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

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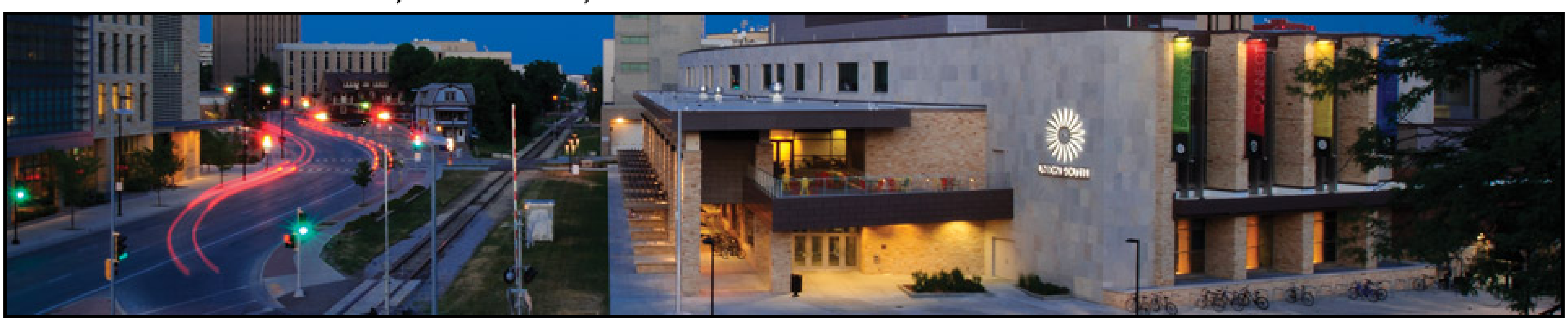
ICECUBE PARTICLE ASTROPHYSICS SYMPOSIUM

IPA2013: May 13-15, Madison, WI



Daedalus and IsoDAR Experiments

A two-phase physics program using cyclotron accelerators to make decay-at-rest neutrino sources.

Phase 1: Very short baseline search for sterile neutrinos (IsoDAR)

- Use an isotope decay-at-rest neutrino source
- Search for $\bar{\nu}_e$ disappearance as a function of energy and distance

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

Phase 2: A new way to search for CP violation in the ν-sector (Daeδalus)

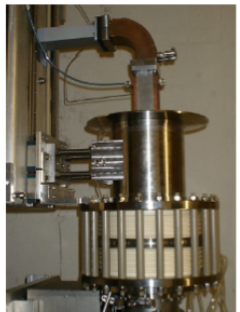
- Traditional approach:
  - A single neutrino beam and multiple detectors at different baselines
  - Compare ν_e to $\bar{\nu}_e$ appearance probability in far detector
- Daeδdalus approach*:
  - A single large detector and multiple pion decay-at-rest neutrino sources
  - Compare $\bar{\nu}_e$ appearance rate as function of energy and distance

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

DAEδDALUS High Power (~1 MW) 800 MeV Cyclotron System

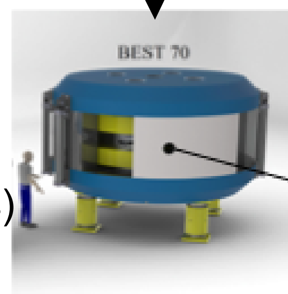
(Under Development with Lab and Industrial Partners)

H_2^+ Ion Source

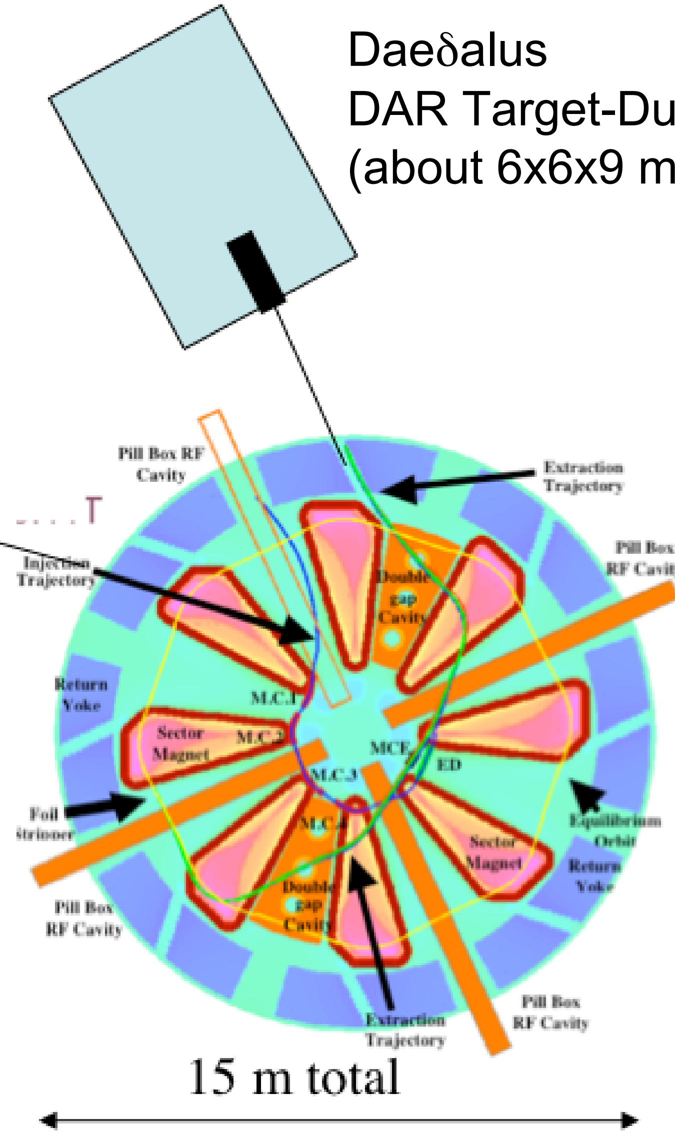


IsoDAR Cyclotron

Injector Cyclotron (Resistive Isochronous)



Daeδalus DAR Target-Dump (about 6x6x9 m³)



Multimegawat Daeδalus Cyclotron for Neutrino Physics

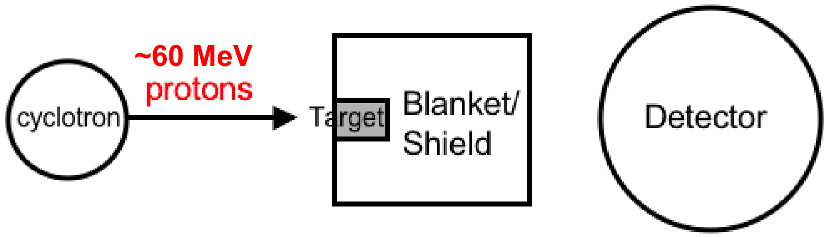
arXiv:1207.4895

Ring Cyclotron (Superconducting)

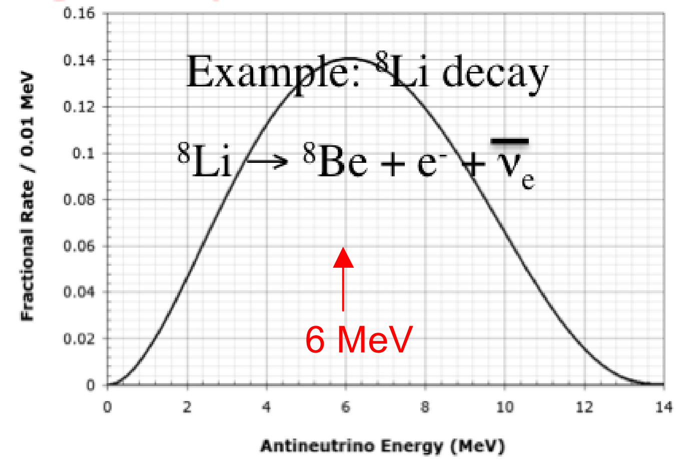
"Isochronous cyclotron" where mag. field changes with radius, but RF does not change with time. This can accelerate many bunches at once.

