Searching for Sterile Neutrinos and CP Violation: The IsoDAR and Daeδalus Experiments

Mike Shaevitz - Columbia University

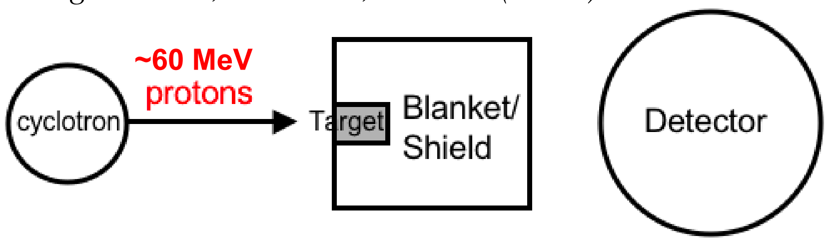
Daeδalus and IsoDAR Experiments

("Cyclotrons as Drivers for Precision Neutrino Measurements" - arXiv:1307.6465)

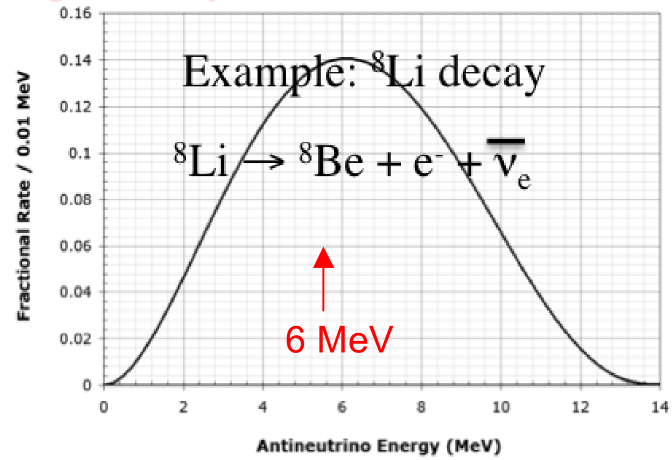
IsoDAR Setup:

Very short baseline search for sterile neutrinos

A. Bungau et al., PRL 109, 141802 (2012)



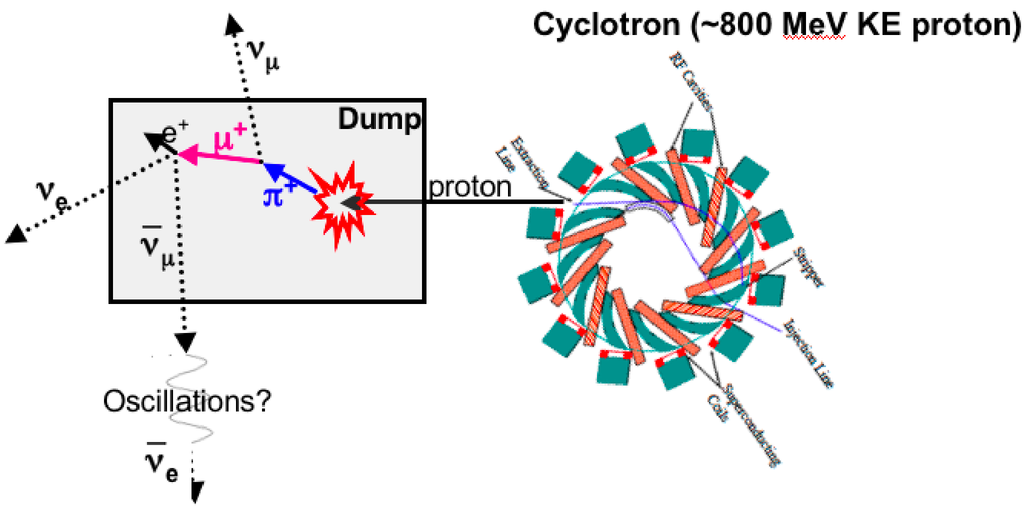
Isotope decay-at-rest



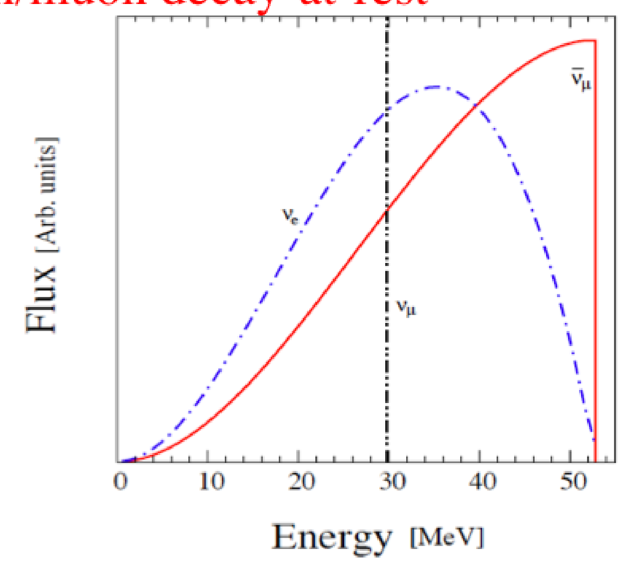
Daeδalus Setup:

A new way to search for CP violation in the ν-sector

J.M Conrad and M. H. Shaevitz, PRL 104, 141802 (2010)

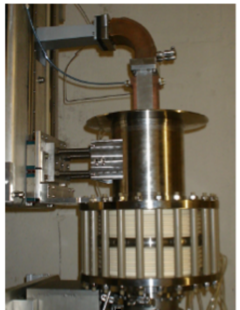


Pion/muon decay-at-rest



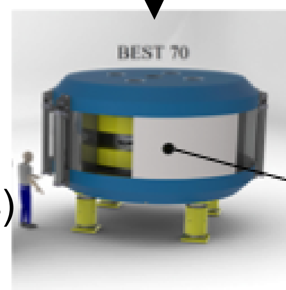
DAEδDALUS High Power (~1 MW) 800 MeV Cyclotron System (Under Development with Lab and Industrial Partners)

H_2^+ Ion Source

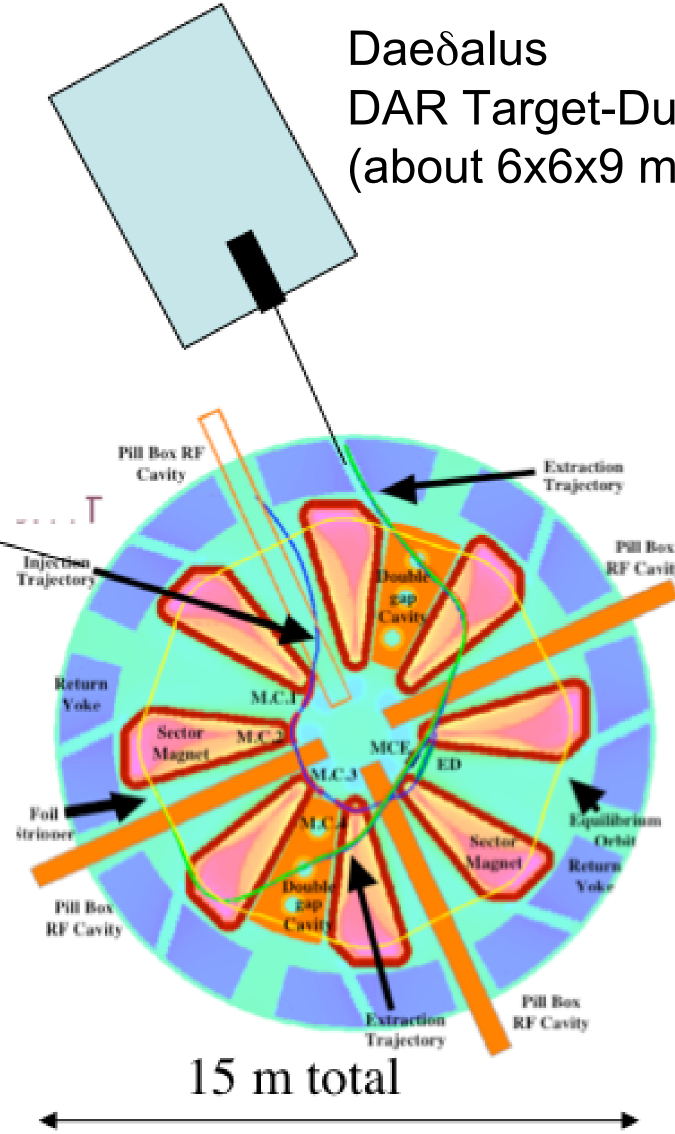


IsoDAR Cyclotron

Injector Cyclotron (Resistive Isochronous)



Daeδalus DAR Target-Dump (about 6x6x9 m³)



Multimegawat Daeδalus Cyclotron for Neutrino Physics

arXiv:1207.4895

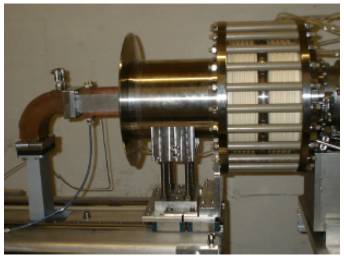
Ring Cyclotron (Superconducting)

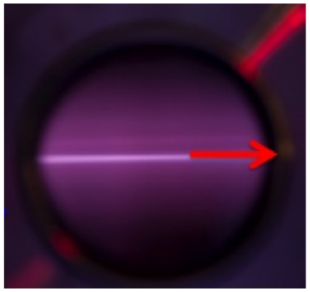
"Isochronous cyclotron" where mag. field changes with radius, but RF does not change with time. This can accelerate many bunches at once.

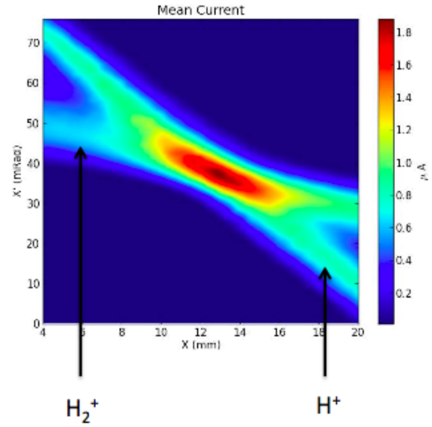
Current Accomplishments and Status

International Partnership Between Universities, Labs, and Industry

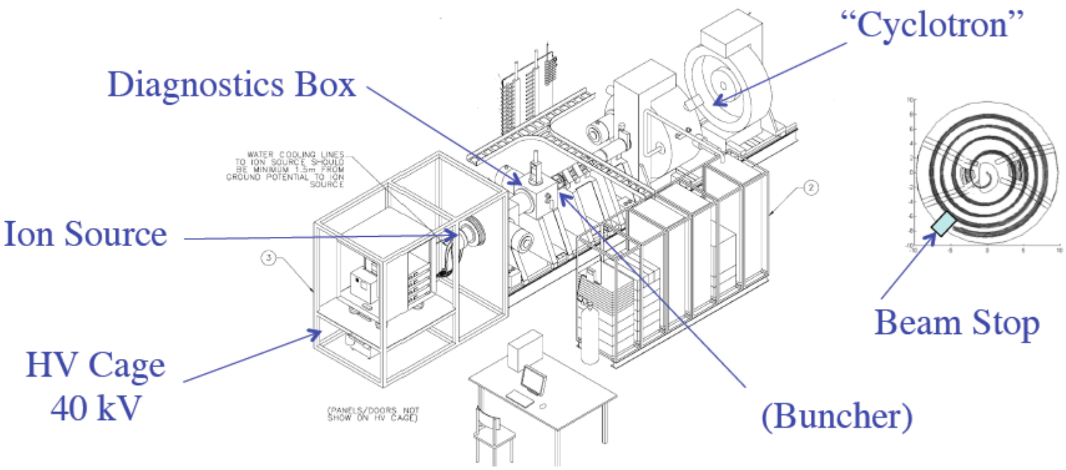
- Ion source developed by collaborators at INFN Catania
  - Reached adequate intensities for the system

