Physics Goals of the IsoDAR Neutrino Experiment

Edward Dunton
Columbia University

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On behalf of the IsoDAR collaboration

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NEVIS LABORATORIES

The IsoDAR Experiment

- Isotope Decay-At-Rest Experiment.
- IsoDAR will utilize an ~8 MeV electron antineutrino beam generated by a cyclotron producing a 60 MeV – 10 mA proton beam to search for physics beyond the standard model.
- Two main physics goals:
  - Search for sterile neutrinos
  - Precision electroweak measurements

Motivation: Sterile Neutrinos

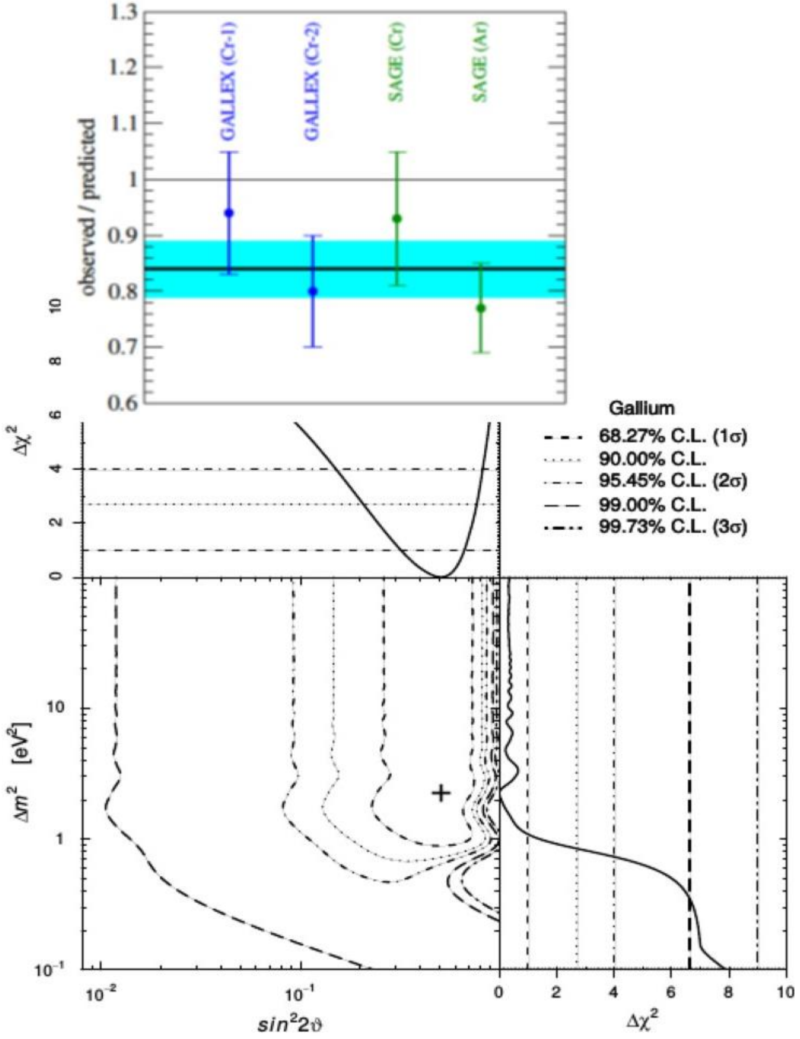
- Several neutrino oscillation experiments have seen anomalous results which may be consistent with a mass splitting at $\Delta m^2 \approx 1\text{eV}^2$. This would require the existence of at least 1 sterile neutrino.
  - Examples: LSND, MiniBooNE (ν_e appearance), DANSS, Gallium (ν_e disappearance)

- More experiments have observed null results.
  - Examples: NOMAD, KARMEN, MiniBooNE (ν_μ), MINOS, NEOS, PROSPECT

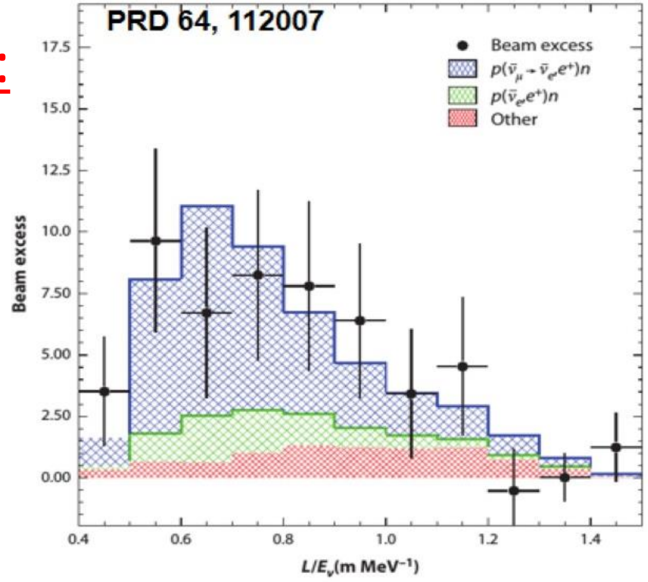
- IsoDAR would provide a very sensitive sterile neutrino search over a large section of the preferred parameter space for global fit studies.

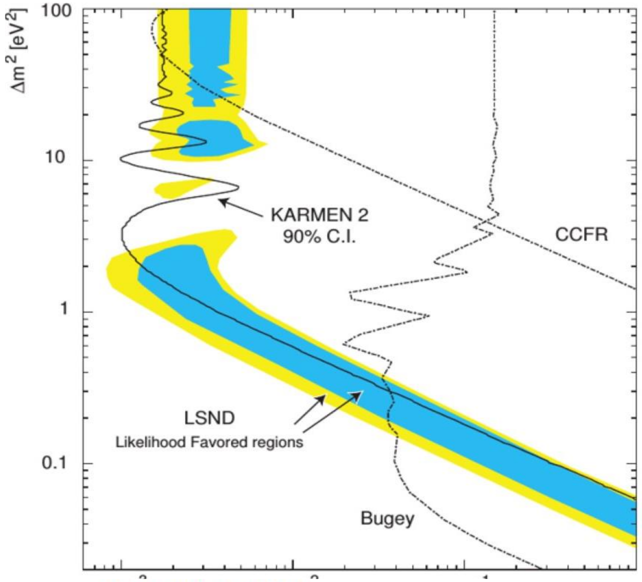
Motivation: Anomalies

Gallium:



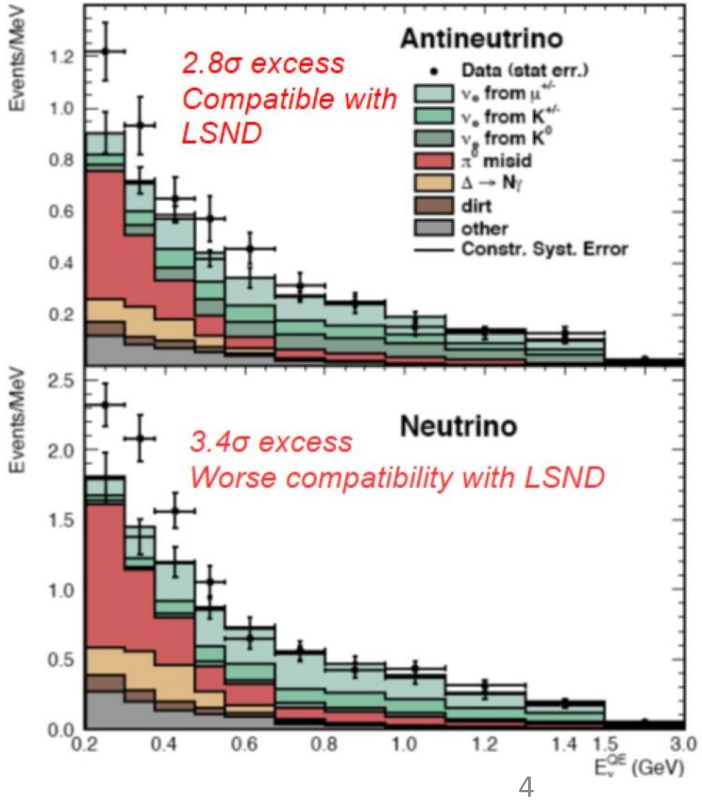
LSND:



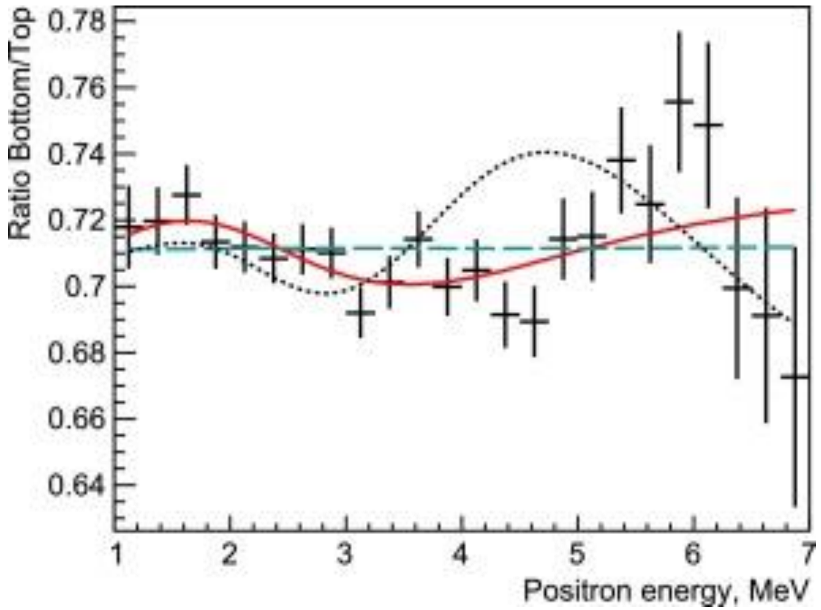


PRL 110, 161801

MiniBooNE:

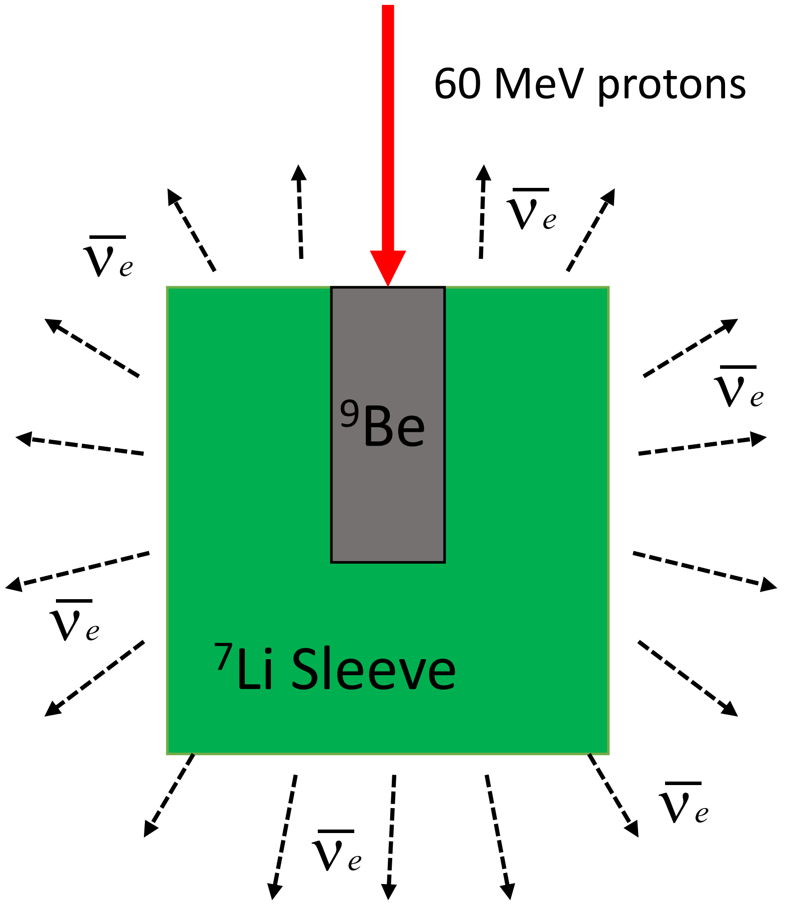


DANSS:



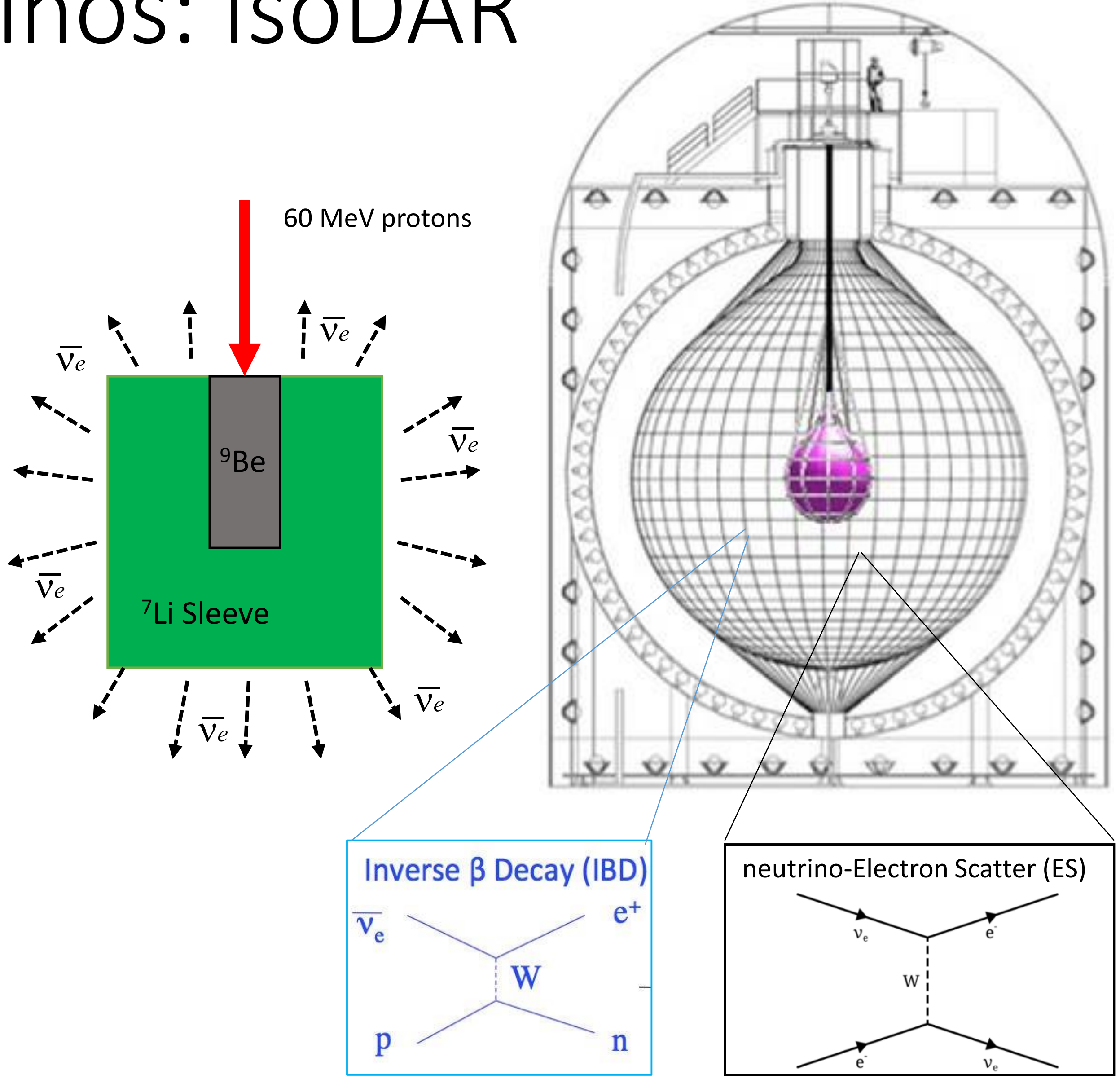
Search for Sterile Neutrinos: IsoDAR

- IsoDAR will take a 10mA beam of 60 MeV protons from a cyclotron source and impinge it onto a ^{9}Be target, producing a large number of neutrons.
- These neutrons will capture on a surrounding sleeve of high purity ^{7}Li, producing ^{8}Li.
- The ^{8}Li will then beta decay to produce an isotropic flus of $\bar{\nu}_e$ with well understood energy spectrum.



