An application of high power cyclotrons in physics: IsoDAR

Josh Spitz (University of Michigan)

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UNIVERSITY OF MICHIGAN

NSF

What is a neutrino?

The main things to know:

-One of our fundamental particles.

-Neutral in charge.

-Very rarely interacts with matter.

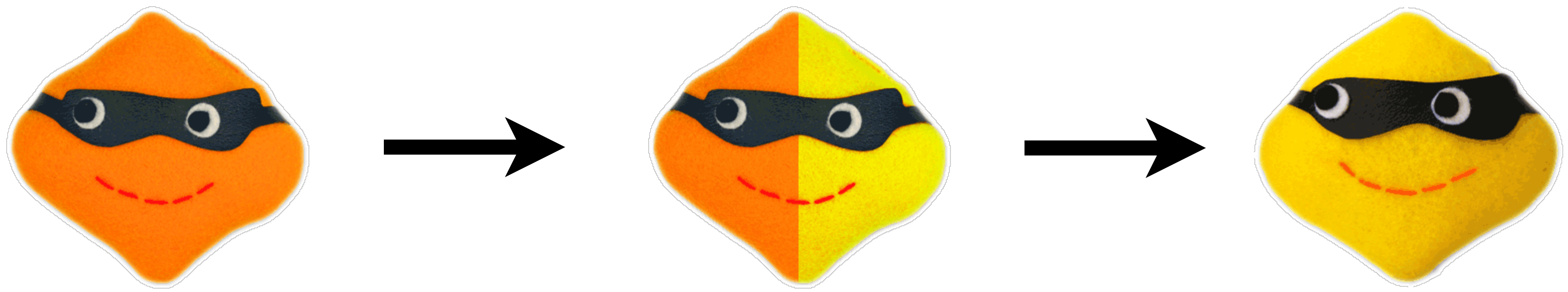
 -65 billion pass through your thumbnail every second.

-Doesn't *directly* affect our daily lives very much.

-But, contributed enormously to the evolution of the Universe.

Neutrino mixing

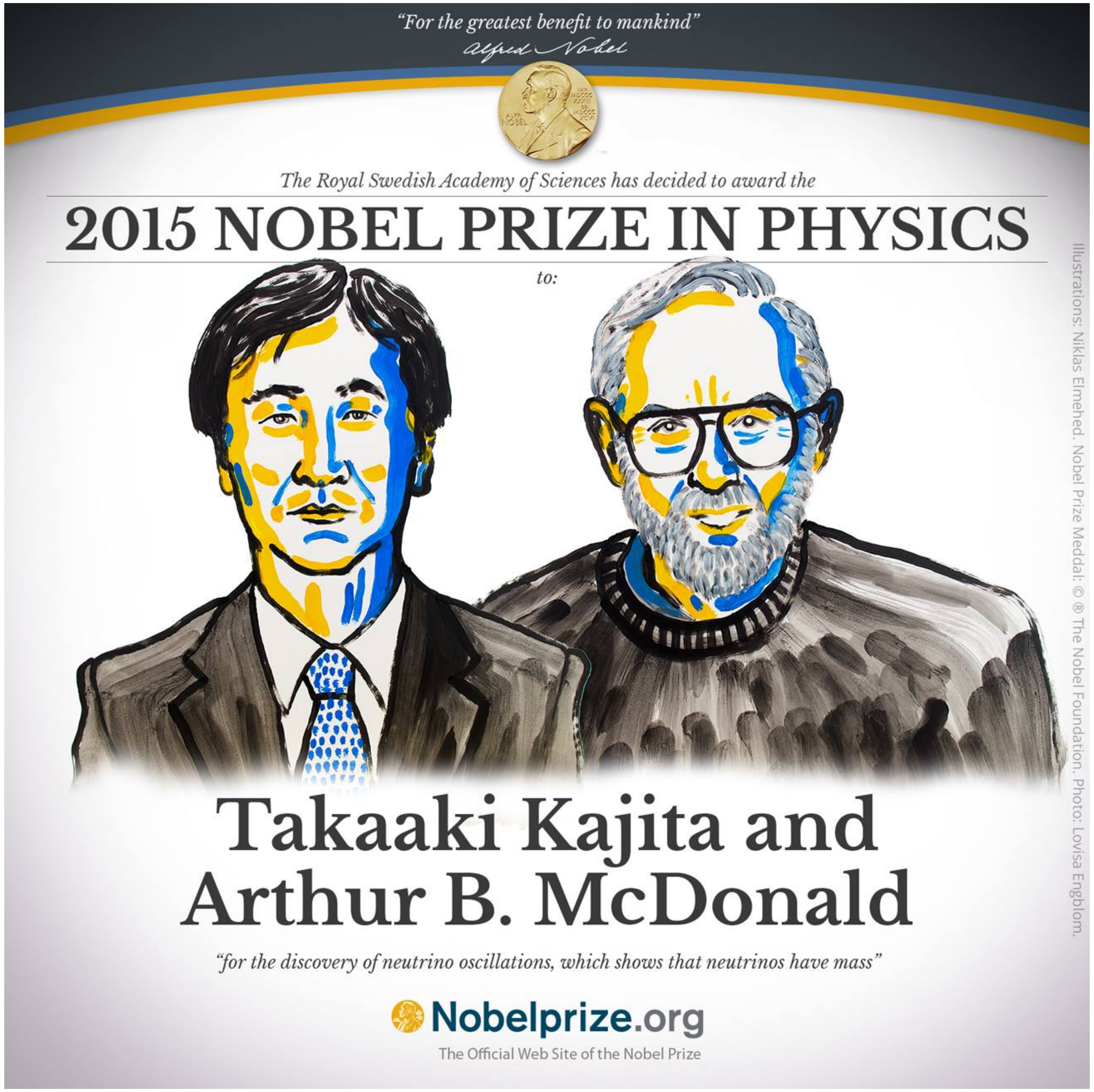
- We know that neutrinos mix.
    - A neutrino created as one flavor can change into another flavor.



Born as a muon neutrino!

Can be detected as an electron neutrino.

This ability to change means that the neutrino has a mass.


"For the greatest benefit to mankind"
Alfred Nobel
The Royal Swedish Academy of Sciences has decided to award the
2015 NOBEL PRIZE IN PHYSICS
to:
Takaaki Kajita and
Arthur B. McDonald
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"
Nobelprize.org
The Official Web Site of the Nobel Prize
Illustrations: Niklas Elmehed. Nobel Prize Medal: © ® The Nobel Foundation. Photo: Lovisa Engblom.

Neutrinos have mass. So what?

- The job of the particle physicist is NOT to tabulate the properties of the fundamental particles for eventual entry into a big, dusty catalog.
- The job of the particle physicist is to measure the properties of the particles and relate them to astrophysics and cosmology.
- Elucidating the nature of neutrino mass, including its value, how the neutrino got its mass, and how the neutrino mixes, can tell us about the evolution of the universe.

→

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

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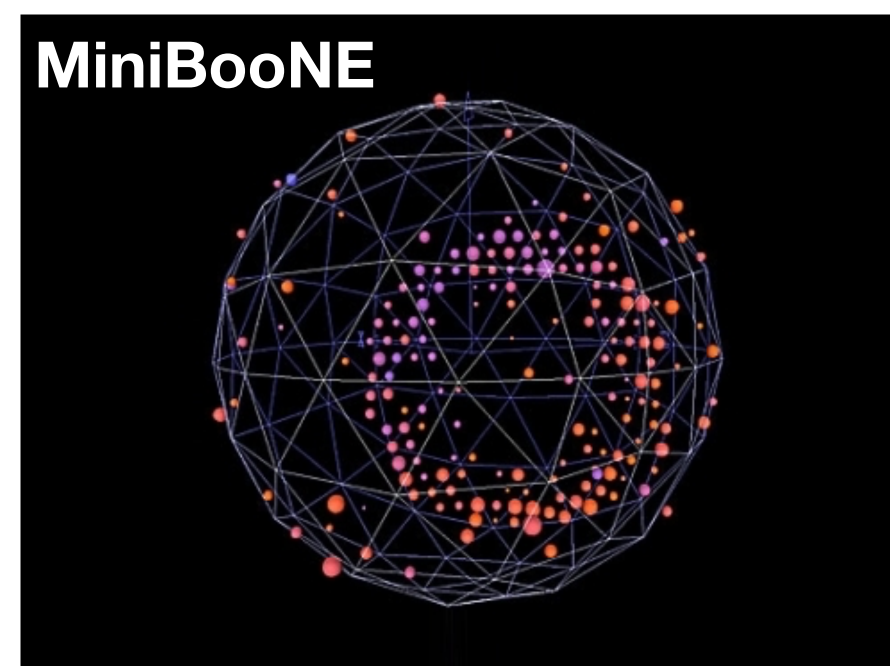
The world is pursuing these anomalies in earnest

