

SoLi $\partial$



# The SoLi $\partial$ experiment @ BR2

## New Reconstruction and Calibration techniques

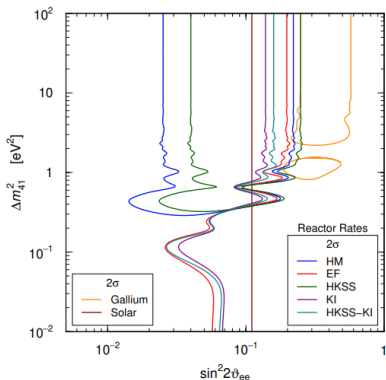
**Mykhailo Yeresko** (LPC, Clermont University and CNRS/IN2P3)  
On behalf of the SoLi $\partial$  collaboration

41th International Conference on High Energy Physics 2022

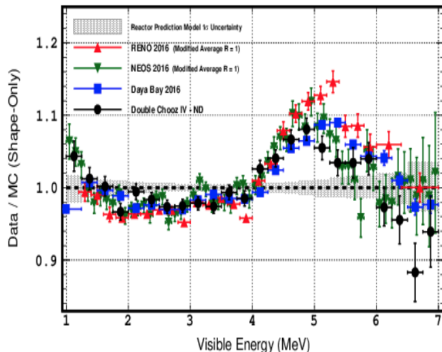
July 8, 2022

# Physics motivation

arXiv:2110.06820v1

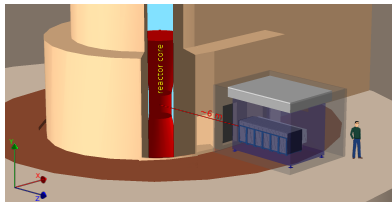


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- ▶ Deficit w.r.t. predictions of reactor/source anti-neutrino flux
- ▶ Oscillations to light sterile neutrino state could account for it
- ▶ Distortion of reactor  $\bar{\nu}$  energy spectrum, aka the "5 MeV bump"

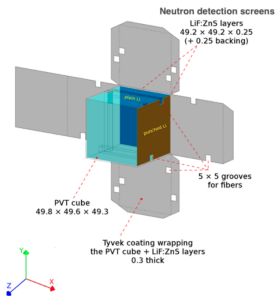
# The SoLi $\partial$ experiment



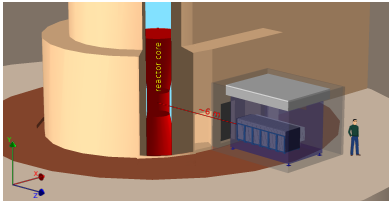
- ▶ Set at the BR2 research reactor (Mol, Belgium)
  - ▶ Compact core ( $\varnothing$  50 cm)
  - ▶  $^{235}\text{U}$  enriched reactor core (95%)
  - ▶ Very short baseline experiment [6.5-9] m
  - ▶  $\approx$  140 days of operation/year

## ▶ Detector layout:

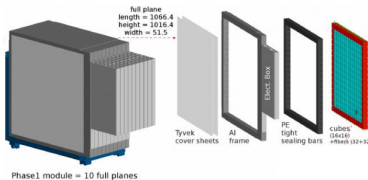
- ▶ 5cm sided cube made of polyvinyltoluene lined with 2 layers of  $^6\text{LiF}:\text{ZnS}$
- ▶ Individual cubes wrapped with Tyvek
- ▶ Light is taken to the boundaries by wavelength-shifting optical fibres
- ▶ Cubes arranged in layers of  $16 \times 16$  units
- ▶ Layers are further optically decoupled with two square Tyvek cover sheets



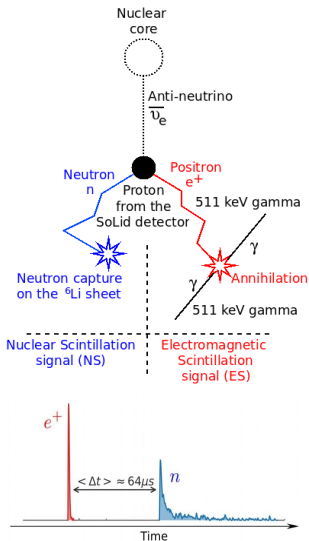
# The SoLi $\partial$ experiment



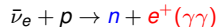
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# The detection principle

