Sterile Neutrinos II

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VIRGINIA TECH

May 24, 2017

Precision Sterile Neutrino Searches

The age of precision sterile neutrino tests started just started within the last few years, upcoming projects include:

- Many new reactor experiments and proposals
- Source experiments, proposals and concepts
- A three baseline liquid argon detector program in Fermilab's Booster Neutrinos Beam, and
- A few powerful new concepts that don't fit into these categories.

These will be the subjects of today's talk…

Reminder: For Disappearance Experiments

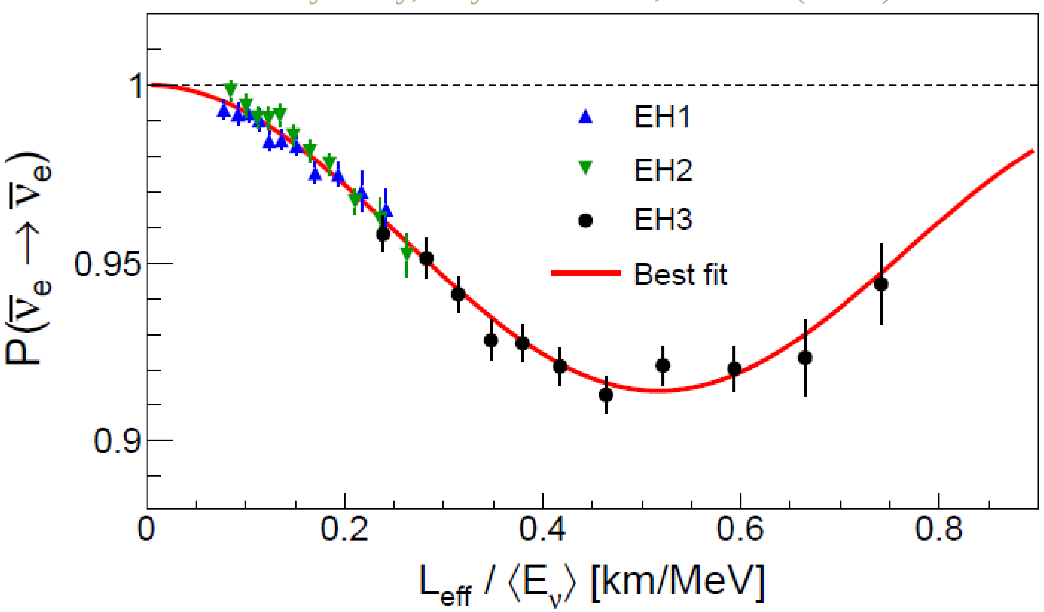
"It don't mean a thing if it ain't got that swing"

–American jazz great Duke Ellington

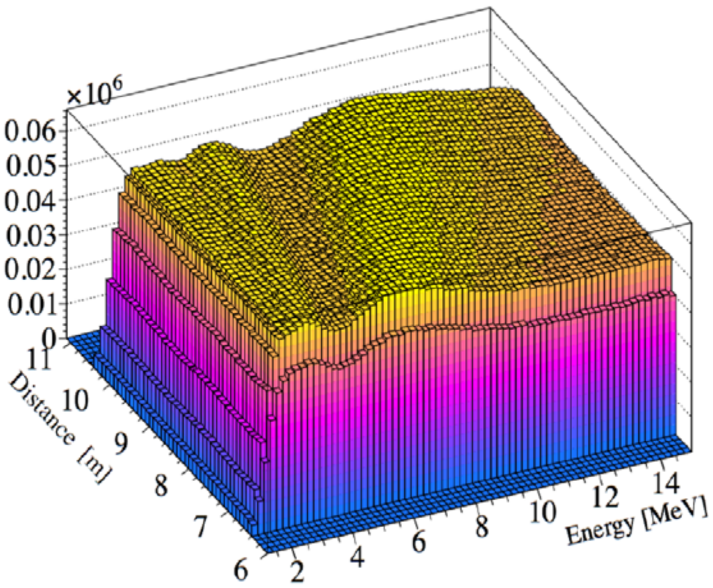
Definition:

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

Daya Bay, Phys.Rev. D95, 072006 (2017)



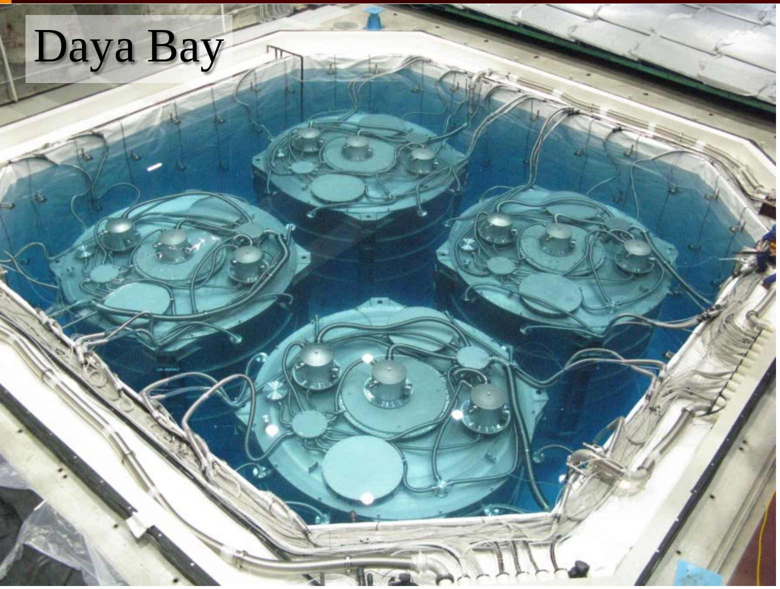
Possible oscillations in a short-baseline reactor experiment



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

Reactor Experiments

Reactor Experiments



Unlike the reactor θ_{13} experiments, short-baseline reactor experiments are

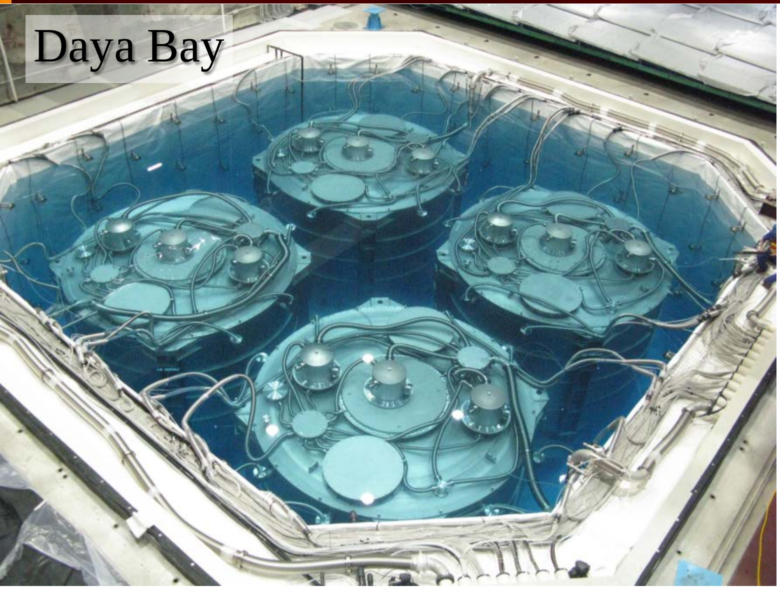
- on the surface
- with smaller detectors, and
- without space for massive clean shielding or gamma catcher

Also the detector is much closer to the reactor so you may have non-neutrino, reactor-correlated backgrounds.

In reactor experiments there are three main types of background:

1. Random coincidence ─ where two unrelated events happen close together is space and time.
2. Fast neutron ─ where a fast cosmic-ray neutron creates a prompt signal, thermalizes, and is captured.
3. β+n decays of spallation isotopes ─ such as ^{9}Li and ^{8}He with β+n decay modes, can be created in a μ spallation on ^{12}C.

Reactor Experiments



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If you ‘re worrying about this on the surface, good for you

Reactor Experiments

A surface-level short-baseline experiment is all about backgrounds:

Random Coincident

1. You can try to add passive shielding
   But it's expensive and you don't have much space
2. Find a way to get unbiased spatial resolution and use a tight spatial cut
   Could gain you a factor of 2000 over Daya Bay
3. Maximize neutron tagging efficiency and purity
   Use ^{6}Li (with pulse shape discrimination) or Gd (with containment)

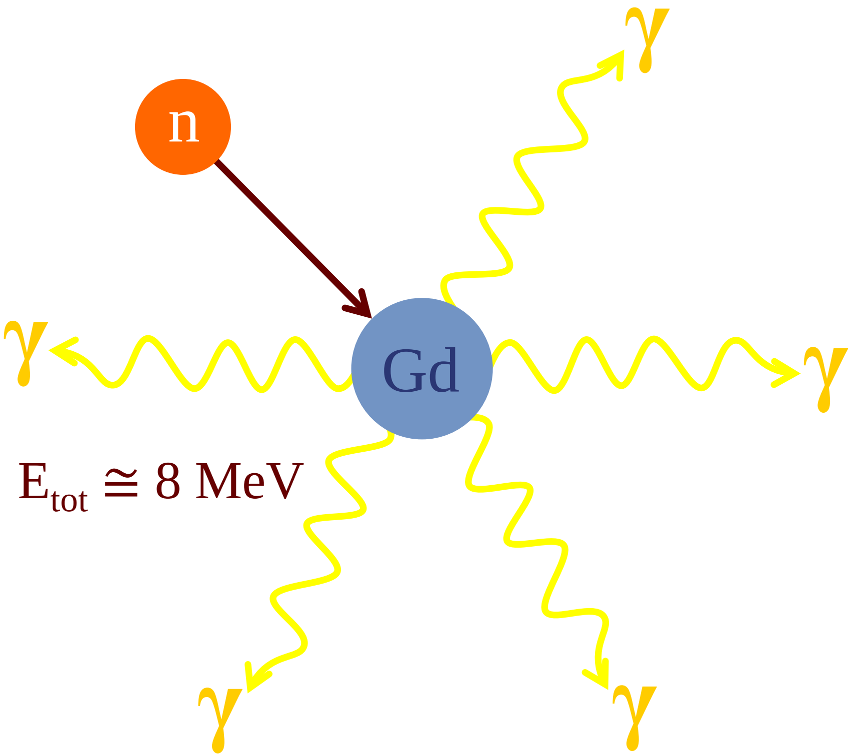
Fast Neutron

Neutron Capture Options

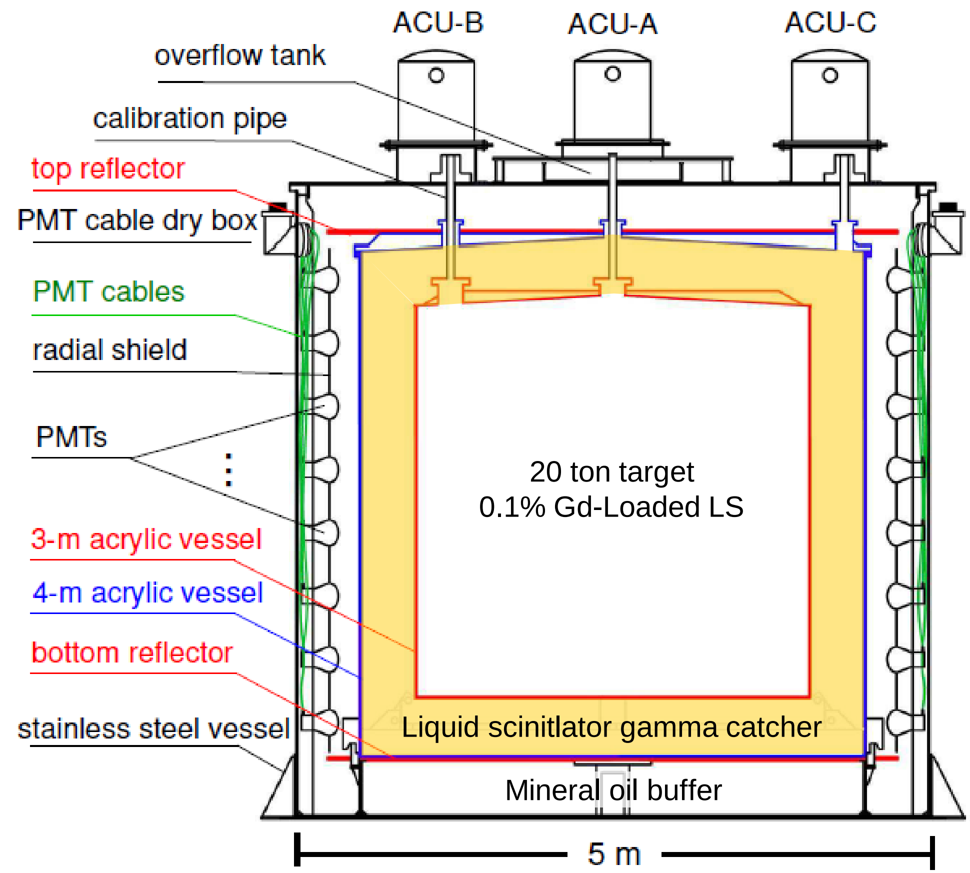
Daya Bay, RENO and Double Chooz tag neutrons with Gd capture. These detectors were designed with a gamma catcher to contain the neutron capture gammas.

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

Neutron Capture on Gadolinium



This gamma spray is poorly contained in small detectors.



Schematic of a Daya Bay Detector

Neutron Capture Options

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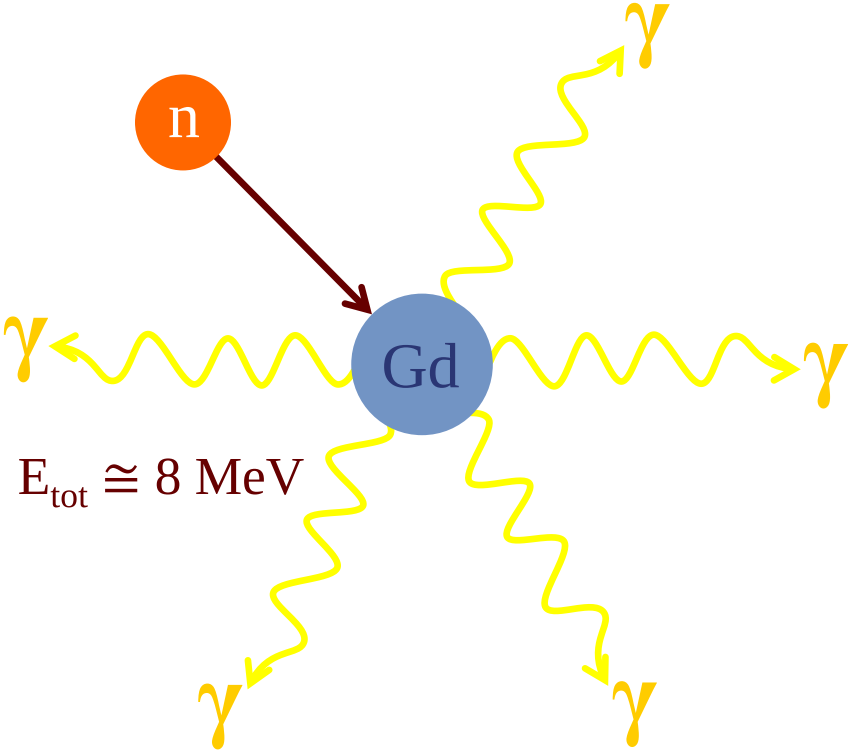
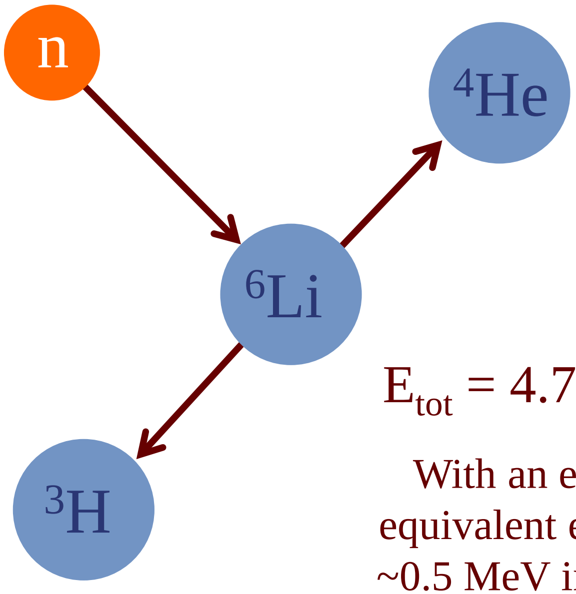


$E_{tot} \cong 8$ MeV

This gamma spray is poorly contained in small detectors.

Neutron Capture on Lithium-6



$E_{tot} = 4.78$ MeV

With an electron equivalent energy of ~0.5 MeV in organic scintillator

The alpha and triton deposit their energy in a few microns

Reactor Experiments

The short-baseline experiment is all about backgrounds:

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   But it's expensive and you don't have much space
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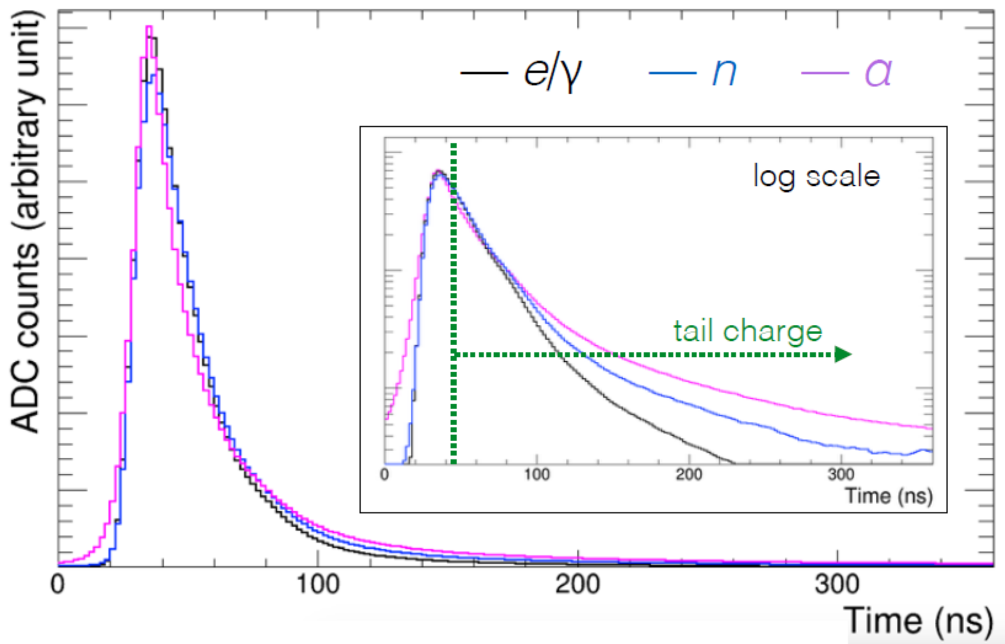
Fast Neutron

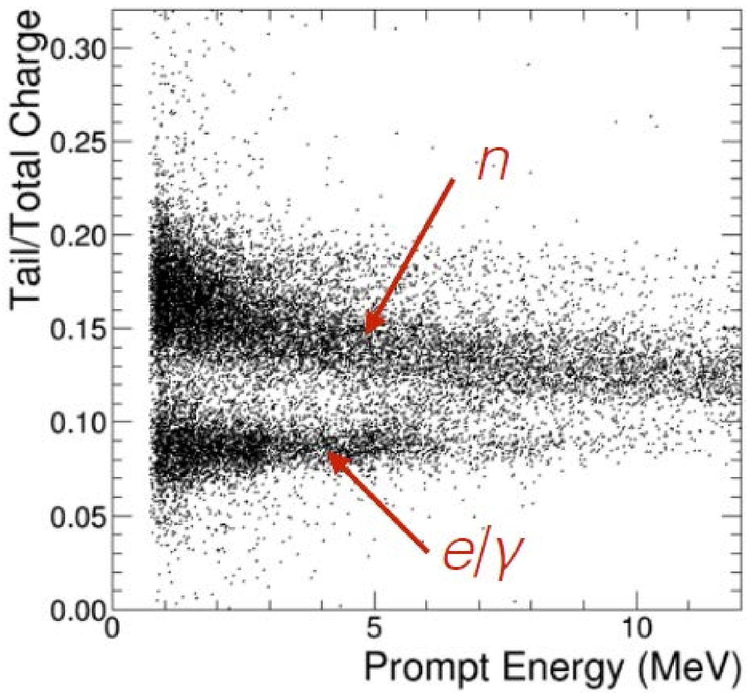
1. Add shielding:
   Requires a large overburden
2. Use pulse shape discrimination to identify recoil protons

Pulse Shape Discrimination

In most liquid organic scintillators, highly ionizing particles have extra delayed light.



