CHANDLER: A New Technology for Surface-level Reactor Neutrino Detection

Jonathan Link

Center for Neutrino Physics, Virginia Tech

IHEP Beijing Seminar

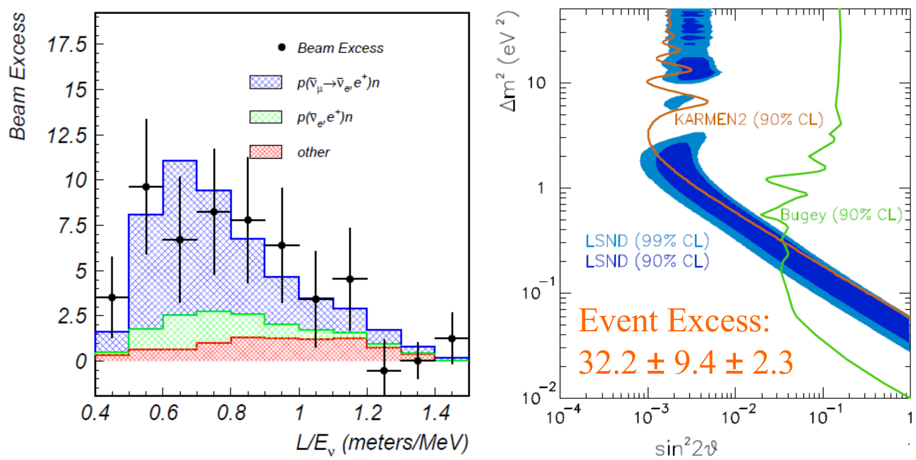
December 16, 2016

Talk Outline

- Motivation – Why do we need better reactor neutrino detectors?
- Technological Foundations – Where do these ideas come from?
- The CHANDLER Technology – The basics idea
- Detector R&D – What we have learned so far
- CHANDLER and SoLid – A sterile neutrino search

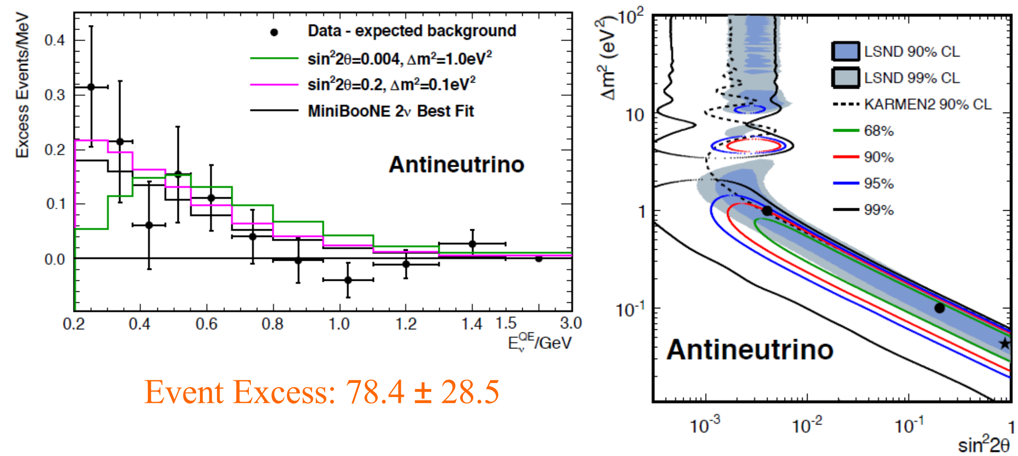
The Evidence for Sterile Neutrinos

LSND ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)



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

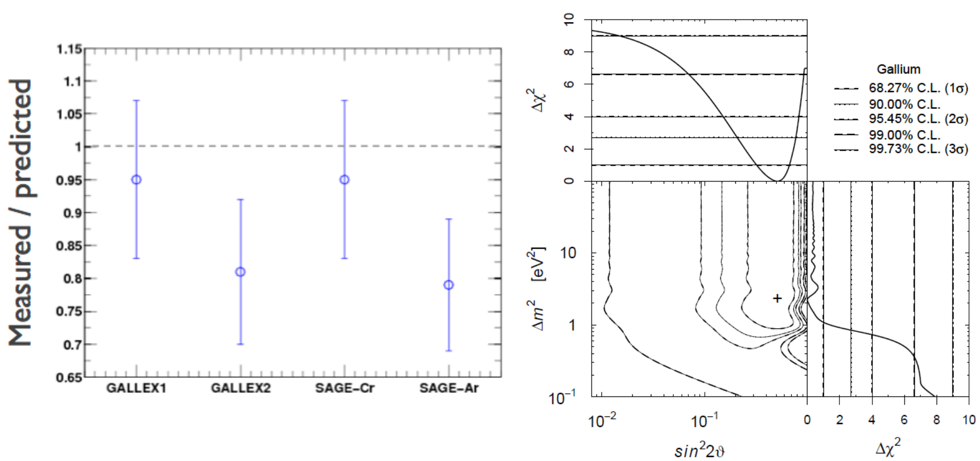
MiniBooNE ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)



Event Excess: 78.4 ± 28.5

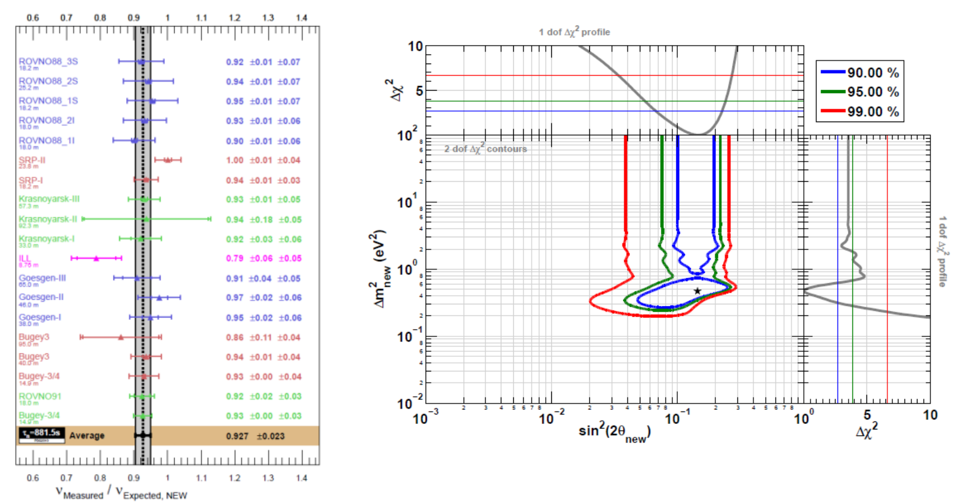
Aguilar-Arevalo *et al.*, Phys.Rev.Lett. 110, 161801 (2013)

Gallium Anomaly (ν_e Disappearance)



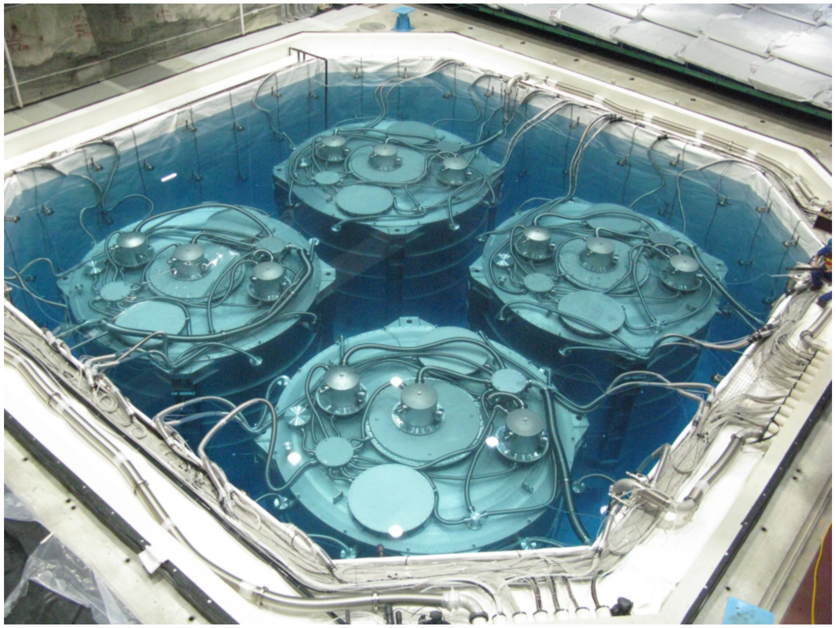
Giunti and Laveder, Phys.Rev.C83, 065504(2011)

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



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

Reactor Experiments



The Daya Bay Far Detectors

In the Daya Bay reactor experiment the mixing amplitude, $\sin^2 2\theta_{13}$ has been measured to an absolute precision of 0.5%.

Extraordinary measures were taken to control backgrounds: deep underground detectors are imbedded in two meters of low-activity water shielding instrumented as a muon detector.

Short-baseline reactor experiments must be done at the surface, with limited space for shielding.

In Daya Bay the oscillation was initially detected as a deficit in detectors at the far site relative to detectors nearer to the reactor cores.

In order to demonstrate the existence of sterile neutrinos, short-baseline reactor experiments must detect the oscillatory pattern as a function of energy and distance in one or more detectors located at baselines of 5 to 15 meters from a reactor core.

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.

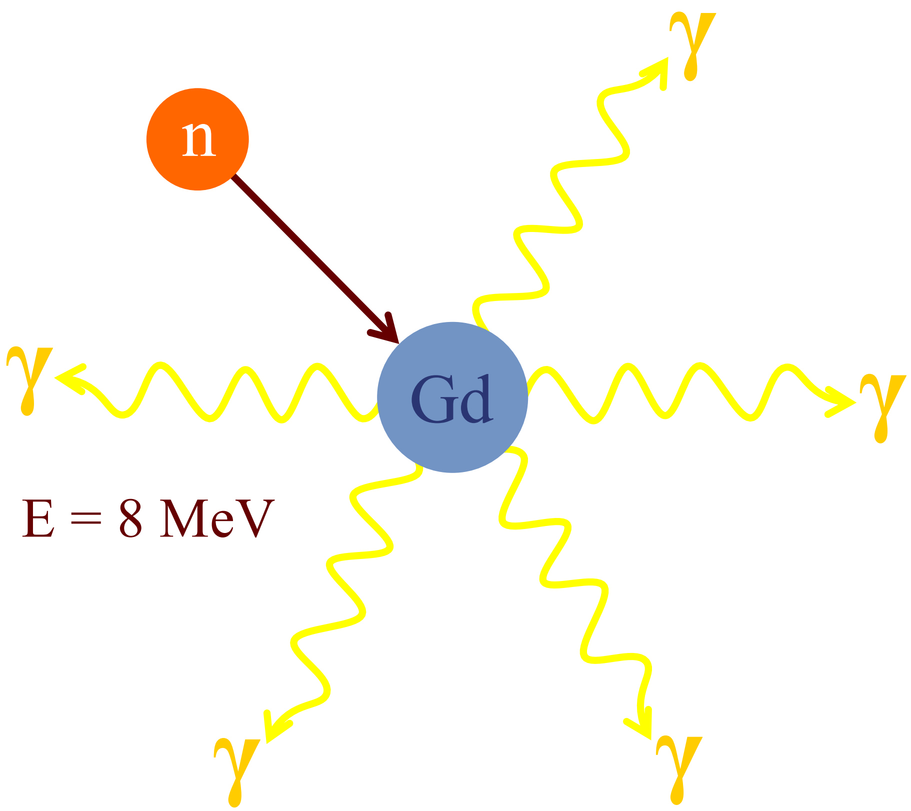
2. Relatively small detectors require careful consideration of isotope used for neutron capture and tagging.

Neutron Capture Options

Daya Bay, RENO and Double Chooz tag neutrons by Gd capture. All three experiments use a large gamma catcher, outside the Gd-doped volume to contain the gammas.

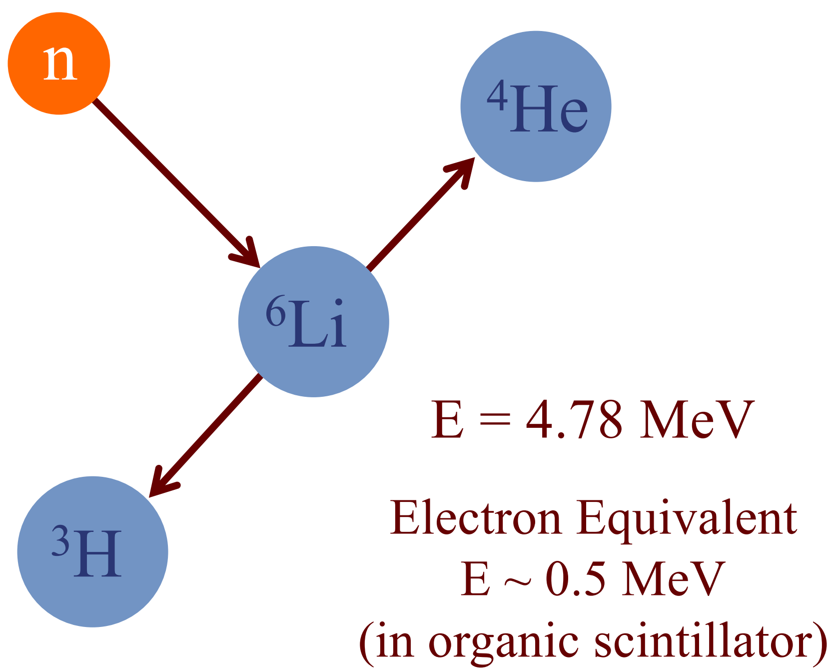
This will not work well in the much smaller short-baseline detectors.

Neutron Capture on Gadolinium



Poorly contained in small detectors

Neutron Capture on Lithium-6



Contained in a few micrometers

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. Backgrounds, particularly from random coincidences are the most significant challenge.

   Random coincident backgrounds can be reduced by:

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

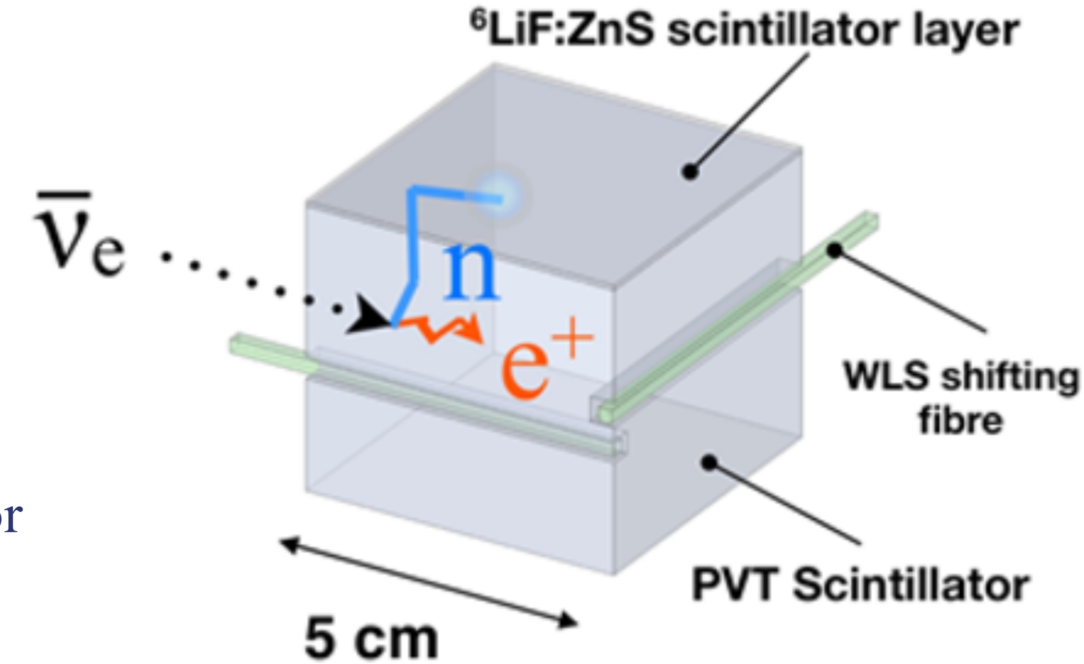
SoLid: Tagging with ^{6}Li in ZnS:Ag Sheets

The SoLid detector tags neutrons in thin sheets of ^{6}Li-loaded, silver activated zinc sulfide scintillator: 6LiF:ZnS(Ag).

ZnS(Ag) releases light with a 200 ns mean emission time which forms a very pure, high efficiency neutron tag.

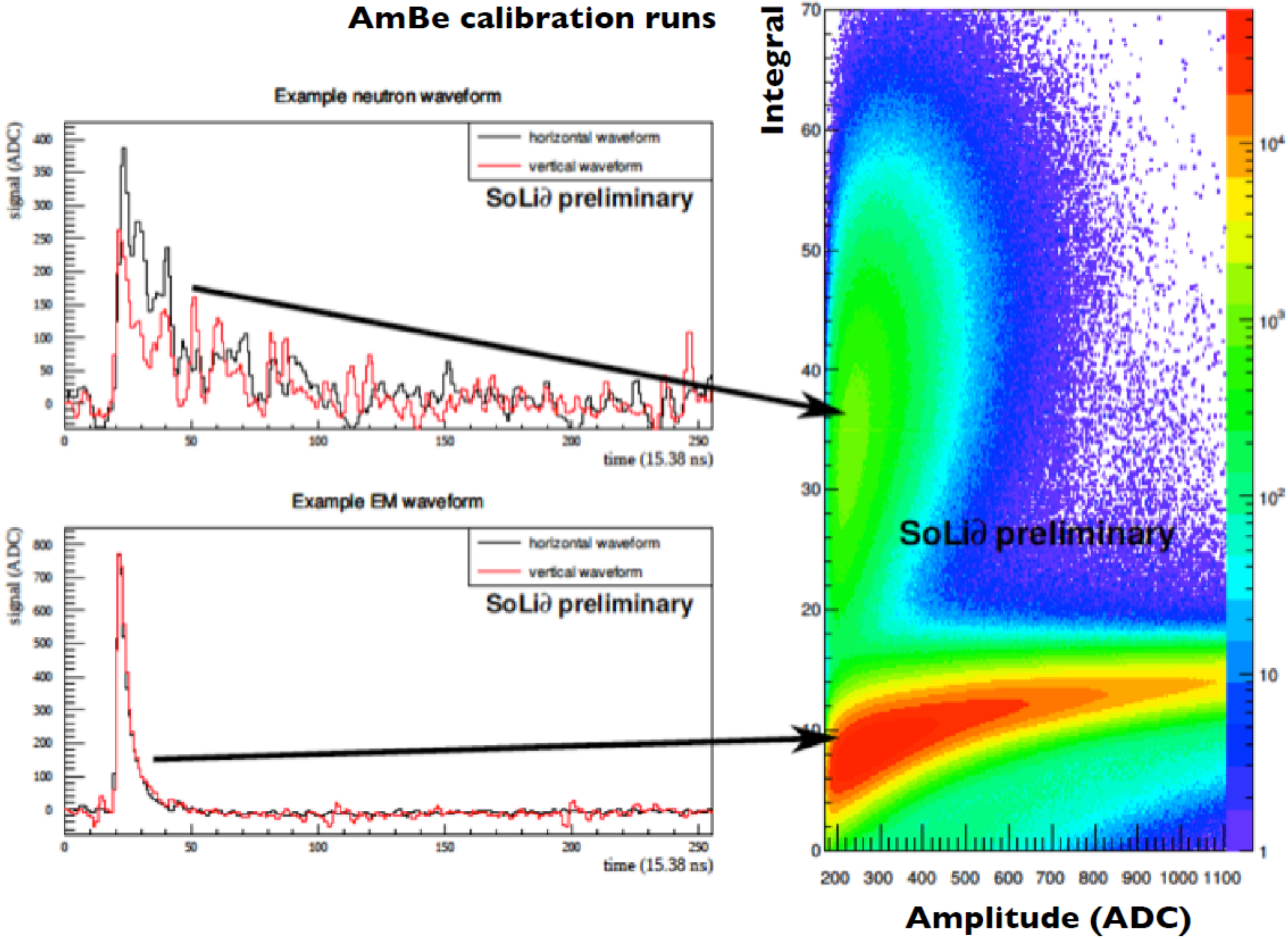
SoLid achieves unprecedented spatial resolution by segmenting its scintillator in cubes which are readout in two dimensions by wavelength shifting fibers.

The fiber readout is inefficient at light collection and limits the energy resolution.



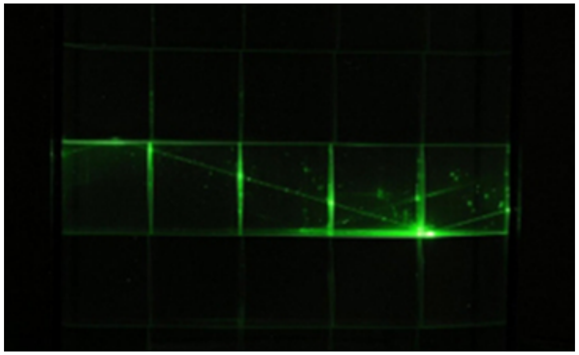
The SoLid Signal

AmBe calibration runs



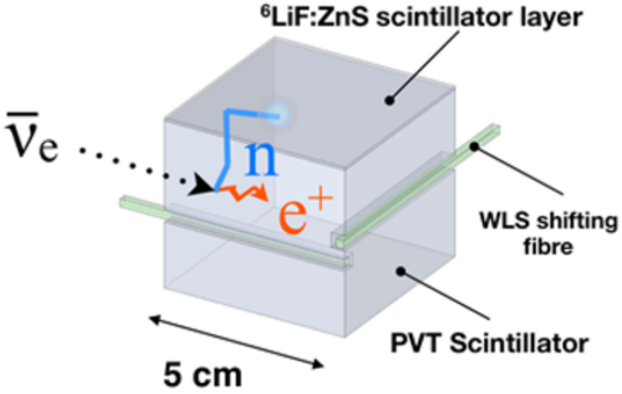
Technological Convergence

LENS



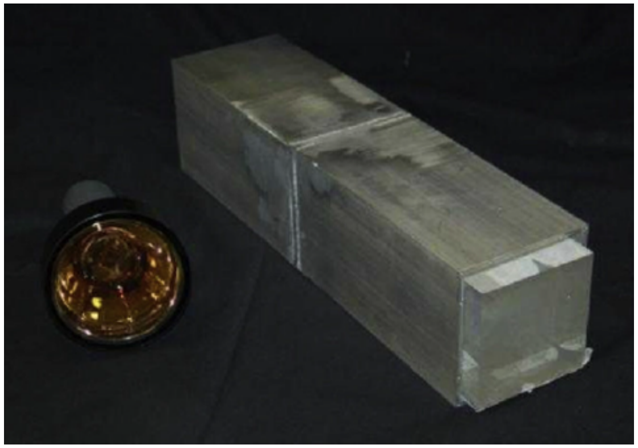
The **Raghavan Optical Lattice** (ROL), invented by the late Virginia Tech professor, Raju Ragahvan, divides a totally active volume into cubical cells that are read-out by total internal reflection. LENS was designed for solar neutrino detection and not optimized for reactor antineutrino detection.

