IsoDAR and DAEδALUS

Janet Conrad for Josh Spitz, MIT
PANIC Conference, 8/25/2014

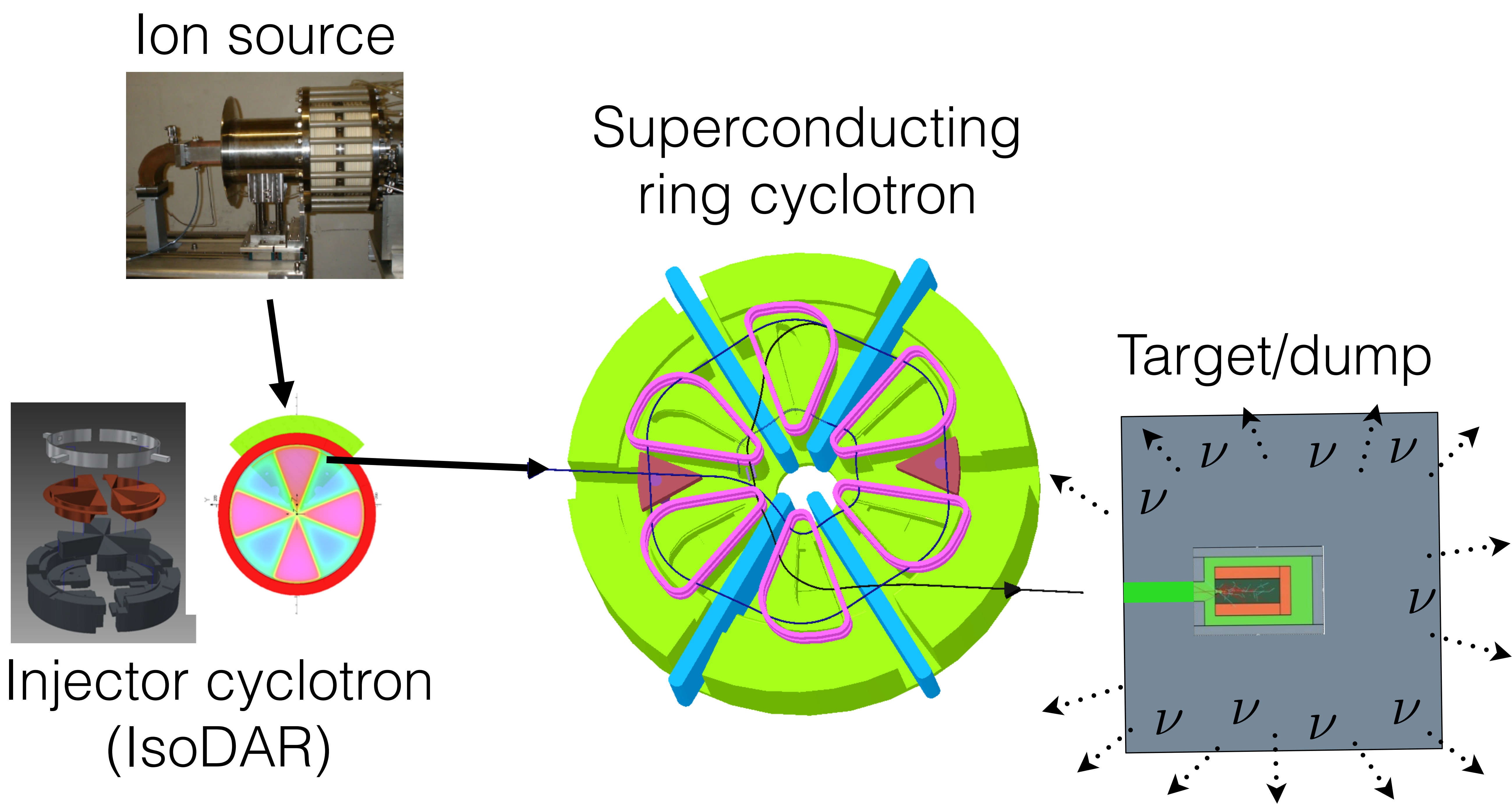
The DAEδALUS program

- 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, …

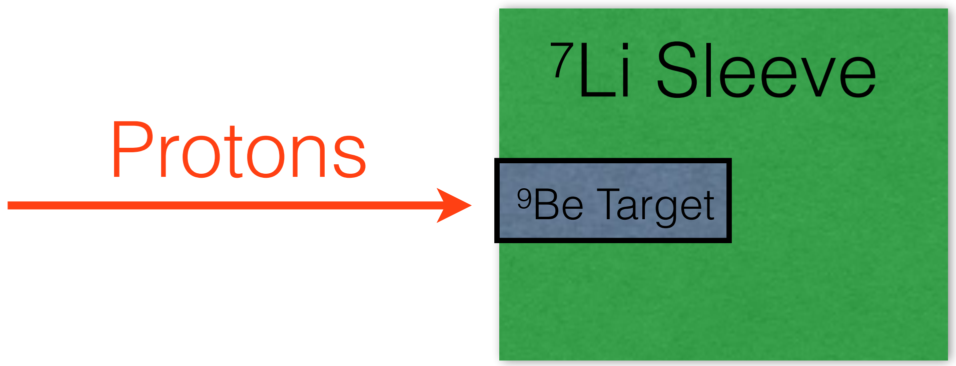
A phased program

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 ^8Li	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}

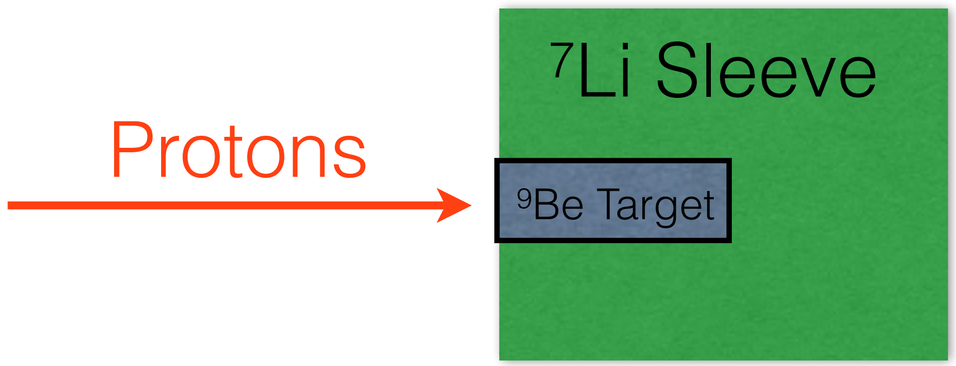
The DAEδALUS program



IsoDAR



IsoDAR

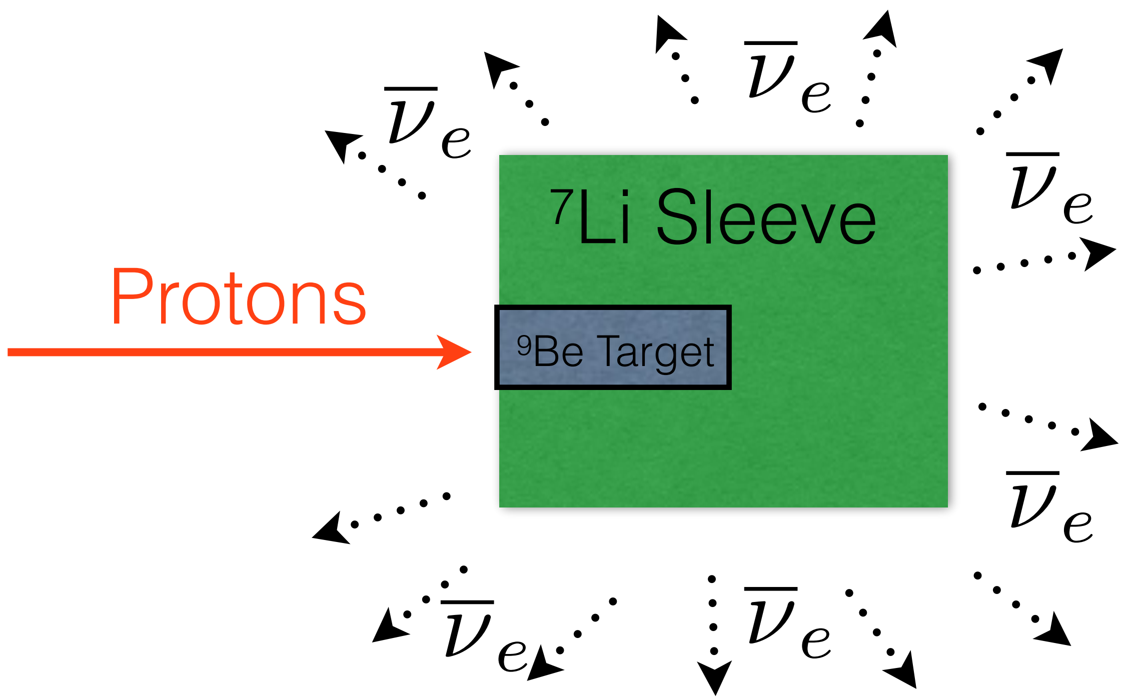


$$p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$$

$$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$$

$$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$$

IsoDAR



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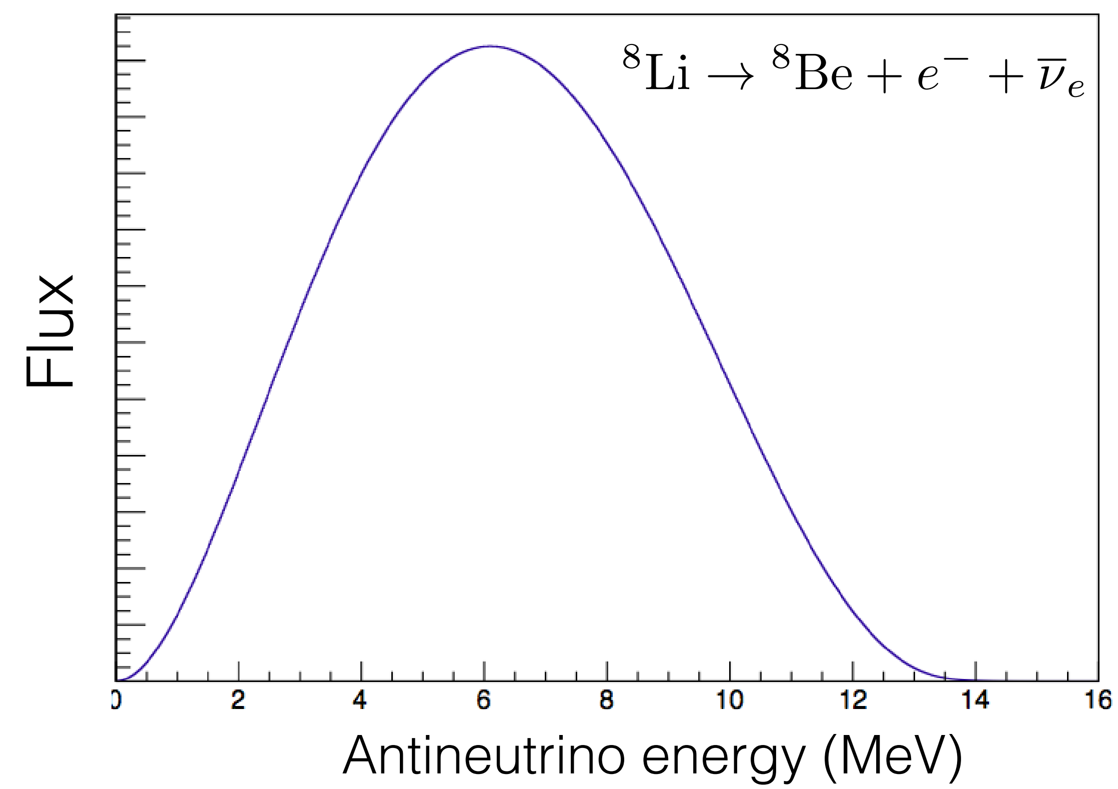
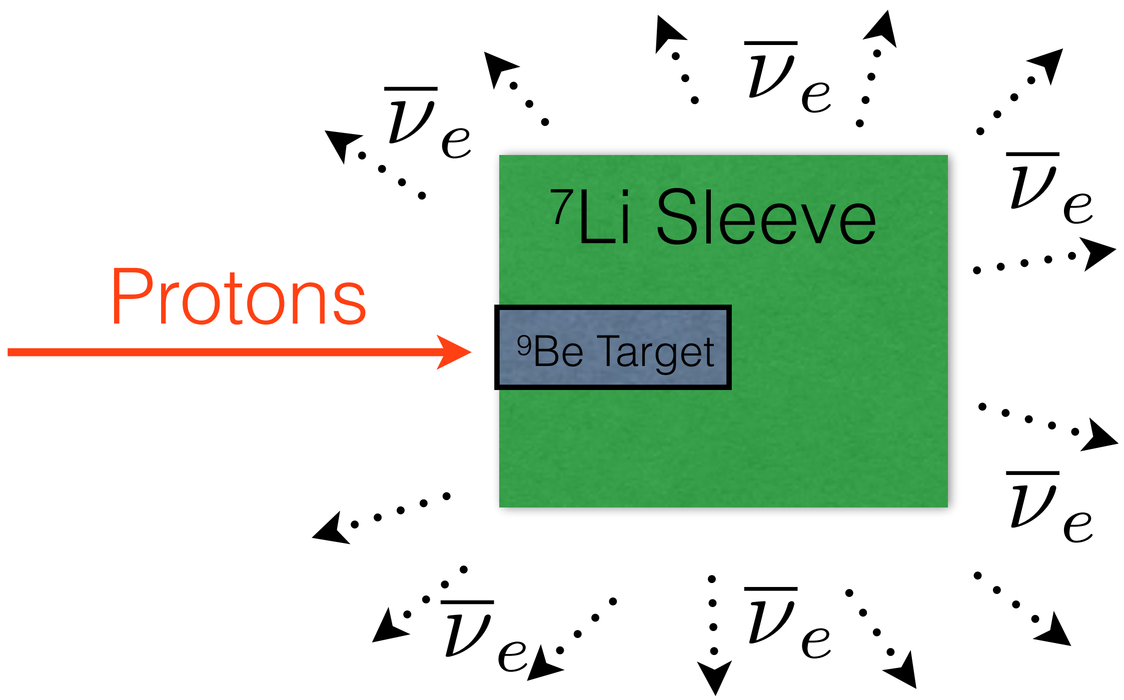
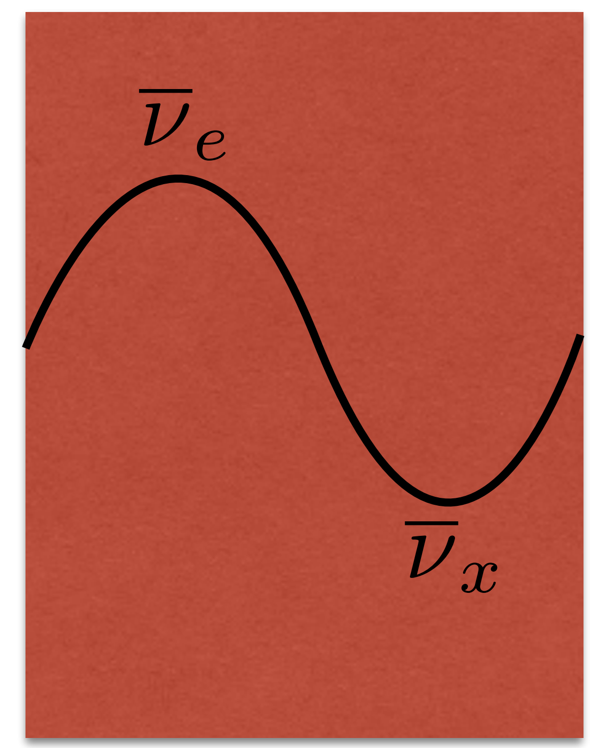


IsoDAR



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

Detector



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

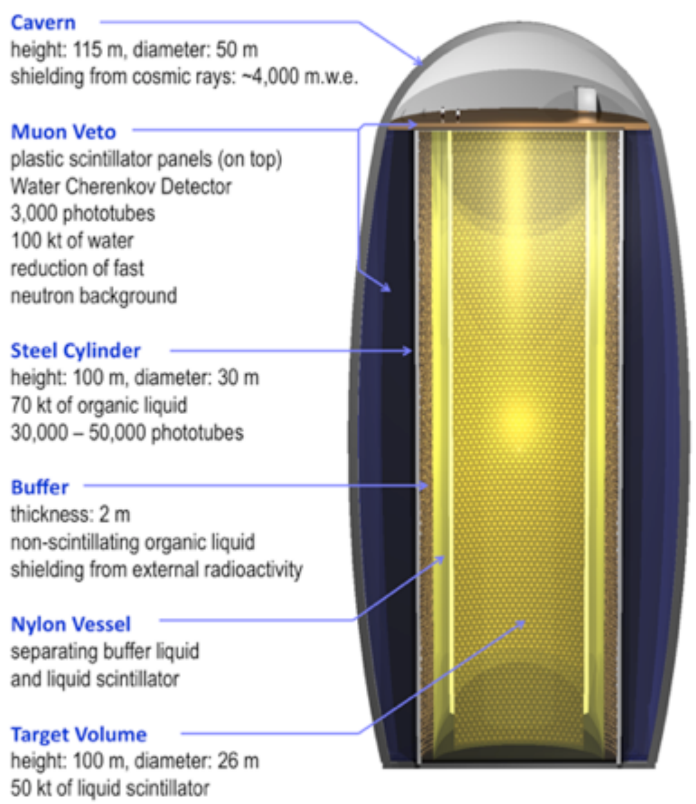
$$p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$$

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

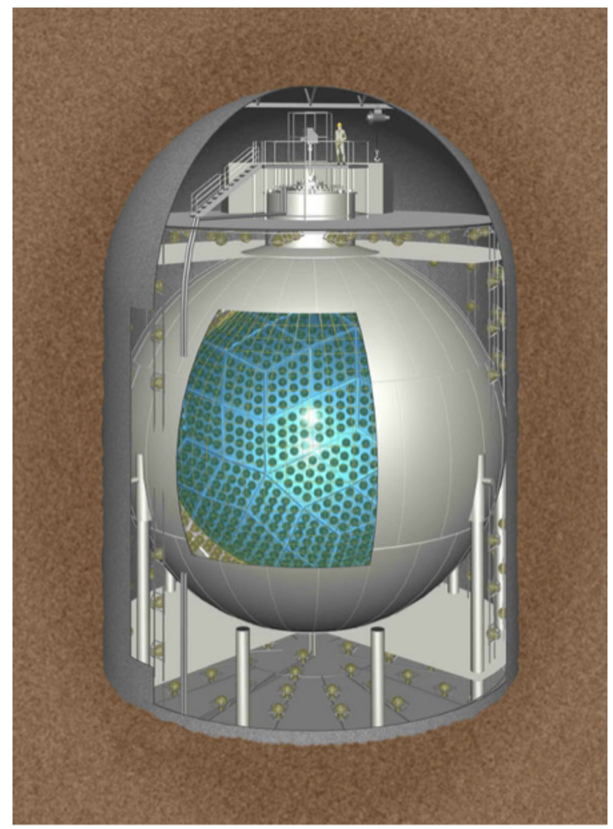
$${}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

Where can IsoDAR run?

