Barium Tagging in Solid Xenon for nEXO

Tim Walton

PhD Defense

2015-12-08

committee:

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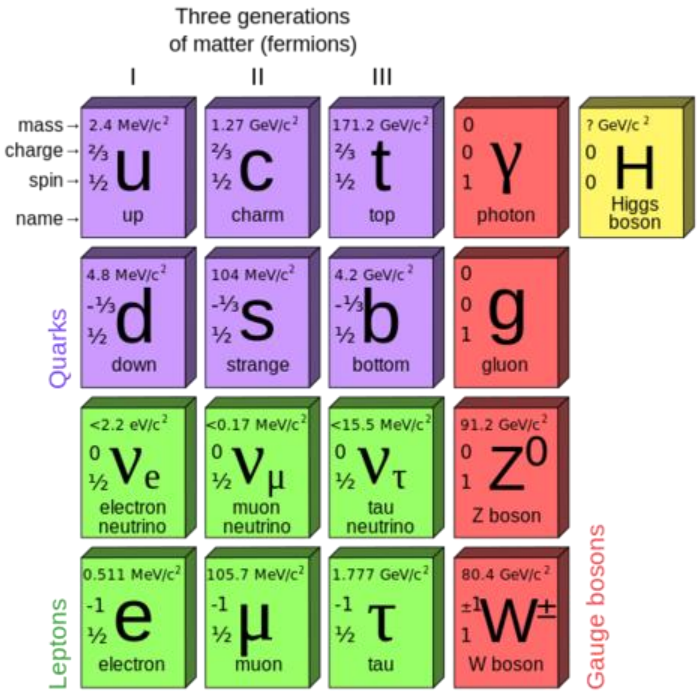
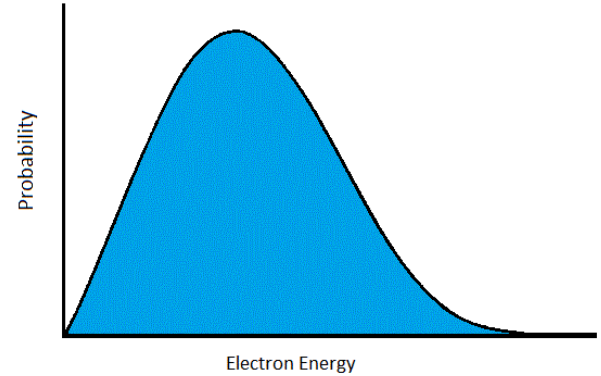
Outline

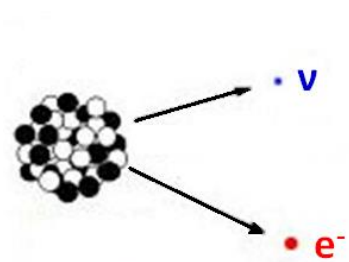
- Neutrinos and neutrinoless double beta decay
- EXO-200 experiment
- nEXO and barium tagging
- Barium tagging in solid xenon (SXe):
  - Part 1: Spectroscopy of Ba and Ba+ in SXe
    - Excitation/emission of Ba in SXe
    - Temperature dependence
    - Bleaching
    - Candidate Ba^+ lines
  - Part 2: Imaging Ba atoms in SXe in focused laser
    - Images of ~10^3 atoms w/ 577- and 591-nm lines
    - Single-atom level imaging w/ 619-nm line

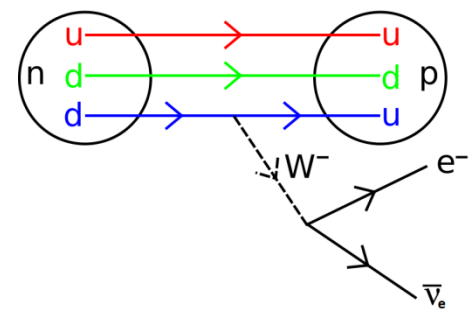
Neutrinos



First indications: **beta decay spectrum**







- Interact only via Weak Force (and Gravity)
- Very small mass

Neutrino oscillation

Neutrinos interact as flavor states $|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle$.

Flavor basis is related to the mass basis $|\nu_1\rangle, |\nu_2\rangle, |\nu_3\rangle$ by PMNS matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, and δ, α_1, α_2 are CP-violating phases.

With $m_\nu \ll p_\nu$, time-evolution is determined by mass squared differences $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{31}^2 = m_3^2 - m_1^2$.

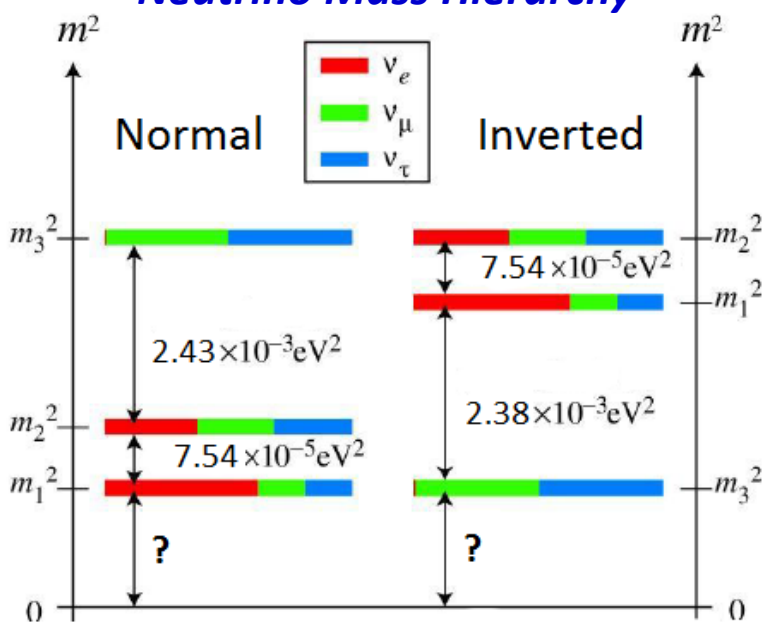
Neutrino oscillation requires non-zero mass squared differences.

Neutrino mixing measurements given Normal (Inverted) Hierarchy:

Parameter	Measurement ($\pm 1\sigma$)
Δm^2_{21}	$7.54^{+0.26}_{-0.22}\ 10^{-5}\ \mathrm{eV}^2$
$\lvert\Delta m^2\rvert$	$2.43 \pm 0.06\ (2.38 \pm 0.06)\ 10^{-3}\ \mathrm{eV}^2$
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$	$0.437^{+0.033}_{-0.023}\ (0.455^{+0.039}_{-0.031})$
$\sin^2\theta_{13}$	$0.0234^{+0.0020}_{-0.0019}\ (0.0240^{+0.0019}_{-0.0022})$
δ/π (2σ range)	$1.39^{+0.38}_{-0.27}\ (1.31^{+0.29}_{-0.33})$

2012 Review by K. Nakamura, U. Tokyo, S.T. Petcov

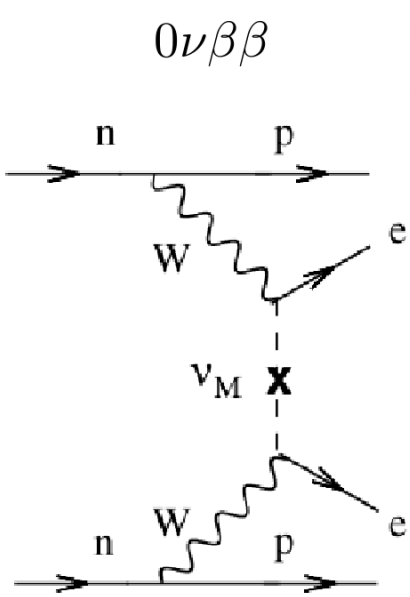
Neutrino Mass Hierarchy



Much yet to learn…

- What is the fundamental nature of neutrinos?
  (How is their mass generated, and why is it so small? Are they Majorana or Dirac particles?)
- What is the absolute mass scale of the neutrinos?
- Do they violate CP and/or Lepton Number conservation?

A method: *search for Neutrinoless Double Beta Decay* (0νββ)



Observation of this decay would:

- prove that neutrinos are Majorana fermions
- measure absolute neutrino mass in the form of effective electron-neutrino mass:

$$\boxed{\langle m_\nu \rangle^2 = [\ \boldsymbol{T^{0\nu}_{1/2}}\ G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ ]^{-1}}$$

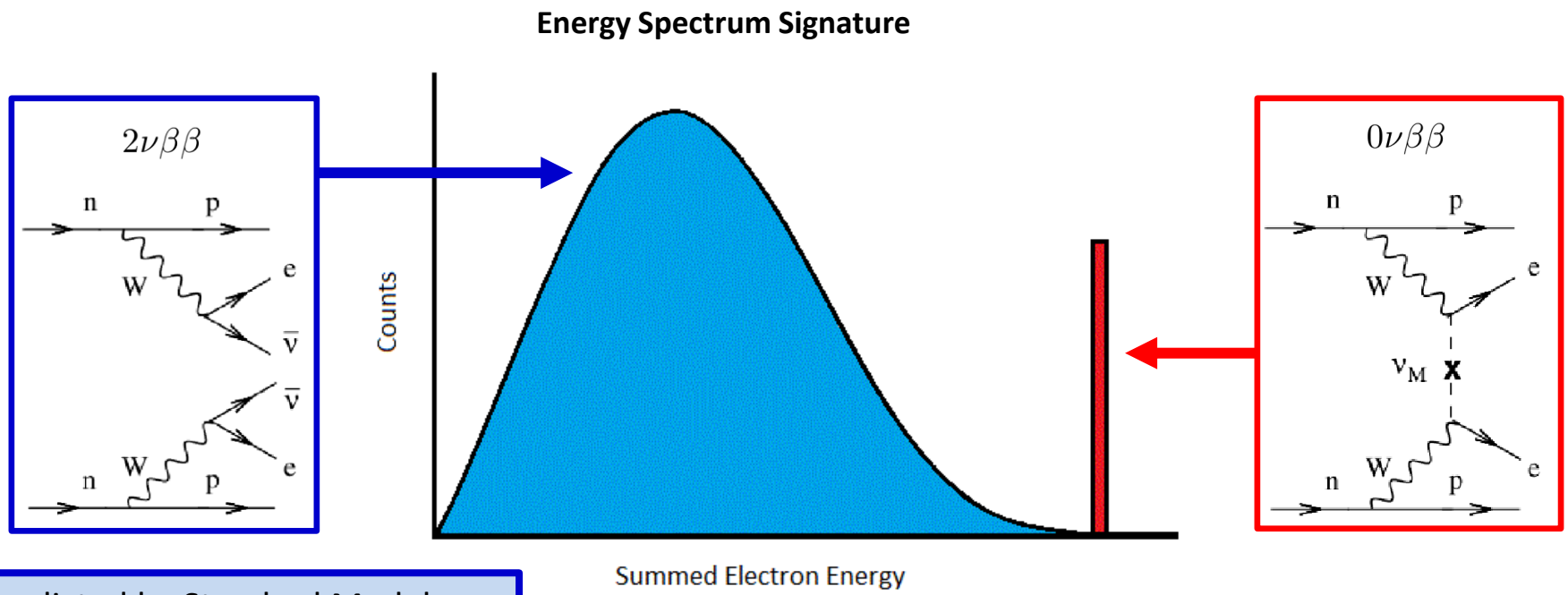
where $\langle m_\nu \rangle = \sum_i U_{ei}{}^2 m_i$

$G^{0\nu}$ is a known phase factor

$M^{0\nu}$ is the nuclear matrix element for 0νββ

$\boldsymbol{T^{0\nu}_{1/2}}$ is the half-life of 0νββ

Search for 0νββ



- Predicted by Standard Model
- Observed in many isotopes, including Xe^{136} in EXO and KamLAND ZEN

Very rare decay

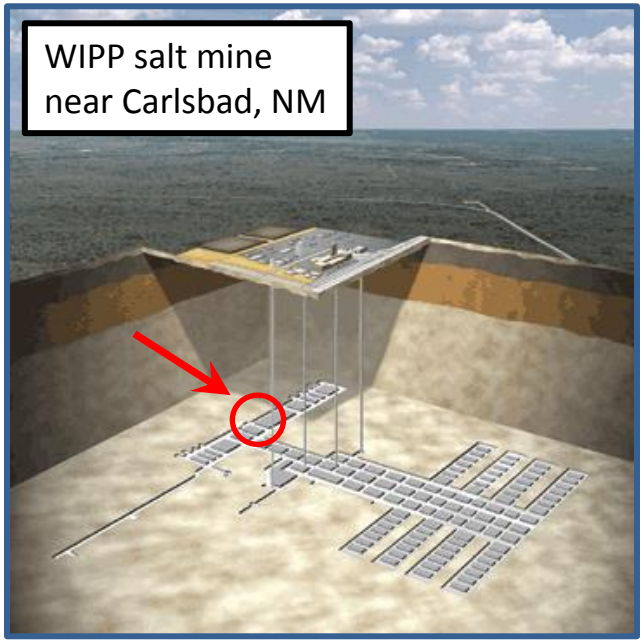
➡ ***Very* low backgrounds are required**

EXO-200:

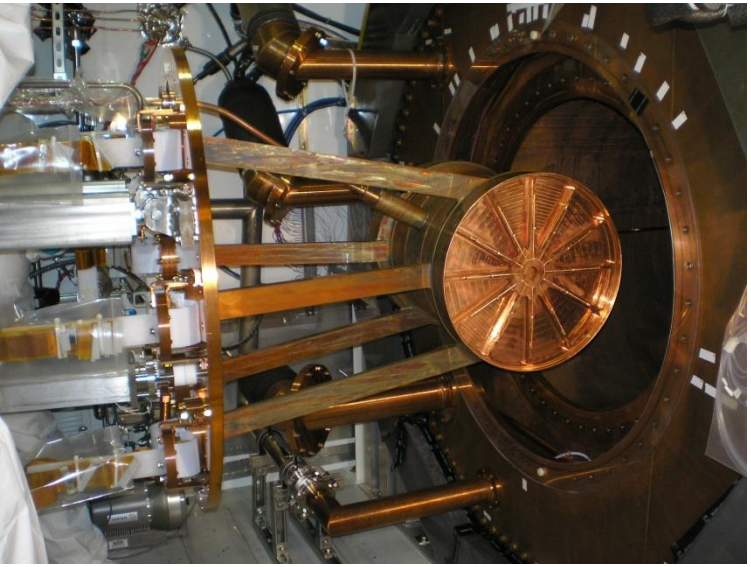
First phase of Enriched Xenon Observatory, for the search for 0νββ mode of

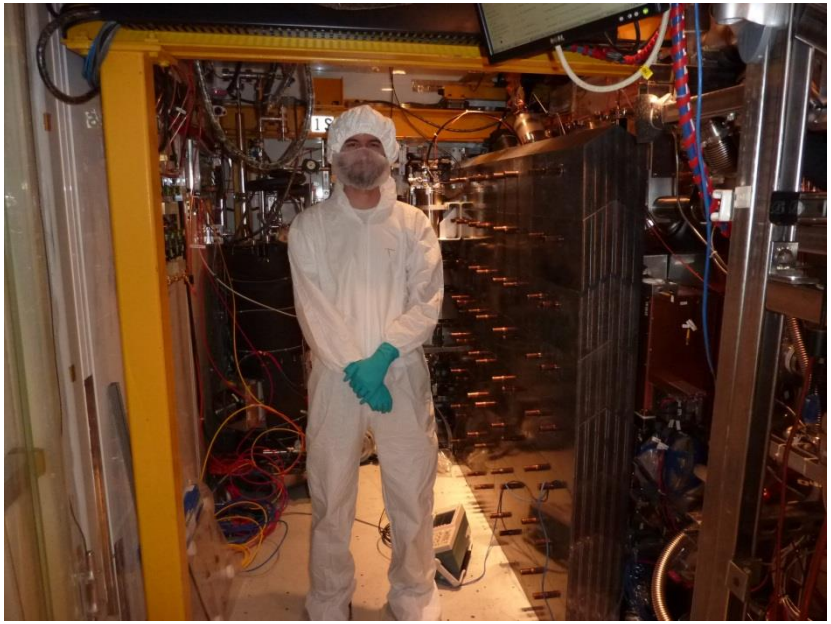
$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

- ~200-kg. liquid Xe (LXe) time projection chamber (TPC), enriched to ~80.6% Xe^{136}
- operates in class 100 cleanroom, 2,150 ft. underground



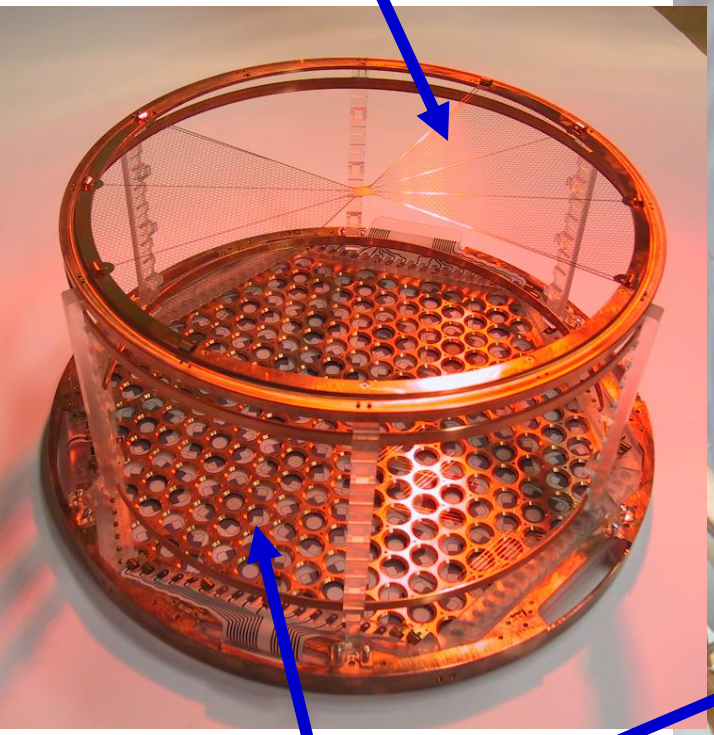
TPC installation into copper cryostat

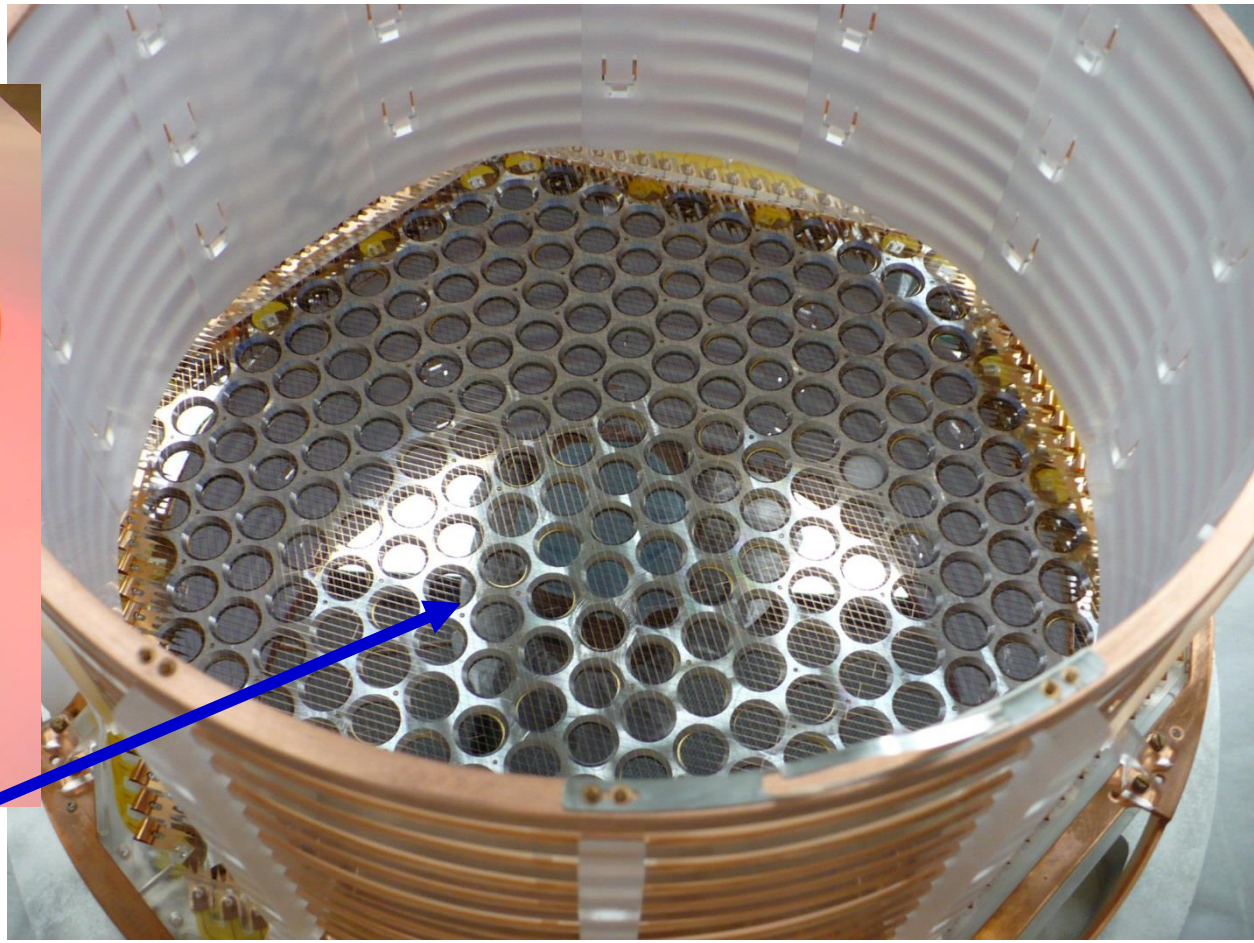




EXO-200 Time Projection Chamber

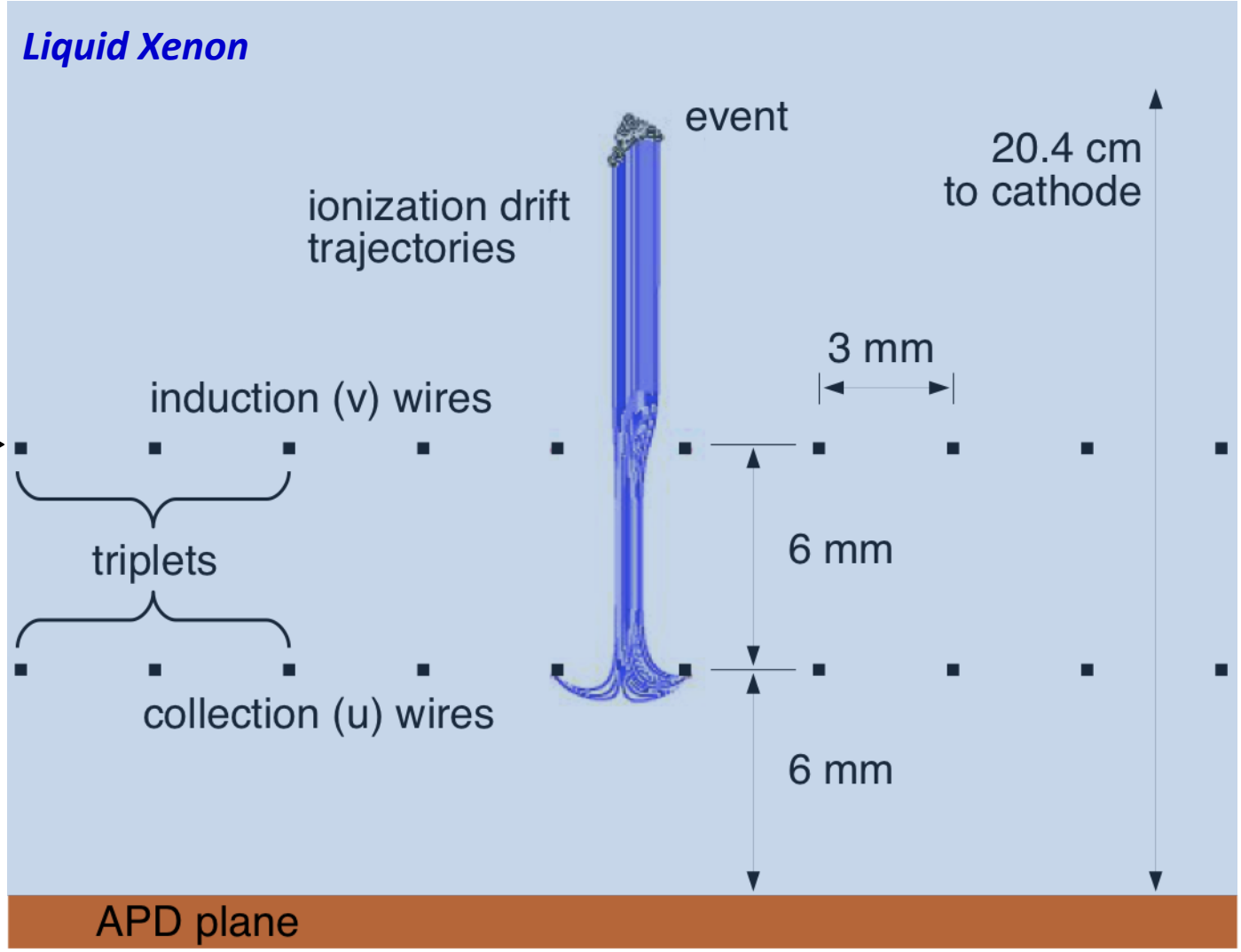
Cathode grid





Detection plane for charge (wires) and scintillation (APDs) from decay events in the LXe

EXO-200 Time Projection Chamber



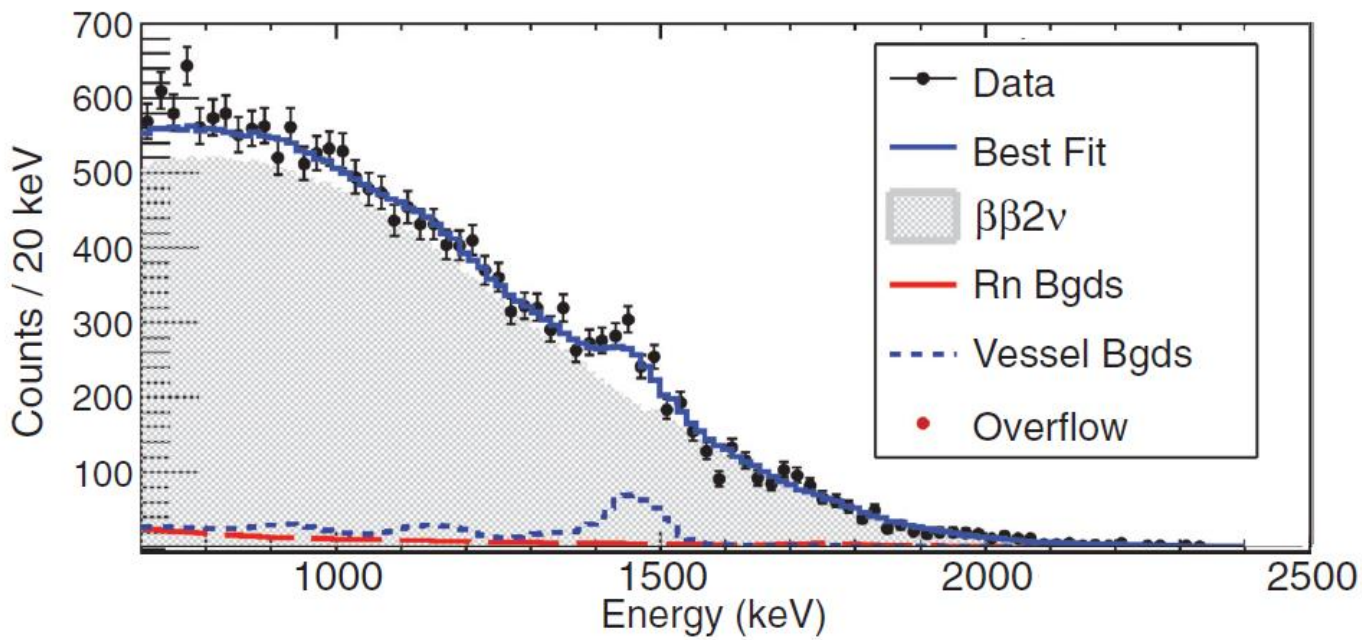
Cross-hatched "u" and "v" wires give x-y position, u-wires collect **ionized charge**

