The IsoDAR Experiment

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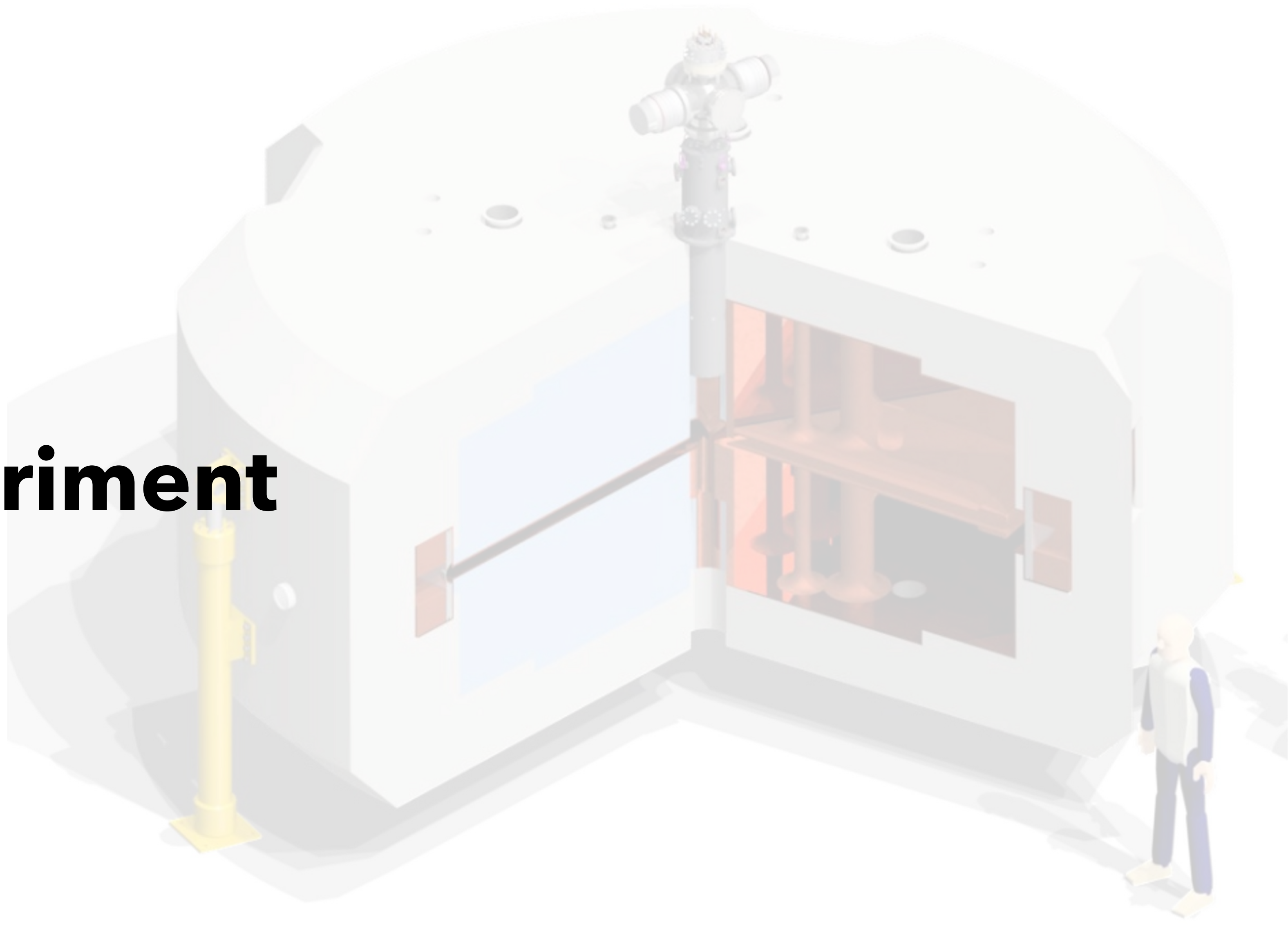
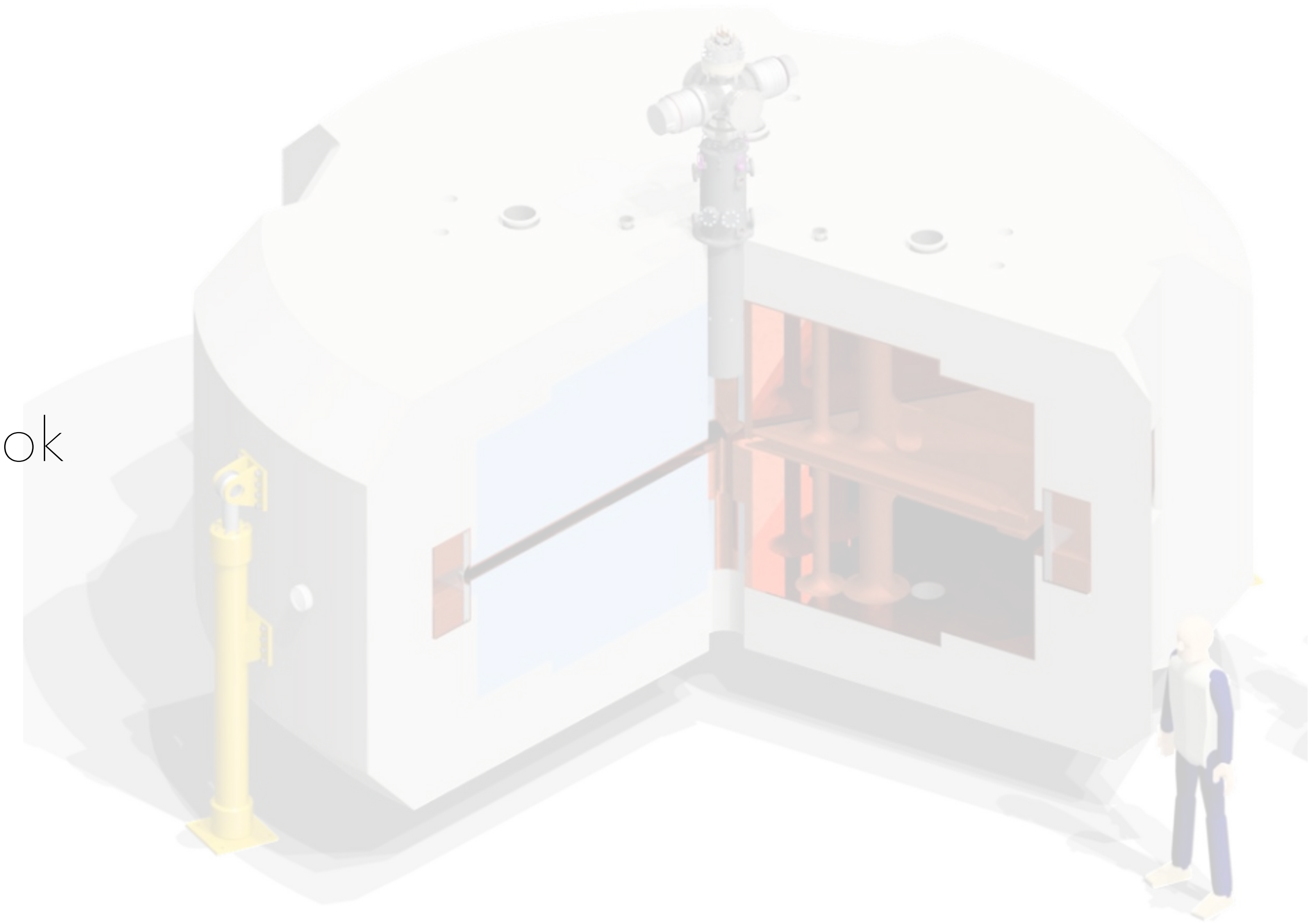
Brookhaven Forum



