DAEδALUS
IsoDAR

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

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for the IsodDAR / DAEδALUS Collaborations

XVI International Workshop on Neutrino Telescopes

2-6 March 2015 *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti*
Europe/Rome timezone

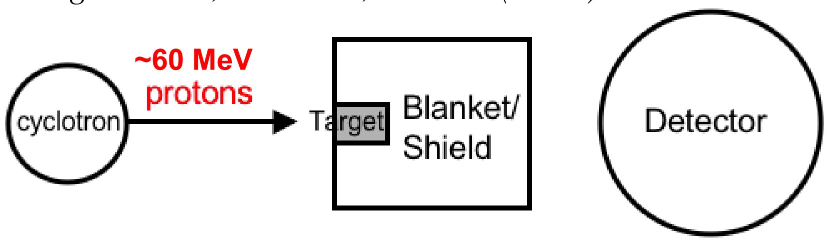
Daeδalus and IsoDAR Experiments

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

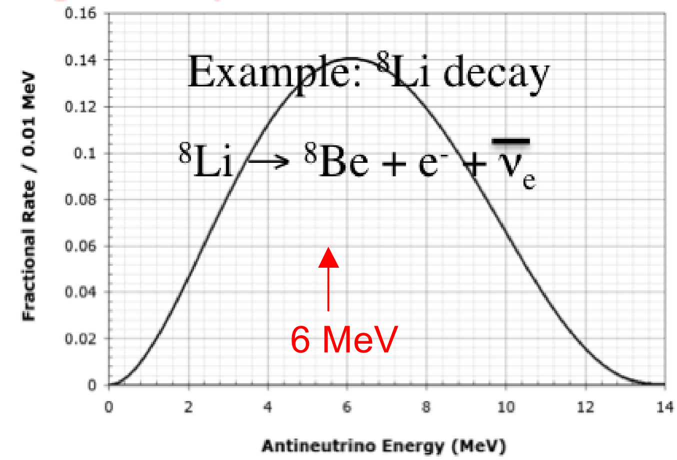
IsoDAR Setup:

Very short baseline **search for sterile neutrinos**

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



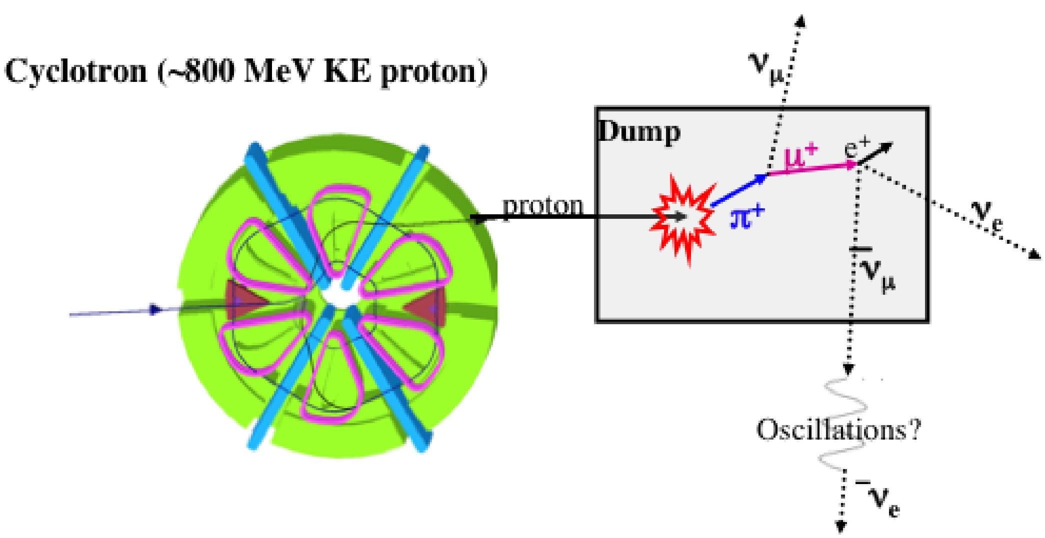
Isotope decay-at-rest



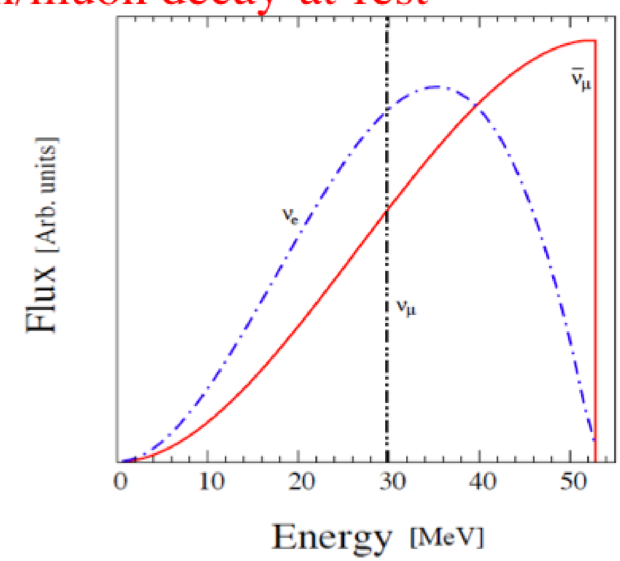
Daeδalus Setup:

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

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

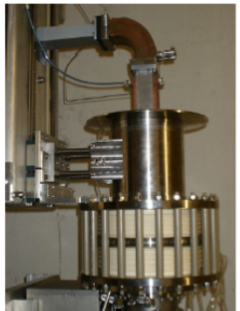


Pion/muon decay-at-rest



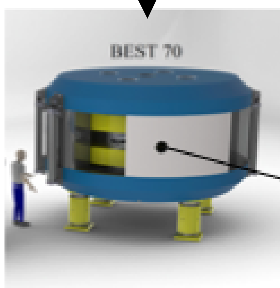
DAEδDALUS High Power (~1 MW) 800 MeV Cyclotron System

H_2^+ Ion Source

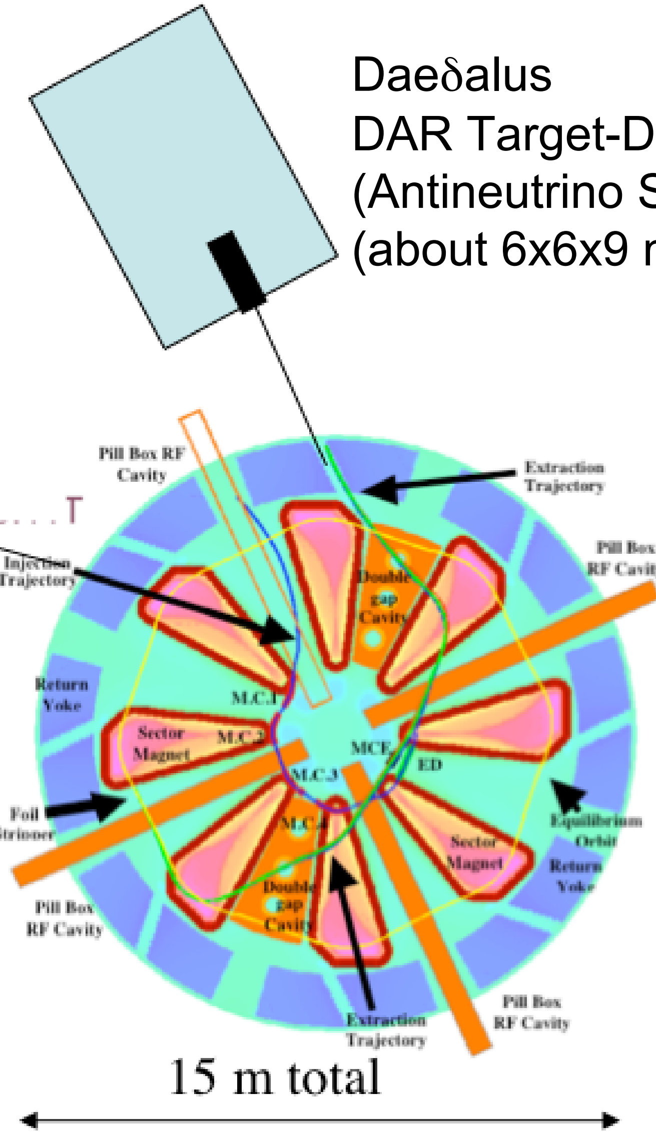


IsoDAR 60 MeV Cyclotron

Injector Cyclotron (Resistive)



Daeδalus DAR Target-Dump (Antineutrino Source) (about 6x6x9 m³)



800 MeV Ring Cyclotron (Superconducting)

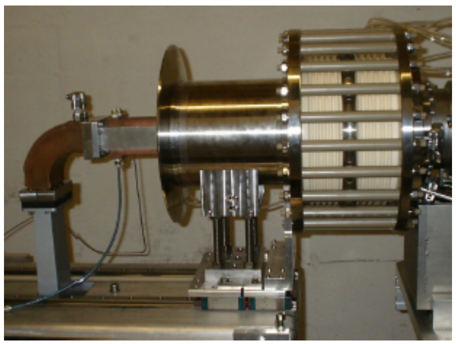
Multimegawat Daeδalus Cyclotron for Neutrino Physics

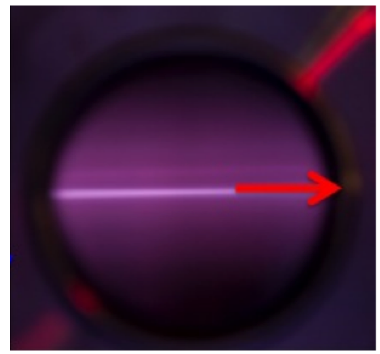
arXiv:1207.4895

IsoDAR Cyclotron Development

International Partnership Between Universities, Labs, and Industry

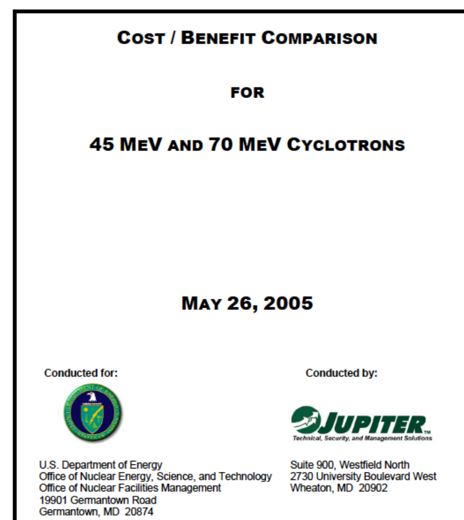
- Ion source developed by collaborators at INFN Catania
  - Reached adequate intensities for IsoDAR experiment





- Industrial interest for high intensity (~10 ma), high energy (~50 to 70 MeV) cyclotrons for medical isotope production.

Isotope	Half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study brain blood-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium.
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs. As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ-emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ-emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{82}Rb, a potassium analogue. This isotope is also directly used as a PET isotope for heart imaging.


COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

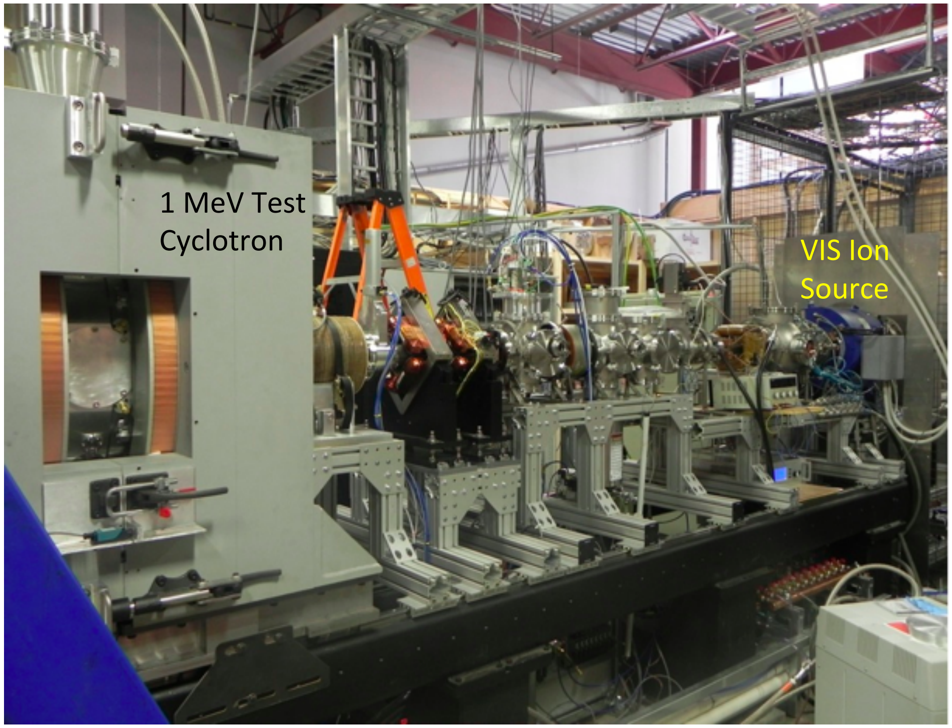
MAY 26, 2005

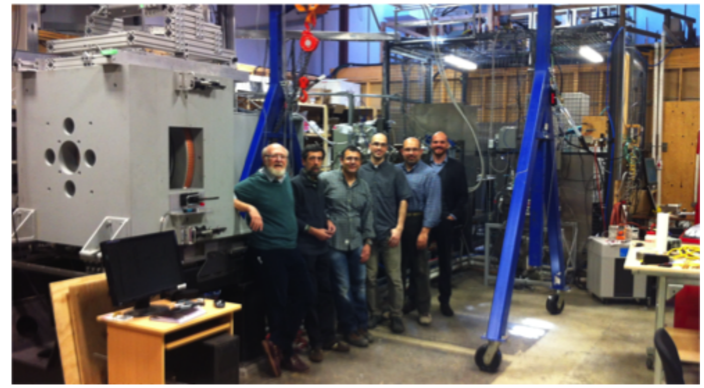
Conducted for:
U.S. Department of Energy
Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
19901 Germantown Road
Germantown, MD 20874

