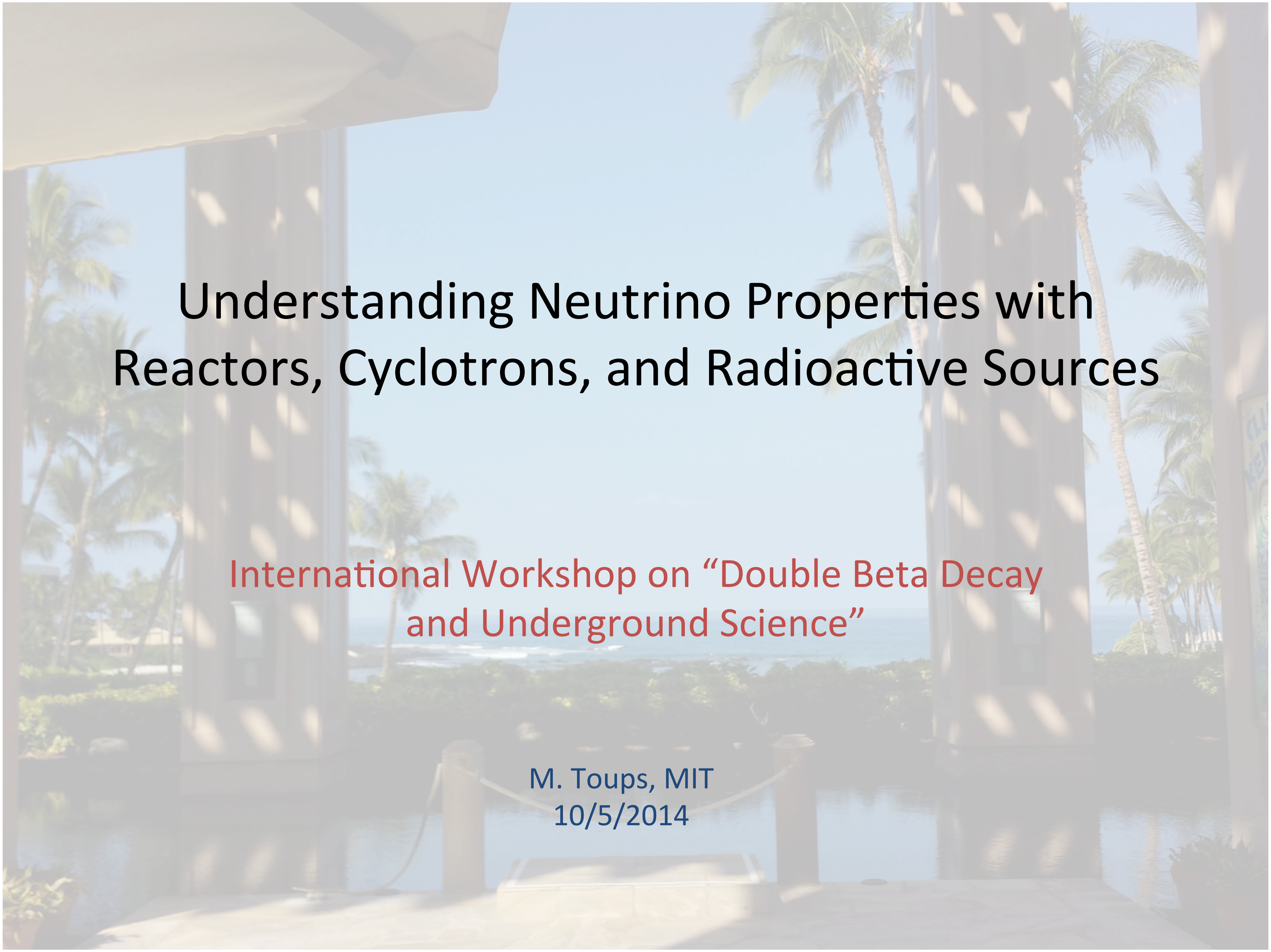

Understanding Neutrino Properties with Reactors, Cyclotrons, and Radioactive Sources

International Workshop on "Double Beta Decay and Underground Science"

M. Toups, MIT

10/5/2014

Outline

- Neutrinos from Reactors, Cyclotrons, and Radioactive Sources
- Neutrino properties
  - Sterile neutrinos oscillations
  - Neutrino electron elastic scattering
- Conclusion

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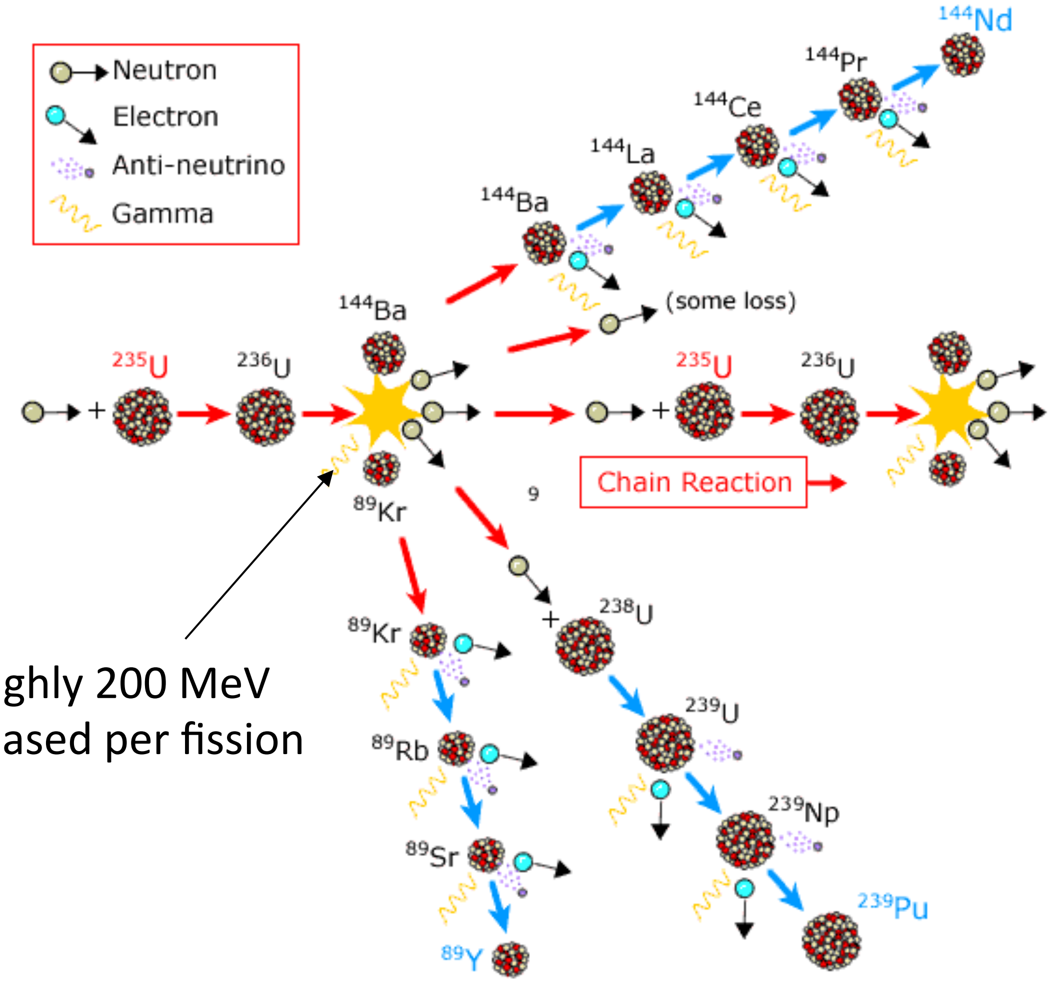
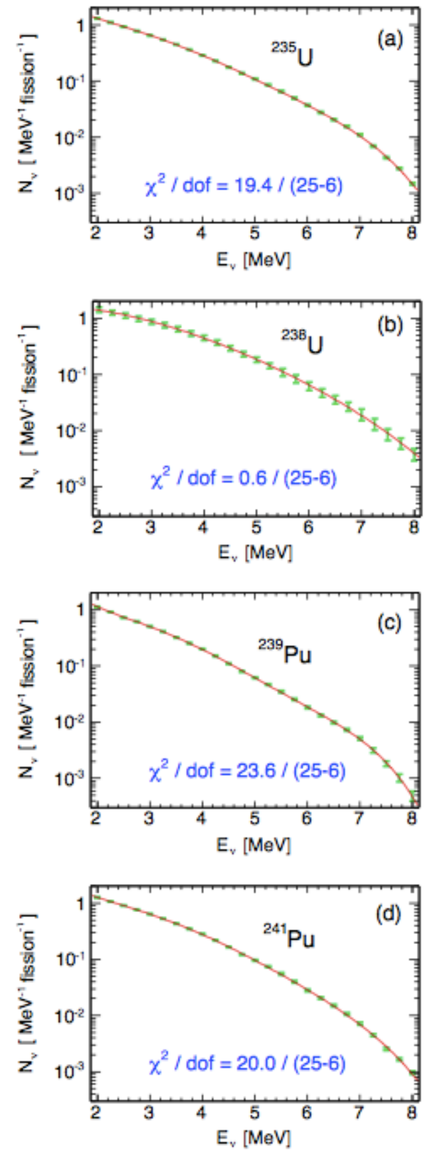
Reactor $\bar{\nu}_e$ Flux = Σ Fission Product β^- Decay Spectra



