Beyond Standard Model Physics with Neutrino Driven Sources Workshop

MIT January 15 – 16, 2018

Welcome and Thanks for Coming

Goals and Background for the Workshop

- The goal of this workshop is to bring theorists and experimentalists together to discuss and elucidate the physics of accelerator-driven, isotope-based neutrino sources.

- Plan to concentrate on IsoDAR as an example but hope to explore other future possibilities.

- The two main IsoDAR physics possibilities looked at so far:
  - Searching for nuebar disappearance at short-baseline via inverse beta decay (arXiv: 1205.4419)
  - Nuebar-electron elastic scattering as a measurement of the weak mixing angle and/or to search for non-standard neutrino interactions. (arXiv 1307.5081)

- Enhancing the physics case for accelerator-driven sources such as IsoDAR is a main impetus for the workshop.
  - Coming up with ideas to explore qualitatively at the workshop and then in more details later.

Schedule and Agenda

Monday morning (1/15):
-9:00-9:30am People gather, eat donuts, and talk
-9:30-10:00am Intro/welcome (Shaevitz)
-10:00-10:30am Physics with IsoDAR@KamLAND (Shaevitz)
-10:30-11:00am How does IsoDAR work? (Conrad)
-11:00-11:30am Kamland's plans and how IsoDAR fits (Winslow)
-11:30-12:00pm IsoDAR at other venues and future sources (Spitz)
-12:00-12:15pm Workshop resources and goals (Spitz)
-12:15pm We will go to lunch together.

Monday afternoon (1/15):
-1:30-2:00pm Status of sterile neutrinos (Huber)
-2:00-2:30pm BSM questions with nuebar-electron (de Gouvea)
-2:30-6:00pm Workshop style session (extra breakout room is 26-528)
-3:00pm-finish IsoDAR ion source tour (optional)
-6:30pm Dinner (At Naco Taco – Please fill out doodle poll)

Tuesday morning and afternoon (1/16):
-9:00am Start working time and discussion (all morning)
-12:00pm Working lunch
-1:00pm Start 10 minute talks/reports from each working group
-3:00pm End

Google Doc to Collect Ideas

We have created an editable google document here, to collect ideas and thoughts on IsoDAR physics. Please feel free to add to this document (any time, including now) as you see fit!

"Ideas: Beyond Standard Model Physics with Neutrino Driven Sources"

-IsoDAR as a source for coherent neutrino-nucleus scattering.
-IsoDAR events in Super-K, perhaps as a source for understanding supernova (nuebar-indcued IBD) efficiencies at low energies.
-IsoDAR at DUNE (neutral current neutrino-nucleus scattering).
-Changing IsoDAR's target to Aluminum so that we have a source of nue, rather than nuebar.
-IsoDAR as a source for a neutrino trident production search.
-Using IsoDAR to inform reactor-based experiments.

-Use 7Li source to produce 8Be and look for 17 MeV e+e- anomaly (see https://arxiv.org/pdf/1504.01527.pdf and https://arxiv.org/pdf/1604.07411.pdf). Need ability to tune proton energy to 0.441 and 1.03 MeV for resonant production, but IsoDAR beam current is 1000 times that of original experiment, so could be promising - YK

- could extend reach of LSND to light DM, signal is either DM-electron scattering or DM decay to e+e- pair in detector (see https://arxiv.org/pdf/1703.06881.pdf). Depends on bremsstrahlung rate or pi0 production rate if the beam energy can be tuned above pion threshold - yK

Possible Working Groups (More Later from Josh on Organization)

- Some ideas for topics:
  - Pushing on ‘already-characterized’ IsoDAR physics
  - IsoDAR as a source for coherent neutrino-nucleus scattering.
  - IsoDAR at other detectors: Super-K, DUNE, JUNO …..
  - IsoDAR as a ν_e , rather than a $\bar{\nu}_e$ source.
  - IsoDAR as a source for a neutrino trident production search.
  - Using IsoDAR to provide measurements important for reactor and geoneutrino measurements
  - Precision β-decay spectrum measurements (i.e ^{8}Li spectrum from $\bar{\nu}_e$ energy distribution.)

- More from Josh on working groups and tools/ntuples etc.

Physics with IsoDAR@KamLAND

IsoDAR

@KamLAND

IsoDAR Experiment

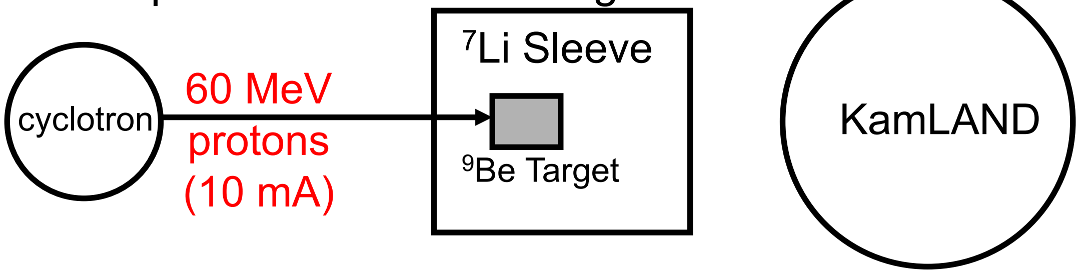
Isotope Decay-At-Rest Neutrino Source
($\bar{\nu}_e$ Disappearance)
to Search for Sterile Neutrinos

What is IsoDAR@KamLAND?

- High intensity $\bar{\nu}_e$ source using β-decay at rest of ^{8}Li isotope ⇒ IsoDAR

- ^{8}Li produced by a high-intensity proton 10 ma (5ma H_2^+) beam from a 60 MeV cyclotron
  - p + ^{9}Be → many n's ⇒ n + ^{7}Li (shielding) → ^{8}Li ⇒ $^8\text{Li} \rightarrow {}^8\text{Be} + e^- + \bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV with 2.6×10^{22} $\bar{\nu}_e$ / yr
  - Continuous (non-bunched) $\bar{\nu}_e$ flux (^{8}Li half-life = 840 ms)

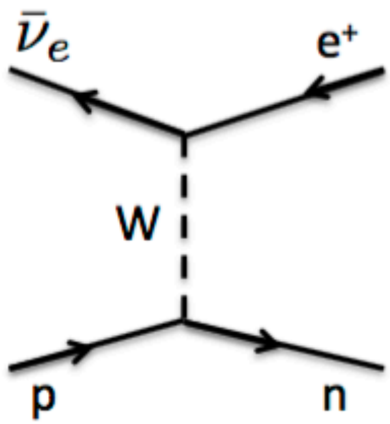
- Put this cyclotron-isotope source near the large KamLAND neutrino detector.



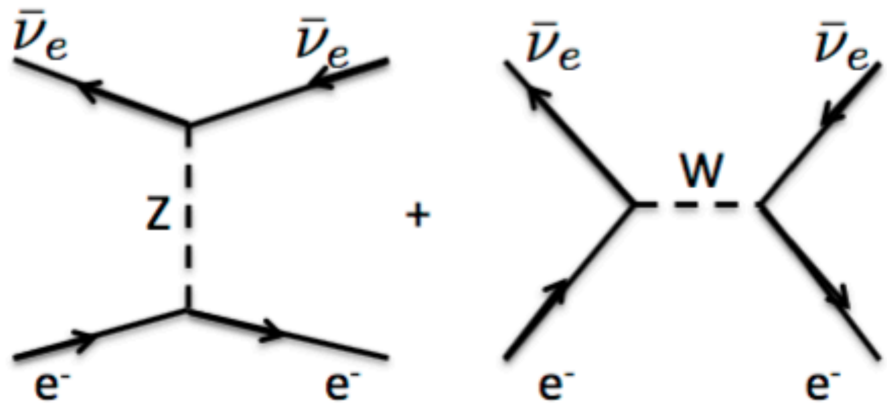
- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector as a function of L and E.
  - Precision electroweak measurements using $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$
  - Other "exotic" physics possibilities

Detection Channels

Sterile ν search:
Inverse β decay (IBD)



BSM physics:
$\bar{\nu}_e$-e elastic scattering (ES)

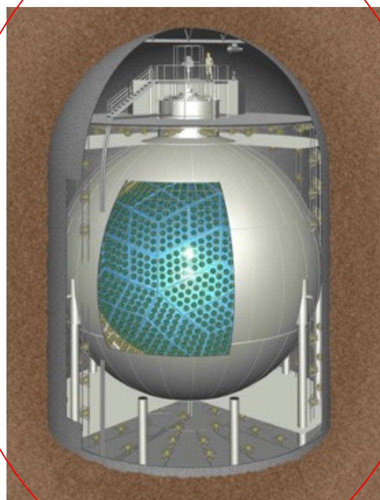


IBD channel:
1. Delayed coincidence
2. Neutrino energy reconstructed
3. Large cross section
4. Cross section known to < 1%
5. Only occurs on free protons
6. 1.8 MeV $\bar{\nu}_e$ energy threshold

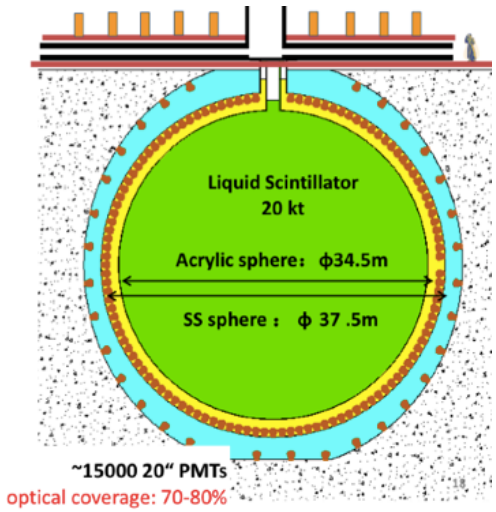
ES channel:
1. Single scatters in detector
2. Outgoing $\bar{\nu}_e$ energy unknown
3. Lower cross section
4. Cross section known to < 1%
5. No $\bar{\nu}_e$ energy threshold

Where Can IsoDAR Run?

