IsoDAR and DAEδALUS

Joshua Spitz, MIT
ICFA meeting, 1/10/2014

The DAEδALUS program

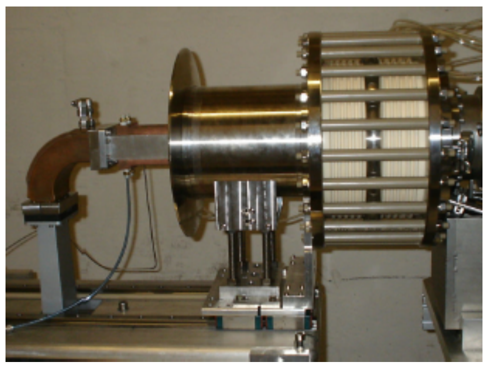
- The cyclotron as a new, intense source of decay-at-rest neutrinos.
  - High-Q isotope $$^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} + e^{-} + \overline{\nu}_e$$
  - Pion/muon $$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$$ $$\mu^{+} \rightarrow e^{+}\nu_e\overline{\nu}_{\mu}$$
- Sterile neutrinos, weak mixing angle, NSI, δ_{CP}, ν-A coherent scattering, supernova xsec, accelerator, …

The DAEδALUS program

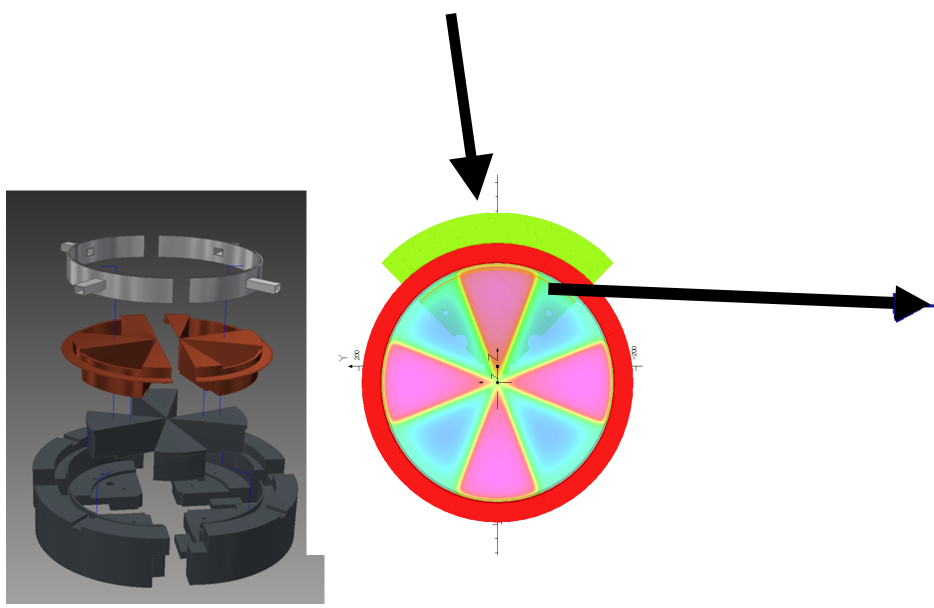
This is a program in search of a home/homes…
and Europe is certainly a possibility

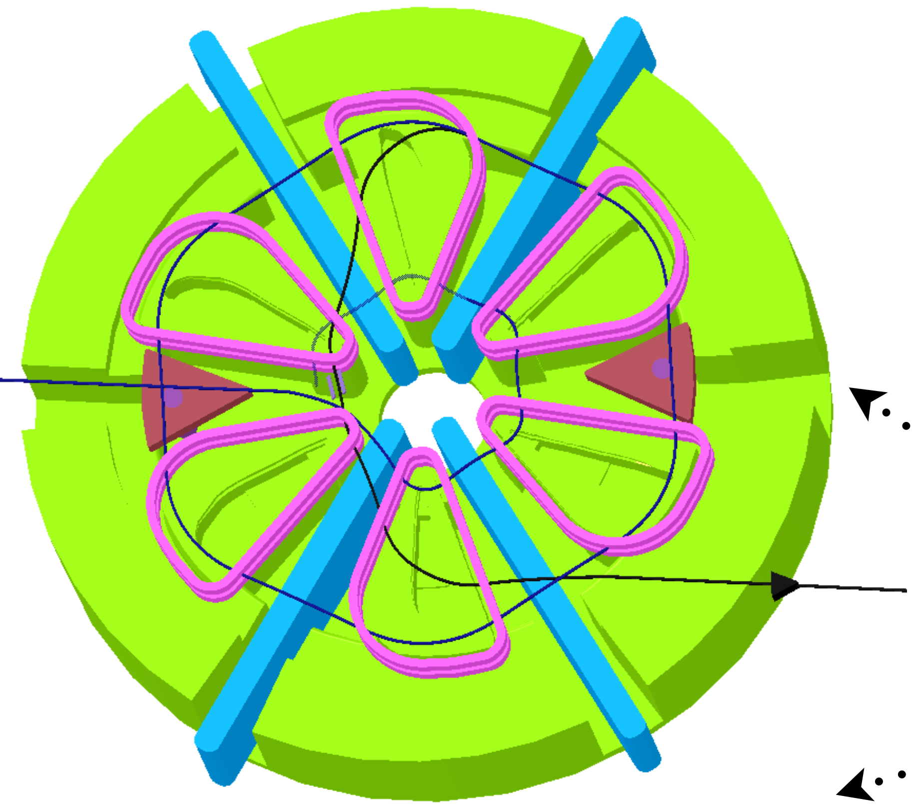
The path to 800 MeV

Ion source

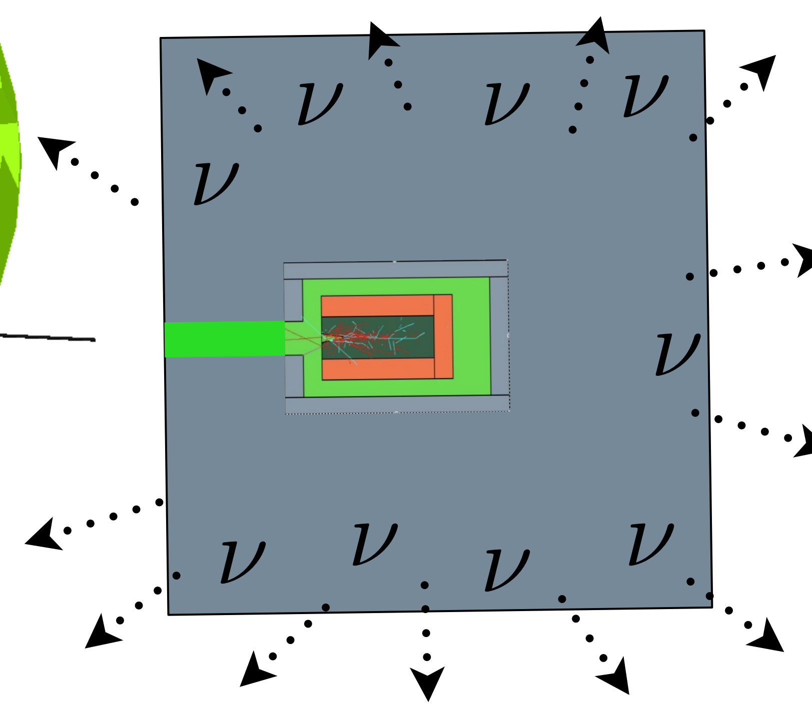


Superconducting ring cyclotron





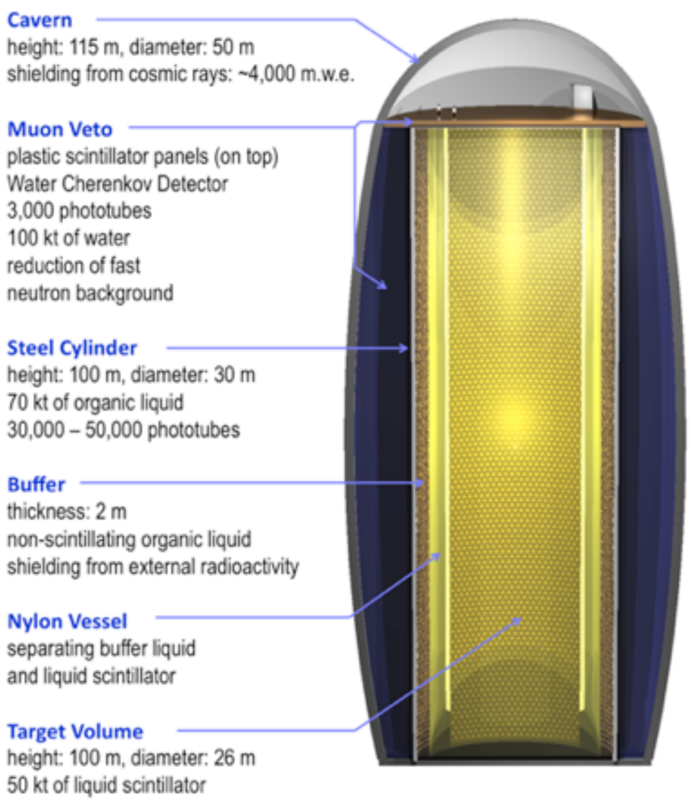
Target/dump



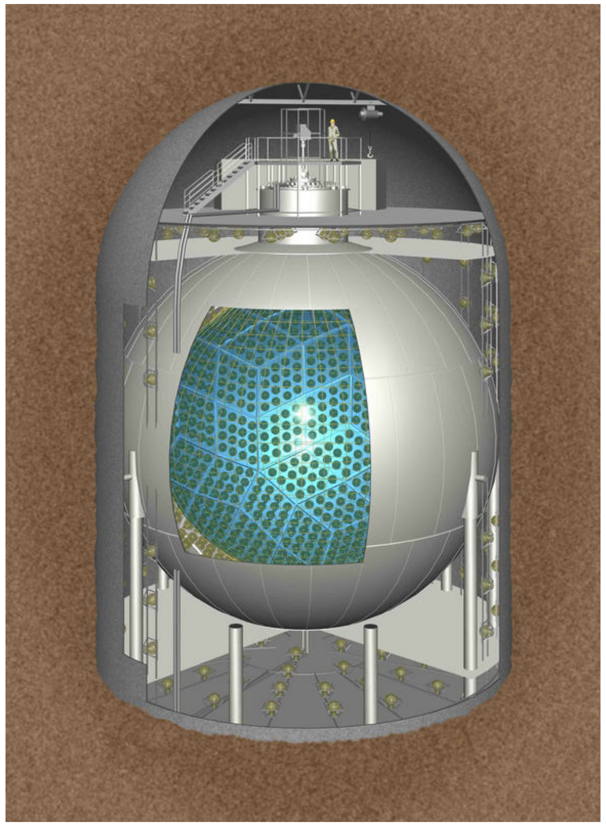
Injector cyclotron (IsoDAR)

Where can IsoDAR run?

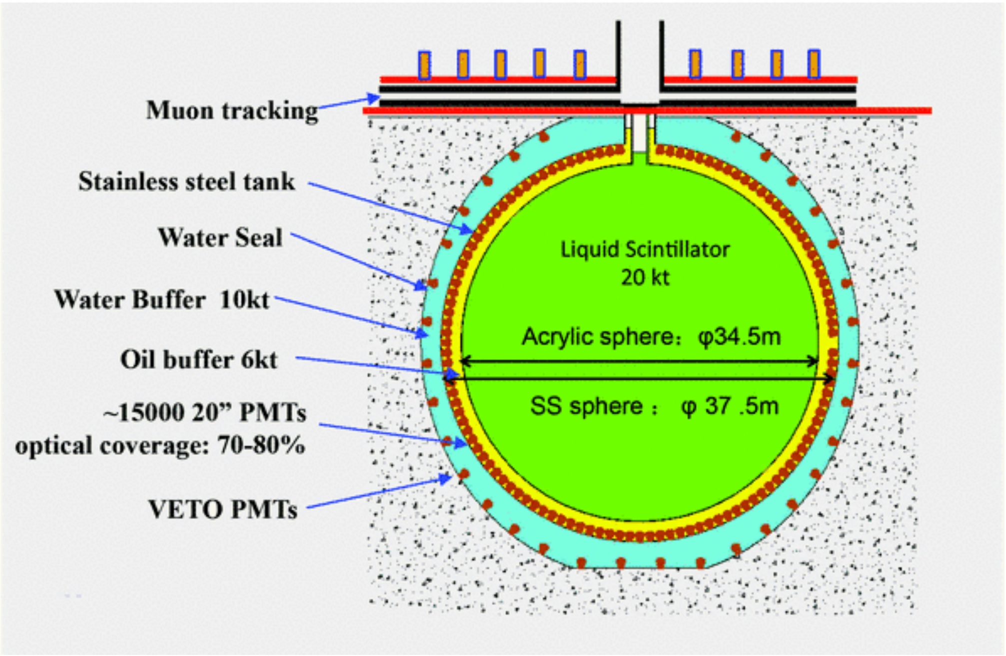
LENA



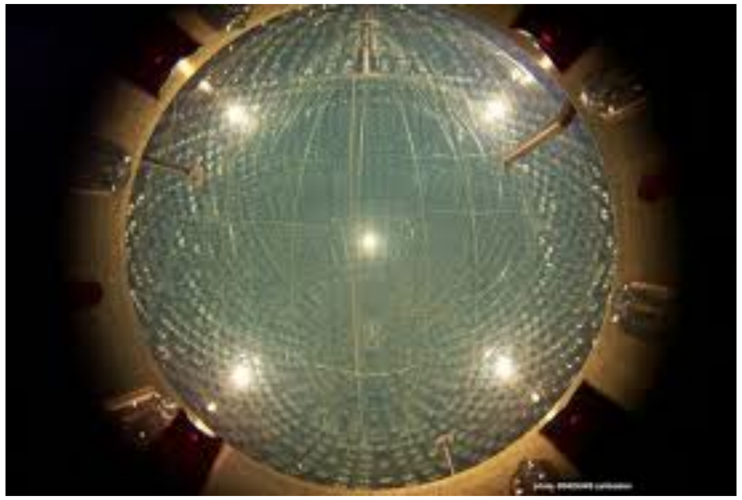
KamLAND



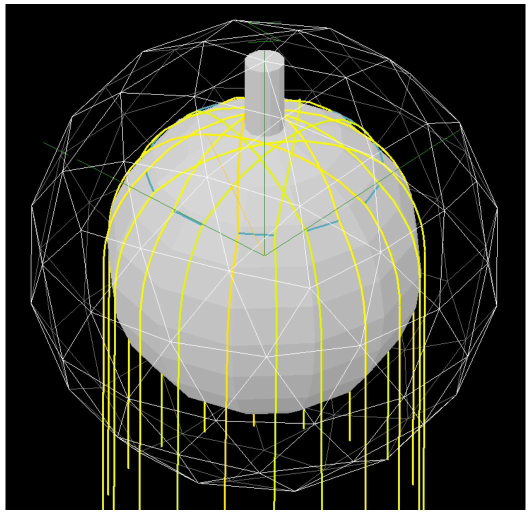
JUNO



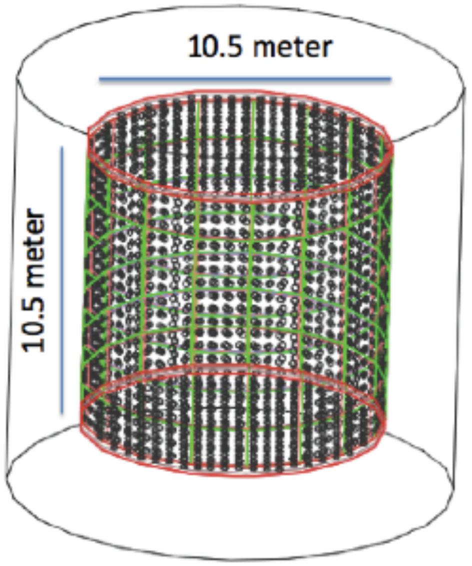
Borexino



SNO+

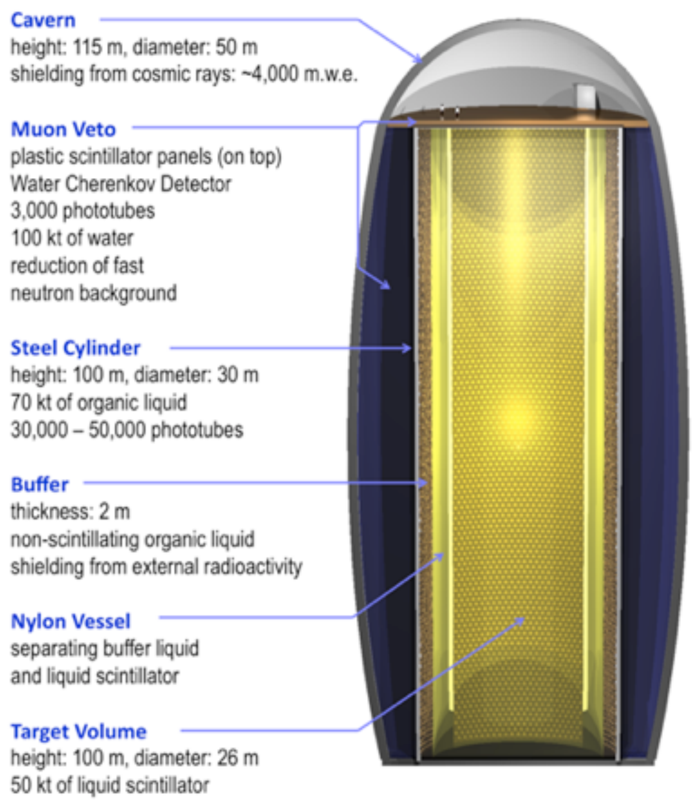


WATCHMAN

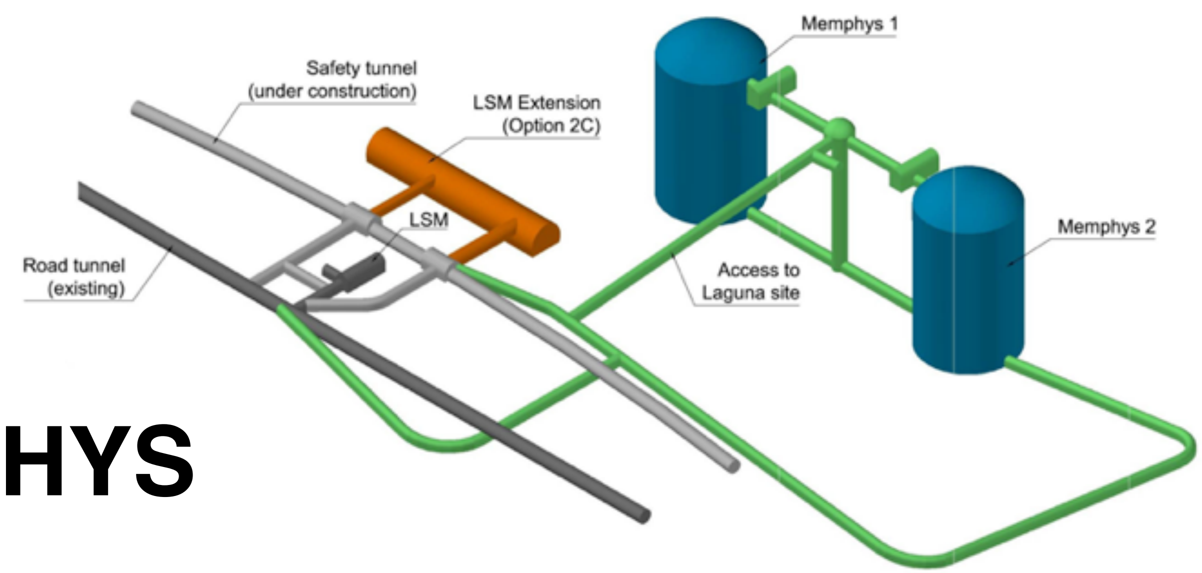


Where can DAEδALUS run?

