# Novel Uses of Low Energy Neutrino Sources

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UVA Seminar

10/1/14

# Modern Neutrino Physics

The most interesting thing to happen in particle physics in the last 20 years is… Controversial statement alert!

Neutrino mass is physics *beyond* the standard model, and not in a trivial way.

Unlike all other masses in the standard model, the very tiny neutrino mass can not be generated through the Higgs mechanism.

The leading candidates to generate neutrino mass are a broad type of theories called see-saws, which postulate heavy, often sterile, neutrino partners for the three known light, active neutrinos ($\nu_e$, $\nu_\mu$ and $\nu_\tau$).

These heavy partners are leading dark-matter candidates and one or more may be light and mix with the active neutrinos.

# Neutrino Oscillations: The Math

If neutrinos have mass then they may oscillate between flavors

The neutrino flavor eigenstates are linear superpositions of the mass eigenstate wave functions

$$\left|\nu_\alpha(t=0)\right\rangle = \sum_{i=1}^{n} U_{\alpha i}\left|\nu_i\right\rangle \xrightarrow{\text{Schrödinger's Eq.}} \left|\nu_\alpha(t)\right\rangle = \sum_{i=1}^{n} U_{\alpha i} e^{-iE_i t/\hbar}\left|\nu_i\right\rangle$$

For simplicity, imagine only that there are only 2 neutrino types then:

$$\left|\nu_\alpha(t)\right\rangle = \cos\theta e^{-iE_1 t/\hbar}\left|\nu_1\right\rangle + \sin\theta e^{-iE_2 t/\hbar}\left|\nu_2\right\rangle$$

The probability that a neutrino, that started life as a $\nu_e$, is detected as a $\nu_\mu$ is given by $L \cong tc$ $\left\langle \nu_i | \nu_j \right\rangle = \delta_{ij}$

$$P(\nu_e \to \nu_\mu) = \left|\left\langle \nu_\mu | \nu_e \right\rangle\right|^2$$

$\hbar \equiv 1 \equiv c$ $E >> m$ $E_i \cong p + m_i^2 / 2E$ $\Delta m^2 = m_2^2 - m_1^2$

Sets oscillation amplitude

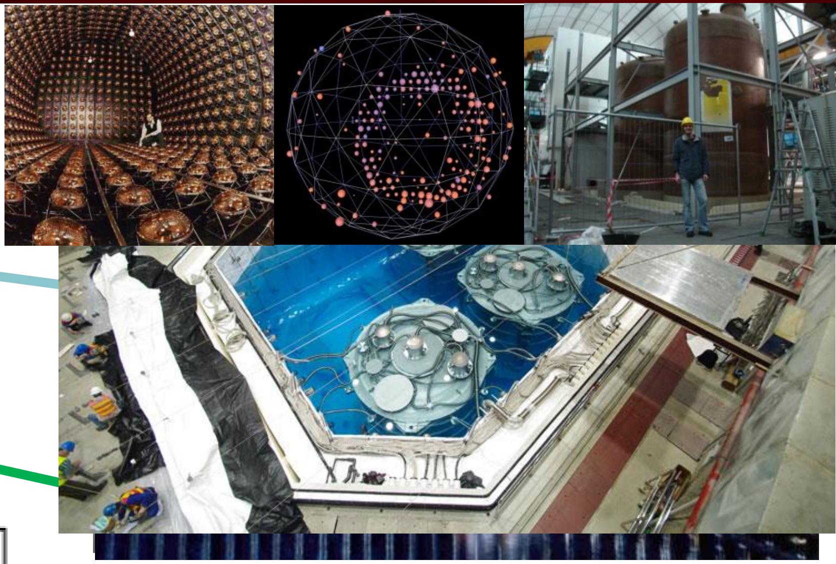
Determines oscillation frequency

# The Neutrino Mixing Matrix

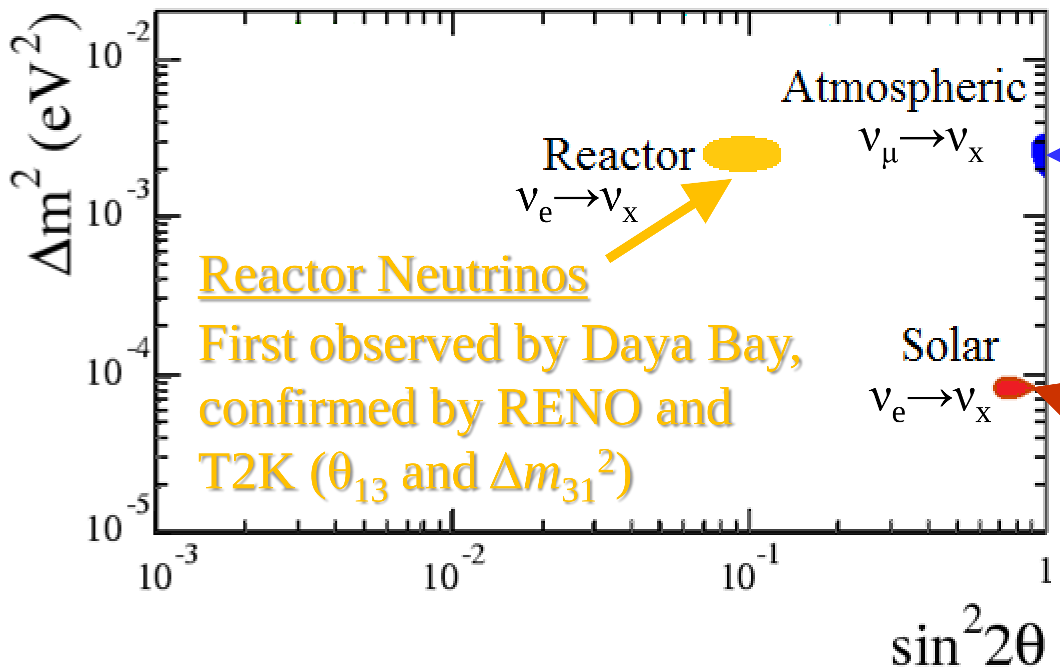
With three neutrinos the mixing is governed by the MNS matrix which relates the mass eigenstates ($\nu_1$, $\nu_2$ and $\nu_3$) to the flavor eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

# Neutrino Oscillations: The Data



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




Reactor Neutrinos

First observed by Daya Bay, confirmed by RENO and T2K ($\theta_{13}$ and $\Delta m_{31}^2$)

Atmospheric Neutrinos

Seen by Super-K, confirmed by K2K and Minos ($\theta_{23}$ and $\Delta m_{32}^2$)

Solar Neutrinos

First observed by Ray Davis. Nailed down by Super-K, SNO and KamLAND. Dominated by mixing of mass states 1and 2 ($\theta_{12}$ and $\Delta m_{21}^2$)

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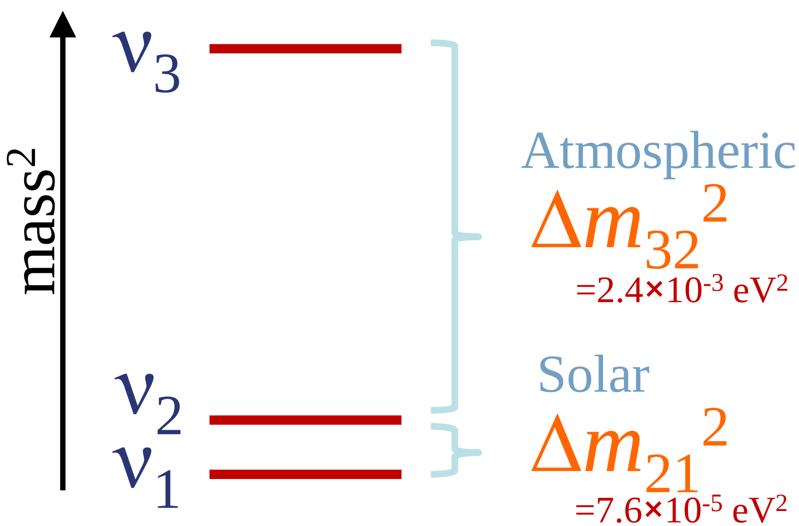
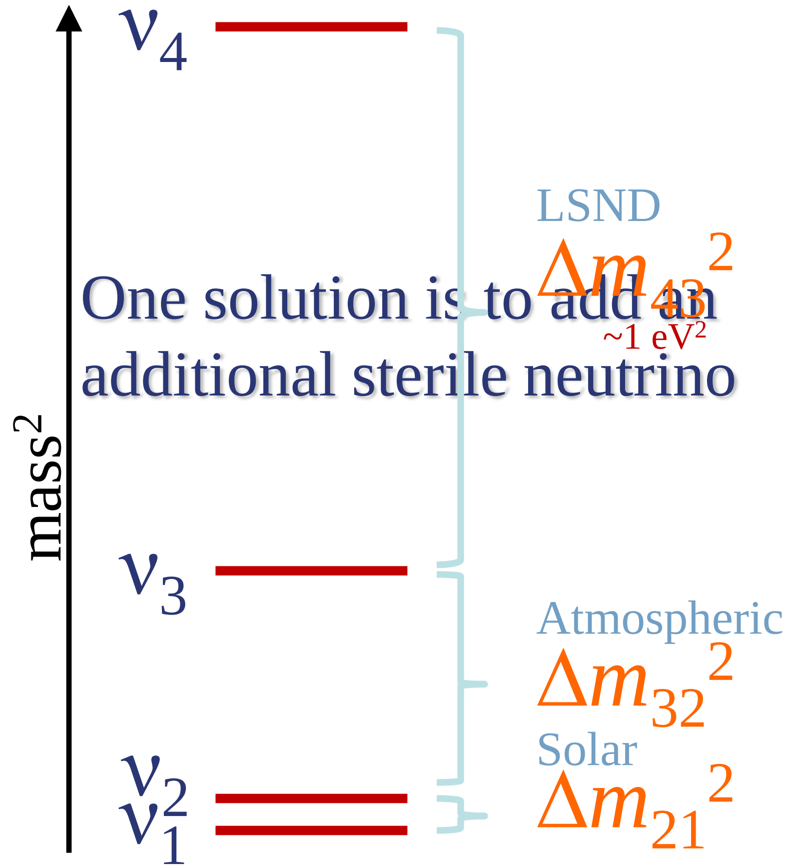
But there are experimental results at 3 different $\Delta m^2$ scales.

# What About that Other $\Delta m^2$ Scale?

Three neutrinos allow only 2 independent $\Delta m^2$ scales




But there are experimental results at 3 different $\Delta m^2$ scales.




One solution is to add an additional sterile neutrino

# The Neutrino Mixing Matrix

With three neutrinos the mixing is governed by the MNS matrix which relates the mass eigenstates ($\nu_1$, $\nu_2$ and $\nu_3$) to the flavor eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

To account for a sterile neutrinos add a column and row to the MNS matrix

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

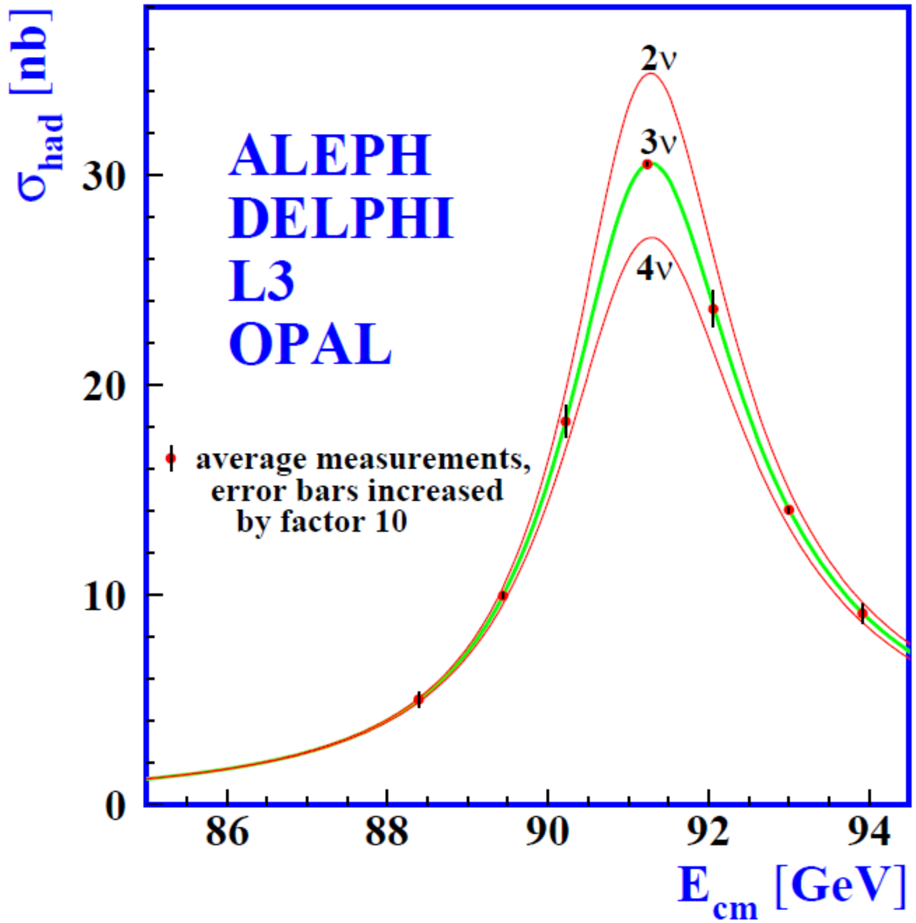
# What Are Sterile Neutrinos?