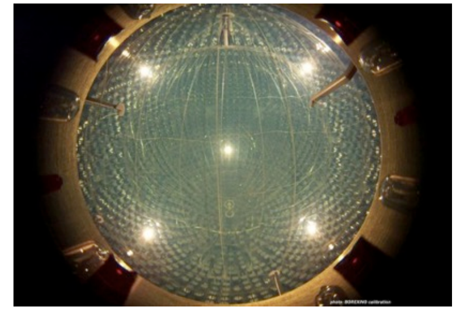
KamLAND – 1 kton Liq Scint



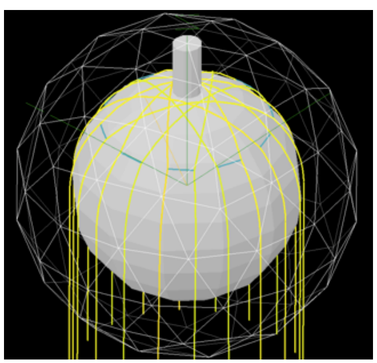
JUNO – 20 kton Liq Scint



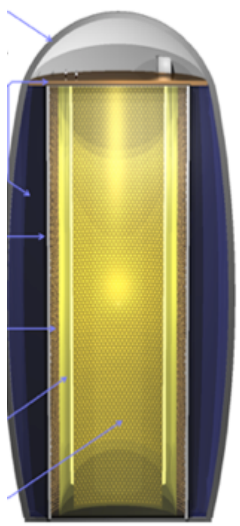
Borexino – 0.25 kton Liq Scint



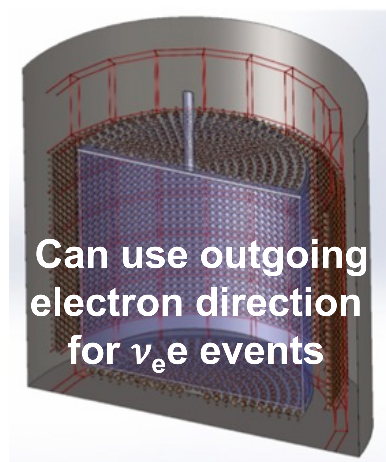
SNO+ - 0.78 kton Liq Scint



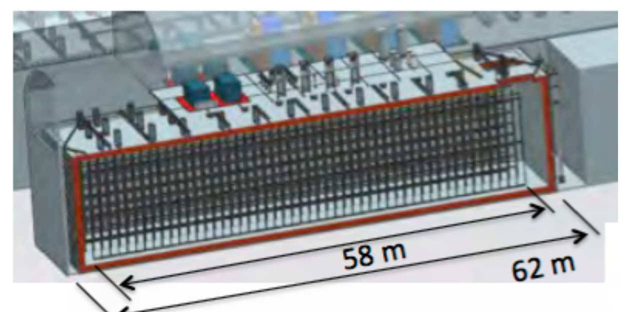
LENA – 50 kton
Liq Scint



SuperK - 22 kton
WATCHMAN – 1kton
Gd-doped water Cherenkov



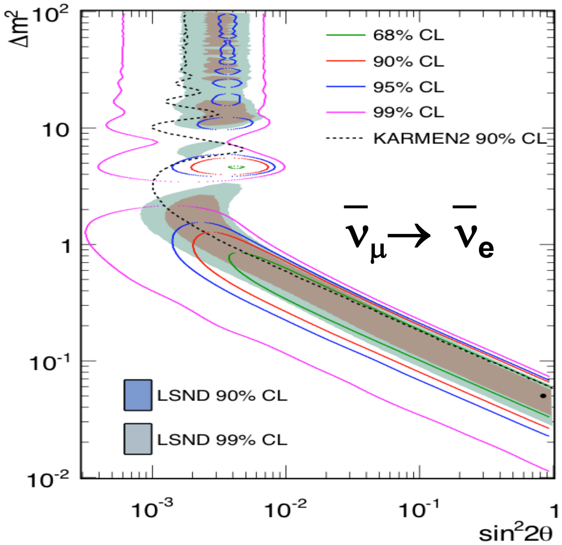
DUNE – 10 kton LAr
but no free protons



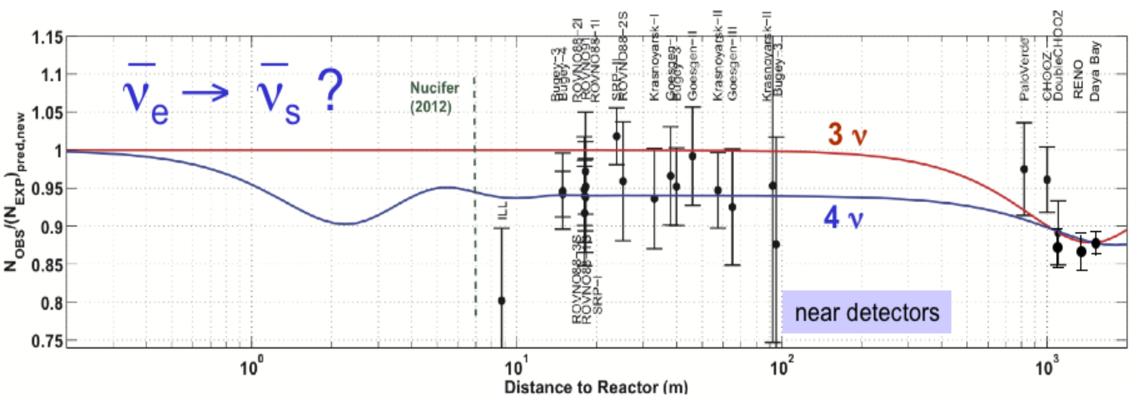
Can use outgoing electron direction for ν_ee events

Many Experimental Hints for Sterile Neutrinos

- MiniBooNE/LSND ν_e / $\bar{\nu}_e$ appearance signals



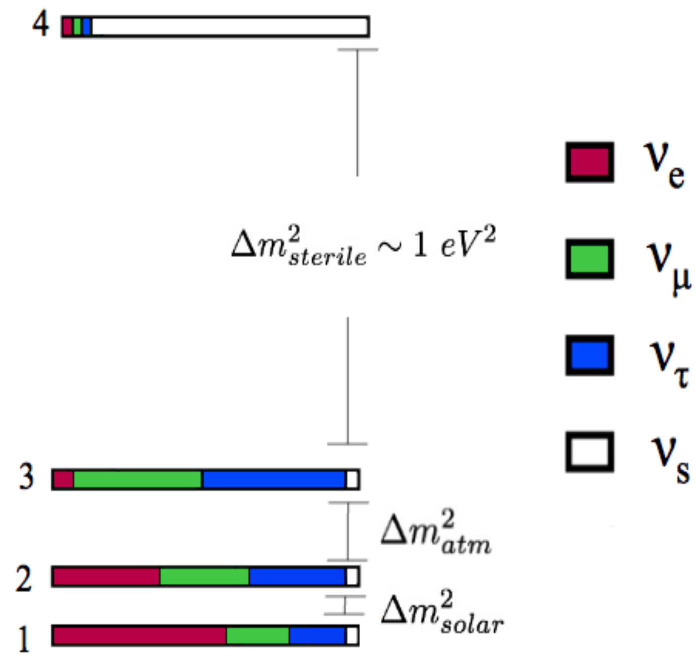
- Reactor Anomaly: $\bar{\nu}_e$ disappearance signals?



- Also, radioactive source anomaly (SAGE/GALLEX)

Data sets indicate a high Δm^2

Can be fit by introducing a new ν,
…but it must be non-interacting (sterile)!



These signals are at the 2-4σ level $\Rightarrow$ Need new "definitive" experiments

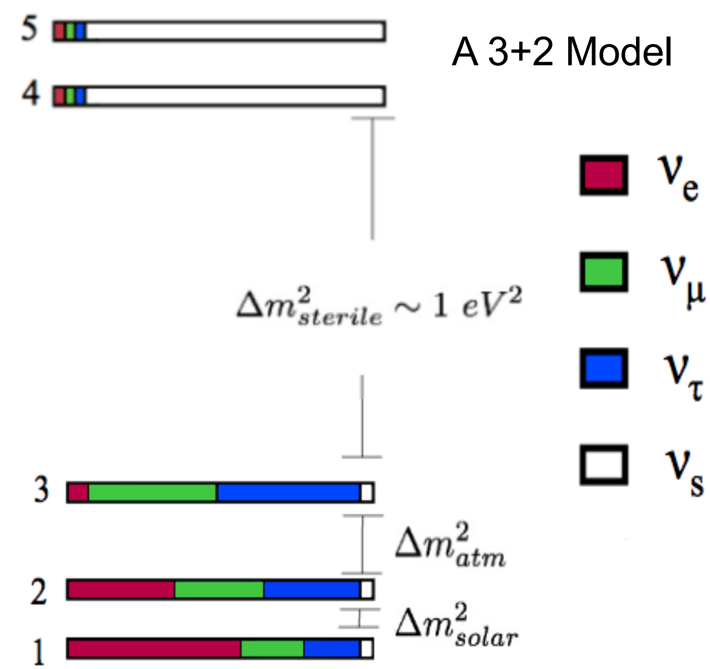
Establishing the existence of sterile neutrinos would be a major result for particle physics

3+1 Models May Not be the Solution.

- There is "tension" for 3+1 models between:
  - Neutrino and antineutrino data
  - Appearance and disappearance data

$\Rightarrow$ *If there are sterile neutrinos, the solution is probably not 3+1*

Global Fit Results		χ^2_{PG} (dof)	PG(%)
3+1	ν vs. $\bar{\nu}$	15.6 (3)	0.14%
3+2	ν vs. $\bar{\nu}$	13.9 (7)	5.3%
3+3	ν vs. $\bar{\nu}$	10.9 (12)	53%



Experiments must be designed to be definitive,
Even in 3+2 or 3+3 models….
$\Rightarrow$ Otherwise we are likely to just end up with more questions.

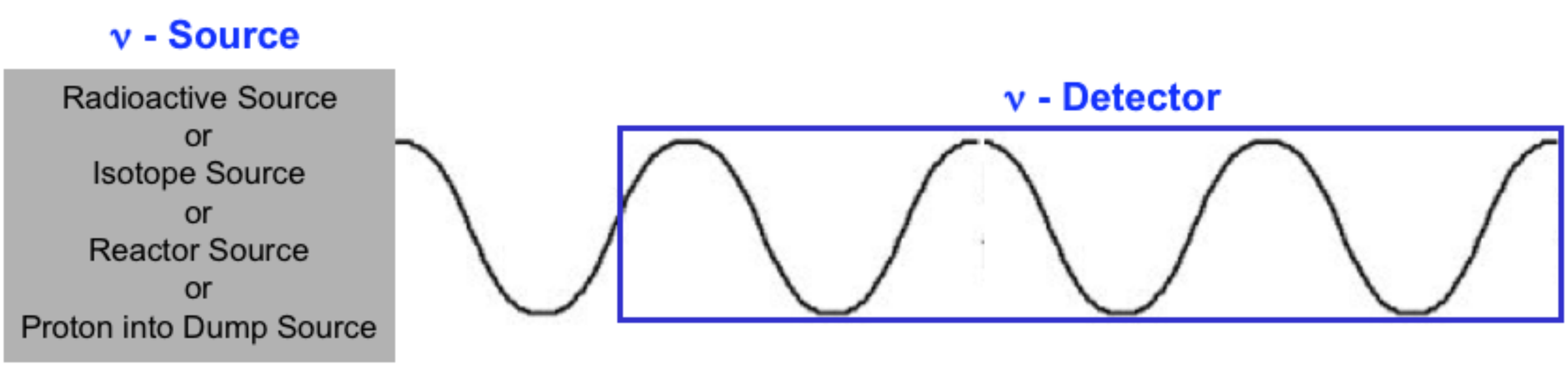
Establishing the Existence of Sterile Neutrinos

- Since sterile neutrino do not interact, can look for them by searching for the disappearance of normal neutrinos
  - $\bar{\nu}_e \rightarrow \bar{\nu}_{sterile} \rightarrow$ Disappears

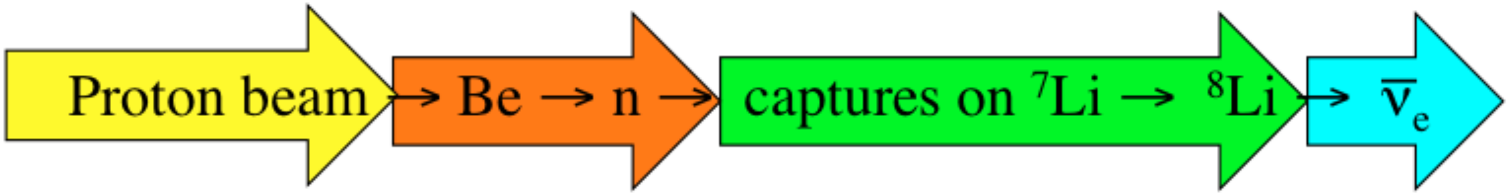
- This happens because the mass of the $\bar{\nu}_e$ and the $\bar{\nu}_{sterile}$ are different ($\Delta m^2 \neq 0$)$\Rightarrow$ Neutrino Oscillations

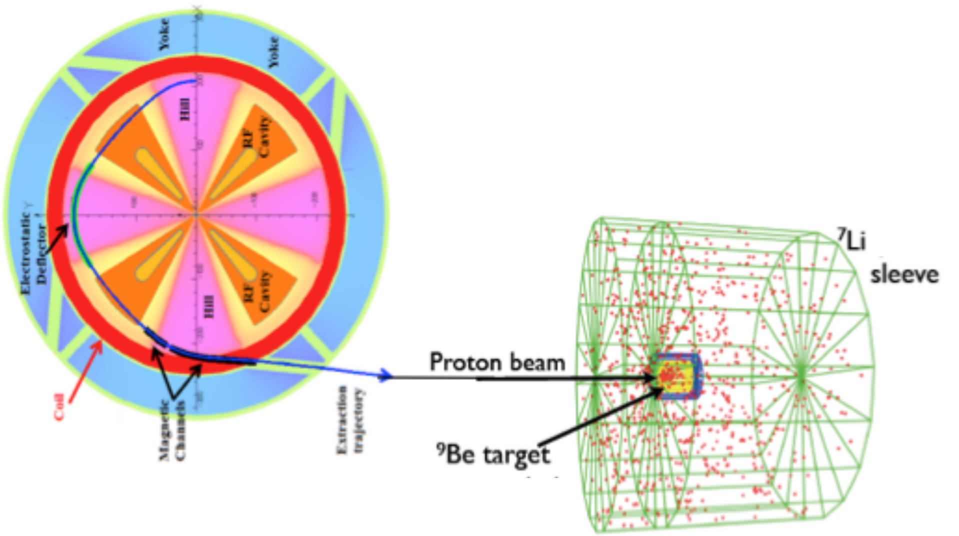
$$\text{Disappearance Probability} = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

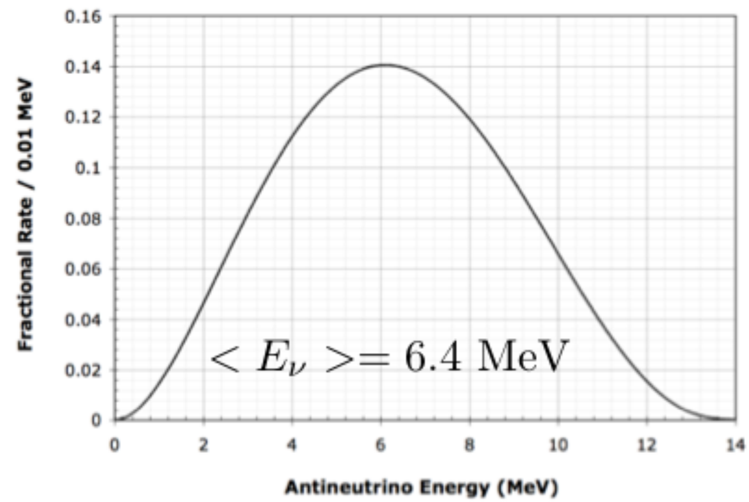
- To establish the existence $\Rightarrow$ Need a definitive experiment
  - High significance at the > 5σ level
  - Smoking gun: Observation of oscillatory behavior within detector



