Sterile Neutrinos

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Fundamental Symmetries, Neutrinos, Neutrons and Related Astrophysics
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Why?

- Neutrinos have a finite mass
- Most models of neutrino mass involve a right-handed, sterile neutrino
- We have no idea what the mass of these sterile neutrinos is
- And thus, we have no good notion of the physics responsible for neutrino mass

Significance

The discovery of a sterile neutrino would

- Point to the scale of physics responsible for neutrino mass
- Provide clues to the actual mechanism
- Potentially open a gateway to the dark sector
- Be the first particle found outside the Standard Model

Sterile neutrinos are well motivated over a very wide range of parameter space – so why not start your search in a region where you found some hints?

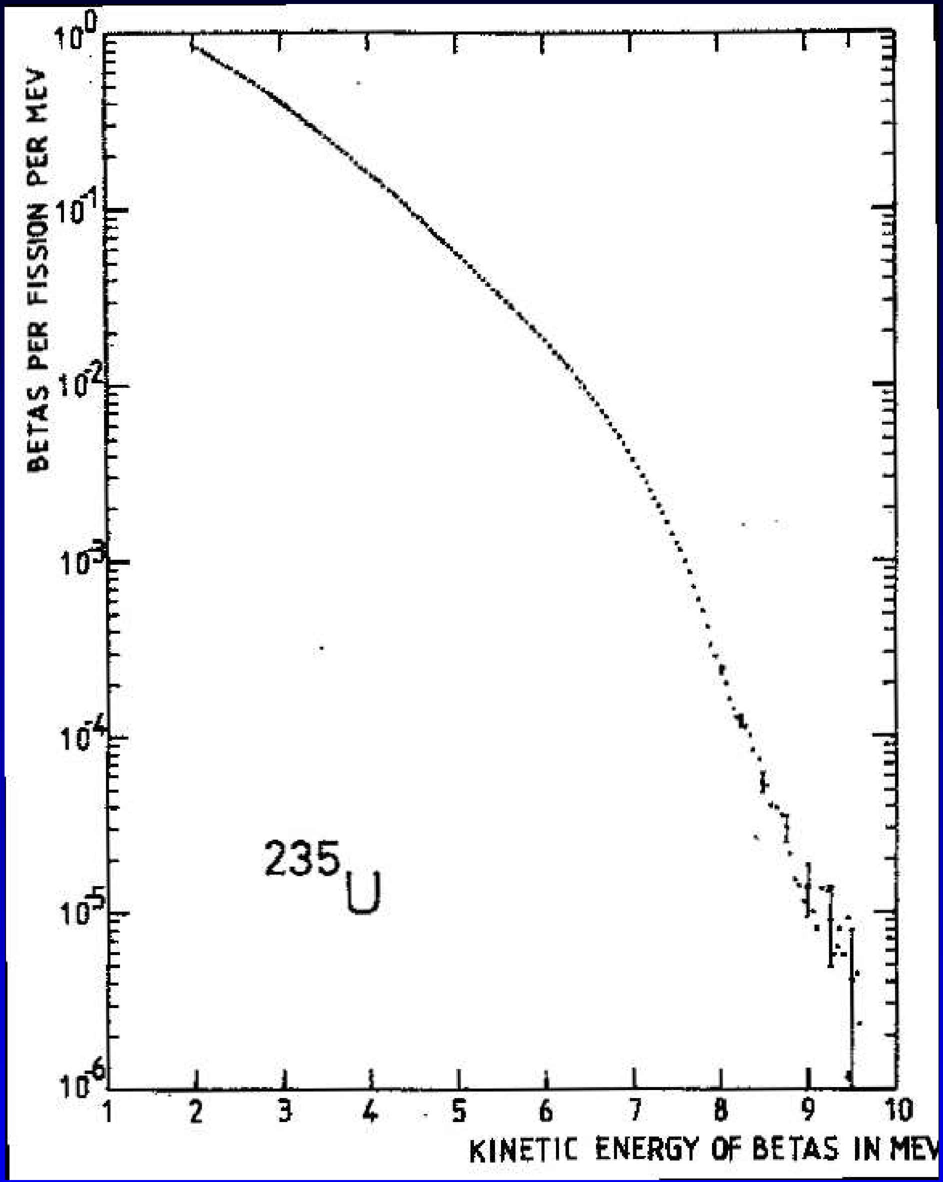
Disclaimer

Given the time constraint, this talk is about eV-scale sterile neutrinos in laboratory settings.

And, I will skip the excellent Fermilab short-baseline program

…but it would be not surprising to have a mild hierarchy of sterile neutrinos, with some at the eV-scale and some at the keV-scale, as motivated by astrophysical considerations.

β-spectrum from fission



Schreckenbach, *et al.* 1985.

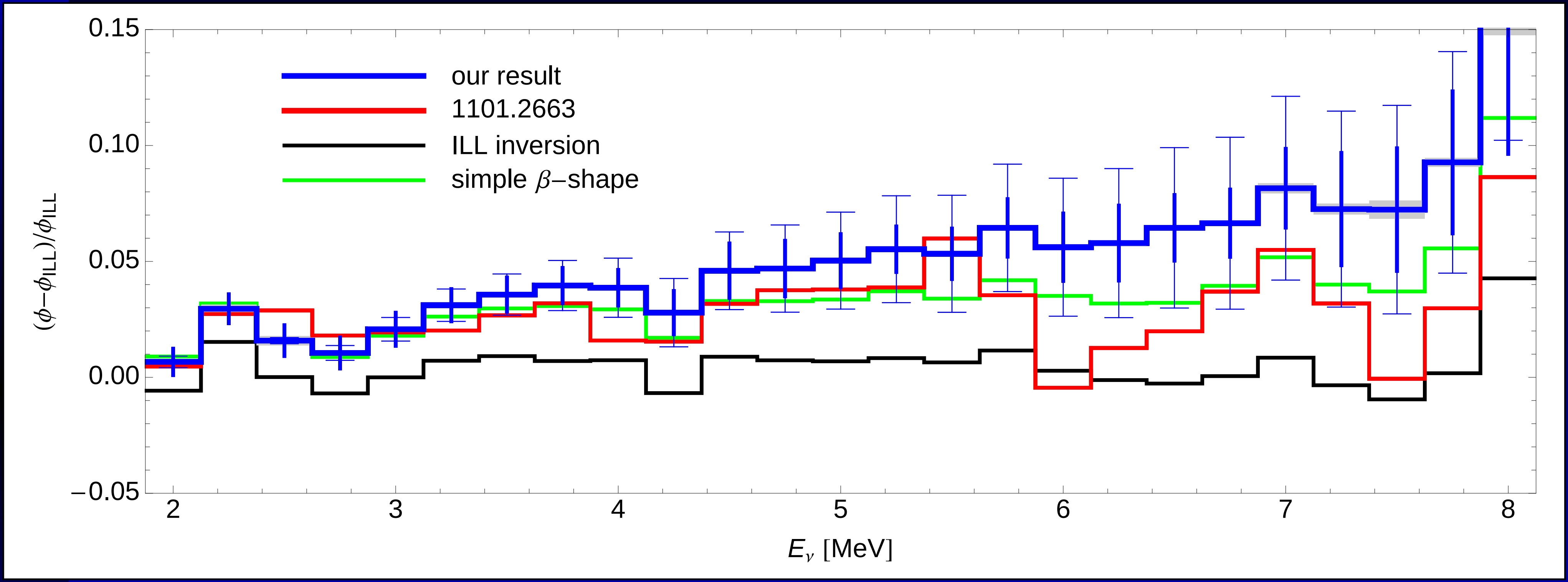
^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

