IsoDAR Physics at Yemilab

Josh Spitz (University of Michigan)

Sterile Neutrino Search Underground Workshop, 7/1/2021

I would like to start this talk with a ‘Conclusions’ slide (taken from my talk at Neutrino 2014; “Future short-baseline sterile neutrino searches with accelerators”).

Taken from my talk at Neutrino 2014; "Future short-baseline sterile neutrino searches with accelerators".

Conclusions

- **The discovery of a light sterile neutrino would be a monumental result for particle physics and cosmology.**

- The light sterile neutrino issue needs to be resolved.

- A truly definitive resolution is difficult to achieve and will likely require multiple detectors/experiments.

- Regardless if there is a sterile neutrino or not, a lot of important physics and R&D can be provided by accelerator-based short-baseline experiments.

Taken from my talk at Neutrino 2014; "Future short-baseline sterile neutrino searches with accelerators".

Unfortunately, (7 years later) the experimental situation is mostly unchanged. In fact, the situation is MORE complicated than ever.

Anomalies remain, null results remain. The worldwide pursuit of understanding this physics is strong, but truly definitive experiments are extremely difficult to achieve.

A definitive resolution is required!

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- Regardless if there is a sterile neutrino or not, a lot of important physics and R&D can be provided by accelerator-based short-baseline experiments.

A number of anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

Experiment name	Type	Oscillation channel	Significance
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	4.8σ
Reactors	Beta decay	electron disappearance (antineutrino)	(varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

Important note: A number of other experiments have probed this parameter space—and see nothing unusual. MINOS(+), NOvA, MiniBooNE, and CDHS see no muon-flavor disappearance at high-Δm^2.

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GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

These anomalies may be the best indication of new physics we currently have.

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The short-baseline anomalies represent one of the most important indications of new physics we have.

But, the situation is complicated and confusing.

Are there one or more experiments with a problem?
If a 3+1 model doesn't work, what alternative models are there?
Are reactor experiments seeing a signal (overall deficit? L/E-wave?)?
Are LSND and MiniBooNE due to the same, possibly new, physics?

Is this new physics or not? A definitive probe is required. And, unfortunately, answering these questions probably requires multiple experiments, including with muon and electron flavor and with appearance and disappearance!

The world is pursuing these anomalies in earnest

IceCube

SoLid

PROSPECT
Precision Oscillation and Spectrum Experiment

STEREO

μBooNE

MINOS

大亞灣 θ_{13}

Daya Bay θ_{13}

SHORT-BASELINE NEAR DETECTOR
SBND

T2K

NEOS
Neutrino-4
DANSS
CCM
IsoDAR

NuPRISM: recision eaction ndependent pectrum easurement

DOUBLE CHOOZ

RENO

NOvA

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

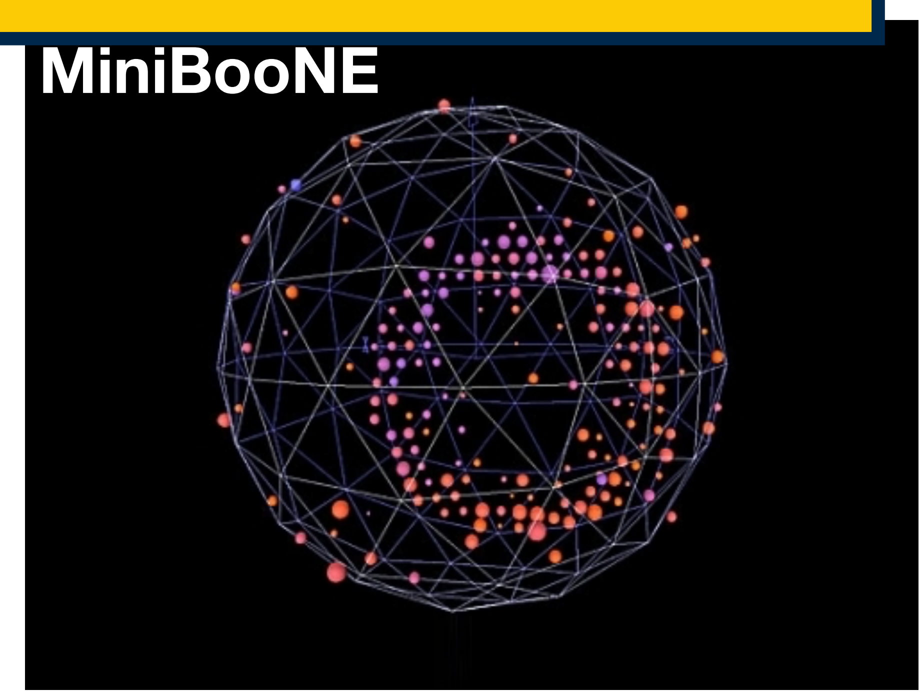
JSNS²
J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

The world is pursuing these anomalies in earnest

IceCube SoLid PROSPECT Precision Oscillation and Spectrum Experiment μBooNE STEREO MINOS NEOS

Among these, IsoDAR@Yemilab would be world-leading, completely unique, and definitive

RENO



NOvA

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

JSNS² J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

Aside: What is required for a truly definitive result?

-Understand the neutrino flux

-Understand the neutrino cross section

-Understand/minimize the backgrounds

-Collect a lot of events

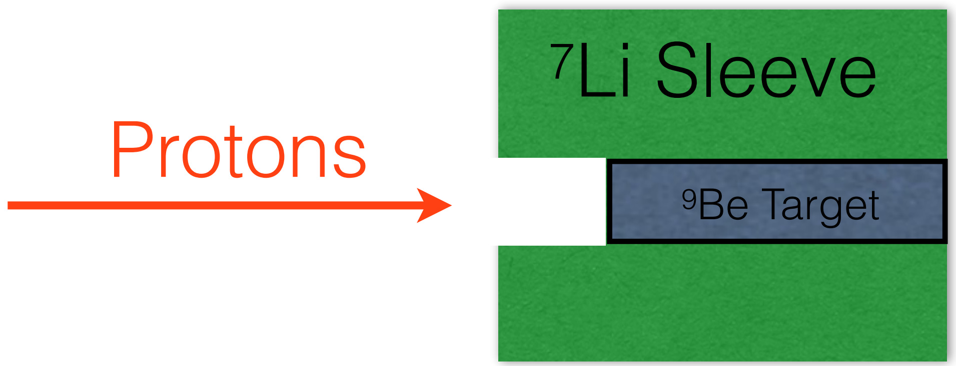
-Provide a chance to see multiple periods of oscillation wave

The IsoDAR concept

Produce lots of neutrinos with an extremely well understood energy spectrum

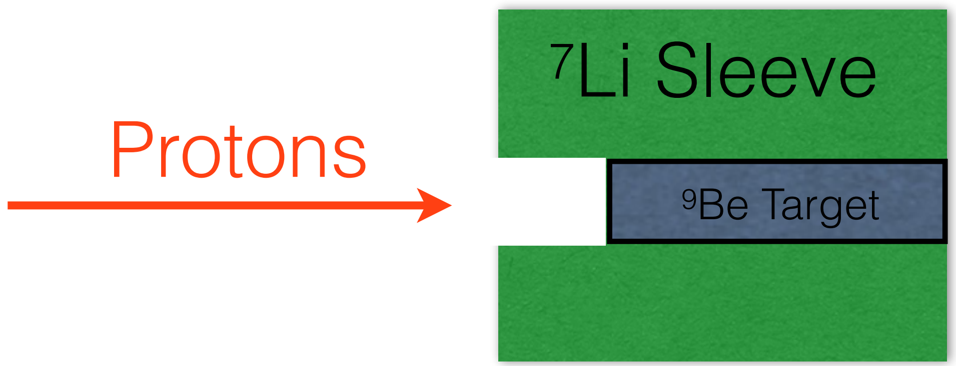
The IsoDAR concept

Produce lots of neutrinos with an extremely well understood energy spectrum



The IsoDAR concept

Produce lots of neutrinos with an extremely well understood energy spectrum



$$p + {}^{9}\mathrm{Be} \rightarrow {}^{8}\mathrm{Li} + 2p$$

$$p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$$
$$n + {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Li} + \gamma$$

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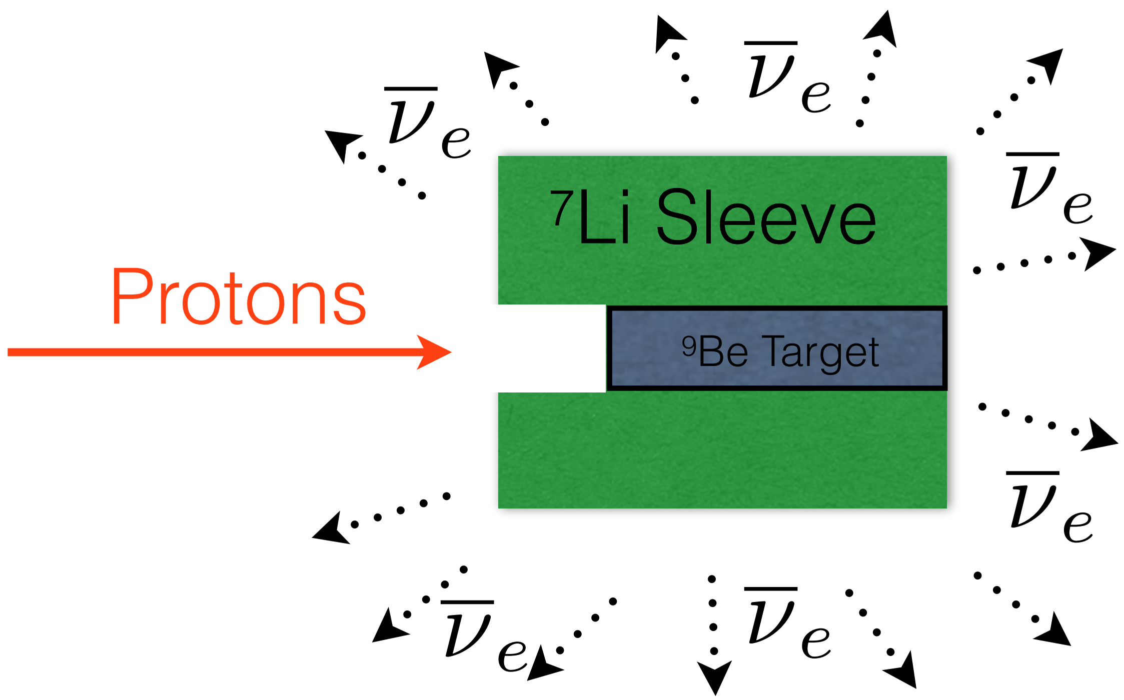
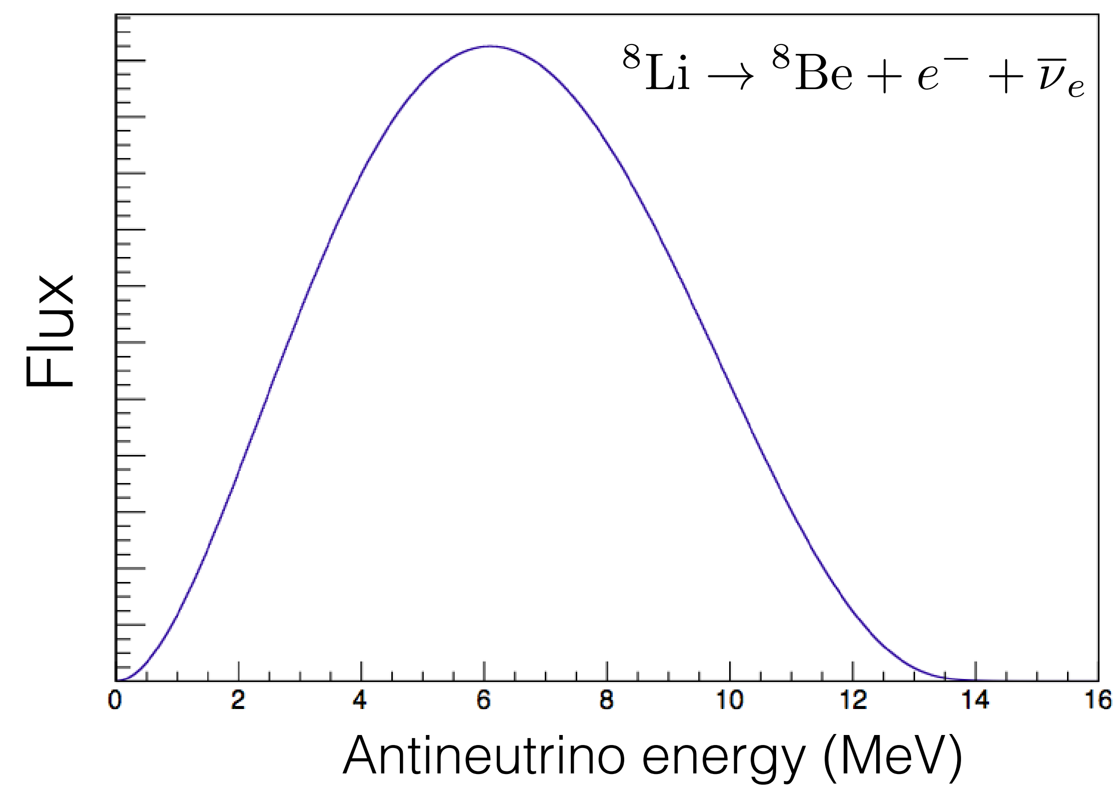