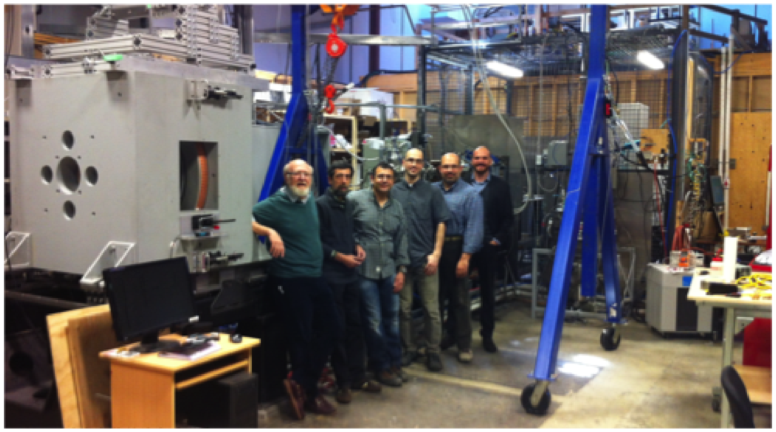






- Ion Source Beam currently being characterized at Best Cyclotrons, Inc, Vancouver



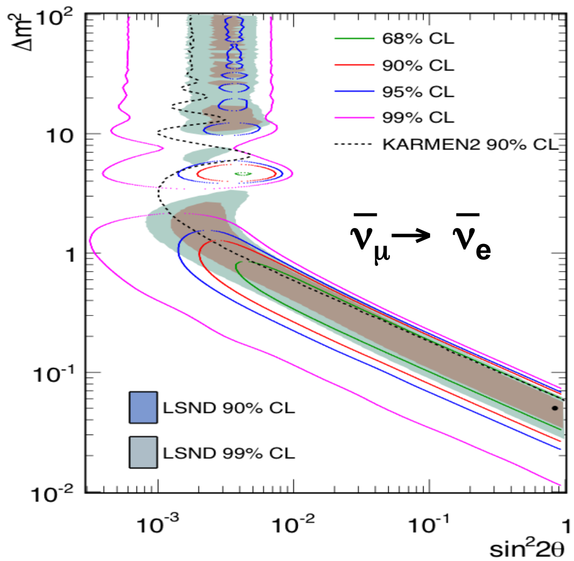


IsoDAR Experiment

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

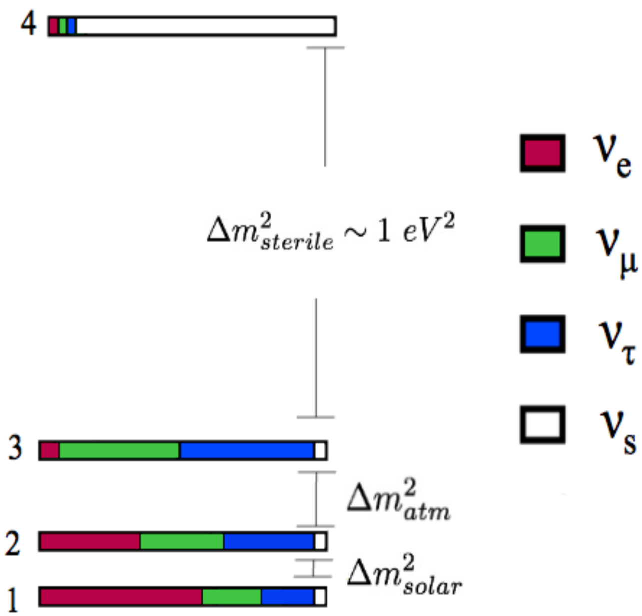
Many Experimental Hints for Sterile Neutrinos

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

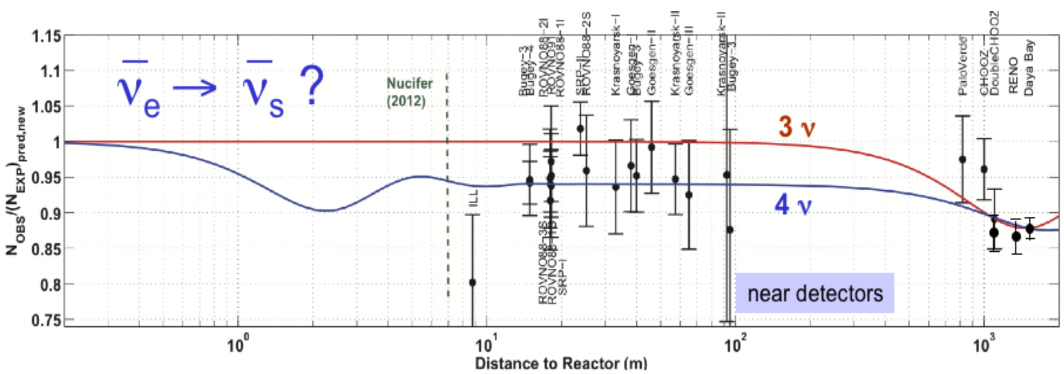


Data sets indicate a high Δm^2

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



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

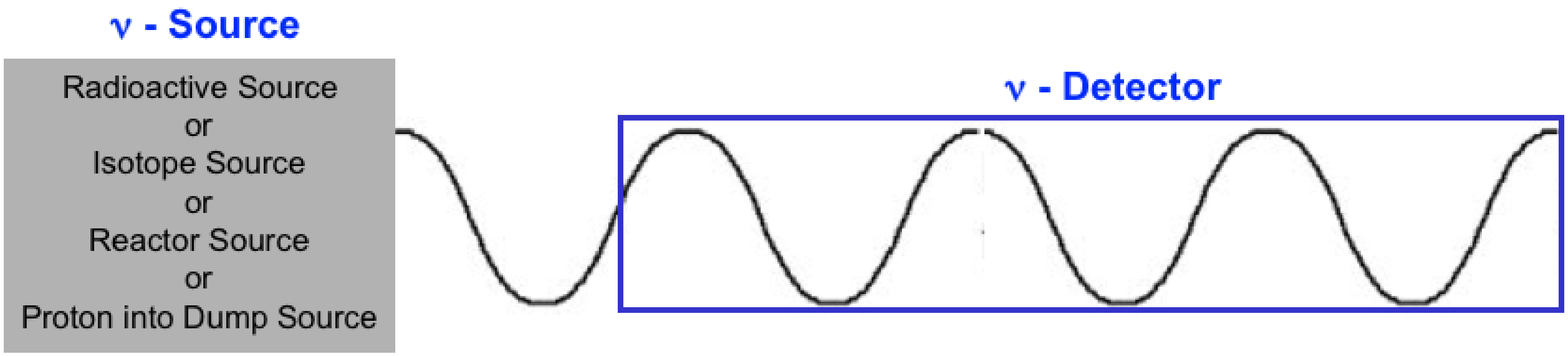


These signals are at the 2-4σ level ⇒ Need new "definitive" experiments

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

Probing $\Delta m^2 \sim 1\ eV^2$ Oscillations

Short and Very-short Baseline Oscillation Experiments



- Need definitive experiments
  - Significance at the > 5σ level
  - Smoking gun: Observation of oscillatory behavior within detector
- Several directions for next generation accelerator experiments
  - Multi-detector accelerator neutrino beam experiments
  - Very short baseline (VSBL) experiments with compact neutrino sources

- Many ideas and neutrino sources:
  - Reactor sources
  - Radioactive sources
  - Isotope sources
  - π / K decay-at-rest sources
  - π decay-in-flight sources
  - Low-energy ν-Factory source


arXiv.org > hep-ph > arXiv:1204.5379

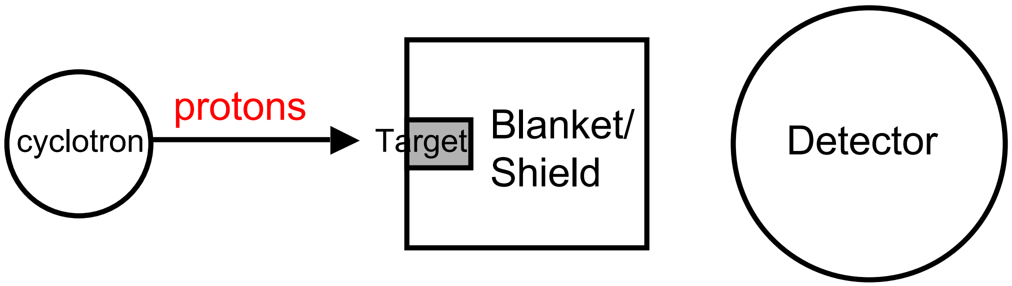
High Energy Physics – Phenomenology

Light Sterile Neutrinos: A White Paper

K. N. Abazajian, M. A. Acero, S. K. Agarwalla, A. A. Aguilar-Arevalo, C. H. Albright, S. Antusch, Barenboim, V. Barger, P. Bernardini, F. Bezrukov, O. E. Bjaelde, S. A. Bogacz, N. S. Bowden, A. B Brice, A. D. Bross, B. Caccianiga, F. Cavanna, E. J. Chun, B. T. Cleveland, A. P. Collin, P. Coloma, J. C. D'Olivo, S. Das, A. de Gouvea, A. V. Derbin, R. Dharmapalan, J. S. Diaz, X. J. Ding, Z. Djurci R. Elliott, D. J. Ernst, A. Esmaili, J. J. Evans, E. Fernandez-Martinez, E. Figueroa-Feliciano, B. T. F Gaffiot, R. Gandhi, Y. Gao, G. T. Garvey, V. N. Gavrin, P. Ghoshal, D. Gibin, C. Giunti, S. N. Gnine shown)

Overview IsoDAR $\bar{\nu}_e$ Disappearance Exp

- High intensity $\bar{\nu}_e$ source using β-decay at rest of ^{8}Li isotope $\Rightarrow$ IsoDAR
- ^{8}Li produced by high intensity (10ma) proton beam from 60 MeV cyclotron
  $\Rightarrow$ being developed as prototype injector for DAEδALUS cyclotron system
- Put a cyclotron-isotope source near one of the large (kton size) liquid scintillator/water detectors such as KAMLAND, SNO+, Borexino, Super-K….

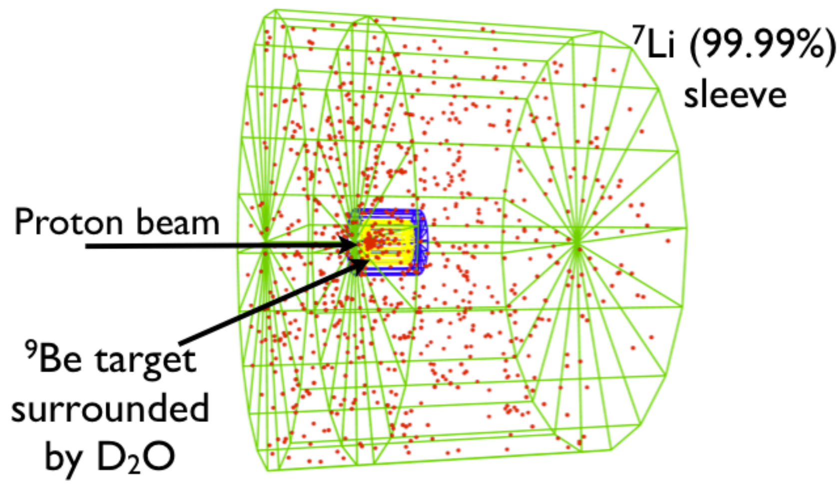


- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector as a function of L and E.

