Neutrinoless double beta decay and the role of barium tagging

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CAP Congress

June 22, 2023

Outline

- What we don't know about the neutrino
- Neutrinoless double beta decay searches ($0\nu\beta\beta$)
- Barium tagging
- Current progress

What is known about neutrinos

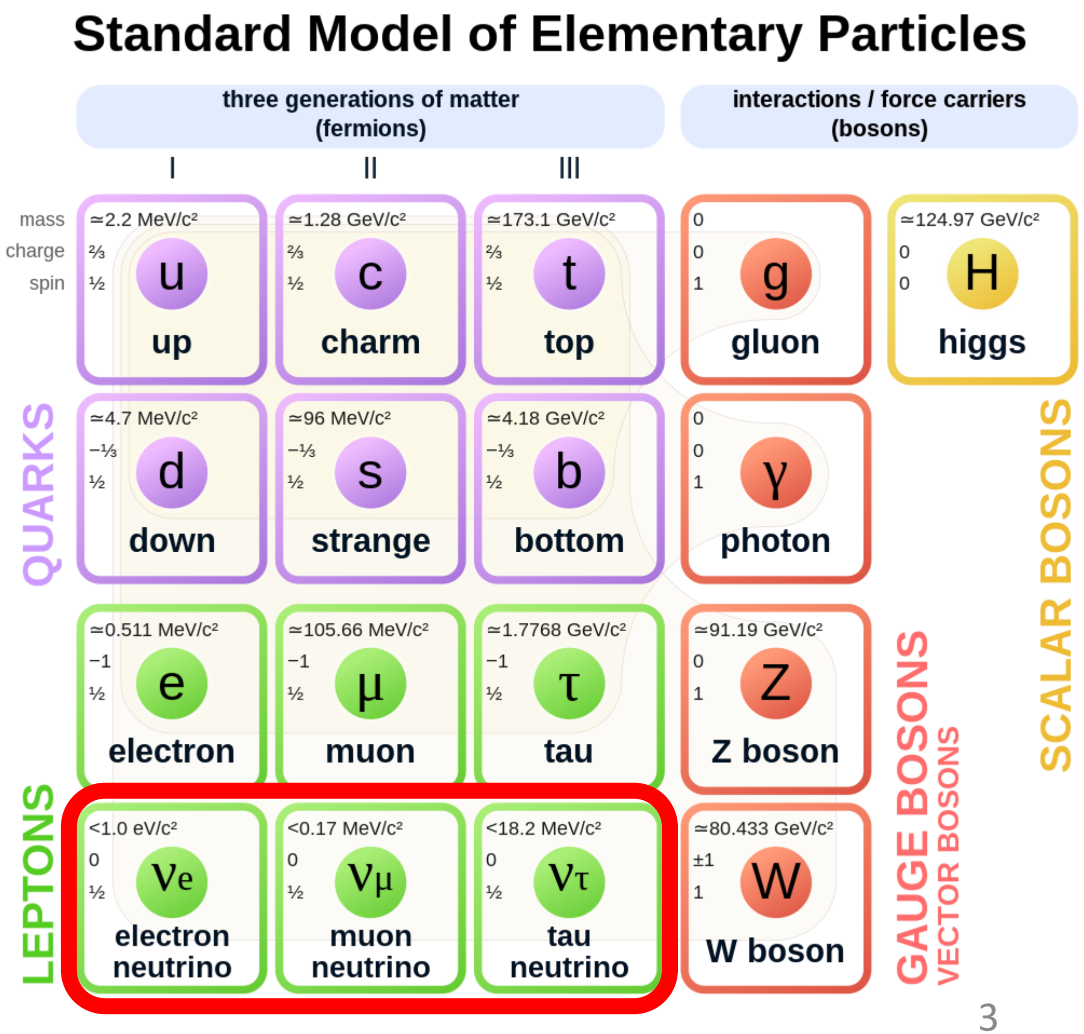
- Weakly interacting neutral Fermions
- 3 leptonic flavours – e, μ, τ
- 3 mass states - m_1, m_2, m_3

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Mass differences from neutrino oscillation measurements

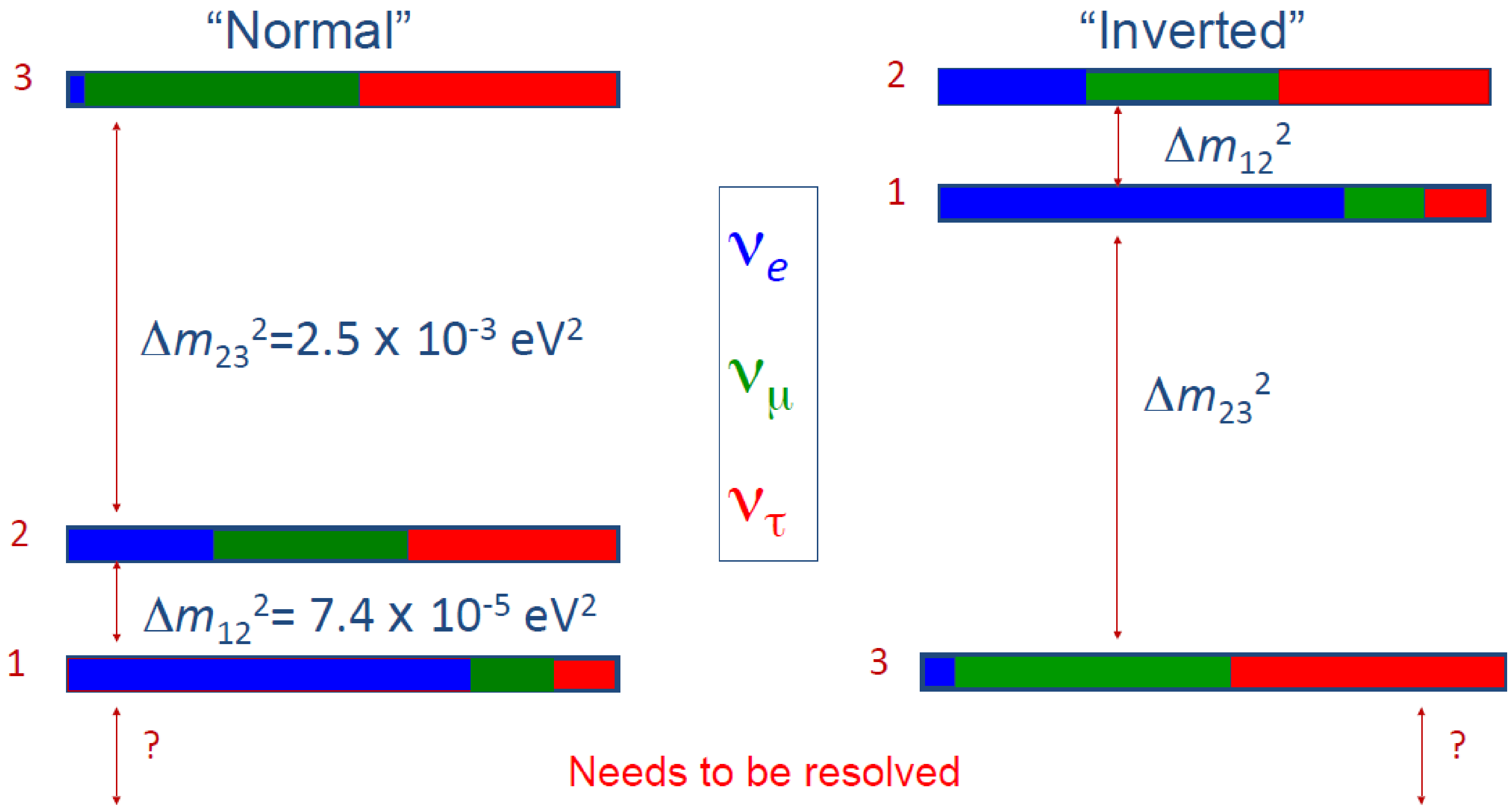
$$\Delta m_{12}^2 = 7.3 \times 10^{-5} eV^2$$
$$\Delta m_{23}^2 = 2.5 \times 10^{-3} eV^2$$



What is unknown about neutrinos

- Mass scale?
- Mass ordering?
- Dirac or Majorana?

Ettore Majorana
1937 - postulated
$\bar{\nu} = \nu$



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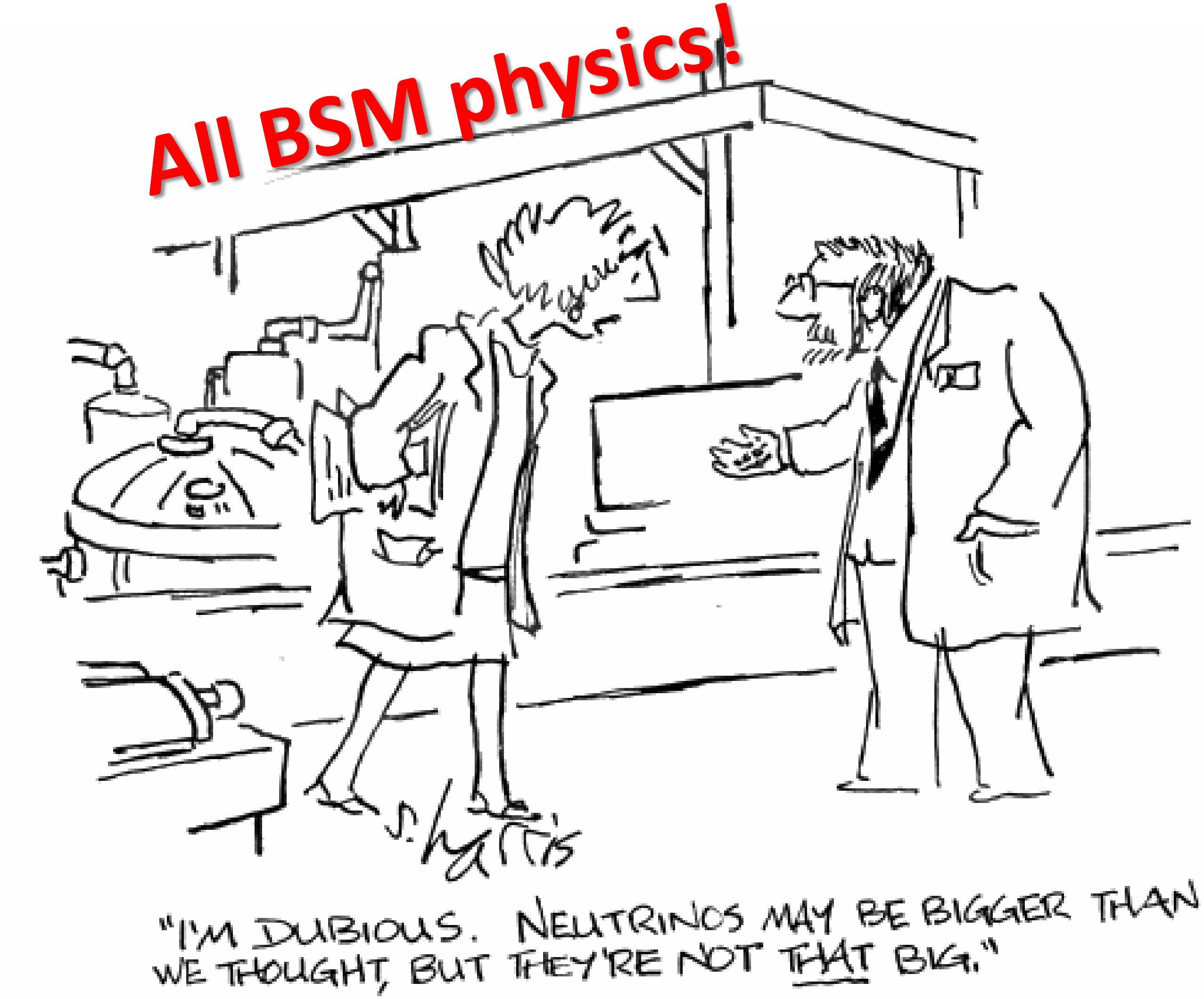
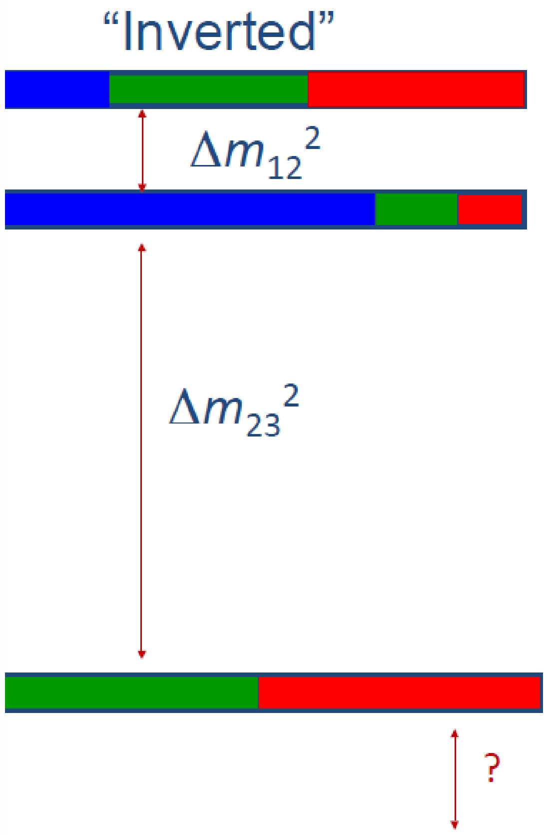
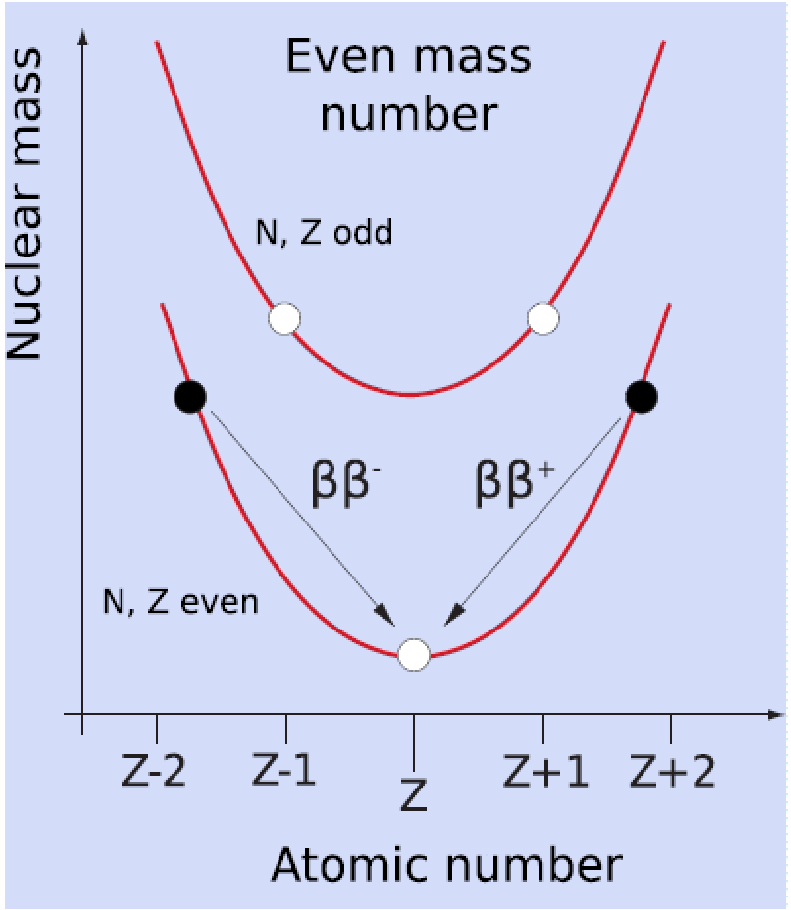
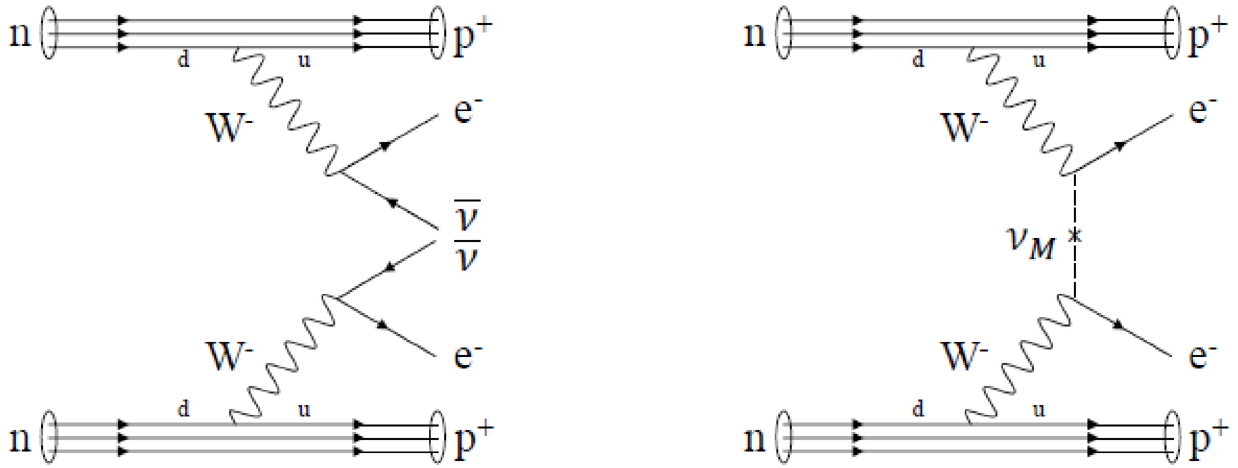
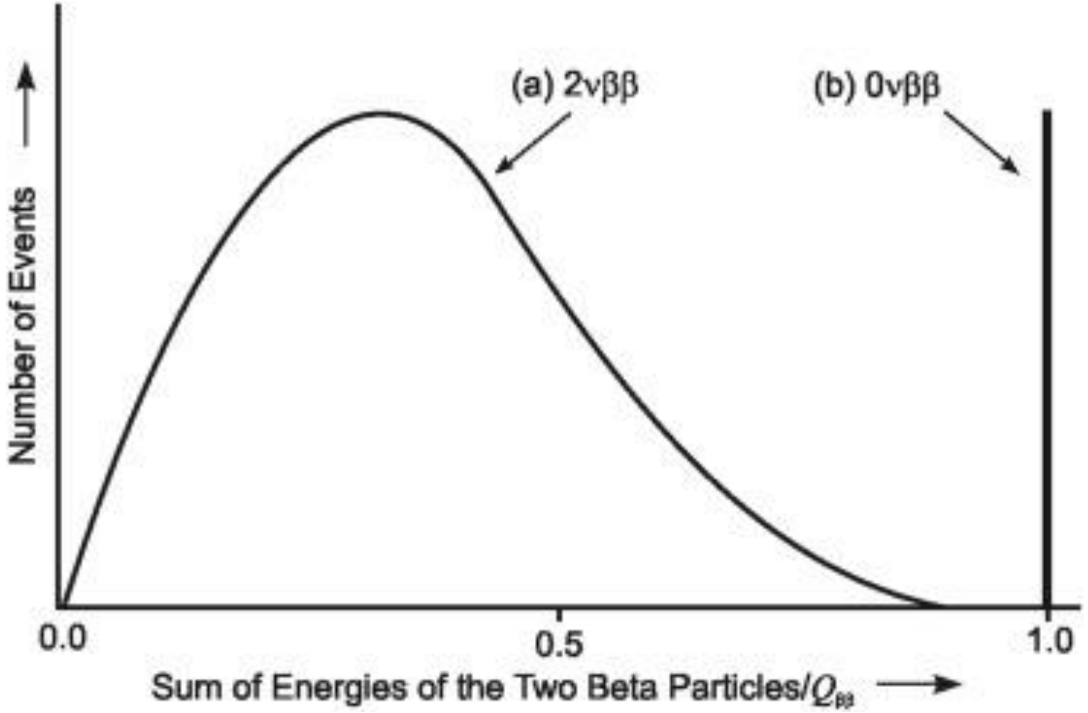