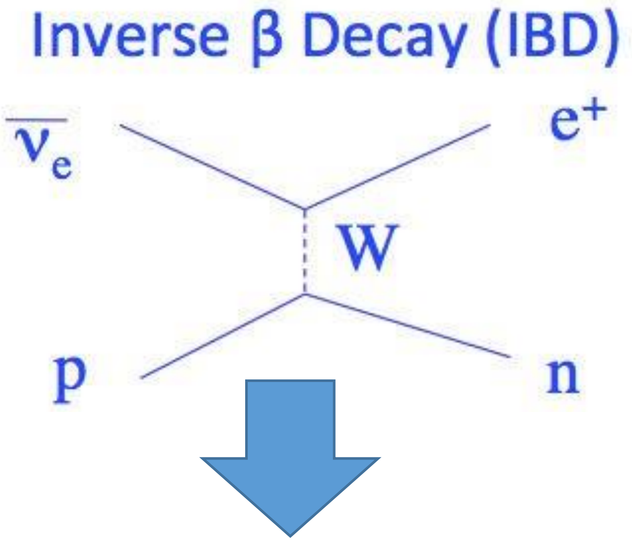
Search for Sterile Neutrinos: IsoDAR

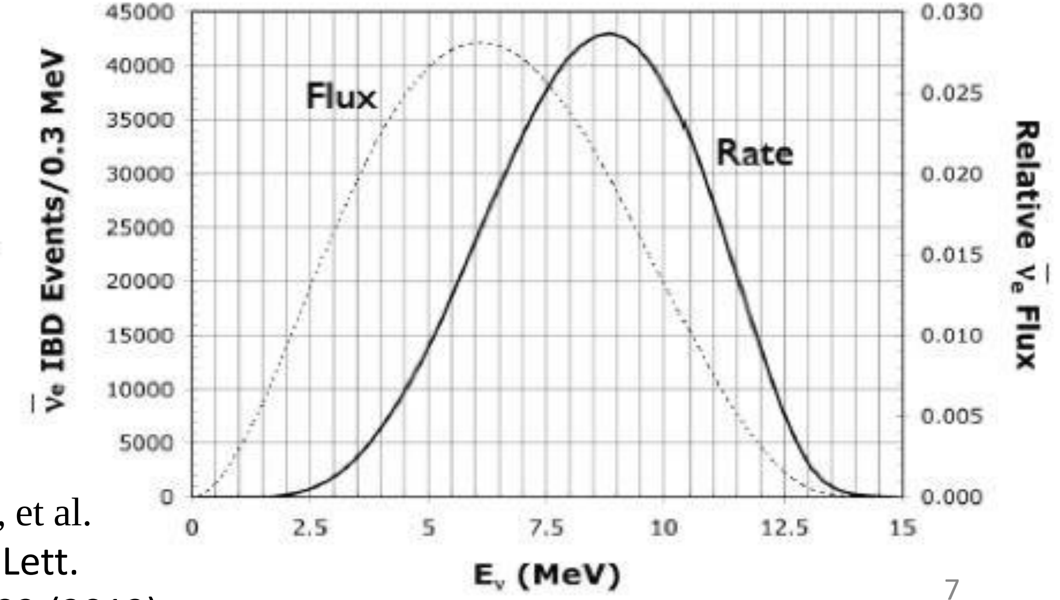
- The IsoDAR target will then be placed in close proximity to a large liquid scintillator detector, which detects neutrinos through Inverse Beta Decay scattering on free protons or scattering on electrons.
- For the purposes of this talk and current proposals, this detector is assumed to be a KamLAND-like detector (~1 kton), placed ~16 meters from the center of the ^{8}Li neutrino source.



Search for Sterile Neutrinos: IsoDAR

- Expected Results over the 5-year run:
  - 820,000 IBD events (500/day)
    - Sterile Neutrino Search
  - 2,600 $\overline{\nu}_e$-electron scattering events
    - Measure $\sin^2\theta_W$ to 3.2%
    - Probe weak couplings and nonstandard interactions (NSIs)

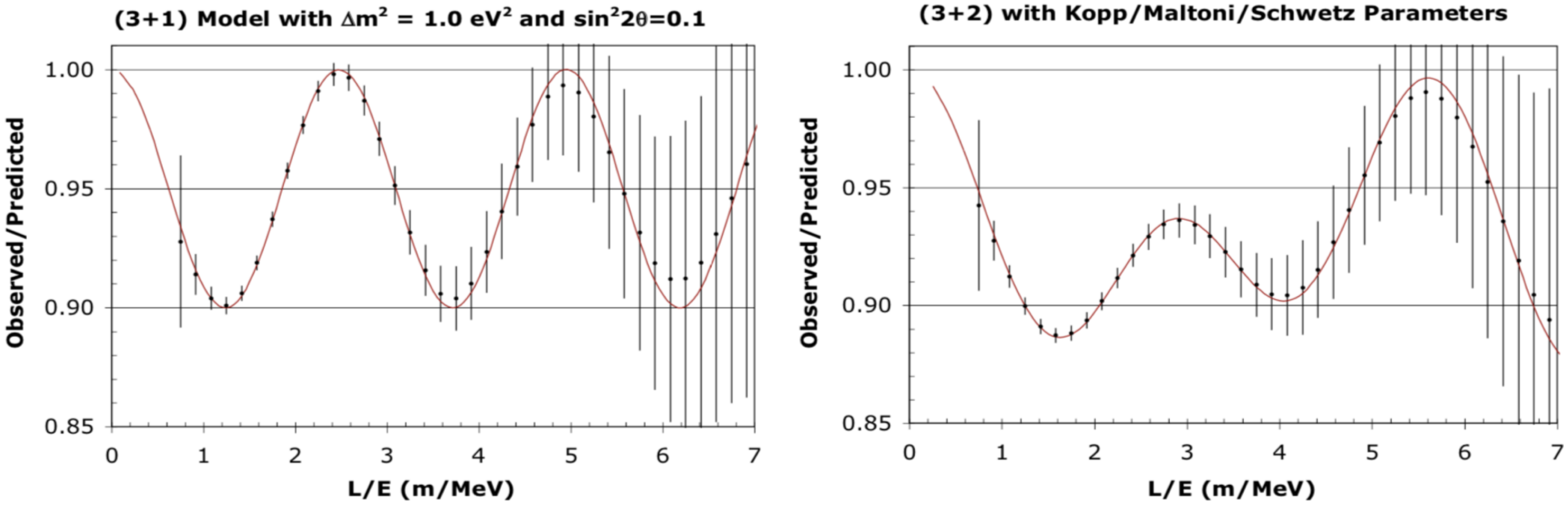




A. Bungau, et al. Phys. Rev. Lett. 109, 141802 (2012)

Search for Sterile Neutrinos

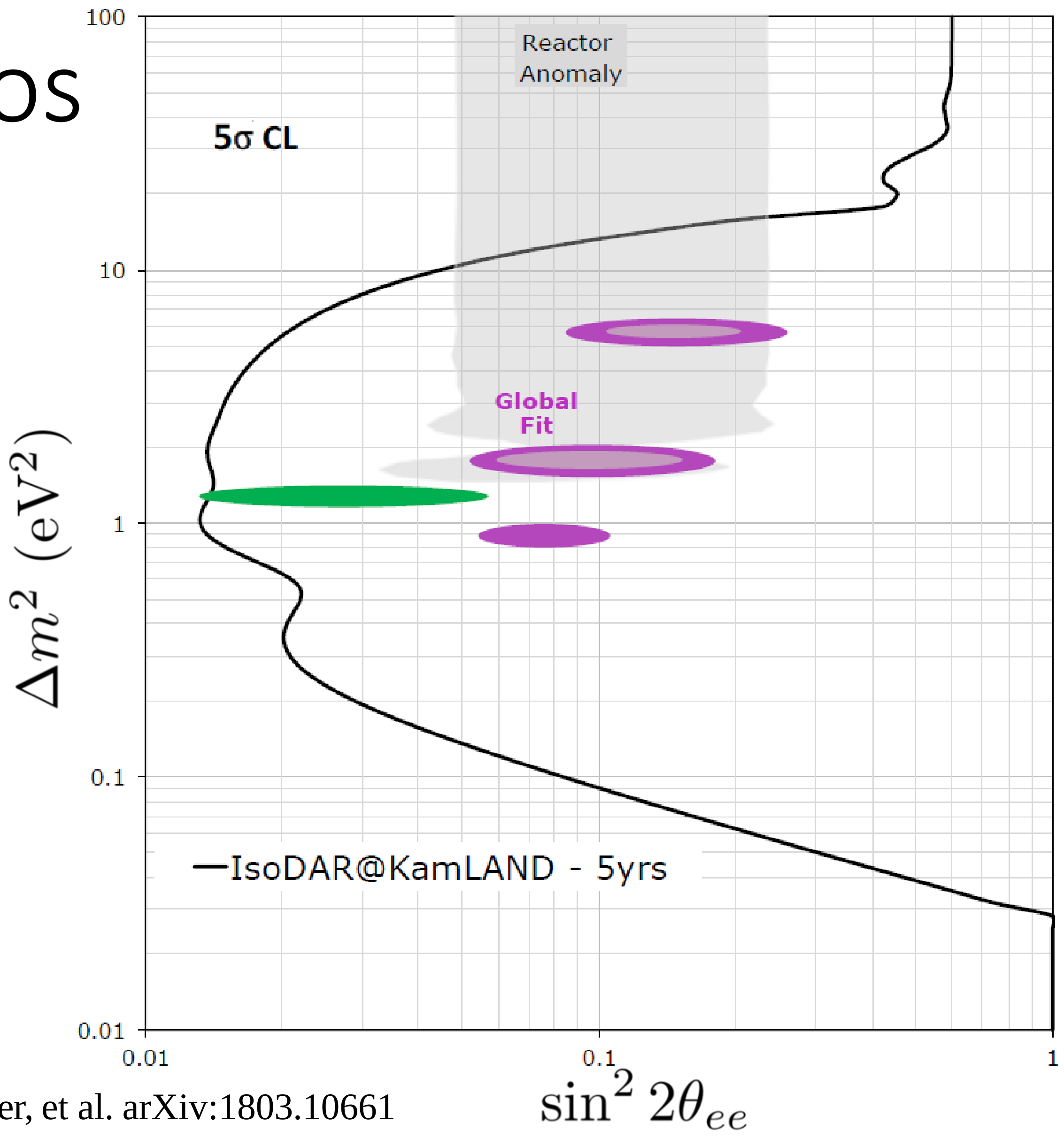
- IsoDAR could definitively establish the existence of sterile neutrinos.
  - $P^{2\nu}_{lx\,(l\neq x)}(L,E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
- Additionally, IsoDAR could distinguish models with 1 sterile neutrino (3+1) from those with 2 (3+2) (or more).



* J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107**, 091801 (2011).

