The SoLid Experiment

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On behalf of the SoLid collaboration

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SoLi∂

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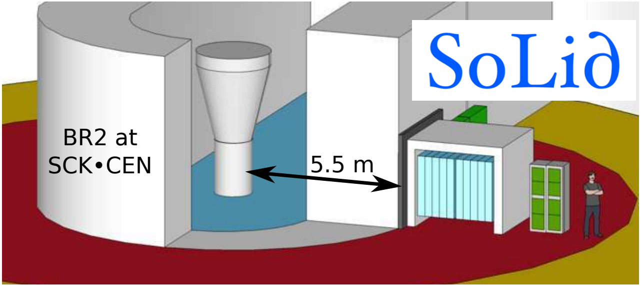
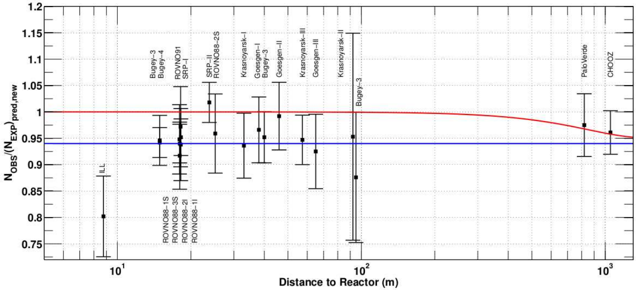
Overview



- Why measure reactor anti-neutrinos?
- Challenges of reactor neutrino experiments
- The SoLid experiment
- Current and future detectors

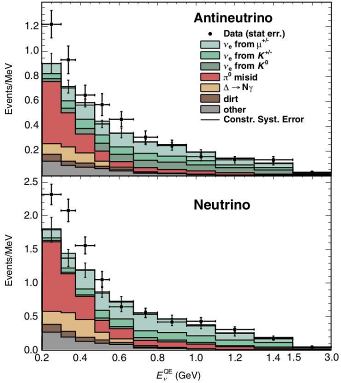
The reactor anomaly

Recent re-calculation of reactor spectrum shows 2.7σ deficit in previously measured rates at distances between 9 m and 1 km (PRD 83 073006).



Other short baseline neutrino anomalies

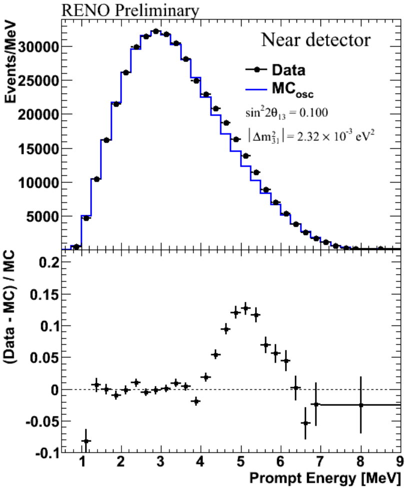
- LSND/MiniBooNE
- 3 σ $\bar{\nu}_e$ / ν_e excesses



- PRL 110, 161801

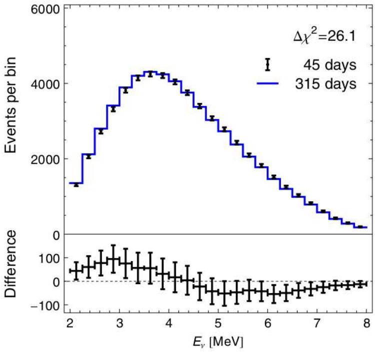
- Gallium anomaly
- SAGE / GALLEX Ga solar neutrino detectors
- Calibrations with ^{51}Cr and ^{37}Ar
- Intense, calibrated sources
- Observed / expected neutrino ratio
- Combined $R = 0.84 \pm 0.05$
- JHEP 1305:050, 2013

The 5 MeV bump



- 5 MeV $\bar{\nu}_e$ excess
  - Daya Bay
  - Double Chooz
  - RENO
- All Gd doped liquid scintillator
- All low enriched power reactors
- High neutrino stats
- Starting to probe structures in reactor anti-neutrino spectrum