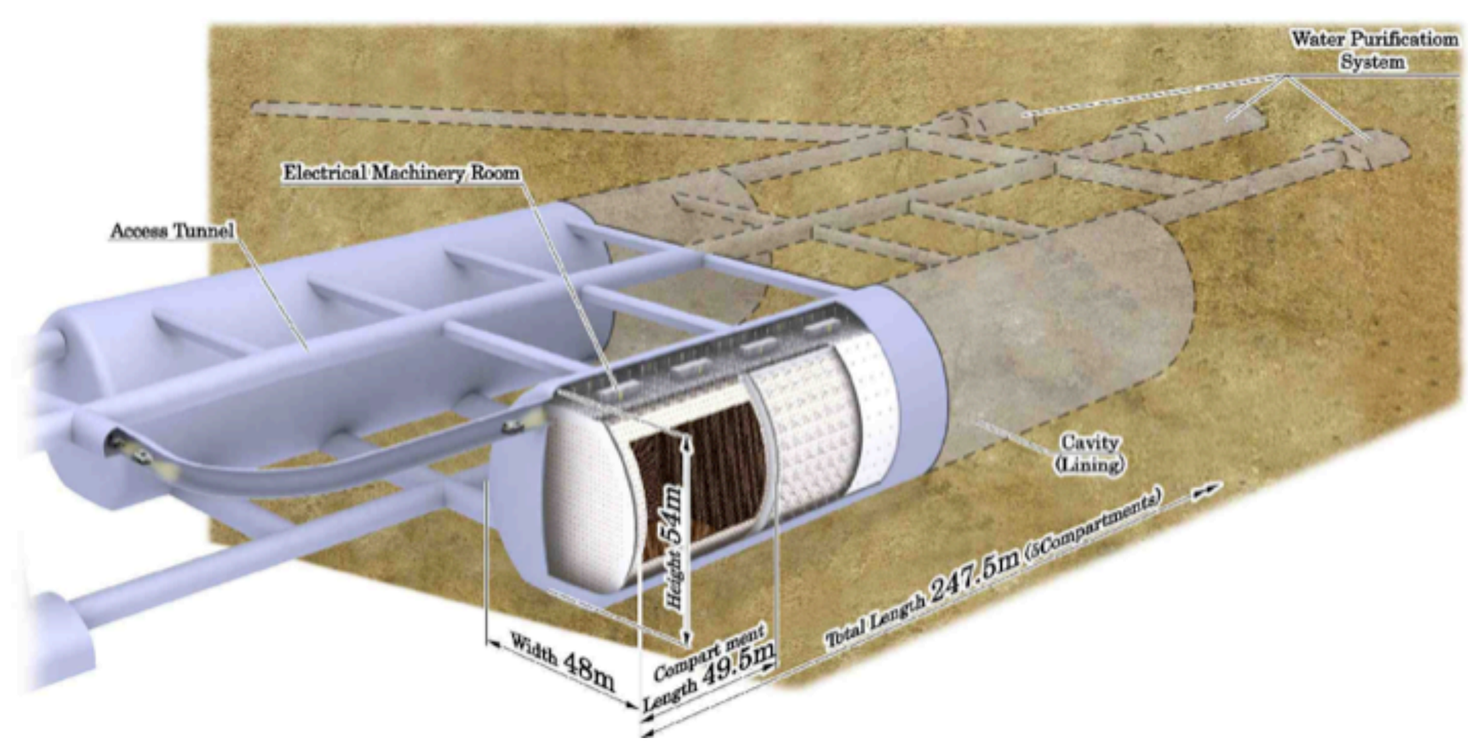
LENA



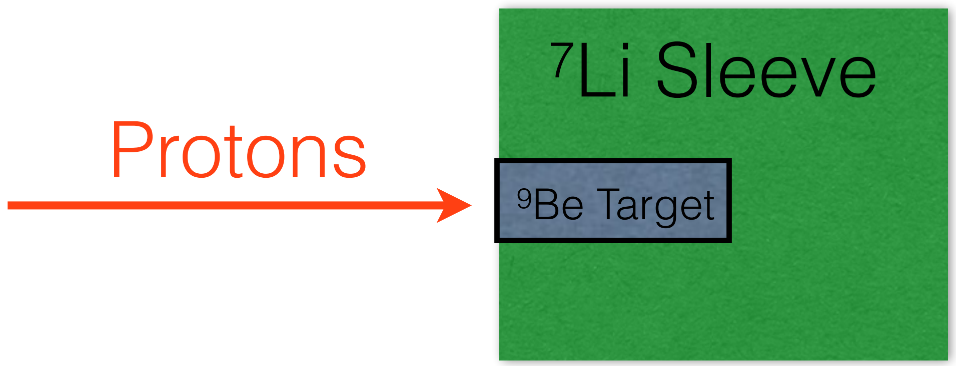
MEMPHYS



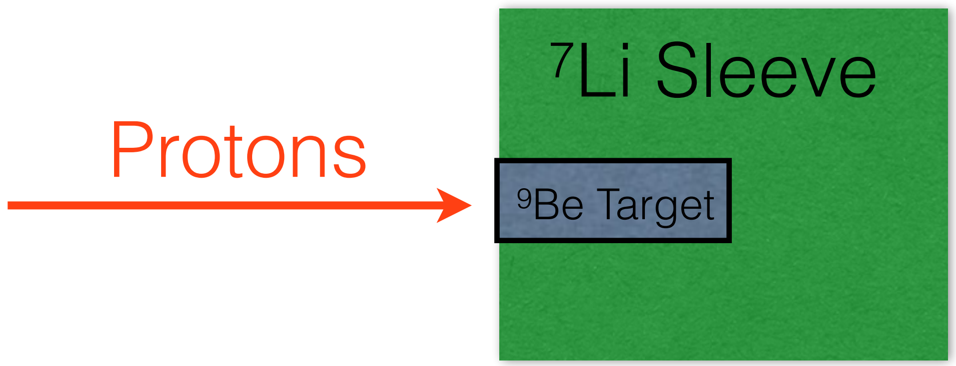
Hyper-K



IsoDAR



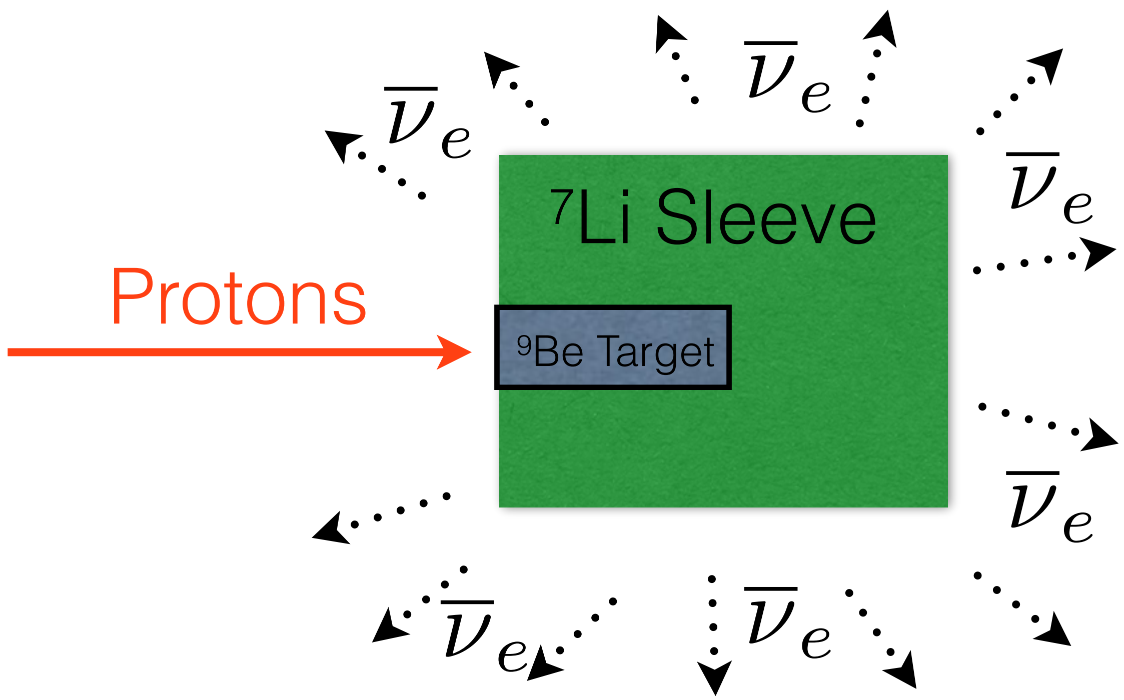
IsoDAR



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

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

IsoDAR



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

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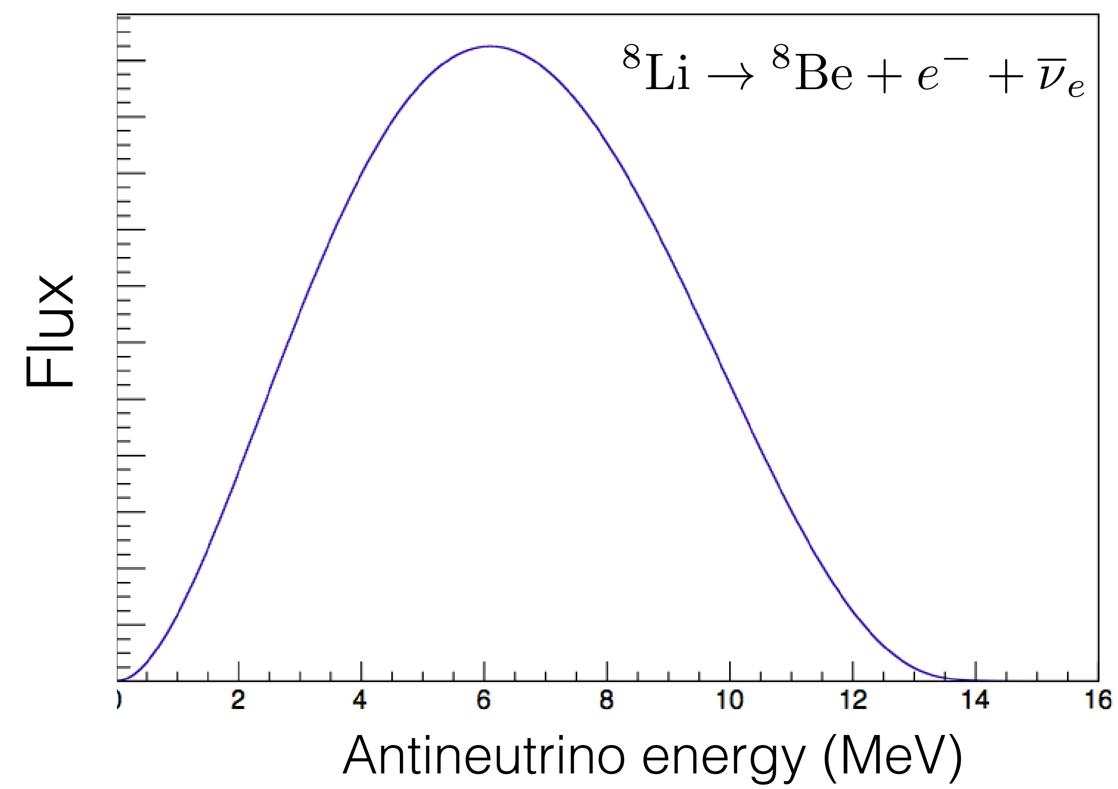
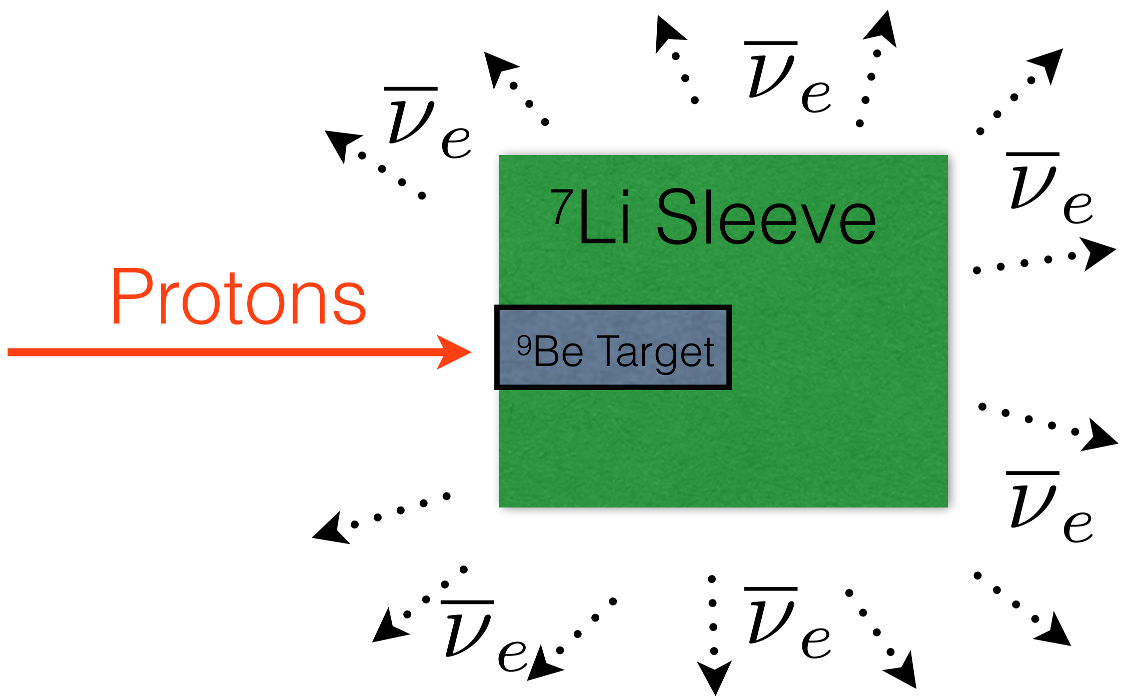
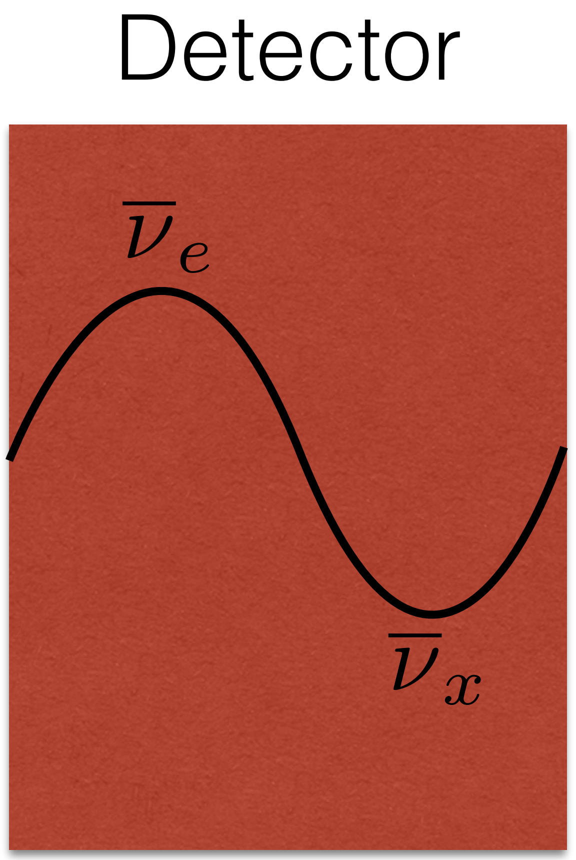


IsoDAR



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



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

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

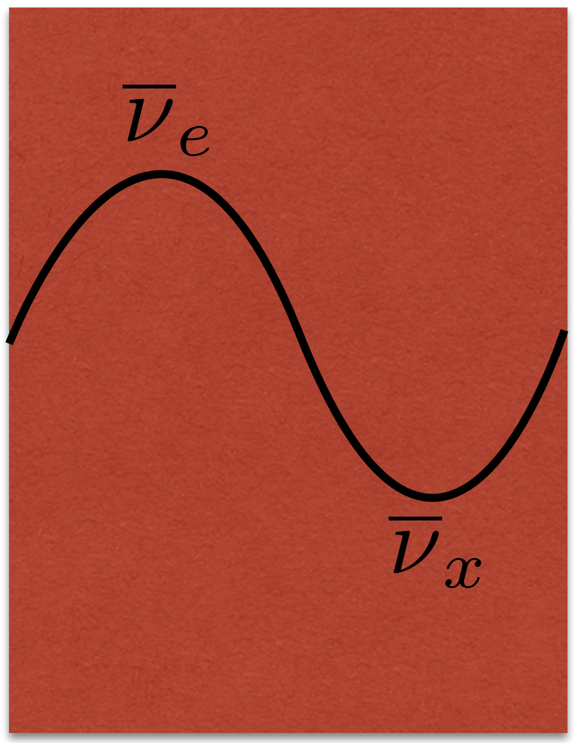
$$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$$
$$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$$

