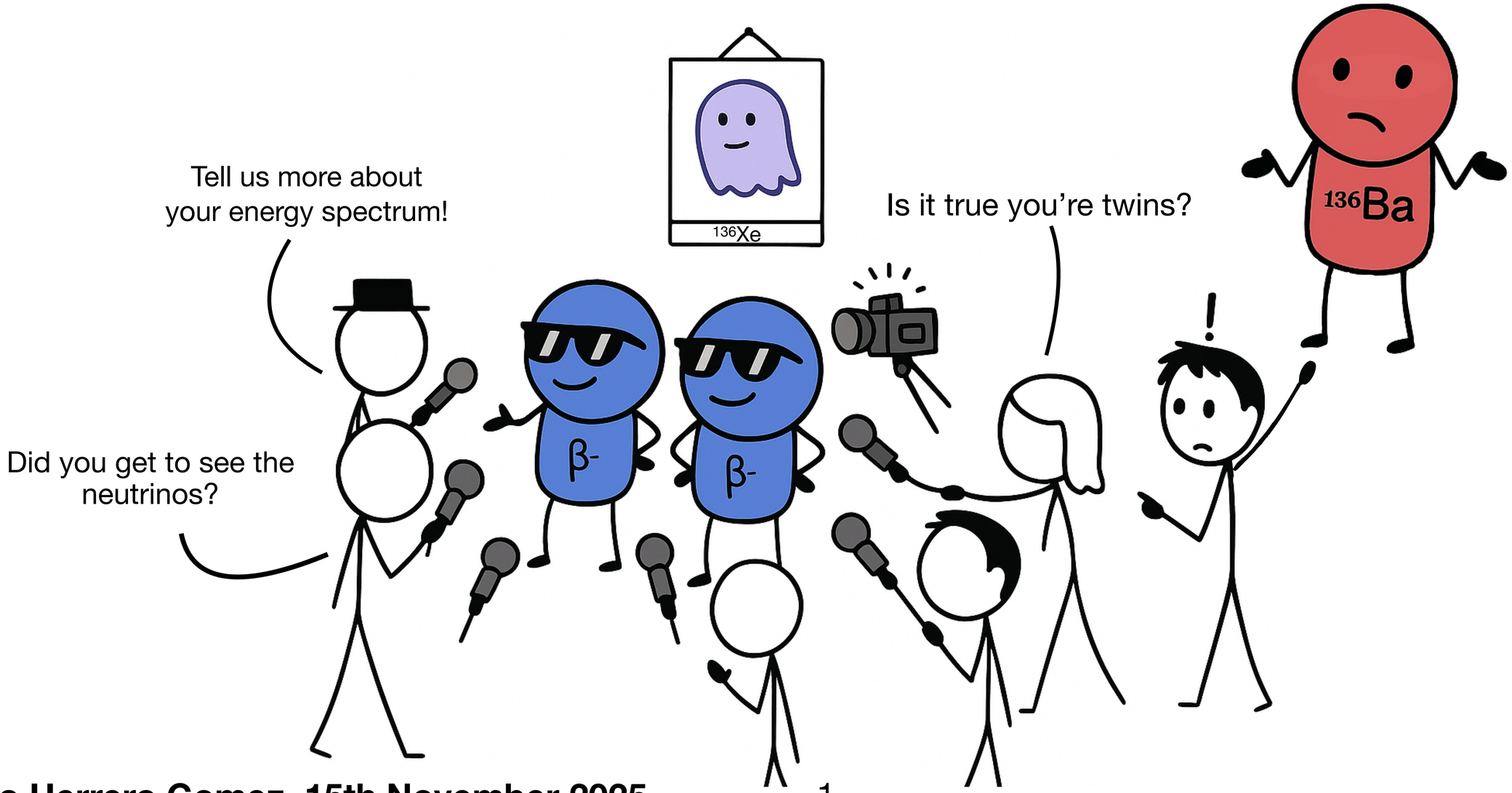
Barium Tagging for 0νββ searches

Overview and current efforts in NEXT and nEXO



Pablo Herrero Gomez, 15th November 2025

Why do we care about Barium?

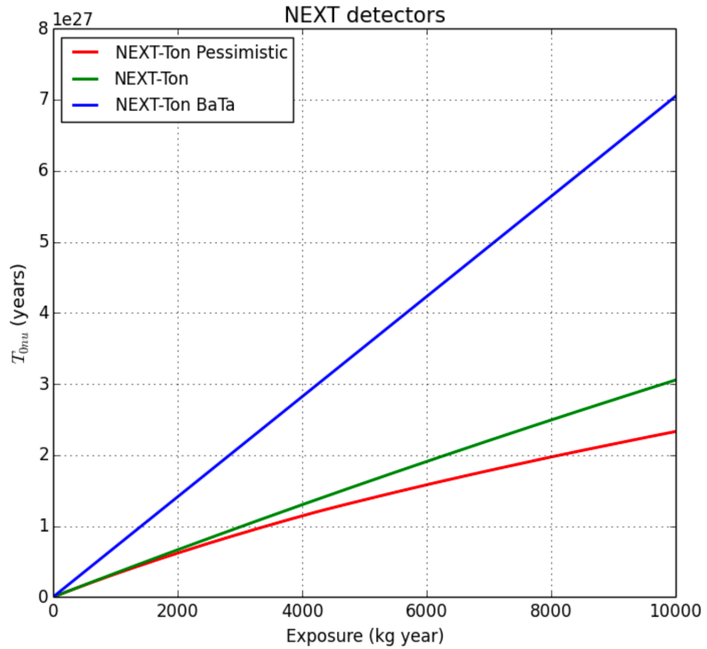
- Next generation Xenon TPCs need to reach lifetimes > 10^{27} years with one or several tons of Xe.
- At the same time, background needs to be mitigated down to the level of 10^{-3} counts/kg/year.
- The presence of Barium is an <u>indisputable evidence</u> of the ββ reaction occurrence:

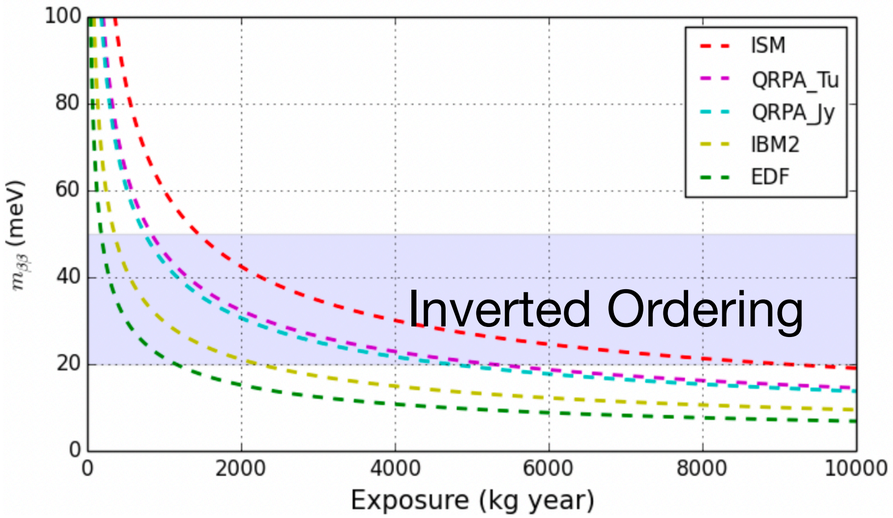
$$^{136}Xe \rightarrow {}^{136}Ba + 2e^{-} (+ 2\nu_e)$$

- Different approaches for GXe (Ba^{2+}) and LXe (Ba^{+}).

How far could we go?

- Linear scale of sensitivity to $\tau_{0\nu\beta\beta}$ would with exposure if zero background.
- The full IO (blue shaded area) of $m_{\beta\beta}$ could be probed with 1 ton $\times$ 10 years exposure.

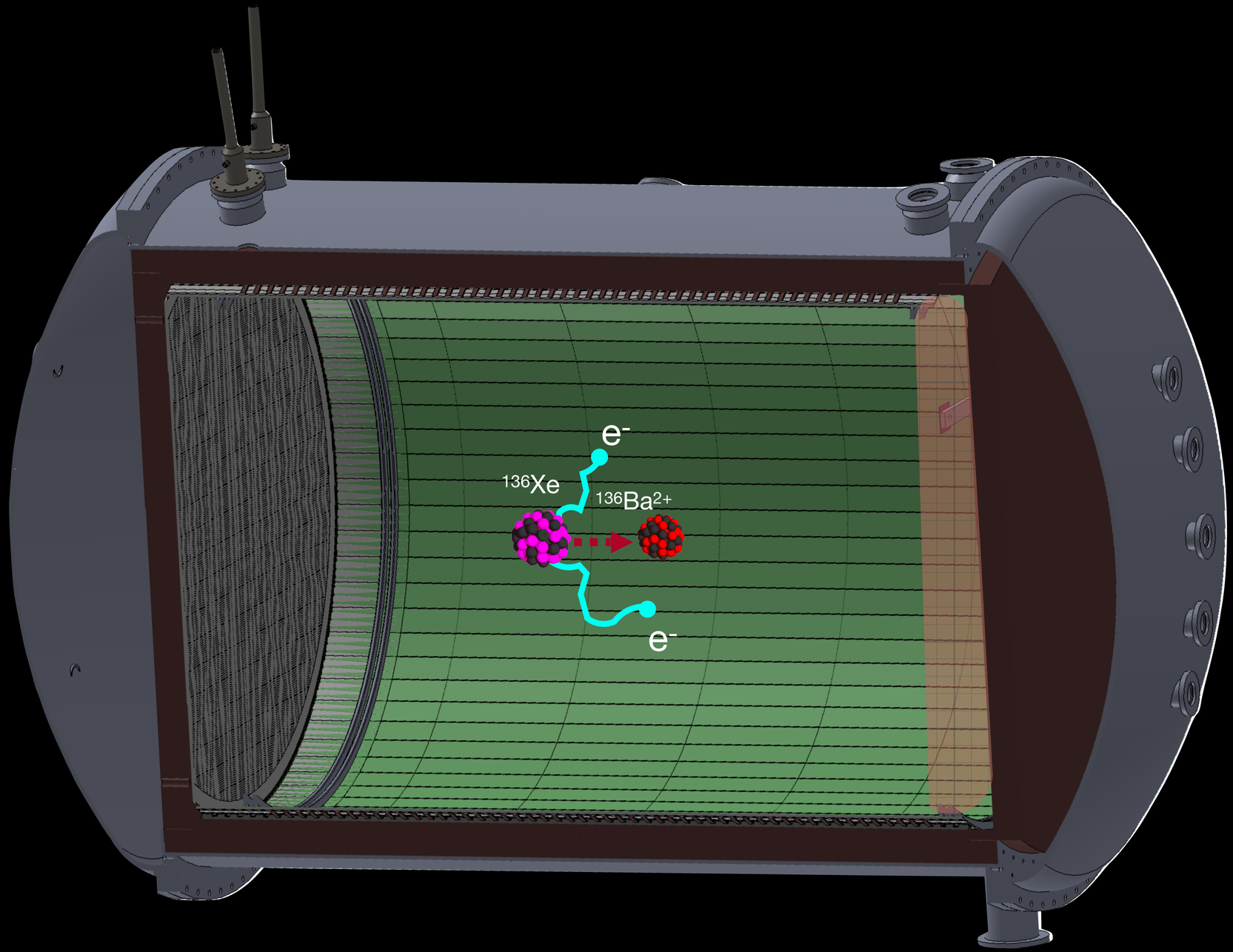


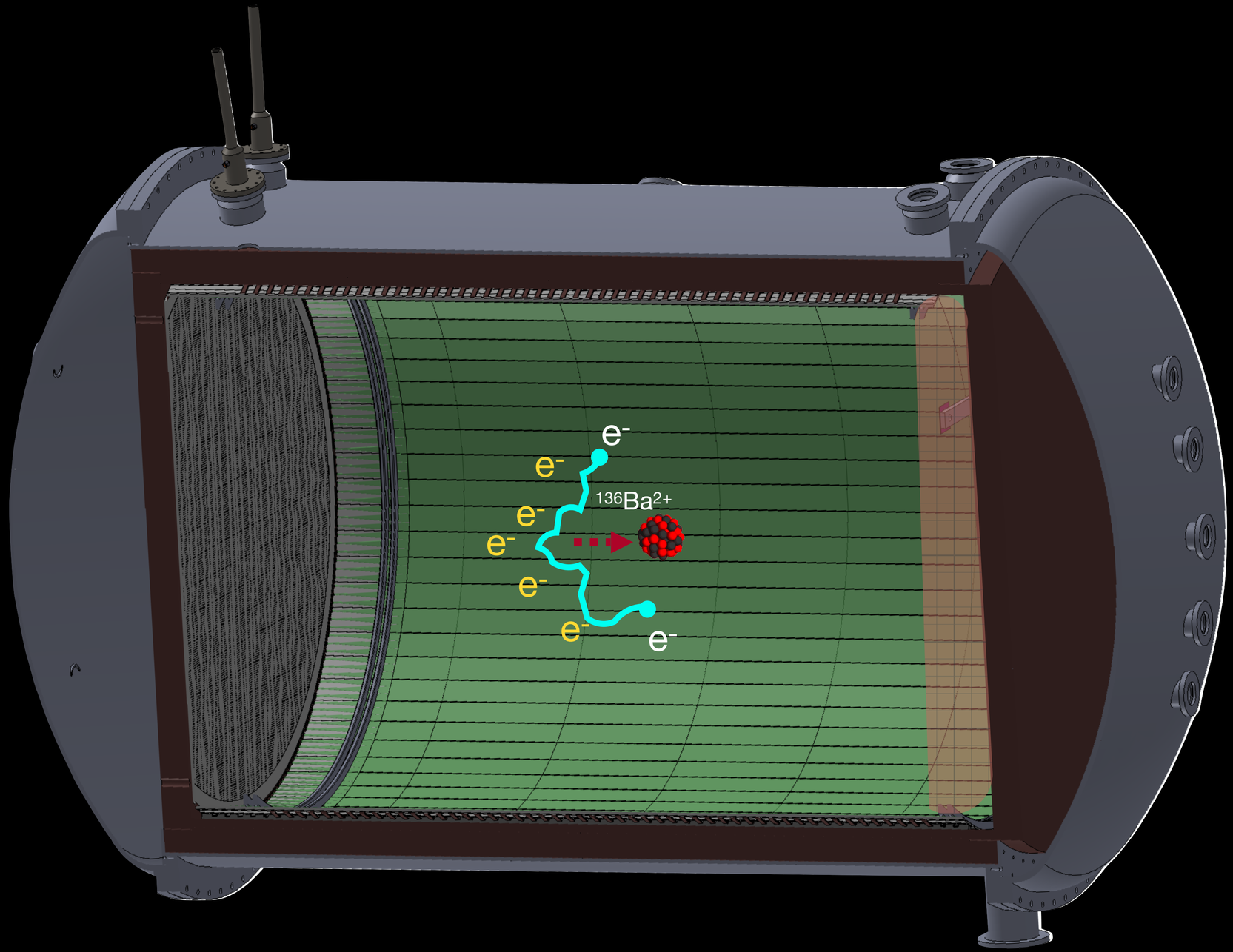


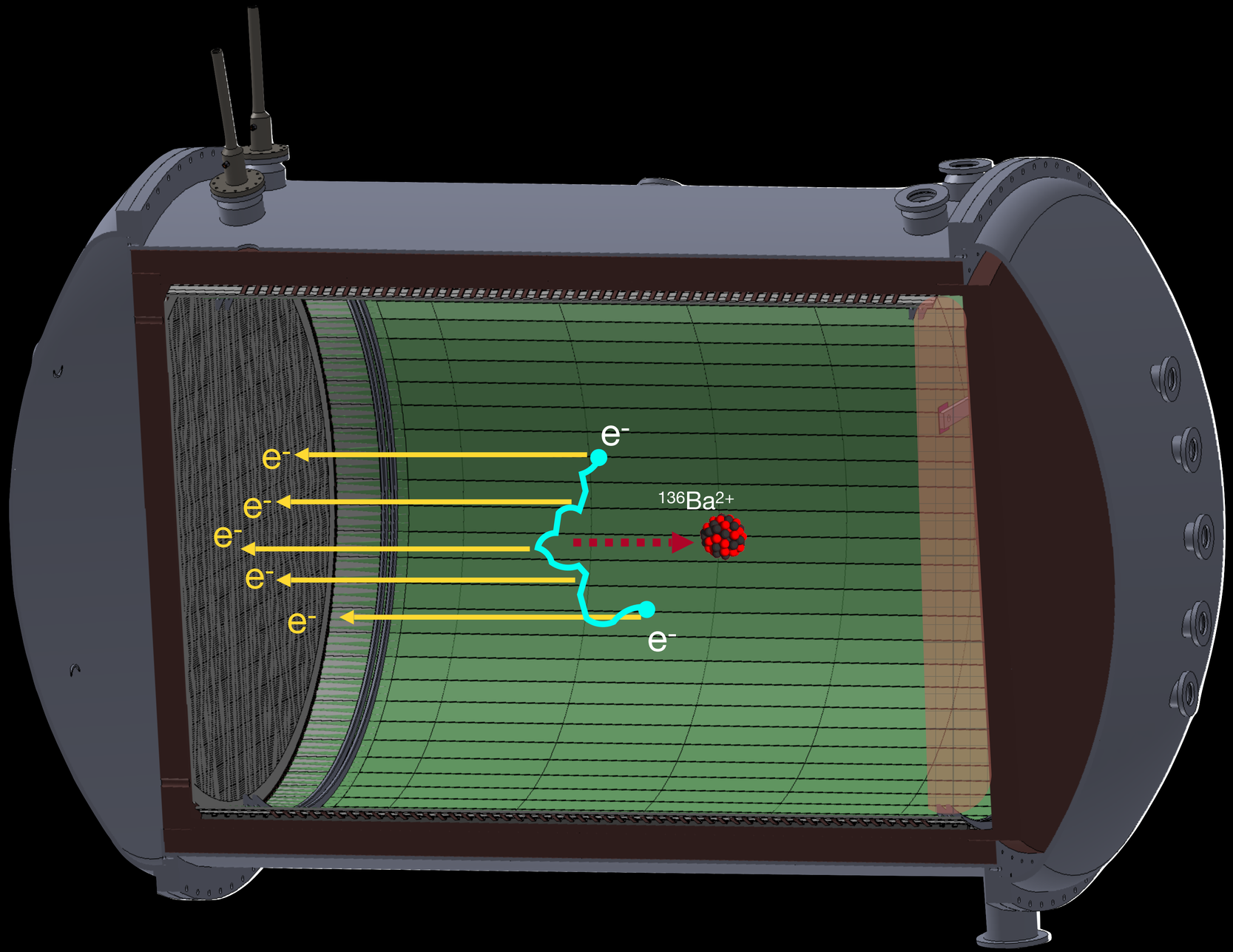
From J. Muñoz (2018) PhD Thesis

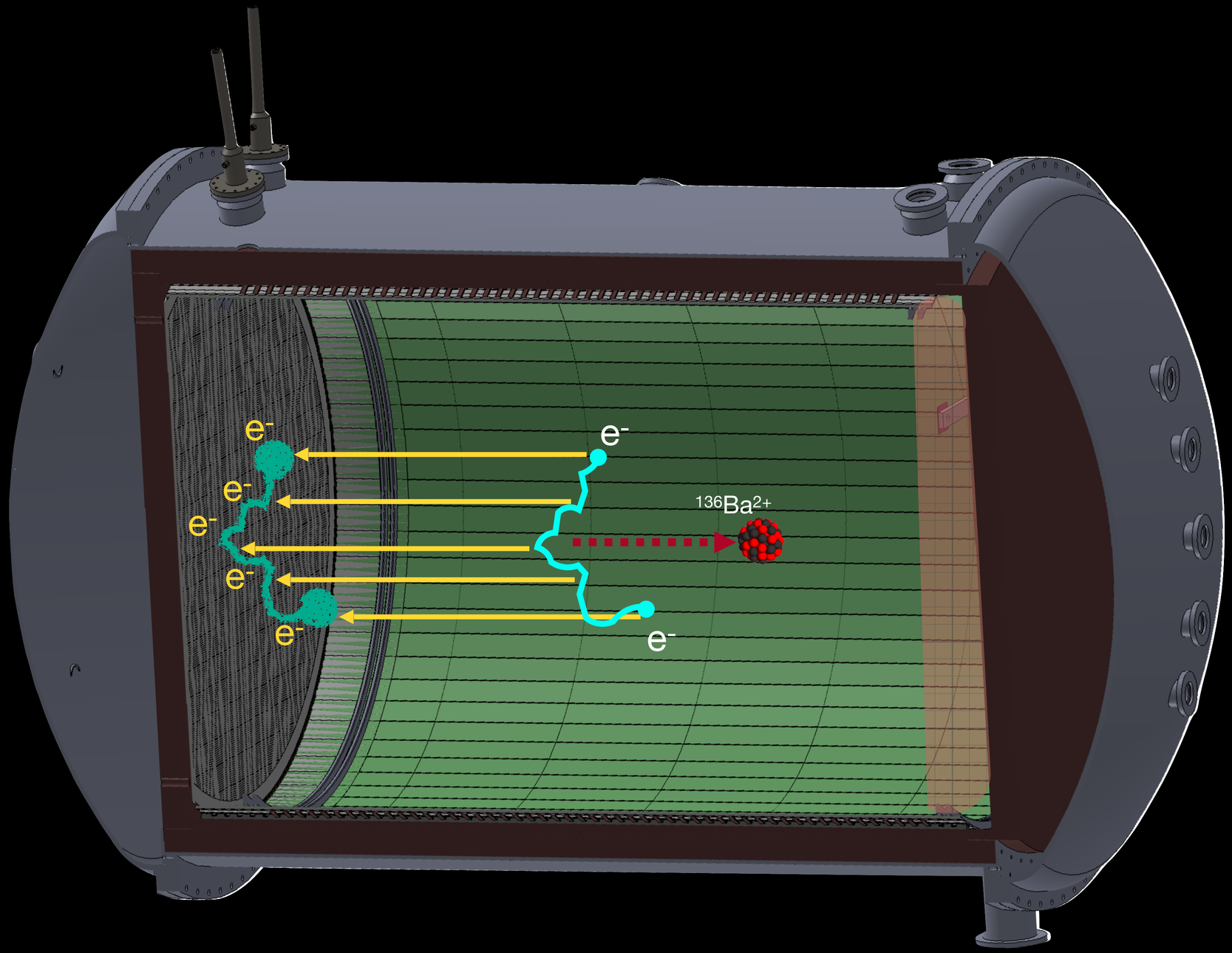
Overview

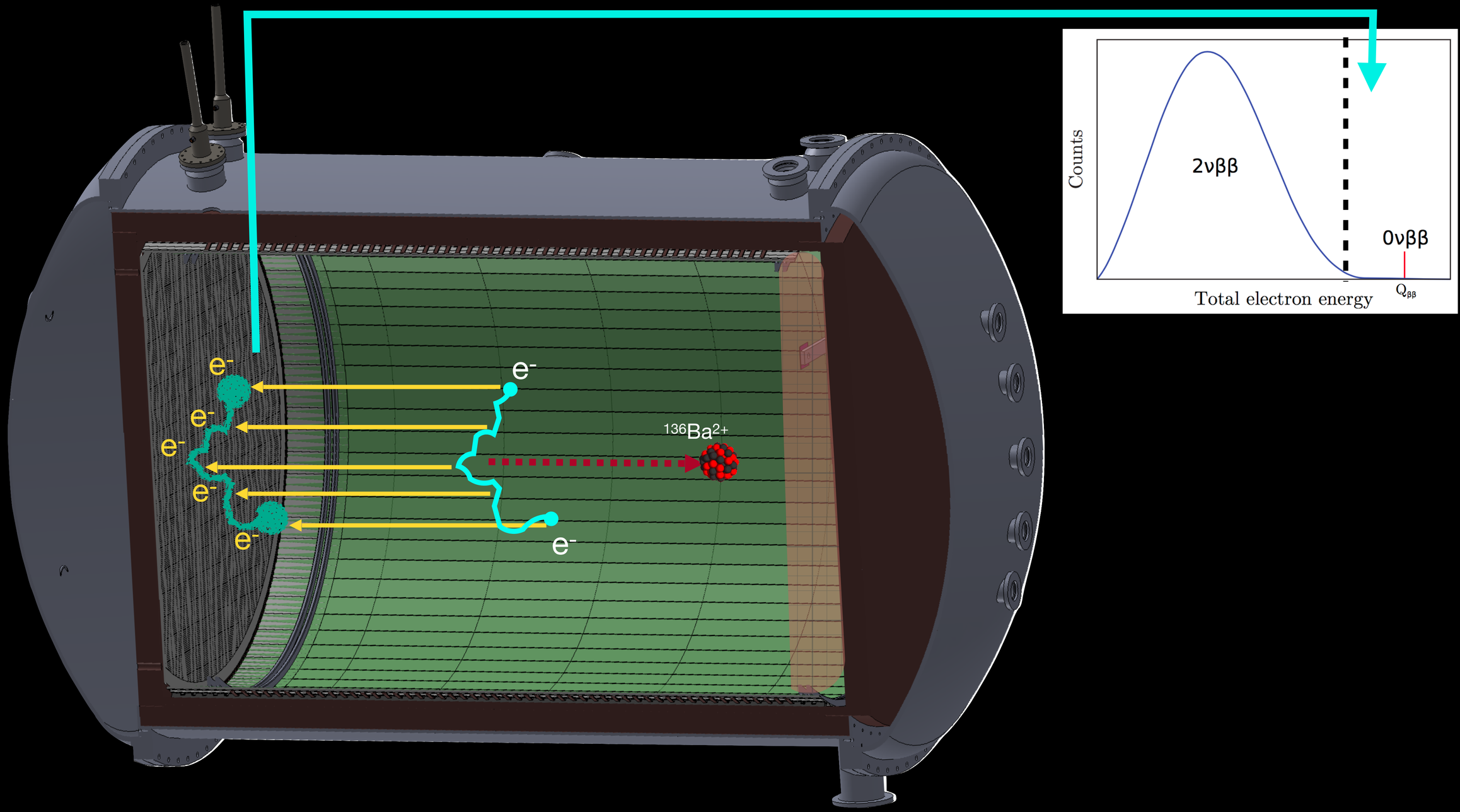
- [x] Introduction to Ba-tagging
- [ ] **Ba-Tagging in NEXT**
  - [ ] **System design**
  - [ ] Chemo-sensors characterization
  - [ ] Optical detection
  - [ ] Ion sources and guiding systems
- [ ] Ba-Tagging in nEXO
- [ ] The road forward

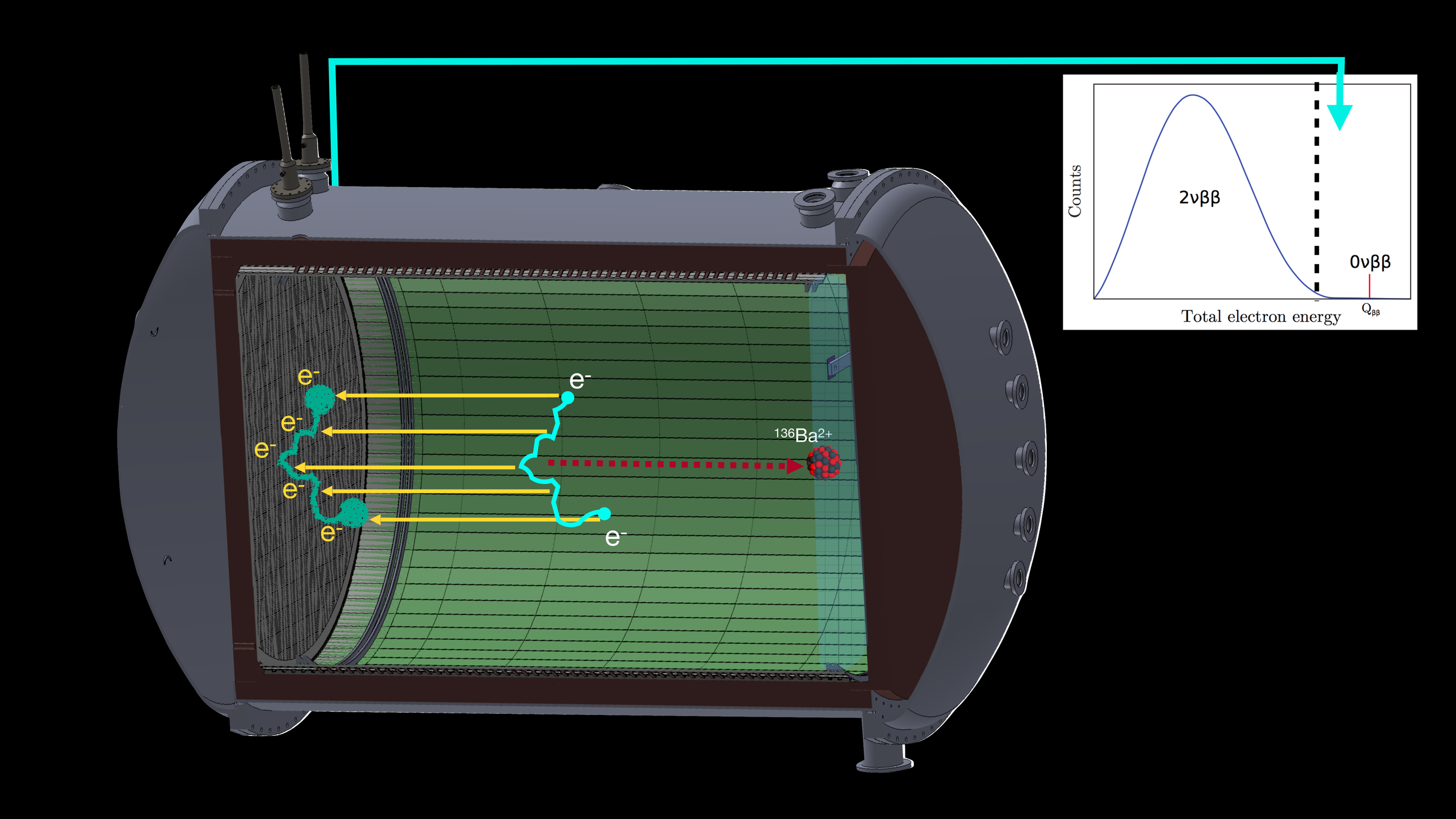

e⁻
^{136}Xe
^{136}Ba^{2+}
e⁻

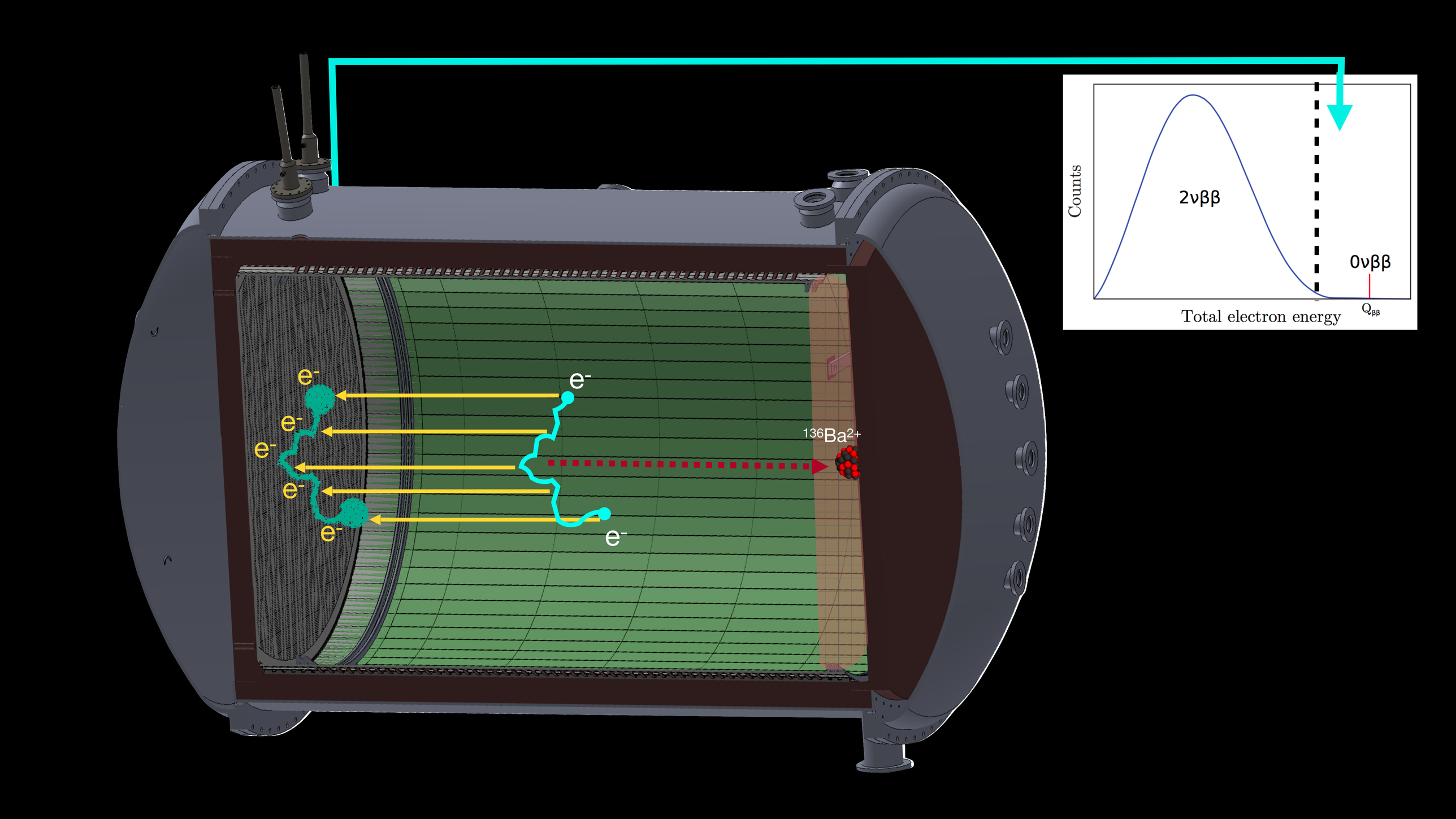

e-
e-
e-
e-
e-
e-
e-
136Ba2+

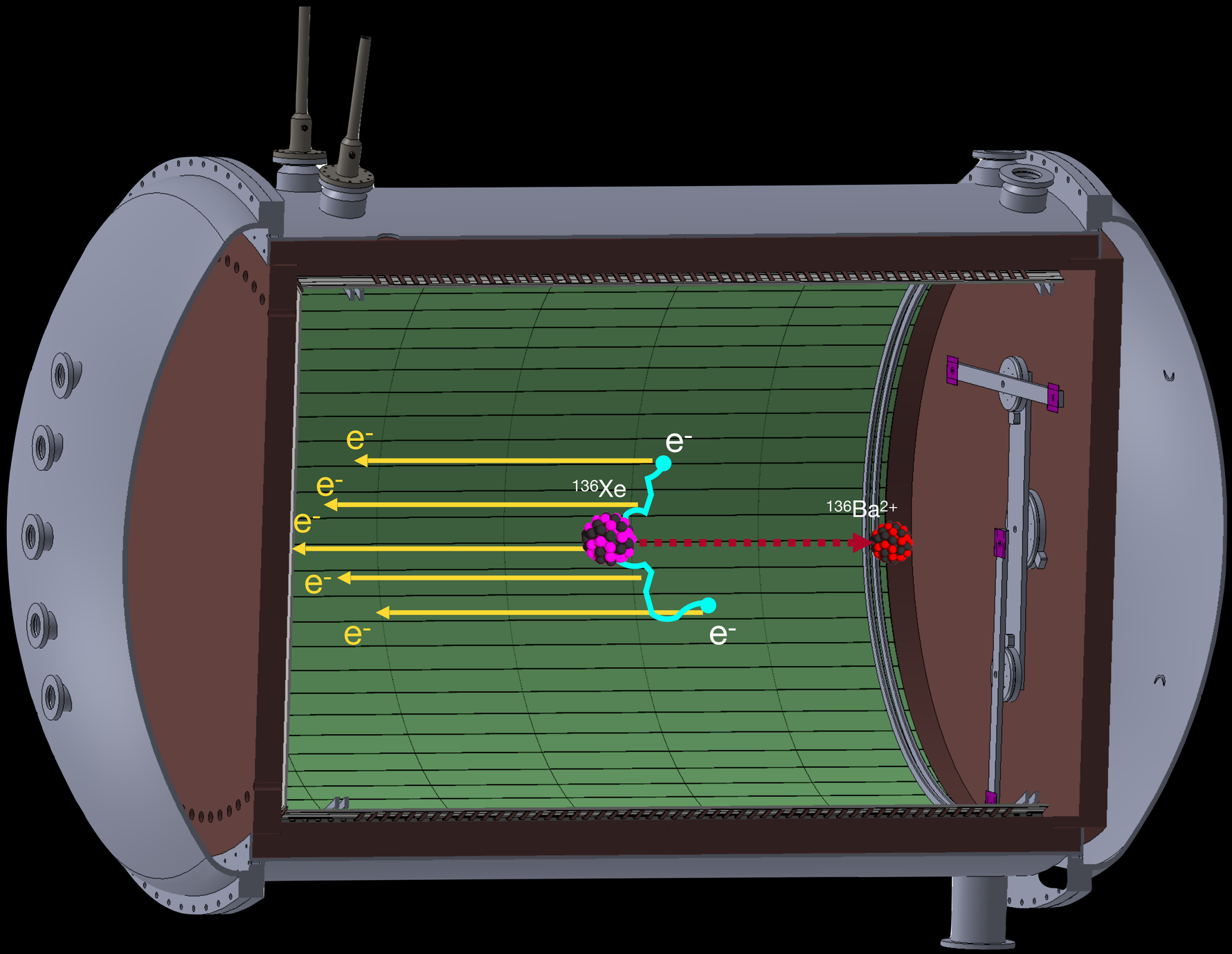

e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
$^{136}Ba^{2+}$
e⁻

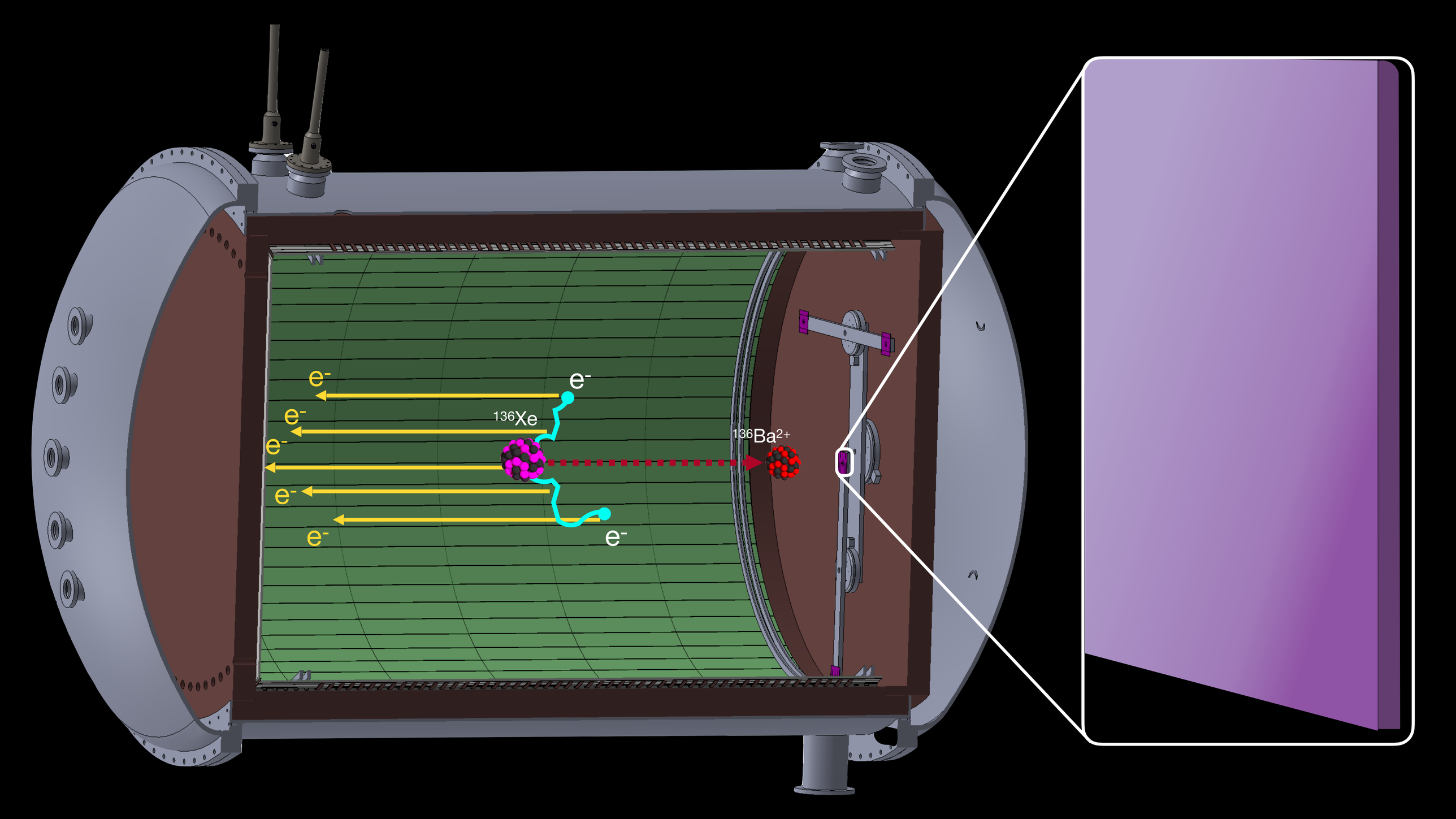

e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
$^{136}Ba^{2+}$

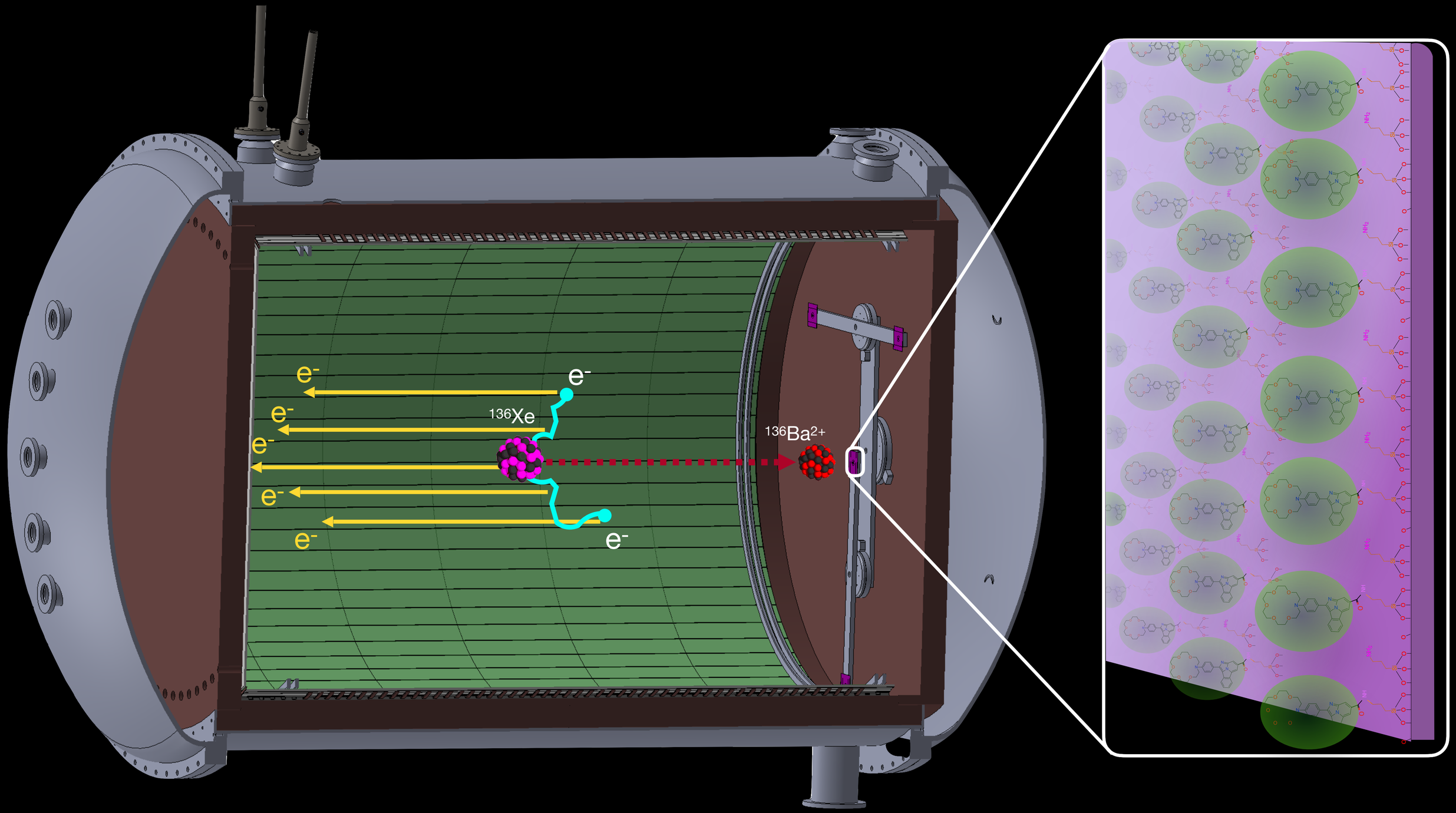

e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
$^{136}Ba^{2+}$
Counts
2νββ
0νββ
Total electron energy
$Q_{ββ}$