Search for Sterile Neutrinos

- IsoDAR should provide a very high sensitivity (5σ!) search of the preferred region from global fits.
- KamLAND:
  - Large volume
    - Fiducial mass: 897 metric tons
  - Good resolution:
    - Position: 12 cm/$\sqrt{E_{MeV}}$
    - Energy: 6.4%/$\sqrt{E_{MeV}}$
- Neutrino source:
  - High $\bar{\nu}_e$ energy for ^{8}Li
    - Endpoint: 14 MeV
    - Mean: 6.5 MeV



M. Dentler, et al. arXiv:1803.10661

G. H. Collin, et al. arXiv:1602.00671

Search for Sterile Neutrinos

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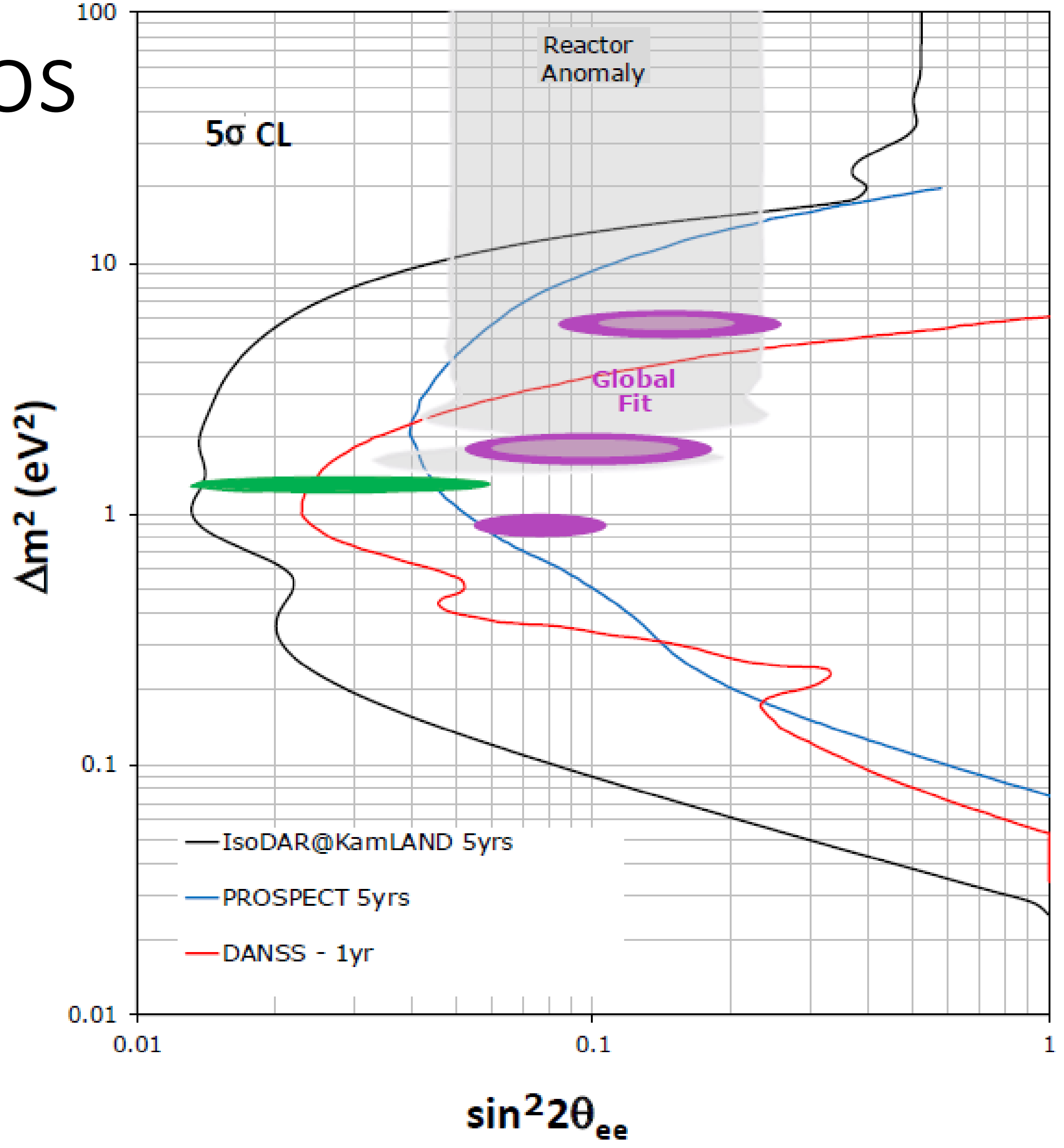
- Neutrino source:
  - High $\overline{\nu}_e$ energy for ^{8}Li
    - Endpoint: 14 MeV
    - Mean: 6.5 MeV
- Better than other experiments in the parameter space of interest!

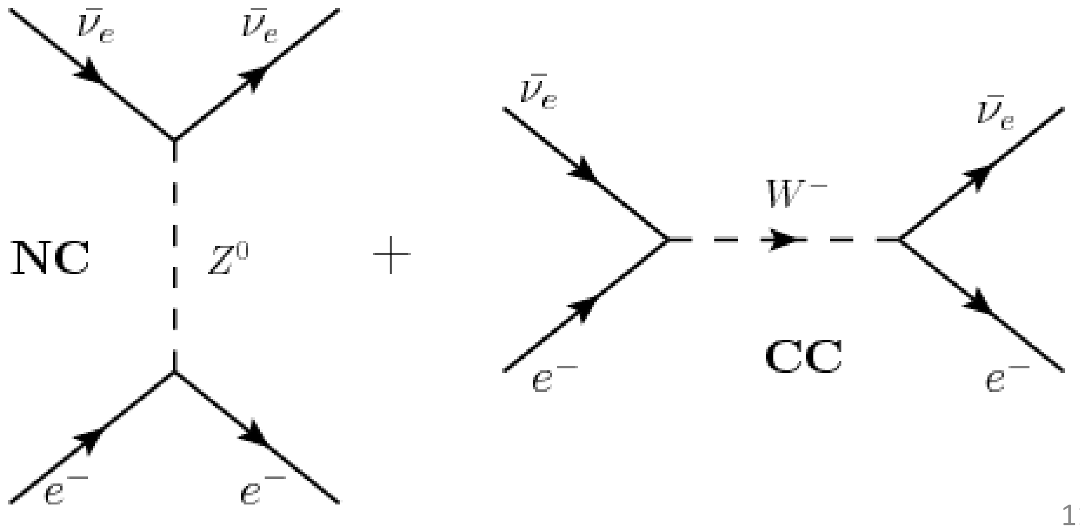


High Precision Tests of the Standard Model

- In addition to the IBD interactions, IsoDAR at KamLAND would collect the largest sample of low energy $\bar{\nu}_e$-electron scattering (ES) events that has been observed to date.
  - Approximately 2600 ES events above a 3 MeV threshold would be collected over a 5-year run.
  - In a detector such as KamLAND, both the rate and the visible energy of each event can be measured.

$\delta \sin^2 \theta_W$	$\frac{\delta \sin^2 \theta_W}{\sin^2 \theta_W}$	$\delta \sin^2 \theta_W^{\text{stat-only}}$
0.0076	3.2%	0.0057

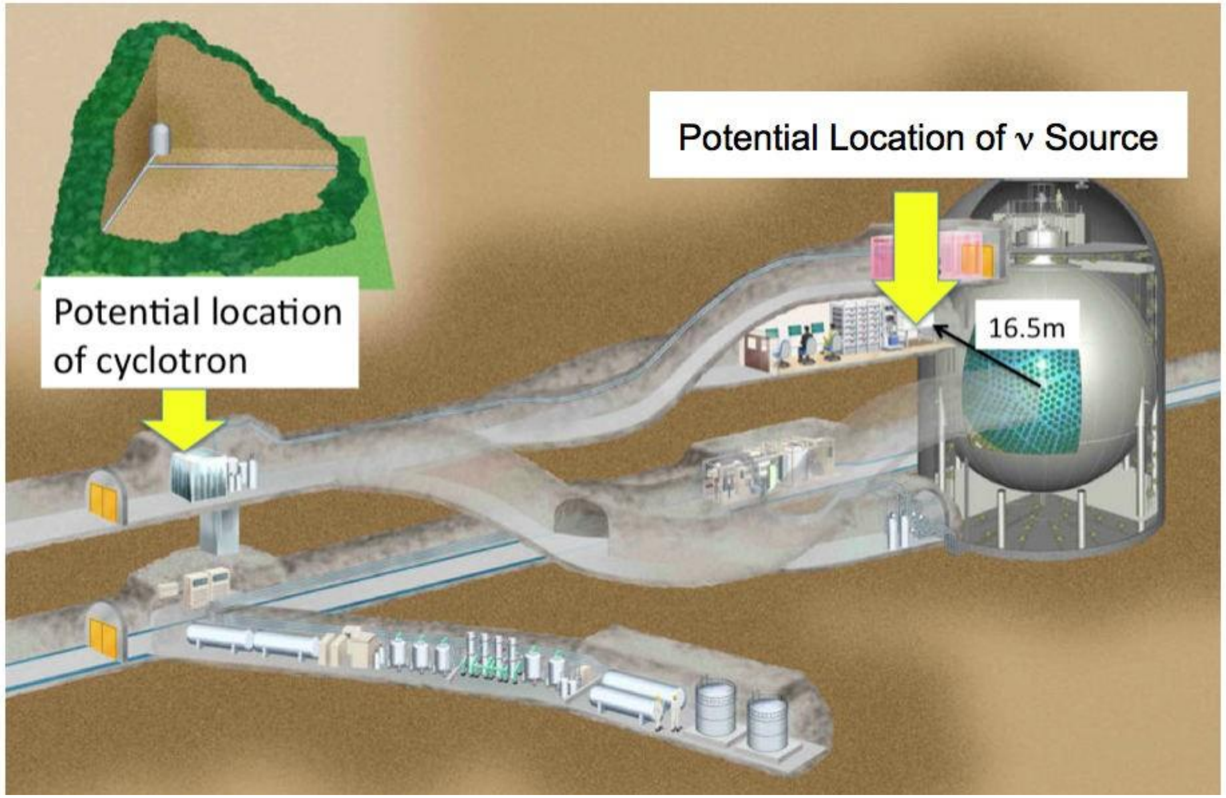
  - These measurements can be used to determine the weak mixing angle to high precision.

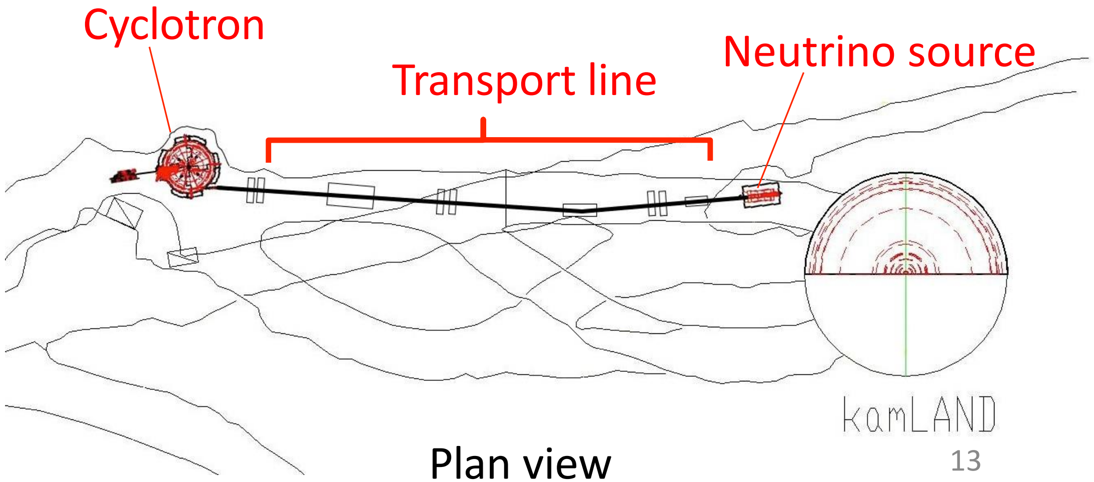


Technical Details and Challenges

Technical Concept: Layout of IsoDAR@KamLAND

- Want to locate particle accelerator and neutrino source within Kamioka Mine next to the KamLAND detector.
- Issues:
  - Limited Space
  - Target Cooling
  - Radiation Issues



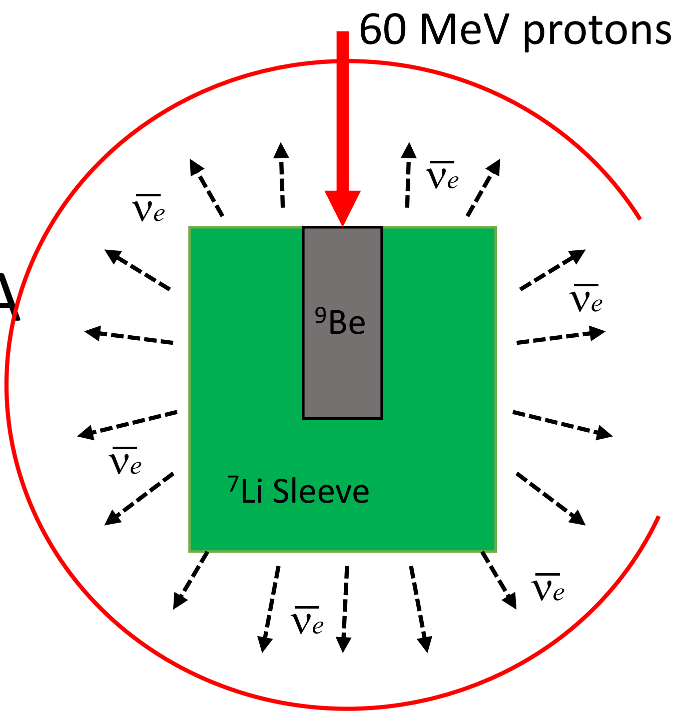


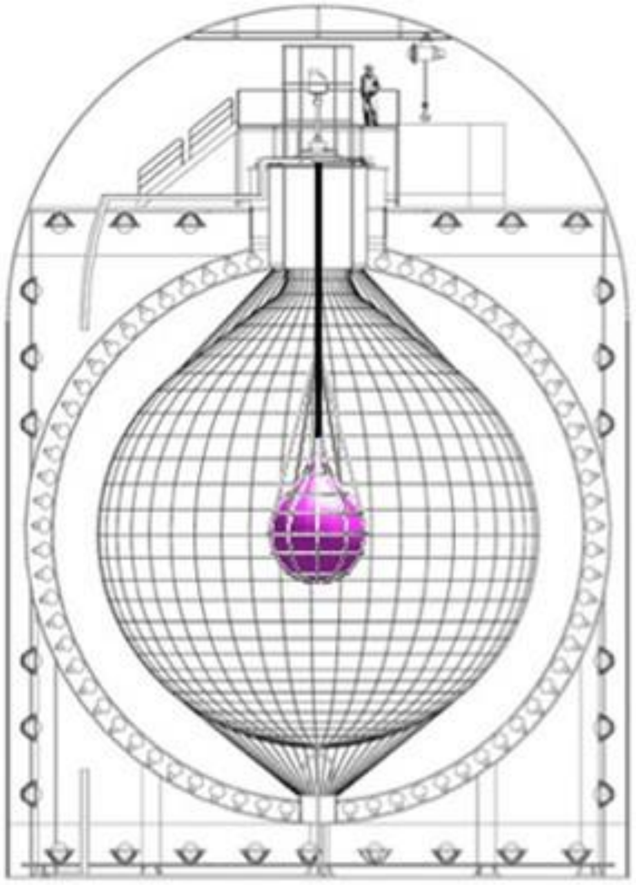
Plan view

For more on the cyclotron, see Joseph Smolsky's talk - *IsoDAR: Neutrino Physics Using a High Current Cyclotron*, 4:00-4:20 Shillman 215.

Technical Details: Beam

- IsoDAR is a Decay-At-Rest experiment, so the neutrino source is isotropic.
- Current proposals call for a 10mA proton beam, 10 times what is commercially available.
- The high intensity proton beam provides high intensity neutrino flux into KamLAND and allows high precision measurements.