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

Active neutrinos:

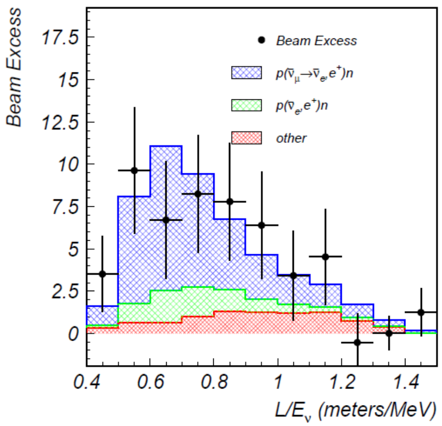
LEP Invisible $Z^0$ Width is consistent with only three light active neutrinos


Phys.Rept. 427, 257 (2006)



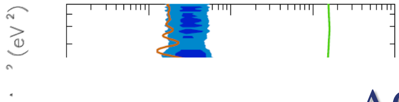
# The Evidence for Sterile Neutrinos

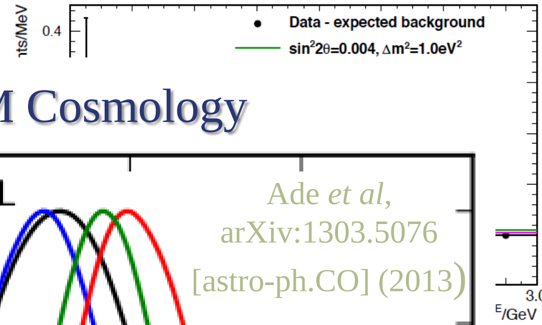
## LSND ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

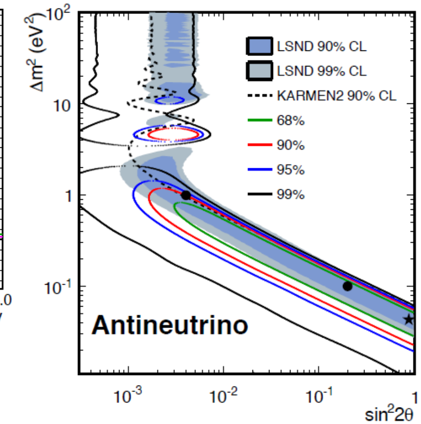



Aguilar-Arevalo *et al.*, Phys

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

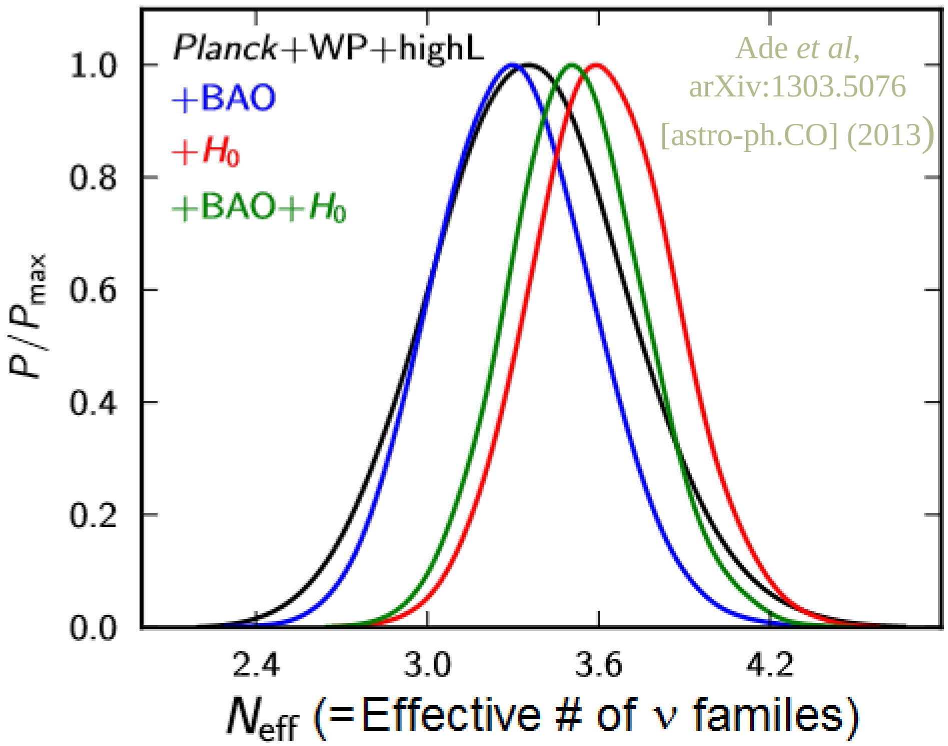




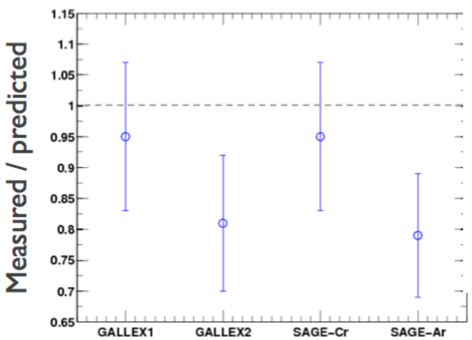



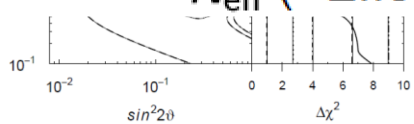

Rev.Lett. 110, 161801 (2013)

## ΛCDM Cosmology



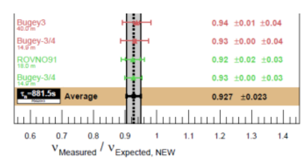

## Gallium Anomaly (

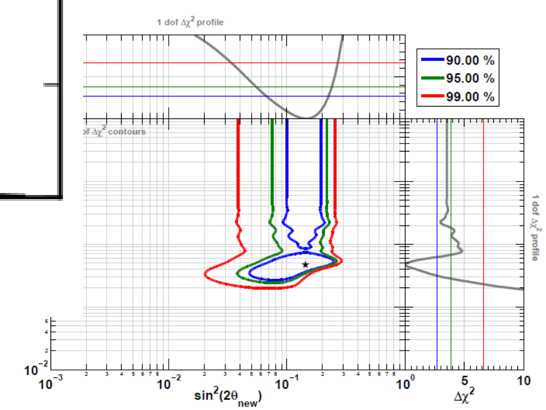



Giunti and Laveder, Phys.Rev.C83, 065504(2011)

## ($\bar{\nu}_e$ Disappearance)

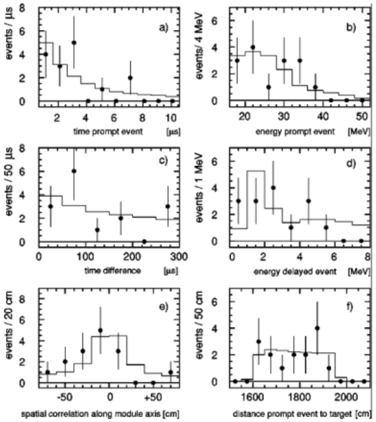


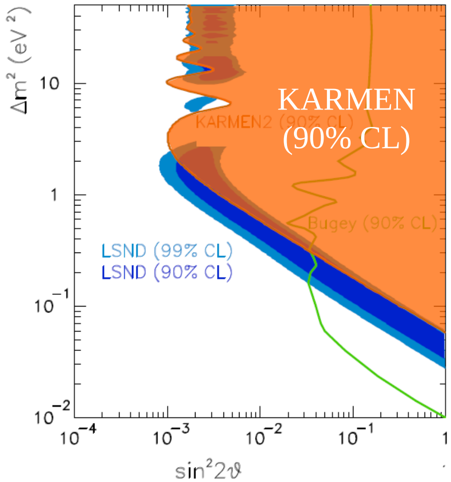




Mention *et al.*, Phys.Rev.D83 073006 (2011)

# Evidence Against the ~1 eV$^2$ Sterile Neutrino

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

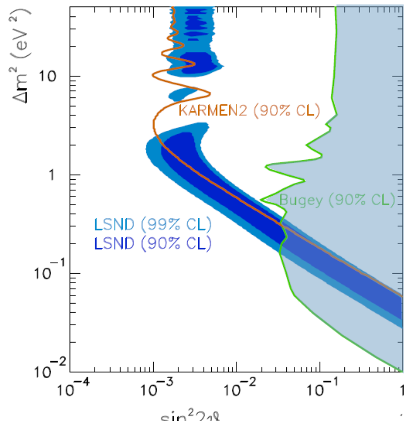


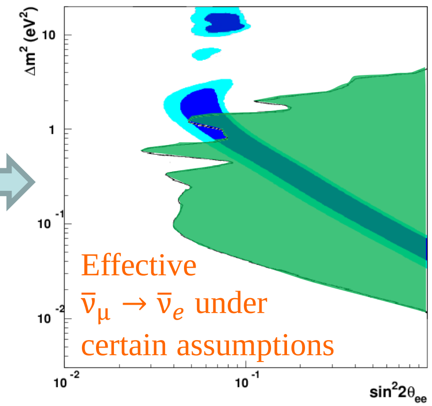



No $\bar{\nu}_e$ Excess

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

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



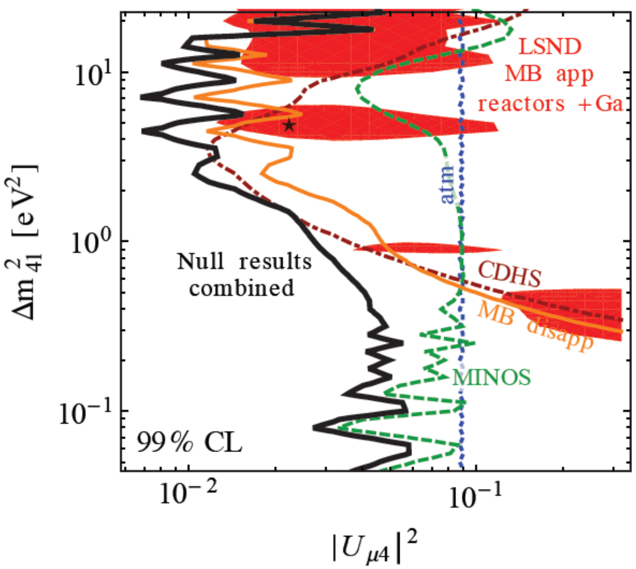



Effective $\bar{\nu}_\mu \to \bar{\nu}_e$ under certain assumptions

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

## $\nu_\mu$ Disappearance (where is it?)

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




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

There are lots of ideas for new sterile neutrino experiments.

(see "Light Sterile Neutrinos: A White Paper" arXiv:1204.5379 [hep-ph])

I'm going to tell you about an approach that I've been working on using:

# Low-Energy Radioactive Neutrino Sources

# Sterile Searches with Neutrino Sources

## LENS-Sterile

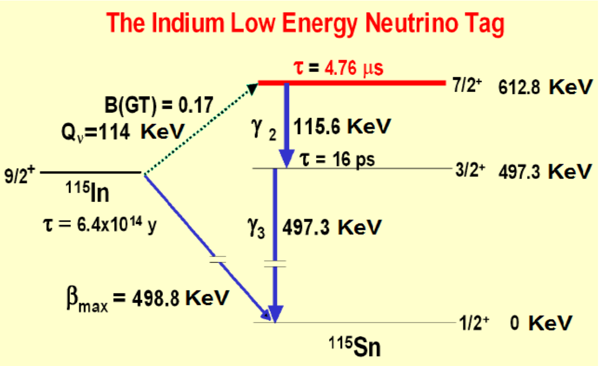
PHYSICAL REVIEW D **75**, 093006 (2007)

### Probing active to sterile neutrino oscillations in the LENS detector

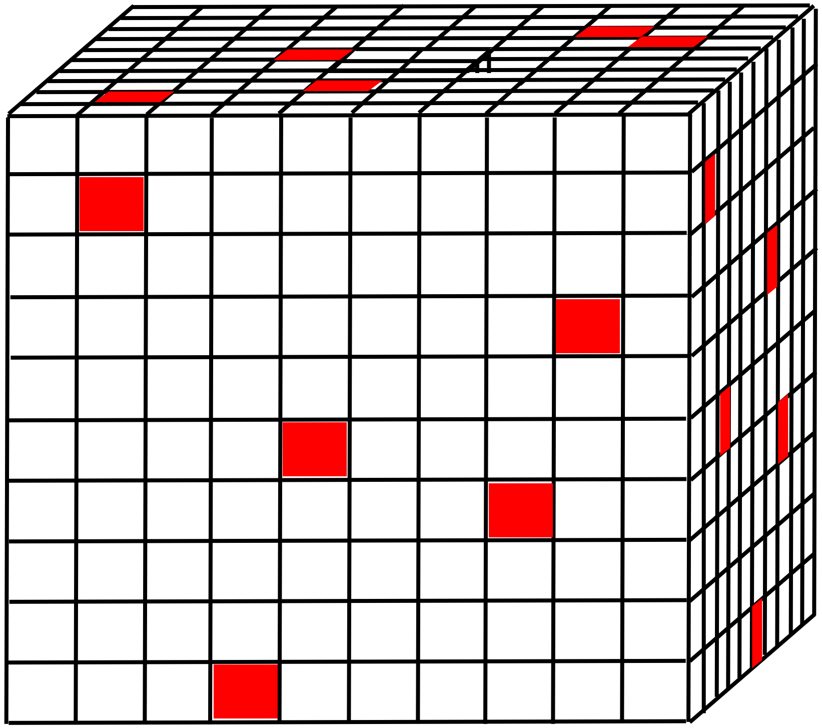
C. Grieb, J. M. Link, and R. S. Raghavan
*Institute of Particle, Nuclear and Astronomical Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA*
(Received 24 December 2006; published 15 May 2007)

Sterile neutrino ($\nu_s$) conversion in meter scale baselines can be sensitively probed using monoenergetic, sub-MeV, flavor-pure $\nu_e$'s from an artificial Megacurie source and the unique technology of the LENS low energy solar $\nu_e$ 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




R.S. Raghavan, Phys. Rev. Lett. 37, 259 (1976)



By inserting a Mega-Curie $^{51}$Cr source in the center of the LENS detector we could observe a full wavelength, or more, of large $\Delta m^2$ oscillations in a detector of just a few meters.

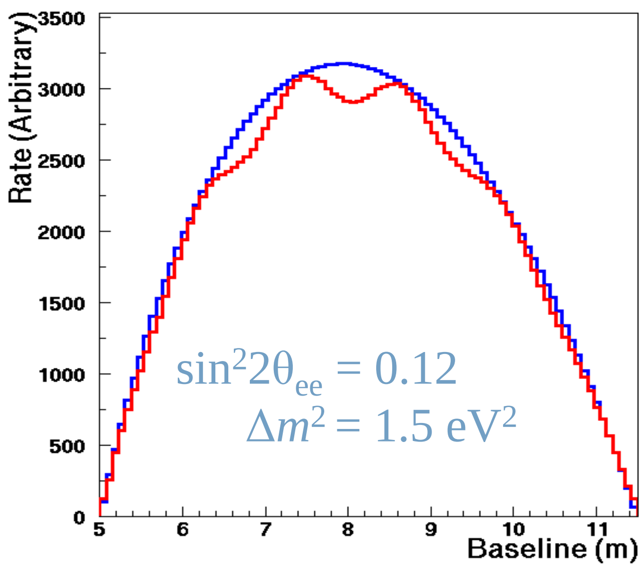
# Note on Short-Baseline Disappearance

To paraphrase Duke Ellington,

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

With all reactor and source experiments, the existence of sterile neutrinos can only be convincingly established through oscillometry.