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

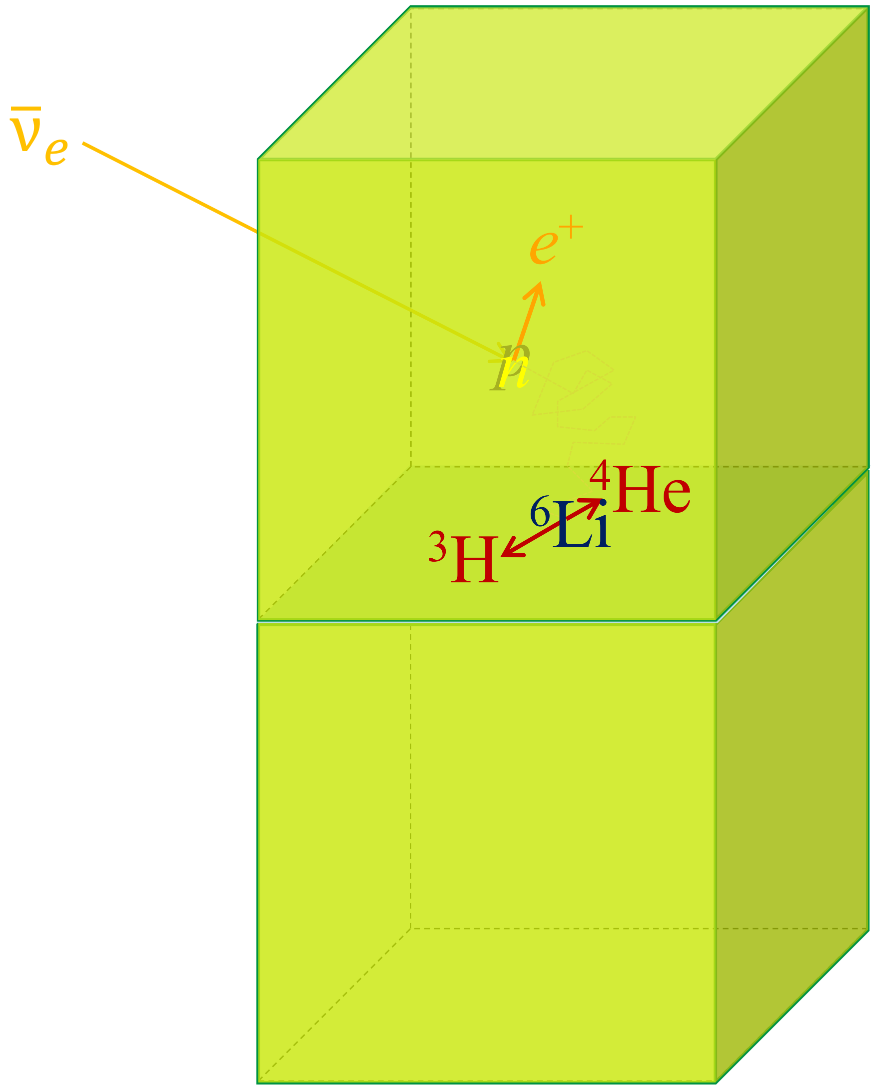


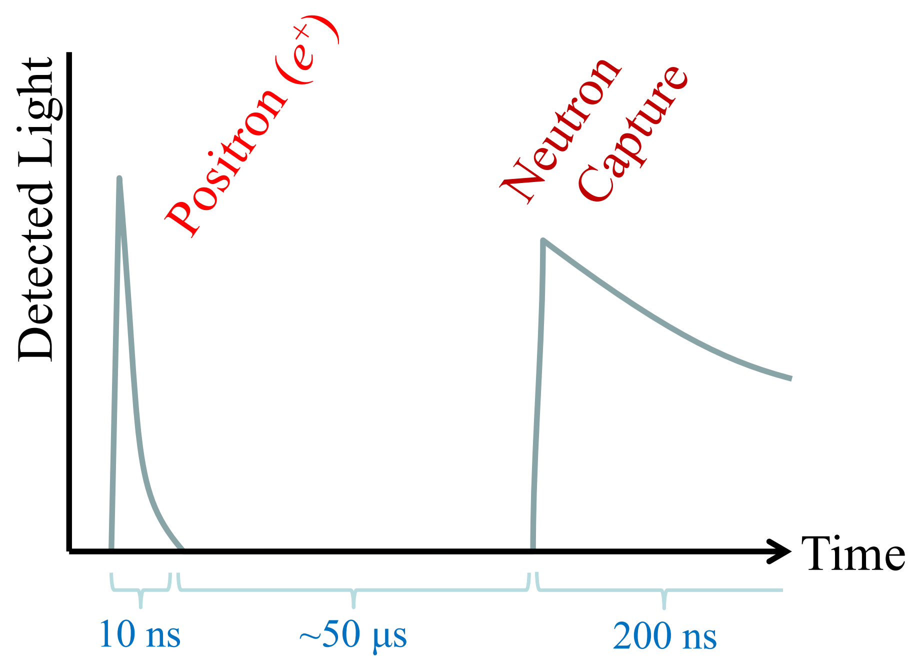
Used ^{6}LiF:ZnS(Ag) sheets mated to a **solid bar of wavelength-shifting plastic scintillator**. This prototype demonstrated the feasibility of pairing the sheets to wavelength shifting plastic, but the long bars do not have the spatial resolution required for good background rejection

CHANDLER

Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced ROL

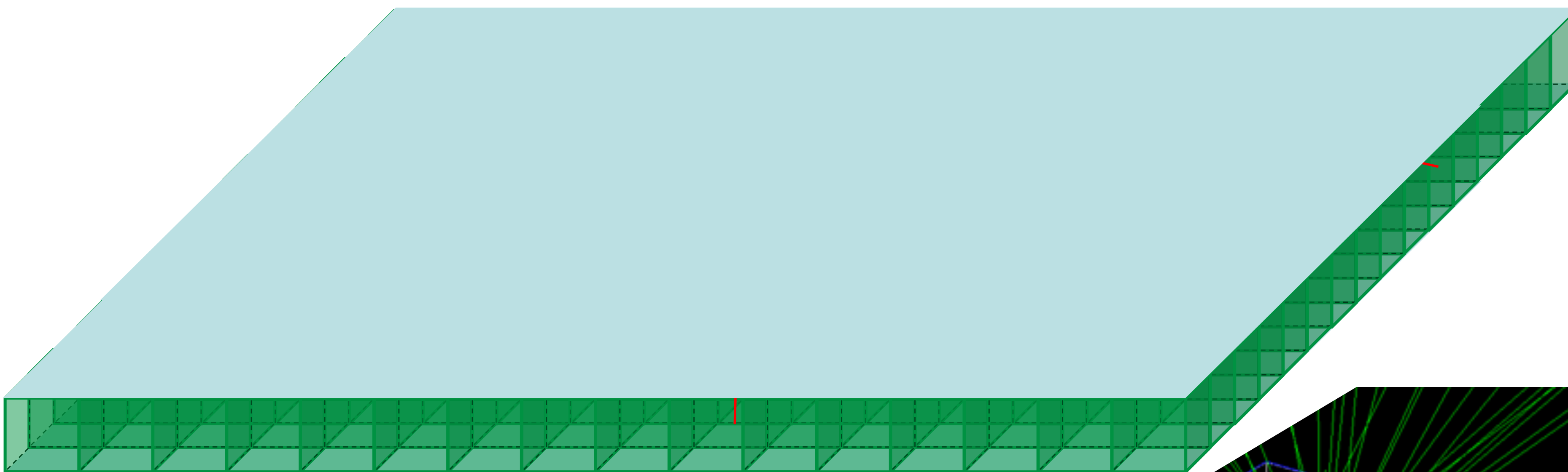
The CHANDLER Detector



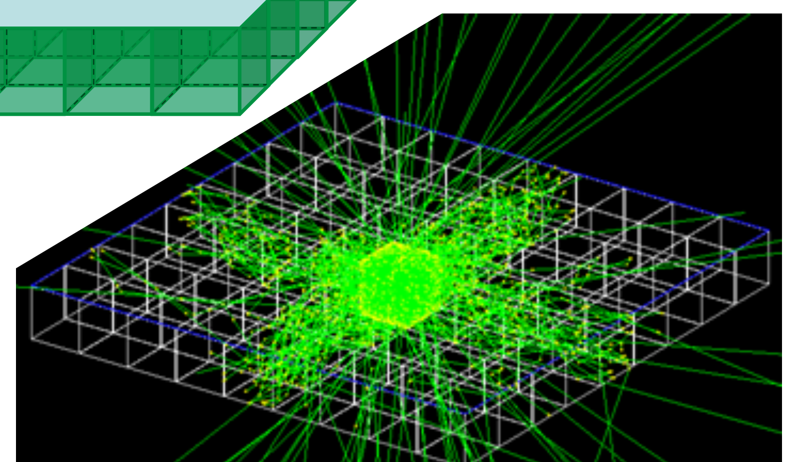


The CHANDLER Detector

CHANDLER will be constructed of cubes (6×6×6 cm^3) of wavelength-shifting plastic scintillator arrayed in planes, between sheets of ^{6}Li-loaded ZnS(Ag) for neutron tagging.



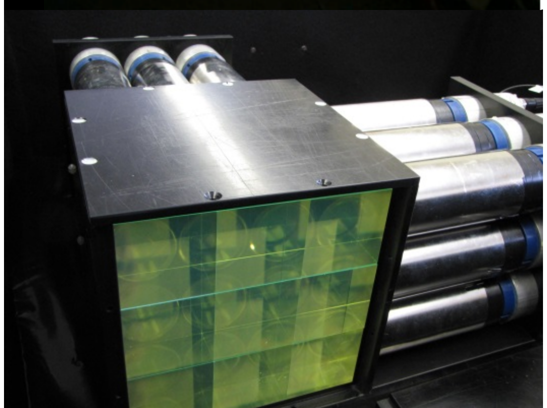
The light is transported by total-internal-reflection and readout on the surface by PMTs



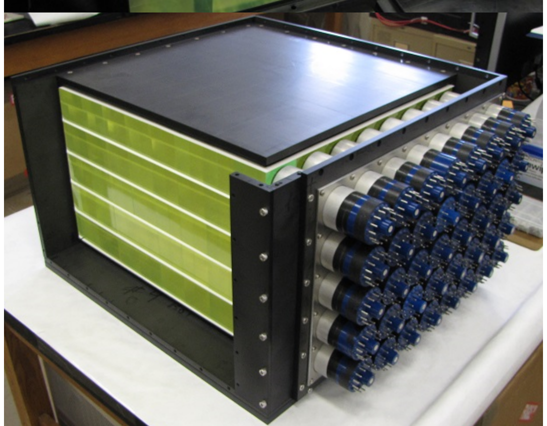
Photon Ray Tracing in GEANT4

Research and Development Effort

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

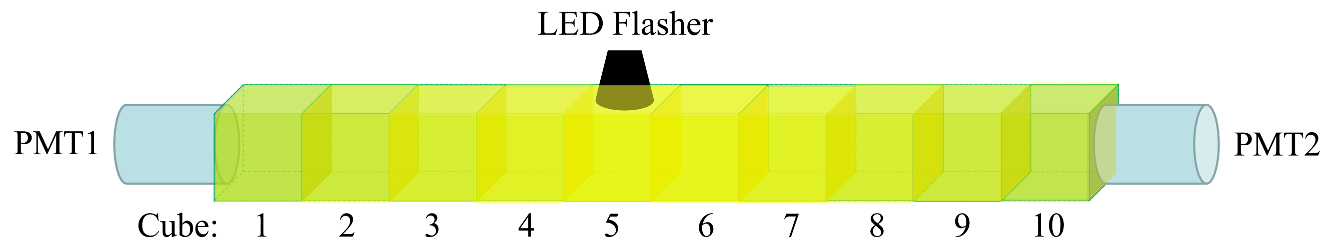


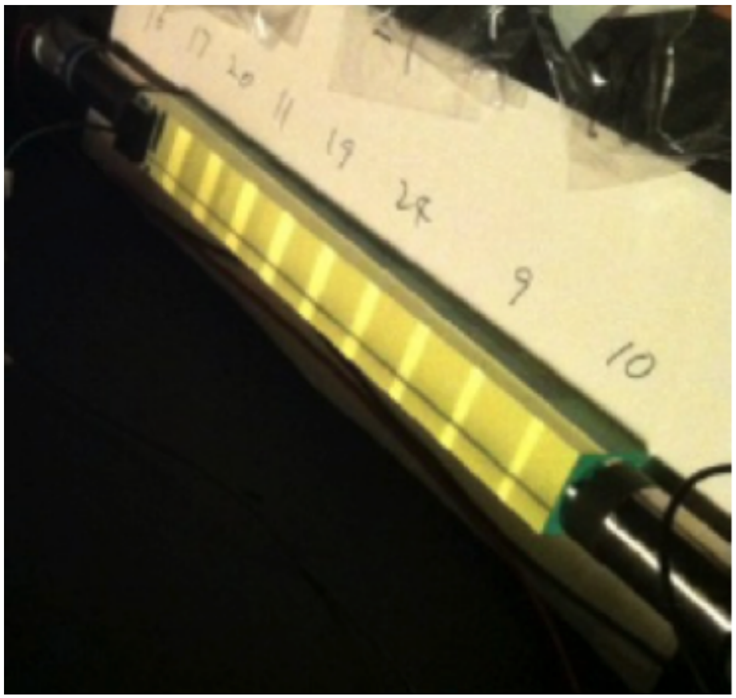
MicroCHANDLER is a 3×3×3 prototype which we are using to test our full electronics chain, develop the data acquisition system, study neutron capture identification and measure background rates.

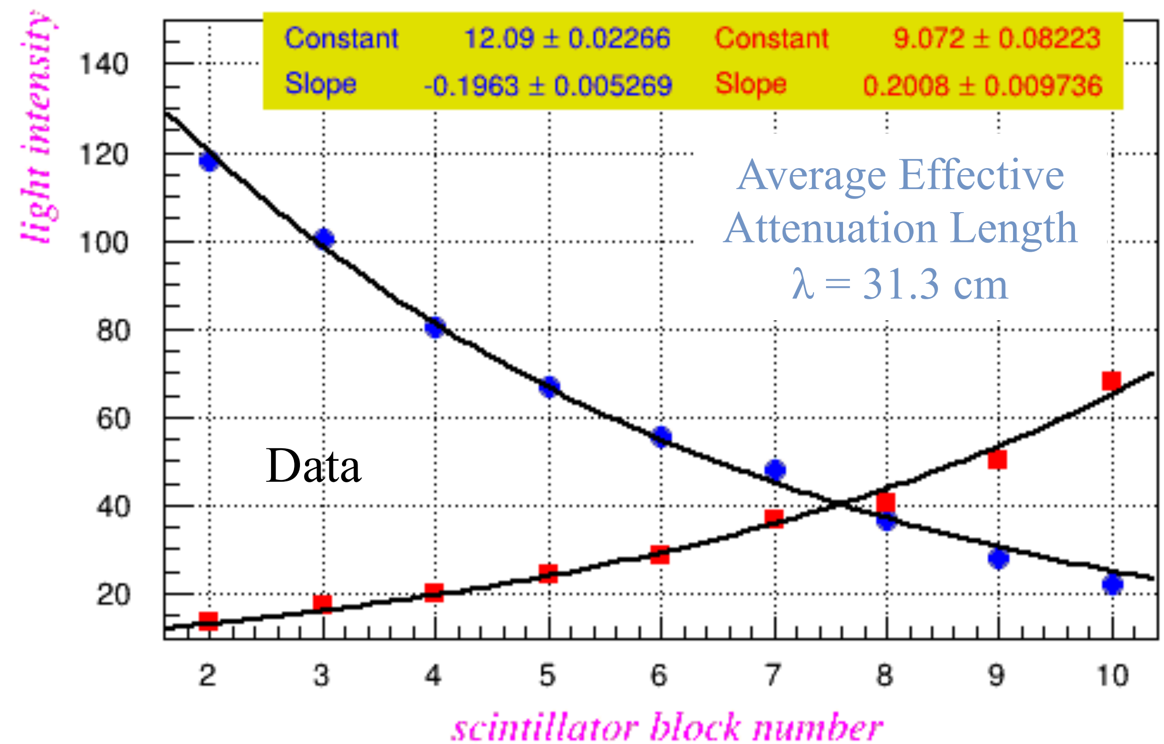


MiniCHANDLER is a full systems test (8×8×5) which is currently commissioned and will be deployed at the North Anna Nuclear Power Plant early next year.

Effective Attenuation Length Study



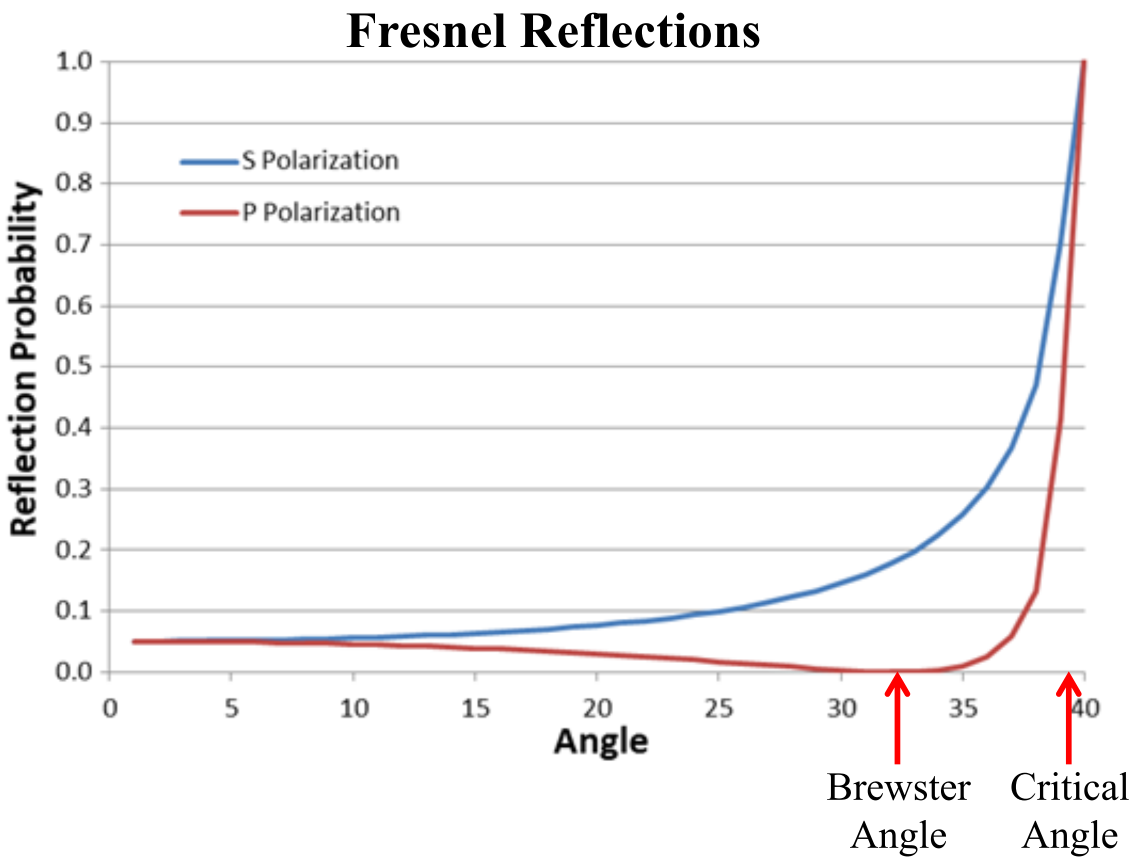




There are two contributions to the effective attenuation:

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

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.

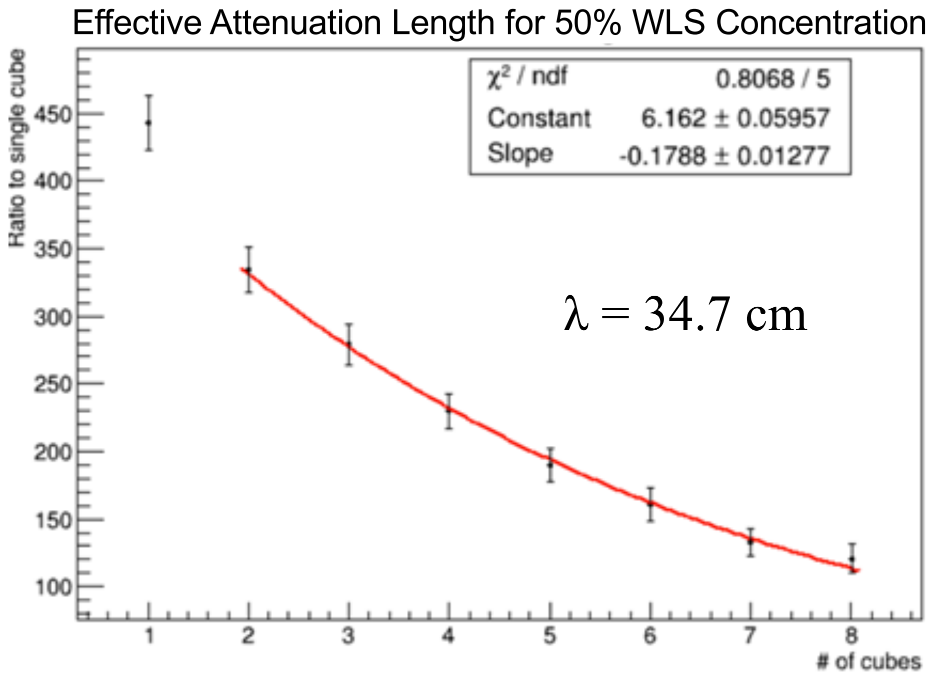
Each of the four TIR channels is open to 11.3% of the light produced in a cube.

Therefore 54.8% of all light can not be channeled.

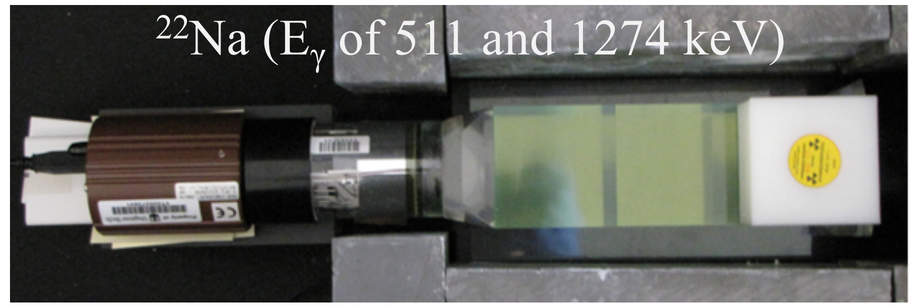
Some channeled light that gets reflected off of a cube surface perpendicular to the channel direction will reach the PMT in the opposite direction.

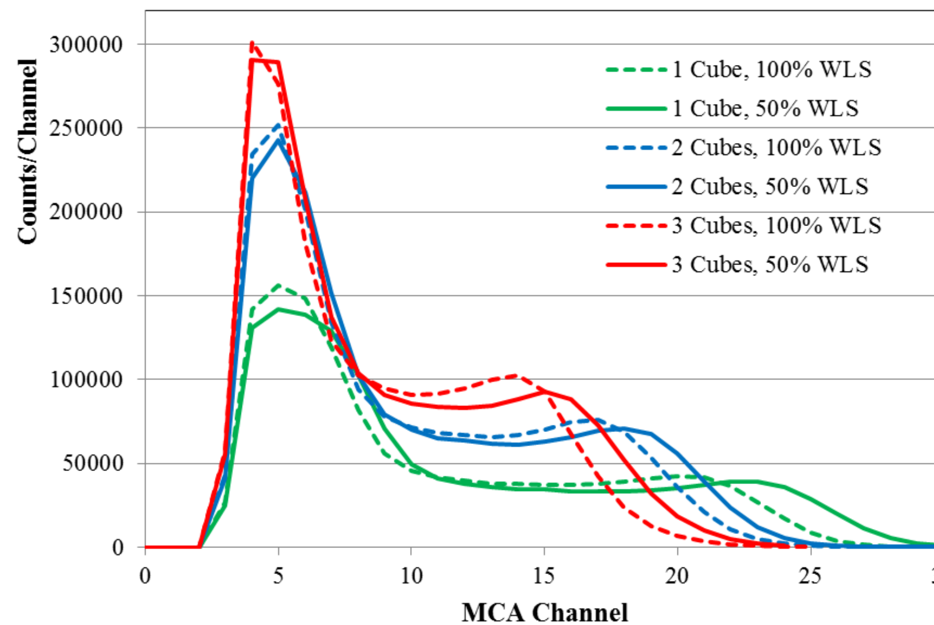
Wavelength Shifter Concentration

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



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





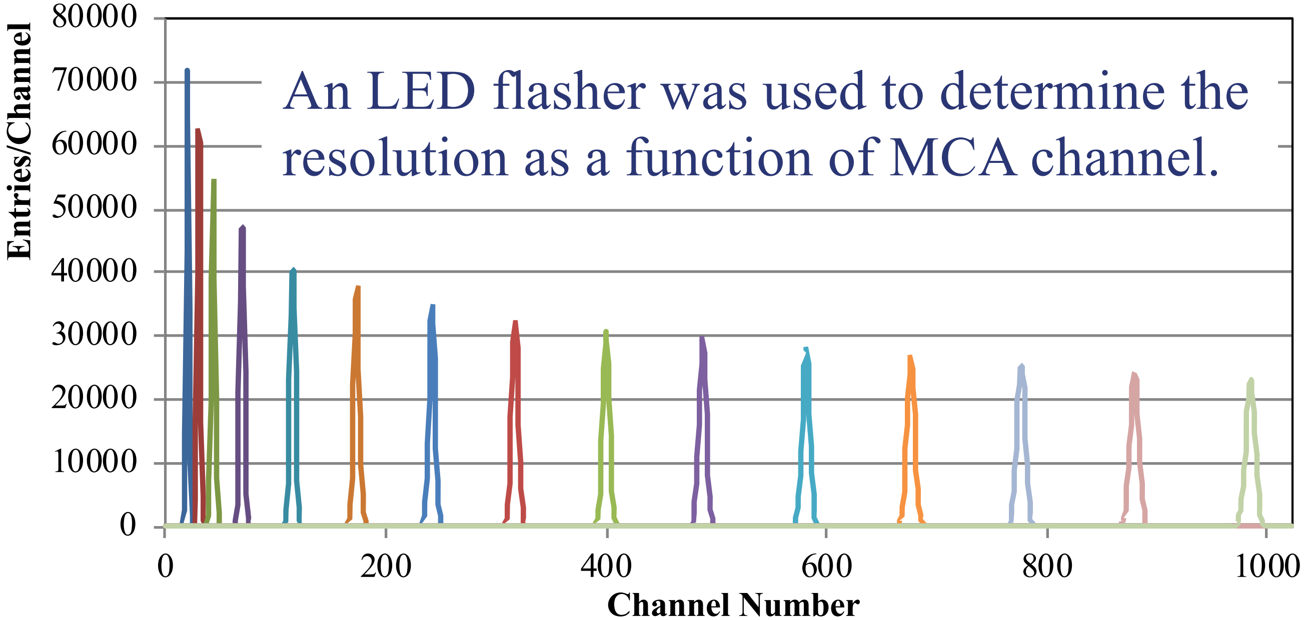
Halving the WLS concentration increases the attenuation length by 10%.

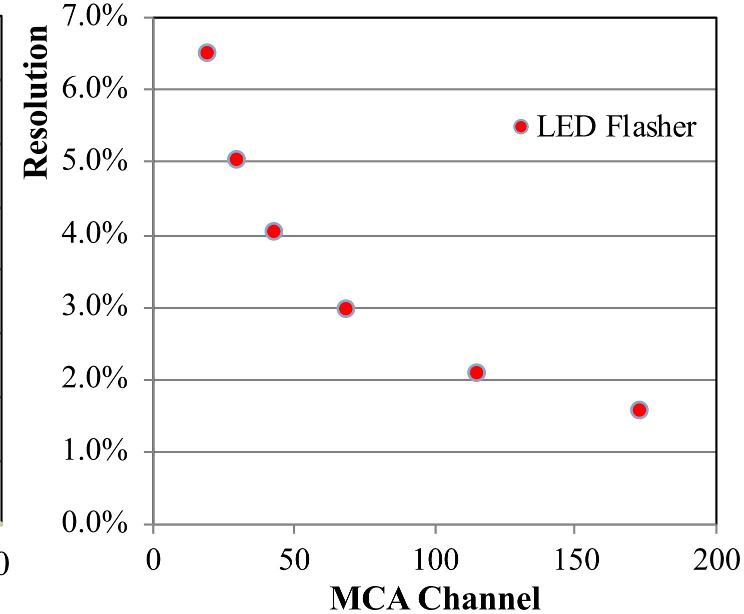
The light collection with lower WLS is greater at each position.

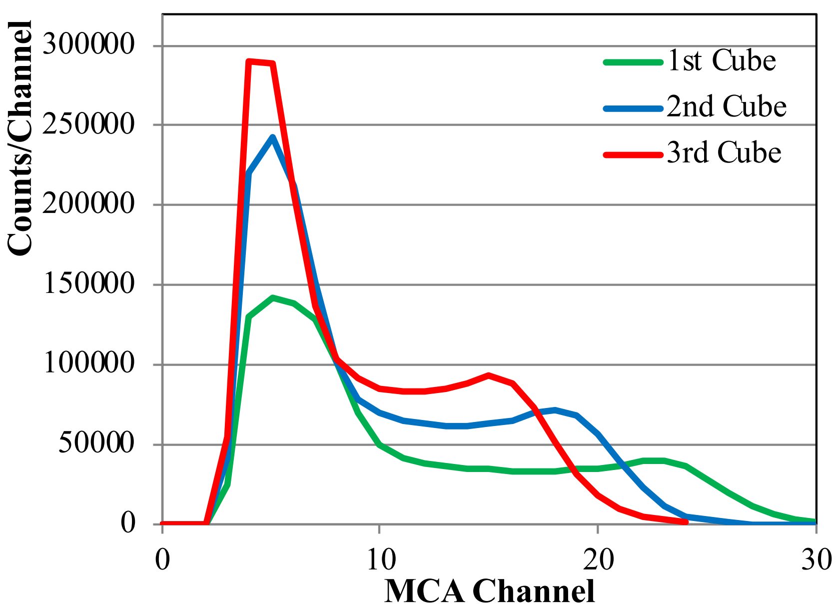
We have plans to study even lower WLS concentrations.