NEOS
Neutrino-4
DANSS
CCM
IsoDAR



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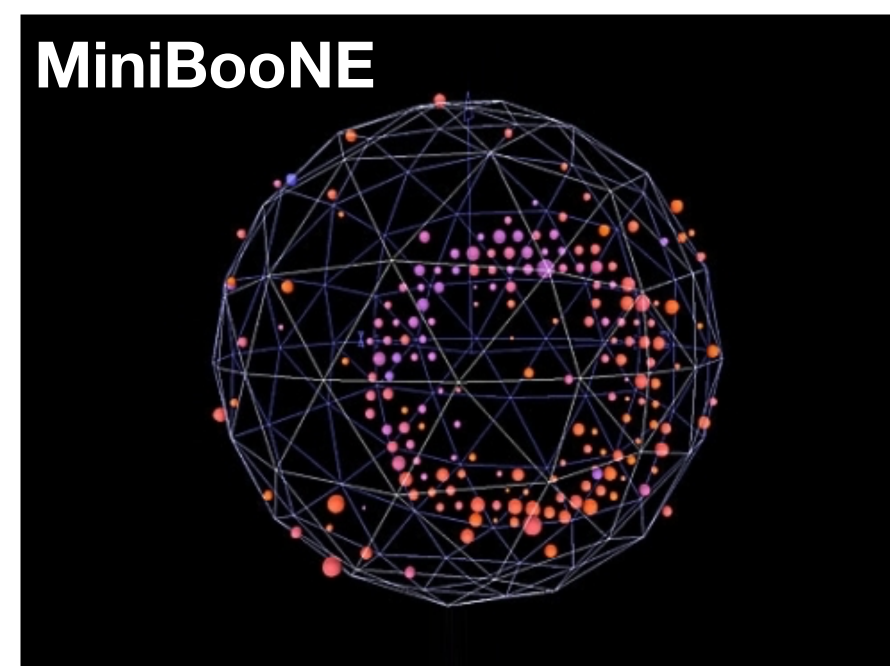

Among these, the IsoDAR concept is at once completely unique and extremely sensitive to new physics

The IsoDAR concept

Produce lots of neutrinos with an extremely well understood energy spectrum

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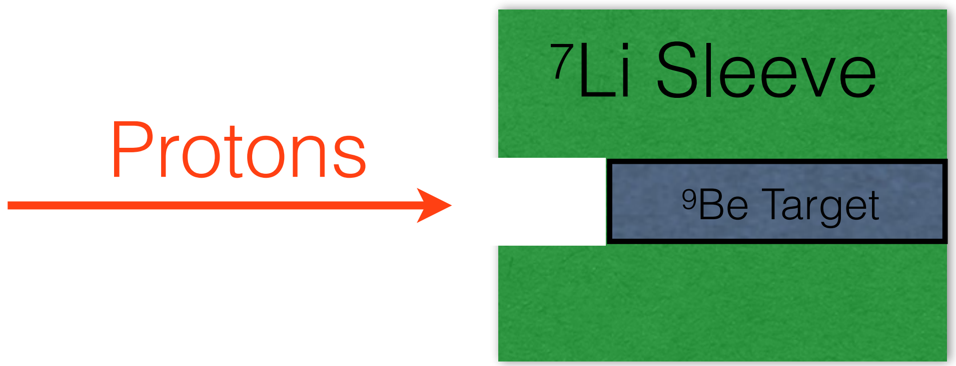
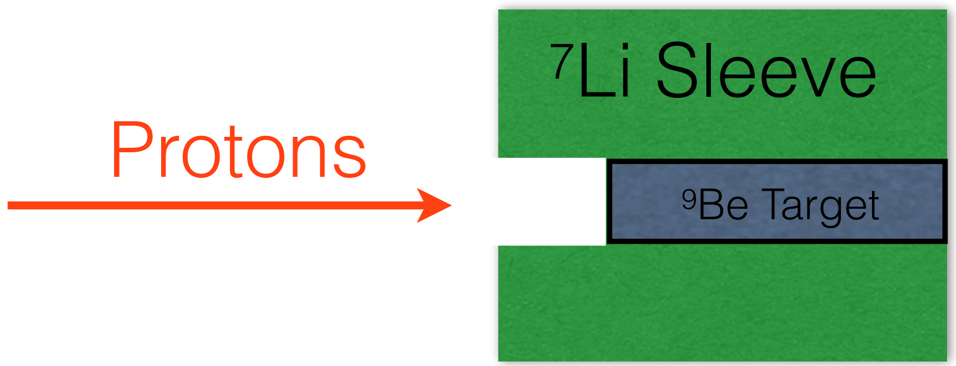