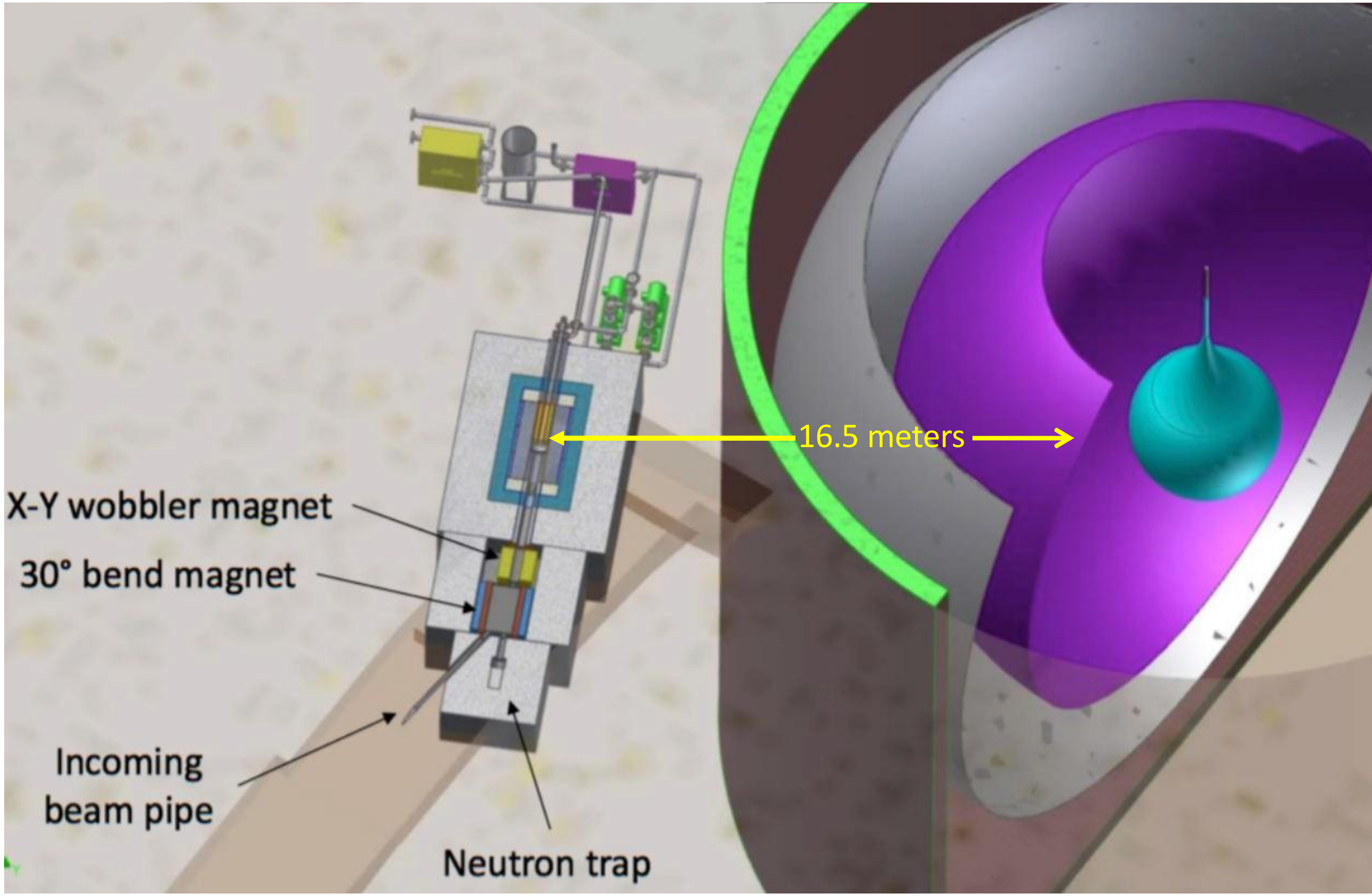


Isotropic: Flux going through red is lost

* Not to Scale

Technical Details: Target

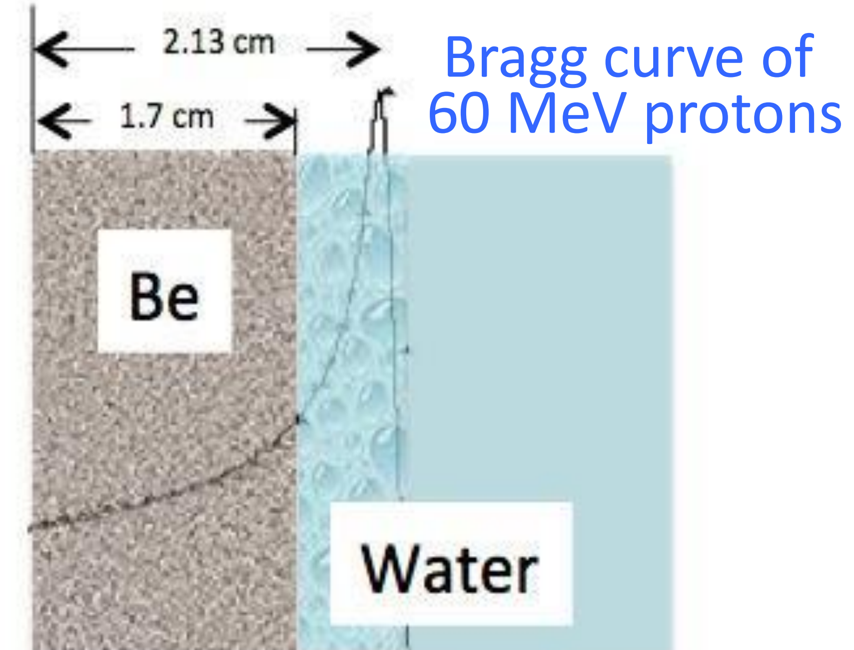
- Beam on Be target:
  - 10 mA 60 MeV protons
- Neutron production:
  - 1 neutron/10 protons
  - 6×10^{15} neutrons/second
- Neutrino producing sleeve: Li + Be mixture
  - Size: 1m diameter x 2m long
  - Isotope of interest ^{8}Li
- Antineutrino yield:
  - ~0.016 $\bar{\nu}_e$ / proton
  - 1×10^{15} $\bar{\nu}_e$ / second
- ->820,000 IBD events in 5 years.

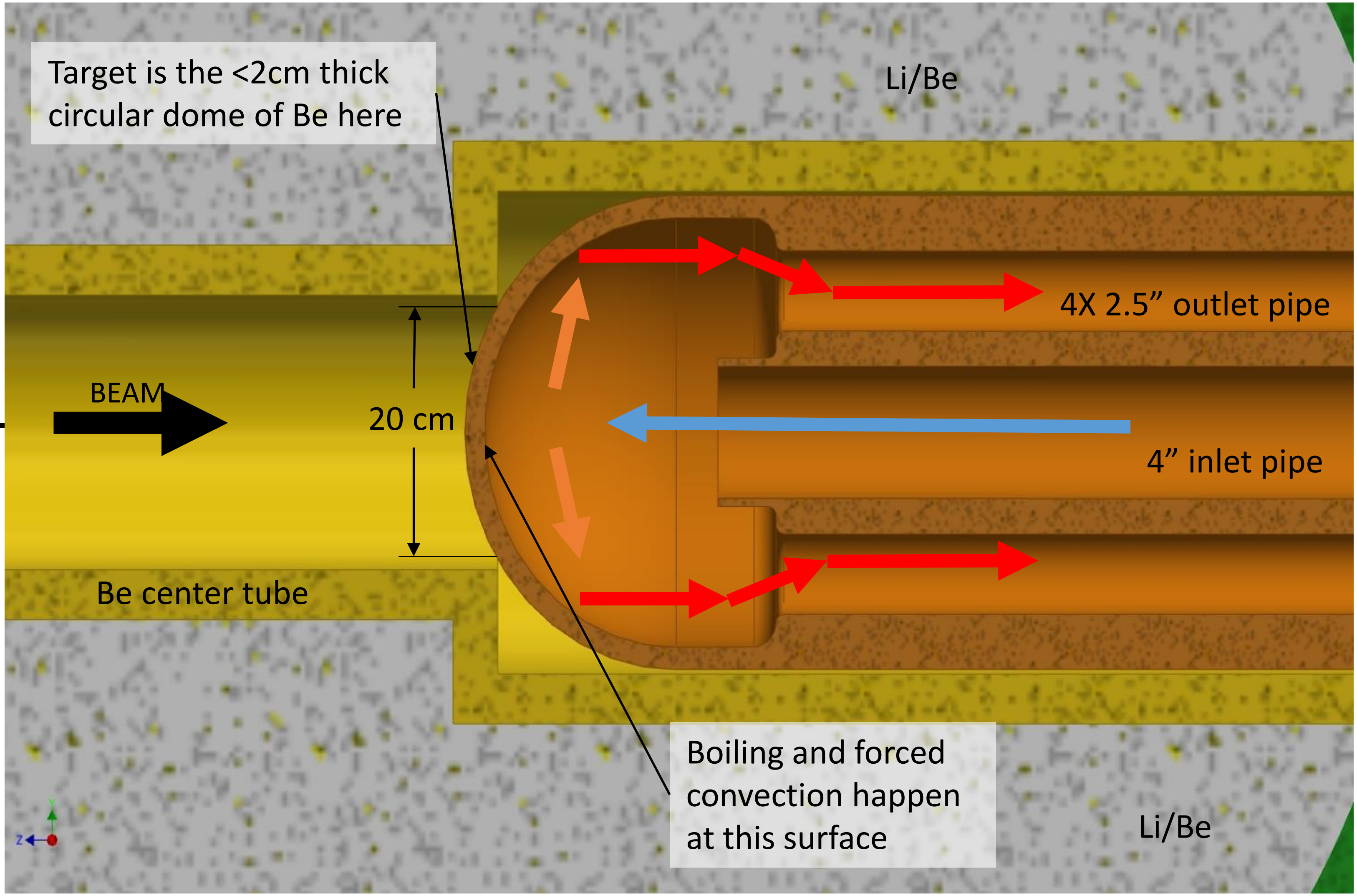


IsoDAR schedule: Post ZEN

Technical Details: Target

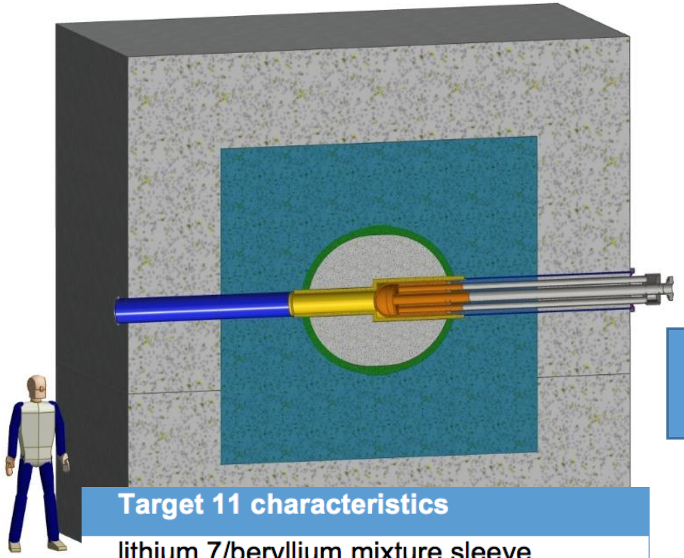
- Beam produces a lot of power => lots of heat in target:
- 10 mA 60 MeV protons
  - 600 kW spread over 300 cm^2.
  - $\approx 2\ kW/cm^2$.
  - Uniform in time.



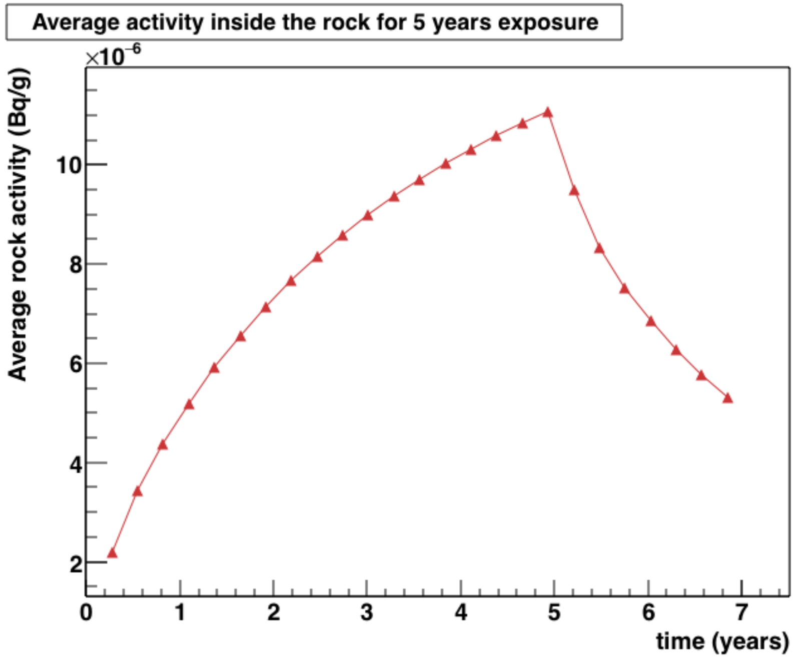


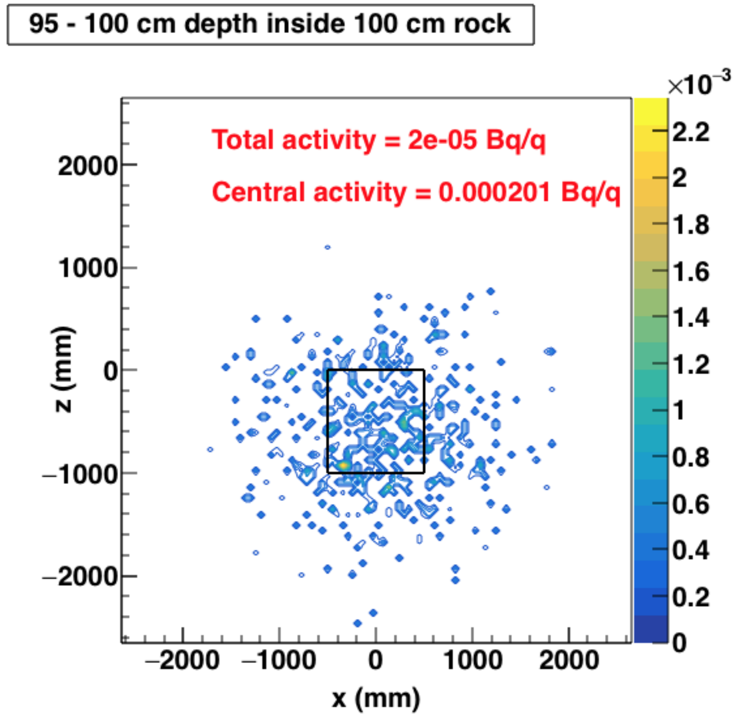
Technical Details: Shielding

- Must protect rock from long-lived activation.
  - Target shielding of 1 m steel and 1 m concrete found to be sufficient by Geant4 simulations.