Avalanche Photo Diodes (APDs) for **scintillation light**

Drift time gives z-position

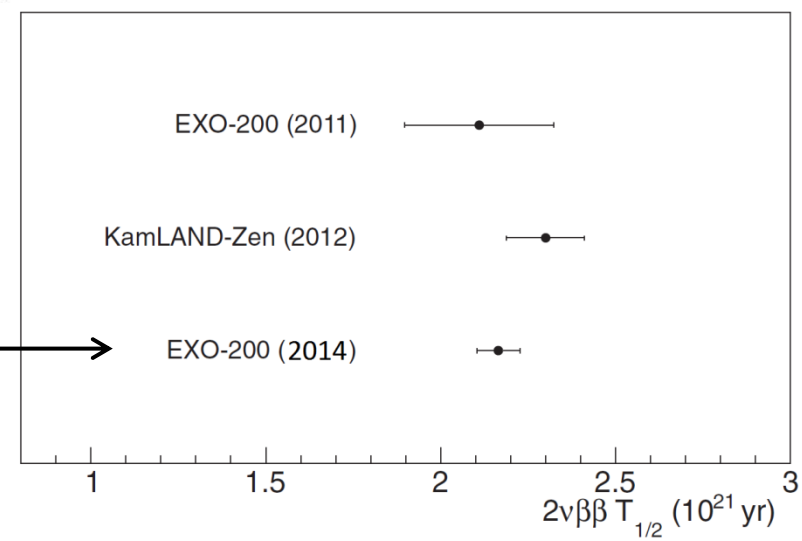
(time between scintillation and charge detection)

EXO-200 Results: 2νββ Measurement

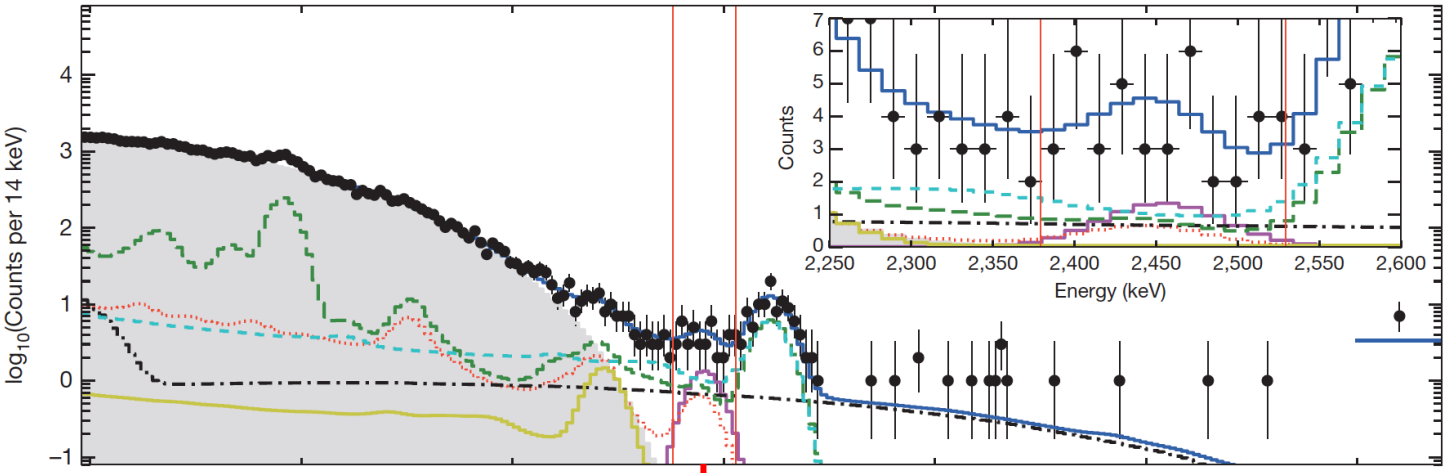


Phys. Rev. C **89**, 015502 (2014)

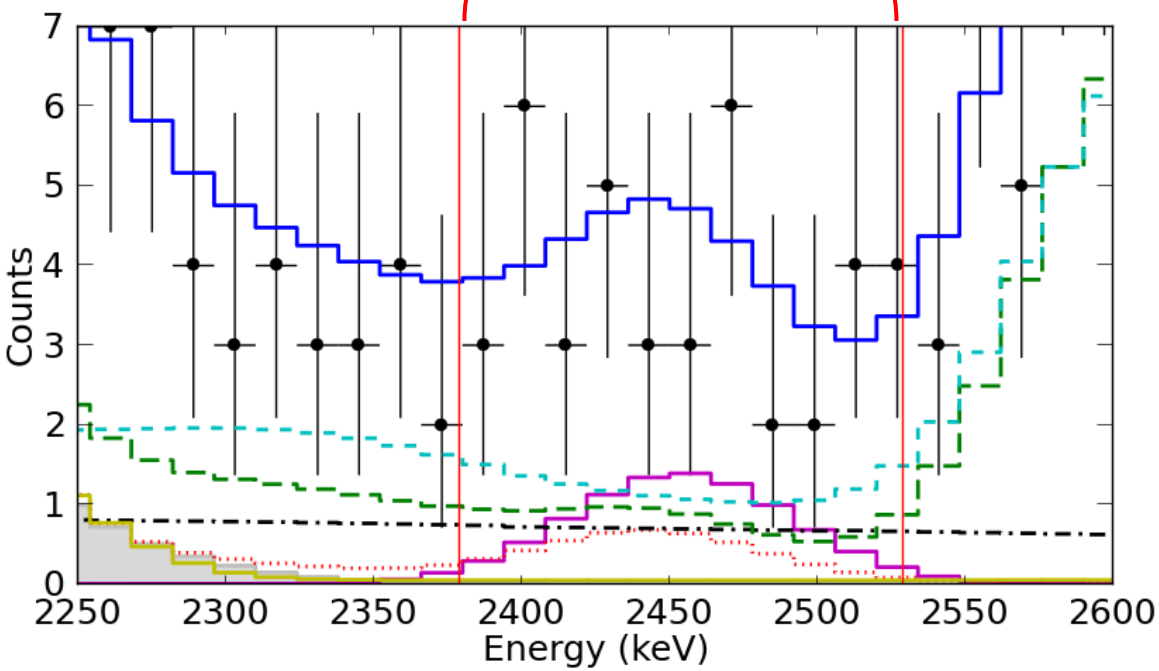
$T_{1/2}^{2\nu}$ = (2.165 ± 0.016 stat. ± 0.059 sys.)×10^{21} yr



EXO-200 Results: 0νββ Search



Zoom into ±2σ region of interest



Nature **510**, 229 (2014)

Events from Fit

Backgrounds	31.1
0νββ decay	9.9
Total	41.0

$T^{0\nu}_{1/2} >$ **1.1×10²⁵ yr (90% CL)**

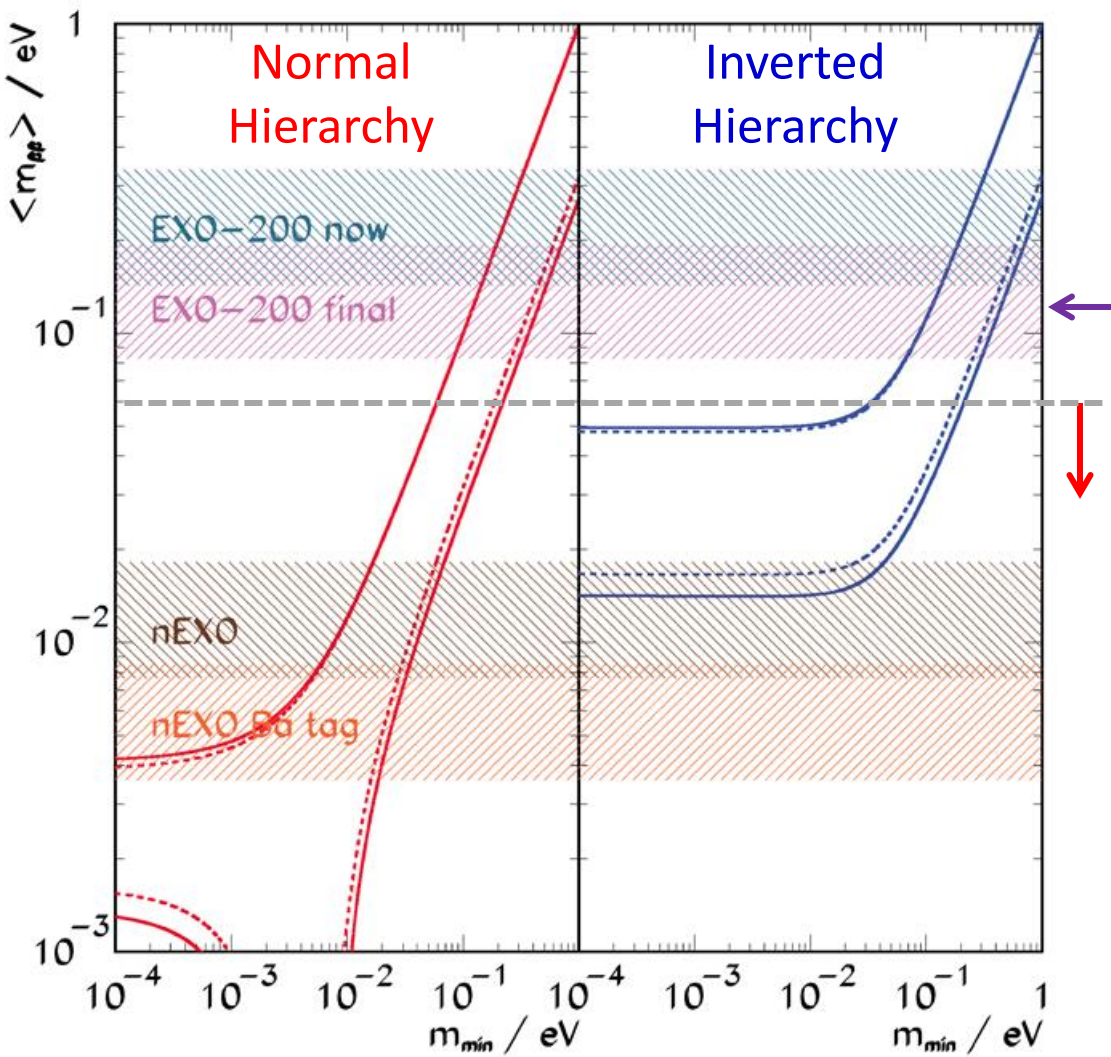
Effective Majorana neutrino mass:

$\langle m_\nu \rangle <$ **190-450 meV**

KamLAND ZEN:

$T^{0\nu}_{1/2} >$ **1.9×10²⁵ yr (90% CL)**

0νββ Sensitivity

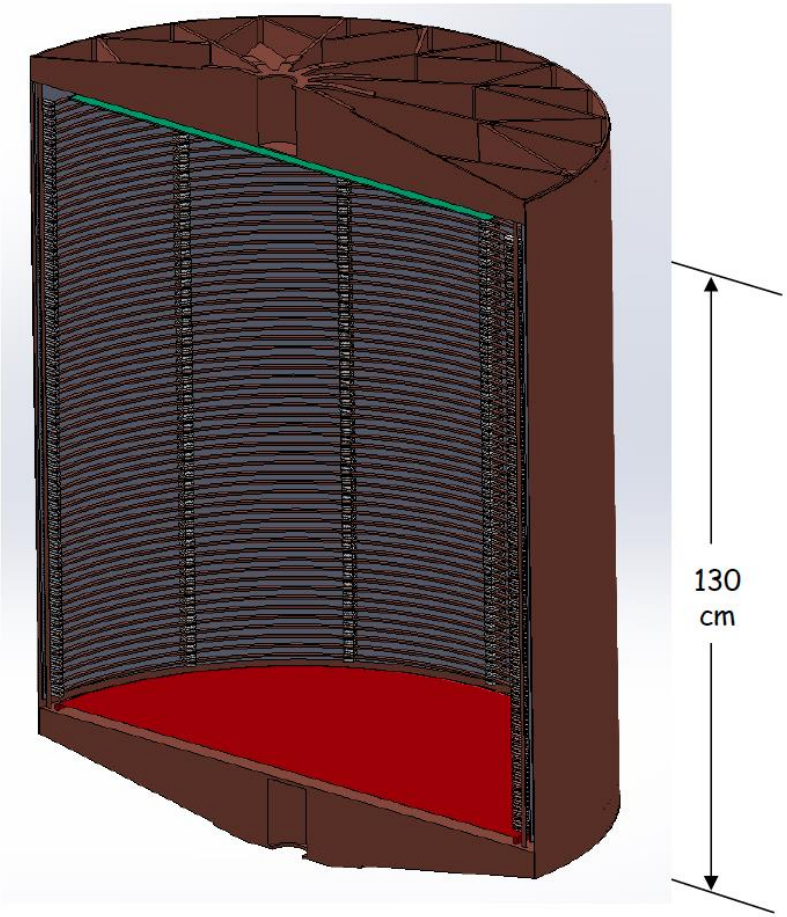


Final (2019) EXO-200 sensitivity in "Quasi-degenerate" region of neutrino masses.

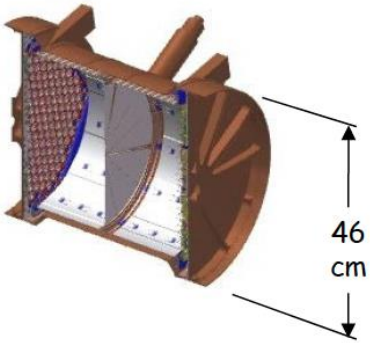
Measurement of $\langle m_\nu \rangle$ could determine mass hierarchy if below this region.
But need bigger detector…

nEXO

Successor to EXO-200: ~5-ton enriched LXe TPC
for more sensitive 0νββ search.



EXO-200: 170 kg enriched LXe



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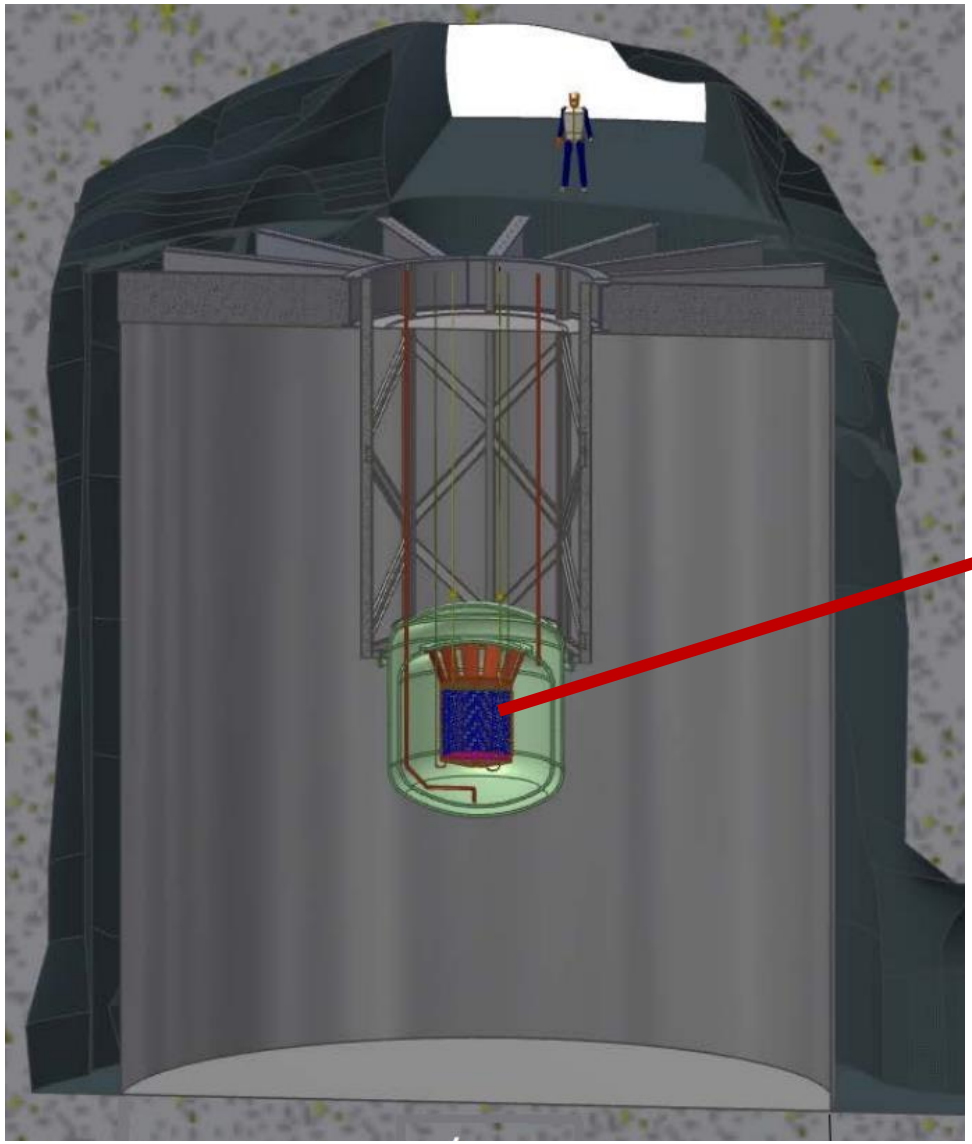
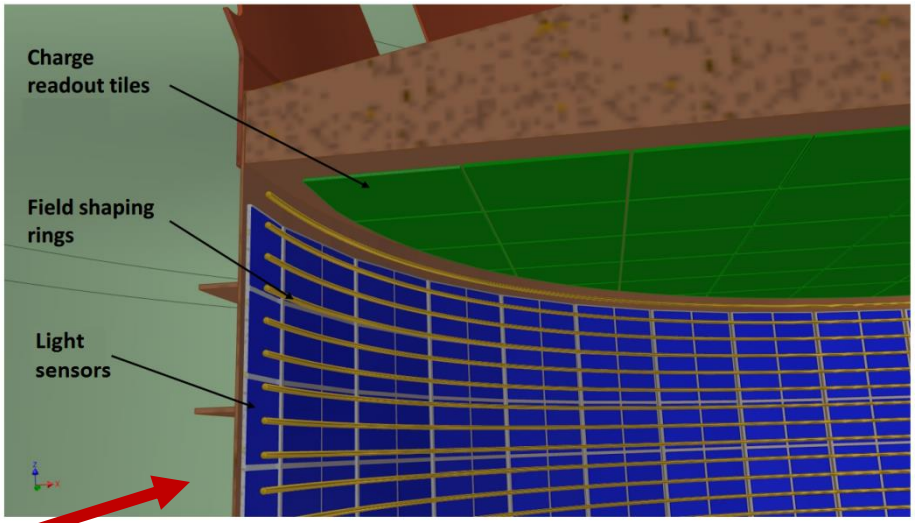
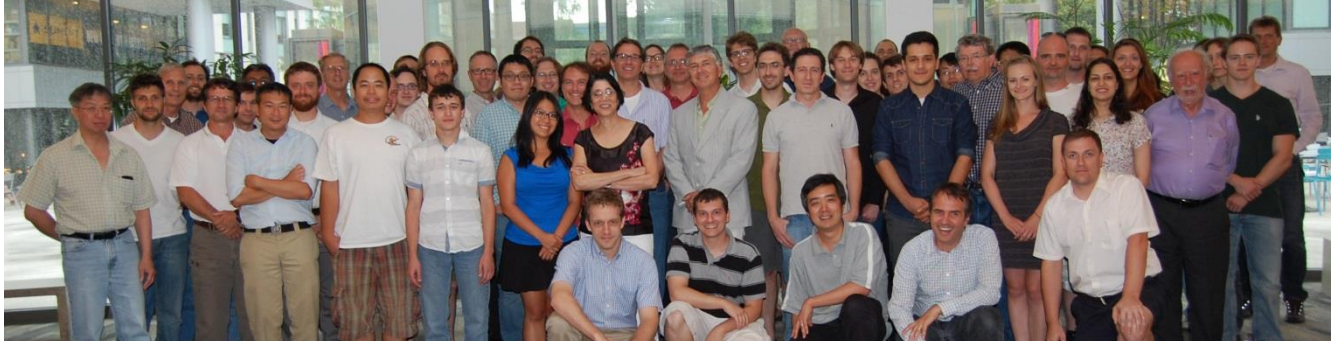




Ba tagging: identify barium daughter for complete background elimination

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

Will require grabbing/detecting a single Ba^{+} out of a macroscopic volume of LXe!



The nEXO Collaboration

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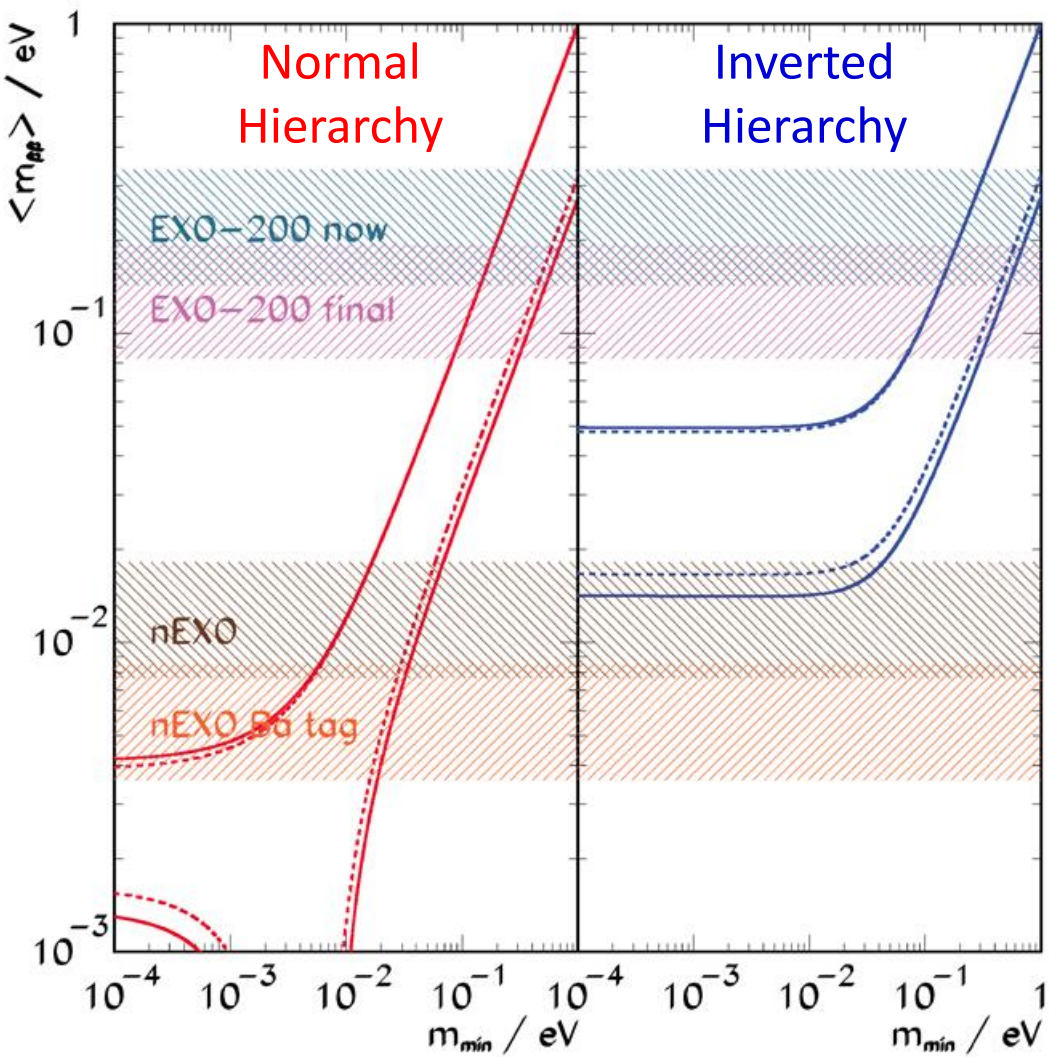
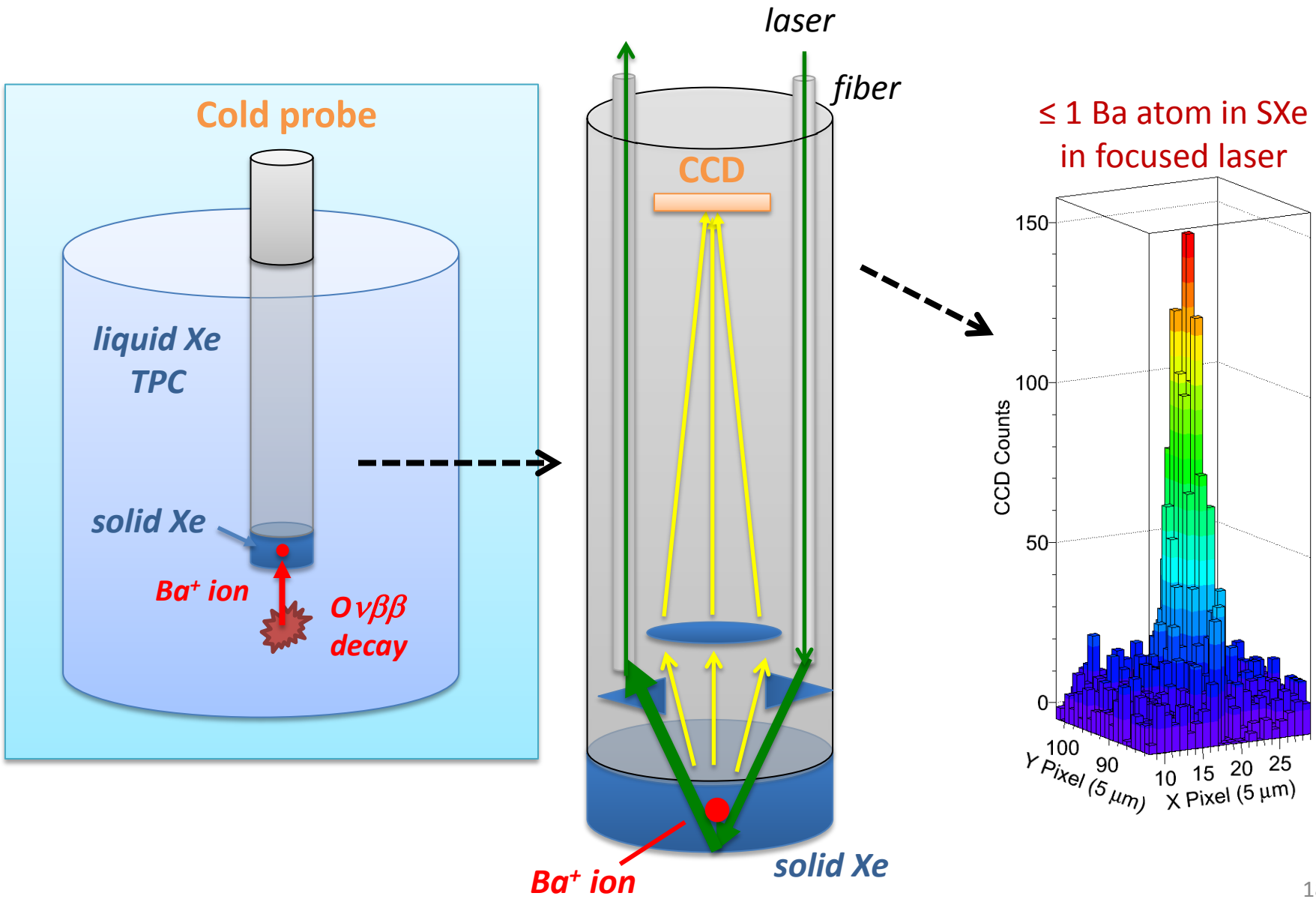
Technical University of Munich, Garching, Germany — P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, F Retière, V Strickland

0νββ Sensitivity



nEXO will probe entire Inverted Hierarchy, and well into Normal Hierarchy with Ba tagging.

