

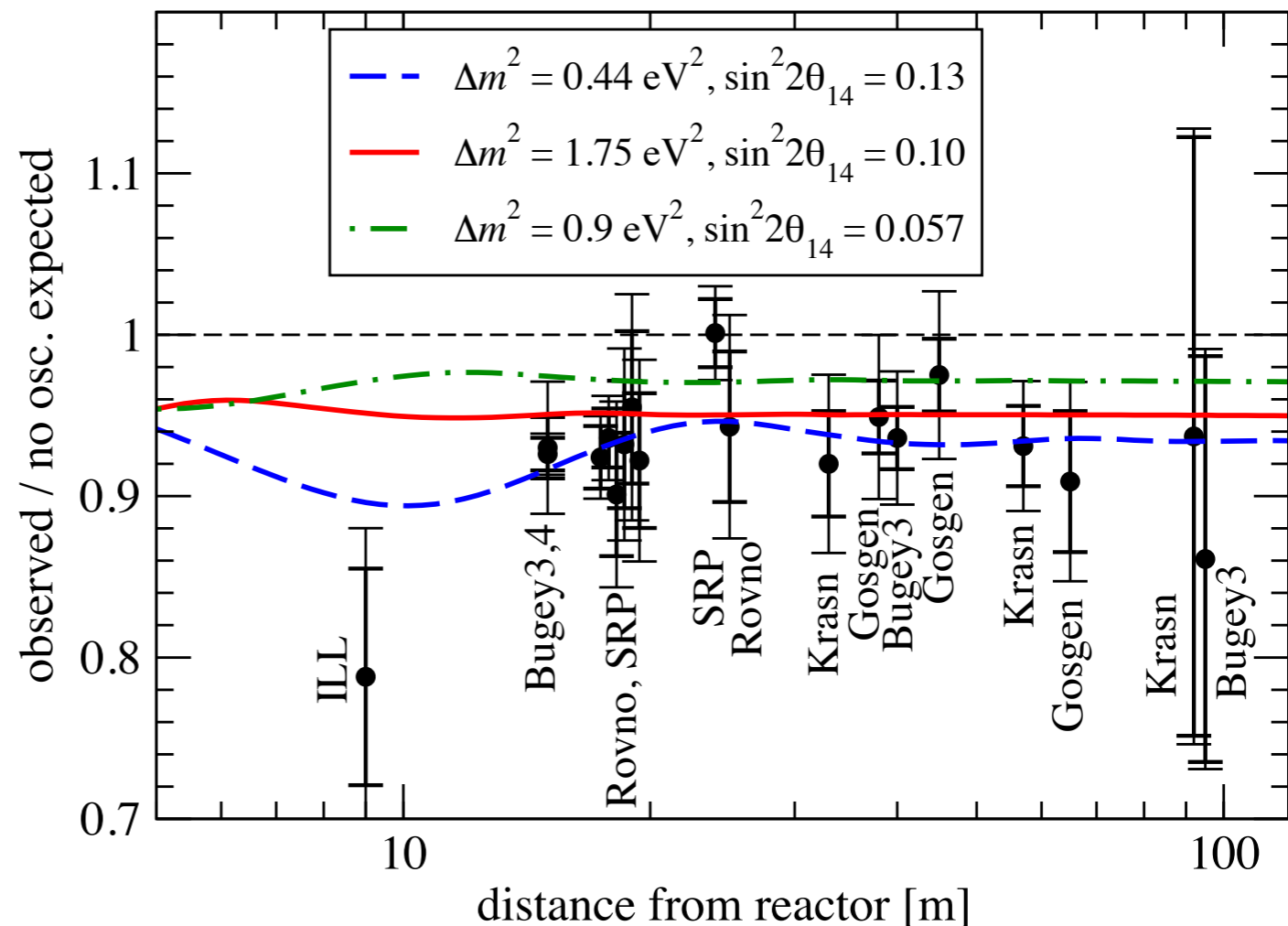
# SoLid: Search for Oscillations with a Lithium-6 Detector at the SCK•CEN BR2 reactor

Recent Analysis Results

*Daniel Saunders, on behalf of the SoLid collaboration*

# Motivation (*reminder*)

- Systematic flux deficit in previous reactor  $\bar{\nu}$  experiments:  $2.7\sigma$  [1, 4] - reactor anomaly
- Other motivations from other experiments at different distance scales - see [2]
  - Gallium anomaly ( $2.8\sigma$ ) [3], tension between beam experiments LSND & MiniBoone [3]
- Could be explained by the existence of a sterile neutrino



# Challenges at VSBL

## Detector

- High resolutions for oscillation search:
  - Spatial
  - Energy
- Effective background rejection:
  - Low overburden
  - Reactor radiation

## Reactor

- Compact core
  - Understood fuel composition
  - Access as close as possible
- Security implications (e.g access rights, reduce flammable liquids)

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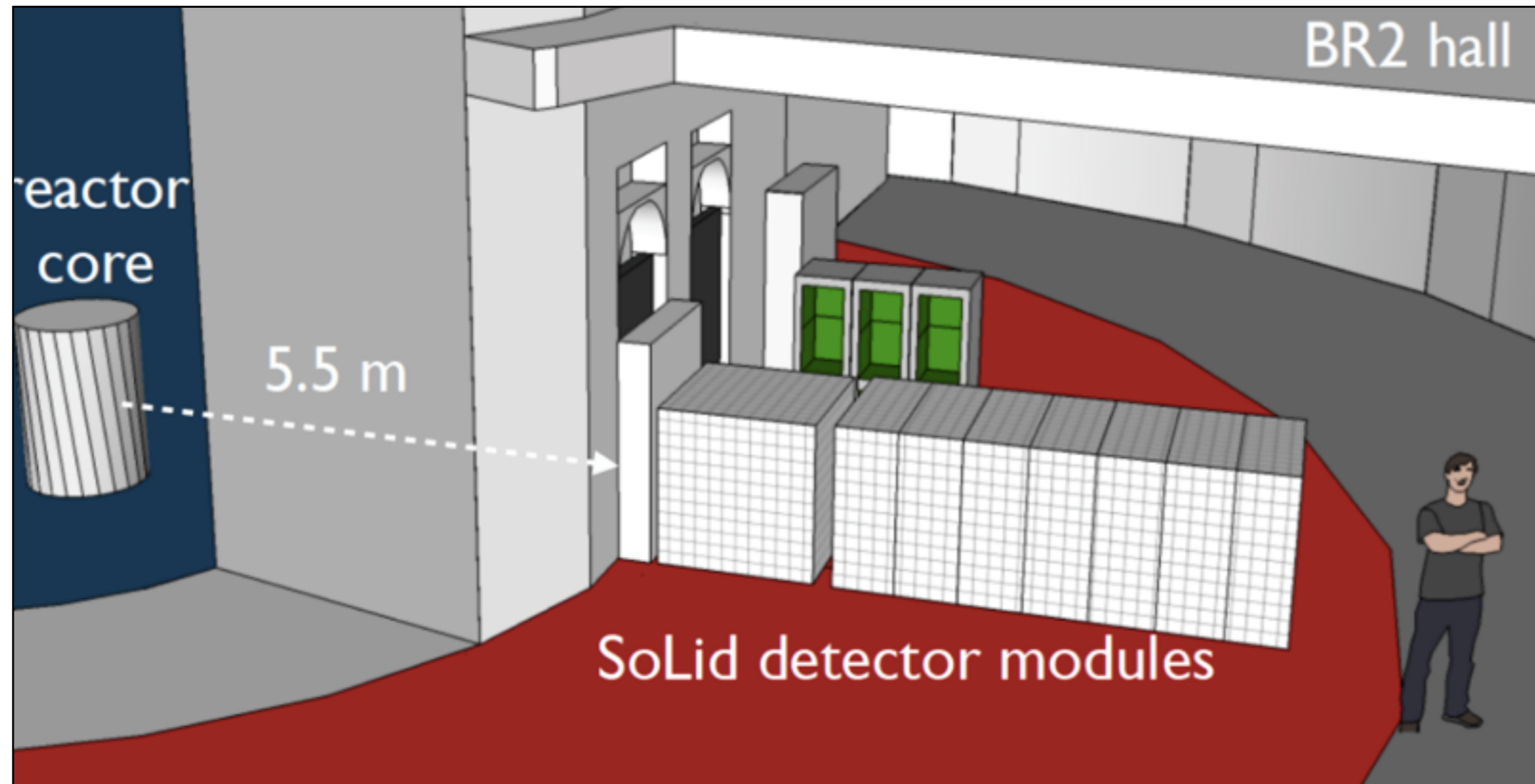
## Reactor

- Compact core
  - Understood fuel composition
  - Access as close as possible
- Security implications (e.g access rights, reduce flammable liquids)

# SoLid Solutions

- Highly segmented detector:
    - Localisation of events
    - (Quasi) 3D topological information
  - Suitable photo detector - SiPMs
  - Active and passive shielding
- 
- Research reactor:
    - Belgian Reactor 2 (BR2) at SCK-CEN
    - Core diameter 0.5m
    - 95% Enriched  $^{235}\text{U}$ , 60MW
    - Access ports for experiments

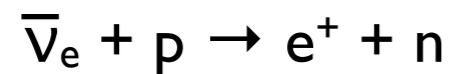
# SoLid



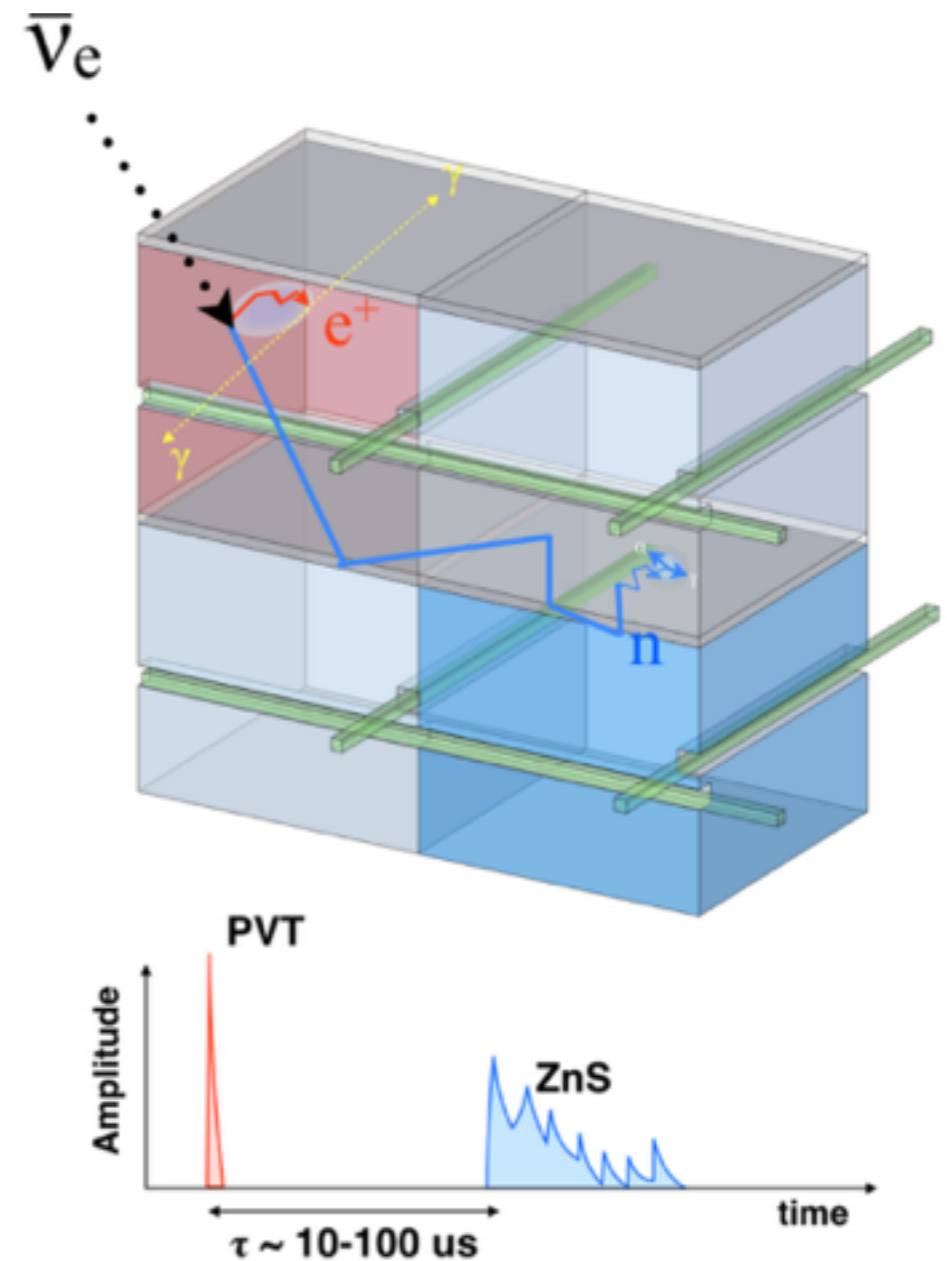
*Sketch of SoLid at BR2 reactor, Belgium*

# Detection Technology

- Neutrinos seen via inverse beta decay (IBD) events (unique topology):



- Prompt  $e^+$  scintillation signal:
  - Energy deposition in small cluster of cubes, away from annihilation  $\gamma$ s
  - Manageable containment of  $\gamma$ s leakage/ pileup - technological advantage
- Delayed  $n$  signal from  ${}^6\text{LiF:ZnS(Ag)}$ :
  - Spatially near the positron
  - Distinguished from PVT via pulse shape discrimination

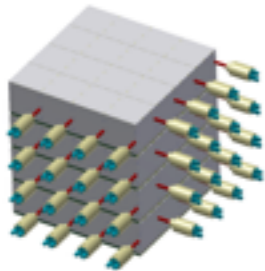


## Advertisement

Dedicated talk on SoLid technology:  
 Leonidas Kalousis, 5<sup>th</sup> Aug 12:00  
 Detector R & D session