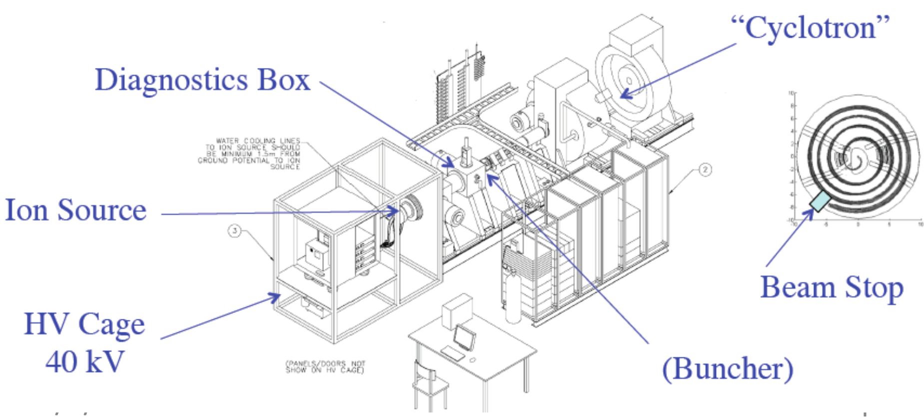
Conducted by:
JUPITER
Suite 900, Westfield North
2730 University Boulevard West
Wheaton, MD 20902

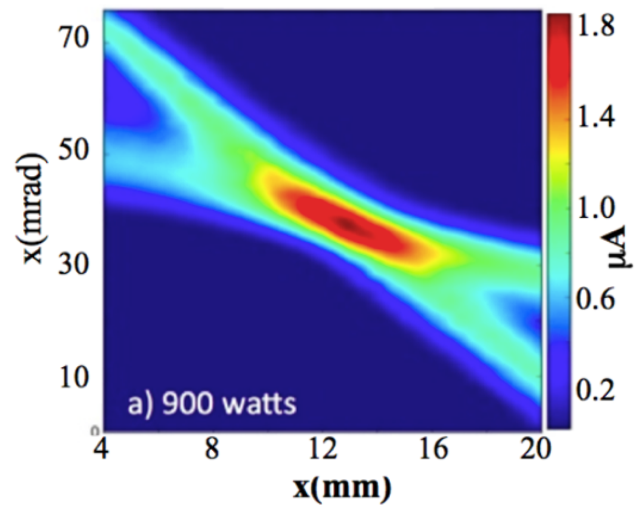
Ion Source Intensity and Cyclotron Capture Efficiency
Characterized and Tested at Best Cyclotrons, Inc, Vancouver

(Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)





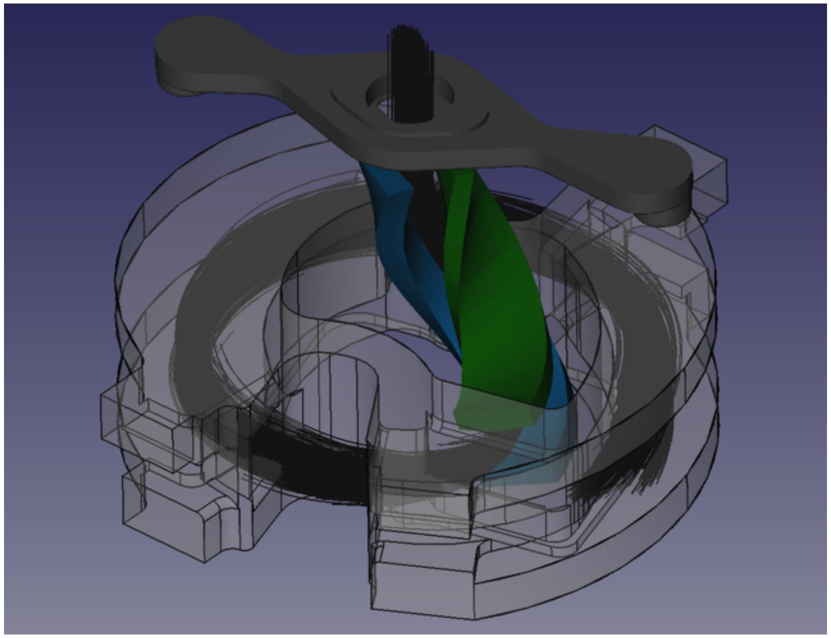


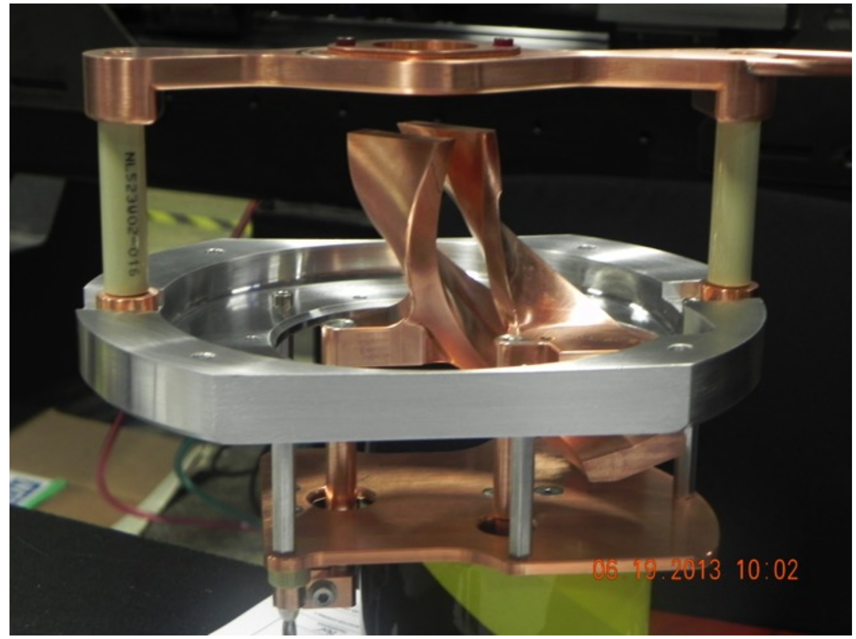


Beam and source characterized

- •Emittance measurements
- •Space charge compensation
- •Inflection and capture

Cyclotron Beam Capture Studies Using Electrostatic Spiral Inflector





Tricky to design:
- B field effects
- Space charge

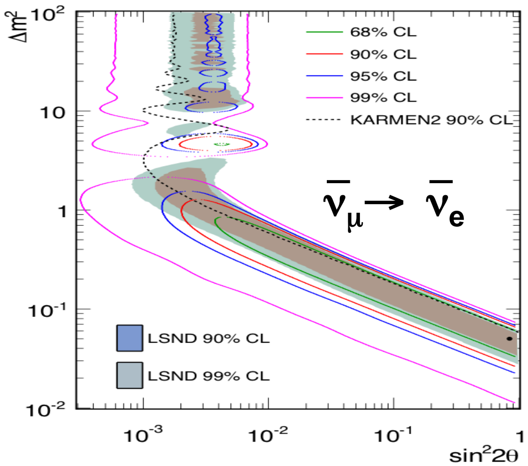
Best Cyclotron tests used to validate simulations.

IsoDAR Experiment

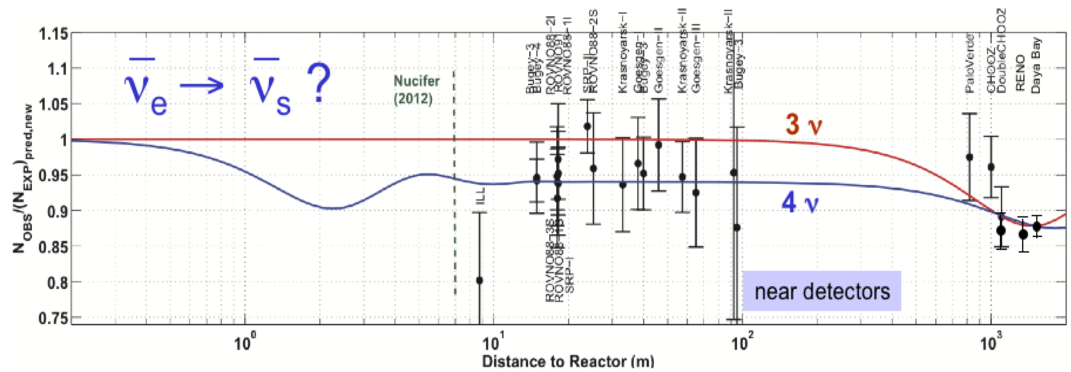
Isotope Decay-At-Rest Neutrino Source
($\bar{\nu}_e$ Disappearance)
to Search for Sterile Neutrinos

Many Experimental Hints for Sterile Neutrinos

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



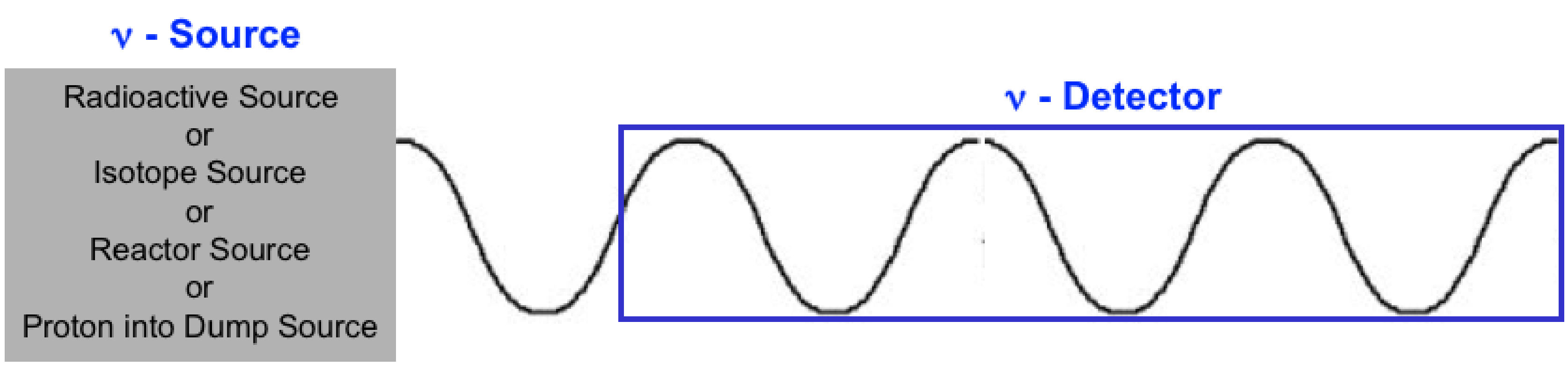
- Reactor Anomaly: $\bar{\nu}_e$ disappearance signals?



