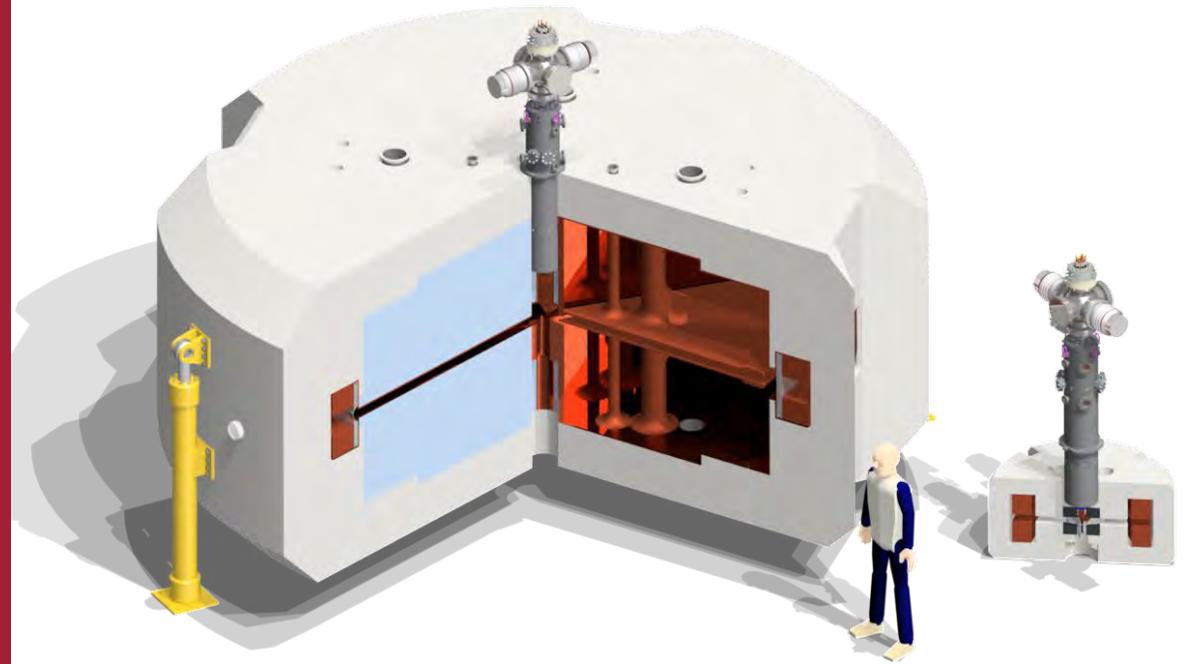


# IsoDAR@Yemilab – A definitive search for exotic neutrinos and other BSM physics

Daniel Winklehner  
for the IsoDAR collaboration

WG3 – Accelerator Physics  
NuFACT'22 - 08/05/2022





# IsoDAR: International collaboration of ~30 scientists

Co-spokesperson: Josh Spitz ([spitzj@umich.edu](mailto:spitzj@umich.edu))

Co-Spokesperson: Daniel Winklehner ([winklehn@mit.edu](mailto:winklehn@mit.edu))

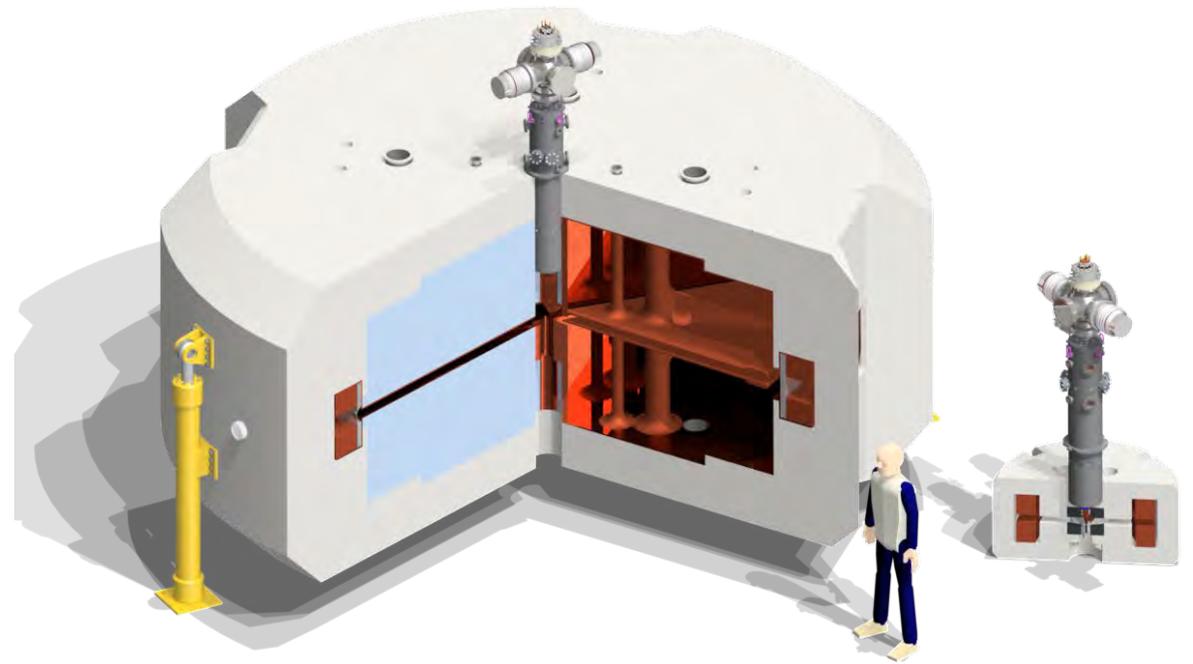


## Industry Partners



# Outline

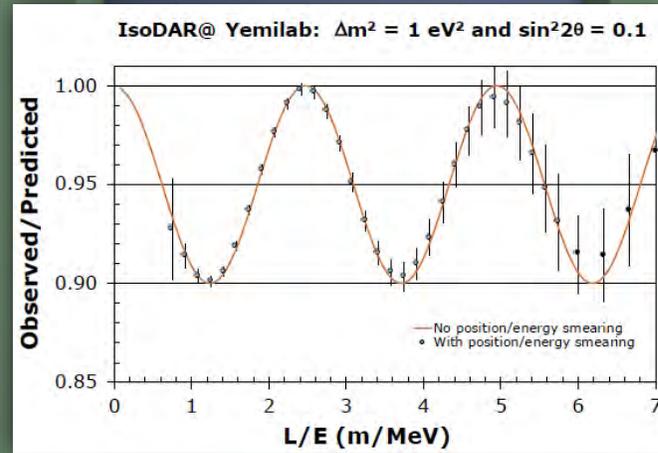
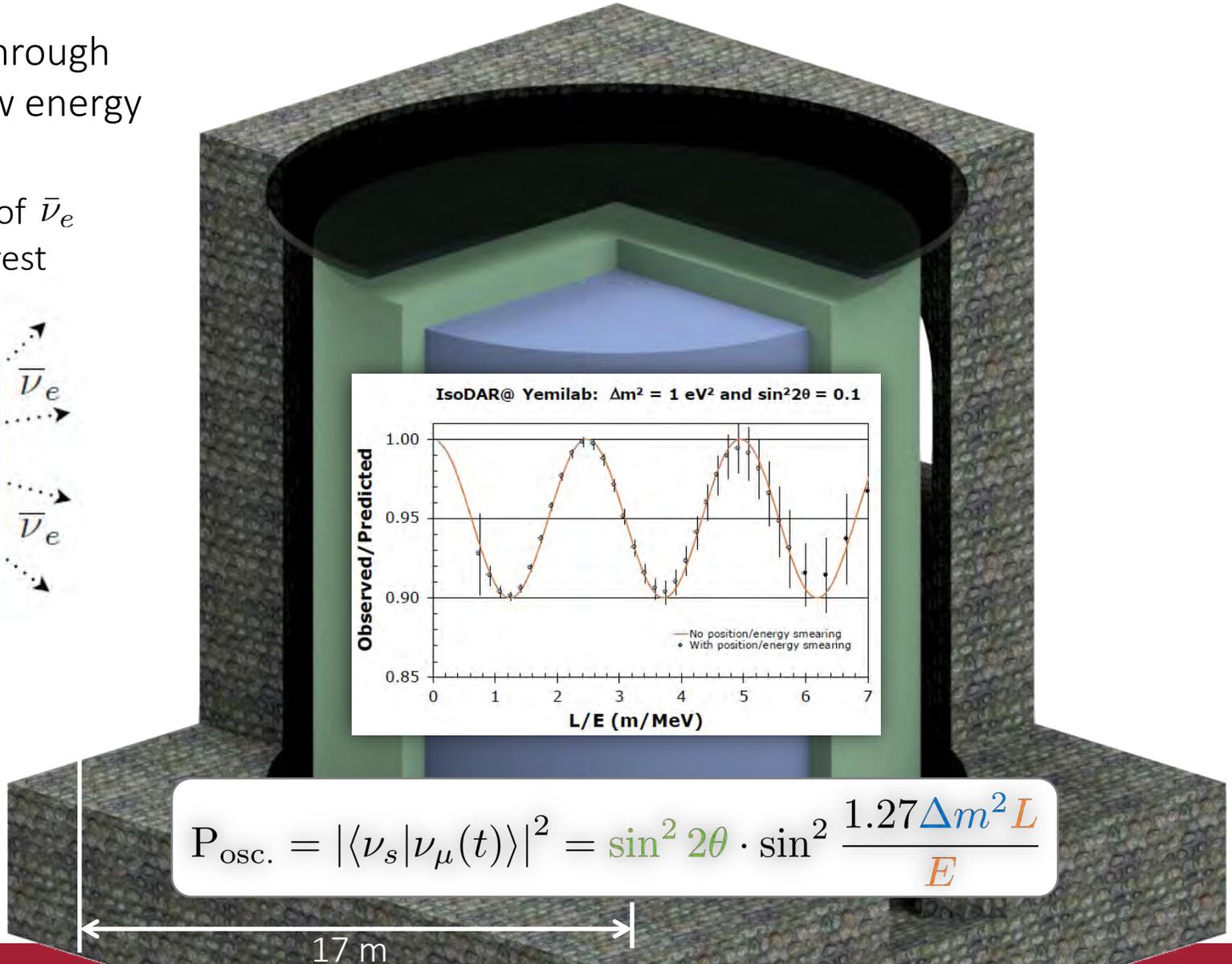
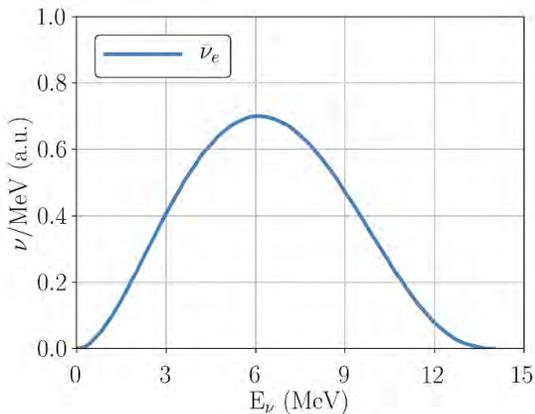
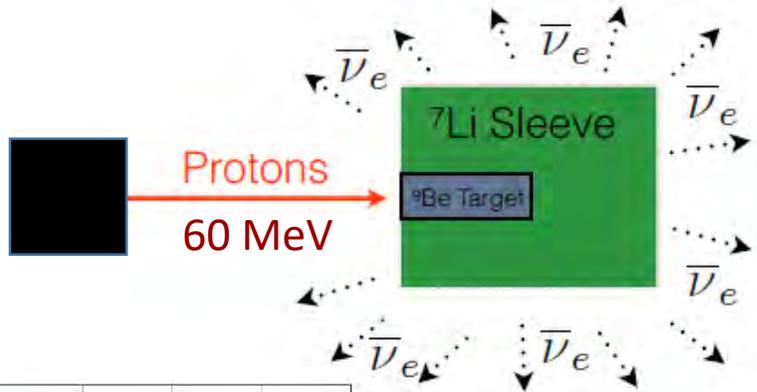
- IsoDAR@Yemilab
  - Overview
  - Physics
- Accelerator
  - Ion Source
  - RFQ
  - Cyclotron
  - Simulations
  - Demonstrations
- Target



# Isotope Decay-At-Rest (IsoDAR) from ${}^8\text{Li}$ produces well understood $\bar{\nu}_e$ flux

Search for noble (sterile) neutrinos through oscillations at short distances and low energy