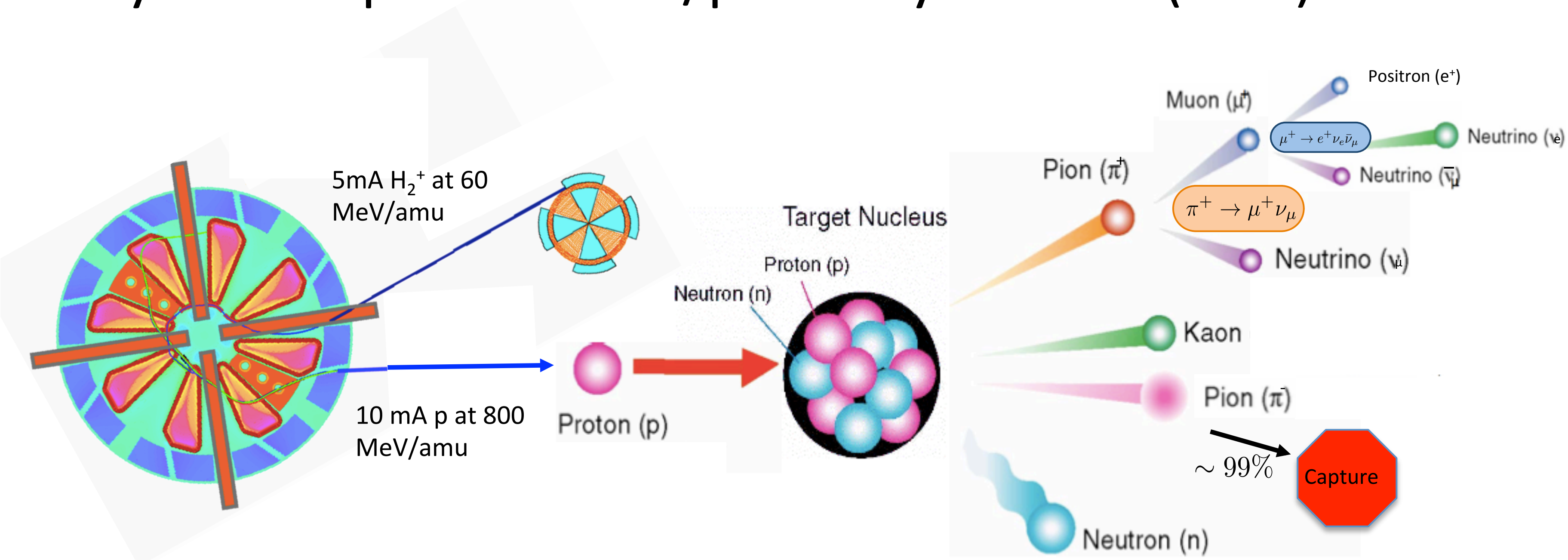
Roughly 200 MeV released per fission

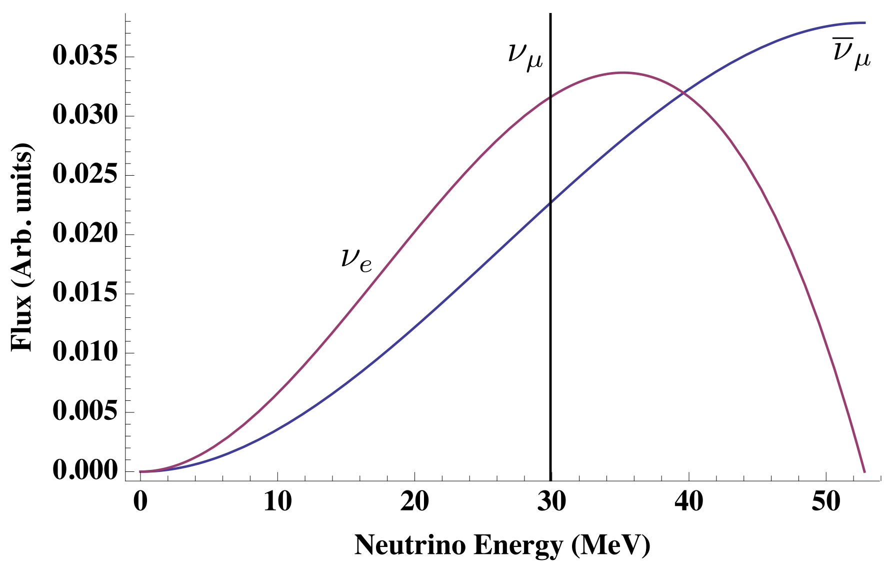


Fission products β^- decay to stable nuclei

→ 6 $\bar{\nu}_e$ per fission

Cyclotron-produced π^+/μ^+ Decay-At-Rest (DAR) Neutrinos





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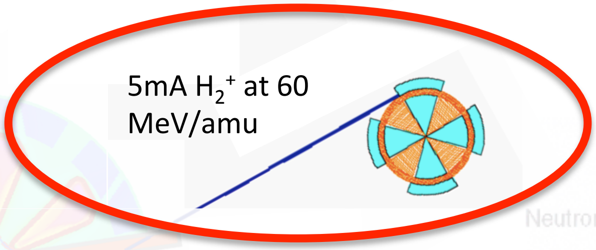
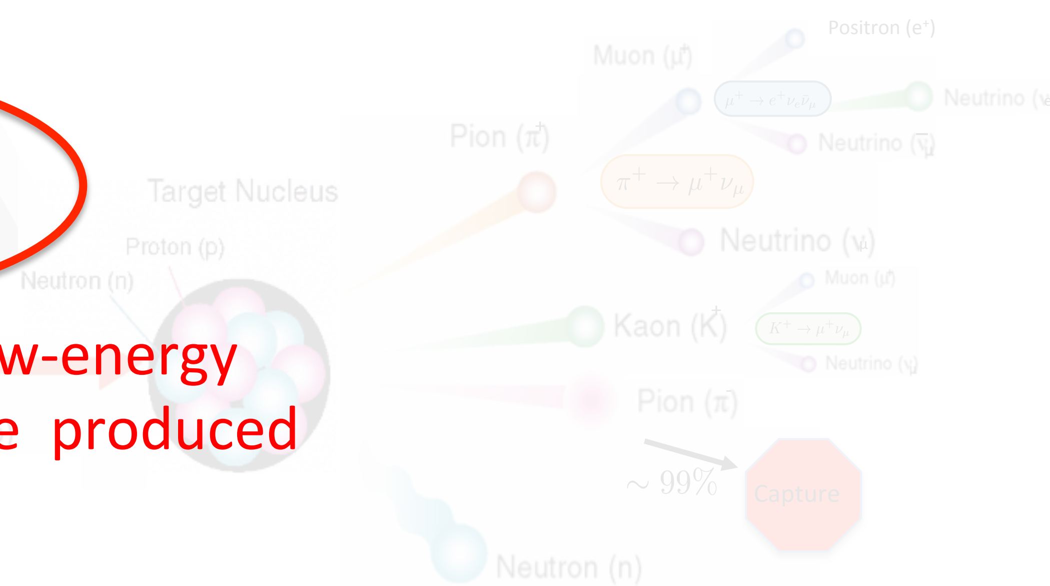
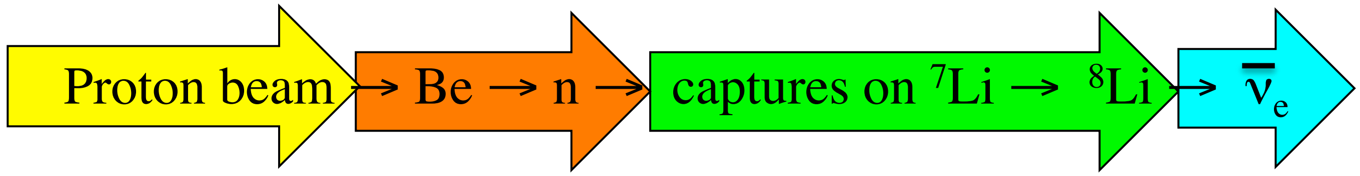
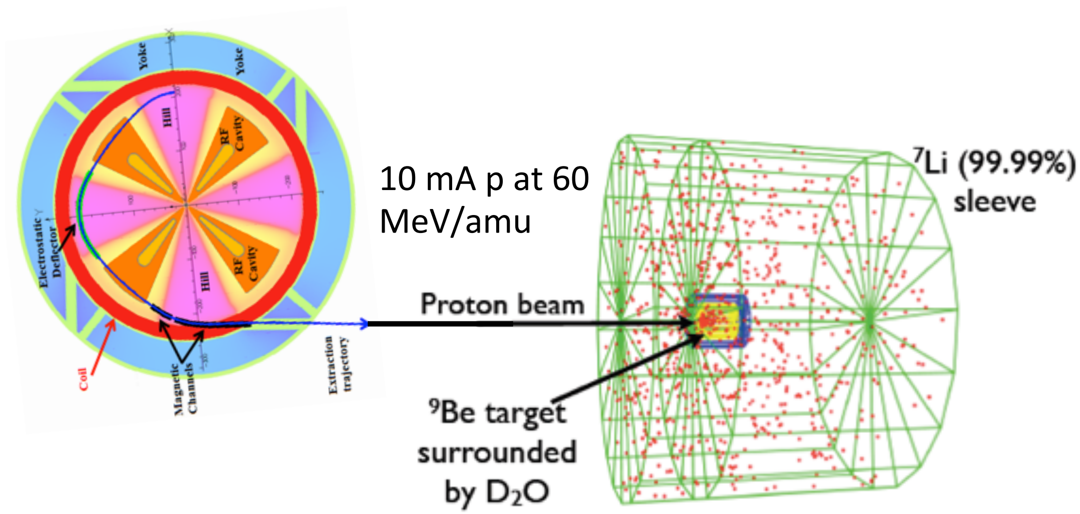


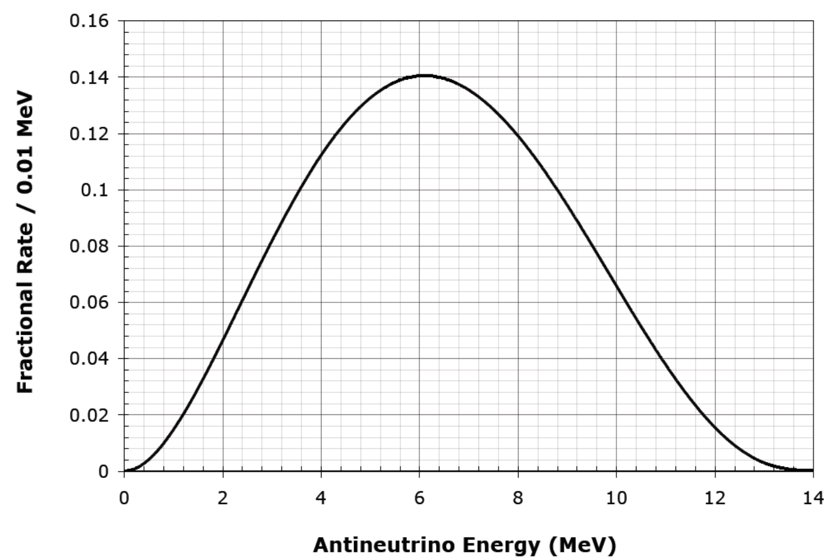


This talk: focus on low-energy neutrinos that can be produced with this cyclotron

Cyclotron-produced Isotope DAR Neutrinos



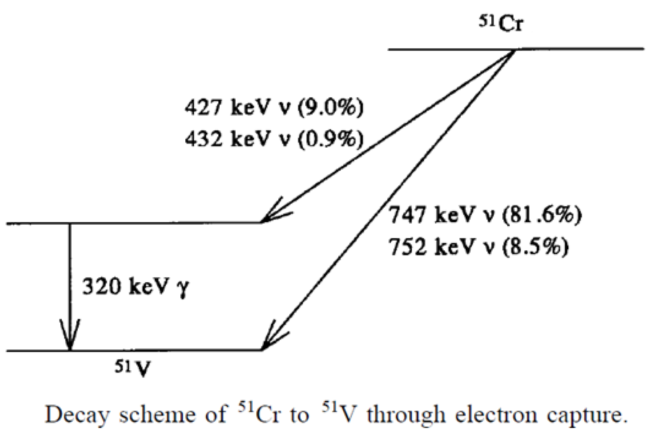




Radioactive sources

^{51}Cr (τ=40 days)

Produced from thermal neutron capture on Cr enriched in ^{50}Cr

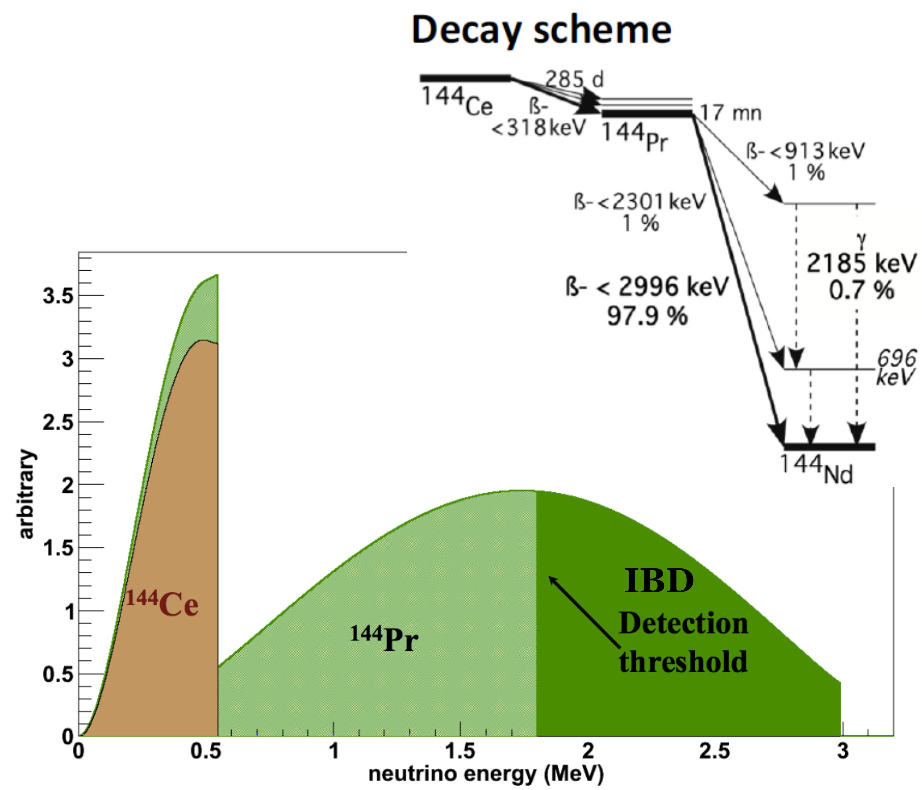


Decay scheme of ^{51}Cr to ^{51}V through electron capture.