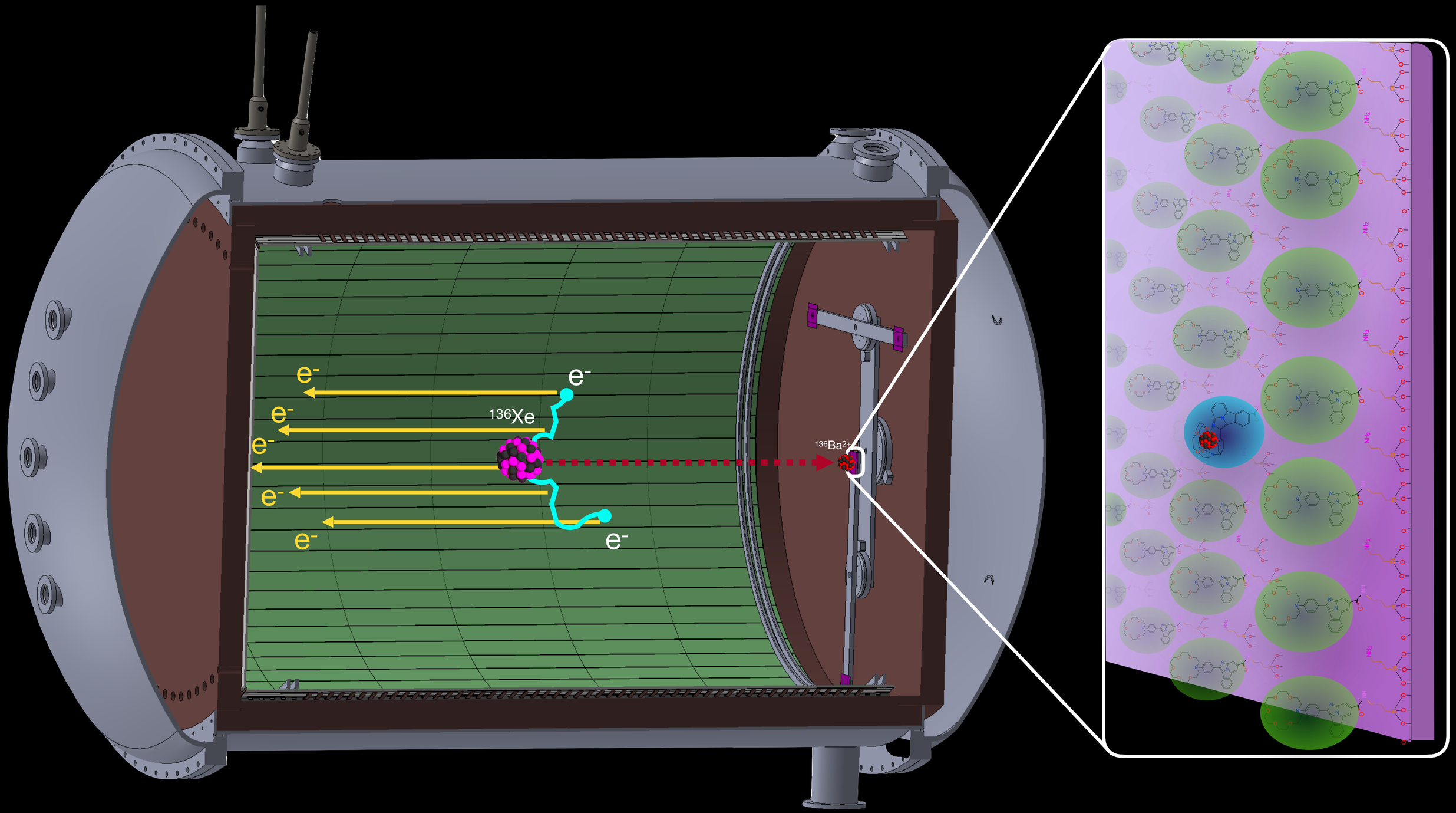

e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
$^{136}Ba^{2+}$
Counts
2νββ
0νββ
Total electron energy
$Q_{\beta\beta}$


e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
$^{136}Ba^{2+}$
Counts
2νββ
0νββ
$Q_{ββ}$
Total electron energy


e-
e-
e-
e-
e-
e-
136Xe
136Ba2+
e-
e-


e-
e-
e-
e-
e-
e-
e-
136Xe
136Ba2+


e-
e-
e-
e-
e-
e-
e-
136Xe
136Ba2+

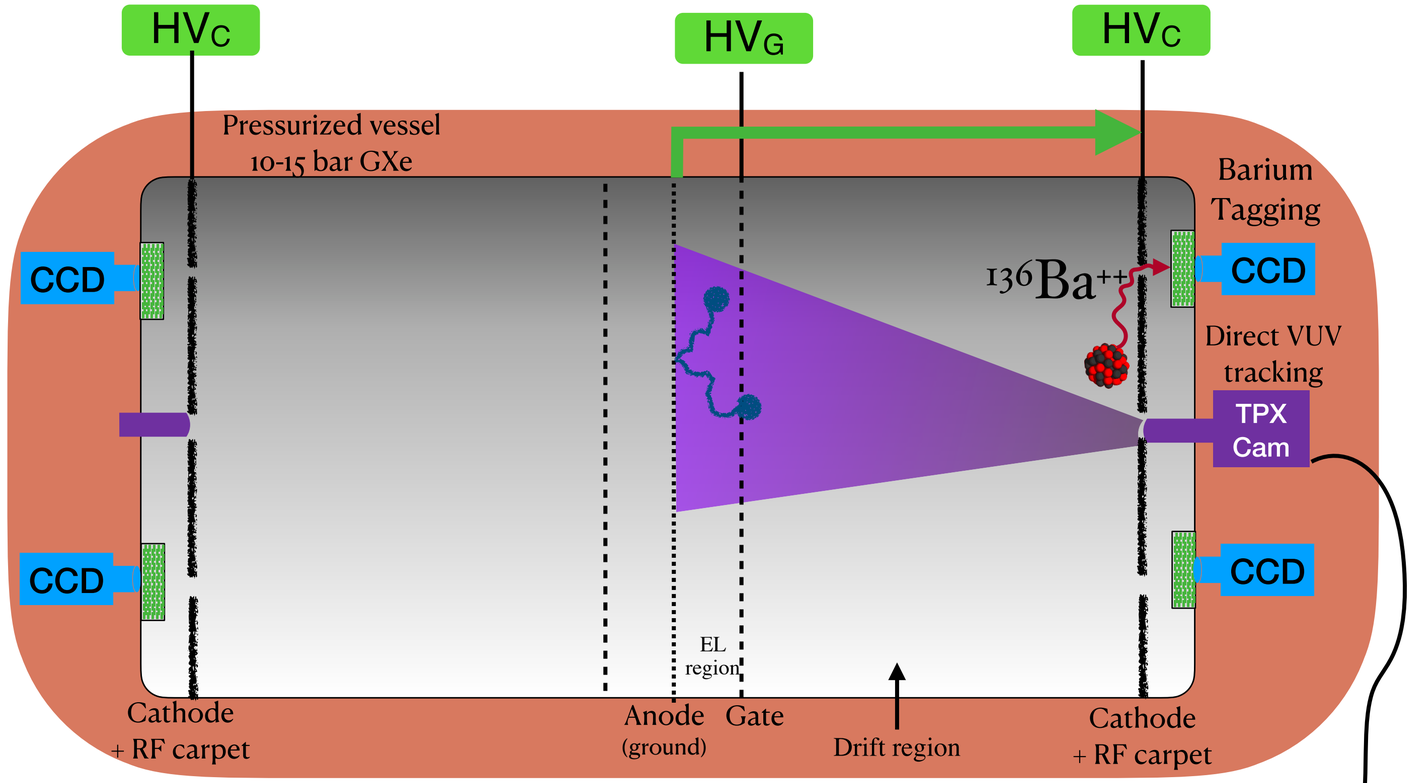

e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
^{136}Xe
$^{136}Ba^{2+}$

Sensor design lines in GXe

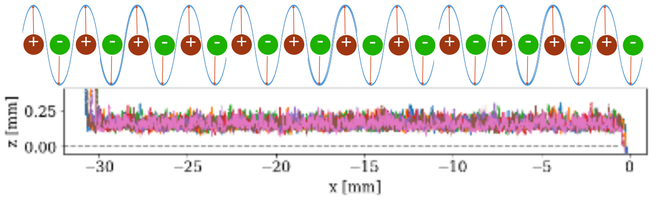
The CRAB concept[a]

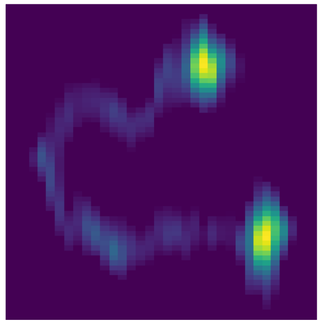
[a] JINST 18 P08006 (**2023**)

- TimePix camera to detect the e- track is detected
- Ba^{2+} ions concentrated by RF carpets into small sensor areas
- In-situ detection by laser microscopy for delayed coincidence signal.



RF Carpet ion transport in Xenon gas





R&D into Chemosensors

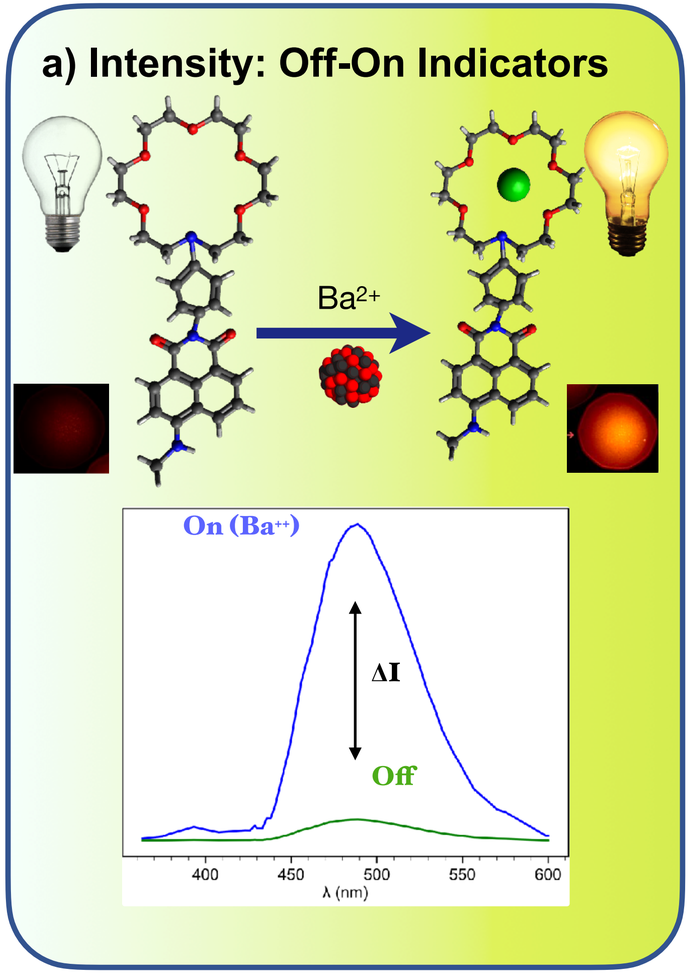
The building blocks of the BaTag system

- Exploit three properties of light emission:

R&D into Chemosensors

The building blocks of the BaTag system

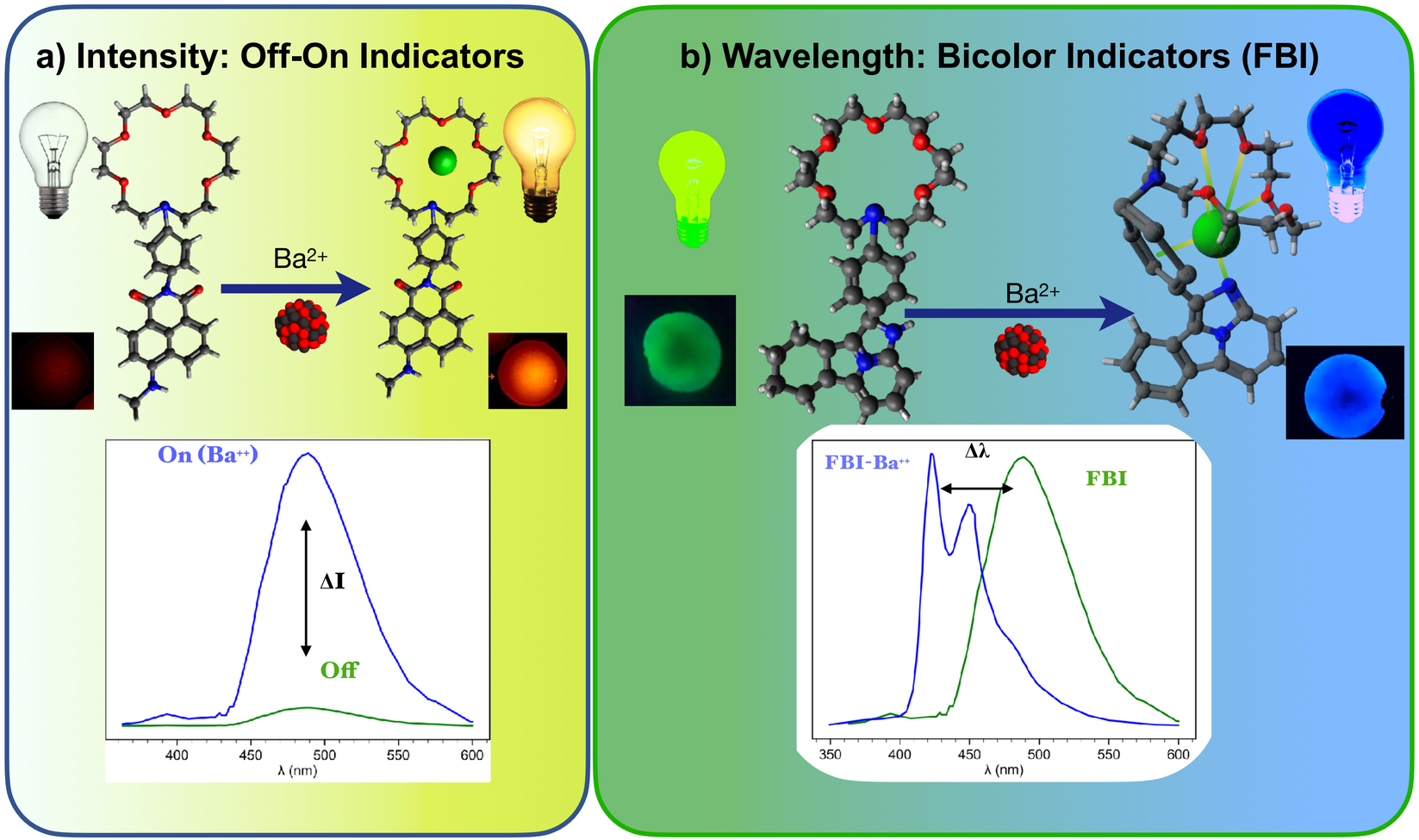
- Exploit three properties of light emission:



R&D into Chemosensors

The building blocks of the BaTag system

- Exploit three properties of light emission:

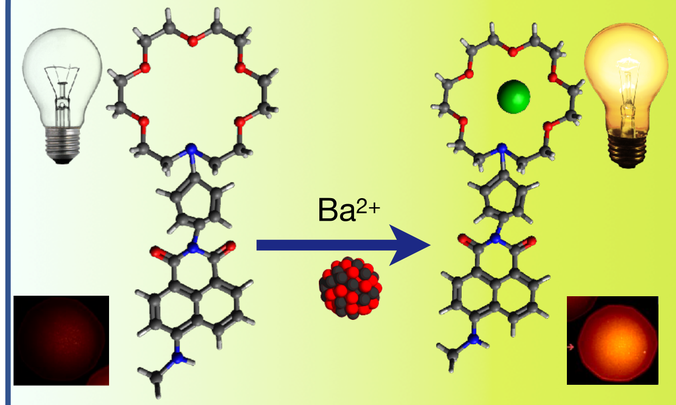


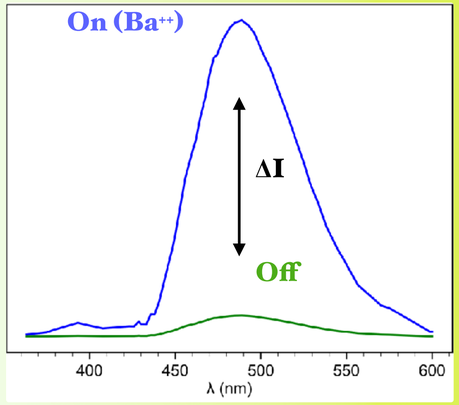
R&D into Chemosensors

The building blocks of the BaTag system

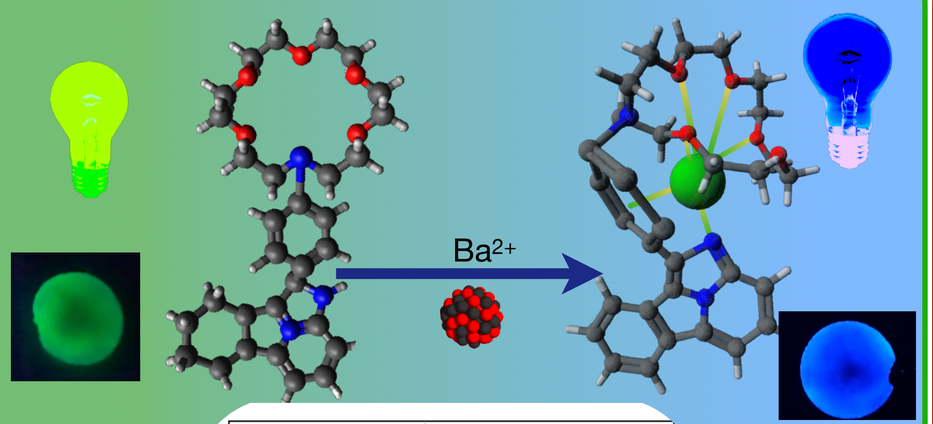
- Exploit three properties of light emission:

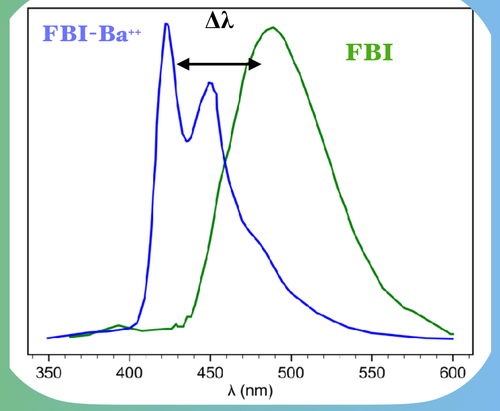
a) Intensity: Off-On Indicators



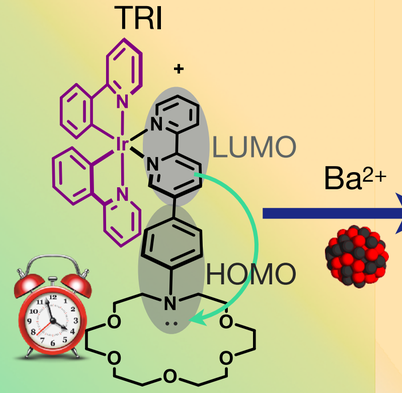


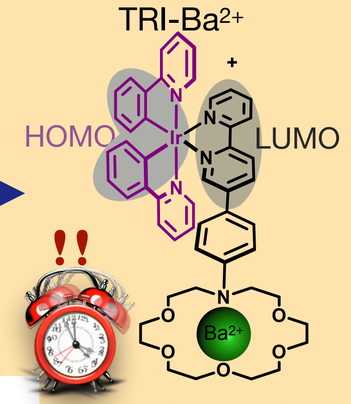
b) Wavelength: Bicolor Indicators (FBI)

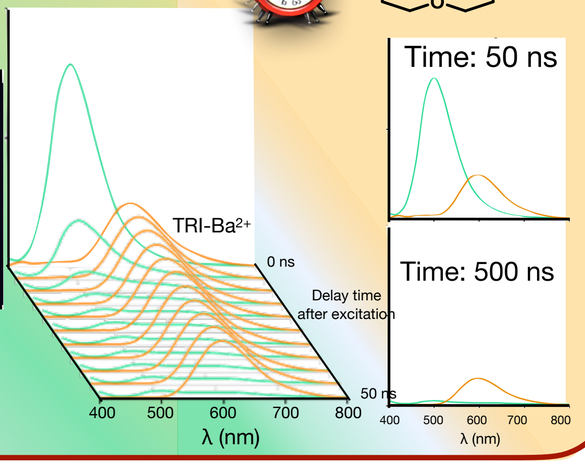




c) Relaxation time: Time-resolved Indicators (TRI)

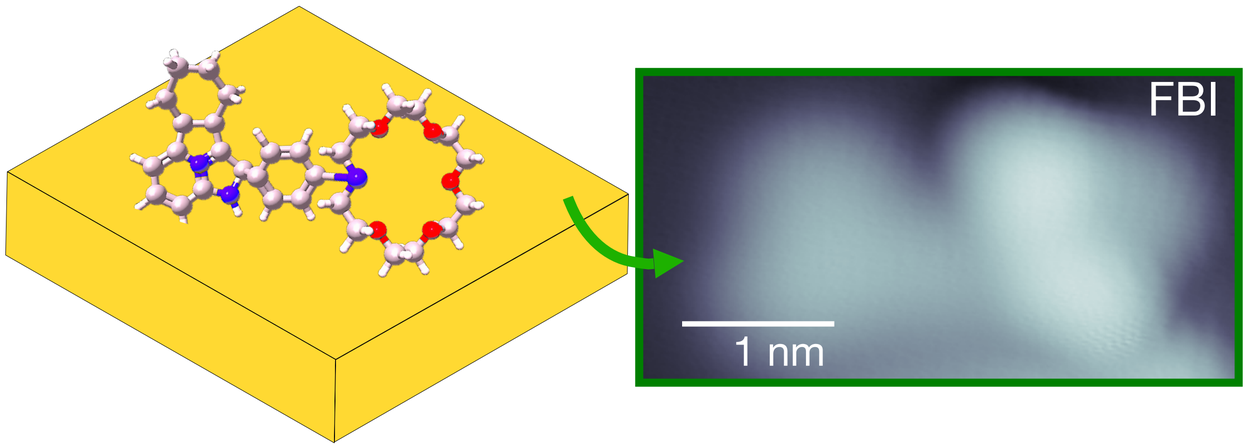






Molecule characterization

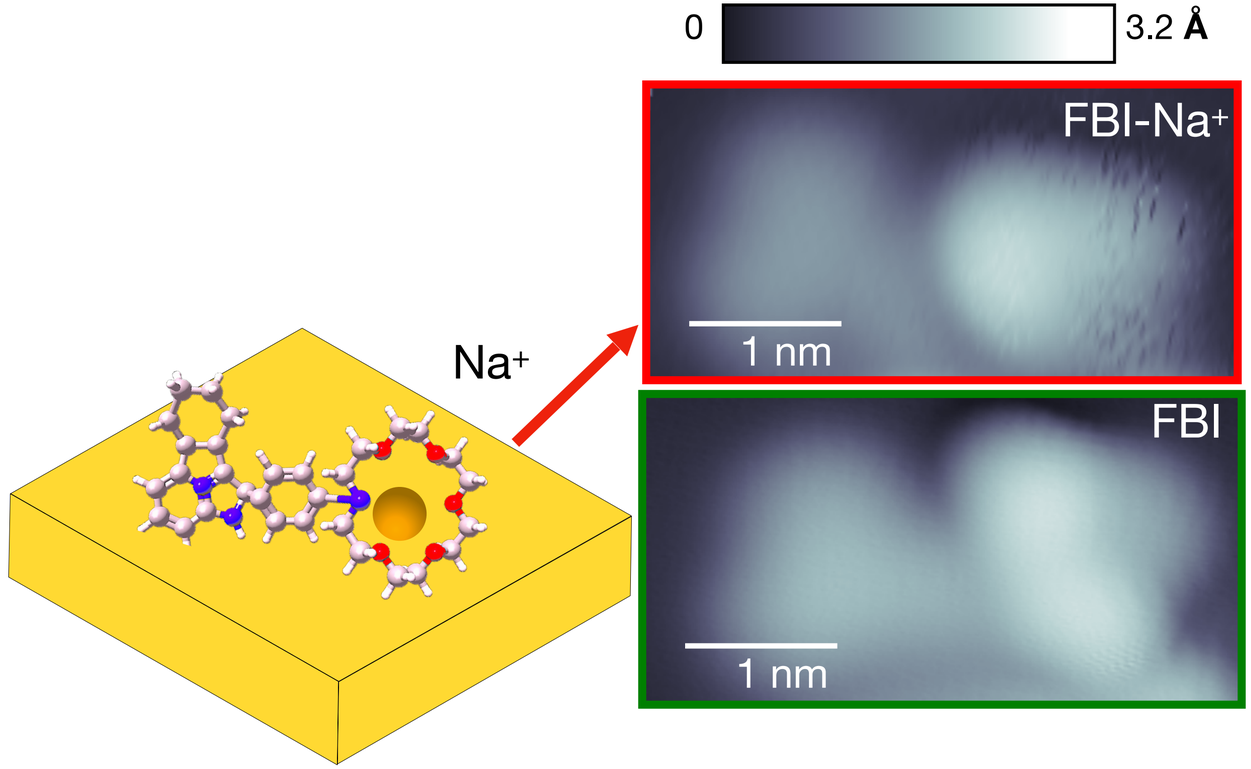
Capture demonstrated in UHV



[b] Nat. Commun. 13, 7741 (**2022**)

Molecule characterization

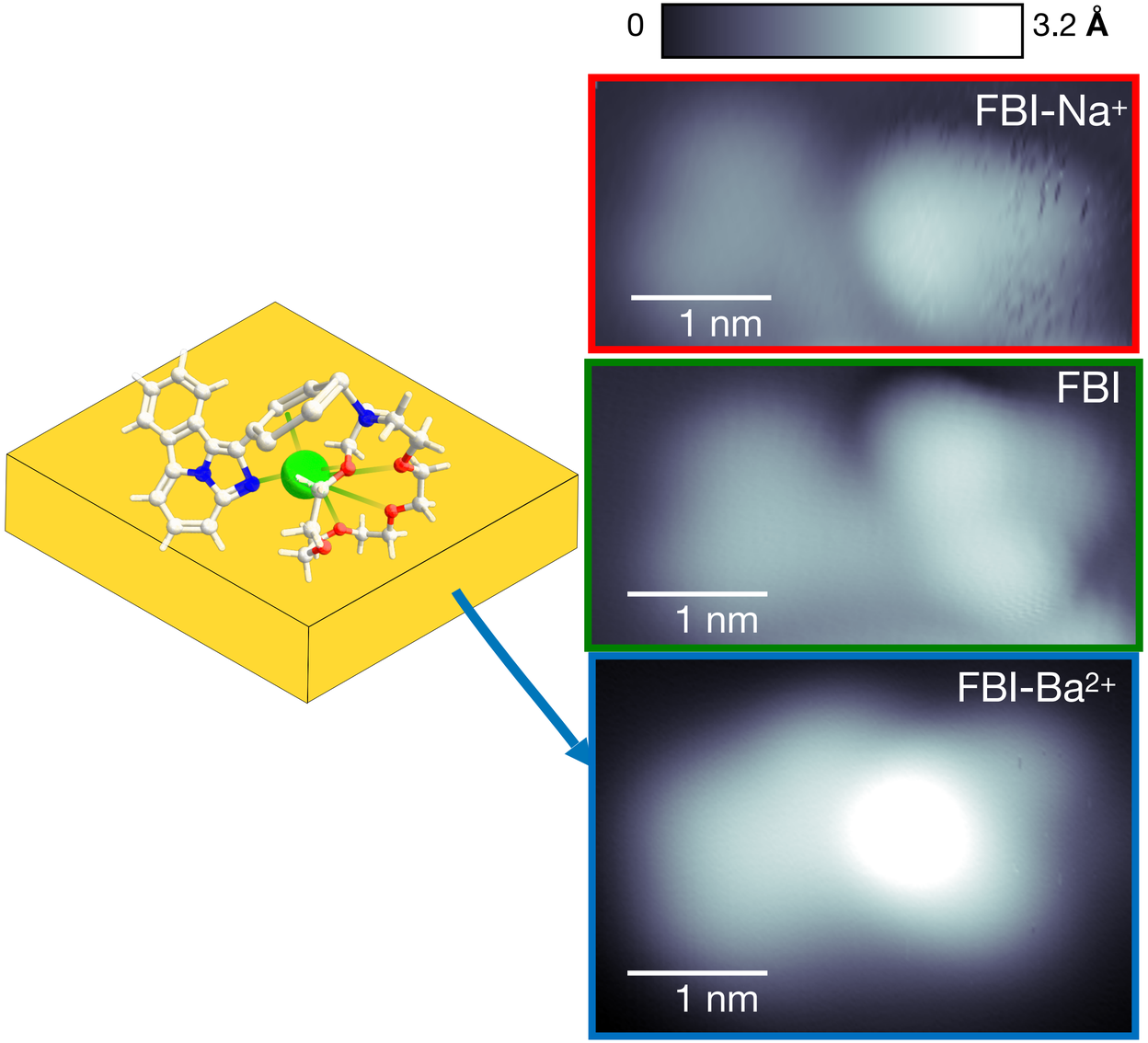
Capture demonstrated in UHV

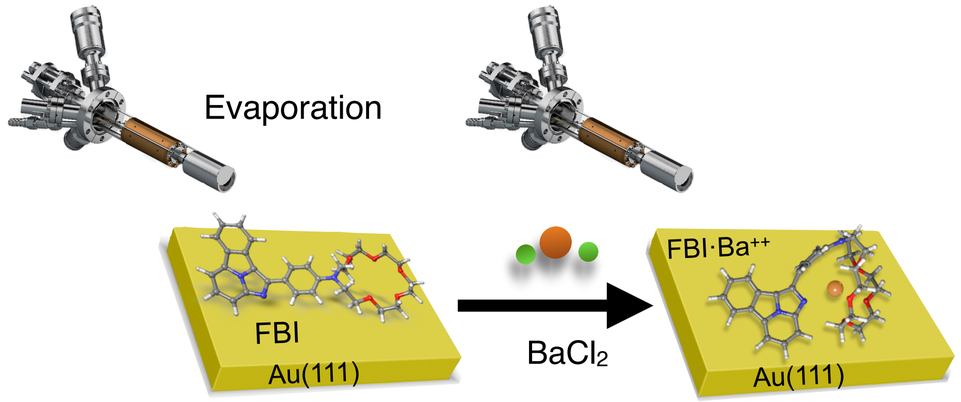


[b] Nat. Commun. 13, 7741 (**2022**)

Molecule characterization

Capture demonstrated in UHV





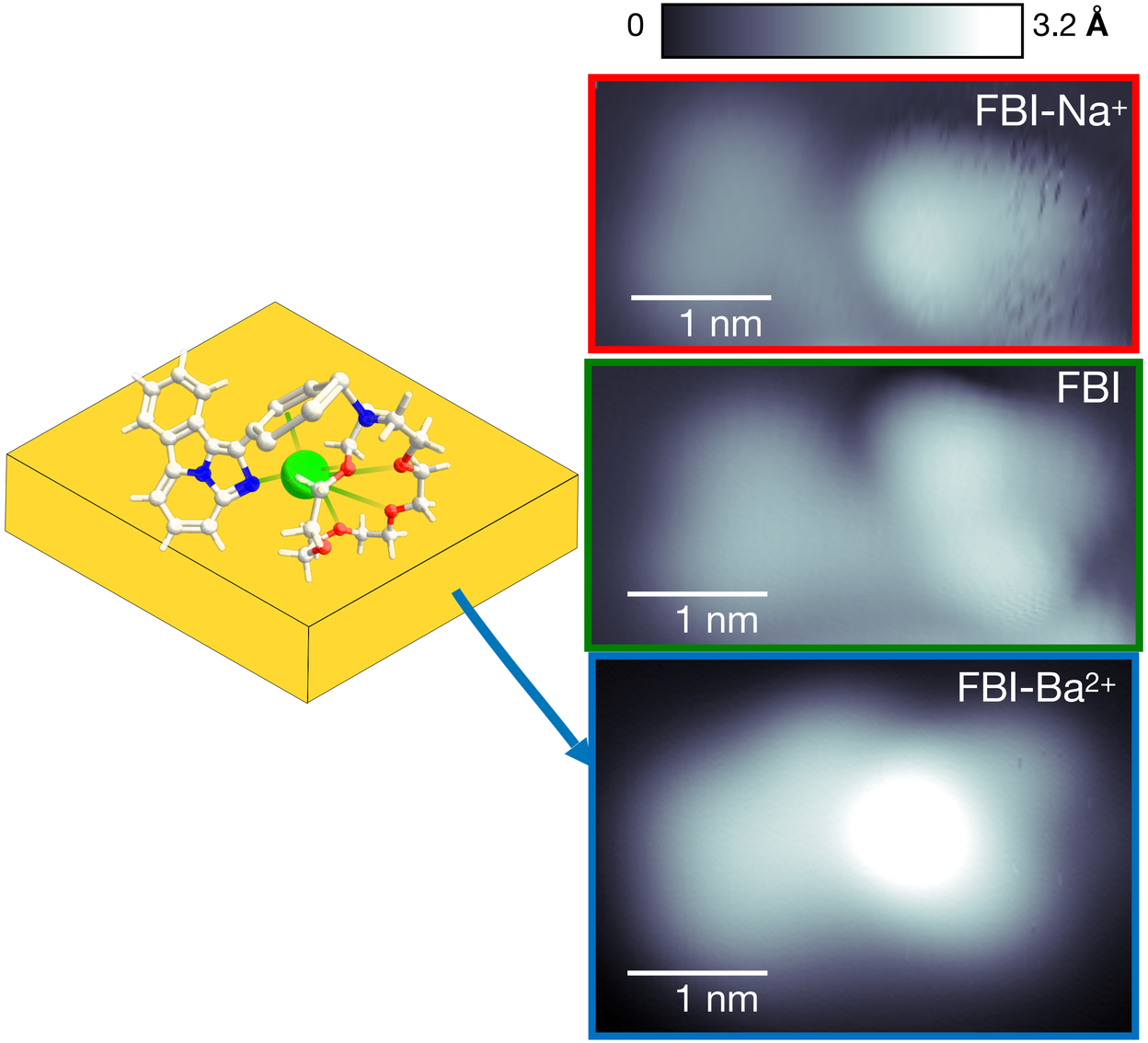
✓ Structural changes (STM)

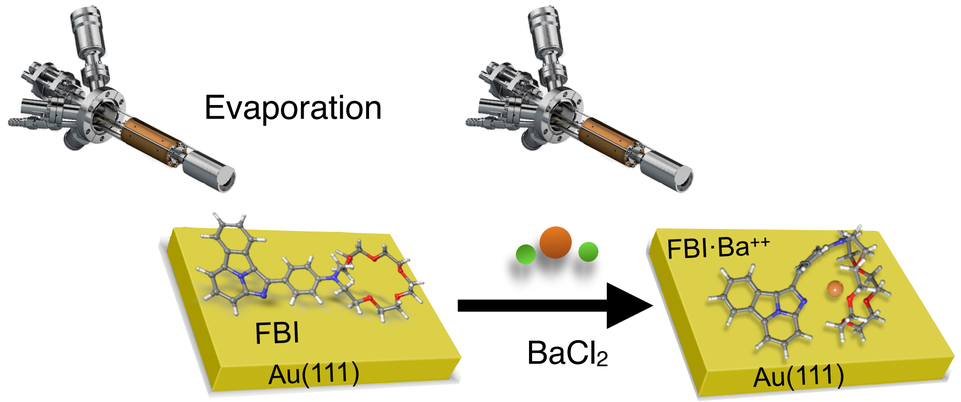
✓ Gap widening compatible with shift in absorption (STS)

[b] Nat. Commun. 13, 7741 (**2022**)

Molecule characterization

Capture demonstrated in UHV



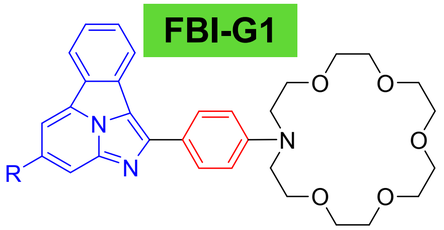


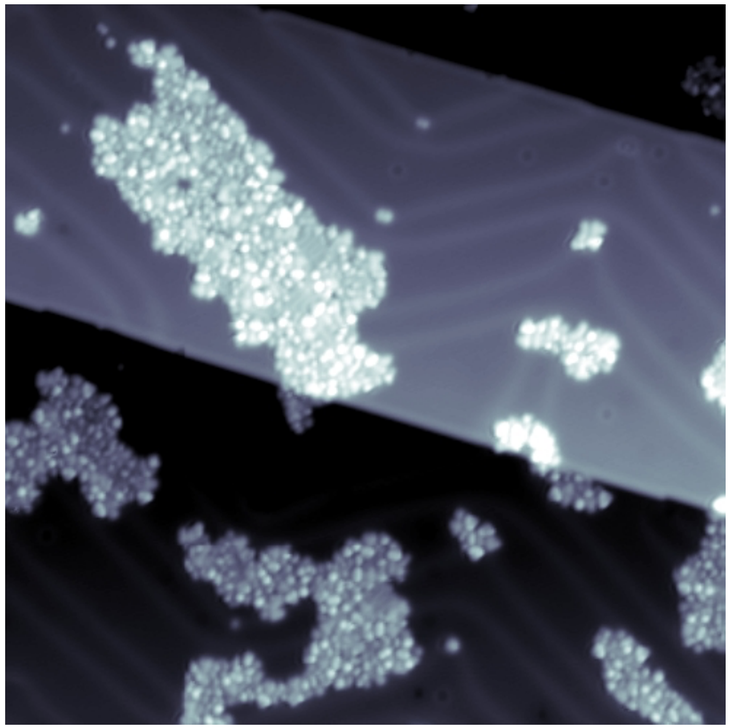
- ✓ Structural changes (STM)
- ✓ Gap widening compatible with shift in absorption (STS)
- ✓ Different effect for Na^+ (selectivity)
- ✓ Chemical interaction (XPS)
- ✓ Independent of substrate (Au, Cu, ITO, silica)

[b] Nat. Commun. 13, 7741 (**2022**)

Arrangement of molecules on Au

Towards assembling the sensor



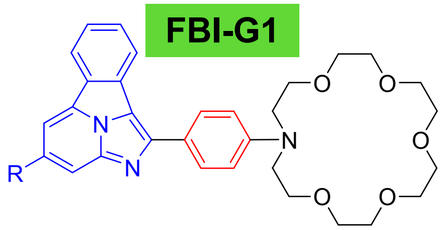


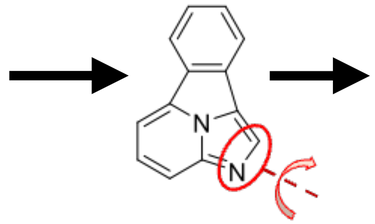
- Mainly islands

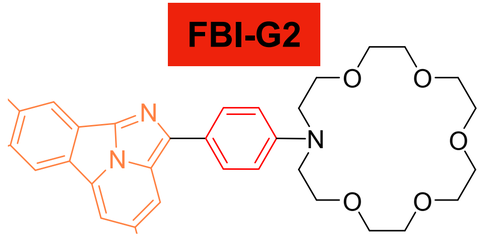
Arrangement of molecules on Au

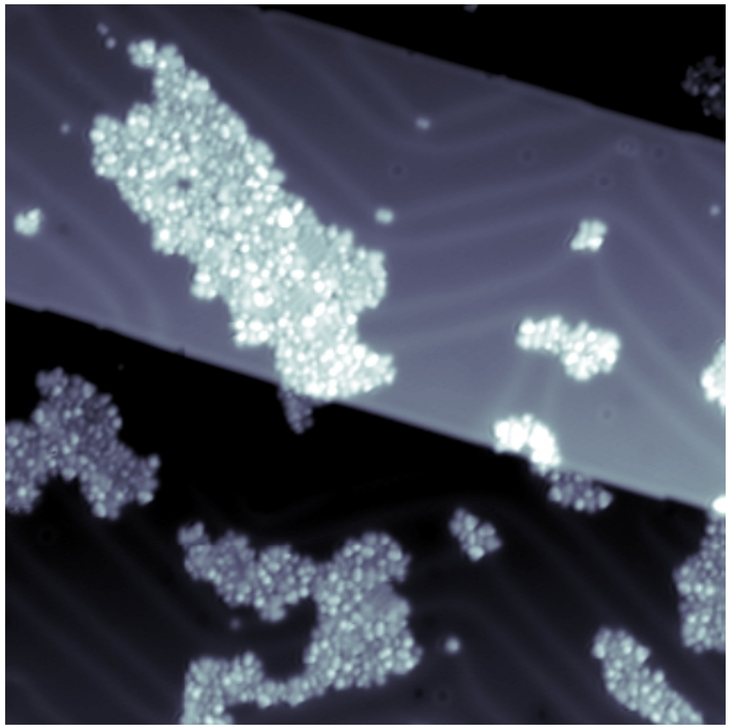
Towards assembling the sensor

- A single C-N switch changes the arrangement completely

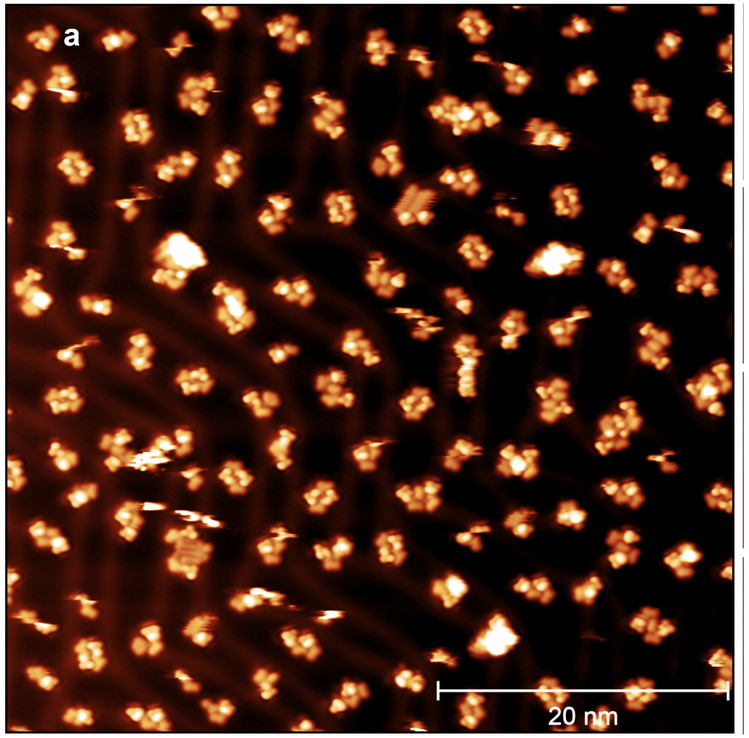








- Mainly islands

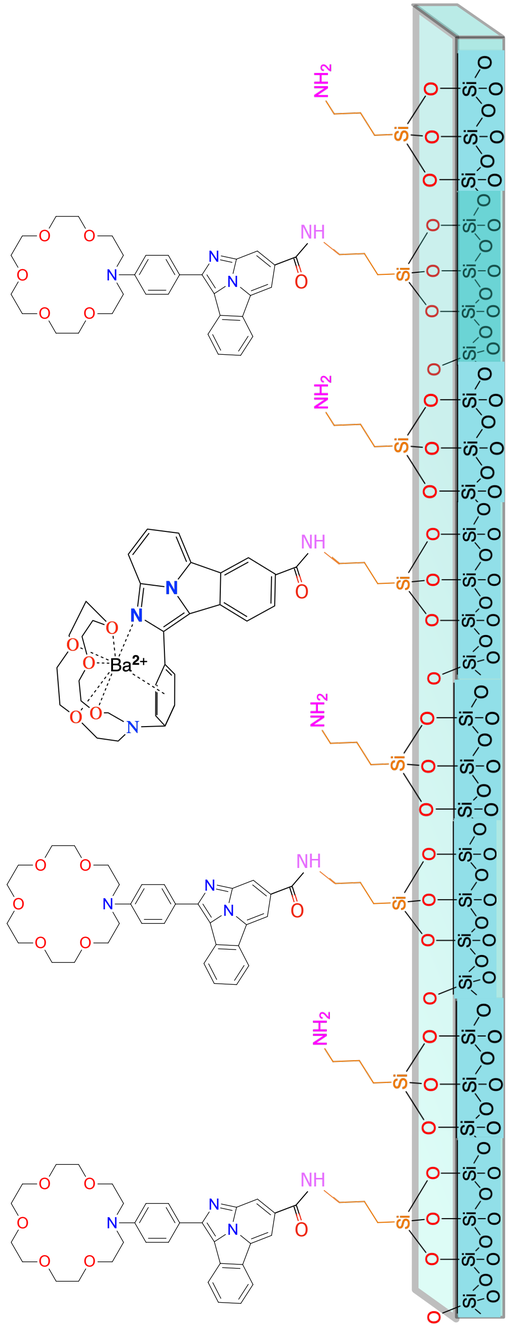


- Mainly dimers

Monolayer formation

Sensor structure in the nano-microscale

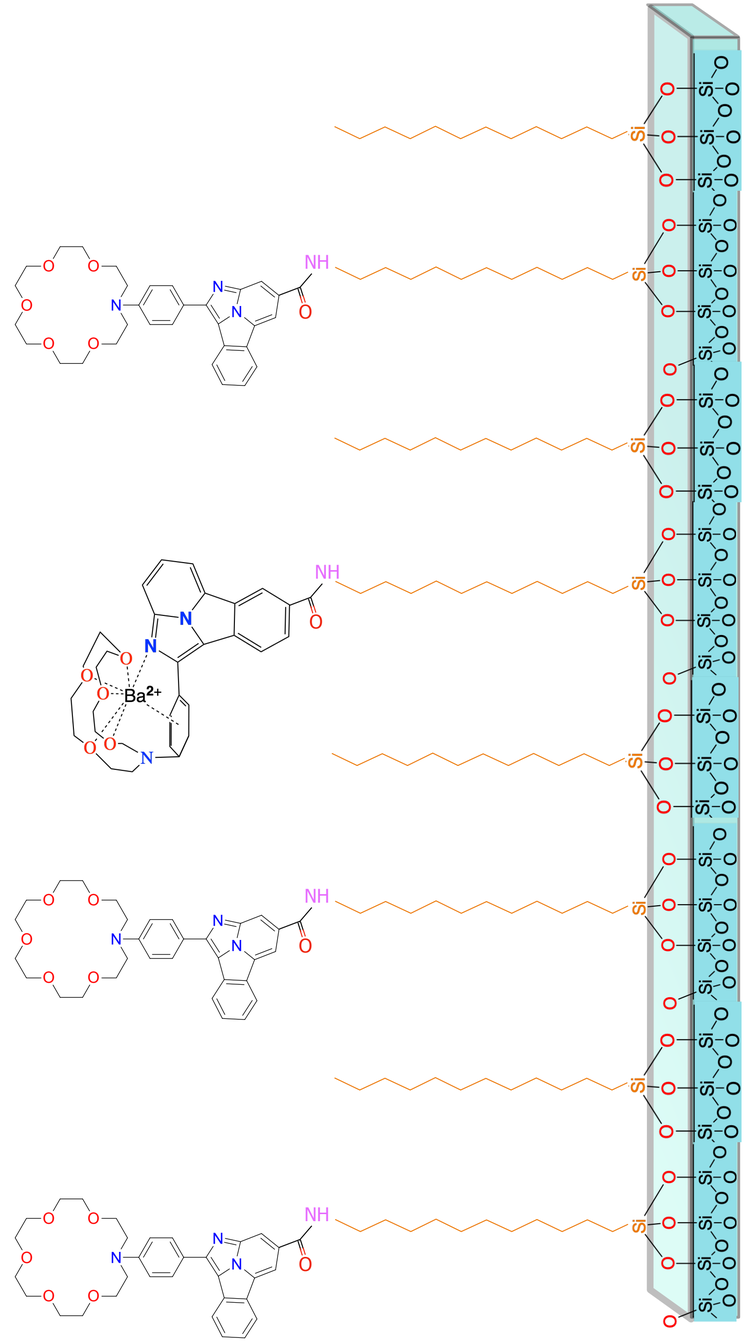
- Chemical bond between molecule and sensor
- Stable location of molecule improves single-molecule detection