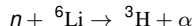


- ▶ Inverse beta decay (IBD) to detect  $\bar{\nu}$ :



- ▶ Neutron scintillation signal [NS]:

- ▶ Generated by the ZnS
- ▶ Energy is issued from  $n$  capture on the  $^6\text{Li}$



- ▶ Electromagnetic scintillation signal [ES]:

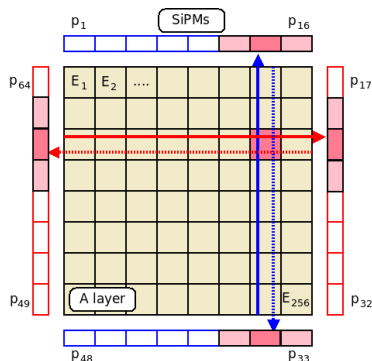
- ▶ Generated by the PVT
  - ▶ Proton-rich  $\bar{\nu}$  target
  - ▶ Measures  $e^+$  ionisation energy
  - ▶ Measures annihilation  $\gamma$  energy
- ▶ **High granularity allows to distinguish ionisation and annihilation contributions!**

- ▶ NS and ES correlated in time:  $\Delta t = t_{NS} - t_{ES}$

# New reconstruction [CCube algorithm]

- ▶ The fibres project the deposited energies to the boundaries of the detector
- ▶ The digitised SiPM readout from the fibers are the raw detector data  
⇒ Reverse engineering is required to restore the list of involved cubes

- ▶ Each layer is a *separate* problem
- ▶ Parametrisation:
  - ▶ Unknowns: PVT deposits ( $E_i$ )
  - ▶  $p_j$  are the SiPM measurements
- ▶ Challenges:
  - ▶ Cube projects through adjacent fibers
  - ▶ Fibers can overflow during the run



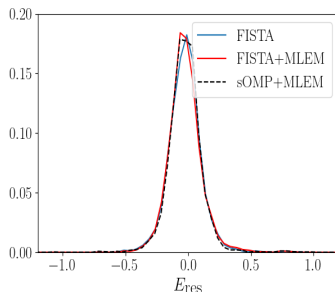
# New reconstruction [CCube algorithm]

The reconstruction problem can be put down as the following:

$$p = AE,$$

where  $A$  is so-called system matrix (SM) which embodies overall response of the detector. This equation has been widely studied in medical imaging and particle physics.

- ▶ Several algorithms has been tested
- ▶ The choice of the initializer has a large impact
  - ▶ Fibers with more light should be preferred to form a cube  $\rightarrow$  Orthogonal Matched Pursuit
- ▶ sOMP+ML-EM shows superior performance:
  - ▶ For the reconstruction efficiency
  - ▶ For the fake cubes ( $\text{👻}$ ) rate
  - ▶ Similar energy resolution = 13%



Method	FISTA	FISTA+ML-EM	sOMP+ML-EM
$\text{👻}$ (%)	15.8	11.4	6.9
$\epsilon$ (%)	75.3	76.3	77.7

# ES calibration overview

- **Calibration w/ horizontal muons:**

- Relative calibration
  - Higher precision
- Access to the Light Leakages
- Time evolution of the response
- Absolute scale calibration(?)
  - dE/dx values

- **Calibration w/ radioactive sources:**

- Relative calibration
- Time evolution of the response
  - Calibration campaigns required
- Absolute scale calibration:
  - $^{22}\text{Na}$ : developed, low energy range
  - AmBe: TBD, desired energy range

## SoLi $\theta$

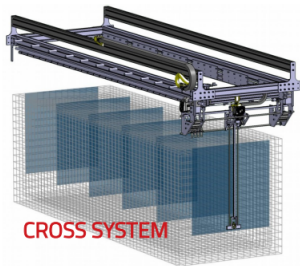
- **Crosschecks:**

- Identification of the well-known sources of the bckg
  - Cosmogenic ( $^{12}\text{B}$ , etc.)

