Simulating barium ion motion in liquid xenon for a future Ba-tagging upgrade of nEXO

Megan Cvitan

CAP Congress 2024

27/05/2024

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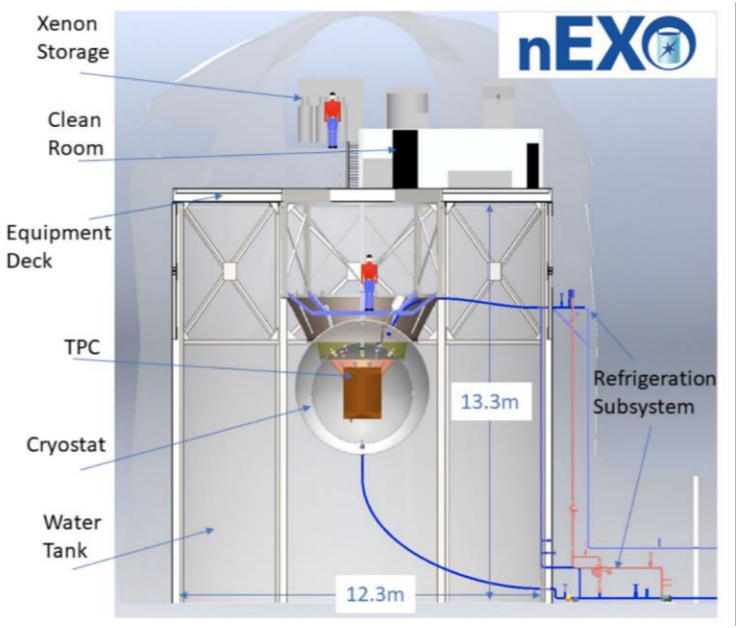
Agenda

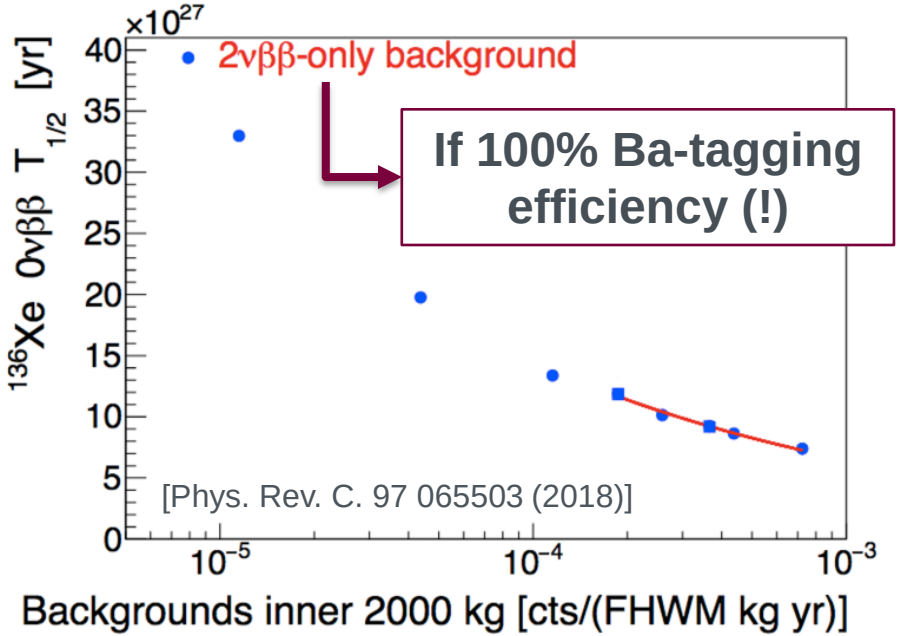
- The nEXO Experiment and barium (Ba) tagging
- Accelerator-driven ion source and ion extraction developments at TRIUMF
- COMSOL simulation groundwork
- Systematic studies
  - Probe bias
  - Ion initial distance from probe
  - Using non-liquid xenon (LXe) media

The nEXO Experiment

- Proposed next generation 5-tonne liquid xenon Time Projection Chamber (TPC)
- Search for 0νββ in ^{136}Xe as a tool to study neutrino mass



Artist's rendition of the nEXO experiment, planned for construction ~2 km underground at SNOLab

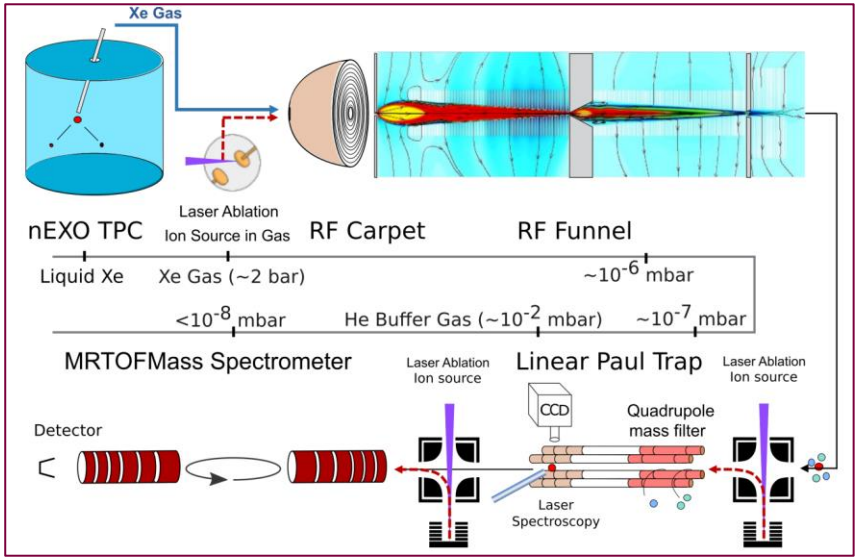


The nEXO detector sensitivity to 0νββ half-lives

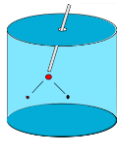
A Proposed Future nEXO Upgrade with Ba-tagging