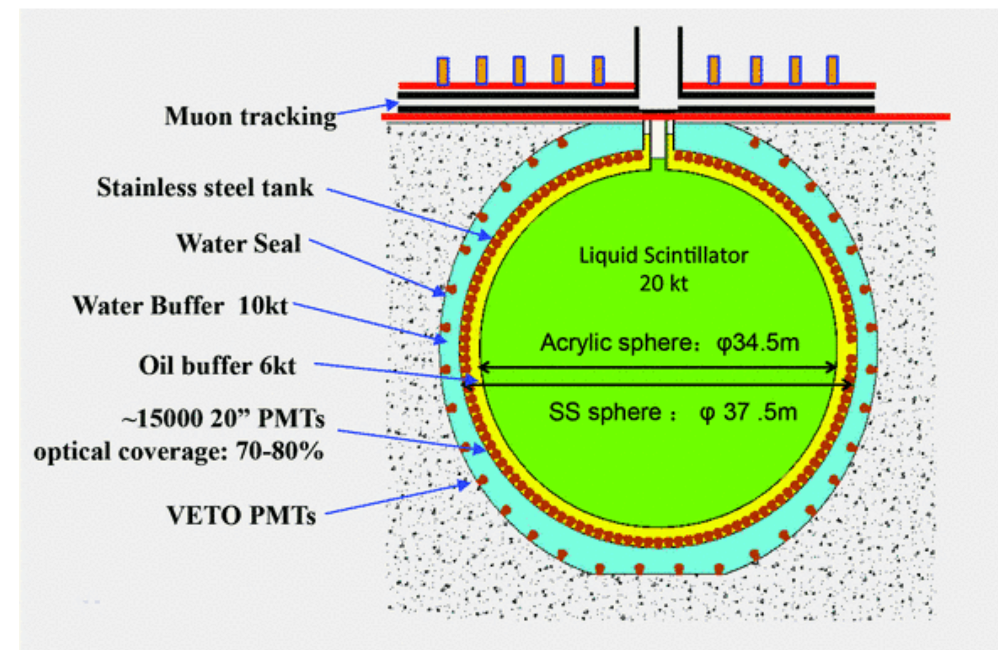
LENA



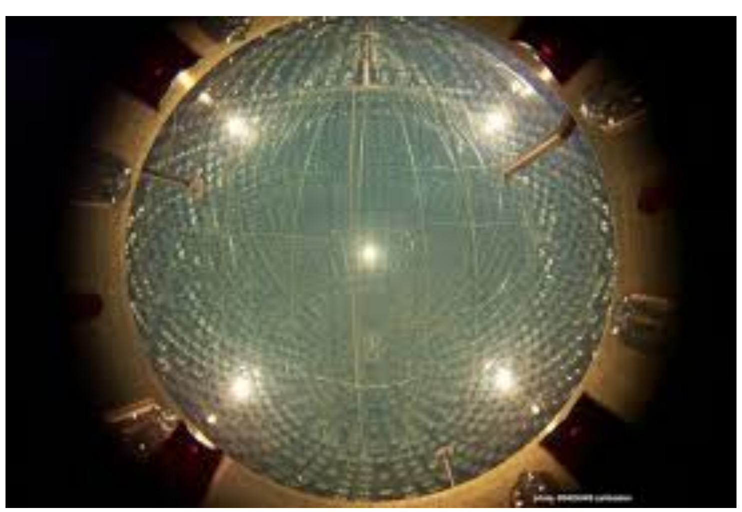
KamLAND



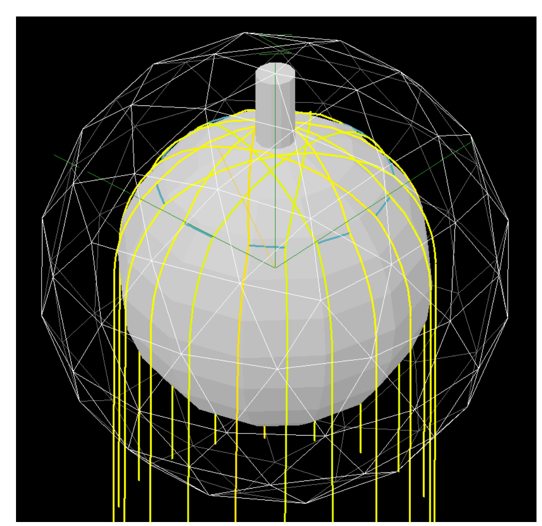
JUNO



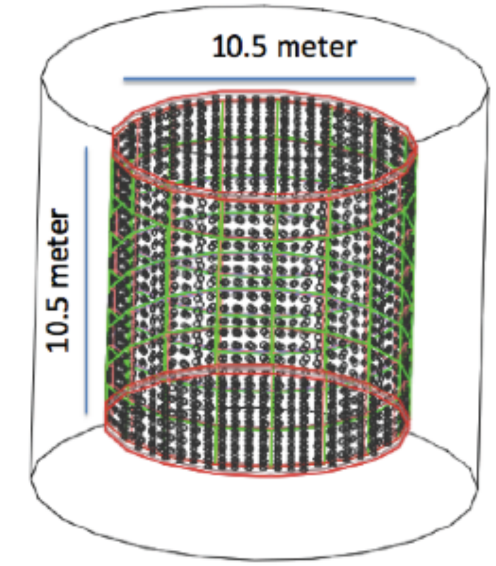
Borexino



SNO+



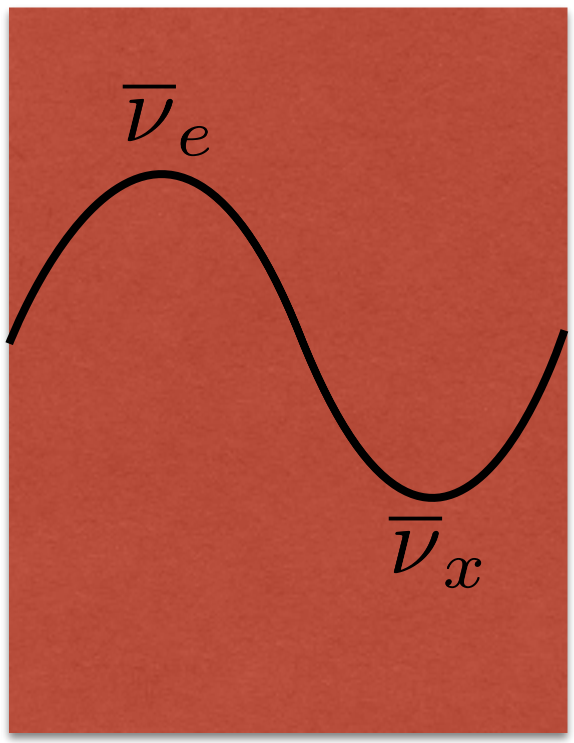
WATCHMAN



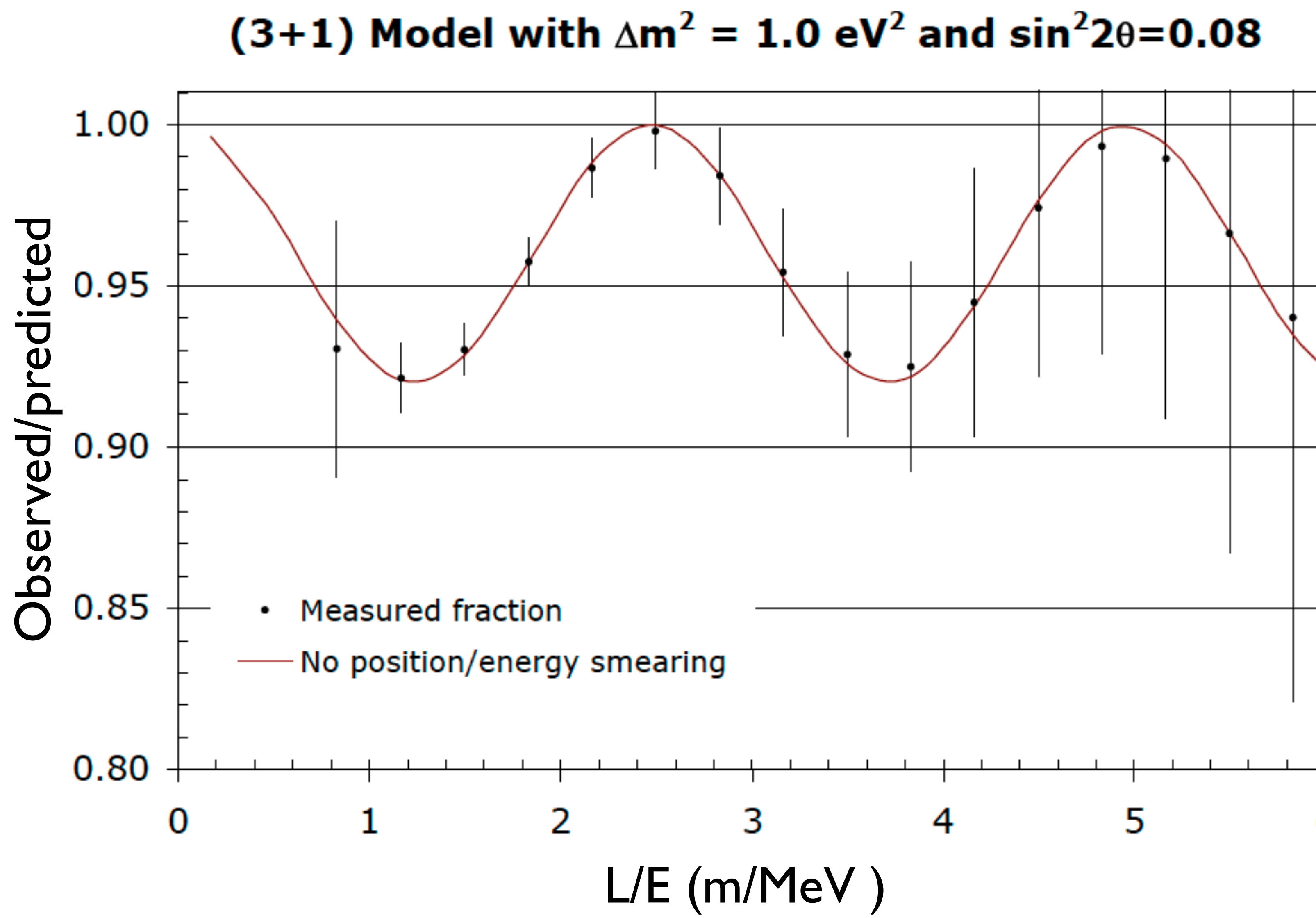
IsoDAR

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

Detector

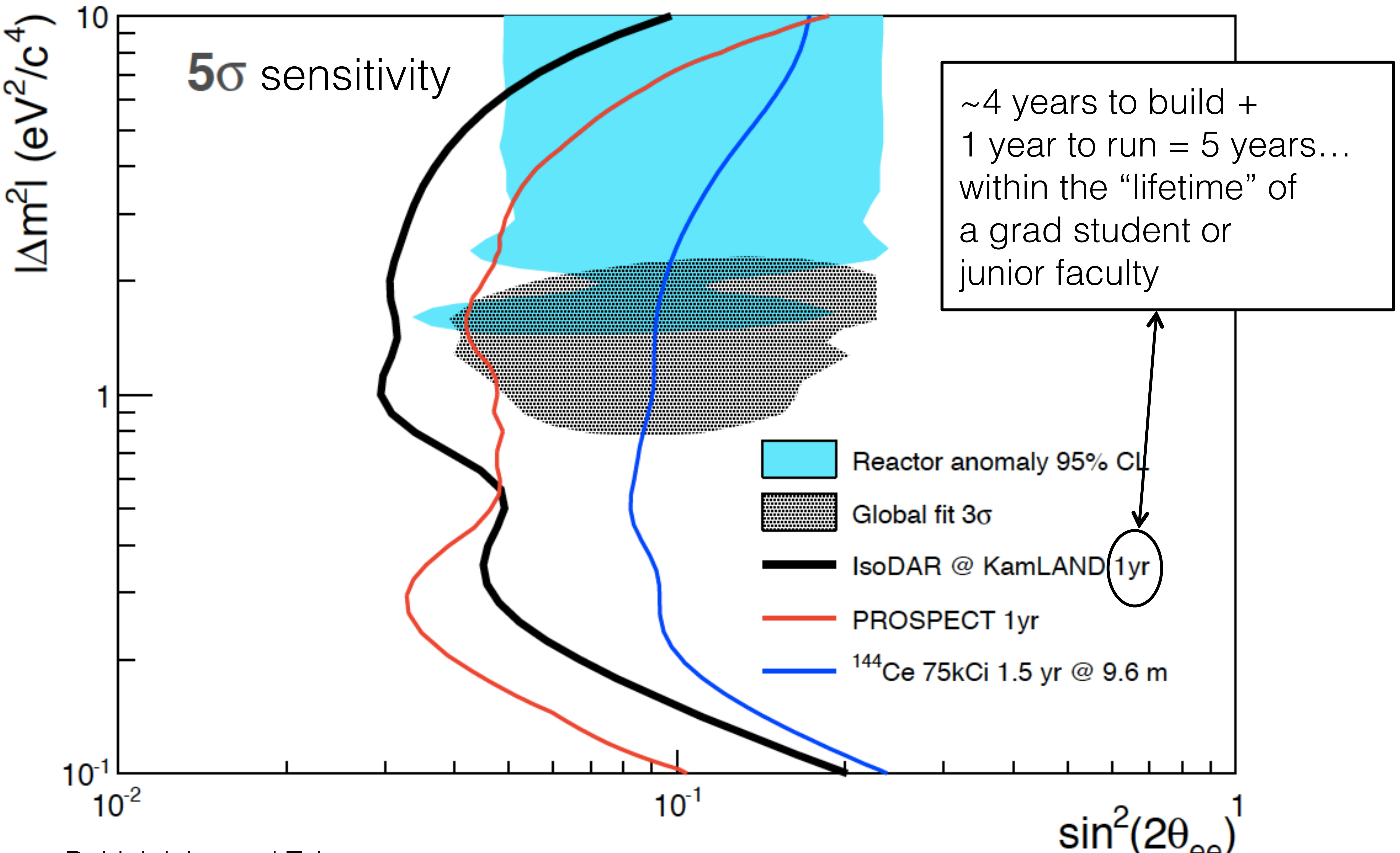


$$\overline{\nu}_e p \rightarrow e^+ n$$



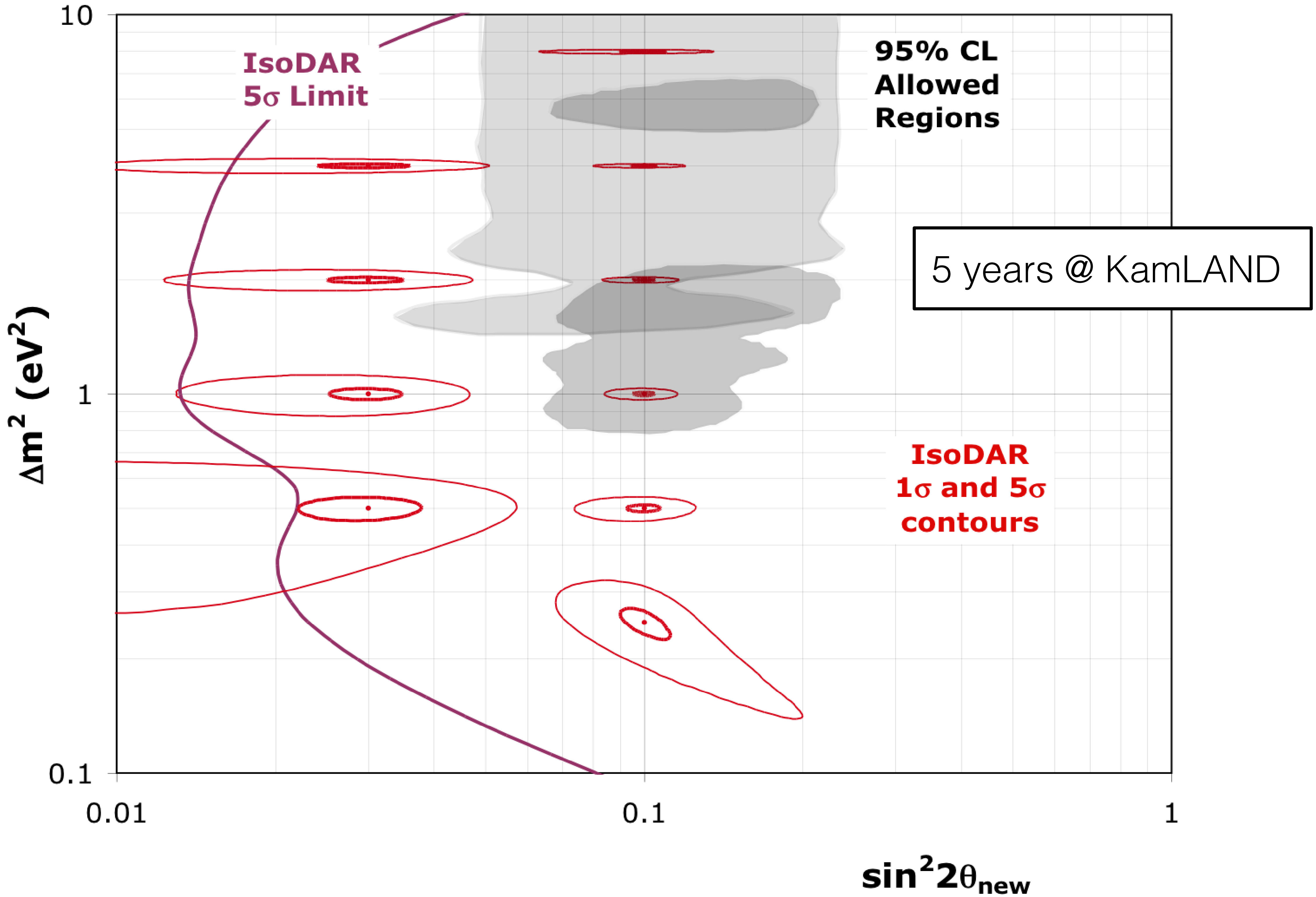
820,000 IBD events in 5 years at KamLAND
(16 m baseline to center of detector)