Reactor monitoring



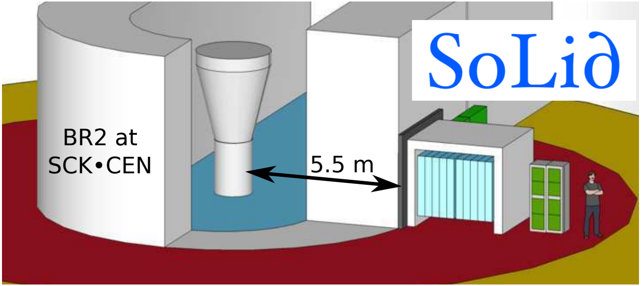
- PRL 113, 042503

- Reactors produce Plutonium
- Aim to detect diversion for weapon production
- Pu $\bar{\nu}_e$ spectrum softer than U
- Spectrum sensitive to isotopic composition
- Current method measure power
- Hard to recover from loss of measurement
- Neutrino detectors can significantly reduce uncertainty in quantity of Plutonium removed from a reactor

Why measure reactor anti-neutrinos?

- Neutrino anomalies
  - Search for oscillations within 10 m
- 5 MeV bump
  - Measure spectrum from highly enriched core
  - Use different technology to Gd doped liquid scintillator
- Reactor monitoring
  - Demonstrate spectrum evolution measurement
  - Demonstrate plug and play detector

Overview



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- Challenges of reactor neutrino experiments
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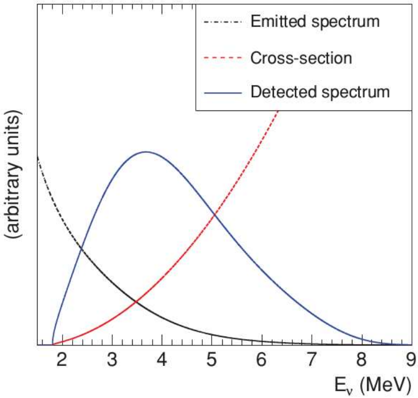
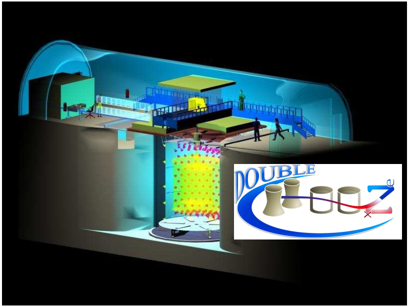
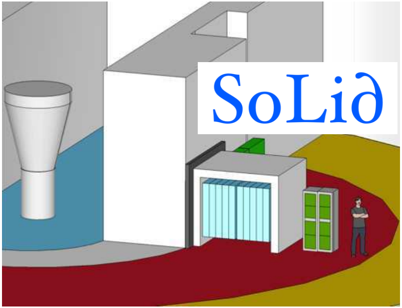
Reactor anti-neutrinos



- Neutrinos from β decays in fuel
- Fuel contains $^{235/238}$U, $^{239/241}$Pu + decay products
- 6 $\bar{\nu}_e$ per primary fission
- $10^{20}\bar{\nu}_e$/s from GW reactor
- Detected by inverse beta decay:
- $\bar{\nu}_e + p \rightarrow e^+ + n$
- Prompt e^+ detection
- Delayed ($< 200\mu$s) n capture
- IBD identified by $\Delta t(e^+, n)$
- 1000s IBD/day/tonne at < 10m

Experimental challenges near a reactor





Experimental challenges

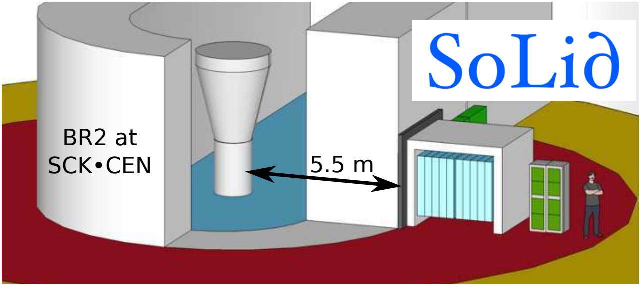
Backgrounds

- Cosmics at ground level
    - Spallation neutrons
    - Cosmogenic decays
- Fast neutrons
    - Nuclear recoil identified as e^+, real neutron detection
- Reactor γs
    - Increase accidentals
    - Impact e^+ energy measurement
    - Can impact neutron detection

