Barium Tagging for EXO

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APS DPF

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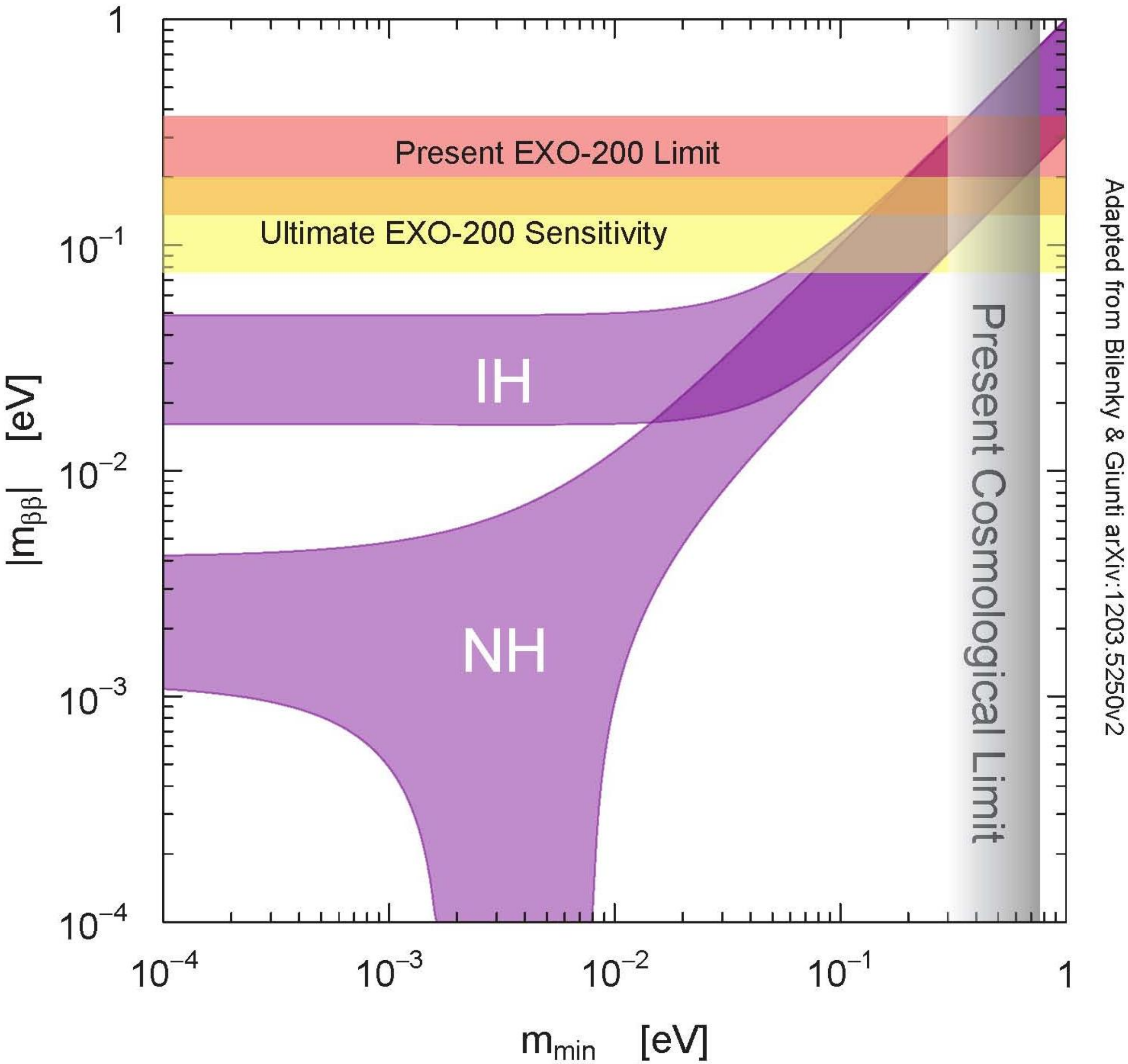
EXO Sensitivity Projections



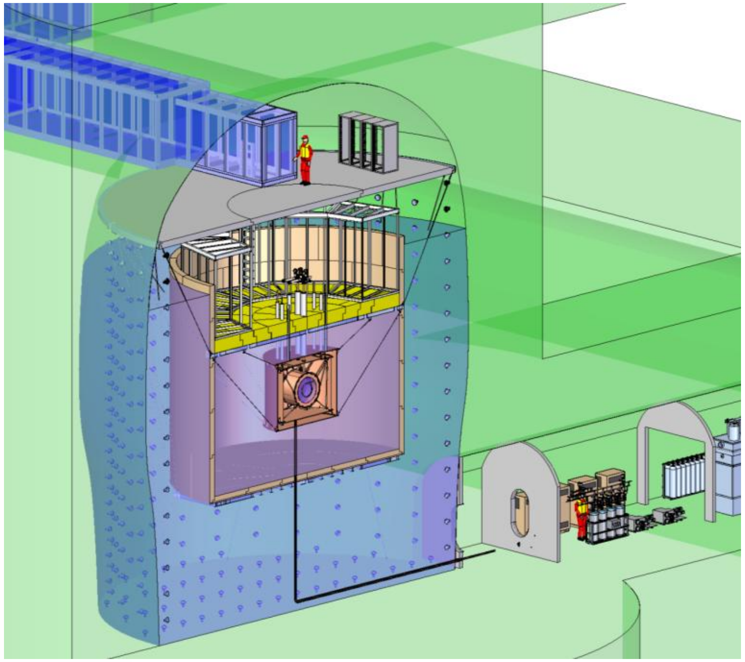
Purple bands are 68%CL from oscillation experiments for inverted and normal mass hierarchy

EXO-200 present limit is the 90%CL envelope of limits (for different NMEs) from PRL 109 (2012) 032505

EXO-200 ultimate sensitivity: 90%CL for no signal in 4 years livetime with new analysis and Rn removal

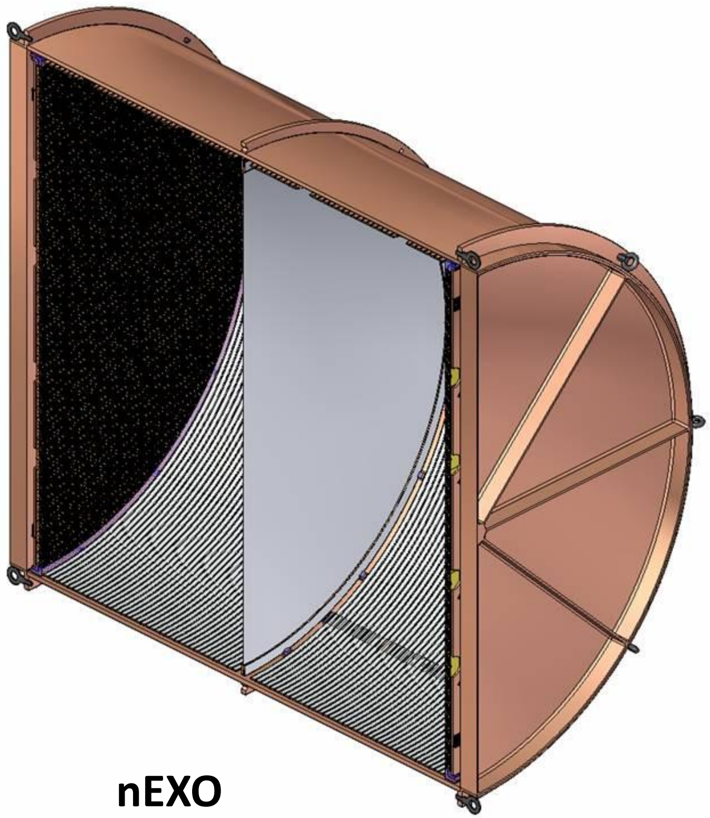
nEXO: EXO-200's Successor

- 5 tonne LXe time projection chamber (TPC) "as similar to EXO-200 as possible"
- Provide access ports for a possible later upgrade to barium tagging

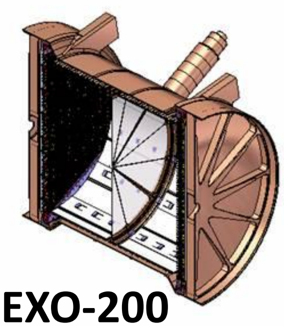


nEXO at the SNOlab cryopit

~150cm



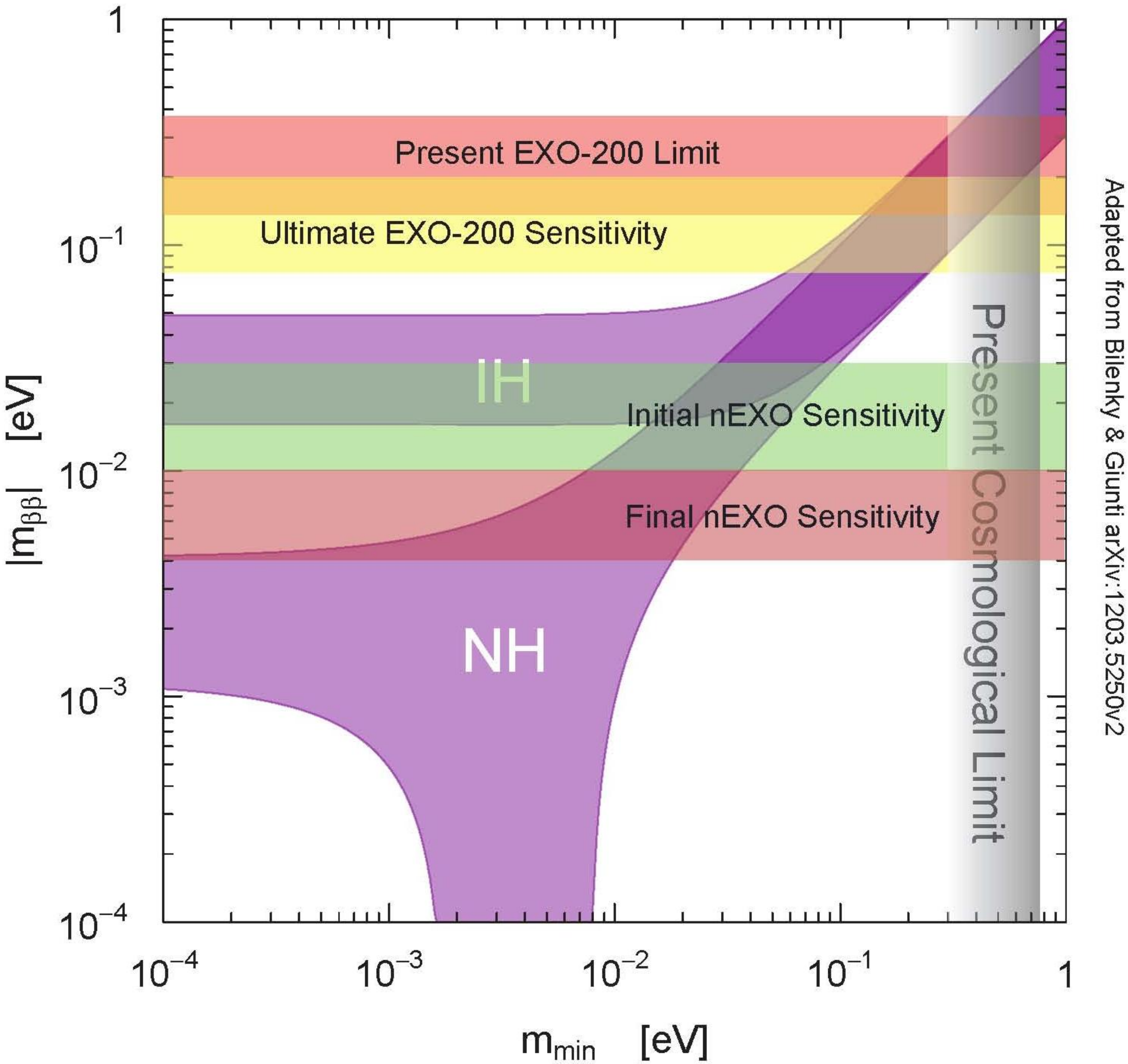
nEXO



~40cm

EXO-200

EXO Sensitivity Projections



Purple bands are 68%CL from oscillation experiments for inverted and normal mass hierarchy

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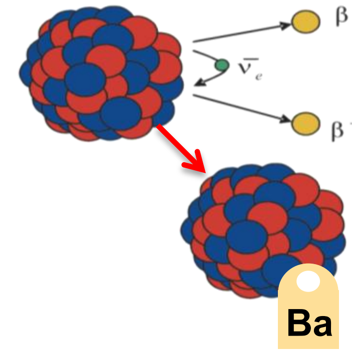
EXO-200 ultimate sensitivity: 90%CL for no signal in 4 years livetime with new analysis and Rn removal

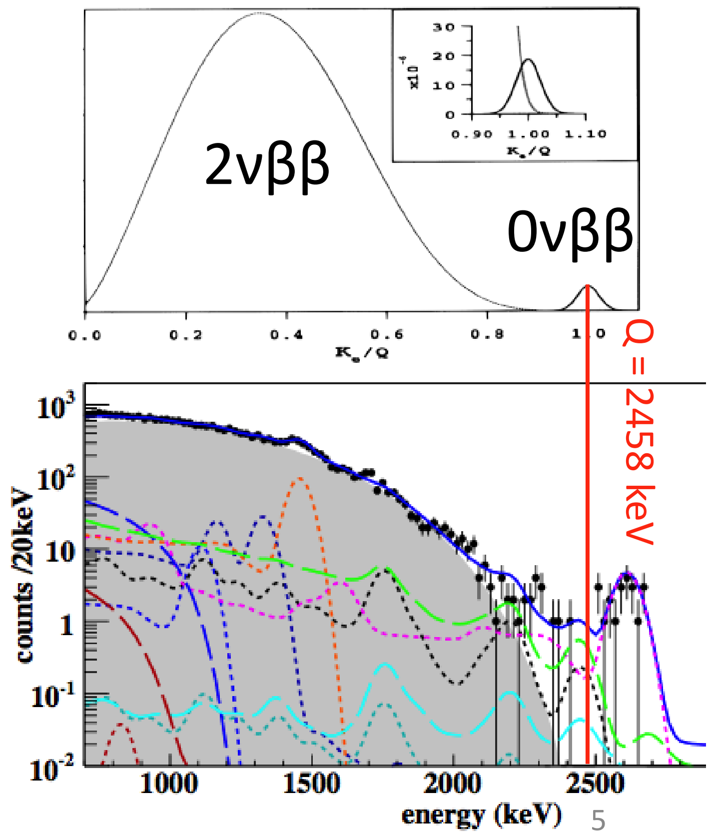
Initial nEXO band refers to a detector directly scaled from EXO-200, including its measured background and 10yr livetime.

