New Compact Low Energy Neutrino Source using Isotope Beta Decay

Mike Shaevitz - Columbia University

Workshop on Low Threshold Detectors for Detection of Coherent Neutrino Scattering

Dec. 6-7, 2012

Livermore Valley Open Campus, Livermore, California

Overview

- High-power cyclotrons can be used to make an intense, compact neutrino source.

- Daedalus CP violation program using 800 MeV proton cyclotrons
  – High intensity DAR source of $\bar{\nu}_\mu$ to complement long-baseline neutrino oscillation program
  – Use NC coherent scattering to search for $\nu \rightarrow \nu_{\mathbf{STERILE}}$ with DAR beam

- IsoDAR sterile neutrino experiment using a 60 MeV proton cyclotron
  – Cost effective, intense , compact $\bar{\nu}_e$ source from ^{8}Li isotope decay.
  – Synergy with industrial interest in medical isotope production

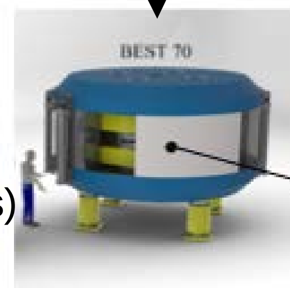
- High intensity IsoDAR type $\bar{\nu}_e$ source could also be used for a neutral current coherent neutrino scattering experiment
  – Need to couple the IsoDAR source with a low threshold (~few keV) 10 to 1000 kg detector

DAEδDALUS 800 MeV Cyclotron System (Under Development)

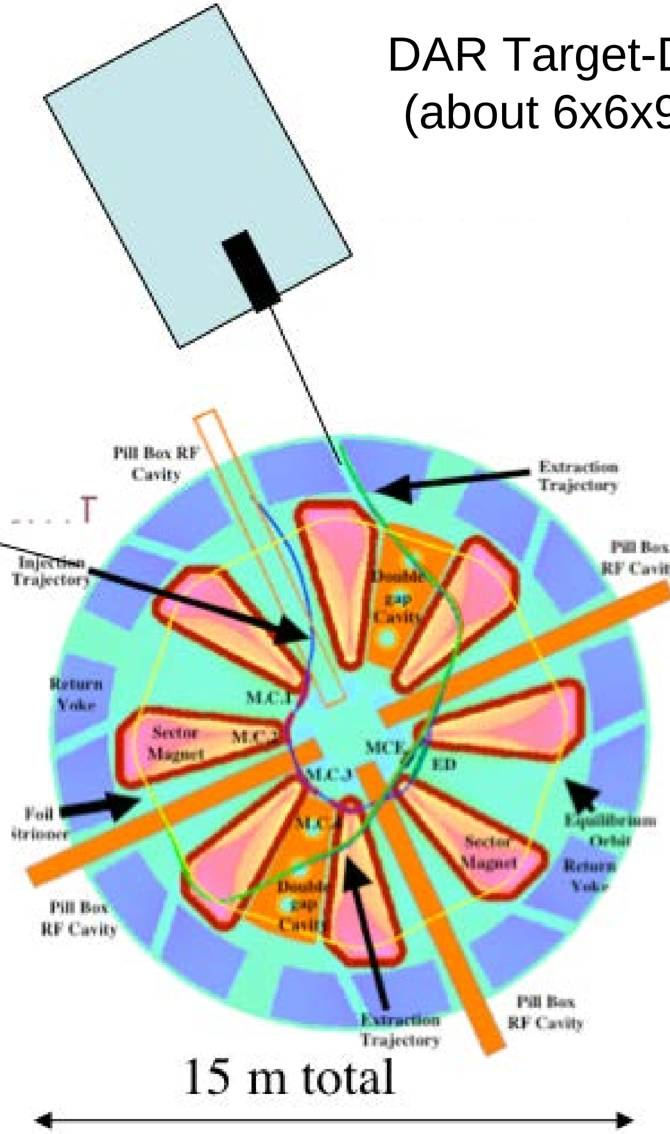
H_2^+ Ion Source

IsoDAR Cyclotron

Injector Cyclotron (Resistive Isochronous)



DAR Target-Dump (about 6x6x9 m^3)



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.

arXiv.org > physics > arXiv:1207.4895

Physics > Accelerator Physics

Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics

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Columbia, Huddersfield, IBA, Maryland, MIT,
PSI, INFN-Catania, INFN –Legnaro, RIKEN, Wisconsin

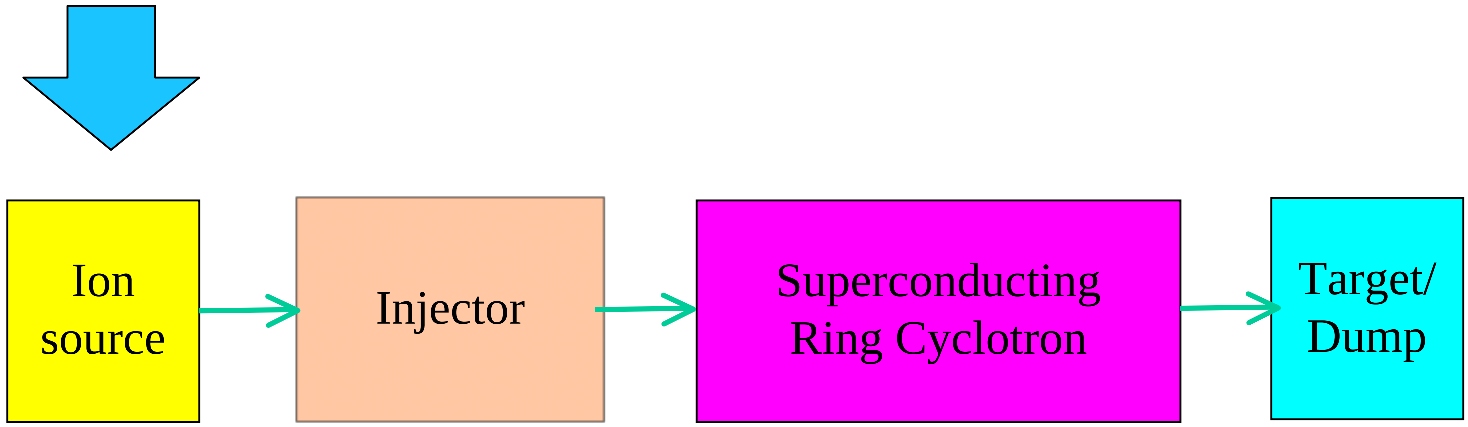
Academics: Neutrino Physicists, Accelerator Physicists
And also Scientists at a Corporation

In this paper we address the most challenging questions regarding a cyclotron-based high-power proton driver in the megawatt range with a kinetic energy of 800 MeV. Aspects of important subsystems like the ion source and injection chain, the magnet design and radio frequency system will be addressed.

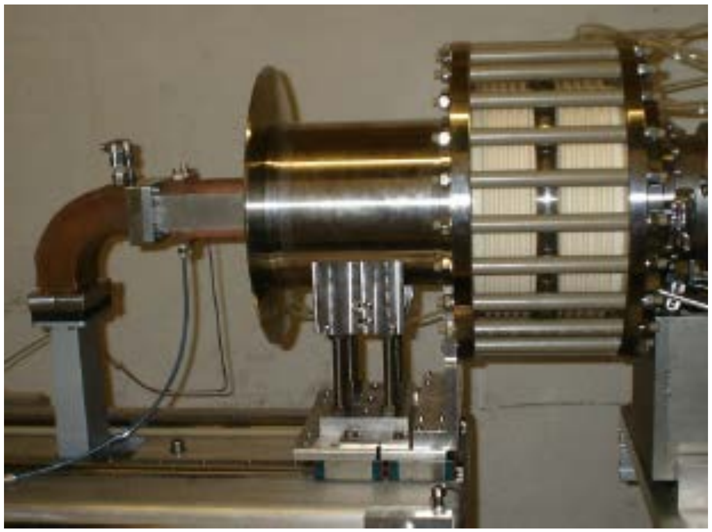
Precise beam dynamics simulations, including space charge and the H_2^+ stripping process, are the base for the characterization and quantification of the beam halo–one of the most limiting processes in high-power particle accelerators.

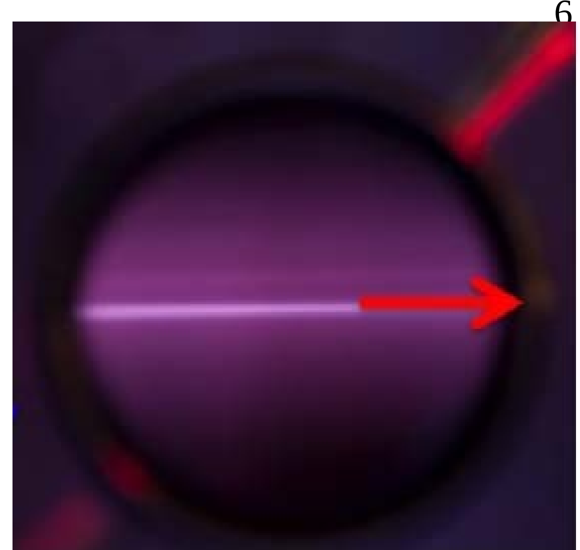
Submitted to NIM

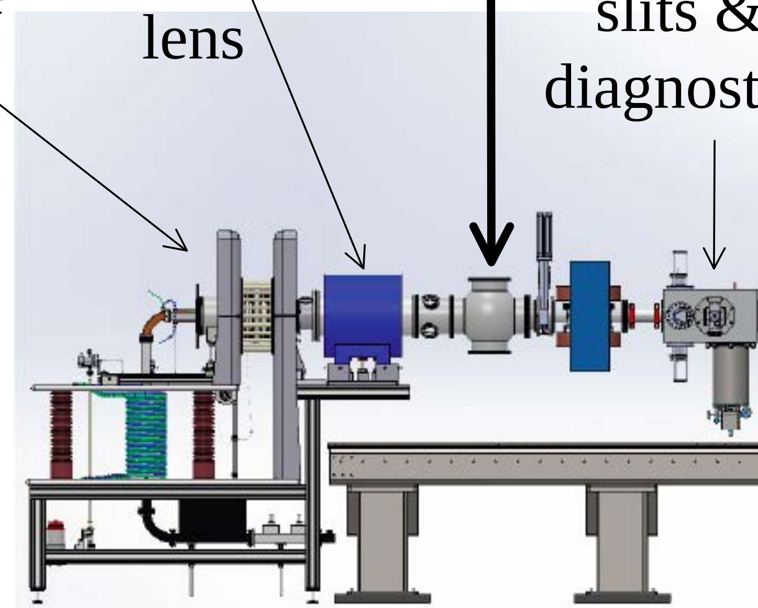
Phase I: The Ion Source



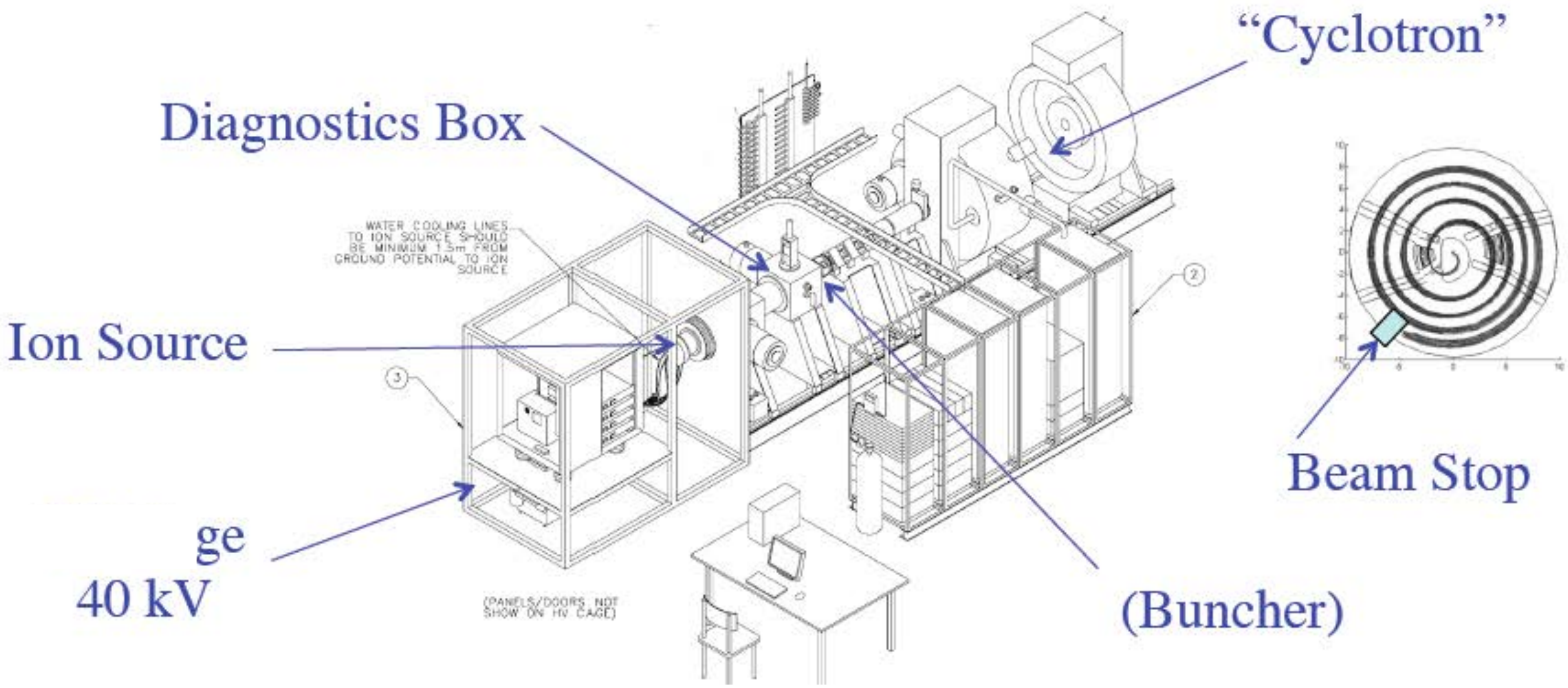
Ion Source:
By our collaborators at INFN Catania.
Produces sufficient H_2^+!





