ION MANIPULATION FOR BARIUM TAGGING IN XENON GAS

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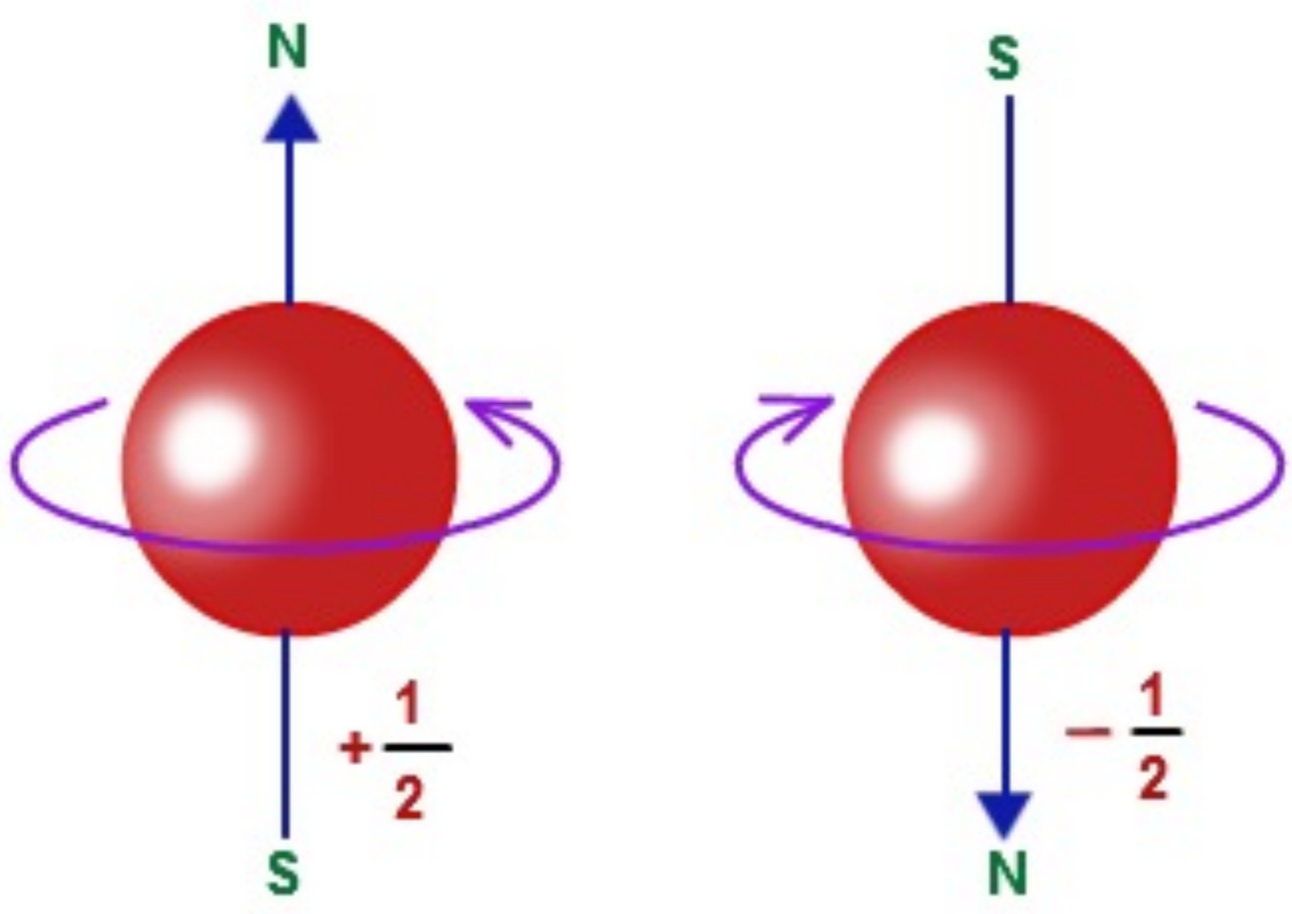
SMI 2023

NEXT

UNIVERSITY OF TEXAS ARLINGTON

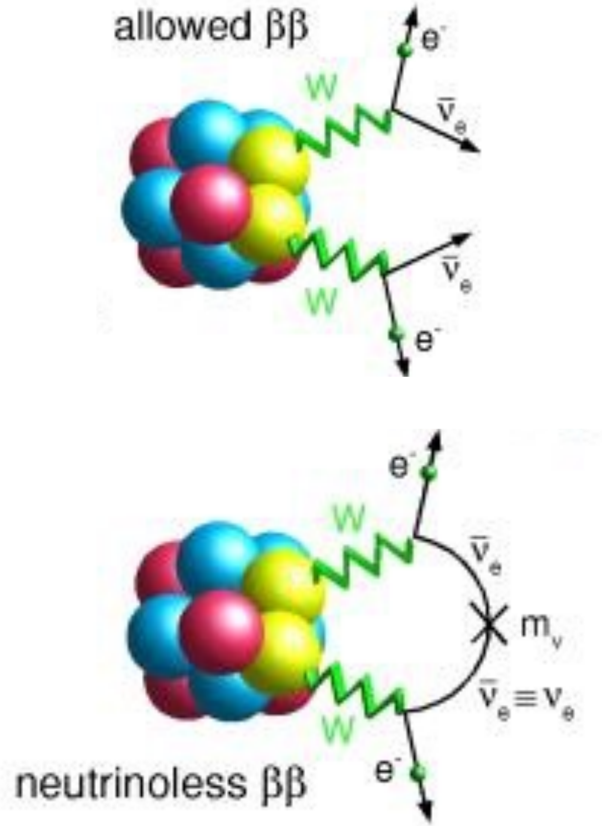
MAJORANA NEUTRINOS IN A NUTSHELL



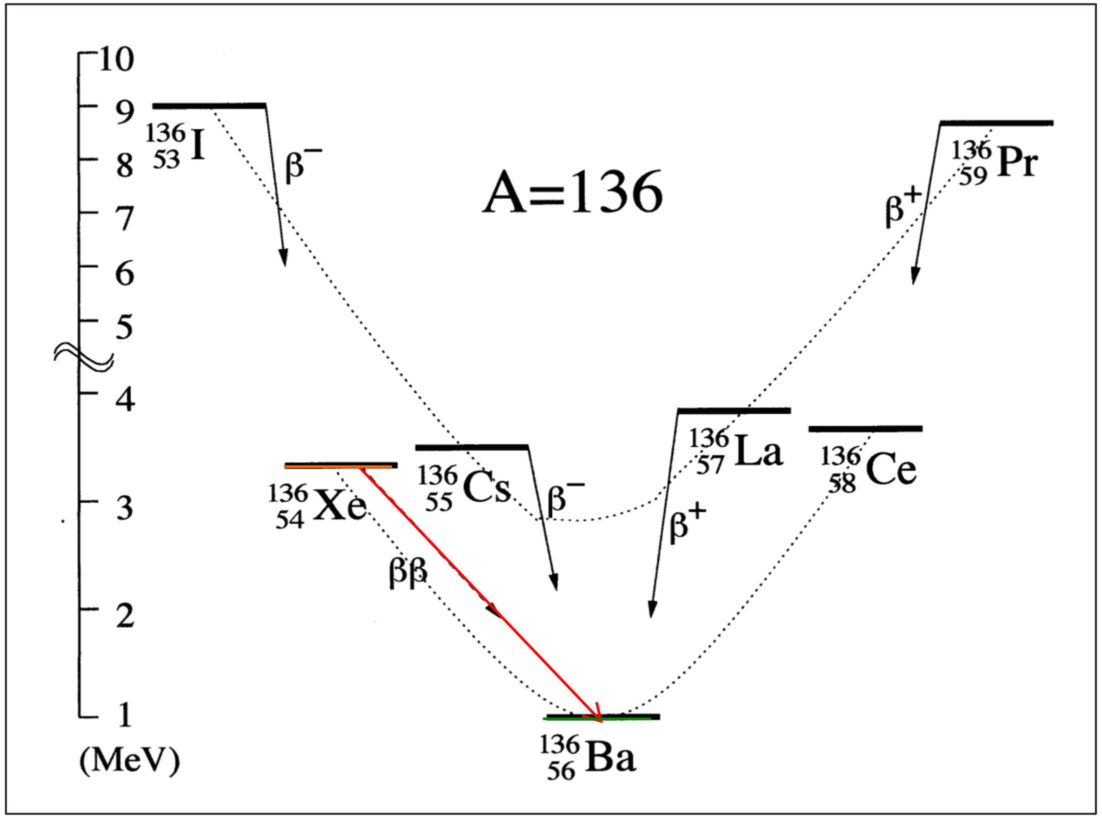
Behaves like matter **Behaves like antimatter**

BARIUM TAGGING FOR 0NUBB

- Barium ion is only produced in a true ββ decay, not in any other radioactive event.
- Identification of Ba ion plus ~1% FWHM energy measurement would give a background-free experiment.
- ***Is it plausible to detect an individual barium ion or atom in a ton of Xe gas?***



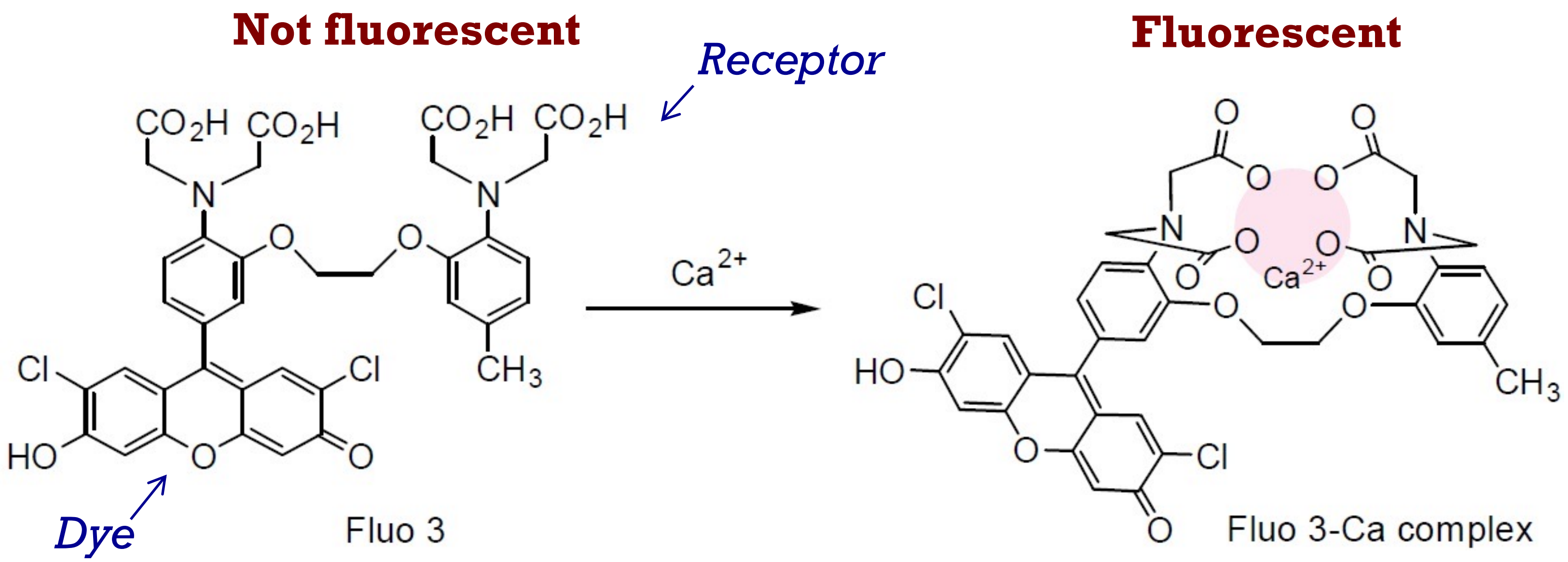
$^{136}Xe \rightarrow {}^{136}Ba + e + e$

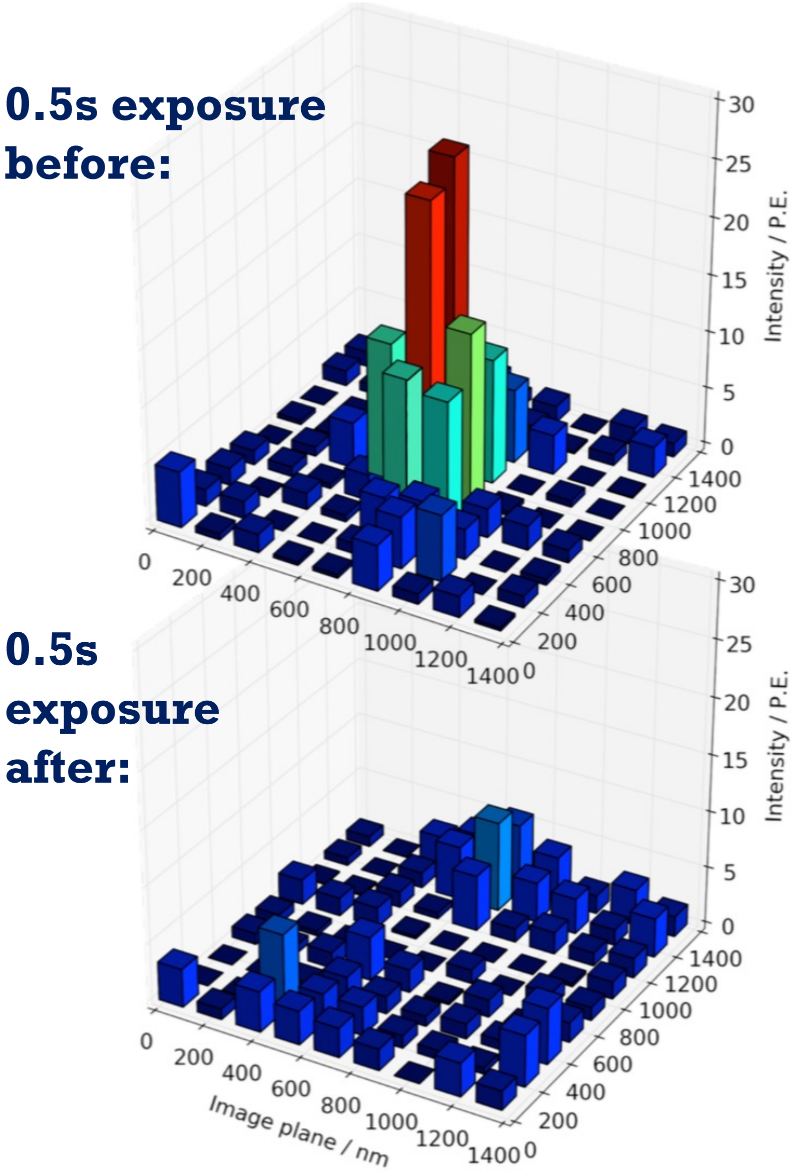


SMFI:

Concept to adapt SMFI for Ba tagging:
D.R. Nygren, J.Phys.Conf.Ser. 650 (2015) no.1, 012002

- A non-fluorescent molecule becomes fluorescent (or vice versa) upon chelation with an incident ion.