The IsoDAR flux is dominated by a single high-Q isotope (^{8}Li)



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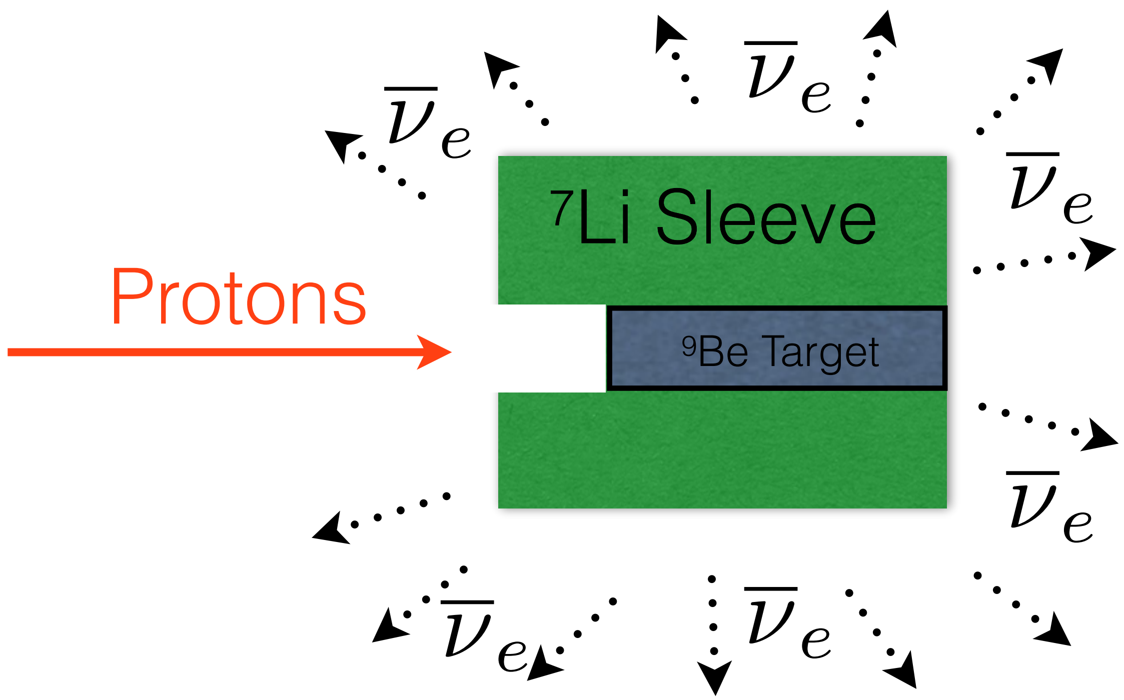
$t_{1/2}$=0.84 s

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

Original IsoDAR idea

Searching for the disappearance wave



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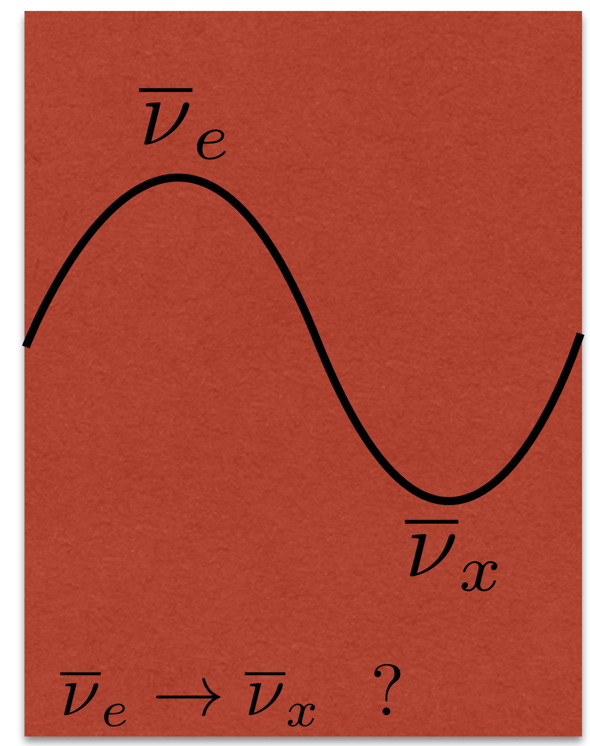
$t_{1/2}$=0.84 s

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

Big detector with free protons
(e.g. $H_2 0$, CH_2)



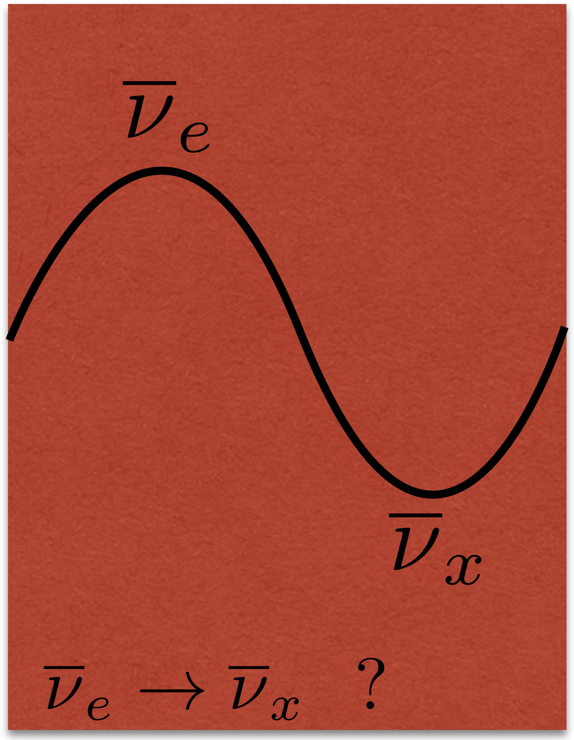
$$\overline{\nu}_e p \rightarrow e^+ n$$

Original IsoDAR idea

Searching for the disappearance wave

$$\overline{\nu}_e \rightarrow \overline{\nu}_x \quad ?$$

Big detector with free protons
(e.g. H_20, CH_2)



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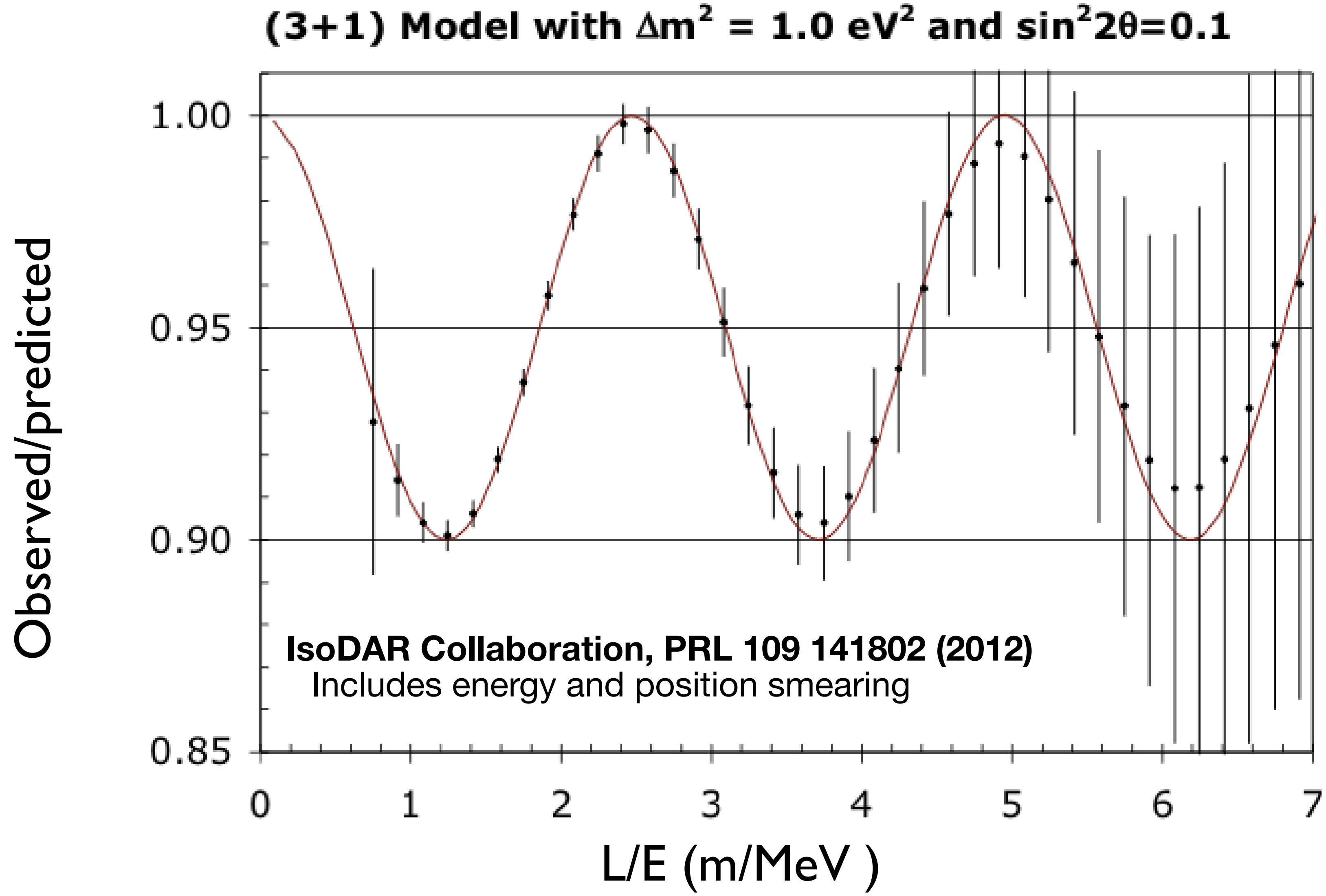
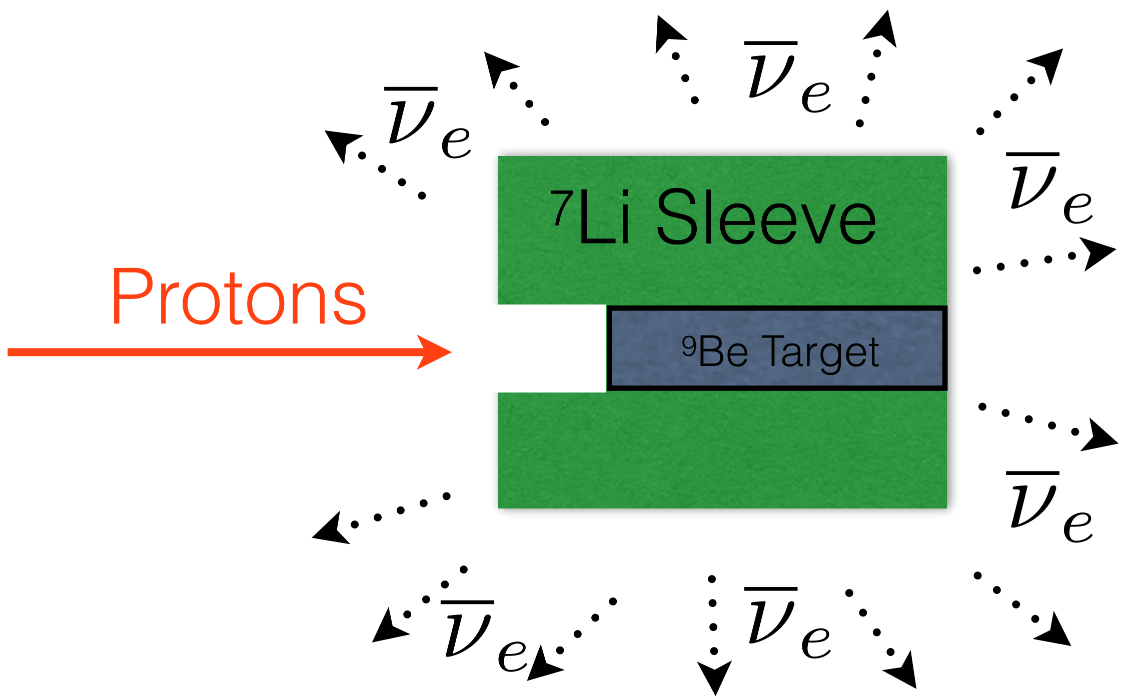