Final nEXO band refers to the same detector and no background other than 2ν

Ba Tagging Motivation



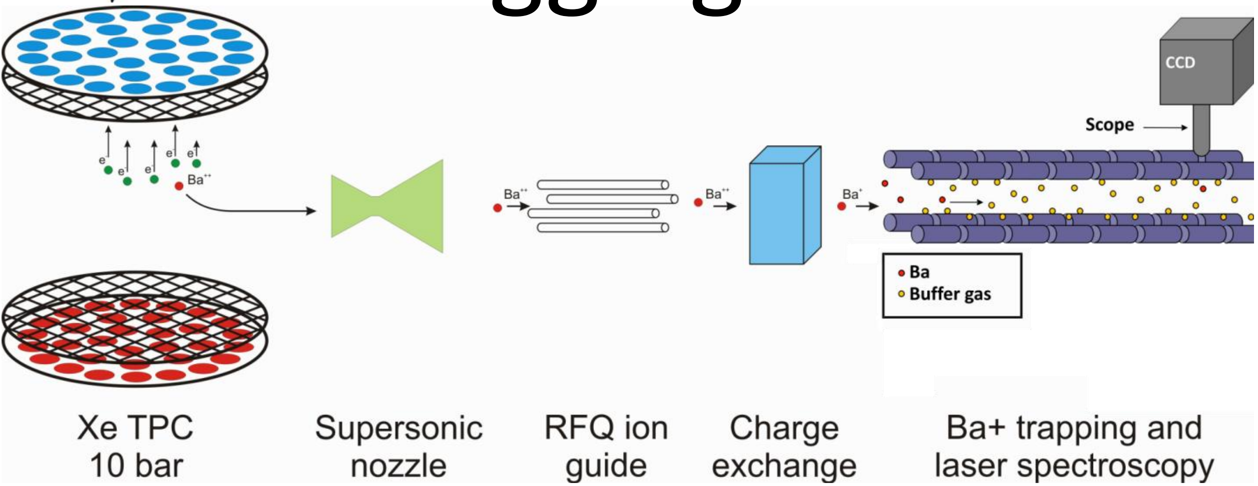
- **Goal: perform background free measurement**
  - Measure candidate decay event positions, energies
  - Recover and identify Ba ion
  - Tag event-recovery coincidences as ββ
  - Reject untagged events
- **Achievement:**
  - A **background-free** detector
  - Better scaling of mass sensitivity
- **Strategy: multipronged approach**

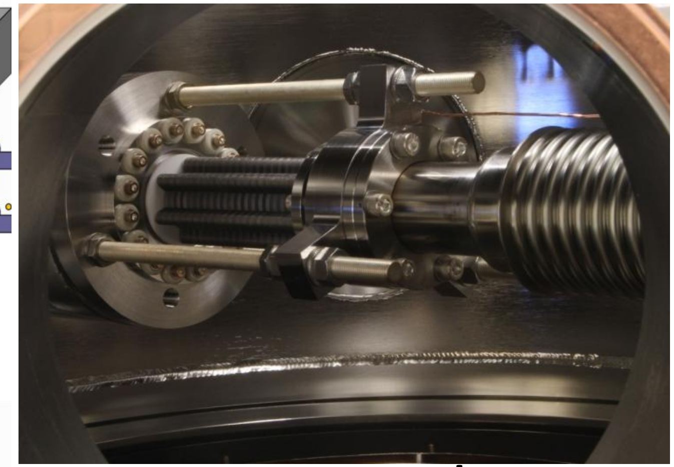


With background: $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

Without background: $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

Tagging from Gas Xenon



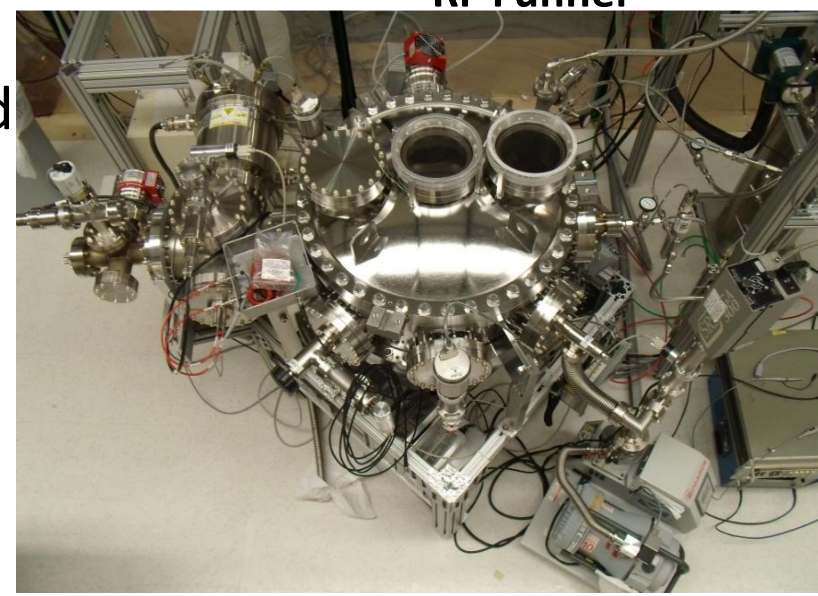


RF Funnel

How it works:

- Extract Ba^{++} from TPC by shaping E-field
- Guide into vacuum
- Convert Ba^{++} to Ba^{+} [1]
- Identify via laser spectroscopy [2]

Current work has demonstrated extraction of ions created by a test Ba source from 10 bar Xe into vacuum

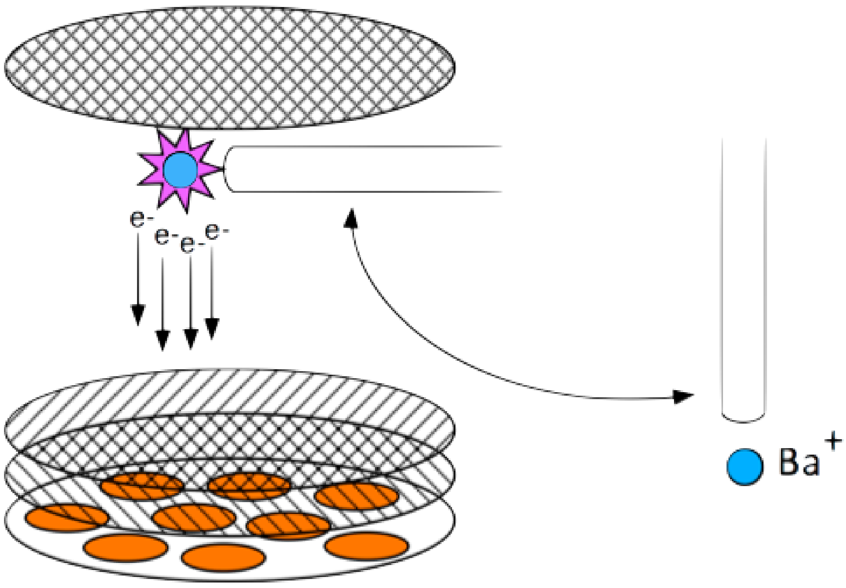


Current Stanford Setup

[1] J. of Phys.: Conf. Ser. 309(2011)12005 [2] Phys. Rev. A 76, 023404 (2007)

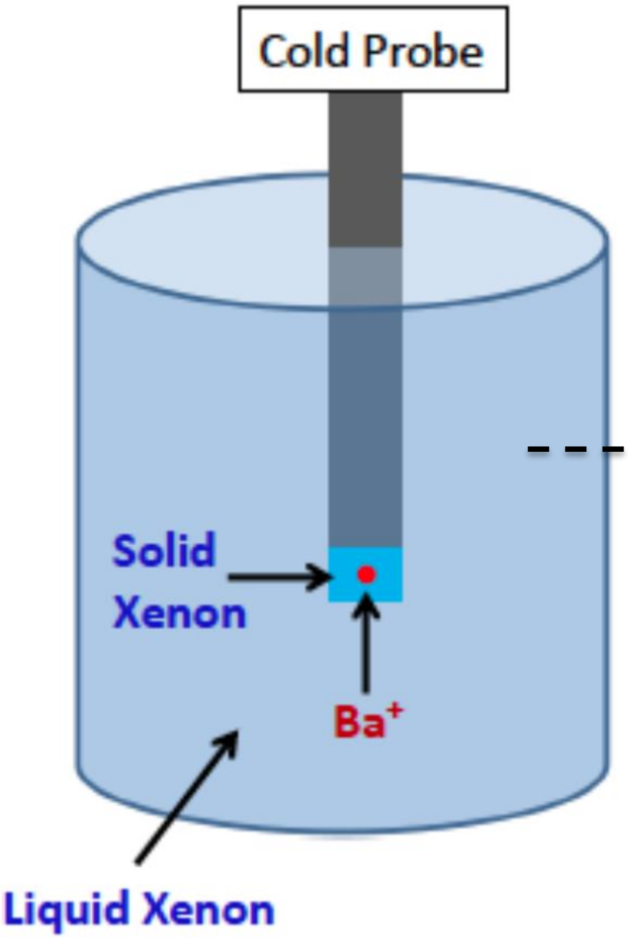
Tagging from Liquid Xenon

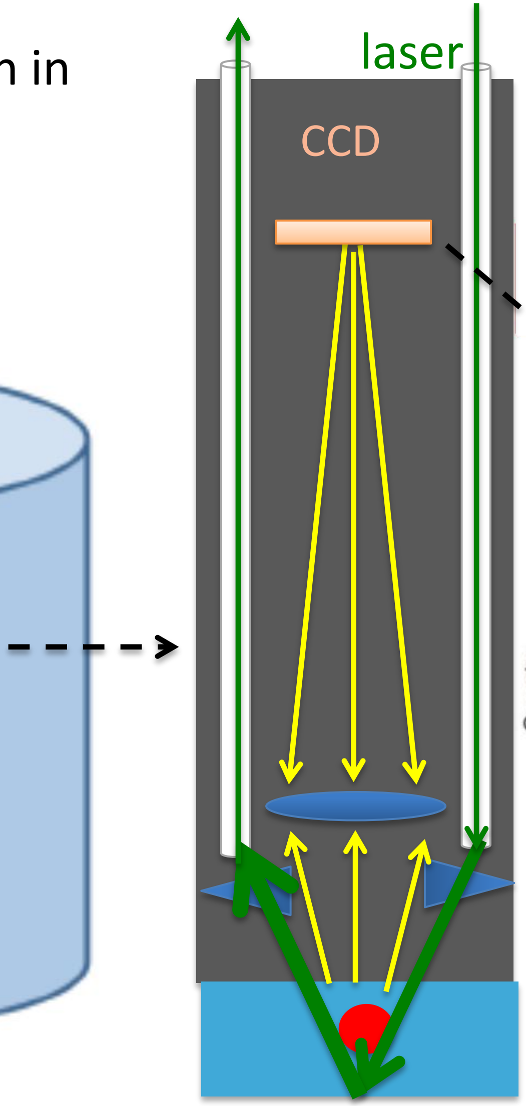
- Decay product in LXe is Ba^+
- Send probe into TPC, deposit Ba^+ onto probe tip (e.g. electrostatically)
- Remove probe to identification chamber
- Ba^+ moves slowly enough in LXe to remain in region of reconstructed decay event
- Investigating two methods of liquid tagging - CSU and Stanford