For ^{238}U recent measurement by Haag *et al.*

Reactor antineutrino fluxes

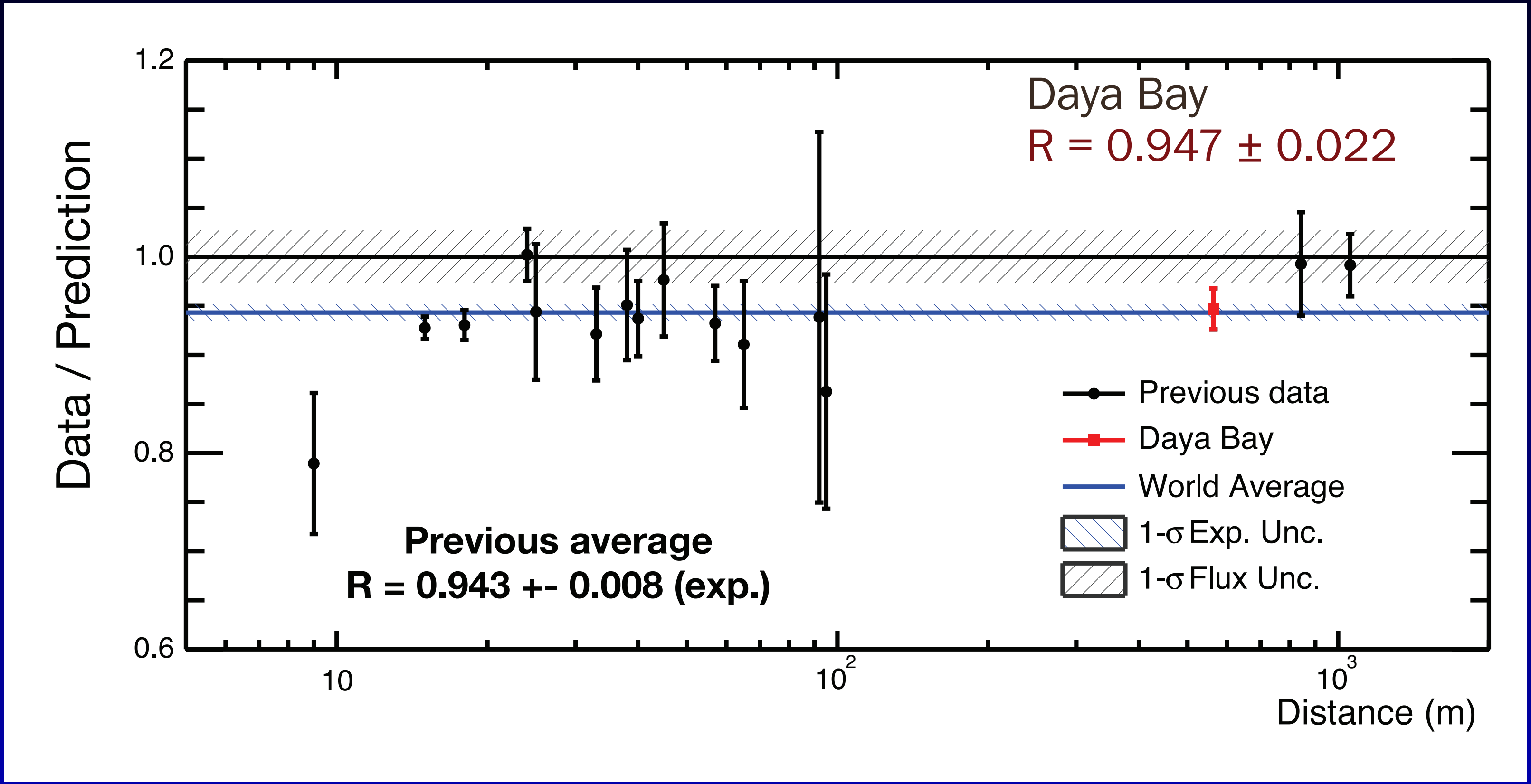


Shift with respect to ILL results, due to

a) different effective nuclear charge distribution

b) branch-by-branch application of shape corrections

The reactor anomaly



Daya Bay, preliminary, 2014

The increase in predicted neutrino fluxes, triggered a re-analysis of existing reactor data

And this was found by Mueller *et al.*, 2011, 2012 – where are all the neutrinos gone?

Contributors to the anomaly

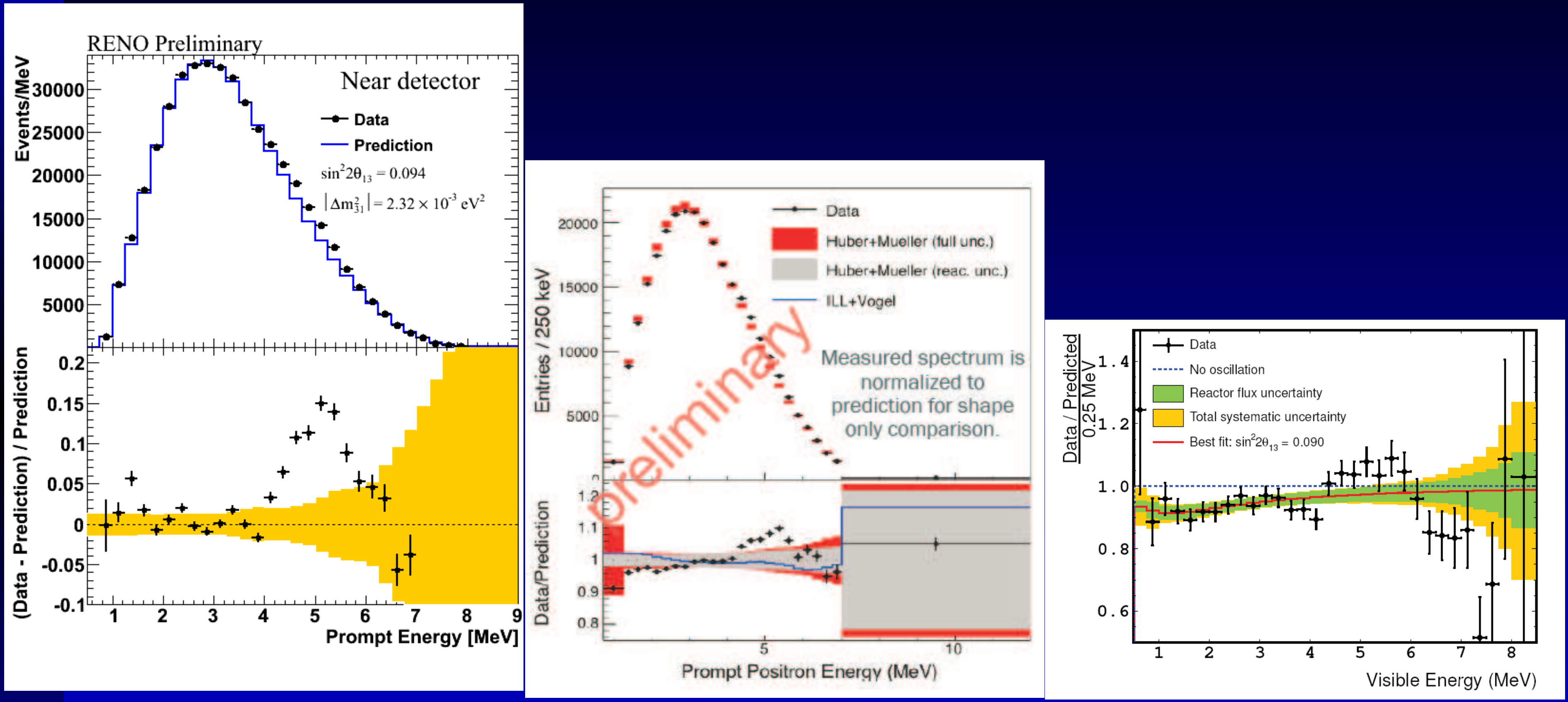
6% deficit of $\bar{\nu}_e$ from nuclear reactors at short distances

- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime (see submitted position paper)
- inclusion of long-lived isotopes (non-equilibrium correction)

The effects is therefore only partially due to the fluxes, but the error budget is clearly dominated by the fluxes.

Note, that even if there is no anomaly, largely increased error bars will impact existing limits from reactors on $\bar{\nu}_e$-disappearance.

The 5 MeV bump



Seen by all three reactor experiments

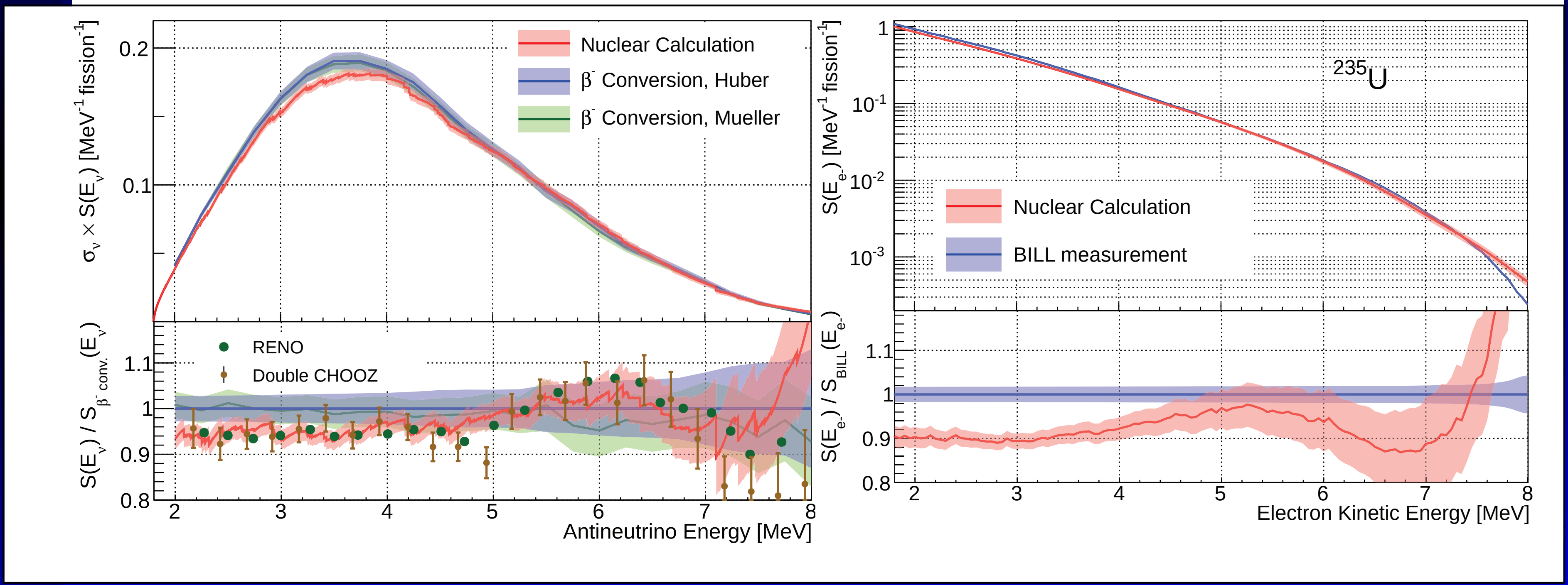
Tracks reactor power

Seems independent of burn-up

Explanations?

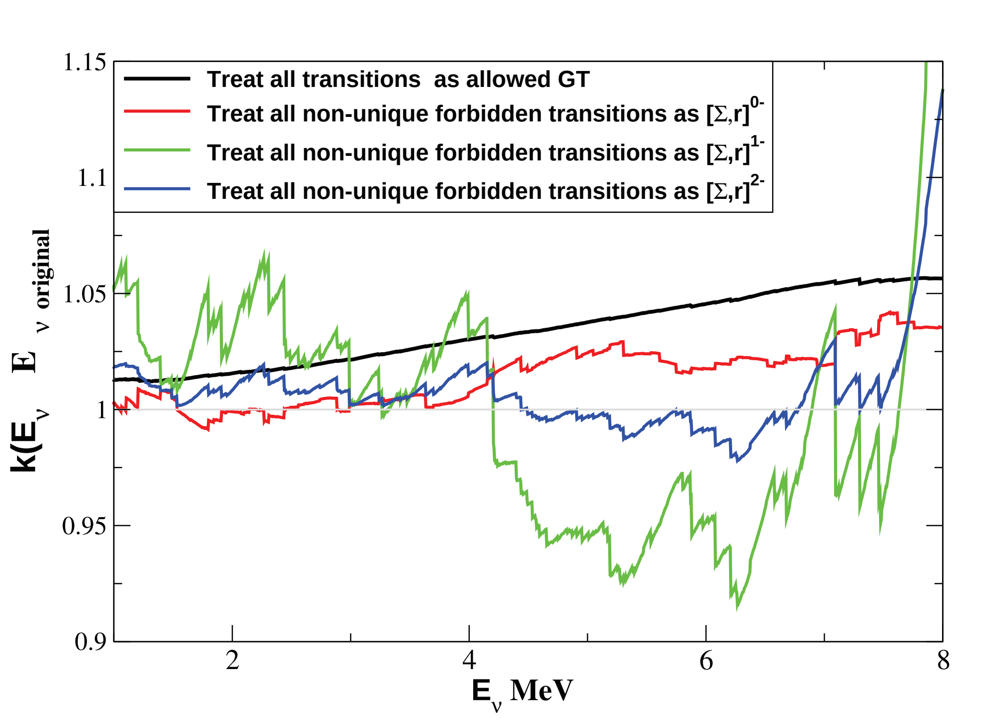
Direct summation of latest ENSDF database, assuming allowed beta-spectrum shape

Dwyer and Langford, 2014



This direct summation, as all other direct summations, does not agree with the Schreckenbach total beta-spectrum.

Another explanation?



