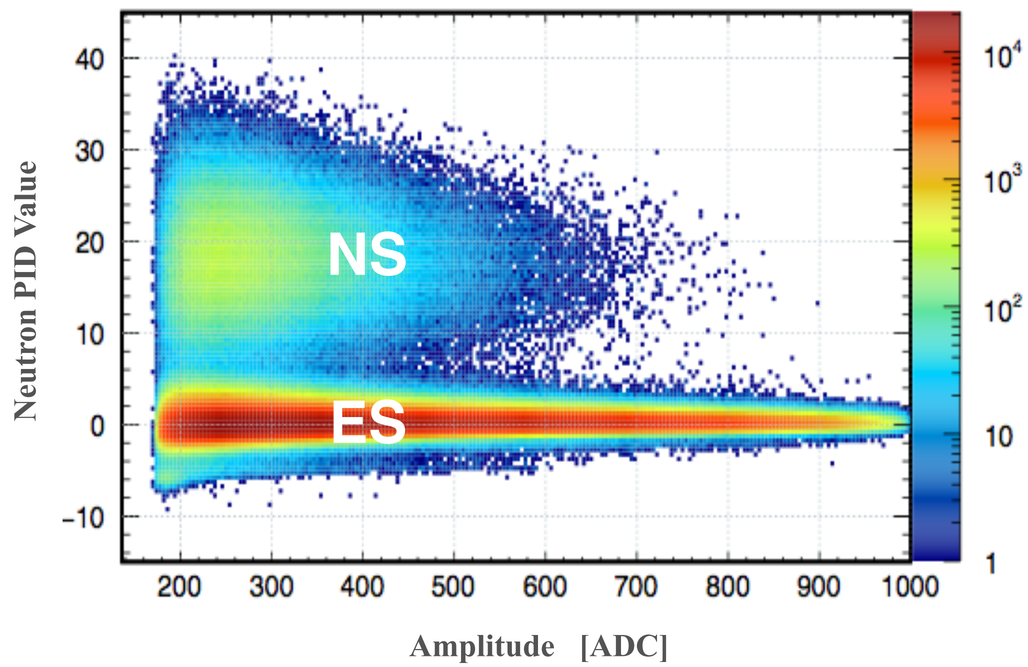
SM1 Prototype Highlights

- Data from February - April 2015
  - 2 days reactor ON / 1 month reactor OFF
  - Detection principle and scalability demonstrated despite very low neutron detection efficiency < 5%

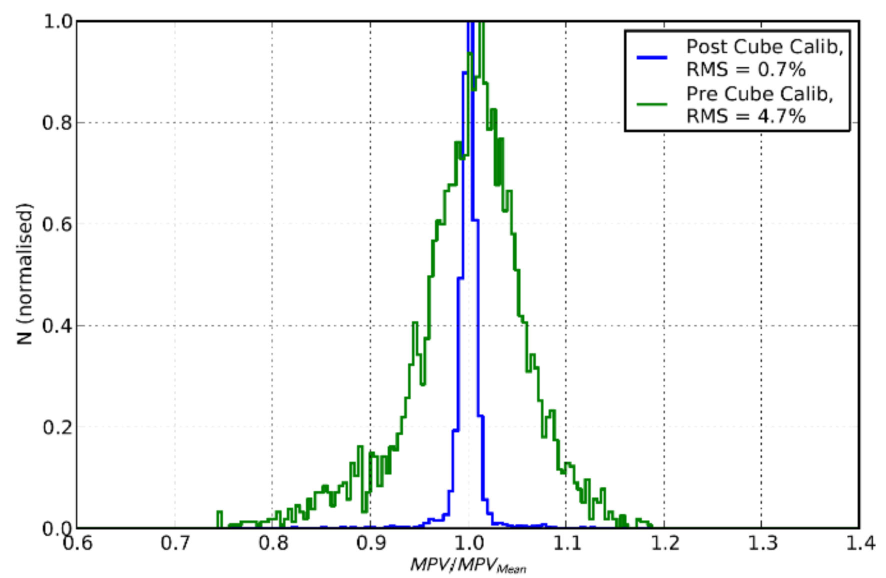
✓ Background rejection capabilities



✓ Pulse shape discrimination



✓ Muons tracking capabilities

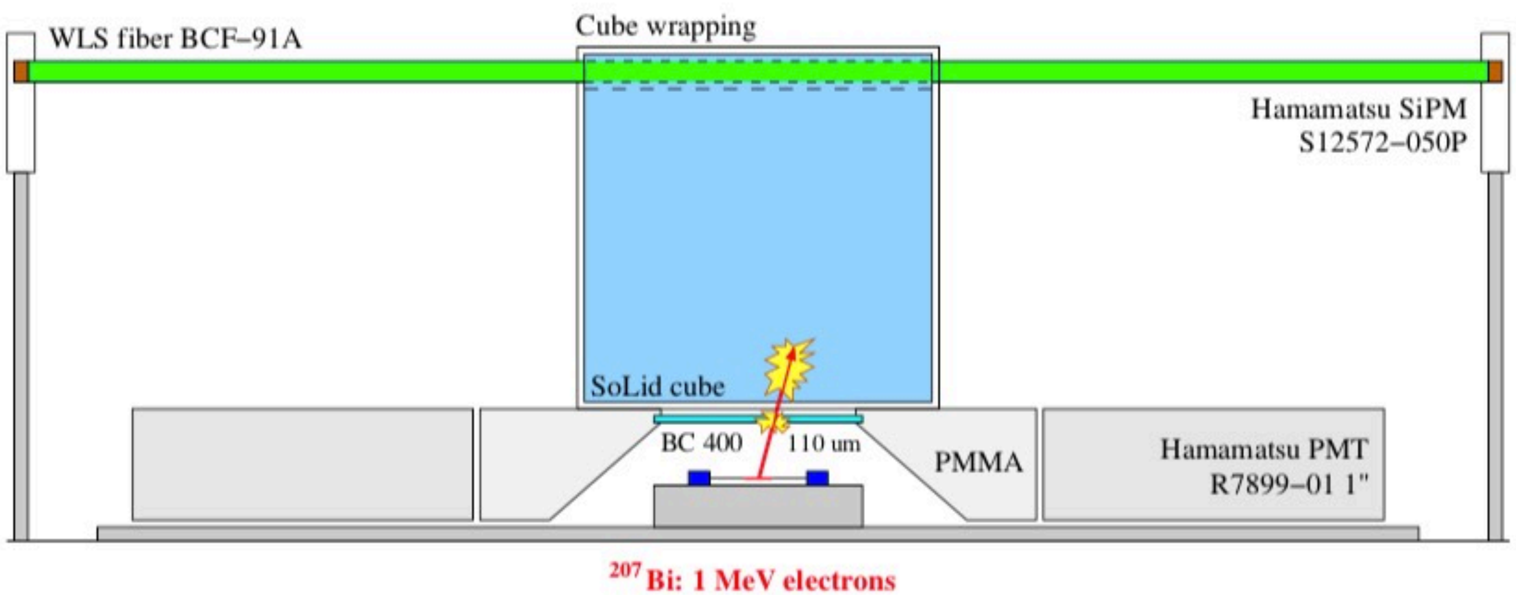


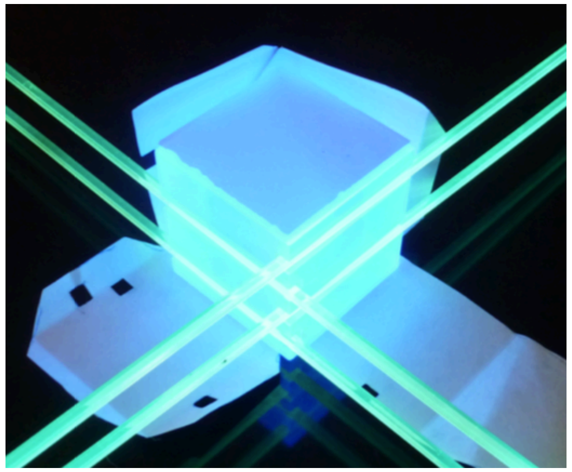
[Y. Abreu et al., A novel segmented-scintillator antineutrino detector, JINST 12 (2017) P04024.]

[Y. Abreu et al., Performance of a full scale prototype detector at the BR2 reactor for the SoLid experiment, JINST 13 (2018) P05005.]

LAL Test-Bench

- Optimize/Improve Light-yield and Plane Uniformity

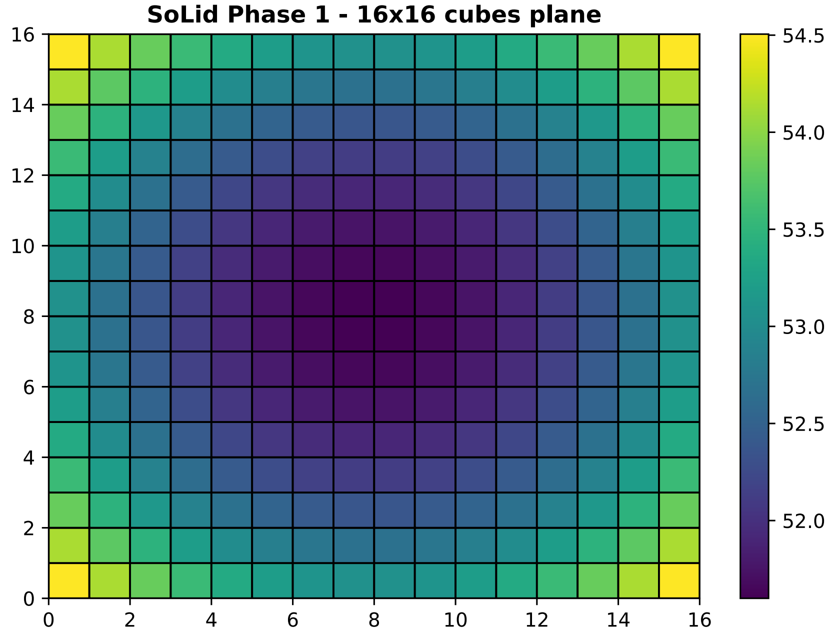




- Double cladding fiber
- Thicker Tyveck reflector
- Cube polishing
- 4 (fibers + SiPMs + Al mylar fiber-end mirror) / cube

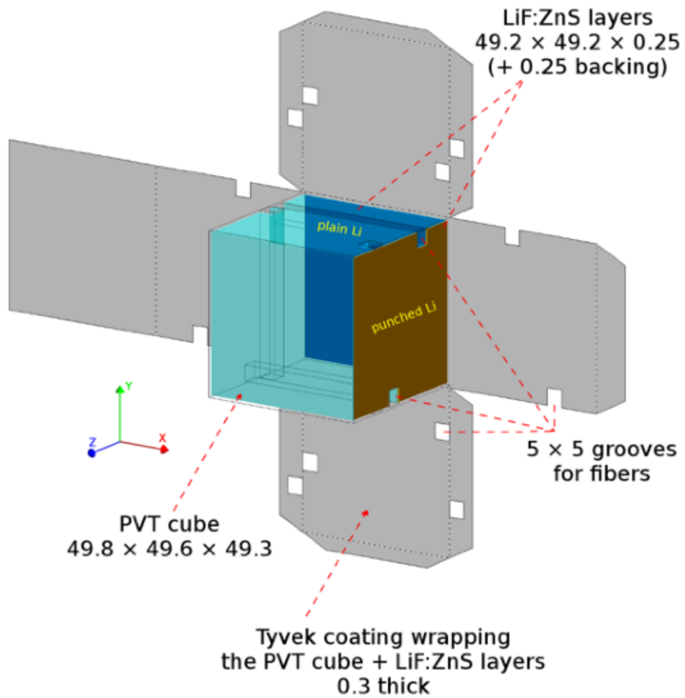
- On target for 14% /√E resolution
  - 52 ± 2 PA/MeV/cube (+150%)
  - 6% total variation across detector plane

[Y. Abreu et al., Optimisation of the scintillation light collection and uniformity for the SoLid experiment, arXiv:1806.02461.]