The IsoDAR concept

Produce lots of neutrinos with an extremely well understood energy spectrum

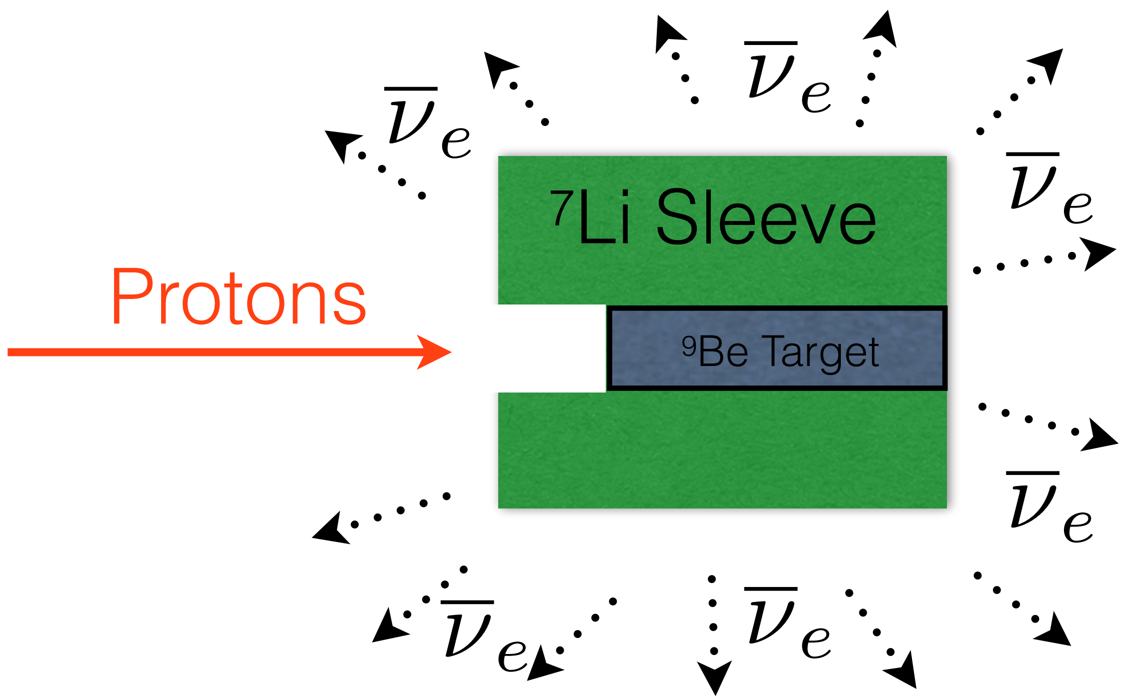


$$p + {}^{9}\mathrm{Be} \rightarrow {}^{8}\mathrm{Li} + 2p$$

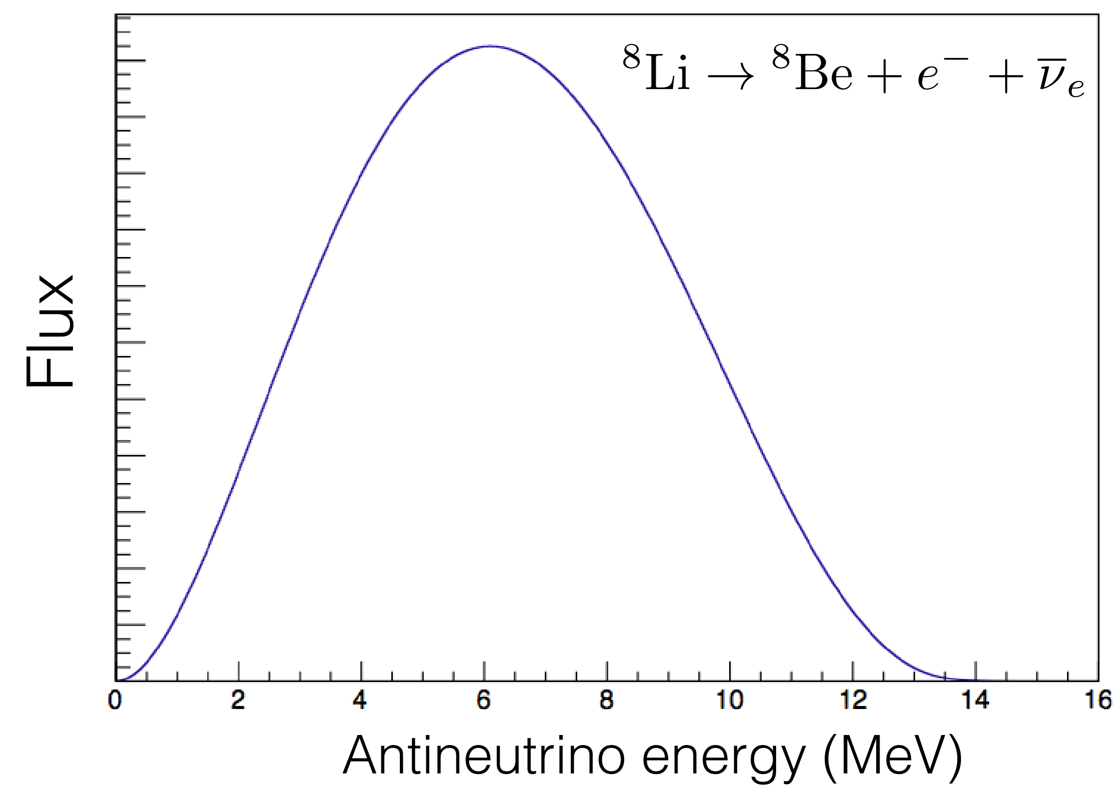
$$p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$$
$$n + {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Li} + \gamma$$

The IsoDAR concept

Produce lots of neutrinos with an extremely well understood energy spectrum



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



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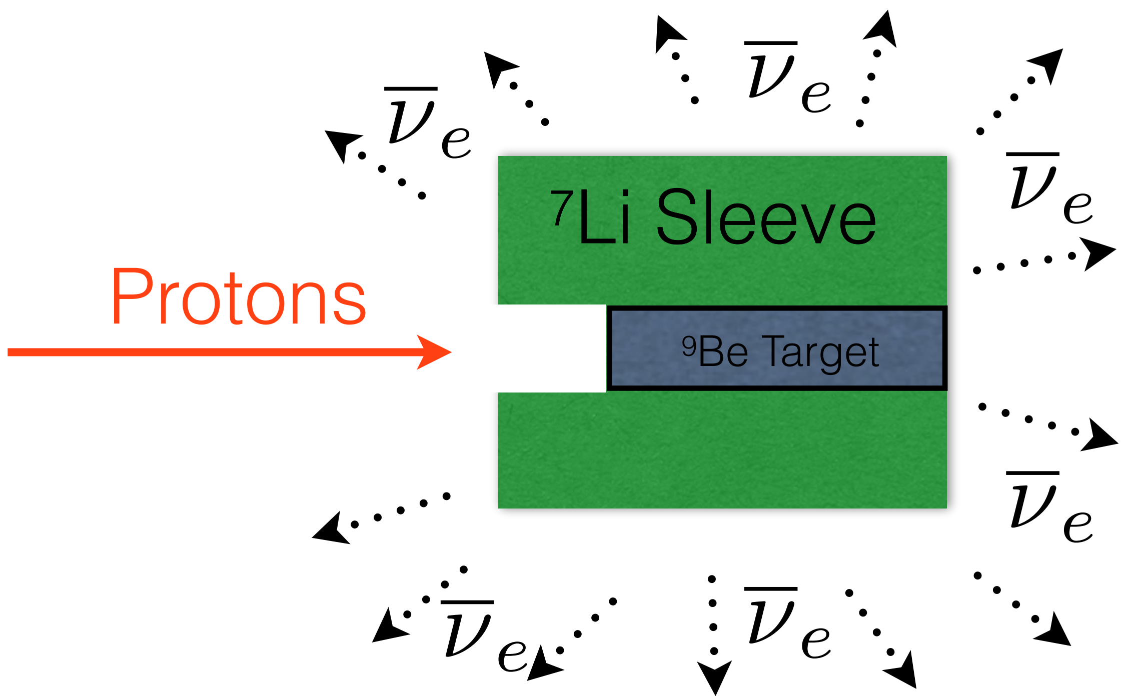
$t_{1/2}$=0.84 s

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

Original IsoDAR idea

Searching for the disappearance wave



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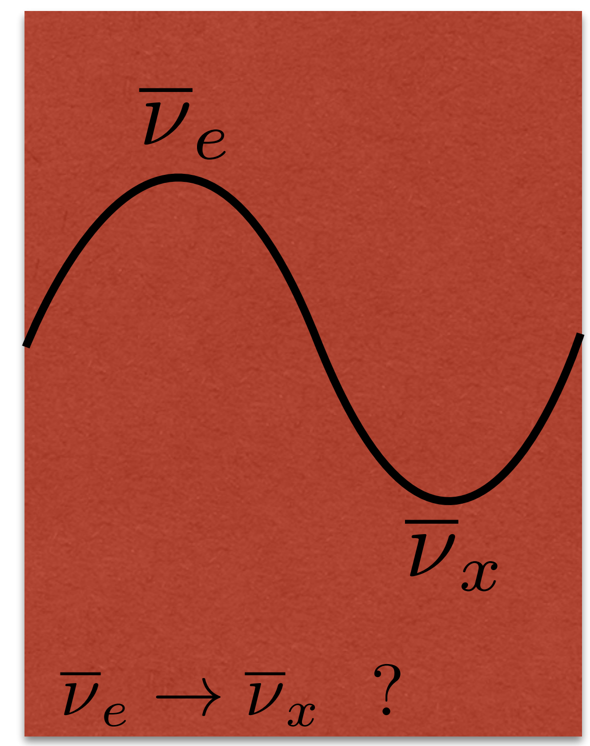
$$^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

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



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

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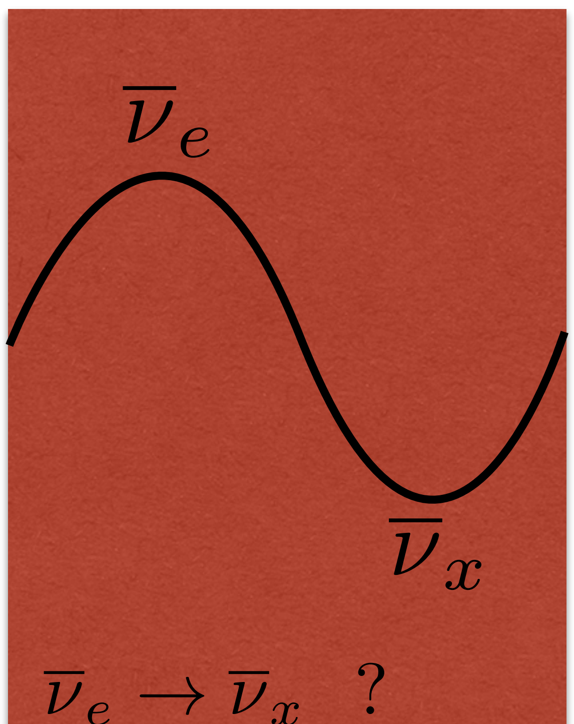
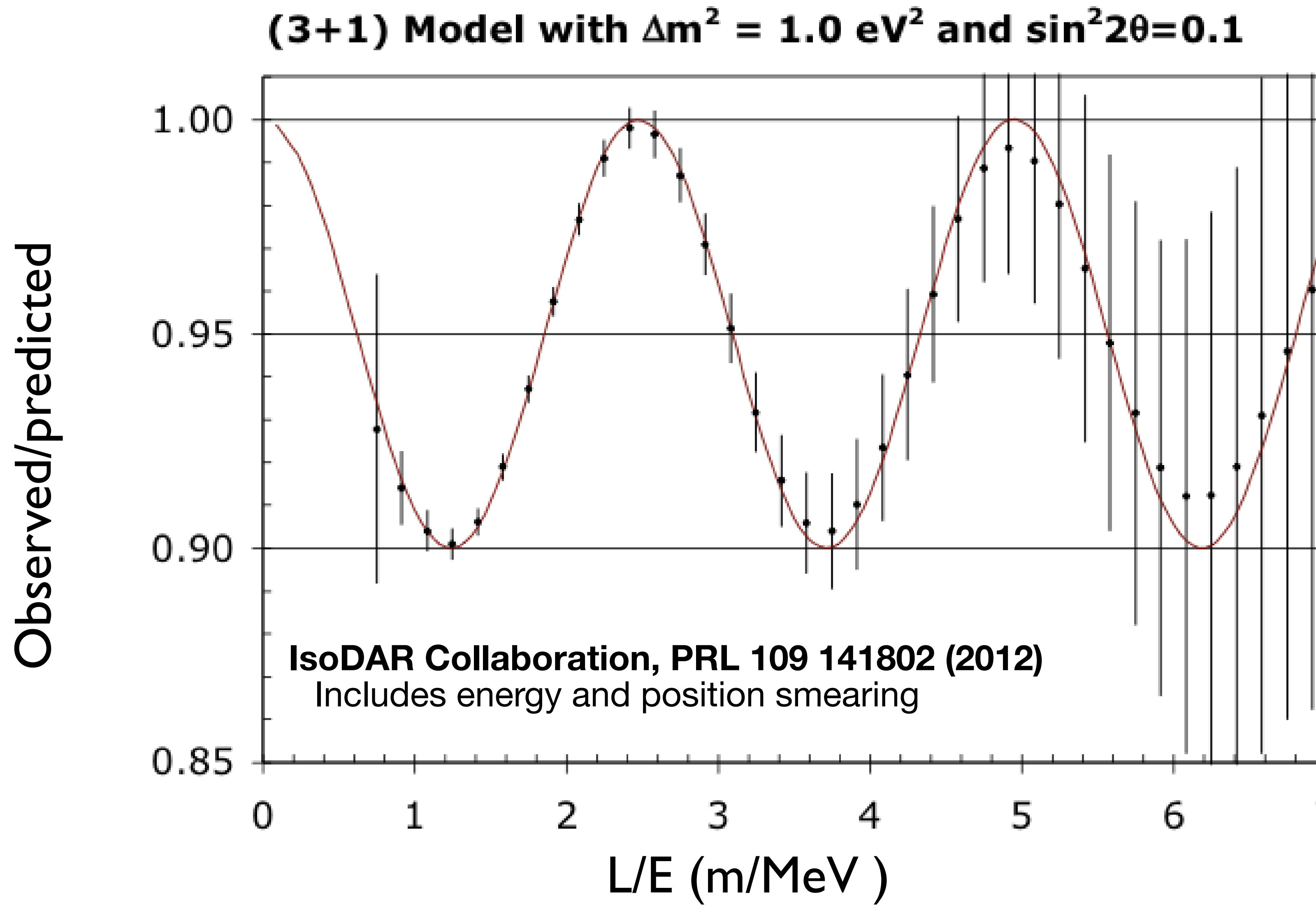