Cyclotron Neutrino Sources

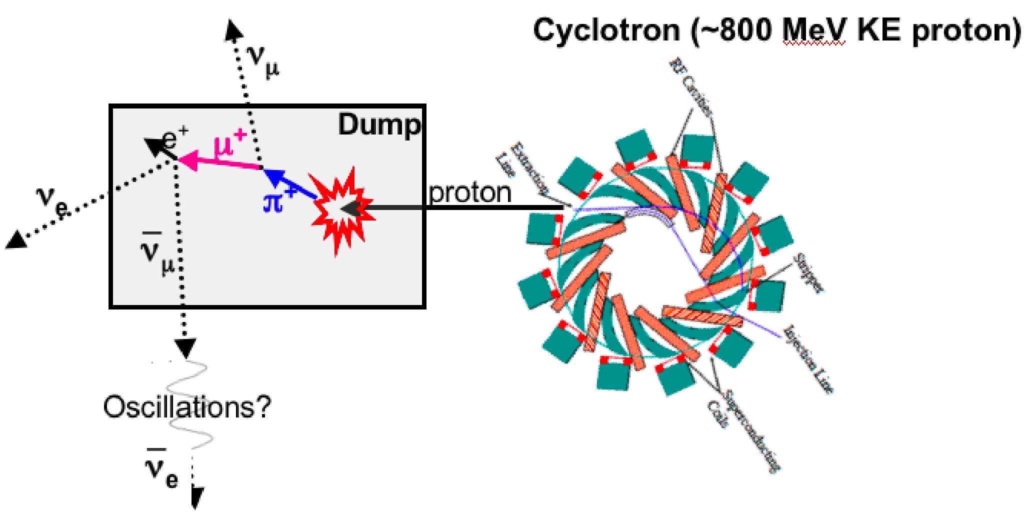
IsoDAR Setup:



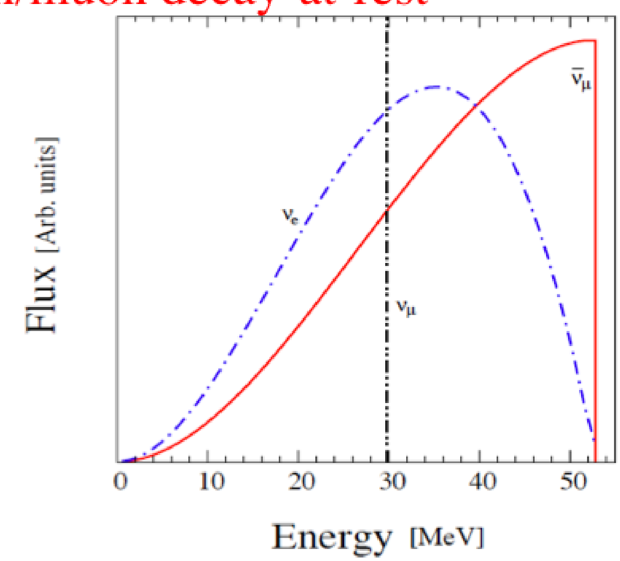
Isotope decay-at-rest



Daeδalus Setup:

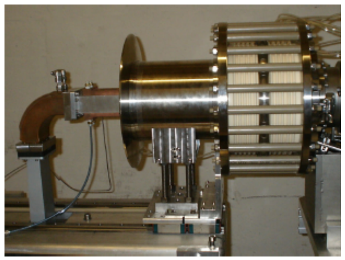


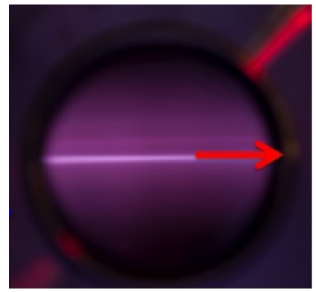
Pion/muon decay-at-rest



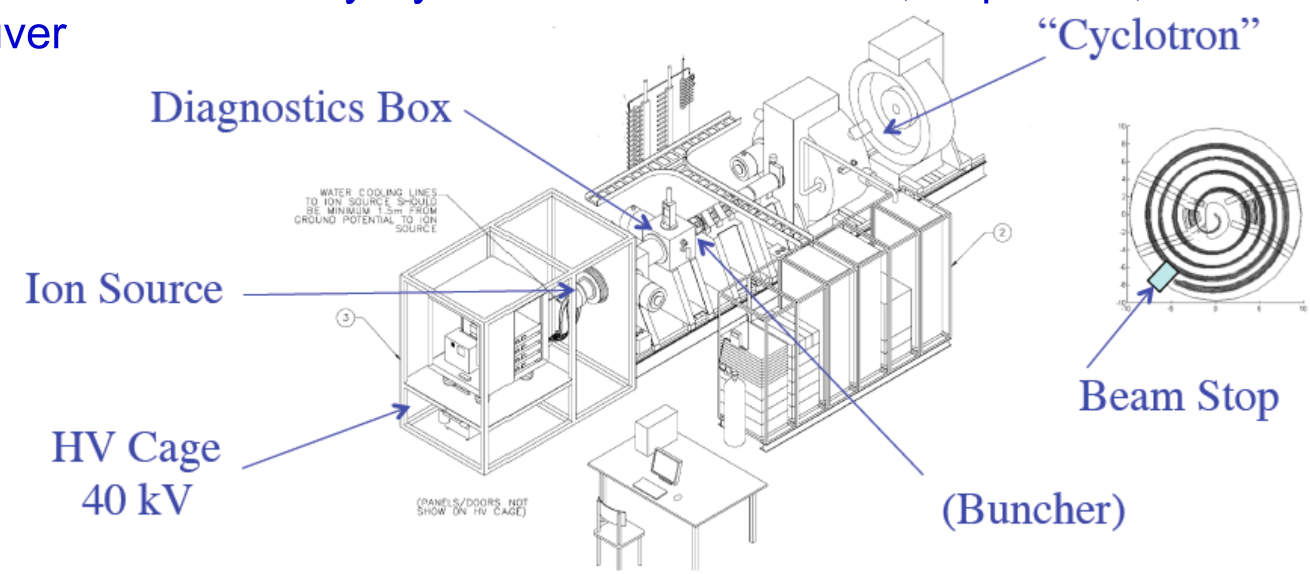
Current Accomplishments and Status

- 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 (NSF funded)
  - Results to be available by Cyclotrons'13 Conference, Sept 2013, Vancouver



IsoDAR Experiment

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

Where Are We With Sterile Neutrinos?

- Several hints of oscillations through sterile neutrino state with $\Delta m^2 \approx 1\ eV^2$
  - LSND / MiniBooNE ν_e / $\bar{\nu}_e$ appearance
  - Reactor $\bar{\nu}_e$ disappearance ("Reactor Anomaly")
  - Radioactive source ν_e disappearance
  - But still no indication of ν_μ disappearance

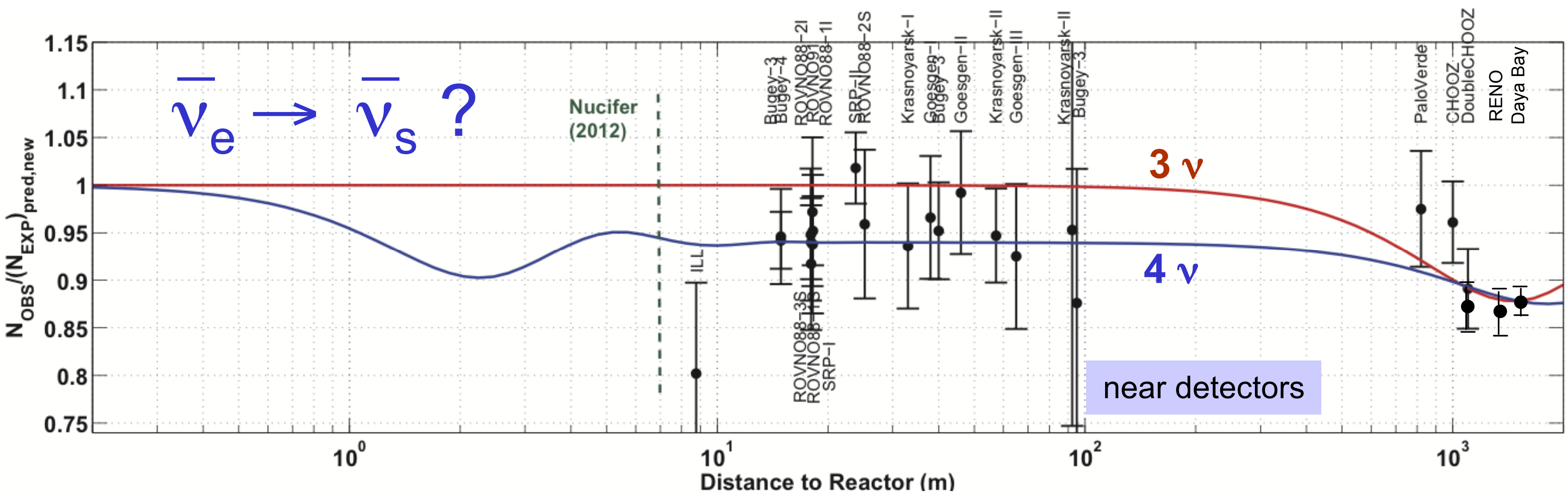
Some difficulty for fits with one or two sterile neutrino models
- App vs Disapp
- ν vs $\bar{\nu}$

- Establishing the existence of sterile neutrinos would be a major result for particle physics but …..