Outline

1. Experimental Setup
2. Physics with IsoDAR
3. Conclusions and Outlook



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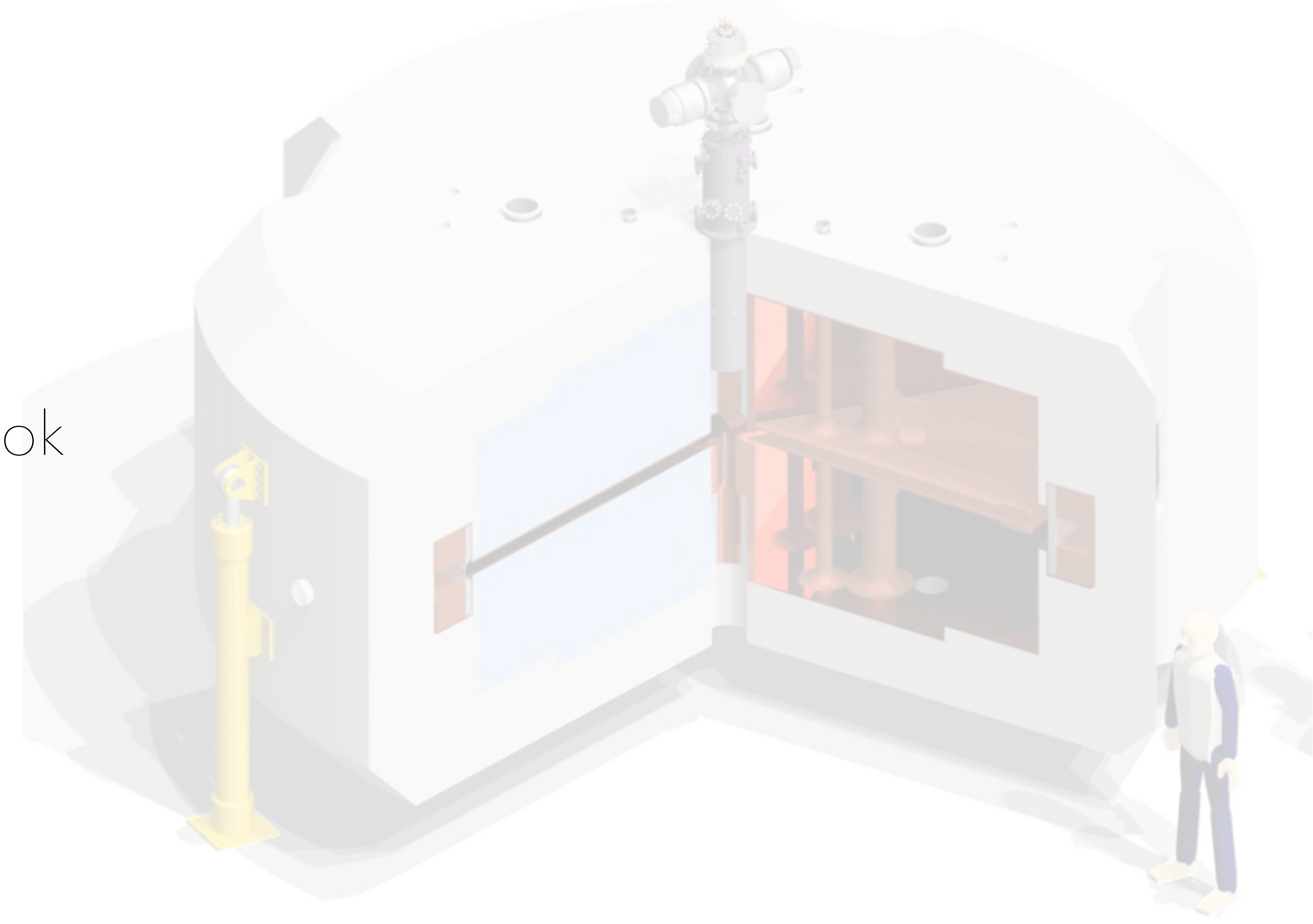
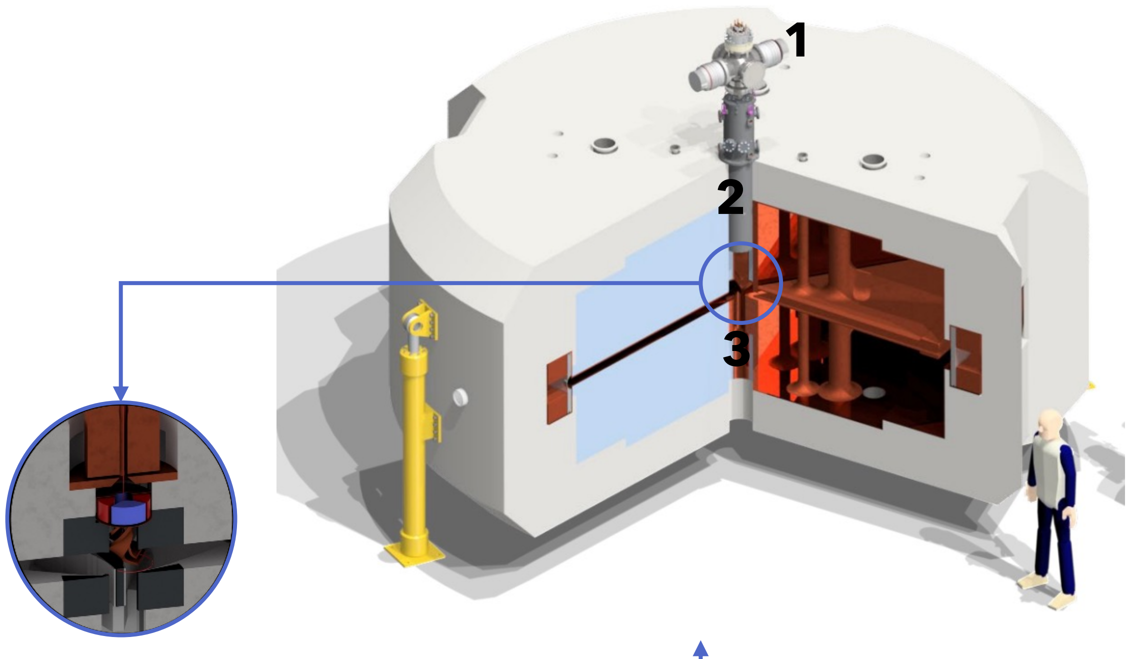
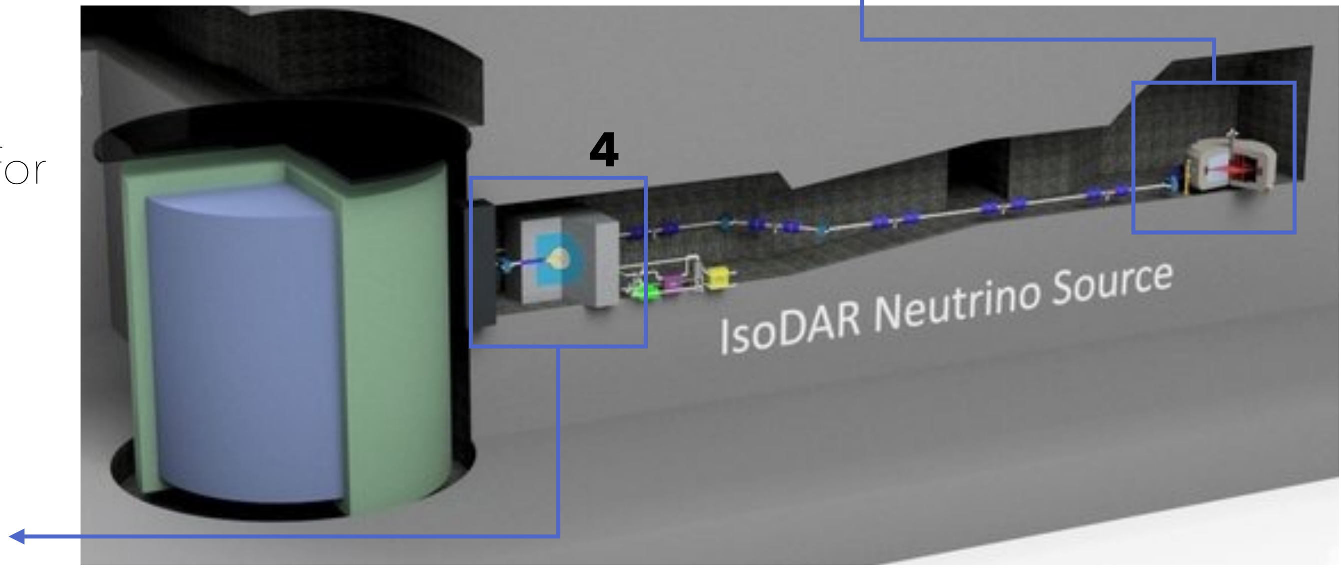
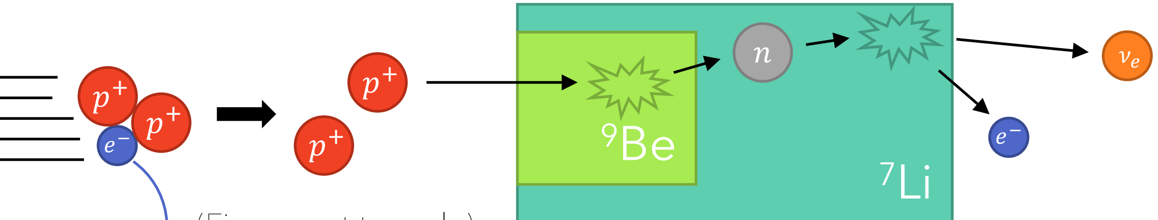