$$\overline{\nu}_e p \rightarrow e^+ n$$

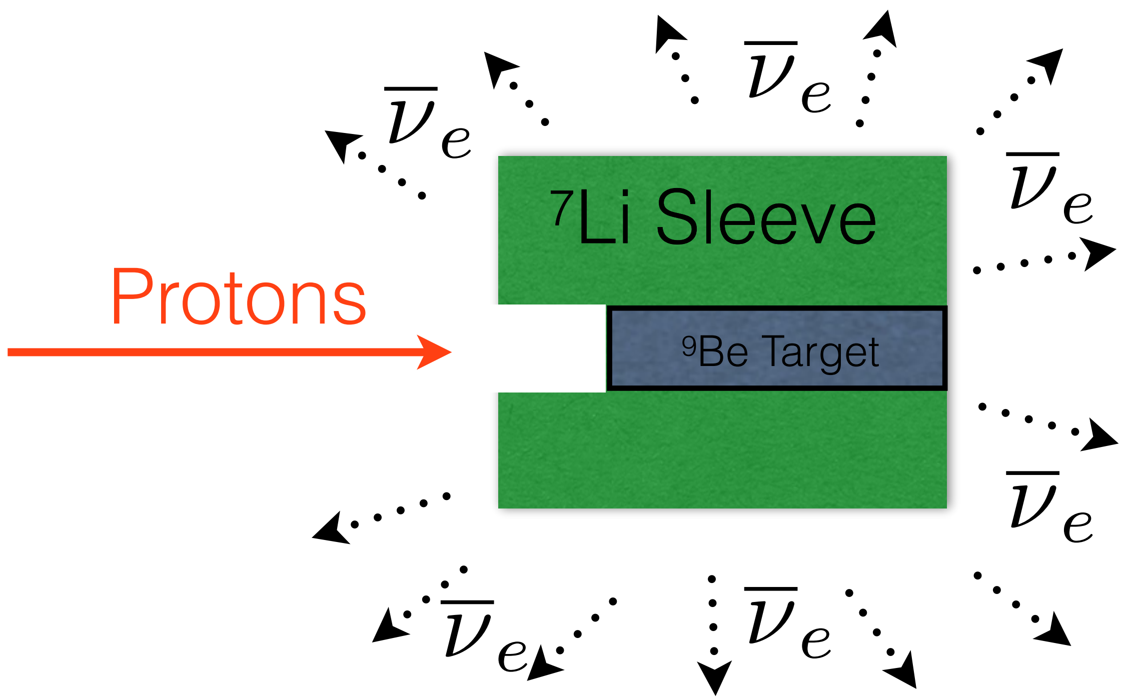
$$\overline{\nu}_e \rightarrow \overline{\nu}_x \quad ?$$



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



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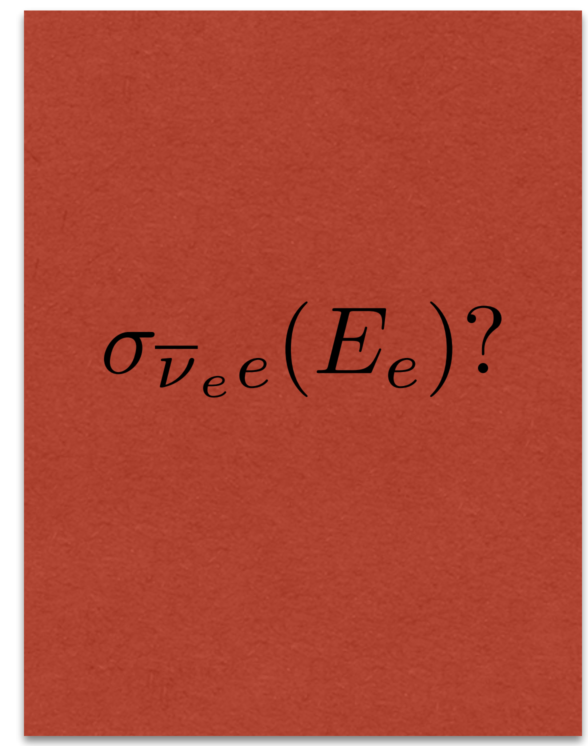
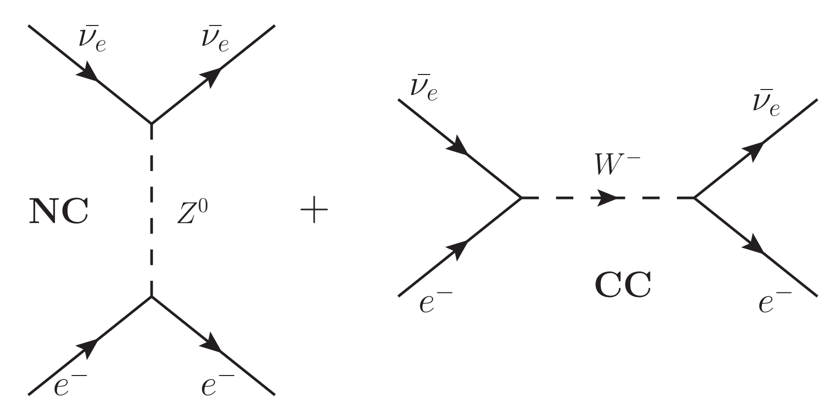
Big detector with free protons (e.g. H_20, CH_2)