Detector constraints

- Small - tonne scale
- Reactor safety - e.g. dislike flammable liquids
- Limited access

Overview



- Why measure reactor anti-neutrinos?
- Challenges of reactor neutrino experiments
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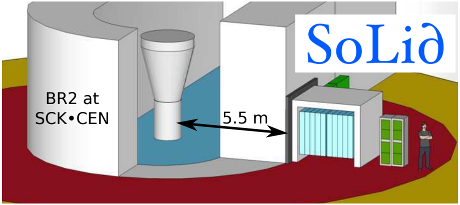
SoLid Collaboration

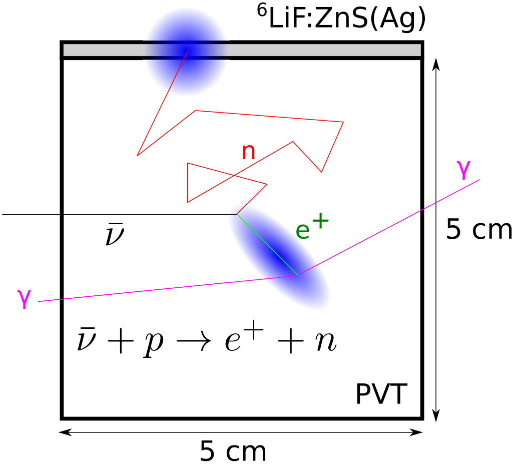
SoLid experiment - Overview

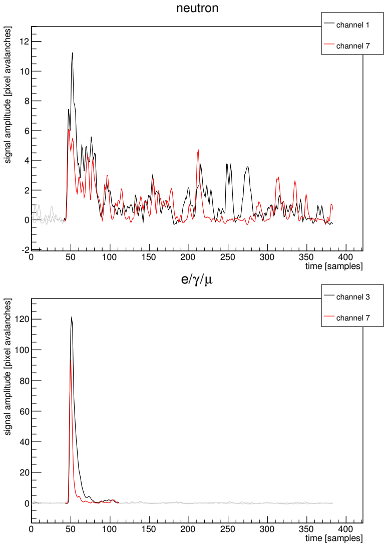
- 5 - 10 m from BR2 reactor core
- 2.88 T detector
- $5 \times 5 \times 5$ cm^3 PVT cubes
- Cubes optically isolated
- ^{6}LiF:ZnS(Ag) layers
- Wavelength shifting fibres
- Silicon photomultipliers



Detection principle - composite scintillator

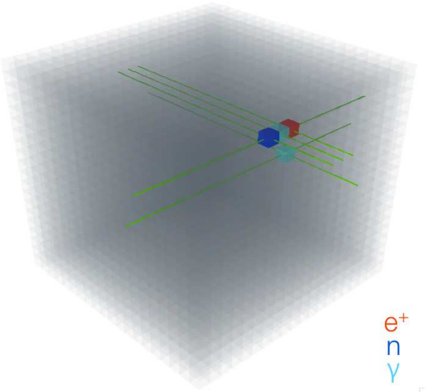
$$n + ^6\mathrm{Li} \rightarrow ^3\mathrm{H} + \alpha + 4.78\ \mathrm{MeV}$$



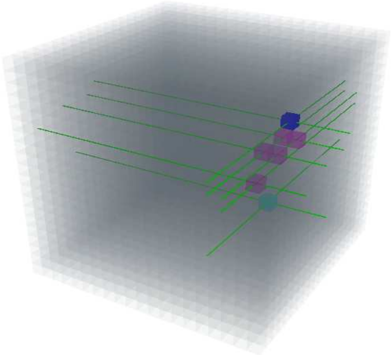


Detection principle - segmentation/topology

Inverse beta decay event

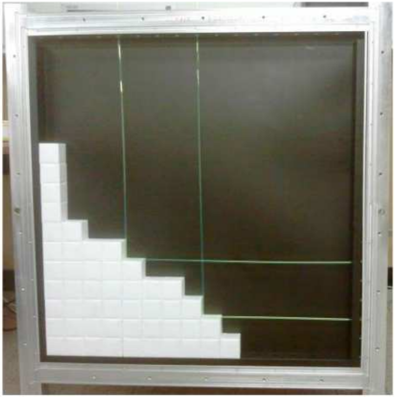


Fast neutron event



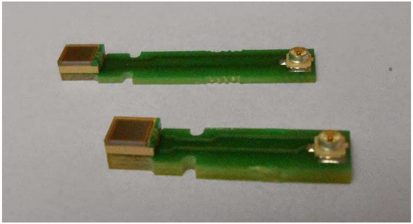
Detection volume and optics

- Detector split into vertical planes
- Optically isolated scintillator cubes
- 16 vertical and 16 horizontal fibres
- 3×3 mm square WLS fibres
- Sensors alternate top/bottom or left/right