- Need definitive experiments
  - Significance at the > 5σ level
  - Observation of oscillatory behavior within detector

- Several directions for next generation experiments
  - Multi-detector accelerator neutrino beam experiments
  - Very short baseline (VSBL) experiments with compact neutrino sources

Has $\bar{\nu}_e$ Disappearance Been Observed? ⇒ Reactor Antineutrino Anomaly



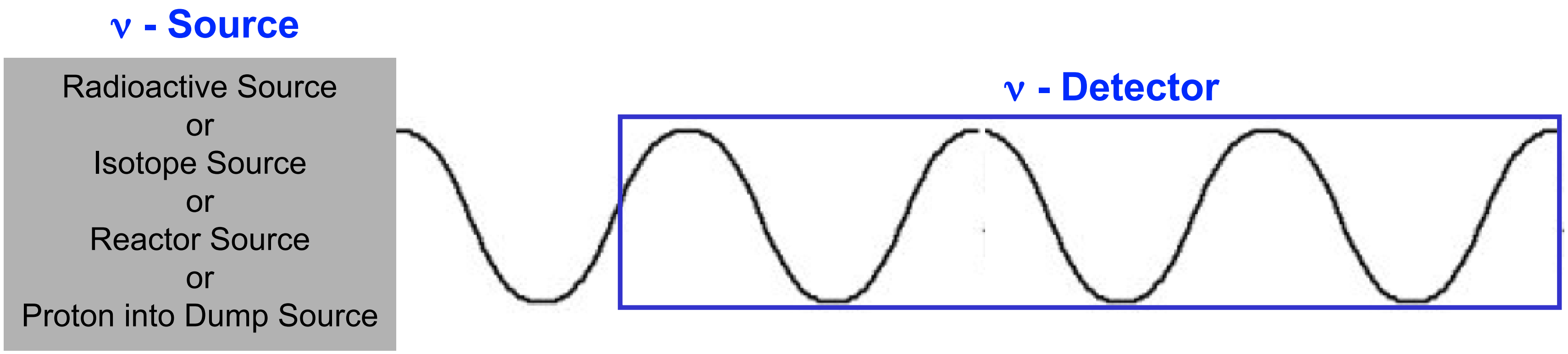
Region to Explore for Sterile Neutrinos

Older Reactor Exps at Close Distances
R = 0.927 ± 0.023 (3.0 σ)

Current Reactor Experiments

Red: 3ν $\sin^2(2\theta_{13}) = 0.15$
Blue: 4ν $\Delta m^2_{new} = 2$ eV^2
and $\sin^2(2\theta_{new})=0.12$,
with $\sin^2(2\theta_{13}) = 0.085$
arXiv: 1204.5379

Very-short Baseline Oscillation Experiments



$$1/L^2 \text{ flux rate modulated by } \text{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L / E\right)$$

- Can observe oscillatory behavior within the detector if neutrino source has small extent .
  - Look for a change in event rate as a function of position and energy within the detector
  - Bin observed events in L/E (corrected for the $1/L^2$) to search for oscillations

- Backgrounds produce fake events that do not show the oscillation L/E behavior and can be separated from signal

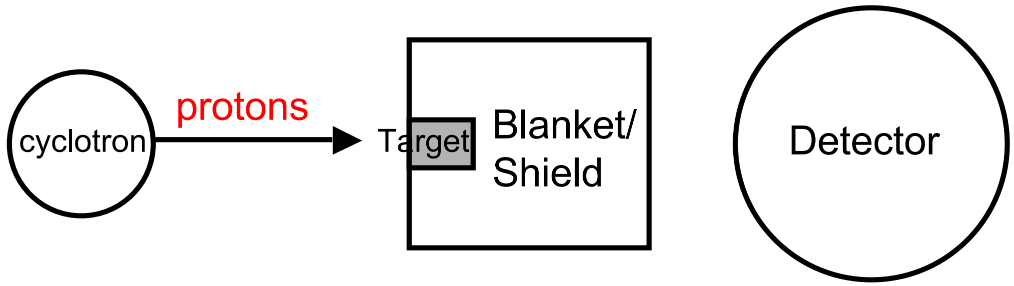
Possible Sources for VSBL Experiments

Need experiments with L/E ~ 1 m/MeV

- Reactor sources
  - E_ν ~ 3 MeV ⇒ optimum distance around 3 to 20 m
  - Reactor core size can also be an issue
- Radioactive sources
  - E_ν ~ few MeV ⇒ see oscillations with wavelengths ~ 1m
  - Compact source can be placed directly into detector or just outside
- Isotope neutrino source
  - E_ν ~ 8 MeV (typical of short lived isotopes, i.e. ^8Li)
  - Compact source that can be set up near an existing large detector
  - Beam can be turned off periodically to measure background
  - Higher energy neutrinos with less background

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

- High intensity $\bar{\nu}_e$ source using β-decay at rest of ^{8}Li isotope ⇒ IsoDAR
- ^{8}Li produced by high intensity (10ma) proton beam from 60 MeV cyclotron
  ⇒ 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….

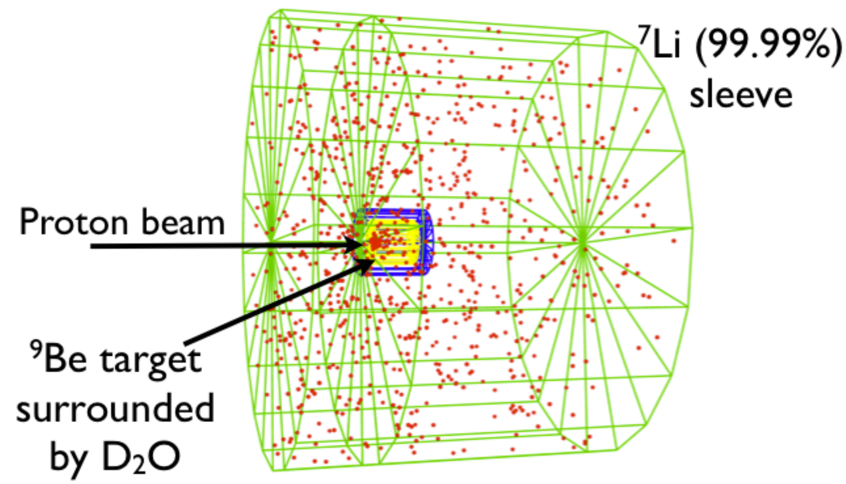


- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector as a function of L and E.

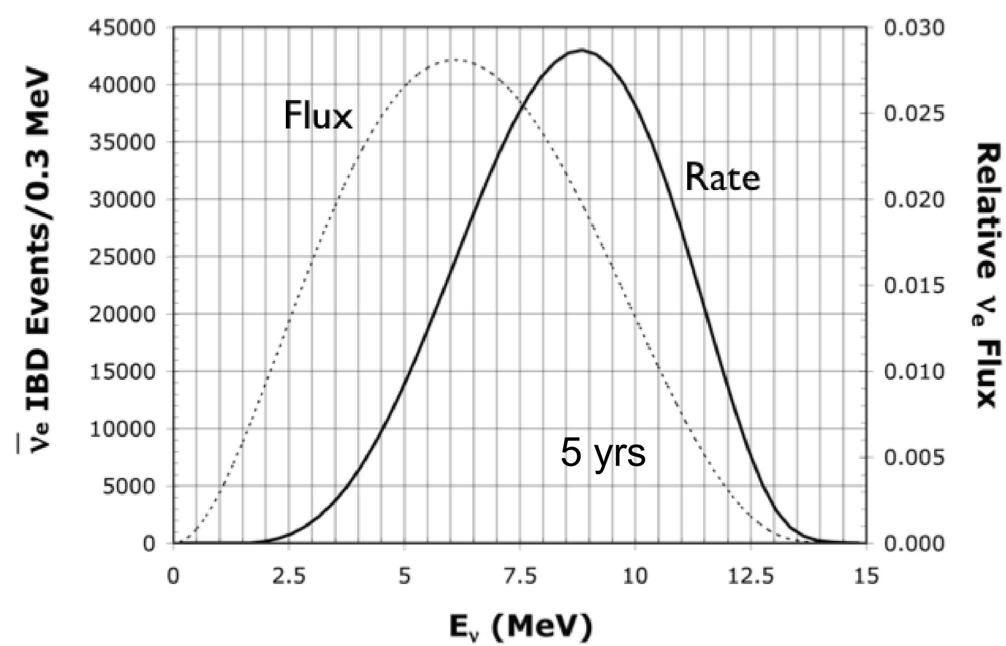
Phys Rev Lett 109 141802 (2012)
arXiv:1205.4419