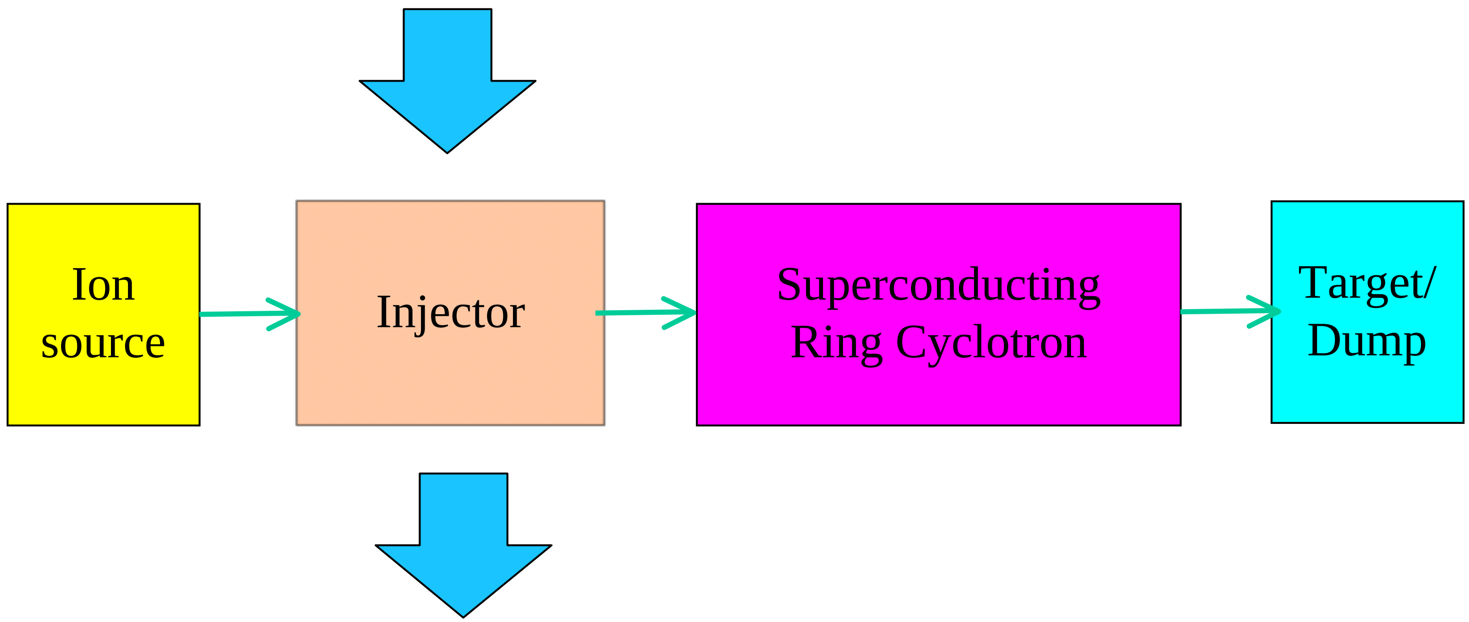


Beam to be characterized at Best Cyclotrons, Inc, Vancouver
This winter (NSF funded)



Results to be available by Cyclotrons'13 Conference, Sept 2013, Vancouver

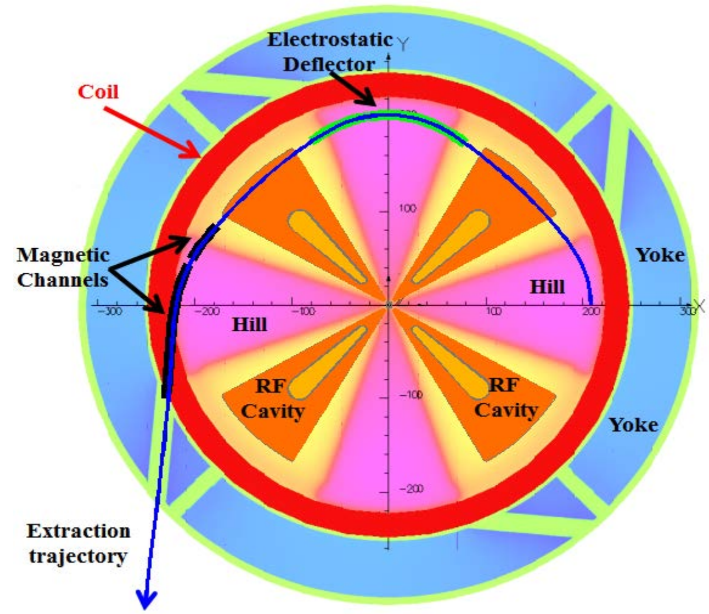
We have a workable ion source for a Phase II



IsoDAR: A sterile neutrino experiment On its own!

Base Design Injector
60 MeV/n @ 5 mA of H_2^+

(That's 10 mA of protons)

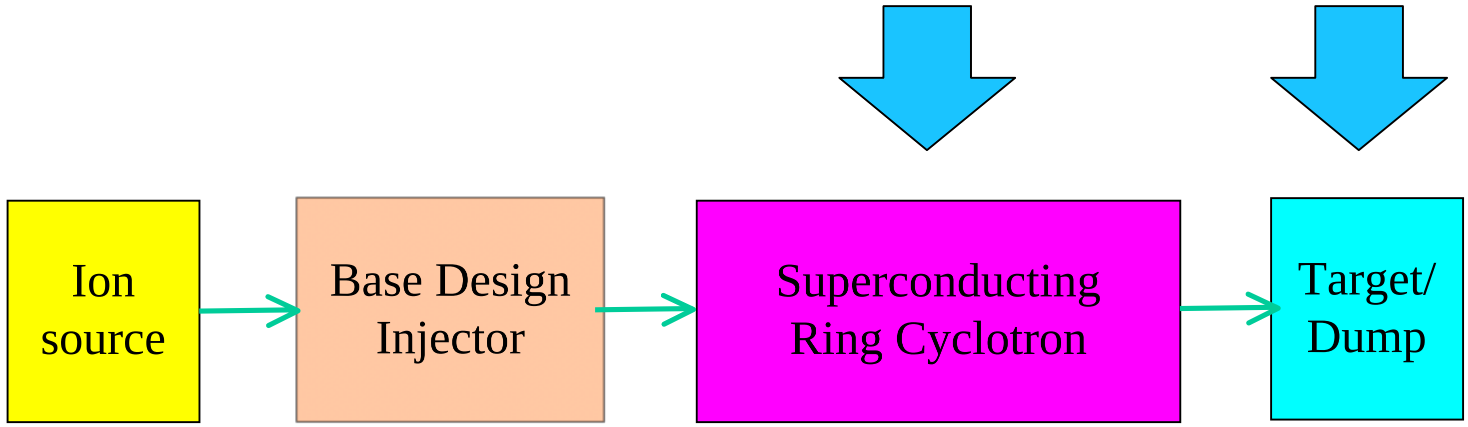


~1 mA p machines are made
By industry (IBA, BEST)
For isotope production

Table 3: Medical isotopes relevant to IsoDAR energies, from Ref. [23].

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 blood brain-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.

Phases III and IV

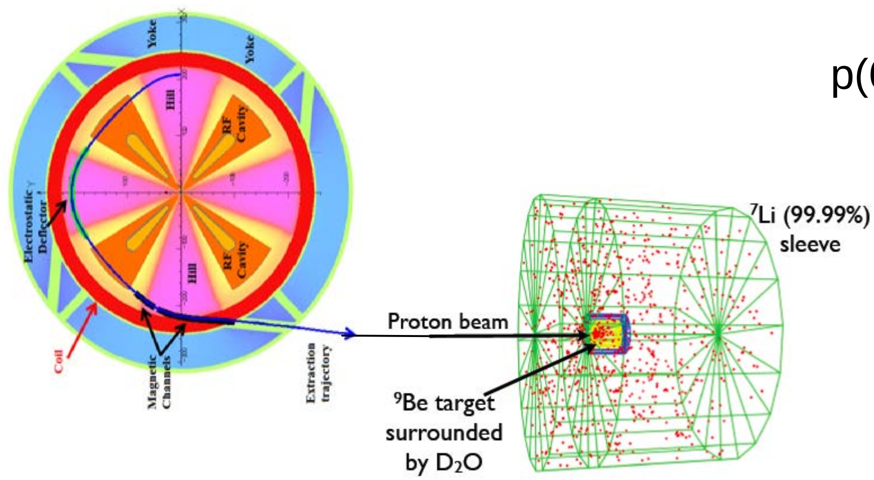


Establish the “standard” system
And the high-power system

Our proposed
800 MeV cyclotron
is very similar to the
existing Riken, Japan,
cyclotron

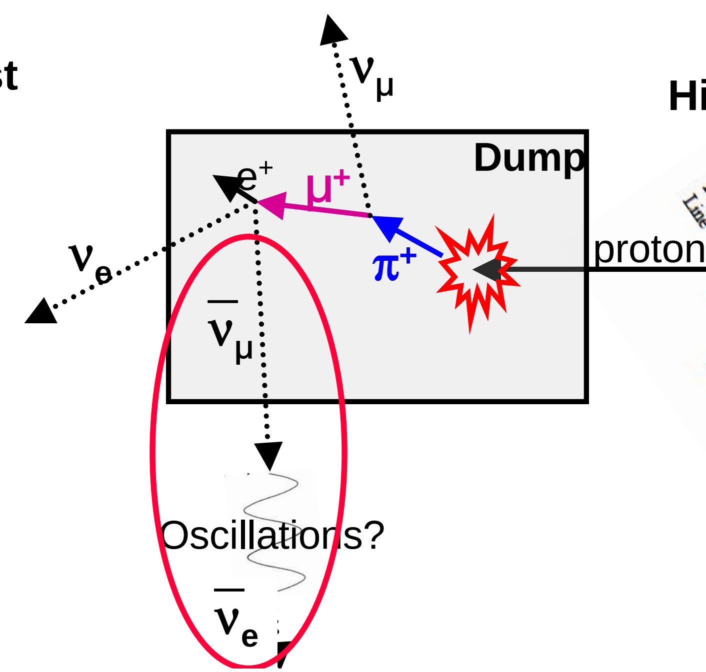
Why Are We Developing These High Intensity Cyclotrons?
⇒ To Make High Intensity Neutrino Sources

High Intensity Injector Cyclotron (60 MeV protons)

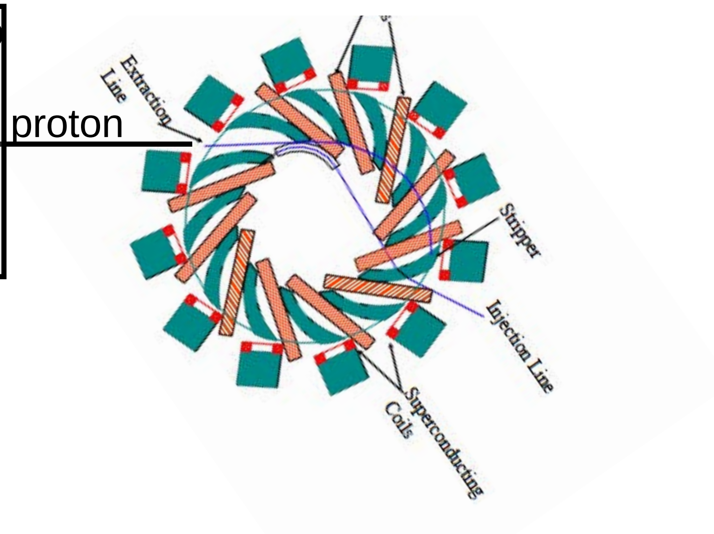


p(60 MeV)
$\rightarrow$ ^{9}Be / ^{7}Li (shielding)
$\rightarrow$ Lots of ^{8}Li
$^{8}Li \rightarrow {}^{8}Be + e^{-} + \bar{\nu}_e$

Decay-at-Rest (DAR) Beam



High Intensity Cyclotron (~800 MeV protons)

