Hunting for Sterile Neutrinos II

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Precision Sterile Neutrino Searches

The age of precision sterile neutrino tests has started in only the last few years. These precision test include:

- New *many* new reactor experiments
- One approved source experiment and other interesting source proposals
- A three baseline liquid argon detector program in Fermilab's Booster Neutrinos Beam, and
- A few powerful new concepts that have been proposed.

Requirement for Disappearance Experiments

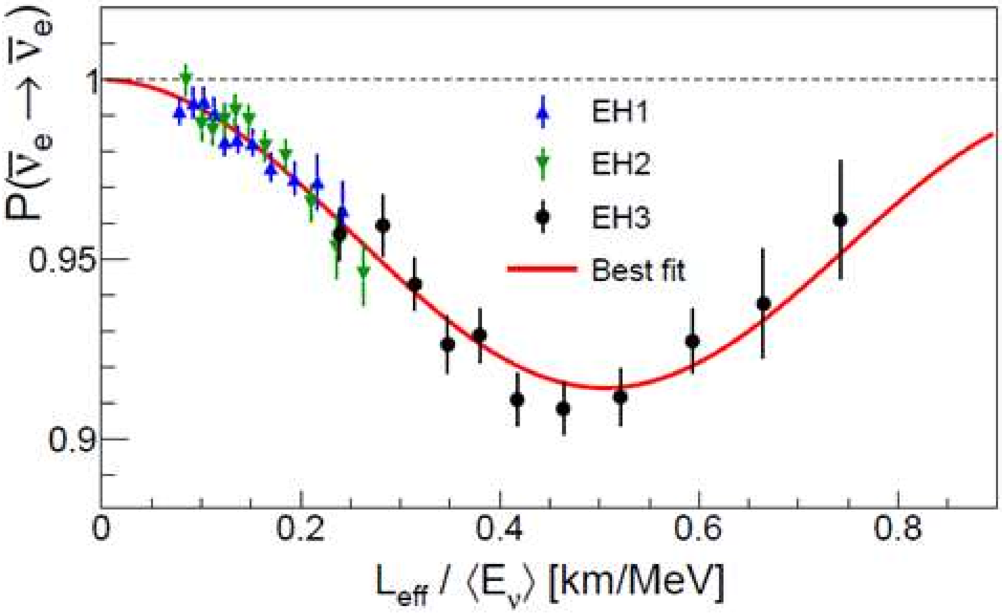
"It don't mean a thing if it ain't got that swing"

–American jazz great Duke Ellington

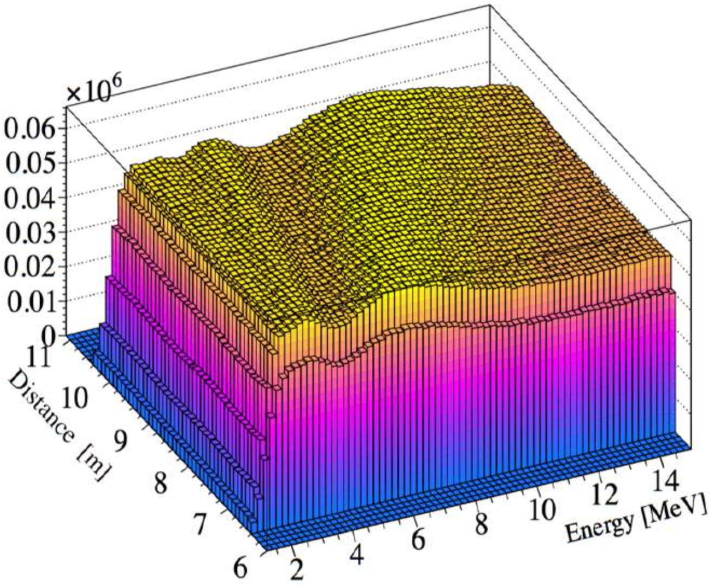
Definition:

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

Daya Bay, arXiv:1505.03456 [hep/ex]



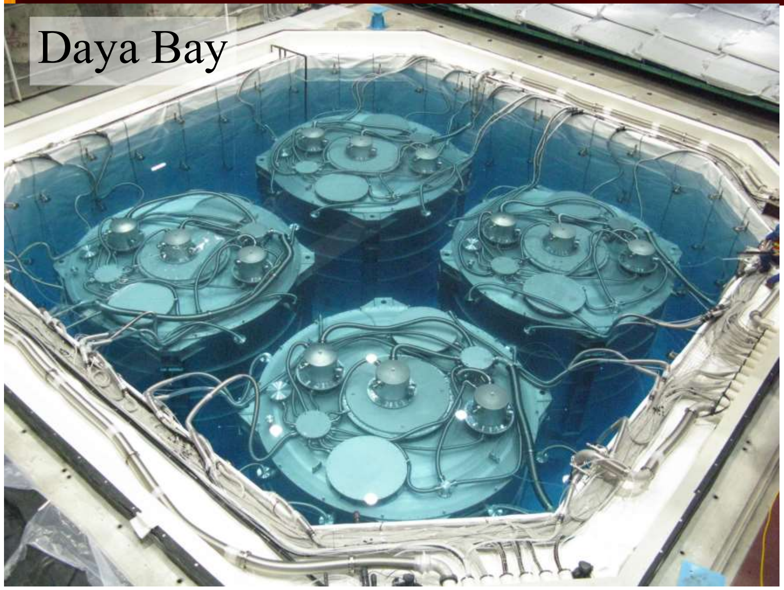
Possible oscillations in a short-baseline reactor experiment



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

Reactor Experiments

Reactor Experiments



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

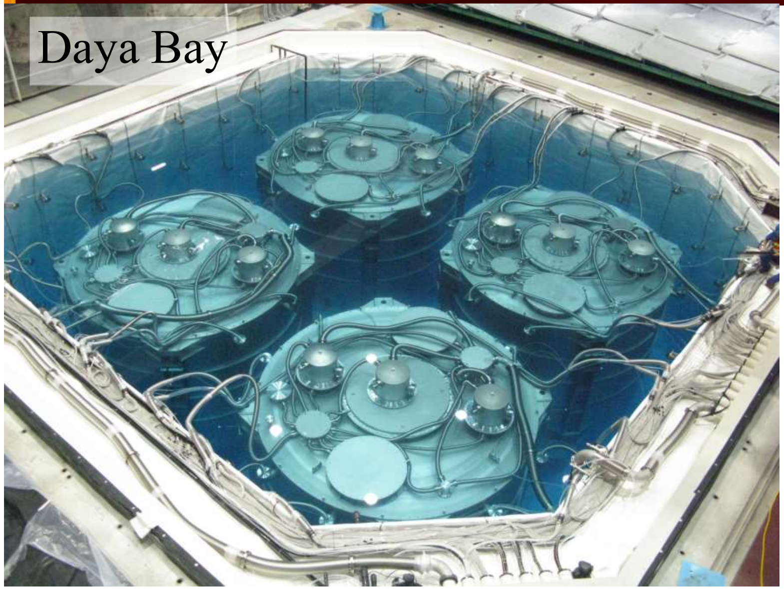
- on the surface
- with smaller detectors
- without space for massive clean shielding
- or gamma catcher

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

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 neutron enters the detector, creates a prompt signal, thermalizes and is captured.
3. β+n decays of spallation isotopes ─ isotopes such as ^{9}Li and ^{8}He with β+n decay modes can be created in a spallation with μ on ^{12}C.

Reactor Experiments


Daya Bay

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If you have to worry about this background at the surface you're doing much better than expected on the other two.

Reactor Experiments

The short-baseline experiment is all about backgrounds:

Random Coincident

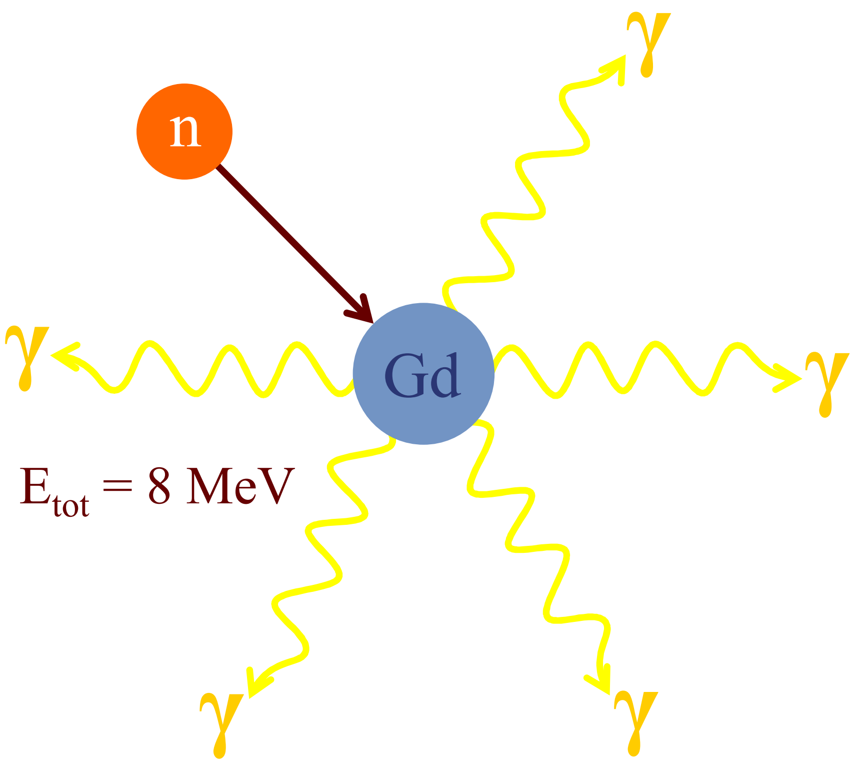
1. You can always add shielding
   But it’s expensive and you don’t have much space
2. Unbiased spatial resolution for a tight spatial cut
   Could gain a factor of 2000 over Daya Bay
3. High neutron tagging efficiency and purity
   Use ^{6}Li (with pulse shape discrimination) or Gd (with containment)

Neutron Capture Options

Daya Bay, RENO and Double Chooz tag neutrons with Gd capture, in conjunction with a large gamma catcher to contain the gammas.

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

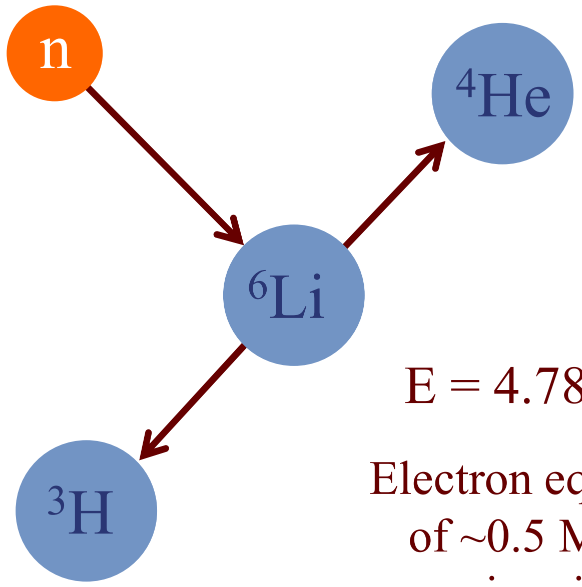
Neutron Capture on Gadolinium



E_{tot} = 8 MeV

Poorly contained in small detectors

Neutron Capture on Lithium-6



E = 4.78 MeV

Electron equivalent of ~0.5 MeV in organic scintillator

Contained in a few microns

Reactor Experiments

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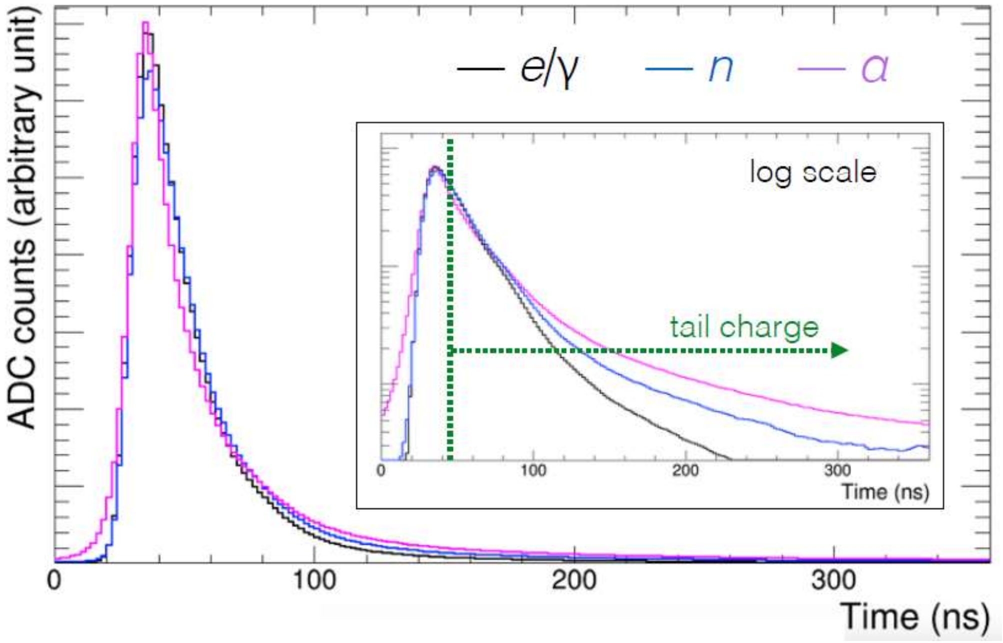
Fast Neutron

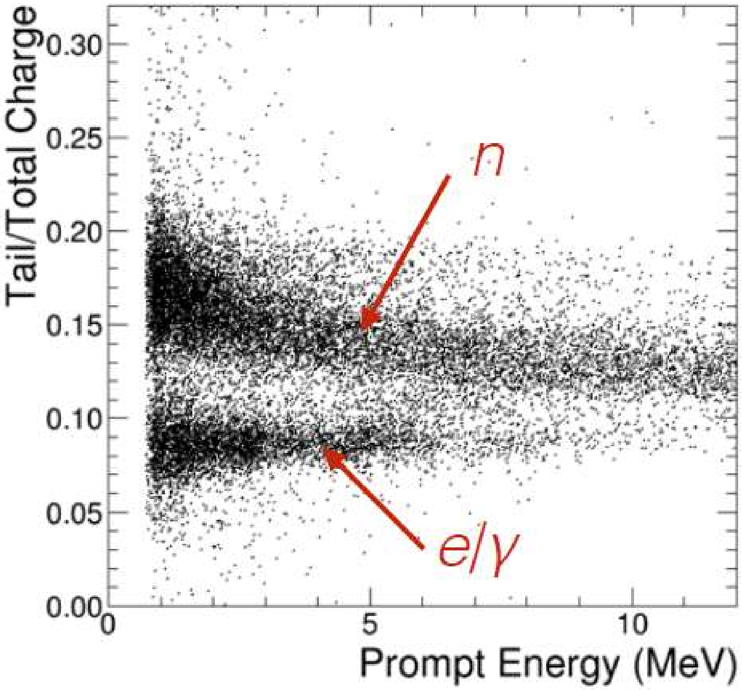
1. Add shielding
   requires large overburden
2. Use pulse shape discrimination on the recoil protons

Pulse Shape Discrimination

In some organic liquid scintillators highly ionizing particles give enhanced delayed light

The plots are from NEOS





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

Reactor Experiments

The short-baseline experiment is all about backgrounds:

Random Coincident

1. You can always add shielding

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

2. Unbiased spatial resolution for a tight spatial cut

   Could gain back a factor of as much as 2000 over Daya Bay

3. High neutron capture efficiency and purity

   Use ^{6}Li (with pulse shape discrimination) or Gd (with containment)

Fast Neutron

1. Add shielding

   requires large overburden

2. Use pulse shape discrimination on the recoil protons

3. Use topological selections: Multiple recoil protons, 511 keV γ tag…

   This requires a highly segmented detector.