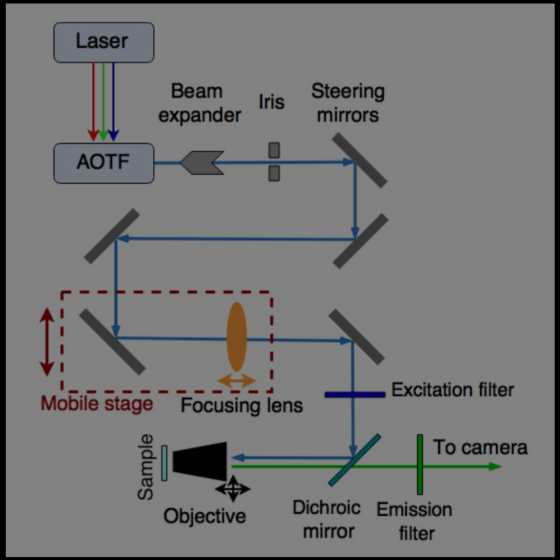


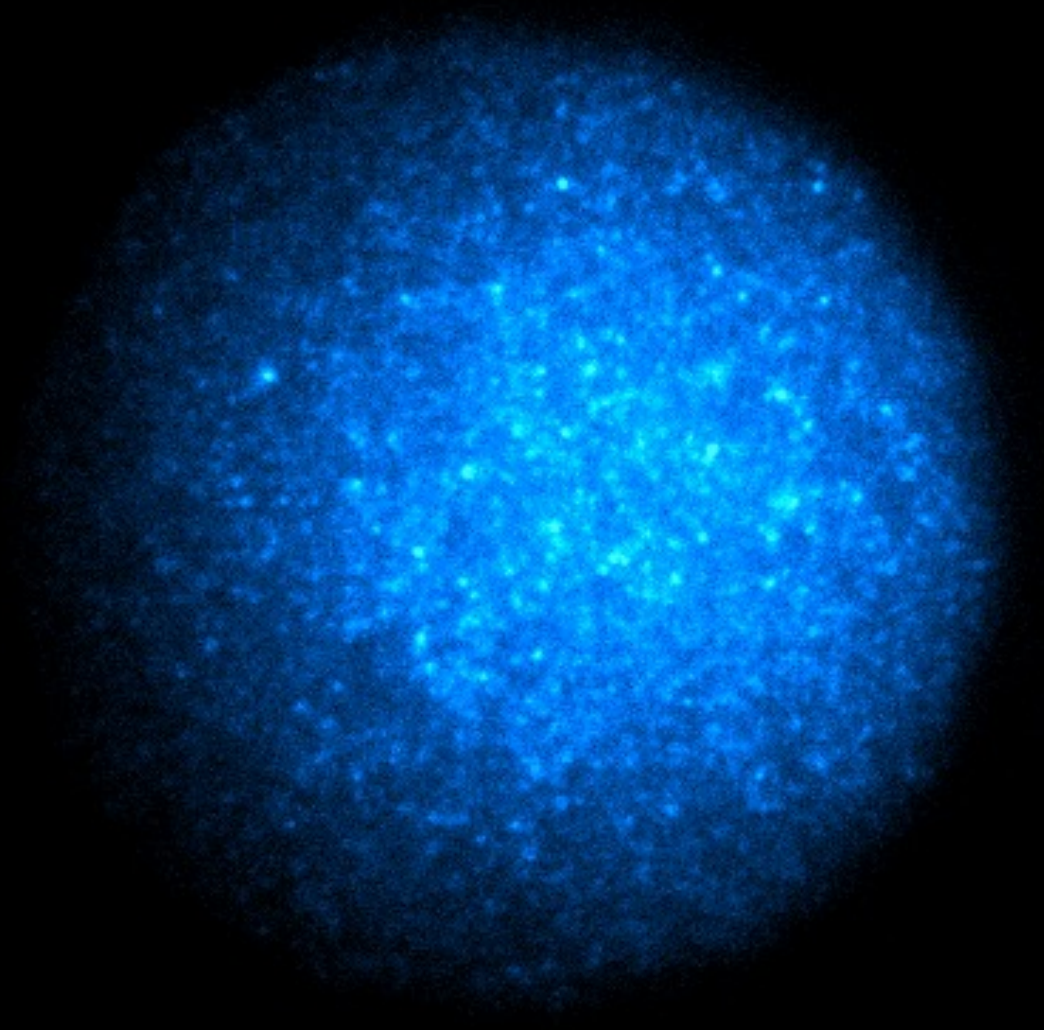


- Many Ca^{2+} sensing molecules shown also to sense Ba^{2+}

- SMFI Enables single ion sensing sensing using fluorescence microscopy techniques.

Phys. Rev. Lett. 120 (2018) 13, 132504

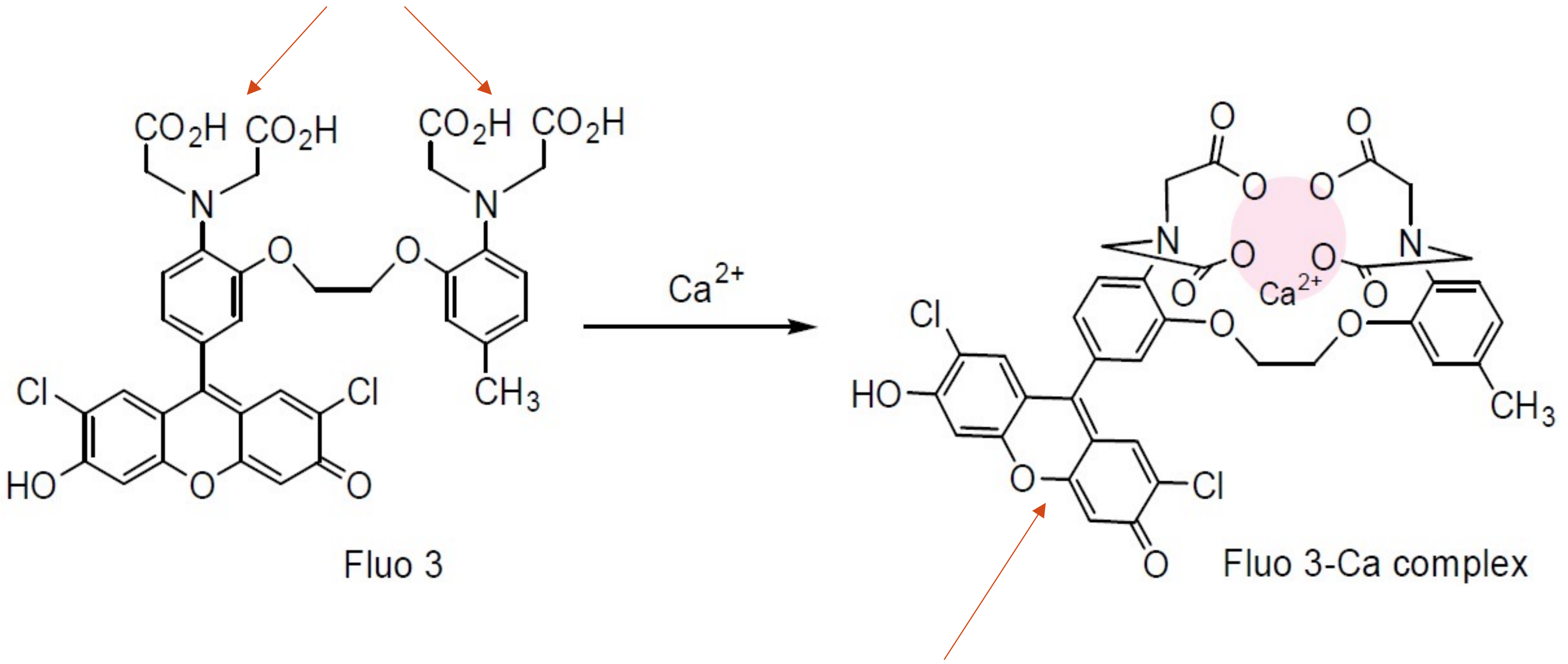




Single Ba^{2+} molecular complexes

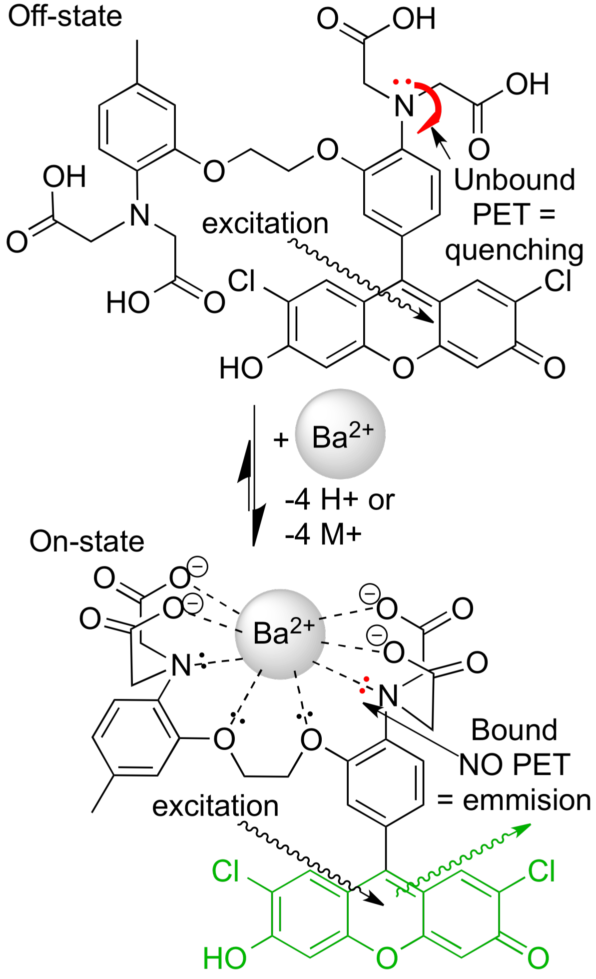
ISSUES WITH THE FLUO FAMILY FOR DRY SENSING

Deprotonation of carboxylic acids is required to accept the ion



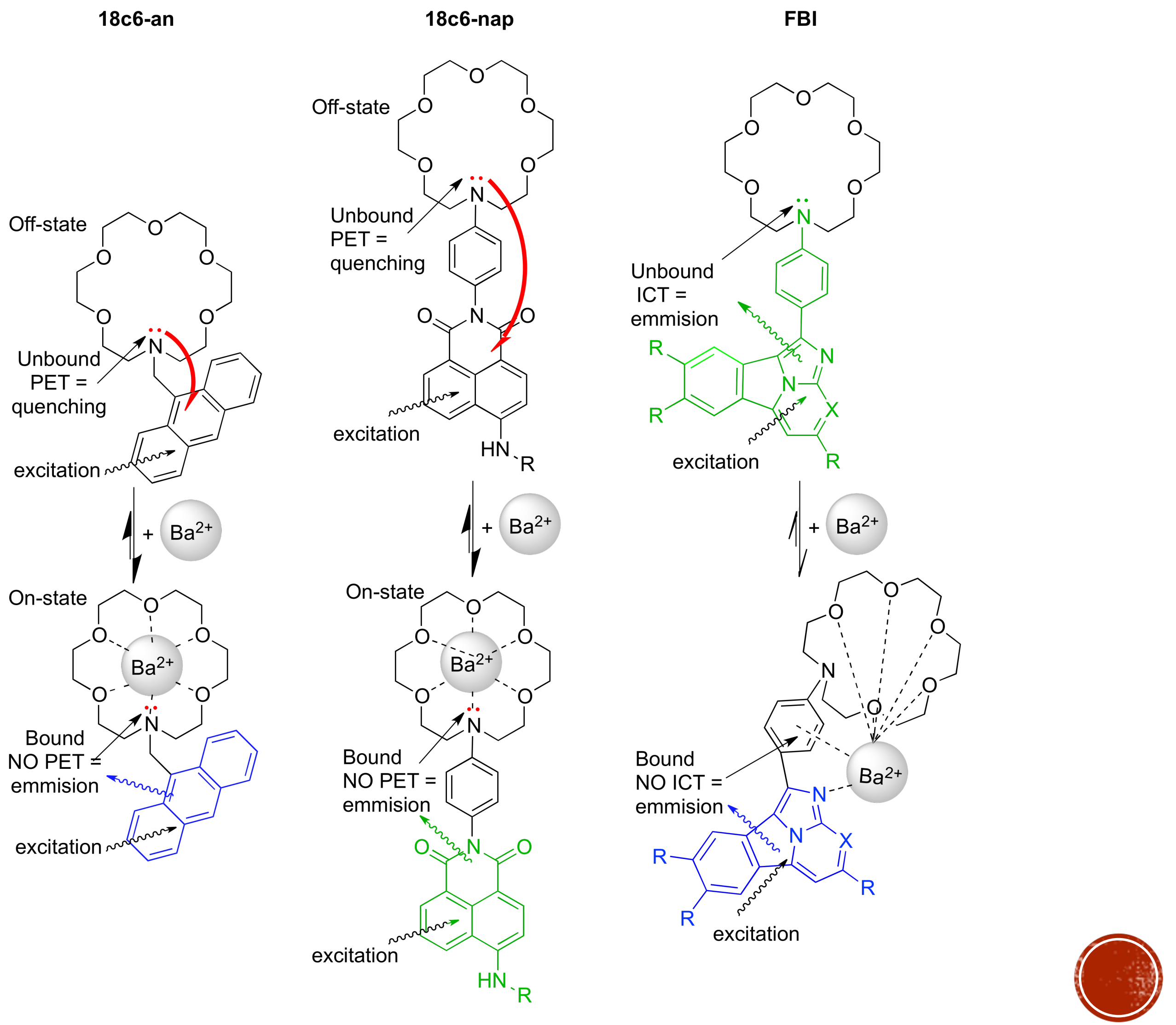
Fluorescein does not shine dry

Out with the old...



And in with the new!