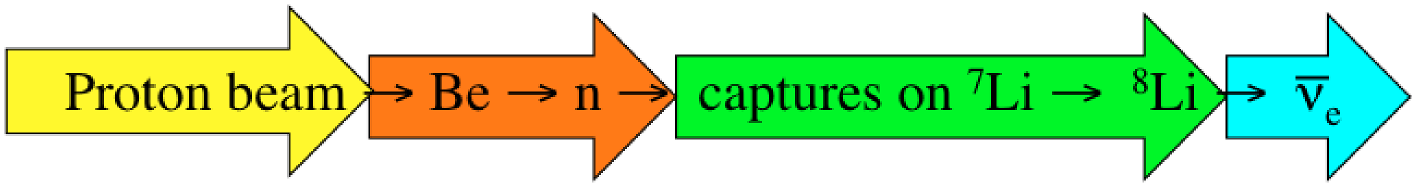
New Short and Very-short Baseline Oscillation Experiments

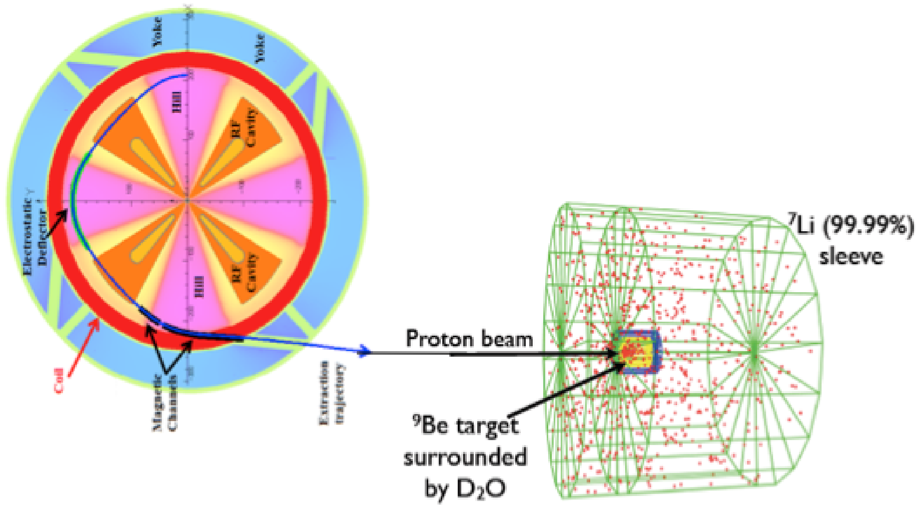
- Need definitive experiments
  - Significance at the > 5σ level
  - Smoking gun: Observation of oscillatory behavior within detector

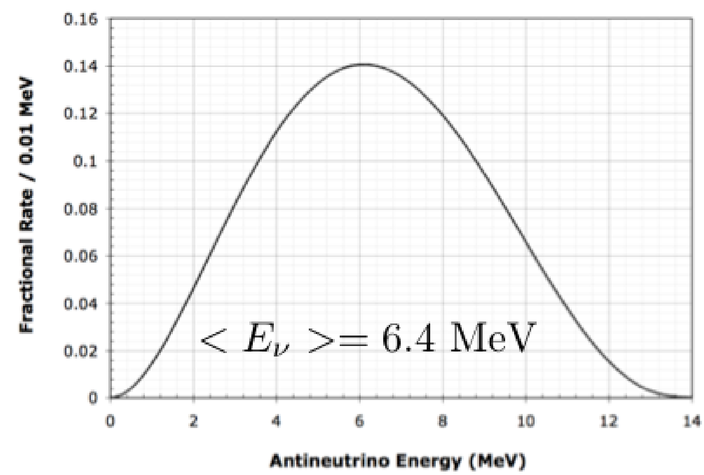
Establishing the existence of sterile neutrinos would be a major result for particle physics



IsoDAR $\bar{\nu}_e$ Source





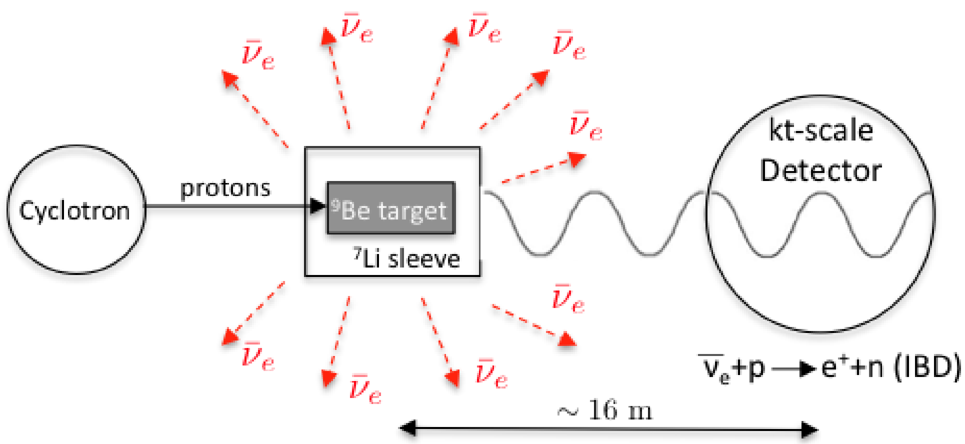


5 mA H_2^+ @ 60 MeV/n
(600 kW proton beam)

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

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

The IsoDAR 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.

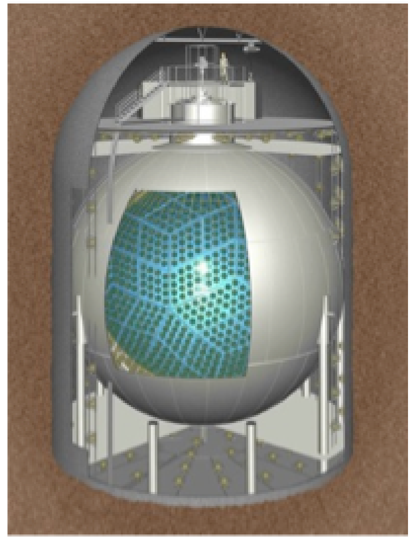
Key features of IsoDAR setup:

- High statistics
- Compact antineutrino source
  - Bring source to underground detector
  - $\sigma_x = s_y = 23$ cm and $s_z = 37$ cm
- Well understood energy spectrum
  - ^{8}Li β-decay dominates ν_e flux
  - Above 3 MeV environmental backgrounds
- Pair with kton-scale underground IBD detector
  - Both L and E accurately reconstructed
  - Delayed coincidence signal reduces backgrounds
  - Backgrounds don't show L/E oscillation behavior

Where Can IsoDAR Run?