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

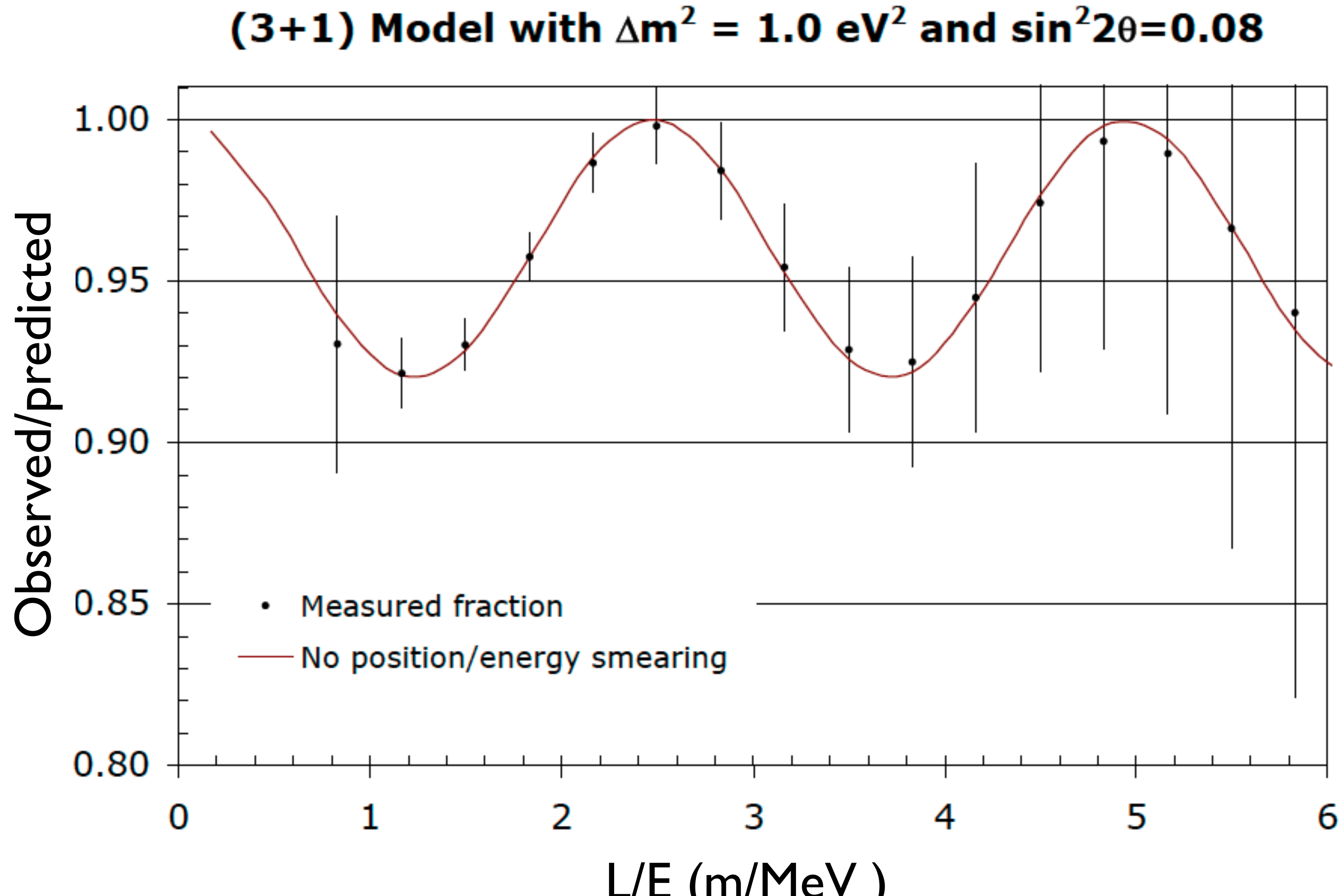
IsoDAR

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

Detector

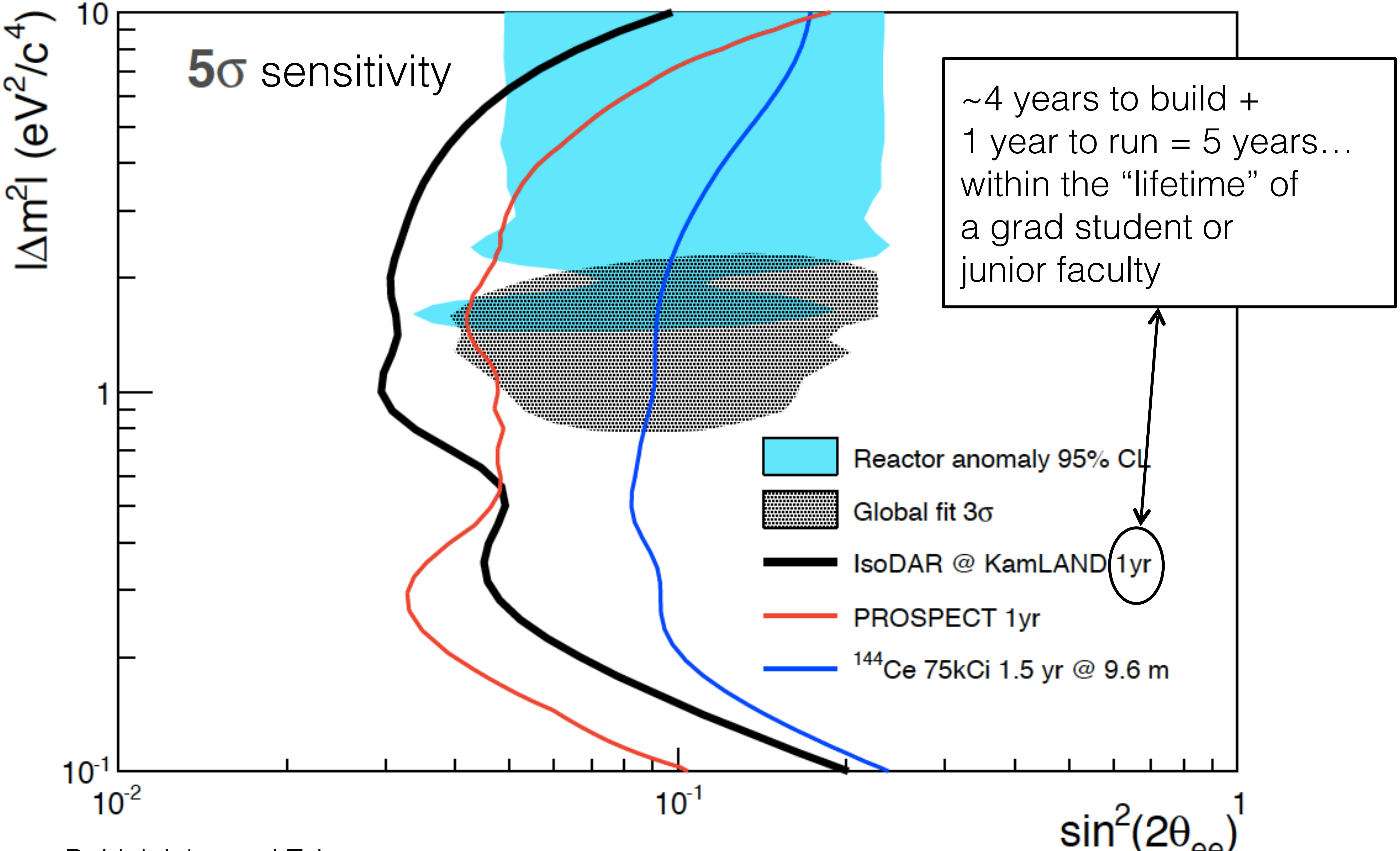


$$\overline{\nu}_e p \rightarrow e^+ n$$



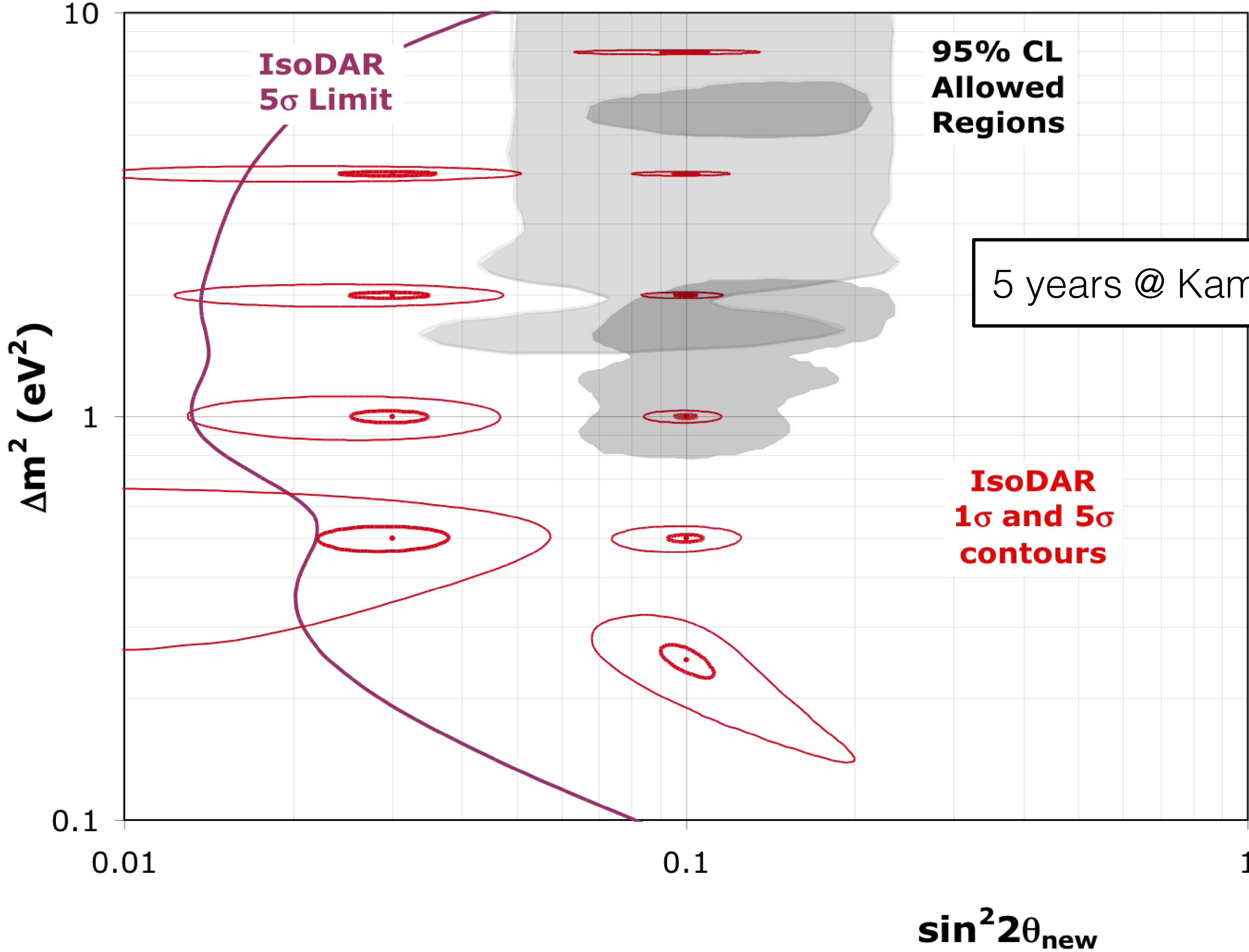
820,000 IBD events in 5 years at KamLAND
(16 m baseline to center of detector)

IsoDAR sensitivity



Thanks to B. Littlejohn and T. Lasserre

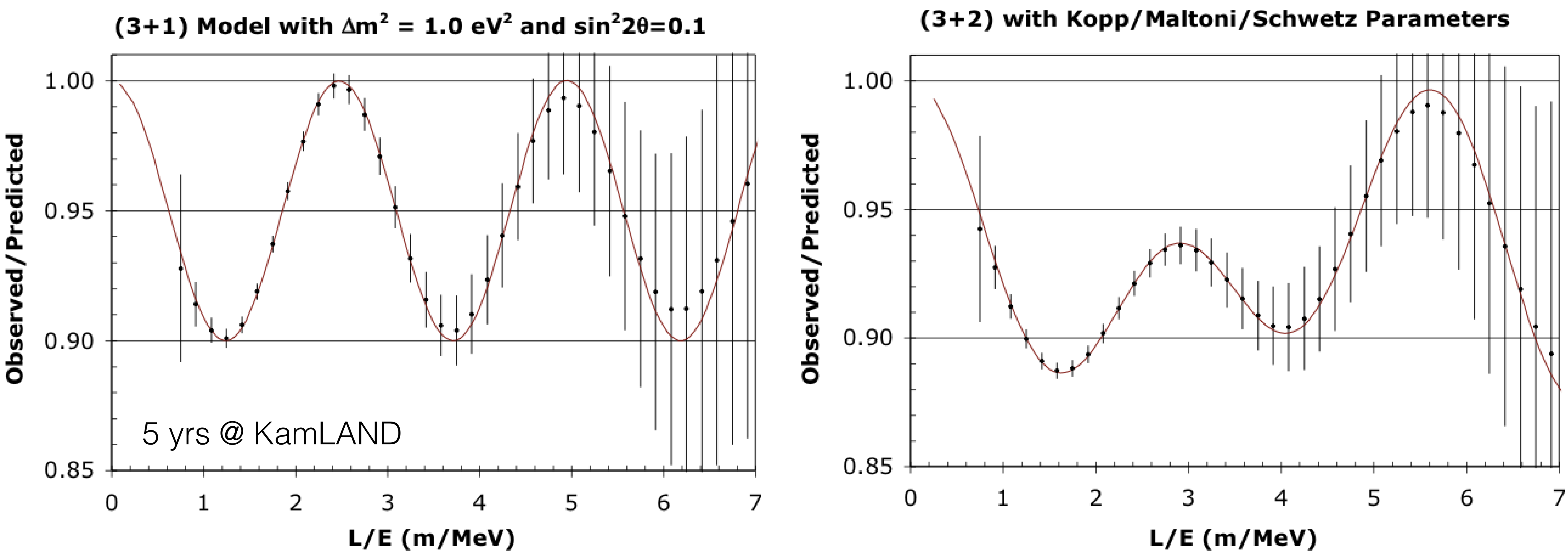
IsoDAR precision



5 years @ KamLAND

How many steriles?

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

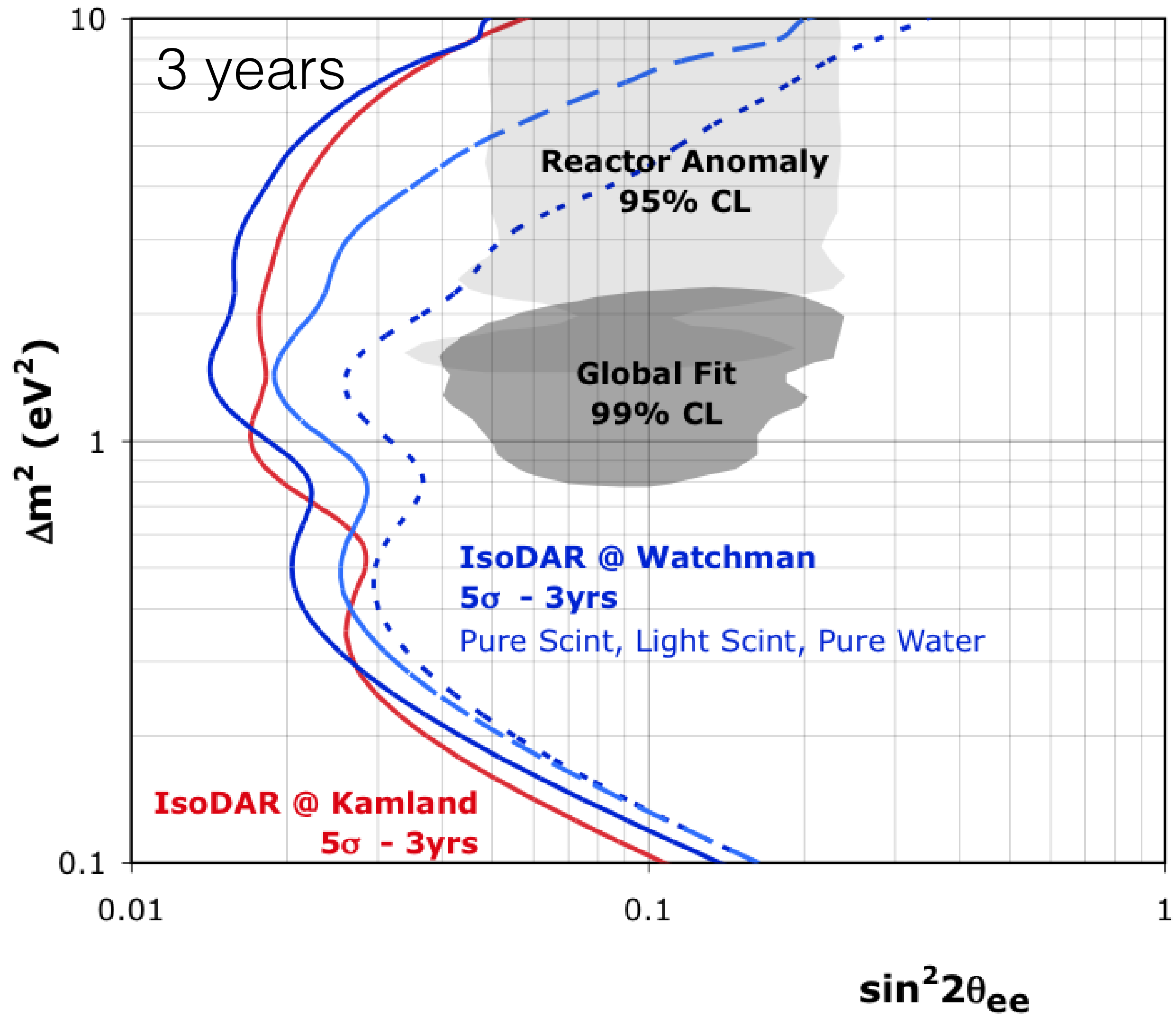


IsoDAR's high statistics and good L/E resolution provide the potential for distinguishing (3+1) and (3+2) oscillation models

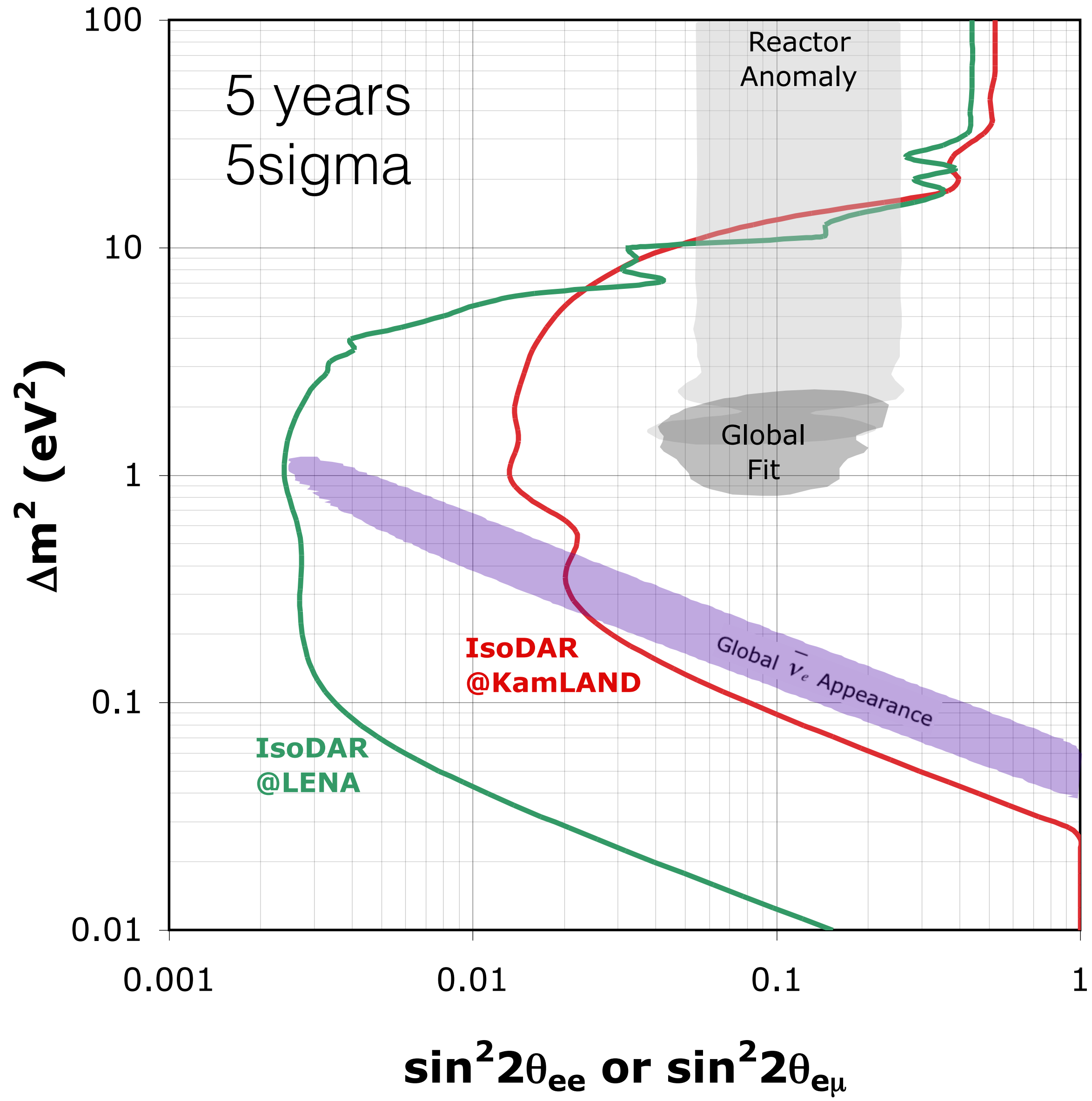
Recent IsoDAR updates

(We are open to considering IsoDAR@Borexino as well)