Plots are from NEOS



Particle identification is formed by looking at the fraction of charge in the tail.

Reactor Experiments

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Fast Neutron

1. Add shielding:
   Requires a large overburden
2. Use pulse shape discrimination to identify recoil protons
3. Use topological selections to tag multiple recoil protons & annihilation γ's
   This requires a highly segmented detector.

Reactor Experiments

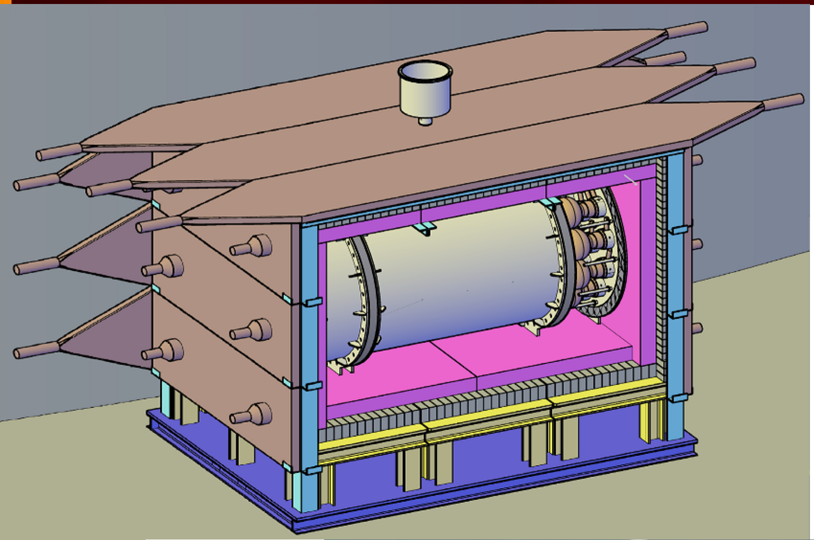
In order to have good sensitivity to Δm^2 above 1 eV^2, you need to maximize the L/E resolution which requires:

1. A compact reactor core (≲50 cm)
2. A close detector site (5 to 7 m)
3. Good energy resolution (< 7% @ 1 MeV)

There are several new reactor experiment running now:

Experiment	Power	Core Size	Mass	n Tag	Baseline	Country
DANSS ❶❷❸	3 GW	3.7 m	1 ton	Gd	10.7-12.7 m	Russia
NEOS ❶❷❸	2.8 GW	3.1 m	1.75 tons	Gd	23.7 m	Korea
Neutrino-4 ❶❷❸	90 MW	42 cm	0.4 tons	Gd	6-12 m	Russia
Stereo ❶❷❸	58 MW	40 cm	2 tons	Gd	9 m	France
Prospect ❶❷❸	85 MW	50 cm	2.5 tons	^6Li	7 m	USA
SoLid ❶❷❸	60 MW	50 cm	1.6 tons	$^6Li/ZnS$	5.5 m	Belgium

NEOS

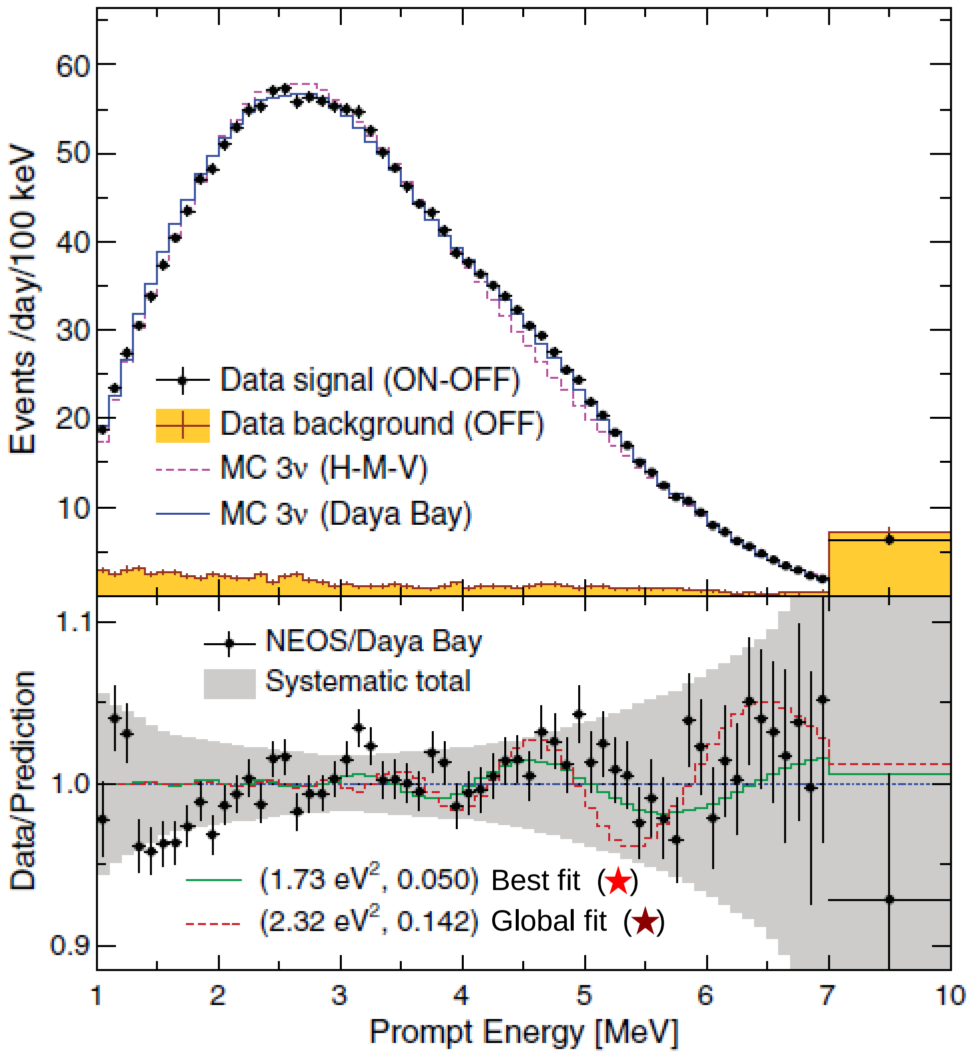


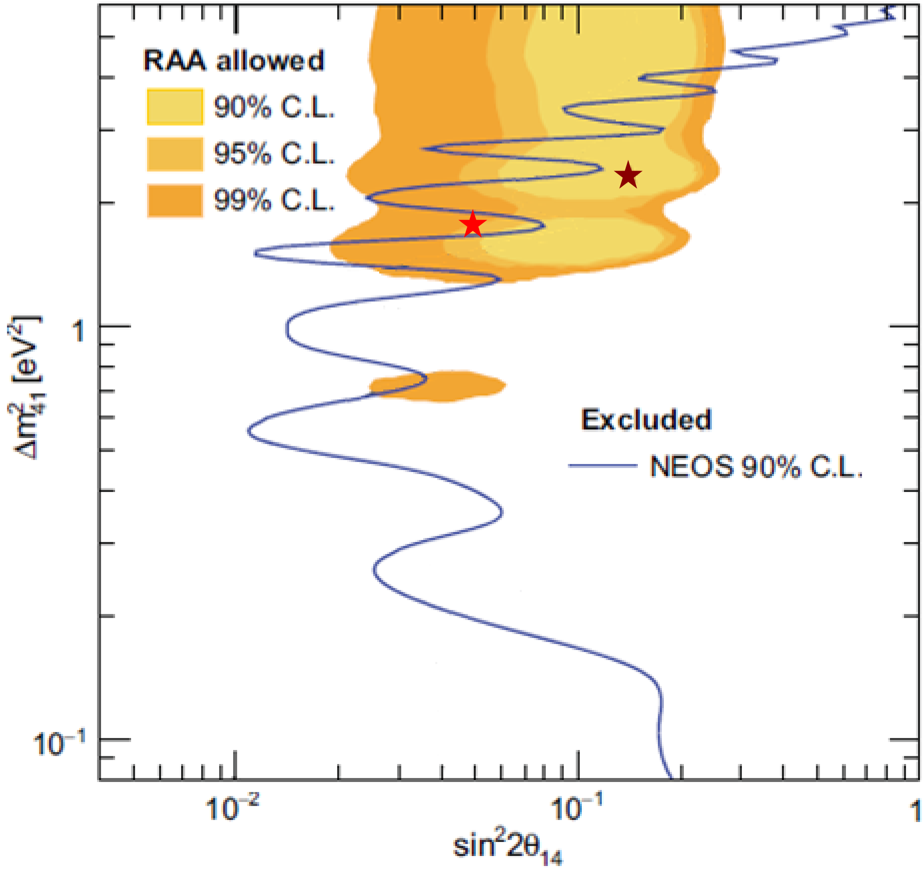
Characteristics:

- 30 m.w.e overburden
- No segmentation
- Gd tag
- Pulse shape discrimination
- Large core reactor

NEOS

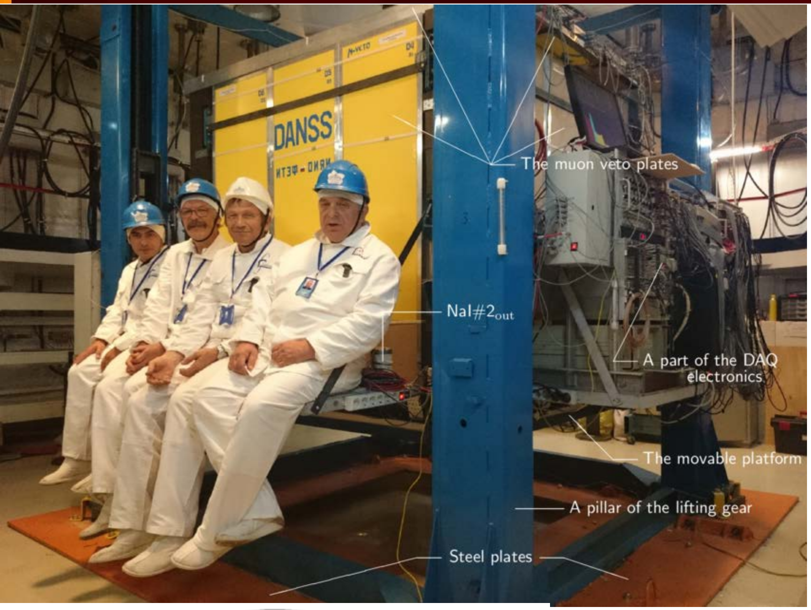
NEOS, Phys.Rev.Lett. 118, 121802 (2017)





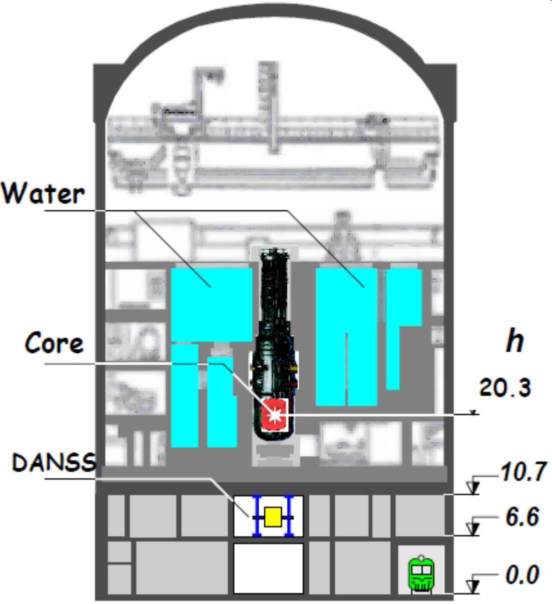
They reported their result as a limit, but a Δm^2 of 1.7 eV^2 seems to be a reasonable fit the fluctuations in their data, which are mostly with their systematic error.

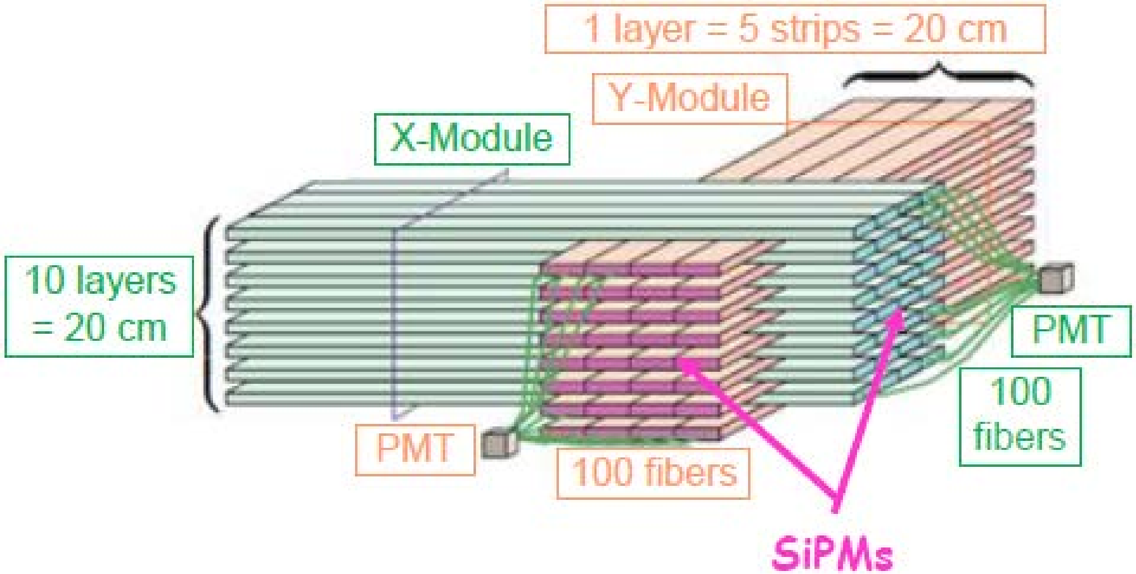
DANSS



Characteristics:

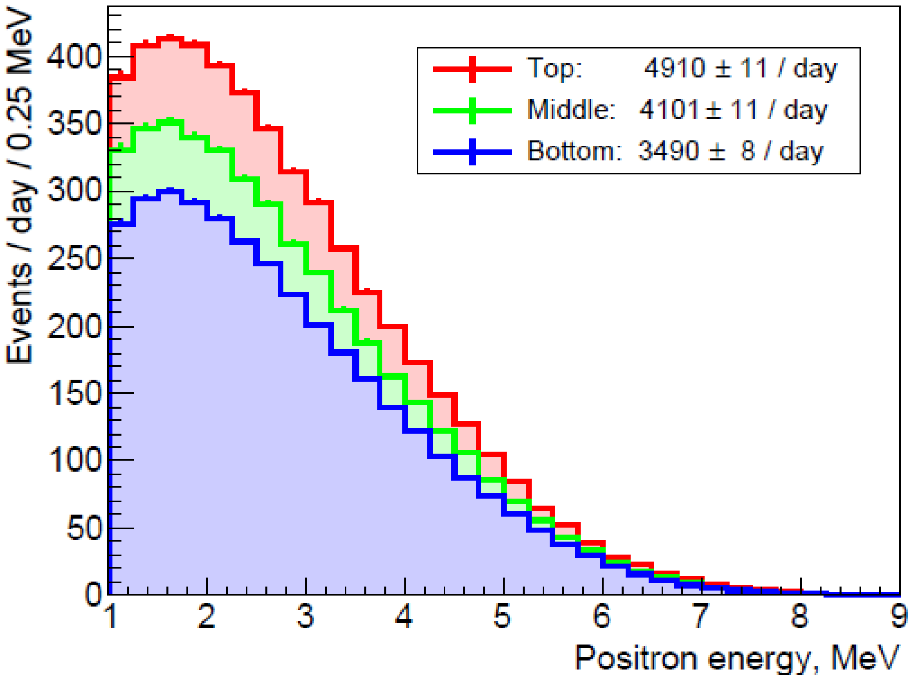
- 50 m.w.e overburden
- Segmentation
- Gd tag
- Variable baseline (10.7 to 12.7 m)
- Large core reactor

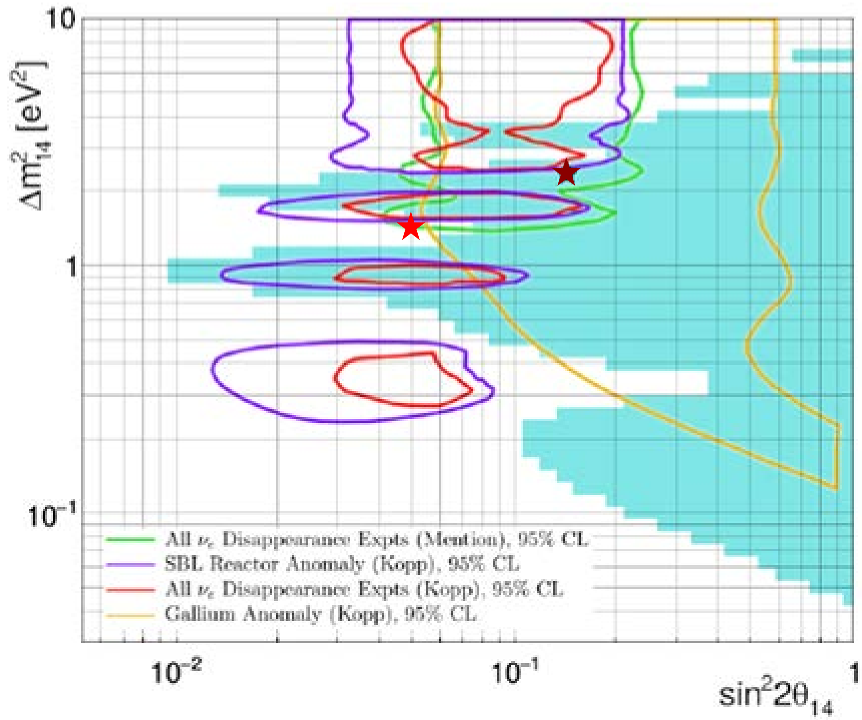




DANSS

No significant oscillation pattern was observed in the spectra from three baselines, a fact which they use to set a limit.





