The Future of EXO:

Ton-scale Xenon TPC with Barium tagging

Carter Hall, SLAC

Xe offers a new tool to reduce radioactive backgrounds to $\beta\beta 0\nu$:

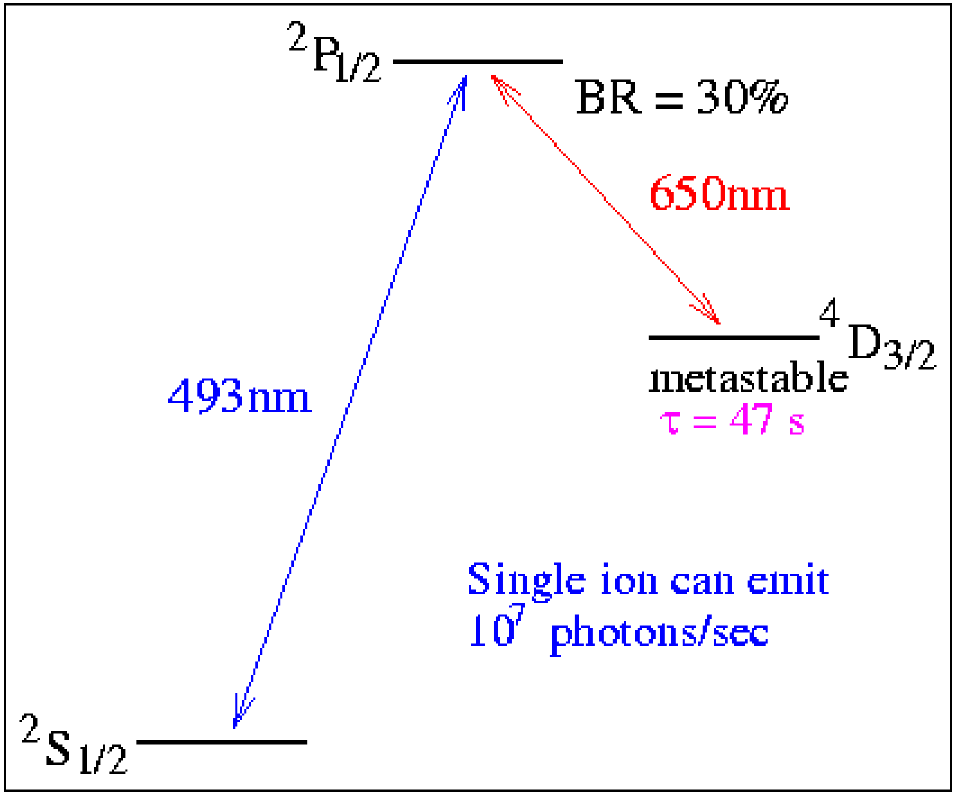
$^{136}Xe \rightarrow {}^{136}Ba^{++}$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

Ba^{+} system best studied.

Very specific signature "shelving"

Single ions can be detected from a photon rate of 10^7/s

Barium tagging would eliminate all radioactive backgrounds, leaving only $2\nu\beta\beta$.



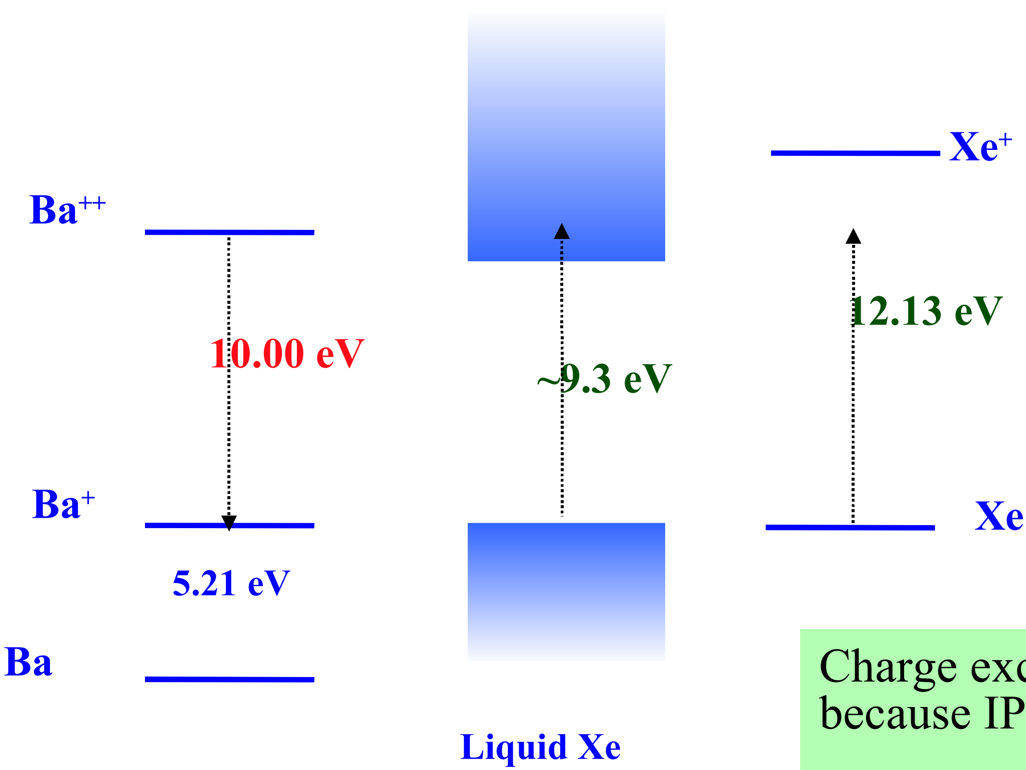
Level structure for Ba^{+}

Conversion of Ba^{++} to Ba^{+}

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

Charge exchange in liquid Xe - **KEY ASSUMPTION**

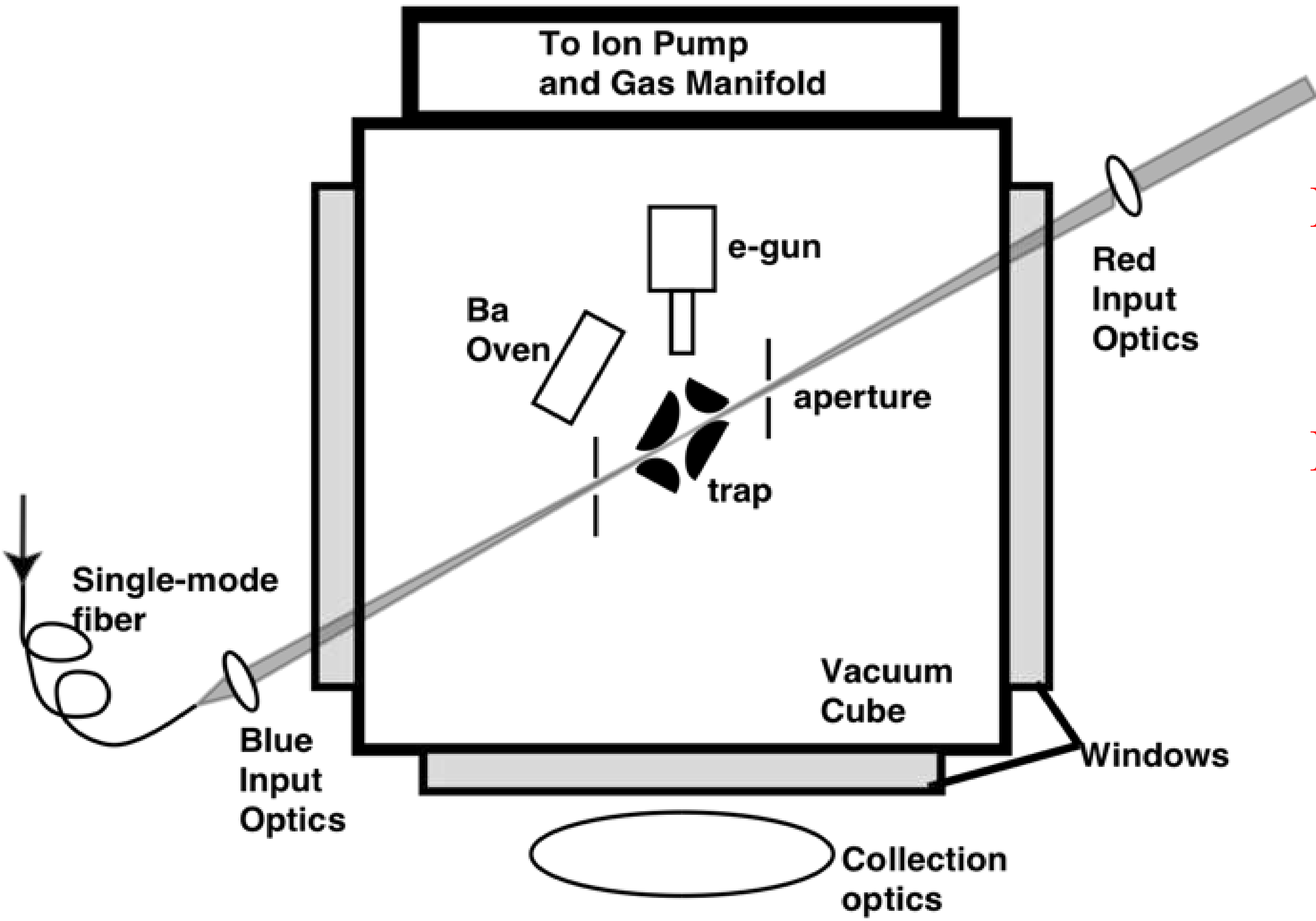
$\rightarrow$ $^{136}Ba^{+}$ + Xe_{h}



It should not happen in pure Xe gas.
This is one motivation for a LXe detector

Charge exchange should occur to Ba^{+} in LXe because IP(Ba^{+}) > bandgap (LXe).