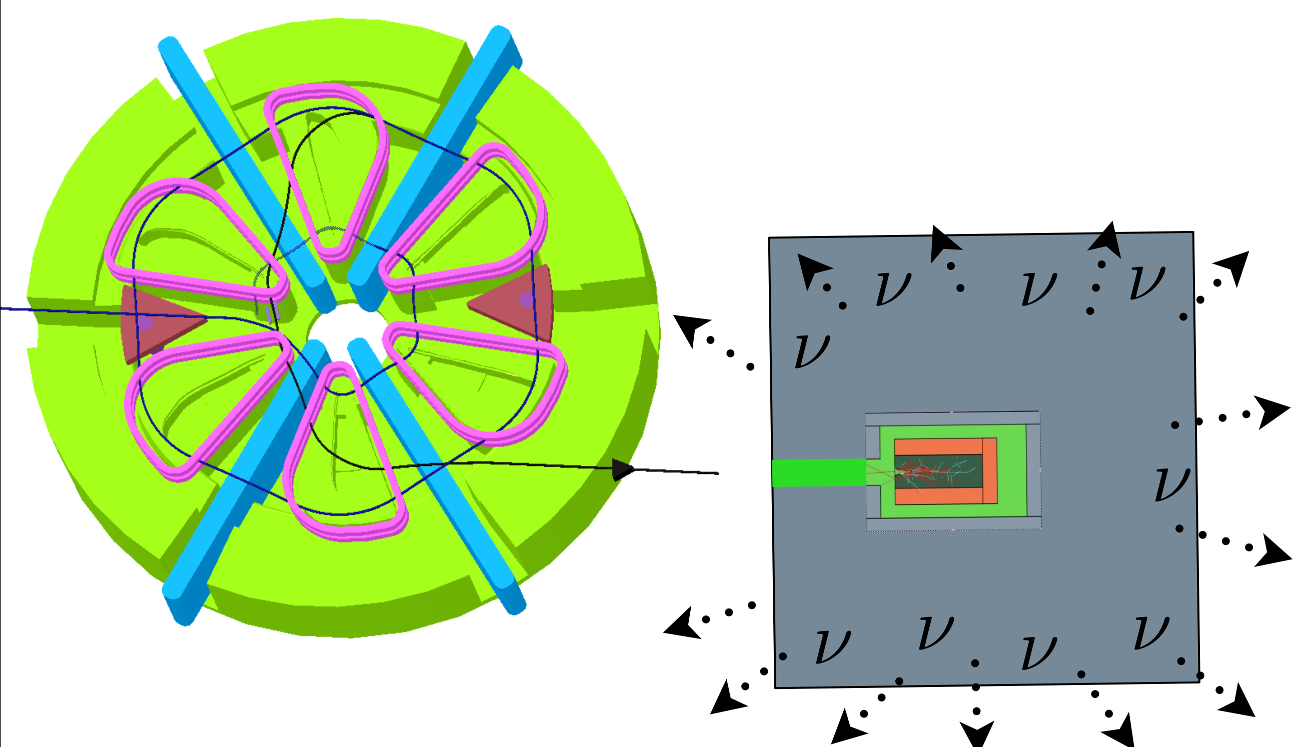
Disappearance sensitivity with **Watchman**
(1 kton Gd-doped water or scintillator)

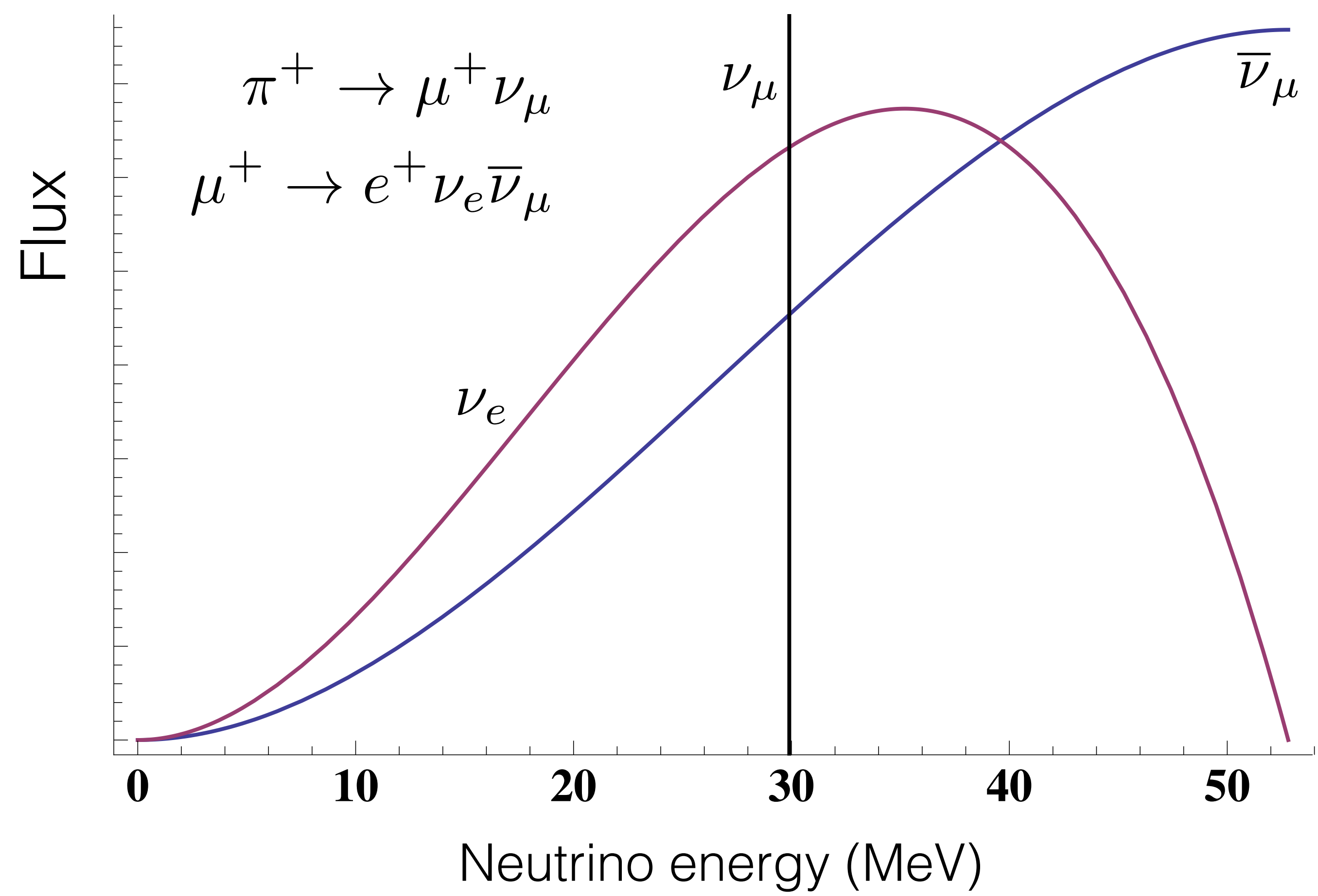


Dis/appearance sensitivity with **LENA**
(50 kton liquid scintillator)

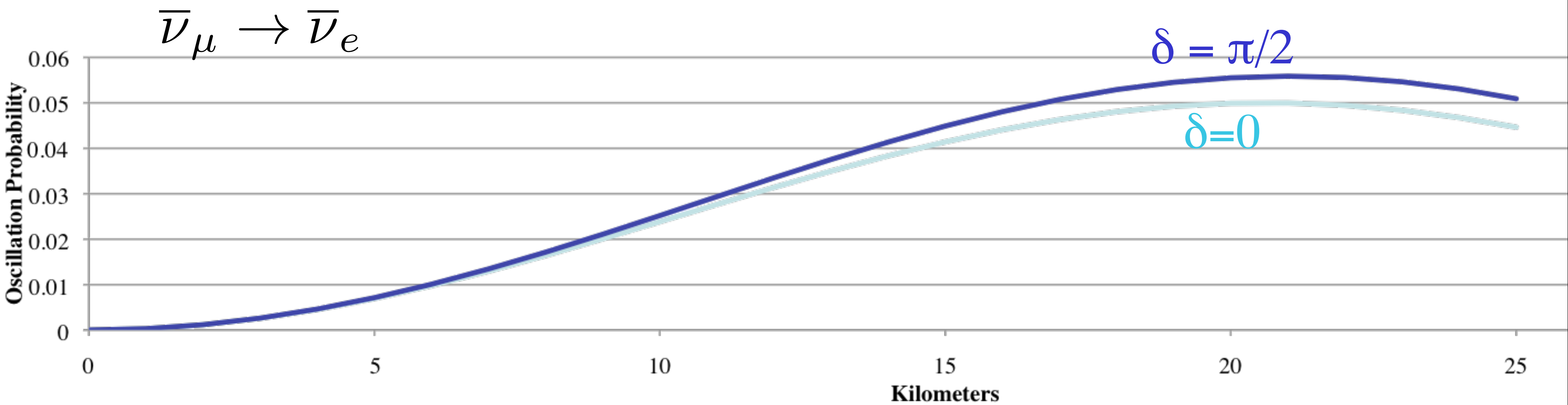


DAEδALUS and δ_{CP}





DAEδALUS and δ_{CP}



Near site → Constrains initial flux

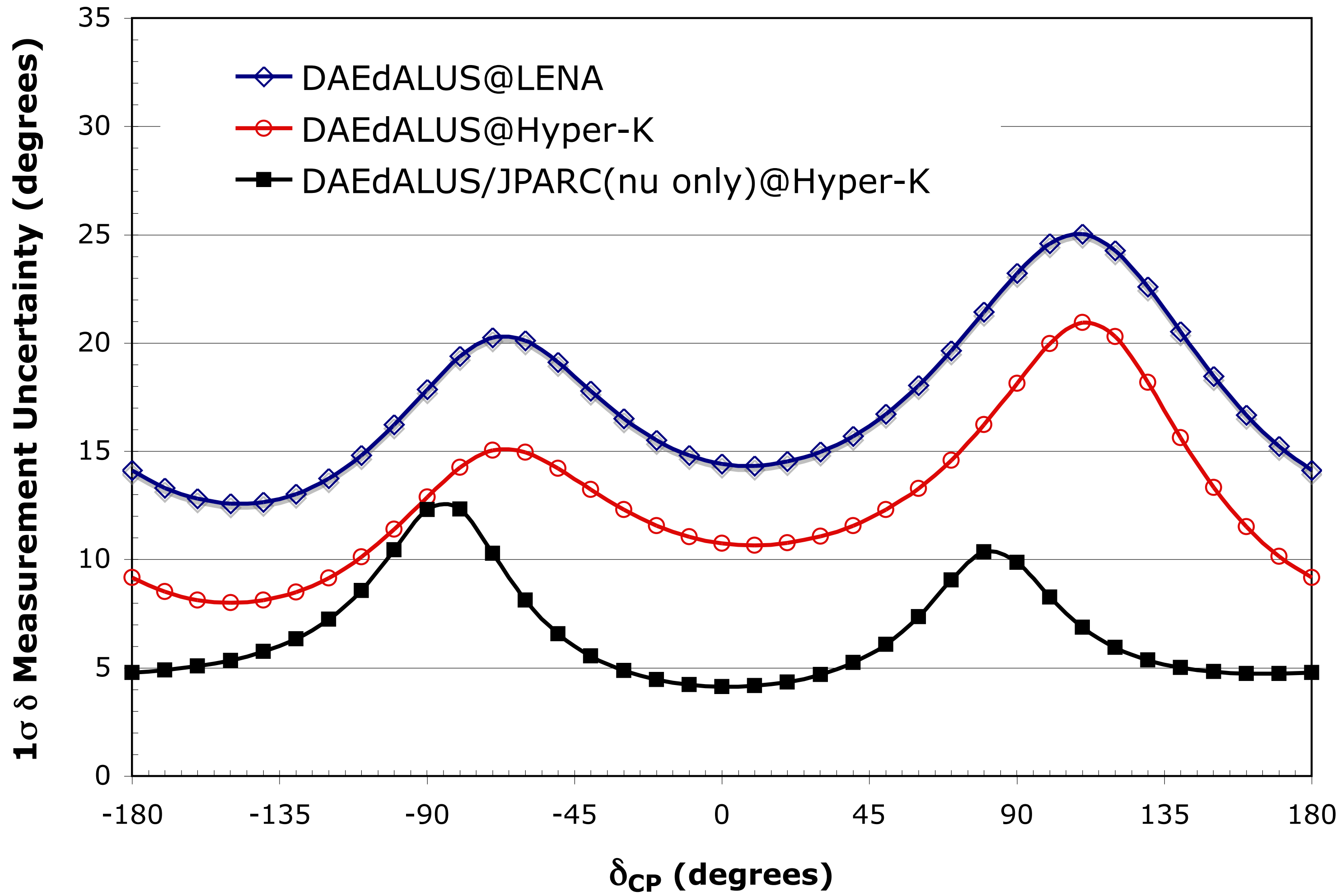
Mid site → Constrains rise probability

Far site → Fit for $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance

Near site gives absolute normalization to 1% via ν_e-e
Relative flux between sites can be constrained with ν_eO (ν_eC)

δ_{CP} sensitivity

- DAEδALUS has strong δ_{CP} sensitivity by itself.
- Can be combined with long-baseline data (e.g. Hyper-K) for enhanced sensitivity.
  - Good statistics with anti-neutrinos, no matter effects, orthogonal systematics.
  - Big discoveries want (need?) multiple, independent experiments.



European collaborators on IsoDAR/DAEδALUS

very active
low level, but interested

LNS-INFN (Catania)*
The Cockcroft Institute for Accelerator Science & the University of Manchester*
Imperial College London
Paul Scherrer Institut*
University of Huddersfield*

*=accelerator physicists involved

Conclusions

- The DAEδALUS collaboration is pursuing a phased approach towards a precise measurement of δ_{CP}.
- There is physics at each phase.
- IsoDAR, in combination with (e.g.) KamLAND, will provide a definitive statement on the sterile neutrino.
- These cyclotrons have applications outside of particle physics and industry is pursuing these machines by our side.
- IsoDAR and DAEδALUS are looking for homes…and Europe is a possibility.

Other (published) physics

Precision Anti-nue-electron Scattering Measurements with IsoDAR to Search for New Physics
arXiv:1307.5081 — PRD

Electron Antineutrino Disappearance at KamLAND and JUNO as Decisive Tests of the Short Baseline Anti-numu to Anti-nue Appearance Anomaly
arXiv:1310.3857 — submitted to PR Brief Reports

Coherent Neutrino Scattering in Dark Matter Detectors
arXiv:1201.3805 — PRD

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

Short-Baseline Neutrino Oscillation Waves in Ultra-Large Liquid Scintillator Detectors
arXiv:1105.4984 — JHEP

IsoDAR

DAEδALUS

Backup

Next steps

- Bring the upstream line to 35-50 mA
- Iterate on the spiral inflector design
- Capture and accelerate up to 7 MeV
- Scientific goals: demonstrate high intensity injection and capture.
- Practical goal: Produce equipment that can move directly to the first IsoDAR program
  - The “front end”
  - The inflector
  - Diagnostic equipment

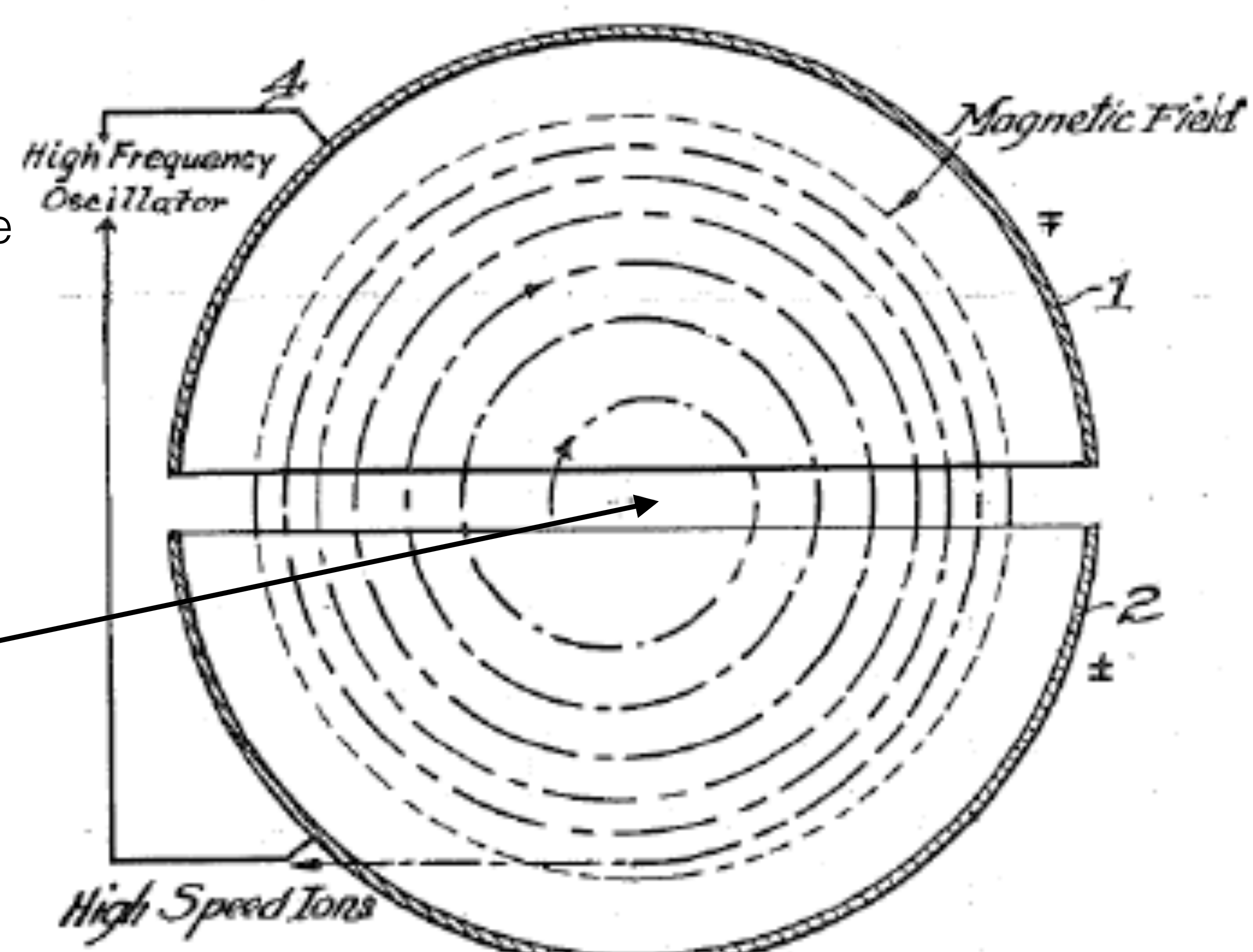
IsoDAR challenges

- Space charge

(The beam width increases because the H_2^+ ions repel each other. This is a big problem at injection and near the outside of the cyclotron where the turn spacing is low)