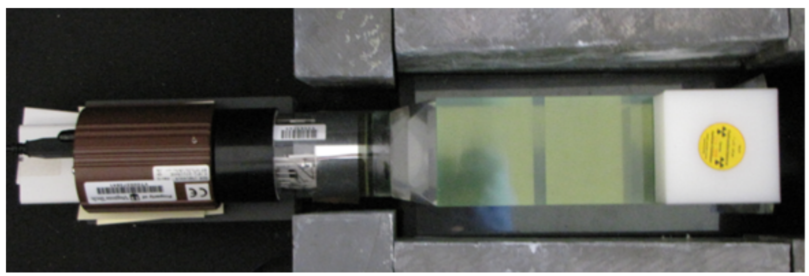
Light Output and Collection

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









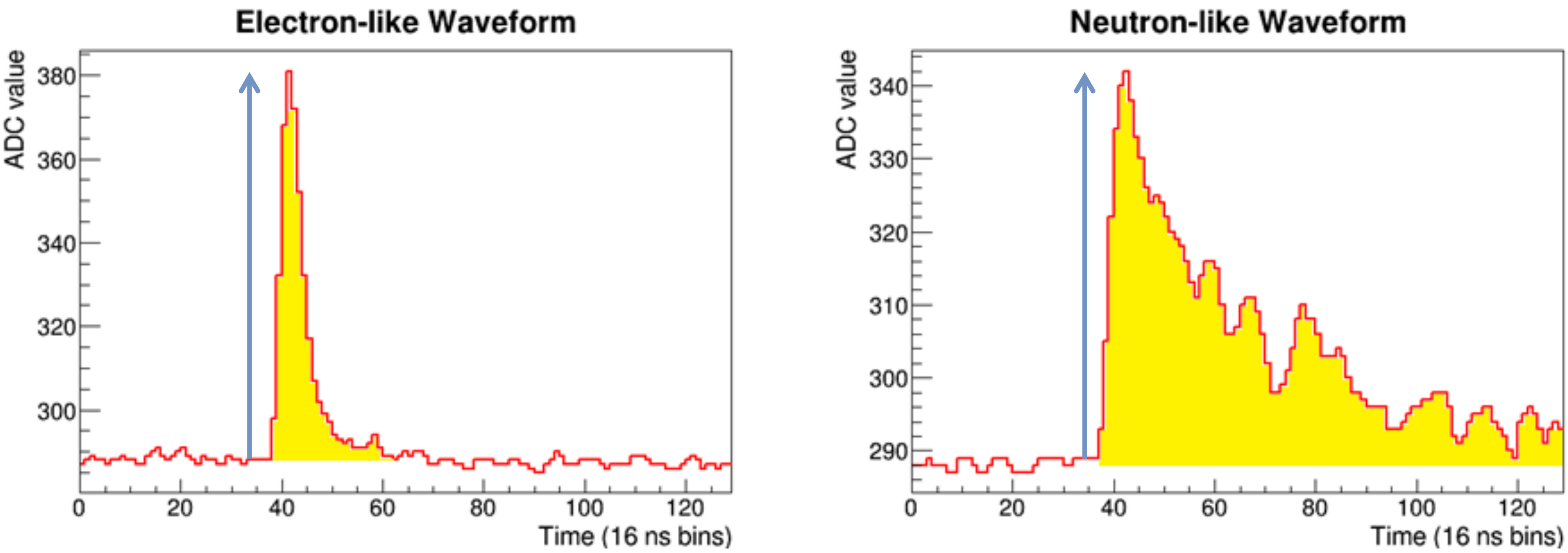
The ^{22}Na Compton edge is at 1.06 MeV, and at two cubes from the PMT it reconstructs at channel 20, which corresponds to an energy resolution of 6.5%.

Neutron Identification in MicroCHANDLER

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

The positron signal (formed in the cubes) is of short duration,

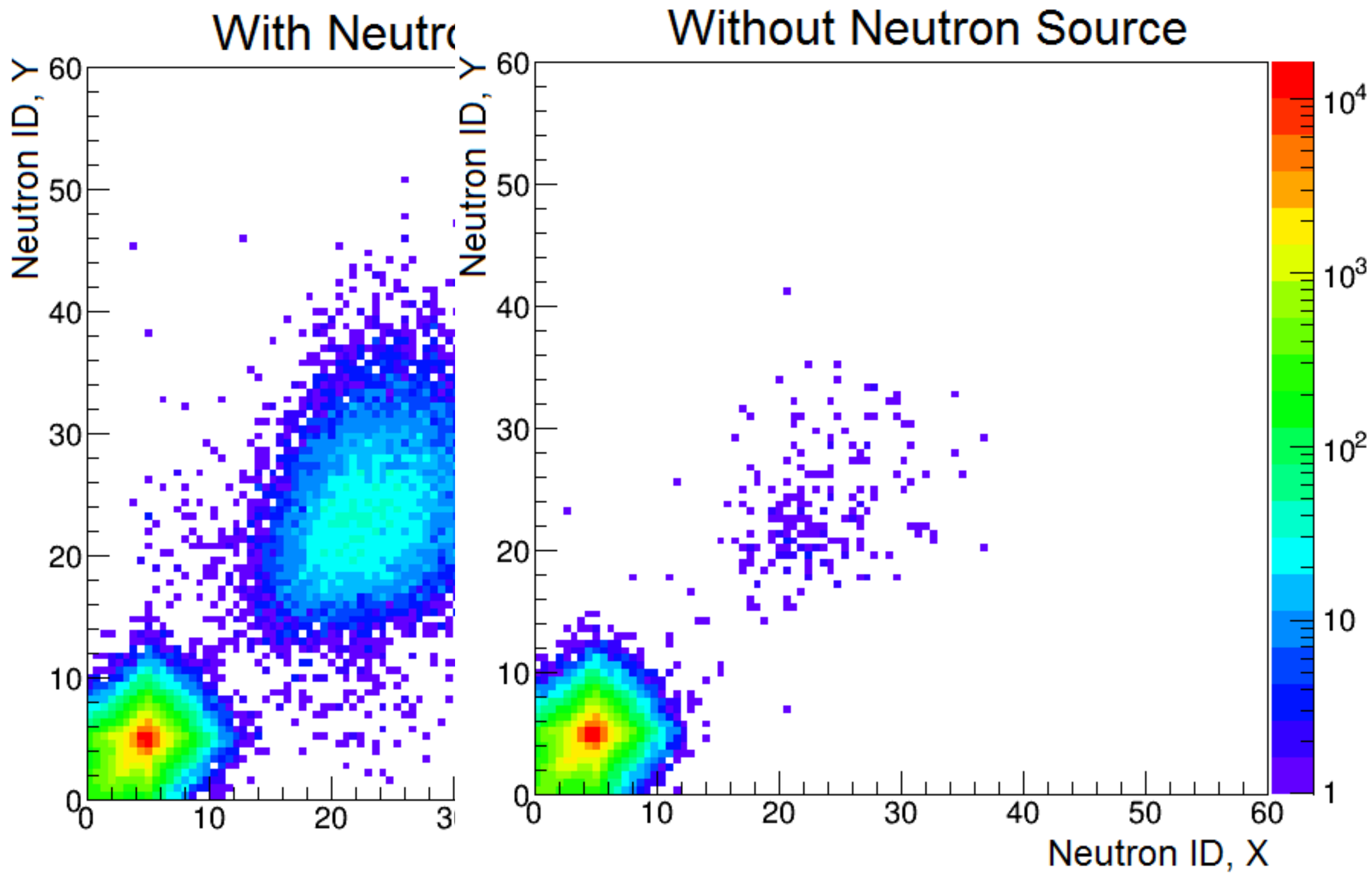
While the neutron signal arrives over a much longer time.



For each hit cell, we compute a simple neutron ID variable as the ratio of the integral of the pulse to the pulse height.

Neutron Identification in MicroCHANDLER

Then we plot the neutron ID from the *x*-view vs. the neutron ID from the *y*-view

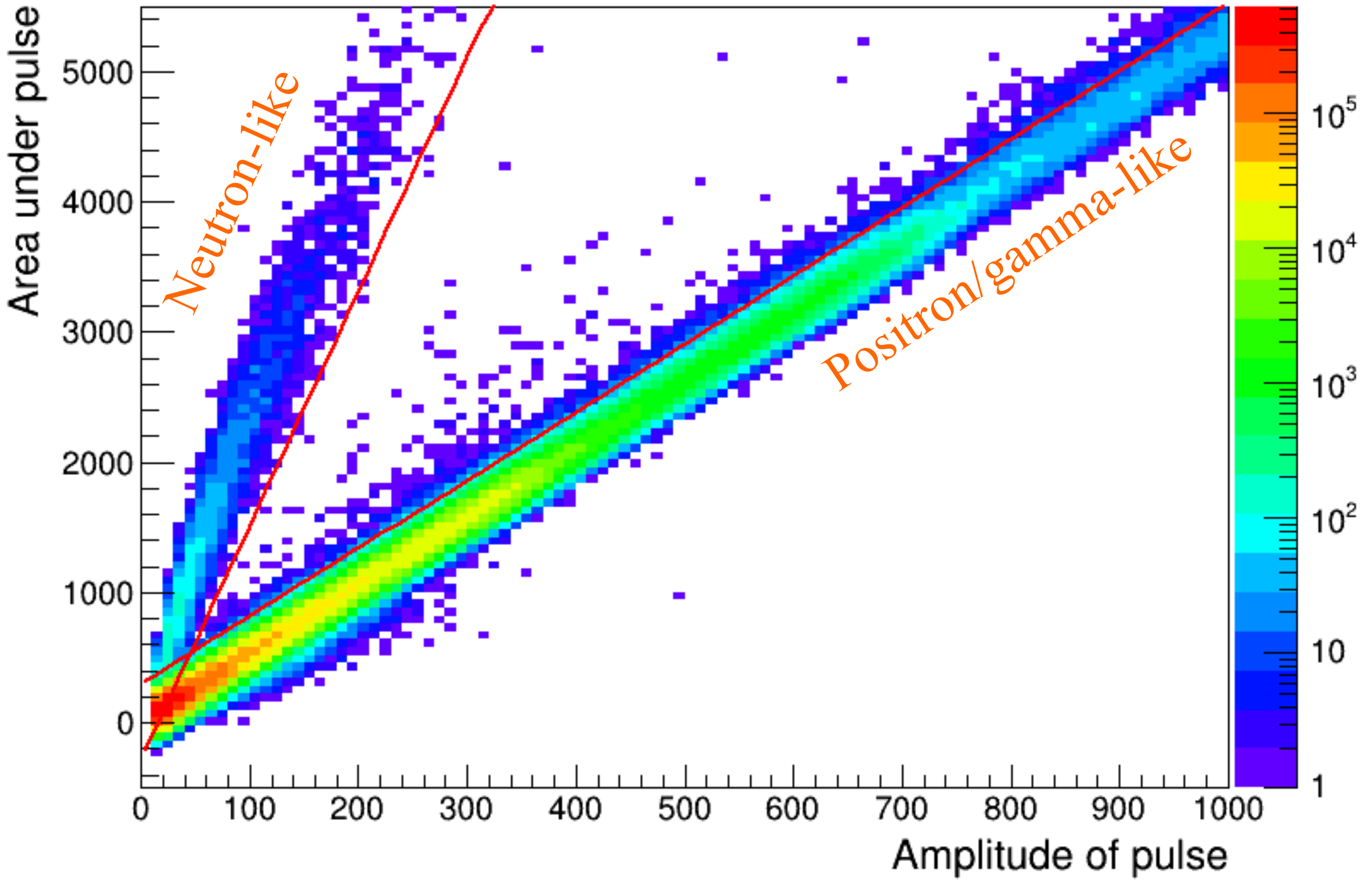


When the source is removed the events in the neutron region mostly go away.

The neutrons candidates that remain are consistent with the cosmic ray flux.

Improved Neutron Selection

The different classes of events clearly separated into distinct bands.



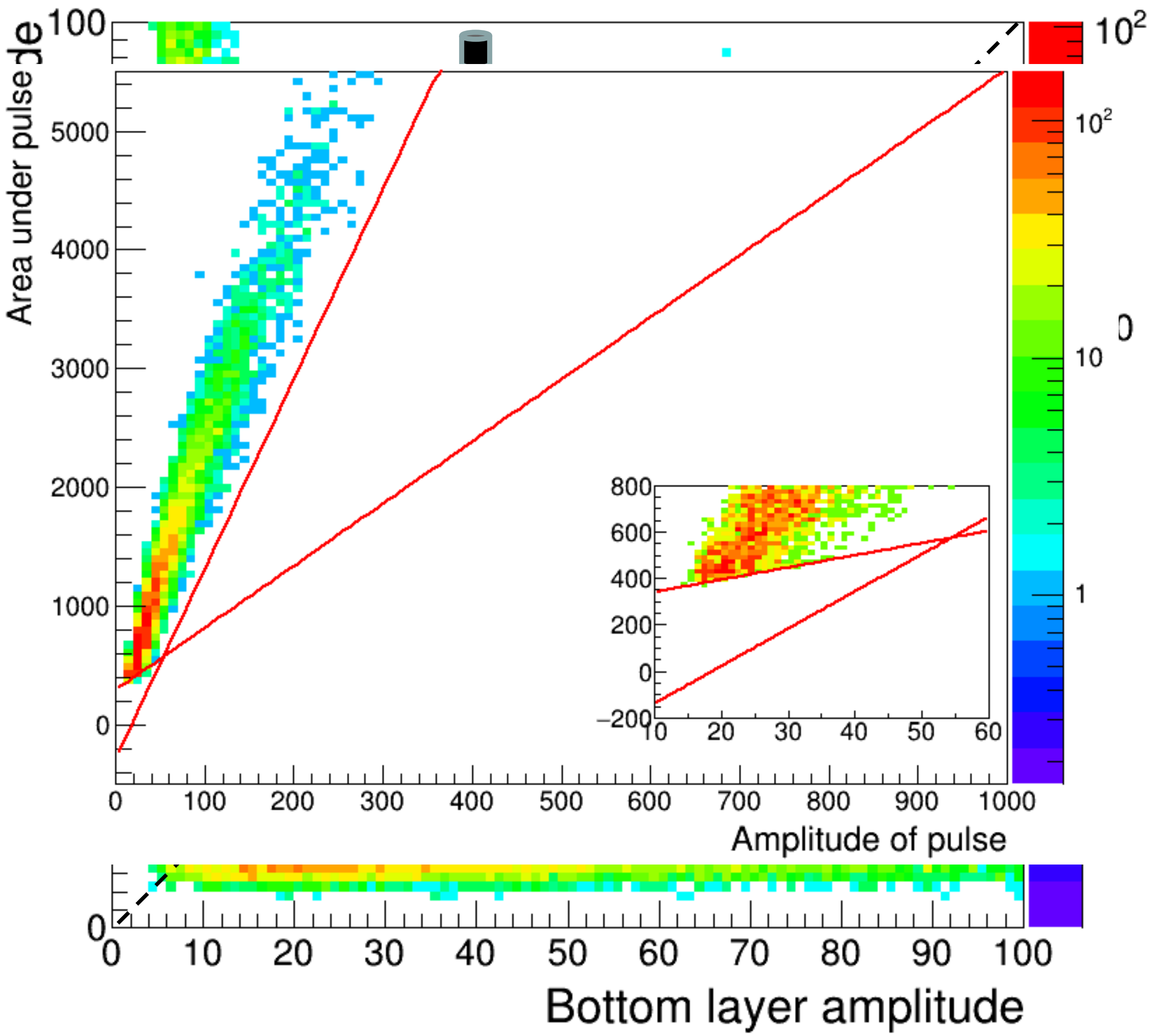
In the overlap region positron-like events out number the neutron candidates.

So good neutrons candidates must be above both red lines.

Is there any way to recover the neutrons in the overlap region?

Improved Neutron Selection

In CHANDLER we can see neutron capture light on both sides of the sheet.



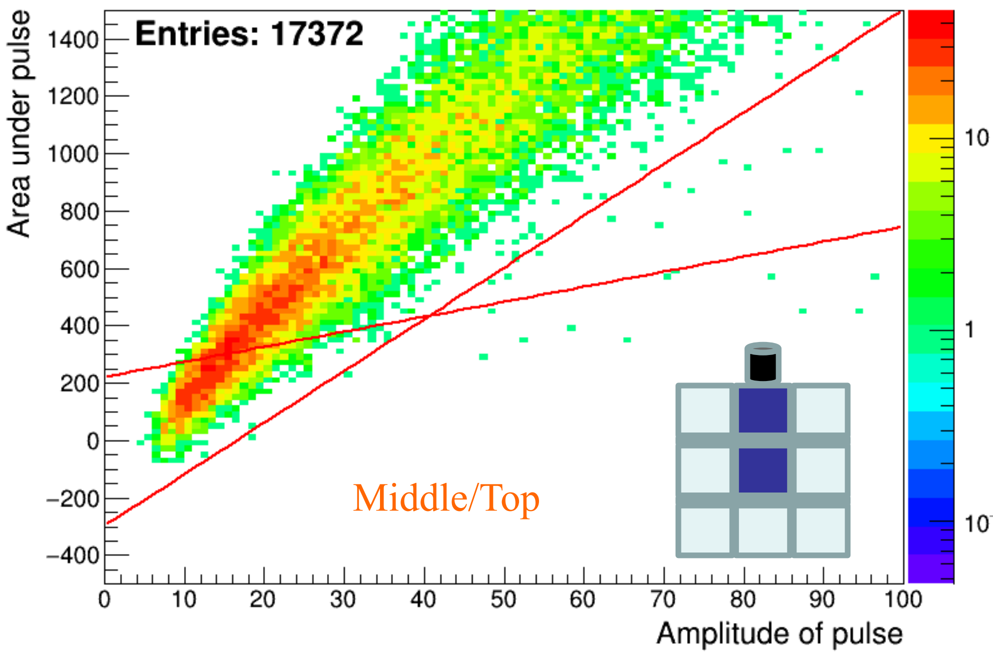
We use this to determine which sheet captured the neutron.

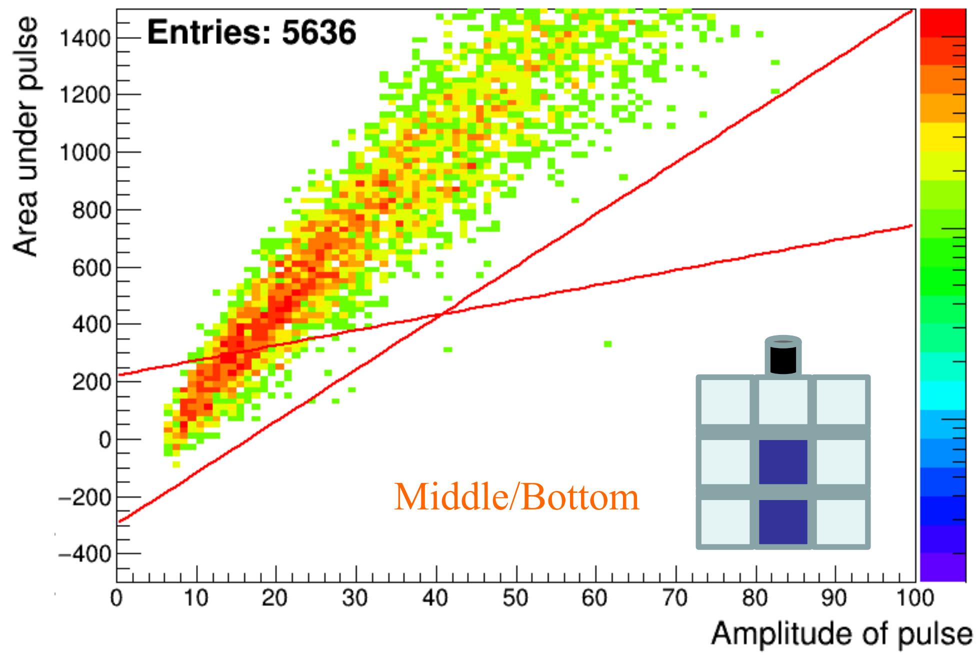
Starting with good neutrons tagged in the middle layer, we look for neutron-like light in the top and bottom layers.

The sheet is determined by the layer with the larger amplitude.

Improved Neutron Selection

Looking at good middle layer neutrons in the top/bottom layer shows the neutron band extending into the overlap region without a hint of contamination from the positron/gamma band.



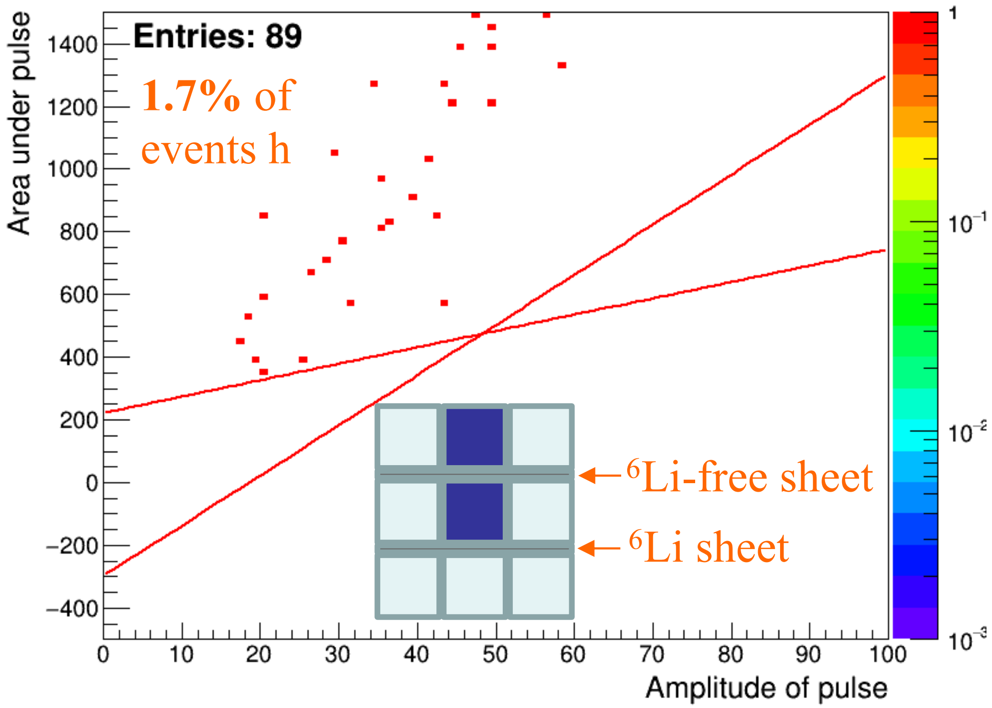


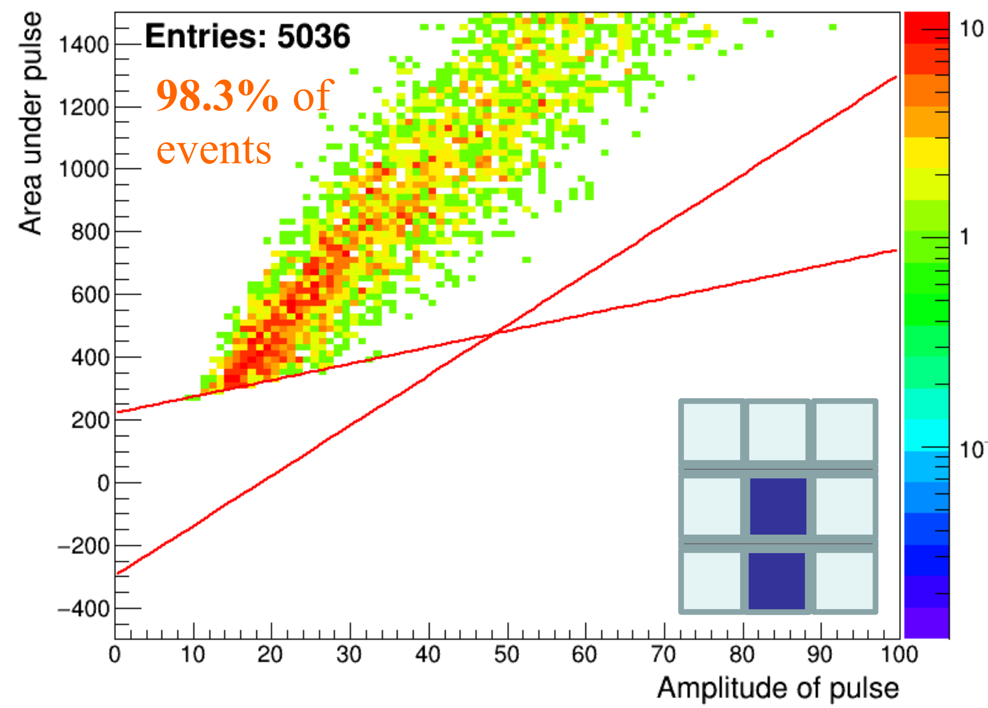
Requiring the neutron to be above the red lines on a single layer recovers most neutrons.

The light in the adjacent layers is used to discriminate between the two sheets.

Neutron Misidentification

To study neutron misidentification we removed the lithium from one of the sheets.