IsoDAR Neutrino Source and Events

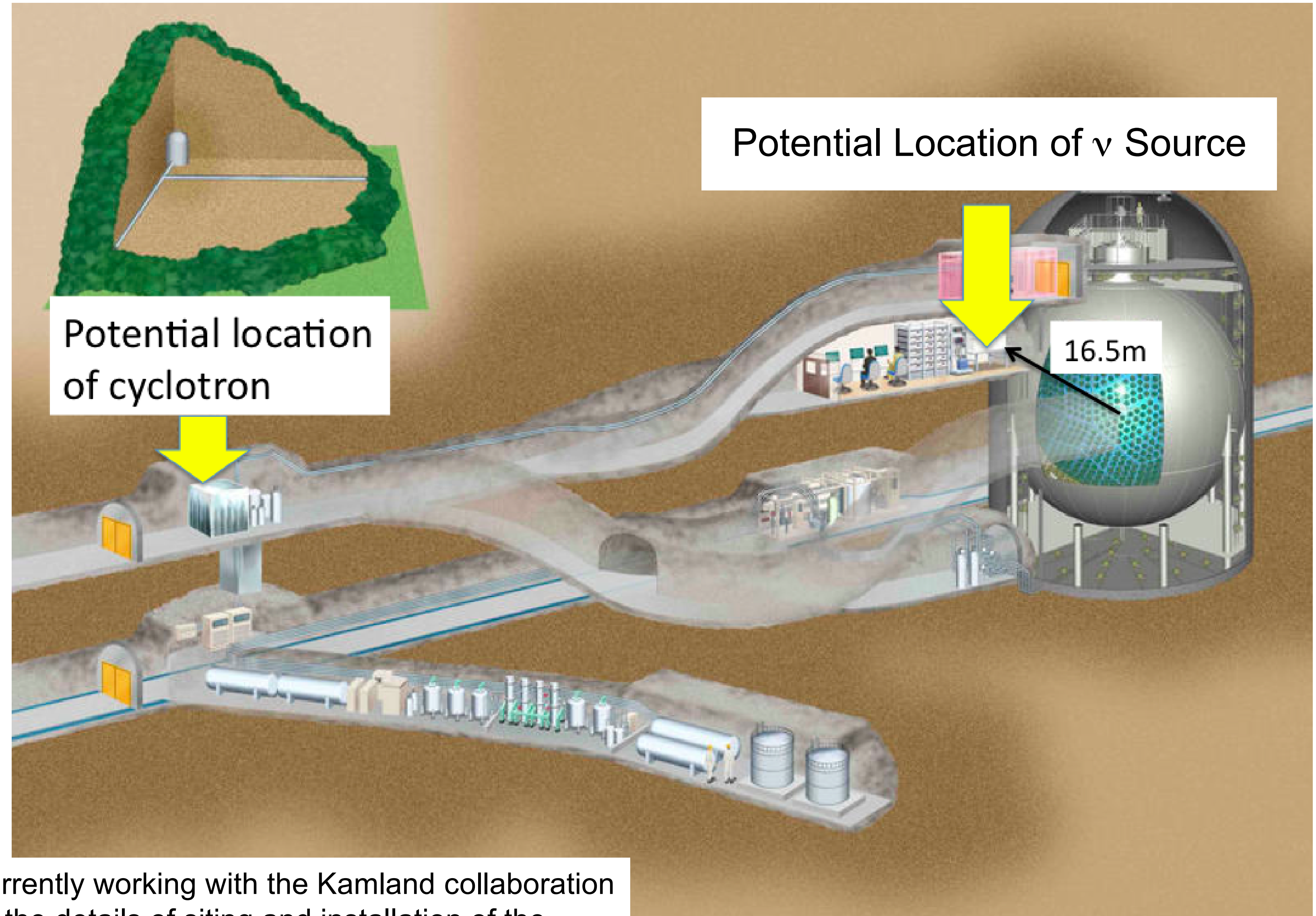
- p (60 MeV) + $^{9}Be \rightarrow {}^{8}Li + 2p$
  - plus many neutrons since low binding energy
- n + ^{7}Li (shielding) $\rightarrow {}^{8}Li$
- $^{8}Li \rightarrow {}^{8}Be + e^{-} + \bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV
  - 2.6×10^{22} $\bar{\nu}_e$ / yr
- Example detector: Kamland (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