Monolayer formation

Sensor structure in the nano-microscale

- Chemical bond between molecule and sensor
- Stable location of molecule improves single-molecule detection
- Chain length affects interaction with substrate and sensor efficiency



Overview

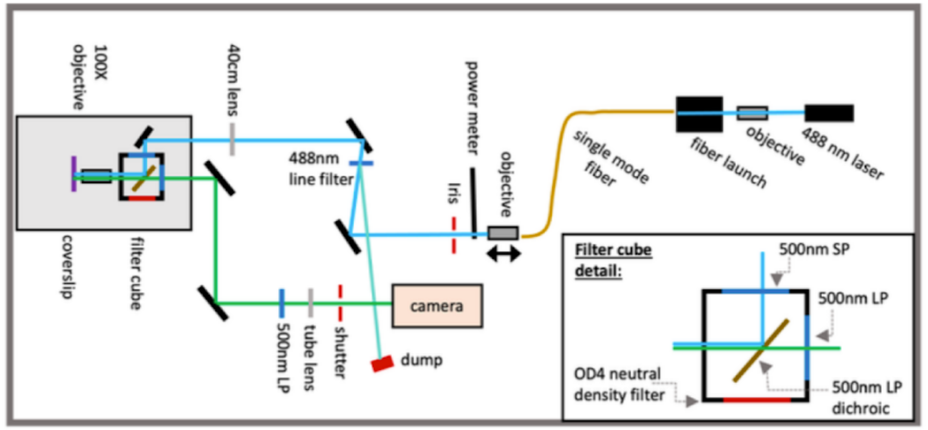
- [x] Introduction to Ba-tagging
- [ ] **Ba-Tagging in NEXT**
  - [x] System design
  - [x] Chemo-sensors characterization
  - [ ] **Optical detection**
  - [ ] Ion sources and guiding systems
- [ ] Ba-Tagging in nEXO
- [ ] The road forward

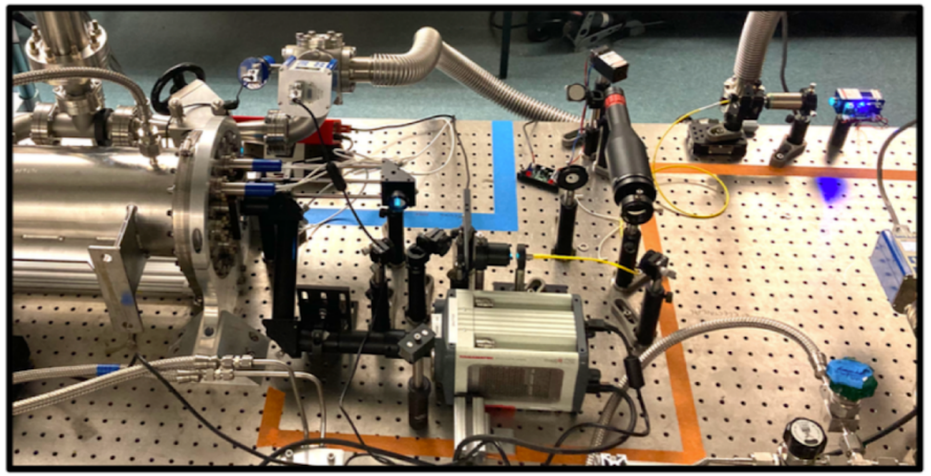
Microscopy efforts

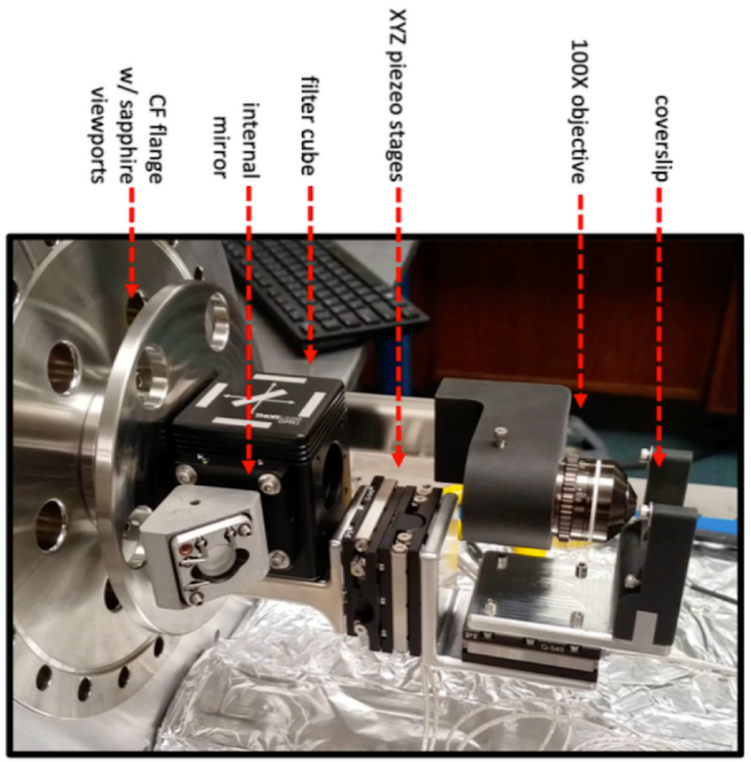
[a] Nat. Commun. 15, 10595 (**2024**).

SMFI in High-pressure Xe

- Observation of single-molecule events in HPGXe
- Microscope Objective (MO) inside pressure chamber





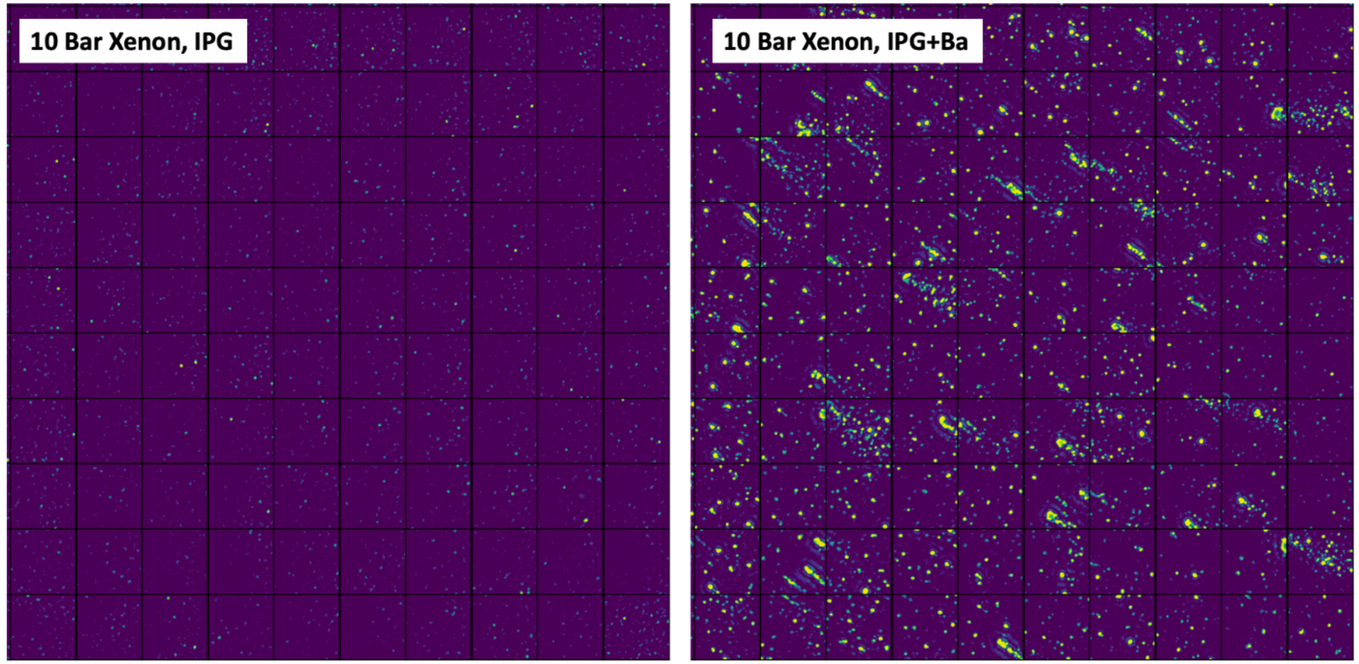


Microscopy efforts

SMFI in High-pressure Xe

[a] Nat. Commun. 15, 10595 (**2024**).

- Raster scans for large-scale characterization of sample fluorescence

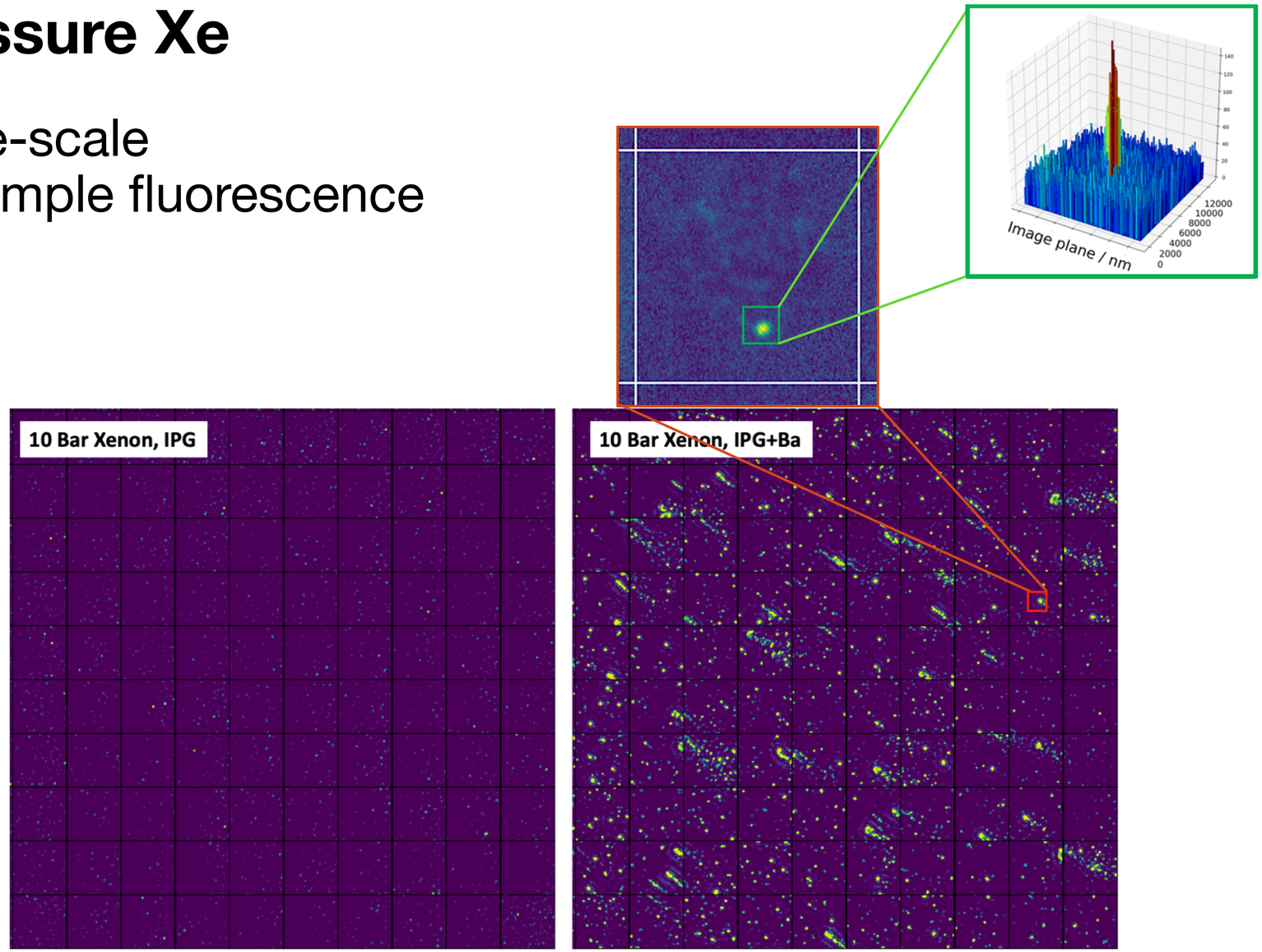


Microscopy efforts

[a] Nat. Commun. 15, 10595 (**2024**).

SMFI in High-pressure Xe

- Raster scans for large-scale characterization of sample fluorescence

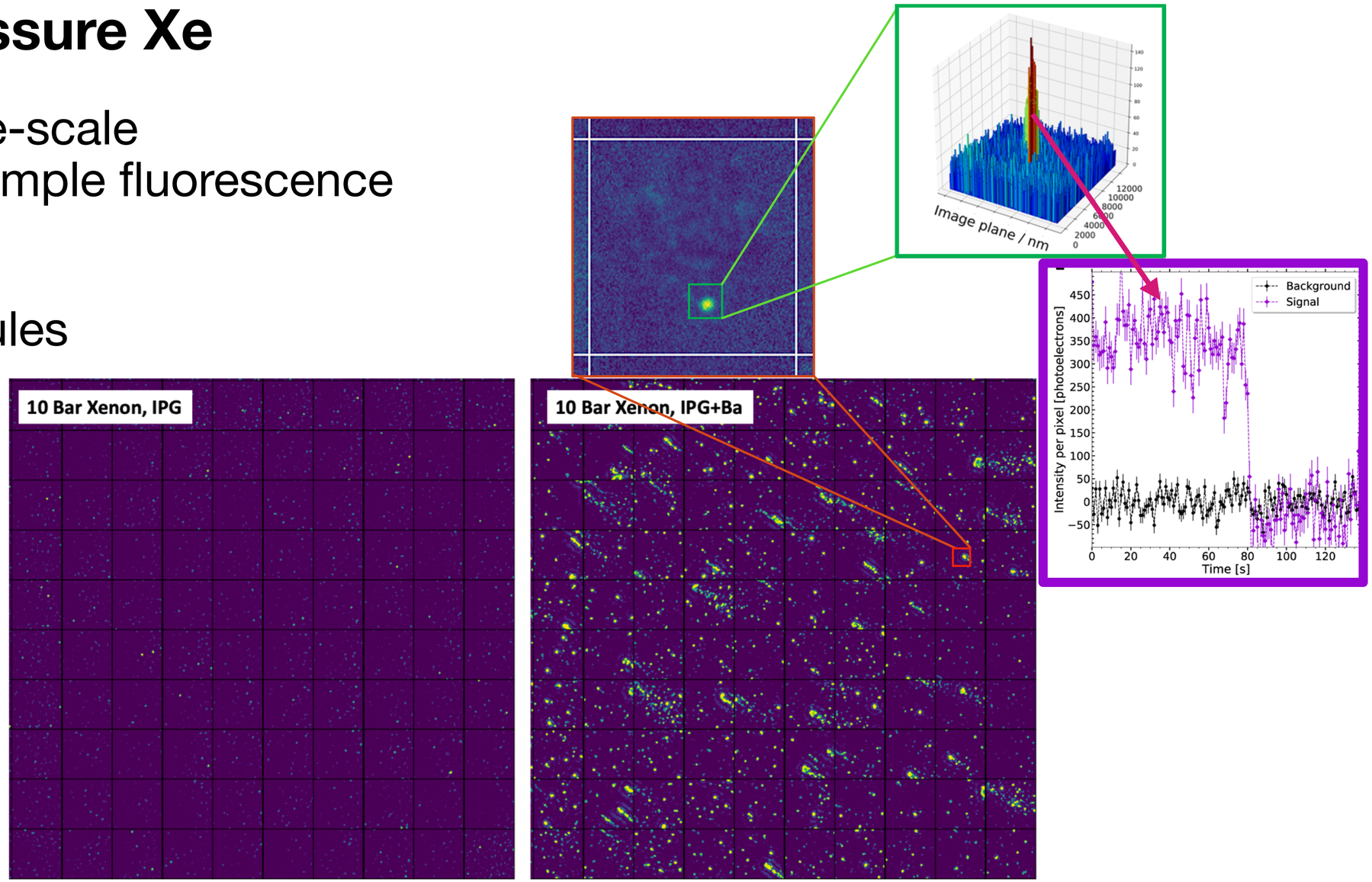


Microscopy efforts

[a] Nat. Commun. 15, 10595 (**2024**).

SMFI in High-pressure Xe

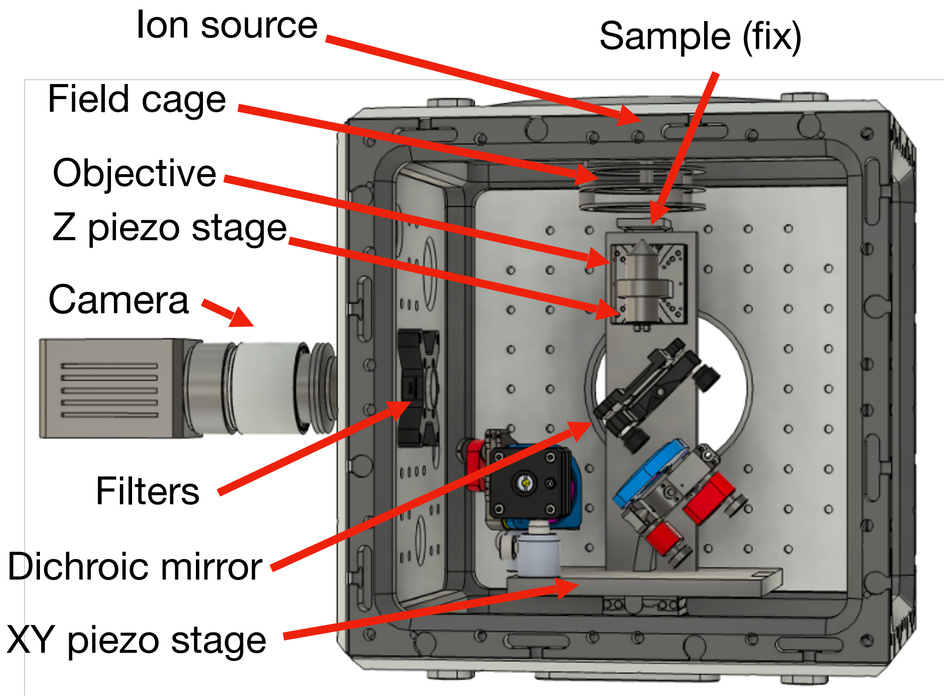
- Raster scans for large-scale characterization of sample fluorescence
- Single-step detection of IPG (+Ba^{2+}) molecules
- Autofocus algorithm with piezo stage

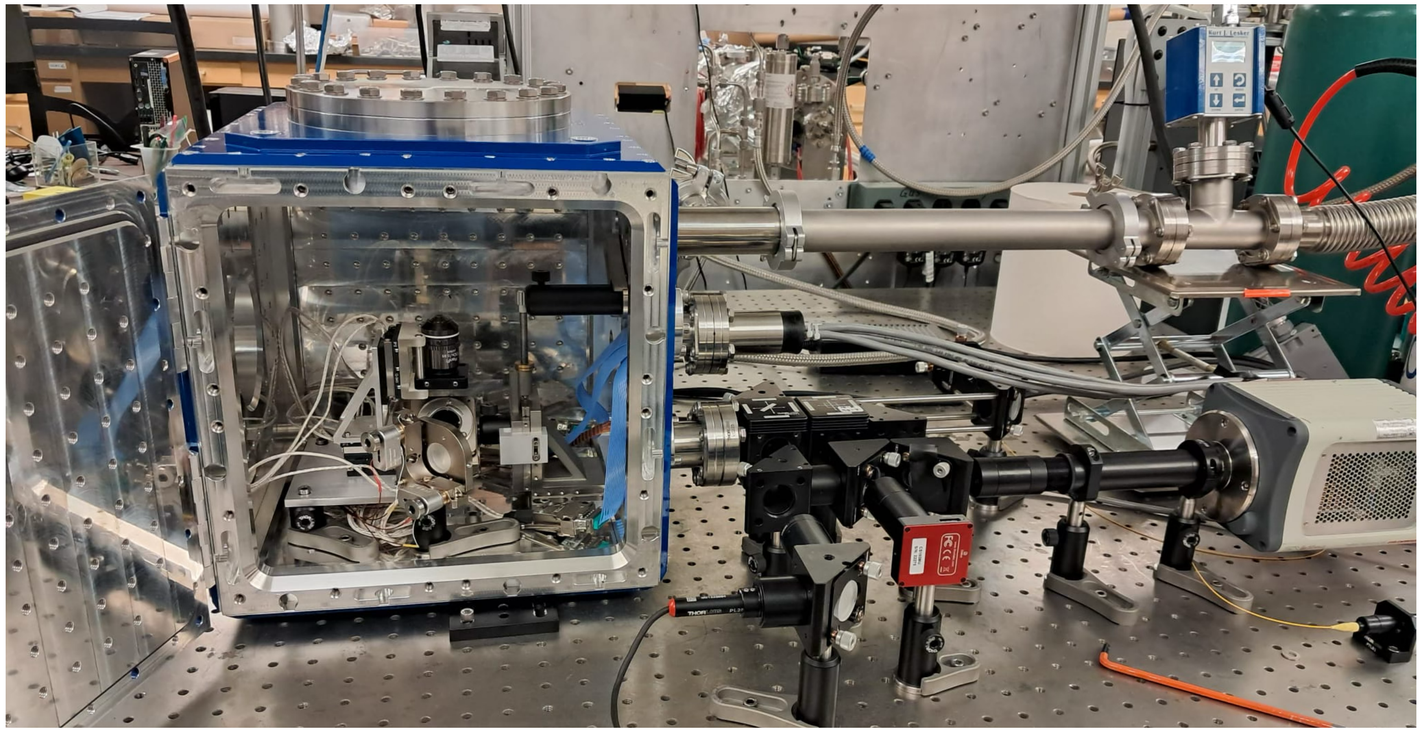


Microscopy efforts

HP Microscope upgrade

- Operating in HPGXe, coupling to Ba^{2+} source
- MO and optics move in scan, not sample

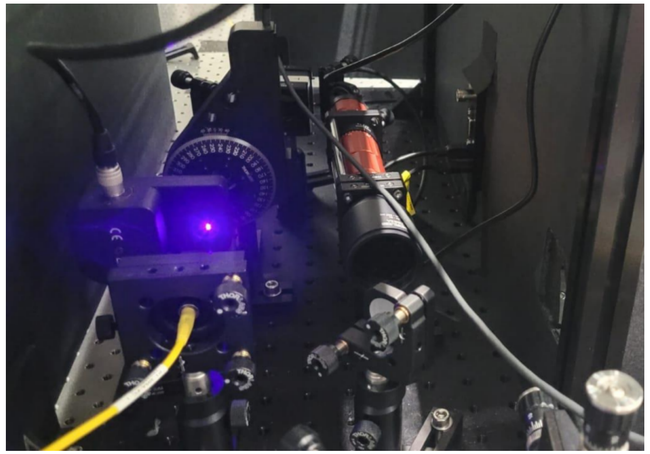


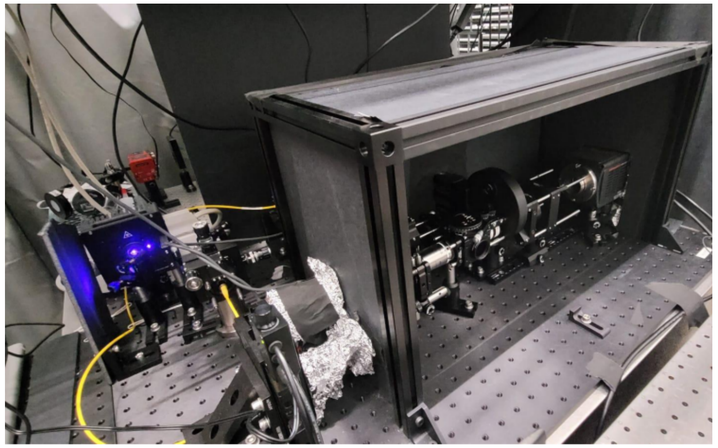


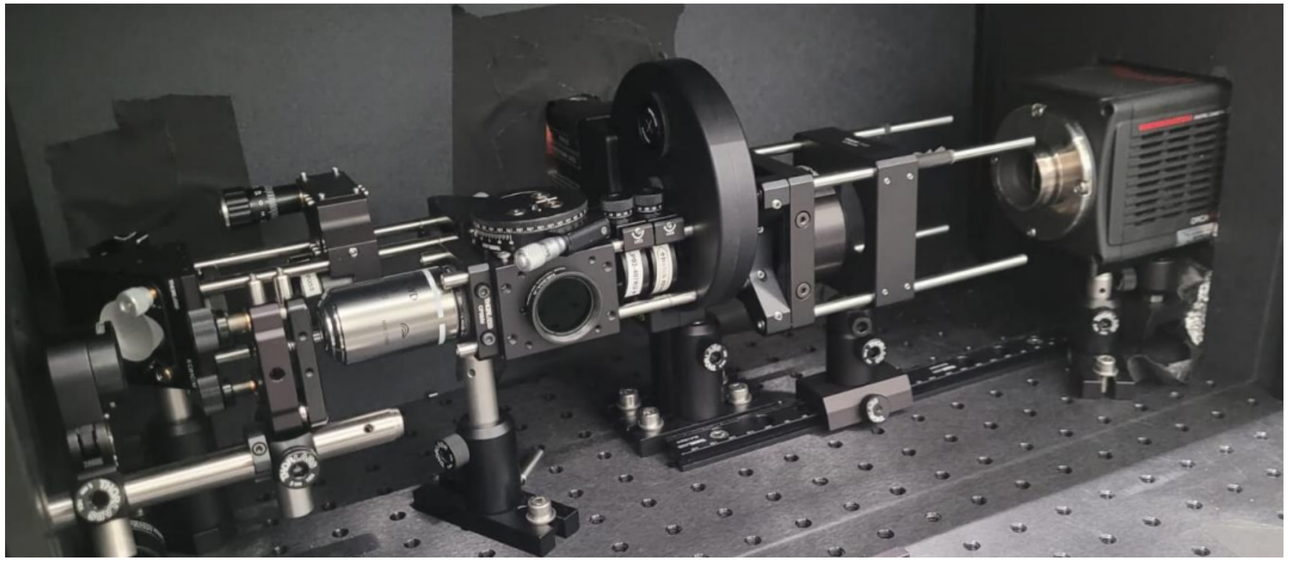
Microscopy efforts

Flexible setup configurations

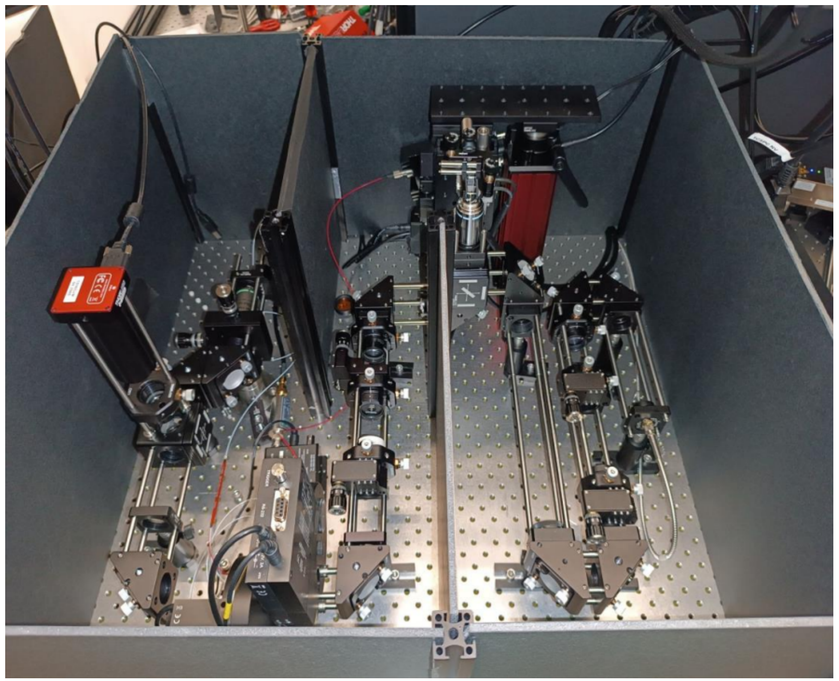
Wide-field microscopy

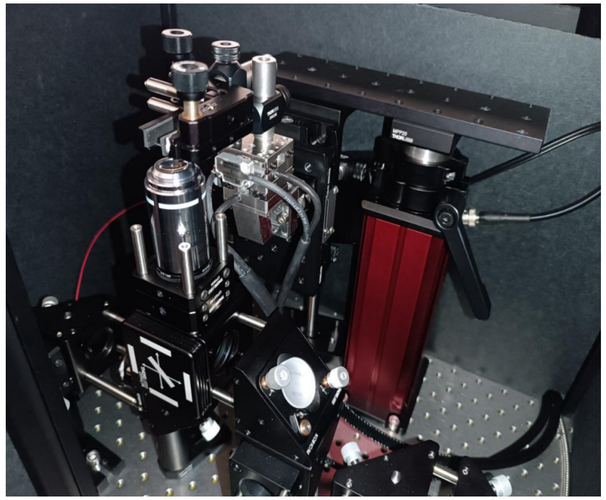






Prototyping/testing new techniques

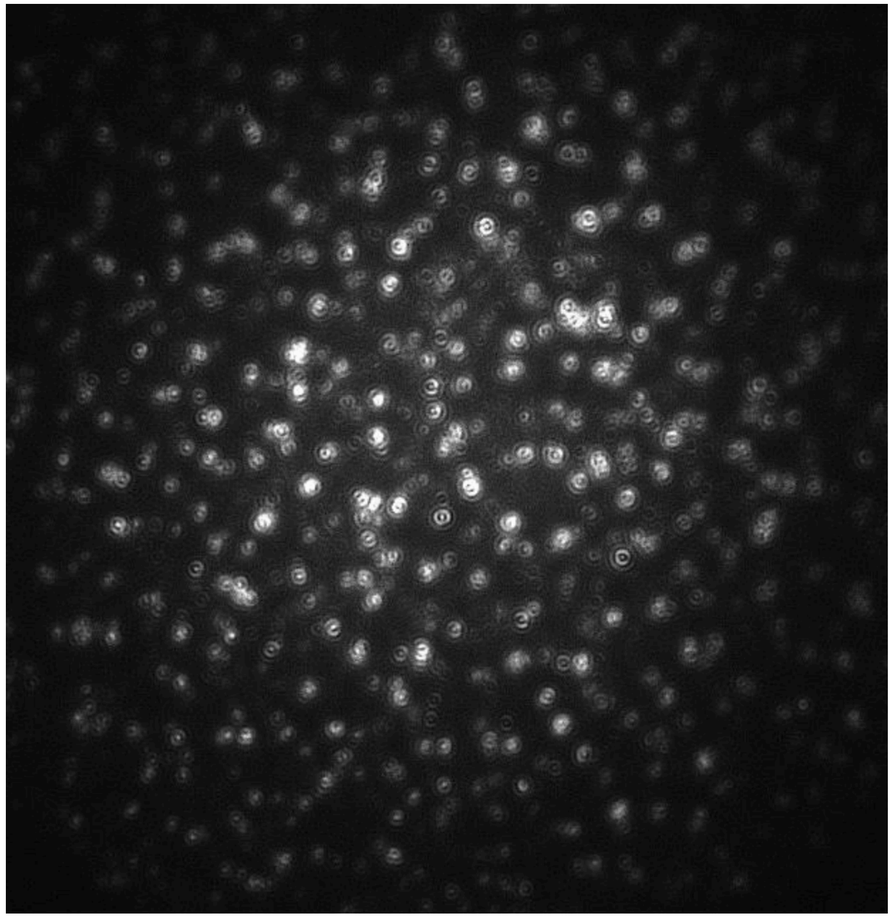




Microscopy efforts

Photochemistry properties

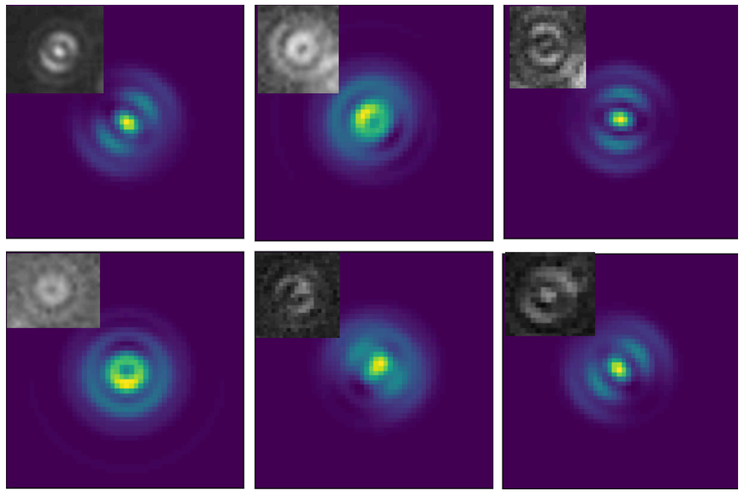
- SMFI and molecular orientation
  - Modeled as dipoles in electric field
  - Match pattern with simulation

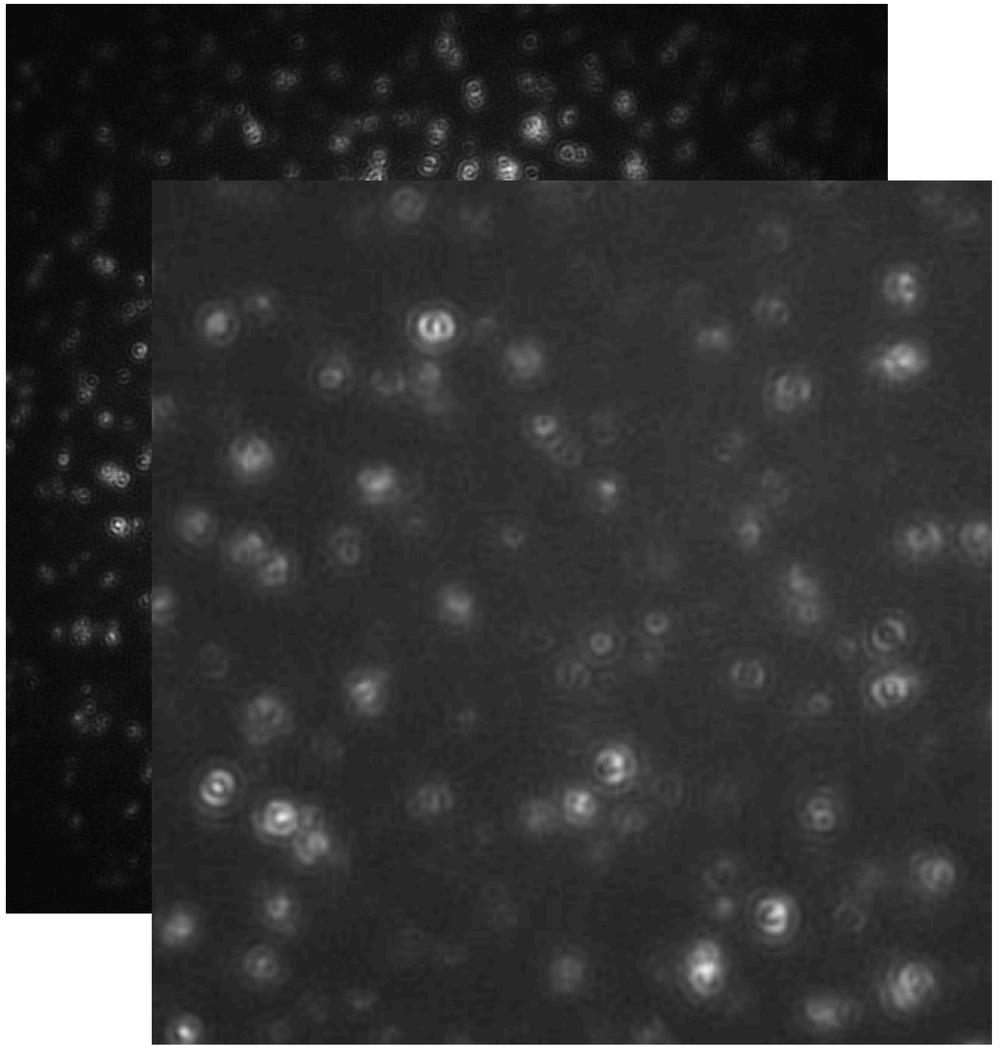


Microscopy efforts

Photochemistry properties

- SMFI and molecular orientation
  - Modeled as dipoles in electric field
  - Match pattern with simulation





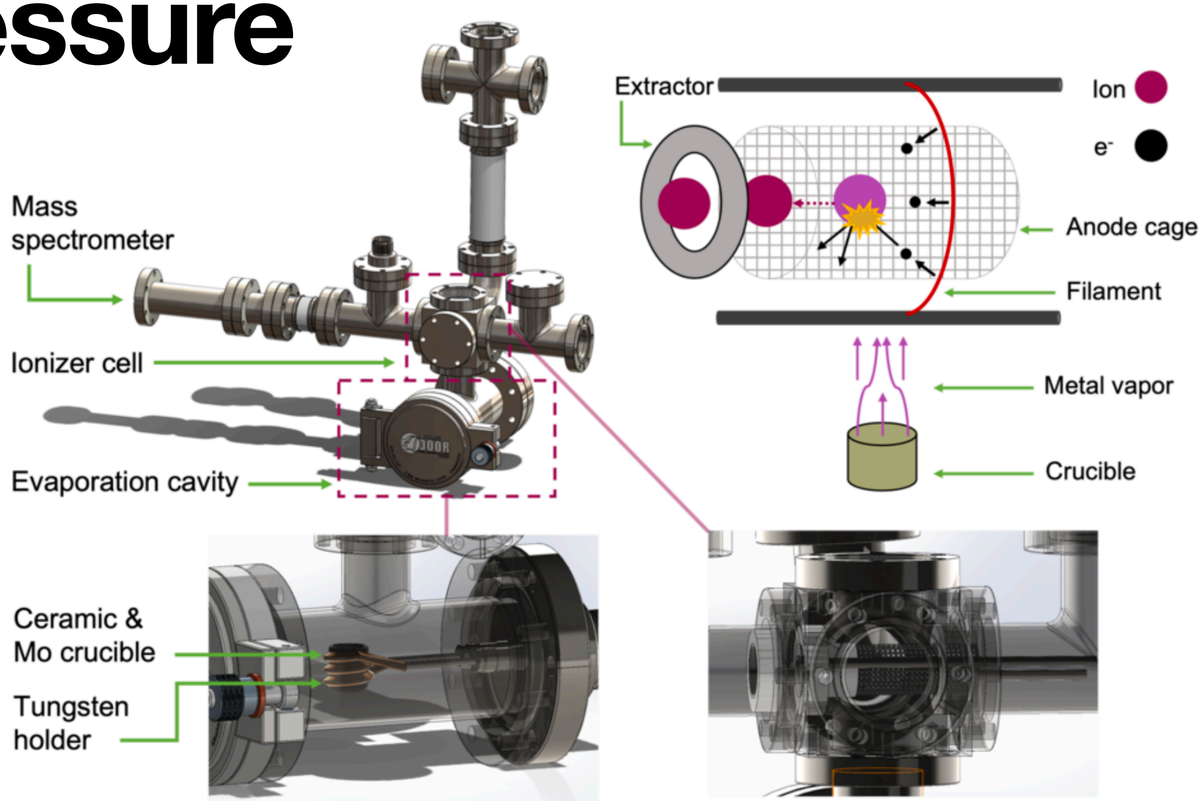
Overview

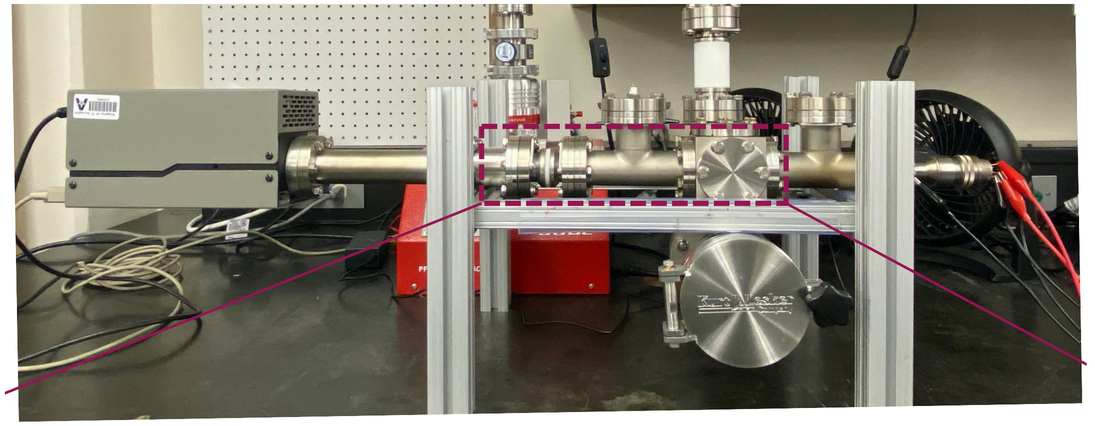
- ☑ Introduction to Ba-tagging
- ☐ **Ba-Tagging in NEXT**
  - ☑ System design
  - ☑ Chemo-sensors characterization
  - ☑ Optical detection
  - ☐ **Ion sources and guiding systems**
- ☐ Ba-Tagging in nEXO
- ☐ The road forward

Ba^{2+} beam in high pressure

Controlled energy ions

- Compact, solvent-free Ba^{2+} ion source
- Combines metal vaporization + electron-impact ionization with tunable voltages.



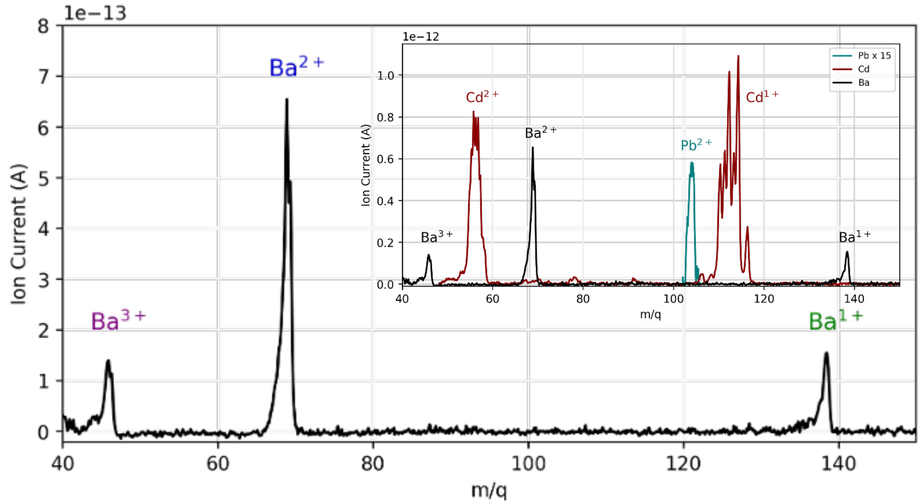


[a] JINST 18 P07044 (**2023**).

Ba^{2+} beam in high pressure

Controlled energy ions

- Compact, solvent-free Ba^{2+} ion source
- Combines metal vaporization + electron-impact ionization with tunable voltages.