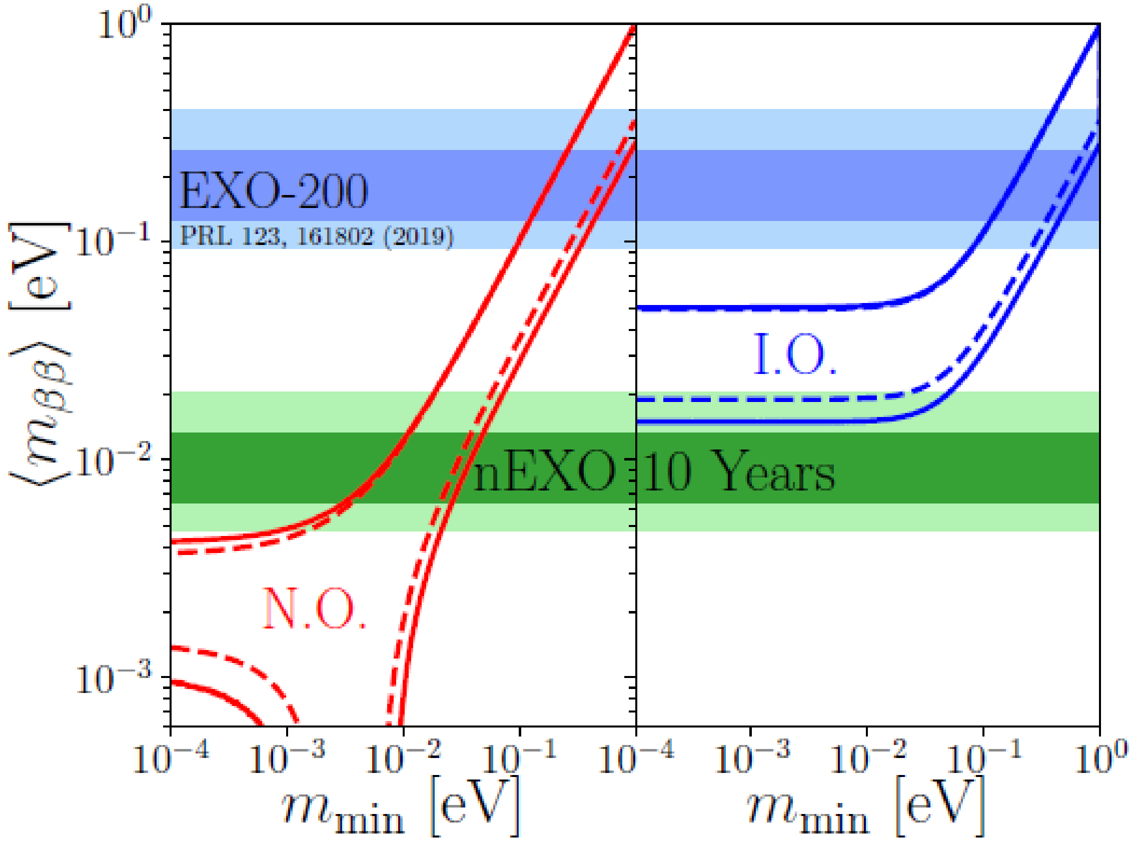
Double beta decay







Neutrino masses and 0νββ



Nuclear matrix elements from theory

Weak axial vector coupling

Phase space factor

- Decay half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2} g_A^4 \left| M_\nu^{0\nu} \right|^2 G^{0\nu}$$

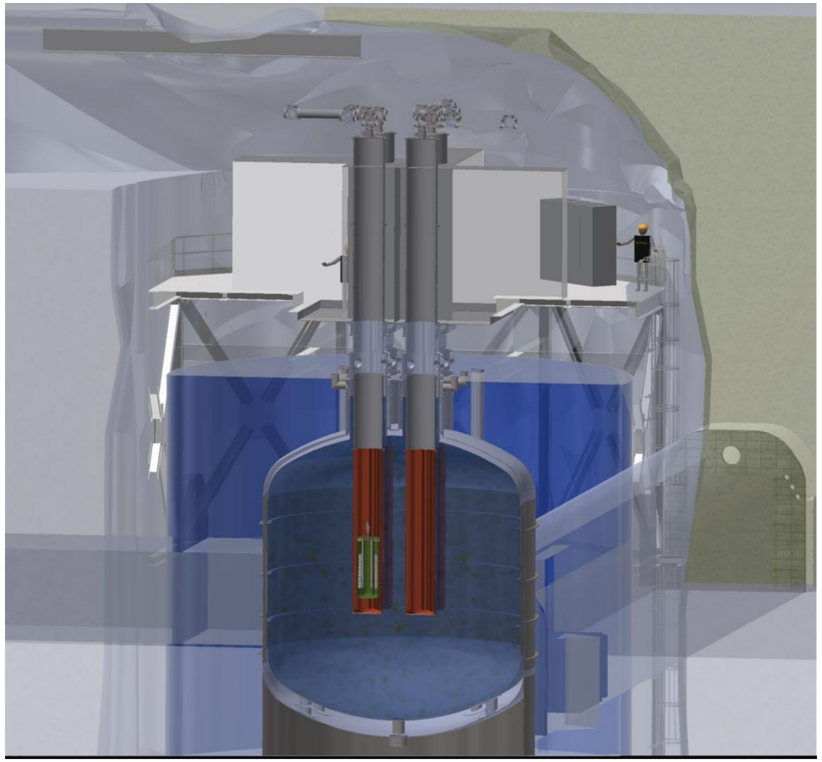
- Combined with oscillation measurements, gives neutrino masses
- Next generation 0νββ should cover Inverted Ordering

Physics implications of 0νββ observation

- Lepton number violation
- Neutrinos are Majorana fermions
- Neutrino mass ordering
- Possible source of CP-violation
    - Leptogenesis

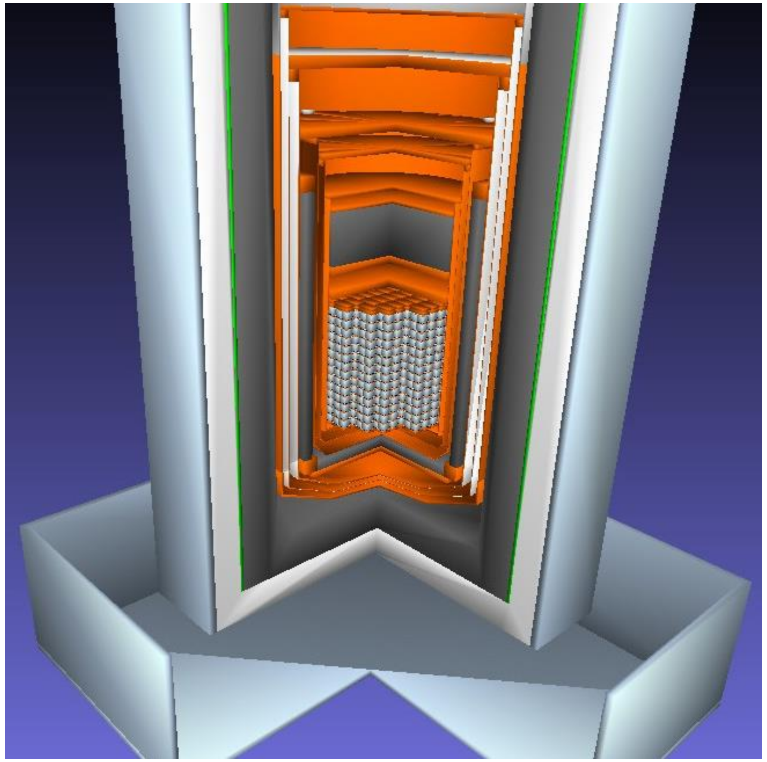
- Absolute neutrino mass scale from rate

Upcoming experiments



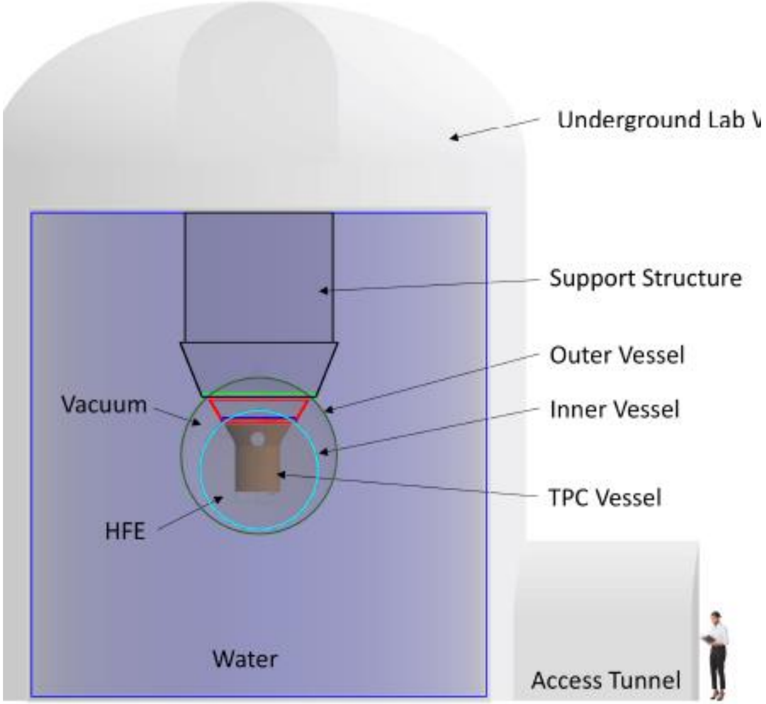
LEGEND – 1t ^{76}Ge enriched detectors

90% CL $T_{1/2}^{0\nu} < 1.6 \times 10^{28}$ yr



CUPID –Li_2MoO_4 scintillators enriched to 250 kg of ^{100}Mo

90% CL $T_{1/2}^{0\nu} < 9.1 \times 10^{27}$ yr



nEXO – 5t enriched Xe in time-projection chamber

90% CL $T_{1/2}^{0\nu} < 1.35 \times 10^{28}$ yr

N. Abgrall et al. LEGEND-1000 Preconceptual Design Report

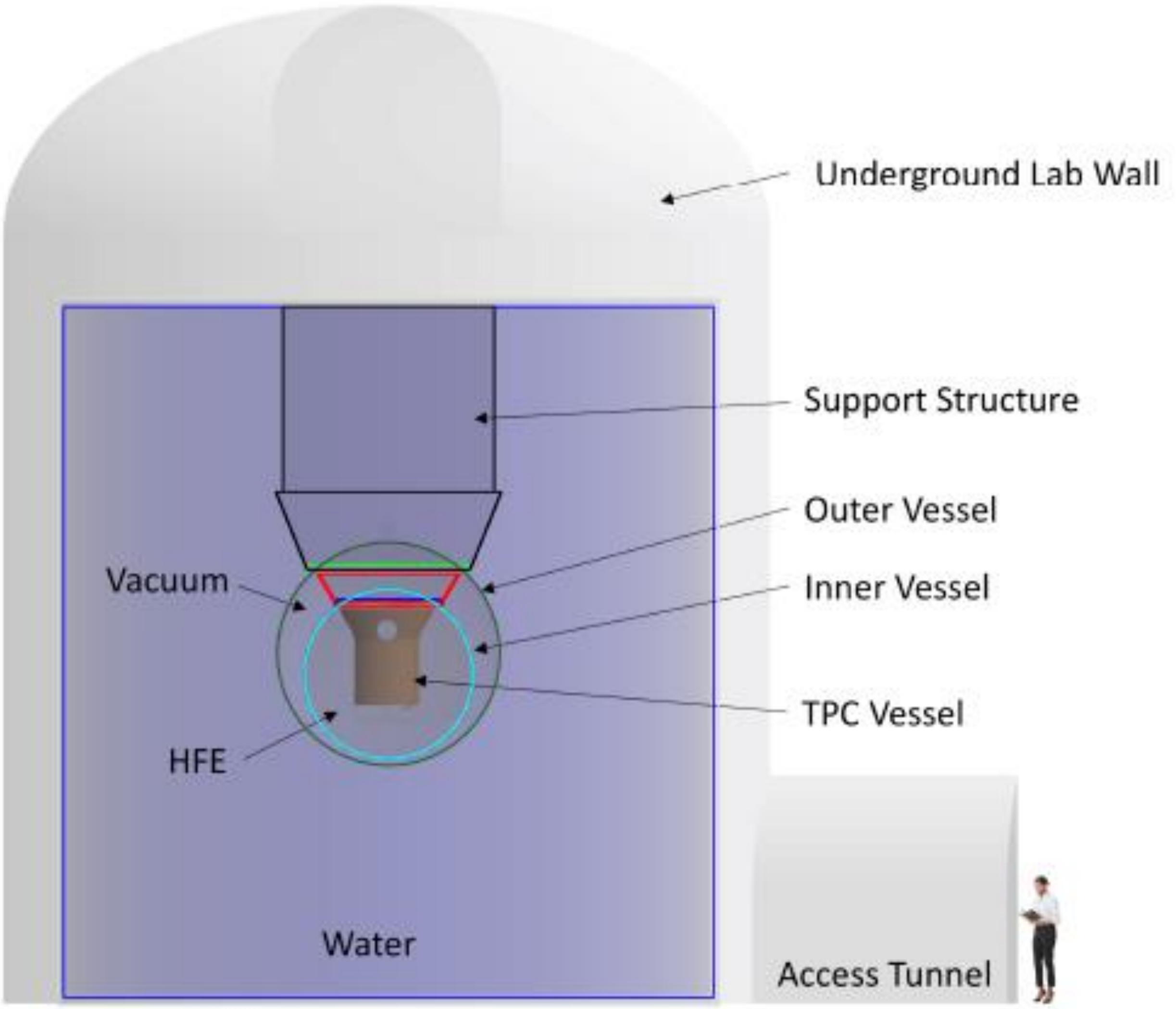
G Adhikari et al 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

K. Alphonso et al. J Low Temp Phys 211, 375–383 (2023).

nEXO

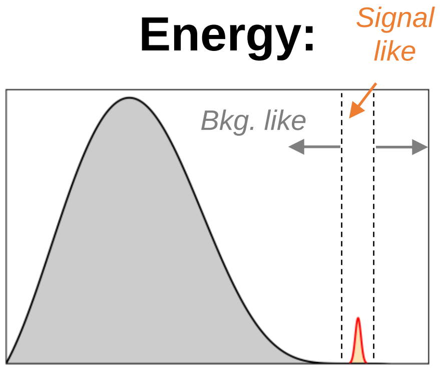
- nEXO – 5t enriched Xe in time-projection chamber
- Layers of passive shielding
- Low intrinsic background
- Deep underground
- Projected sensitivity (90% CL)