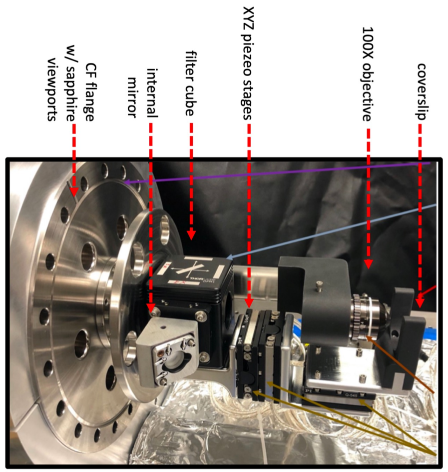
Sci. Rep. 9, 15097 (2019) ACS Sens 2021, 6, 1, 192–202 Nature 583 (2020) 7814, 48–54

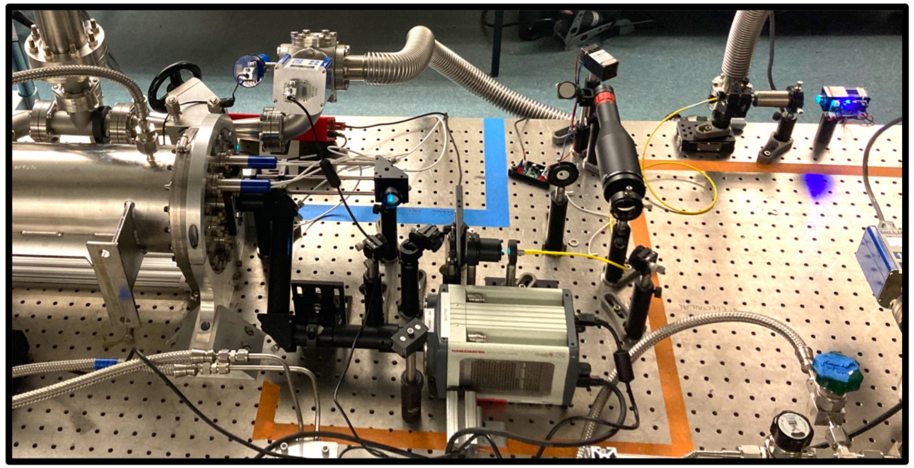


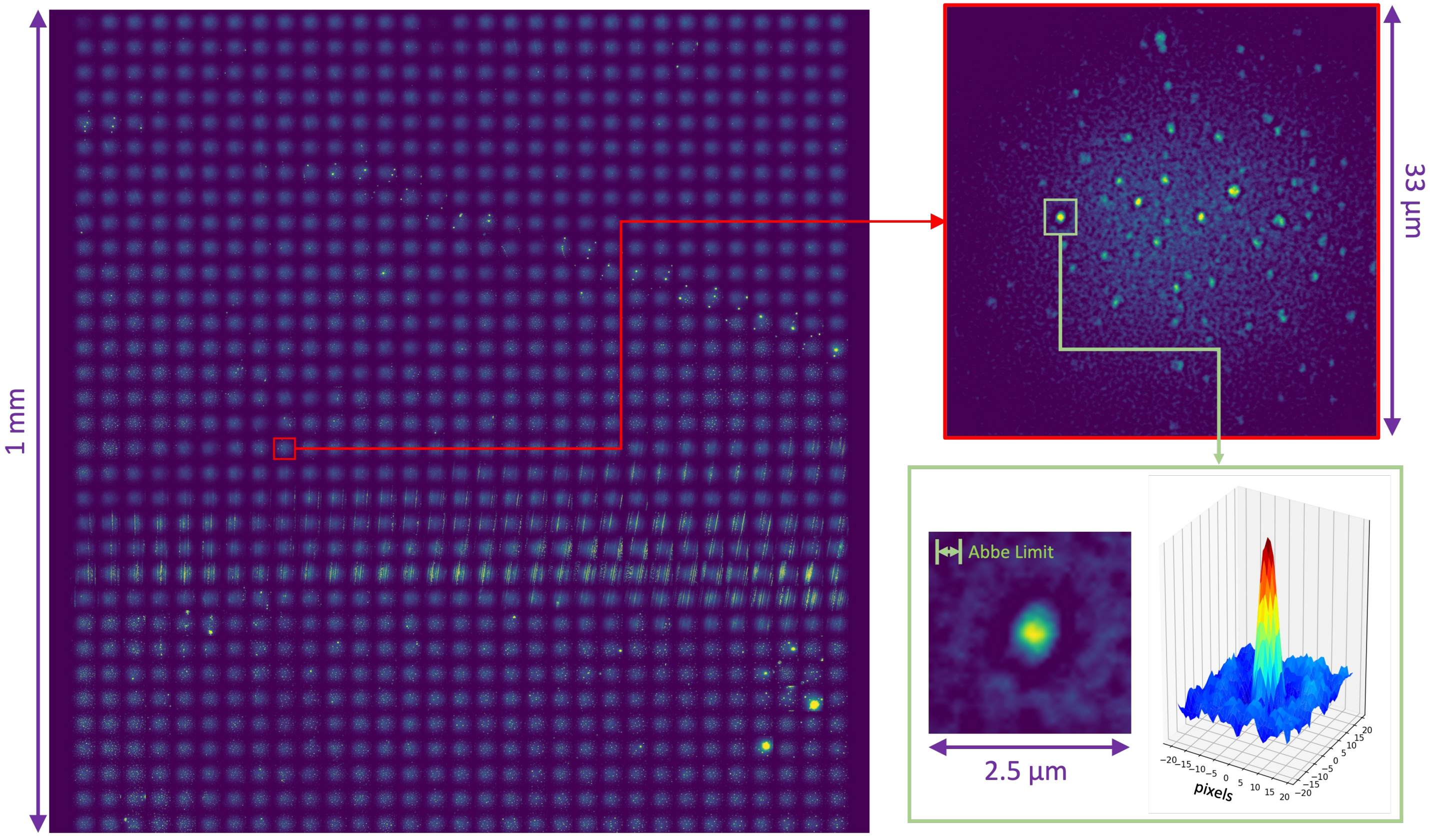
NEXT is producing novel fluorophores specially engineered for dry, in-gas SMFI.

HIGH PRESSURE GAS SMFI

- Novel fluorescence microscopes developed for operation over large surfaces in high pressure gases.



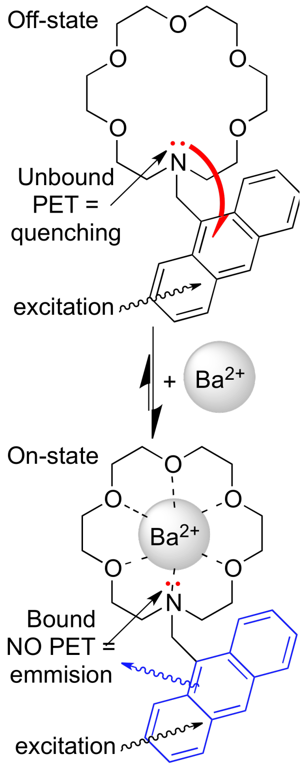


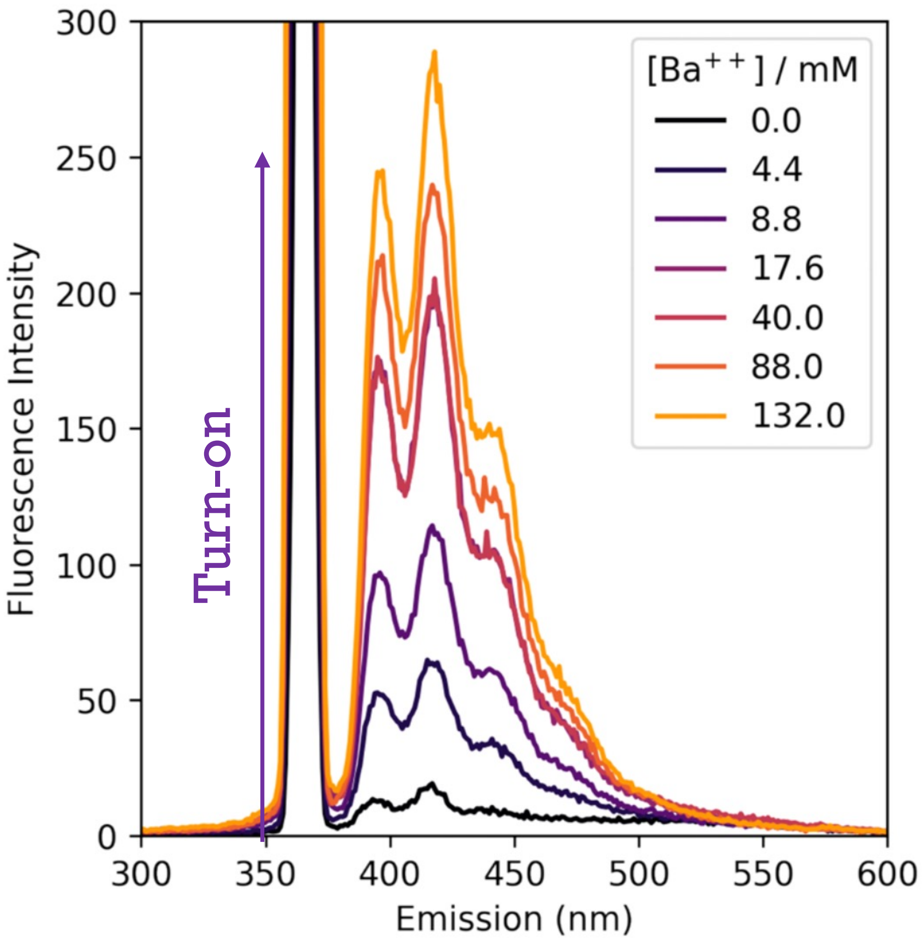


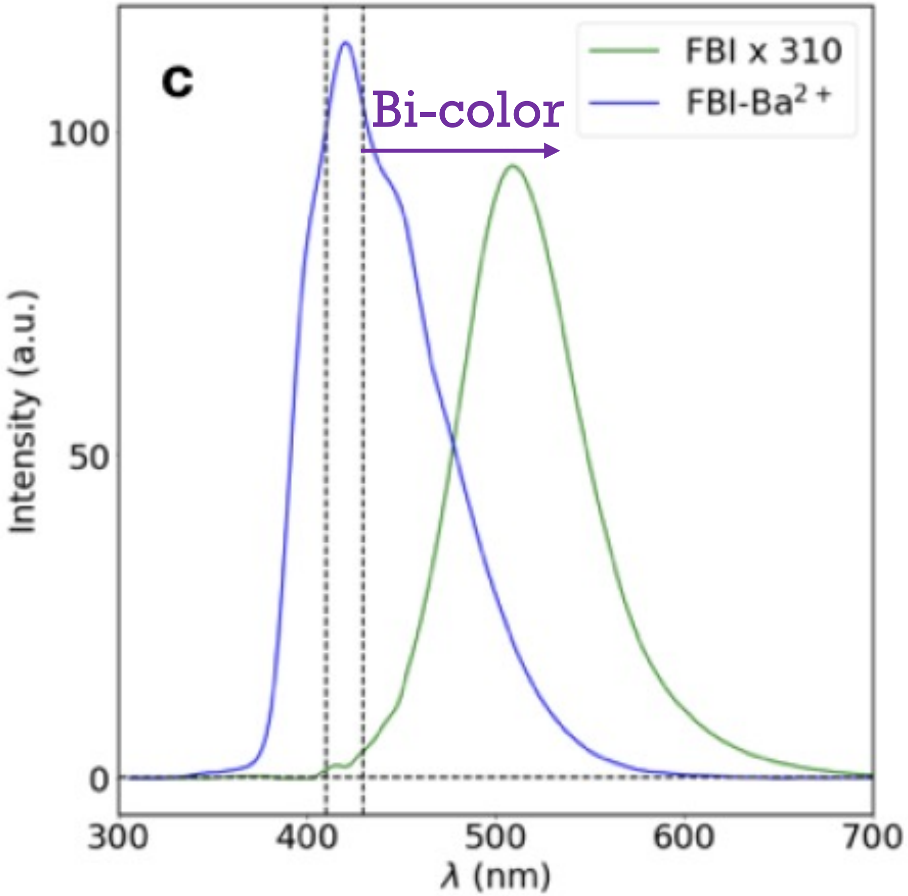
- Single molecule resolution achieved in high pressure xenon gas over 1x1 mm^2, working at at the Abbe diffraction limit.

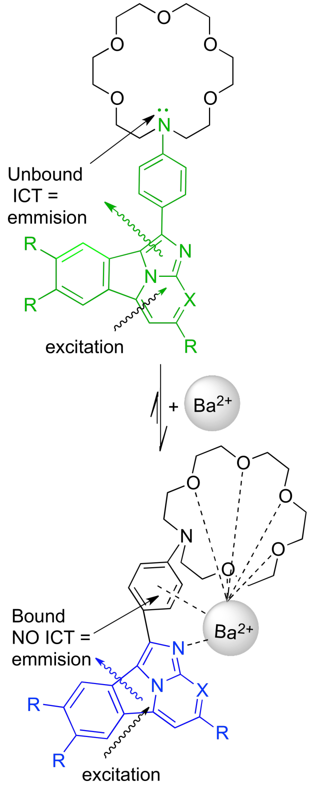
- Single Ba^{2+} + chemosensor complexes imaged in Xe gas → first demonstration of single Ba^{2+} imaging in a working TPC medium.

Paper in prep.









An addition to the toolkit…

DYNAMICS OF BINDING

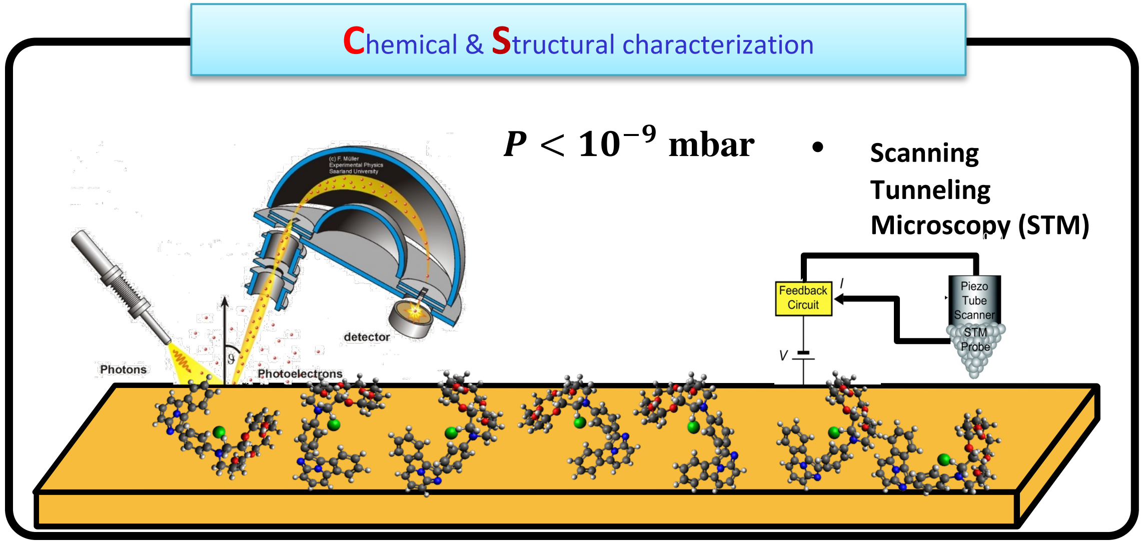
- Recent work has studied mechanisms of ion binding in NEXT barium sensing molecules.