Present machines inject p or H^-

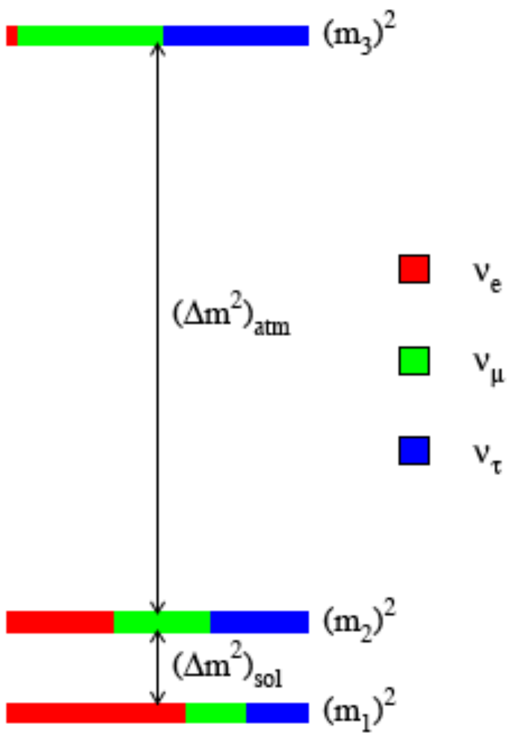
We inject H_2^+



Comparing strength of space charge at injection:

5 mA, 35 keV/n of H2+ = 2 mA, 30 keV of p (already achieved in commercial cyclotrons)

The oscillation of muon-flavor to electron-flavor
at the atmospheric Δm^2
may show CP-violation dependence!



in a vacuum…

$$
\begin{aligned}
P = \; & (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\
& \mp \underline{\sin\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \underline{\cos\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\,(\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

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

IsoDAR cost estimates at present

Cost-effective design options for IsoDAR
A. Adelmann et al. arXiv:1210.4454

1st source constructed -> $30M base cost (2013 $)

If more sources are constructed: $15M each

recommended contingency as of now: 50%
after first engineering design: 20%

DOE-sponsored study on a 2 mA proton machine

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

EXECUTIVE SUMMARY

A cost/benefit study was conducted by *JUPITER* Corporation to compare acquisition and operating costs for a 45 MeV and 70 MeV negative ion cyclotron to be used by the Department of Energy in the production of medical radioisotopes. The study utilized available information from Brookhaven National Laboratory (BNL) in New York and from the University of Nantes in France, since both organizations have proposed the acquisition of a 70 MeV cyclotron. Cost information obtained from a vendor, Advanced Cyclotron Systems, pertained only to their 30 MeV cyclotron. However, scaling factors were developed to enable a conversion of this information for generation of costs for the higher energy accelerators.

Two credible cyclotron vendors (IBA Technology Group in Belgium and Advanced Cyclotron Systems, Inc. In Canada) were identified that have both the interest and capability to produce a 45 MeV or 70 MeV cyclotron operating at a beam current of 2 mA (milliamperes).

The results of our analysis of design costs, cyclotron fabrication costs, and beamline costs (excluding building construction costs) resulted in total acquisition costs of:

- $14.8M for the 45 MeV cyclotron, and
- $17.0M for the 70 MeV cyclotron.

Annual operating cost estimates for a 70 MeV cyclotron ranged between $1.9M and $1.1M; the large uncertainty is due to the lack of specificity in available data in comparing costs from BNL and the University of Nantes.

Overall power requirements (exclusive of facility heating and air conditioning) were estimated to be:

- 560 kW for the 45 MeV cyclotron, and
- 831 kW for the 70 MeV cyclotron.

Operational lifetime is expected to be in excess of 30 years for the main components of the accelerator.

Considerable scientific and economic benefits are gained in using the 70 MeV cyclotron compared to use of the 45 MeV cyclotron in terms of the variety and quantity of isotopes that can be produced. Selected examples of benefits in isotope production are discussed.

This is a simpler machine.

IsoDAR will cost more because the machine is larger…but this sets the scale.

Other options?

Assessment: Good / Moderate / Bad

	IsoDAR Base Design	RFQ/Separated Sector Cyclotron	LINAC, 30 MeV, 40 mA	Modified Beta Beam Design	New Detector at Existing Beam
1. Cost	Good	Moderate	Bad	Moderate	Bad
2. $\bar{\nu}_e$ rate	Good	Good	Good	Bad	Good
3. Backgrounds low	Good	Good	Good	Good	Moderate
4. Technical risk	Moderate	Moderate	Moderate	Moderate	Good
5. Compactness	Good	Moderate	Bad	Good	Moderate
6. Simplicity u'ground	Good	Moderate	Moderate	Bad	Moderate
7. Reliability	Good	Good	Good	Bad	Good
8. Value to other exps	Good	Good	Good	Bad	Bad
9. Value to Industry	Good	Moderate	Moderate	Bad	Bad

DAEδALUS cost estimates at present

$130M near accelerator, $450M for the 3 sites.
This includes various contingencies, 20% to 50%

Assumes component cost drops by 50% after first production.
Does not include site-specific cost (buildings)

SRC is the cost driver. See: "Engineering study for the DAEdALUS sector magnet"; Minervini et al. arXiv:1209.4886

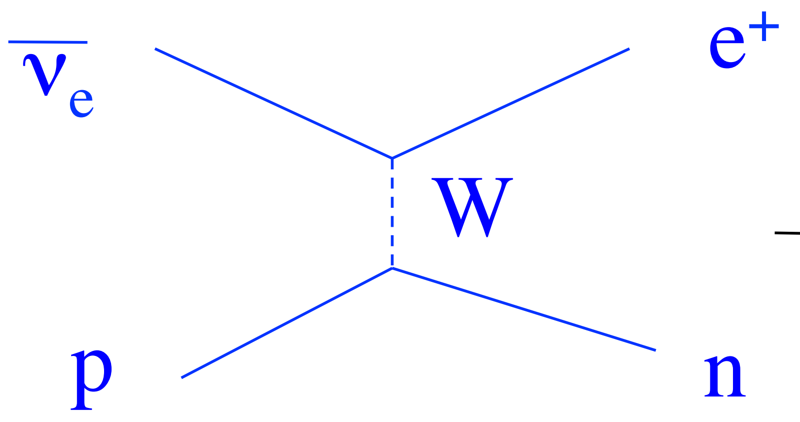
The RF is based on the PSI design, for which we have a cost.

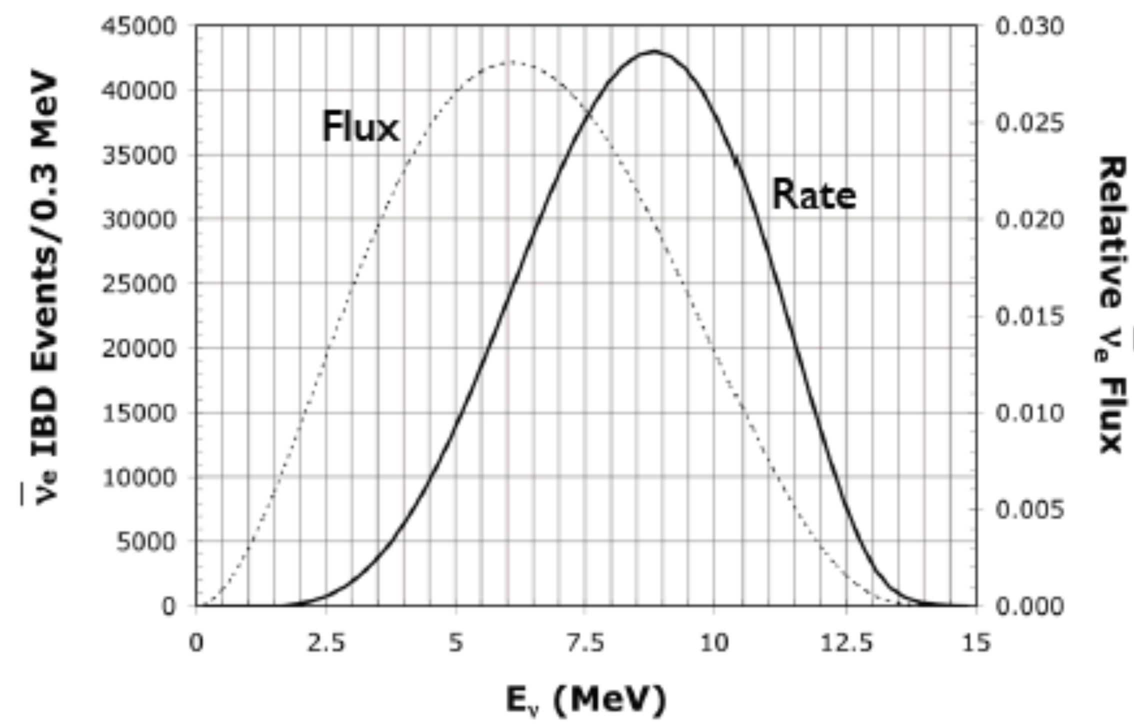
The similarity to RIKEN allows a cost sanity check. We have a cost for this.

All targets are ~1 MW (similar to existing), noting that each cyclotron can have multiple targets.

Five Years of Running at KamLAND

Inverse β Decay (IBD)





Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Duty cycle	90%
Run period	5 years (4.5 years live time)
Target	^{9}Be surrounded by ^{7}Li (99.99%)
$\overline{\nu}$ source	^{8}Li β decay ($\langle E_\nu \rangle$=6.4 MeV)
$\overline{\nu}_e$/1000 protons	14.6
$\overline{\nu}_e$ flux	1.29×10^{23} $\overline{\nu}_e$

Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Detection efficiency	92%
Vertex resolution	12 cm/$\sqrt{E}$ (MeV)
Energy resolution	6.4%/$\sqrt{E}$ (MeV)
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5
$\overline{\nu}_e$-electron event total	7200

820,000 IBD events

- **Sterile neutrino search**

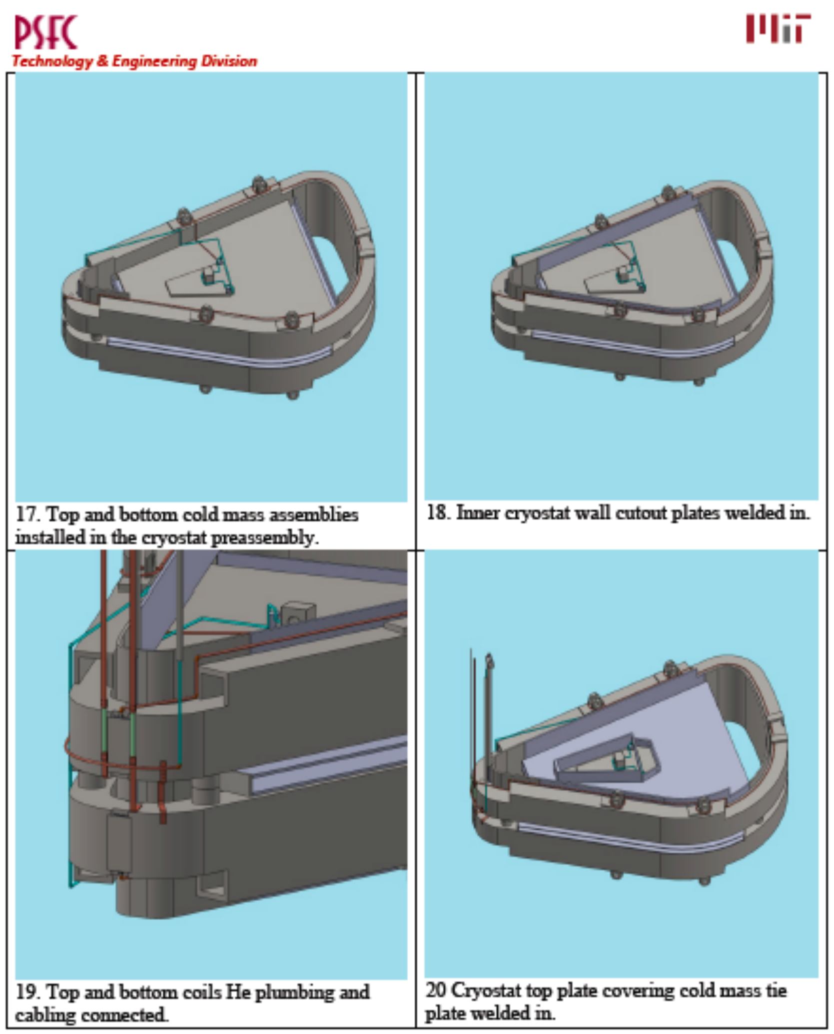
7,200 $\overline{\nu}_e$-electron events

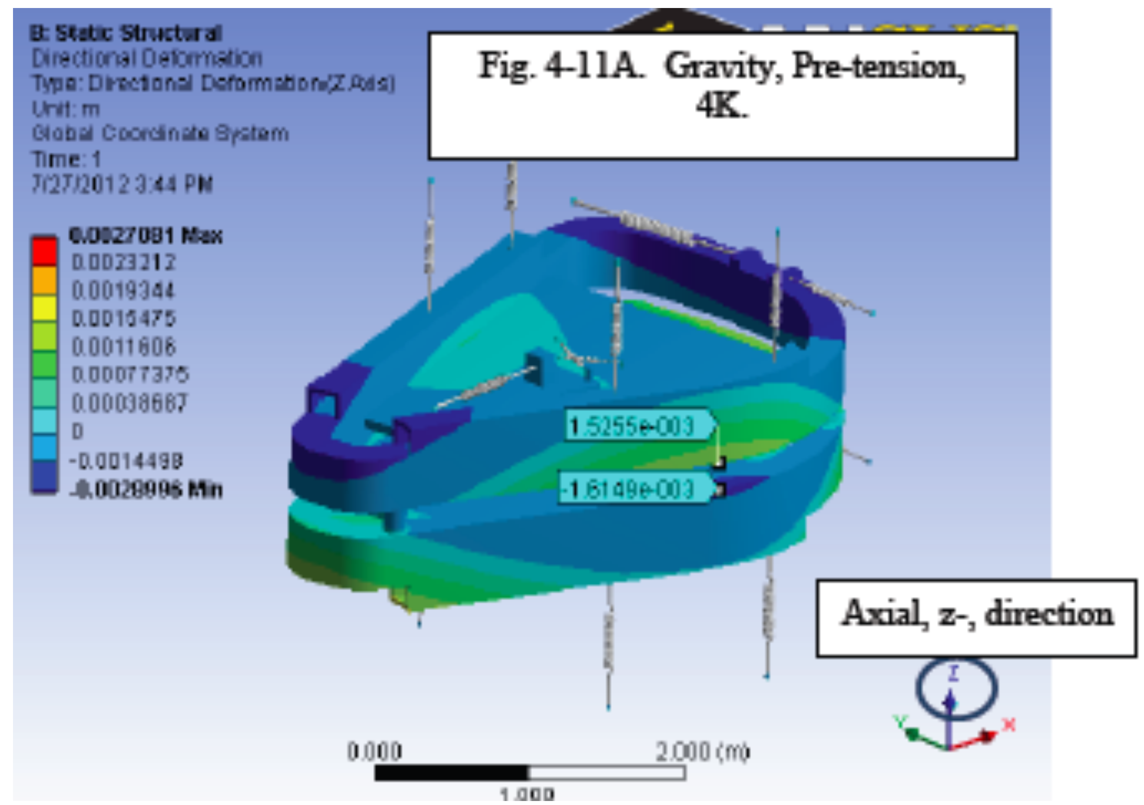
- Measure $\sin^2\theta_W$ to 3.2%
- Probe weak couplings and nonstandard interactions (NSIs)