→ Mono-energetic 750 keV ν_e 90% of the time

^{144}Ce-^{144}Pr (τ=411 days)

Produced via chemical extraction from spent nuclear fuel



Neutrino Source Characteristics Summary

- Produce low energy (<15 MeV) $\bar{\nu}_e$ or ν_e
  - Radioactive sources with suitable lifetimes lower in energy
- Artificial
  - Beam-off background subtraction
- Isotropic (flux falls as $1/L^2$)
  - Can be located within $\mathcal{O}(10\ \mathrm{m})$ of detector
- Intense fluxes:

Neutrino Source	Neutrino Flux (ν/s)
Reactor	2×10^{17} per MW
Cyclotron (600 kW, 10 mA p)	9×10^{14}
10 MCi ^{51}Cr	4×10^{17}
75 kCi ^{144}Ce-^{144}Pr	3×10^{15}

Understanding Neutrino Properties

Reactor ν's	**Cyclotron DAR ν's**	**Radioactive source ν's**
Sterile ν searches	Sterile ν searches	Sterile ν searches
ν-electron scattering	ν-electron scattering	ν-electron scattering
Coherent ν-A scattering	Coherent ν-A scattering	Coherent ν-A scattering?
3ν oscillation parameters	CP violation (π^+/μ^+ DAR)	Absolute neutrino masses
ν Mass Ordering (hierarchy)	ν-C, ν-Ar cross sections	ν Mass Ordering (hierarchy)

And much more not included in this list…

Understanding Neutrino Properties

Reactor ν's	Cyclotron DAR ν's	Radioactive source ν's
Sterile ν searches	Sterile ν searches	Sterile ν searches
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I will not have time to talk about these…

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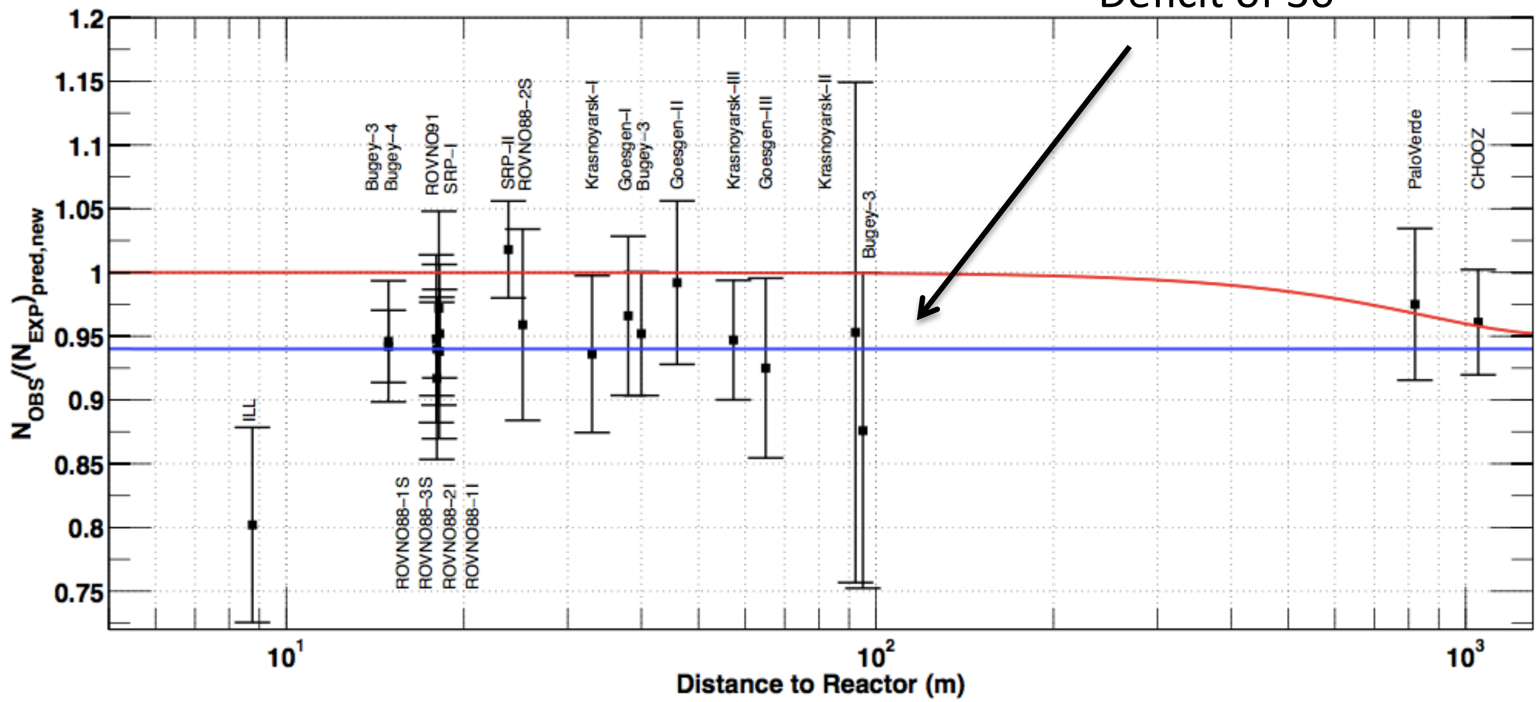
Reactor Neutrino Anomaly

Phys. Rev. D 83, 073006 (2011)

Very short baseline reactor experiments measure fewer neutrinos than predicted

→ Can be interpreted as oscillations into a sterile neutrino

Deficit of 3σ



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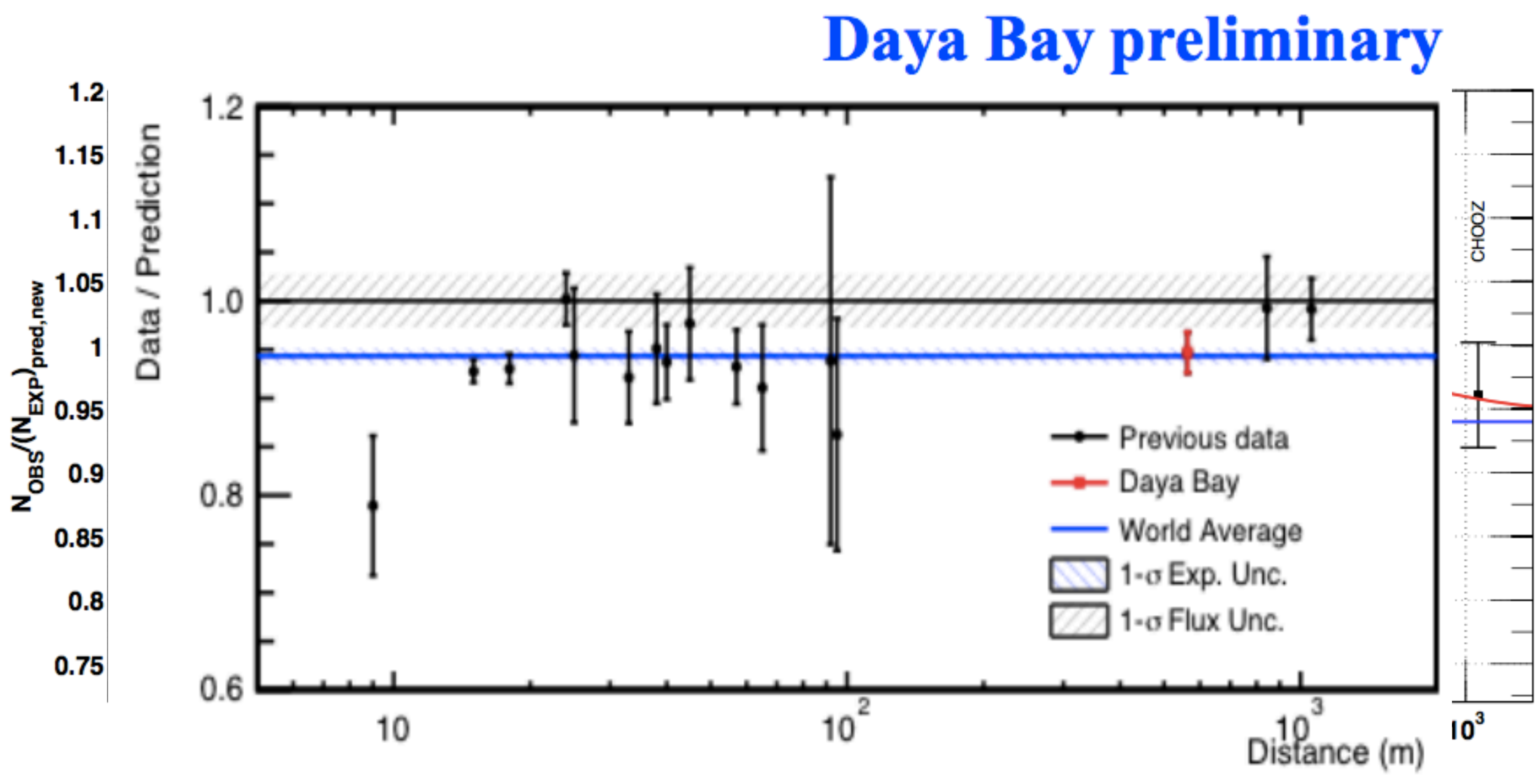
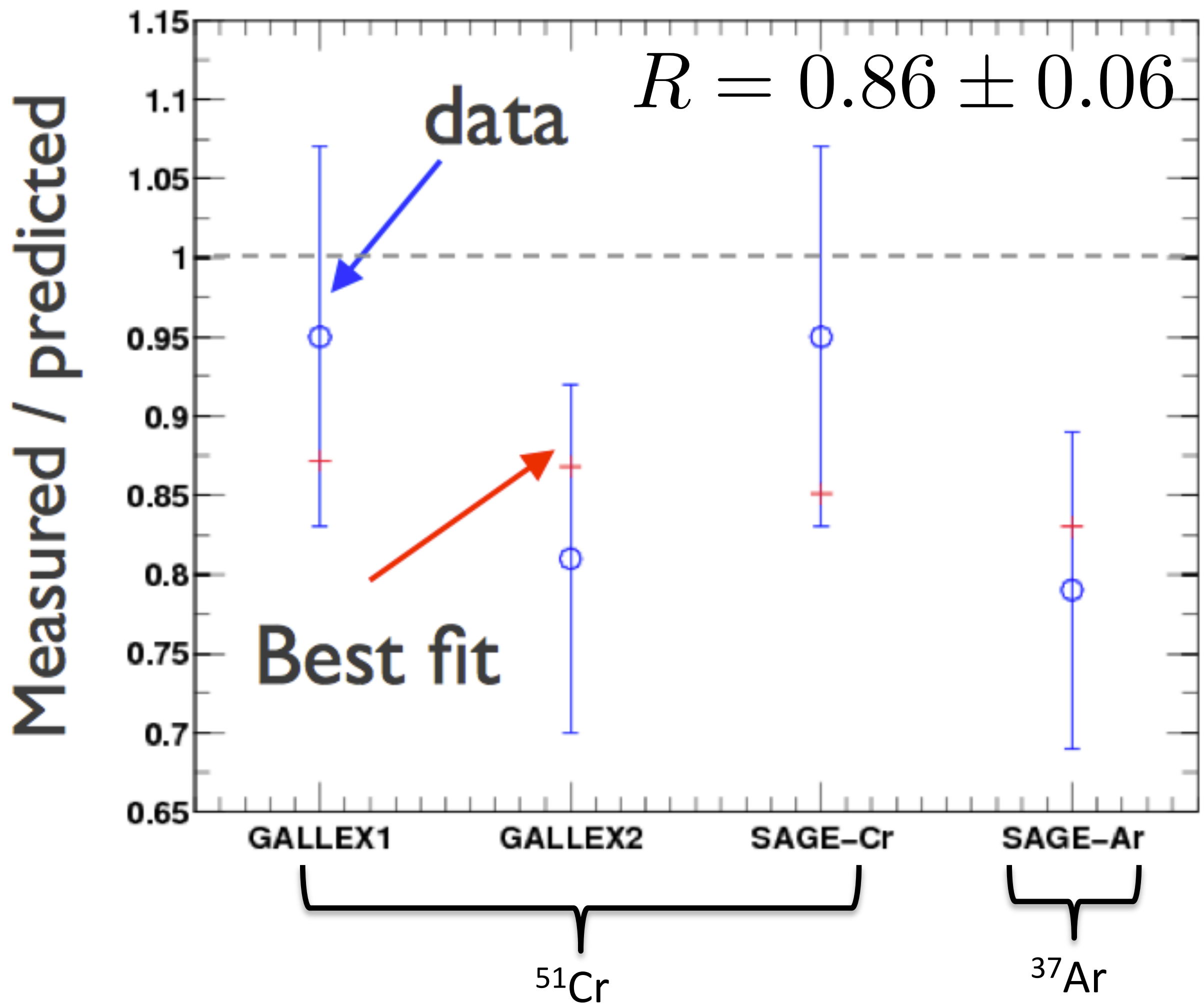