Experimental Setup
Overview

- IsoDAR is a proposed $\bar{\nu}_e$ source in which:
    1. H_2 plasma is created in the ion source
    2. Beam is pre-accelerated, focused, and bunched in the radiofrequency quadrupole (RFQ)
    3. Beam is injected into cyclotron & accel. to 60 MeV
    4. Electrons are dissociated from H_2^+, resulting 10 mA of 60 MeV protons irradiate target producing $\bar{\nu}_e$
- Installation planned at Yemilab beside a kiloton-scale liquid scintillator
- IsoDAR's high $\bar{\nu}_e$ production rate paves the way for state-of-the-art sensitivities to sterile neutrino searches and exotic neutrino property studies.







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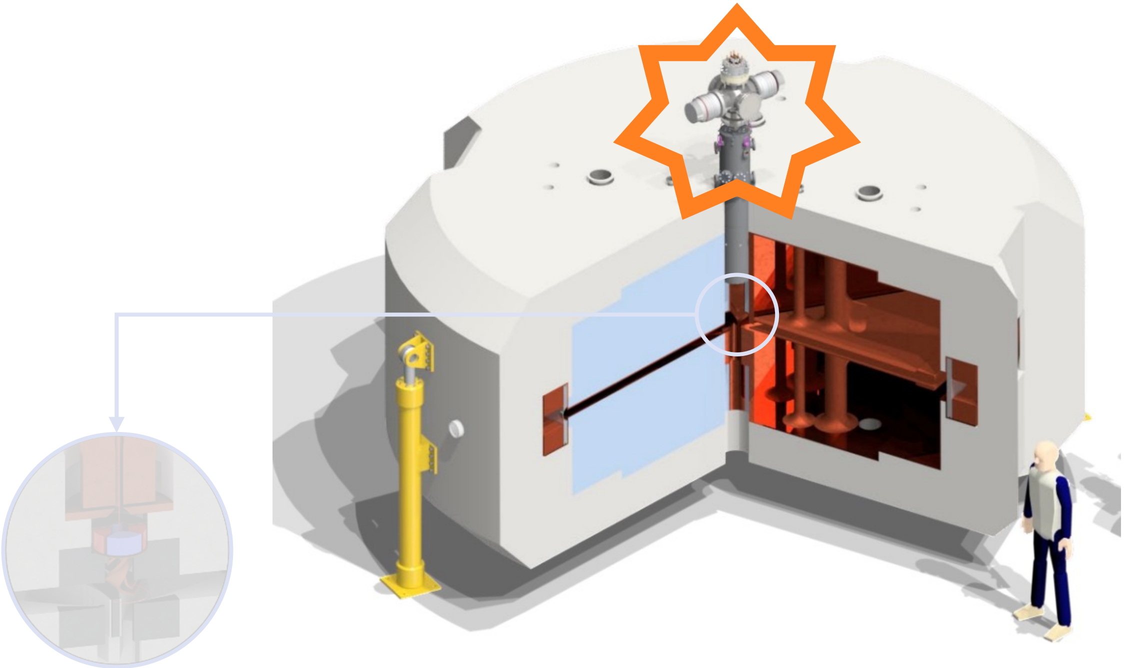
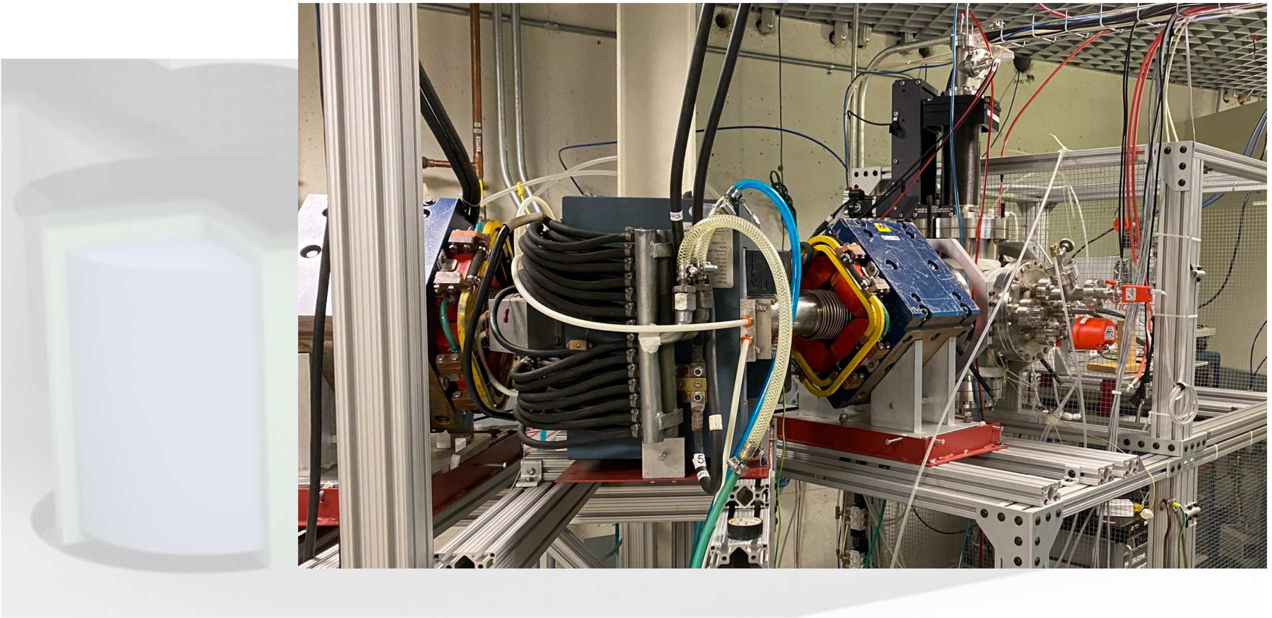
Experimental Setup
Ion Source

- Currently under commission at MIT's Plasma Science and Fusion Center
- Direct axial injection into the cyclotron require the ion source to have:
    - Low beam emittance
    - Minimally contaminated beam of H_2^+
    - High current (10 mA)
- Uses a multicusp ion source, with modifications, developed at LBNL
- Demonstrated this technology's feasibility by reaching an unprecedented 1 mA beam, low emittance (<0.05 π-mm-mrad, RMS, normalized), and high purity (80% H_2^+)