# Experiment Status

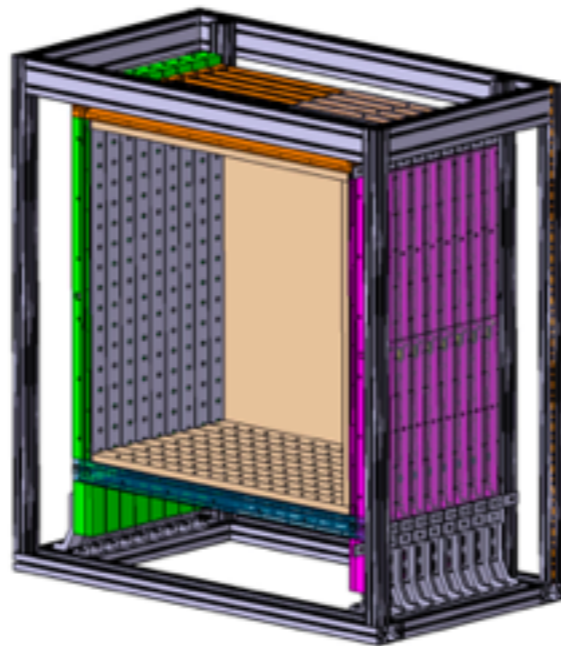
2013



## Nemenix (8kg)

- Proof of concept
- Demonstrate PID

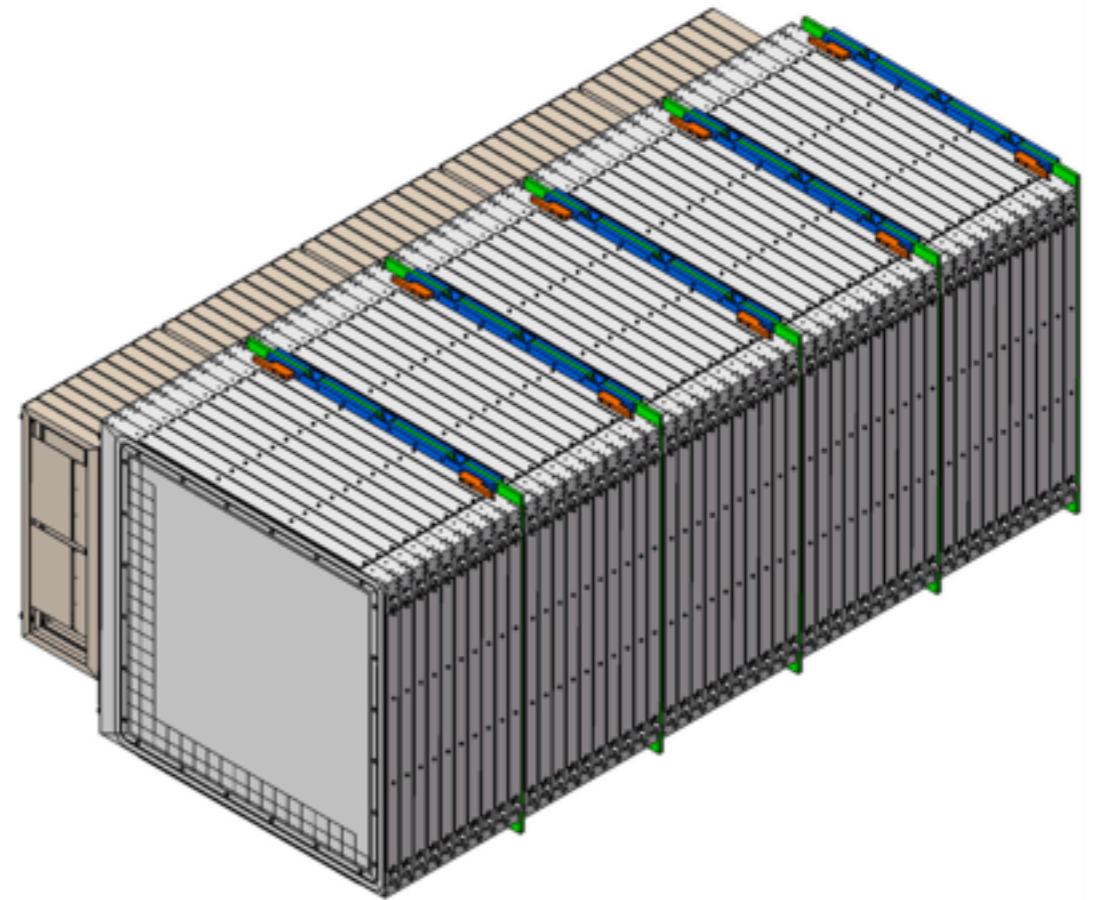
2014-15



## SMI Prototype (288kg)

- Test scalability and production
- Prove power of segmentation

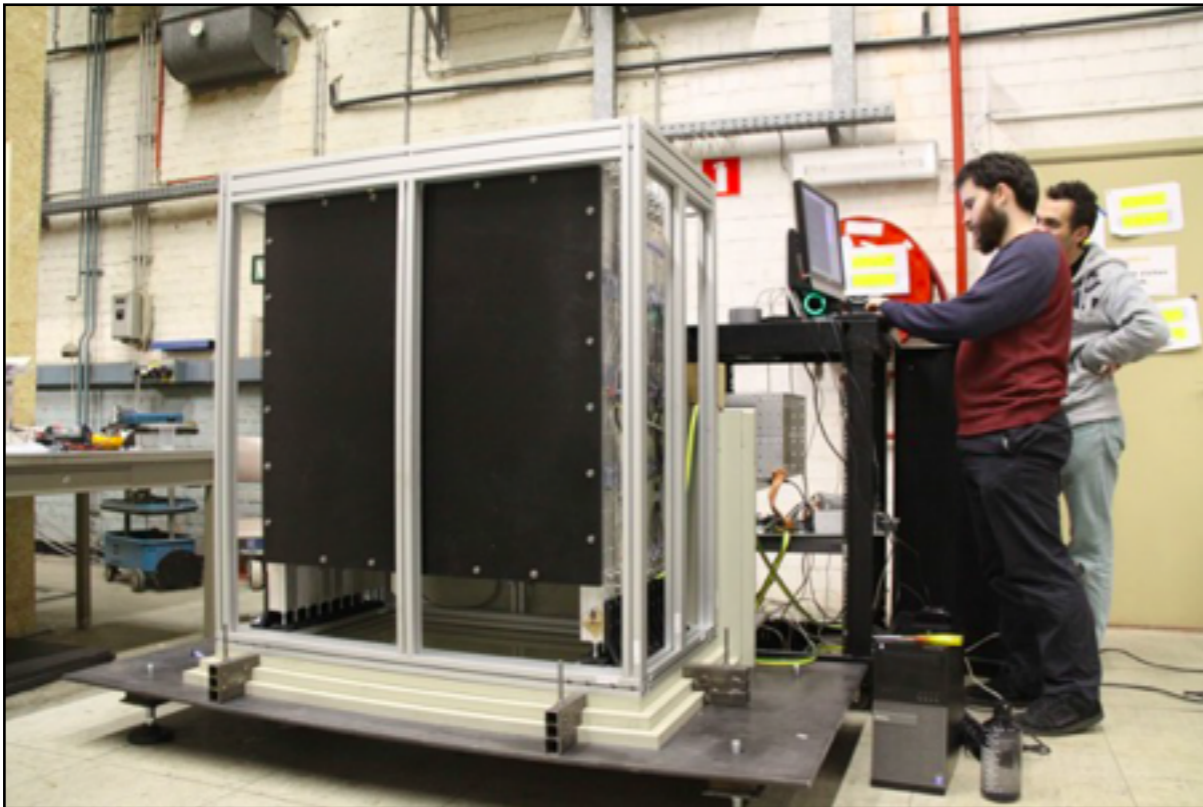
2016-17



## SoLid Phase I (1.6 T)

- 12k cubes with 3.2k channels, ~300 events/day
- Perform initial oscillation search

# Prototype SoLid Module I (SMI)



*Commissioning at Gent, Nov 2014*



*Deployment at BR2, Dec 2014*

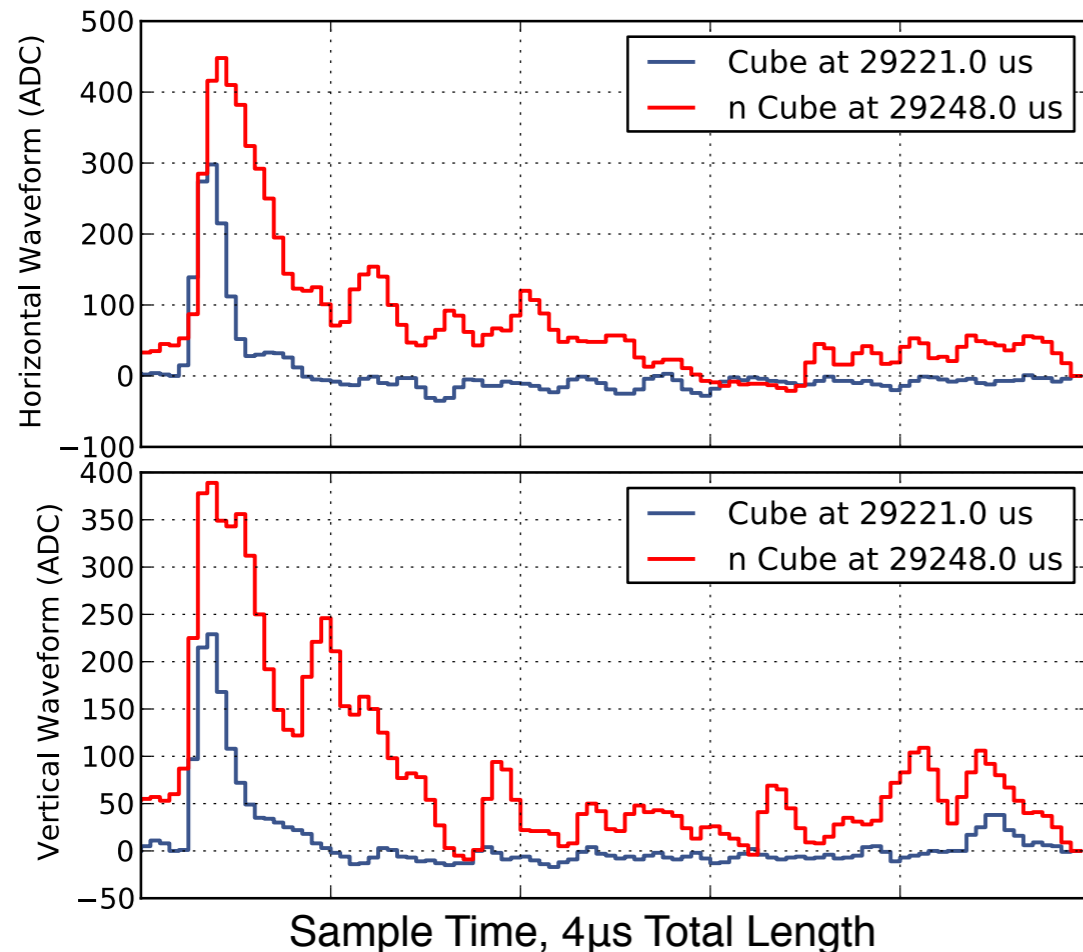
- Deployed at BR2 reactor late 2014 prior to 1 year reactor refit
- 50hr reactor on run. Long reactor off and source calibration runs
- Non-optimal trigger and no passive shielding:  $\nu_e$  signal *not* expected

## Advertisement

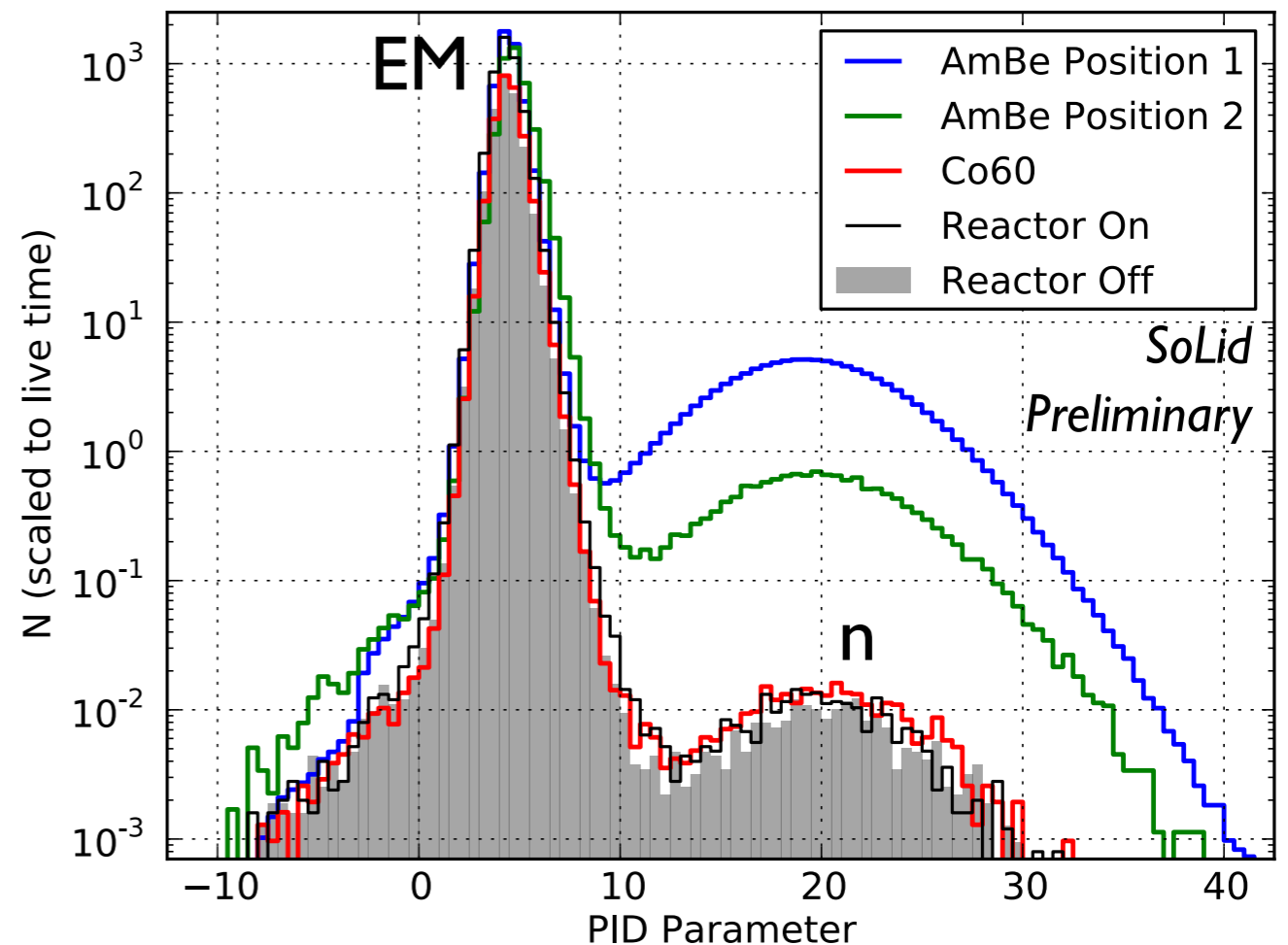
Dedicated poster on construction:  
*Celine Moorgat, 6<sup>th</sup> Aug 18:00*

# Prototype Results

# IBD Reconstruction - Neutrons



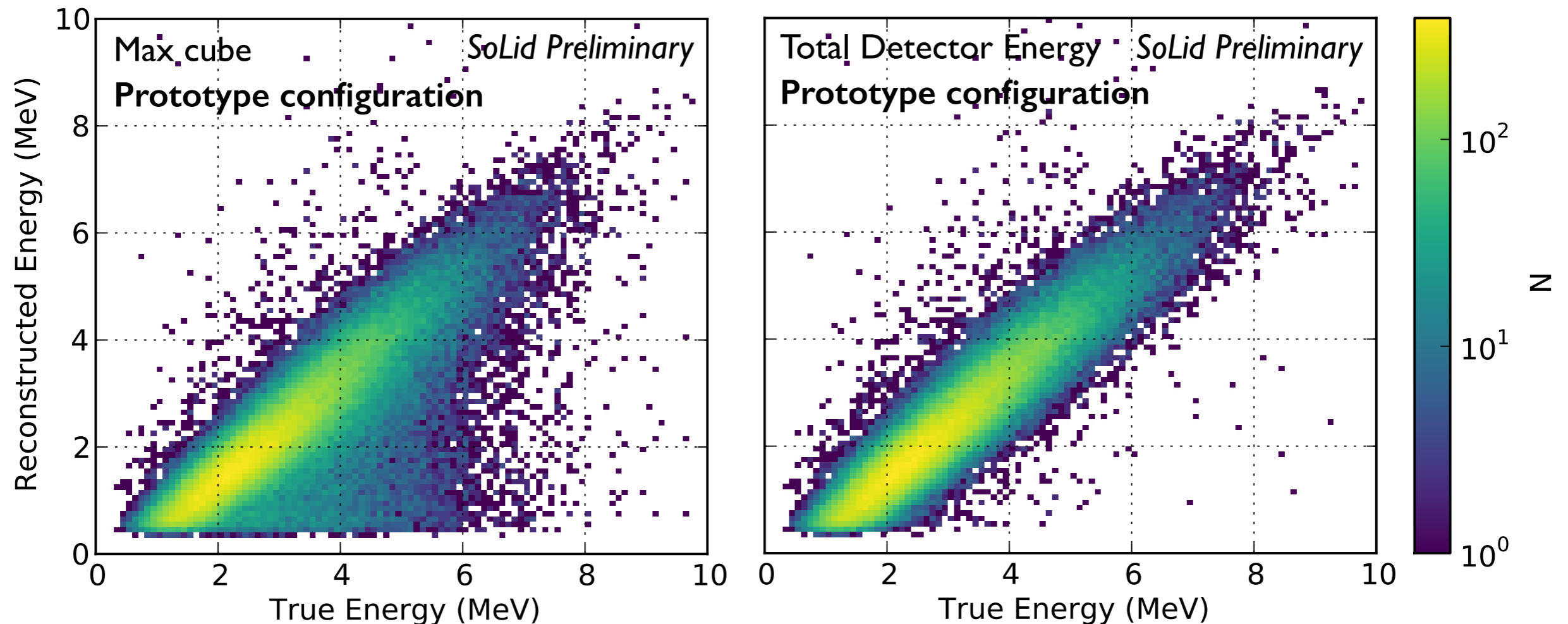
Example IBD candidate SiPM waveforms - **Data**  
**EM signal** and **Neutrons**



Neutron PID for reactor on/off periods and source calibration runs

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

# IBD Reconstruction - Positrons

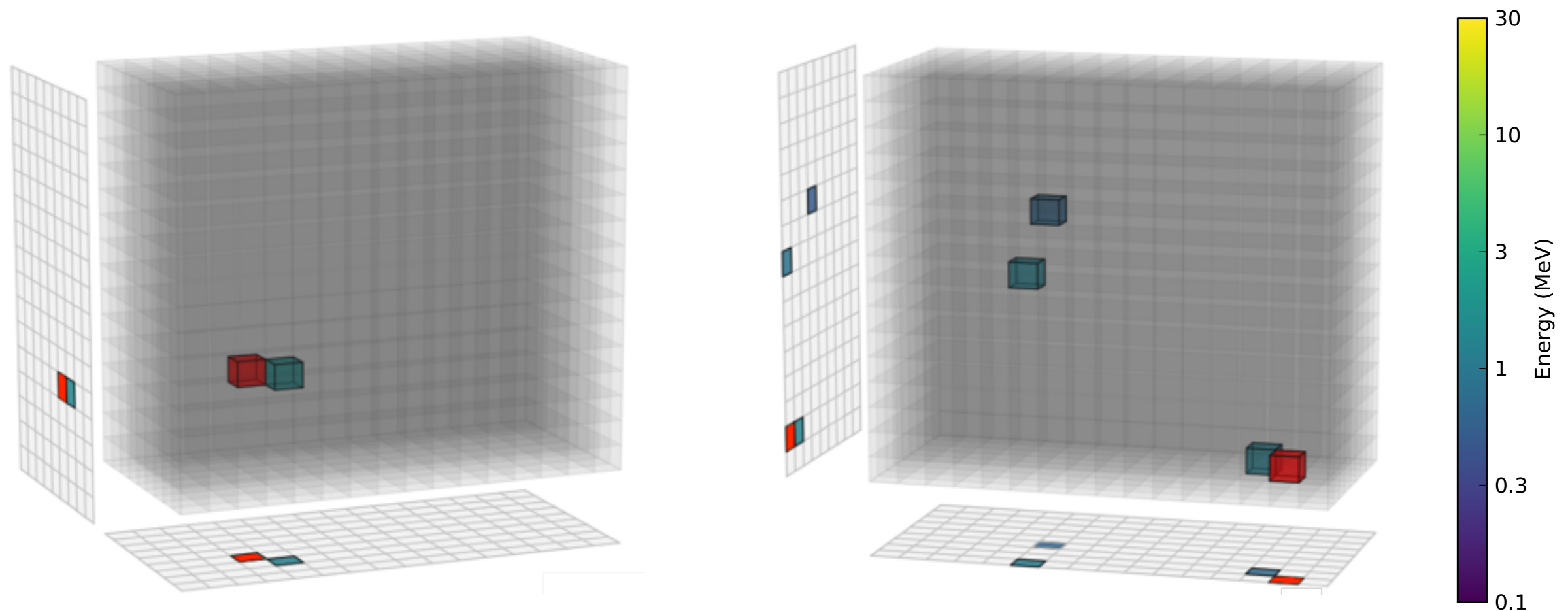


Positron reconstruction algorithm comparison for SM configuration - **Sim.** Readout effects included