Goal: identify ββ-decay product in ^{136}Xe

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



1. Localize event ✓
2. Event of interest? Near Q-value? ✓
3. Extract ion from xenon volume
   - Not well-understood yet
   - Create new tools to explore this step
4. Identify ion, is it Ba? ✓

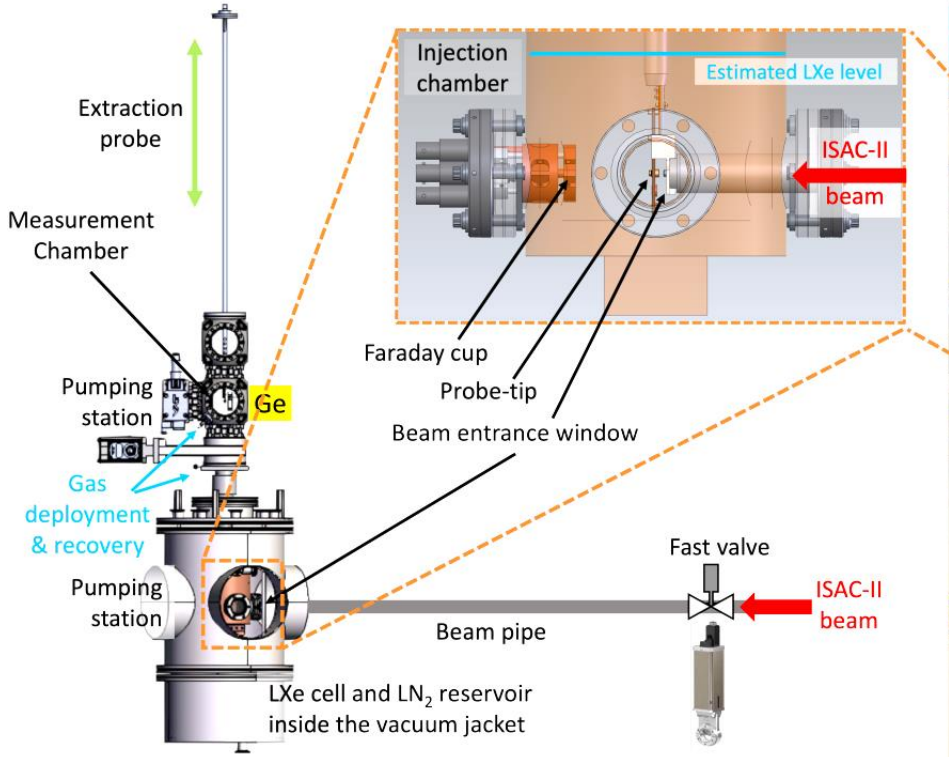

nEXO TPC

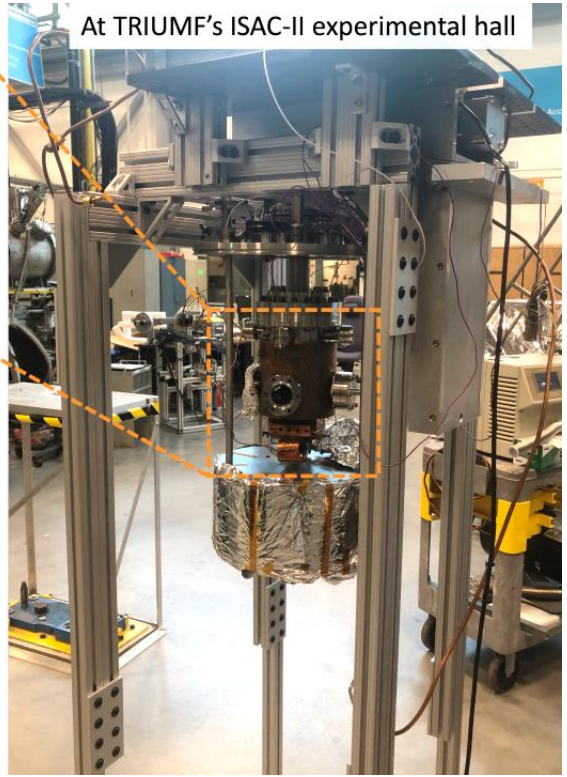
To test extraction approaches: need a characterized in-liquid Xe Ba-source