Target 11 characteristics
lithium 7/beryllium mixture sleeve
Surrounded by 5 cm thick Be reflector
ASME flanged & dished heads on sleeve
1 m steel shield around reflector
1 m concrete shield around steel

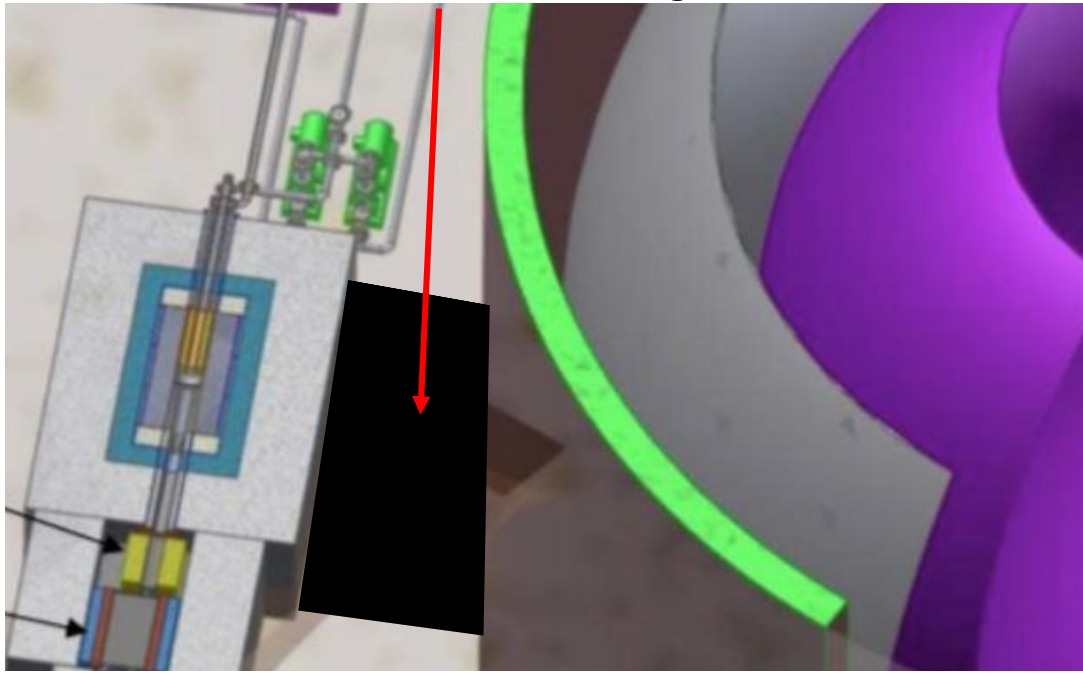


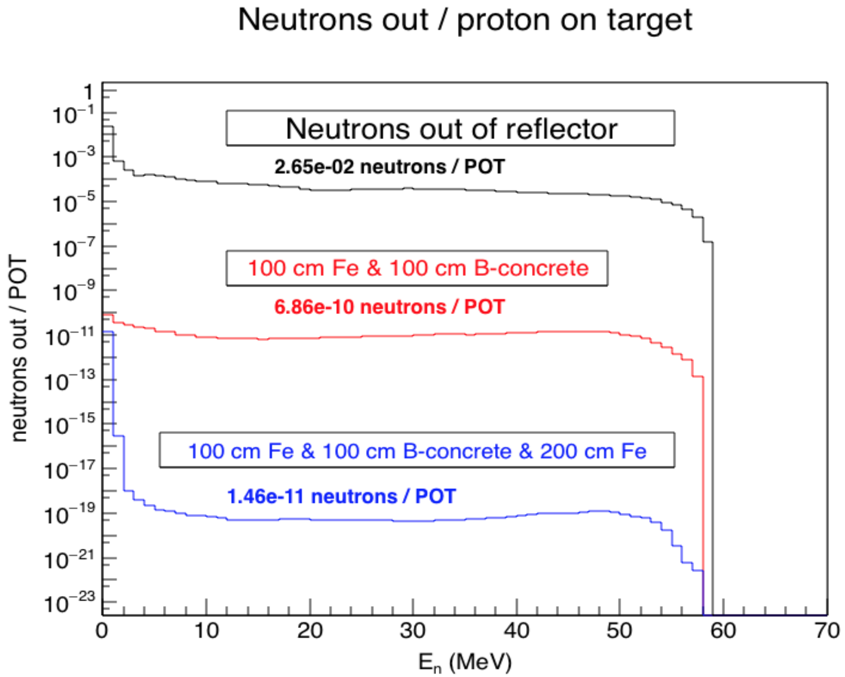


Technical Details: Shielding

- ES events need extremely low rates of beam related neutrons and gammas.
  - Additional shielding reduces the beam related neutrons above 3MeV in KamLAND to 2.78 x 10^{-24} /POT.
    - Just 22 neutrons over 5 year run.
  - The same shielding setup reduces gammas to 2.71 x 10^{-24} /POT above 3 MeV, most of which are produced by neutrons in the detector.

Extra Shielding Location

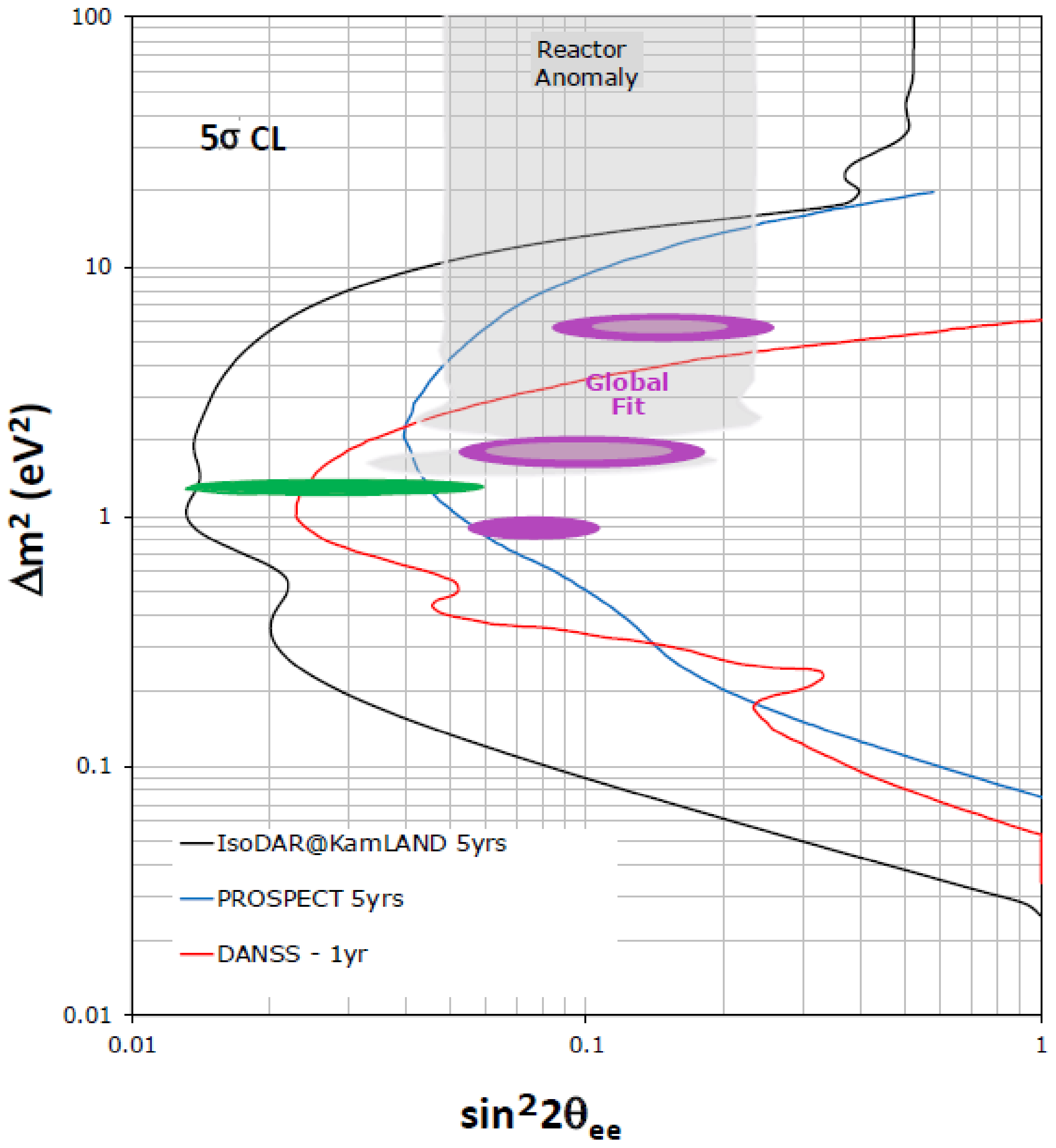




Conclusions

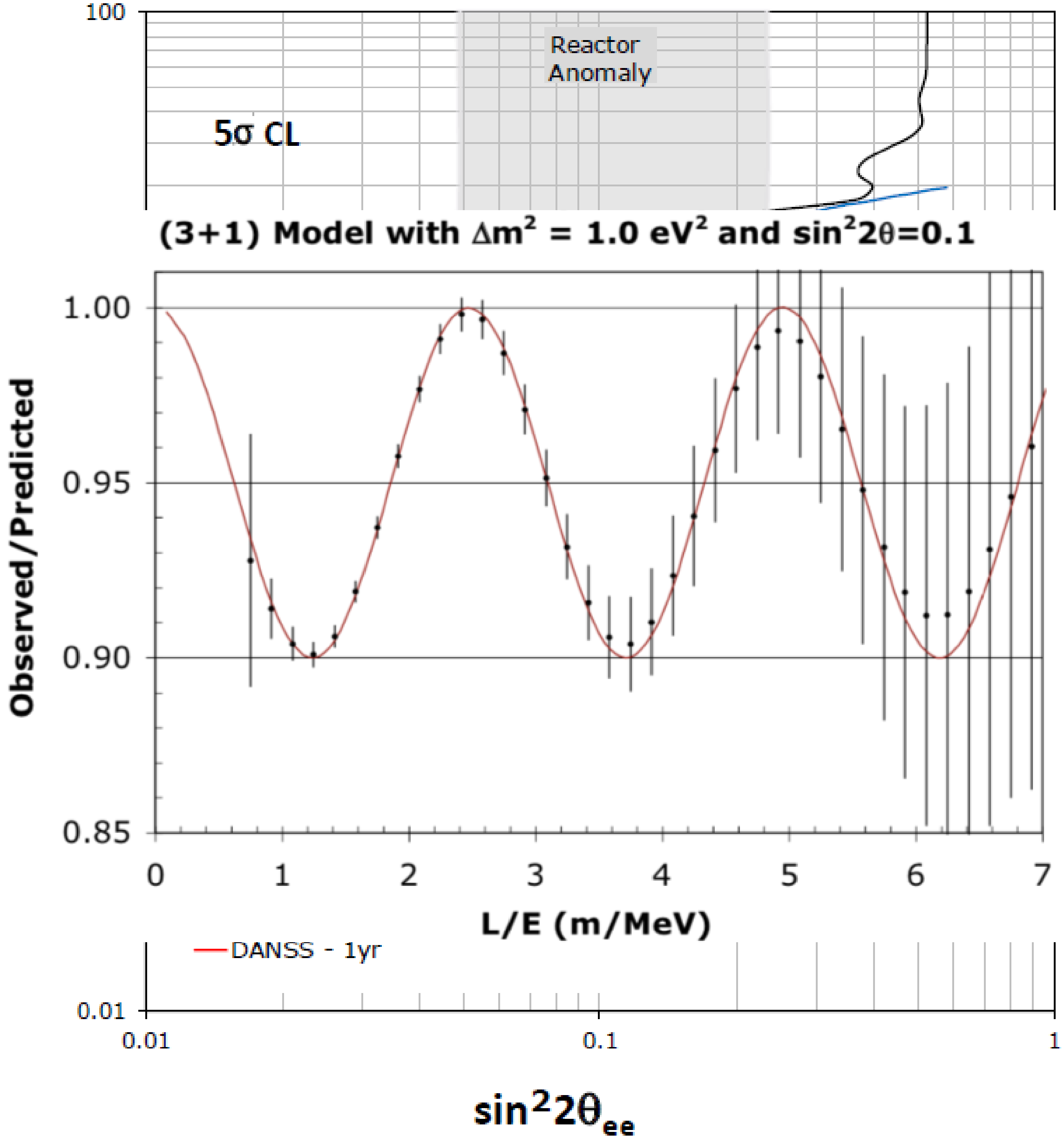
- The IsoDAR experiment offers a definitive radioactive source based search for $\bar{\nu}_e$-disappearance in the preferred parameter space for sterile neutrinos, with several advantages over reactor or source based experiments.

- IsoDAR will also enable other physics analyses, as well as technical advancements that will benefit the field and technology.



Conclusions

- The IsoDAR experiment offers a definitive radioactive source based search for $\bar{\nu}_e$-disappearance in the preferred parameter space for sterile neutrinos, with several advantages over reactor or source based experiments.
  - Oscillation Waves are a smoking gun for sterile neutrinos.
- IsoDAR will also enable other physics analyses, as well as technical advancements that will benefit the field and technology.



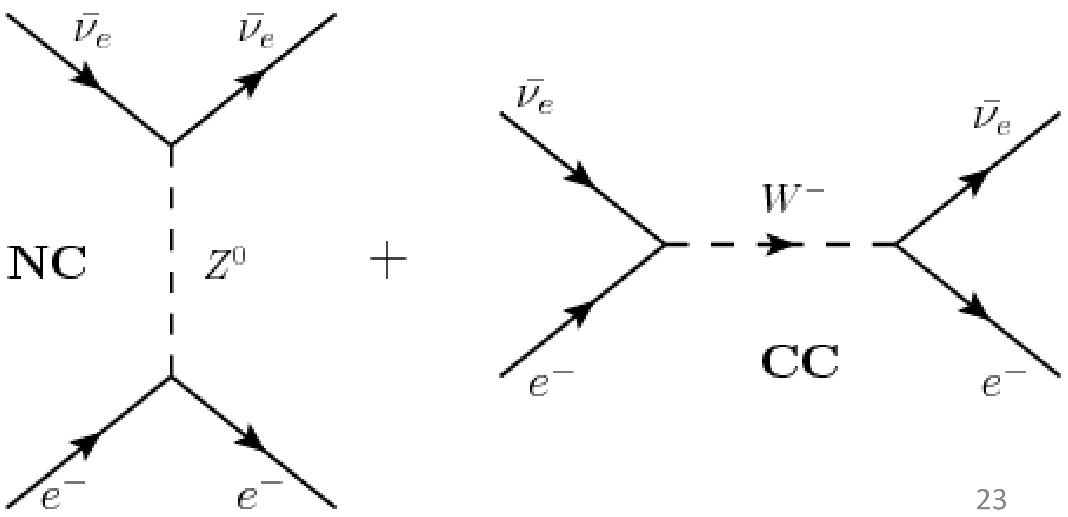
Backups

High Precision Tests of the Standard Model

- In the standard model, the ES differential cross section is given by:

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2\left(1-\frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2}\right],$$

- T is electron recoil energy, E_ν is the energy of the incoming ν_e, and the weak coupling constants g_R and g_L are given at tree level by $g_R = \sin^2\theta_W$ and $g_L = 1/2 + \sin^2\theta_W$.