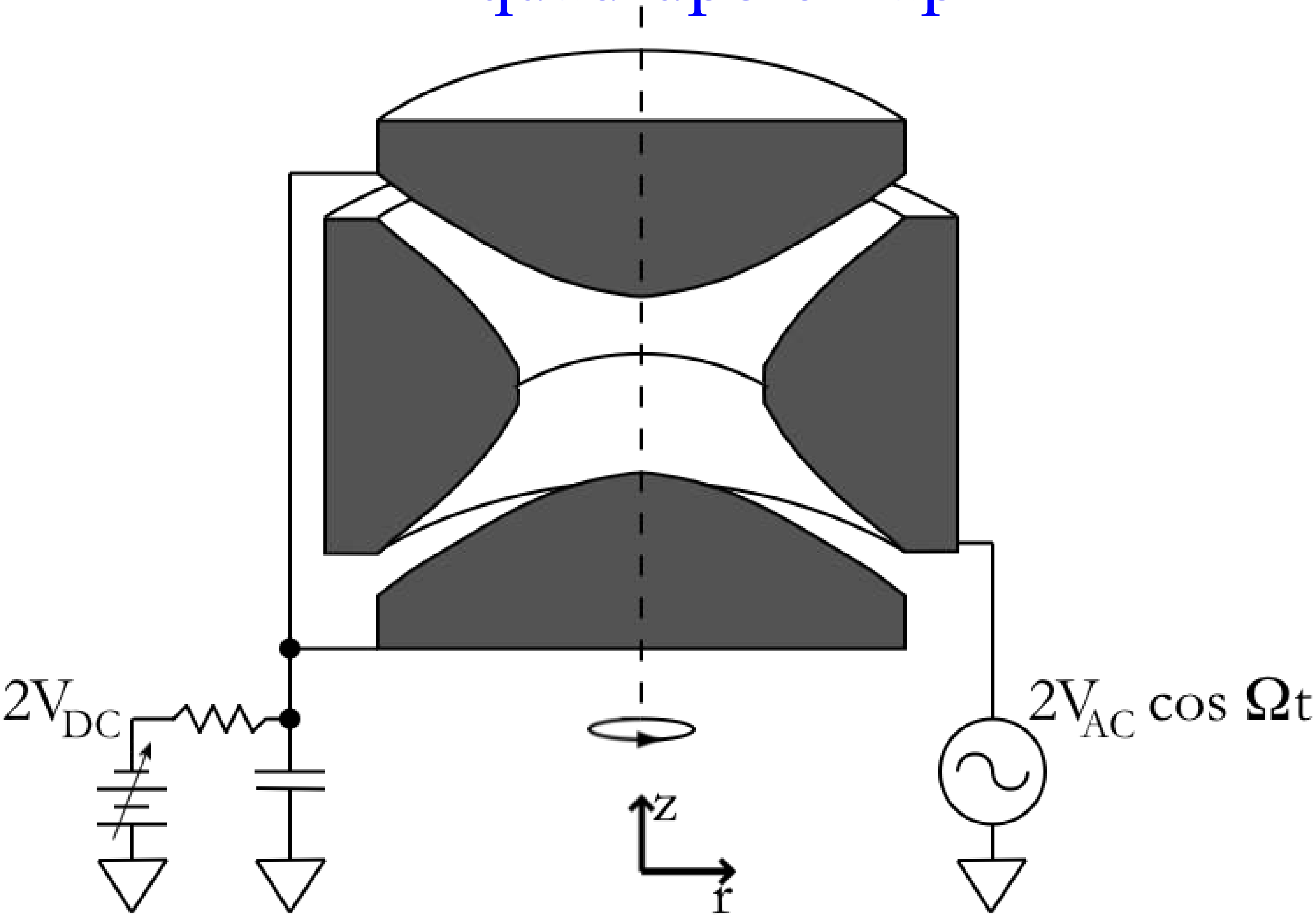
EXO ion trapping experiments



He, N_2, Ar, Kr, Xe gases

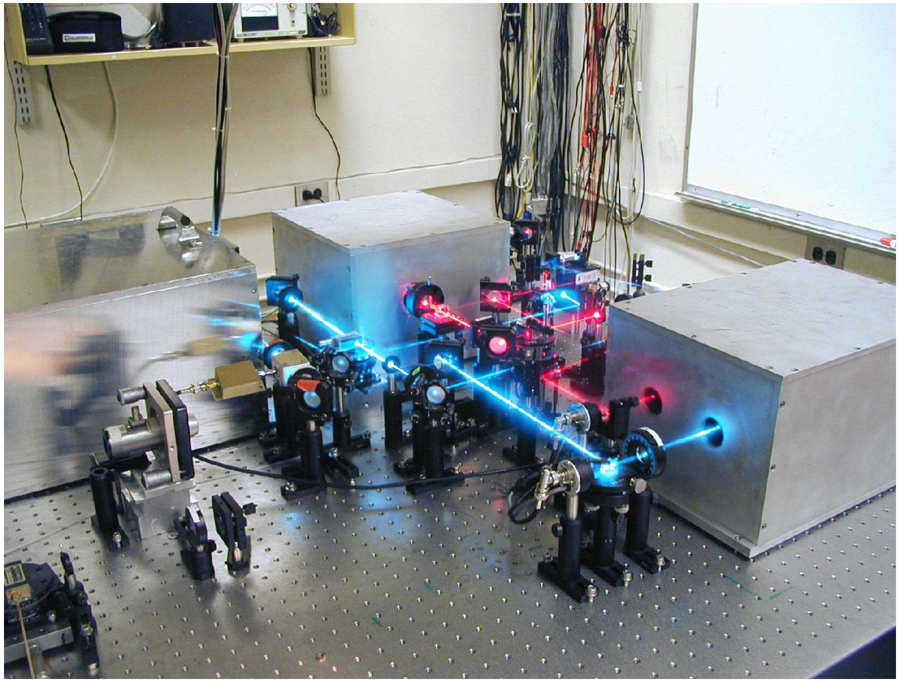
$P = 10^{-10}$ torr to 0.1 torr

RF quadrupole trap



RF voltage confines ions to the center of the electric pseudo potential given by $\psi \sim |E|^2$.

EXO spectroscopy lab

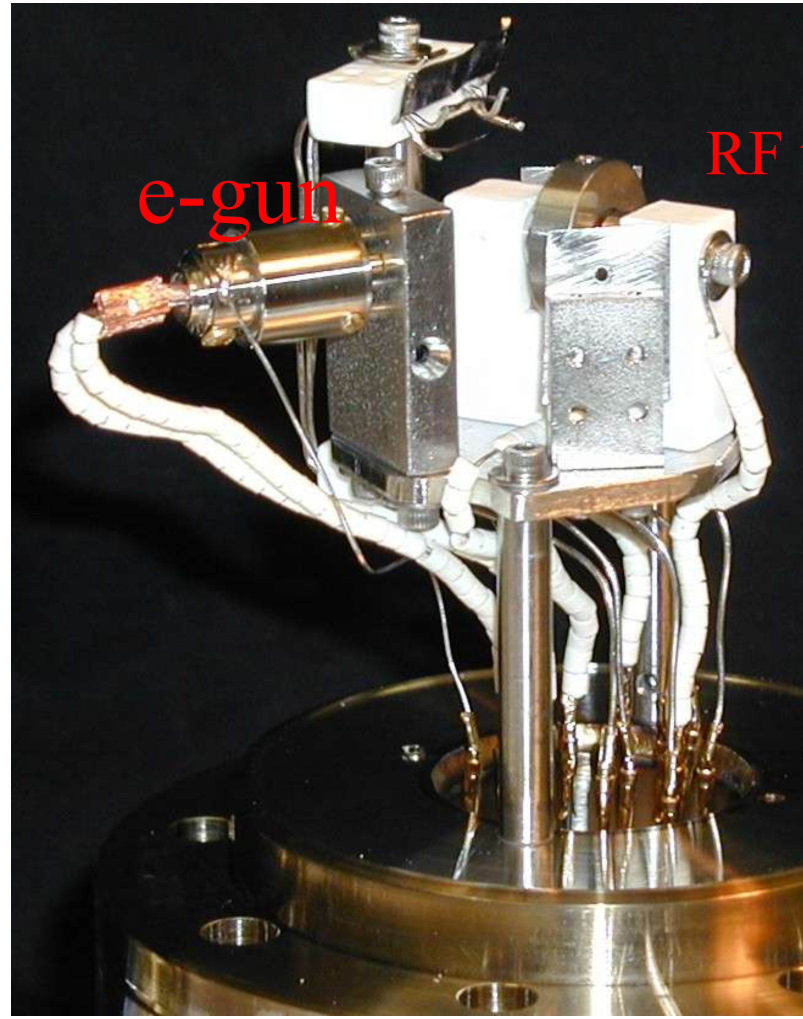


650 nm: External Cavity Diode Laser (ECDL)