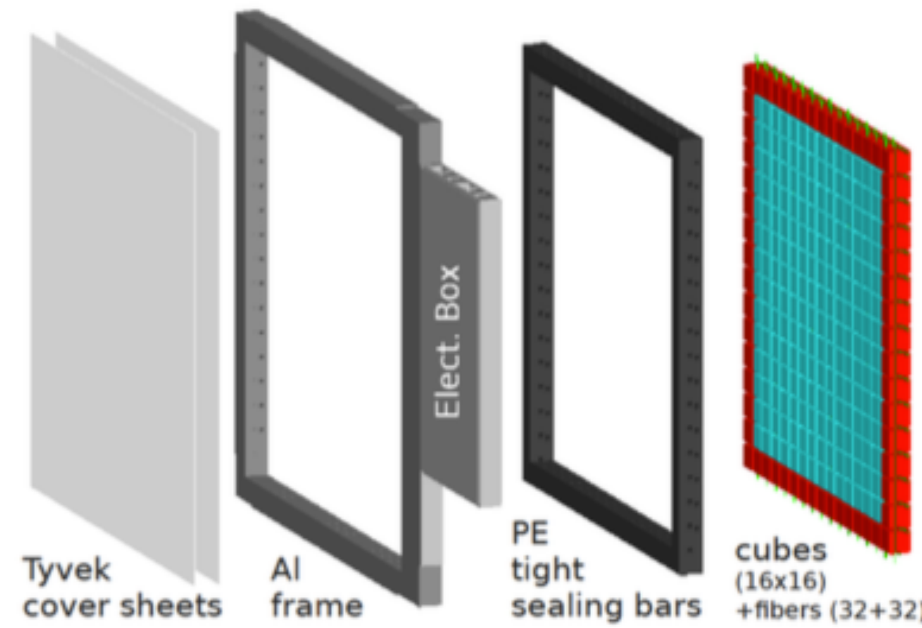


Full scale design

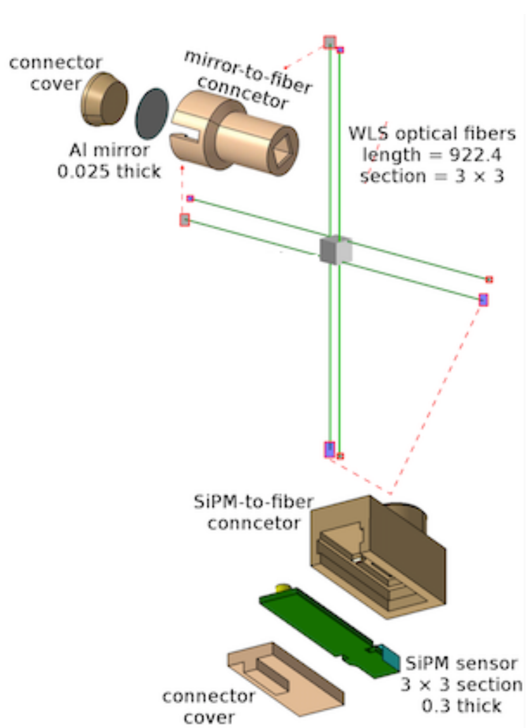
12 800 Elementary detection cells



50 Detection Planes (16x16 cubes array)



64 optical readout (fiber + SiPM + Al-mirror) / plane

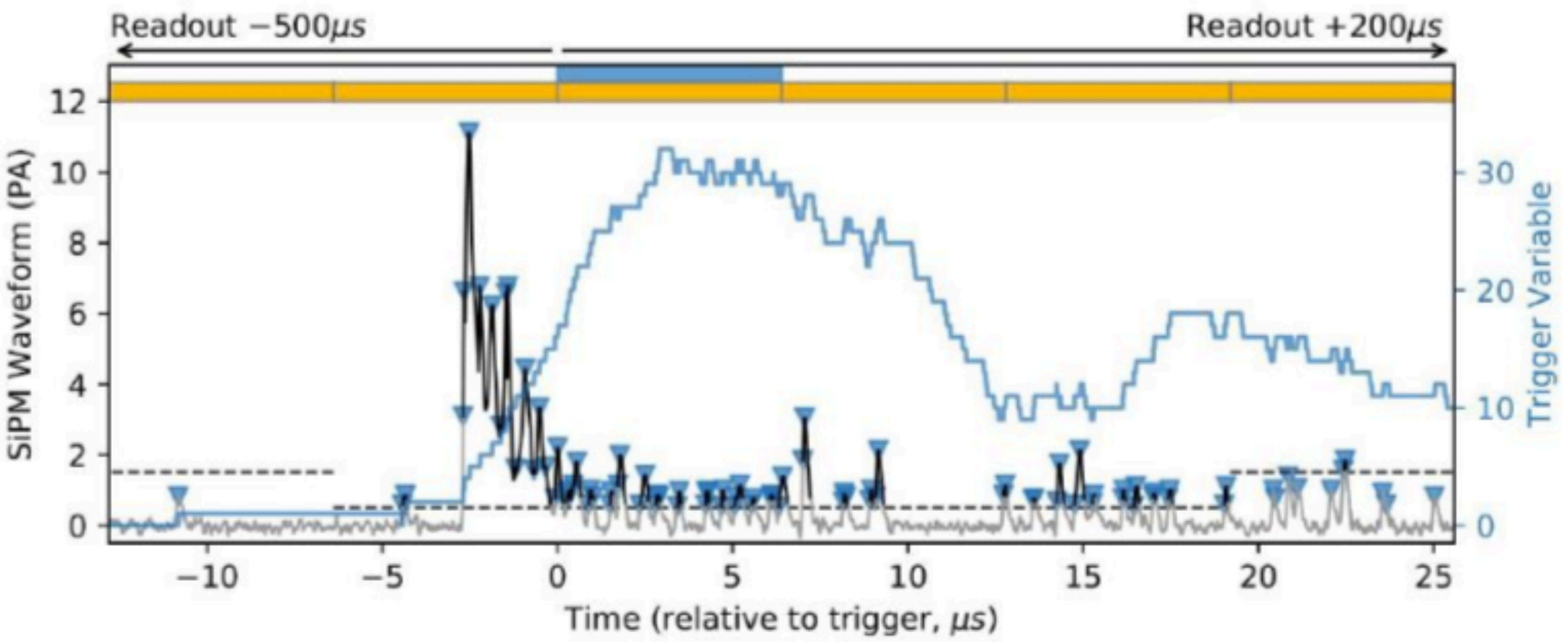


5 Modules of 10 planes (1.6 t fiducial mass)

Electronic and Triggers

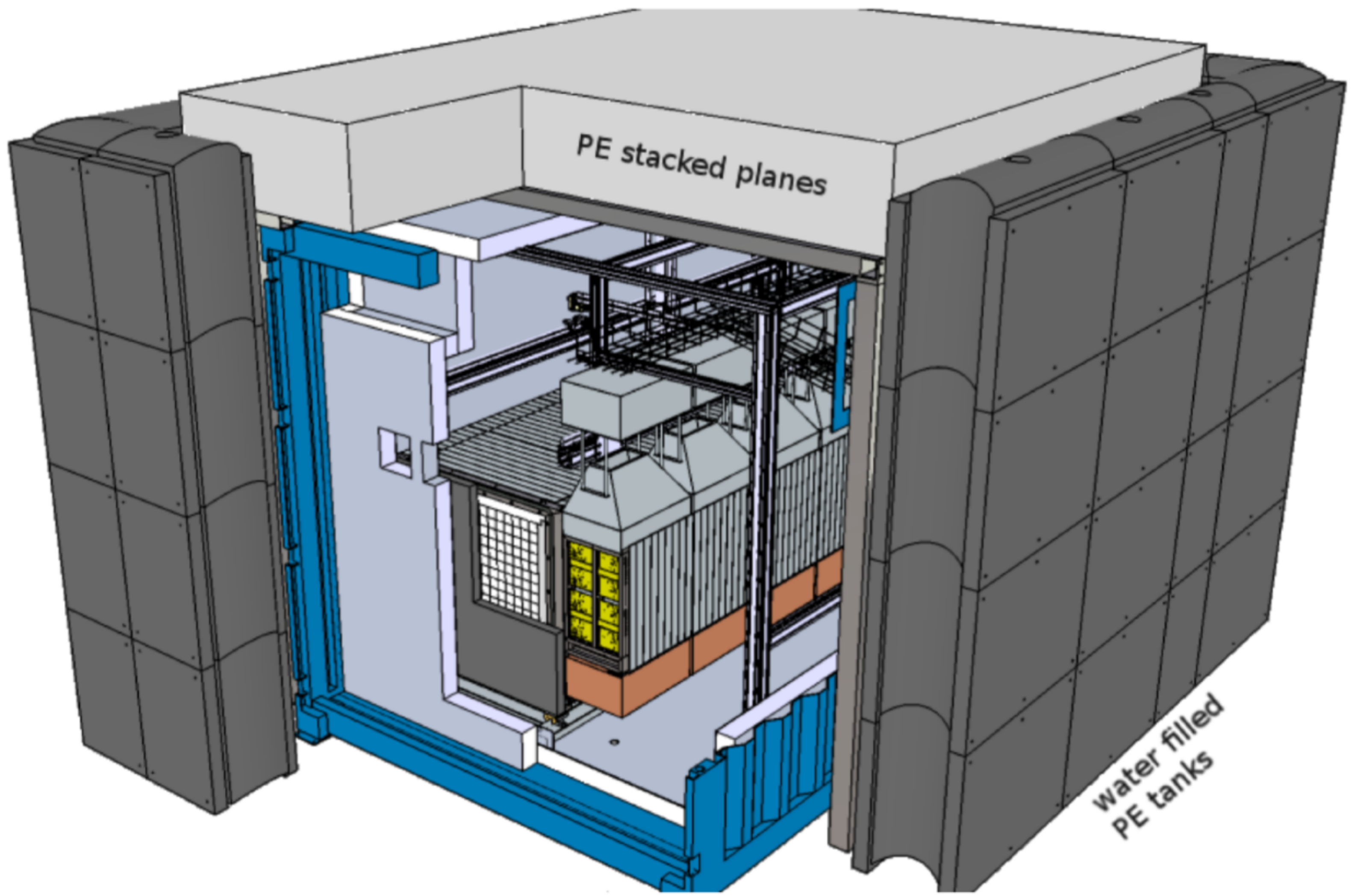
- Custom readout electronics
  - Analog amplification
  - Each detector plane can run stand-alone
  - Digitisation at 40 MHz - 2 Tb/s output for full detector (pre-trigger)
  - 20 MB/s post-trigger and after Zero-Supression

- Three triggers (logic implemented in FPGAs)
  - Random: Full detector read-out 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 NS
    - Based on peak counting
    - Long time buffer: [-500 µs, +200µs]
    - Multiplane readout (+/ 3 planes)



Full scale design

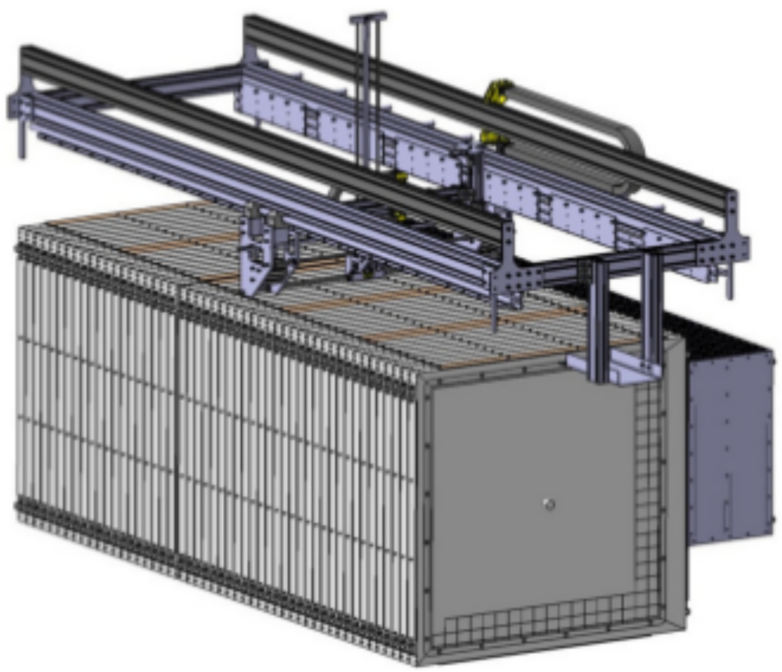
- Detector inside container [2.4x2.6x3.8 m] cooled at ~10 °C → SiPM dark-count rate reduction (/10)
- Low Z Passive Shielding: Water wall on side (50 cm, 28 t) & Polyethylene ceiling (50 cm thick, 6 t)
- Cadmium lining (2mm thick)

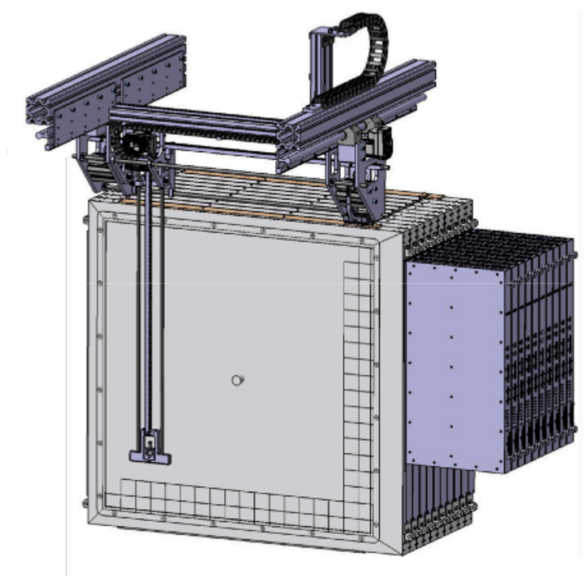


- Environmental survey: Temperature, Pressure, Humidity and Luminosity sensors
- Background survey: NaI-PMT coupled and Radon detector

CROSS Calibration System

- **In situ** Calibration @ BR2
  - Automated Robot sits above detector planes
  - Mechanically open/close gaps between modules (railway)
  - Source free to move in gap (2D)
  - Keep integrity/uniformity of the entire fiducial volume

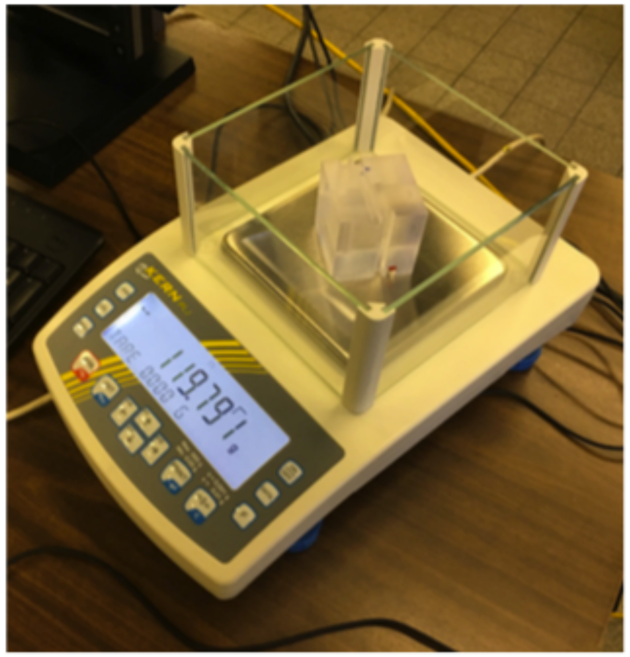


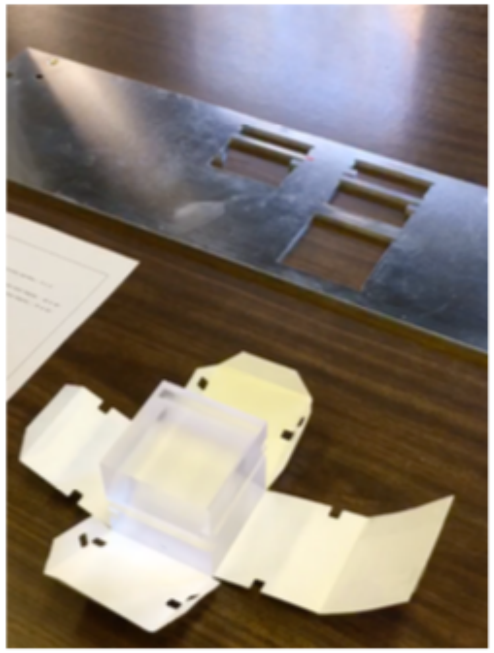


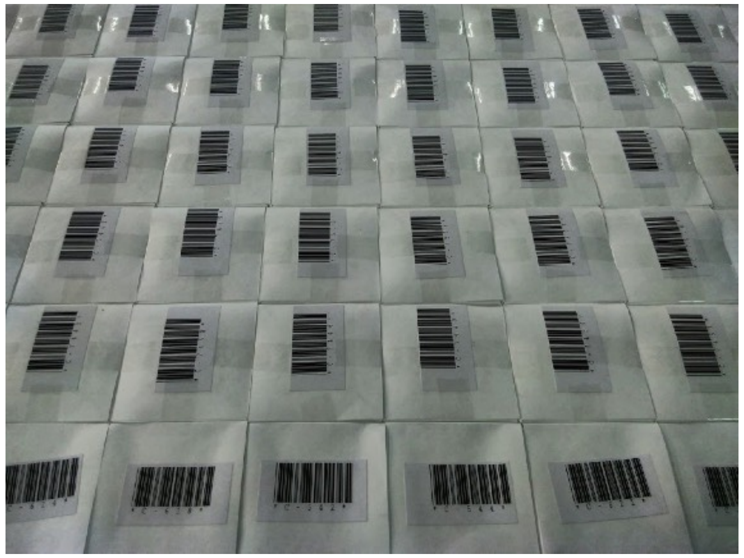
- Radioactive sources on both sides of each module
  - Neutron sources (AmBe, ^{252}Cf)
  - Gamma sources (^{22}Na, ^{60}Co, ^{137}Cs, ^{207}Bi)
- Calibration campaigns (2 - 4 days) during Reactor-OFF period

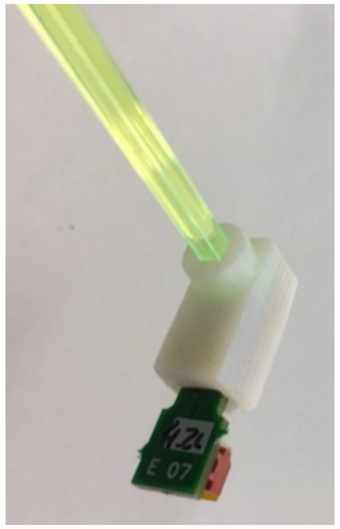
Detector Construction [end 2016-2017]

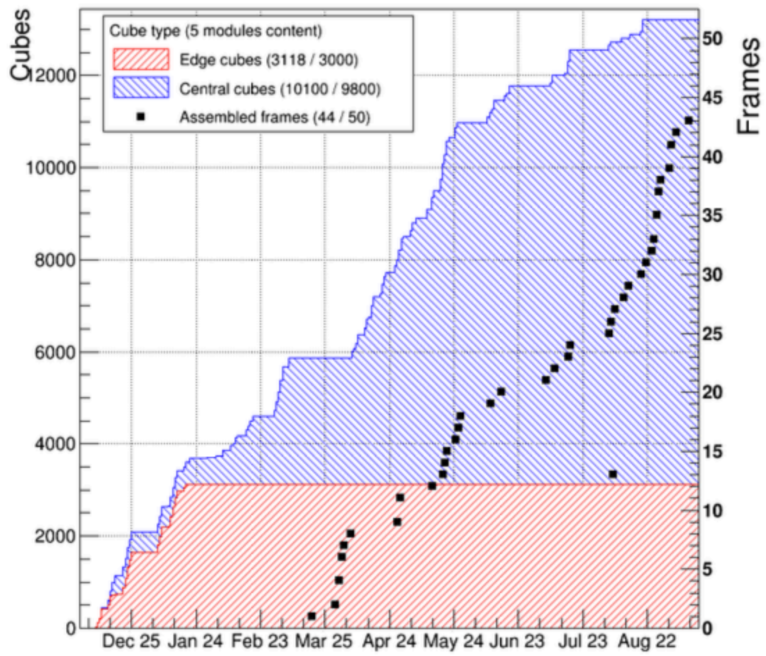
- Assembly line @ Ghent [French shifts ~ 50 person.week]
  - 13 000 cubes manually washed, weighted, wrapped, stacked