IsoDAR sensitivity



Thanks to B. Littlejohn and T. Lasserre

IsoDAR precision



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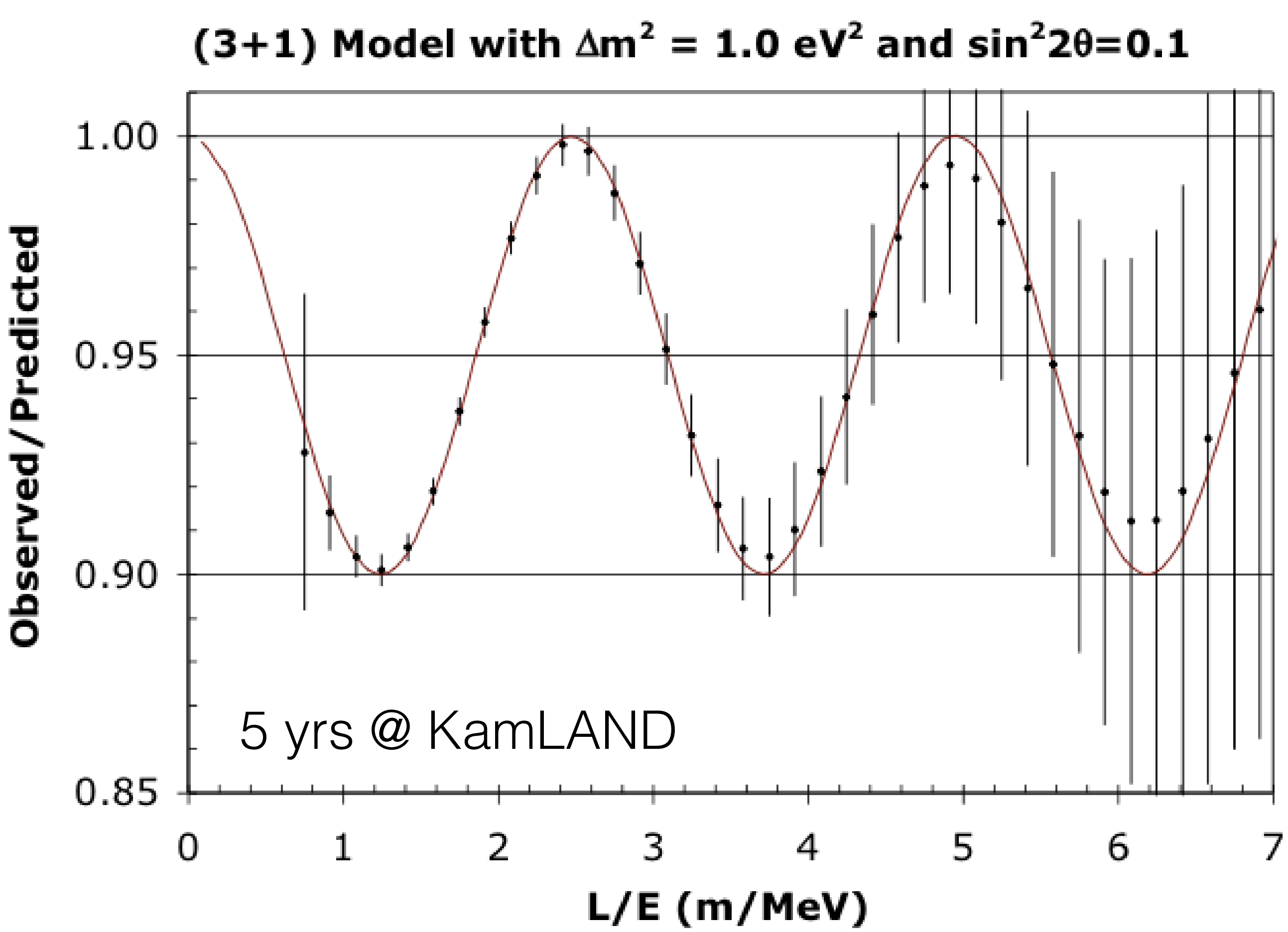
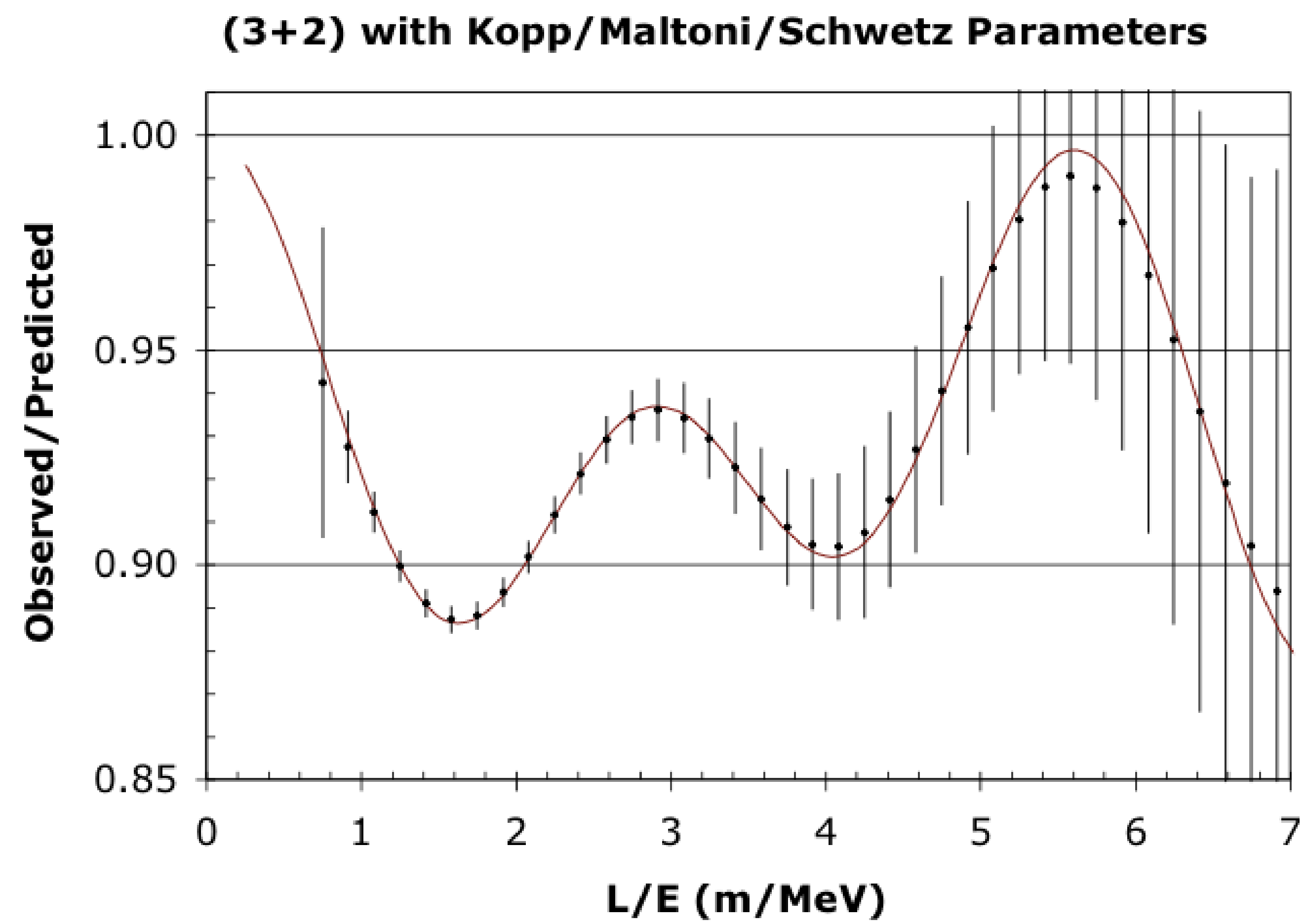
How many steriles?

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



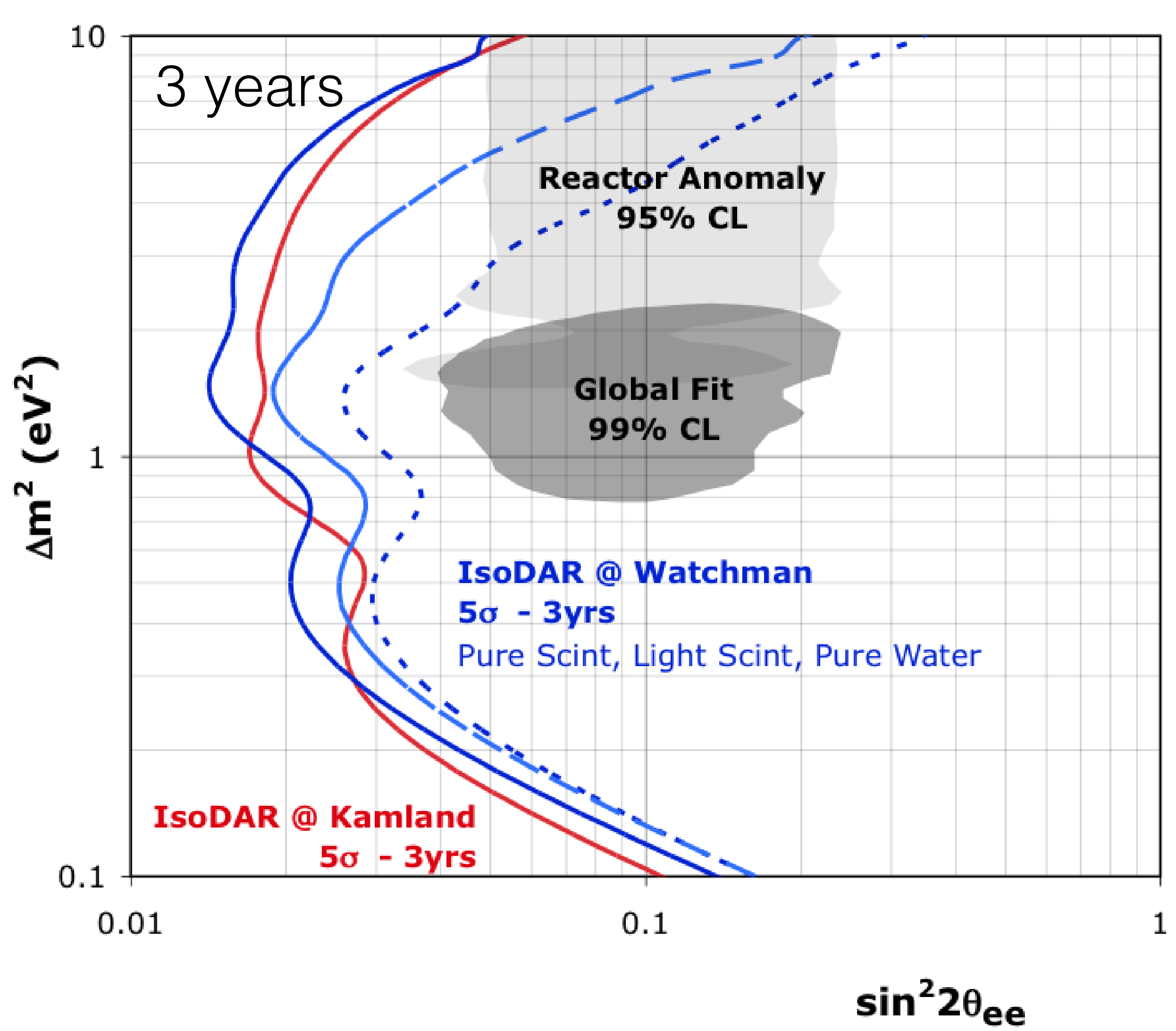


IsoDAR's high statistics and good L/E resolution provide the potential for distinguishing (3+1) and (3+2) oscillation models

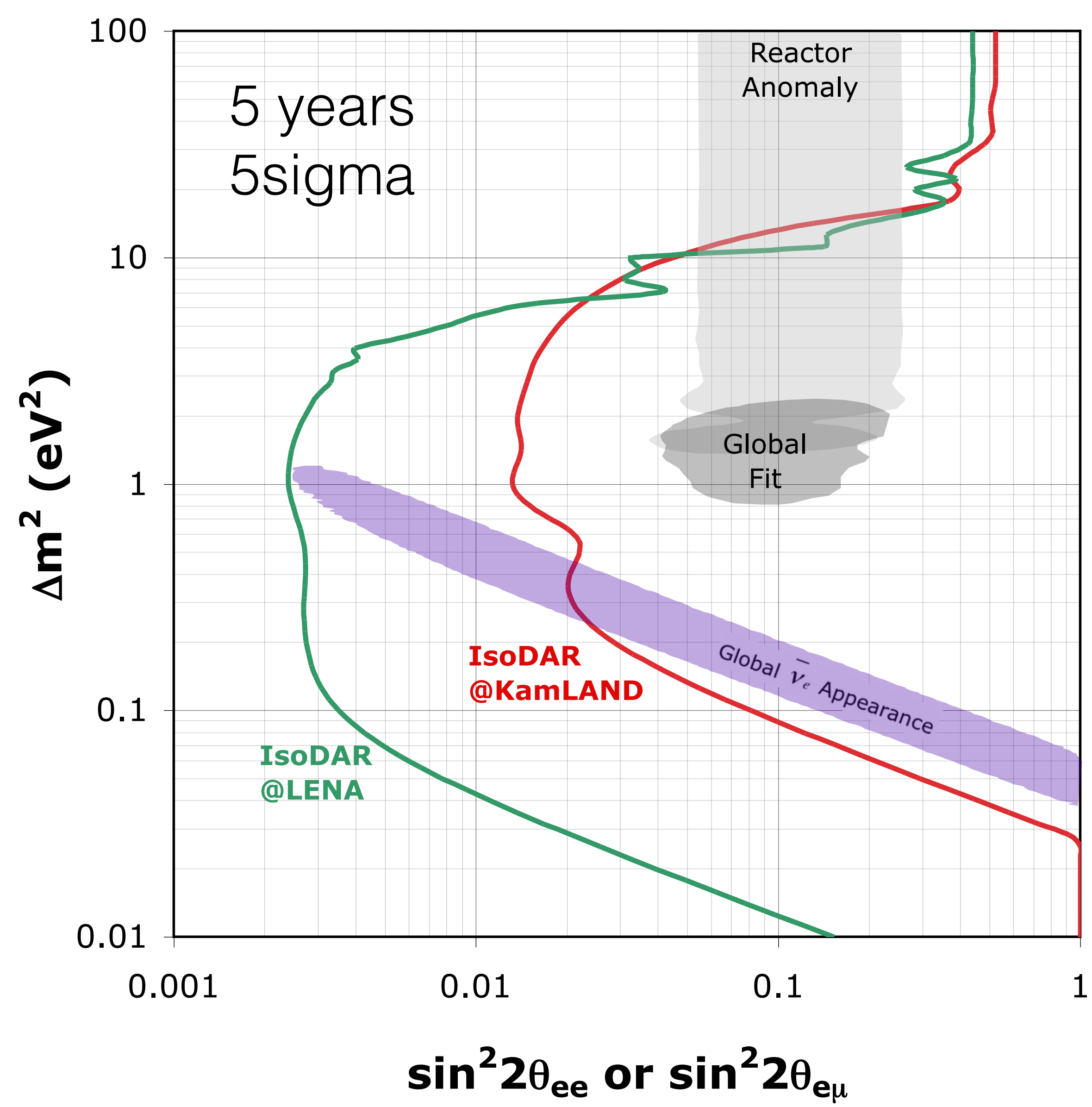
Recent IsoDAR updates

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

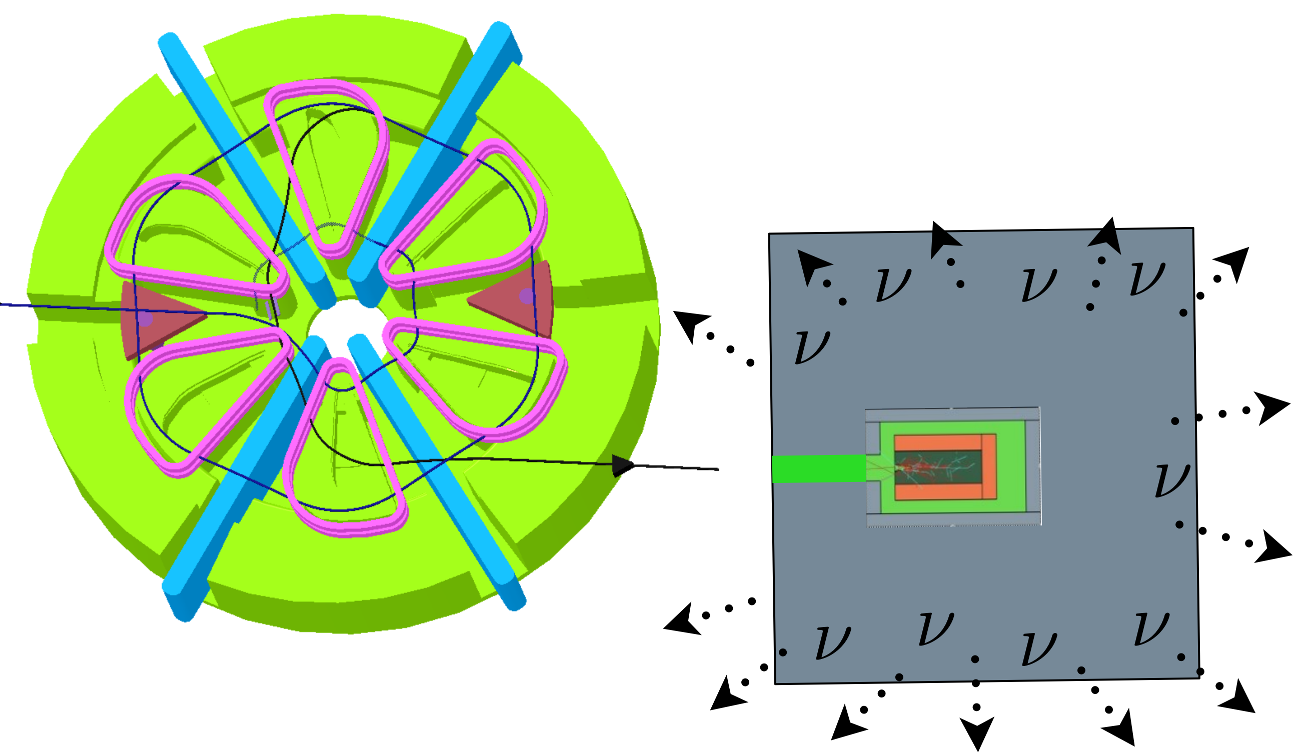
Disappearance sensitivity with **Watchman**
(1 kton Gd-doped water or scintillator)