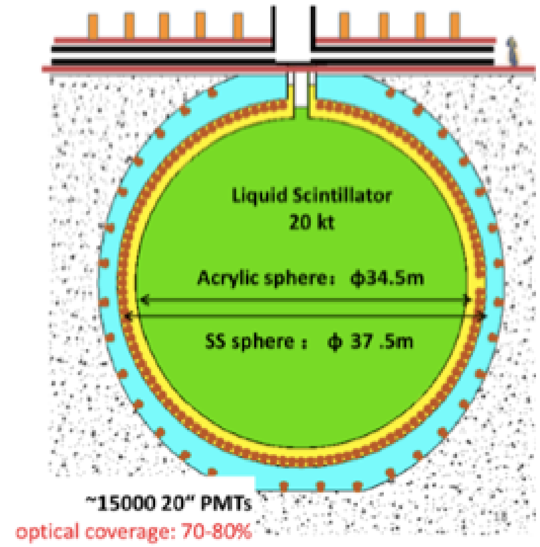
LENA

KamLAND

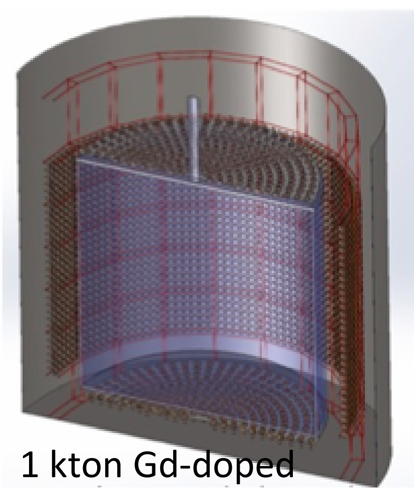


1 kton liquid scintillator

JUNO

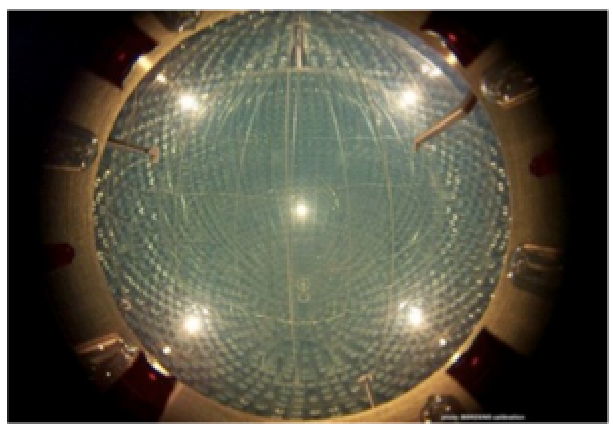


WATCHMAN

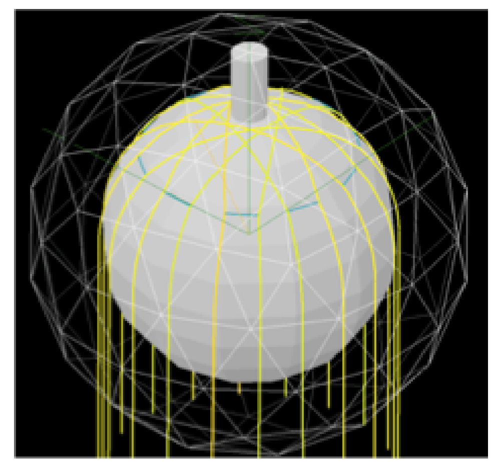


1 kton Gd-doped
water Cerenkov

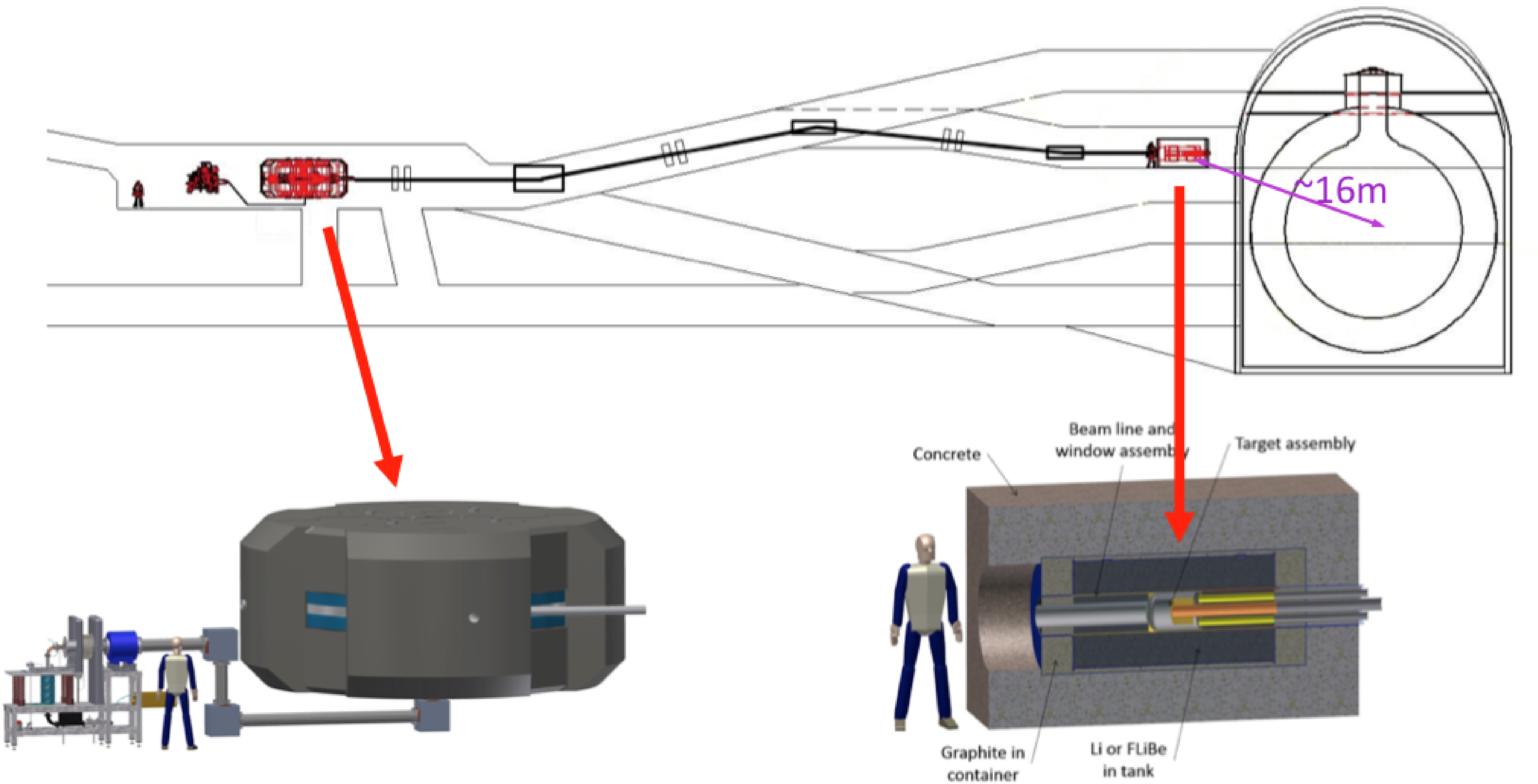
Borexino



SNO+



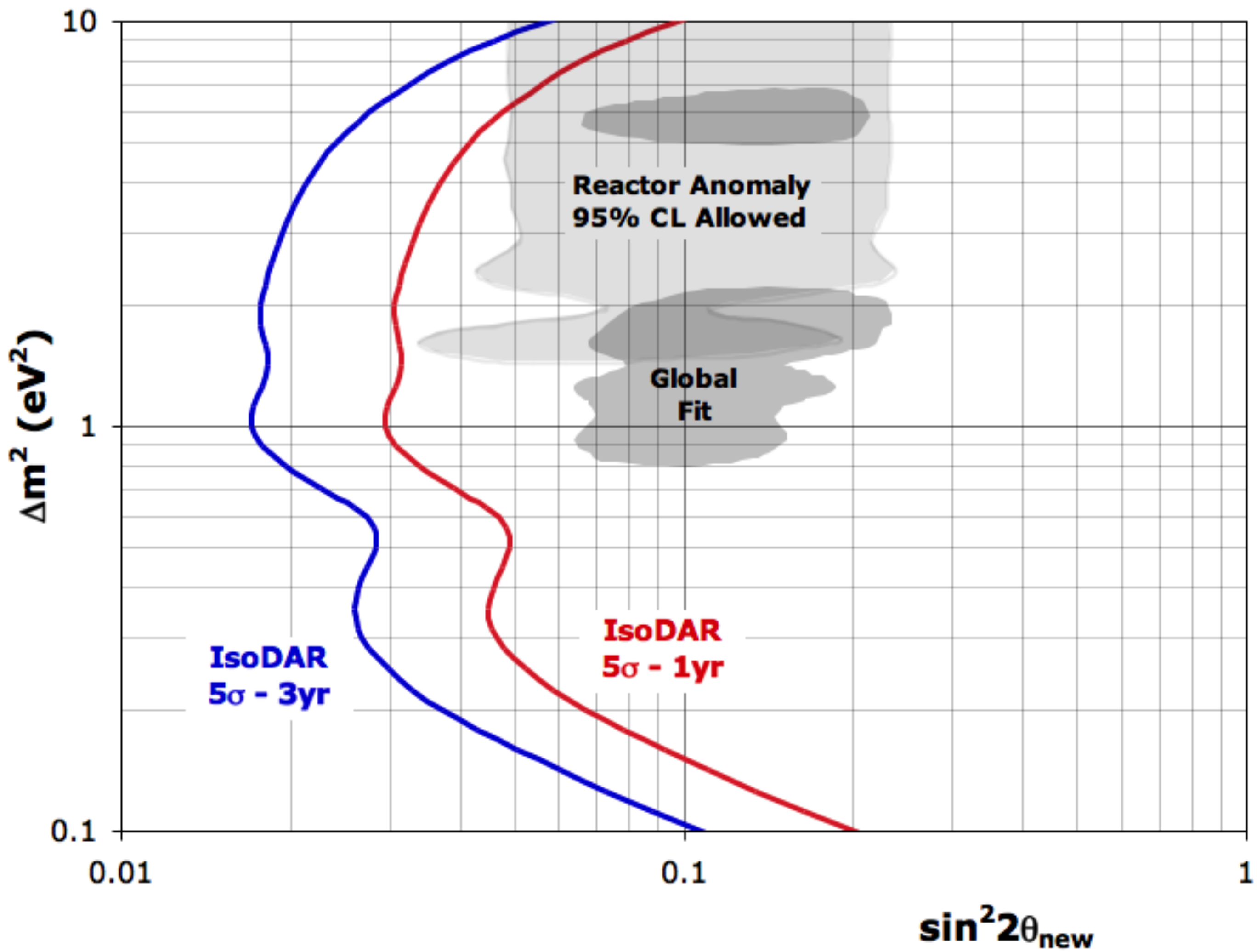
Initial Proposal to Run at KamLAND



60 MeV/n 5 mA H_2^+ Cyclotron

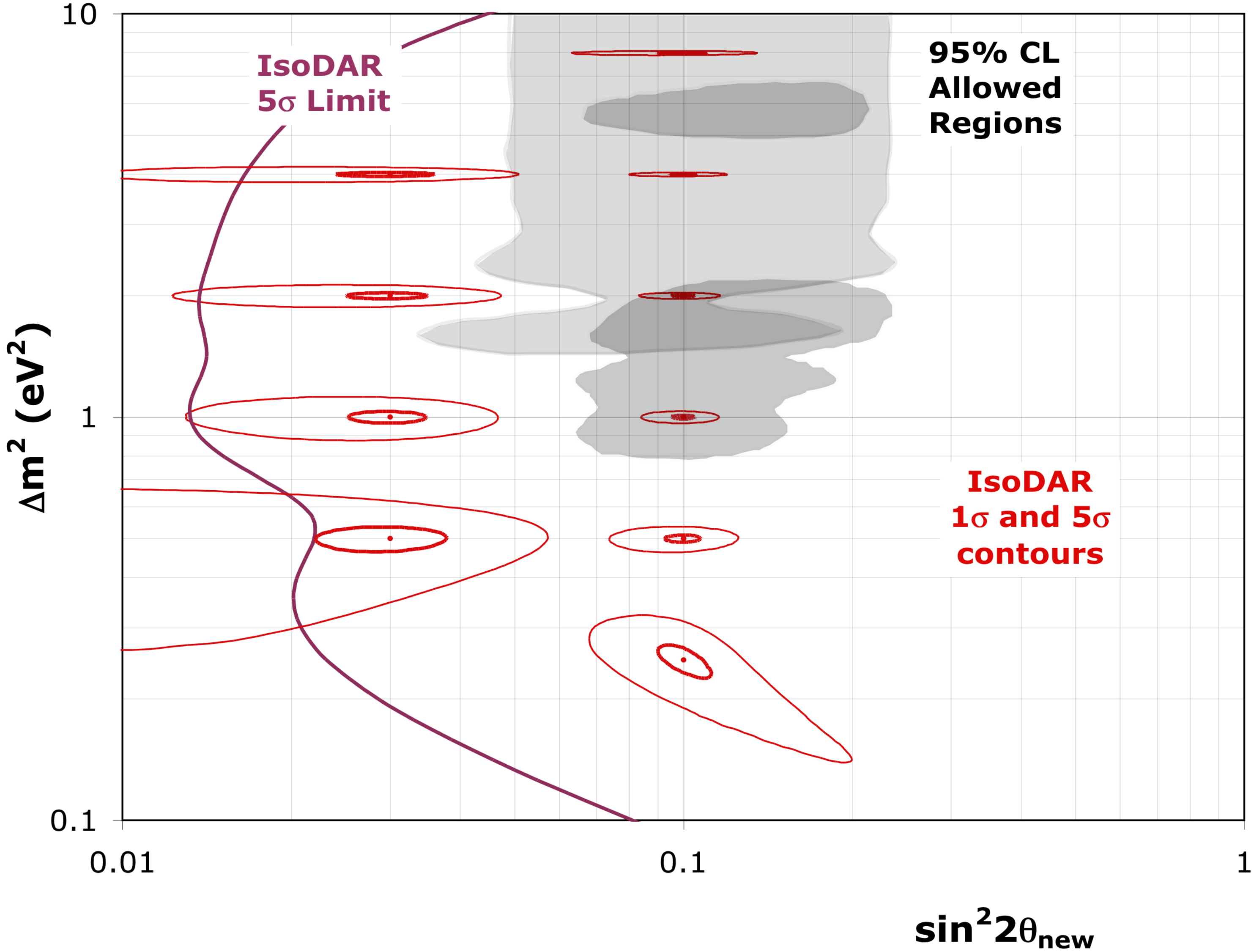
$^9Be/^7Li$ Target and $\bar{\nu}_e$ Source

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



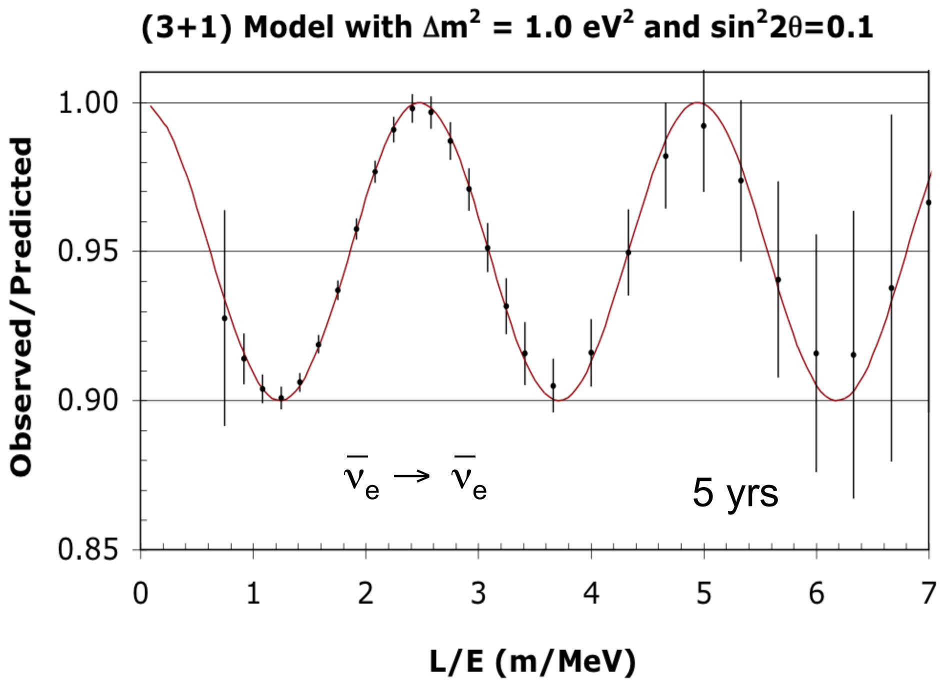
⇒ Global fit region can be ruled out at > 5σ in 4 months of running!

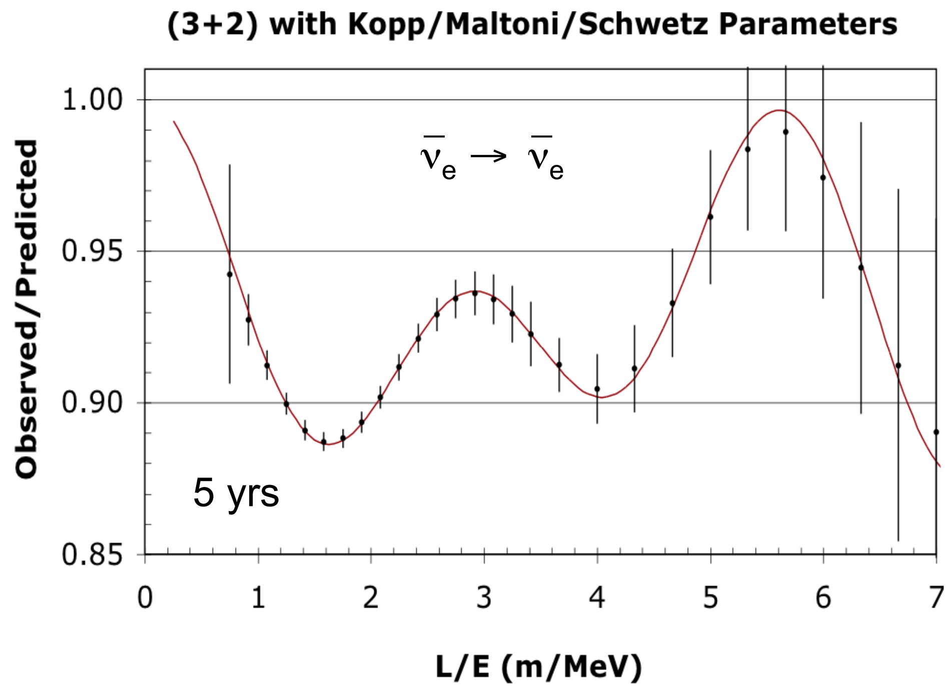
IsoDAR at KAMLAND Measurement Sensitivity (5 yrs)



Oscillation L/E Waves in IsoDAR at KAMLAND

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

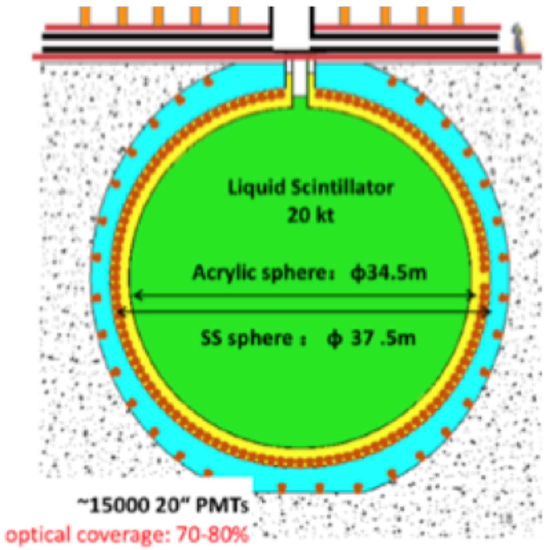




IsoDAR's high statistics and good L/E resolution has potential to distinguish (3+1) and (3+2) oscillation models