820,000 IBD events in 5 years at KamLAND
(897 tons, 16 m to center of detector)
[Flux uncertainty is negligible. IBD xsec uncertainty is <1%]

Original IsoDAR idea

Searching for new physics with $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$



$$p + {}^9\text{Be} \rightarrow {}^8\text{Li} + 2p$$

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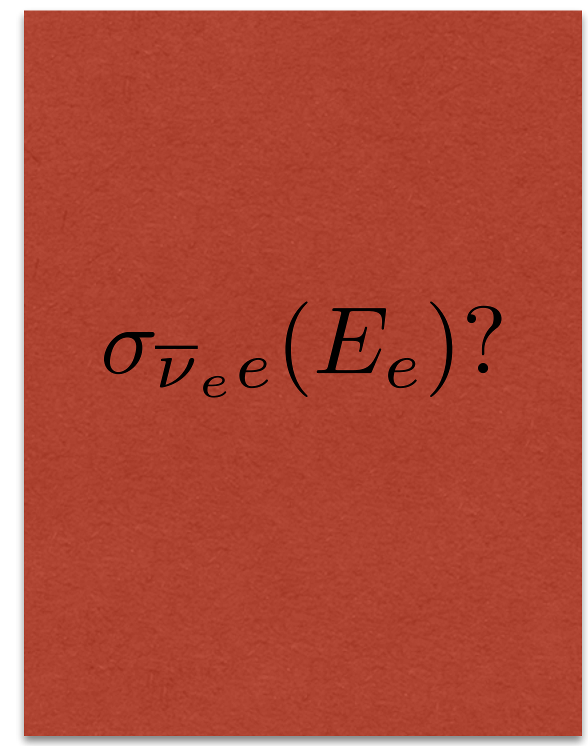
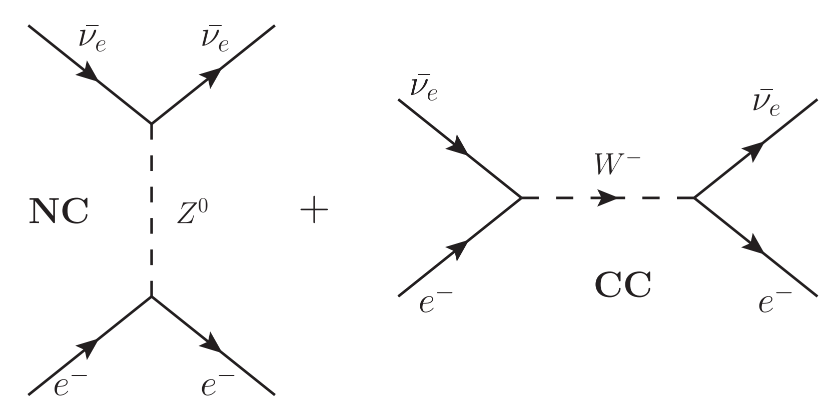
$$ {}^8\text{Li} \rightarrow {}^8\text{Be} + e^- + \overline{\nu}_e$$

Big detector with free protons
(e.g. $H_2$0, CH_2)



$$\overline{\nu}_e e \rightarrow \overline{\nu}_e e$$



Original IsoDAR idea

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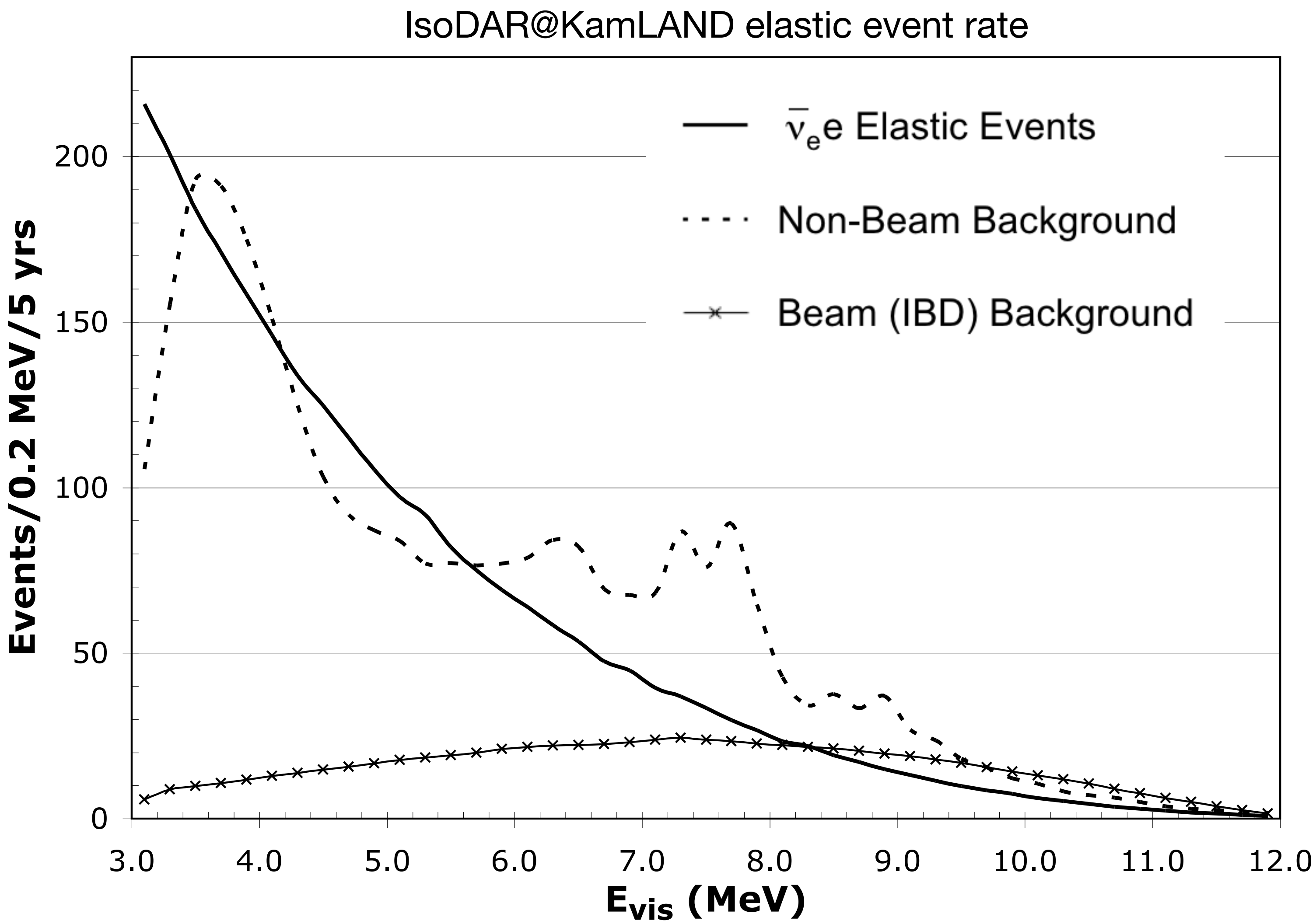


$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}[g_R^2 + g_L^2(1-\frac{T}{E_\nu})^2 - g_R g_L \frac{m_e T}{E_\nu^2}]$$

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

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

A precision measurement of the weak mixing angle is sensitive to new physics contributions

2,600 elastic signal events in 5 years at KamLAND
(897 tons, 16 m to center of detector)

J.M. Conrad, M.H. Shaevitz, I. Shimizu, J. Spitz, M. Toups, L. Winslow, PRD 89 072010 (2014)

IsoDAR@Yemilab

How well could IsoDAR@Yemilab perform?

Accelerator	60 MeV/amu of H_2^+
Beam Current	10 mA of protons on target
Beam Power (CW)	600 kW
Duty cycle	80%
Protons/(year of live time w/ 100% duty)	1.97×10^{24}
Run period	5 years
Live time	5 years×0.80=4.0 years
Target	^{9}Be with 99.99% pure ^{7}Li sleeve
Neutrino creation point spread (1σ)	41 cm
$\overline{\nu}$ source	^{8}Li β decay (6.4 MeV mean energy flux)
$\overline{\nu}$ flux during 4.0 years of live time	1.147×10^{23} $\overline{\nu}_e$
$\overline{\nu}$ flux uncertainty	5% (shape-only is also considered)
Location	Yemilab
Fiducial mass	2.57 ktons
Distance between source and target (min-max)	9.5-25.9 m
Fiducial radius	7.5 m
IBD Detection efficiency	100%
Vertex resolution	12 cm/$\sqrt{E\text{ (MeV)}}$
Energy resolution	3.0%/$\sqrt{E\text{ (MeV)}}$
Angular resolution	under study
Visible energy threshold (IBD and $\overline{\nu}_e$-electron)	3 MeV
IBD event total (w/ 100% efficiency)	2.02×10^6
$\overline{\nu}_e$-electron event total (after cuts, 34% efficiency)	7060

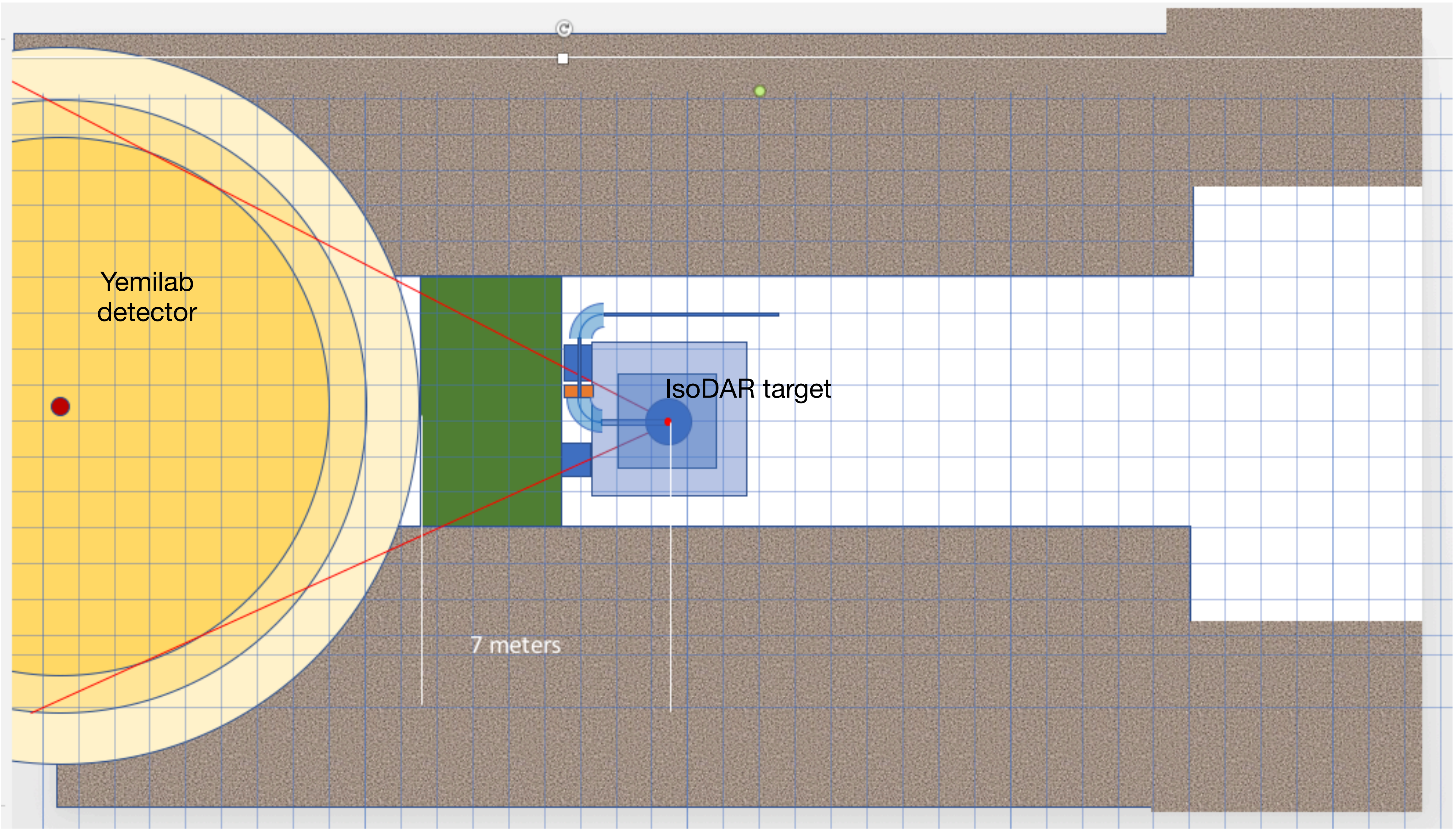
"Detector at Yemilab" assumptions are basically consistent with "KamLAND—897 tons, but bigger (and with the *possibility* of directional reconstruction)"

Any/all assumptions are easy to change. Feedback is very welcome!