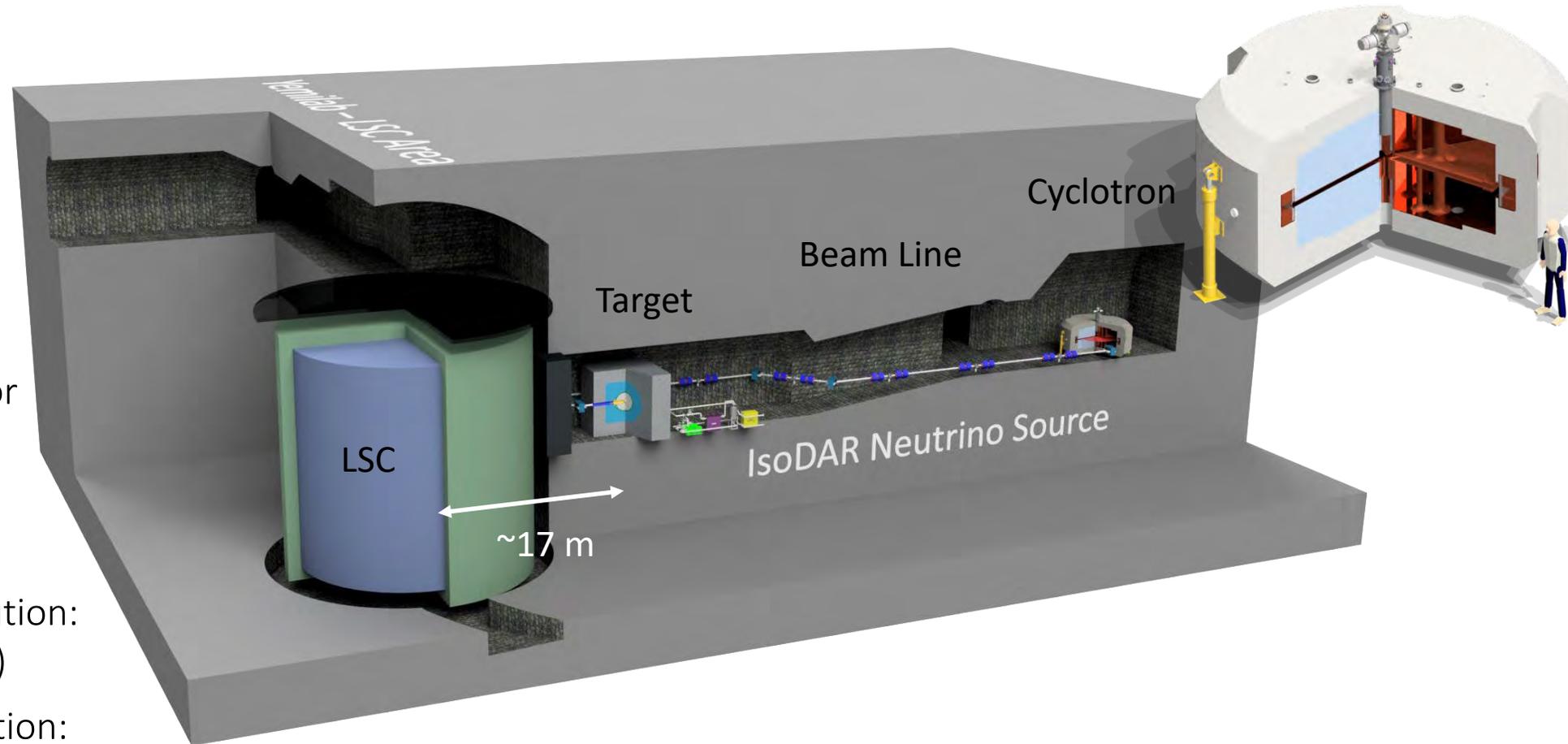
Isotropic source of  $\bar{\nu}_e$  through decay at rest



$$P_{\text{osc.}} = |\langle \nu_s | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

17 m

# Bringing the $\bar{\nu}_e$ to the Detector...at Yemilab in Korea



- Target:  
2.26 kton liquid scintillator  
15 m x 15 m cylinder
- Buffer: 1.14 kton
- Veto 2.41 kton
- Prompt ( $e^+$ ) energy resolution:  
 $\sigma(E) = 6.4 \%/ \sqrt{E}$  (MeV)
- Prompt ( $e^+$ ) vertex resolution:  
 $\sigma(\text{vertex [cm]}) = 12/ \sqrt{E}$  (MeV)
- Total  $\bar{\nu}_e$  IBD efficiency: 92%

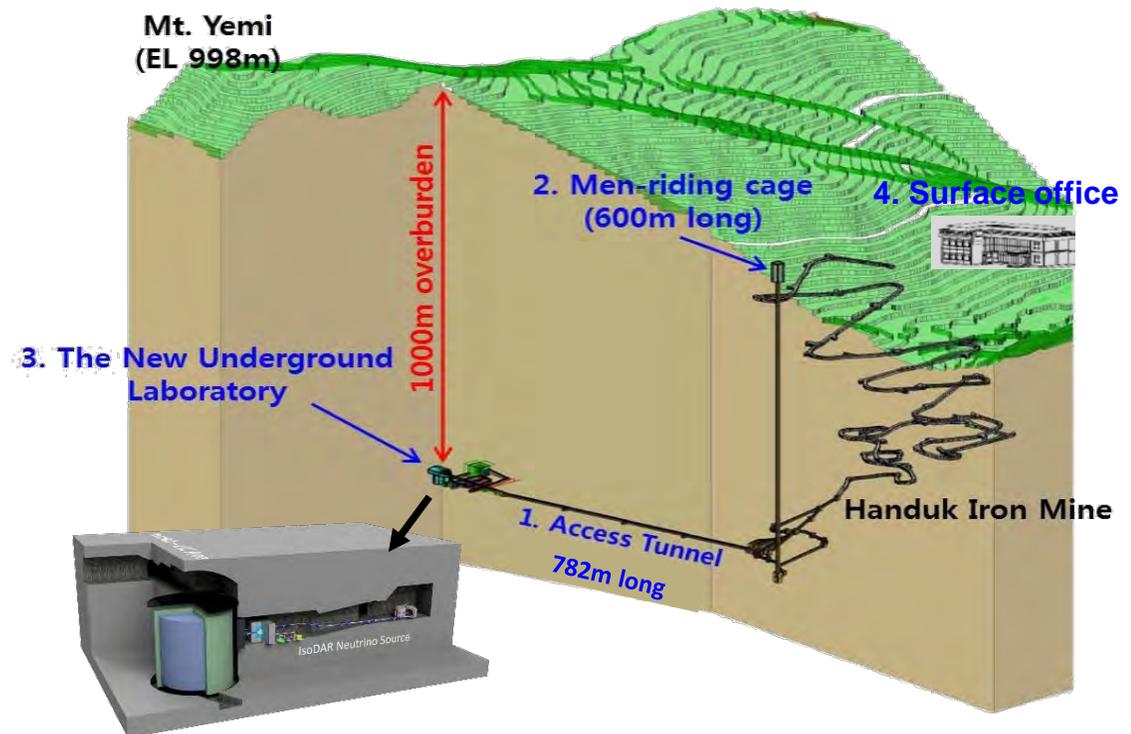
Physics Paper: <http://arxiv.org/abs/2111.09480>, PRD 2022

IsoDAR@Yemilab – CDR: <http://arxiv.org/abs/2110.10635> arXiv 2021 5



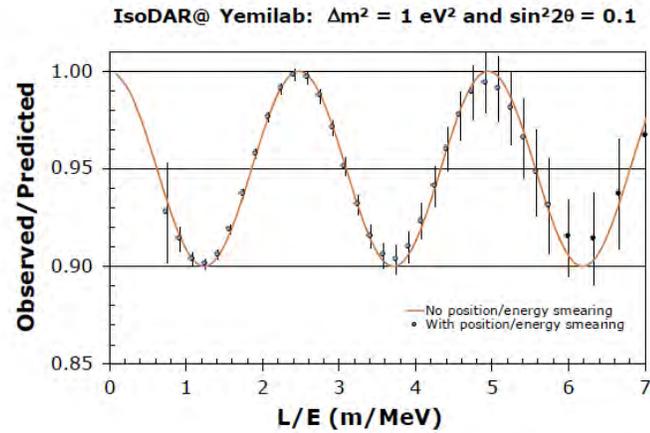
# Yemilab

- Underground facility at Mt. Yemi in Korea
- Operated by Institute of Basic Science (IBS)
- > 1000 m overburden (cosmic ray shielding)
- Excavation finished, LSC proposal underway
- Drive-in access

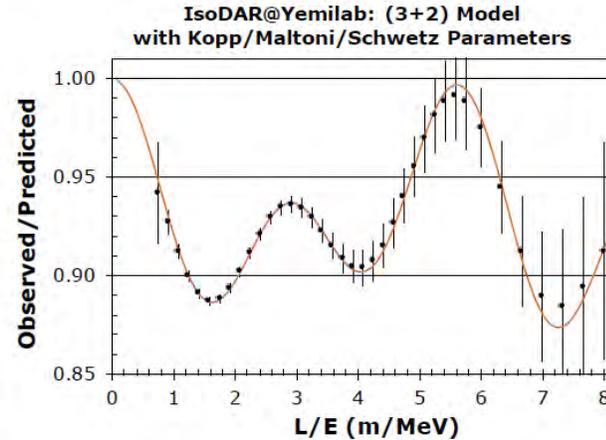


# Physics 1: World-leading search for noble (sterile) neutrinos through precision L/E measurements

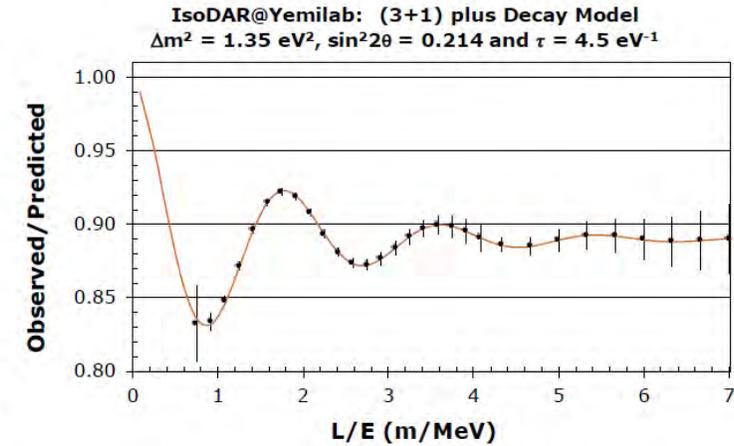
one noble neutrino



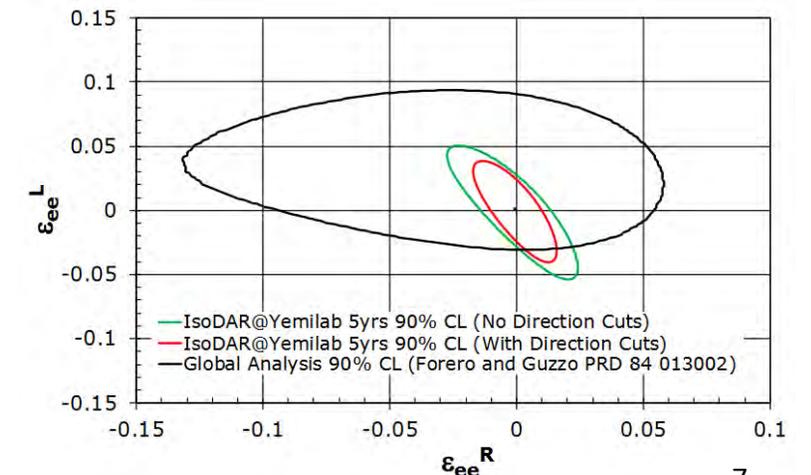
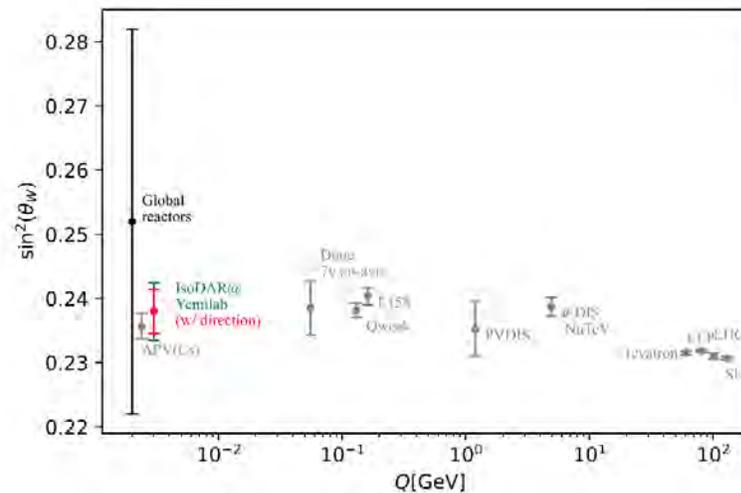
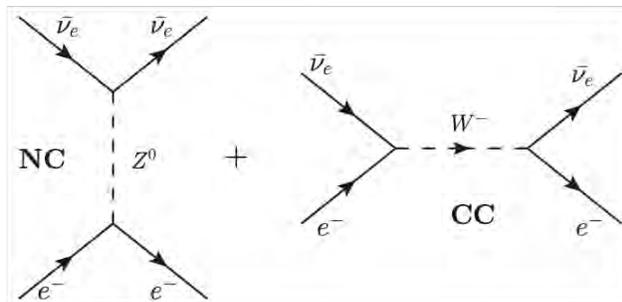
two noble neutrinos



one that decays...