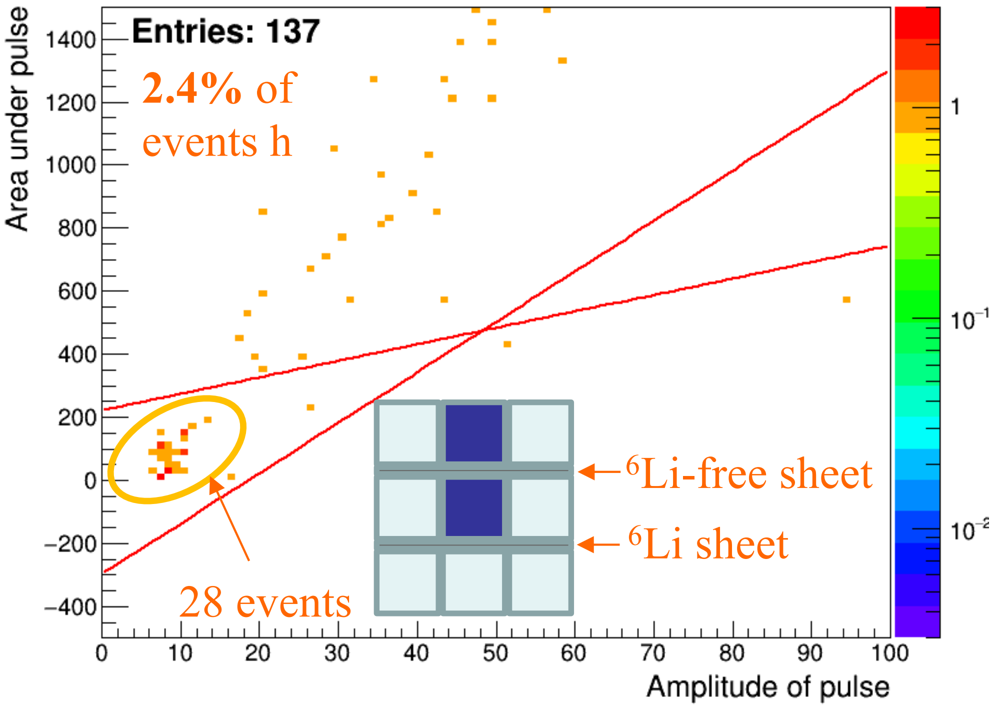


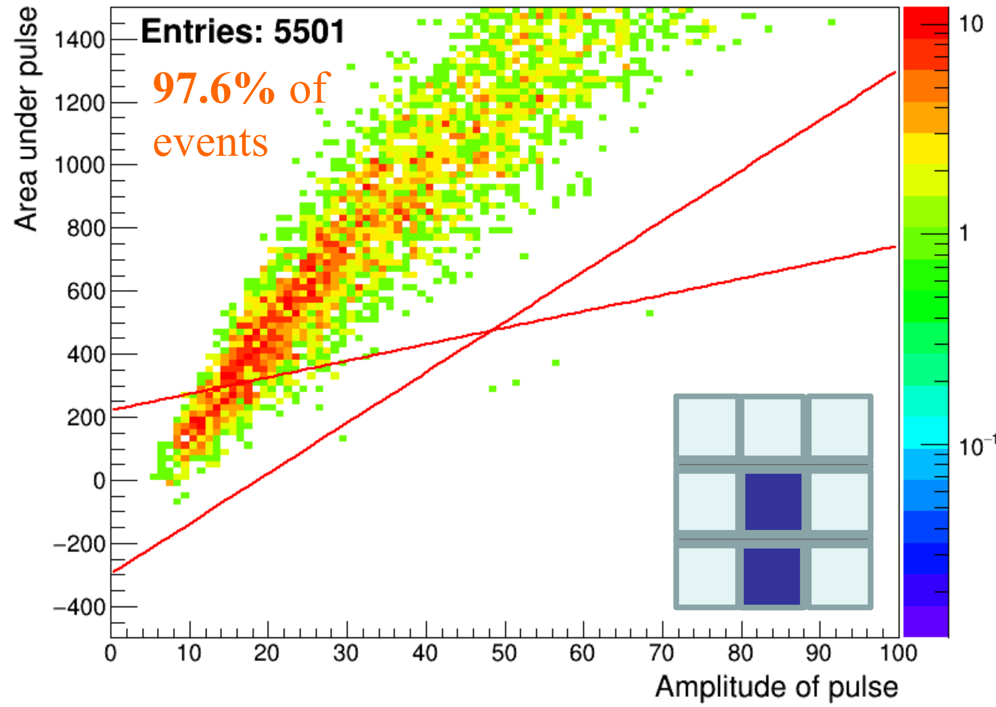


With cosmogenic neutrons candidates, less than 1 in 50 comes from the ^{6}Li-free sheet, therefore fake neutrons are a tiny fraction of the cosmic neutron background.

Neutron Misidentification

To study neutron misidentification we removed the lithium from one of the sheets.





With cosmogenic neutrons candidates, less than 1 in 50 comes from the ^{6}Li-free sheet, therefore fake neutrons are a tiny fraction of the cosmic neutron background.

In the overlap region of above the ^{6}Li sheet we see a collection of events, where the sheet determination was incorrect due to insufficient light on either side.

It represents less than 1% of all events.

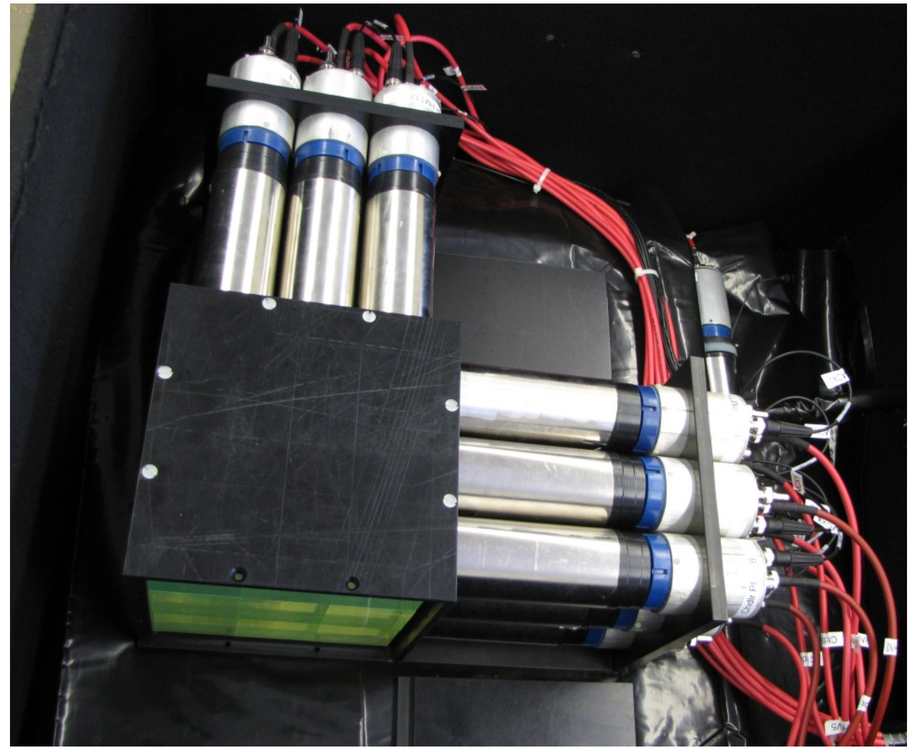
Design Studies with MicroCHANDLER

The first MicroCHANDLER prototype was built with $5,000 as a preliminary feasibility study.

It used old PMTs found in the basement.

It was not designed to be light tight.

It had no light guide to match the 62 mm cube to the 51 mm PMT



For the full-scale detector we intend to use

High Q.E. PMTs with good linearity over a Wide range (Hamamatsu R6231-100),

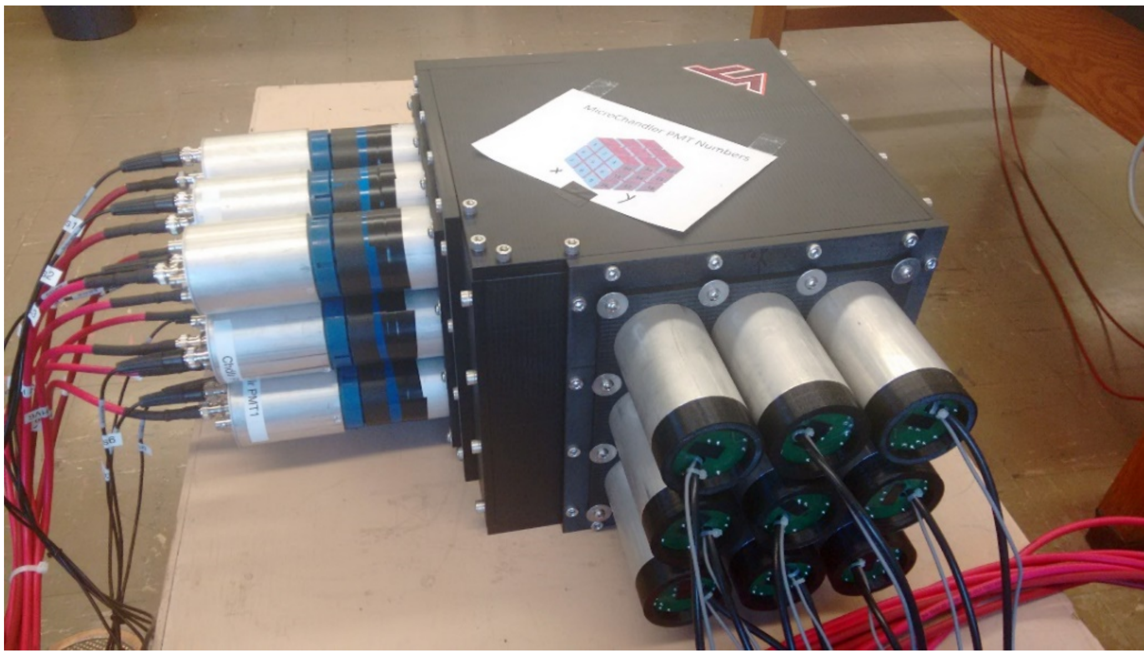
A light tight mechanical structure, and

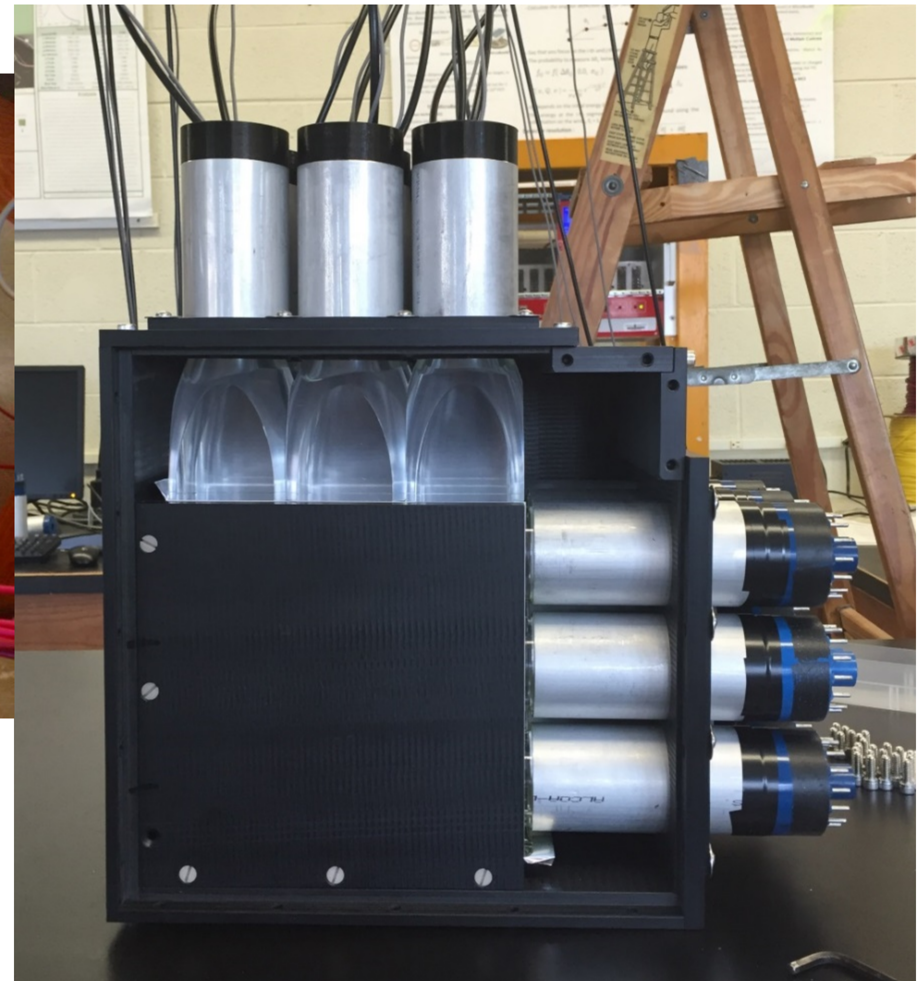
A compound parabolic light guide which boosts the light collection by 64%.

Design Studies with MicroCHANDLER

We built a new MicroCHANDLER with a fully engineered mechanical structure.

Half of the PMTs in the new design are Hamamatsu R6231-100 with acrylic light guides.

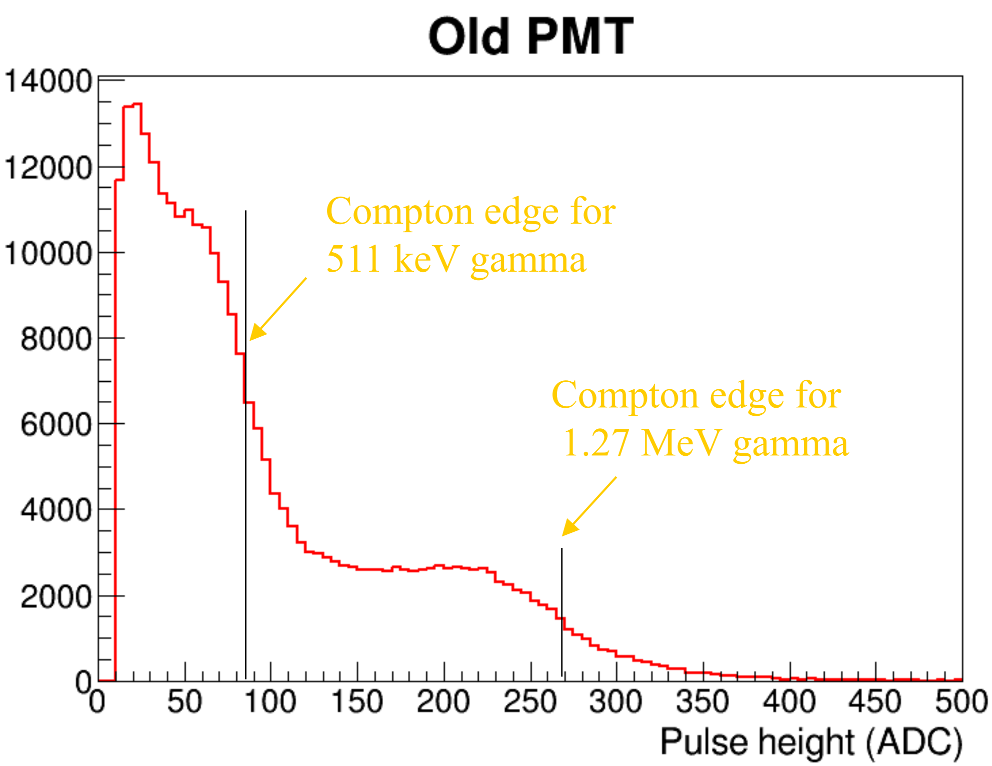


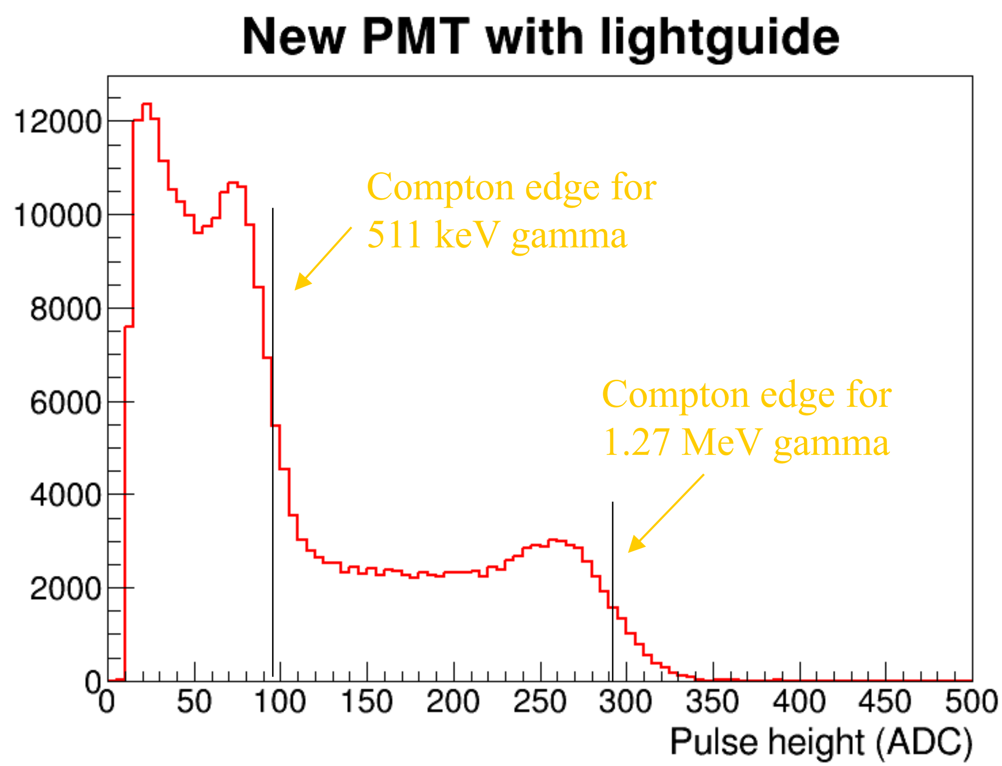


MicroCHANDLER was used to test the mechanical structure concept for the MiniCHANDLER detector.

Gamma Study in the New MicroCHANDLER

Using a ^{22}Na source, we studied the detector resolution with new tubes and light guides:





The new light collection results in a significant improvement in energy resolution.

CHANDLER Electronics

Shaper Board

Digitizer

We're using a CAEN V1740 waveform digitizer:

- 64 channels per board
- Samples every 16 ns
- 12 bit digitizer

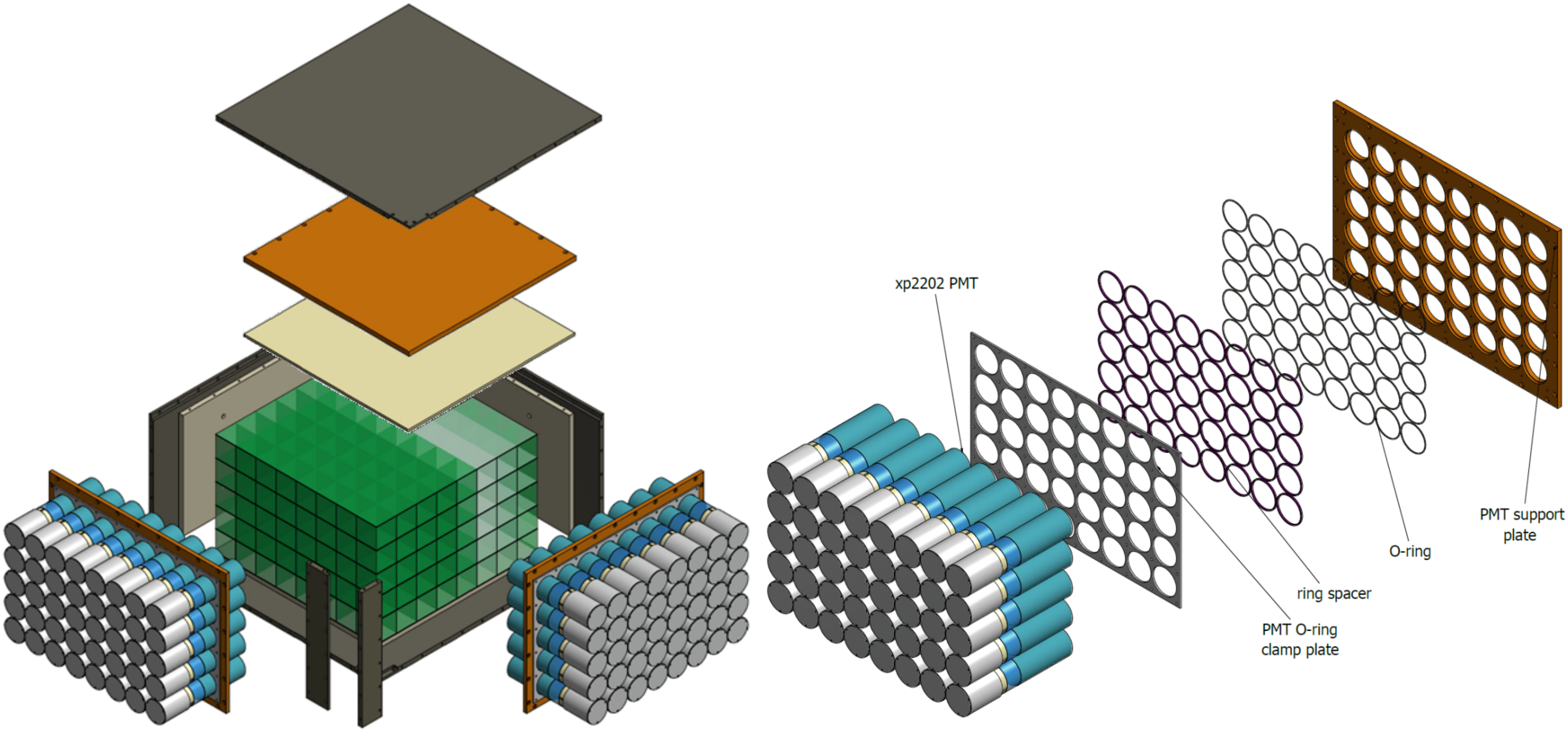
The digitizer is feed by a custom amplifier/shaper

- 16 channels per board
- 2× gain
- Shapes the PMT signal in 25 ns

This combination takes advantage of the huge difference in scintillator time scales to minimize the sampling rate, while maximizing the energy resolution.

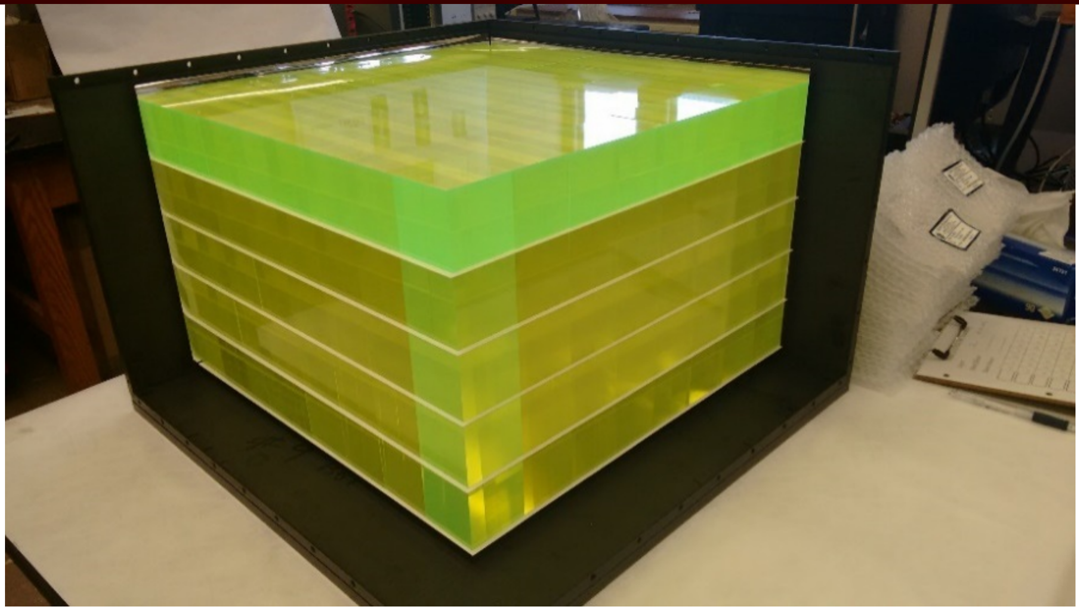
MiniCHANDLER Mechanical Structure

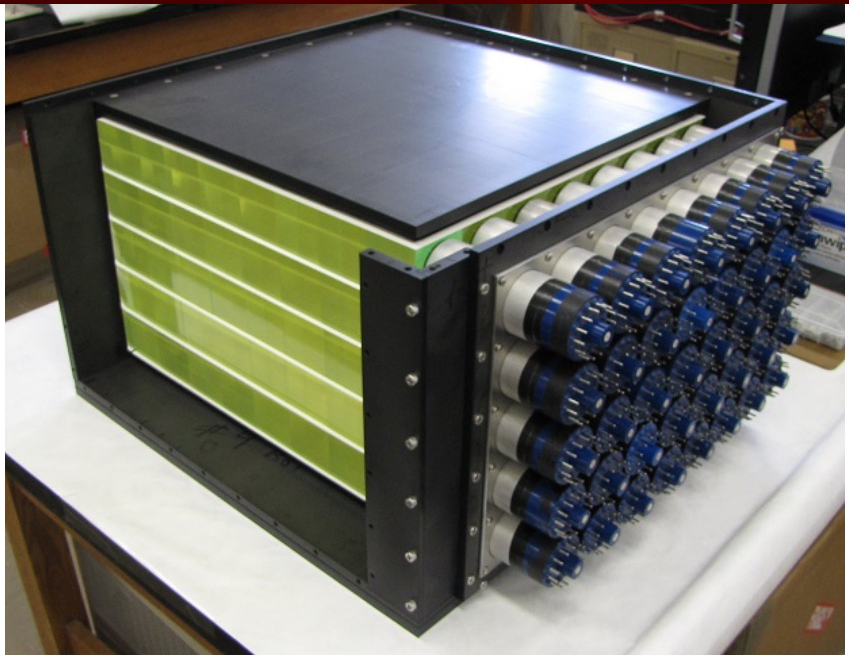
The MiniCHANDLER mechanical structure uses rubber o-rings, aluminum spacers and clamp plate to provide a light tight seal around each PMT.

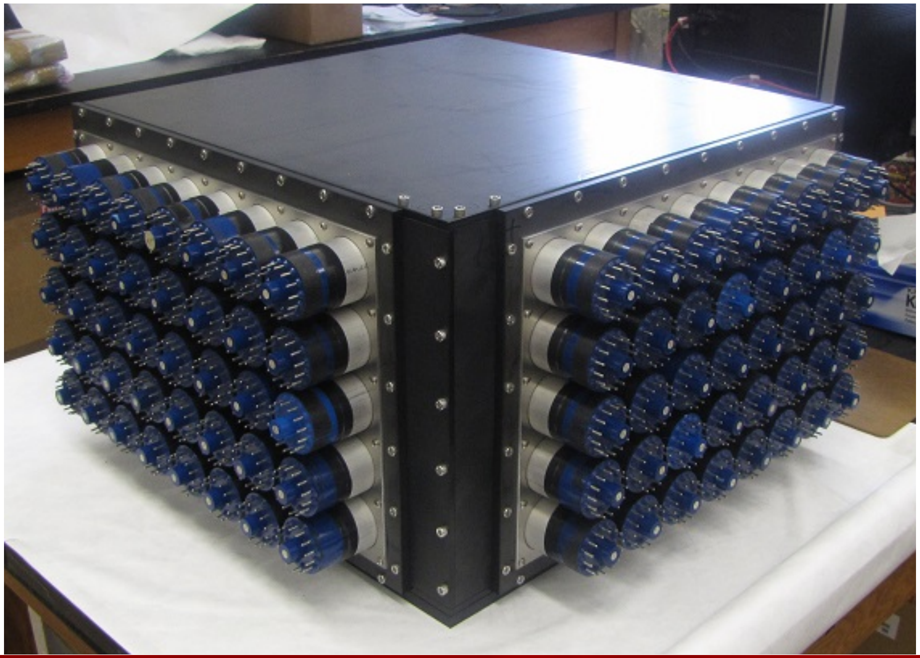


The result is a light tight box that supports each PMT centered on its cube row or column.