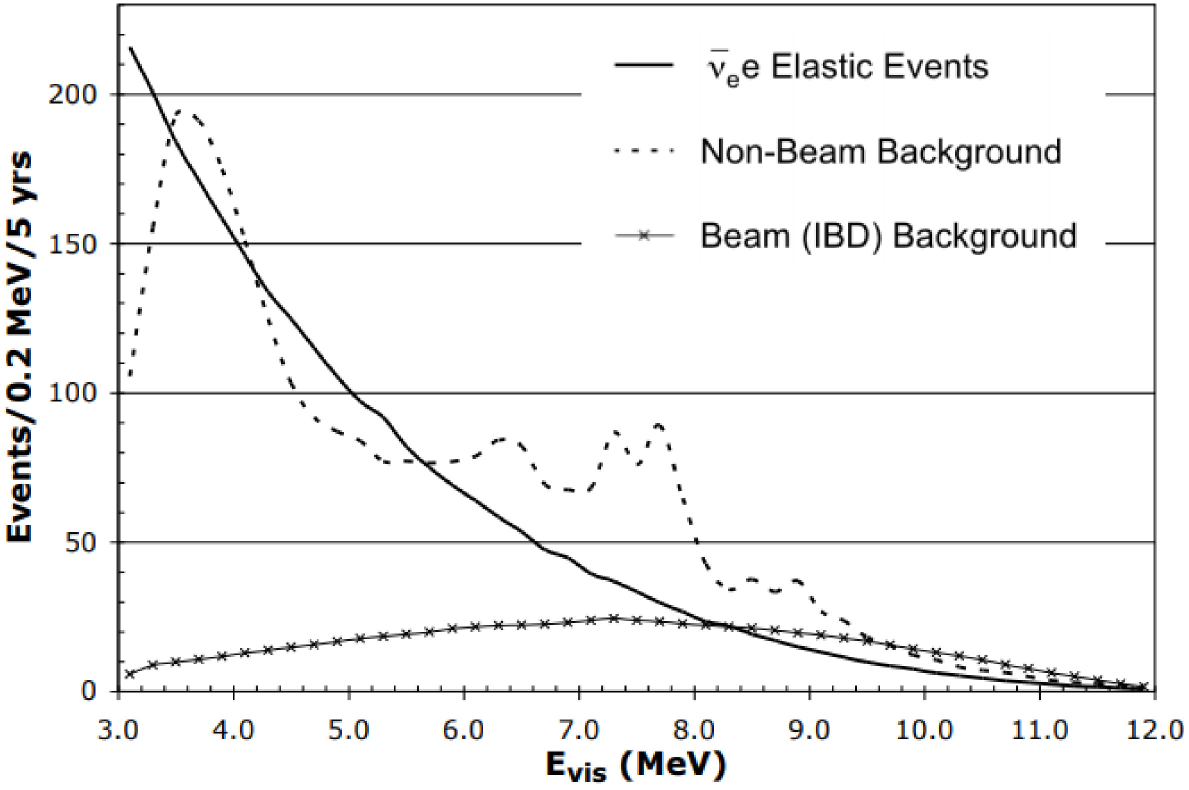
High Precision Tests of the Standard Model

- ES cross section measurements can thus determine the weak couplings g_L and g_R, as well as the weak mixing angle $\sin^2 \theta_W$.

Bkg factor	$\delta \sin^2 \theta_W$	$\frac{\delta \sin^2 \theta_W}{\sin^2 \theta_W}$	$\delta \sin^2 \theta_W^{\text{stat-only}}$
1.0	0.0076	3.2%	0.0057

- The ES cross section is also sensitive to new physics in the neutrino sector arising from nonstandard interactions (NSIs).

ES Signal and Background Events for IsoDAR at KamLAND



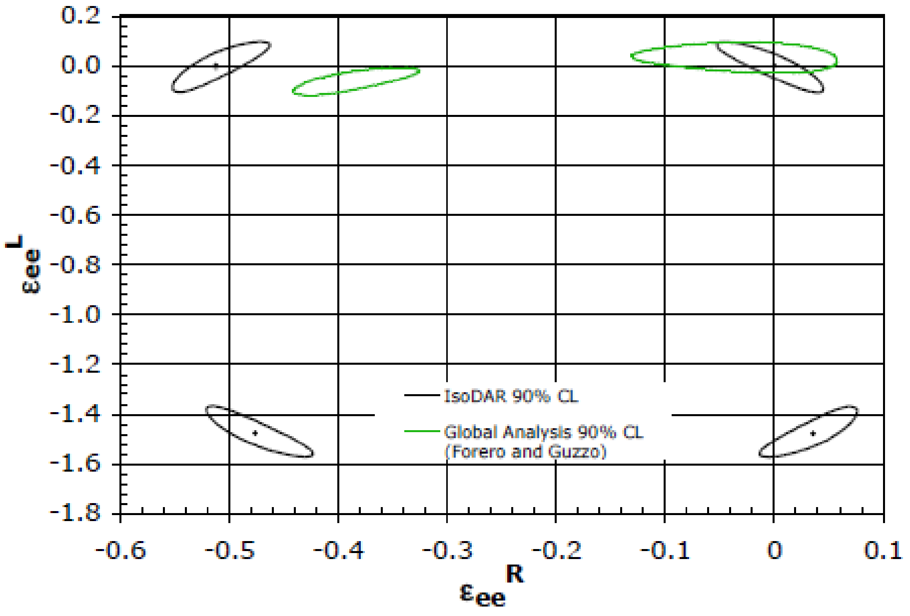
A. Bungau, et al.
Phys. Rev. Lett. 109, 141802 (2012)

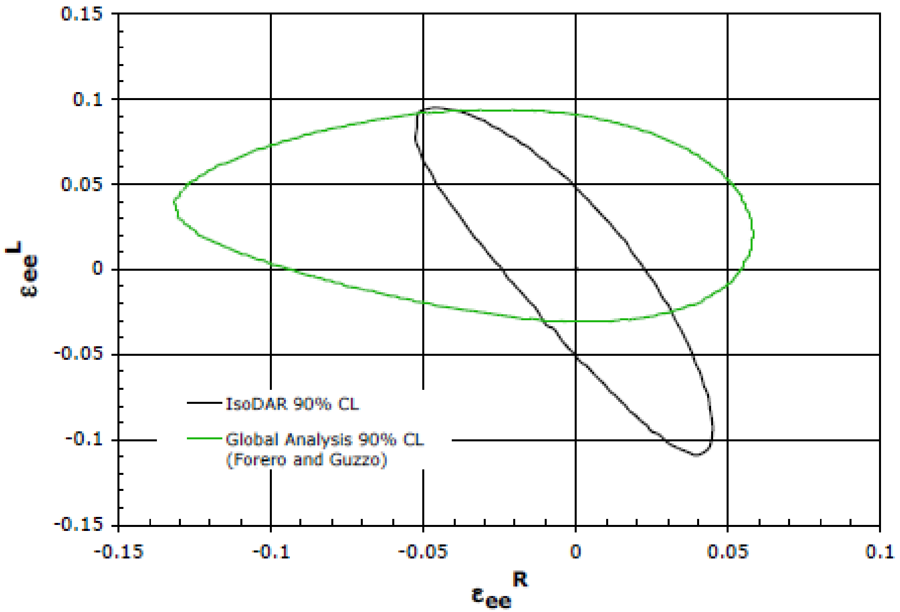
Non-Standard Interactions

- Deviations of the the $\overline{\nu}_e$-electron scattering (ES) cross section from Standard Model Calculations would hint at new physics.
  - Follow up on previous high precision neutrino measurements which showed deviations, such as the NuTEV at Fermilab with neutrino-quark scattering.
- NSI terms may modify the ES cross section to:

$$
\begin{aligned}
\frac{d\sigma(E_\nu, T)}{dT} = \frac{2G_F^2 m_e}{\pi} & [(\tilde{g}_R^2 + \sum_{\alpha \neq e} |\epsilon_{\alpha e}^{eR}|^2) + \\
& (\tilde{g}_L^2 + \sum_{\alpha \neq e} |\epsilon_{\alpha e}^{eL}|^2) \left(1 - \frac{T}{E_\nu}\right)^2 - \\
& (\tilde{g}_R \tilde{g}_L + \sum_{\alpha \neq e} |\epsilon_{\alpha e}^{eR}||\epsilon_{\alpha e}^{eL}|) m_e \frac{T}{E_\nu^2}] \, ,
\end{aligned}
$$

where $\bar{g}_R = g_R + \varepsilon_{ee}^{eR}$ and $\bar{g}_L = g_L + \varepsilon_{ee}^{eL}$.





IsoDAR's sensitivity to ε_{ee}^{eL} and ε_{ee}^{eR}. The current global allowed region is also shown.

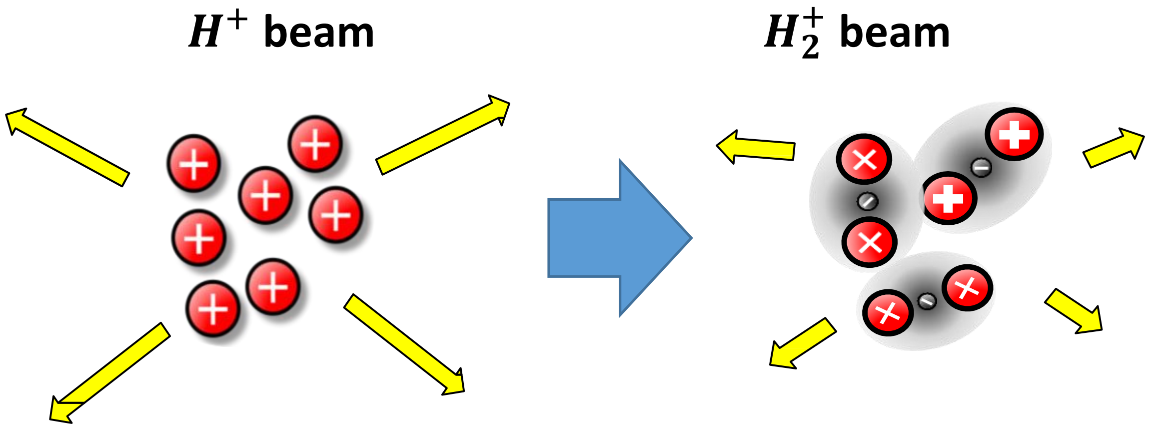
Other Potential Results

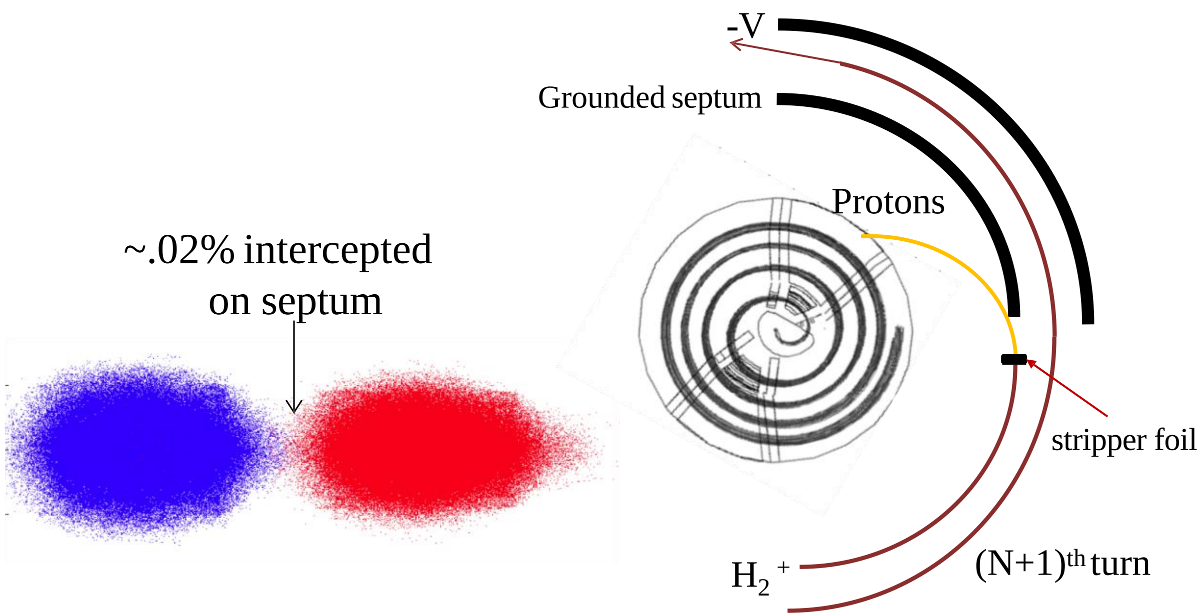
- The measured positron spectra of the IBD events may be interesting to ^{8}B solar neutrino analyses like those done by Super-K and SNO.
  - The ^{8}Li decay proceeds through the same wide excited state of ^{4}Be as ^{8}B. These measurements would be a good test of the conversion procedure from accelerator based beta and alpha spectrum ^{8}B experiments to the ^{8}B neutrino spectrum.
- Studies have also shown that IsoDAR should be able to determine the ^{8}Li endpoint.
  - Preliminary estimates give an uncertainty of around 0.015 MeV.

Technical Details: Beam

- Accelerate H_2^+ instead of H^+ for space charge management.
  - Only need 5 mA of beam current before stripping the ions, doubling the effective rate.