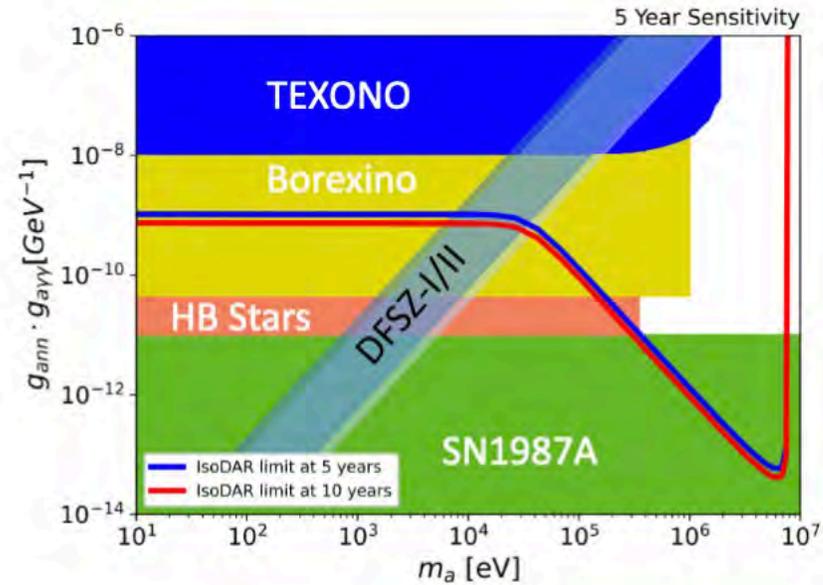
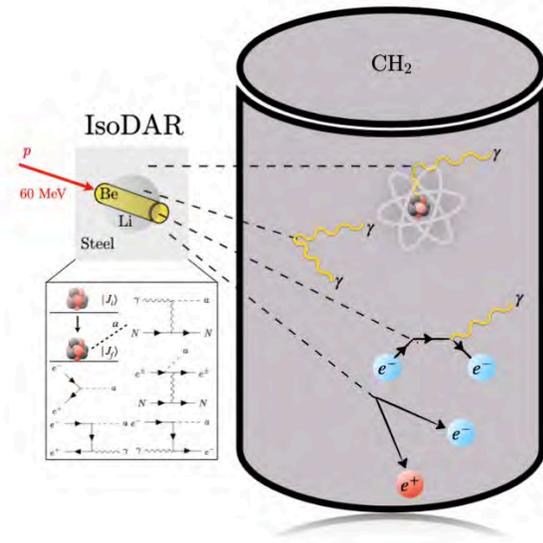
# Physics 2: Unprecedented $\bar{\nu}_e - e^-$ elastic scatter sample (>7000 events) at low Q



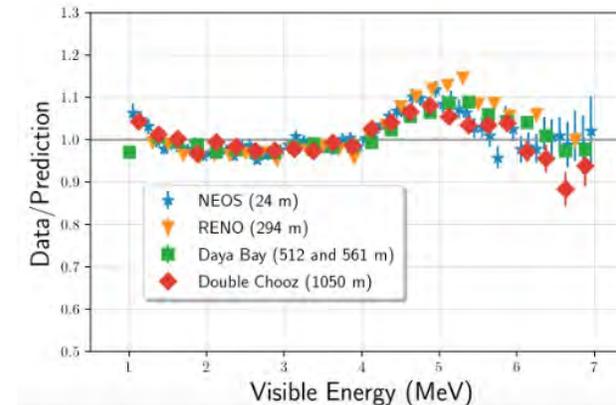
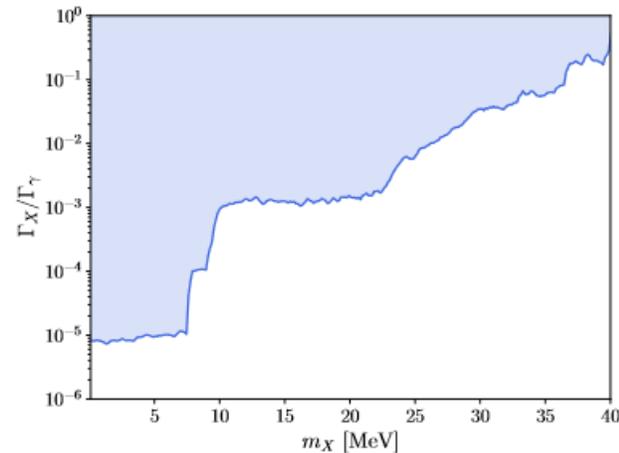
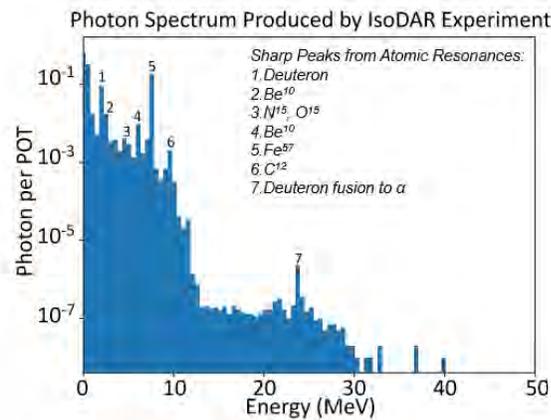
# Physics 3: Search for Axion-Like Particles (ALPs)

<https://arxiv.org/abs/2111.09480>

<https://arxiv.org/abs/2207.13659>



# Physics 4: Bump hunt in the neutrino spectrum, *light X particles* produced in the target $\rightarrow \nu_e \bar{\nu}_e$

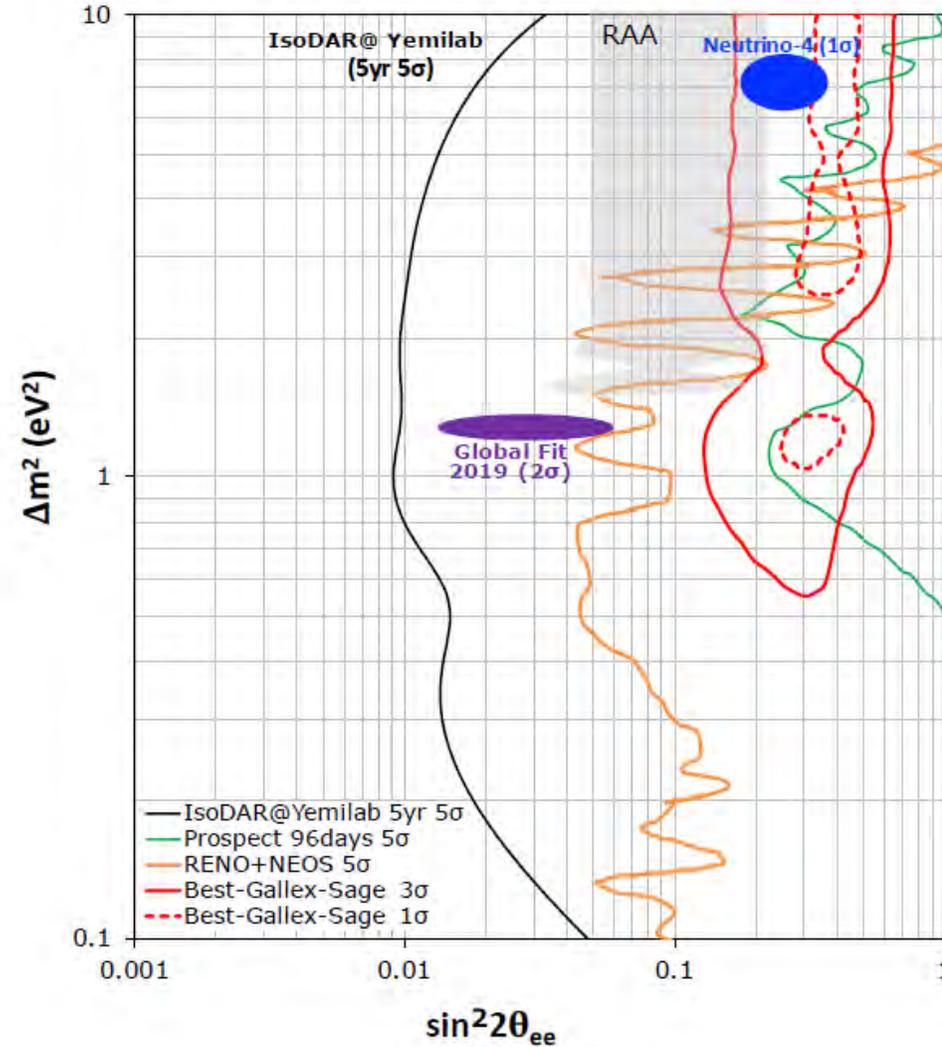


Produced by mixing w/ photons in target

Sensitivity

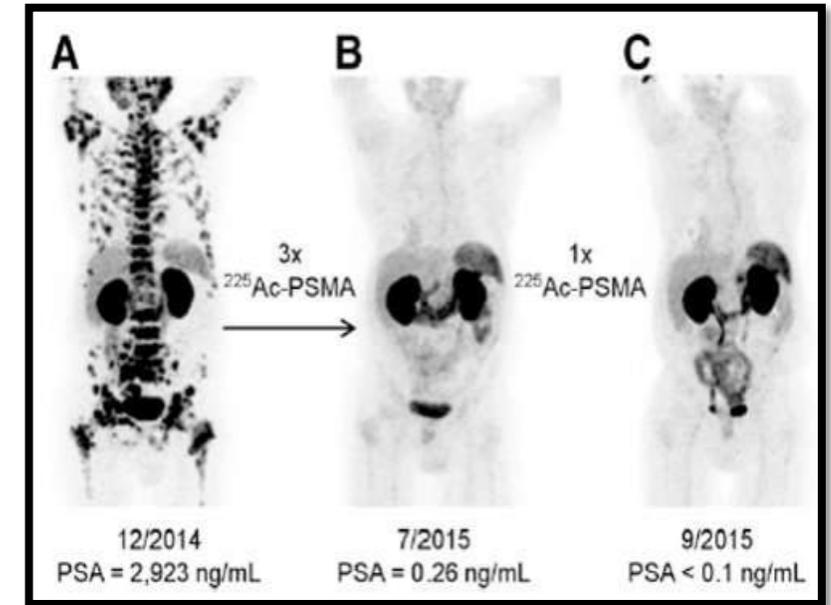
Help explain 5 MeV bump in reactors?

# IsoDAR@Yemilab - 5y/5 $\sigma$ sensitivity to 3+1 model



# Other applications - isotopes

- Few 60 MeV/amu accelerators,
  - On market machines < 1 mA
  - Lab-based accelerators are not at dedicated facilities
  - HCHC-XX could be built by consortia of hospitals
- There is real need for...
  - $^{68}\text{Ge}/^{68}\text{Ga}$ : PET isotope
  - $^{225}\text{Ac}$ : Alpha emitter
  - Many others
- Currently single targets can't handle 600 kW - but
  - Split beam inside-
  - Or outside Cyclotron

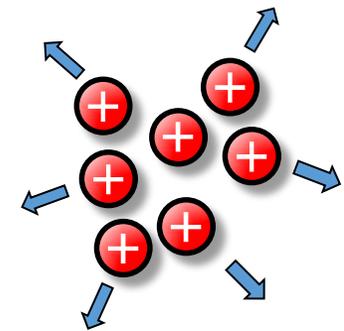
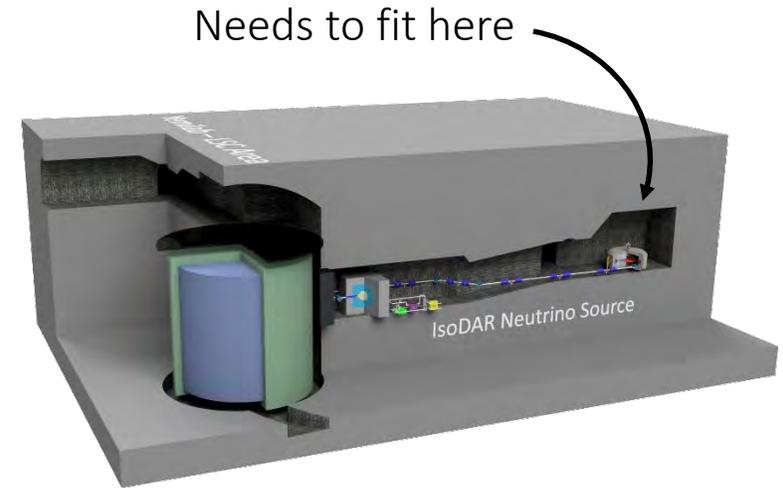