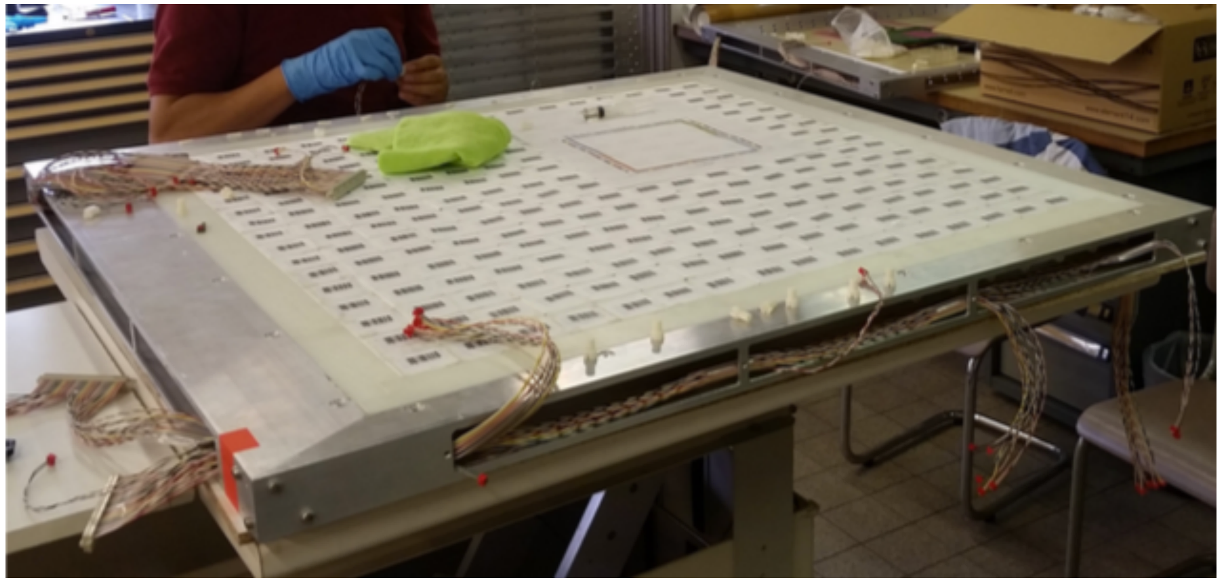


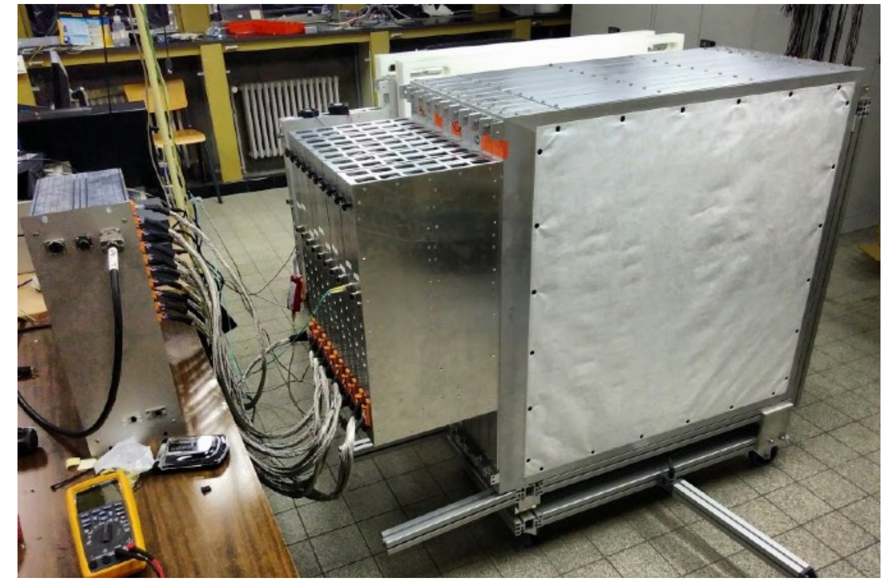




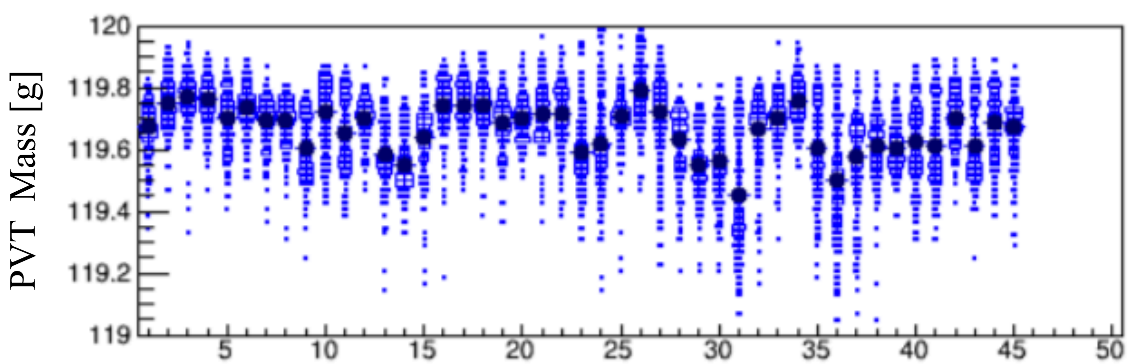
Detector Construction [end 2016-2017]

- 2 800 readout channels and 50 planes instrumented

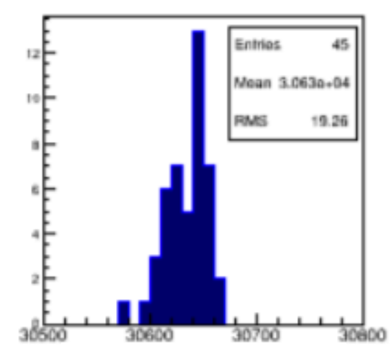


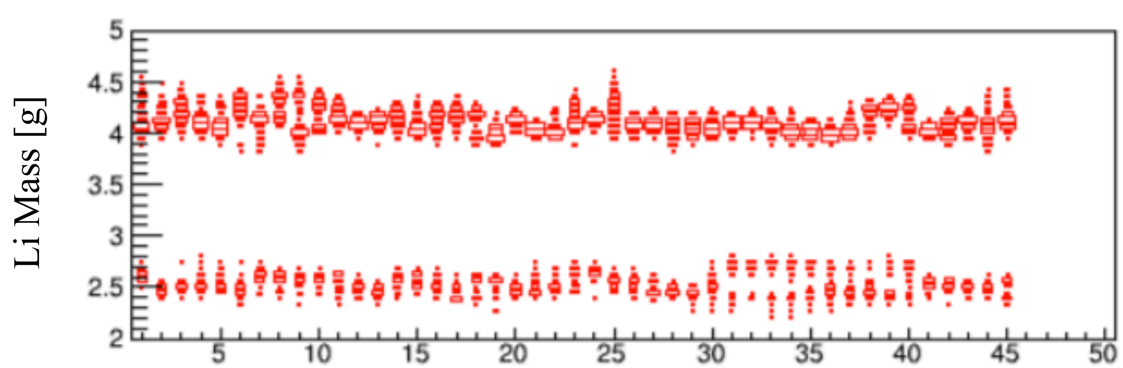


- All components informations (batch, weight) stored in dedicated database

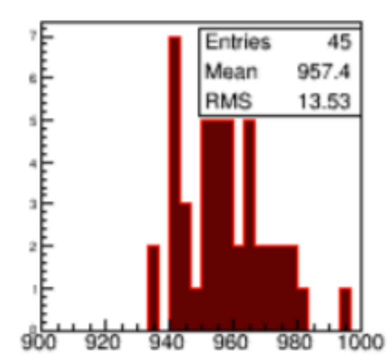


Frame PVT Mass





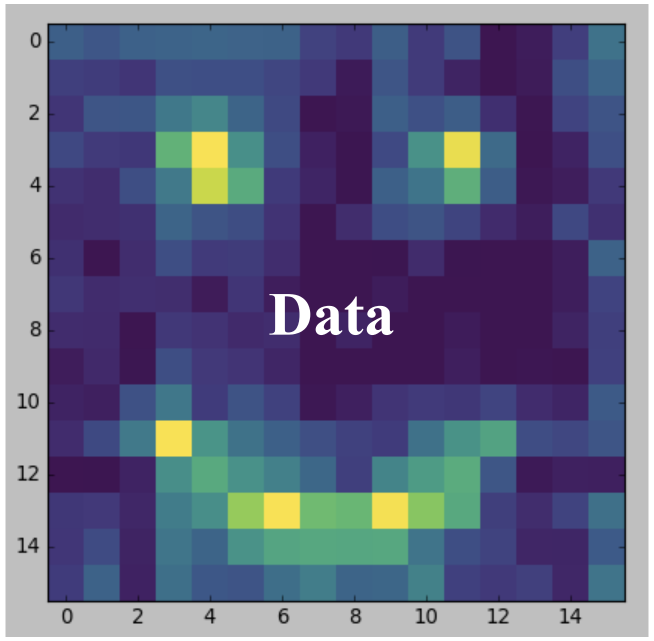
Frame Li Mass



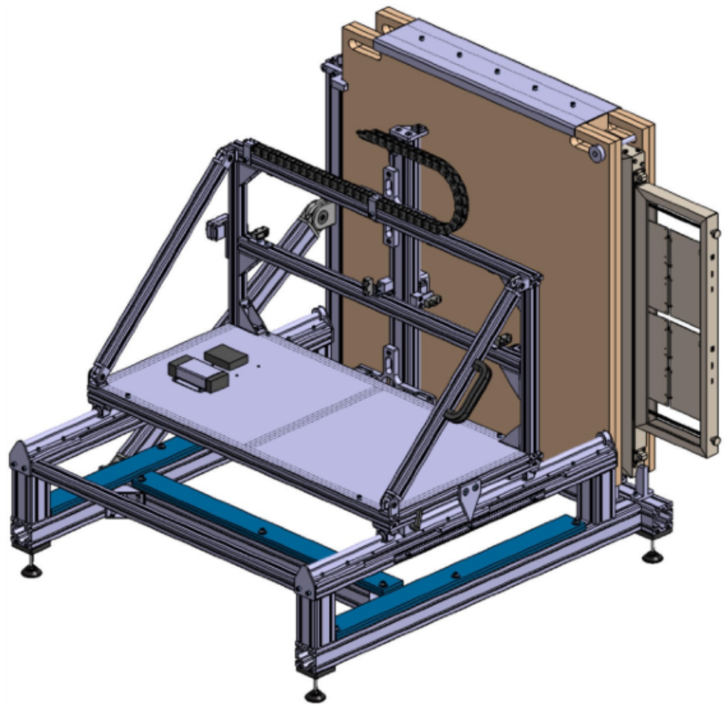
Proton content controlled at per-mil level

Quality Assurance with CALIPSO

- Ensure quality and uniformity response of all the 50 planes
  - Automated calibration system: 2D-scanning robot
  - Radioactive sources in front of each cube
    - Two modes : neutron and gamma
  - Allowed qualification/calibration of 1 plane/day



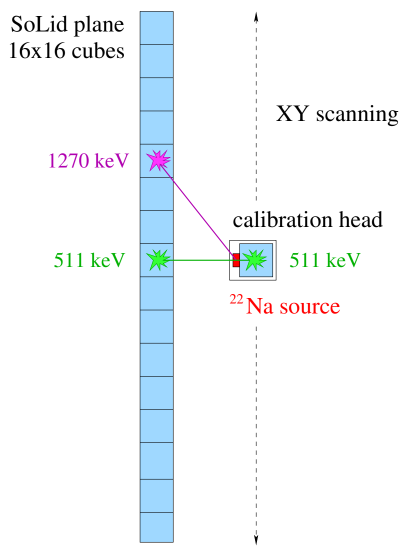
- Early identification/fix of defective components
  - Bad $^{6}LiF:ZnS$ screens batch, optical coupling loose …

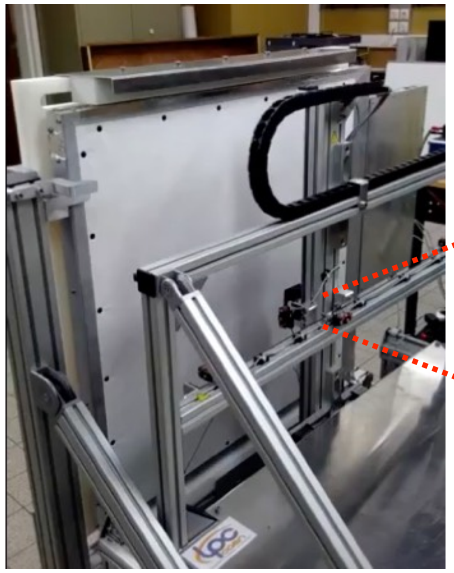


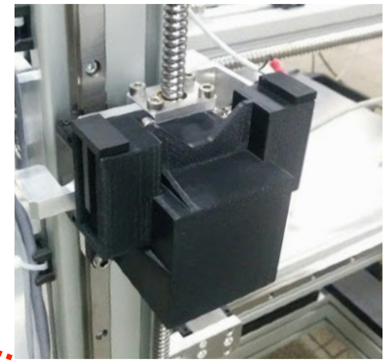
- **QA campaign was a success**, and allowed an "*in real condition*" test of every components of the detector, trigger settings and event reconstruction

Light Yield QA with CALIPSO

- Gamma mode: ^{22}Na source with external trigger



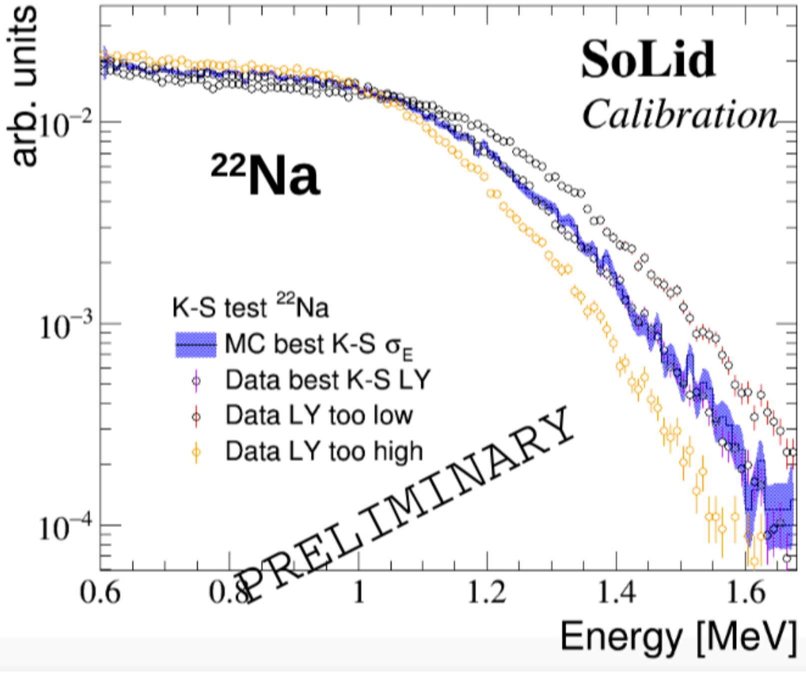




- Compton edge to determine PVT light yield (~~photopeak~~)