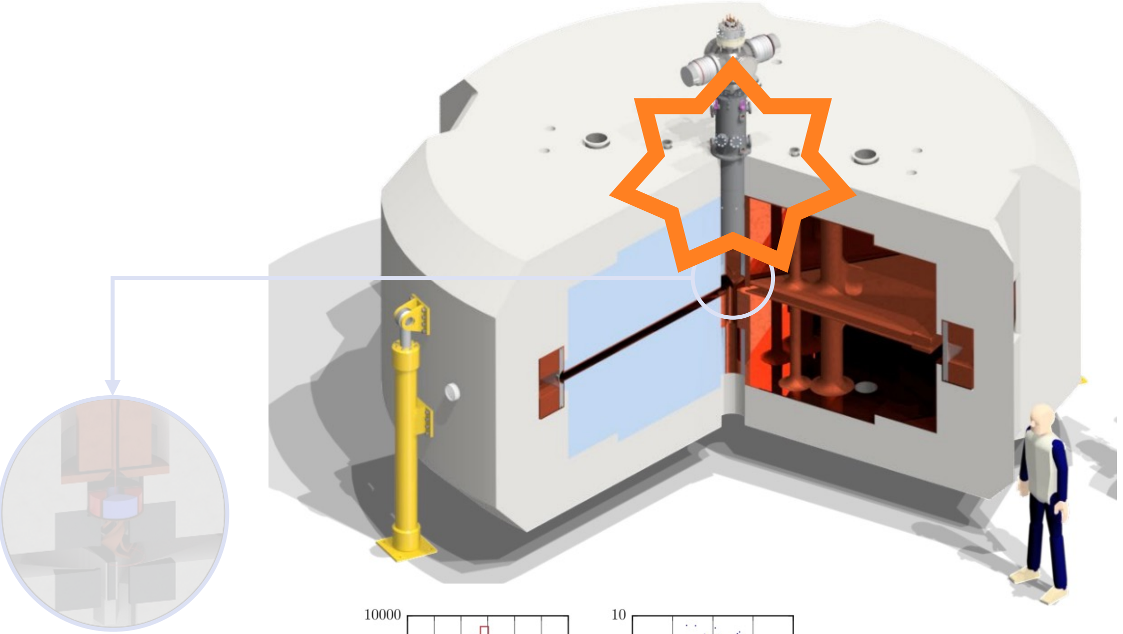




DOIs: 10.1063/1.4932395 & 10.1063/5.0063301

Experimental Setup
Pre-injection RFQ

- Currently being built at BEVATECH GmbH in Frankfurt, Germany
- Beam injection into cyclotrons generally difficult: has been shown that beam acceptances previously cap at 20%
- RFQs are especially useful for focusing, bunching, and even accelerating beams of low energy with high transmission while maintaining low beam emittances
- Necessary for clean injection into IsoDAR's spiral inflector and cyclotron
- Embedded in cyclotron yoke



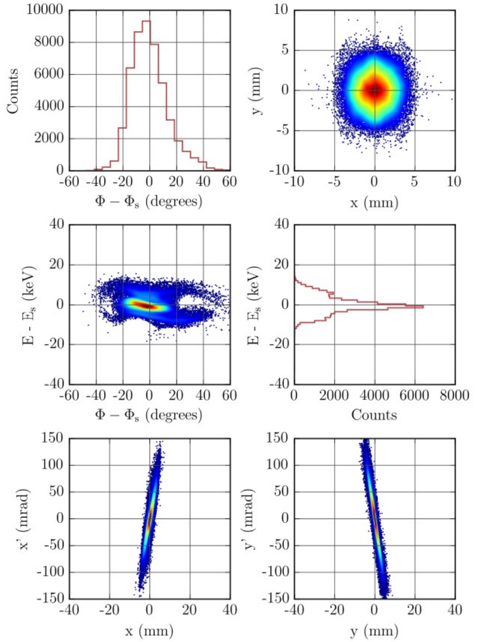
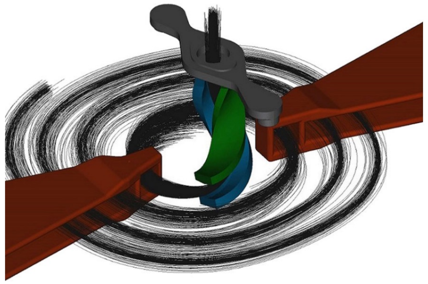


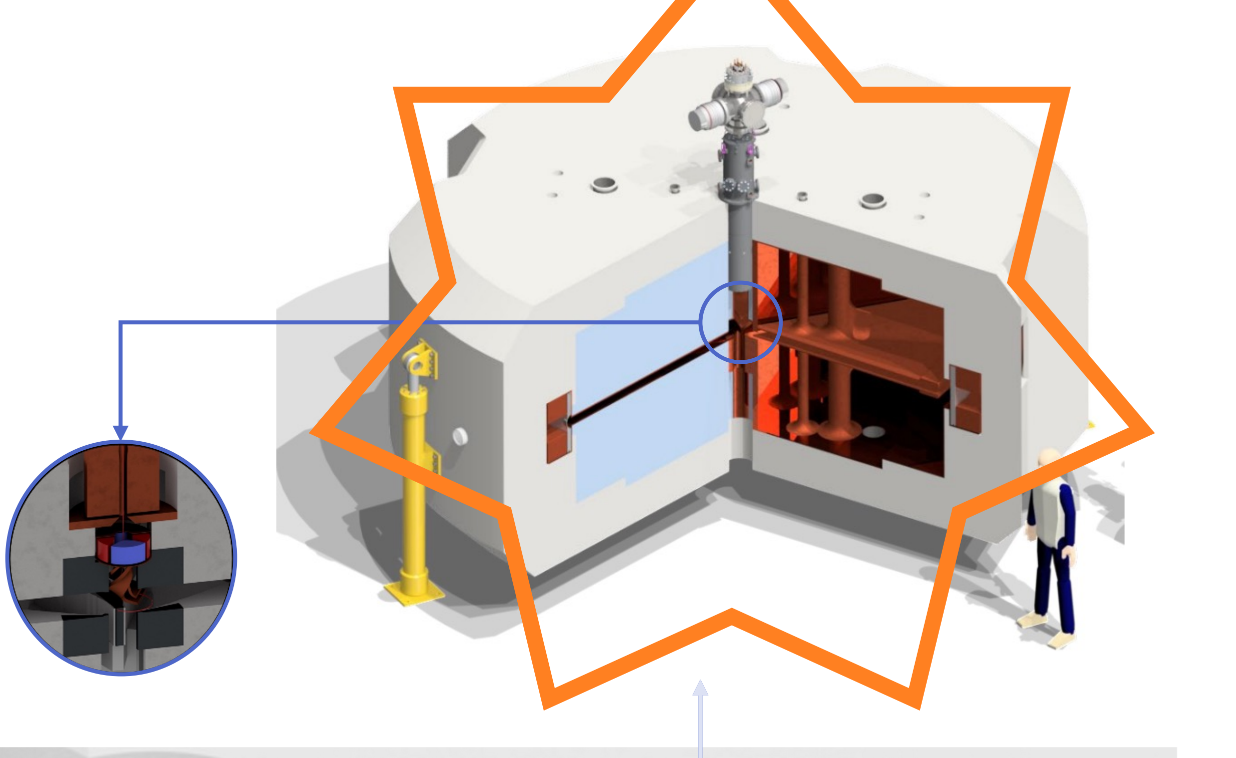
Figure 3: Phase Spaces of the RFQ output beam.

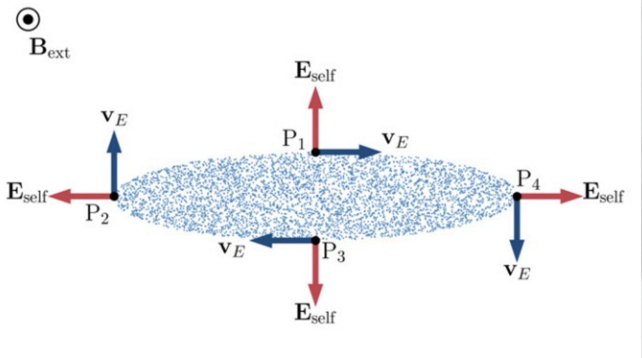
arXiv: 1710.00441, 1507.07258

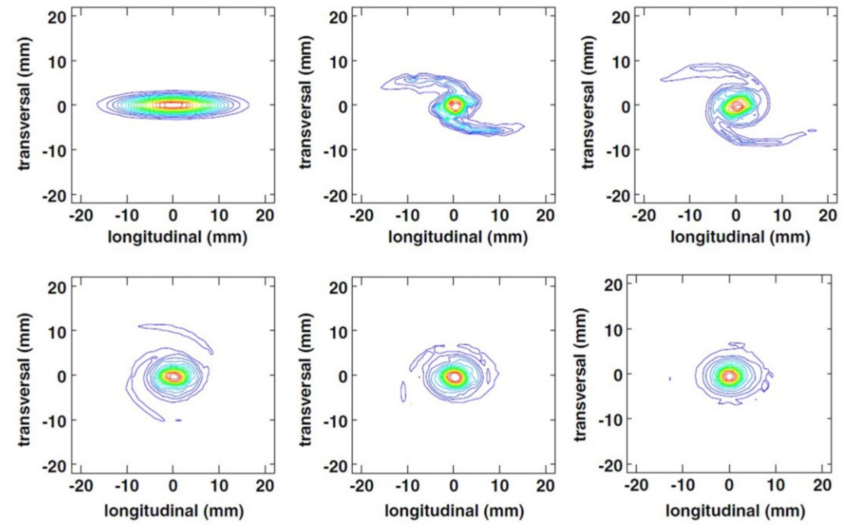
Experimental Setup
Injection and Cyclotron