J. Alonso et al. *Nature* (2019) <https://www.nature.com/articles/s42254-019-0095-6>

L. Waites et al. *EJNMMI* (2020) <https://doi.org/10.1186/s41181-020-0090-3>

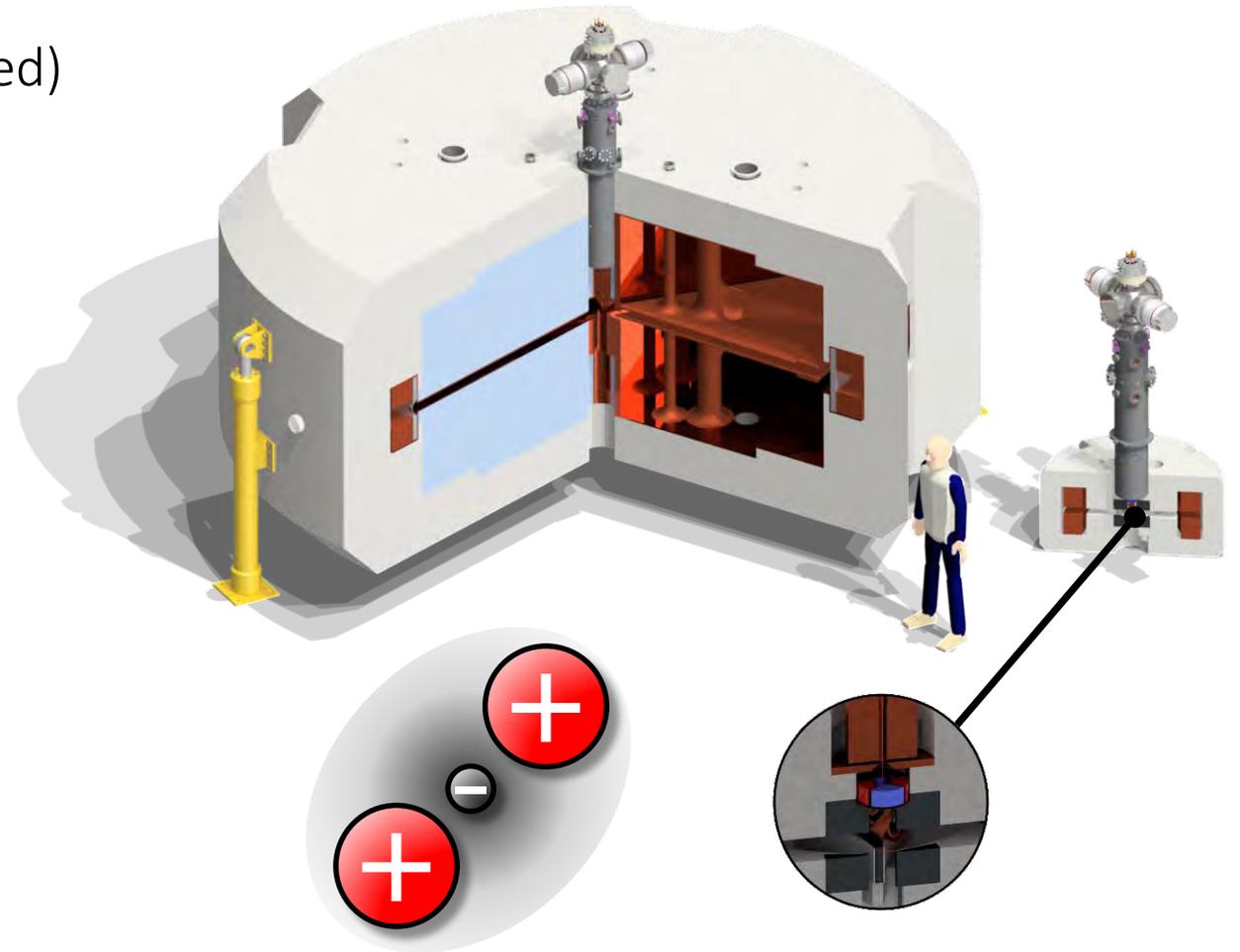
# Accelerator Requirements/Challenges

- Requirements (for IsoDAR):
  - Compact, robust, cost-effective (underground installation)
  - Continuous Wave (CW) operation, 80% duty factor (for maintenance)
  - 10 mA, 60 MeV protons on target
- Challenges:
  - Related to space-charge (Coulomb-repulsion of particles in bunch)
  - Leads to beam spread and non-linear behavior
  - Beam losses which lead to activation of the machine (limit is 200 W in extraction region – PSI experience)



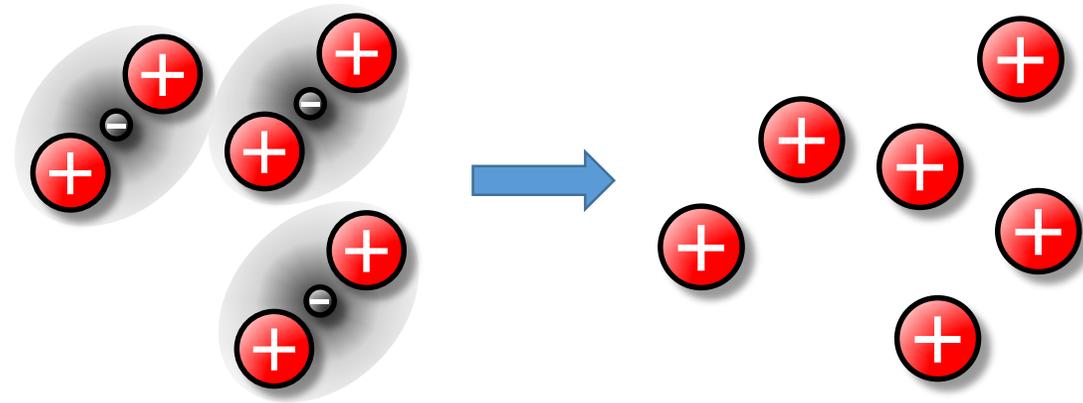
# The HCHC-XX design addresses these challenges

- Room-temperature coils (no cryogenics needed)
- Isochronous, cw, 80% duty factor
- Operates at 32.8 MHz (4<sup>th</sup> harmonic)
- 4 double-gap cavities  
→ high energy gain/turn
- Accelerates  $H_2^+$  ions instead of protons
- Direct axial injection through a **Radiofrequency Quadrupole (RFQ)**
  - Efficient bunching
  - Moderate pre-acceleration
- Utilizes **vortex motion**  
(a beam dynamics effect during acceleration)

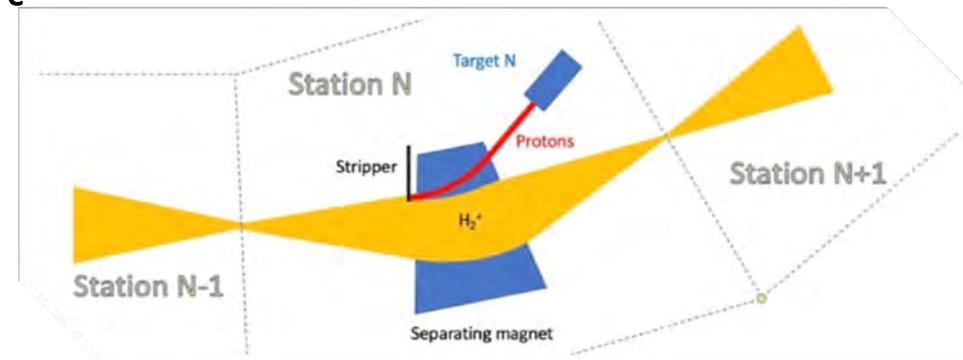


5 mA of  $\text{H}_2^+$  = 10 mA of protons

- Two units of charge for one
- Remove electron by stripping  
→ get two protons per  $\text{H}_2^+$
- Helps with Injection
- Helps with Low Energy Beam Transport

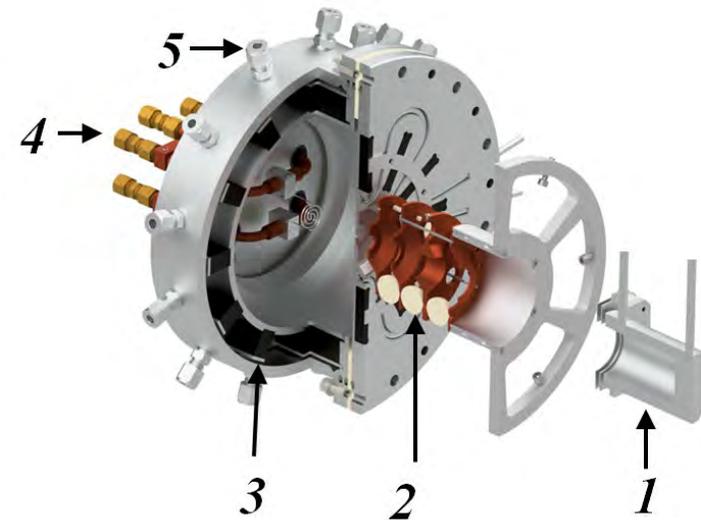
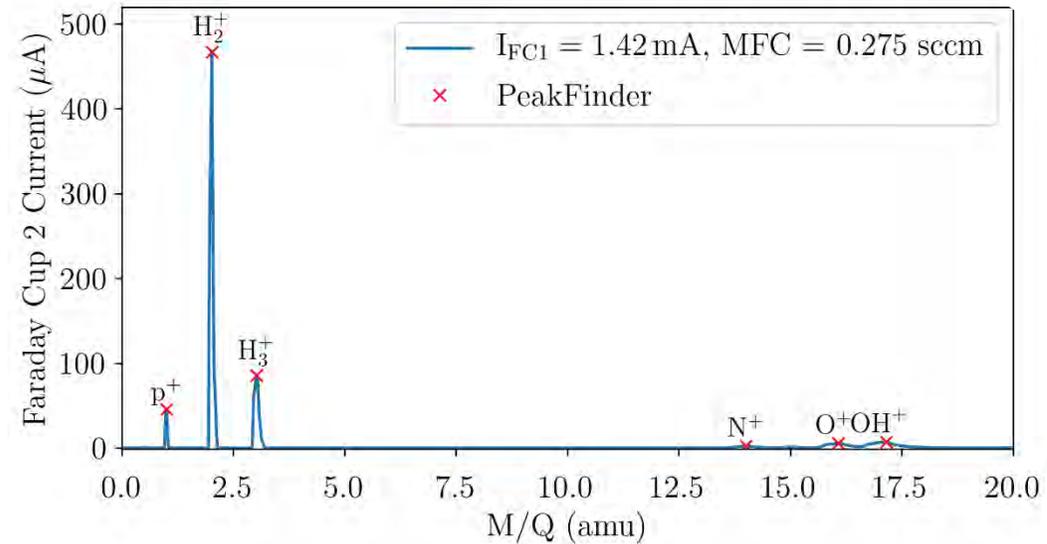


- This is also how we can split the beam to go to different target stations!



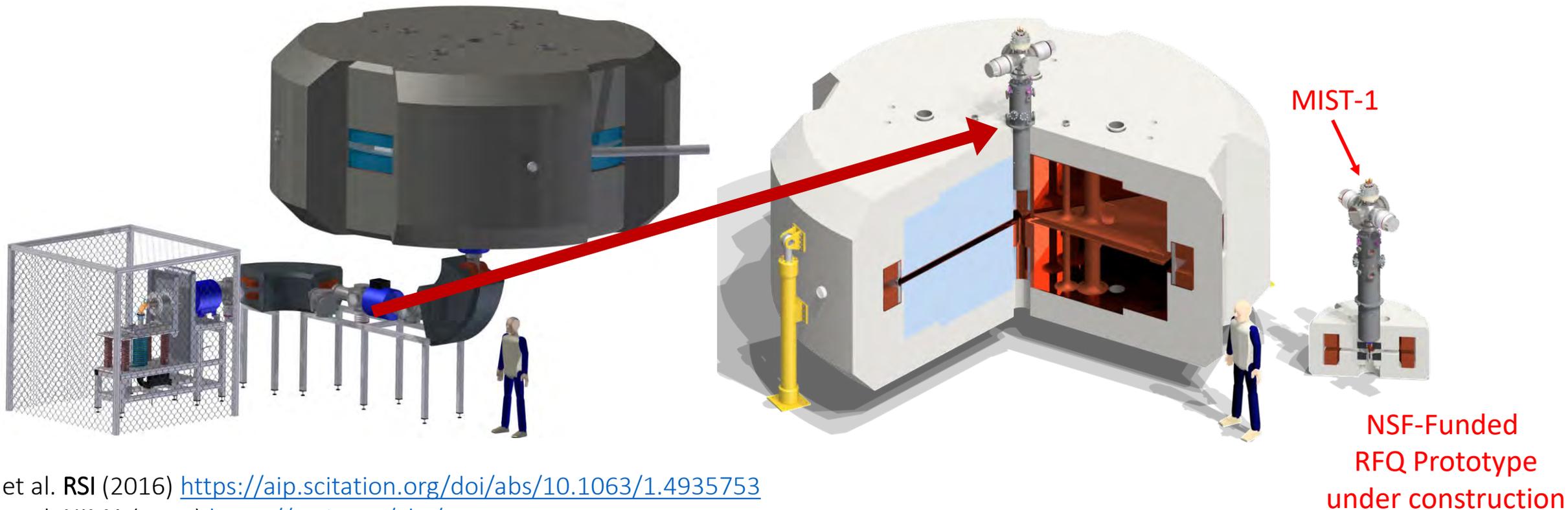
# MIT-built $\text{H}_2^+$ ion source (MIST-1) → commissioned at 25% power

- Filament-driven multicusp ion source
- $> 1 \text{ mA}$  of  $\text{H}_2^+$
- 80% purity
- High quality beam emittance:  $0.05 \pi\text{-mm-mrad}$  (RMS, norm.)
- Now ramping up to 100% power



# RFQ-DIP

- Radio Frequency Quadrupole – Direct Injection Project
  - Bunch and focus → Increased injection efficiency
  - Pre-accelerate and select  $H_2^+$  → More compact

