Solid/CHANDLER experiment at the BR2/North Anna reactor

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Outline

- Motivation for sterile neutrino oscillation search
- Keys to a short baseline reactor neutrino experiment
- Signal and Background characteristics
- SoLid Experiment
  - BR2 reactor
  - Submodule 1 design and performances
  - Submodule 1 deployment (2014-2015)
- Chandler detector technology
- Outlook of sensitivity for SoLid/Chandler

Neutrino Oscillations

- 2-Flavor Oscillation:

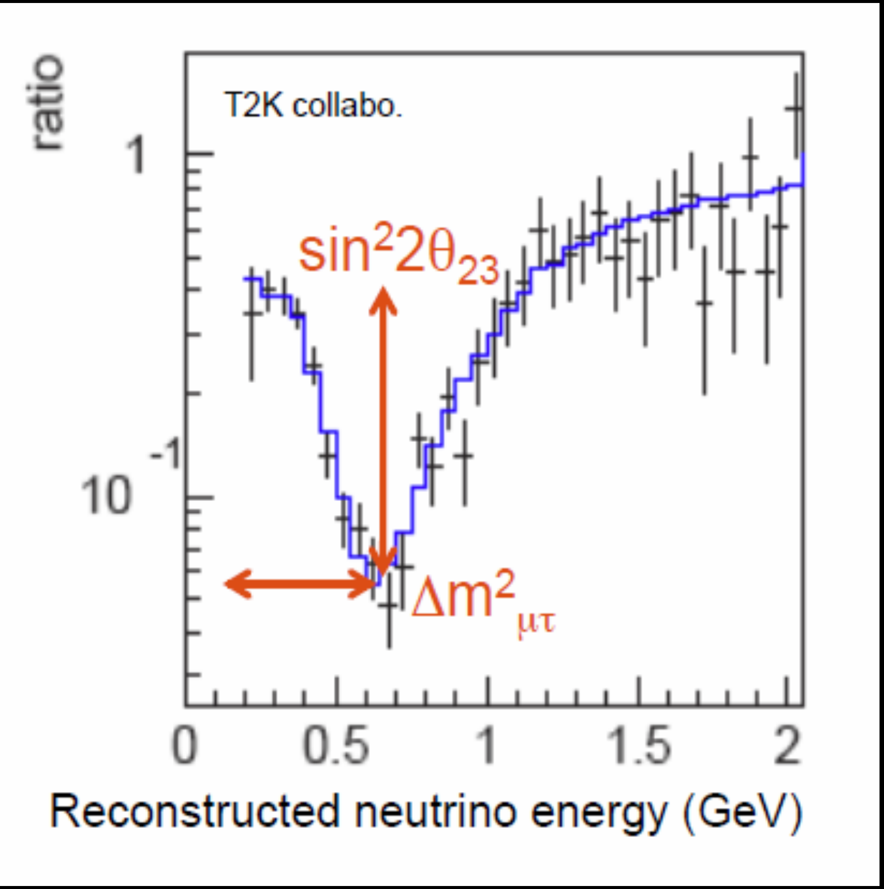
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4 E_\nu} \right)$$

Know: L, need E_ν to determine Δm^2, θ

- 3-Flavor Oscillation: allows for CP violation

Observable Oscillation Parameters

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



Oscillation probability

Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = &\ 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \ (1 - 2S_{13}^2)
\end{aligned}
$$

⇒ These extra dependencies are both a "curse" and a "blessing"

Reactor Disappearance Experiments

- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

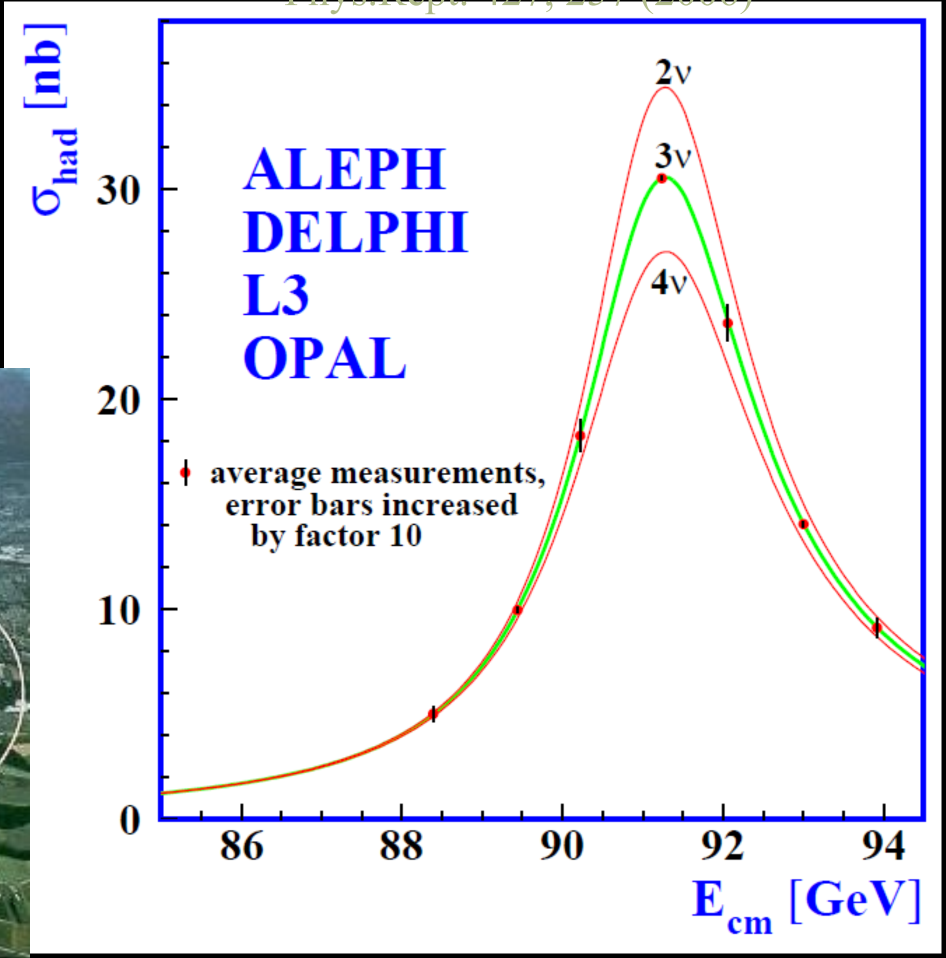
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \ small\ terms$$

Sterile Neutrinos

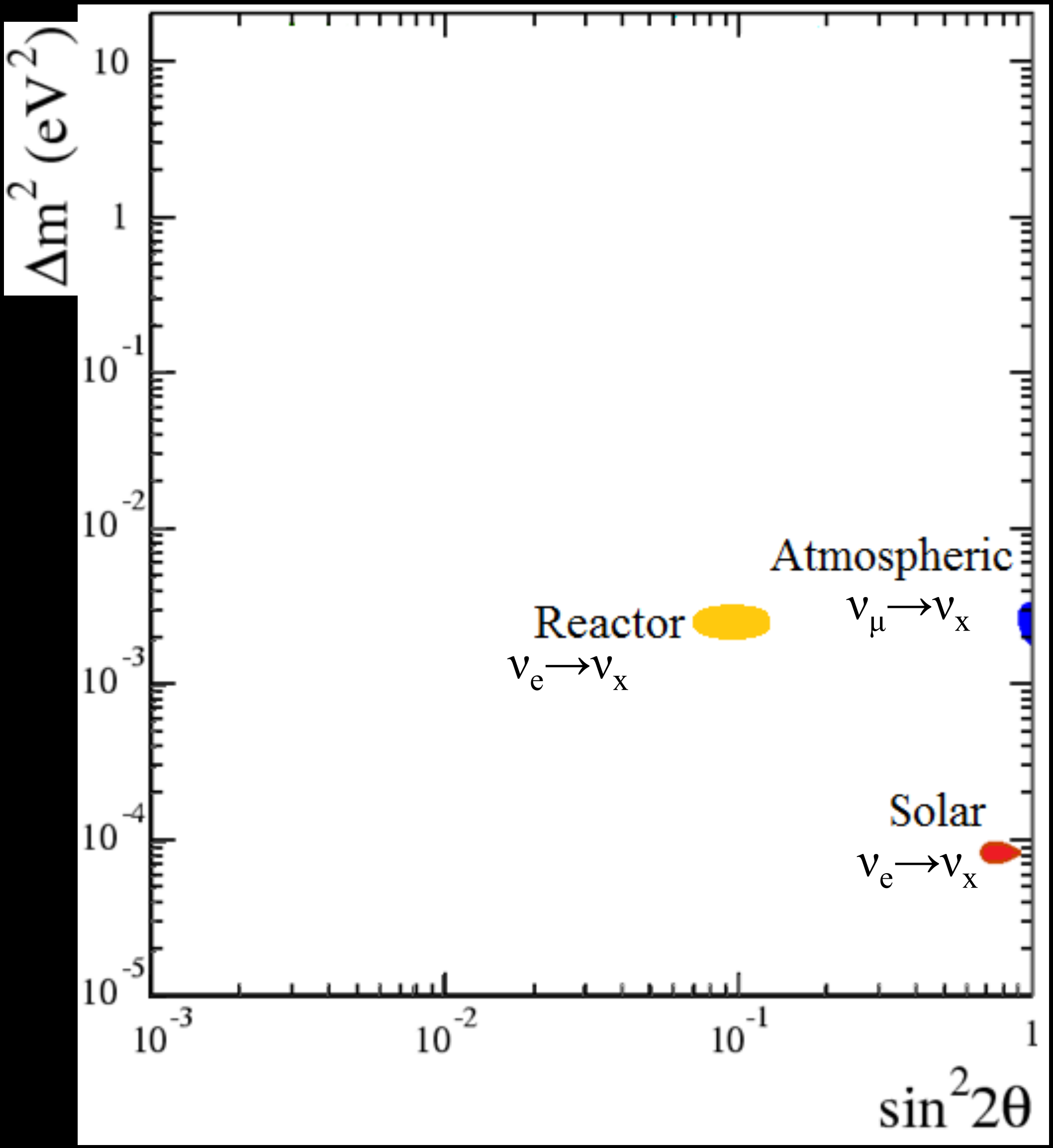
A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing.

Active neutrinos:
LEP Invisible Z^0 Width is consistent with only three light active neutrinos

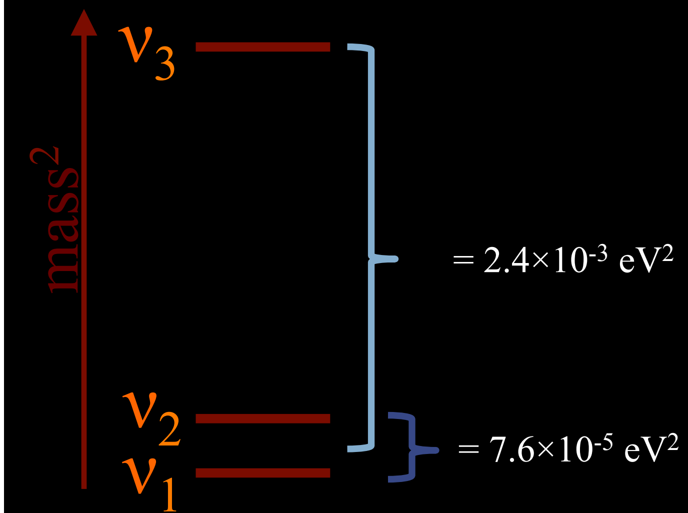
Phys.Rept. 427, 257 (2006)



The Neutrino Oscillation Data



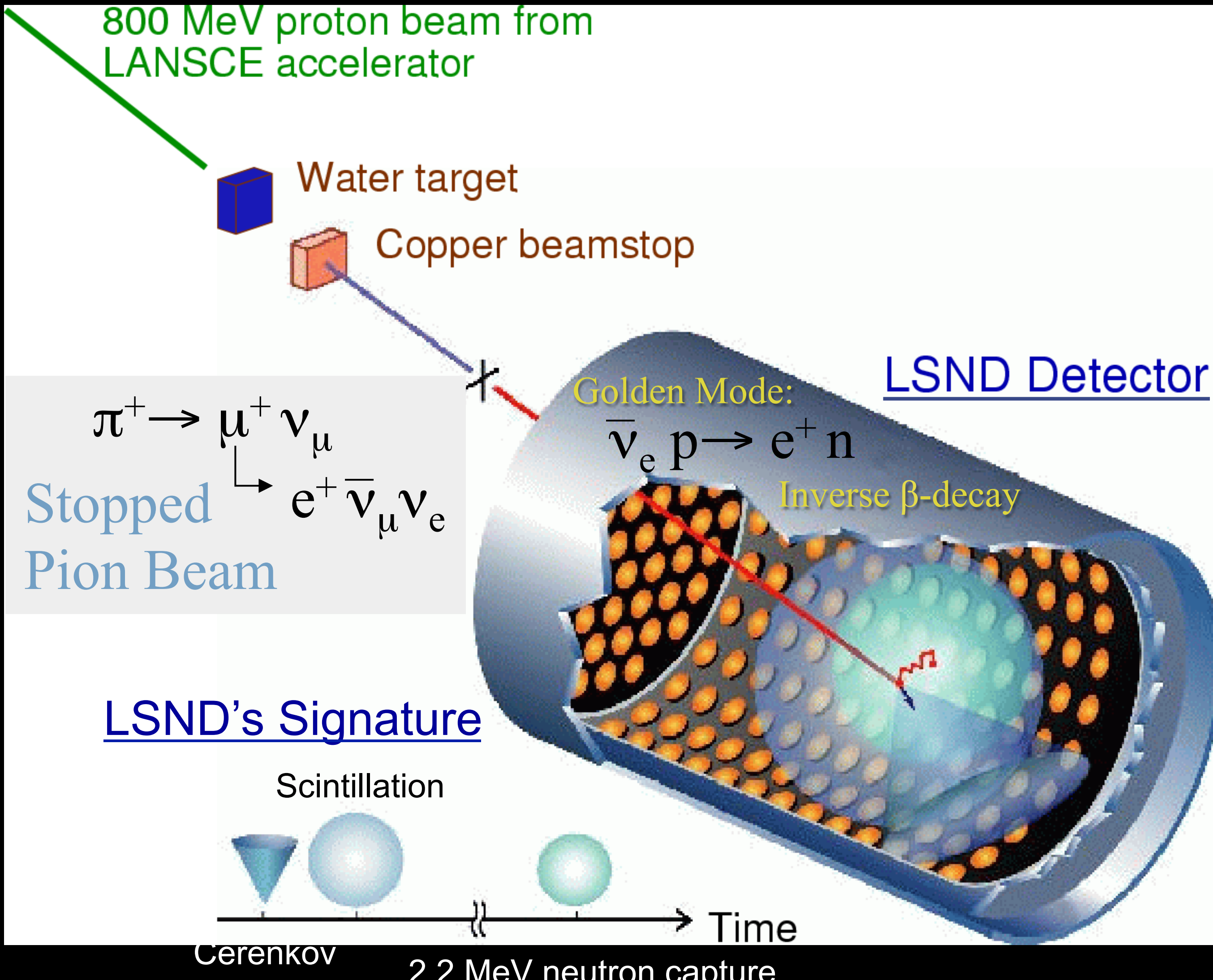
The data for the three neutrino mixing model is nearly complete and extraordinarily self-consistent



$\Delta m^2 eV^2$ does not fit the three neutrino model

The LSND Experiment

LSND took data from 1993-98



The full dataset represents nearly 49,000 Coulombs of protons on target.

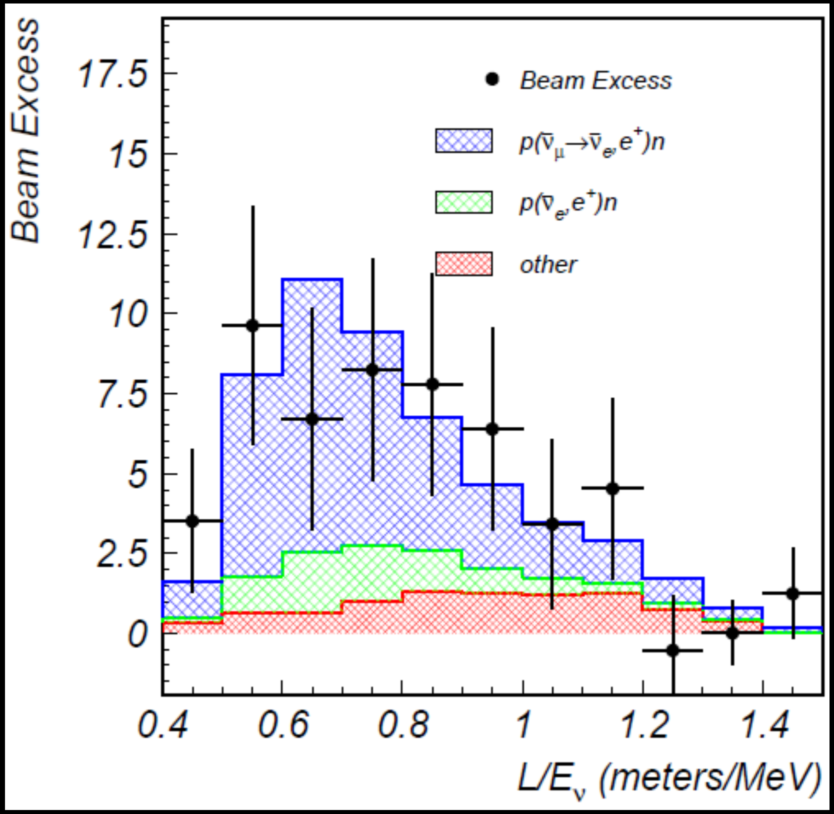
Baseline: 30 m

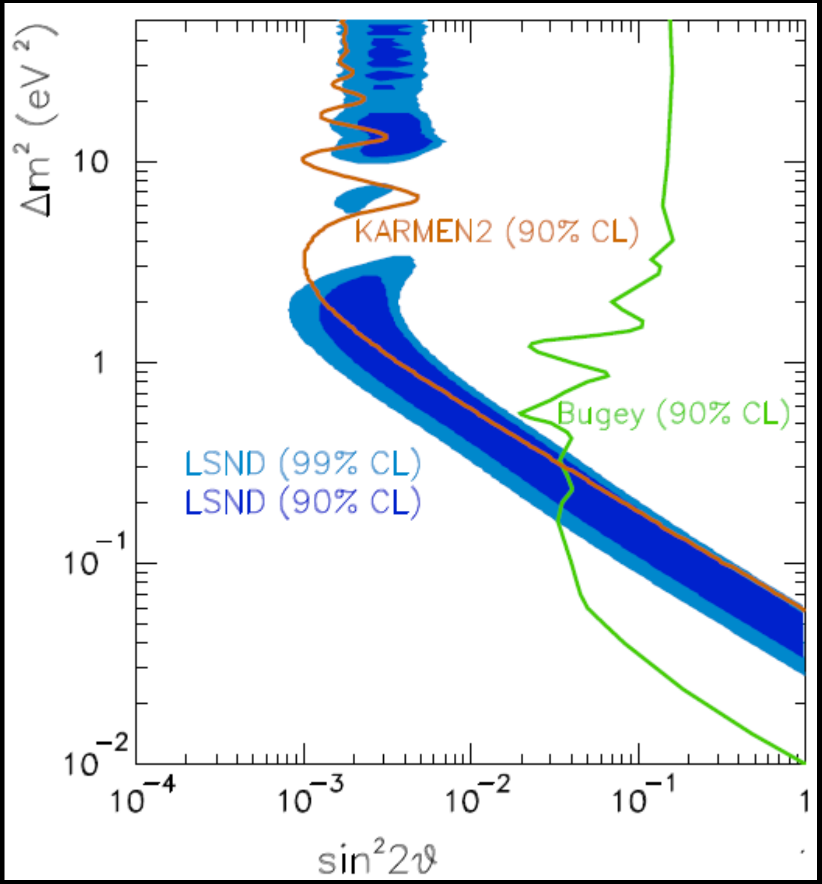
Energy range: 20 to 55 MeV

L/E ~ 1 m/MeV

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance

Aguilar-Arevalo *et al.*, Phys.Rev. D64, 112007 (2001)

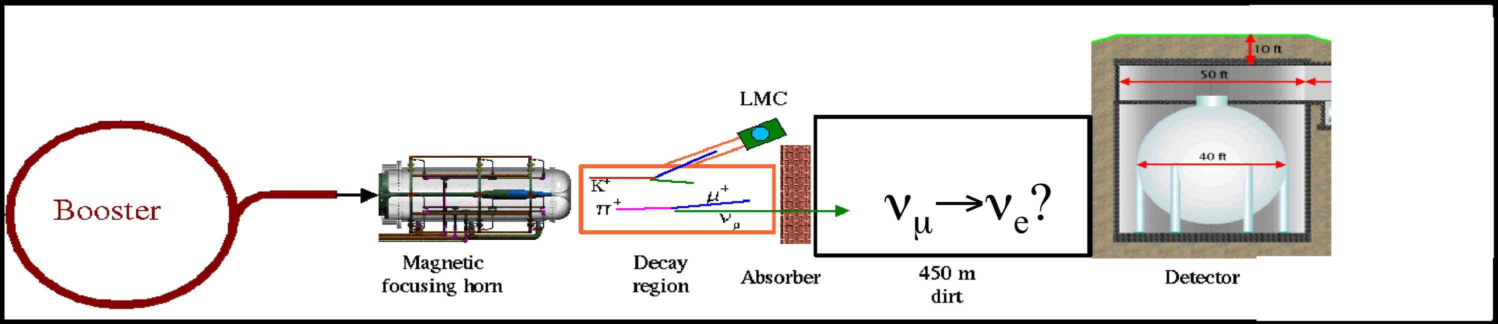




Event Excess: 32.2 ± 9.4 ± 2.3

MiniBooNE $\nu_\mu \rightarrow \nu_e$ Appearance Search

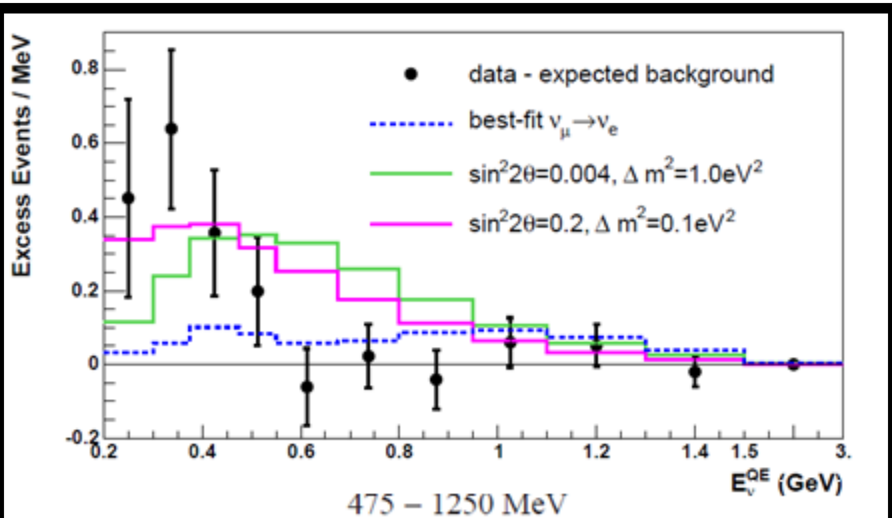
MiniBooNE uses a π^+ (π^-) decay in flight beam and a liquid Cherenkov detector (pure mineral oil) to search for ν_e ($\bar{\nu}_e$) appearance in a ν_μ ($\bar{\nu}_\mu$) beam