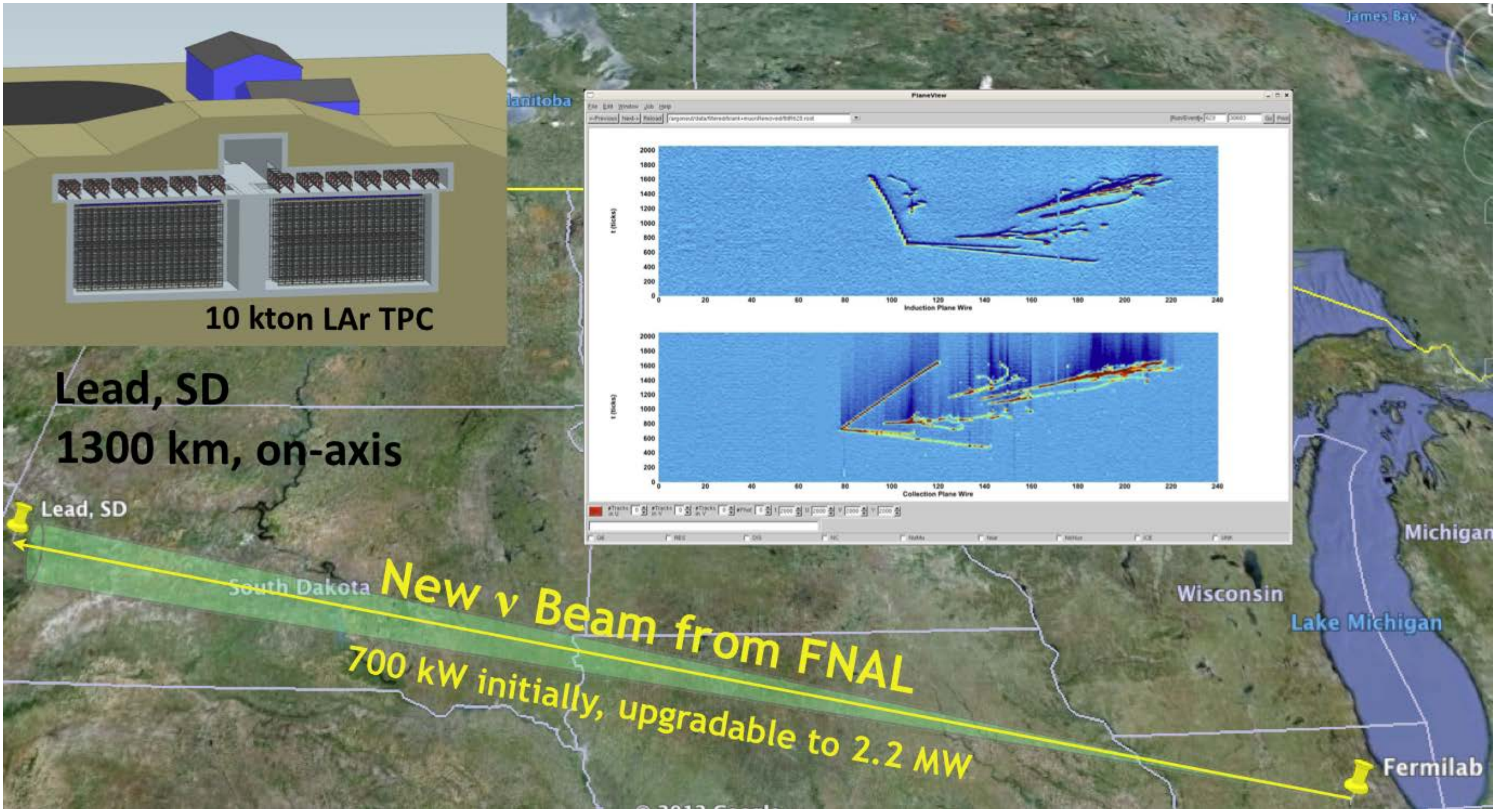


Daedalus CP Violation Program
in Combination with Longbaseline Neutrino Exps

Long-Baseline Neutrino Experiment (LBNE)

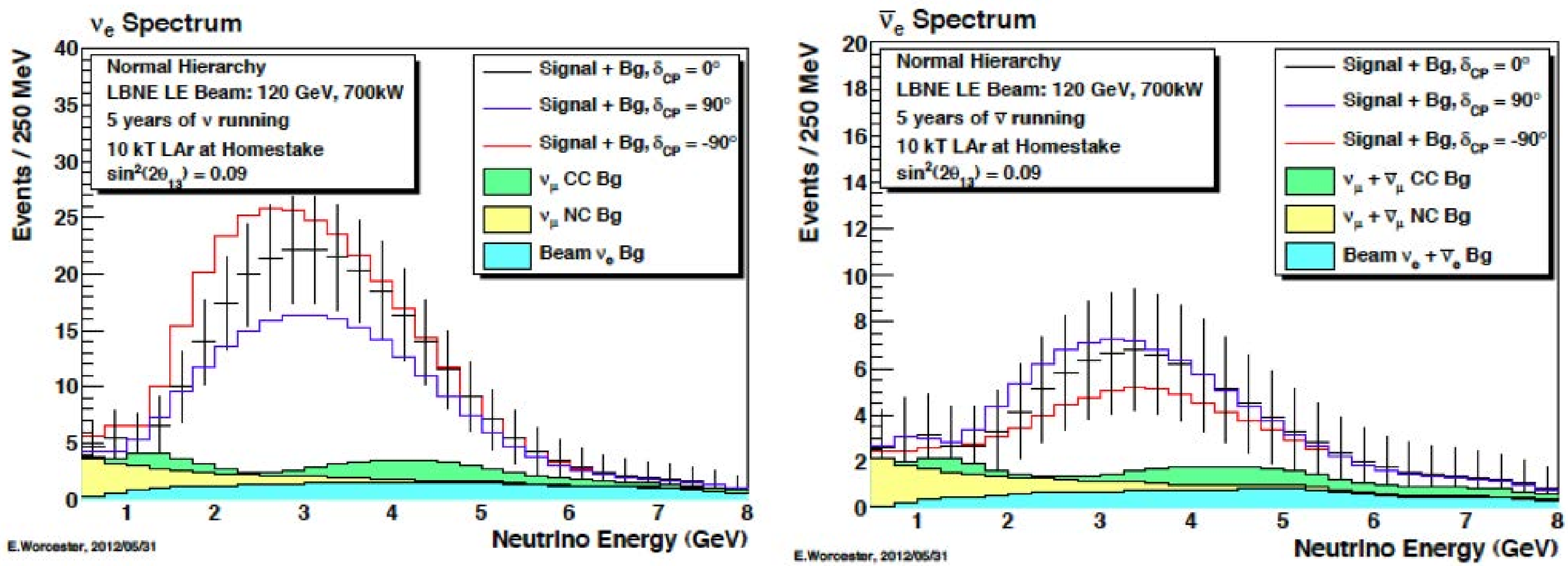
(Being set up to measure the mass hierarchy and ν CP violation)

Phase 1: 700kW beam with 10kton LiqArgon Detector on surface (data in ~2023)
Phase 2: >1MW beam with >20kton LiqArgon Detector underground



Main Limitation of LBNE Approach

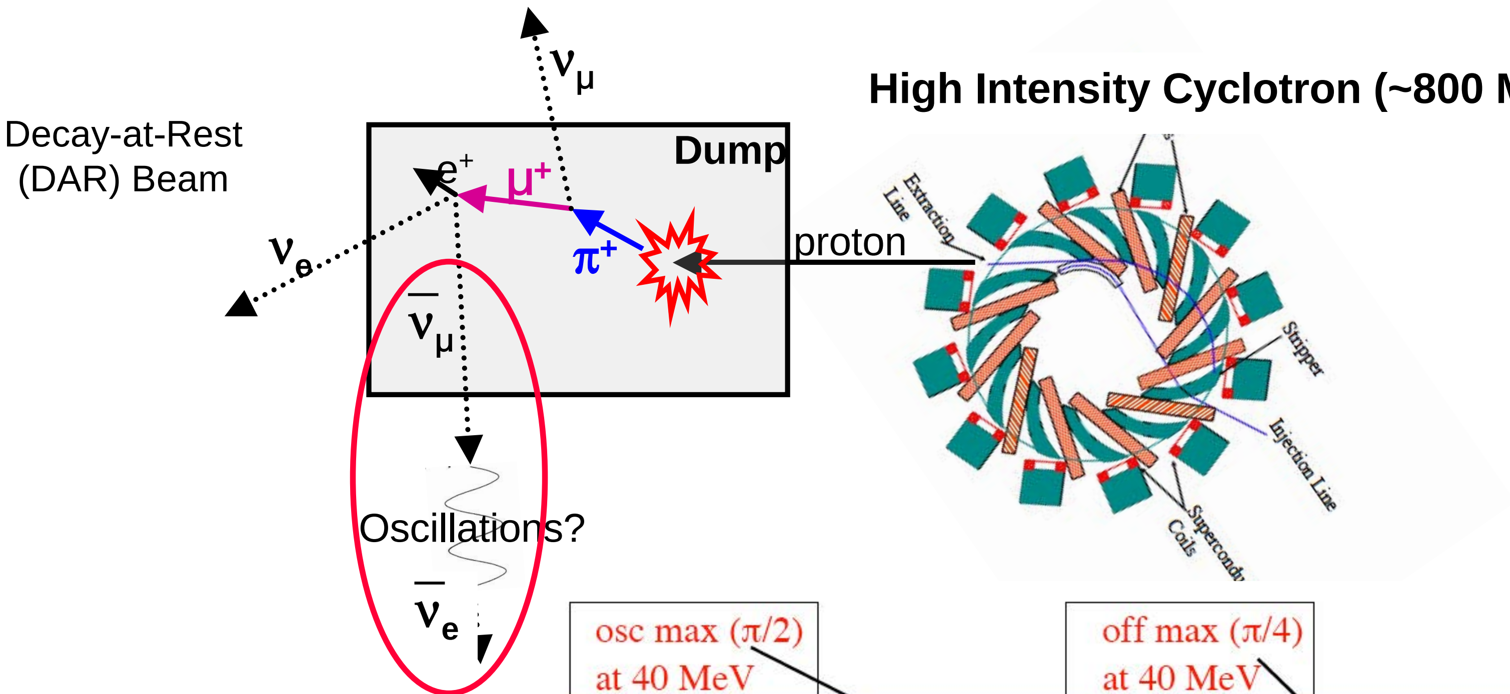
Long Baseline experiments are usually low in antineutrino statistics
$\rightarrow$ due to lower π^- production and $\bar{\nu}$ cross section



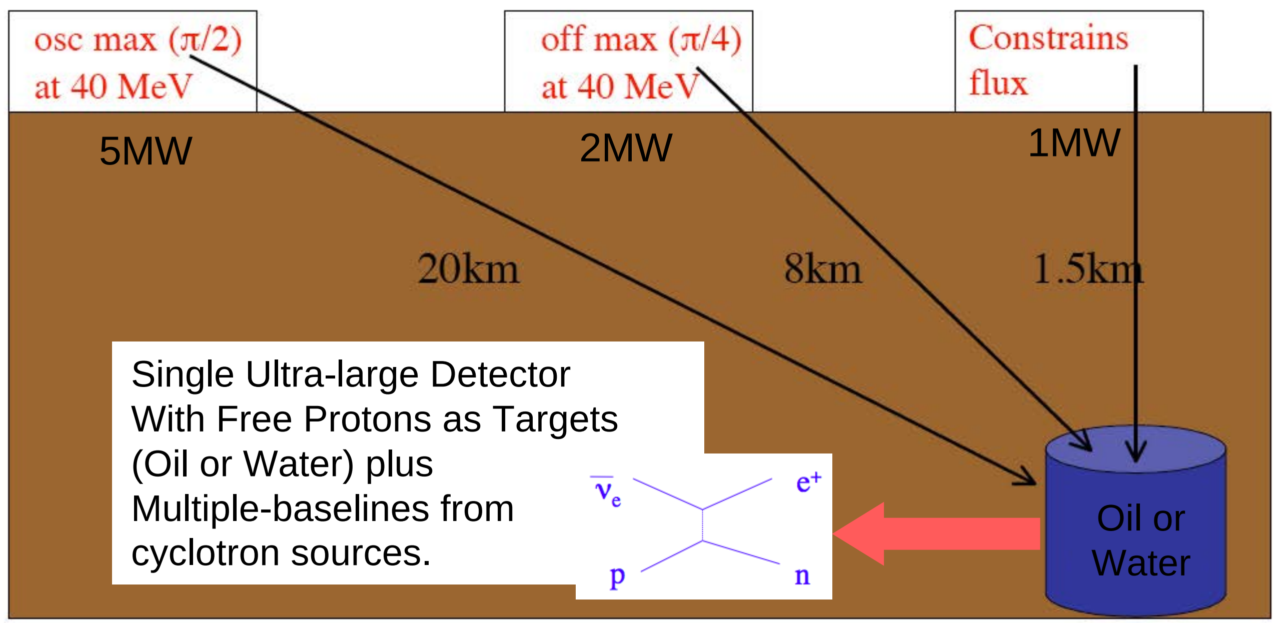
… and the backgrounds are significant compared to signal
plus the antineutrino beam has neutrino contamination

DAEδALUS Experiment: Antineutrino Source for CP Measurements

High Intensity Cyclotron (~800 MeV KE proton)



- Combine:
  - High statistics Daeδalus Antineutrinos $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - High statistics Longbaseline Neutrinos $\nu_\mu \rightarrow \nu_e$



(Described in: Conrad/Shaevitz, PRL104,141802 (2010), Alonso et al., arXiv:1006.0260 [physics.ins-det] and 1008.4967 [hep-ex])