IsoDAR@Yemilab

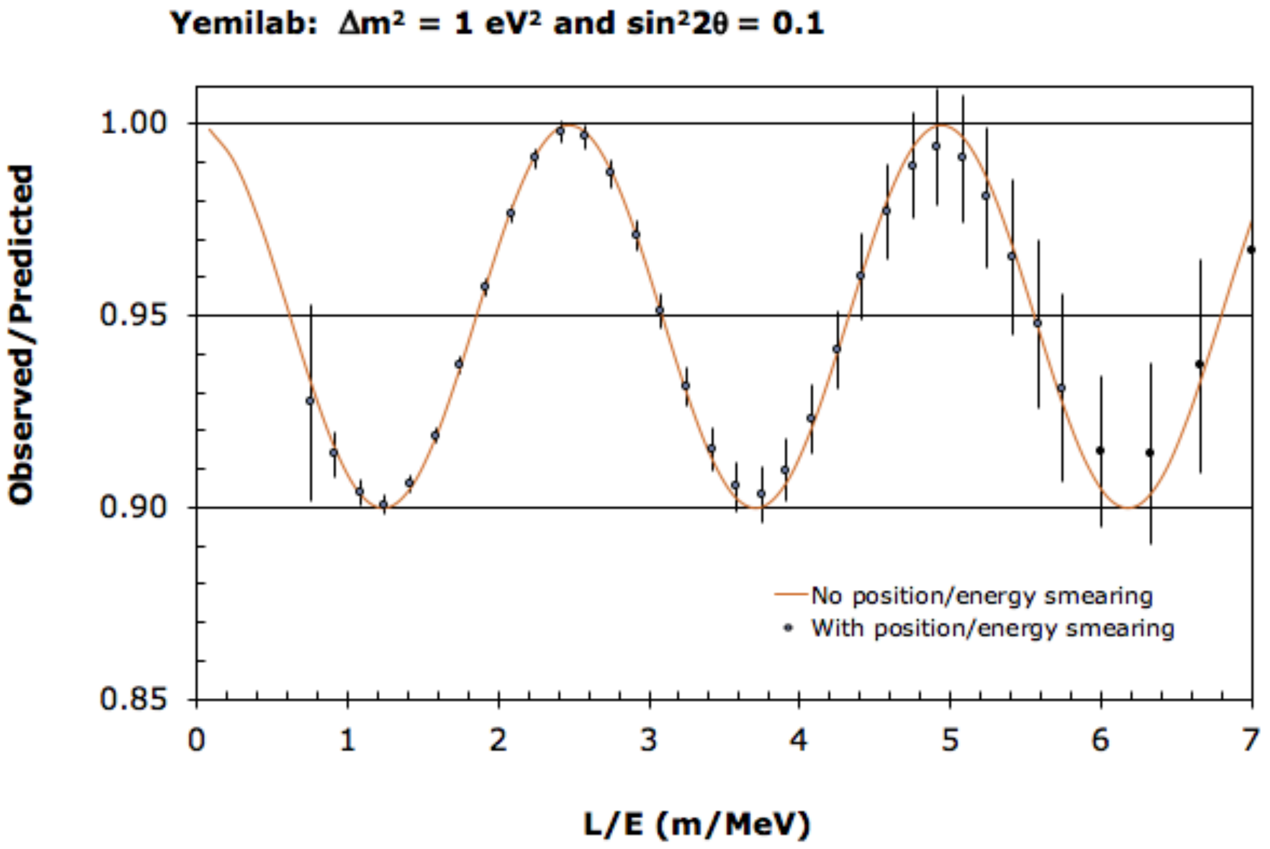
IsoDAR@Yemilab (2.02e6 events / 5yrs)
Detector: Radius = 7.5m Height = 17m Mass = 2569 tons
Buffer = 1m Veto = 1.5m Green_Shield = 4m
BeamPipe = 1.5m IsoDAR_shield = 2m
Distance IsoDAR_center to Detector_center = 17m

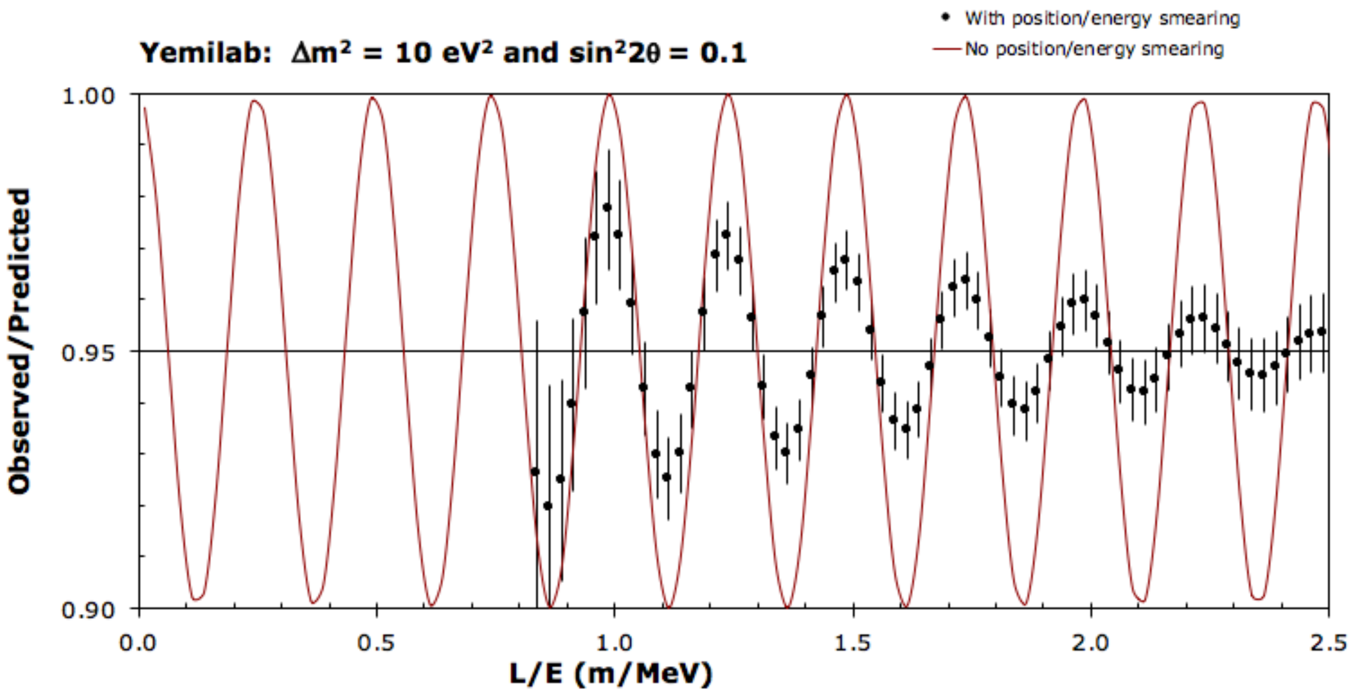
IsoDAR@KamLAND (0.82e6 events/5yrs)
Detector: Radius = 6.5m Mass = 897 tons
Distance IsoDAR center to Detector = 16m



IsoDAR@Yemilab IBD event rate

Searching for the disappearance wave



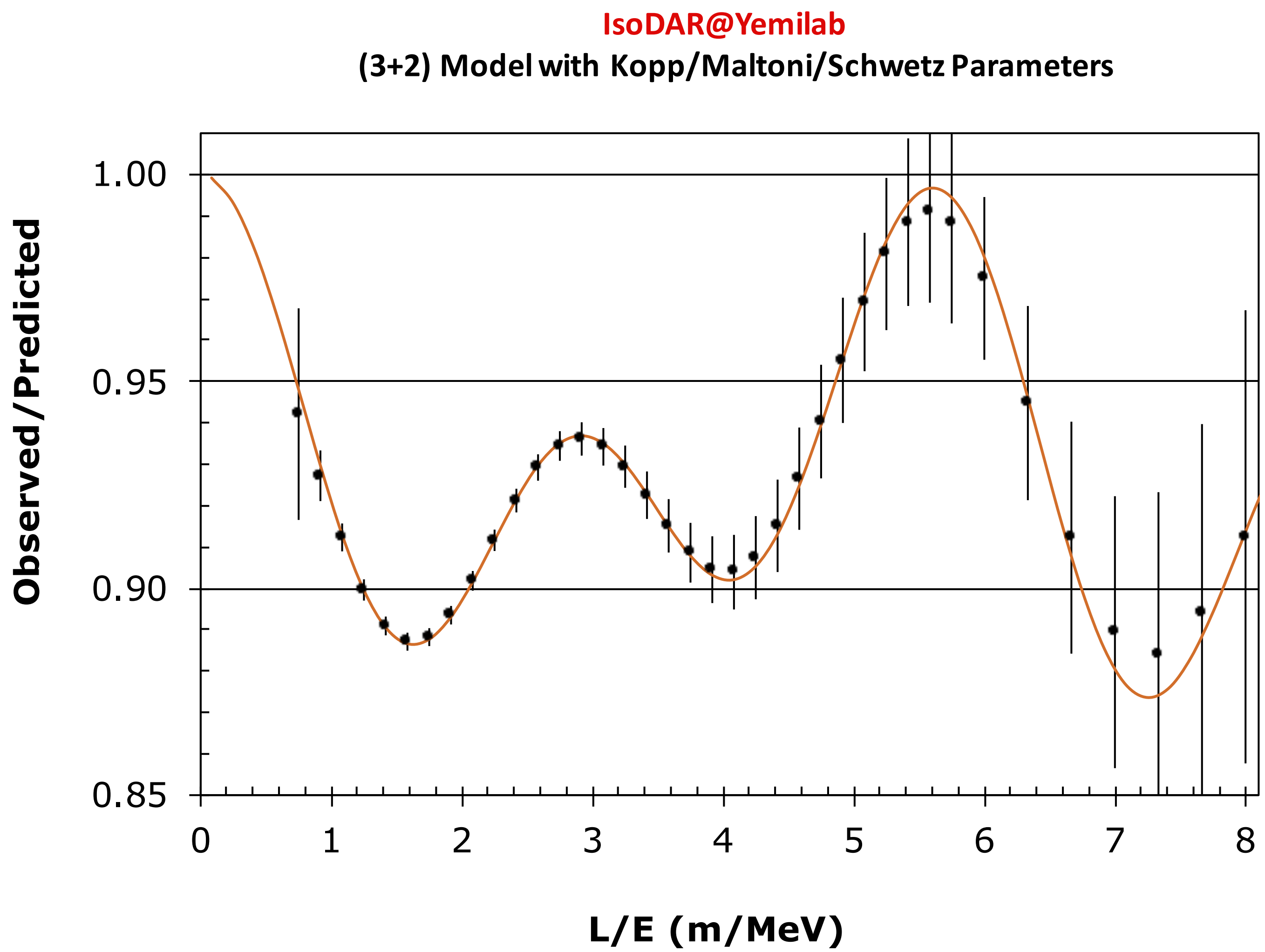


Includes energy and position smearing

2.0 million IBD events in 5 years at Yemilab
[Flux uncertainty is negligible. IBD xsec uncertainty is <1%]