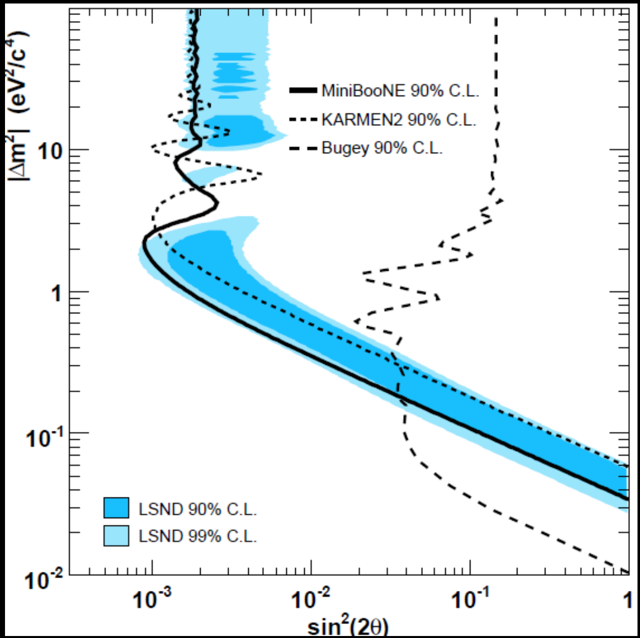
Baseline ~ 500 m

E_ν ~ 600 MeV

L/E ~ 1m/MeV



475 – 1250 MeV	
Data	408
Background	385.9 ± 19.6 ± 29.8
Excess	22.1 ± 19.6 ± 29.8
Significance	0.6σ



Phys.Rev.Lett. 98, 231801 (2007)

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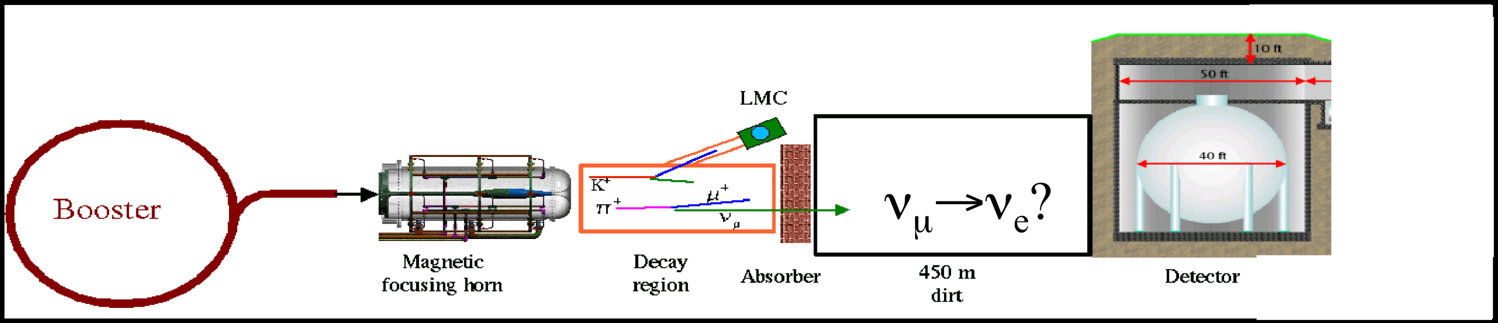
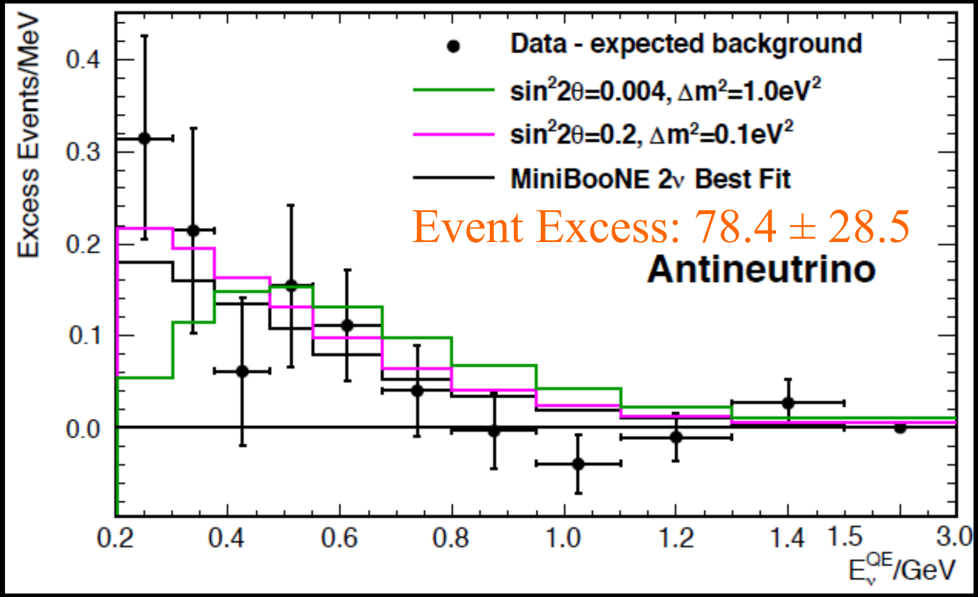
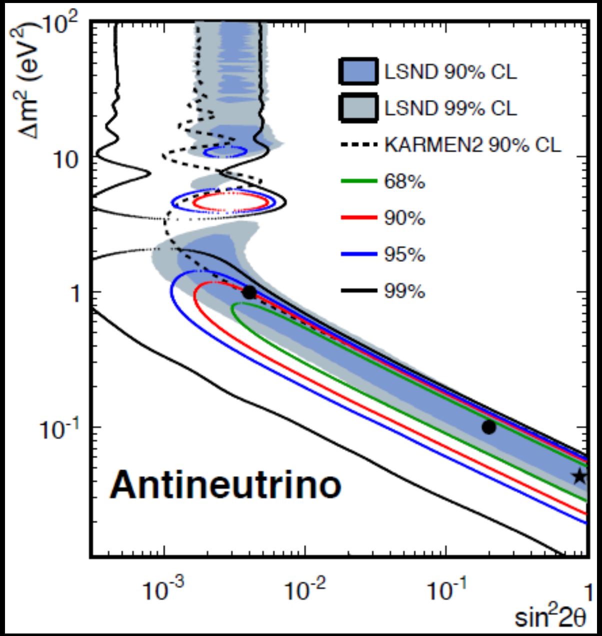


- Baseline ~ 500 m
- E_ν ~ 600 MeV
- L/E ~ 1m/MeV

Phys.Rev.Lett. 110, 161801 (2013)





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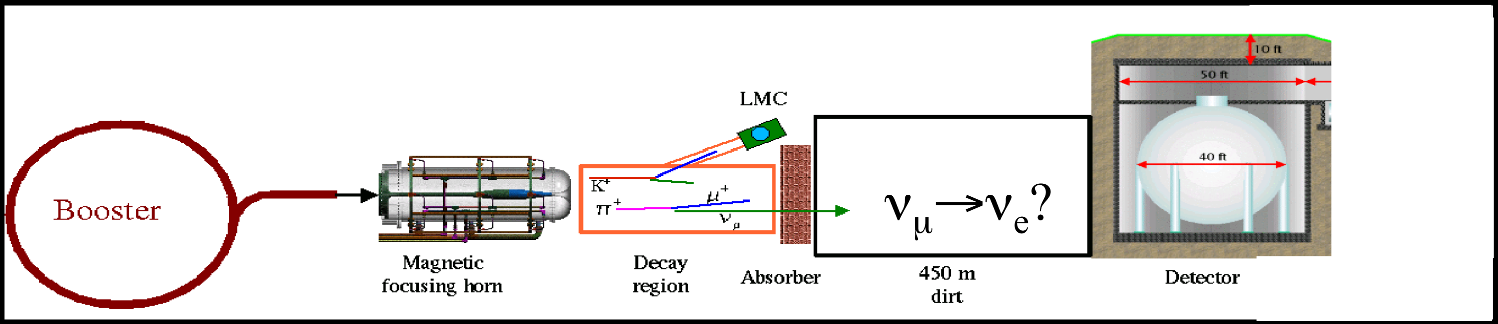

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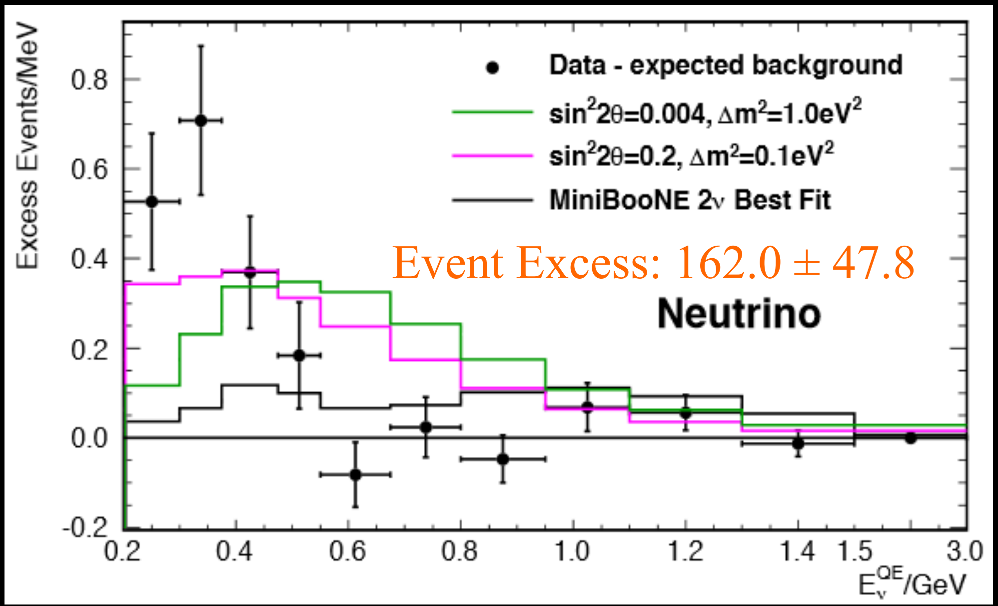
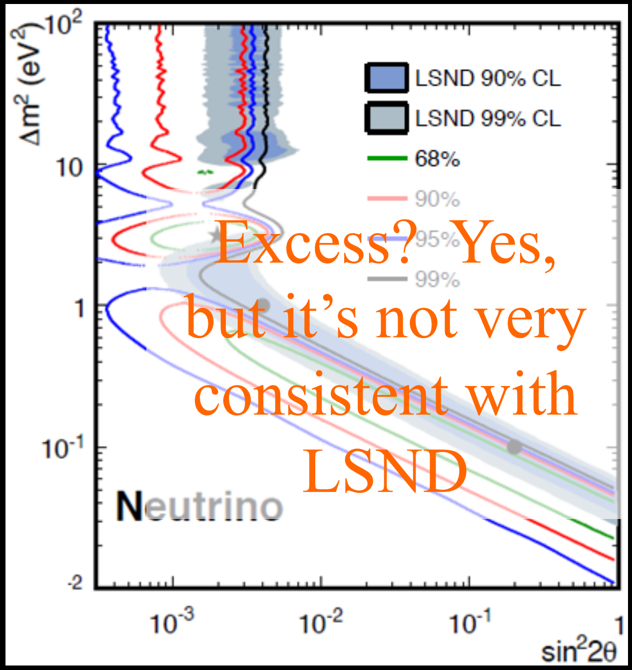


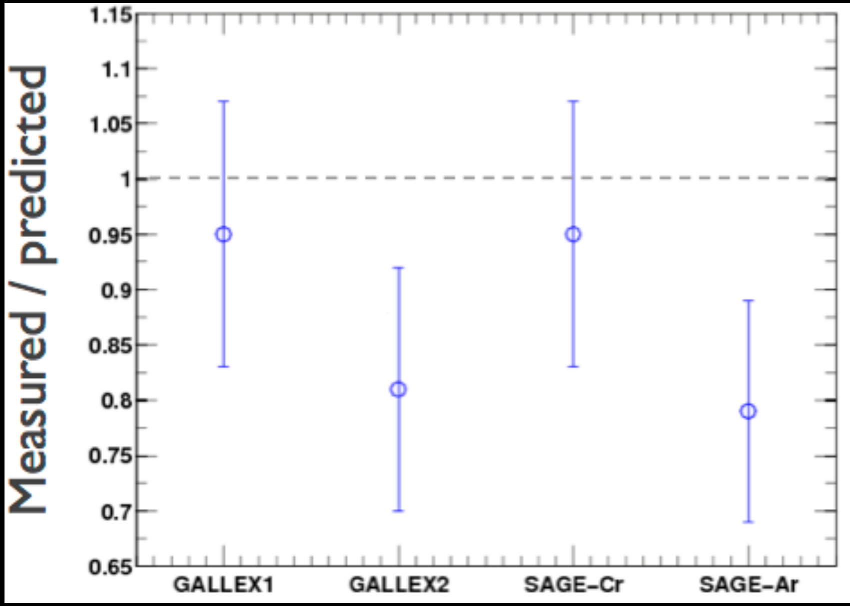


Excess? Yes, but it's not very consistent with LSND

Gallium Anomaly (ν_e Disappearance)

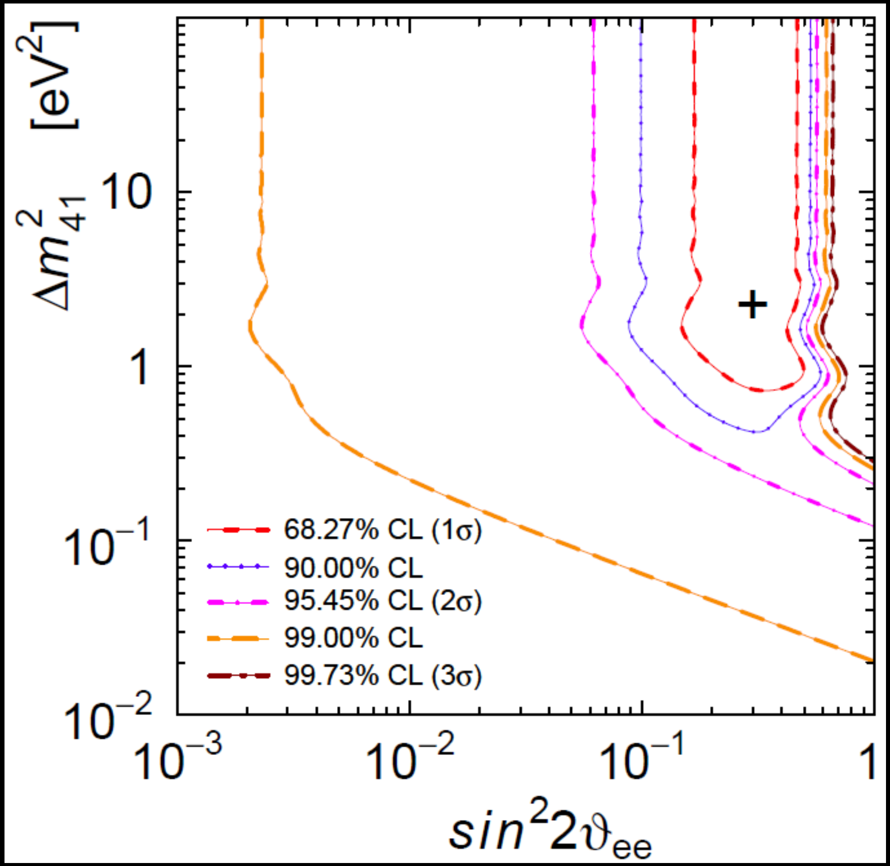
The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources (^{51}Cr and ^{37}Ar) to "calibrate" the $\nu_e\,^{71}Ga$ interaction/detection rate.

A reanalysis, based on new cross section calculations, suggests that were too few events.

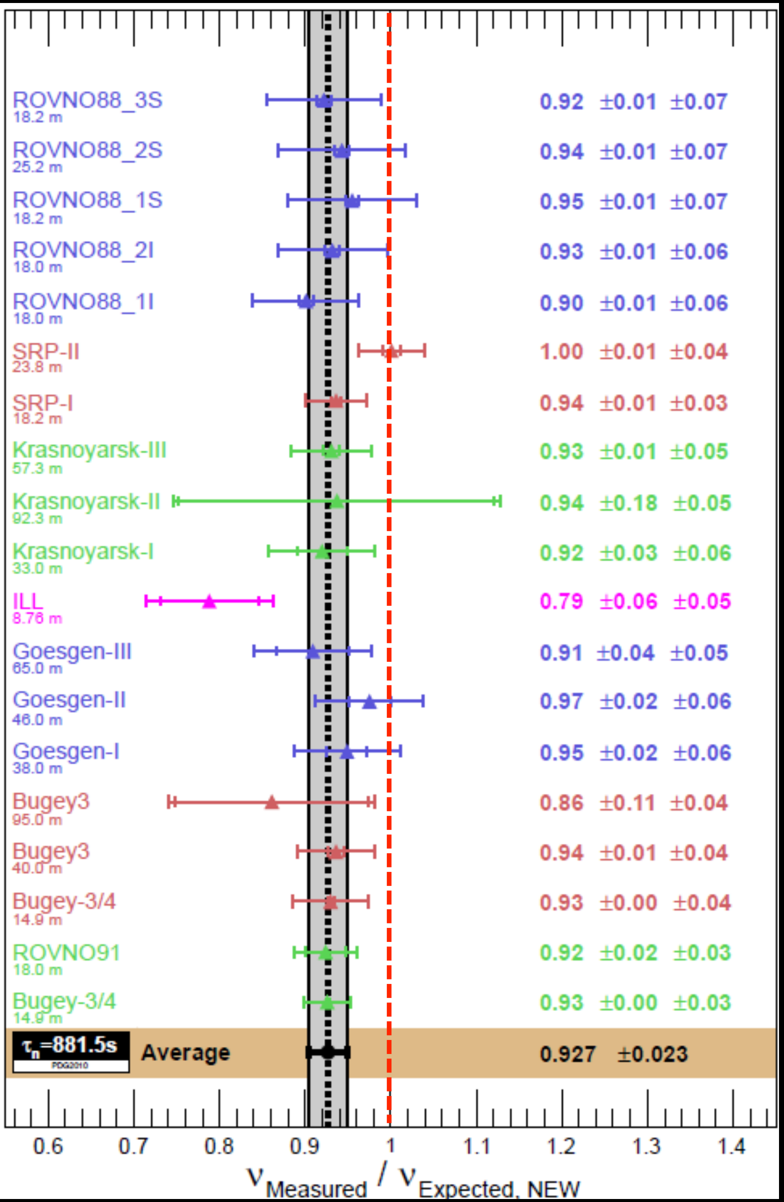


Giunti & Laveder, Phys.Rev.C83, 065504 (2011)

Giunti *et al.*, Phys.Rev.D86, 113014 (2012)

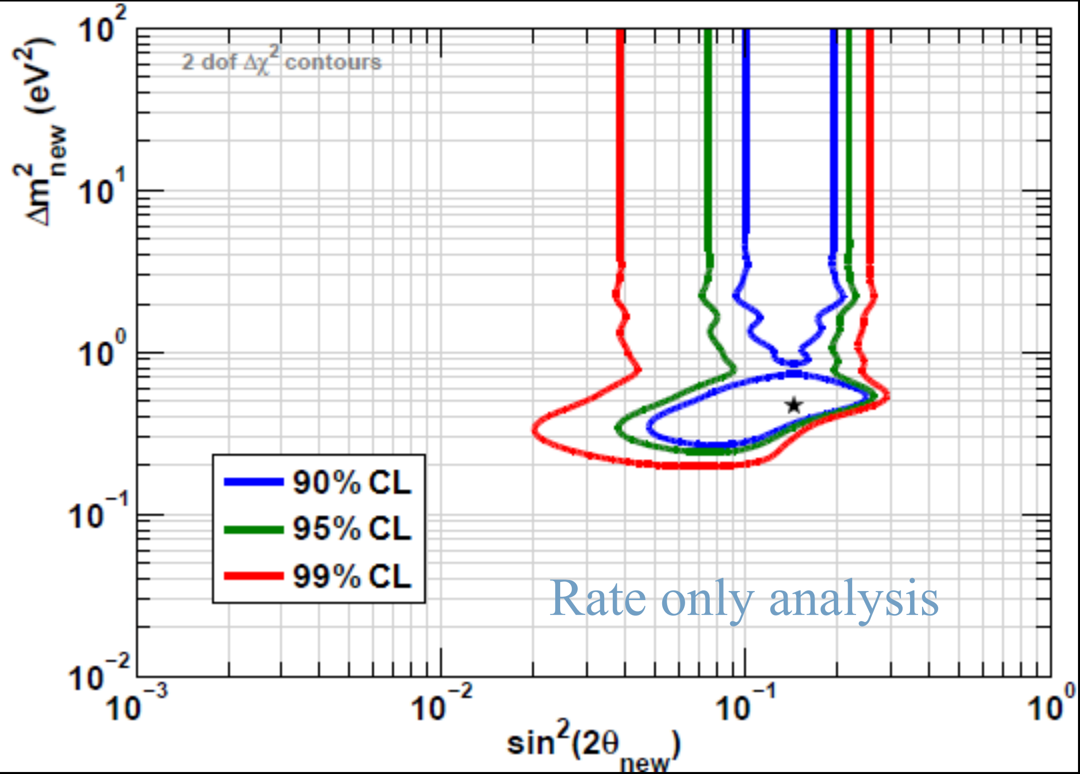


Reactor Anomaly ($\bar{\nu}_e$ Disappearance)



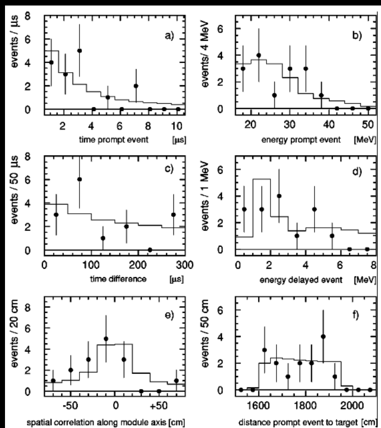
Recent calculations of the reactor flux and spectrum predict a higher rate than the earlier calculation. This resulted is an apparent deficit of reactor neutrinos across all experiments.