Using Cyclotron Neutrino Sources to Search for Sterile Neutrinos

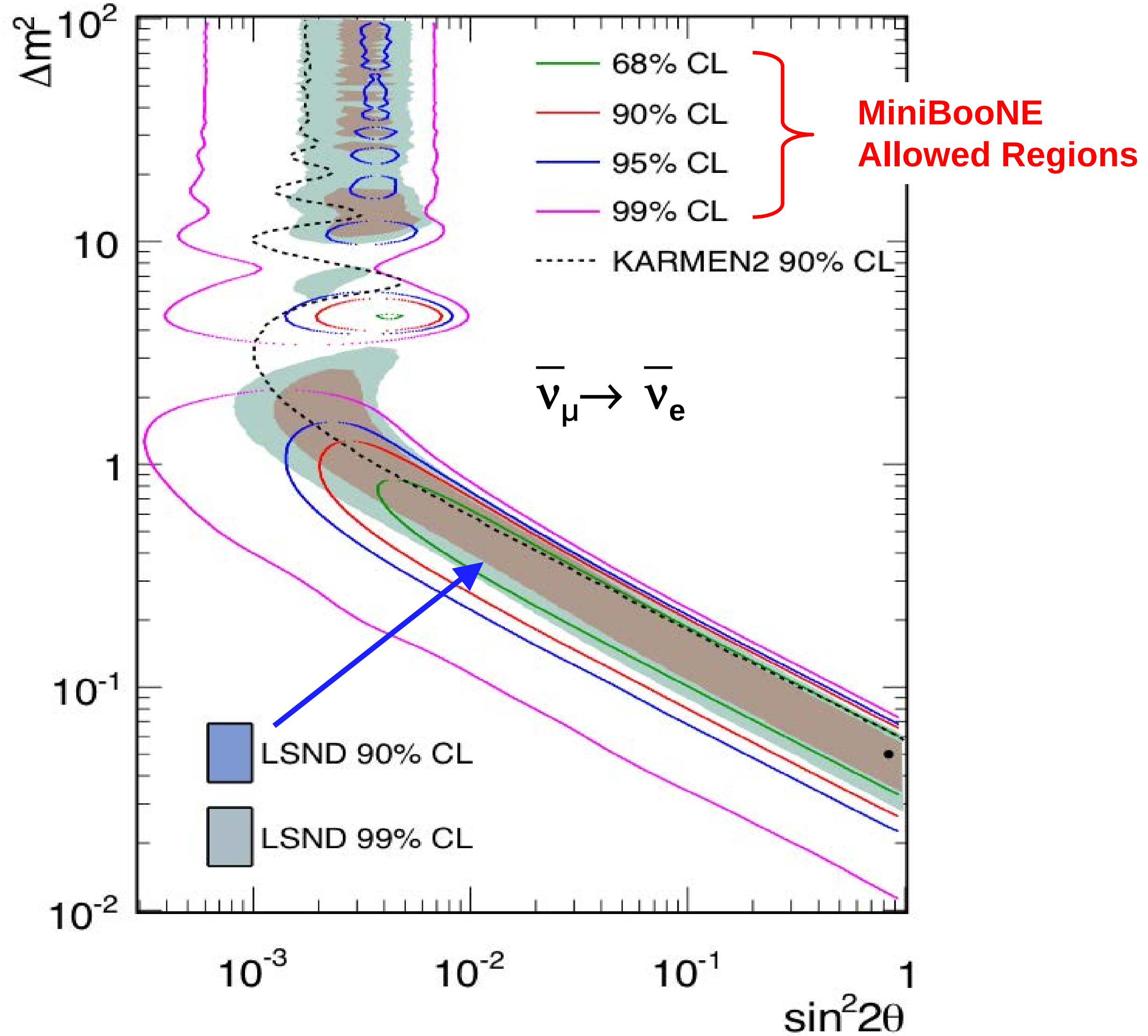
Possible Oscillations to/thru Sterile Neutrinos

- Several hints for neutrino oscillations with large $\Delta m^2 \sim 1\ eV^2$
  - Cannot be explained with the 3 standard neutrinos (ν_e, ν_μ, ν_τ), since already have two Δm^2 value at 2.5×10^{-3} and $7.6\times10^{-5}\ eV^2$
  - And there are strong constraints that there are only 3 neutrinos with normal weak interactions

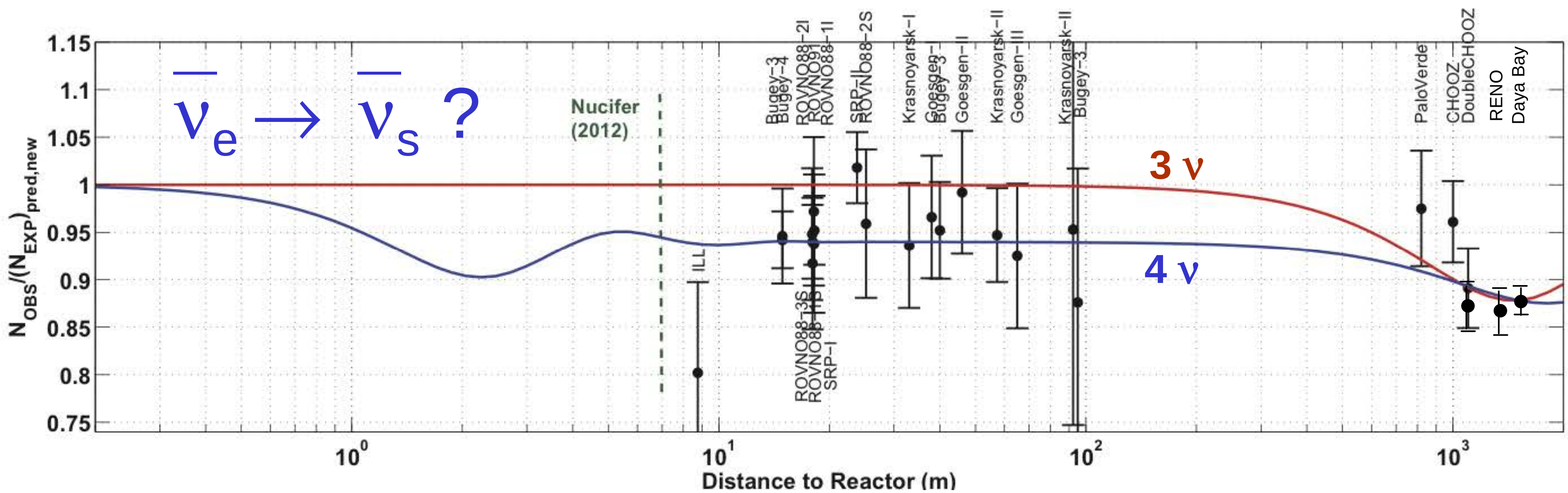
  ⇒ **Need a new type of neutrino that does not interact weakly and therefore is "sterile"**

- Sterile neutrinos
  - Have no weak interactions (through the standard W/Z bosons)
  - Would be produced and decay through mixing with the standard model neutrinos
  - Can affect oscillations through this mixing

LSND and MiniBooNE Indications of $\bar{\nu}_e$ Appearance



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



Region to Explore for Sterile Neutrinos

Older Reactor Exps at Close Distances
$R = 0.927 \pm 0.023$ (3.0 σ)

Current Reactor Experiments

- **At least three alternatives:**
  - Wrong prediction of ν-spectra ?
  - Bias in all experiments ?
  - New physics at short baselines: Mixing with 4^{th} ν-state

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

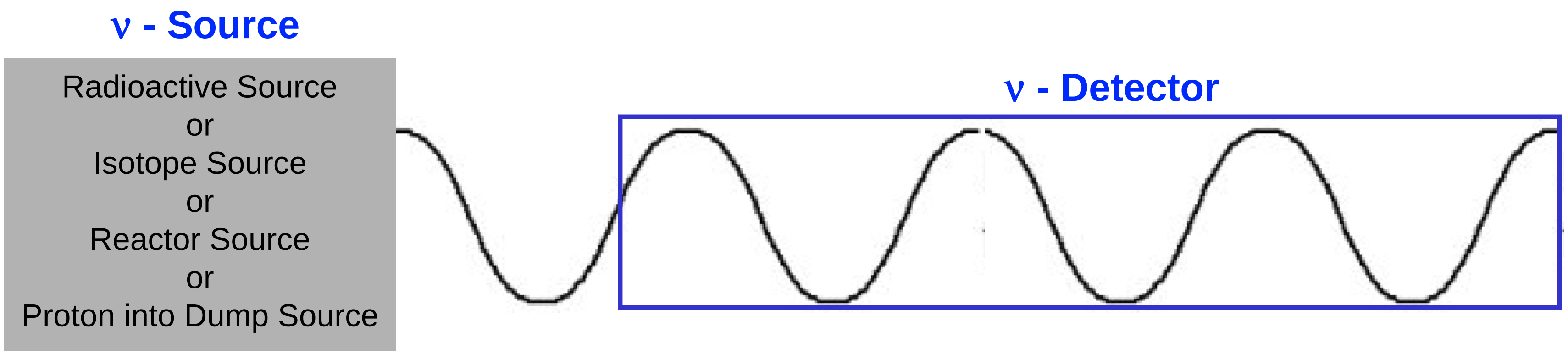
Many Ideas for Future Experiments

- 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
- The disappearance of neutrinos using the neutral current interactions is a strict probe of active-to-sterile oscillations.
  - Observation of oscillations for coherent NC scattering would definitively establish the existence of sterile neutrinos.

Future Experimental Oscillation Proposals/Ideas

Type of Exp	App/Disapp	Osc Channel	Experiments
Reactor Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Ricochet, SCRAMM, NIST, Neutrino4, DANSS
Radioactive Sources	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$ $(\nu_e \to \nu_e)$	Baksan, LENS, Borexino, SNO+, CeLAND, Daya-Bay
Isotope Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest Source	Appearance & Disapp	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Accelerator $\overset{(-)}{\nu}$ using Pion Decay-in-Flight	Appearance & Disapp	$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-Energy ν-Factory	Appearance & Disapp	$\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	νSTORM at Fermilab

Very-short Baseline Oscillation Experiments



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

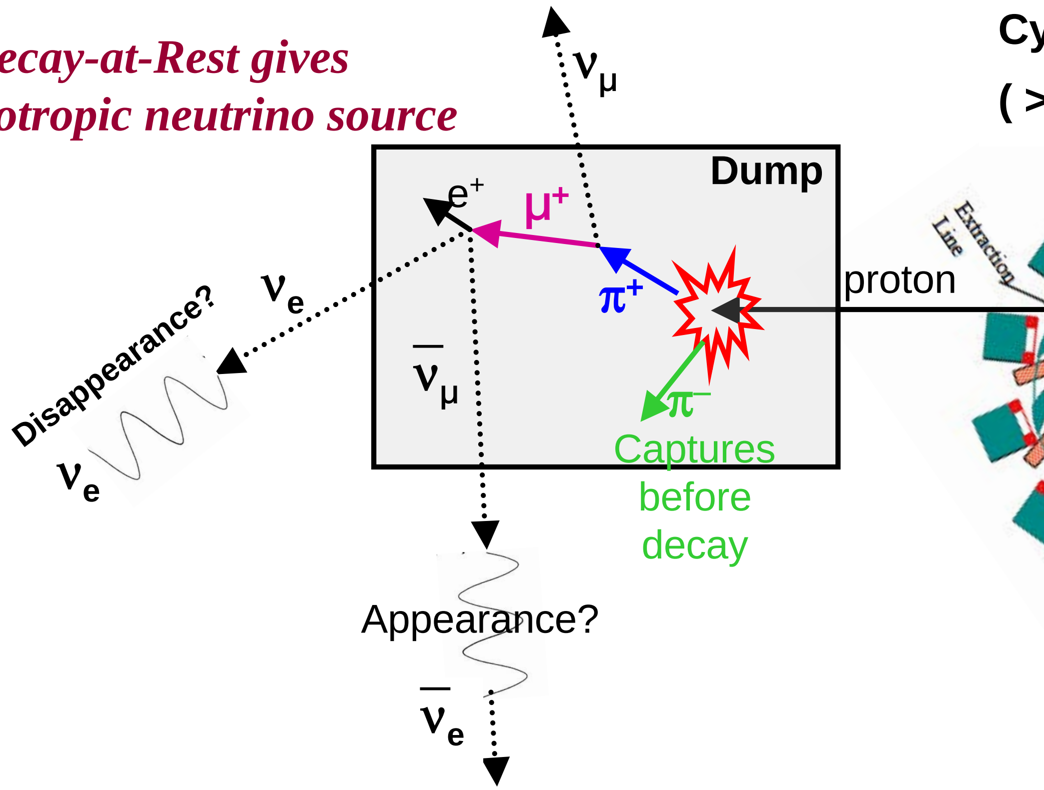
- Can observe oscillatory behavior within the detector if neutrino source has small extent .
  - Look for a change in event rate as a function of position and energy within the detector
  - Bin observed events in L/E (corrected for the $1/L^2$) to search for oscillations

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

Pion or Kaon Decay-at-Rest Neutrino Sources

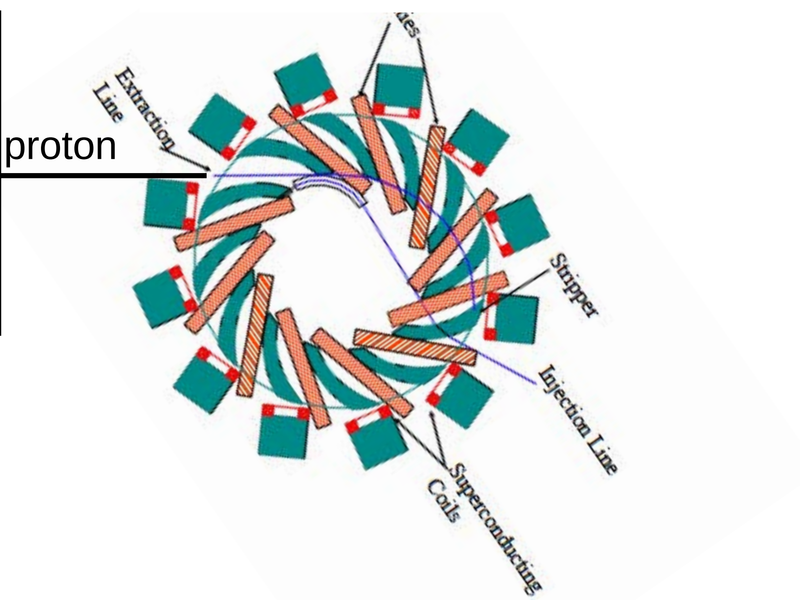
Decay-at-Rest (or Beam Dump) Neutrino Sources

Decay-at-Rest gives isotropic neutrino source

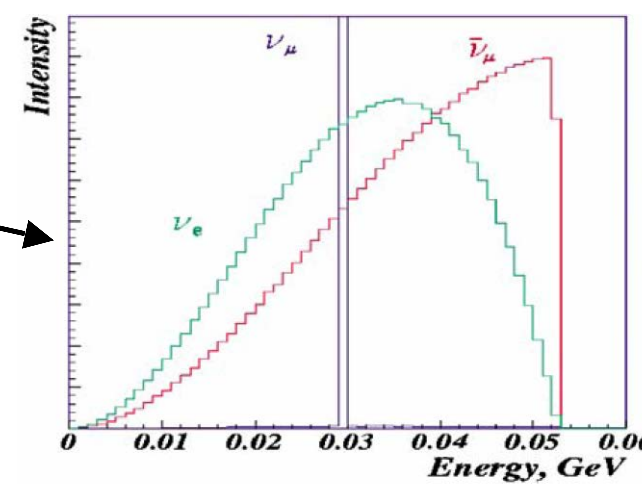


Cyclotron or Other Proton Source

(>800 MeV proton for π production)