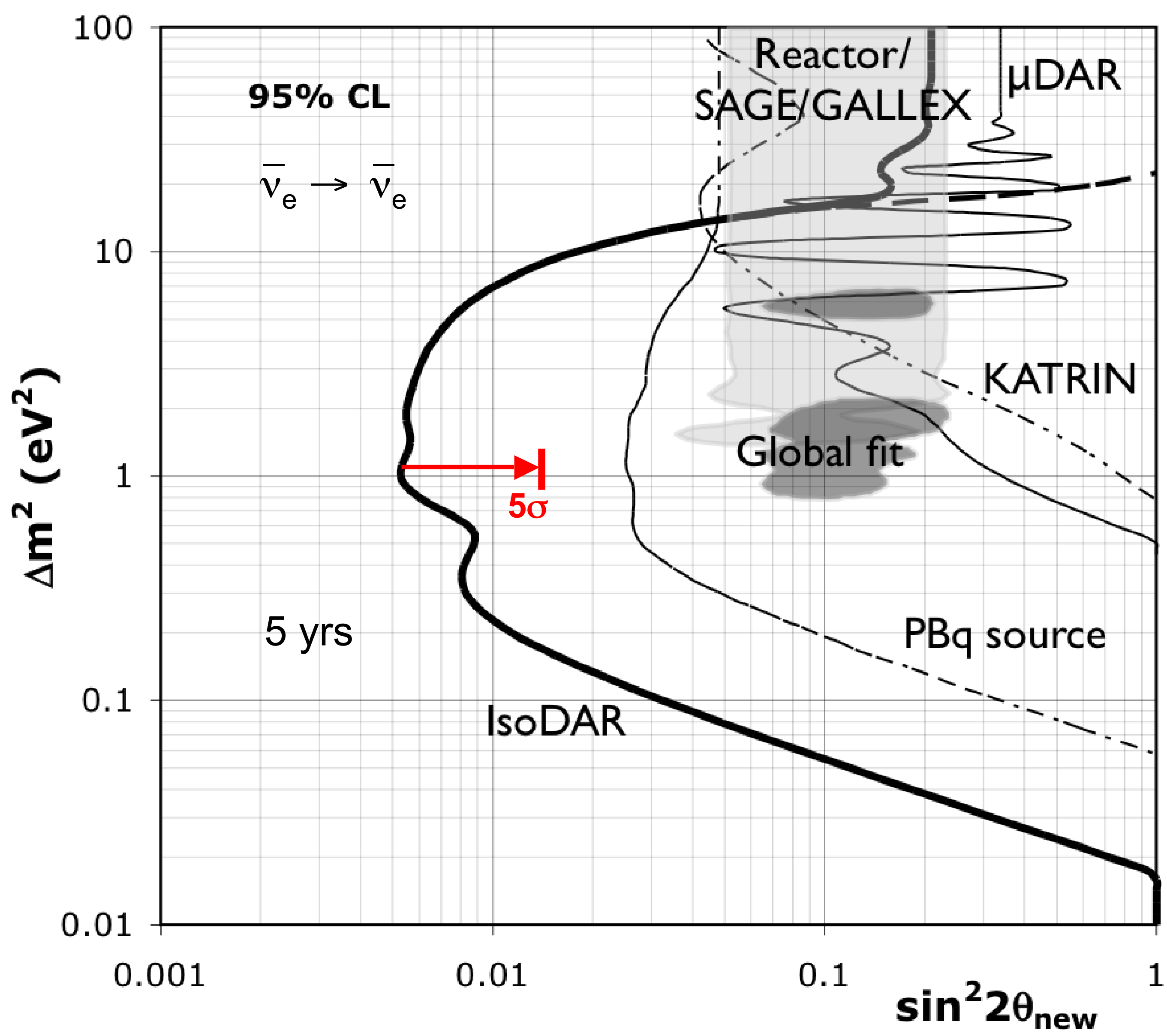


IsoDAR at Kamland

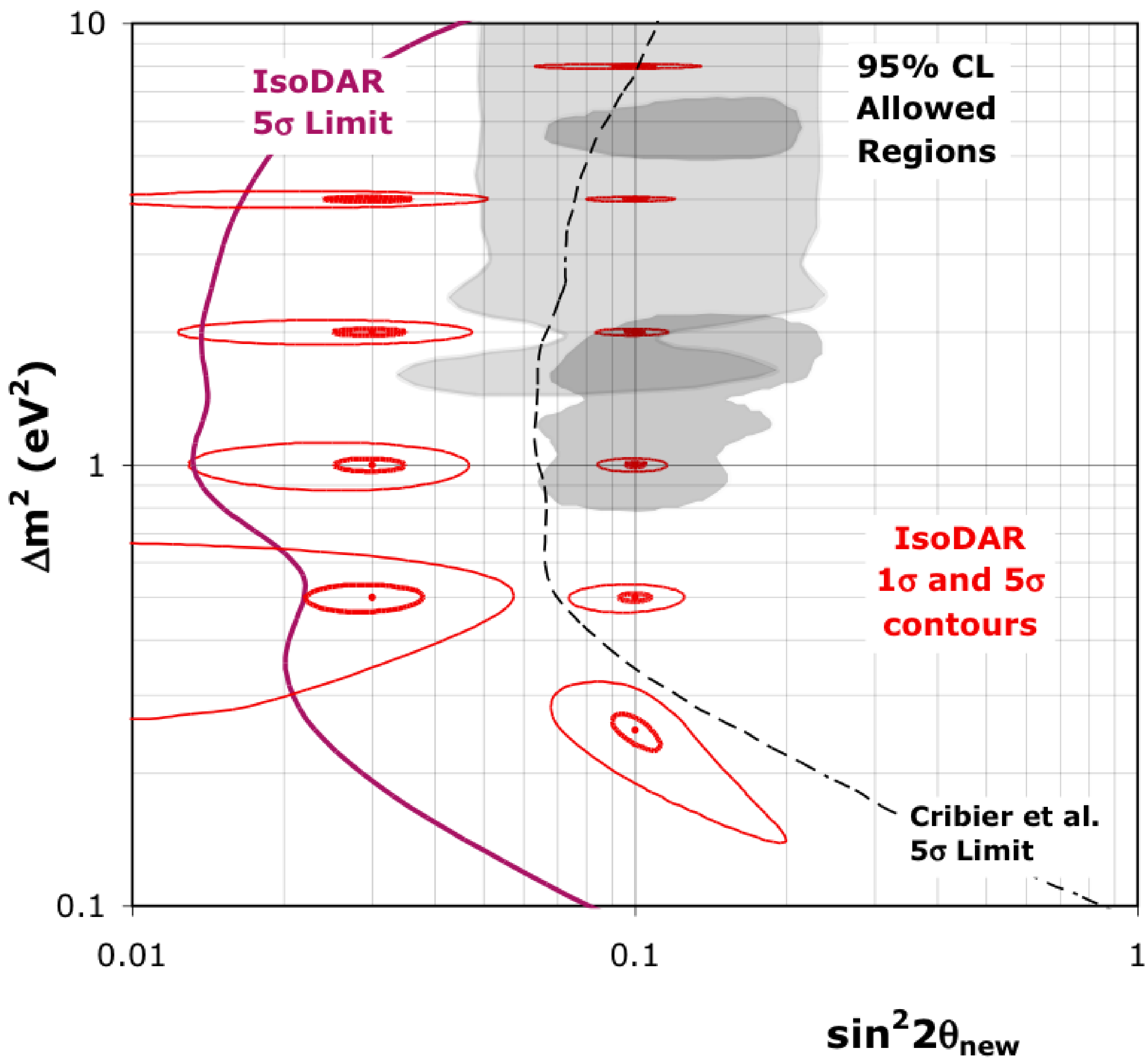


Currently working with the Kamland collaboration on the details of siting and installation of the cyclotron, beamline, and neutrino source.

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

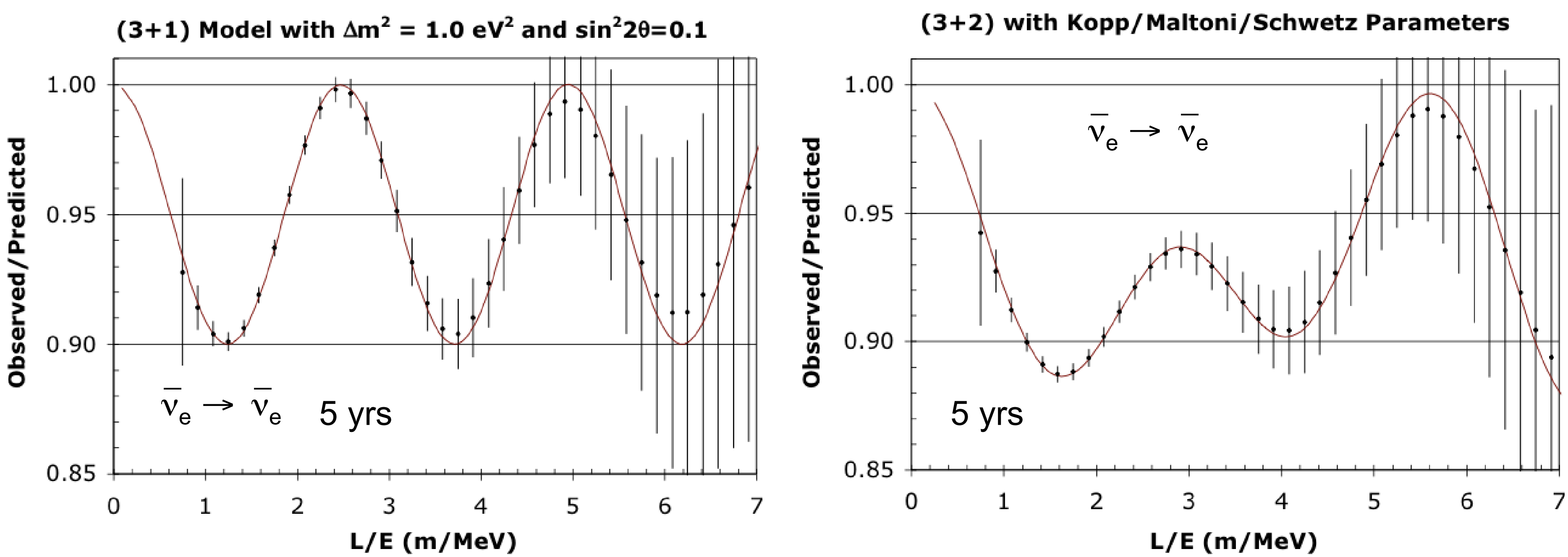


IsoDAR Measurement Sensitivity



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

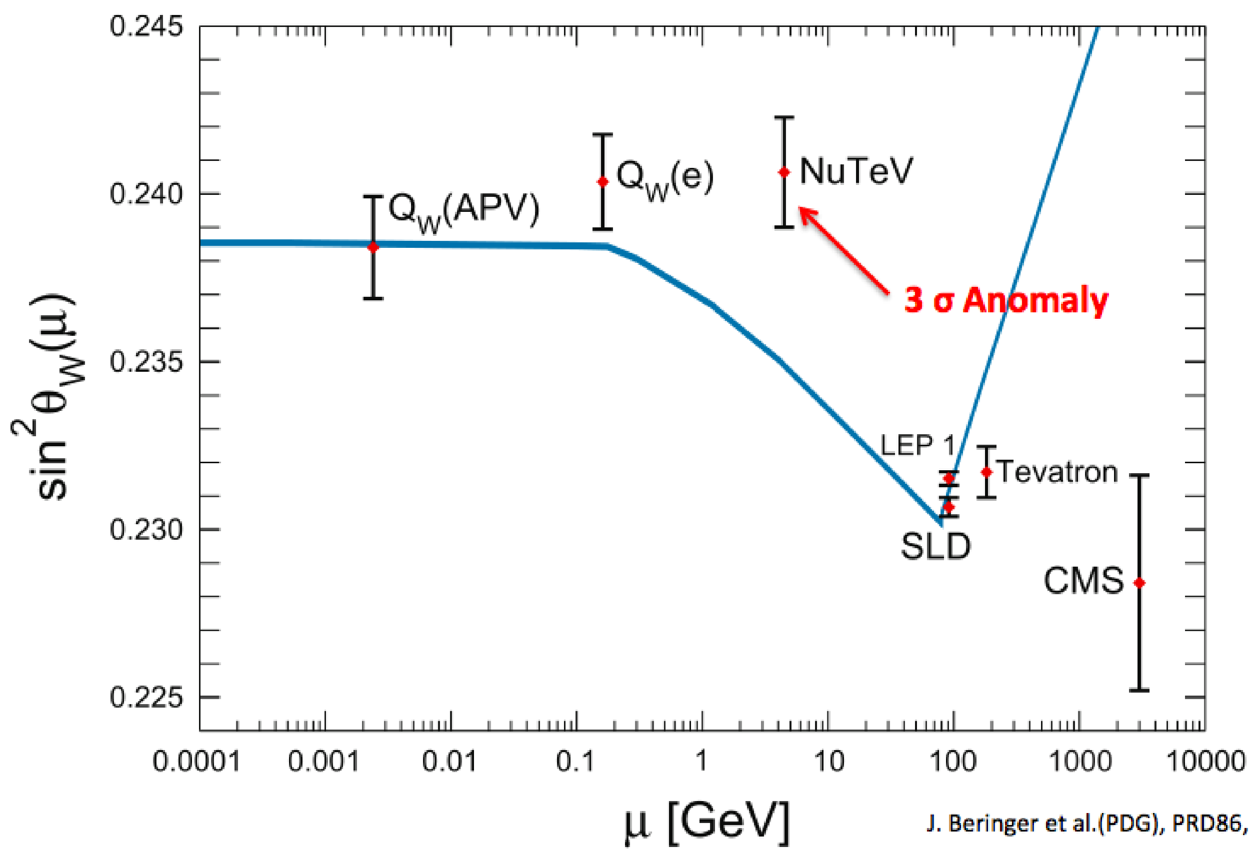
Beyond Oscillations:

IsoDAR $\sin^2\theta_W$ Measurement

$\bar{\nu}_e$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: $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$