- Demonstration of positron energy reconstruction algorithms
  - Nb negligible  $\gamma$  detection efficiency for SM

# IBD Candidates

- IBD analysis techniques developed → cross checked with simulation
- Granularity of the detector allows detailed topological studies

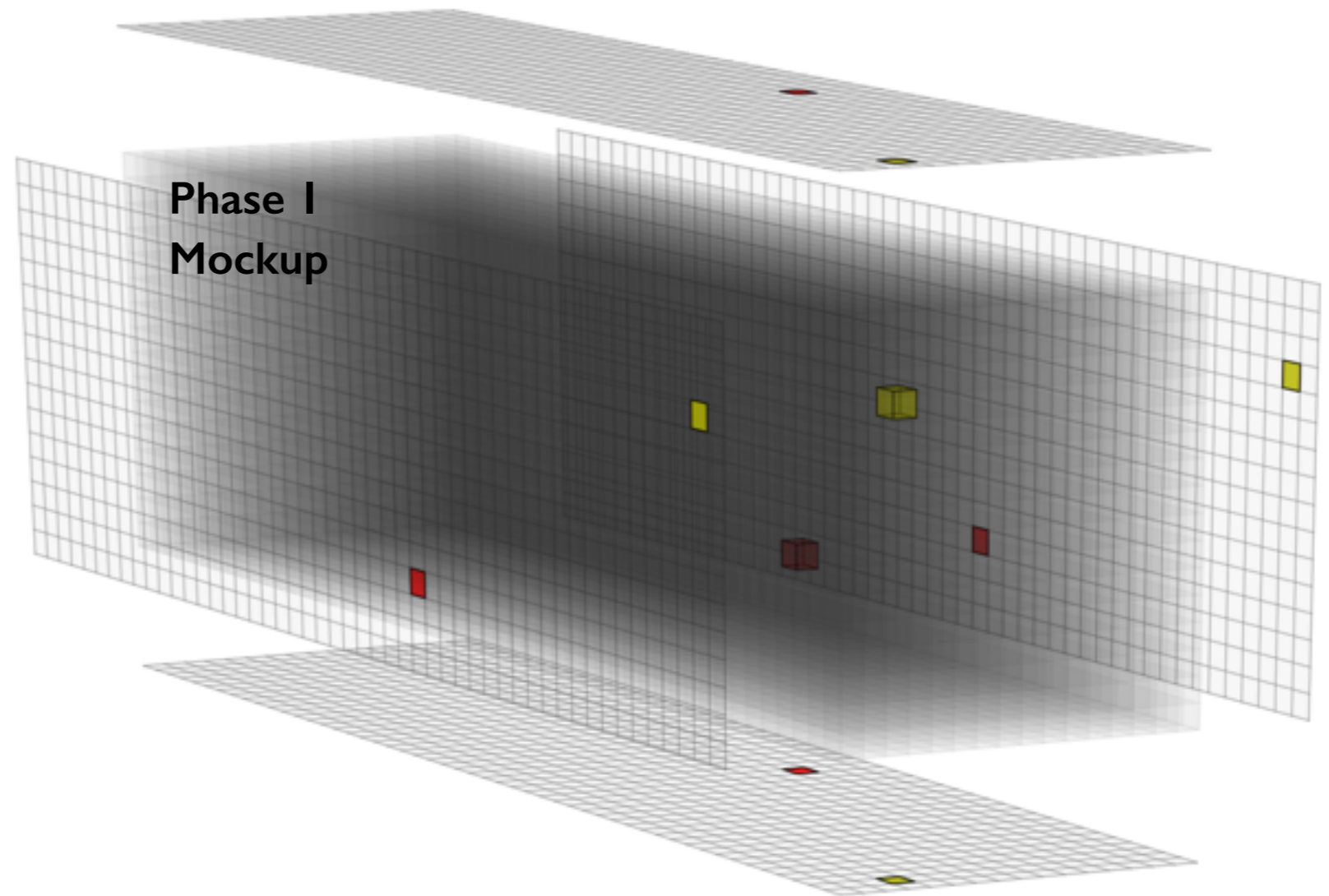


IBD candidates from SMI. Neutrons in **red**, EM signals use colour scale

Left: isolated candidate (waveforms above). Right: candidate with accidental gammas - can be used in analysis

# Backgrounds - Accidental

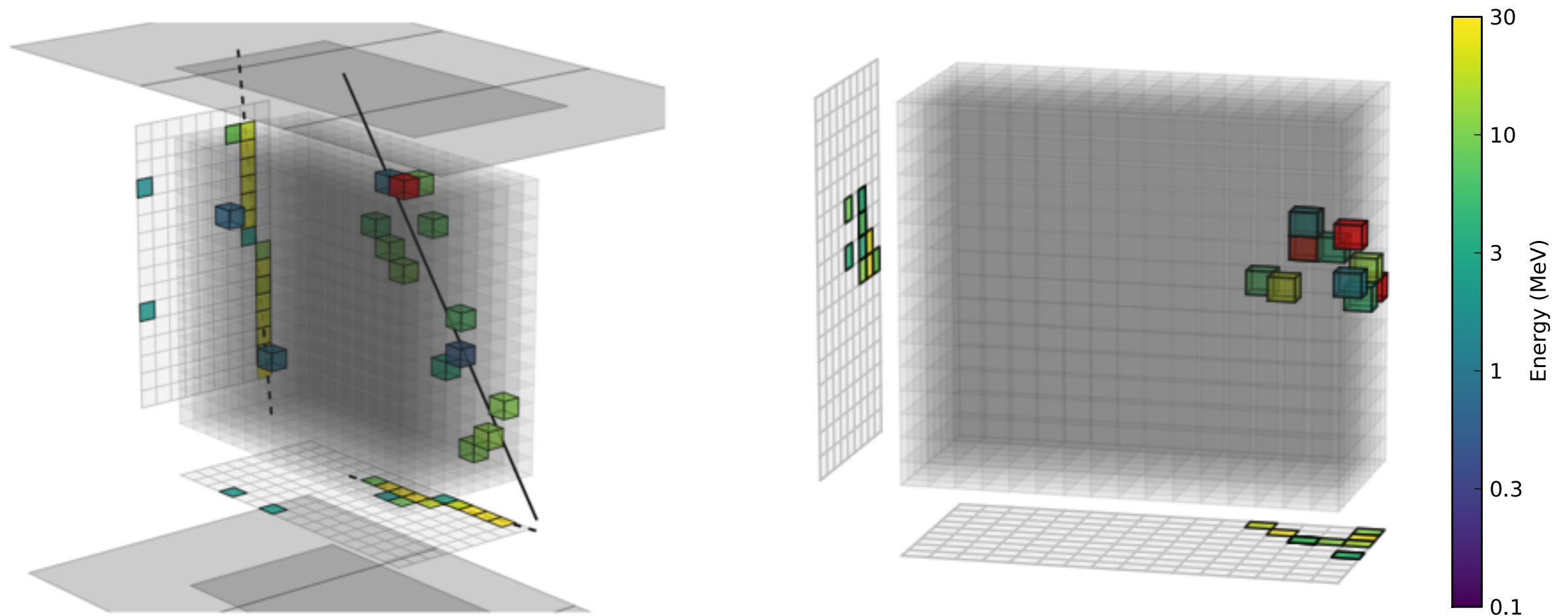
- Random EM event (e.g. reactor  $\gamma$ ) associated to a random neutron (e.g. reactor neutron)
- Studied using off-time windows (reactor on and reactor off)
- Combated with topology and energy selections



*Accidental Background candidates example using phase I configuration*

# Backgrounds - Correlated

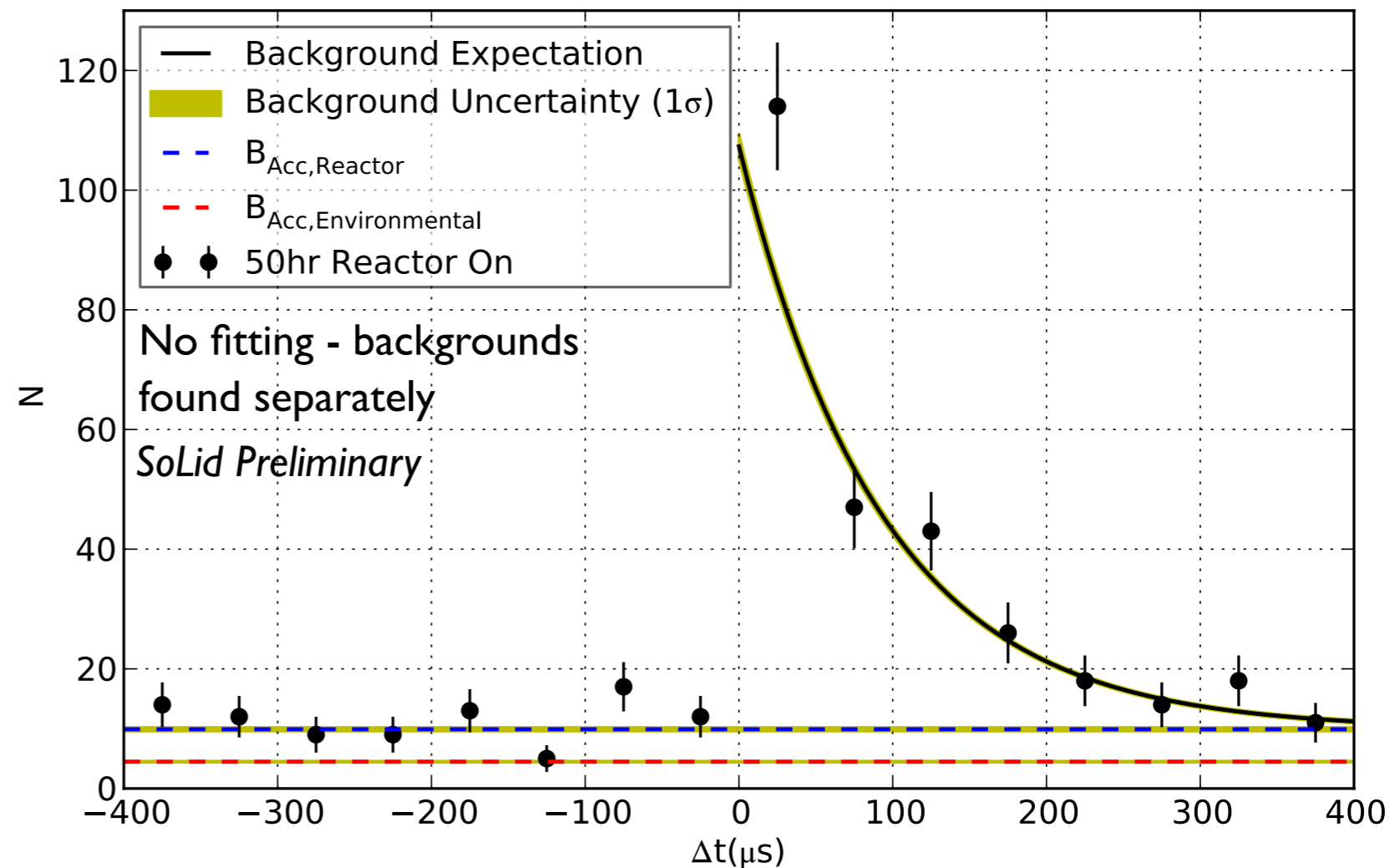
- EM event and neutron produced in same process. Studied using reactor off data, e.g:
  - Muon spallation in the detector - combat with muon ID (energy and channel topology)
  - High energy neutron - combat with multiplicity selections (proton recoils)



*Background candidates. Neutrons in **red**, EM signals use colour scale.  
Left: muon spallation event (**Data**). Right: cosmic neutron event (**Sim**).*

# IBD Features

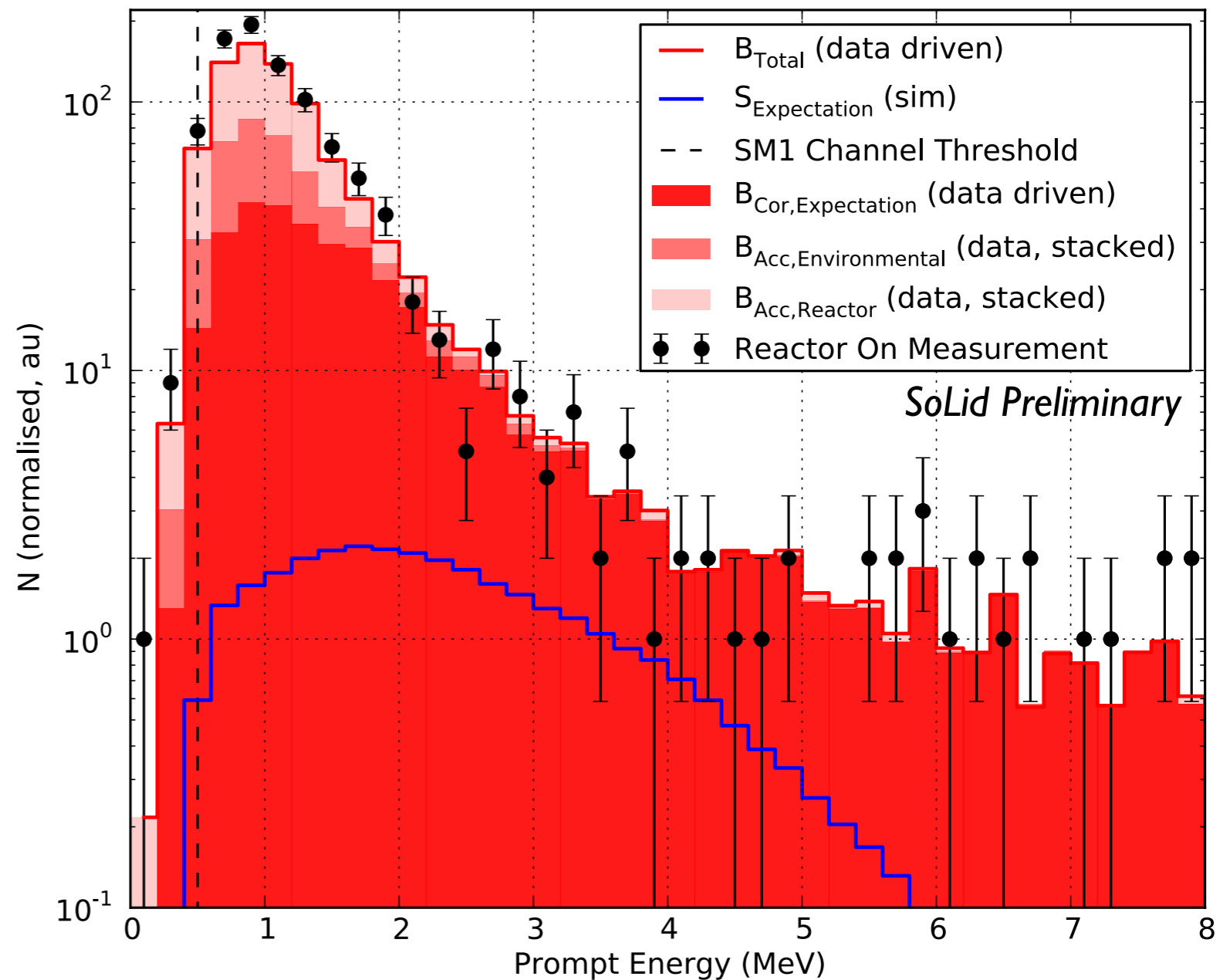
- Reconstruction parameters for each IBD:
  - $\Delta t = t_{\text{Prompt}} - t_{\text{Delayed}}$



*Reactor on-off comparison for time separation between prompt and delayed events. Background components shown (data driven)*

# IBD Features

- Reconstruction parameters for each IBD:
  - $\Delta t = t_{\text{Prompt}} - t_{\text{Delayed}}$
  - Prompt Energy