That is: one must show evidence of the oscillating pattering as a function of *L/E* (or *L* in the case of mono-energetic EC sources).




The range of oscillometric sensitivity is determined by:

The size of the detector on the low $\Delta m^2$ side

And

The spatial resolution on the high $\Delta m^2$ side

# $^{51}Cr$ as a Mono-Energetic Neutrino Source

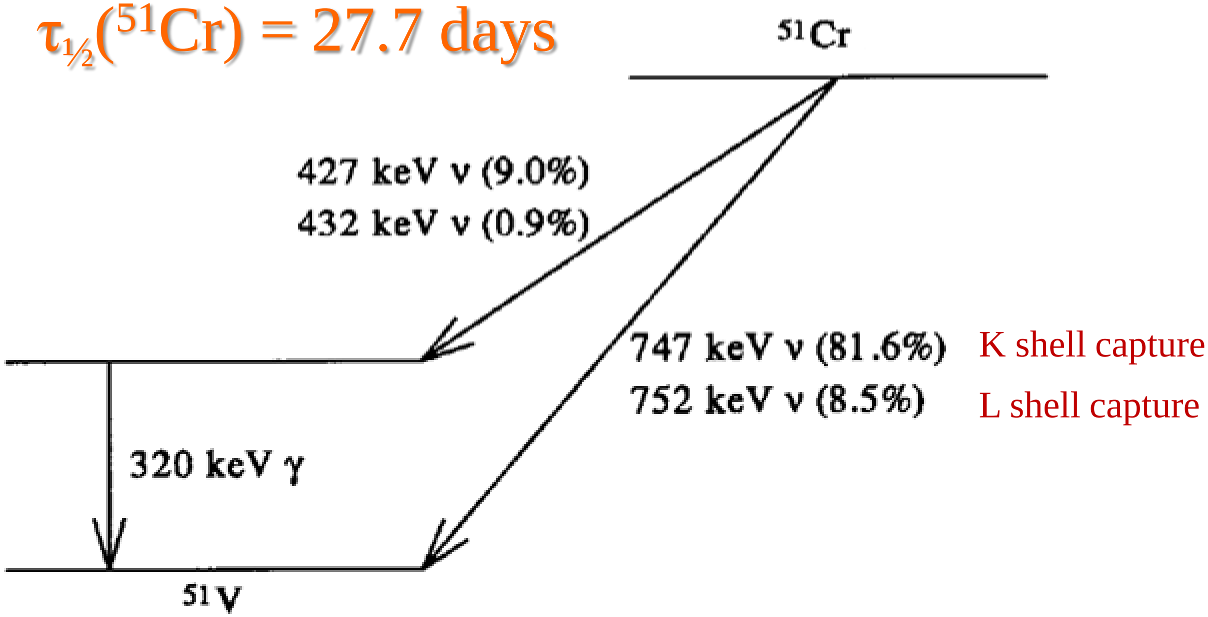
Electron capture isotopes decay to two bodies producing an isotropic mono-energetic flux of neutrinos at low energies.

$$^{51}Cr + \text{s-shell } e^- \rightarrow {}^{51}V + \nu_e \text{ (+ x-ray)}$$

With $^{51}Cr$, 90% of the time the capture goes directly to the ground state of $^{51}V$ giving a 750 keV neutrino. 10% of the time you get a 320 keV gamma.

Mega-Curie-scale $^{51}Cr$ sources were used by the GALLEX and SAGE radiochemical solar neutrino experiments to constrain the nuclear matric element for the $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$ process, which was a large source of theoretical uncertainty.

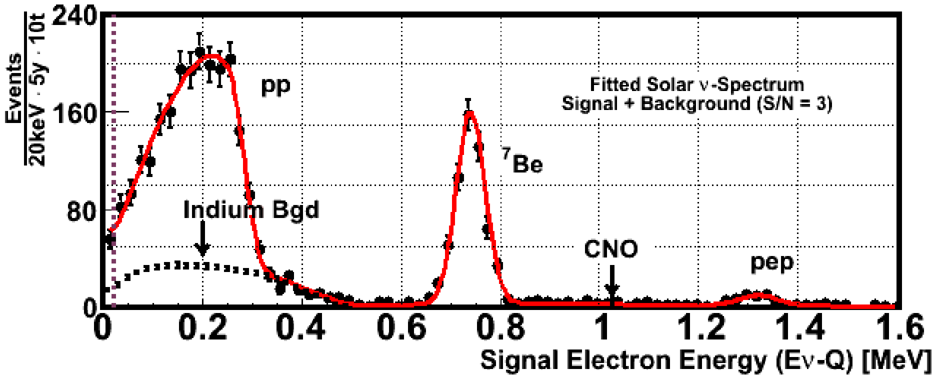
$\tau_{1/2}(^{51}Cr) = 27.7$ days



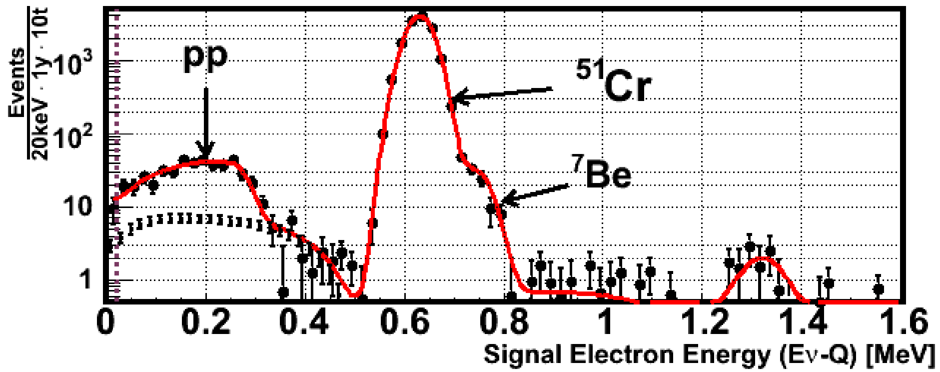

Decay scheme of $^{51}Cr$ to $^{51}V$ through electron capture.

# LENS-Sterile

LENS stands for "Low-Energy Neutrino Spectroscopy". It was designed to make a spectral measurement of the solar neutrino flux:



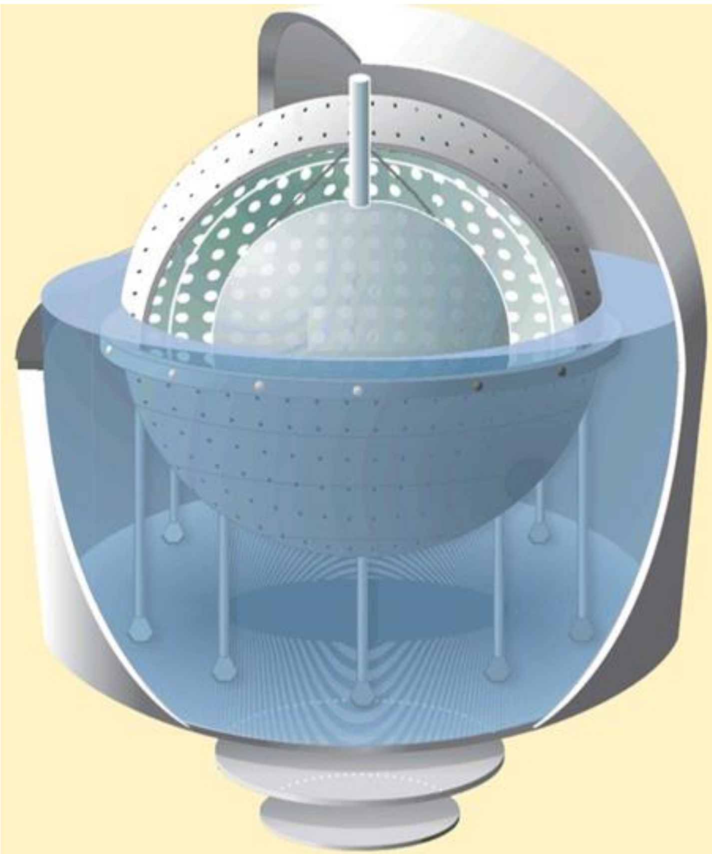

The spectral measurement requires a charged current interaction to return the neutrino energy, but with a mono-energetic source, CC is just an extravagance:




Perhaps other, less capable, solar neutrino detectors could be used…

# SOX: Borexino Source Experiment

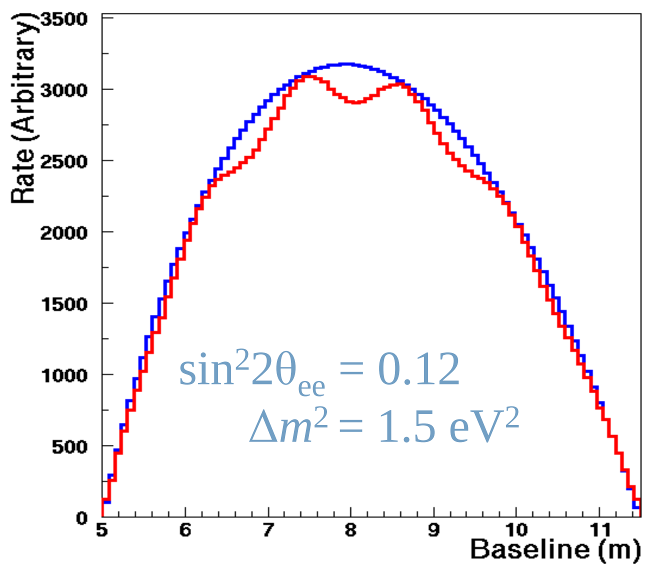
Combine a mega-Curie $^{51}$Cr source with the Borexino detector to search for $\nu_e$ disappearance



$^{51}$Cr
Source

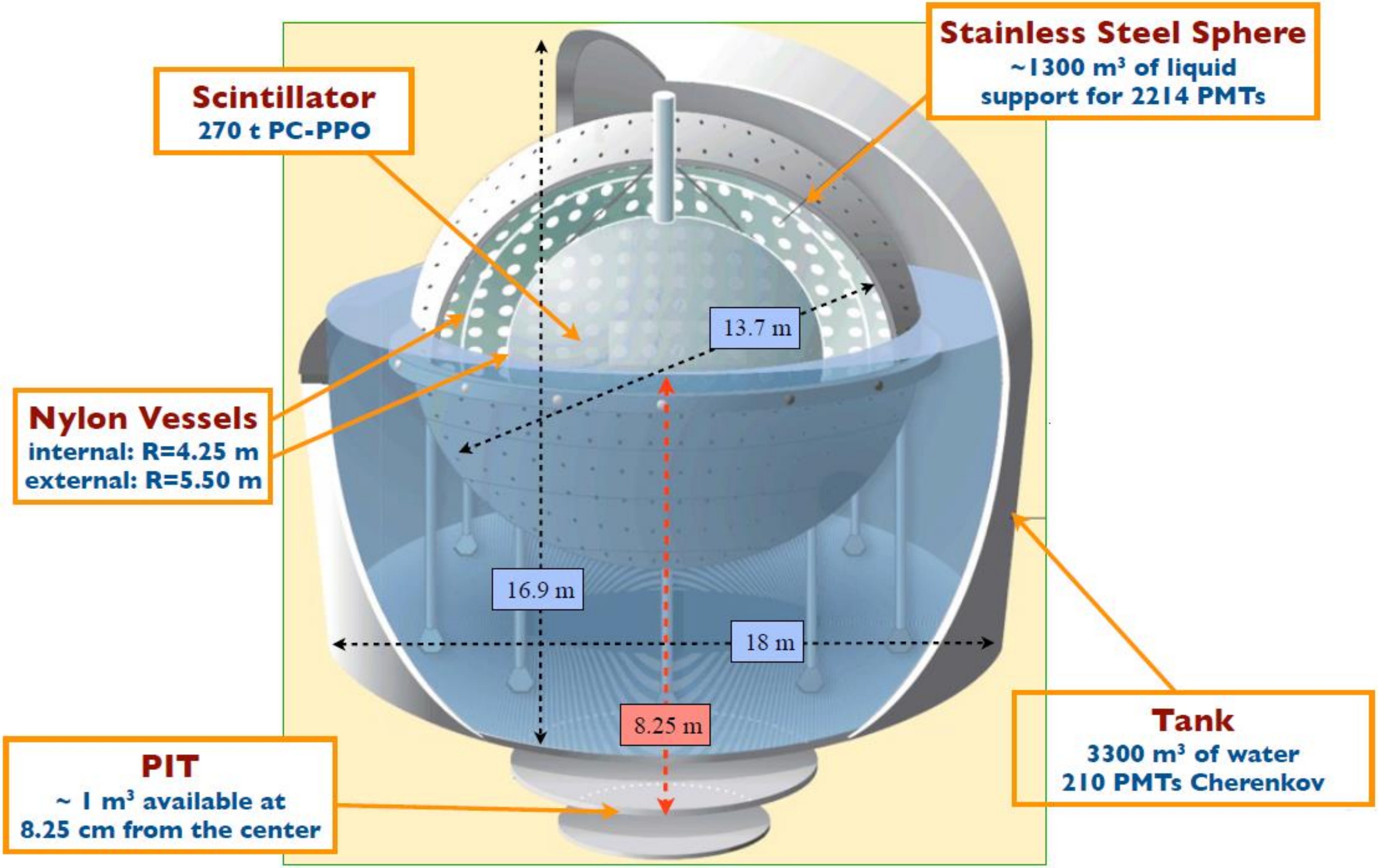
Mono-energetic $^{51}$Cr neutrinos that oscillate as a pure function of *L*

Multiple oscillation wavelengths inside the detector for the sterile $\Delta m^2$