Mention *et al.*, Phys.Rev.D83 073006 (2011)

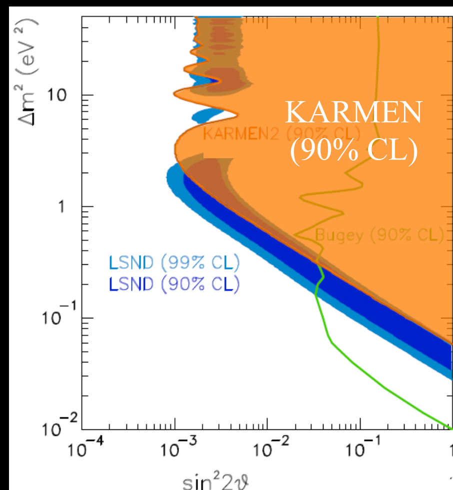


Evidence Against the ~1 eV^2 Sterile Neutrino

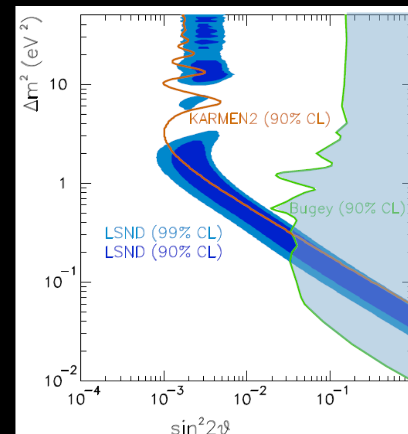
KARMEN (ν_μ to ν_e)

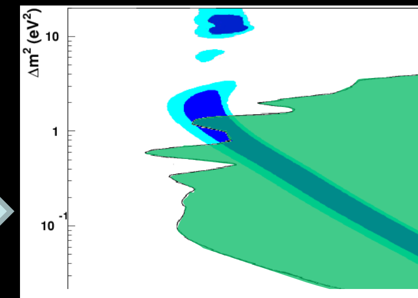


Armbruster *et al.*, Phys.Rev.D65 112001 (2002)



Bugey Reactor (ν_e disappearance)



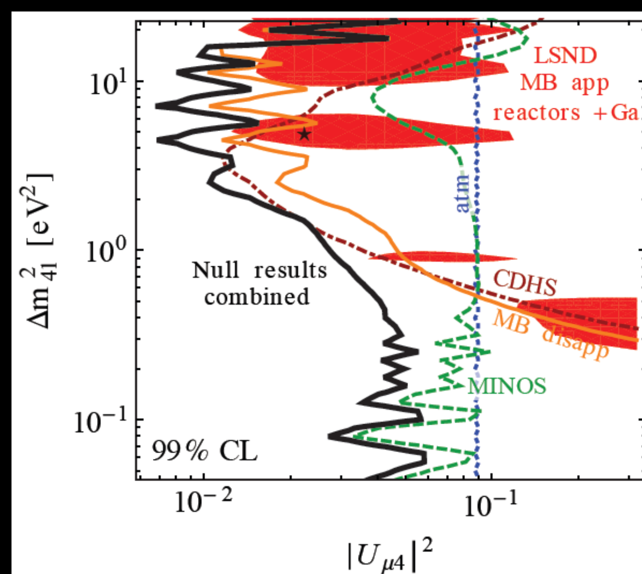


Effective (ν_μ to ν_e)

Achkar *et al.*, Nucl.Phys.B434, 503 (1995)

ν_μ Disappearance
(where is it?)

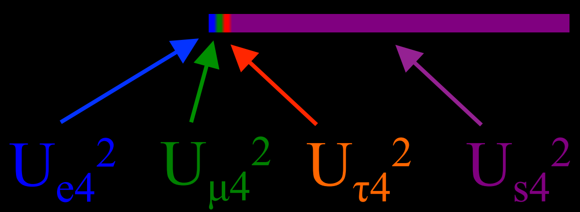
For to happen there must be both and disappearance



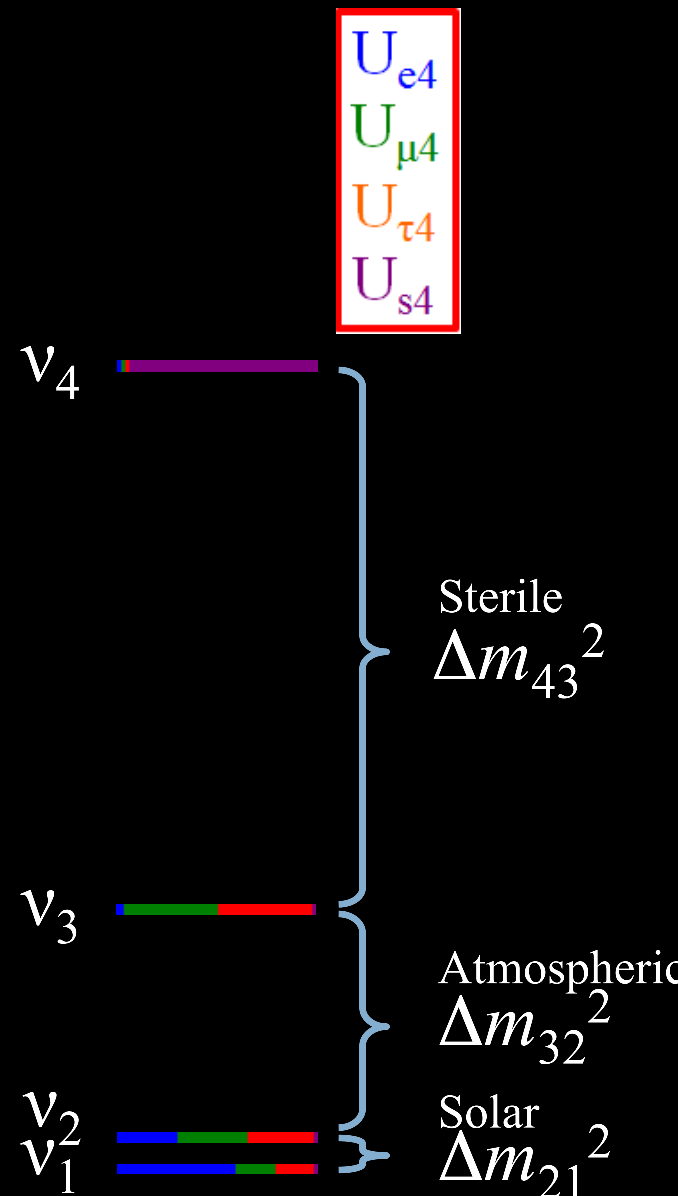
Kopp *et al.*, JHEP 1305, 050 (2013)

Relating Appearance and Disappearance Probabilities

With a single sterile neutrino we get a 4×4 PMNS mixing matrix and 3 independent Δm^2s.



(PMNS Unitary)



The appearance probability:

$$P_{\mu e} = 4U_{e4}^2\, U_{\mu 4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

The ν_e disappearance probability:

$$P_{ee} \approx P_{es} = 4U_{e4}^2\, U_{s4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

The ν_μ disappearance probability:

$$P_{\mu\mu} \approx 4U_{\mu 4}^2\, U_{s4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

Keys to a Short-Baseline Reactor Experiment

1. Sensitivity to the higher Δm^2 range (2 eV^2 and above) requires a compact reactor core and good energy resolution.

2. Relatively small detectors require careful consideration of isotope used for neutron capture and tagging.

3. Background is important, needs to be characterized

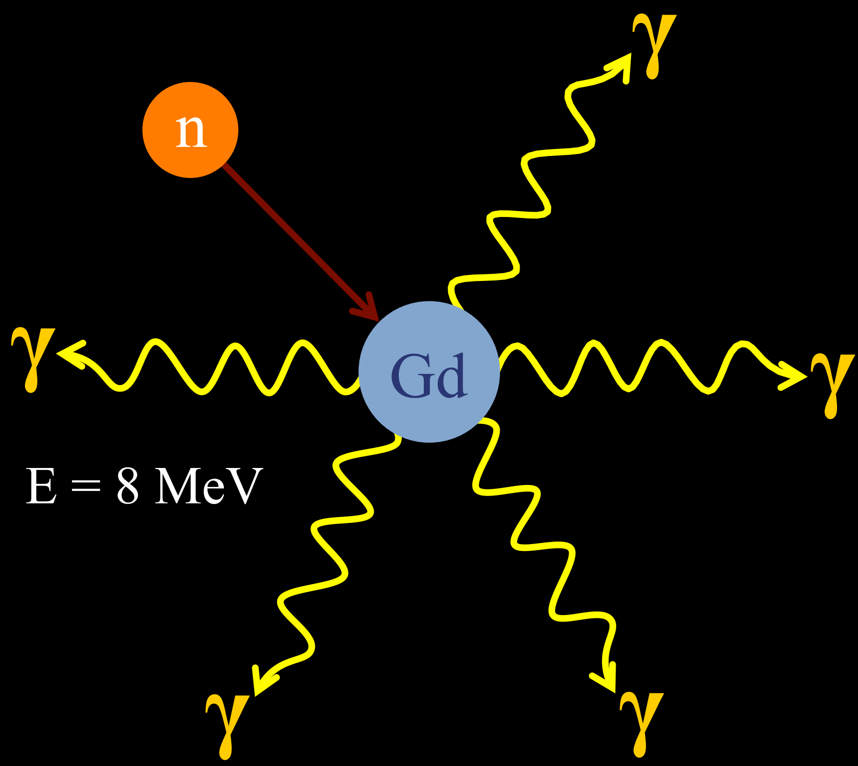
4. Detector should be able to work on the surface or with very small overburden

5. Detector should be portable, cannot use tons of shielding material

Neutron Capture Options

- Not the same as in a reactor experiment
- Similar backgrounds but different overburden
- Detector dimensions and event containments are very different

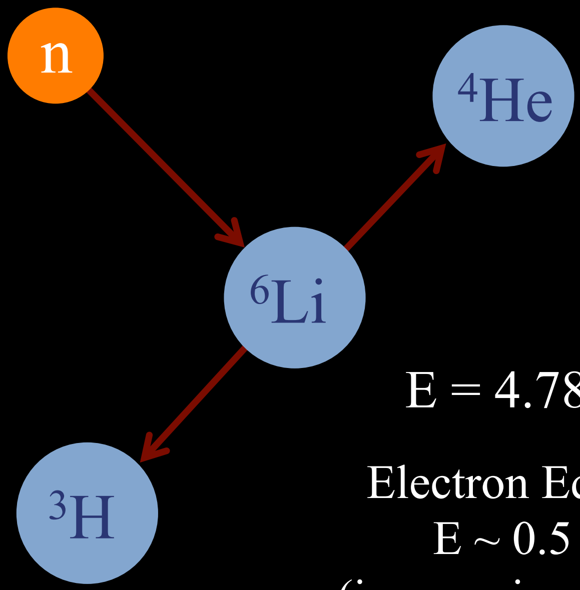
Neutron Capture on Gadolinium



E = 8 MeV

Poorly contained in small detectors

Neutron Capture on Lithium-6



E = 4.78 MeV

Electron Equivalent
E ~ 0.5 MeV
(in organic scintillator)

Contained in a few micrometers

Backgrounds

Backgrounds, particularly from cosmic induced neutrons are the most significant challenge.

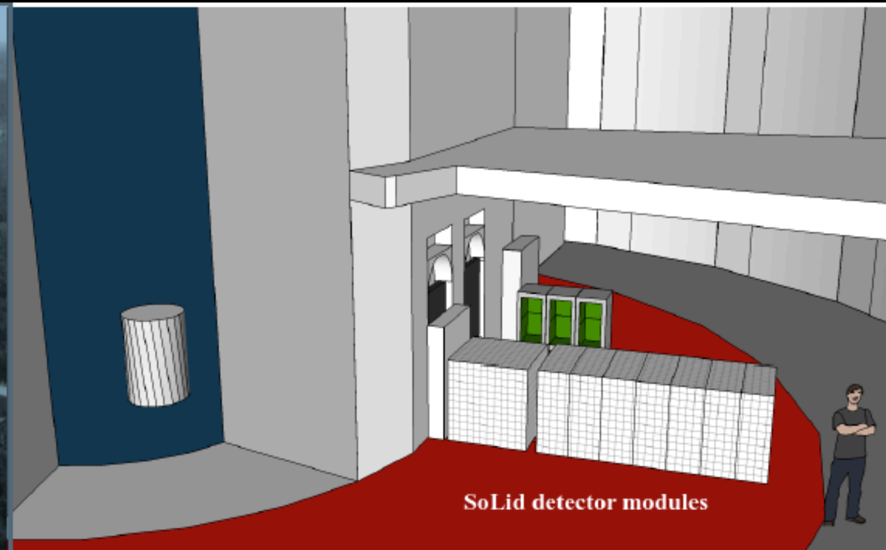
Difficult to shield muons, and shielding will contribute to enhance the number of neutrons produce by muons.

Multiple neutrons in particular will constitute a problem. Need to measure this on reactor site with a sizable detector.

Random coincident backgrounds is also a problem but can be mitigated by:

a. Reducing background rates (shielding)
b. Improving signal pattern recognition, and
c. Tightening coincidence criteria

The SoLid Experiment



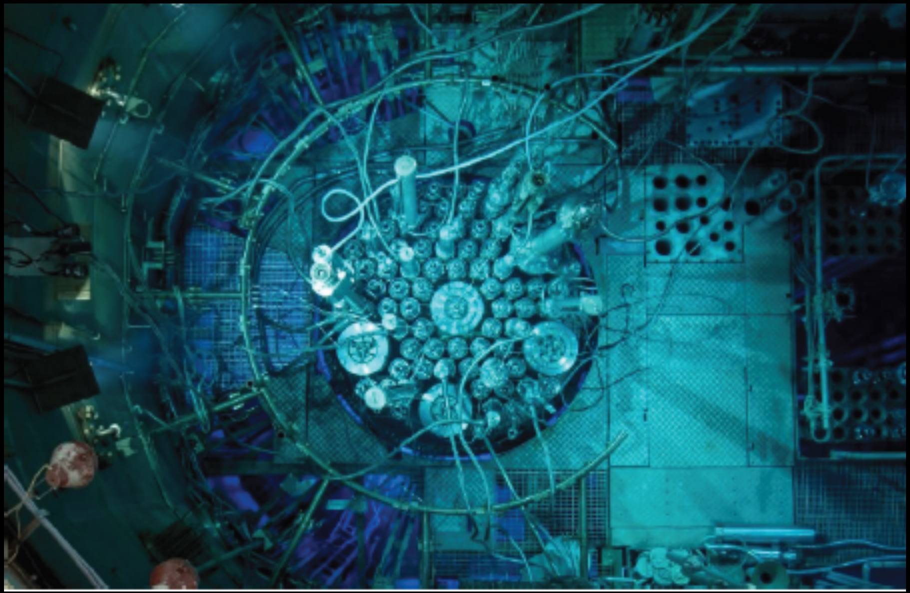
- Search for short baseline neutrino oscillations
  - Precise position and energy measurement
  - Existence of a fourth massive ”sterile” neutrino ?
- Precise measurement of the anti-ν_e spectrum of ^{235}U from 5.5 m @ BR2 reactor
- Demonstrate detector technology as feasible reactor monitoring safeguard application

The BR2 Reactor

The 60 MW BR2 reactor is a facility at the Belgian National Nuclear Lab, SCK•CEN.

With a 5.5 meter closet approach this site has the highest reactor antineutrino flux of any publically knowable compact reactor site.

The absence of any beam portals makes for a relatively low-background site with backgrounds dominated by the typical environmental sources.



The BR2 Reactor

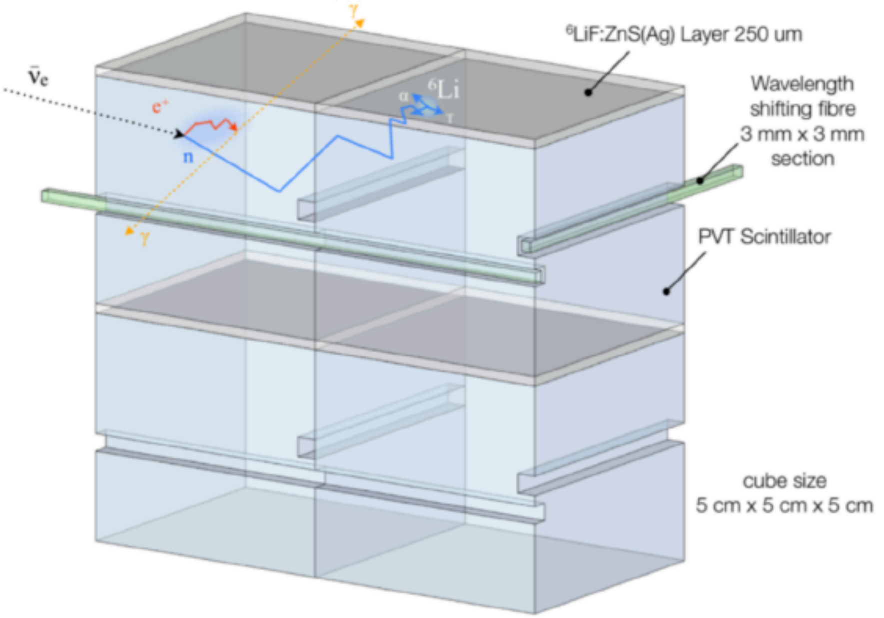
- Research reactor
  - Highly enriched in ^{235}U
  - Neutrino flux (~10^{19} ν/s)
  - Compact core (d~50 cm)
  - Well shielded core (low background)
  - Thermal power 40 to 80 MW
- Reactor hall allows baselines from 5.5 to 10 m
- 150 days per year duty cycle
  - Reactor off data for background estimation and subtraction

SoLid detector: operation principle

Detection through the Inverse Beta Decay (IBD)

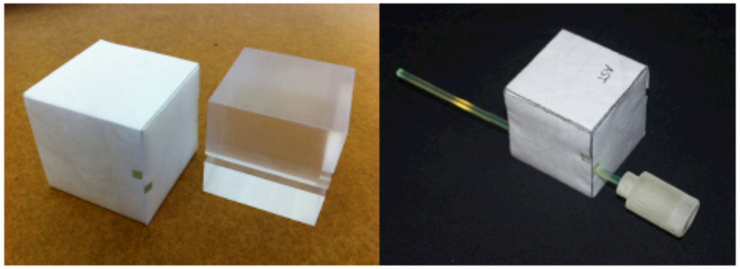
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

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

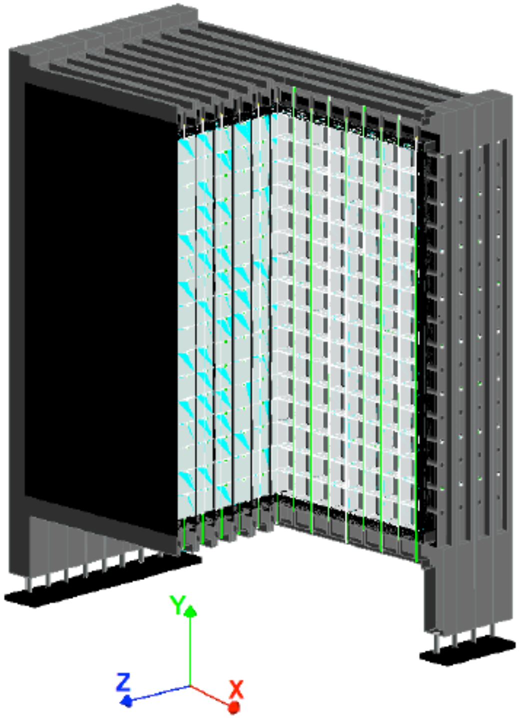


Composite scintillator

- PVT Cubes of 5x5x5 cm + ^{6}Li:ZnS(Ag).
- Cubes are optically separated (Wrapped with Tyvek)