→ ISAC-II (Isotope Separator and Accelerator) at TRIUMF

Ba-tagging at TRIUMF: Experimental Setup

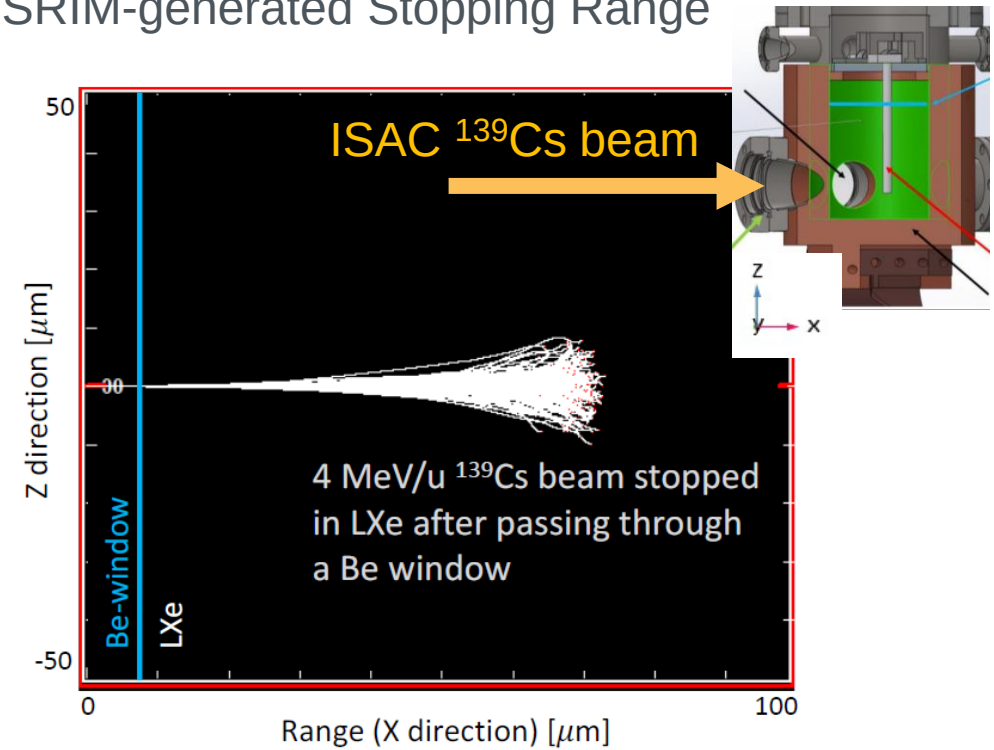
Novel radioactive beam approach for ion implantation into LXe volume and subsequent extraction



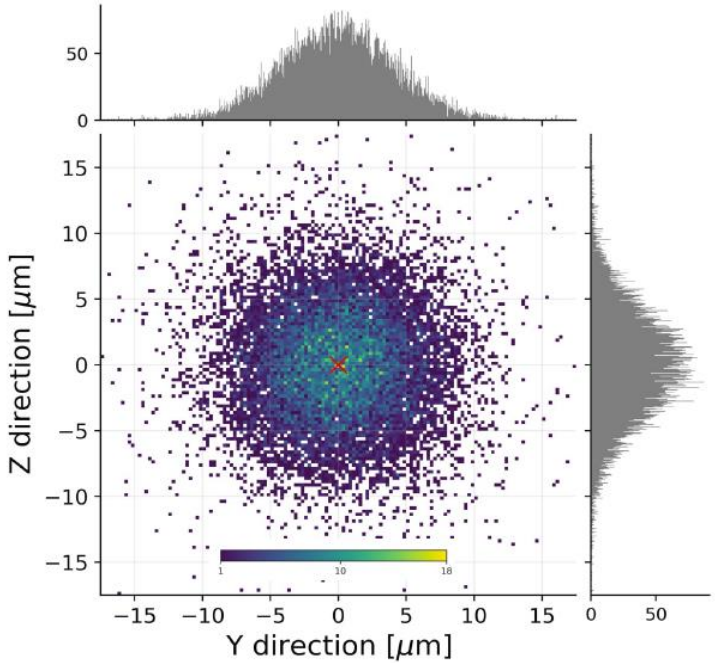


Ba-tagging at TRIUMF: Beam Ion Implantation

SRIM-generated Stopping Range



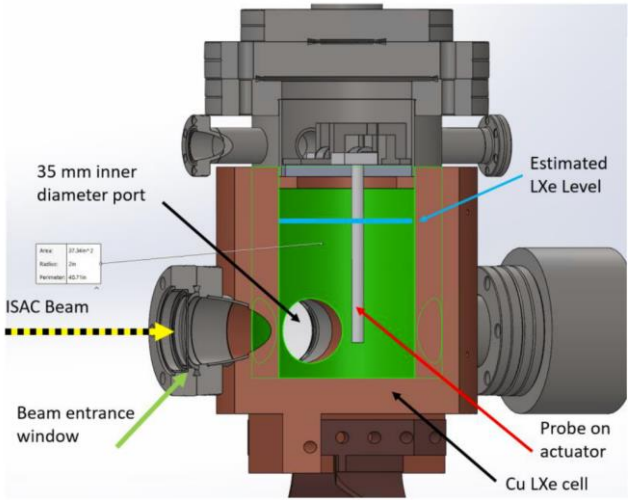
Implanted beam position profile relative to probe tip

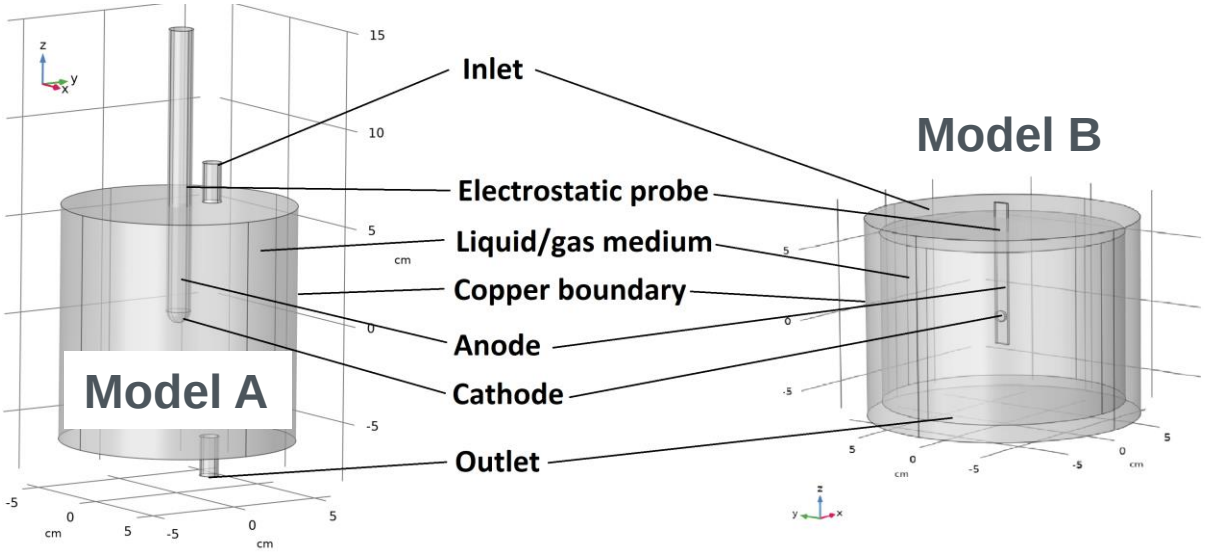


COMSOL Multiphysics Simulation Geometry

How to attract ions onto a DC biased probe for extraction?