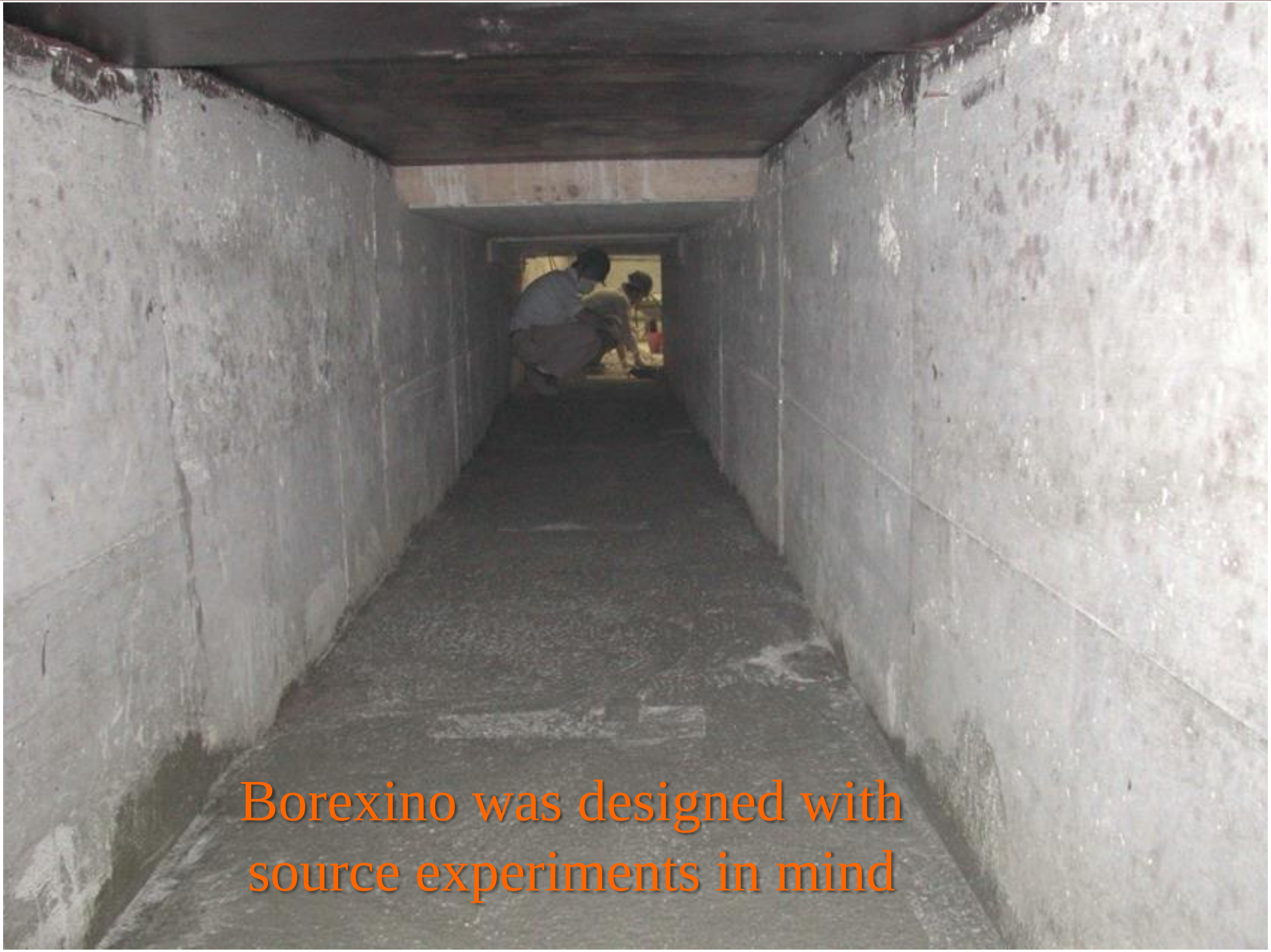



Has the oscillometry signature that was so appealing in the LENS-Sterile concept

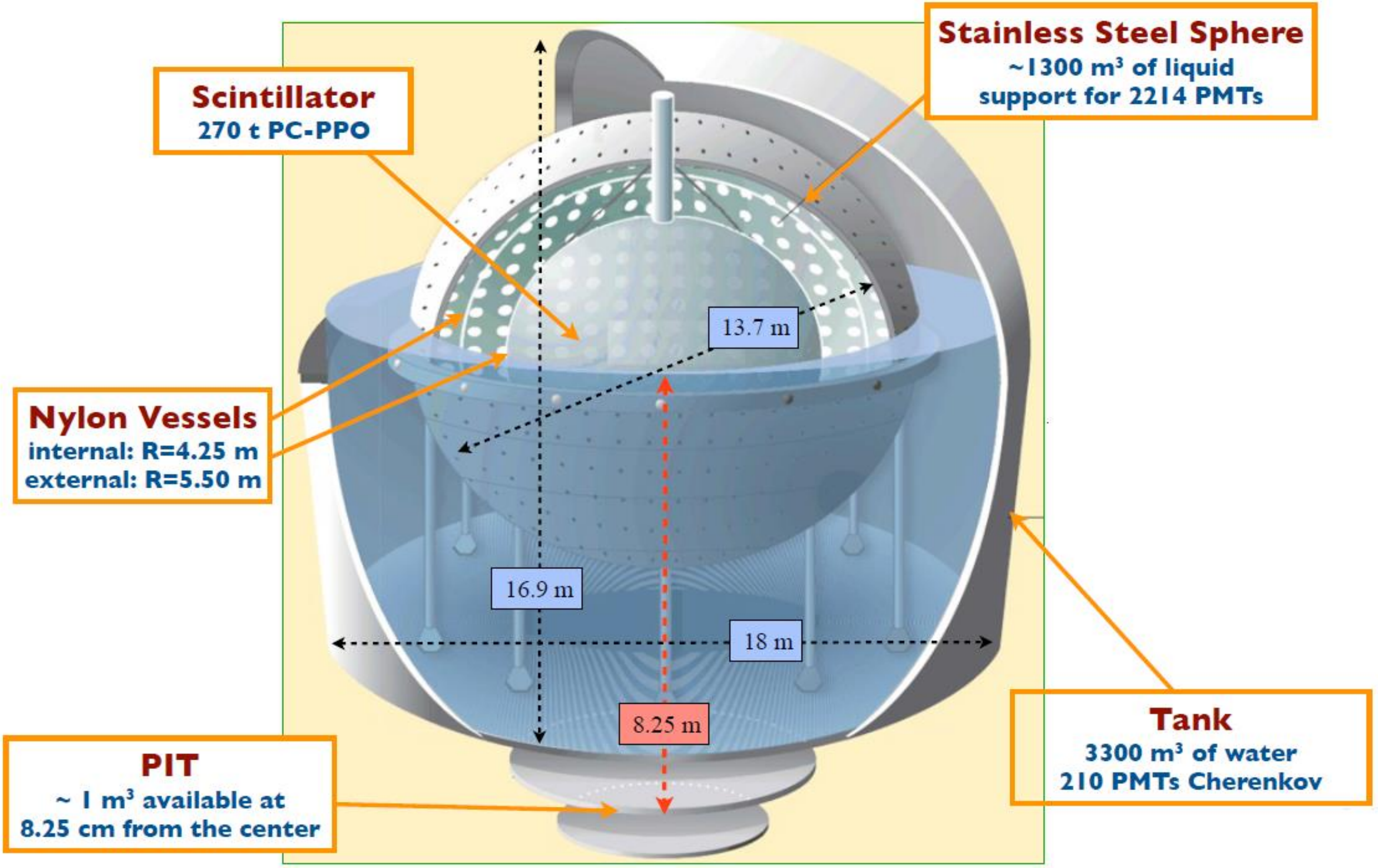
# The Borexino Detector



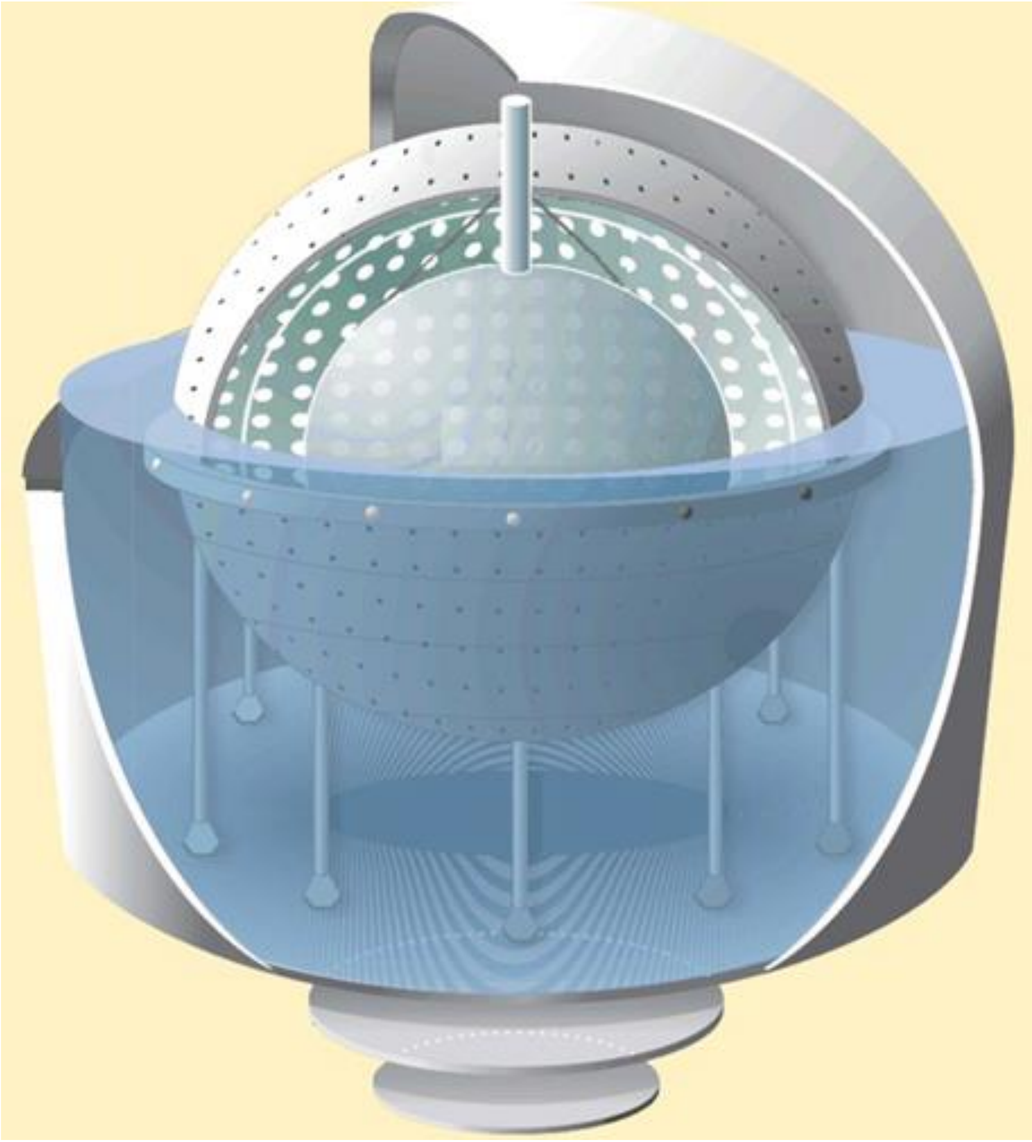
# Tunnel Beneath the Detector



# The Borexino Detector



# The Borexino Detector

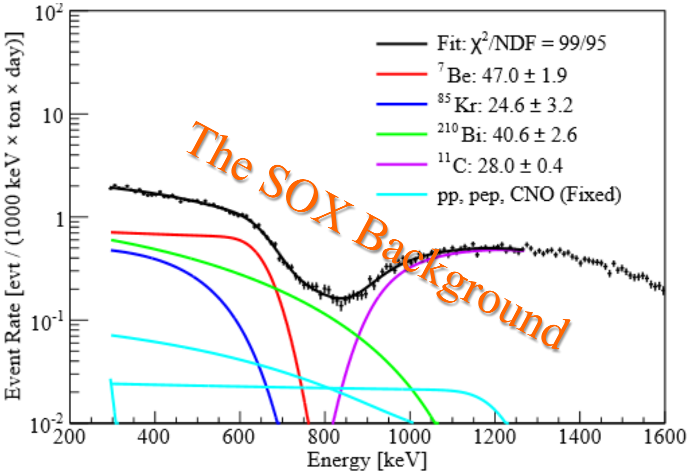


Unprecedented and still unmatched radio-purity

Nested vessels contain increasingly more pure materials from outside in

Observes $\nu_e$ by neutrino-electron elastic scattering with a 250 keV threshold

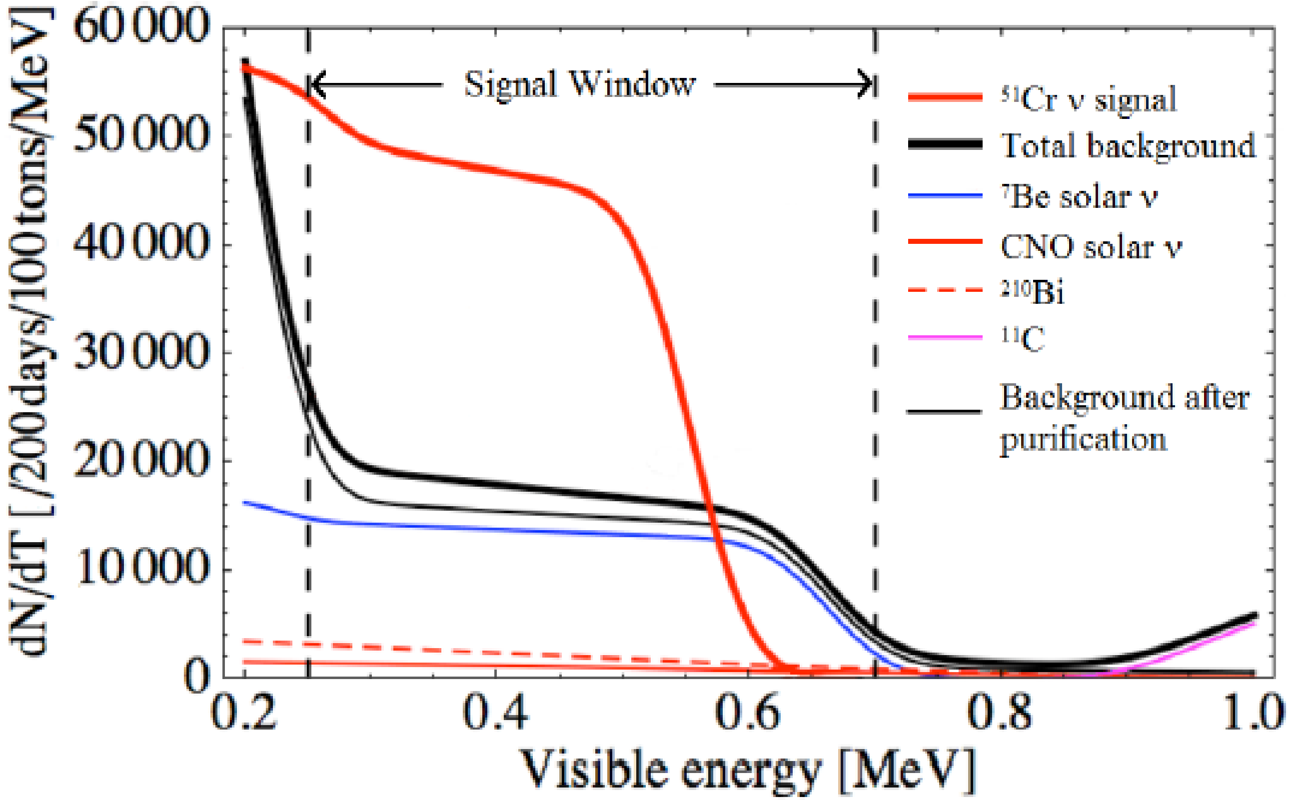
The only detector to have observed $^7$Be solar neutrinos (862 keV)