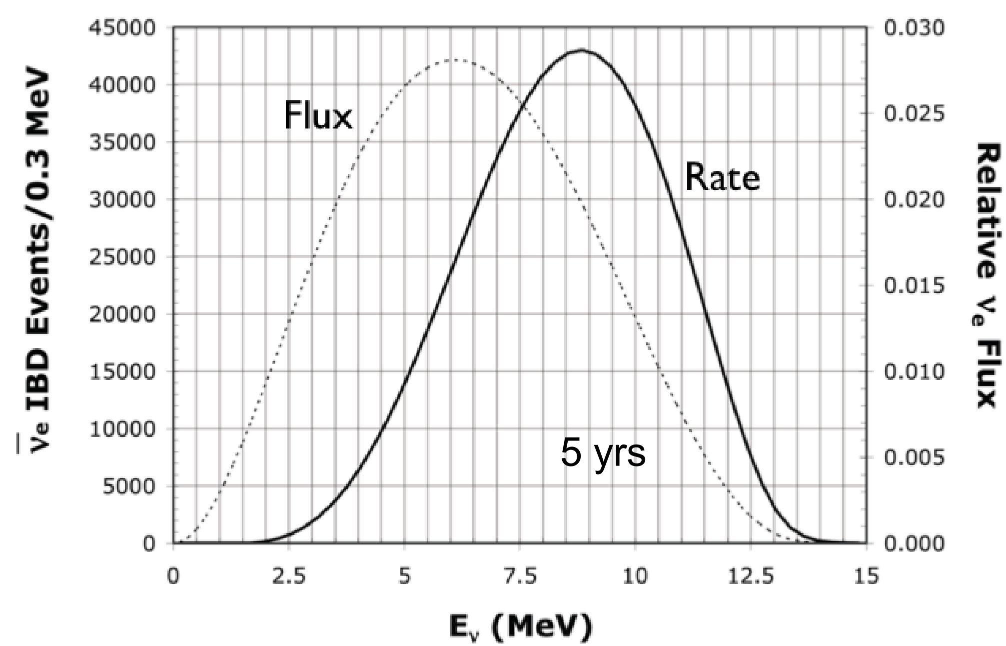
Phys Rev Lett 109 141802 (2012)
arXiv:1205.4419

IsoDAR Neutrino Source and Events

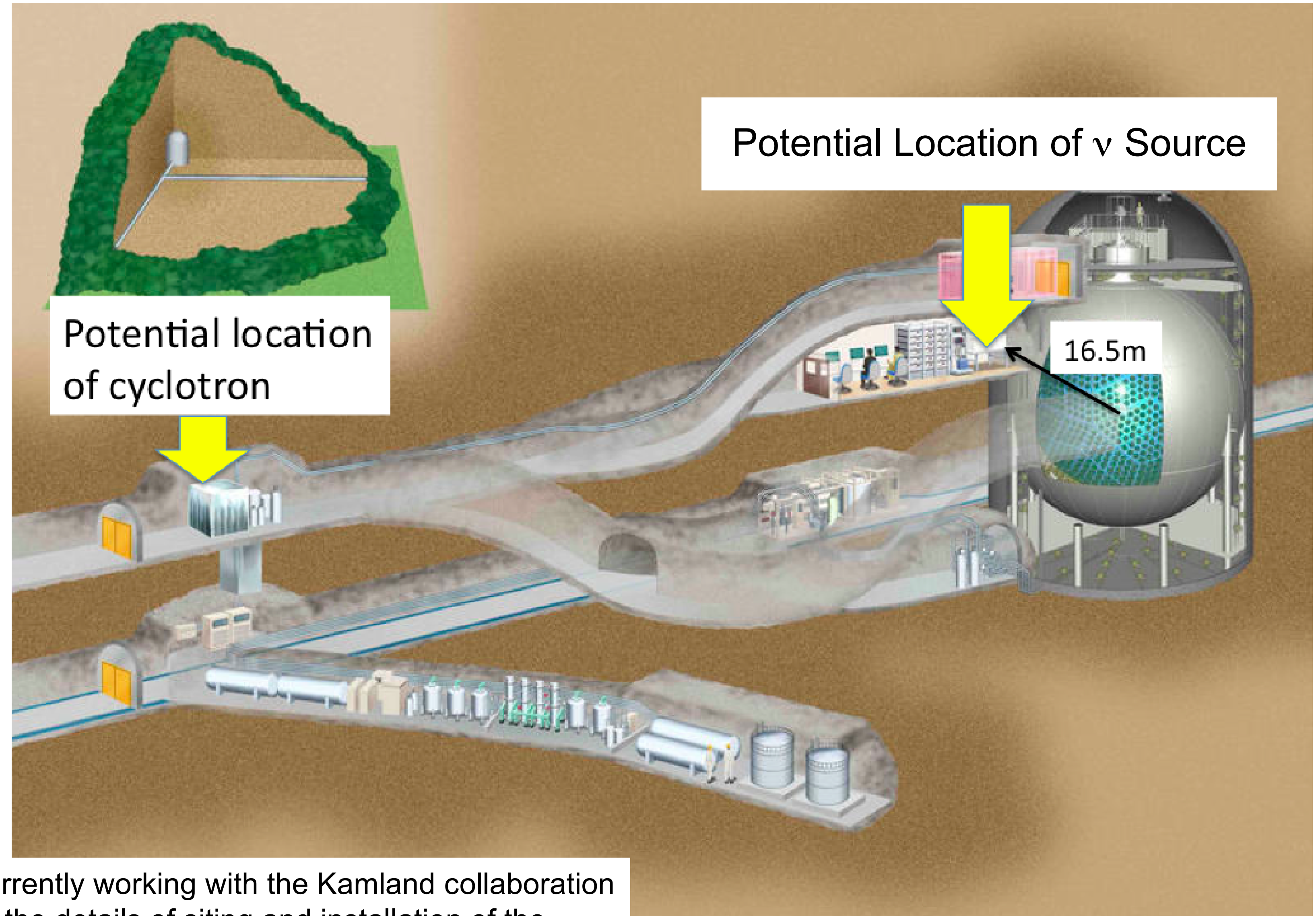
- p (60 MeV) + ^{9}Be → ^{8}Li + 2p
  - plus many neutrons since low binding energy
- n + ^{7}Li (shielding) → ^{8}Li
- ^{8}Li → ^{8}Be + e^- + $\bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV
  - 2.6×10^{22} $\bar{\nu}_e$ / yr
- Example detector: Kamland (900 t)
  - Use IBD $\bar{\nu}_e + p \rightarrow e^+ + n$ process
  - Detector center 16m from source
  - ~160,000 IBD events / yr
  - 60 MeV protons @ 10ma rate
  - Observe changes in the IBD rate as a function of L/E