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



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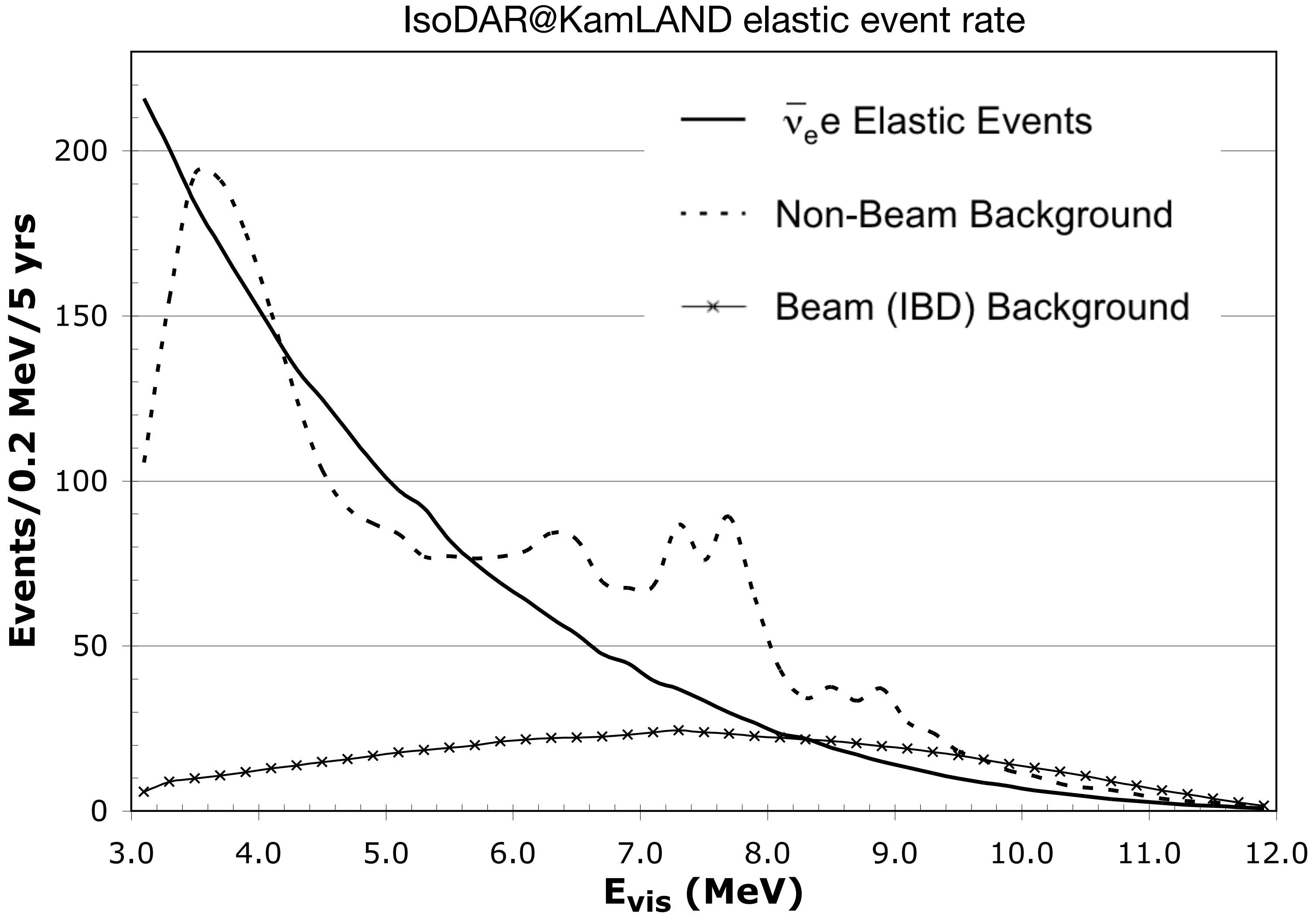
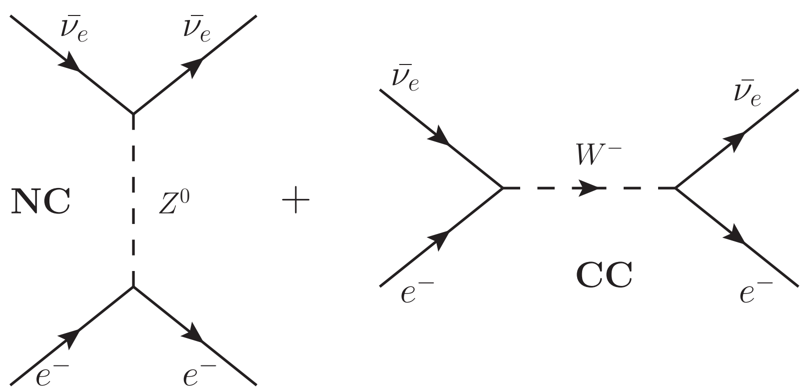


A precision measurement of the weak mixing angle is sensitive to new physics contributions

Purely leptonic process



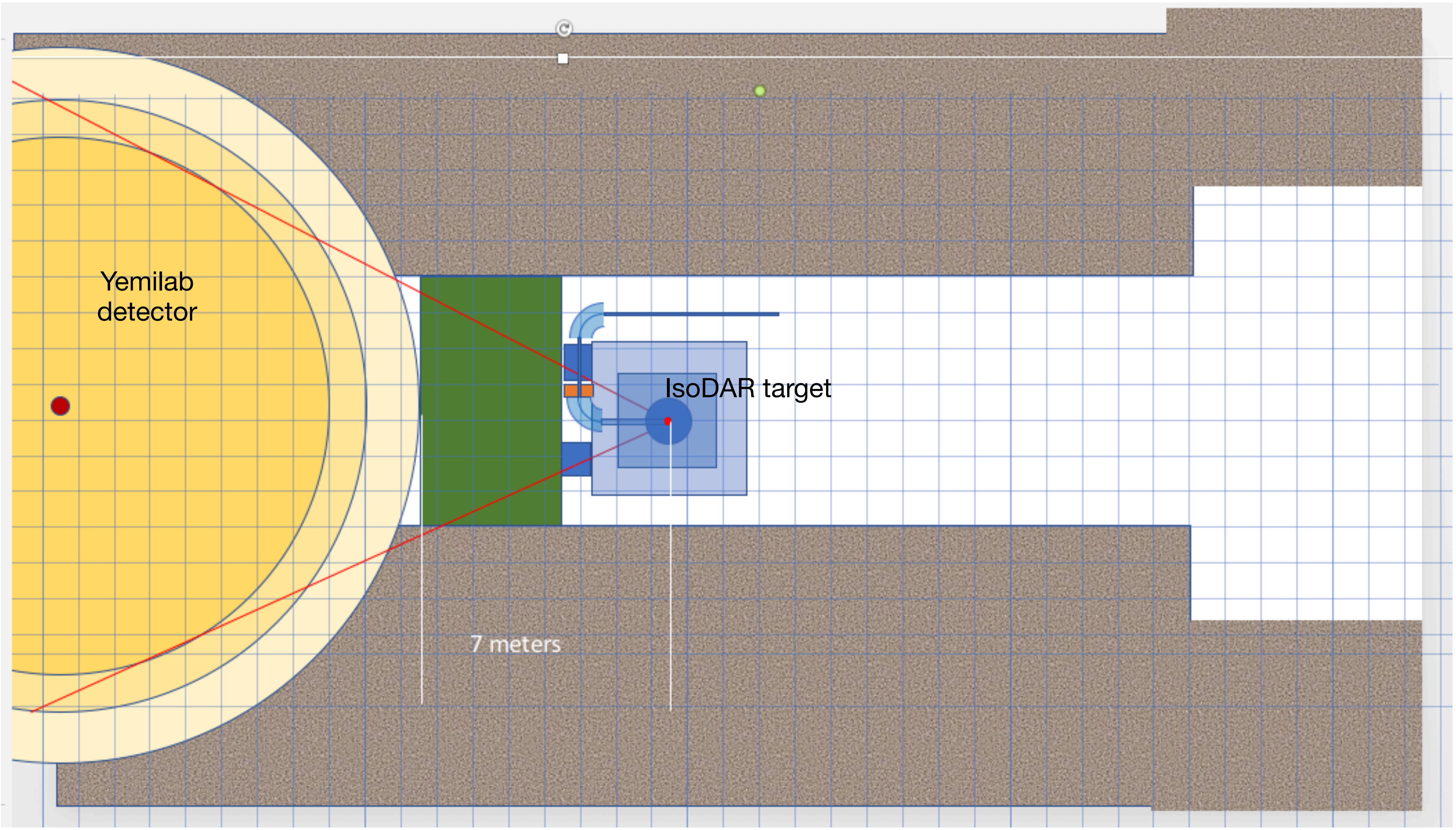
2,600 elastic signal events in 5 years at KamLAND
(897 tons, 16 m to center of detector)

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

What can IsoDAR do in combination with an even bigger detector?