Hayes *et. al*, 2013, shown is the relative shift between beta and neutrino spectra

All results discussed so-far assume allowed beta decays – independent of nuclear structure

In reality, as much as 30-40% of neutrinos come from forbidden decays – nuclear structure can not be ignored

For certain operators there is a feature at 5 MeV resulting from the ensemble of all decays.

It has not been quantitatively shown that these forbidden decays can both reproduce the Schreckenbach data and the neutrino data,

but they might. . .

Gallium anomaly

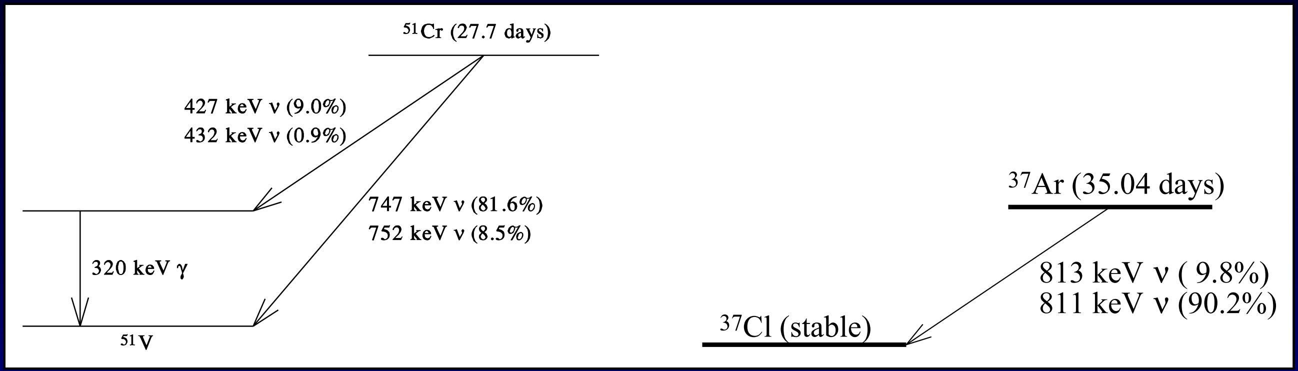
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R_B^k	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm {}^{+0.084}_{-0.078}$
R_H^k	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm {}^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

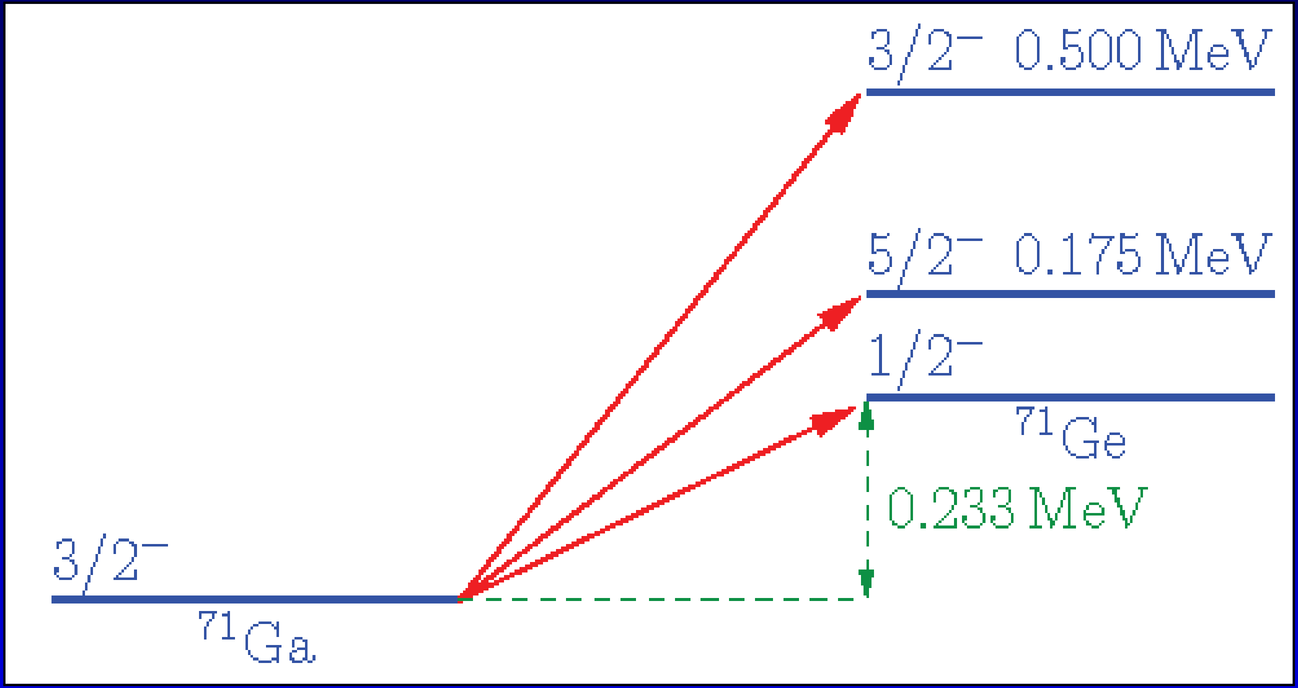
25% deficit of ν_e from radioactive sources at short distances

Effect depends on nuclear matrix elements

This measurement was intended as a calibration – is R a physics measurement or a calibration constant?

Nuclear matrix elements





Recent measurements of $Ga^{71}(He^3,H^3)Ge^{71}$ seem to support the Gallium anomaly Frekers *et al.*, 2011

Sterile oscillation

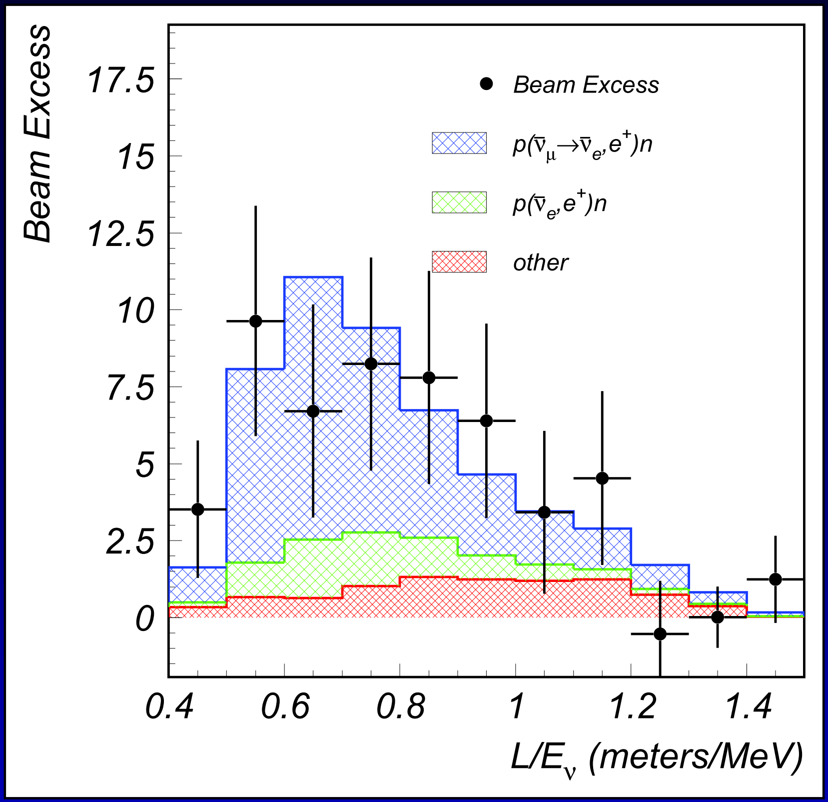
In general, in a 3+N sterile neutrino oscillation model one finds that the energy averaged probabilities obey the following inequality