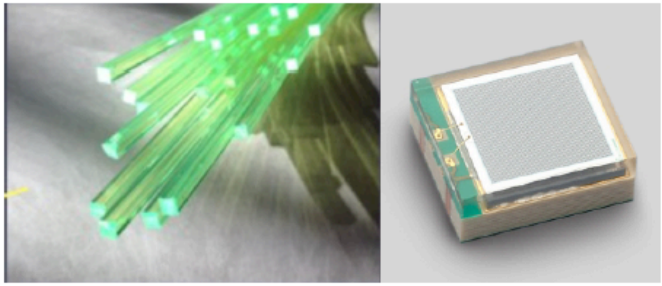


Detector (SM1) deployment: 2014-2015



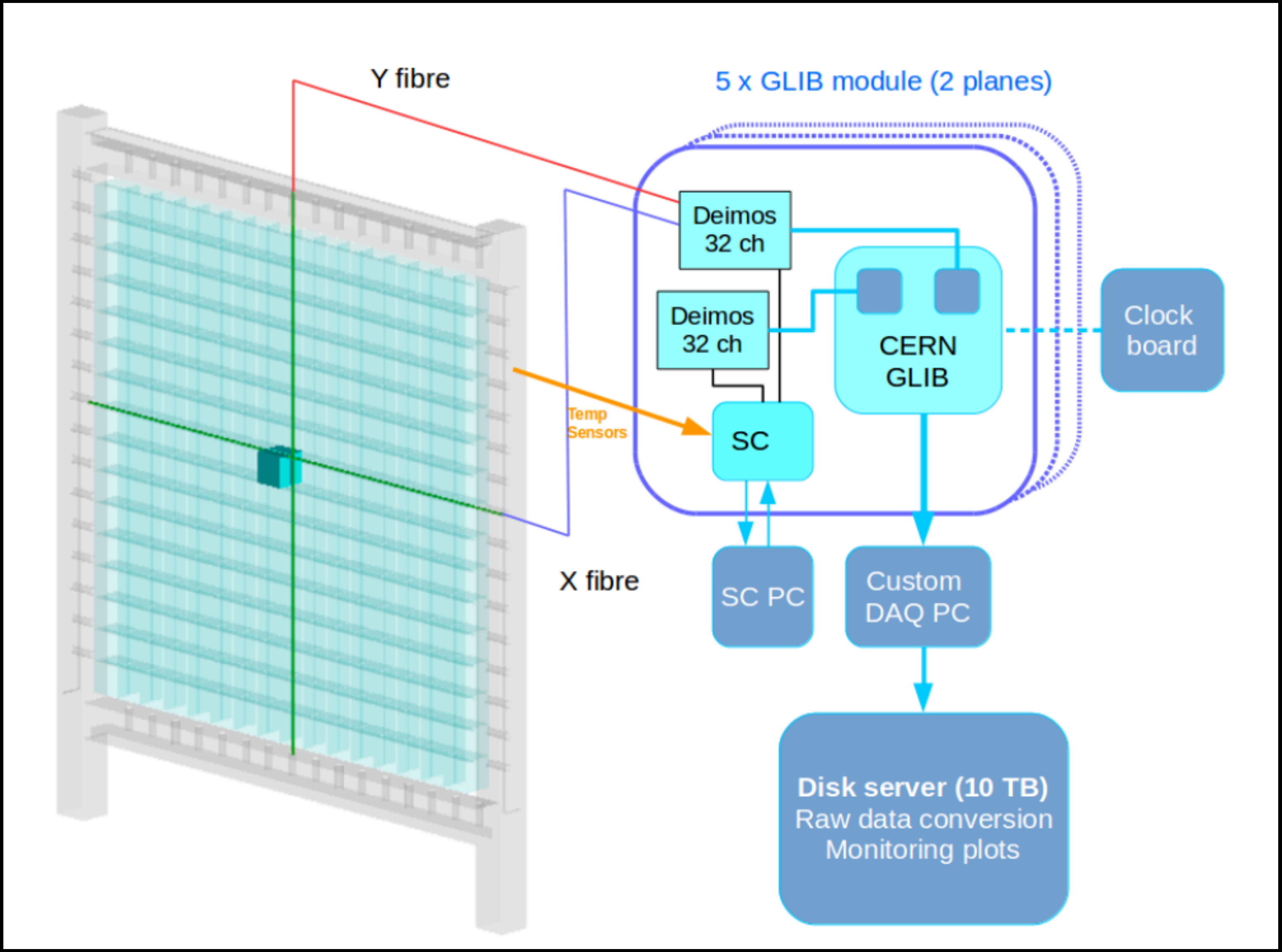
- 16 x 16 x 9 PVT Cubes + ^{6}Li:ZnS(Ag).
- 9 detector frames of Al with HDPE internal reflectors

- High segmentation
  - Spatial resolution of IBD vertex
  - Allow exploitation of IBD event topology
  - Background rejection
- Light collected with WLS fibers and multi–pixel photon counters (MPPCs) Hamamatsu S12572-050P

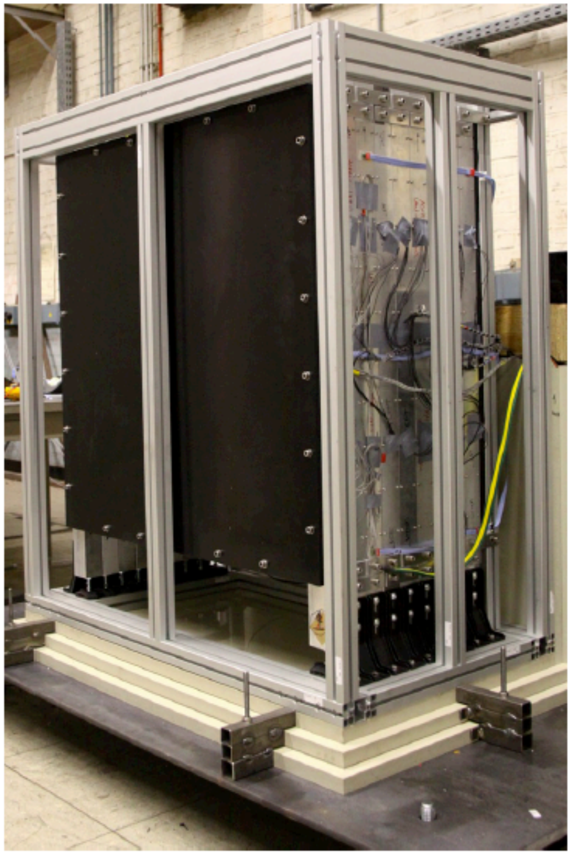


- 288 readout channels
- ≈ 290 kg

SM1 readout and electronics



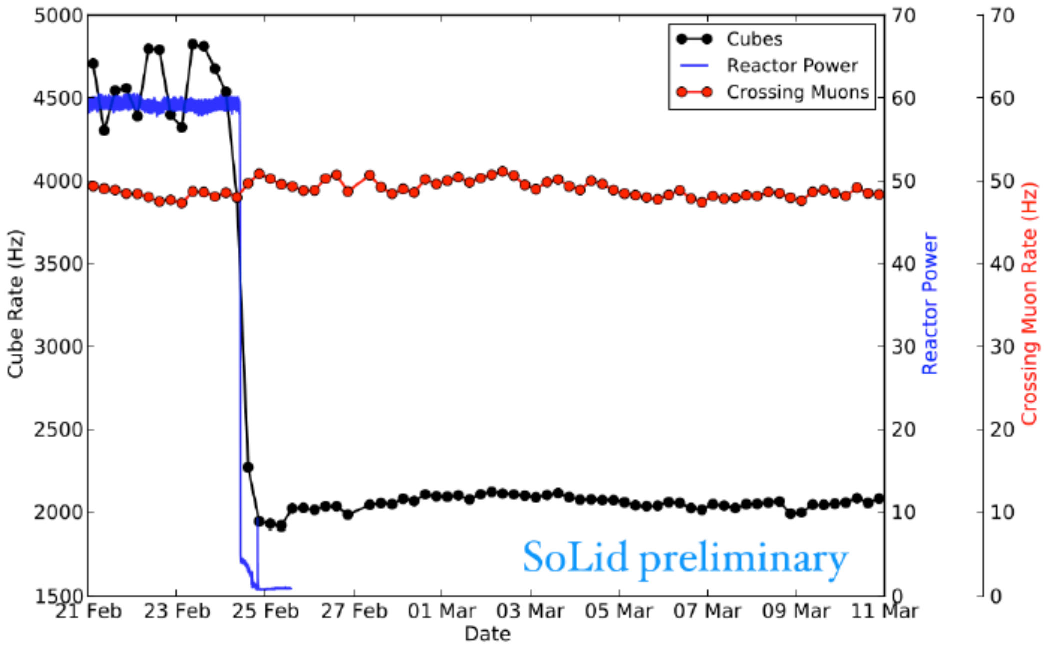
SM1 deployment at BR2: 2014-2015



- ADC: 62.5MHz rate (16 ns sample)
- Light yield $\sim$ 25 PA/MeV (X+Y)
- Energy resolution of 20 % at 1 MeV
- 50 ns coincidence window (X&Y)
- Threshold at 0.6 MeV
- Trigger algorithms
  - Trigger by threshold and coincidence
  - Random trigger

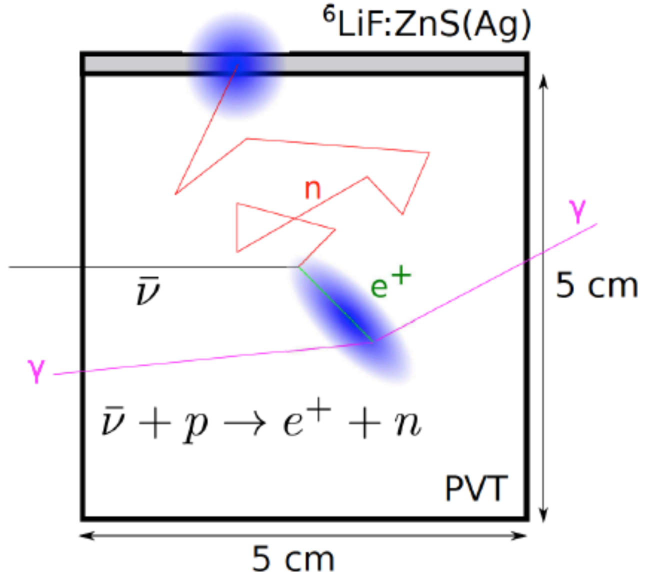
SM1 run at BR2

- Data from Dec 2014 to March 2015
  - 3 – 4 days Reactor on
  - ∼ 1 month Reactor off
- Detector calibration
  - ^{60}Co, ^{137}Cs and cosmic muons for energy calibration
  - AmBe and ^{252}Cf for neutron calibration



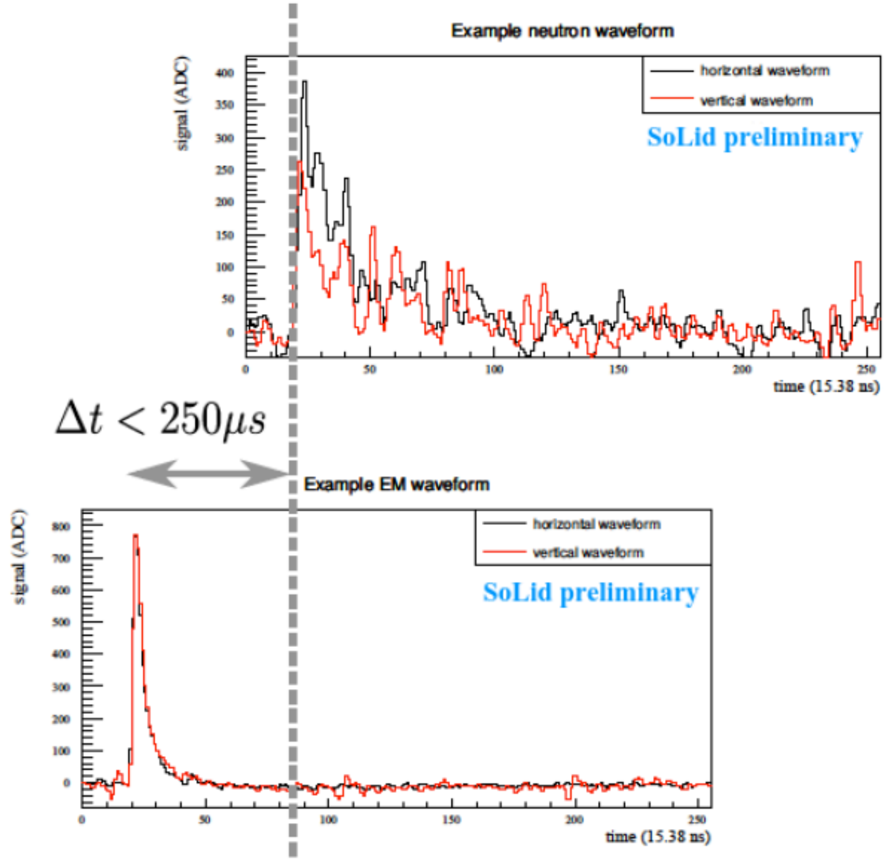
Signal discrimination

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



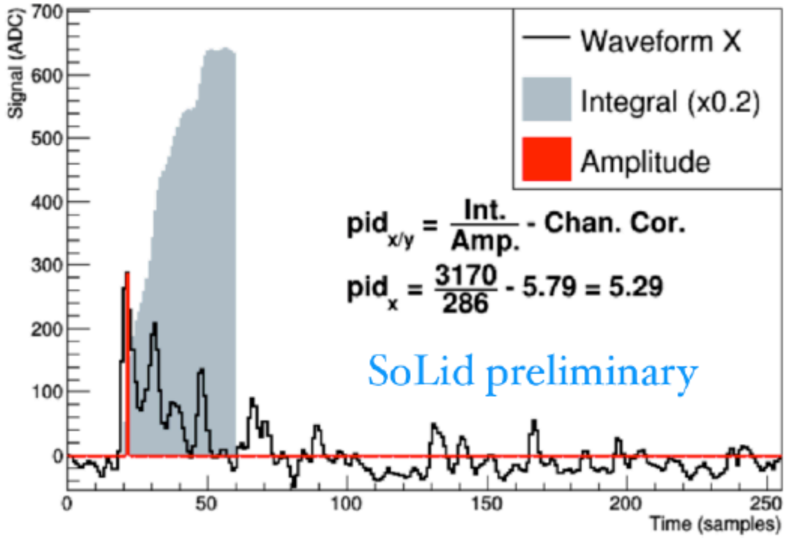
Particle discrimination capabilities based on the pulse shape difference between the ^{6}Li:ZnS(Ag) and PVT.

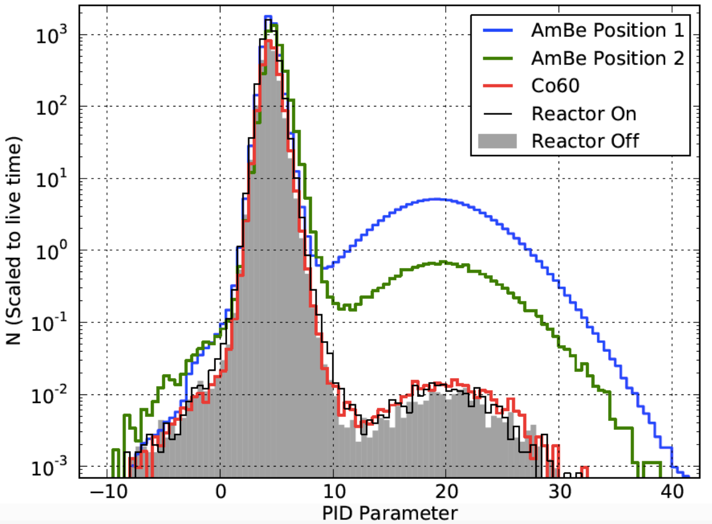
Prompt-delayed coincidence

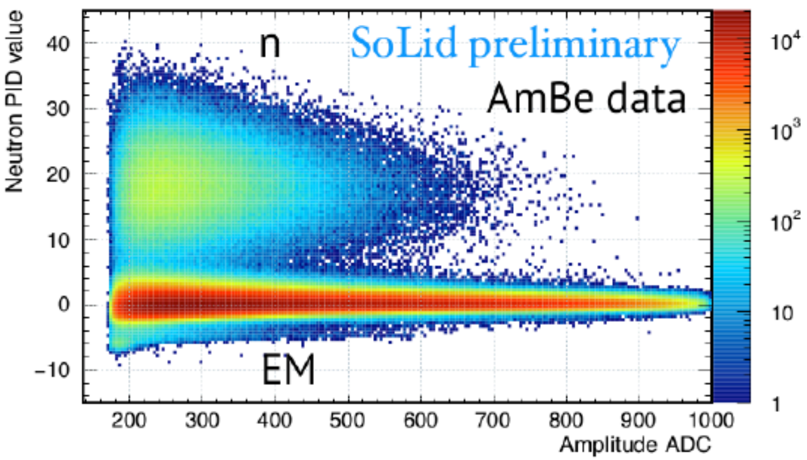


Neutron identification

- Particle identification based on the pulse shape.
  - Integral / Amplitude
- The $^{6}Li:ZnS$ neutron discrimination power is confirmed.

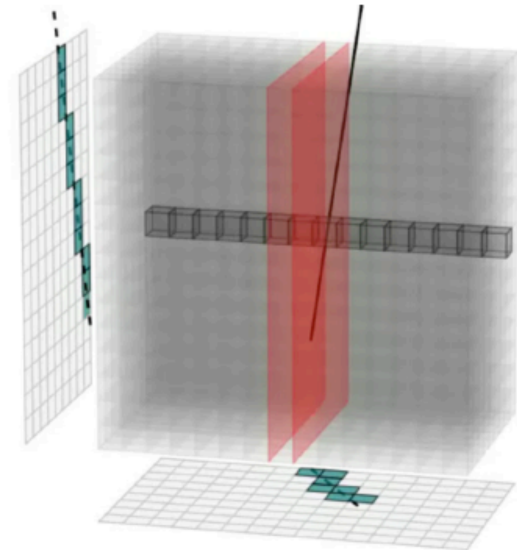




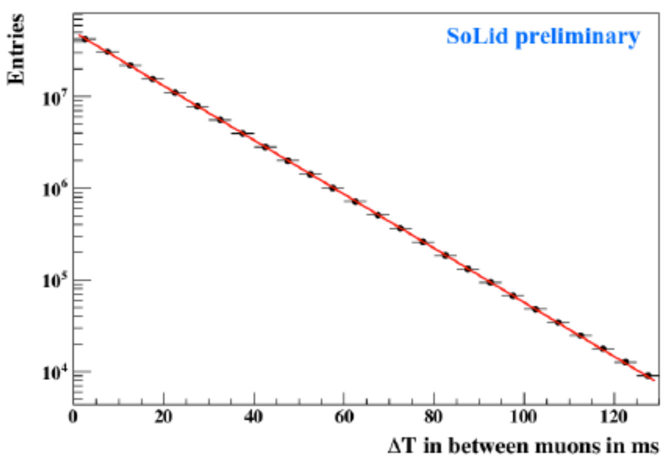


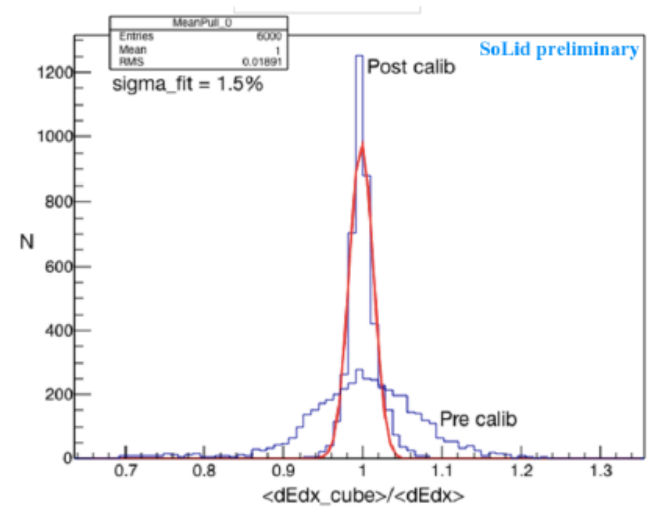
Detector response to cosmic muons

- Muon tracks can be reconstructed due to detector segmentation
  - In-situ calibration and monitoring with dE/dx



R_μ = 69.42 ± 0.01(stat) Hz

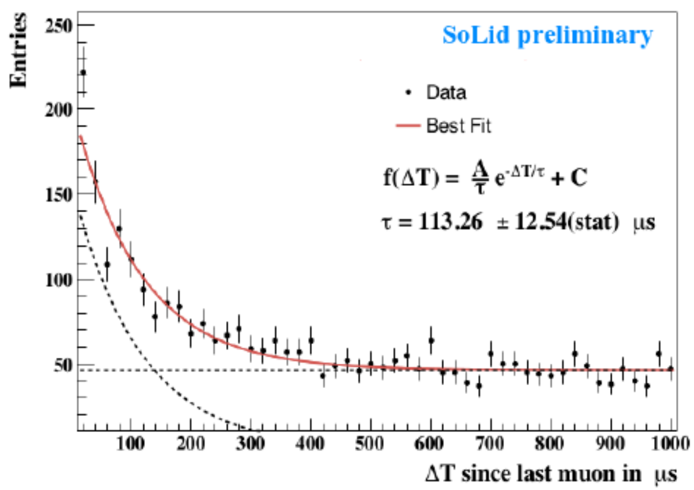




Background rejection capabilities

Muons passing the detector making fast neutrons:

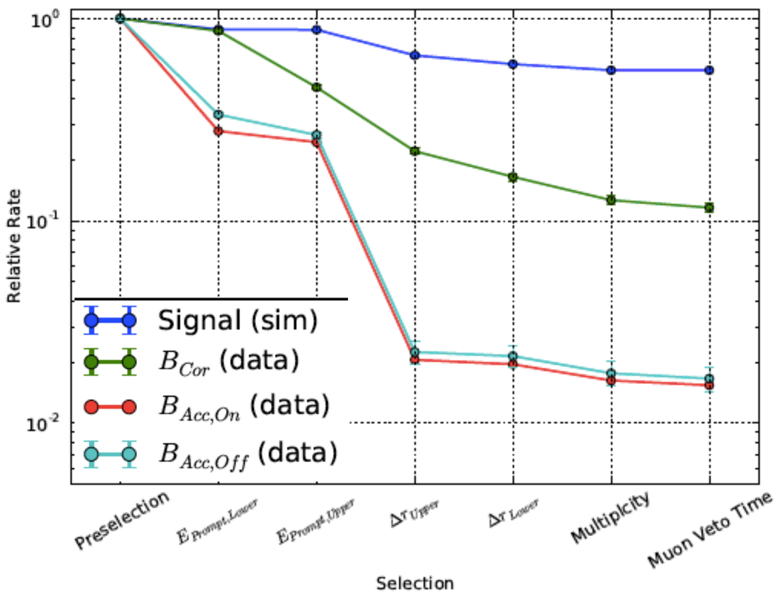
- Correlation between muons and neutrons is observed