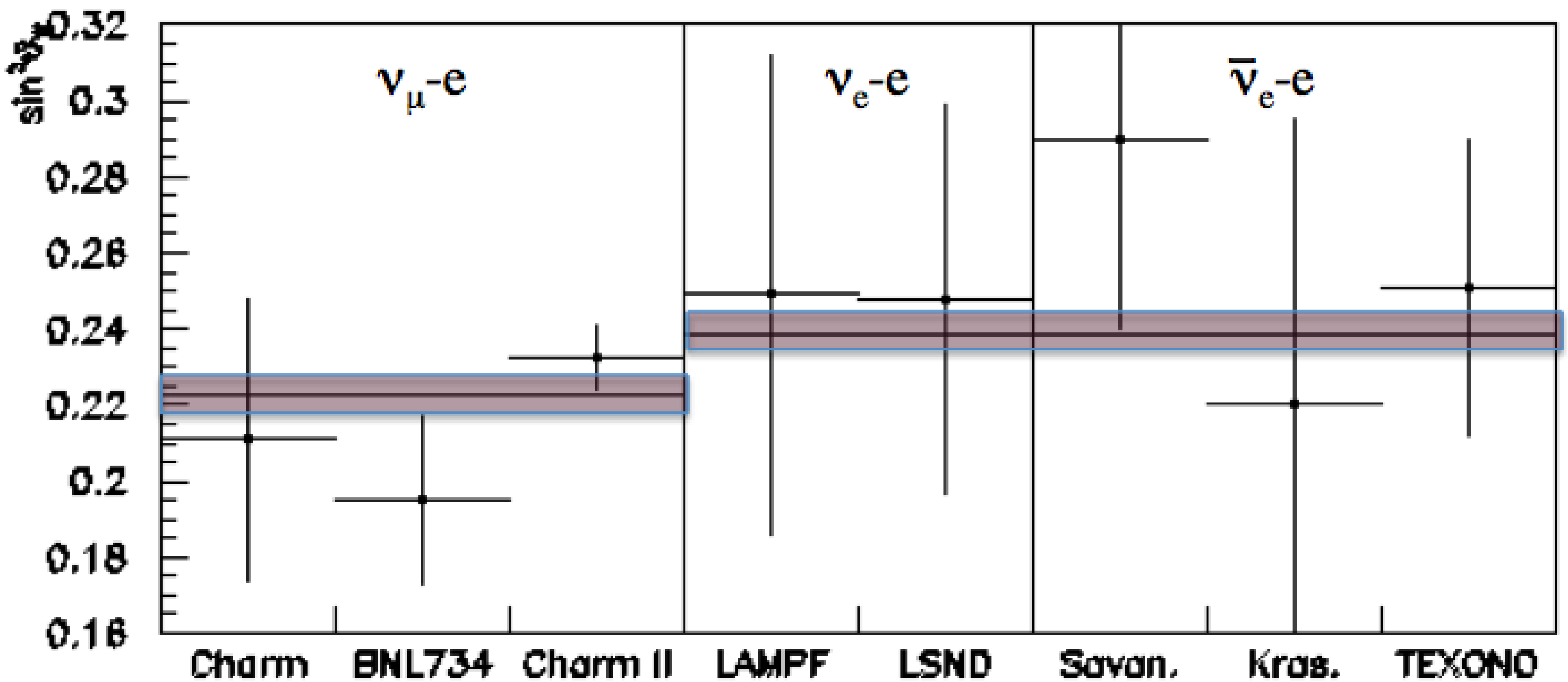
J. Beringer et al.(PDG), PRD86, 010001 (2012)

IsoDAR $\sin^2\theta_W$ Measurement Sensivity

- 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 ν_ee) elastic scattering measurement (See 3% band below)