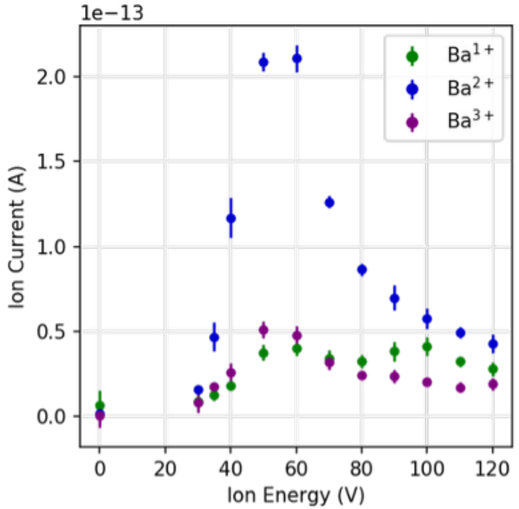


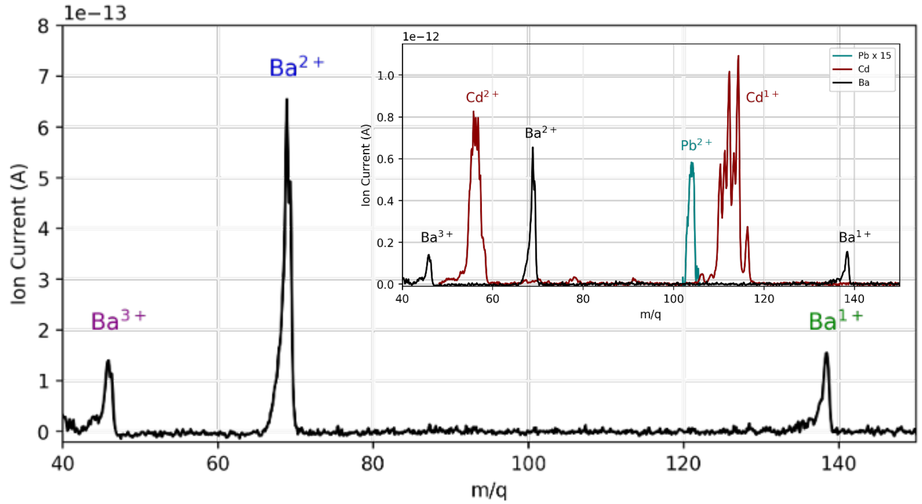
[a] JINST 18 P07044 (**2023**).

Ba^{2+} beam in high pressure

Controlled energy ions

- Compact, solvent-free Ba^{2+} ion source
- Combines metal vaporization + electron-impact ionization with tunable voltages.
- Achieved stable, controllable Ba^{2+}, Pb^{2+}, Cd^{2+} beams confirmed via mass spectrometry.
- Optimized parameters (I_e, V_e, V_i) → majority Ba^{2+} flux.



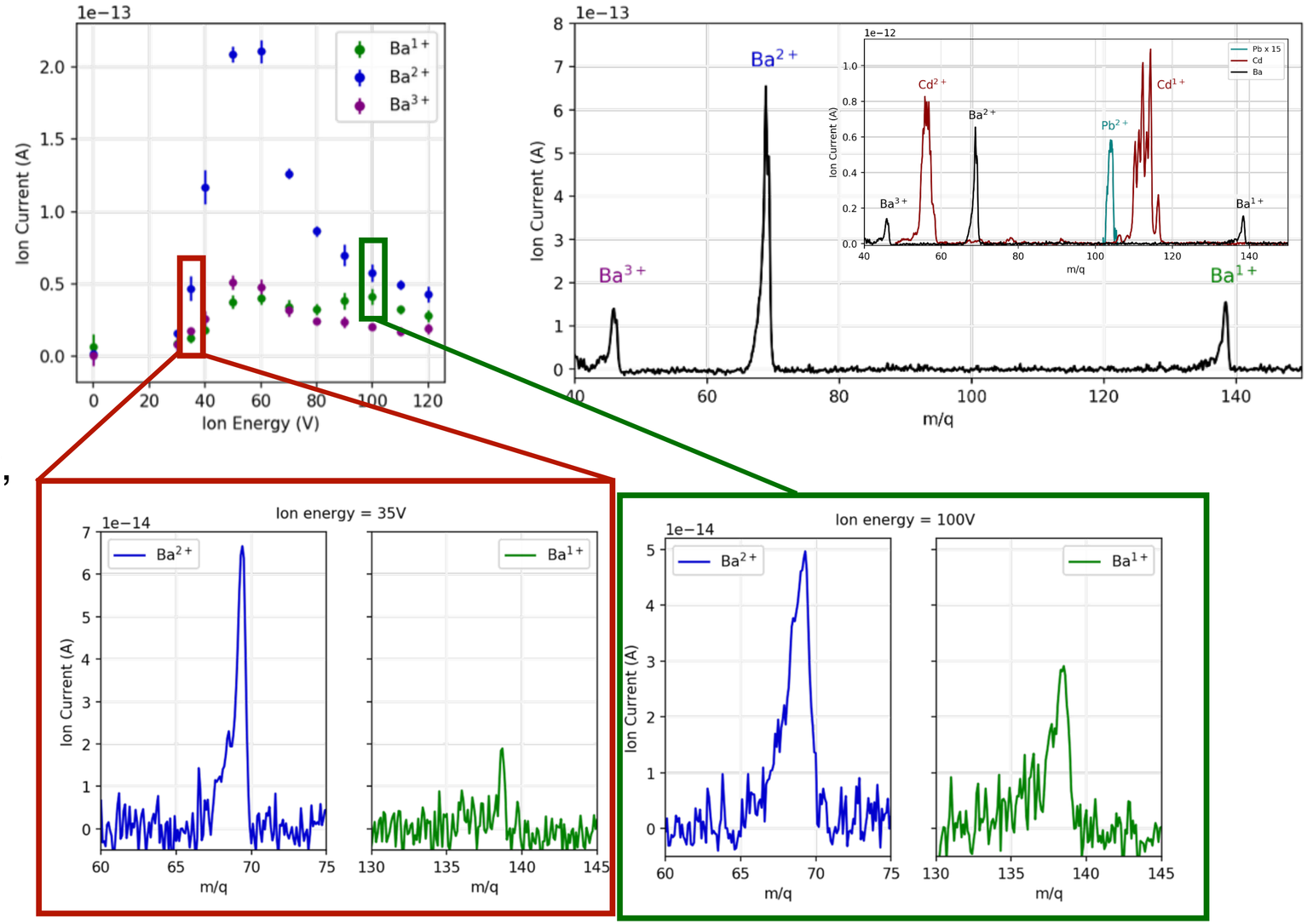


[a] JINST 18 P07044 (**2023**).

Ba^{2+} beam in high pressure

Controlled energy ions

- Compact, solvent-free Ba^{2+} ion source
- Combines metal vaporization + electron-impact ionization with tunable voltages.
- Achieved stable, controllable Ba^{2+}, Pb^{2+}, Cd^{2+} beams confirmed via mass spectrometry.
- Optimized parameters (I_e, V_e, V_i) → majority Ba^{2+} flux.
- Need thermalization of ions for testing with molecules

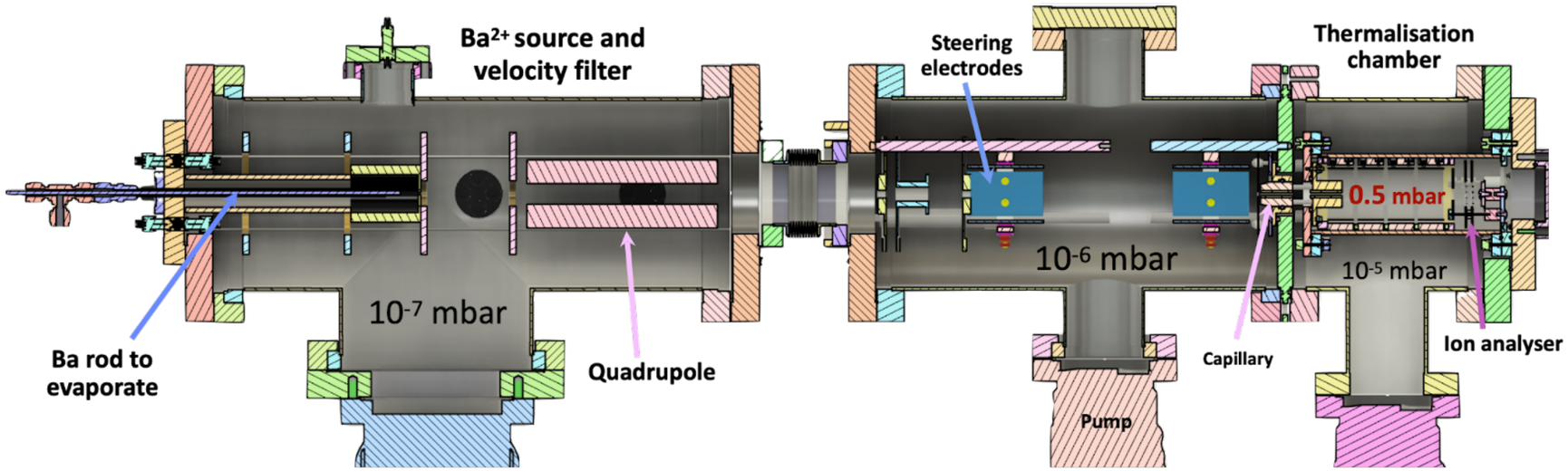


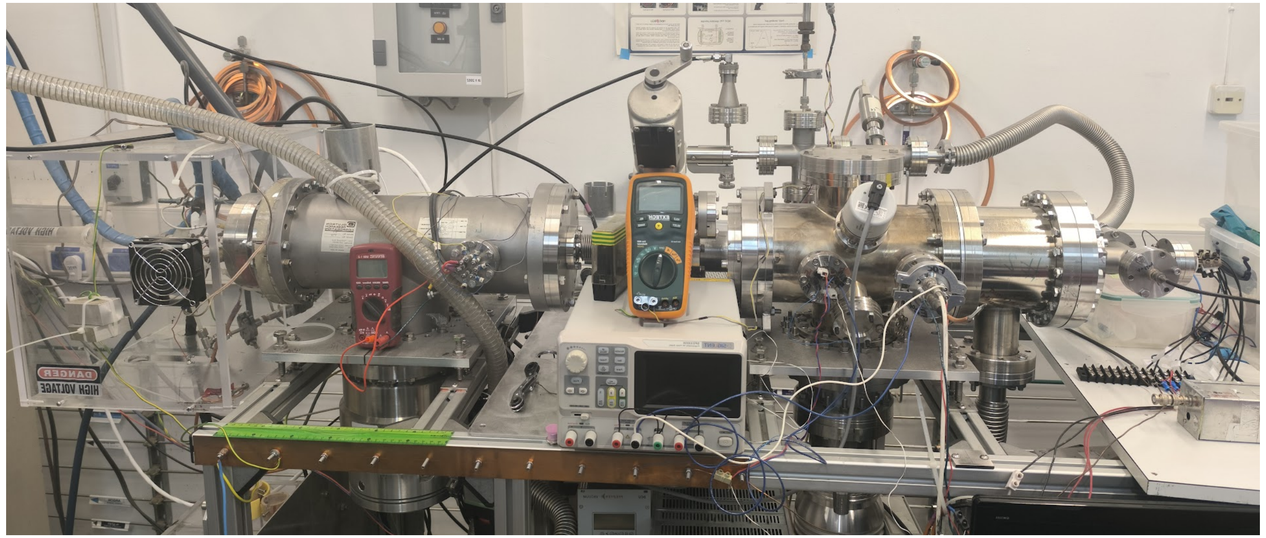
[a] JINST 18 P07044 (**2023**).

Ba^{2+} beam in low pressure

Thermal ions

- Sublimation of Ba → filtering from other ions
- Steering into thermalization chamber though differential pumping
- Collision with GHe at ~0.5 mbar

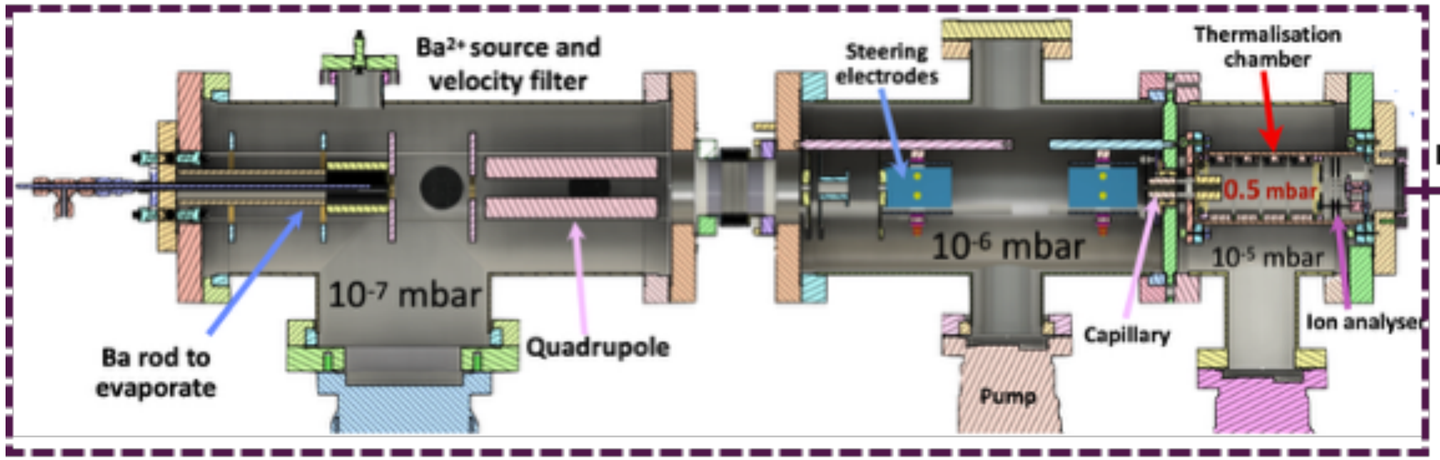


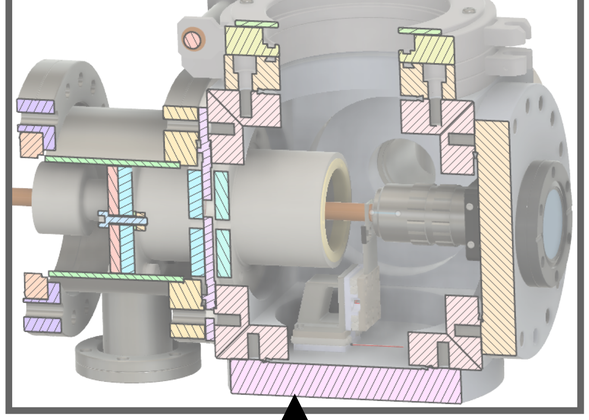


Ba^{2+} beam in low pressure

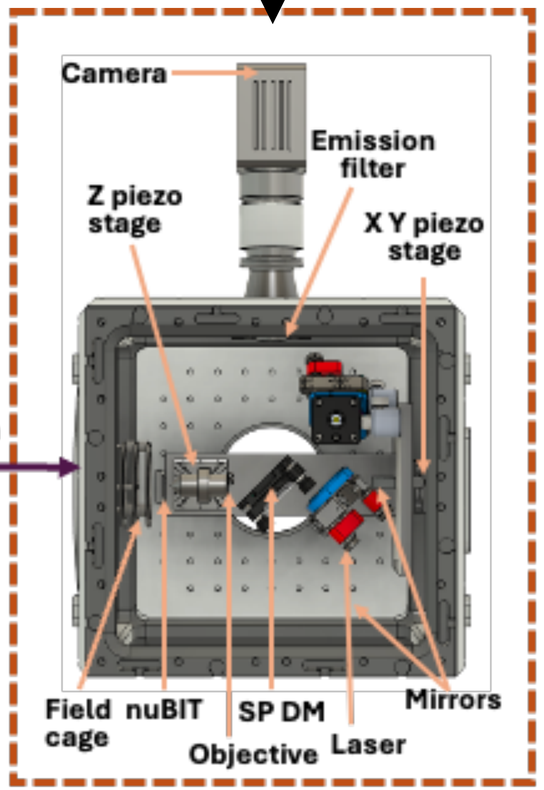
Coupling to microscope

- Aim: Testing detection of single Ba-chelated molecules *in-situ* at vacuum with thermal ions.
- Optimized HP microscope already available, coupling to low-energy beam planned.



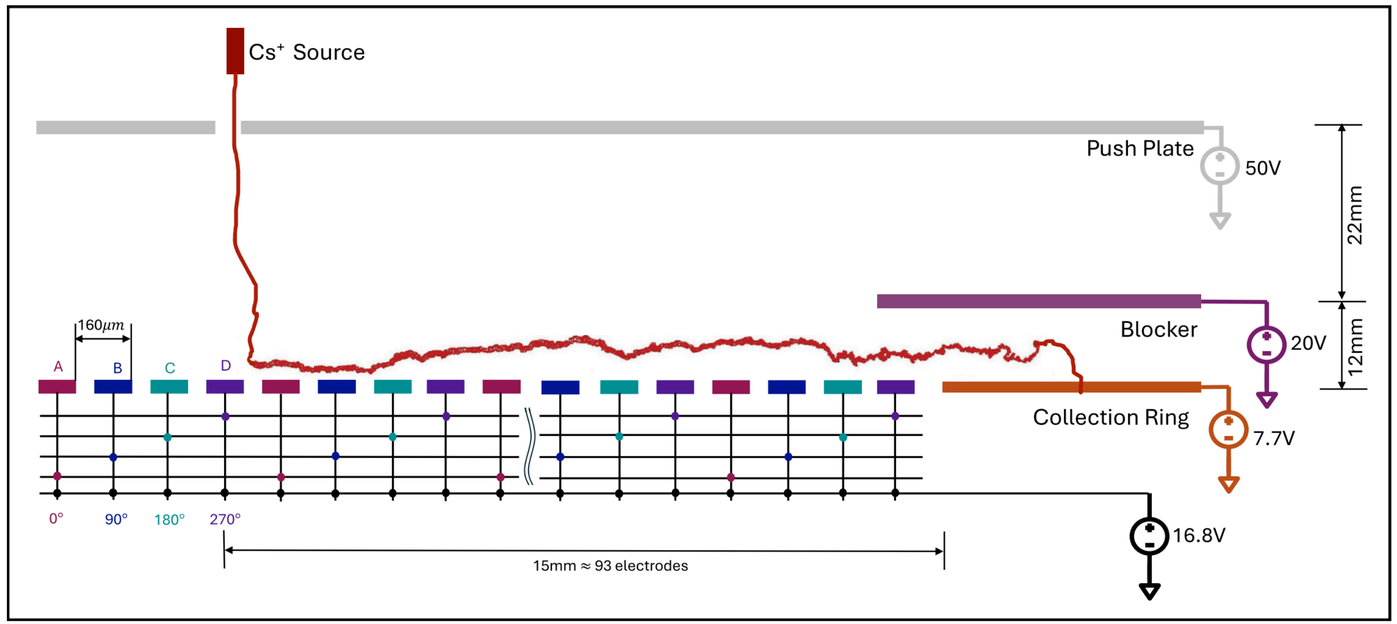


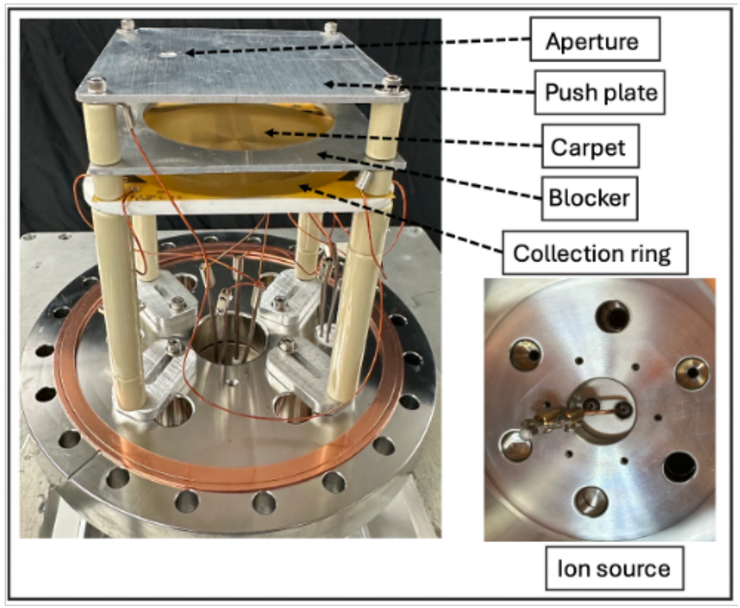
Ba2+ beam

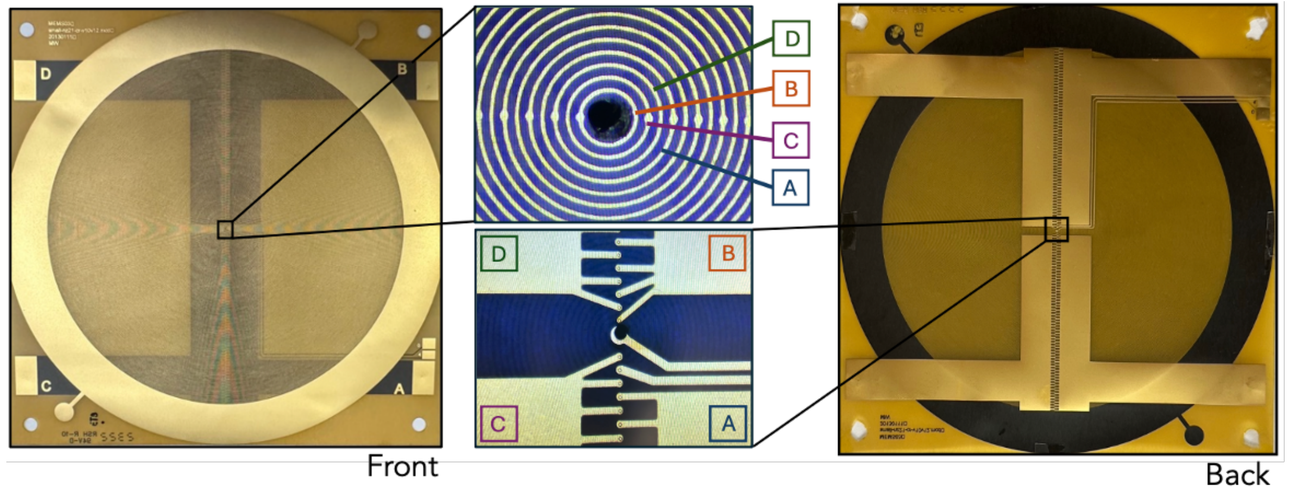


Ba^{2+} guide in GXe with RF carpet

- Using Cs^{+} as Ba^{+} conservative stand-in
- 160 μm electrode pitch, at 2 MHz, up to 300 V
- Maximum efficiency for four-phase mode, as predicted from simulation



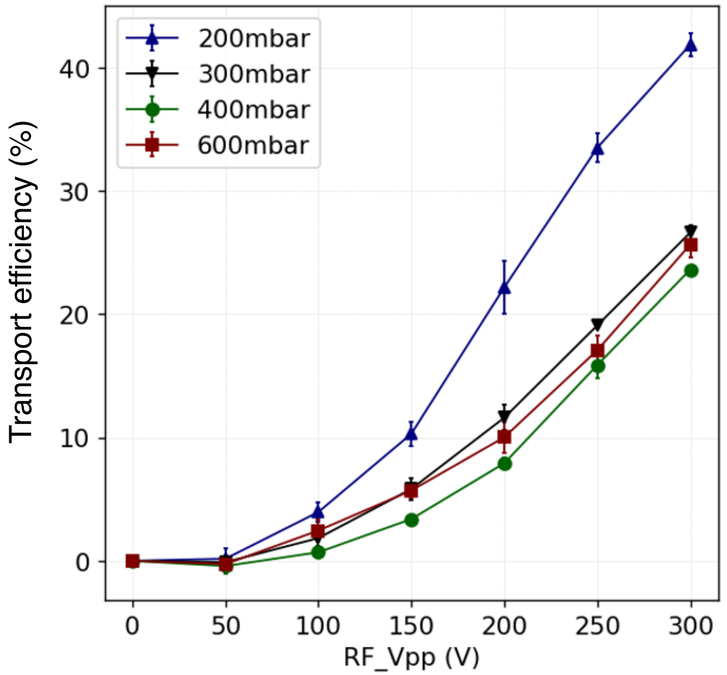




Eur. Phys. J. C 85, 688 (2025).

Ba^{2+} guide in GXe with RF carpet

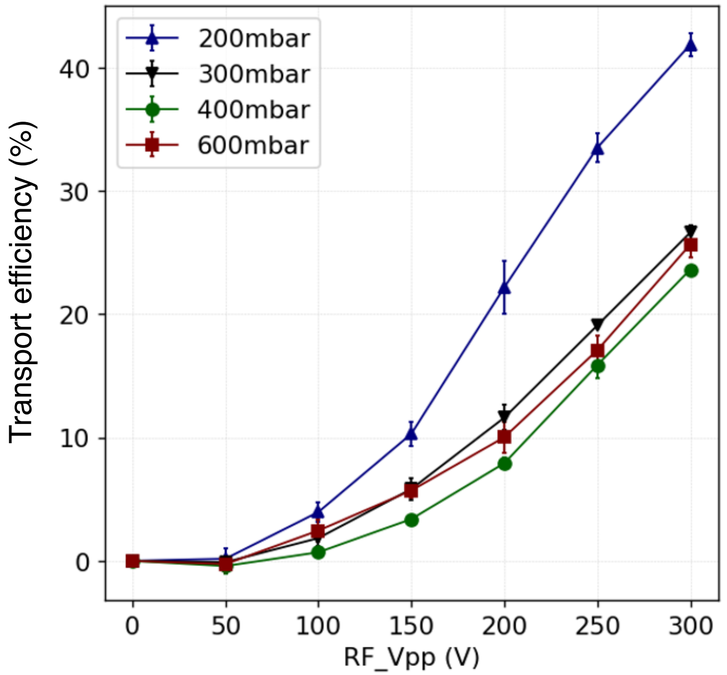
- Using Cs^{+} as Ba^{+} conservative stand-in
- 160 μm electrode pitch, at 2 MHz, up to 300 V
- Maximum efficiency for four-phase mode, as predicted from simulation
- Successful ion transport at up to 600 mbar
- Transport efficiency depends on with RF voltage and phase difference

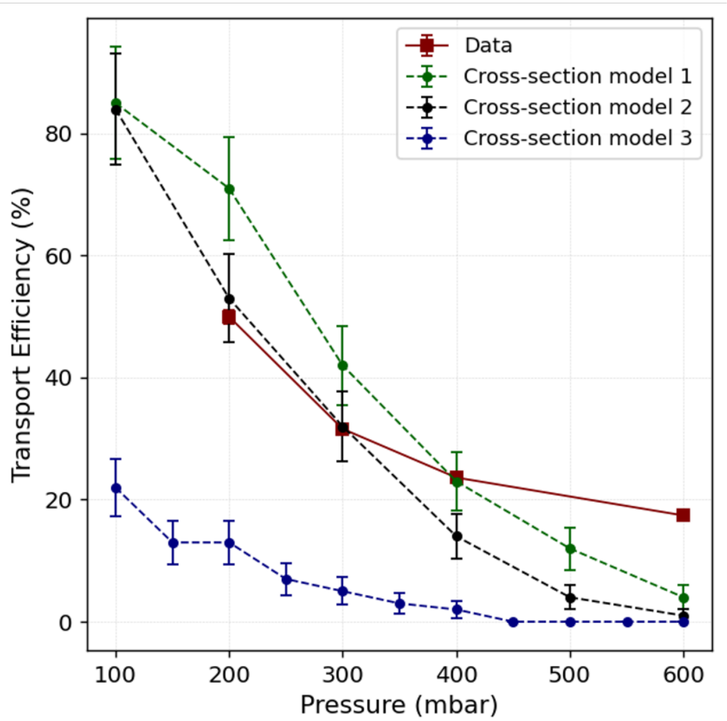


Eur. Phys. J. C 85, 688 (2025).

Ba^{2+} guide in GXe with RF carpet

- Using Cs^{+} as Ba^{+} conservative stand-in
- 160 µm electrode pitch, at 2 MHz, up to 300 V
- Maximum efficiency for four-phase mode, as predicted from simulation
- Successful ion transport at up to 600 mbar
- Transport efficiency depends on with RF voltage and phase difference
- 3 cross-section models in qualitative agreement; clustering model (3) too restrictive





More on clustering: Phys. Rev. A. 97, 062509 (**2018**)

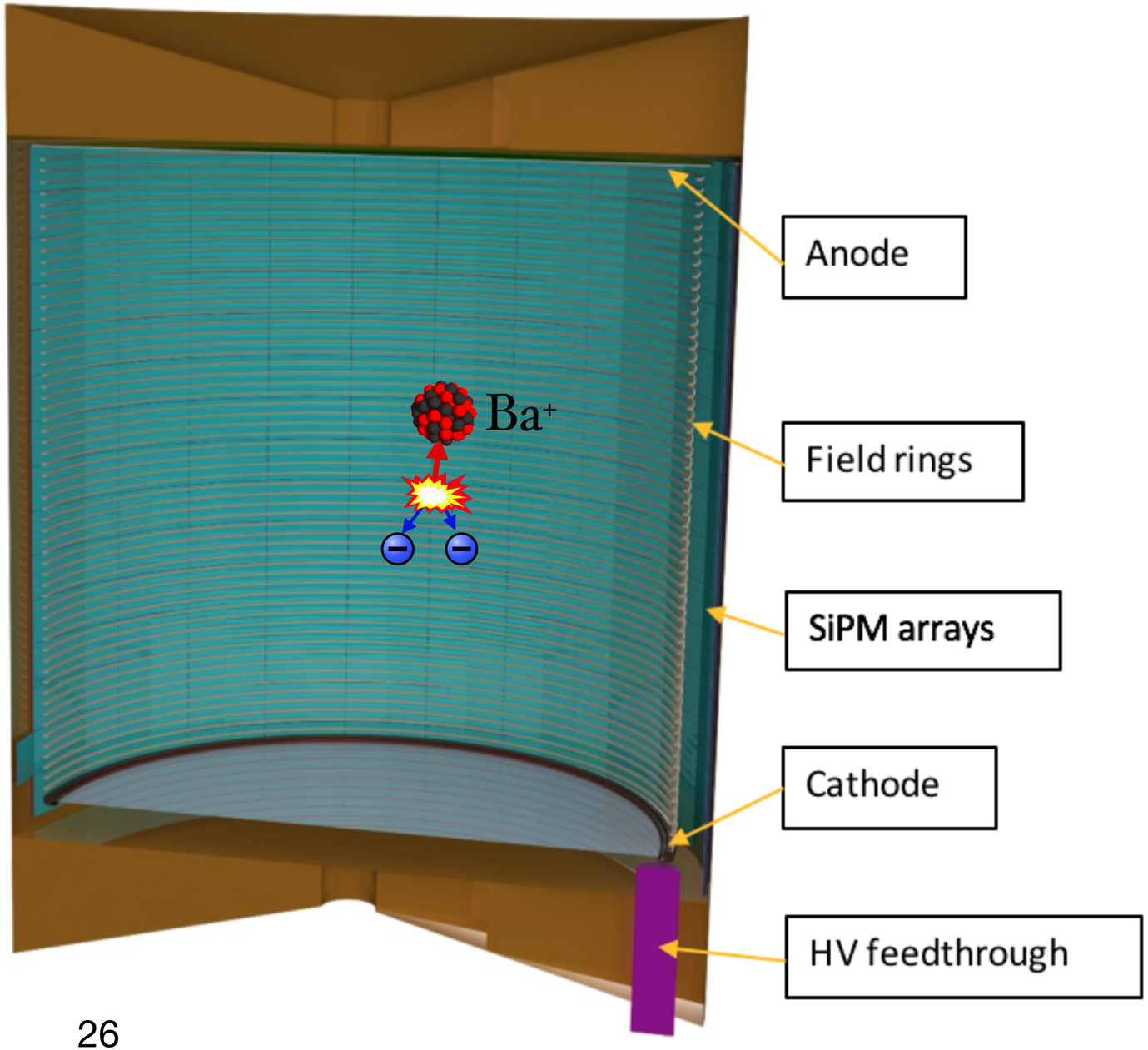
Eur. Phys. J. C 85, 688 (2025).

Overview

- ☑ Introduction to Ba-tagging
- ☑ Ba-Tagging in NEXT
- ☐ **Ba-Tagging in nEXO**
- ☐ The road forward

Ba-Tagging in LXe

Concept

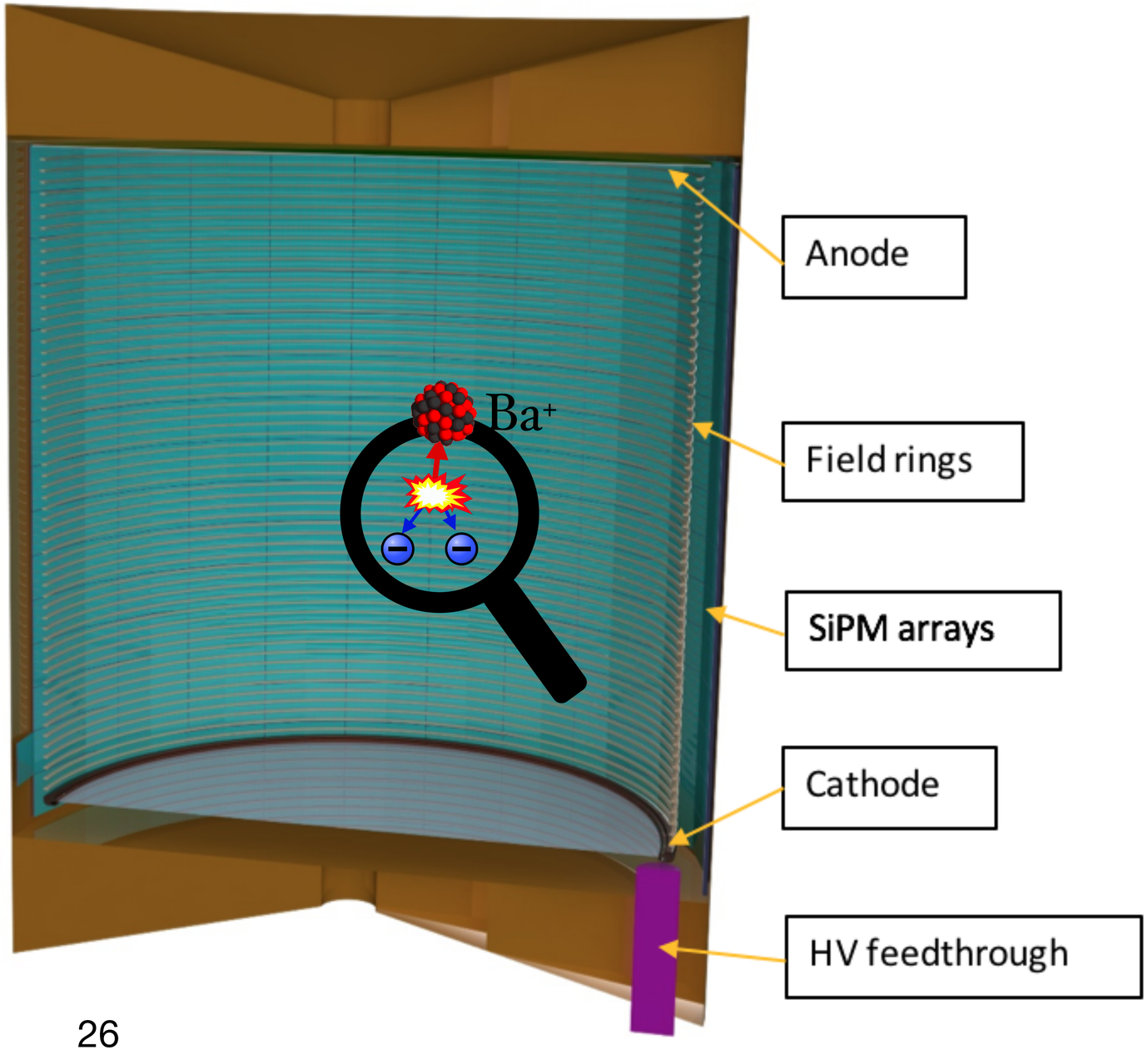


[a] Phys. Rev. C 89, 015502 (**2014**) (EXO-200 $T_{2\nu\beta\beta}$ meas.)

Ba-Tagging in LXe

Concept

1. Localization[a]

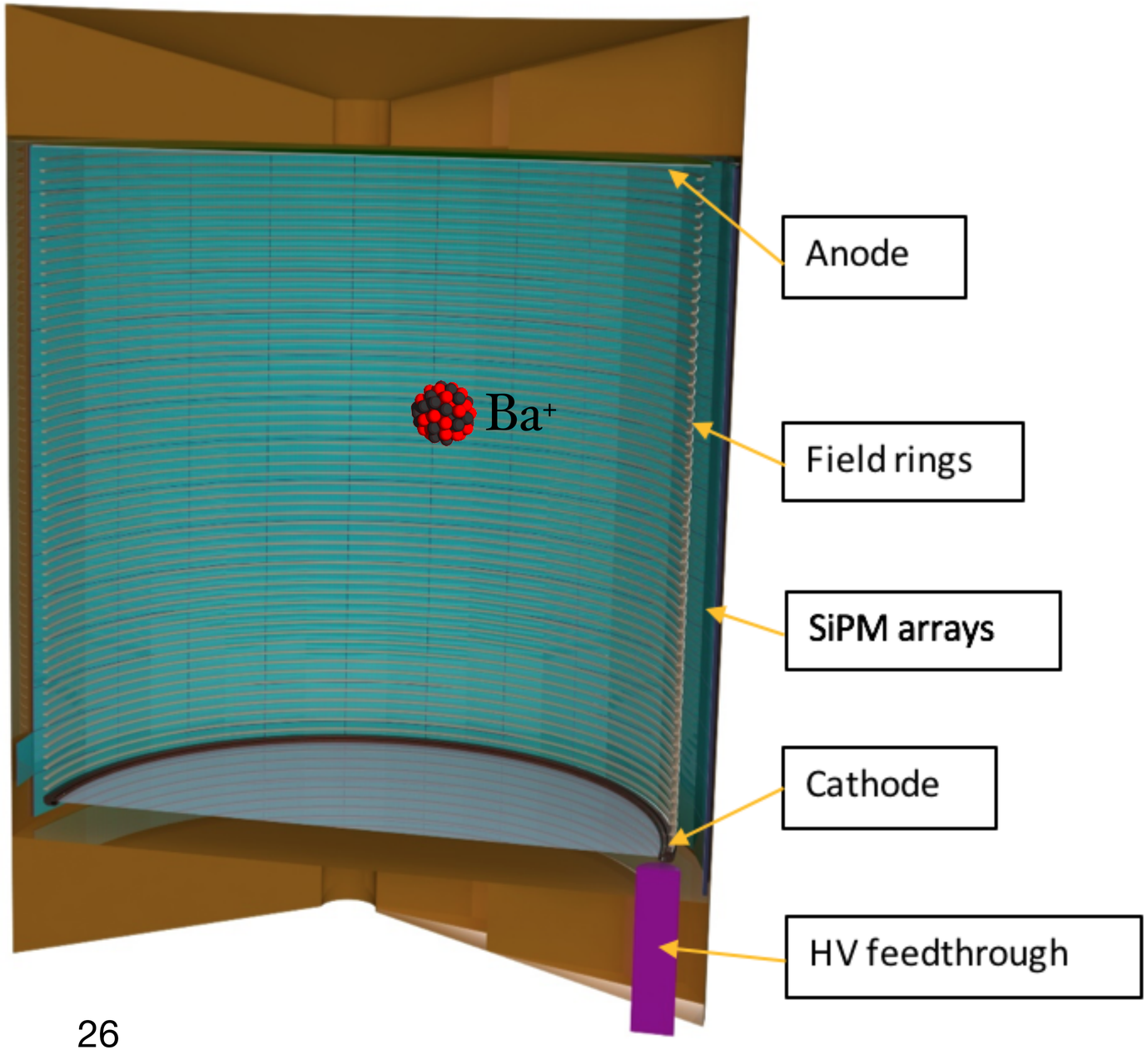


[a] Phys. Rev. C 89, 015502 (**2014**) (EXO-200 $T_{2\nu\beta\beta}$ meas.)

Ba-Tagging in LXe

Concept

1. Localization[a]
2. Extraction

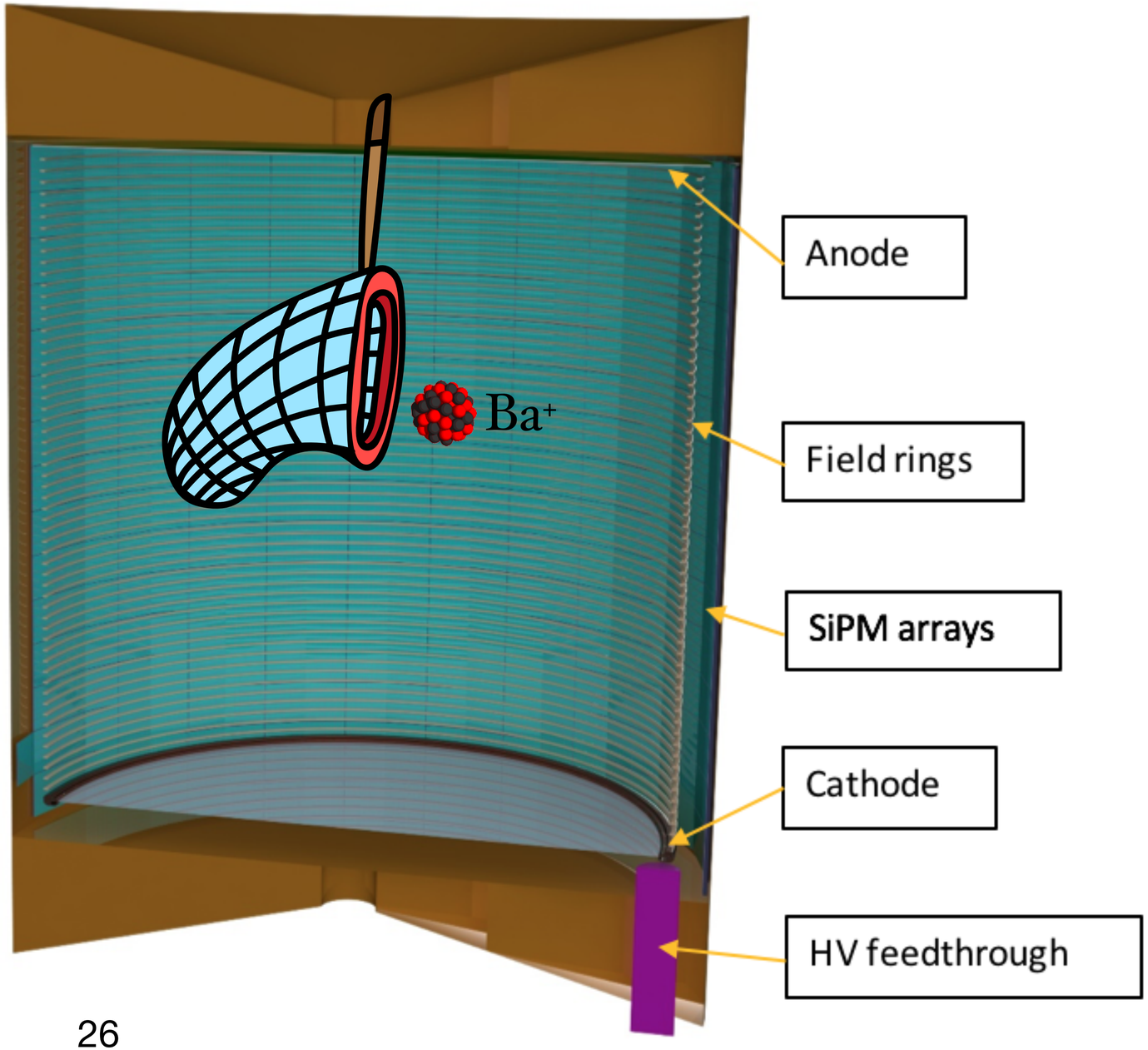


[a] Phys. Rev. C 89, 015502 (**2014**) (EXO-200 $T_{2\nu\beta\beta}$ meas.)

Ba-Tagging in LXe

Concept

1. Localization[a]
2. Extraction
    A. Cryoprobe

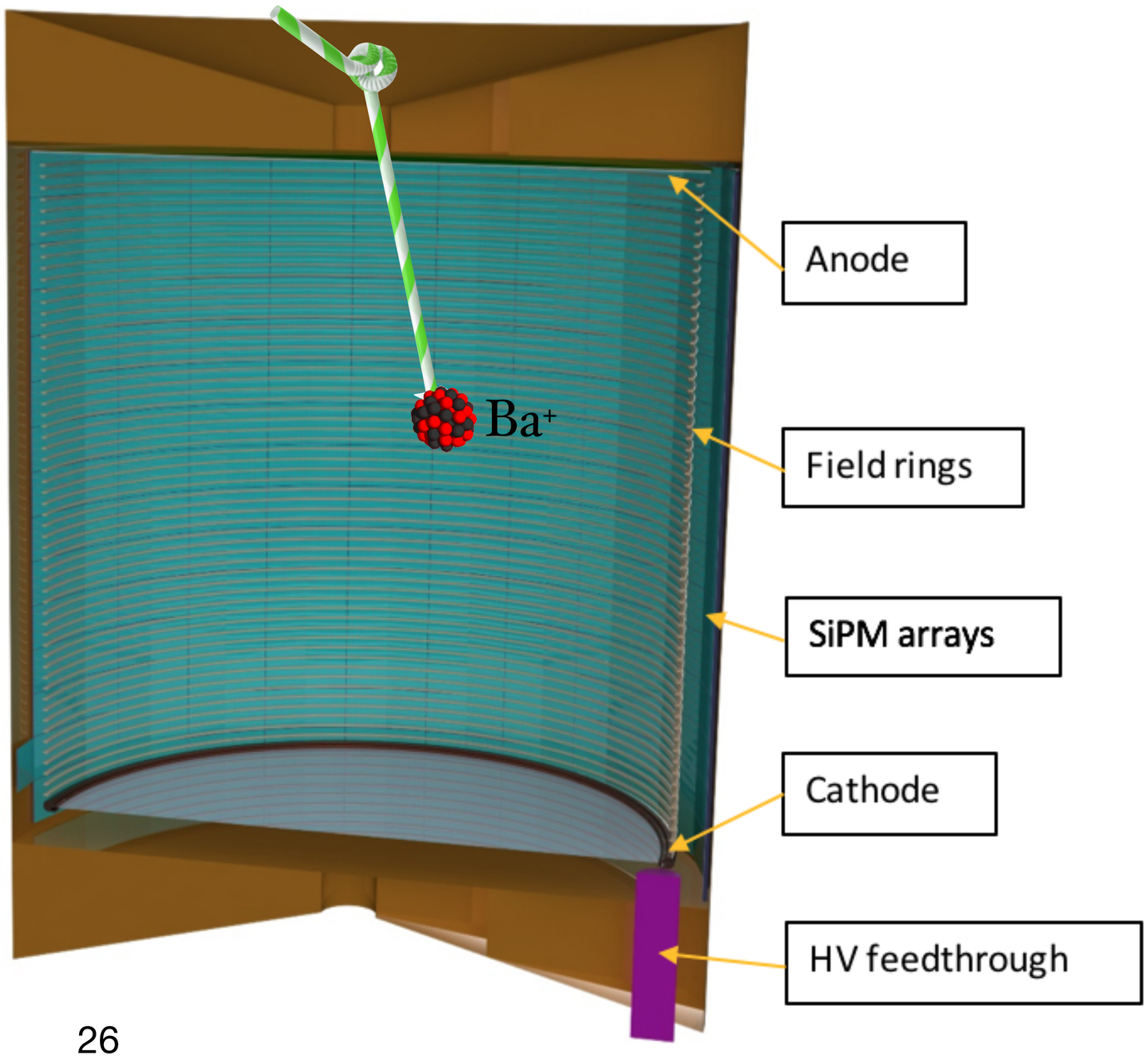


[a] Phys. Rev. C 89, 015502 (**2014**) (EXO-200 $T_{2\nu\beta\beta}$ meas.)