- Rejection of muon correlated background
  - Muon Veto cut

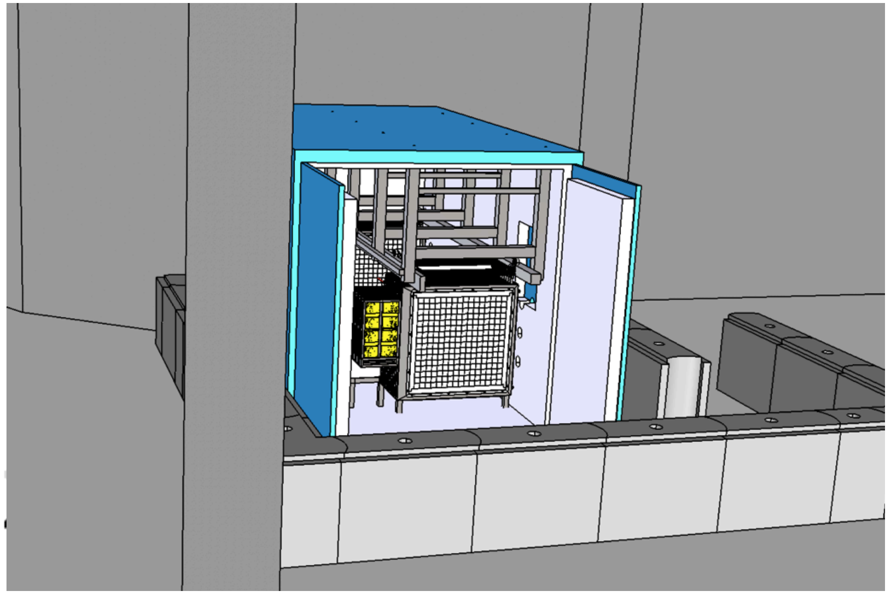
SoLid particular cut: Δr can be chosen to retain most of the signal and cut hard on Accidental backgrounds (B_{Acc})

SoLid preliminary



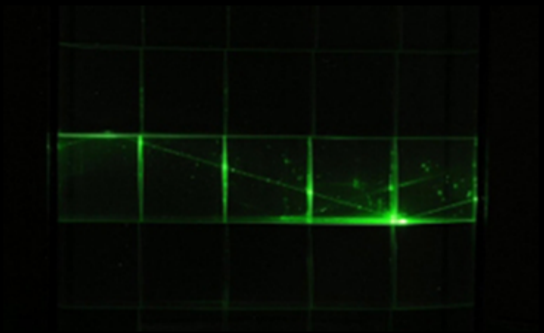
(Simulation)

Solid detector: Phase 1 (2016-2017)



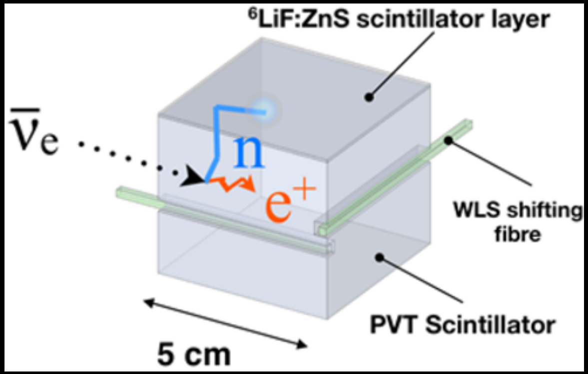
- Double electronic readout compared to SM1
  - Reduce dark count rate (noise)
  - Increase the light yield
  - Better energy resolution: $\sim 14 - 16$ % at 1 MeV
  - 3200 readout channels
- Trigger algorithms
  - Neutron waveform trigger with zero suppression readout
  - Threshold trigger
  - External trigger

Technological Convergence



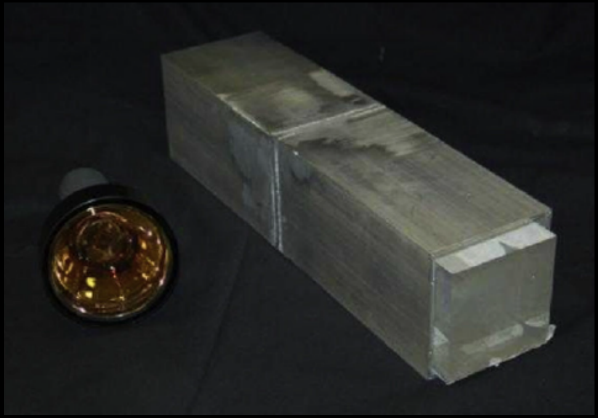
The **Raghavan Optical Lattice** (ROL), invented by the late Virginia Tech professor, Raju Ragahvan, divides a totally active volume into cubical cells that are read-out by total internal reflection. LENS was designed for solar neutrino detection and not optimized for reactor antineutrino detection.

SoLid



Optically isolated cubes, mated to **^{6}LiF:ZnS(Ag) sheets**, are used to tag IBD. Light is read-out by wavelength shifting fibers in orthogonal directions. It has the spatial resolution of the ROL optimized for reactor antineutrino detection. The small cross-sectional area of the fibers limits the light collection, dilutes the energy resolution and lowers the efficiency.

Sweany et al., NIMA 769, 37

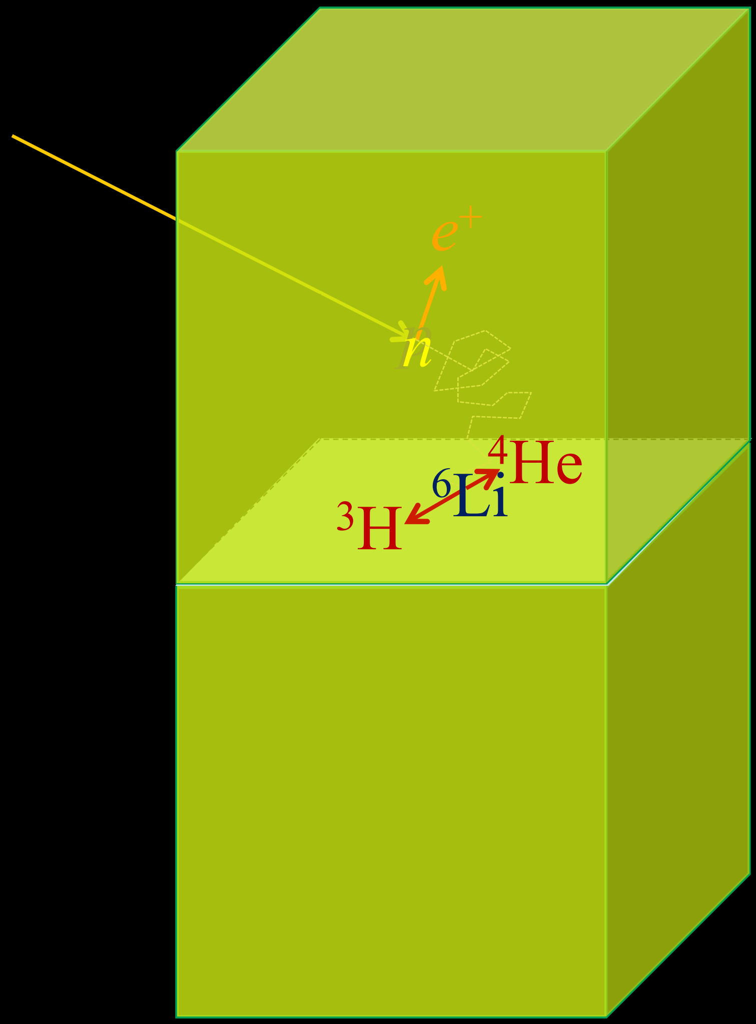


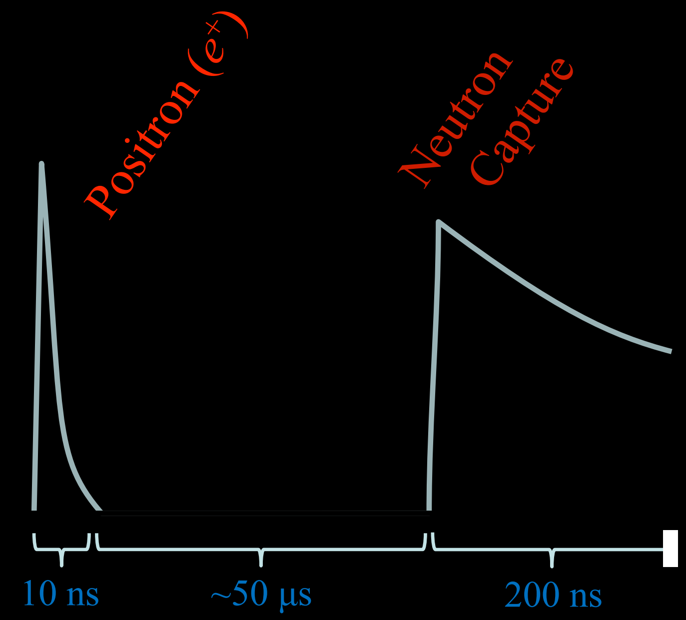
Used ^{6}LiF:ZnS(Ag) sheets mated to a **solid bar of wavelength-shifting plastic scintillator**. This prototype demonstrated the feasibility of pairing the sheets to wavelength shifting plastic, but the long bars do not have the spatial resolution required for good background rejection

CHANDLER

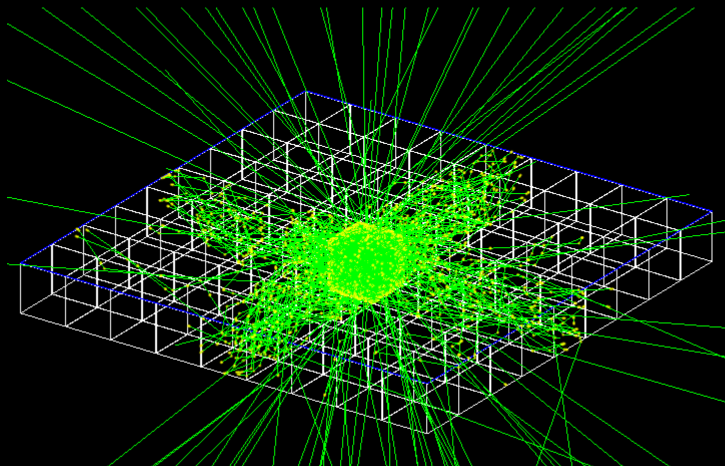
Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced ROL

CHANDLER Detector





Light is transported by total-internal-reflection

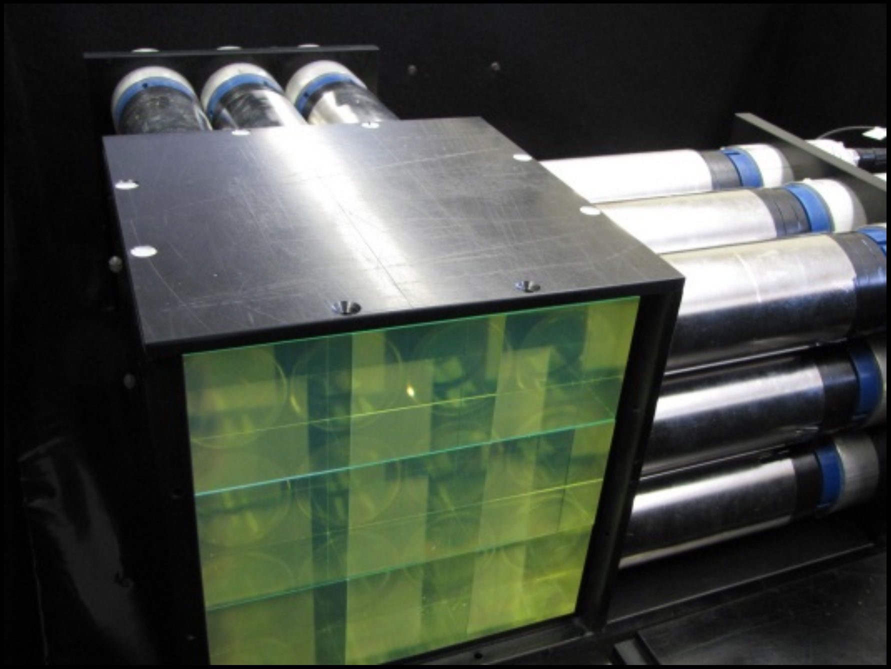


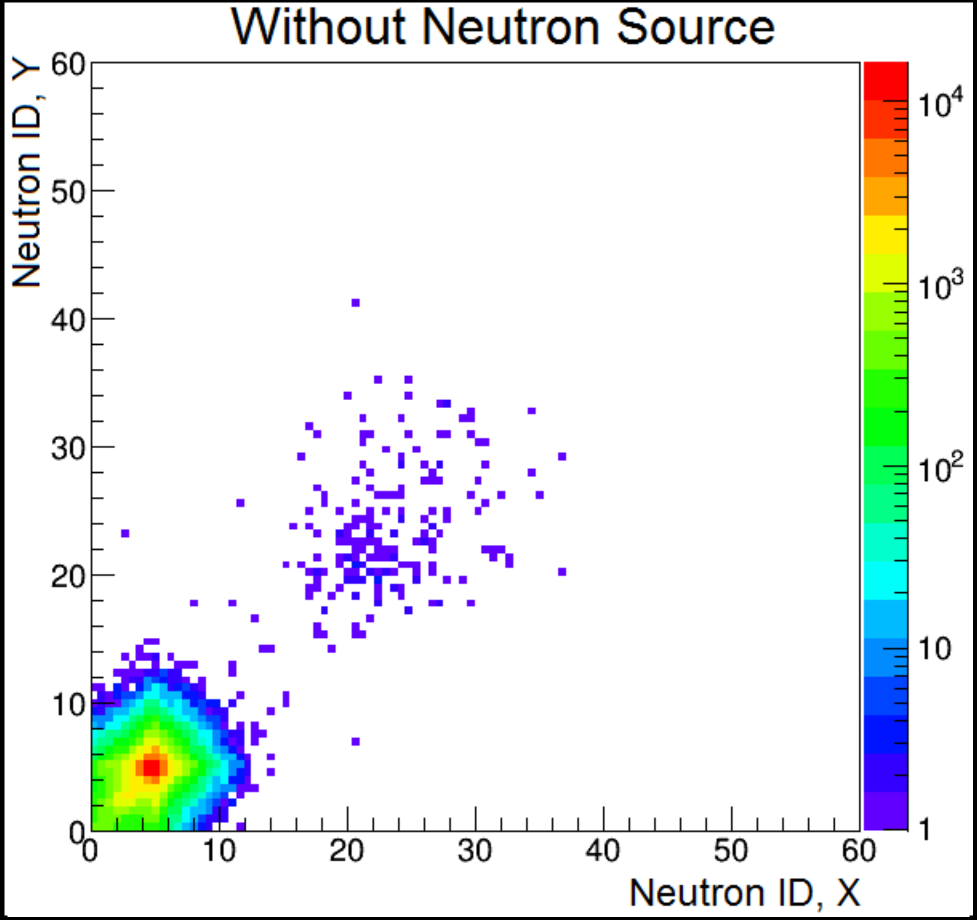
Photon Ray Tracing in GEANT4

Neutron Capture in MicroCHANDLER

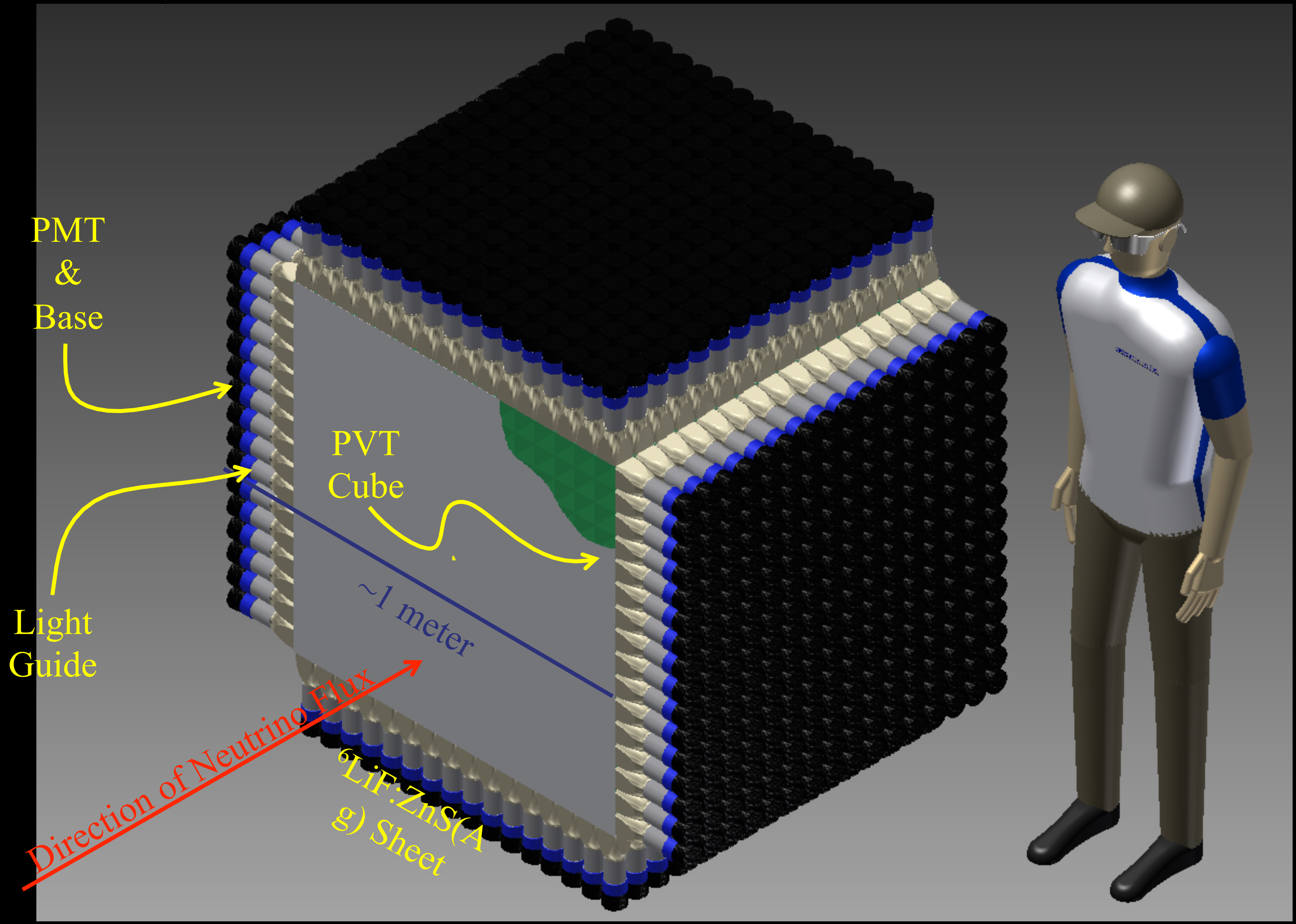
The 18-channel MicroCHANDLER prototype is idea for testing neutron tagging.

For each hit cell, we compute the neutron ID variable as the ratio of the integral of the pulse to the pulse peak value.



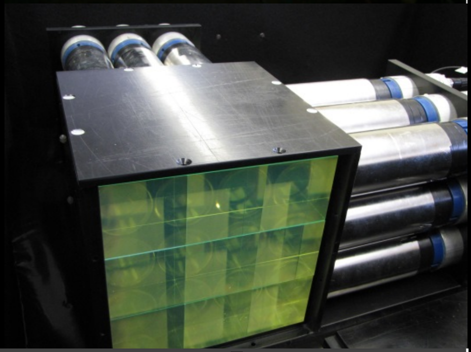


CHANDLER

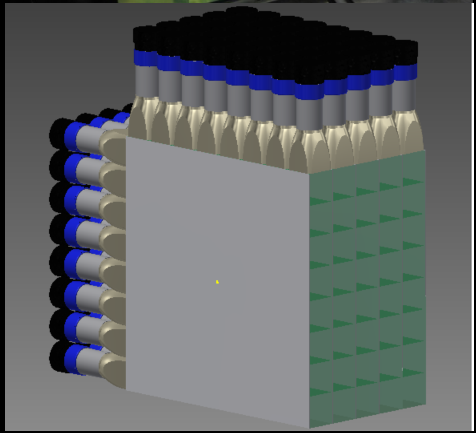

PMT
&
Base
PVT
Cube
Light
Guide
~1 meter
Direction of Neutrino Flux
^{6}LiF:ZnS(Ag) Sheet

Research and Development Effort

<u>Cube String Studies</u> have been used to study light production, light collection, light attenuation, energy resolution and wavelength shifter concentration.



<u>MicroCHANDLER</u> is a 3×3×3 prototype which we are using to test our full electronics chain, develop the data acquisition system, study neutron capture identification and measure background rates.



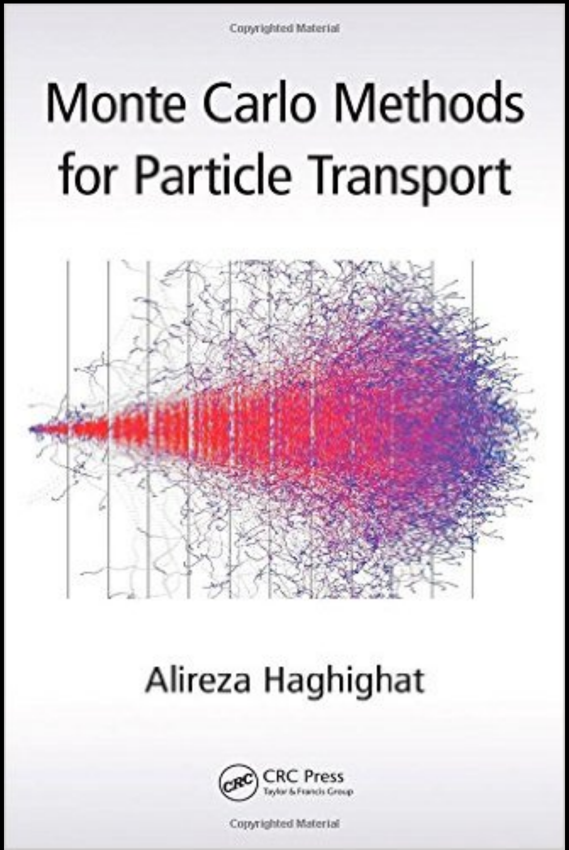
<u>MiniCHANDLER</u> is a **fully funded** systems test (8×8×5) which is currently under construction and will be deployed at a commercial nuclear power plant. It will be used to test any remaining options and optimizations. It will be operational by winter 2016.