DANSS, arXiv:1804.04046 [hep-ex]

Their baseline variation is smaller than the core size, and their energy resolution is not very good. Together these result in a rather weak limit.

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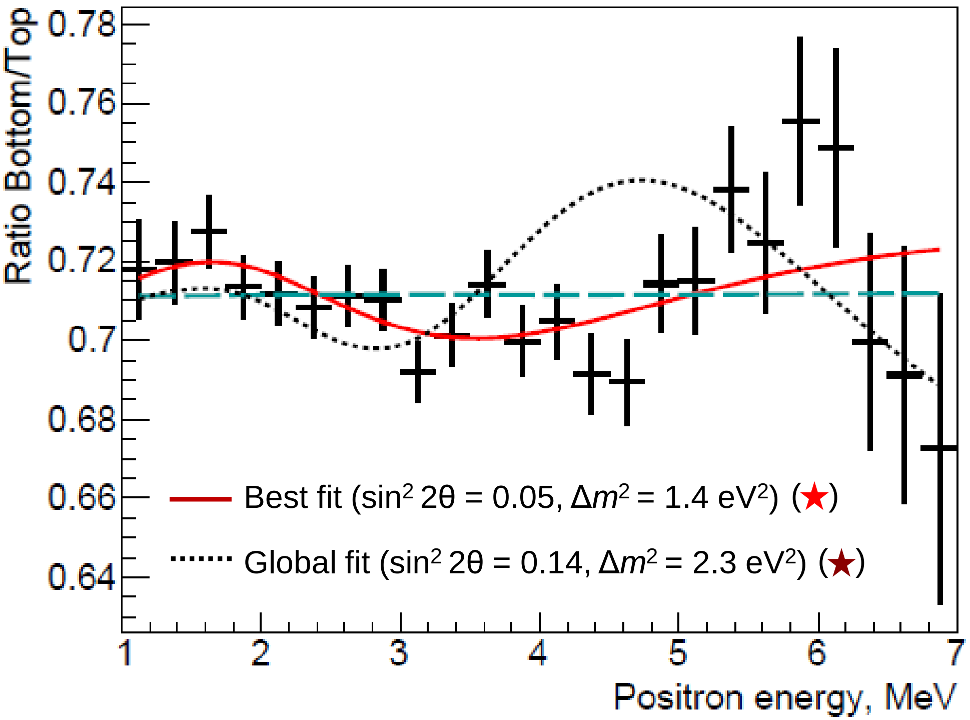

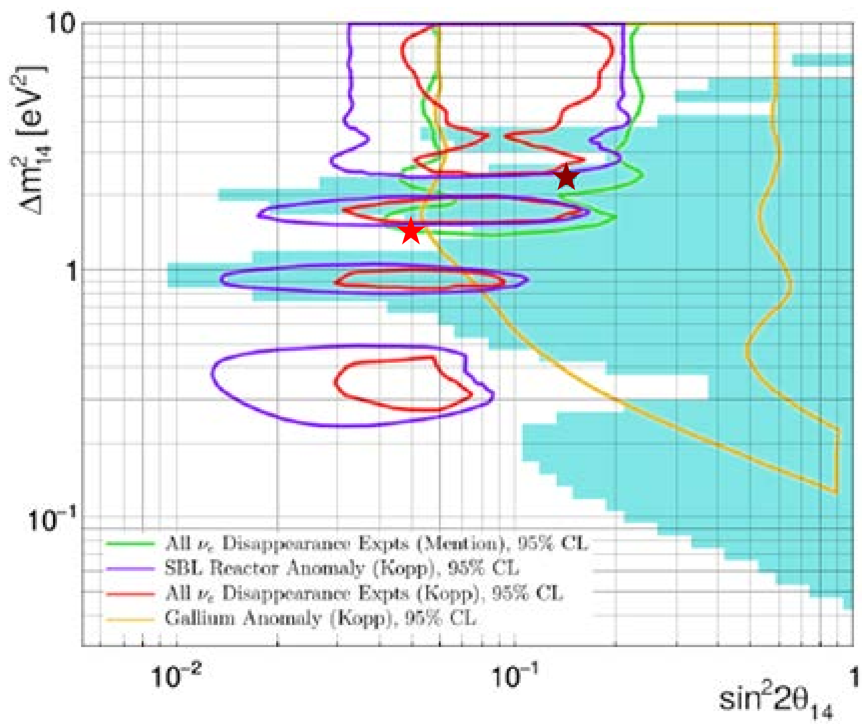

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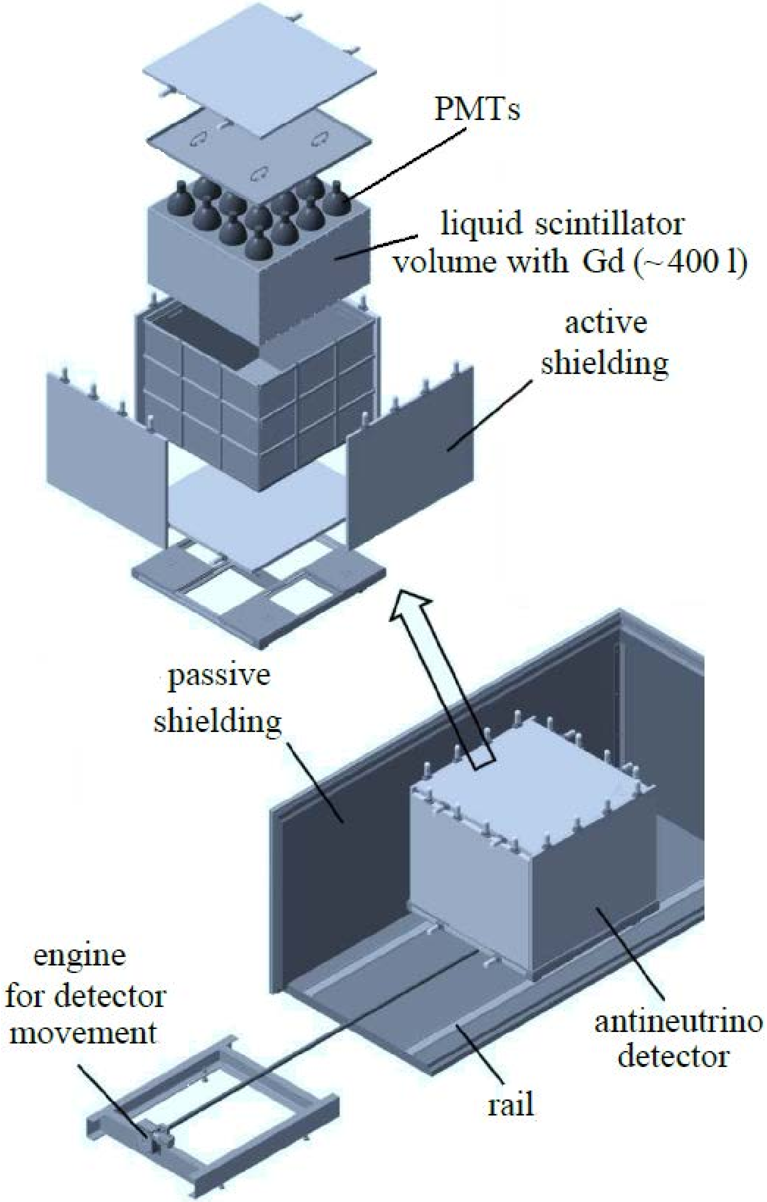
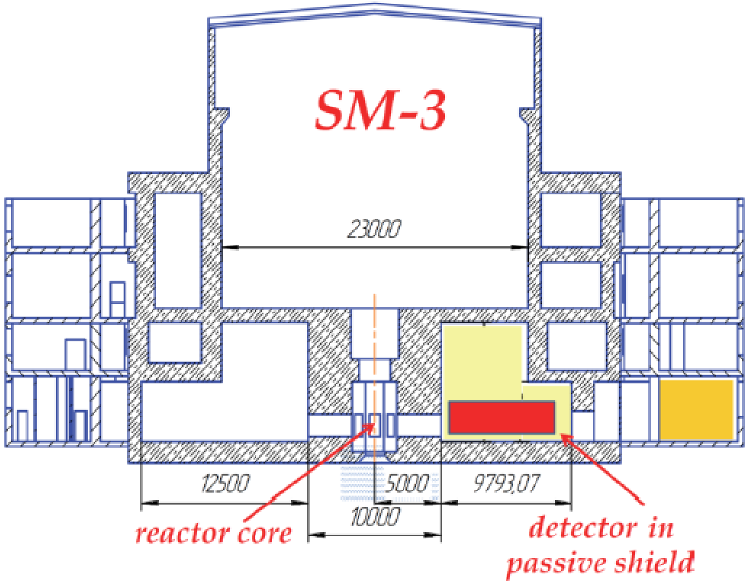
Neutrino-4



Characteristics:

- Some overburden
- Course segmentation
- Gd tag
- Variable baseline (6 to 12 meters)
- Compact core reactor



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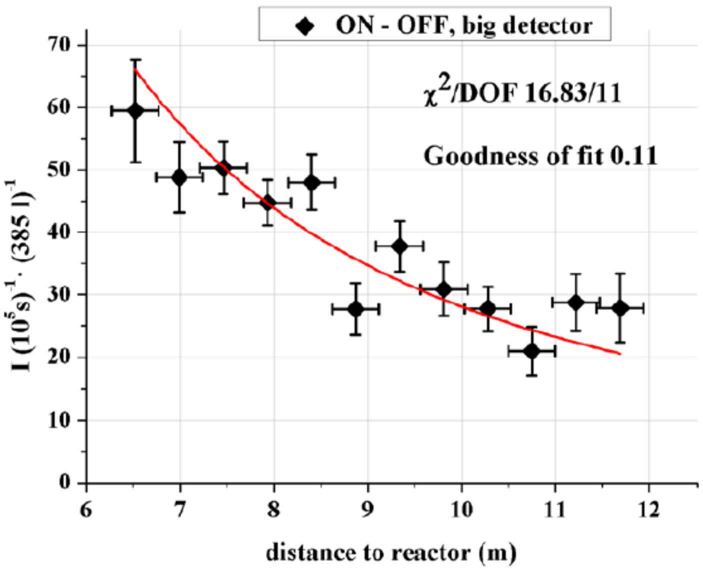
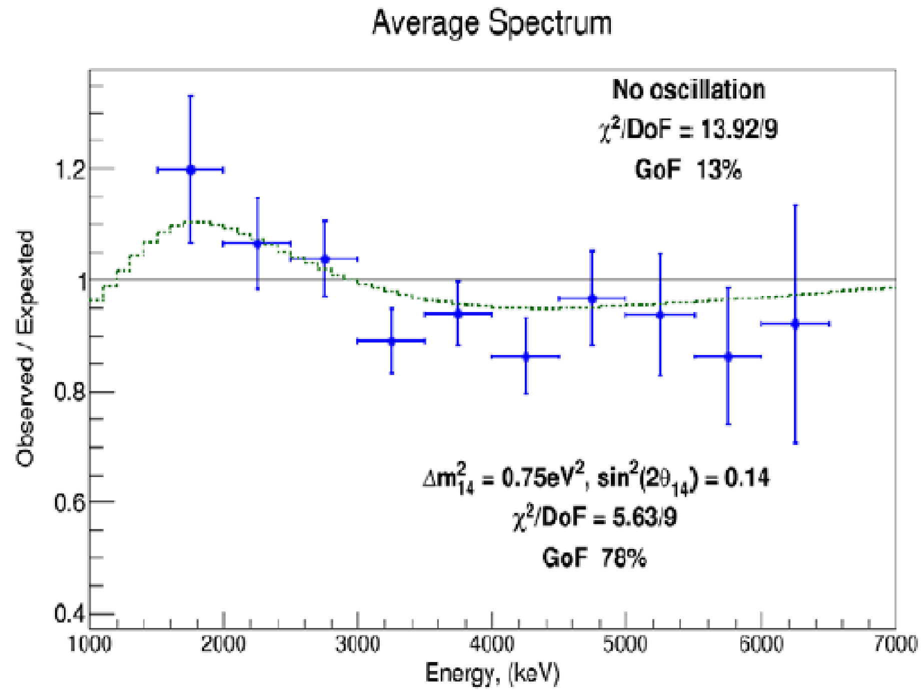
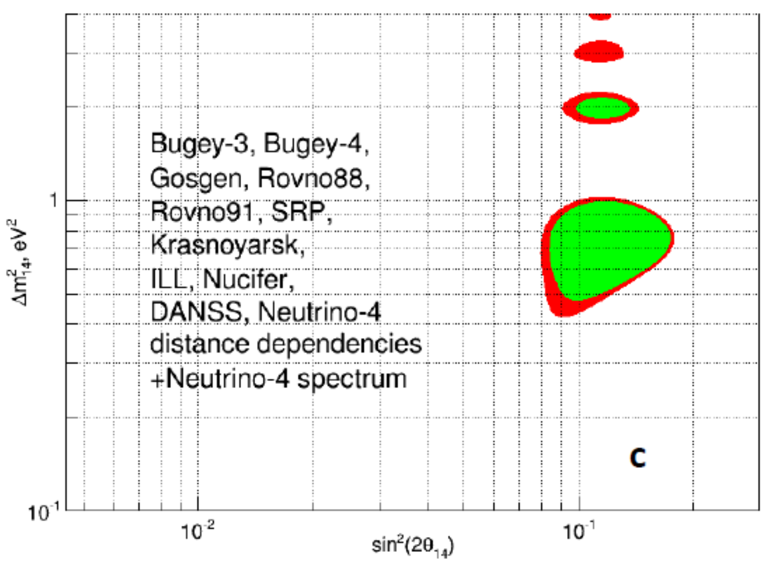






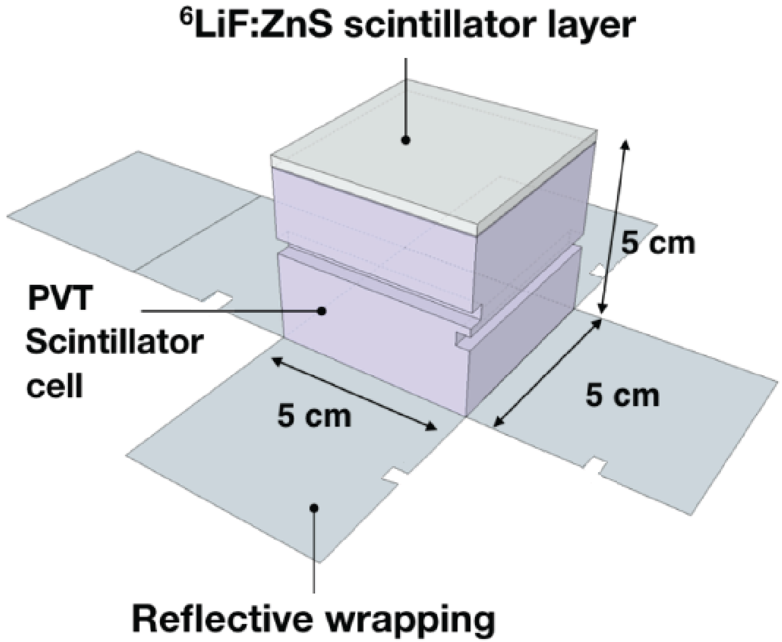
This analysis is consistent with oscillations (and no oscillations), but the statistics are still low.

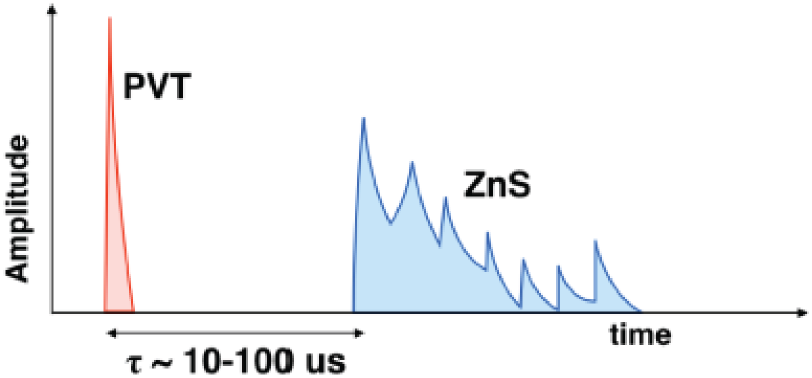
SoLid

The SoLid detector used optically isolated cubes paired with thin sheets of ^{6}Li-loaded, silver activated zinc sulfide scintillator: ^{6}LiF:ZnS(Ag).