arXiv:1205.4419

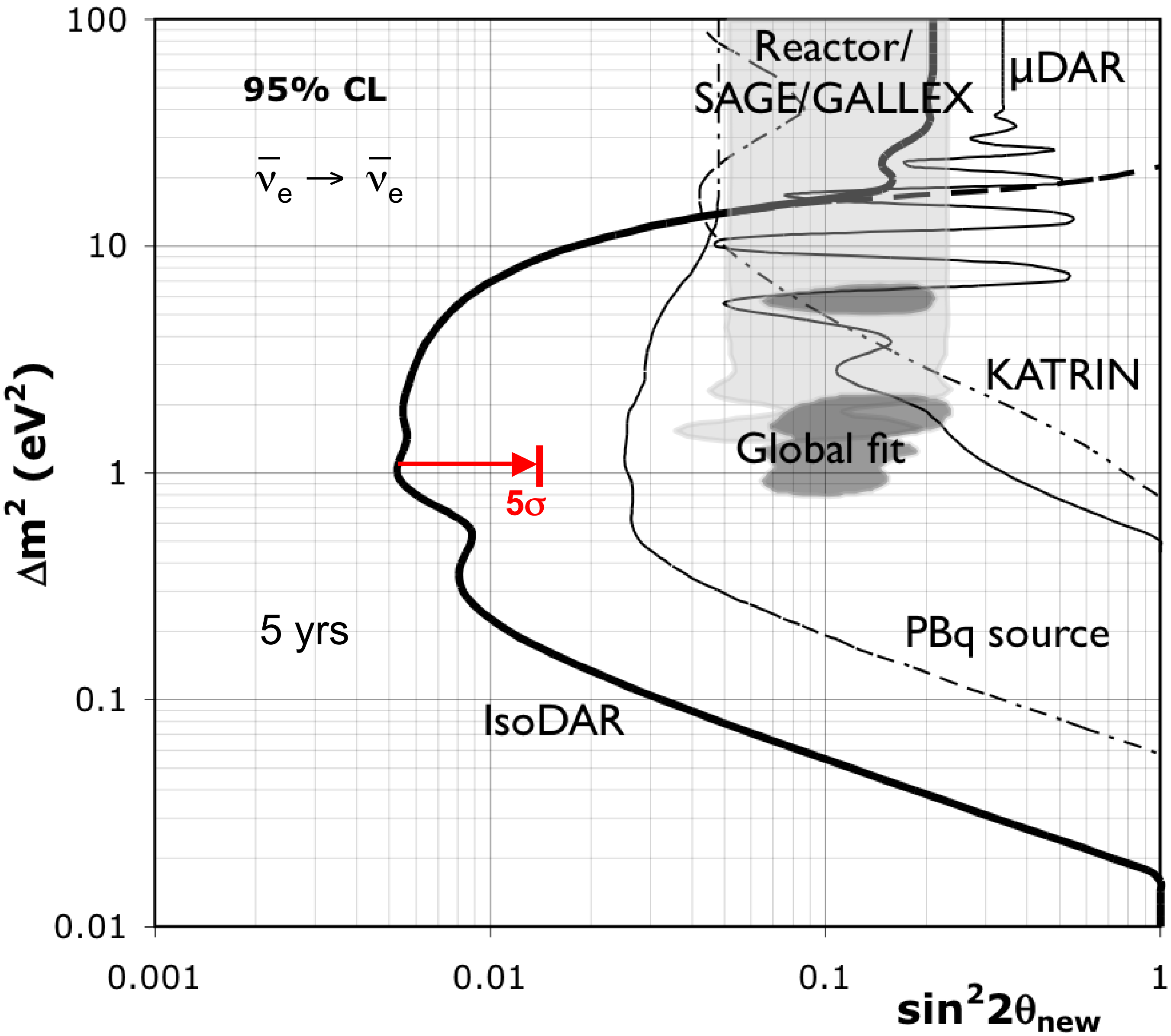


IsoDAR at Kamland

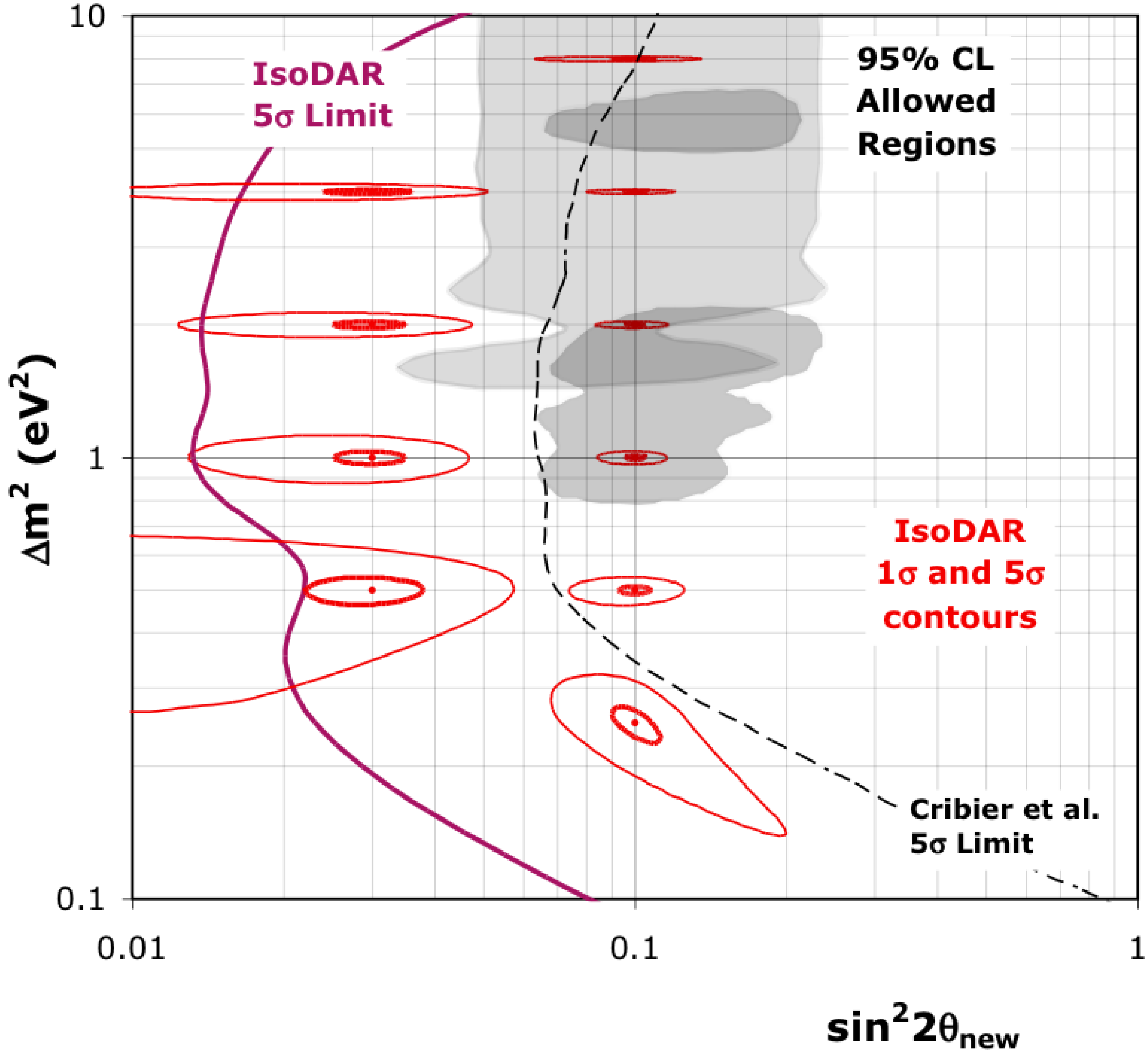


Currently working with the Kamland collaboration on the details of siting and installation of the cyclotron, beamline, and neutrino source.

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

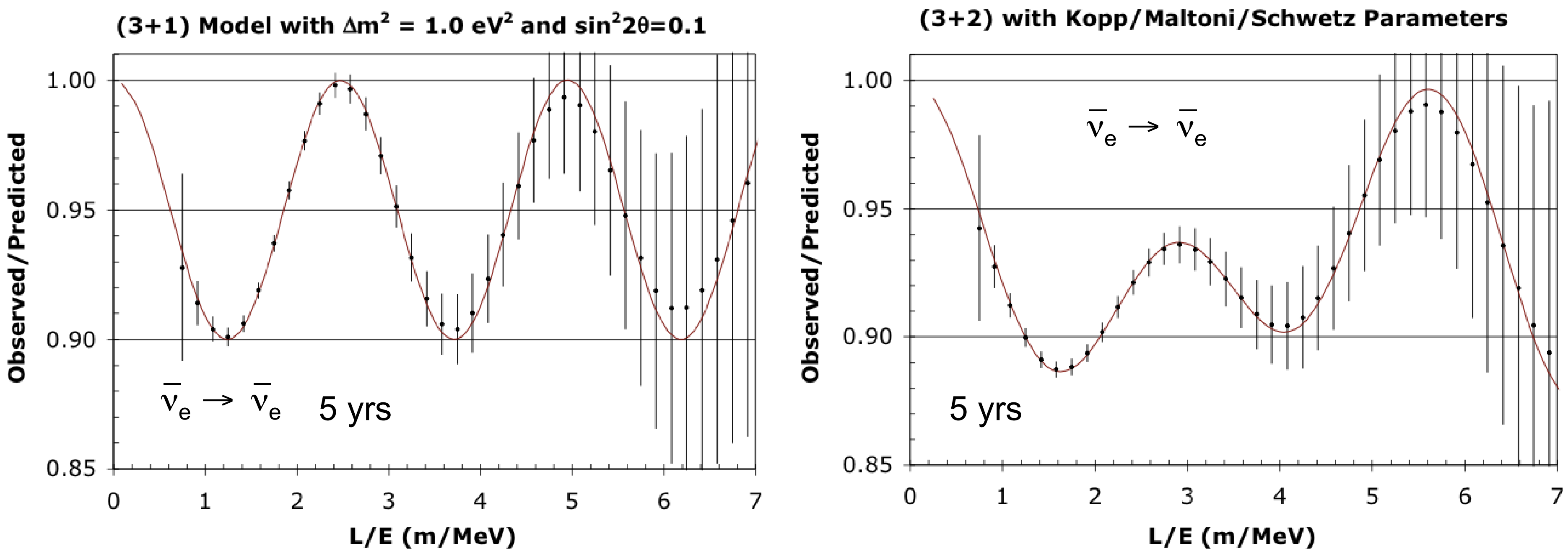


IsoDAR Measurement Sensitivity



Oscillation L/E Waves in IsoDAR

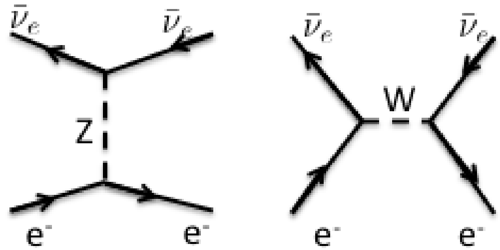
Observed/Predicted event ratio vs L/E including energy and position smearing

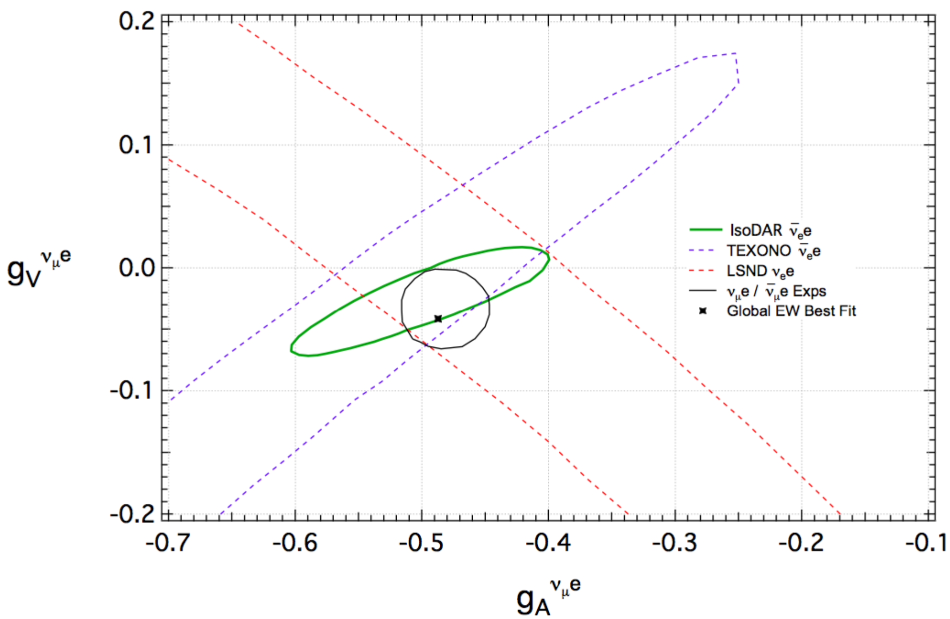


IsoDAR's high statistics and good L/E resolution has potential to distinguish (3+1) and (3+2) oscillation models

IsoDAR Also Has Excellent Electroweak Measurement Sensivity ($\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$)

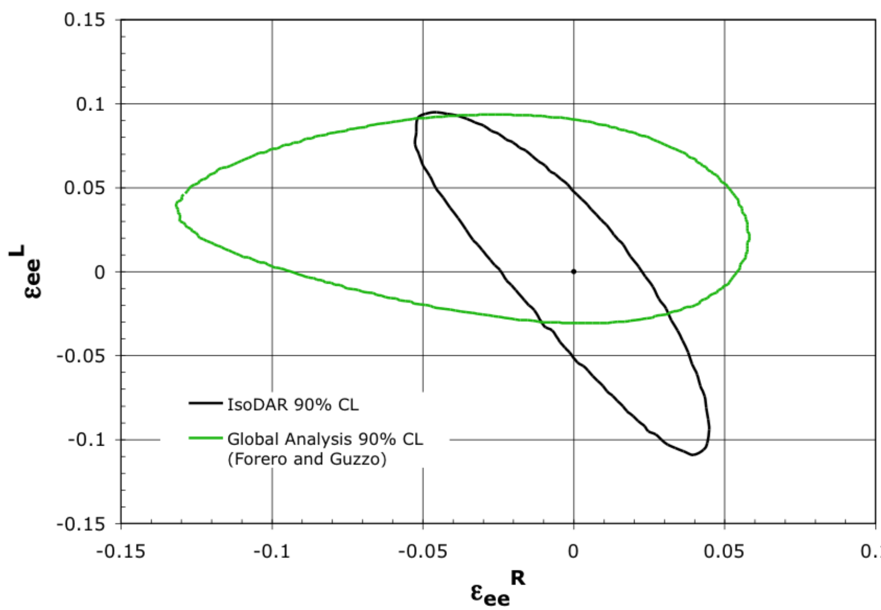
- 5yr data ⇒7200 evts with E_{vis}>3MeV ⇒ IsoDAR@Kamland:
  $\delta\sin^2\theta_W$ = 0.0075 (~3%)
  - Would be the best $\bar{\nu}_e e$ (or $\nu_e e$) elastic scattering measurement





- Precision neutrino-electron scattering can also probe Non-Standard Interactions (NSI) since it is a well-understood Standard Model process

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



DAEδDALUS Experiment

Search for CP Violation using $\bar{\nu}_e$ Appearance with a Pion Decay-at-Rest Neutrino Beam

Use L/E Dependence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to Measure δ_{CP}

$$
\begin{aligned}
P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) = & \left(\sin^2\theta_{23}\sin^2 2\theta_{13}\right)\left(\sin^2\Delta_{31}\right) \\
& \mp \underline{\sin\delta}\left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin^2\Delta_{31}\sin\Delta_{21}\right) \\
& + \underline{\cos\delta}\left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}\right) \\
& \qquad + \left(\cos^2\theta_{23}\sin^2 2\theta_{12}\right)\left(\sin^2\Delta_{21}\right).
\end{aligned}
$$