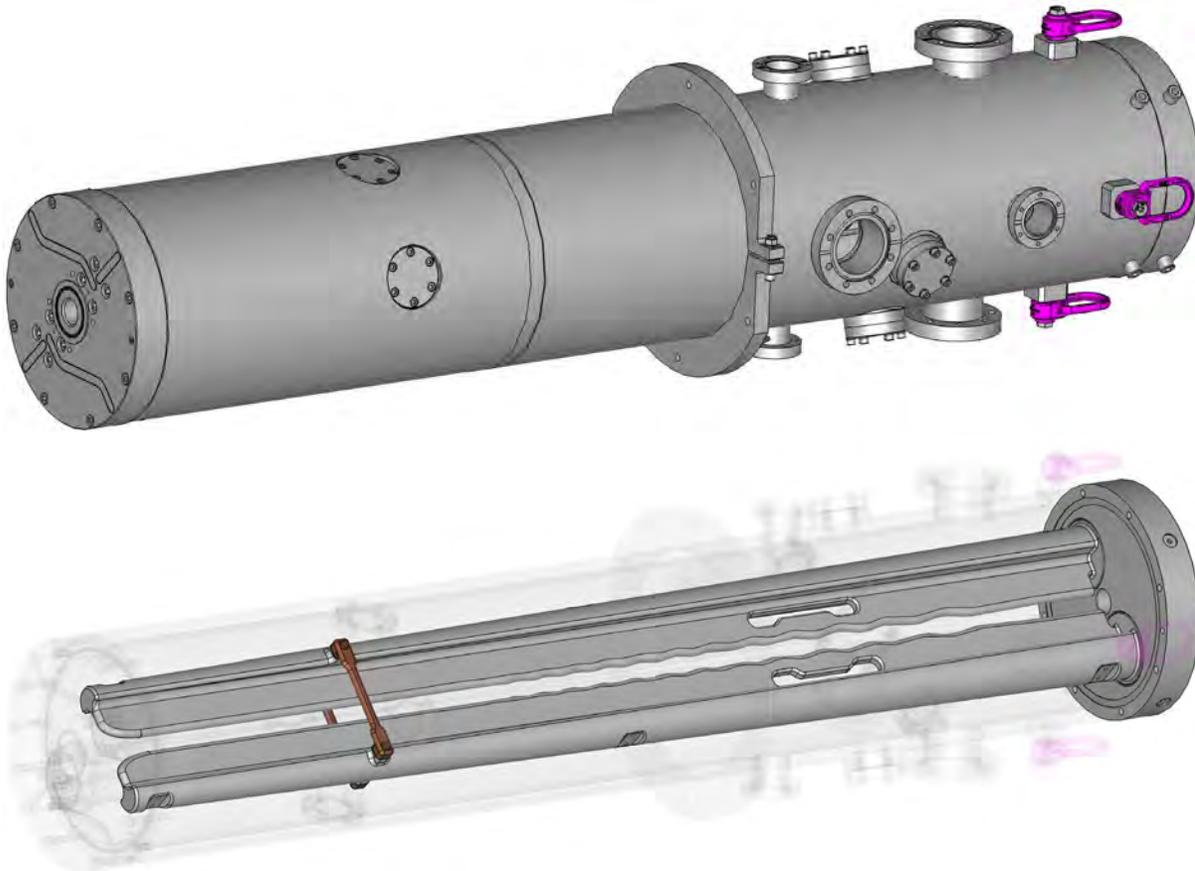


DW et al. RSI (2016) <https://aip.scitation.org/doi/abs/10.1063/1.4935753>

DW et al. NIMA (2018) <https://arxiv.org/abs/1807.03759>

DW et al. JACoW IPAC2021-TUXB07 (2021) <https://inspirehep.net/literature/1962316>

# Split-coaxial RFQ bunches the beam at 32.8 MHz

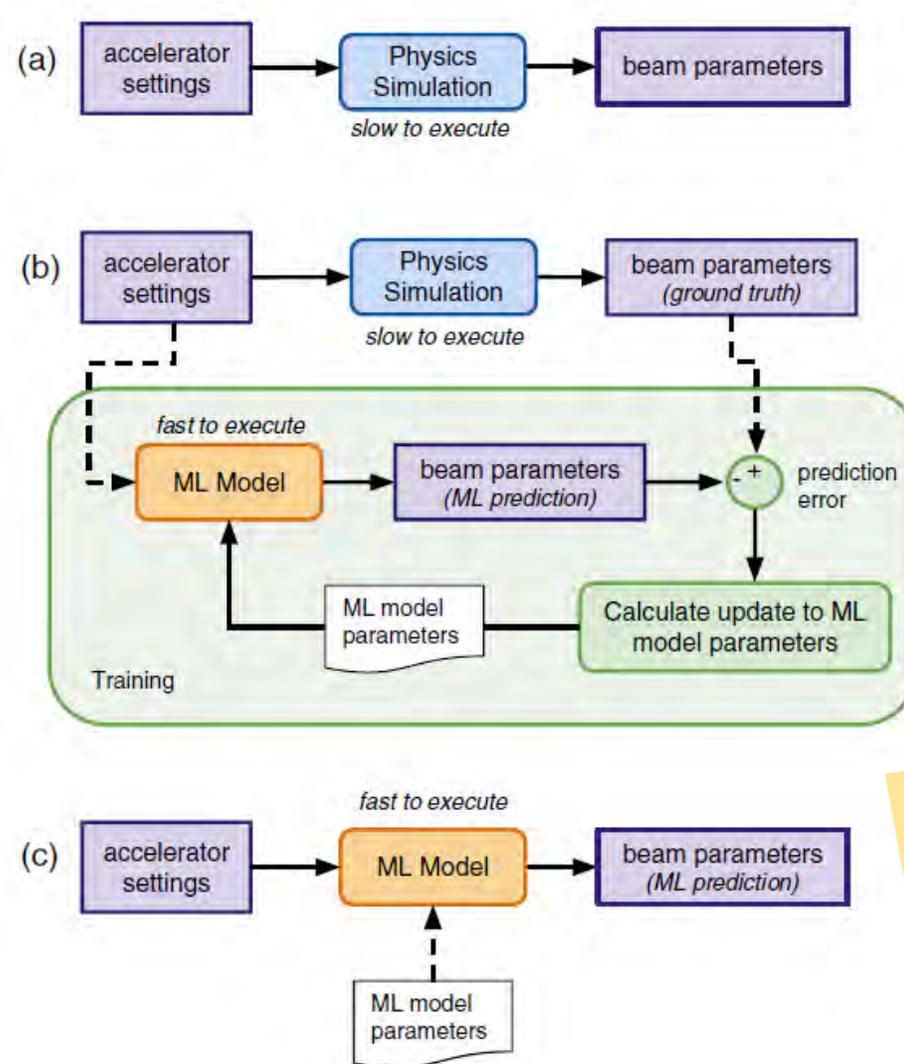


Elements	Unit	Design parameters
Frequency	MHz	32.8
Particle	A/q	H <sub>2</sub> <sup>+</sup> (2)
<b>Length</b>	<b>mm</b>	<b>1378.69</b>
No. of cells		58
Transmission rate	%	97.27
Beam energy	keV	15 → 70
Input Trans. emit (rms, norm)	mm-mrad	0.25
Trans. emittance (rms, norm)	mm-mrad	0.25
<b>Long. emittance (rms)</b>	<b>keV-deg</b>	<b>30</b>
Vane voltage	kV	20.14
min. vane-tip aperture	mm	6.83
vane-tip curvature	mm	9.30
r <sub>0</sub> , mid-cell aperture	mm	9.30
Octupole term		0.070
Power:	kW	< 6

**Split-Coaxial RFQ**  
Eigenmode of tank  
allows low frequency  
with small diameter

# Excellent opportunity to use machine learning ("Virtual Accelerators")

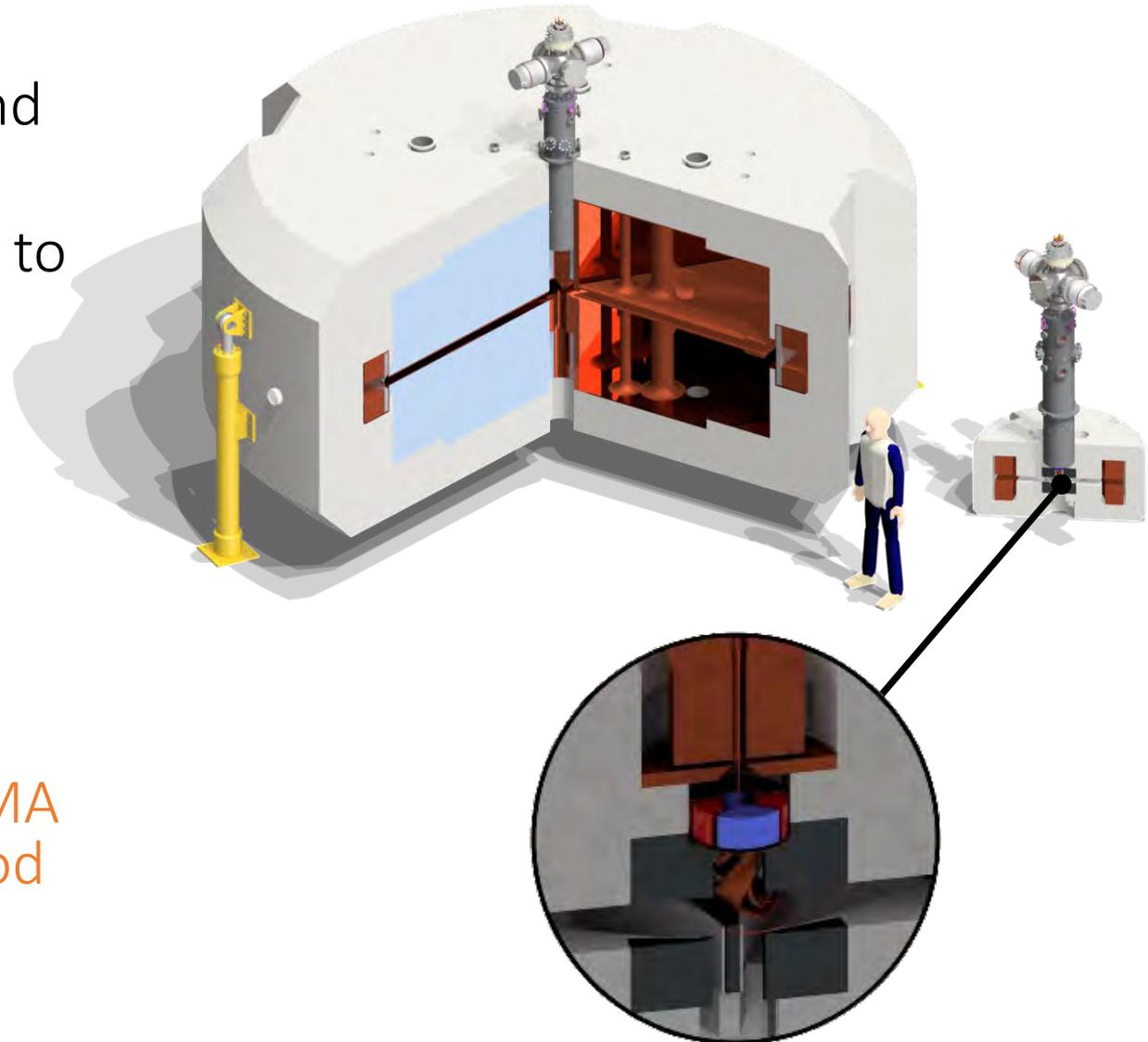
- Particle accelerator simulations can be complex with large sets of input parameters
- Optimization requires repeated evaluation of points in parameter-hyperspace.
- Surrogate model: train neural net on sparse set of points in this hyperspace
- Evaluation of surrogate model is orders of magnitude faster than original simulation
  - Optimization
  - Real-Time Feedback