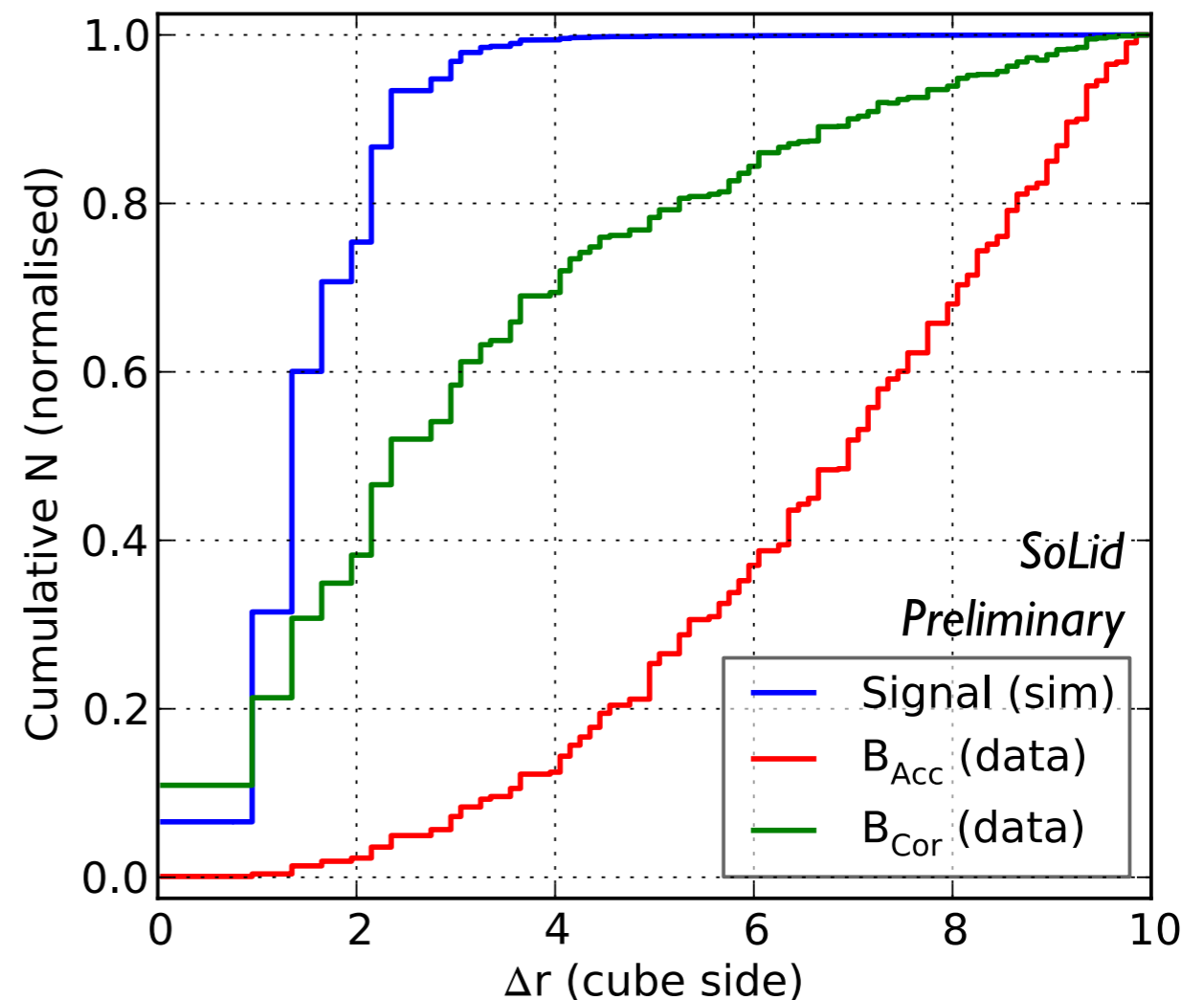


*Reactor on-off comparison of prompt energies*

*N.b Prototype had no shielding and high trigger thresholds*

# IBD Features

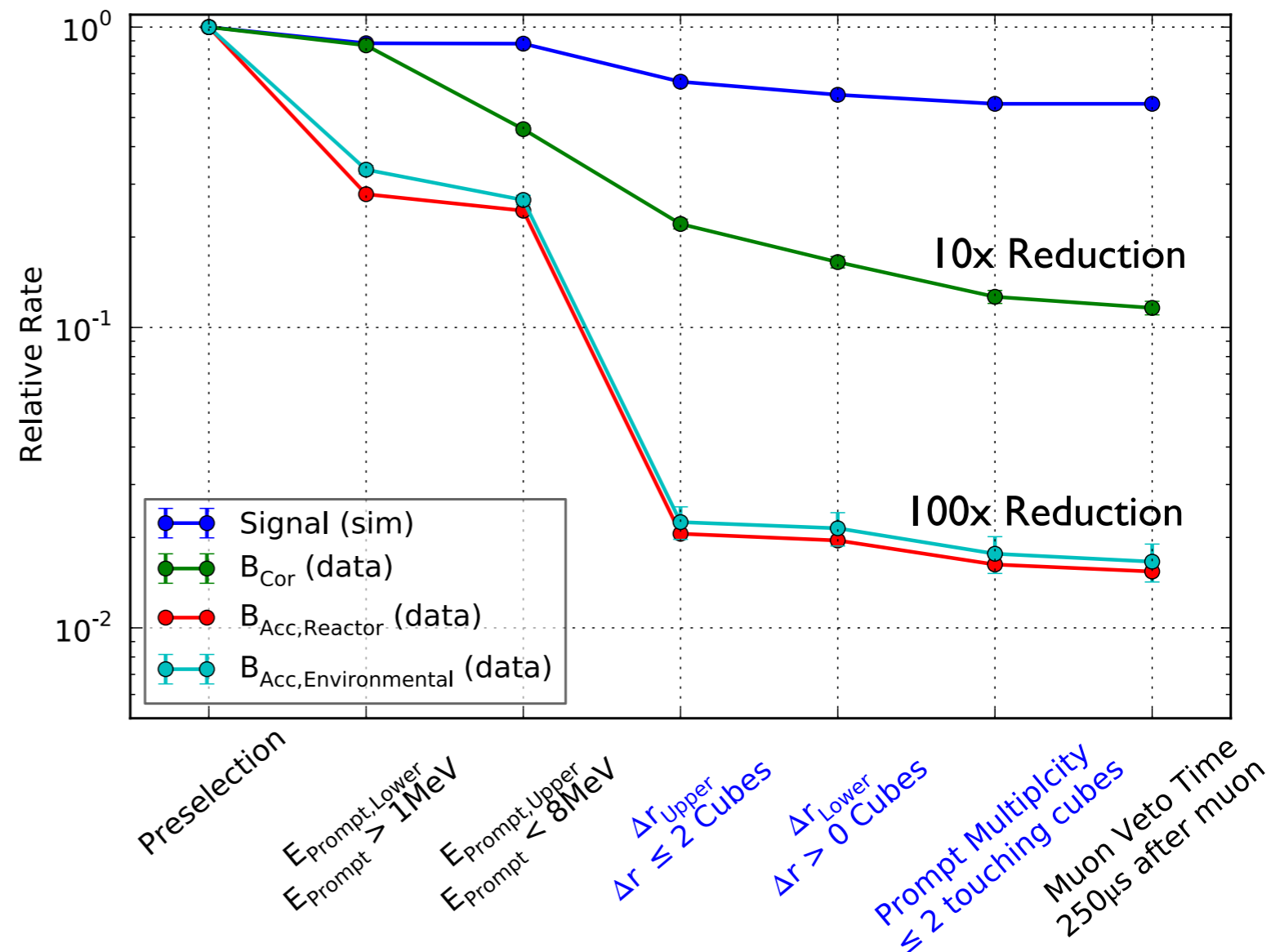
- Reconstruction parameters for each IBD:
  - $\Delta t = t_{\text{Prompt}} - t_{\text{Delayed}}$
  - Prompt Energy
  - $\Delta r = | \underline{r}_{\text{Prompt}} - \underline{r}_{\text{Delayed}} |$
- Others include multiplicity, directionality and fiducial layer
- Good agreement between reactor on data and expectation:
  - Validation of background understanding



*Radial separation between prompt and delayed events for signal and background IBD candidates*

# Signal Selection

- S:N critical in sterile search
- **Segmentation** provides many handles for tackling backgrounds:
  - Spatial separation
  - Directionality
  - Multiplicity
- Simple cut based analysis shows significant reductions in backgrounds

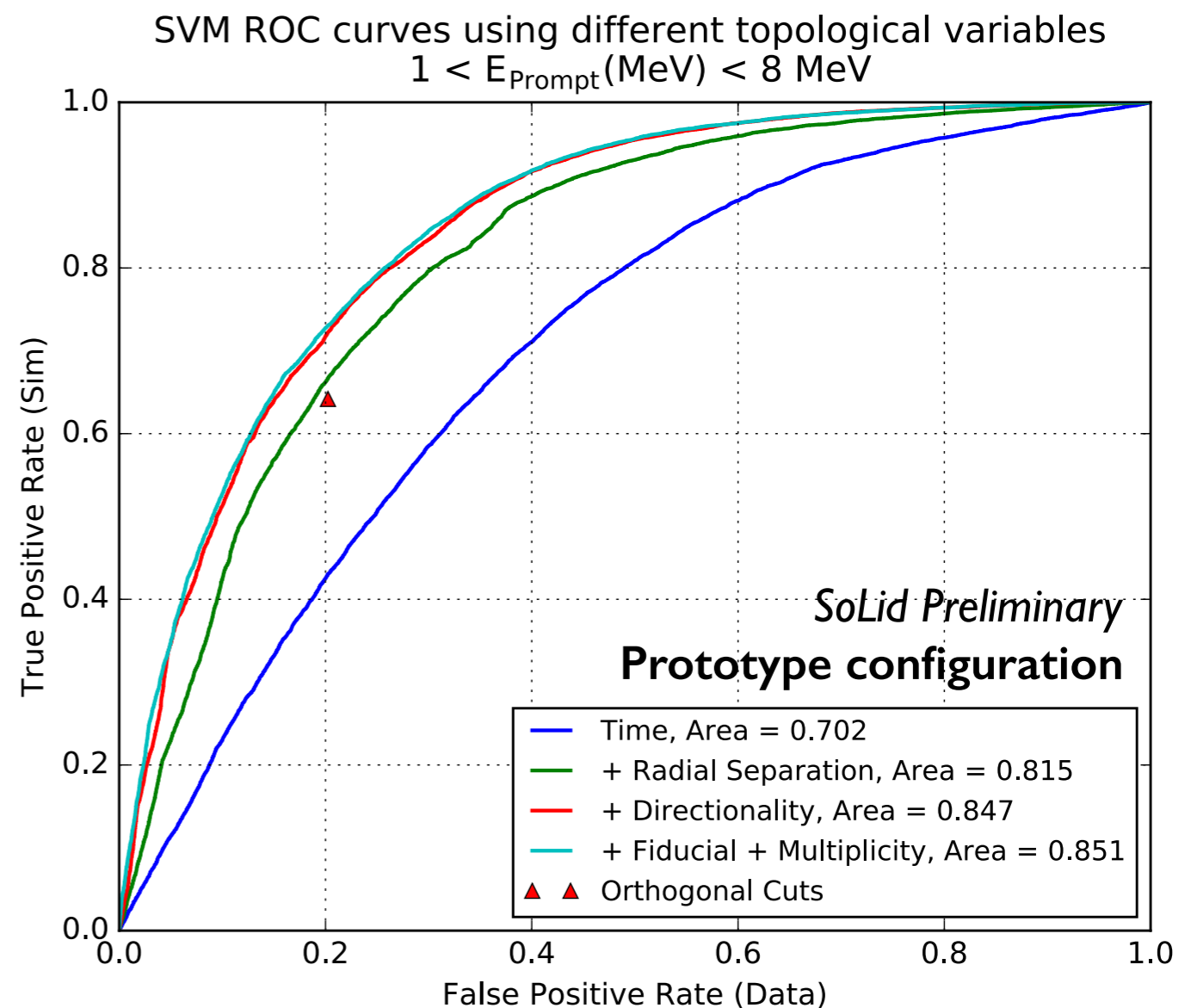


## Advertisement

Dedicated poster on IBD studies:  
*Ianthe Michiels, 6<sup>th</sup> Aug 18:00*

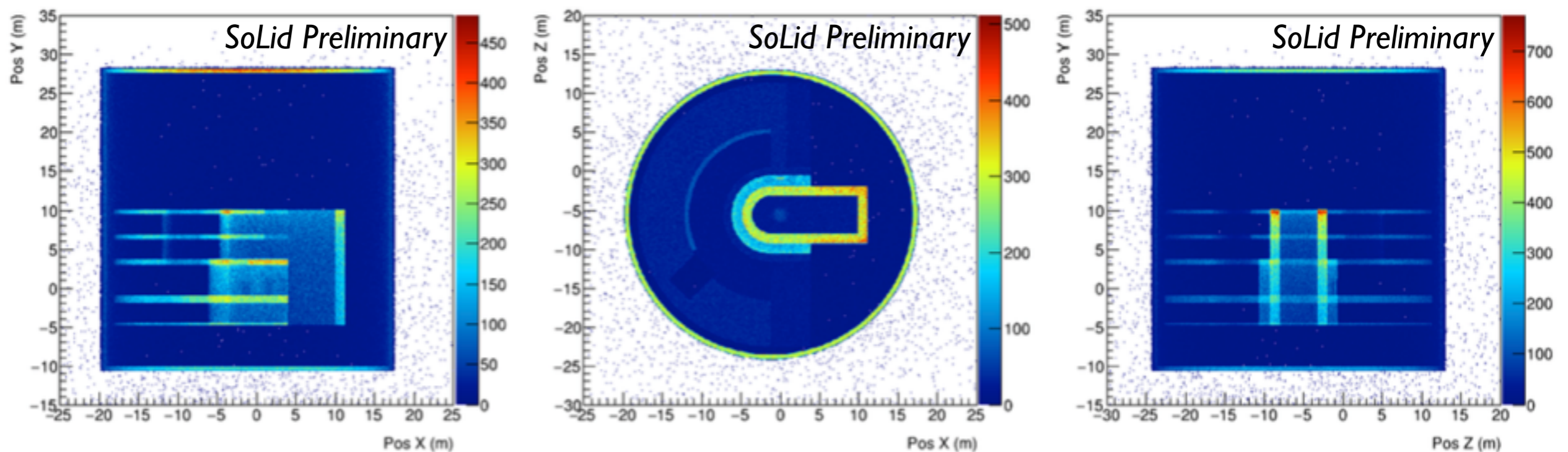
# Signal Selection

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- **Segmentation** provides many handles for tackling backgrounds:
  - Spatial separation
  - Directionality
  - Multiplicity
- Simple cut based analysis shows significant reductions in backgrounds
- Beginning to explore multi variable analysis techniques:
  - Likelihood discriminators and SVM
  - Initial results show further factor ~1.5 reduction in background rate



# Simulations

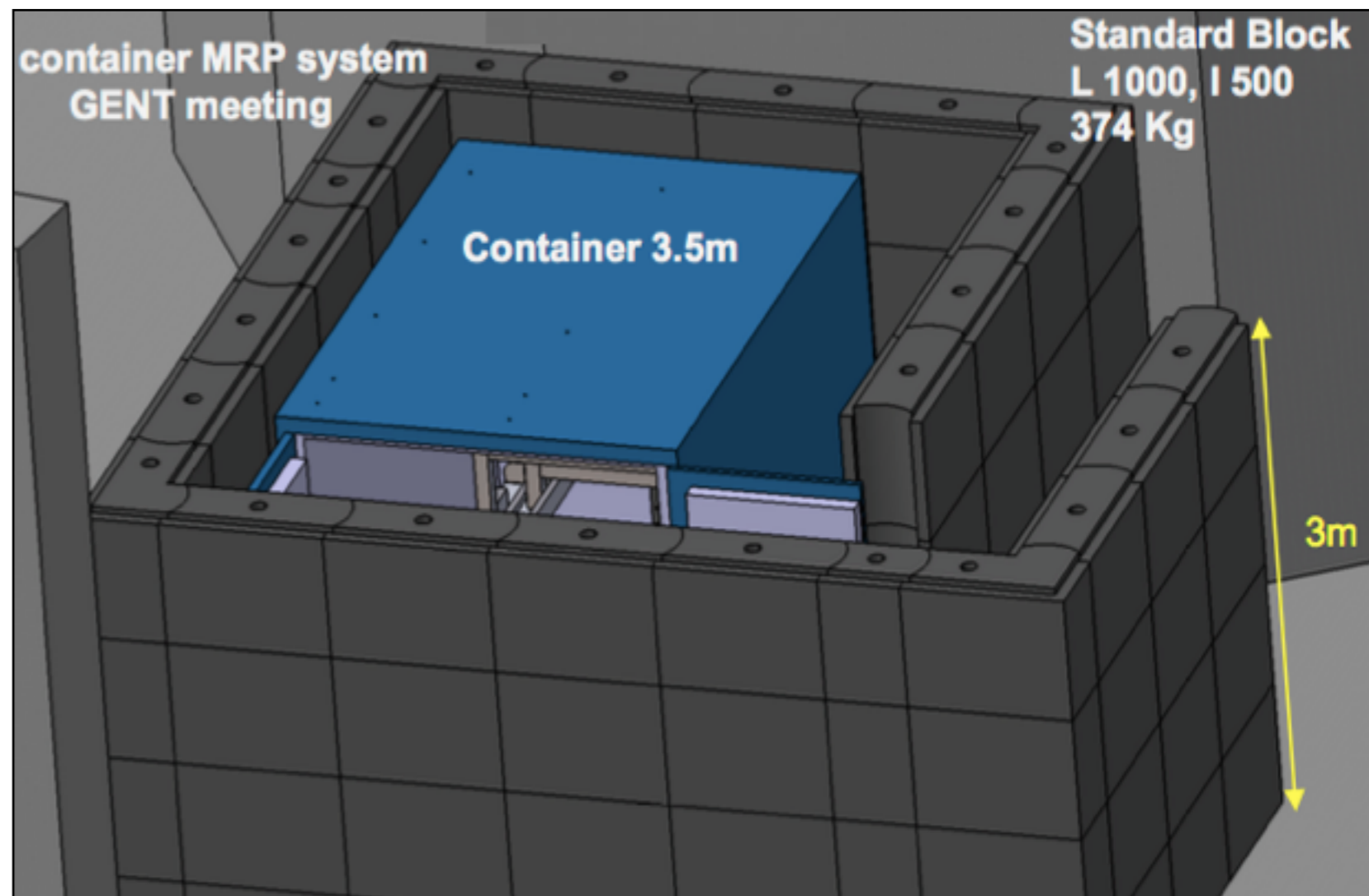
- Full cosmic simulation of BR2 reactor environment (geometry, detector, shielding etc)
  - Multiple generators: Guang, Cry, Gordon
- Neutron transport validated using G4 and MCNP
- Good agreement between sim and prototype data → key SMI results:
  - Background shapes, neutron capture time, muon angular distributions etc.