Tagging Spectroscopically in SXe (Colorado State University)

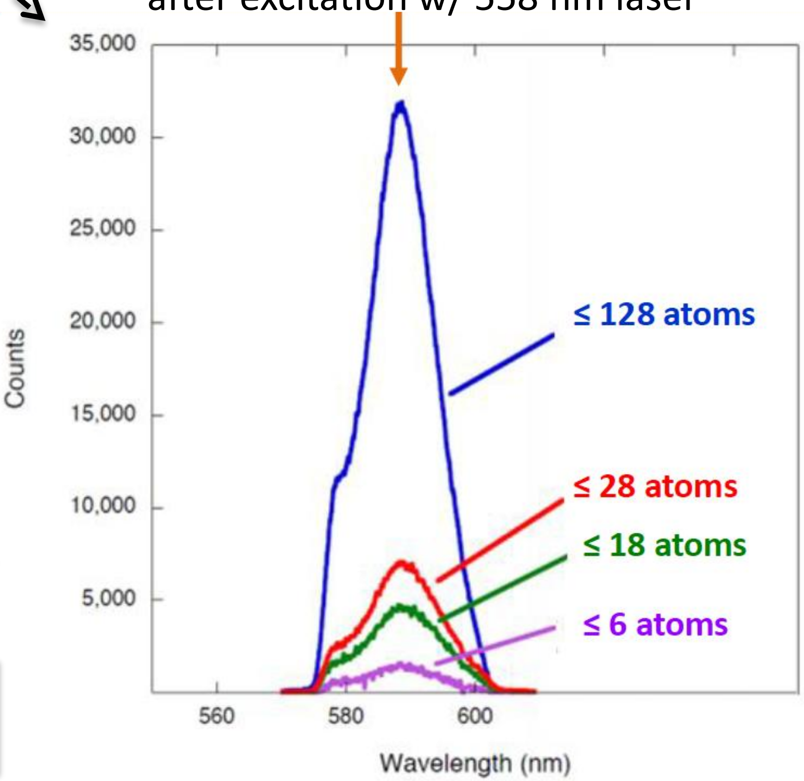
Trap barium daughter ion in solid xenon on a probe:





Detect single ion or atom on the probe with laser-induced fluorescence:

Fluorescence peak of Ba in SXe
after excitation w/ 558 nm laser

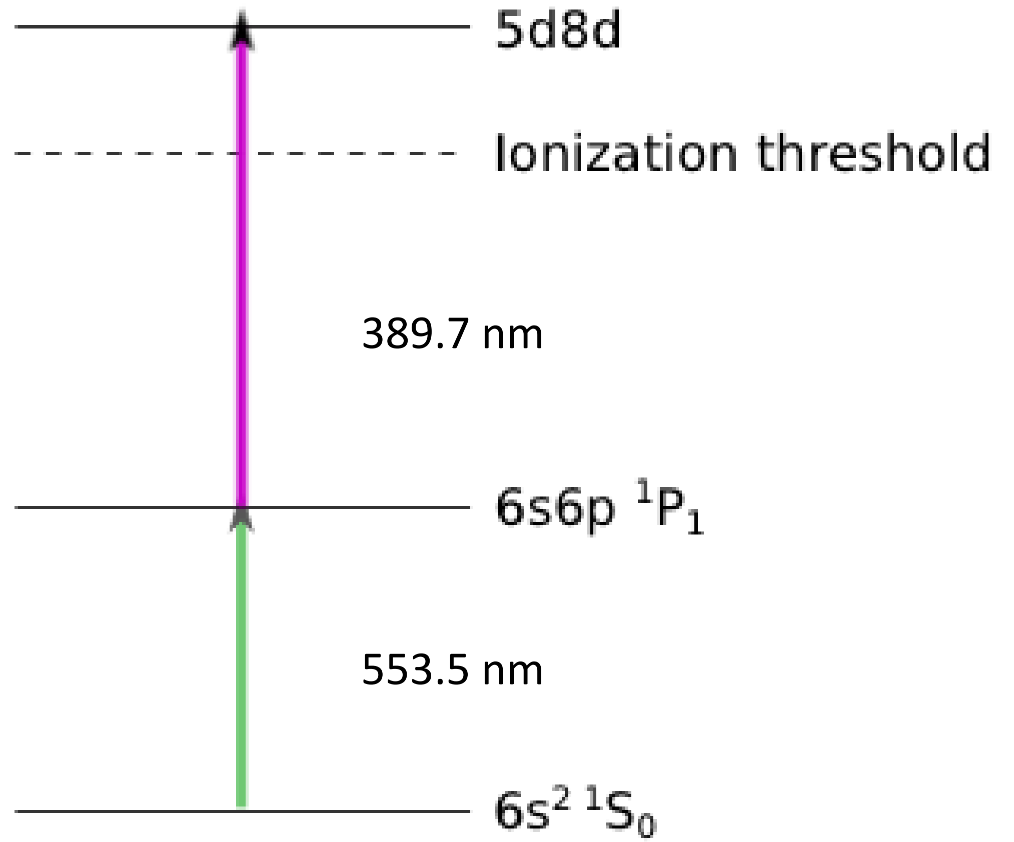


Resonance Ionization Spectroscopy

Challenge:
Recover and identify single Ba, ignoring all else

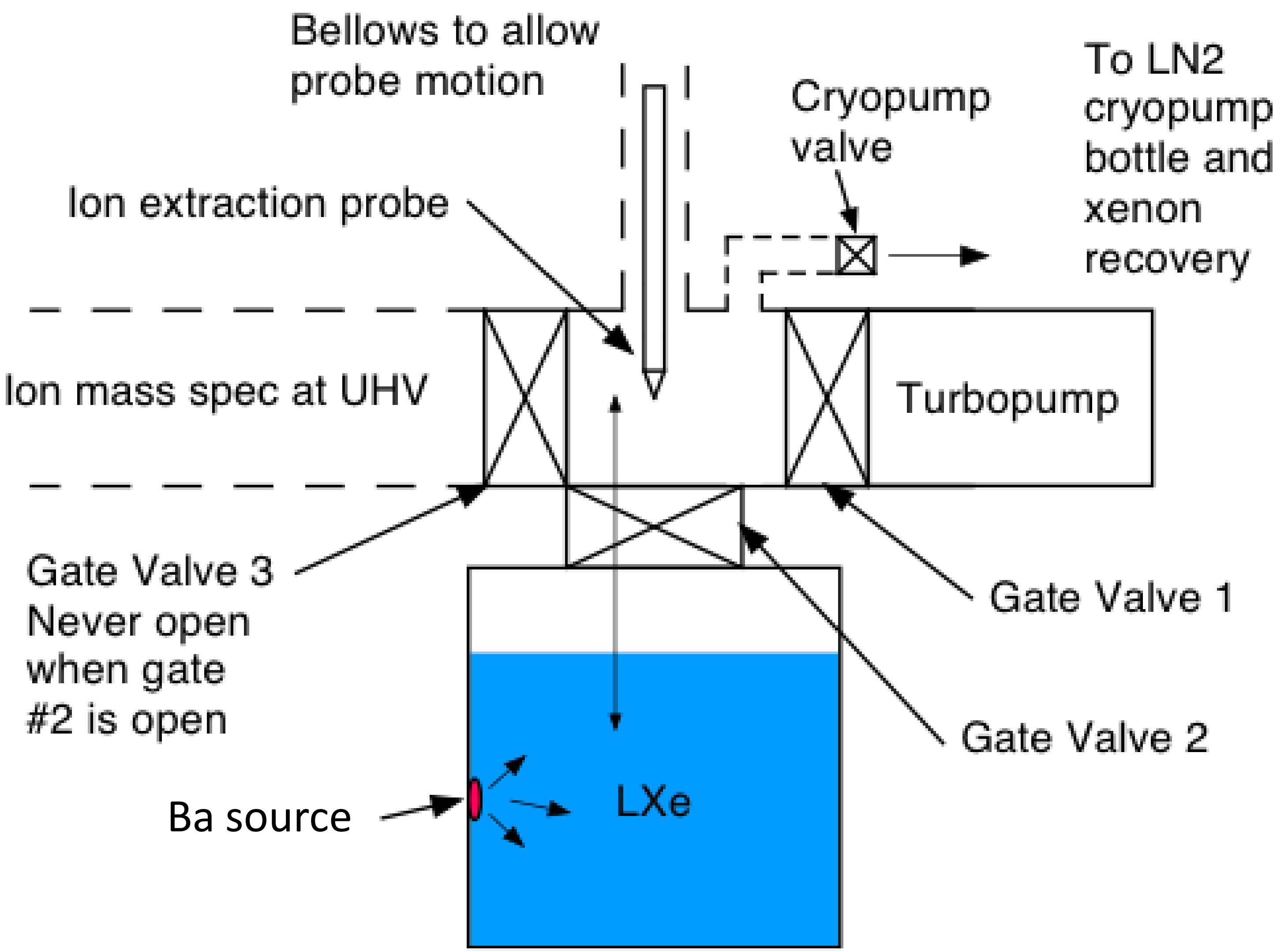
Solution:
Efficiently and *selectively* re-ionize barium using its atomic spectroscopy