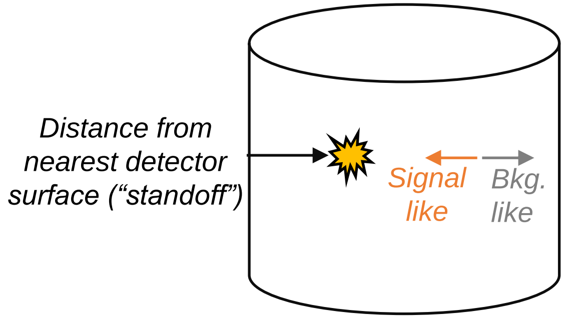
$$T_{1/2}^{0\nu} < 1.35 \times 10^{28} \text{ yr}$$

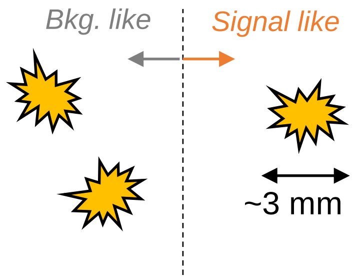


nEXO Signal and Background

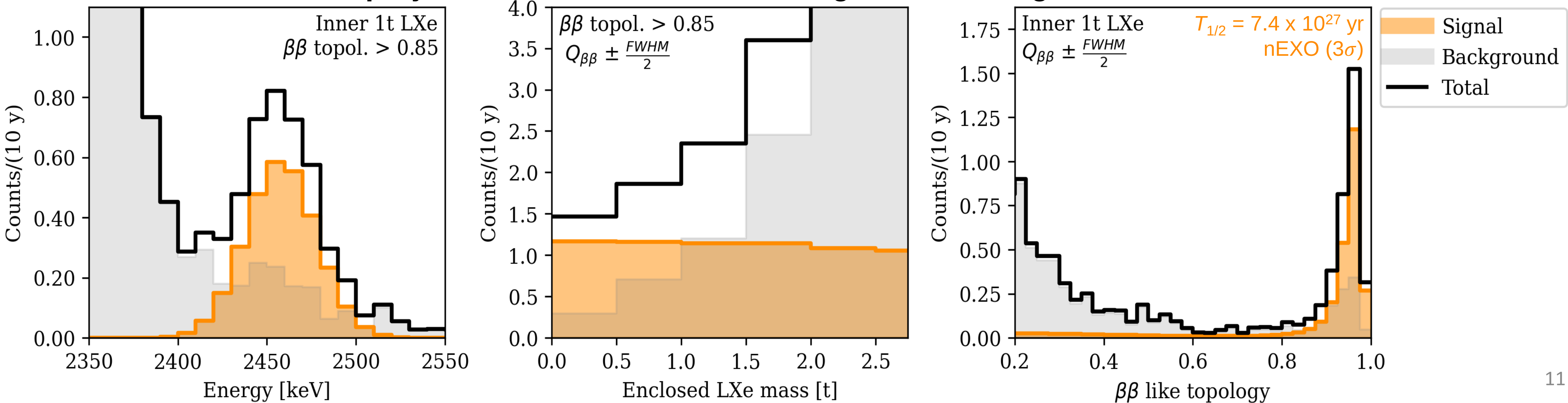
- nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal
- As a fully homogeneous detector, it precisely measures backgrounds in situ
  - No internal materials (other than Xe), making nEXO uniquely robust against unknown backgrounds







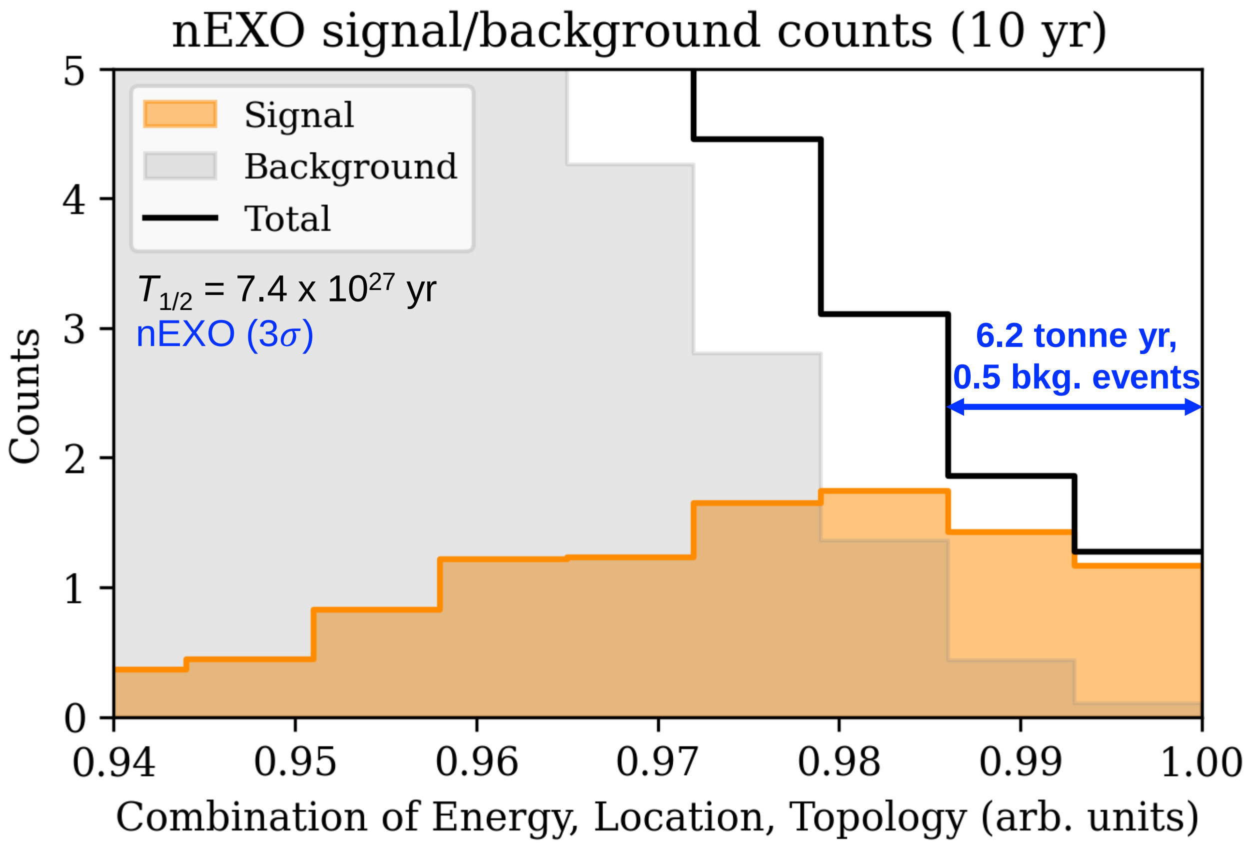
1D projections of simulated nEXO signal and backgrounds:



nEXO Signal and Background

- Likelihood fit allows optimal weighting between signal and background combining energy, topology, and standoff over full 3D parameter space
    - Arranging the 3D bins into 1D, ordered by signal-to-background ratio, helps visualize the signal and background separation in nEXO

Combine energy, topology, and standoff (preserving correlations)



0 ← Background-like ***Signal-like → 1***

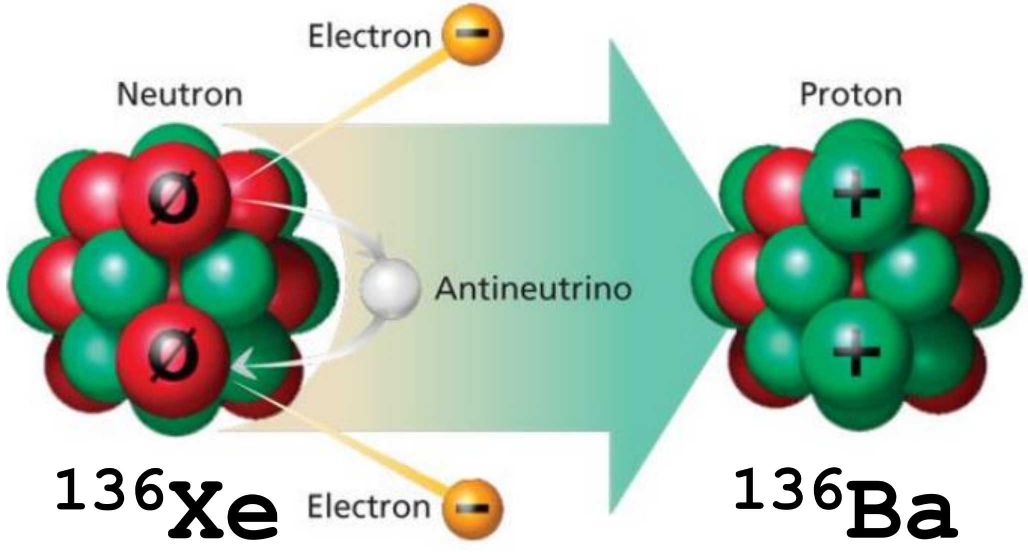
nEXO is a background free experiment in its full 3D parameter space

Barium tagging, unique to Xe 0νββ searches

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

- Identify barium daughter ion at decay site
- Complete non-ββ elimination, Positive signal of ββ decay
- Requires location identification and accessibility

- Simple!



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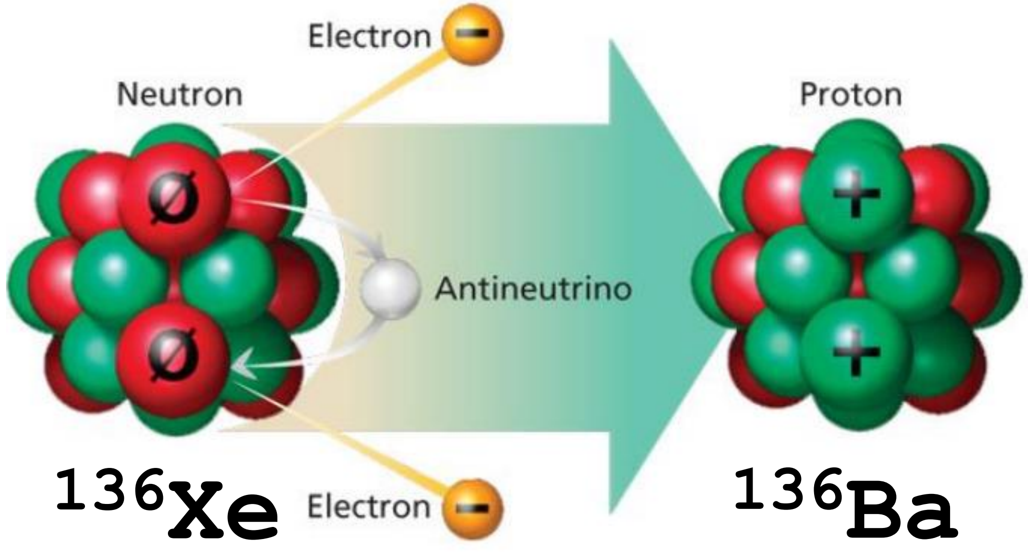
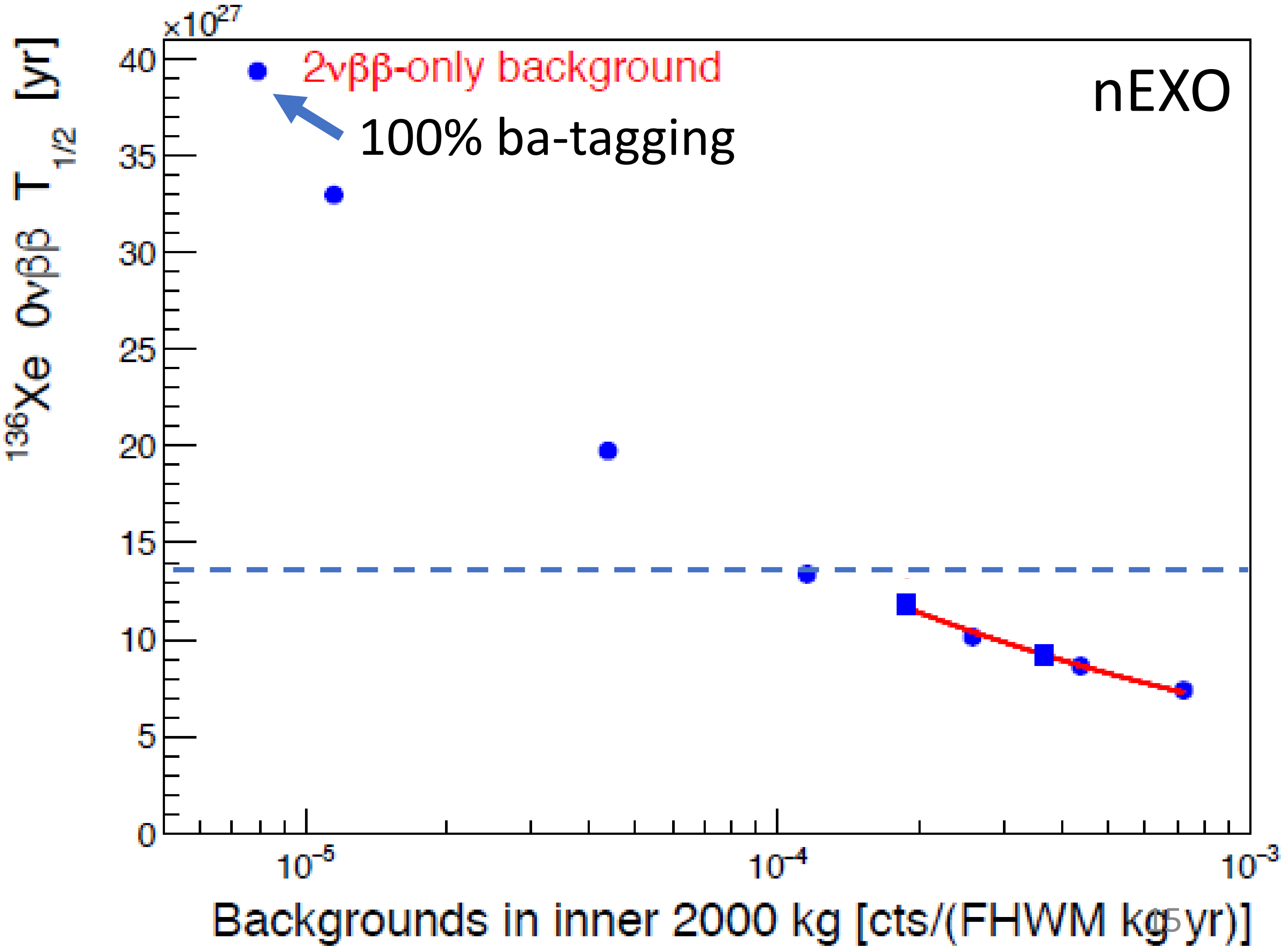
- How can you find a single ion in tons of xenon?