Bellini *et al.*, Phys.Rev.Lett. 107, 141302 (2011)

# The SOX Signal

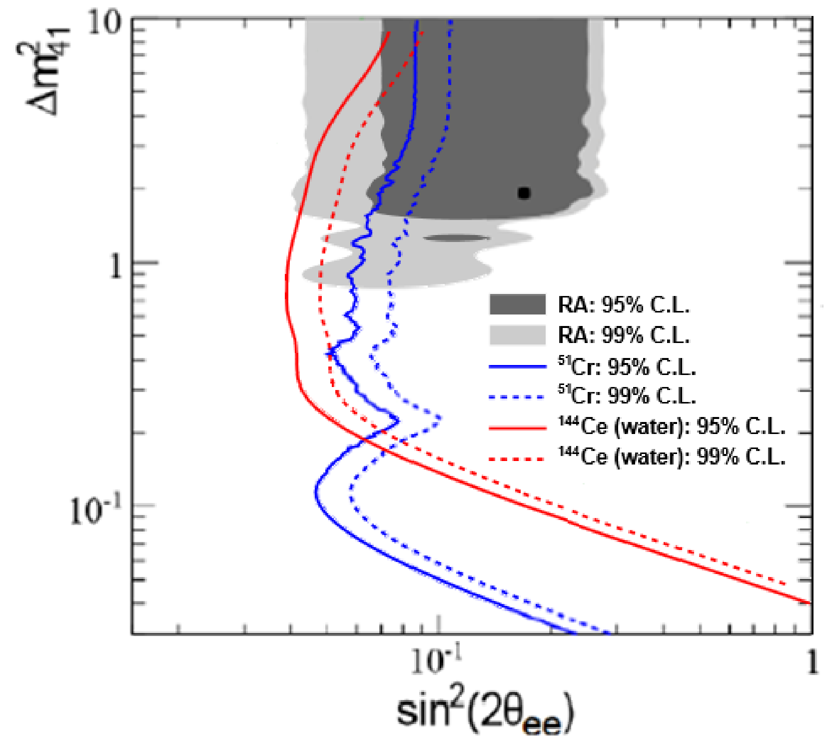
The elastic scattering signal is an edge and continuum in the electron recoil energy:




$^{7}$Be solar neutrinos are the largest background to $^{51}$Cr neutrino signal.

# SOX Sensitivity

SOX covers much of the $\nu_e$ disappearance allowed region, with a great discovery potential.




In addition to the to the $^{51}$Cr source a $^{144}$Ce antineutrino source is also planned as a part of the SOX program.

Frankly, I am not satisfied with SOX sensitivity, but this is a funded project in the European Community, and a great opportunity to initiate a $^{51}$Cr program in the US.

# Other Applications for $^{51}Cr$ Sources

# Neutrino-Electron Elastic Scattering

PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

**Neutrino electromagnetic form factors**

P. Vogel and J. Engel
*Physics Department, California Institute of Technology, Pasadena, California 91125*
(Received 27 December 1988)

It has been suggested that an apparent correlation of the flux of detected solar neutrinos with solar activity is due to a neutrino magnetic moment. Here several terrestrial experiments that might observe the magnetic moment are considered, with emphasis on those employing reactor neutrinos. The neutrino charge radius, and prospects for observing it, are also discussed. An appendix collects all relevant neutrino scattering cross sections.

## Neutrino-Electron Elastic Scattering Cross Section

Weak Part E&M Part

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2+(g_V-g_A)^2\left[1-\frac{T}{E_\nu}\right]^2+[g_A^2-g_V^2]\frac{m_e T}{E_\nu^2}\right]+\frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\,\frac{1-T/E_\nu}{T}$$

where $g_V = 2\sin^2\theta_W + \frac{1}{2}$ and $g_A = \frac{1}{2}$ for $\nu_e$

The E&M contribution to the elastic scattering cross section would be a consequence of a non-zero neutrino magnetic moment.

# Signature of ν Magnetic Moment in Elastic Scattering

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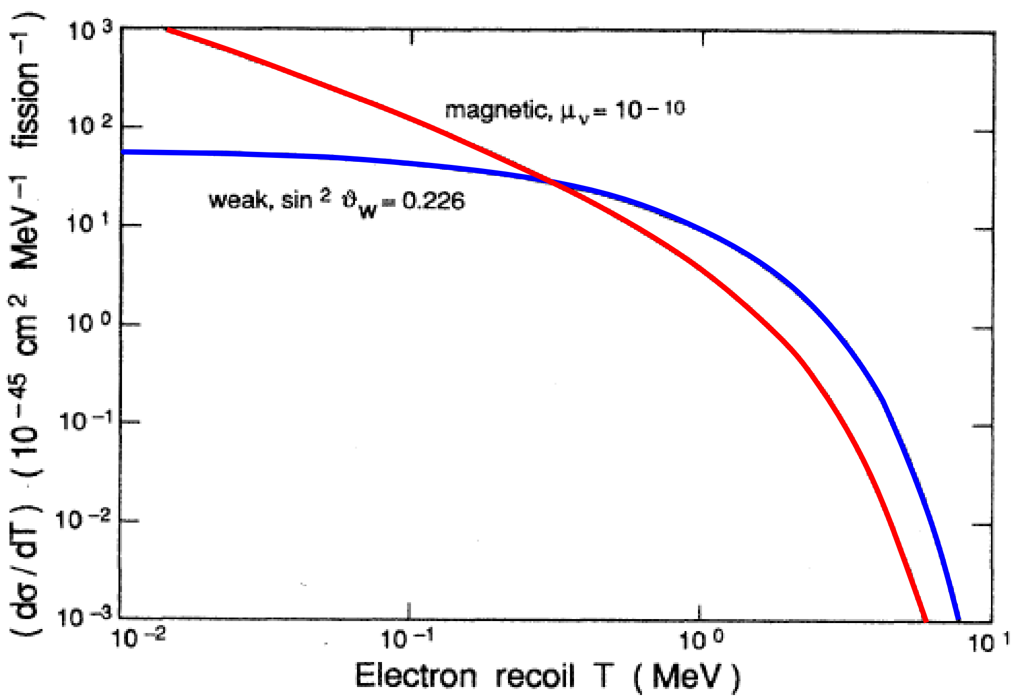
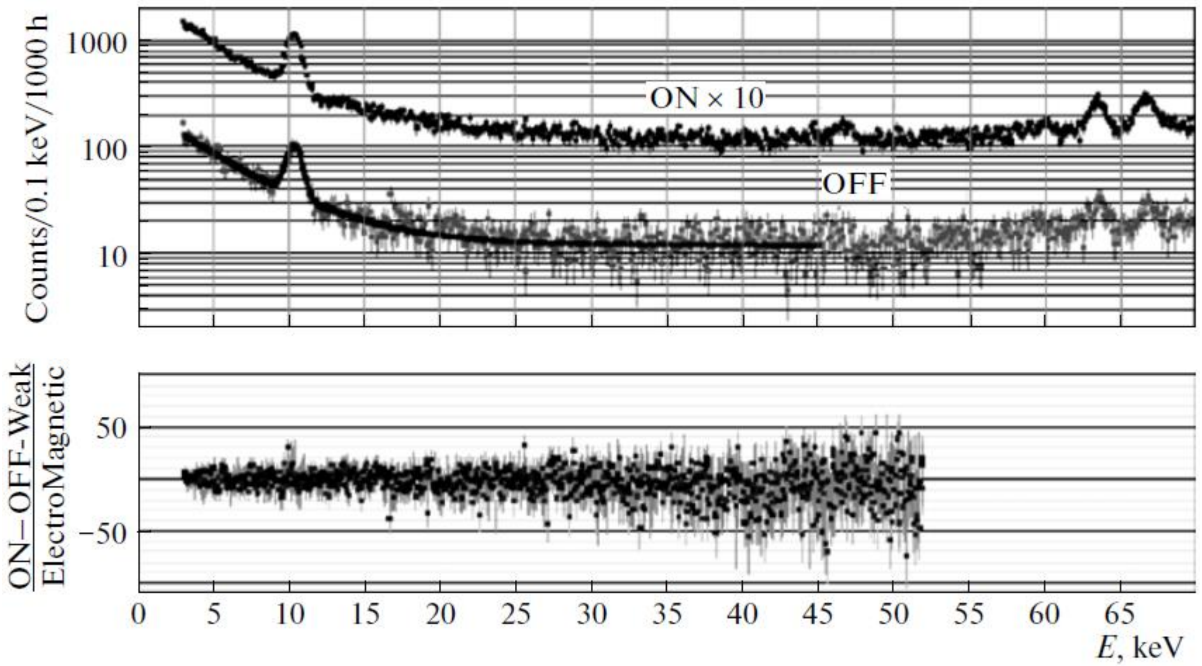



Evidence of a non-zero neutrino magnetic moment would appear as a dramatic increase in the scattering rate for the lowest energy recoil electrons.

# Best Direct Limit of the Neutrino Magnetic Moment

The best limit comes from the Gemma Experiment, which used a 1.5 kg Ge detector at a 3 $GW_{th}$ commercial reactor in Russia.

$$\mu_\nu < 2.9 \times 10^{-11} \mu_B \text{ (90\% CL)}$$




Reactor neutrino magnetic moment experiments are dominated by backgrounds

They are unable to tell reactor-on from reactor-off.

Nevertheless, the limit is based on the absence of any increase in the on/off ratio at low recoil energy.

# Possible Use of Source in ν Magnetic Moment Search

PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

## Neutrino electromagnetic form factors

Noted in 1989!

P. Vogel and J. Engel
*Physics Department, California Institute of Technology, Pasadena, California 91125*

(Received 27 December 1988)

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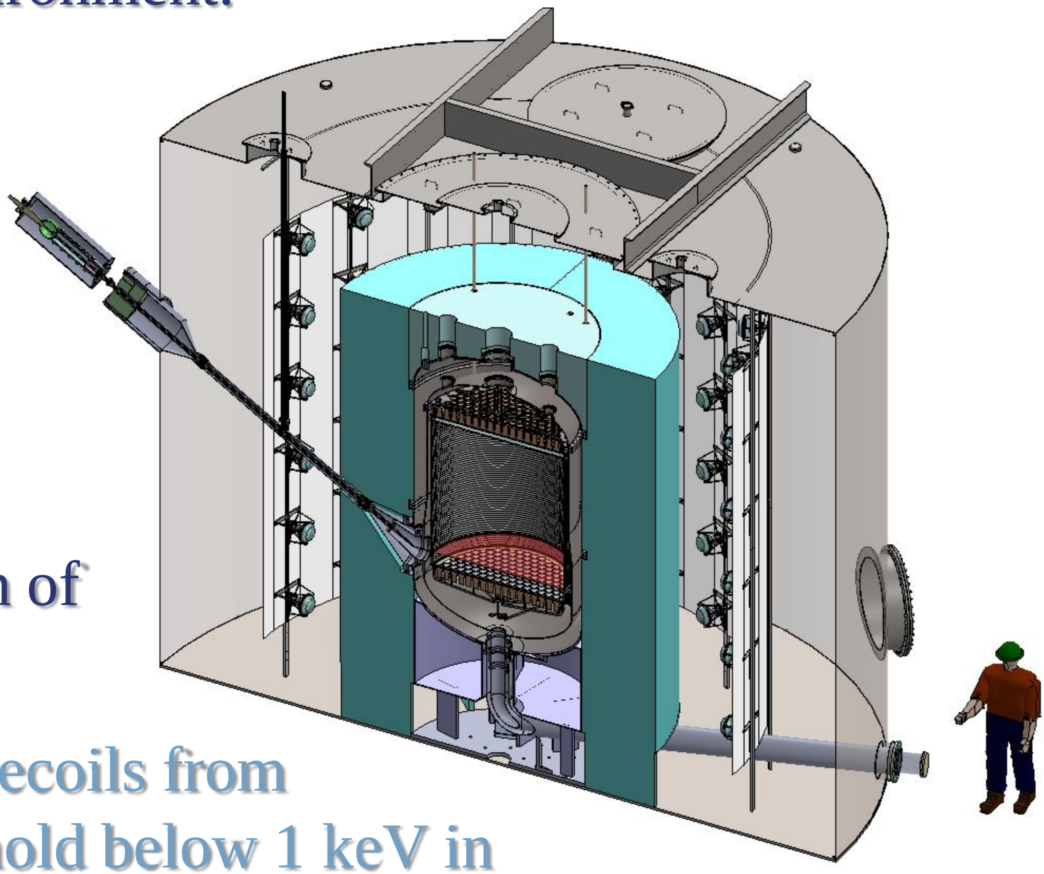
"Instead of a nuclear reactor an electron-capture radioactive source could in principle be used. The advantage is a possible $4\pi$ geometry; i.e., the detector might completely surround the source. The whole apparatus could be placed in an underground laboratory in order to minimize background. To illustrate such an experiment, let us consider the same 600-kCi $^{51}$Cr source that is to be used for calibration in the GALLEX project."