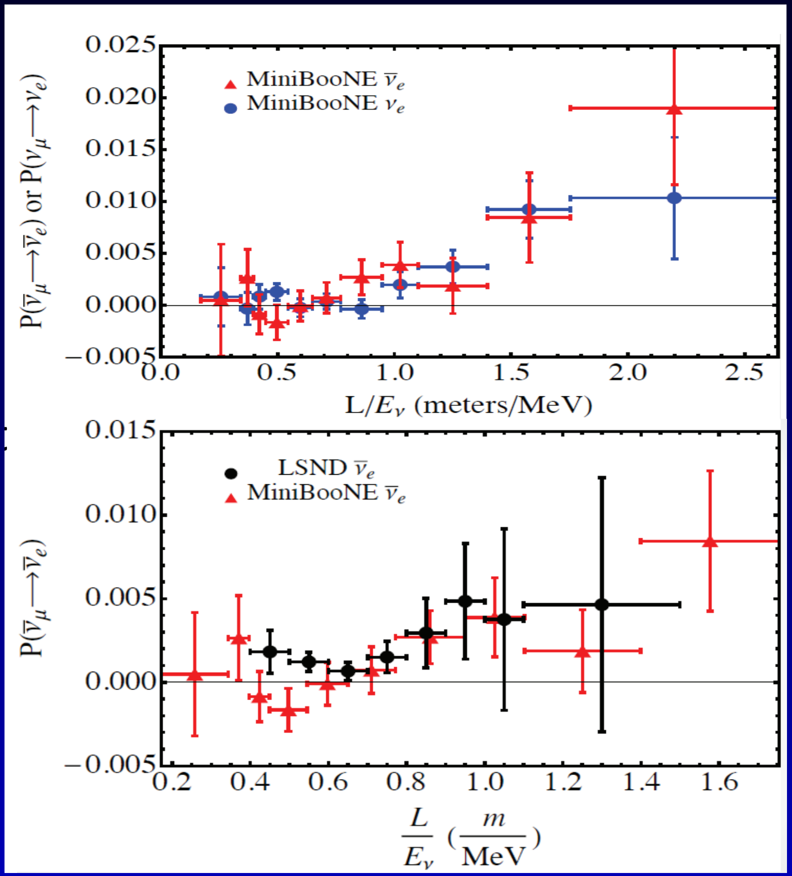
$$P(\nu_\mu \to \nu_e) \leq 4[1 - P(\nu_e \to \nu_e)][1 - P(\nu_\mu \to \nu_\mu)]$$

independent of CP transformations. Therefore, a stringent test of the model is to measure

- $P(\nu_\mu \to \nu_e)$ – appearance
- $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ – appearance
- $P(\nu_\mu \to \nu_\mu)$ or $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – disappearance
- $P(\nu_e \to \nu_e)$ or $P(\bar{\nu}_e \to \bar{\nu}_e)$ – disappearance

LSND and MiniBooNE

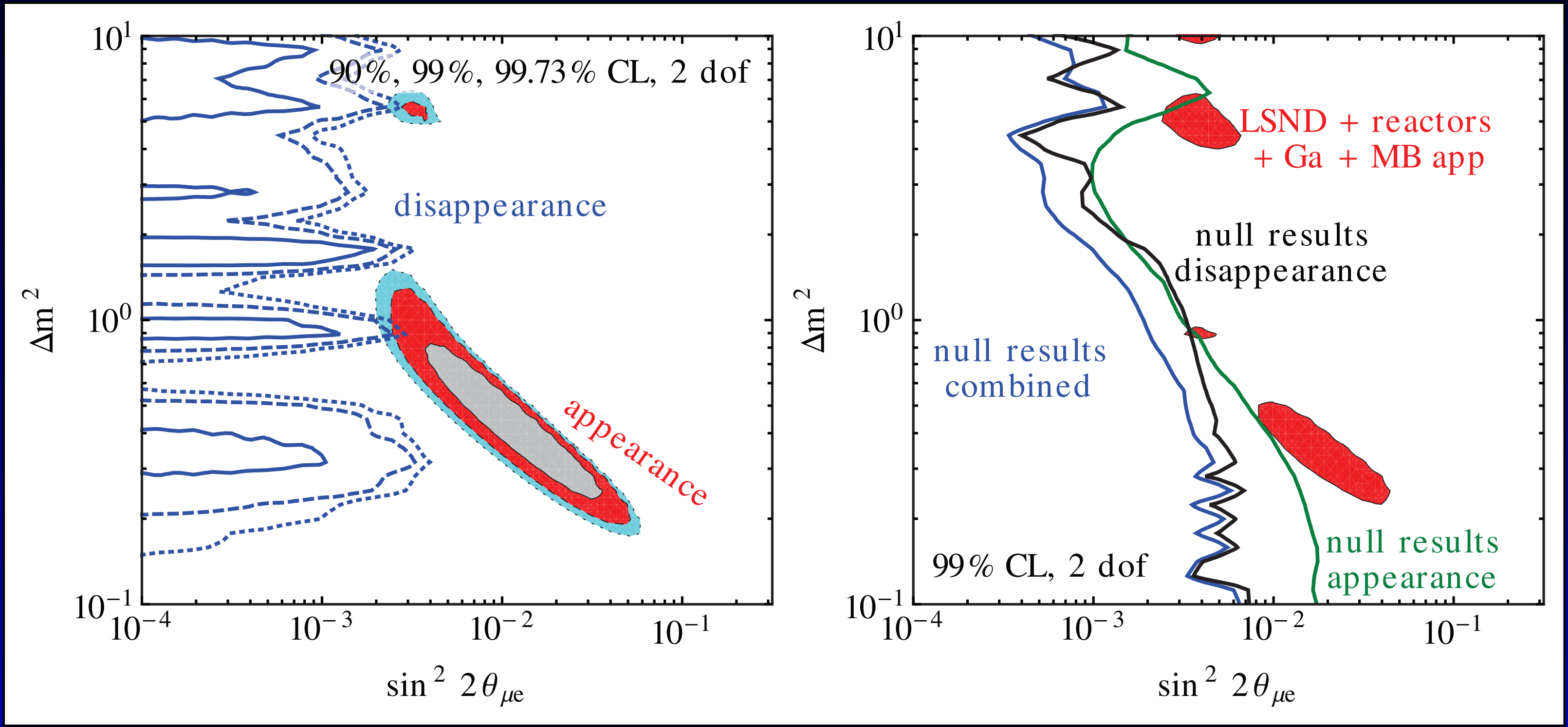




$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

The L/E values correspond to a $\Delta m^2 \sim 0.1 - 10\,\mathrm{eV}^2$

Disappearance constraints



No effects in

- atmospheric
- Bugey
- CDHS
- MINOS
- ...