Barium Tagging in Solid Xenon



Barium Tagging in Solid Xenon

Requires:

- Position of 2β decay known (TPC)
- Understanding of Ba/Ba^+ fluorescence in solid xenon
- Detection sensitivity at single atom/ion level

Barium Tagging in Solid Xenon

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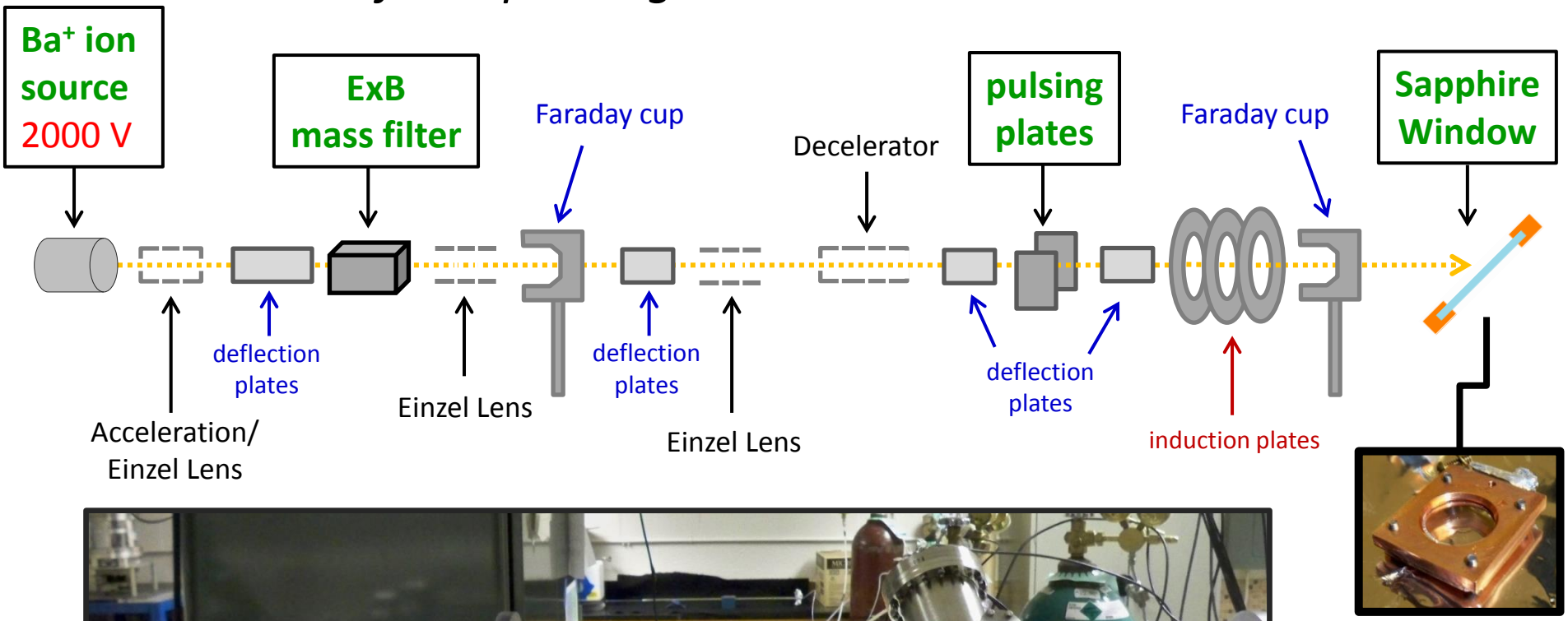
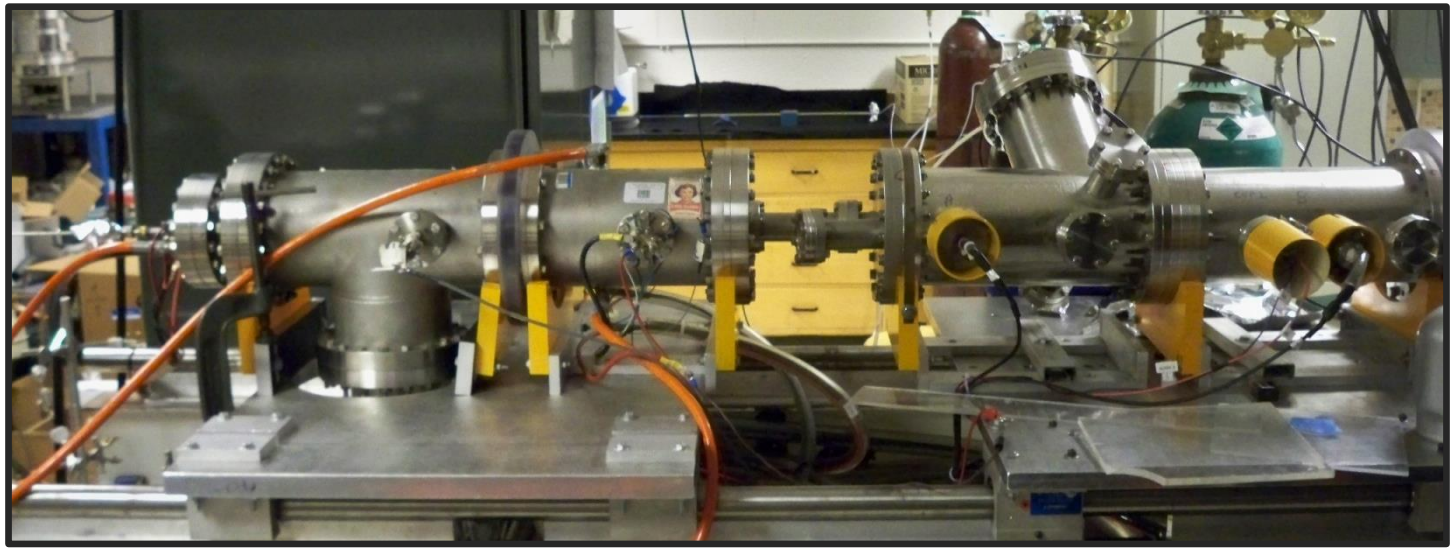
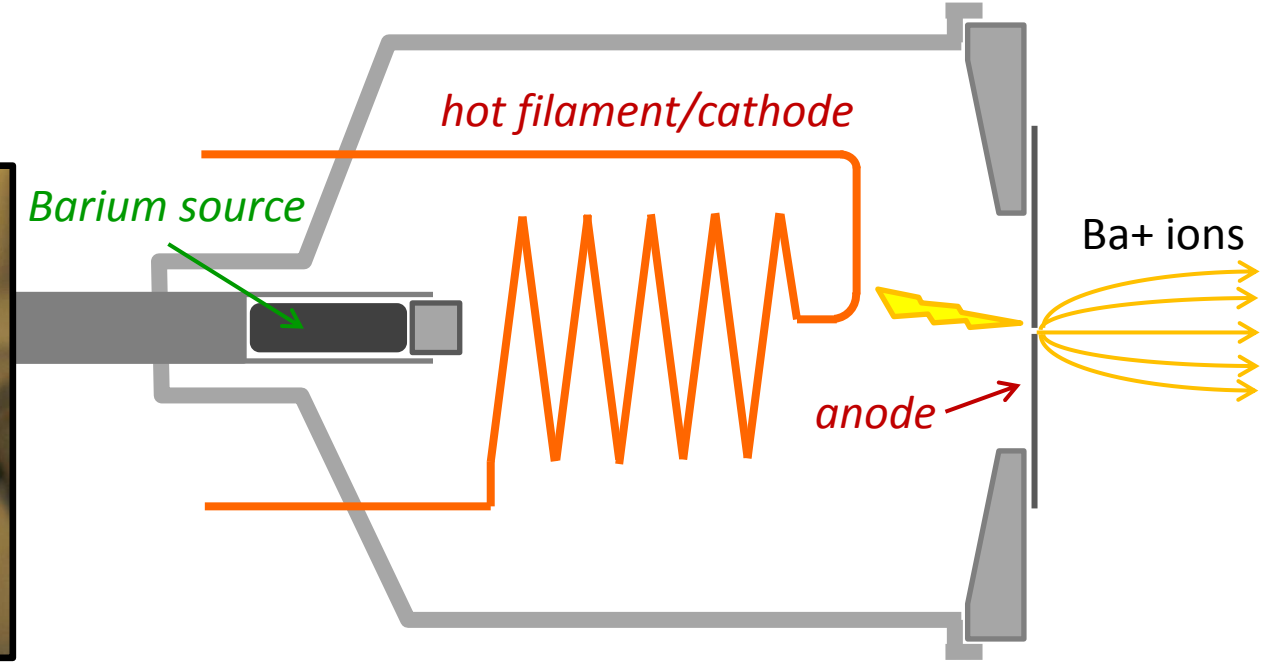
Ion Beam

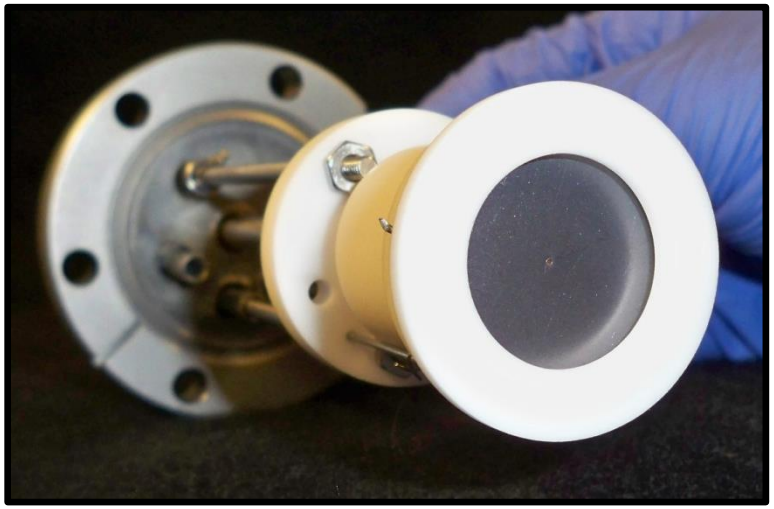
for depositing Ba^+ ions into Solid Xenon

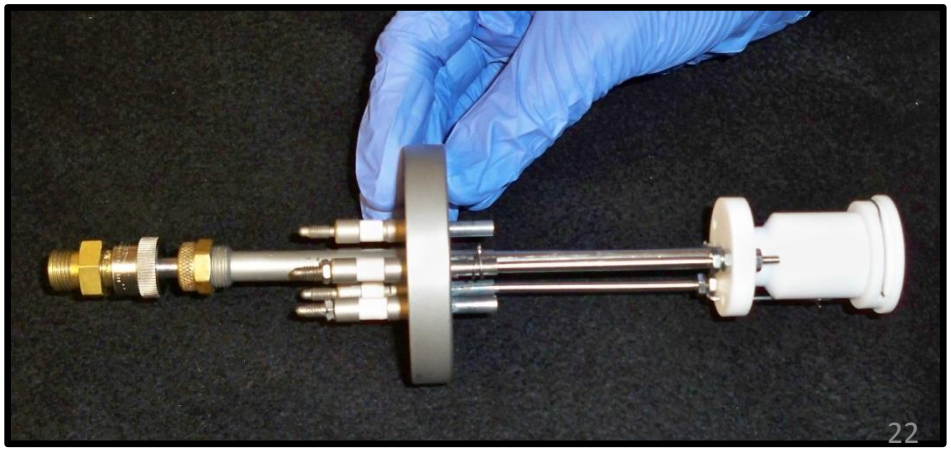




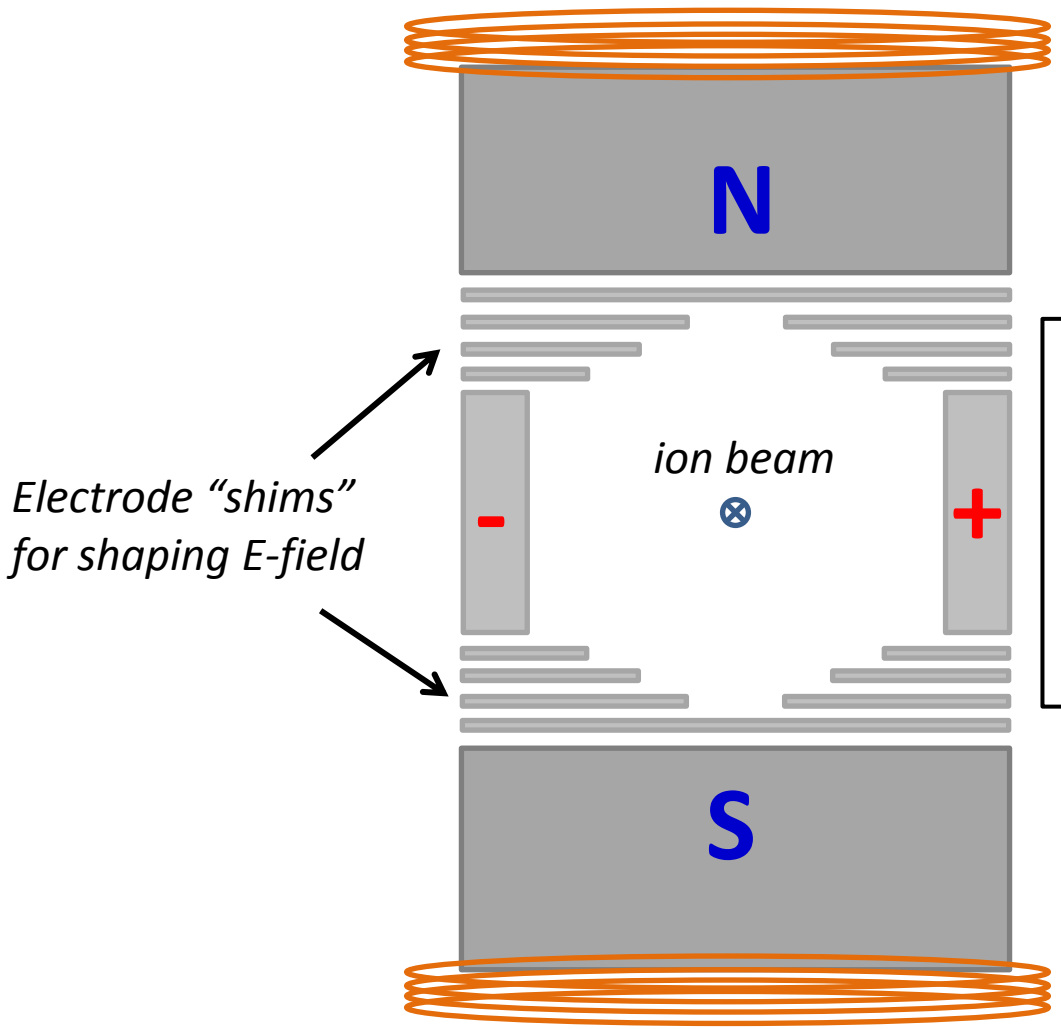
Ion Source







E x B Mass Filter for selecting Ba^+

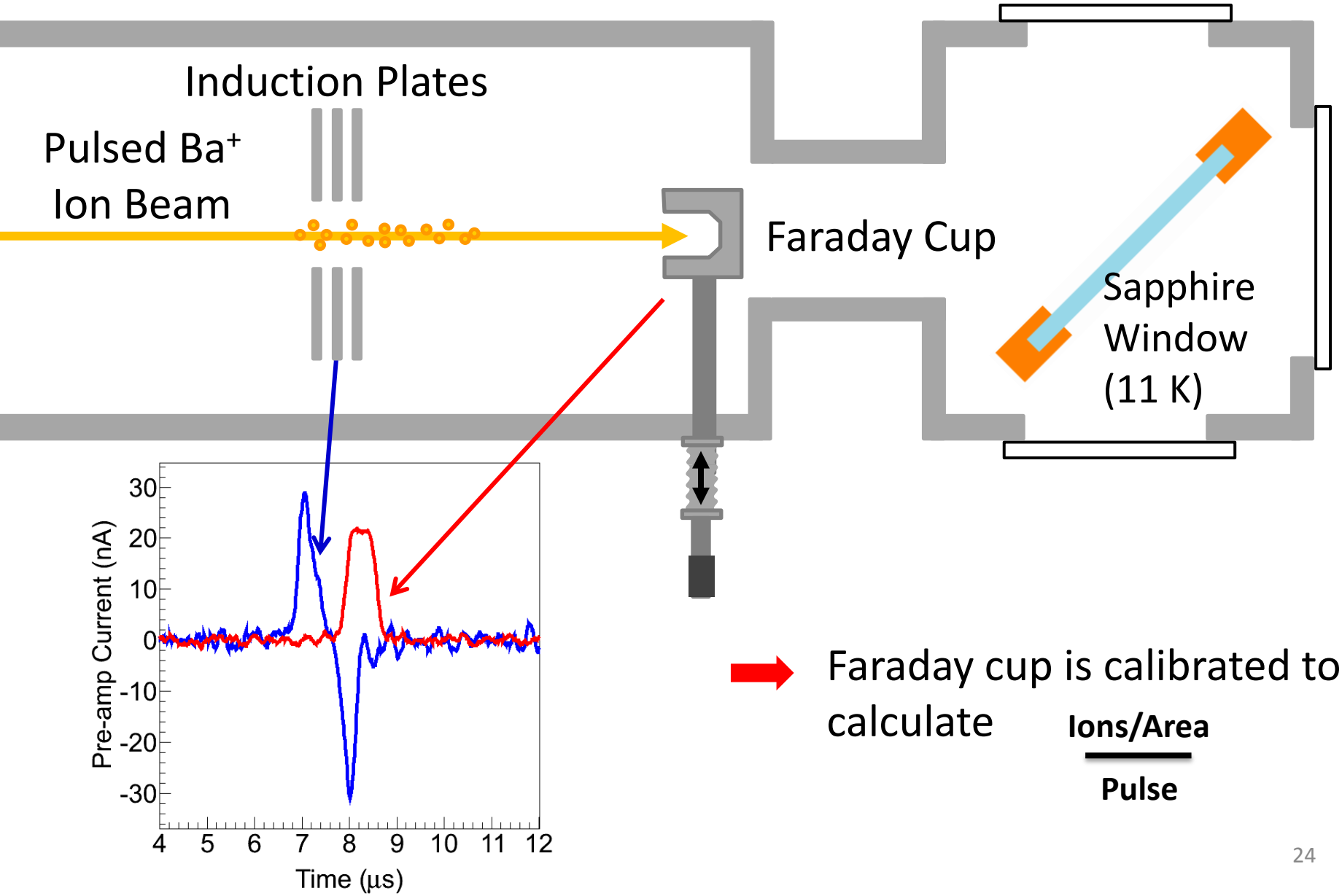


Only ions with velocity satisfying

$$qE = qvB$$

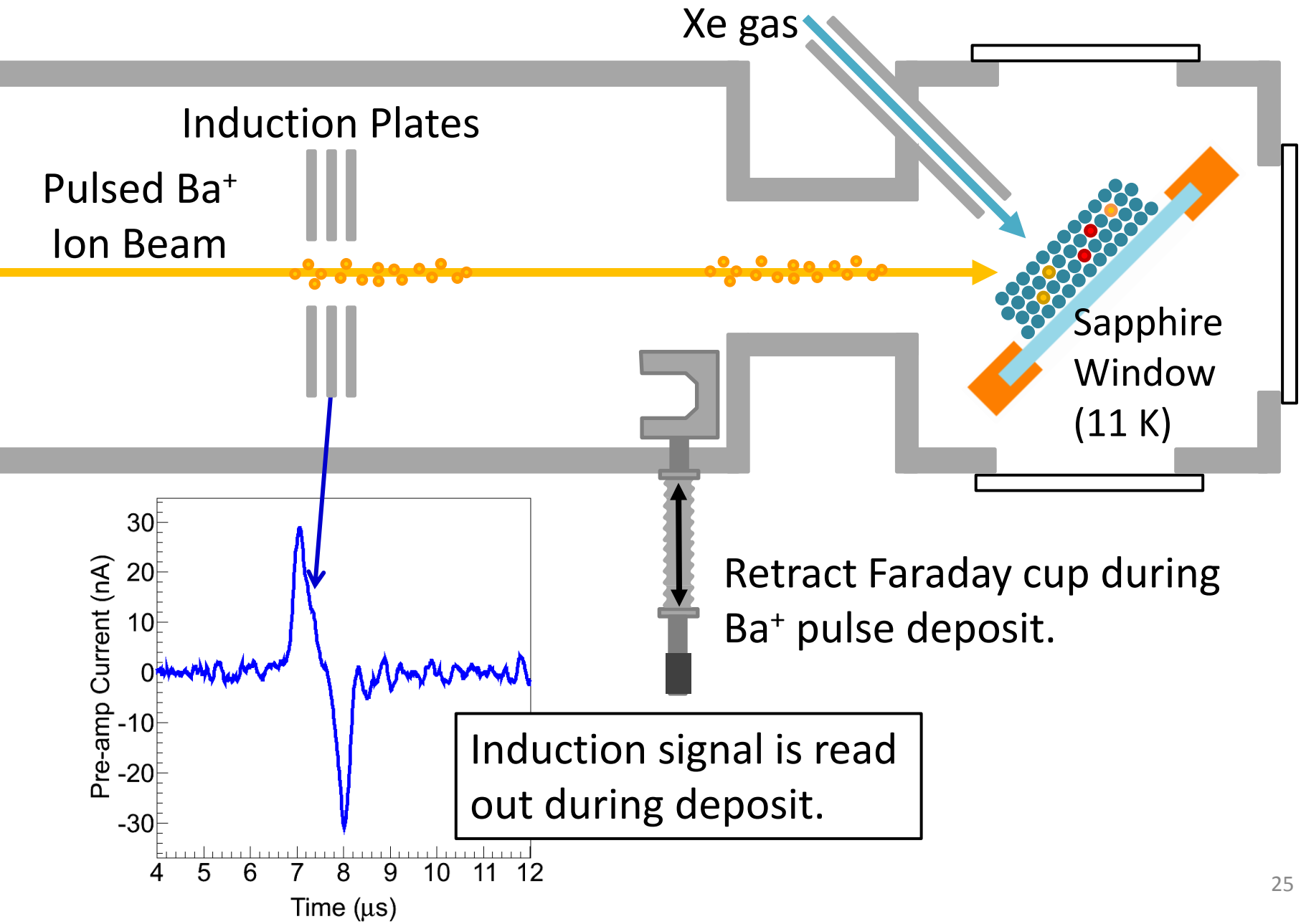
will move through filter undeflected, thus selecting specific ***m/q***, which have different velocities due to initial acceleration.