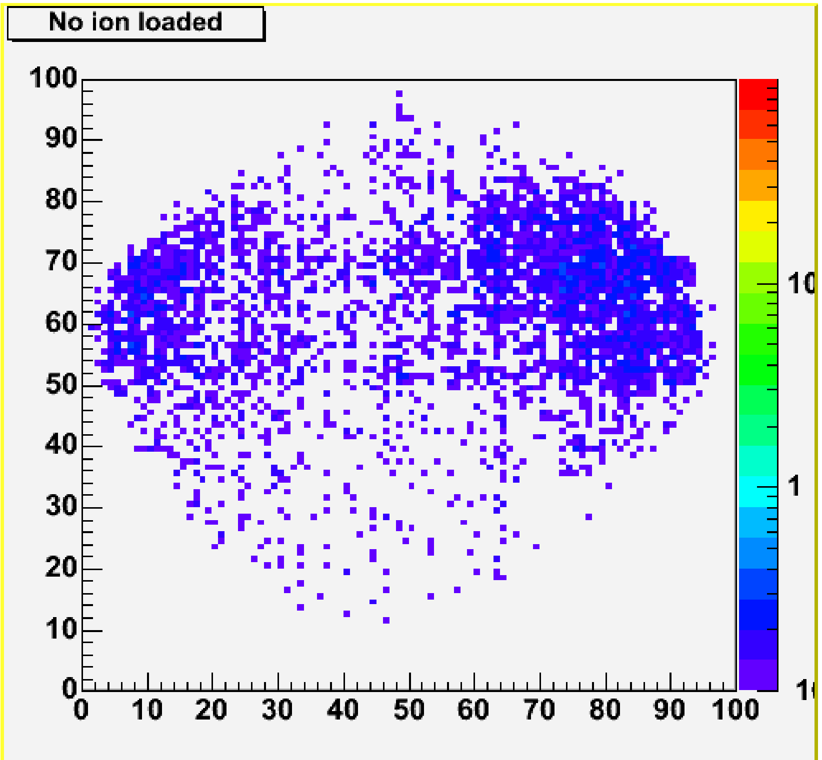
493 nm: Frequency doubled 986 nm

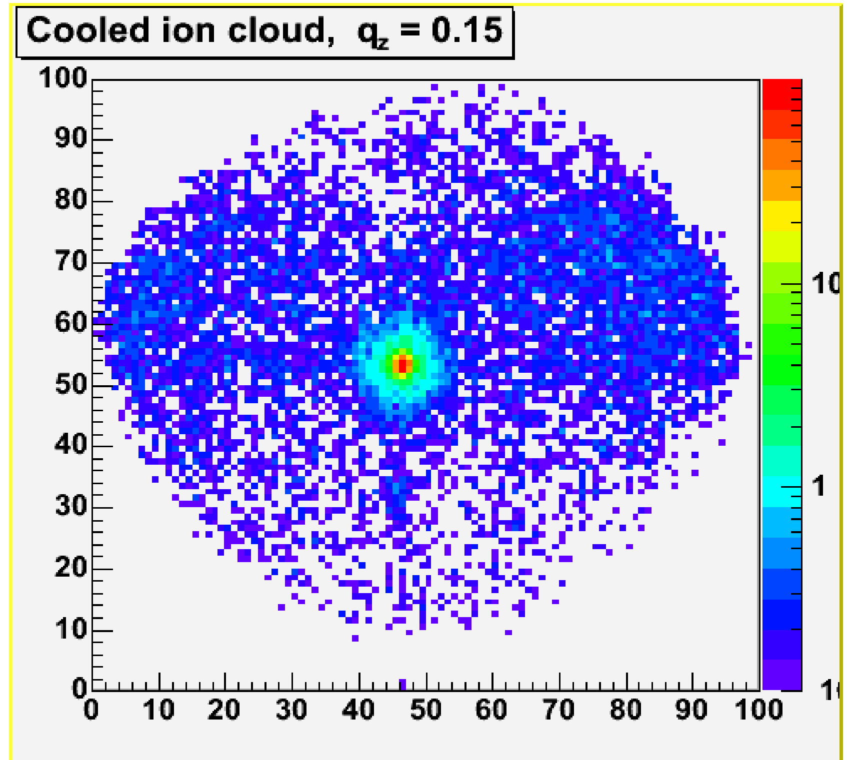
both lasers cavity stabilized

Ba Oven



Vacuum Ba+ ion cloud picture





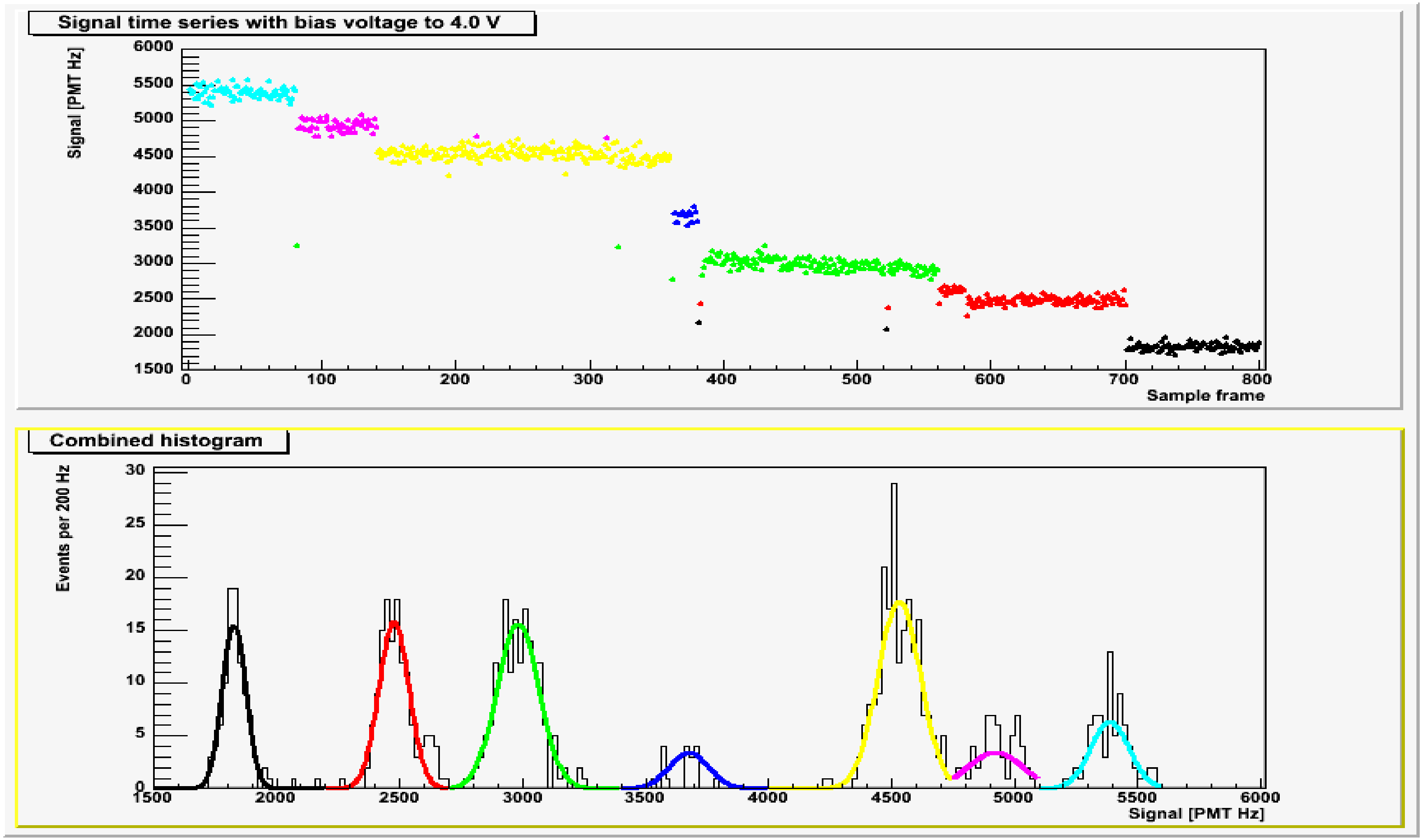
Hz/bin

850 μm

150:1 Signal to noise

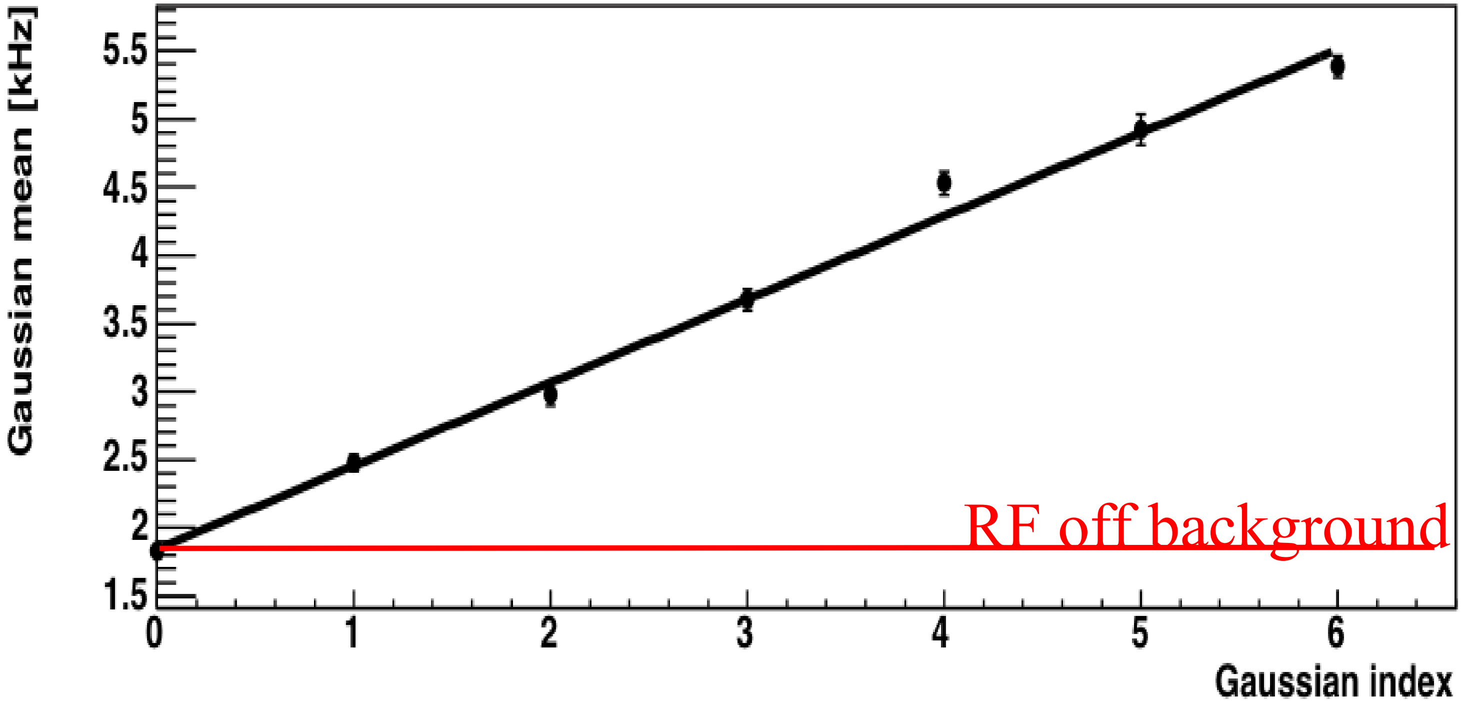
From imaging PMT

Milikan ion dropping experiments



Quantization of PMT signal demonstrates single ion sensitivity

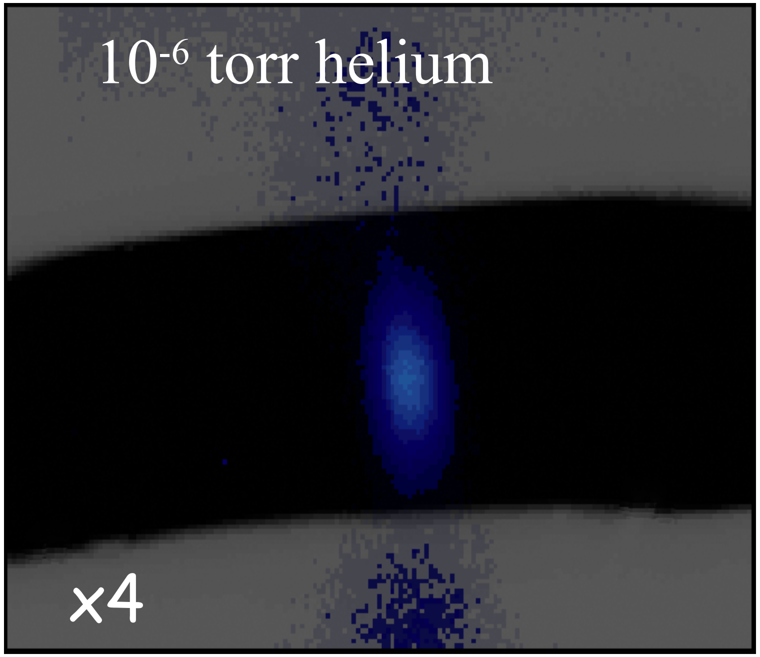
Single Ion signal = 610 +/- 13 Hz

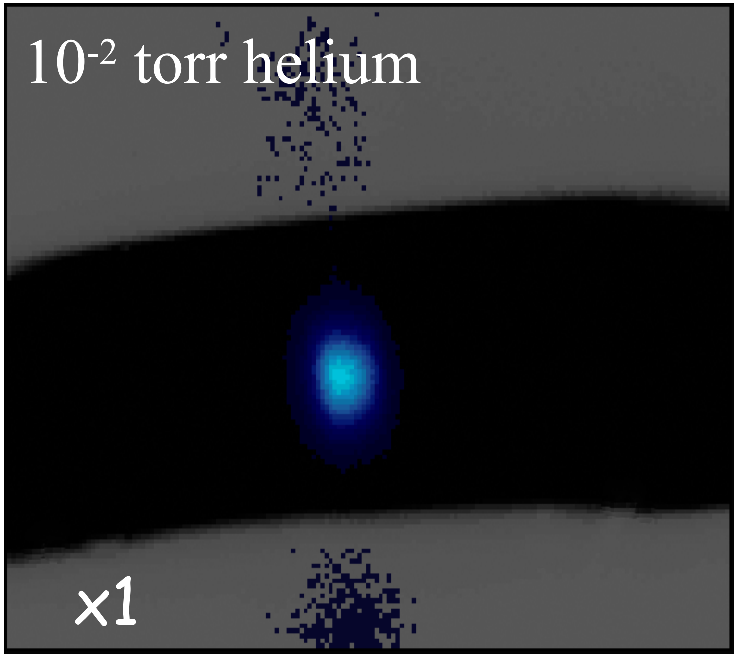


Signal limited by:

Detector Q.E.	2×10^{-1}
Doppler broadening	1.5×10^{-1}
Numeric aperture	10^{-2} - 10^{-3}
	~ 500 Hz

Ba+ in helium buffer gas



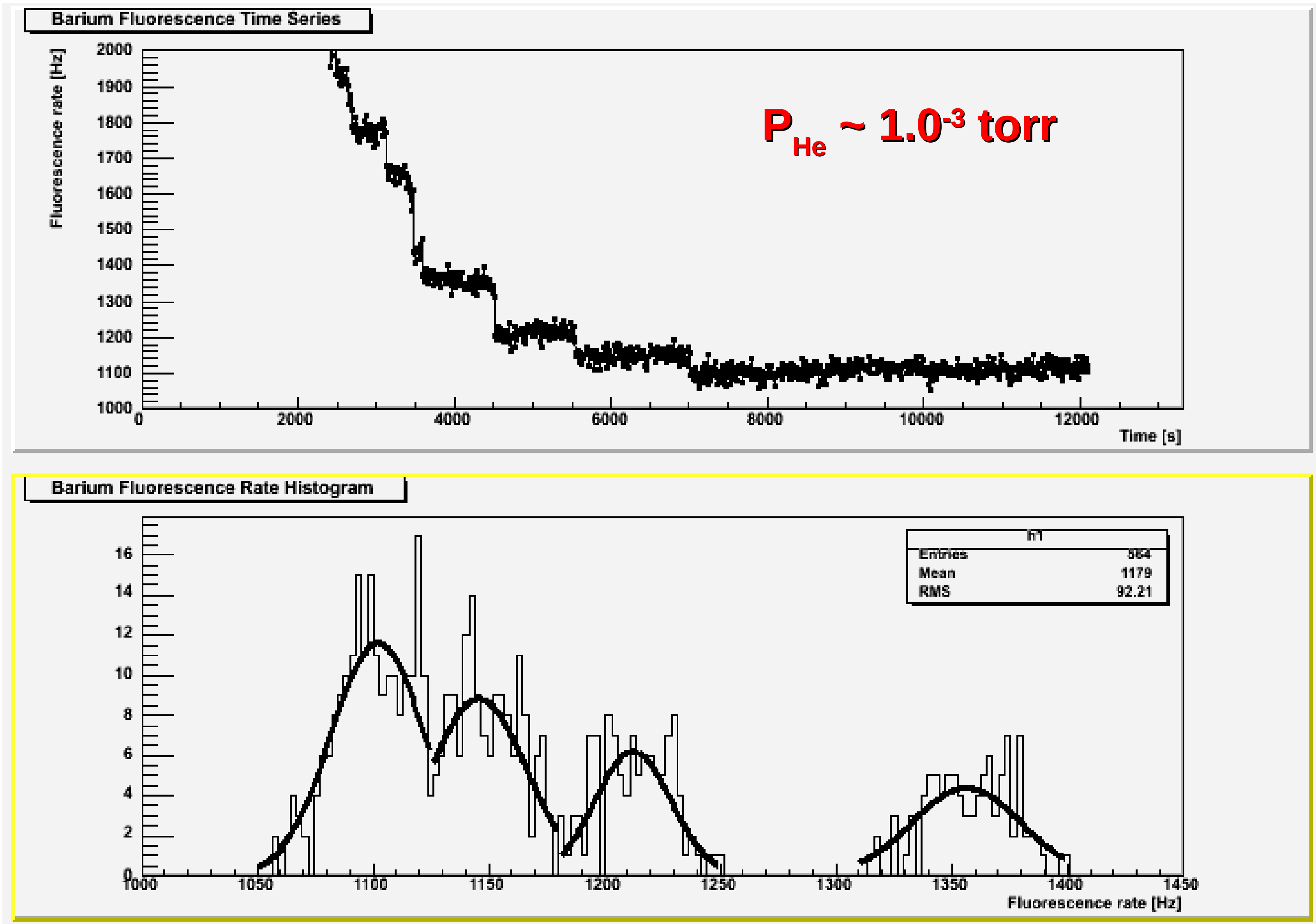


Helium helps localize the Ba+ in the trap.