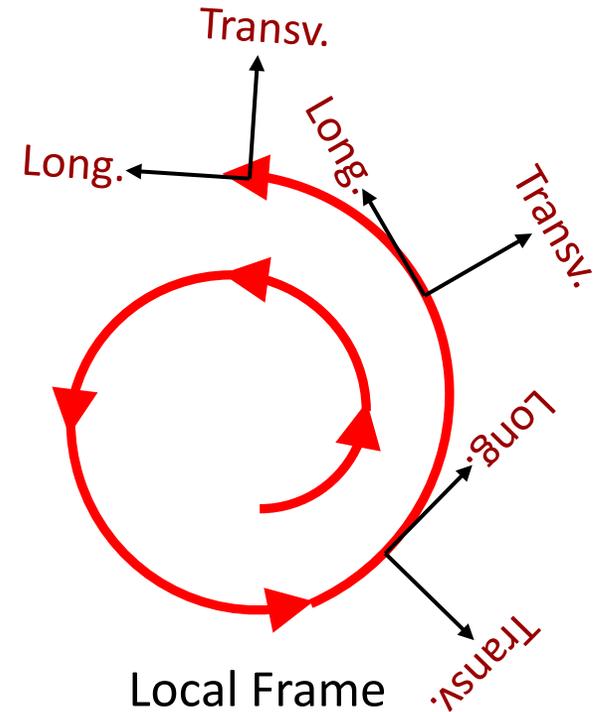
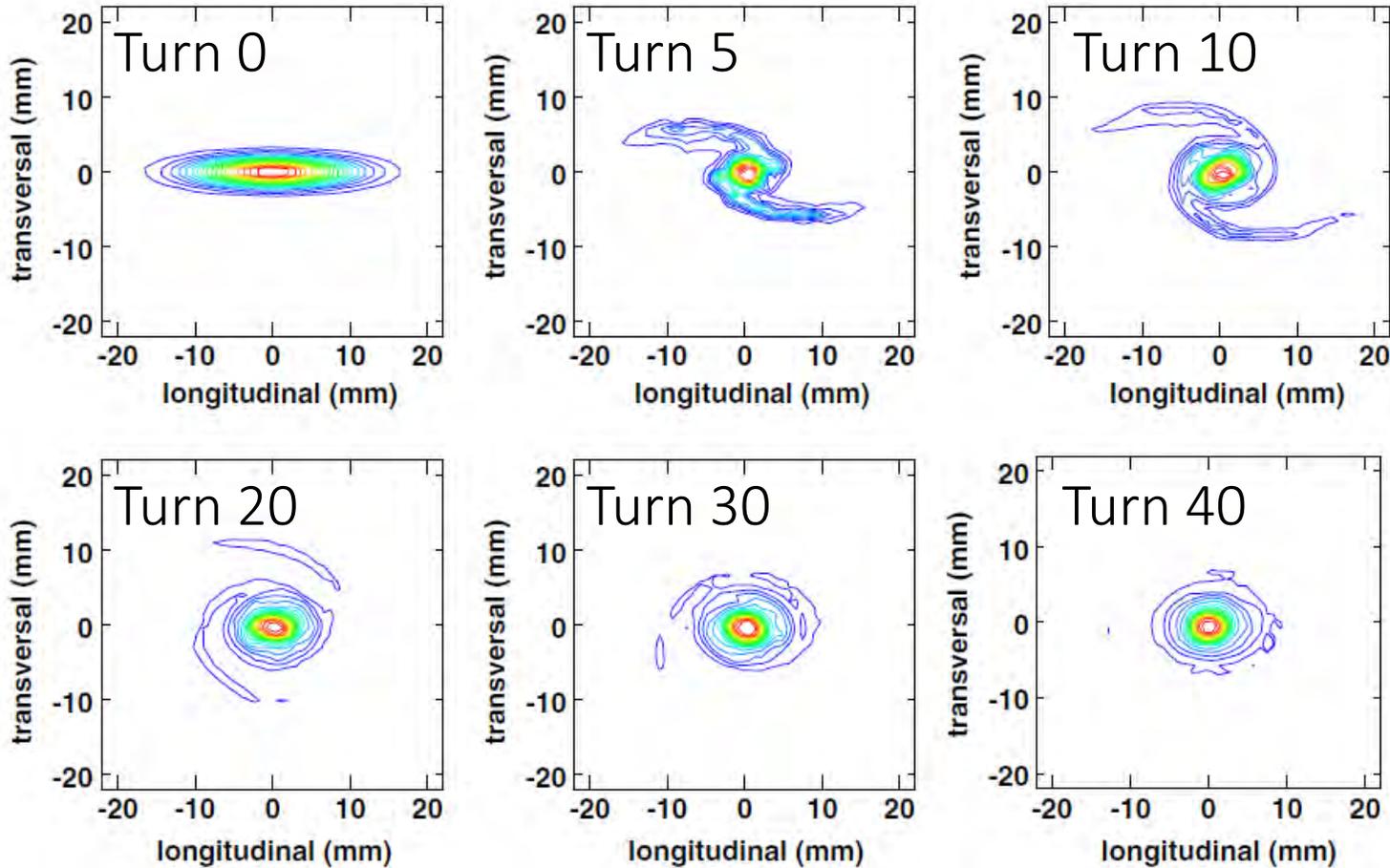
**Surrogate Model**  
A ML-trained NN to replace costly PIC simulations.

# The central region

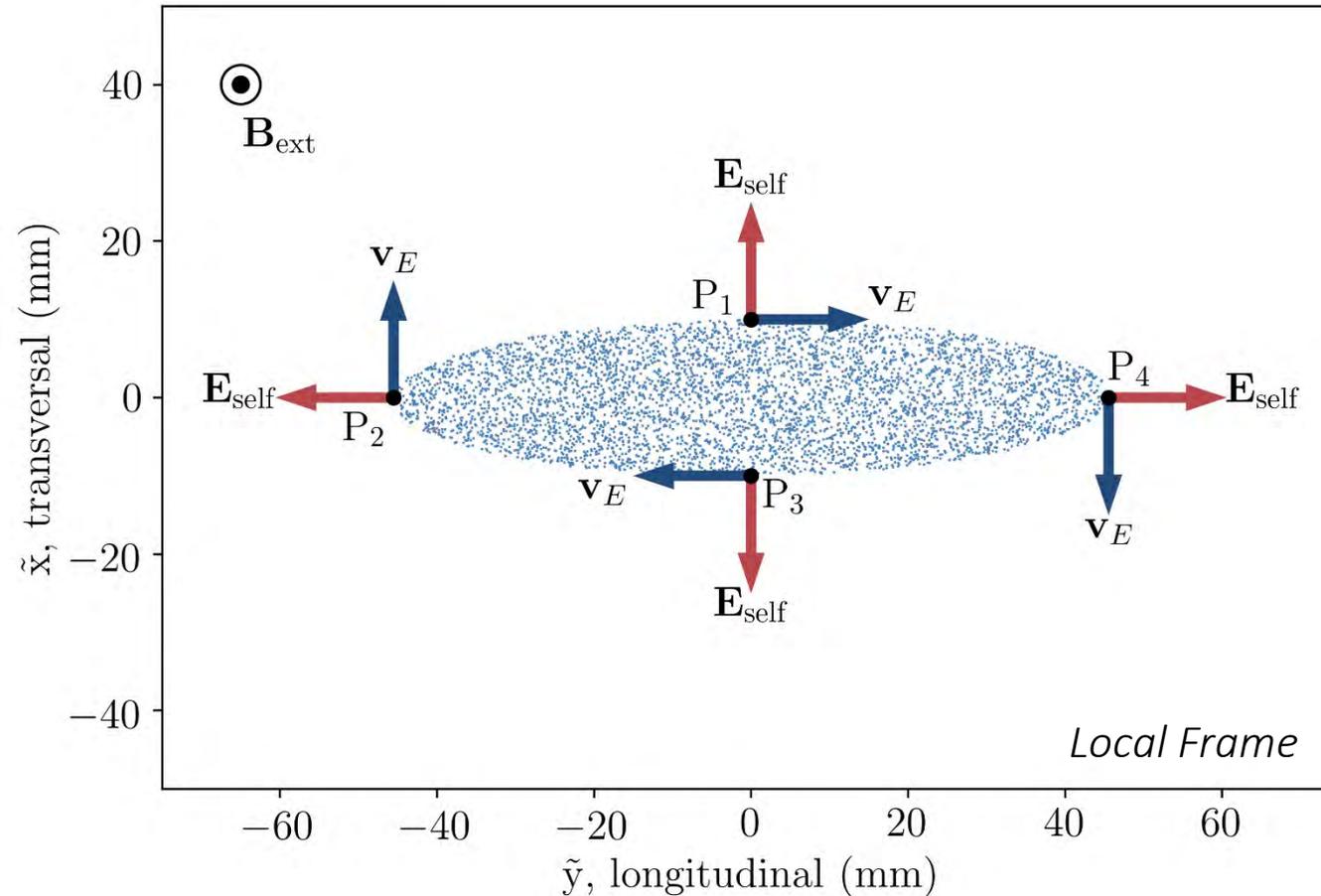
- Beam from the RFQ debunches and diverges quickly
  - Bring RFQ exit as close as possible to median plane
  - Add transverse focusing element
  - Guide through spiral inflector
  - Place collimators in first turns
- Note: Full Start-To-End Simulation Ongoing. Preliminary Study by AIMA showed acceptable losses and good vertical acceptance.