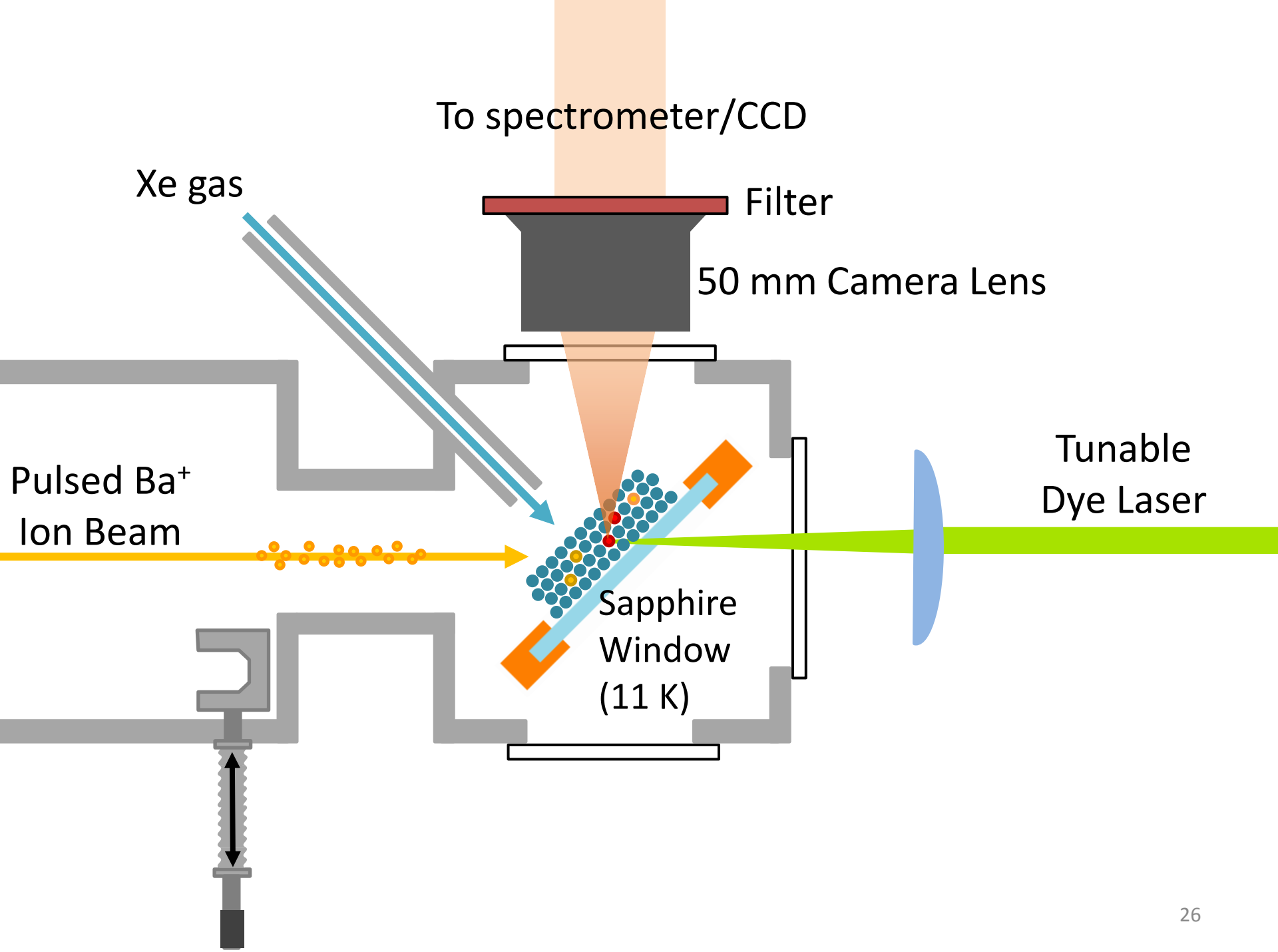
Ba^+/Ba Deposition

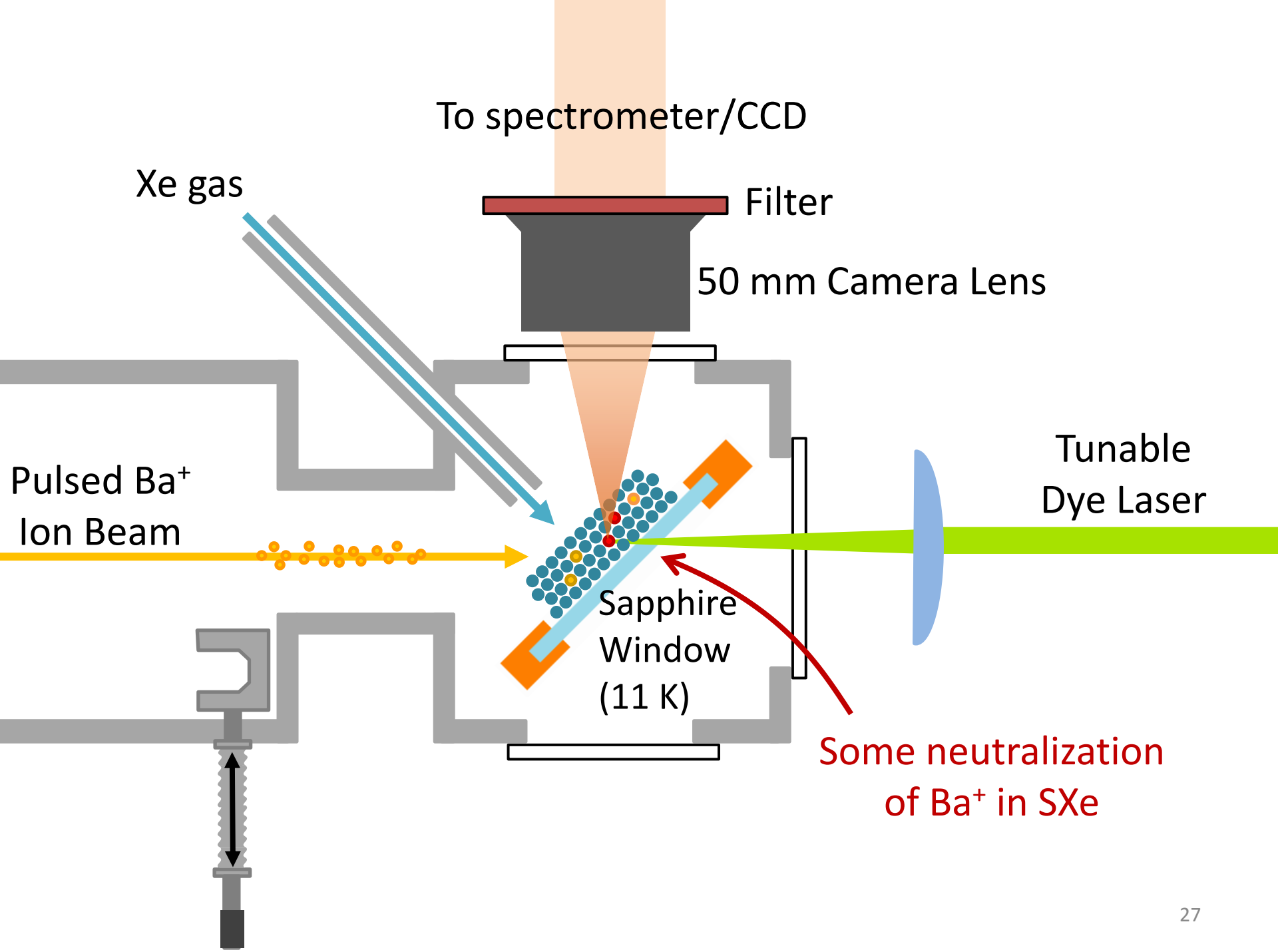


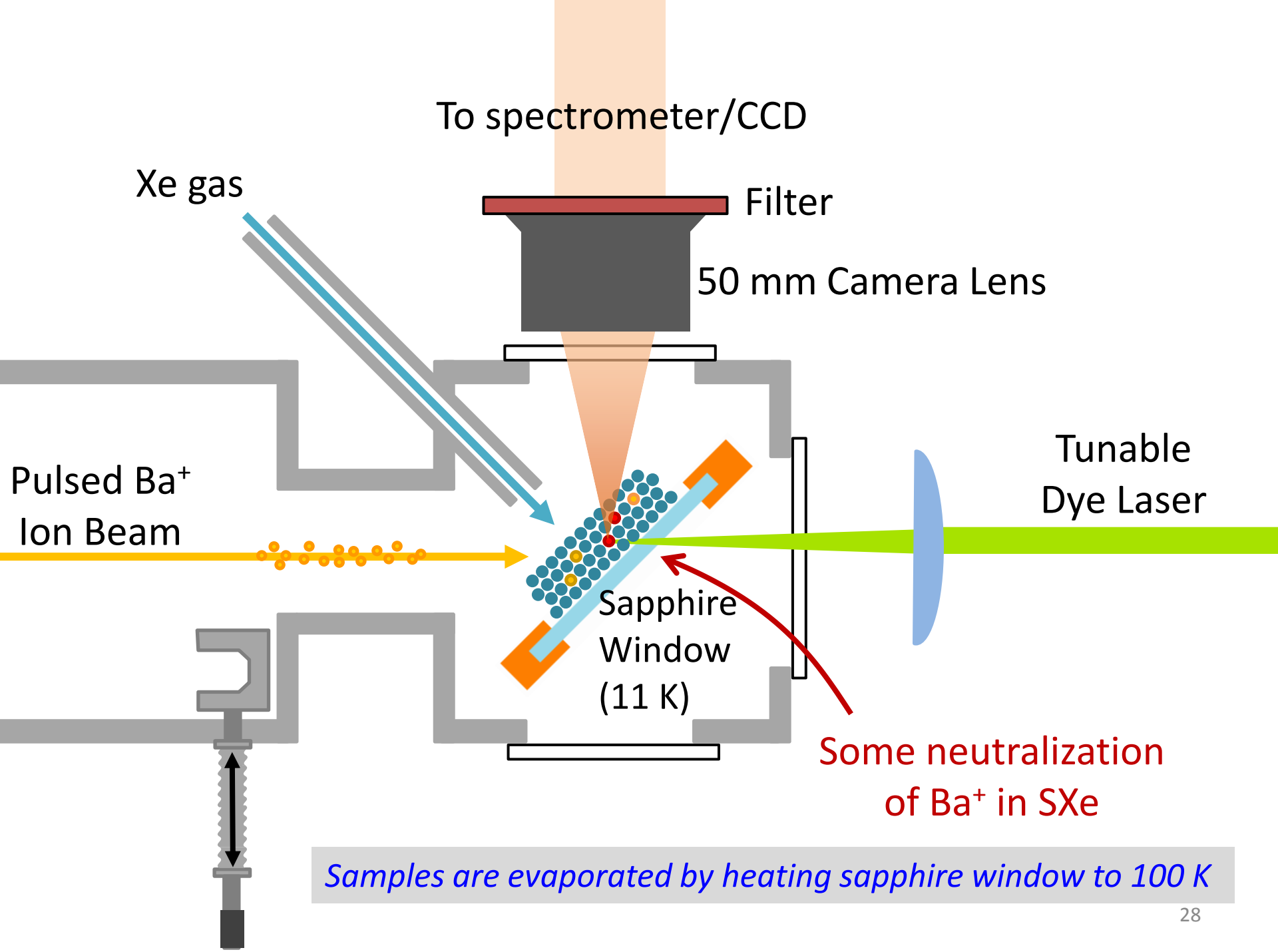
Faraday cup is calibrated to calculate $\frac{\textbf{Ions/Area}}{\textbf{Pulse}}$

Ba^+/Ba Deposition



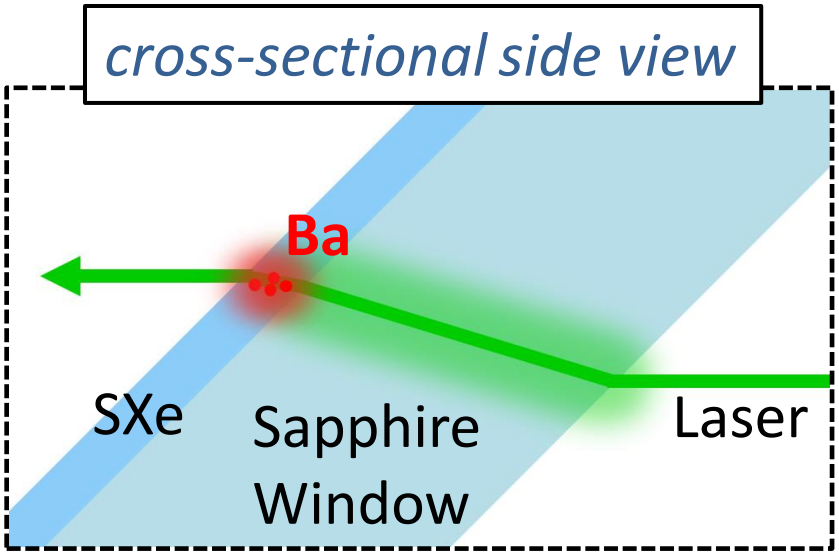

To spectrometer/CCD
Xe gas
Filter
50 mm Camera Lens
Pulsed Ba+
Ion Beam
Tunable
Dye Laser
Sapphire
Window
(11 K)

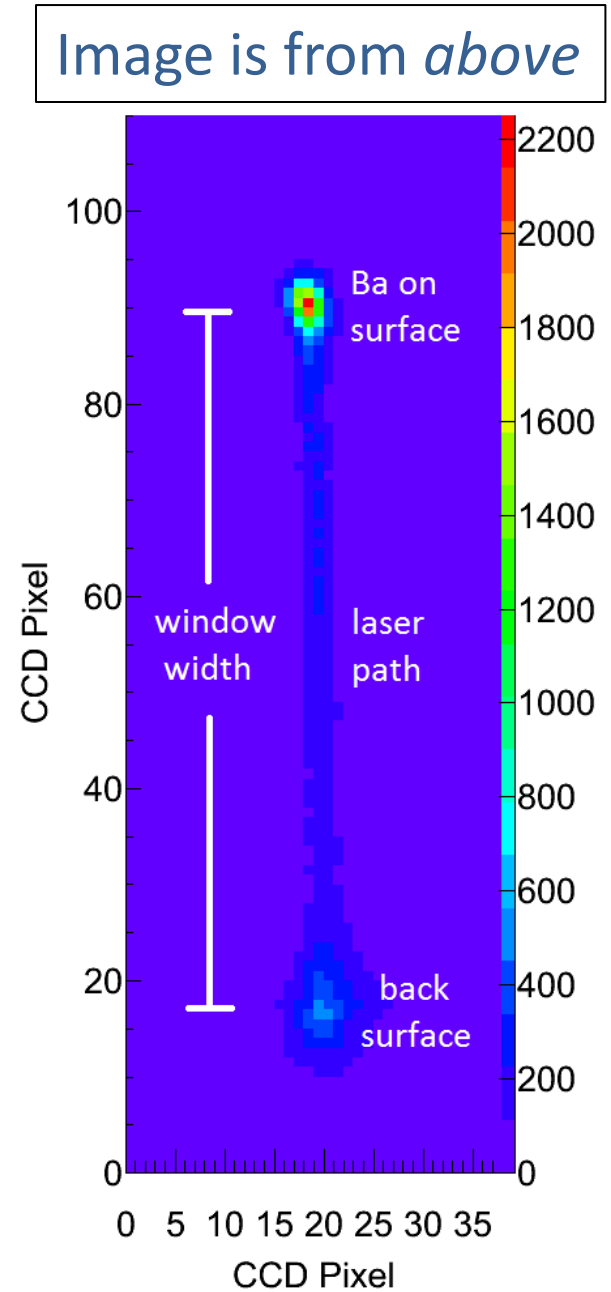

To spectrometer/CCD
Xe gas
Filter
50 mm Camera Lens
Pulsed Ba+
Ion Beam
Tunable
Dye Laser
Sapphire
Window
(11 K)
Some neutralization
of Ba+ in SXe



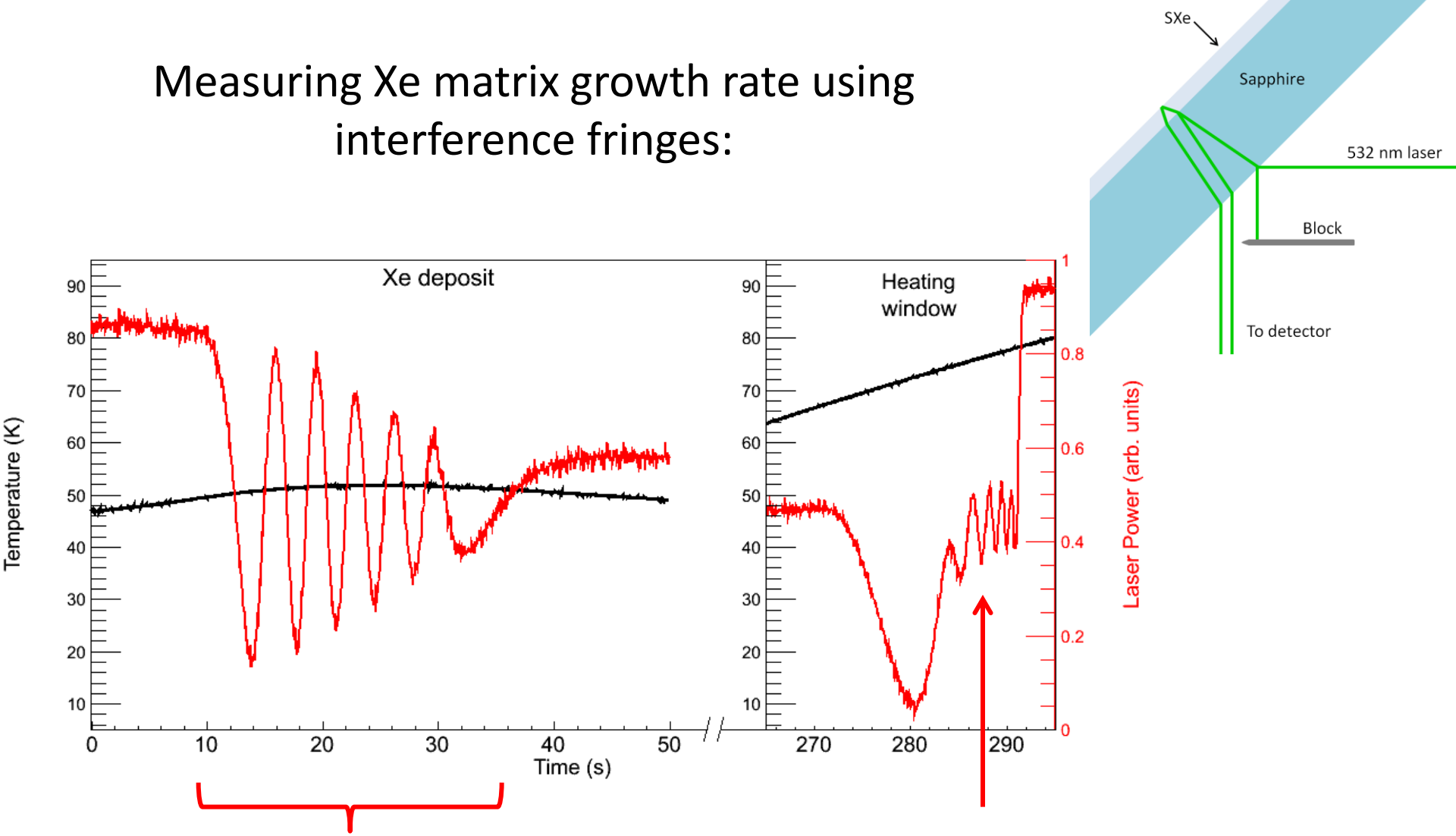
Samples are evaporated by heating sapphire window to 100 K

Imaging Ba in SXe on Cold Sapphire Window





Measuring Xe matrix growth rate using interference fringes:



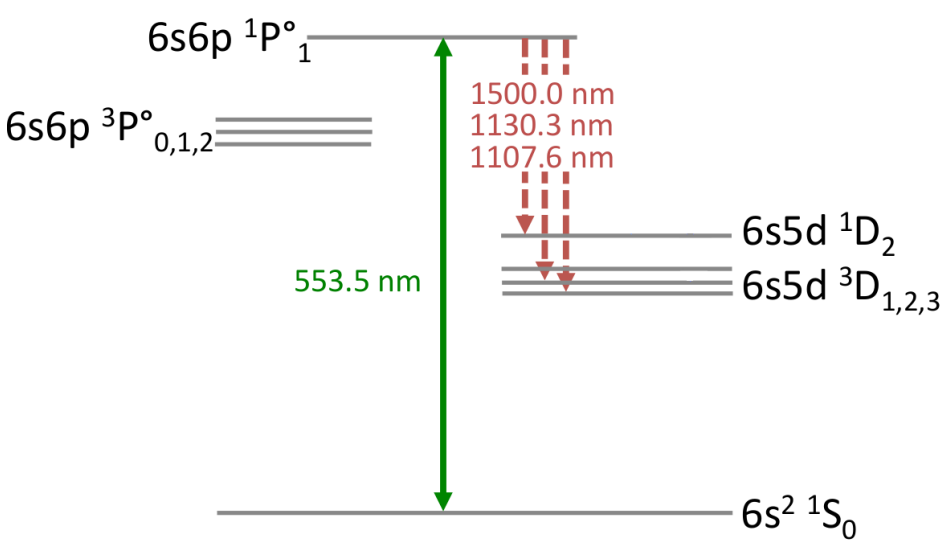
Xe deposit at 50 K

➡ Deposition rate of ~30 nm/s

Observe same number of fringes when evaporating sample

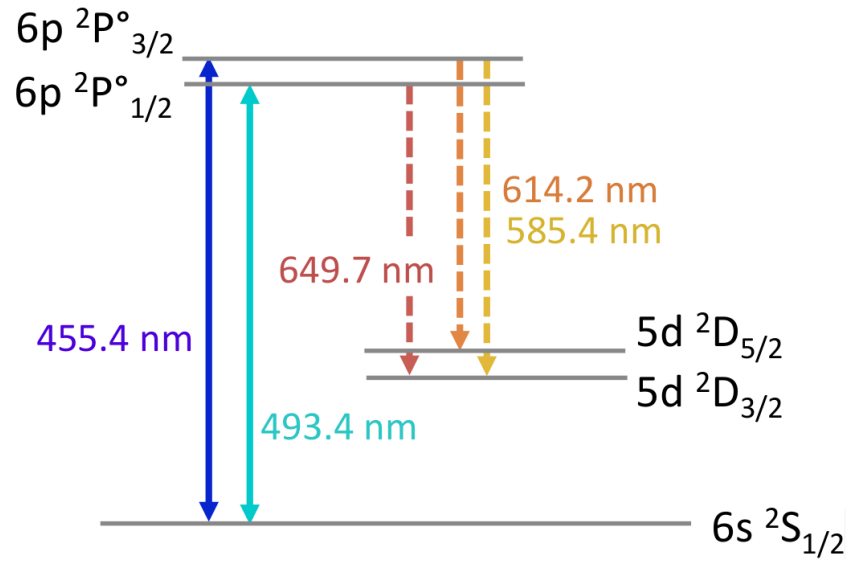
Ba and Ba^+ Transitions in Vacuum

Ba

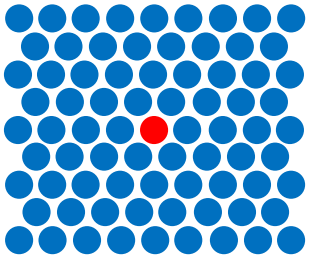


~1 in 330 decays from $^1P_1$ state are into metastable D states

Ba^+

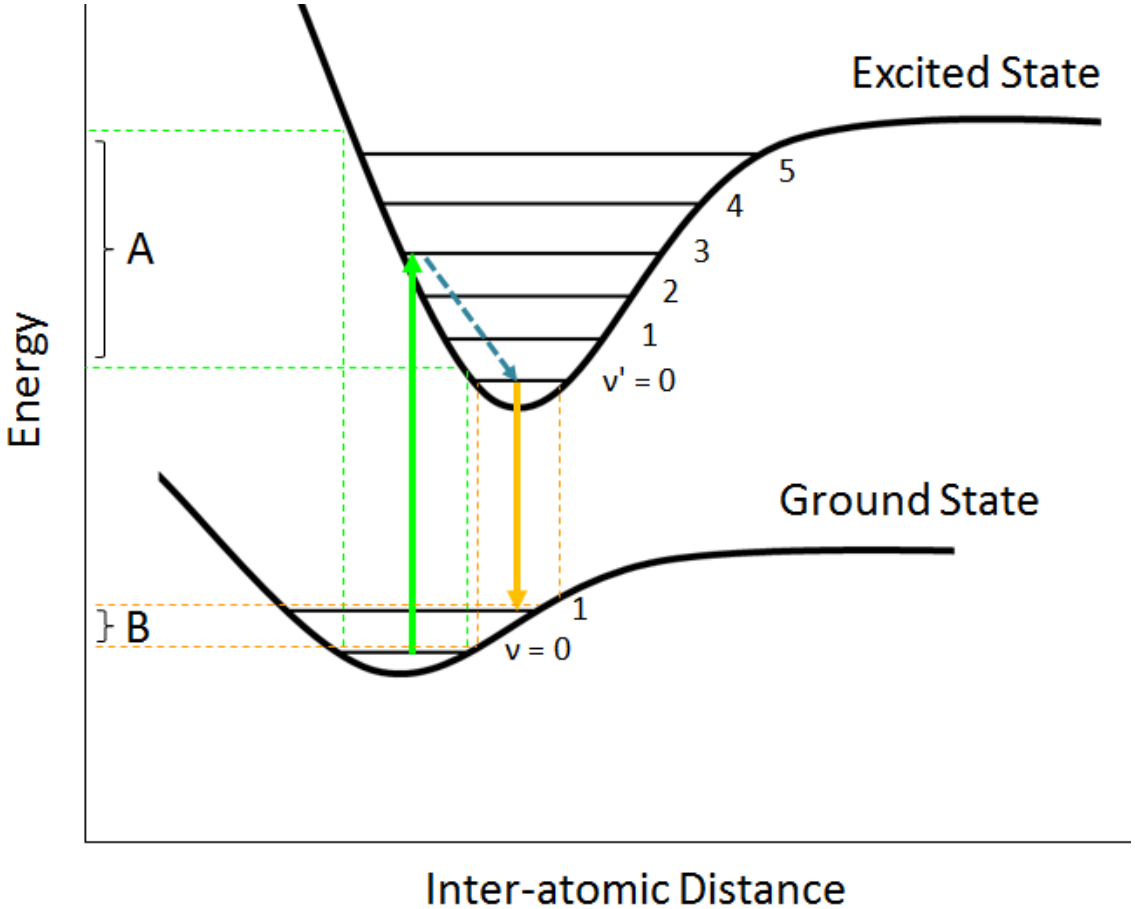


~1 in 4 decays from $^2P_{1/2}$ state are into metastable D state



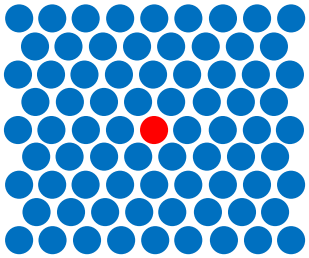
Interactions with neighboring host atoms (xenon)

Ba/Xe interaction is different in ground vs. excited state:



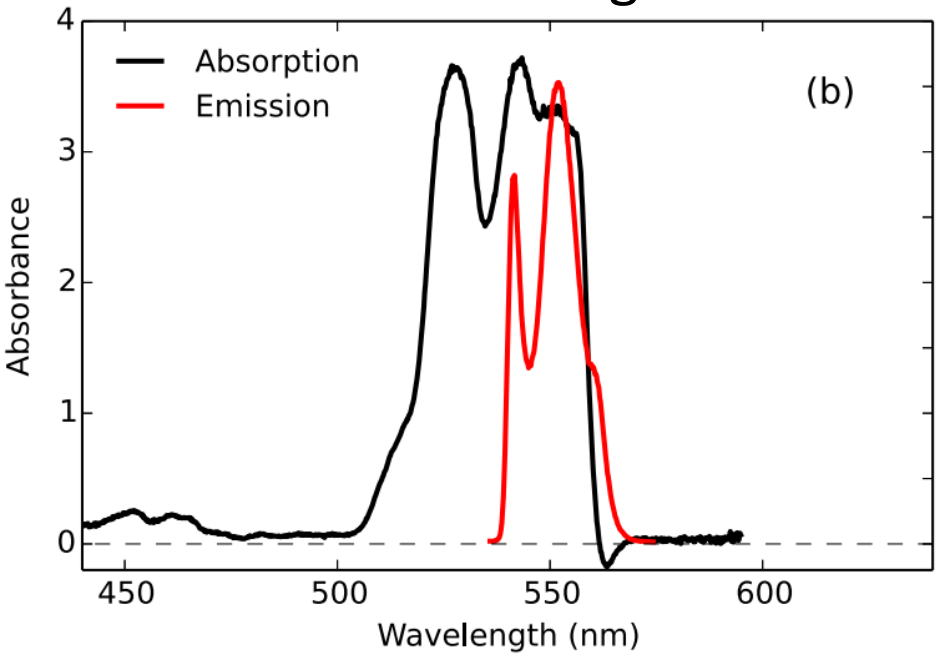
Franck-Condon principle: Strongest excitation occurs to vibrational states whose wavefunctions overlap

Shifts and broadening in absorption (A) and emission (B)

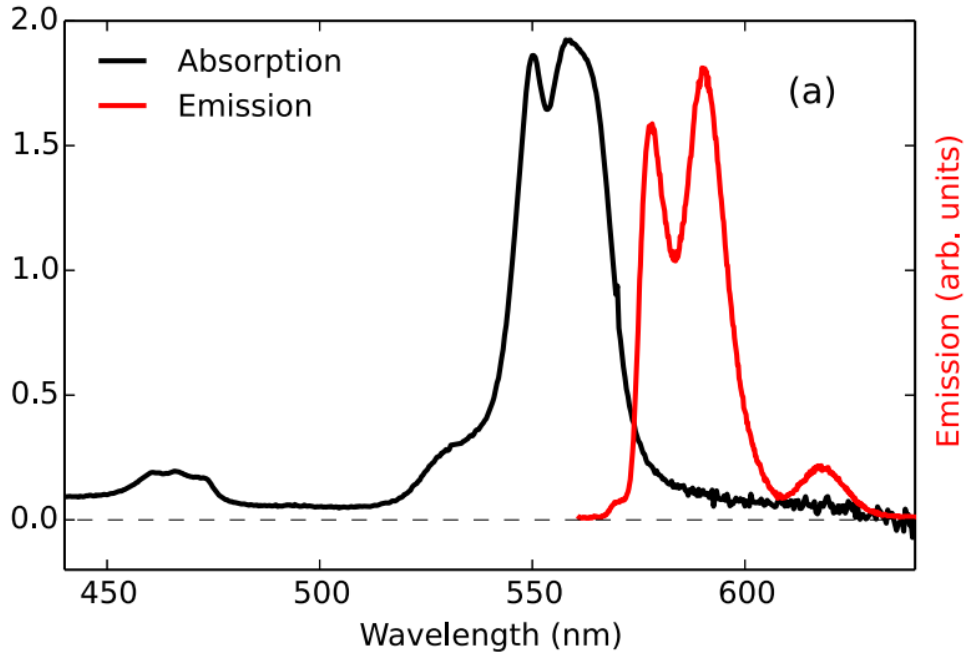


Interactions with neighboring host atoms (xenon)

Ba in solid argon

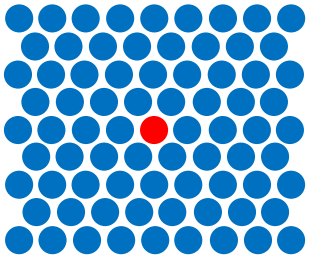


Ba in solid xenon



Phys. Rev. A **91**, 022505 (2015).