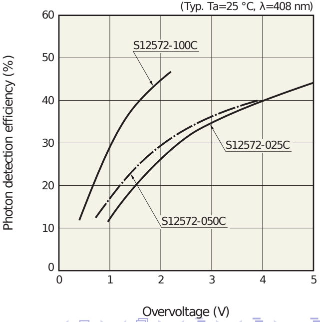


Light sensors - MPPCs

- Silicon photomultiplier
- 3 × 3 mm active area
- 3600 parallel Geiger mode APDs
- Charge sum from number of pixels that avalanche
- Operating voltage < 70 V
- Temperature dependant breakdown voltage
- High dark count rate (MHz @ single pixel)
- Cross talk (10 - 30%)



Photon detection efficiency vs. overvoltage

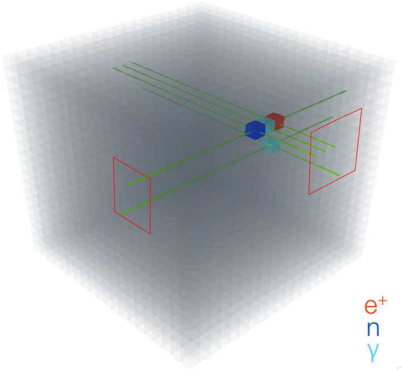


Readout system

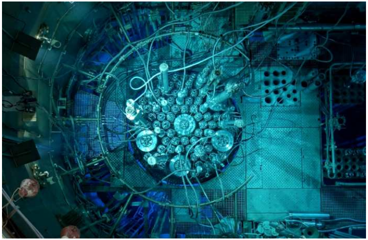
- Individual sensor bias control
- Front end amplification and shaping
- 50 MS/s digitisation
- FPGA based neutron/EM discrimination
- Signals buffered in FPGA
- Data read out following neutron trigger

Neutron trigger scheme

- Buffer signals in on all channels
- Front end neutron ID
- Unambiguous neutron location
- eg 5 - 5 channels
- 250 μs window
- Independent of neutrino energy
- No trigger bias in spectrum
- Neutron is lowest rate background
- Large data reduction

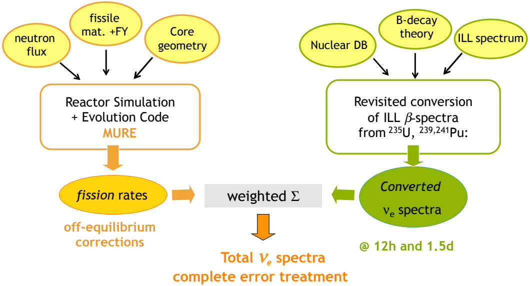


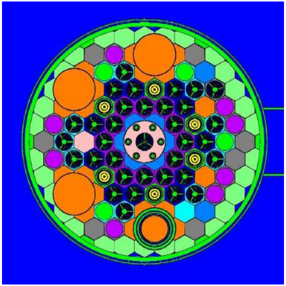
BR2 reactor at SCK CEN



- Highly enriched uranium
- Compact reactor core
- Low background rate
- No nearby experiments
- Approx. 50 % duty cycle
- SCK•CEN are awesome