IsoDAR@Yemilab Center for Underground Physics (Korea; 1 km underground, 2.6 ktons)

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@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$\times$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)"

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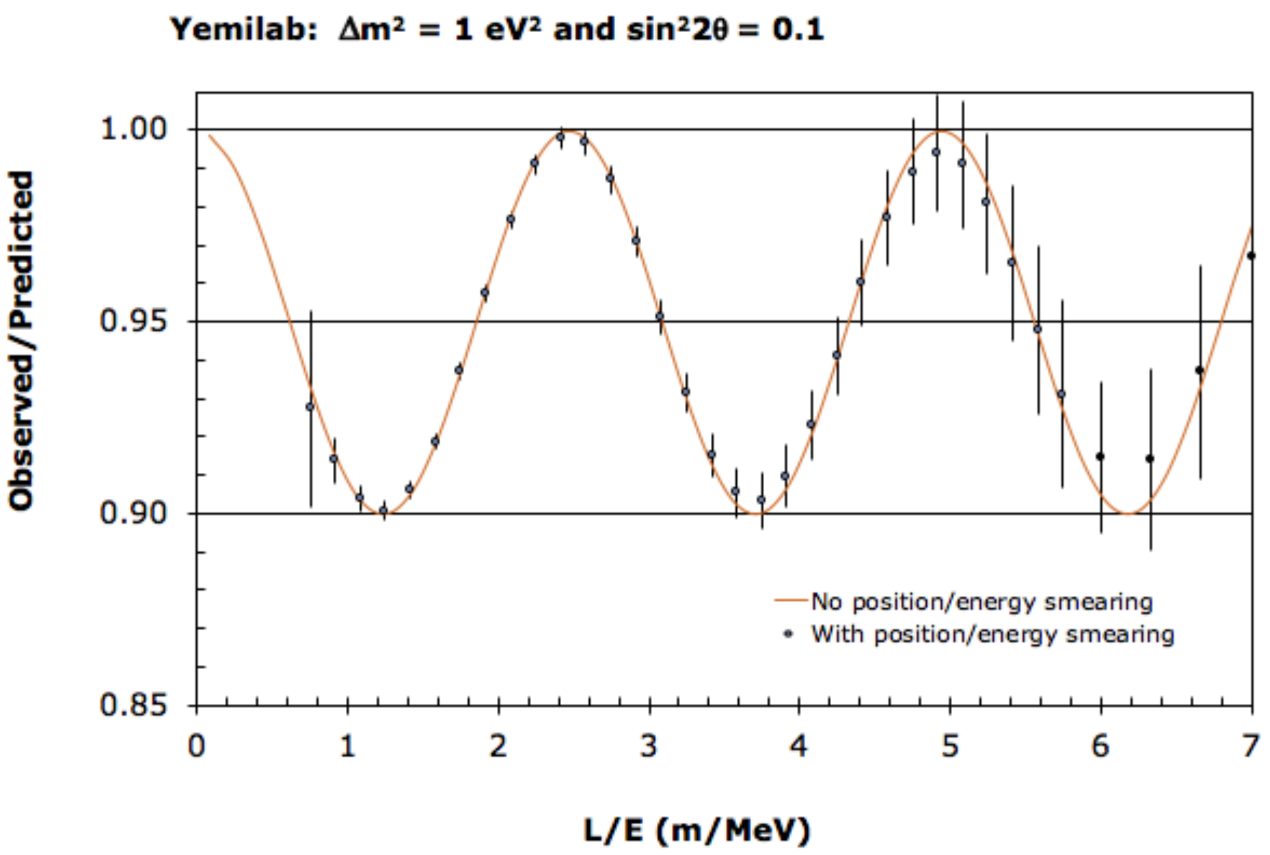
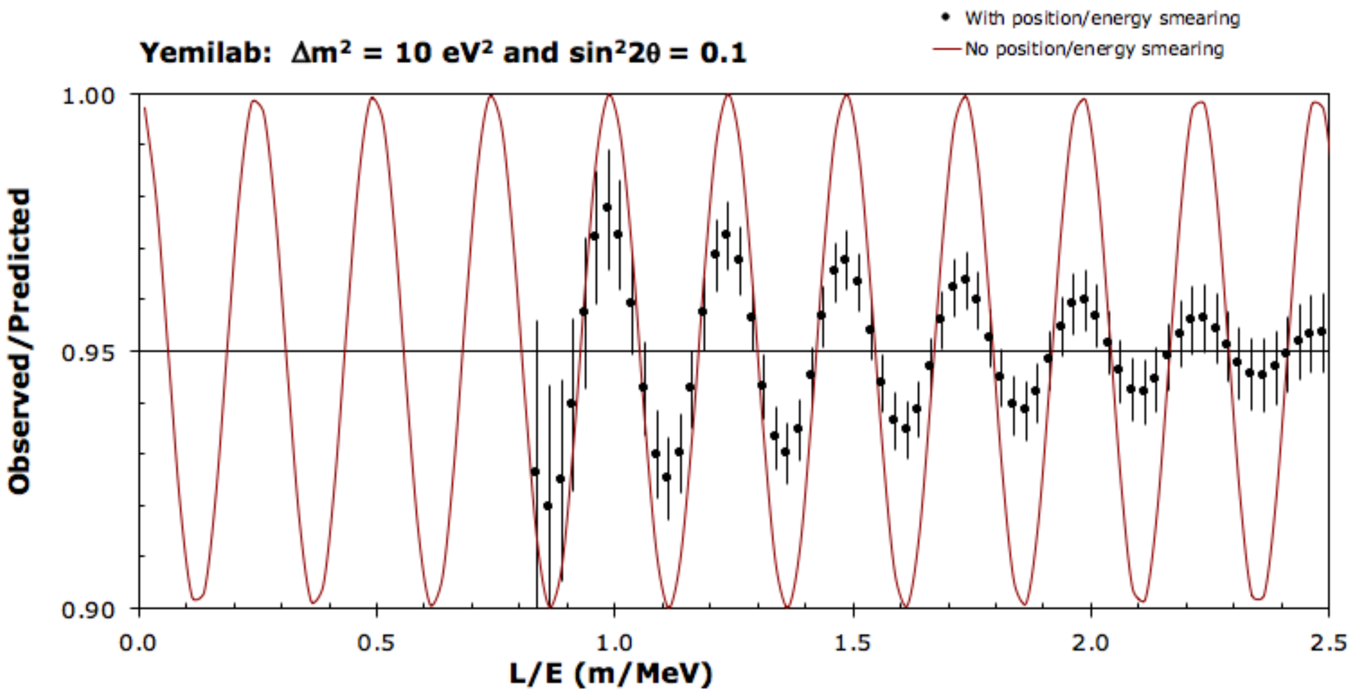
IsoDAR@Yemilab IBD event rate

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

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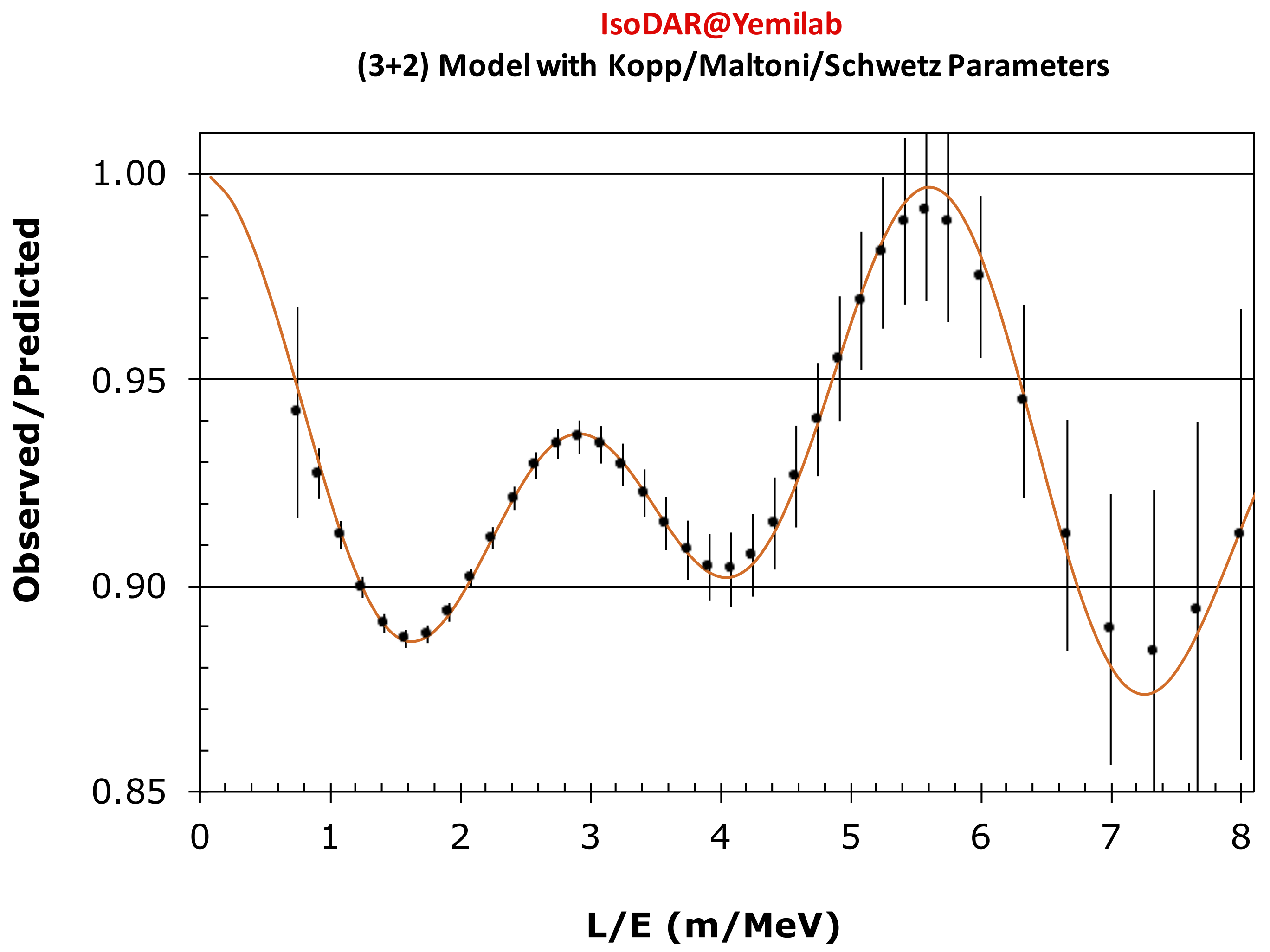