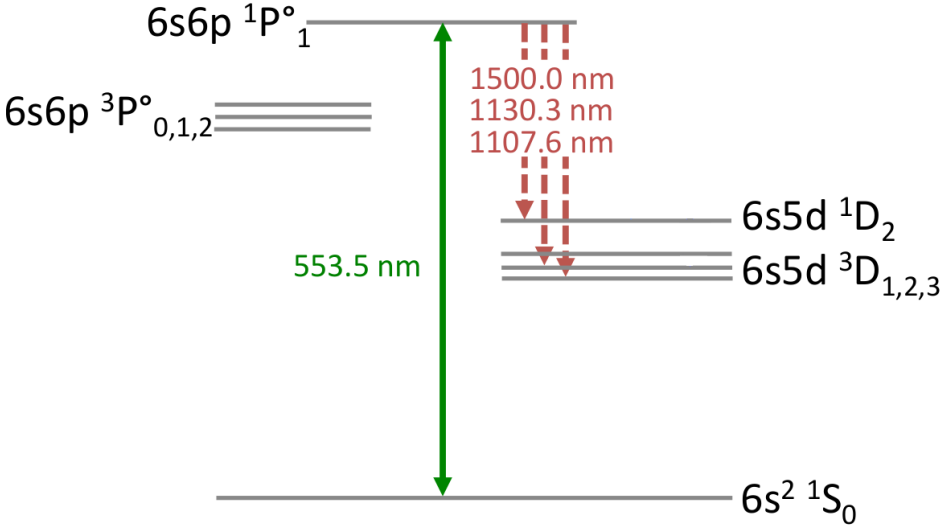
- Excitation and emission are broadened
- Excitation is shifted from vacuum wavelength
- Emission is shifted from excitation



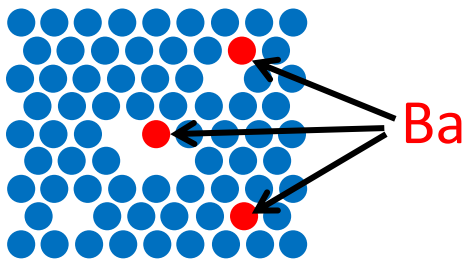
Interactions with neighboring host atoms (xenon)

Rate changes:

- Non-radiative, e.g. crossing of potential energy curves
- Radiative, e.g. parity change

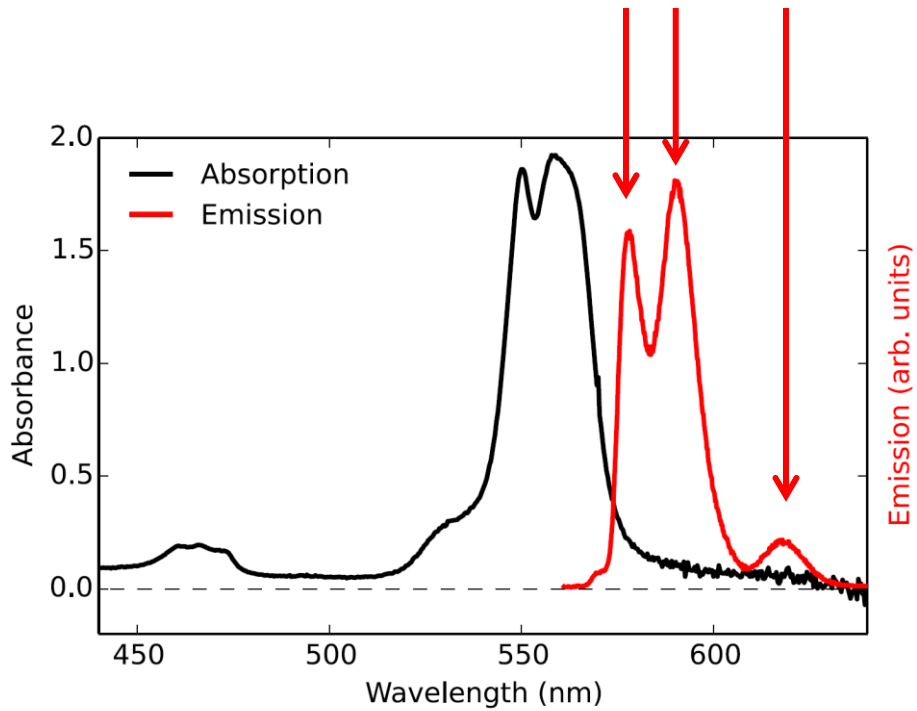


Matrix Sites



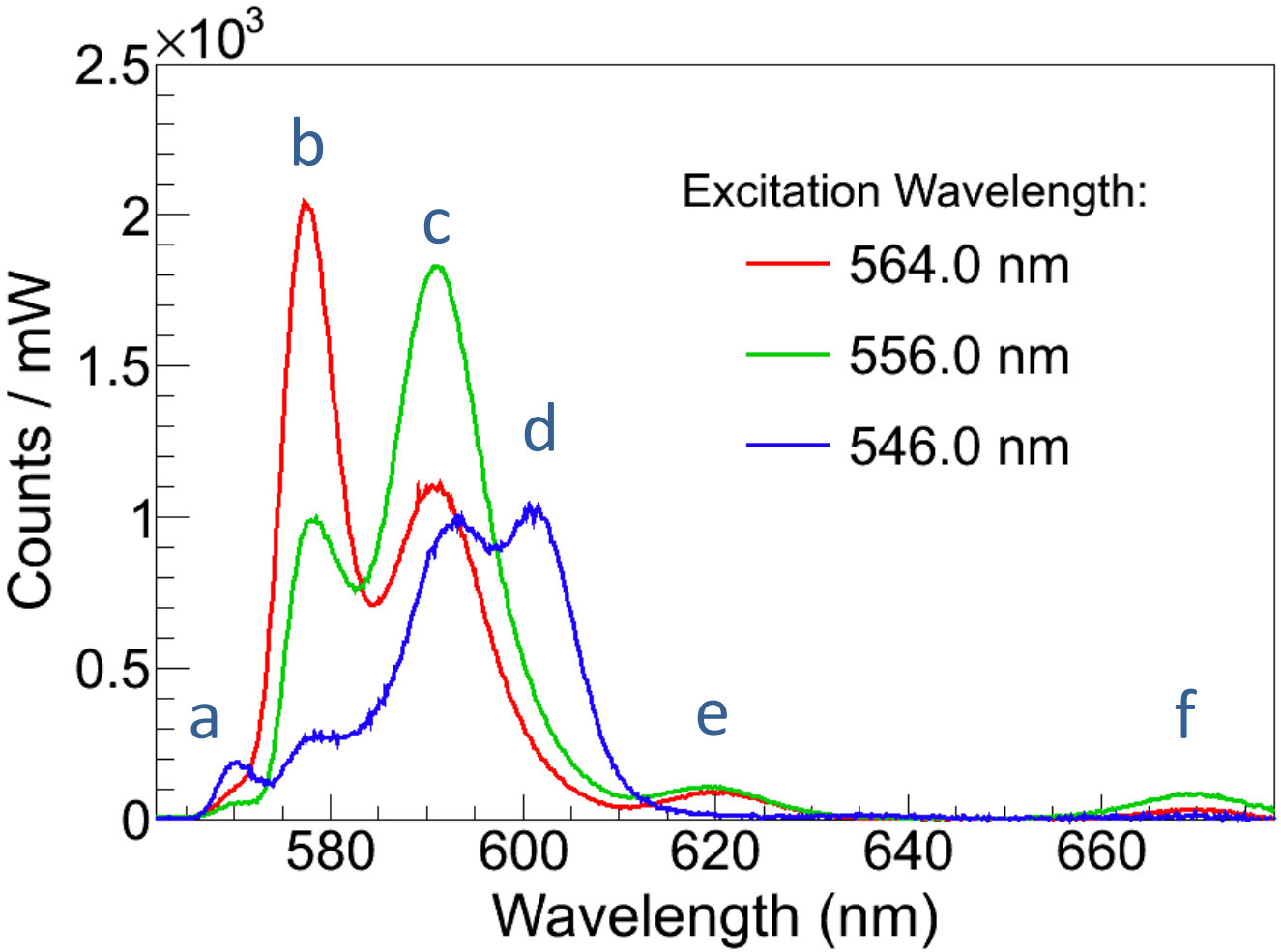
Matrix effects (shifts, broadening, and transition rates) can be matrix site dependent.

Emission from Ba occupying different sites



Part 1: Spectroscopy

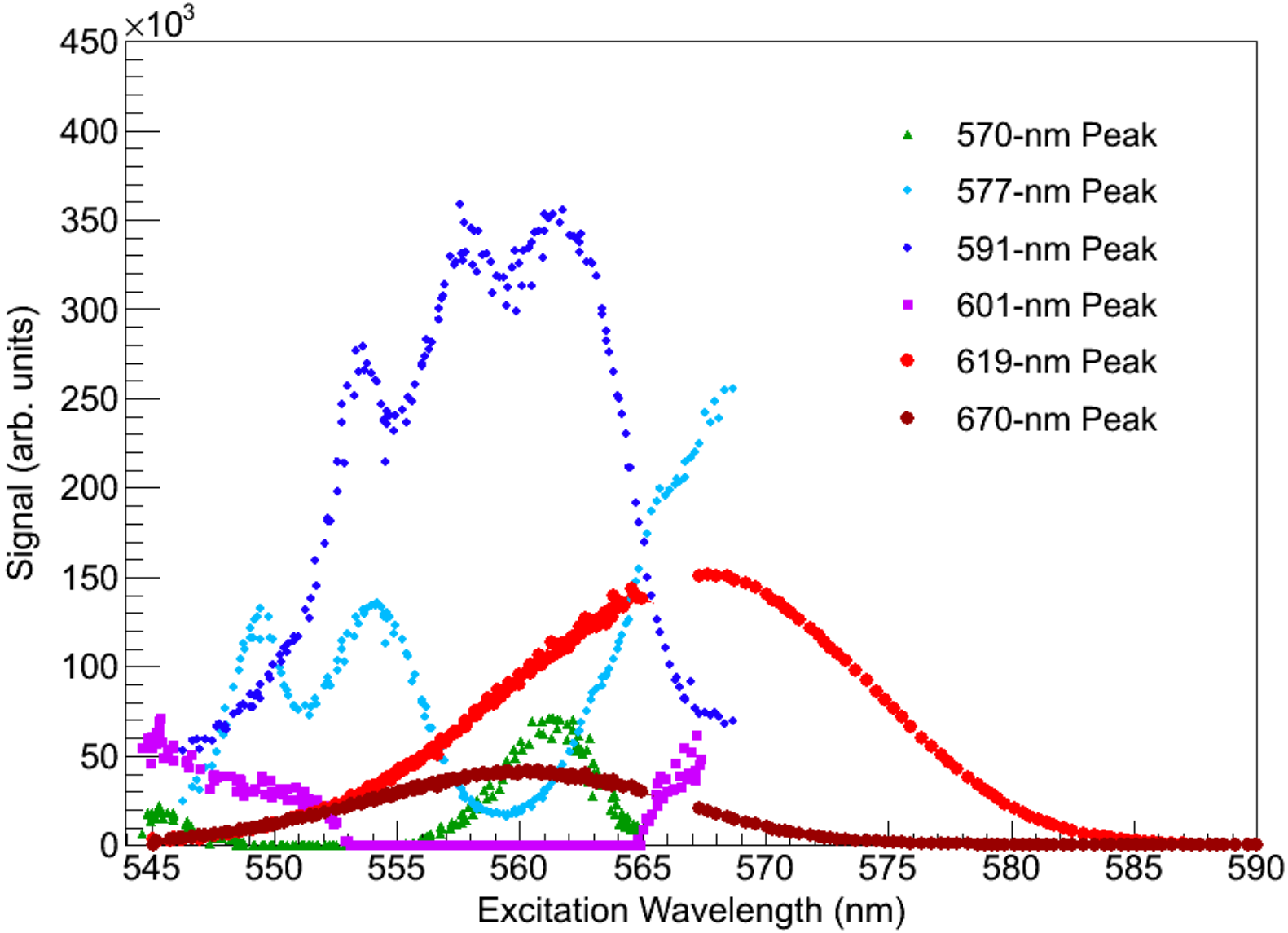
Emission of Ba in Solid Xe



Peaks observed at:

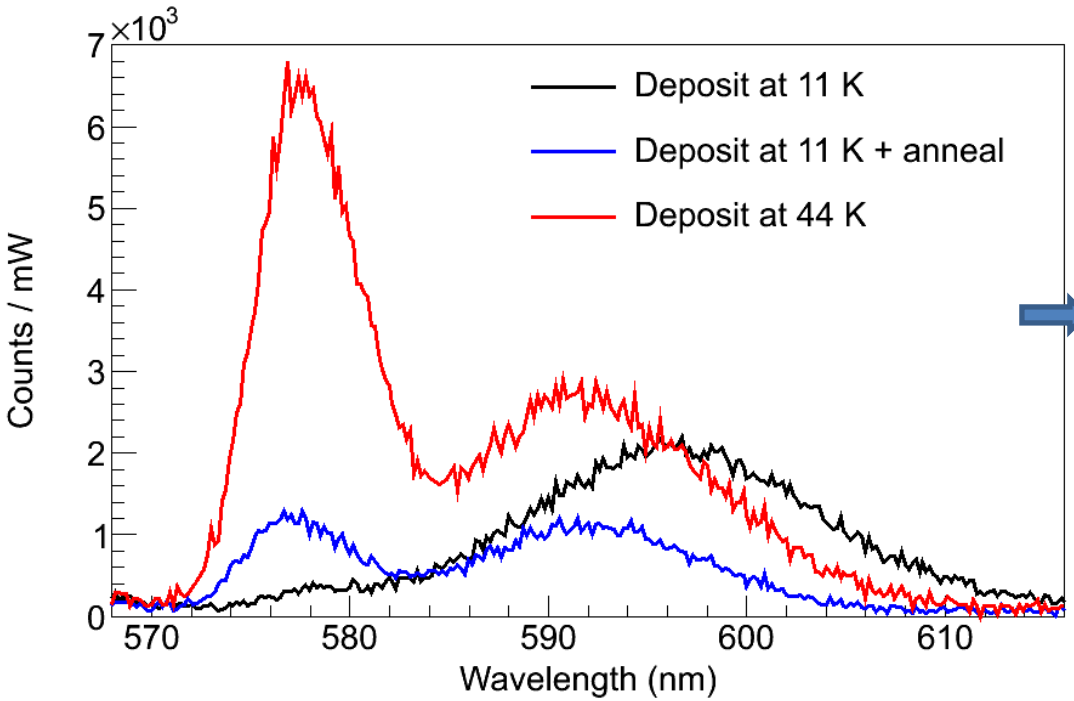
a) 570 nm
b) 577 nm
c) 591 nm
d) 601 nm
e) 619 nm
f) 670 nm

Excitation Spectra of Ba Emission Peaks



Thermal History Dependence

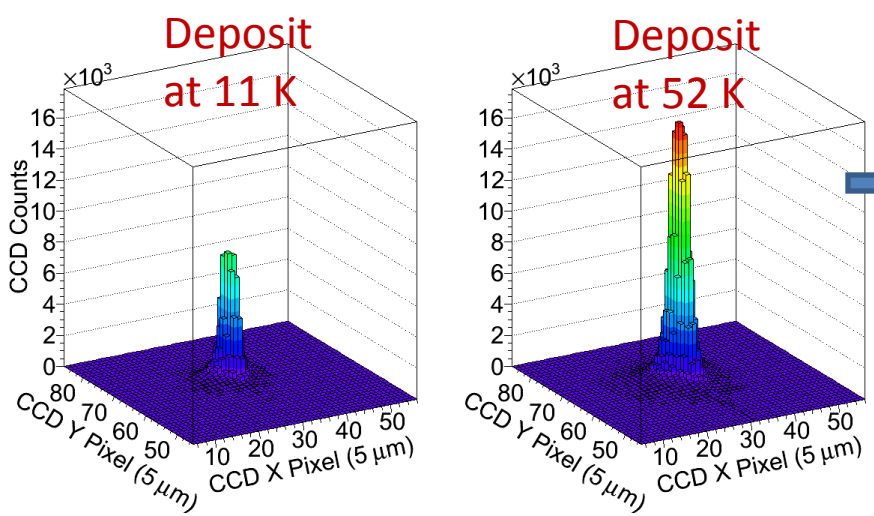
Matrix site populations can depend on thermal history:



Deposits at higher temperature (50 ± 5 K) result in larger 577-nm and 591-nm.

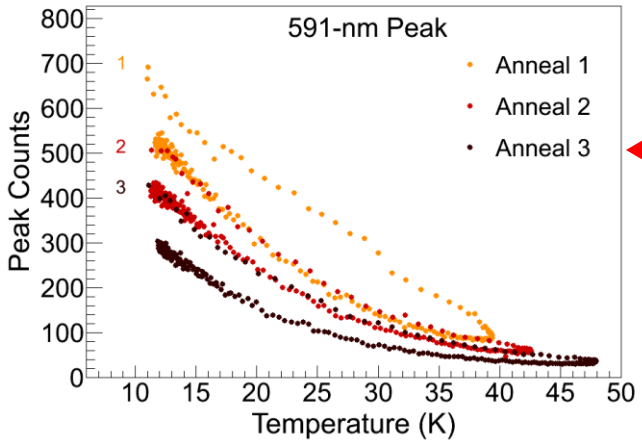
All observation is at 11 K

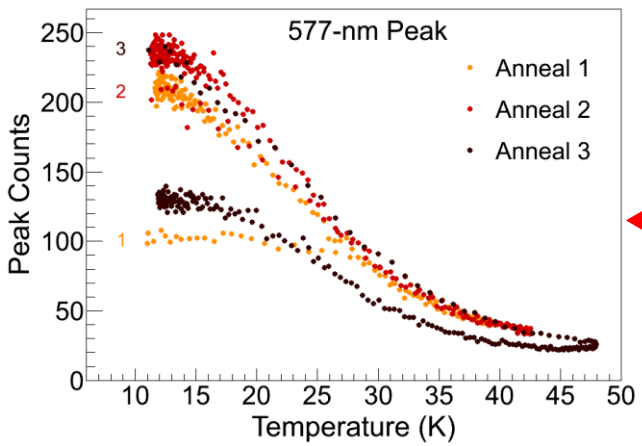
Images of 619-nm Ba fluorescence in focused laser (discussed later):

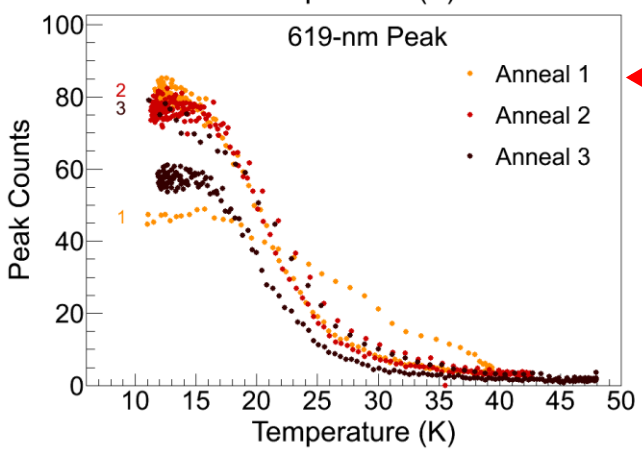


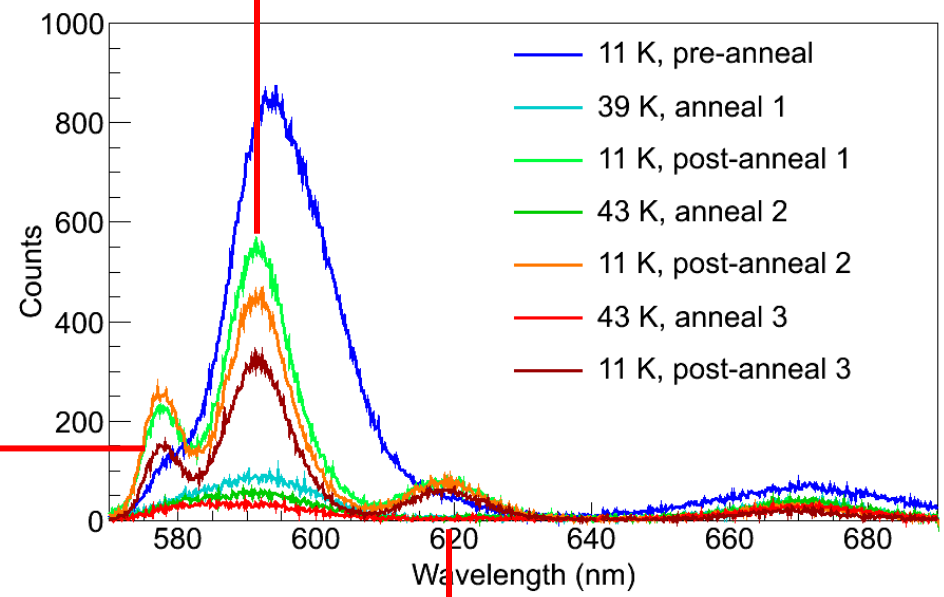
619-nm signal also higher w/ 50 ± 5 K deposit.

Annealing







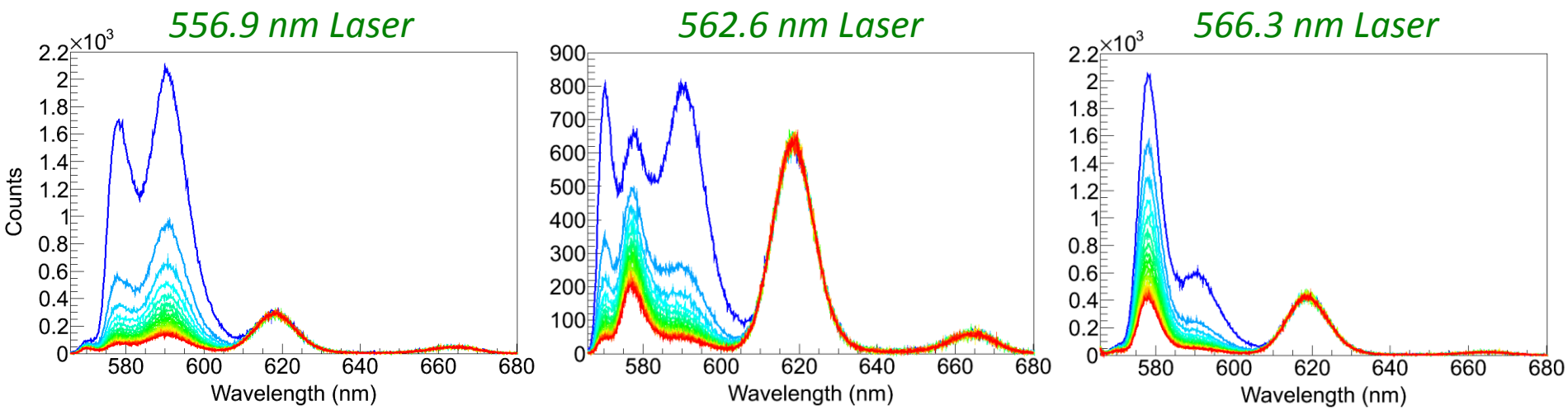


- Gain in 577-nm and 619-nm peaks after Cycle 1 (to 39 K), with modest loss in 591-nm.
- Loss in fluorescence after Cycle 3 (to 48 K).
- *Overall, fluorescence is highest at 11 K.*

Bleaching

Decay of Fluorescence w/ Laser Exposure

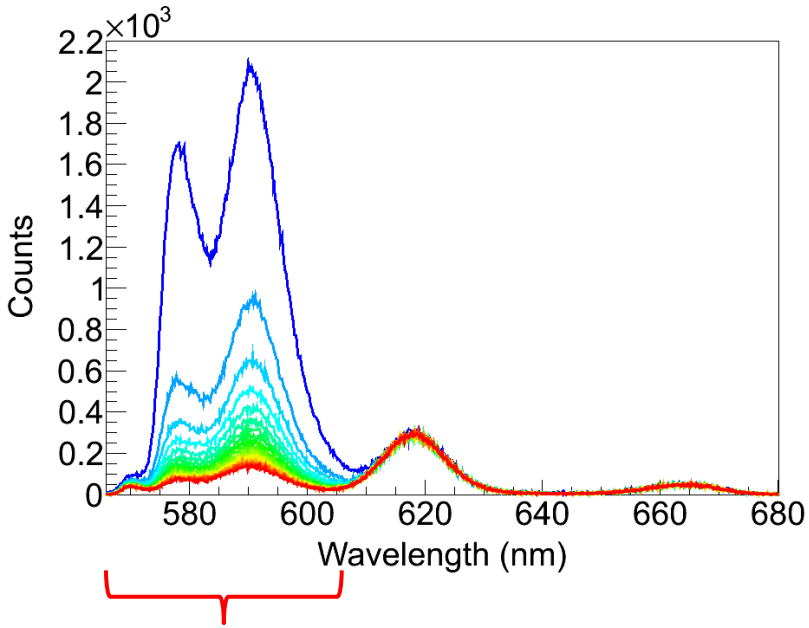
Spectra of Ba in SXe at different moments in time:



- Rapid bleaching in 570-nm, 577-nm, 591-nm peaks.
- 619-nm and 670-nm peaks **do not bleach** at this laser intensity

Bleaching

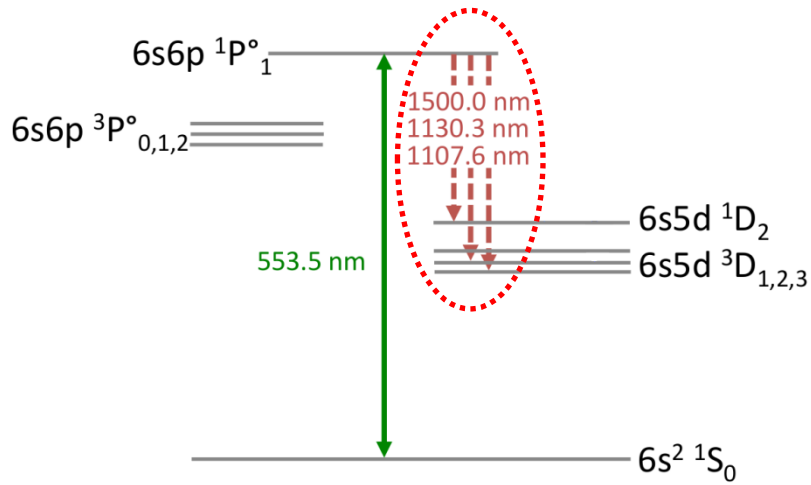
Decay of Fluorescence w/ Laser Exposure



Bleaching is an obstacle for observing single atoms in these matrix sites: *need more photons/atom.*

What causes bleaching?

Likely: optical pumping into metastable states, as in Ba in vacuum:



Re-pumping with IR lasers may be required for continued fluorescence cycle.