Each π^+ decay gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ with known energy spectrum



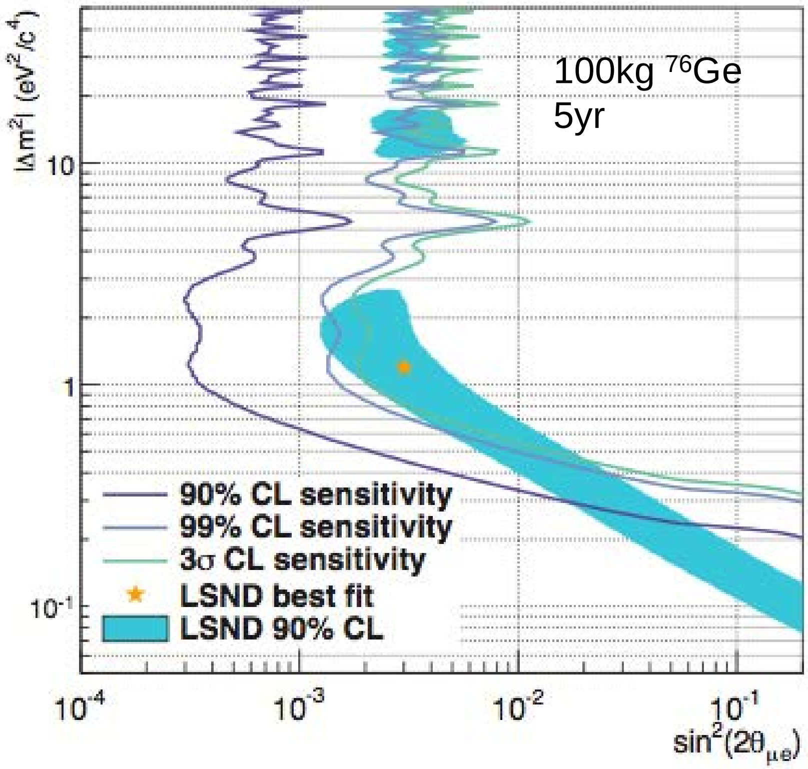
~1 ma of 800 MeV protons (like LSND)

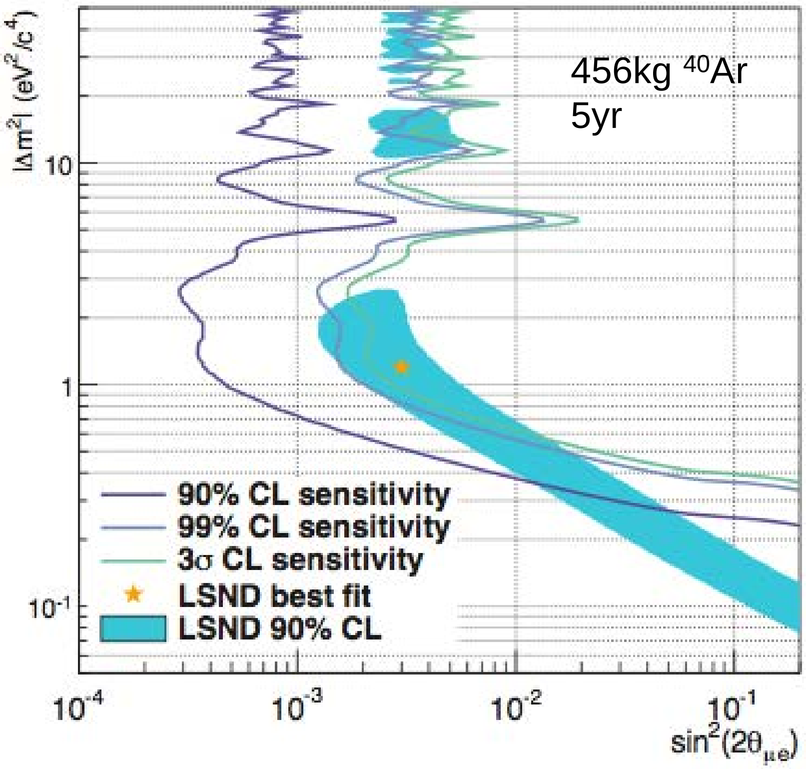
$\Rightarrow$ 0.17 π^+/proton $\Rightarrow$ 2.3×10^{24} ν / yr

Using Coherent Scattering with DAR Beam

Measuring Active-to-Sterile Neutrino Oscillations with Neutral Current Coherent Neutrino-Nucleus Scattering arXiv: 1201.3805

A.J. Anderson,[1] J.M. Conrad,[1] E. Figueroa-Feliciano,[1] C. Ignarra,[1]
G. Karagiorgi,[2] K. Scholberg,[3] M.H. Shaevitz,[2] and J. Spitz[1]



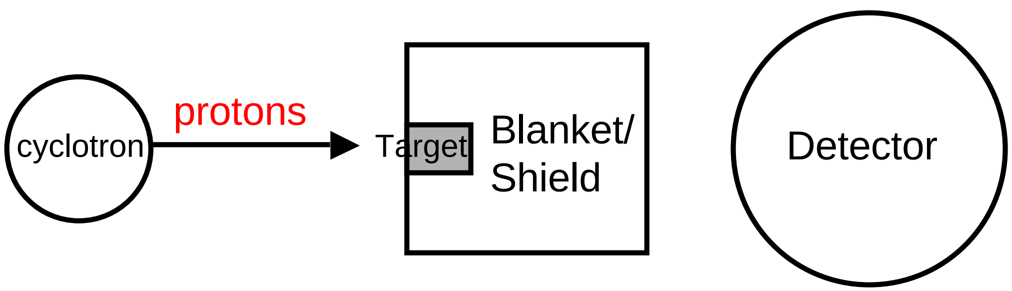


IsoDAR Experiment

Isotope Decay-at-Rest Neutrino Source
($\bar{\nu}_e$ Disappearance)

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….

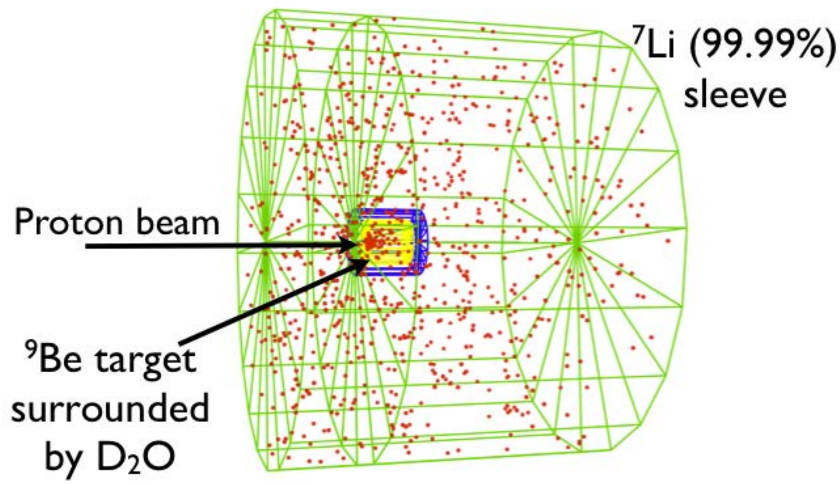


- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector.

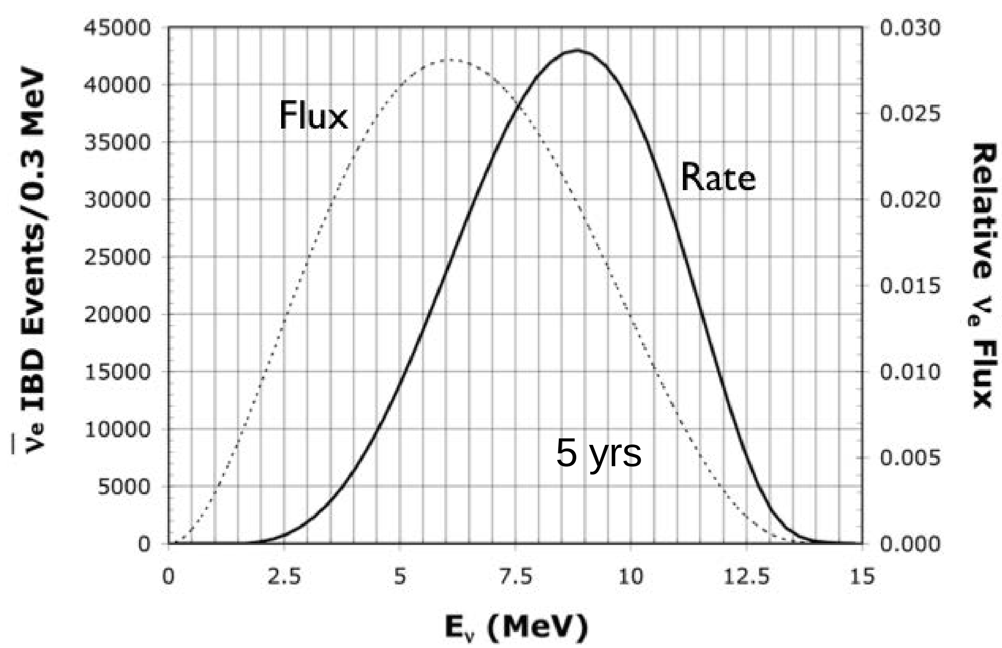
Phys Rev Lett 109 141802 (2012)
arXiv:1205.4419

IsoDAR Neutrino Source and Events

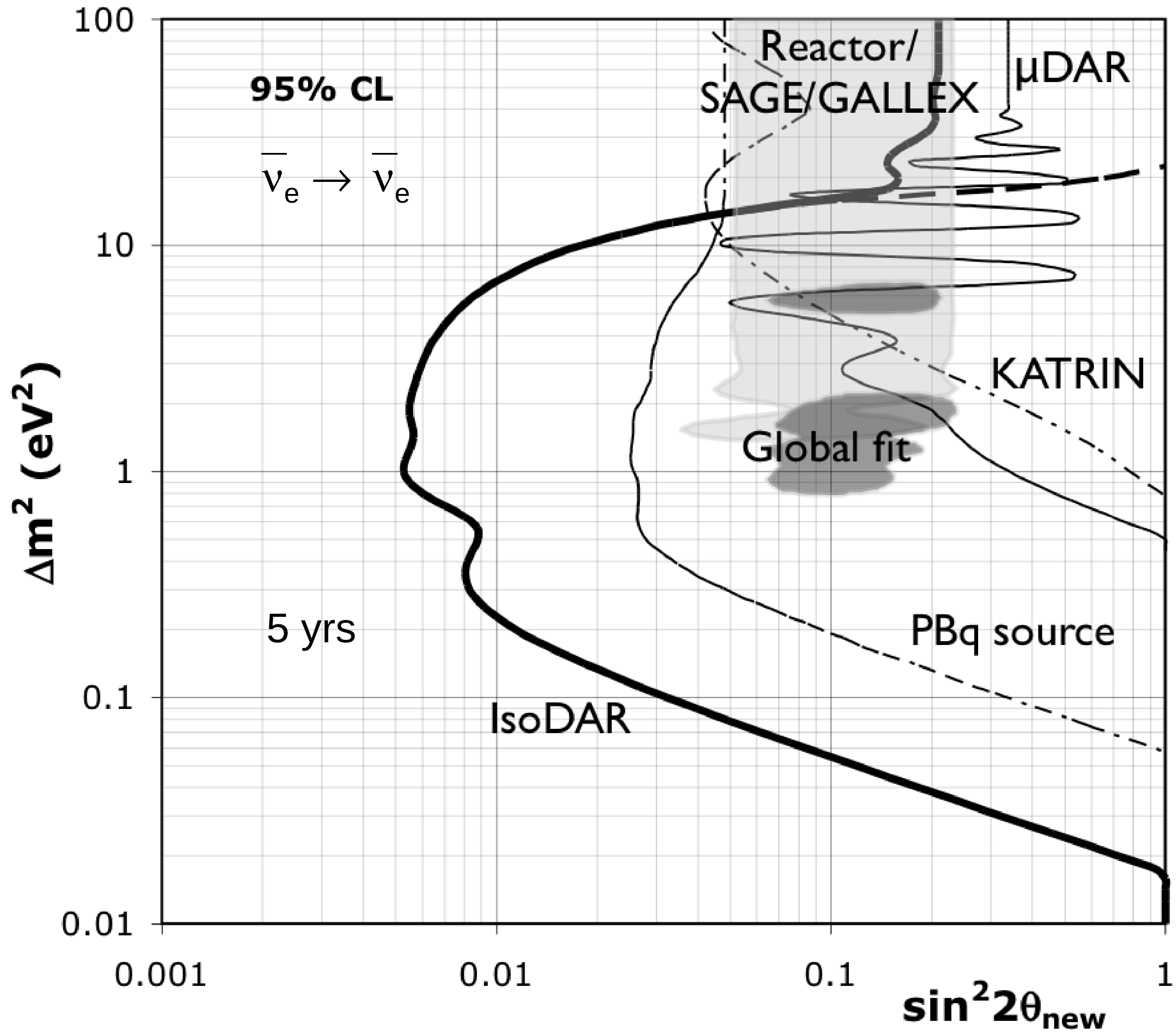
- p (60 MeV) + ^{9}Be $\rightarrow$ ^{8}Li + 2p
  - plus many neutrons since low binding energy
- n + ^{7}Li (shielding) $\rightarrow$ ^{8}Li
- ^{8}Li $\rightarrow$ ^{8}Be + e$^-$ + $\bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV
  - 2.6×10^{22} $\bar{\nu}_e$ / yr
- Example detector: Kamland (900 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