Ba-tagging eliminates all non-ββ backgrounds

- Identifying daughter ion following decay strictly eliminates all non-ββ
  - 2νββ still present, mostly rejected by energy

  → background free as possible



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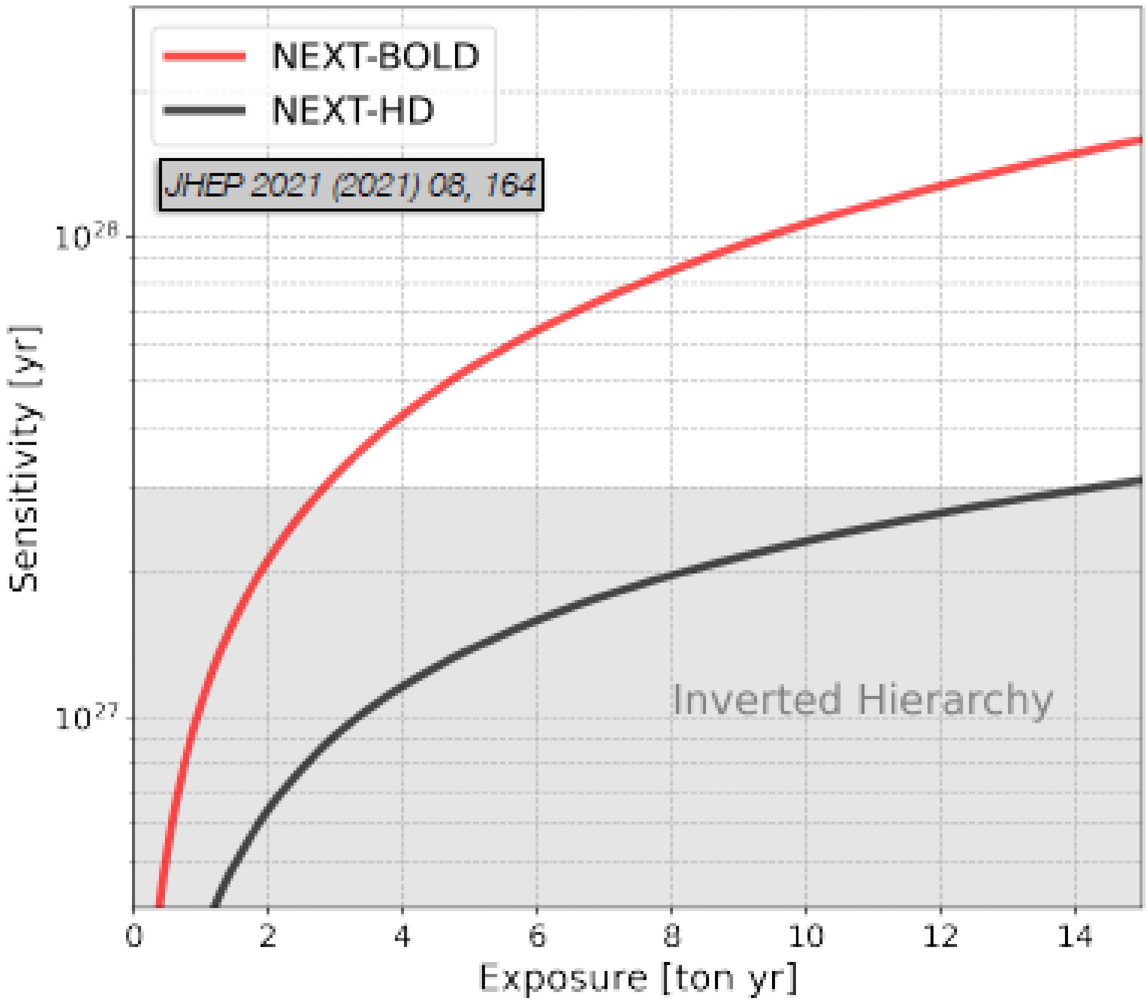
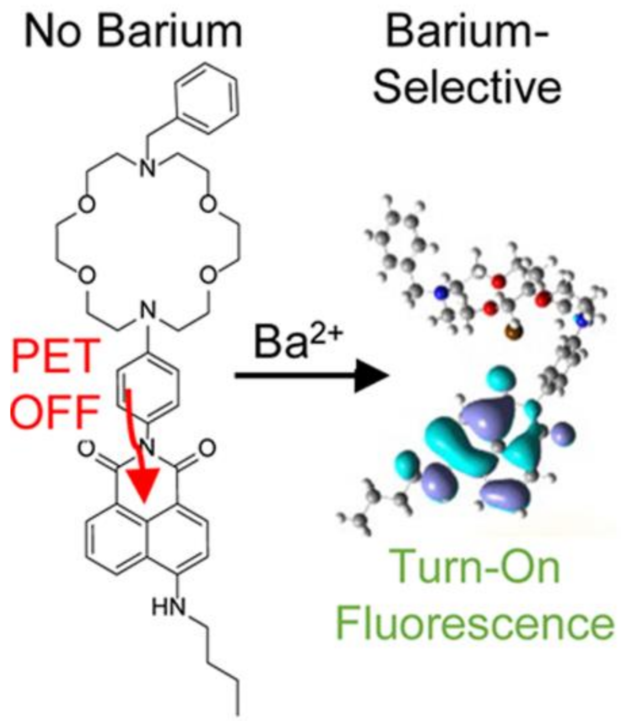


- NEXT – high pressure Xe gas TPC
- Chemosensor Ba^{++}-tagging



Ion extraction Ba-tagging in LXe

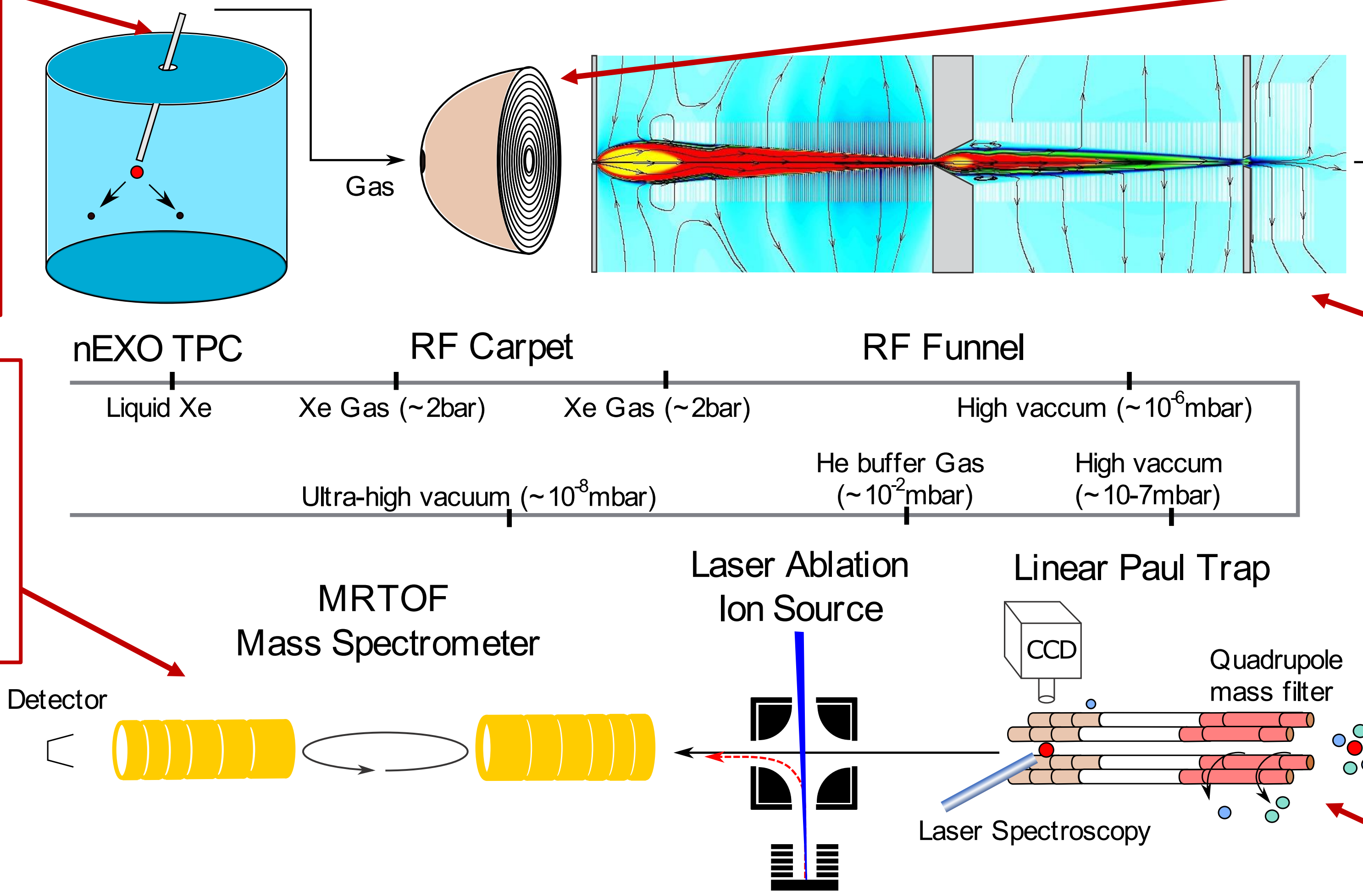
Stage1: Extraction of detector volume around the location of the decay to gas phase using a capillary tube.

Stage2: RF carpet for efficient transfer of ion from capillary to RF funnel

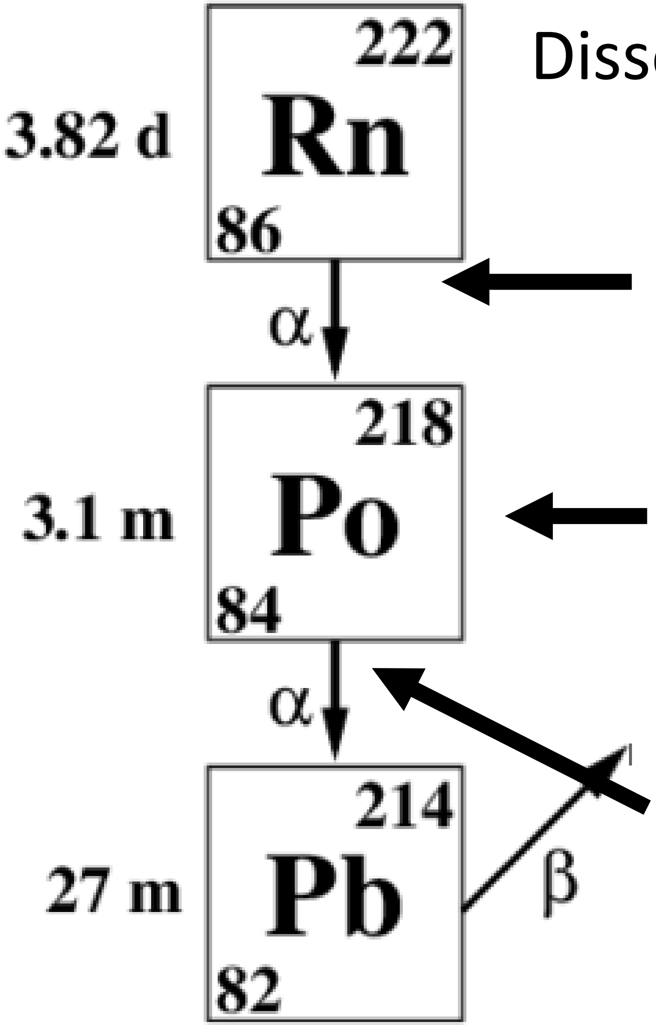
Stage3: RF funnel facilitates separation of xenon accompanying the Barium ion.

Stage4: The Linear Paul trap for detection of barium ion via laser fluorescence spectroscopy.

Stage5: Multiple Reflection TOF Spectrometer for systematic studies and determination of ion mass.



Ion extraction and transport from liquid xenon - Carleton

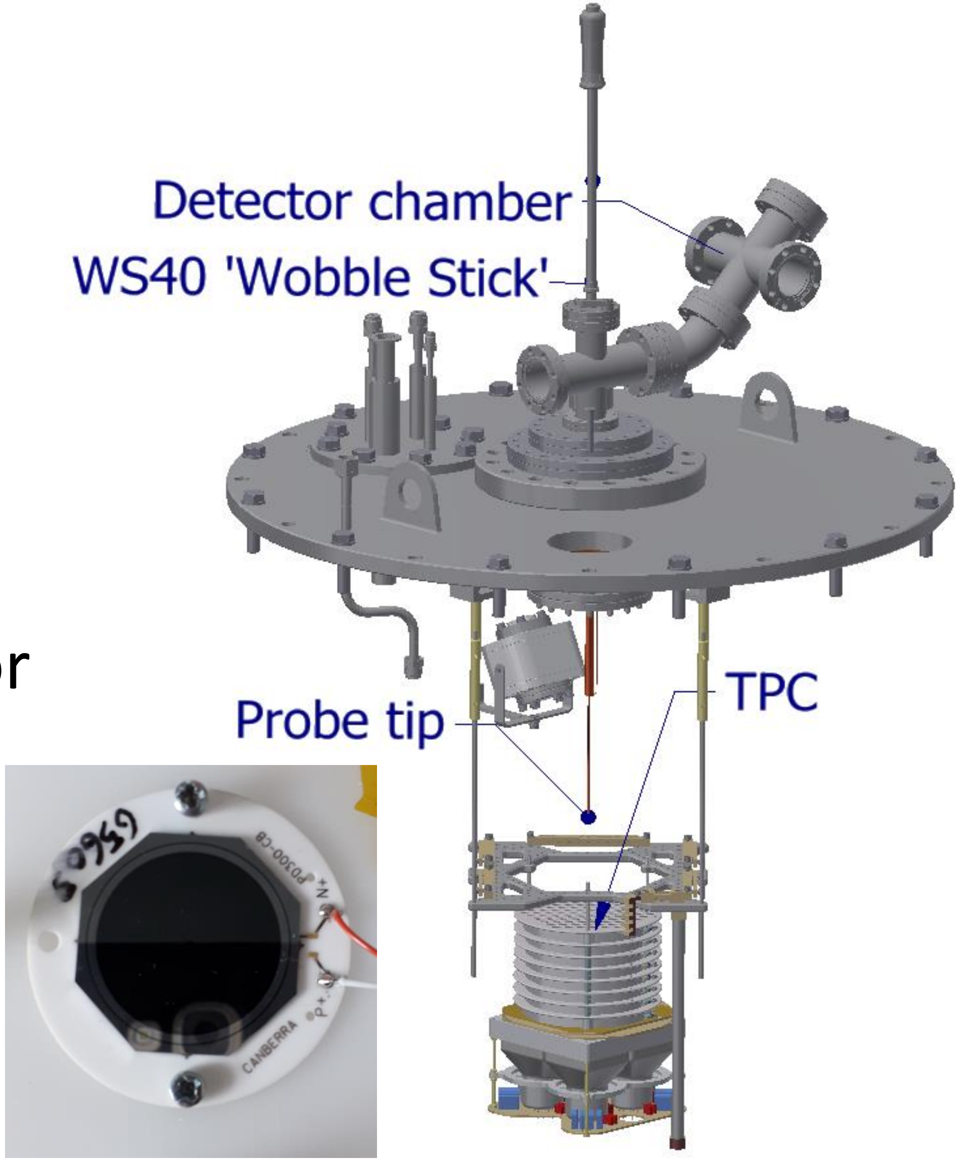


Dissolved in LXe

Distinctive signature detected by TPC; location determined for extraction

Ion extracted by capillary, transported to PIPS detector with high efficiency

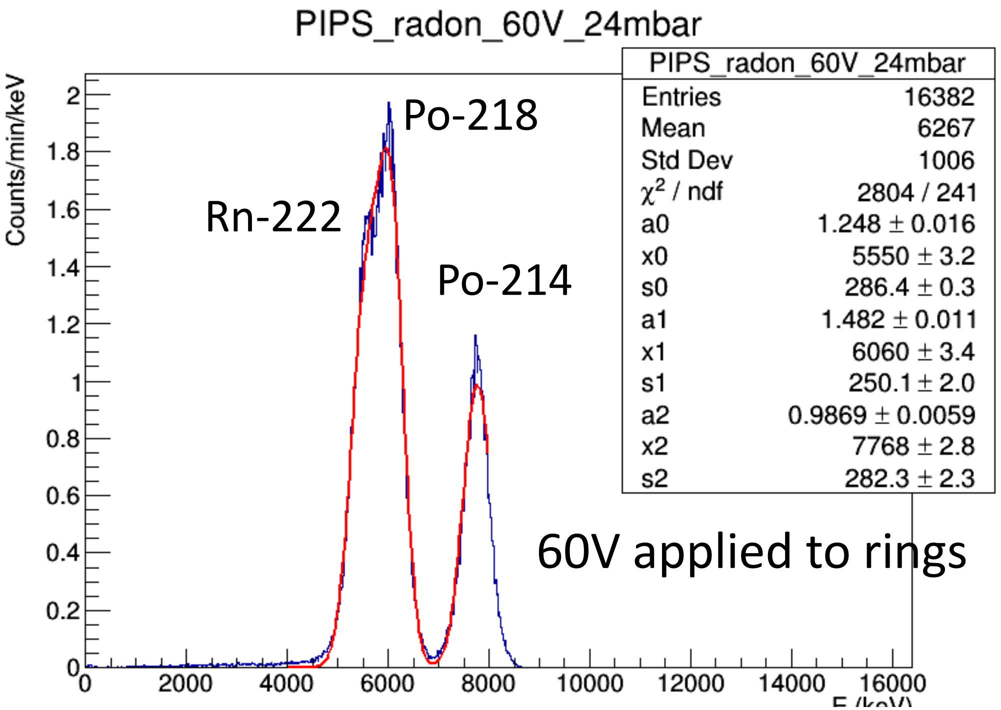
Decay identified by energy deposited in PIPS

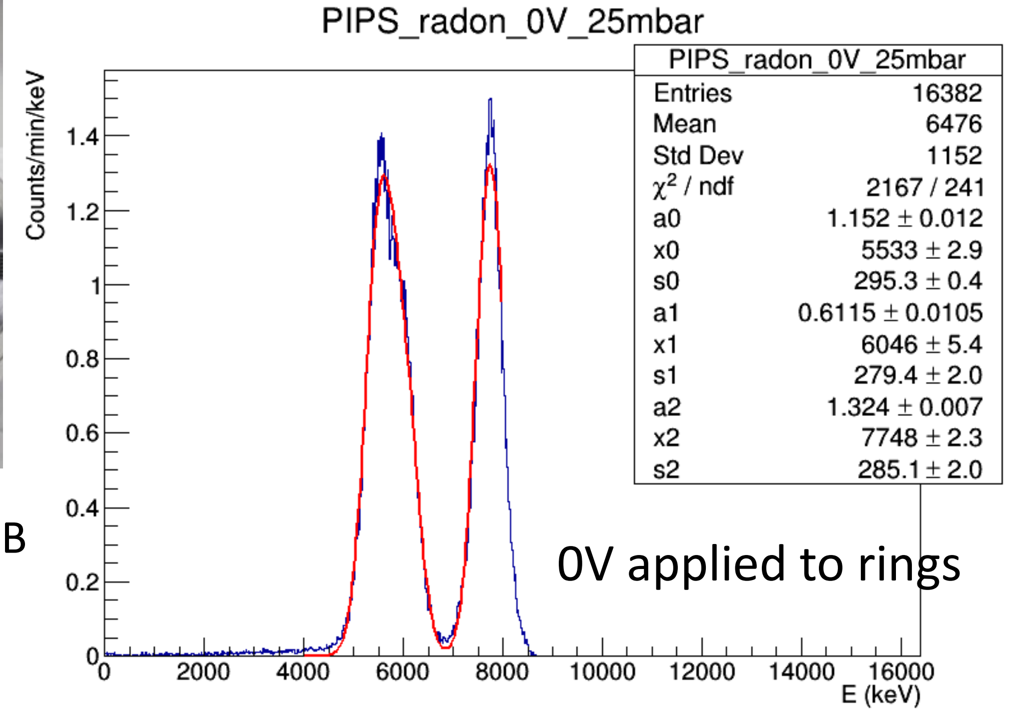


PIPS detector with Rn-222

- PIPS back operates at +40 V
- ~10 V/cm E-field needed to push ions from gas stream onto detector
- Commissioned with Rn-222 emitted into vacuum chamber
- Rn-222, Po-218, Po-214 alphas observed with field on
- Po-218 peak suppressed with field off → ions not guided onto detector