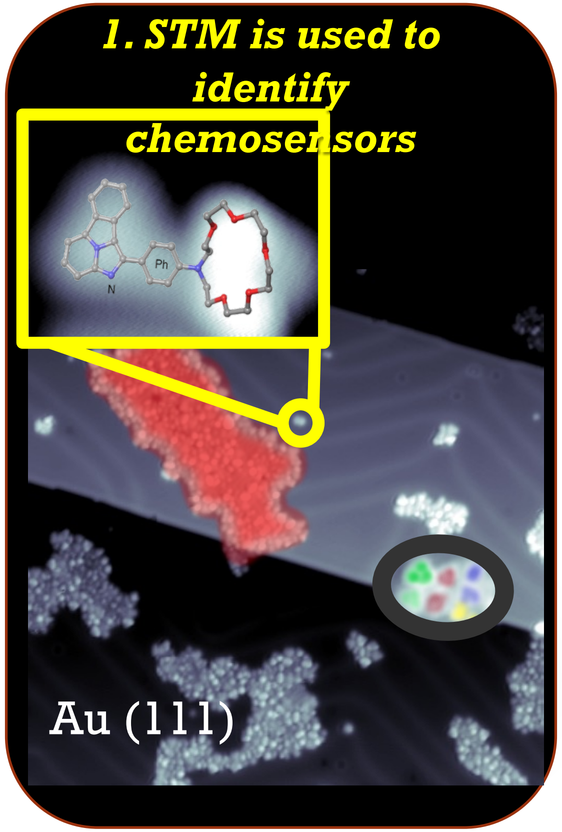
Nat.Comm.13, 7741 2023,

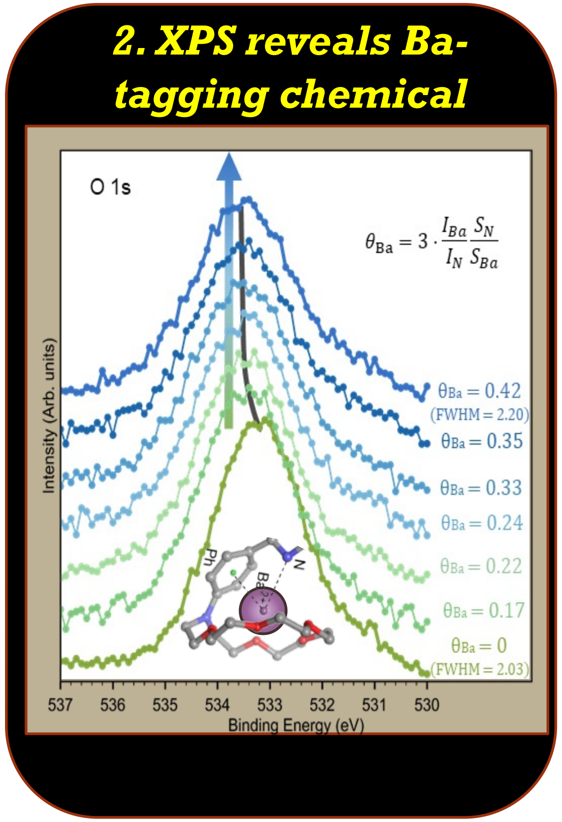
- Barium perchlorate evaporated in vacuum onto sub-monolayer of crown ether chemosensors.

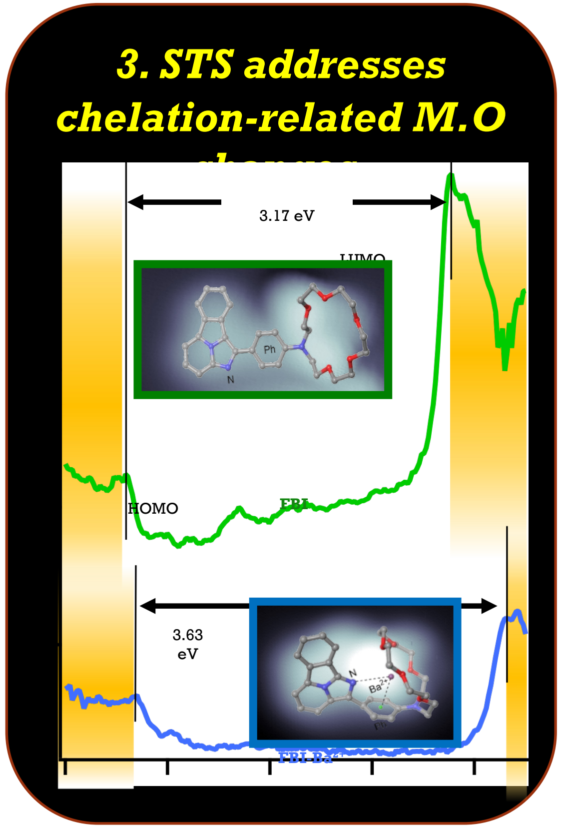
- Molecules chemically react with the Ba$[ClO_4]_2$ to capture the Ba^{2+} into the receptor.

- Combination of STM, XPS and STS illuminates changes in electronic configuration, studying mechanism of the reaction at single molecule level.





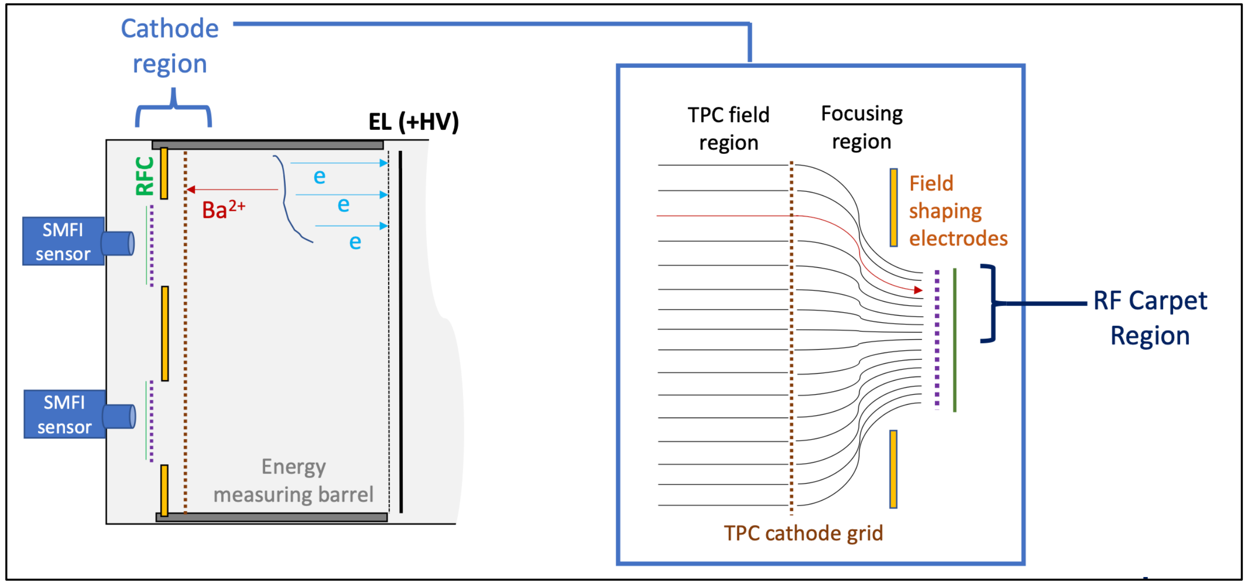




RF CARPETS FOR NEXT

The field of view of our demonstrated sensor is ~1mm² - we now need to either:

- **A) Deliver the ion to those sensors**
- **B) Deliver the sensors to the ion**

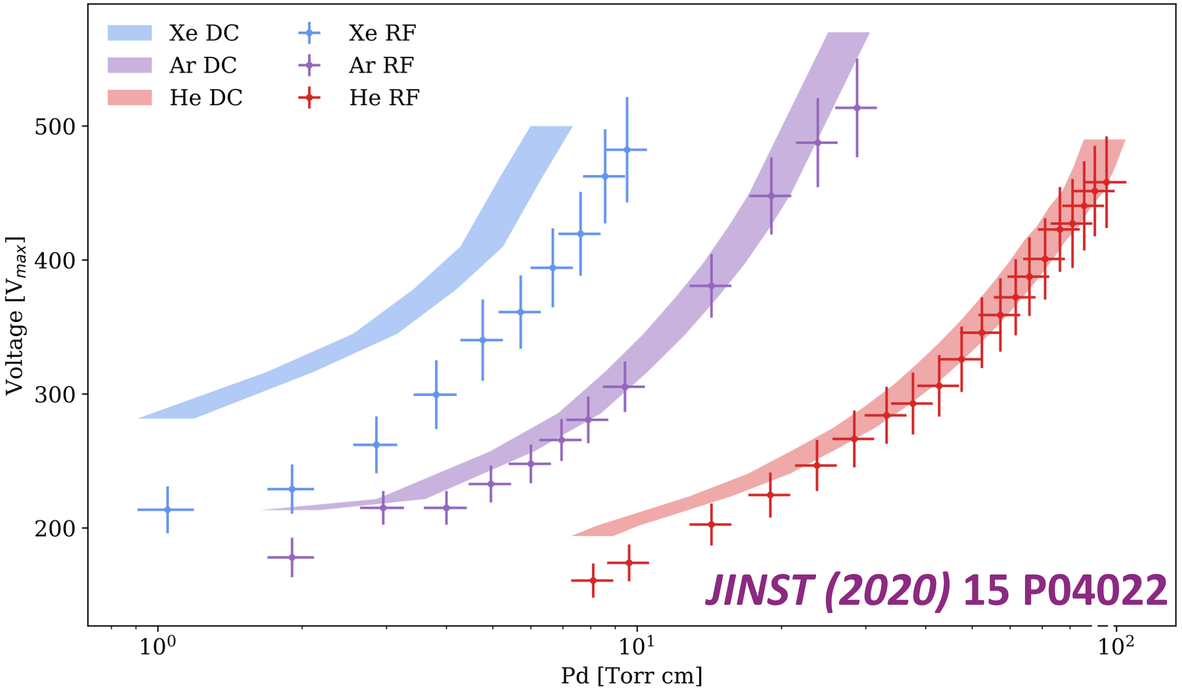


- One potentially plausible way to do (A) is through fine-pitch RF carpets.

- **What is the ultimate pressure limitation of this technique?**

- In 1bar+ xenon, breakdown through gas is not limiting, breakdown through insulator is.

- We are exploring 4-phase traveling wave systems (no surfing, no DC drag field).



STABILITY CRITERIA – VISCOUS MODEL

(this work much inspired by: S. Schwarz, IJMS 299 (2011) 71-77)

- Stable ion motion is only possible when pseudo-potential well exists.

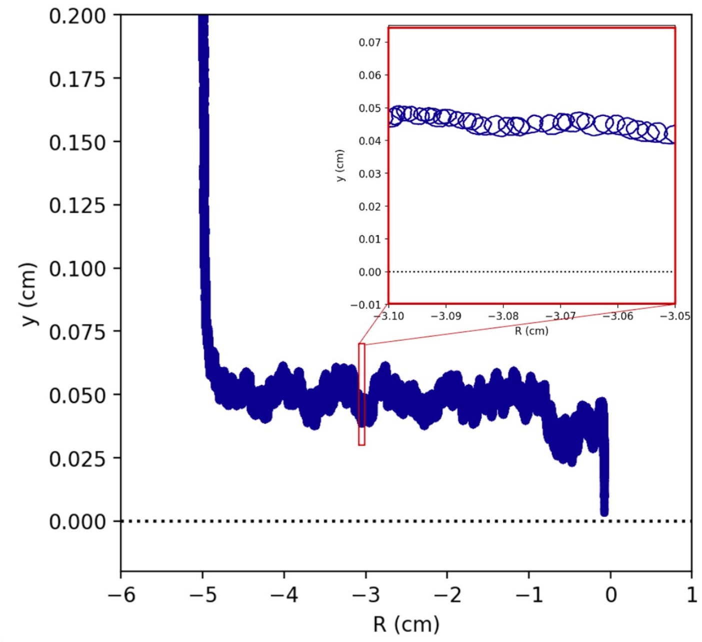
First part of our calculation extends the work of Schwartz to find the pseudopotential and drag speed in an **N-phased array.**

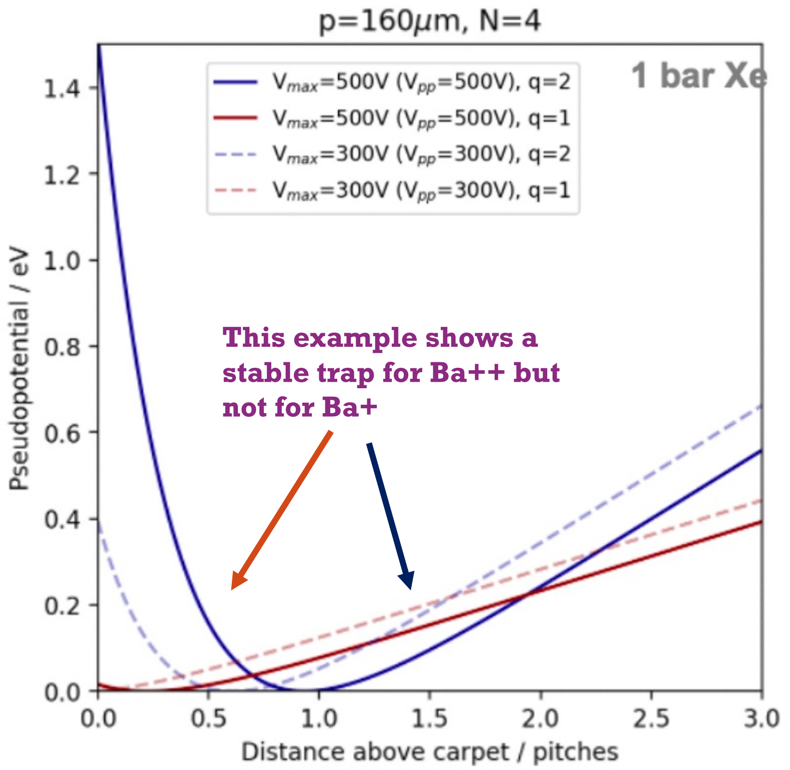
$$\bar{y} = -\frac{Np}{4\pi}\log\left[\frac{m\left(D^2+\tilde{\Omega}^2\right)E_{push}}{2qV_{pp}^2}\left(\frac{Np}{\pi}\right)^3\right]$$

Mean well-to-wall distance

$$V_{pp} \geq \sqrt{\frac{m\left(D^2+\tilde{\Omega}^2\right)E_{push}}{2q}\left(\frac{Np}{\pi}\right)^3}$$

Criterion for existence of a minimum

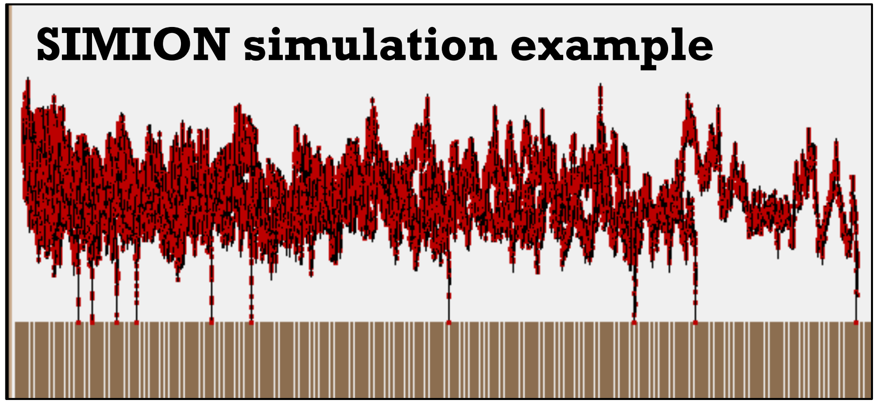


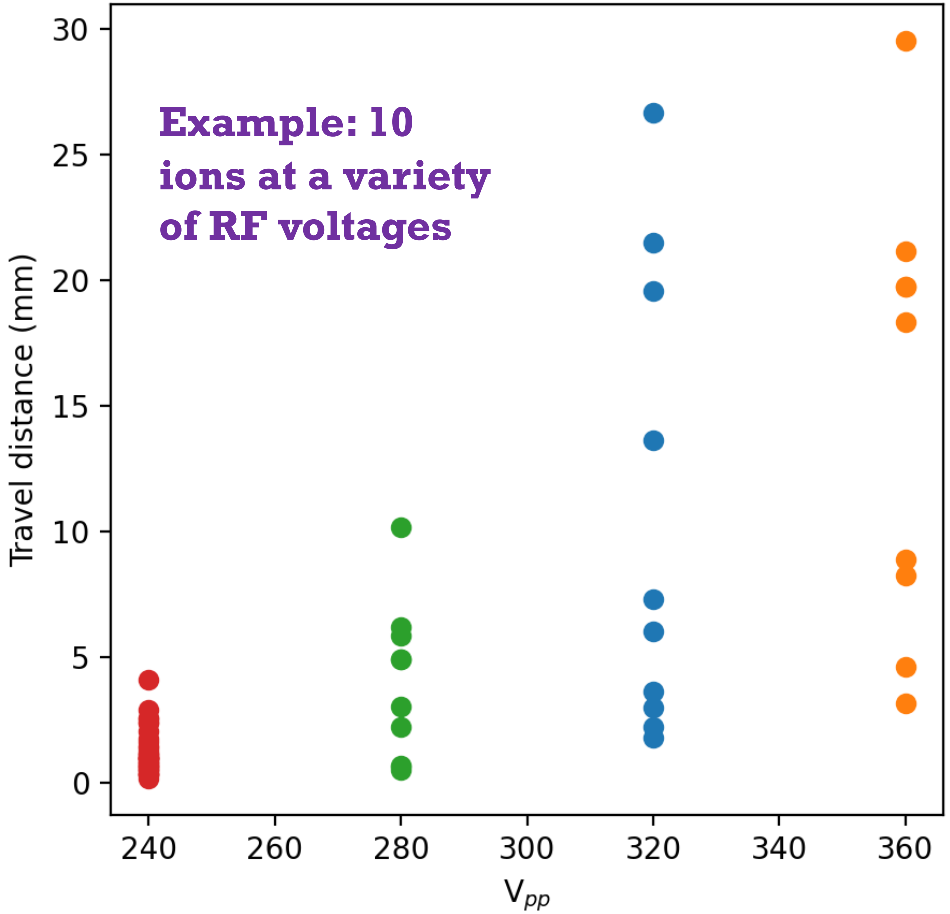


Next few slides all draw from:
B.J.P Jones et. al. (NEXT collab), NIMA 1039 (2022) 167000

STOCHASTIC/ BROWNIAN LOSSES

- Stable ion motion is only possible when an effective potential well exists.
- This is **necessary but not sufficient** condition, since even for trapped ions, collisions with gas molecules can kick them into walls, which dominates losses.
- Typically the only way to model stability is to simulate collision-by-collision. Generally the community finds these simulations reliable.
- But at these pressures the simulations take **days**.
- Can we account for these fluctuations analytically somehow, to make this problem tractable at high buffer gas density?