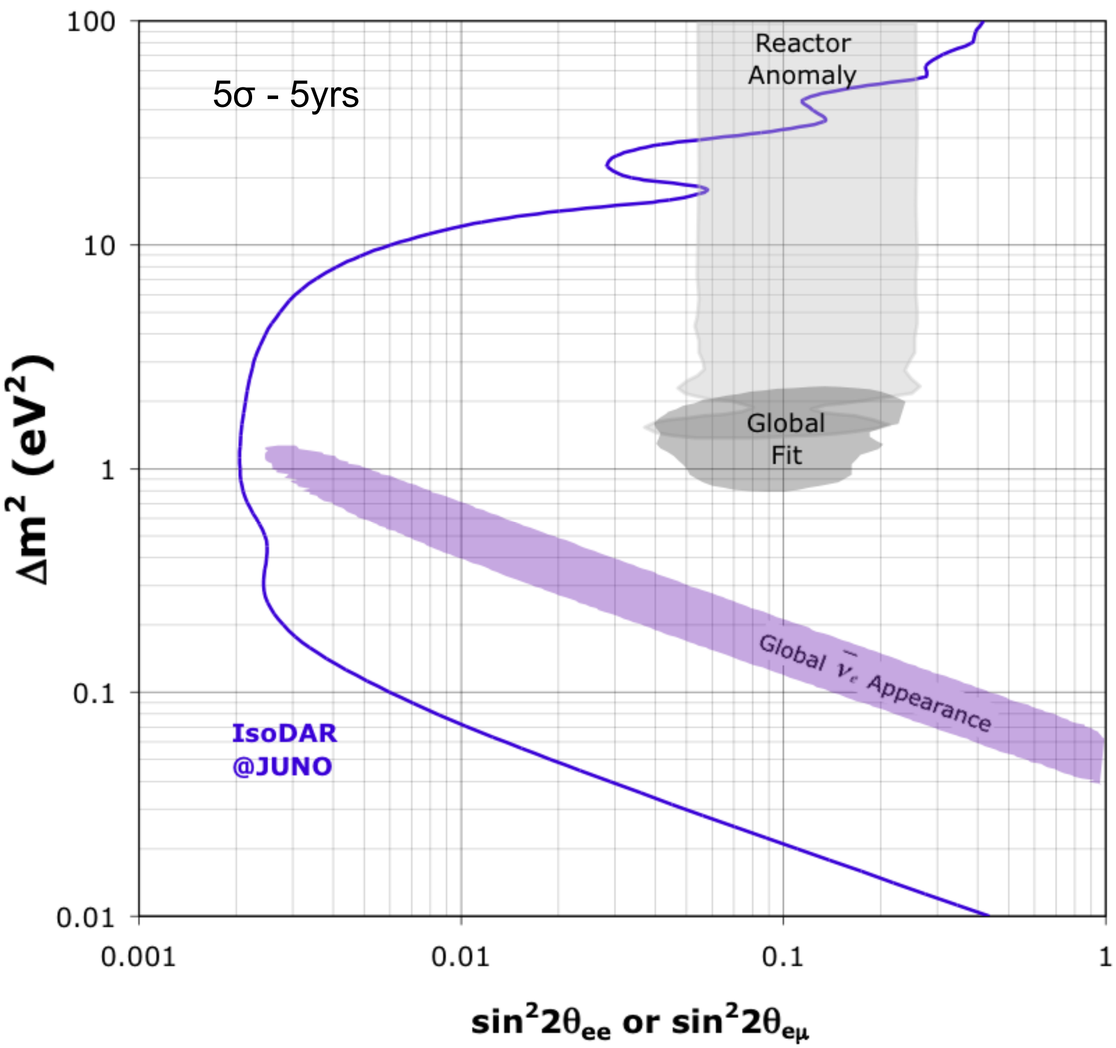
IsoDAR at JUNO Experiment

Jiangmen Underground Neutrino Observatory (JUNO)



- Fiducial mass 20 kton with 34.5m diamter
- IsoDAR source located at 25m from detector center
- JUNO has excellent energy and vertex resolution for L/E studies

Full coverage of "Global $\bar{\nu}_e$ Appearance" and Disappearance regions



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}

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

We want to see if δ is nonzero

terms depending on mixing angles

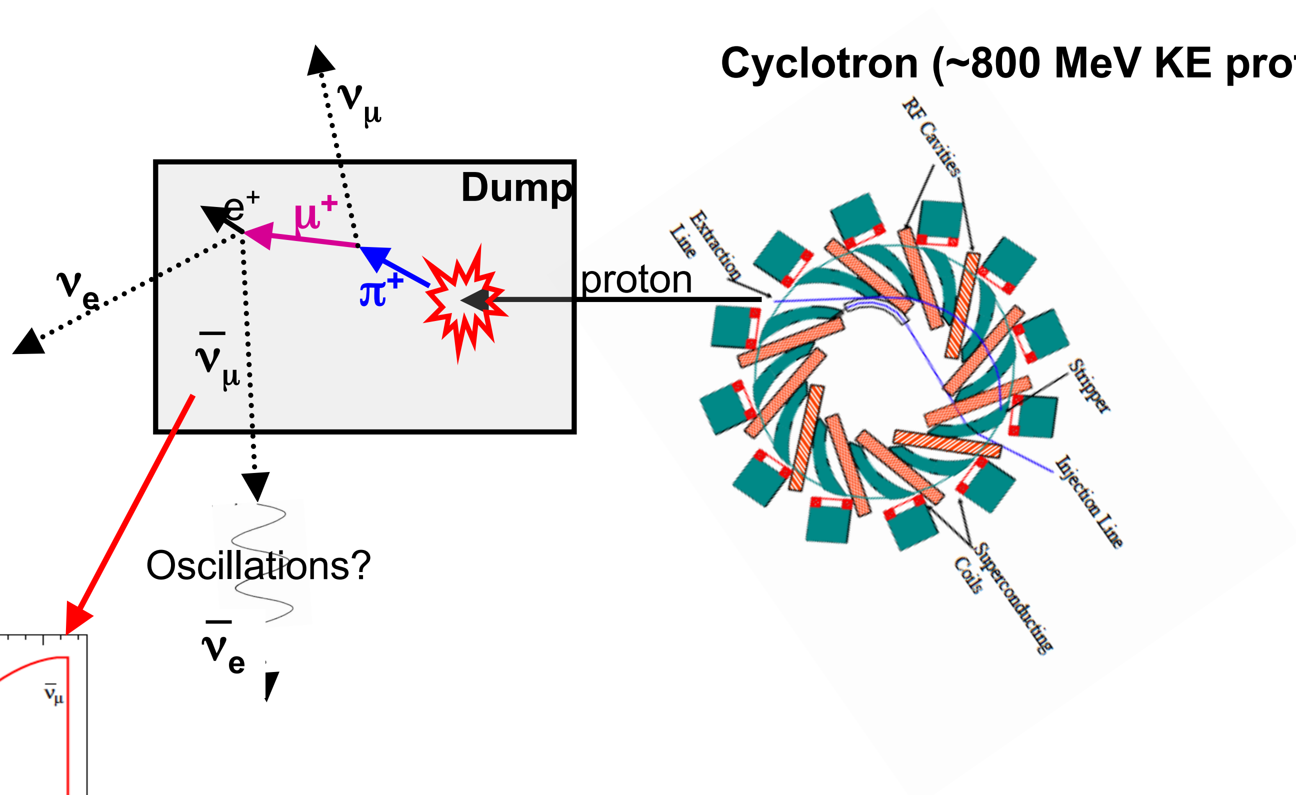
terms depending on mass splittings

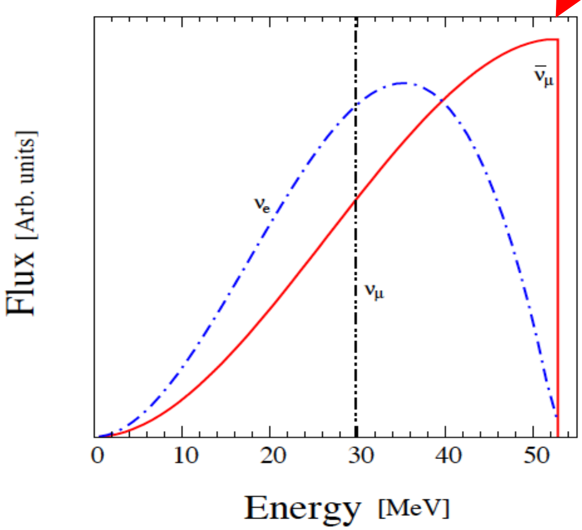
$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

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

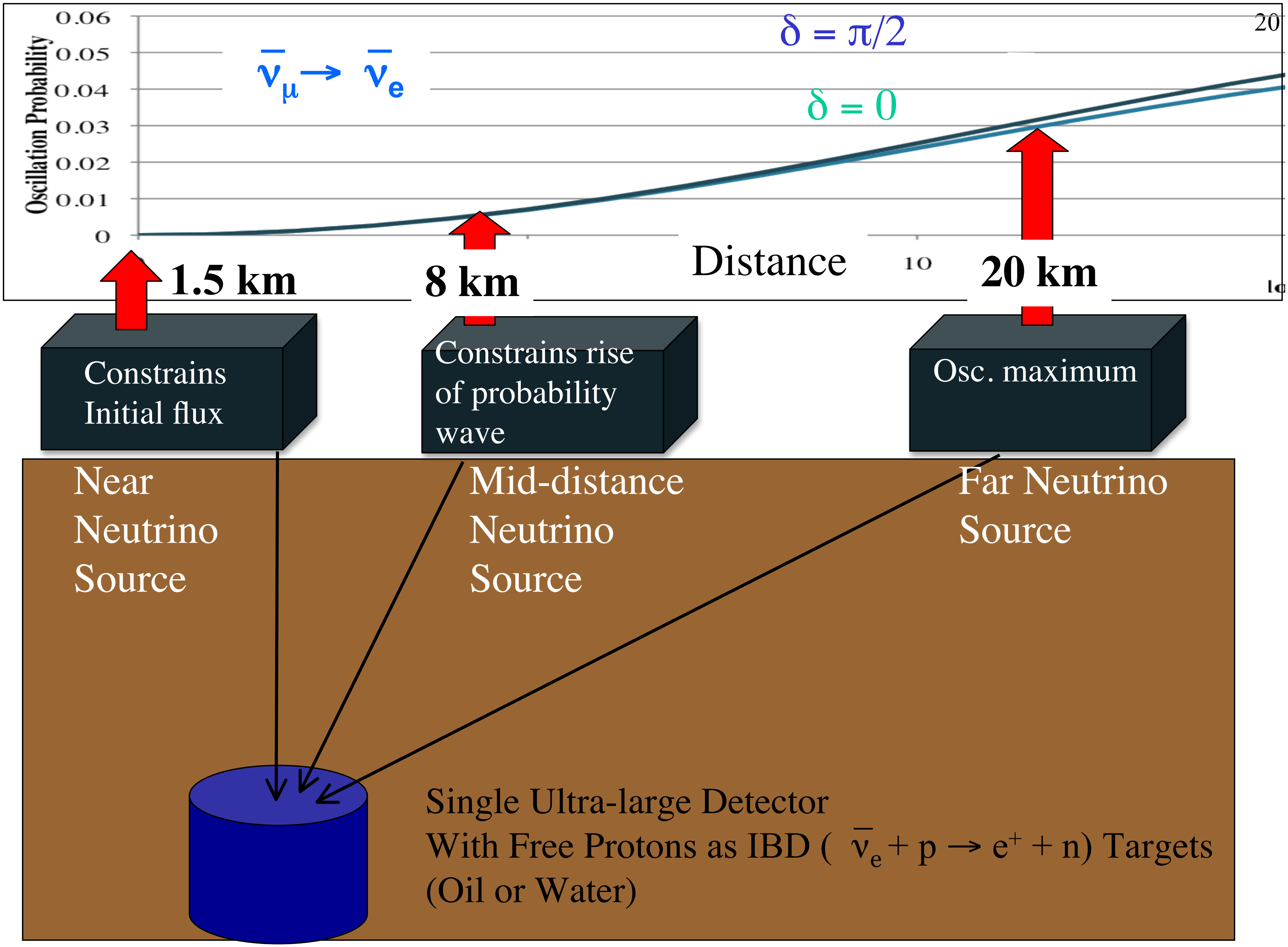
Pion/muon decay-at-rest beam

- Very small $\bar{\nu}_e$ cont.
- Flux normalization using ν_e - e events.





Neutrino beam flux vs energy fixed by the physics of muon decay

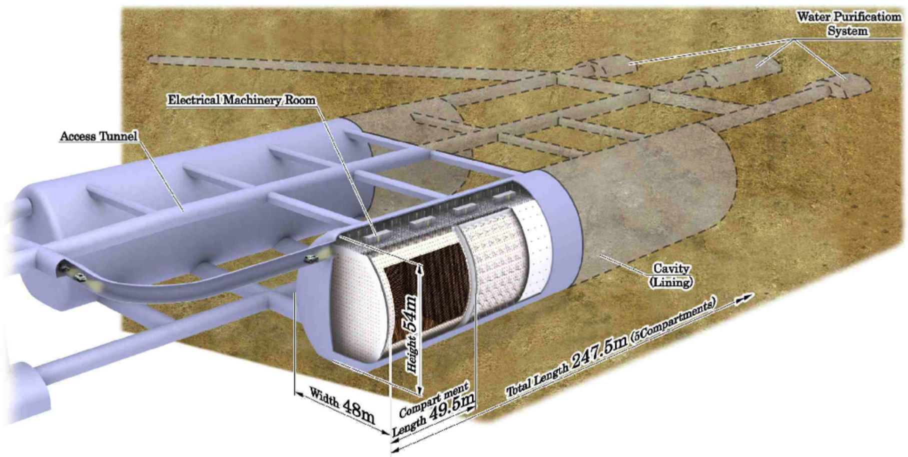


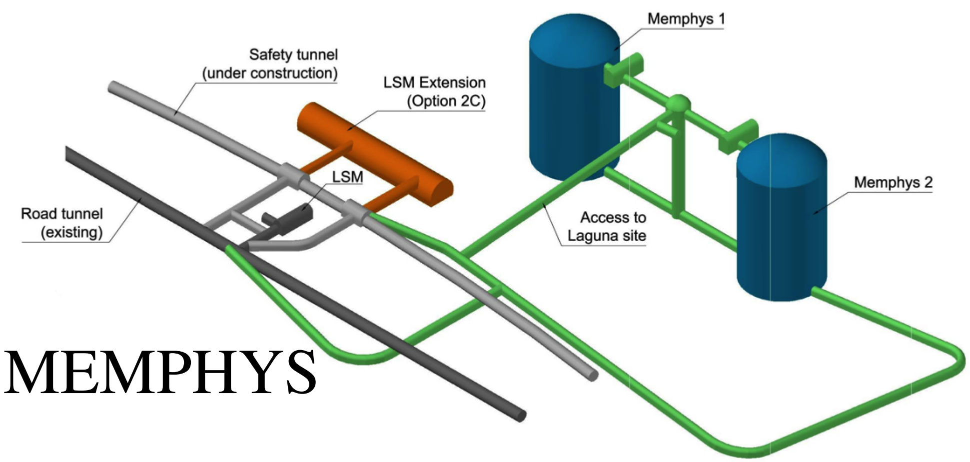
0.06
0.05
0.04
0.03
0.02
0.01
0
Oscillation Probability
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\delta = \pi/2$
$\delta = 0$
20
Distance
10
1.5 km
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source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

Where can DAEδALUS run?