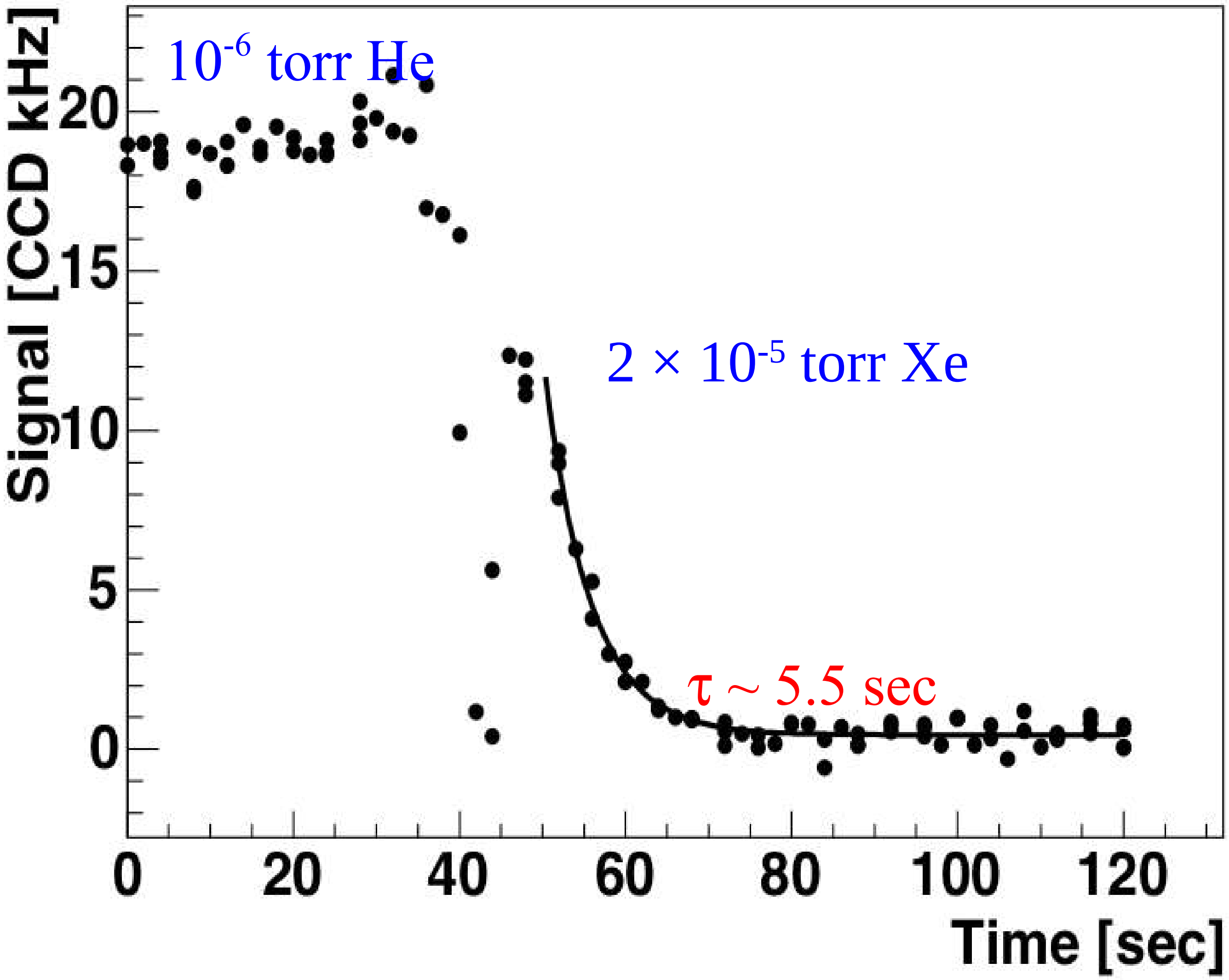
Ions trapped at helium pressures from 10^{-10} to 10^{-1} torr.

Ion cloud lifetime > 24 hours in helium.

Ion dropping in helium

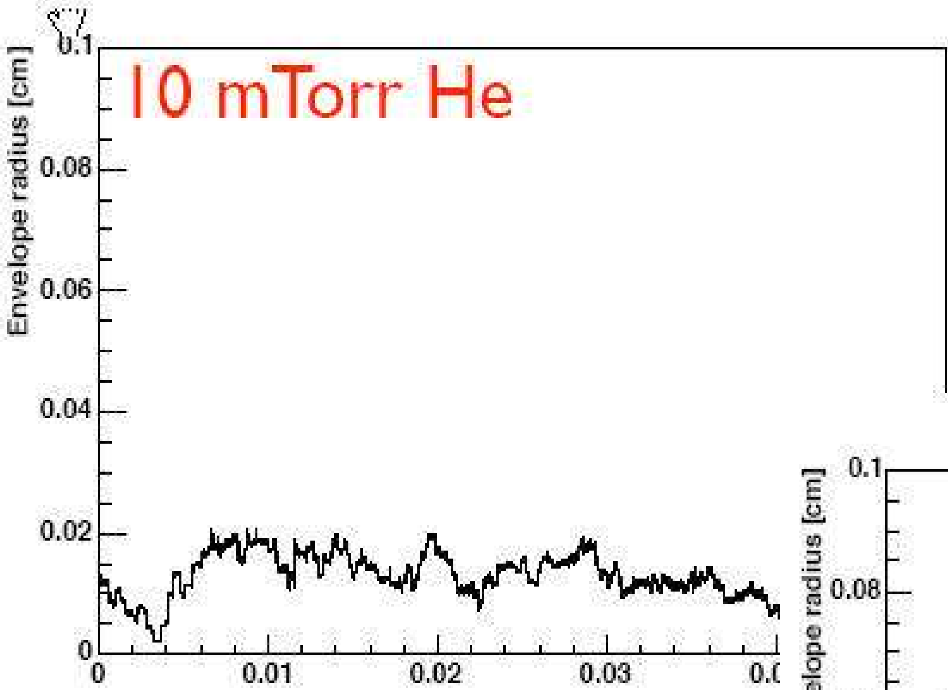


Ba+ signal has short lifetime in xenon gas

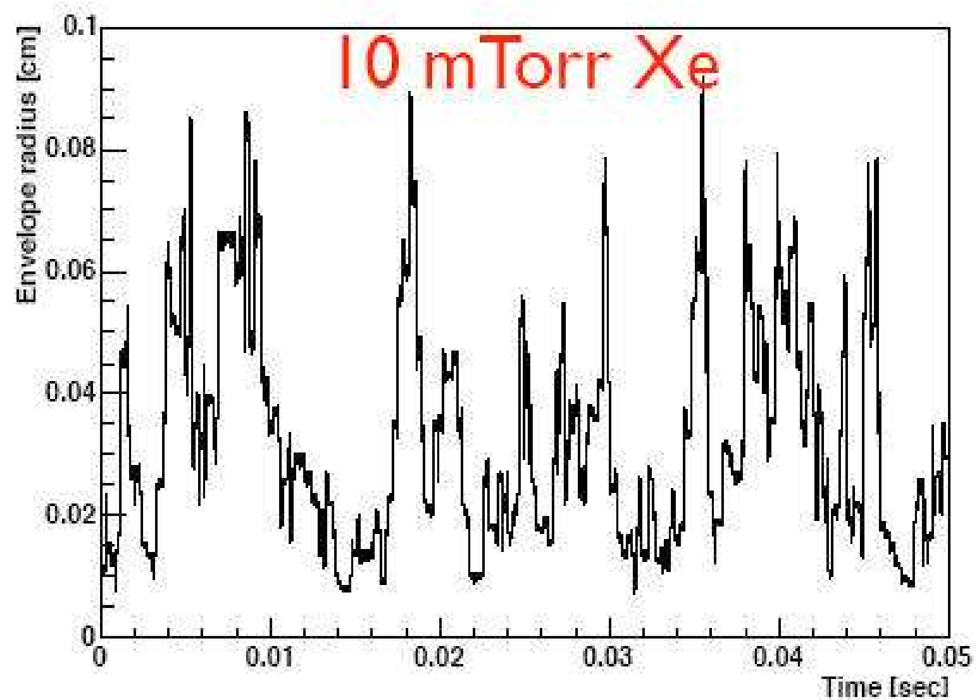


Similar phenomenon seen in krypton.

Simulated random walks in He and Xe

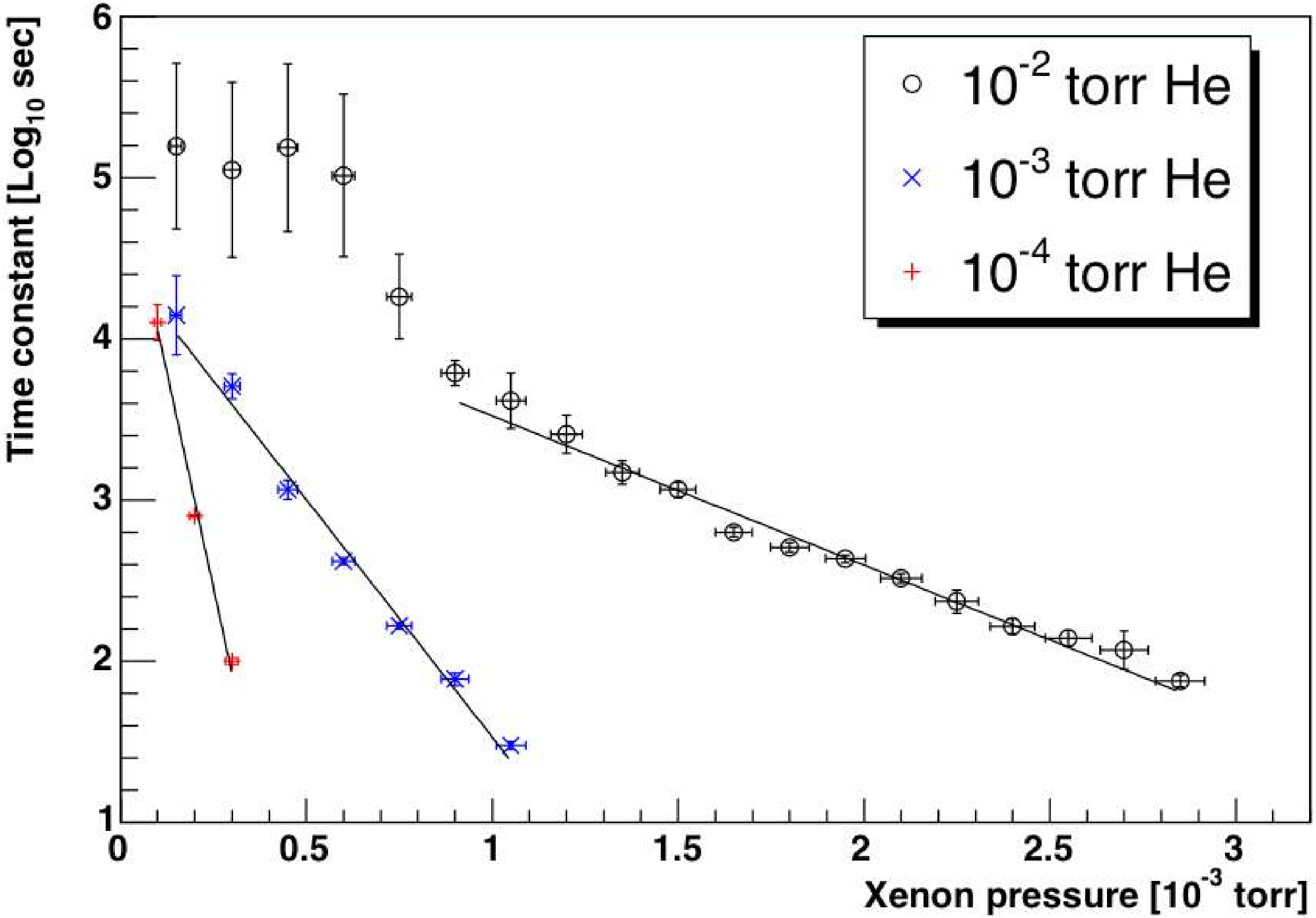


Collisions between Ba+ and Xe can transfer large momentum due to equal masses.