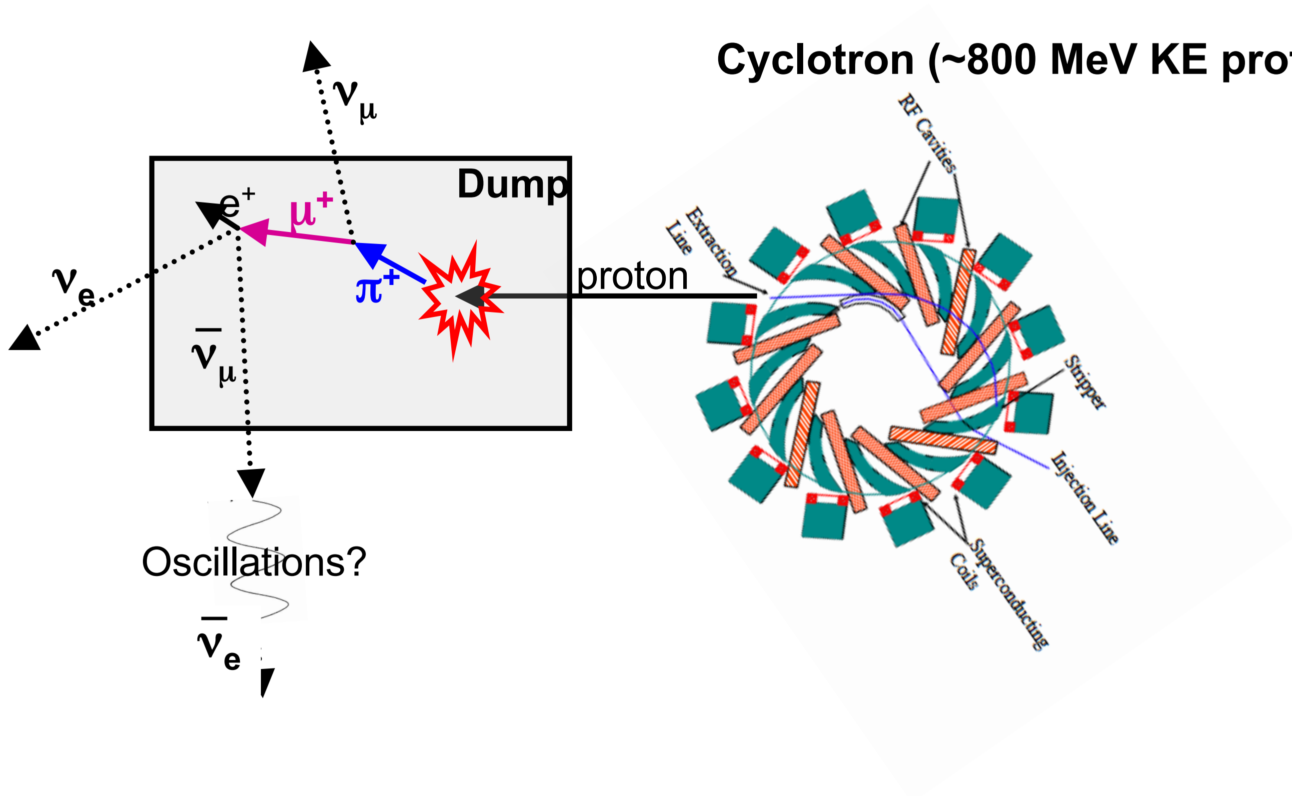
We want to see if δ is nonzero

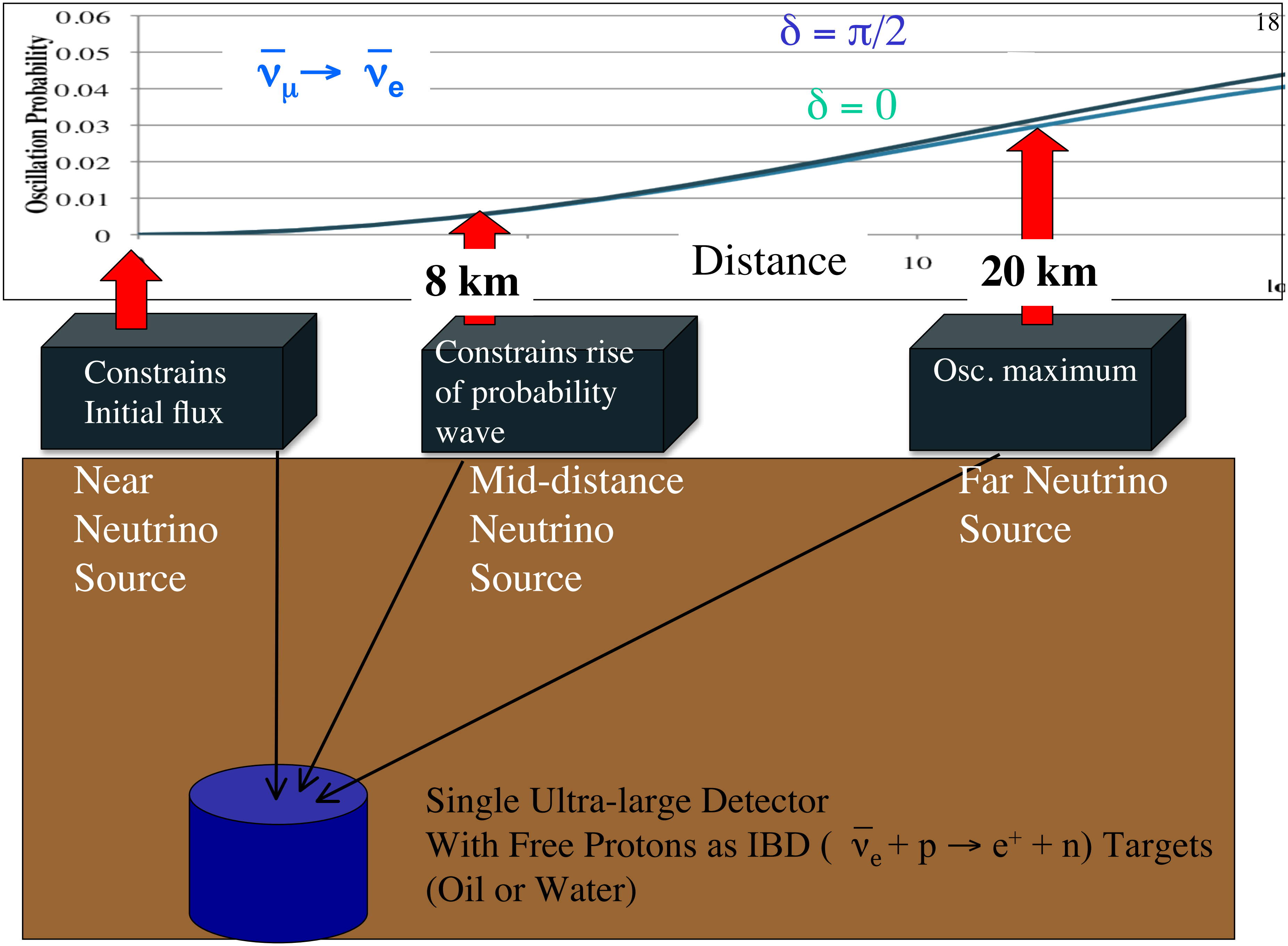
terms depending on mixing angles

terms depending on mass splittings

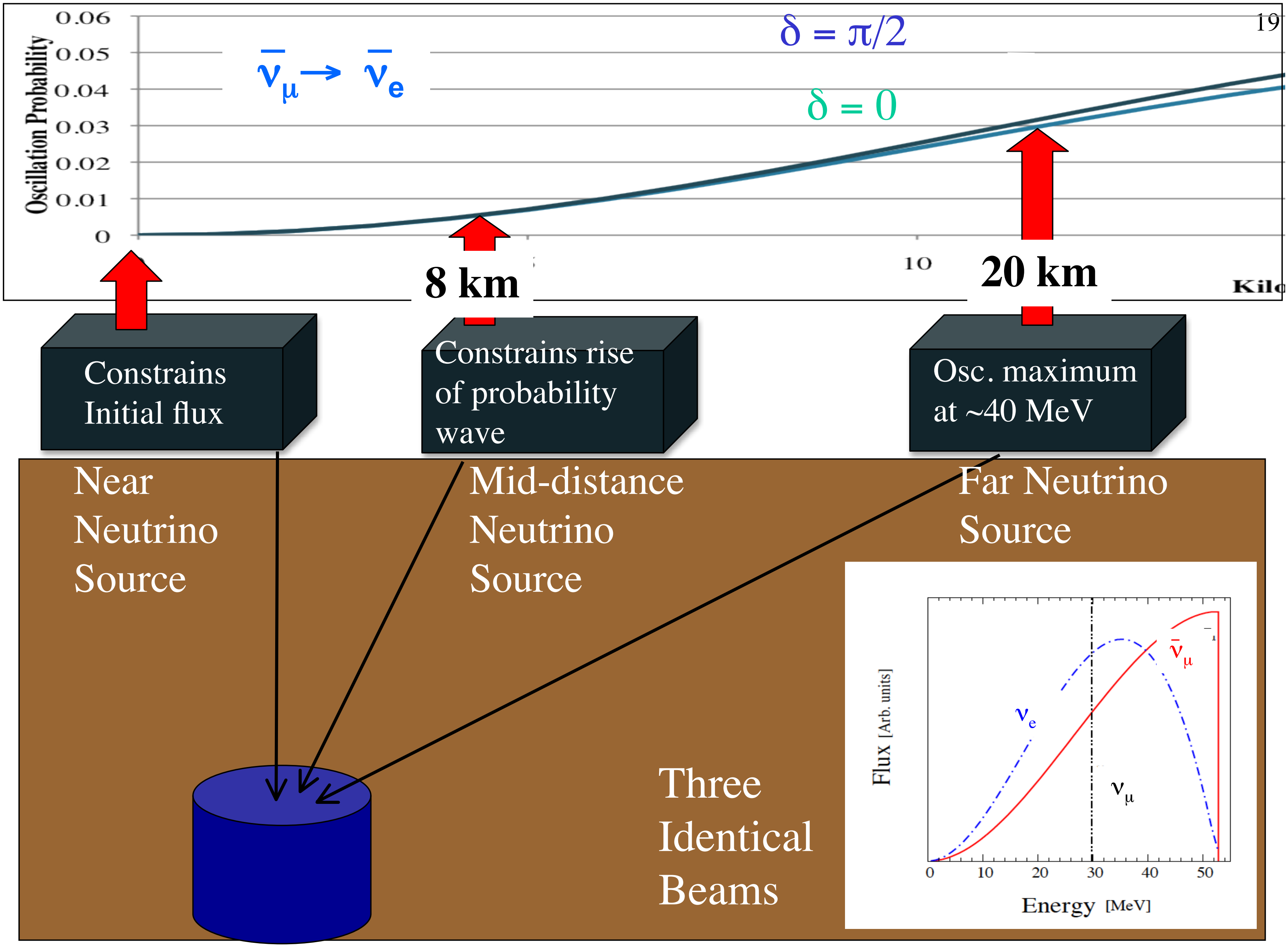
$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

Use Multiple Neutrino Sources at Different Distances to Map Out $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Rate

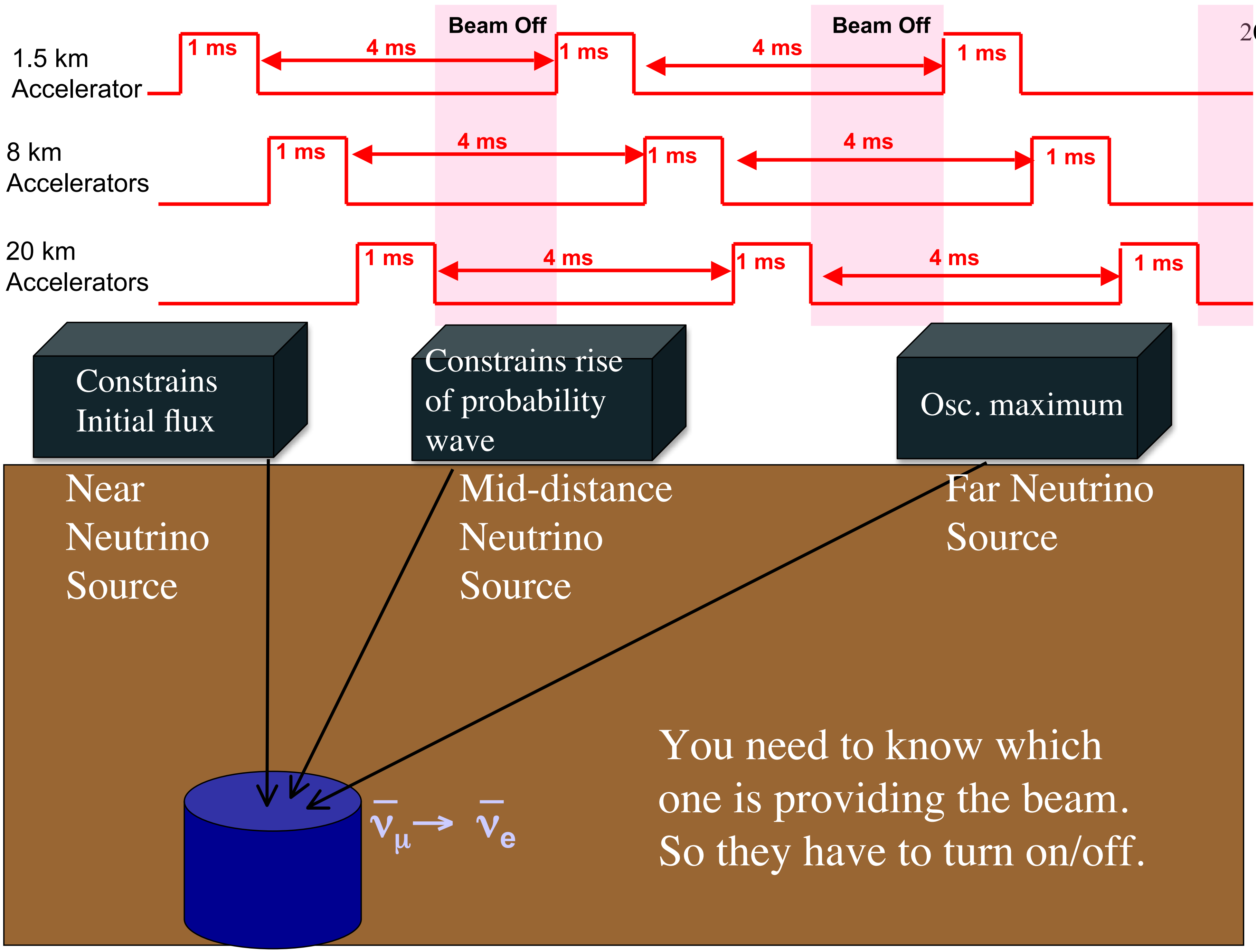




0.06
0.05
0.04
0.03
0.02
0.01
0
Oscillation Probability
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\delta = \pi/2$
$\delta = 0$
Distance
10
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Single Ultra-large Detector
With Free Protons as IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) Targets
(Oil or Water)