Reactor spectrum calculation

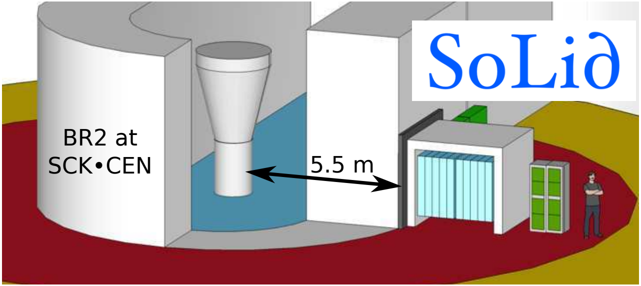




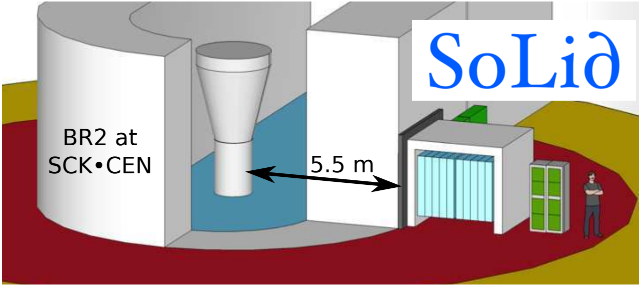
- BR2 has complex, unusual twisted geometry
- Calculation a collaboration between SCK and Subatech
- SCK understand BR2 reactor well, usually do calculations for neutrons
- Subatech experts in calculating neutrino spectra

The SoLid experiment - summary

- Novel detector design for challenging measurement
- Composite solid scintillator
  - Clear neutron signal for trigger and analysis
  - Neutron ID insensitive to high γ background
- Highly segmented detector
  - Event topology to select IBD from large backgrounds
- World's best reactor for these measurements
- Experts to calculate expected spectrum



Overview



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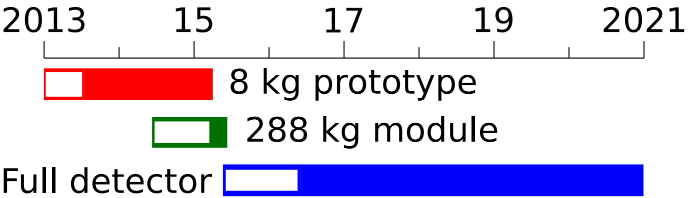
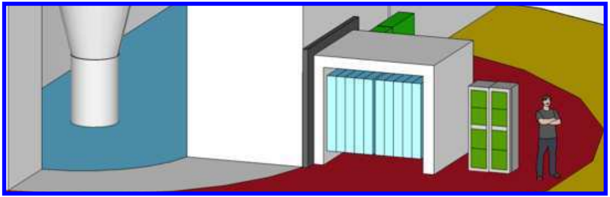
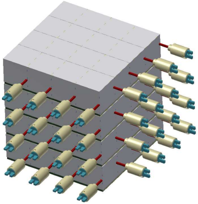
Experimental phases

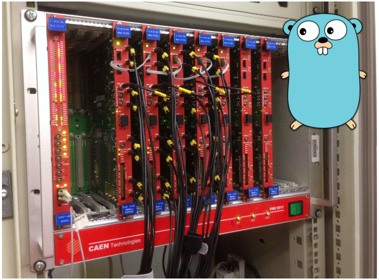




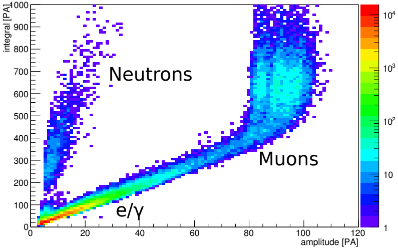
8 kg prototype detector

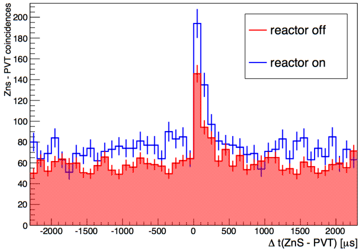
- 4 layers of 4×4 cubes
- 32 fibres / MPPCs
- 4 muon veto panels w/ PMTs
- Front end amplifier only
- V1724 14 bit 100 MS/s ADC
- Coincidence trigger in layer
- 5 pixel avalanche threshold
- Concurrent DAQ software in Go





8 kg prototype detector





- Deployed 5.5 m from BR2 core
- Ran summer 2013 - spring 2015
- neutron calibration tests planned