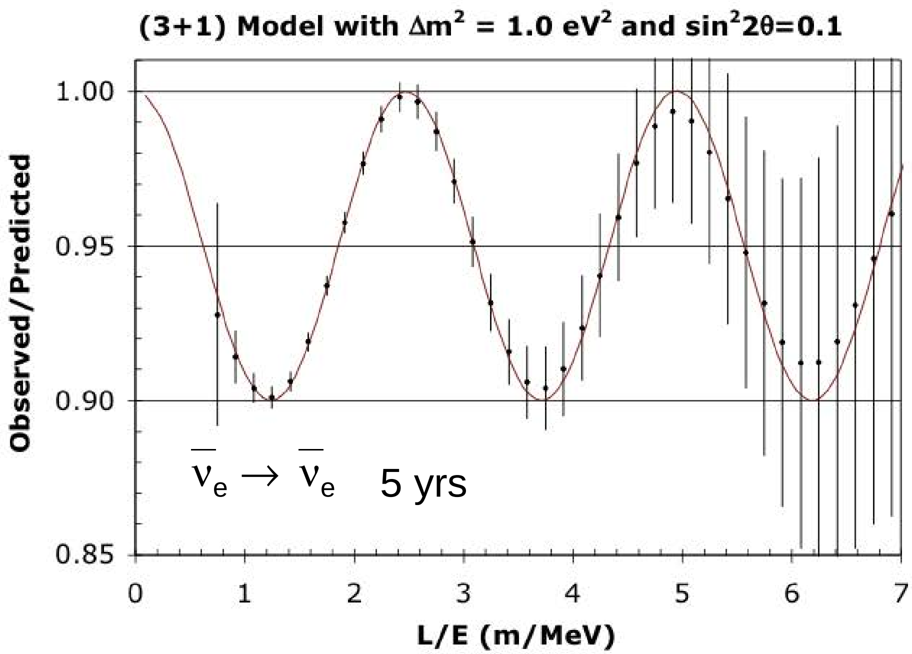


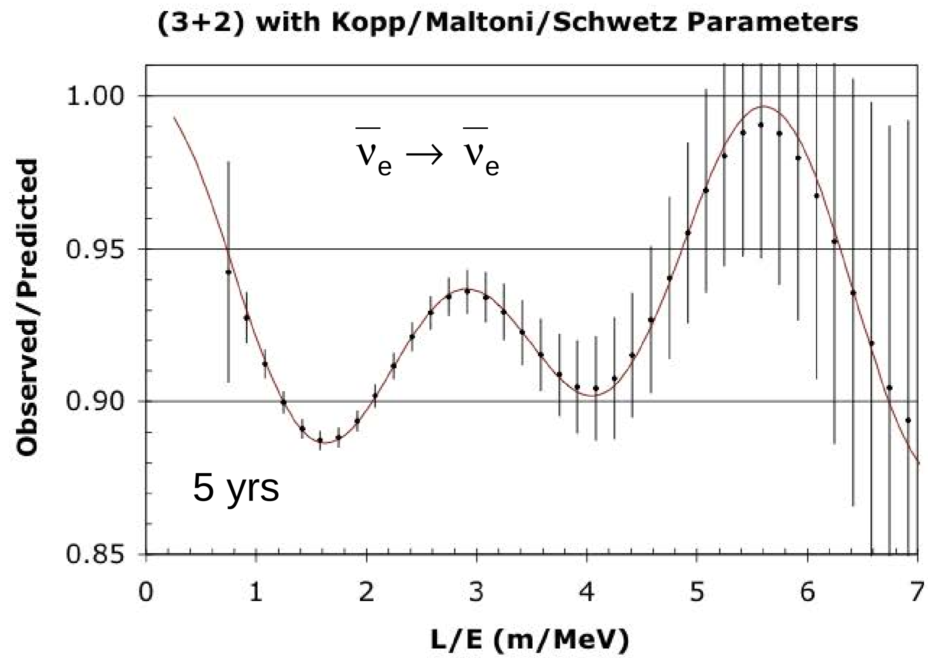
IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)



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 gives good sensitivity to distinguish (3+1) and (3+2) oscillation models

Use IsoDAR $\bar{\nu}_e$ Source for Coherent NC Measurement

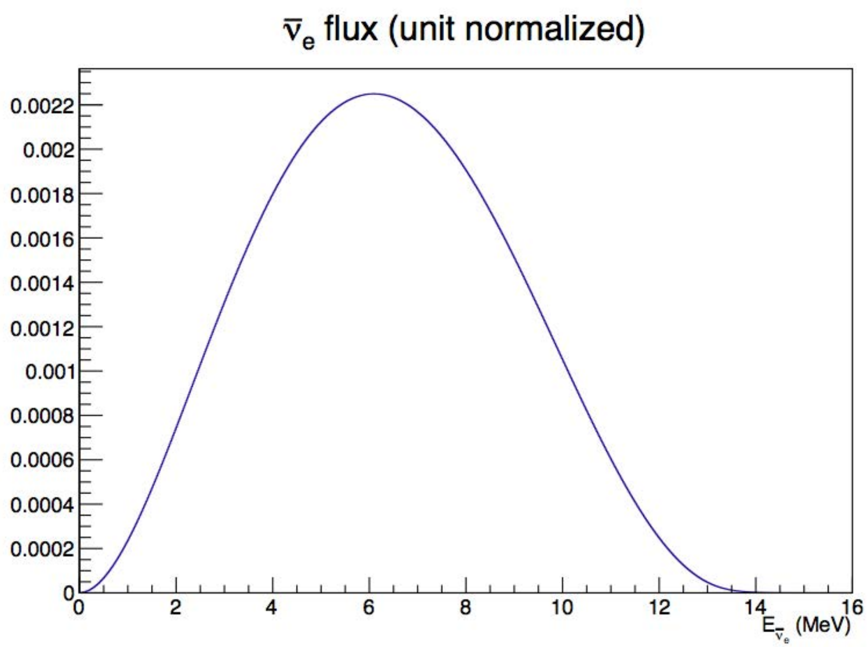
- Cyclotron driven neutrino source from beta decay of isotopes produced in proton target/dump system
  - High intensity isotropic neutrino beam with well known spectrum

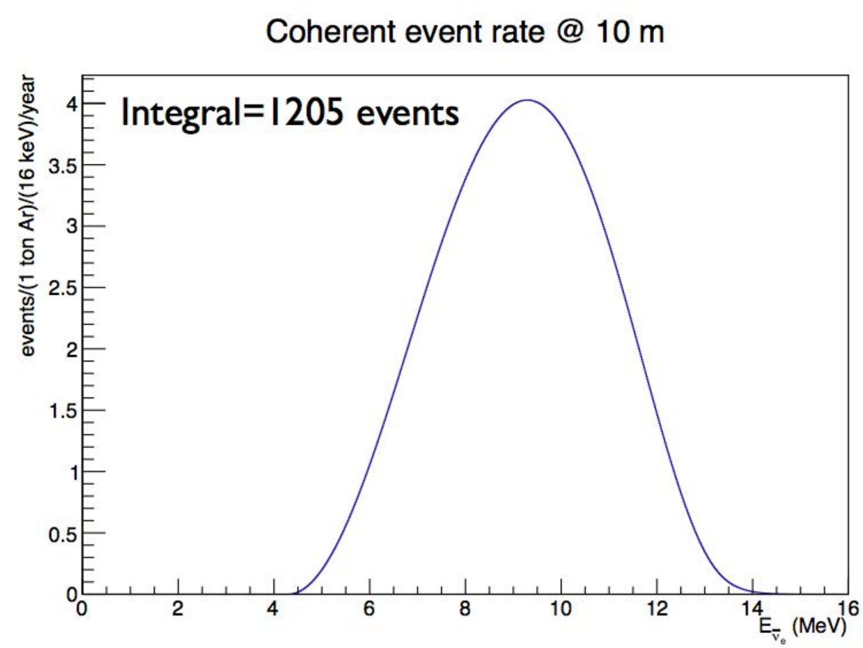
- Advantages:
  - About x2 higher energy than reactor neutrinos (but lower flux)
  - IsoDAR experimental site should offer a close, low-background location to put a ~ton scale coherent scattering detector
  - Can turn off cyclotron to give measurement of non-beam backgrounds
  - Source size ~0.5m so might explore doing an oscillation search with coherent scattering events.
  - Can vary distance with cyclotron beam to multiple ν sources
  - Can go deep to reduce cosmic backgrounds
  - Do dark matter searches during cyclotron-off periods

- Disadvantage:
  - To get needed rates, one needs to push the detection thresholds down to the few keV range
  - High-intensity cyclotron needs to be developed

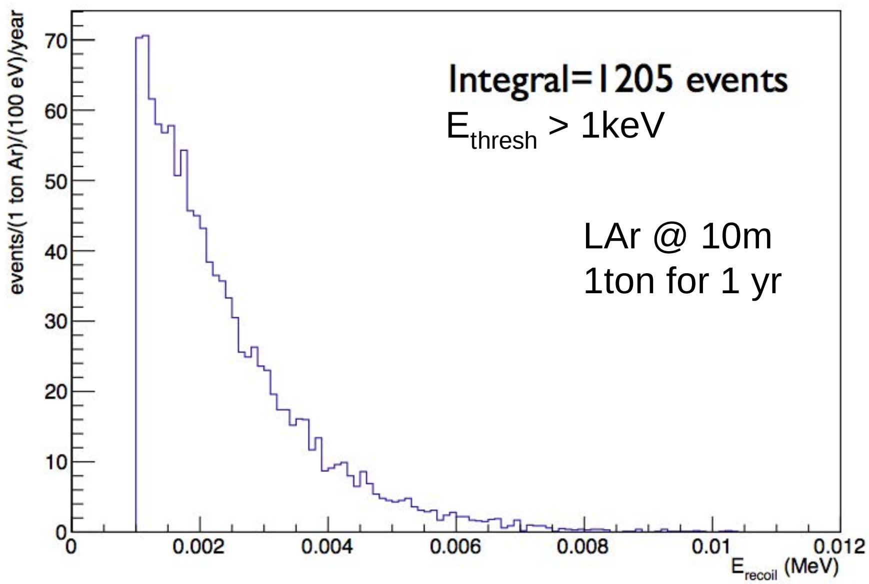
Example Coherent Rates with 1ton LArgon with IsoDAR

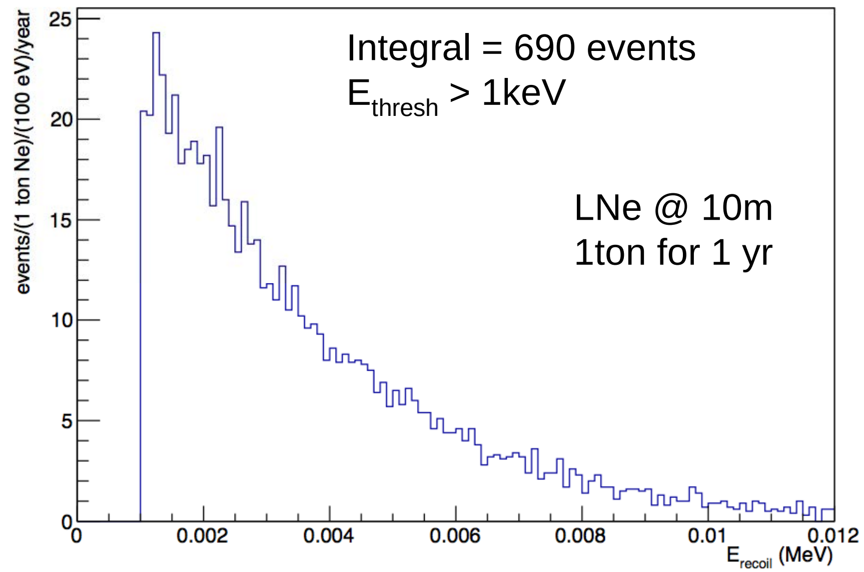
IsoDAR coherent assumptions	
Target	Ar
Detector mass	1000 kg
Recoil energy resolution	20%
Threshold	1 keV
Detection efficiency	100%
Distance	10 m
Flux	2.58E22 $\overline{\nu}_e$/year