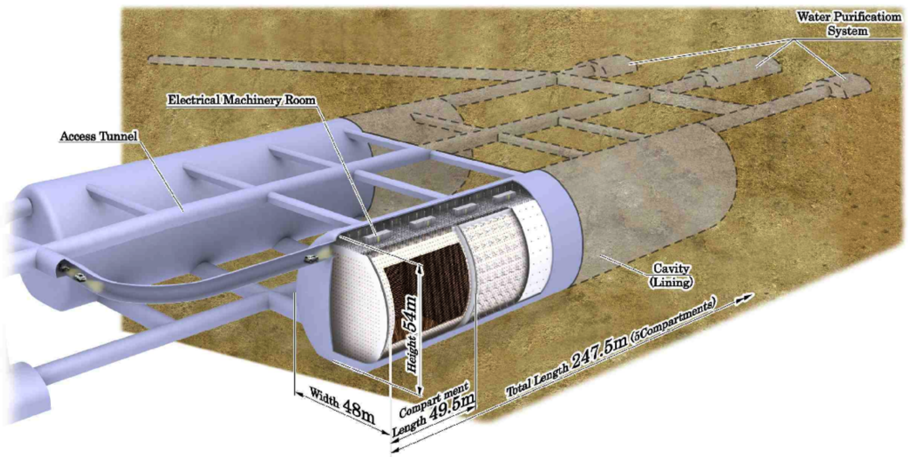
Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
10
Kil
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\delta = \pi/2$
$\delta = 0$
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Three Identical Beams
Flux [Arb. units]
Energy [MeV]
0
10
20
30
40
50
ν_e
$\bar{\nu}_\mu$
ν_μ

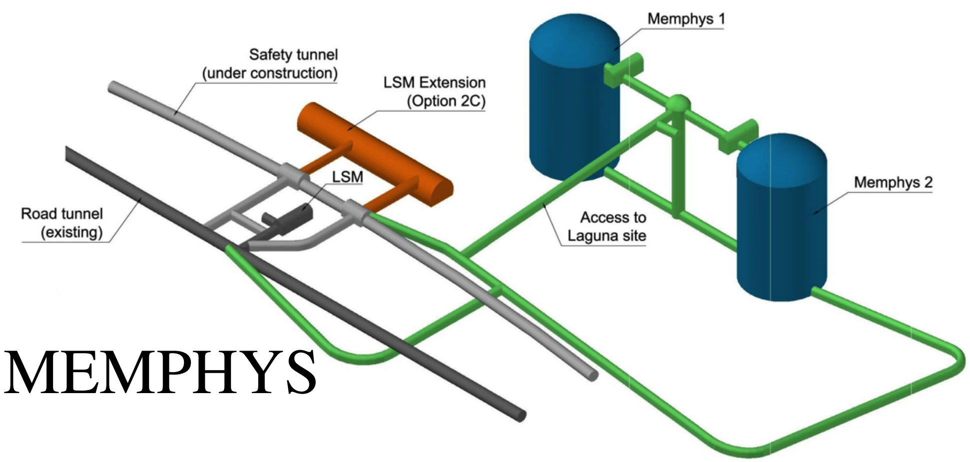

1.5 km
Accelerator
8 km
Accelerators
20 km
Accelerators
Beam Off
Beam Off
1 ms
4 ms
Constrains
Initial flux
Constrains rise
of probability
wave
Osc. maximum
Near
Neutrino
Source
Mid-distance
Neutrino
Source
Far Neutrino
Source
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
You need to know which
one is providing the beam.
So they have to turn on/off.

Where can DAEδALUS run?

Hyper-K (or initially, Super-K)

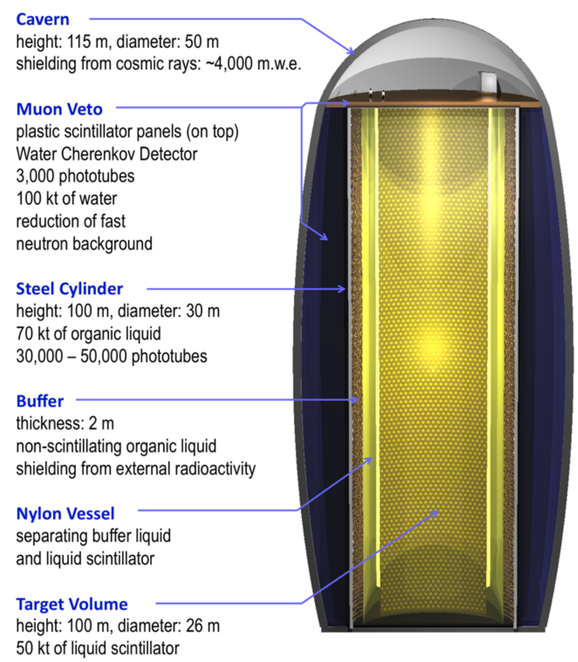
(Focus for current studies)