- Beam is injected axially into cyclotron through a spiral inflector, where most of beam loss is expected to occur (~50%)
- IsoDAR cyclotron beam energy on-par to cyclotrons used for medical isotope production, but IsoDAR has much higher beam intensity
- High beam current poses space charge as a threat to clean extraction, but IsoDAR's cyclotron is designed to take advantage of *vortex motion* to allow for cleaner beam extraction
- Awarded ARDAP grant to develop 1.5 MeV/amu test cyclotron









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Experimental Setup
Target and Detector

- Target consists of a ^{9}Be, surrounded by a sleeve of a powdered ^{7}Li-^{9}Be mixture
- Produced neutrons are captured by ^{7}Li, resultant ^{8}Li immediately β-decays to produce flux of isotropic $\overline{\nu}_e$ with an average energy 6.4 MeV
- Antineutrinos detected by liquid scintillator through IBD events
  - Coincidence signal with prompt positron + delayed neutron capture (giving a 2.2 MeV γ)
  - Expecting ~10^6 such events in 5 years of running

PRD 105.052009

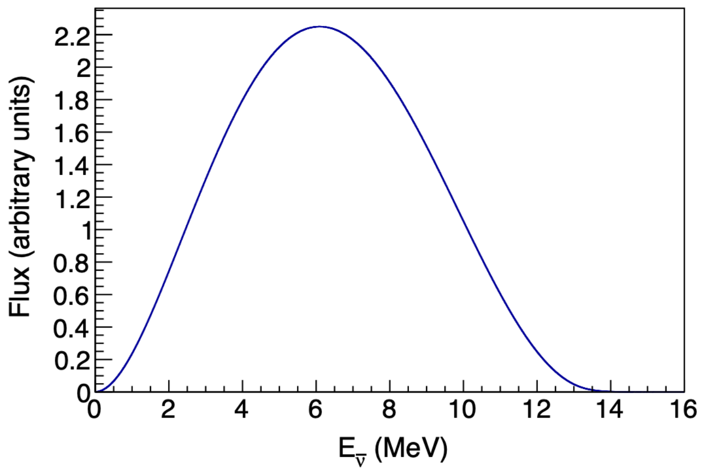
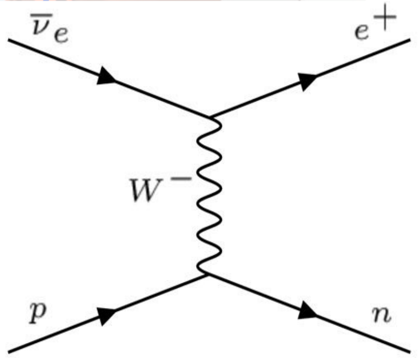
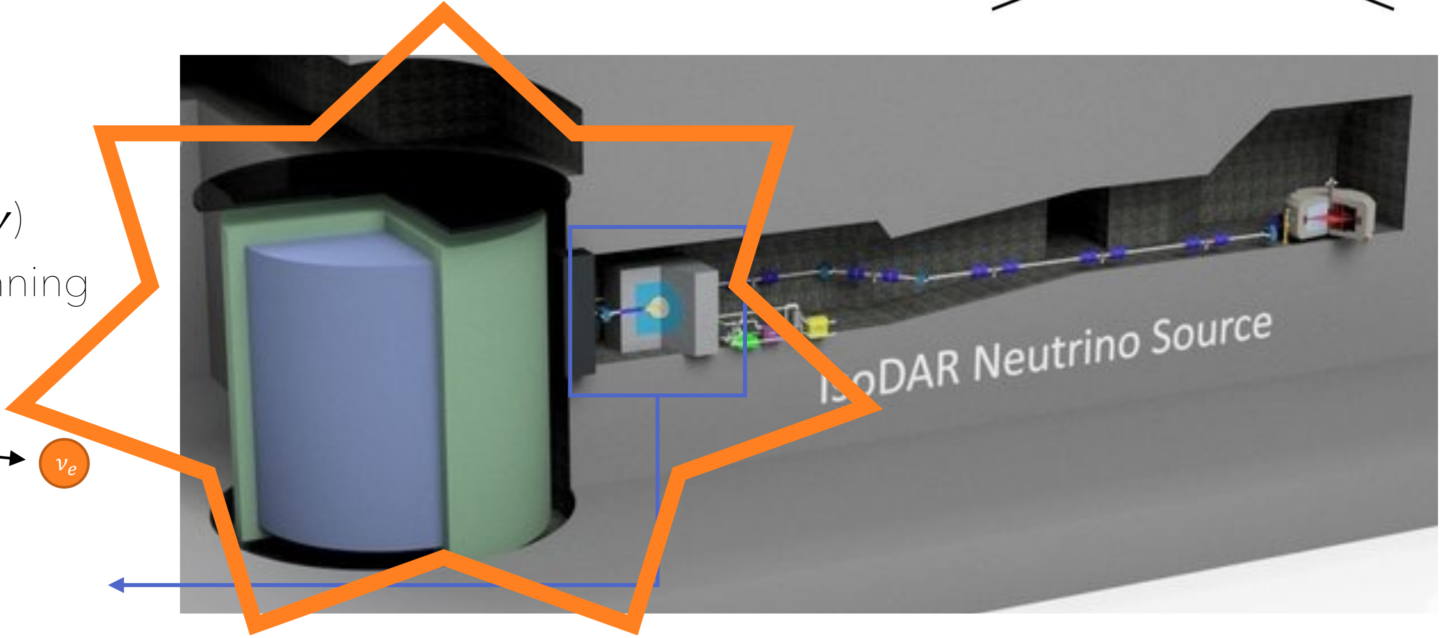
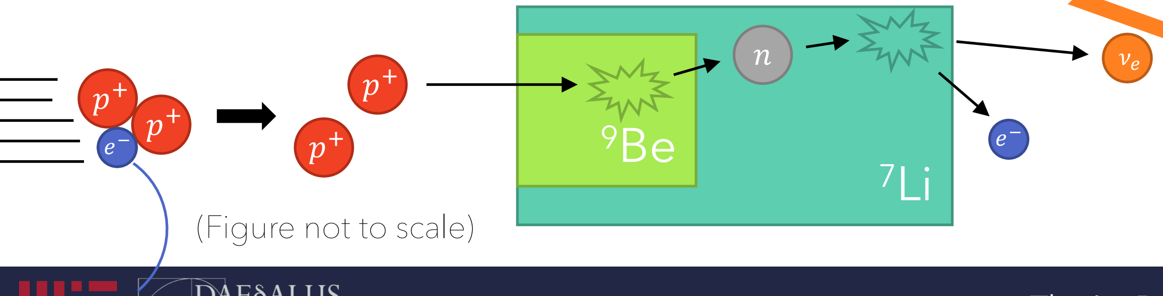


FIG. 1. The IsoDAR $\bar{\nu}_e$ flux arising from ^{8}Li beta decay, adapted from Ref. [4].