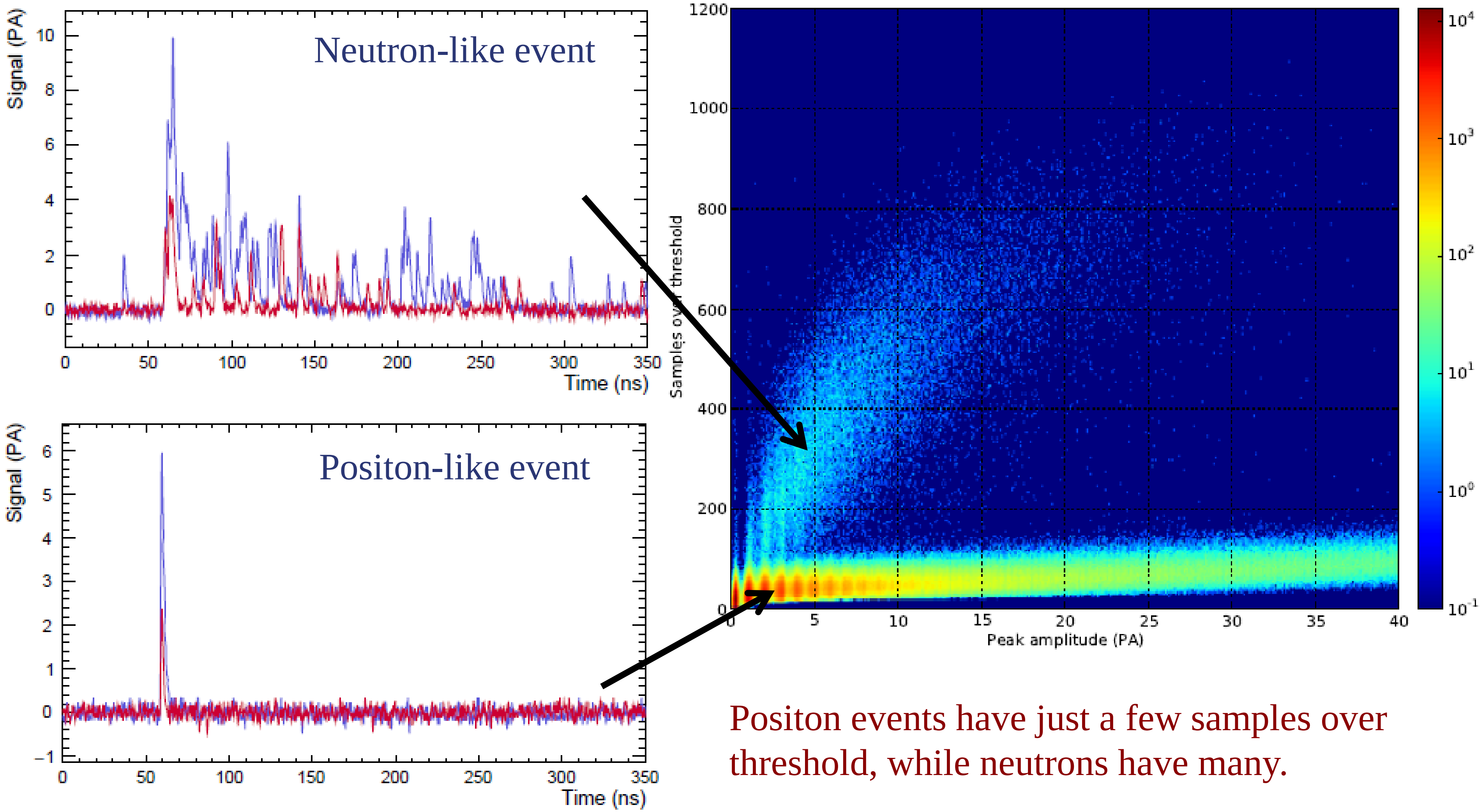
Neutrons capture on the ^{6}Li and are tagged by the ZnS(Ag) scintillator.

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





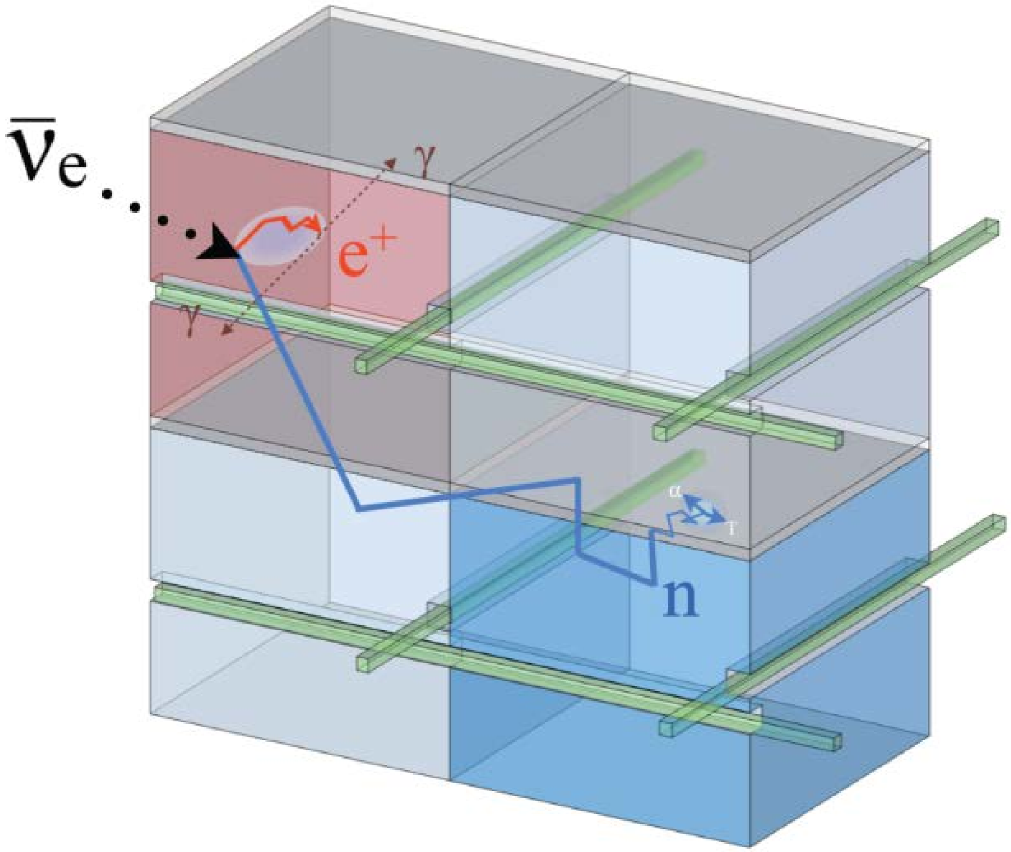
The SoLid Signal



Positon events have just a few samples over threshold, while neutrons have many.

SoLid

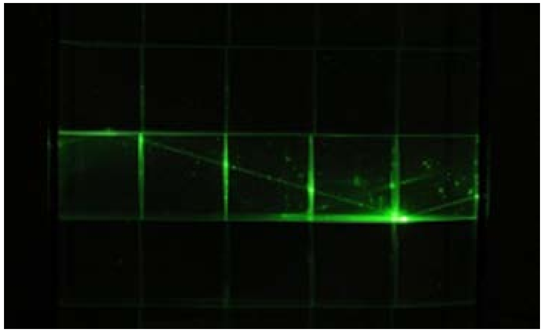
SoLid achieves unprecedented spatial resolution by segmenting the scintillator into cubes which are readout in two dimensions by wavelength shifting fibers.



The fiber readout is inefficient and that limits the energy resolution.

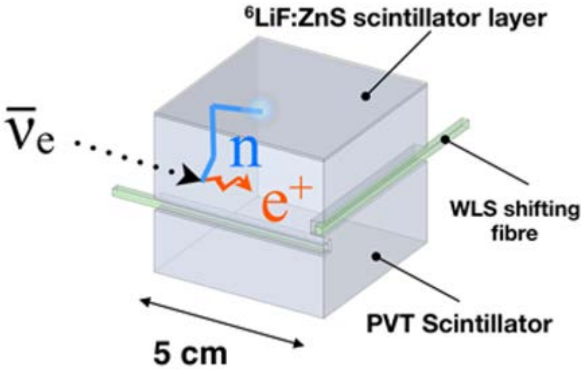
Technological Convergence

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.

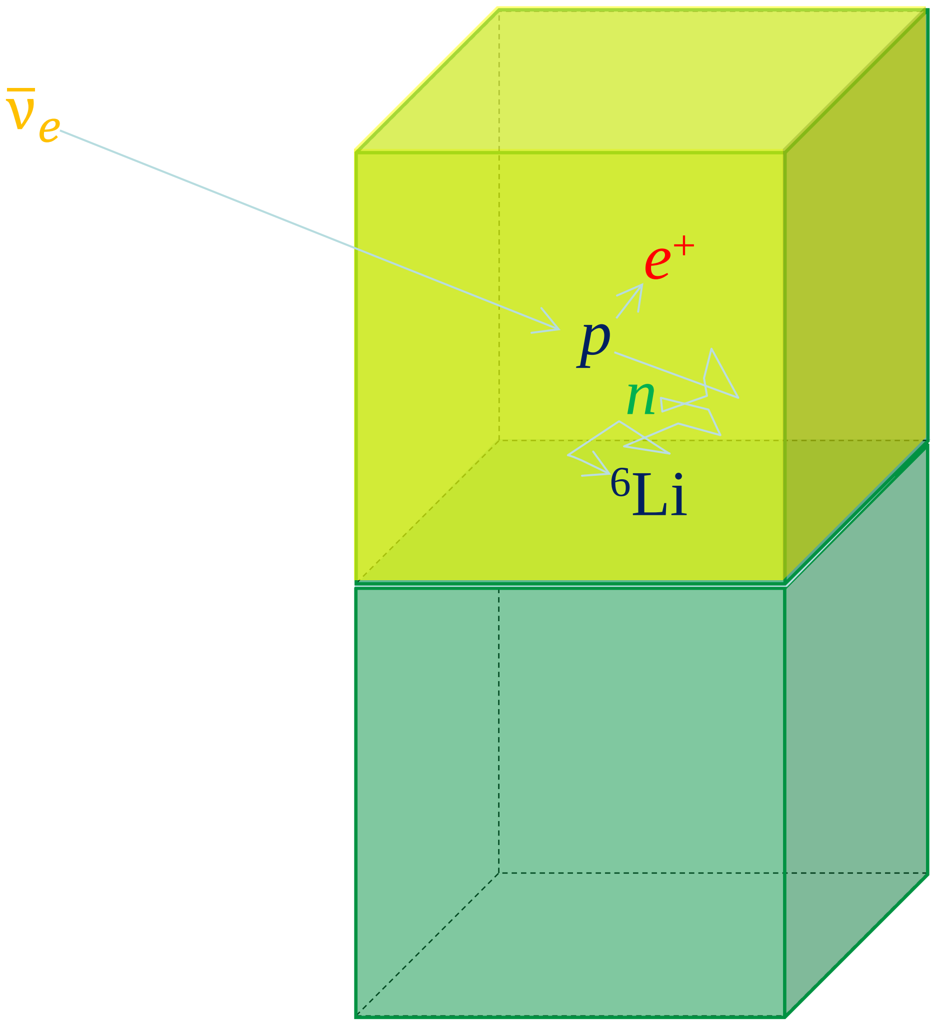
Sweany et al., NIMA 769, 37

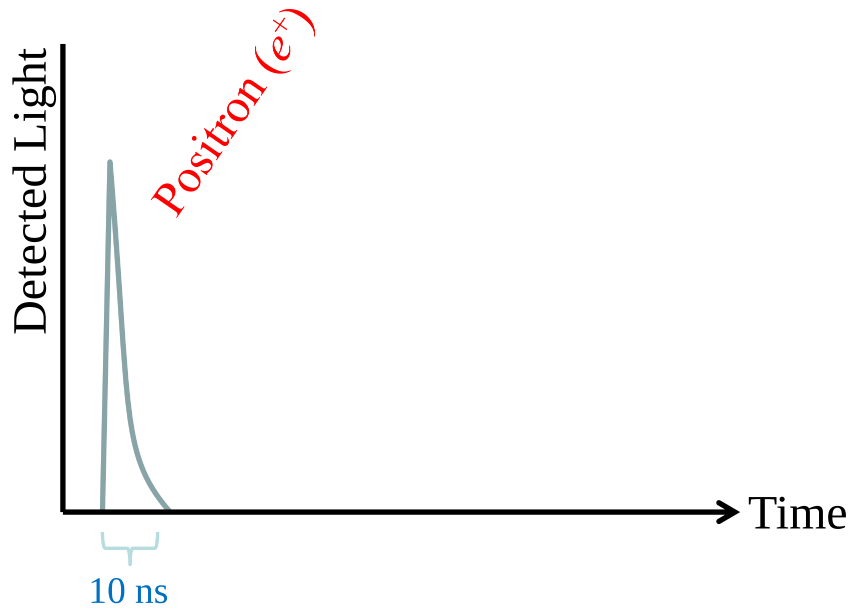
Used ^{6}LiF:ZnS(Ag) sheets mated to a **solid bar of wavelength-shifting plastic scintillator**. This prototype demonstrated the feasibility of pairing the sheets to wavelength shifting plastic, but the long bars do not have the spatial resolution required for good background rejection

CHANDLER

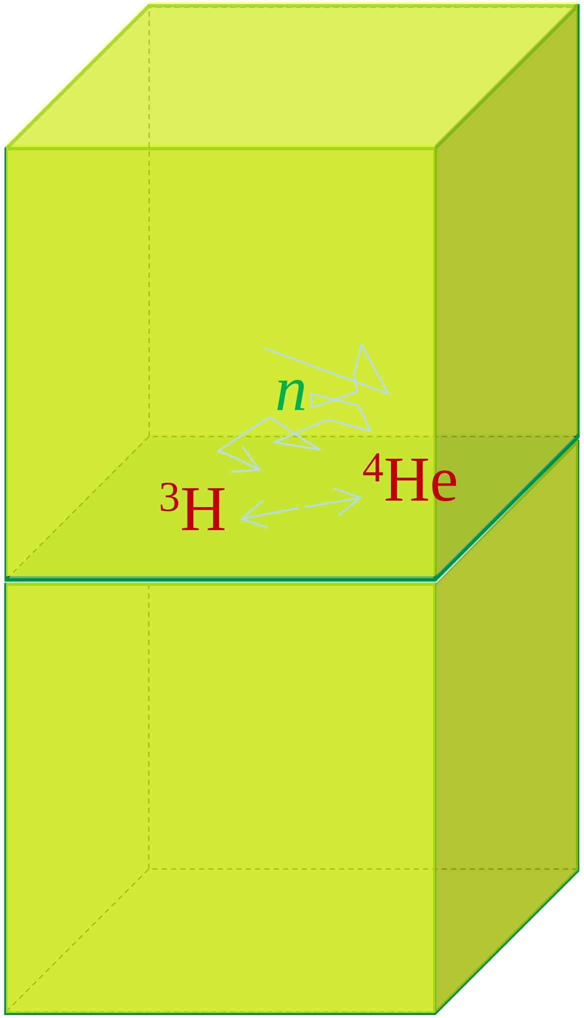
Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced ROL

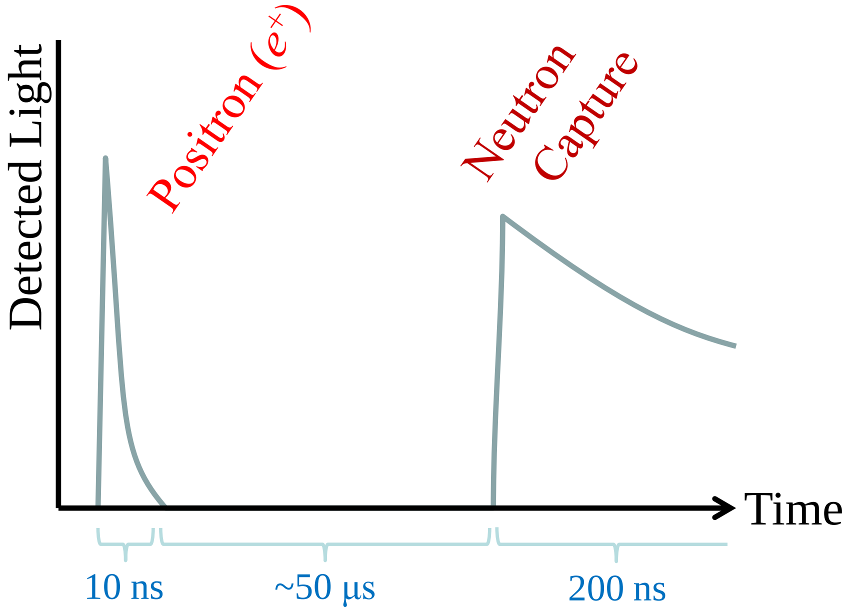
The CHANDLER Detector





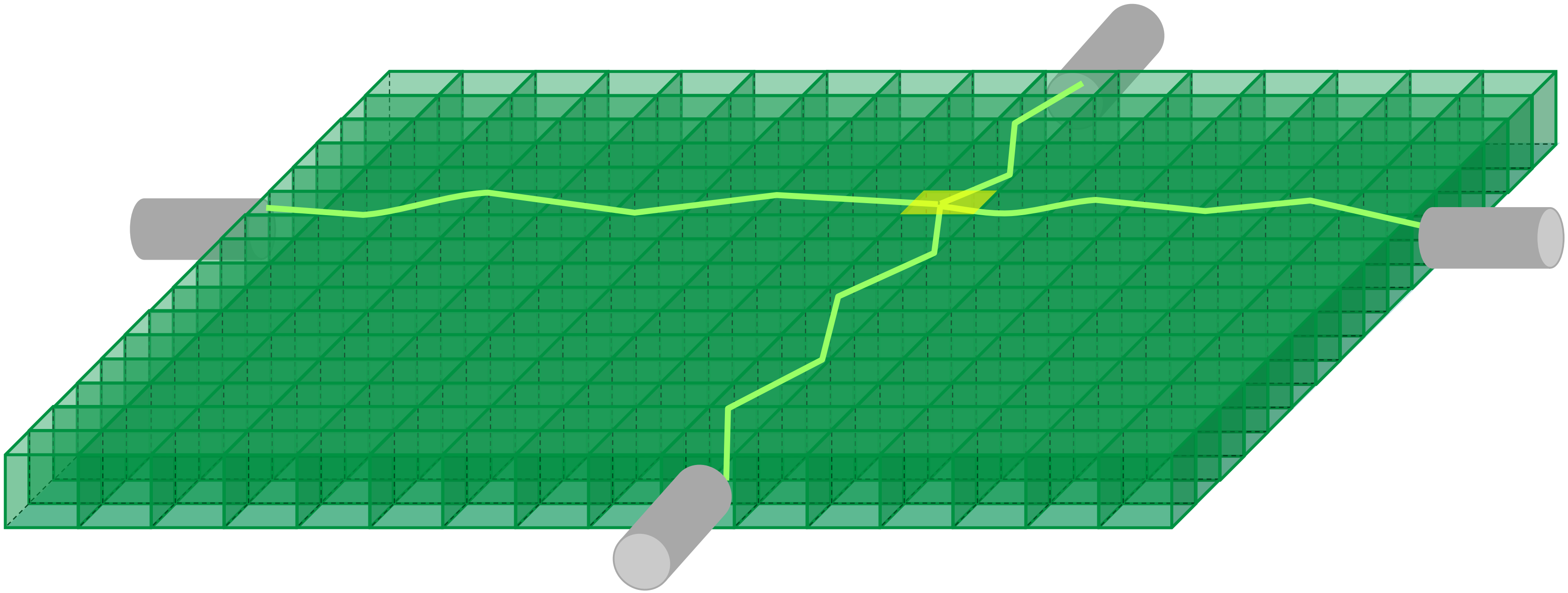
The CHANDLER Detector





The CHANDLER Detector

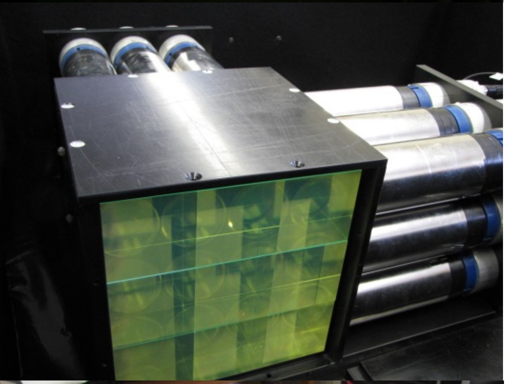
CHANDLER will be constructed of cubes (6×6×6 cm^3) of wavelength-shifting plastic scintillator arrayed in planes, between sheets of ^{6}Li-loaded ZnS(Ag), for neutron tagging.