MiniCHANDLER Mechanical Structure







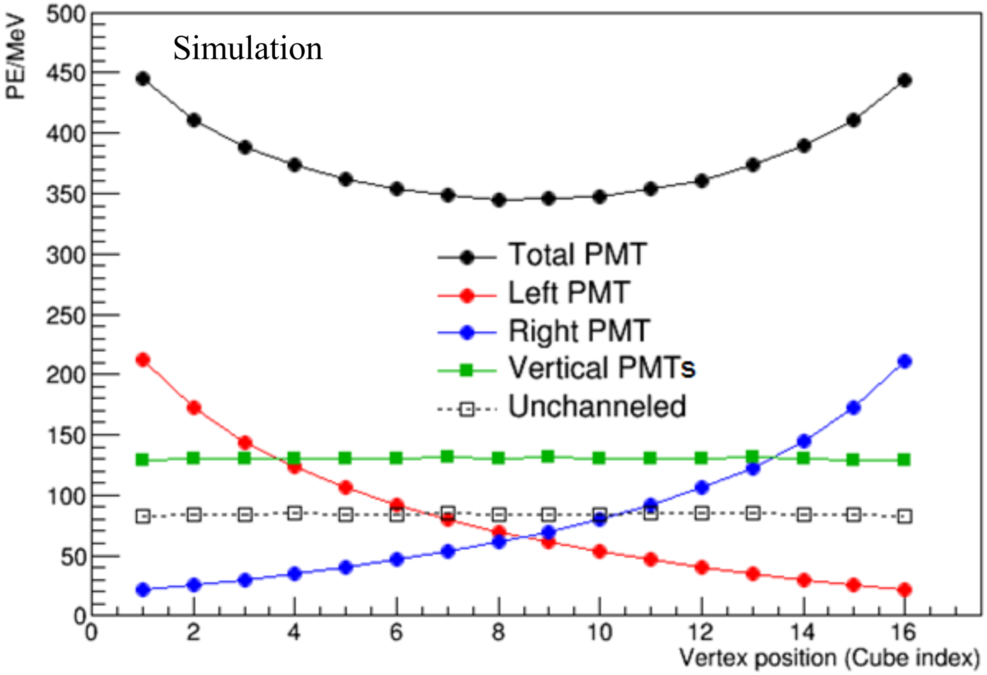
The 80 channel MiniCHANDLER detector is now fully assembled and is being commissioned

Next Steps in R&D Program…

Once commissioned, the MiniCHANDLER Detector will be deployed that the North Anna Nuclear Power Station.

We expect about 100 observed events/day. If successful, this will be the world's smallest neutrino detector at 80 kg.

GEANT4: Detector Response vs. Cube Position



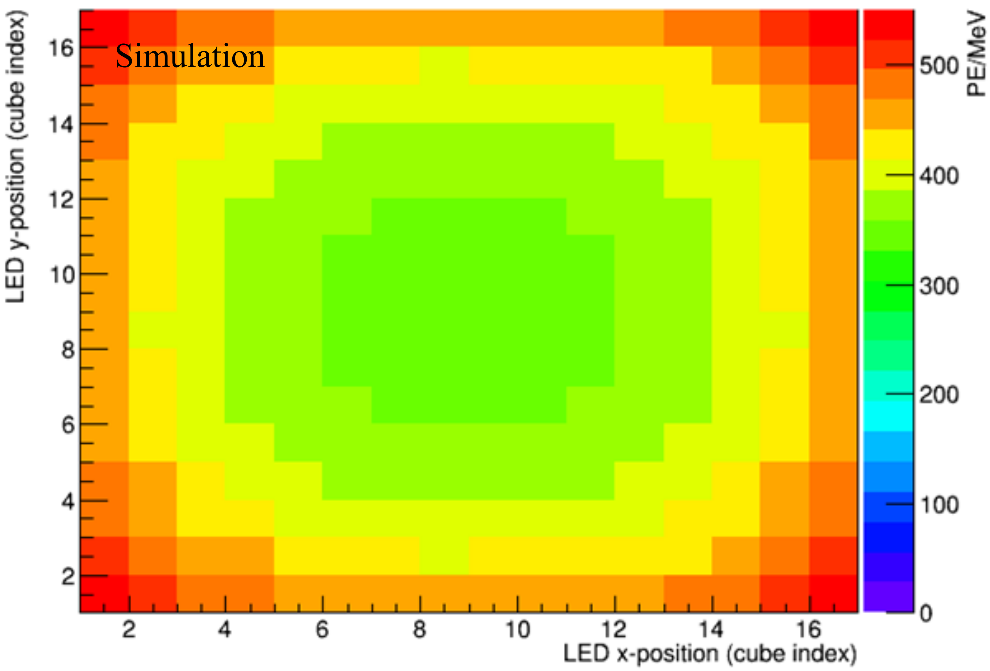
Most of the light is collected in the 4 PMTs in the TIR channel directions.

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.

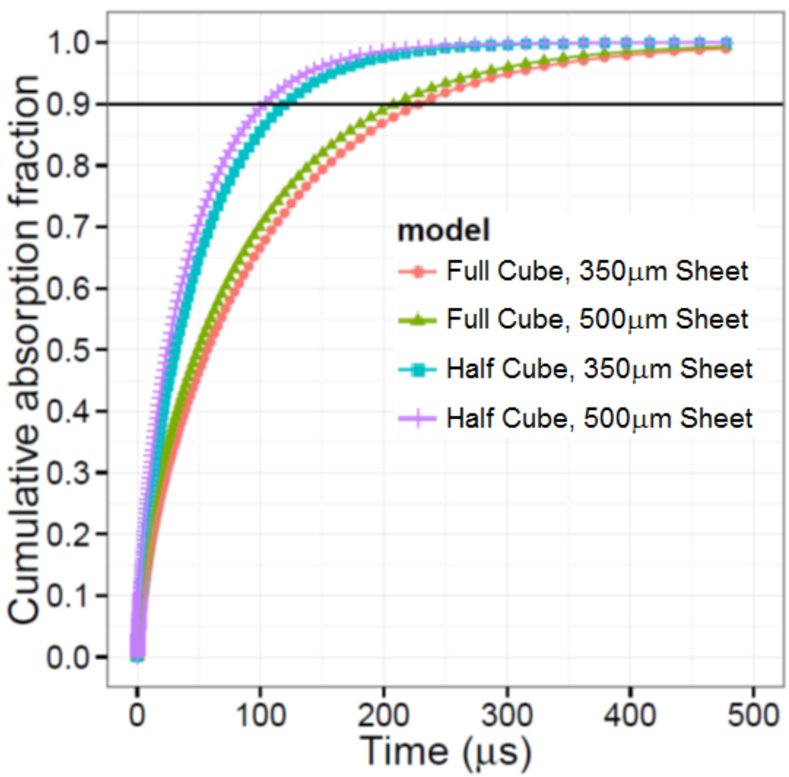
The largest excursion from the mean is in the corner cells.

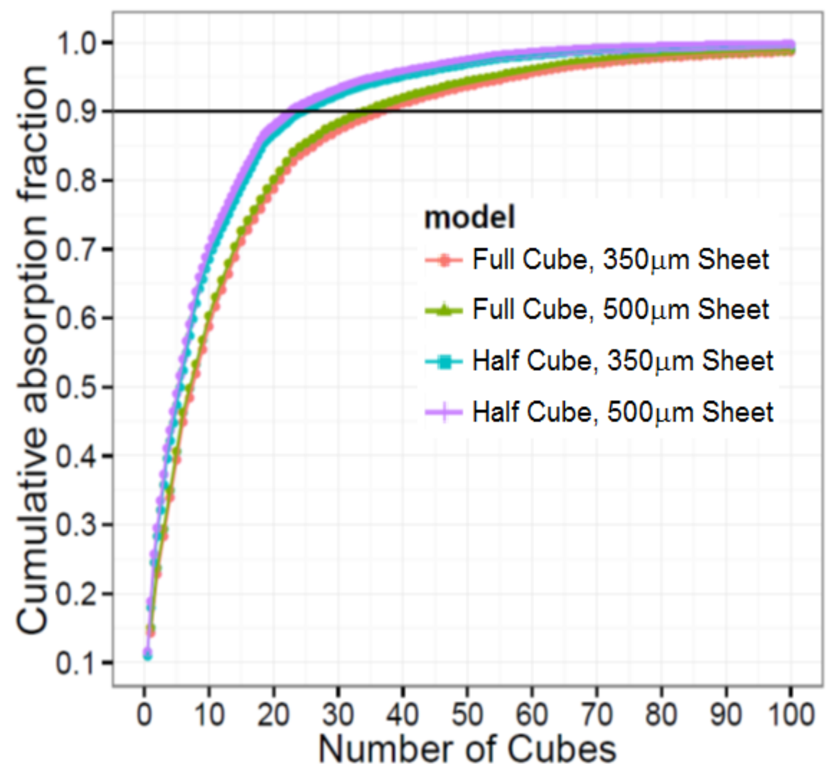
The conversion to p.e./MeV assumes light guides, and a PMT maximum quantum efficiency of 25%.



MCNP6: Neutron Transport and Capture

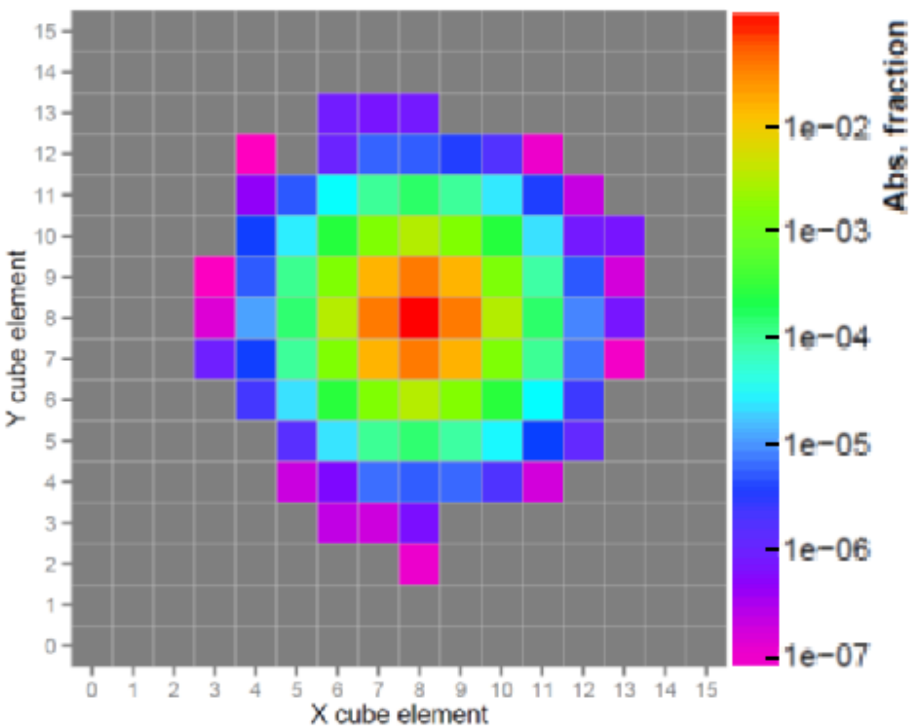
	^{6}Li Capture	Time to 90% Capture	Volume for 90% Capture
Full Cube, 350 μm Sheet	51%	229 μs	37 cubes
Full Cube, 500 μm Sheet	55%	209 μs	35 cubes
Half Cube, 350 μm Sheet	69%	120 μs	24.5 cubes
Half Cube, 500 μm Sheet	73%	103 μs	23 cubes

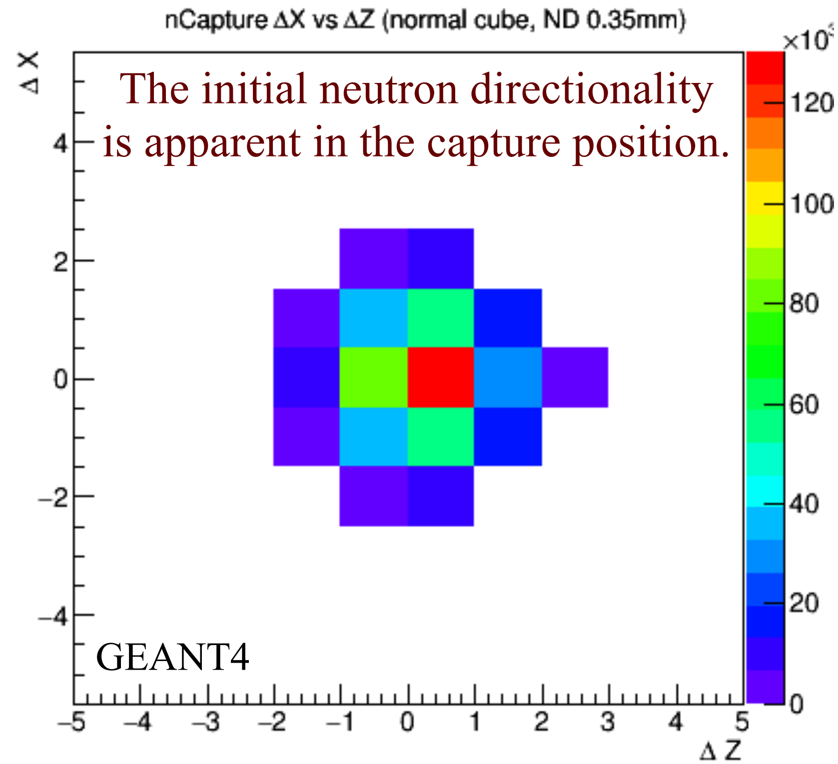


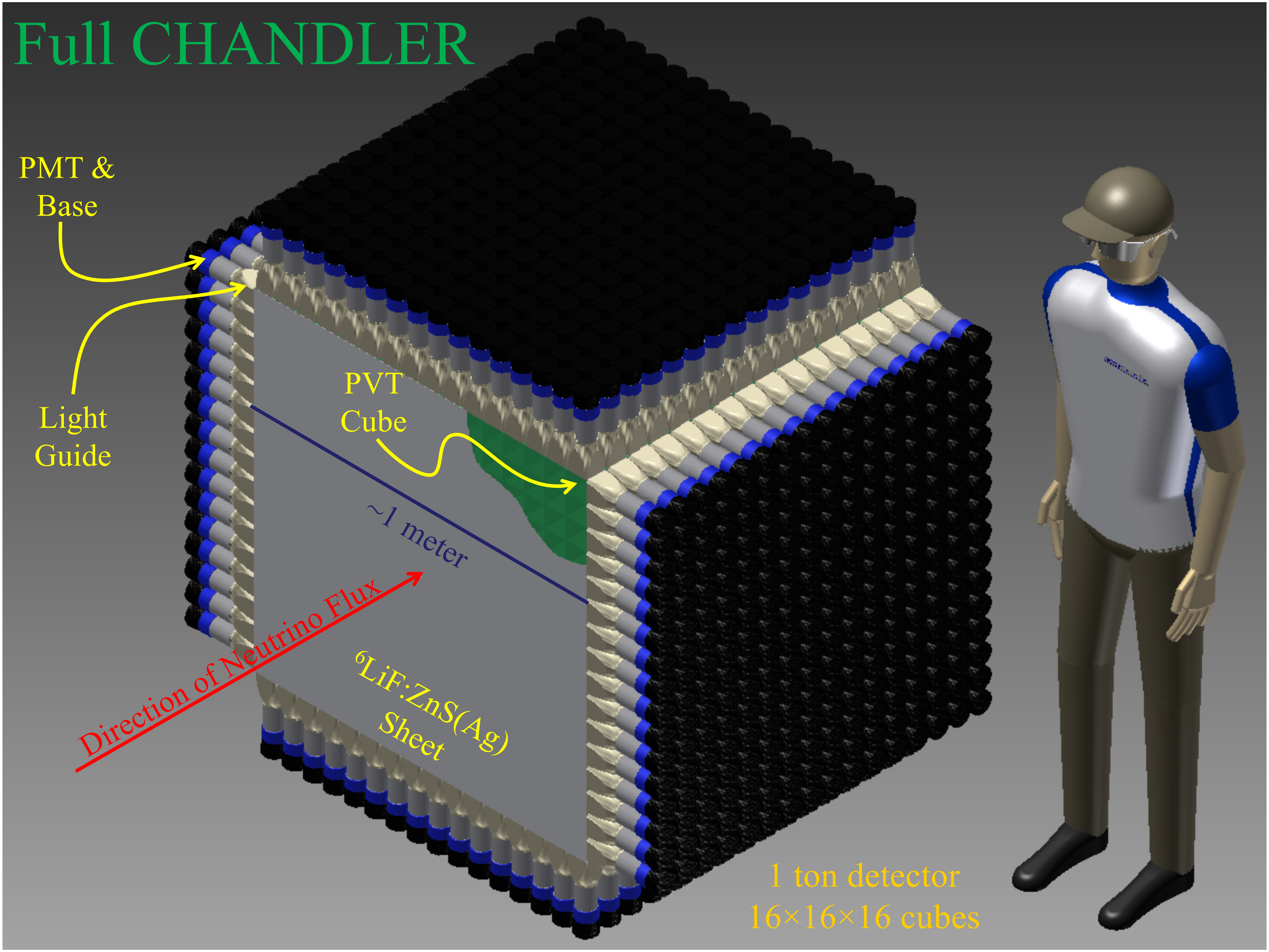


MCNP6: Neutron Transport and Capture

	^{6}Li Capture	Time to 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

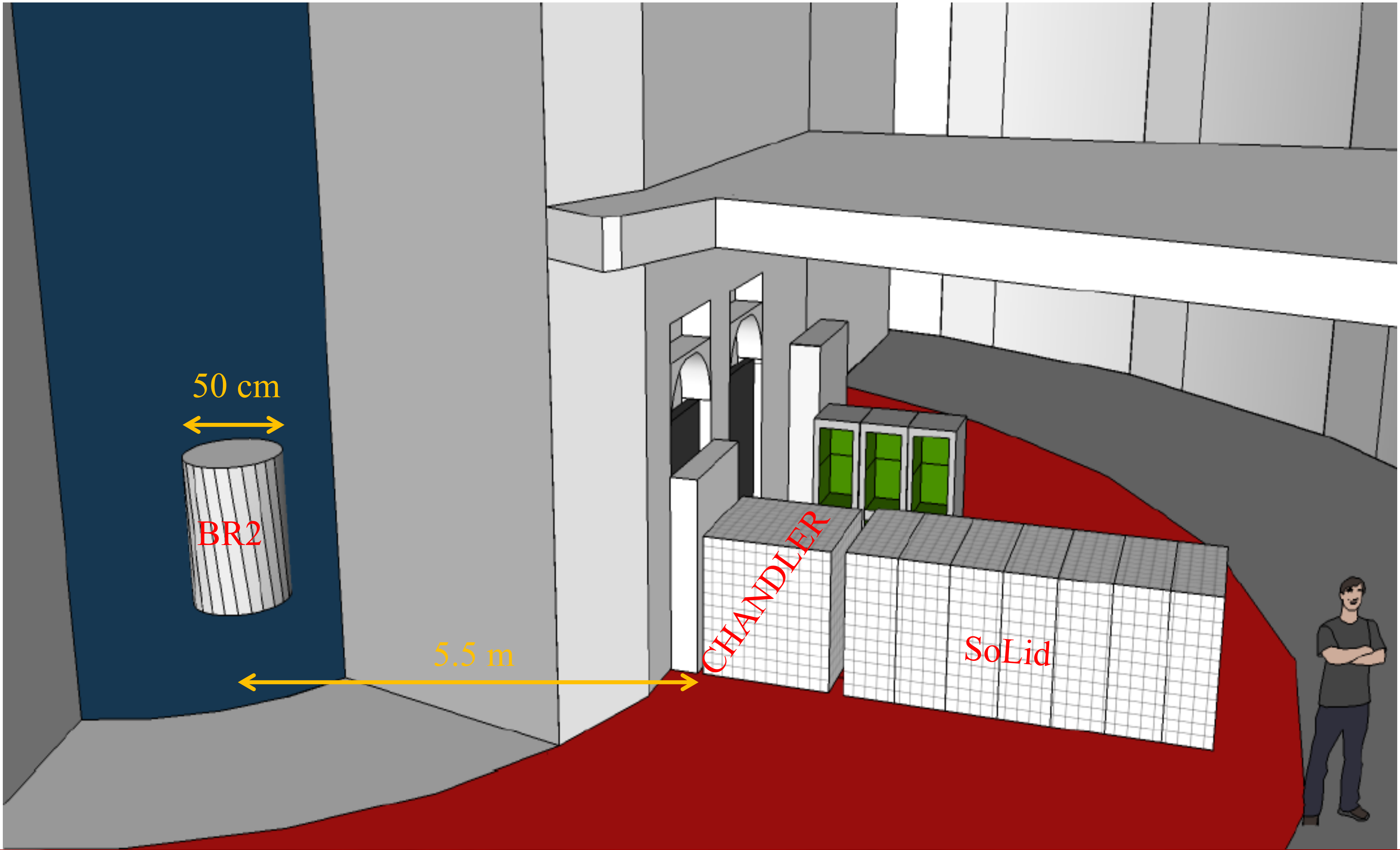





Full CHANDLER
PMT &
Base
Light
Guide
PVT
Cube
~1 meter
Direction of Neutrino Flux
^{6}LiF:ZnS(Ag)
Sheet
1 ton detector
16×16×16 cubes

CHANDLER and SoLid

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

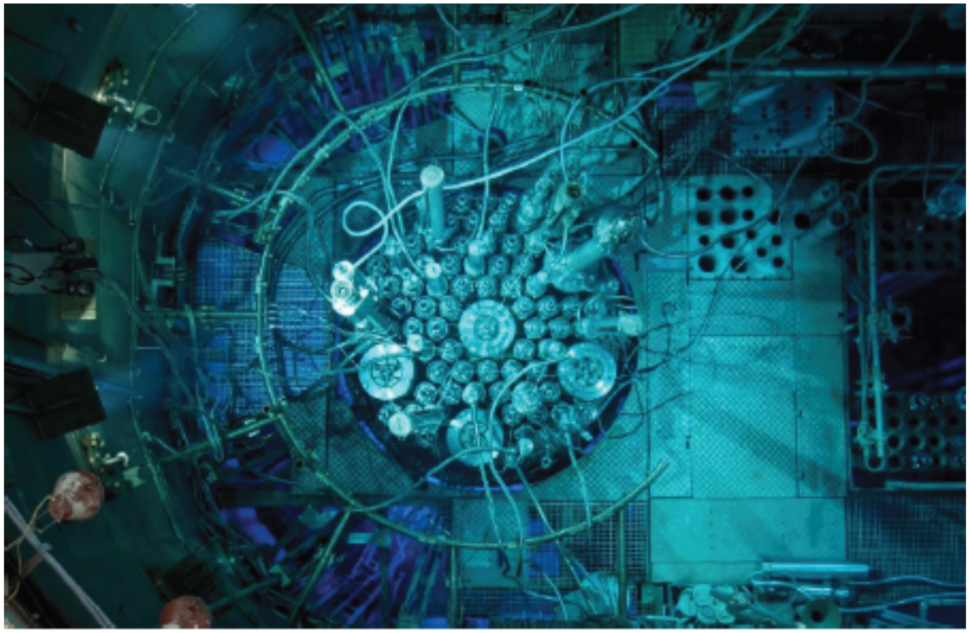


The BR2 Reactor

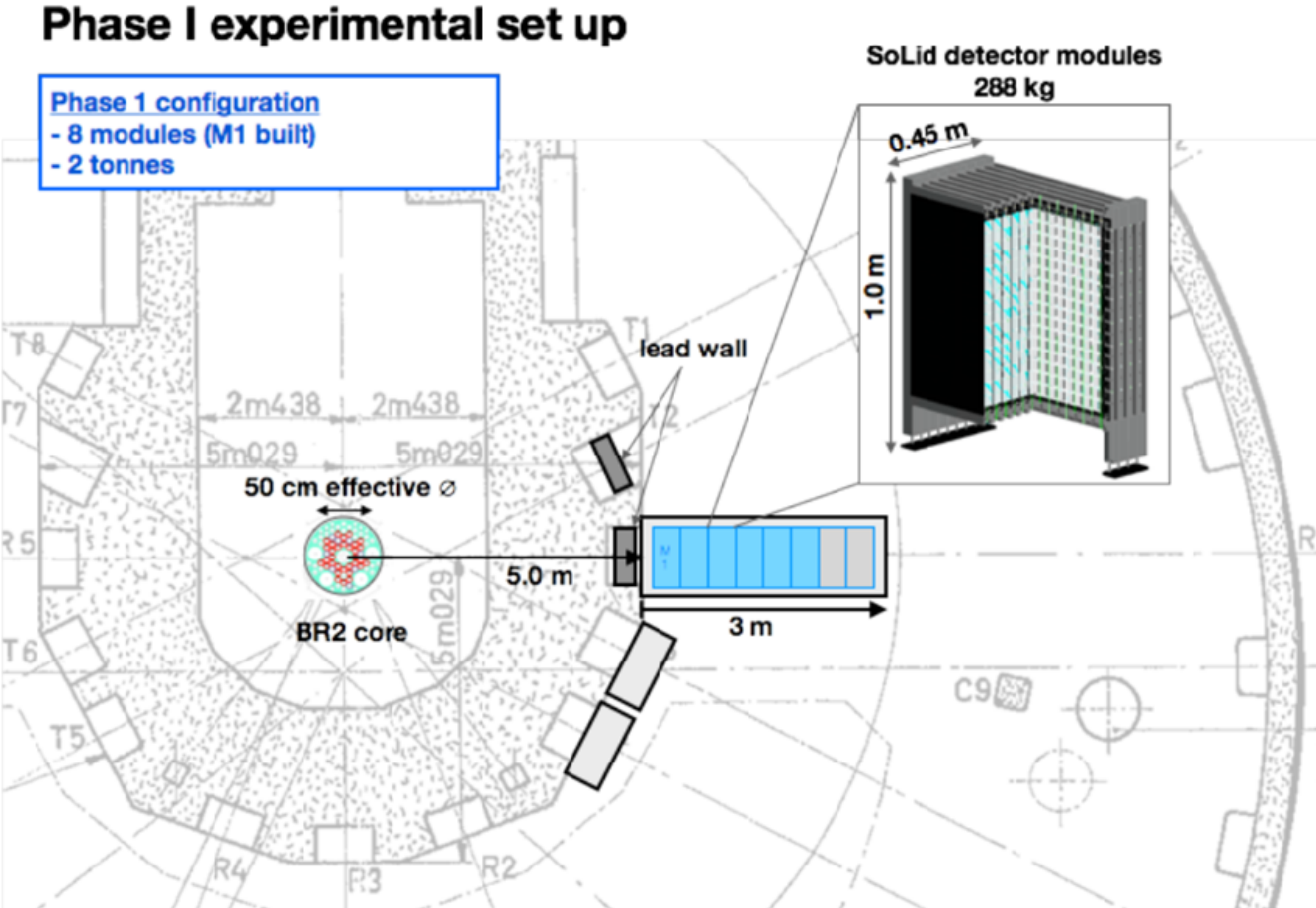
The 60 MW BR2 reactor is a facility at the Belgian National Nuclear Lab, SCK•CEN.