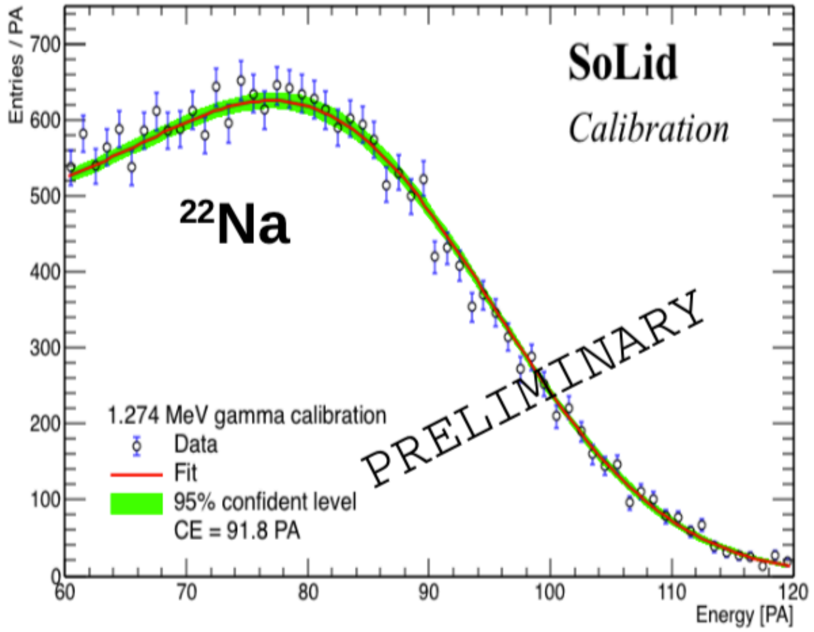
Kolmogorov test (K-S)

Compare measured sample to a Geant4 MC sample



Analytical fit

Use pdf based on Klein-Nishina Cross-Section

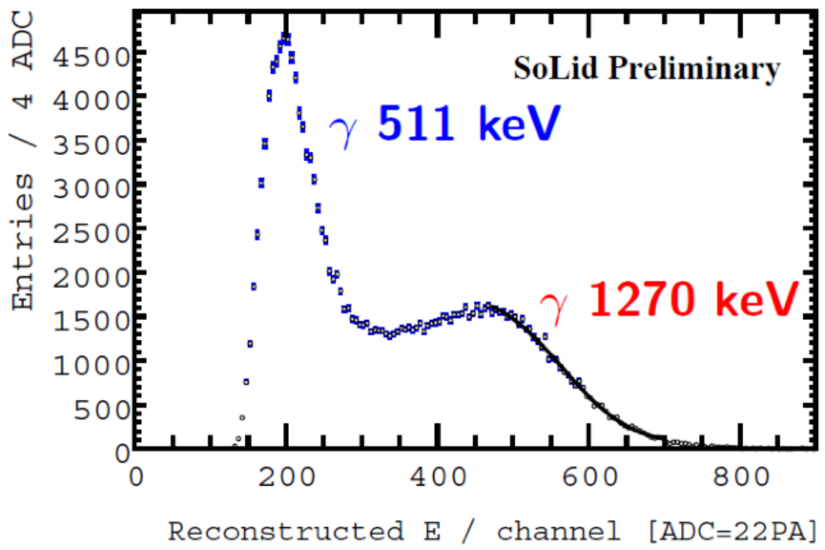


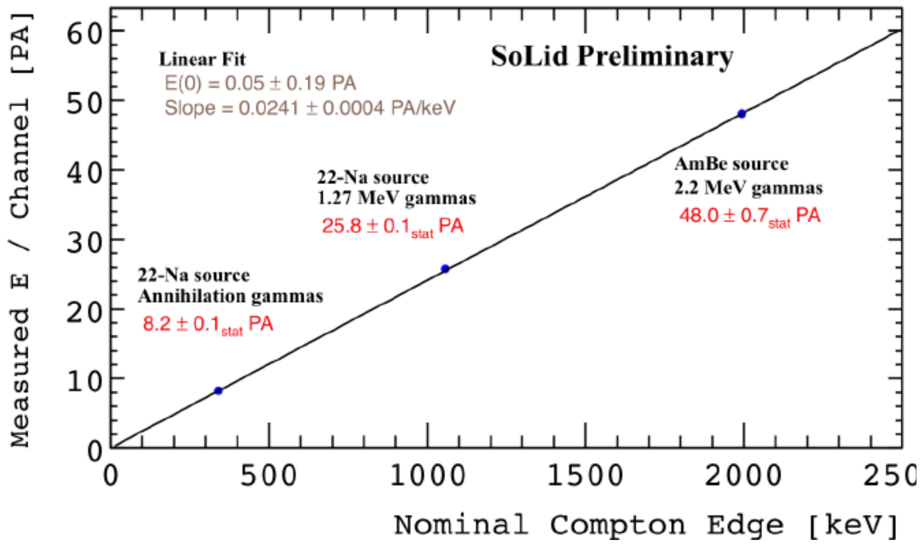
Agreement between both methods at the 1% level!

Good control of systematics

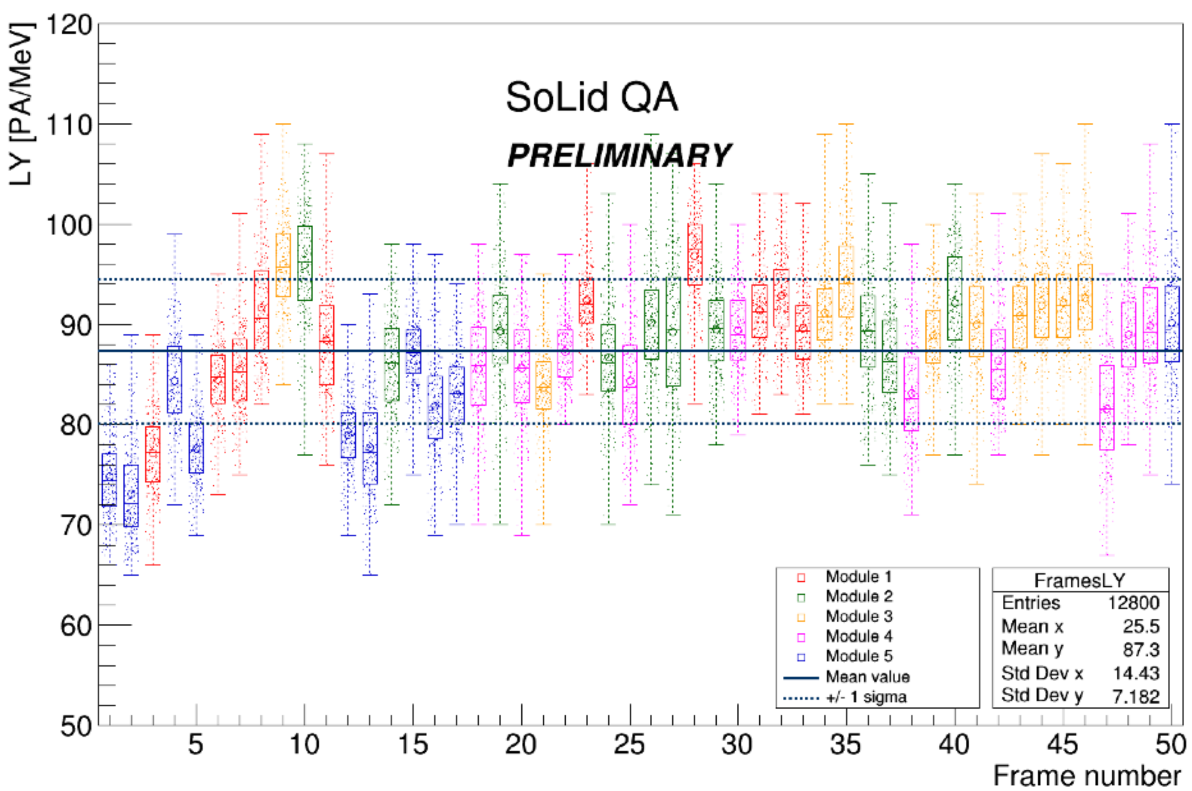
Light Yield QA with CALIPSO

- Check linearity of the energy response (1 cube)





- Preliminary estimation of LY in all 12800 cubes

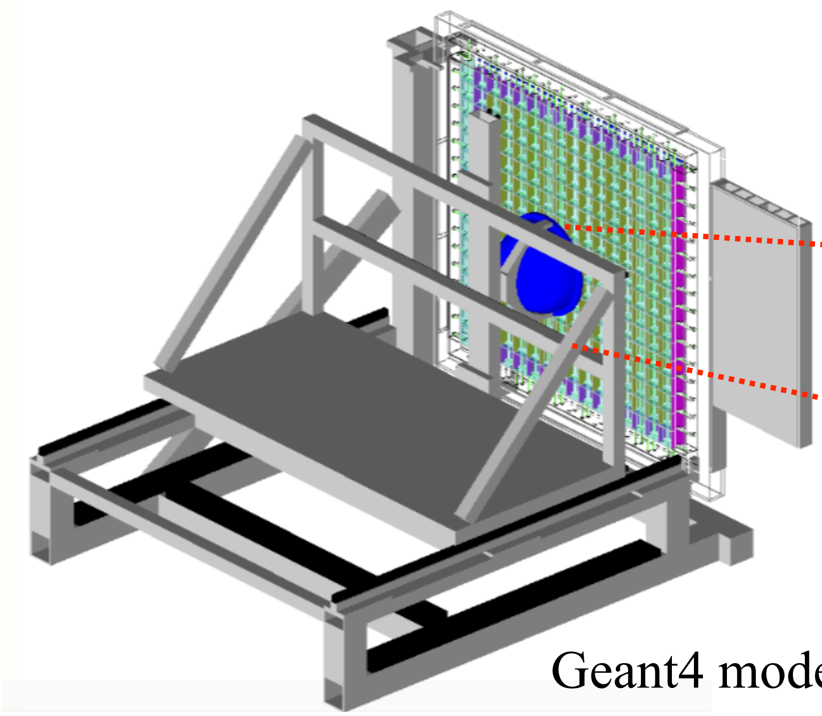


- Homogeneous response, can be improved with correction from attenuation length
- Exceeds SoLid requirements

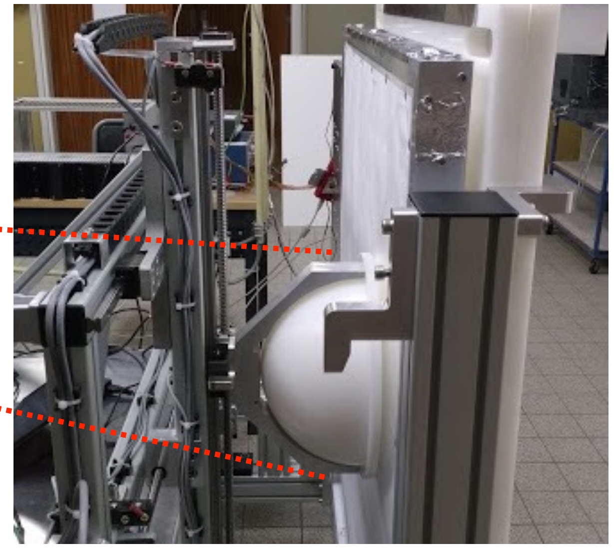
Light Yield > 60 PA/MeV

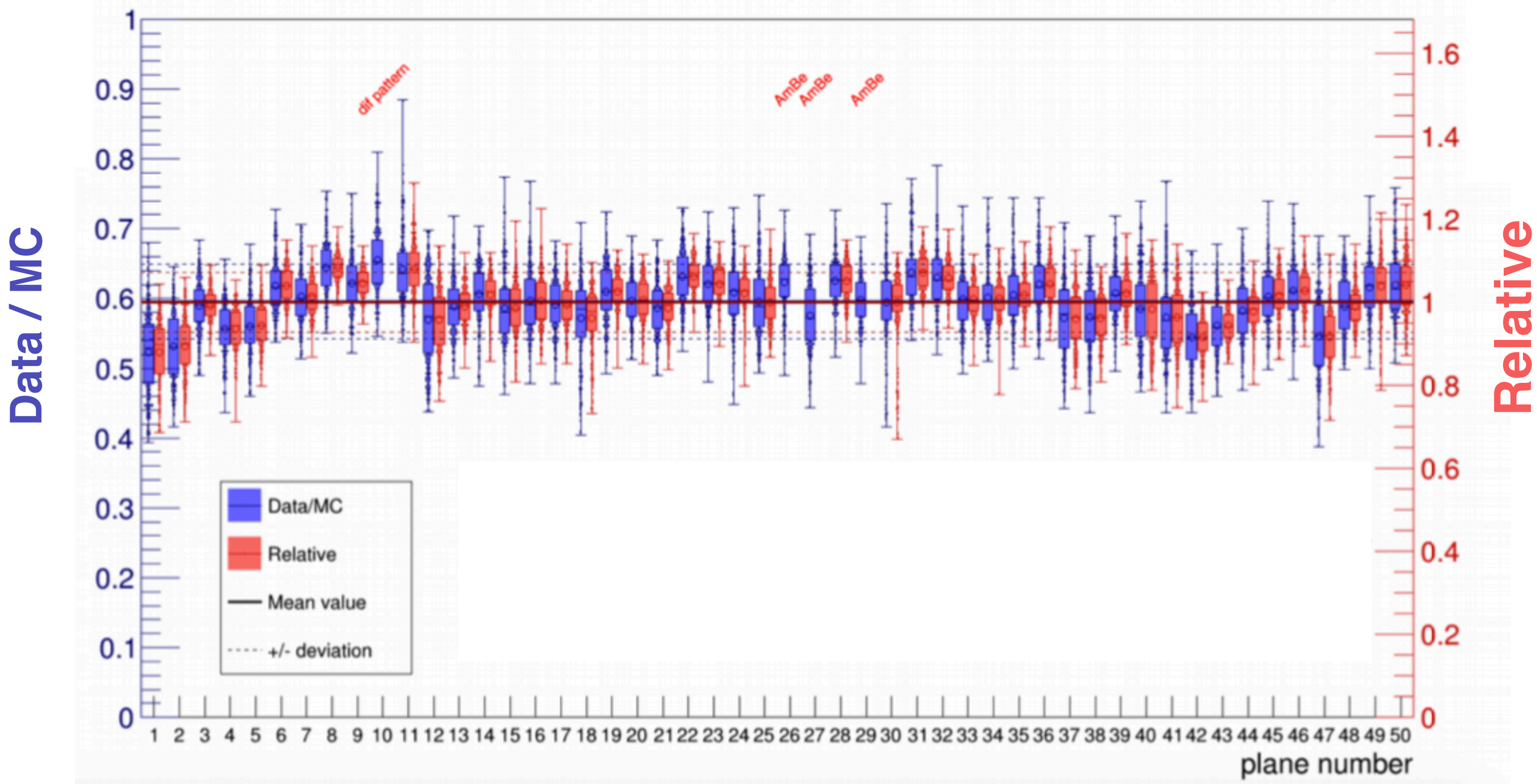
Neutron QA with CALIPSO

- Neutron mode
  - ^{252}Cf neutron source
  - Polyethylene collimator / reflector
  - MCNPX/Geant4 transport model
  - 25 positions per plane in 3 h
  - 100 M reconstructed neutron