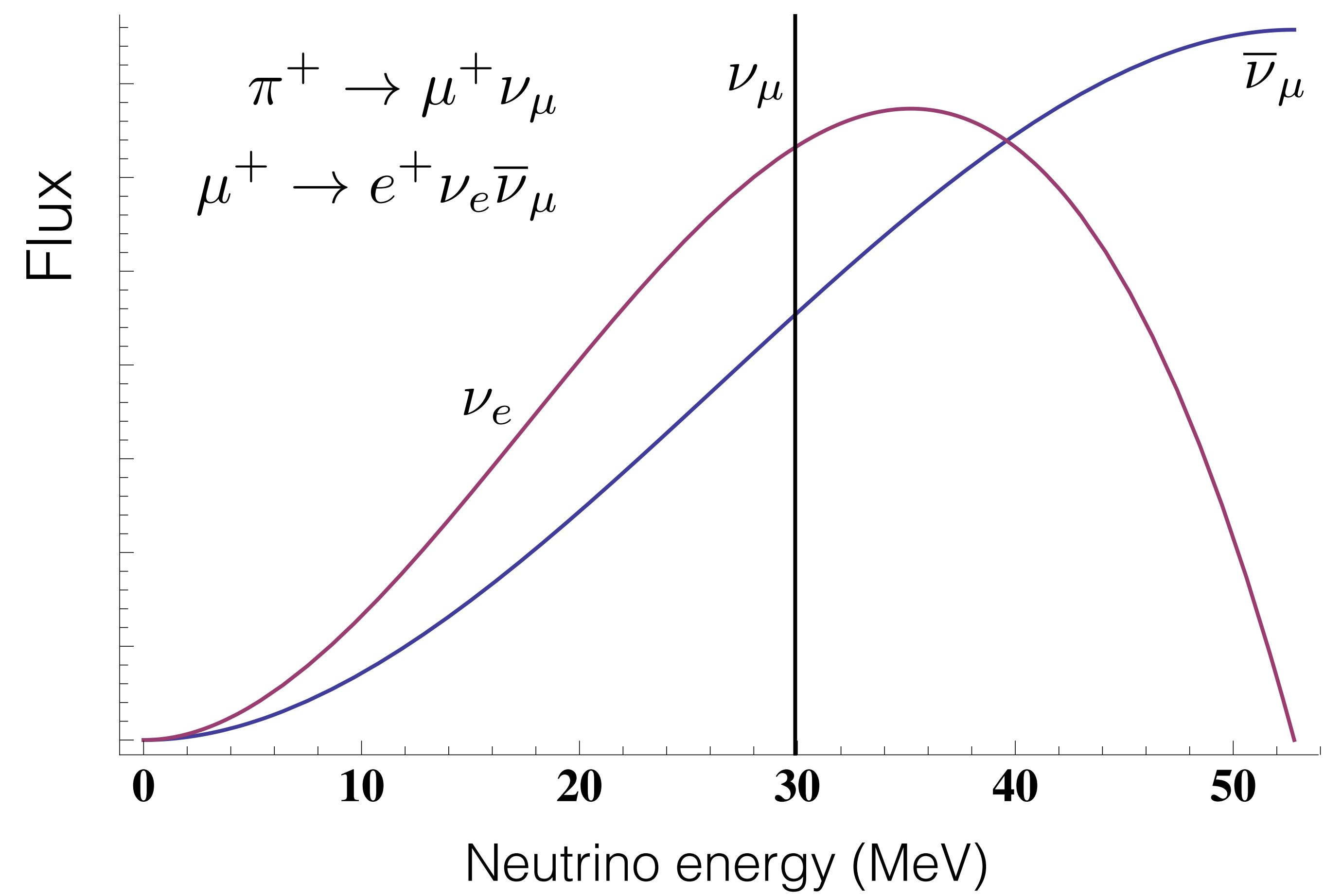


Dis/appearance sensitivity with **LENA**
(50 kton liquid scintillator)

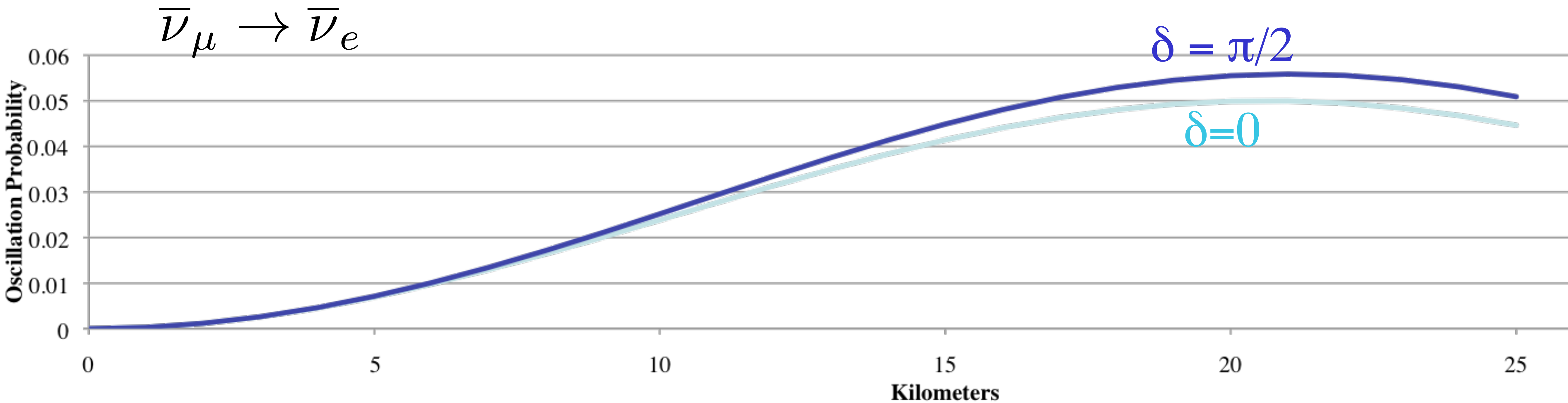


DAEδALUS and δ_{CP}





DAEδALUS and δ_{CP}



Near site → Constrains initial flux

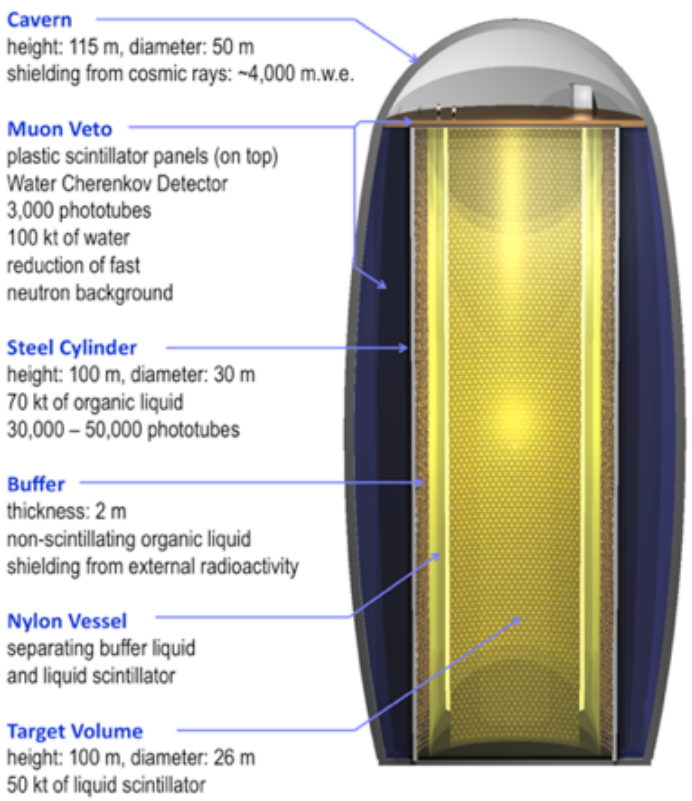
Mid site → Constrains rise probability

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

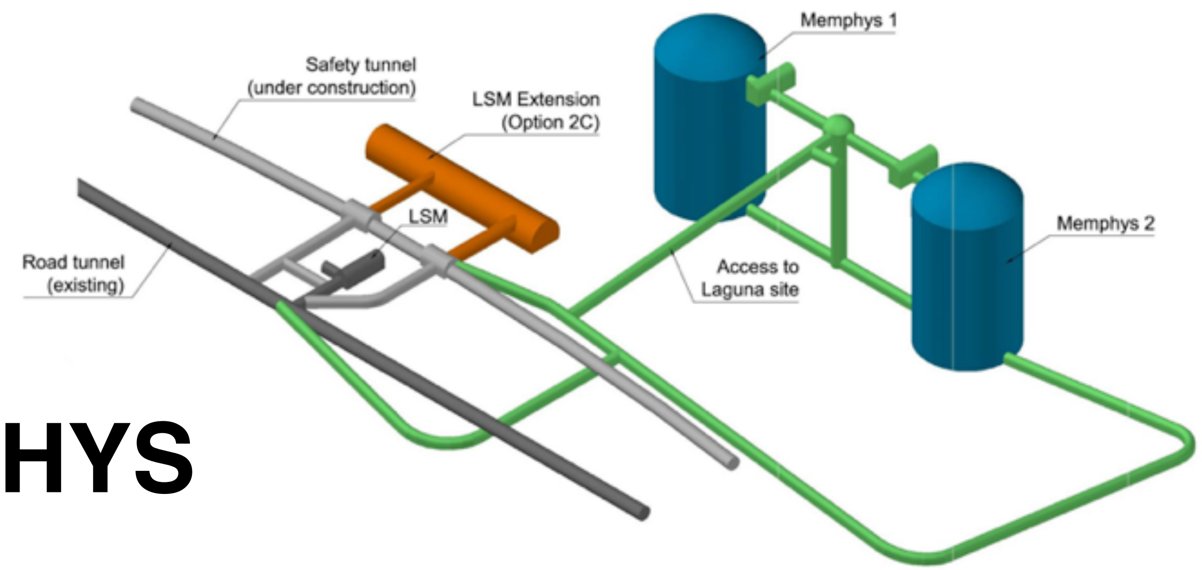
Near site gives absolute normalization to 1% via ν_e-e
Relative flux between sites can be constrained with ν_eO (ν_eC)

Where can DAEδALUS run?