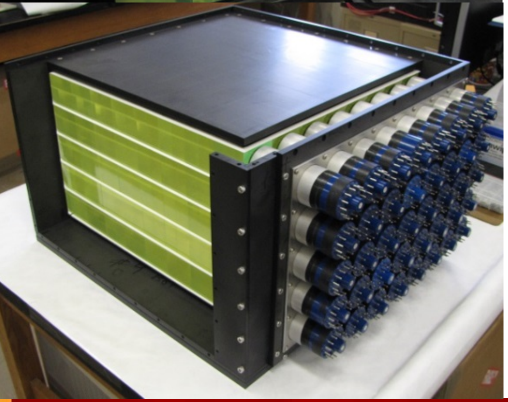
The light is transported to the detector's edge by total-internal-reflection and readout by PMTs.

Research and Development Effort

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

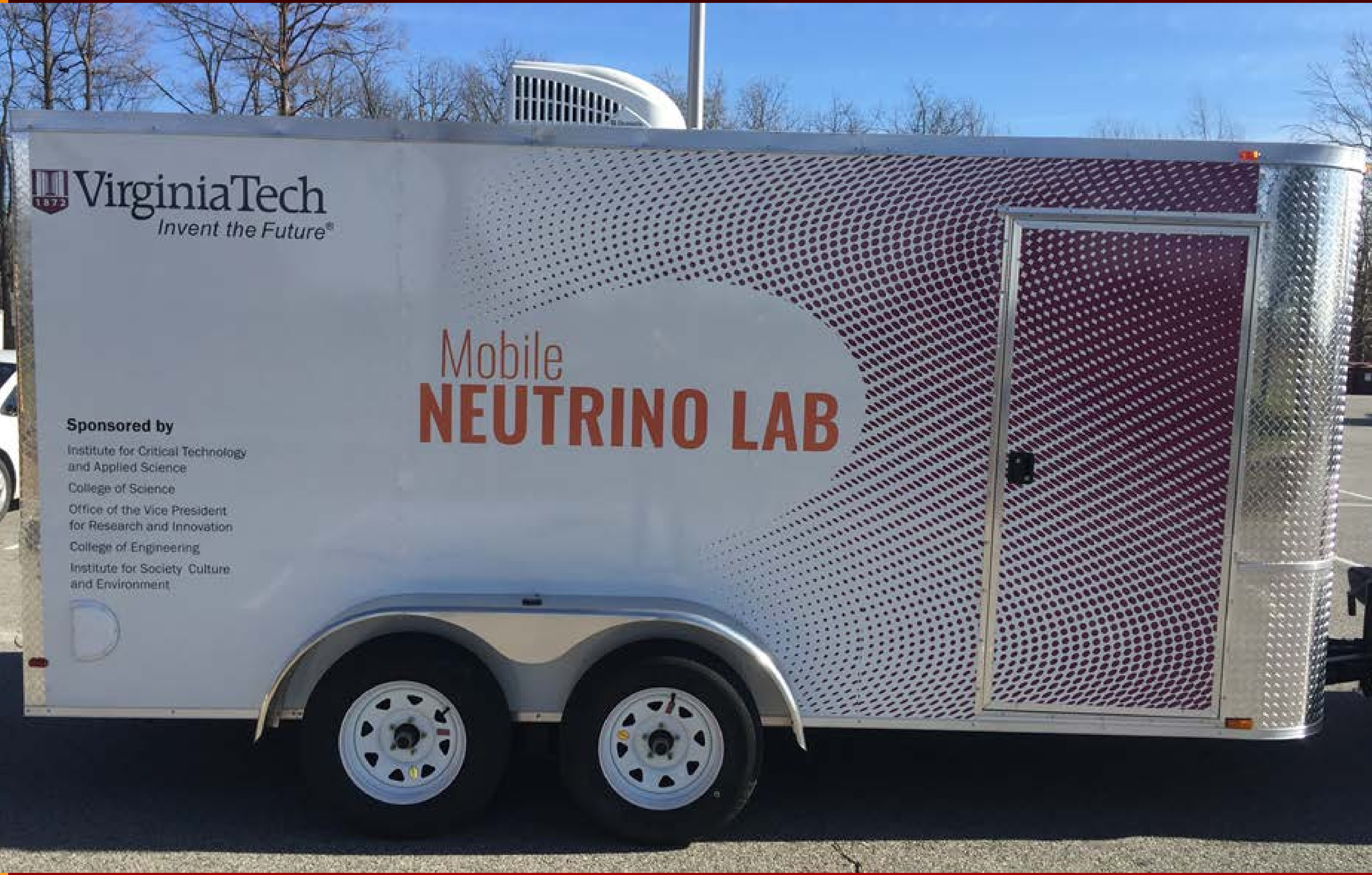


MicroCHANDLER is a 3×3×3 prototype which we used to test the full electronics chain, develop the data acquisition system, study neutron capture identification and measure background rates.



MiniCHANDLER is a full systems test (8×8×5) which was deployed for 4 months at the North Anna Nuclear Power Plant, with the goal of demonstrating neutrino detection.

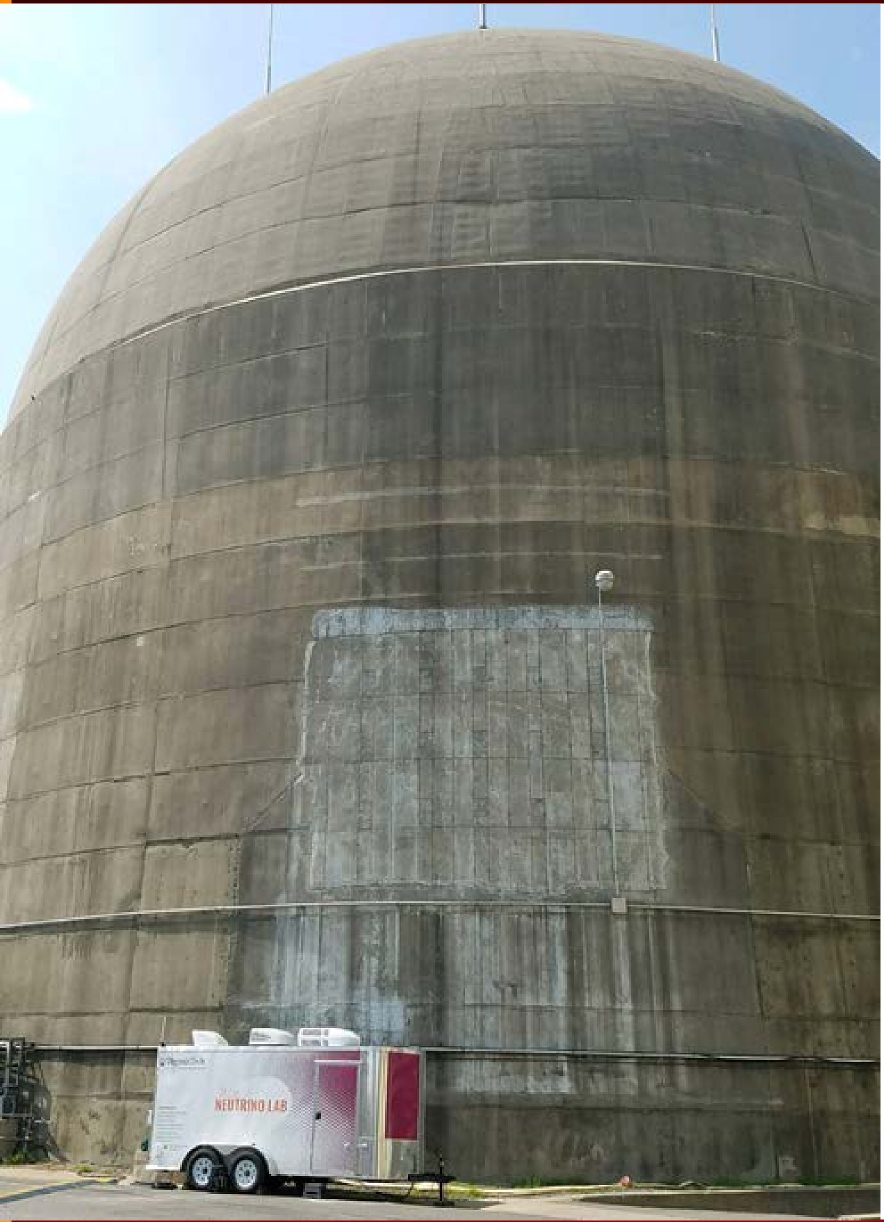
The Mobile Neutrino Lab



The Mobile Neutrino Lab

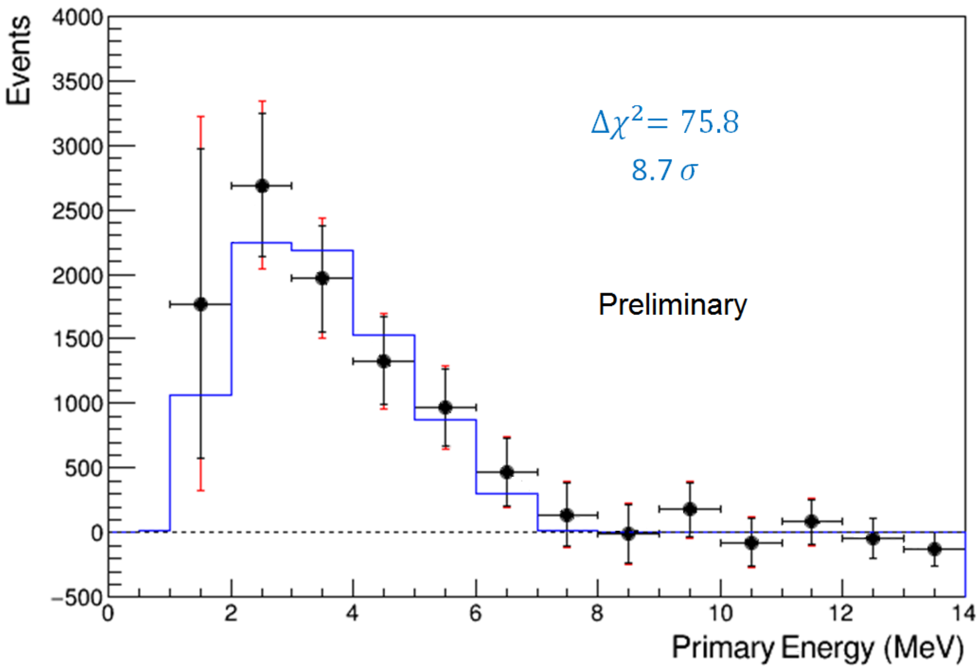
The MiniCHANDLER detector was installed in the Mobile Neutrino Lab with its electronics and DAQ computing.

MiniCHANDLER Deployment



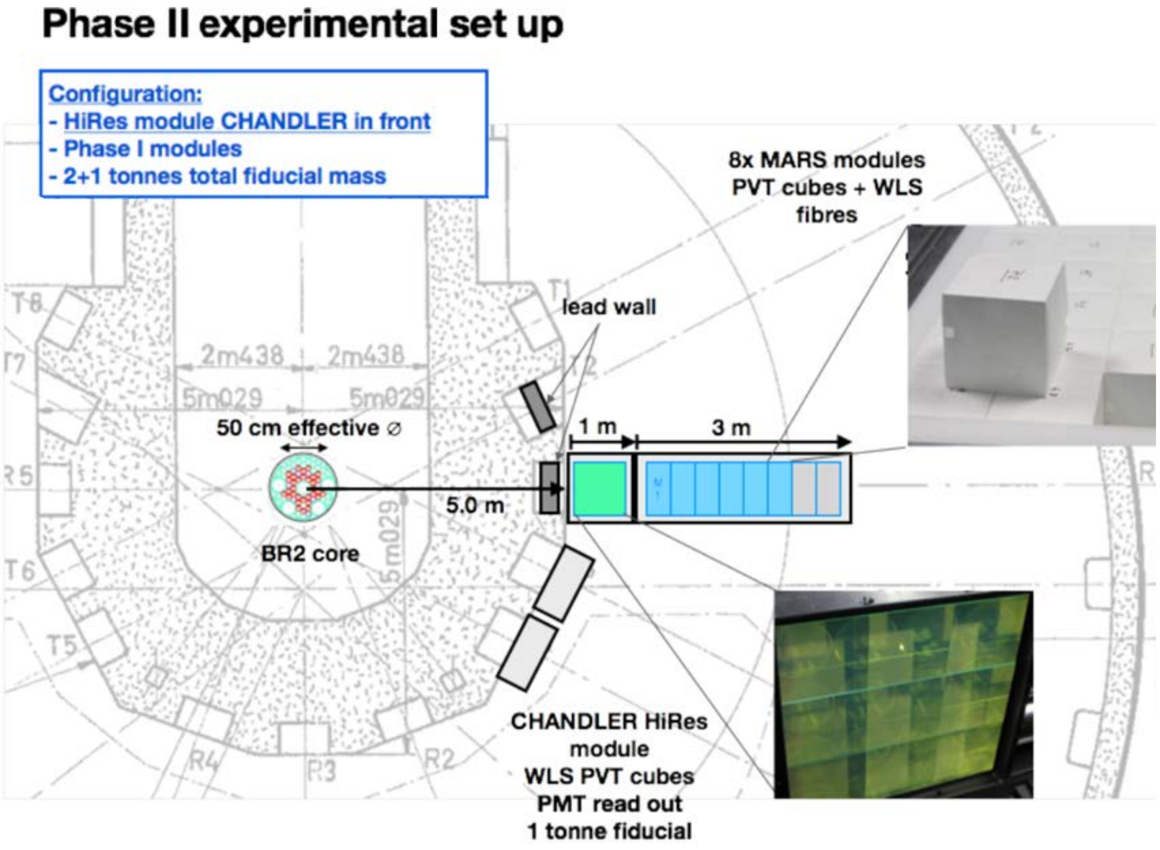
The Mobile Neutrino Lab was deployed at the North Anna Nuclear Power plant:

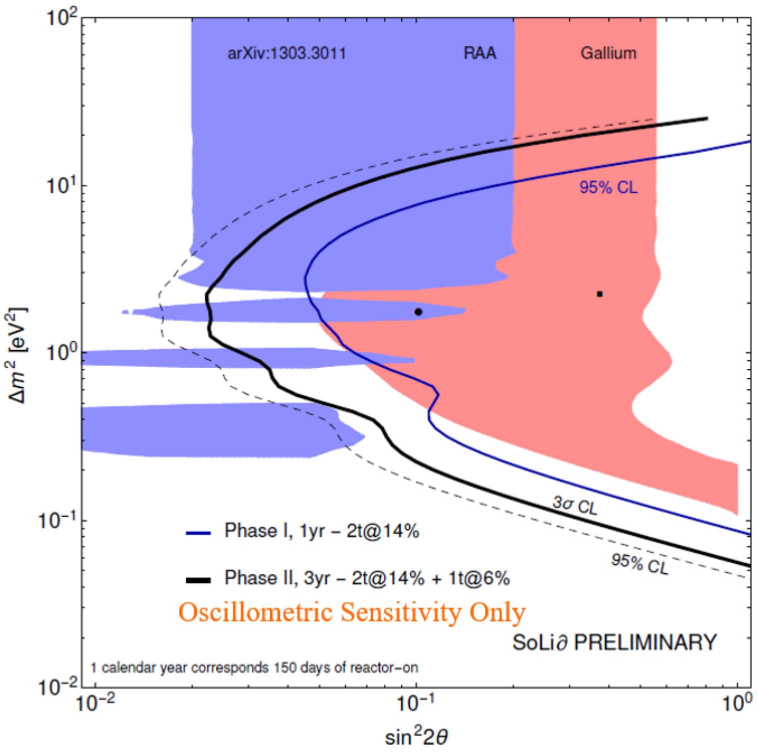
- 25 meters from core center
- Essentially no shielding
- Was taking data with 24 hours



SoLid/CHANDLER at the BR2 Reactor

The plan is to eventually co-deploy a ton-scale CHANDLER detector with SoLid at the BR2 Reactor.





Combined, SoLid plus CHANDLER could be the most sensitive short-baseline reactor experiment.