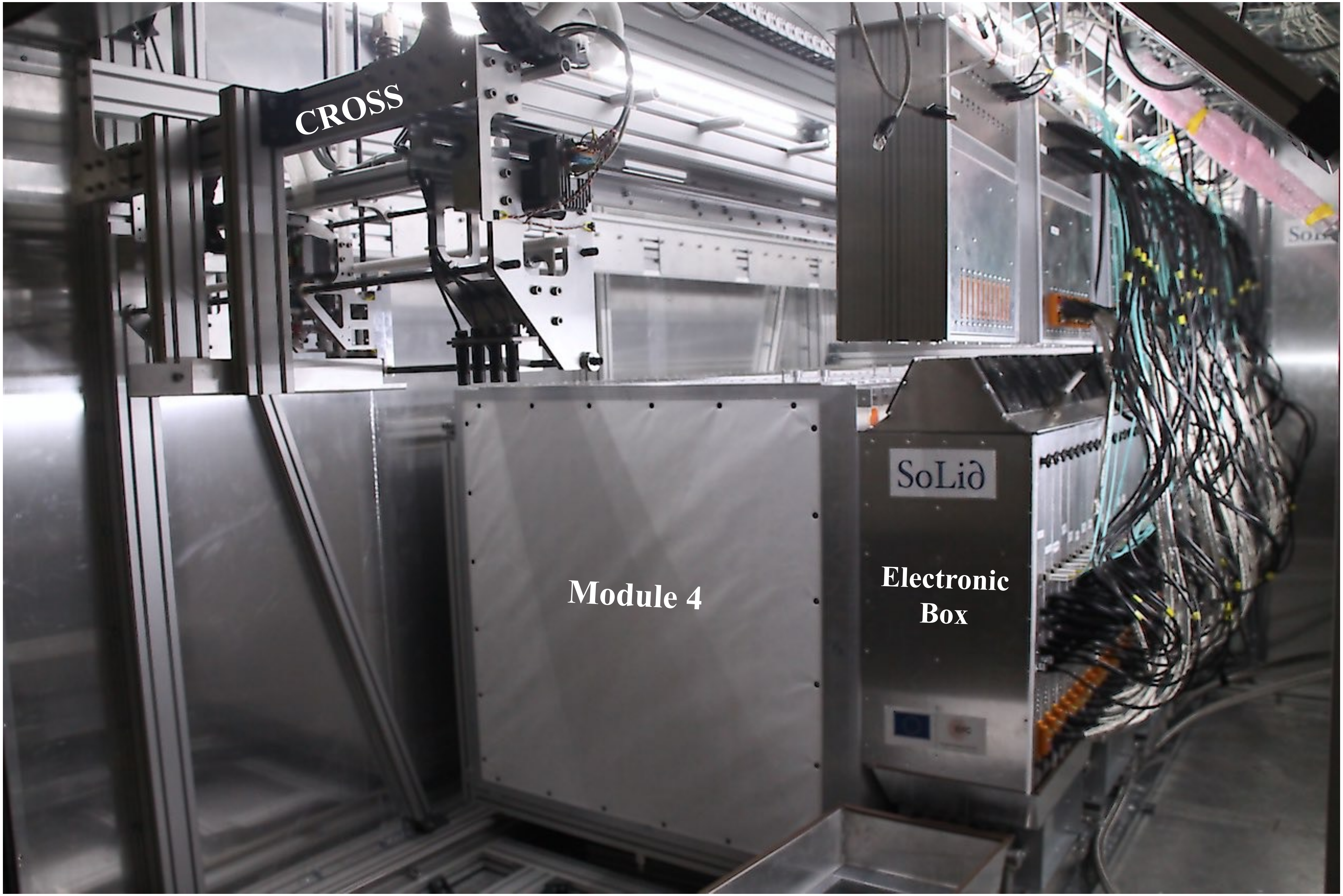
Geant4 model





Very good neutron reconstruction efficiency **> 60%** and uniformity

SoLiD Detector [10/2017]



Integration @ BR2



November/December 2017

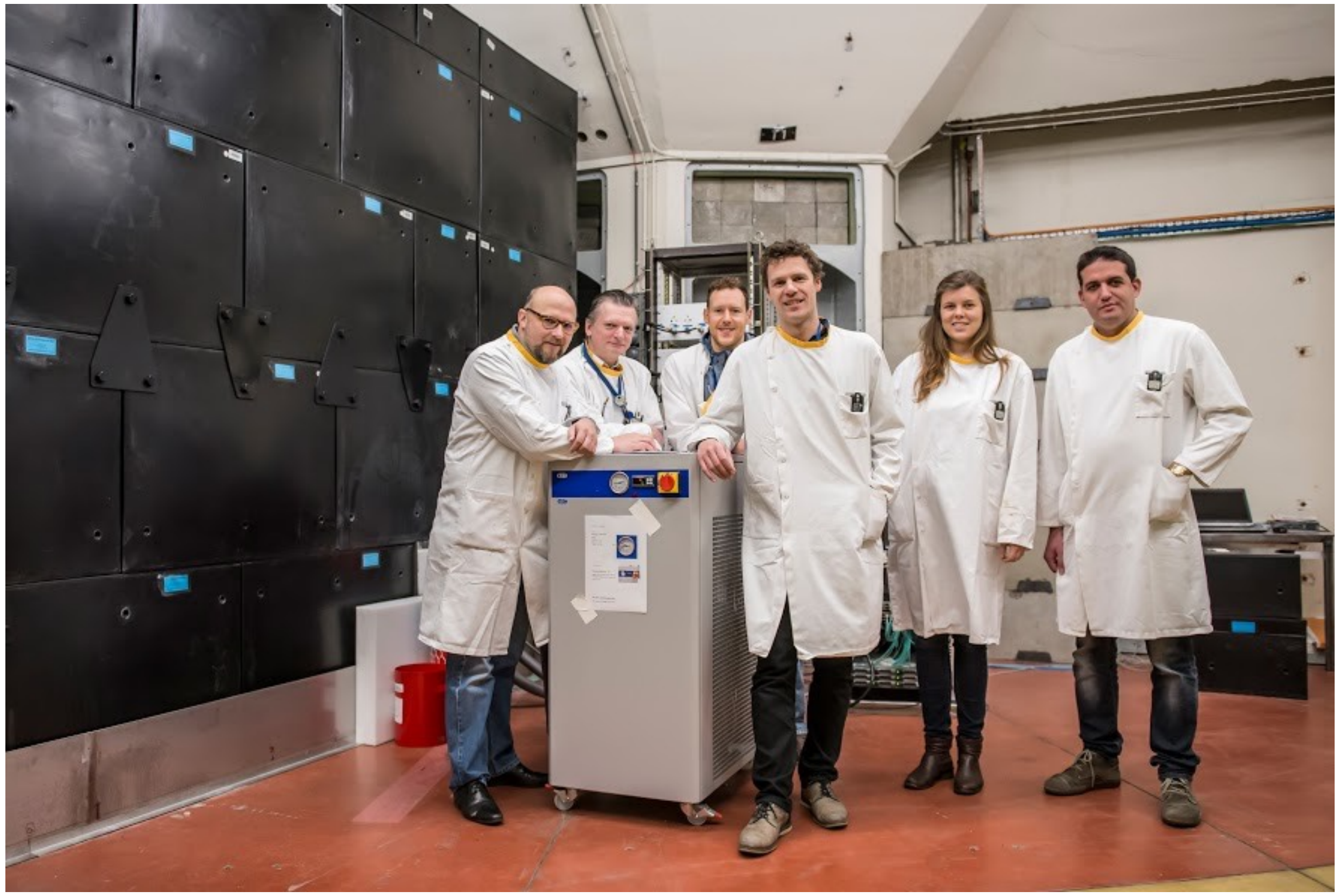
Commissioning with 4/5 modules: Reactor ON/OFF

Not fully shielded

February 2018

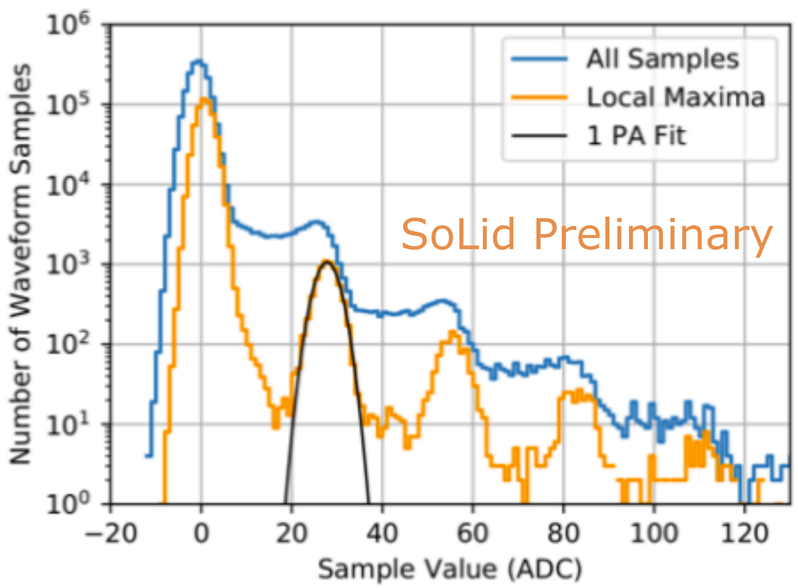
Physics Mode with 5 modules

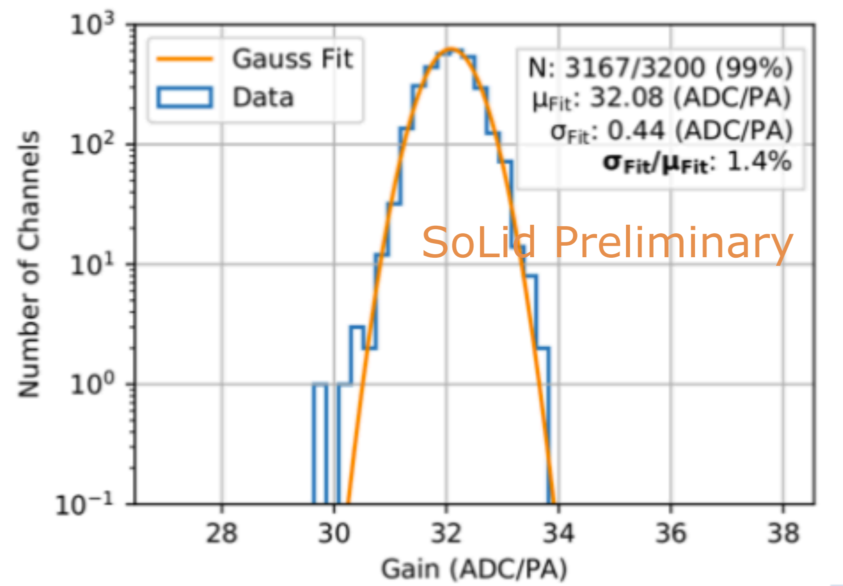
3 years data taking planned



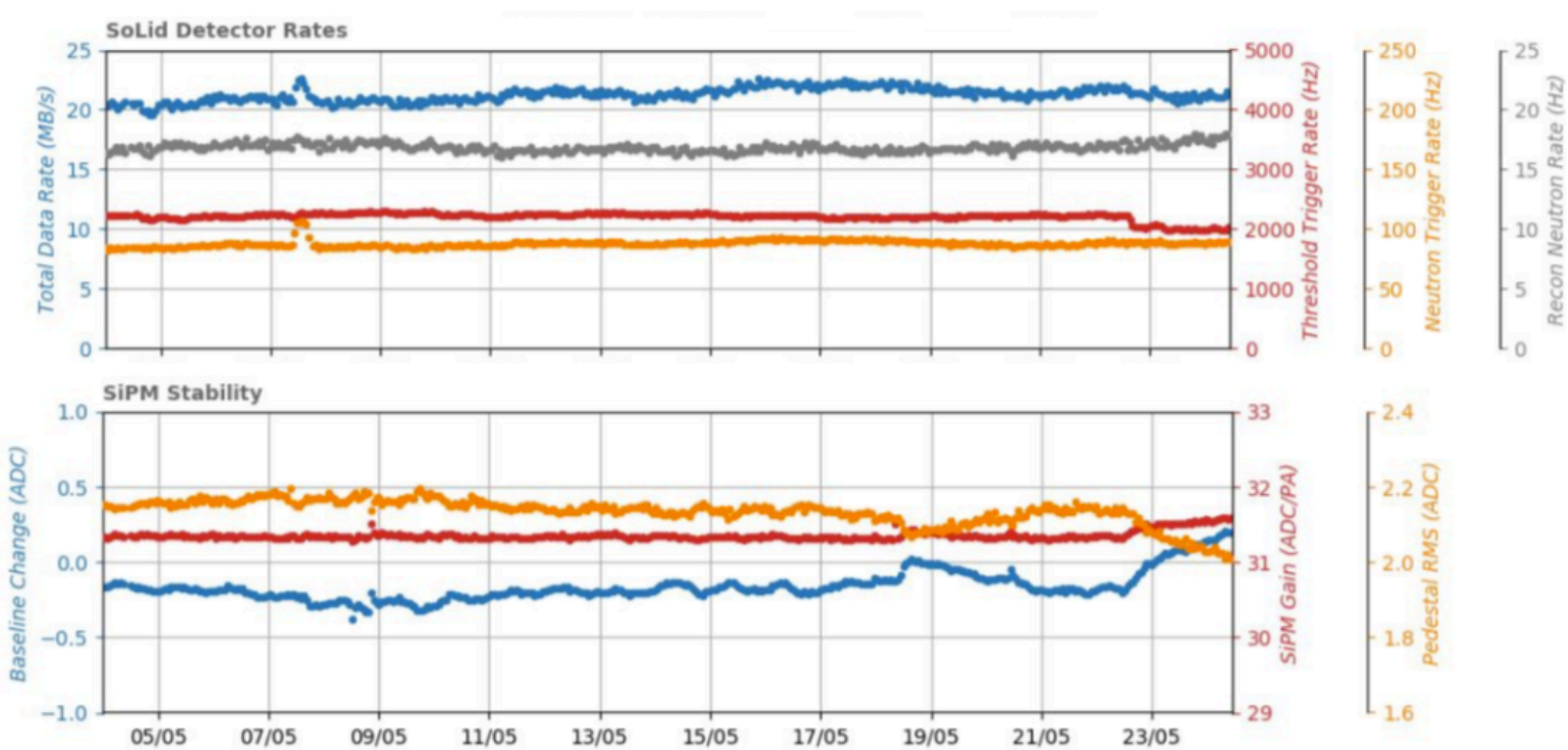
Detector operation

- Channel response (gain) equalized at 1.4% level
  - Voltage scans for individual SiPM breakdown voltages and amplification
  - Gain response of ~32.0 ADC/PA