Ba-Tagging in LXe

Concept

1. Localization[a]
2. Extraction
    A. Cryoprobe
    B. Capillary tube

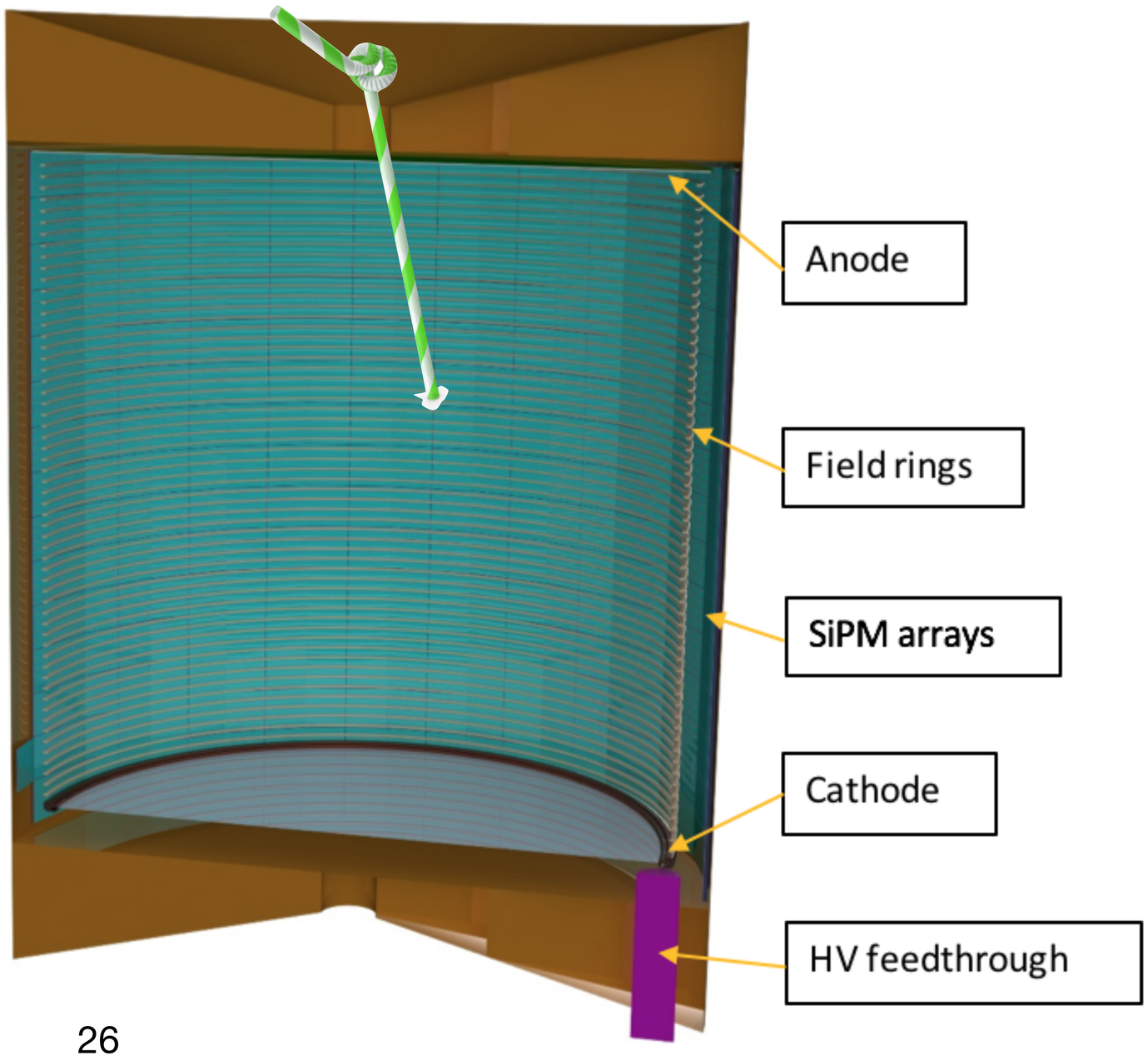


[a] Phys. Rev. C 89, 015502 (**2014**) (EXO-200 $T_{2\nu\beta\beta}$ meas.)

Ba-Tagging in LXe

Concept

1. Localization[a]
2. Extraction
   A. Cryoprobe
   B. Capillary tube
3. (Separation)

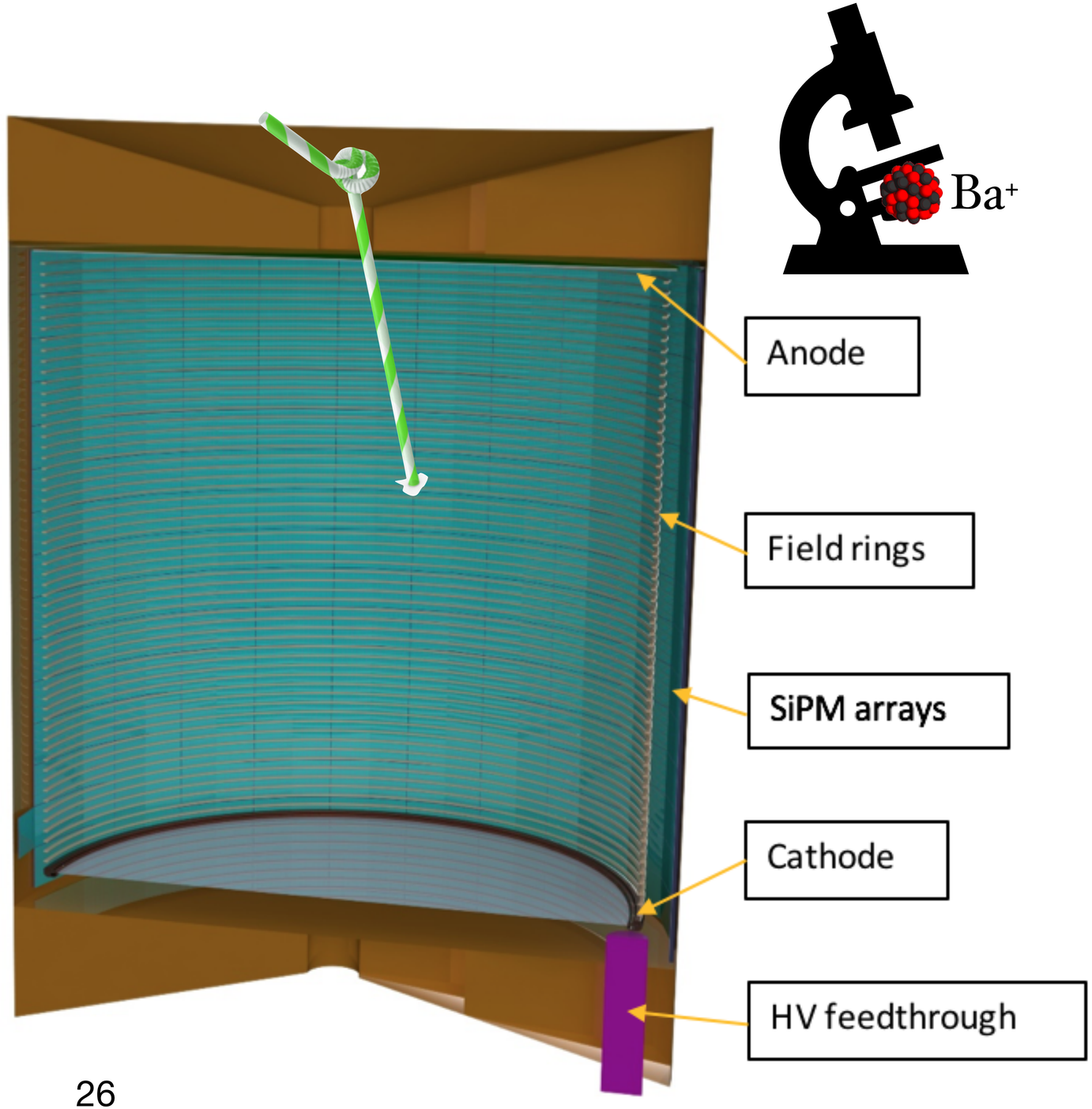


[a] Phys. Rev. C 89, 015502 (**2014**) (EXO-200 $T_{2\nu\beta\beta}$ meas.)

Ba-Tagging in LXe

Concept

1. Localization[a]
2. Extraction
   A. Cryoprobe
   B. Capillary tube
3. (Separation)
4. Identification

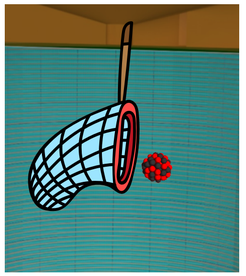


[a] Phys. Rev. C 89, 015502 (**2014**) (EXO-200 $T_{2\nu\beta\beta}$ meas.)

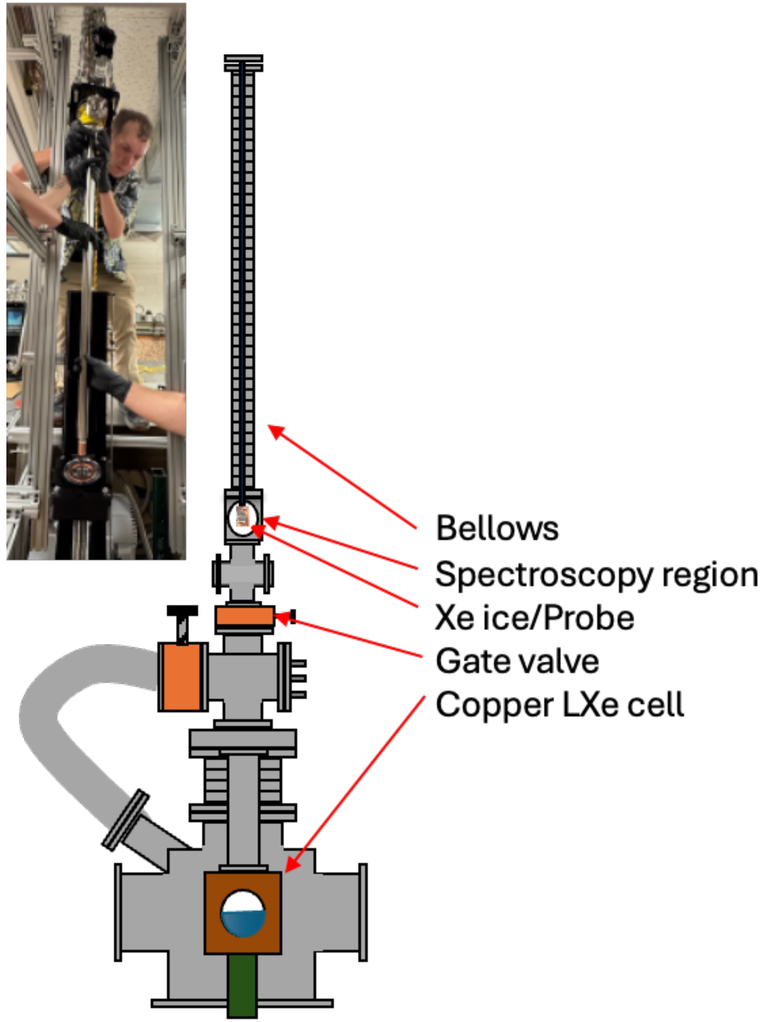
Overview

- ☑ Introduction to Ba-tagging
- ☑ Ba-Tagging in NEXT
- ☐ **Ba-Tagging in nEXO**
  - ☐ **Extraction through cryoprobe**
  - ☐ Extraction through capillary
- ☐ The road forward

Extraction with cryoprobe (cont.)

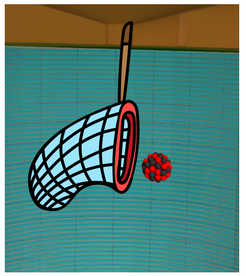


- Capture Ba in SXe from LXe at >161K.
- Proper SXe ice is transparent, not frosty or cracked
- After gate valve, reduce probe *T* and *p* → 10-40 K for single Ba/Ba$^+$ imaging.

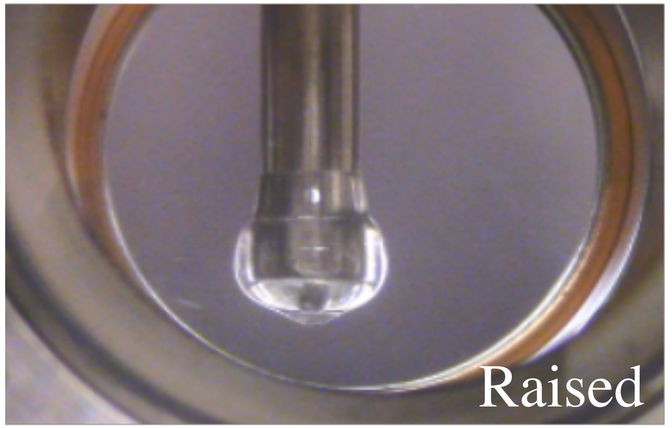


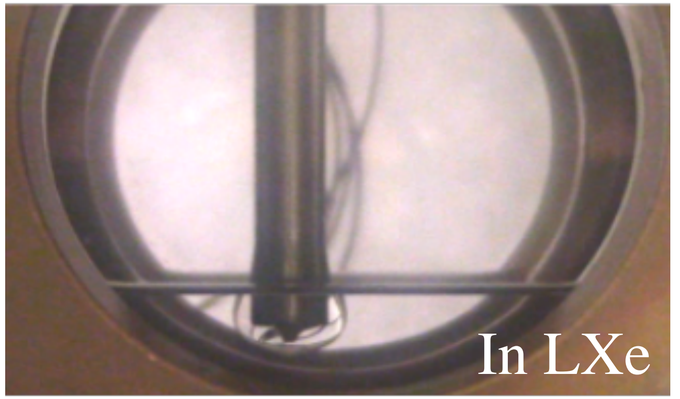
[a] Rev. Sci. Instrum. 85, 095114 (**2014**) + unpublished recent results

Extraction with cryoprobe (cont.)



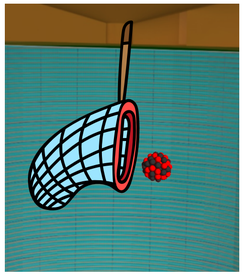
- Capture Ba in SXe from LXe at >161K.
- Proper SXe ice is transparent, not frosty or cracked
- After gate valve, reduce probe *T* and *p* → 10-40 K for single Ba/Ba$^+$ imaging.





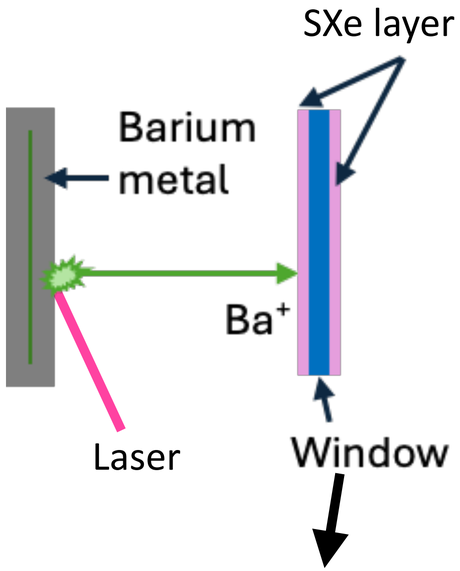
[a] Rev. Sci. Instrum. 85, 095114 (**2014**) + unpublished recent results

Extraction with cryoprobe (cont.)

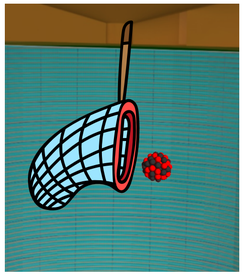


Previous work:

- Laser desorption in **GXe**
- Ba fluorescence at 160 K
- Expanding LN_2/Ar for cryoprobe

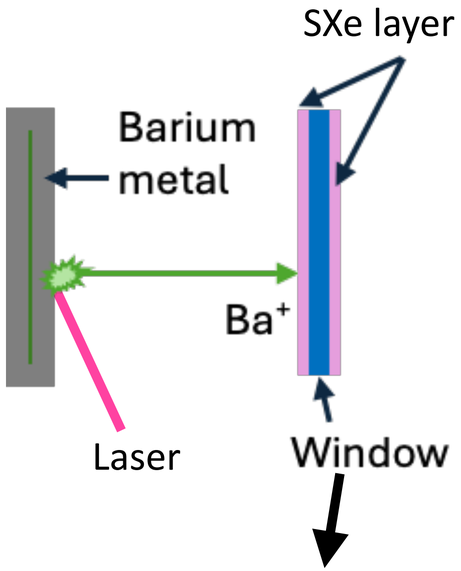


Extraction with cryoprobe (cont.)



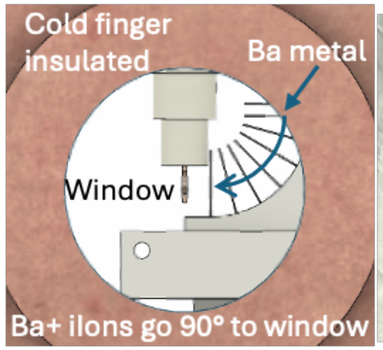
Previous work:

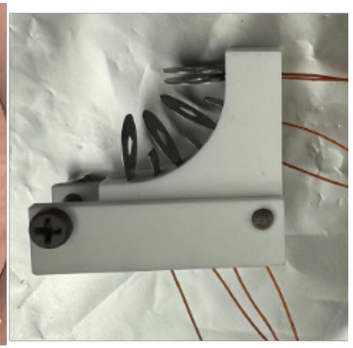
- Laser desorption in **GXe**
- Ba fluorescence at 160 K
- Expanding LN_2/Ar for cryoprobe



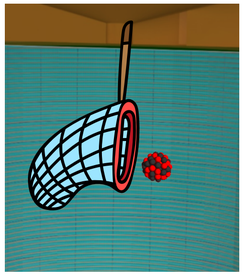
Latest upgrades:

- Electrodes to guide Ba+ in **LXe** to SXe window
- Commercial He cryoprobe → 10-40 K



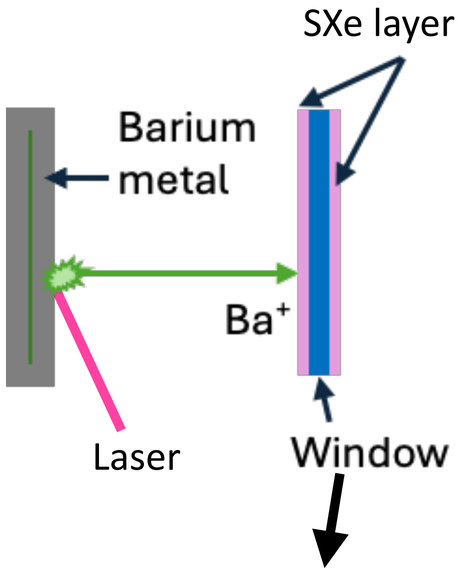


Extraction with cryoprobe (cont.)



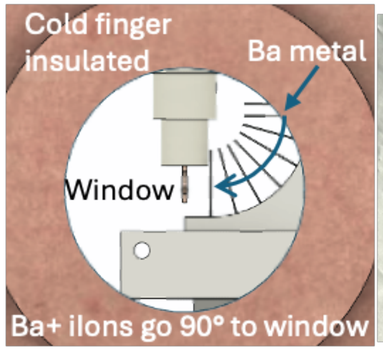
Previous work:

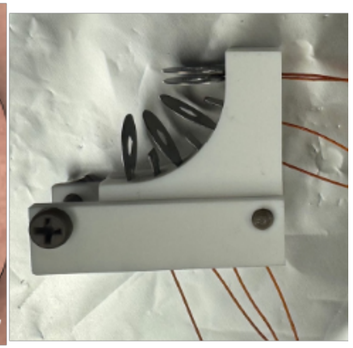
- Laser desorption in **GXe**
- Ba fluorescence at 160 K
- Expanding LN_2/Ar for cryoprobe

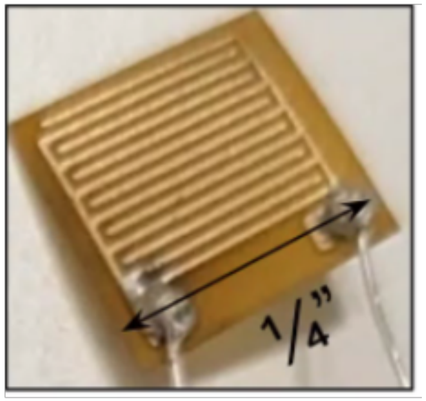


Latest upgrades:

- Electrodes to guide Ba+ in **LXe** to SXe window
- Commercial He cryoprobe → 10-40 K
- Thickness control of SXe: ~10's μm



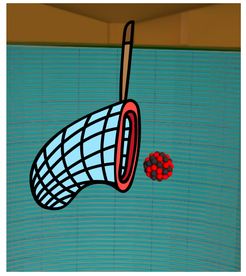




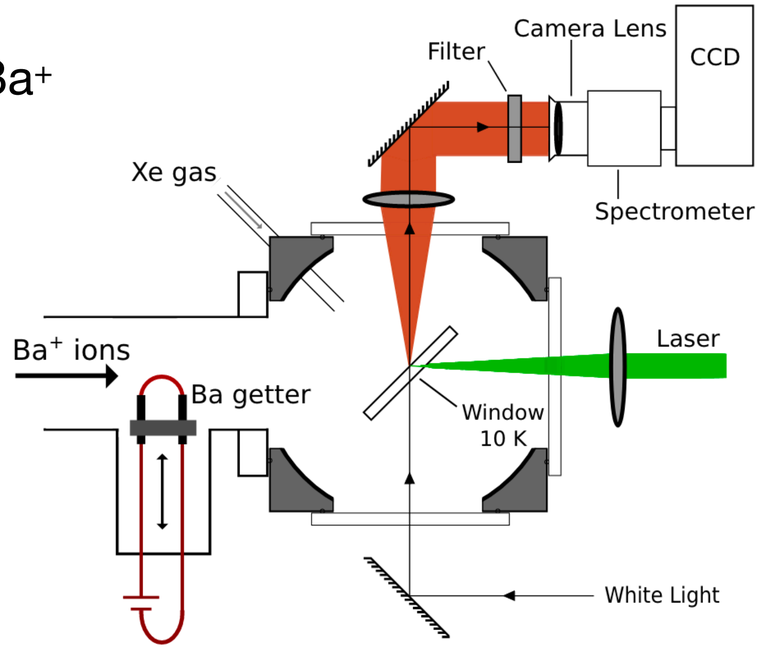
Flexible Capacitance sensor measures SXe thickness UCSD

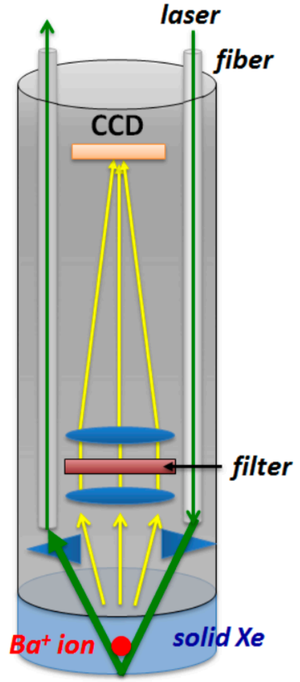
Implantation of Ba^+ on SXe

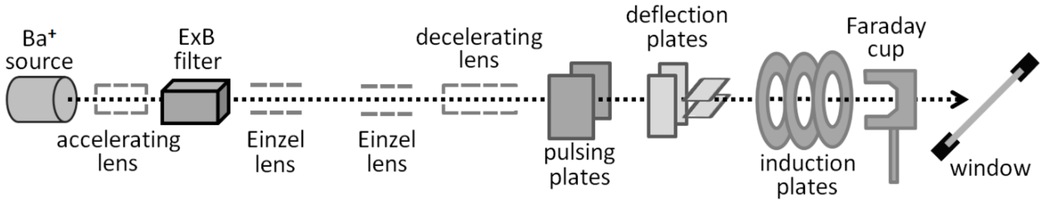
First laser spectroscopy results



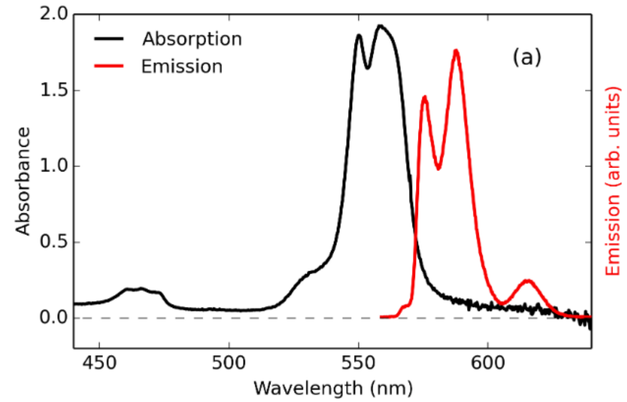
- Absorption and fluorescence spectra of Ba/Ba^+ in SXe and SAr.
- Ba^+ ion source and neutral Ba from getter.
- Multiple emission bands corresponding to different matrix sites and partial Ba^+ neutralization
- Fluorescence images of ≈10^4 Ba atoms





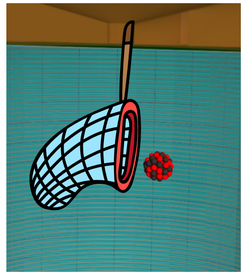


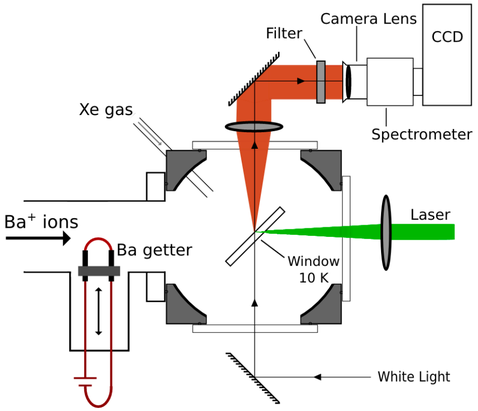
Absorption/emission spectra of Ba in SXe



[a] Phys. Rev. A 2015, 91, 022505. (**2015**) (Spectroscopy of Ba in SXe)

Single-ion detection in SXe

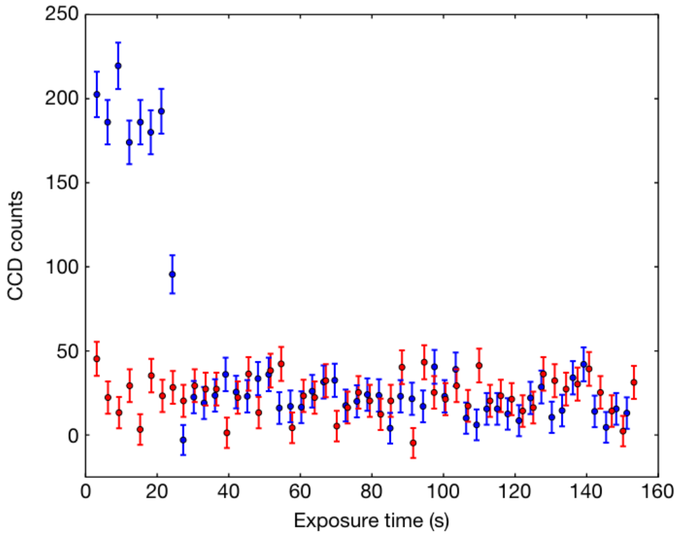


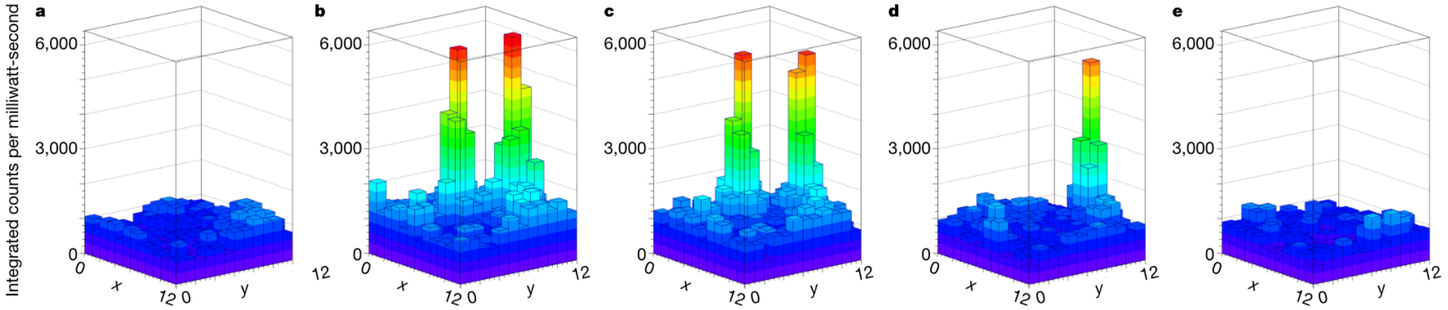


Matrix Vacancy study

- Extended result of Mong et al. at the single Ba level (observed single photobleaching step)
- Corresponding to single-vacancy Ba in SXe matrix.
- Different behavior of the Tetra- and Hexa-Vacancy.
- Annealing causes fluorescence recovery (anti-bleaching) at the HV site (577 nm)

Single-steps of Ba in SXe

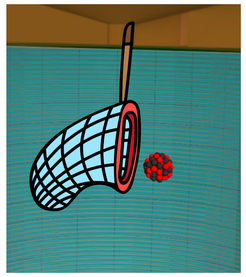


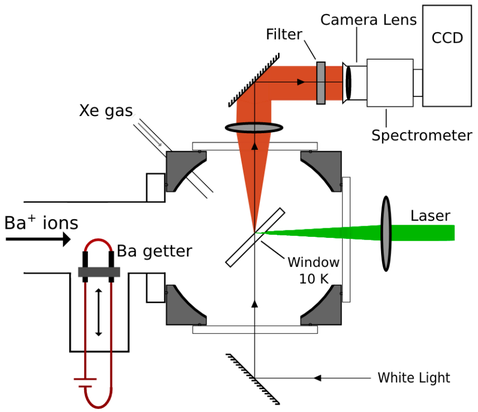


[a] Nature 2019, 569, 203–207. (**2019**) (Single Ba⁺ detection)

Single-ion detection in SXe

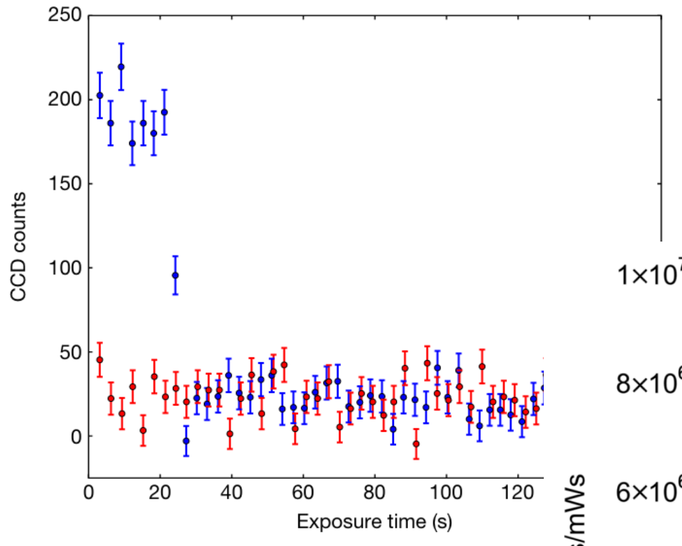
Matrix Vacancy study



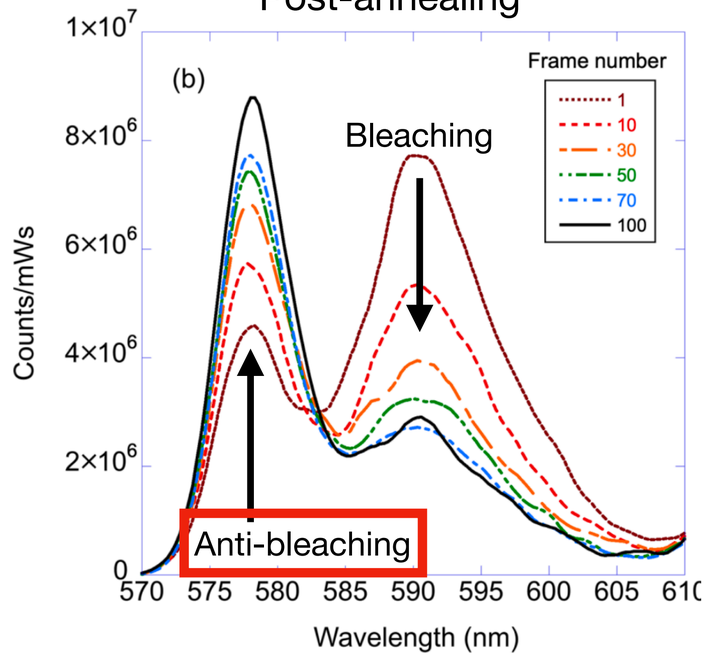


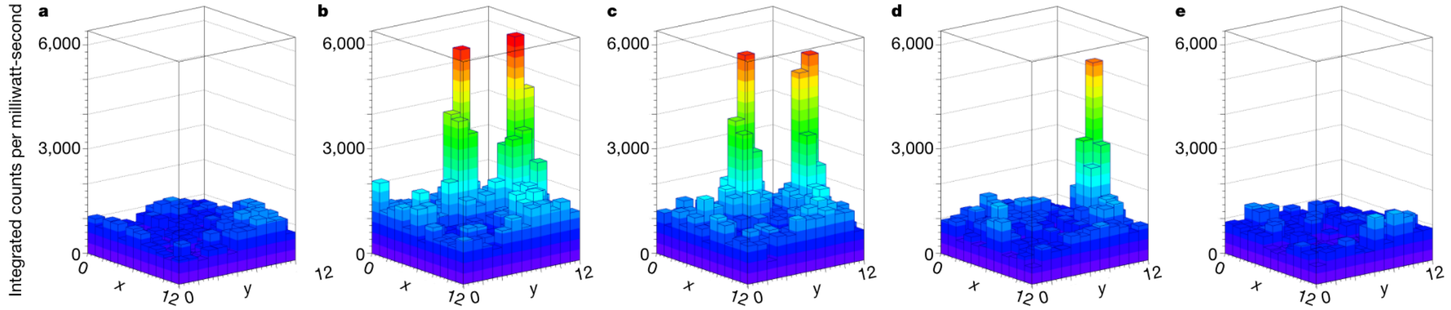
- Extended result of Mong et al. at the single Ba level (observed single photobleaching step)
- Corresponding to single-vacancy Ba in SXe matrix.
- Different behavior of the Tetra- and Hexa-Vacancy.
- Annealing causes fluorescence recovery (anti-bleaching) at the HV site (577 nm)

Single-steps of Ba in SXe



Post-annealing

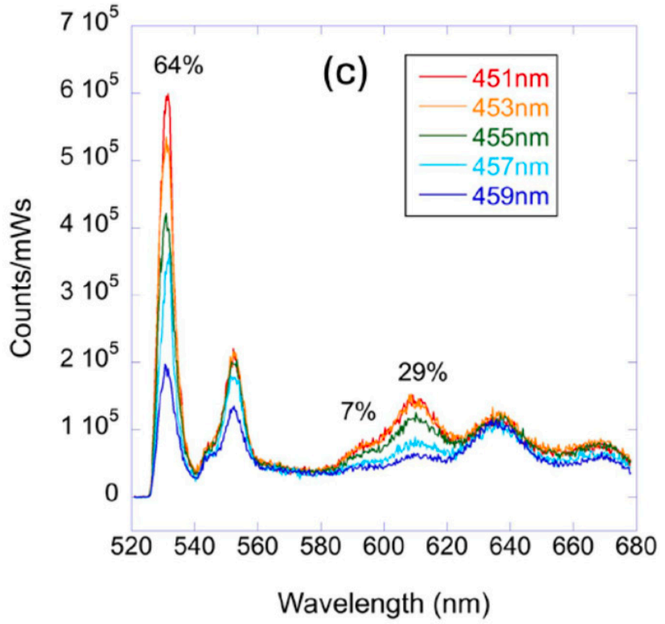


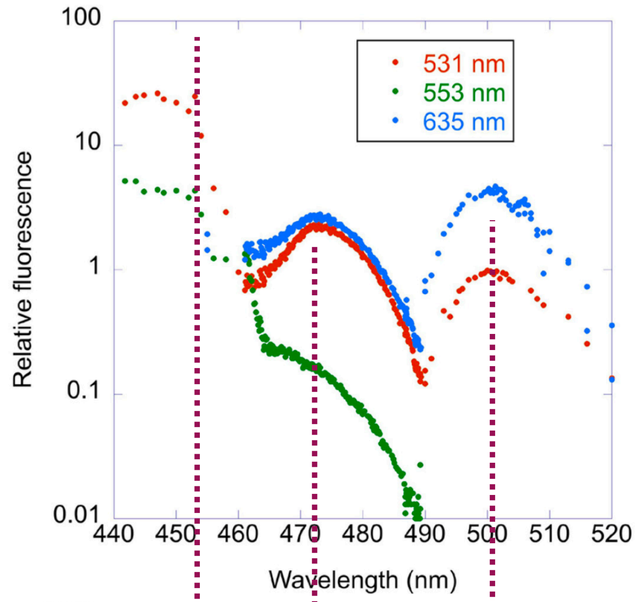


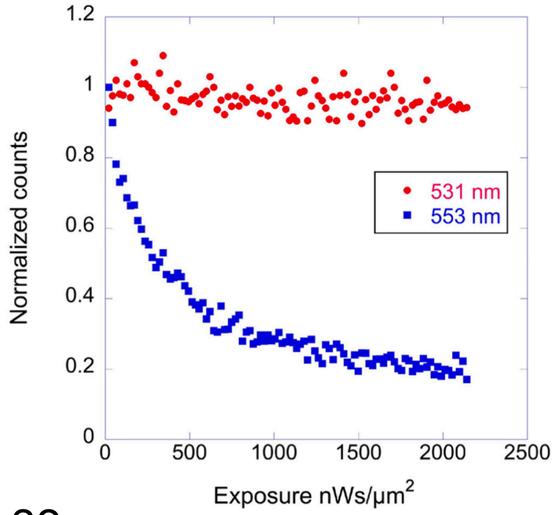
[a] Nature 2019, 569, 203–207. (**2019**) (Single Ba⁺ detection)

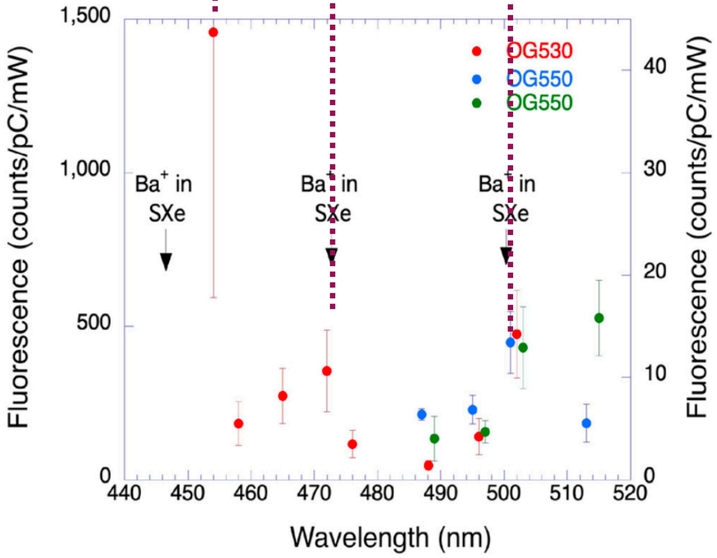
Complete spectroscopy of Ba^+ in SXe

- 3 excitation bands (446, 473, 500 nm) and 2 emission groups tied to different SXe sites.
- Moderate bleaching, high fluorescence → feasible for single-ion imaging
- Thick SXe layers cut surface background by ×10
- Spectra match Ba^+ in liquid Xe, confirming Ba^+ tagging viability for nEXO









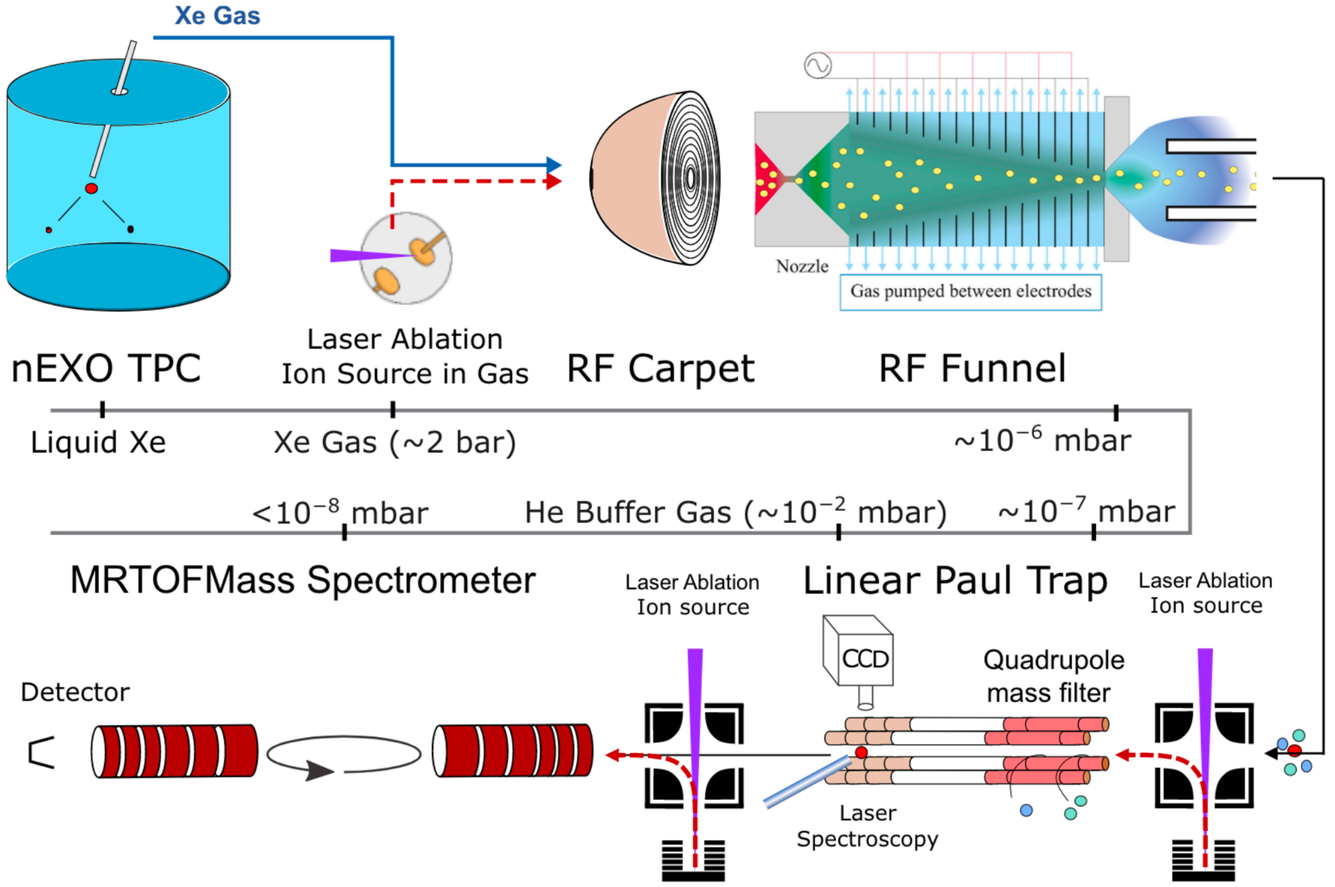
[a] Low Temp. Phys. 51, 460–468, (**2025**)

Overview

- ☑ Introduction to Ba-tagging
- ☑ Ba-Tagging in NEXT
- ☐ **Ba-Tagging in nEXO**
  - ☑ Extraction through cryoprobe
  - ☐ **Extraction through capillary**
- ☐ The road forward