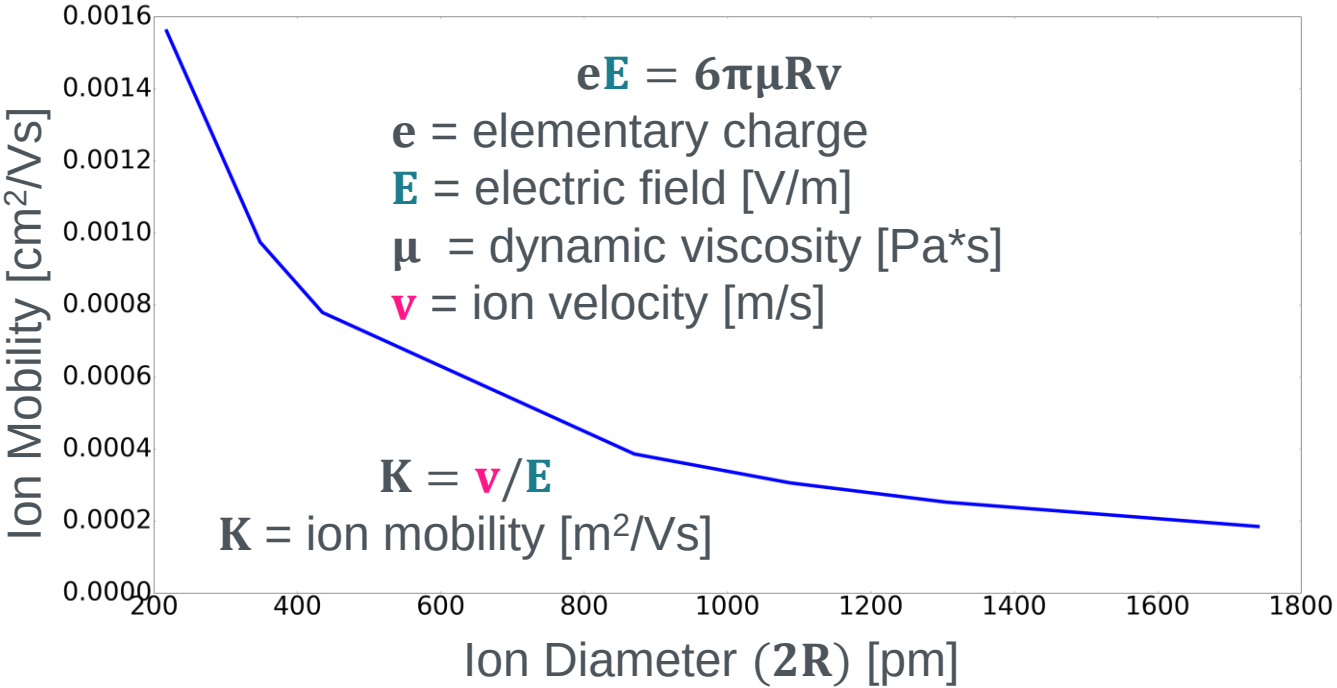
Investigate this with two different models, depending on the simulation needs





Basis for Ion Motion in COMSOL Model: Setting the Ion Mobility

Set the ion mobility by varying the ion diameter



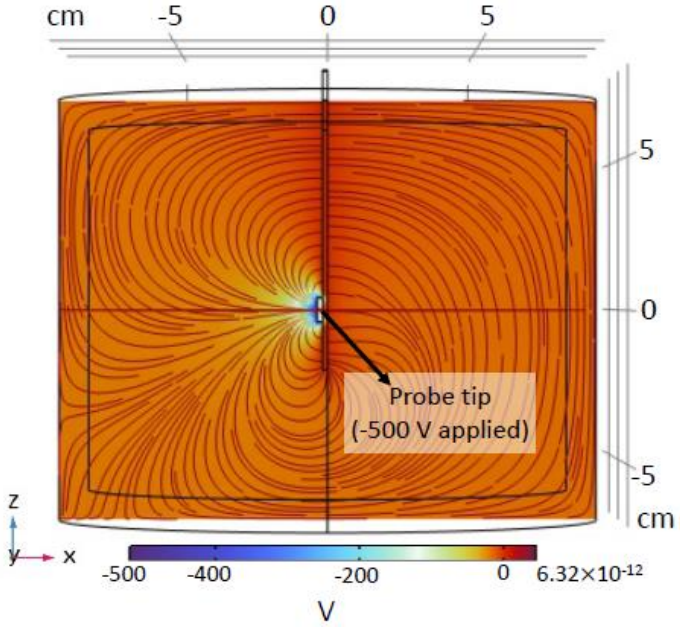
- The mobility of $^{139}Ba^{+}$ in LXe is 2.11e-4 cm^2/Vs
- Encapsulates the "Clustering Effect" of Ba ions in LXe

[S.-C. J. et al. Phys. D: Appl. Phys. 42 (2008), E. Bainglass et al. Mobility and clustering of barium ions and dications in high pressure xenon gas. Physical Review A 97(6) (2018).]