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.



SoLid at the BR2 Reactor in Belgium



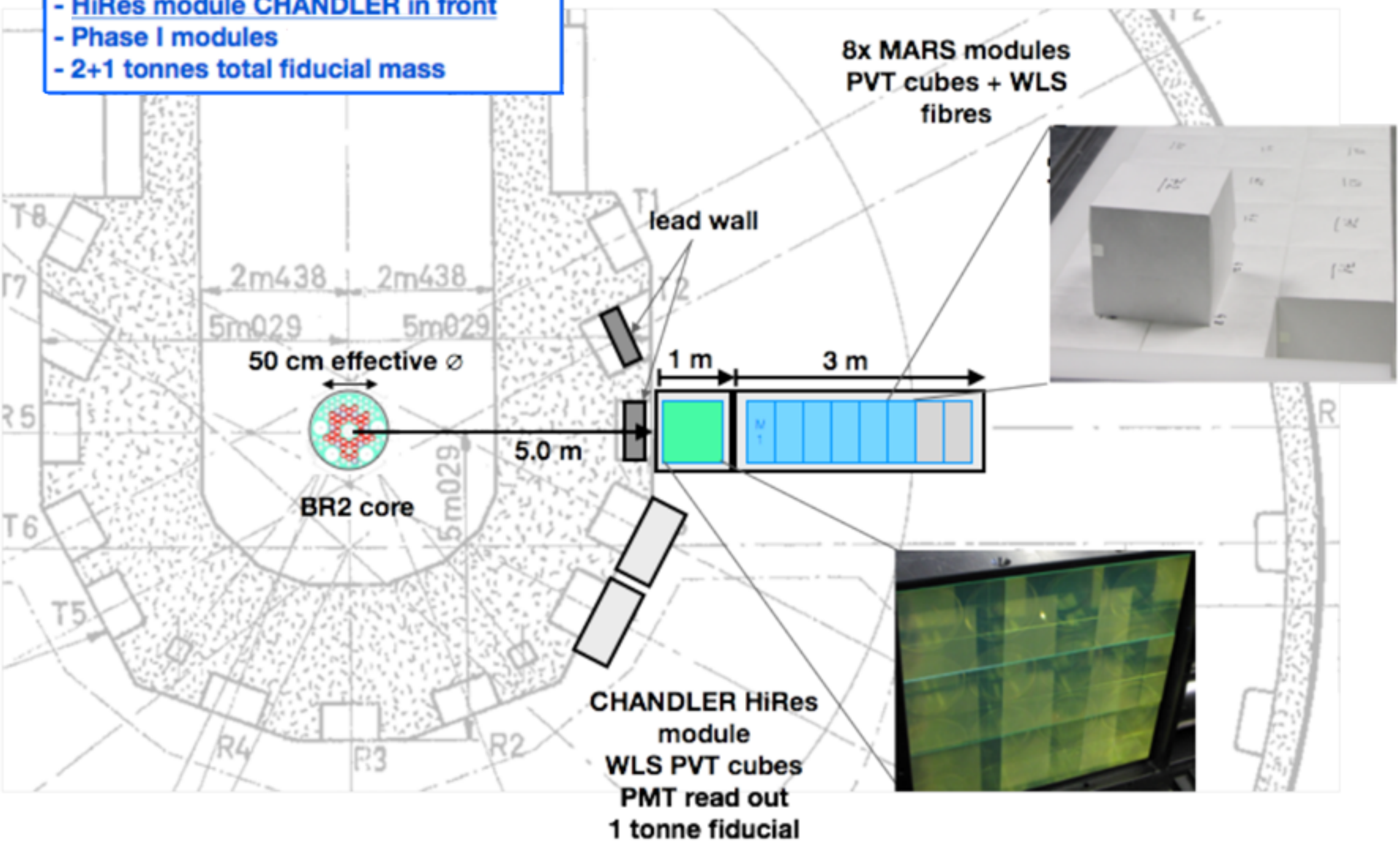
150 Days of Reactor on

SoLid at the BR2 Reactor in Belgium

Phase II experimental set up

450 Days of Reactor on

Configuration:
- HiRes module CHANDLER in front
- Phase I modules
- 2+1 tonnes total fiducial mass



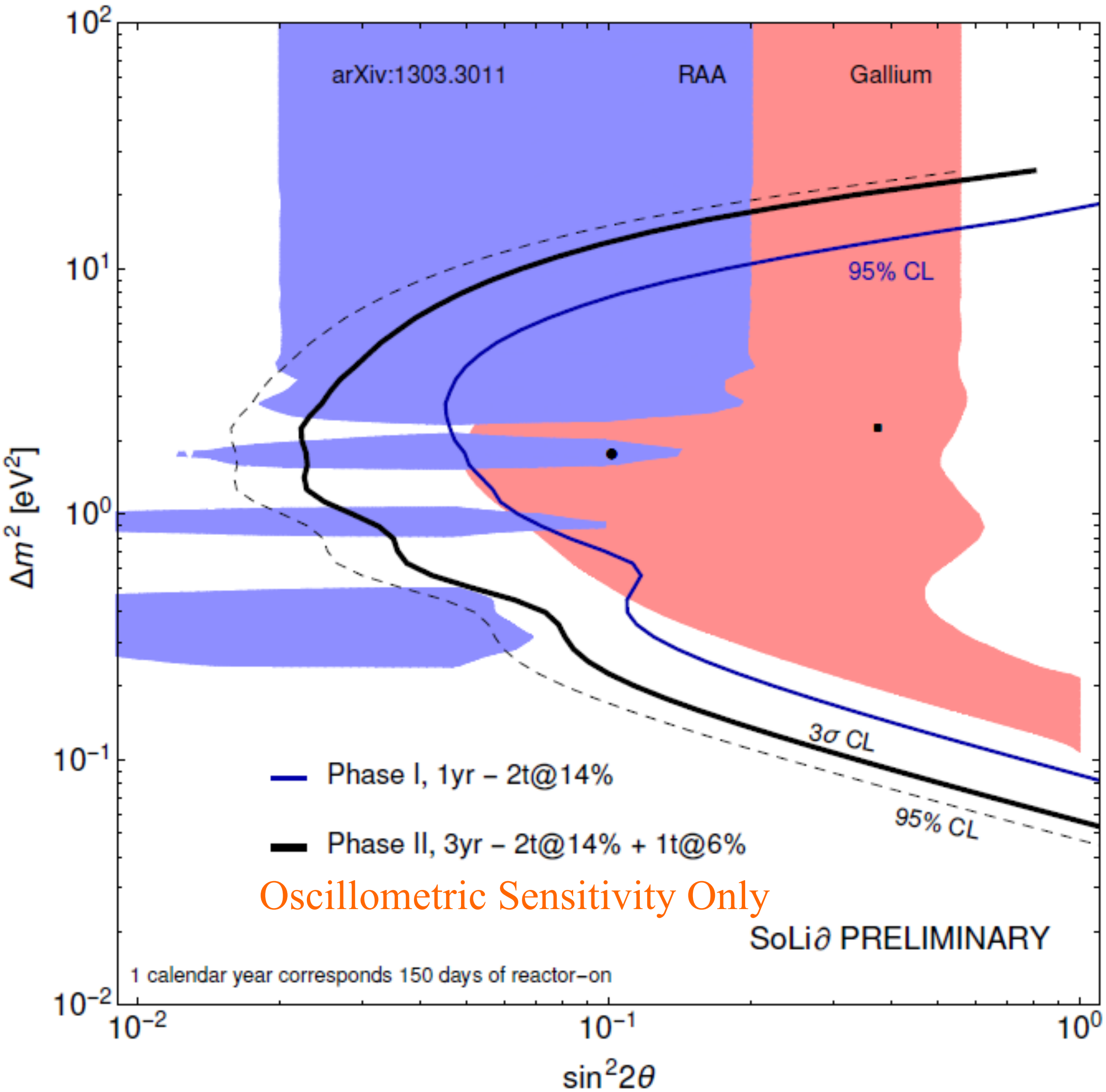
SoLid and CHANDLER Sensitivity

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.

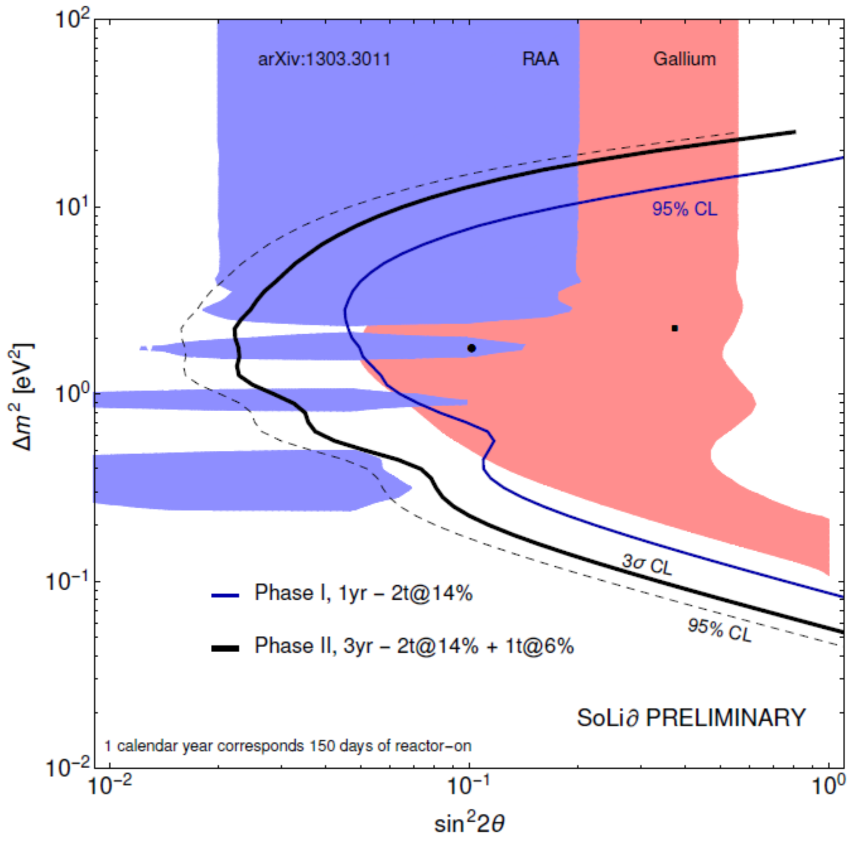
Adding CHANDLER to the three-year Phase II extends the coverage to higher Δm^2 and pushes the reach well into the Reactor Anomaly.

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



Conclusions

1. The CHANDLER Detector is a new technology for precision surface-level reactor neutrino detection.
2. CHANDLER uses wavelength shifting plastic scintillator cubes and ^{6}Li-loaded ZnS sheets to detect IBD events.
3. The detector is readout by a Raghavan optical lattice in which light is collected by total internal reflection.
4. The high light yield, high spatial resolution and pure neutron tag make this an ideal technology for the high background surface environment.
5. Together CHANDLER and SoLid cover most of the $\bar{\nu}_e$ disappearance allowed space.



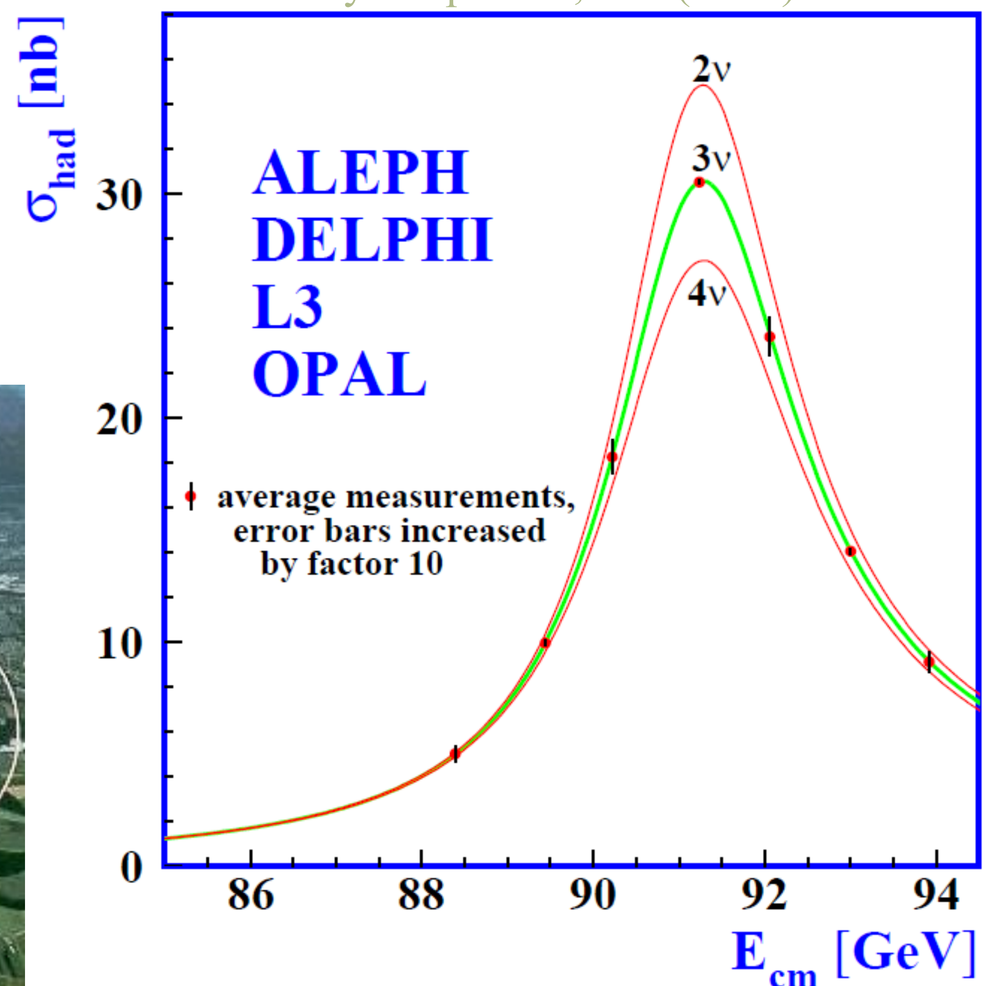
[redacted]

Sterile Neutrinos

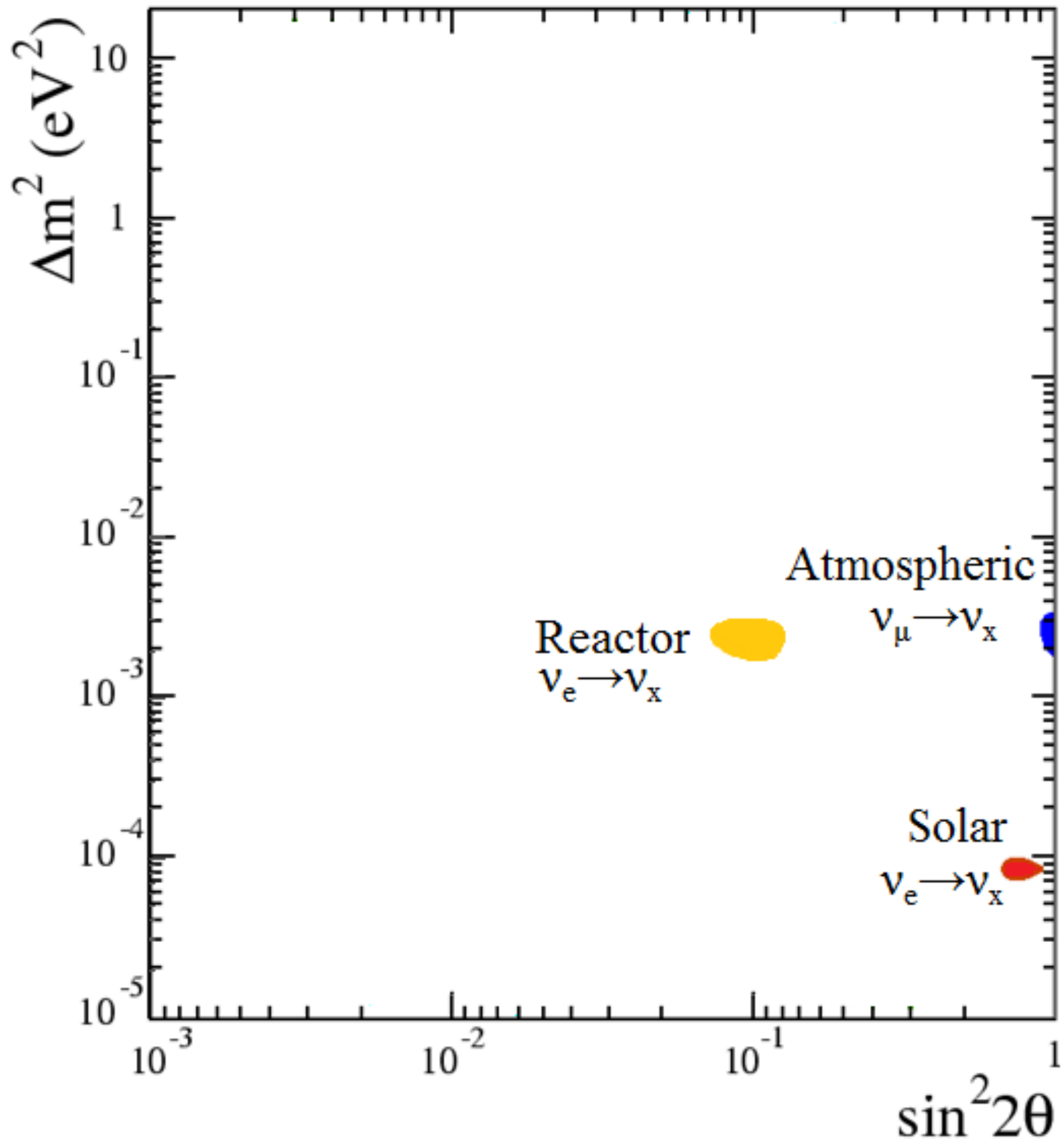
A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing.

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

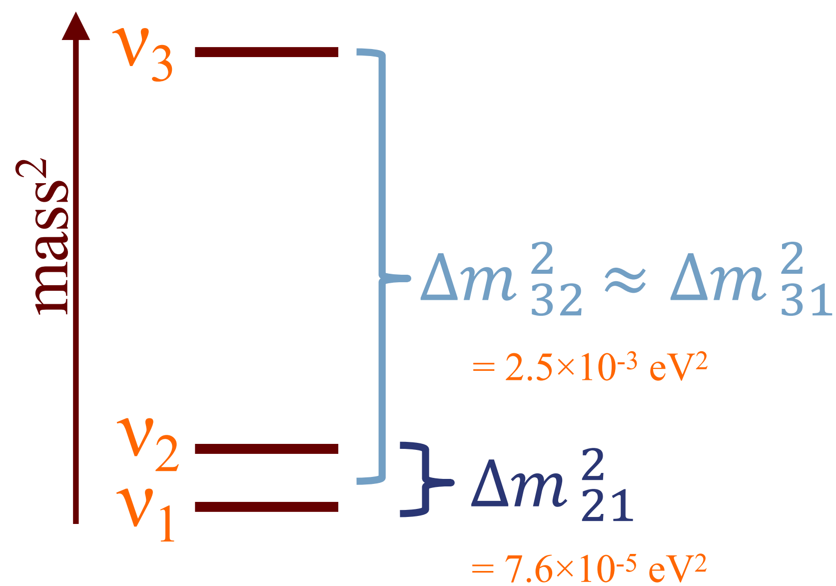
Phys.Rept. 427, 257 (2006)



The Neutrino Oscillation Data



The data for the three neutrino mixing model is nearly complete and extraordinarily self-consistent: (θ_{12}, θ_{23}, θ_{13}, Δm^2_{21}, Δm^2_{31}, and Δm^2_{32} are measured, δ_{CP} unknown)

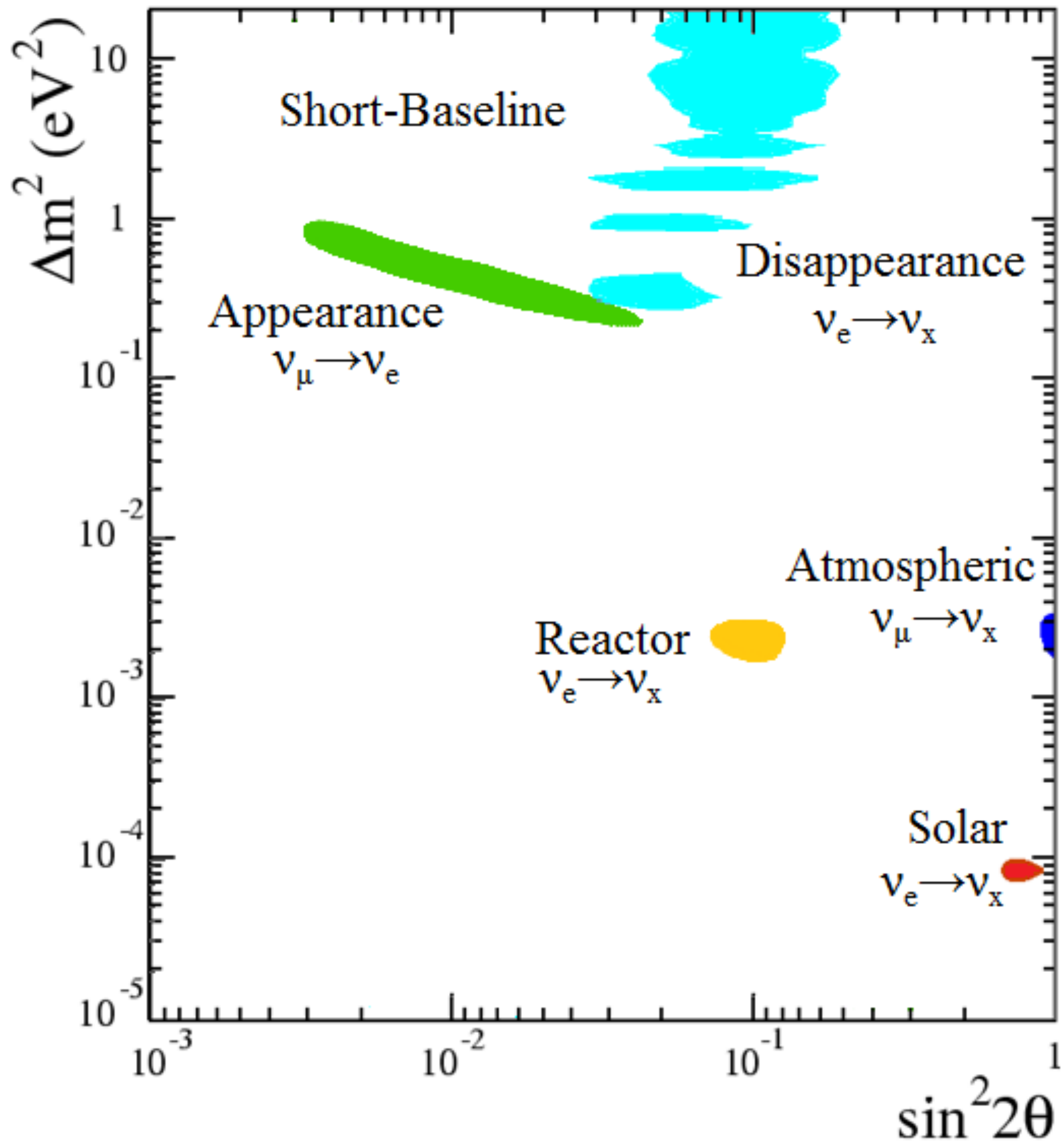


The Laurels Have Already Been Handed Out…

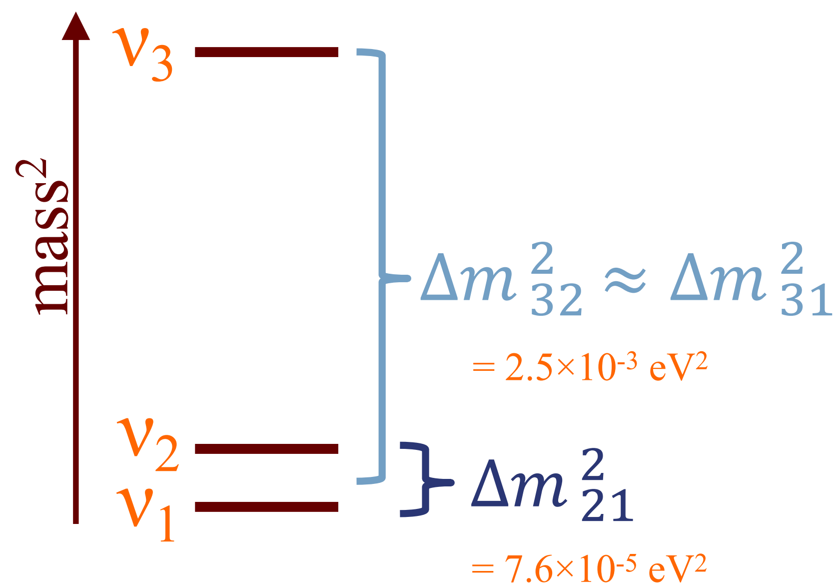
2015 Nobel Prize in Physics:
Takaaki Kajita of Super-K and
Arthur B. McDonald of SNO

2016 Breakthrough Prize in Fundamental Physics:
To the members of the Super-K, SNO KamLAND, Daya Bay, K2K and T2K Collaborations.