Canberra PD300-CB with field rings

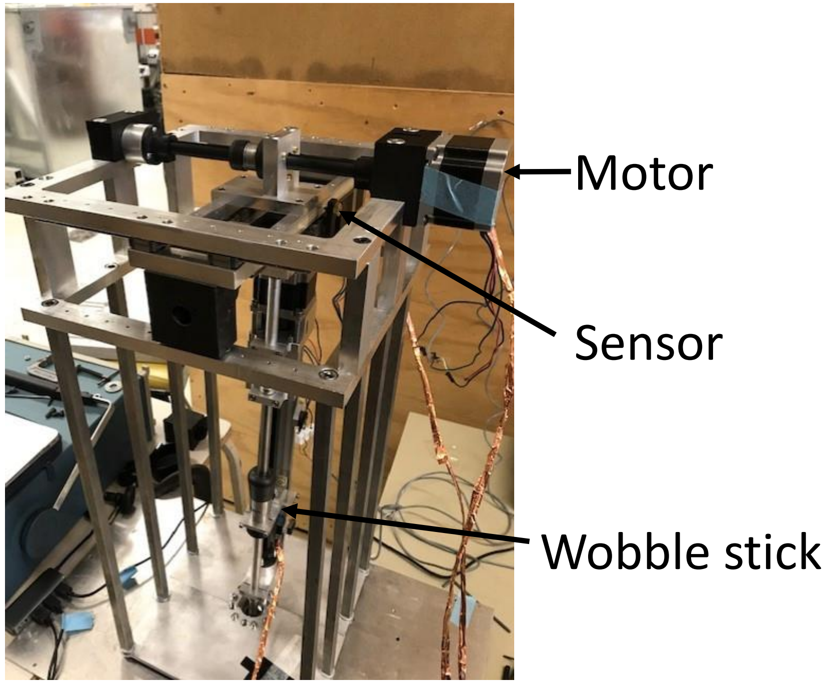


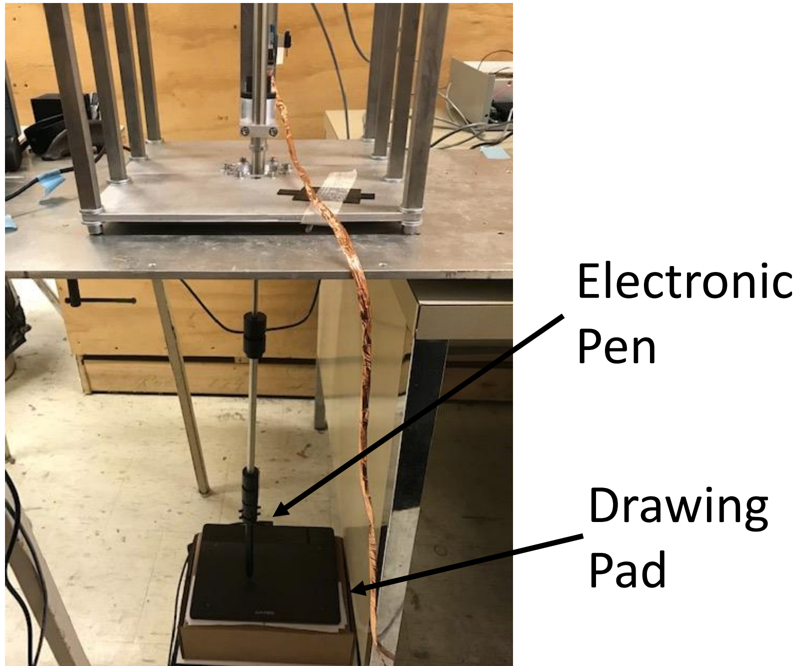


Talk by R. Elmansali W3-4

Displacement device

- Displacement device manipulates wobble stick in 3-D
- Moves tip (bottom) at speeds up to 14 mm/s to any point in space with 0.0002 mm^3 spatial tolerance
- Linear sensor strips provide individual motor positioning feedback with 0.15 mm precision
- Tested accuracy of motion by touching specific points on an electronic drawing pad





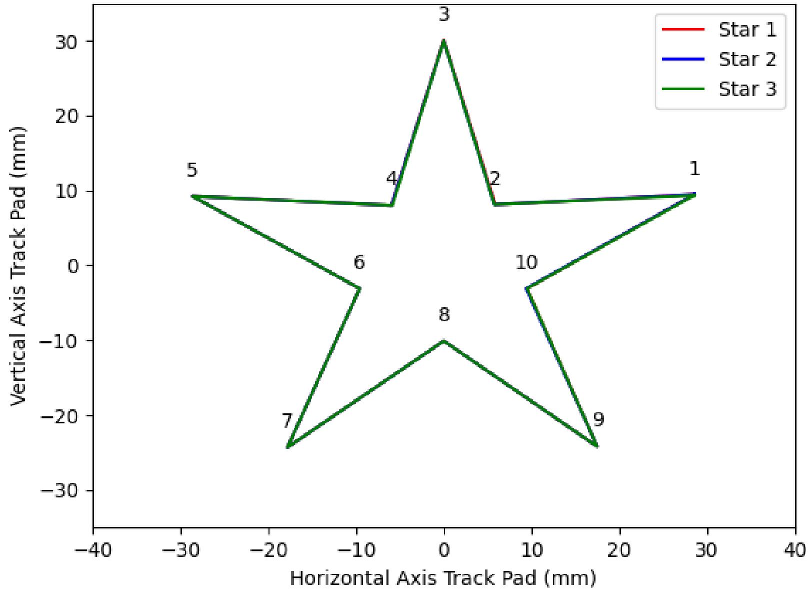
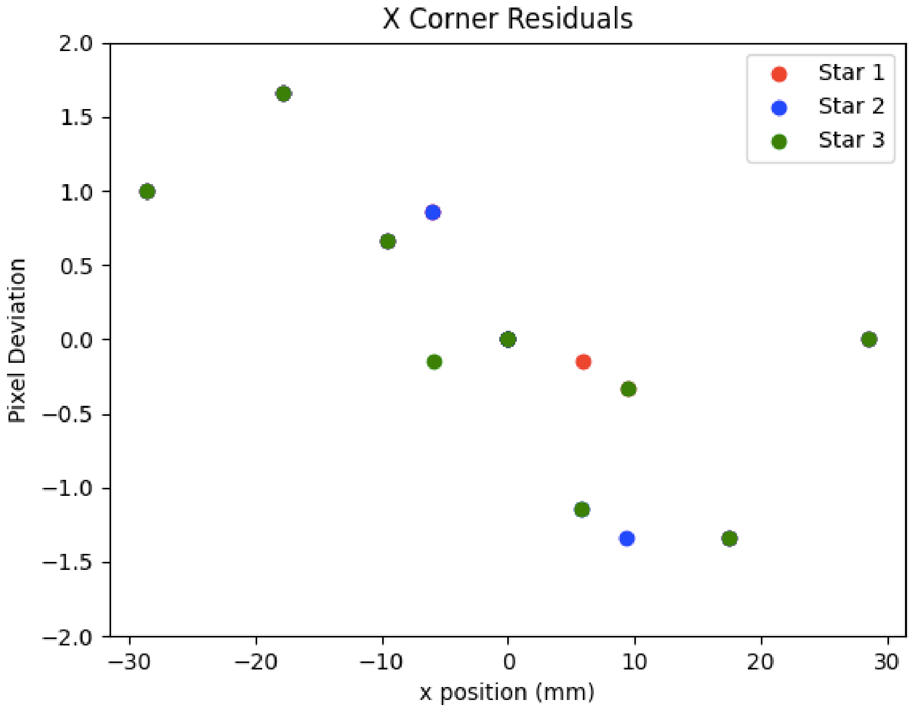
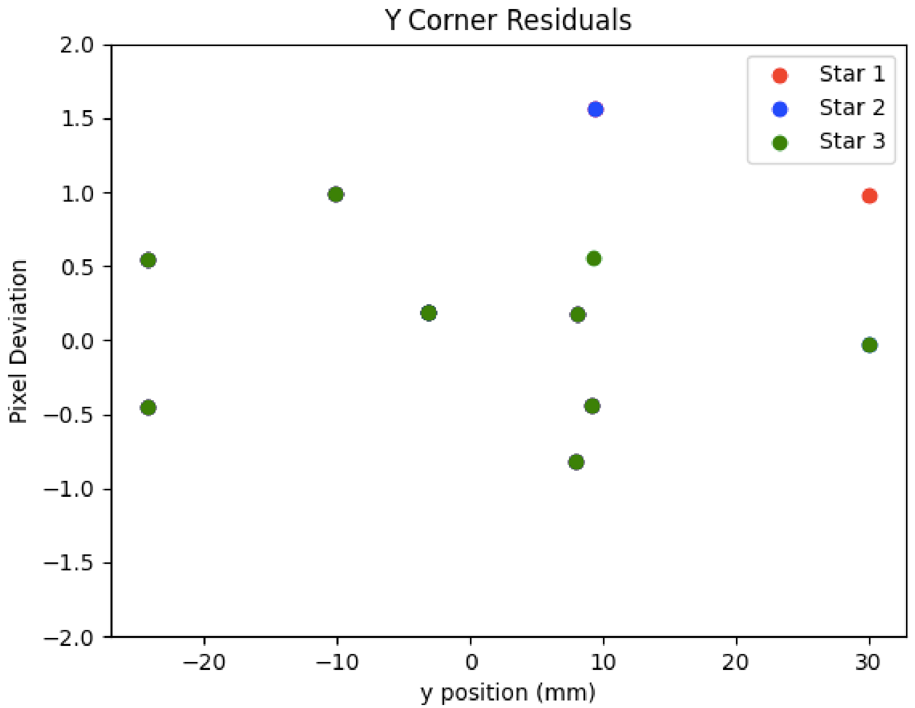


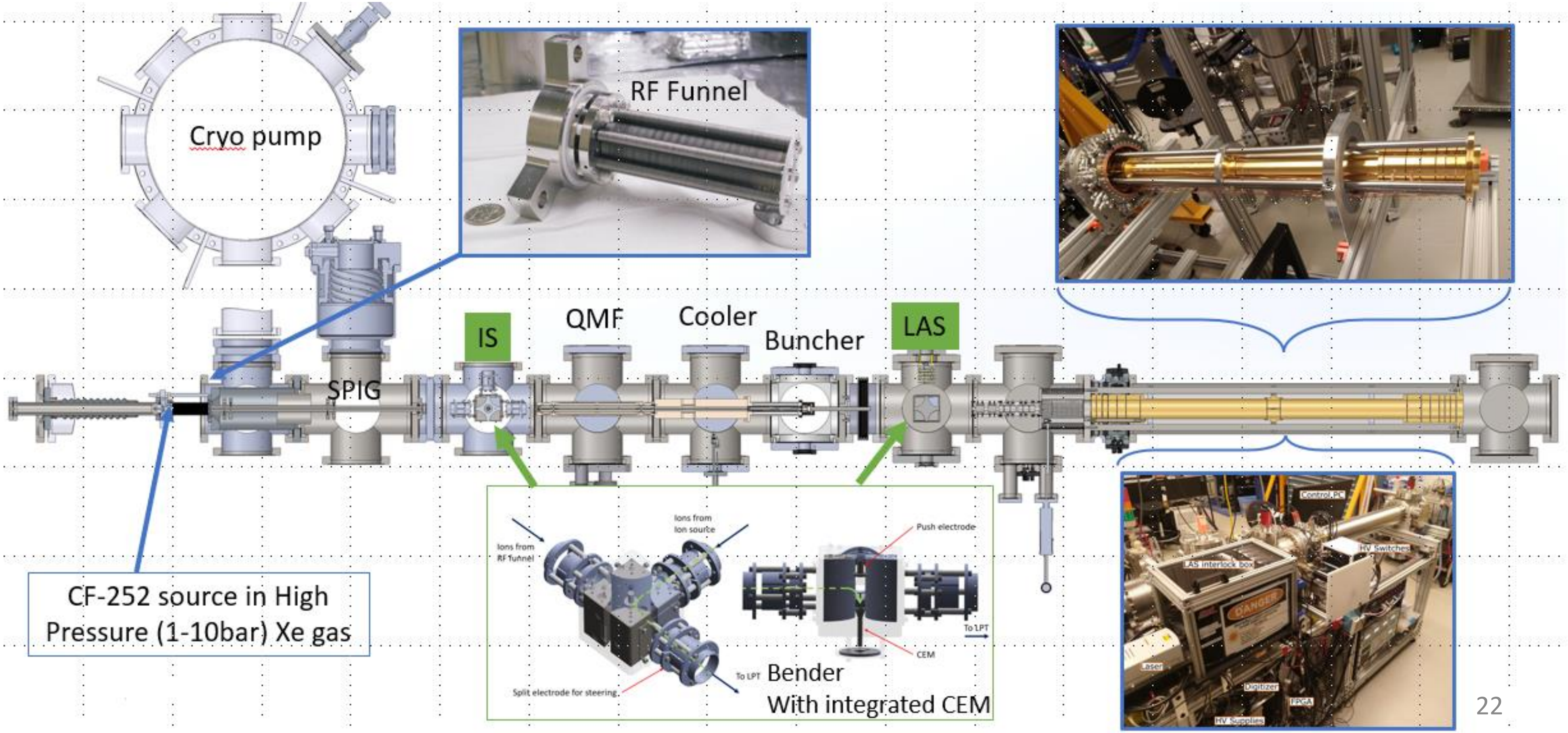
Table 13: Star corners data points

Corner Number	Experimental Position (mm)	Theoretical Position (mm)
1	(28.53, 9.44)	(28.53, 9.27)
2	(5.75, 8.11)	(5.88, 8.09)
3	(0.00, 29.99)	(0.00, 30.00)
4	(-5.97, 8.00)	(-5.88, 8.09)
5	(-28.64, 9.22)	(-28.53, 9.27)
6	(-9.59, -3.11)	(-9.51, -3.09)
7	(-17.81, -24.33)	(-17.63, -24.27)
8	(0.00, -10.11)	(0.00, -10.00)
9	(17.48, -24.22)	(17.63, -24.27)
10	(9.35, -3.11)	(9.51, -3.09)