Detector Simulation

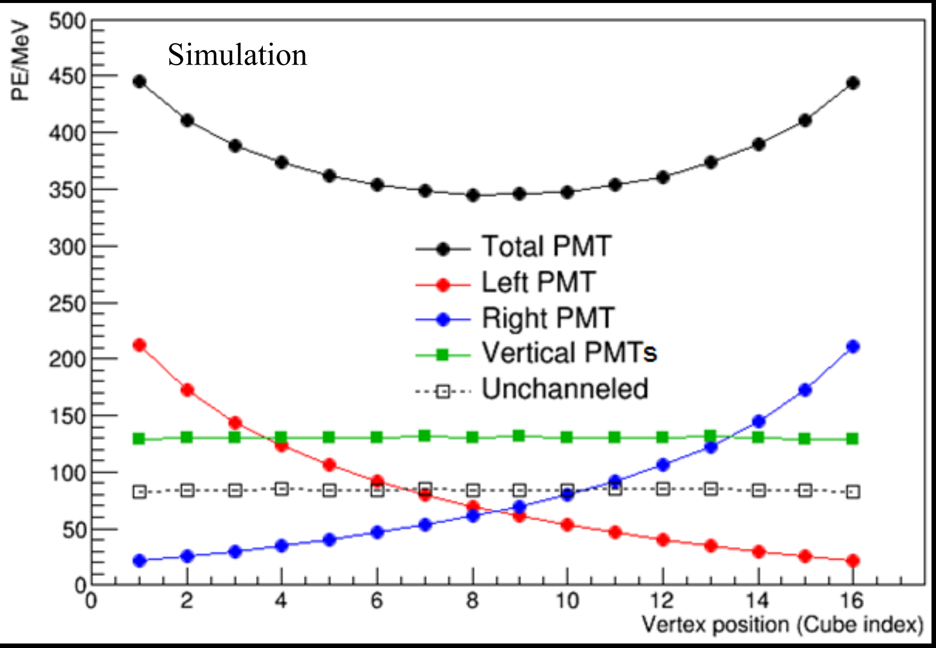
We have a full-scale GEANT4 simulation, developed by J. Park (VT), which we are using to study light transport and collection, and neutron transport and capture.

We also have a full-scale MCNP6 simulation, developed by W. Walters (VT) and A. Haghighat (VT), which we are using to study neutron transport and capture.

The neutron transport models in GEANT4 and MCNP6 are in very good agreement.



GEANT4: Detector Response vs. Cube Position



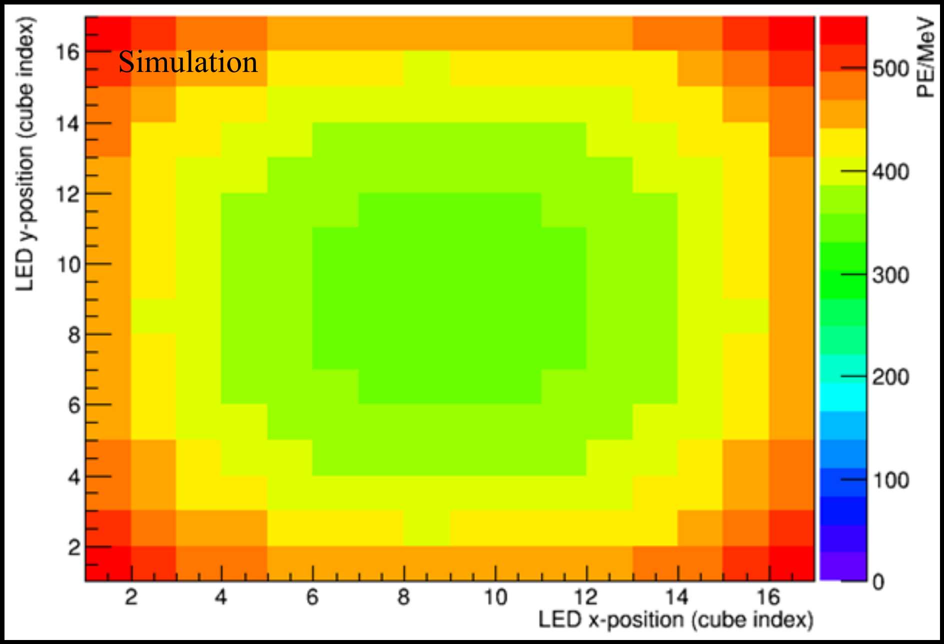
Most of the light is collected in the 4 PMTs in the TIR channel directions.

About 20% of light is unchanneled, with the largest share in the adjacent PMTs.

Collected light falls off as you move away from the PMT.

The largest excursion from the mean is in the corner cells.

The conversion to p.e./MeV assumes light guides, and a PMT with quantum efficiency of 25%.

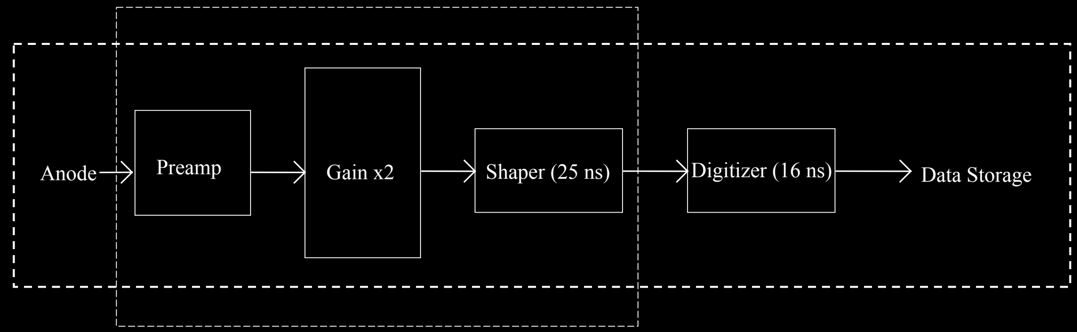


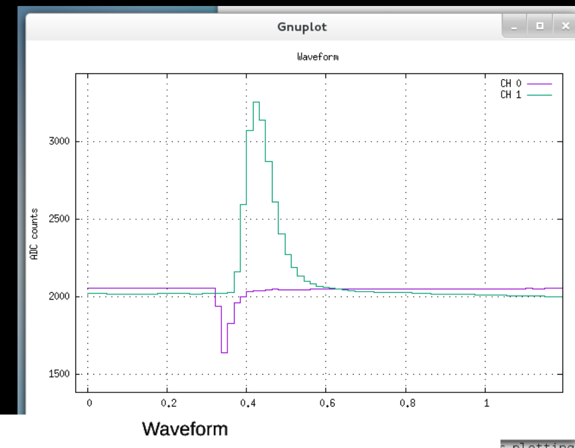
Electronics and DAQ

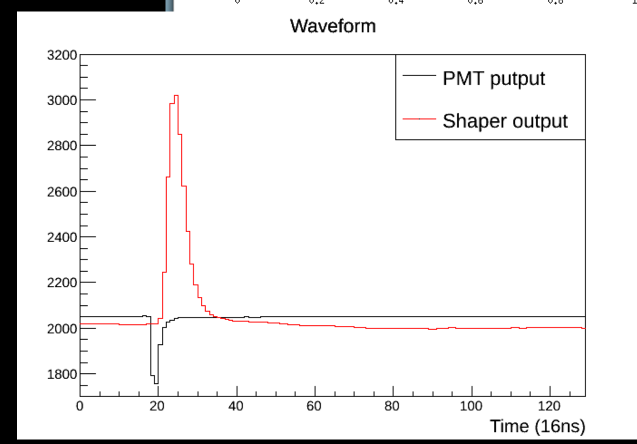
CHANDLER Readout Electronics

- 2 inch high quantum efficiency PMT (R6231-100)
- VME 16 ch - Analog Pre-amp and shaper circuit (VT+CREMAT)
- VME 64 ch, 16 ns, 12 bit digitizer card (CAEN V1740)

VME Shaper module 16 ch







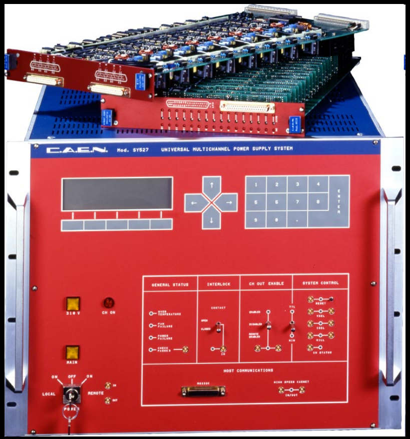
Readout Software

- VT customized readout system (based on CAEN WaveDump)
- Each digitizer connected by dedicated single optical link to the optical card in the computer
- Each link speed up to 80 MB/s
- Multi-Board readout via parallel processing
  - Each DAQ processes run on a separate core
- DAQ reads out each link as a separate data stream via optical card
- Data streams are combined and sorted to identify events via event builder process running on raw data

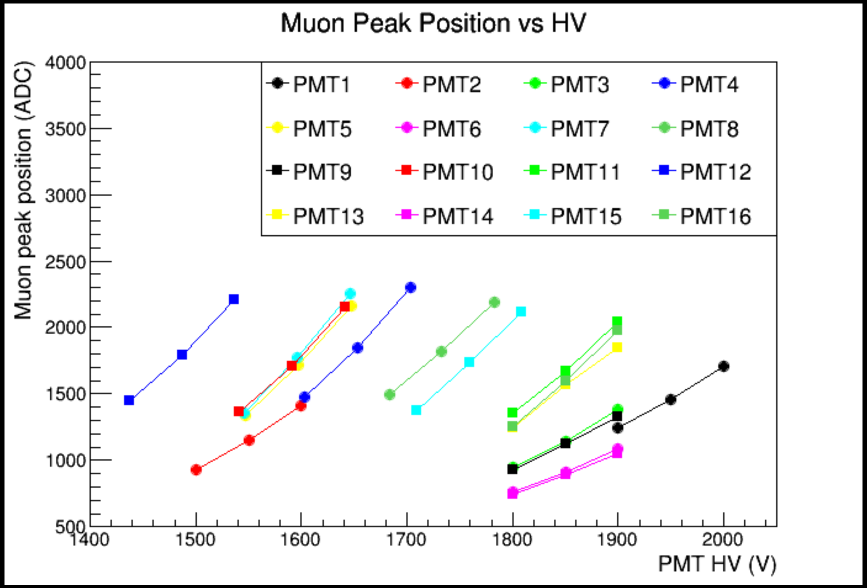
HV system

High Voltage

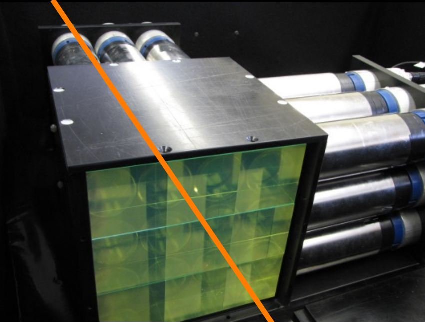
- CAEN SY527 HV Mainframe
- 3-5 CAEN A734N HV cards
- HV Software developed at VT



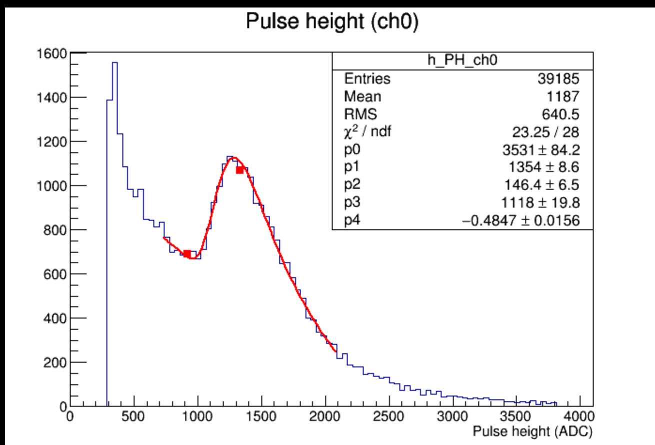
Possibility to fine control each HV channel good for calibration and monitoring



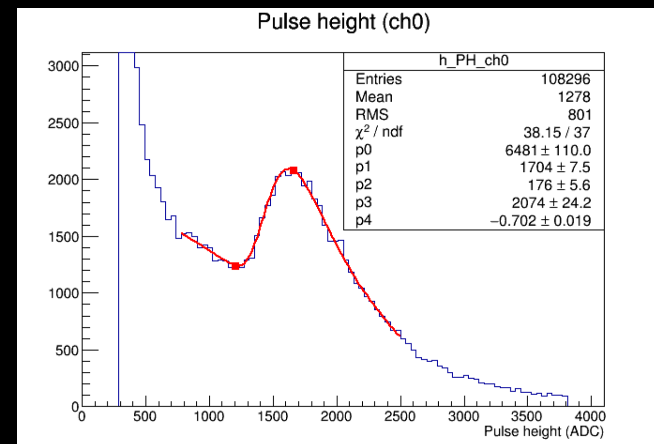
Calibration scheme

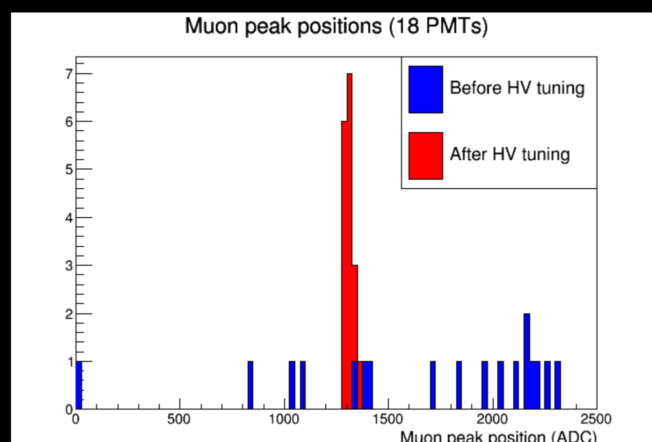


Use muons, simple and they are present in the detector, avoiding complicated calibration scheme (not so effective in past experiments while considering the complication of the calibration system and of the risk of the deployment.

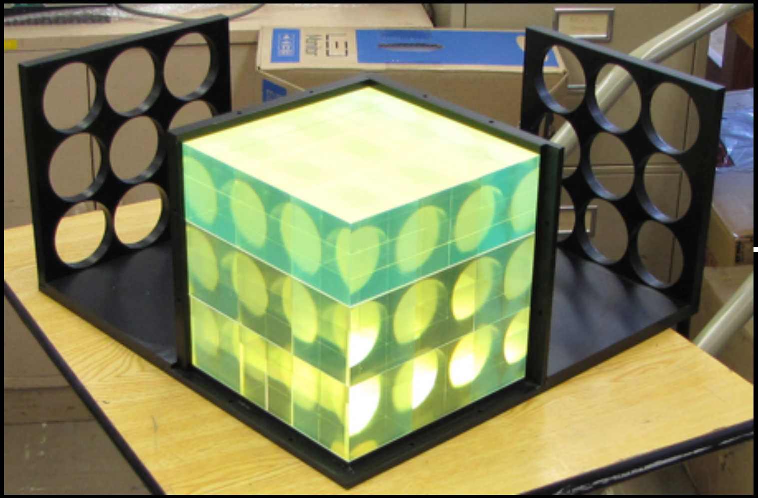


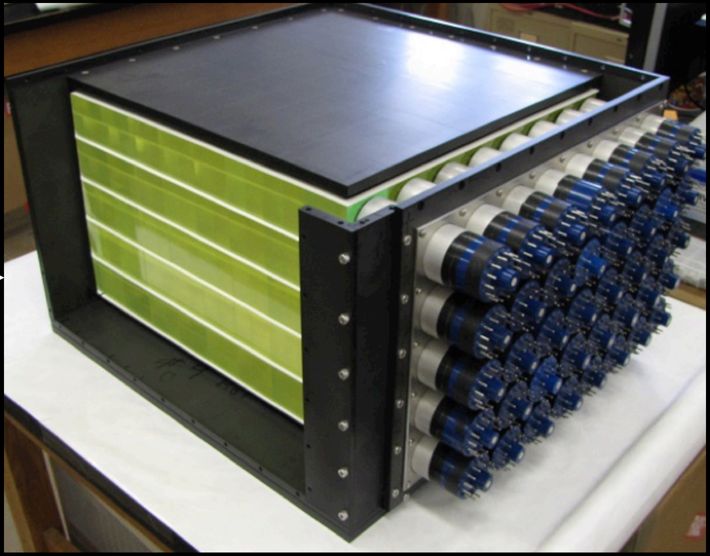
Fit model Landau
+
Exponential

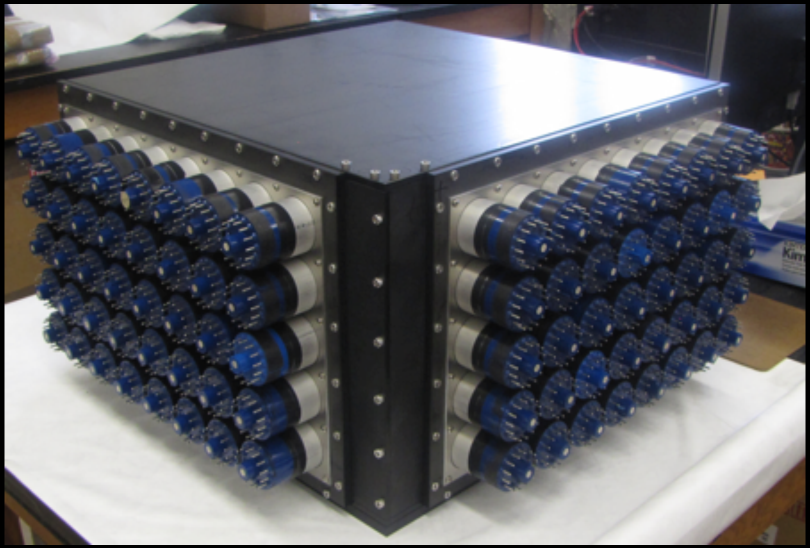




From micro to mini – Summer - Fall 2016







80 Channels

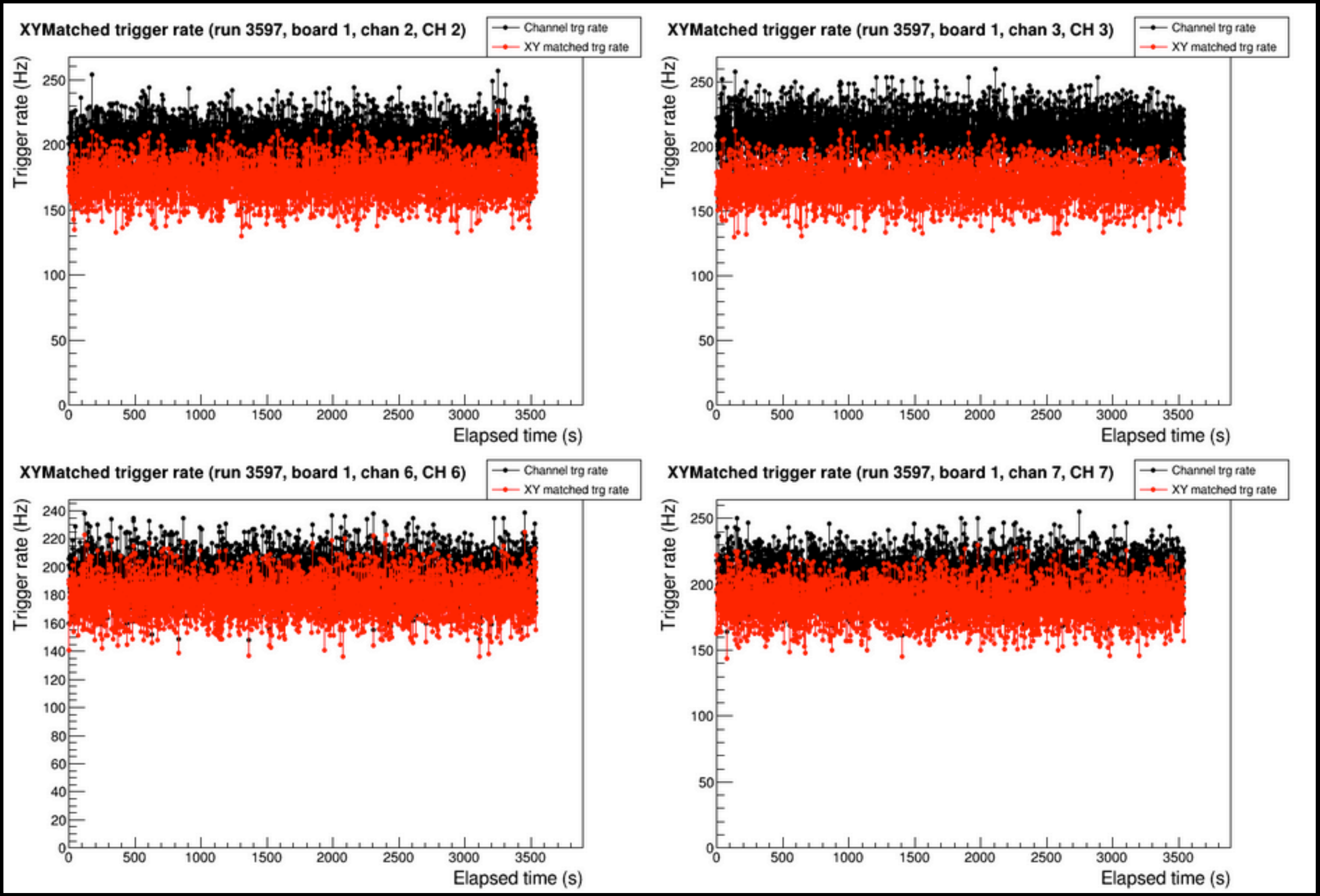
2 waveform cards (64 channels each)

- Timing synchronization - done
- Event Builder – done
- Data Reduction scheme
- Monitoring - done
- Long term stability – in progress
- Muon reconstruction – in progress
- Muon calibration