- **Crosschecks:**

- Validation with natural radiation source ( $^{214}\text{Bi}$ )
- Data/MC comparison

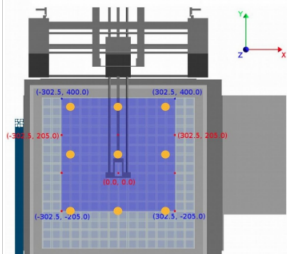
# Calibration with sources



- ▶ Automated calibration system (CROSS)
- ▶ 9 radioactive source positions in 6 gaps
- ▶ Each gap is used to calibrate  $\pm 5$  planes around ( $\sim 25$  cm)  $\Rightarrow$  Need for penetrating sources
- ▶ Available calibration sources:
  - ▶ Gamma sources:  $^{137}\text{Cs}$ ,  $^{207}\text{Bi}$ ,  $^{22}\text{Na}$ , AmBe
  - ▶ Neutron sources:  $^{252}\text{Cf}$  and AmBe

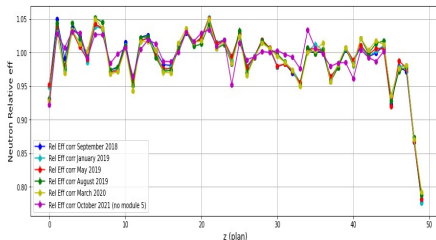
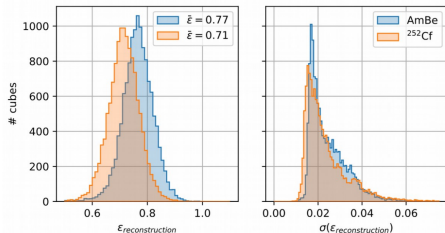
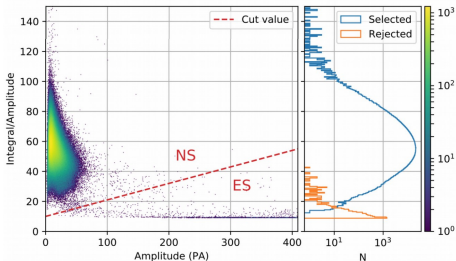
## Challenges:

- ▶ Calibrate 12 800 detection cells and 3 200 channels with several calibration parameters:
  - $\Rightarrow$  > 20 000 parameters to measure and correct
- ▶ Cube signal that combines signals of 4 fibers:
  - ▶ Difficult to split cube effect from fiber effect
  - ▶ Each fiber is shared by 16 cubes inducing correlations between cubes



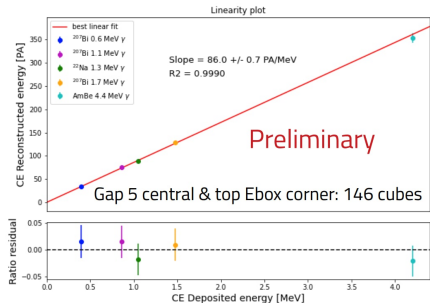
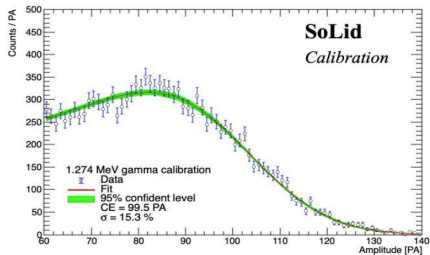
# Calibration with sources [NS]

- ▶ Good NS/ES discrimination
- ▶ Good agreement between the 2 sources
- ▶  $\epsilon_{\text{Neutron}} = 73.9^{+4.0}_{-3.3}\%$  measured per cube
- ▶ Relative module detection efficiency within 3% (< 1% for 4 modules)