IsoDAR $\overline{\nu}_e$ Source





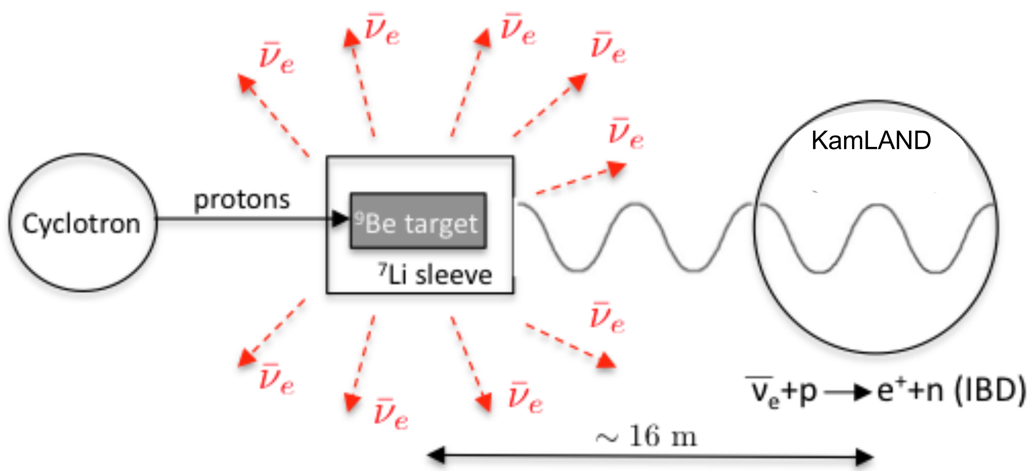


5 mA H_2^+ @ 60 MeV$/n$
(600 kW proton beam)

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

Produces 1.29×10^{23} $\bar{\nu}_e$ in 5 years (with 90% duty factor)

The IsoDAR at KamLAND Experiment



- IsoDAR Setup
  - Small Backgrounds
  - Good control of systematic uncertainties

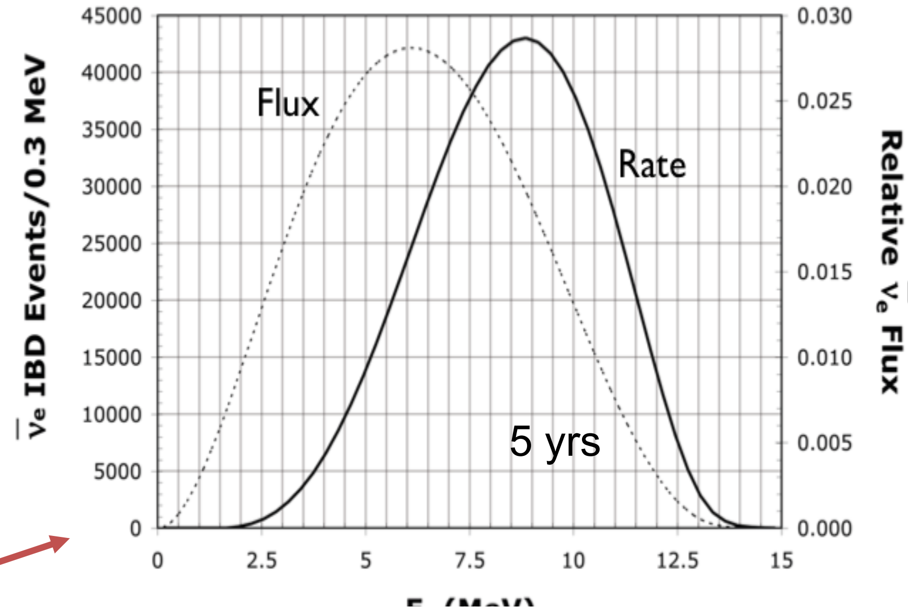
- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector as a function of L and E.

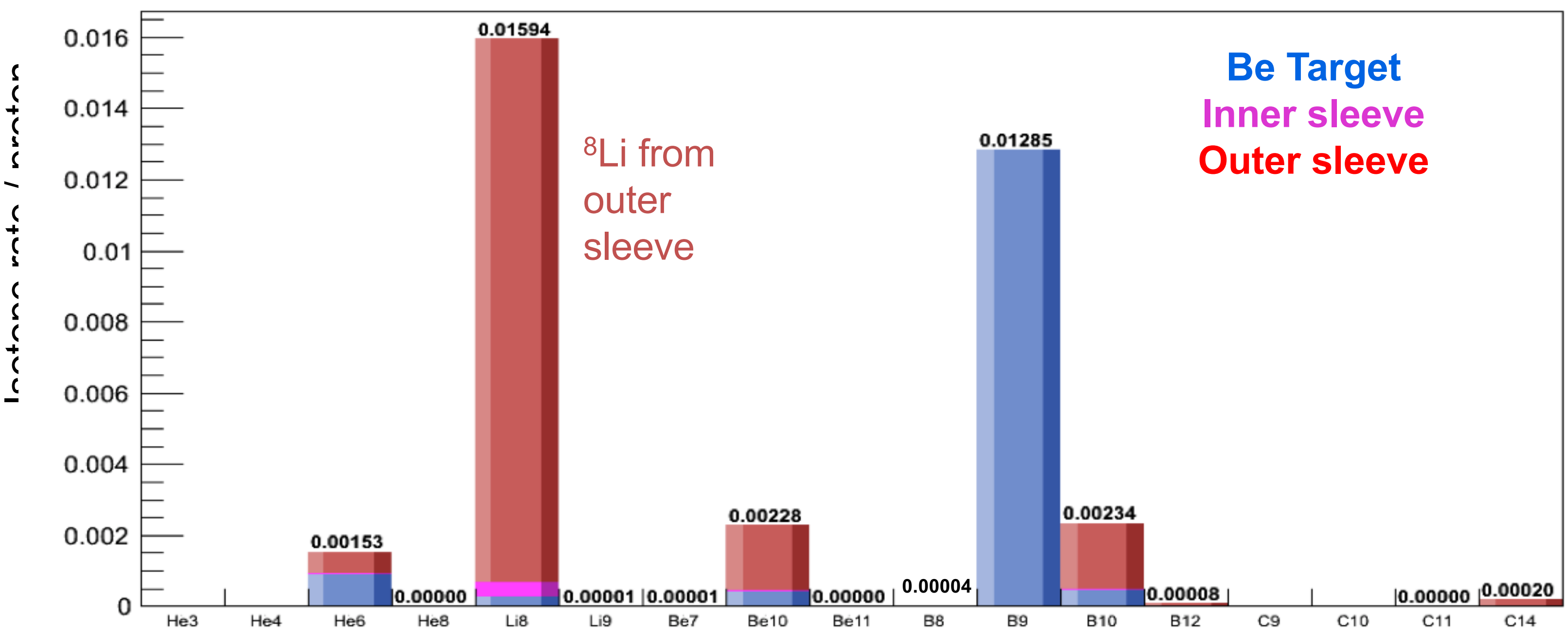
Key features of IsoDAR setup:

- High statistics
- Compact antineutrino source
  - Bring source to underground detector
  - $\sigma_x = \sigma_y = 23$ cm and $\sigma_z = 37$ cm
- Well understood energy spectrum
  - ^{8}Li β-decay dominates ν_e flux
  - Above 3 MeV environmental backgrounds
- Pair with the underground KamLAND detector
  - Both L and E accurately reconstructed
    - vertex: 12cm/√E(MeV)
    - energy: 6.4% → 3%/√E(MeV)
  - Delayed coincidence signal reduces backgrounds
  - Backgrounds don't show L/E oscillation behavior

Advantage of IsoDAR $\Rightarrow$ High-intensity, well-understood $\bar{\nu}_e$ beam

- IsoDAR $\bar{\nu}_e$ beam
  - About 0.016 ^{8}Li isotopes per proton produced
    - Giving a very high-intensity $\bar{\nu}_e$ flux
  - ^{8}Li is the only significant neutrino producing isotope
    - Well-understood energy spectrum
  - ^{8}Li production mainly from neutron capture on ^{7}Li sleeve