RIS is sensitive to single ions



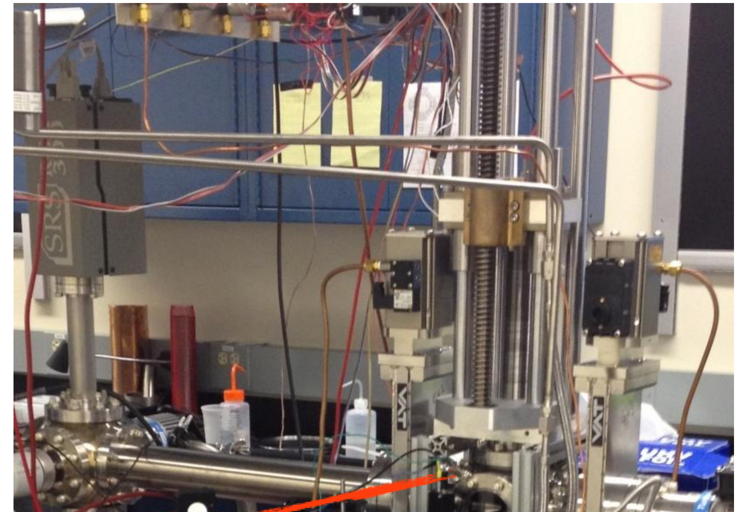
Neutral barium spectroscopy

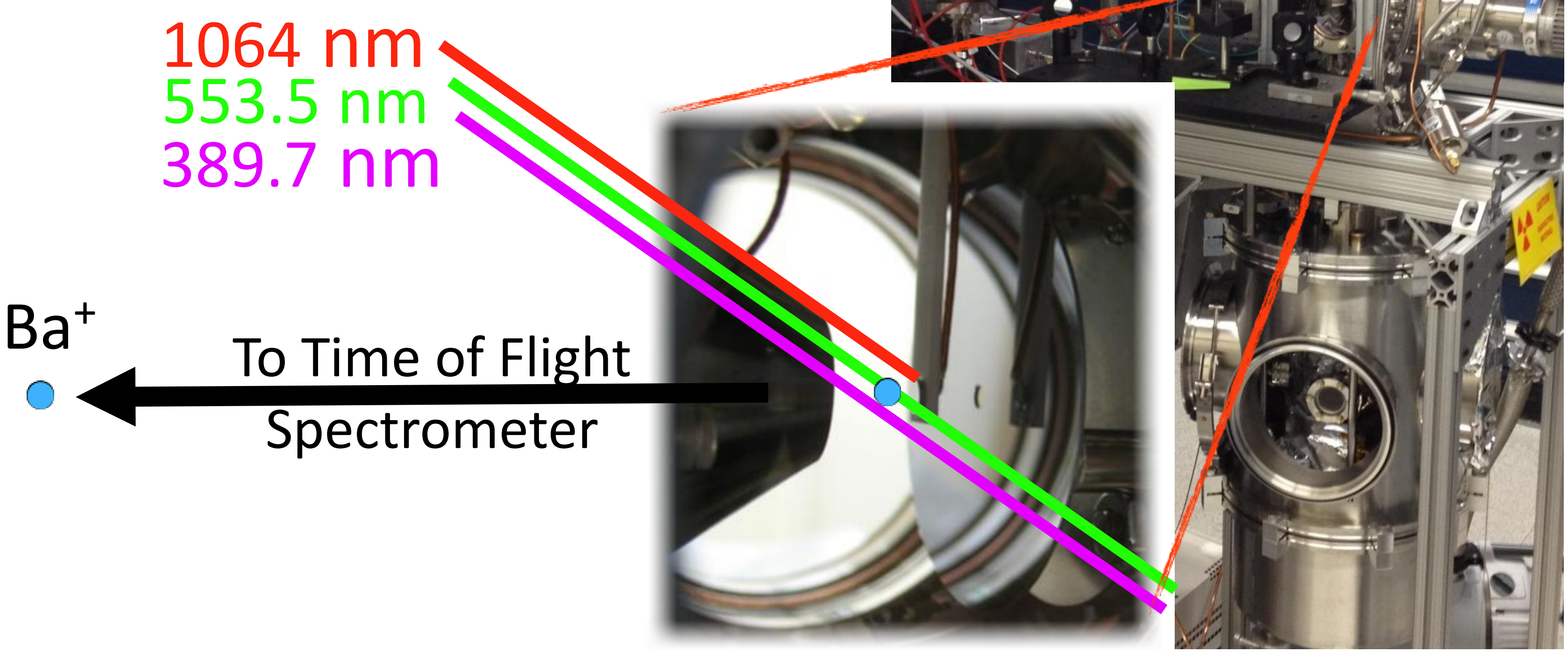
Liquid Tagging Setup Schematic



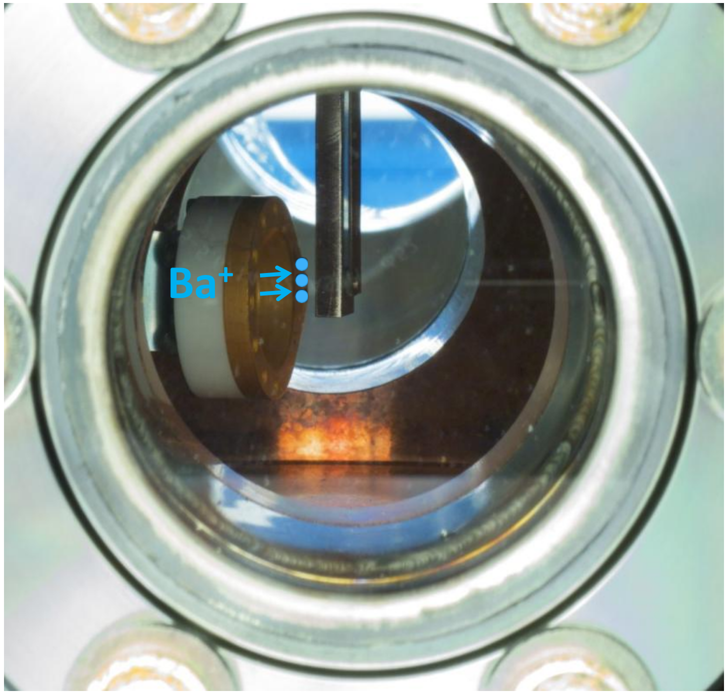
RIS at Stanford

- Thermally desorb with IR laser
- Ionize resonantly just Ba
- Detect and identify by mass using ToF spectrometer

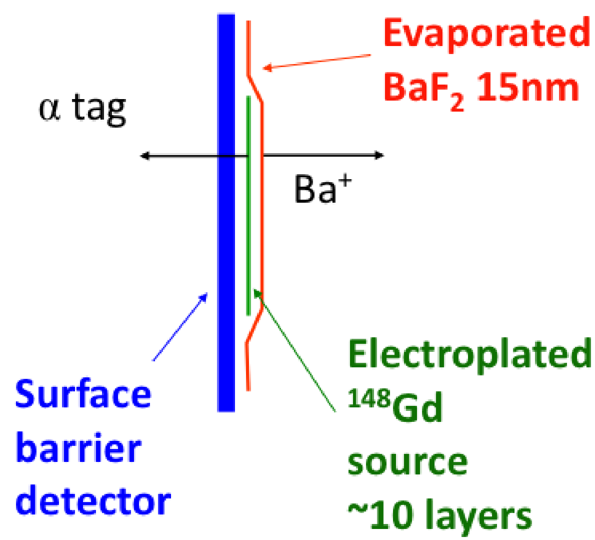




Barium Loading in Vacuum

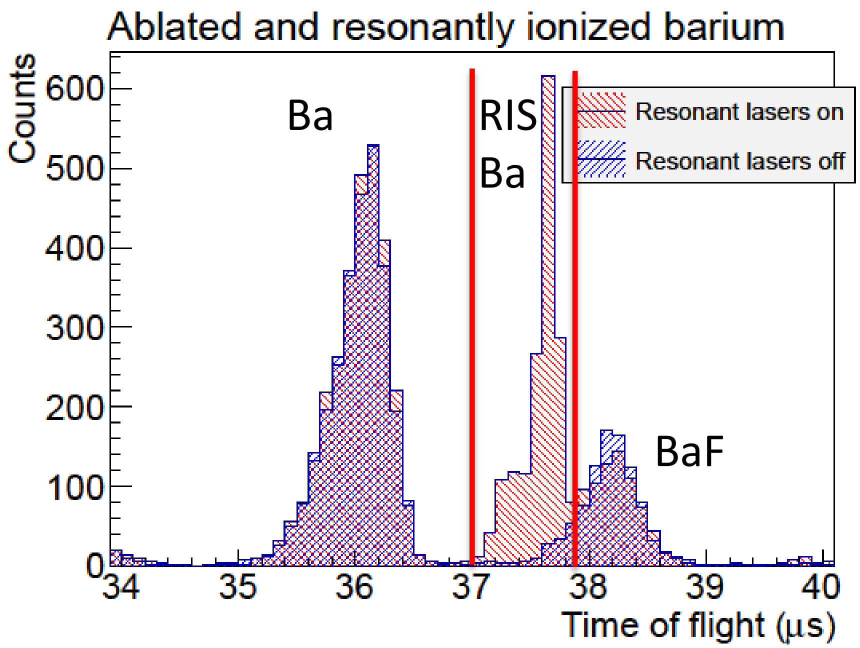


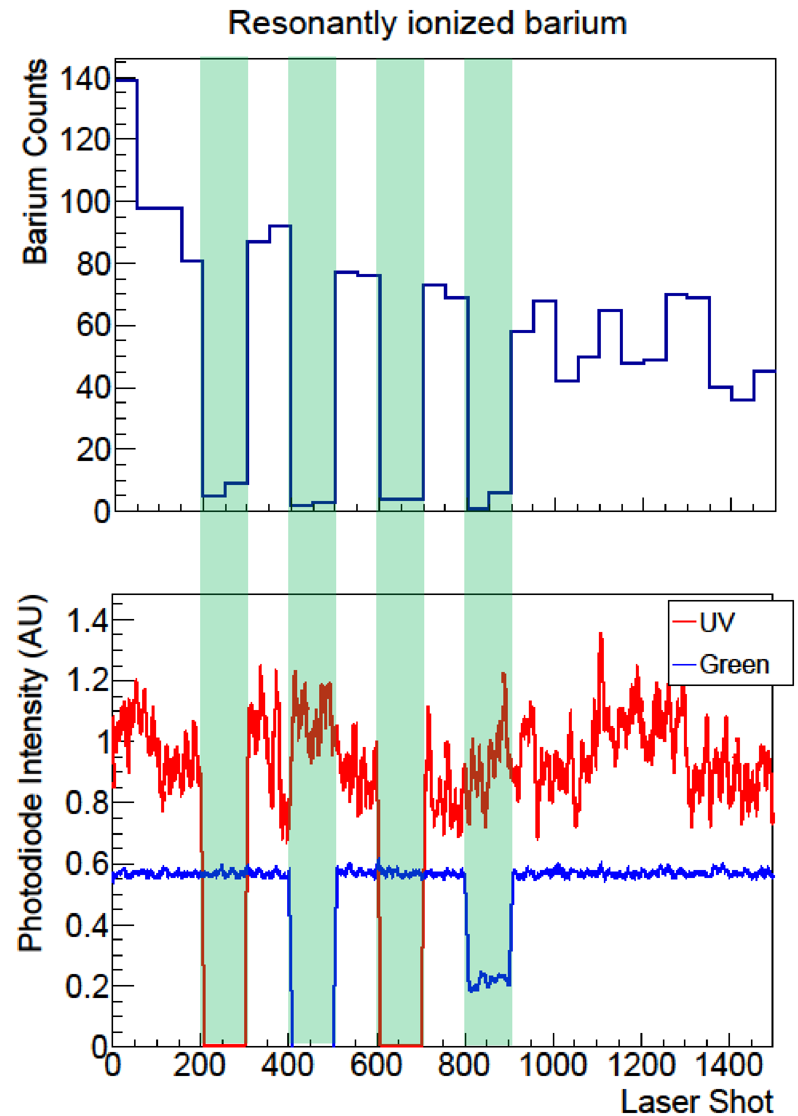
- Before liquid, test in vacuum
- ^{148}Gd-driven Ba ion source developed for testing
- Deposit ~10-100k Ba^+ initially



Rev. Sci. Inst. 81, 113301 (2010)

Full RIS Tests

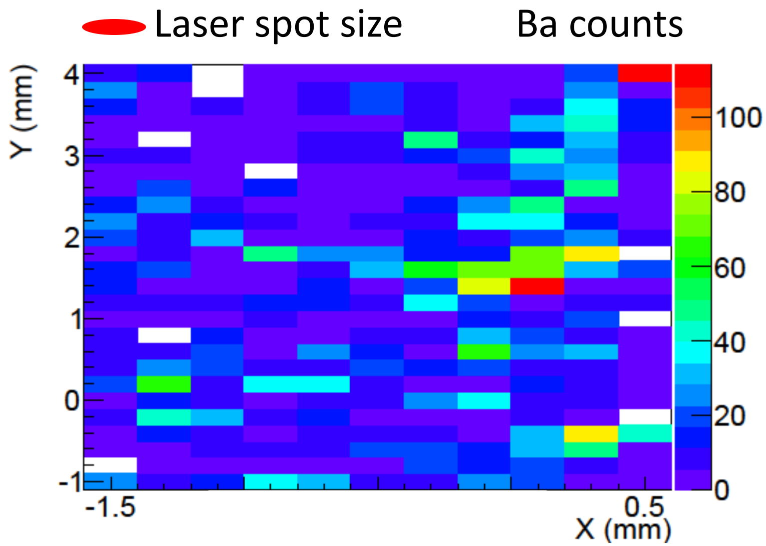


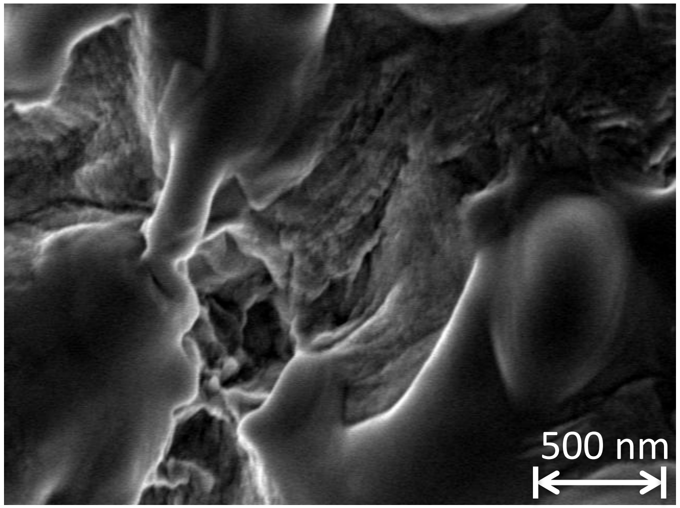


- Many masses present
  - Alkalis dominate (low ionization E)
  - Clusters of substrate at high desorption power
  - Ba and BaF from desorption laser as well as RIS Ba
- Resonant behavior observed

Desorption Challenges

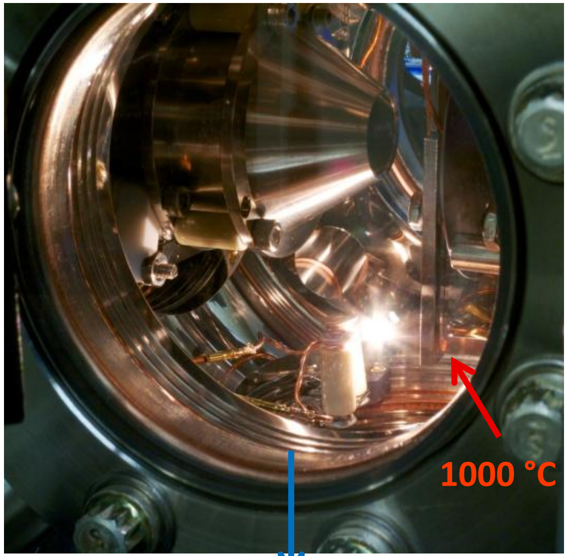
- Usually desorption laser must be powerful enough to ablate several species to see RIS signal
- Ba signal from localized hotspots
- Surface contamination or structural defects could harm (help?) desorption
- Nature of bonding to surface is crucial; must choose the right material and surface prep