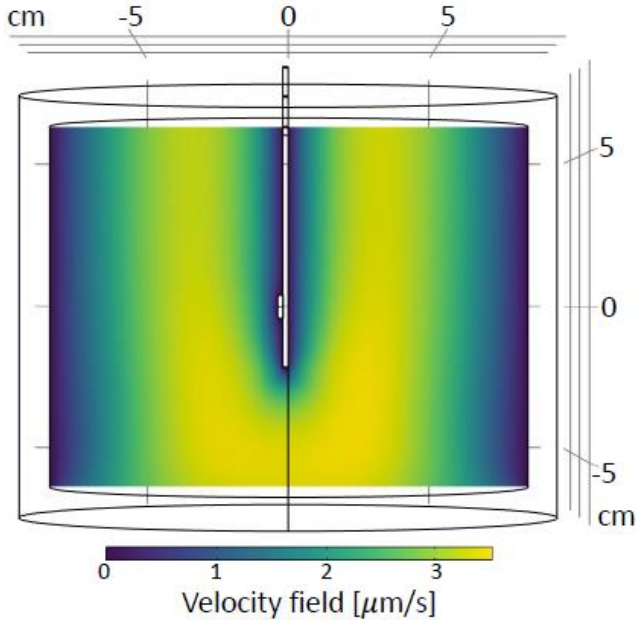
Typical COMSOL Multiphysics Solutions

Electrostatics and fluid dynamics converged solutions

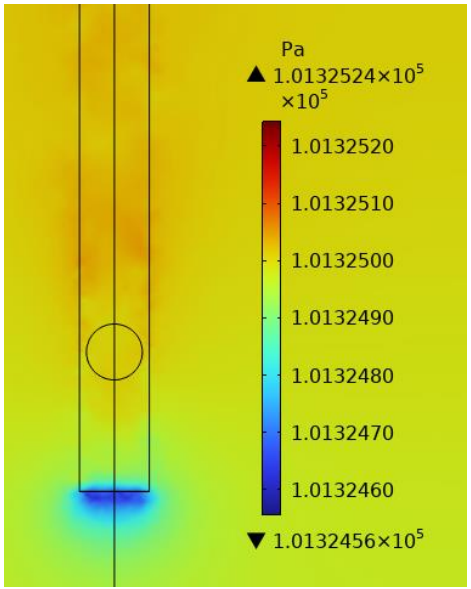
$\vec{E}$-field converges at probe tip



Minimal flow field



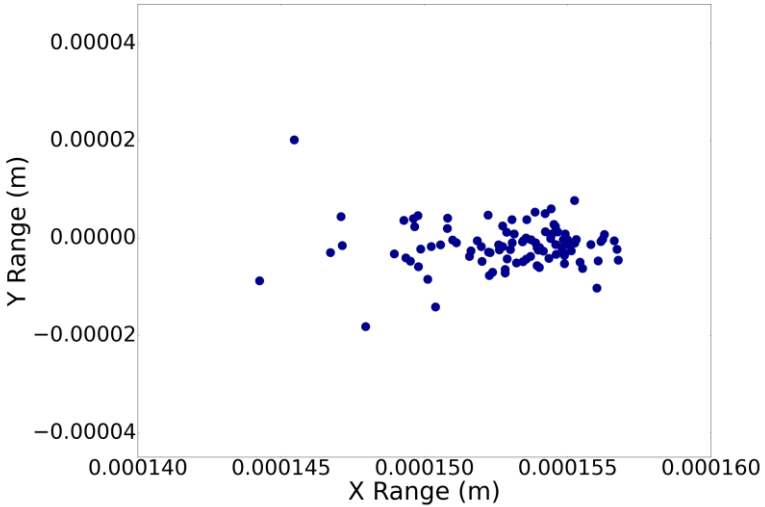
Keeping constant pressure

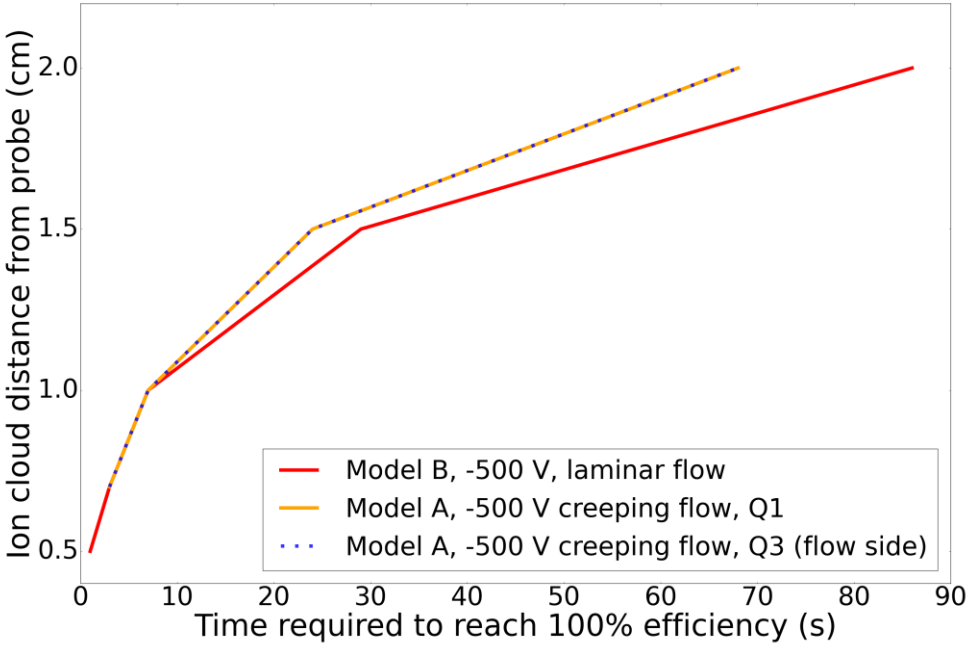


Simulation Results

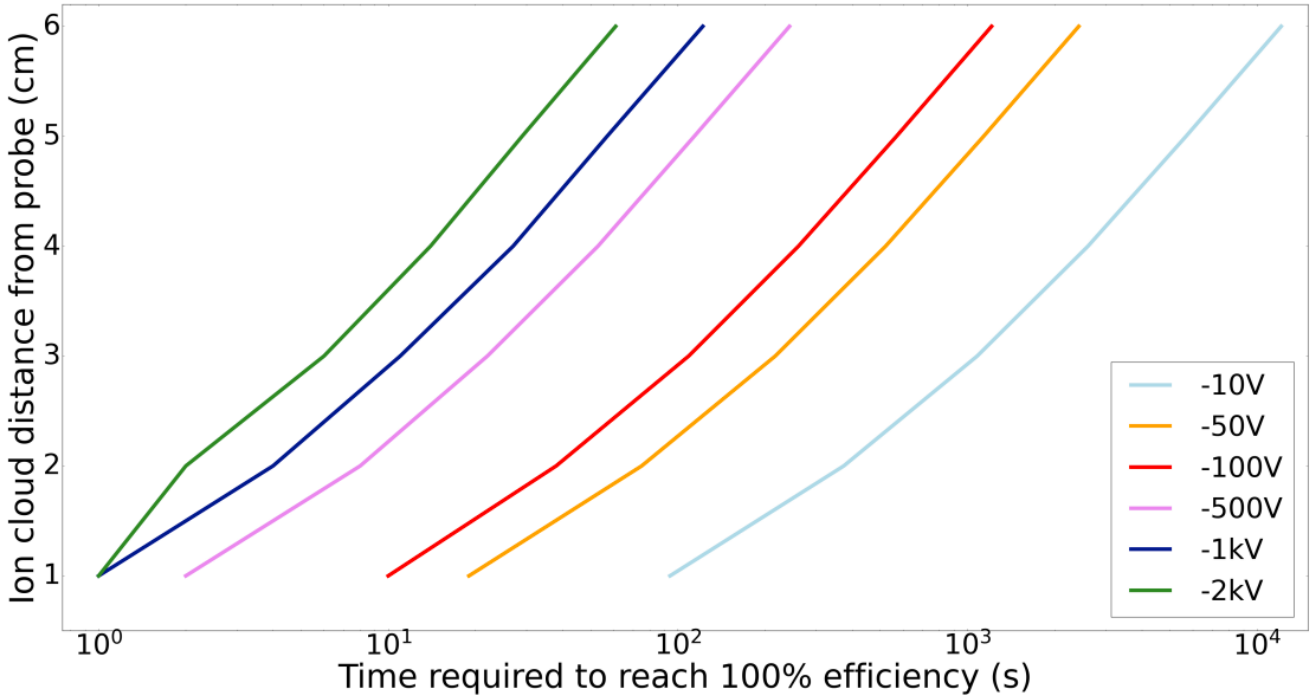
Initial Ion Position Effect on Extraction Efficiency

SRIM distribution of 100 $^{139}Ba^{+}$ ions





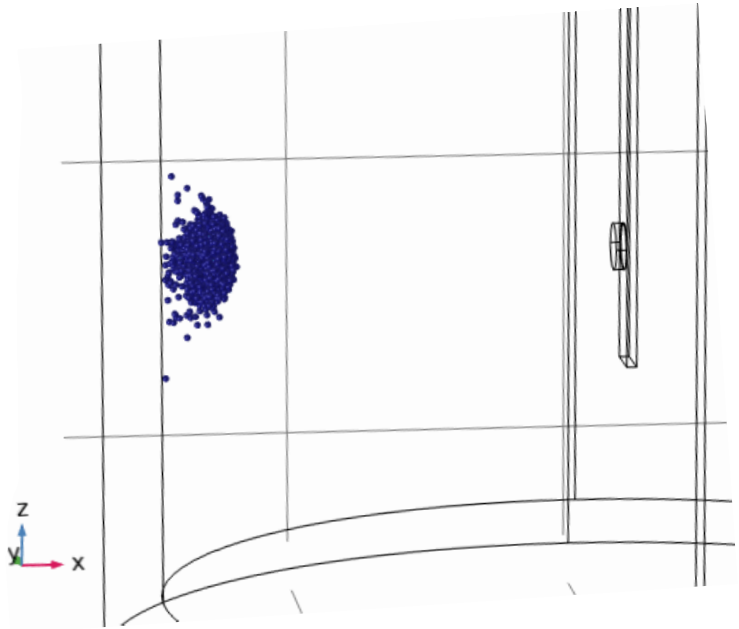
Probe Bias Sweep and Extraction Efficiency for Ba^+ in Argon Gas



Simulated with ion mobility of $^{139}Ba^+$ in Ar at 273 K & 1 atm = 2.32 cm^2/Vs

Summary & Outlook

15,000 ions in GAr, released from edge of vessel



- Search for 0νββ in ^{136}Xe with nEXO and implications on neutrino mass measurements
- Development of in-LXe Ba-source for testing ion extraction methods
- Role of ion mobility definitions in setting realistic COMSOL simulation environments
- Quantitative studies on how LXe fluid velocity, probe bias, and ion distance from probe vary the ion extraction efficiency
- Future simulations can incorporate
  - Field shaping rings, and studies on the Ba ion accumulation on the probe tip
  - Particle-particle interactions