*Cosmic simulation of the BR2 reactor hall - example showing muon induced neutron production locations*

# Upgrades

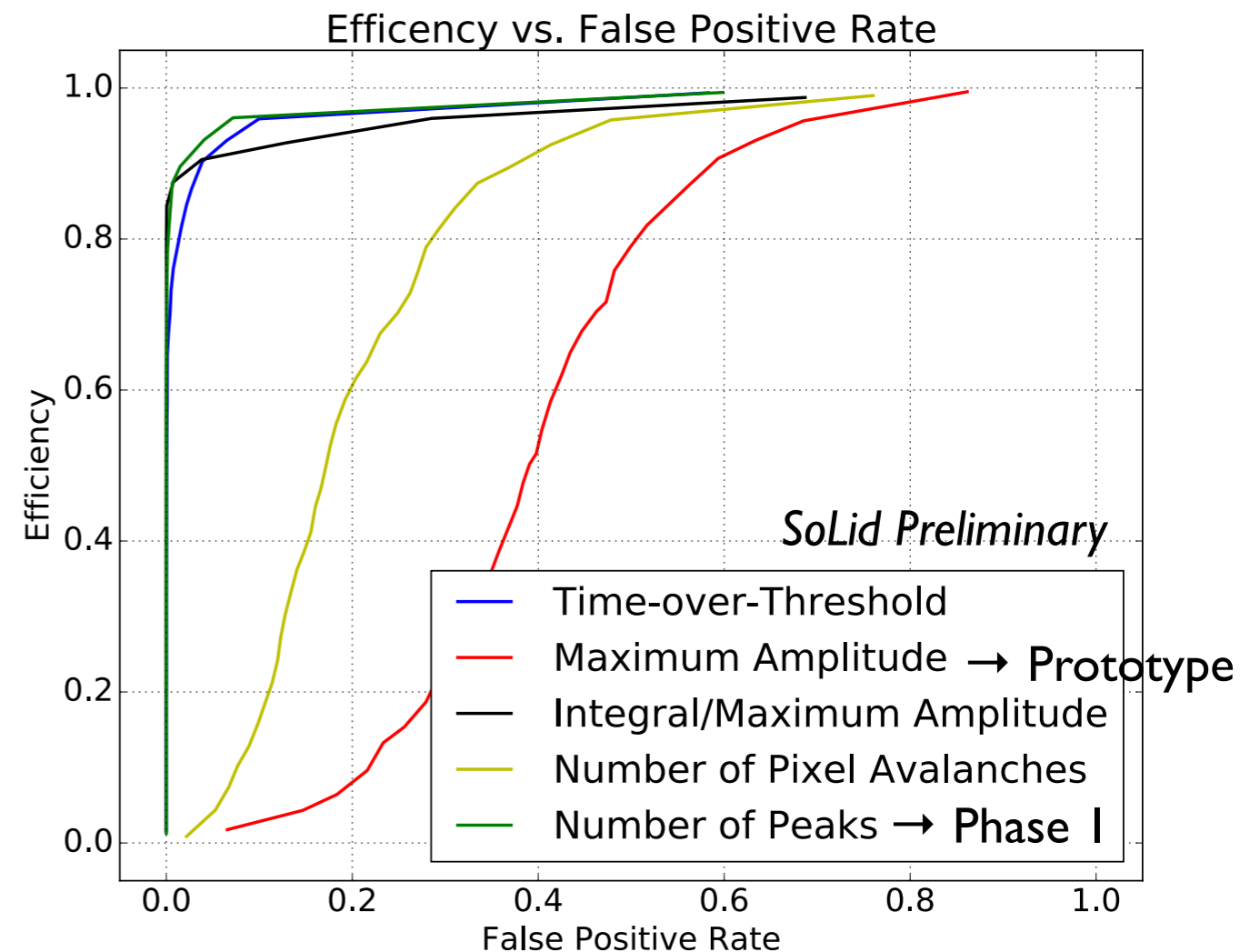
- Passive shielding:
  - 50cm water shielding to tackle cosmic neutron background



*SoLid Phase I setup, including container and example water shielding*

# Upgrades

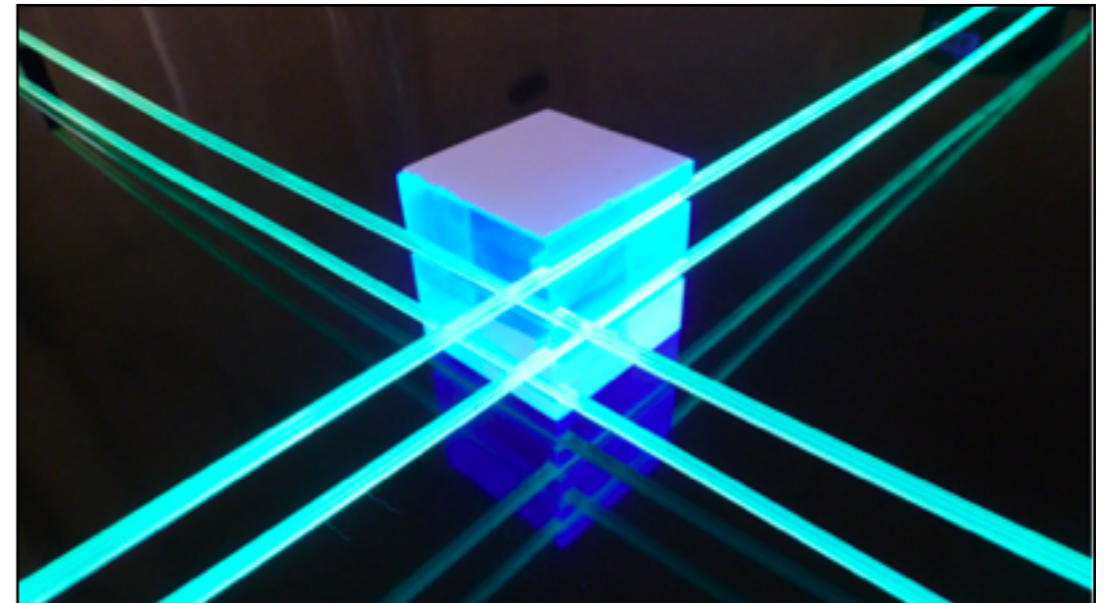
- Passive shielding:
  - 50cm water shielding to tackle cosmic neutron background
- Neutron (neutrino) trigger:
  - Neutron ID algorithms to be *migrated into electronics trigger*
  - Large buffer ( $\sim 1\text{ ms}$ ) readout for *prompt* detection ( $\pm 2$  planes around  $n$ )
    - *Prompt trigger efficiency (given  $n$ ) determined by zero suppression only*



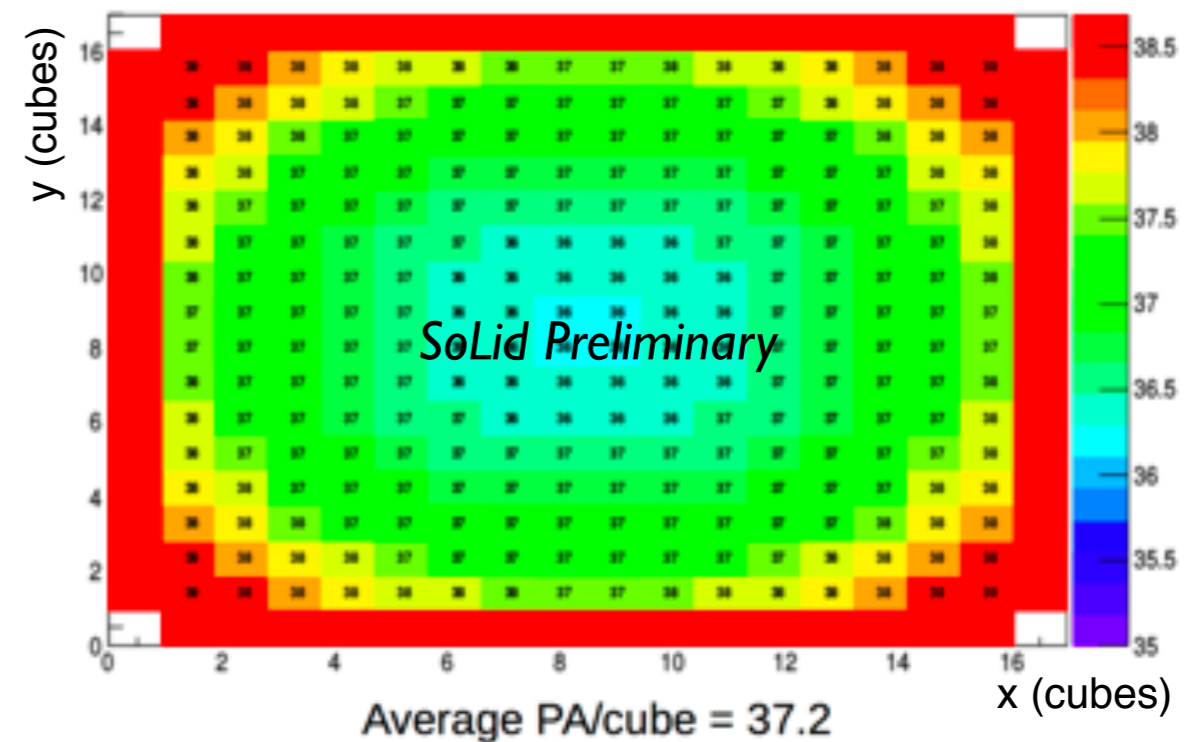
Neutron trigger ROC curves for various PID algorithms

# Upgrades

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  - Large buffer ( $\sim 1\text{ ms}$ ) readout for *prompt* detection ( $\pm 2$  planes around  $n$ )
- Light yield increased  $\sim 1.6\times$ :
  - Material choice (tyvec, fibres) optimised
  - Number of channels (inc. fibres) doubled
  - Expect  $\sim 50$  photons per MeV per cube - on track for energy resolution  $\sim 14\%/\sqrt{E}$



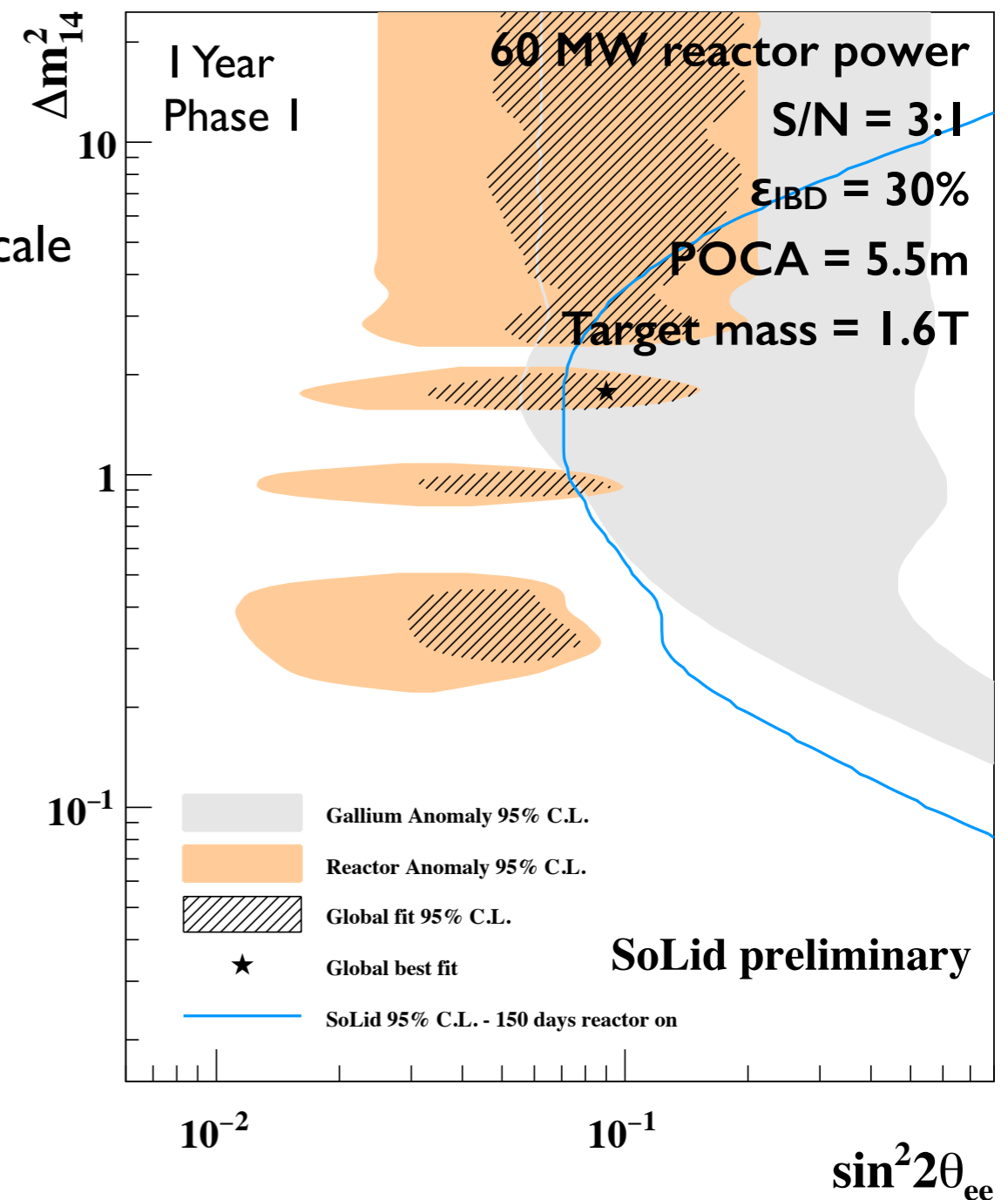
Upgrade cube - 4 fibres and 2 Li screens



Light yield of Phase I cubes for a single plane

# Outlook

- Deployment and analysis of prototype complete:
  - Experience running new technology at large scale
  - Power of segmentation demonstrated:  $\sim 100\times$  reduction  $B_{Acc}$ ,  $\sim 10\times$  reduction  $B_{Cor}$
  - Validation of simulation and data driven background studies
  - Developed software and analysis techniques
- Construction of phase I SoLid began:
  - 1.6T, to perform initial sterile search
  - Upgrades for reduced background, energy resolution and trigger efficiency
  - Deployed early 2017
  - On track for S:N  $\sim 3:1$  with  $\epsilon_{IBD} \sim 30\%$



*Thank you!*



*The SoLid Collaboration at Brussels - ca 50 people*

Further thanks to the Bristol Alumni Foundation for travel funding!