Hyper-K (or initially, Super-K)

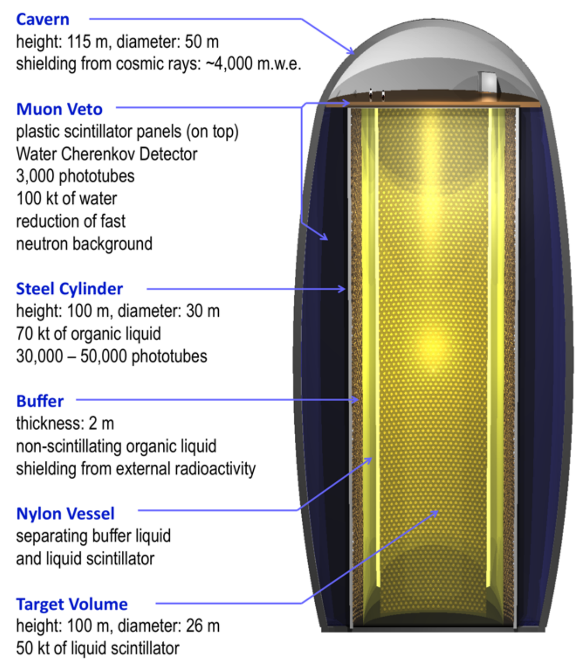
(Focus for current studies)





MEMPHYS

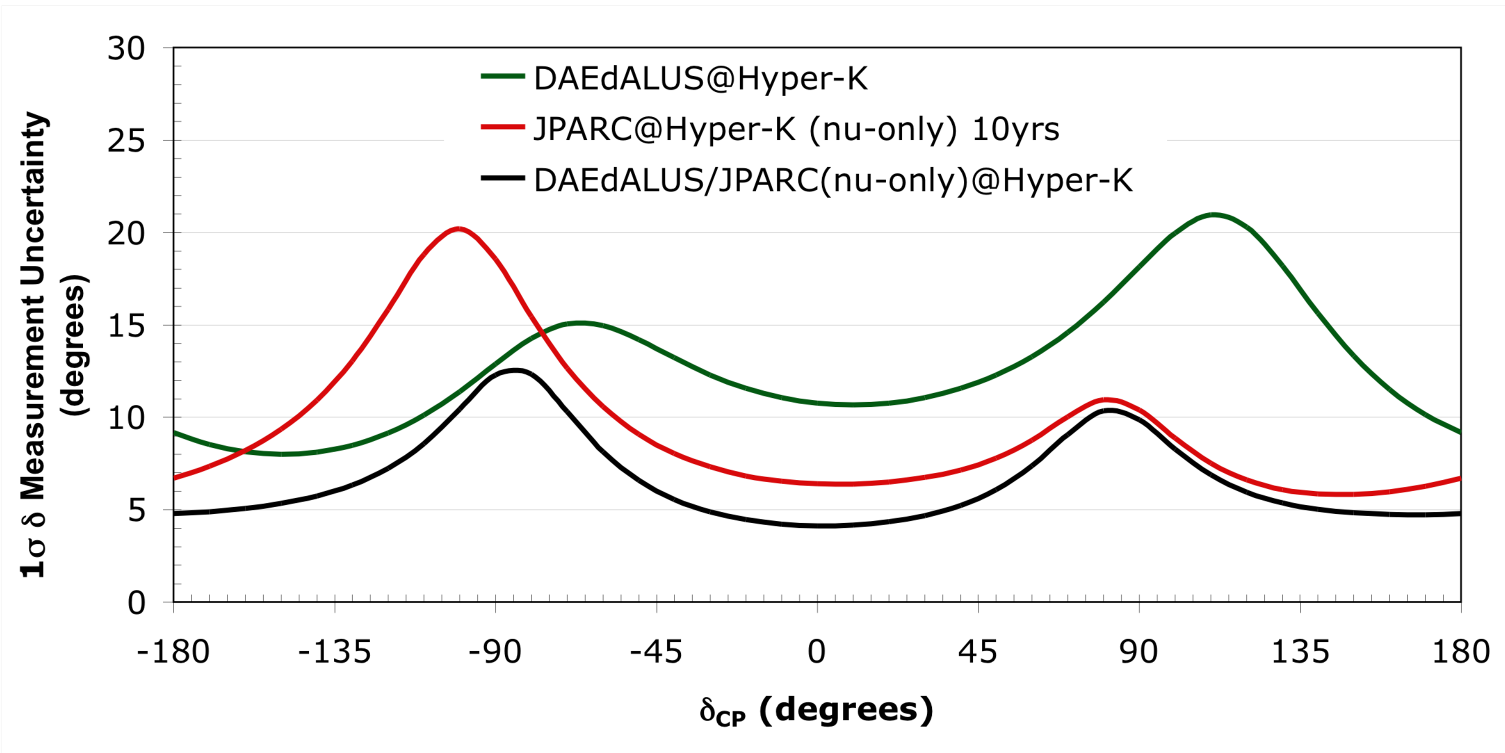
LENA - Scintillator Dectector



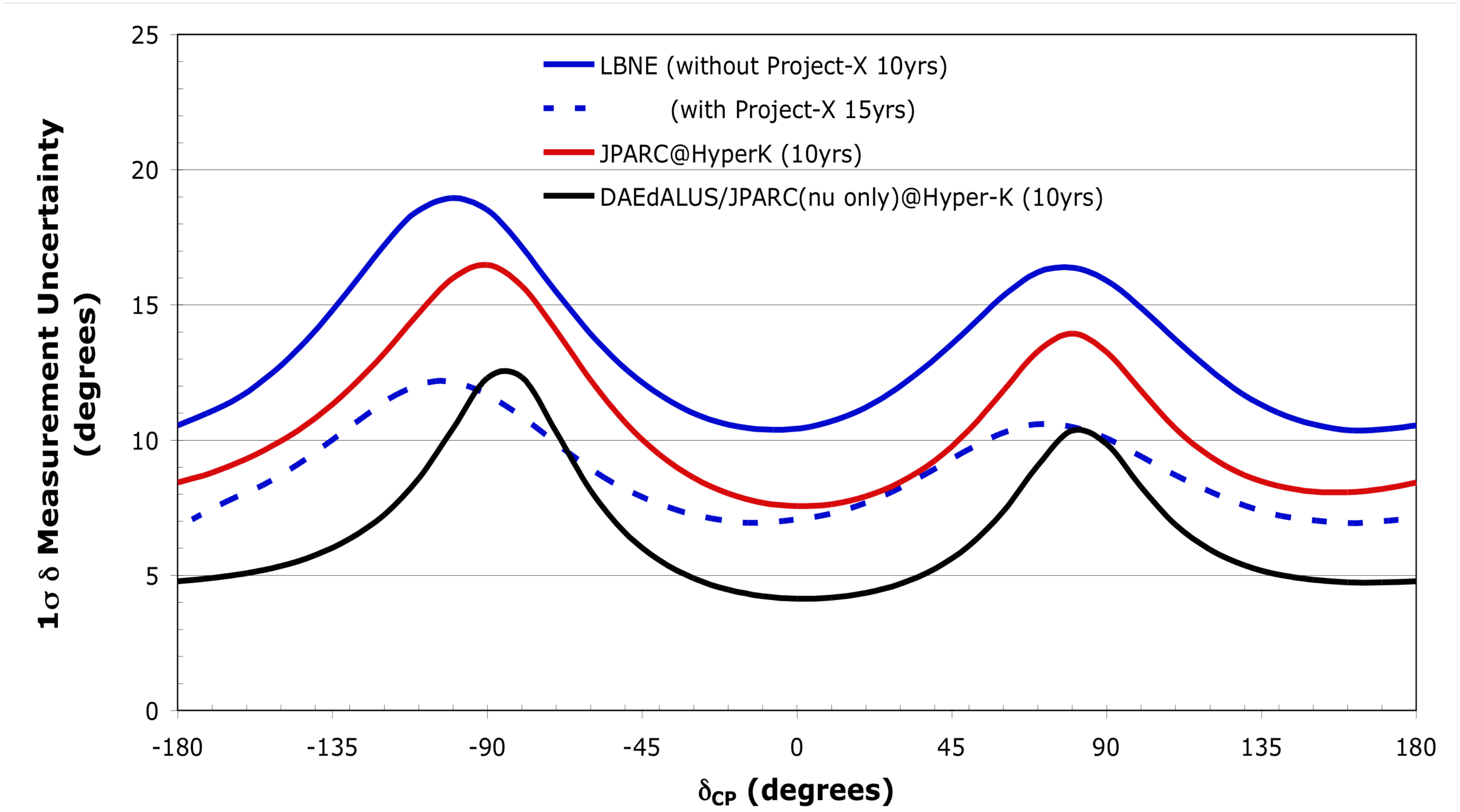
Detector needs to have free protons to capture neutrons from IBD ⇒ liquid argon is not an option

CP Violation Sensitivity

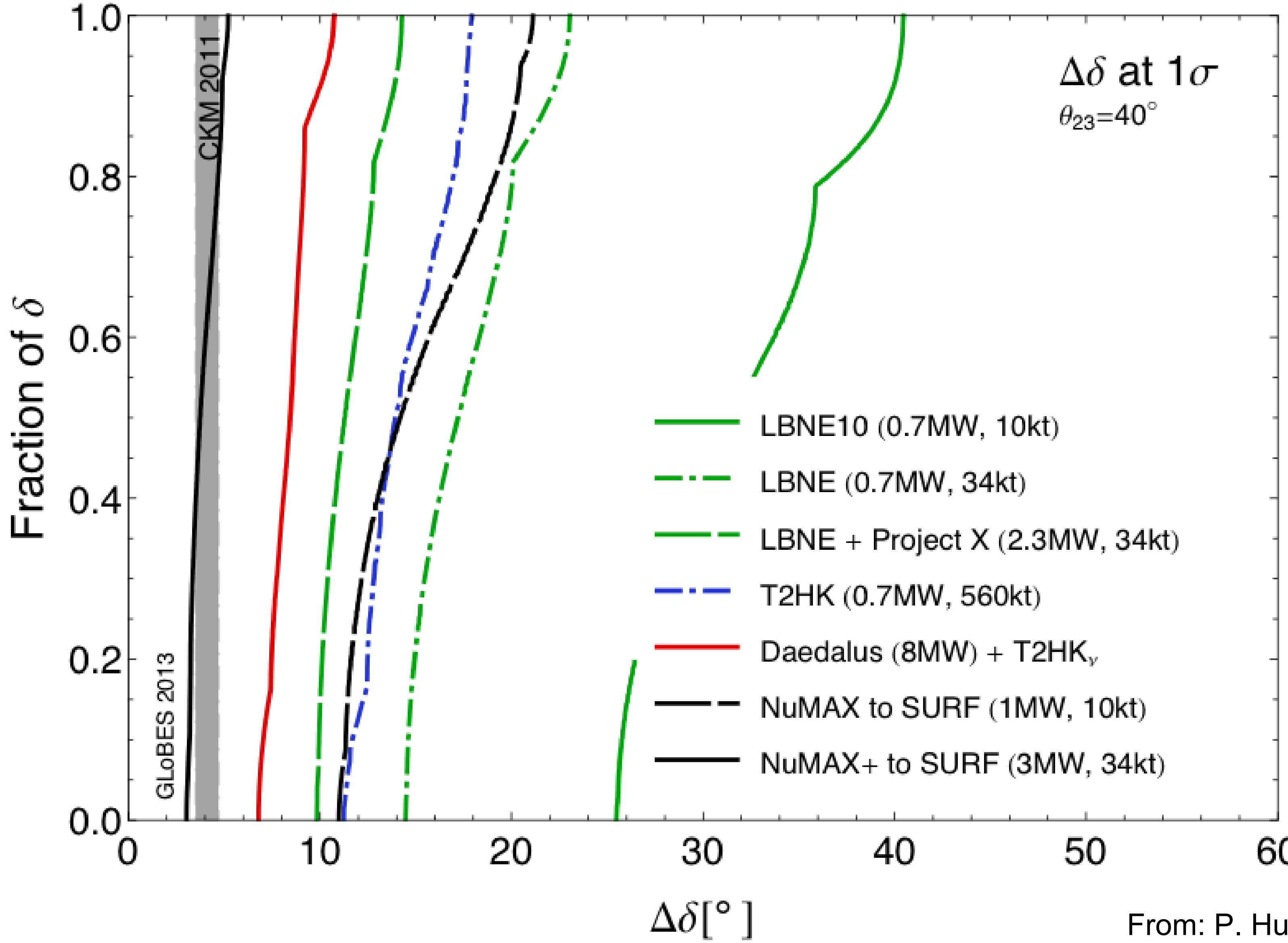
- Daeδalus has good CP sensitivity as a stand-alone experiment.
  - Small cross section, flux, and efficiency uncertainties
- Daeδalus can also be combined with long baseline ν-only data to give enhanced sensitivity, i.e. Hyper-K
  - Long baseline experiments have difficulty obtaining good statistics 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)