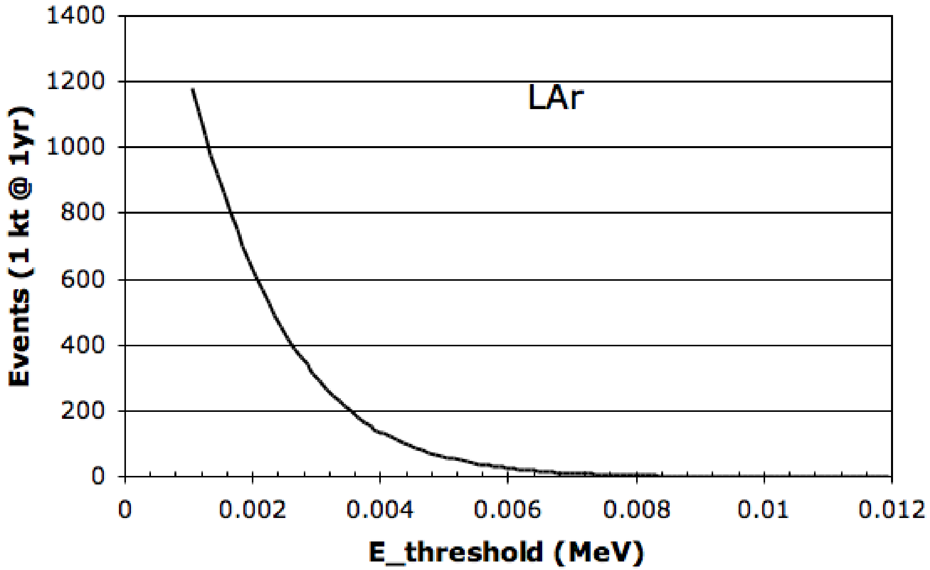


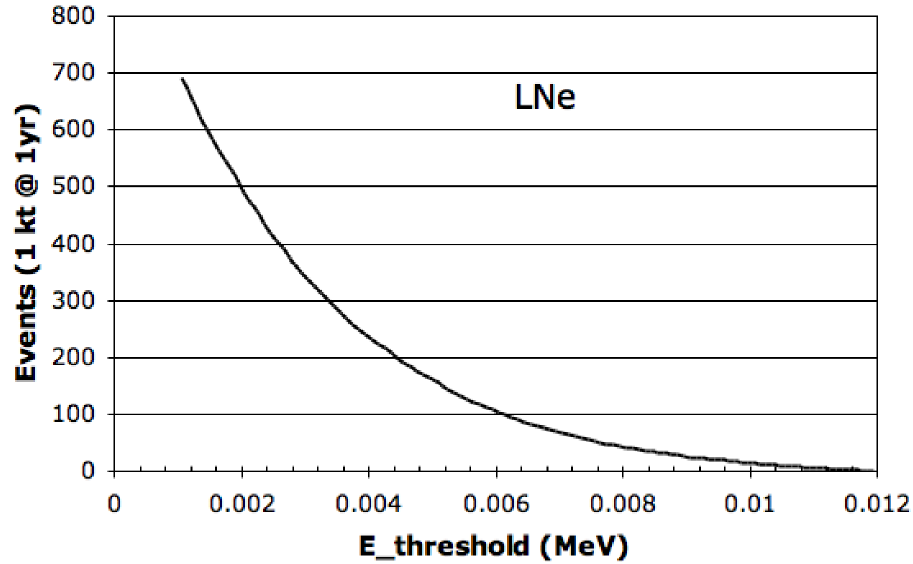


Visible Energy Spectrum for LAr and LNe



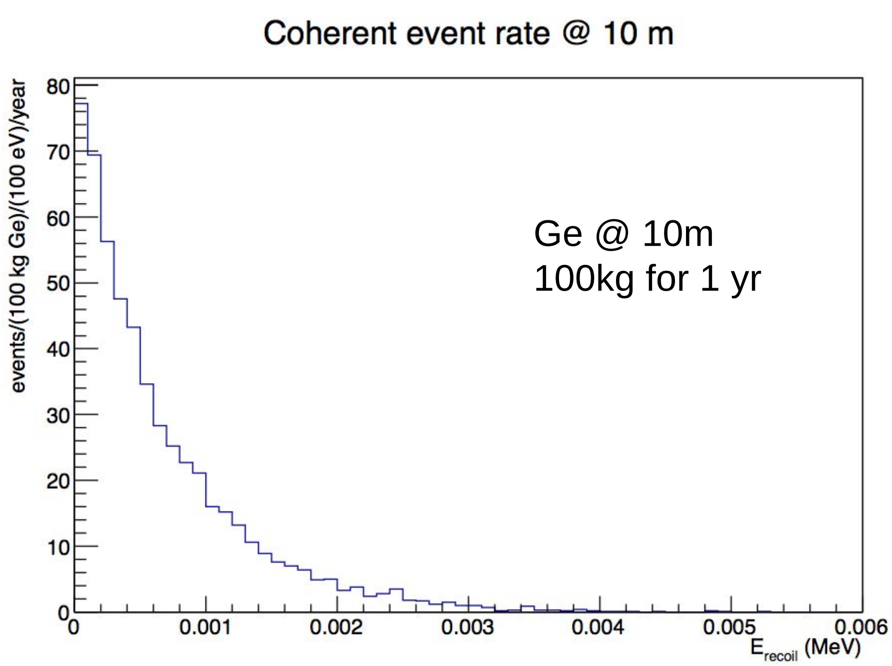


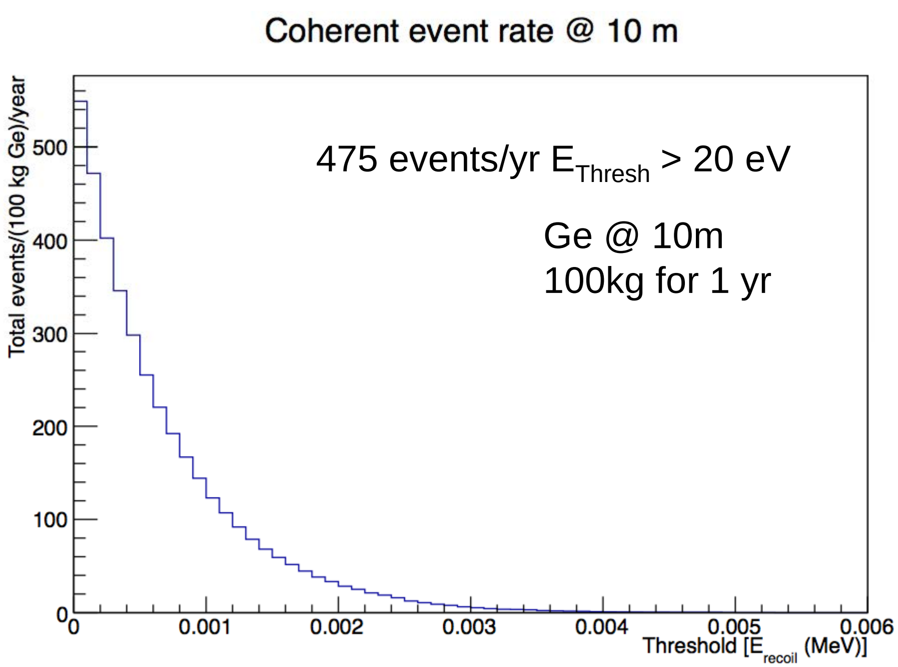




Visible Energy Spectrum for Ge Detectors

IsoDAR coherent assumptions	
Target	Ge
Detector mass	100 kg
Recoil energy resolution	20%
Detection efficiency	100%
Distance	10 m
Flux	2.58E22 $\overline{\nu}_e$/year





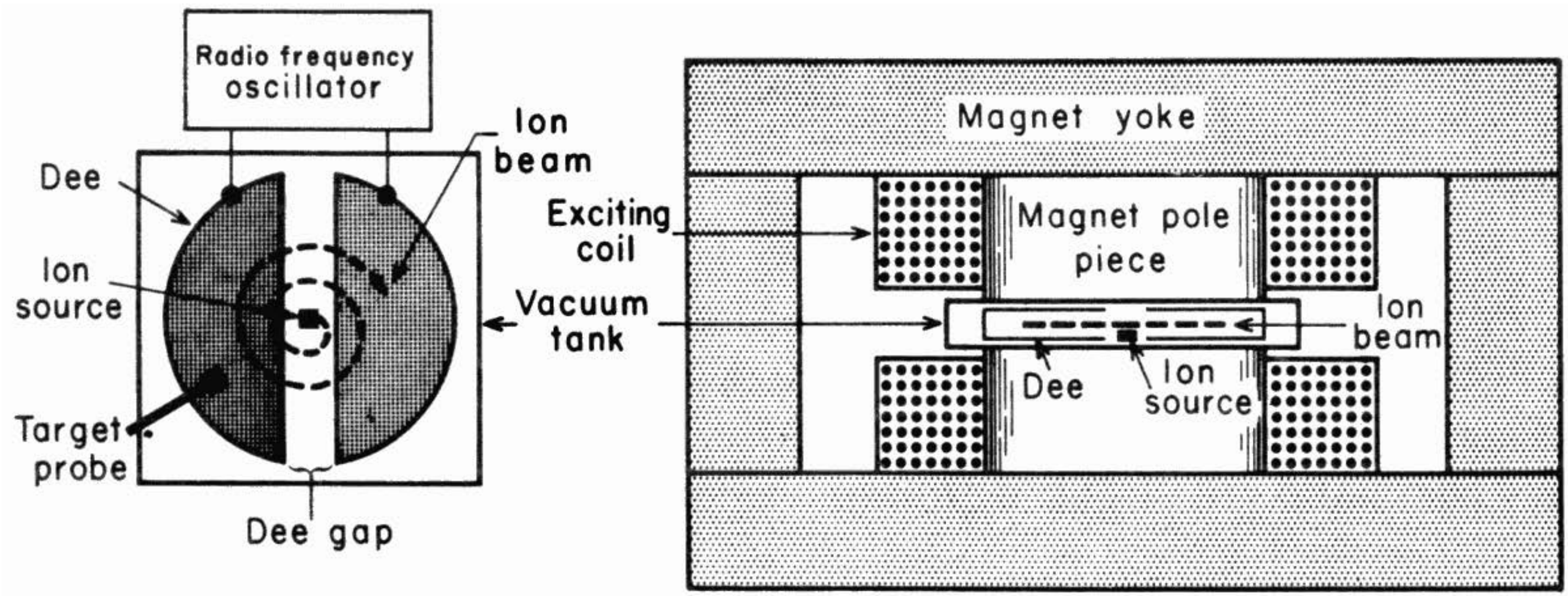
Summary

- Cyclotron neutrino sources are an option for a number of neutrino measurements
  - CP violation studies using a DAR beam
  - Oscillation searches using a DAR beam with IBD events
  - Sterile neutrino searches using an IsoDAR type isotope decay beams

- Coherent scattering studies are also possible with both the DAR and IsoDAR type beams
  - Measurements of the coherent scattering cross section
  - Use coherent scattering events to search for sterile neutrinos

Backup

Use Cyclotrons to produce the 800 MeV protons!



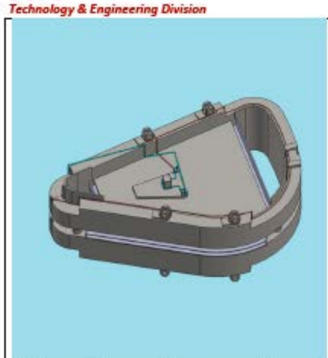
Inexpensive,
Only practical below ~1 GeV
(ok for us!)
Only good if you don't need
short timing structure (ok!)
Typically single energy (ok!)
Taps into existing industry

An "isochronous cyclotron" design:
magnetic field changes with radius
Allowing multibunch acceleration

Engineering Study of Sector Magnet for the Daedalus Experiment, http://arxiv.org/abs/1209.4886

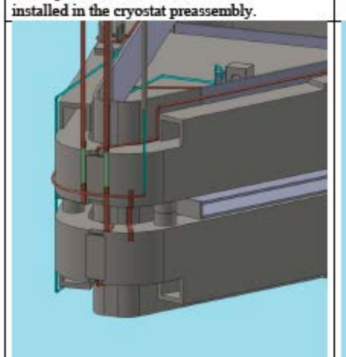
Engineering design,
Assembly Plan,
Structural analysis,
Cryo system design

PSFC
Technology & Engineering Division

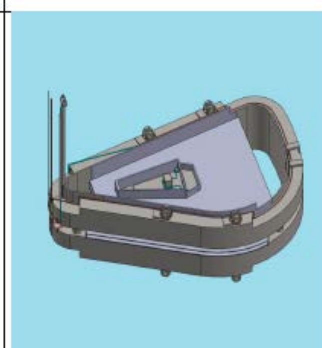


17. Top and bottom cold mass assemblies installed in the cryostat preassembly.

18. Inner cryostat wall cutout plates welded in.



19. Top and bottom coils He plumbing and cabling connected.



20 Cryostat top plate covering cold mass tie plate welded in.

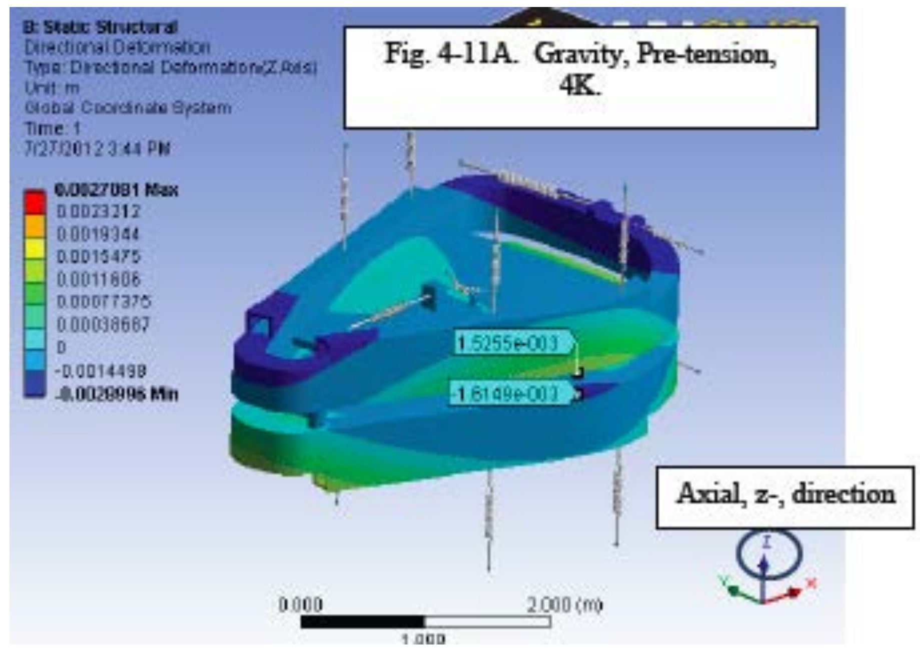


Fig. 4-11A. Gravity, Pre-tension, 4K.