Reactor Experiments

In order to have good sensitivity to Δm^2 of 1 eV^2 and above, you need to maximize the L/E resolution.

This requires:

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

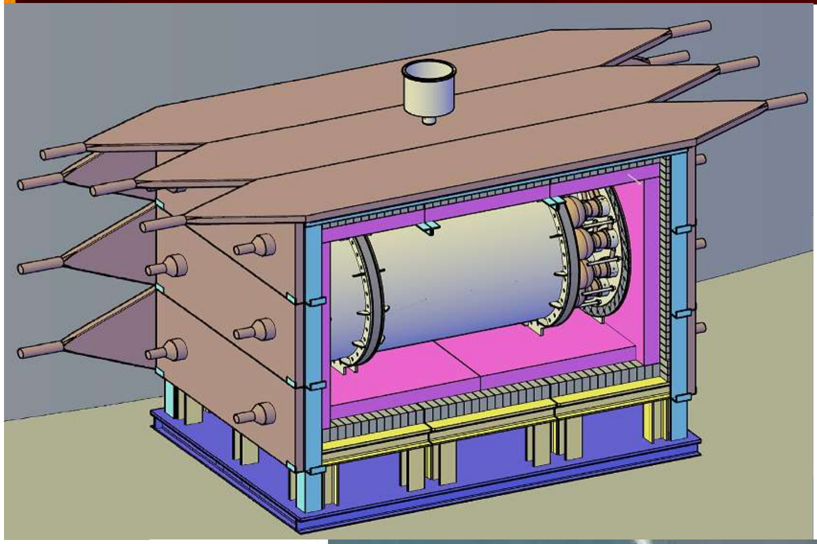
Next Generation Reactor Experiments

There are many new reactor experiments:

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

There have been other proposals/concepts from China, Japan…

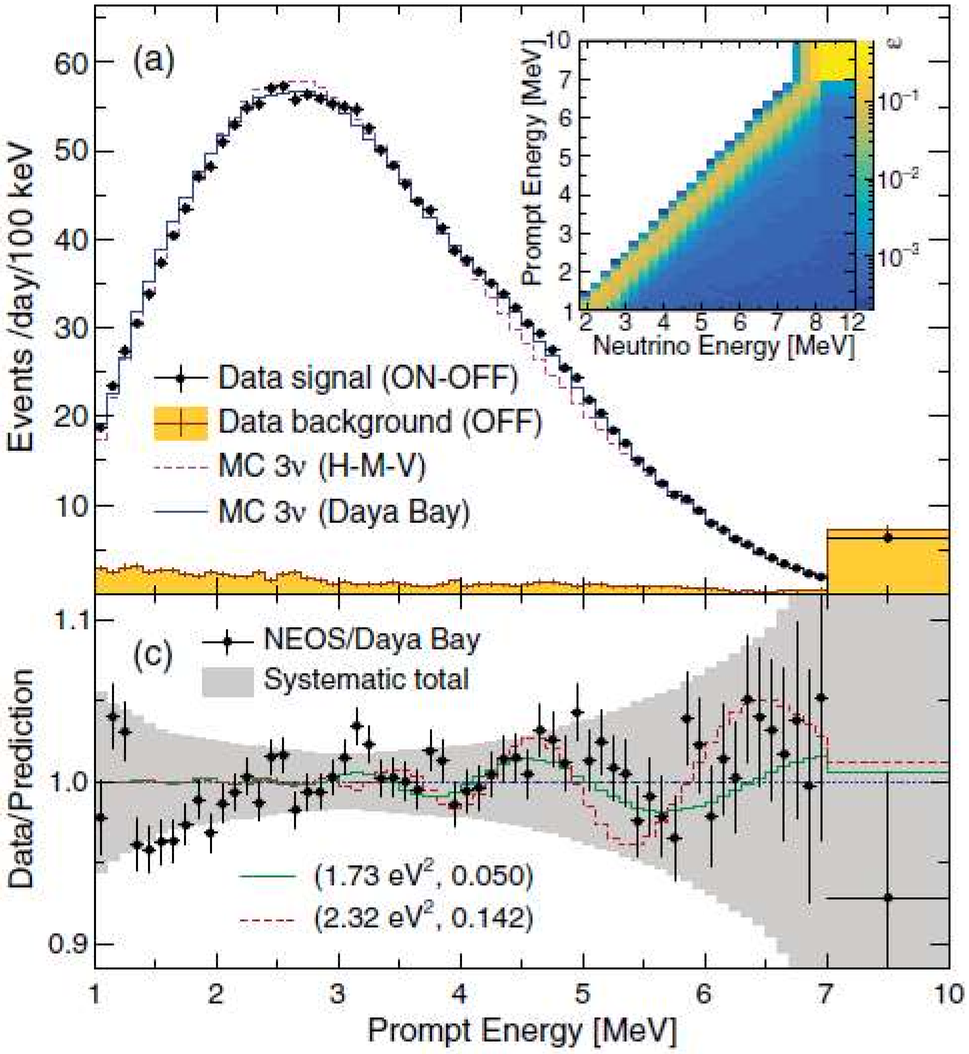
NEOS

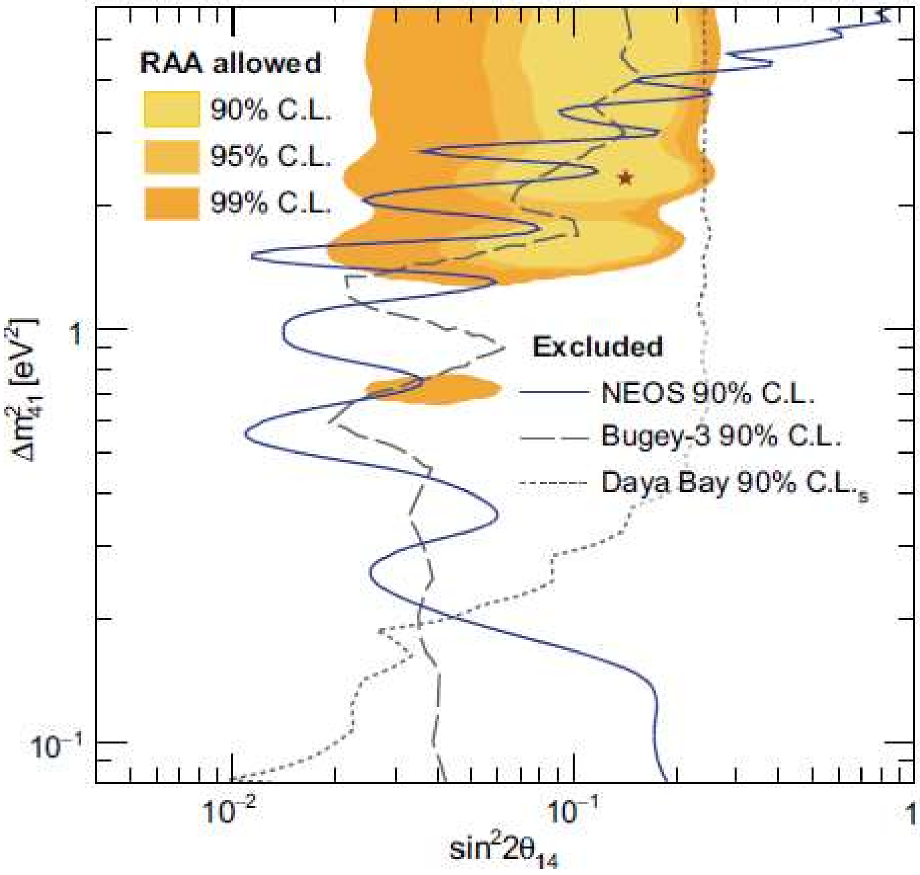


Characteristics:

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

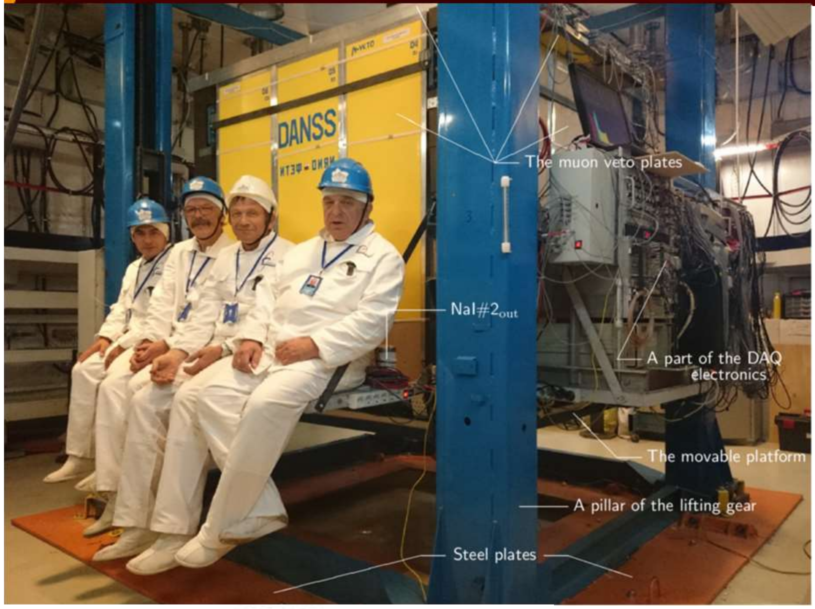
NEOS





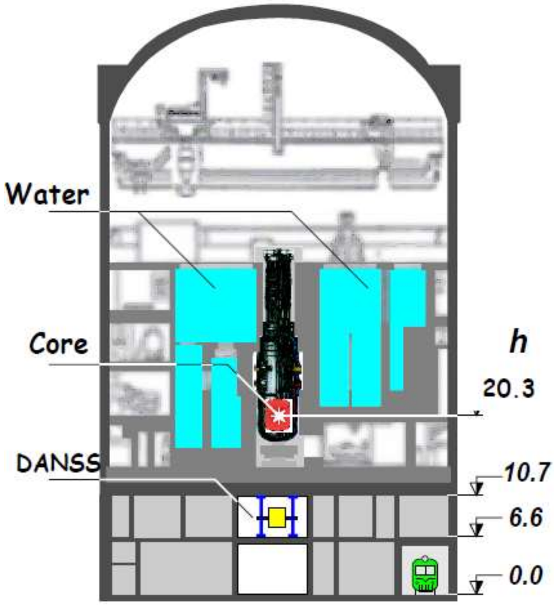
Reported as a limit, but Δm^2s near 2 eV^2 seem to fit the data reasonably well.

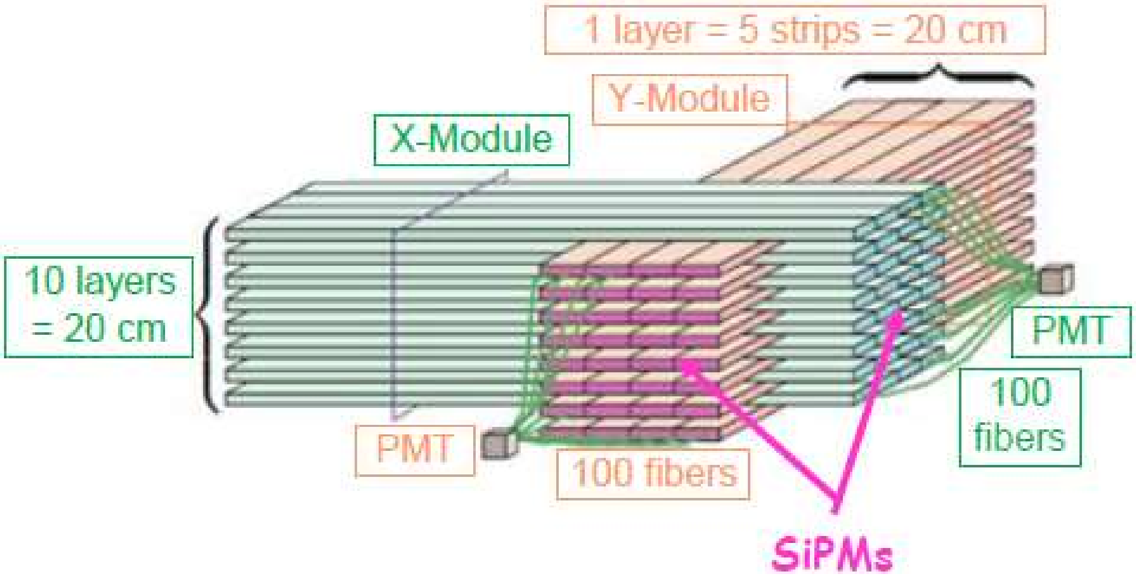
DANNS



Characteristics:

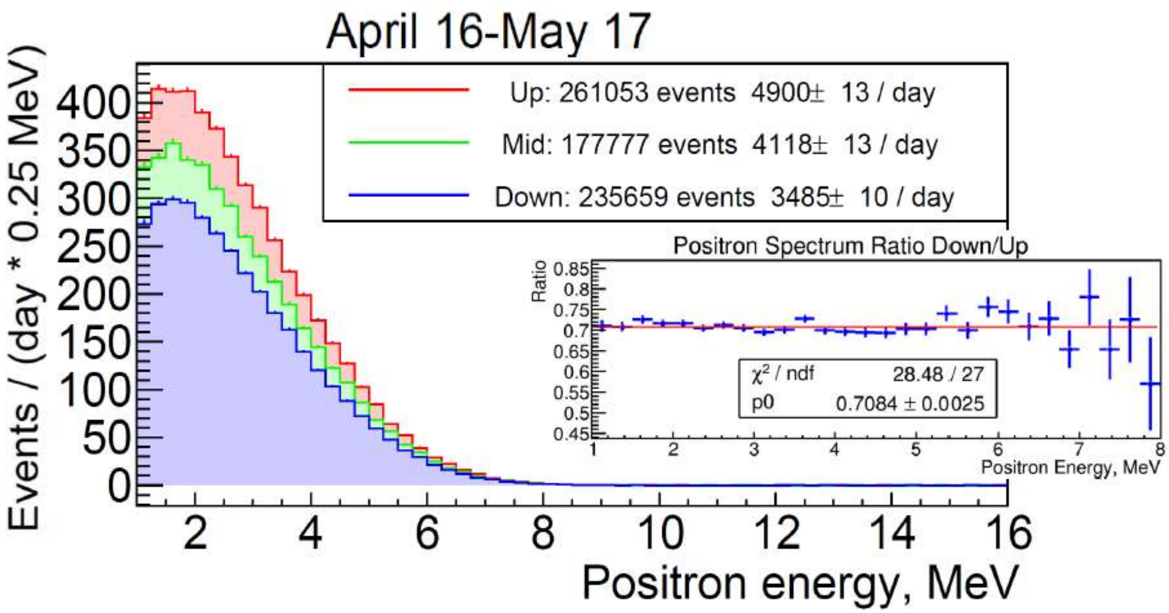
- 50 m.w.e overburden
- Segmentation
- Gd tag
- Variable baseline (±1 meter)
- Large core