Deficits also observed from ν_e calibration sources



1. **Light Sterile Neutrinos: A White Paper**
K.N. Abazajian (UC, Irvine), M.A. Acero (Mexico U., CEN), S.K. Agarwalla (Valencia U.), A.A. Aguilar-Arevalo (Mexico U., CEN), C.H. Albright (Fermilab & Northern Illinois U.), S. Antusch (Basel U.), C.A. Arguelles (Lima, Pont. U. Catolica), A.B. Balantekin (Wisconsin U., Madison), G. Barenboim (Valencia U.), V. Barger (Wisconsin U., Madison) *et al.*. Apr 2012. 281 pp.
FERMILAB-PUB-12-881-PPD
e-Print: **arXiv:1204.5379 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service
Detailed record - Cited by 205 records 100+

Too much to cover in one talk!

Experiment	ν Source	ν Type	Channel
CeLAND [259]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.
Daya Bay Source [260]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.
SOX [261]	^{51}Cr	ν_e	disapp.
	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.
BEST [64]	^{51}Cr	ν_e	disapp.
PROSPECT [262]	Reactor	$\bar{\nu}_e$	disapp.
STEREO	Reactor	$\bar{\nu}_e$	disapp.
DANSS [263]	Reactor	$\bar{\nu}_e$	disapp.
OscSNS [205]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.
LAr1 [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.
LAr1-ND [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.
MiniBooNE+ [203]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.
MiniBooNE II [265]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.
ICARUS/NESSiE [266]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.
IsoDAR [111]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.
nuSTORM [192]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.

CSS 2013 (Snowmass) Neutrino Report, arXiv:1310.4340 (2013)

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FERMILAB-PUB-12-881-PPD
e-Print: arXiv:1204.5379 [hep-ph] | PDF

I will focus on these

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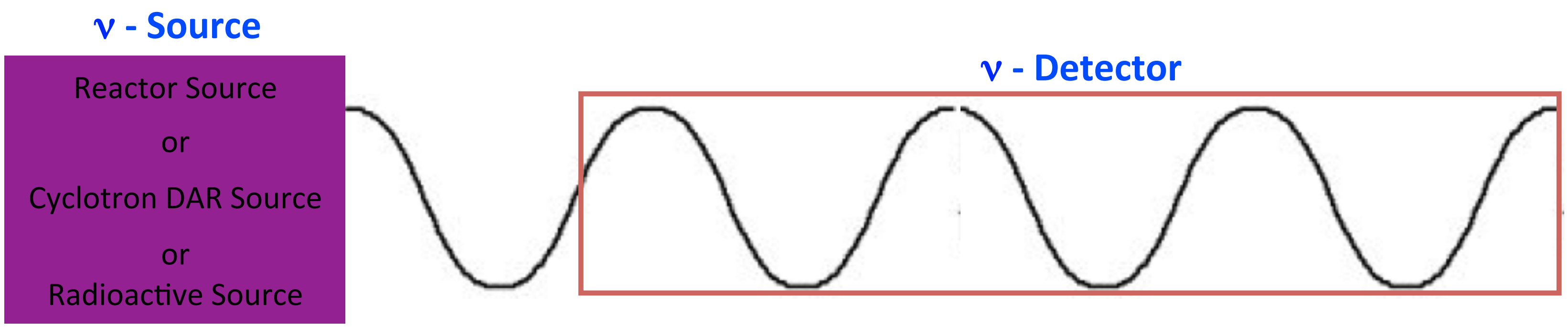
CSS 2013 (Snowmass) Neutrino Report, arXiv:1310.4340 (2013)

Very-short Baseline Disappearance Experiments



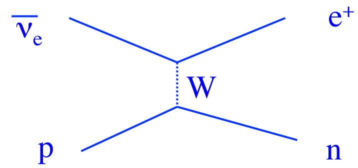
$$1/L^2 \text{ flux rate modulated by } \mathrm{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L/E\right)$$

- Can observe oscillatory behavior within the detector if neutrino source has small extent
  - Look for a change in event rate as a function of position and energy within the detector
  - Bin observed events in L/E (corrected for the $1/L^2$) to search for oscillations

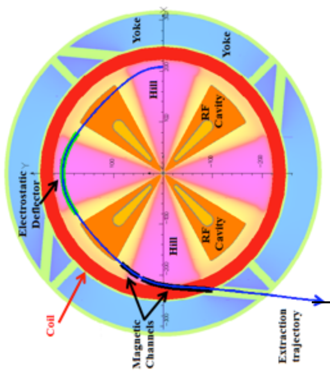
- Backgrounds produce fake events that do not show the oscillation L/E behavior and can be separated from signal

The Isotope Decay-At-Rest Experiment (IsoDAR)

Delayed coincidence
"IBD" signal:

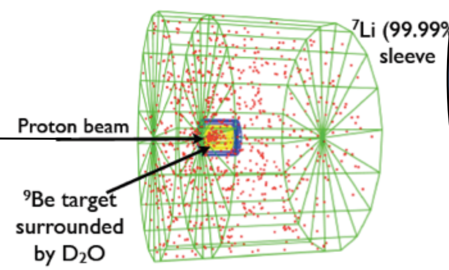


Accelerates 5mA H_2^+
to 60 MeV/amu

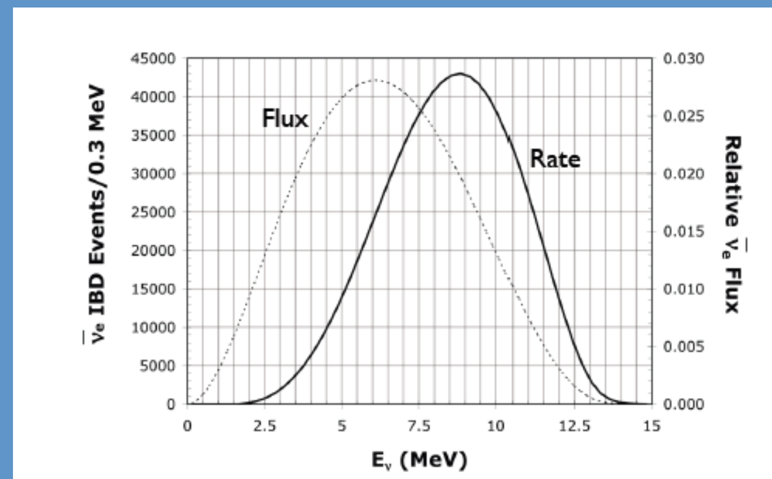


Not to scale

$^8Li \rightarrow {}^8Be + e^- + \bar{\nu}_e$



1 kton LS detector,
e.g. KamLAND



Produces ~10^{23} $\bar{\nu}_e$ (5 years of running)

~16 m

Phys.Rev.Lett. 109 (2012) 141802

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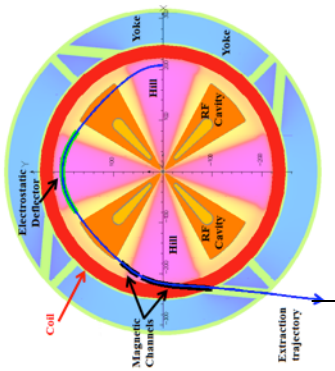