The Neutrino Oscillation Data



The data for the three neutrino mixing model is nearly complete and extraordinarily self-consistent: (θ_{12}, θ_{23}, θ_{13}, Δm^2_{21}, Δm^2_{31}, and Δm^2_{32} are measured, δ_{CP} unknown)

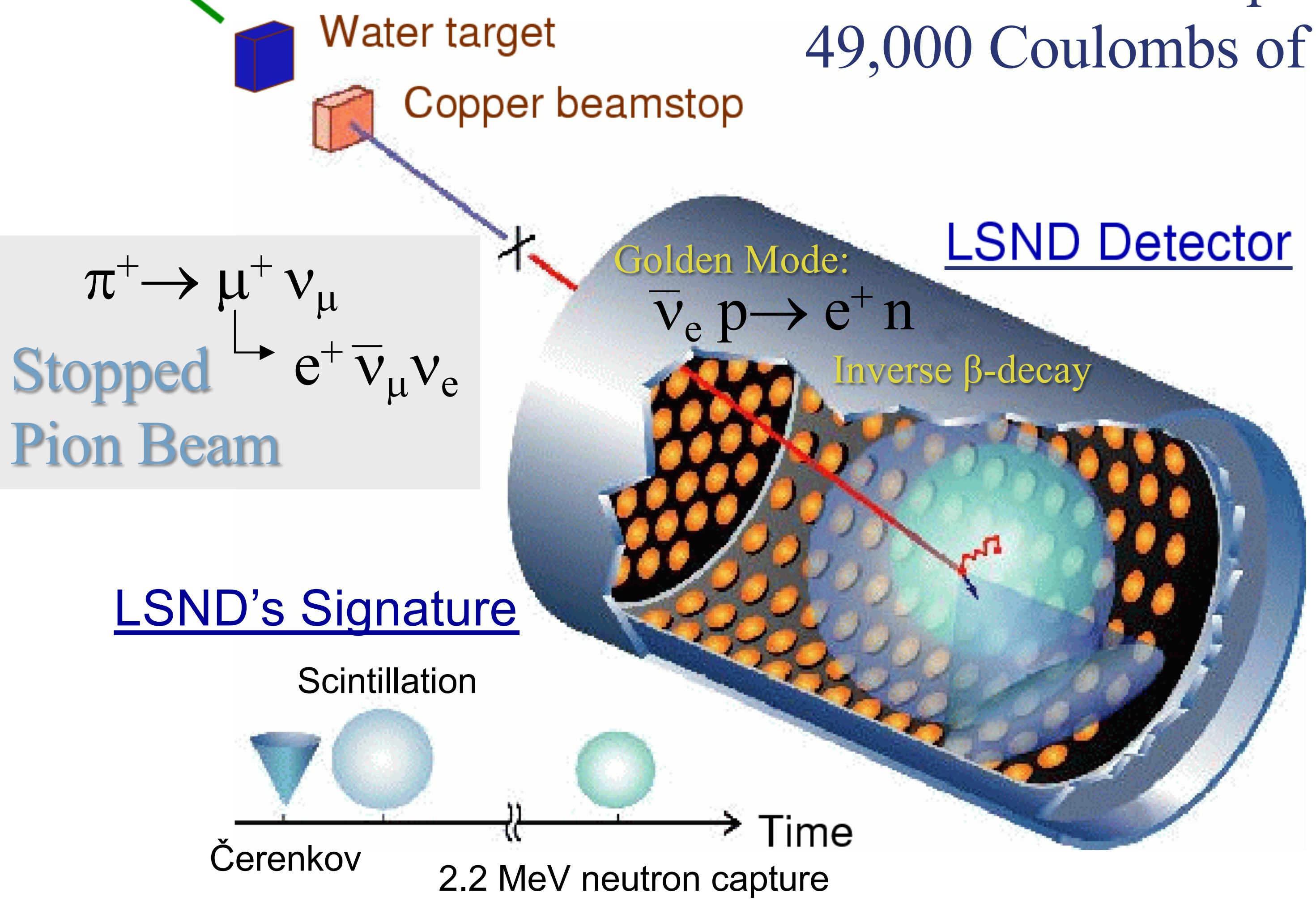


$\Delta m^2 \sim 1$eV^2 does not fit the three neutrino model

The LSND Experiment

LSND took data from 1993-98

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



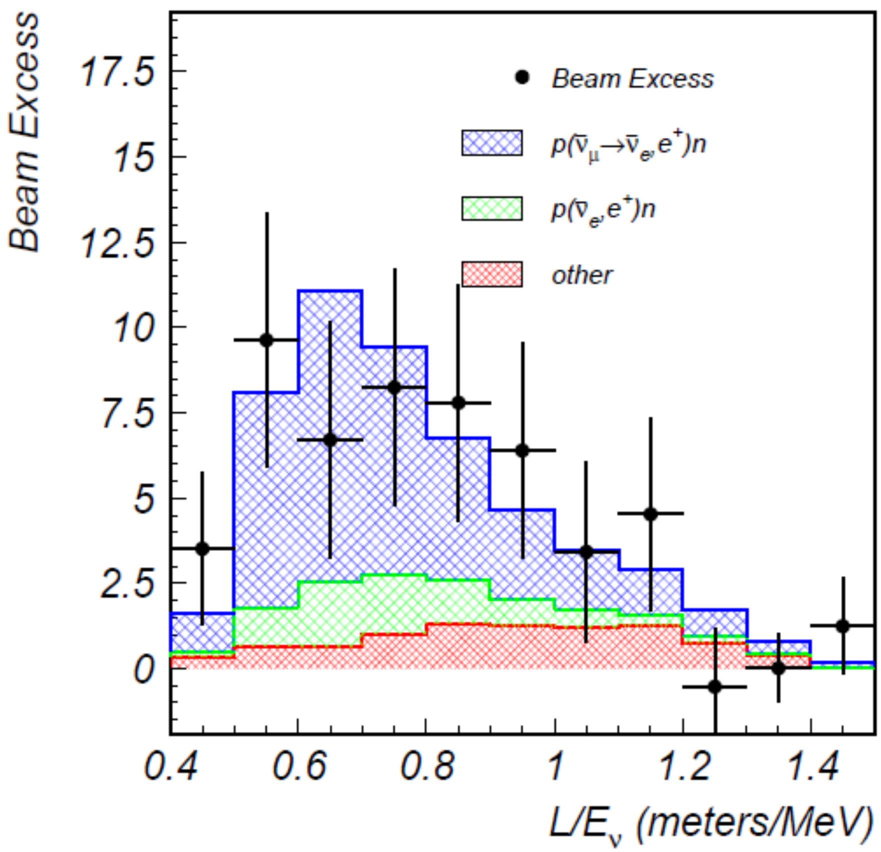
Baseline: 30 m

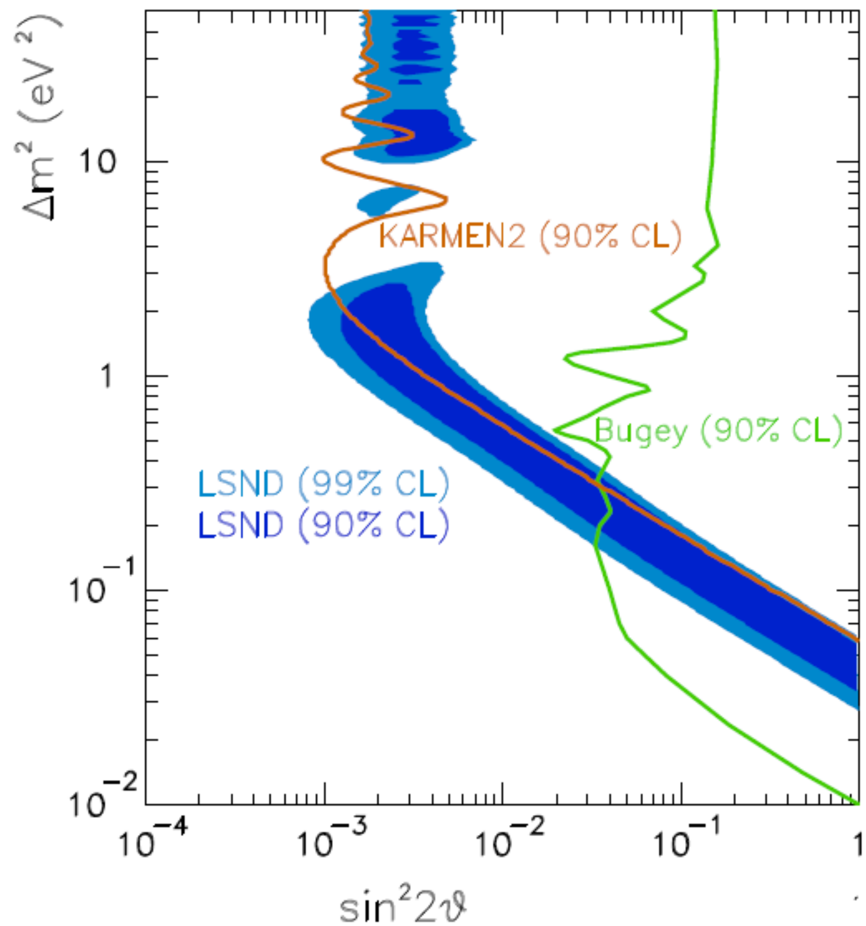
Energy range:
20 to 55 MeV

L/E ~ 1 m/MeV

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

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

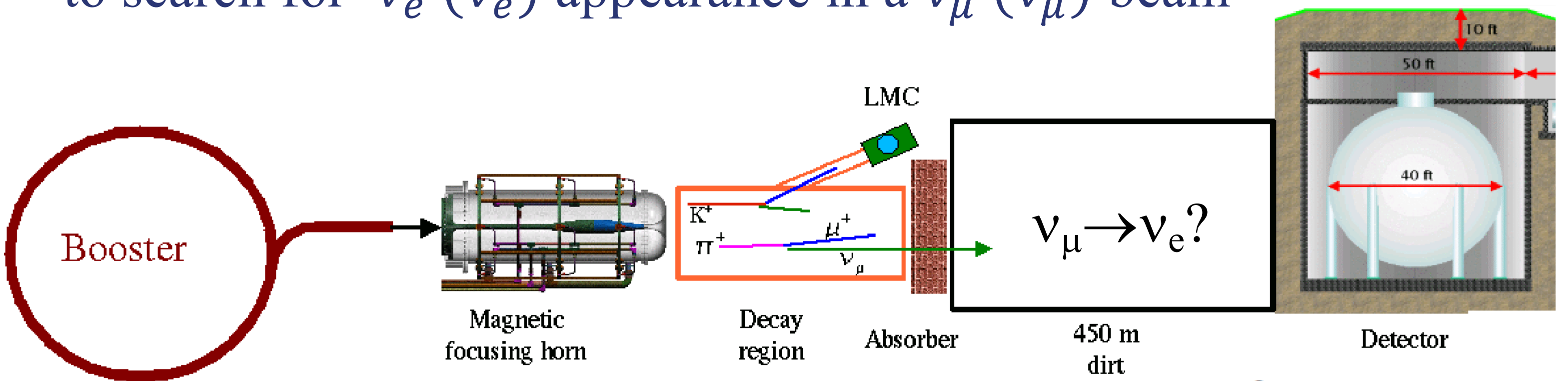




Event Excess: 32.2 ± 9.4 ± 2.3

MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Search

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

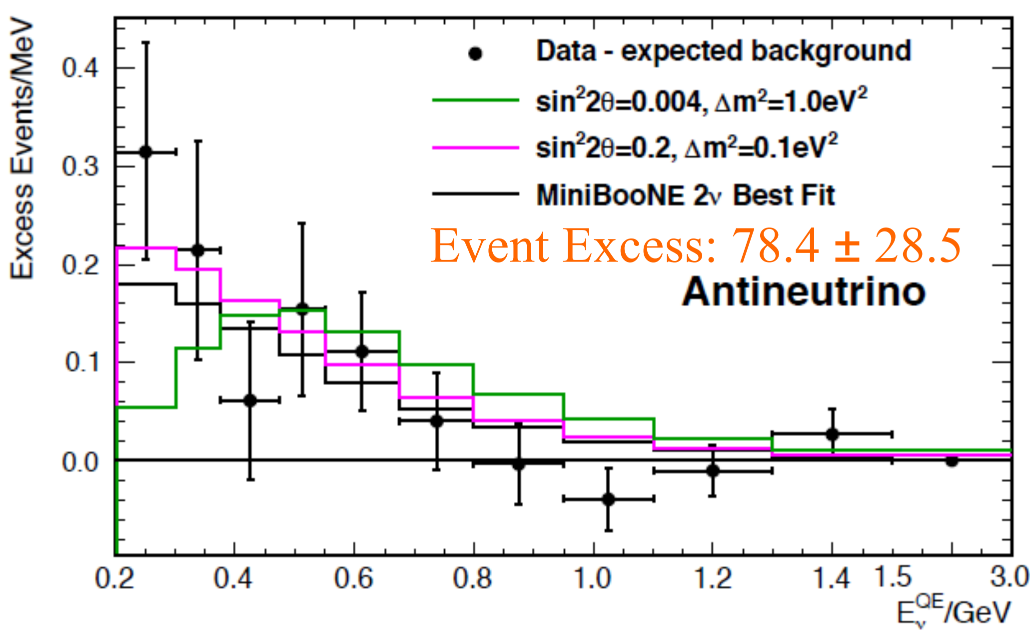


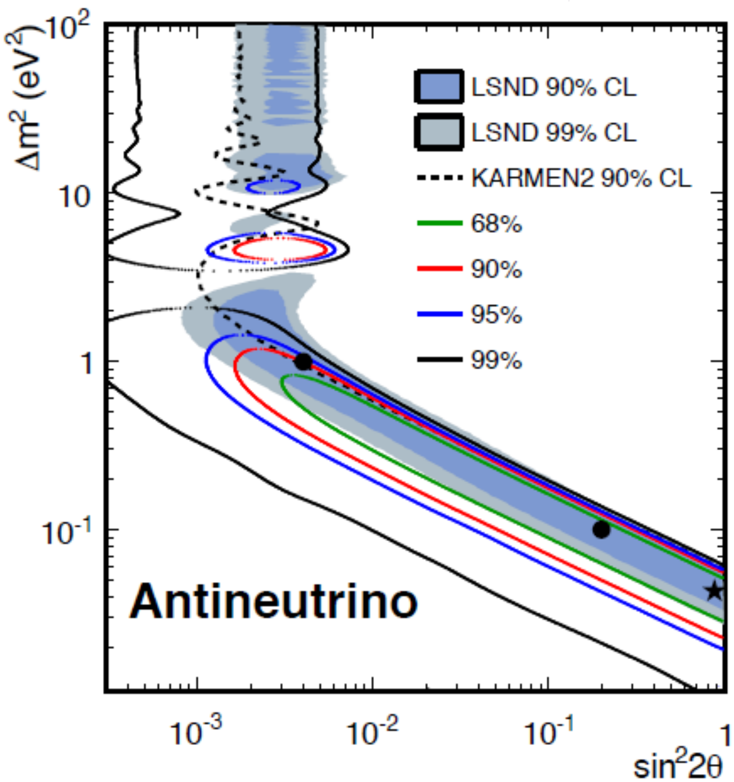
Baseline ~ 500 m

$\langle E_\nu \rangle$ ~ 500 MeV

L/E ~ 1 m/MeV

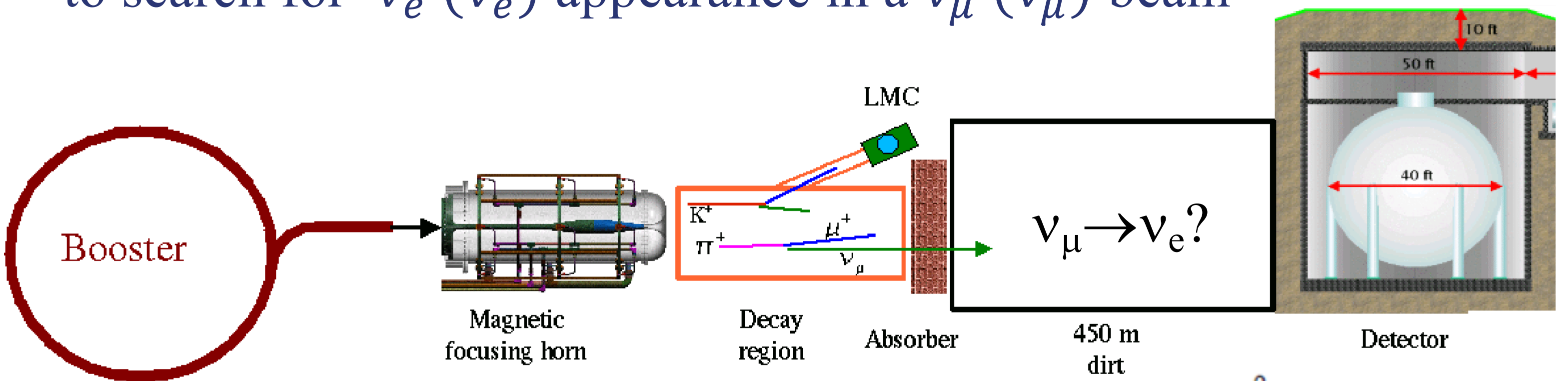
Phys.Rev.Lett. 110, 161801 (2013)





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

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

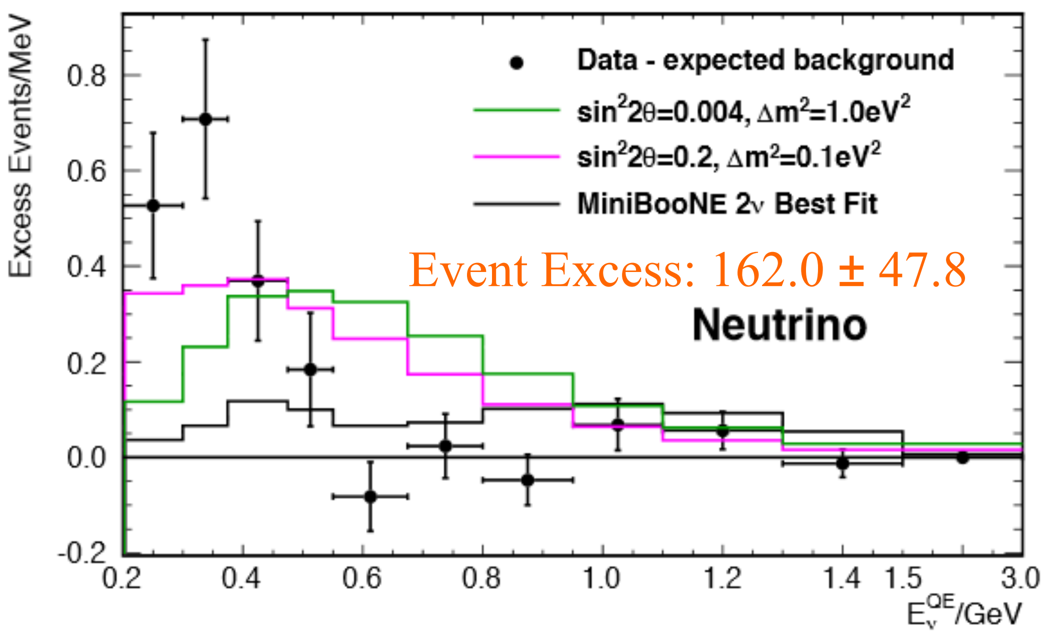


Baseline ~ 500 m

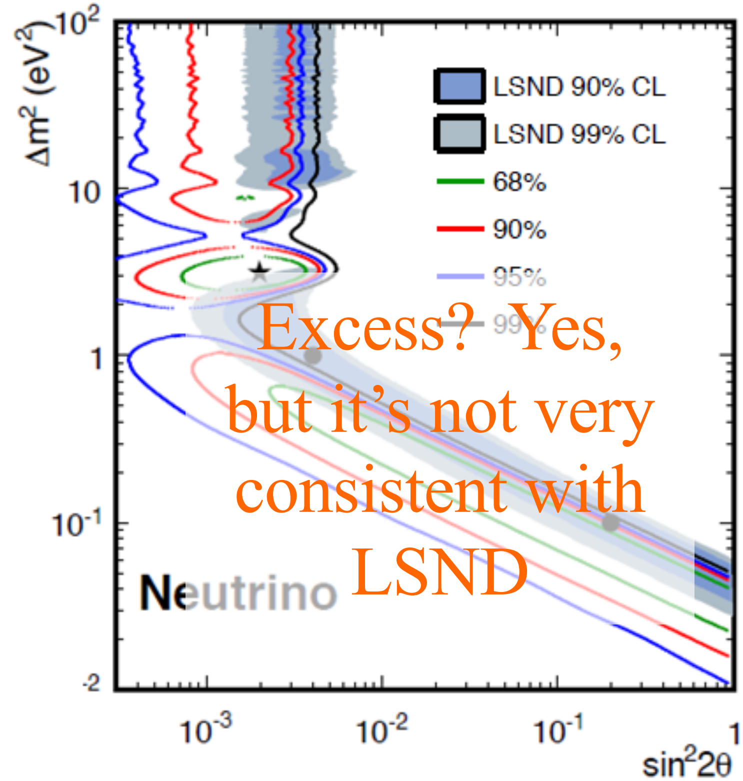
$\langle E_\nu \rangle$ ~ 500 MeV

L/E ~ 1 m/MeV

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



Event Excess: 162.0 ± 47.8

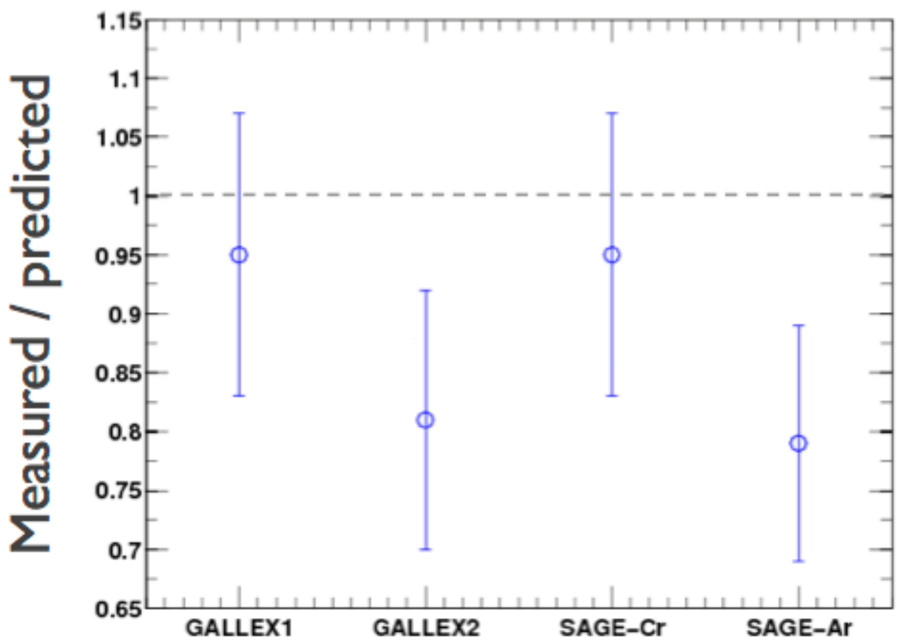


Excess? Yes, but it's not very consistent with LSND

Gallium Anomaly (ν_e Disappearance)

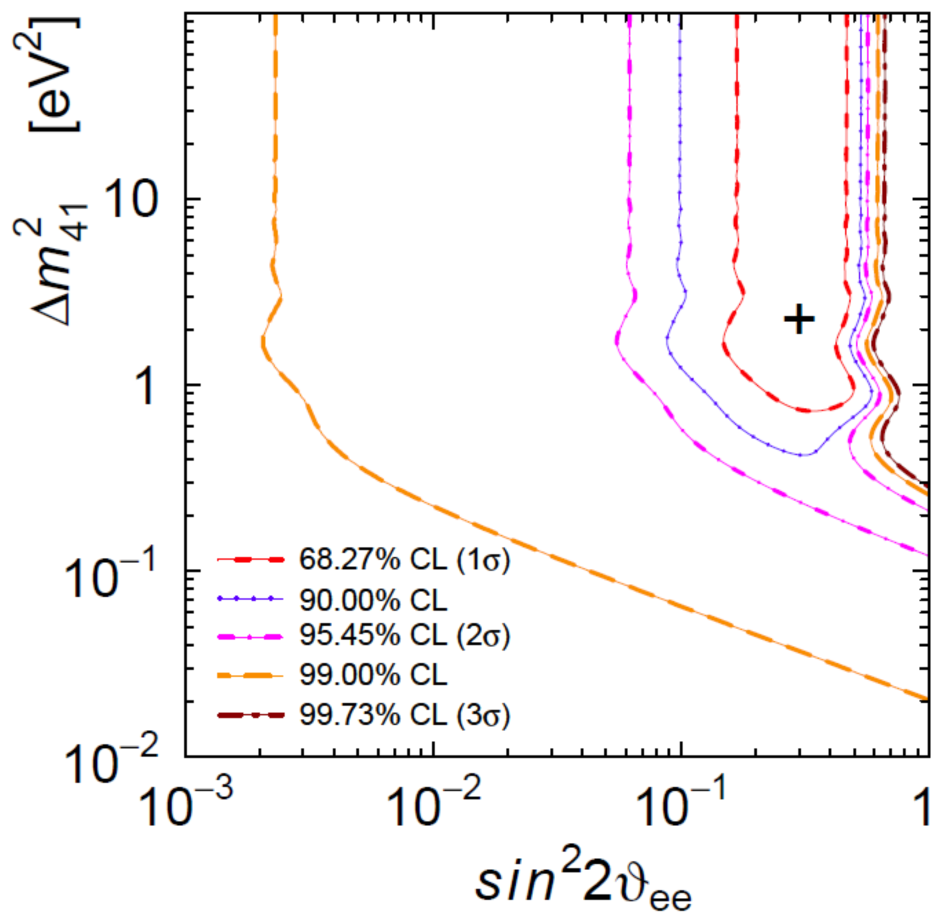
The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources (^{51}Cr and ^{37}Ar) to "calibrate" the $\nu_e{}^{71}Ga$ interaction/detection rate.