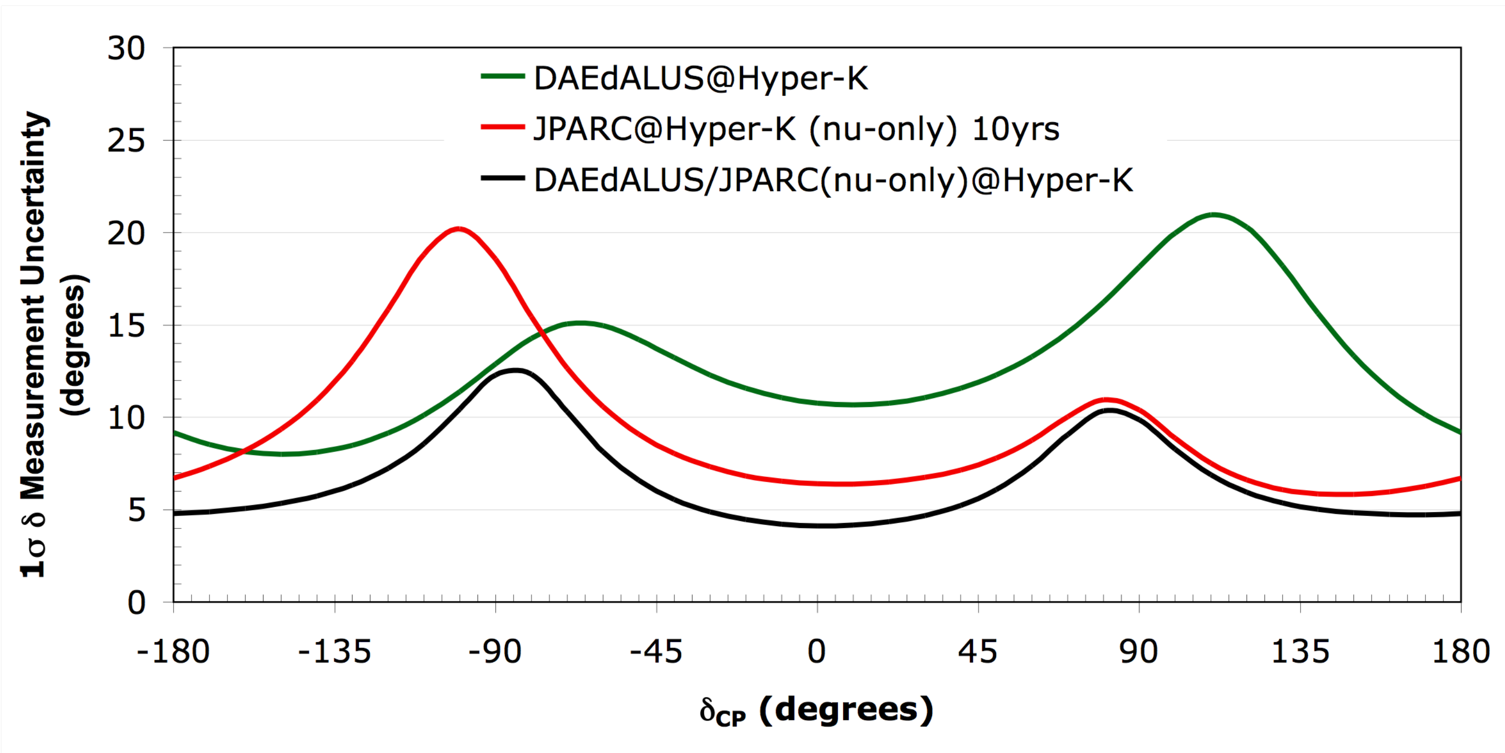
MEMPHYS

LENA - Scintillator Dectector

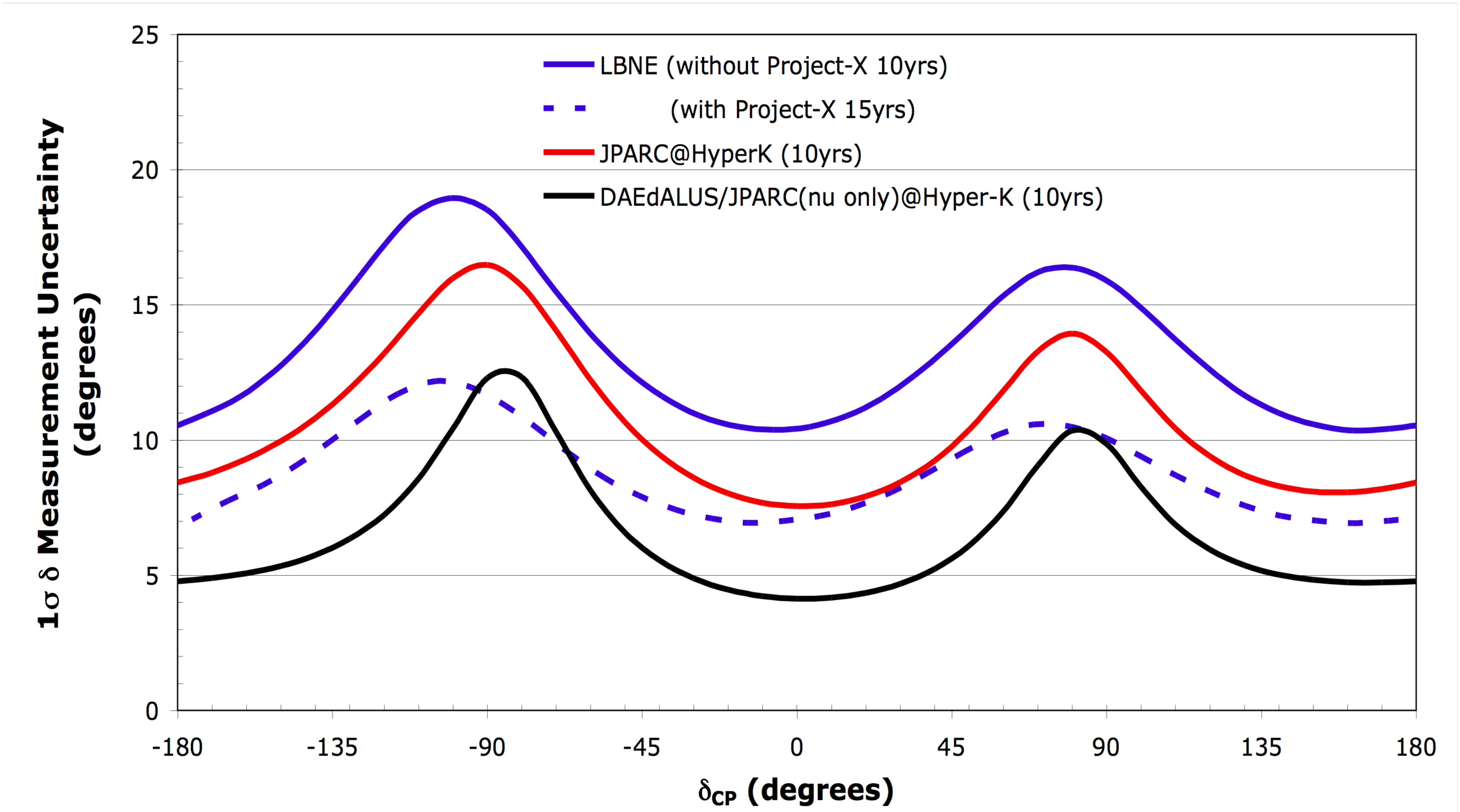


CP Violation Sensitivity

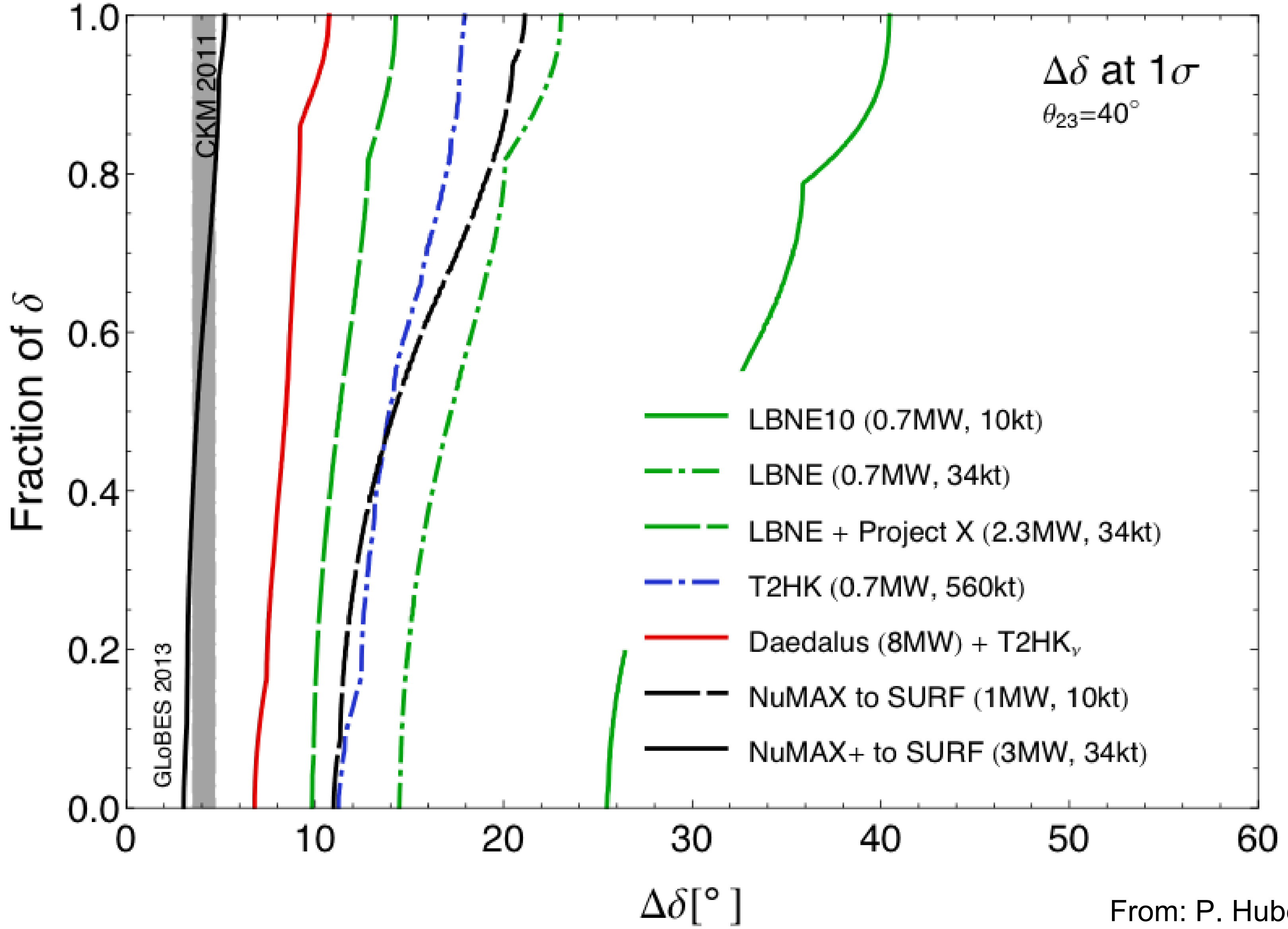
- Daeδalus has good CP sensitivity as a stand-alone experiment.
  - Small cross section, flux, and efficiency uncertainties
- Daeδalus can also be combined with long baseline ν-only data to give enhanced sensitivity, i.e. Hyper-K
  - Long baseline experiments have difficulty obtaining good statistics for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ which Daeδalus can provide
  - Daeδalus has no matter effects and can help remove ambiguities.



δ_{CP} Sensitivity Compared to Others



Comparison of δ_{CP} Measurement Uncertianties



From: P. Huber
Globes 2013

Final Comments

- High-power (~1MW) class cyclotrons are becoming a reality
  - For physics, they can provide high intensity neutrino sources
  - Important industrial interest for medical isotope production
  - Other applications in connection with accelerator driven reactors (ADS)

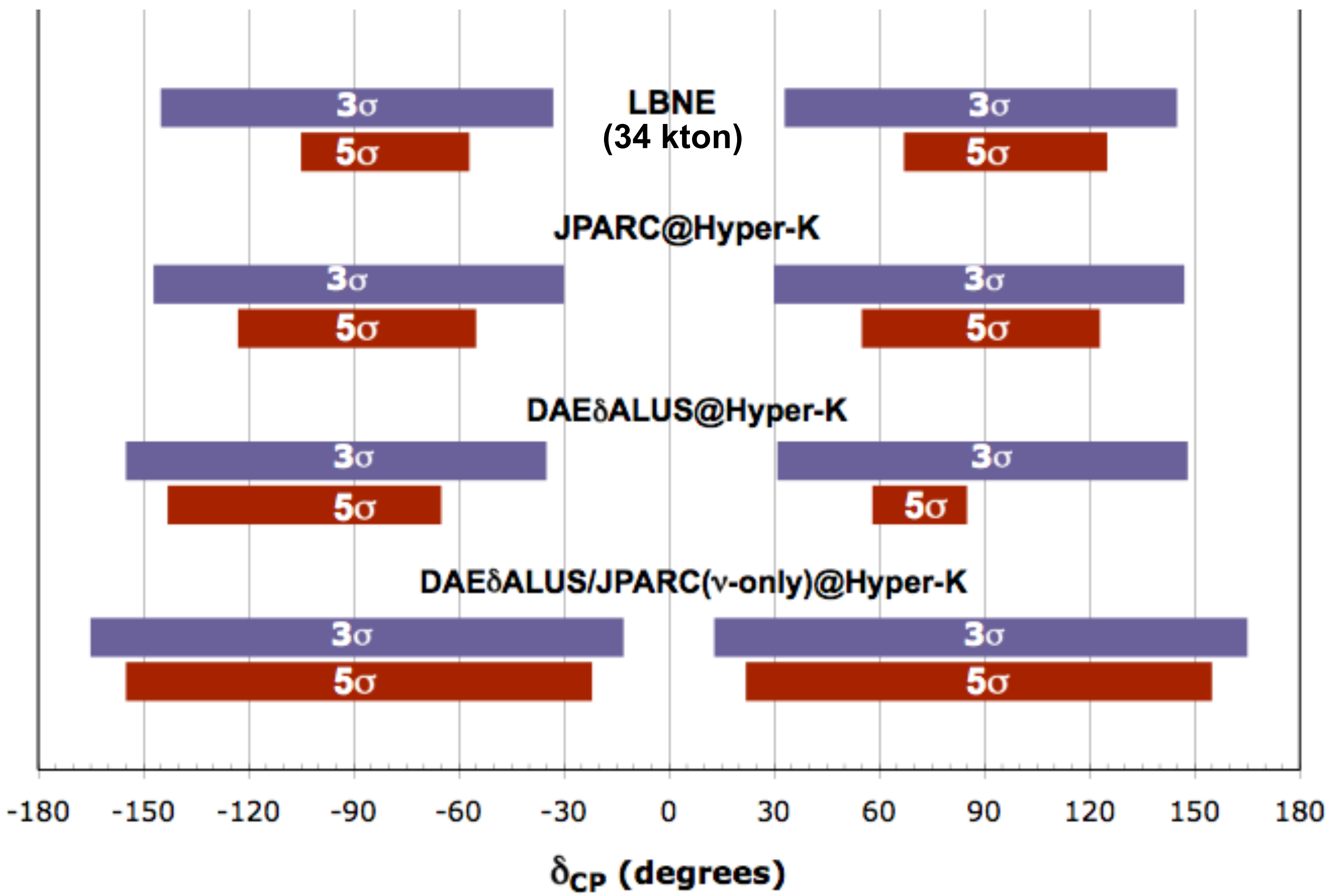
- Establishing the existence of sterile neutrinos would be a major result for particle physics
  - IsoDAR can make a definitive search for sterile neutrinos
    - Combined L and E analysis with good resolutions can isolate the oscillatory behavior and reduce backgrounds

- Daeδalus is another method to probe for CP violation in the ν-sector
  - Can provide high statistics $\bar{\nu}_e$ data with no matter effects and reduced systematic uncertainties
  - Can give enhanced sensitivity when combined with long baseline ν_e appearance data