Extraction with capillary

The Canadian approach

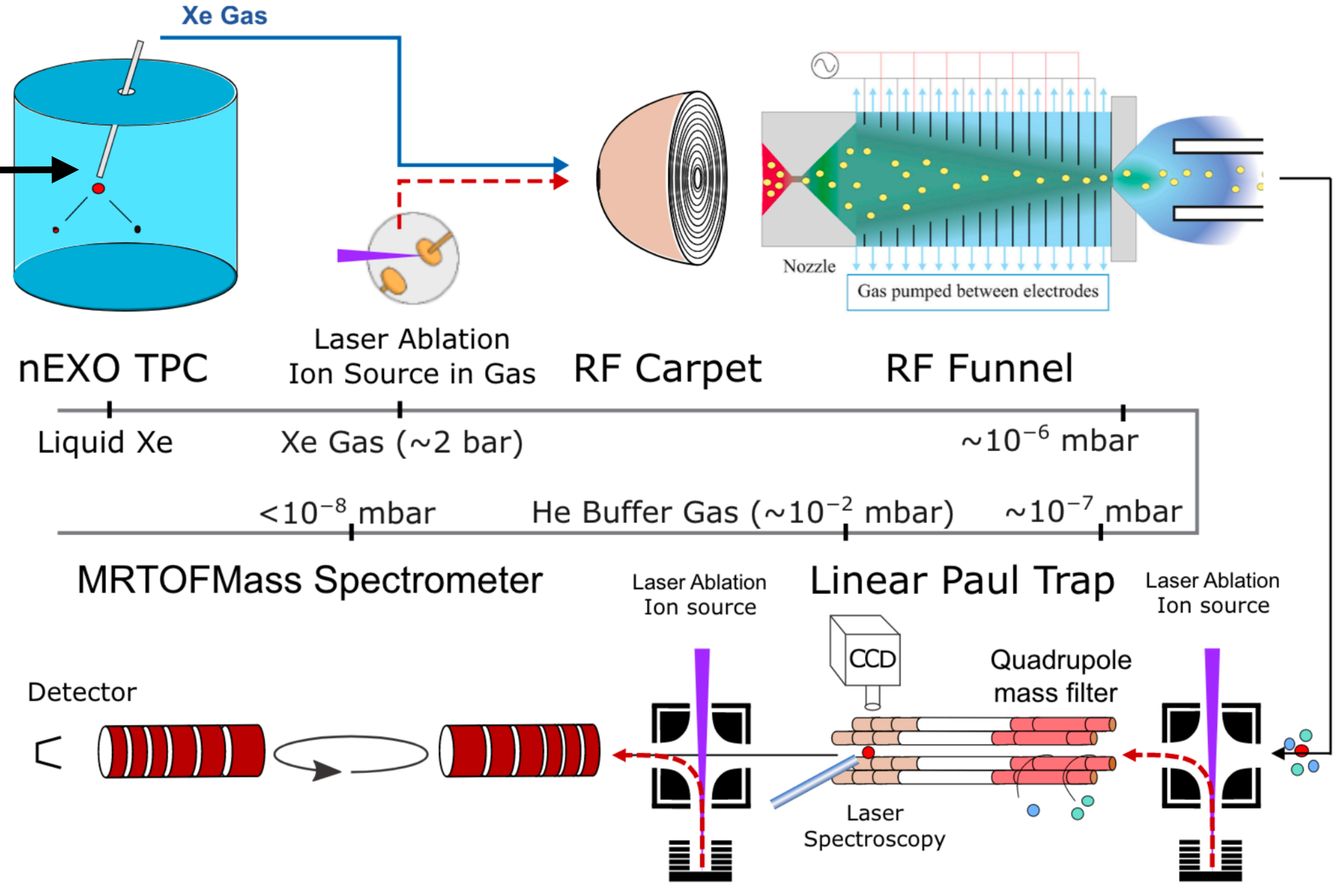


[a] Atoms 2024, 12, 71 (**2024**) (Ba^+ extraction from LXe to vacuum)
[b] Hyperfine Interact 240: 97 (**2019**) (MRTOF design)

Extraction with capillary

The Canadian approach

TRIUMF In-LXe Ba^+ source



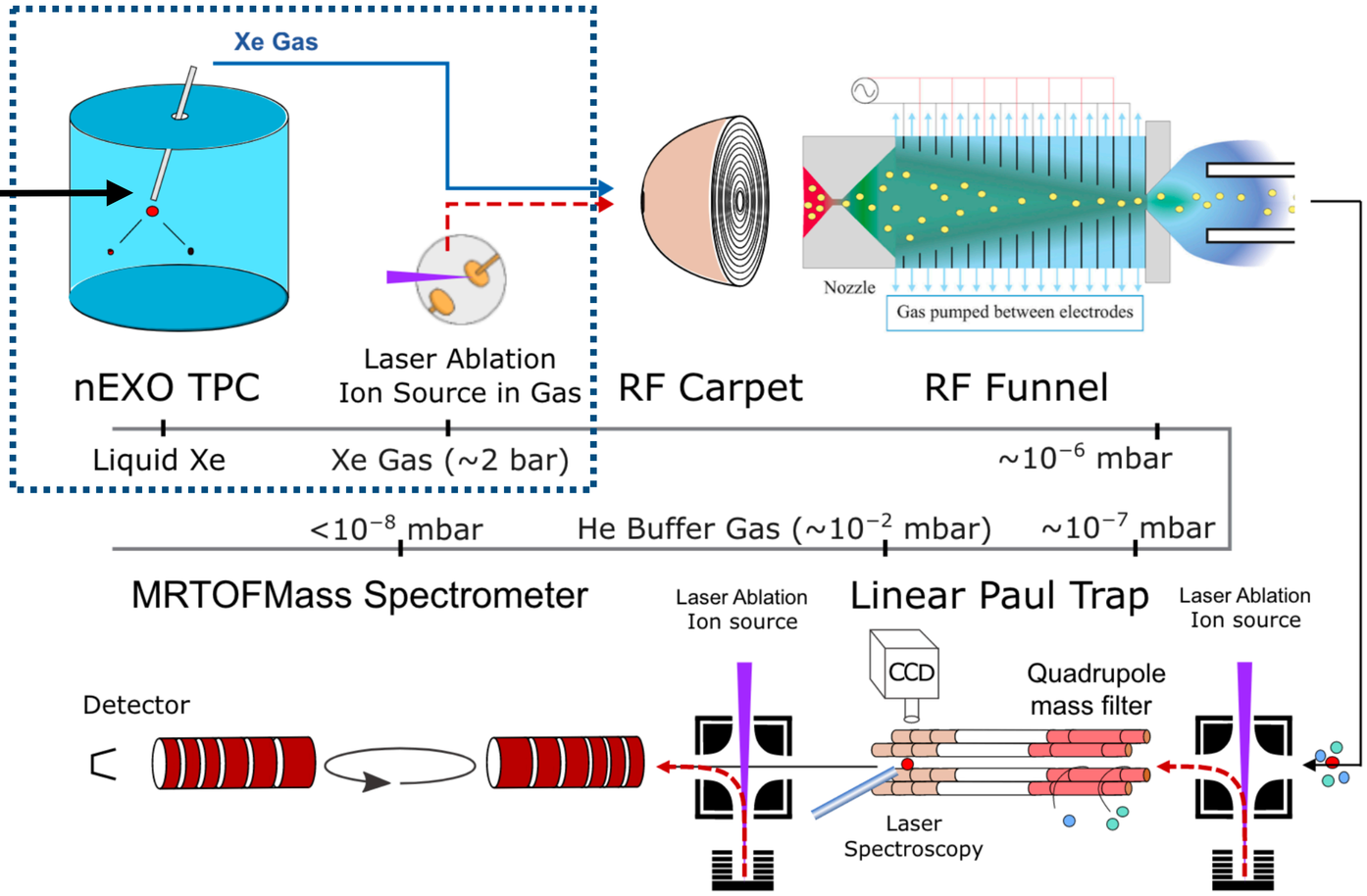
[a] Atoms 2024, 12, 71 (**2024**) (Ba^+ extraction from LXe to vacuum)
[b] Hyperfine Interact 240: 97 (**2019**) (MRTOF design)

Extraction with capillary

The Canadian approach

TRIUMF In-LXe Ba^+ source

- Extraction through capillary tube mounted in XYZ moving platform.



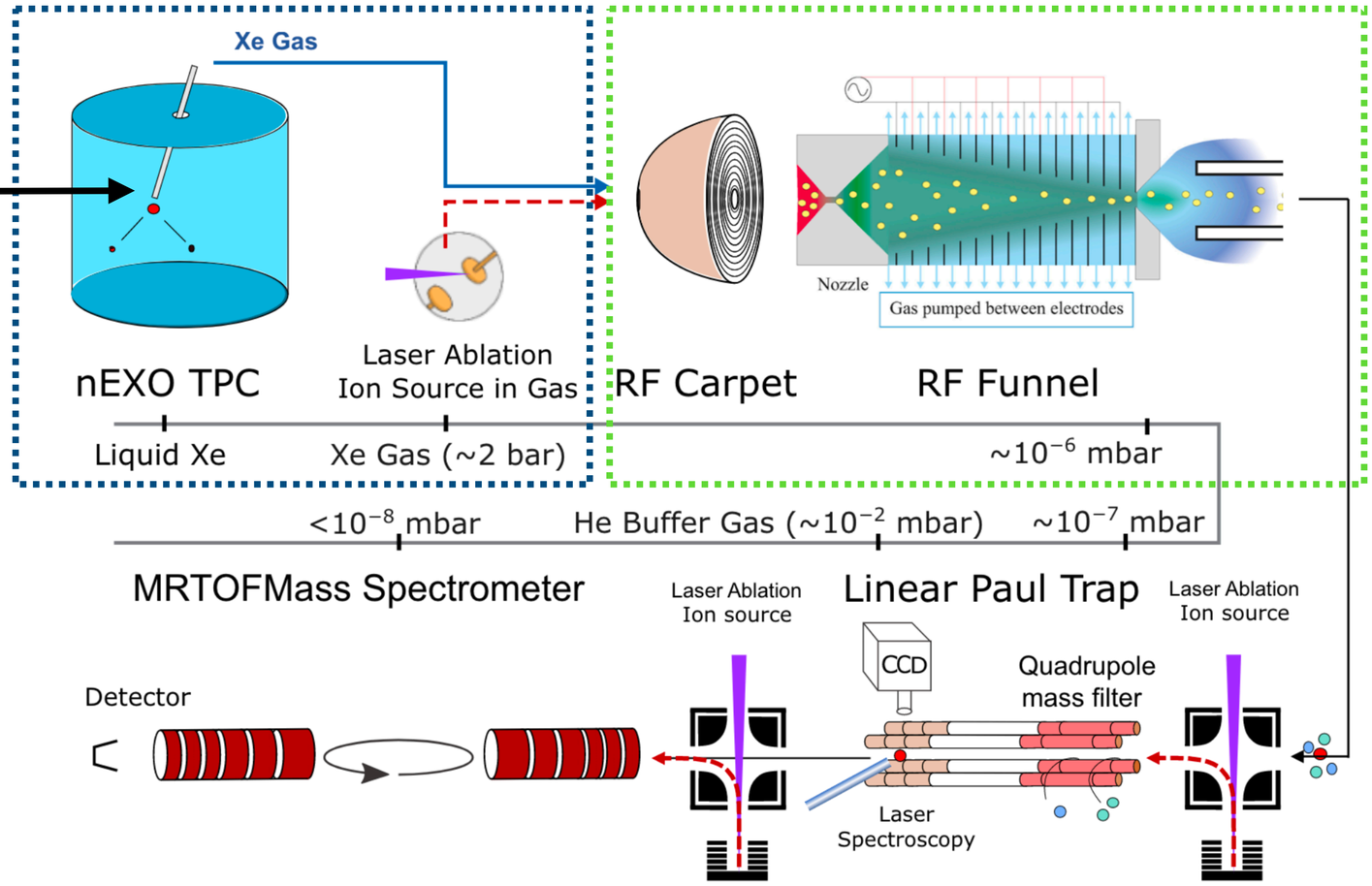
[a] Atoms 2024, 12, 71 (**2024**) (Ba^+ extraction from LXe to vacuum)
[b] Hyperfine Interact 240: 97 (**2019**) (MRTOF design)

Extraction with capillary

The Canadian approach

TRIUMF In-LXe Ba^+ source

- Extraction through capillary tube mounted in XYZ moving platform.
- Differential pumping in RF Funnel to separate Ba^+ from GXe.



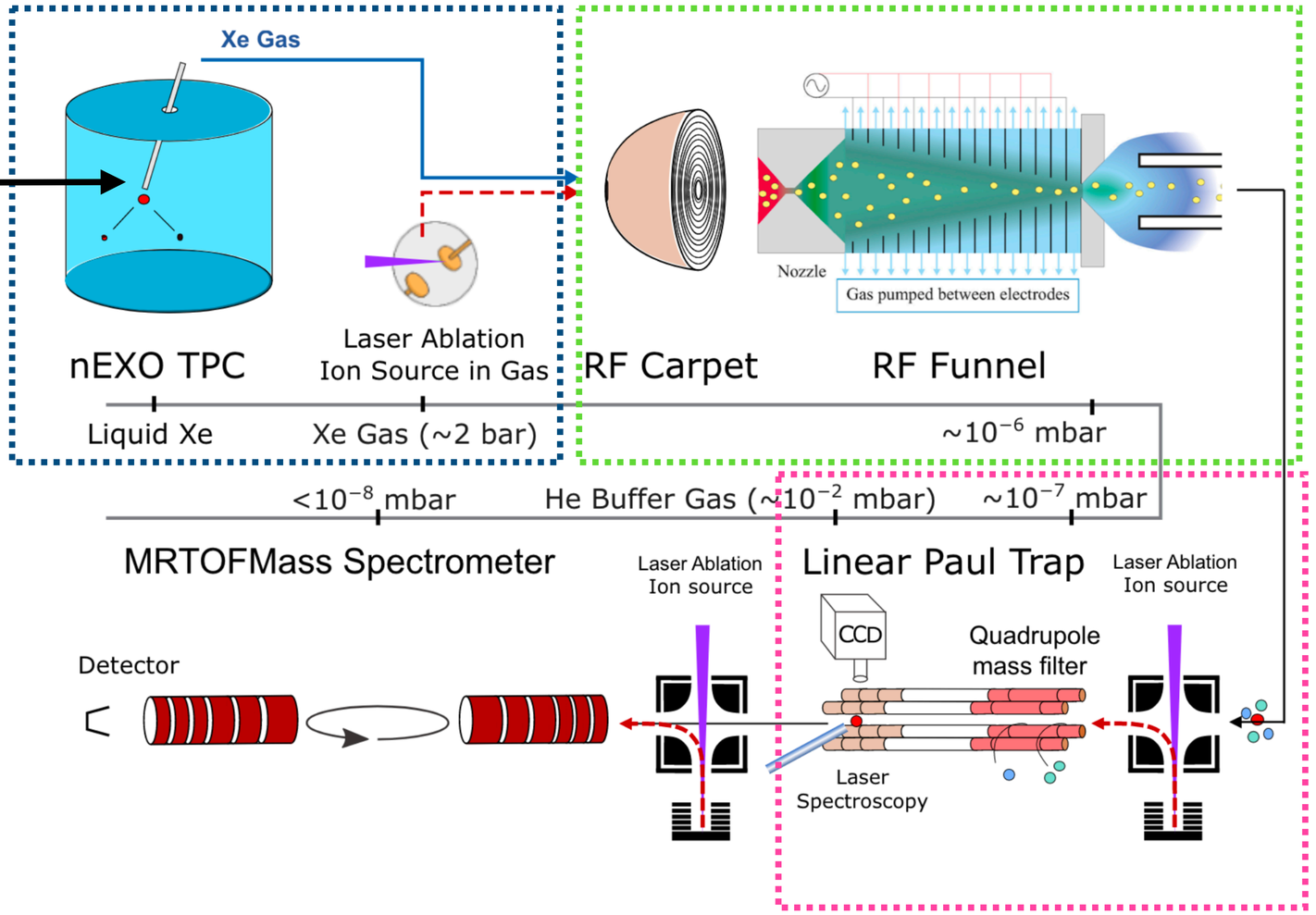
[a] Atoms 2024, 12, 71 (**2024**) (Ba^+ extraction from LXe to vacuum)
[b] Hyperfine Interact 240: 97 (**2019**) (MRTOF design)

Extraction with capillary

The Canadian approach

TRIUMF In-LXe Ba^+ source

- Extraction through capillary tube mounted in XYZ moving platform.
- Differential pumping in RF Funnel to separate Ba^+ from GXe.
- Detection of Ba element through LPT and laser spectroscopy



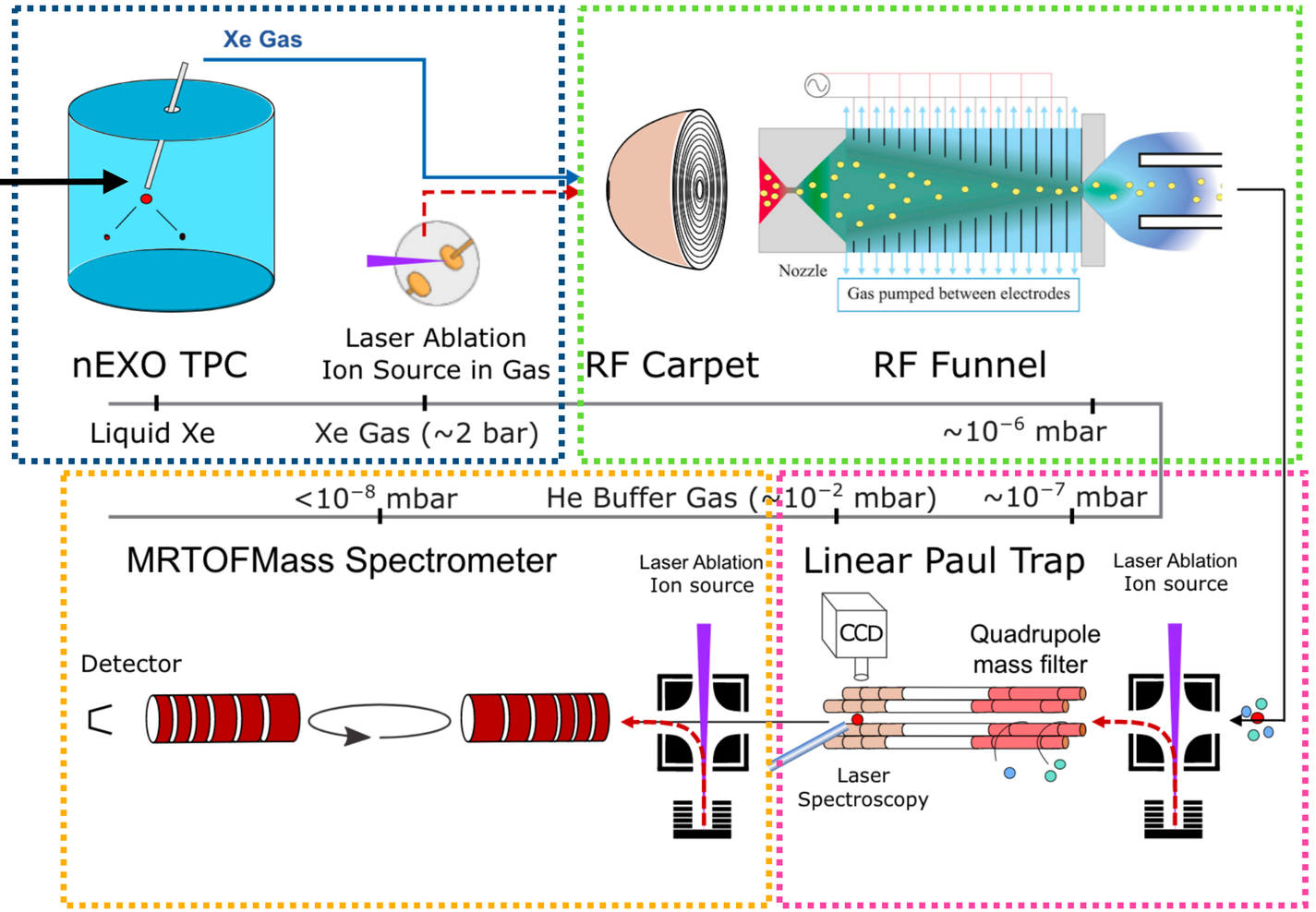
[a] Atoms 2024, 12, 71 (**2024**) (Ba^+ extraction from LXe to vacuum)
[b] Hyperfine Interact 240: 97 (**2019**) (MRTOF design)

Extraction with capillary

The Canadian approach

TRIUMF In-LXe Ba^+ source

- Extraction through capillary tube mounted in XYZ moving platform.
- Differential pumping in RF Funnel to separate Ba^+ from GXe.
- Detection of Ba element through LPT and laser spectroscopy
- Identification of ^{136}Ba isotope through MRTOF-MS

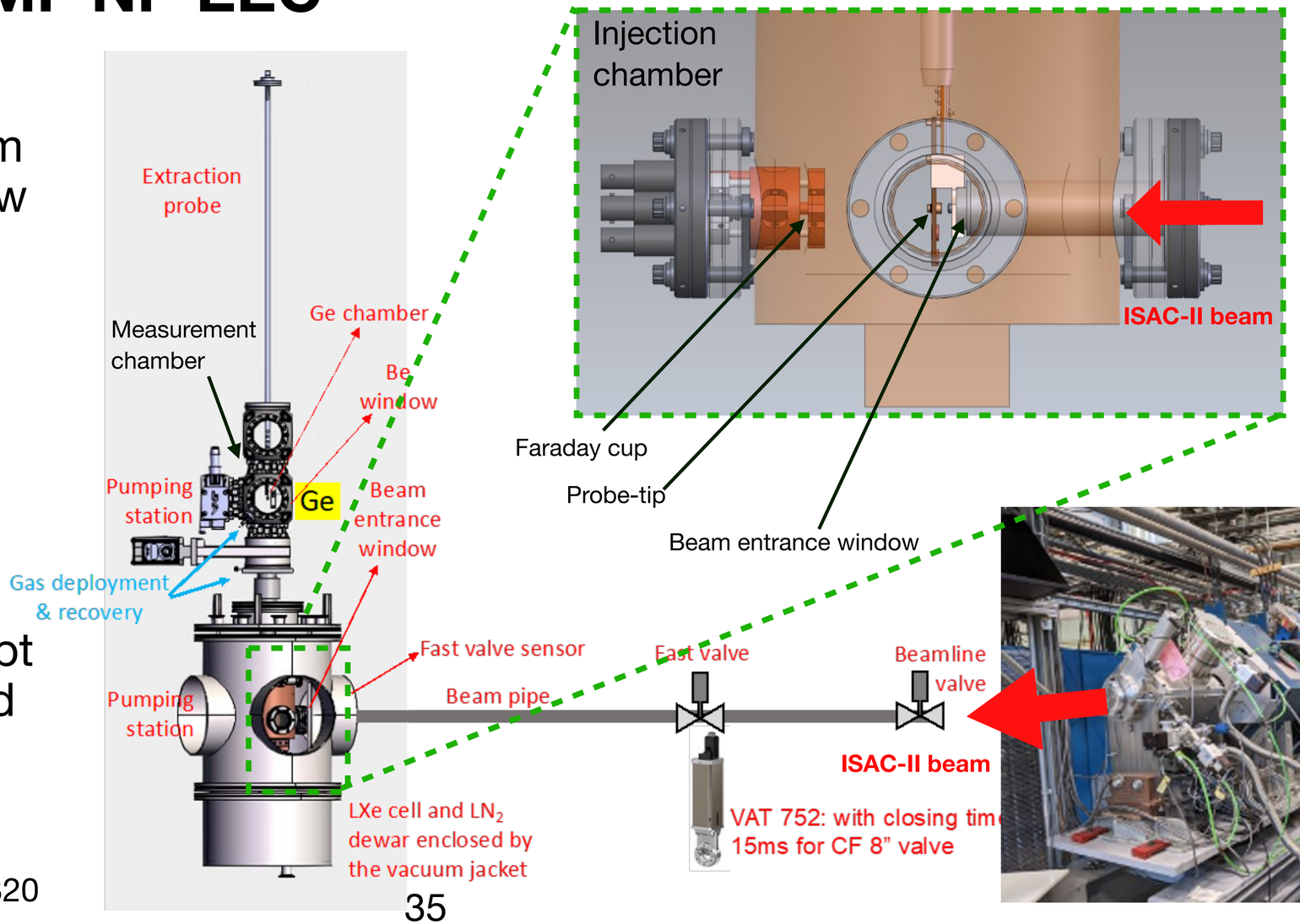


[a] Atoms 2024, 12, 71 (**2024**) (Ba^+ extraction from LXe to vacuum)
[b] Hyperfine Interact 240: 97 (**2019**) (MRTOF design)

In-LXe ion source

Proposal for TRIUMF NP EEC

- Inject ^{139}Cs or ^{136}Cs from ISAC through Be window
- Stopped ions in LXe
- Cs decays into Ba
- Collect the daughter Ba with <u>electroprobe</u>
- Future upgrades to adapt source to cryoprobe and capillary

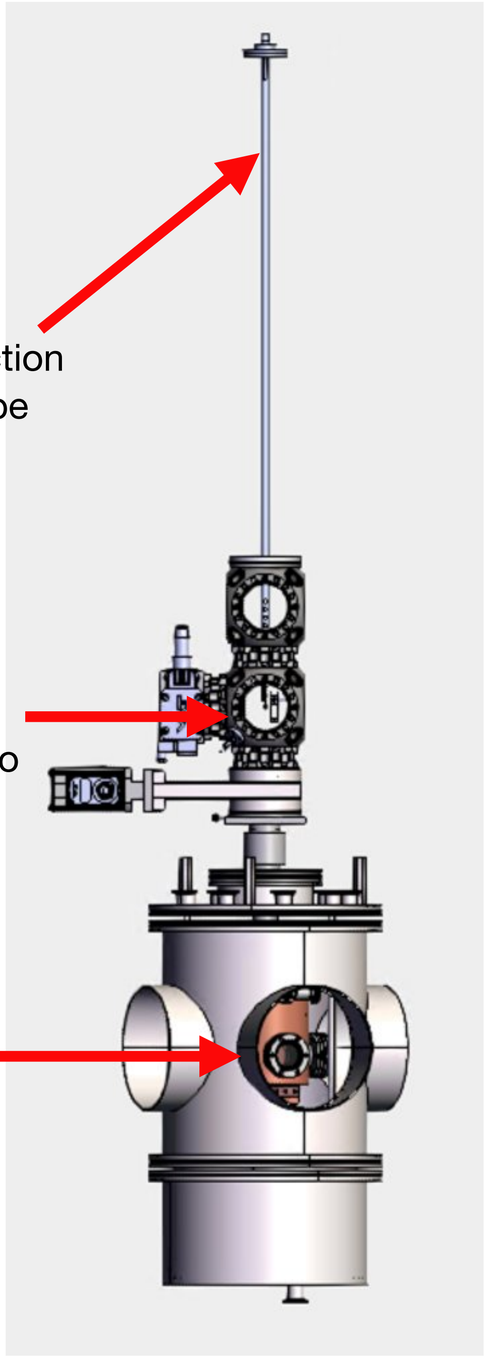


[a] TRIUMF - EEC submission, Exp n° S2320

In-LXe ion source

Proposal for TRIUMF NP EEC

- Inject ^{139}Cs or ^{136}Cs from ISAC through Be window
- Stopped ions in LXe
- Cs decays into Ba
- Collect the daughter Ba with electroprobe
- Future upgrades to adapt source to cryoprobe and capillary

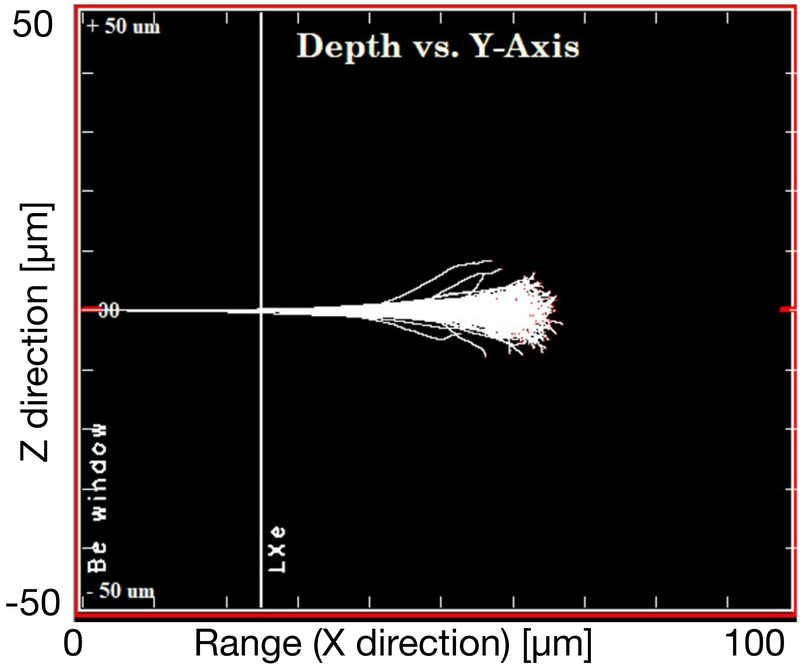


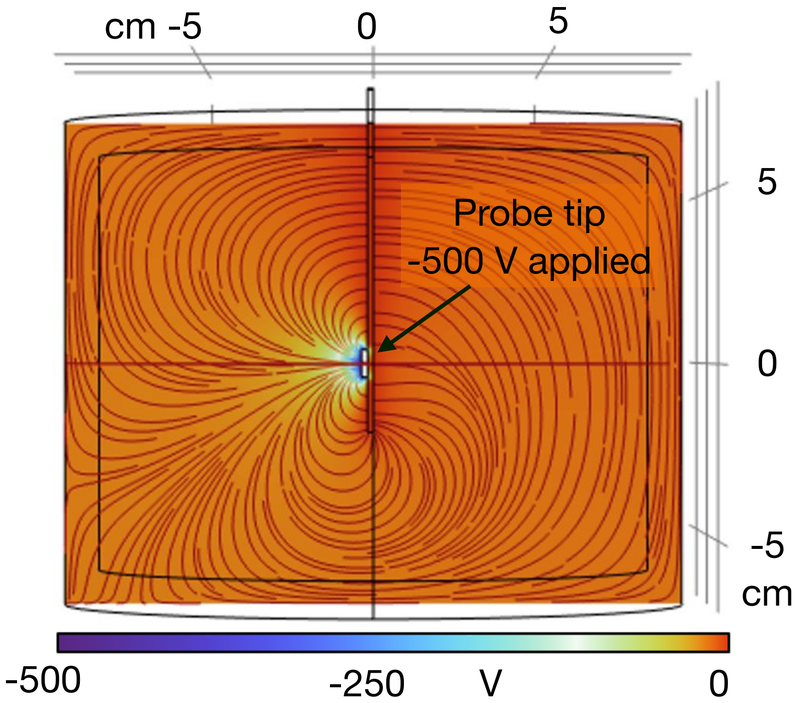
[a] TRIUMF - EEC submission, Exp nº S2320

In-LXe ion source

Proposal for TRIUMF NP EEC

- Stopping 4 MeV/u ^{139}Cs after 25 µm Be window and 35 µm in LXe
- Solved electrostatic and fluid dynamics with COMSOL
- 100% collection efficiency at -500 V after ~100 s



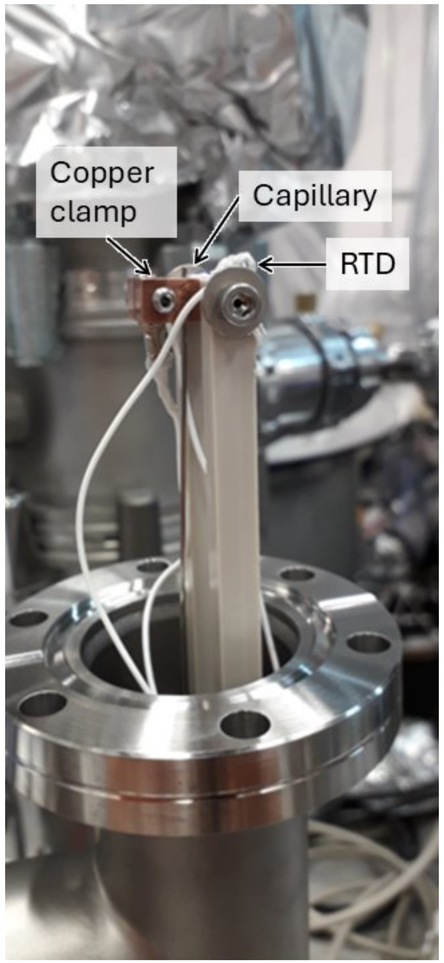


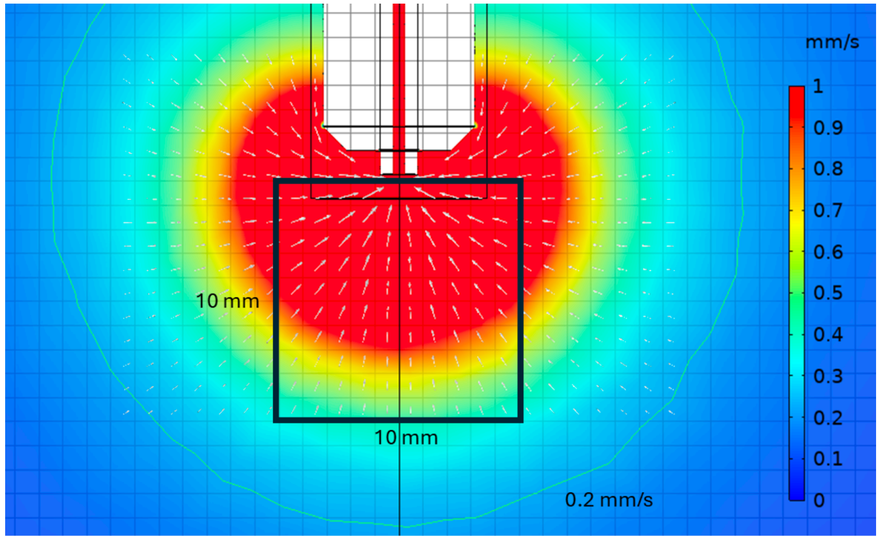
[a] Atoms 2024, 12, 71 (**2024**)

The capillary

Ba^+ extraction from LXe

- Target volume: 1 cm^3. Precision of 0.11 mm
- Once inside, the tube is heated to transport Ba in LXe-GXe mixture
- Successful proof-of-principle untargeted ion transfer using ^{222}Rn



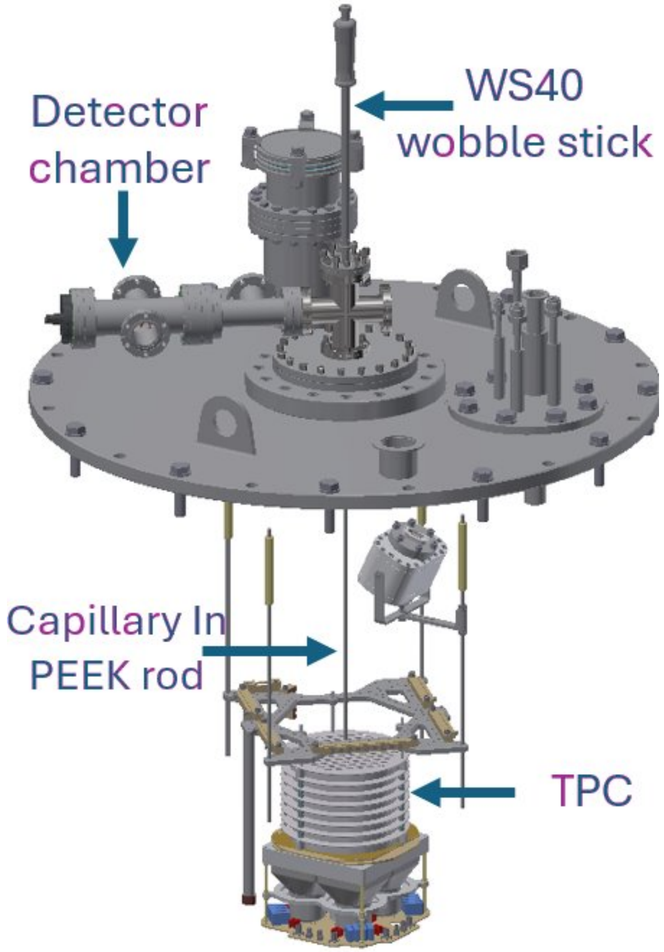


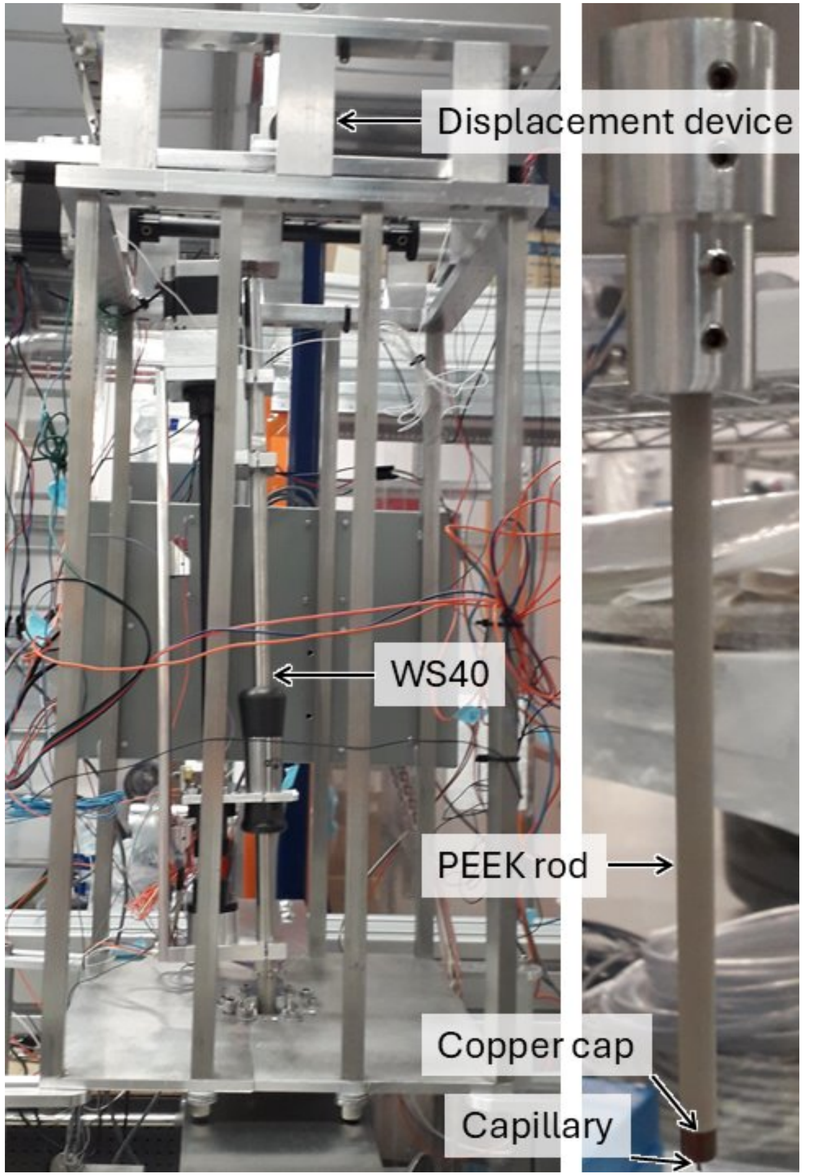
[a] Atoms 2024, 12, 71 (**2024**)

The capillary

Ba^+ extraction from LXe

- Target volume: 1 cm^3. Precision of 0.11 mm
- Once inside, the tube is heated to transport Ba in LXe-GXe mixture
- Successful proof-of-principle untargeted ion transfer using ^{222}Rn



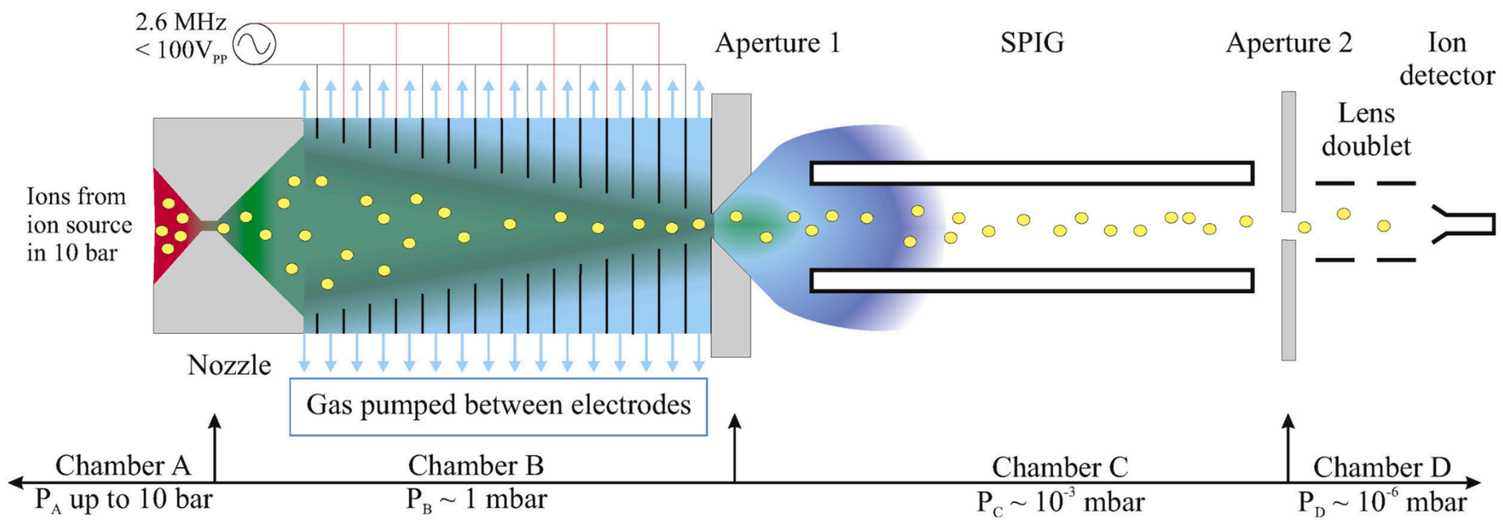


[a] Atoms 2024, 12, 71 (**2024**)

Separation of Ba from GXe

RF funnel + diff. pumping from 10 bar to 10^{-6} mbar

- Extracted GXe up to 10 bar
- RF-only → no axial drift field → less contaminants
- Mass spectrum with Sixtupole Ion Guide (SPIG)
- Faraday/CEM detector operating at 10^{-6} mbar

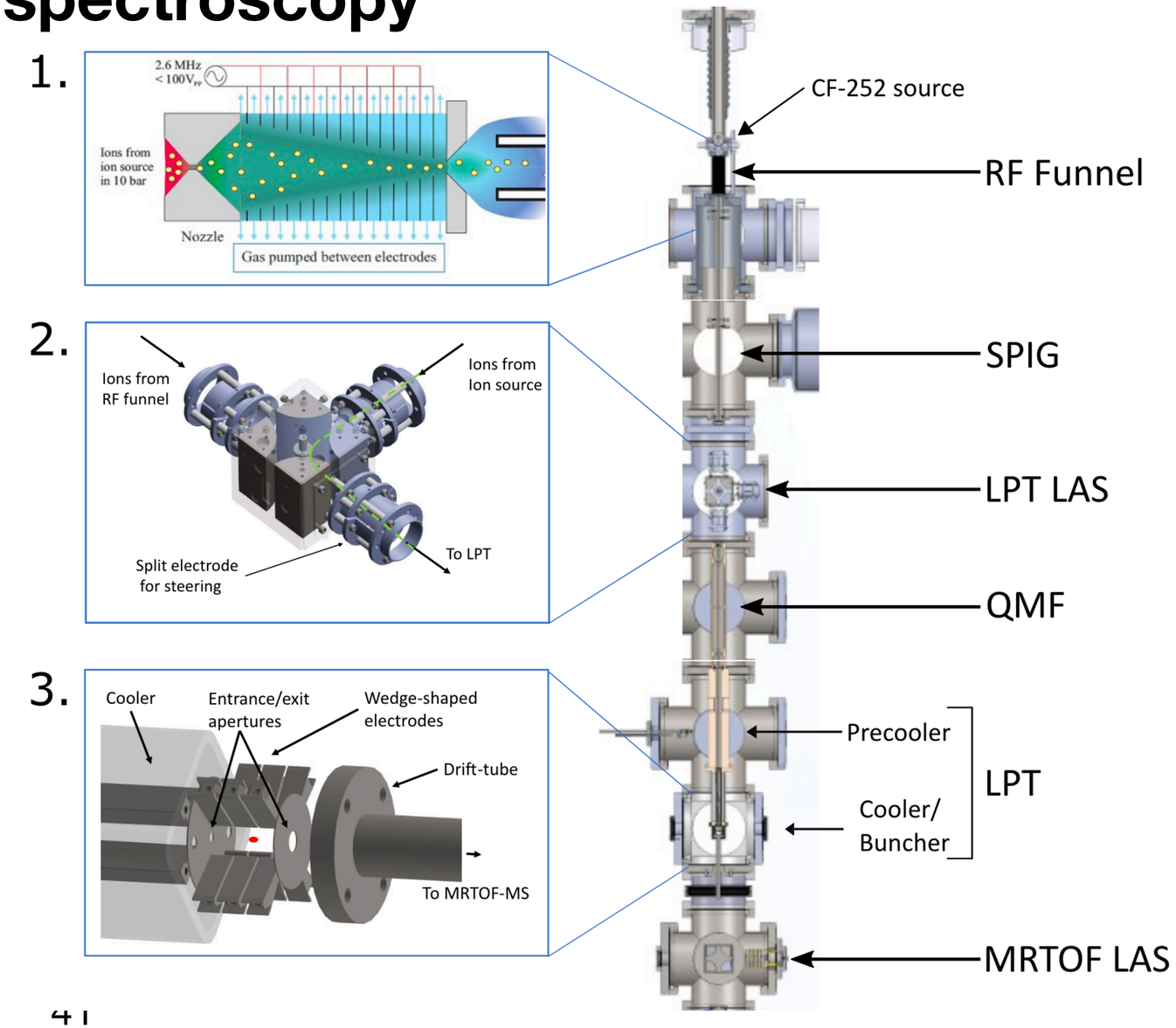


[a] Int. J. Mass Spectrom. 379, 110–120 (**2015**)