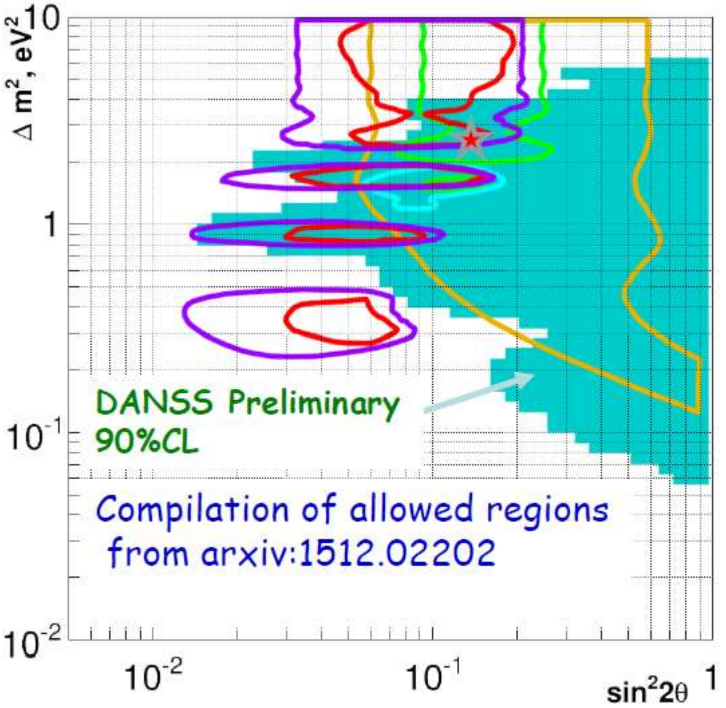




DANSS

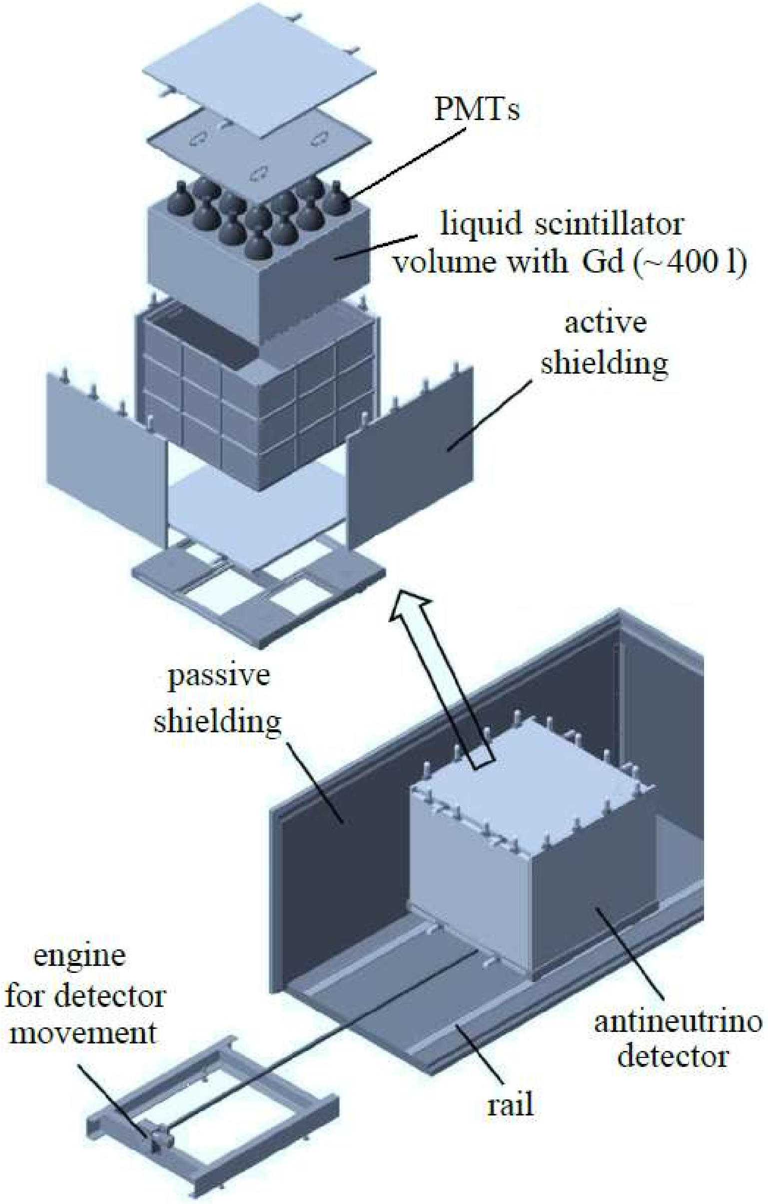
No difference seen in the spectrum from different baselines, and that is used to set a limit.





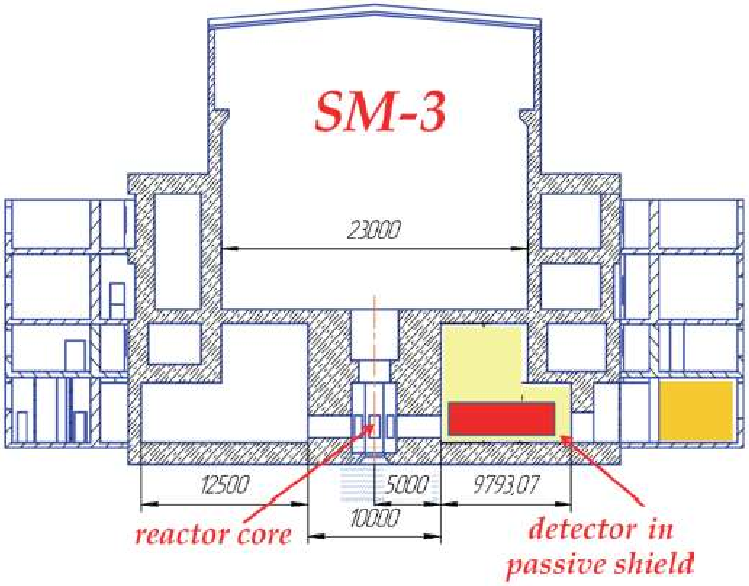
The baseline variation is smaller than the core size and the fact that they don’t see the 5 MeV bump calls their energy resolution into question.

Neutrino-4

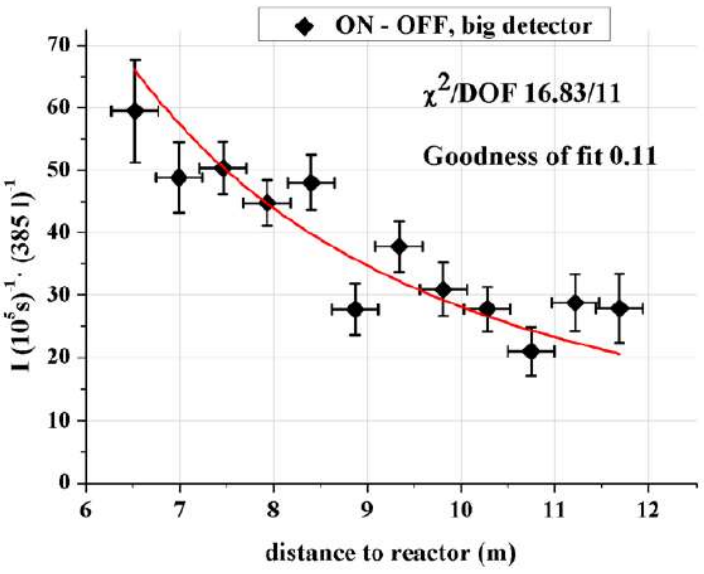


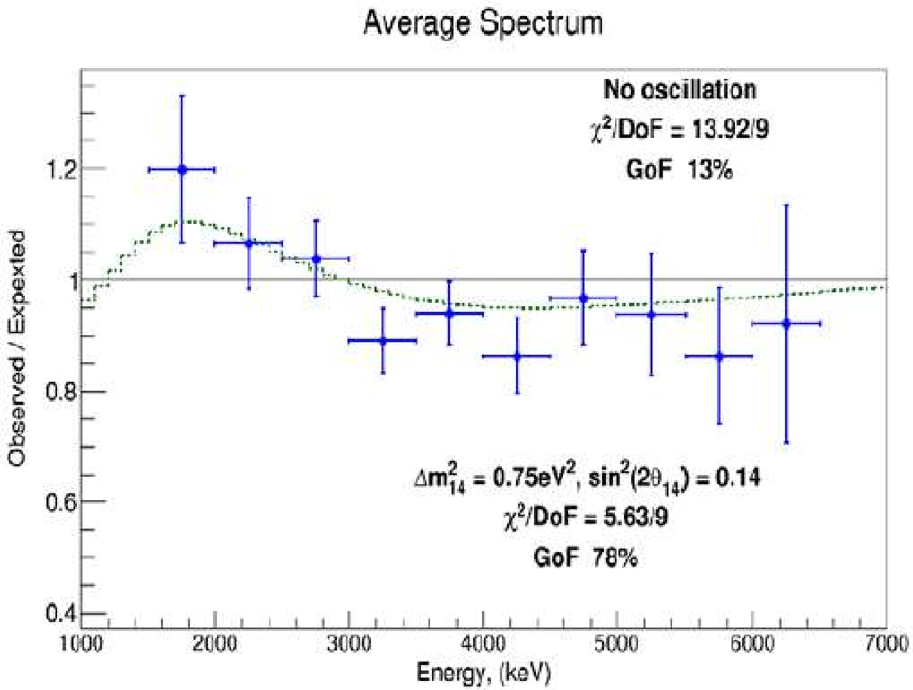
Characteristics:

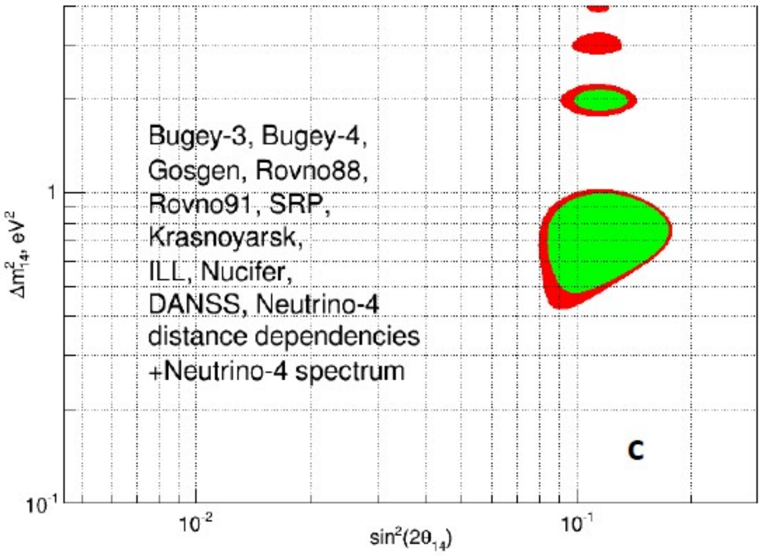
- Some overburden
- Course segmentation
- Gd tag
- Variable baseline (6 to 12 meters)
- Compact core



Neutrino-4





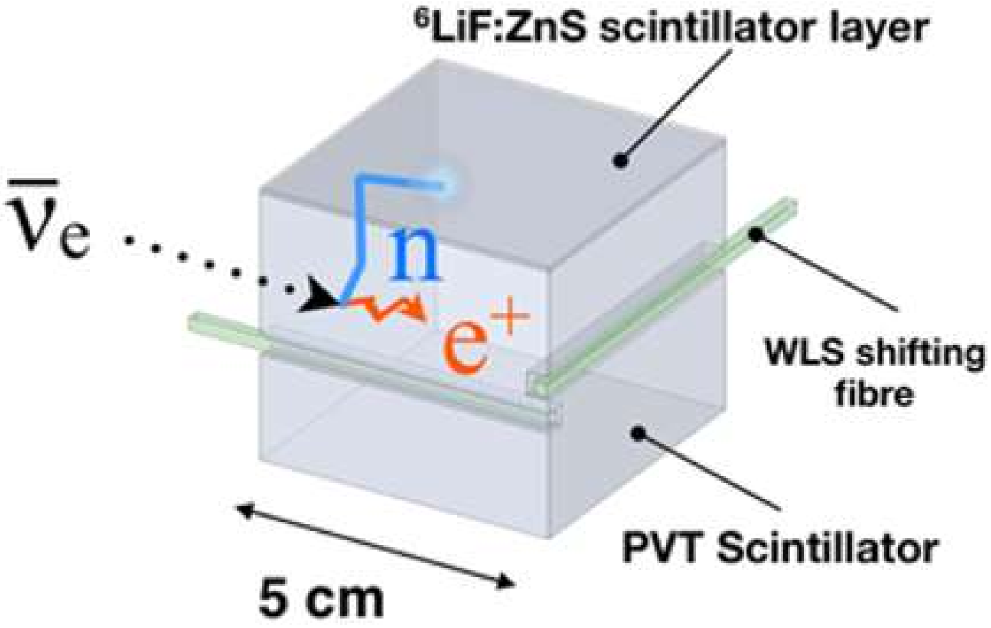


This analysis is consistent with oscillations, but the statistics are still low.