Bleaching Model

$$\frac{dN_1}{dt} = -W_{12}N_1 + A_{21}N_2 + A_{31}N_3 + A_{41}N_4 + A_{51}N_5$$

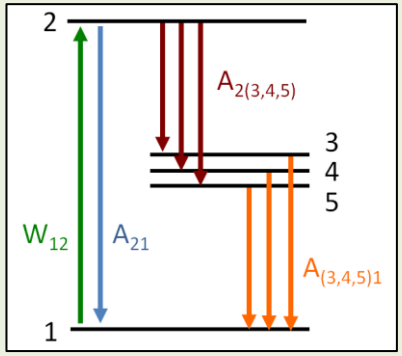
$$\frac{dN_2}{dt} = W_{12}N_1 - (A_{21} + A_{23} + A_{24} + A_{25})\,N_2$$

$$\frac{dN_3}{dt} = A_{23}N_2 - A_{31}N_3$$

$$\frac{dN_4}{dt} = A_{24}N_2 - A_{41}N_4$$

$$\frac{dN_5}{dt} = A_{25}N_2 - A_{51}N_5$$

$$N_1 + N_2 + N_3 + N_4 + N_5 = N_{atoms}$$



Rates in vacuum:

A_{21}=1.2x10^8 s^{-1}

A_{23}=2.5x10^5 s^{-1}

A_{24}=1.1x10^5 s^{-1} *branching ratio 0.003*

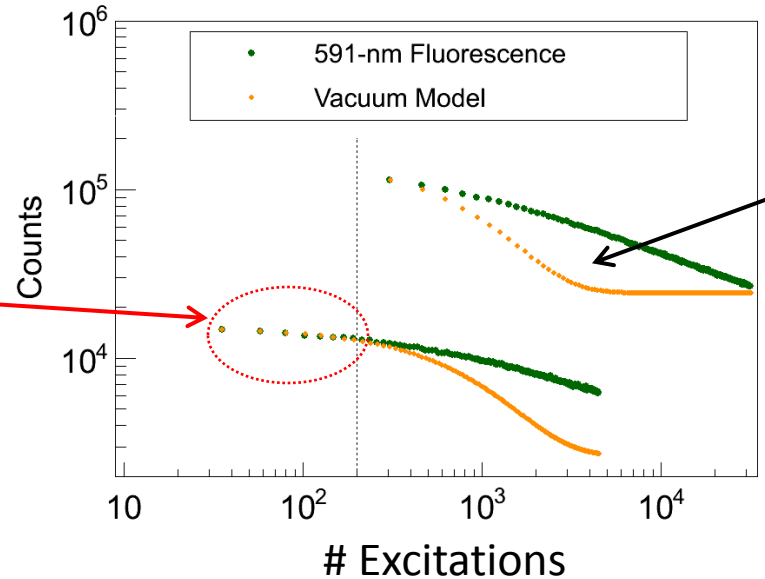
A_{25}=3.1x10^3 s^{-1}

A_{31}=5 s^{-1}

A_{41}=0.014 s^{-1} *very slow metastable decay*

A_{51}=0.017 s^{-1}

Compare numerical solution to above equations (normalized) to 591-nm Ba fluorescence data:



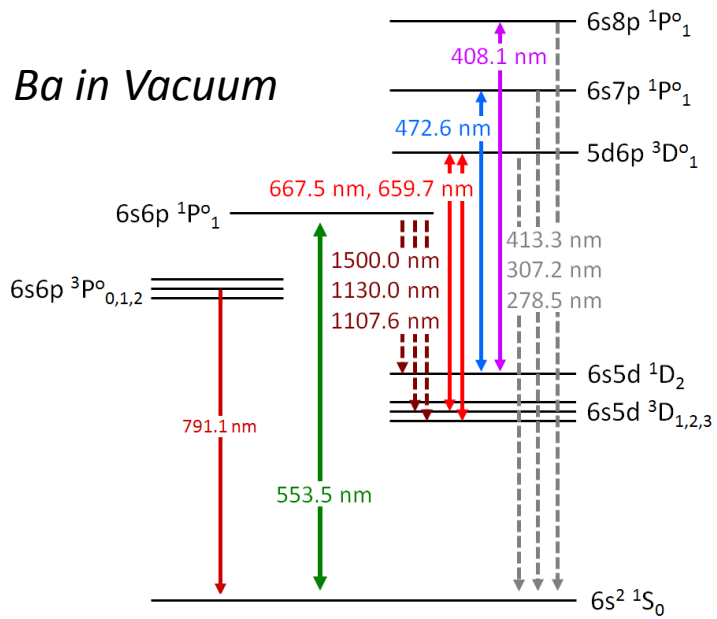
Agreement for first ~200 excitations

Disagreement may be due to altered rates in SXe

Still, re-pump lasers may eliminate/reduce bleaching.

Re-pump Attempts

w/ Inexpensive and On-hand Lasers



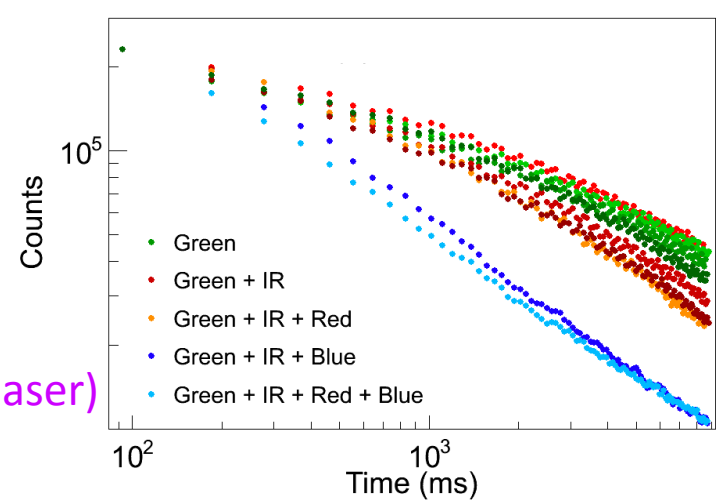
Higher-level states may provide re-pump paths (in addition to direct IR transitions).

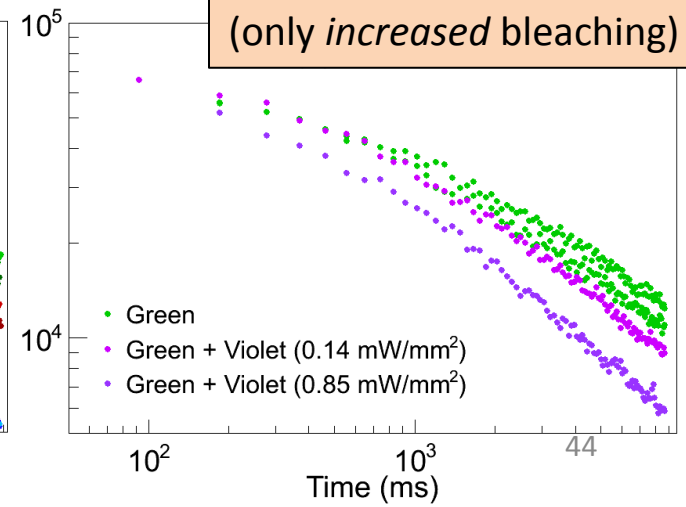
e.g., 659.7 nm used along with 1130.0 nm and 1500.0 nm for Ba MOT in *Phys. Rev. A* **79**, 041402(R) (2009)

591-nm fluorescence vs. time w/ and w/o additional lasers:

No positive effect from these additional lasers (only *increased* bleaching)

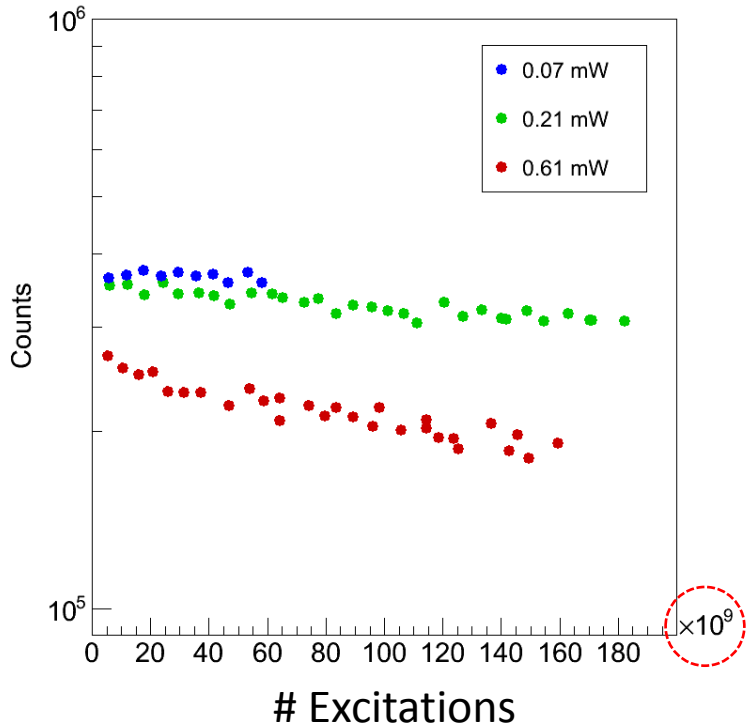
Green: 555 nm (dye)
IR: 1064 nm (Nd:YAG)
+ 1550 nm (diode)
Red: 657 nm (diode)
Blue: 473 nm (dye)
Violet: 406 nm (Kr ion laser)





Bleaching of 619-nm Peak

619-nm fluorescence counts from a focused laser:

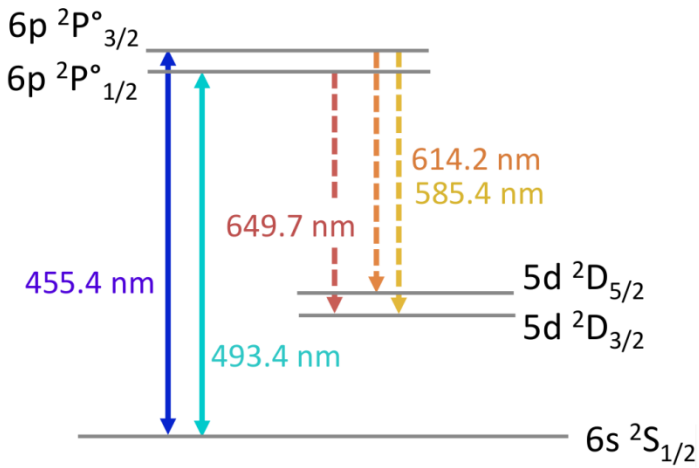


Much higher excitation rate due to focused laser

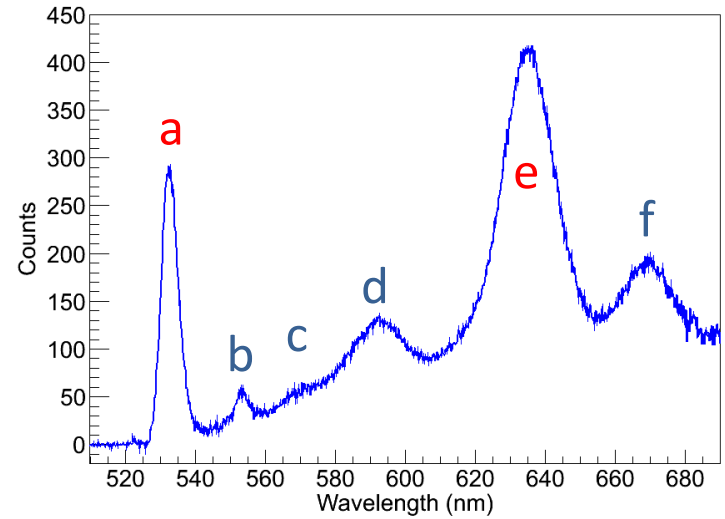
Though some bleaching is observed with the higher 0.61 mW laser power, the long-lasting 619-nm fluorescence is intriguing for single-atom detection w/o the need for re-pump lasers…

Blue Excitation: Candidate Ba^+ Lines

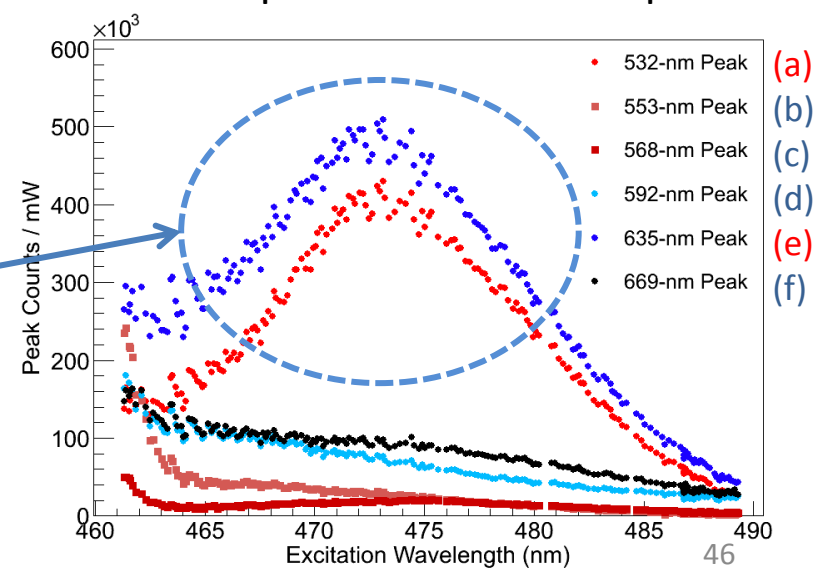
Ba^+ in vacuum:



Emission of Ba^+ deposit w/ 468.25-nm excitation:



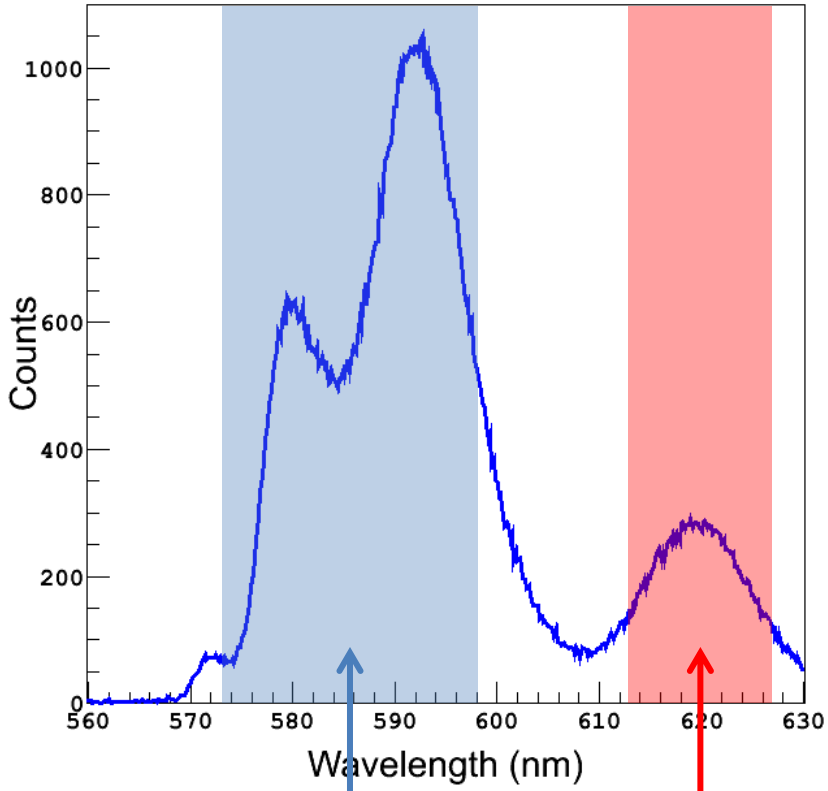
Excitation spectra for emission peaks:



Similarity between excitation spectra for 532 nm line and 635 nm line suggests they are related, and could be fluorescence of P→S and P→D, respectively, for Ba^+.

Part 2: Imaging

Band-pass Filters for Imaging

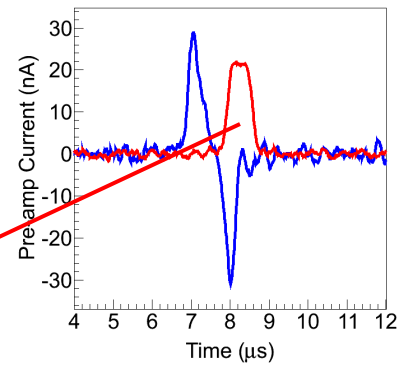


620-nm band-pass
For 619-nm peak

586-nm band-pass
For 577-nm and 591-nm peaks together

Calculating # Ba atoms in focused laser region

Ba$^+$ ion pulses:



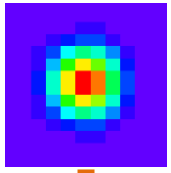
Due to unknown neutralization fraction

From calibrated Faraday signal

Per pulse of ion beam:

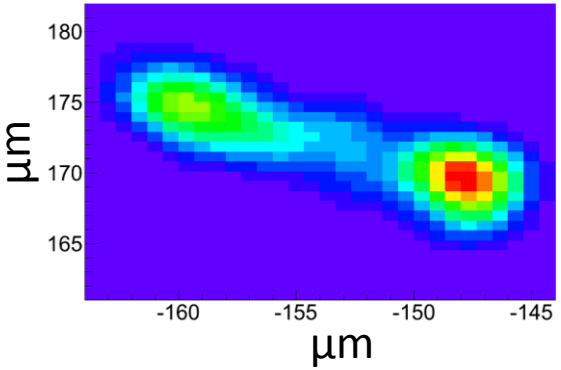
$$\#\text{atoms} \leq \#\text{ions} = \left[\text{charge}/(1.6\times10^{-19}\ \text{C})\right]/\text{m}^2 \times \text{Laser Area}$$

Simulated laser spot of radii $w_x \times w_y = 2.06\mu m \times 2.66\ \mu m$:



vibrations

Laser spot size overlain on cryostat vibration data:

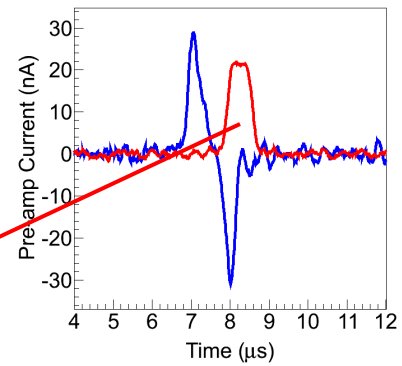


Two definitions for number of atoms:

1) Those *instantaneously illuminated* by laser spot
   ➡ 8.6 μm^2
2) *Total illuminated* over vibrations
   ➡ 40 μm^2

Calculating # Ba atoms in focused laser region

Ba^+ ion pulses:



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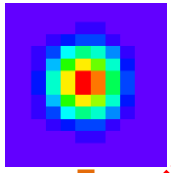

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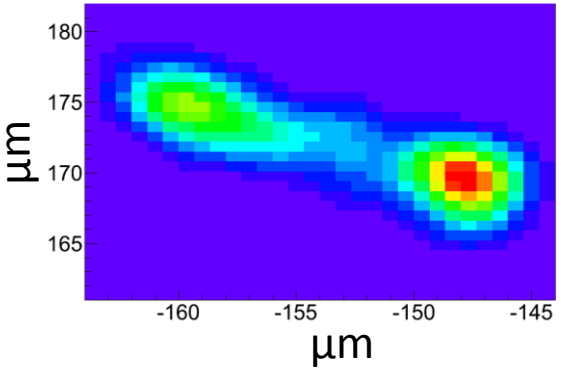

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2) *Total illuminated* over vibrations
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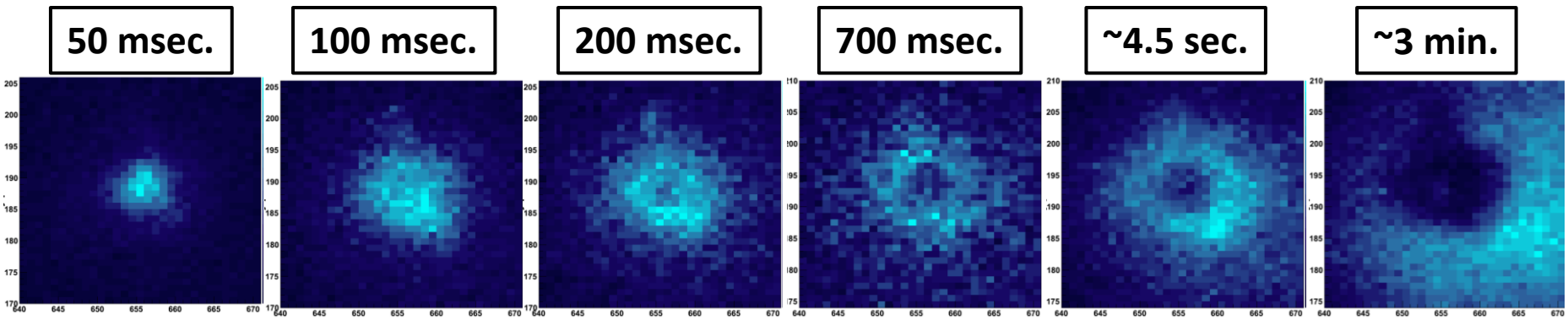
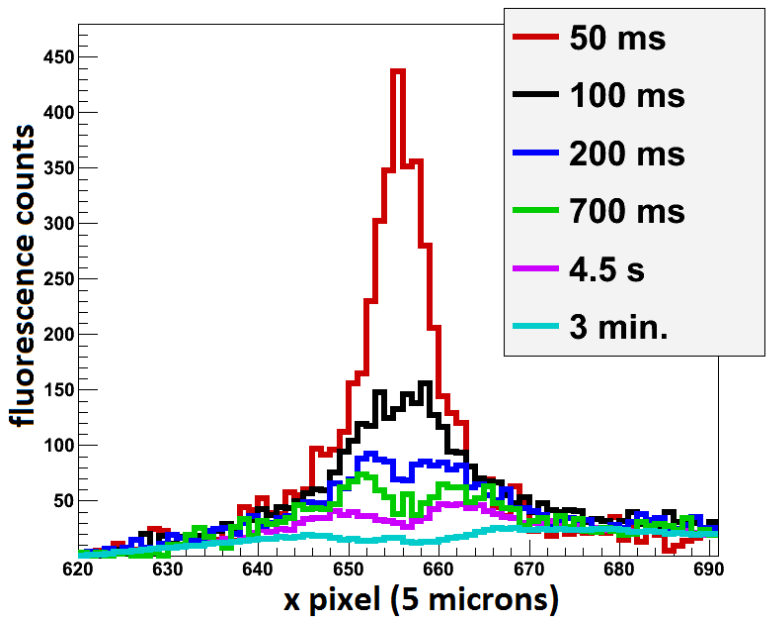
Imaging 591-nm Fluorescence w/ Focused Laser, ~1 mW



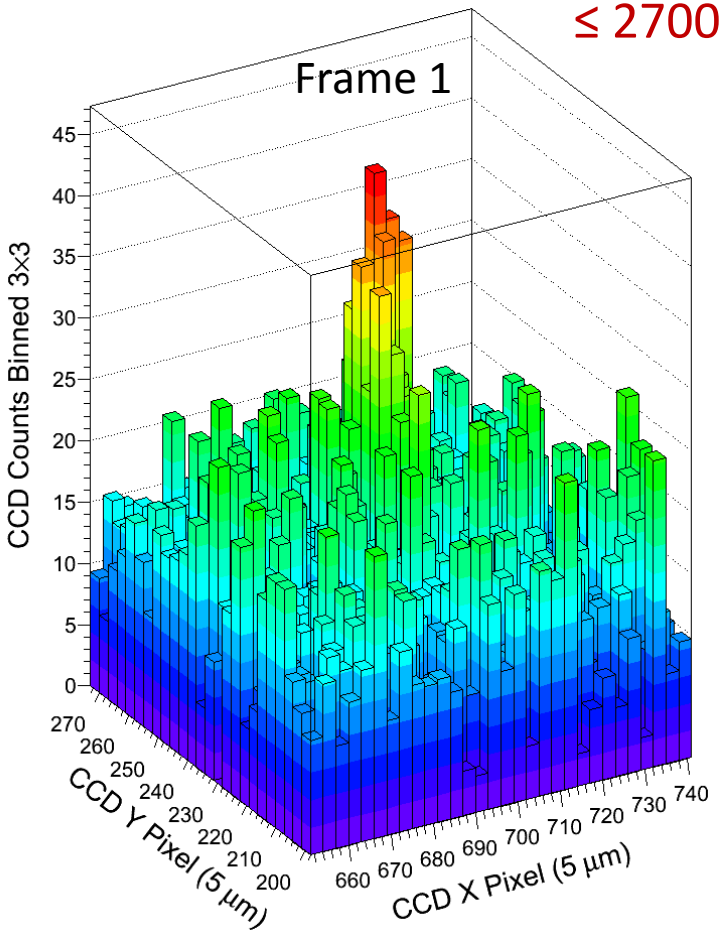
Cross-section at focus position:



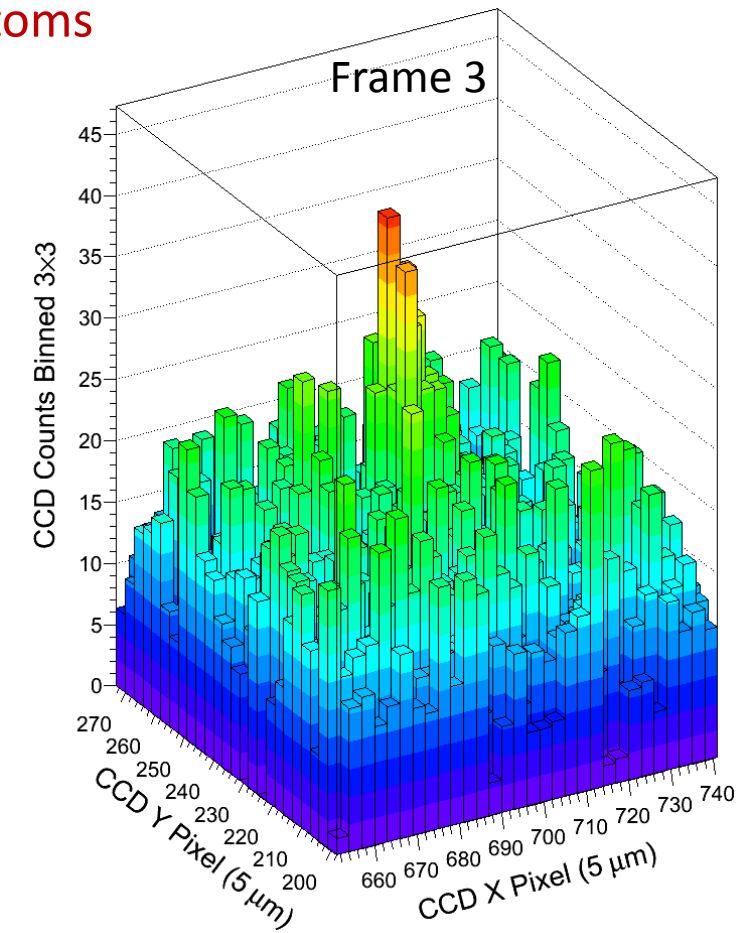
- Hole-bleaching occurs rapidly at high laser intensity.
- Need to use low laser power to image only atoms within focused laser region.

Imaging 577-nm and 591-nm Fluorescence w/ Focused Laser, **0.03 μW**

≤ 2700 Ba atoms



...