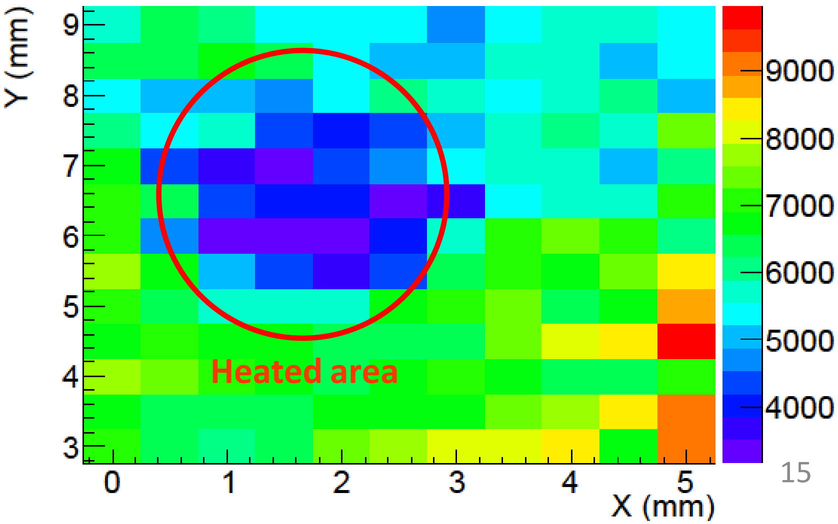


Surface Material and Prep

- Desired surface properties:
  - Weak Ba bond
  - Resistant to oxidation
  - Available at high purity
- Small/no RIS signal from Si, Re, Pt
- Notable RIS signal from W, Ni, Ta
- Surface cleaning:
  - Bare deposition substrate may facilitate Ba desorption
  - Reduce backgrounds
- Cleaning results:
  - Reduced backgrounds
  - No loss of signal



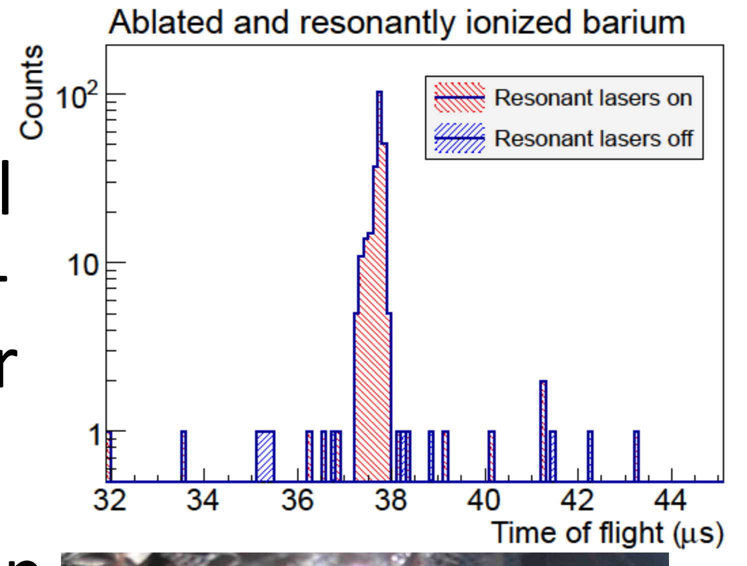
Total counts (all masses)

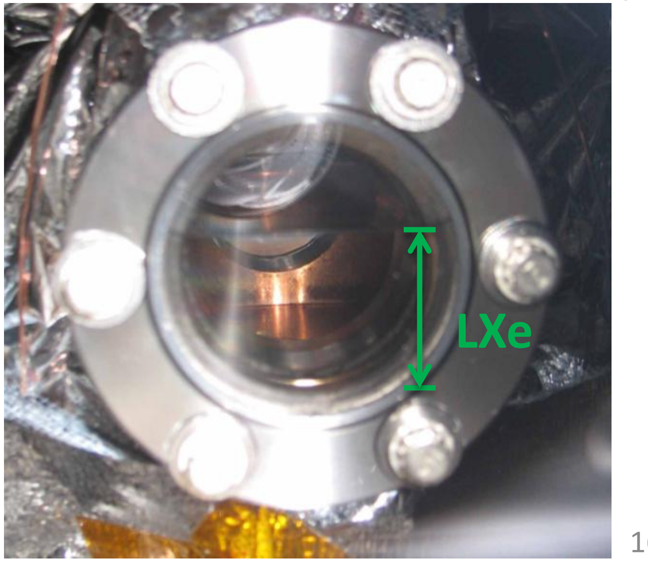


Results and Next Steps

- Proper choice of material and surface prep produces a signal with almost no backgrounds – not even Ba ionized by IR laser
- Ideal conditions + luck:

  >5% efficiency from deposition to final detection
- **Next:**
  - Continued work on improving repeatability, efficiency
  - Testing in LXe





The EXO Collaboration

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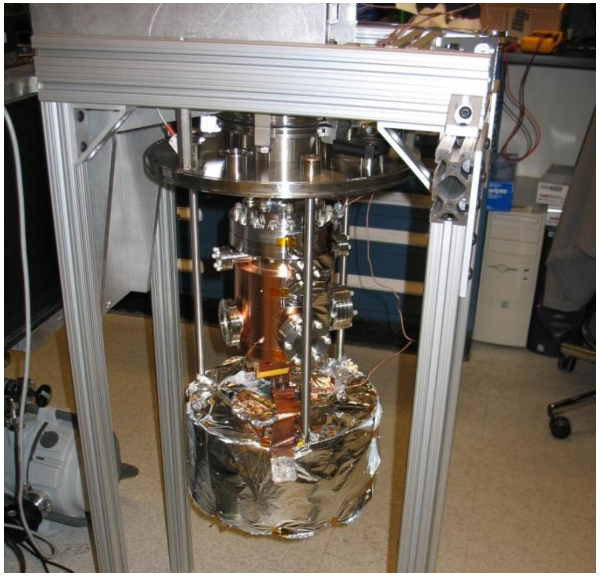
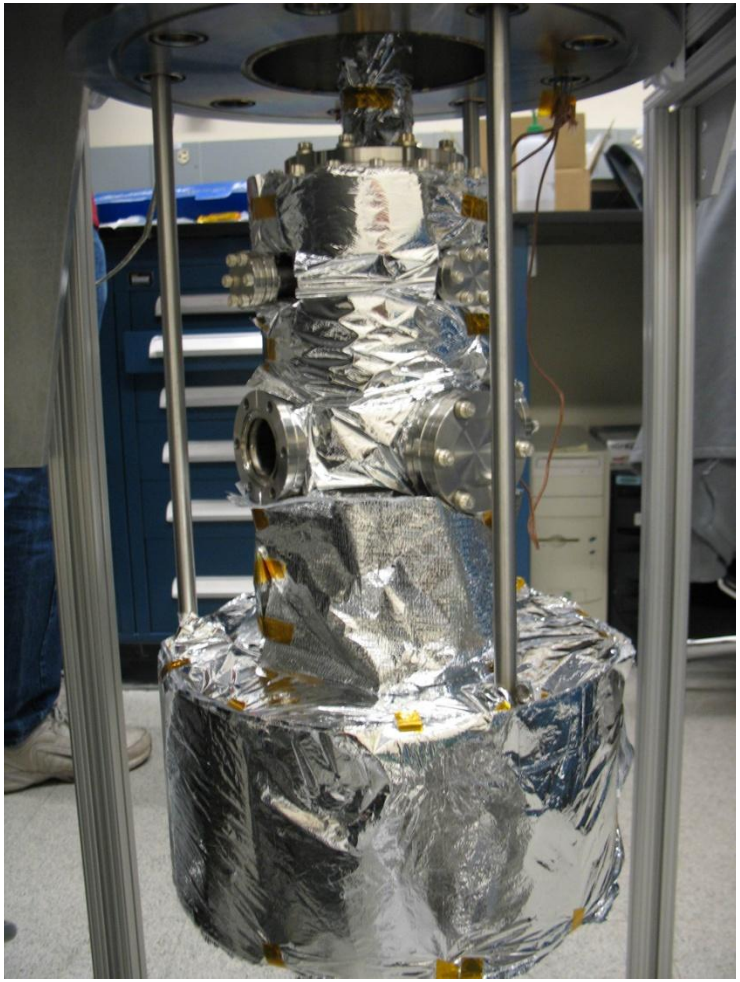
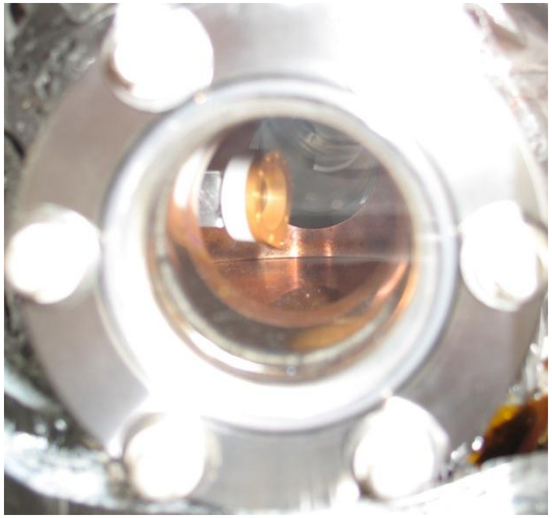
Backup Slides

LXe Cell and Ba Source







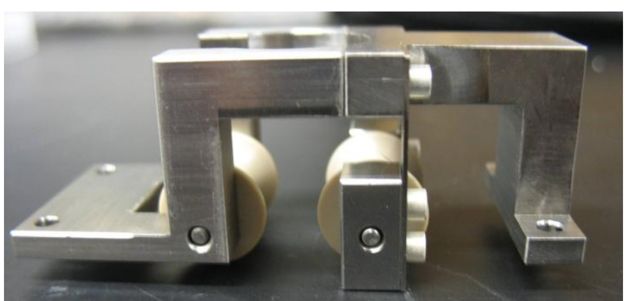
Loading ≈10^4 Ba/hr

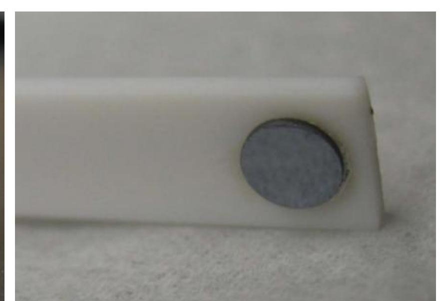
Effects of bias on Ba deposition?

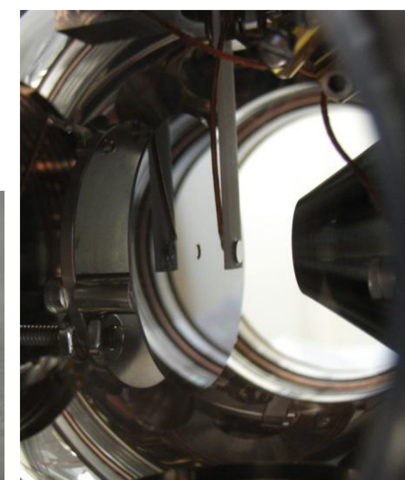
Enriched Xenon Observatory
EXO
for double beta decay

Probe

- Probe is a 0.5” diameter tube
- Rollers constrain lateral movement
- Target mounted on ceramic tab with vacuum-safe conductive epoxy
- Target charged via feedthrough at the top
- Second probe machined, allows for ohmic heating of the target