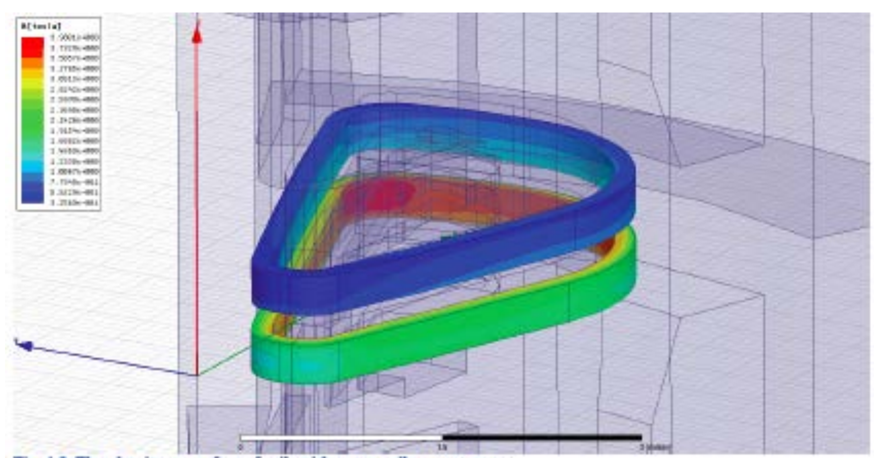
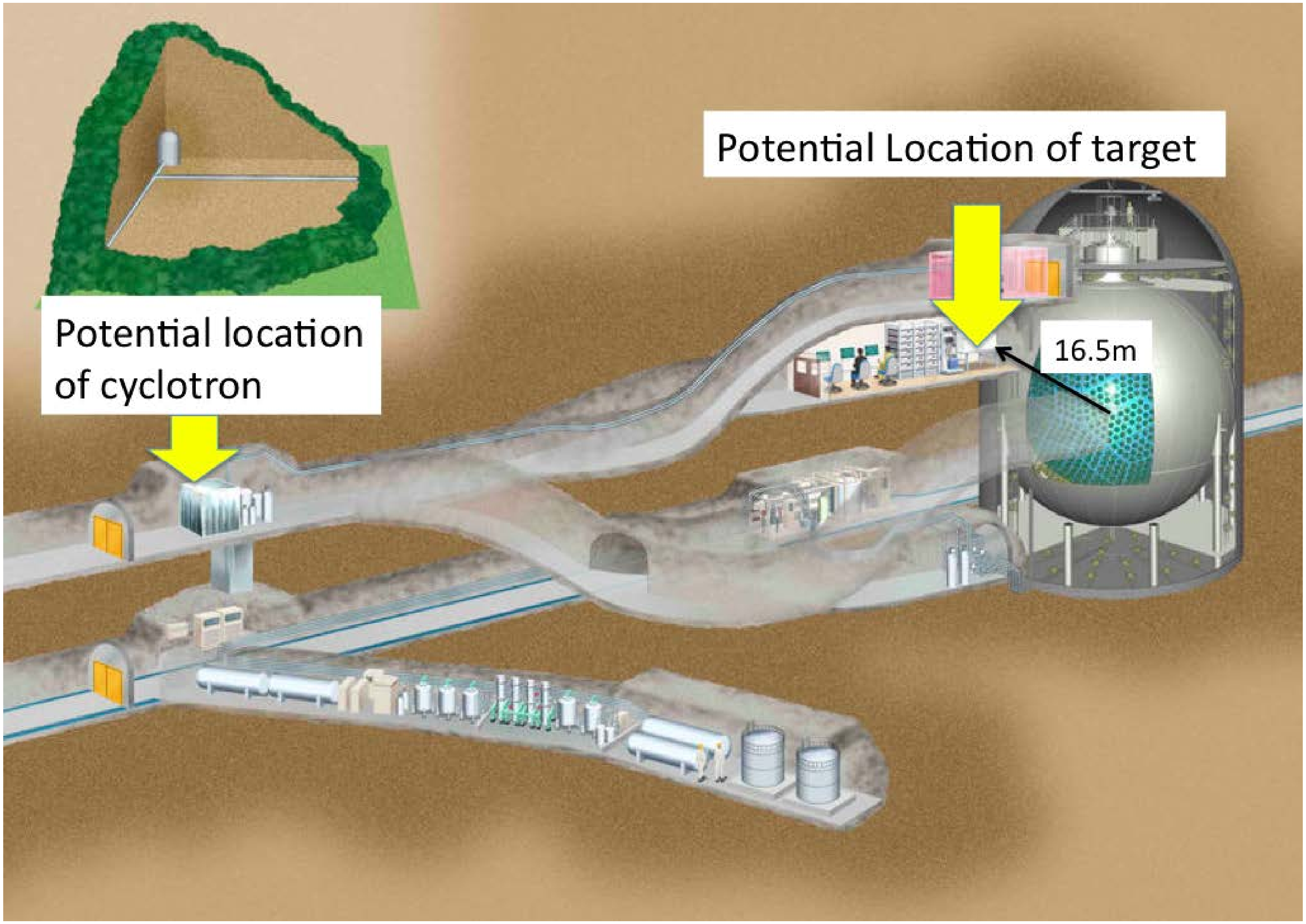
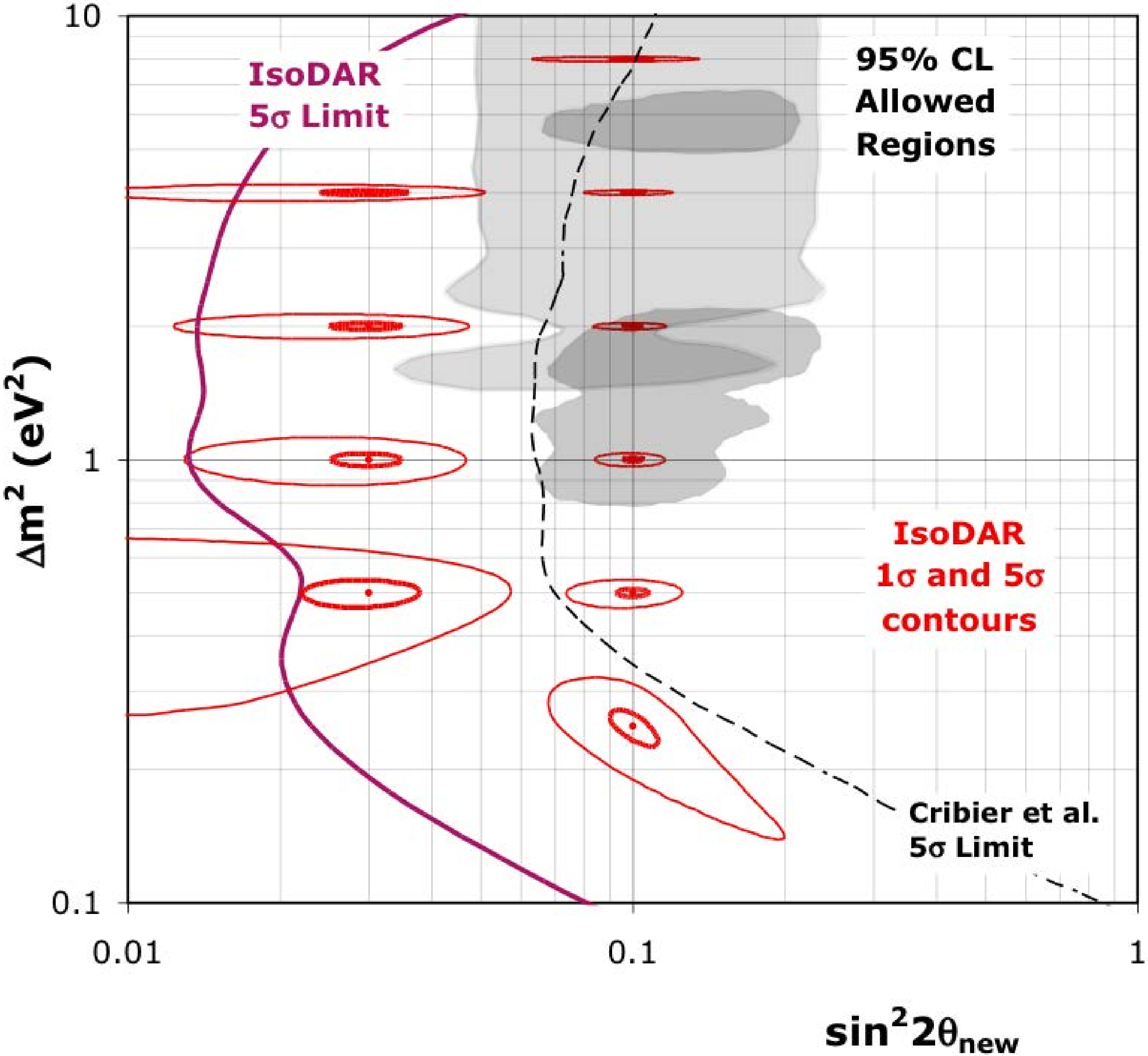


Fig. 4-9. Flux density on surface of coils with upper coil current zero.

IsoDAR at Kamland

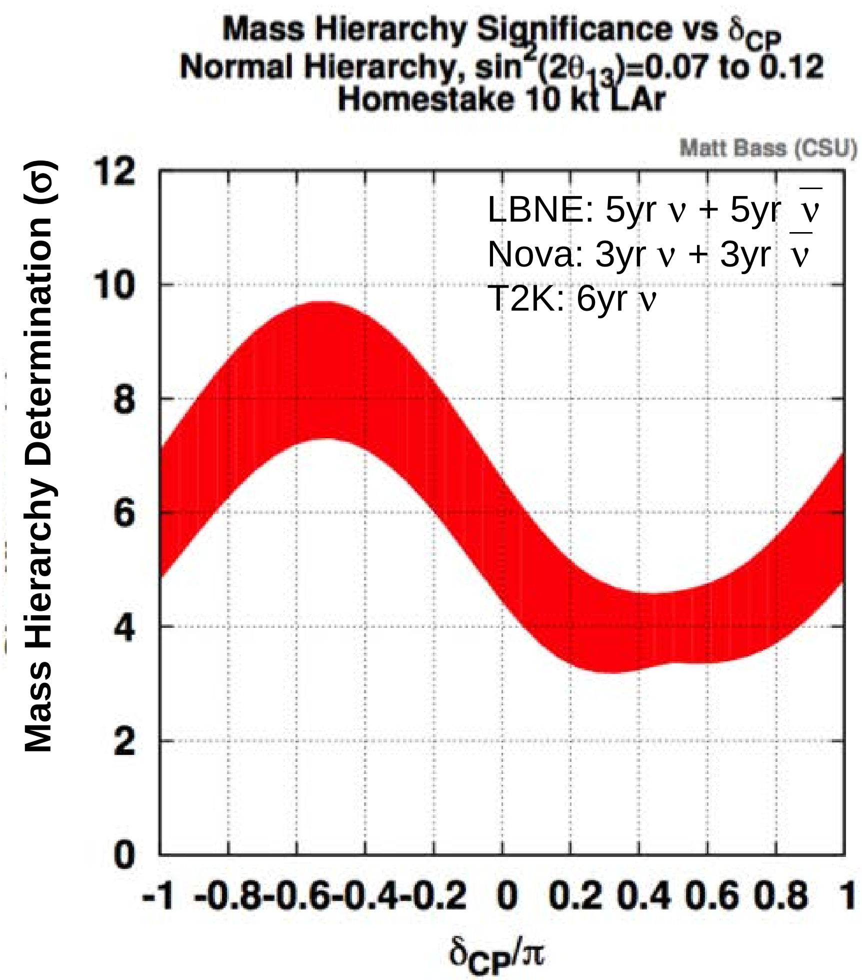


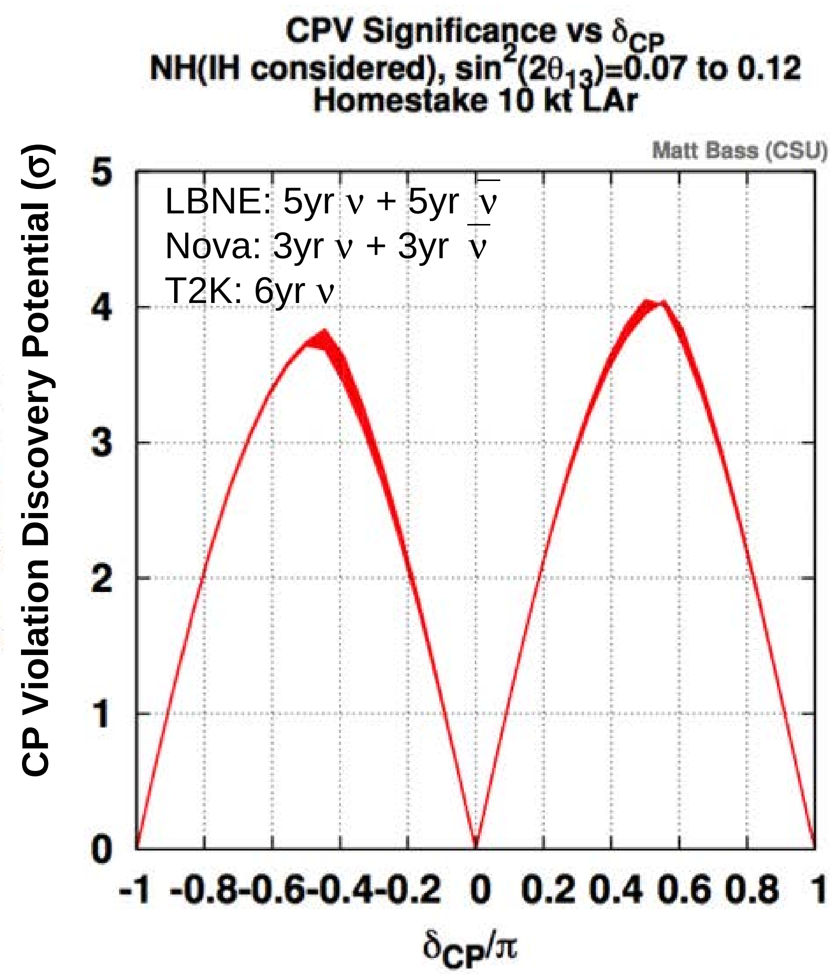
IsoDAR Measurement Sensitivity



LBNE: Mass Hierarchy and CP Violation Sensitivity

- Phase I: 10 kton LiqAr surface detector at the Homestake site (Start 2023 with 5yr ν plus 5yr $\bar{\nu}$)





Example: 200kt Water Cherenkov + Daeδalus