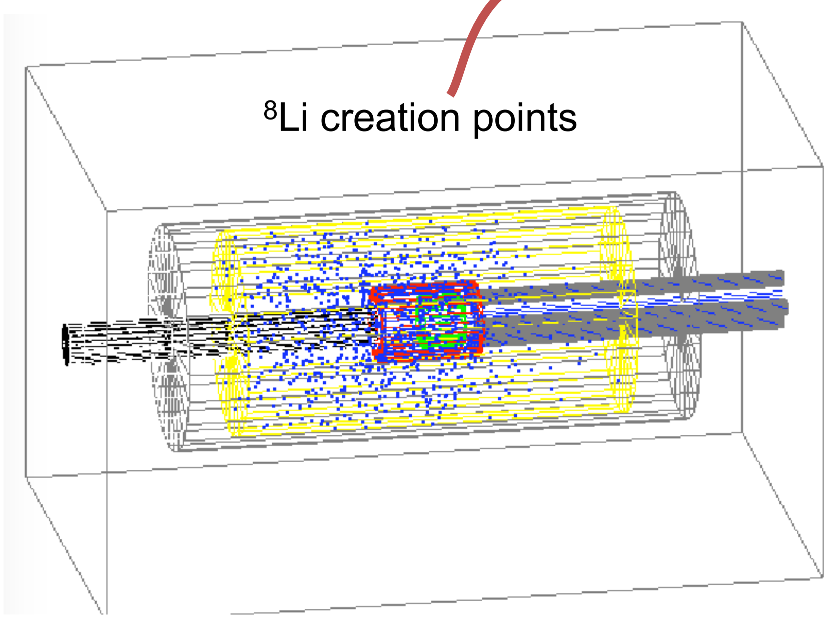


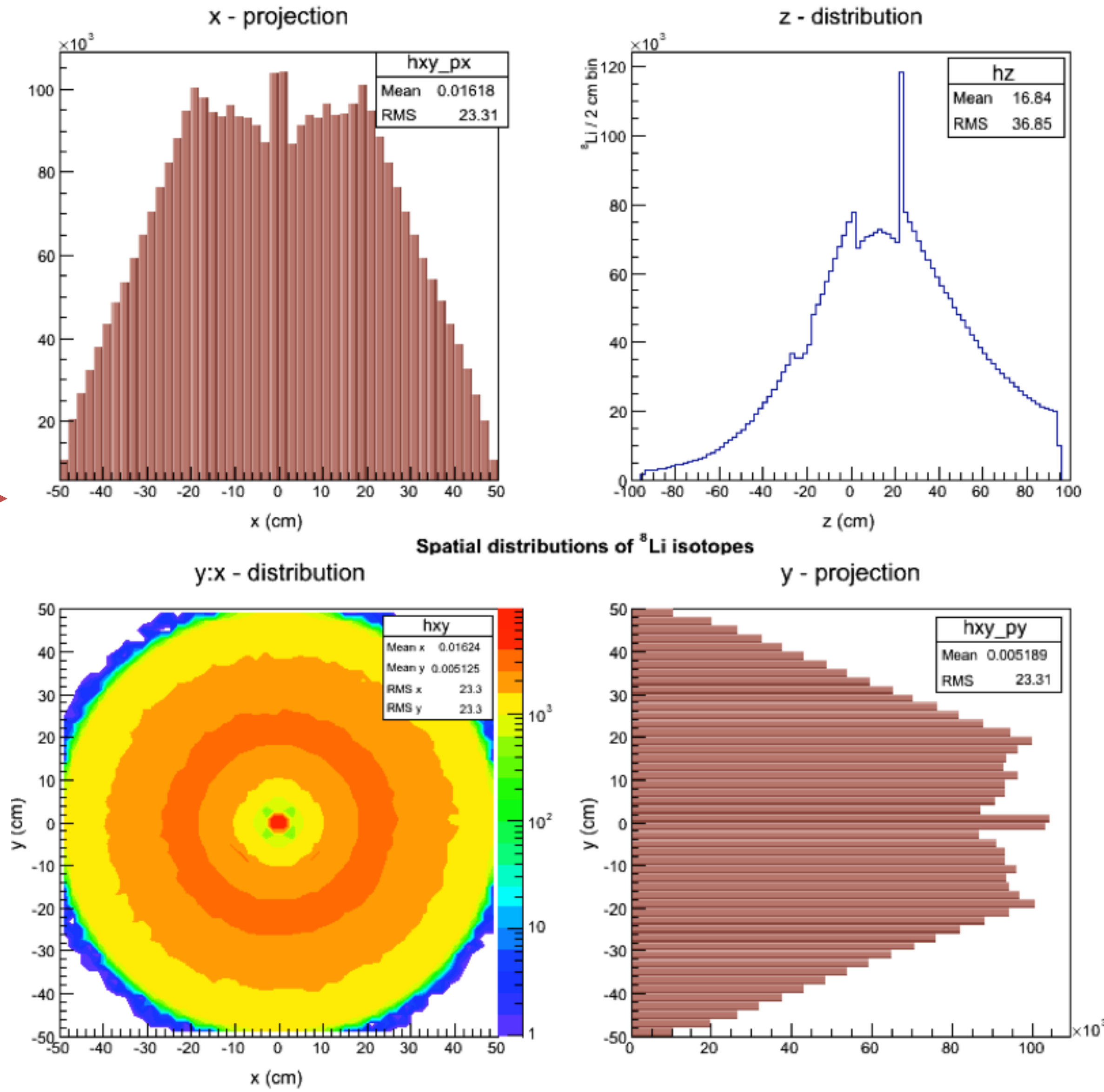


Advantage of IsoDAR ⇒ Compact neutrino source

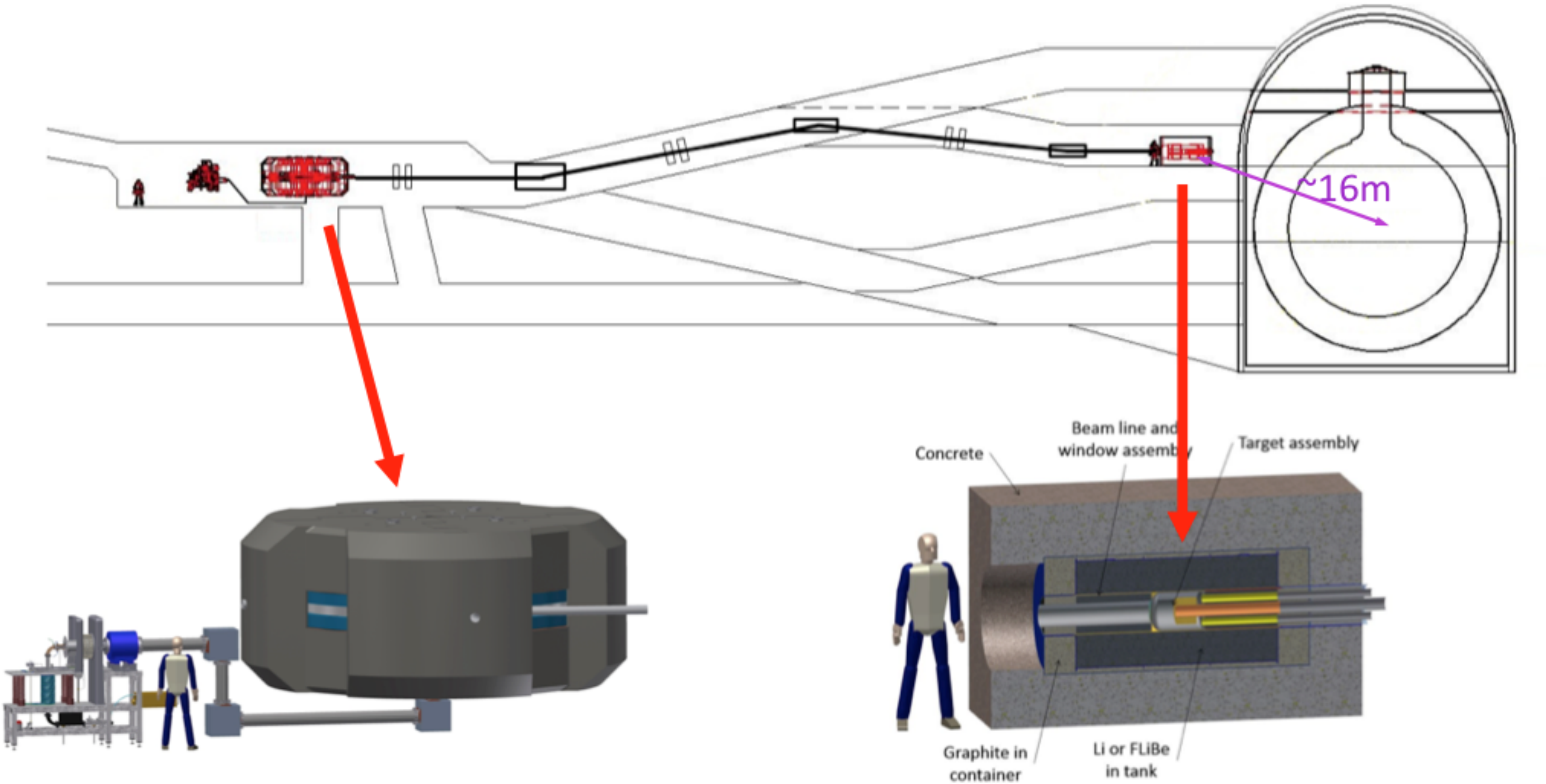
- IsoDAR produces compact neutrino source:
  - $\sigma_x = \sigma_y = 23$ cm and $\sigma_z = 37$ cm
  - Well-understood energy spectrum
- Couple with KamLAND resolutions
  - vertex: 12cm/√E(MeV)
  - energy: 6.4%/√E(MeV)

⇒ These combine to give excellent L/E resolution for oscillation studies





Proposal to Run at KamLAND

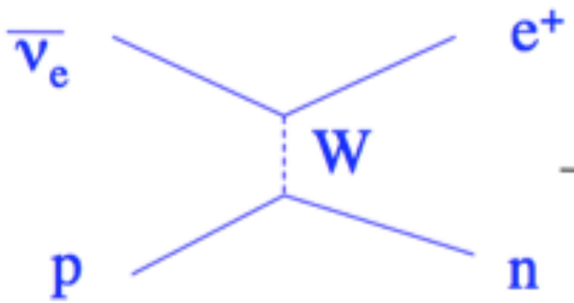


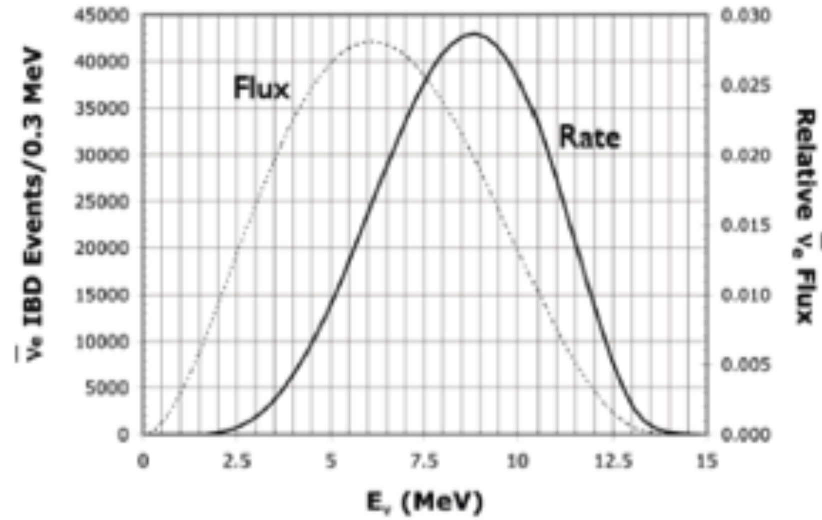
60 MeV/n 5 mA H_2^+ Cyclotron

^{9}Be/^{7}Li Target and $\bar{\nu}_e$ Source

Five Years of Running at KamLAND

Inverse β Decay (IBD)





Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Duty cycle	90%
Run period	5 years (4.5 years live time)
Target	^{9}Be surrounded by ^{7}Li (99.99%)
$\bar{\nu}$ source	^{8}Li β decay ($\langle E_\nu \rangle$=6.4 MeV)
$\bar{\nu}_e$/1000 protons	14.6
$\bar{\nu}_e$ flux	1.29×10^{23} $\bar{\nu}_e$
Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Detection efficiency	92%
Vertex resolution	12 cm/$\sqrt{E\text{ (MeV)}}$
Energy resolution	3% /$\sqrt{E\text{ (MeV)}}$
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5
$\bar{\nu}_e$-electron event total	2600

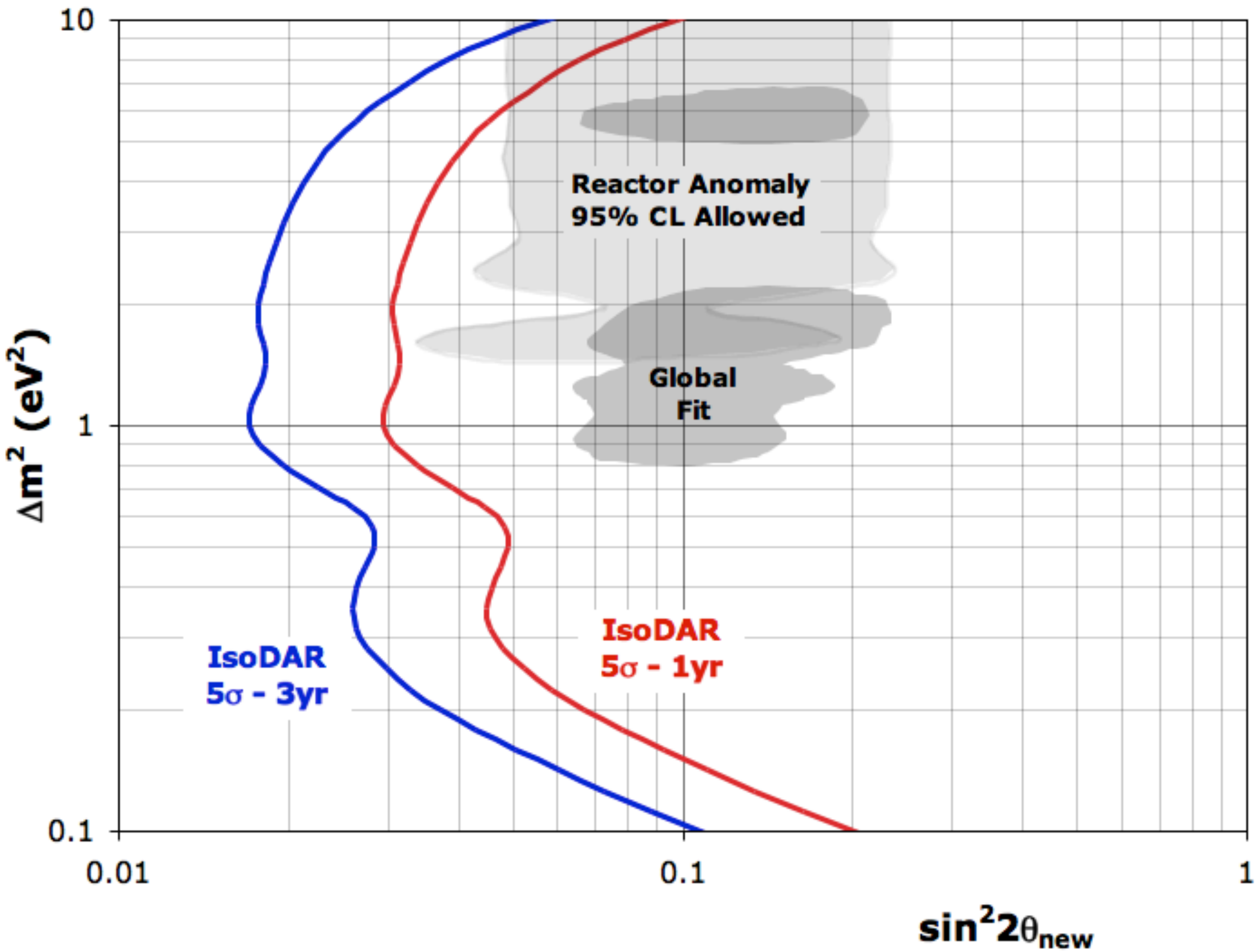
820,000 IBD events

- Sterile neutrino search

2,600 $\bar{\nu}_e$-electron events

- Measure $\sin^2\theta_W$ to 3.2%
- Probe weak couplings and nonstandard interactions (NSIs)

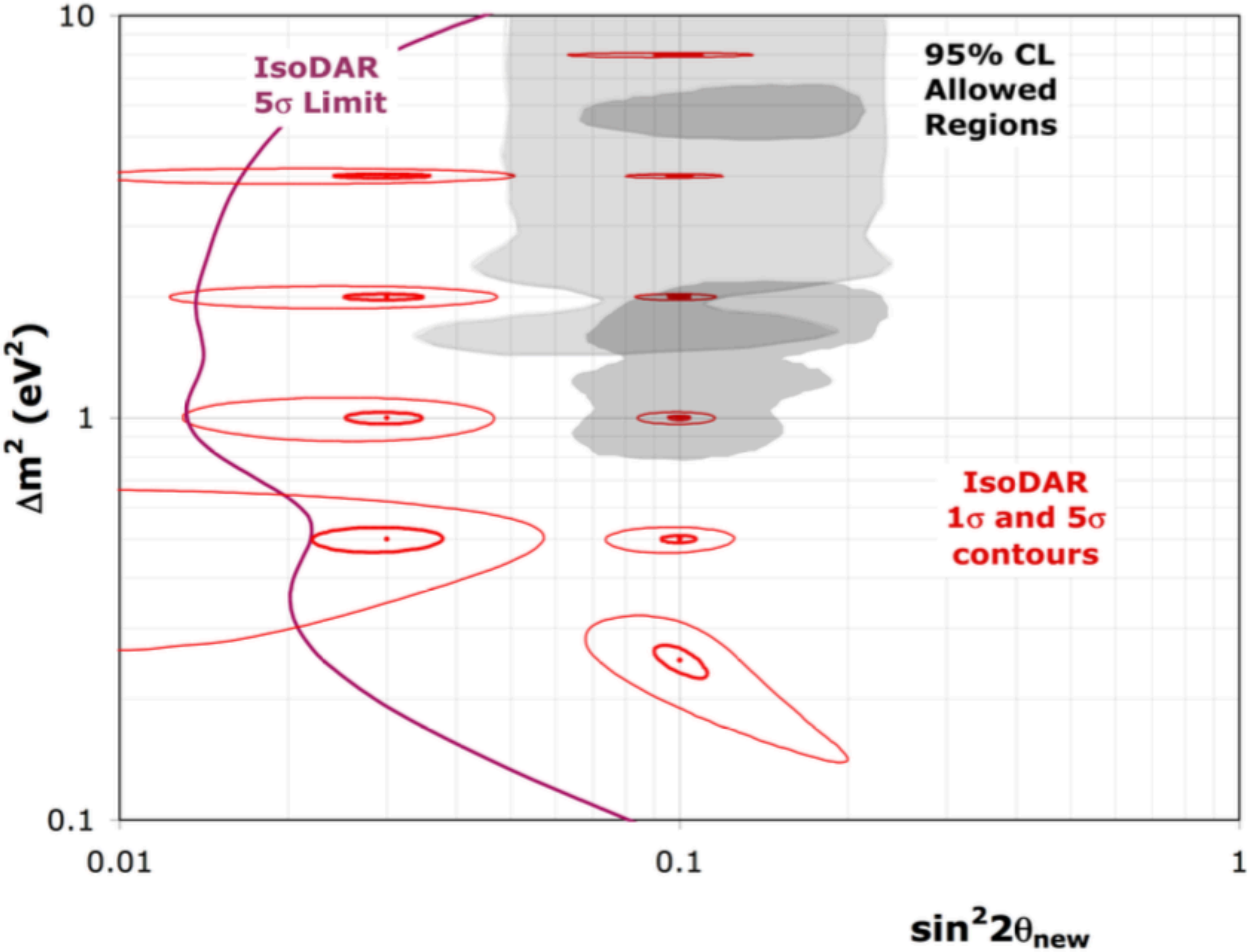
IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)



⇒ Global fit region can be ruled out at > 5σ in 4 months of running!