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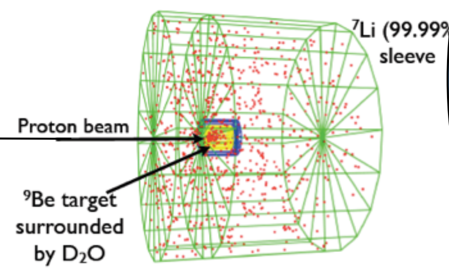
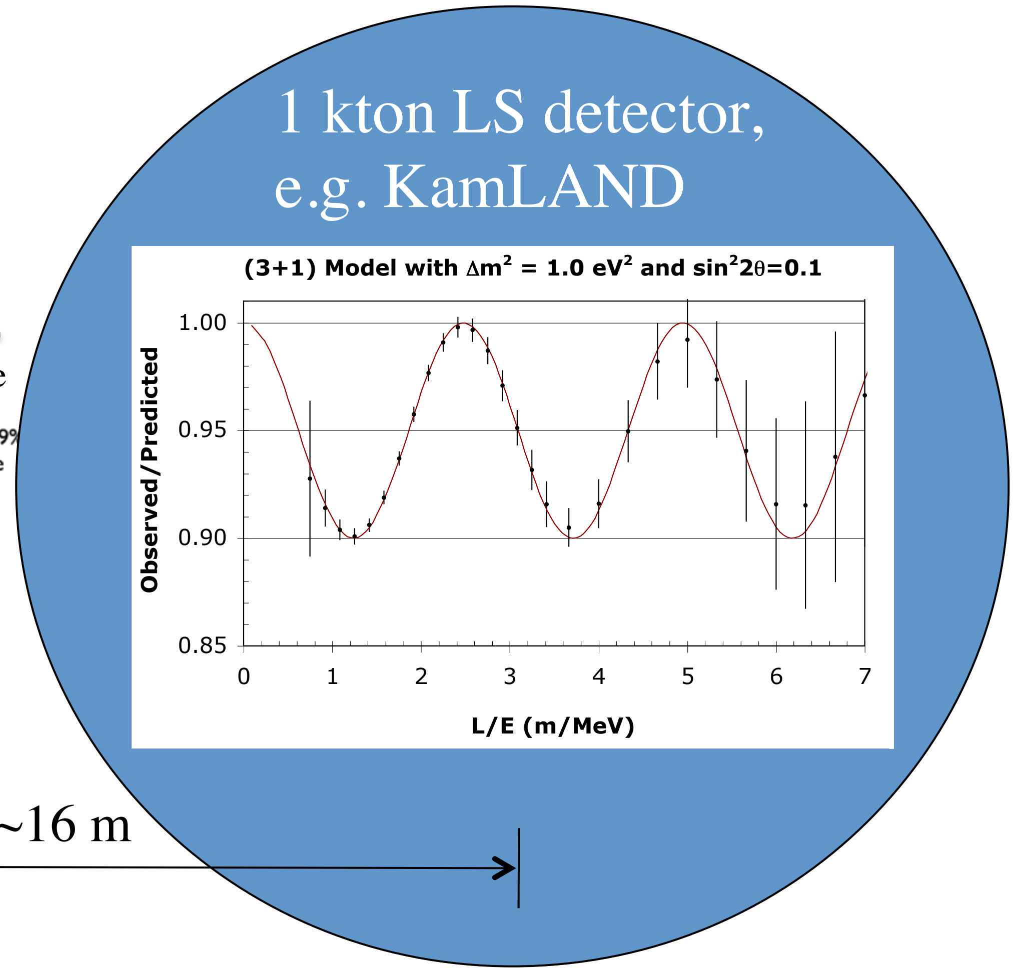
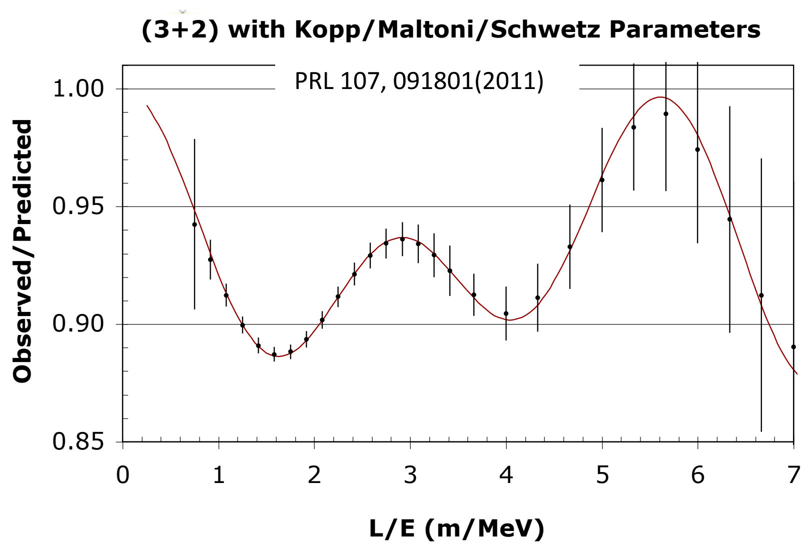
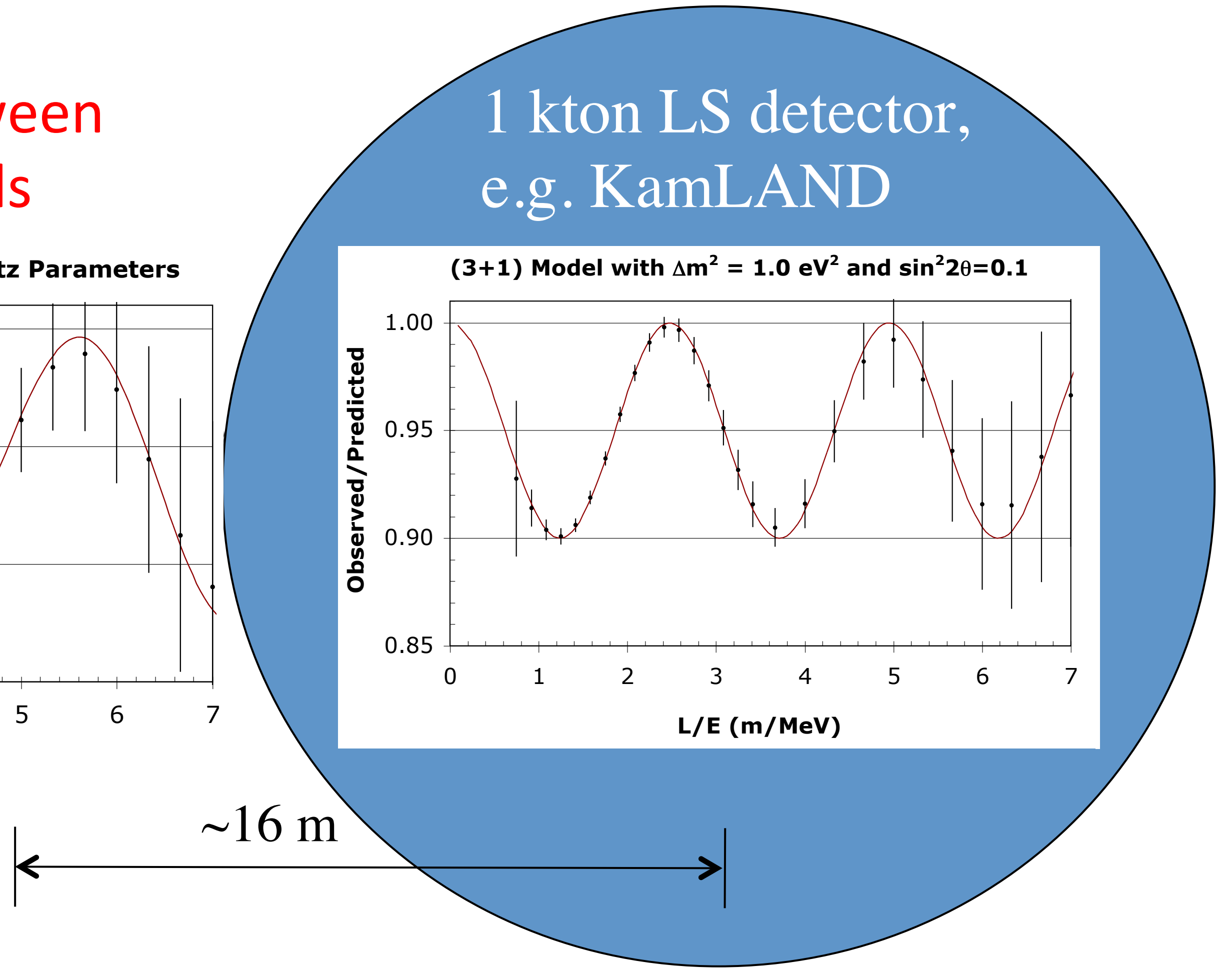




The Isotope Decay-At-Rest Experiment (IsoDAR)

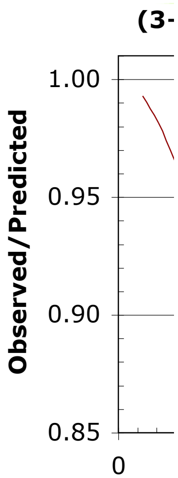
Can discriminate between sterile neutrino models

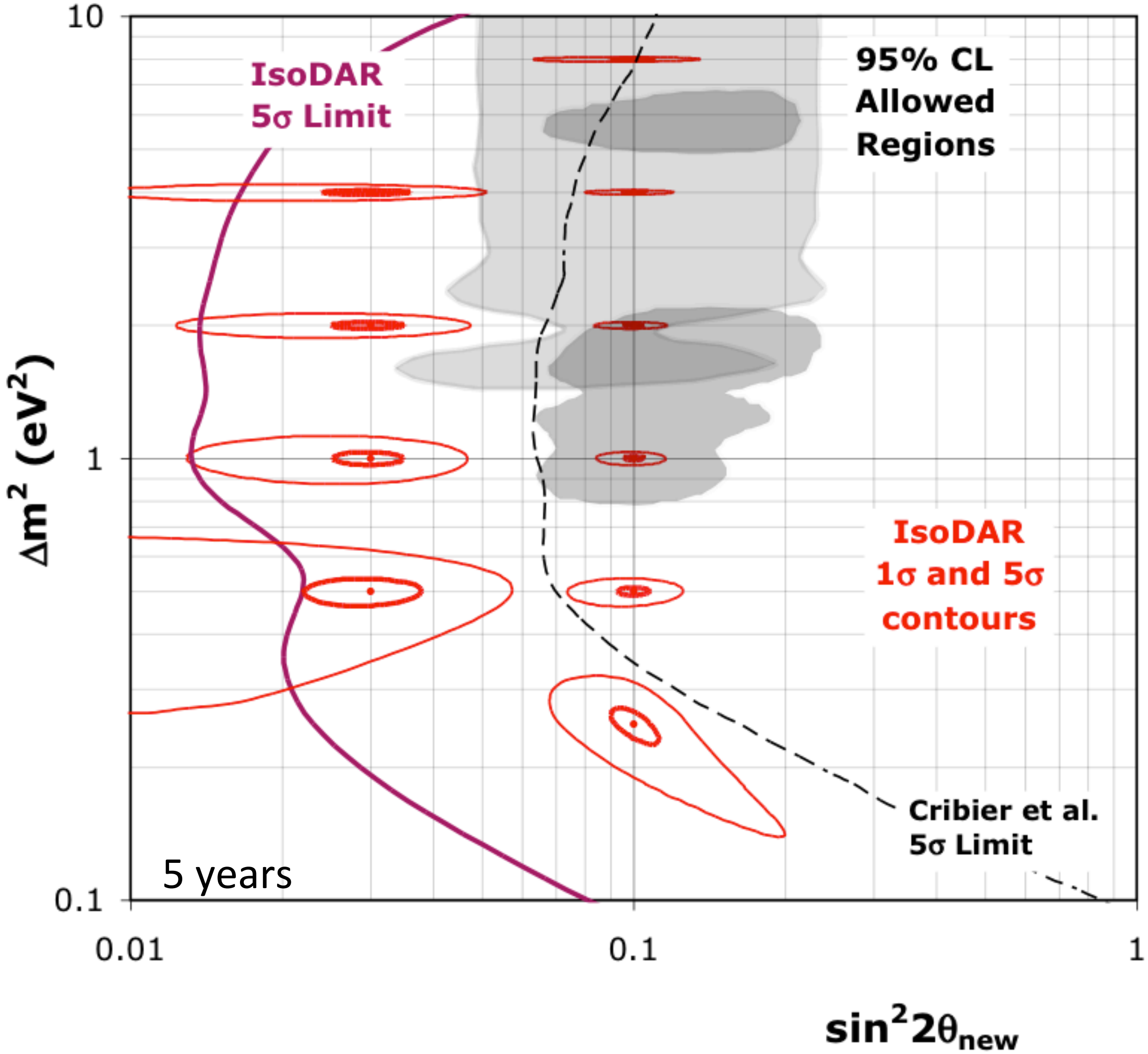




The Isotope Decay-At-Rest Experiment (IsoDAR)