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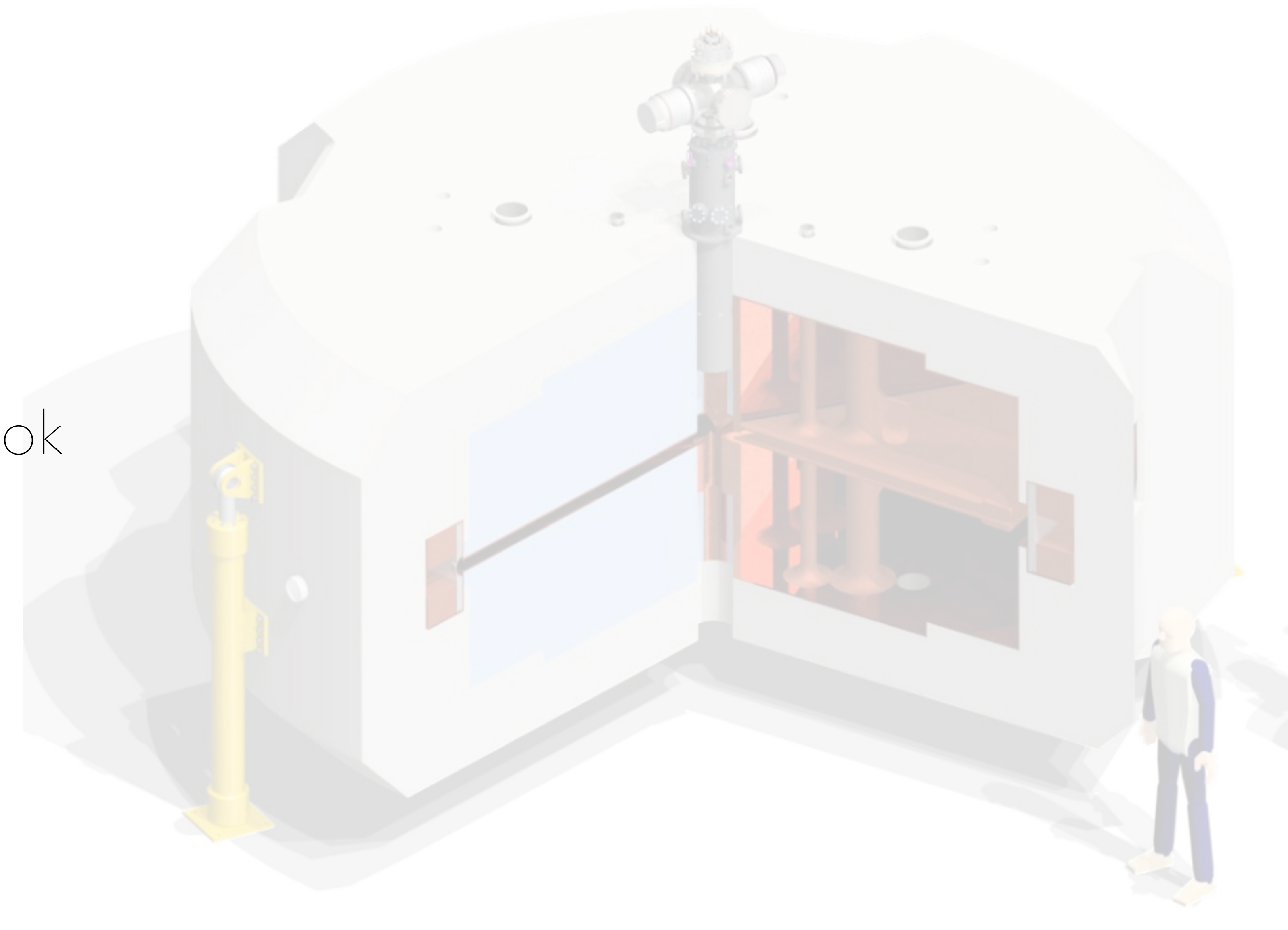
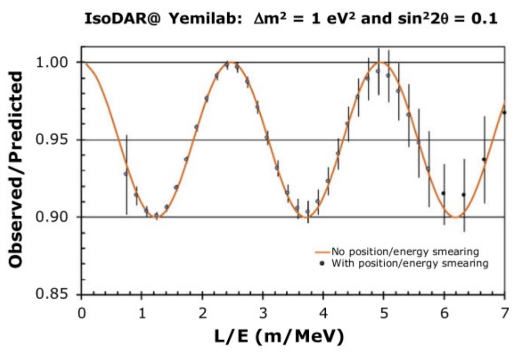


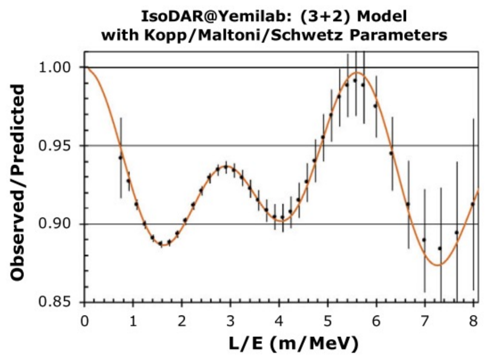
Physics with IsoDAR
Sterile Neutrino Searches

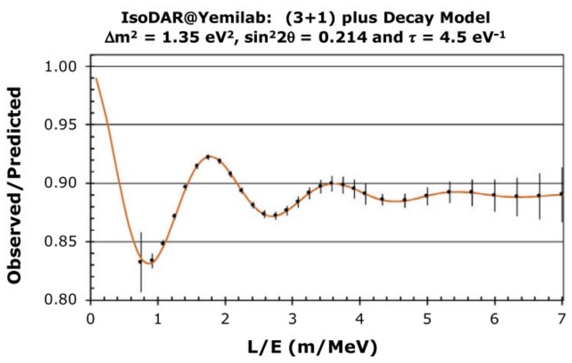
- As mentioned previously, IsoDAR will expect ~10^6 IBD events in 5 years of running. This allows us to reach 5σ sensitivity!
- IsoDAR primarily searches for sterile neutrino in the $\overline{\nu}_e$ disappearance channel. In the 3+1 case:

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27\, \Delta m_{41}^2 L/E)$$

- There are other sterile neutrino models IsoDAR can test:







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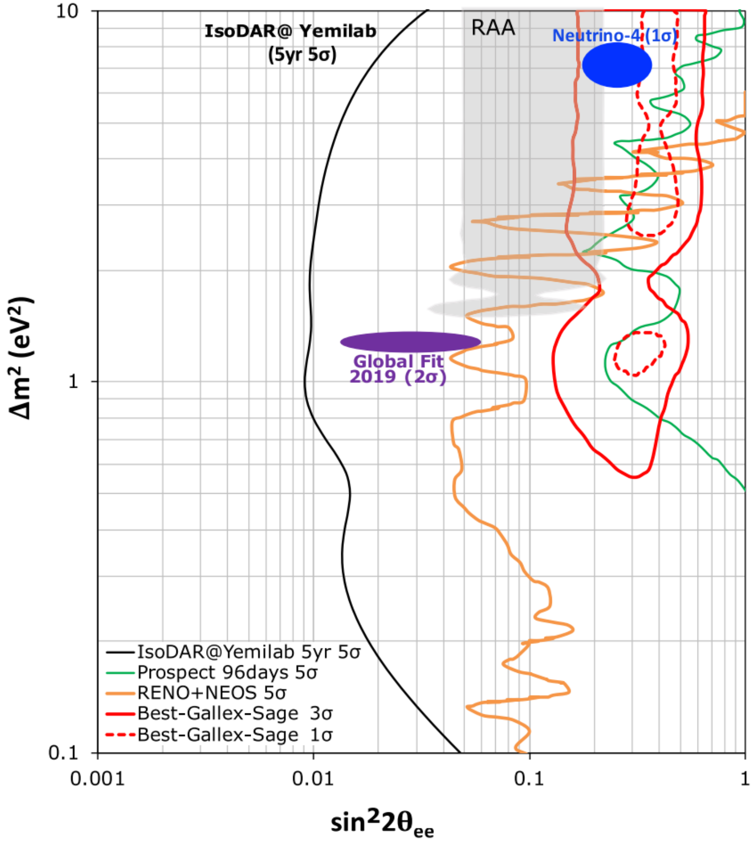


FIG. 5. The 5σ sensitivity achievable by the IsoDAR@Yemilab experiment in 5 years of running, compared to a number of existing electron-flavor disappearance measurements.