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

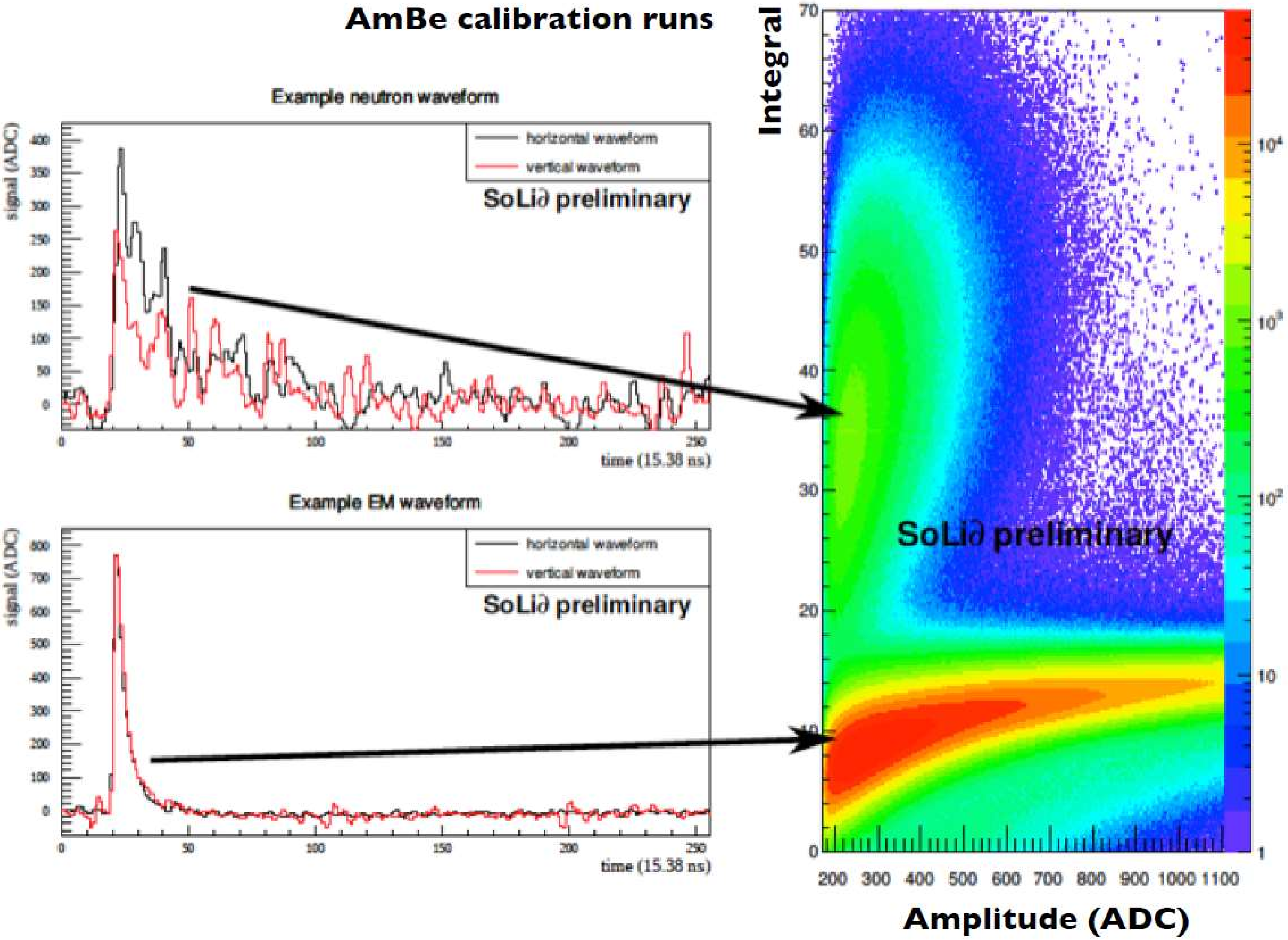
The SoLid detector tags neutrons in thin sheets of ^{6}Li-loaded, silver activated zinc sulfide scintillator: ^{6}LiF:ZnS(Ag).

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



The SoLid Signal

AmBe calibration runs



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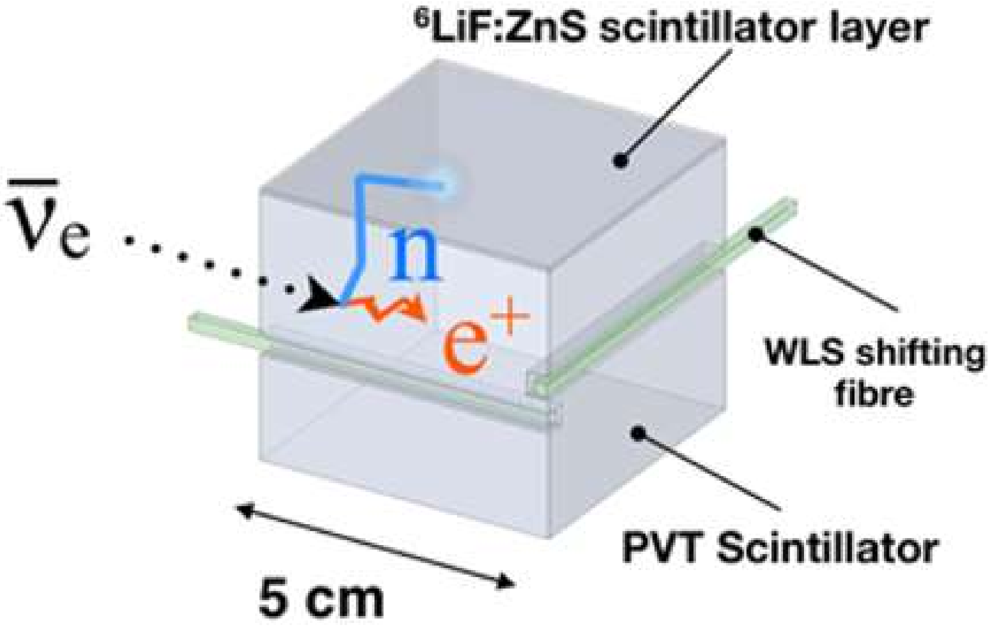
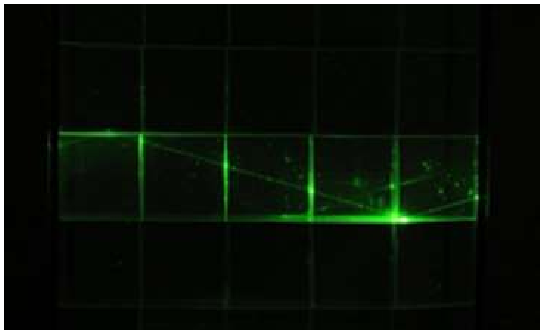
SoLid achieves unprecedented spatial resolution by segmenting its scintillator in cubes which are readout in two dimensions by wavelength shifting fibers.

SoLid's fiber readout is inefficient and it limits their energy resolution.



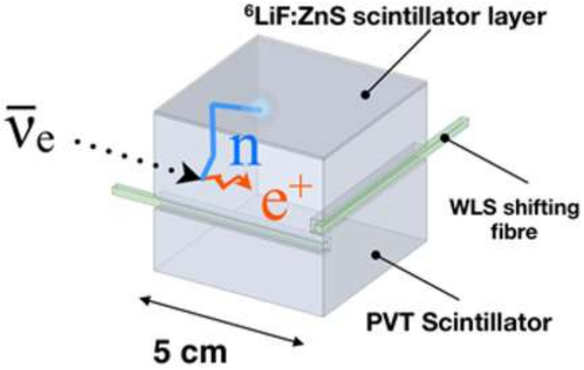
Technological Convergence

LENS



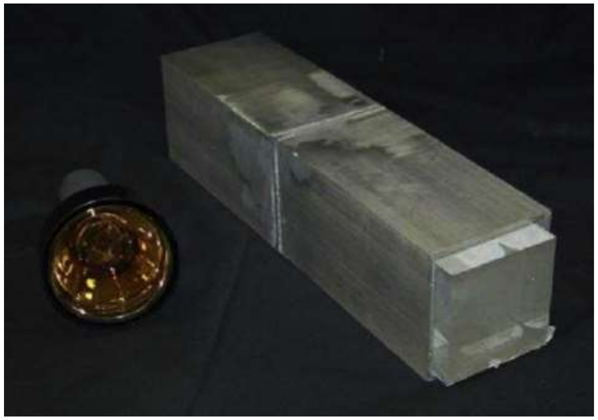
The **Raghavan Optical Lattice** (ROL), invented by the late Virginia Tech professor, Raju Ragahvan, divides a totally active volume into cubical cells that are read-out by total internal reflection. LENS was designed for solar neutrino detection and not optimized for reactor antineutrino detection.

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

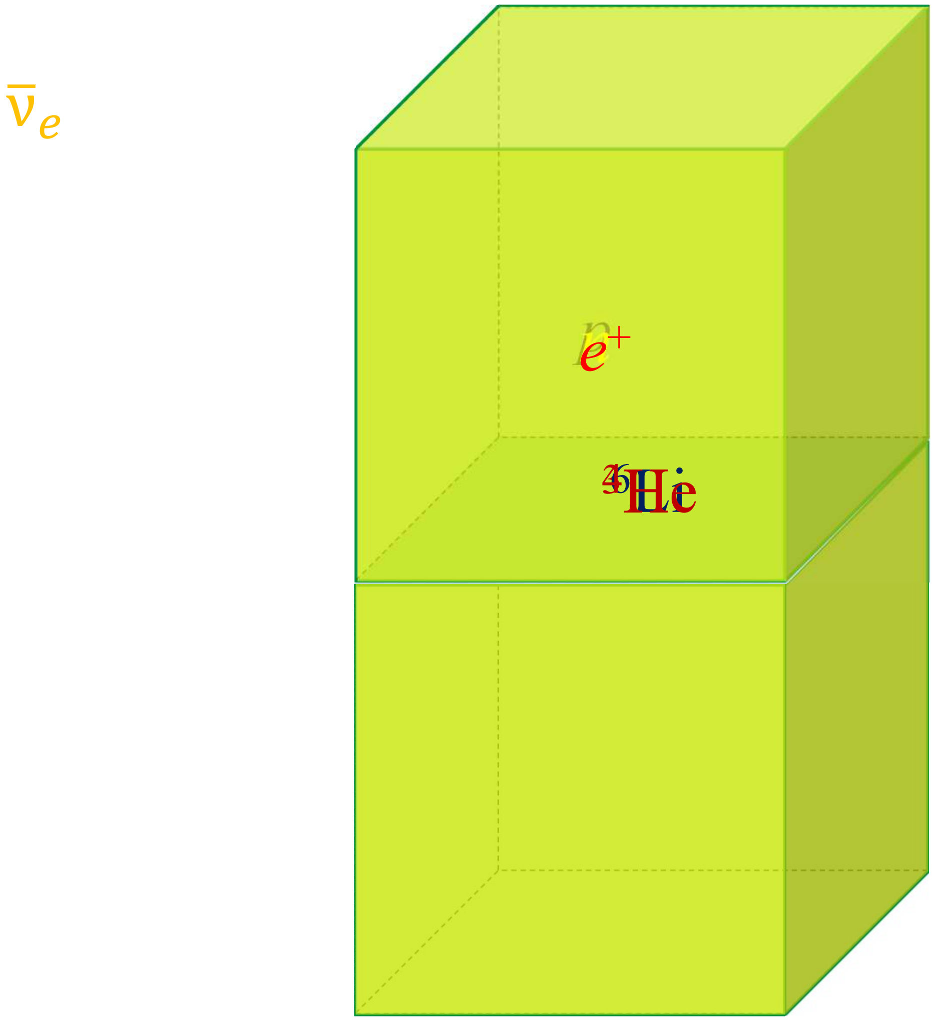


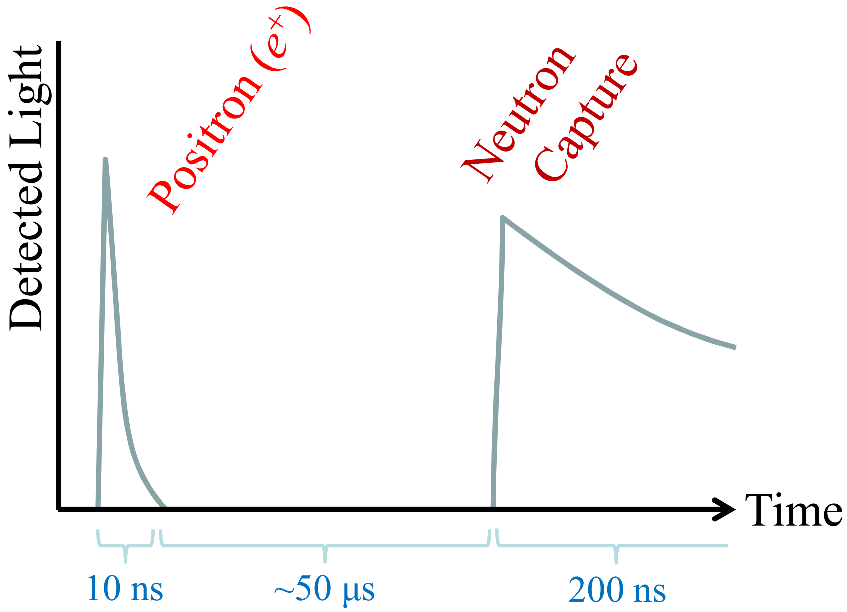
Used ^{6}LiF:ZnS(Ag) sheets mated to a **solid bar of wavelength-shifting plastic scintillator**. This prototype demonstrated the feasibility of pairing the sheets to wavelength shifting plastic, but the long bars do not have the spatial resolution required for good background rejection

CHANDLER

Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced ROL

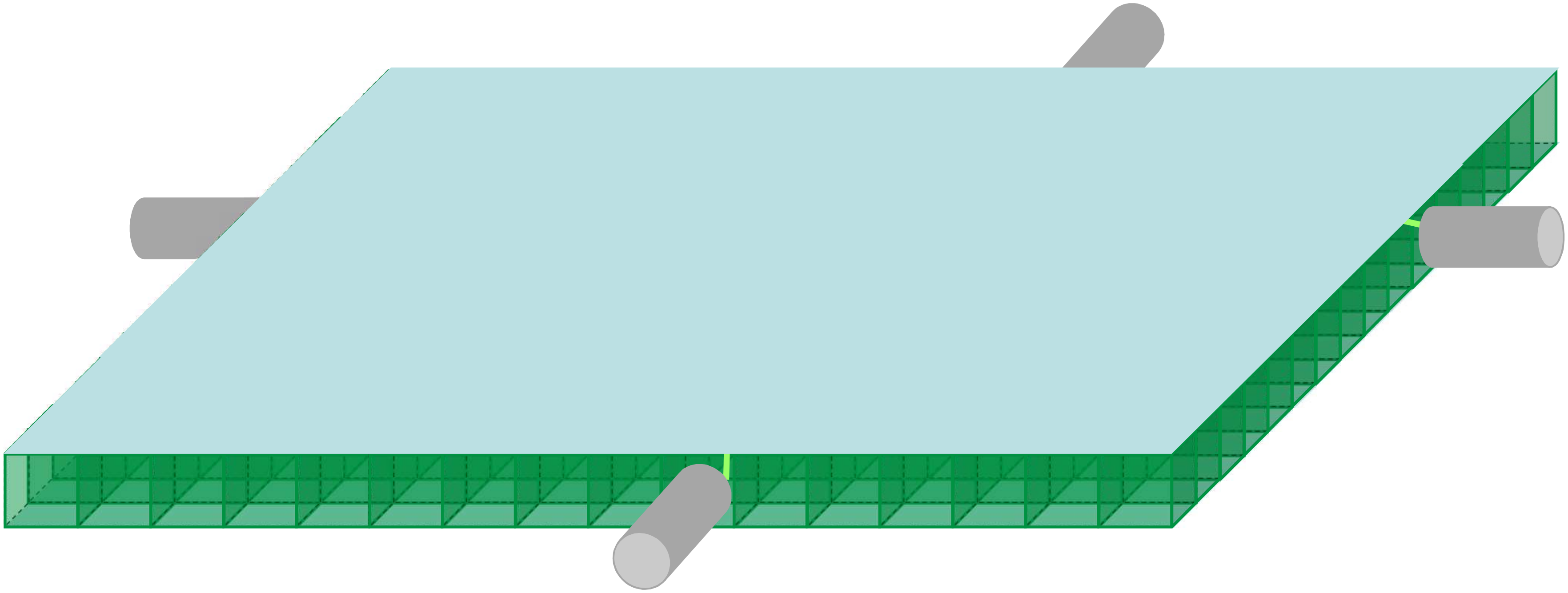
The CHANDLER Detector





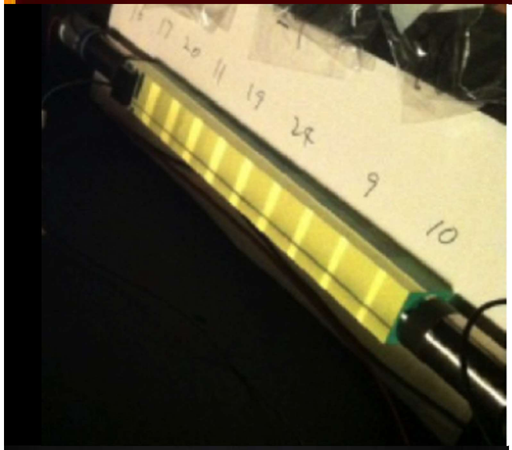
The CHANDLER Detector

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.