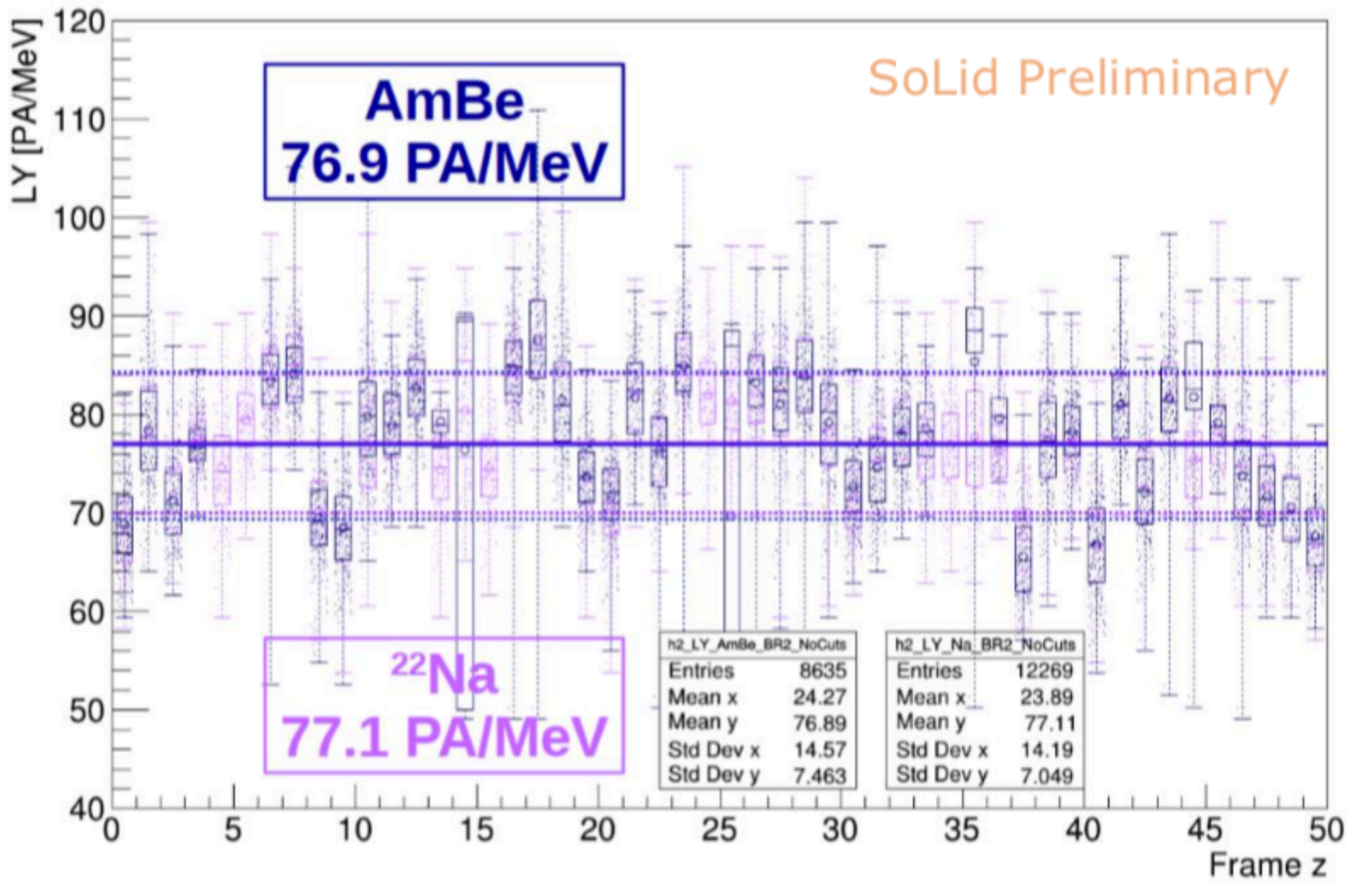
- Online remote detector monitoring (Physics variables for subsample of data)



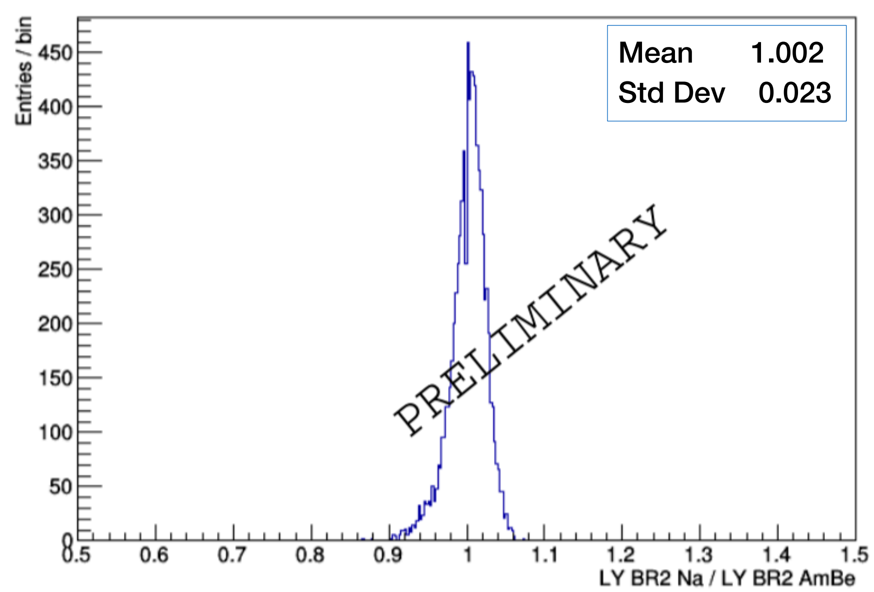
Stable data taking for both reactor on and off since February

ES Calibration

- First calibration campaign (94 hours) with ^{22}Na and AmBe
  - 100% of cubes (w/4ch) have been calibrated
  - Average of **77 PA/MeV**
  - Currently running at higher OV (1.5 → 1.8V): LY should increase of ~ 15%



Excellent agreement

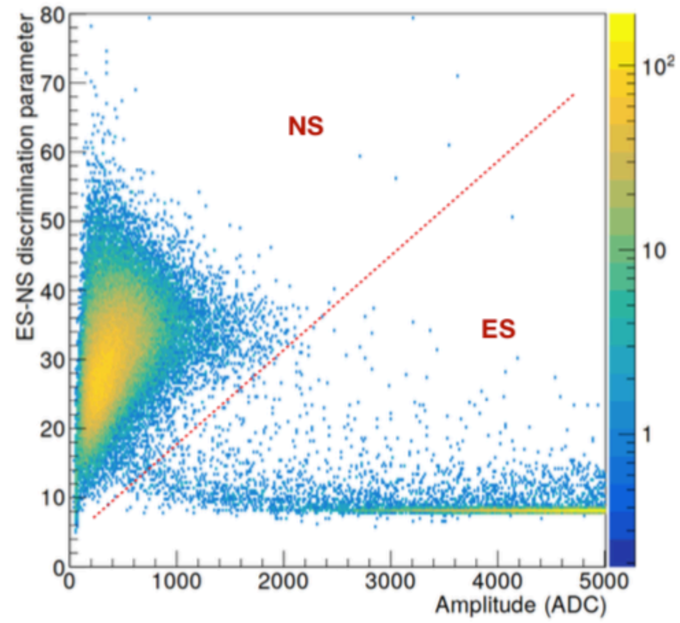


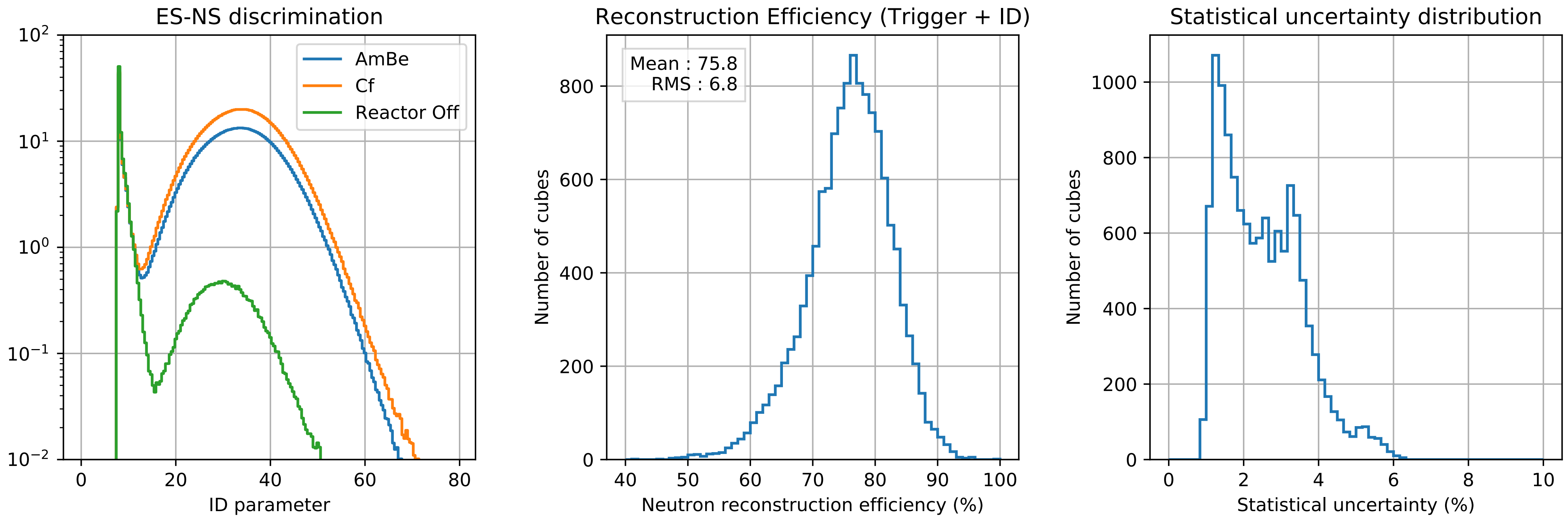
→ Exceed the Energy Resolution requirement of 14% @ 1 MeV

- Next calibration campaign dedicated to linearity studies: ^{137}Cs, ^{60}Co, ^{207}Bi and muons

NS Calibration

- Calibration with AmBe (~ 4 MeV) and ^{252}Cf (~2 MeV) sources
  - Both calibrated below 2% level at National Physics Laboratory (UK)
- Neutron reconstruction efficiency per cube
  - 3% agreement between both source
  - Stat. uncertainties ~ 2.5 %

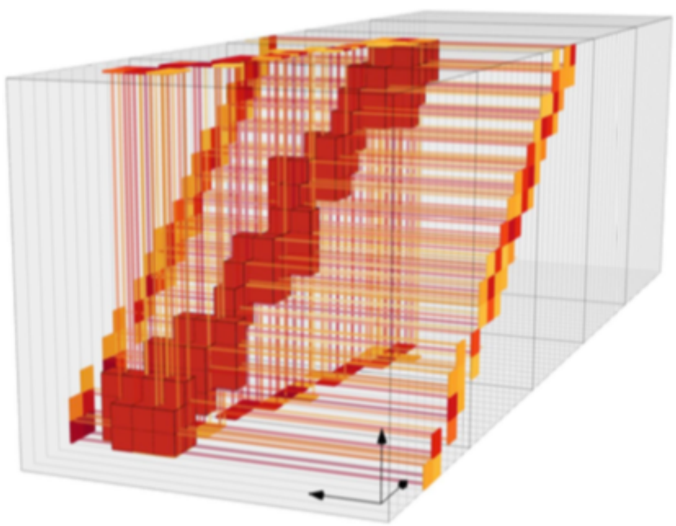


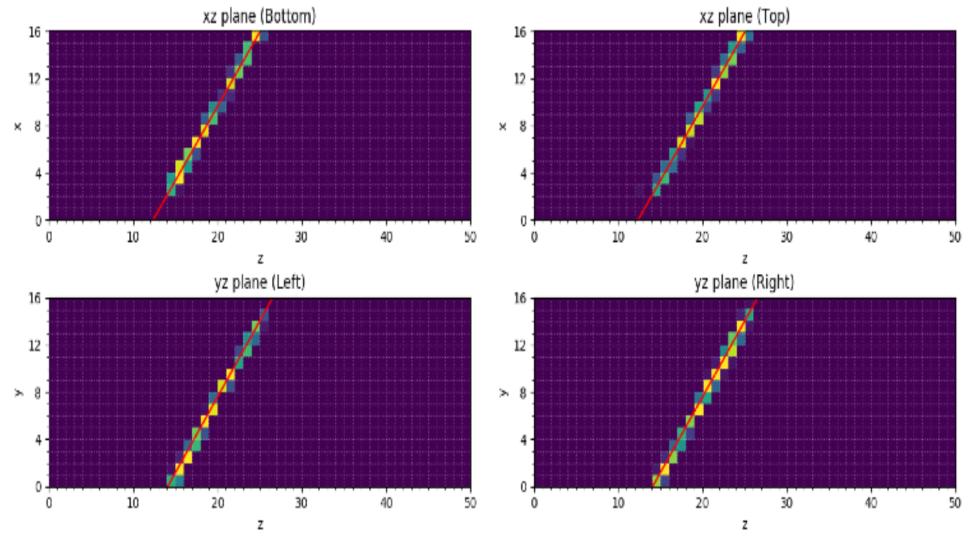


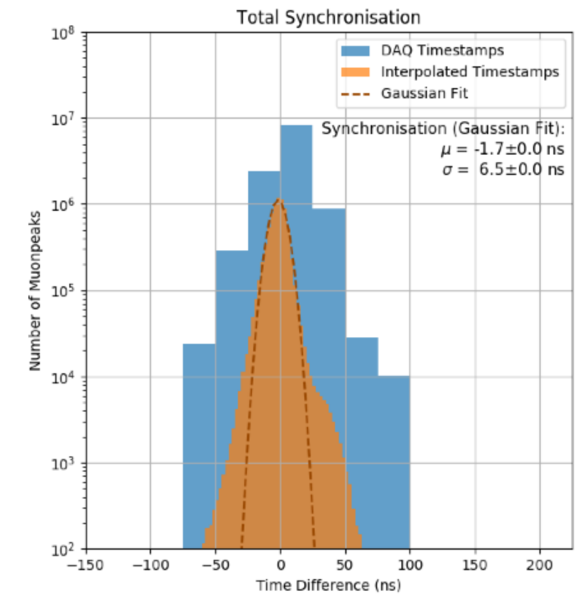
- Global neutron reconstruction efficiency: 75.8% ± 0.02 % (stat.) ± 3.10 % (syst.)
- Next step: Fine tuning of Monte-Carlo models (air gap thickness, …) to reduce systematics

Muon Reconstruction

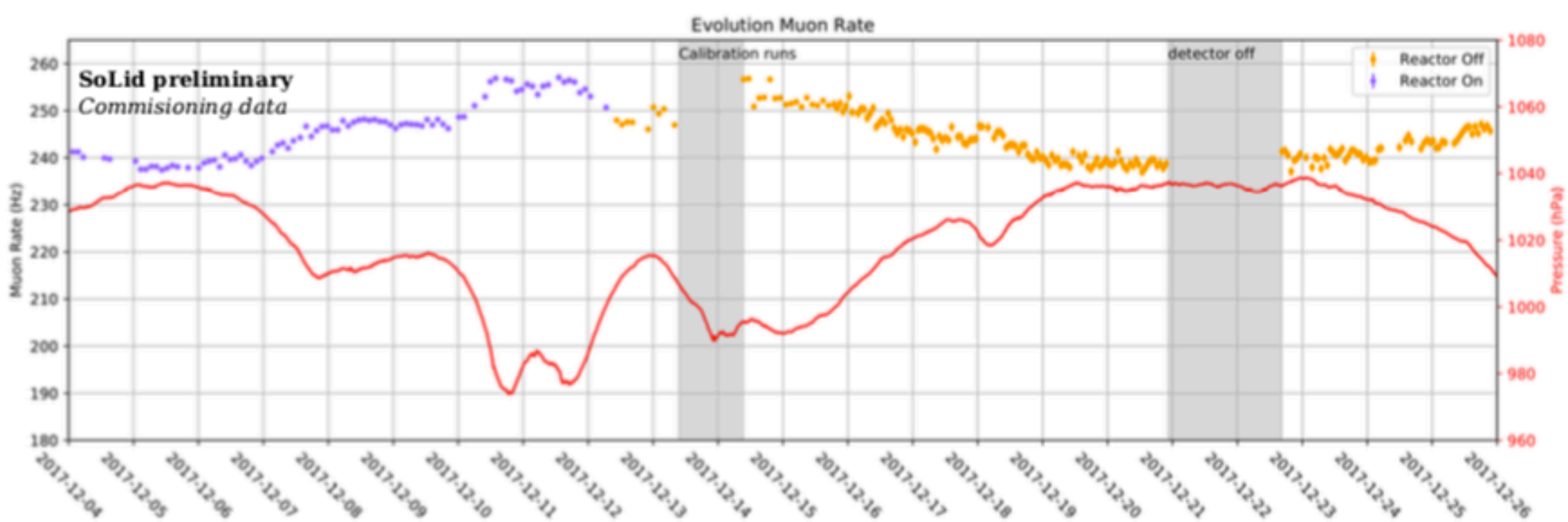
- Very good tracking capabilities: PSD, deposit energy, topology, timing