Can di
sterile





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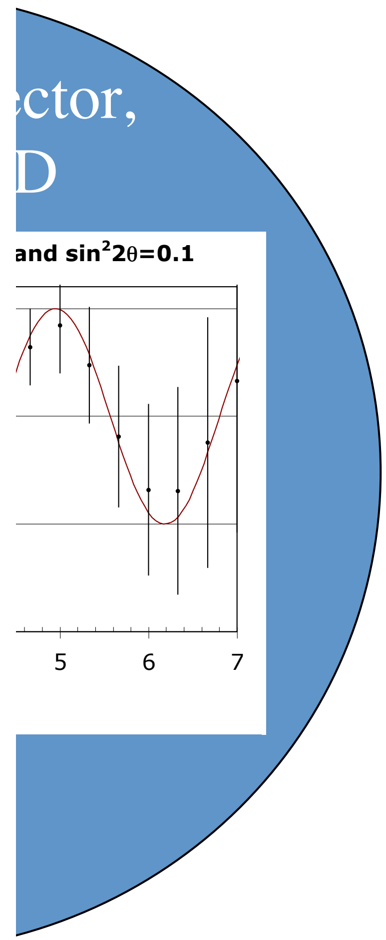
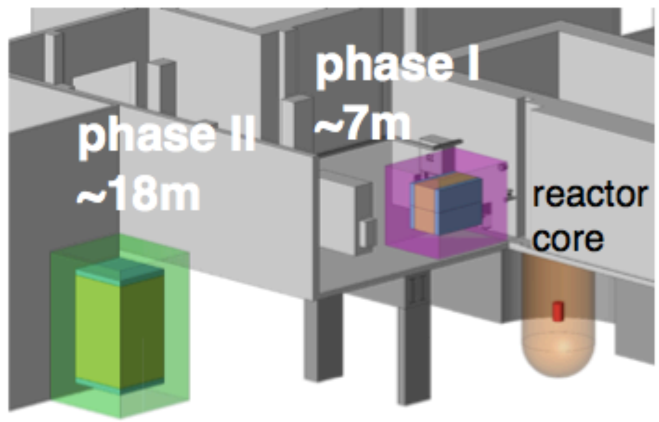


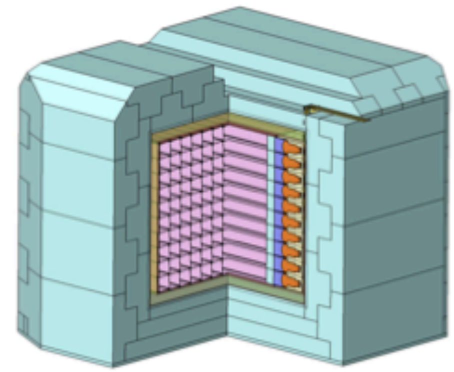
PROSPECT

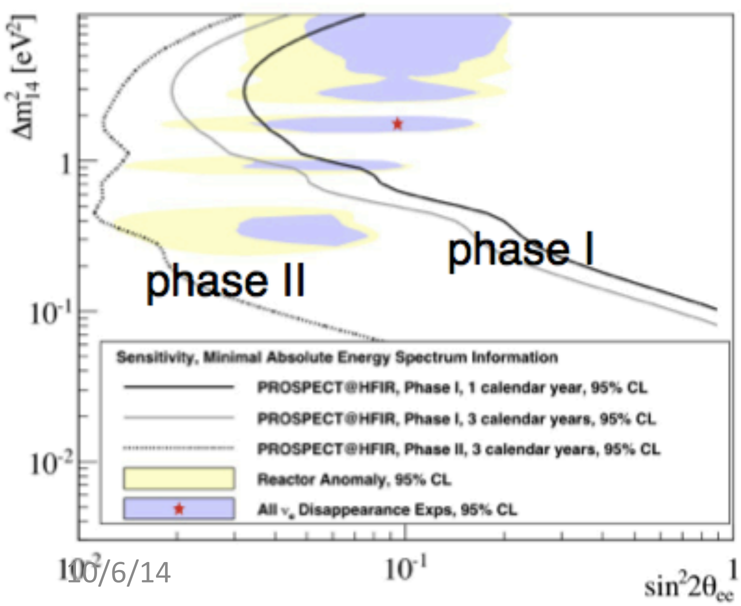
A Precision Reactor Oscillation and Spectrum Experiment at HFIR, ORNL

Physics Objectives

- Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum for physics and safeguards
- Search for short-baseline oscillation within near detector and between near and far detector

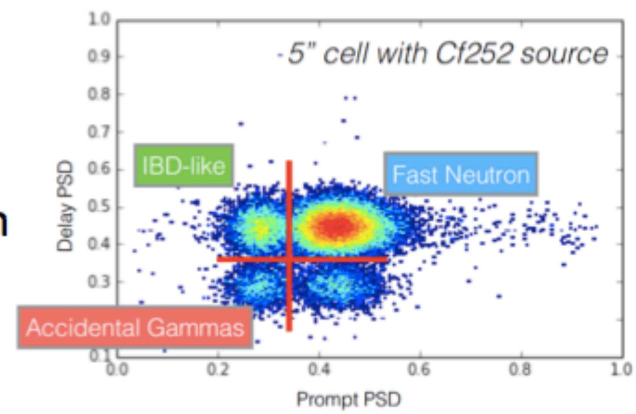






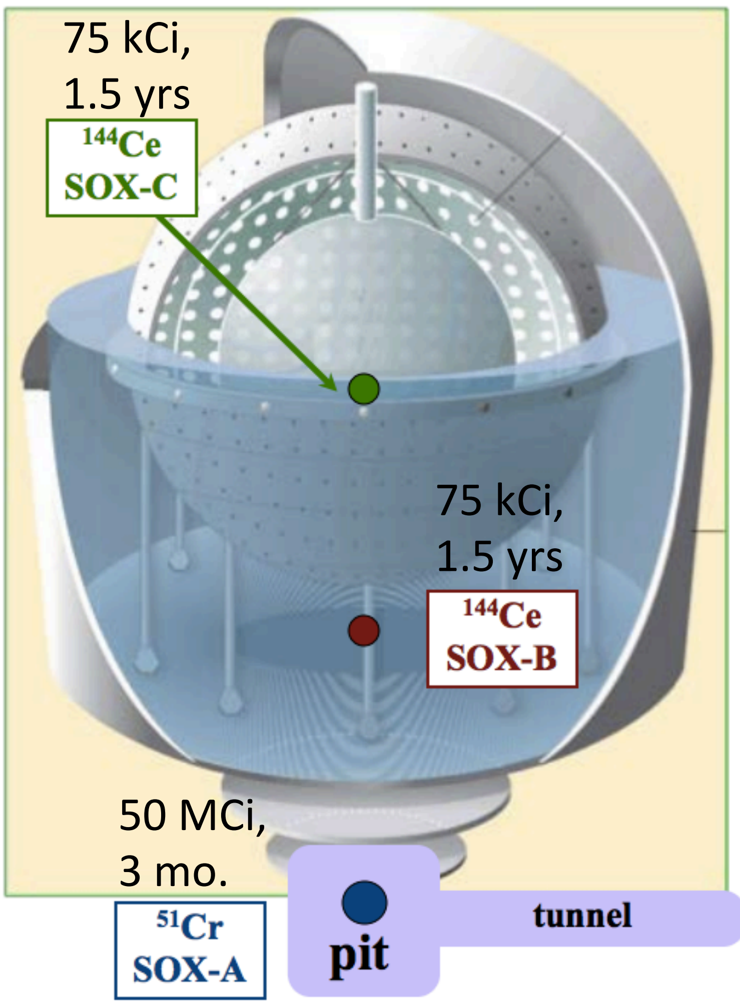
Phase I Detector

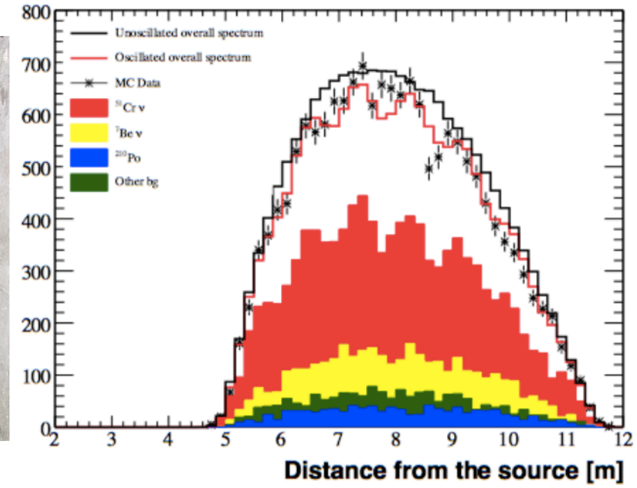
- 2.5 ton of LiLS
- ~ 140 segments, thin wall, optical separation
- double-ended readout
- movable detector

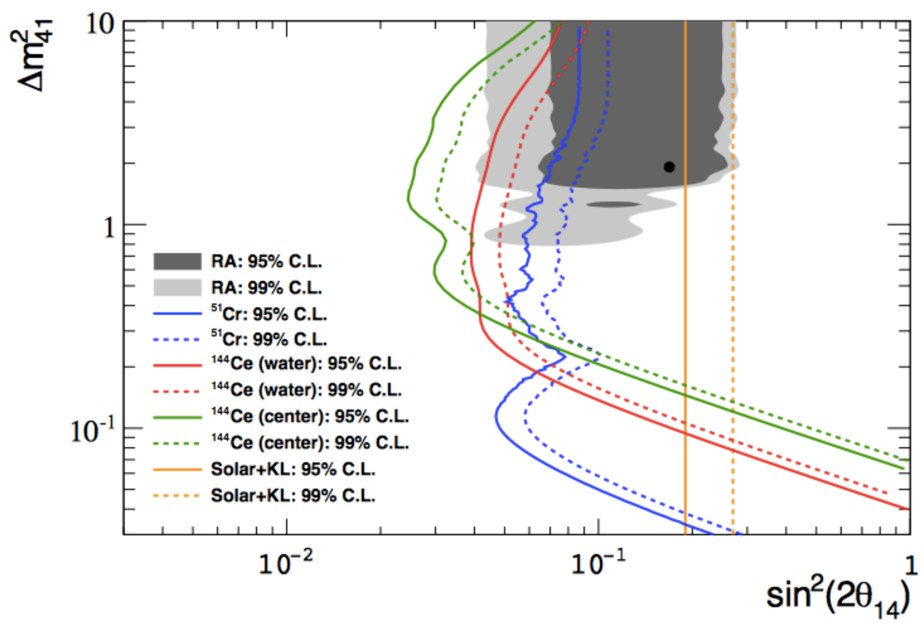


PROSPECT collaboration: prospect.yale.edu

Radioactive Source at Borexino (SOX)