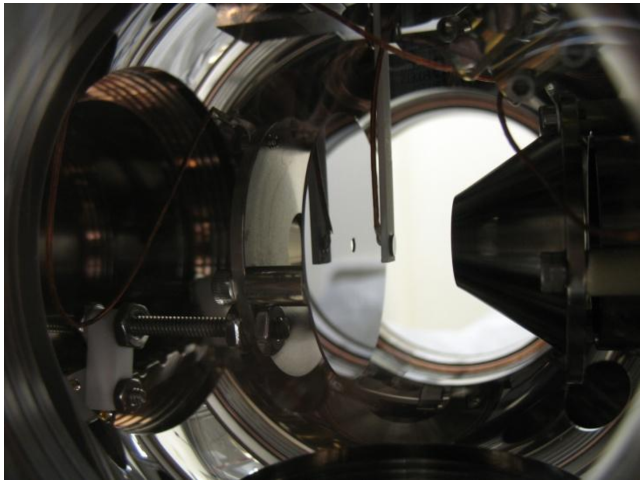


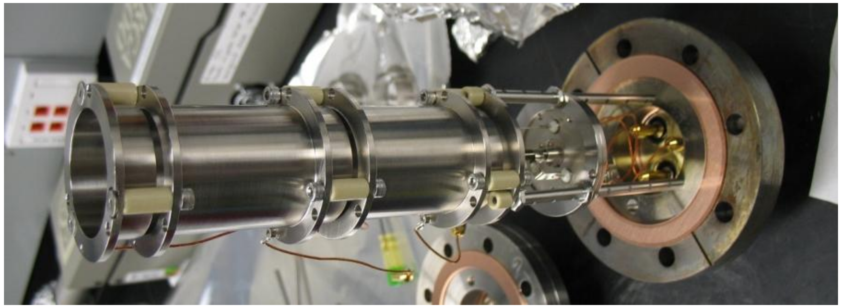




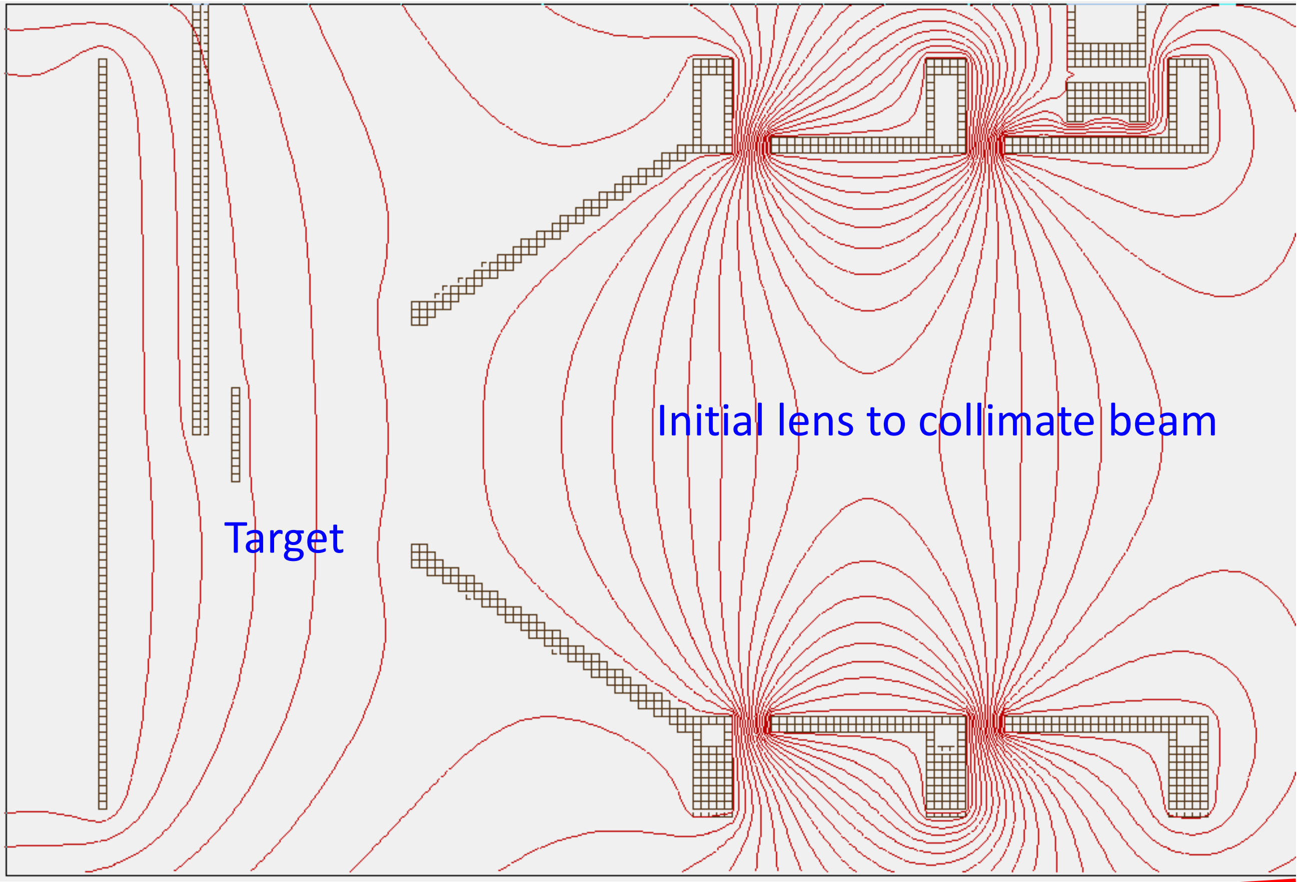
Spectrometer Design

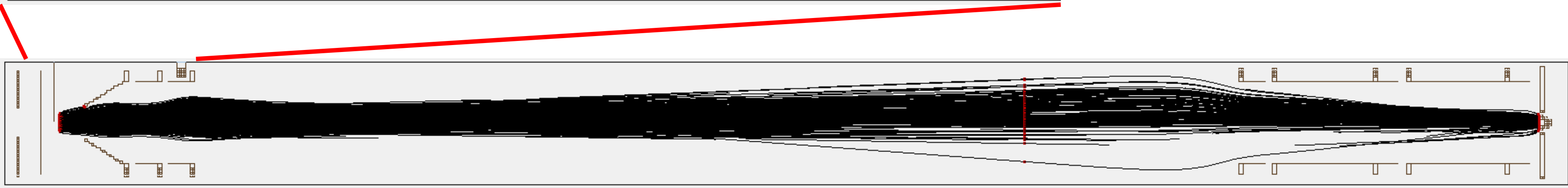
- Ions are produced at target, guided by electrodes and detected by CEM
- Transit time determines ion mass
- Front electrodes capture, shape and accelerate ions
- Back electrodes refocus and detect ions





SIMION for time of flight

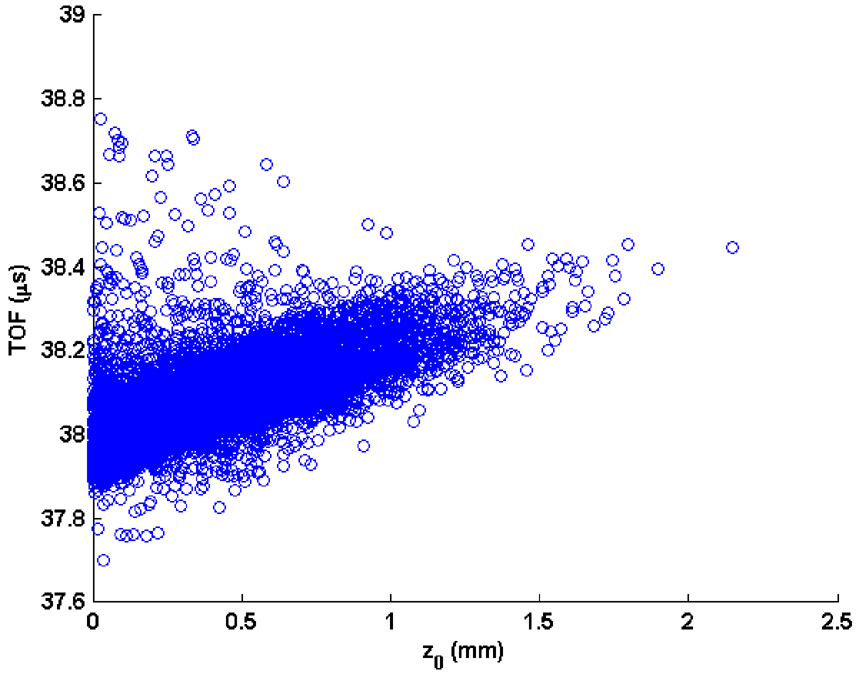


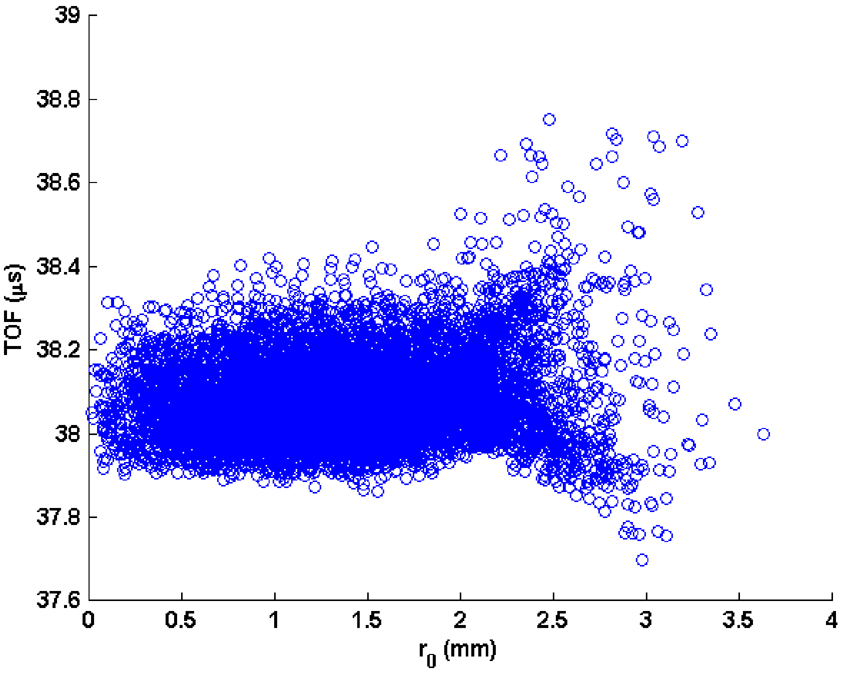


Predicted RIS time of flight: 38.6 us

This includes an initial energy and spatial distribution for barium.