IsoDAR@Yemilab IBD event rate

Searching for the disappearance wave



Includes energy and position smearing

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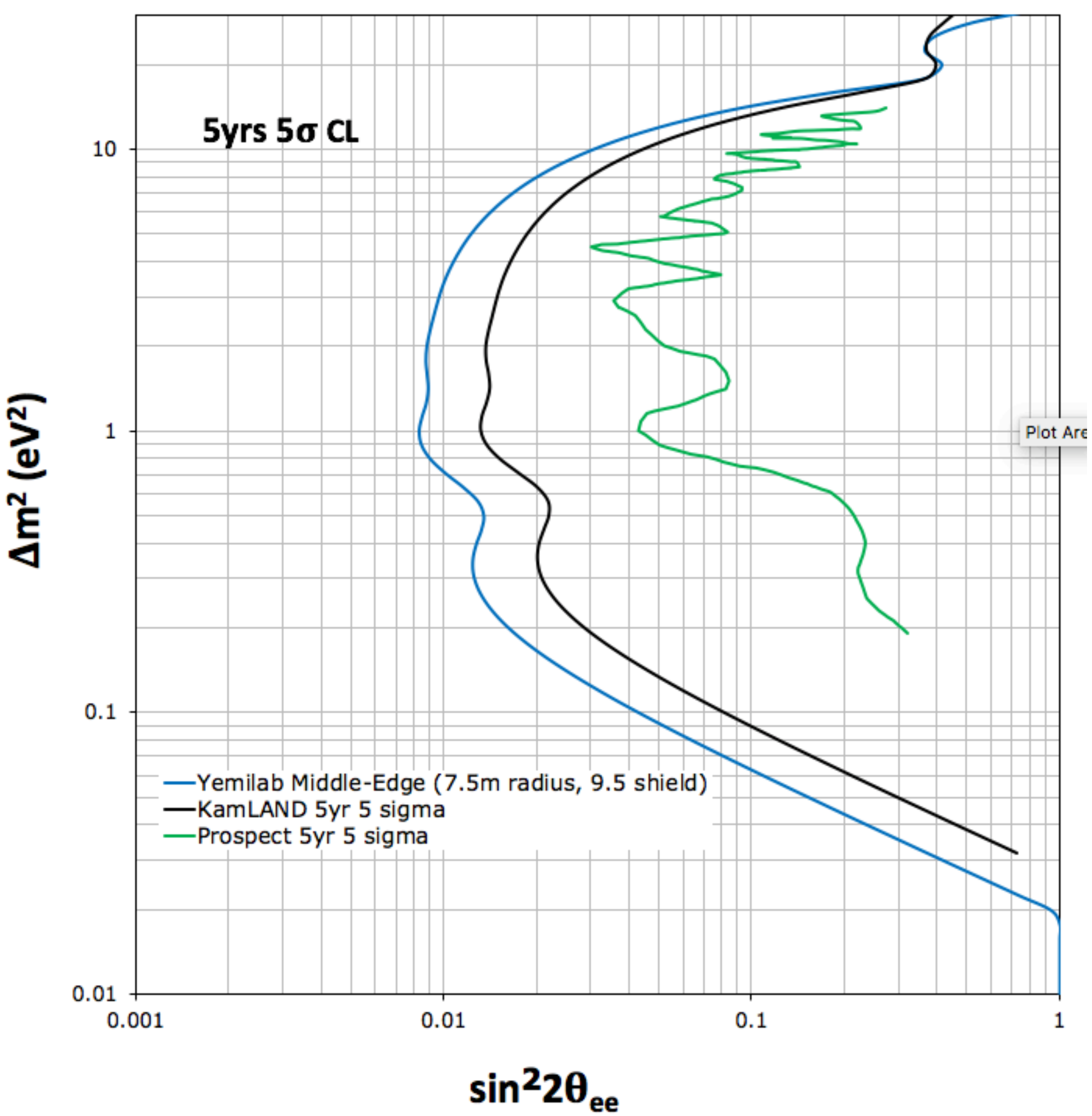
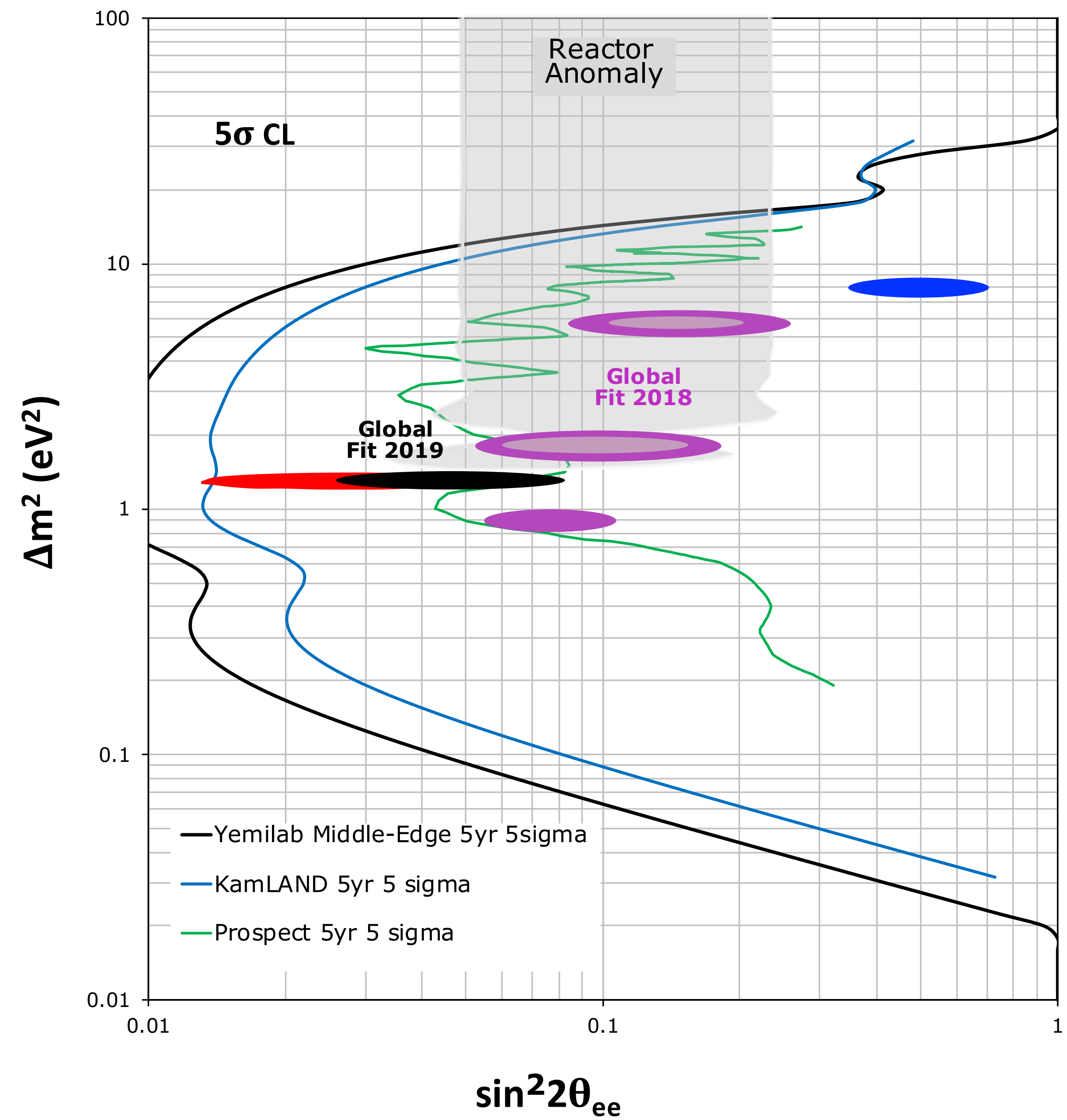
IsoDAR@Yemilab sensitivity

Searching for the disappearance wave





Sensitivity considered in a 3+1 oscillation model:

$$P_{ee} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

Global Fit 2019: A. Diaz, C.A. Arguelles, G.H. Collin, J.M. Conrad and M.H. Shaevitz, Phys. Rep. 84 1 2020.

IsoDAR@Yemilab elastic scattering

Searching for new physics with $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$

- What is the current landscape for $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$?

From TEXONO paper:

arXiv:0911.1597v2 [hep-ex] 7 Apr 2010

TABLE I: Summary of published ν_e- and $\bar{\nu}_e - e$ scattering cross-section and $\sin^2\theta_W$ measurements. Unavailable entries are denoted by "N/A".

Experiment	E_ν (MeV)	T (MeV)	Events [14]	Published Cross-Section	$\sin^2\theta_W$
Accelerator ν_e :					
LAMPF [5]	$7 < E_\nu < 50$	7−50	236	$[10.0 \pm 1.5 \pm 0.9] \cdot E_\nu \times 10^{-45}$ cm^2	0.249 ± 0.063
LSND [6]	$20 < E_\nu < 50$	20−50	191	$[10.1 \pm 1.1 \pm 1.0] \cdot E_\nu \times 10^{-45}$ cm^2	0.248 ± 0.051
Reactor $\bar{\nu}_e$:					
Savannah River					
Original [7] {	$1.5 < E_\nu < 8.0$	1.5−3.0	381	$[0.87 \pm 0.25] \cdot \sigma_{V-A}$	} 0.29±0.05
	$3.0 < E_\nu < 8.0$	3.0−4.5	77	$[1.70 \pm 0.44] \cdot \sigma_{V-A}$	
Re-analysis [13] {	$1.5 < E_\nu < 8.0$	1.5−3.0	N/A	$[1.35 \pm 0.4] \cdot \sigma_{SM}$	} N/A
	$3.0 < E_\nu < 8.0$	3.0−4.5	N/A	$[2.0 \pm 0.5] \cdot \sigma_{SM}$	
Krasnoyarsk [8]	$3.2 < E_\nu < 8.0$	3.2−5.2	N/A	$[4.5 \pm 2.4] \times 10^{-46}$ cm^2/fission	$0.22^{+0.7}_{-0.8}$
Rovno [9]	$0.6 < E_\nu < 8.0$	0.6−2.0	41	$[1.26 \pm 0.62] \times 10^{-44}$ cm^2/fission	N/A
MUNU [10]	$0.7 < E_\nu < 8.0$	0.7−2.0	68	$[1.07 \pm 0.34]$ events/day	N/A
TEXONO (This Work)	$3.0 < E_\nu < 8.0$	3.0−8.0	414±80±61	$[1.08 \pm 0.21 \pm 0.16] \cdot \sigma_{SM}$	$0.251 \pm 0.031 \pm 0.024$