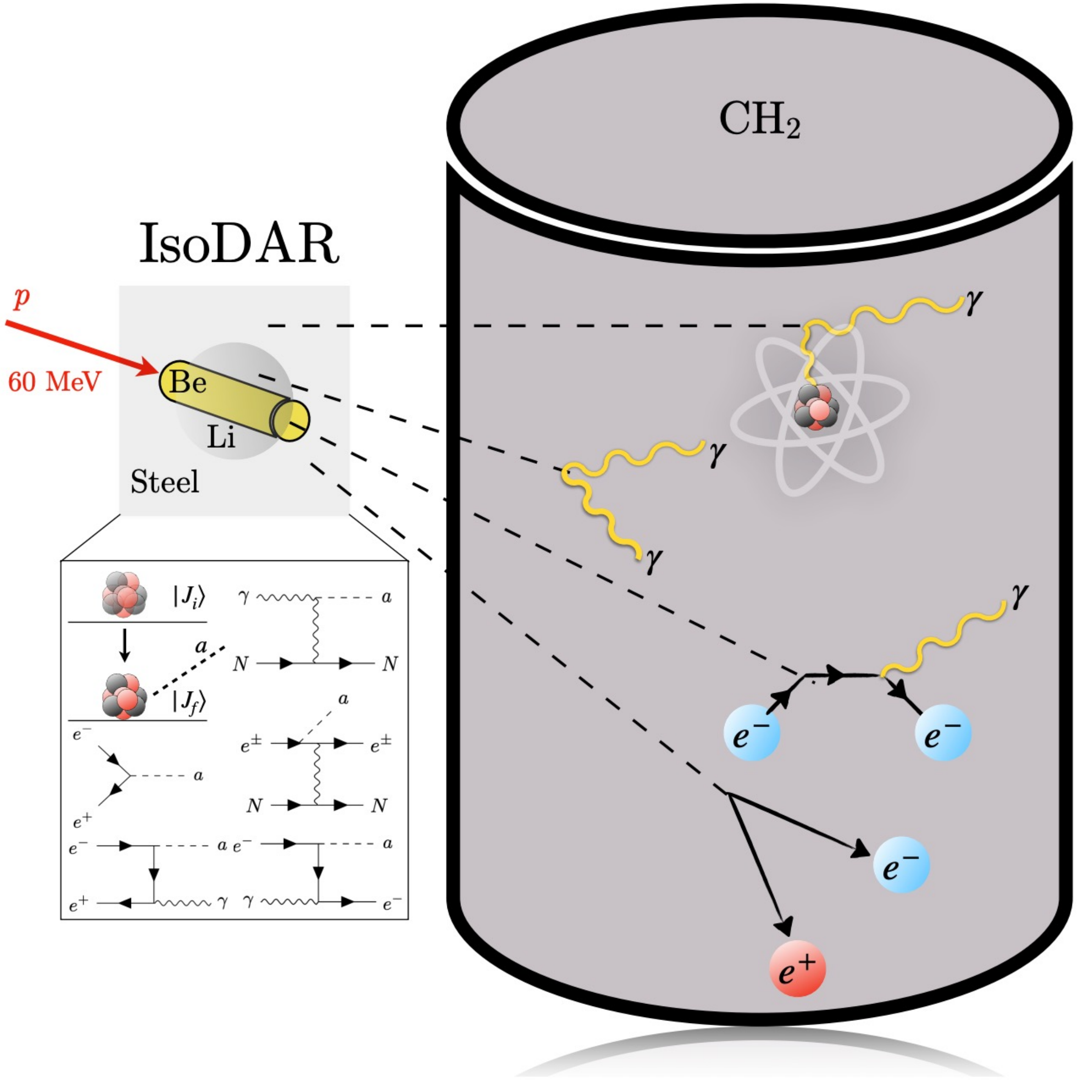
Physics with IsoDAR
ALP Searches

- As IsoDAR's target is irradiated with protons, nuclei de-excite producing an isotropic flux of photons (with energy ~ a few MeV)
- Assuming electromagnetic ALP couplings:

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \ \mathcal{L}_{ae} \supset i g_{ae} a \overline{\psi}_e \gamma^5 \psi^e$$

  ALPs can be produced via QED-like channels: $\gamma e^- \to a e^-$, $e^+ e^- \to a$, $e^+ e^- \to a\gamma$, $e^\pm N \to e^\pm N a$, and detected through similar scattering or decays ("light shining through walls")

- IsoDAR can improve sensitivity to measurements of couplings to photons, electrons, and nucleons + photons / nucleons + electrons in 5 or 10 years of running



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Physics with IsoDAR
And more…

- Dark neutrons (n') (2201.02603)
  - Dark matter candidate that may explain baryon number asymmetry, discrepancies in neutron lifetime measurement between beam and bottle experiments
  - γ emitted through neutron capture in the scintillator are mono-energetic
- Medical isotope production (Nature Rev. Phys. 1, 533-535)
  - Once IsoDAR is operational, its technology becomes plug-and-play: choose an ion to accelerate and a target
  - Cheap*, domestic production of medical isotopes like Germanium-68, Actinium-225

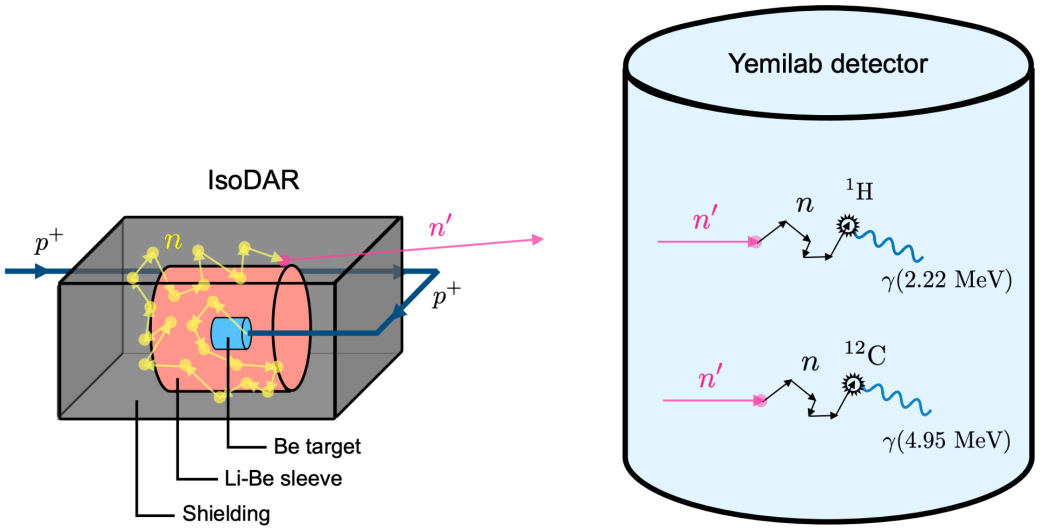

Table 1 | **Comparison of IsoDAR with IBA cyclotrons**

Parameter	IsoDAR	IBA C-30	IBA C-70
Ion species accelerated	H_2^+	H^-	H^-
Maximum energy (MeV AMU^{-1})	60	30	70
Proton beam current (mA)	10	1.2	0.75
Available beam power (kW)	600	36	52
Pole radius (m)	1.99	0.91	1.24
Outer diameter (m)	6.2	3	4
Iron weight (tonne)	450	50	140
Electric power required (MW)	2.7	0.15	0.5

IsoDAR, isotope decay at rest.