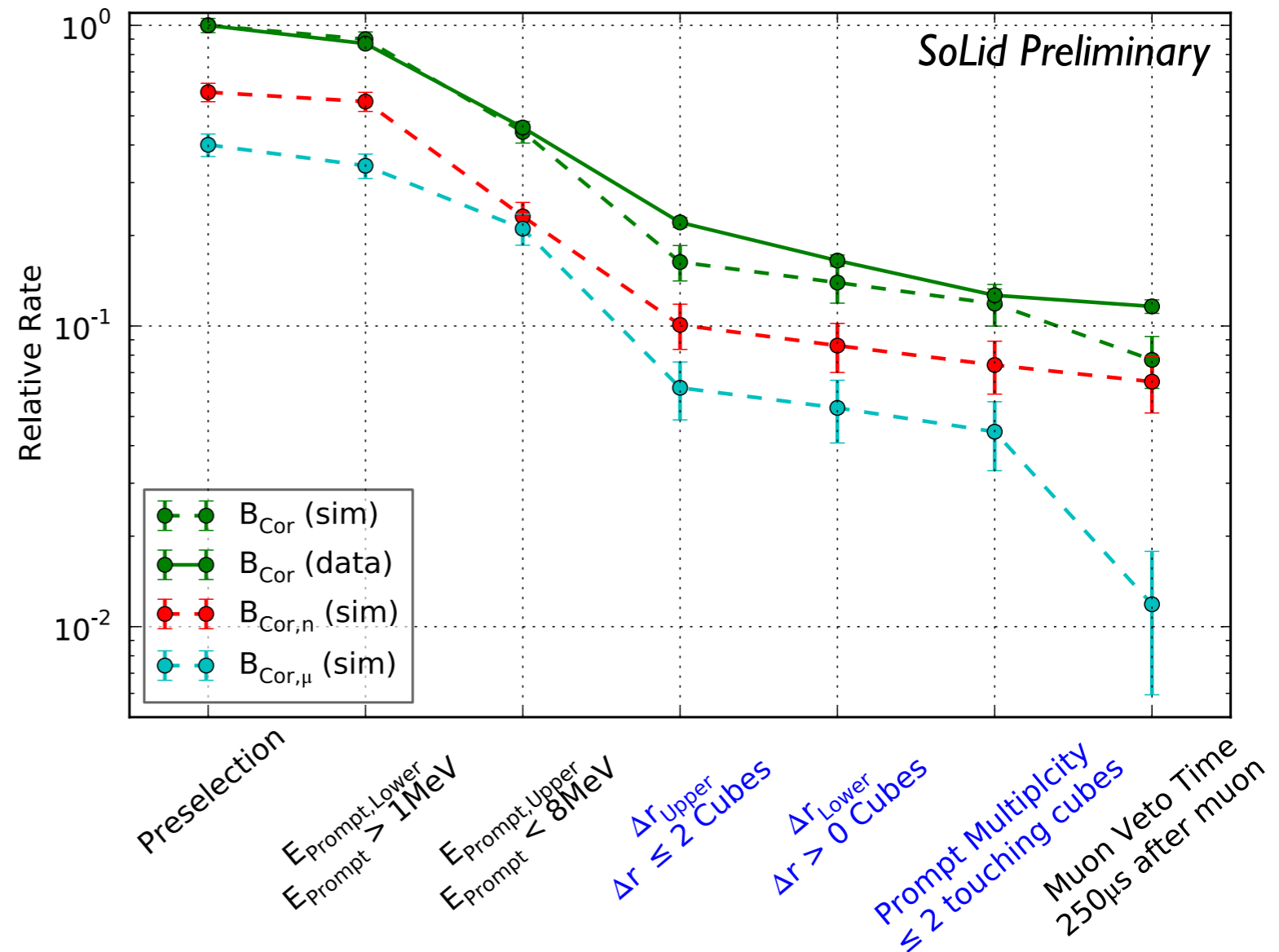
# References

- [1] B. Kayser @ Moriond EW 2012:arXiv:1207.2167
- [2] K. N. Abazajian et al., arXiv:1204.5379 [hep-ph]
- [3] Kopp, Machado, Maltoni and Schwetz, JHEP05(2013)050
- [4] Mention et al., Phys. Rev. D 83 073006 (2011)

# Backup

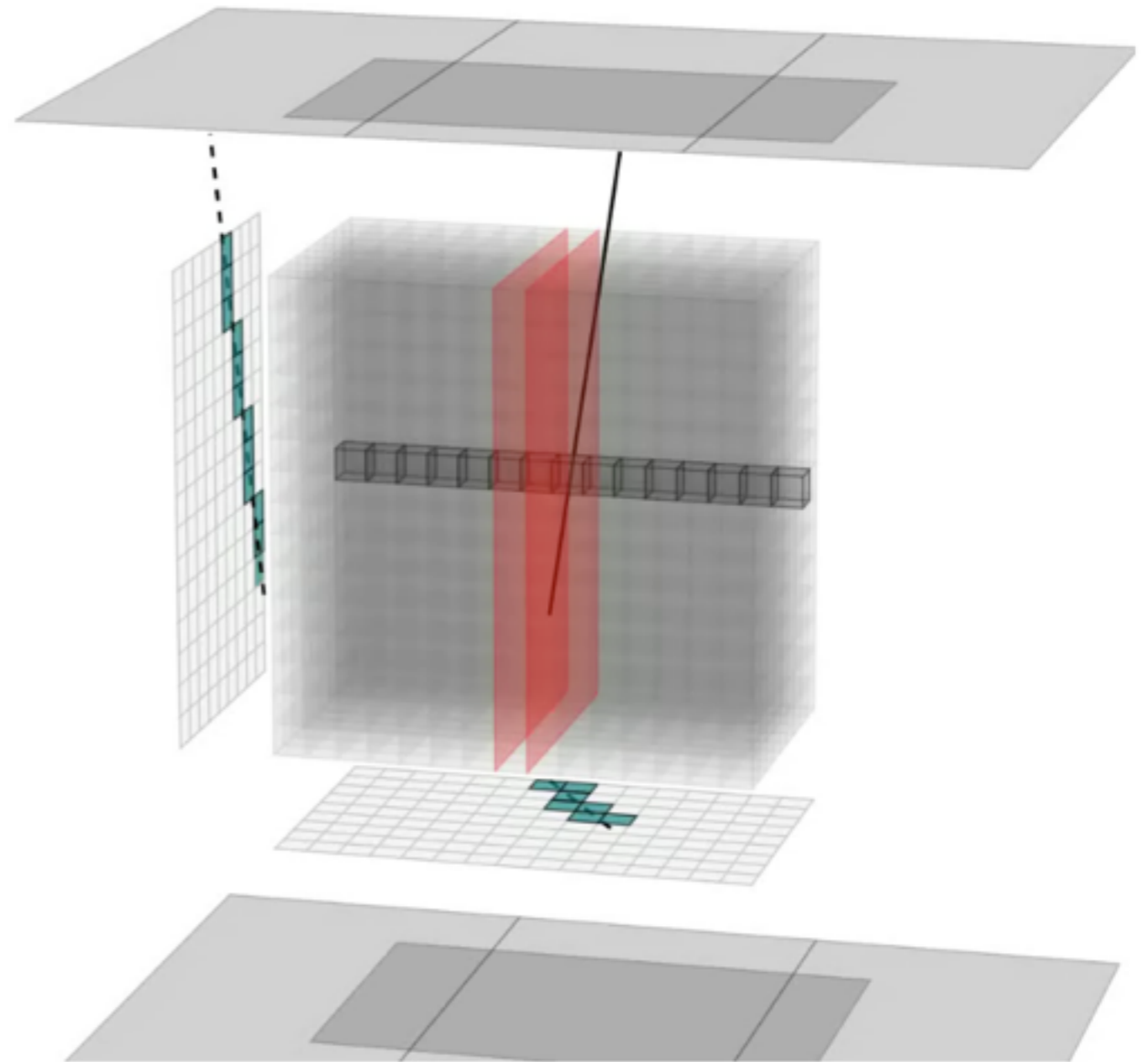
# Sim/Data Comparison

- Full cosmic simulation of BR2 reactor environment (geometry, detector, shielding etc)
  - Multiple generators: Guang, Cry, Gordon
- Neutron transport validated using G4 and MCNP
- Good agreement between sim and prototype data:
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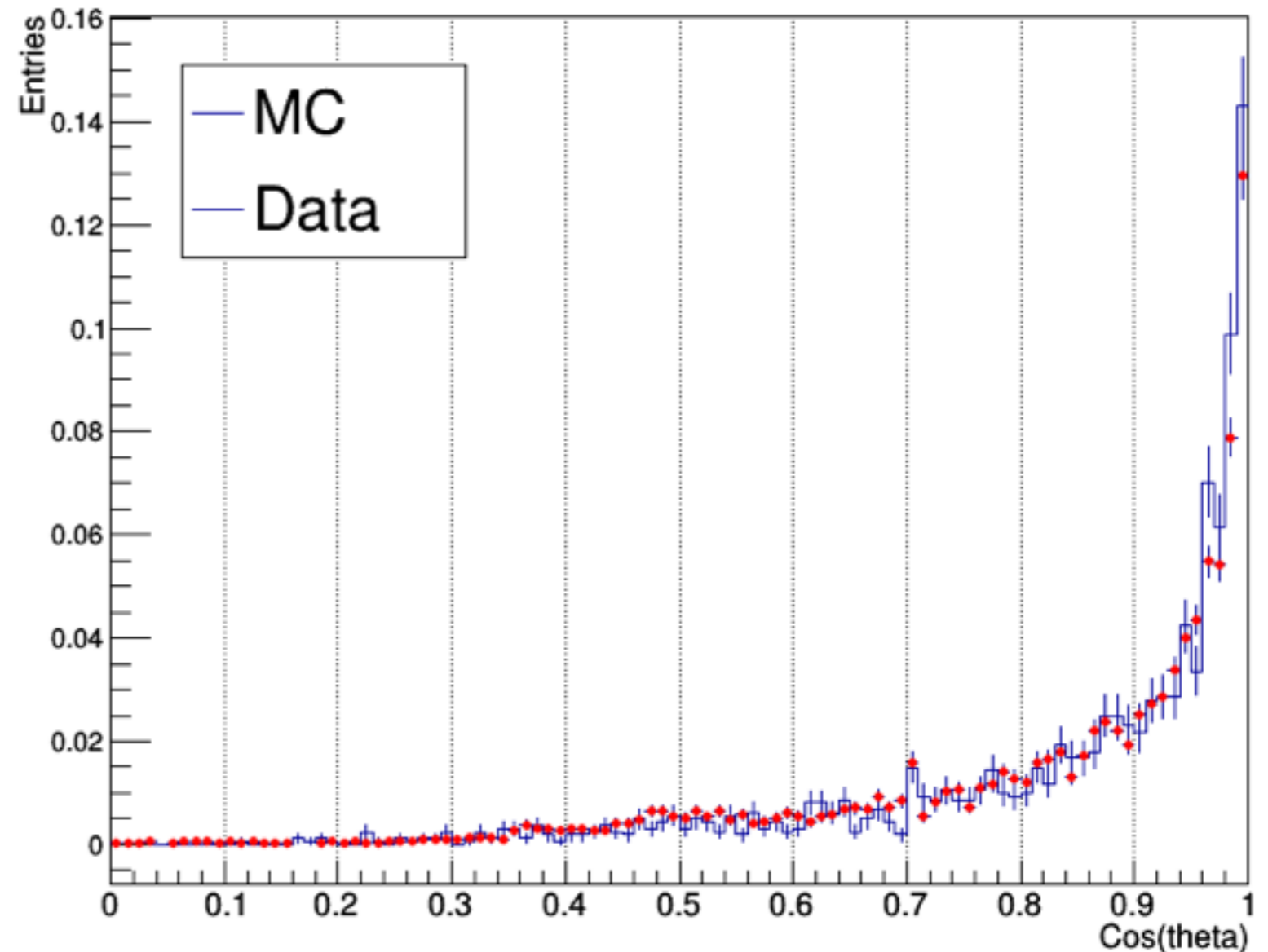
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*Tracked muon example (highlights  
refer to calibration purposes)*

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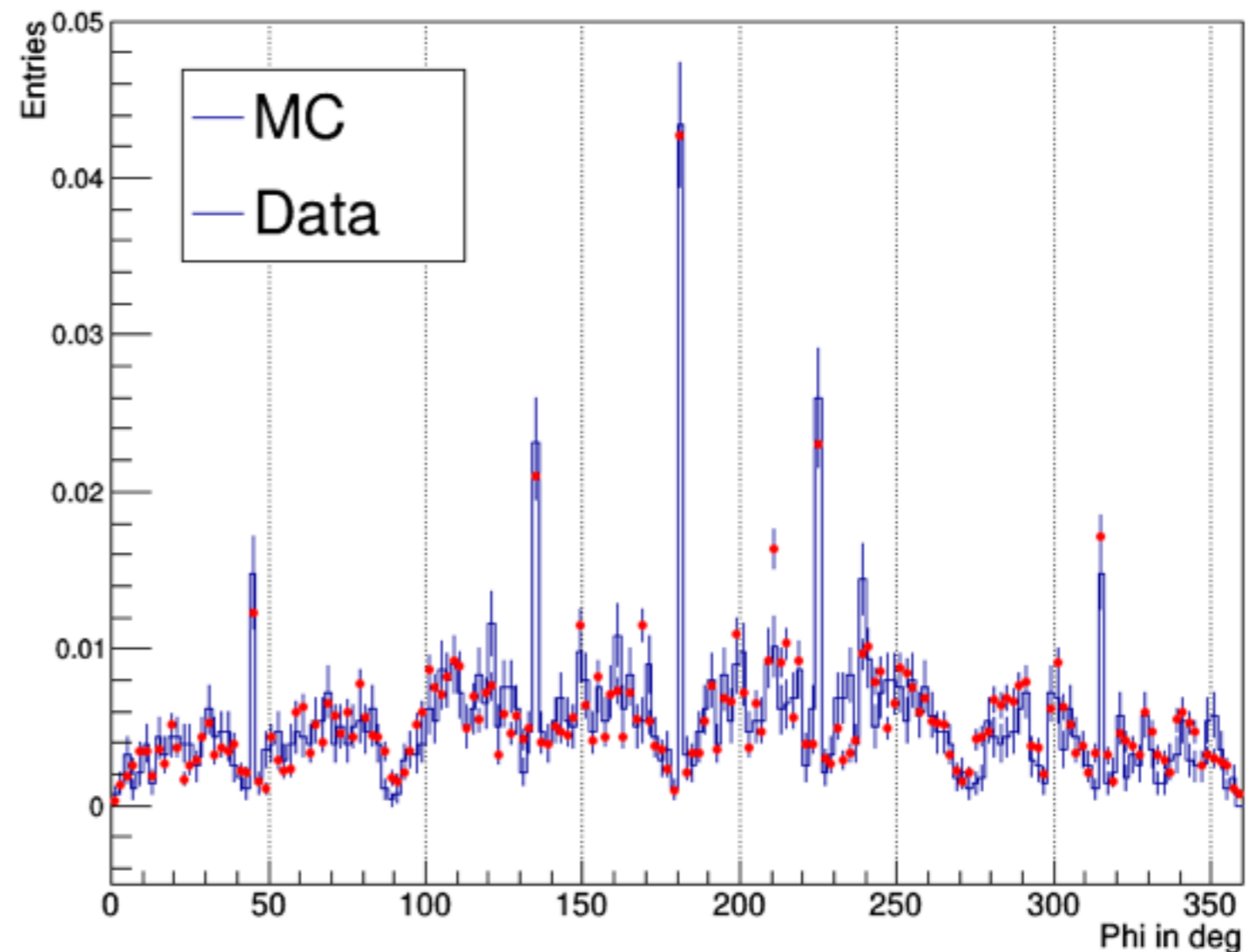
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*MC-sim comparison for muon track angle-from-vertical*