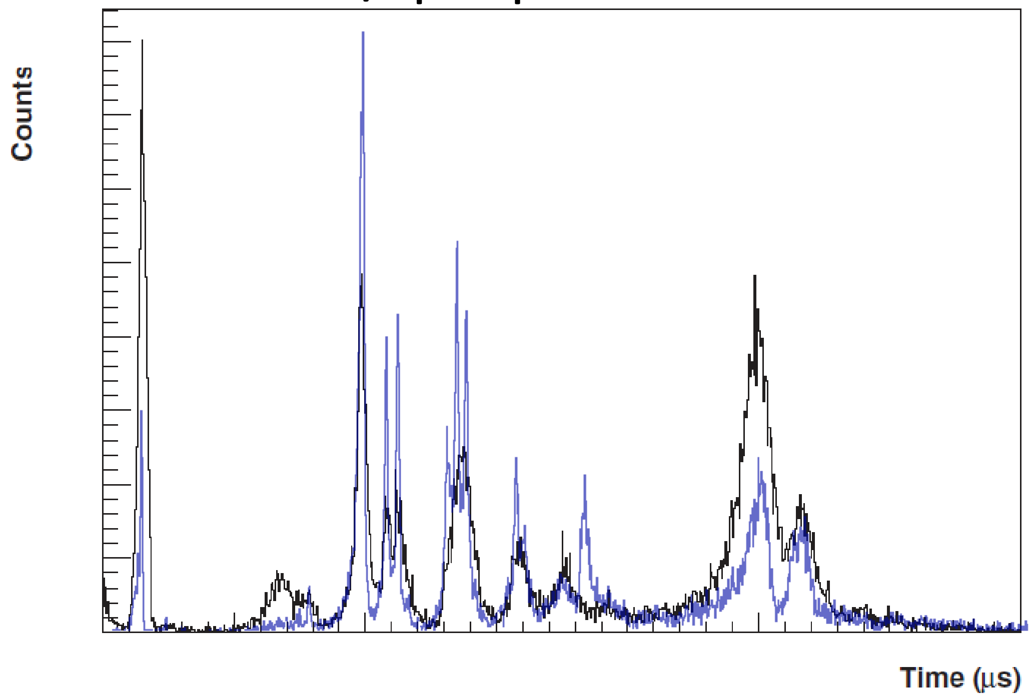
Target TOF Dependence

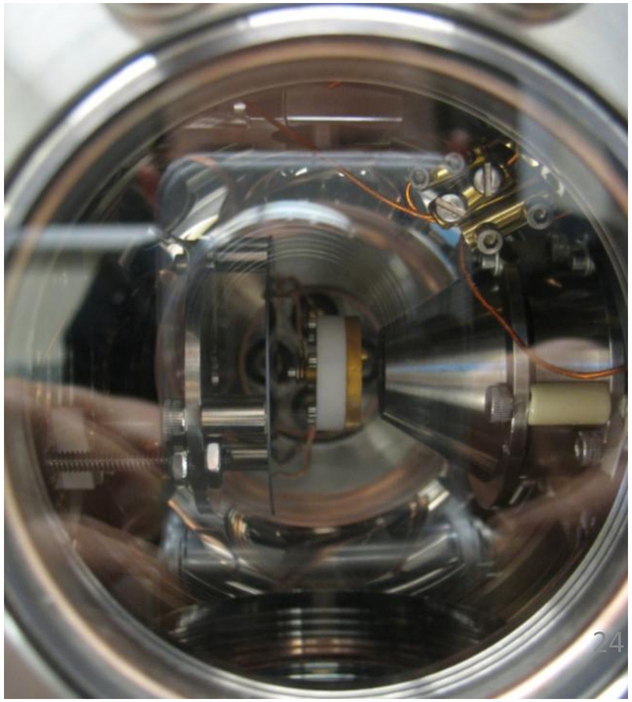




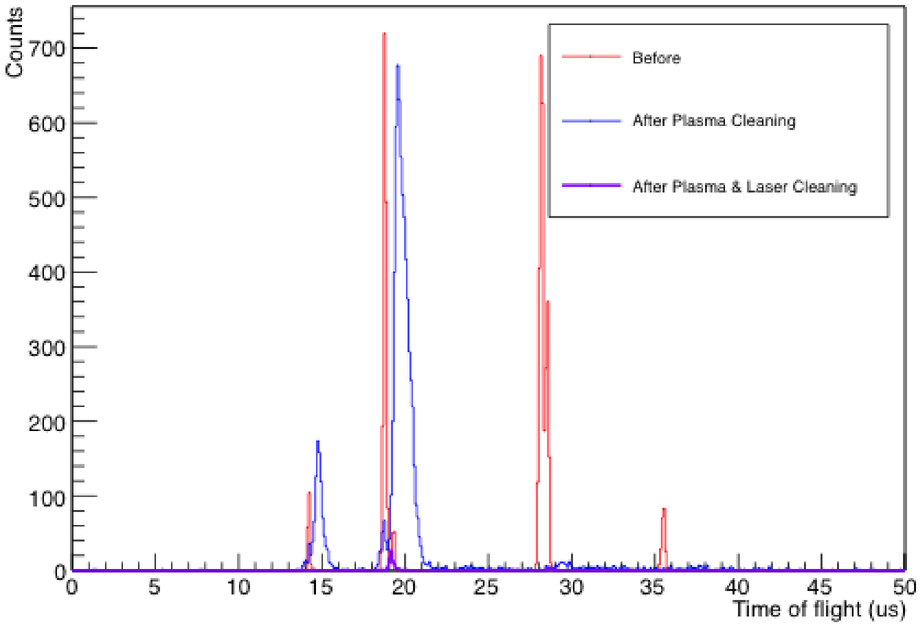
Direct Testing with Gd Source

- Spectrometer simulations: >99% efficiency, few amu resolution
- Want to test performance
- Move Ba source directly in front of spectrometer
- Previous spectrum is well-reproduced ⟶ success
- Peak ratios change (different source)
- Narrower/split peaks ⟶ better resolution



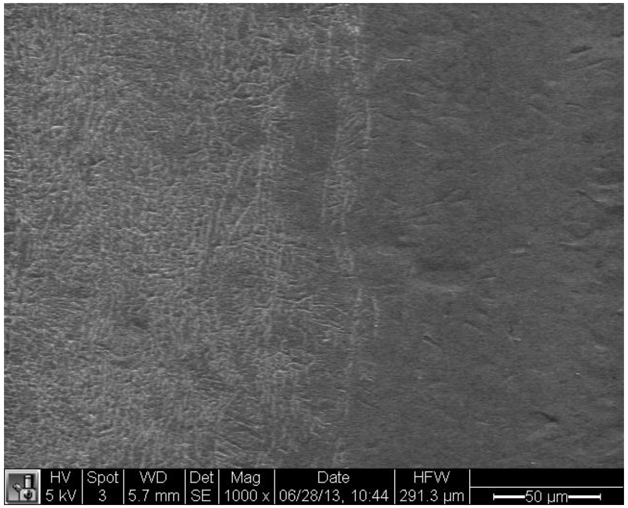


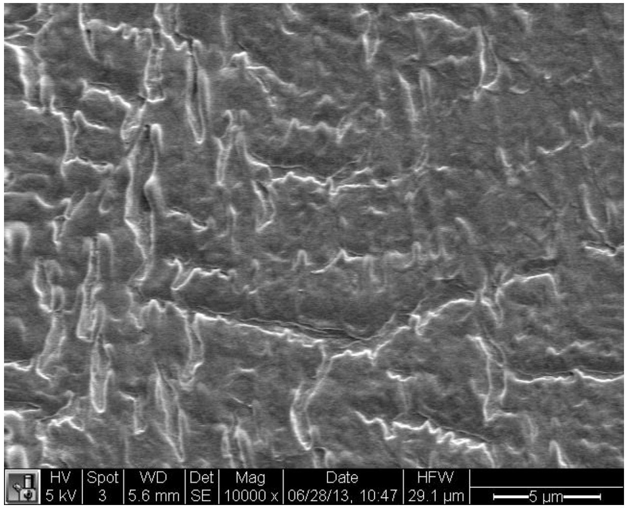
Xenon Sputtering

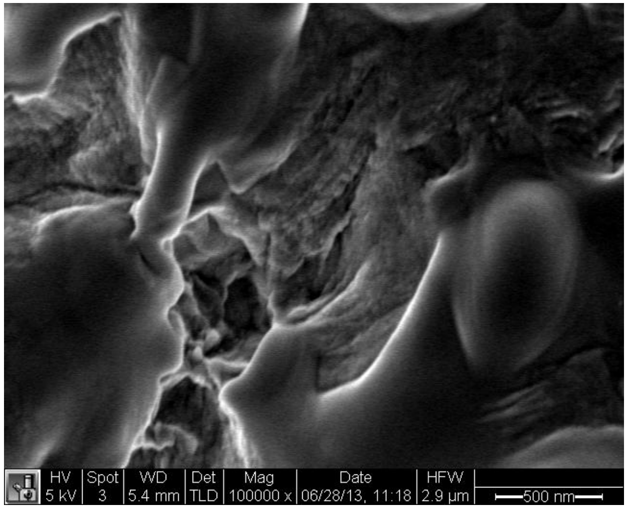


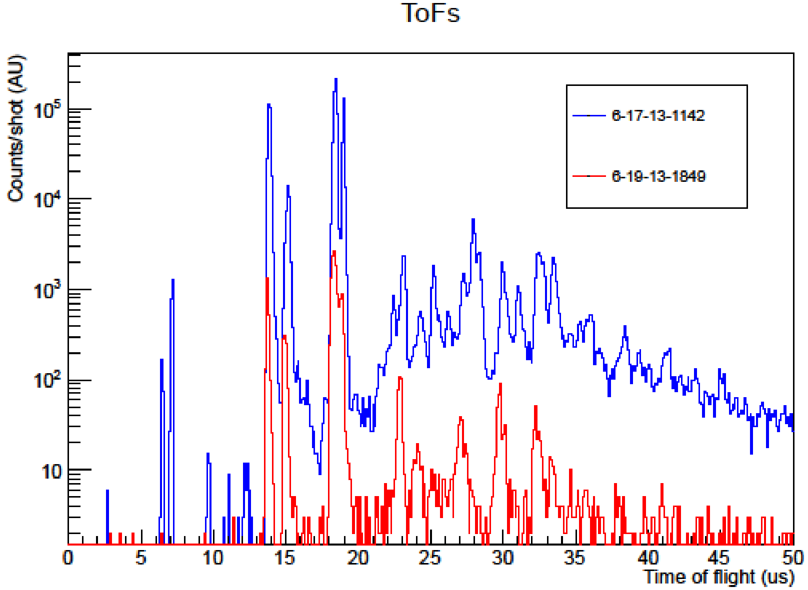
We can clean the surface by bombarding it with noble gas ions—xenon is handy!
The spike on the left is the anode, and the target (on the right) is the cathode.

Surface Damage



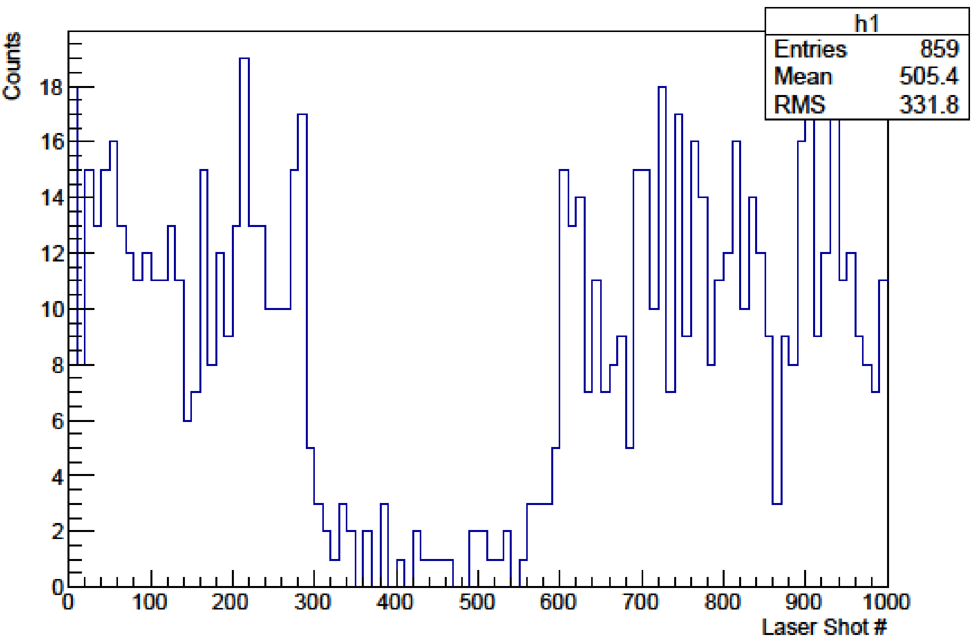


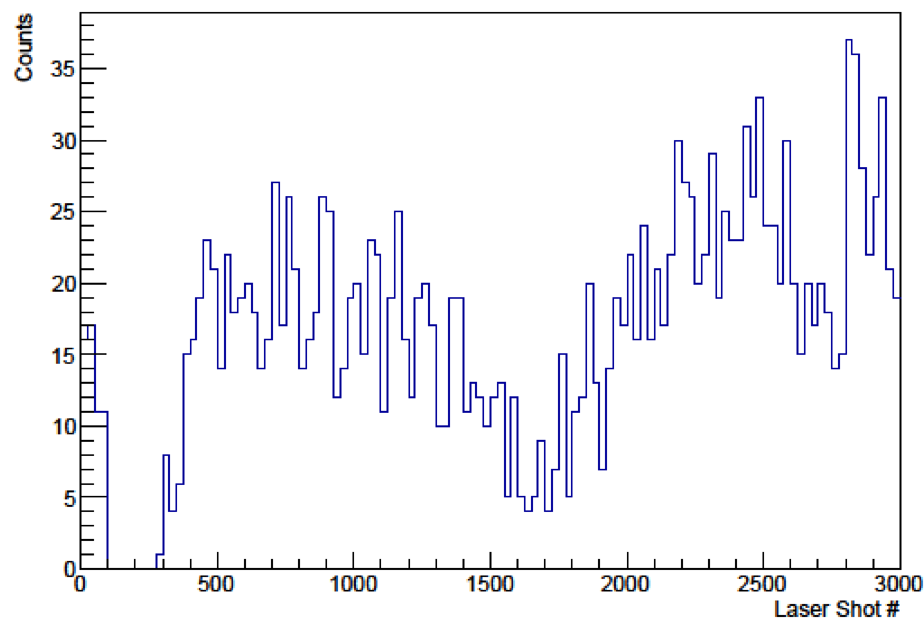




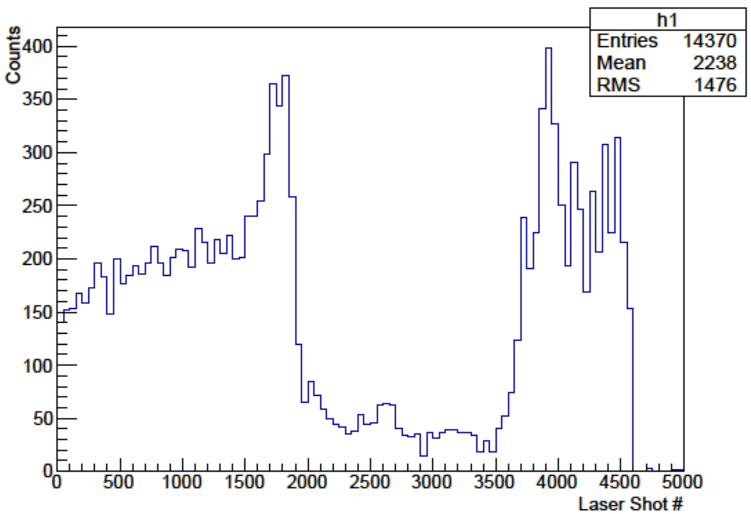
Detuning Tests

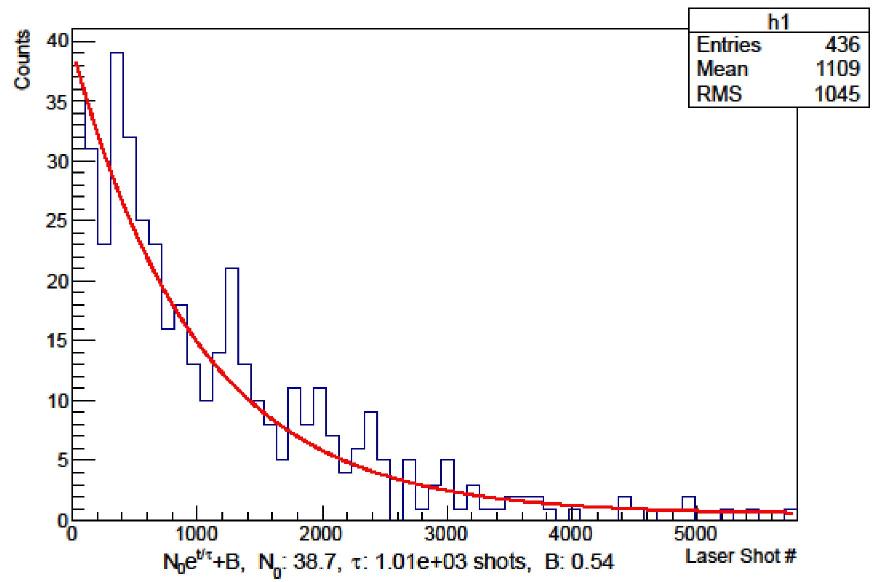
- Signal does depend on RIS laser wavelengths