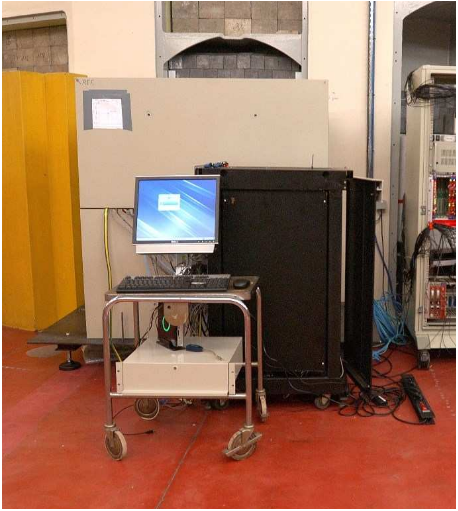
- Easily ID neutron vs $e^+/\gamma/\mu$
- See time EM/neutron time coincidences
- Measured background rates
- Hints of neutrino signals?

288 kg detector module

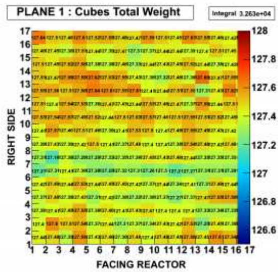
- 9 layers of 16 $\times$ 16 cubes
- 288 fibres / MPPCs
- Running Feb - May
- 1 week with reactor on
- Should measure c. 1000 of $\bar{\nu}$
- Now: source calibrations

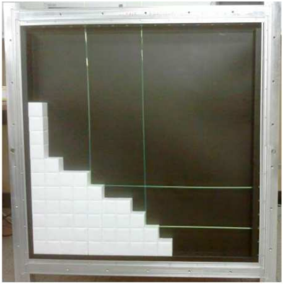
Goals:

- Proof of event topology concept
- Measure $\bar{\nu}_e$ rate and spectrum
- Compare with calculated spectrum

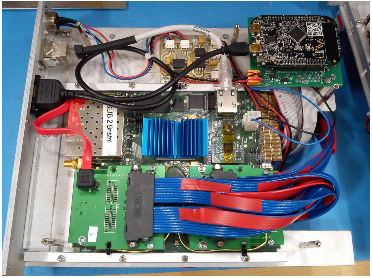


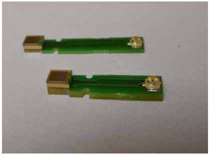
288 kg detector module - construction

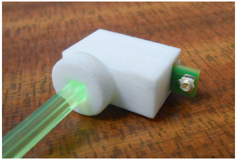




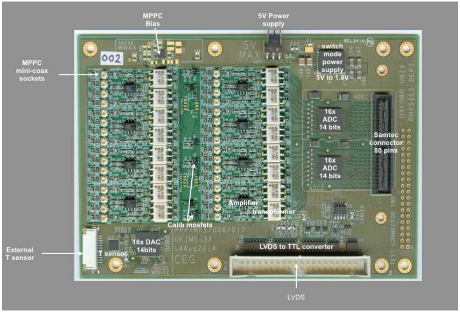
288 kg detector module - electronics



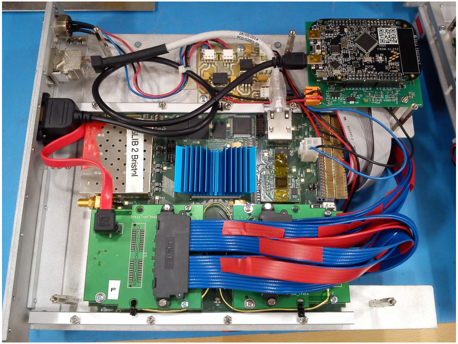




288 kg detector module - Front end electronics

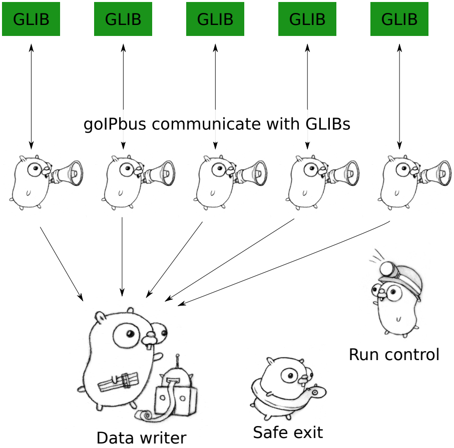


- Custom 32 channel board
- 1 detector layer / board
- Individual MPPC bias control
- Charge injection system
- Transimpedance amplifier
- 14 bit, 65 MS/s ADCs
- On detector temperature sensors
- Control via Cortex M0+ board