"We assume that at our disposal is a 50-cm-thick liquid-argon detector…"

# The Proposed LZ Dark Matter Detector

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

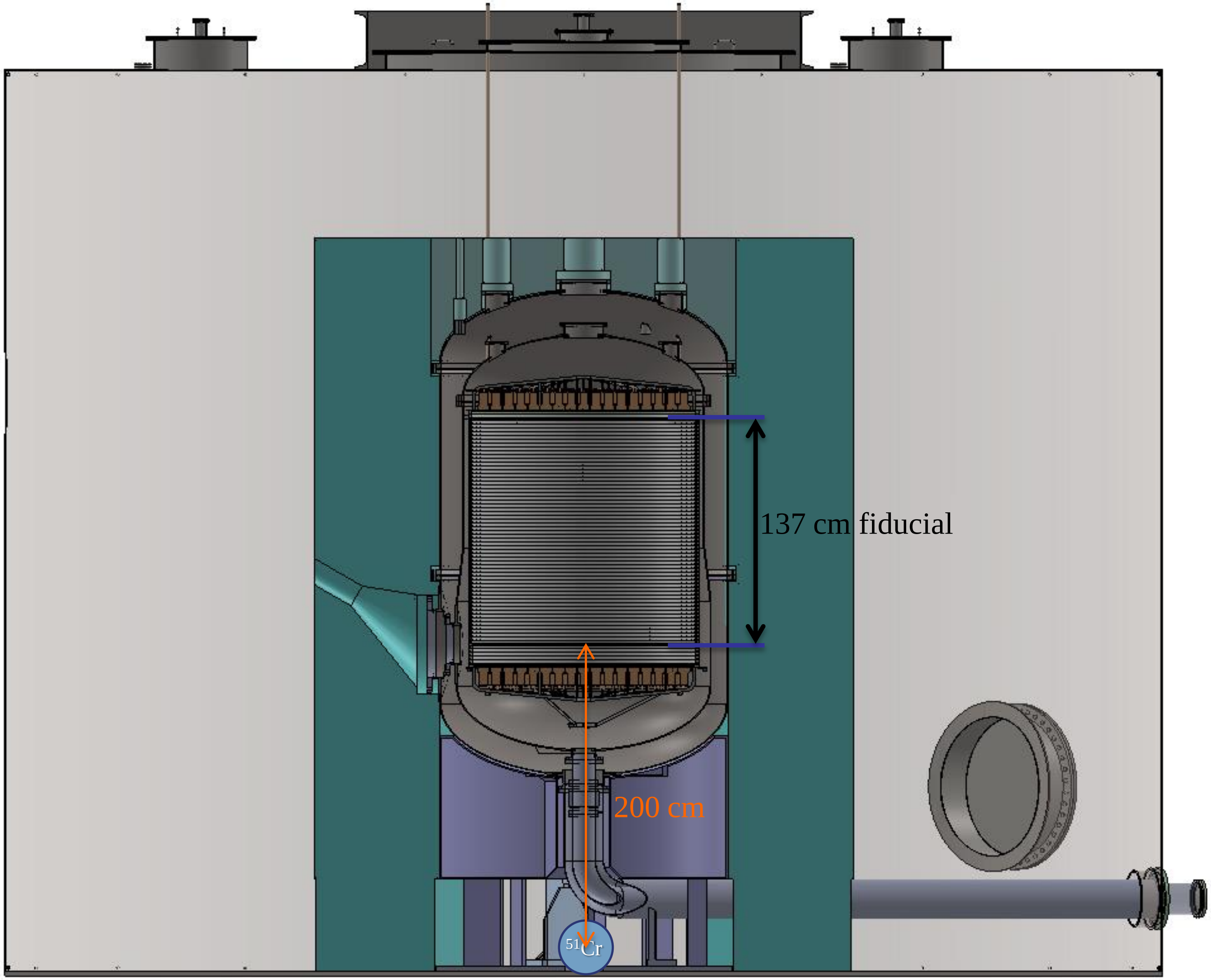
LZ is a two-phase detector that will be sensitive to both the primary scintillation in LXe and scintillation in the gas phase from individual accelerated drift electrons.



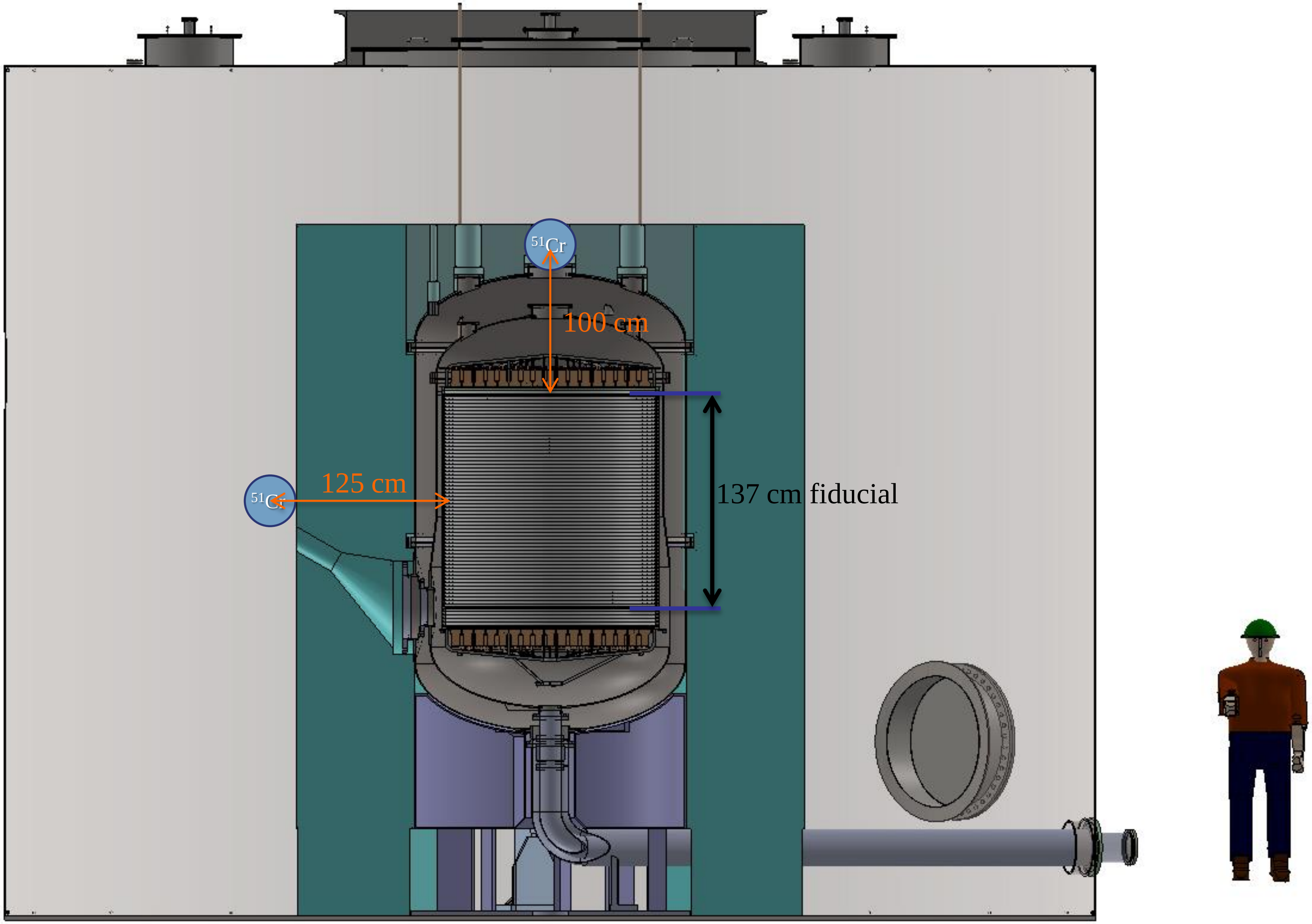
It will have a spatial resolution of better than 1 cm.

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

# Possible Source Implementation at LZ

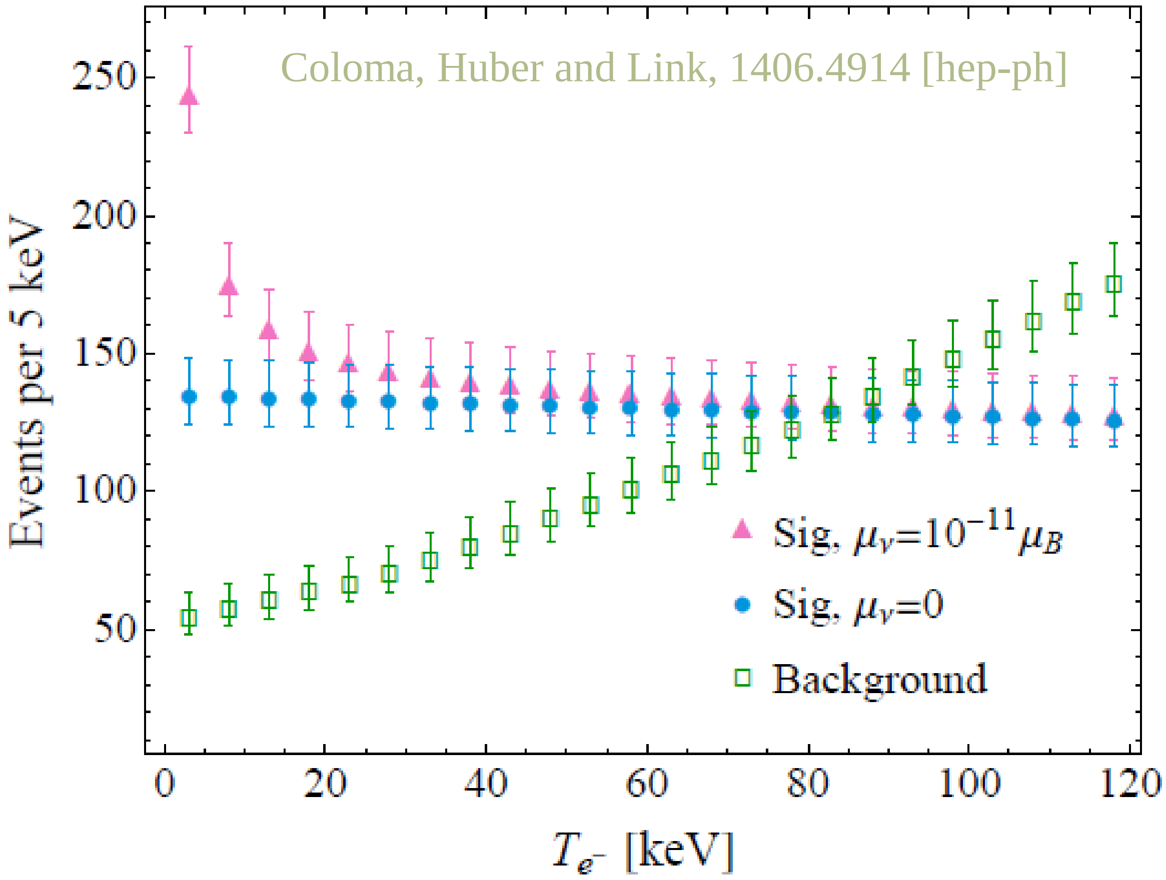


# Alternate Implementations



# Calculation of Elastic Scattering Rate in LZ

Assuming an exposure of 100 days from a single 5 MCi source ($5.8\times10^{23}$ emitted neutrinos), and the source center located 1 m from the edge of the fiducial volume.

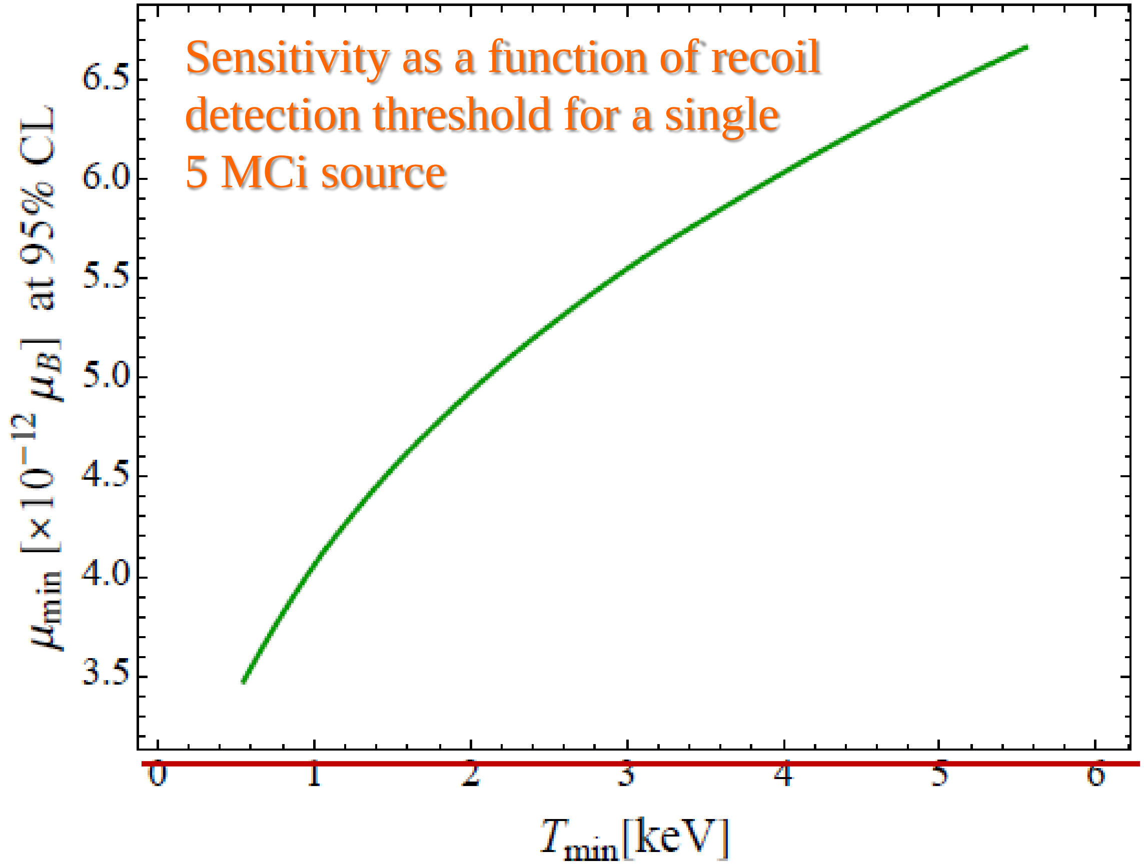



The expected number of weak interaction events is ~12,500.

At the Gemma limit, E&M interactions would add more than 3,000 events.

# Neutrino Magnetic Moment Sensitivity in LZ

Sensitivity is a strong function of the low-energy detection threshold, but this is the real strength of dark-matter detectors.




Coloma, Huber and Link, 1406.4914 [hep-ph]

The measurement is statistics limited, meaning that added runs should take the sensitivity below the astrophysical limit.