Backup

δ_{CP} Discovery Potential

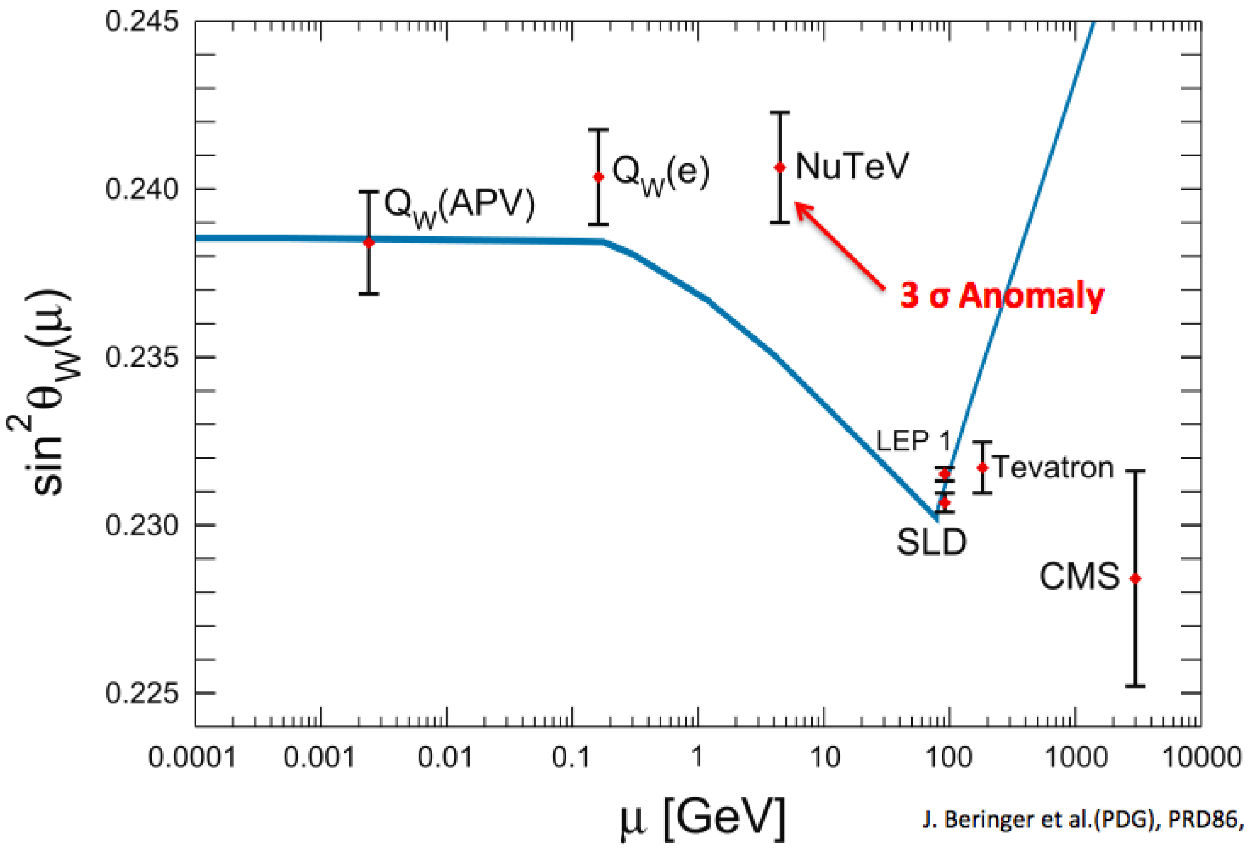
(exclude 0^0 and 180^0 with σ significance in 10yrs)



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

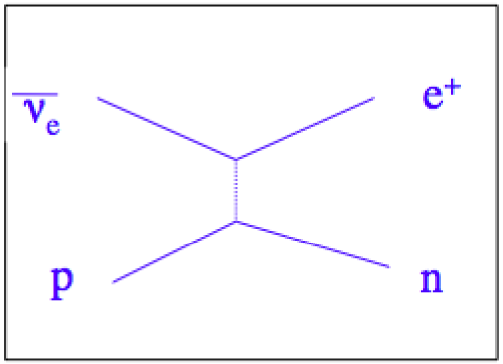
- NuTeV weak mixing angle measurement using neutrino neutral current scattering differs from expectation by 3σ
  - Is there something special with neutrinos or difficulty in NuTeV analysis?

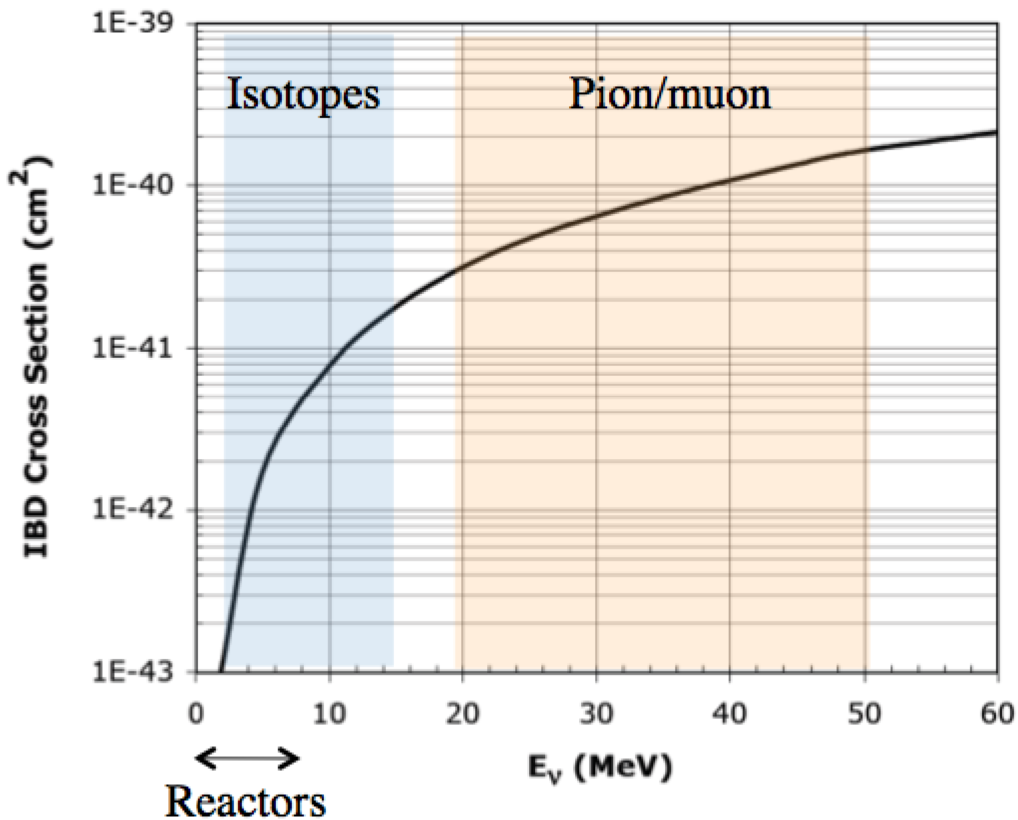
⇒ Use IsoDAR/Kamland to measure $\sin^2\theta_W$ with pure lepton process antineutrino-electron elastic scattering: $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$



J. Beringer et al.(PDG), PRD86, 010001 (2012)

Detect $\bar{\nu}_e$ Events using Inverse Beta Decay (IBD)

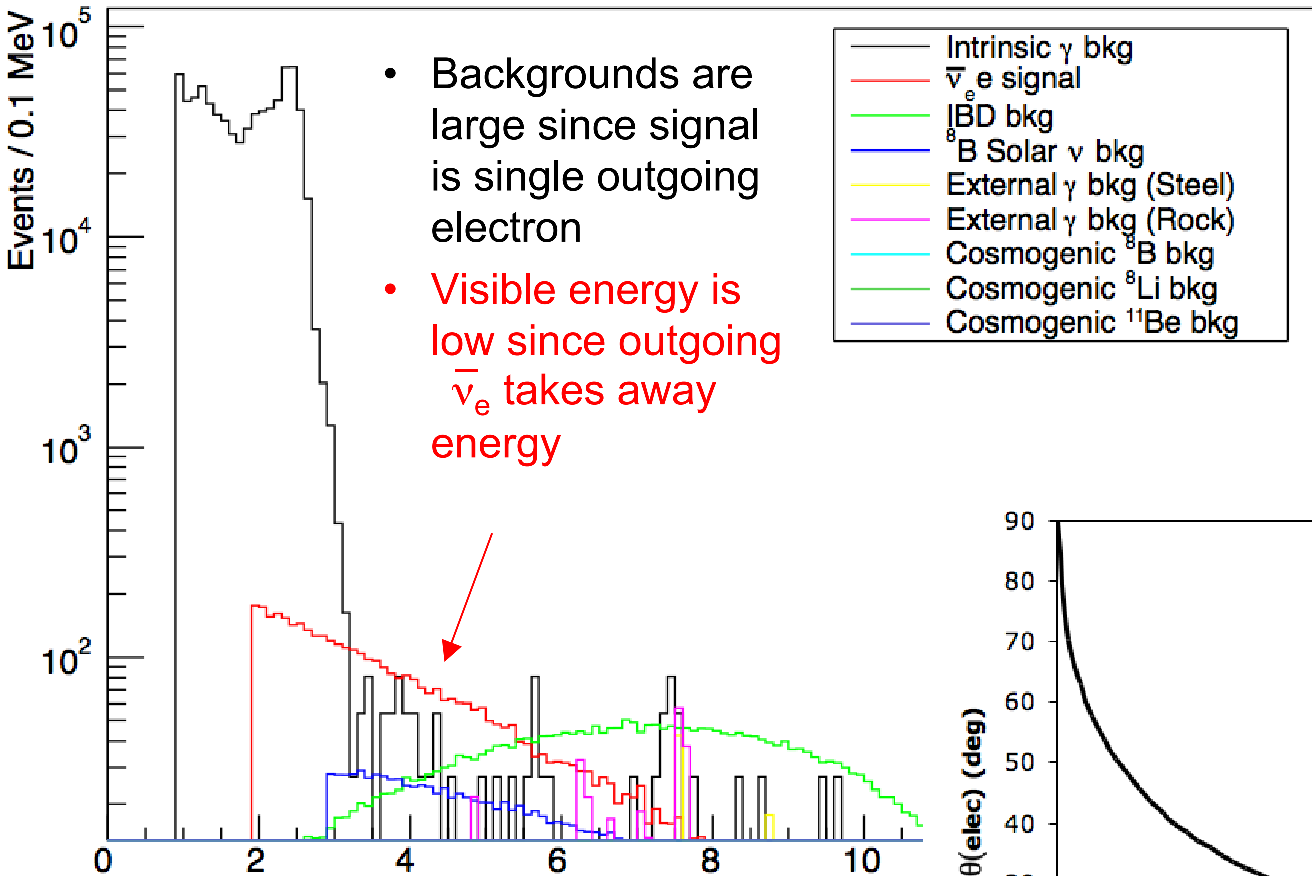




- Scintillator or Gd-doped water detector
- prompt positron signal followed by neutron capture
- $E_{\bar{\nu}_e} \cong E_{prompt} + 0.78$ MeV

Kamland Backgrounds to $\bar{\nu}_e e$ Signal

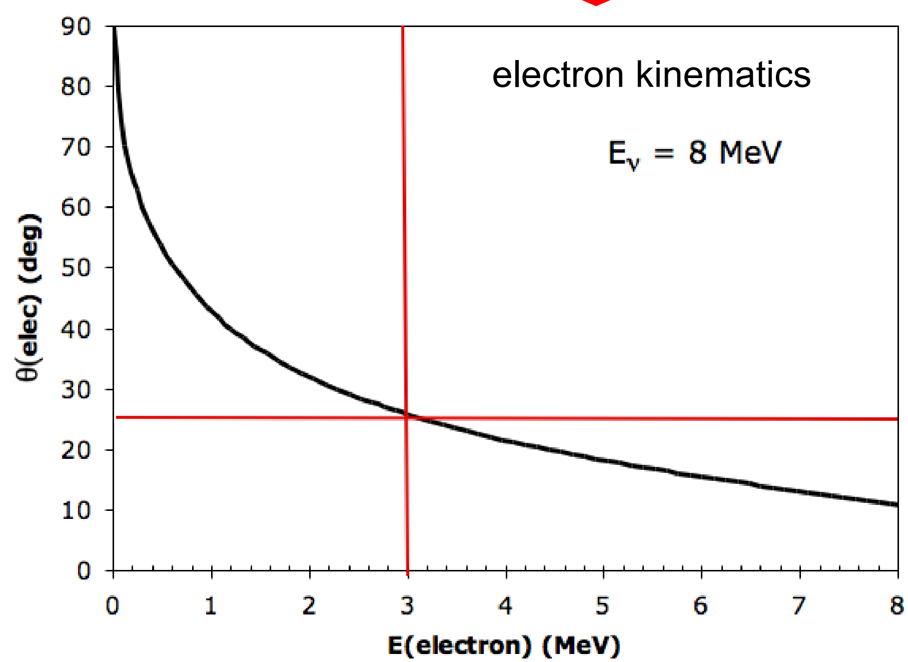
- Backgrounds are large since signal is single outgoing electron
- Visible energy is low since outgoing $\bar{\nu}_e$ takes away energy



From L. Winslow

Cuts:
- Evis > 3 MeV
- θ (to source) < 25^0

⇒ Reduce isotropic bkgnd by x2



Use large sample of IBD events to constrain normalization to 0.2%