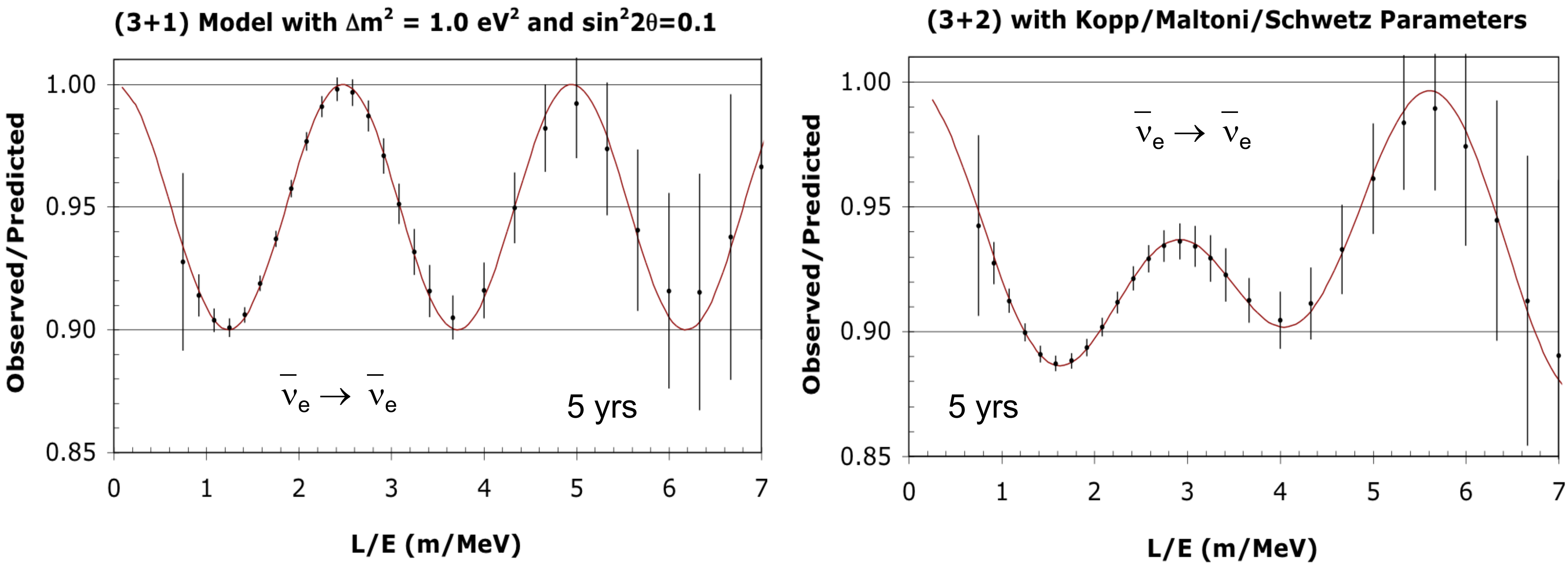
https://arxiv.org/abs/1205.4419

IsoDAR at KAMLAND Measurement Sensitivity (5 yrs)



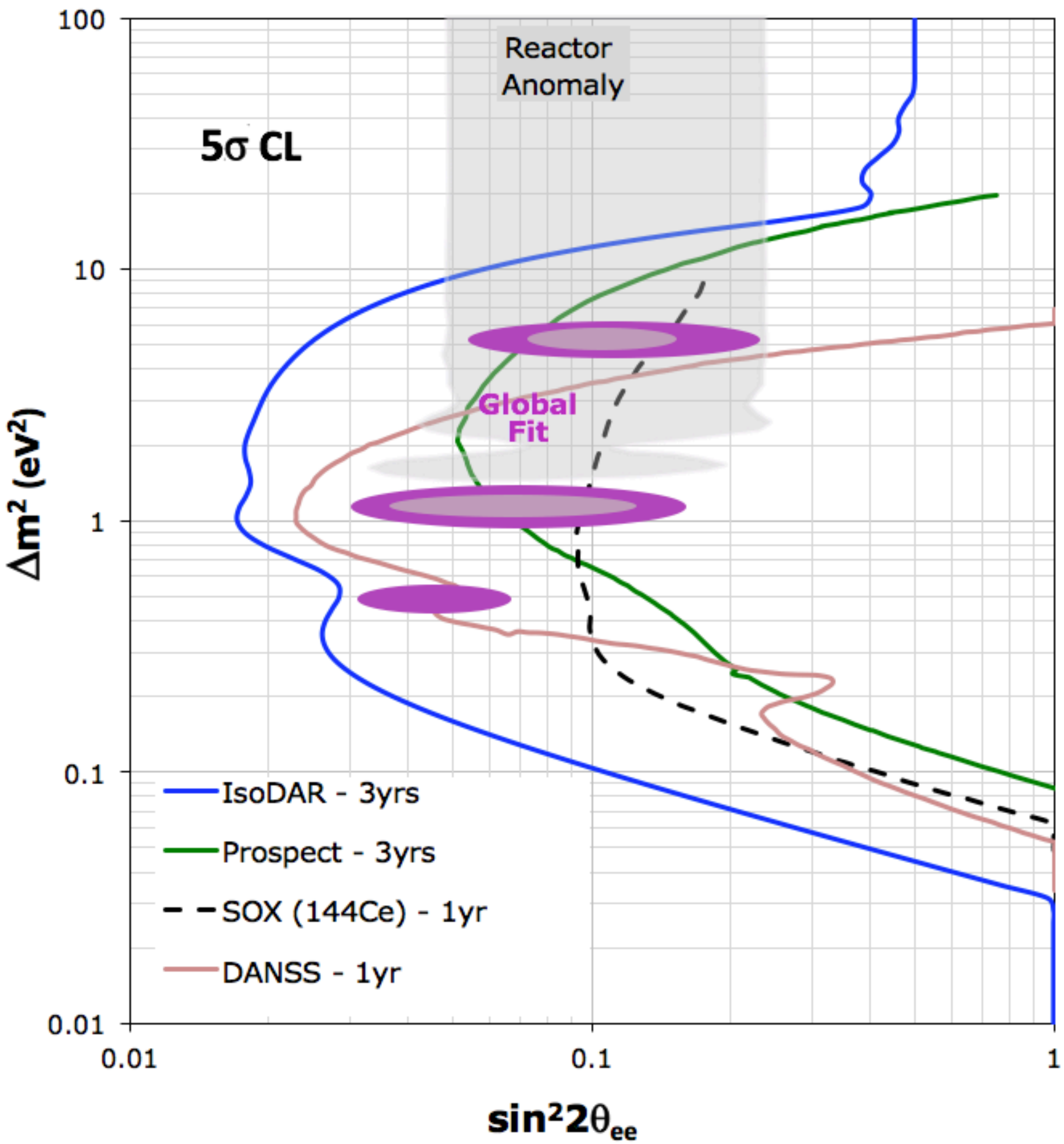
Oscillation L/E Waves in IsoDAR at KAMLAND

Observed/Predicted event ratio vs L/E including energy and position smearing

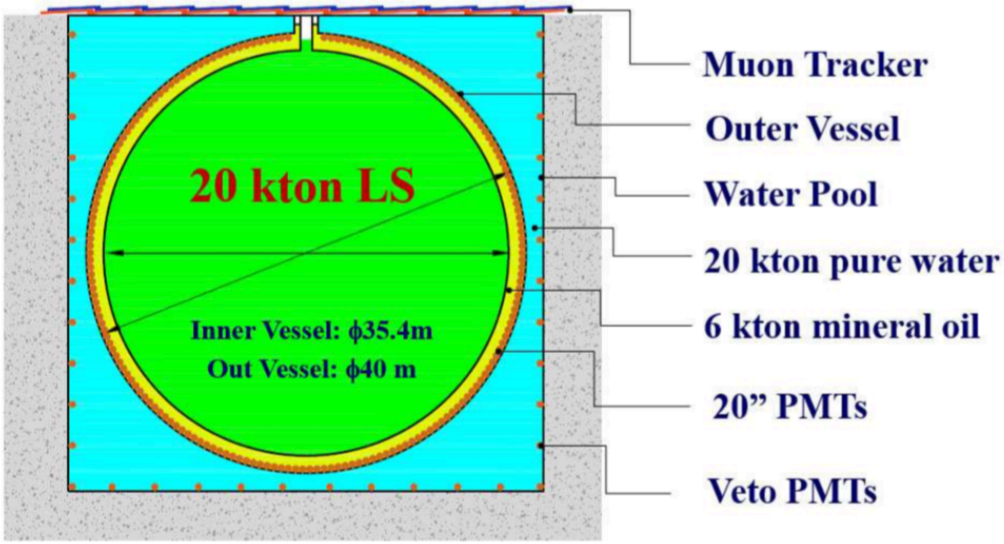


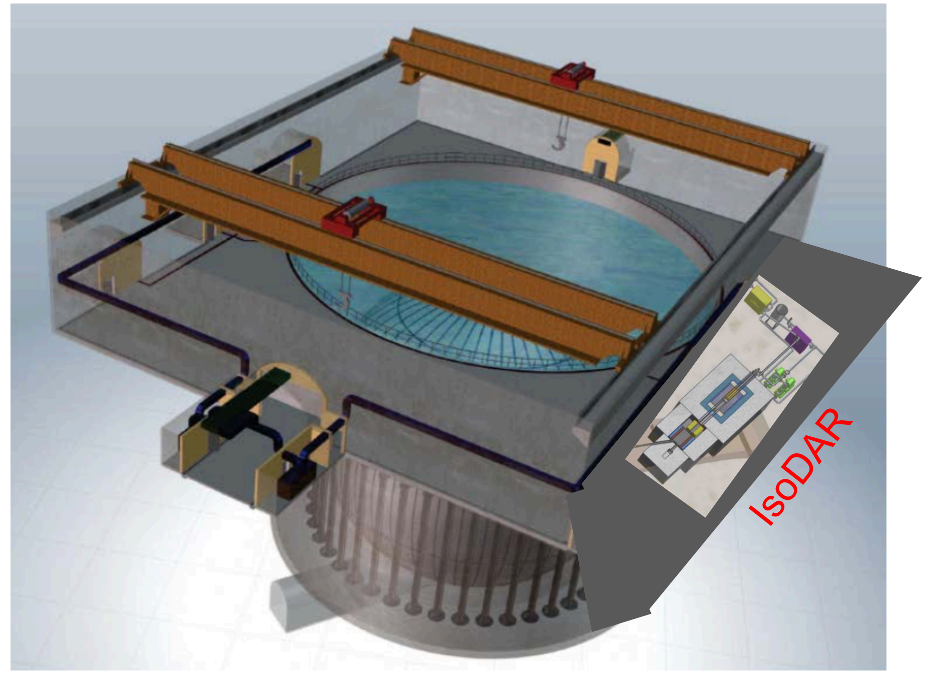
IsoDAR's high statistics and good L/E resolution has potential to distinguish (3+1) and (3+2) oscillation models

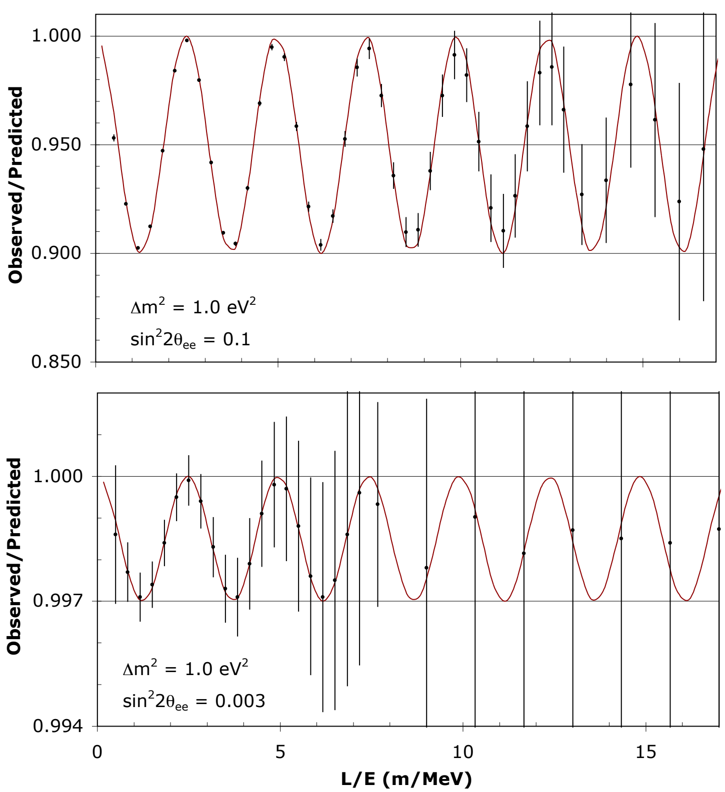
IsoDAR Comparison to Other $\bar{\nu}_e$ Disappearance Proposals