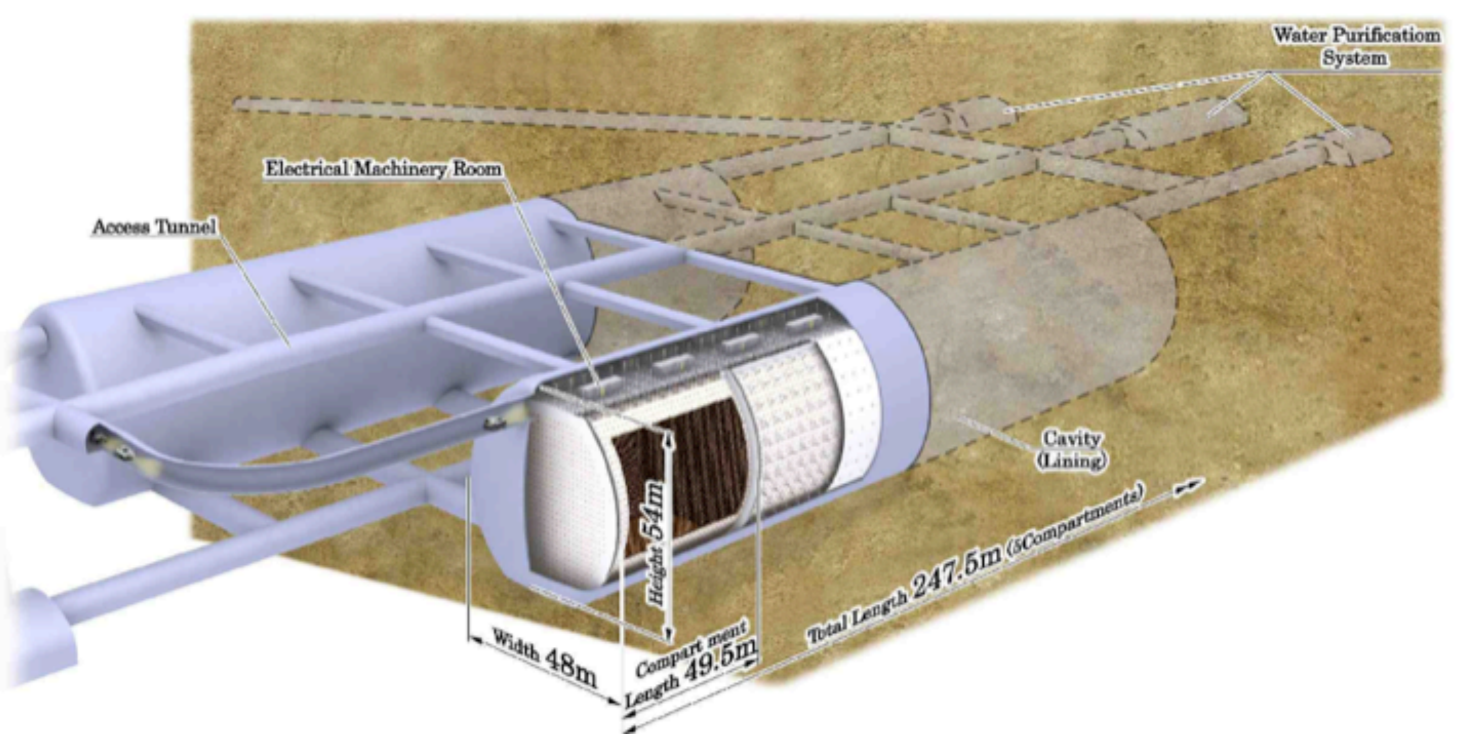
LENA



MEMPHYS

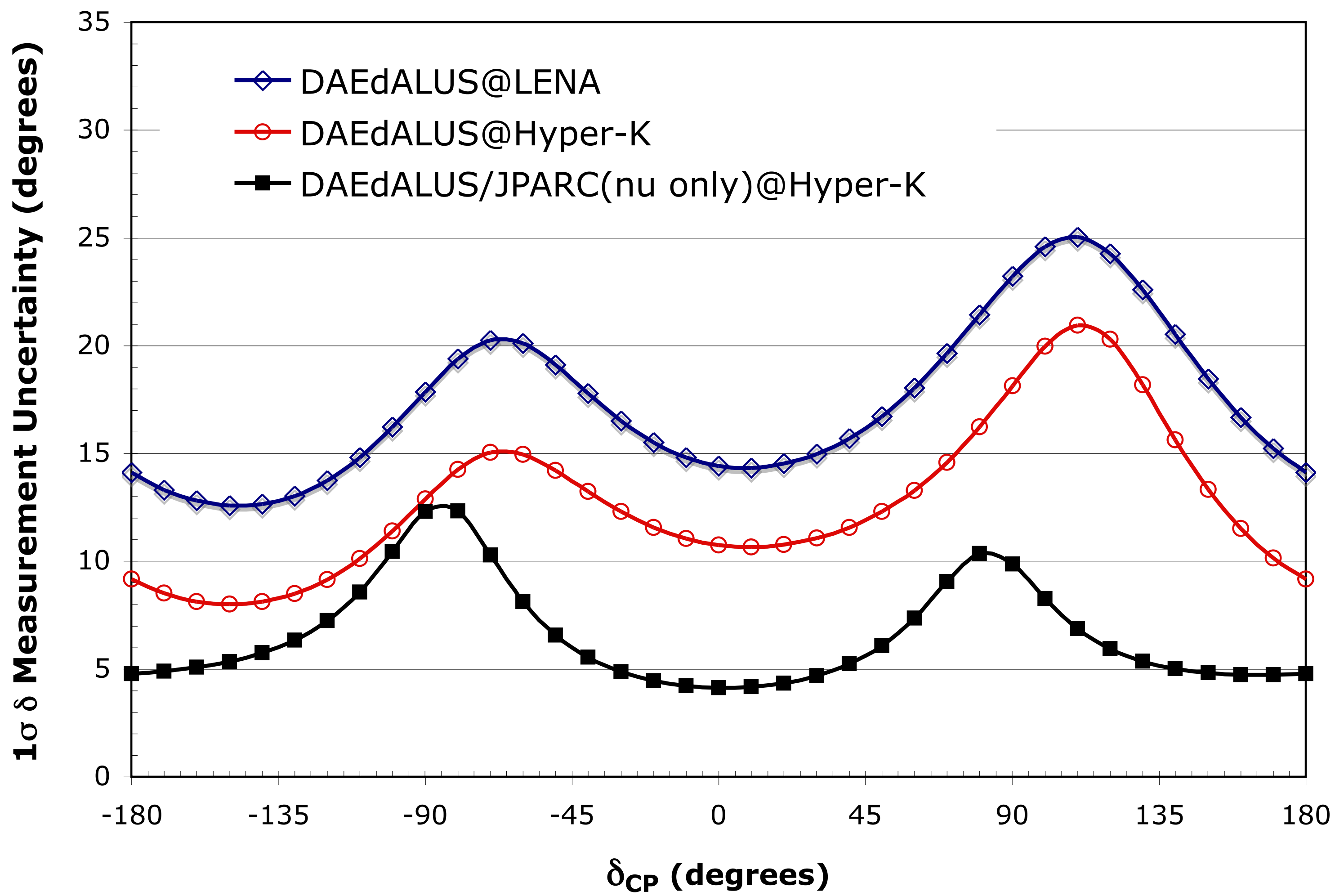


Hyper-K



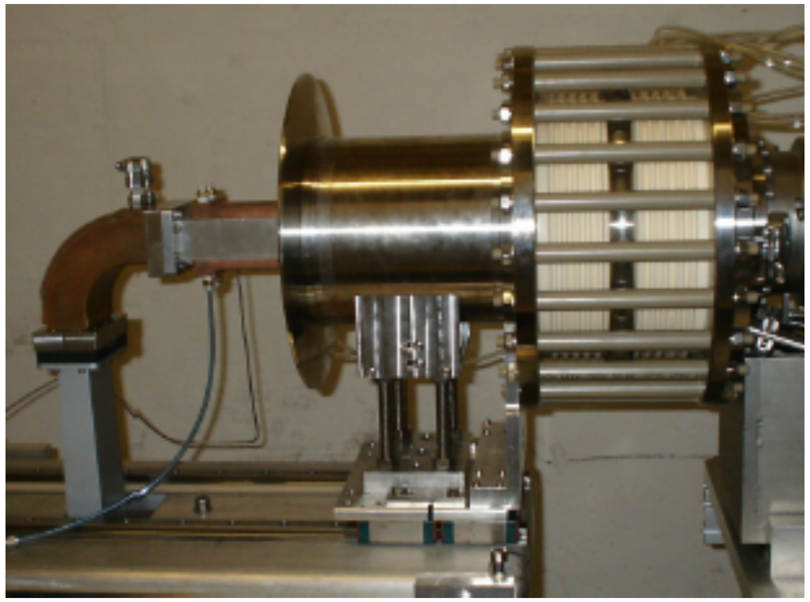
δ_{CP} sensitivity

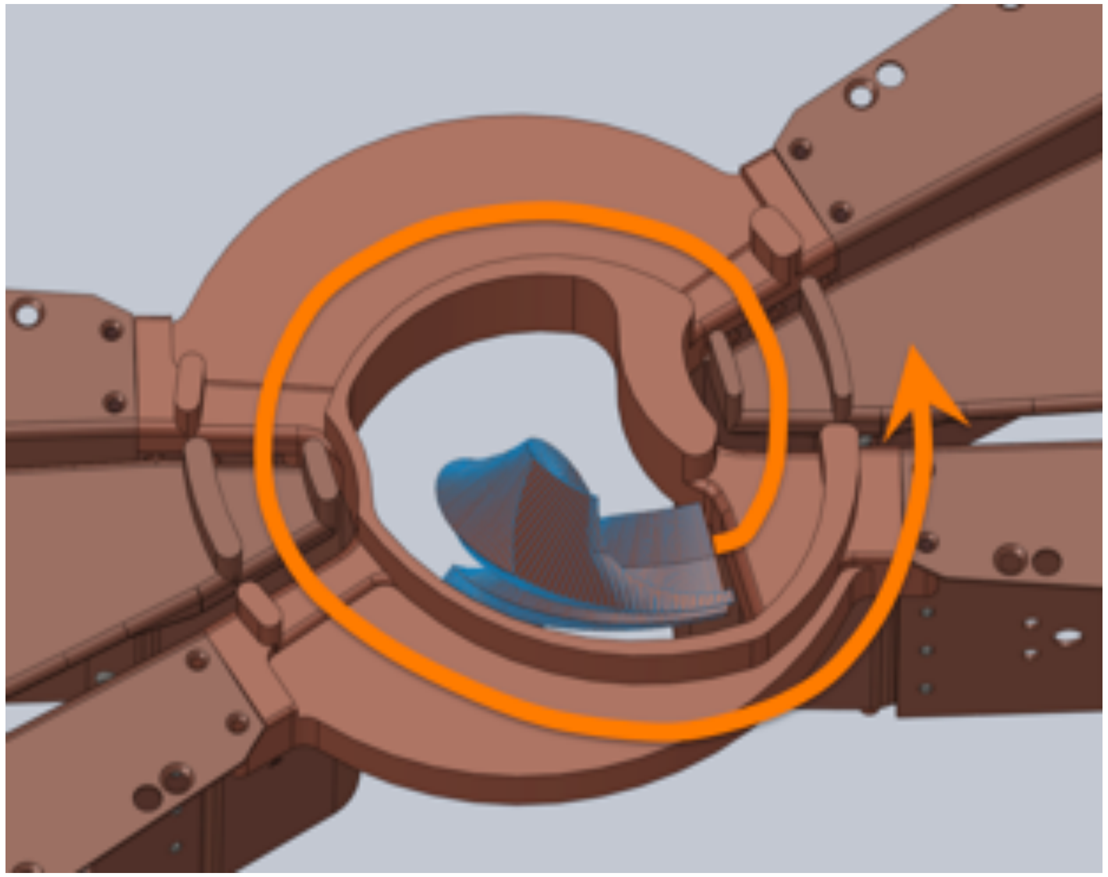
- DAEδALUS has strong δ_{CP} sensitivity by itself.
- Can be combined with long-baseline data (e.g. Hyper-K) for enhanced sensitivity.
    - Good statistics with anti-neutrinos, no matter effects, orthogonal systematics.
    - Big discoveries want (need?) multiple, independent experiments.



Challenges

- Ion source intensity


The ion source

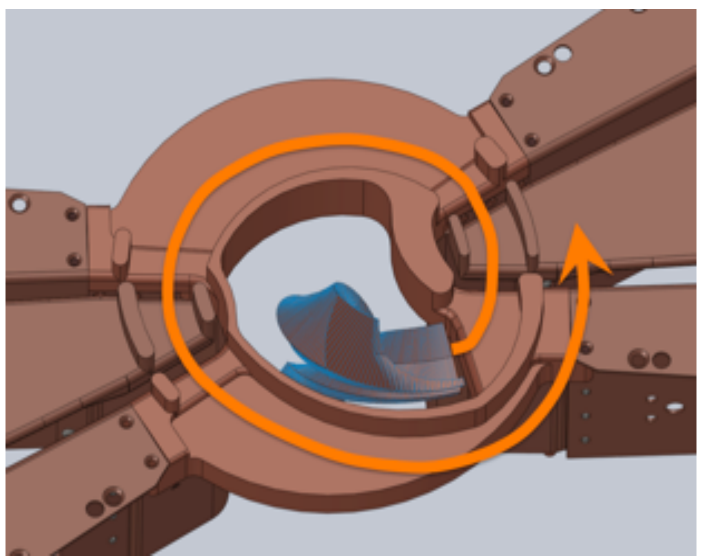

The first turn after axial inflection

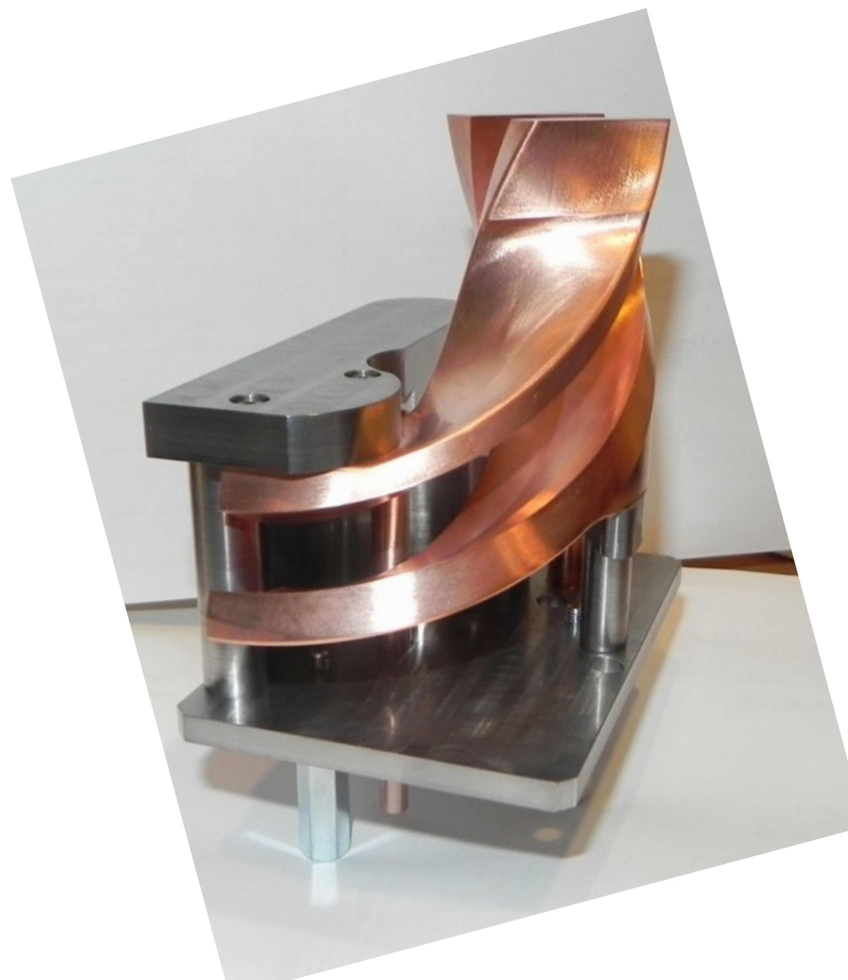
Most ions are lost in the first “turn” because they hit material.

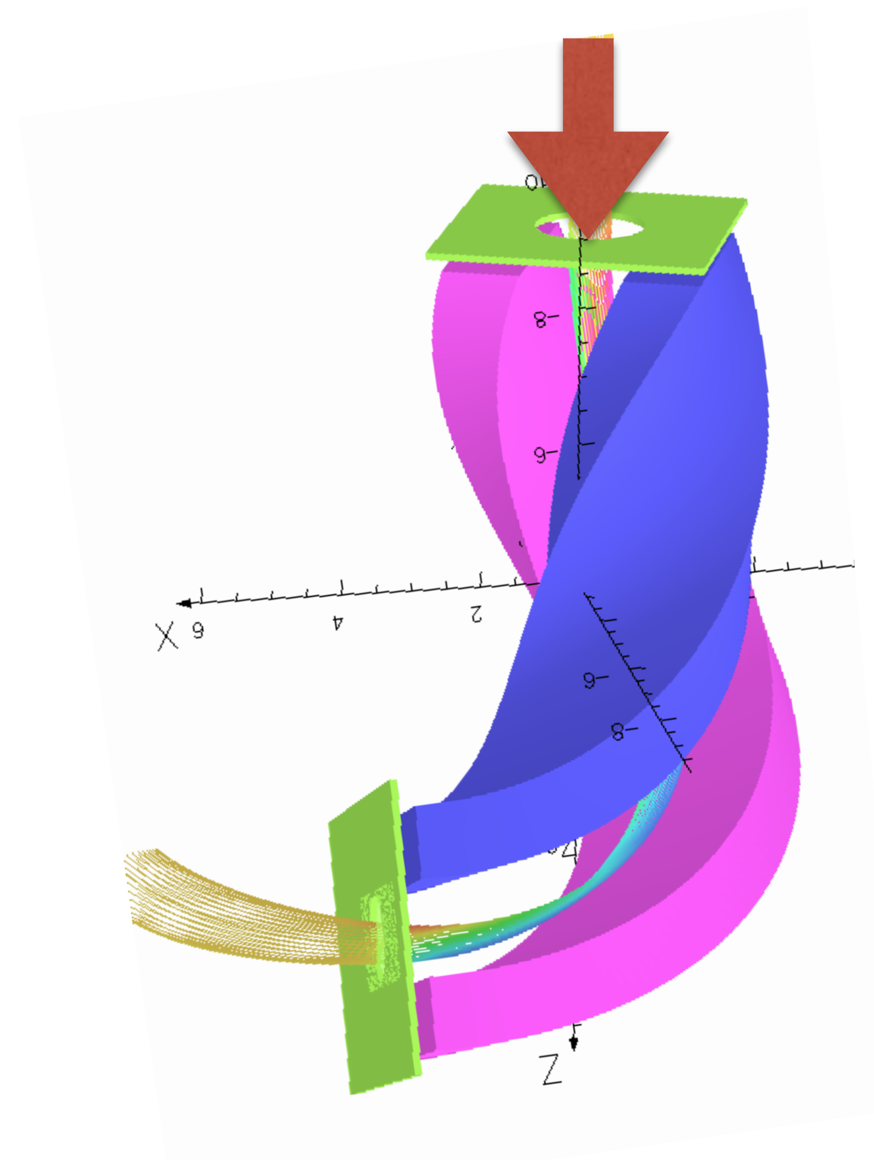
To capture 5 mA we will need between 35 and 50 mA injected.

Challenges

- Inflection



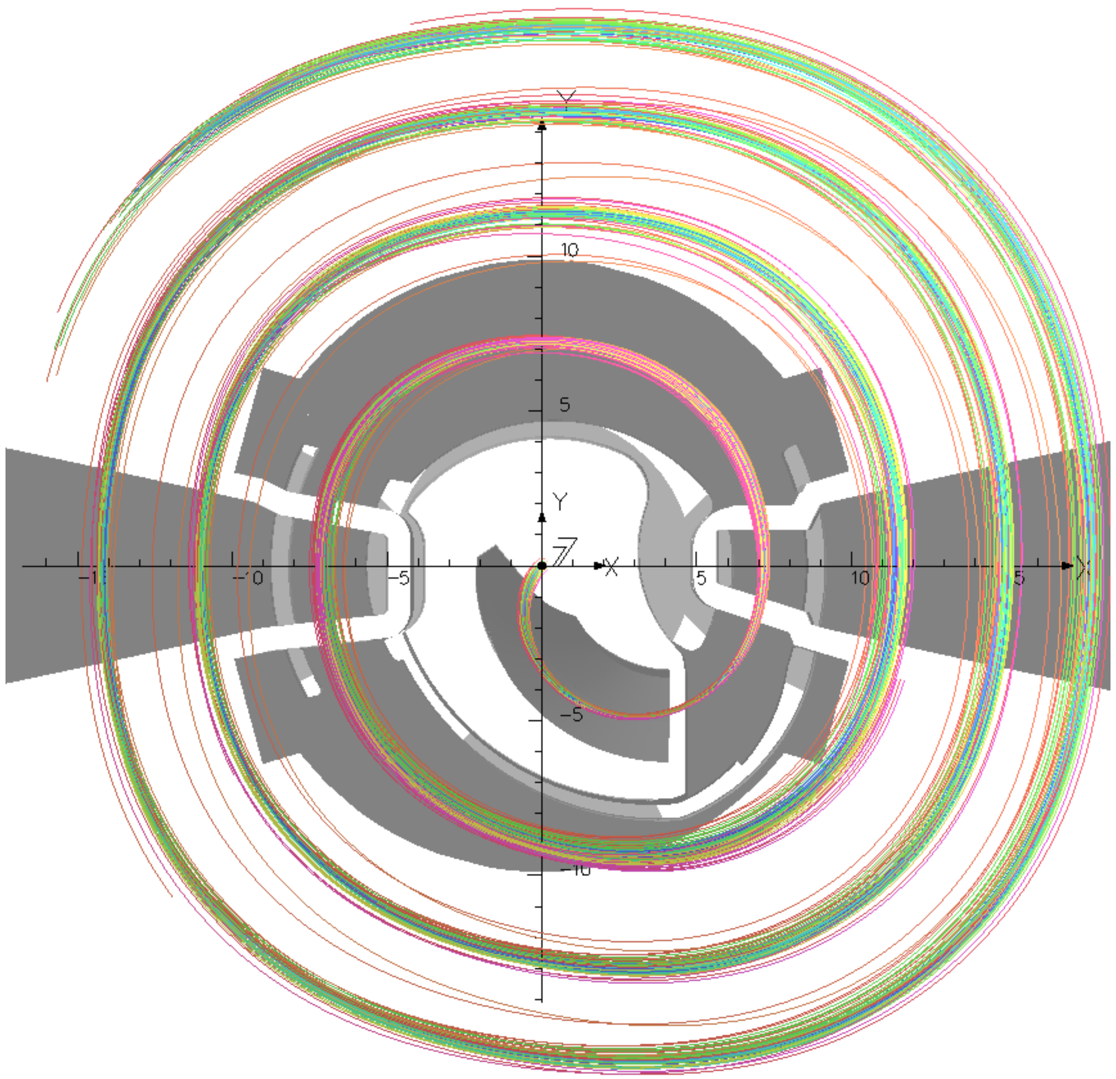




Getting the beam into the cyclotron requires taking it from the vertical to the horizontal plane. This is hard.

->an iterative R&D process.