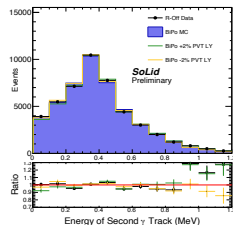
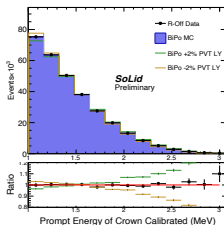
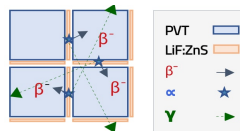
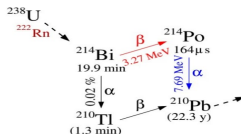
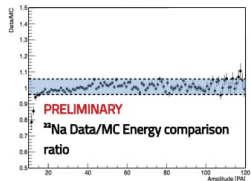
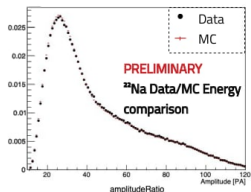
# Calibration with sources [ES]

- ▶ No access to the photoelectric peak  
⇒ Compton edge fit
- ▶ Two approaches ⇒ [Light Yield (LY - #PA/MeV) + energy resolution]:
  - ▶ Klein-Nishina based analytical fit
  - ▶ Kolmogorov-Smirnov test
- ▶ Channel parameters measured/quantified
  - ▶ SiPMs equalized at 1% level
  - ▶ Individual Fiber attenuation
  - ▶ Fiber – SiPM optical coupling
- ▶ < 5% LY variations module per module
- ▶ Linearity in the [.5 – 4] MeV region
- ▶ Eres  $\sim$  15% at 1 MeV



# Crosschecks and validations

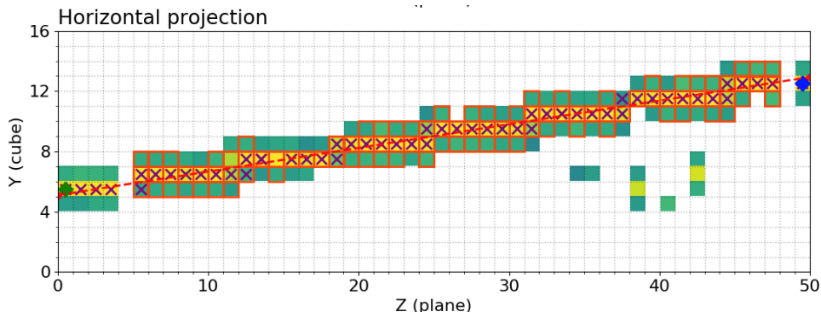
- ▶ An important work has been done to achieve good Data/Monte Carlo agreement
- ▶  $^{22}\text{Na}$  source  $\Rightarrow$  Data/MC at low energy for cubes and fibers.  $<5\%$  in  $[.2, 1.2]$  MeV region
- ▶  $^{214}\text{Bi}$  induced internal background as a proxy for IBD signal
  - ▶ Pure BiPo sample is selected w/ employing 187 days of ROFF
  - ▶ Probe MC's ability to describe complex topologies



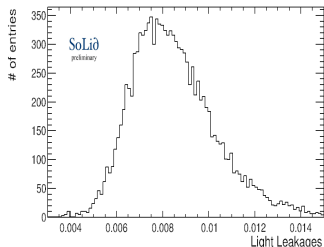
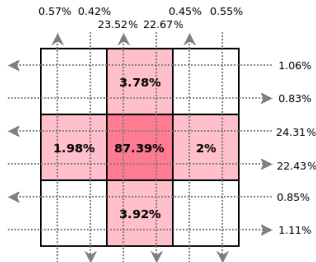
# Calibration with horizontal muons

Horizontal muons as the calibration tool allows to:

- ▶ Complete the relative calibration of the whole detector
  - ▶ Control the time evolution of the detector response
  - ▶ Extract the amount of the light leakages to the neighbouring cubes
  - ▶ Provide the ballpark for the absolute energy scale calibration
- ⇒ To be compared and checked with the calibration sources



# Relative calibration with horizontal muons



- ▶ 1 crossed cube per plane  $\Rightarrow$  clear posed problem
- ▶ With a track fit,  $\frac{dE}{dx}$  per hit cube can be calculated
- ▶  $>1$  impacted cube per plane  $\Rightarrow$  access to the LL!
- ▶ For the hit and adjacent cubes fibers define the fractions:
 
$$f = \frac{E_{\text{Fibre}}}{E_{\text{Plane}}}$$
- ▶ Fit the Kullback–Leibler divergence
- ▶ Build the  $\frac{dE}{dx}$  distribution per cube [1]
- ▶ Build an average detector  $\frac{dE}{dx}$  distribution [2]
- ▶ Set the fit result scaled by  $\frac{[2]}{[1]}$  as a SM element  
 $\Rightarrow$  Relative calibration!
- ▶ 10 days provides  $<1\%$  statistical uncertainty