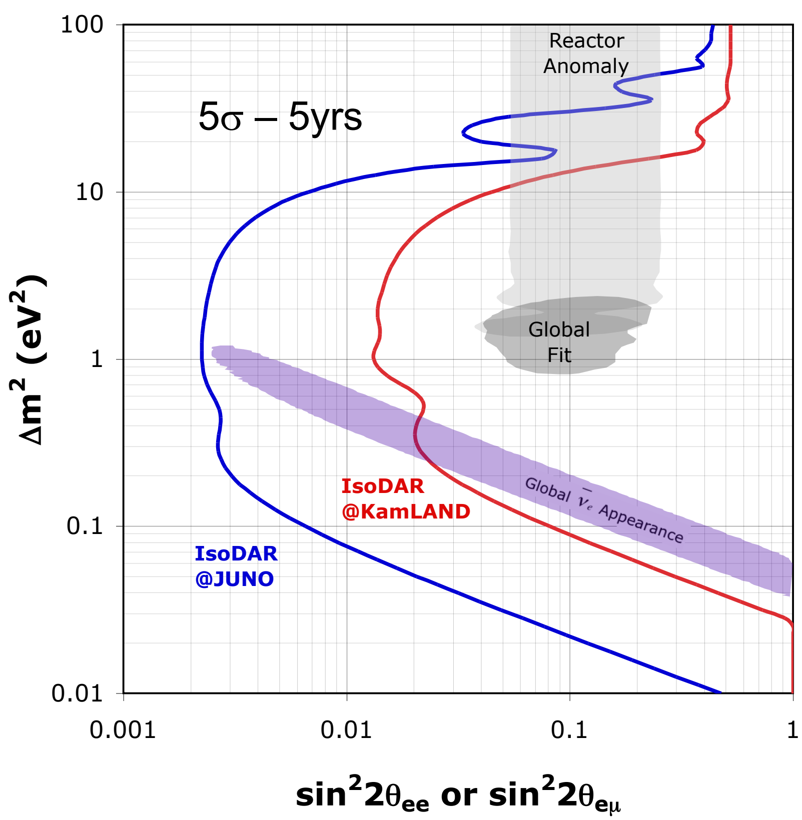


IsoDAR @ JUNO


20 kton LS
Inner Vessel: ϕ35.4m
Out Vessel: ϕ40 m
Muon Tracker
Outer Vessel
Water Pool
20 kton pure water
6 kton mineral oil
20" PMTs
Veto PMTs

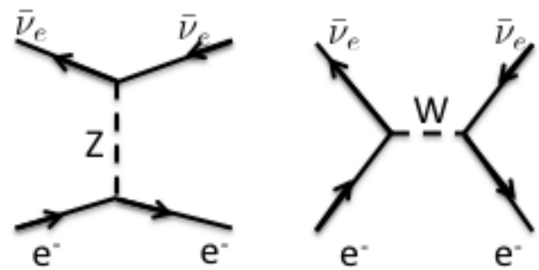

IsoDAR


Observed/Predicted
1.000
0.950
0.900
0.850
Δm² = 1.0 eV²
sin²2θee = 0.1
1.000
0.997
0.994
Δm² = 1.0 eV²
sin²2θee = 0.003
0
5
10
15
L/E (m/MeV)


5σ – 5yrs
Reactor
Anomaly
Global
Fit
Global ν̄e Appearance
IsoDAR
@KamLAND
IsoDAR
@JUNO
Δm² (eV²)
100
10
1
0.1
0.01
0.001
0.01
0.1
1
sin²2θee or sin²2θeμ

IsoDAR Also Has Excellent Measurement Capability for $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

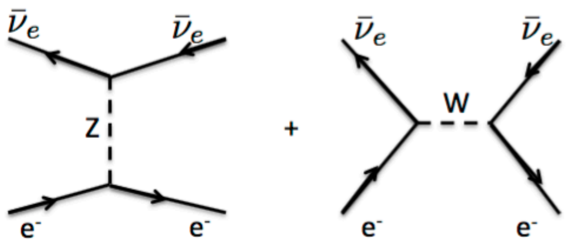
- Precision neutrino-electron scattering is one of the cleanest way to probe the electroweak interactions of the neutrino
  - Purely leptonic process so no QCD corrections and uncertainties



- Cross section is extremely small so a difficult measurement
  - Need a very high flux neutrino source and a large detector
- Since this standard model process is very well understood, one can use these studies to look for new physics.
  - Some hints that neutrinos could have anomalous weak interactions
  - Extensions to the standard model can have new mediators for this type of process
- IsoDAR coupled with KamLAND could make the world's best $\bar{\nu}_e$e elastic scattering measurement

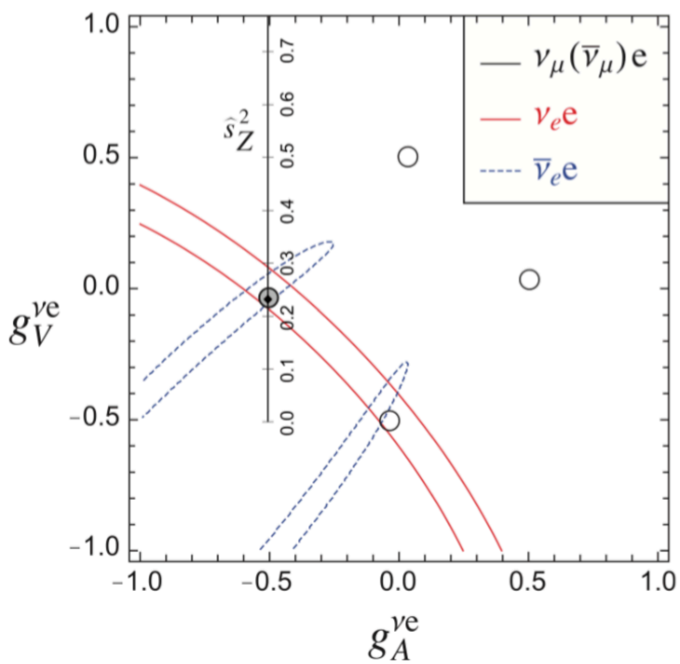
$\bar{\nu}_e$e Elastic Scattering

Standard Model

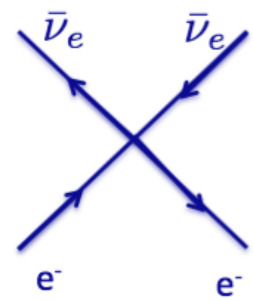


$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2\left(1-\frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2}\right]$$

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

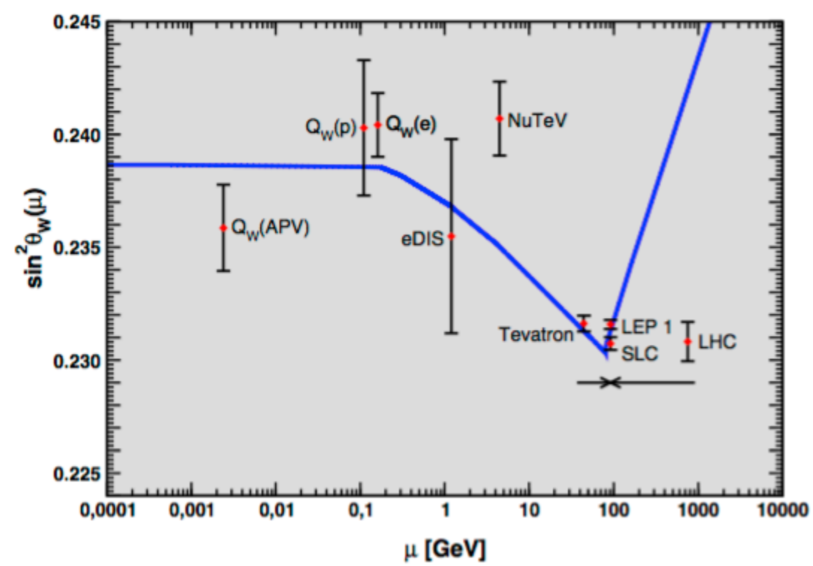


Non-Standard Interactions (NSI)

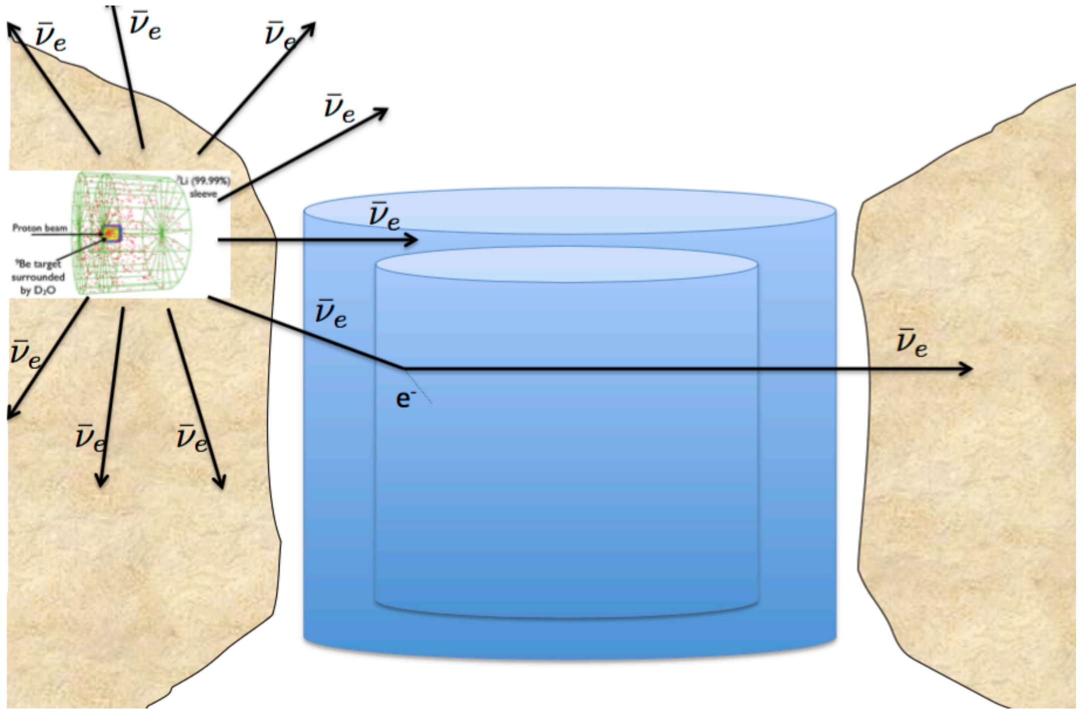


$$\frac{d\sigma(E_\nu,T)}{dT} = \frac{2G_F^2 m_e}{\pi}\Big[\big(\tilde{g}_R^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eR}|^2\big) + \big(\tilde{g}_L^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eL}|^2\big)\left(1-\frac{T}{E_\nu}\right)^2 - \big(\tilde{g}_R\tilde{g}_L + \sum_{\alpha\neq e}|\epsilon_{\alpha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

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



$\bar{\nu}_e$ e Elastic Scattering Signal



- Characteristics
  - Single scatters in the detector from the low xsec $\bar{\nu}_e$ process
  - Can't measure incoming $\bar{\nu}_e$ energy since outgoing $\bar{\nu}_e$
  - Normalization of incoming $\bar{\nu}_e$ flux known from 800K IBD events
  - Cross section known to <1%
  - No $\bar{\nu}_e$ energy threshold
  - IsoDAR produces a continuous beam $\Rightarrow$ No beam timing cuts
  - **Both beam and non-beam backgrounds**

Beam Backgrounds

⇒ IBD events where you miss the neutron tag

- IBD rejection inefficiencies come from
  - Neutrons wandering outside target region
  - Neutron capture γ's which escape target region
  - Finite energy resolution
  - Neutron capture on other isotopes
  - Very long/short neutron capture times

Beam Backgrounds

- IBD rejection inefficiencies come from
  - ~~Neutrons wandering outside target region~~
  - ~~Neutron capture γ's which escape target region~~
  - ~~Finite energy resolution~~
  - ~~Neutron capture on other isotopes~~
  - ~~Very long/short neutron capture times~~