Ba element identification

Linear Paul Trap (LPT) + Laser spectroscopy

- Can introduce different ions by LAS + bender for calibration
- A Quadrupole Mass Filter removes out remaining BaH, BaOH
- Cooling with 0.1 mbar He to $E < 1$ eV in pre-cooler
- Identification of bunches through laser-induced fluorescence + CCD



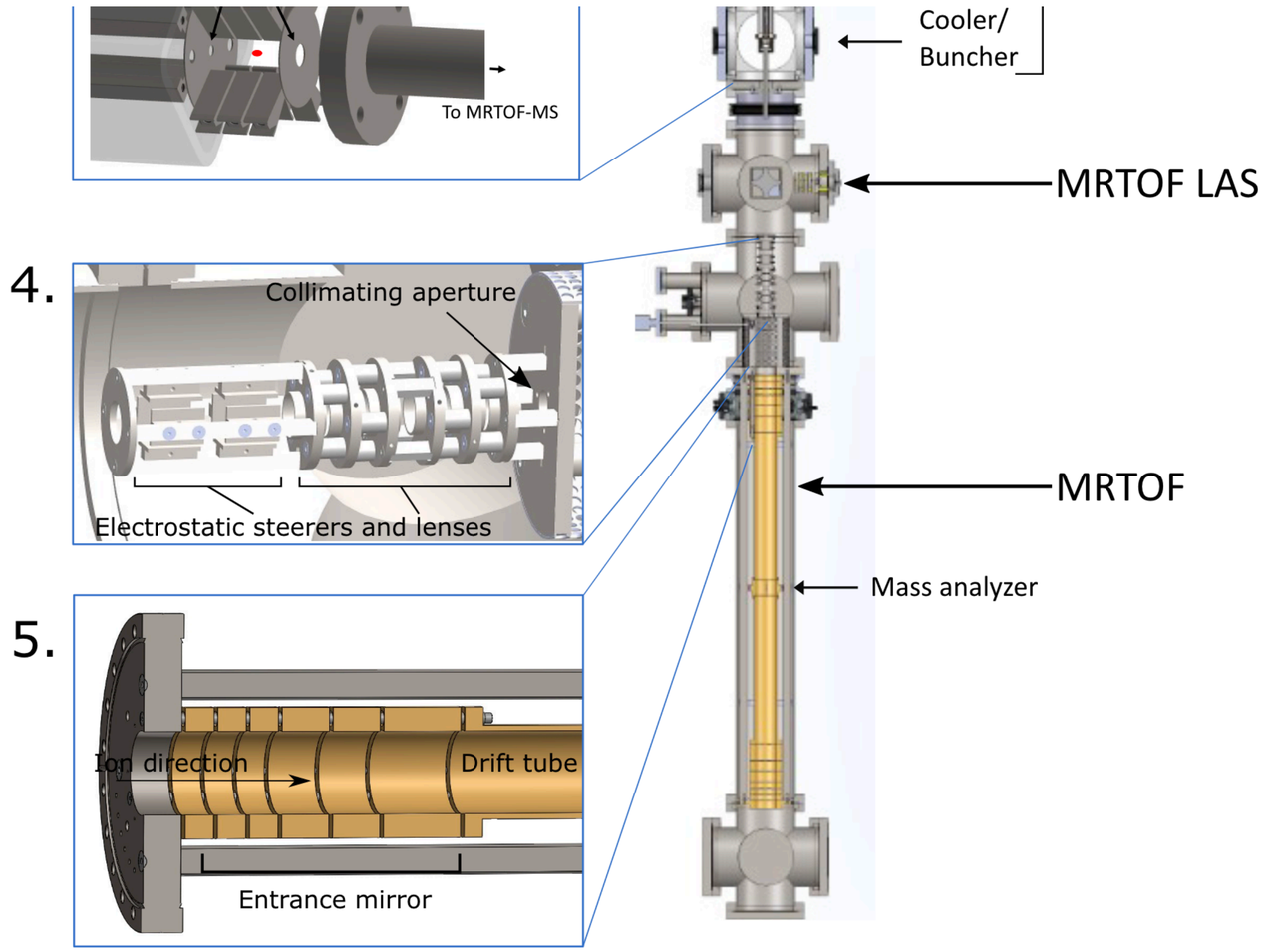
[a] Atoms 2024, 12, 71 (**2024**)

[b] Nucl. Instrum. Methods Phys. Res., B 541 (**2023**) 298–300

Isotopic identification of ^{136}Ba

Multiple Reflection Time-of-Flight Mass Spectrometer (MRTOF-MS)

- Reflections increase difference in their TOF and thus m/q.
- 2 electrostatic mirrors, each of 6 electrodes
- Steerers and focusing (einzel) lenses for injection
- Achieved $m/\Delta m$ ~ 20,000 with unbunched ions from LAS



[a] Hyperfine Interact 240: 97 (**2019**)

Overview

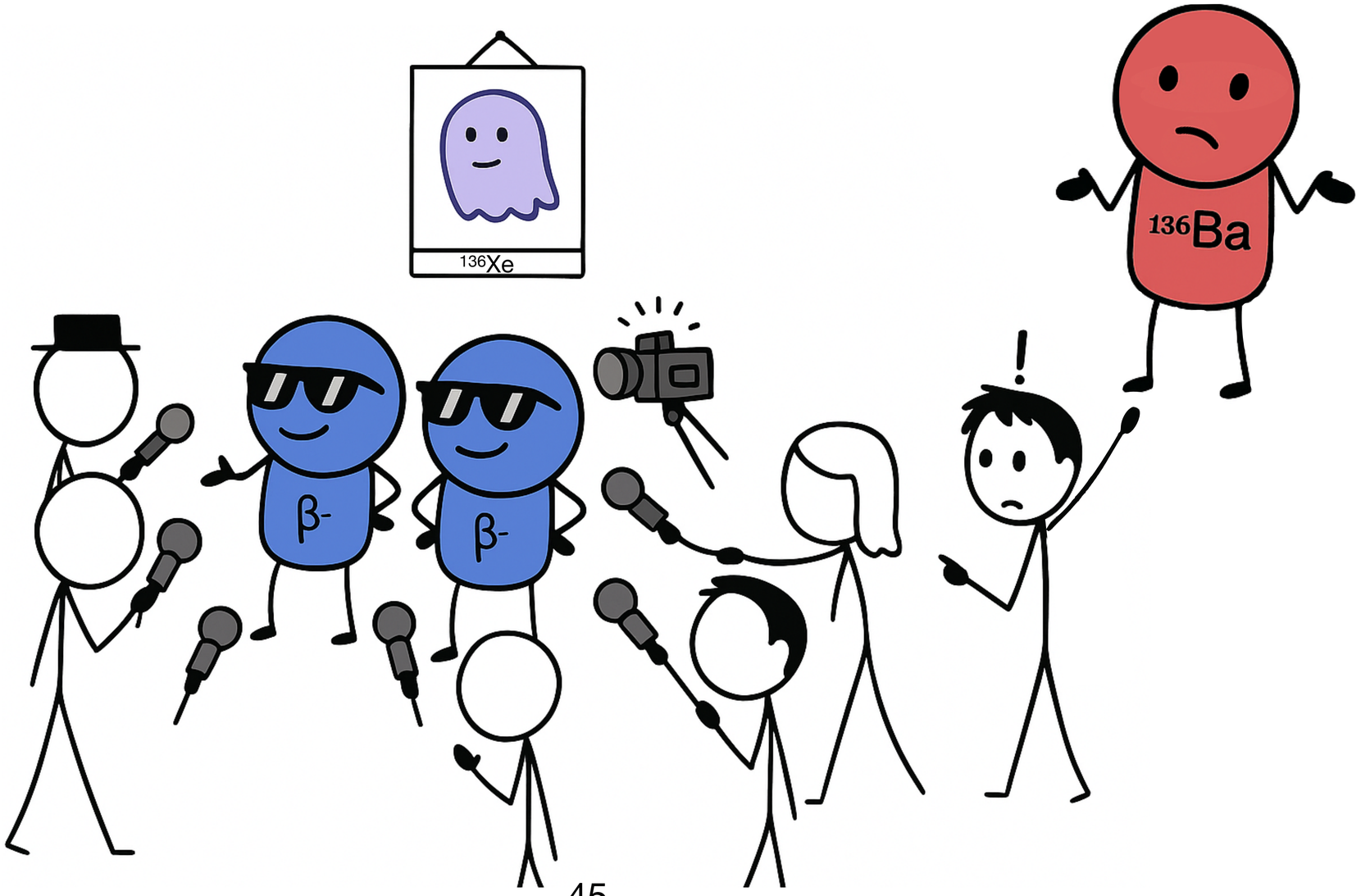
- ☑ Introduction to Ba-tagging
- ☑ Ba-Tagging in NEXT
- ☑ Ba-Tagging in nEXO
- ☐ **The road forward**

Synergies in Ba-Tagging

Regardless of LXe/GXe

- Can we neutralize Ba^{2+} in GXe to Ba^{+} and use laser spectroscopy?
- Can we use chemosensors with neutral Ba or mono cation Ba^{+}?
- …

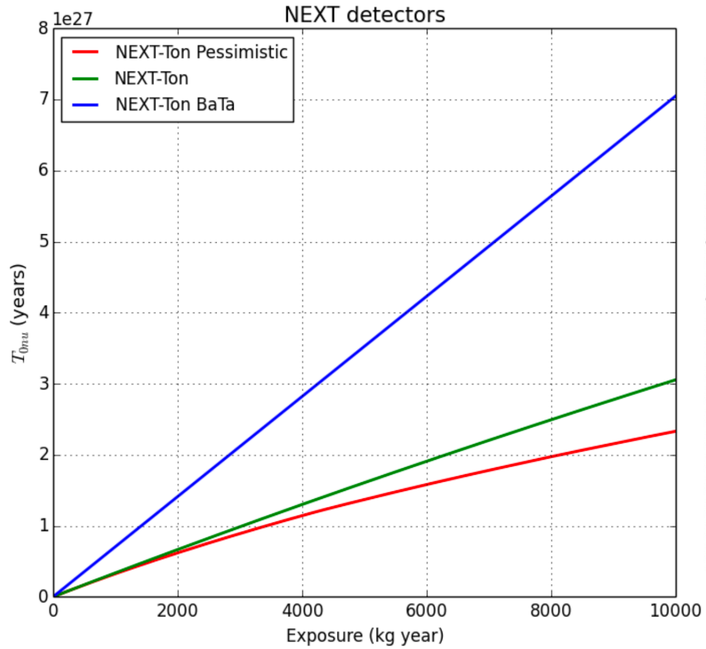
Thank you for your attention!

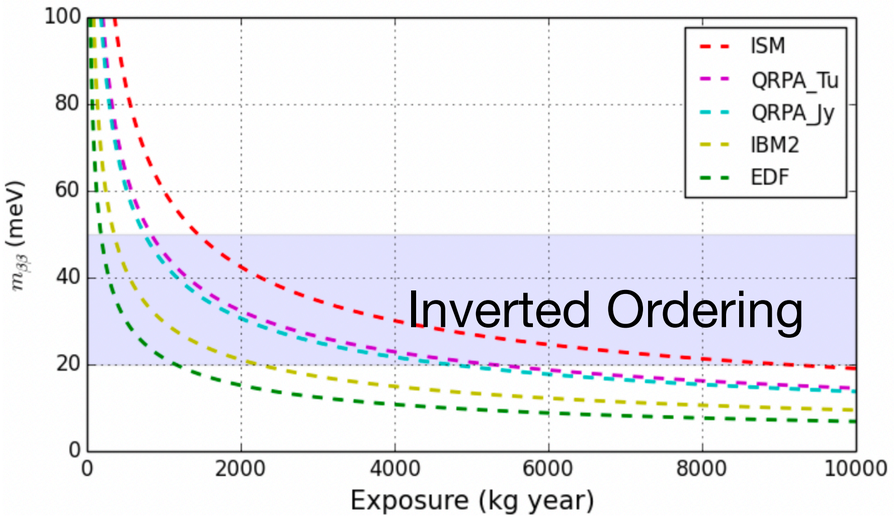


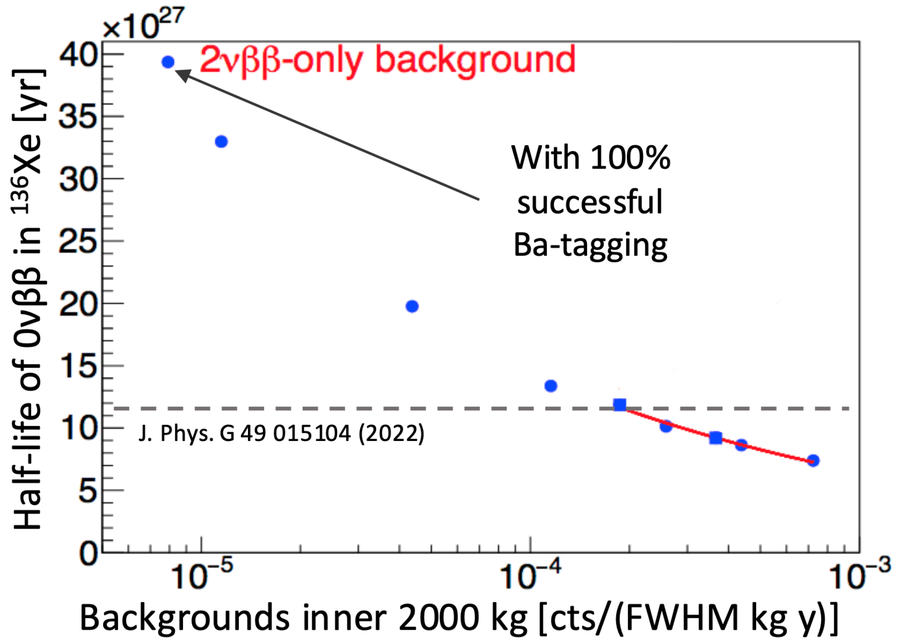
Backup slides (NEXT)

How far could we go?

- Linear scale of sensitivity to $\tau_{0\nu\beta\beta}$ would with exposure if zero background.
- The full IO (blue shaded area) of $m_{\beta\beta}$ could be probed with 1 ton × 10 years exposure.



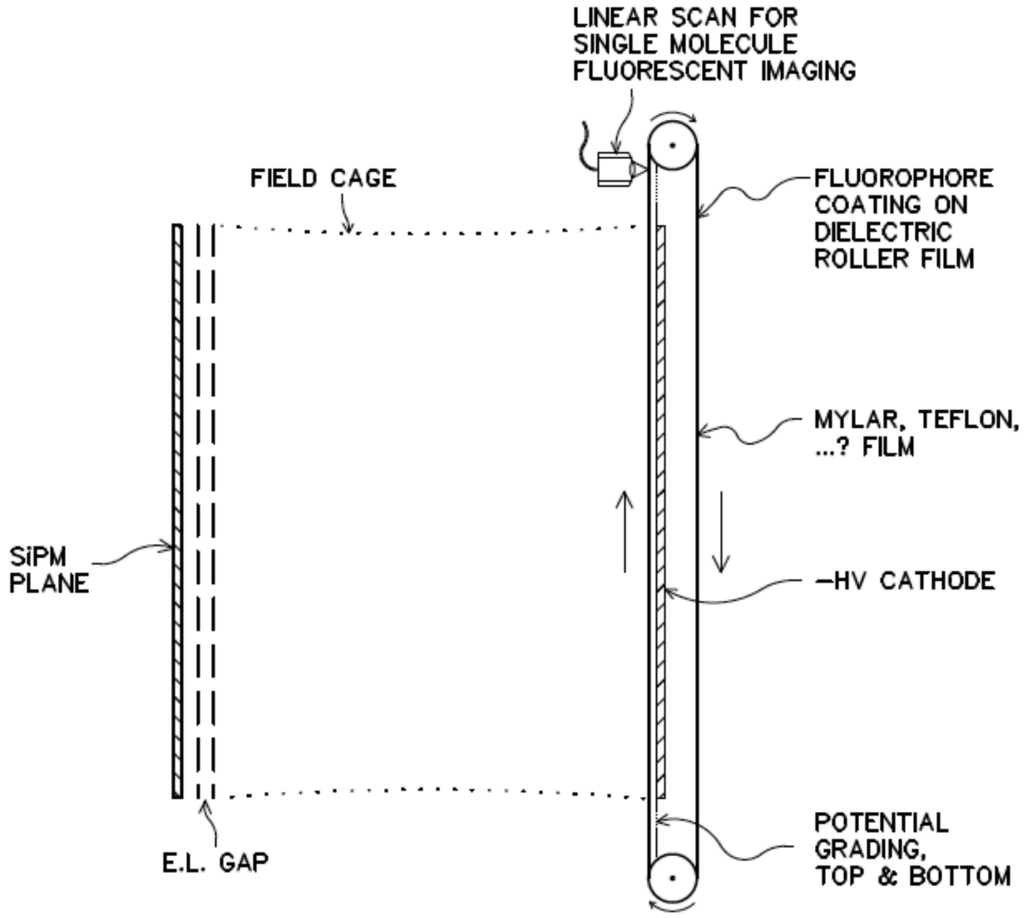




From J. Muñoz (2018) PhD Thesis

Historic precedents

- M. K. Moe (1991) first proposed using **Ba^{+}** as a handle for detection of 0νββ in coincidence with the 2 electrons.
- D. Nygren (2015) suggests using **Ba^{2+}** detection via Microscopy Imaging of chemosensors in GXe.



HIGH PRESSURE XENON GAS ELECTROLUMINESCENT TPC
WITH SINGLE MOLECULE FLUORESCENT IMAGING OF BARIUM DAUGHTER

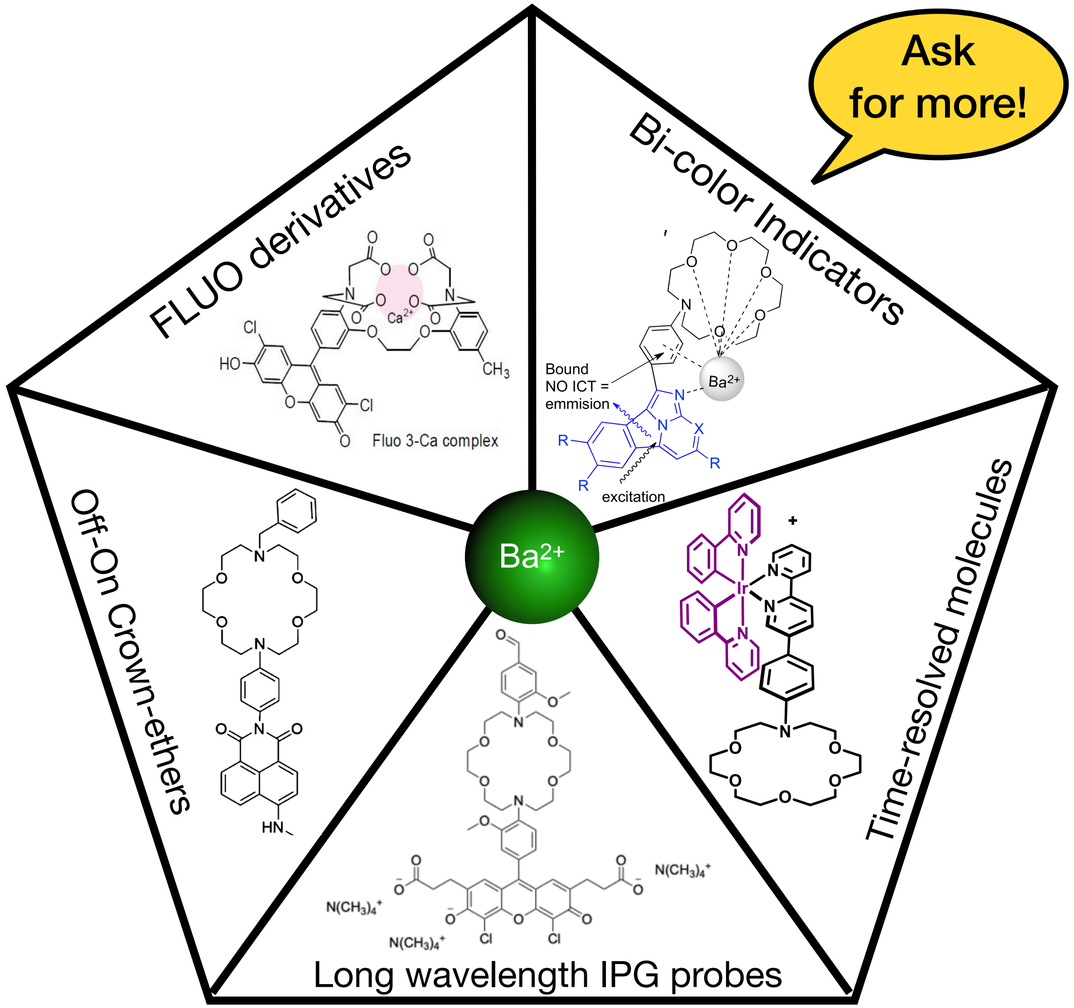
From D. Nygren J. Phys.: Conf. Ser. 650 012002 (2015)

M.K. Moe Phys. Rev. C **44**, R931(R) (1991)

R&D into Chemosensors

The building blocks of the BaTag system

- Most based on crown-ether
- Highly selective to Ba^{2+} ions



Molecule characterization

Chelation demonstrated in UHV

- 4 different substrates:

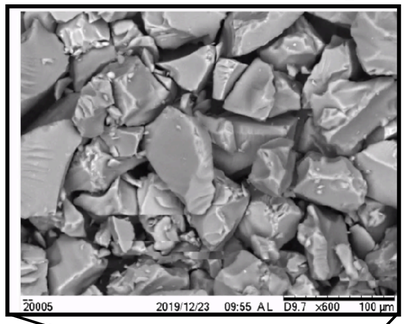
  ➡Au, Cu, ITO[b], silica[a]

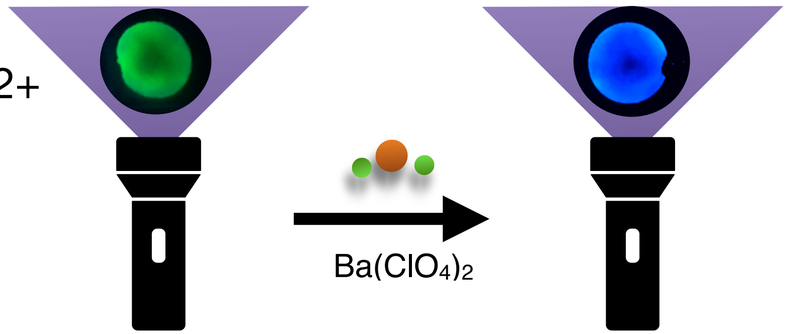
- Fluorescence color change preserved in silica pellets[a]

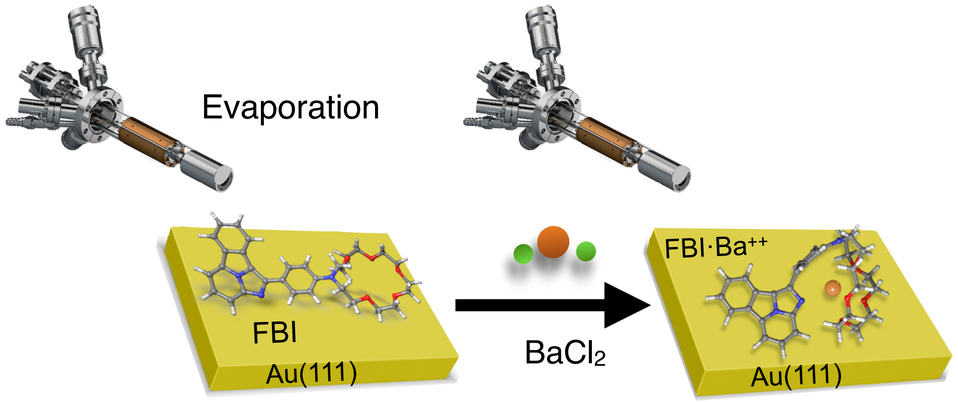
- Evidence of chemical interaction[b] of the crown-ether with Ba^{2+}

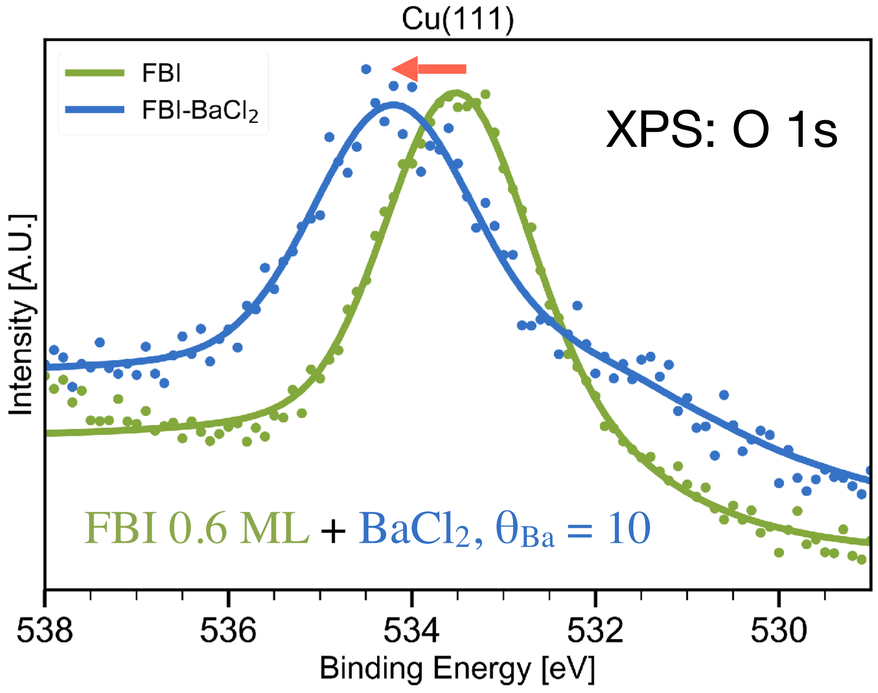
- $BaCl_2$ added in UHV conditions

Silica, SEM image









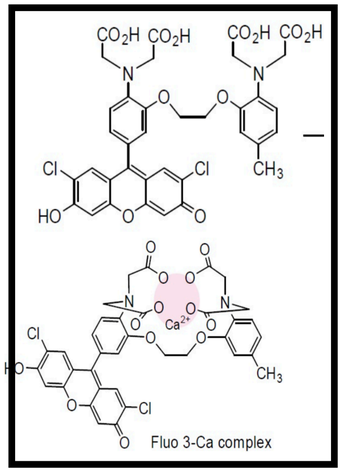
[a] *Nature* 583, 48–54 (**2020**)

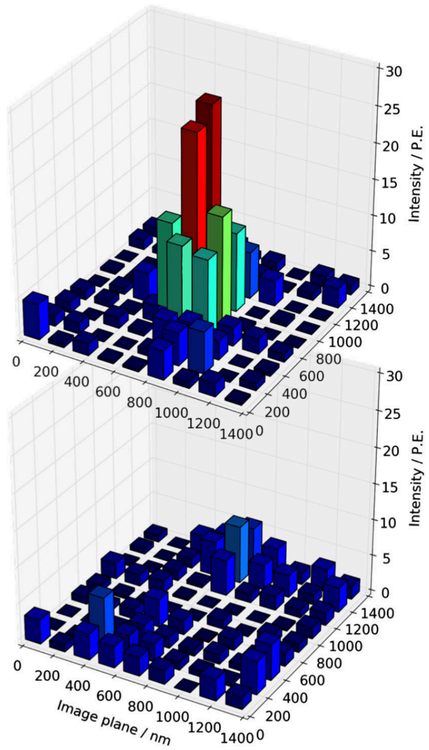
[b] Nat. Commun. 13, 7741 (**2022**)

SMFI with on-off molecules

Extensive research with several chemosensor families

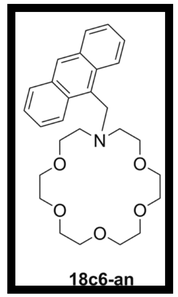
- Studies in solution and dry surfaces

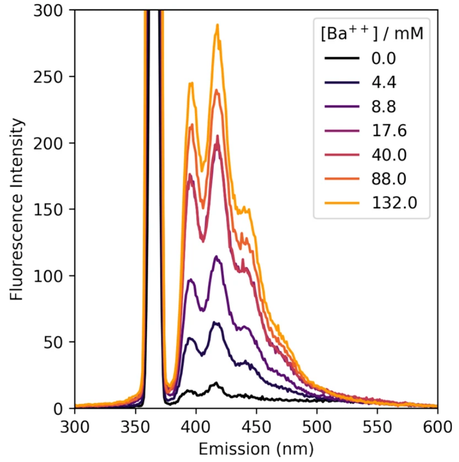


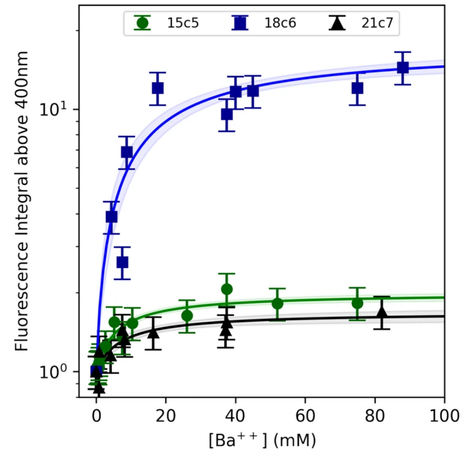


[a] JINST 11 P12011 (**2016**)

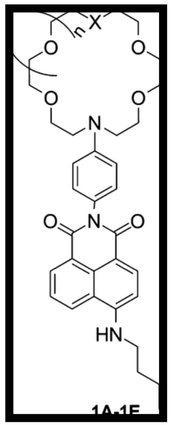
[b] Phys. Rev. Lett. 120, 132504 (**2018**)



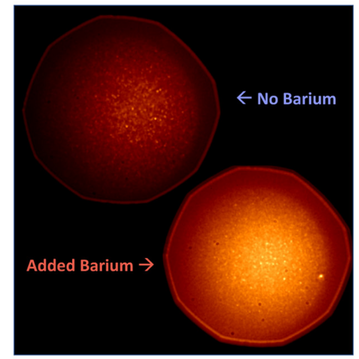




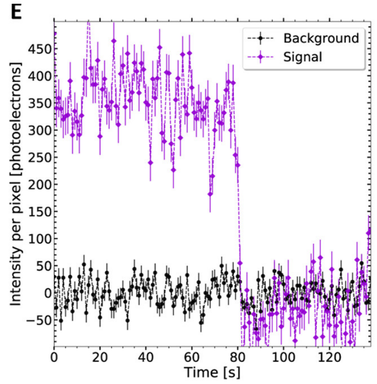
[c] Sci. Rep. 9, 1, 15097 (**2019**)

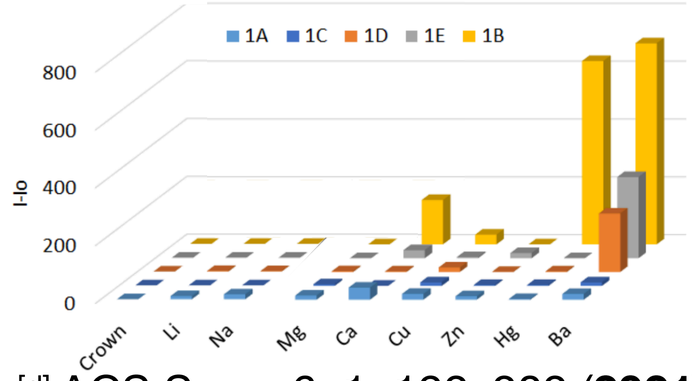


C.i



E

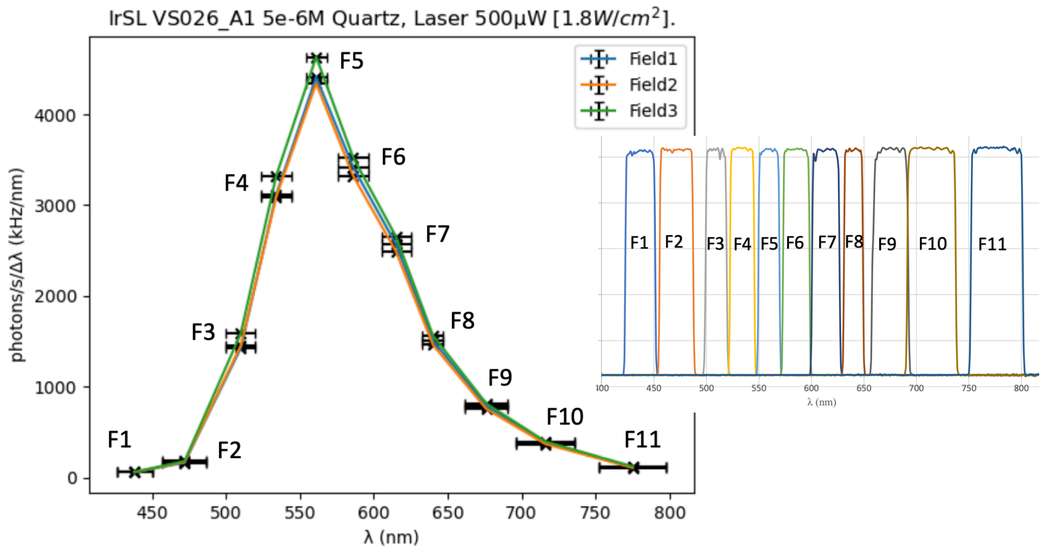


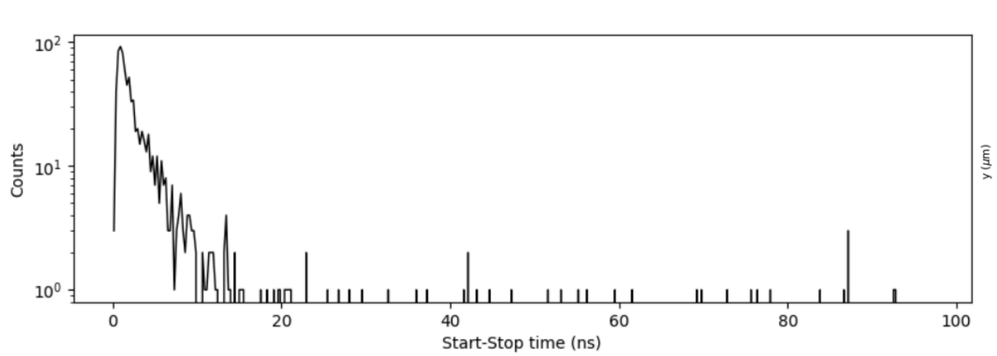


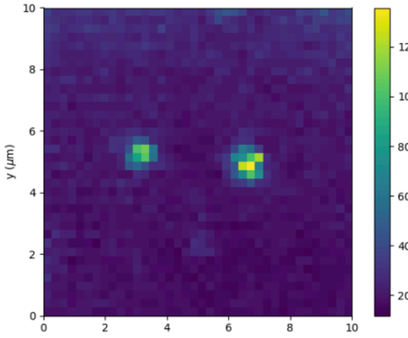
[d] ACS Sens. 6, 1, 192–202 (**2021**)

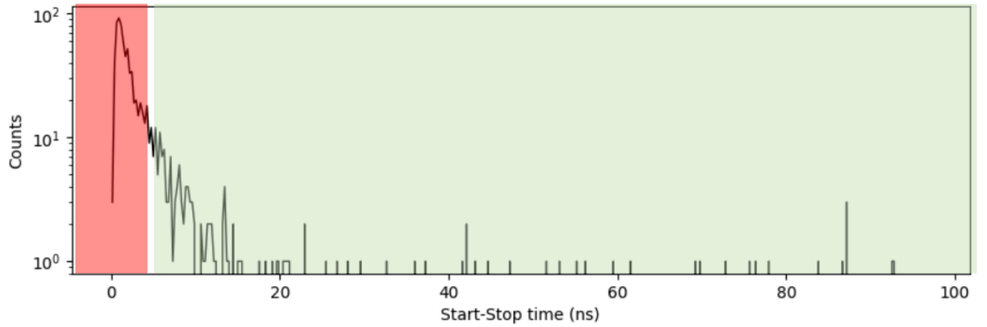
Other approaches:

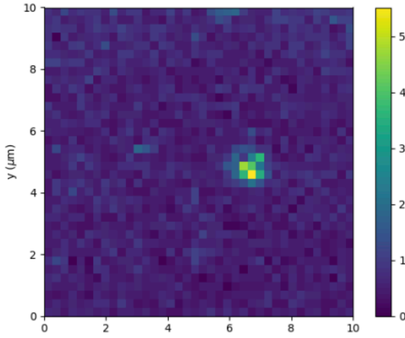
- TIRF vs epi-illumination, wide-field, confocal, 2PA.
- Emission spectrum reconstruction (bicolor molecules)
- Fluorescence-lifetime imaging microscopy (FLIM) for temporal molecules

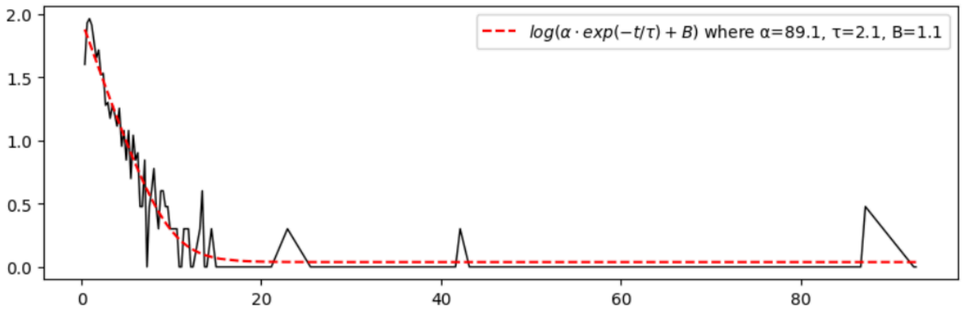


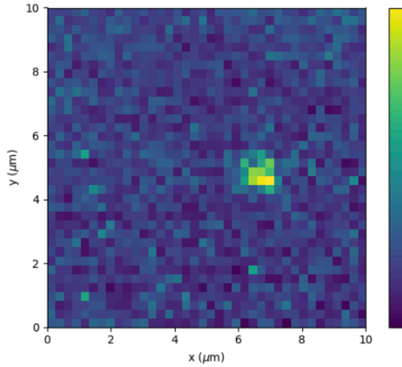










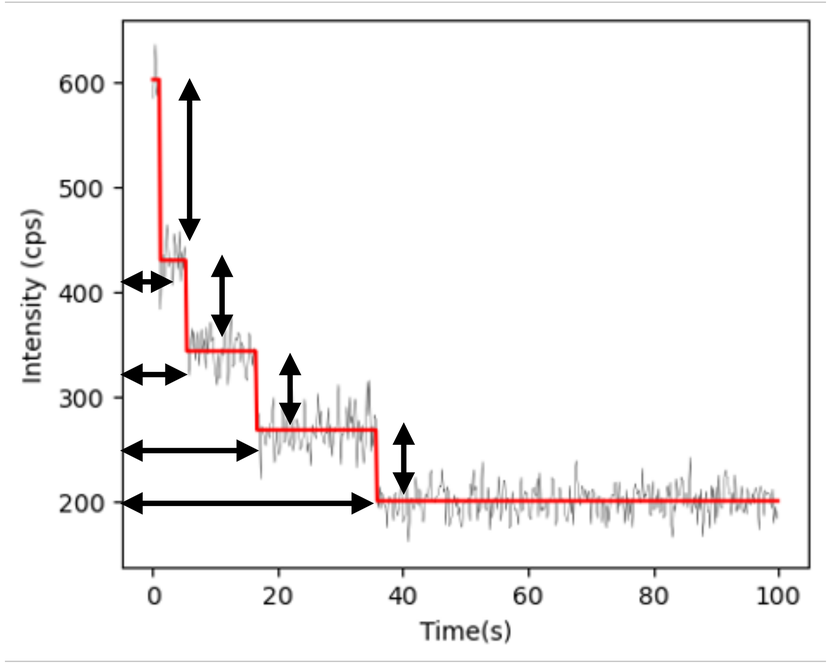


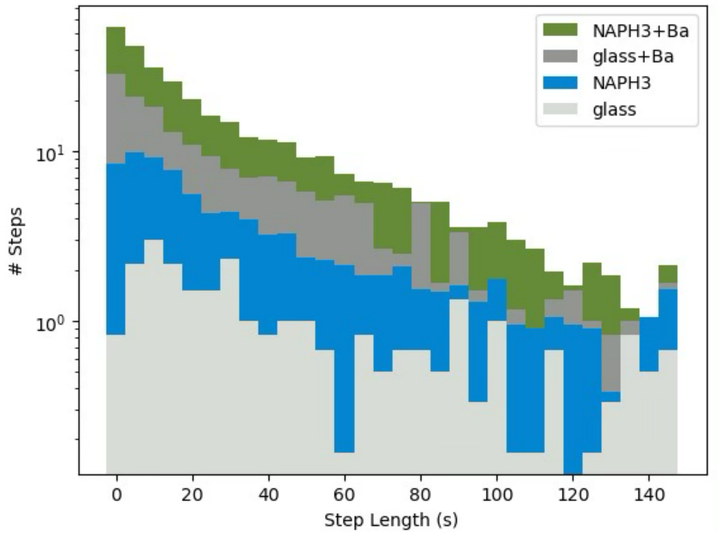
Microscopy efforts

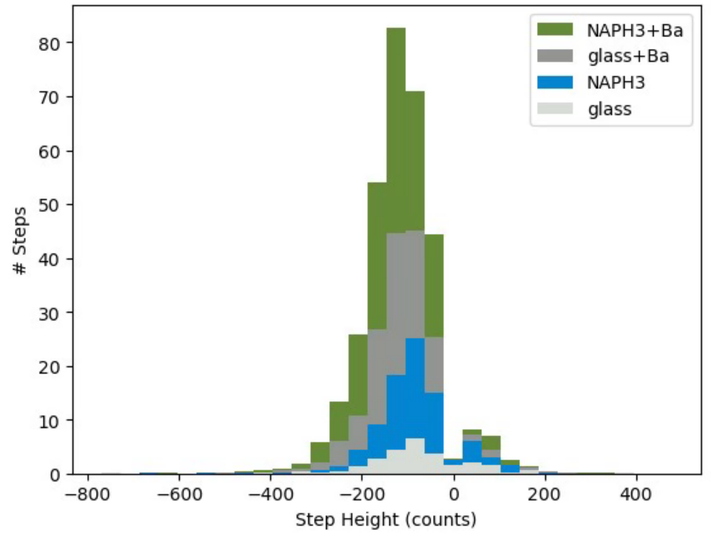
Statistics on step properties

Ask for more!