DAEδALUS progress

Engineering study of SRC, arXiv:1209.4886

Engineering design
Assembly plan
Structural analysis
Cryo system design





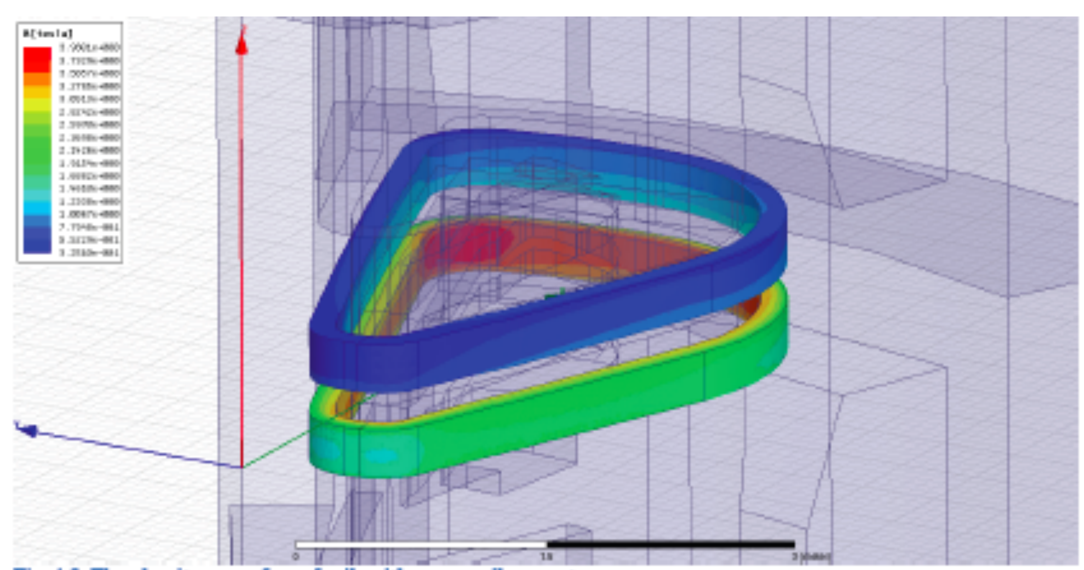
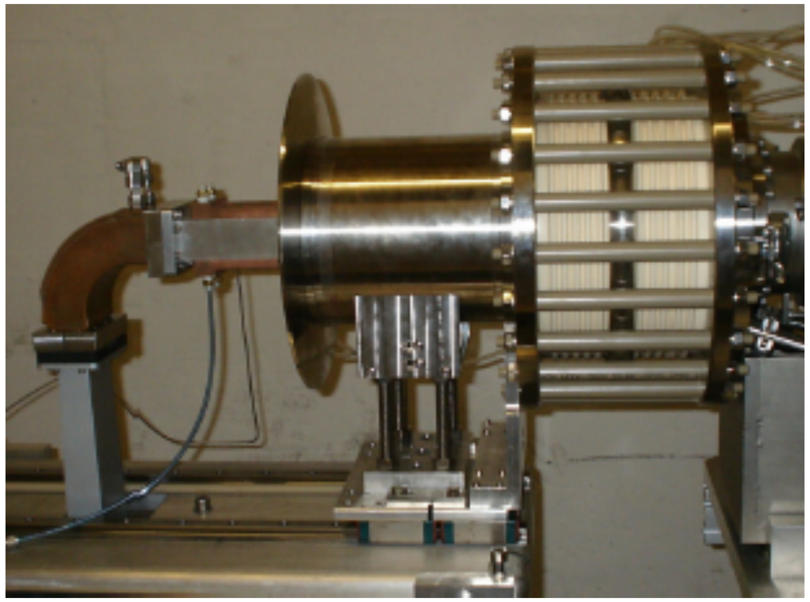
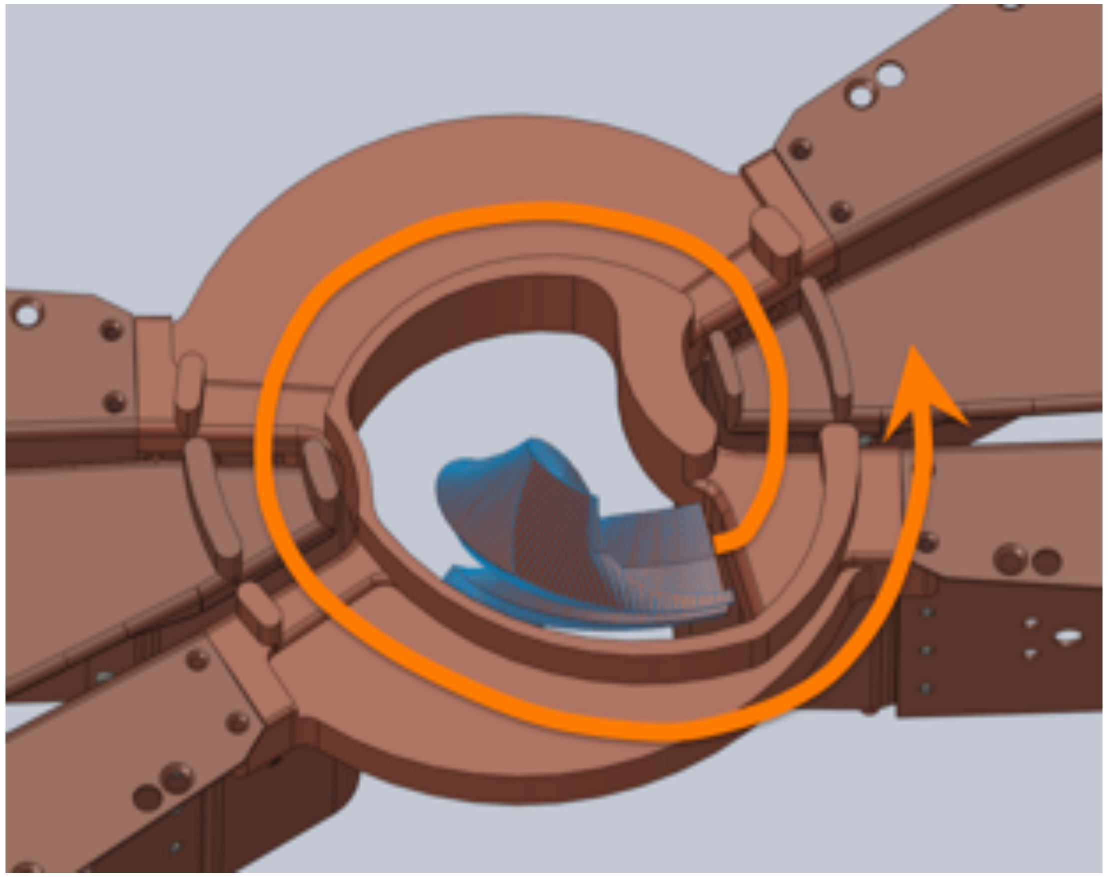


Fig. 4-9. Flux density on surface of coils with upper coil current zero.

IsoDAR challenges

- Ion source intensity


The ion source

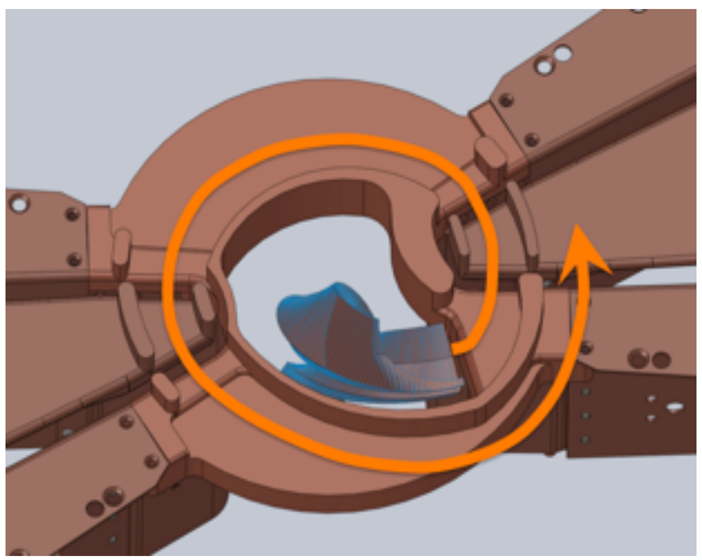

The first turn after axial inflection

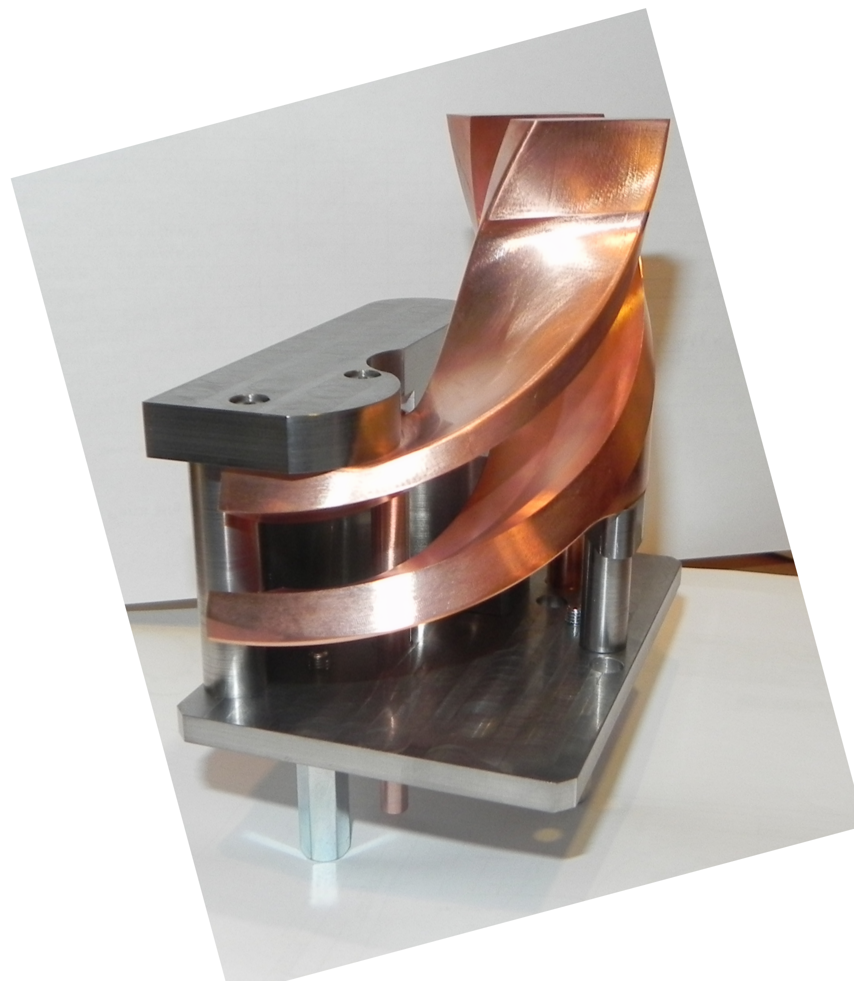
Most ions are lost in the first “turn” because they hit material.

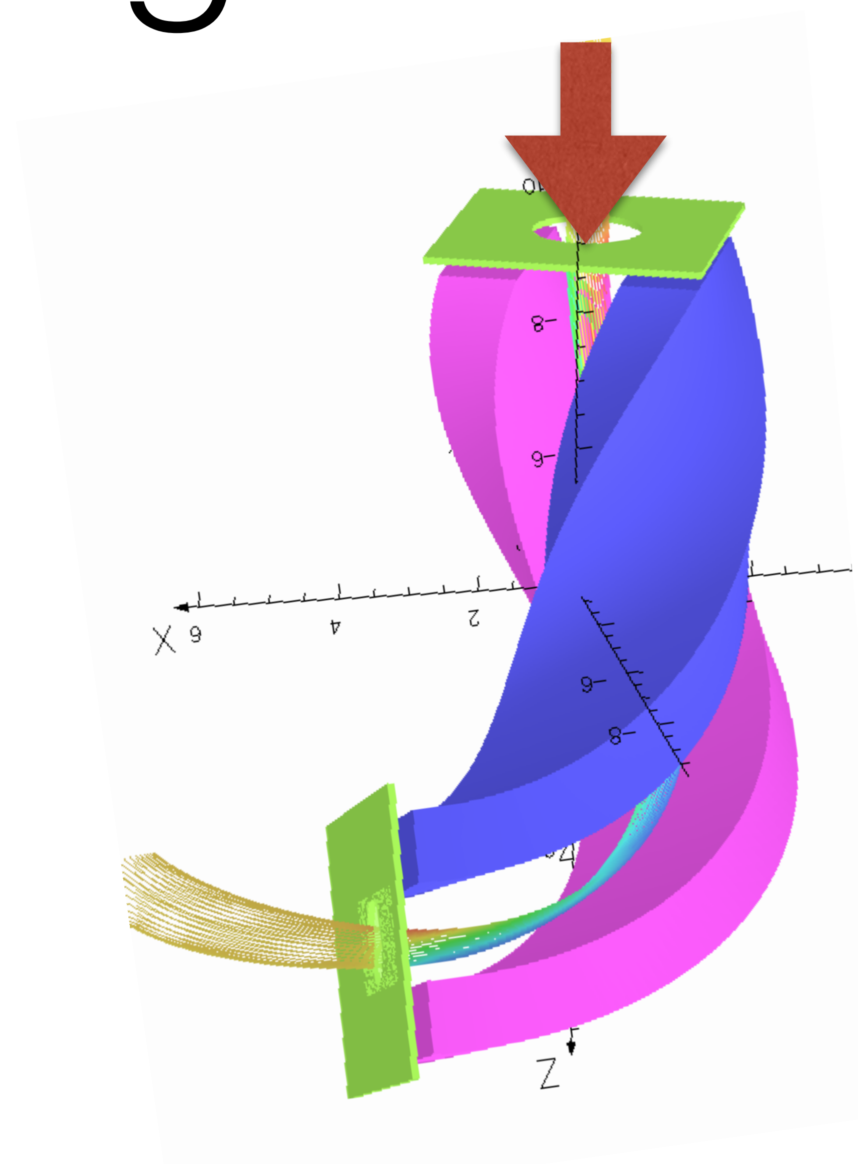
To capture 5 mA we will need between 35 and 50 mA injected.

IsoDAR challenges

- Inflection





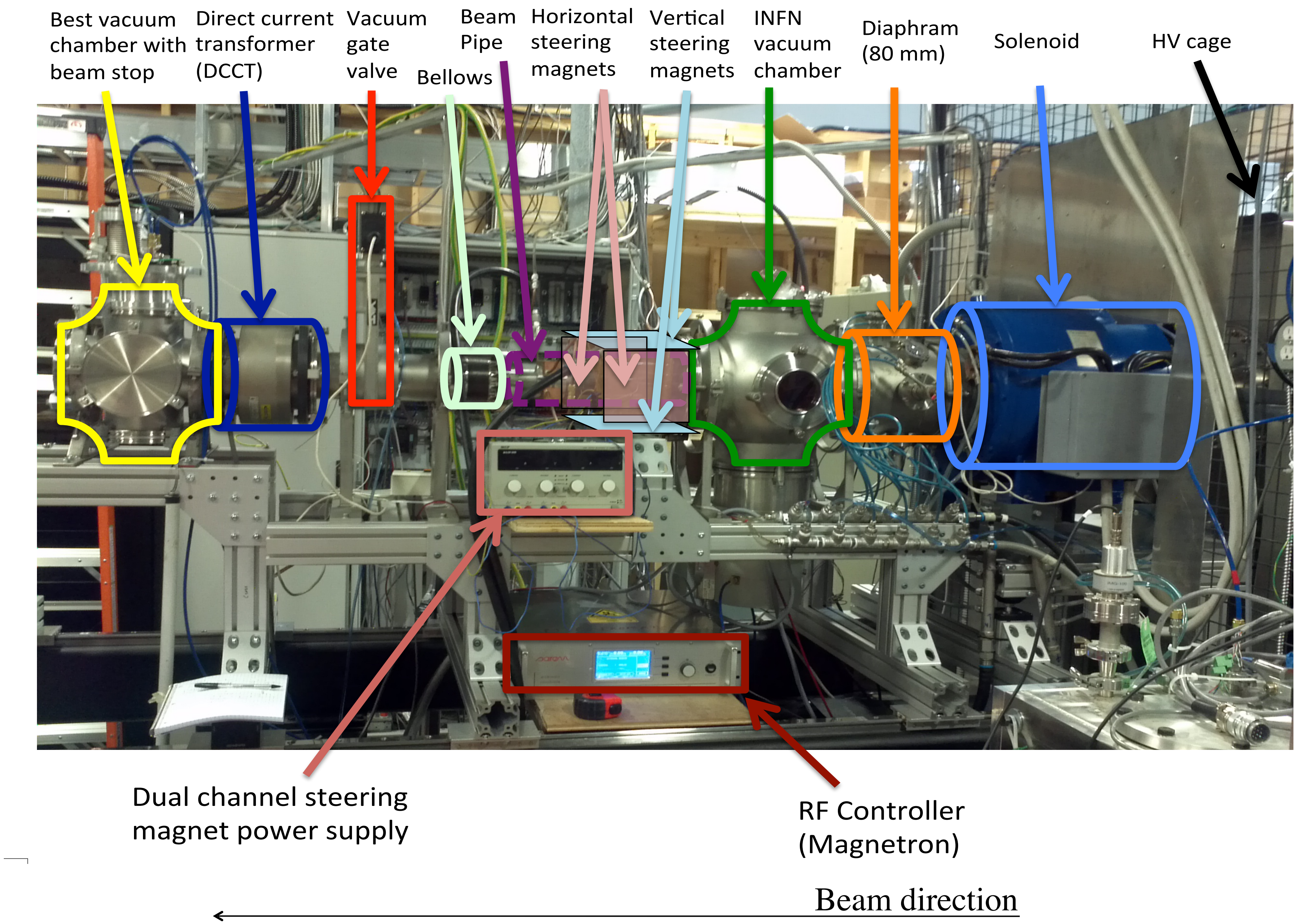


Getting the beam into the cyclotron requires taking it from the vertical to the horizontal plane. This is hard.

->an iterative R&D process.