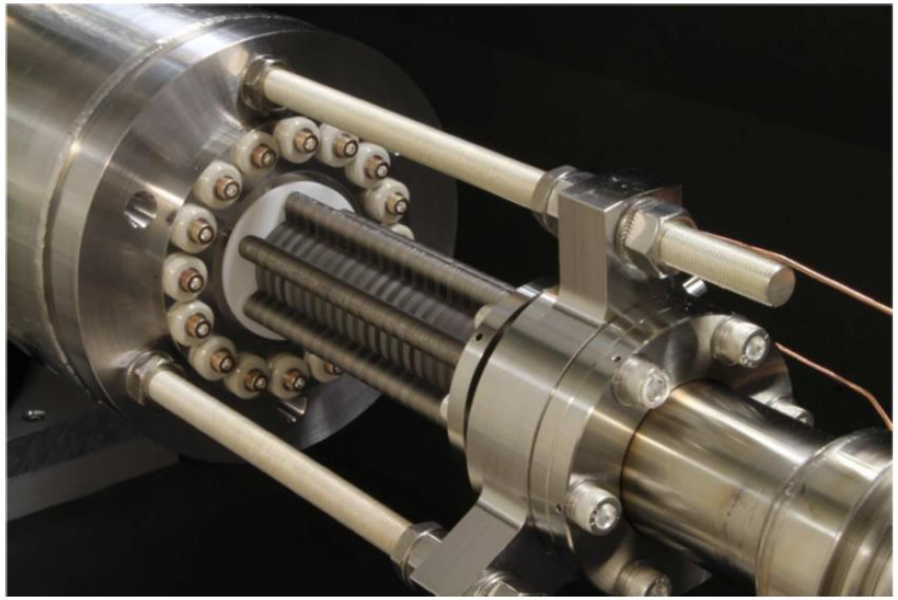


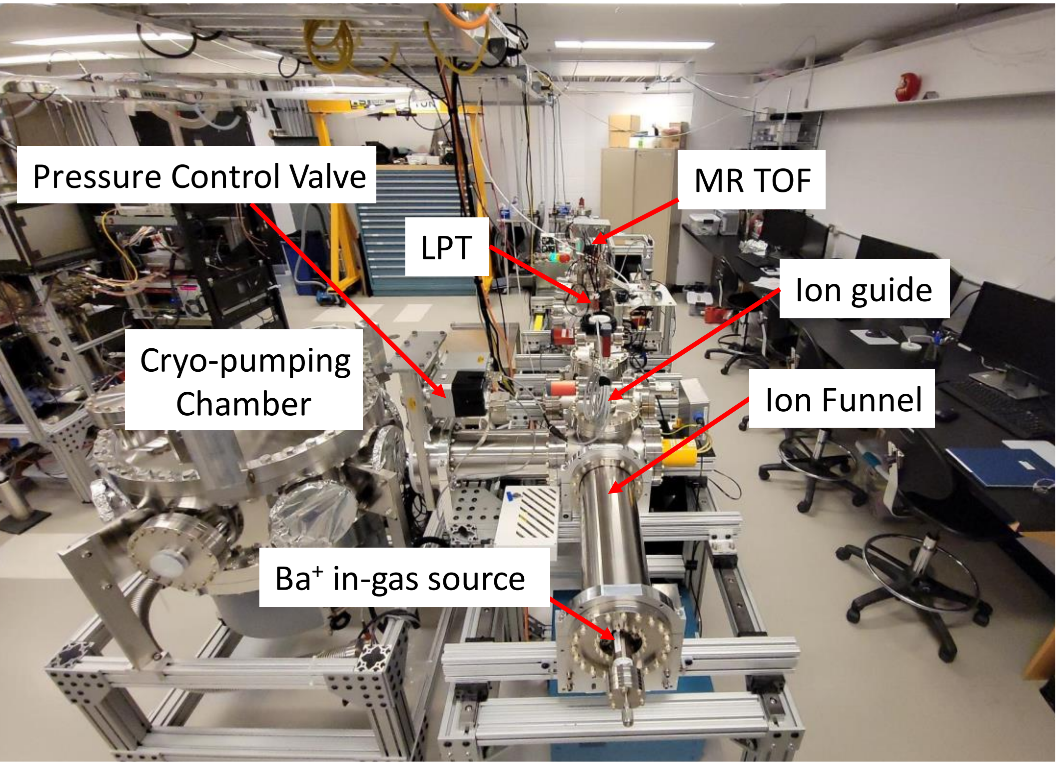


Ion separation and identification - McGill

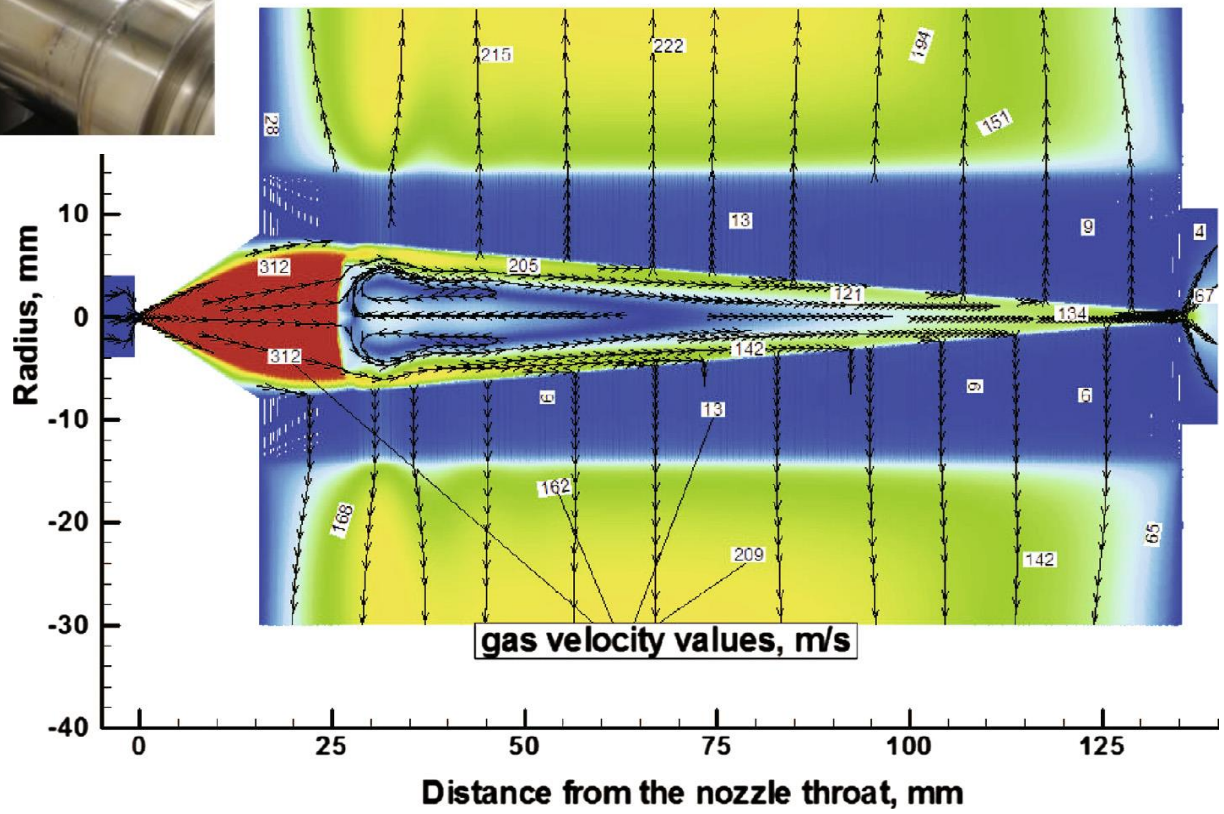


RF Funnel



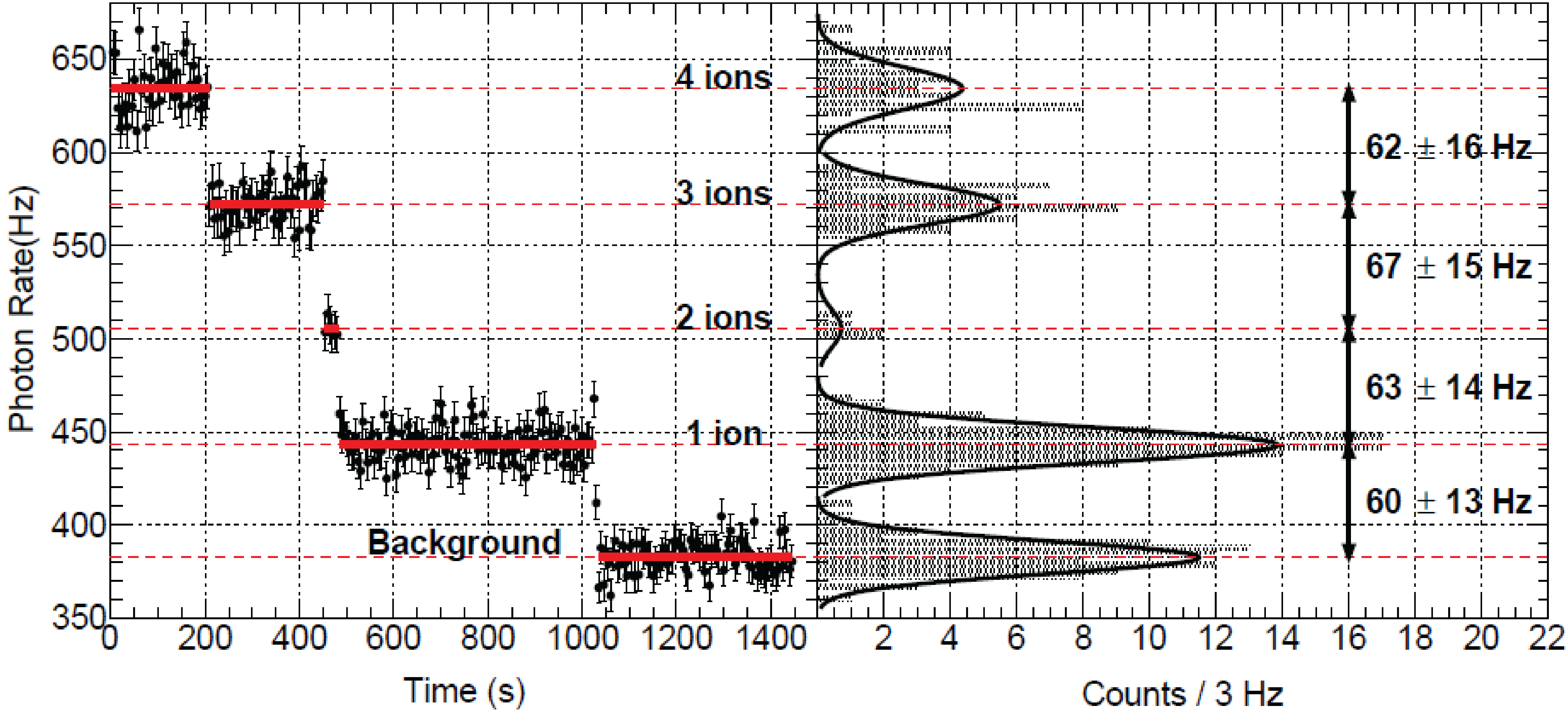


Calculated Xe gas velocity flow field

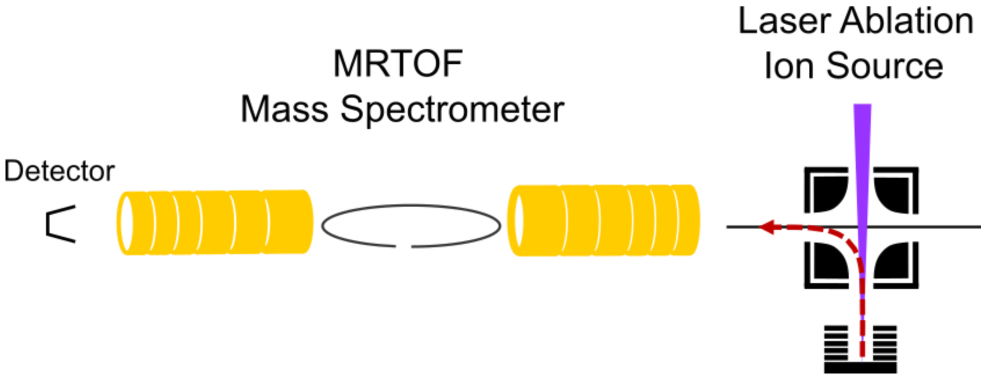


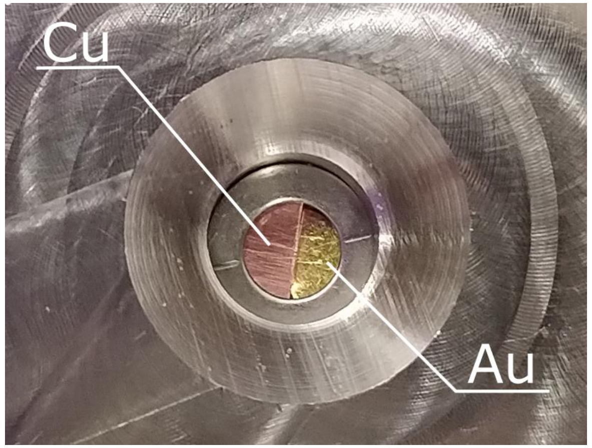
More on LPT by H. Rasiwala next!

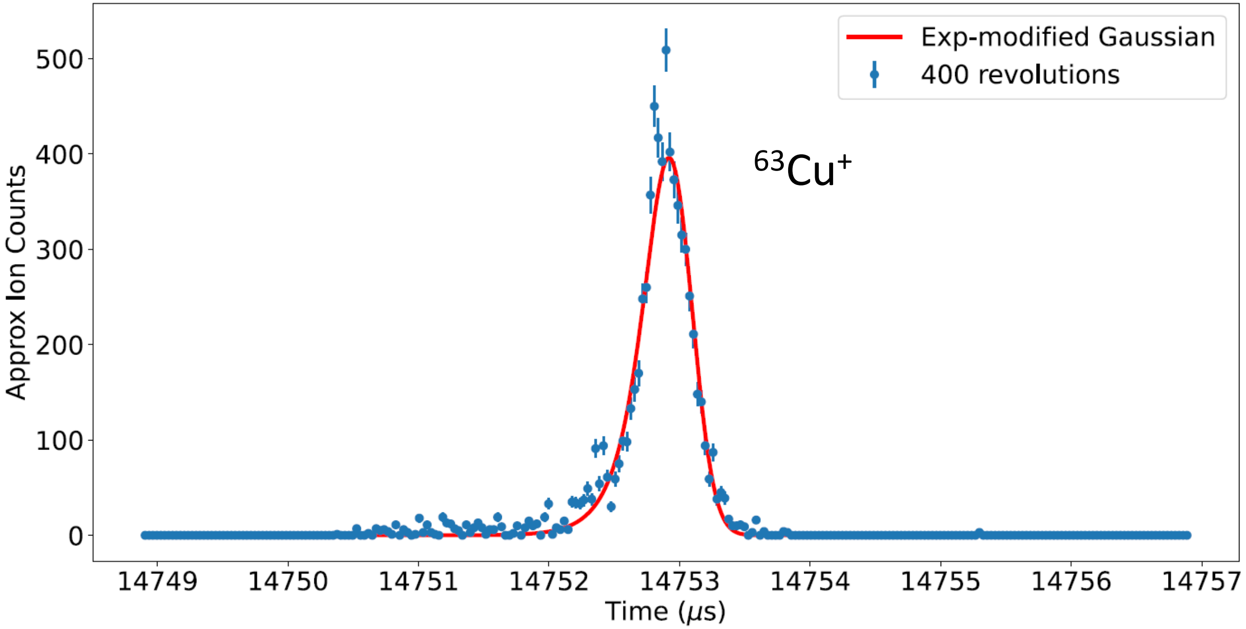
Single-ion spectroscopy in LPT



MRTOF







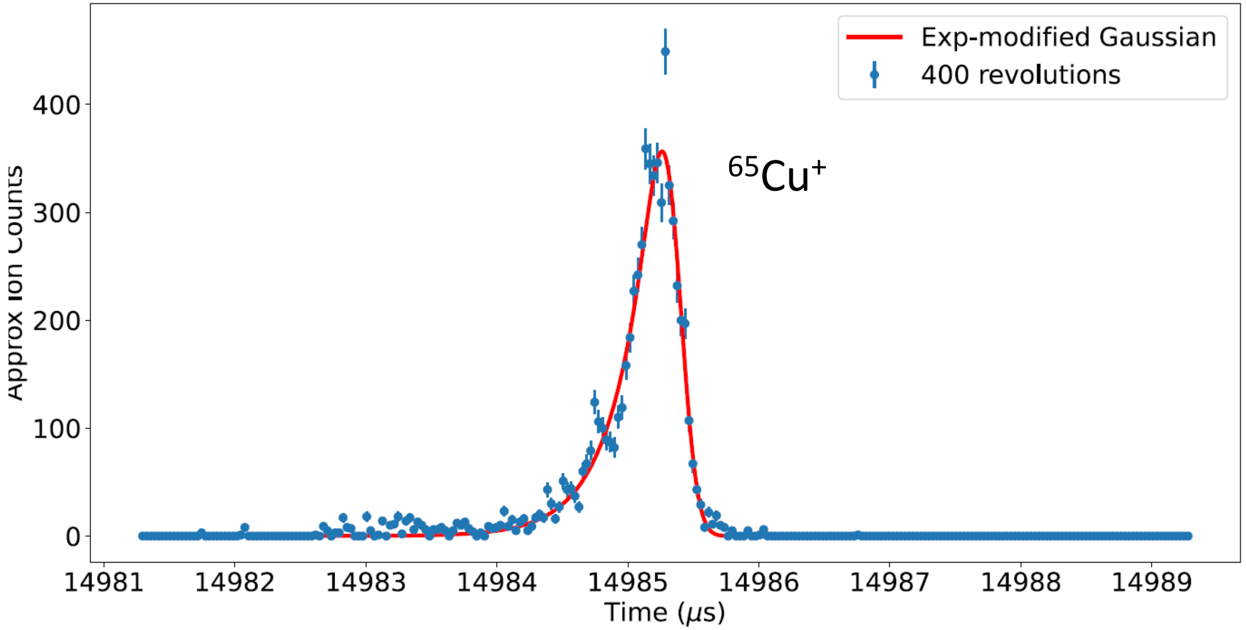


Table 7.2 TOF meausurements for Cu isotopes at 400 revolutions, atomic mass and relative abundance figures are taken from ref [134].