Acknowledgements: nEXO is a Worldwide Effort

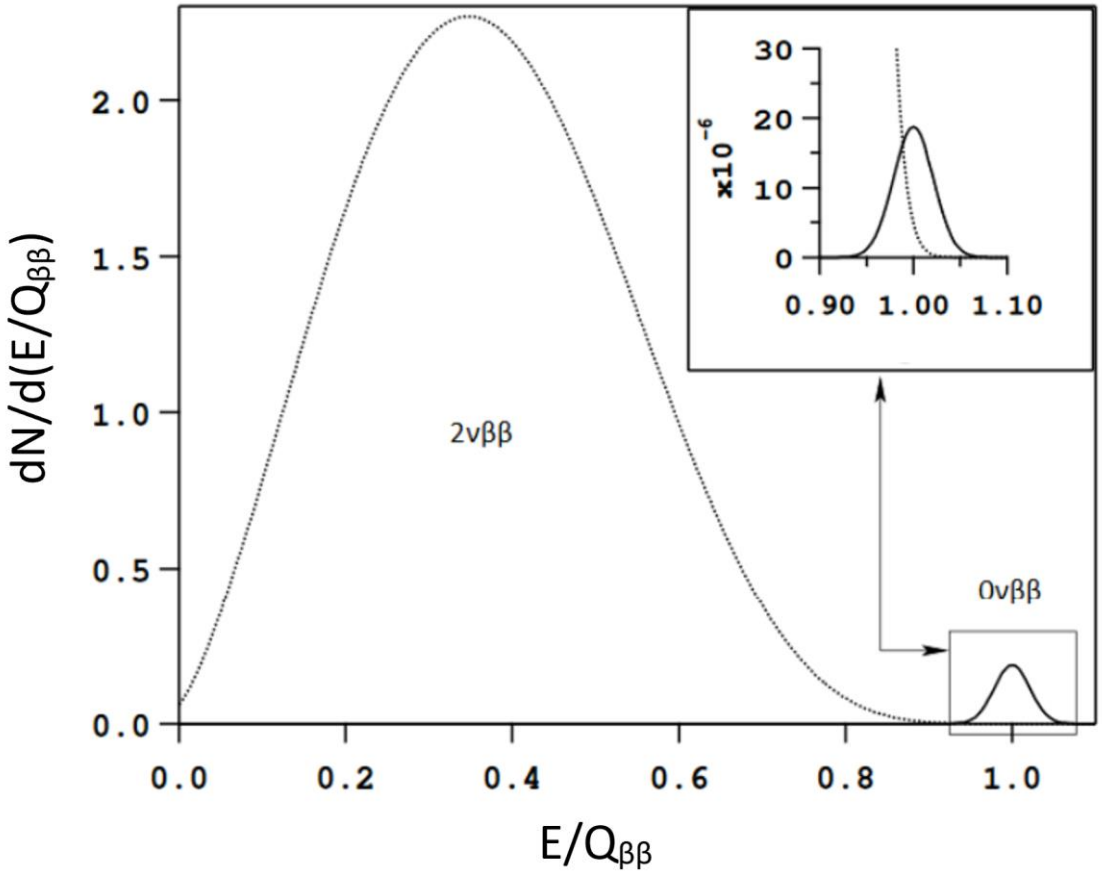
nEXO

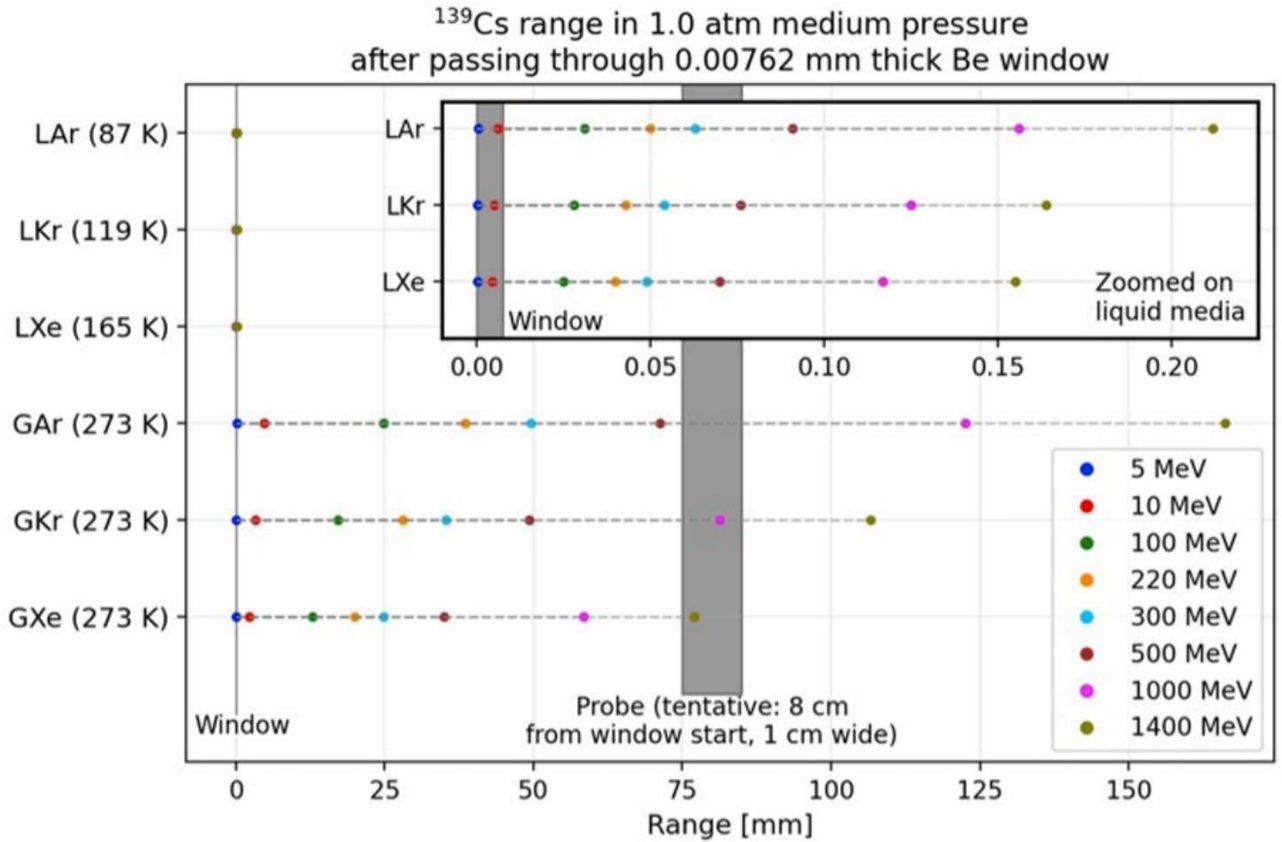
Thank you to the nEXO Ba-tagging Teams at TRIUMF, McGill and Carleton Universities!