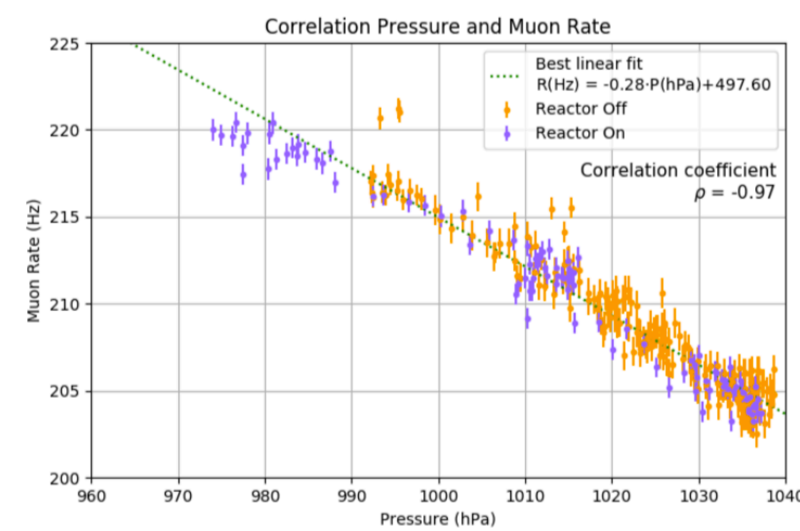






- Correlation with pressure

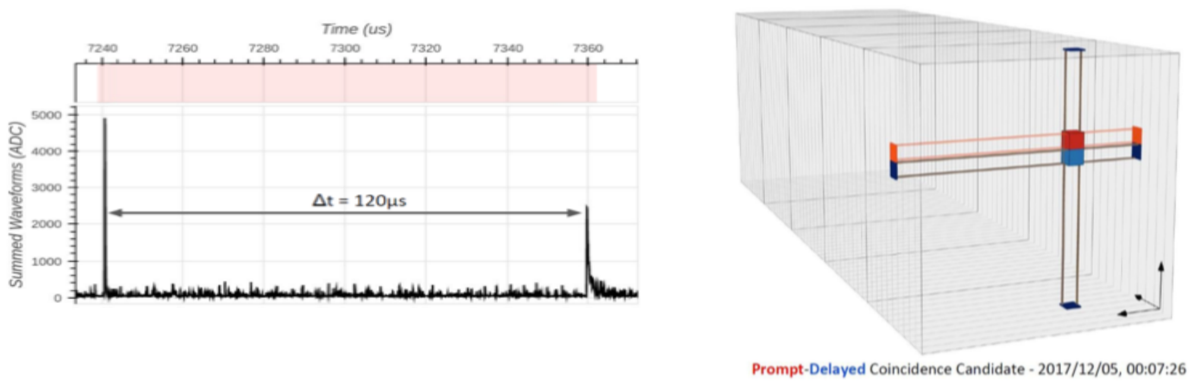




- Well known dE/dx
  - Online monitoring (detector stability survey)
  - Check Linearity at high energy

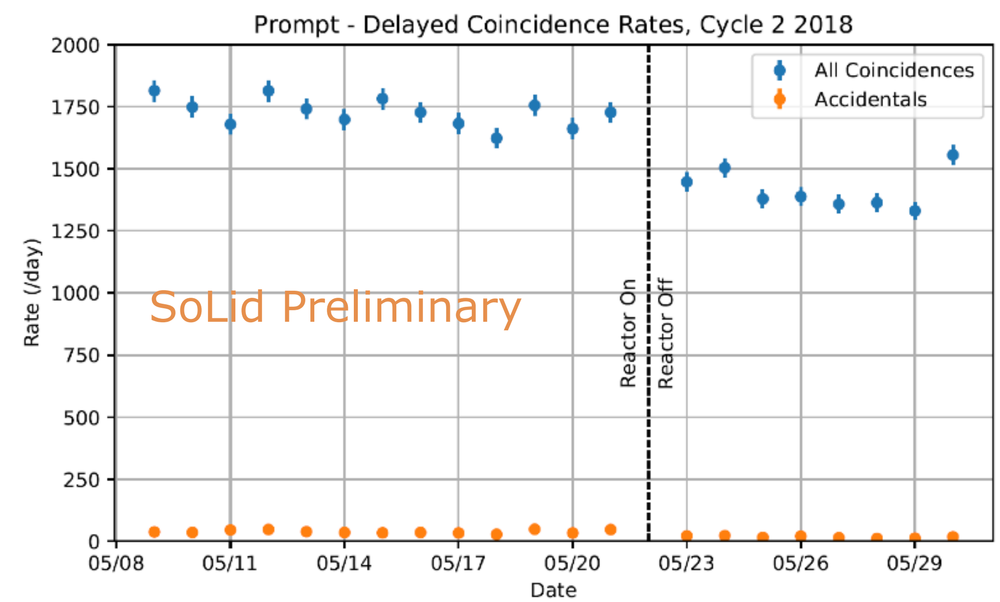
IBD-like events check

- IBD-like events monitored by using basic cuts: Timing, Topology, μ-veto, Energy

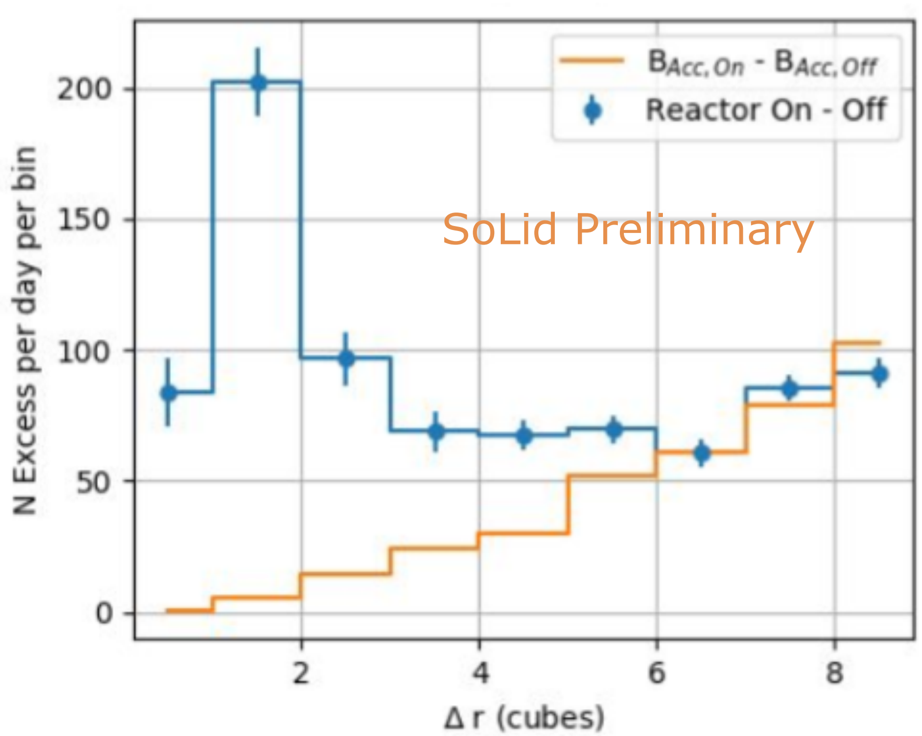


Prompt-**Delayed** Coincidence Candidate - 2017/12/05, 00:07:26

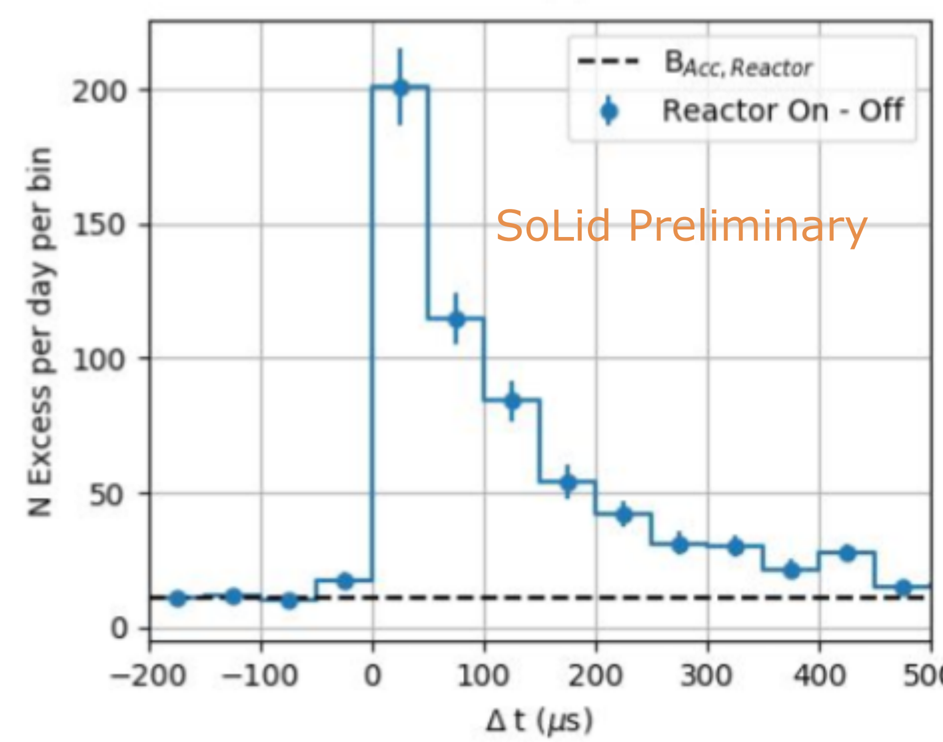
Reactor On excess



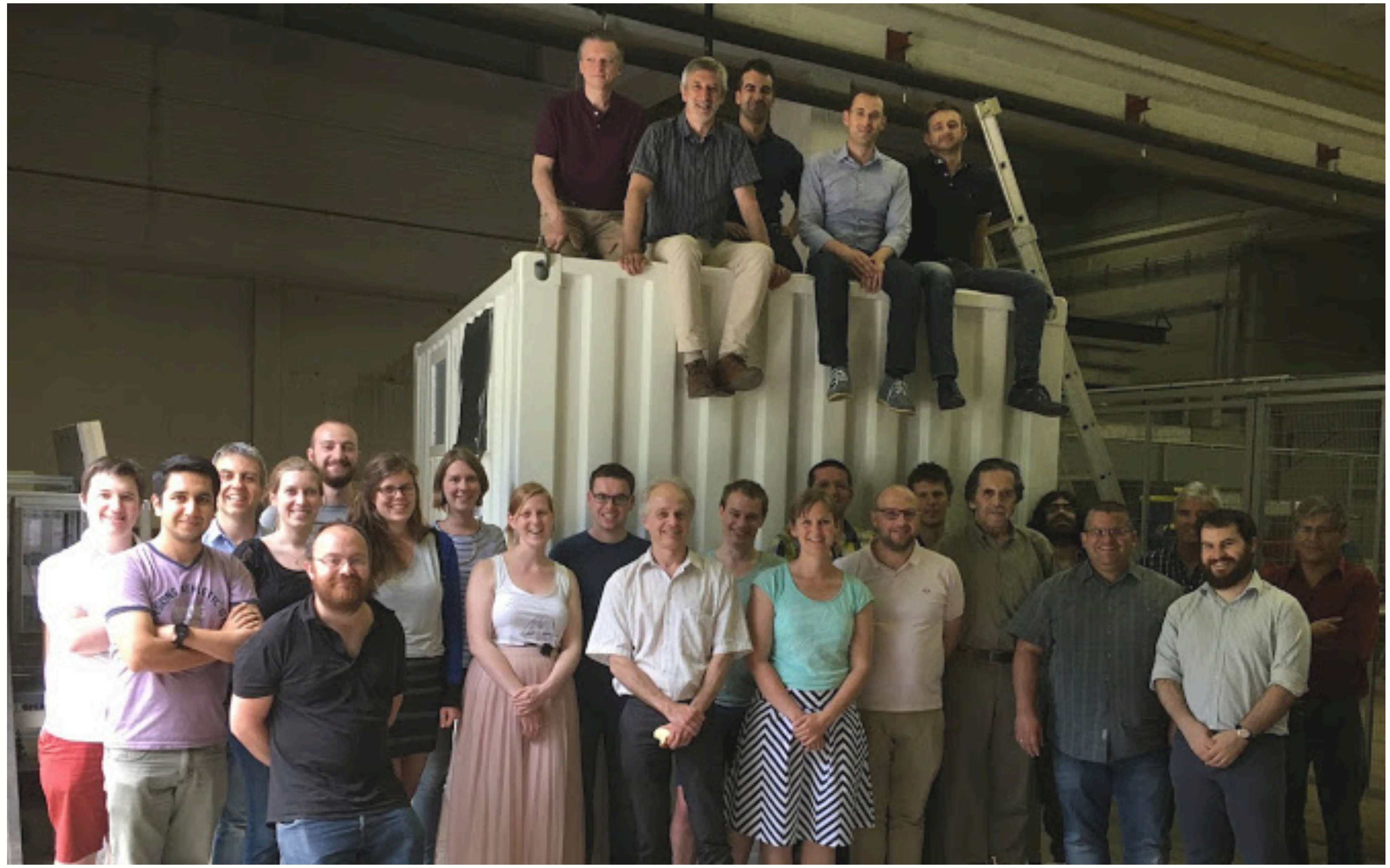
Spatially confined



Δt consistent with thermalized n capture



SoLid collaboration



Oxford University	*A. Weber, B.C. Castle, N. Ryder*
Bristol University	*D.Newbold, D.Cussans, K.Petridis, J.Rademacker, S. Manley*
Imperial College	***A. Vacheret** (spokesperson), D. Saunders, B. Hosseini, K. Graves*
SCK-CEN	*S. Van Dyck, B. Coupé, S. Kalcheva, L. Ghys, J. Mermans*
Antwerp University	*N. Van Remortel, A. De Roeck, Y. Abreu, M. Verstraeten (Phd.)*
Vrije University Bruxel	*J. D'Hondt, P. Van Mulders, L. N. Kalousis, S. Vercaemer (Phd.)*
Gent University	*D. Ryckbosch, I. Michiels (Phd.), C. Moortgat (Phd.), G. Vandierendonck (Phd.)*
LPC-Caen	*B. Guillon, G. Lehaut, D. Durand, G. Ban, V. Pestel (Phd.)*
Subatech Nantes	*F. Yermia, B. Viaud, M. Settimo, M. Fallot, L. Giot, D. Henaff (Phd.)*
LAL Orsay	*M. Bongrand, L. Simard, M-H Schune, Y. Amhis, L. Manzanilas, D. Boursette (Phd.)*
LPC-Clermont	*S. Monteil, H. Chanal, P. Crochet, D. Boumediene*
Virginia-Tech	*J. Link, P. Huber, C. Mariani*