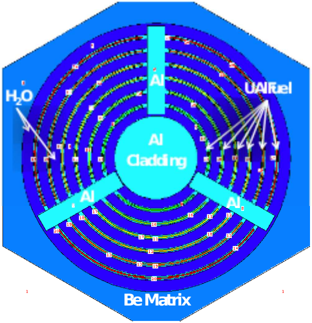
- GLIB FPGA board
- 2 detector layers / board
- Per channel time alignment
- Per channel threshold trigger
- Programmable waveform length
- Vertical / horizontal coincidence
- All communication by IPbus

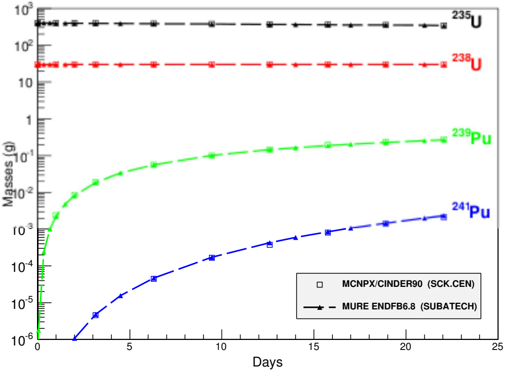
288 kg detector module - DAQ software



- Concurrent program design
- Go runtime handles parallelism
- Go IPbus implementation
- Single GLIB per goroutine
- Run level configuration
- Polls readout buffer for data
- Data merged data into single file

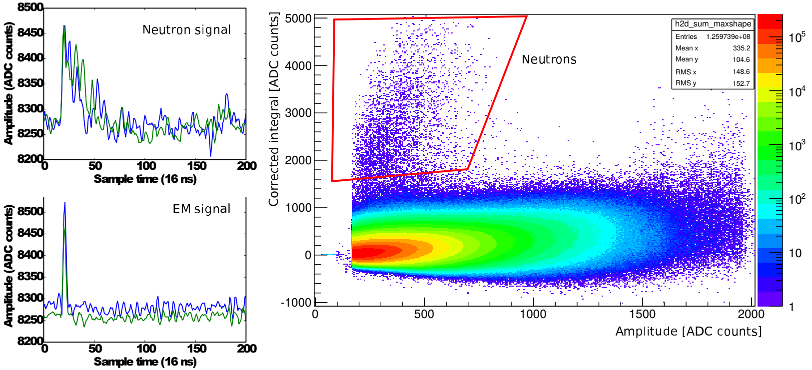
288 kg detector module - reactor calculations