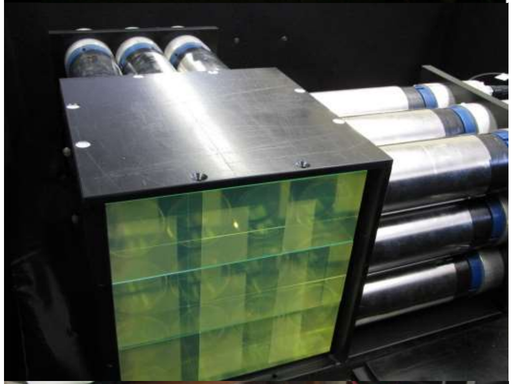


The light is transported to the detector's edge by total-internal-reflection and readout by PMTs.

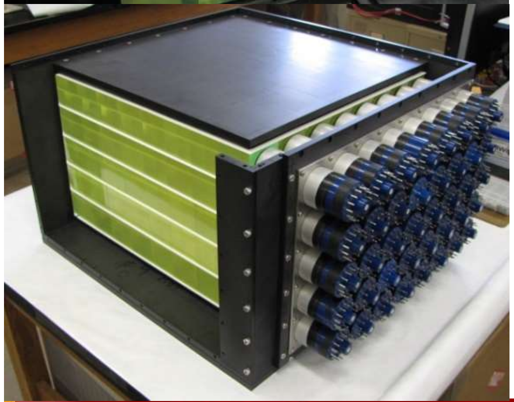
Research and Development Effort



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 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 will be deployed at the North Anna Nuclear Power Plant in the next few weeks, with the goal of demonstrating neutrino detection.

MiniCHANDLER Deployment

MiniCHANDLER has been deployed at the North Anna Nuclear Power Plant since June 15th.

The purpose of this deployment is to demonstrate reactor neutrino detection.

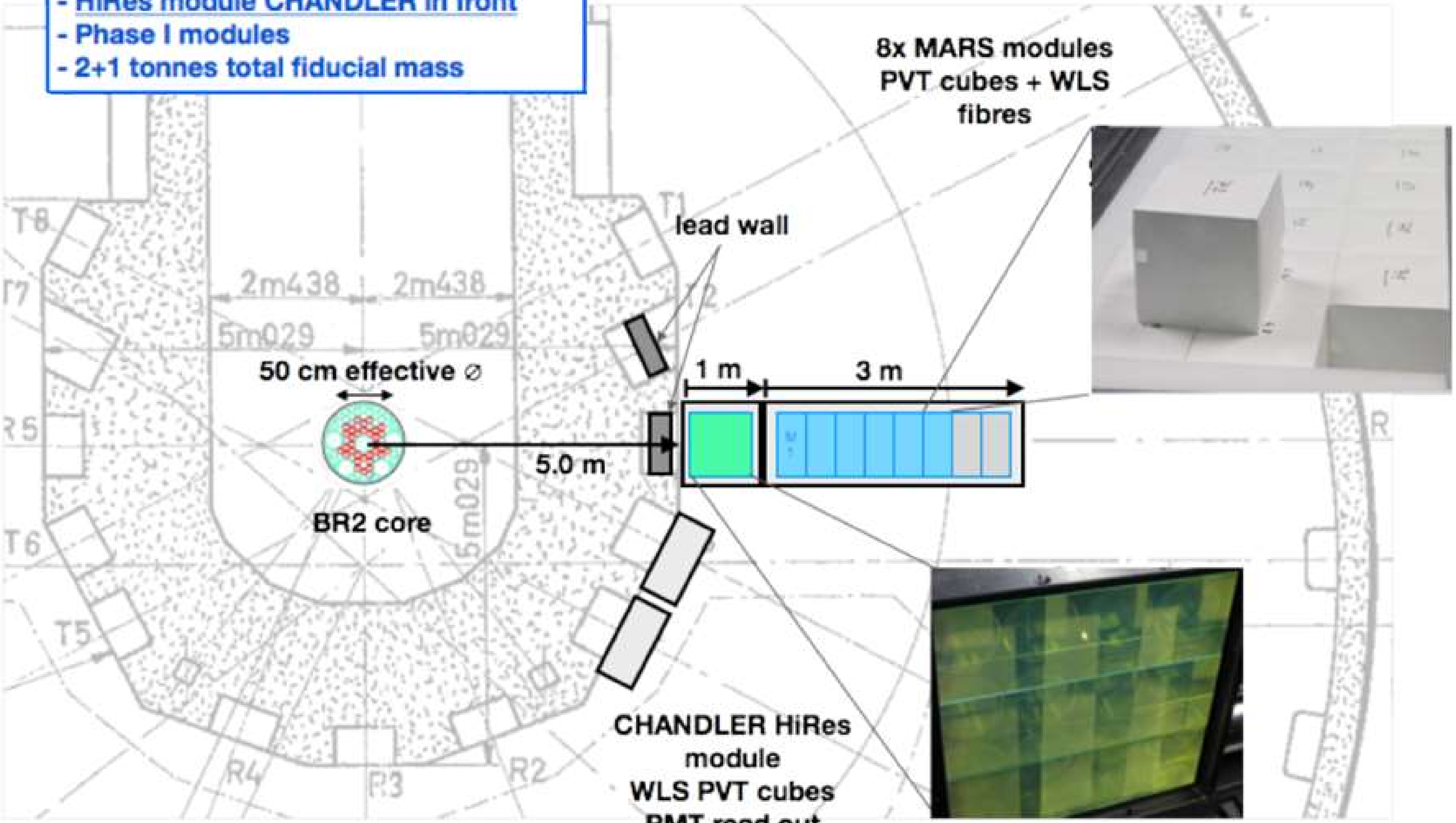
We expect to see about 100 neutrino events per day.

SoLid/CHANDLER at the BR2 Reactor

Phase II experimental set up

450 Days of Reactor on

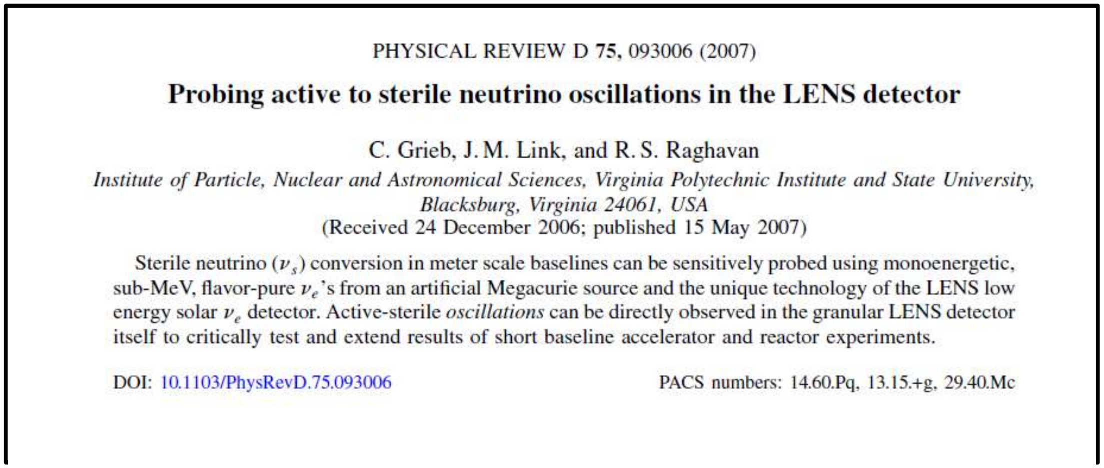
Configuration:
- HiRes module CHANDLER in front
- Phase I modules
- 2+1 tonnes total fiducial mass



CHANDLER HiRes module
WLS PVT cubes
PMT read out
1 tonne fiducial

Source Experiments

The LENS-Sterile Concept



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

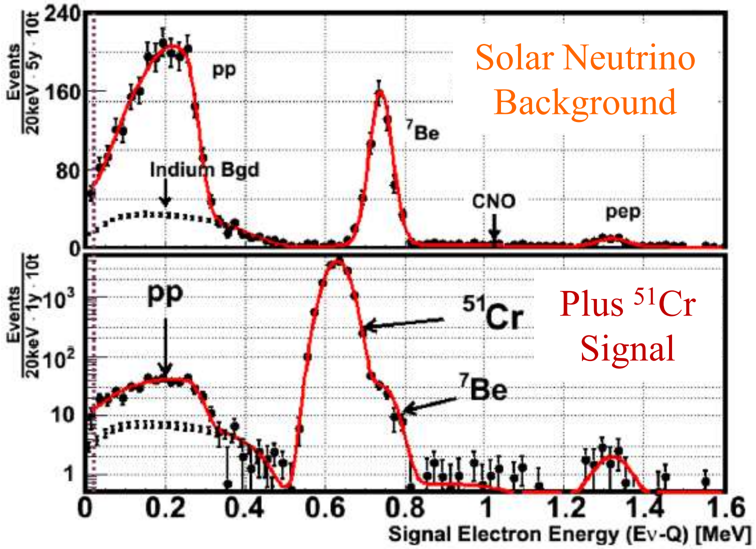
Probing active to sterile neutrino oscillations in the LENS detector

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

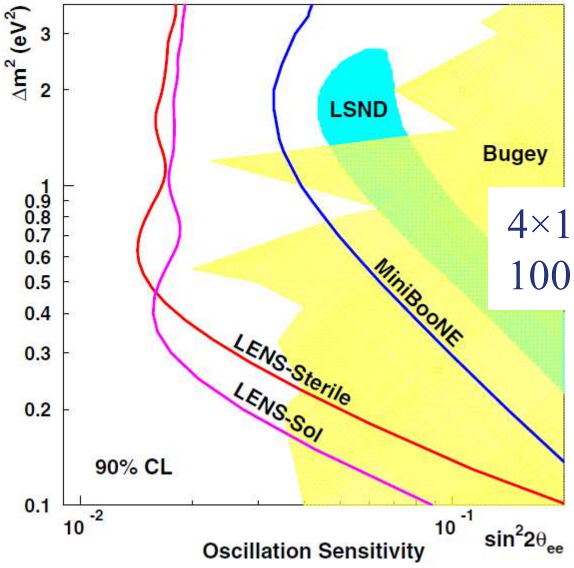


Solar Neutrino Background

Plus ^{51}Cr Signal

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

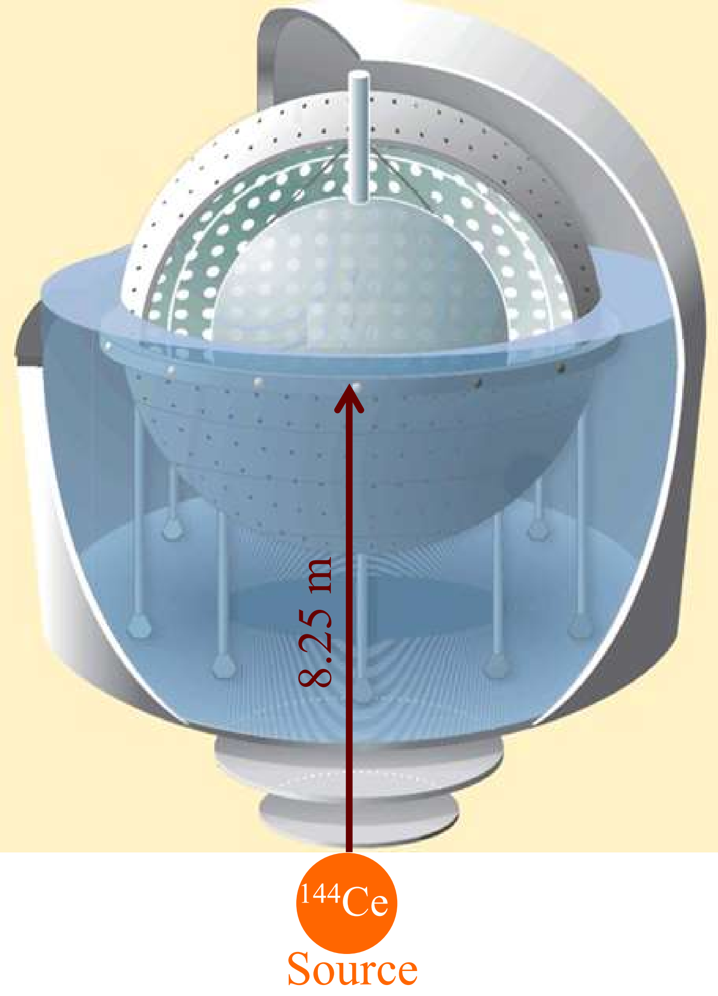
By inserting a Mega-Curie ^{51}Cr source in the center of the LENS detector one could observe a full wavelength, or more, of large Δm^2 oscillations in a few meters.



4×10 MCi
100 days each

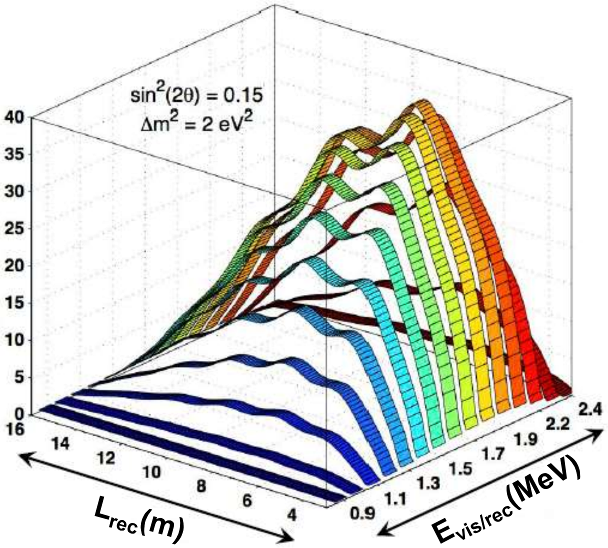
SOX: Source Oscillations at BoreXino

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



SOX will use a ^{144}Ce source.