Includes energy and position smearing

2.0 million IBD events in 5 years at Yemilab
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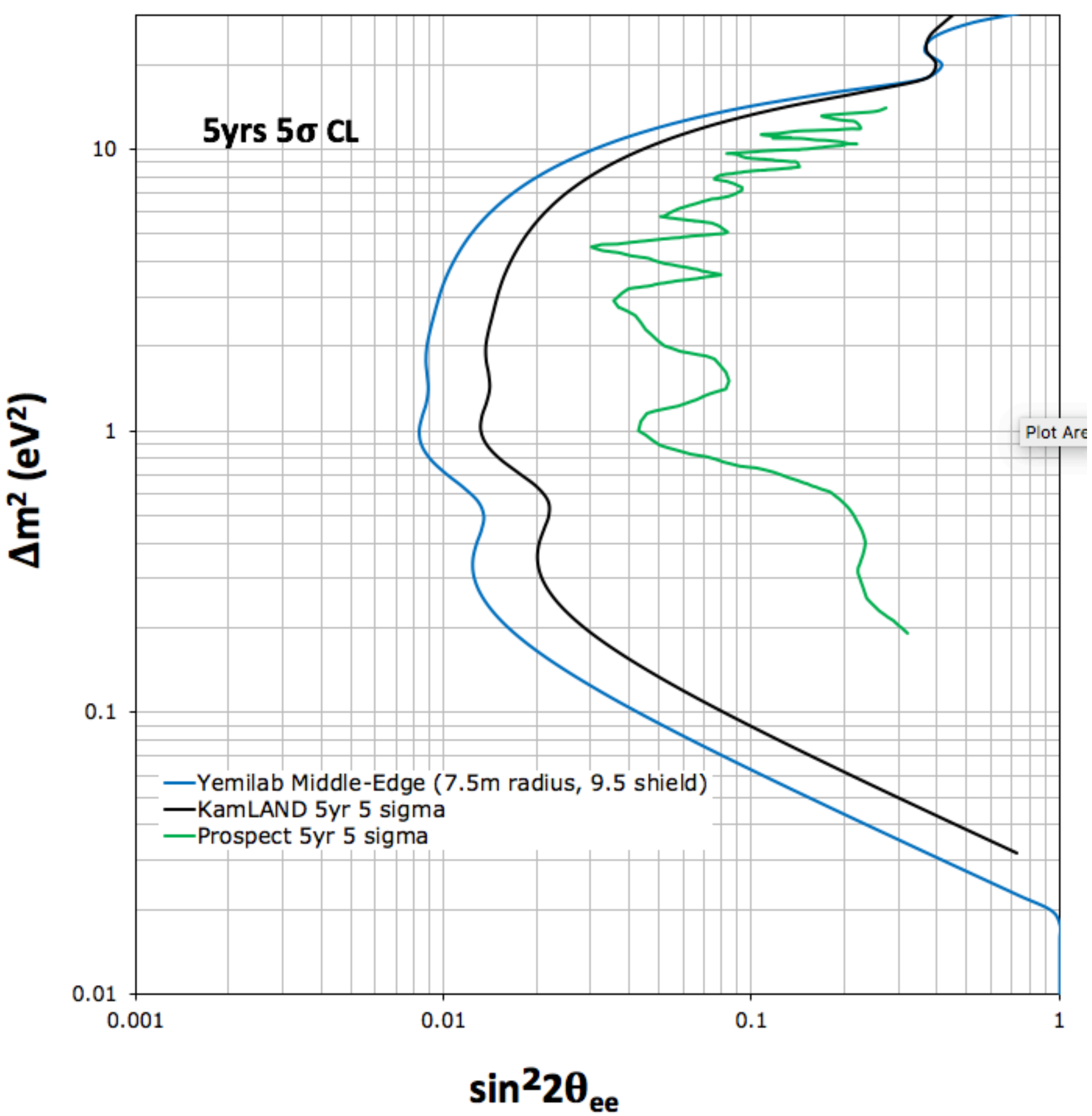
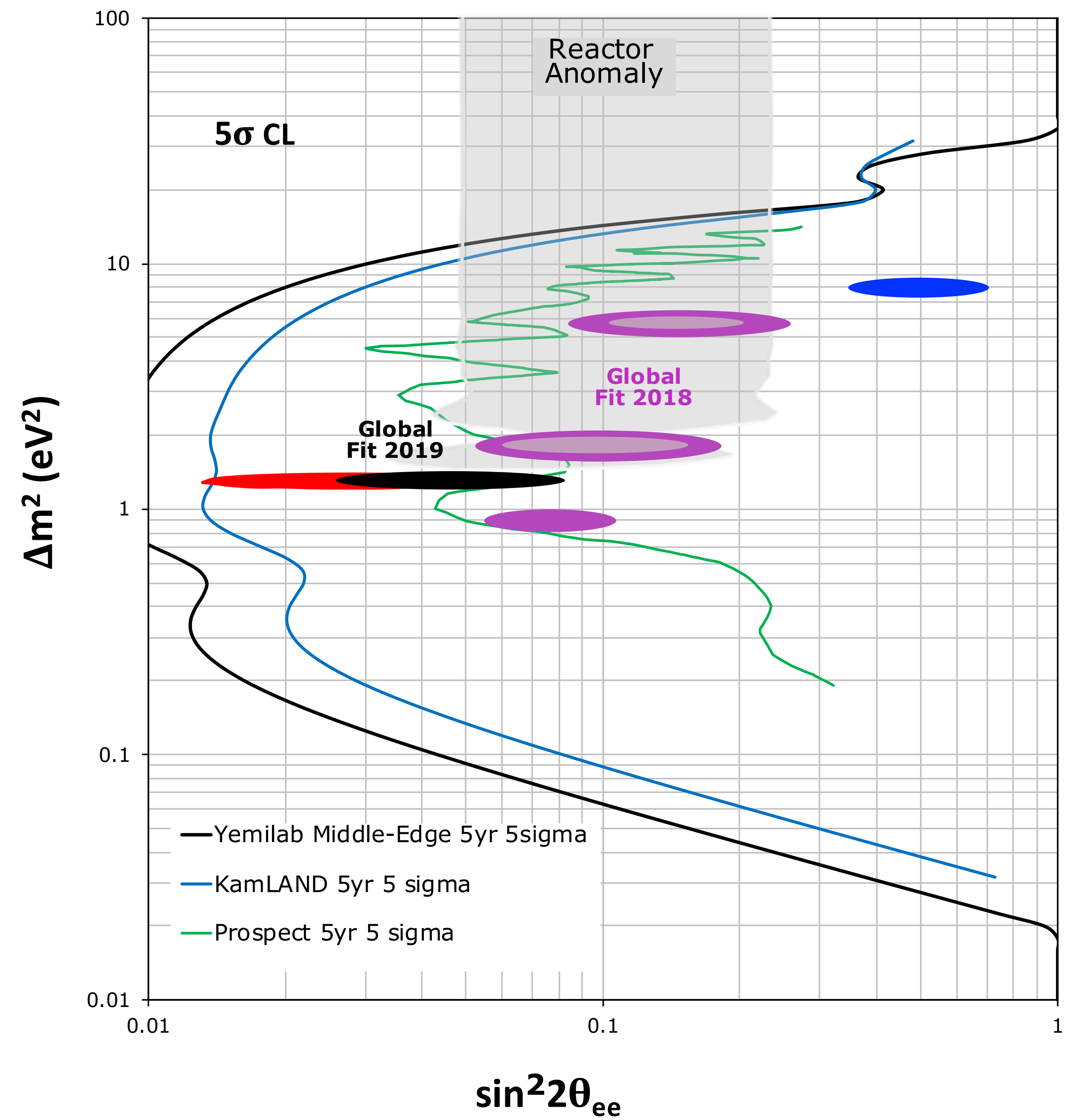
IsoDAR@Yemilab sensitivity

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:

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".