# Crosschecks and validations [ $^{12}\text{B}$ ]

- ▶ Reconstruction & calibration technique is checked by searching the cosmogenic bckg

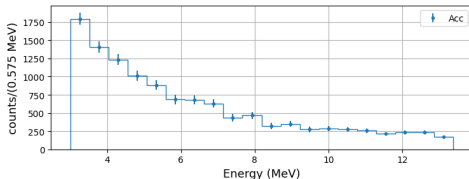
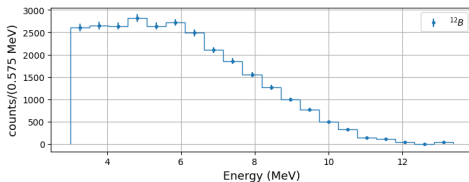
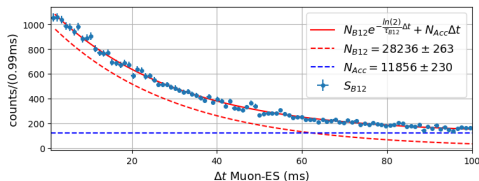
$$\mu^- + {}^{12}\text{C} \rightarrow \nu_{\mu}^- + {}^{12}\text{B} \rightarrow \beta^-$$

- ▶ Selection a la STEREO:
  - ▶ Stopping muon identified
  - ▶ Distance ES  $\rightarrow$  muon end point  $\leq 1$  cube
  - ▶ Time correlation in the range of  $[1, 100]\mu\text{s}$
  - ▶ Time to another muon tracked  $> 200\mu\text{s}$
- ▶ Total energy of the event  $> 3$  MeV to further reject background
- ▶ The  $^{12}\text{B}$  yield is estimated by the difference in time fit with the following model:
  - ▶ An exponential component with the  $^{12}\text{B}$  decay time
  - ▶ A flat accidental background contribution

$$\Delta t(\text{Muon} - \text{ES}) = N_{\text{B}_{12}} \exp\left(-\frac{\Delta t}{\tau_{\text{B}_{12}}}\right) + N_{\text{Acc}} \Delta t$$

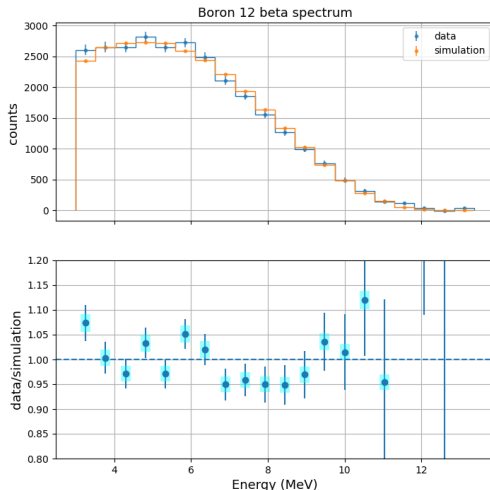
# Crosschecks and validations [ $^{12}\text{B}$ ]

- ▶ Stats for 100 ROff days is shown
- ▶ Fit results:
  - ▶  $\chi^2/\text{ndf} = 0.95$
  - ▶  $\text{S/B} = 2.4$
- ▶ Next: check the energy spectrum
- ▶ **sPlot technique** is used to statistically subtract the background
- ▶  $\Delta t(\text{Muon} - \text{ES})$  is considered as a discriminative variable



# Crosschecks and validations [ $^{12}\text{B}$ ]

- ▶ The acquired energy spectrum is compared with Monte-Carlo simulation
- ▶ Not only the  $^{12}\text{B}$  is identified, but proper energy spectrum is obtained