Reactor Experiments

In order to have good sensitivity to Δm^2 above 1 eV^2, you need to maximize the L/E resolution which requires:

1. A compact reactor core (≲50 cm),
2. A close detector site (5 to 7 m), and
3. Good energy resolution (< 7% @ 1 MeV)

There are several new reactor experiment running now:

Experiment	Power	Core Size	Mass	n Tag	Baseline	Country
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SoLid ❶❷❸	60 MW	50 cm	1.6 tons	^{6}Li/ZnS	5.5 m	Belgium

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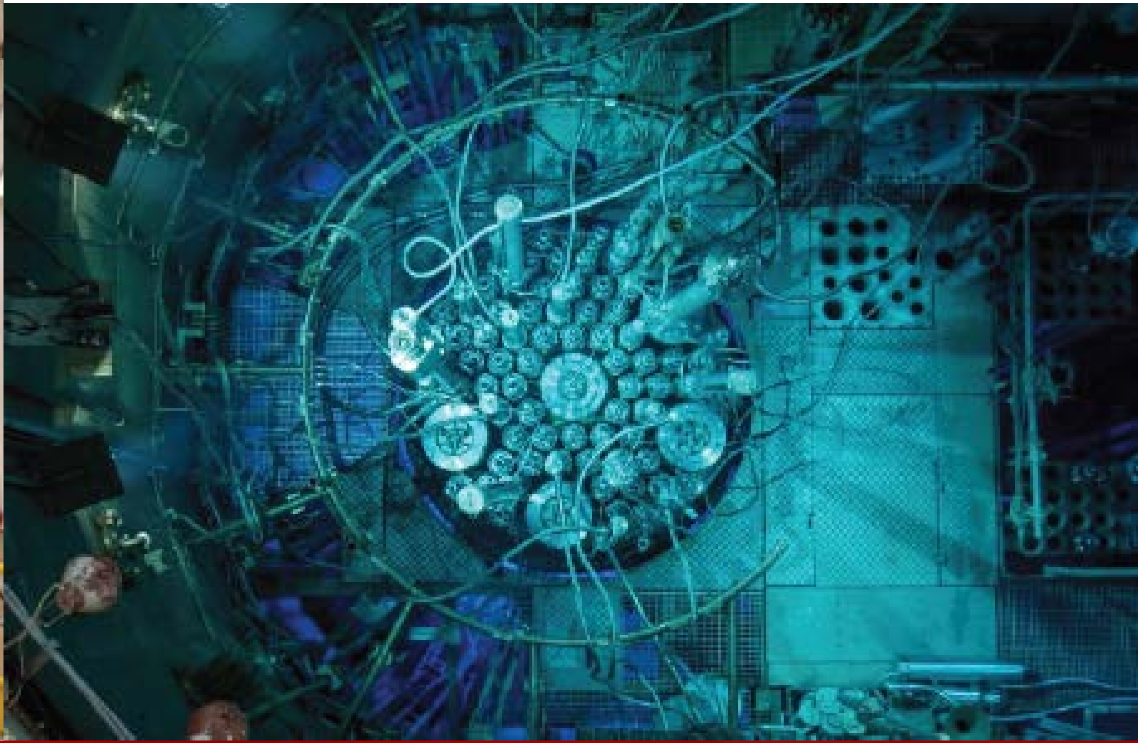
SoLid/CHANDLER ❶❷❸	60 MW	50 cm	3.1 tons	$^6Li/ZnS$	5.5 m	Belgium

SoLid/CHANDLER at the BR2 Reactor

BR2 is the only compact reactor with enough space to host a truly definitive reactor experiment.

Additional detector mass could be added over time.



Source Experiments

The LENS-Sterile Concept

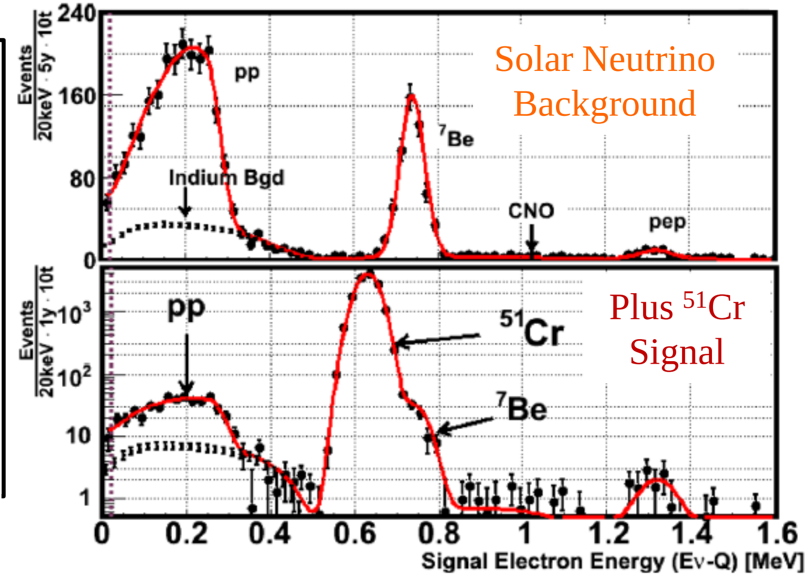
PHYSICAL REVIEW D **75**, 093006 (2007)

Probing active to sterile neutrino oscillations in the LENS detector

C. Grieb, J. M. Link, and R. S. Raghavan
Institute of Particle, Nuclear and Astronomical Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA
(Received 24 December 2006; published 15 May 2007)

Sterile neutrino (ν_s) conversion in meter scale baselines can be sensitively probed using monoenergetic, sub-MeV, flavor-pure ν_e's from an artificial Megacurie source and the unique technology of the LENS low energy solar ν_e detector. Active-sterile *oscillations* can be directly observed in the granular LENS detector itself to critically test and extend results of short baseline accelerator and reactor experiments.

DOI: 10.1103/PhysRevD.75.093006 PACS numbers: 14.60.Pq, 13.15.+g, 29.40.Mc

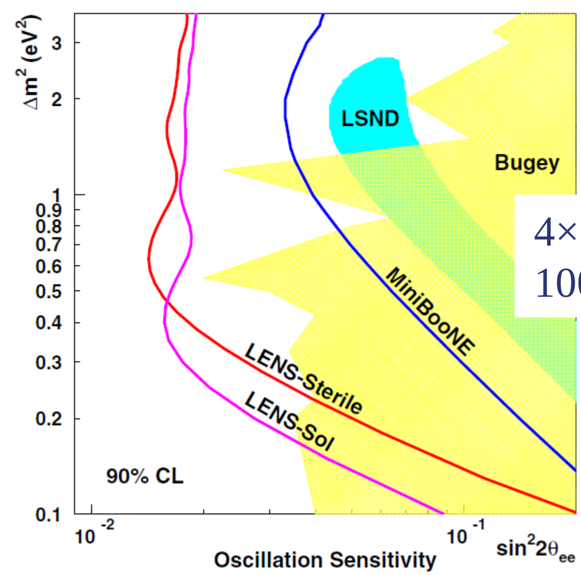


LENS is a proposed *pp* solar neutrino detector based on a CC transition in ^{115}In to measure the solar ν spectrum.

$$^{115}\text{In} + \nu_e \rightarrow {}^{115}\text{Sn}^* + e^-$$

$$(\tau = 4.76\ \mu\text{s}) \qquad \hookrightarrow {}^{115}\text{Sn} + 2\gamma\text{'s}$$

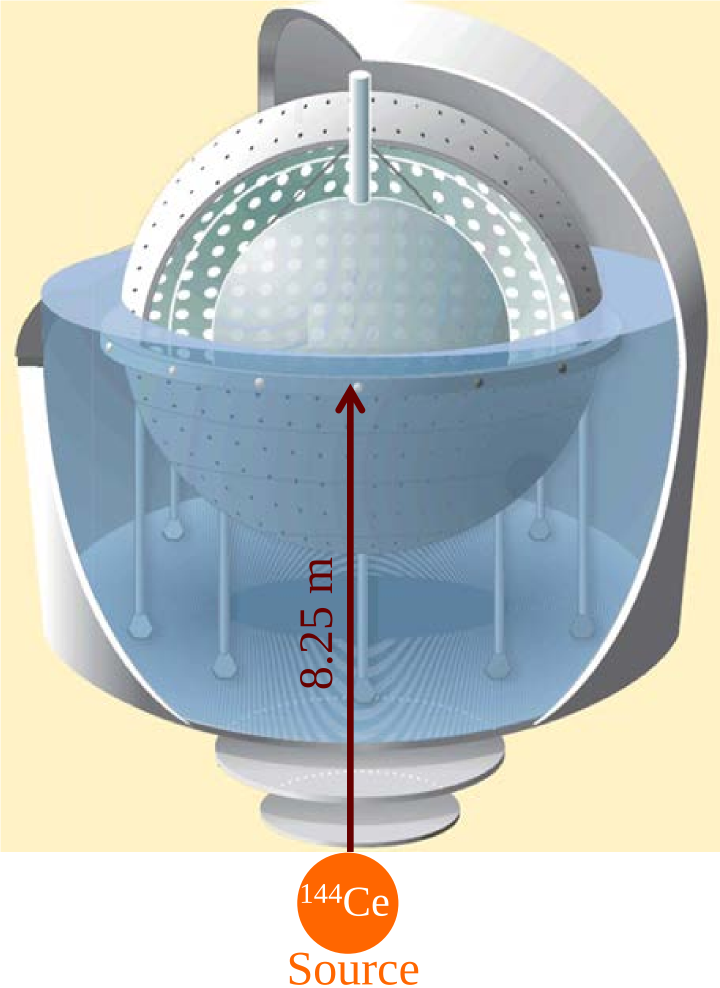
By inserting a mega-Curie, ^{51}Cr source in the center of LENS would make it sensitive to a wavelength, or more, of large Δm^2 oscillations.



4×10 MCi
100 days each

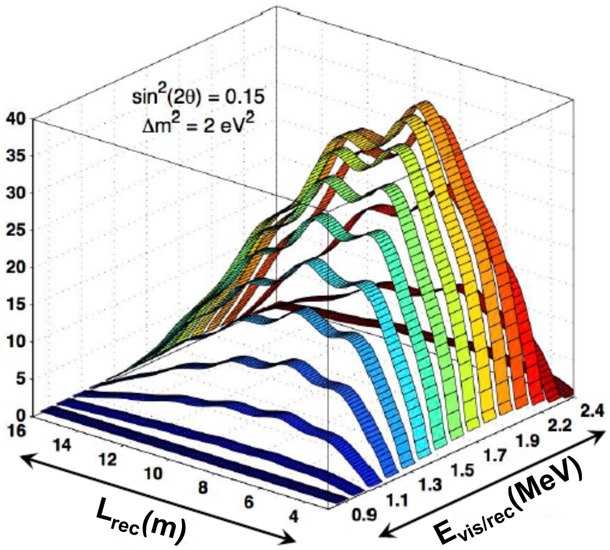
SOX: Source Oscillations at BoreXino

Combine a radioactive neutrino source with the Borexino detector to search for ν_e disappearance. JHEP 1308, 038 (2013) 1304.7721



SOX planned to use a ^{144}Ce source.

Multiple oscillation wavelengths could be observed inside the detector for the sterile Δm^2.



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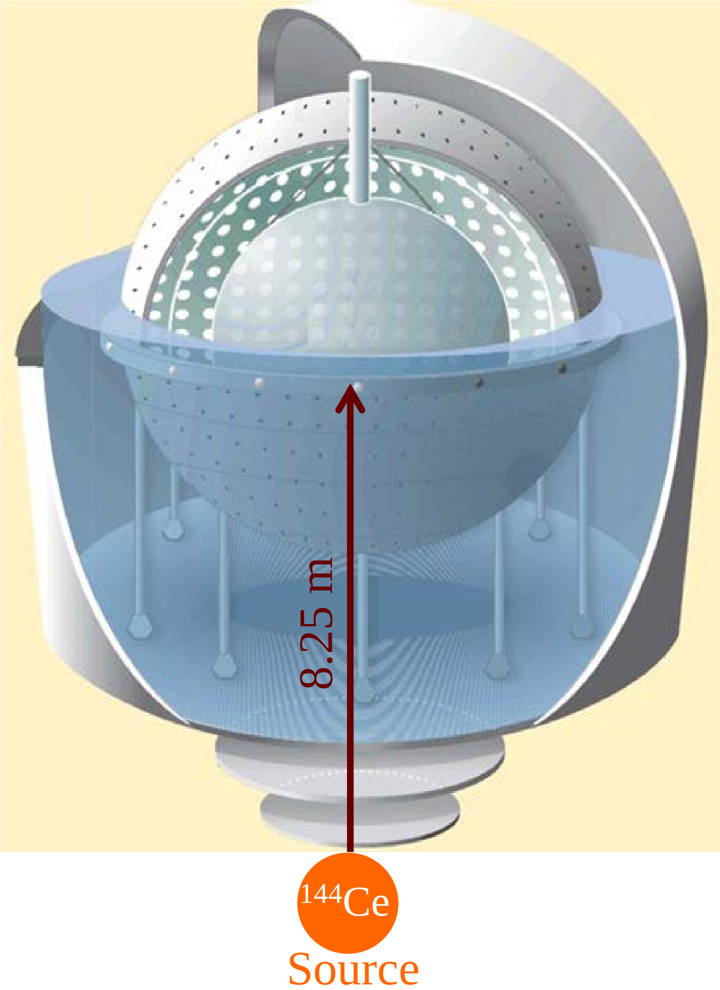

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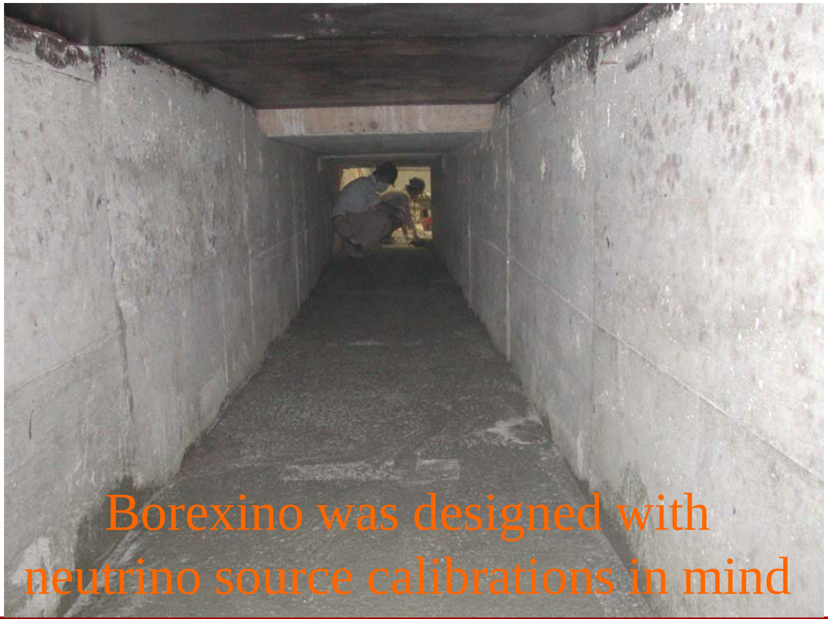
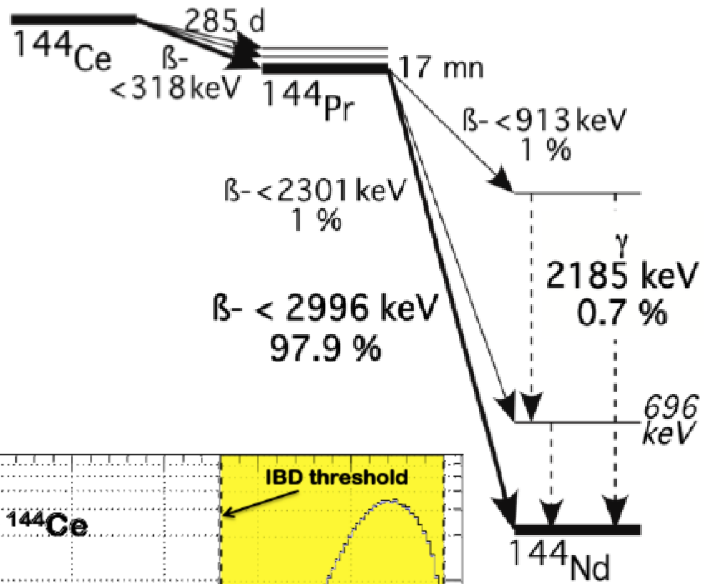
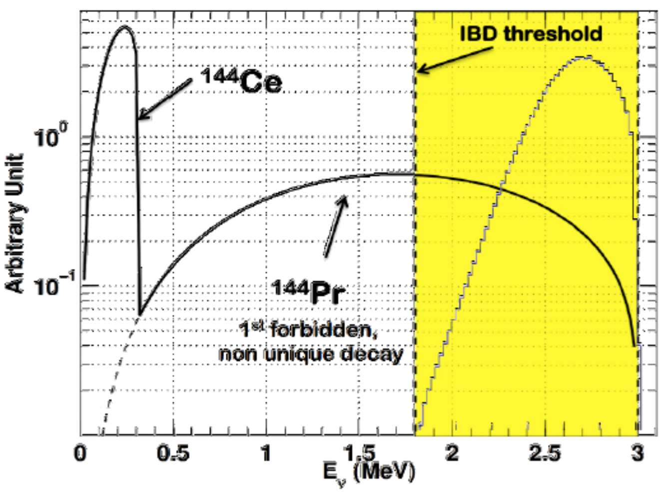


^{144}Ce Source at Borexino

Cribier *et al.*, Phys.Rev.Lett. 107, 201801

Decay scheme

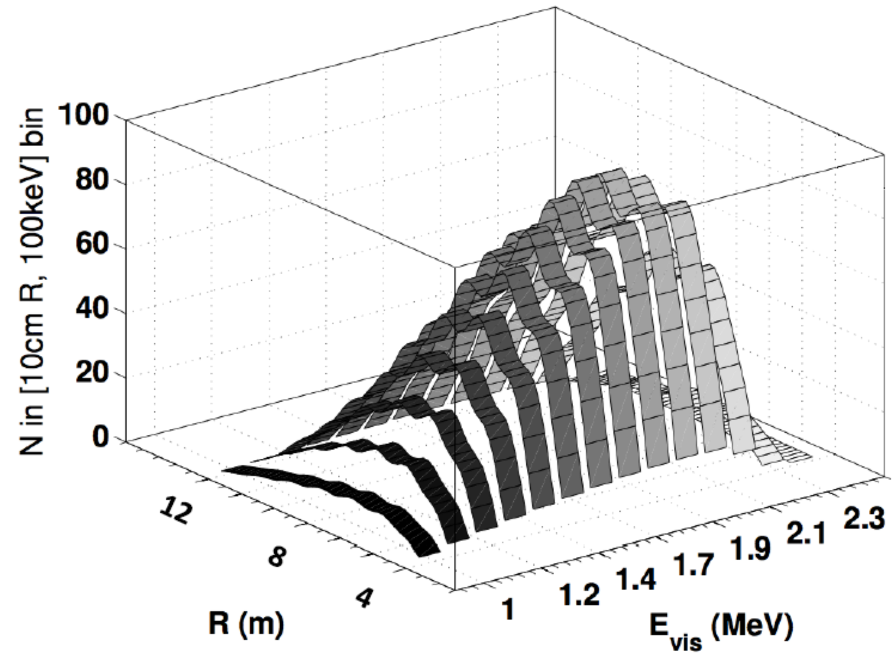




$\bar{\nu}_e$ detected by inverse beta-decay.

The source is made from spent nuclear fuel.

The source is not monoenergetic, so oscillations must be studied in L/E.



100 kCi of ^{144}Ce gives a similar number of events as 5 MCi of ^{51}Cr.