Simulation reproduces the observed trap unloading time with no free parameters.

Ba+ trapping lifetime depends on He and Xe pressure



Ba+ can be trapped for several days with
He pressure ~ 10^{-2} torr and Xe pressure < 10^{-3} torr

Lessons from EXO spectroscopy work

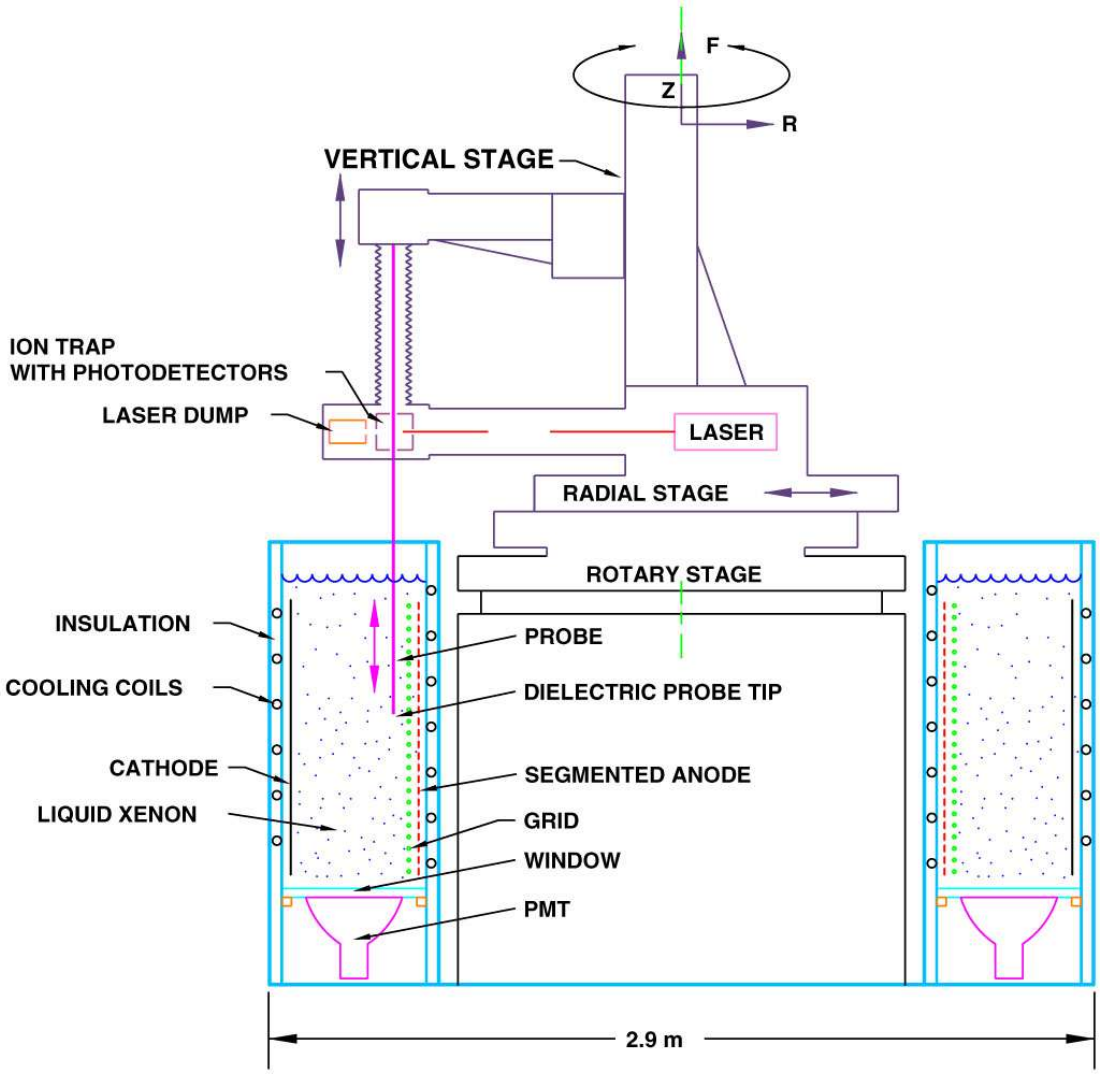
- Single Ba+ ions can be trapped and observed with good signal to noise.
- Helium buffer gas improves trap stability, make Ba+ identification easier.
- Xe gas can be present at low pressures.
- EXO will need differential and/or cryo-pumping to reduce Xe pressure in the trap to acceptable level.

Liquid Xenon EXO conceptual design

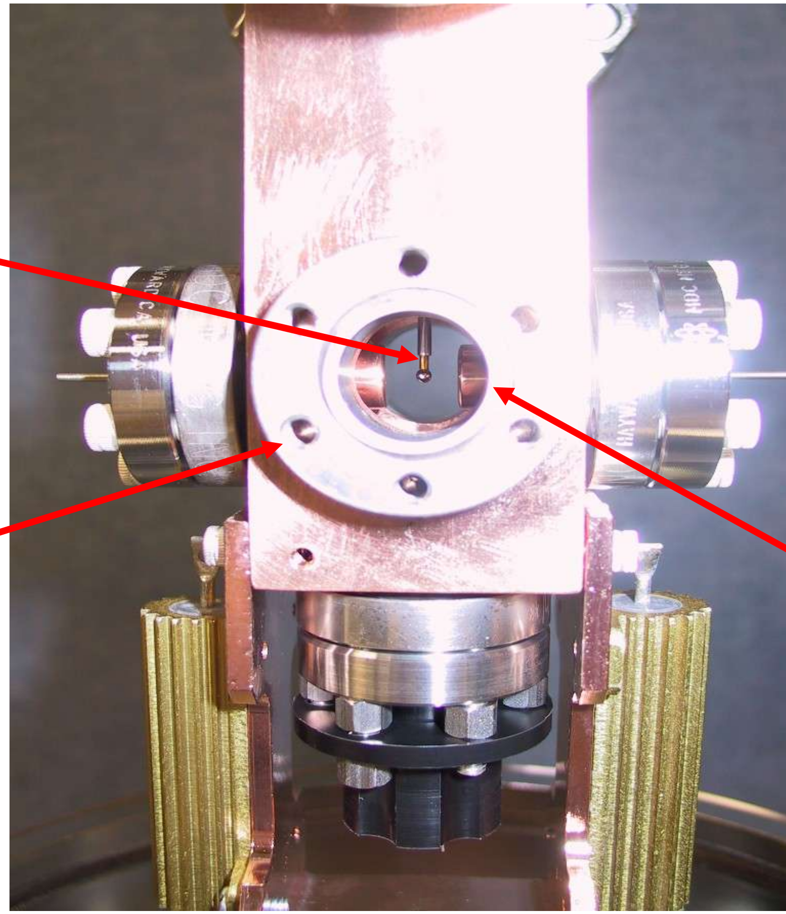
- Use ionization and scintillation light in the TPC to determine the event location, and to do precise calorimetry.

- Extract the Barium ion from the event location with an electrostatic probe.

- Deliver the Barium to a laser system for Ba^{136} identification.



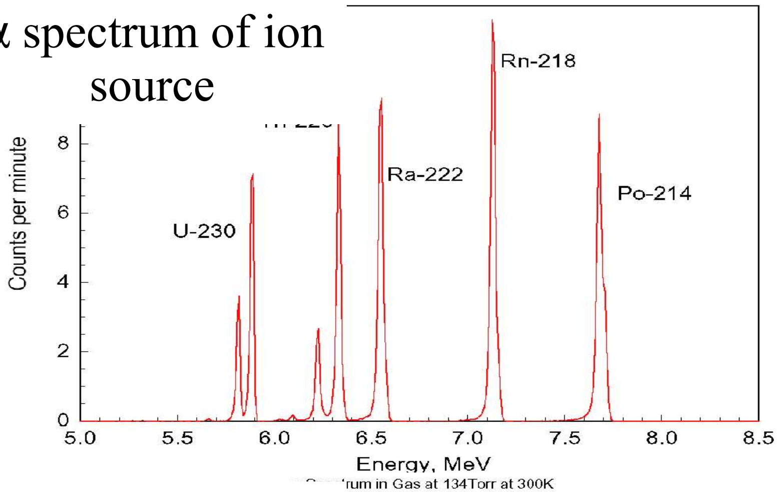
Prototype electrostatic probe to study ion grabbing and release



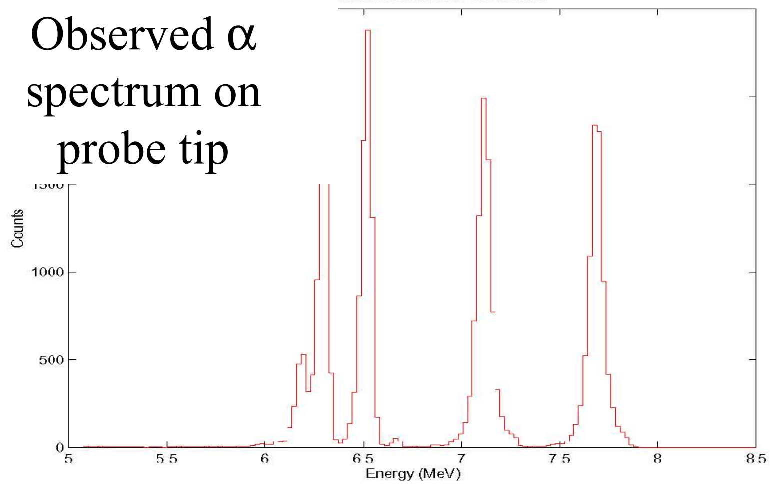
Probe collects Th+ in liquid xenon,
then we observe them with an α counter above the liquid surface.