IsoDAR challenges

Beam is now being characterized at Best Cyclotrons, Inc, Vancouver
(Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)



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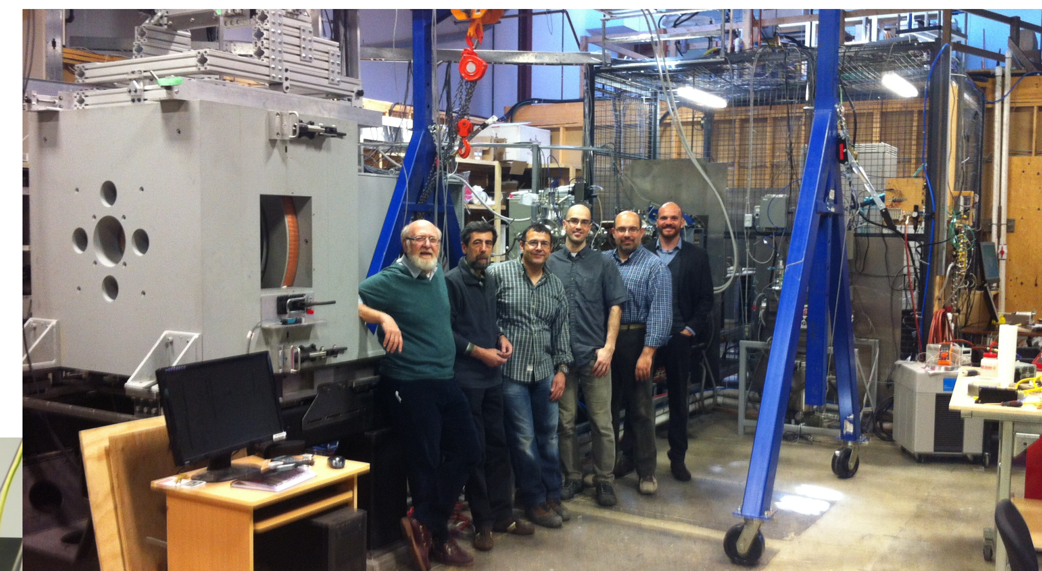
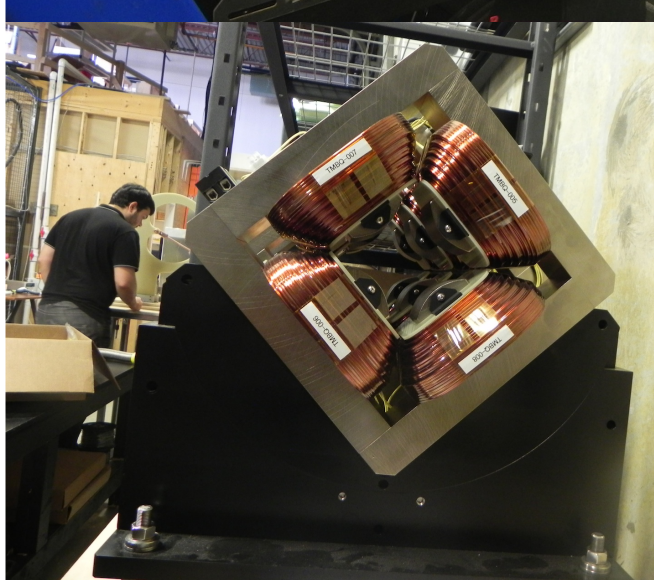
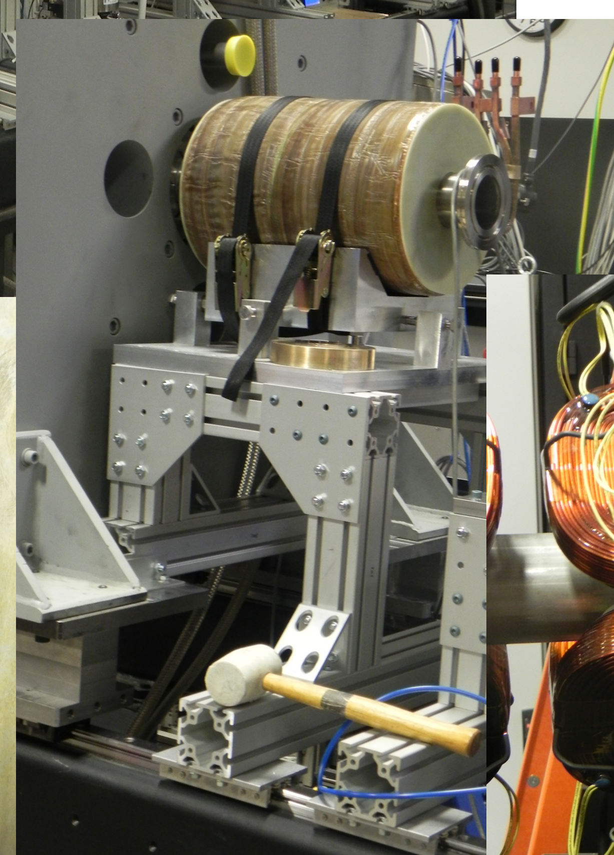
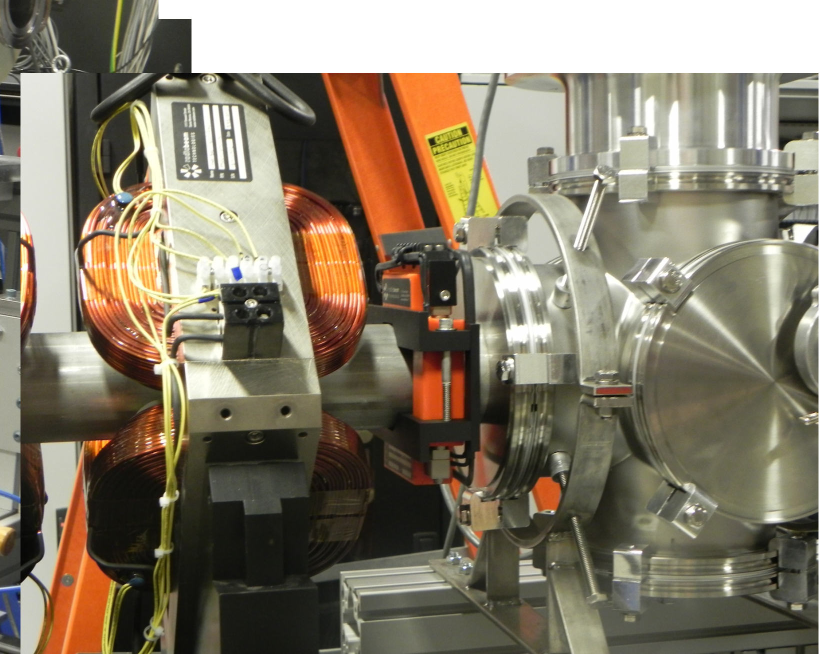
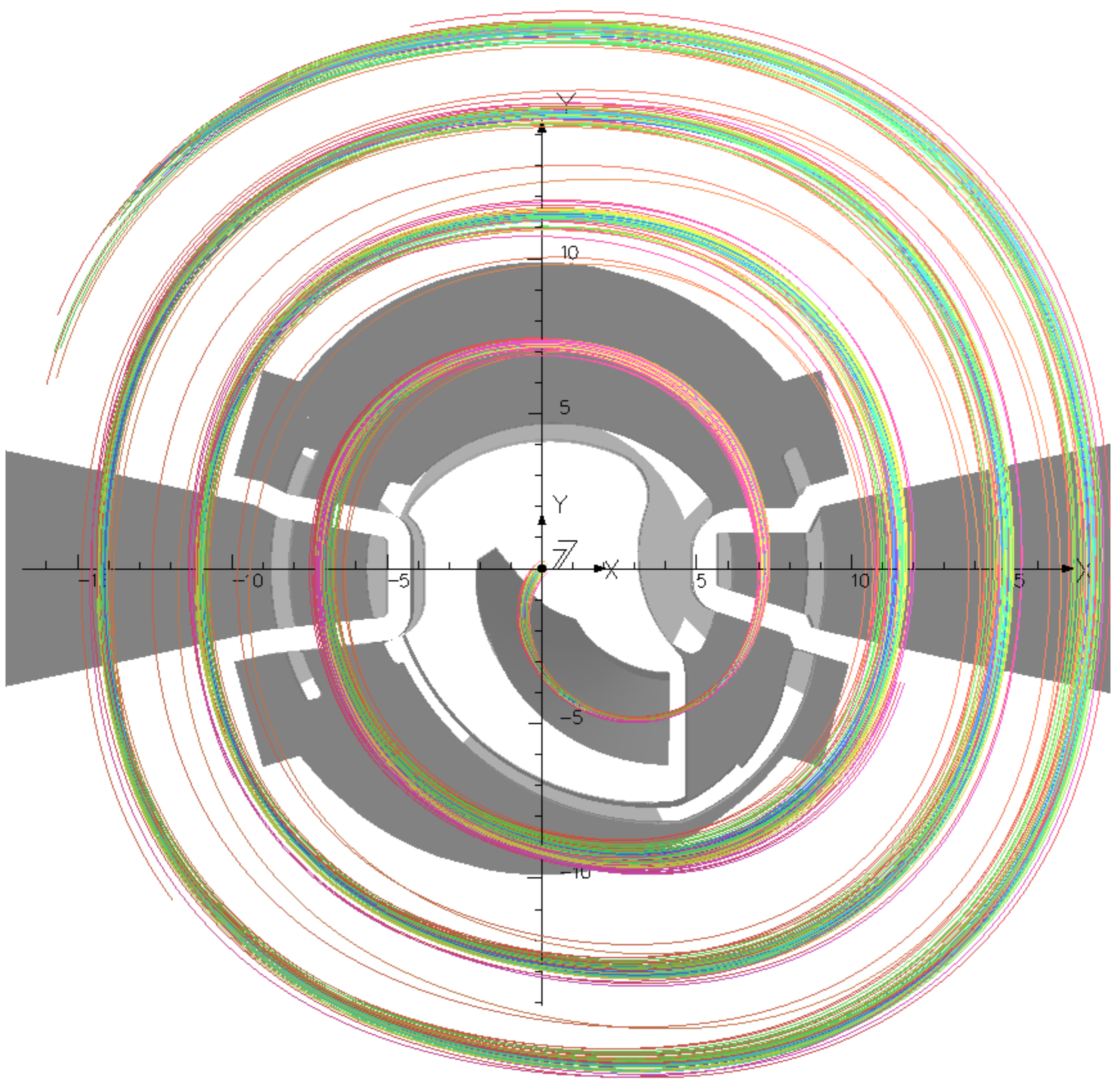
Beam is now being characterized at Best Cyclotrons, Inc, Vancouver
(Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)

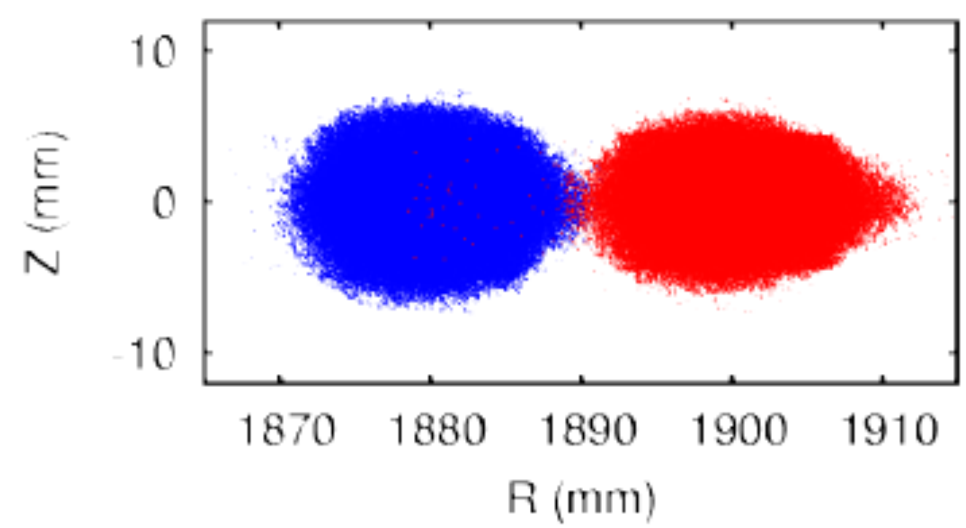
IsoDAR challenges

How much beam can we accelerate?
A question for simulation and experiment!

- Intense ion source
- Limit space charge
- Control emittance
- Remove high-vibrational states
- Limit losses at extraction



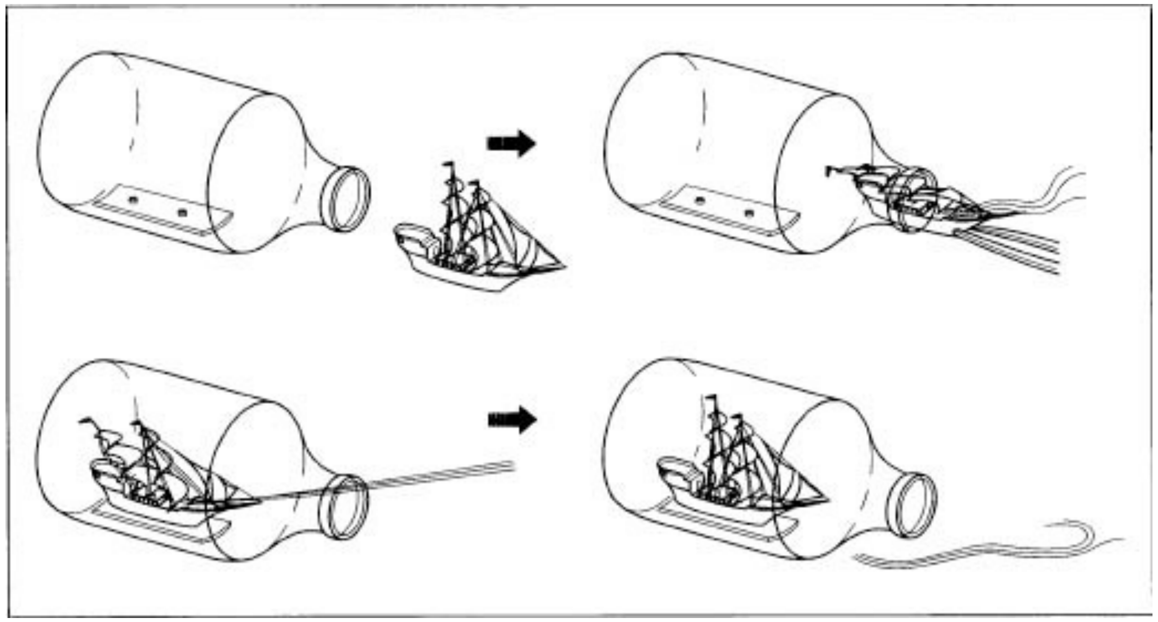
Beam dynamics sim



The final turns in the injector

IsoDAR challenges

- The target, shielding, and implementation
  - Obtaining 99.99% pure ^{7}Li. Molten salt reactors use this. High end of estimate is 2.5M. There is 50 kg under study at MIT now.
  - Forming the sleeve. Working with Bartoszek engineering.
  - Heat dissipation (600 kW). Beam will be painted across embedded Be target face.
  - Activation and shielding studies are a priority now.
  - Fast/thermal neutrons as a background antineutrino events.

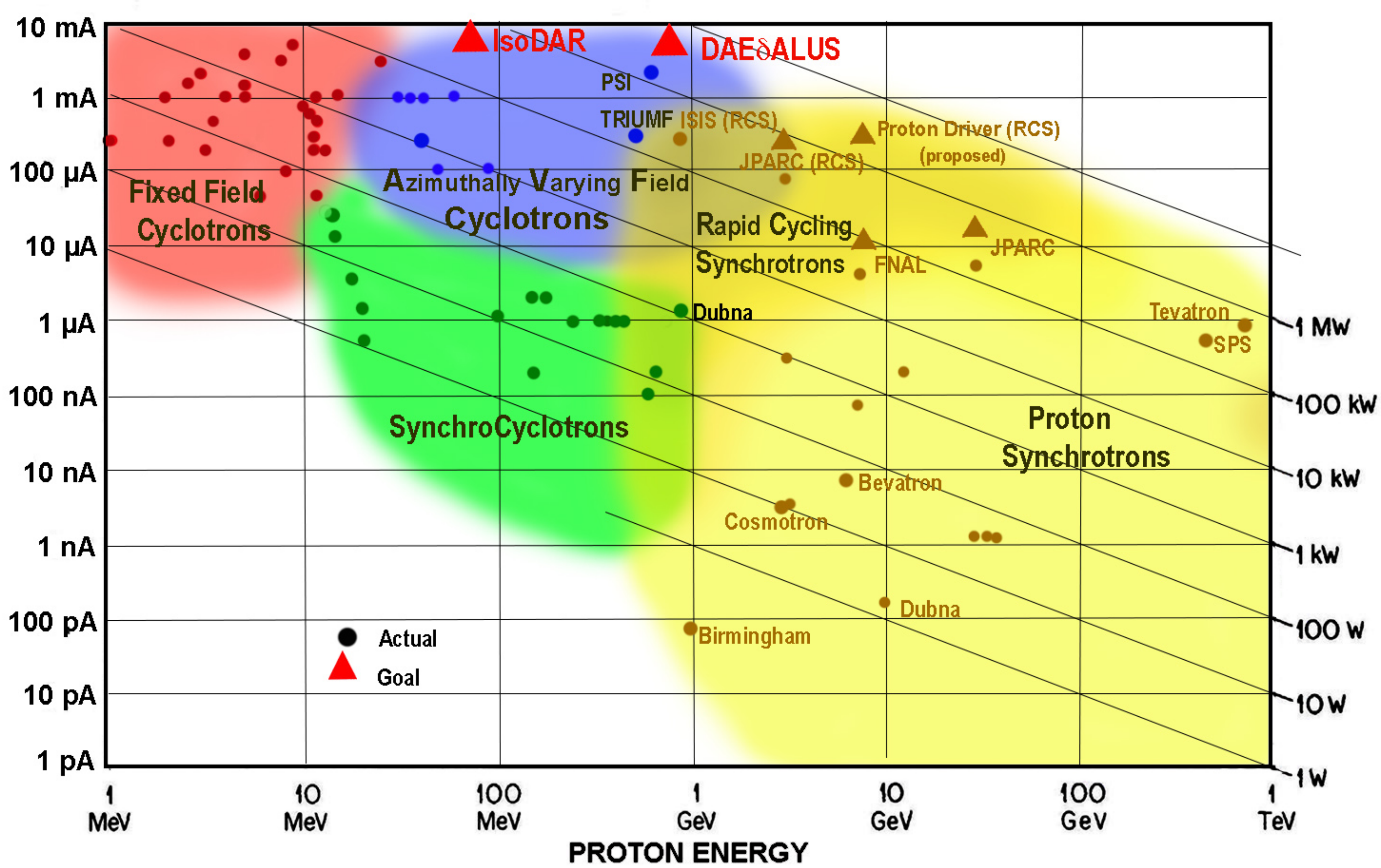


- Underground location

δ_{CP} sensitivity assumptions

Configuration Name	Source(s)	Average Long Baseline Beam Power	Detector	Fiducial Volume	Run Length
DAEδALUS@LENA	DAEδALUS only	N/A	LENA	50 kt	10 years
DAEδALUS@Hyper-K	DAEδALUS only	N/A	Hyper-K	560 kt	10 years
DAEδALUS/JPARC (nu only)@Hyper-K	DAEδALUS & JPARC	750 kW	Hyper-K	560 kt	10 years
JPARC@Hyper-K	JPARC	750 kW	Hyper-K	560 kt	3 years ν + 7 years $\bar{\nu}$ [3]
LBNE	FNAL	850 kW	LBNE	35 kt	5 years ν 5 years $\bar{\nu}$ [6]

Keys to higher current:
H_2^+, intense ion source, inflect and extract with low losses, limit space charge



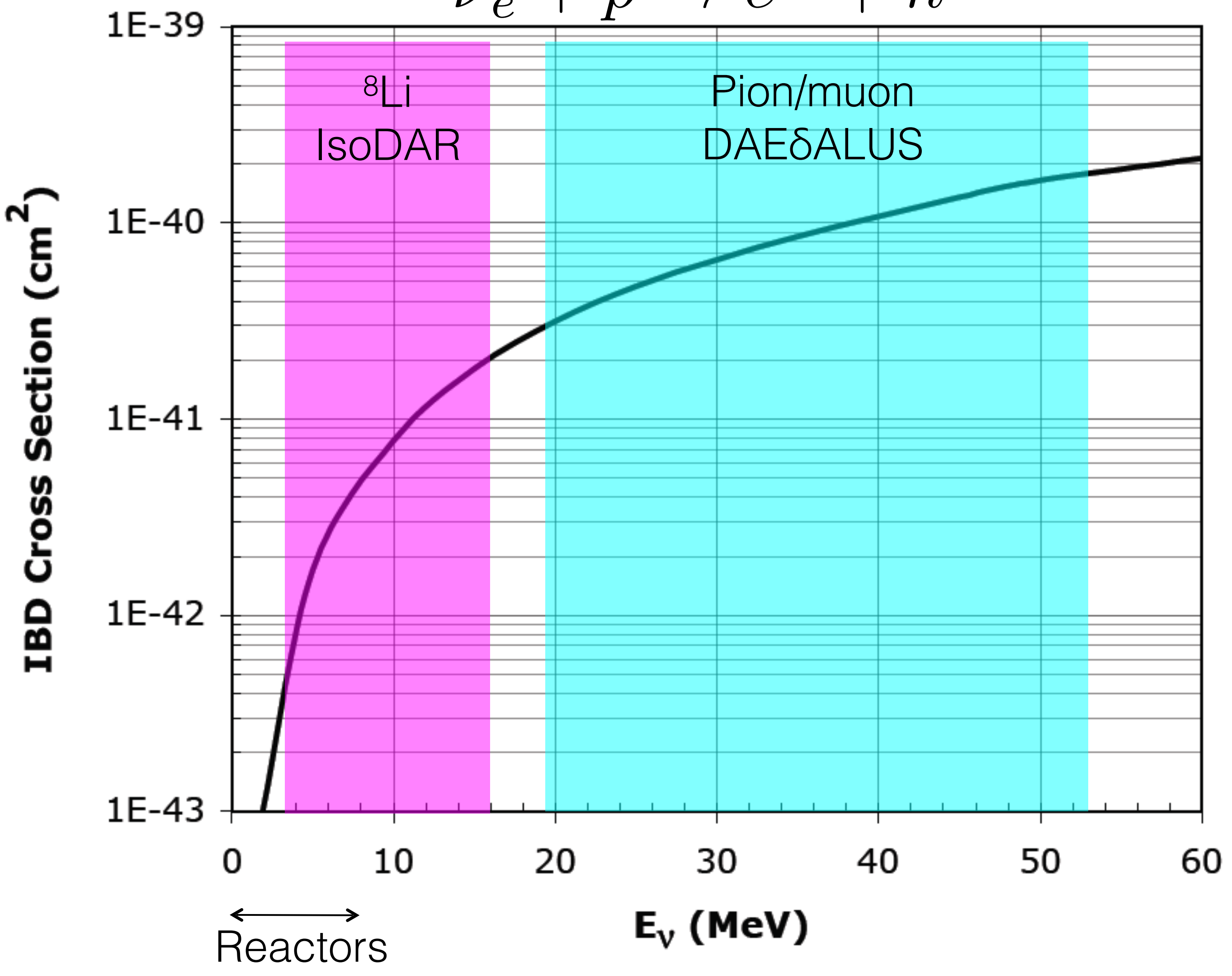
TRIUMF accelerates H- but with a much lower peak field because of Lorentz stripping.