→ **Blue band**: 3% measurement

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}

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

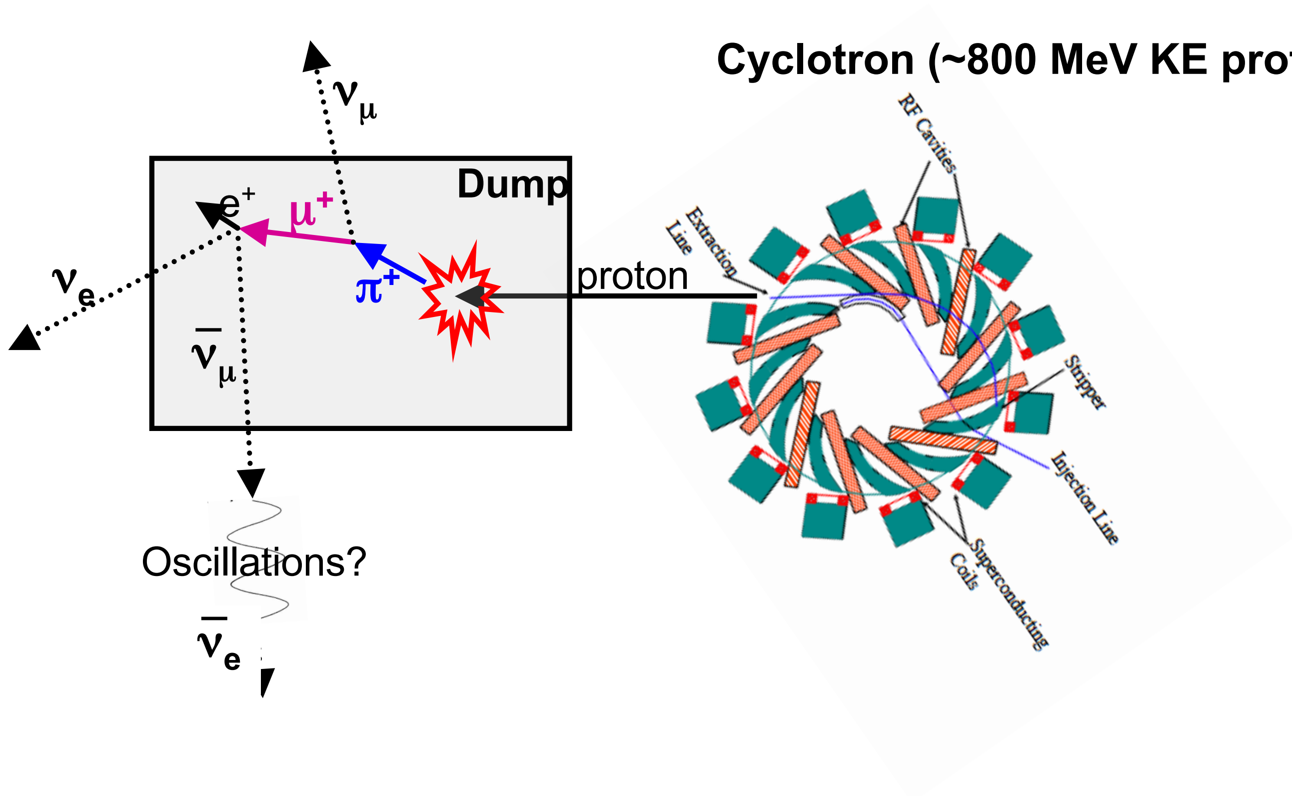
We want to see if δ is nonzero

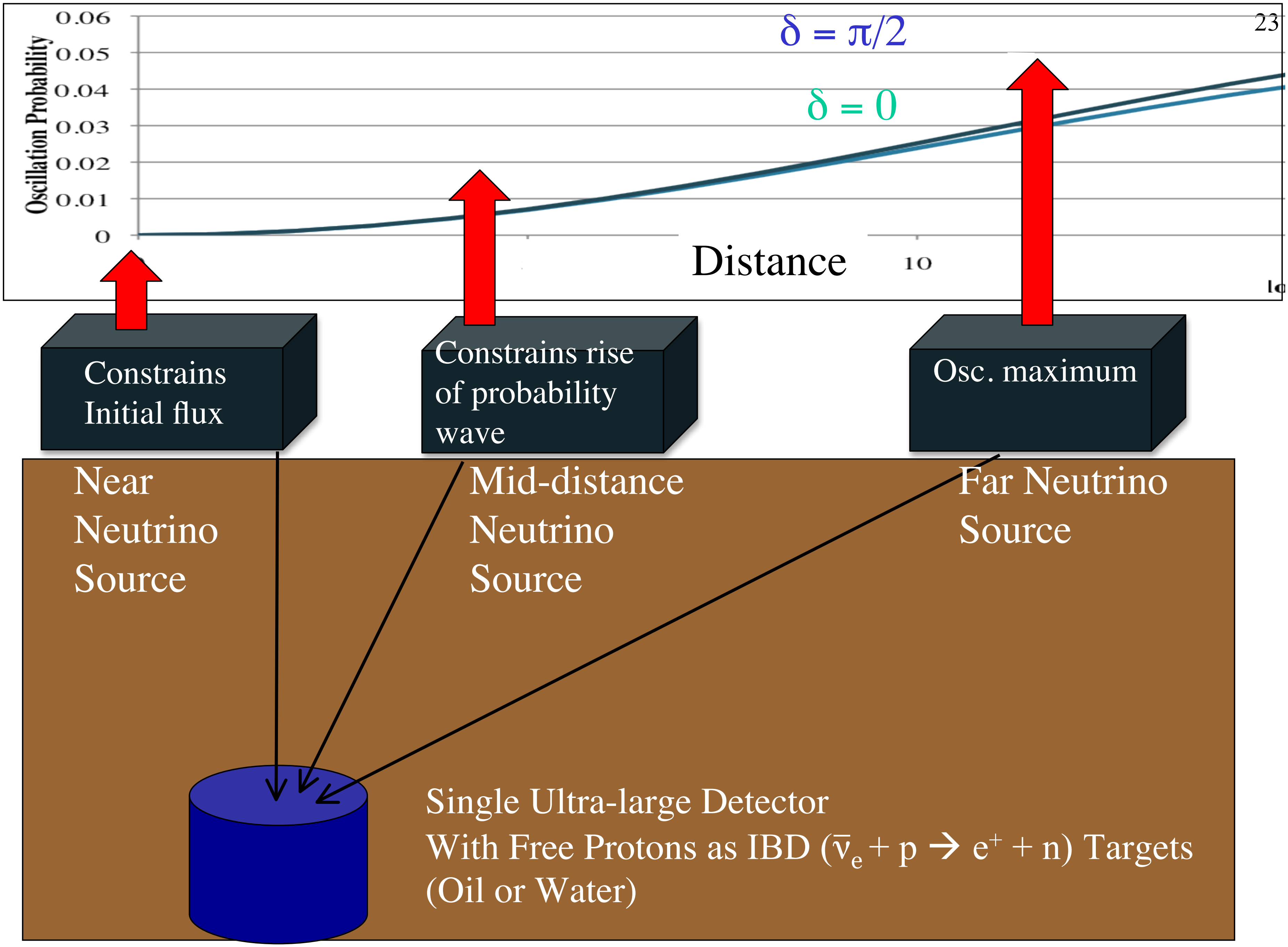
terms depending on mixing angles

terms depending on mass splittings

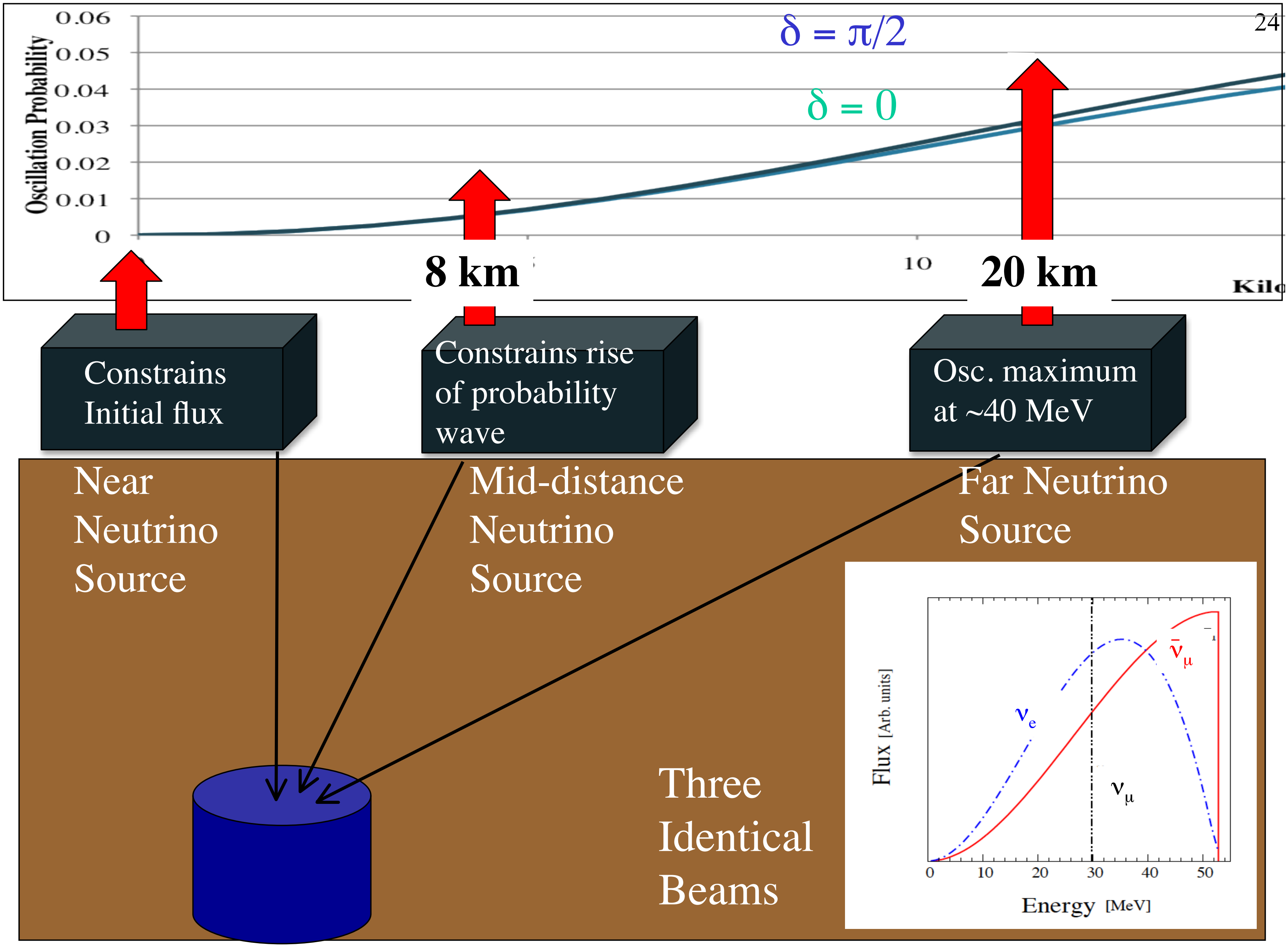
$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

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

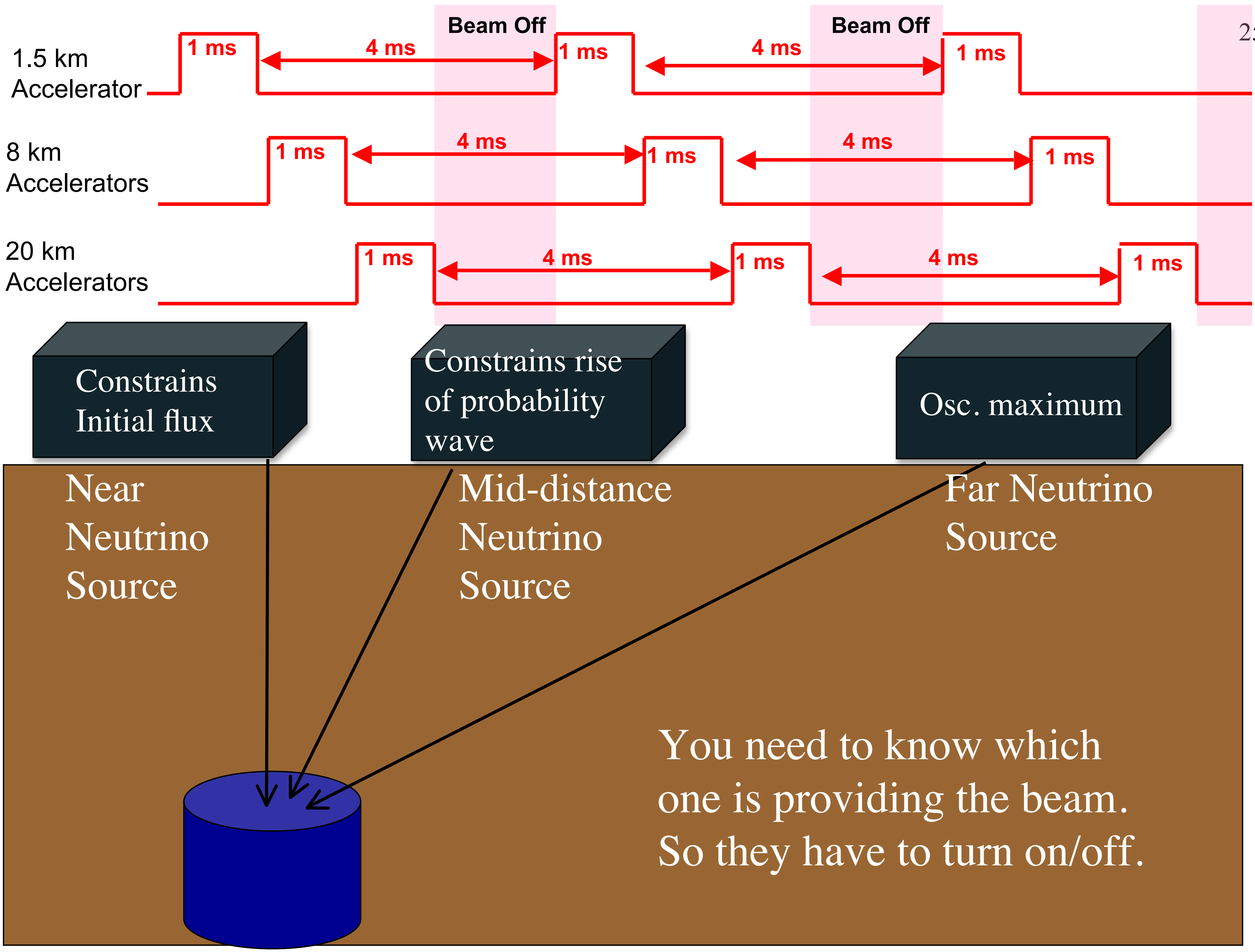




Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
δ = π/2
δ = 0
Distance
10
23
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Single Ultra-large Detector
With Free Protons as IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) Targets
(Oil or Water)