Th+ grabbing in Liquid Xe works

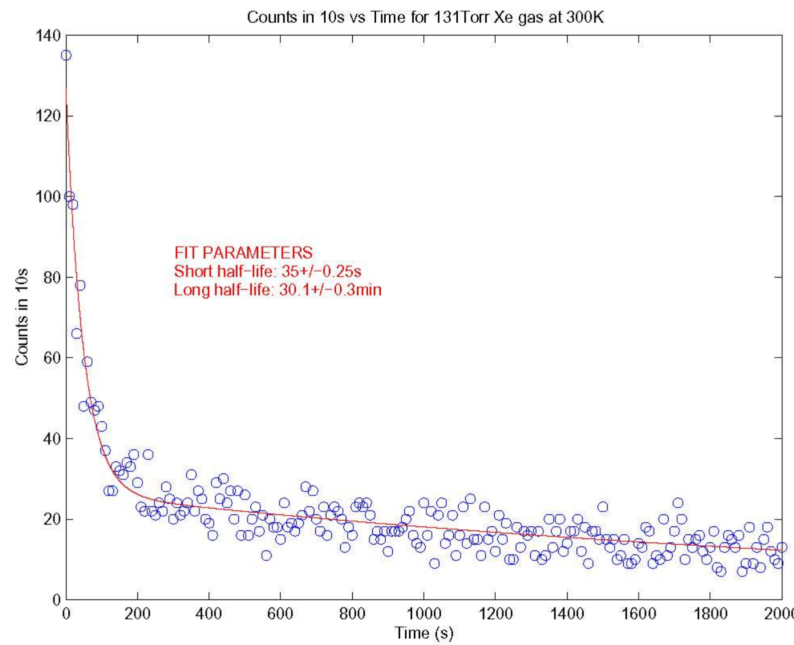
α spectrum of ion source



Observed α spectrum on probe tip



α decay lifetimes on probe tip agree with expectation for ^{226}Th and ^{222}Ra

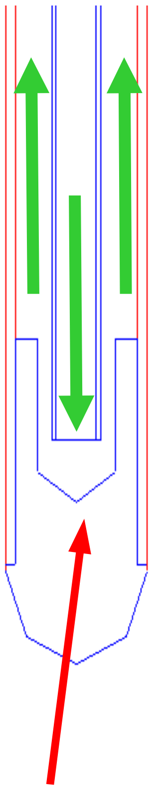


Also: Th ion mobility in LXe measured:

$$\mu = 0.24 \pm 0.02 \frac{cm^2}{kV \cdot s}$$

Ion release: cold probe

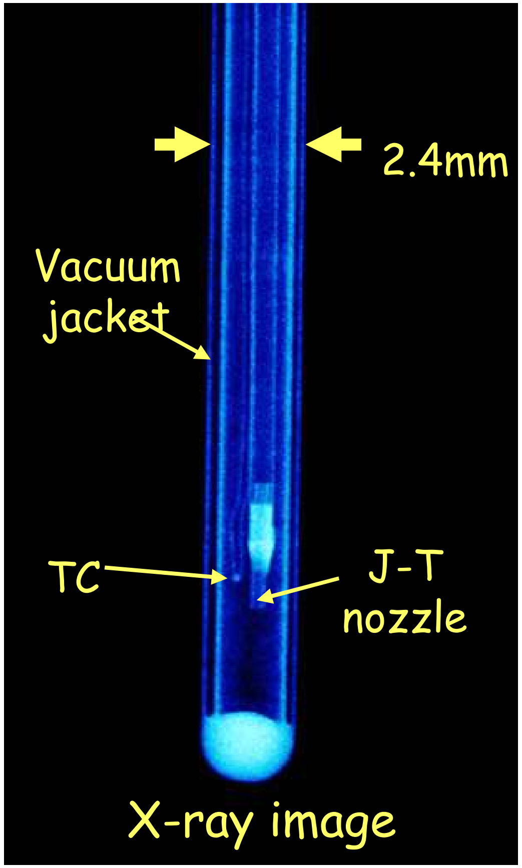
Capture ion in xenon ice layer,
then melt the ice to deliver ion to trap.

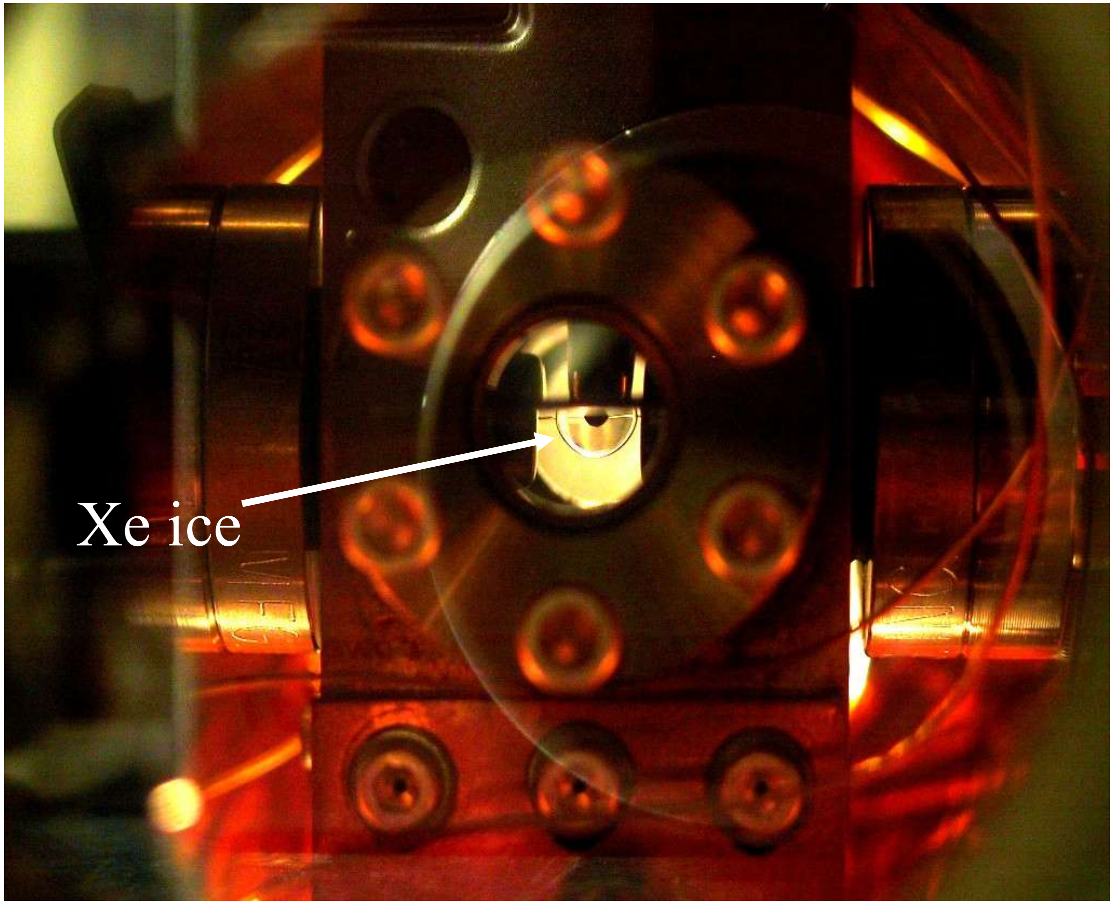


High pressure Ar
cools tip through
Joule-Thomson effect

Endocare medical cryoprobe

Cold probe prototype shows promise

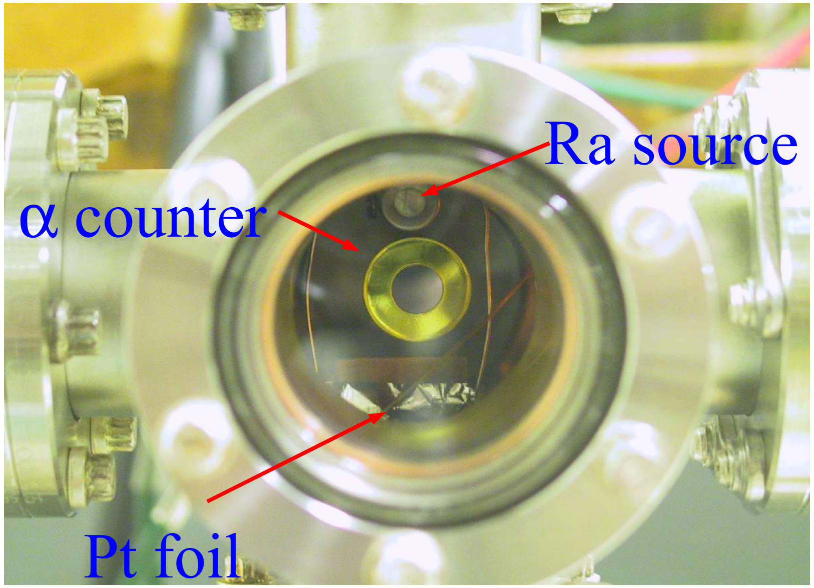




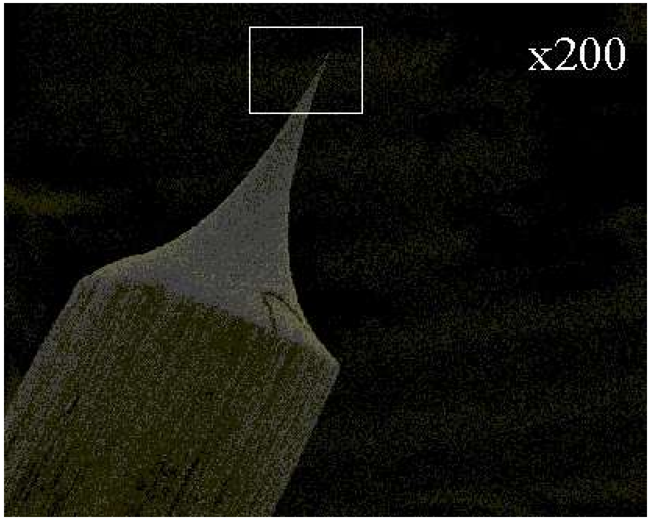
Cold probe has demonstrated ion capture in ice and release through melting.

Need to demonstrate that ice formation and melting can be precisely controlled, and that ion can be loaded into the trap.

Other probe technologies under development

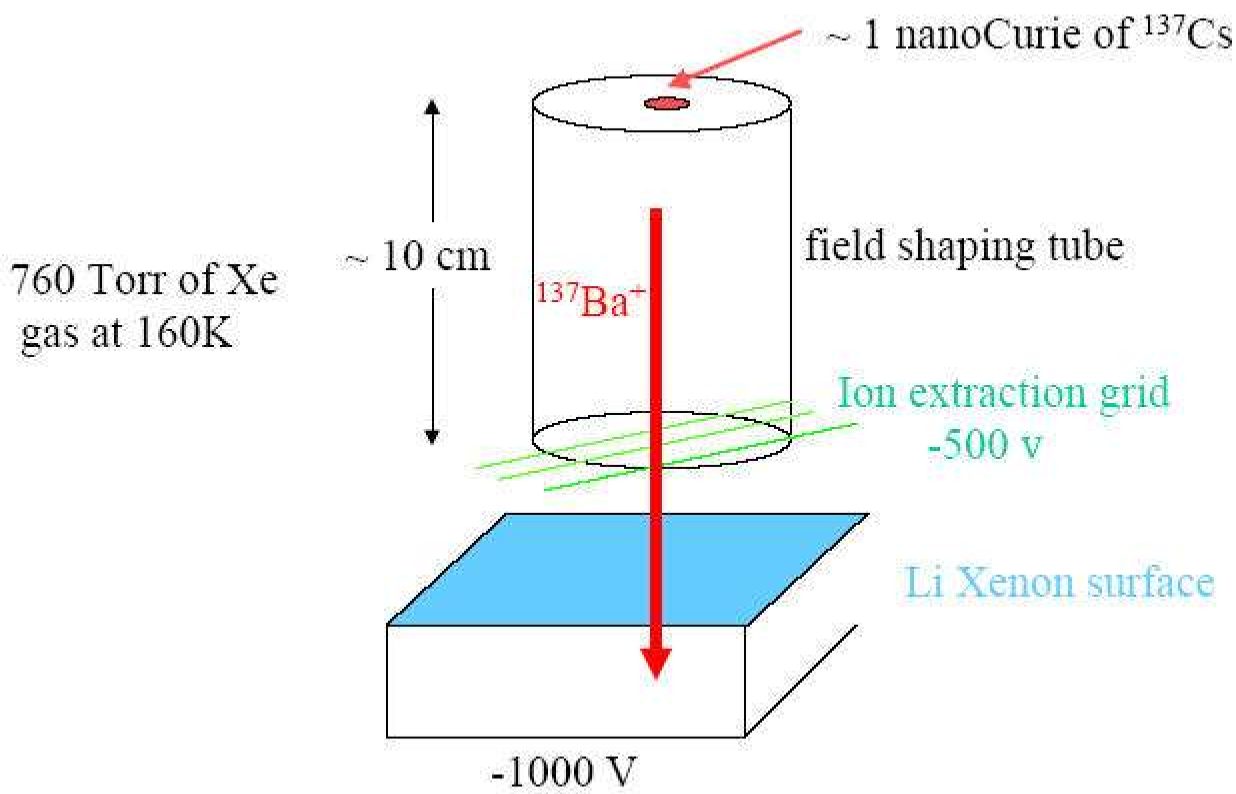


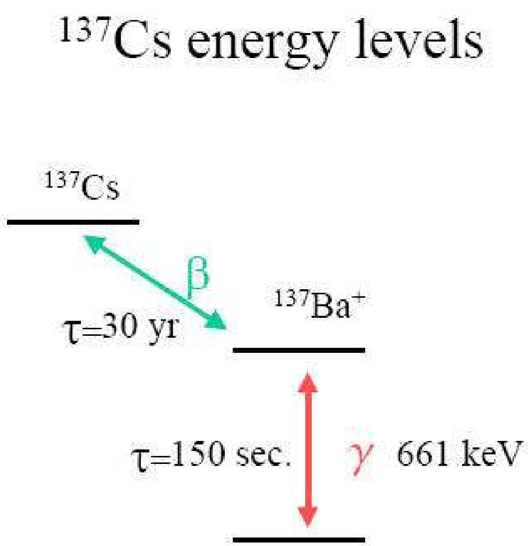
Hot probe: Ba+ ions should “boil” off a hot platinum surface. Experiments with Ra+ ions in progress.