Resolution will require new experiments, both for appearance and disappearance

Figure from arXiv 1303.3011

Future reactor efforts

Future experiments will control reactor flux uncertainty by near/far measurements

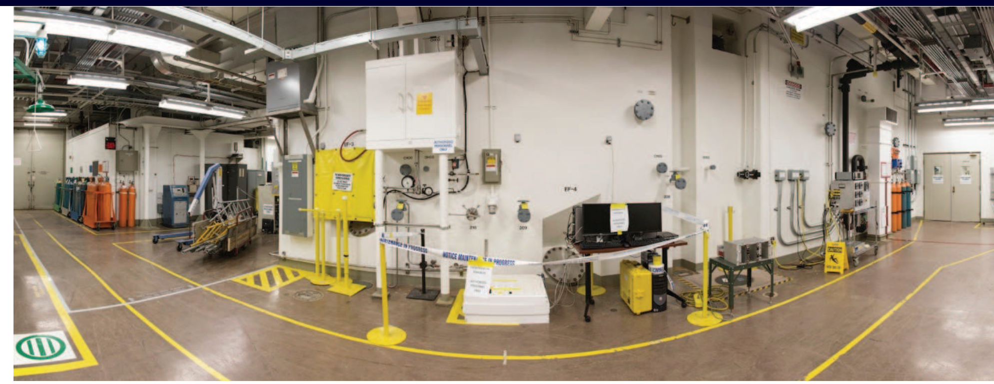
Nucifer	France	research	liquid (Gd)	data taking
DANSS	Russia	PWR	plastic (Gd)	under construction
Stereo	France	research	liquid (Gd)	under construction
SoLid	Belgium	research	plastic (^{6}Li)	prototype
Prospect	USA	research	liquid (^{6}Li)	R&D
Poseidon	Russia	research	liquid (Gd)	R&D
Neutrino 4	Russia	researc	liquid (Gd)	under construction
Hanaro	Korea	TBD	liquid	R&D
NuLat	USA	naval	solid (B)	R&D

They all face the same challenge: backgrounds at a few meters from a reactor core – if solved, would provide detectors for potential safeguards applications

U.S. reactor proposals

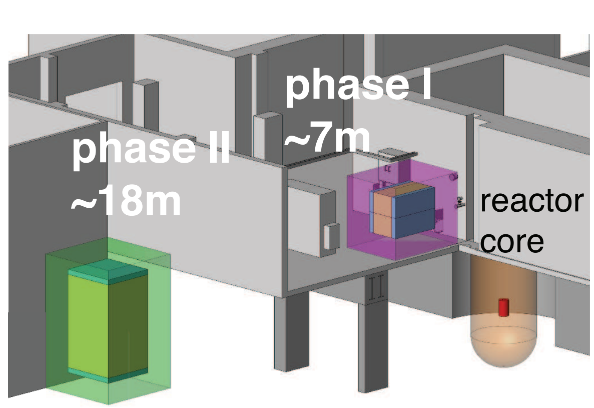
PROSPECT

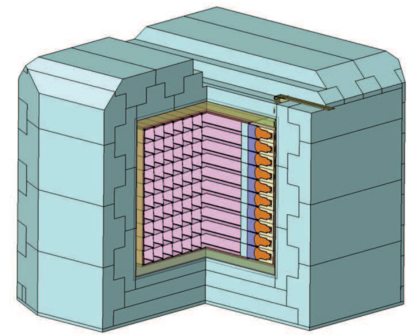
A Precision Reactor Oscillation and Spectrum Experiment at HFIR, ORNL

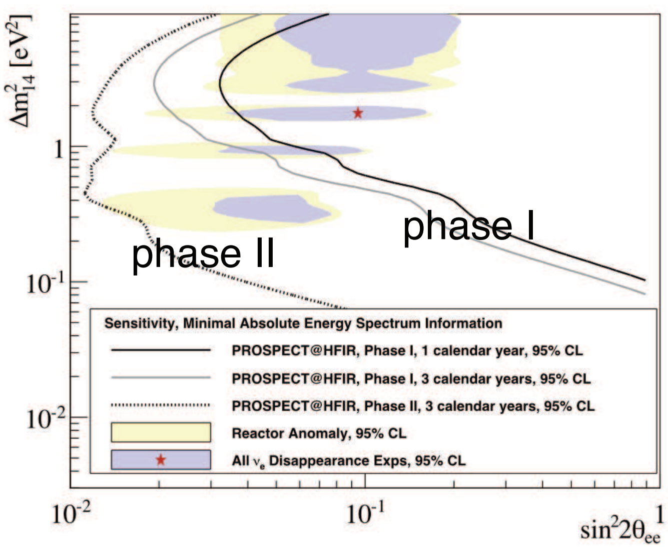


Physics Objectives

- 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

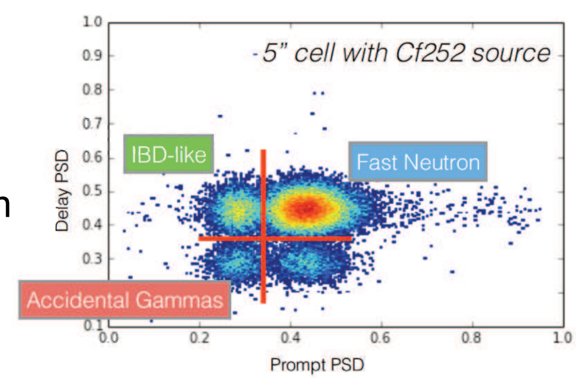






Phase I Detector

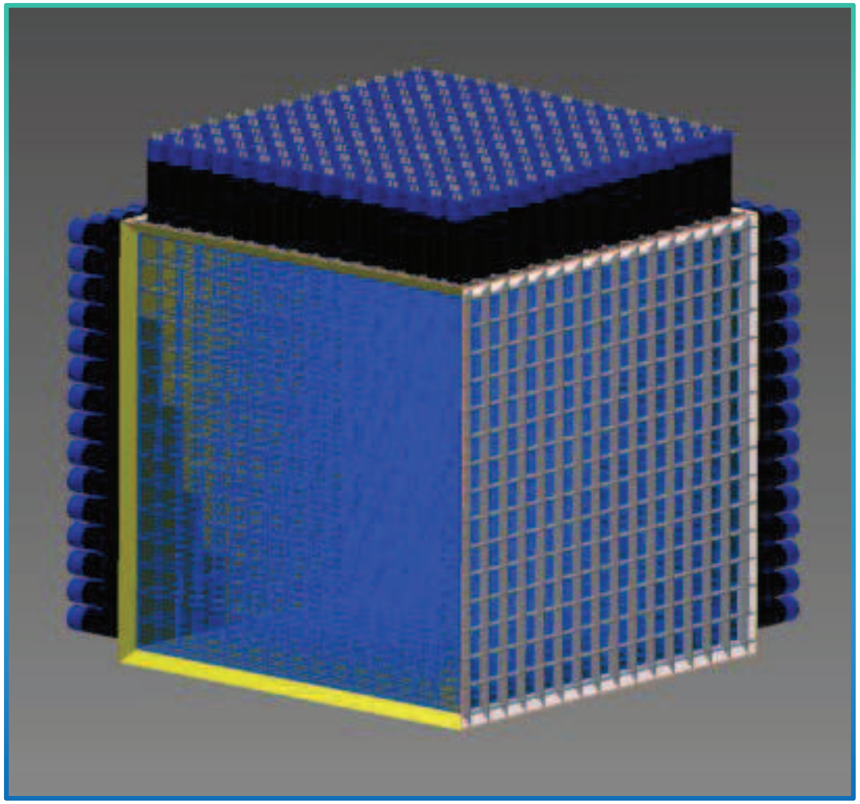
- 2.5 ton of LiLS
- ~ 140 segments, thin wall, optical separation
- double-ended readout
- movable detector