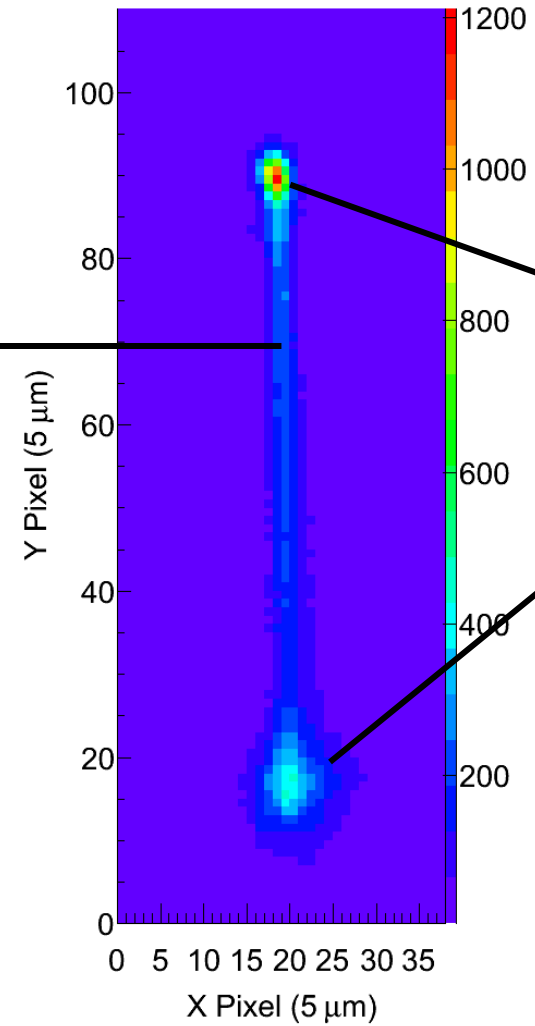


- Only slight bleaching at this intensity in 100-s exposures
- Backgrounds are negligible at this intensity

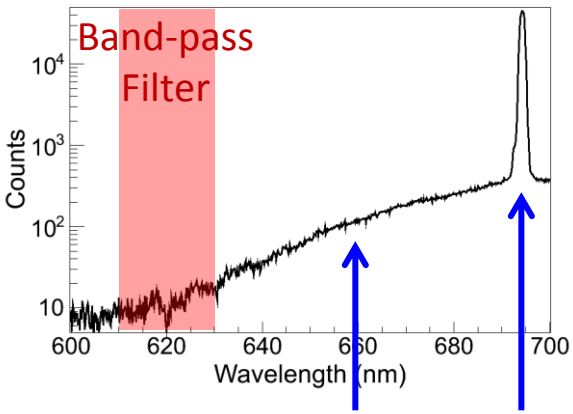
Imaging 619-nm Fluorescence

Backgrounds become important at high laser intensity

Image w/ 620-nm band-pass filter:



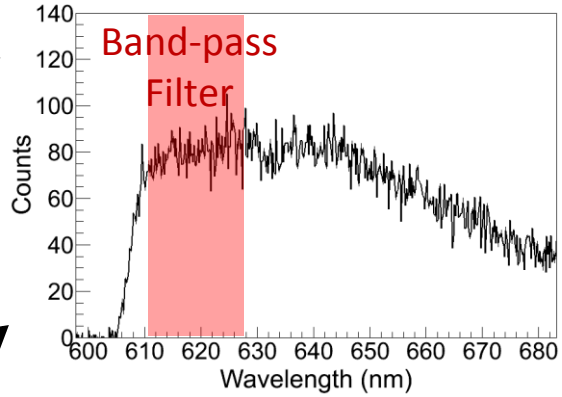
Sapphire Emission Spectrum:



Broad and sharp emission from Cr^{3+} impurities in sapphire window

- Minimized by high-purity windows
- Only low tail is passed by filter

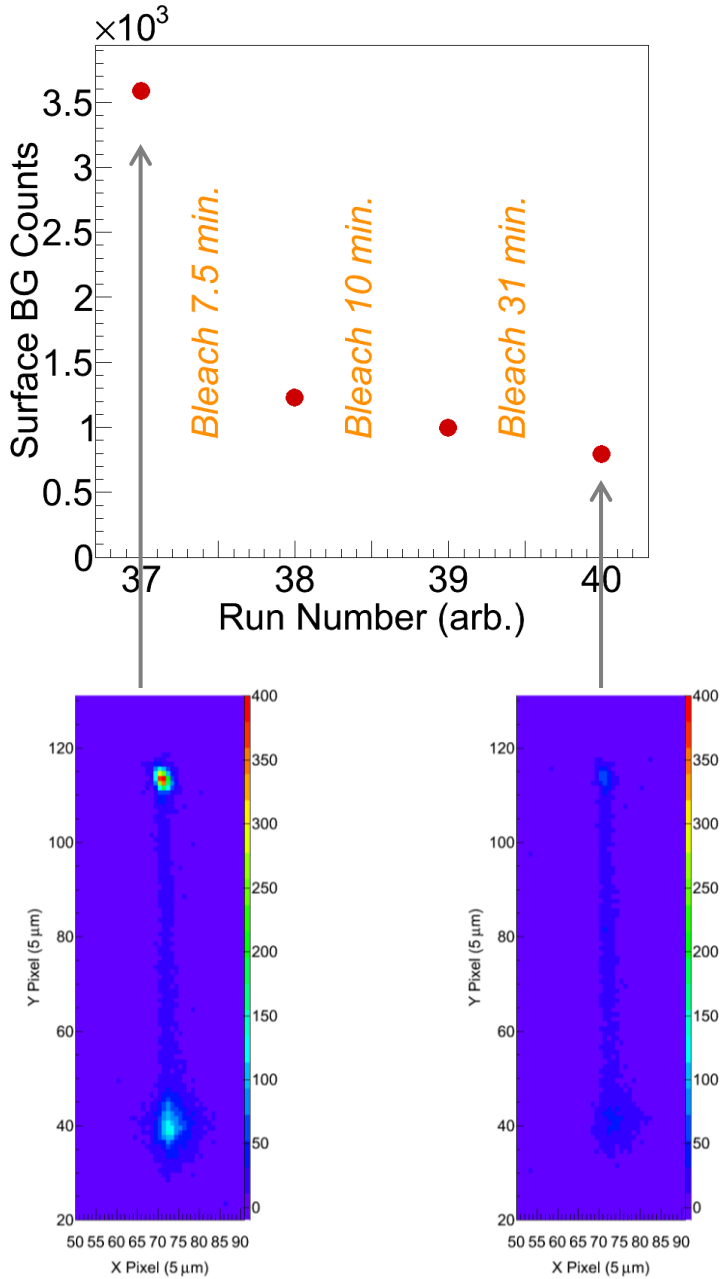
Surface Background Spectrum:



- Dominant background
- Bleaches with laser exposure – can be reduced

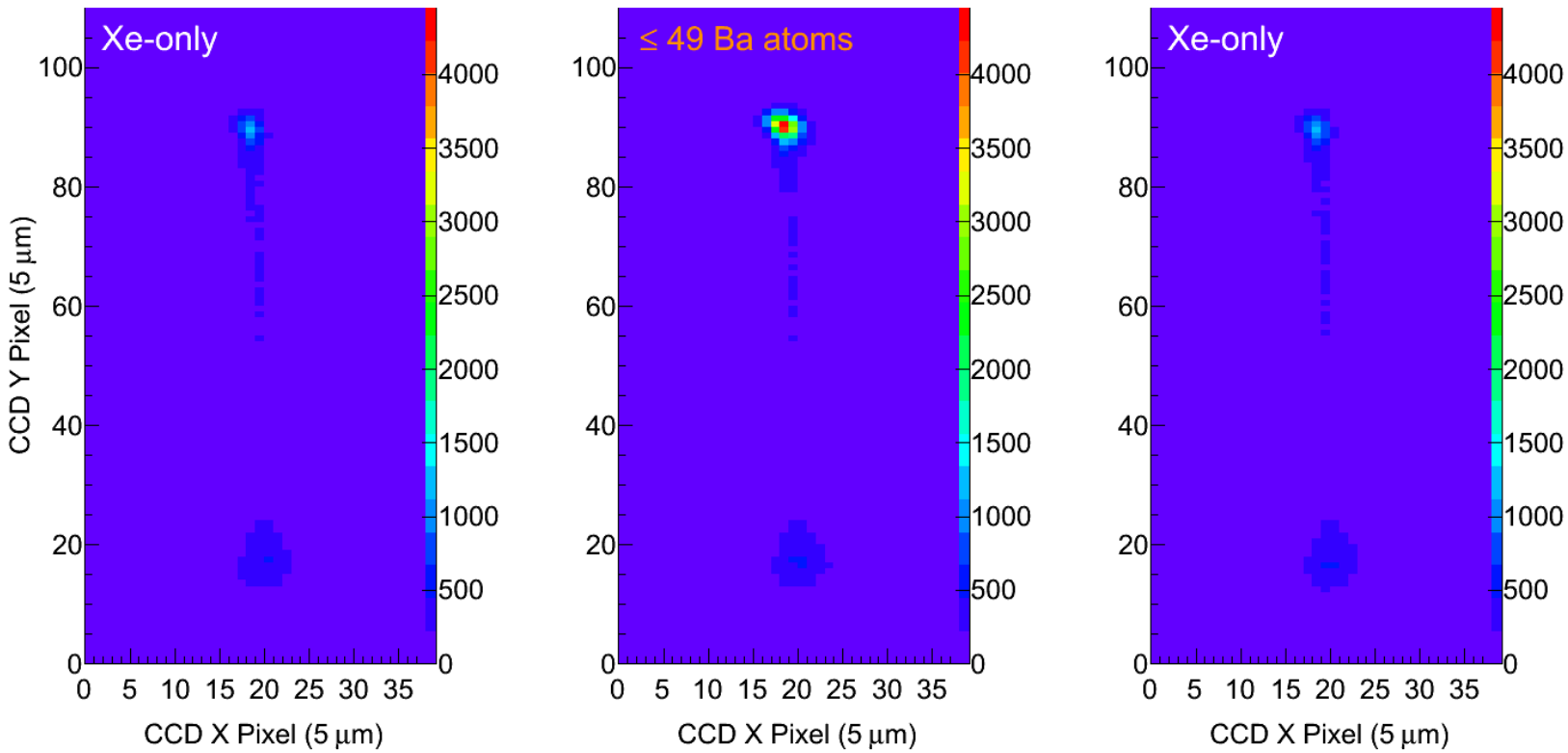
Bleaching of the Surface Background

Surface background counts during pre-bleaching process:



Imaging 619-nm Fluorescence

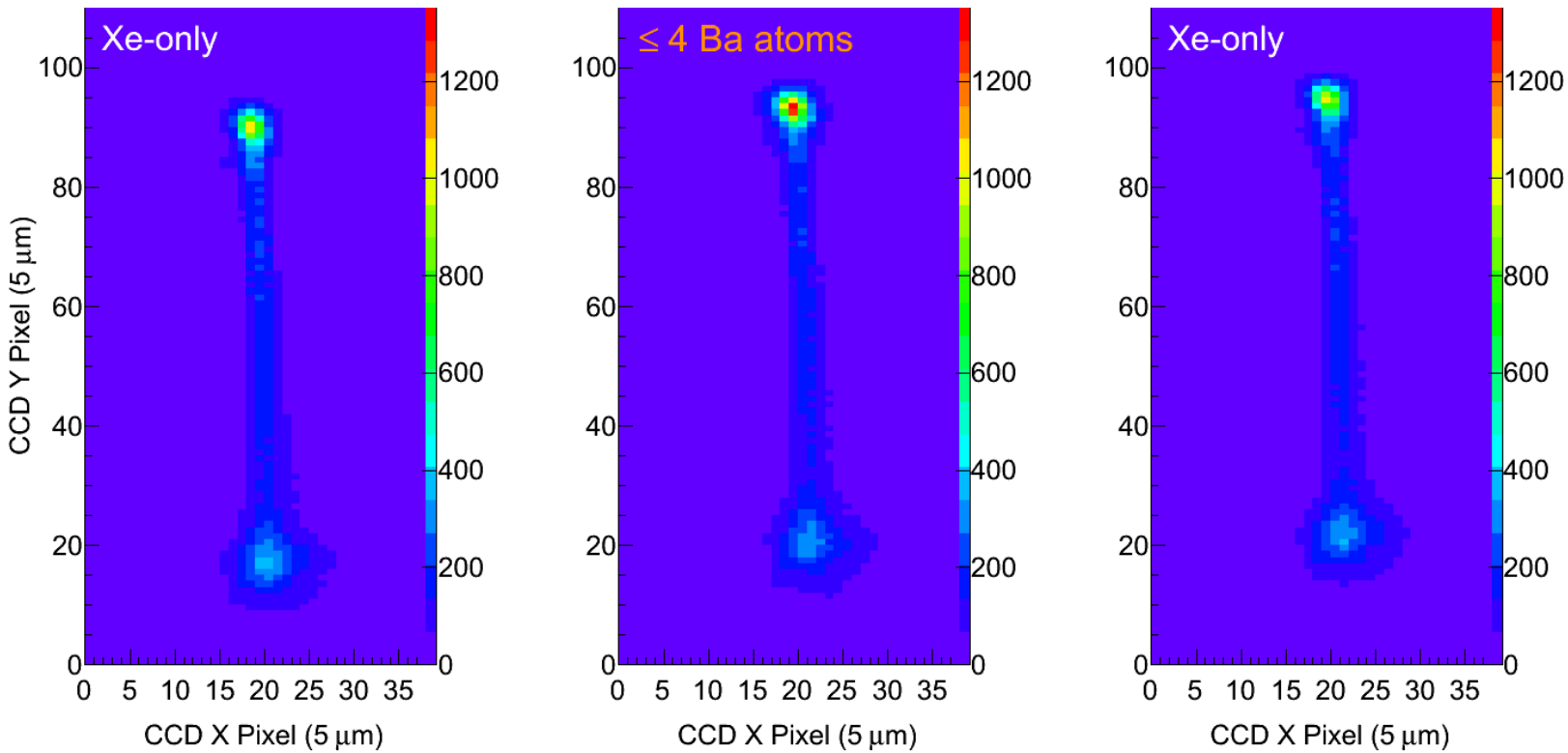
Xe-only deposits are observed in between Ba+ deposits
to monitor surface background:



Ba signal is clear over background

Imaging 619-nm Fluorescence

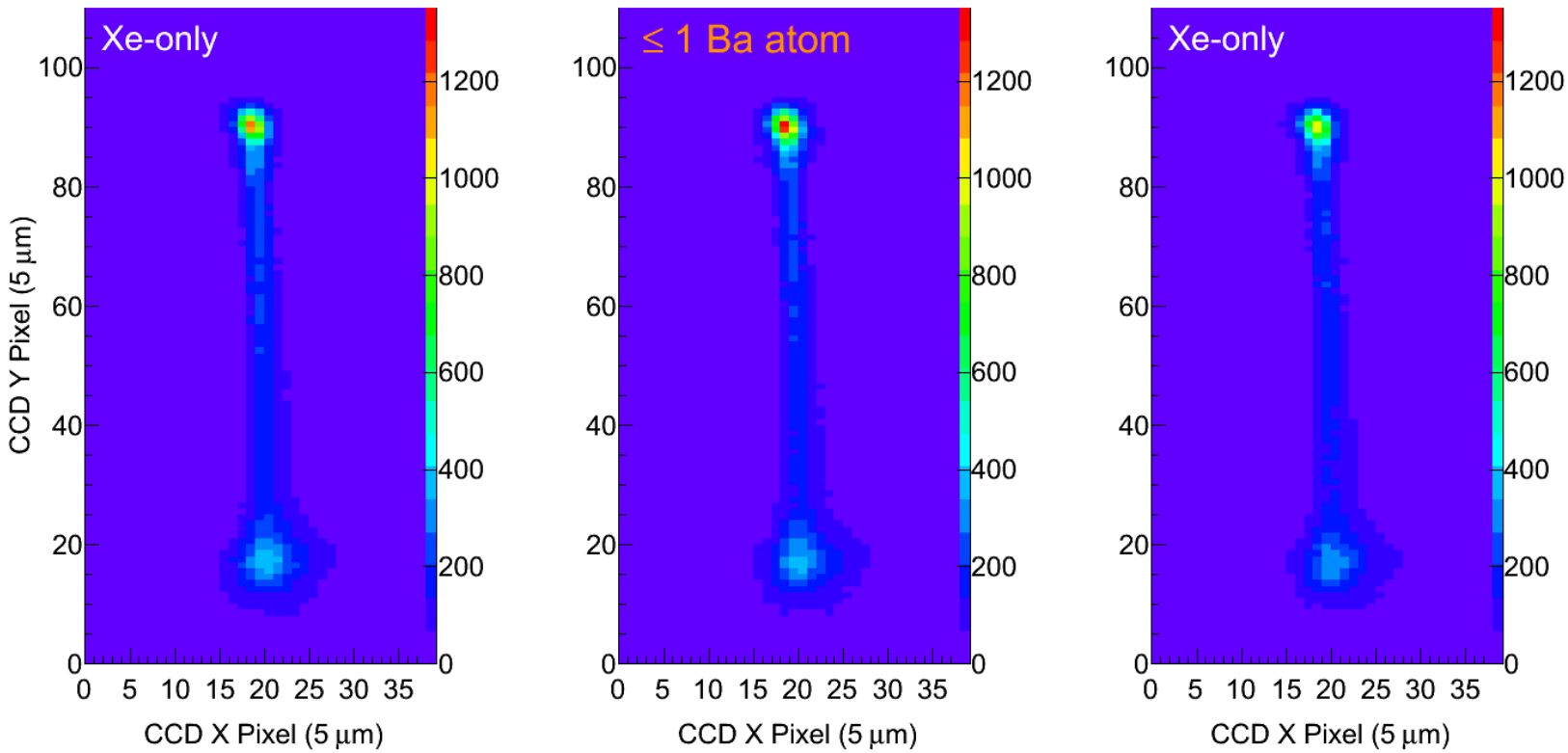
Xe-only deposits are observed in between Ba+ deposits
to monitor surface background:



Ba signal is clear over background

Imaging 619-nm Fluorescence

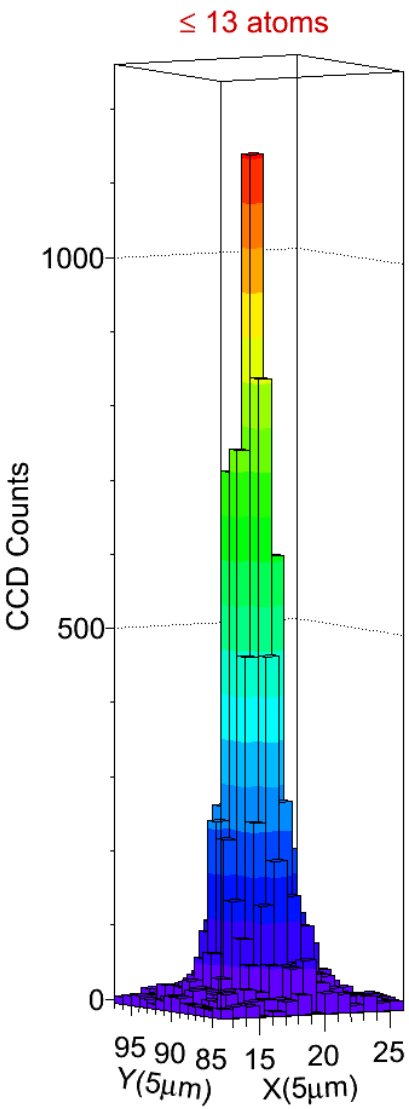
Xe-only deposits are observed in between Ba+ deposits
to monitor surface background:

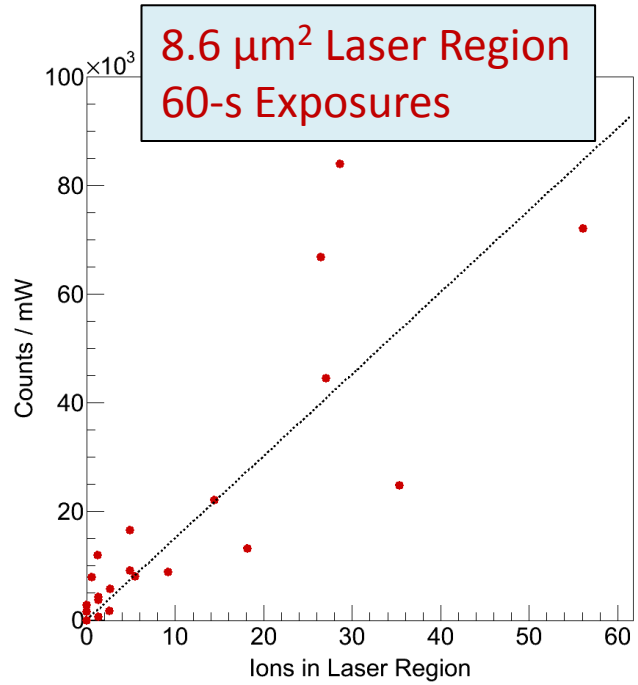


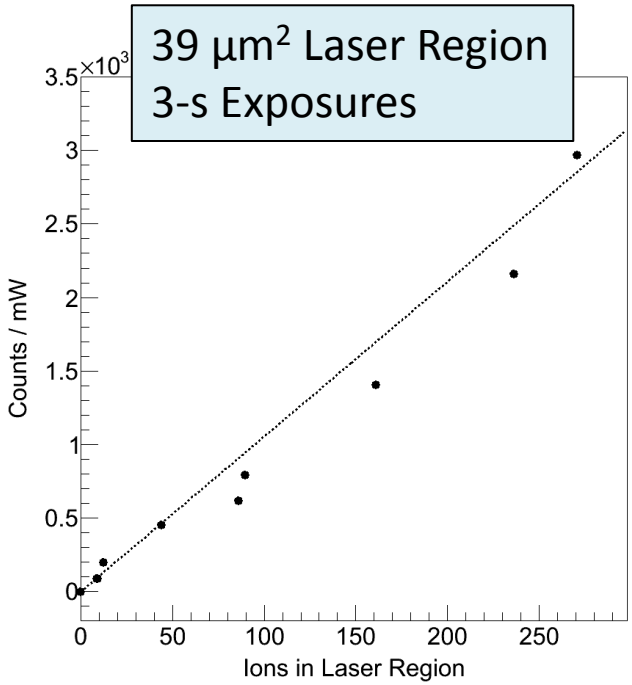
Single-atom signal is distinguishable by eye!

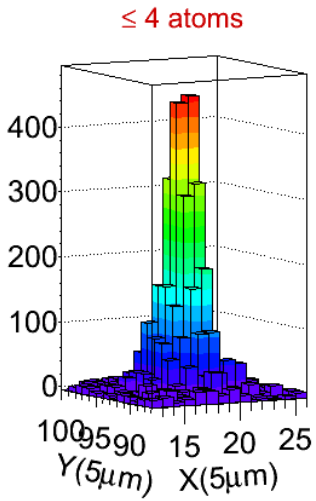
Imaging 619-nm Fluorescence

619-nm signal vs. ions in laser for two different experiments:

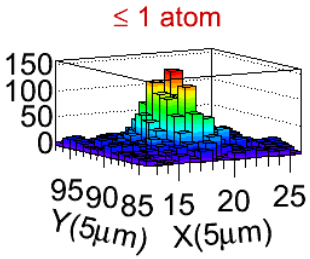


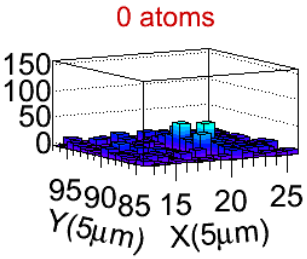






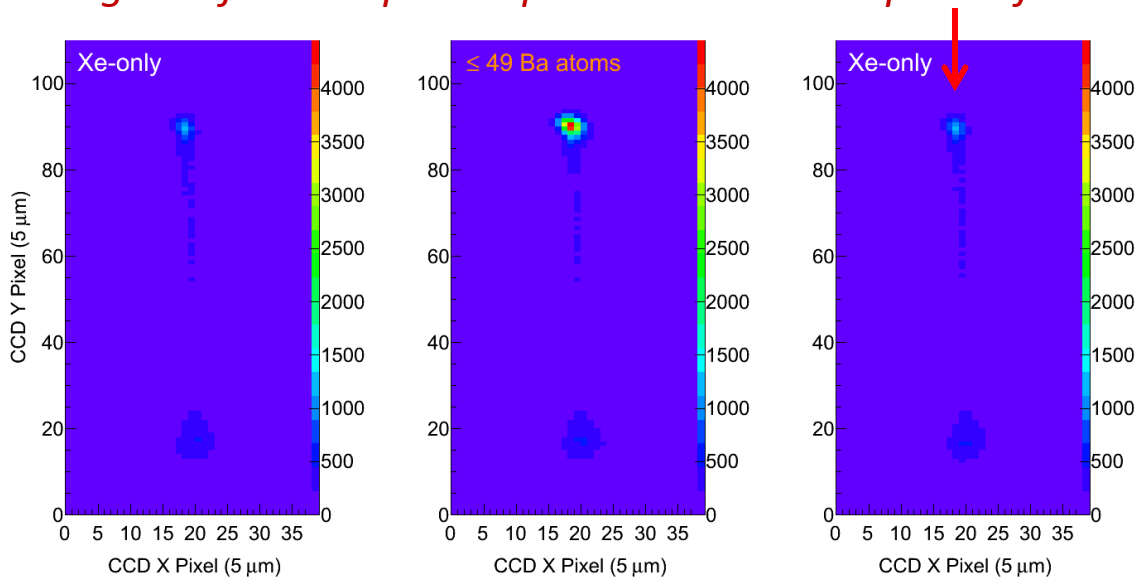
- 1500 ± 160 counts/mW from single atoms w/ 8.6 μm² laser region, 60-s exposures
- Linear relationship rules out Ba_2 molecule



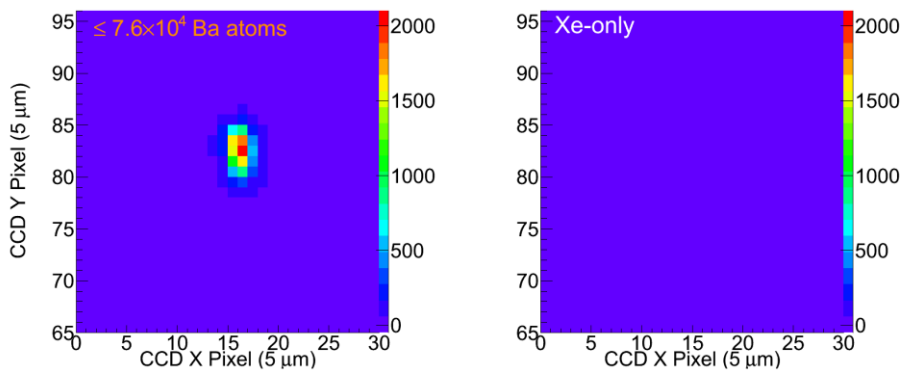


Imaging 619-nm Fluorescence

No Ba signal after sample evaporation and re-deposit of Xe-only



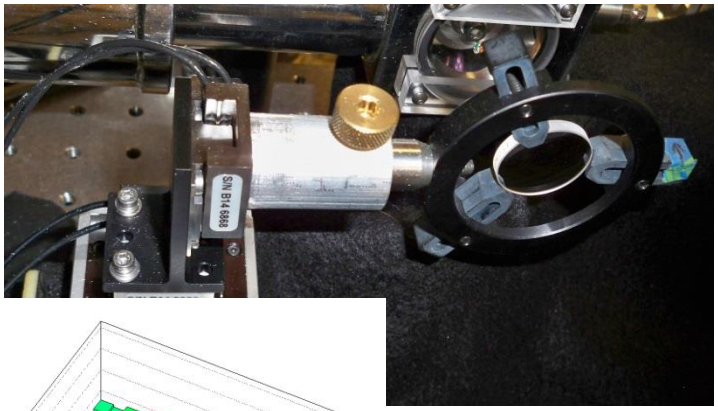
Even in large Ba deposits:



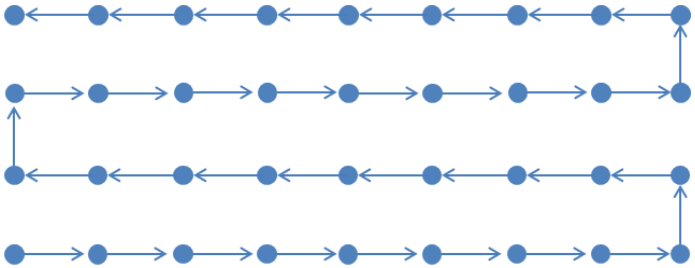
Very important result for a Ba tagging cold probe in nEXO