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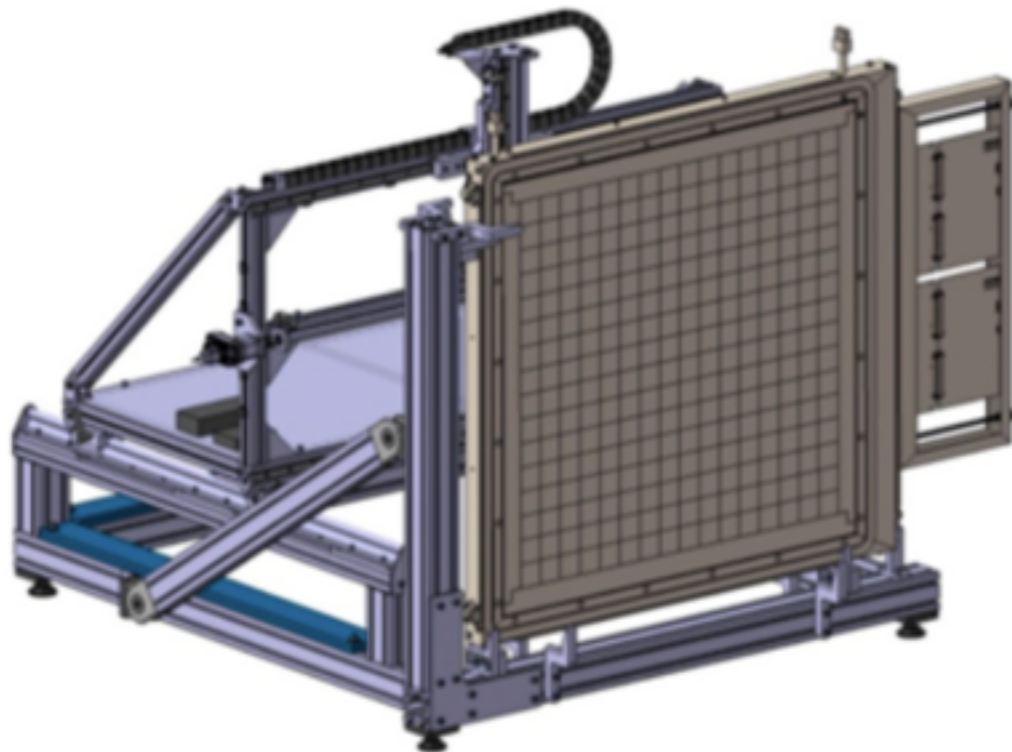
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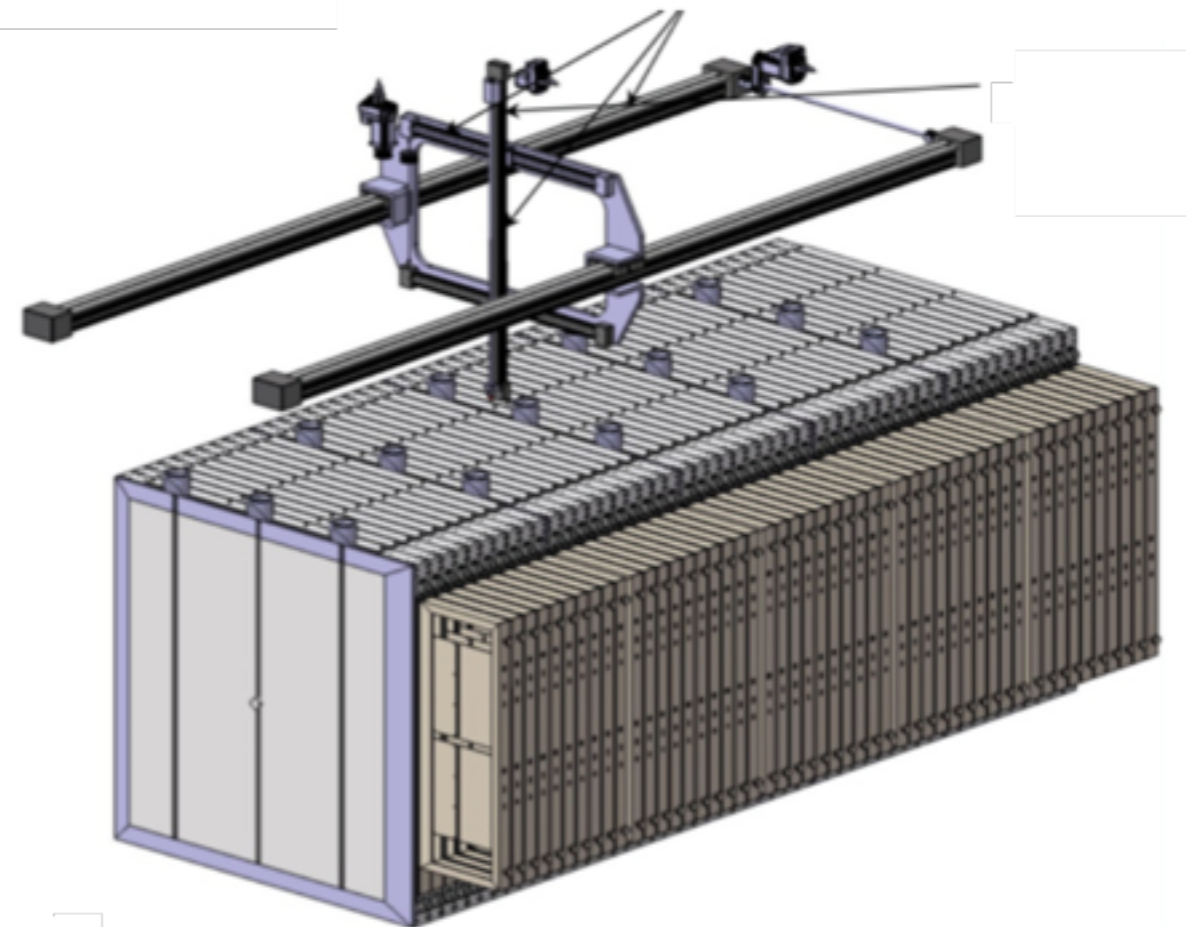
*MC-sim comparison for muon track angle-from-horizontal*

# Source Calibration

- Off-site calibration system (CALIPSO)
  - Plane characterisation
  - Neutrons and EM sources used to allow precise cube to cube equalisation

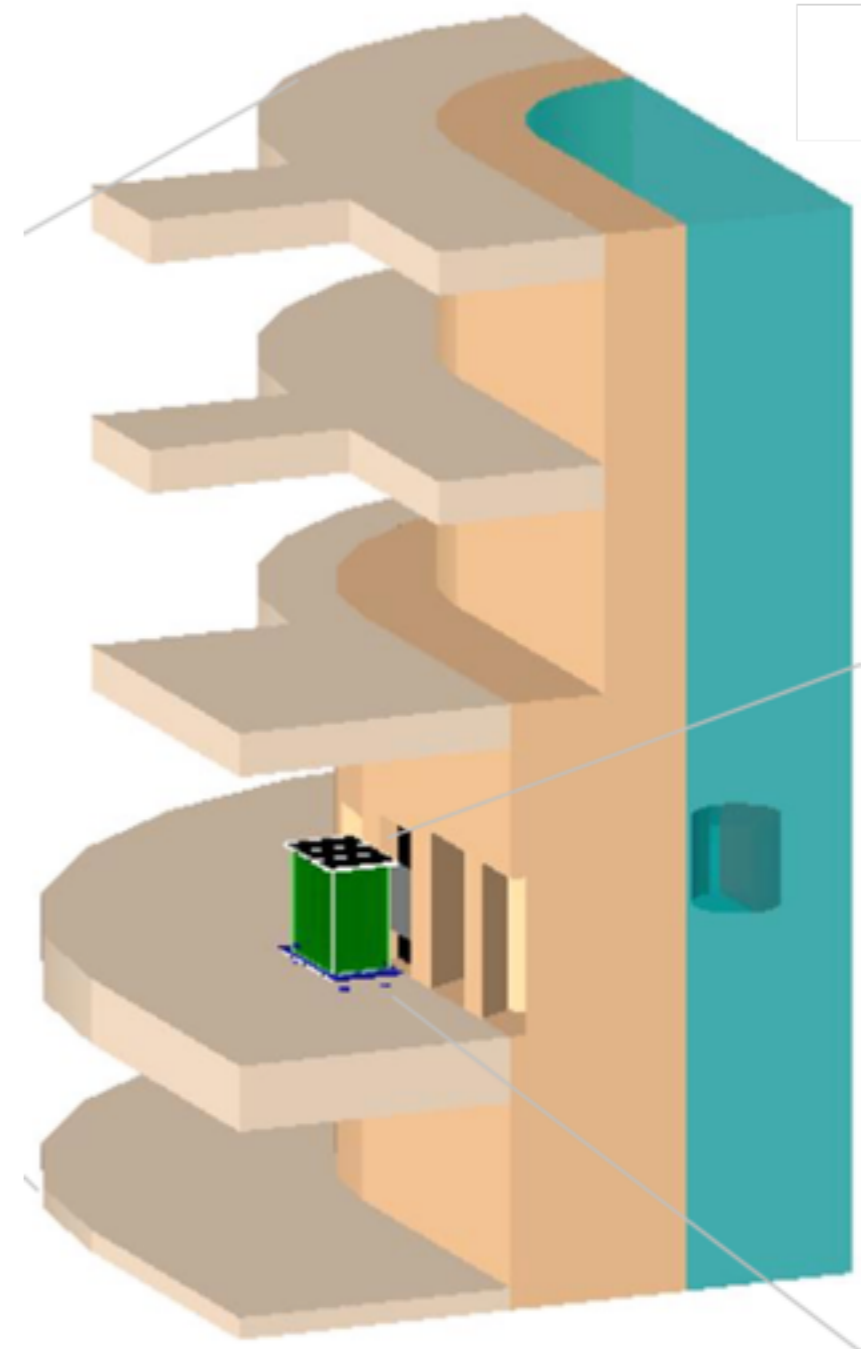


- In-situ calibration system (CROSS)
  - Energy scale determination (% level)
  - Absolute neutron detection efficiency (target ~3% precision)



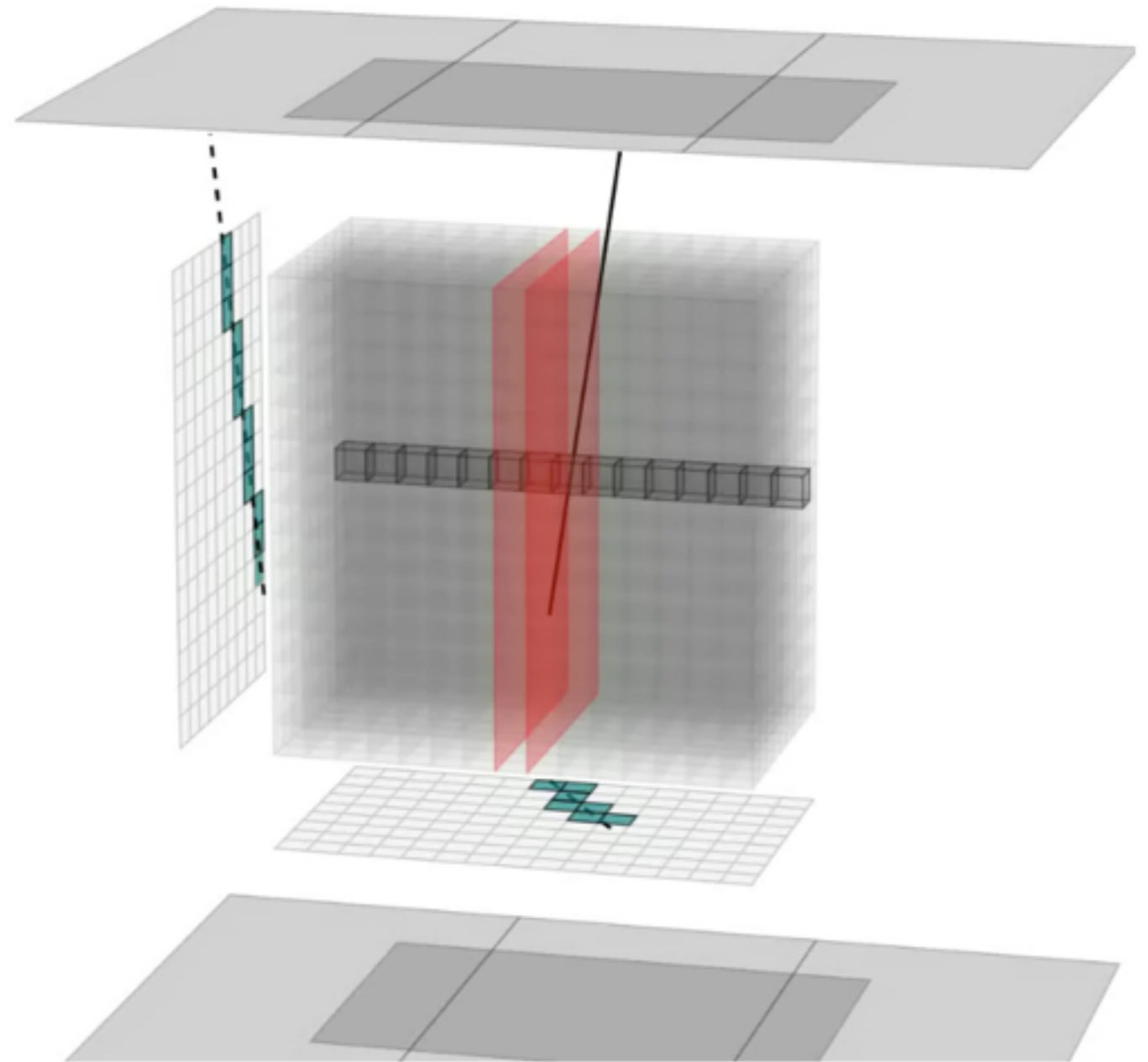
# Belgian Research Reactor (BR2)

- Research reactor:
  - Belgian Reactor 2 (BR2) at SCK-CEN
  - 95% Enriched  $^{235}\text{U}$
  - Core diameter 0.5m
  - Access ports for experiments
- Low vertical overburden ( $<10\text{m WE}$ )
- SoLid is on-axis with reactor core
- No other users



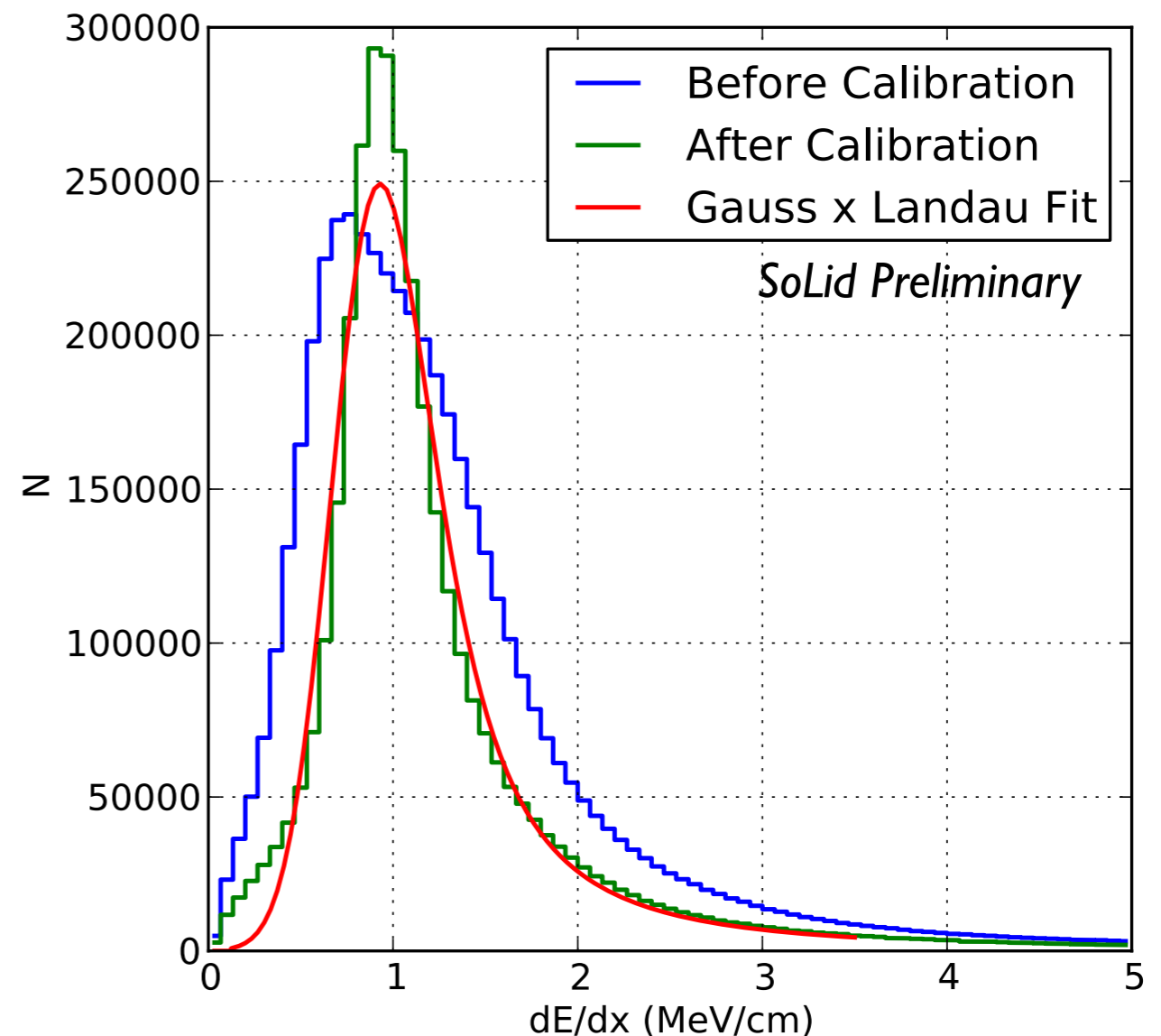
# Energy Calibration

- SMI EM calibration performed using cosmic muons:
  - High quality reconstruction tracks
  - $dE/dx$  distribution found for each cube
  - Selection criteria applied to remove non-degenerate cases
  - Allows for equalisation signal and energy scale estimation