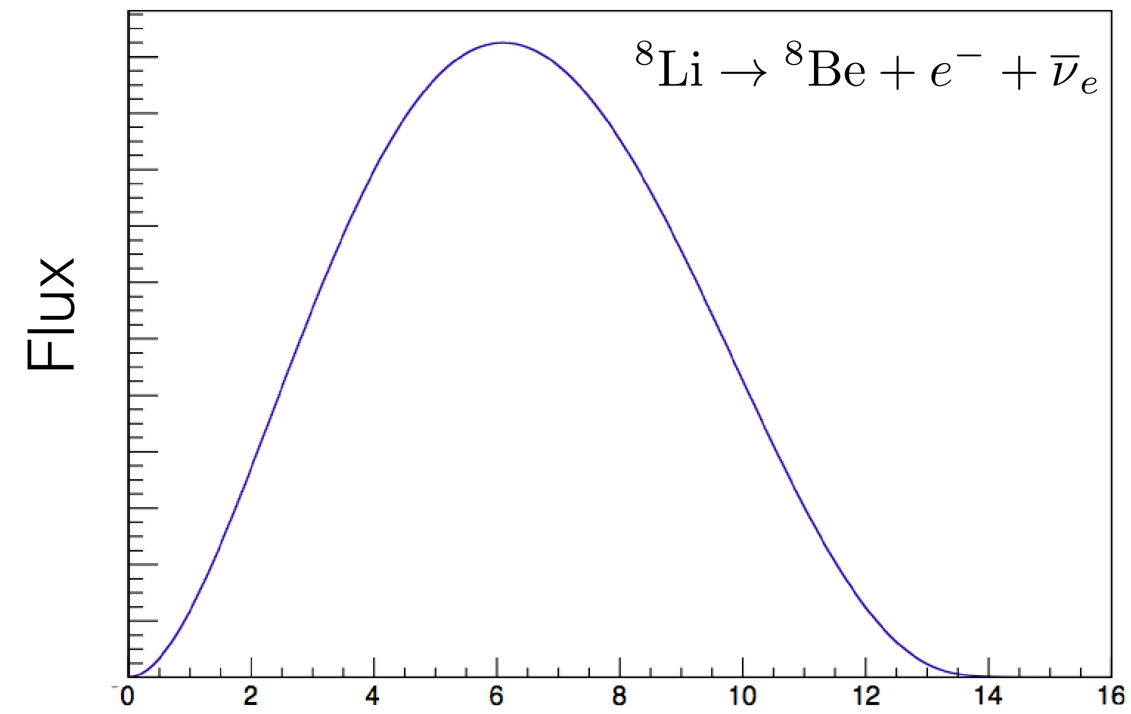
PSI is an 8-sector normal conducting machine.

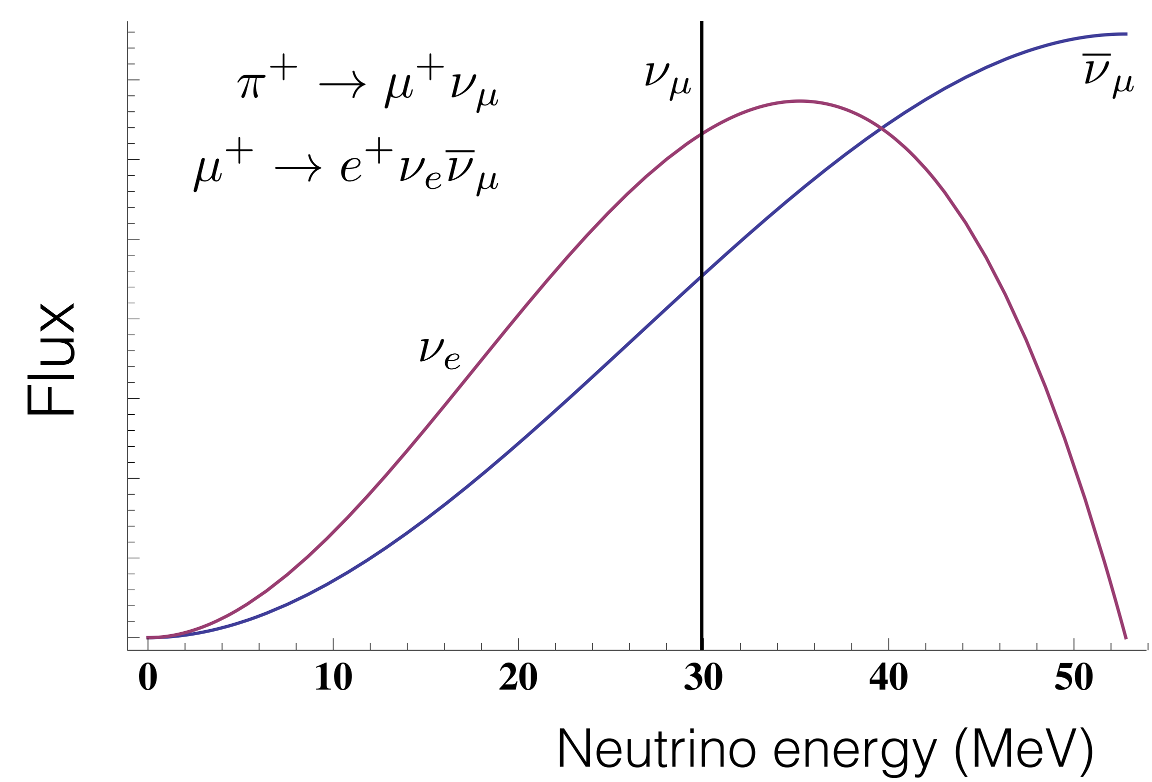
RIKEN is a heavy ion SRC and is most similar to our current design.

Flux and cross section

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







- Scintillator or Gd-doped water detector
- Prompt positron signal followed by neutron capture

$$E_{\overline{\nu}_e} \cong E_{\mathrm{prompt}} + 0.78 \text{ MeV}$$

DAEδALUS @ LBNE?

No.

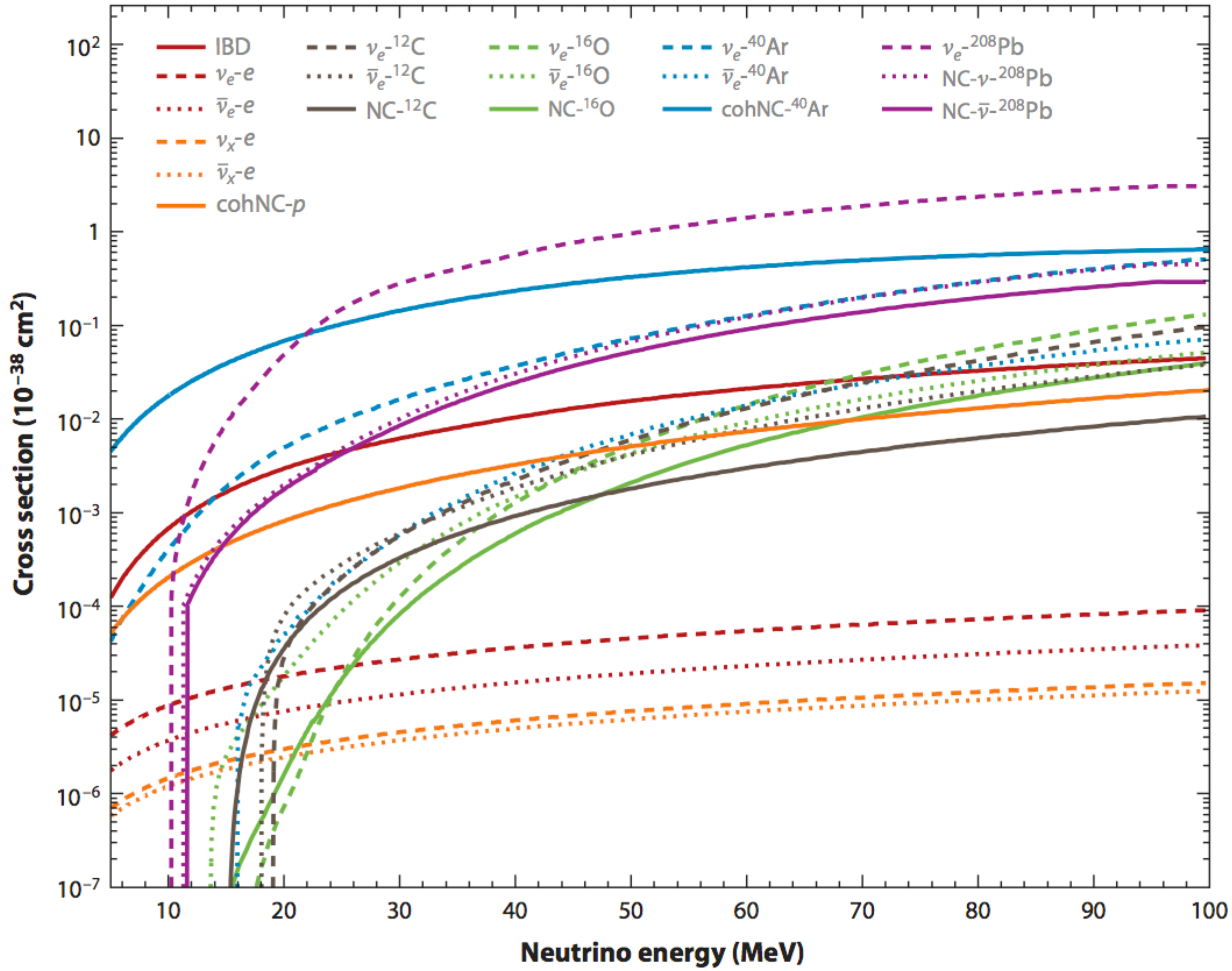


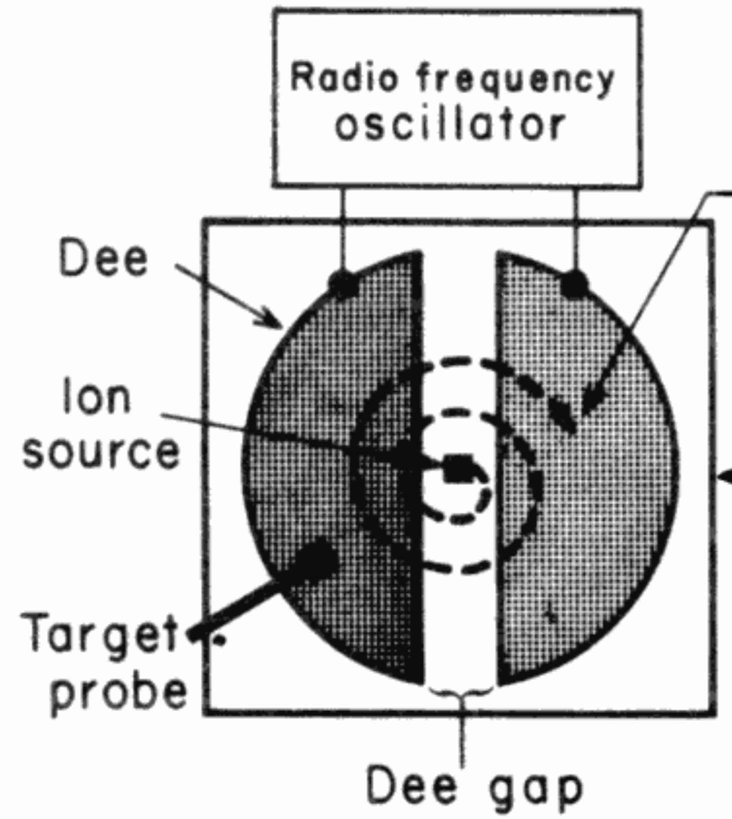
Figure 2

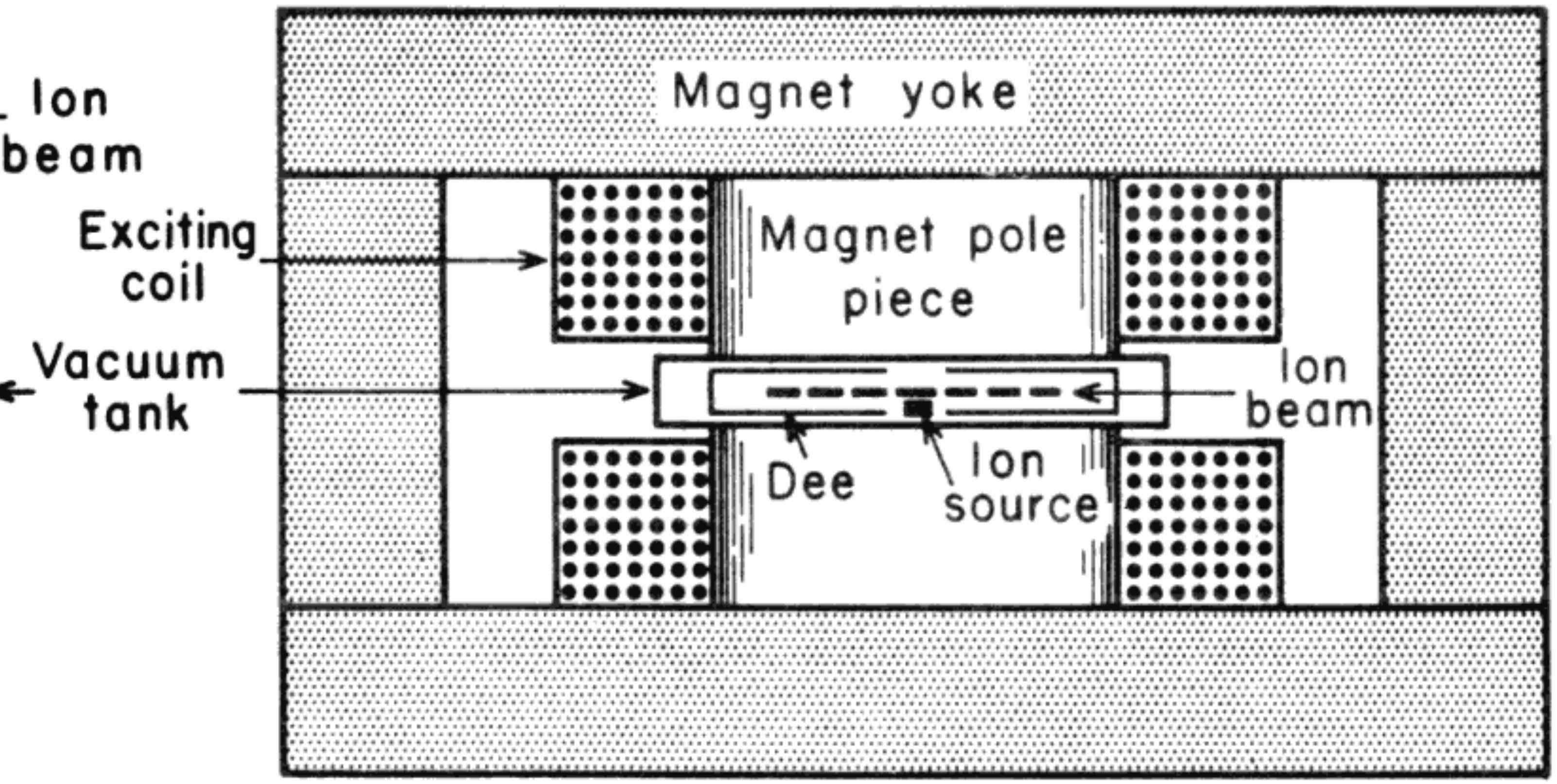
Cross sections per target for relevant interactions. See **http://www.phy.duke.edu/~schol/snowglobes** for references for each cross section plotted. Abbreviations: IBD, inverse β decay; NC, neutral current.

A phased program

Phase	What?	Where?	Science?
I	Produce 50 mA H_2^+ source, inflect, capture 5 mA and accelerate	Best Inc. test-stand INFN Catania	Accelerator science
II	Build the injector cyclotron, extract, produce antinu flux via ^{8}Li	Watchman KamLAND Borexino JUNO	SBL
III	Build the first SRC, run this as a "near accel." at existing large detector	NOvA LENA Super-K	SBL
IV	Build the high power SRC, construct DAEδALUS	JUNO Hyper-K LENA MEMPHYS	δ_{CP}

Cyclotrons





An “isochronous cyclotron” design: magnetic field changes with radius, allowing multibunch acceleration

- Inexpensive (relatively)
- Practical below ~1 GeV
- Good for ~10% or higher duty factor
- Typically single energy
- Taps into existing industry

Broader impacts

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.

IsoDAR design is uniquely applicable for medical isotope production

Thorium reactor community is interested in DAEδALUS

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

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L. Calabretta, INFN/LNS, Catania, Italy; A. Calanna, CSFNSM, Catania, Italy

Abstract

This paper addresses an attempt to start investigating the use of the Superconducting Ring Cyclotron (SRC) developed for DAEδALUS experiment for ADS application [1, 2], focusing on the magnet design and its implication for lattice parameters and dynamic aperture performance.