NSERC CRSNG

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Backup Slides


dN/d(E/Qββ)
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
E/Qββ
2νββ
0νββ
x10⁻⁶
30
20
10
0
0.90
1.00
1.10

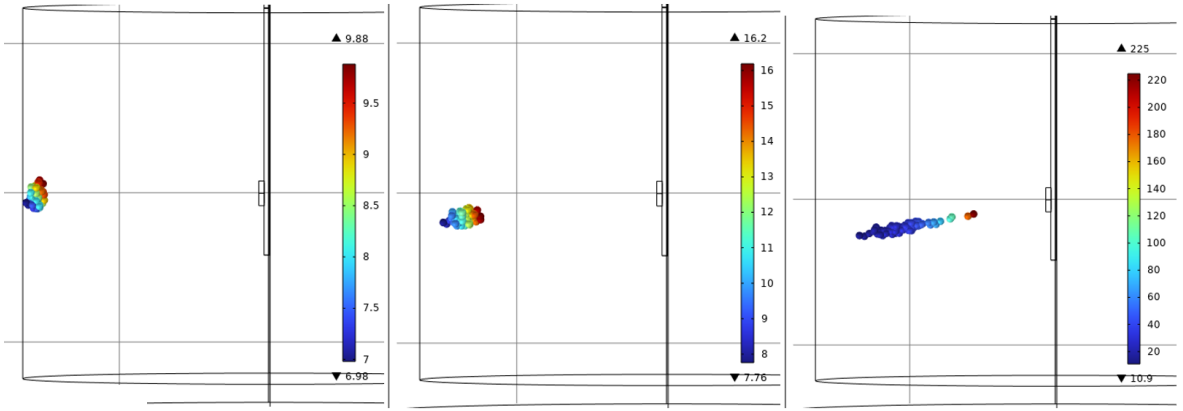

^{139}Cs range in 1.0 atm medium pressure
after passing through 0.00762 mm thick Be window
LAr (87 K)
LKr (119 K)
LXe (165 K)
GAr (273 K)
GKr (273 K)
GXe (273 K)
LAr
LKr
LXe
Window
Zoomed on
liquid media
0.00
0.05
0.10
0.15
0.20
5 MeV
10 MeV
100 MeV
220 MeV
300 MeV
500 MeV
1000 MeV
1400 MeV
Window
Probe (tentative: 8 cm
from window start, 1 cm wide)
0
25
50
75
100
125
150
Range [mm]

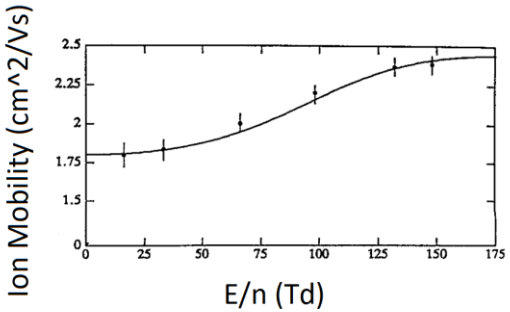
Taken from [5]

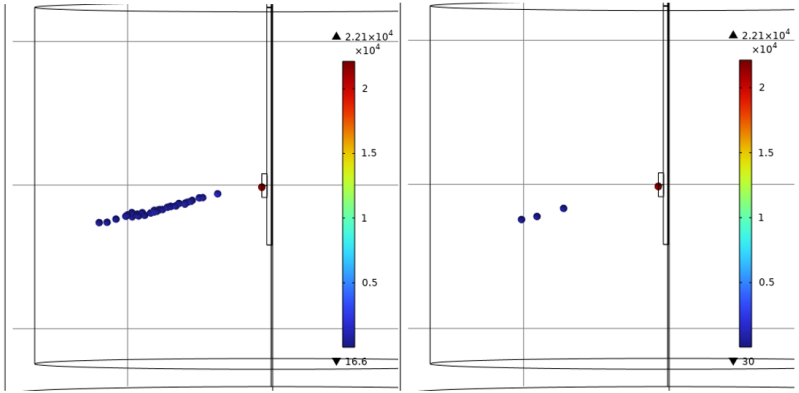
Simulating Ba ion motion in argon gas

K = 1.80 cm^2/Vs

Corresponding ion diameter of 4.49 pm [4]







- 1 atm, 273 K
- 100 Ba ions
- -500 V bias