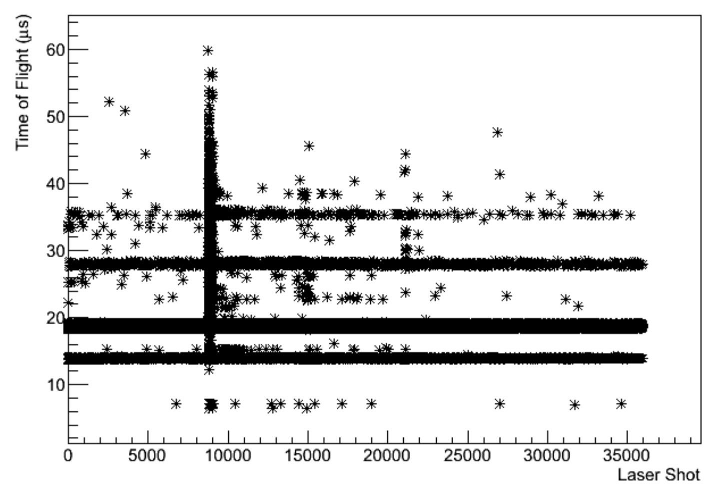


Time Structure



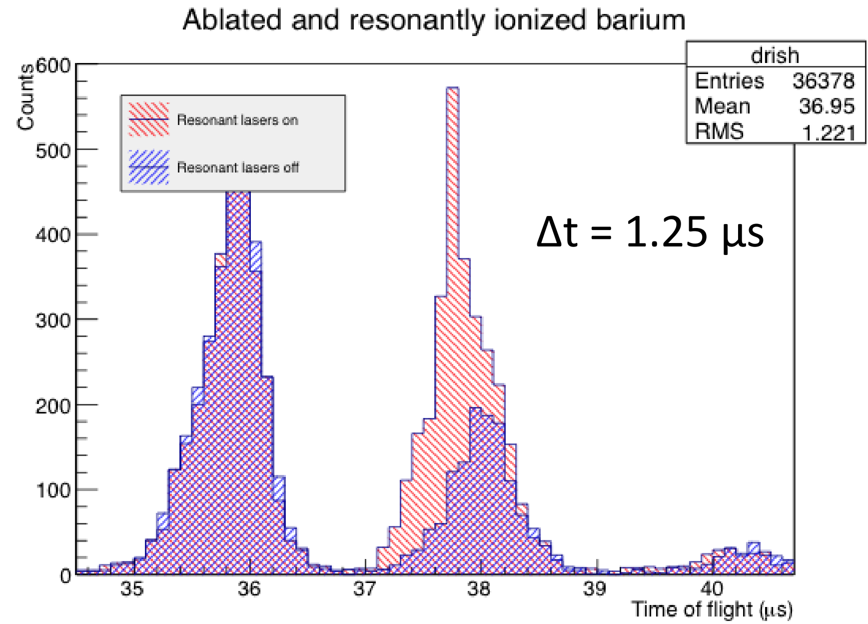


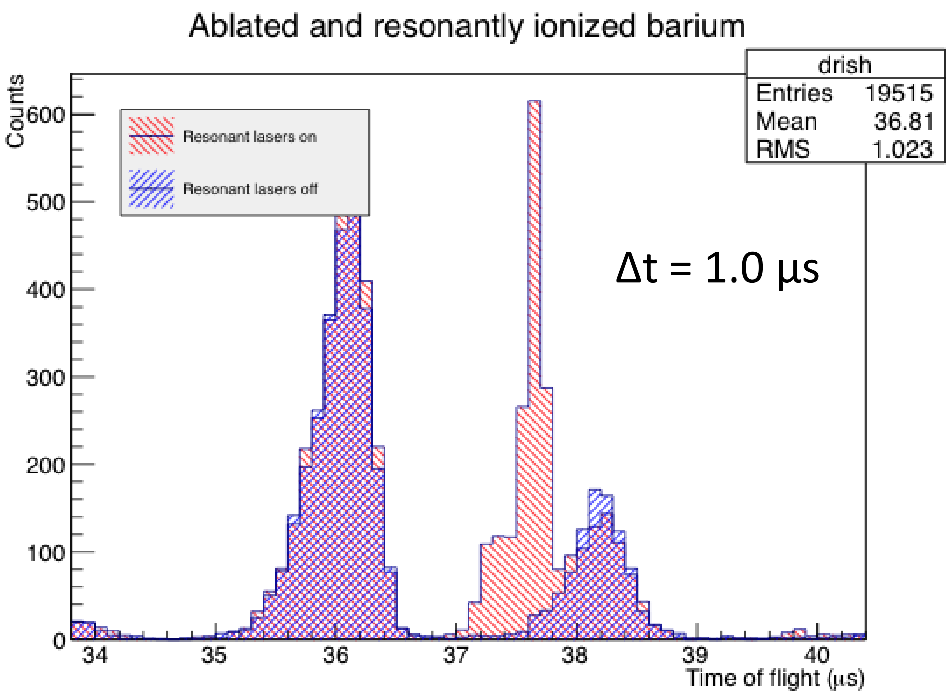
- Sometimes a nice exponential decay
- Others, have sudden arrival of signals

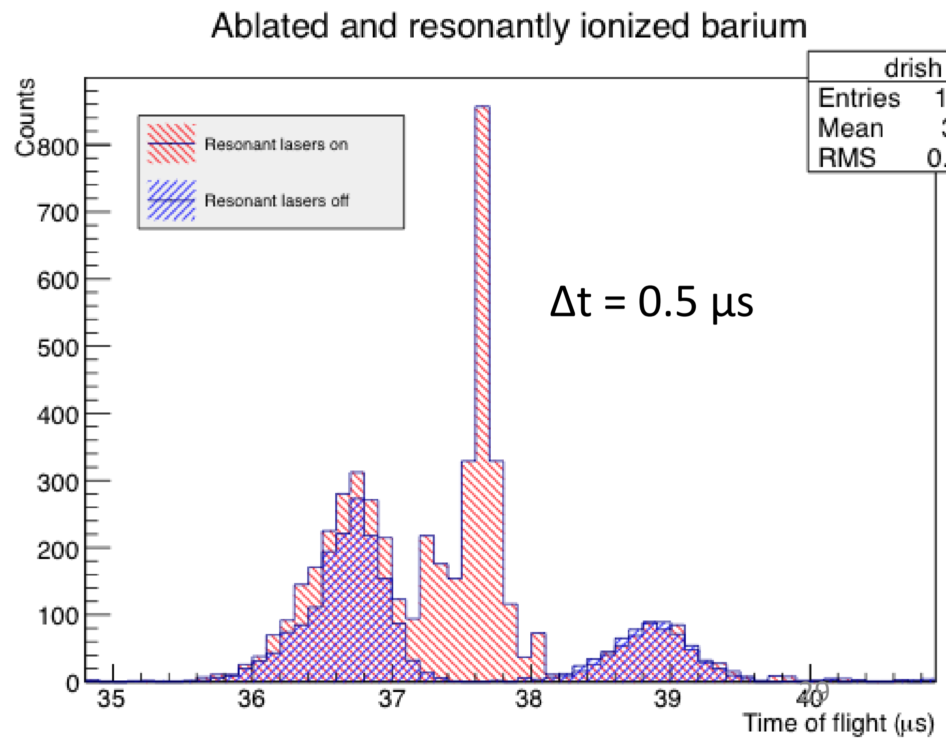


Laser Delay Shifts

By reducing the delay between the desorption laser and the RIS laser, we can shift the arrival time of the peak



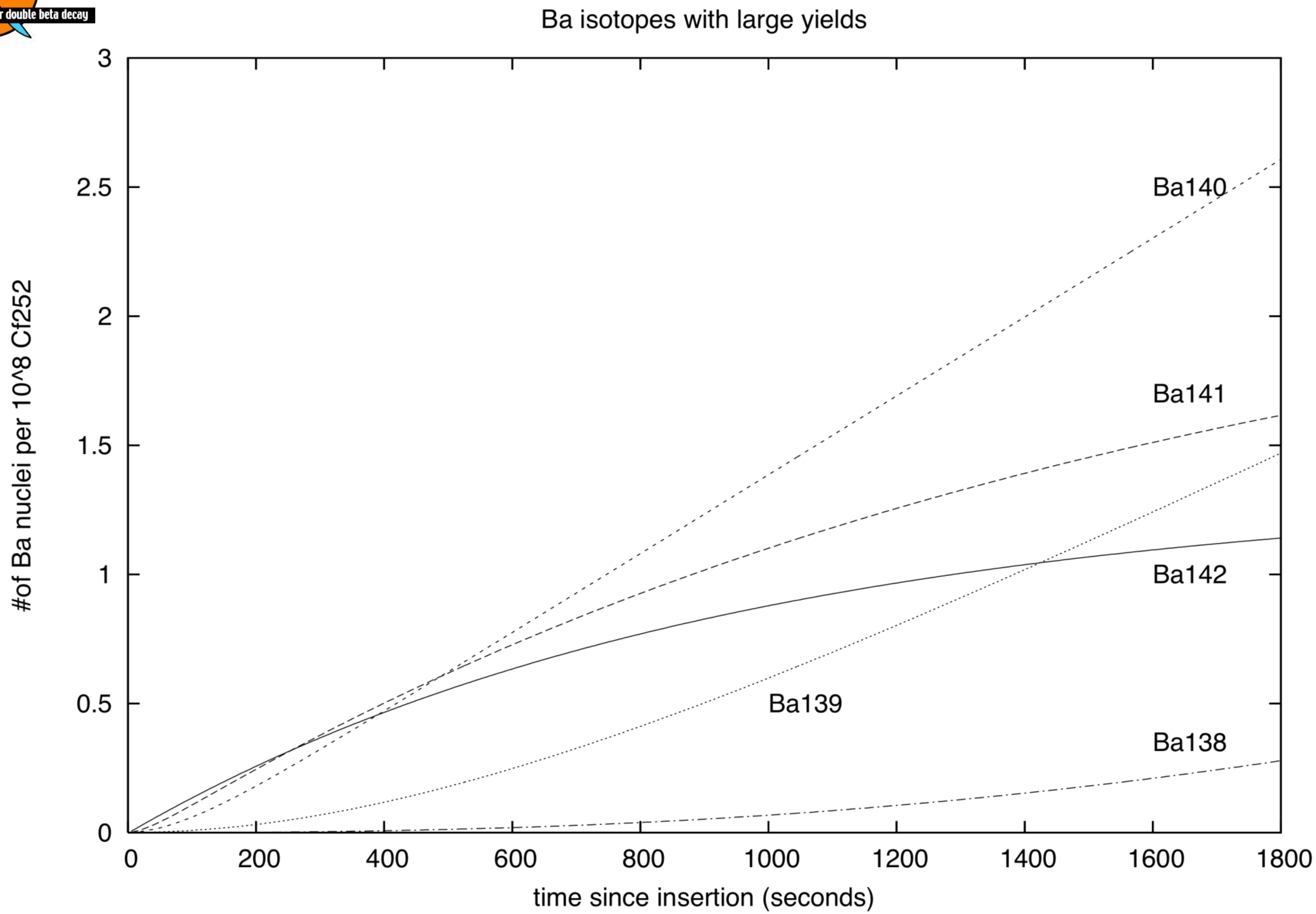




^{252}Cf Fission Source

- ^{252}Cf undergoes spontaneous fission
- Barium is ~5% of the fission fragments
- Most isotopes are radioactive, ^{138}Ba is not.
- The number of all Ba isotopes will constantly change.

Ba Isotope	Half-Life
138	Stable
139	83 min
140	13 days
141	18 min
142	11 min
143	15 sec
144	12 sec
145	4.3 sec
146	2.2 sec



10^8 ^{252}Cf is 0.83 Bq = 22 pCi

Plot courtesy of Petr Vogel