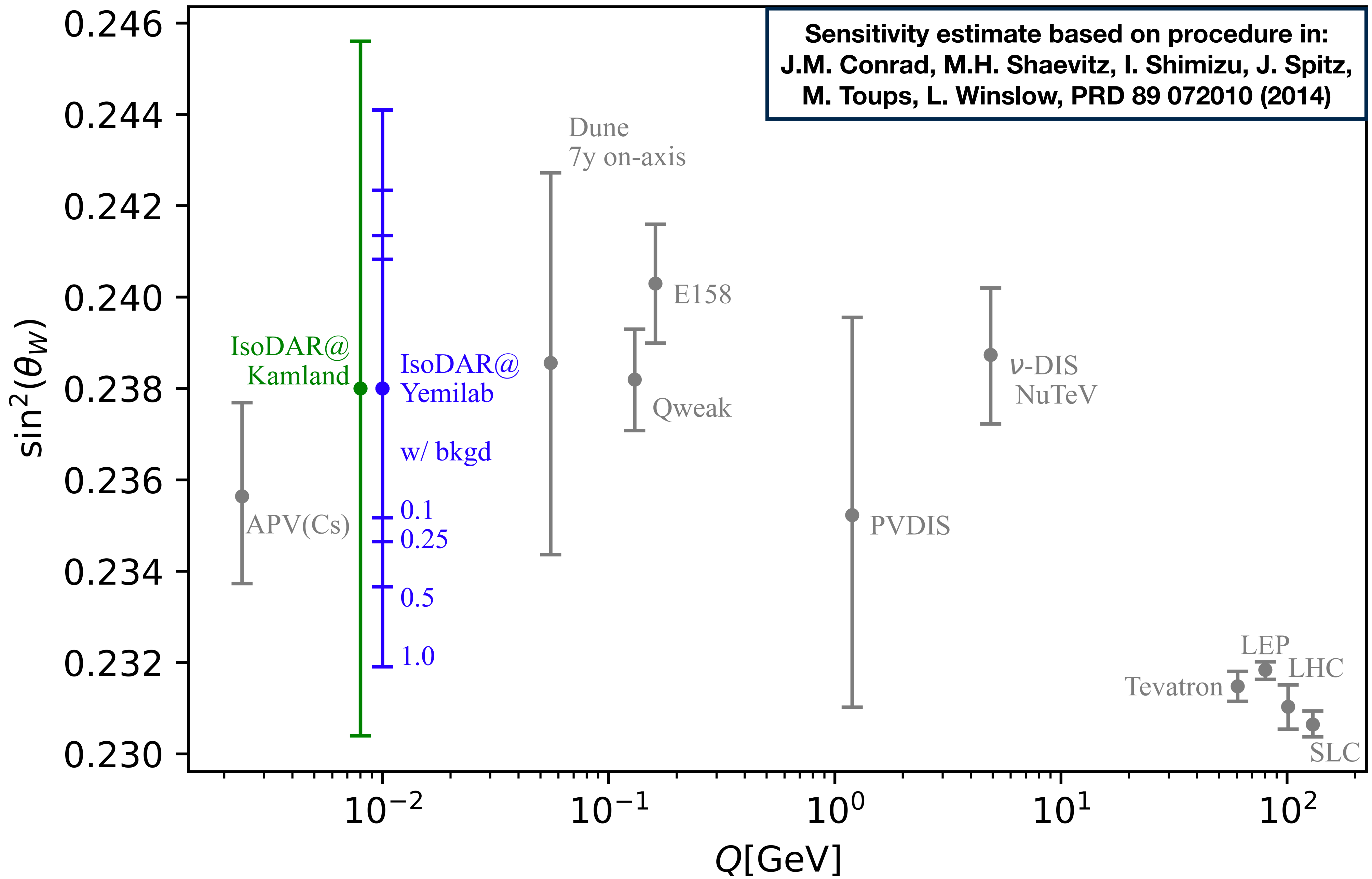
Experiment	E_ν (MeV)	T (MeV)	Events [14]	Published Cross-Section	$\sin^2\theta_W$
Accelerator ν_e :					
LAMPF [5]	$7 < E_\nu < 50$	7−50	236	$[10.0 \pm 1.5 \pm 0.9] \cdot E_\nu \times 10^{-45}$ cm^2	0.249 ± 0.063
LSND [6]	$20 < E_\nu < 50$	20−50	191	$[10.1 \pm 1.1 \pm 1.0] \cdot E_\nu \times 10^{-45}$ 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 $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$

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)

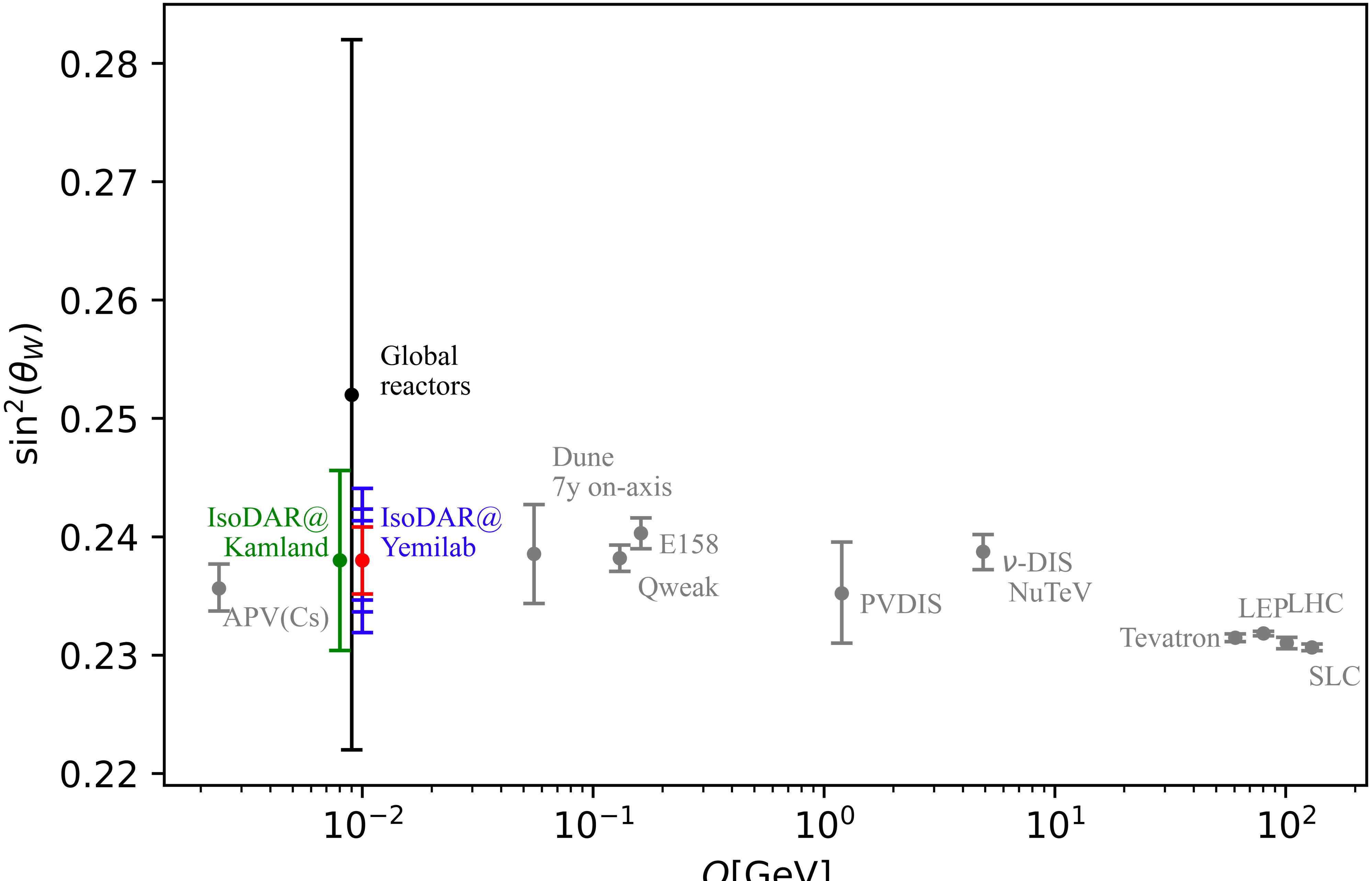


IsoDAR@Yemilab elastic scattering

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): $\sin^2\theta_W = 0.252 \pm 0.030$



Conclusions

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

*There are other physics opportunities with an IsoDAR cyclotron as well:
coherent antineutrino-nucleus scattering, neutrino (rather than antineutrino) scattering studies, and searches for axion-like particles