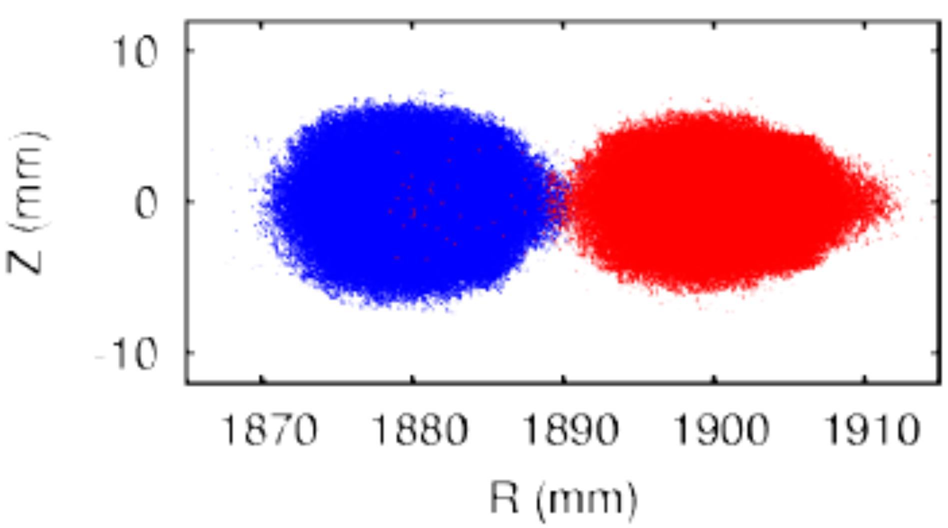
Challenges



Beam dynamics sim

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

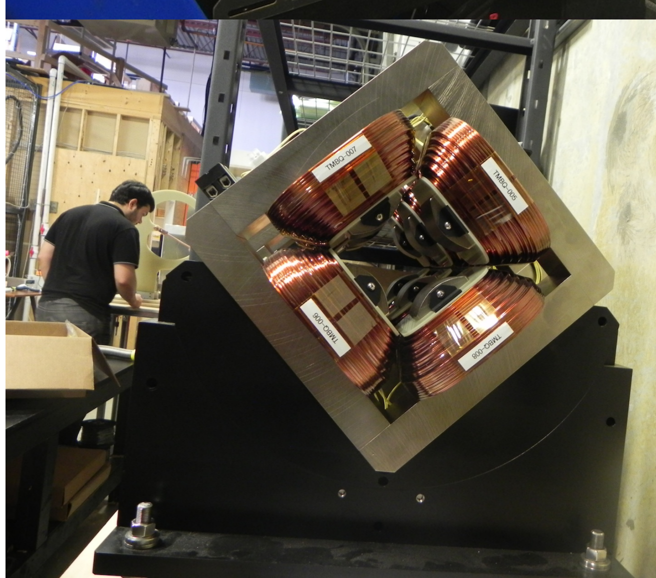


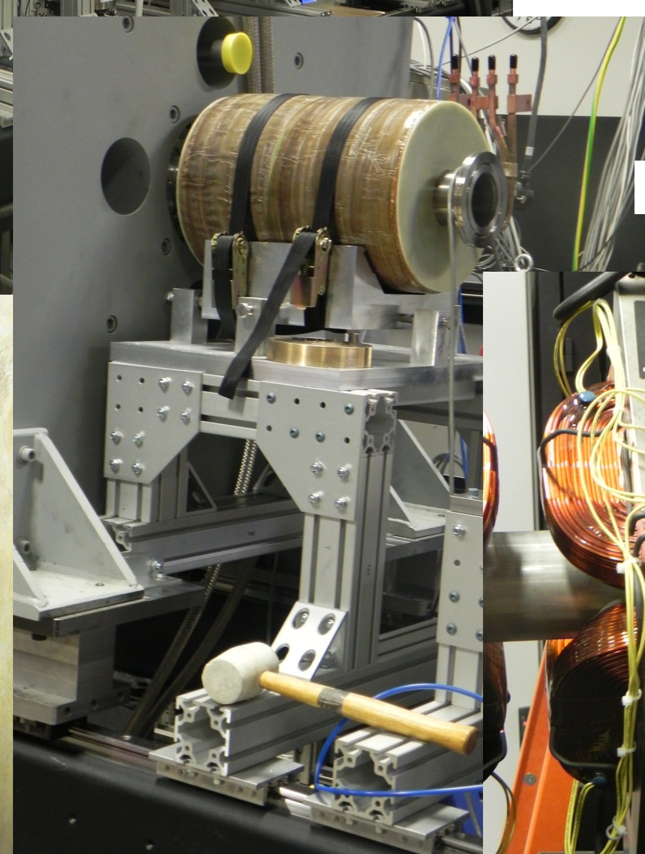
The final turns in the injector

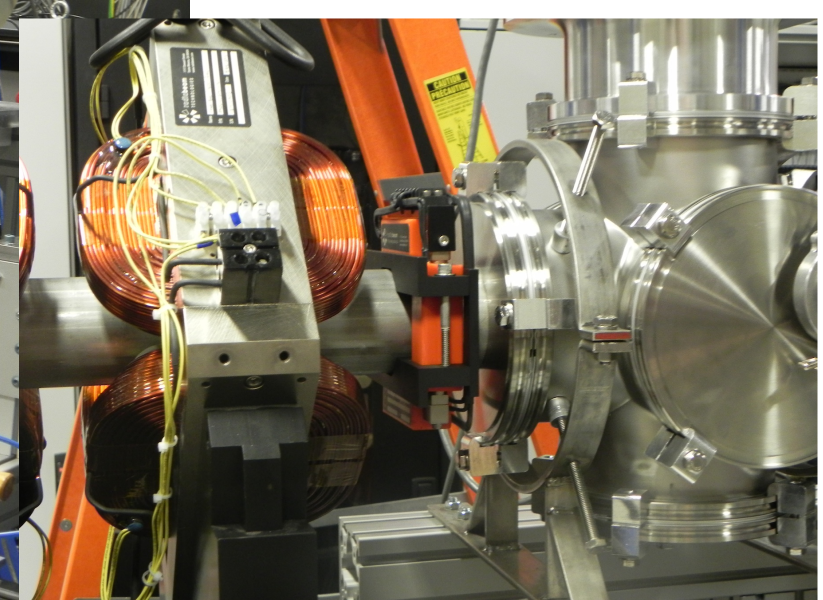
Beam is now being characterized at Best Cyclotrons, Inc, Vancouver (Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)

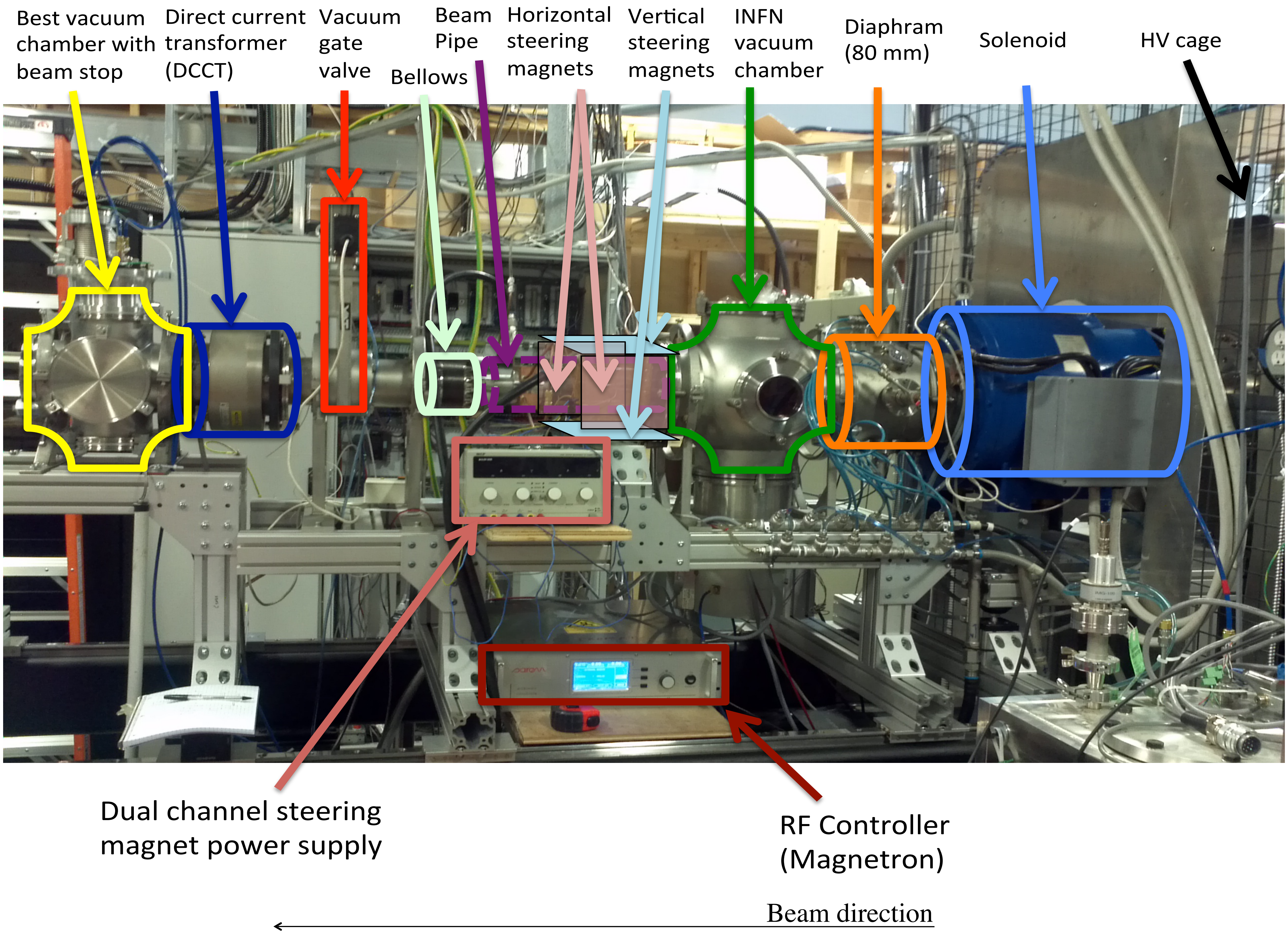
GOALS

- How much beam can be captured?
- What are the properties of the captured beam?
- Develop experience for designing the central region of the IsoDAR injector cyclotron.



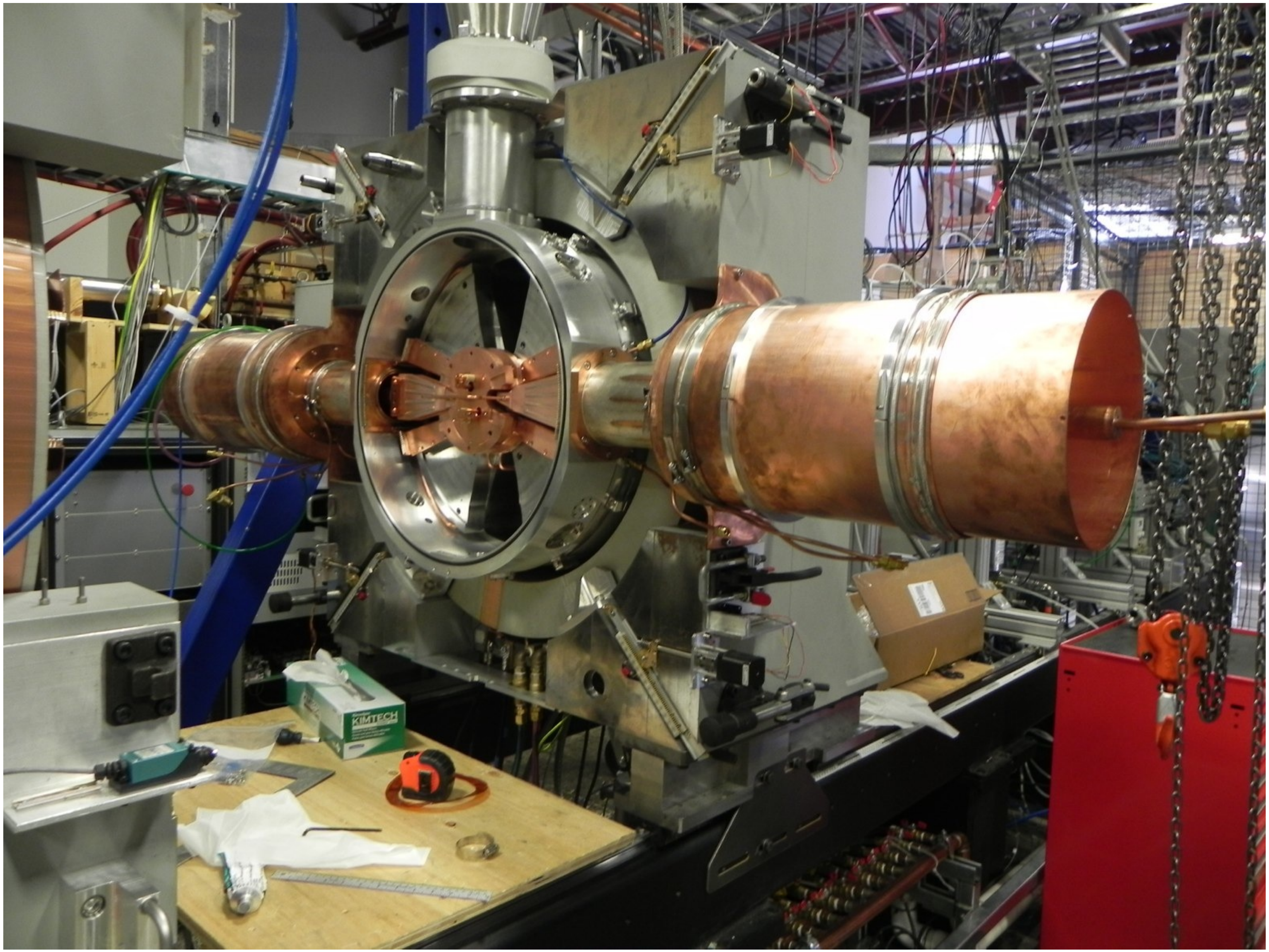




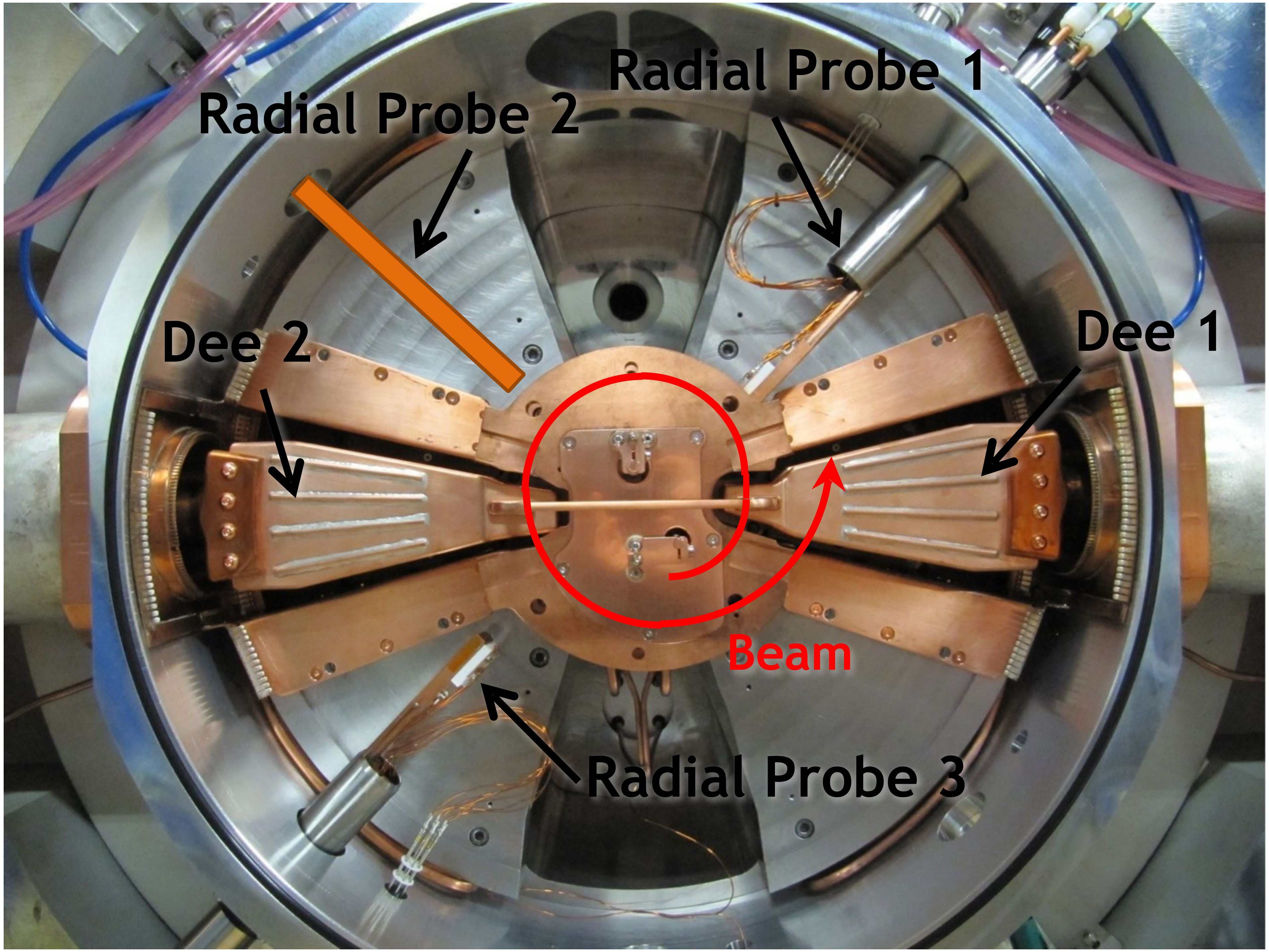


Best vacuum chamber with beam stop
Direct current transformer (DCCT)
Vacuum gate valve
Bellows
Beam Pipe
Horizontal steering magnets
Vertical steering magnets
INFN vacuum chamber
Diaphram (80 mm)
Solenoid
HV cage
Dual channel steering magnet power supply
RF Controller (Magnetron)
Beam direction