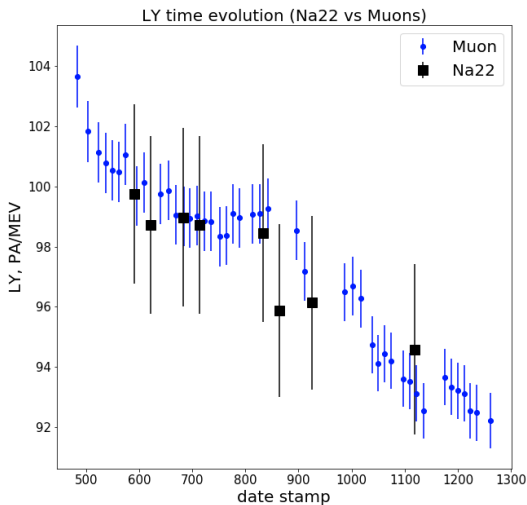


# Absolute energy scale calibration

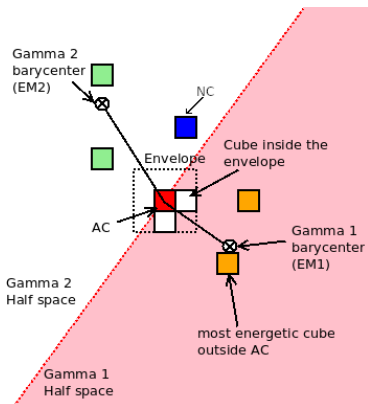
- ▶ Split relative and absolute calibrations is a feature of the muon calibration  $\Rightarrow$  various inputs can be used as an absolute energy scale
- ▶ Available options are the following:
  - ▶ From muons:  $\frac{dE}{dx}$  value from Geant4 MC simulation or from PDG  
 $\Rightarrow$  Disadvantages: high region of the energy spectrum
  - ▶ From  $^{22}\text{Na}$ : 1.06 MeV CE. Method developed and crosschecked  
 $\Rightarrow$  Disadvantages: low region of the energy spectrum
  - ▶ From AmBe: 4.2 MeV CE. At the heart of the desired energy spectrum. Similar to  $^{22}\text{Na}$  techniques can be employed.
- ▶ The differences b/w possible choices are currently under investigation

# Absolute energy scale calibration

- ▶ Light yield time evolution comparison for the two calibrations
- ▶ First  $^{22}\text{Na}$  point is scaled (increased by 3%) to match the first muon point



# Prospects for the analysis



- ▶ Newly implemented methods allow to fully use the high granularity of the detector:
  - ▶ Precisely define the position of the event
  - ▶ Split ionisation & annihilation energy deposits
- ▶ Open new opportunities for the bckg rejection based on the geometrical topologies analysis
  - ▶ Events w/ annihilation  $\gamma$  provide way more complicated patterns to mimic by the bckg
- ▶ Three independent analysis ongoing in parallel:
  - ▶ 2 employ splitting the detector in half-spaces based on the back-to-back  $\gamma$  property
  - ▶ 1 which tracks  $\gamma$  w/ Klein–Nishina formula
- ▶ S/B of 1 is targeted for the  $2\gamma$  events
  - ▶ Has been reached for the open data set! [1,2]

# Summary and Outlook

- ▶ The novel reconstruction of the EM signal in the SoLi $\partial$  detector has been discussed
- ▶ Recent works on the calibration of the SoLi $\partial$  detector have been reviewed.
- ▶ Relative calibration of the cube responses at 1% level per fiber as well as the light leakages is obtained by means of horizontal muons
- ▶ This novel calibration allows to follow the evolution of the detector.
- ▶ The system matrix is constructed for 10 days of data taking
- ▶ Calibration with radioactive source are concurrently performed. To be used in the determination of the absolute energy scale
- ▶ Several successful cross-checks (e.g. identification and reconstruction of the energy spectrum of  $^{12}\text{B}$ ) provide confidence in the methods employed
- ▶ These novel reconstruction and calibration procedures allow to maximally benefit of the spatial granularity of the SoLi $\partial$  detector
- ▶ They are currently being used to finalise the selection of antineutrino candidates
- ▶ Stay tuned for the full Phase I data set oscillation analysis!

BACKUP