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

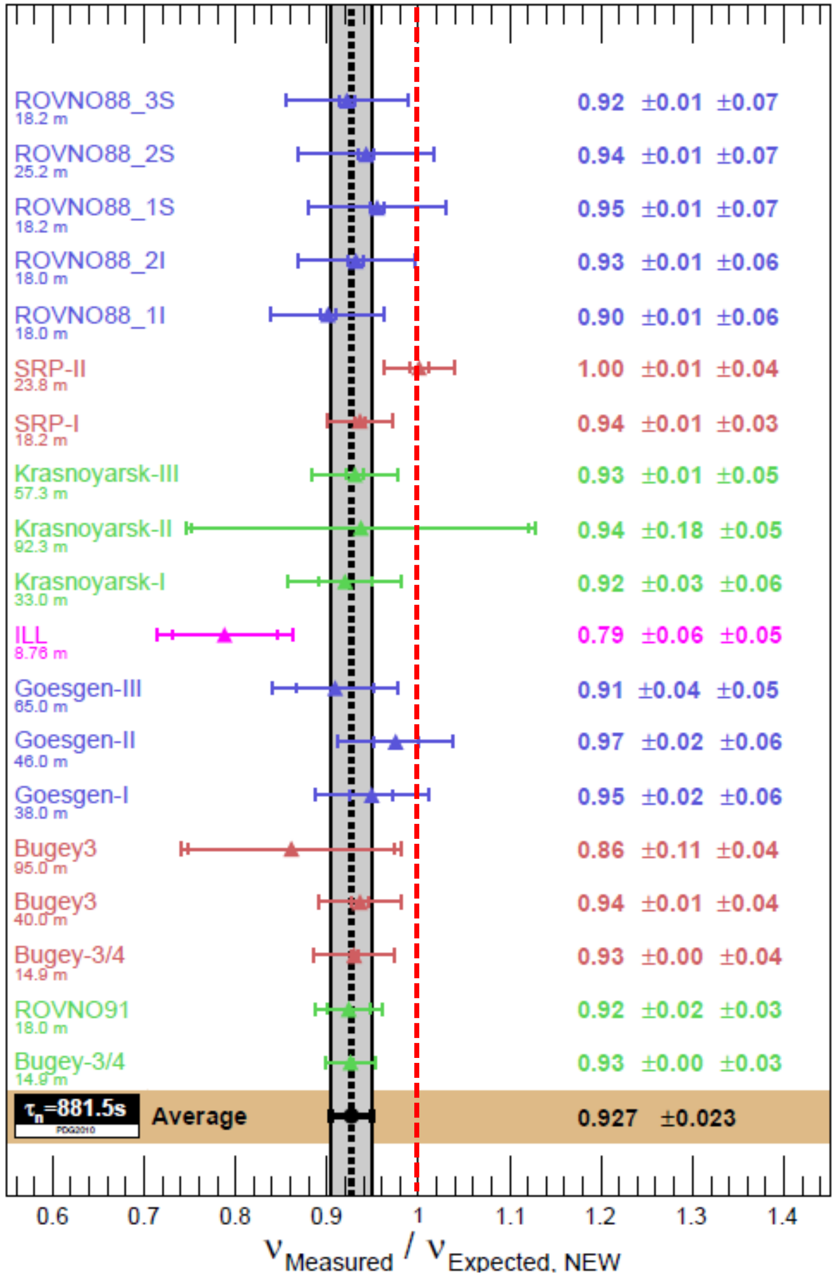


Giunti & Laveder, Phys.Rev.C83, 065504 (2011)

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

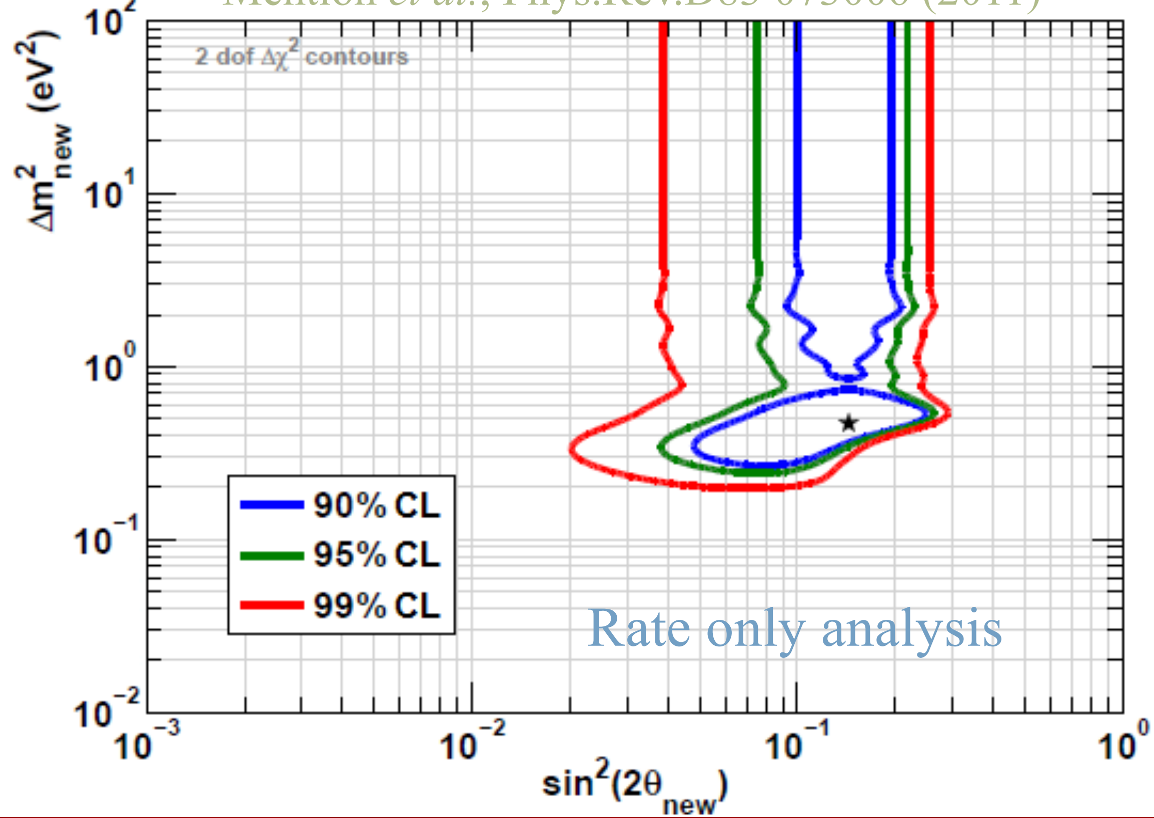


Reactor Anomaly ($\bar{\nu}_e$ Disappearance)



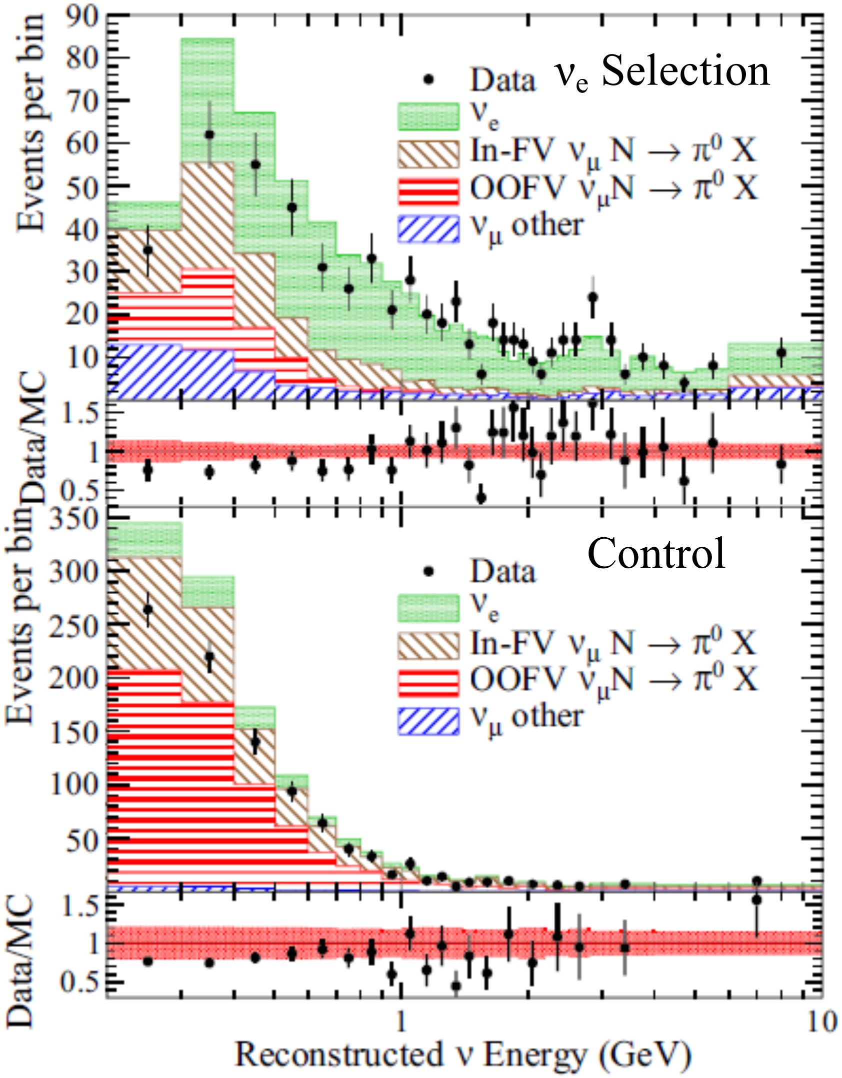
Recent calculations of the reactor $\bar{\nu}_e$ flux and spectrum predict a higher rate than the earlier calculation. This resulted is an apparent deficit of reactor neutrinos across all experiments.

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

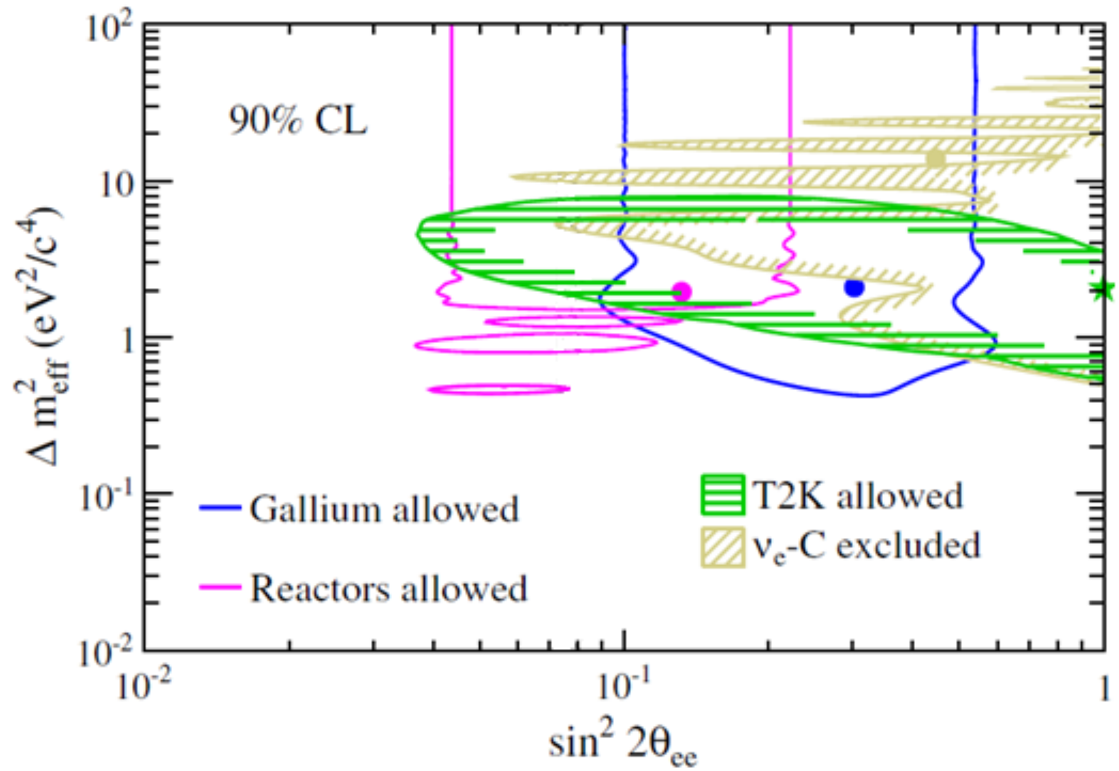


T2K Near Detector (ν_e Disappearance)

Although the T2K beam is predominantly a ν_μ beam, the small ν_e component can be used in the near detector for a ν_e disappearance search.



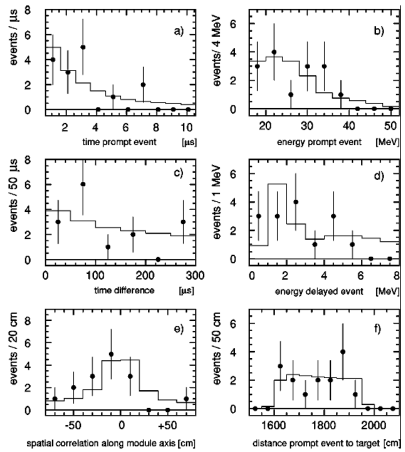
Phys.Rev. D91, 051102(R) (2015)



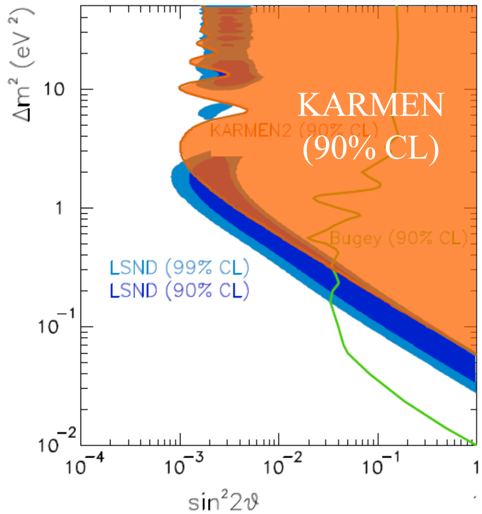
Short-baseline ν_e appearance from the much larger ν_μ component of the beam could fill in the exact region depleted by ν_e disappearance, so $\nu_\mu \rightarrow \nu_e$ is assumed to be zero in this analysis.

Evidence Against the ~1 eV^2 Sterile Neutrino

KARMEN ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

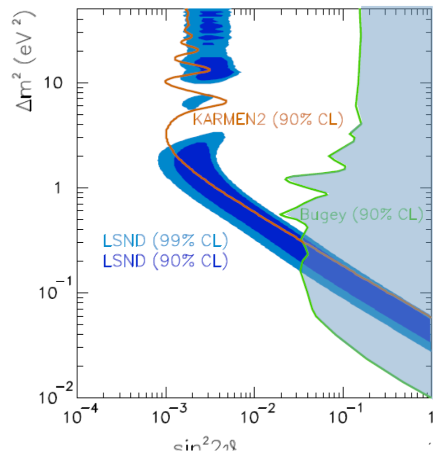


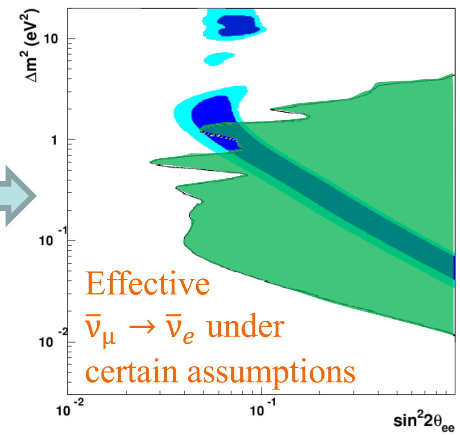
No $\bar{\nu}_e$ Excess



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

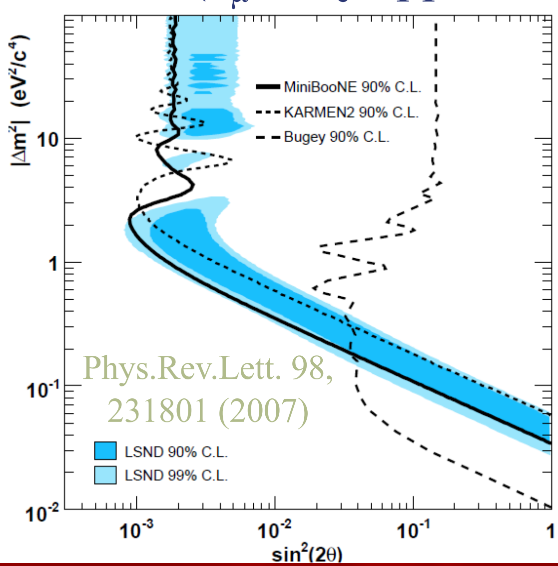
Bugey Reactor ($\bar{\nu}_e$ Disappearance)





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

MiniBooNE ($\nu_\mu \rightarrow \nu_e$ Appearance)



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

ν_μ Disappearance

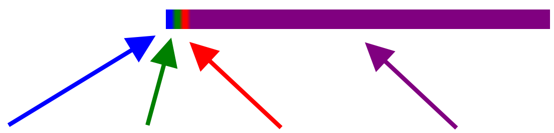
(where is it?)

For $\nu_\mu \rightarrow \nu_e$ to happen there must be both ν_e and ν_μ disappearance

Relating Appearance and Disappearance Probabilities

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



$$U_{e4}^2 + U_{\mu 4}^2 + U_{\tau 4}^2 + U_{s4}^2 = 1 \quad \text{(PMNS Unitarty)}$$

The appearance probability:

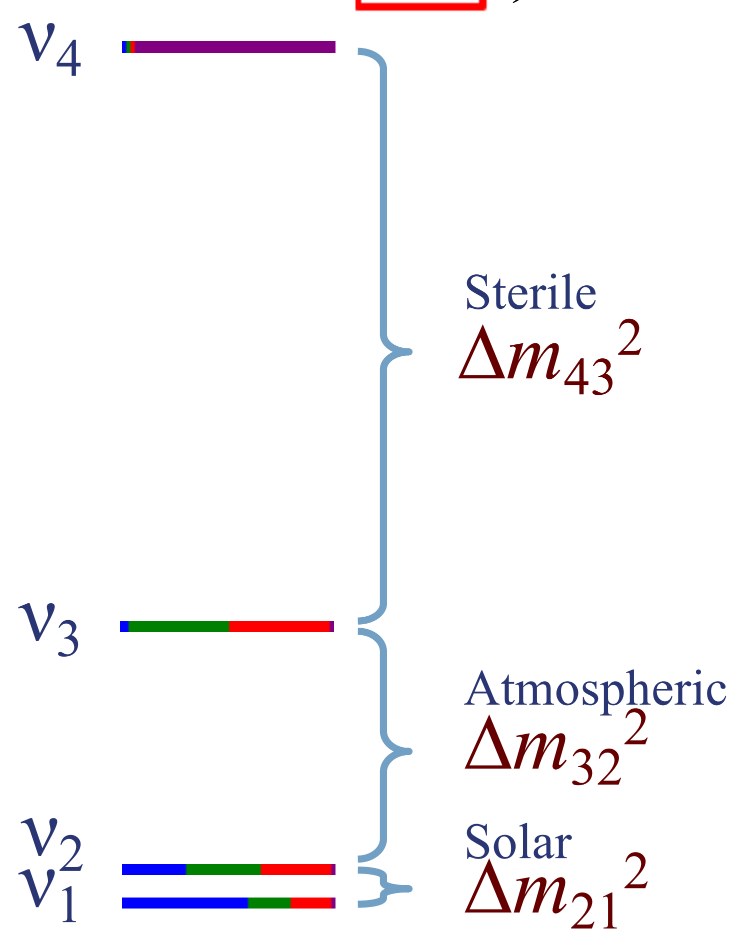
$$P_{\mu e} \approx 4U_{e4}^2 U_{\mu 4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

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:

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



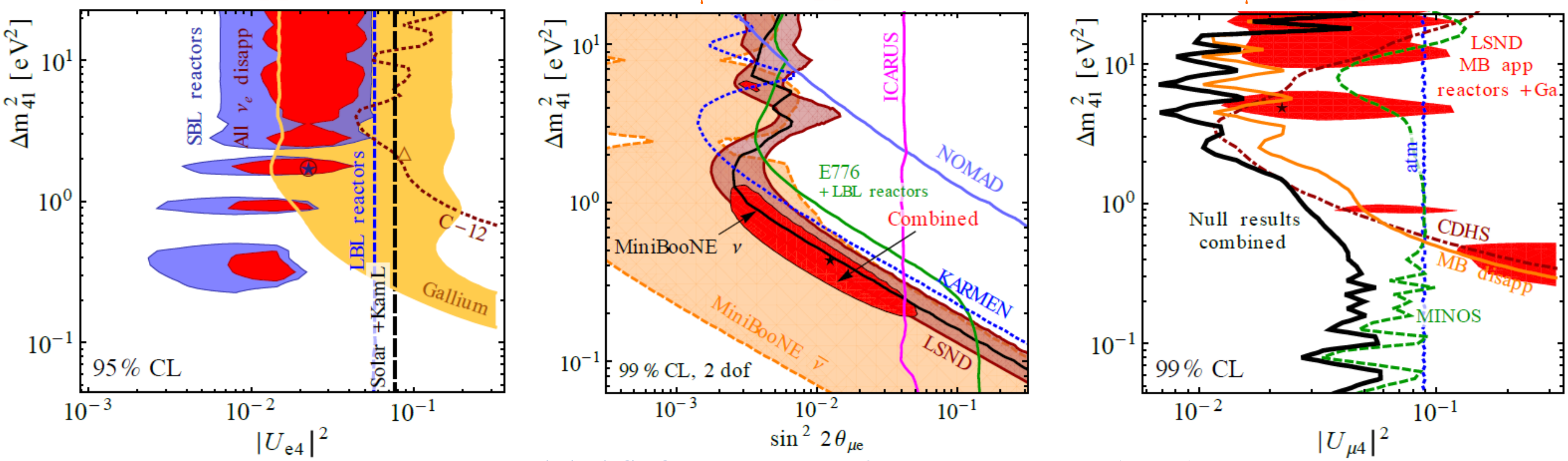
Appearance vs. Disappearance

1. Since any 4th mass state is predominantly sterile ($U_{s4} \approx 1$),

$$P_{\mu e} \approx \tfrac{1}{4} P_{ee} \times P_{\mu\mu}$$

2. $P_{\mu e}$ depends on both U_{e4} and $U_{\mu4}$, so you can have ν_e disappearance without ν_e appearance, but you can't have ν_e appearance without ν_μ disappearance.

ν_e Disappearance | $\nu_\mu \to \nu_e$ Appearance | ν_μ Disappearance



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

The absence of ν_μ disappearance is a huge problem for the LSND and MiniBooNE signals, while the ν_e disappearance anomalies are consistent with all existing data.

Requirement for Disappearance Experiments

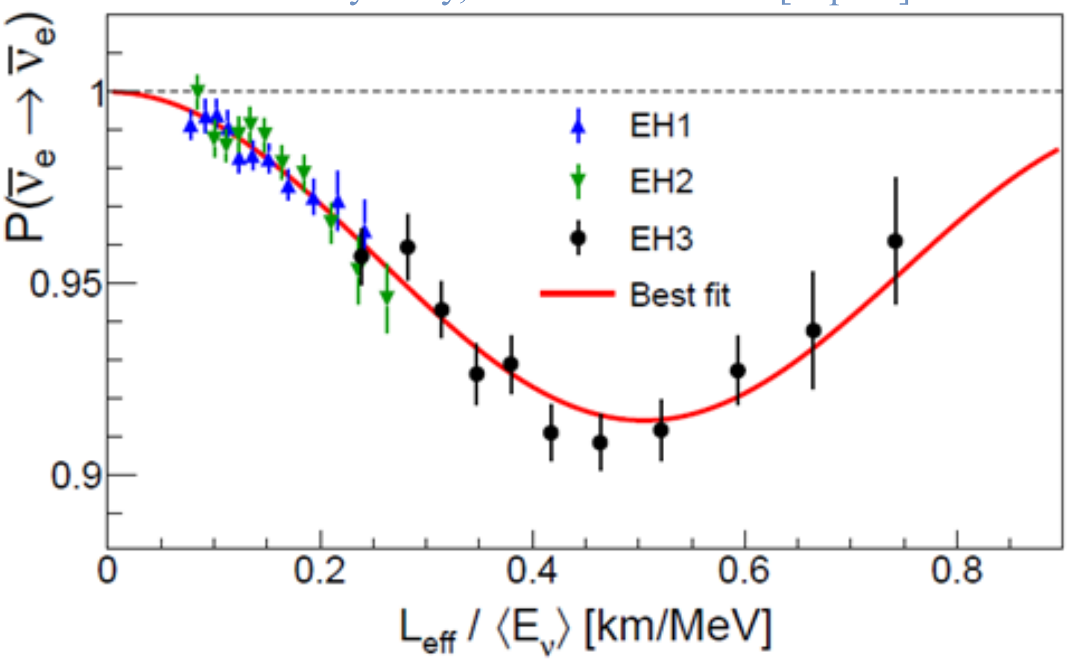
"It don't mean a thing if it ain't got that swing"

–American jazz great Duke Ellington

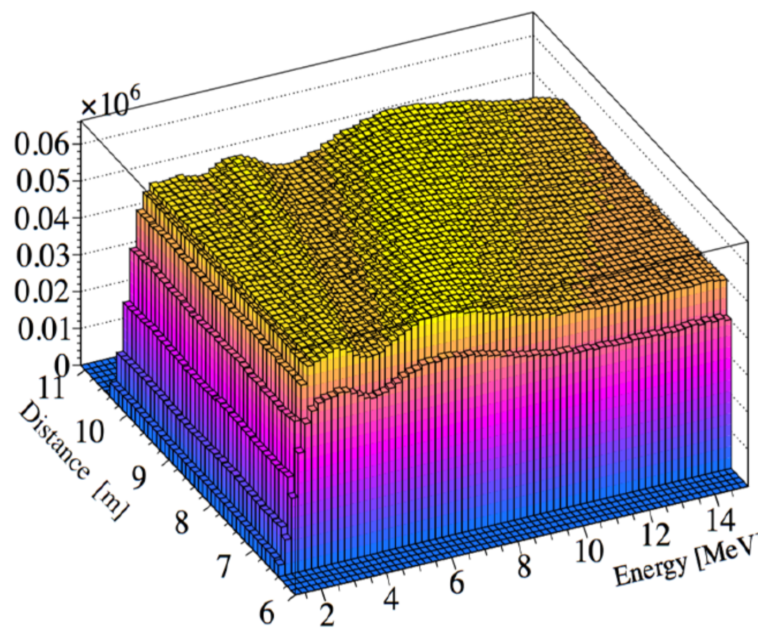
Definition:

oscillometry, *n.*, The observation and measurement of oscillations.

Daya Bay, arXiv:1505.03456 [hep/ex]



Possible oscillations in a short-baseline reactor experiment



In disappearance experiments the existence of sterile neutrinos can ***only*** be convincingly established through oscillometry.

Application to Nuclear Non-Proliferation

Neutrino monitoring has been proposed as a **non-invasive** verification scheme to be used in nuclear treaties with nations such as Iran and North Korea. This possibility is currently under study by the IAEA and the US Departments of State and Energy.

The basic idea is to look for changes in the neutrino energy spectrum indicative of diversions of weapons grade plutonium.

The main stumbling block to the full embrace of neutrino safeguards has been the inability to demonstrate a viable detector technology.

Safeguards detectors must:

- be portable, reliable and low-cost;
- have good energy resolution;
- and be free of potential hazards such as flammable liquids (this requirement comes from the IAEA).