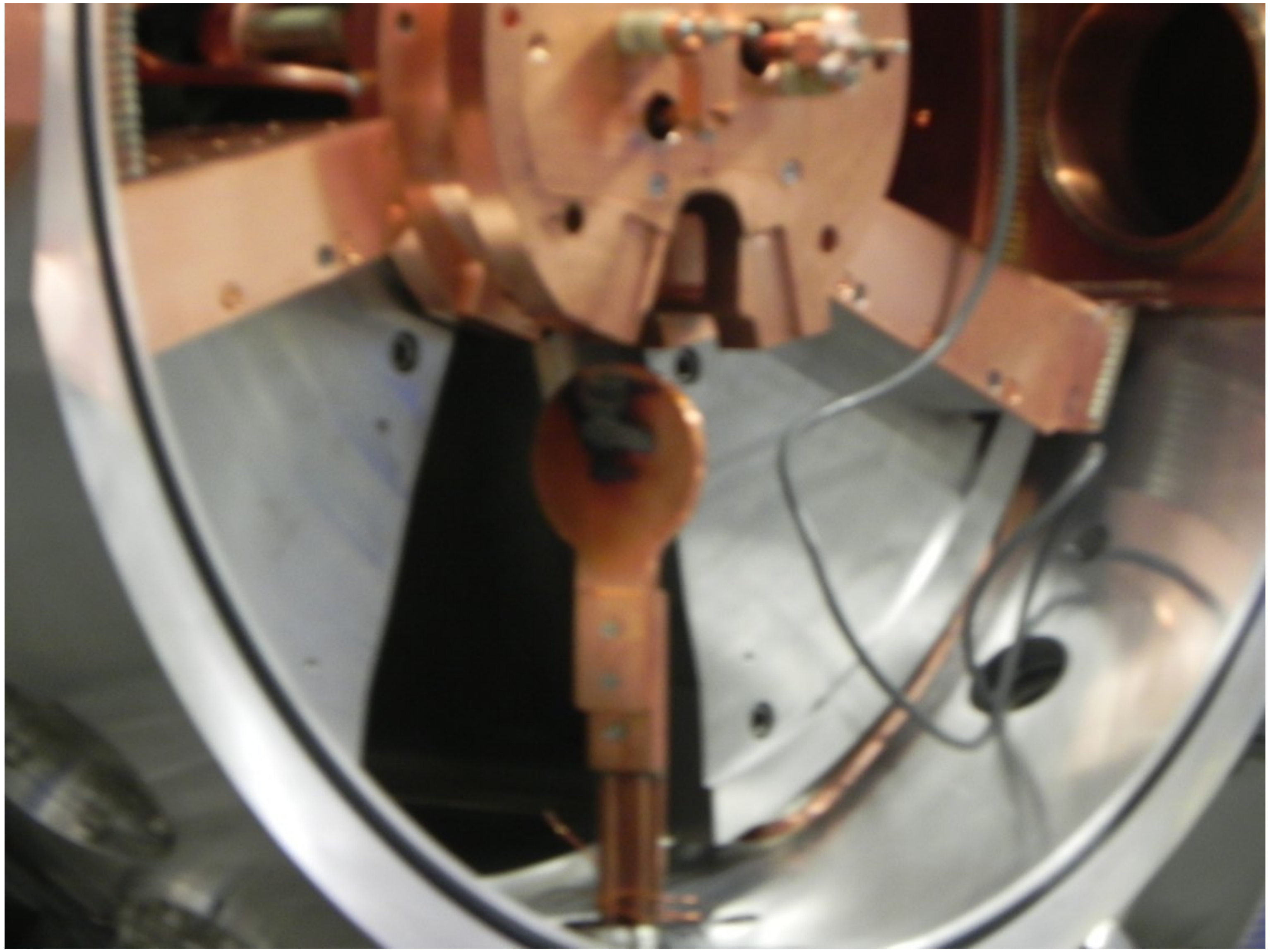
A cyclotron sits at the end of the line

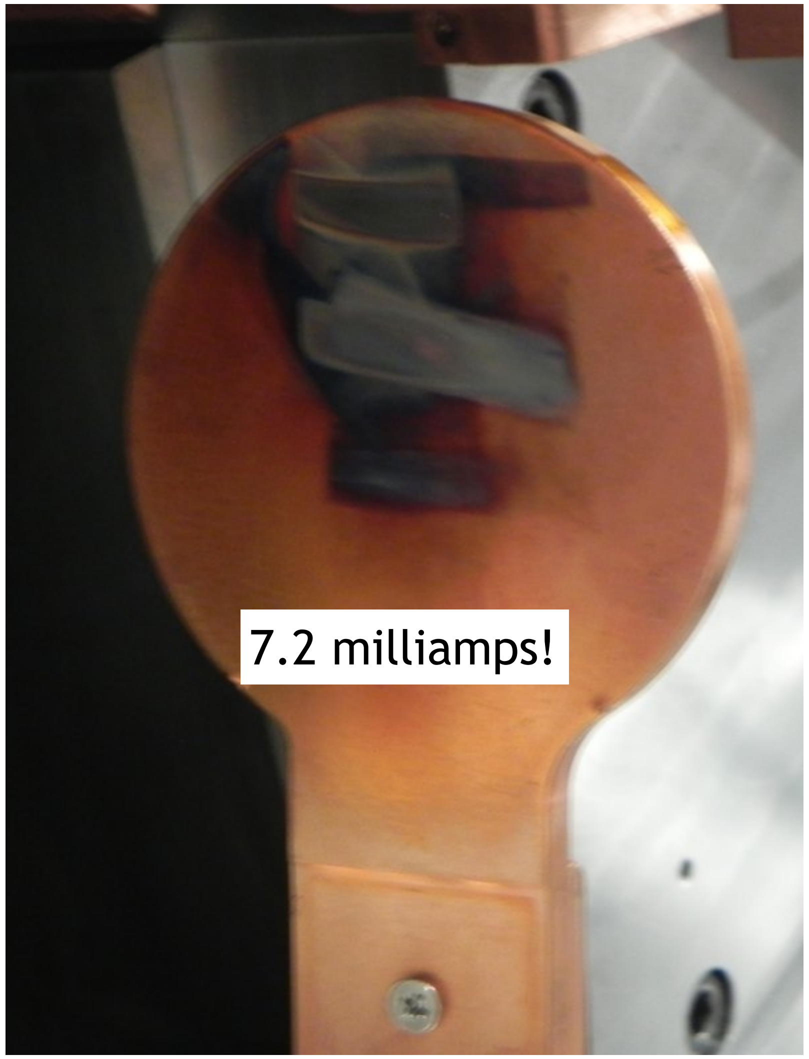


Work is ongoing…
but there have been a number of milestones reached in the past two weeks.



Beam has been brought from the ion source, through the low energy beam transport, through the axial inflector, and into the cyclotron where it is accelerated and makes two turns!



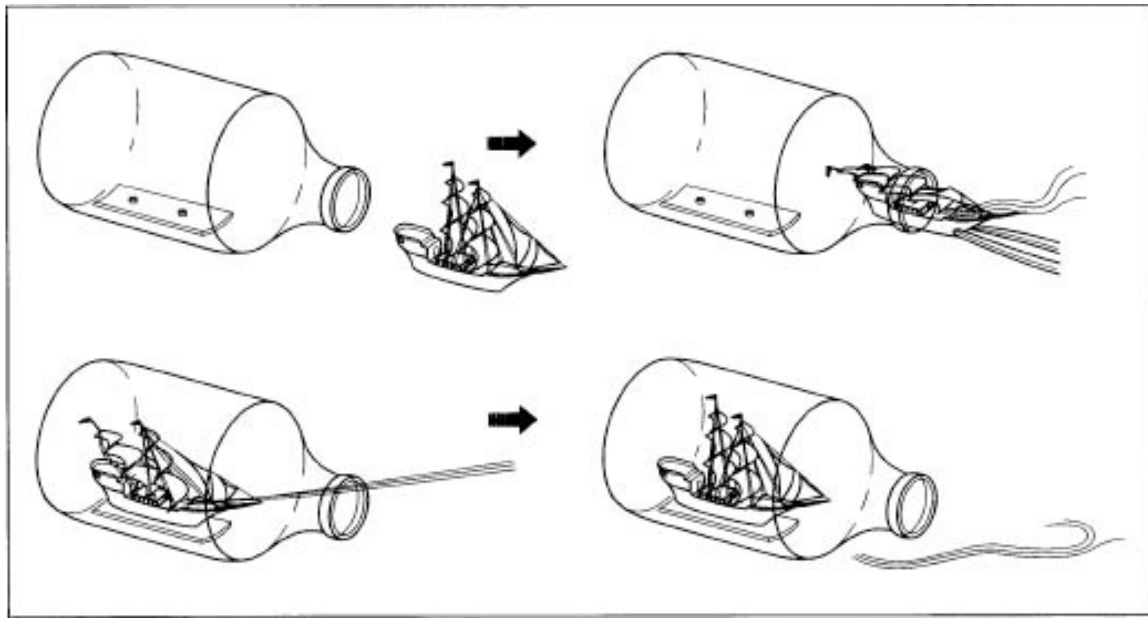


7.2 milliamps has been brought from the beam transport line (axial plane) and into the cyclotron (transverse plane)!

IsoDAR challenges

- The target, shielding, and implementation

- Obtaining 99.995% 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 for antineutrino events.



- Underground location

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.

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 — PRD

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

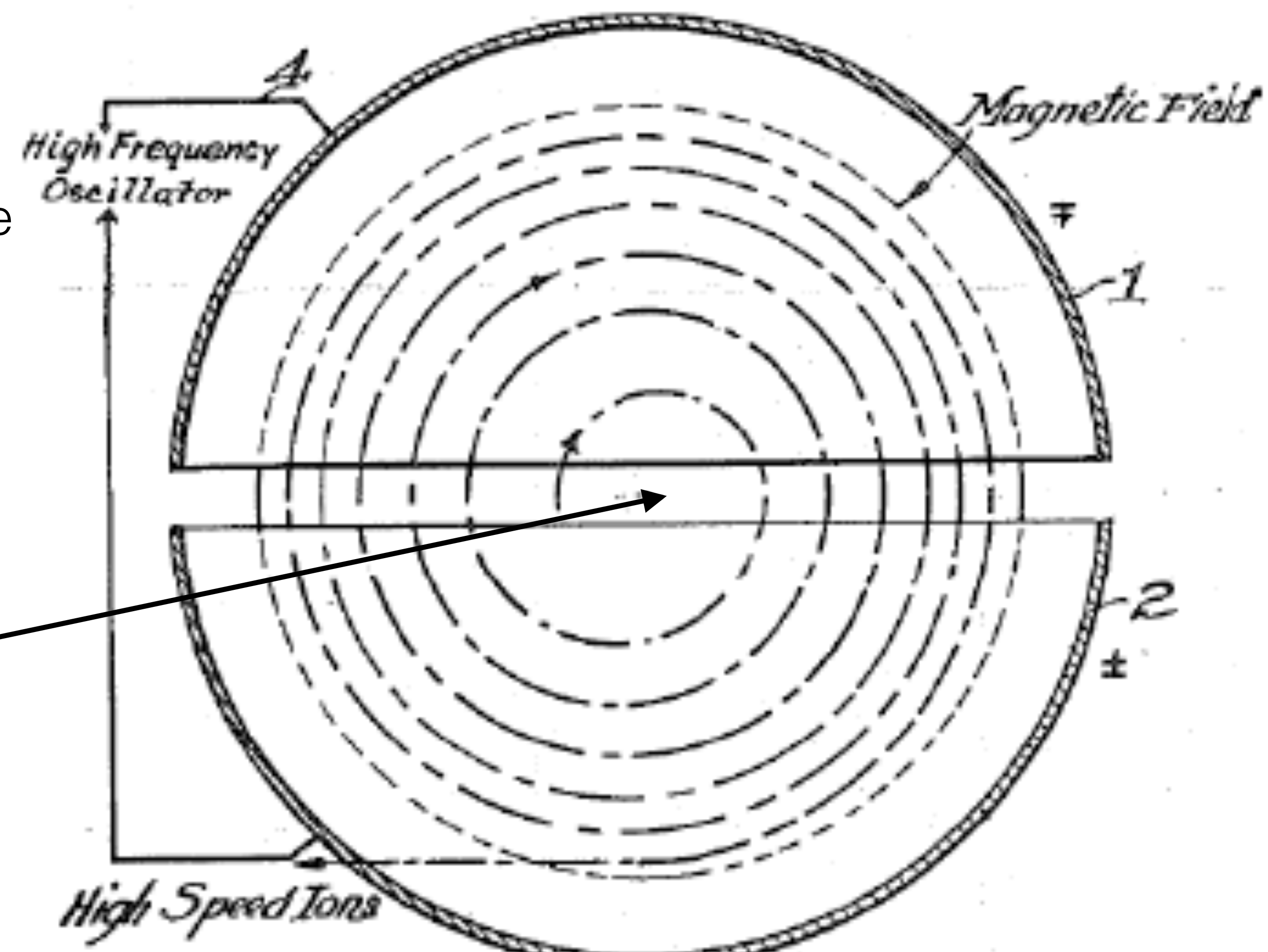
IsoDAR challenges

- 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^-

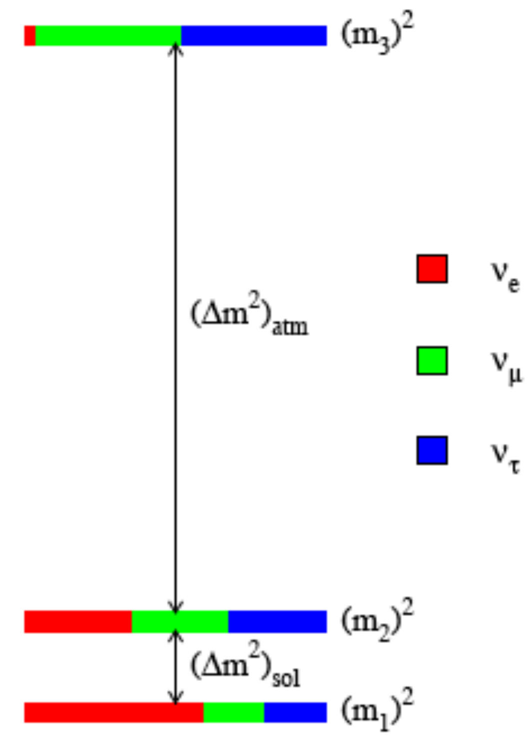
We inject H_2^+



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…

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

We want to see if δ is nonzero

terms depending on mixing angles

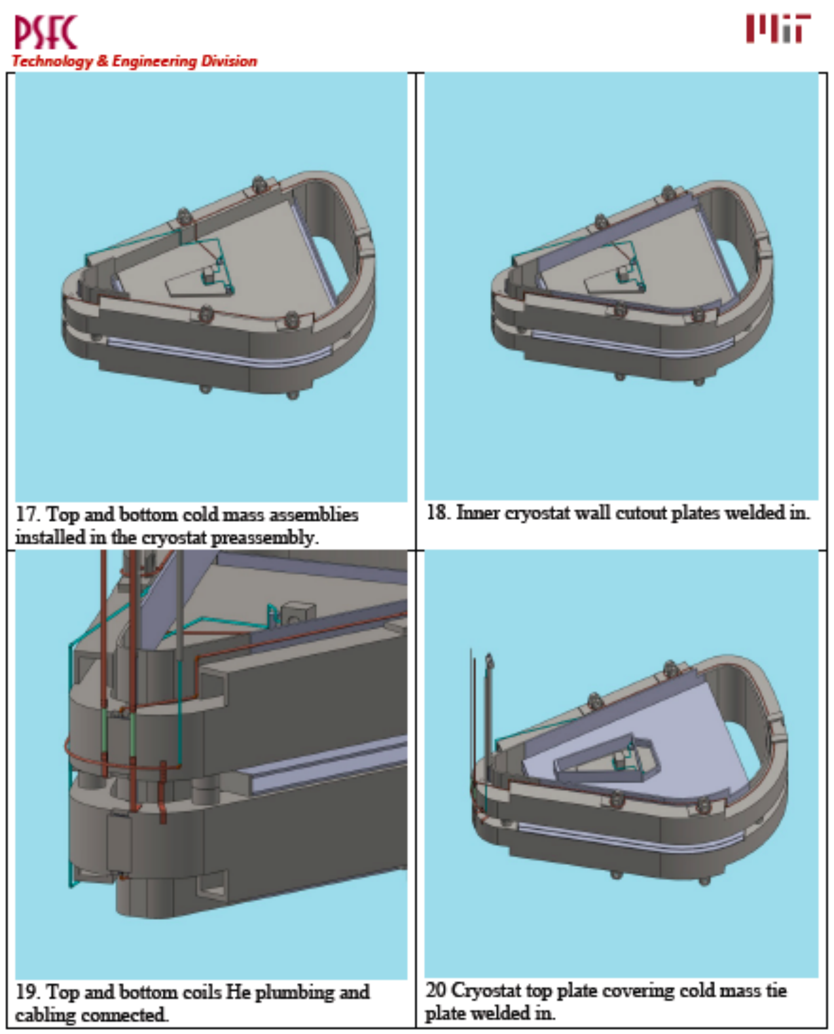
terms depending on mass splittings

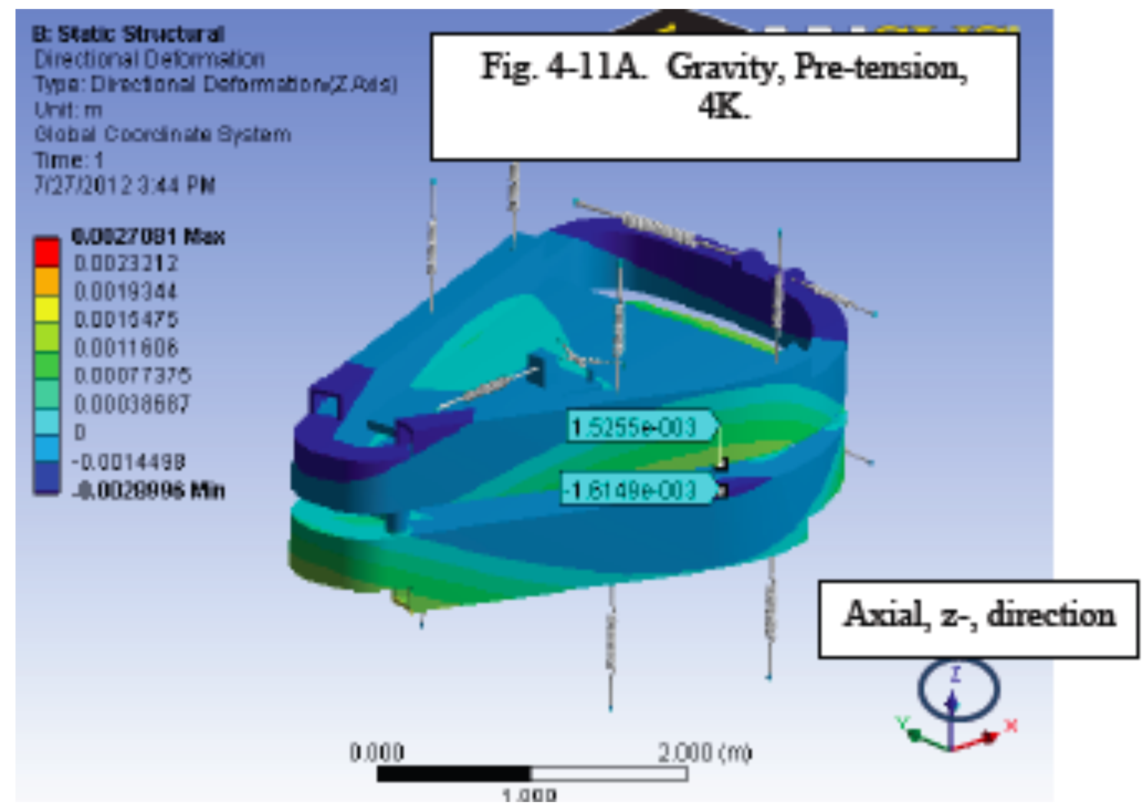
$$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$$