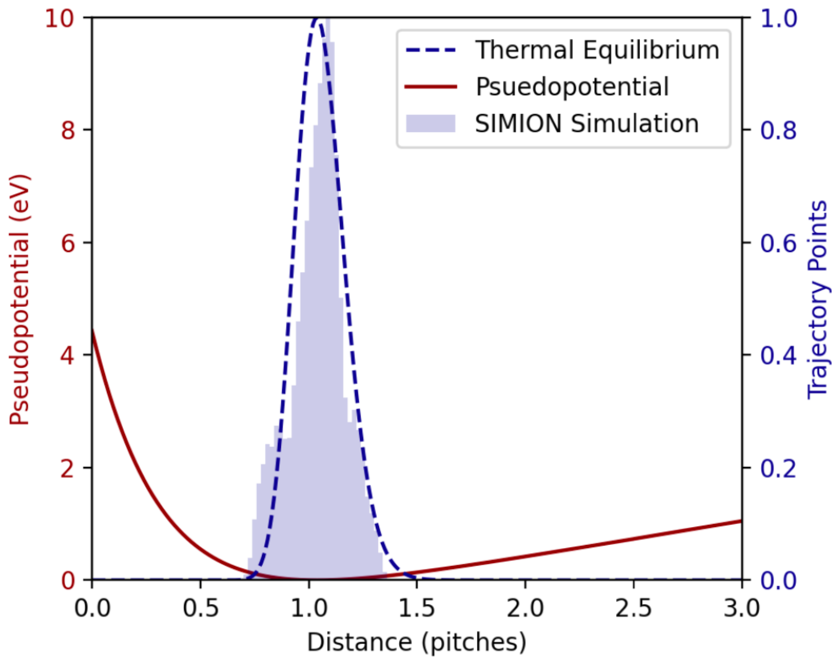


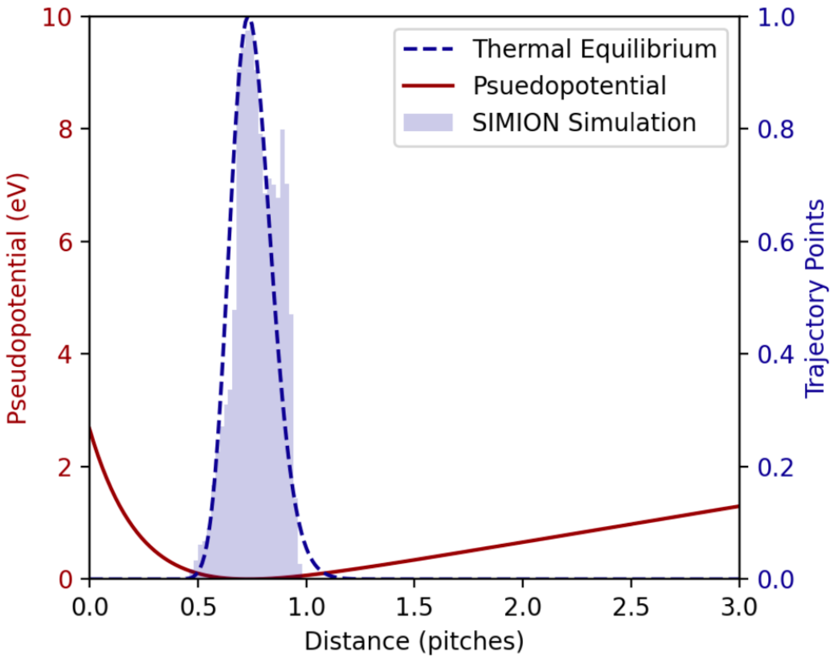


THERMALIZATION CONJECTURE

- Idea: ions are colliding constantly with Maxwellian gas to thermalize into the effective potential at finite temperature.
- A non-trivial conjecture since the trapping potential is emergent, and T of RF-driven ions is not necessarily well defined.
- However, it works and is predictive!

$$\rho_{Therm}(y) = \frac{\exp\left[-qV(y)/k_B T\right]}{\int_0^\infty dy' \, \exp\left[-qV(y')/k_B T\right]}$$





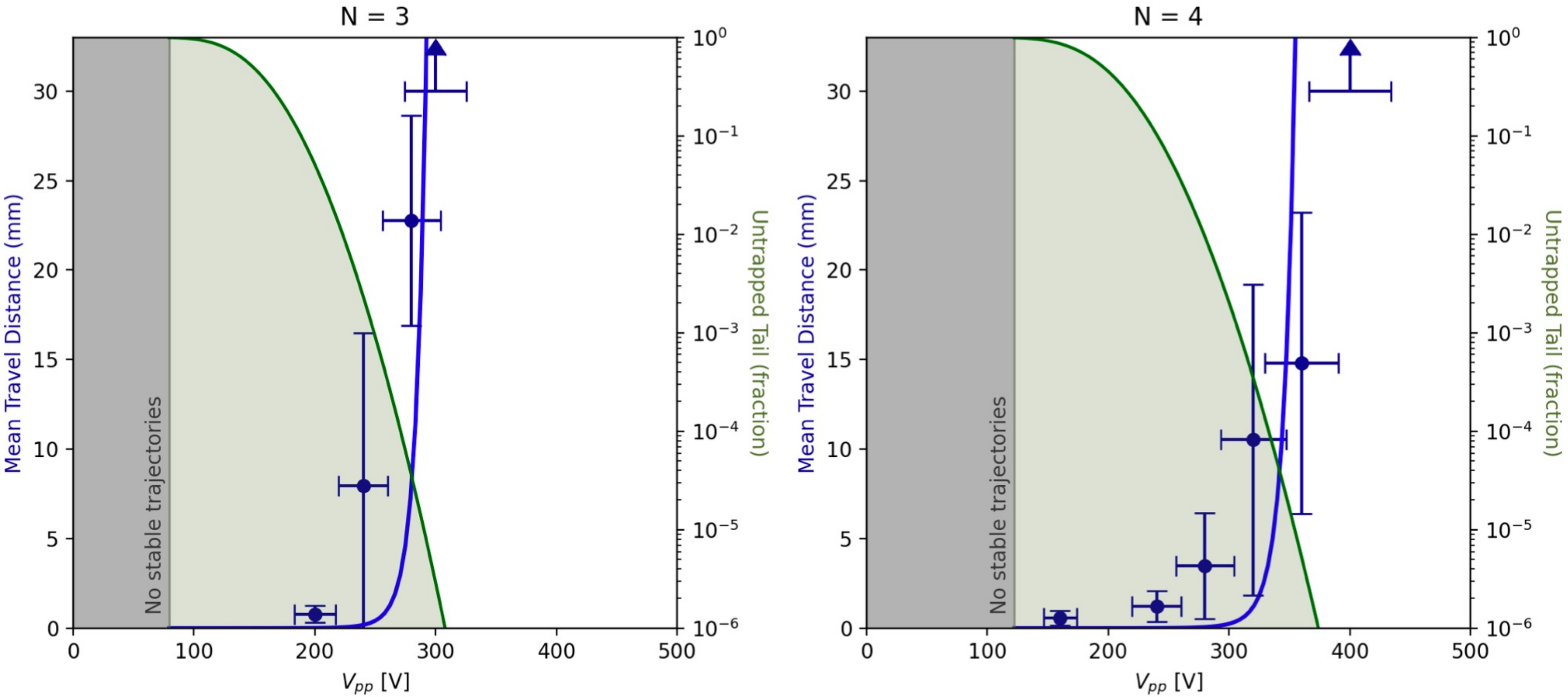
KINETIC LOSS RATES

- On its own, thermalized distribution is not enough to predict loss rates - evolution with losses is a non-thermal-equilibrium scenario.
- However, adding a little kinetic theory into the mix, we can accurately predict flux from approximately thermal distribution into the walls.

- **Analytically predictive model of RF carpet transport efficiencies at high pressure →**

$$\Gamma_t = \frac{1}{T}\mathcal{P}(T) = \sqrt{\frac{kT}{2\pi m}}\rho(0)$$

$$\Gamma_d = \frac{1}{\bar{v}}\Gamma_t.$$

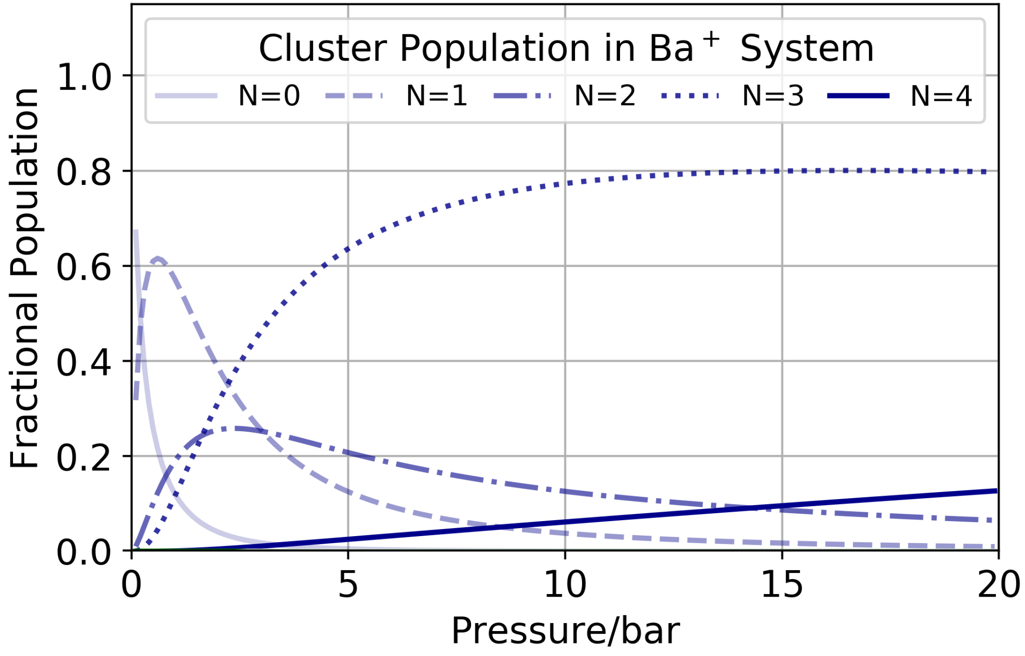


MOBILITY (AS AN INPUT)

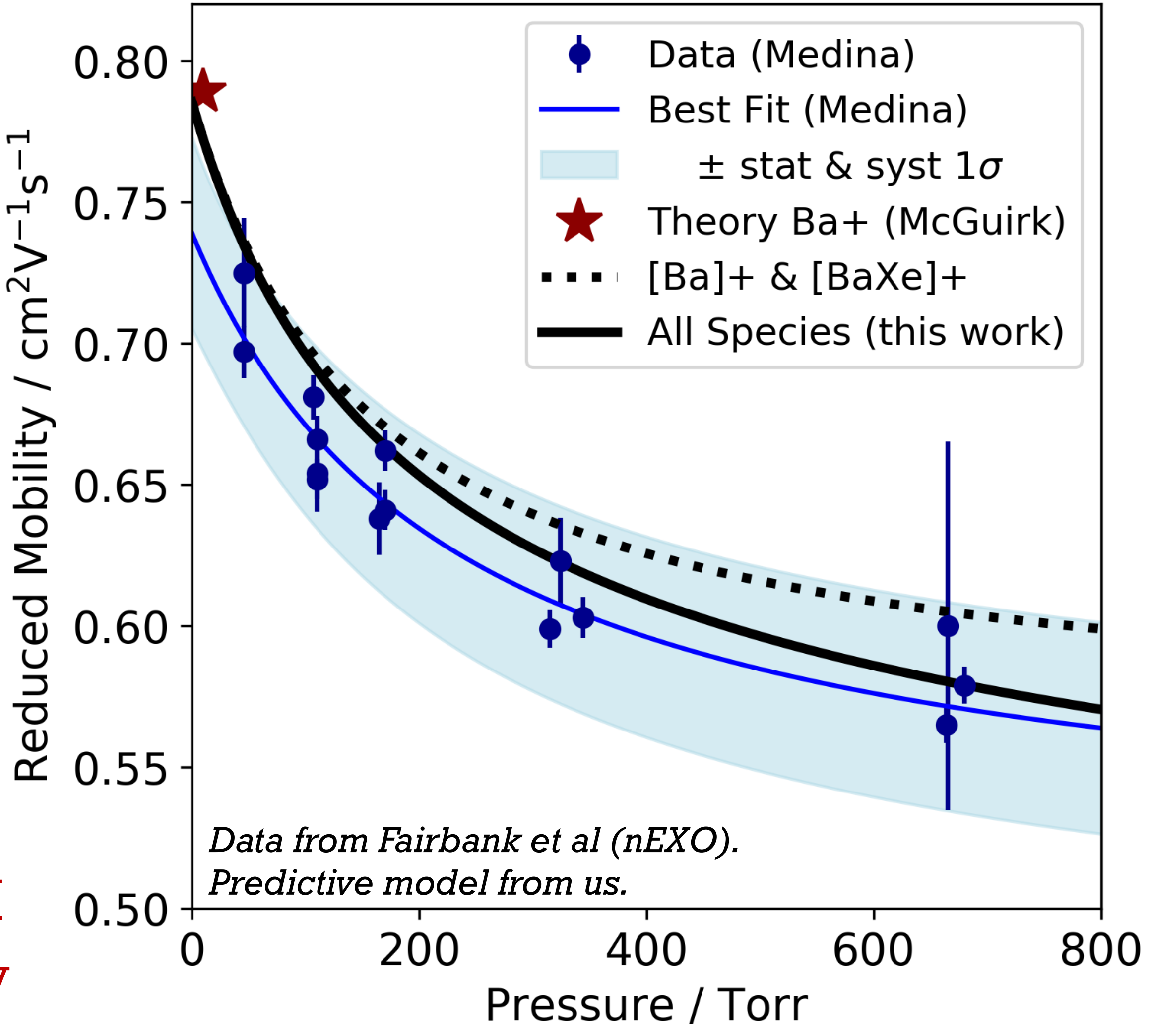
Understanding the RF carpet design criteria involves understanding microscopic behavior of drifting Ba^{++}