# Vortex motion – Discovered in PSI Injector II Simulated with OPAL → Good Agreement

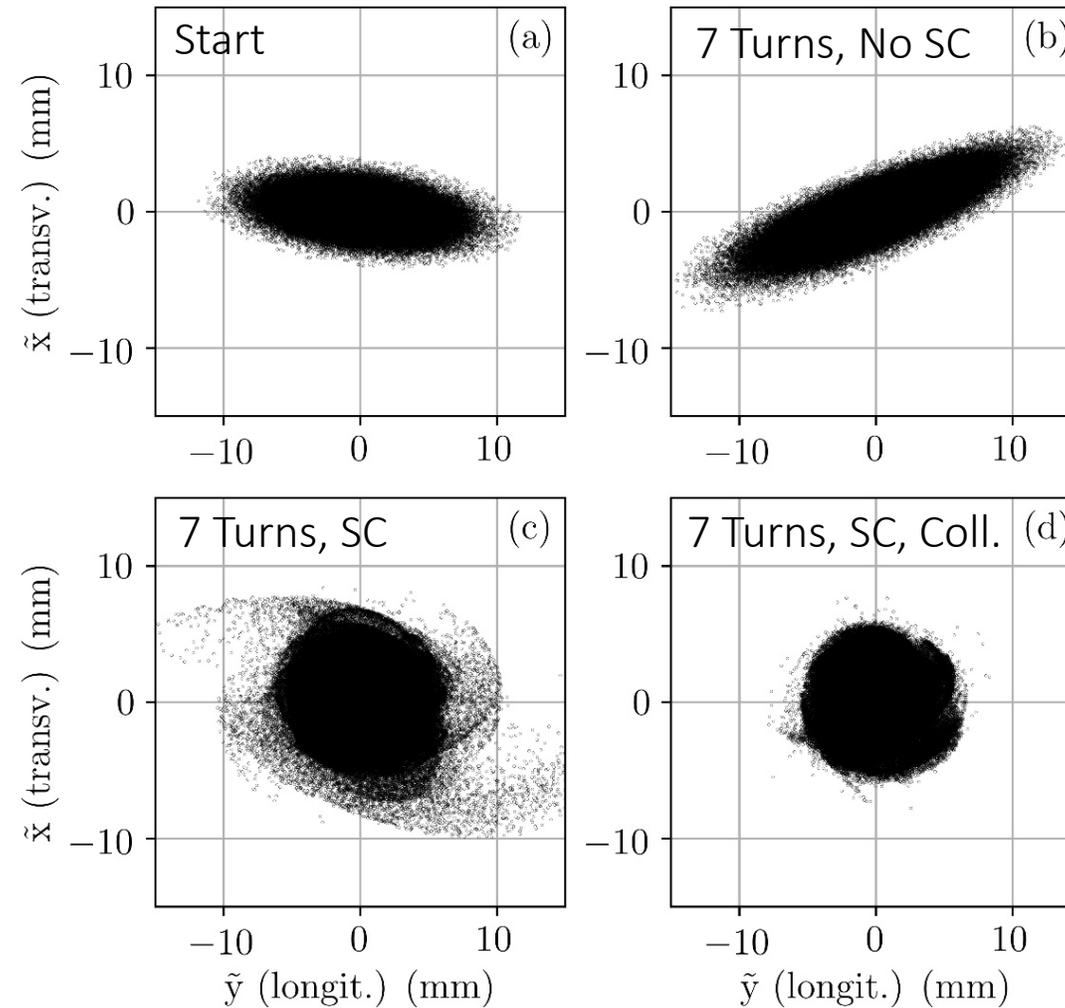


# Vortex Motion – Highly Simplified Picture



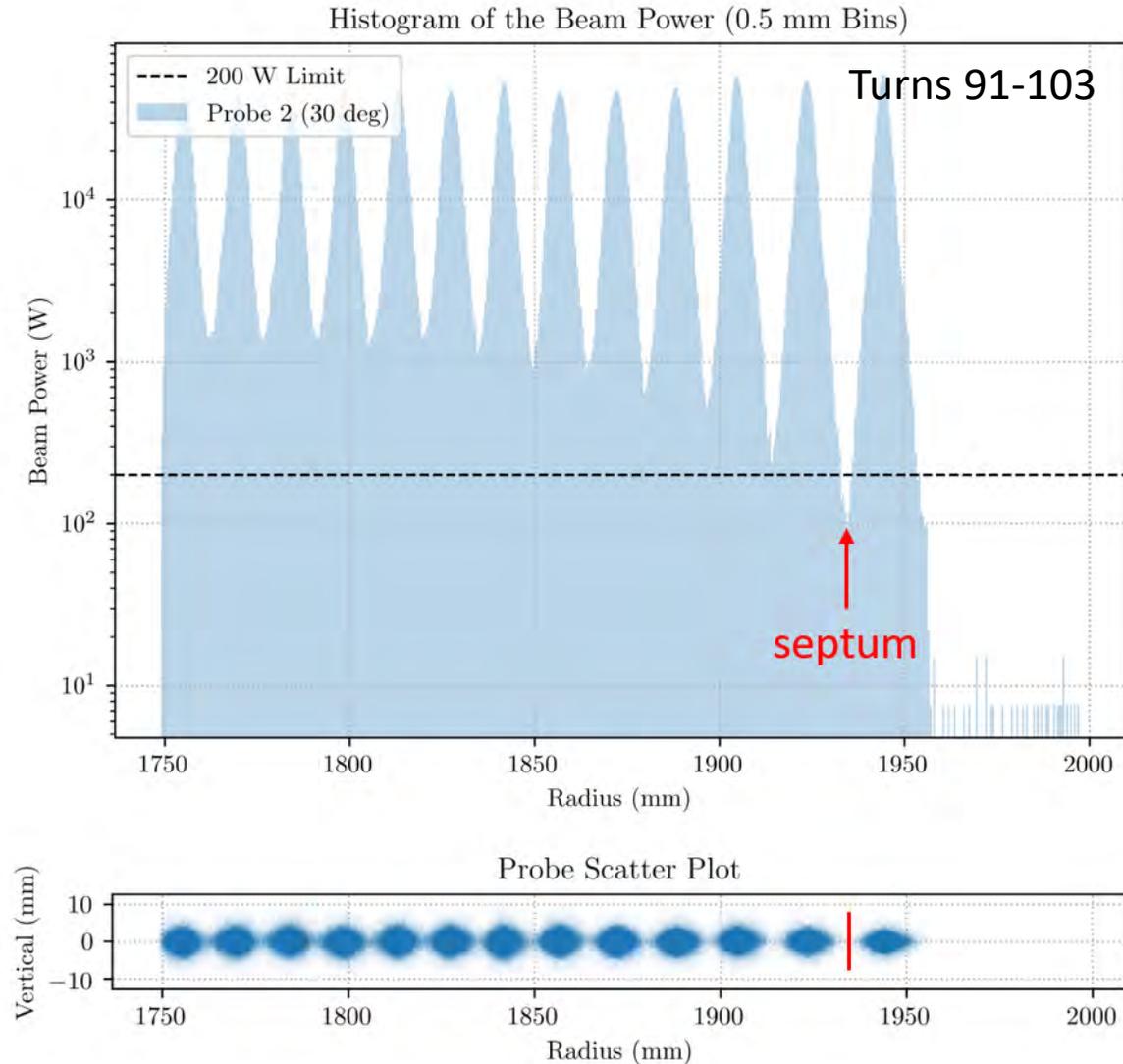
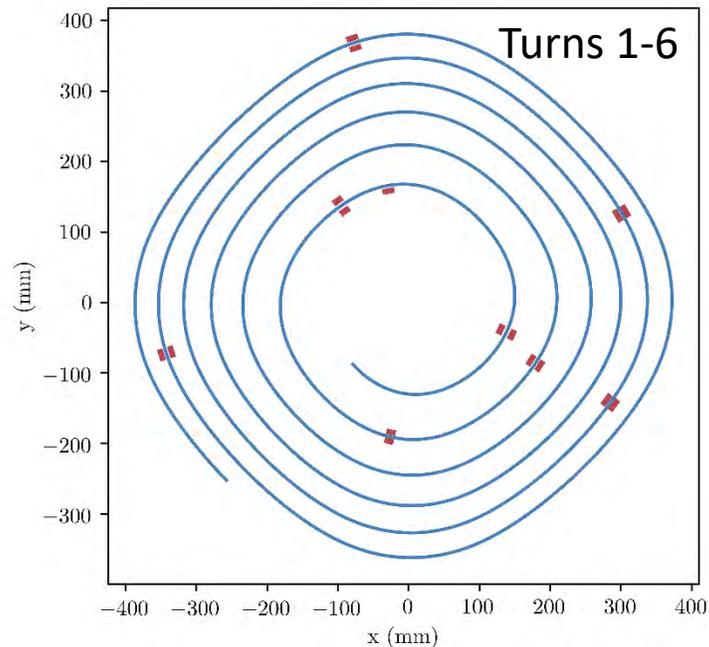
Lorentz force:  $\mathbf{F} = q \cdot (\mathbf{v} \times \mathbf{B}_{\text{ext}}) + q \cdot \mathbf{E}_{\text{self}}$       E x B drift:  $\mathbf{v}_E = \frac{\mathbf{E}_{\text{self}} \times \mathbf{B}_{\text{ext}}}{B_{\text{ext}}^2}$

# Vortex Motion in the IsoDAR 60 MeV/amu cyclotron



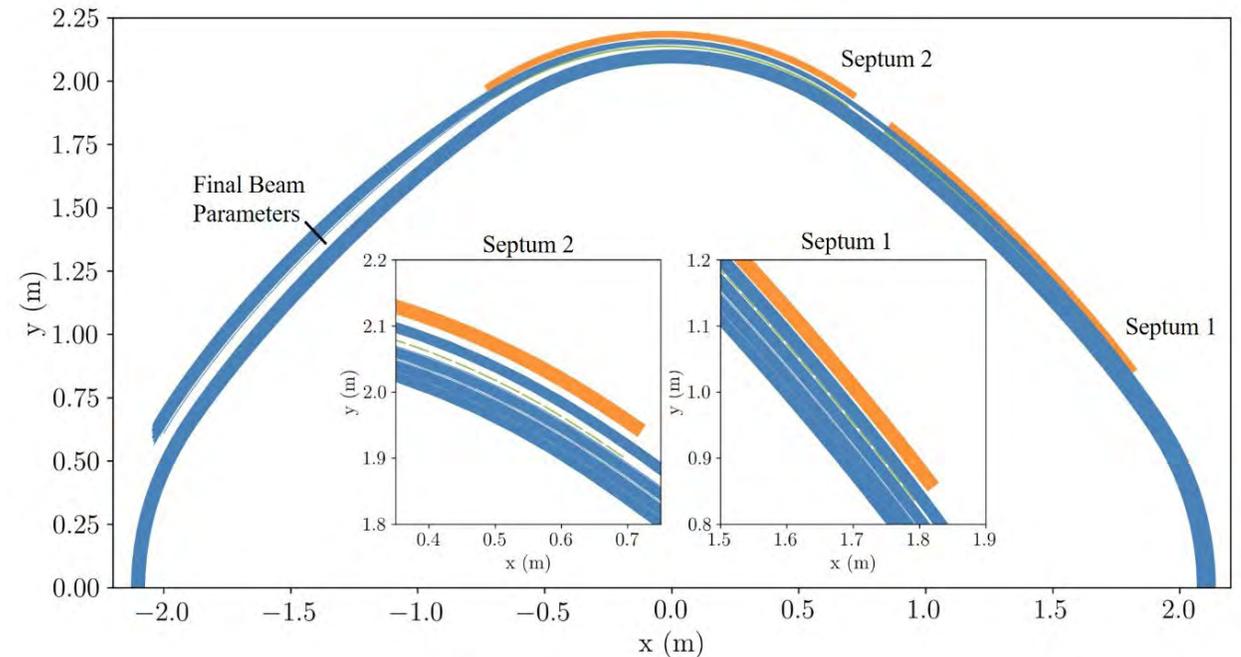
# Optimize phase, RF voltage, cavity shape, collimator placement

- Phase:  $-5^\circ$ ,  $V = 70\text{-}240\text{kV}$
- Collimate Halo  $\rightarrow \sim 30\%$  loss
- 98 W on septum ( $\sim 1e-4$  rel.)



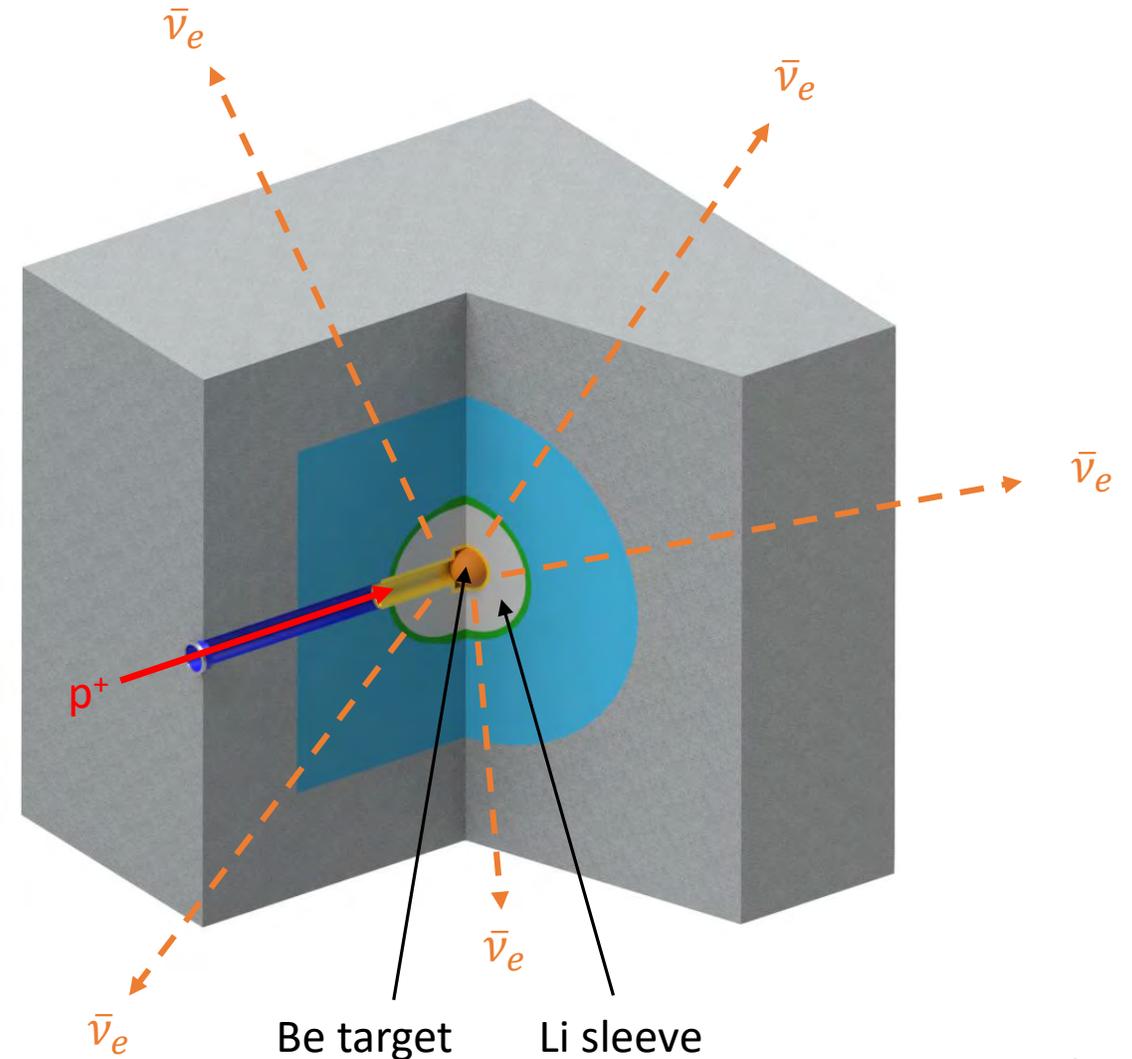
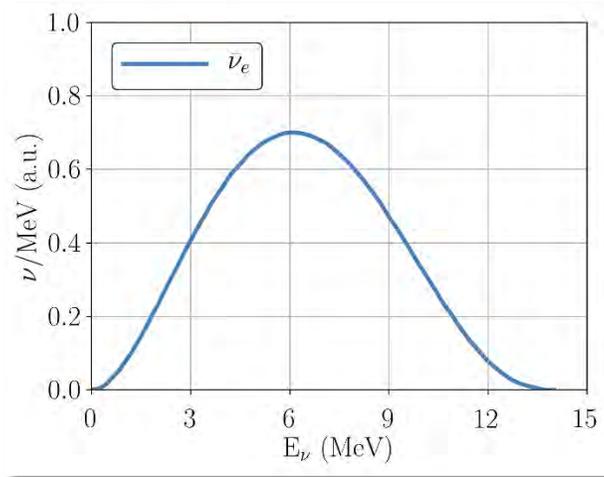
# Beam can be extracted with good quality

- Minimal losses at 60 MeV/amu: < 100 Watt (factor 2 below safety limit)!
- RMS Size:
  - Radial: 7.5 mm
  - Longitudinal: 11 mm
  - Vertical: 1.9 mm
- RMS, normalized emittance:
  - vertical: 0.44 mm-mrad
  - Radial: 3.8 mm-mrad
- Longitudinal emittance:
  - 0.1 MeV-deg
- Note: Also used Surrogate Modeling for uncertainty quantification here