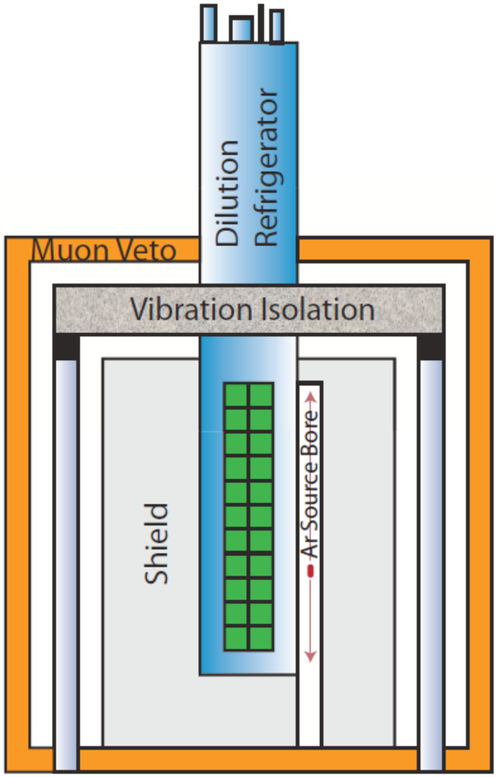
The fence of the Mayak facility in southern Russia, where French scientists say an accident may have taken place last fall. THE BELLONA FOUNDATION

Mishandling of spent nuclear fuel in Russia may have caused radioactivity to spread across Europe

By Edwin Cartlidge | Feb. 14, 2018 , 2:35 PM

Total NC Disappearance: RICOCHET

RICOCHET would combine an array of low energy bolometers with an electron capture source to look for the baseline dependence of coherent elastic neutrino-nucleus scattering (CEνNS).

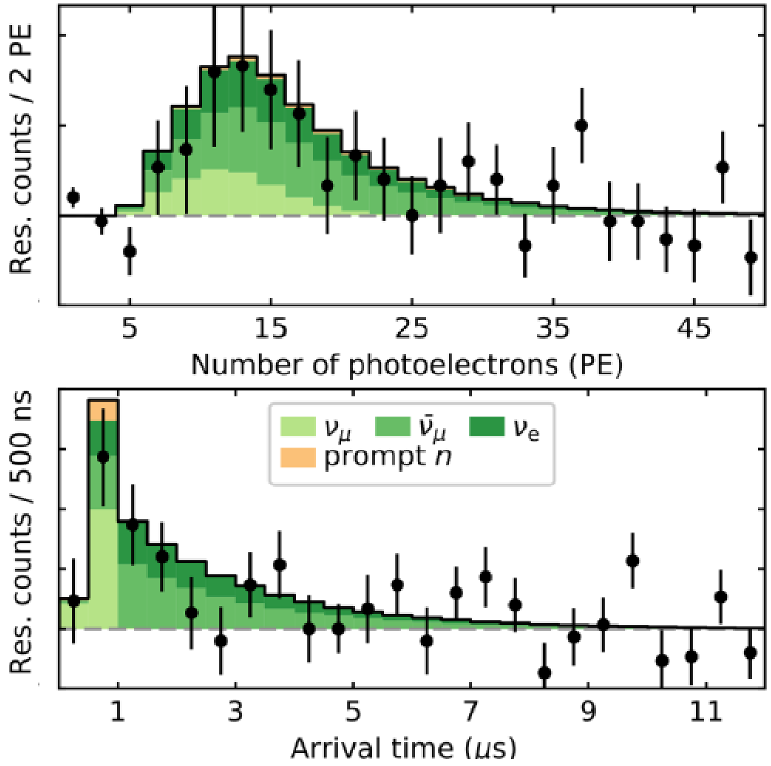


Formaggio & Figuroa, Phys.Rev.D 85, 013009 (2012)

CEνNS has only recenlty been observed, making this proposal more feasible than it seemed 6 years ago.

But the source recoil energies are two orders of magnitude smaller than the discovery experiment, which was only 50 keV.

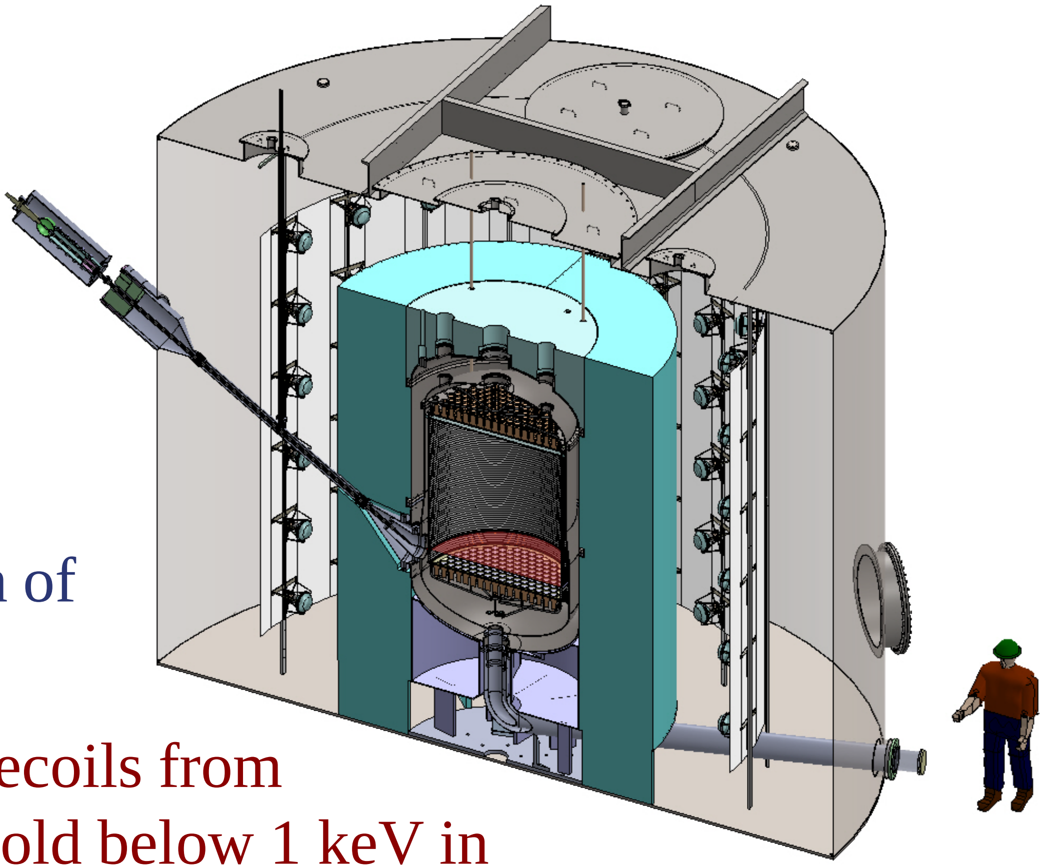
Akimov *et al.*, Science (2017)



Combining Sources with Dark Matter Detectors

The LZ detector is 6 tons of liquid xenon embedded in a very low-background environment.

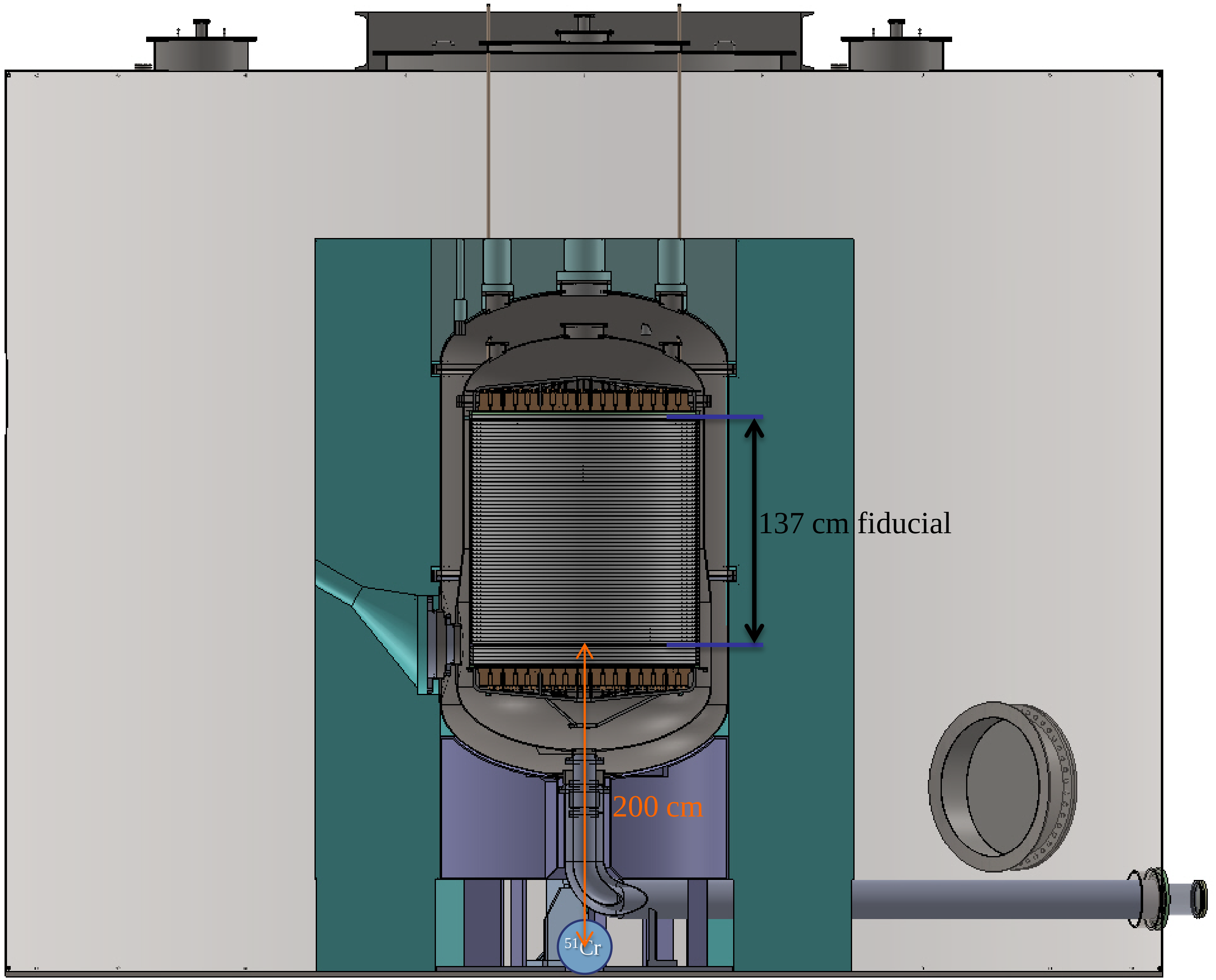
LZ is a two-phase detector that will be sensitive to both the primary scintillation in LXe and scintillation in the gas phase from individual accelerated drift electrons.



It will have a spatial resolution of better than 1 cm.

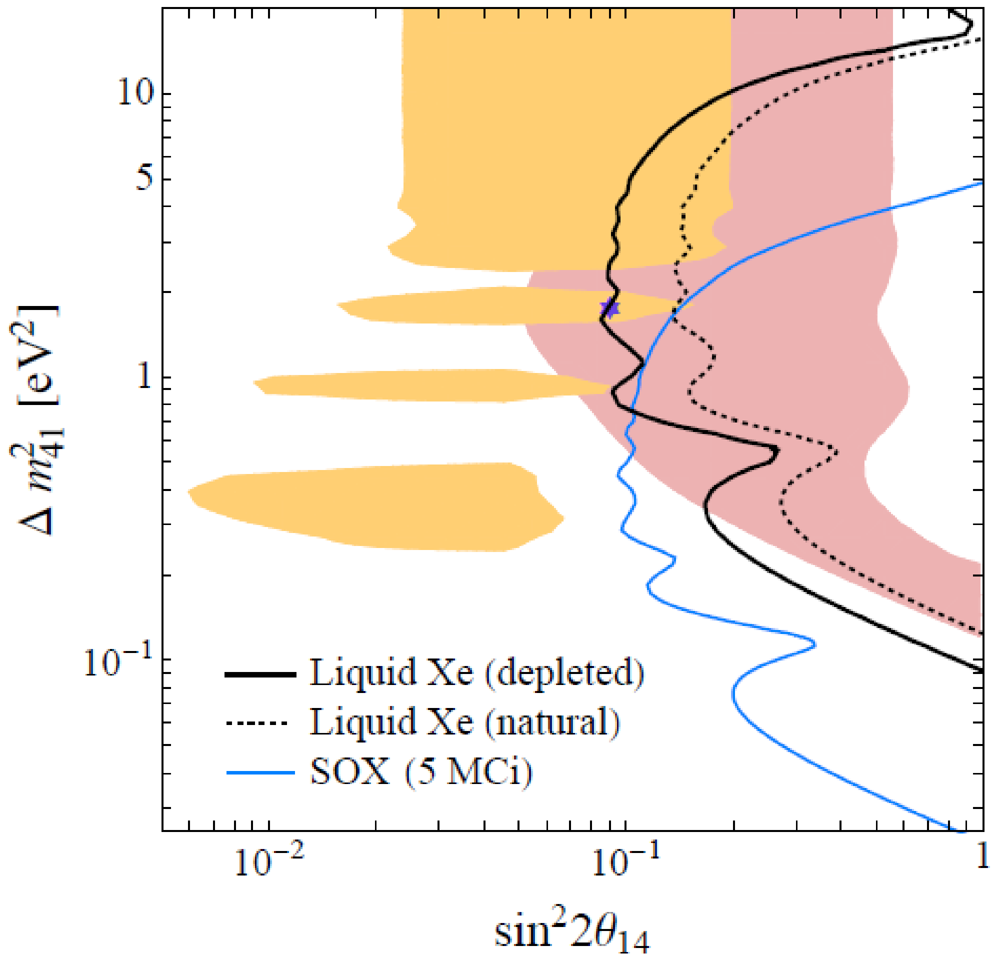
Its goal is to look for nuclear recoils from WIMP scattering with a threshold below 1 keV in electron equivalent energy.

Possible Source Implementation at LZ

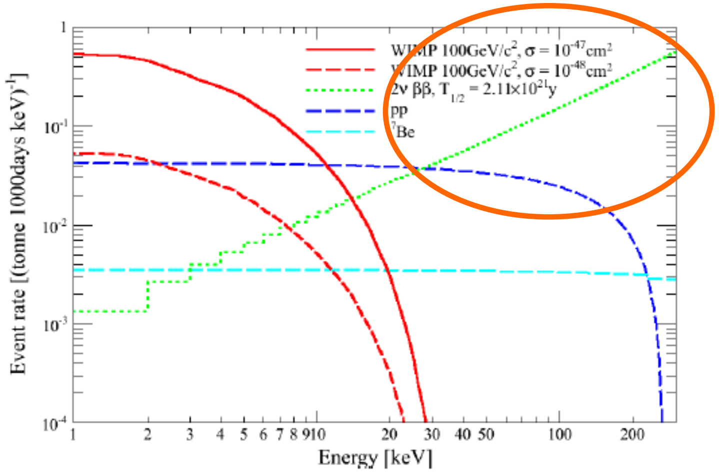


LZ Sterile Oscillation Sensitivity

The shape only sensitivity shows the oscillometric sensitivity.



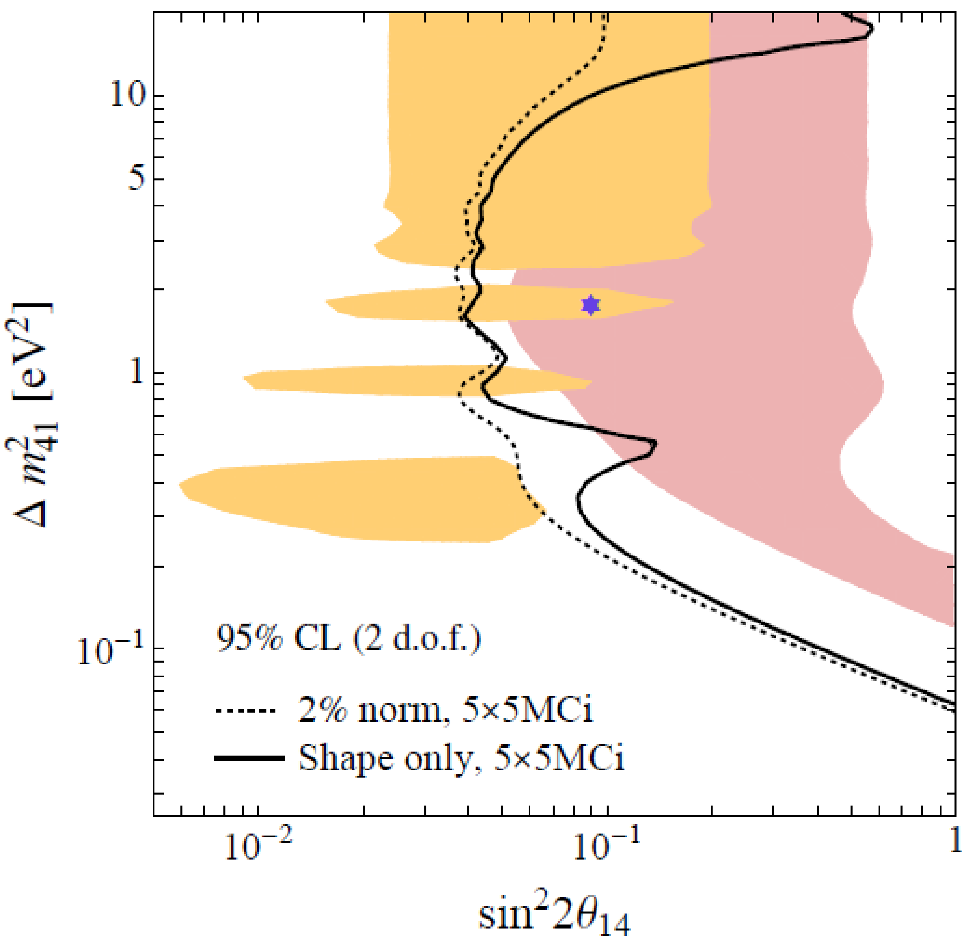
Across the full Cr neutrino energy, the double β-decay isotope, ^{136}Xe, is a significant source of background.



Fortunately, neutrinoless double beta decay experiments need enriched ^{136}Xe.

LZ-Source Ultimate Sensitivity

What would the ultimate source experiment look like?