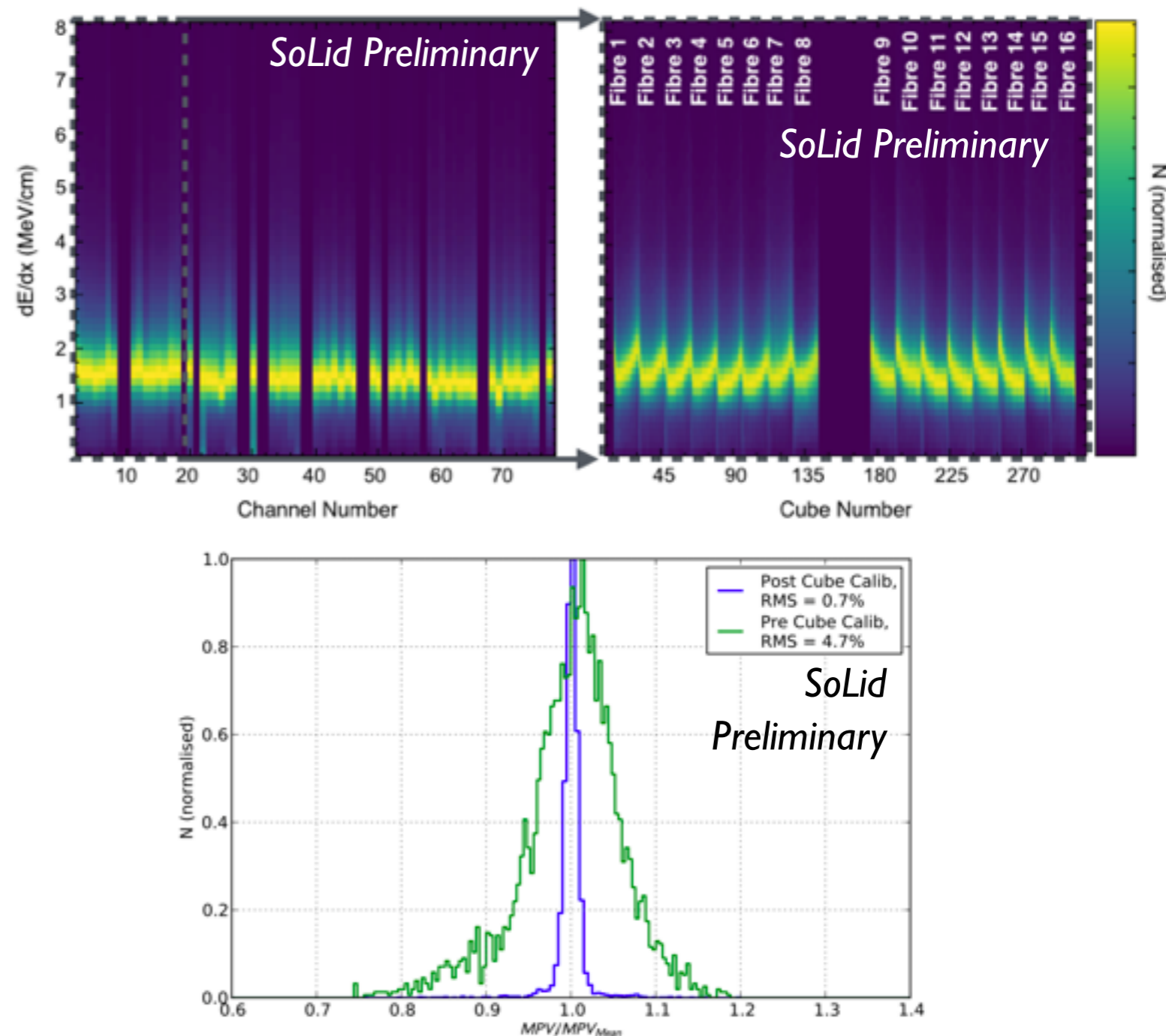
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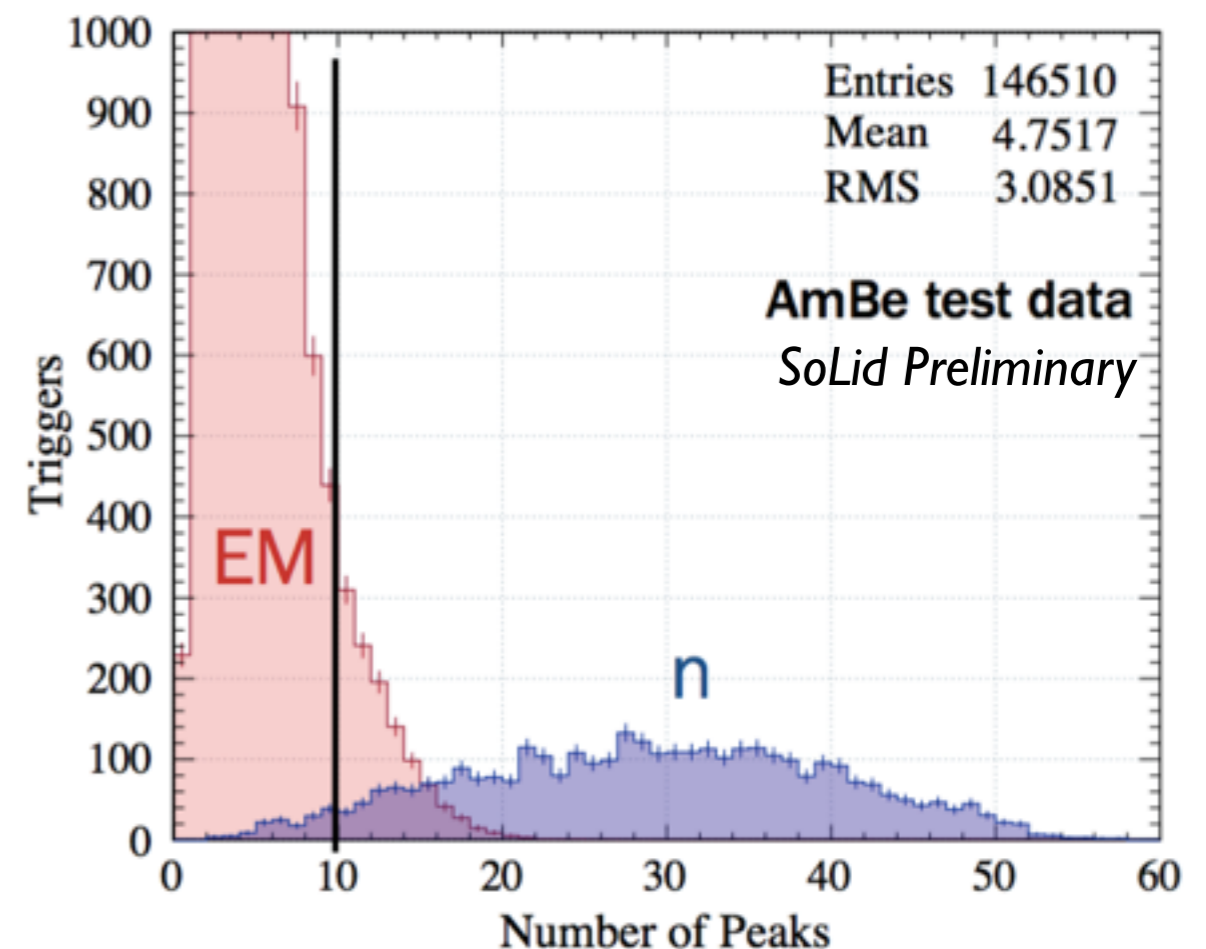
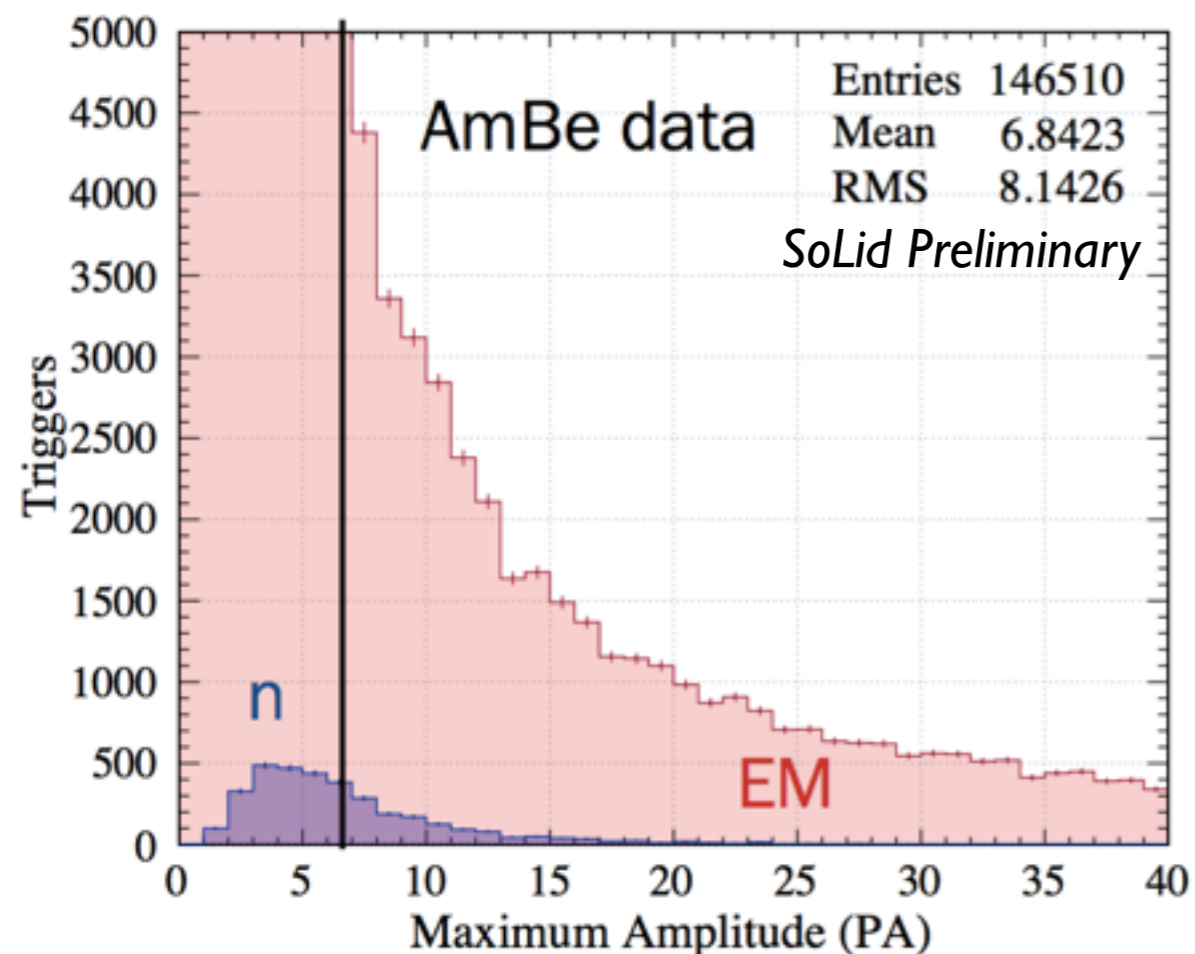
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  - Allows for equalisation signal and energy scale estimation
- Used to correct:
  - Channel-to-channel variations
  - Attenuation losses down fibres
  - Cube-to-cube differences in light collection efficiency



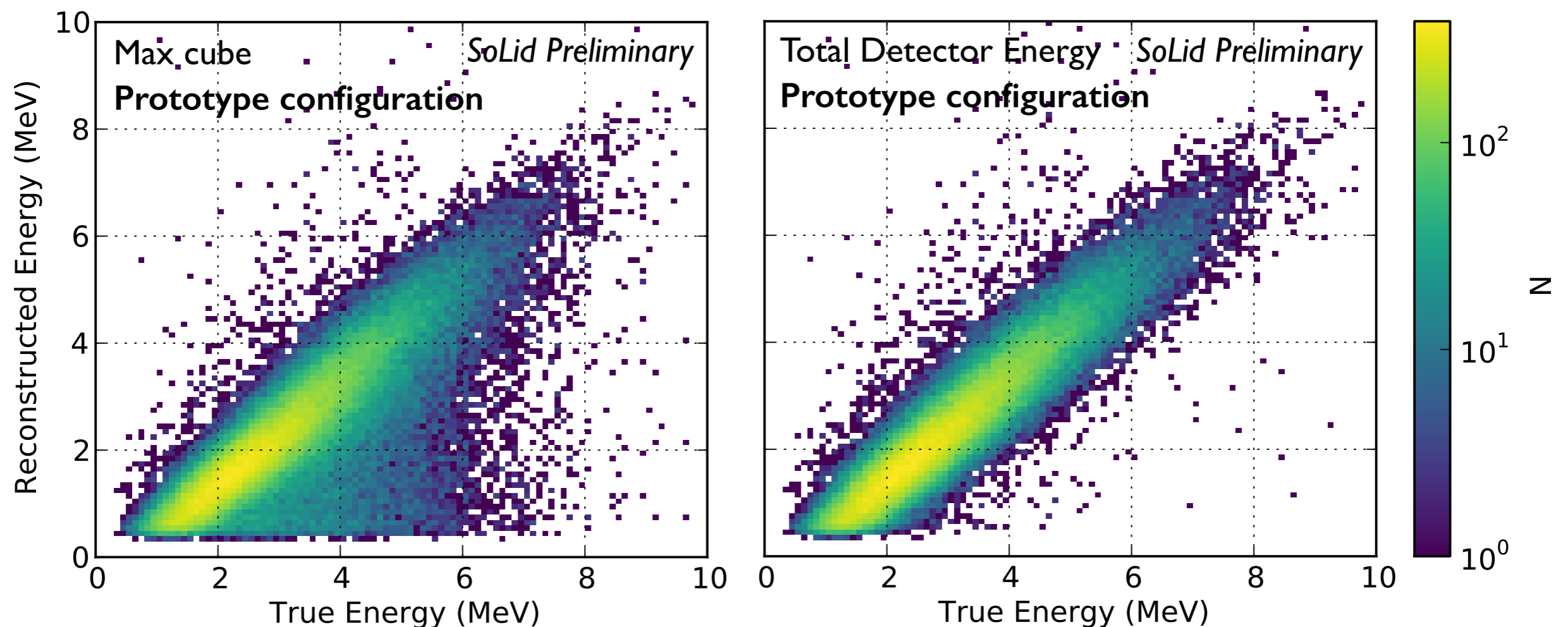
# SMI Prototype Trigger Efficiency

- Simple trigger due to time constraints:
  - Amplitude threshold used for all signals with fast **co-incidence** demanded between x and y fibres
  - High threshold set to manage data rates: efficiency  $\sim 5\%$
- Number of peaks in neutron waveform (rolling calculation) gives far better separation



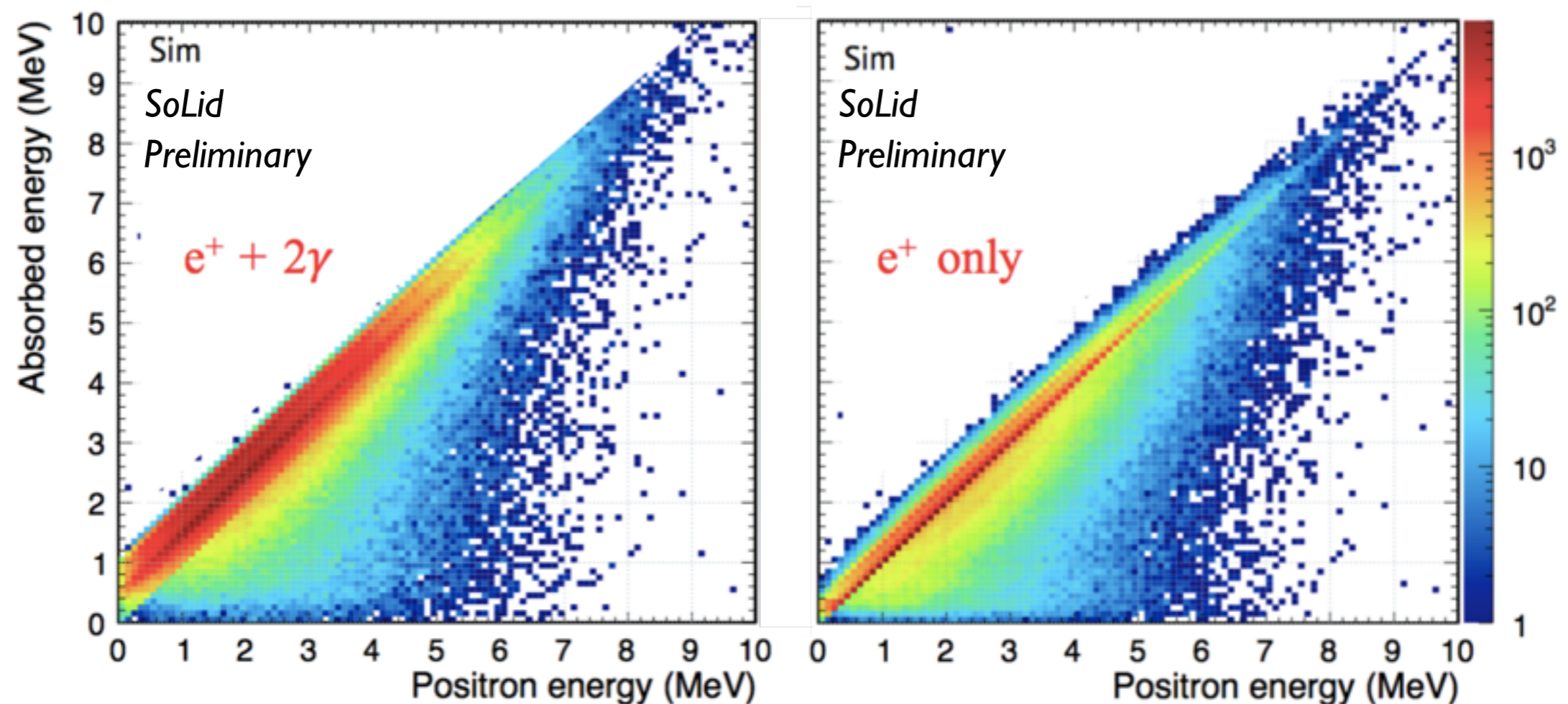
# Energy Reconstruction - Phase I

- Phase I energy estimator re-optimised compared to prototype:
  - $P(\text{gamma detection}) \sim 0.5$  for phase I ( $\sim 0$  for SMI)
- Gamma leakage affects energy resolution is using total energy deposited in detector
- Recovered by selecting only positron energy (possible due to high granularity)



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- Gamma leakage affects energy resolution is using total energy deposited in detector
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# Phase 2 Sensitivity (P. Huber)

- Phase 2 would include CHANDLER detector placed in-front of SoLid (2T)