- SMFI and molecular orientation
- Photochemical studies from step distributions
- Development of efficient step finding algorithms

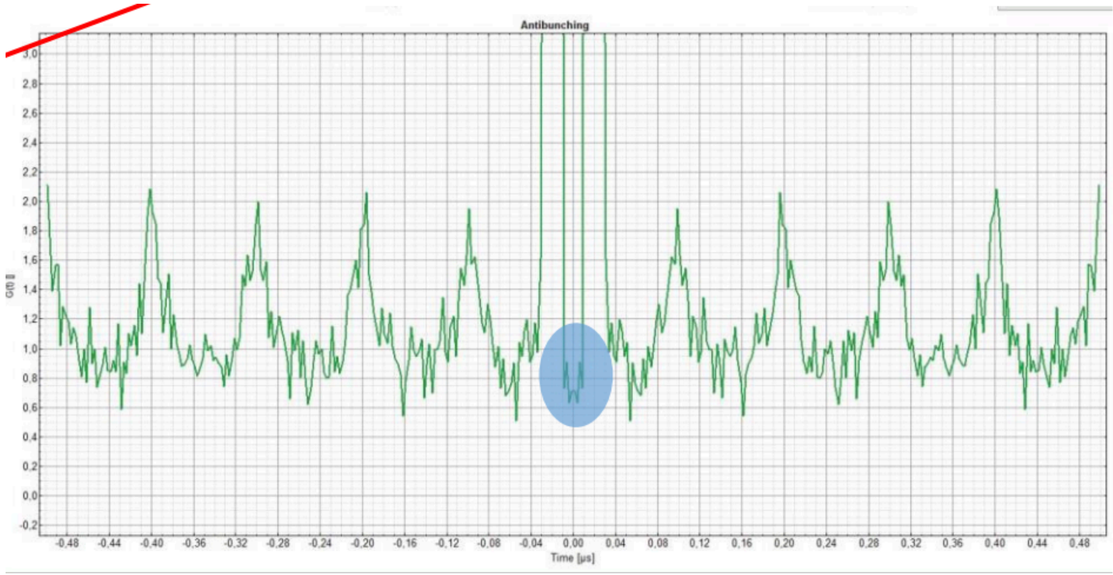






Other approaches:

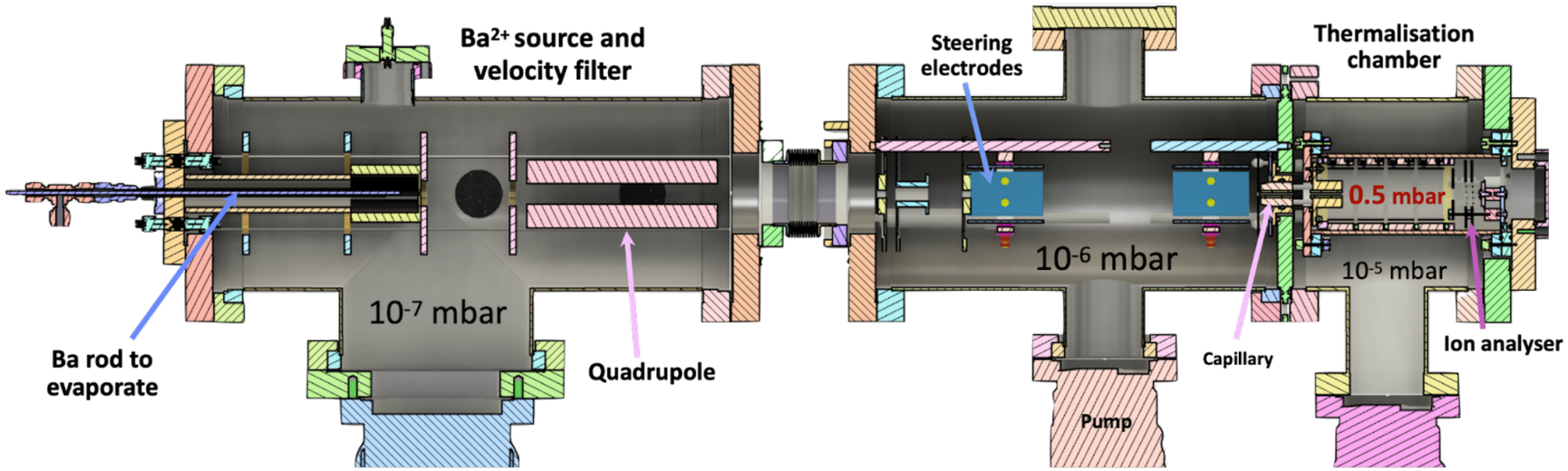
- Illumination through TIRF vs epi-illumination (wide-field, confocal), 2PA.
- Emission spectrum reconstruction (bicolor molecules)
- Fluorescence-lifetime imaging microscopy (FLIM) for temporal molecules
- Non-destructive SMFI: Antibunching

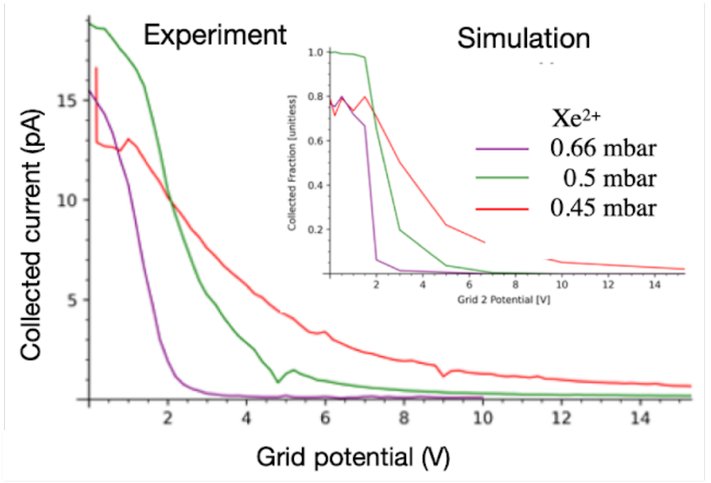


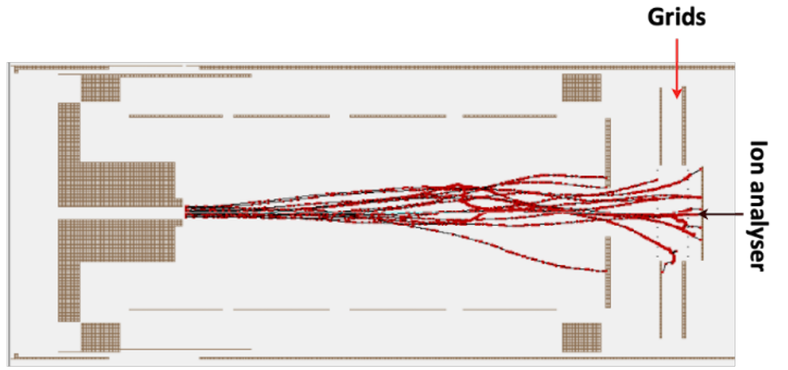
Ba^{2+} beam in low pressure

Thermal ions

- Sublimation of Ba → filtering from other ions
- Steering into thermalization chamber though differential pumping
- Collision with GHe at ~0.5 mbar
- Beam characterization with Xe^{2+}
- Optimization with Ba^{2+} undergoing



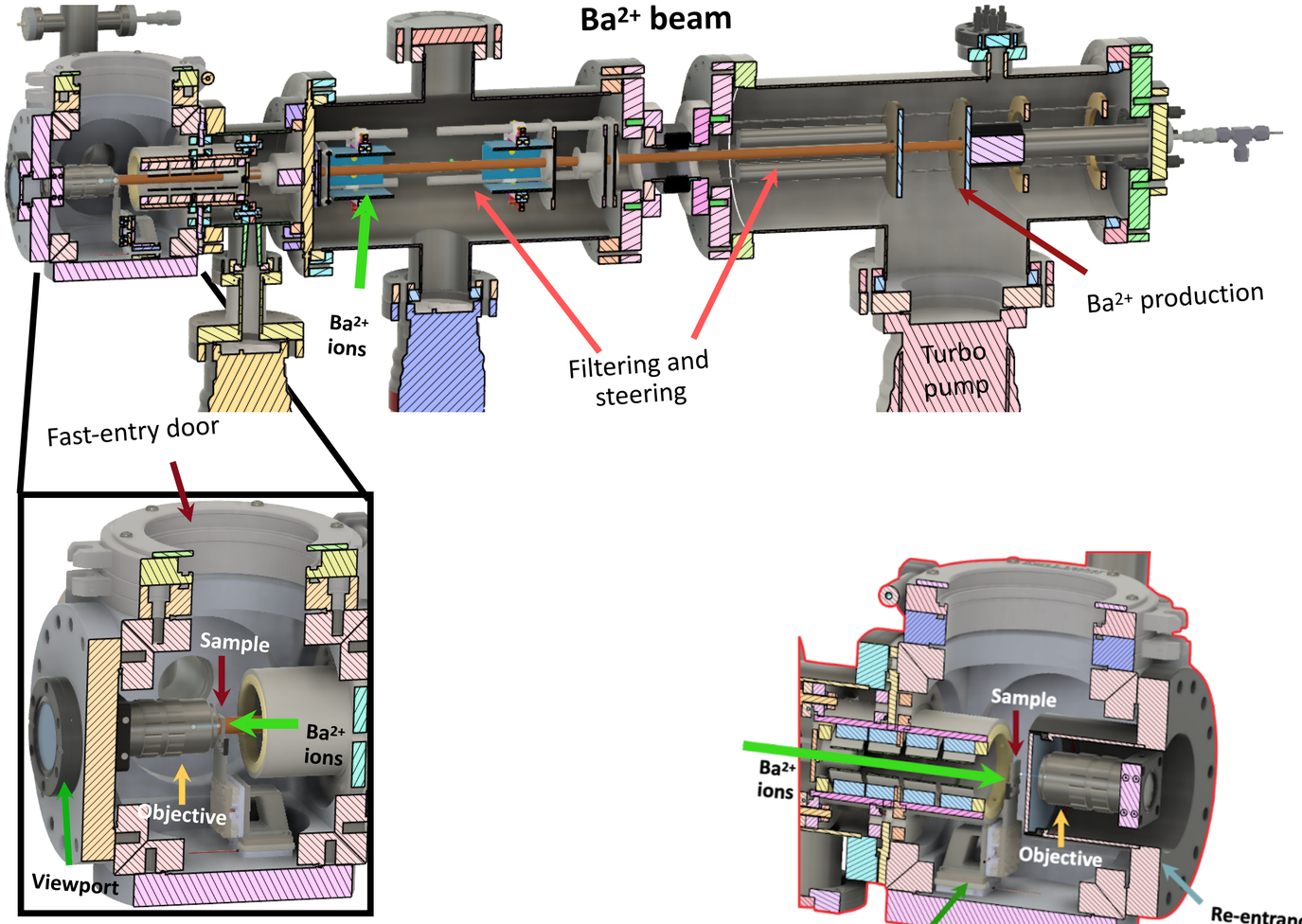




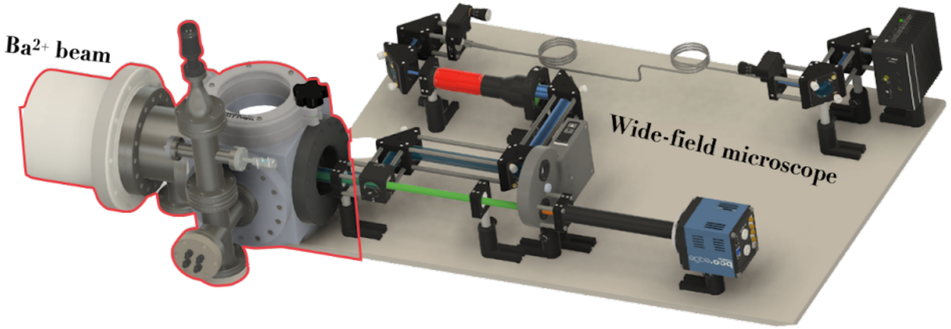
Thermalization chamber simulation, ions passing through the capillary can reach the analyser

Ba^{2+} beam in low pressure

Coupling to microscope



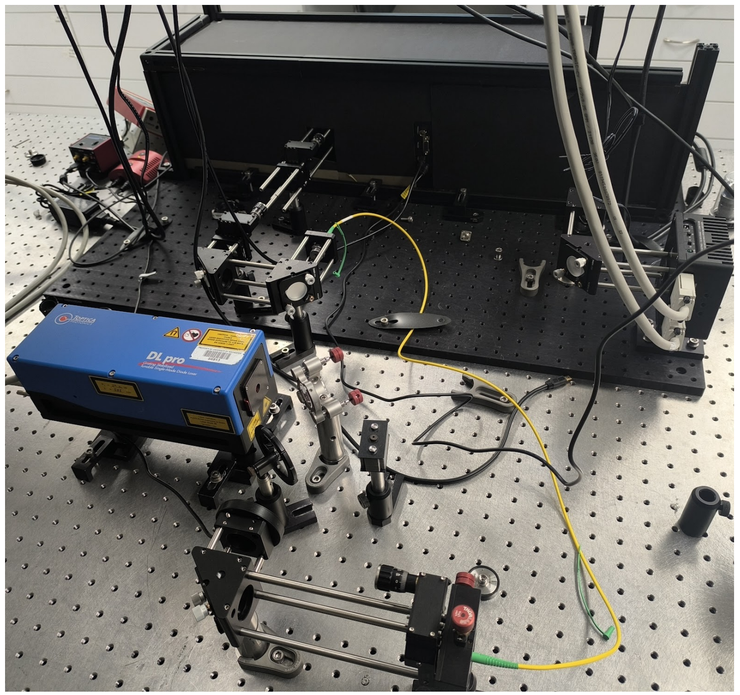
- Beam coupled to chamber with MO, working at low pressure ~1mbar
- Alternative: long WD MO outside the chamber
- Reconciling with high NA limitation is challenging

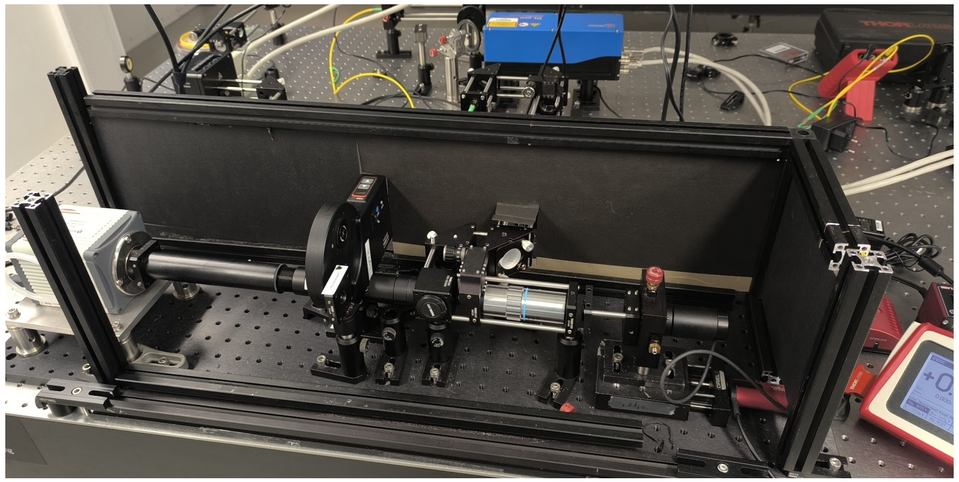


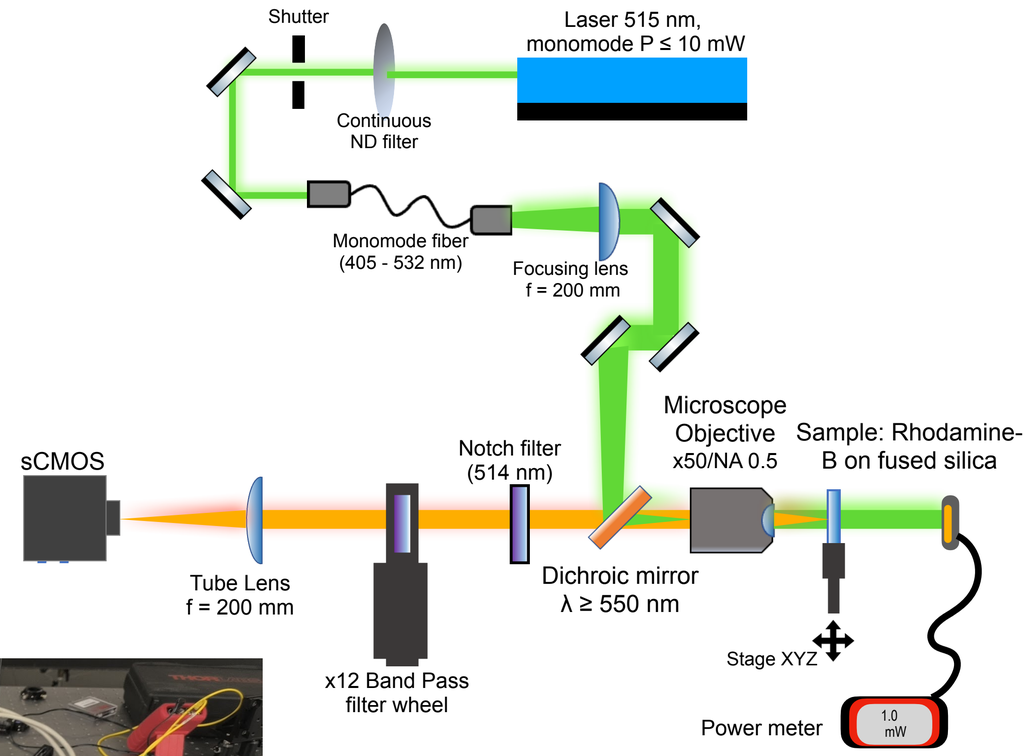
Ba^{2+} beam in low pressure

Coupling to microscope

- Wide-field microscope for coupling to beam



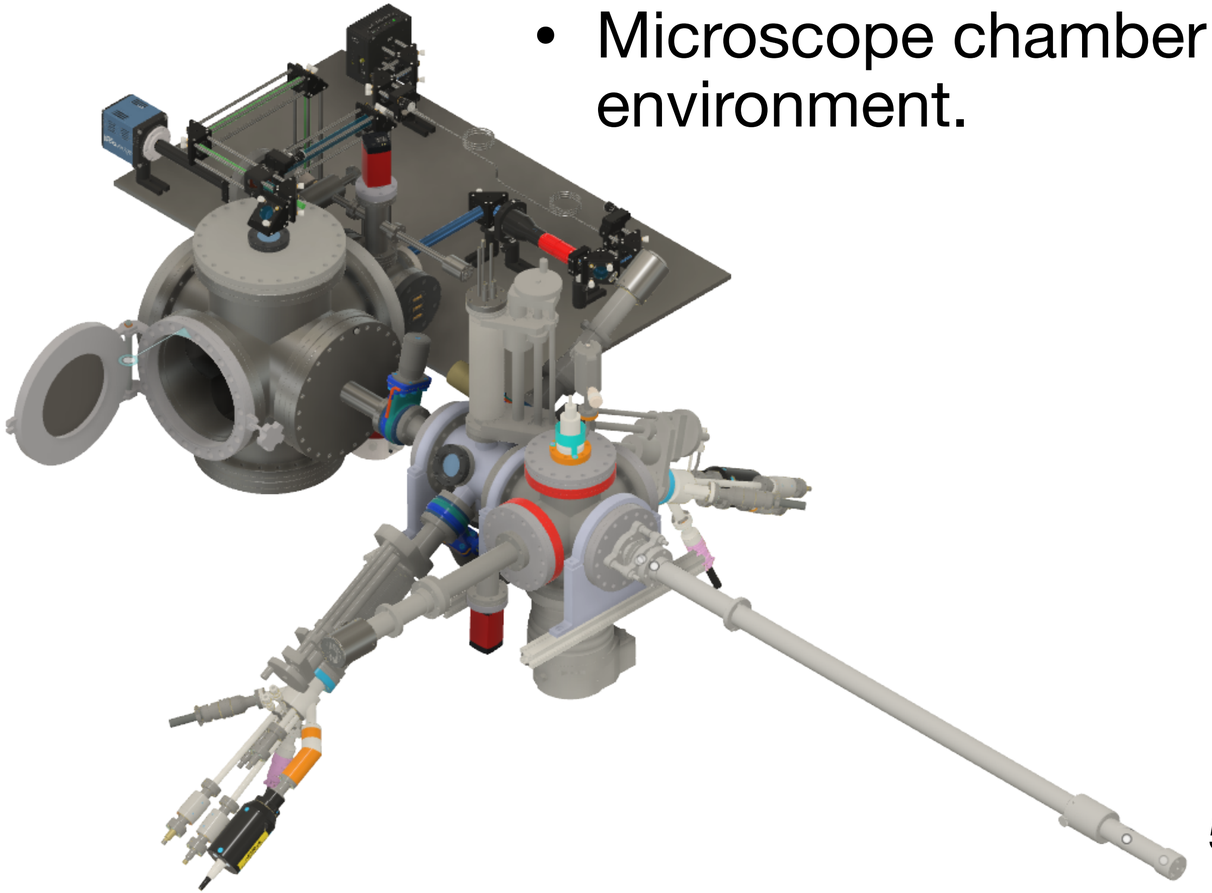


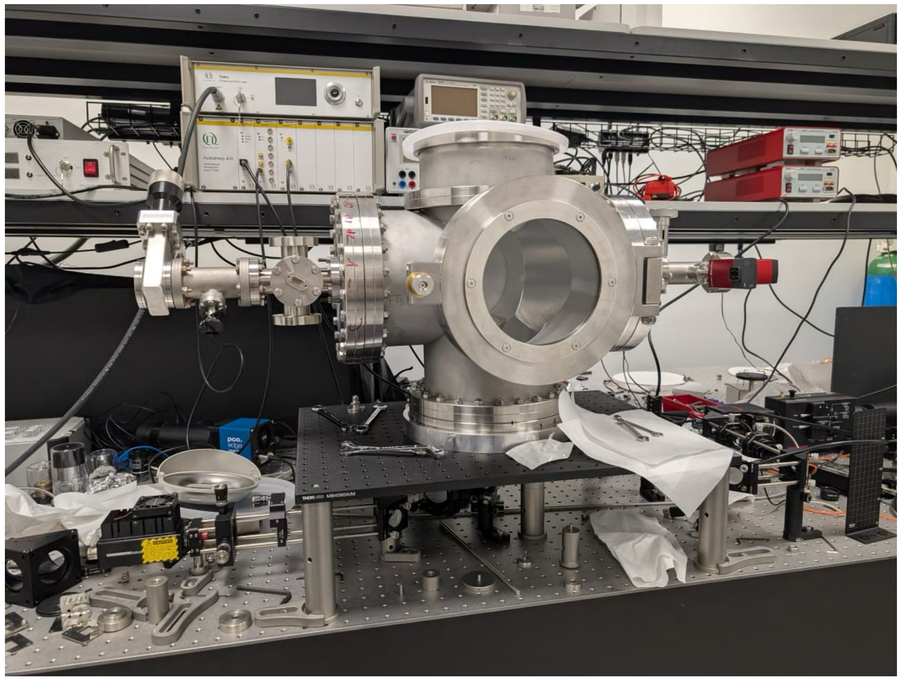


Microscopy efforts

Coupling to Ba/molecular evaporators

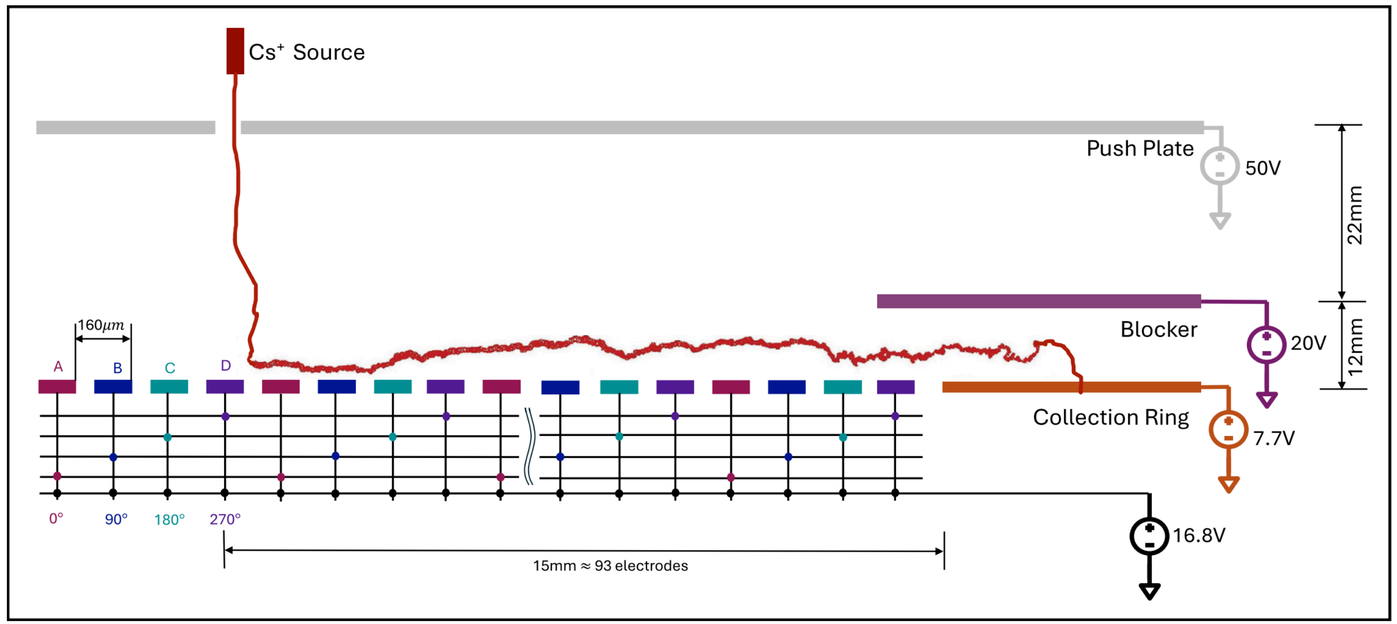
- Next step: couple to evaporation chamber (in vacuum)
- Grow Monolayer and deposit Ba^{2+} in UHV
- Microscope chamber can operate in controlled 1 atm Ar environment.

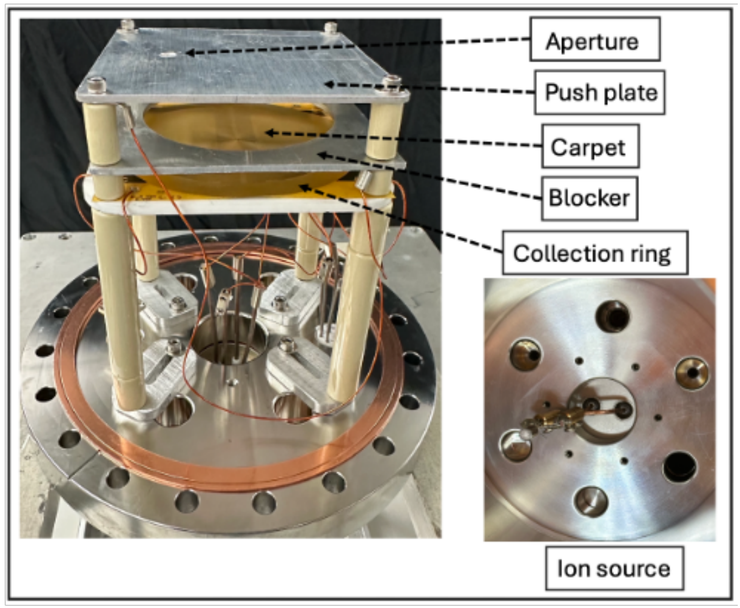


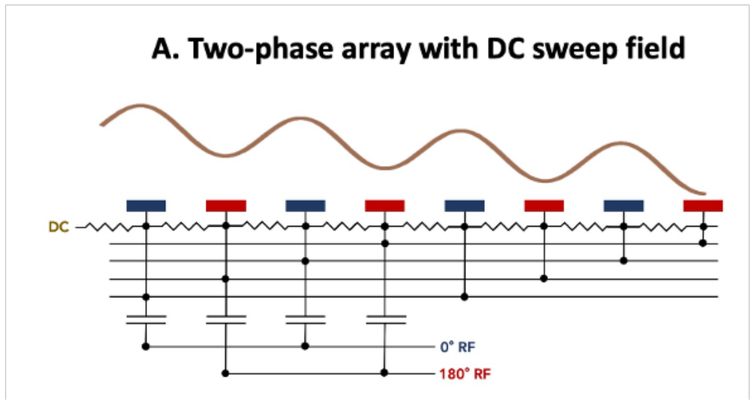


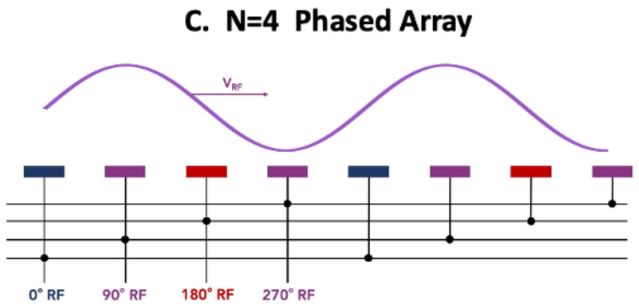
Ba^{2+} guide in GXe with RF carpet

- Using Cs^{+} as Ba+ stand-ins
- 160 μm electrode pitch, at 2 MHz, up to 300 V
- Maximum efficiency for four-phase mode, as predicted from simulation





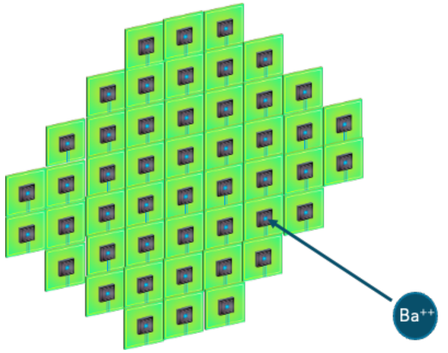


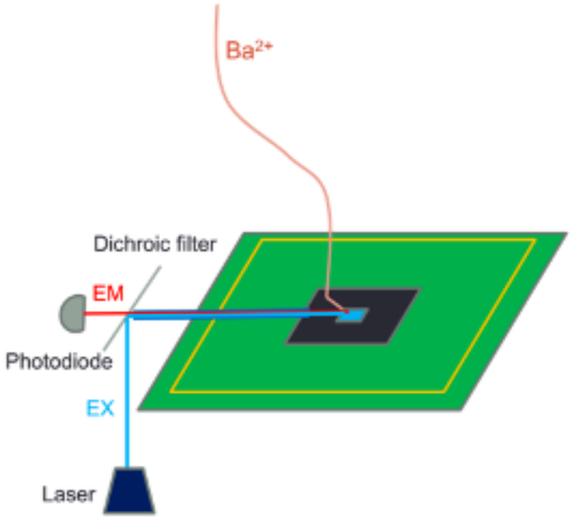


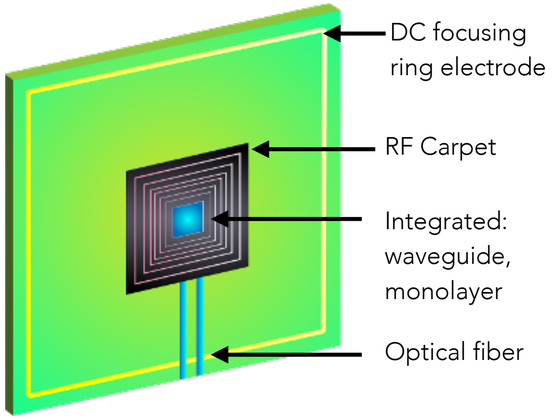
[a] Eur. Phys. J. C 85, 688 (**2025**).

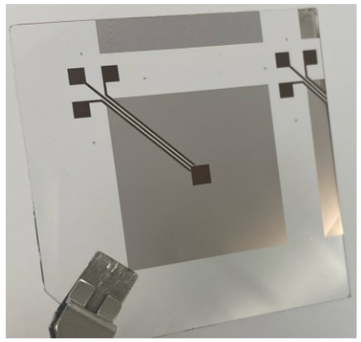
Ba^{2+} collection and sensing: vBit

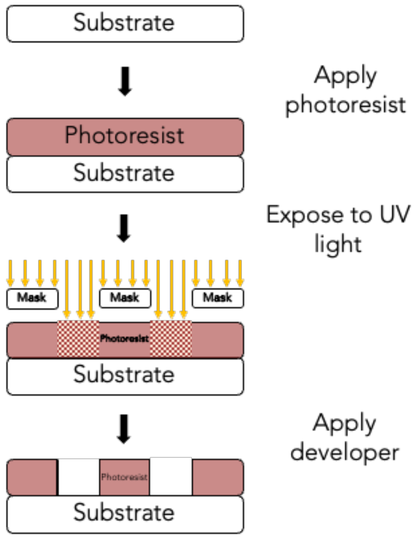
- Array of small-pitch RF carpets with molecular sensing region: vBIT
- Optimization of production pipeline is being finished
- Working on integrating with Fused silica and spin-coated molecules

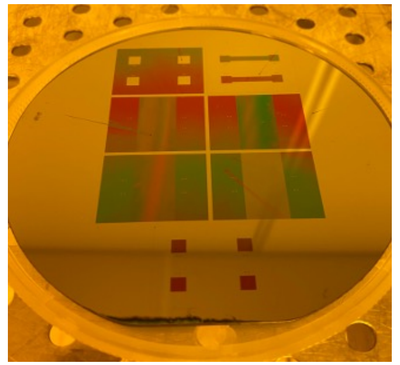






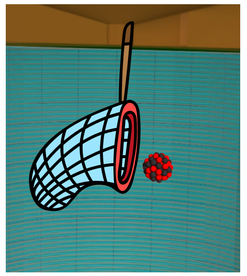




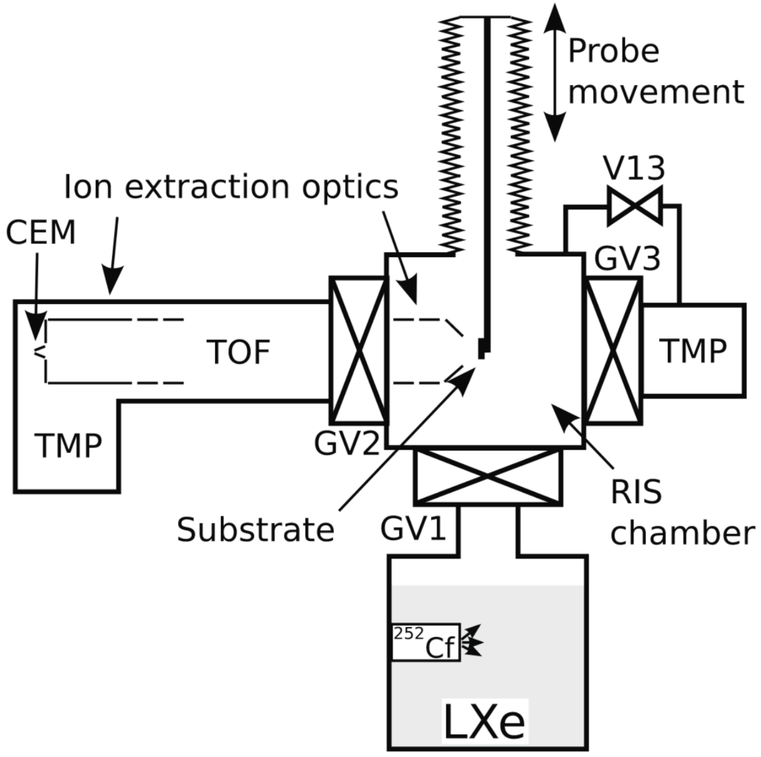


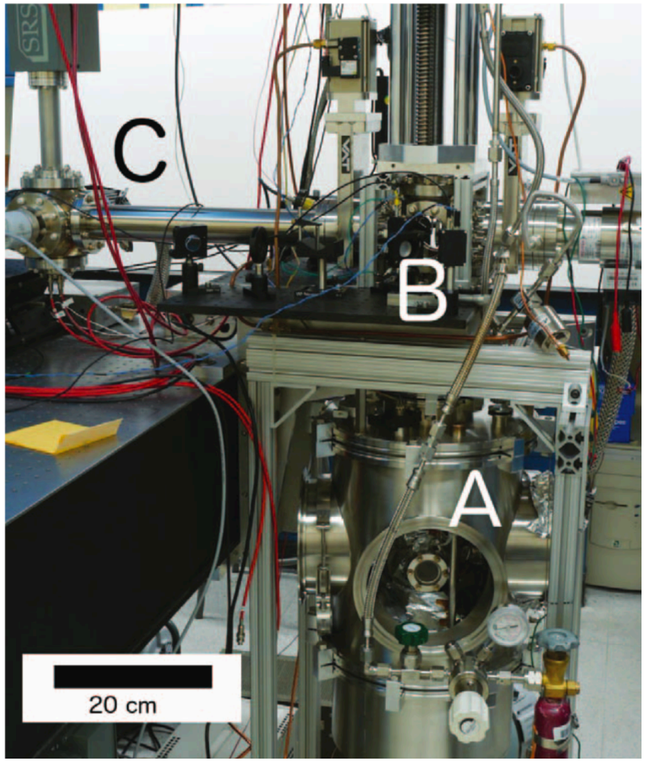
Backup slides (nEXO)

Extraction with cryoprobe



- ^{252}Cf source in LXe TPC
- Laser Induced Thermal Desorption (LITD) of Ba from probe
- Detection through Resonance Ionization Spectroscopy (RIS) and Time of Flight (TOF) Spectrometry

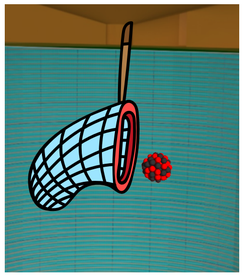




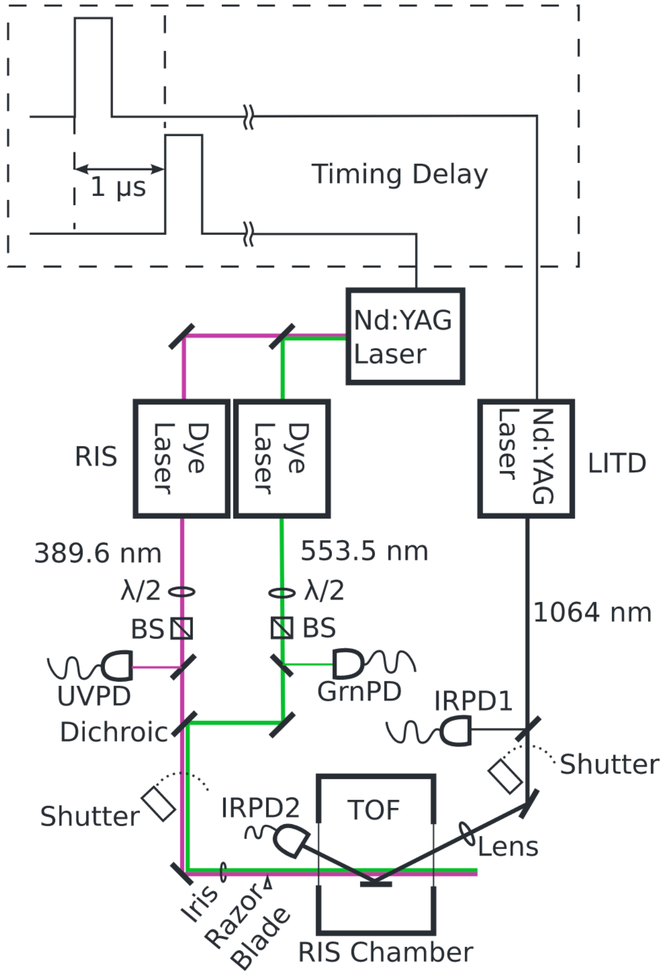
[a] Rev. Sci. Instrum. 85, 095114 (**2014**) (1st paper on nEXO Ba-Ta!)

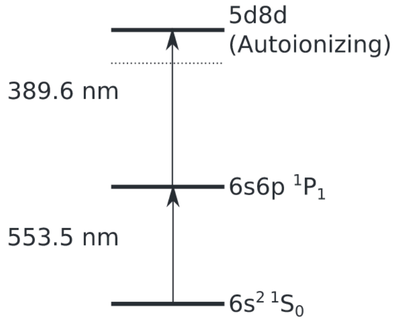
Extraction with cryoprobe

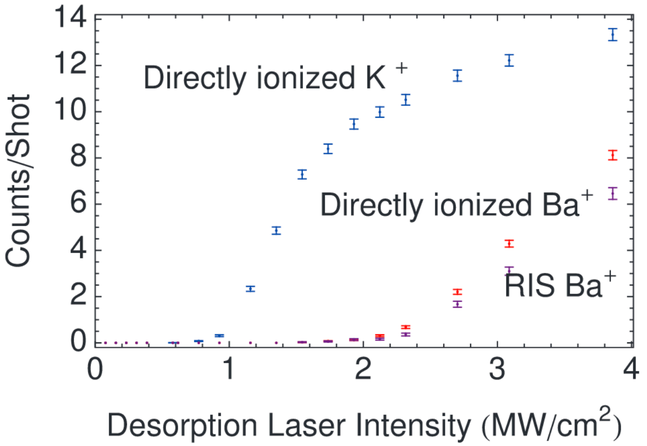
The RIS approach



- Demonstration of LITD+RIS tech (Selective ionization of Ba^+).
- Discrimination of direct desorption and non-resonant ionization Ba^+ from background.
- Measure different desorption thresholds from Si for K^+ and Ba^+.





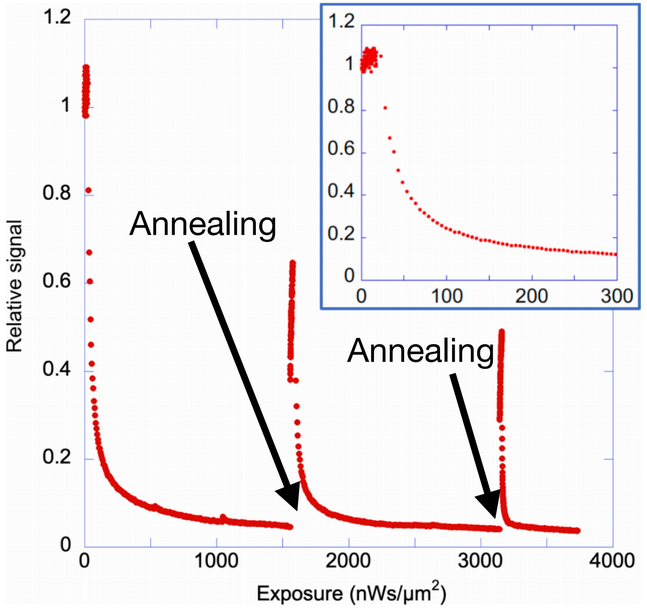


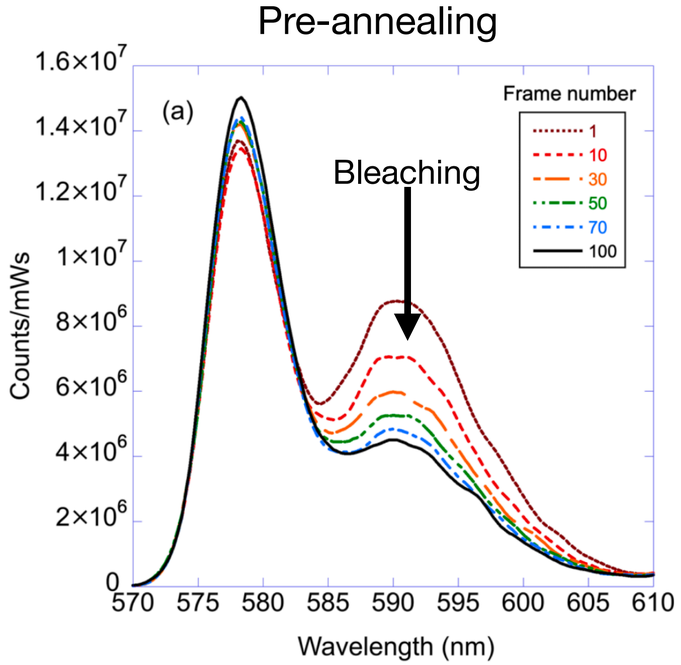
[a] Rev. Sci. Instrum. 85, 095114 (**2014**) (1st paper on nEXO Ba-Ta!)

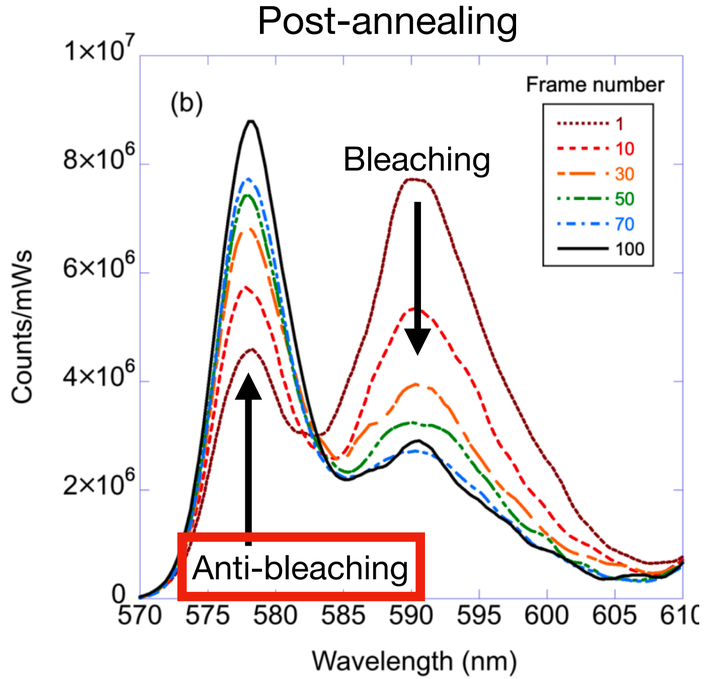
Single-ion detection in SXe

Overcoming photobleaching

- Extended result of SV Ba in SXe matrix for Tetra- (TV) and Hexa-Vacancy (HV) sites.
- Annealing causes fluorescence recovery (anti-bleaching) at the HV site (577 nm)
- Bleaching is irreversible in the TV site (590 nm).



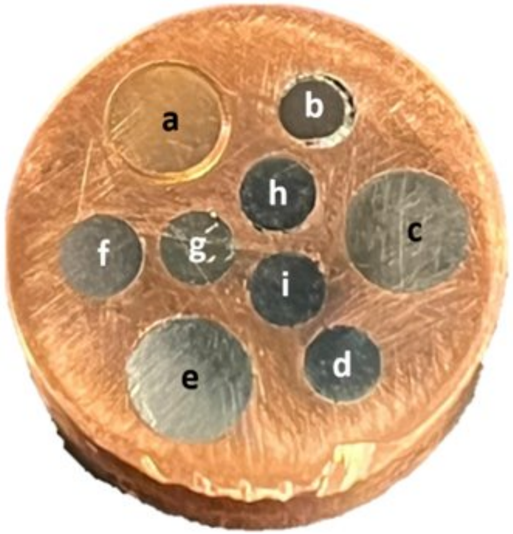


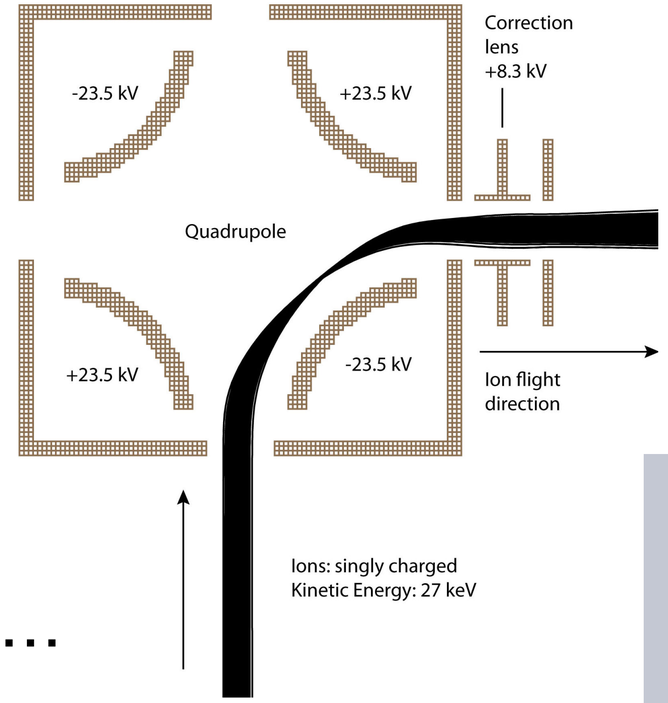


[a] Nature 2019, 569, 203–207. (**2019**) (Single Ba^+ detection)

System calibration

Laser Ablation Source (LAS) + Quadrupole bender





- Custom ablation target:
  Ti, Mb, Ni, Ta, W, CuSn, SS…
- Used to calibrate MRTOF and LPT with other elements