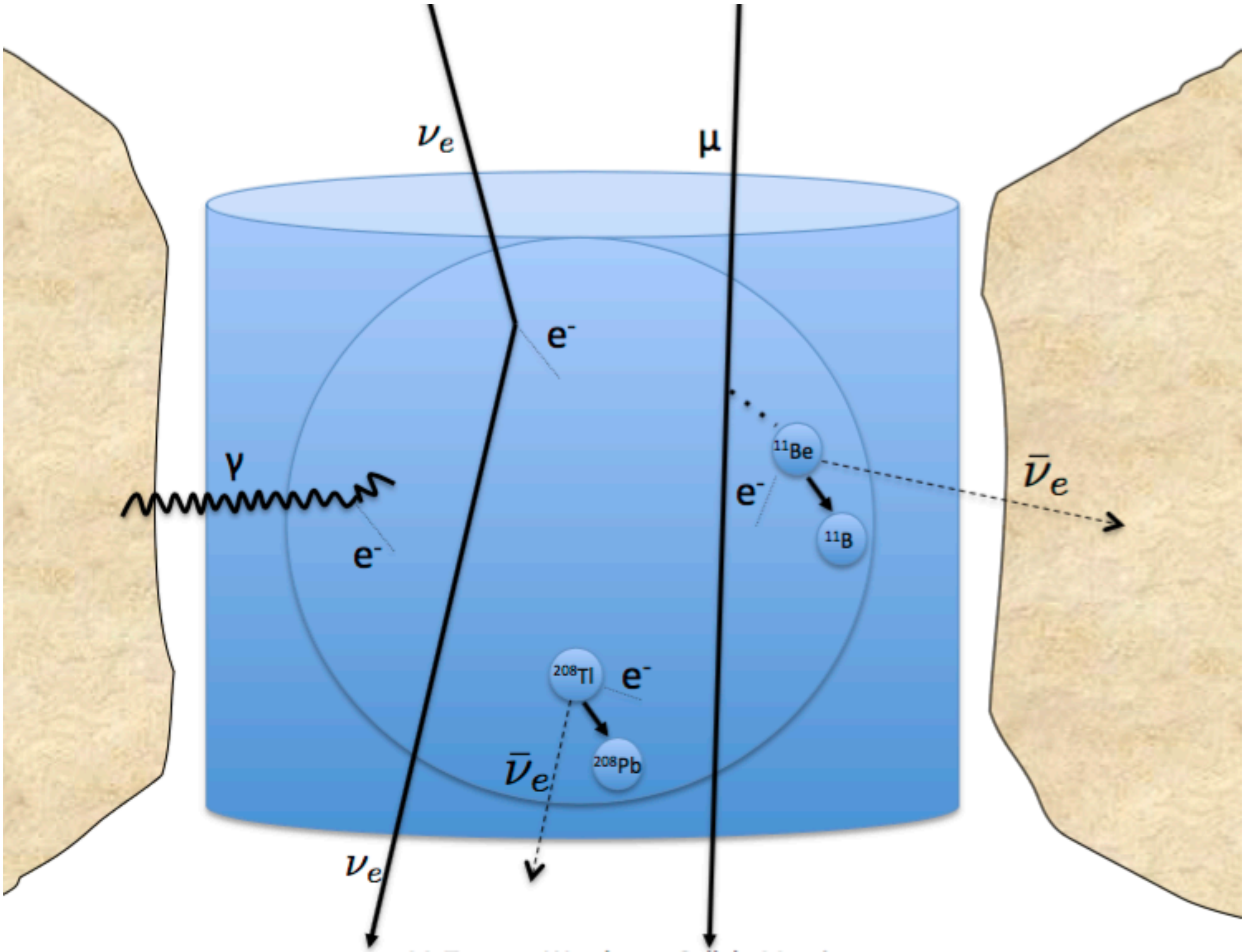
Fiducial Volume Cut

Loose Delayed Energy Cut

Loose Time Coincidence Cut

→ IBD rejection efficiencies of 99.75% are achievable

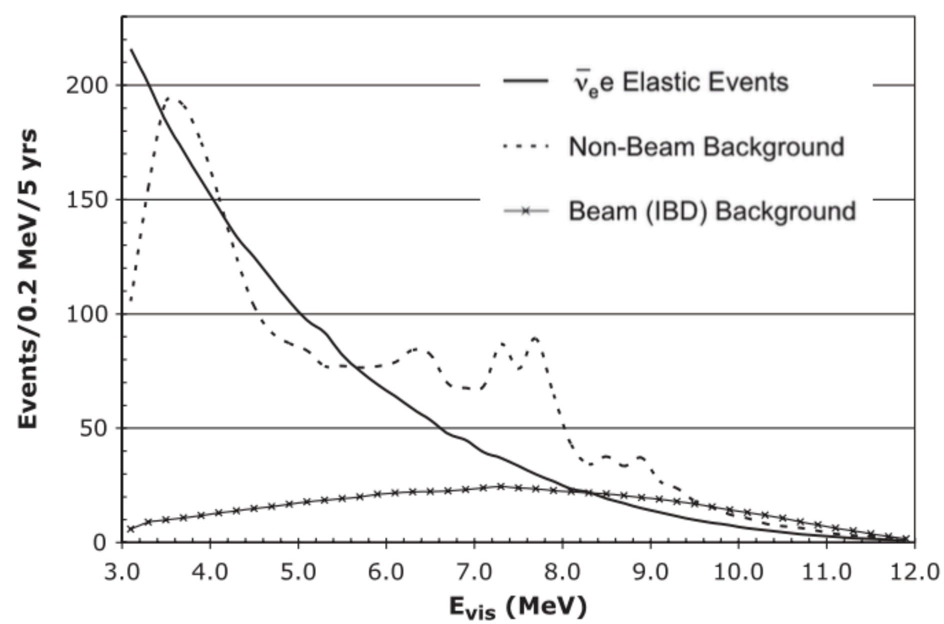
Non-beam Background



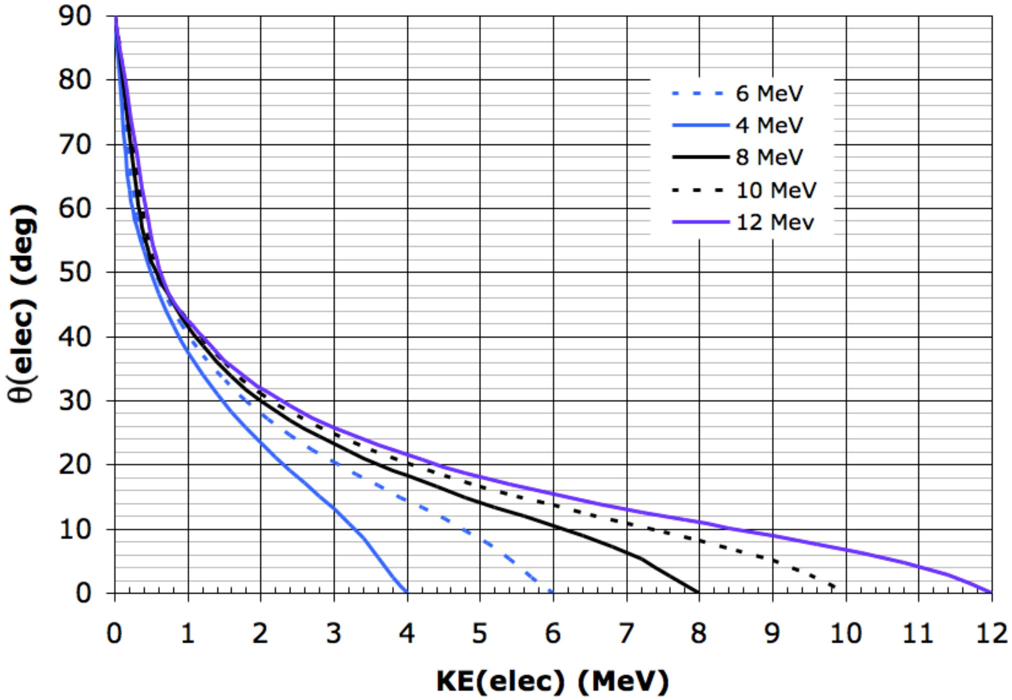
Non-beam Background

- Background reduction strategies:
  - Long muon veto
    - Remove muon spallation production of cosmogenics
  - 3 MeV energy threshold
    - Remove natural radioactivity from rock and material
  - 5 meter radius cut on fiducial volume
    - Remove external gammas
  - Can measure and subtract non-beam background using the large sample of KamLAND beam-off running

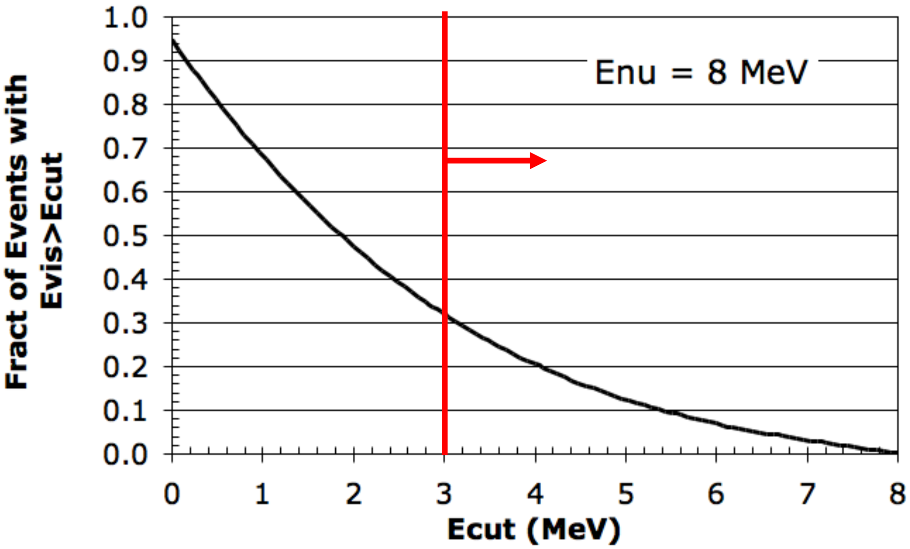
	Events
^{8}B solar neutrino	890.1
^{208}T1	594.3
External γ stainless	227.4
External γ rock	533.7
Spallation ^{8}B	42.5
Spallation ^{8}Li	94.9
Spallation ^{11}Be	490.0
Total	2872.9