In Ba^{+}, situation is already somewhat complex due to molecular ion formation:

$$\mathrm{Ba}^{+} + \mathrm{Xe} + \mathrm{Xe} \longleftrightarrow \mathrm{BaXe}^{+} + \mathrm{Xe}$$



Pop-weighted mean velocity gives mobility

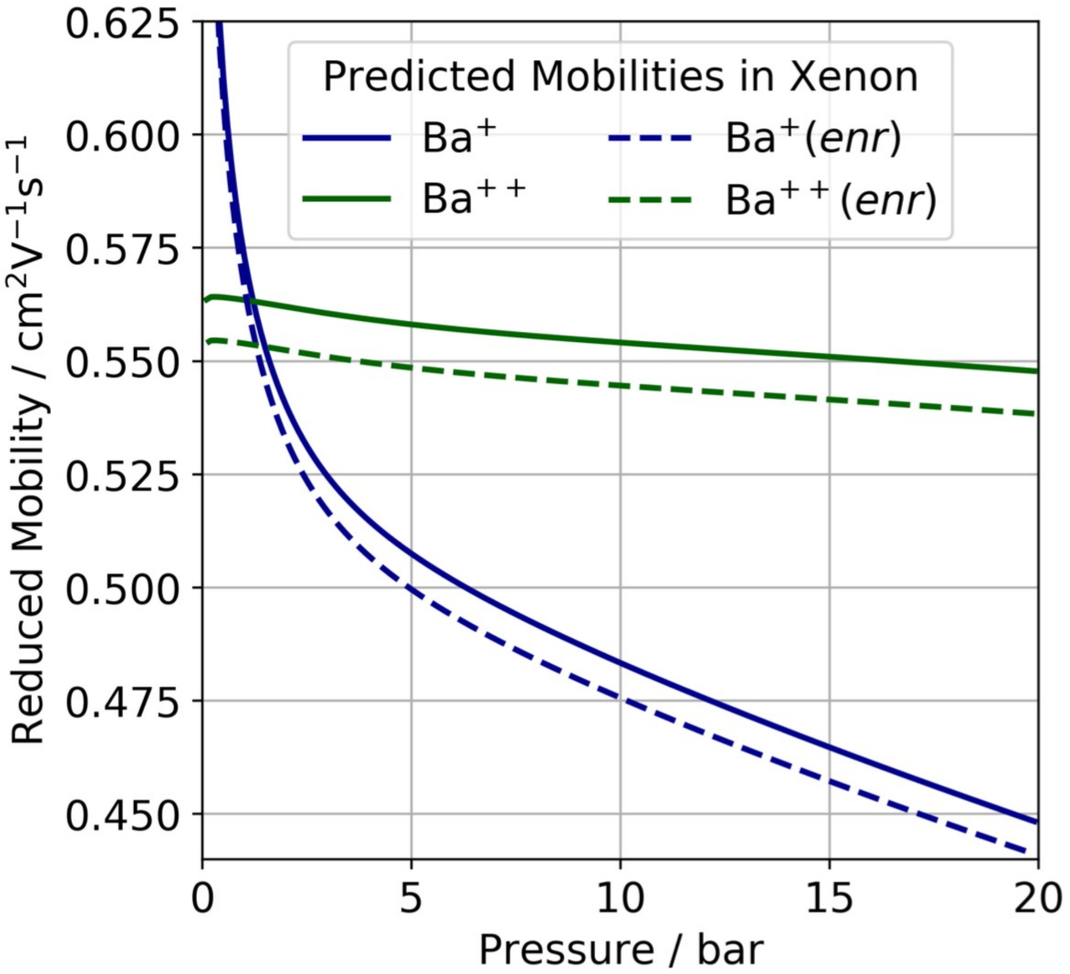


Excellent agreement with data for Ba+

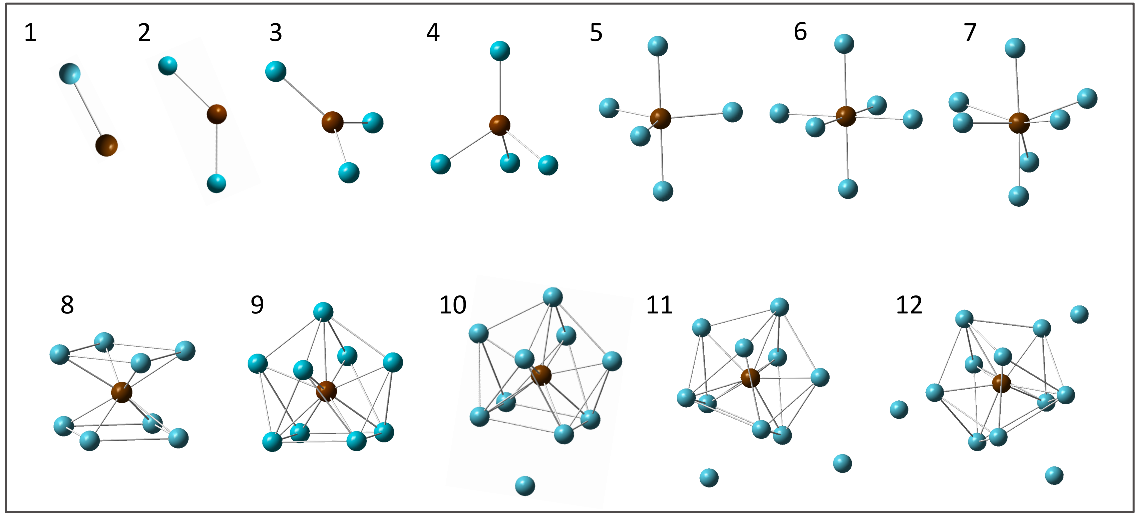
Mobility and Clustering of Barium Ions and Dications in High Pressure Xenon Gas

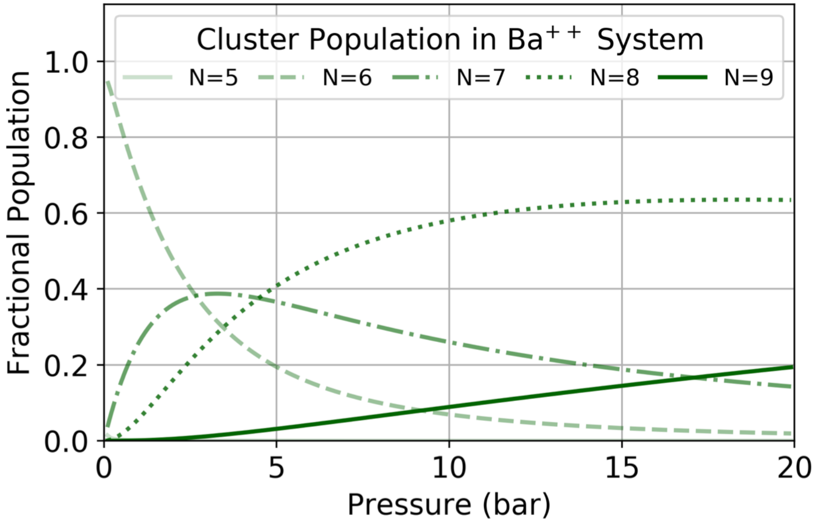
Phys.Rev. A97 (2018) no.6, 062509

FOR BA++ THE CLUSTERS ARE BIGGER:



Calculated Ba++ clusters:

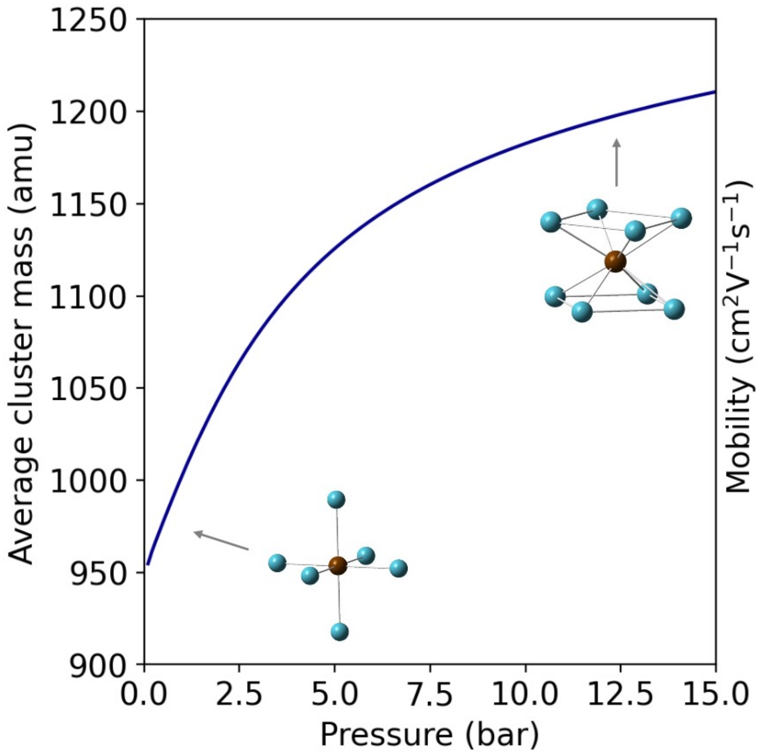


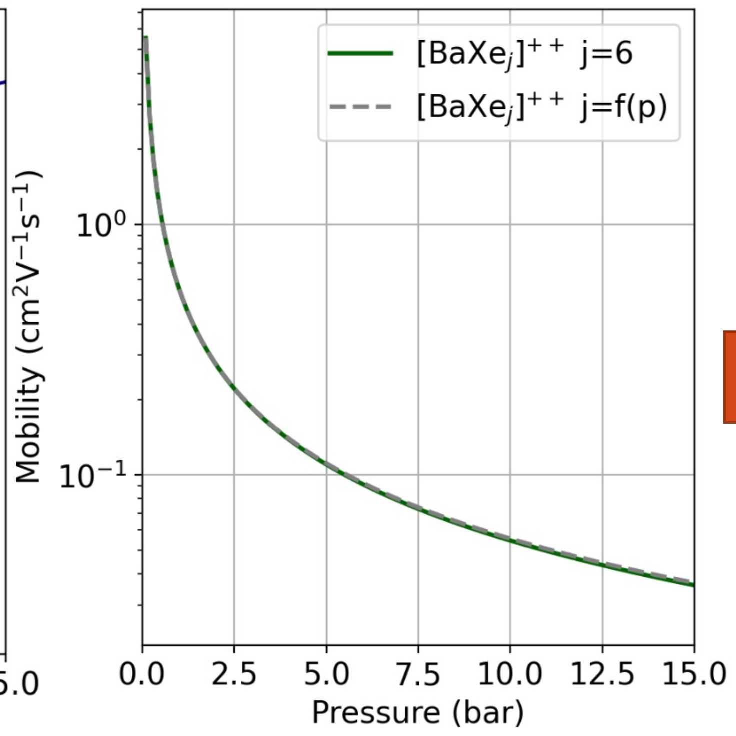


Bigger clusters more similar to each other, so less pressure dependence in Ba++ than Ba+.

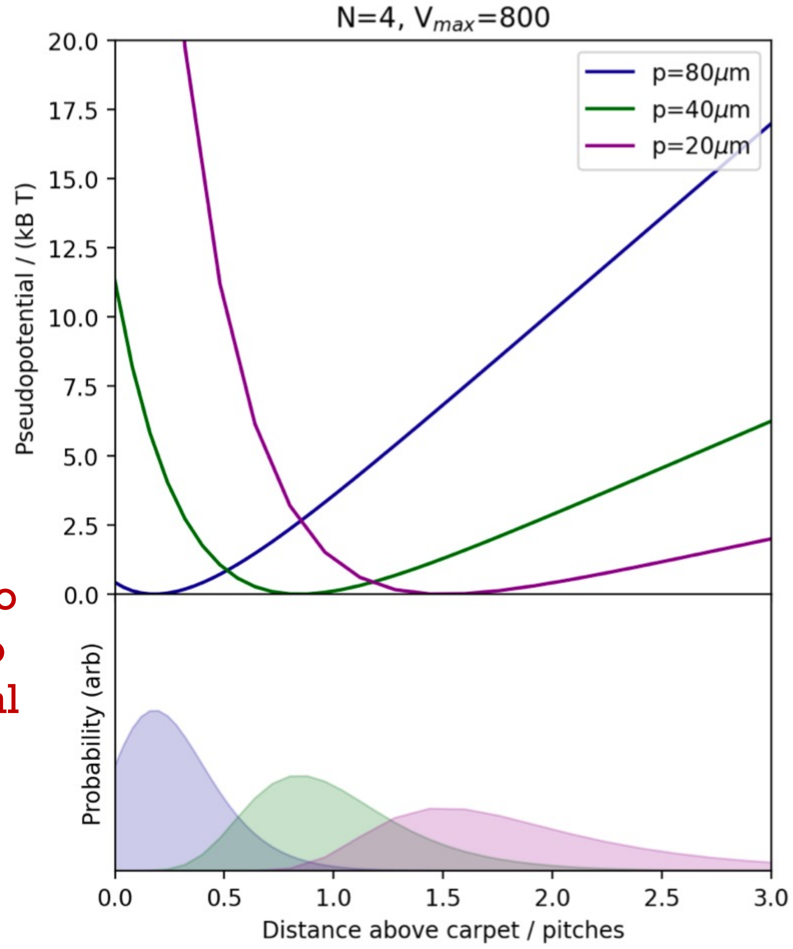
ION DRIFT MICROPHYSICS FOR QUANTITATIVE PREDICTIONS

- Putting it all to use in xenon at high pressures involves some non-trivial calculations to obtain molecular ion masses and mobilities that determine the RF carpet dynamics.