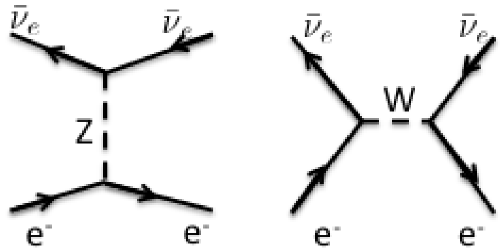
- Establishing the existence of sterile neutrinos would be a major result for particle physics
  - IsoDAR can make a definitive search for sterile neutrinos
    - Combined L and E analysis with good resolutions can isolate the oscillatory behavior and reduce backgrounds

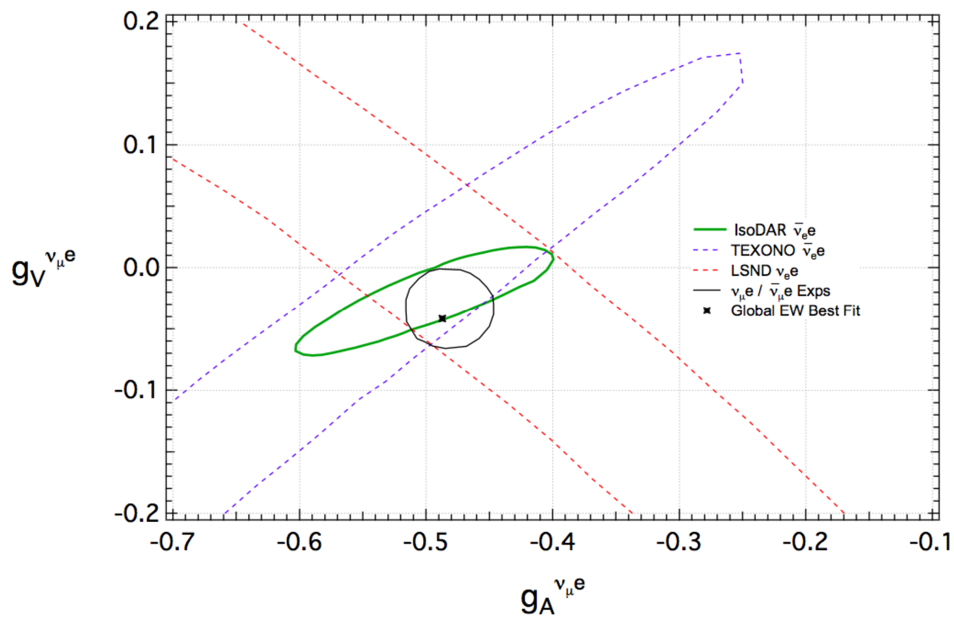
- Daeδalus is another method to probe for CP violation in the ν-sector
  - Can provide high statistics $\bar{\nu}_e$ appearance data with no matter effects and reduced systematic uncertainties
  - Can give enhanced sensitivity when combined with long baseline ν_e appearance data

Backup

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

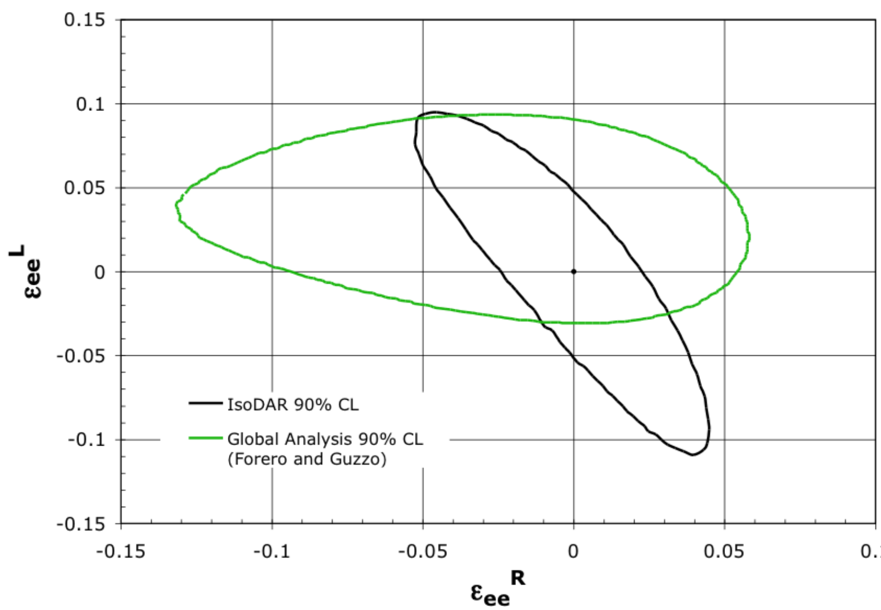
- 5yr data ⇒7200 evts with E_{vis}>3MeV ⇒ IsoDAR@Kamland:
  $\delta\sin^2\theta_W$ = 0.0075 (~3%)
  – Would be the best $\bar{\nu}_e e$ (or $\nu_e e$) elastic scattering measurement



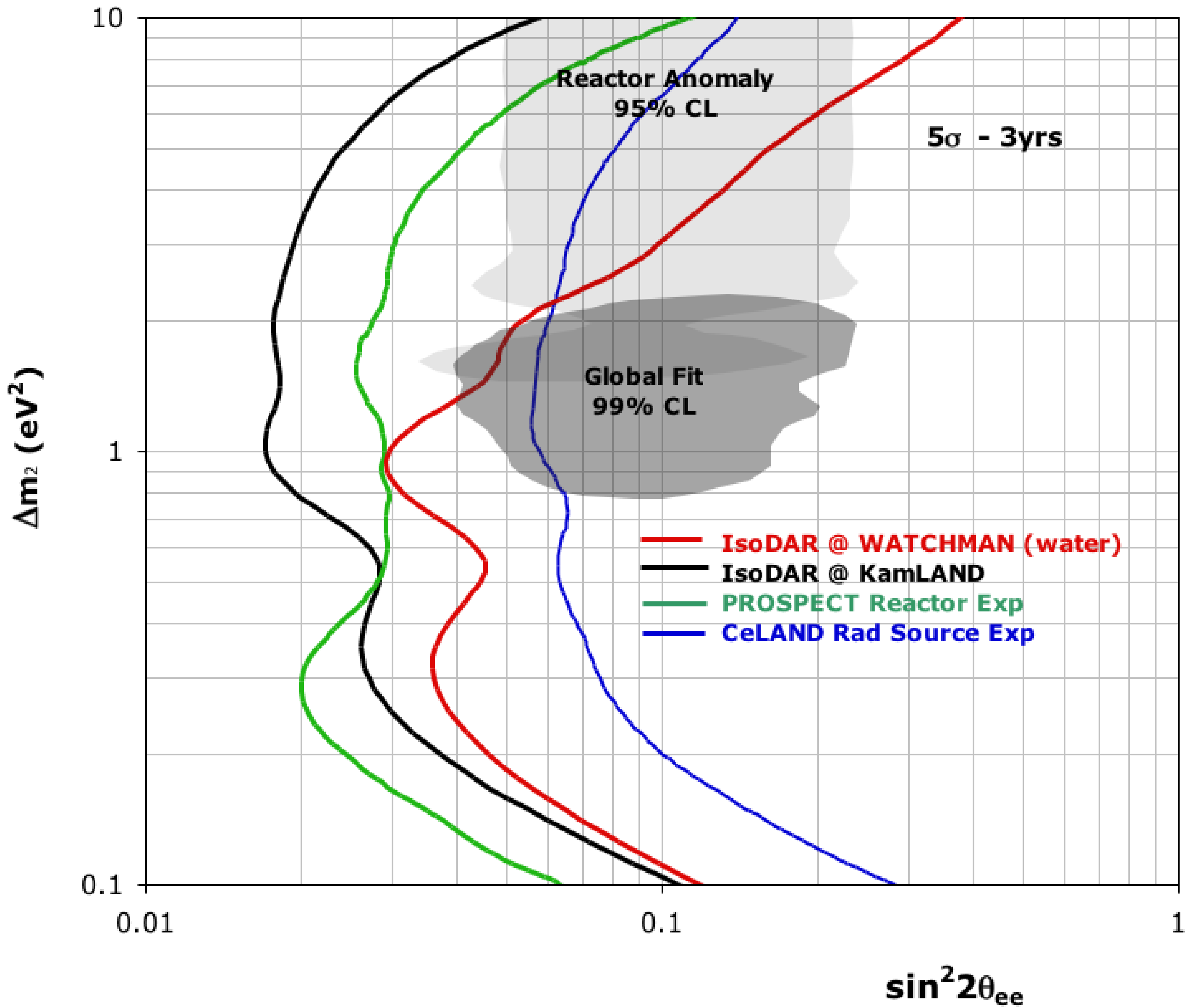


- Precision neutrino-electron scattering can also probe Non-Standard Interactions (NSI) since it is a well-understood Standard Model process

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

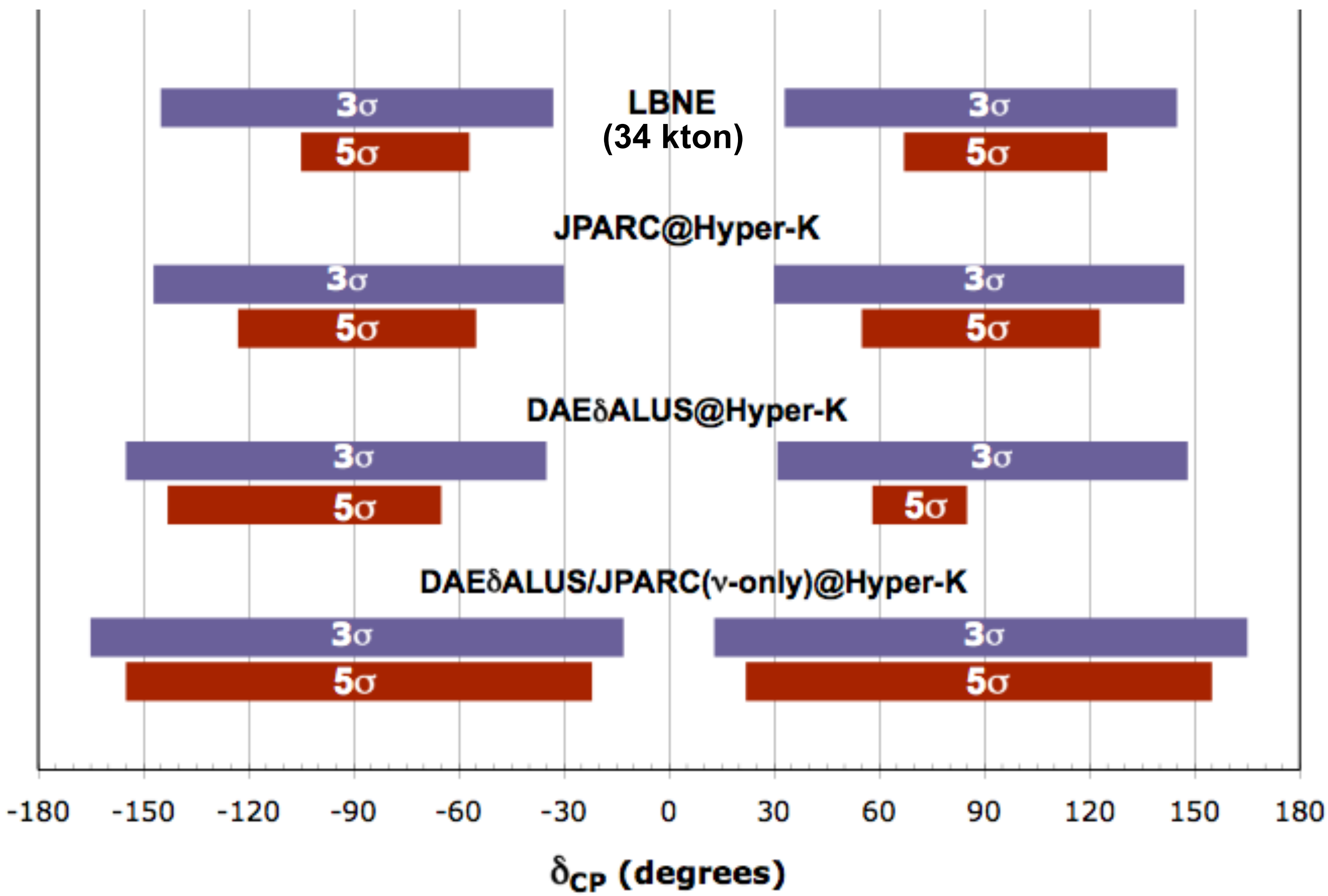


IsoDAR Comparison to Other Proposals



δ_{CP} Discovery Potential

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



DAEδALUS Measurement Strategy

Using the **near** neutrino source
measure **absolute flux normalization** with ν_e-e events to ~1%,
Also, measure the (ν_eO) ν_eC event rate.