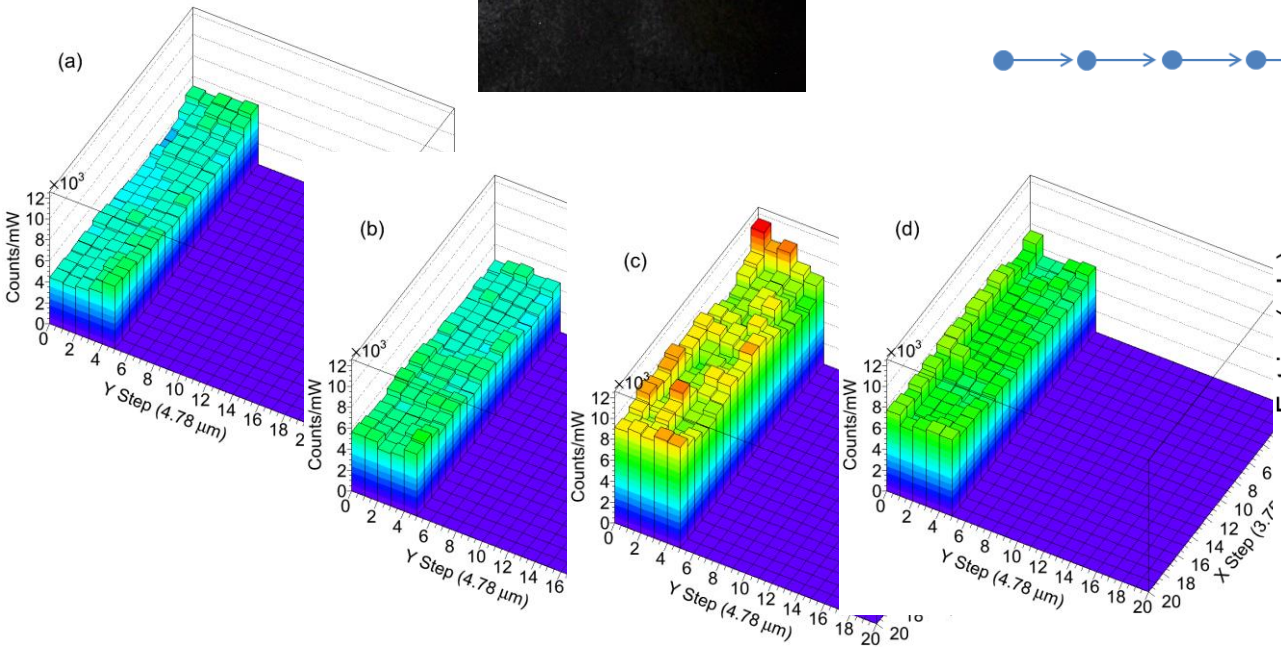
Next Step: Scanned Images of Ba atoms

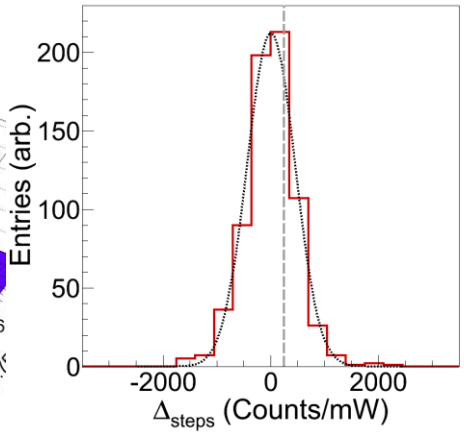
Scan laser by scanning focusing lens:



Each camera exposure is for a position in a grid:



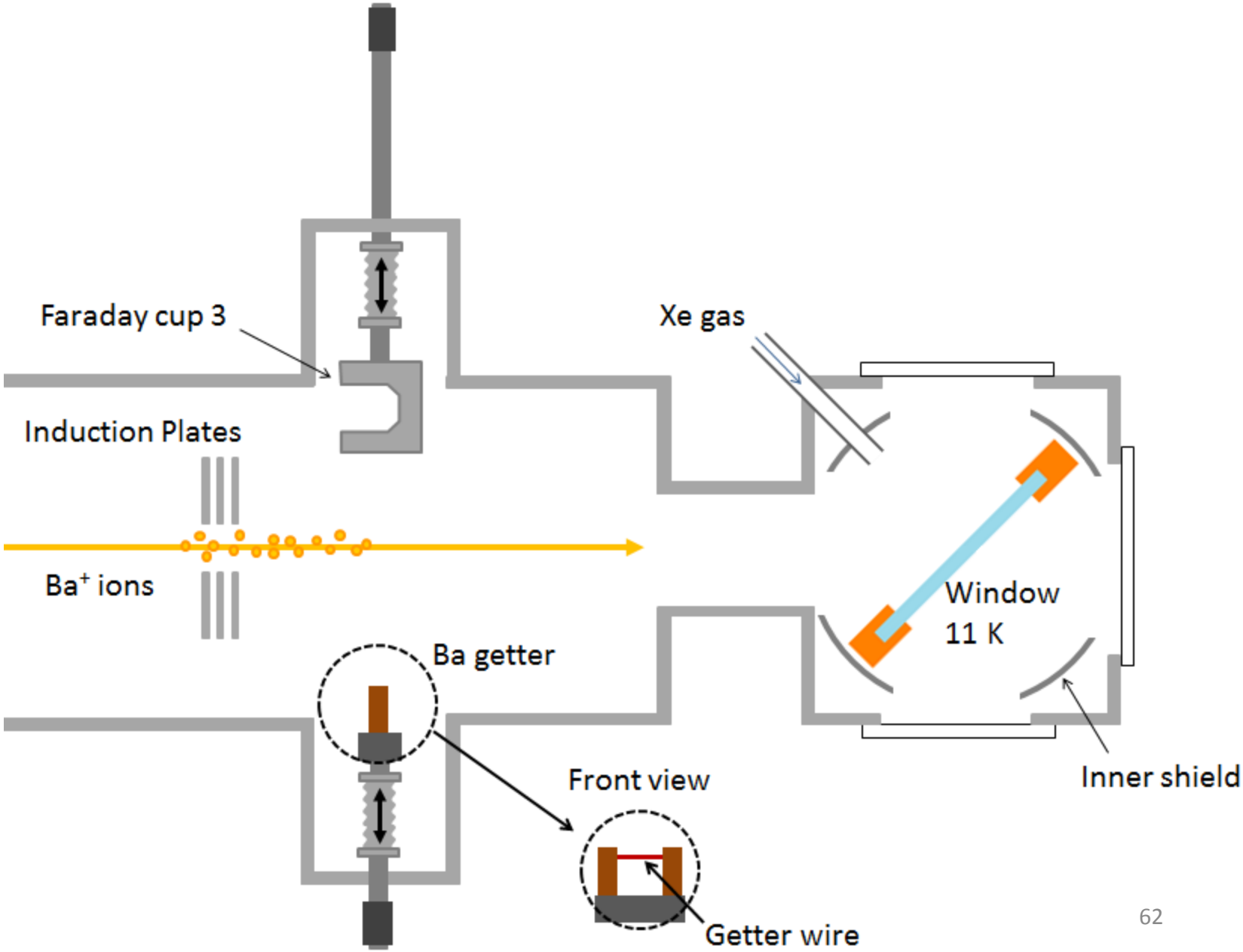


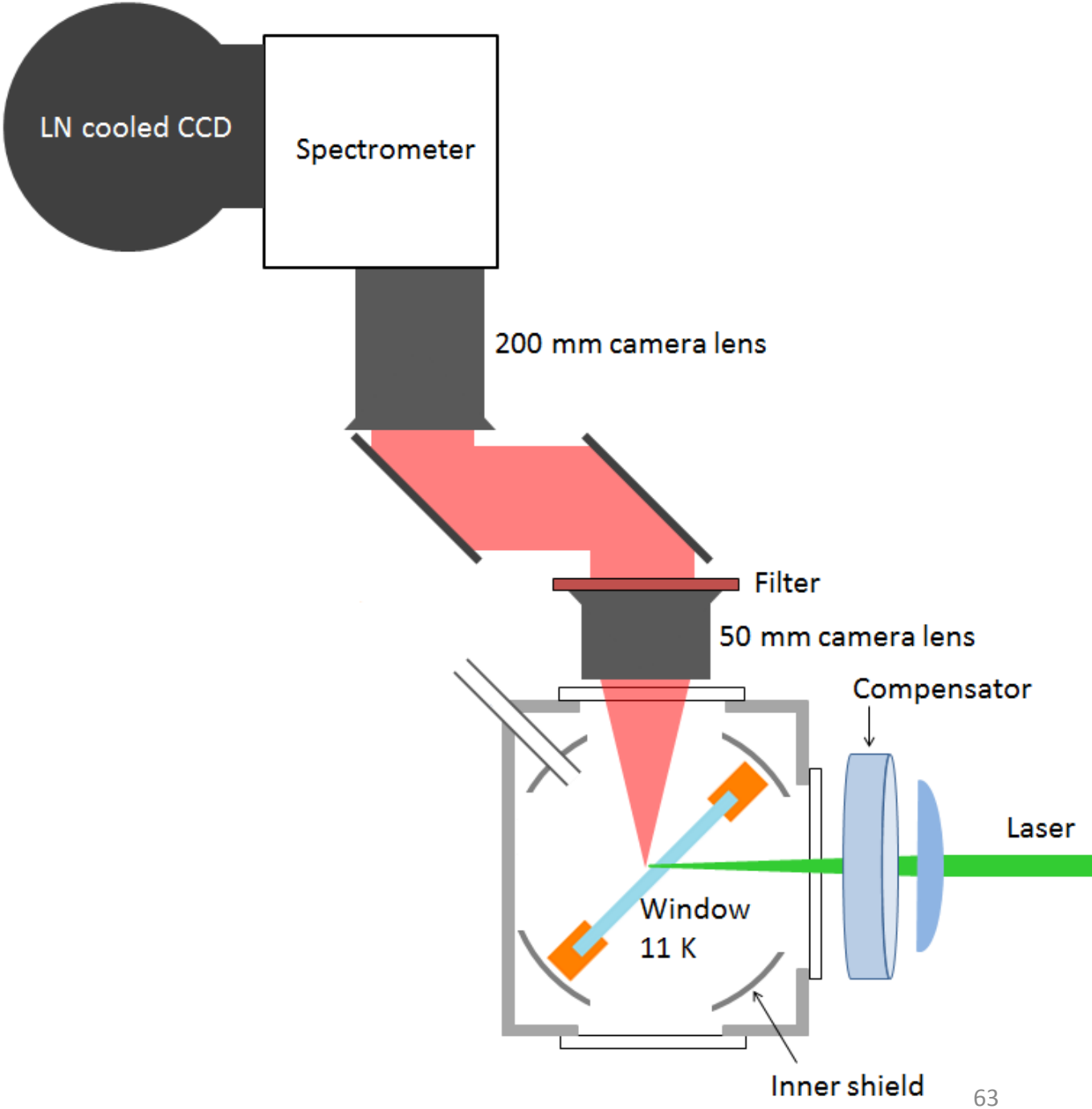


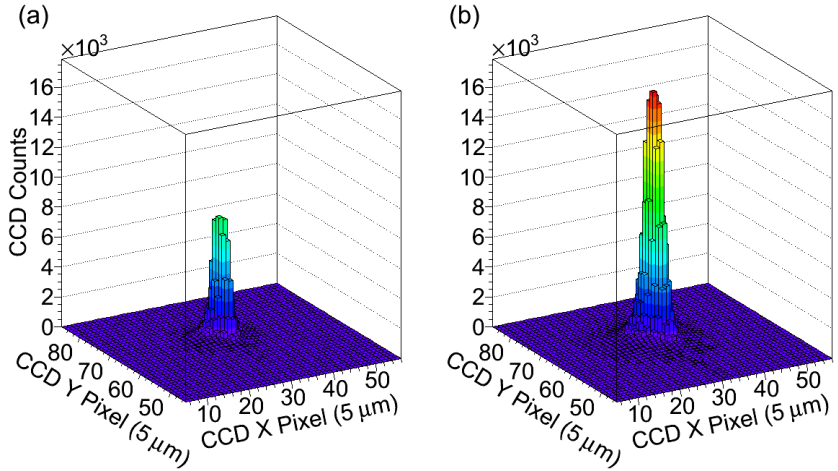
Conclusions

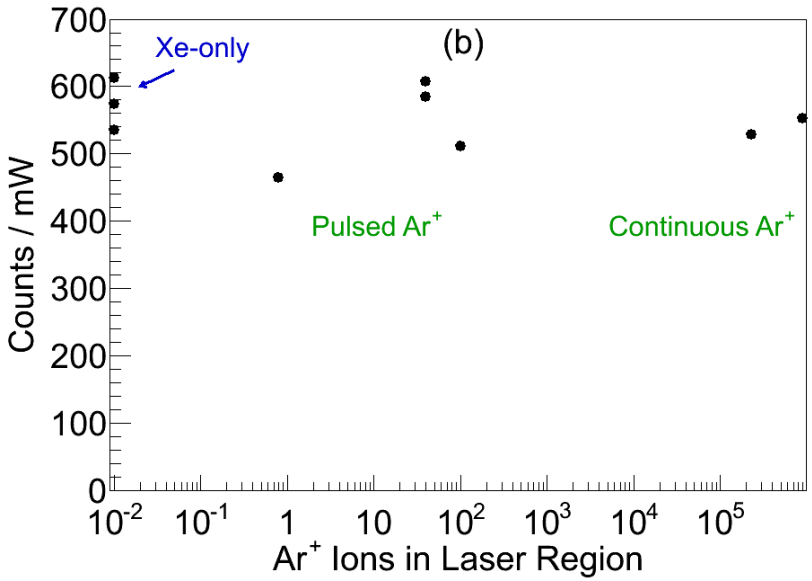
- Summarized study of neutrinos by neutrinoless double beta decay in EXO
- um

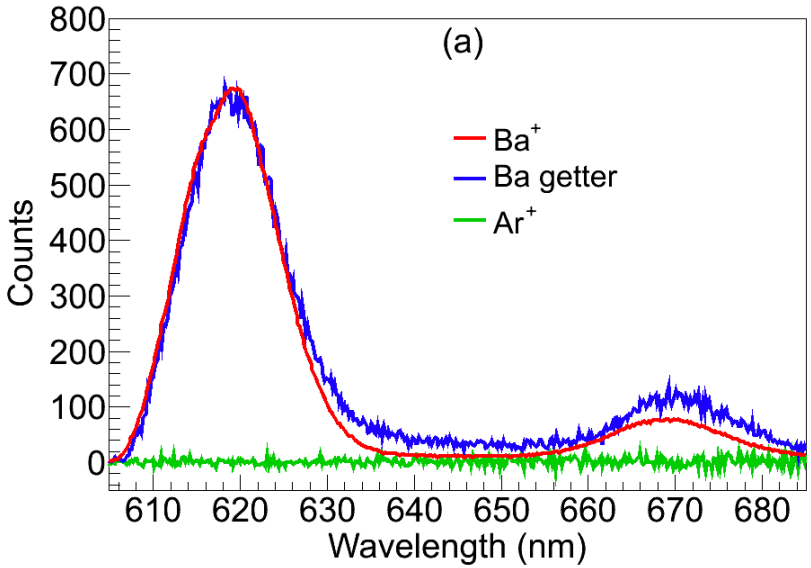
Ba^+/Ba Deposition




LN cooled CCD
Spectrometer
200 mm camera lens
Filter
50 mm camera lens
Compensator
Laser
Window
11 K
Inner shield

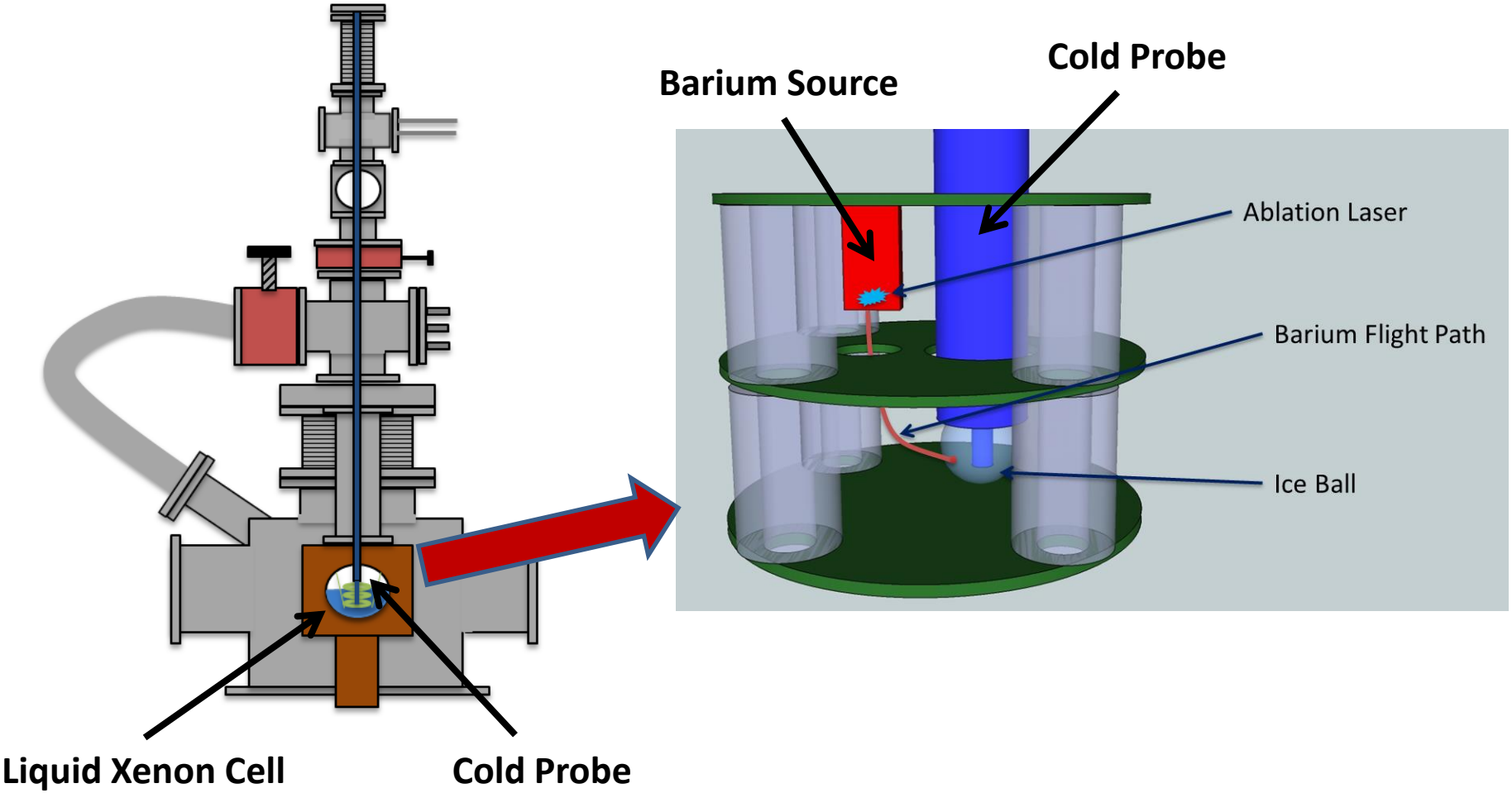

(a)
(b)
×10³
CCD Counts
CCD Y Pixel (5 μm)
CCD X Pixel (5 μm)


(b)
Xe-only
Pulsed Ar+
Continuous Ar+
Counts / mW
Ar+ Ions in Laser Region


(a)
Ba+
Ba getter
Ar+
Counts
Wavelength (nm)

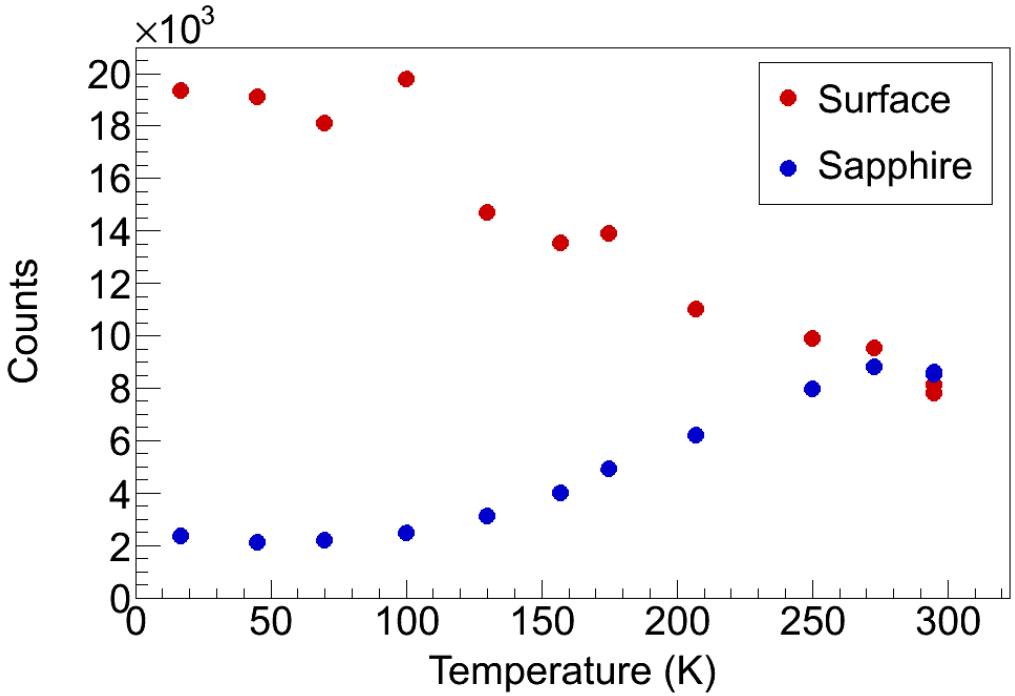
Ion Extraction from Liquid Xenon

Currently underway in parallel, by Chris Chambers and Adam Craycraft

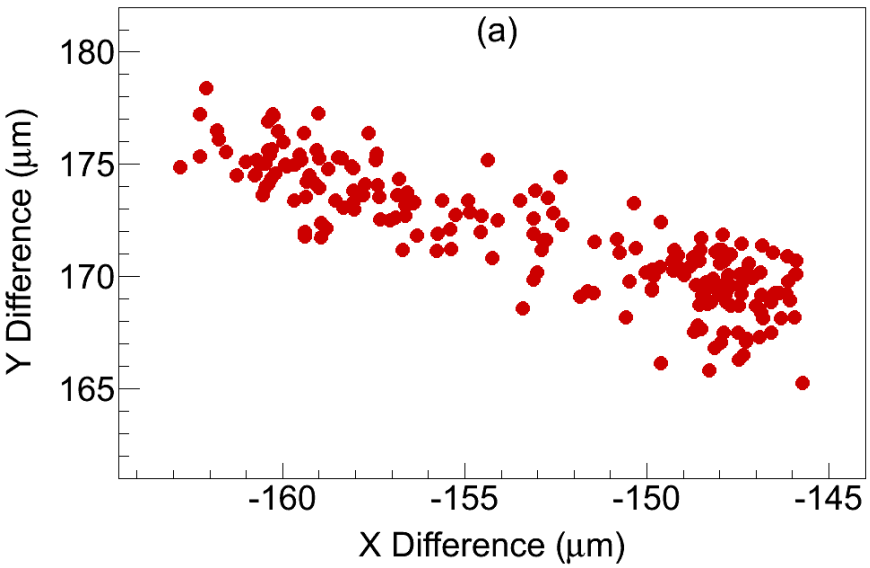


9.9 events in 2 sigma is consistent w/ null at 1.2 sigma level

Backgrounds vs. Temperature:



Cryostat Vibrations:



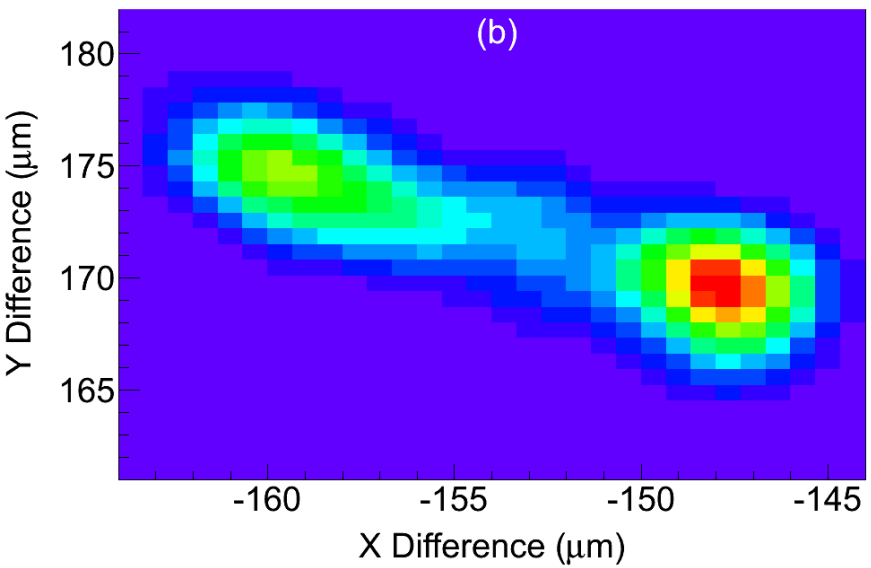
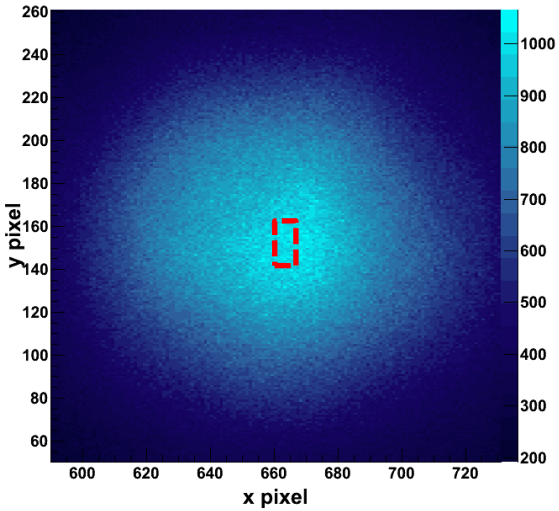
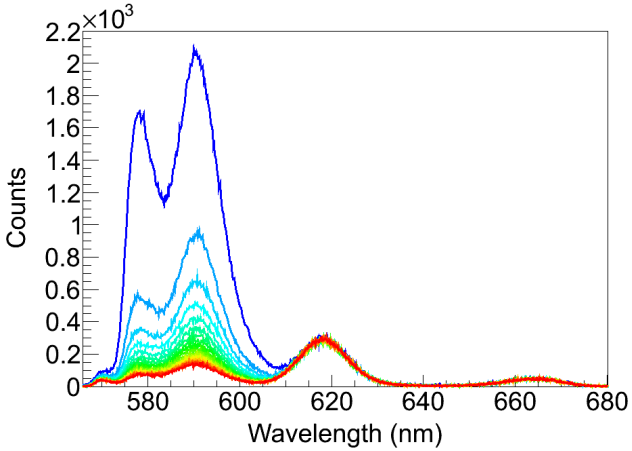


Image of fluorescence
by semi-focused laser:





Summary: optimal conditions for observing Ba in SXe

1) Deposit at 50 ± 5 K, observe at 11 K