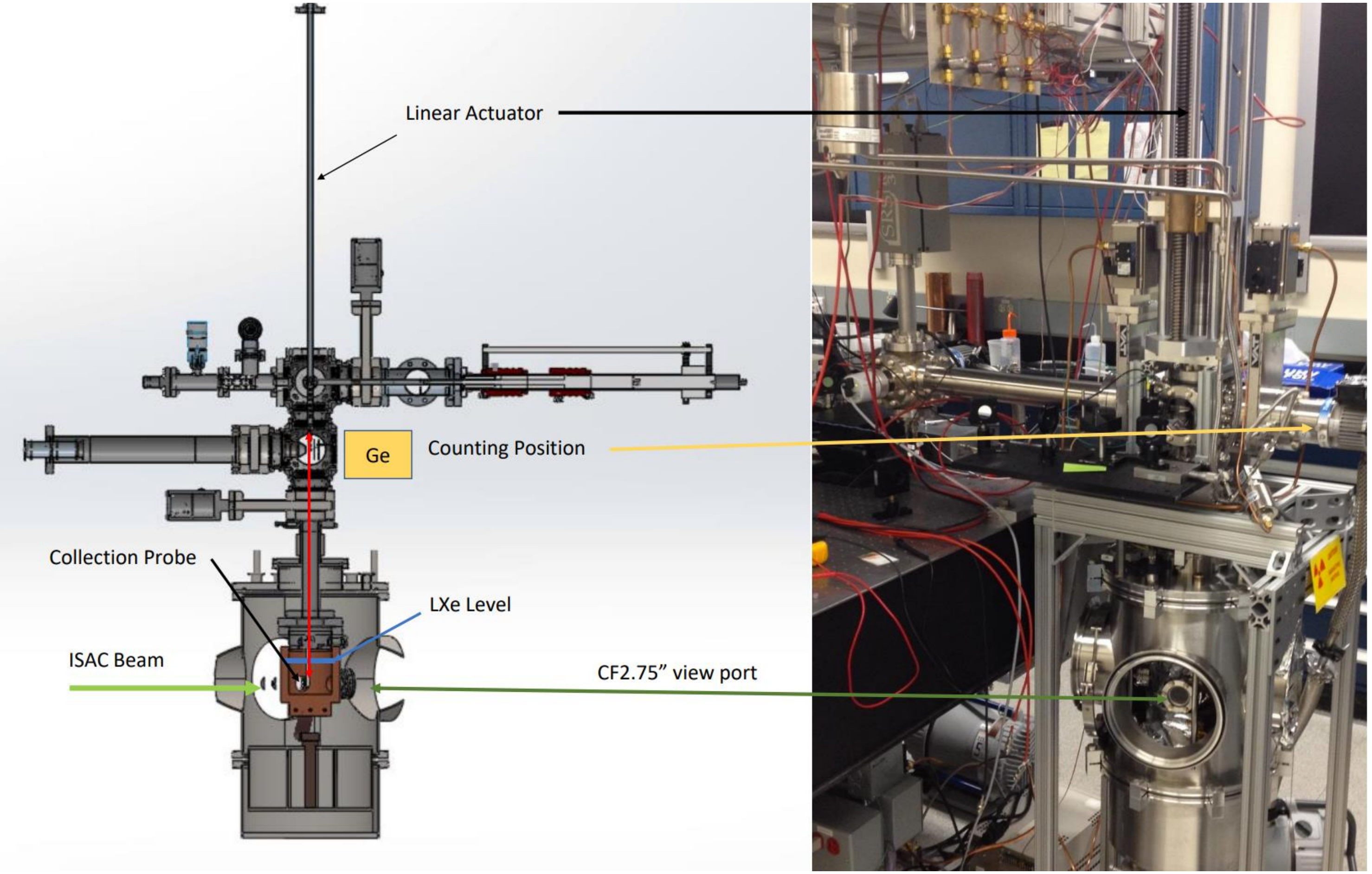
Isotope	Center (μs)	FWHM (μs)	t_{rev} (μs)	Atomic Mass	Abundance (%)
$^{63}Cu^{+}$	14753.442	0.331	36.793	62.92959772(56)	69.15(15)
$^{65}Cu^{+}$	14985.467	0.290	37.373	64.92778970(71)	30.85(15)

MRP: 20,000, limited by initial ion kinetic energy spread

Talk by D. Ray M1-1

Online in-LXe barium source

- Inject radioactive beam into LXe at ISAC
- Collect radioactive ions on electrostatic probe
- Remove them from LXe.
- Ge counter for identification.



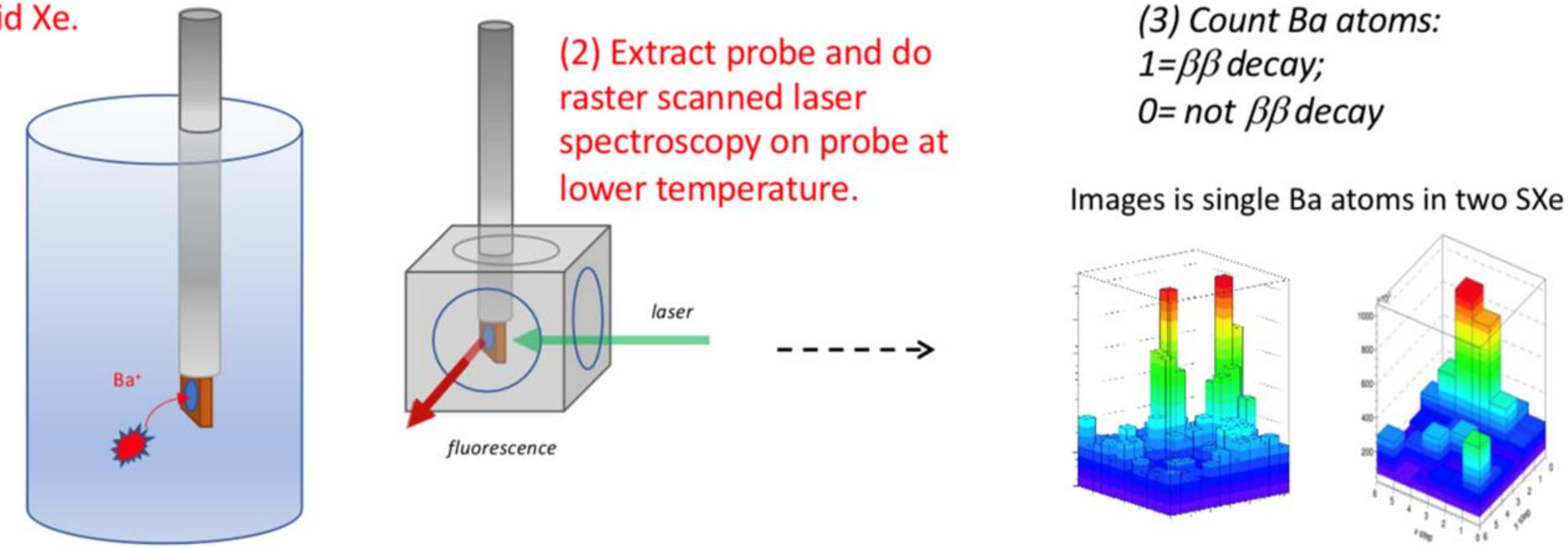
Alternative approach – cryogenic probe

(1) Capture Ba^+ using a cryogenic probe to trap Ba/Ba^+ in solid Xe.

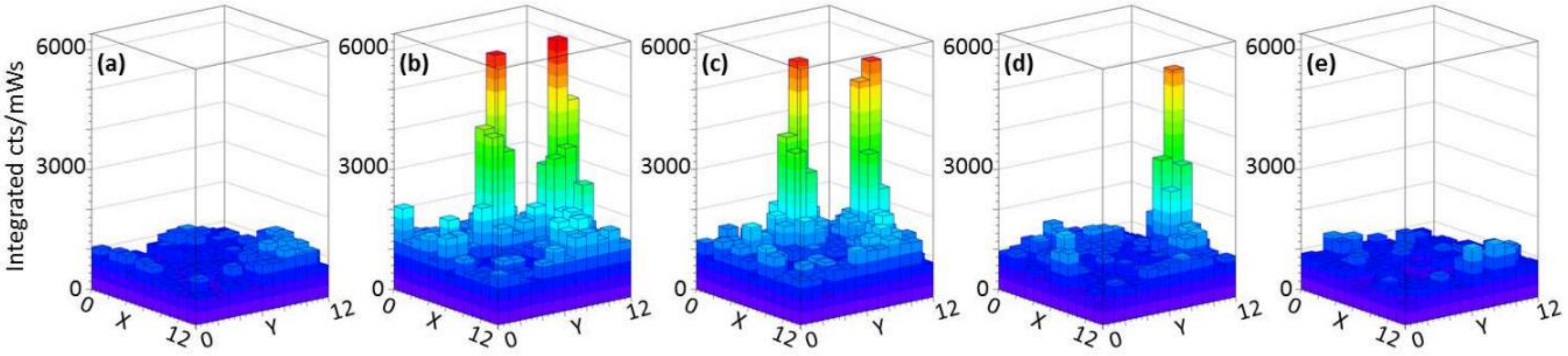
(2) Extract probe and do raster scanned laser spectroscopy on probe at lower temperature.

(3) Count Ba atoms:
1= $\beta\beta$ decay;
0= not $\beta\beta$ decay

Images is single Ba atoms in two SXe matrix sites



Single atoms observed in xenon ice



SXe Ba Ba (rescan 1) Ba (rescan 2) SXe

Summary

- Double beta decay is a unique portal to BSM physics in neutrino sector
- Upcoming experiments will cover I.O. of neutrino masses
- Background rejection is key to high sensitivity
- Barium tagging promises to eliminate all non-ββ backgrounds

- Work continues to demonstrate all aspects of ion extraction and tagging

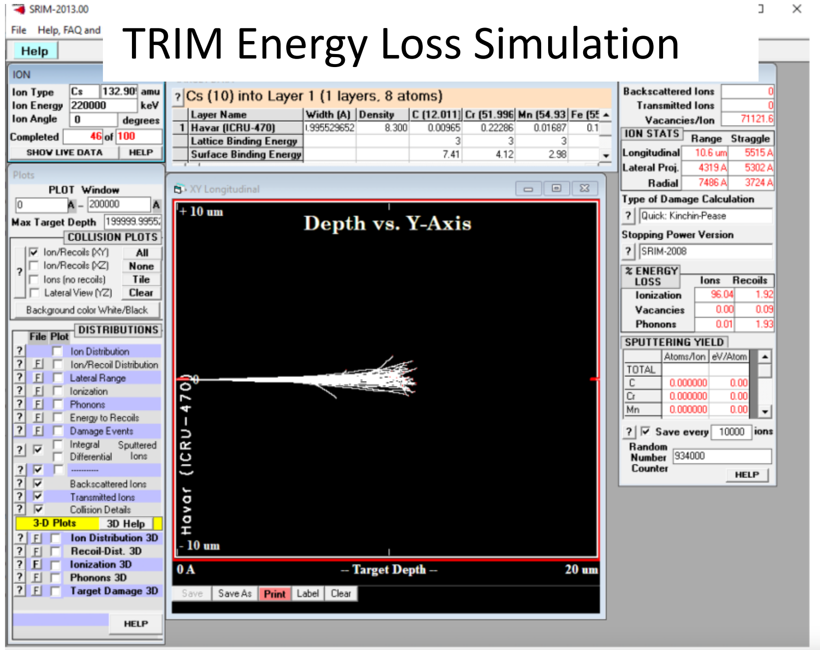
Ba-tagging groups associated with nEXO

Extra slides

Beam Window

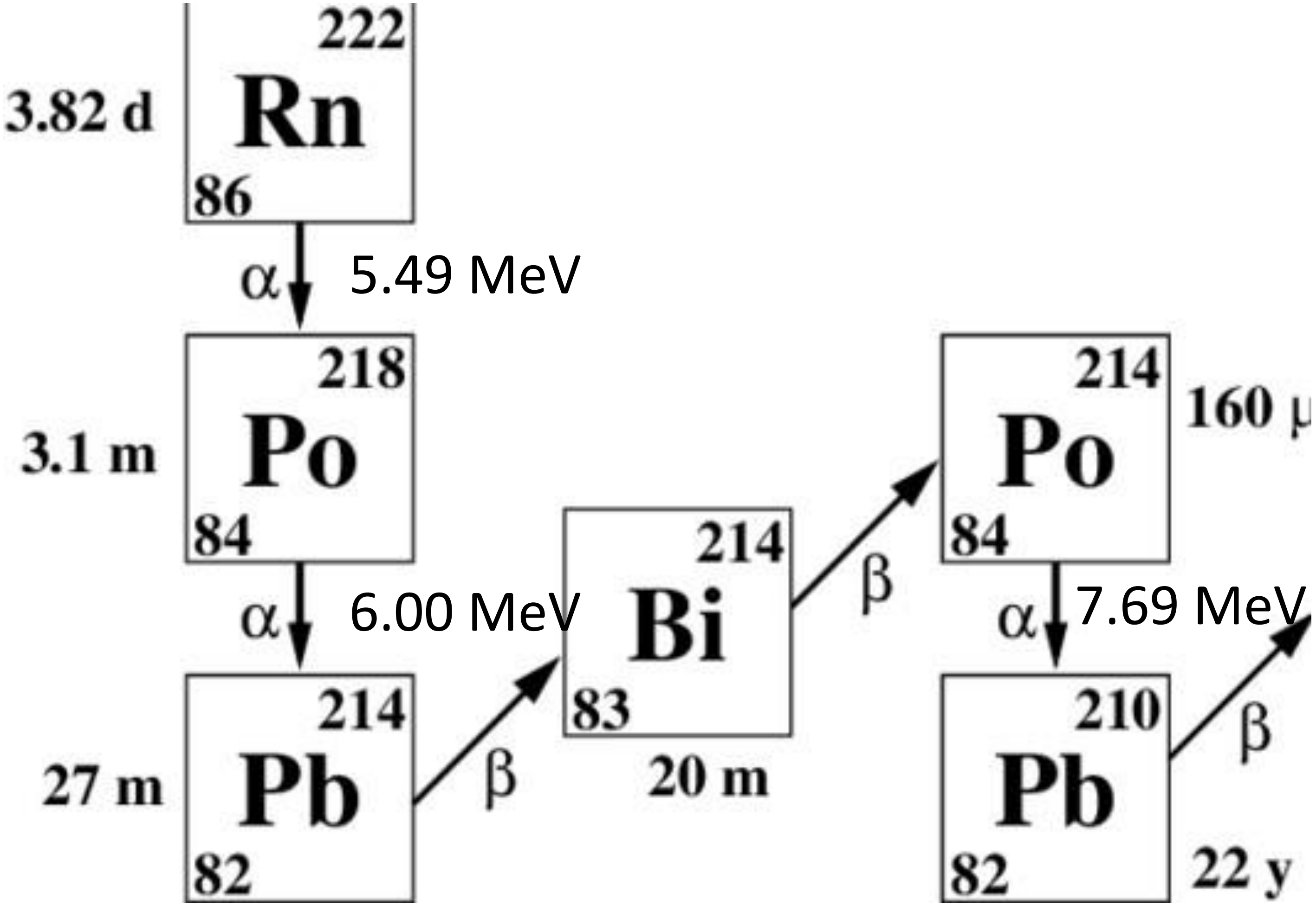
- Must admit ions while containing LXe at ~1 bar and 165 K.
- Likely 8 micron Be foil commercially affixed by either diffusion bonding or epoxy.
- Custom mount design being finalized, will go on existing CF port.
- Vendor pressure test at room temp, but we will have to repeat at LXe.
- Alternative 1 mil Kapton foil assemblies already being tested warm and cold at UNCW.