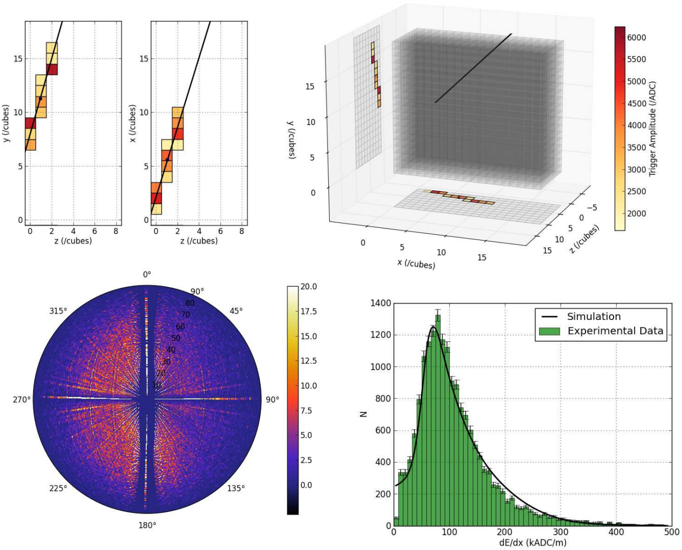


288 kg detector module - deployment

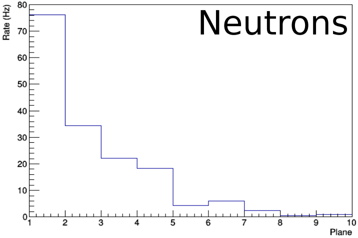
288 kg detector module - neutron ID

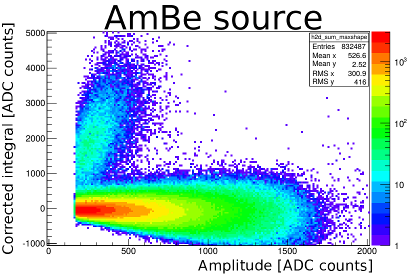


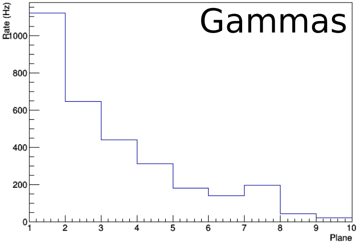
288 kg detector module - muons

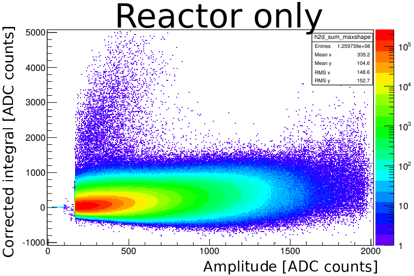


288 kg detector module - source measurements

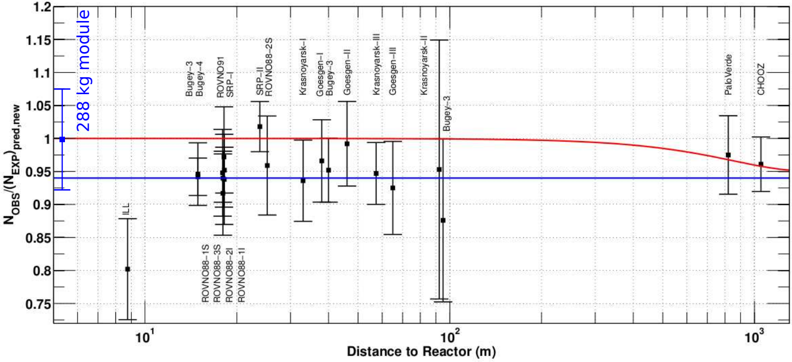






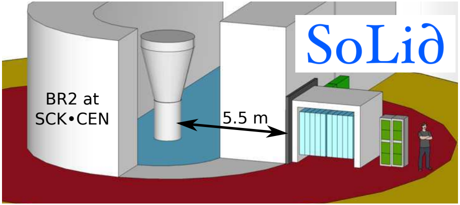


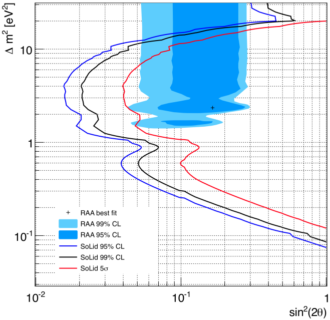
288 kg detector module - analysis goal



Purposes:

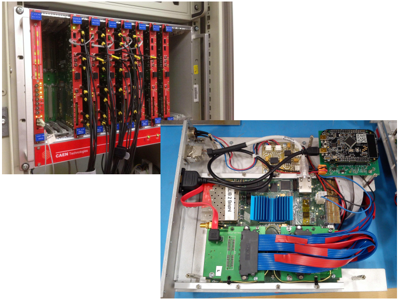
- Measure or rule out short baseline oscillations
- Compare measured and calculated flux and spectrum
- Near/far oscillation search
- Industrial detector production
- Online long reactor monitoring
- Fuel composition measurements
- Running 2016-2018+





Next phase: Upgrades

- Readout upgrade:
  - Noise reduction
  - Neutron trigger
  - Cost reduction
- Large scale production
- Detector optimisations:
  - energy resolution
  - cost reduction



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Conclusions

- Range of motivations for very short baseline reactor anti-neutrino experiment
- Challenging environment needs new detector technologies
- SoLid collaboration built and deployed 8 and 288 kg detectors
- Neutrino measurements from these detectors in preparation
- Construction of 2.88 T detector starting soon
- Full scale experiment to run 2016 - 2020+

SoLid