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



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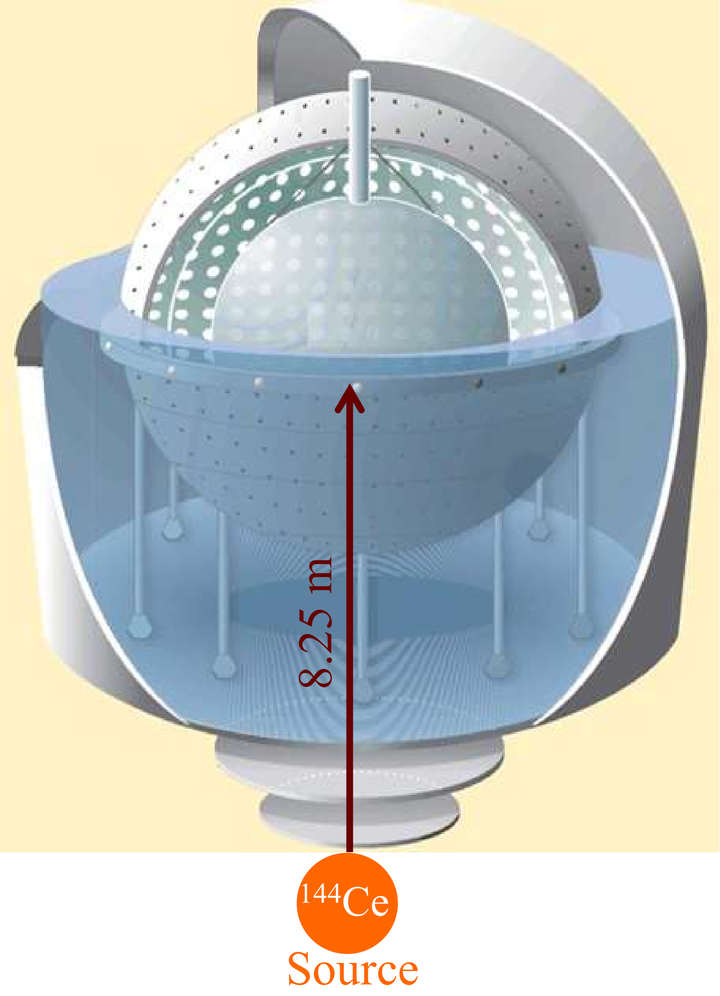

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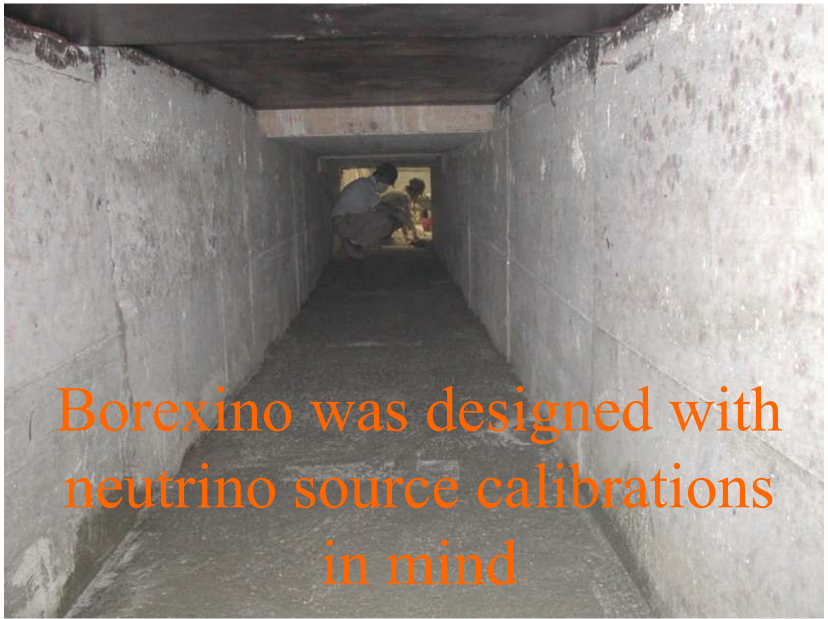
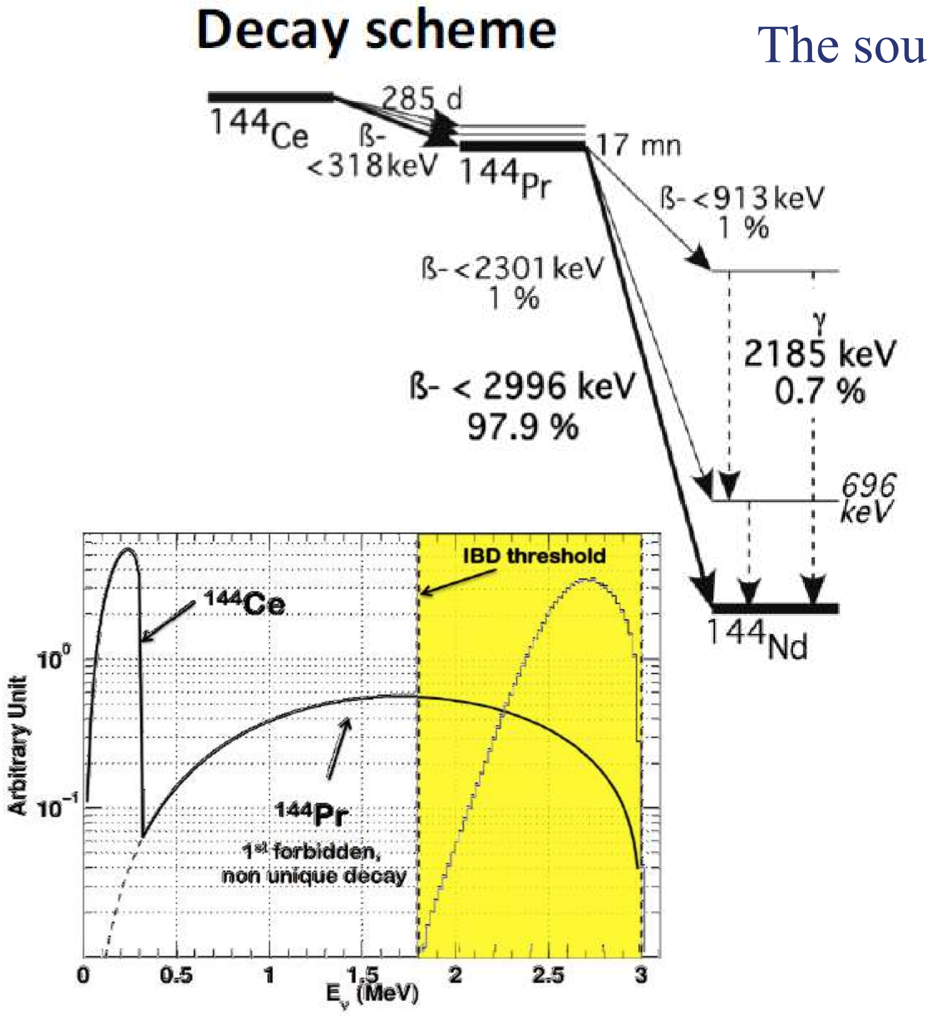


Borexino was designed with neutrino source calibrations in mind

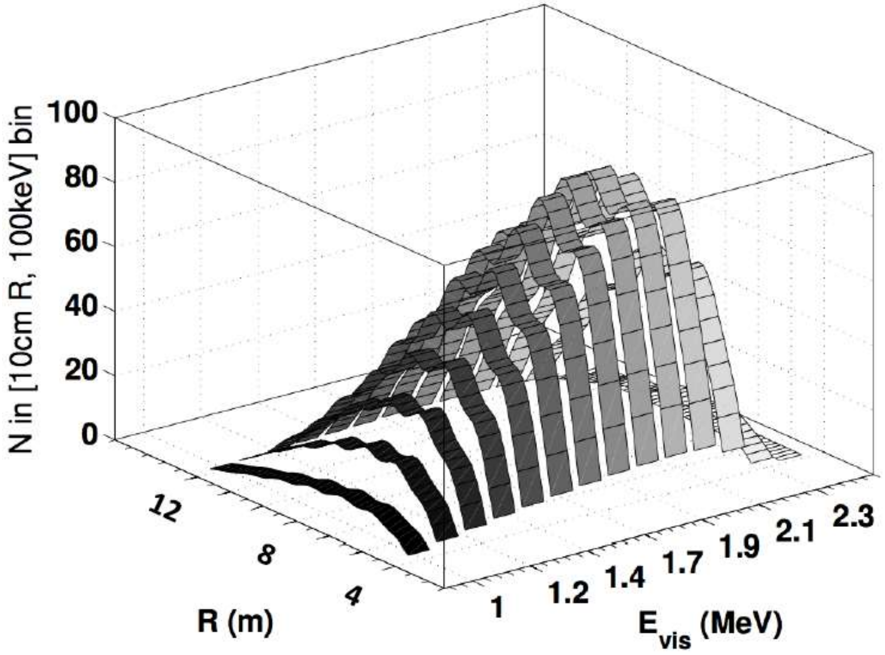
^{144}Ce Source at Borexino

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



The source is made from spent nuclear fuel.

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

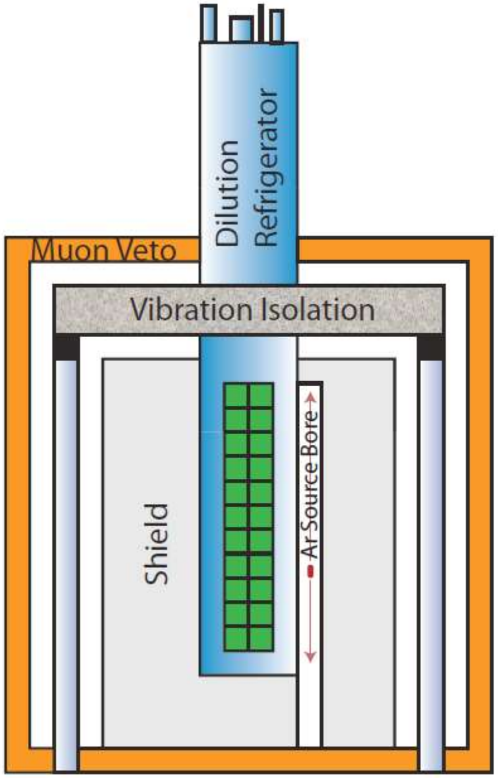


$\bar{\nu}$ detected by inverse beta-decay.

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

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 NC coherent neutrino-nucleus elastic scattering (CEνNS).

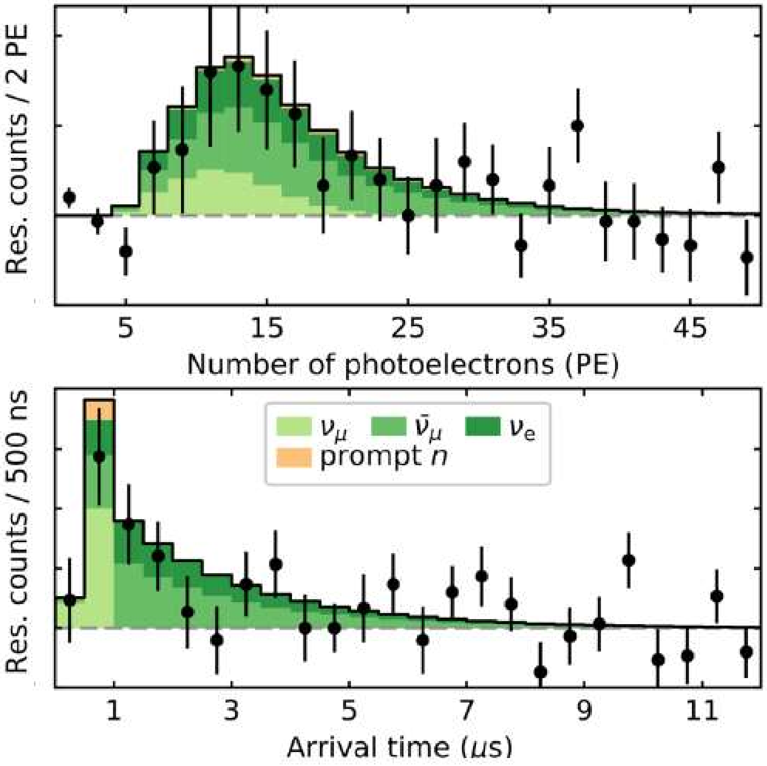


Formaggio & Figuroa, Phys.Rev.D 85, 013009 (2012)

CEνNS has just been observed for the first time making this proposal more feasible than it seemed 6 years ago.

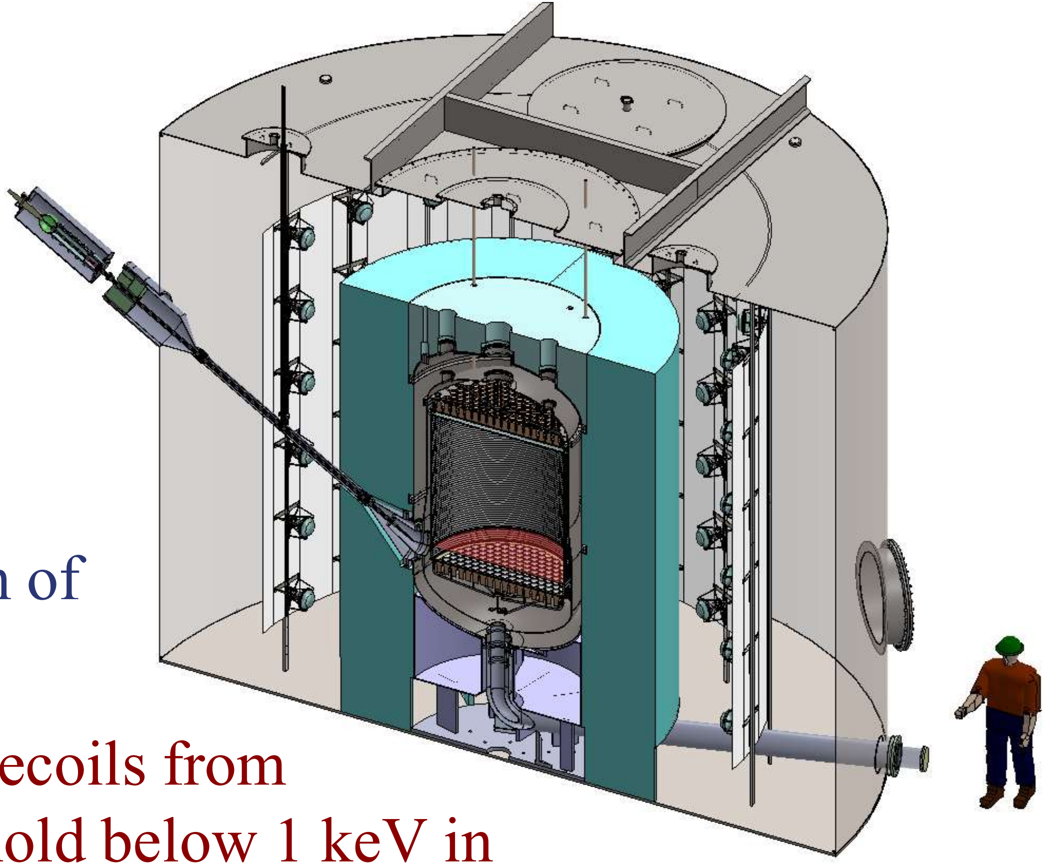
But the source recoil energies are two orders of magnitude smaller than the discovery experiment, which was only 50 keV.