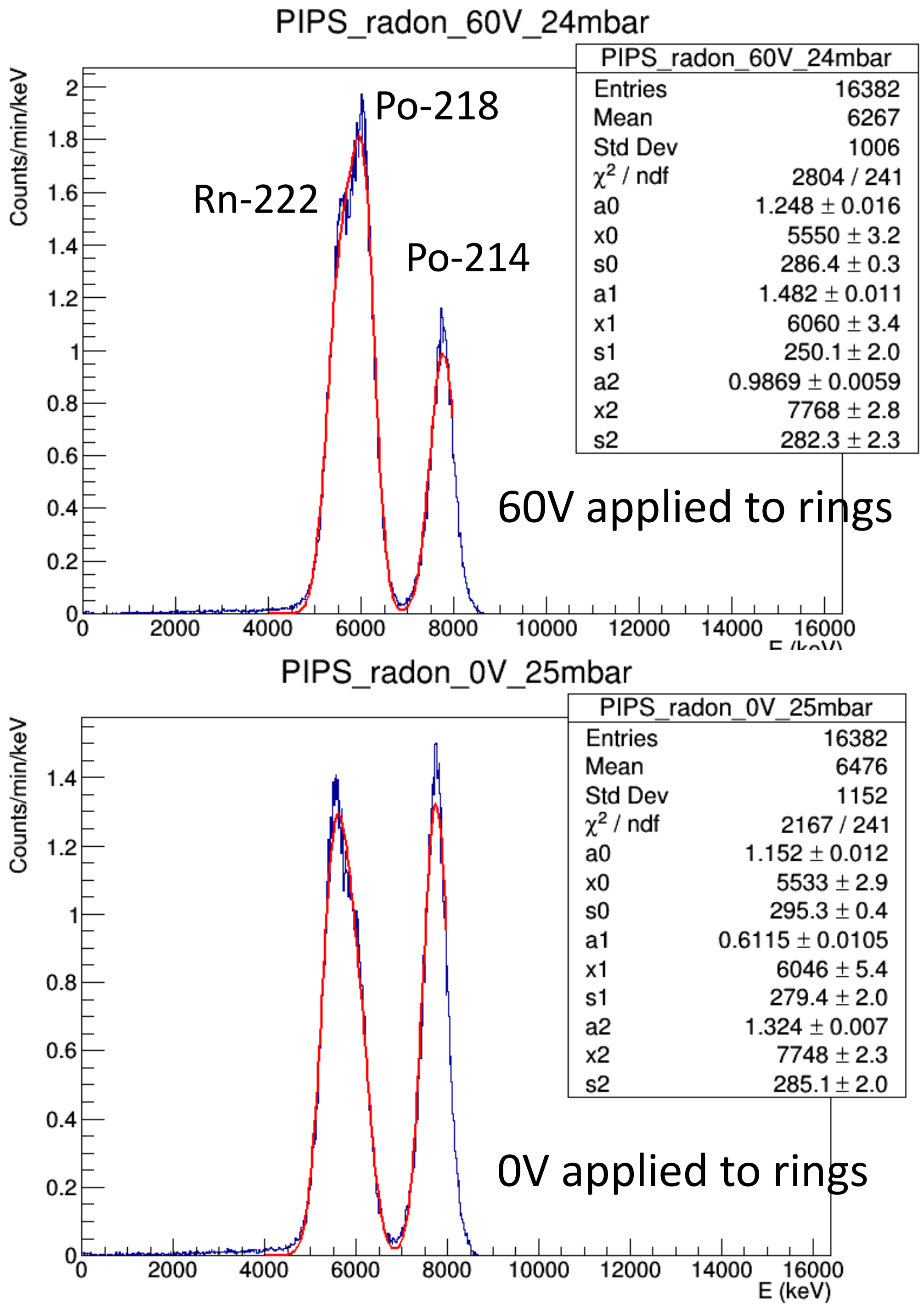
TRIM Energy Loss Simulation



Kapton Test Piece

PIPS commissioned





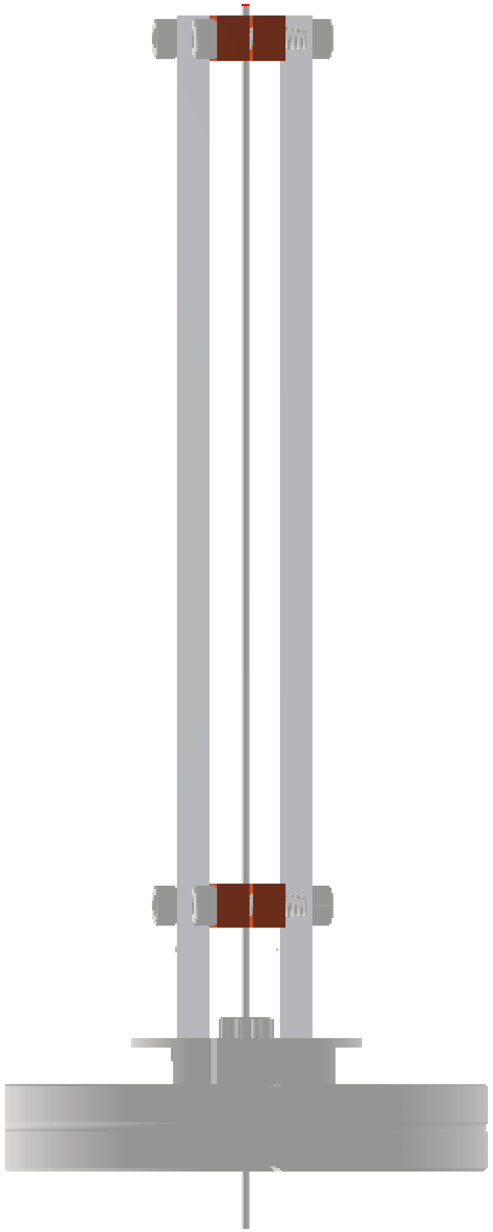
Capillary heating

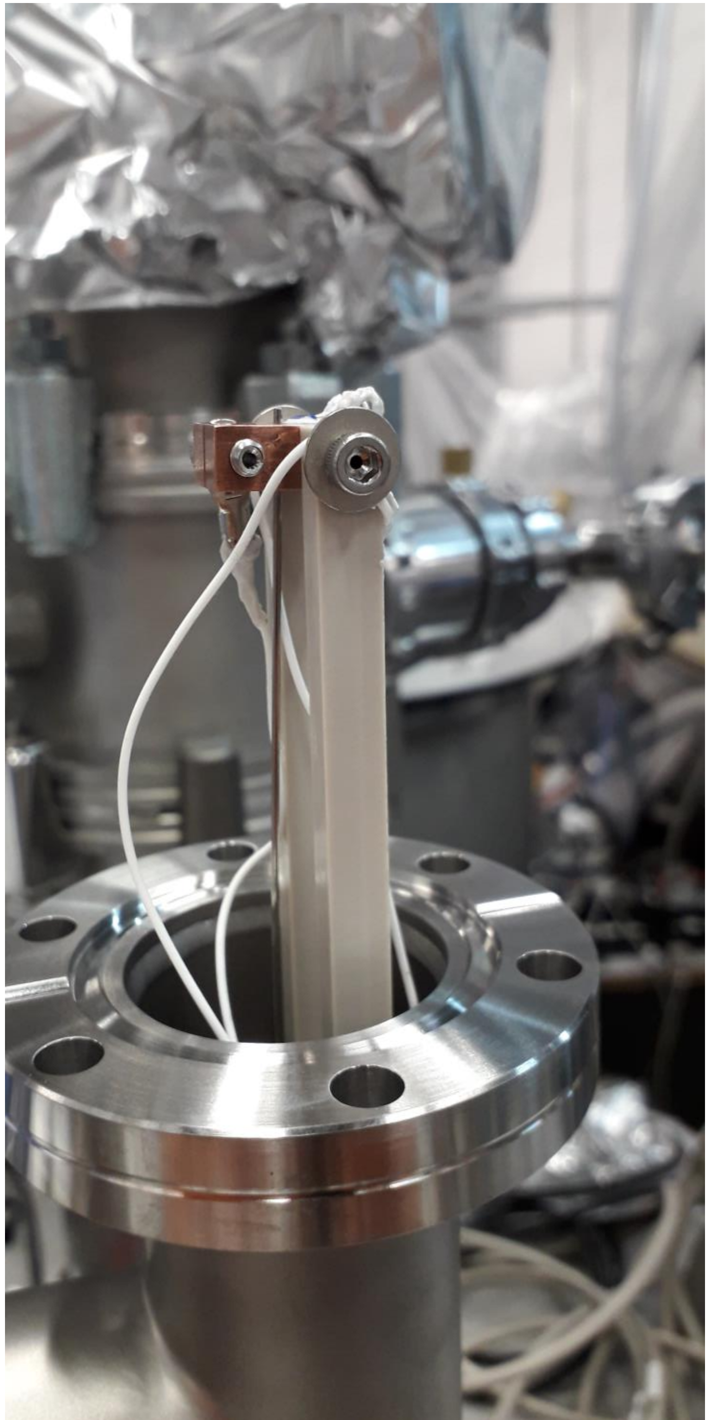
- Heat capillary with electric current
- Resistance ~ 0.3 Ohms for 10 cm

  → ~5 A for ~7.5 W
- RTDs measure temperature on top and bottom clamp
- In testing:

V (V)	I (A)	T_top (C)	T_bot (C)	T_cap (C)
0.5	1.5	25	30	55
0.7	2.5	25	30	90

Work by Raad Shaikh

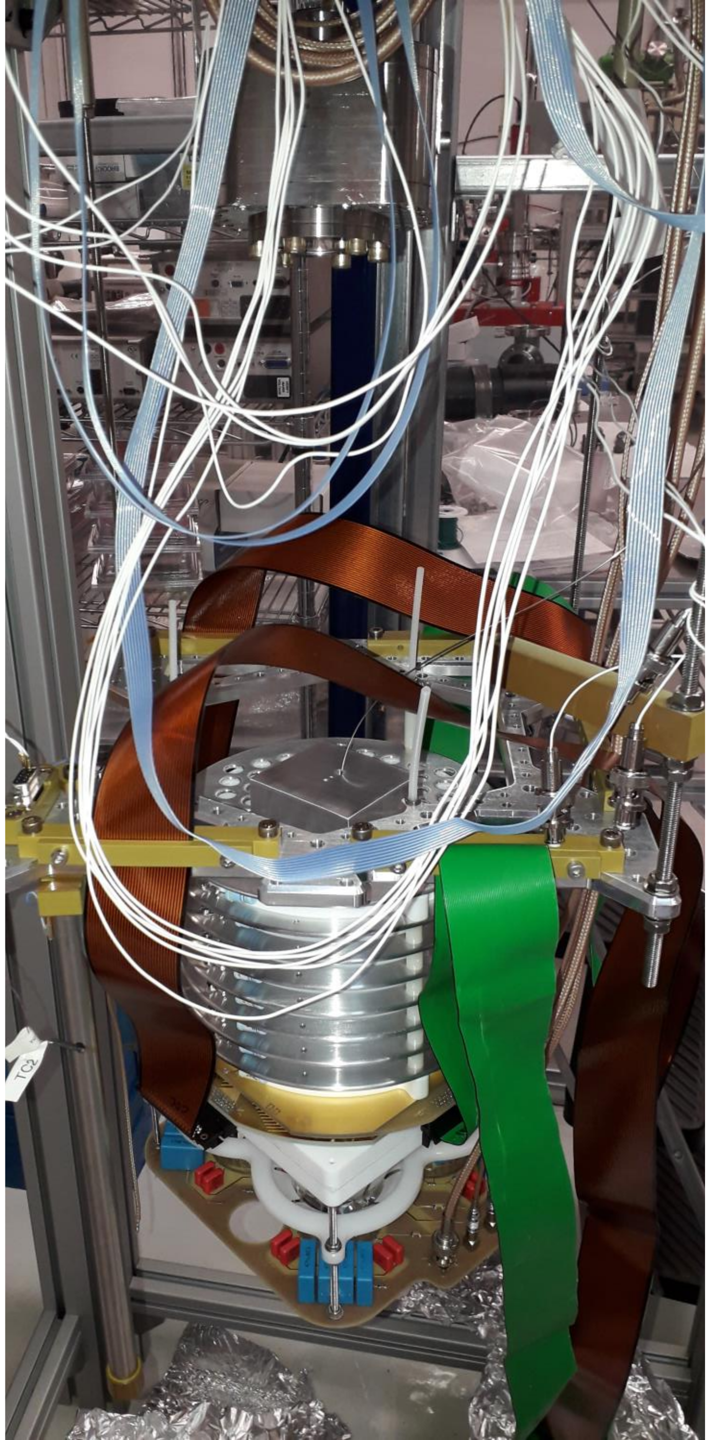




Cryostat modifications

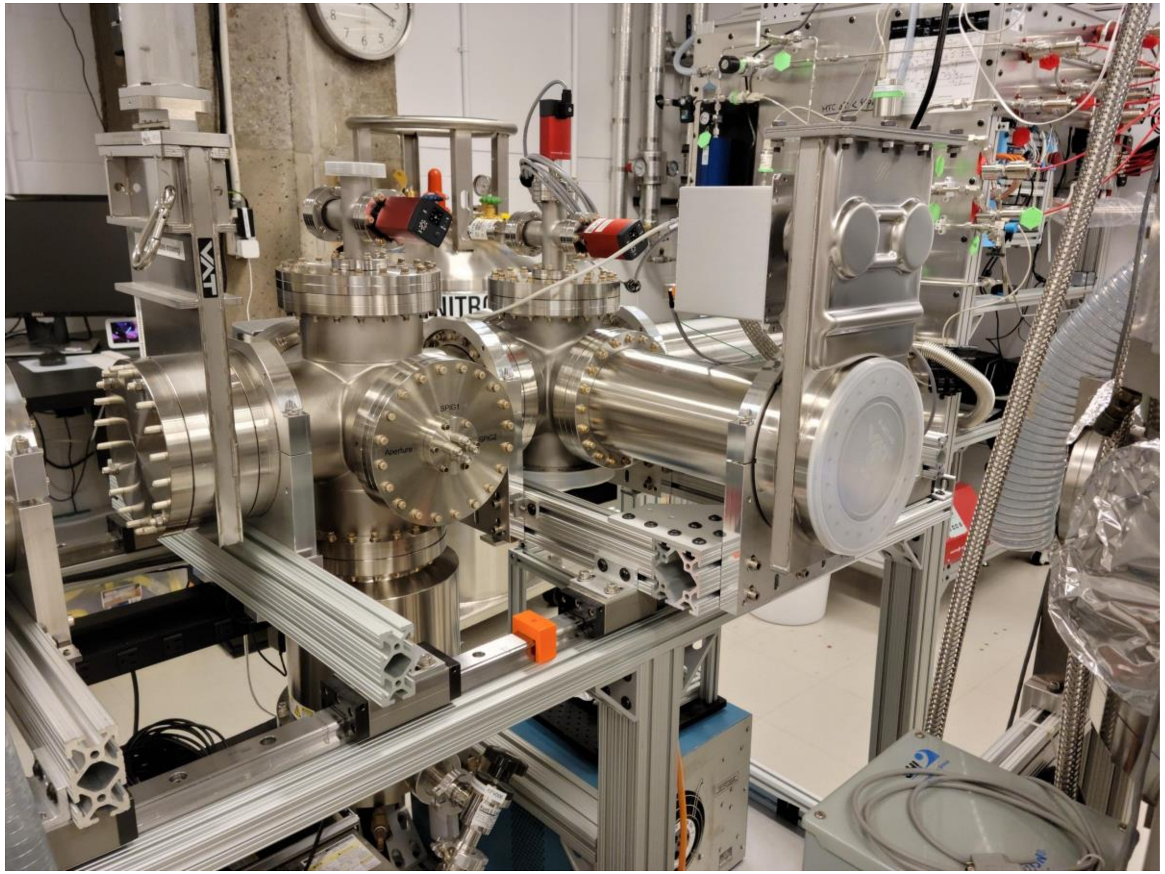
- Cryostat swapped to EXO-100 TPC
- Installed capillary
- Software development for controlling capillary heating and cryopumping rate

- Soon: in-gas ion extraction, for testing detector in ion-tagging conditions
- Further out: untargeted ion extract from liquid xenon



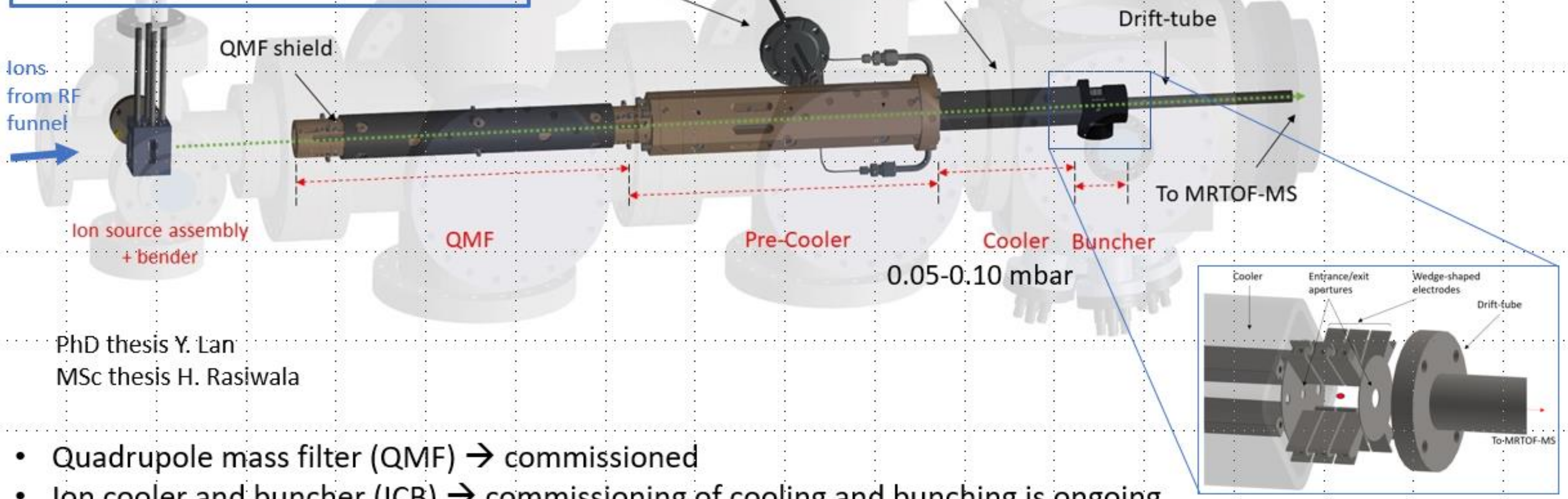
RF Funnel (re)commissioning in progress

- Vacuum system and all electrical connections are in place.
- Pending installation of several vacuum gauges.
- Currently working on setting up LabVIEW control for the compressor and cryopump.
- Upon completion the system will be tested with Argon gas after which ion extraction studies can be performed.



Linear Paul trap

Designed for dual purpose:
1. Ion cooling and bunching for MRTOF
2. Ion storage for laser spectroscopy



- Quadrupole mass filter (QMF) → commissioned
- Ion cooler and buncher (ICB) → commissioning of cooling and bunching is ongoing

Ion bunching with LPT

Ion bunching is currently being tested and optimized to achieve low ToF spread ~O(1 ns).

- Image on the right shows waveform of signal from the CEM.
- Work is underway to optimize the operational parameters such as buffer gas pressure and buncher potentials.