Field emission: Tungsten tips with radius ~10 nm generate 100 MV/cm fields, enough to repel an ion from the surface. Ion release is well known, need to demonstrate operation in liquid xenon and ion trap.

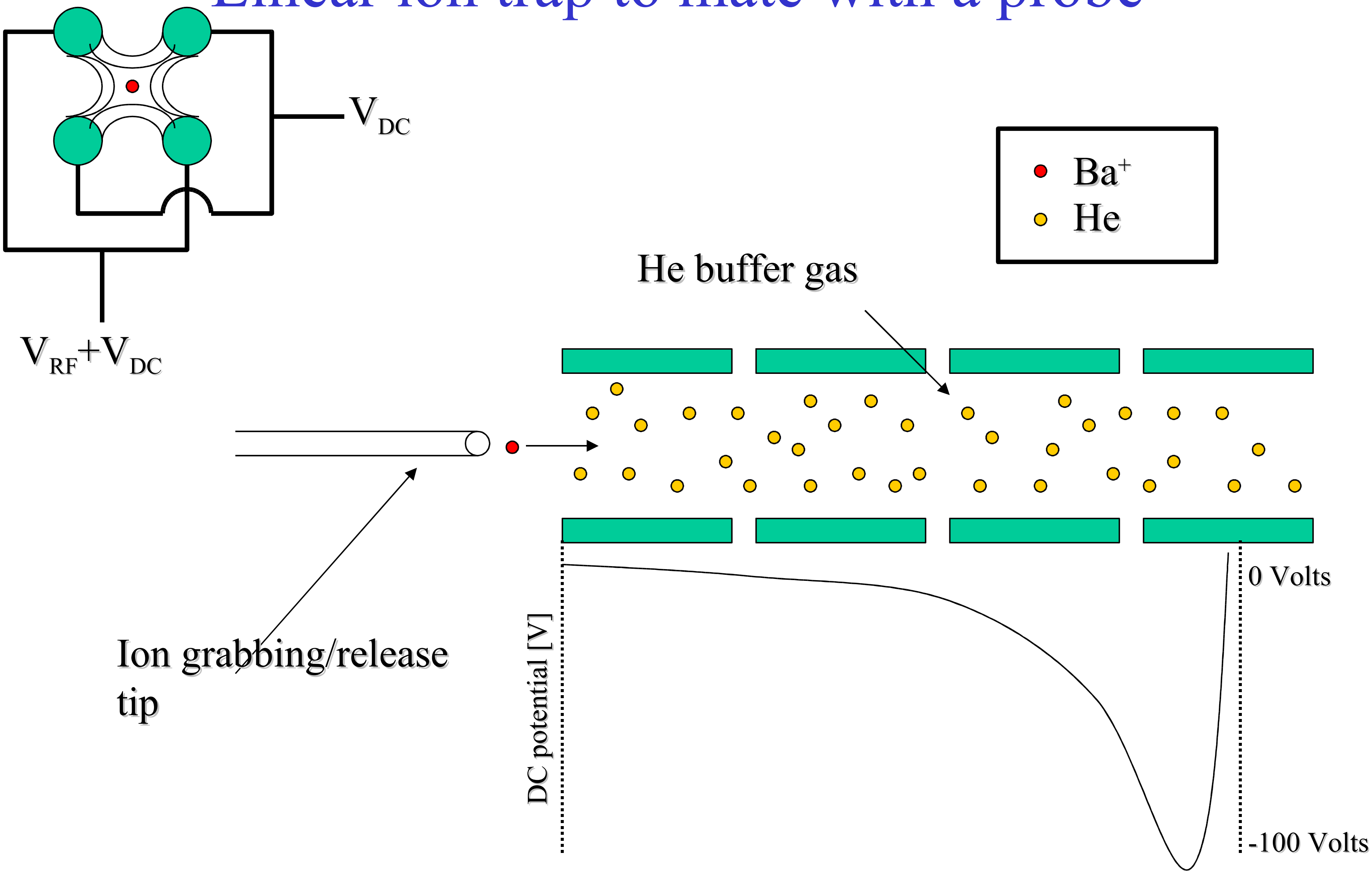
^{137}Cs vapor source of $^{137}Ba^{+}$ ions





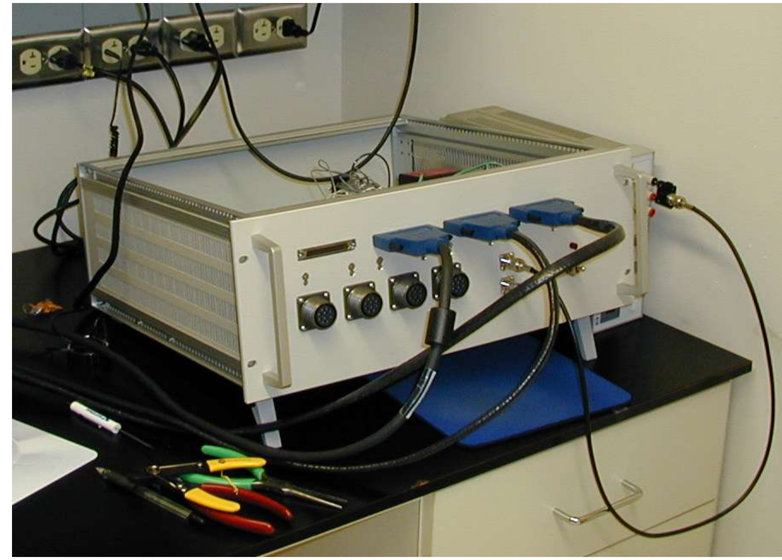
- CsCl evaporates from source at 500 C.
- ^{137}Cs β decay tags creation of ^{137}Ba+, which then drifts into the liquid xenon.
- Probe can grab ^{137}Ba+ in liquid xenon and release it into a trap.
- Observation of 661 keV γ measures the trap loading efficiency.
- Work in progress.

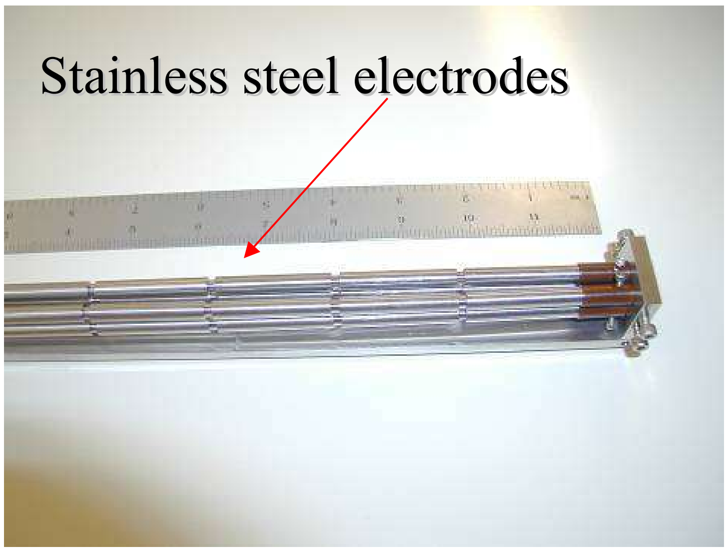
Linear ion trap to mate with a probe



Linear Trap Construction

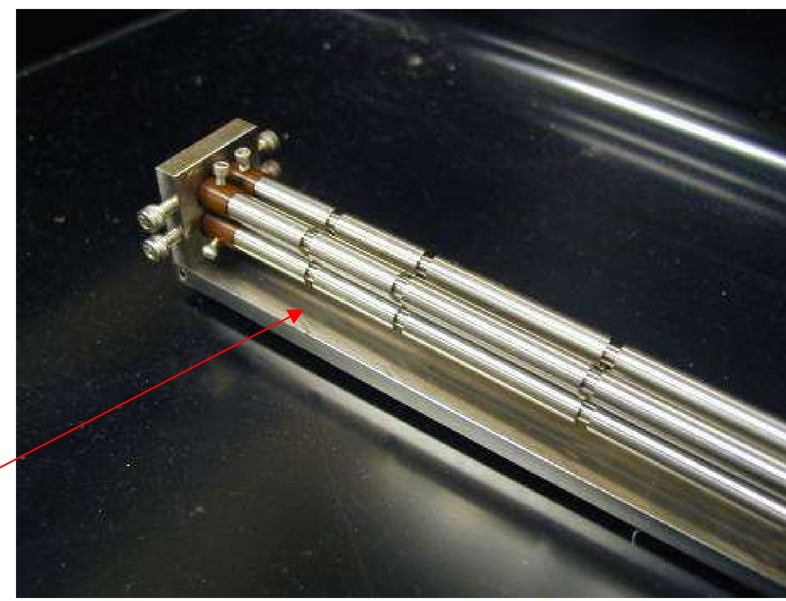
Full computer control of RF+DC on each electrode for ion transport