Commissioned – 90%

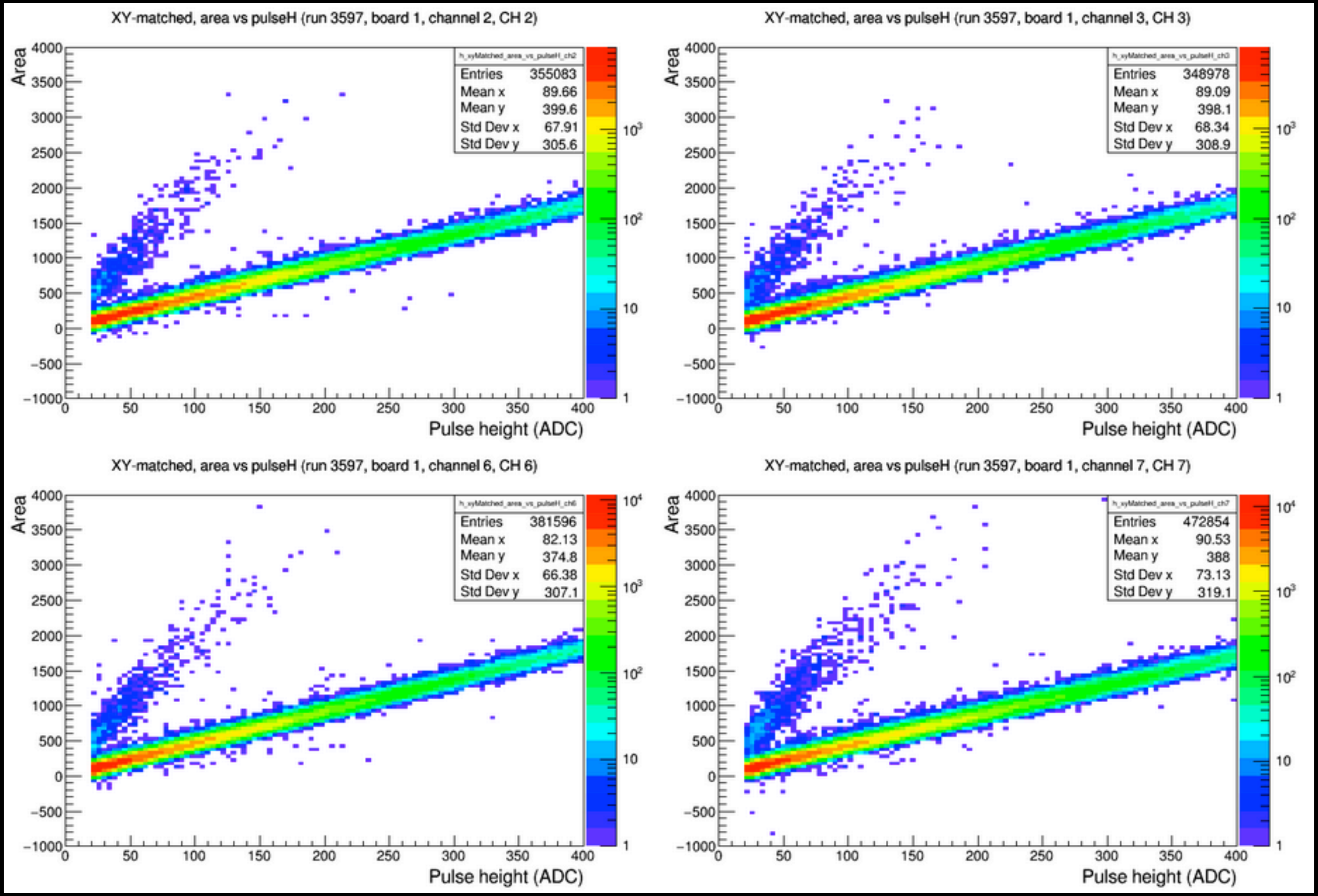
Few plots from Online monitor

Single Rate and x&y rate



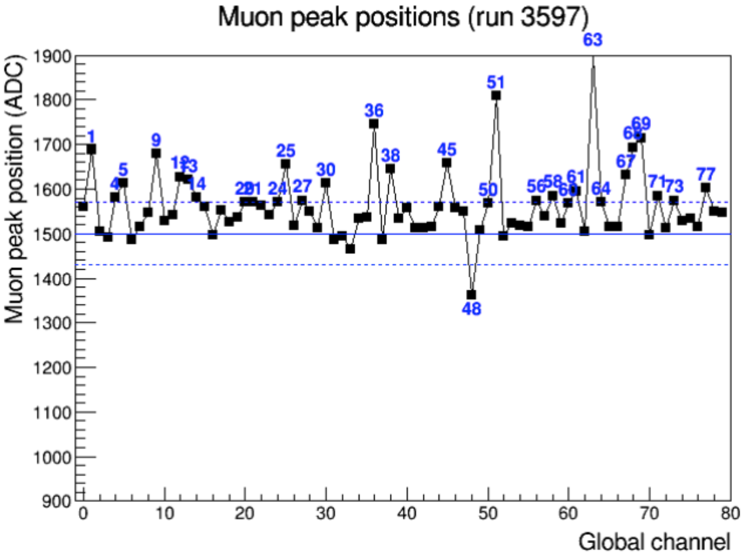
Few plots from Online monitor

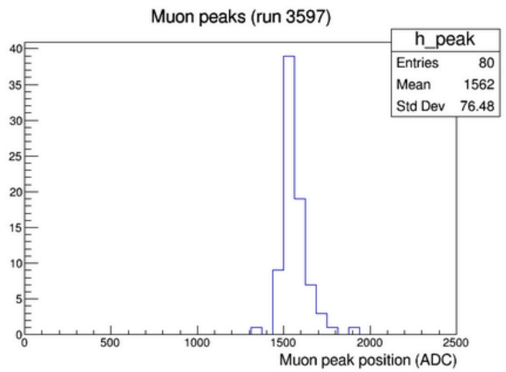
PID Neutron vs gammas

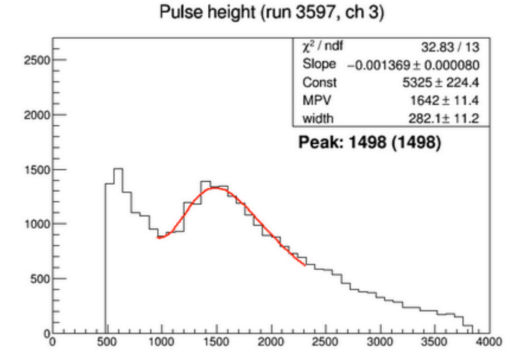


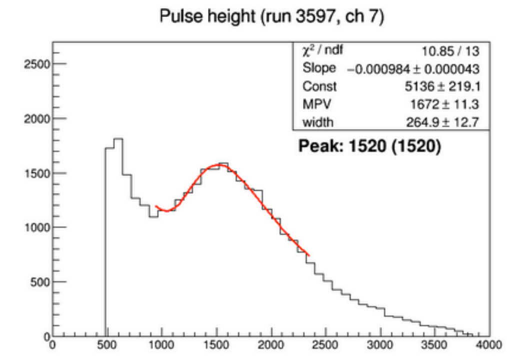
Few plots from Online monitor

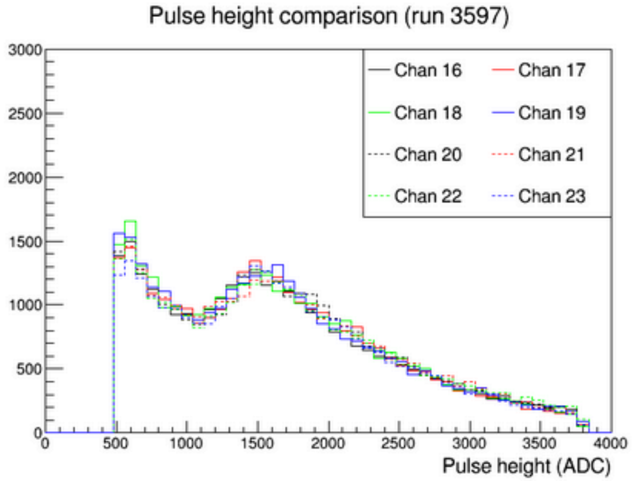
Gain stability and Fit

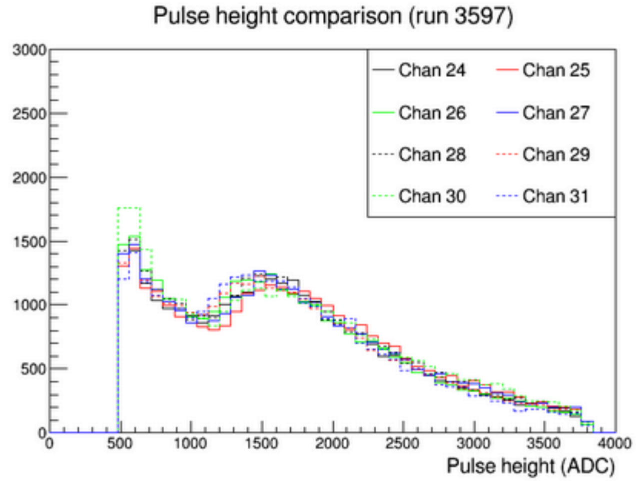










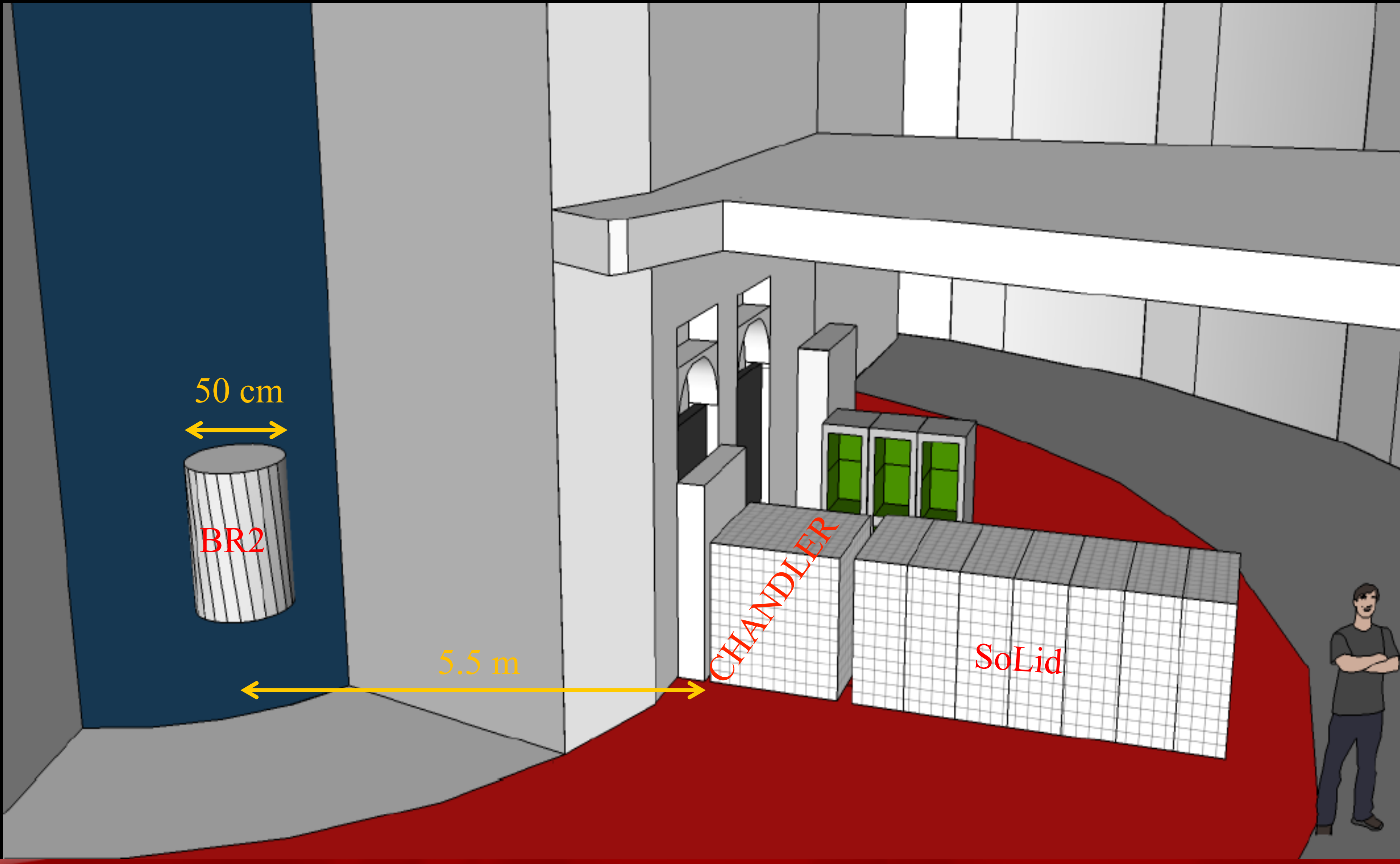


Near term plan

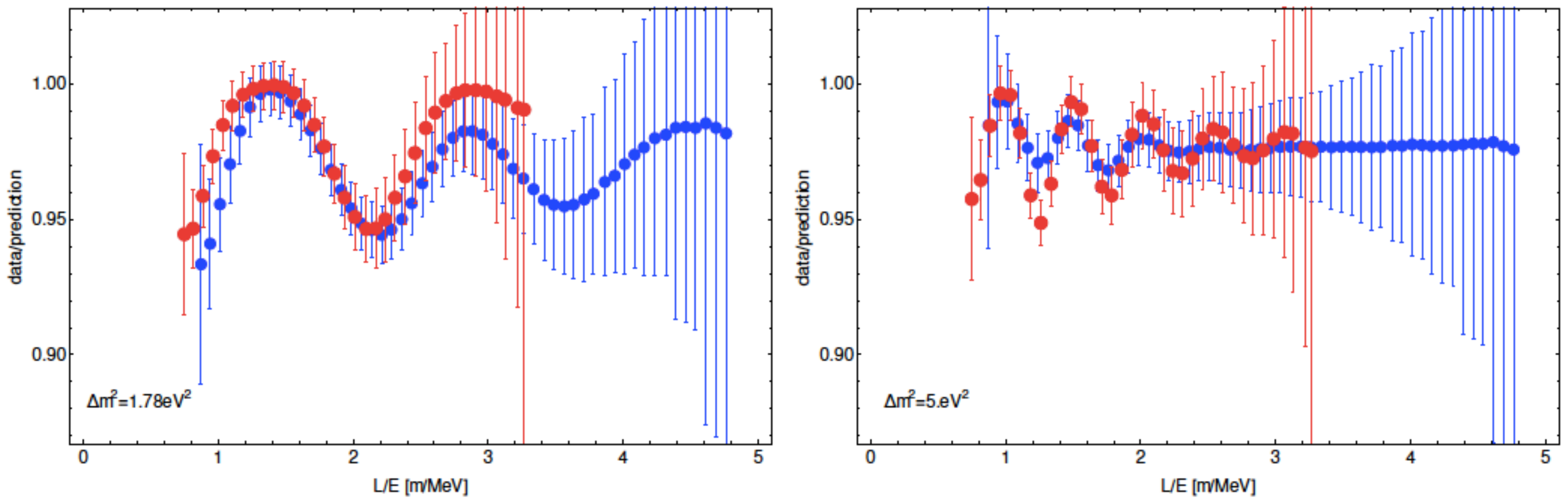
Move the detector in the Mobile Neutrino Lab trailer at the North Anna Plan by Middle May 2017

CHANDLER and SoLid

The two detectors will be deployed at the BR2 reactor operating as a single experiment.



SoLid and CHANDLER Sensitivity



Distribution of events as a function of L/E for two different values of Δm^2 .
The red data points are for CHANDLER and the blue data points are for SoLid.
Resolutions are fully included and the error bars represent the statistical errors after background subtraction.

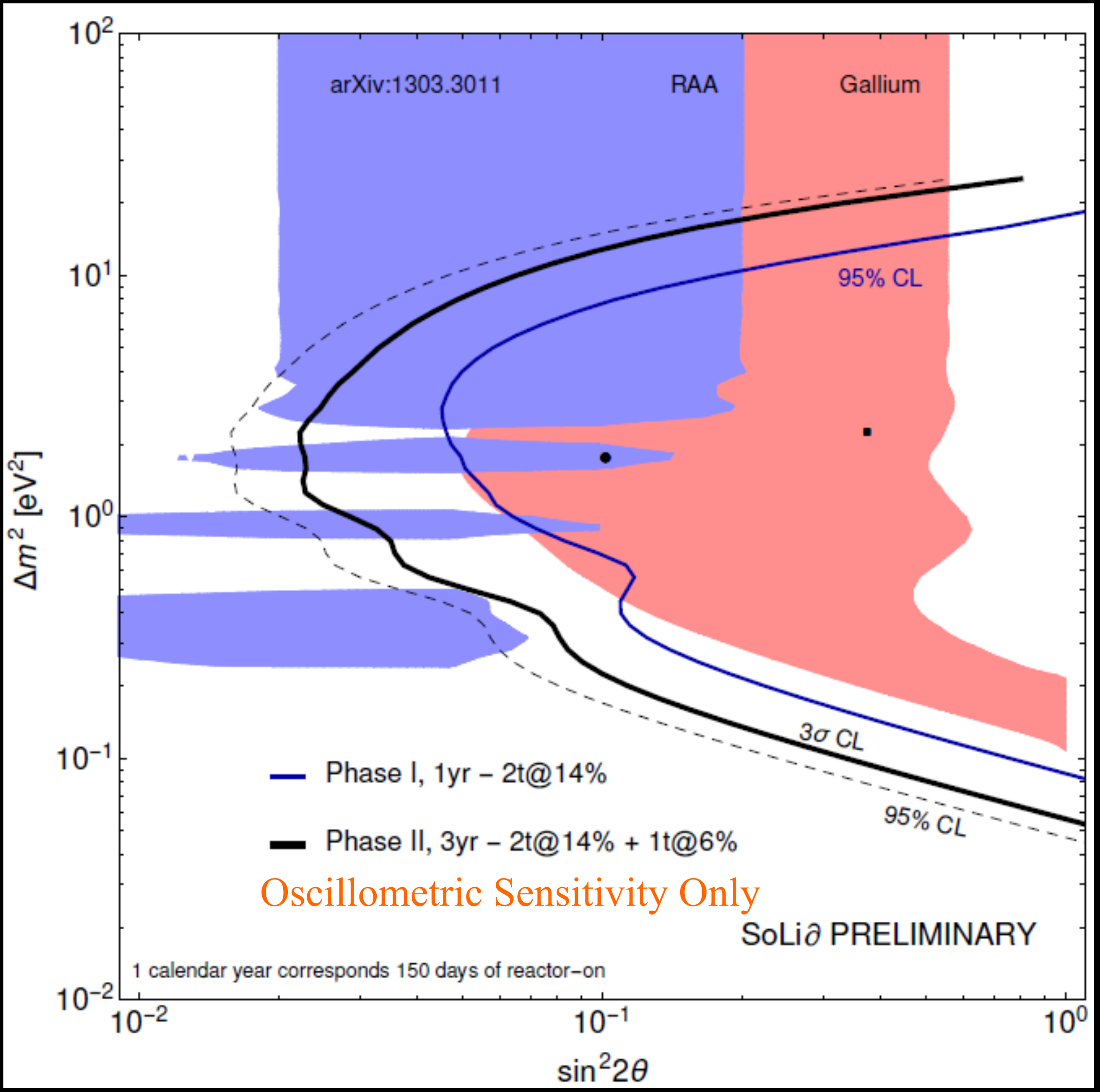
CHANDLER and SoLid sensitivities

The combined sensitivity for the SoLid/CHANDLER deployment at BR2 is compared to the Gallium and Reactor Anomalies.

The one-year, Phase I SoLid deployment covers most of the low Δm^2 part of the Gallium Anomaly at 95% CL.

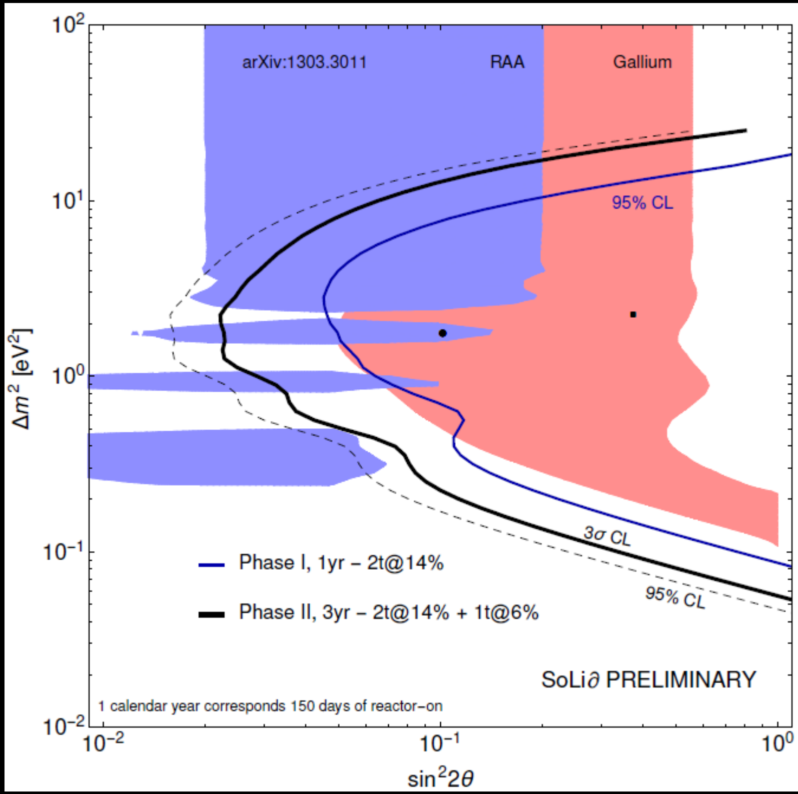
Adding CHANDLER to the three-year Phase II extends the coverage to higher Δm^2 and pushes the reach well into the Reactor Anomaly.

These sensitivities are purely oscillometric, based on energy spectrum and baseline information alone.