JHEP 1308 (2013) 038

Outline

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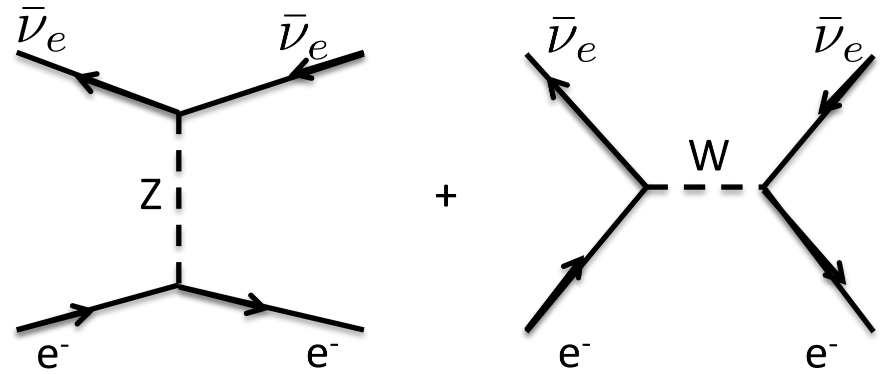
Neutrino-electron scattering—g_V, g_A, $\sin^2\theta_W$



$$g_L = \frac{1}{2}(g_V + g_A)$$
$$g_R = \frac{1}{2}(g_V - g_A)$$

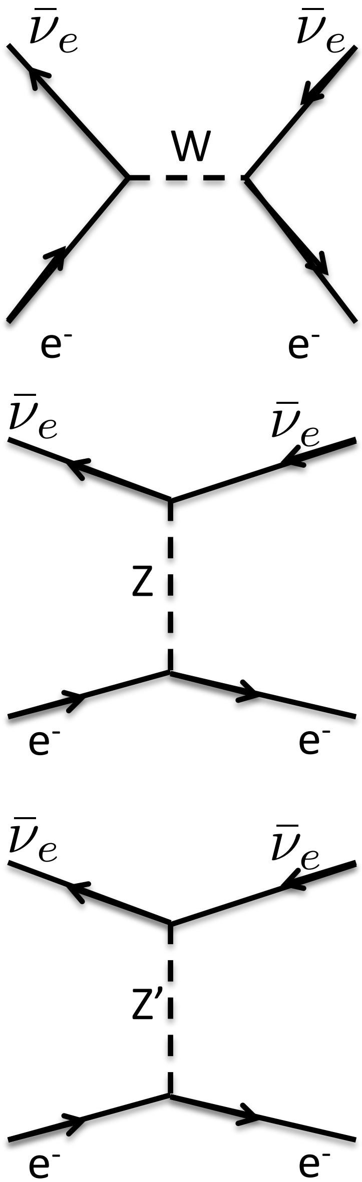
$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2}\right]$$

$$g_L = \frac{1}{2} + \sin^2\theta_W; \quad g_R = \sin^2\theta_W$$

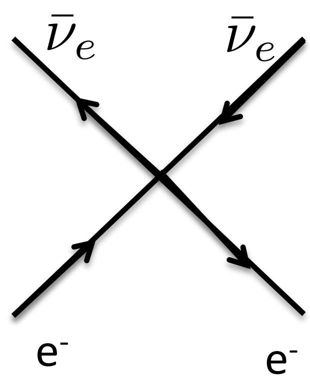
Precisely-known standard model cross section

⟶ Sensitive to g_V, g_A, $\sin^2\theta_W$

Neutrino-electron scattering - NSIs



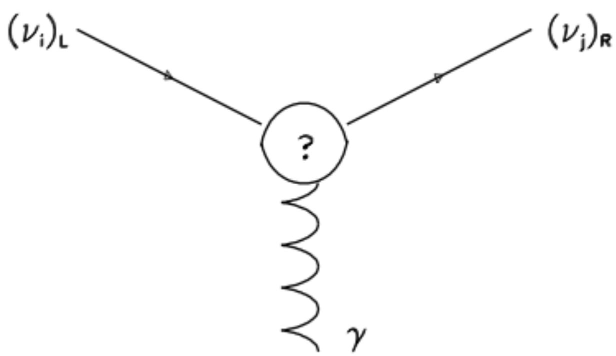
→ Also sensitive to nonstandard interactions (NSIs)

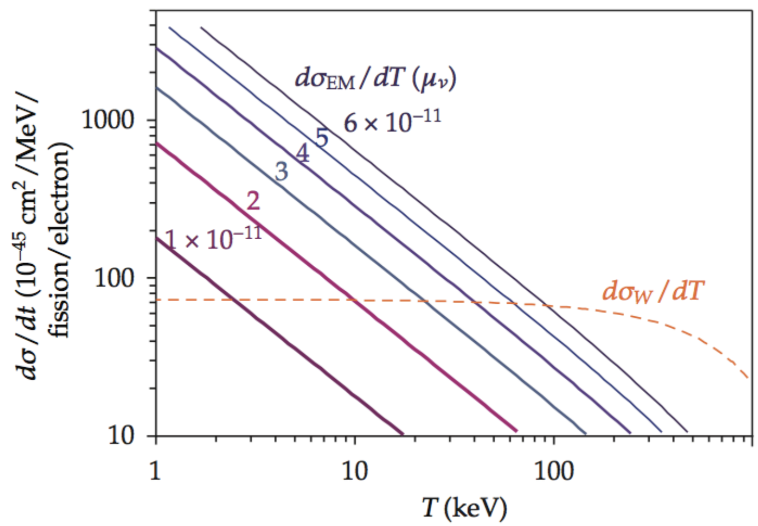


$$\frac{d\sigma(E_\nu,T)}{dT} = \frac{2G_F^2 m_e}{\pi}[(\tilde{g}_R^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eR}|^2) + (\tilde{g}_L^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eL}|^2)\left(1-\frac{T}{E_\nu}\right)^2 - (\tilde{g}_R\tilde{g}_L + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eR}||\epsilon_{\alpha e}^{eL}|)m_e\frac{T}{E_\nu^2}]$$

$$\tilde{g}_L = g_L + \epsilon_{ee}^{eL} \qquad \tilde{g}_R = g_R + \epsilon_{ee}^{eR}$$

Neutrino-electron scattering—ν magnetic moment





$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}[g_R^2 + g_L^2(1-\frac{T}{E_\nu})^2 - g_R g_L\frac{m_e T}{E_\nu^2}] + \frac{\pi\alpha_{em}^2{\mu_\nu}^2}{m_e^2}[\frac{1-T/E_\nu}{T}]$$

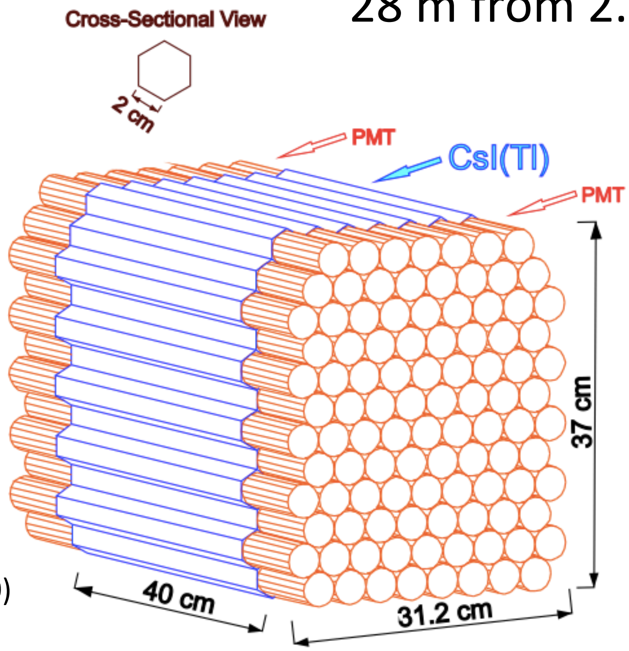
Astrophysical limit: $\mu_\nu \lesssim 3\times10^{-12}\mu_B$ Phys. Rept. 320 (1999) 319-327

Naturalness: $|\mu_\nu| \gtrsim 8\times10^{-15}\mu_B$ implies neutrinos are Majorana

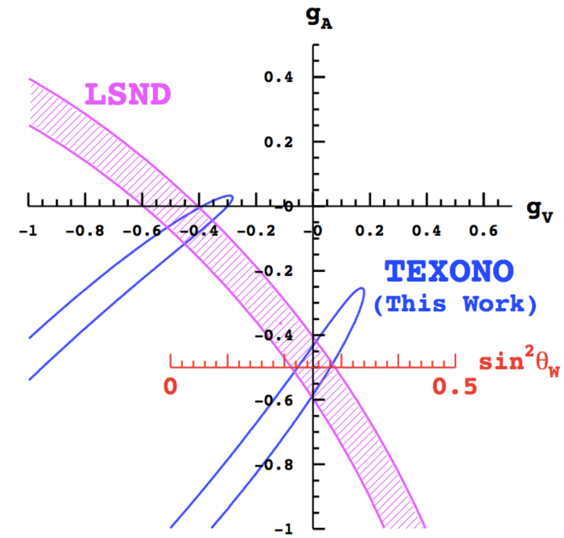
Phys. Rev. Lett. 95, 151802

Reactor Neutrinos—TEXONO

28 m from 2.9 GW_{th} reactor, 30 m.w.e.