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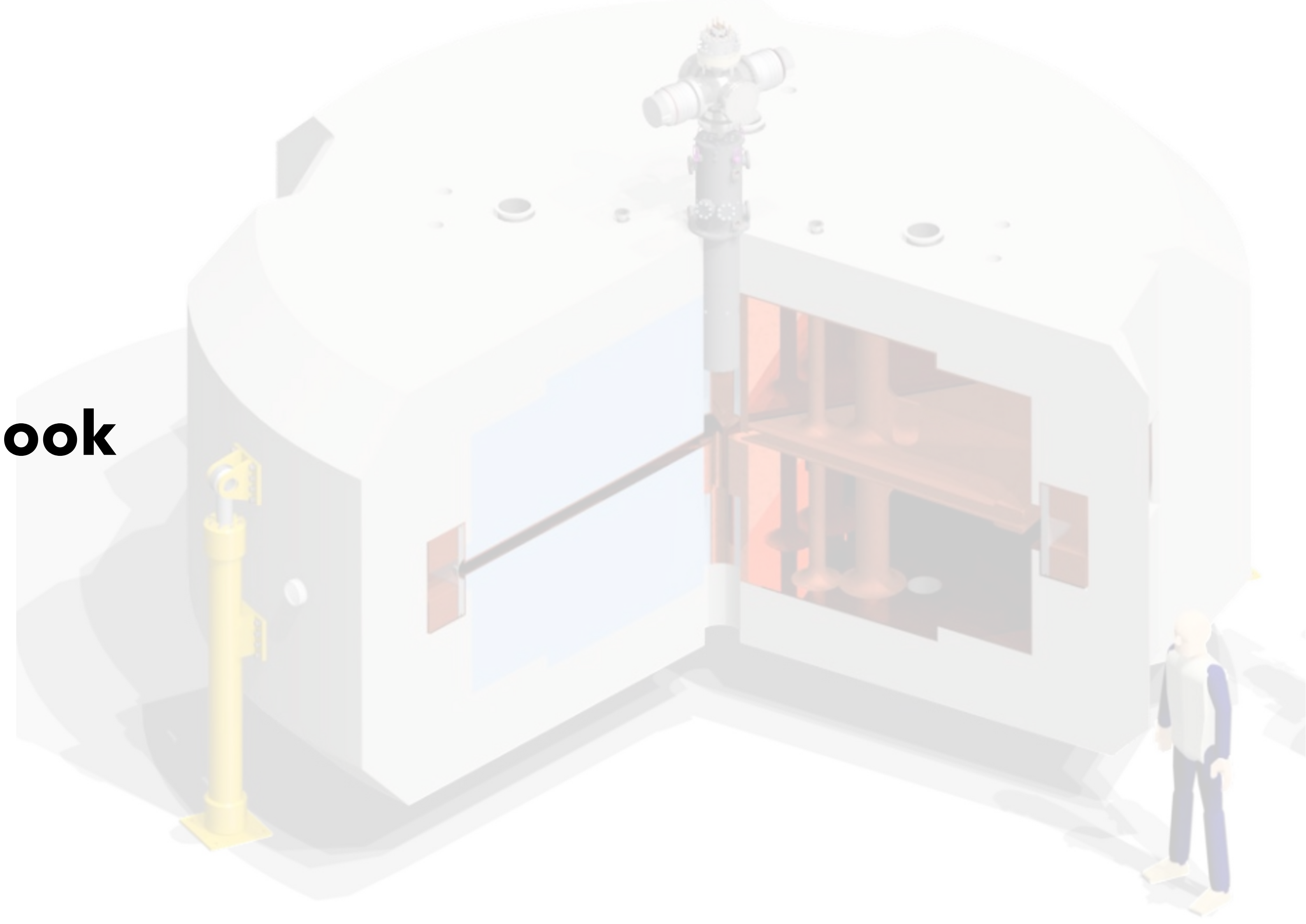


Conclusions and Outlook

- The development of IsoDAR has is a treasure trove of innovation for accelerator physics
- Building high-power cyclotrons is of immediate relevance to neutrino and BSM physics, but also has cross-cutting applications in medical physics
- Cyclotrons for particle physics can be cost-effective and shareable

Questions?

Backup

Details on ALP Searches

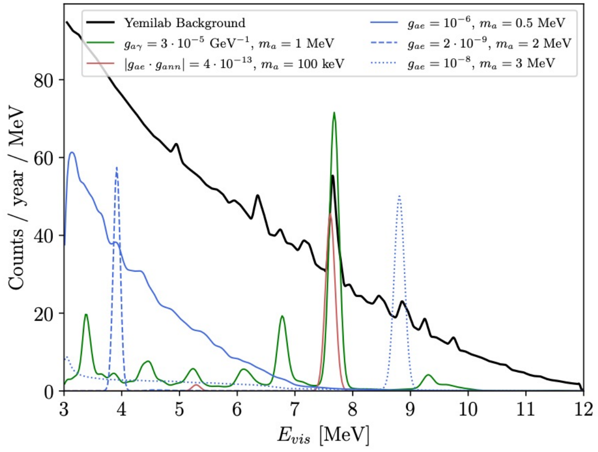
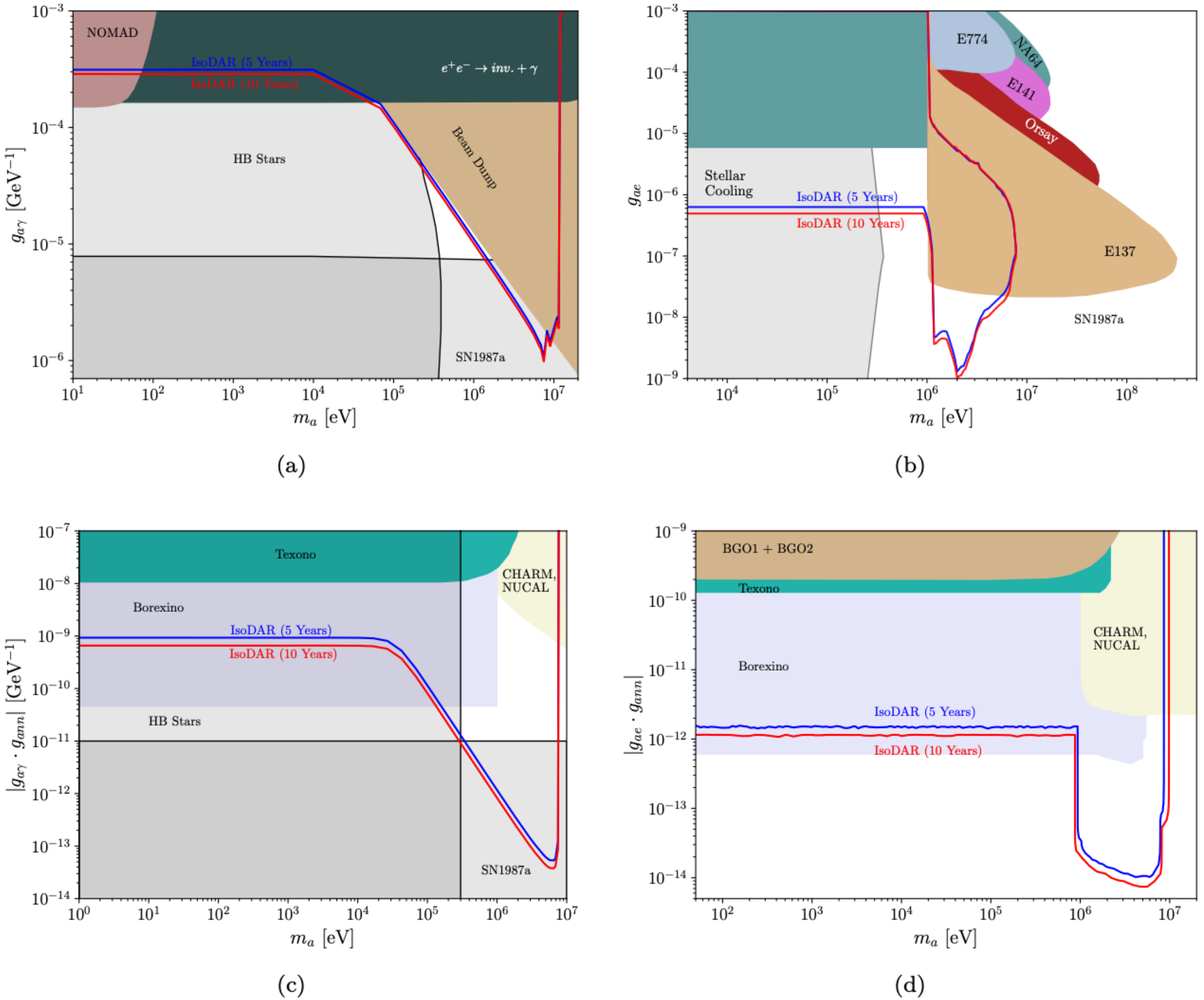


FIG. 3. ALP production and detection in various coupling combinations. Nuclear transitions and emission lines in the photon flux showing up for $g_{a\gamma}$ and g_{ann} dependent signals (red, green) while resonantly produced ALPs through e^+e^- to sharp peaks positioned at $\propto m_a^2$ (blue), provided that $m_a > 2m_e$. The Yemilab background is shown in black for comparison. A detector energy resolution of 3% is applied.



TL: axion-photon. TR: axion-electron. BL: axion-nucleon + axion-photon. BR: axion-nucleon + axion-electron.

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Details on Dark Neutron Searches

Limits on the neutron-dark neutron transition amplitude $\epsilon_{nn'}$ as a function of the absolute mass splitting $|\delta m|$. The solid (dashed) curves correspond to $\delta m > 0$ ($\delta m < 0$). We show the 10 events/year sensitivity of the near-future IsoDAR experiment at Yemilab as a black band.