French human ressources

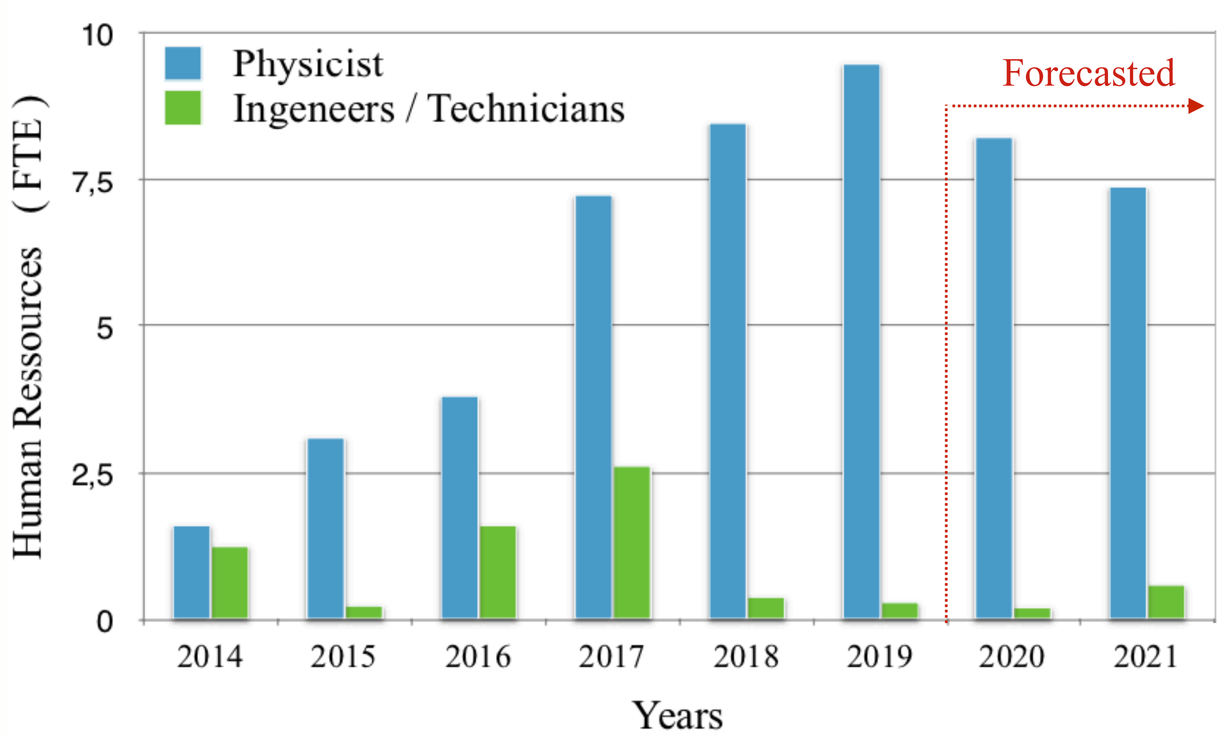
- 4 IN2P3 laboratories gathering 17 physicists, 3 PhDs, 1 Post-Doc: ~ **7.5 – 9.5 FTE**

Laboratory	Names (position)	Main contributions
LAL Laboratoire de l'Accélérateur Linéaire	**M. Bongrand** (CR), L. Simard (PR), Y. Amhis (CR), M.H. Schune (DR), L. Manzanilas (Post-doc), D. Boursette (PhD) / S. Jenzer (IE), A. Blot (TCN), A. Migayron (AI)	Mechanics, Analysis, Calibration, BiPo
LPC Caen	**B. Guillon** (MCF), G. Lehaut (CR), D. Durand (DR) G. Ban (PR), V. Pestel (Phd) / B. Carniol (IE), D. Goupilliere (AI), B. Bougard (TCN), C. Vandamme (TCN), J. Perronel (AI)	Reactor modelization, Mechanics, Analysis, Calibration
LPC Laboratoire de Physique de Clermont	**S. Monteil** (PR), H. Chanal (MCF), P. Crochet (DR) D. Boumediene (CR) / S. Binet (IR)	Instrumentation, Analysis
Subatech	**F. Yermia** (MCF), B. Viaud (CR), M. Settimo (CR), M. Fallot (MCF,), L. Giot (MCF), D. Henaff (PhD) / H. Carduner (IE), J. M. Buhour (IE), T. Milletto (TCN) Y. Bortoli (TCN), S. Fresneau (TCN)	Analysis, Calibration, Mechanics, Reactor modelization

… also involved in others *ν* projects: SuperNEMO (LAL, LPC-Caen) Double-Chooz, JUNO (SUBATECH)

- Next coming years focus on Data-Analysis
  - Two Post-Doc positions (ANR-funded) in 2018 @ LPC-Caen and SUBATECH

- Sizeable technical supports during:
  - SM1 design/construction (2014)
  - SoLid design/construction (2016-2017)
  - … Decommissioning (2021)



French Impacts

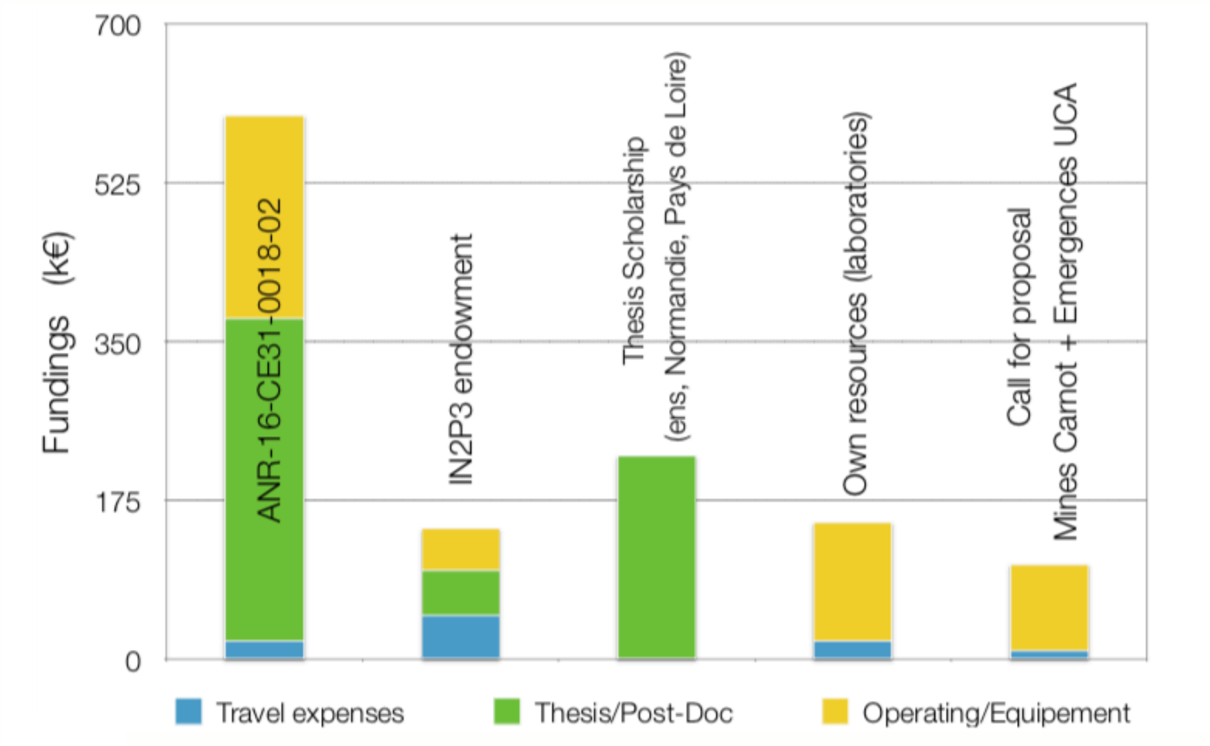
- Common expertise and strong interplay: mechanics, reactor physics, neutron calibration, energy reconstruction, BiPo background, neutrino oscillation analysis …

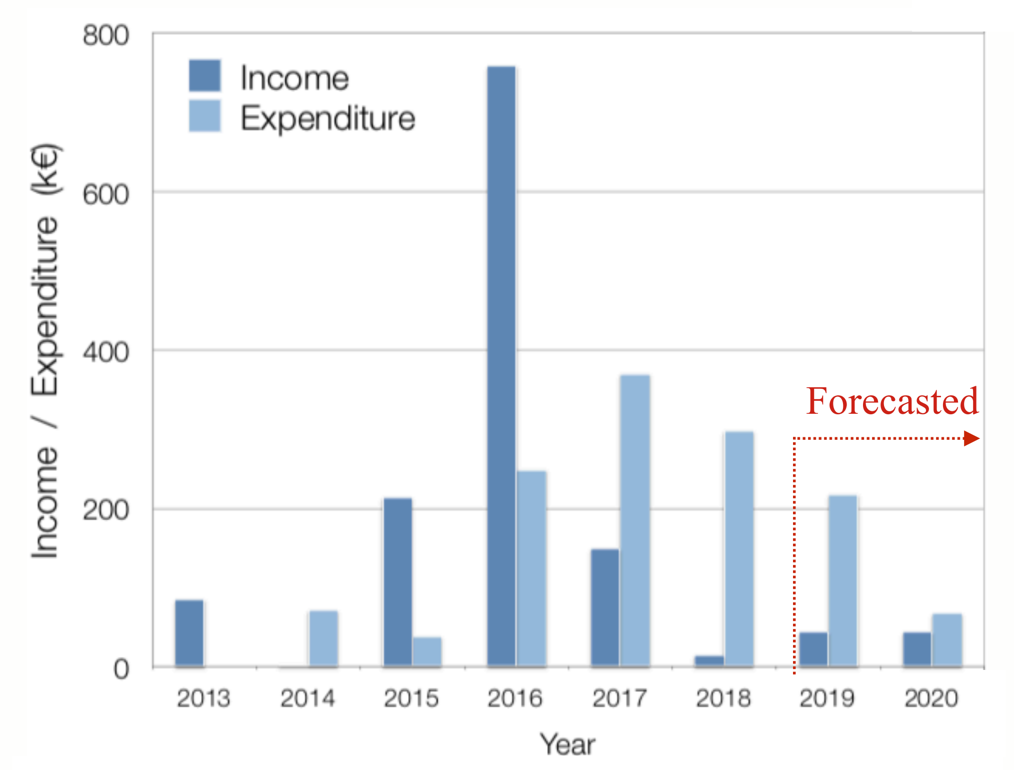
- Central/Leading role and major responsibilities within the collaboration
  - Analysis Coordinator : Frederic Yermia (SUBATECH)
  - Run Co-Coordinator : Luis Manzanillas (LAL)
  - QA/Calibration Coordinator : Luis Manzanillas (LAL) / Valentin Pestel (LPC-Caen)
  - ES WG Coordinators : Benoît Viaud (SUBATECH) / Mathieu Bongrand (LAL)
  - NS WG Coordinators : Valentin Pestel / Benoît Guillon (LPC-Caen)
  - Reactor WG Coordinator : Muriel Fallot (SUBATECH)
  - Pub/Com Board : Mathieu Bongrand (LAL)

- CCIN2P3 ressources
  - Data transfer and storage (1.5 TB per day) on HPSS tapes : already 150 TB
  - Significant CPU resources for data processing used by French groups and some foreign partners
  - Computing tools are under preparation on grid side for UK and Belgium … not favoured at CCIN2P3

French fundings

- Detector construction (~1/3 of the overall) secured:
  - Mines-CARNOT (SUBATECH-2013): **100 k€** → SM1 Prototype
  - Own laboratory ressources (LAL, SUBATECH, LPC-Caen-2015): **150k€** → 1 module target
  - ANR-16-CE31-0018-03, coord F. Yermia (LAL, SUBATECH, LPC-Caen): **600k€** → 1 module target + 3 Post-Docs
  - UCA (LPC-Clermont-2017): **20k€** → Container Instrumentation
  - IN2P3 dotations (2016-2017-2018): **95k€** → Travel expenses, CROSS





- Funding needed for the next coming years
  - Travel expenses, detector maintenance, decommissioning

Summary & Perspectives

- Successful NEMENIX and SM1 runs

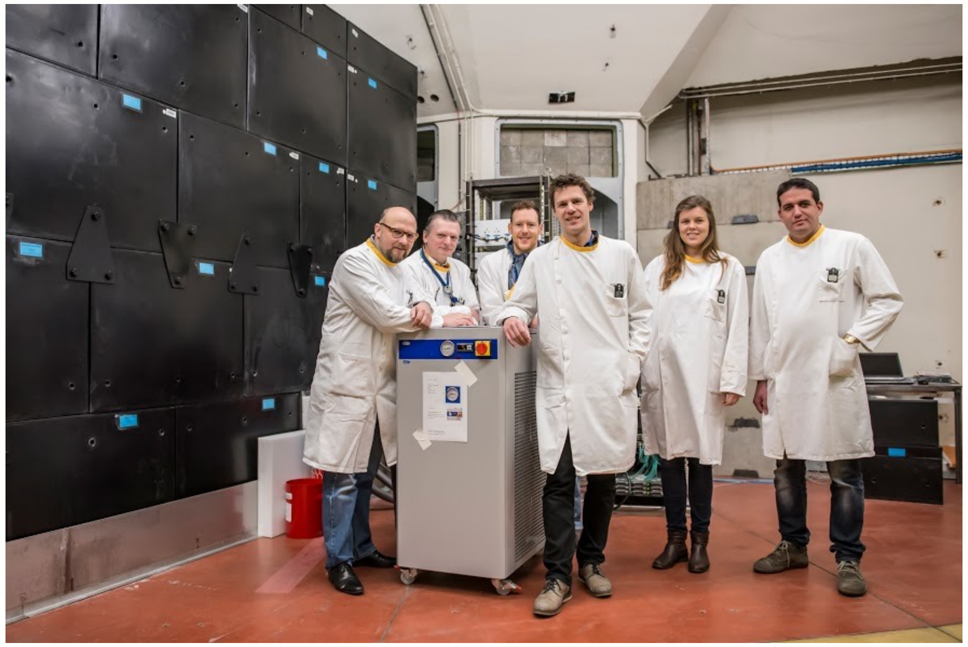
[Y. Abreu et al., A novel segmented-scintillator antineutrino detector, JINST 12 (2017) P04024.]
[Y. Abreu et al., Performance of a full scale prototype detector at the BR2 reactor for the SoLid experiment, JINST 13 (2018) P05005.]

- Detector construction & QA completed end 2017

Funded by

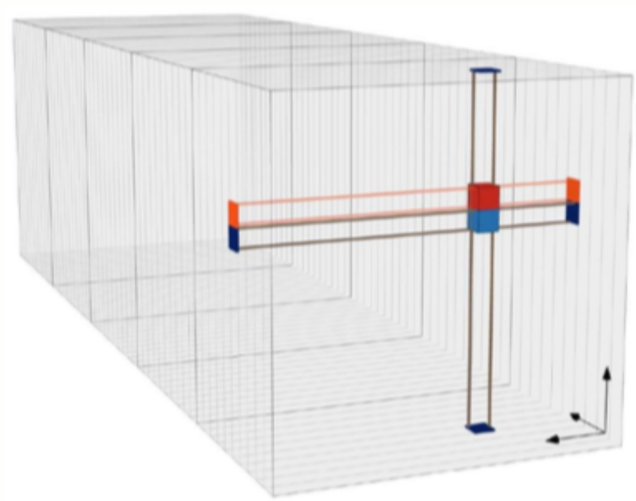
[Y. Abreu et al., Optimisation of the scintillation light collection and uniformity for the SoLid experiment, arXiv:1806.02461.]
['Quality assurance process for the Phase-I SoLid experiment' … currently being written]
['Solid Phase-I detector design' … currently being written]

- Successful commissioning @ BR2
  - SiPMs equalized at the 1.4% level
  - LY > 60 PA/ MeV
  - Neutron trigger efficiency > 70 %
  - Stable running conditions



Summary & Perspectives

- SoLid is currently taking good quality physics data
  - First physics results coming real soon !!!
  - Six BR2 cycles (150 days Reactor-On) in 2018
    - First Oscillation Analysis [Rate-Only]
    - ^{235}U energy spectrum measurement



- Intense activities the next four coming years within a competitive international framework
  - SoLid data-taking planned for 3 years
  - Sterile neutrino search at eV-scale
    - Event reconstruction under continuous development
      (Cut-based, MVA, Deep Learning ...)
  - ^{235}U energy spectrum measurement and deviation study
    - HEU-LEU fuel comparison (Double-Chooz,…)
    - 'Ab initio' summation method
  - Enhance the technology development
    - Neutron detection, Non-proliferation

[Gariazzo et al., JHEP06(2017)135]