Akimov *et al.*, Science (2017)



Combining Sources with Dark Matter Detectors

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

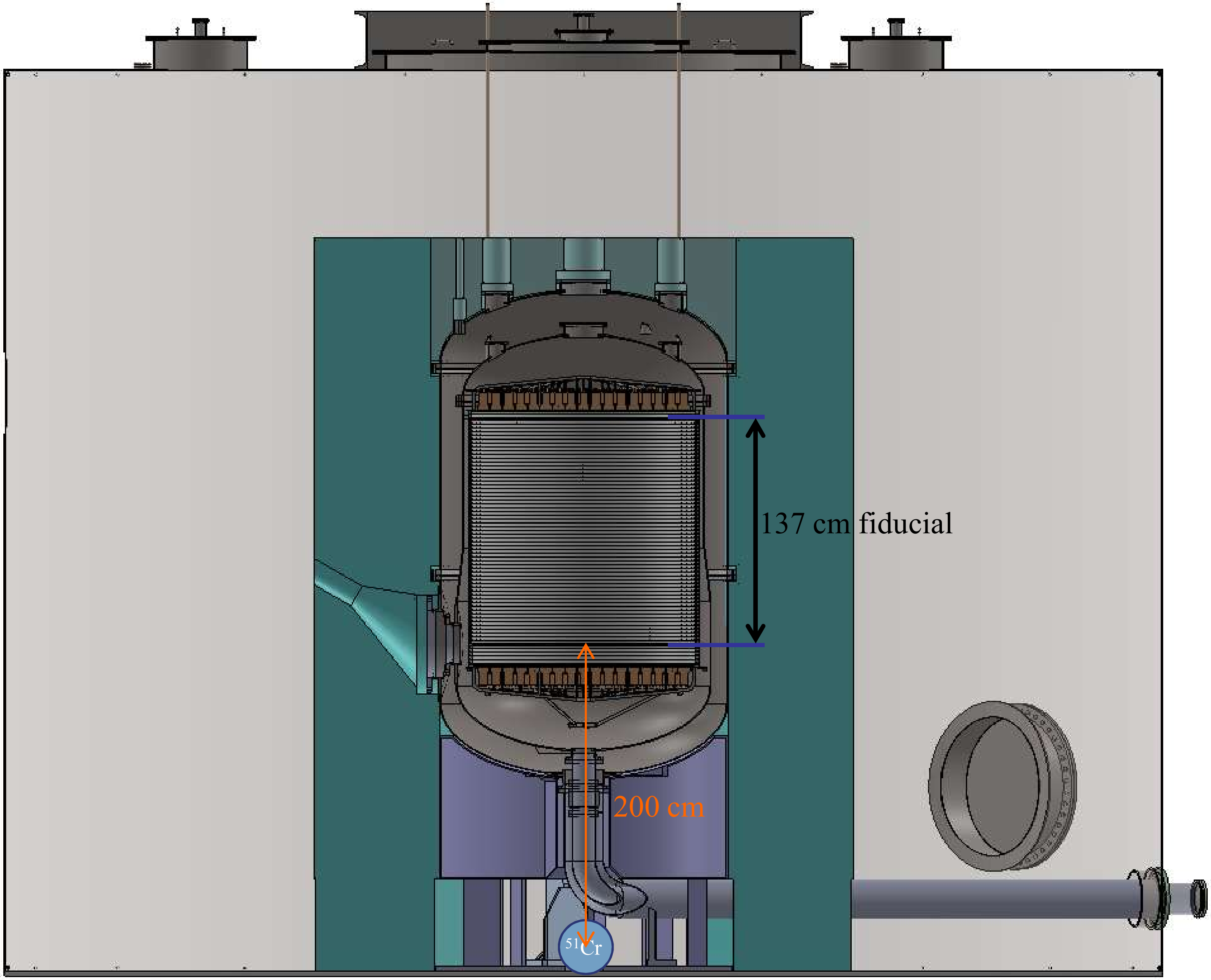


LZ is a two-phase detector that will be sensitive to both the primary scintillation in LXe and scintillation in the gas phase from individual accelerated drift electrons.

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

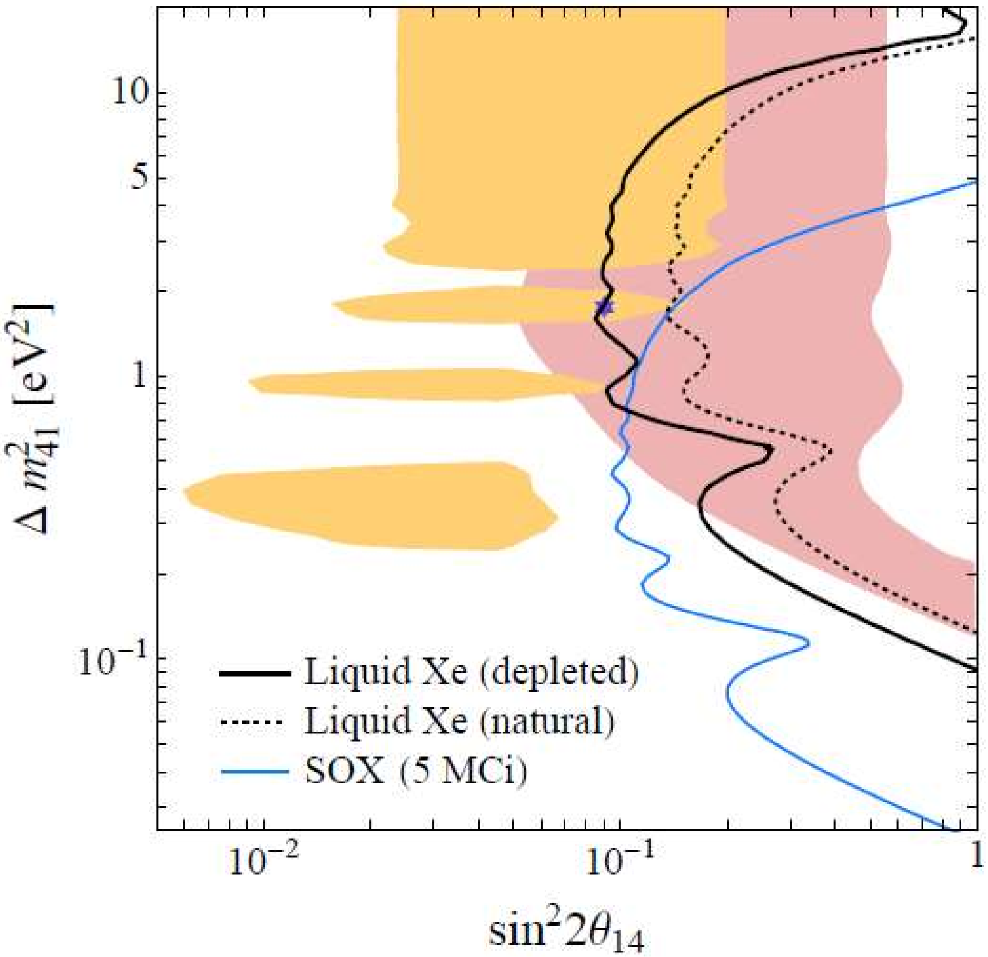
Its goal is to look for nuclear recoils from WIMP scattering with a threshold below 1 keV in electron equivalent energy.

Possible Source Implementation at LZ

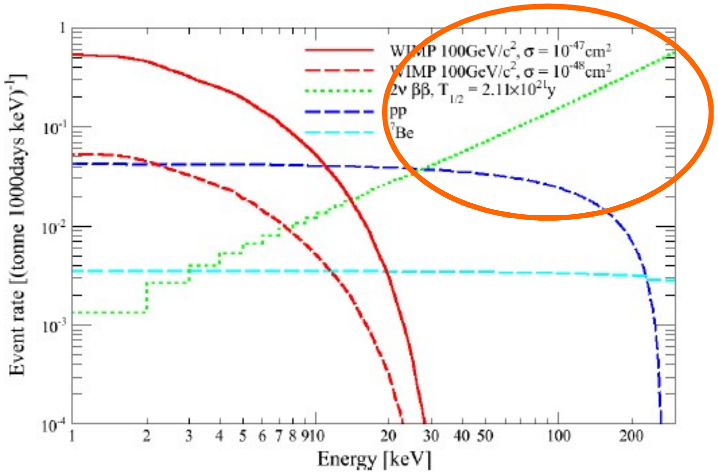


LZ Sterile Oscillation Sensitivity

The shape only sensitivity shows the oscillometric sensitivity.



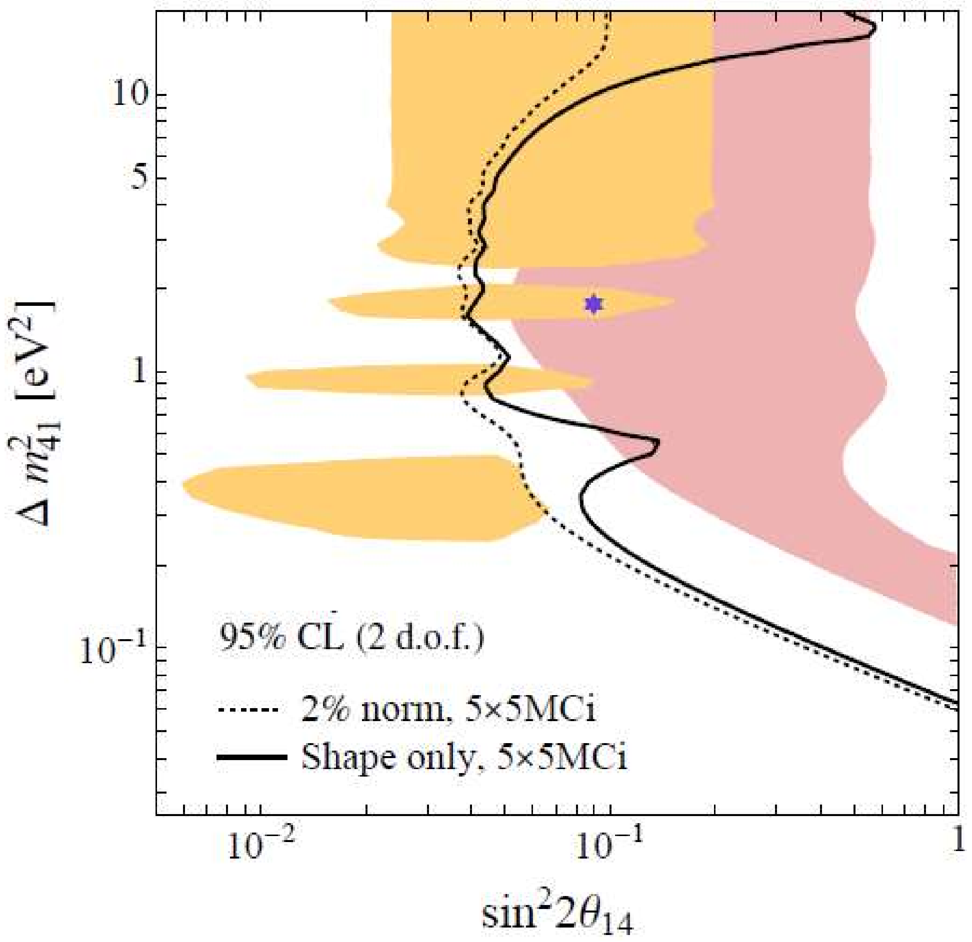
Across the full Cr neutrino energy, the double β-decay isotope, ^{136}Xe, is a significant source of background.



Fortunately, 2β0ν experiments need enriched ^{136}Xe.

LZ-Source Ultimate Sensitivity

What would the ultimate source experiment look like?

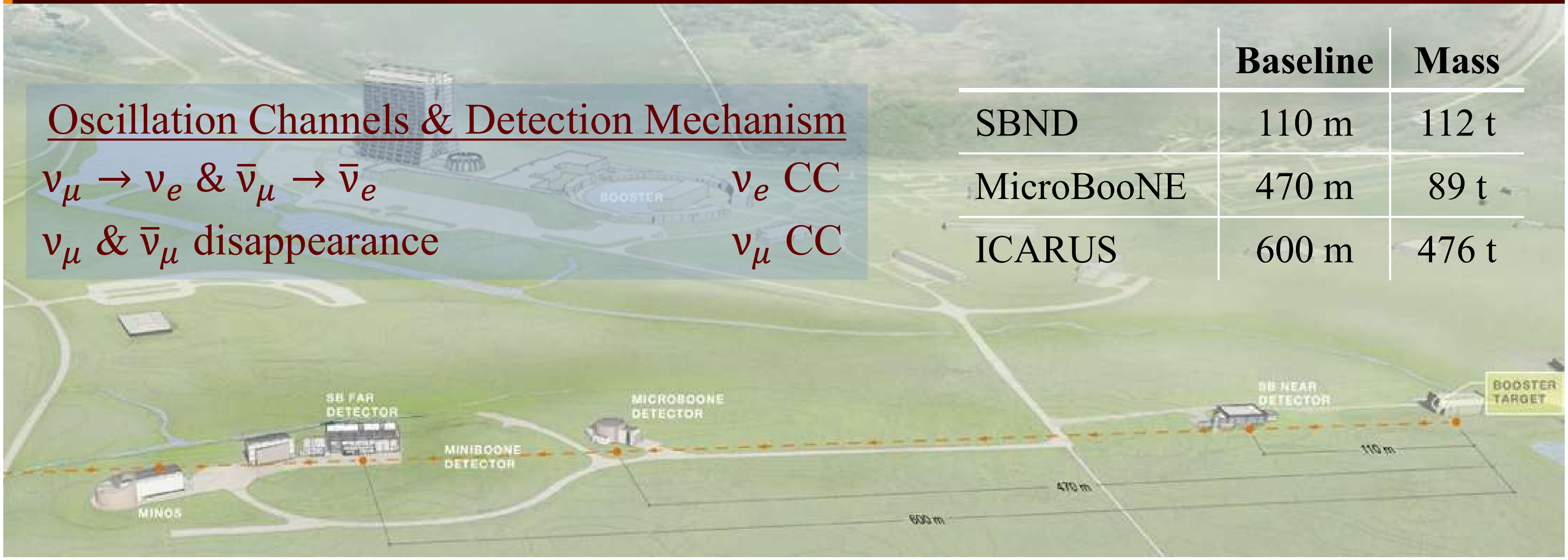


Five runs with a 5 MCi ^{51}Cr source and a 2% normalization uncertainty (as claimed by GALLEX and SAGE) would fully cover the Ga anomaly.

With its mono-energetic neutrinos and high spatial resolution the oscillometric sensitivity is limited by the size of the source which is assumed to be a 5 cm cylinder.

Accelerator Experiments

The Fermilab Short-Baseline Program



Oscillation Channels & Detection Mechanism

$\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$	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.