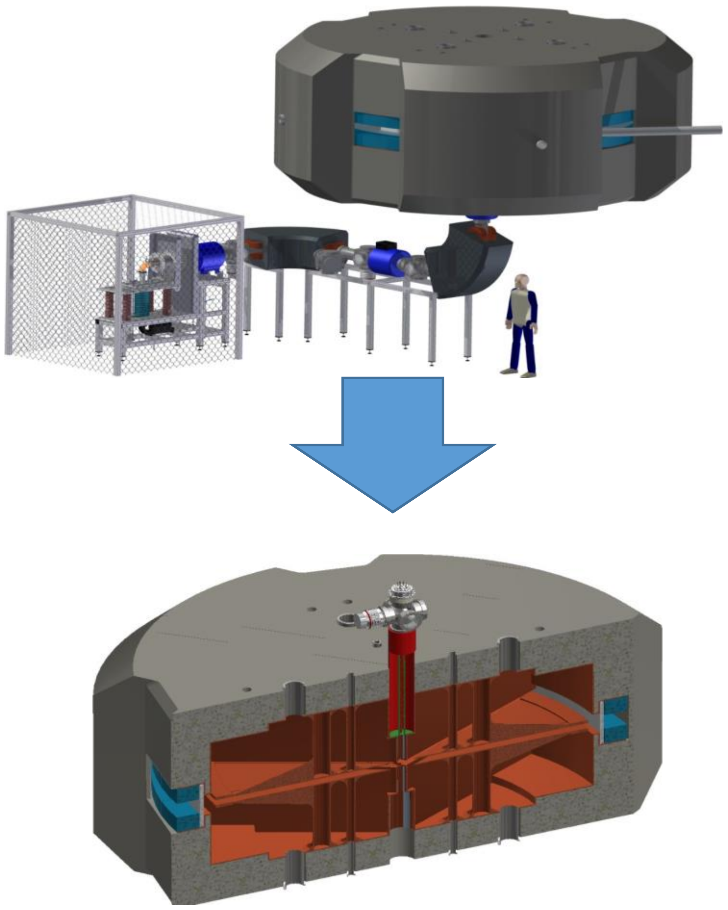
- Also eases Extraction:
  - The septum needed to extract the beam can only tolerate 200W of power. Including a stripper foil before, disassociates the H_2^+ and causes many of the damaging ions to spiral away.

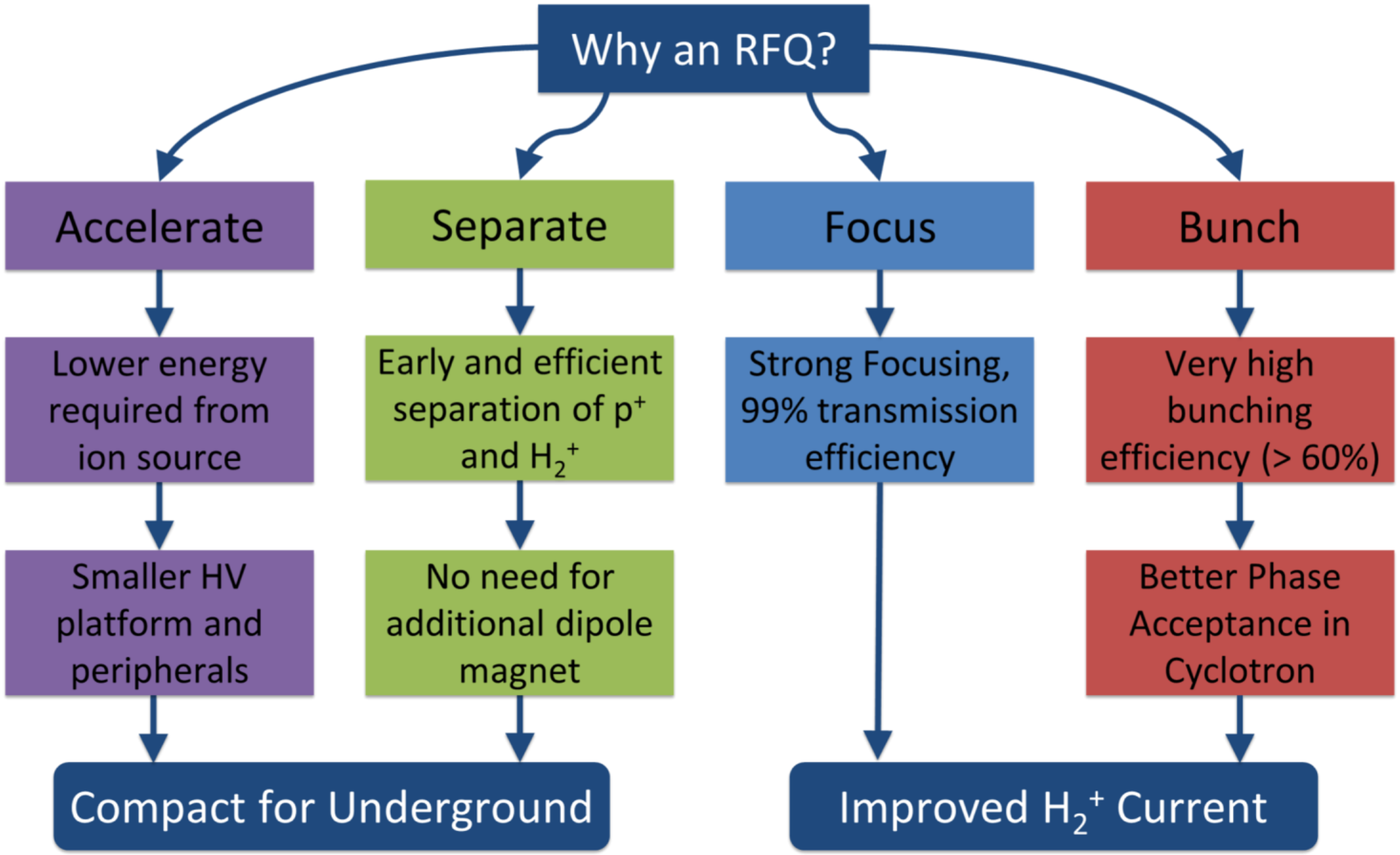




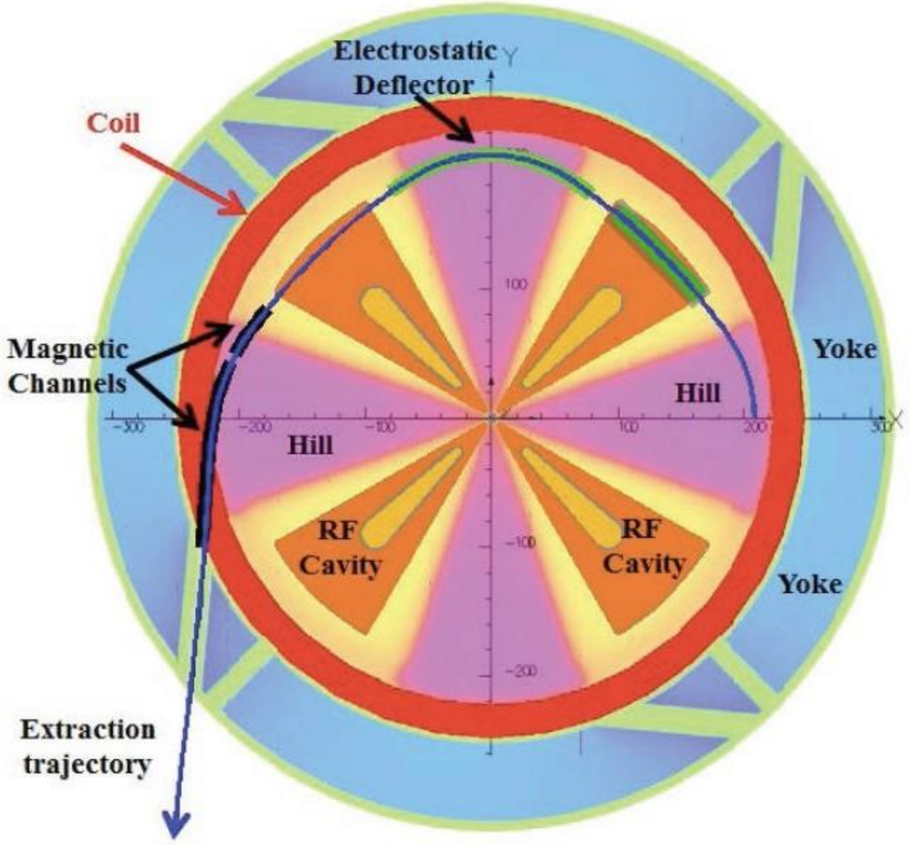
Technical Details: Beam

- Replace the conventional Low Energy Beam Transport (LEBT) with a Radio Frequency Quadropole (RFQ) based injection.





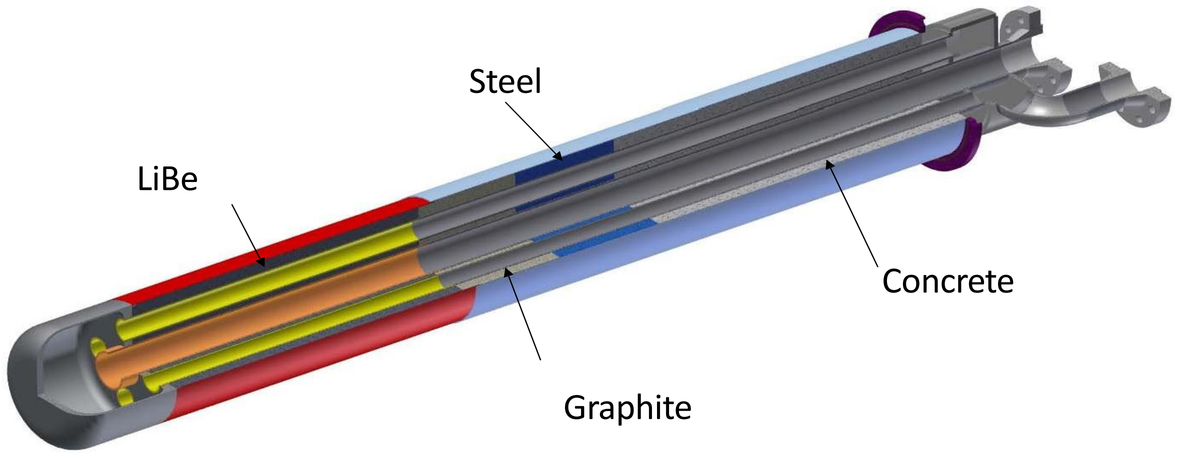
Technical Details: Cyclotron

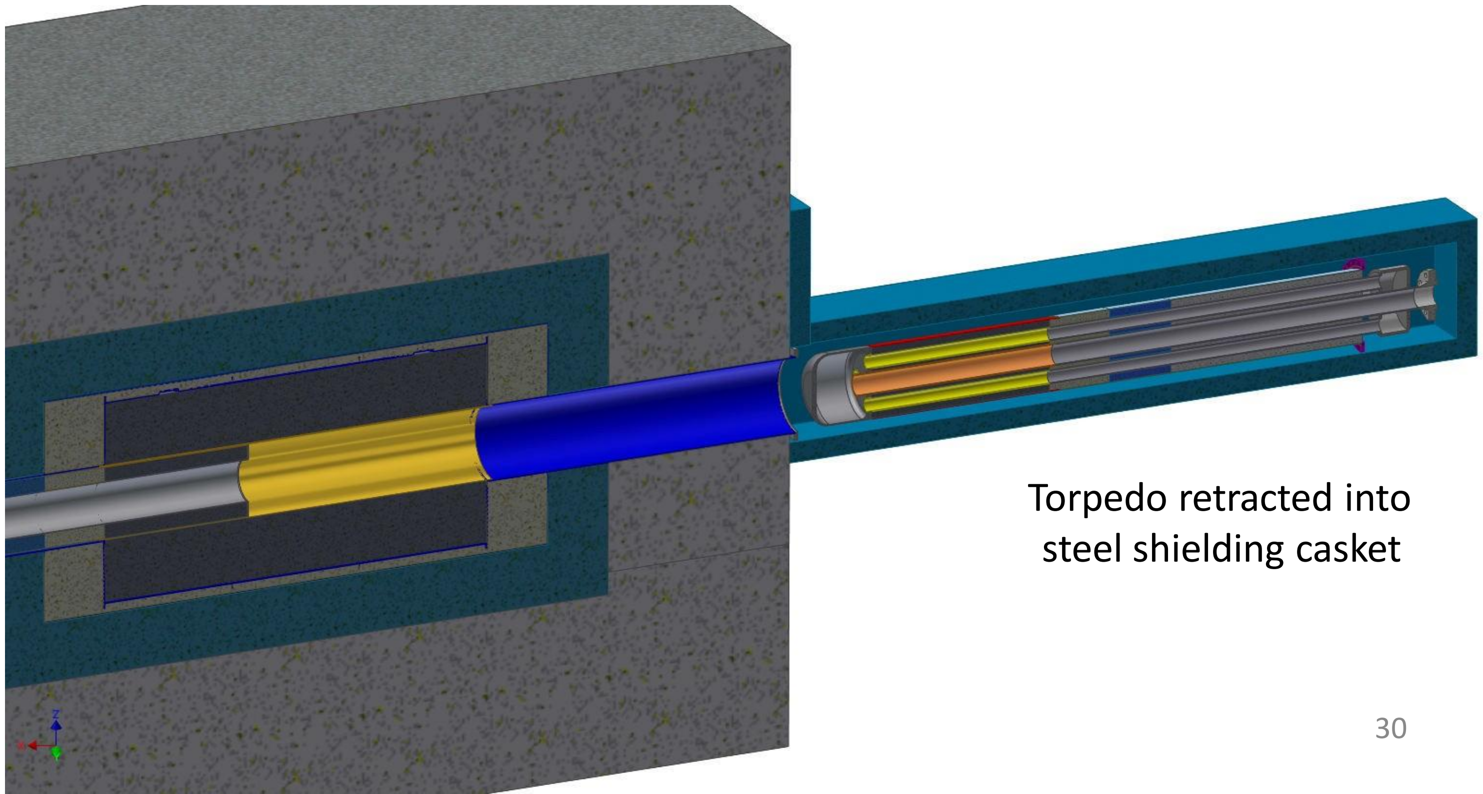


Parameter	Value
Ion accelerated	H_2^+
Max Energy	60 MeV/amu
Extraction radius	1.99 meters
Average magnetic field	1.16 tesla
Number of sectors	4
RF frequency	32.8 MHz
Accel. Voltage	70 – 240 kV
ΔE/turn	(ave) 1.7 MeV
Turns	95
Outer diameter	6.2 meters
Iron weight	450 tons

Technical Details: Target

- Target needs to be replaced when it wears out.
  - Without exposing workers to radioactivity.
- Modular target torpedo can be easily removed and replaced.