↓

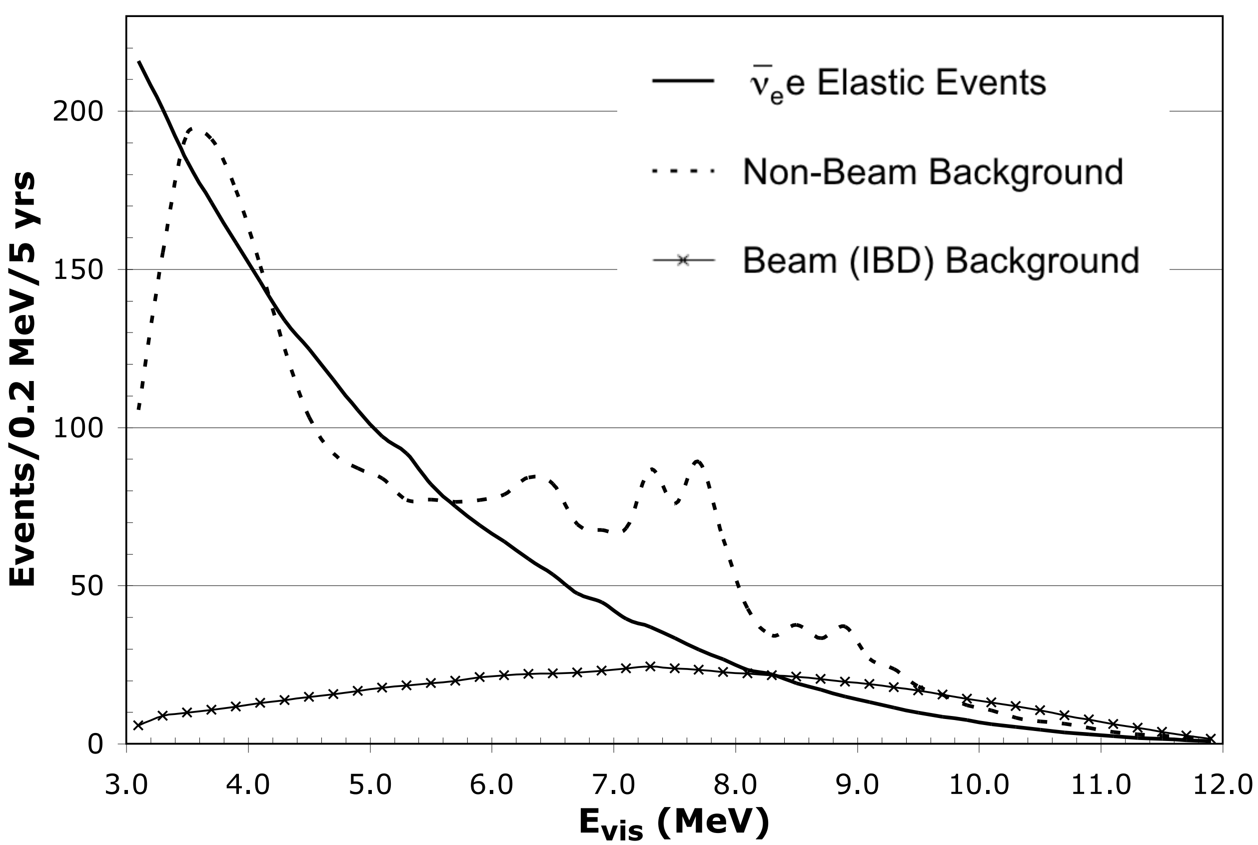
IsoDAR@Yemilab would collect about 7,000 events in 5 years (with extremely well-known flux and cross section predictions)

IsoDAR@Yemilab elastic scattering

Searching for new physics with $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$

- To study IsoDAR@Yemilab elastic scattering, we scale the signal and background estimates from IsoDAR@KamLAND. About 7,000 events in 5 years are expected with IsoDAR@Yemilab.
- Then, we consider direction reconstruction as a way to mitigate the background.
  - The signal electron is very forward, while the backgrounds are basically isotropic.

IsoDAR@KamLAND elastic event rate



Signal and background:

	Events
Elastic scattering (ES)	2583.5
IBD Mis-ID Bkgnd	705.3
Non-beam Bkgnd	2870.0
Total	6158.8

Non-beam background breakdown:

	Events
^{8}B Solar Neutrino	890.1
^{208}Tl	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

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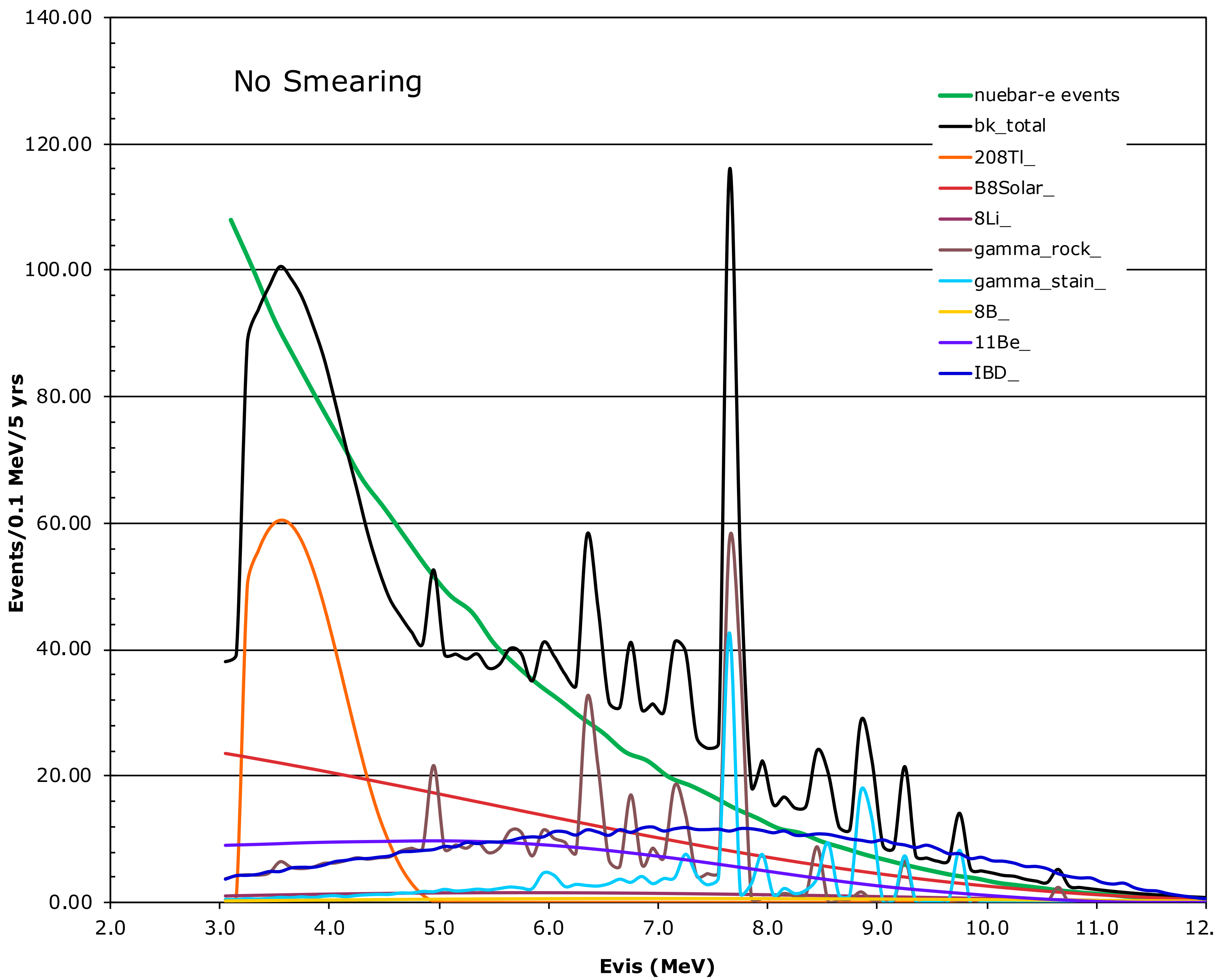

IsoDAR@KamLAND backgrounds

Backgrounds are currently being studied
Current Yemilab-specific questions: Intrinsic radioactivity and cosmogenic rates

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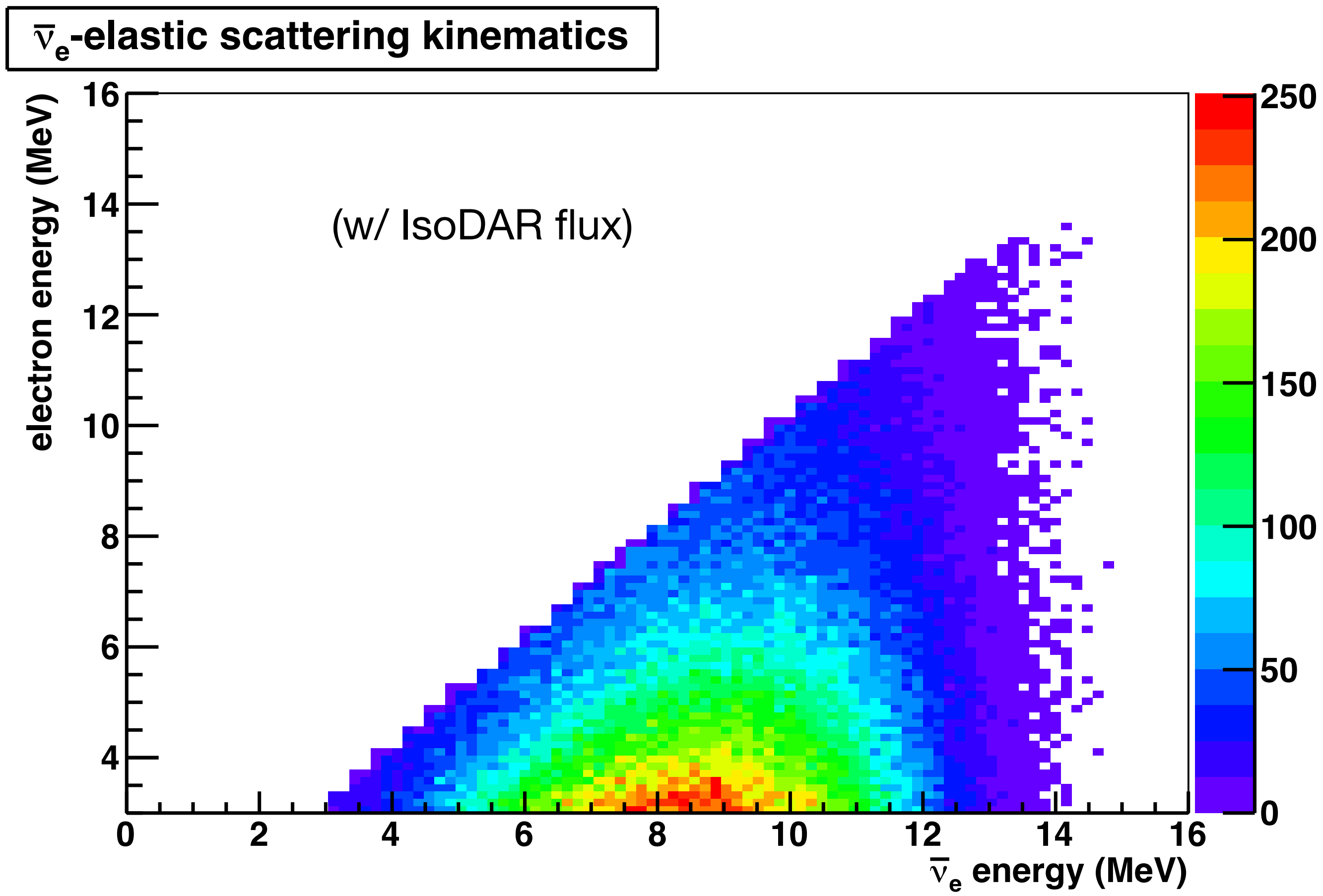