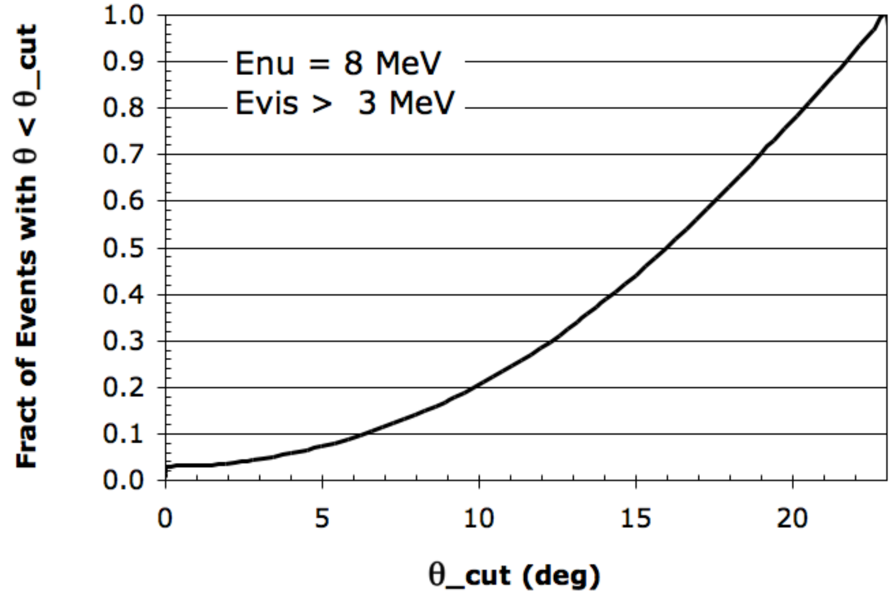


$\bar{\nu}_e e$ Elastic Scattering Kinematics

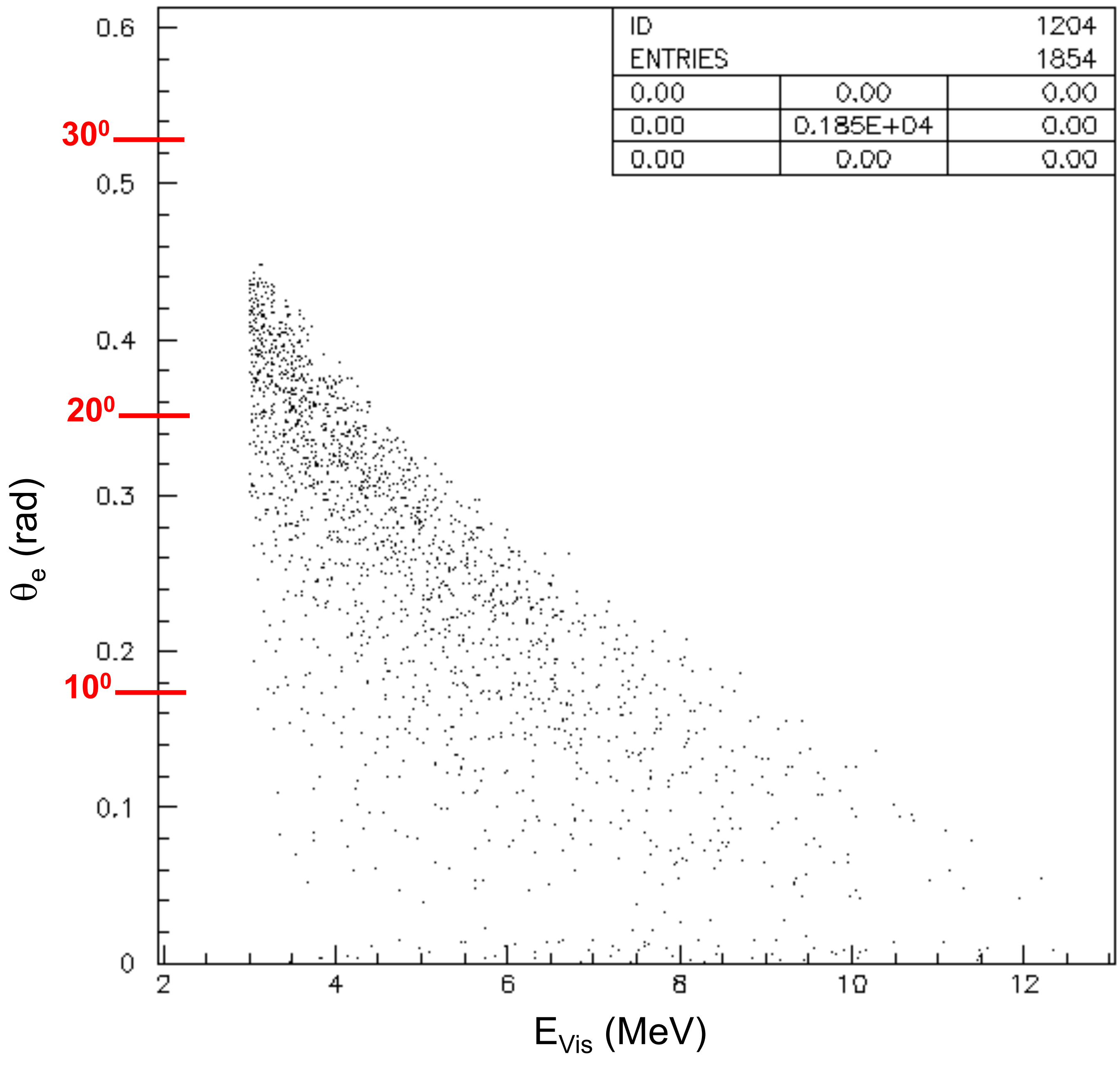


- Reduction of non-beam backgrounds by cutting on outgoing electron angle wrt IsoDAR target
  - No directionality available for liquid scintillator detectors.
  - **Only can be done for water Cherenkov or LAr detectors**
  - 30^0 cut would reduce non-beam background by x6





$\bar{\nu}_e e$ ES Events with IsoDAR Spectrum for E_{Vis} > 3 MeV (θ_e vs E_e)



Sensitivity Estimates

$$s_0 = \sin^2\theta_W^0 \text{ and } s_f = \sin^2\theta_W^{\text{Fit}}$$

$$\chi^2(s_f) = \sum_i \frac{\left(N_i(s_0) - (N_i(s_f) + \alpha * ES_i(s_f) + \beta * B_i^{on})\right)^2}{\left(N_i(s_0) + B_i^{off}\right)} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 ,$$

ES Signal → $ES_i(s)$; Beam-off → B_i^{off}; Beam-on Bkgnd → B_i^{on}

$$N_i(s) = ES_i(s) + B_i^{\text{off}} + B_i^{\text{on}}$$

Beam-on Bkgnd uncertainty: $\sigma_\beta = 0.02/0.25 = 0.08$

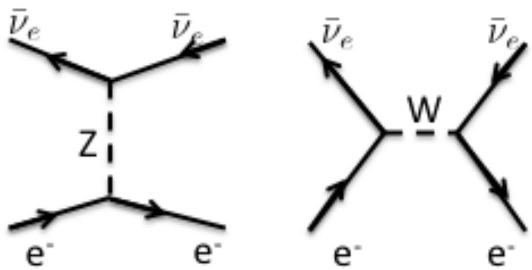
$\bar{\nu}_e$ Flux uncertainty: $\sigma_\alpha = 0.007$

$\sin^2\theta_W^0 = 0.238$

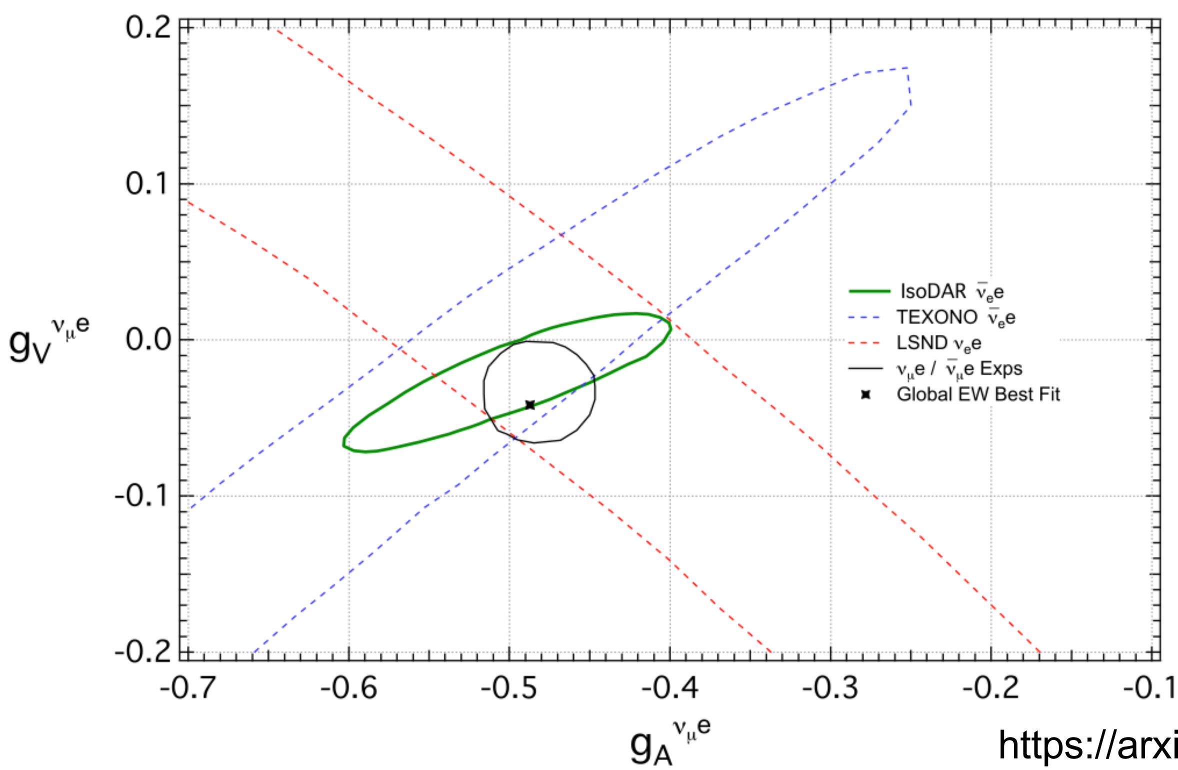
IsoDAR at KamLAND

Use $\bar{\nu}_e e$ Elastic Scattering ⇒ Measure $\sin^2\theta_W$

- 5yr data gives 2600 events with E_{vis}>3MeV **⇒ $\delta\sin^2\theta_W$ = 0.0076 (~3.2%)**
  - Would be world's best $\bar{\nu}_e e$ (or $\nu_e e$) elastic scattering measurement



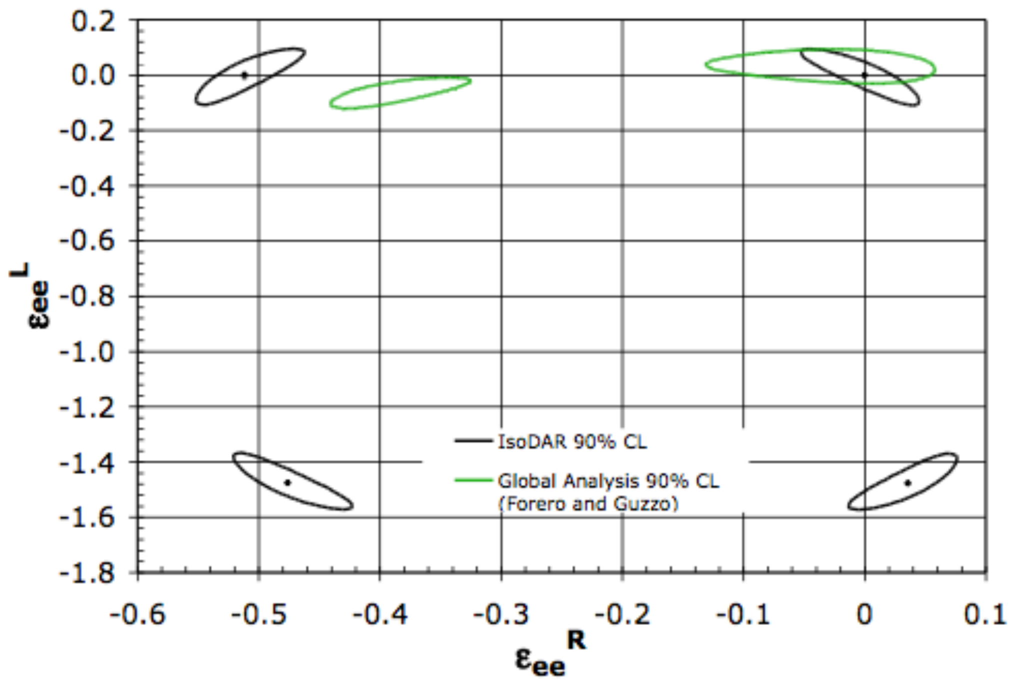
	Bkg factor	$\delta\sin^2\theta_W$	$\frac{\delta\sin^2\theta_W}{\sin^2\theta_W}$	$\delta\sin^2\theta_W^{\text{stat-only}}$
Rate + shape	1.0	0.0076	3.2%	0.0057
Shape only	1.0	0.0543	22.8%	0.0395
Rate only	1.0	0.0077	3.2%	0.0058
Rate + shape	0.5	0.0059	2.5%	0.0048
Rate + shape	0.0	0.0040	1.7%	0.0037

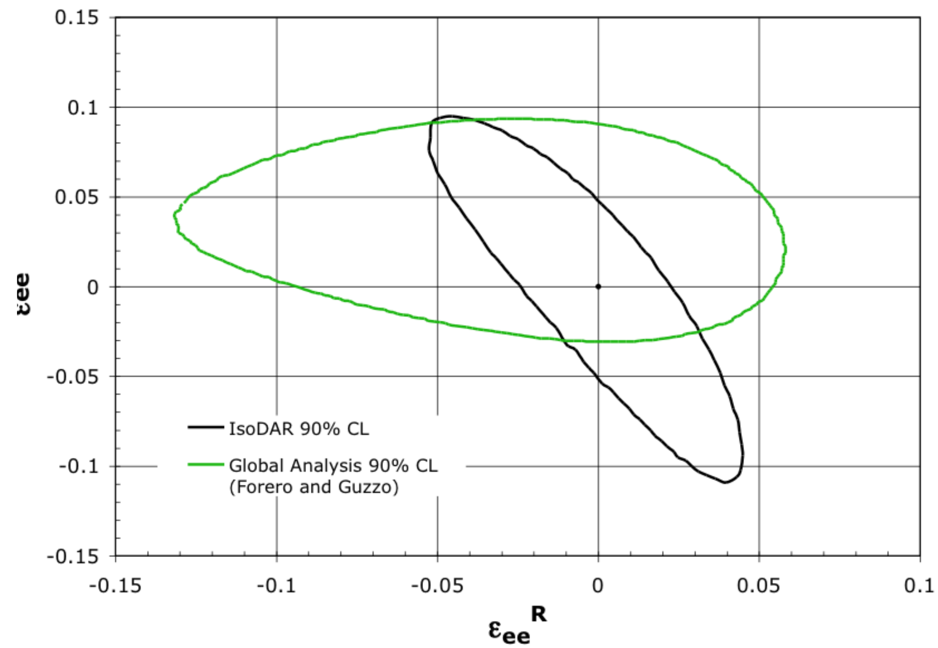


https://arxiv.org/abs/1307.5081

IsoDAR at KamLAND
Search for Non-Standard Neutrino Interactions

- Use precision neutrino-electron scattering to probe for Non-Standard Interactions (NSI) since it is a well-understood Standard Model process
  - Sensitivity comparable to current world average
  - IsoDAR@KamLAND measurement would constrain and restrict allowed regions as well as possibly see indications of new physics





$$g_L \longrightarrow g_L + \epsilon_{ee}^{eL} \quad g_R \longrightarrow g_R + \epsilon_{ee}^{eR}$$

IsoDAR at KamLAND Physics Program

- Two physics measurements have been investigated:
  - Sterile neutrino search using $\bar{\nu}_e$ disappearance
  - Precision electroweak measurements and NSI searches
- Going beyond the work done on these two core topics is an important component for strengthening the IsoDAR physics case.
  - Making these two measurements better and finding ways to apply the data to other physics might be possible.
  - Expanding the use of the IsoDAR@KamLAND experiment to other processes (i.e. ν_e instead of $\bar{\nu}_e$ scattering)
  - Possibility of using IsoDAR with other detectors or other types of setups.

$\Rightarrow$ Next Talk

How does IsoDAR work?

- Janet Conrad