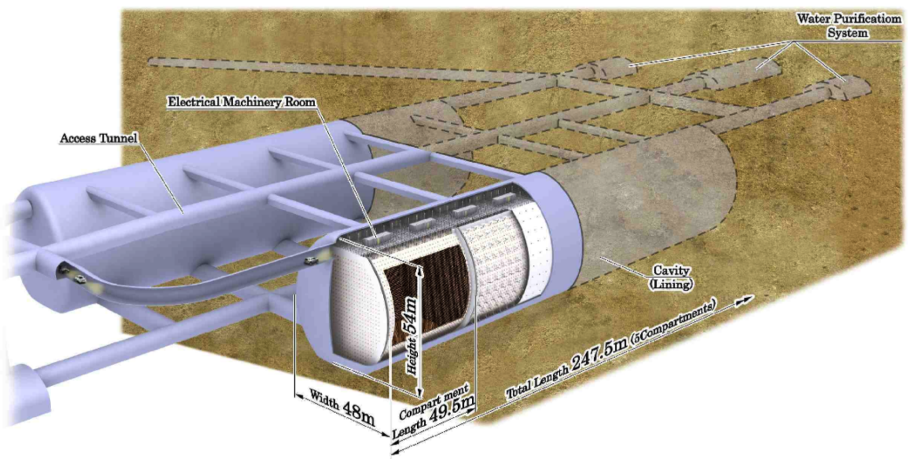
Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
10
Kilo
δ = π/2
δ = 0
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Three Identical Beams
Flux [Arb. units]
Energy [MeV]
0
10
20
30
40
50
ν_e
ν̄_μ
ν_μ



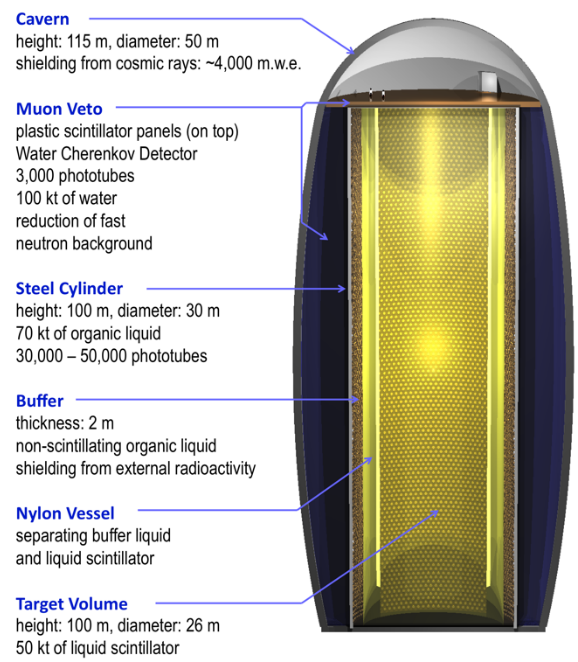
1.5 km
Accelerator
8 km
Accelerators
20 km
Accelerators
Beam Off
Beam Off
1 ms
4 ms
Constrains
Initial flux
Constrains rise
of probability
wave
Osc. maximum
Near
Neutrino
Source
Mid-distance
Neutrino
Source
Far Neutrino
Source
You need to know which
one is providing the beam.
So they have to turn on/off.

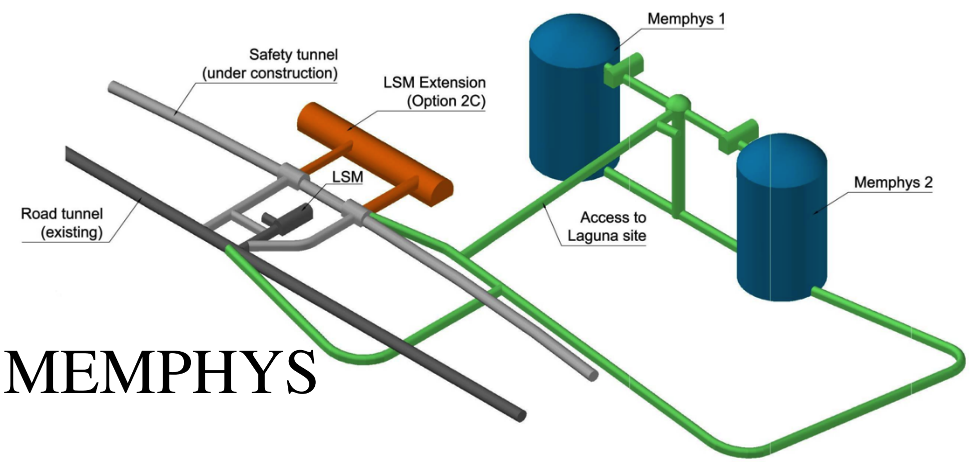
Where can DAEδALUS run?

Hyper-K (or initially, Super-K)



LENA - Scintillator Dectector



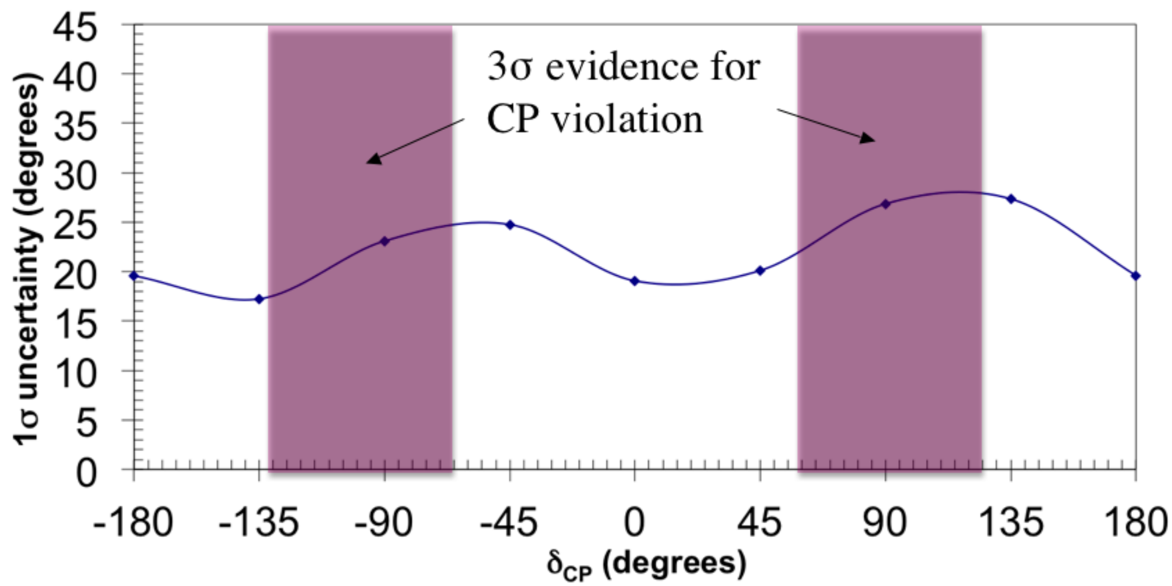


MEMPHYS

CP Violation Sensitivity

- Daeδalus has good CP sensitivity as a stand-alone experiment.

Coverage of CP violation parameter at LENA, 10 years



- Daeδalus can also be combined with long baseline data to give enhanced sensitivity
  - 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.

Final Comments

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

- Establishing the existence of sterile neutrinos would be a major result for particle physics
  - Several hints in the $\Delta m^2 \sim 1\ eV^2$ region
    - Some tension with lack of ν_μ disappearance signals
  - Many proposals and ideas for sterile neutrino searches
    - New experiments to have better sensitivity (~5σ level) with capabilities to see oscillatory behavior.

- 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 be used to probe for CP violation in the ν-sector
  - Can provide high statistics $\bar{\nu}_e$ data with no matter effects
  - Can give enhanced sensitivity when combined with long baseline ν_e appearance data