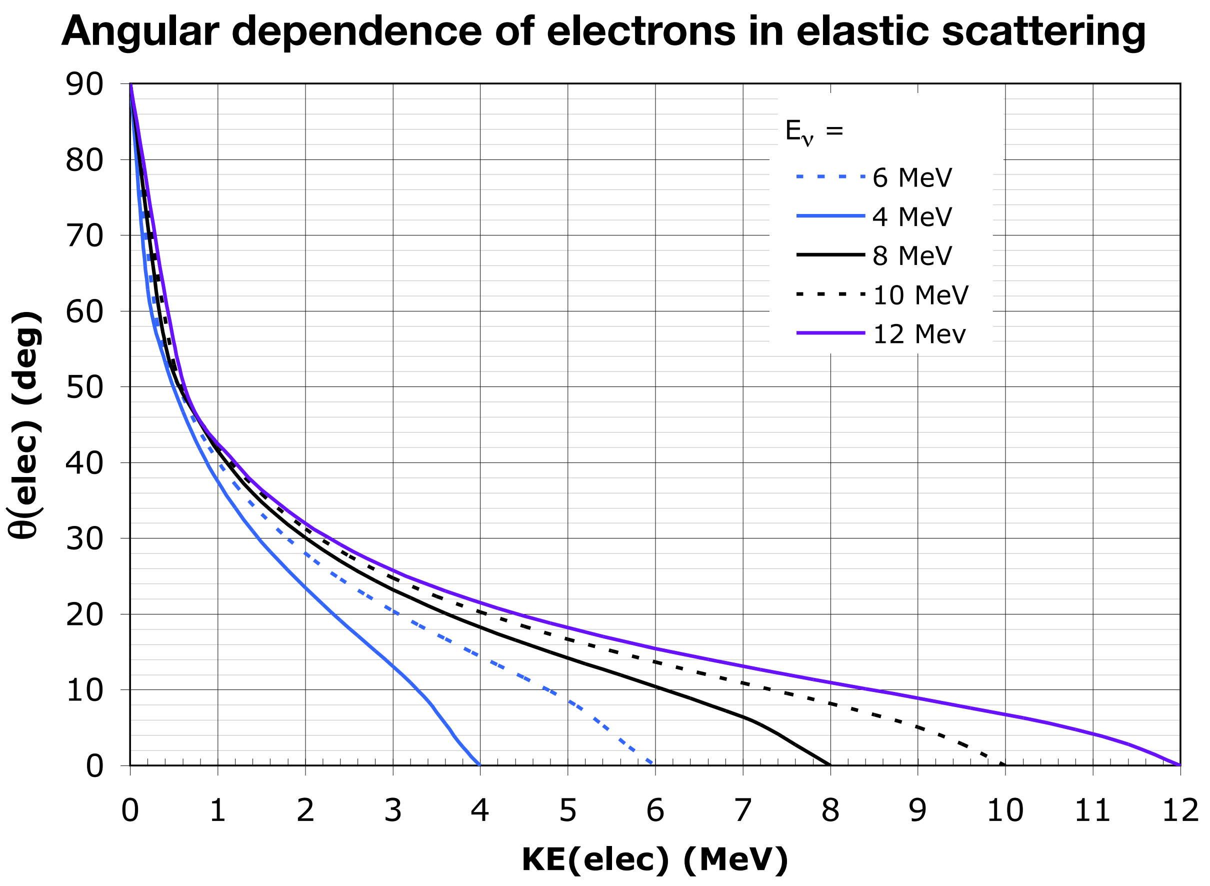

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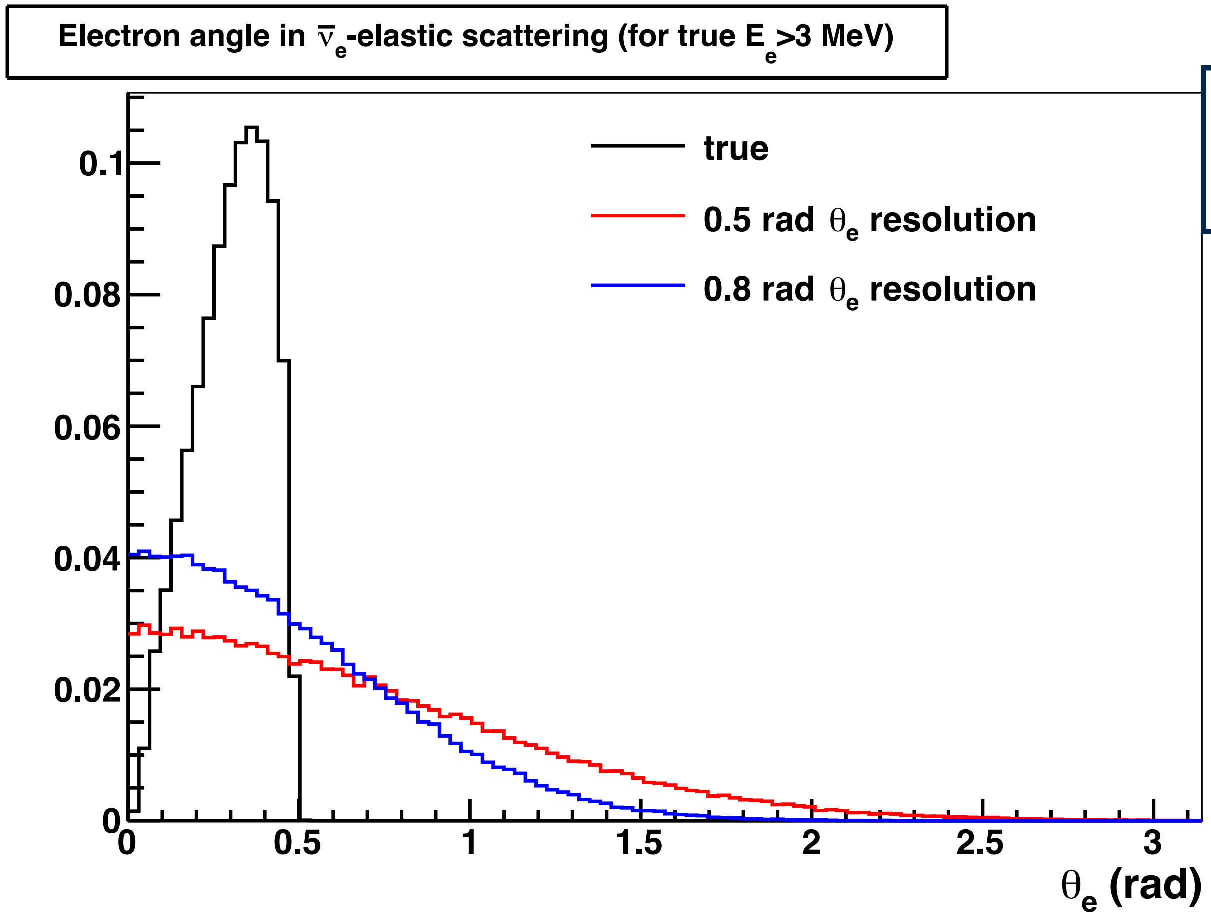


Electron direction reconstruction; true spectrum, and with two different resolutions

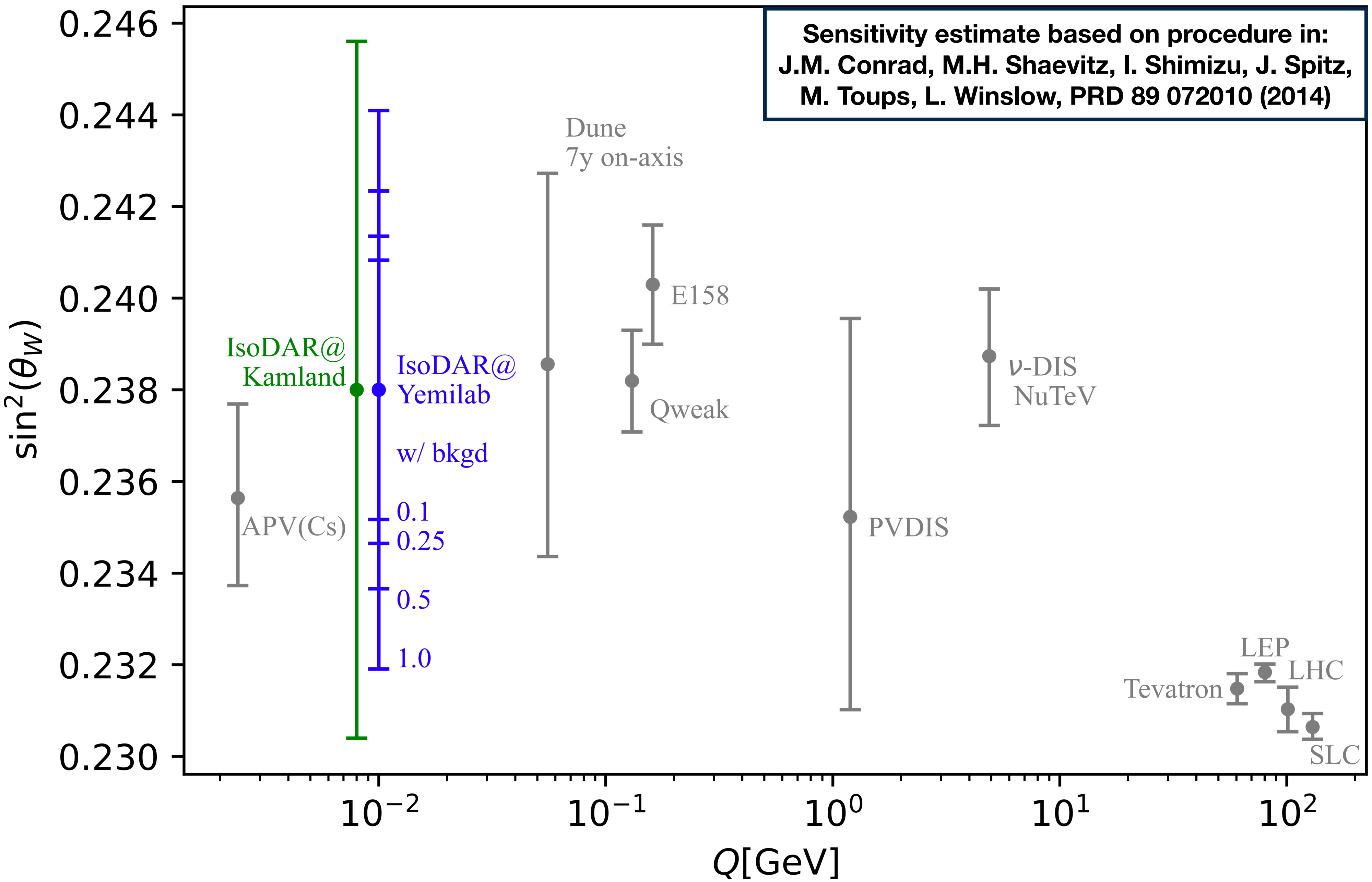
We consider different background scaling factors to reflect the reduction possibilities available with direction reconstruction.

Background scales considered: 1.0, 0.5, 0.25, 0.1

IsoDAR@Yemilab elastic scattering

Searching for new physics with $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$

Sensitivity to the weak mixing angle as a function of background reduction factor compared to KamLAND (1.0=no directional reconstruction and identical, mass-scaled backgrounds)