# The IsoDAR high power neutrino target

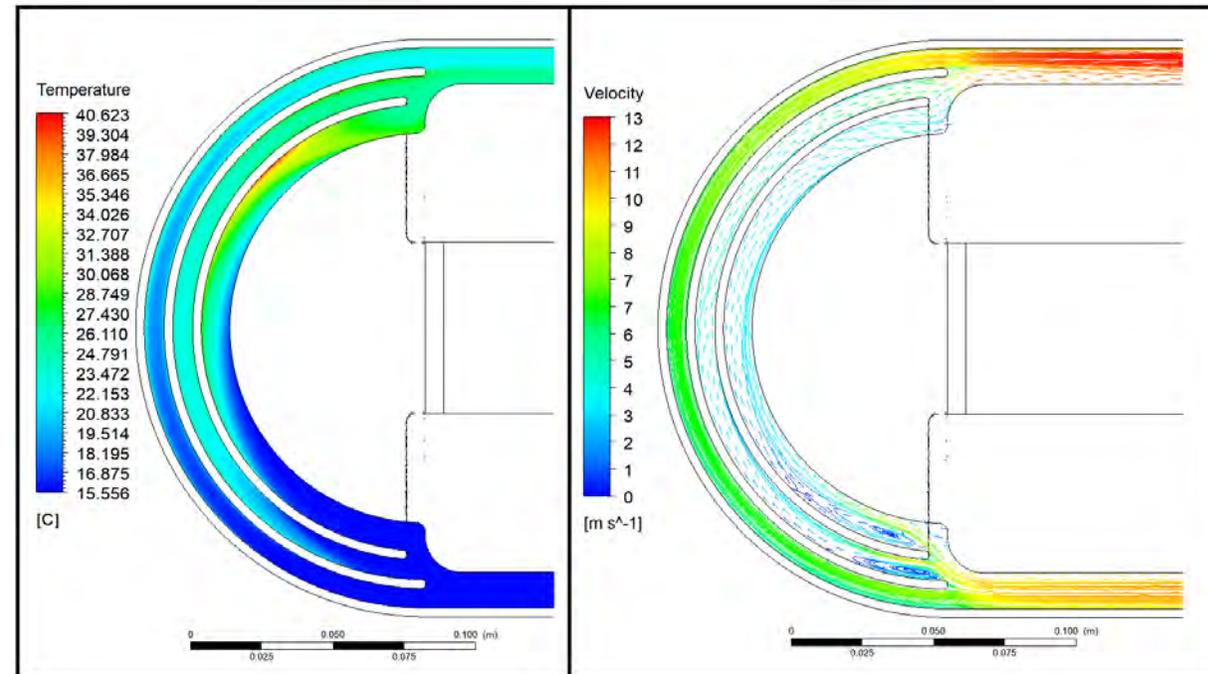
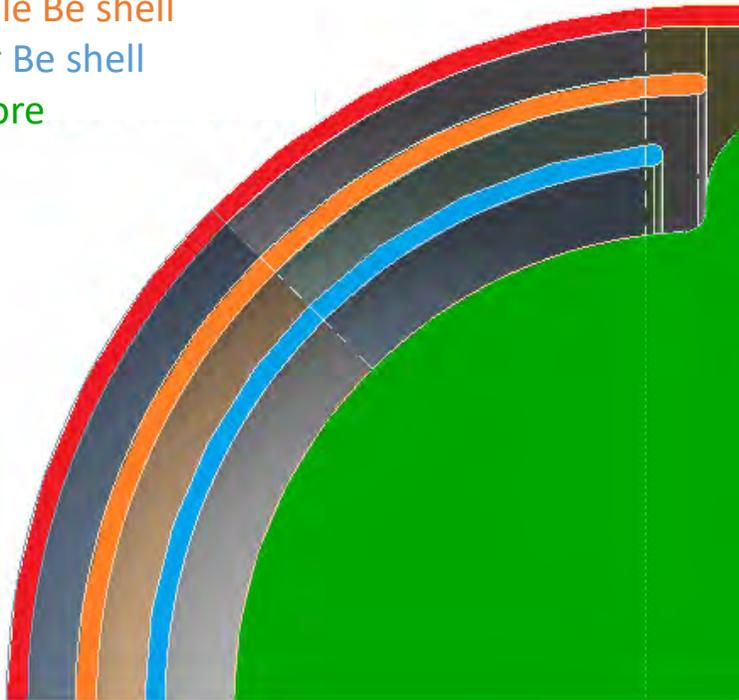
- The 10 mA proton beam is spread out transversally and “painted” across the  $\sim 20$  cm Be target.
- 99.99% pure  ${}^7\text{Li}$  sleeve around target
- $p^+ + {}^9\text{Be} \rightarrow$  spallation neutrons
- $n + {}^7\text{Li} \rightarrow {}^8\text{Li}^* \rightarrow {}^8\text{Be} + e^- + \bar{\nu}_e$



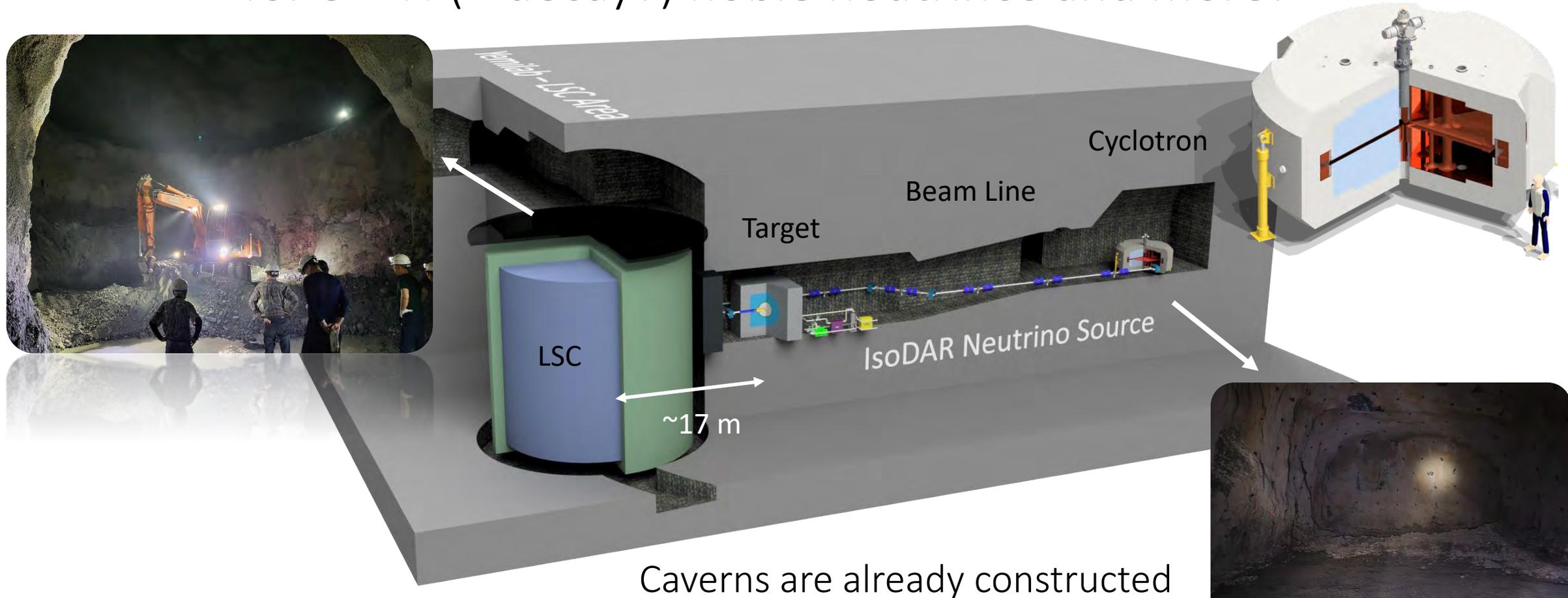
# Target cooling with heavy water

- Heavy water is pumped through a nested-shell beryllium structure
- CFD/FEA calculations show adequate cooling, stresses, and deformation

Outer Be shell  
Middle Be shell  
Inner Be shell  
Be Core



Bringing it all together for a definitive search for  $3 + N$  (+ decay?) noble neutrinos and more!



Caverns are already constructed

- Testing Hardware prototypes (injector, target)
- Writing Proposals for full accelerator & detector
- Planning for 2027 – 2032 run --- Stay tuned!

Particle accelerators open a window into a beautiful, diverse,  
vast landscape, ripe with opportunity!

# References

- IsoDAR@Yemilab – CDR: IsoDAR Collaboration **arXiv** (2021) [arxiv:2110.10635](https://arxiv.org/abs/2110.10635)
- IsoDAR@Yemilab – Physics: J. Spitz, ... DW, ... **PRD** (2022) [arxiv:2111.09480](https://arxiv.org/abs/2111.09480)
- ALP search with IsoDAR – L. Waites et al. <https://arxiv.org/abs/2207.13659>
- Ion Source: D. Winklehner et al. **RSI** (2021) <https://arxiv.org/abs/2008.12292>
- RFQ-DIP: D. Winklehner et al. **RSI** (2016) <https://aip.scitation.org/doi/abs/10.1063/1.4935753>
- RFQ-DIP: D. Winklehner et al. **NIMA** (2018) <https://arxiv.org/abs/1807.03759>
- ML for RFQ: D. Koser, ..., DW, ... **Front. Phys.** (2022) <https://arxiv.org/abs/2112.02579>
- Spiral Inflector: D. Winklehner et al. **PRAB** (2017) <https://arxiv.org/abs/1612.09018>
- Cyclotron: D. Winklehner et al. **New Journ. Phys.** (2022) <https://doi.org/10.1088/1367-2630/ac5001>
- Isotopes: J. Alonso et al. **Nature** (2019) <https://www.nature.com/articles/s42254-019-0095-6>
- Isotopes: L. Waites et al. **EJNMMI** (2020) <https://doi.org/10.1186/s41181-020-0090-3>
- Target,  $^8\text{Li}$  yield: A. Bungau et al. **arXiv** (2018) <https://arxiv.org/abs/1805.00410>
- Target, shielding: A. Bungau et al. **arXiv** (2019) <https://arxiv.org/abs/1909.08009>
- First experimental tests: D. Winklehner et al. **JINST** (2015) [arXiv:1508.03850](https://arxiv.org/abs/1508.03850)
- Yang et al. **PRSTAB** (2010) [PhysRevSTAB.13.064201](https://arxiv.org/abs/1306.4201)
- The OPAL Code: Adelman, ..., DW, ... **arXiv** (2019) <https://arxiv.org/abs/1905.06654>
- High-Power Cyclotron Report: D. Winklehner et al. **arXiv** (2022) <https://arxiv.org/abs/2203.07919>

Backup

# Latest ALP sensitivities

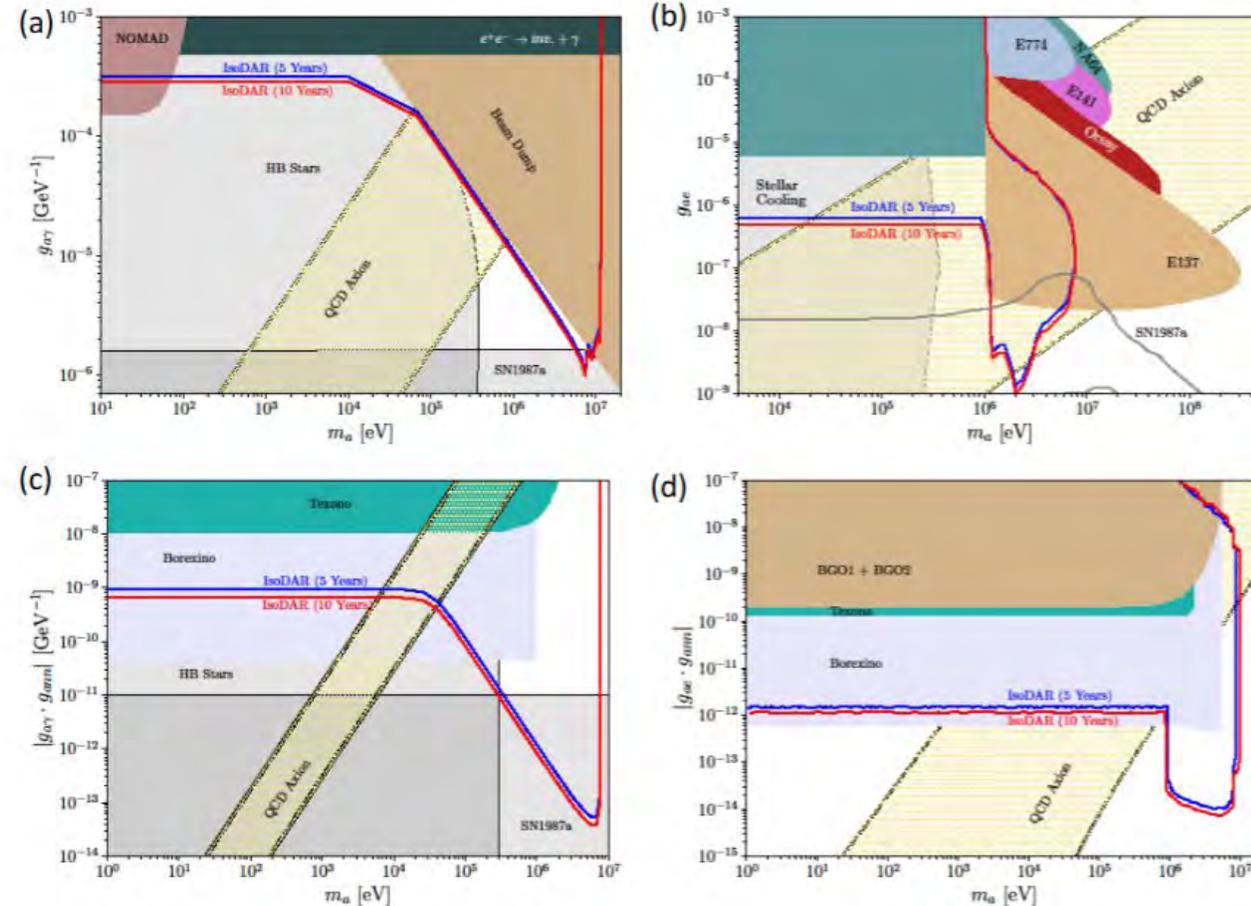


FIG. 4. Sensitivity contours at 90% CL, for 5 and 10 year exposures, using (a) couplings to photons, (b) couplings to electrons, (c) couplings to nucleons and photons, and (d) couplings to nucleons and electrons. In (c) and (d), ALPs are produced via nuclear transitions and propagate to the detector to subsequently scatter or decay via electron coupling (inverse Compton,  $a \rightarrow e^+e^-$  decay) or photon coupling (inverse Primakoff,  $a \rightarrow \gamma\gamma$  decay) channels.