↓

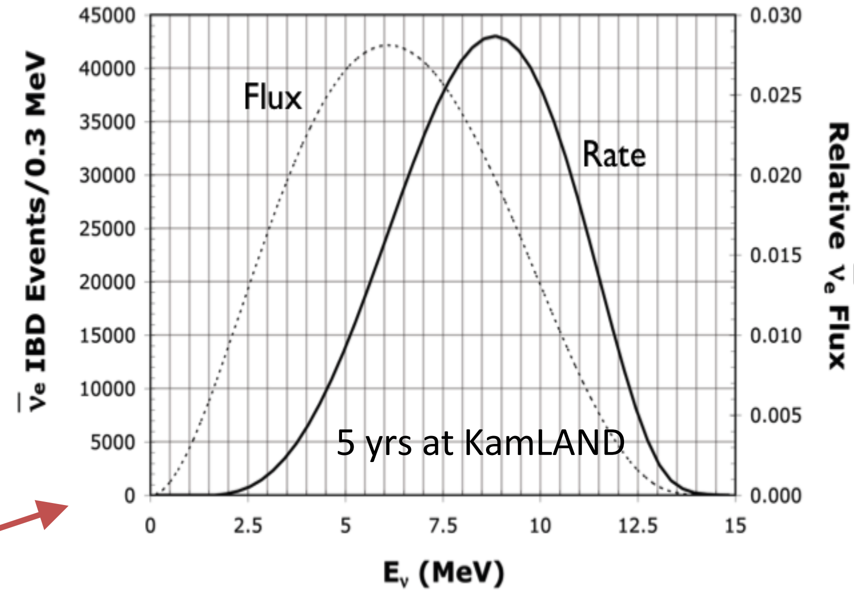
At far and mid-distance neutrino source,
Compare predicted to measured ν_eO (ν_eC) event rates
to get the **relative flux normalizations between 3 sites**

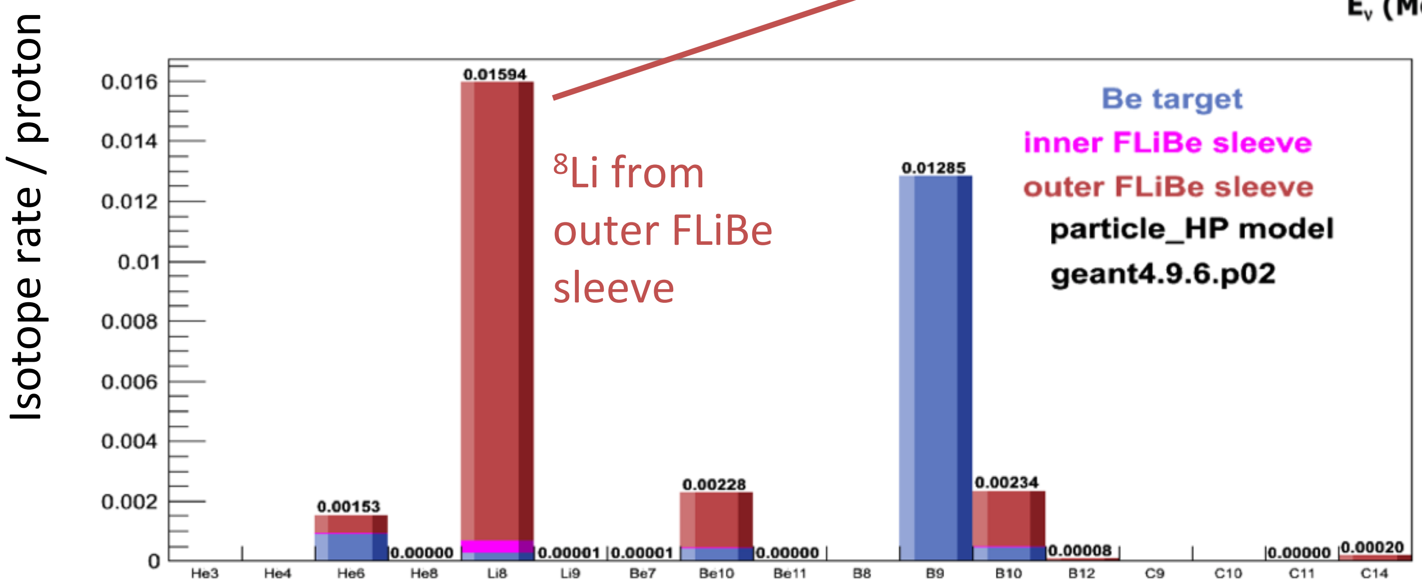
↓

For all three neutrino sources,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with δ as a free parameter

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 FLiBe ^{7}Li sleeve

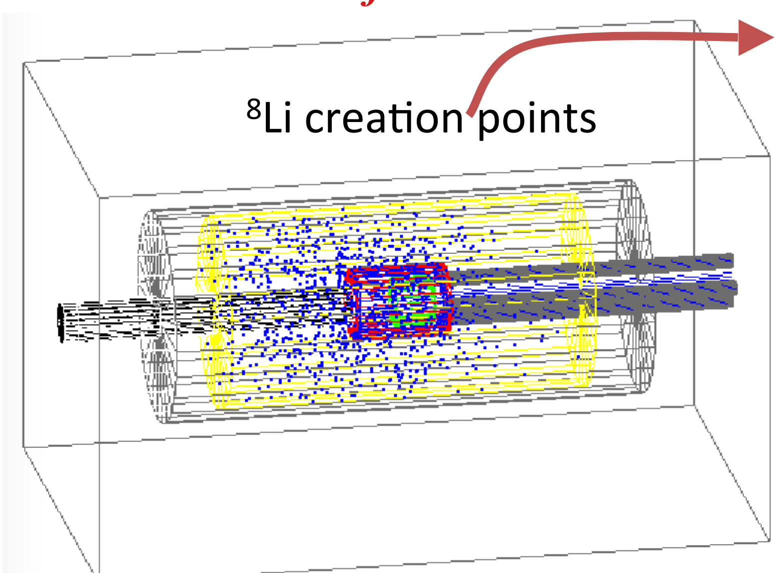


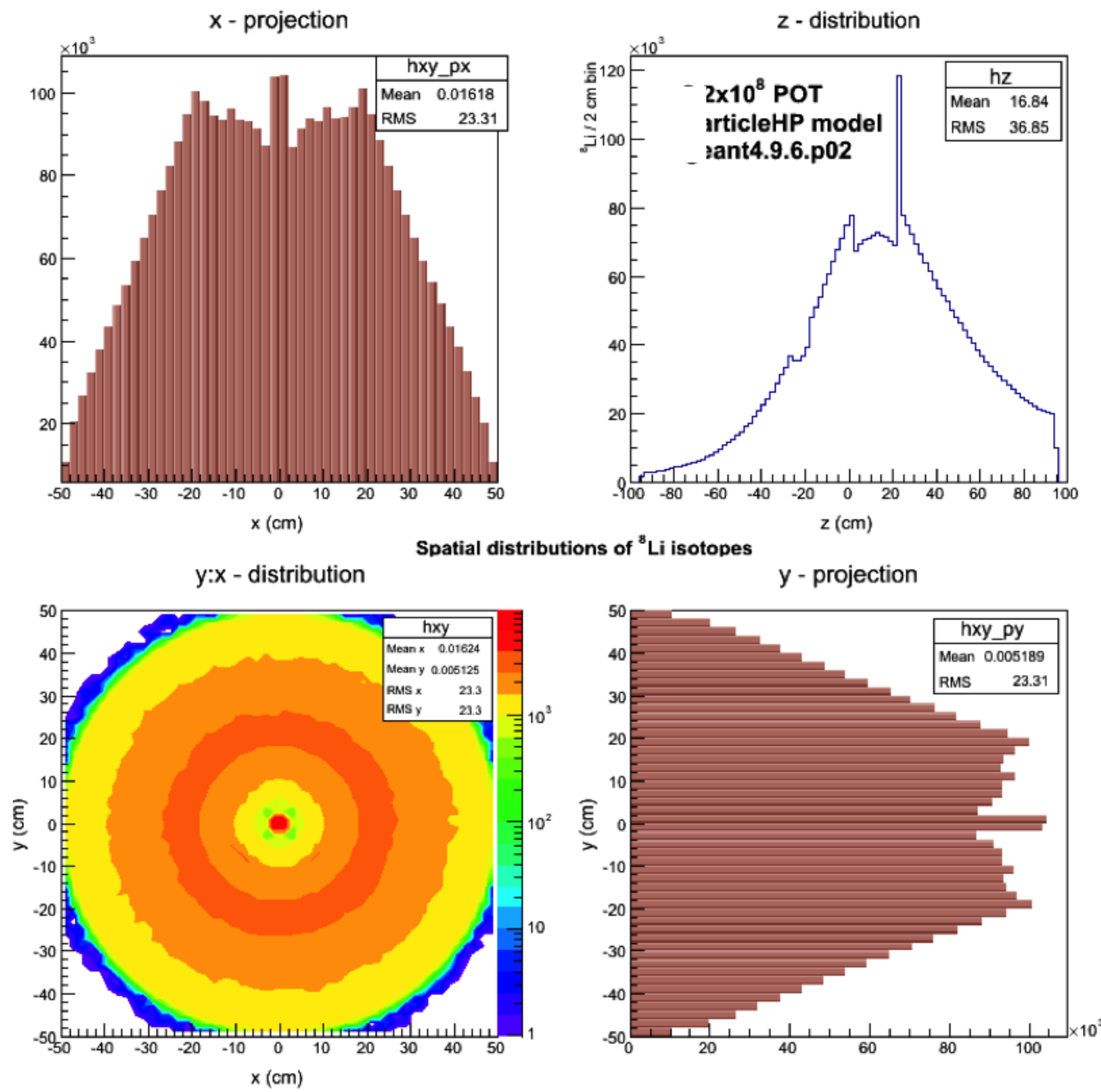


Compact neutrino source plus KamLANDs good L and E resolution

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

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





IsoDAR Cyclotron Cost Estimate (from IBA Cost Estimate)

ISODAR budget Report

August 2014
Page 1

ISODAR Injector Cyclotron Budget Report

Prepared by: INFN	Prepared by: IBA *Michel Abs* *Albert Blondin* *Eric Forton* *Benoit Nactergal* *Thomas Servais*
Keywords:	

Contents

Cost for the first Cyclotron: <$21M

Opens up possibility to produce a new type of neutrino source

DAEδALUS Top Level Cost Estimate

- $130M near accelerator plus $320M for 2nd and 3rd sites.
  - Includes various contingencies from 20% to 50%.
- The cyclotron magnet is the cost driver.
  - For this we have: Engineering Study for Daedalus Sector Magnet; Minervini, et al., arXiv:1209.4886
- The RF is based on the PSI design and scaled from those costs.
- The strong similarity to RIKEN cyclotron allows cost cross check.
- All targets are ~1 MW (similar to existing targets).

Cyclotron Development as Value to Society

1. IsoDAR design would give enhanced medical isotope production - much industry interest

Isotope	Half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain upt
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study brain bl
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs. As a potassium analog, this is used for heart and blood-fl
^{97}Ru	2.79 d	A γ-emitter used for spinal fluid and liver studie
^{117m}Sn	13.6 d	A γ-emitter potentially useful for bone studies
^{82}Sr	25.4 d	The parent of positron emitter ^{82}Rb, a potassium an This isotope is also directly used as a PET isotope for hea

COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

MAY 26, 2005

Conducted for:

U.S. Department of Energy
Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
19901 Germantown Road
Germantown, MD 20874

Conducted by:

JUPITER
Technical, Security, and Management Solutions

Suite 900, Westfield North
2730 University Boulevard West
Wheaton, MD 20902

2. DAEδALUS design applicable to Accelerator Driven Systems (ADS) Reactors

MW-CLASS 800 MeV/n H_2^+ SC-CYCLOTRON FOR ADS APPLICATION, DESIGN STUDY AND GOALS*

F. Méot, T. Roser, W. Weng, BNL, Upton, Long Island, New York, USA
L. Calabretta, INFN/LNS, Catania, Italy; A. Calanna, CSFNSM, Catania, Italy

Thorium reactor community interested in DAEδALUS development.

⇒ Cyclotrons are practical and cheap compared to linacs.