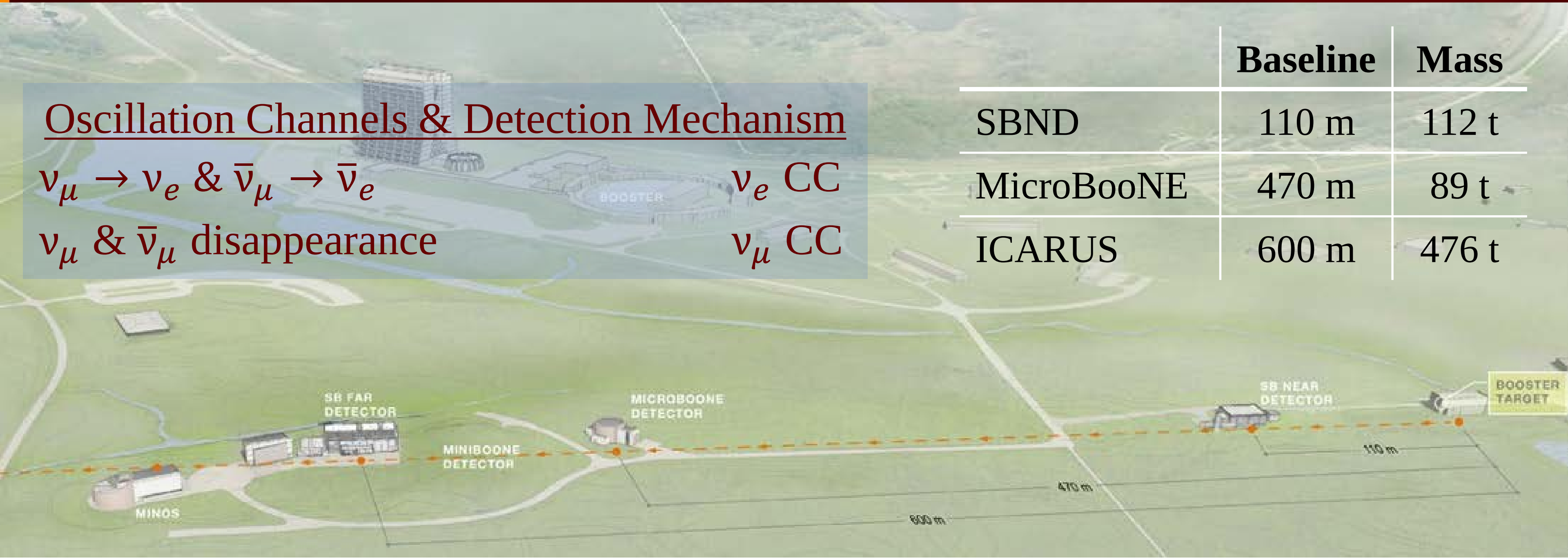


Five runs with a 5 MCi ^{51}Cr source and a 2% normalization uncertainty (as claimed by GALLEX and SAGE) would fully cover the Ga anomaly.

With mono-energetic neutrinos and LZ's high spatial resolution the oscillometric sensitivity is limited at high Δm^2 by the size of the source.

Accelerator Experiments

The Fermilab Short-Baseline Program



<u>Oscillation Channels & Detection Mechanism</u>

$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	ν_e CC
ν_μ & $\bar{\nu}_\mu$ disappearance	ν_μ CC

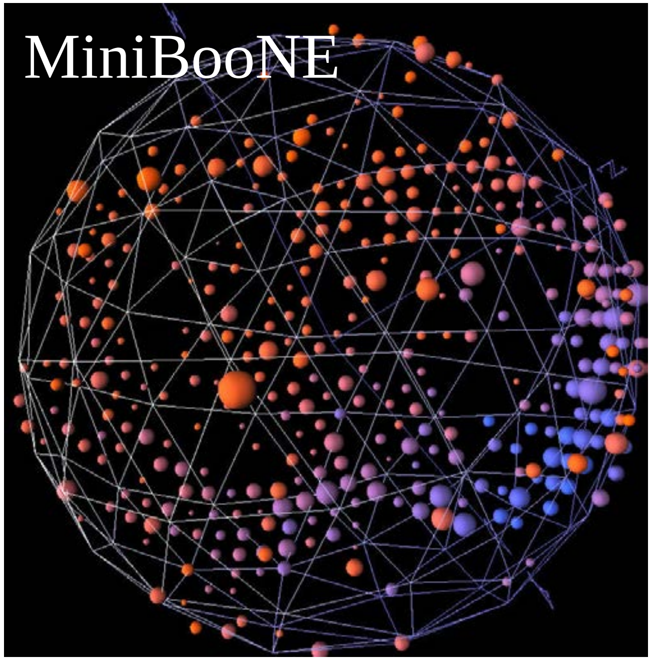
	Baseline	**Mass**
SBND	110 m	112 t
MicroBooNE	470 m	89 t
ICARUS	600 m	476 t

The liquid argon TPC pattern recognition is expected to significantly reduce misID backgrounds.

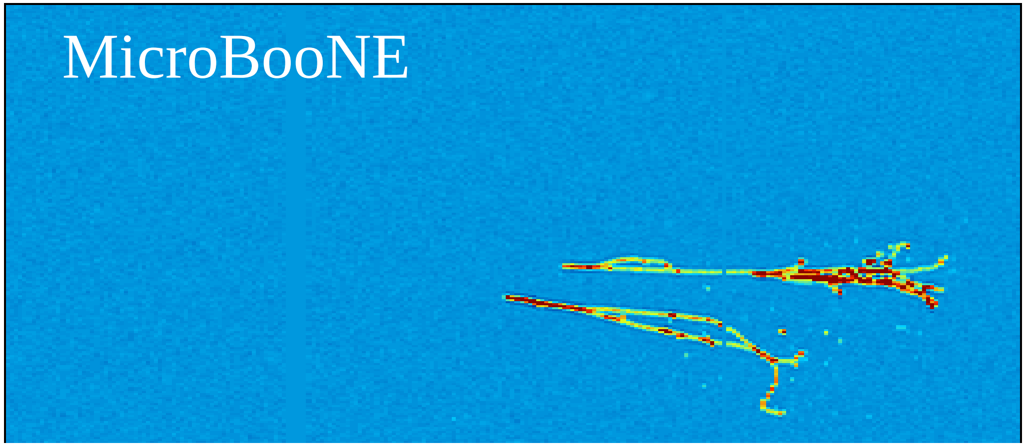
Liquid Argon Detectors

The primary advantage of a liquid argon TPC is pattern recognition.

In particular, neutral current π^0 production can fake a ν_e interaction in a Cerenkov detector, or even in a lower resolution tracking detector.



π^0 Candidates



NC π^0 Production:

$\nu + N \rightarrow \nu + \Delta$ followed by $\Delta \rightarrow N + \pi^0$

LAr TPCs can even identify NC radiative photon events with dE/dx:

NC γ Production: $\nu + N \rightarrow \nu + \Delta$ followed by $\Delta \rightarrow N + \gamma$

0.5% decay fraction

The Fermilab Short-Baseline Program

<u>Oscillation Channels & Detection Mechanism</u>

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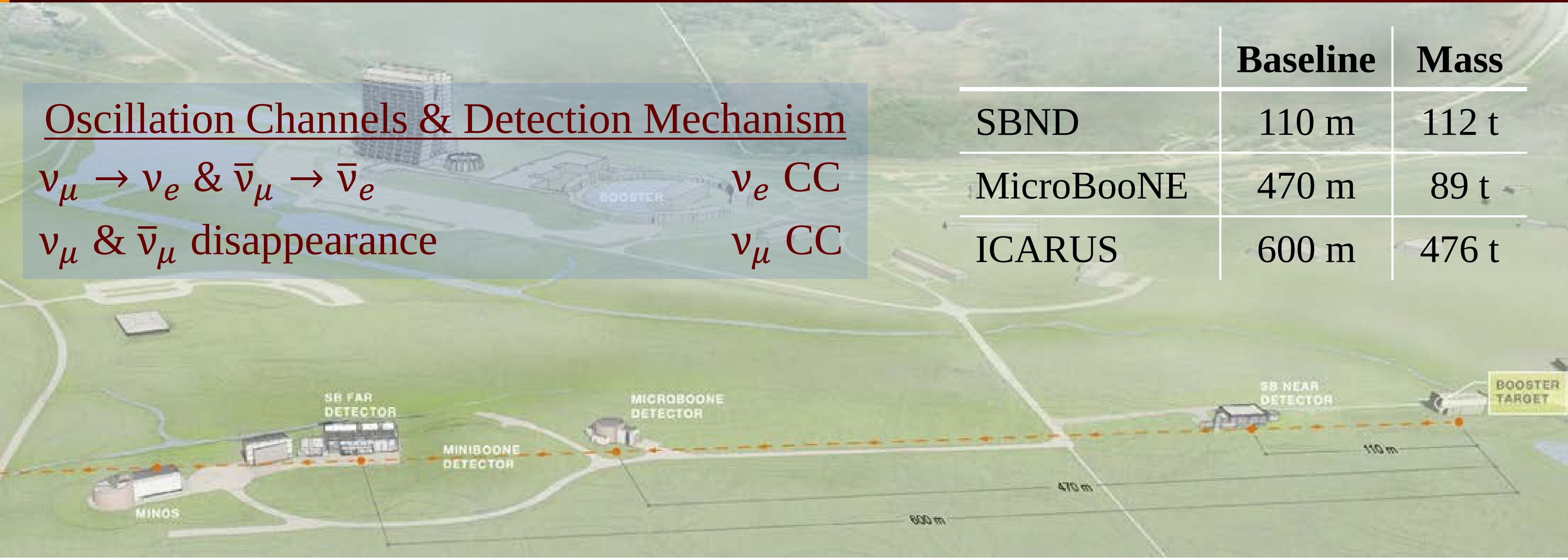
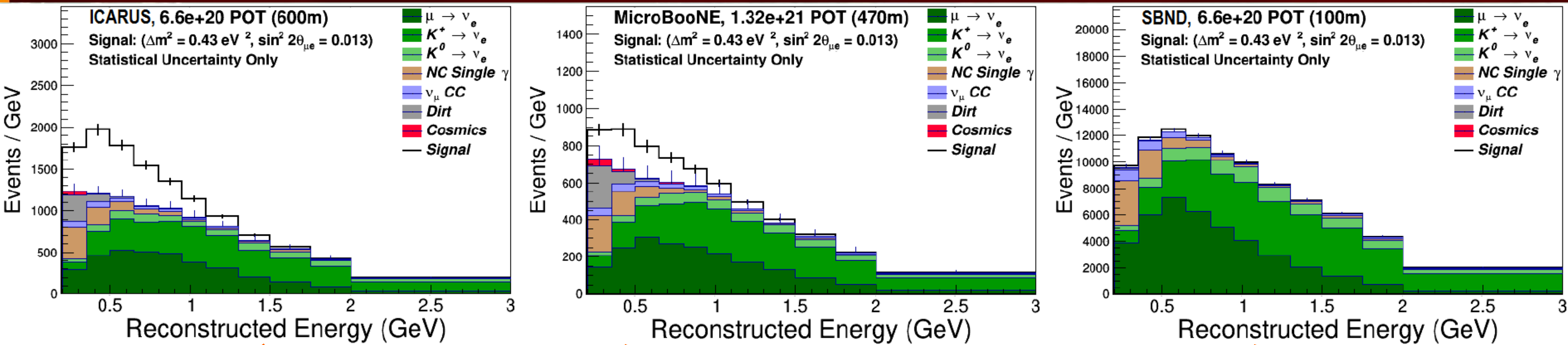


The liquid argon TPC pattern recognition is expected to significantly reduce misID backgrounds.

The near detector provides an inclusive measurement of the beam and misID backgrounds.

The ICARUS T600 at a third baseline significantly boosts the statistics and the dynamic range in L/E.

The Fermilab Short-Baseline Program



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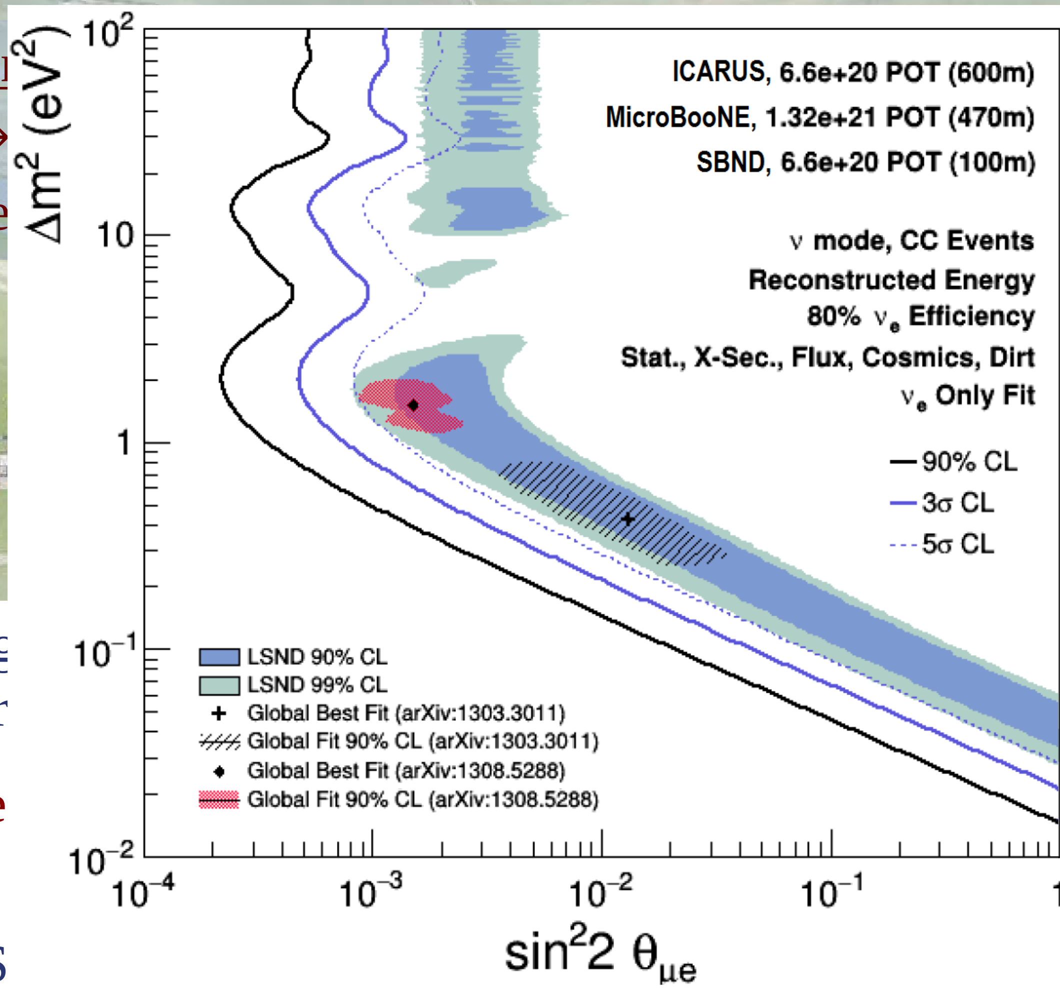


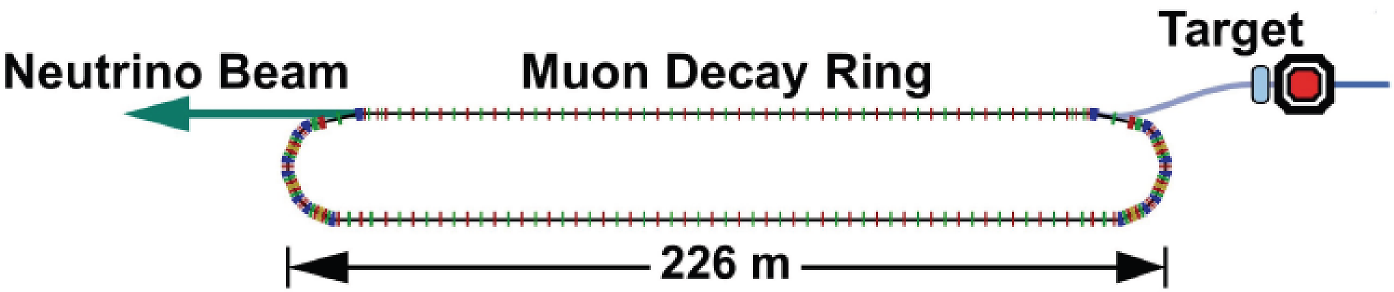
The liquid arg … antly reduce misID backgr

The near dete … m and misID backgrounds.

The ICARUS … tatistics and the dynamic range in L/E.

Muon Storage Ring: nuSTORM

nuSTORM is a low-energy muon storage ring that produces pure and well-characterized beams of ν_μ and $\bar{\nu}_e$, or $\bar{\nu}_\mu$ and ν_e depending on which sign muons are stored.



In the ν_μ appearance channel, observing wrong sign muons is all that's needed to establish oscillations. So, all you need is a magnetized detector (like Minos).

Oscillation Channels & Detection Mechanism		
$\nu_e \to \nu_\mu$ & $\bar{\nu}_e \to \bar{\nu}_\mu$	Golden Mode	ν_μ CC
$\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$		ν_e CC
$\nu_\mu, \bar{\nu}_\mu, \nu_e$ & $\bar{\nu}_e$	disappearance	ν_μ CC

Cyclotron Produced Isotopes: IsoDAR

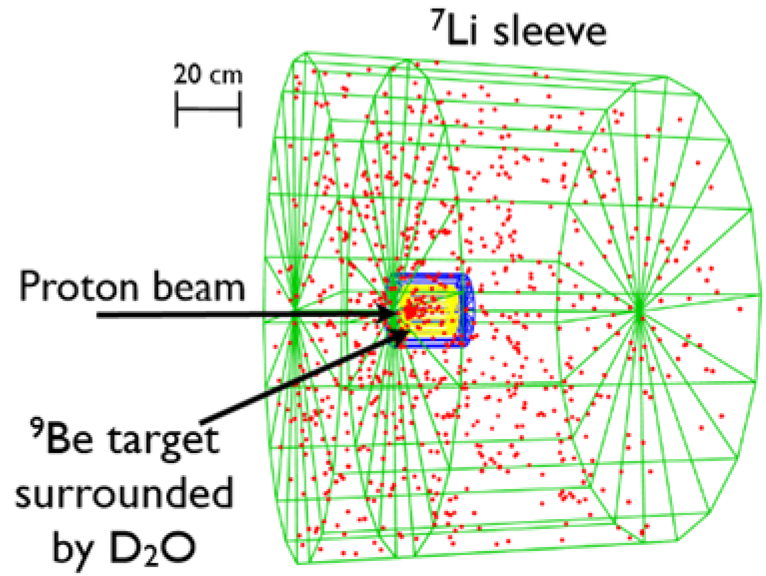
The IsoDAR proposal uses an intense beam of protons to produce ^{8}Li in a ^{9}Br target. The ^{8}Li decays producing $\bar{\nu}_e$ with a β-spectrum (13 MeV endpoint).

Neutrinos are detected via inverse β-decay. KamLAND is a possible host detector.

Oscillations would be observed through the disappearance channel.

<u>Oscillation Channels & Detection Mechanism</u>

$\bar{\nu}_e$ disappearance	Inverse β-decay Golden Mode



Final Thoughts…

With all of the purpose built sterile neutrino experiments running or coming online soon we can hope that a resolution of this long standing problem may soon be at hand.

Until that time there is still plenty to be done and room for more new ideas and creativity.

The search for sterile neutrinos covers many scales in experimental effort, including some with just a handful of collaborators.

If a light sterile neutrino is discovered or ruled out in the next few years, it may be done by one of these small groups. You can't say that about many other questions in particle physics.