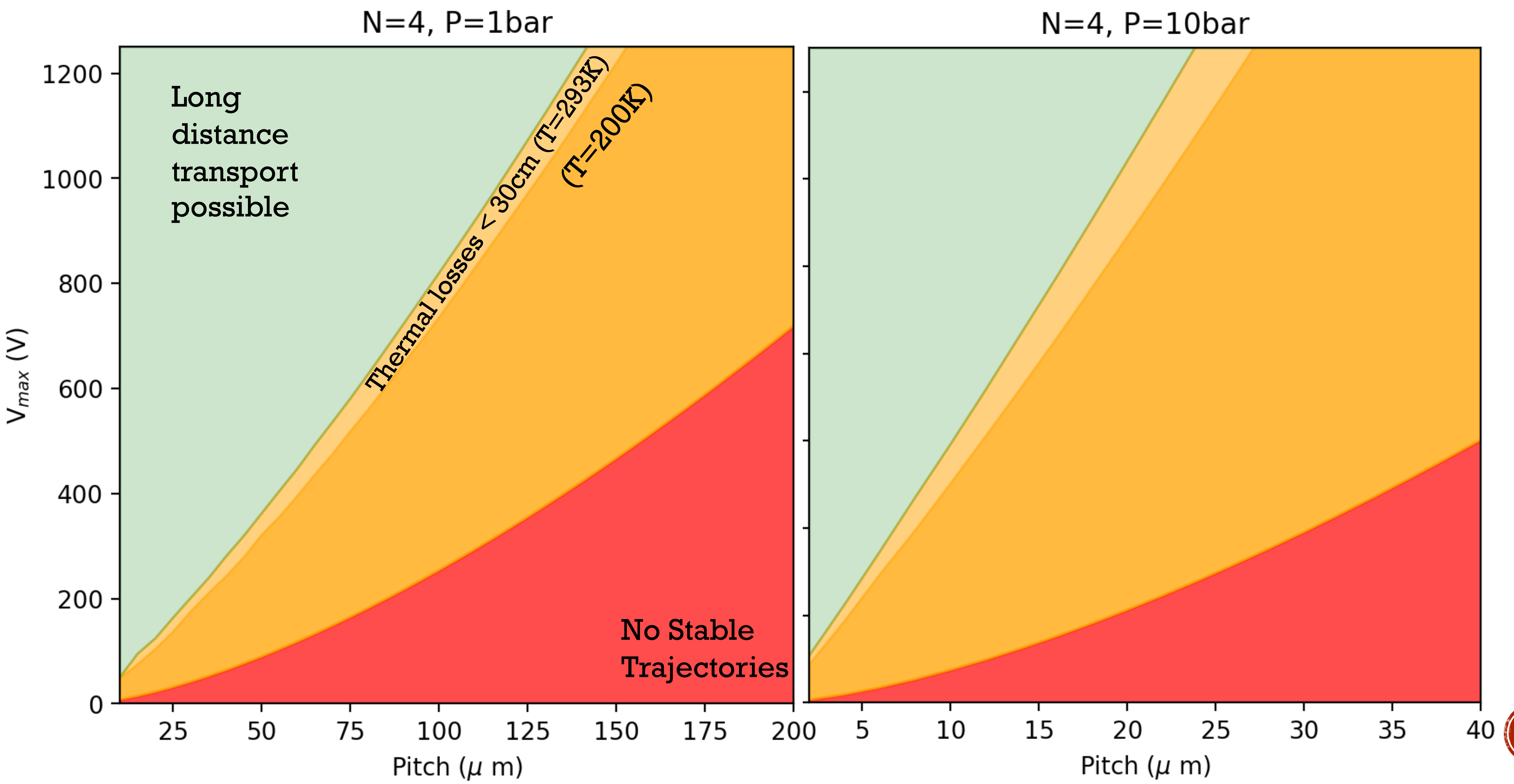




Inputs to pseudo potential

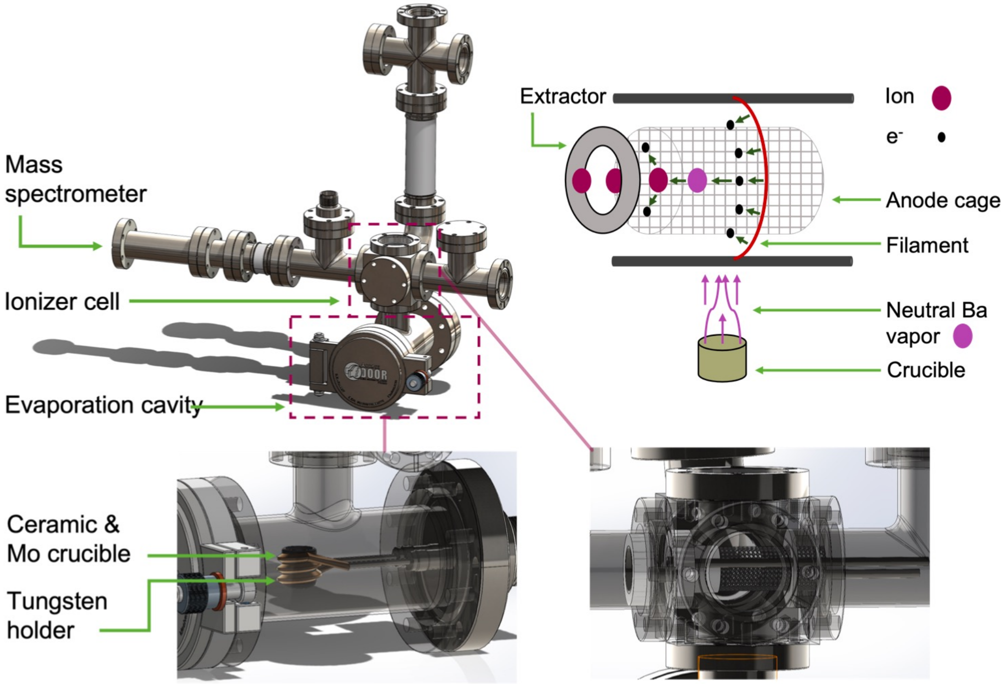


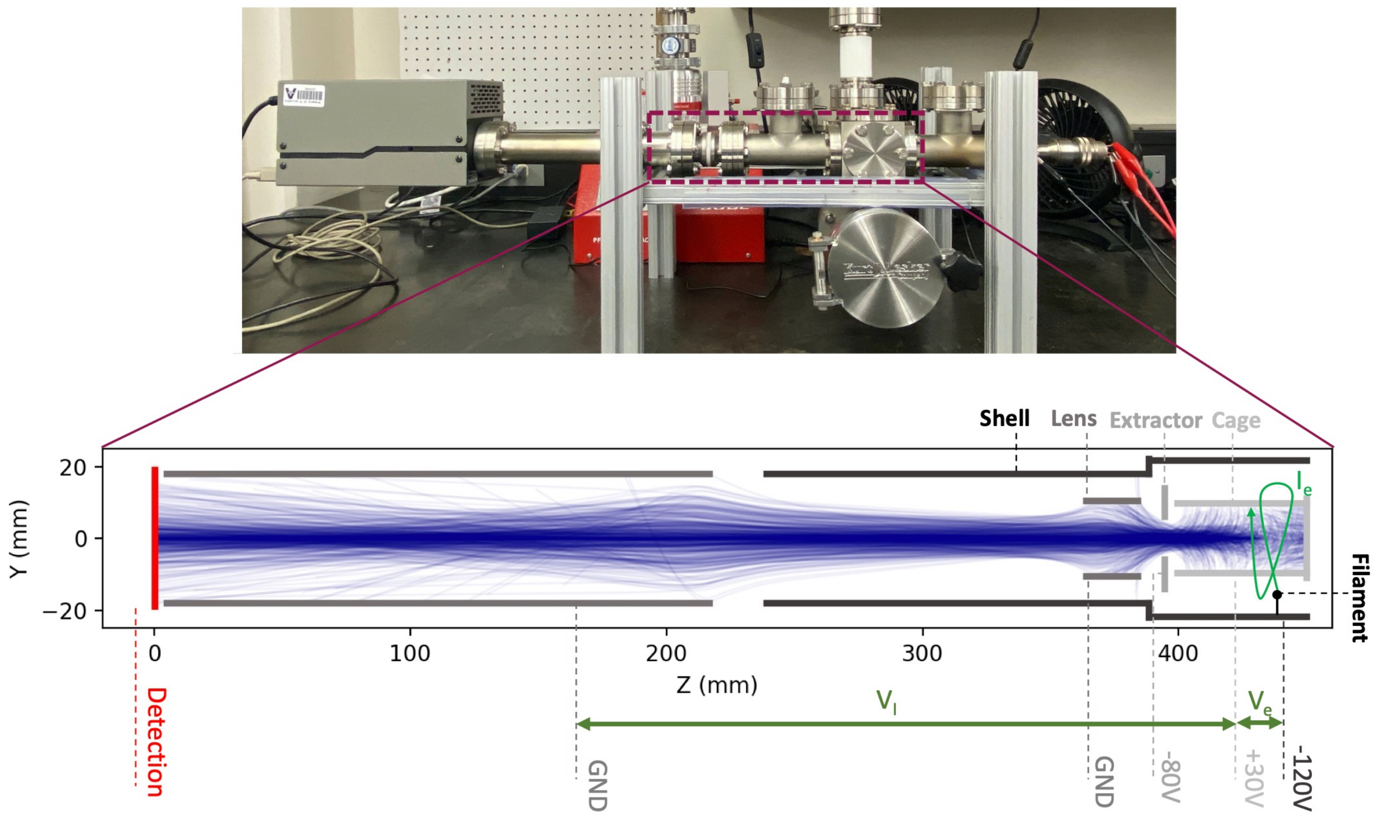
PREDICTED KINETIC LOSS RATES



EXPERIMENTAL TESTS

- We are preparing experimental tests of these predictions at UTA. We have a home-brewed Ba^{2+} source.



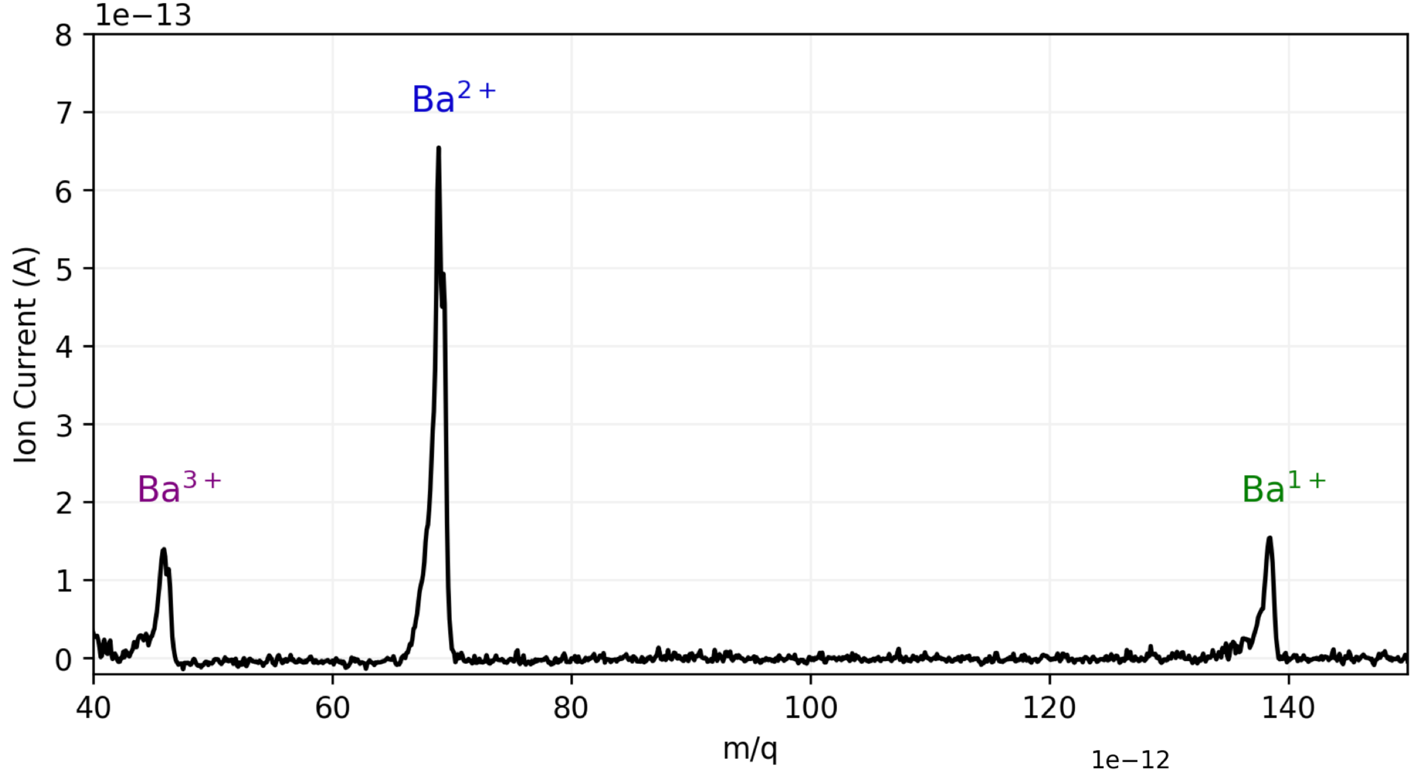


Developed a benchtop ion beam system based on vaporization followed by multiple impact ionization to breed Ba^{2+}.

(We can also do 1+ ions using aluminosilicate sources.)

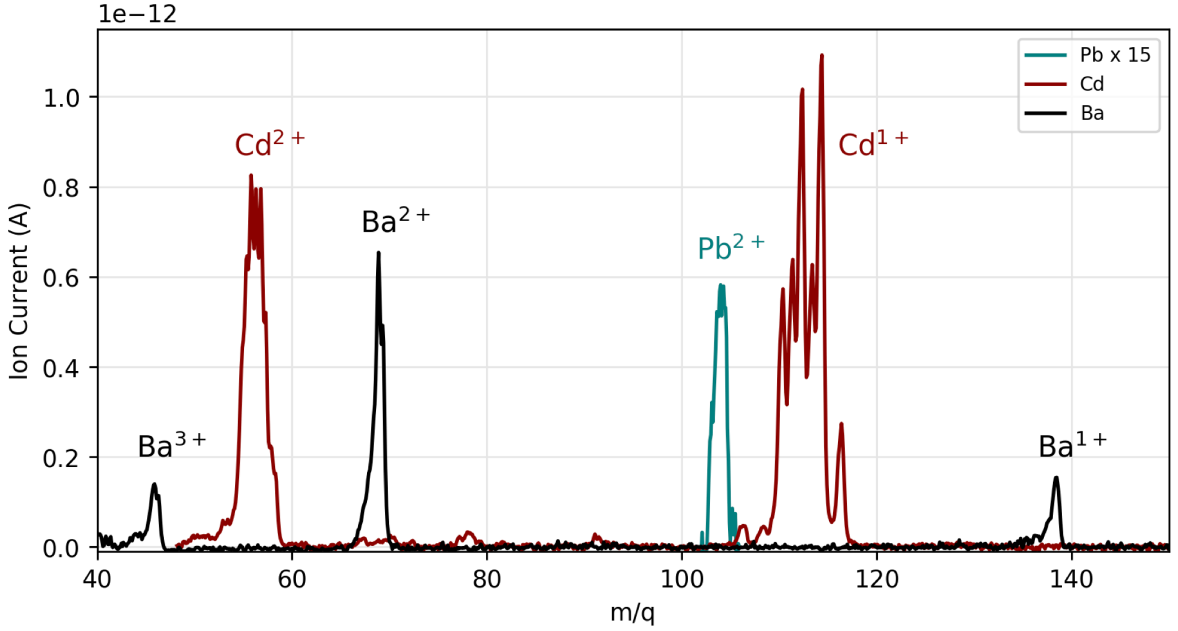
A Compact Dication Source for Ba2+ Tagging and Heavy Metal Ion Sensor Development