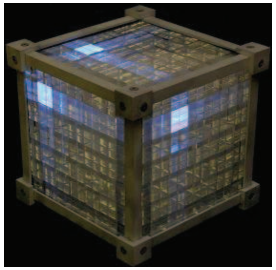


PROSPECT collaboration: prospect.yale.edu

U.S. reactor proposals

NuLat





<u>NuLat:</u>
15^3 = 3375 voxels
Cubes 2.25” each
Boron Doped PVT scintillator
0.005” air gap between cells
6 *15^2 = 1350 of 2” PMTs

<u>Compact version:</u>
Mirrors on 3 faces
675 PMTs
Fits in mTC cave at NIST for test

Neutrino lattice based on Raghavan Optical Lattice for LENS Experiment

Future source experiments

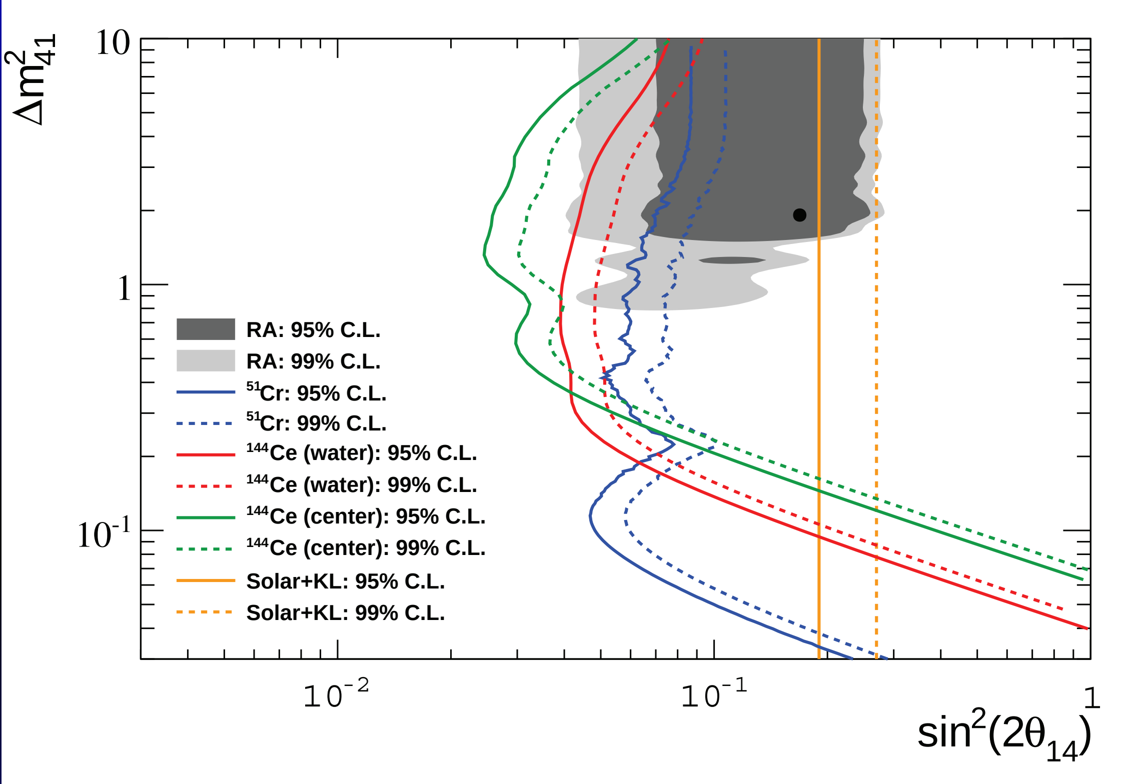
^{51}Cr	EC	40 d	750 keV (90%)	Th. n on ^{50}Cr
^{144}Ce	β^-	411 d	$<$2.997 MeV	Fission product
^{8}Li	β^-	868 ms	$<$12.9 MeV	ISODAR

Challenges

- Intensity
- Shielding
- for Cr and Ce, detection threshold
- Ce - neutrino spectrum prediction?

For Ce and Cr, liquid scintillator, Li may also work with Gd-doped water Cerenkov detectors.

Future source experiments



Bellini *et al.*, 2013

10 MCi ^{51}Cr source with a 100 t liquid scintillator detector (Borexino – SOX)

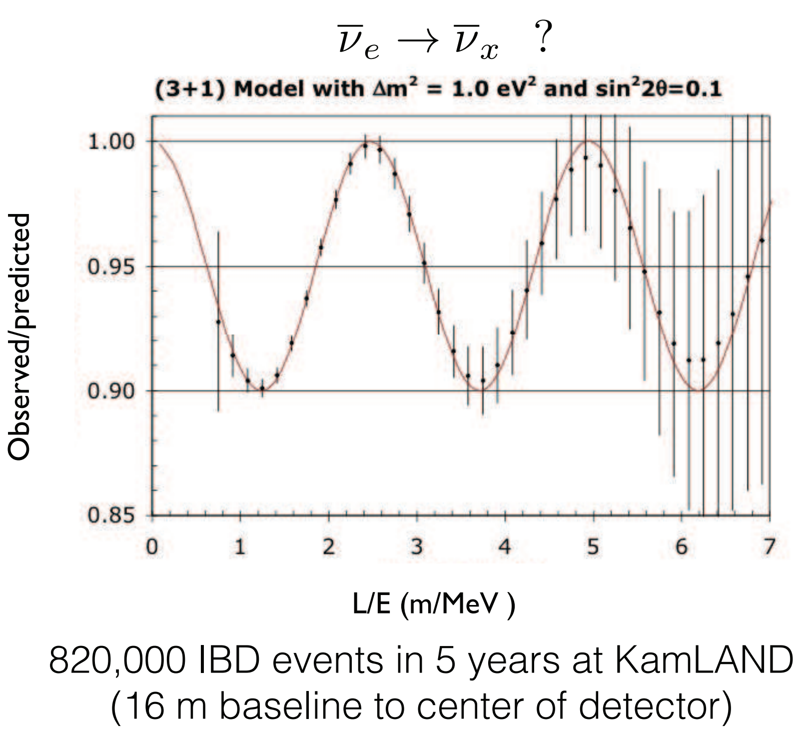
or a 6 t liquid Xe detector (LZ-like)