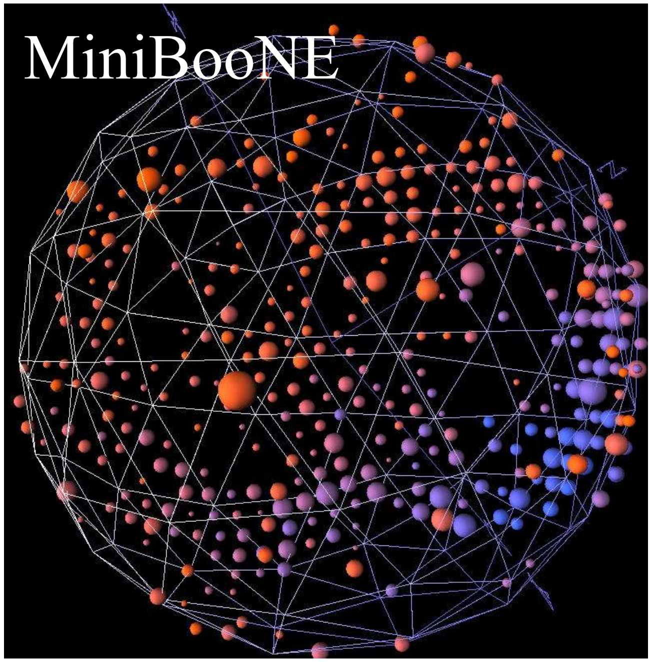
The near detector provides an inclusive measure of beam and misID backgrounds.

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

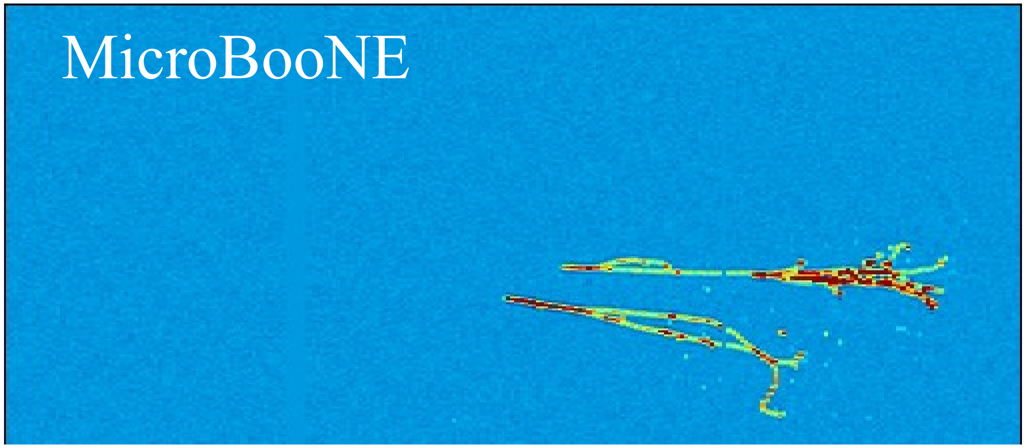
Liquid Argon Detectors

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:

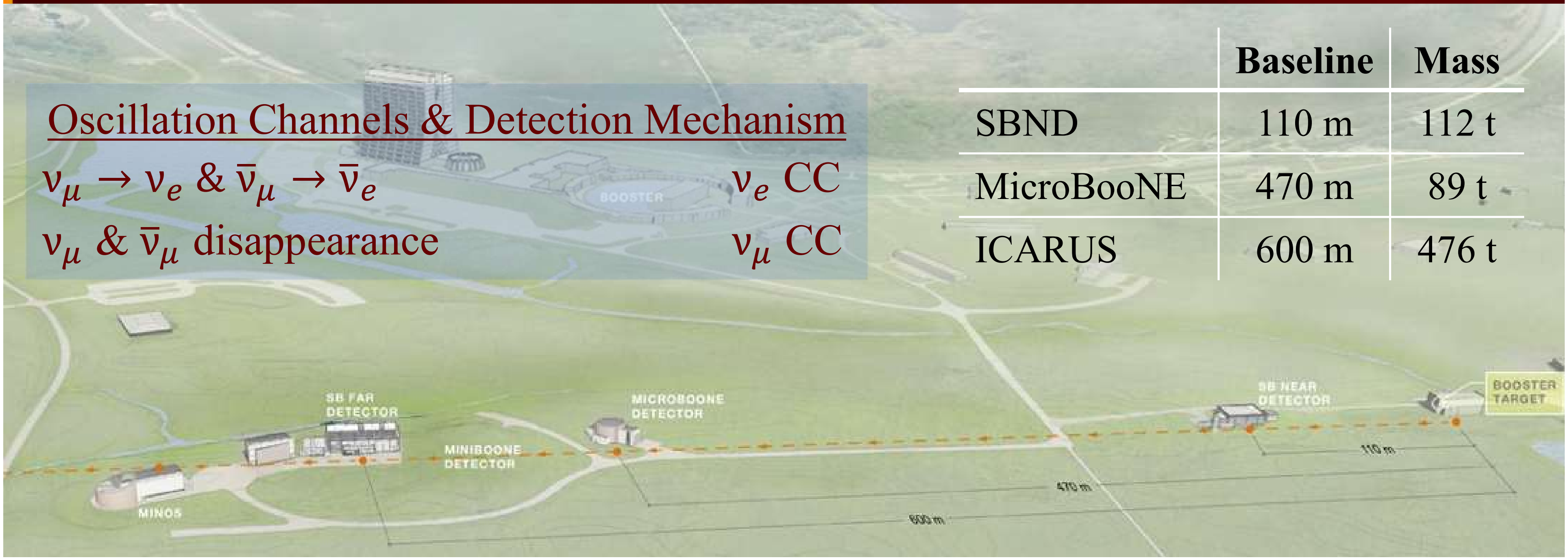
$\nu + N \rightarrow \nu + \Delta$ followed by $\Delta \rightarrow N + \pi^0$

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



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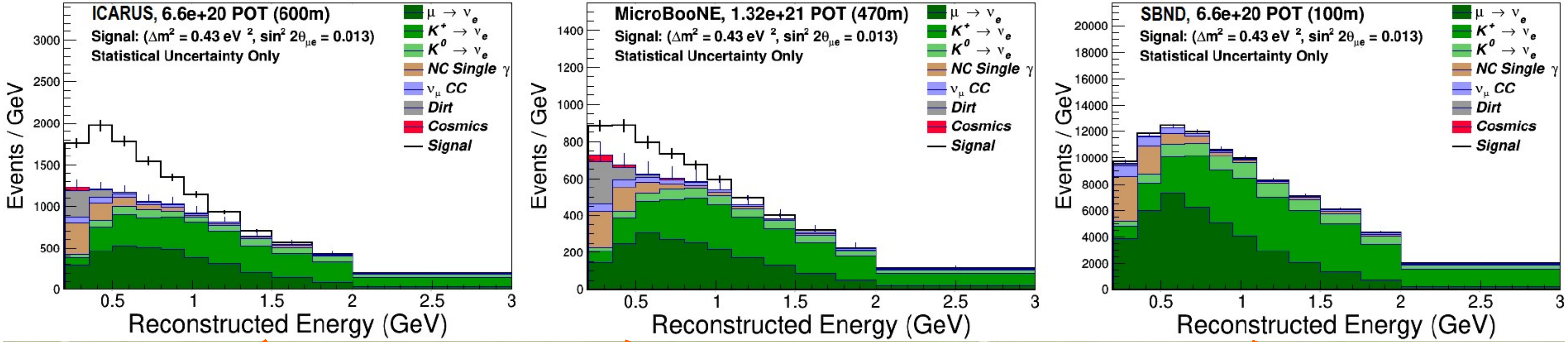
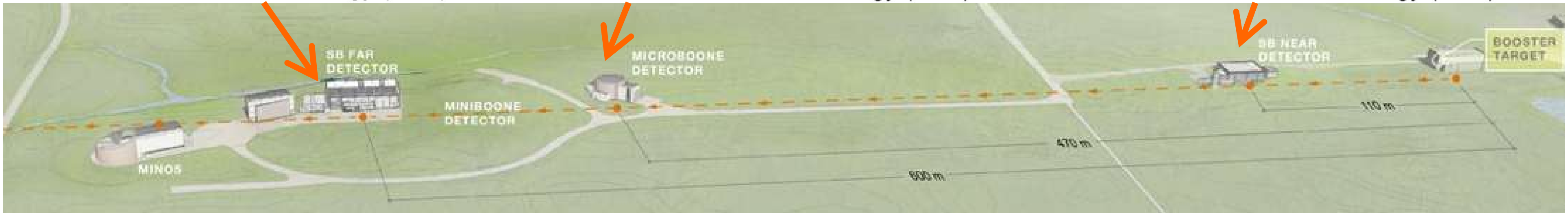
The Fermilab Short-Baseline Program





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The Fermilab Short-Baseline Program

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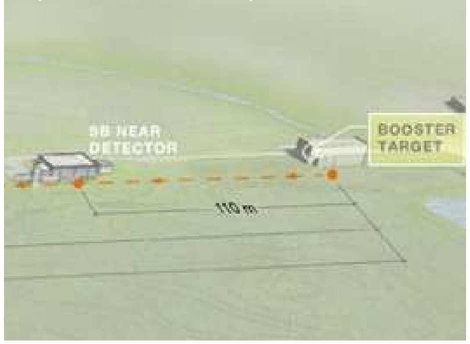
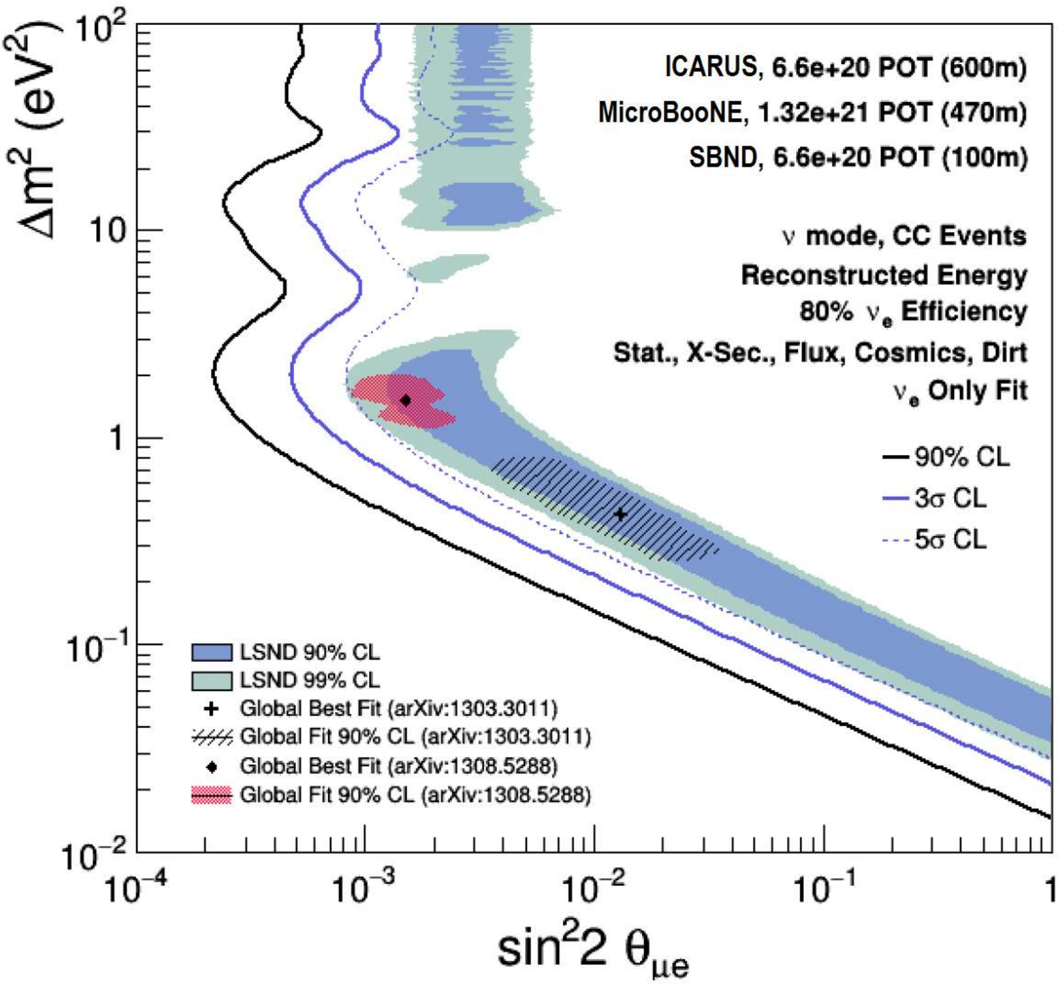




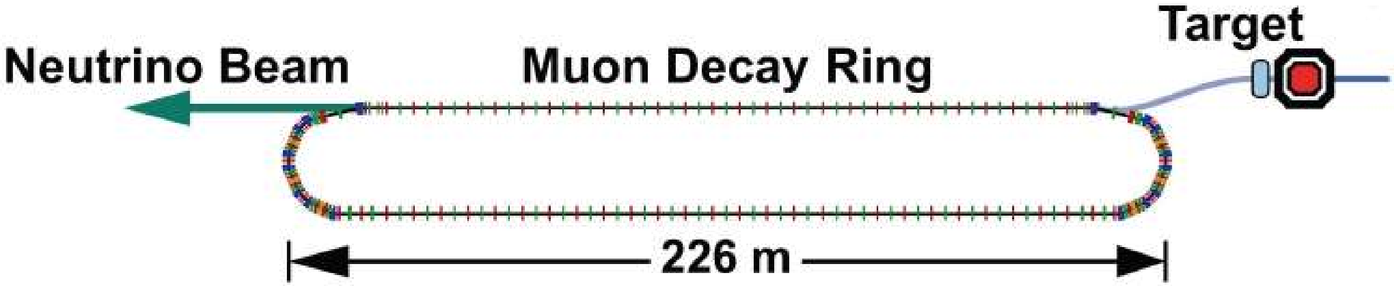
The liquid arg … antly reduce misID backgr

The near dete … isID 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 you need 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

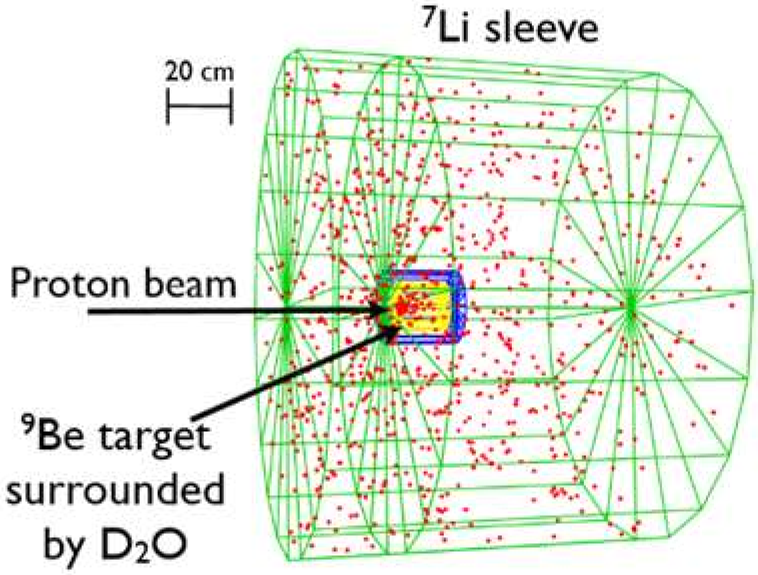
The IsoDAR proposal uses an intense beam of protons to produce ^{8}Li in a ^{9}Br target. The ^{8}Li decays producing $\bar{\nu}_e$ with a β-spectrum (13 MeV endpoint).

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

Oscillations would be observed through the disappearance channel.

Oscillation Channels & Detection Mechanism

$\bar{\nu}_e$ 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 the some with just a handful of collaborators.

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