# How About an Oscillation Search with LZ?

At one meter offset the LZ event rate is 2× larger than SOX and the S/N ratio is a factor of 20 better (geometry and the solar ν flux).

LZ's 1 cm resolution is complimentary to Borexino's 15 cm. In fact the uncertainty in *L* will be driven by the source dimensions ($\sigma_L \sim 3$ cm)

| $\Delta m^2$ ($eV^2$) | 0.5 | 1 | 5 | 10 | 20 |
|---|---|---|---|---|---|
| Wavelength (m) | 3.7 | 1.9 | 0.37 | 0.19 | 0.09 |

750 keV

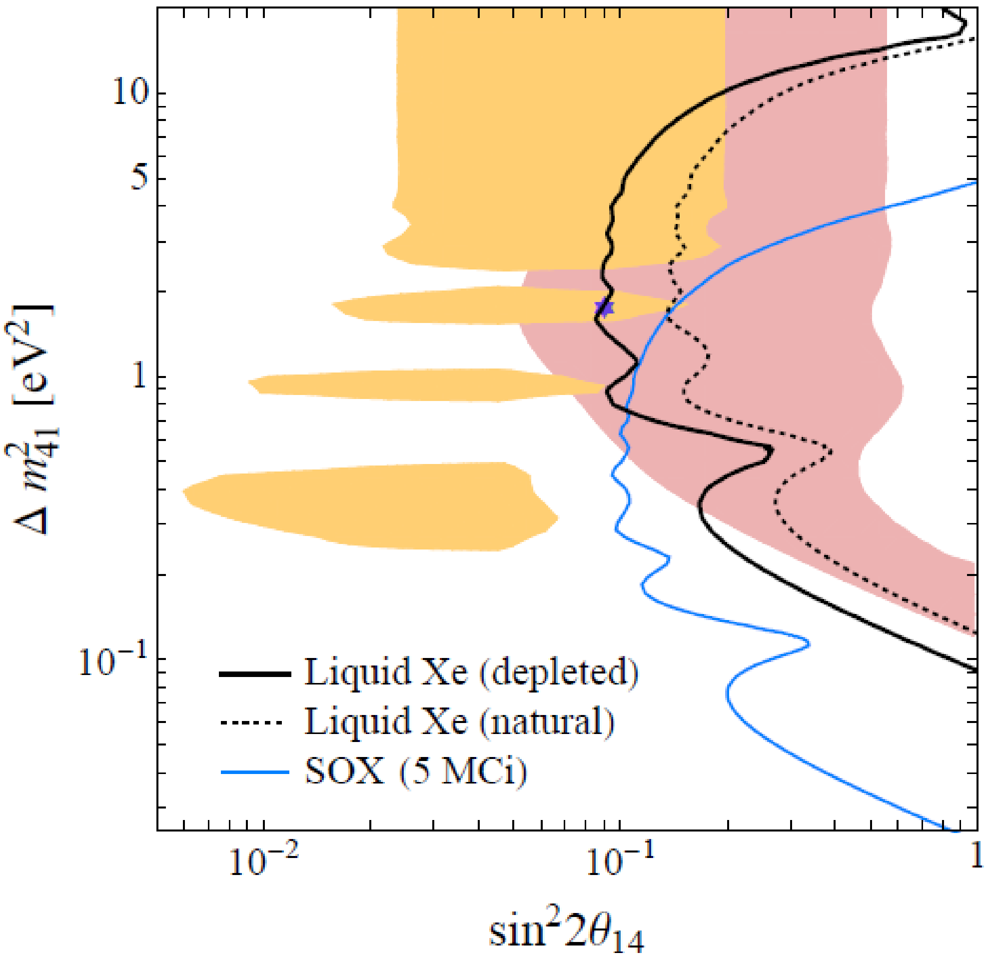
430 keV

Unlike SOX, LZ will have to consider the lower energy neutrino which will account for about 5% of the events.

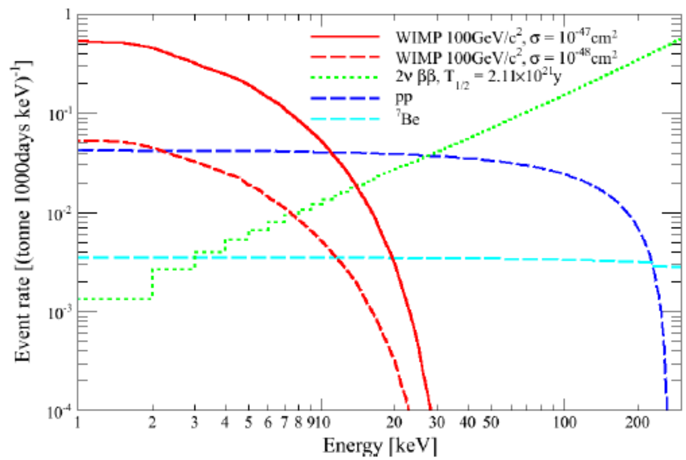
With its 1 cm resolution, LZ can do oscillometry up to 20 $eV^2$ and cover below 1.5 $eV^2$ where the SOX oscillometry starts to fail.

# LZ Sterile Oscillation Sensitivity

The shape only sensitivity shows the oscillometric coverage.



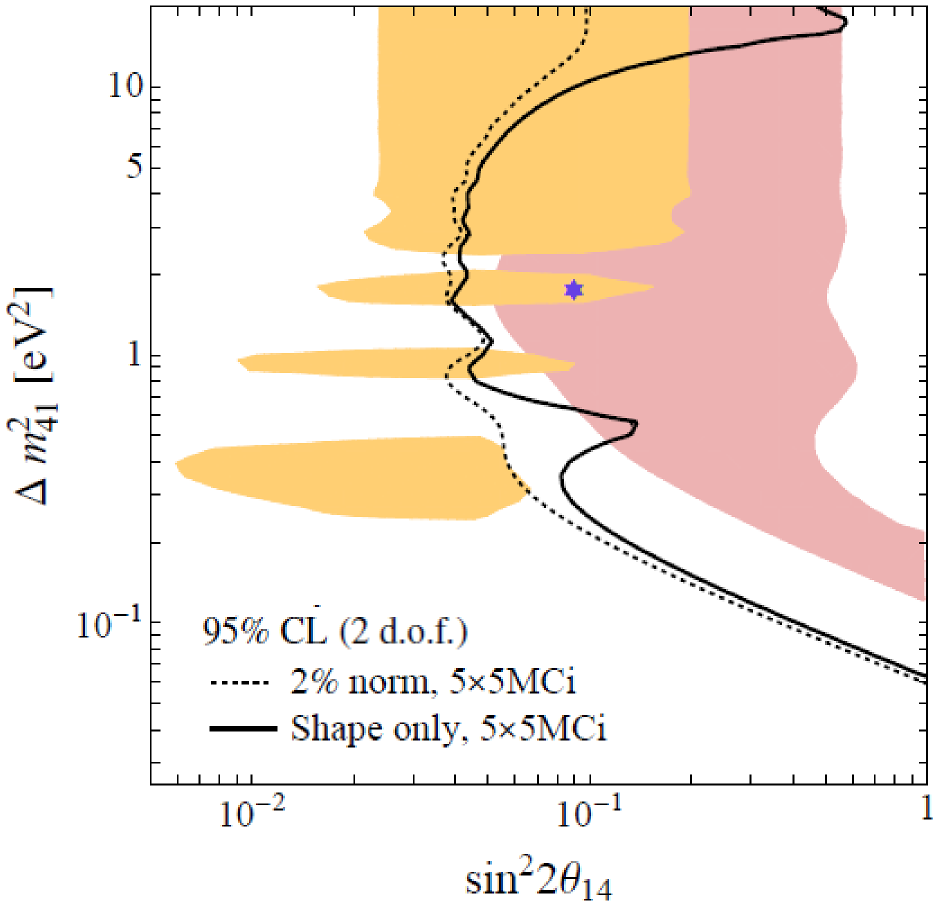

Across the full Cr neutrino energy, the double β-decay isotope, $^{136}Xe$, is a significant source of background.




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

# LZ Sterile Oscillation Sensitivity

## How do you do the ultimate source experiment?




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 five source runs, the magnetic moment sensitivity, assuming a very conservative 2 keV low-end threshold, is $3.3\times10^{-12}\ \mu_B$ (at 95% CL).

# $^{51}Cr$ Source Production

Mega-Curie-scale $^{51}Cr$ sources have been produced in the past. Between the GALLEX and SAGE experiments, three mega-Curie-scale $^{51}Cr$ sources have been produced.

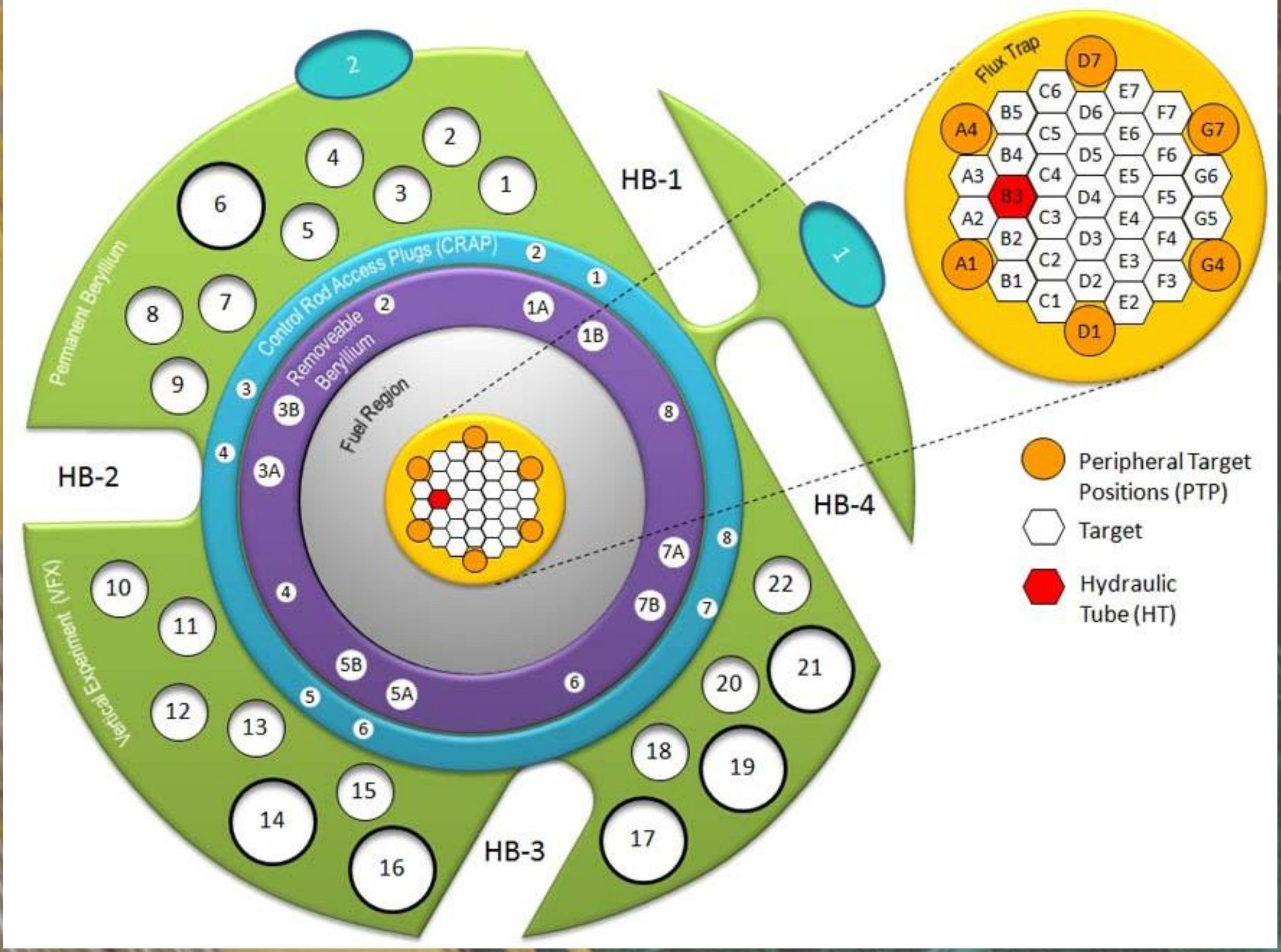
$^{51}Cr$ is made by thermal neutron capture on $^{50}Cr$, which has a 17 barn thermal neutron capture cross section.

Cr must be enriched in $^{50}Cr$ (it is only 4.35% of natural Cr) and depleted of $^{53}Cr$, which has an 18 barn thermal capture cross section.

SOX will use the GALLEX source material: 36 kg of 38% enriched $^{50}Cr$. More highly enriched material would be desirable for LZ.