Conclusions

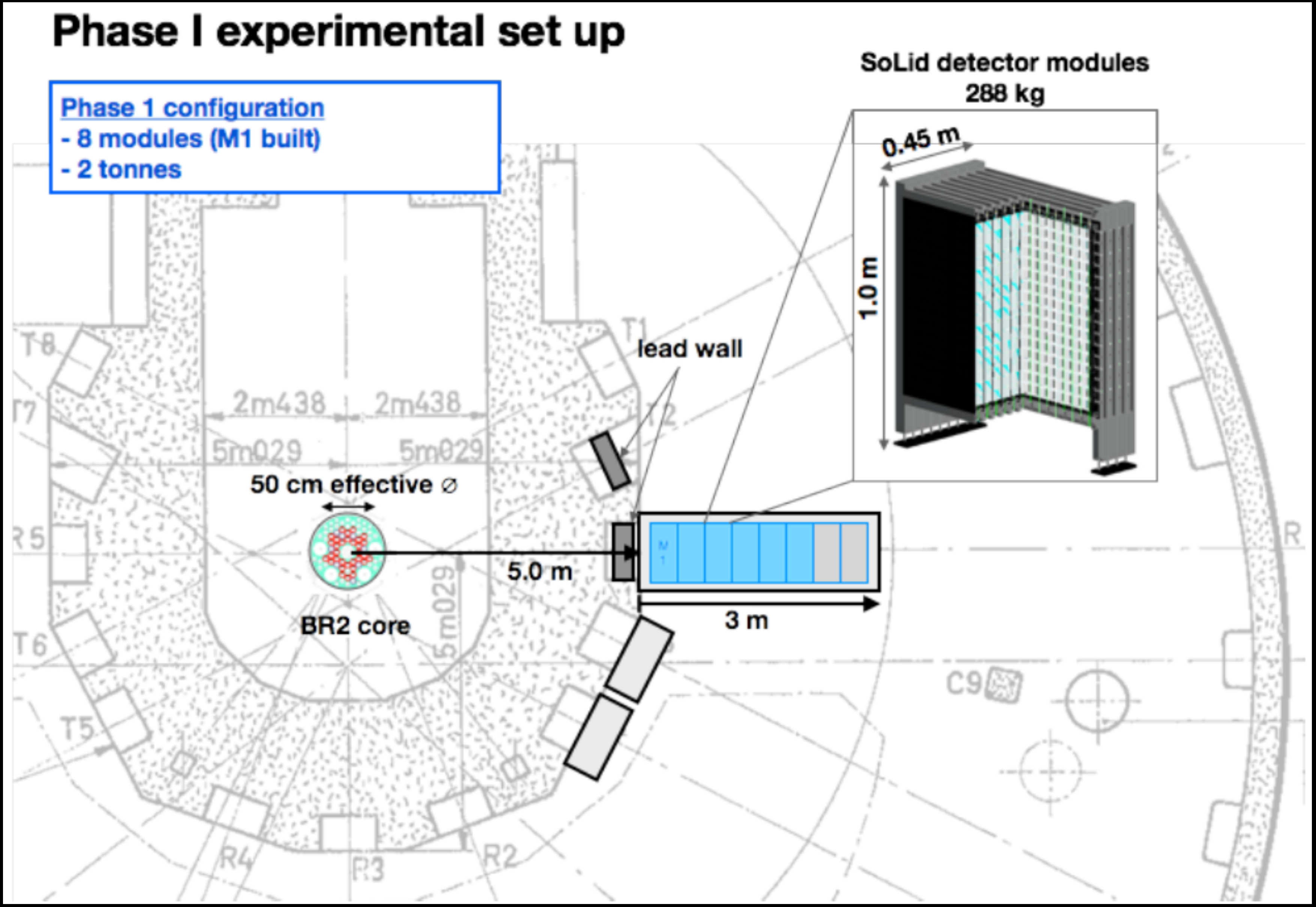
1. The evidence for a 1 eV^2 sterile neutrino is persistence but inconclusive.
2. Electron neutrino disappearance, which must exist if any of the oscillation hints are true, is the most promising way to resolve the sterile neutrino question.
3. Radioactive source and reactor neutrino experiments will soon be operating to search for short-baseline oscillations.
4. CHANDLER is a new detector technology with high purity, high efficiency neutron tag and good energy resolution.
5. Together CHANDLER and SoLid cover most of the anti-ν_e disappearance allowed space.



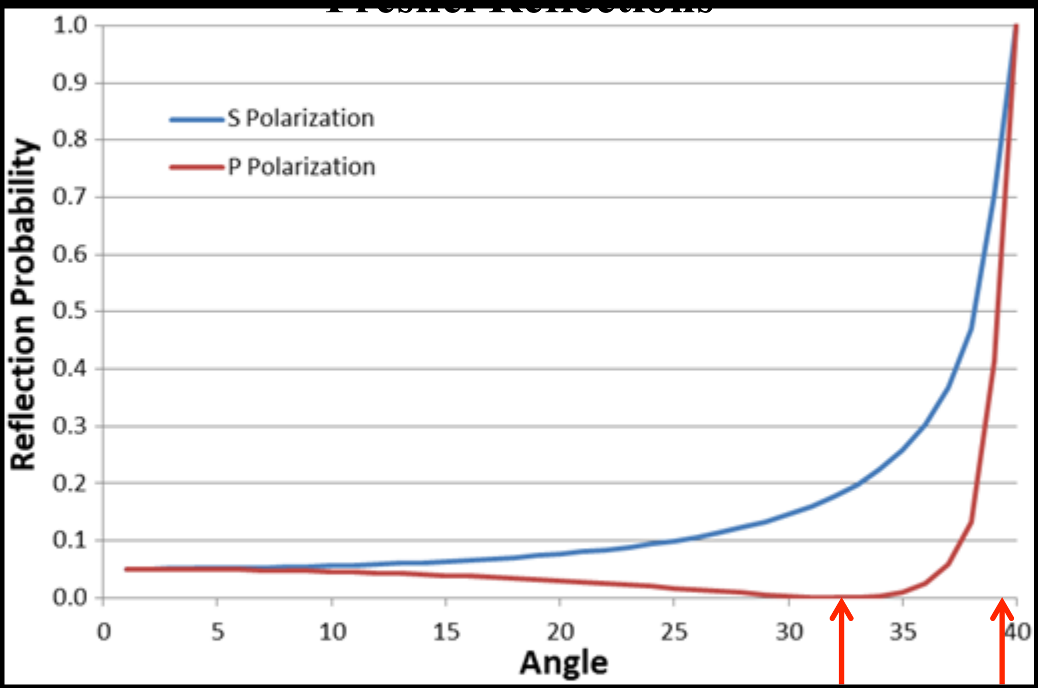
Thank you

Backup

SoLi∂ at the BRR Reactor in Belgium



Optics of the Raghavan Optical Lattice



The optics are based on the interface of PVT (n=1.58) and air (n=1).

The critical angle (θ_c) is 39.27°

The Brewster angle is 32.22°

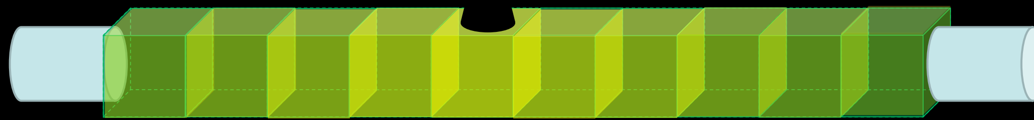
Because $\theta_c < 45°$ any light capable of passing between cubes will necessarily fall into the total-internal-reflection (TIR) channel in that direction.

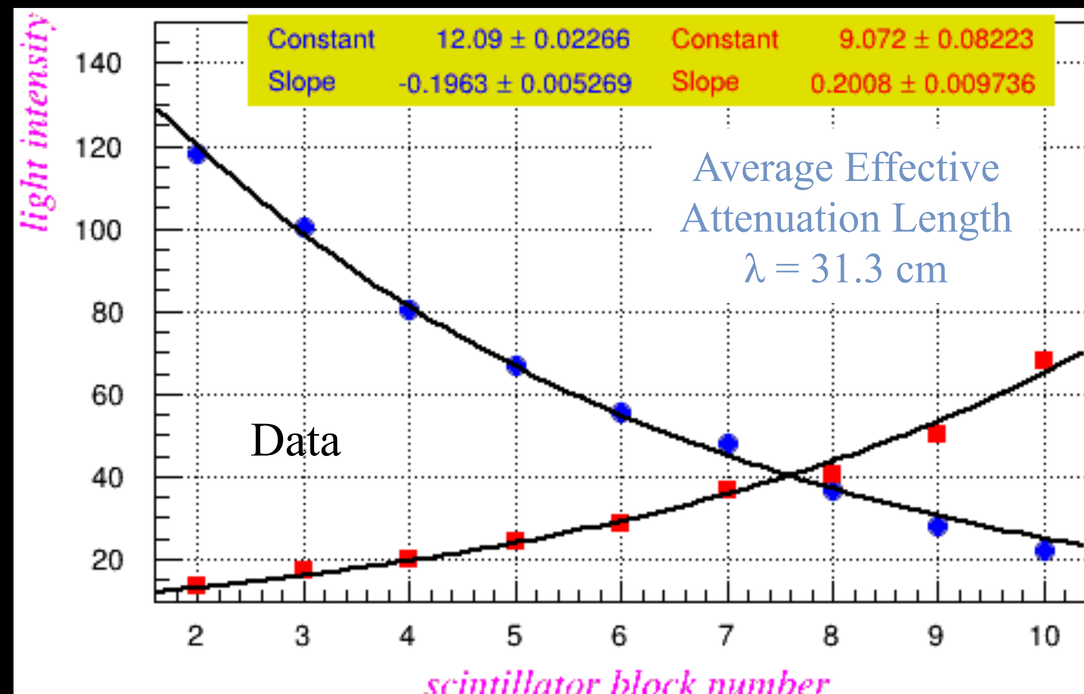
Each of the four TIR channels is open to 11.3% of the light produced in a cube.

54.8% of all light can not be channeled.

Some channeled light that gets reflected off of a cube surface perpendicular to the channel direction will reach the PMT in the opposite direction.

Effective Attenuation Length Study



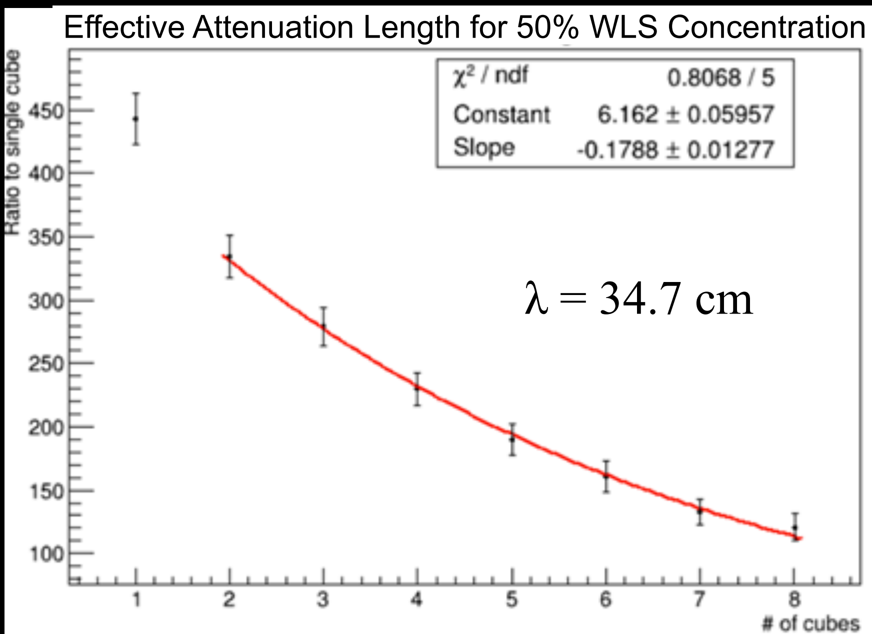


There are two contributions to the effective attenuation:

1) bulk attenuation in the PVT and
2) Fresnel reflection at the cube interfaces.

Wavelength Shifter Concentration

The wavelength shifter (WLS) dopant can be a significant source of attenuation.

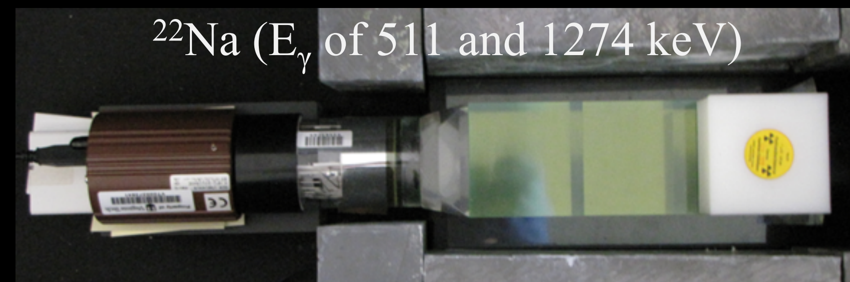


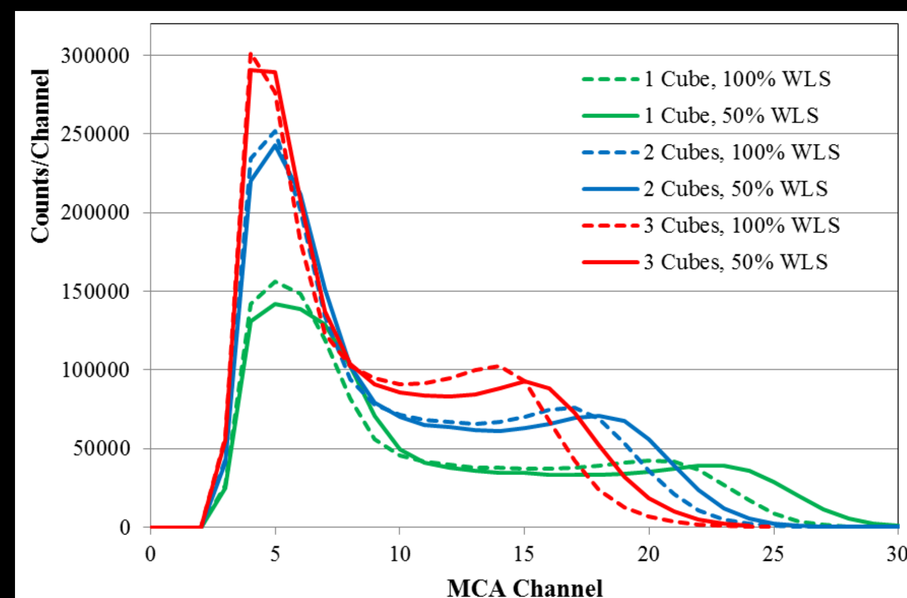
Halving the WLS concentration increases the attenuation length by 10%.

The light collection with lower WLS is greater at each position.

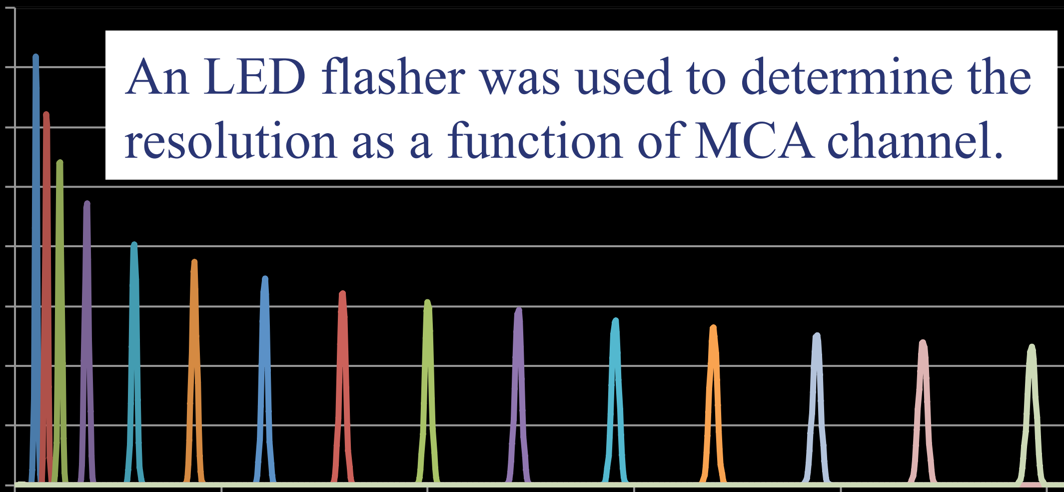
We will also be studying WLS concentrations of 75% and 25%.

The Compton edge of ^{22}Na was used to study the relative light output.

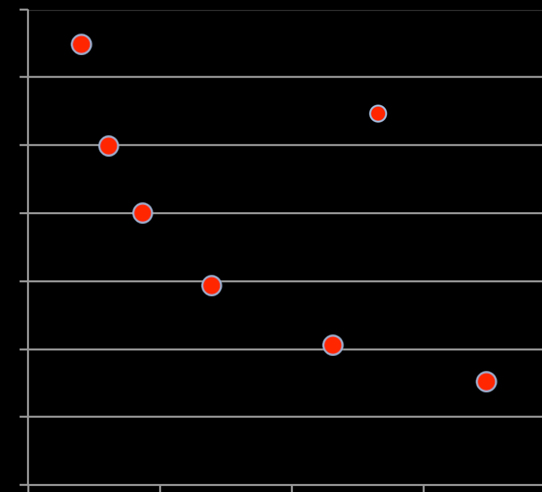


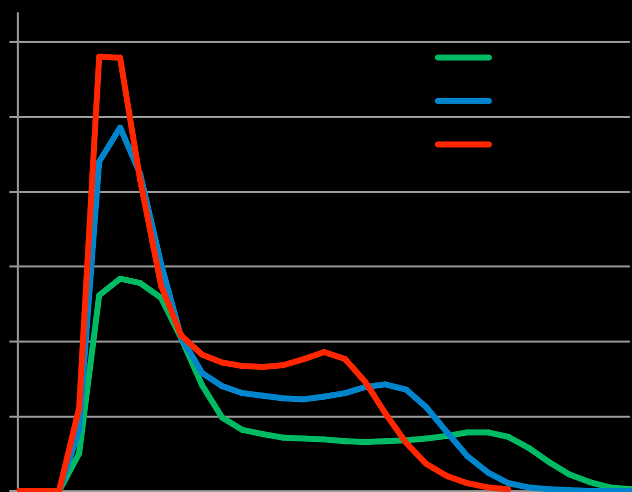


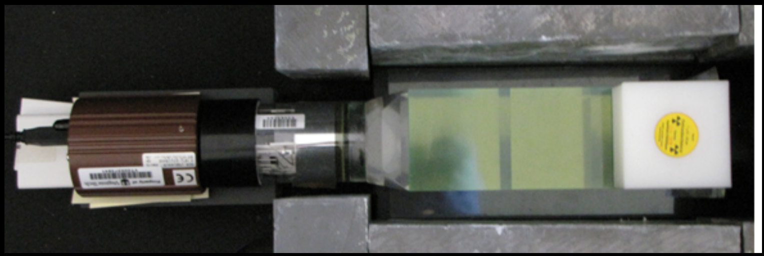
Light Output and Collection



An LED flasher was used to determine the resolution as a function of MCA channel.



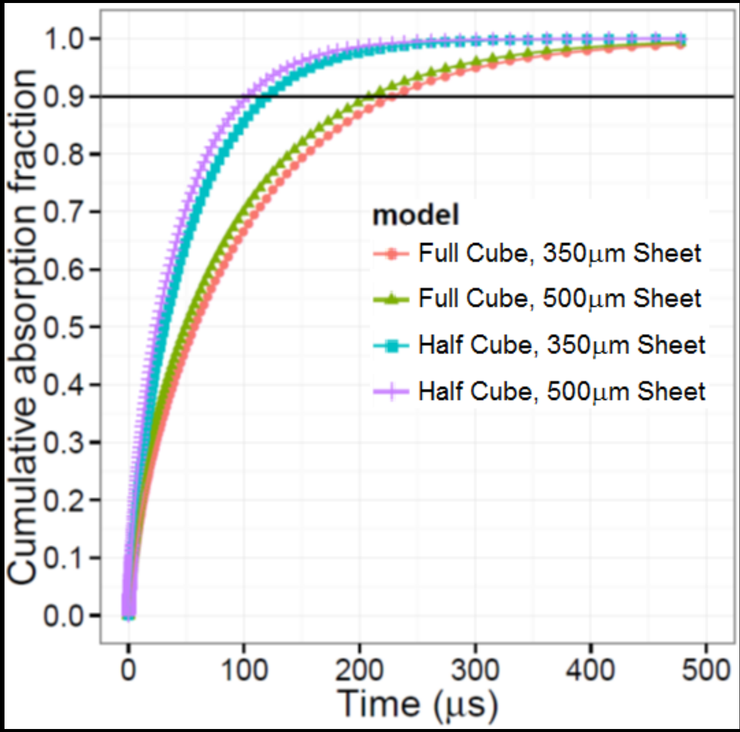


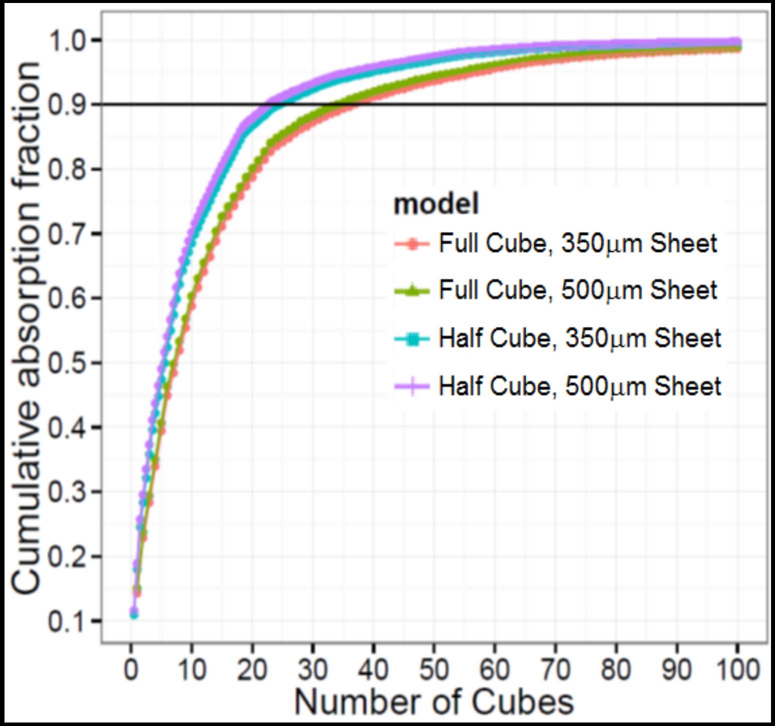


The ^{22}Na Compton edge is at 1.06 MeV, and at two cubes from the PMT it reconstructs at channel 20, which corresponds to an energy resolution of 6.5%.

MCNP6: Neutron Transport and Capture

	^{6}Li Capture	Time for 90% Capture	Volume for 90% Capture
Full Cube, 350 μm Sheet	51%	229 μs	37 cubes
Full Cube, 500 μm Sheet	55%	209 μs	35 cubes
Half Cube, 350 μm Sheet	69%	120 μs	24.5 cubes
Half Cube, 500 μm Sheet	73%	103 μs	23 cubes





First solution: Fixed wall and chicane