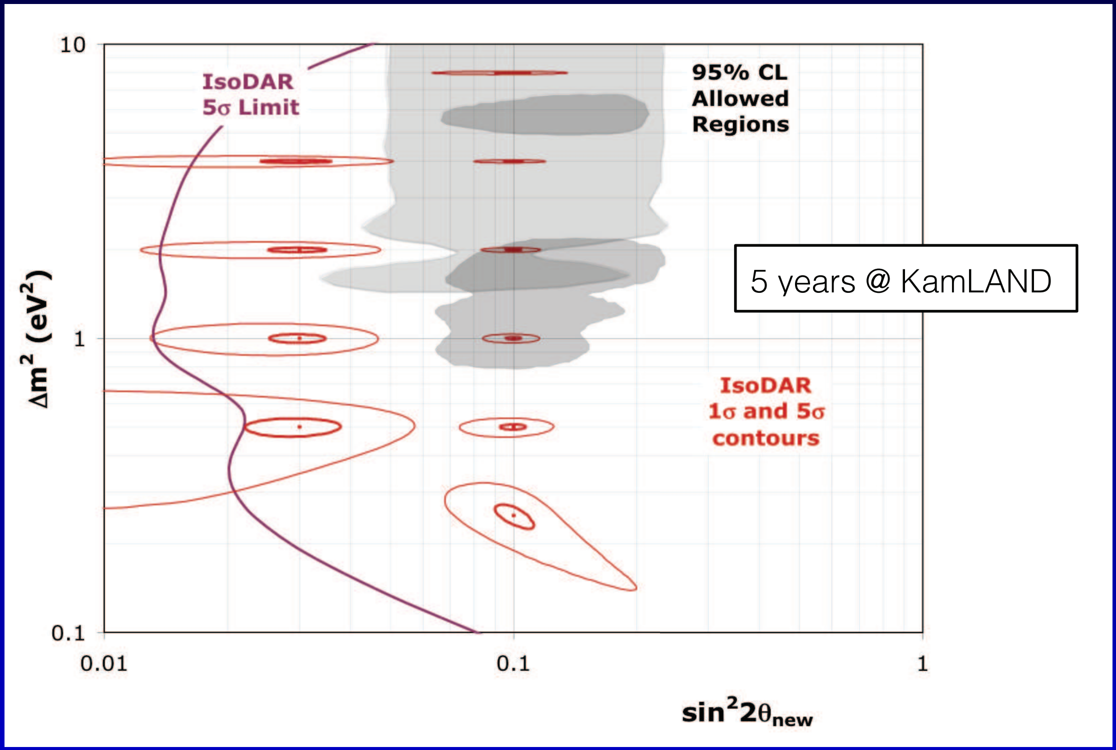
75 kCi ^{144}Ce source combined with Borexino. Ce data taking may start already in 2015.

Cr source can in principle produced at HFIR

ISODAR

Online production using spallation neutrons from a 60 MeV proton beam





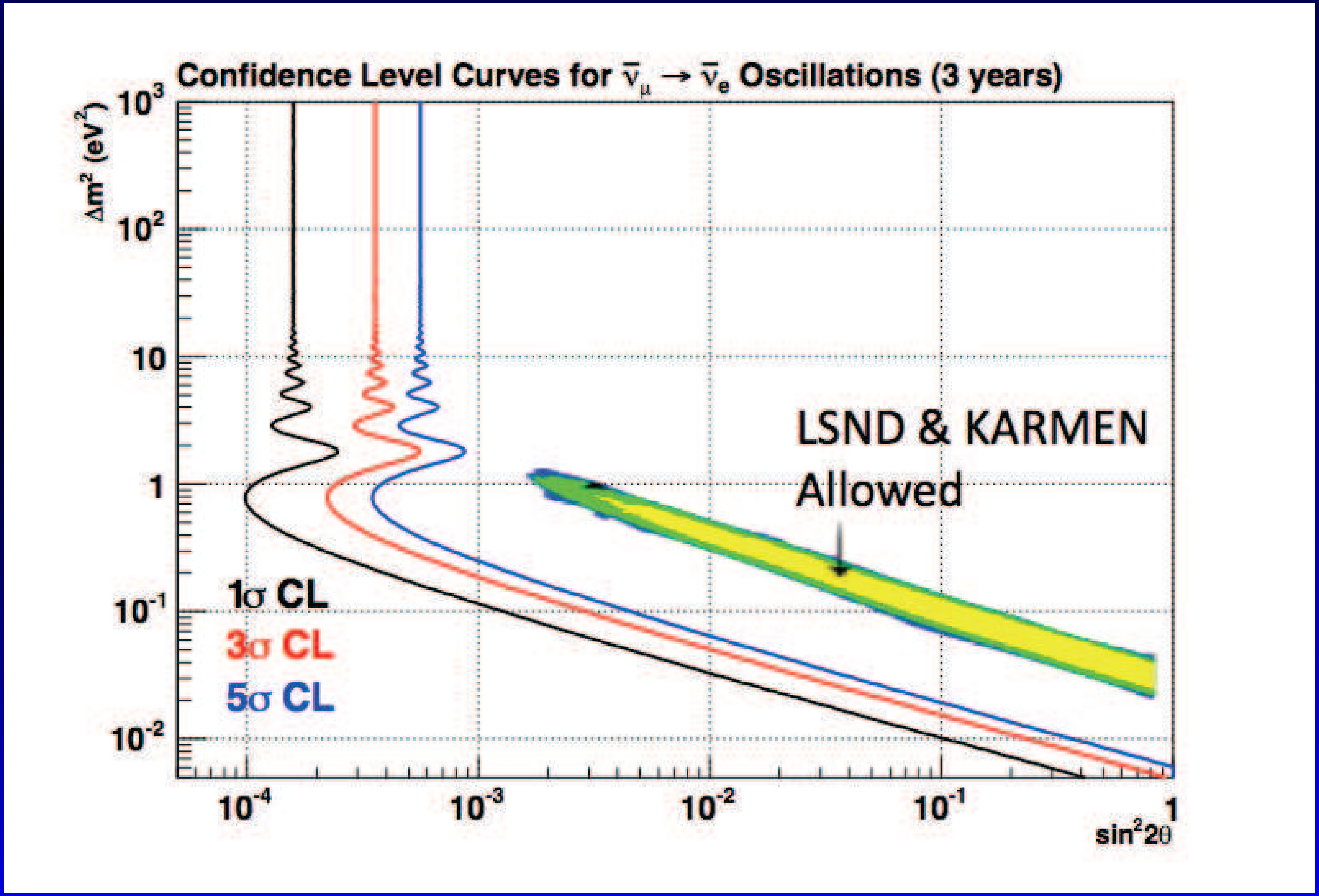
Spitz, Nu 2014

Spitz, Nu 2014

ISODAR cyclotron technology needs to be shown to be feasible (and affordable!)

OSC-SNS

Redo LSND at the SNS, most direct test of LSND possible, see also submitted position paper



Summary

- The reactor anomaly may be a true deficit in neutrinos or just a result of the complexity of the source
- International competition for reactor experiments – if the U.S. wants to play, a timely decision is needed
- Other hints for sterile neutrinos, but tension with disappearance signals
- Many possible small-scale experiments on a 5 year time scale – some can do more than just sterile neutrinos
- Discovery of sterile neutrinos would be paradigm shifting. . .
- . . . and we are running out of places to look for BSM physics on the high-energy side