DAEδALUS progress

Engineering study of SRC, arXiv:1209.4886

Engineering design
Assembly plan
Structural analysis
Cryo system design





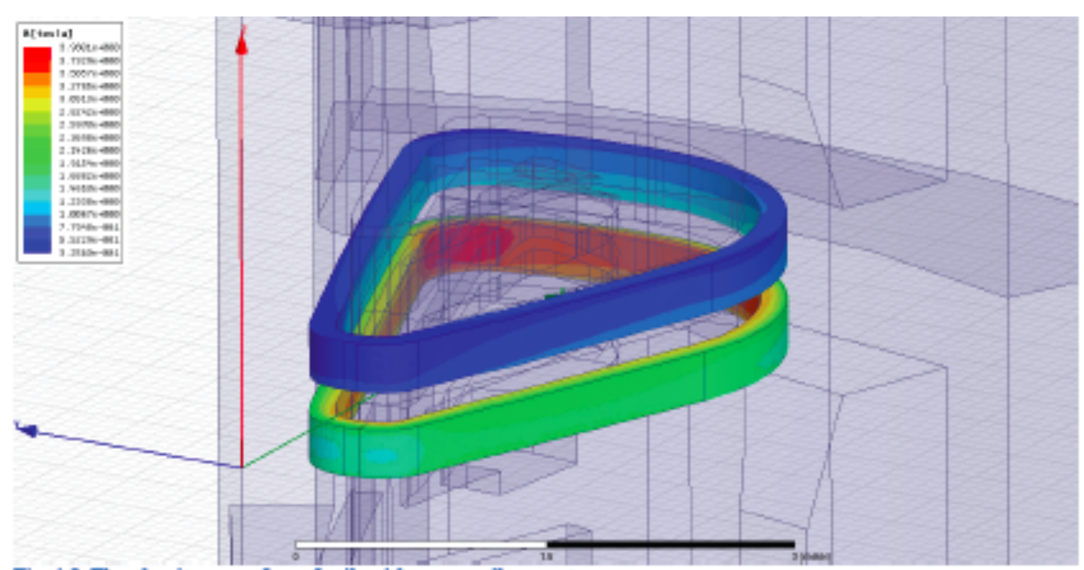
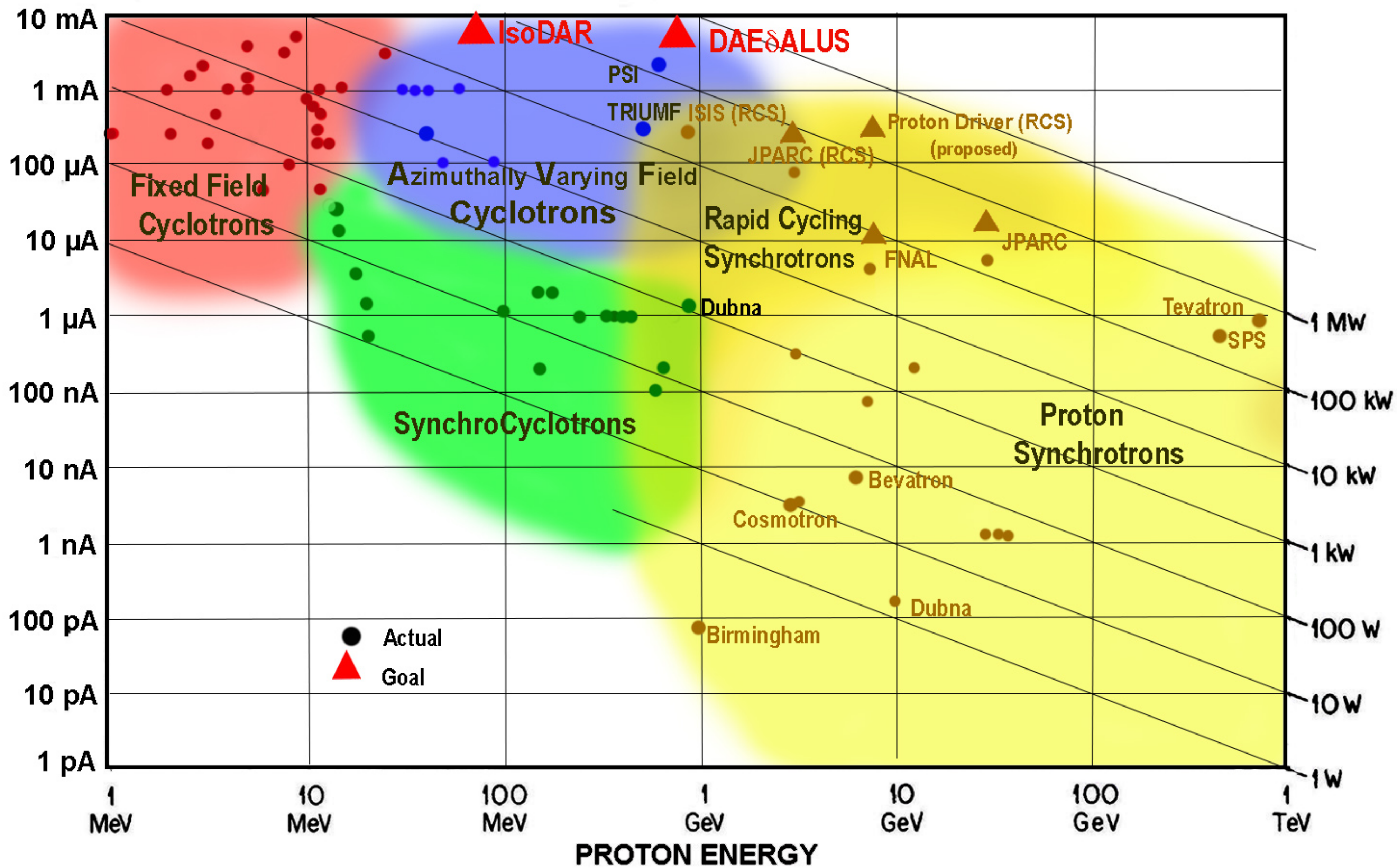


Fig. 4-9. Flux density on surface of coils with upper coil current zero.

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

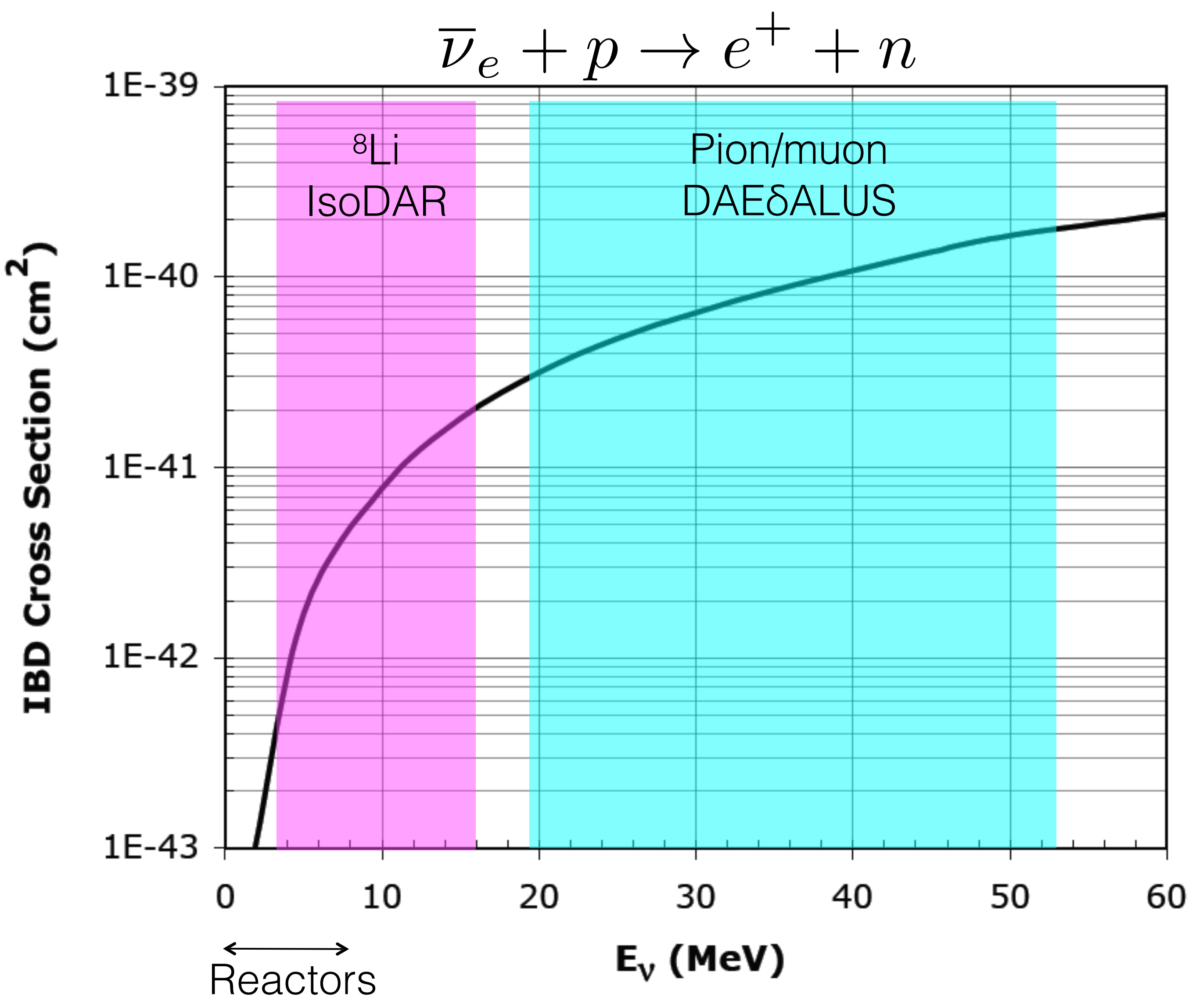


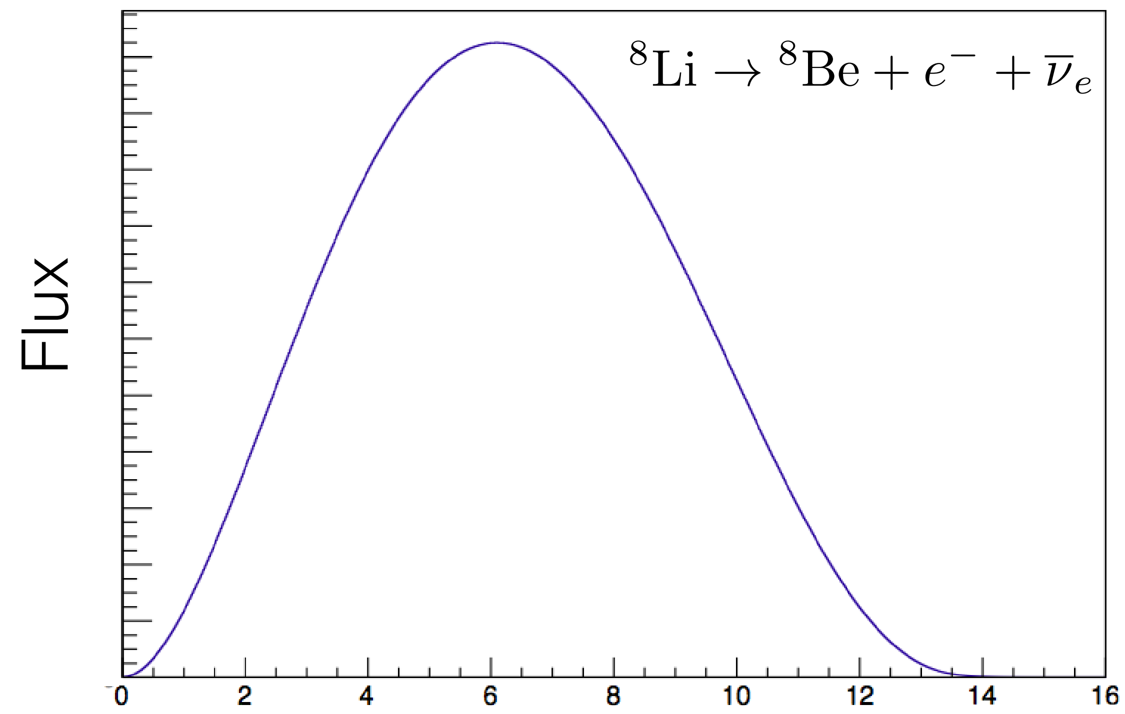
TRIUMF accelerates H- but with a much lower peak field because of Lorentz stripping.

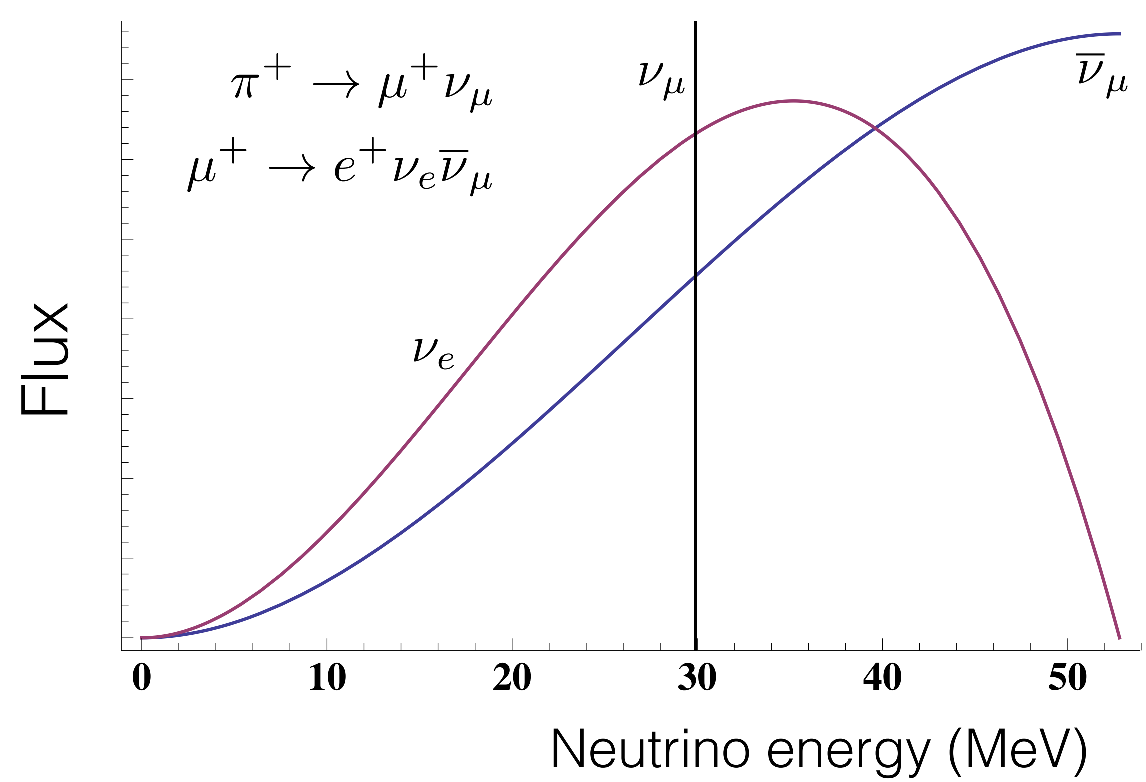
PSI is an 8-sector normal conducting machine.

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

Flux and cross section



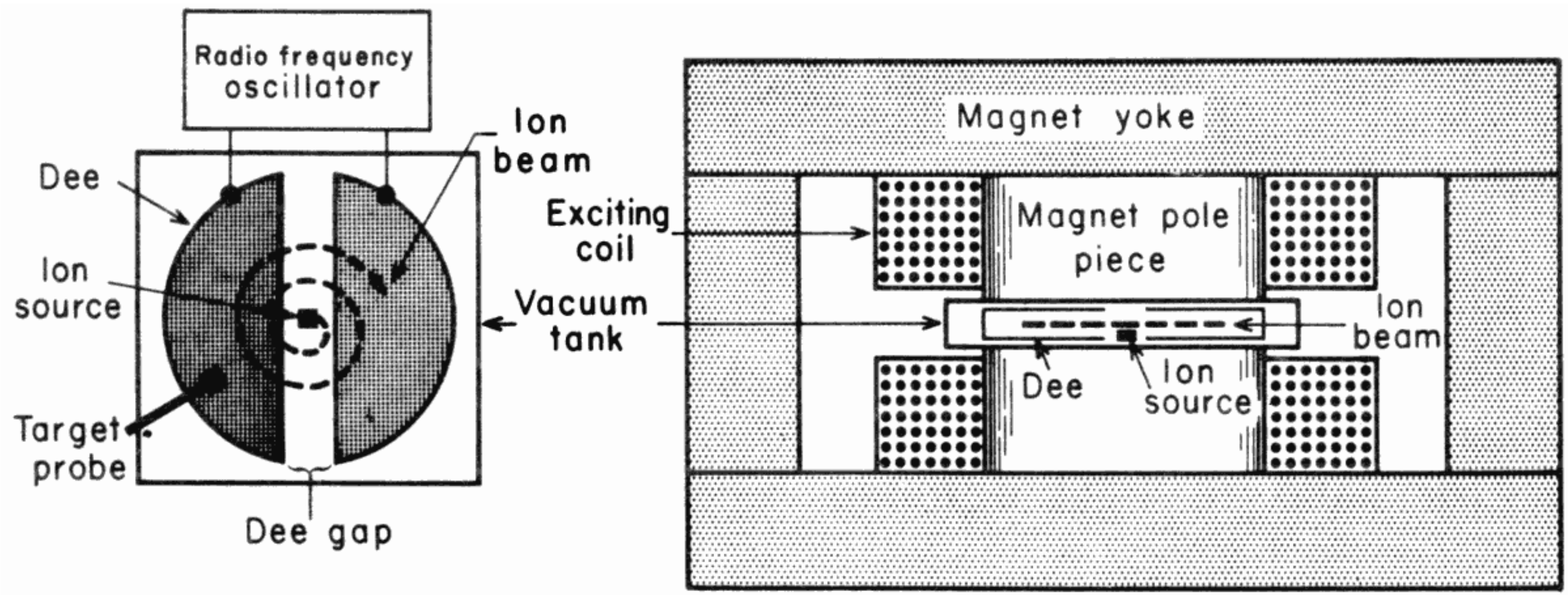




- Scintillator or Gd-doped water detector
- Prompt positron signal followed by neutron capture

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

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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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.