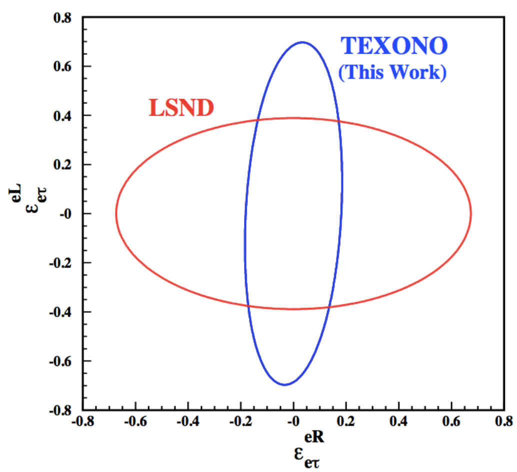


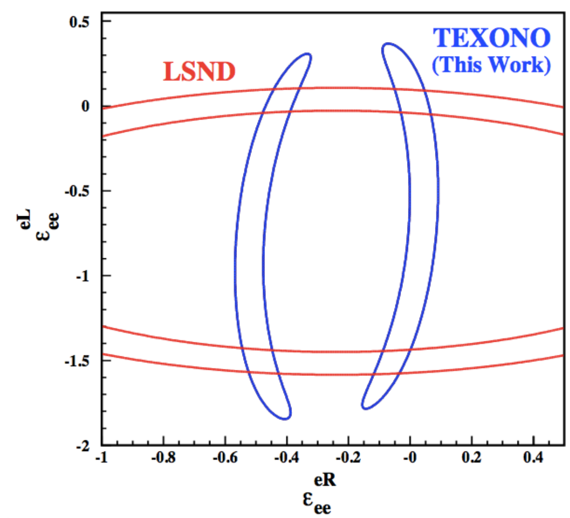
Phys.Rev. D81 (2010) 072001



$$\sin^2\theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$

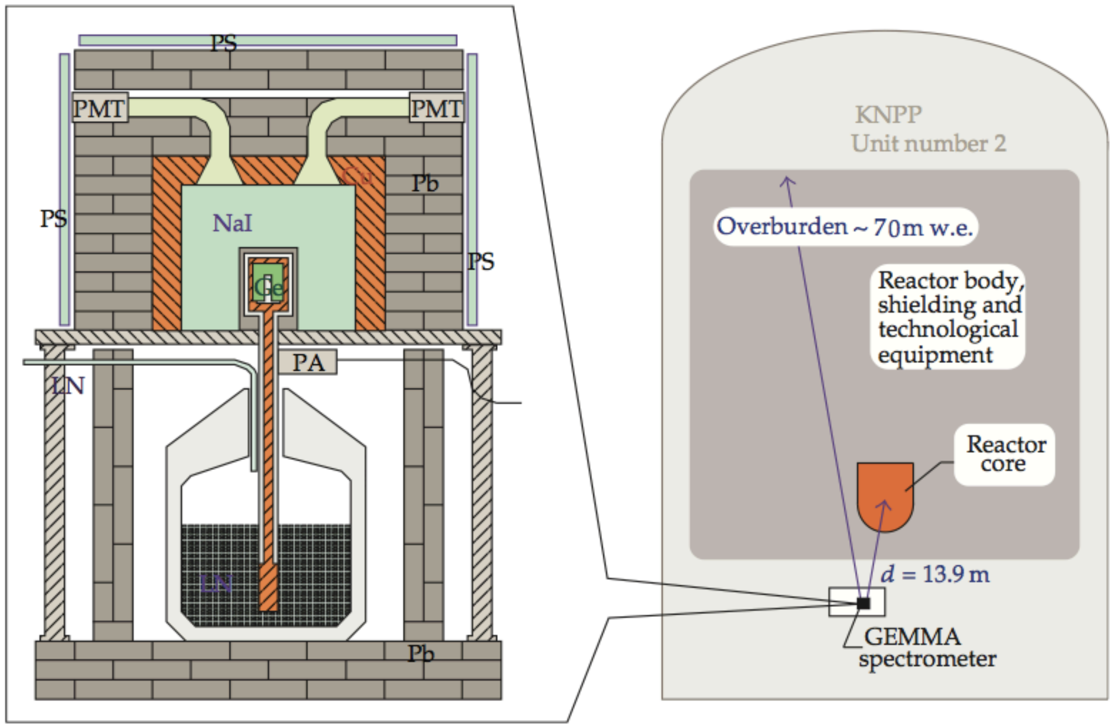
Phys.Rev. D82 (2010) 033004





Reactor Neutrinos—Gemma experiment

Adv.High Energy Phys. 2012 (2012) 350150



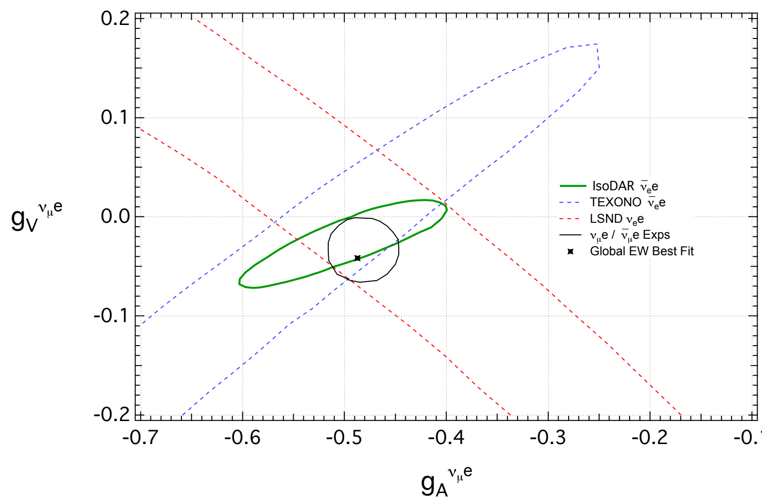
1.5 kg Ge detetector, at a 3 GW_{th} commercial reactor

$\longrightarrow |\mu_\nu| < 2.9 \times 10^{-11}\ \mu_B$ at 90% C.L.

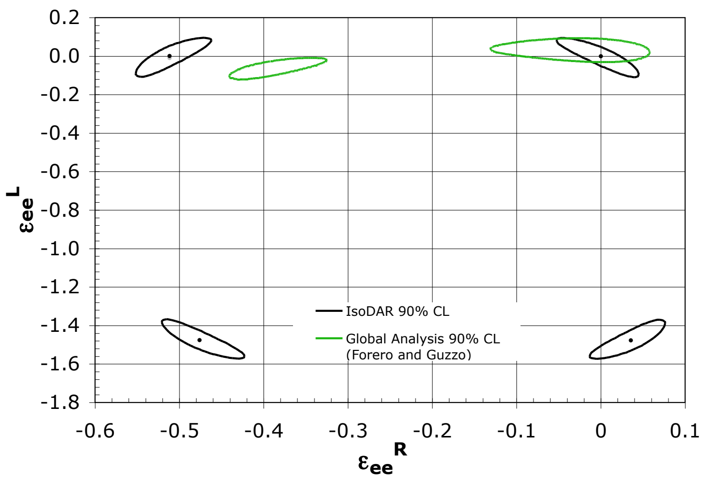
IsoDAR neutrino-electron scattering at KamLAND

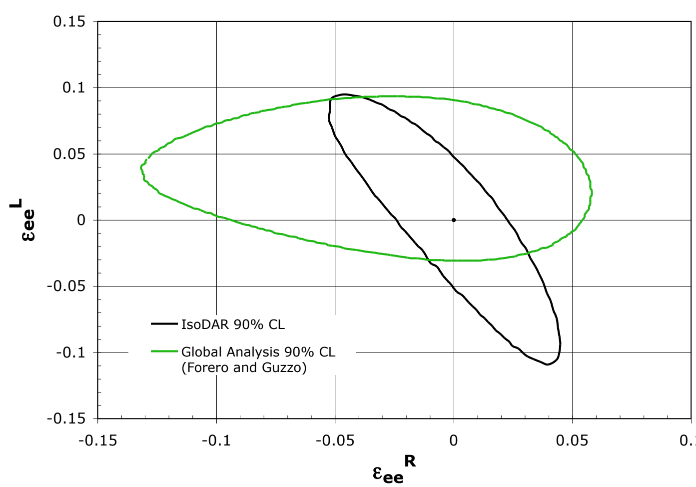
7,200 $\overline{\nu}_e e$ events in 5 years of running

Phys.Rev. D89 (2014) 072010

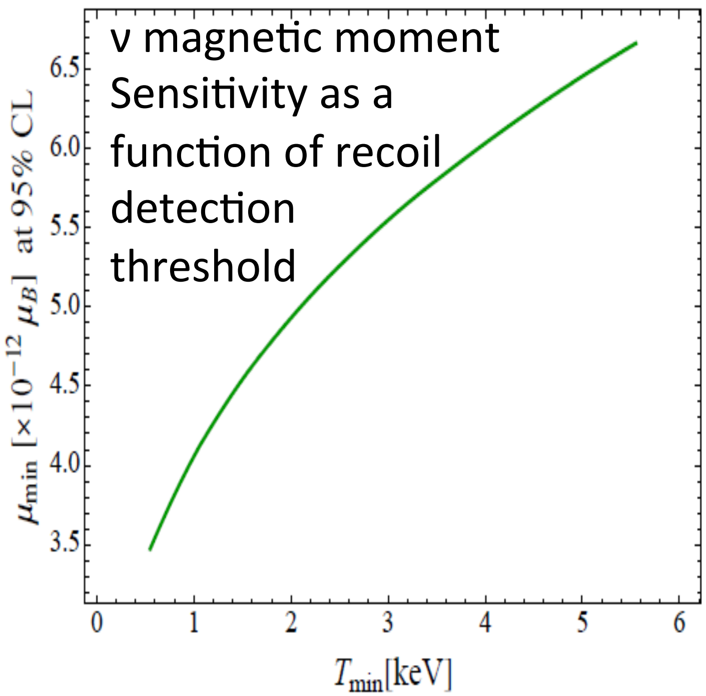


Can also measure $\sin^2\theta_W$ to 3.2%

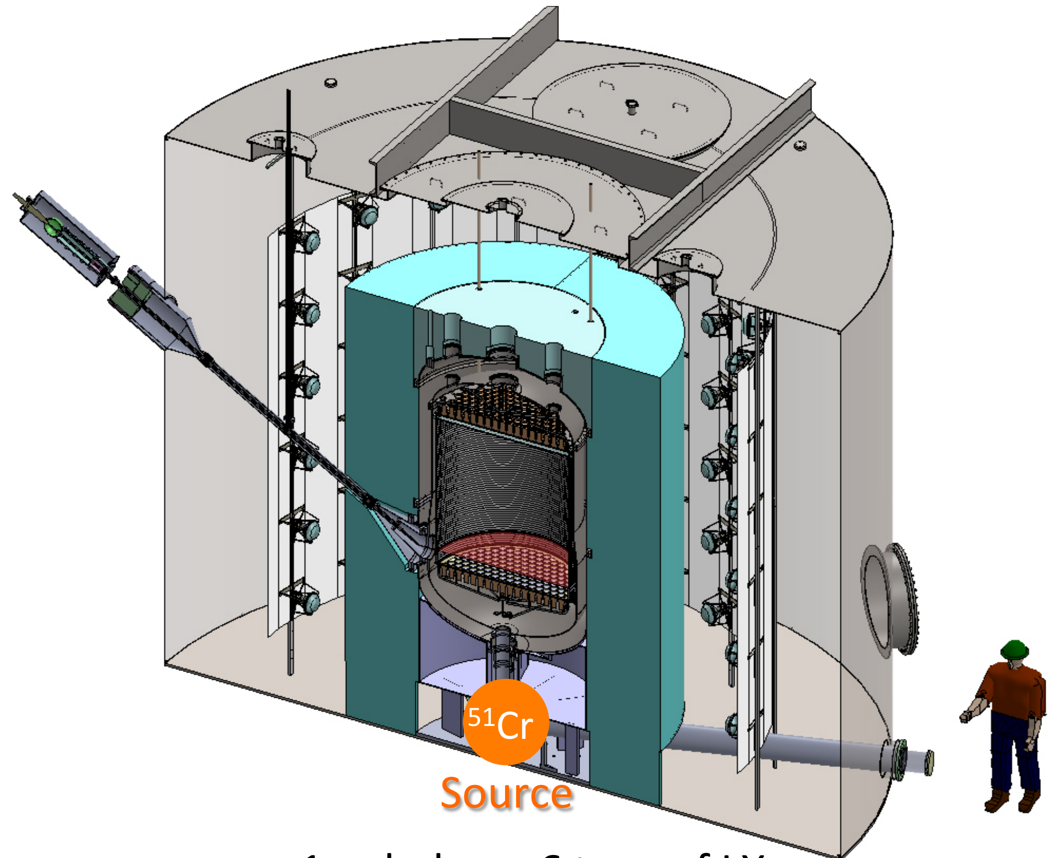




5 MCi ^{51}Cr Source For 100 days at LZ



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



1 m below ~6 tons of LXe (cylinder 137.2 cm diameter, 137.2 cm height)

Conclusion

- Exciting beyond-the-standard model physics can be probed with low energy neutrinos
- Discovery of a sterile neutrino would be a major result for particle physics
- Robust program searching for new physics with neutrinos from reactors, cyclotrons, and radioactive sources

End