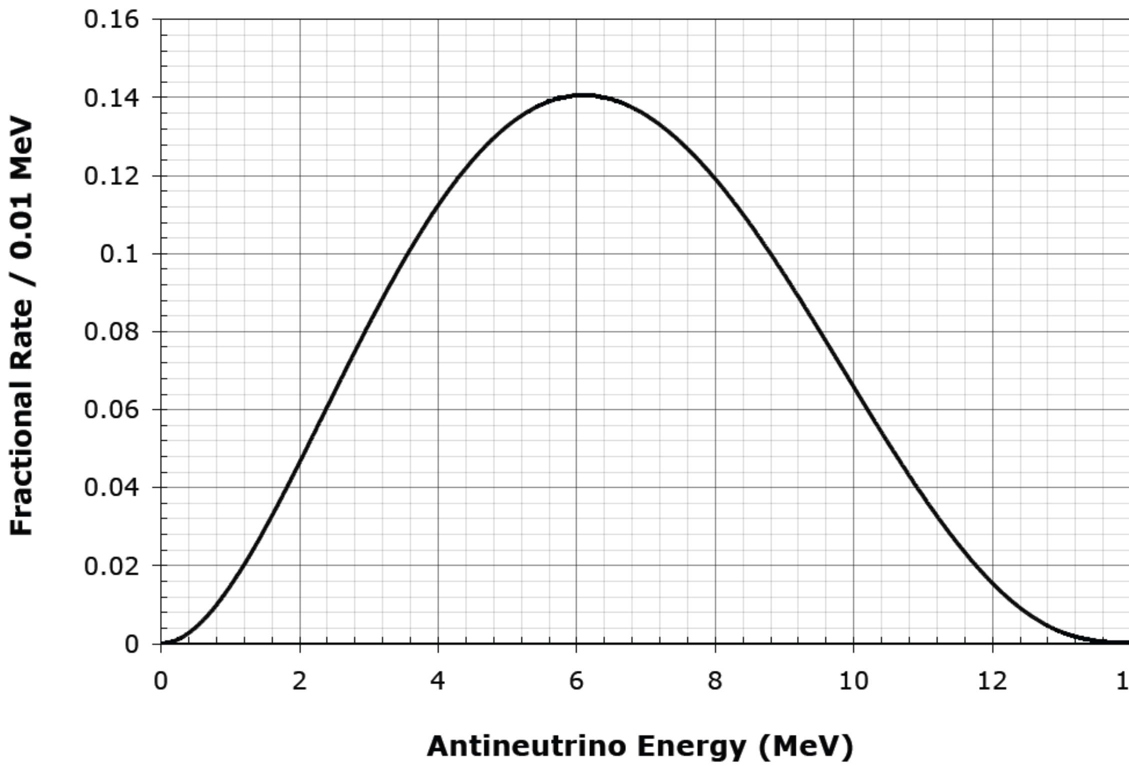


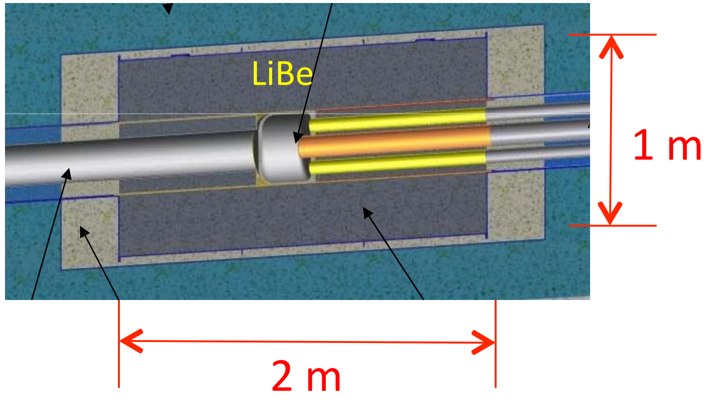


Torpedo retracted into steel shielding casket

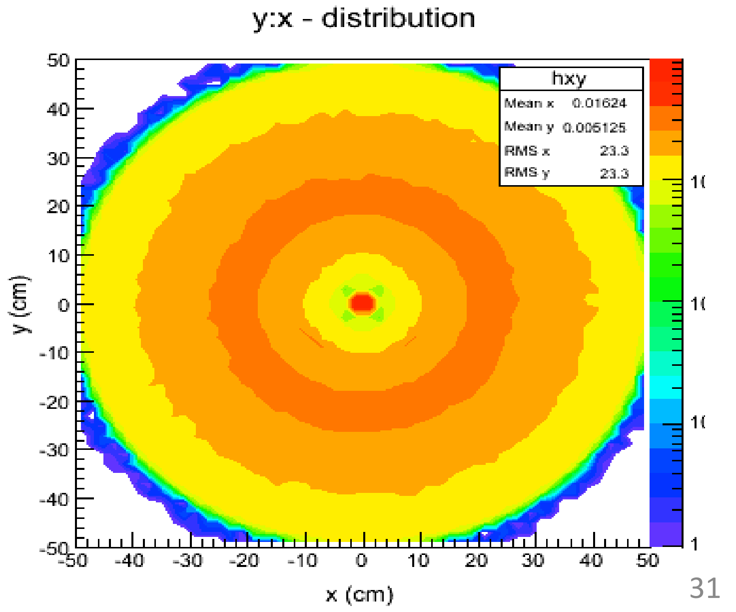
Technical Details: Target

- Lithium is 99.995% enriched ^7Li
  - $n + {}^7Li \Rightarrow \gamma + {}^8Li$
- ^8Li has $t_{1/2}$ = 840 ms
- End point energy of $\bar{\nu}_e$ is 14 MeV
  - Average ~6.5 MeV
- ^8Li spectrum and position distribution shown=>
- KamLAND:
  - Large volume
  - Fiducial mass: 897 metric tons
  - Good resolution:
    - Position: 12 cm/$\sqrt{E_{MeV}}$
    - Energy: 6.4%/$\sqrt{E_{MeV}}$

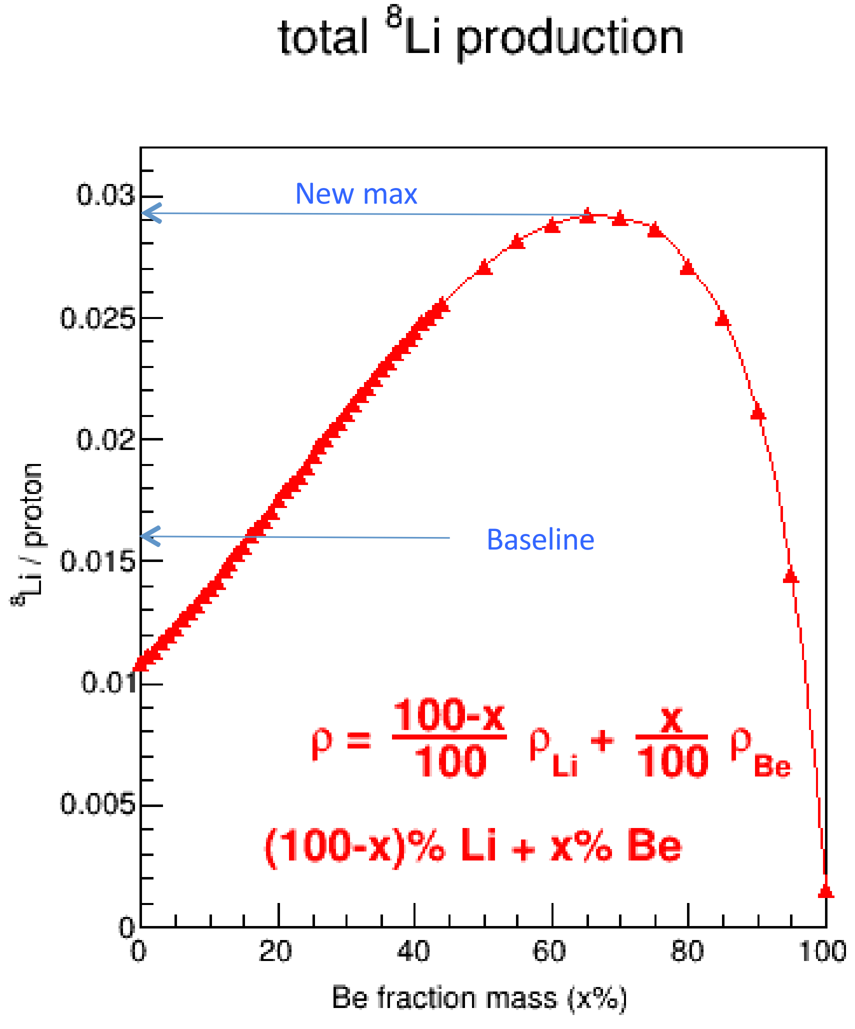


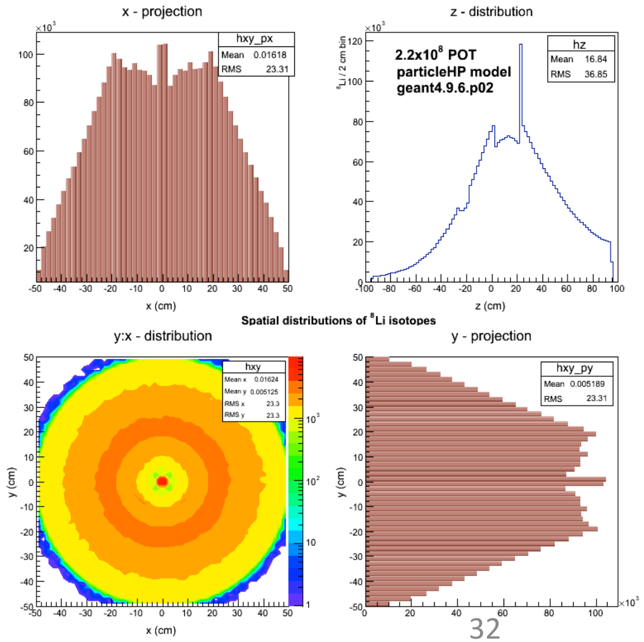


Beryllium is a great neutron multiplier



Maximizing Li7 Production





*Adriana Bungau, Huddersfield University

Context: DAEδALUS

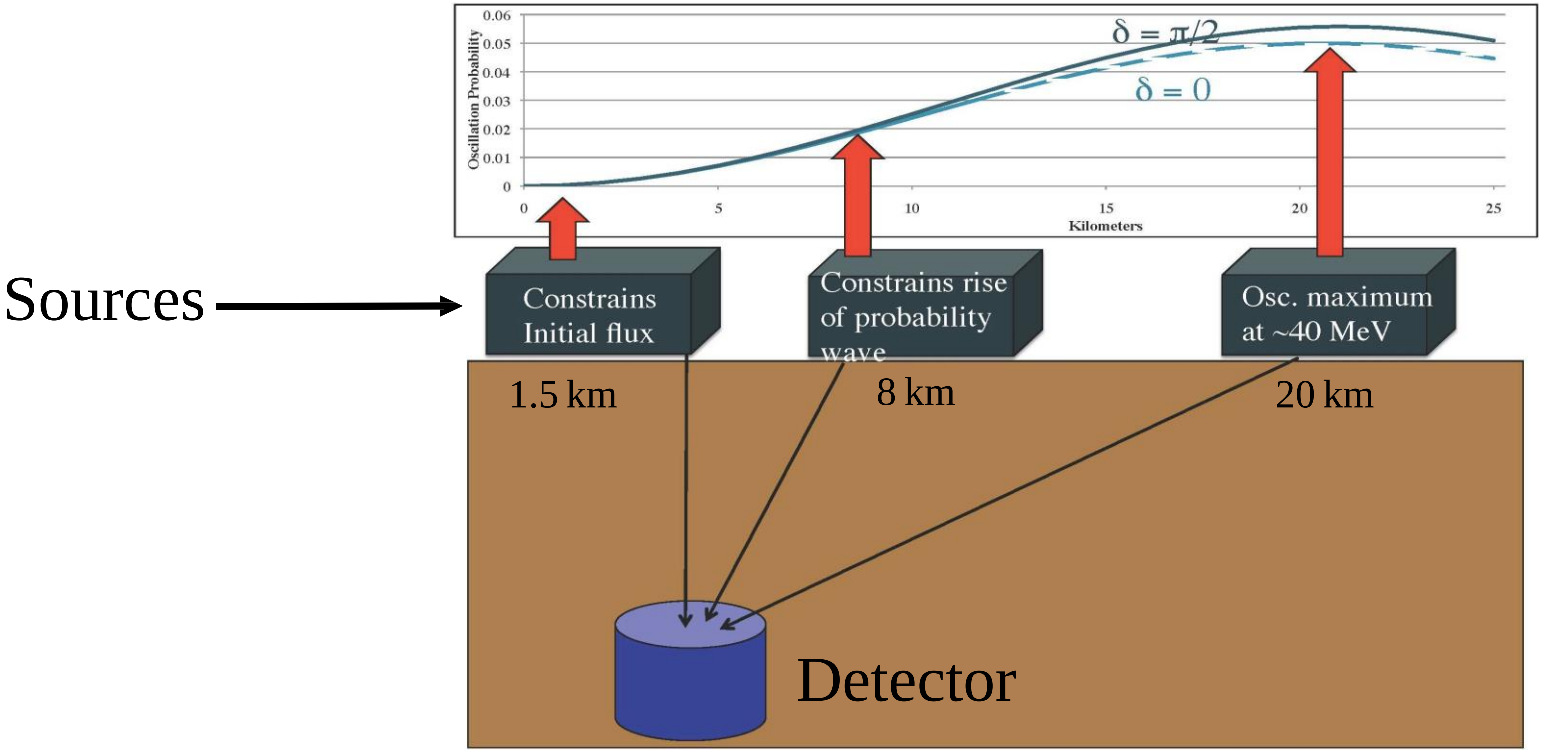
- Decay-At-rest Experiment for δ_{cp} studies At a Laboratory for Underground Science
- Goal is to measure δ_{cp}, the CP-violating phase of the neutrino sector. This phase will help resolve the matter-antimatter asymmetry observed in the universe.

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\boxed{\delta_{cp}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\boxed{\delta_{cp}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\boxed{\delta_{cp}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\boxed{\delta_{cp}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\boxed{\delta_{cp}}} & c_{23}c_{13} \end{bmatrix}$$

- DAEδALUS will run with antineutrinos, while other LBL experiments can run in neutrino mode.

Context: DAEδALUS

- DAEδALUS hopes to measure the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation spectrum from 3 ~40 MeV ν_μ sources at varying distances from a single detector.



Context: DAEδALUS

- The three sources are composed of:
  - A H_2^+ ion source, producing a beam of ions.
  - A DAEδALUS injector cyclotron which accelerates these ions to 60 MeV/amu,
  - A DAEδALUS superconducting ring cyclotron furtl accelerates the ions to 800 MeV/amu, then strips th electrons to produce a beam of protons.
  - Finally, a target on which these protons interact to produce mesons, which are stopped by a shield, and then decay (at rest) to produce neutrinos.