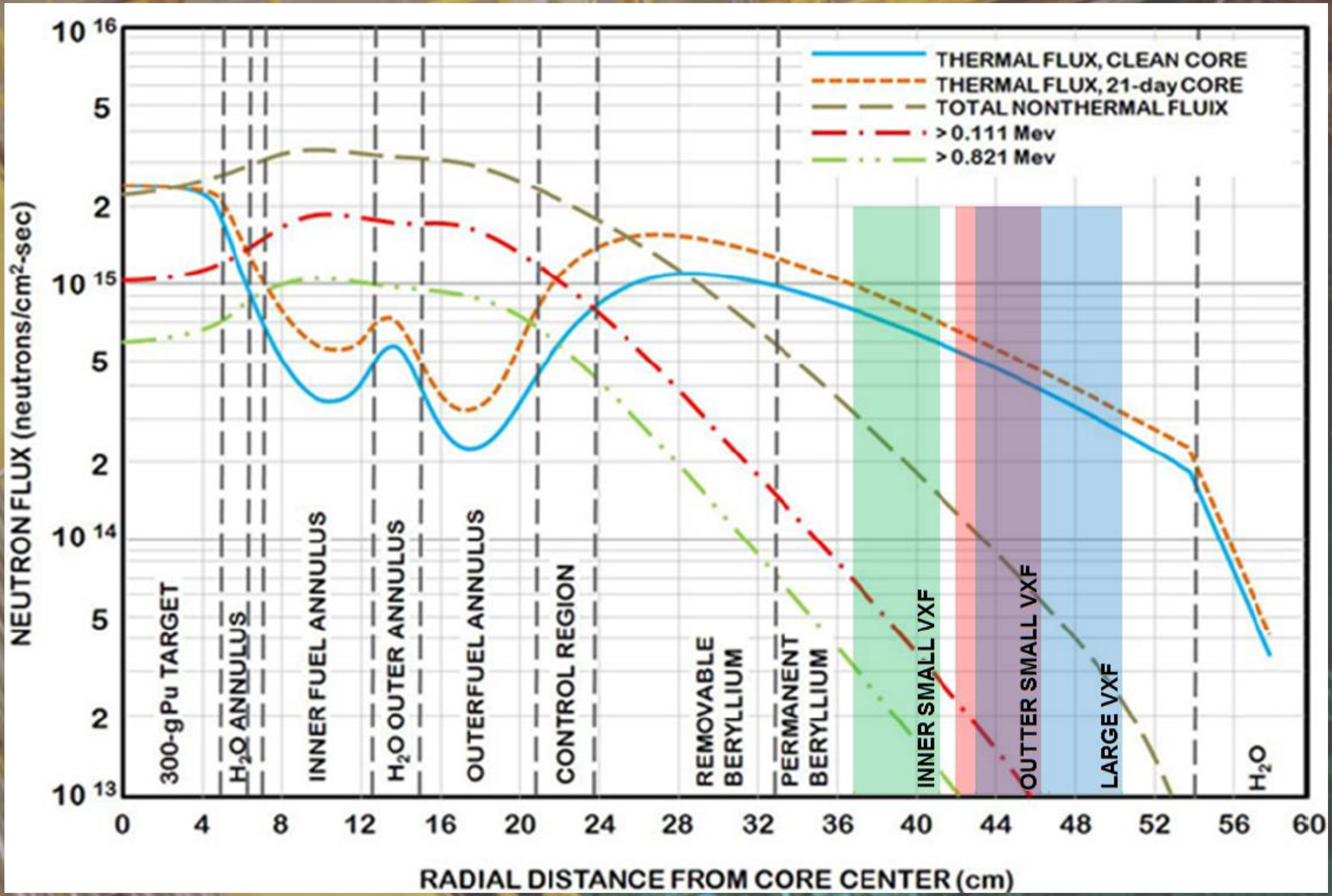
# The High Flux Isotope Reactor (HFIR) at ORNL

HFIR operates at 85 MW with 25 operating days each fuel cycle.



# The High Flux Isotope Reactor (HFIR) at ORNL

Thermal neutron flux of $3\times10^{14}$ /cm$^2$/s in the Vertical Exp. Facilities




5 times larger neutron flux than the Siloè reactor used by GALLEX

# The High Flux Isotope Reactor (HFIR) at ORNL

Simple scaling arguments predict that 12 MCi should be achievable at HFIR, but such calculations fail to account for the impact that a large neutron absorber has on the thermal neutron flux.

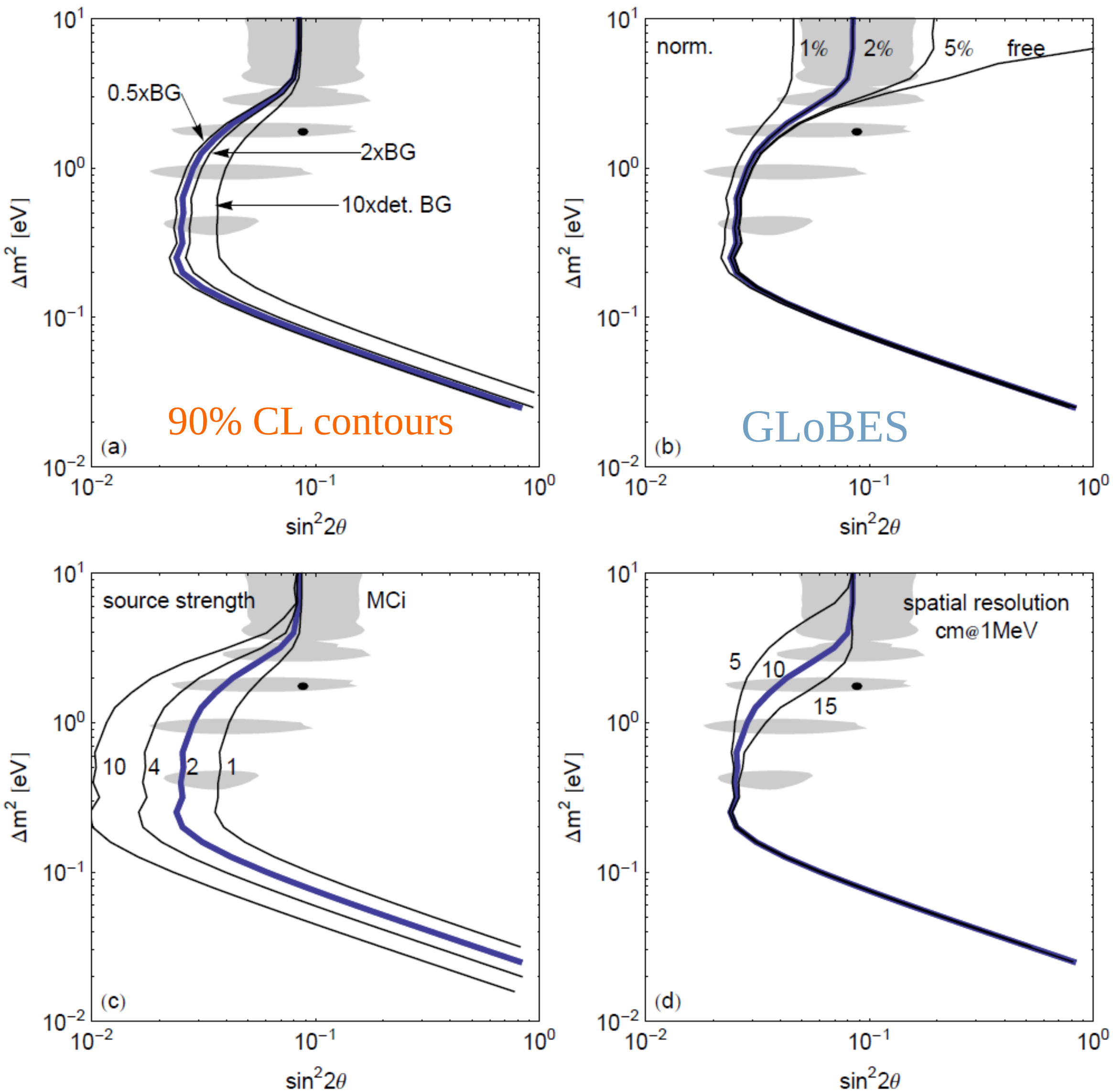
We are studying $^{51}Cr$ production in HFIR with a full MCNP simulation.

Starting with the GALLEX source material, the simulations show that a source of 5 MCi should be possible.

# Conclusions

- $^{51}Cr$ can be made into an intense, well-understood, mono-energetic neutrino source for a wide range of applications including:
  - Detector calibrations
  - Sterile neutrino searches
  - Neutrino magnetic moment searches
- The SOX experiment will deploy $^{51}Cr$ sources totaling 10 MCi and cover much of the allowed sterile space.
- Combining a $^{51}Cr$ source with LZ could result in an improvement in the reach in neutrino magnetic moment by factors of 3 to 10.
- Simultaneously, LZ can make a nice sterile search with oscillometric coverage that is complimentary to SOX.
- These measurements are statistics limited. The ultimate experiments can be done with additional source deployments.

# SNO+Cr Central $^{51}$Cr Source Study

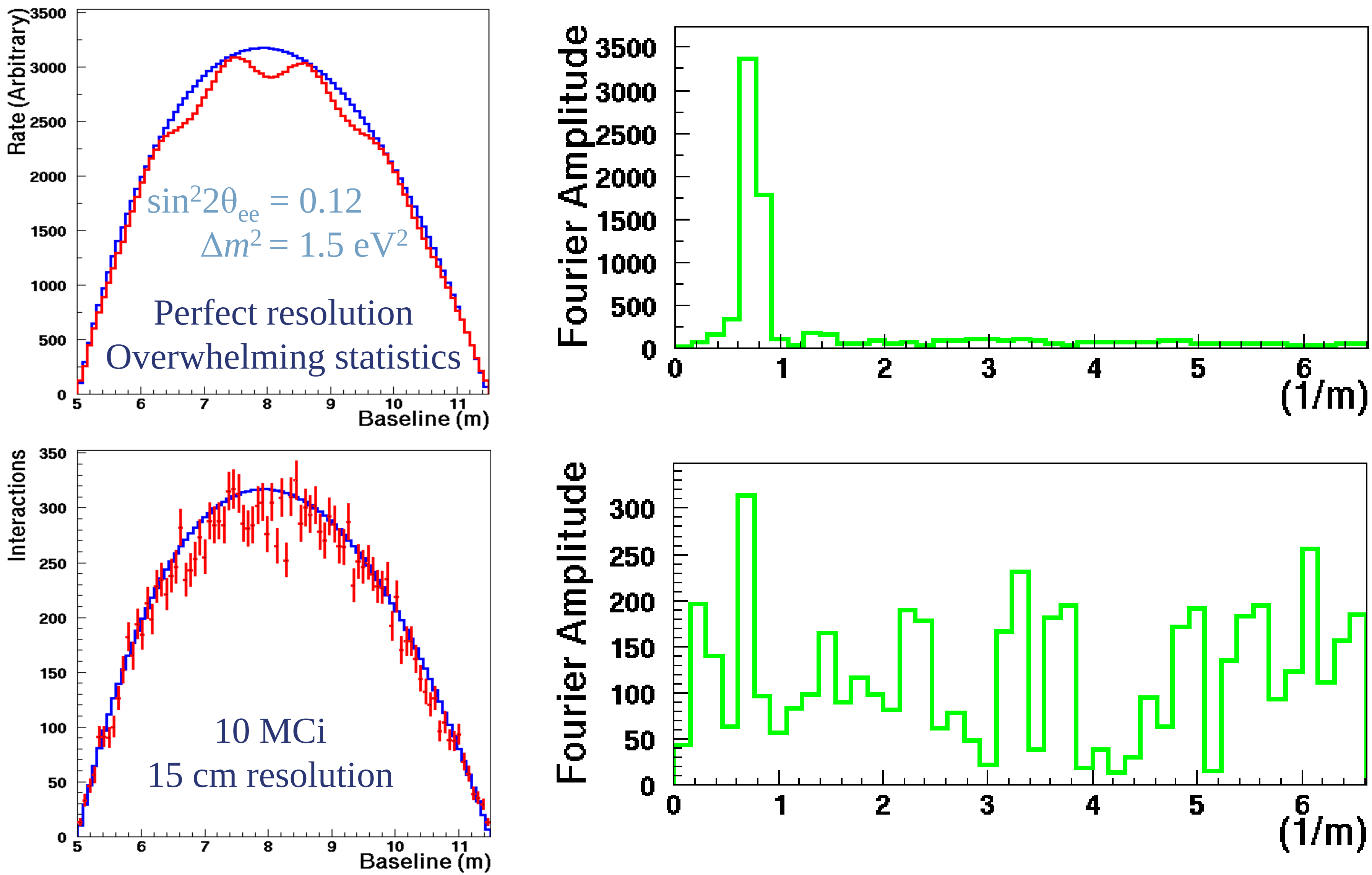



Sensitivity from a $\chi^2$ fit to signal and BG over the full energy range.

1. Not that sensitive to backgrounds
2. Source normalization and spatial resolution are critical to large $\Delta m^2$ resolution.
3. Statistics limited measurement.

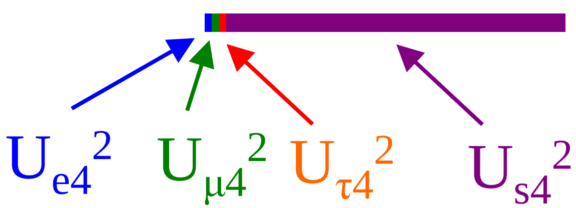
3+1 contours from Kopp, Maltoni & Schwetz arXiv:1103.4570 [hep-ph]

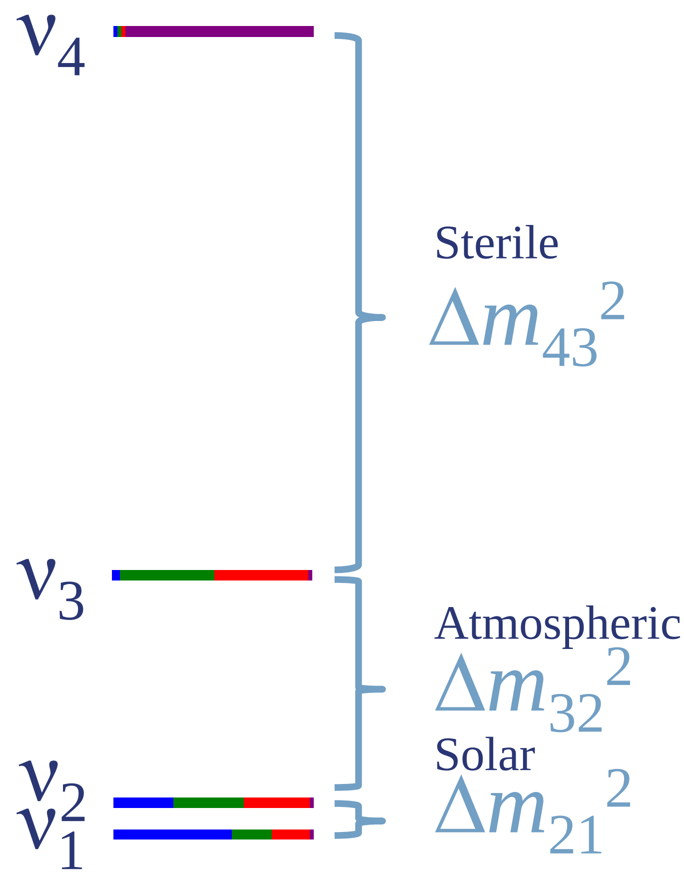
# Oscillometry in SOX



# Mixing with a Fourth, Mostly Sterile, Mass Eigenstate

Comparing appearance probabilities (like LSND) with disappearance probabilities (like Bugey) requires some care…




The appearance probability:

$$P_{\mu e} \approx 4U_{e4}^2 U_{\mu 4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

The disappearance probability:

$$P_{e\not{e}} \approx P_{es}$$

If $U_{e4} \approx U_{\mu 4}$ and $U_{s4} \approx 1$ then $P_{e\not{e}} \approx 2\sqrt{P_{\mu e}}$ (at oscillation maximum)