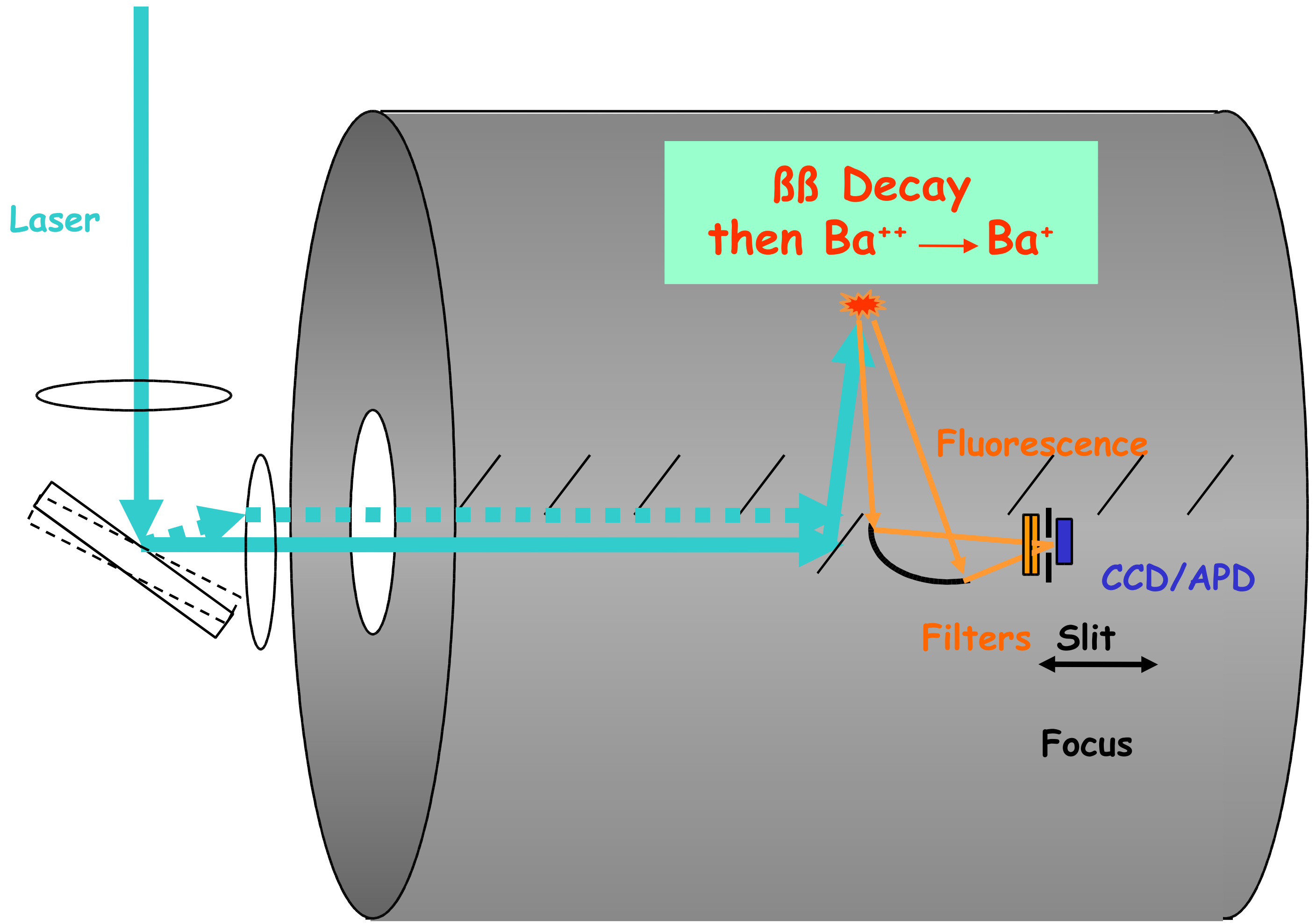


Constructed according to results of simulation including background gas damping

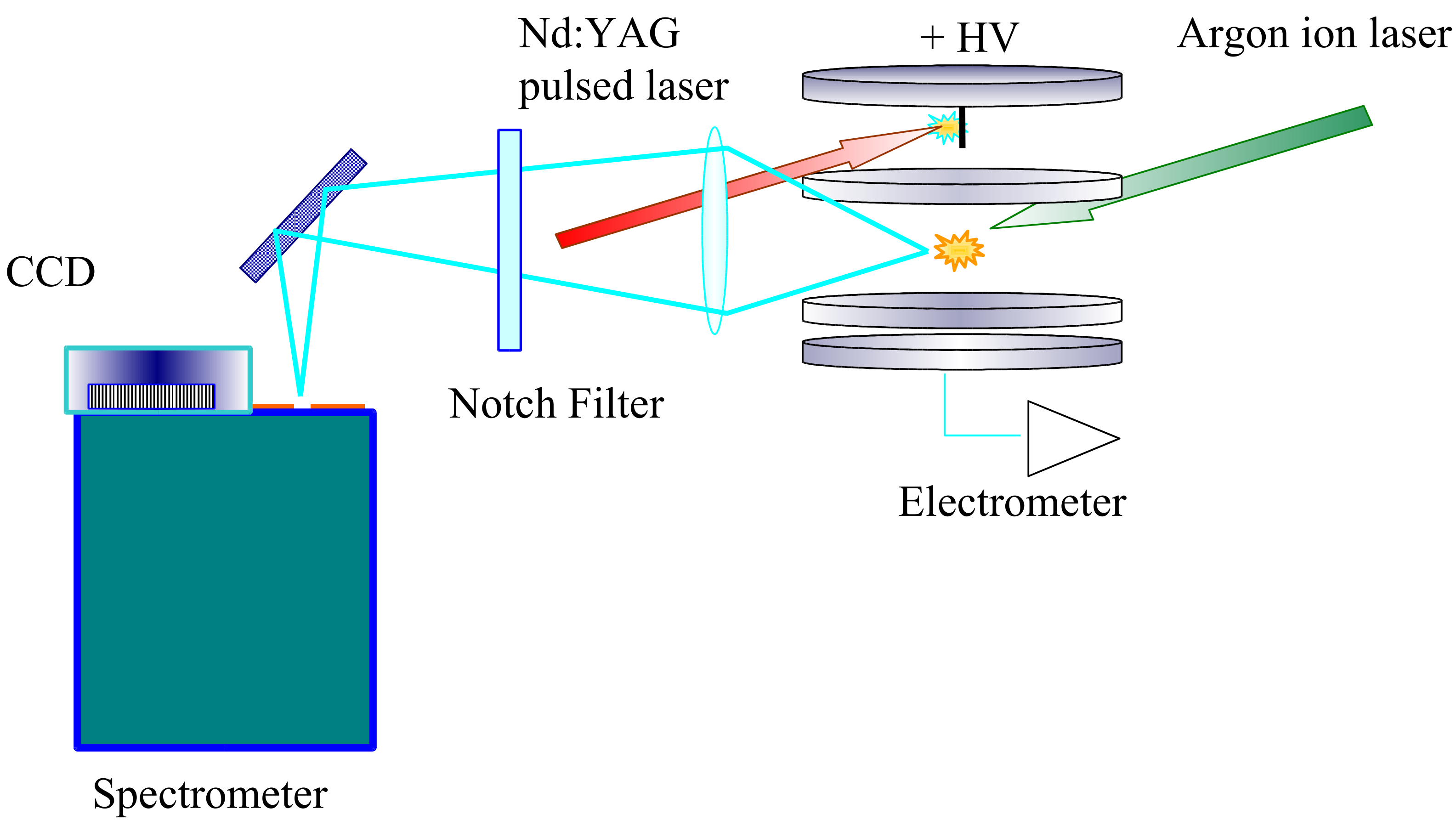
Observation region



Alternative barium tagging schemes under study:
Direct tagging in liquid xenon.



Apparatus for Ba^+ fluorescence spectra

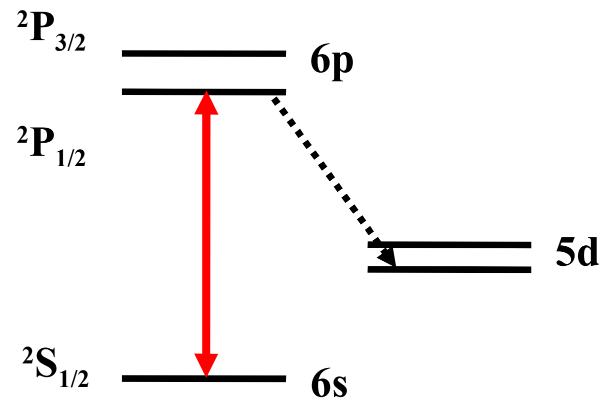


Whole fluorescence spectrum can be measured in one laser shot

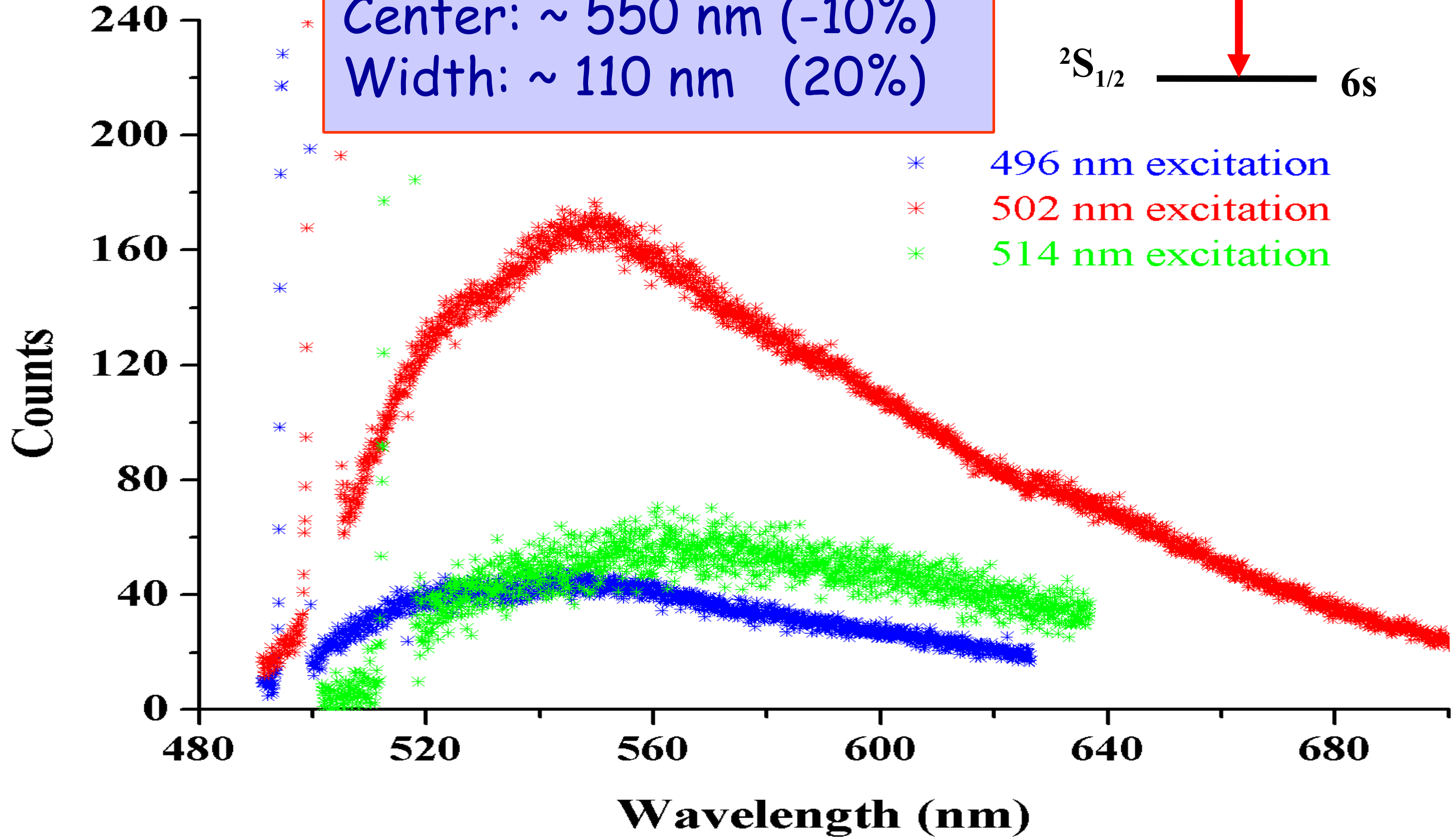
Ba^+ fluorescence spectra in LXe

$P_{1/2} \rightarrow S_{1/2}$ emission

$P \rightarrow D$ emission ???



Center: ~ 550 nm (-10%)
Width: ~ 110 nm (20%)



Is barium tagging truly background free?

- $\beta\beta2\nu$: Creates Ba+ in liquid xenon, but TPC electric field sweeps these out.

- Environmental barium in liquid xenon: Should be neutral, so that electrostatic probe will not grab it.

- Random barium on probe tip: Possible problem for hot probe and field emission probe. Not an issue for cold probe.

- ^{136}Cs β decay to ^{136}Ba+: ^{136}Cs is produced by (p,n) and (ν_e,e-) reactions on ^{136}Xe, but multi-gamma signature makes these decays easy to reject.

Sensitivity of ton-scale EXO with barium tagging

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90% CL)	Majorana mass (meV) QRPA‡	(NSM)#
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	33	(95)
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	7.3	(21)

One-ton scenario sensitive to inverted hierarchy
Ten-ton scenario sensitive to normal hierarchy.

Conclusions

Barium tagging remains an ambitious but potentially rewarding method for eliminating radioactive backgrounds to ββ0ν.

R&D work has found no show-stoppers yet. Many pieces of the puzzle now have experimental proof-of-principle.

Ba+ spectroscopy in Xe and He gas is now understood.

Ion release from the probe is the primary missing element to a liquid xenon EXO.

A $^{137}Ba^+$ source is being developed to measure the efficiency of transferring ions from the liquid xenon to the trap.

Other schemes which do not use a probe are under investigation.

EXO-200 and barium tag R&D expected to come together in ~3 years in a proposal for a ton scale ββ0ν experiment.

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