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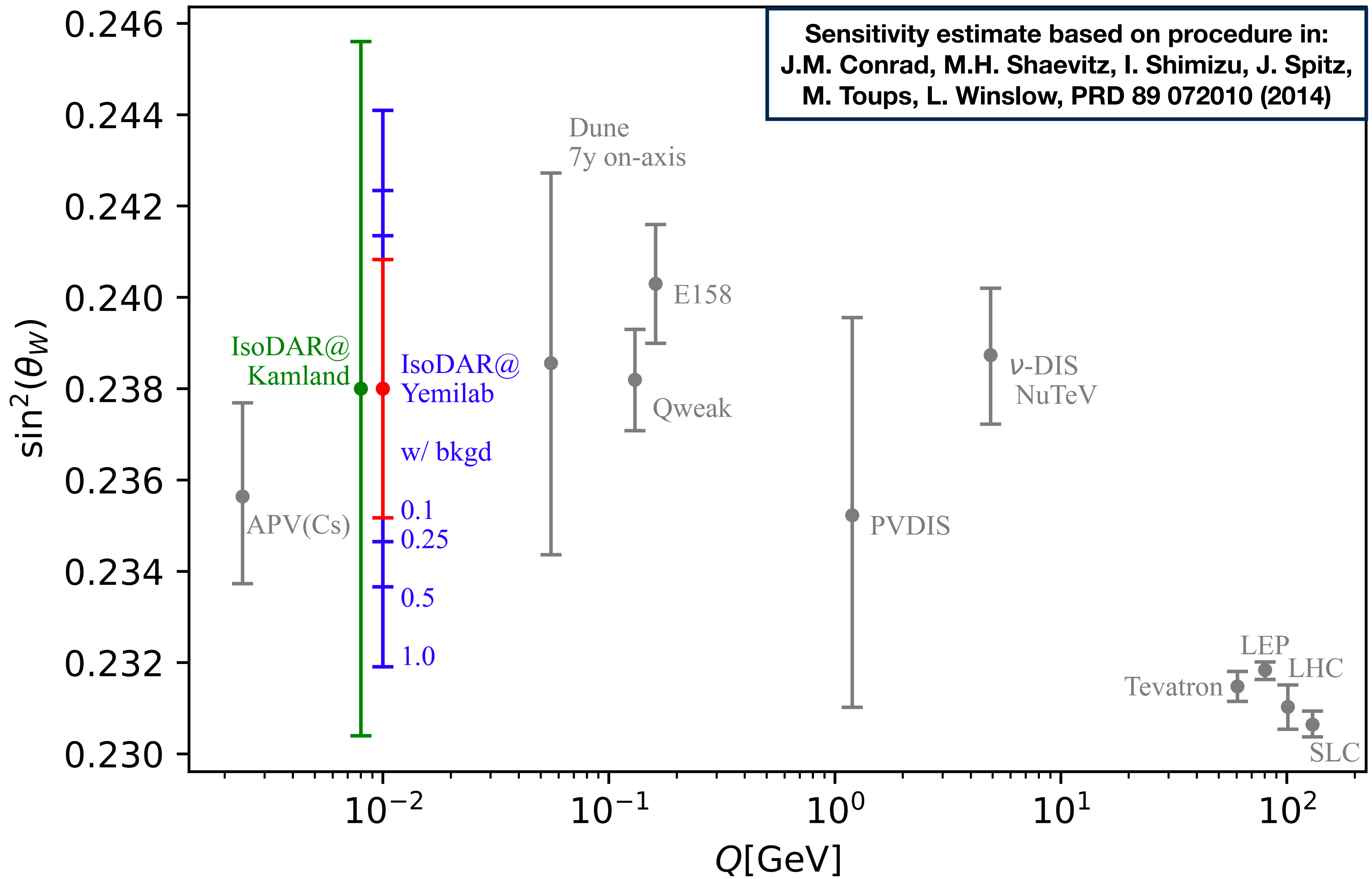
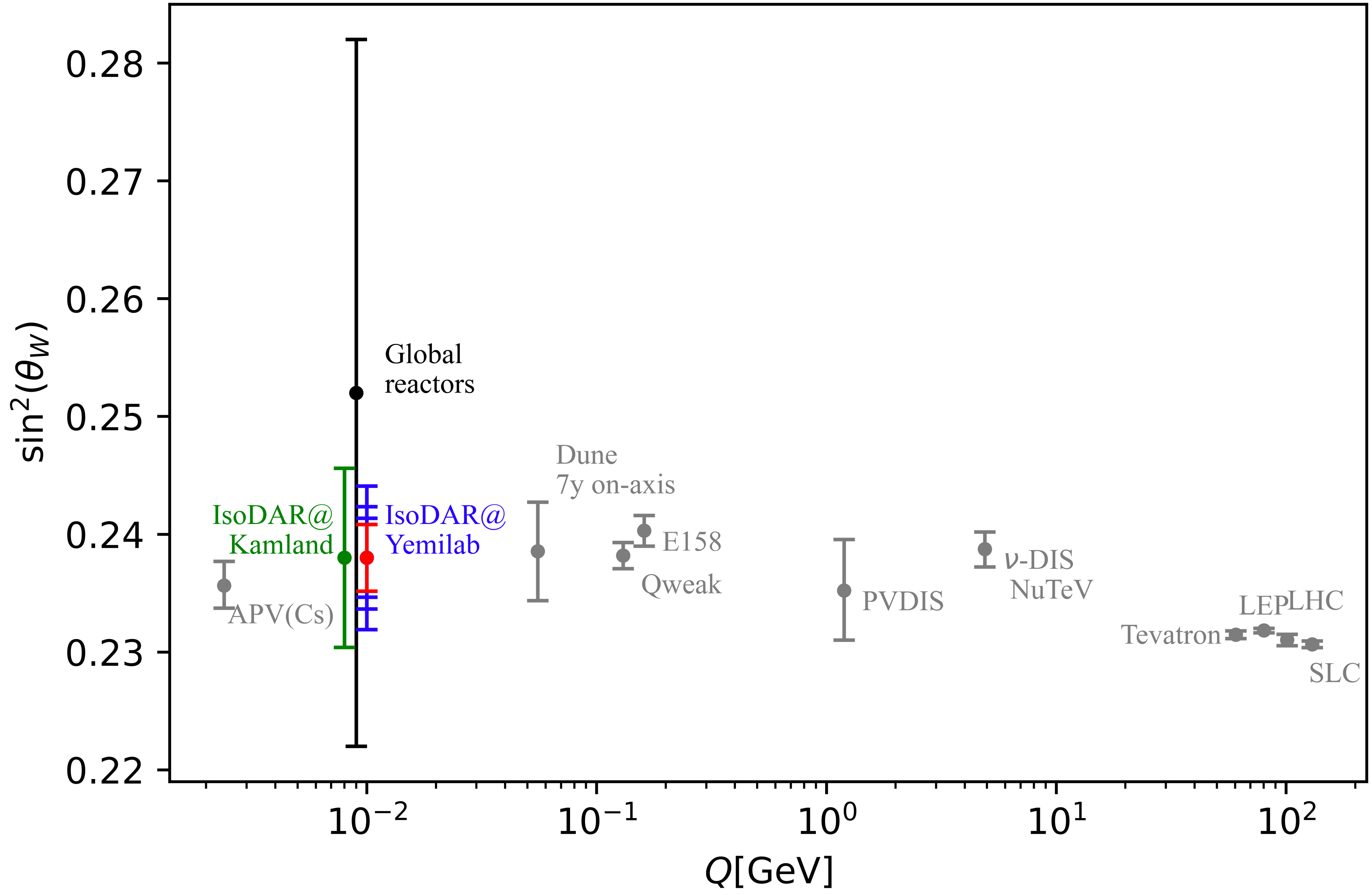


IsoDAR@Yemilab elastic scattering

Searching for new physics with $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$

World-leading reactor measurement, TEXONO: $\sin^2\theta_W = 0.251 \pm 0.039$

Global, all-reactor analysis (PLB 761 450 2016): $\sin^2\theta_W = 0.252 \pm 0.030$



IsoDAR@Yemilab capabilities would be world-leading.

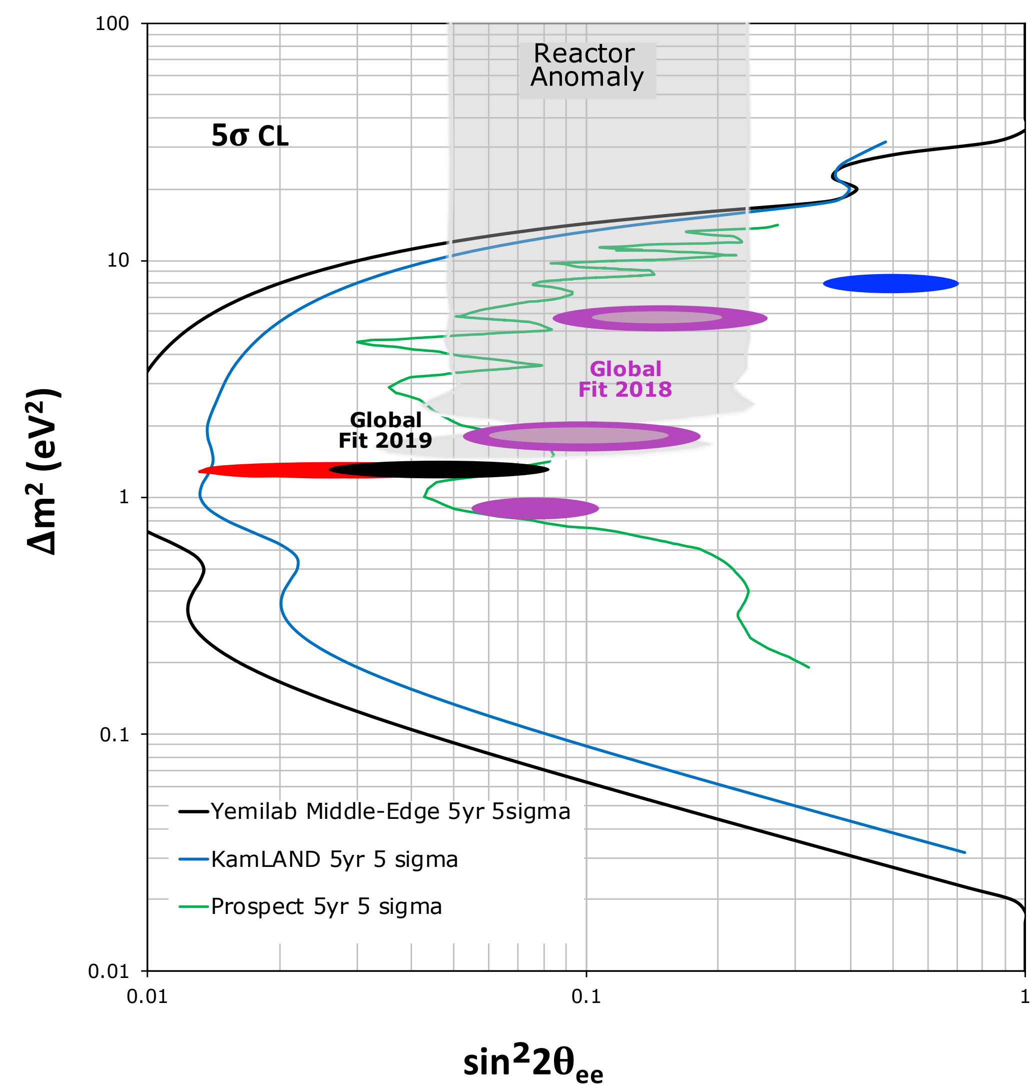
But, do we really need order-of-magnitude improvements?!

Need for order-of-magnitude improvement

Searching for the disappearance wave

We need a truly **definitive** experiment to confirm or disconfirm short-baseline oscillations.
A factor of 2 improvement in sensitivity is not going do it. We need an order-of-magnitude.

Case in point: the LSND anomaly is now 20 years old!



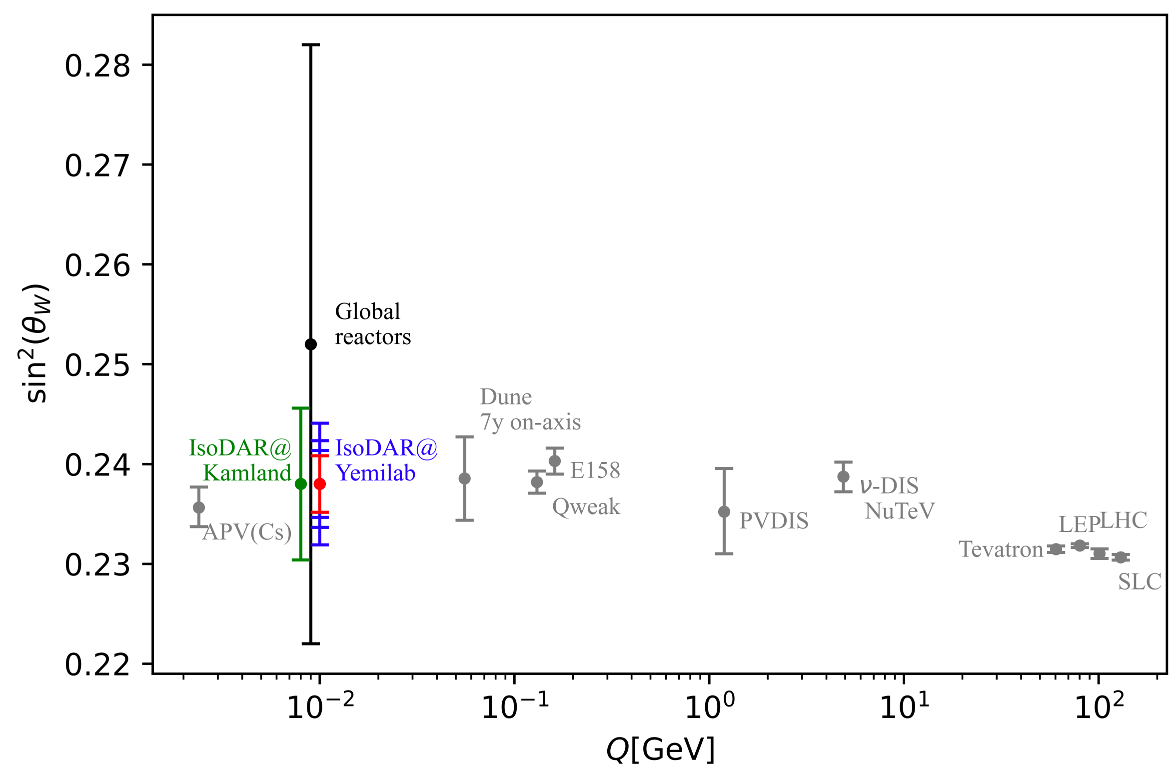
Need for order-of-magnitude improvement

Searching for new physics with $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$

- Purely leptonic test of the SM is highly sensitive to new physics (e.g. new electroweak gauge bosons, heavy partners that couple to light neutrinos, flavor-changing neutral currents, …).

Consistency between neutrino-based electroweak probes and others (APV, ePV, colliders, etc.) is required in the SM.

But, the SM is known to be incomplete… and, neutrino-based electroweak probes are almost non-existent below Q~5 GeV.



Conclusions

Combining the IsoDAR $\overline{\nu}_e$ source (<6.4 MeV>) with a kton-scale detector at Yemilab would provide *world-leading* (by an *order-of-magnitude*) sensitivity to short-baseline oscillations and non-standard interactions.

We are extremely excited to be thinking about IsoDAR at Yemilab and hope to make the experiment a reality.