arXiv:2303.01522



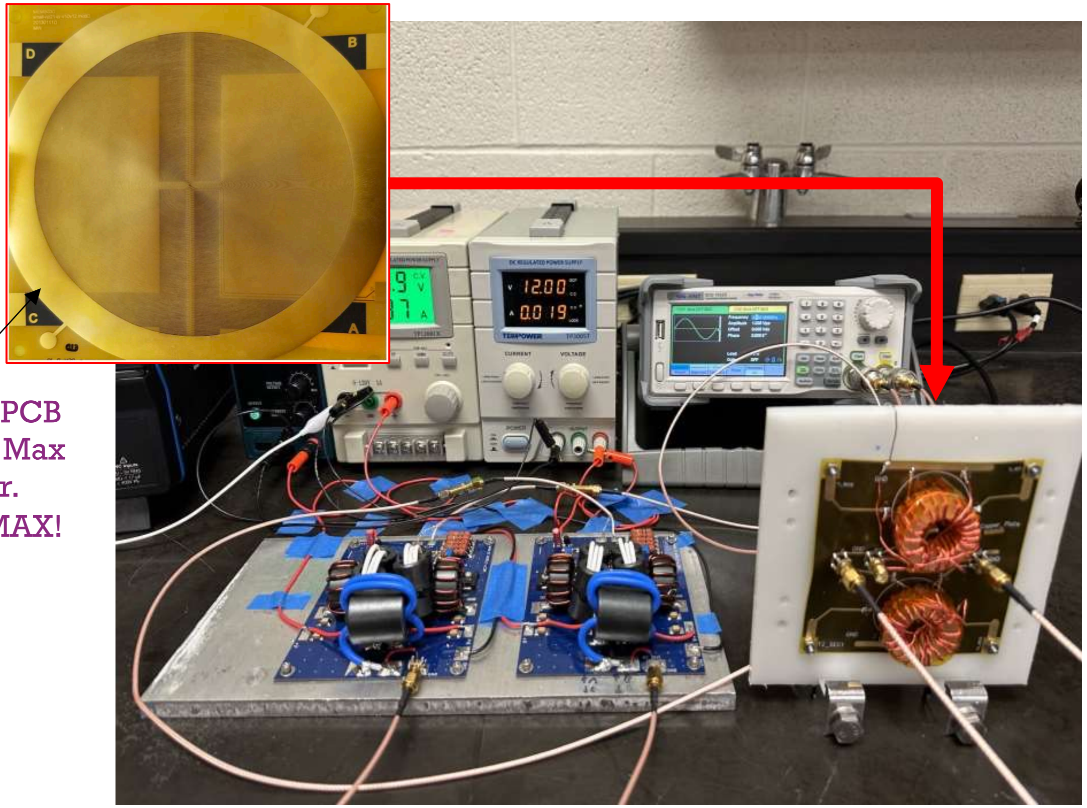
← Ba1+, 2+,3+,4+ all tune-ably accessible

Also producing other gas-phase metal ions (Pb2+, Cd2+, etc), for environmental assay applications →



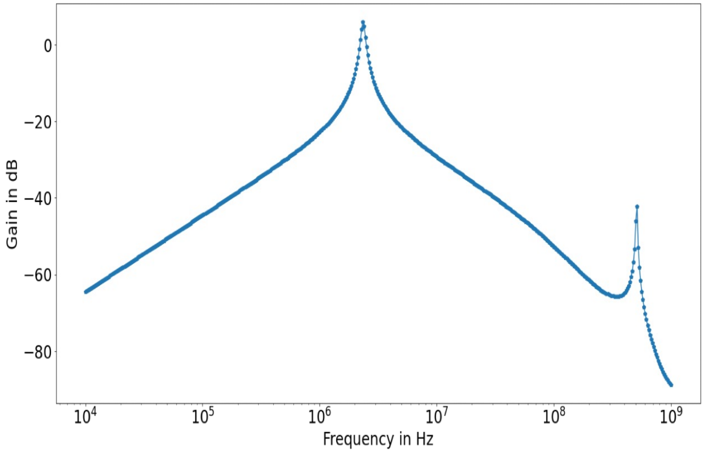
RF CARPET DRIVE SYSTEM

- We are using an N=4 phased approach (no DC sweep or surfing wave)
- MHz broadband amplifiers fed by 90 degree-shifted signals from a signal generator.
- RF amplifier is coupled to carpet through 2x center-tapped transformers.
- Transformer windings are tuned for impedance matching.
- Frequency on RF resonance at ~2MHz.
- No ions flying yet, but **soon**!!

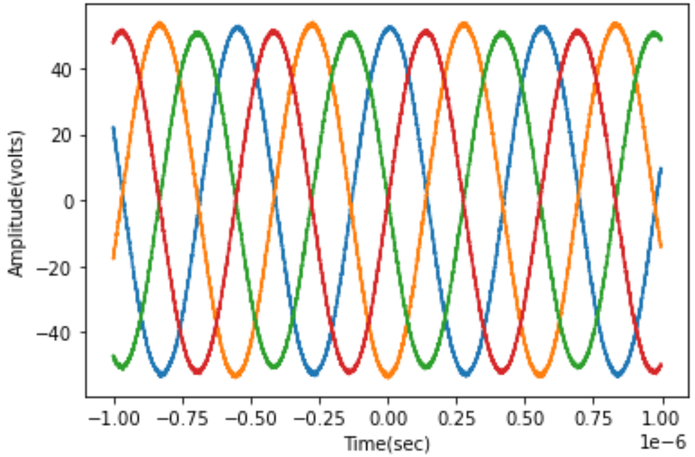


RF carpet PCB loaned by Max Brodeur. THANKS MAX!

Few MHz "sweet spot"

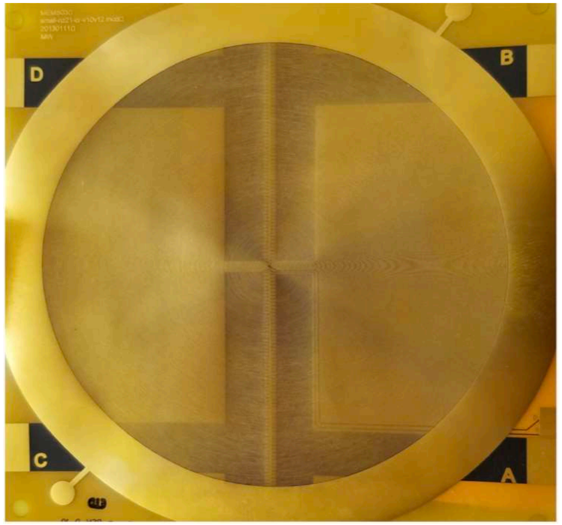


4-phases with equal amp

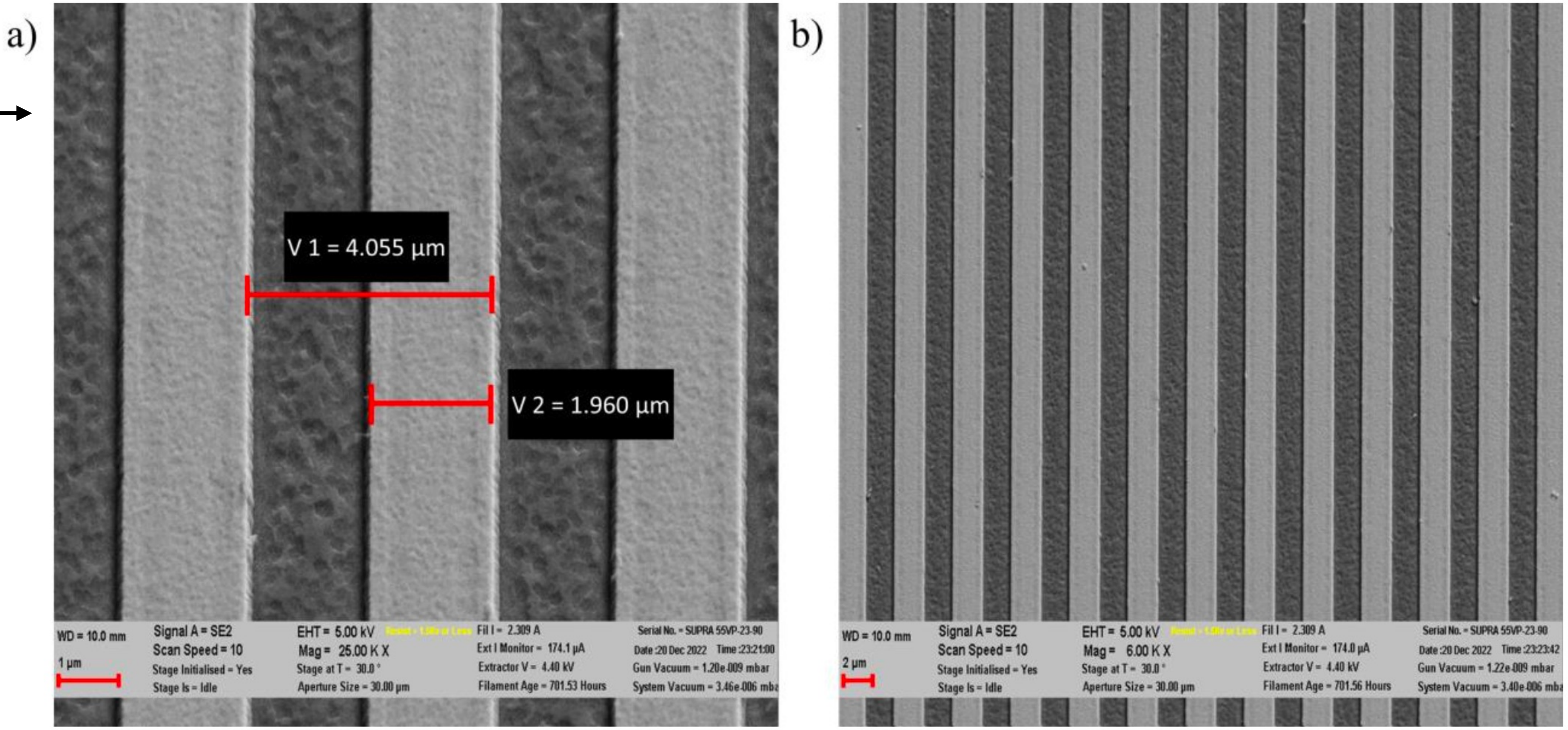


THERE'S PLENTY OF ROOM (AND NECESSITY) AT THE BOTTOM…

- The carpet we are borrowing from Maxime has 160 um pitch, predicted to top out a bit under 1 bar in Xe.



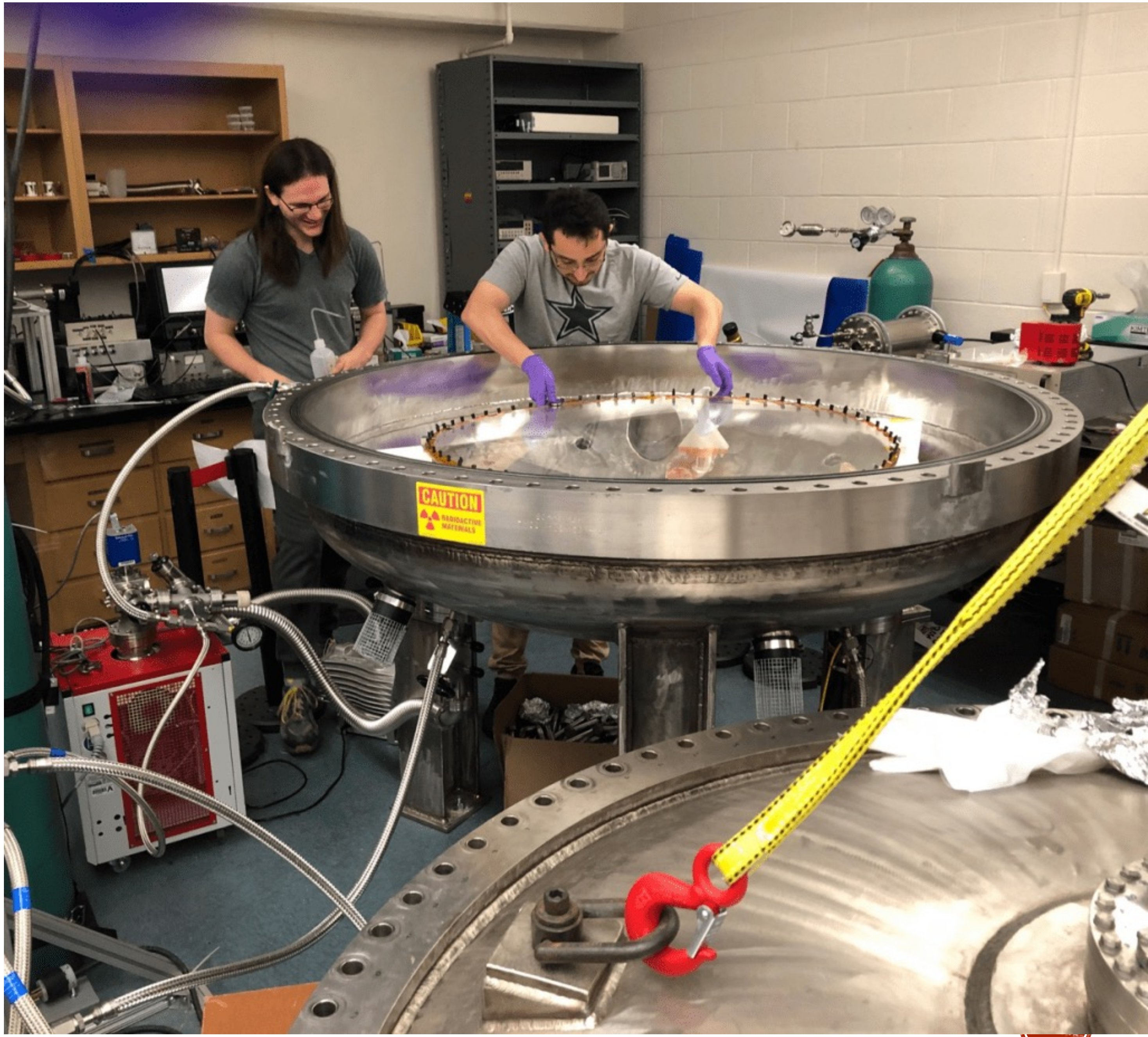
- Photo shows SEM of device made at UTA Nanofab.
- Electrode pitch few μm achieved, with very high quality edges.
- Plan to wire-bond between subarrays for N-phases (distance limit of this not yet clear).
- We think we can do this at 10cm scale in house.
- If so, several bar operation *should* be possible.



Credit: Vivek Khichar, UTA

LARGE TEST SYSTEM

- Available 1.2 m diameter test system with gas circulation and purification.
- Thermionic source can be actuated with internal robotic arm to any theta/phi.
- When we eventually get there, we are set up to test big carpets…
- We also welcome collaborators if anyone is interested to use this system for RFC work!



CONCLUSIONS

- Single ion sensors based on SMFI with novel organic fluorophores demonstrated that can image single Ba^{2+} ions over 1mm^2 surface areas.
- Concentrating ions onto sensors remains a difficult / unsolved problem.
- High pressure RF carpets look hard, but may be a viable solution for large surface sensitization.
- We have extended prior calculational techniques to apply them to high density media where losses are dominated by Brownian terms.
- We are ramping up an experimental program to test these models and explore the prospects of high pressure RF carpet operation for 0nubb.