UNIVERSITY OF TEXAS ARLINGTON

Development of Barium Tagging:

A Background Free Method to Search for Majorana Neutrinos

Austin D McDonald
Department of Physics

Supported by

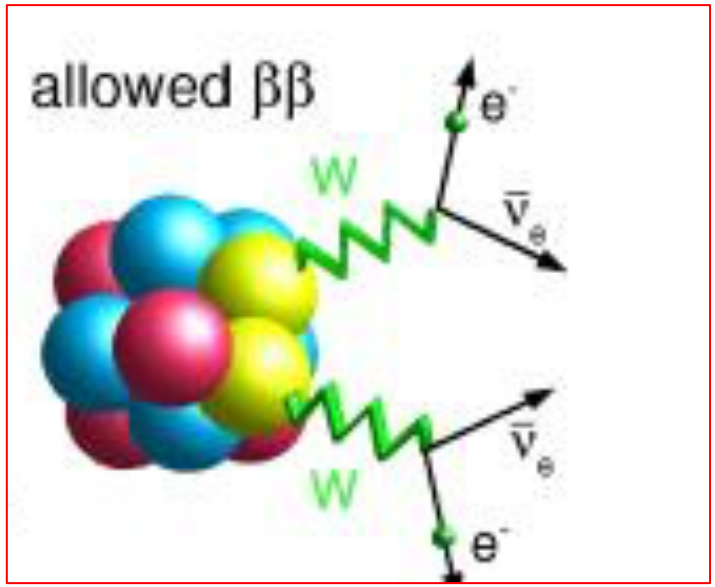
U.S. DEPARTMENT OF ENERGY | Office of Science

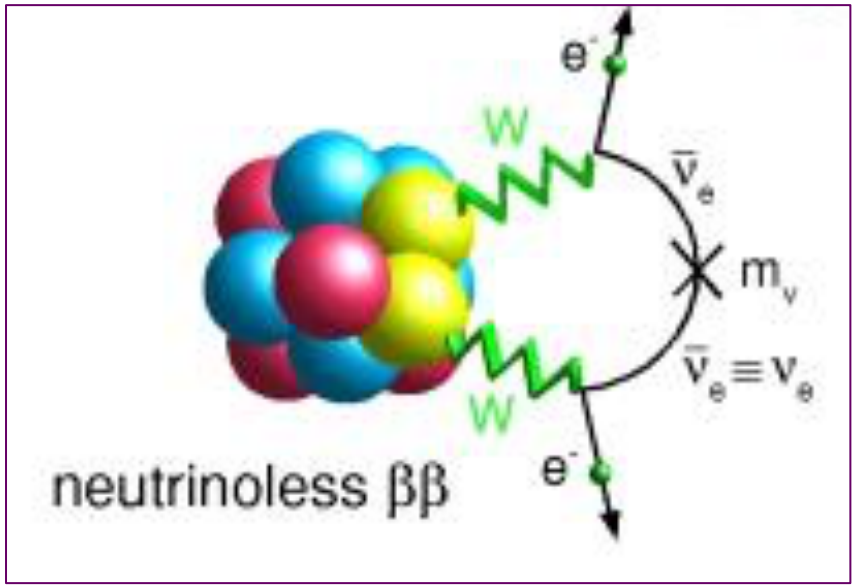
Neutrino-less?

$$T_{\frac{1}{2}} \approx 10^{19-21}\, yrs.$$

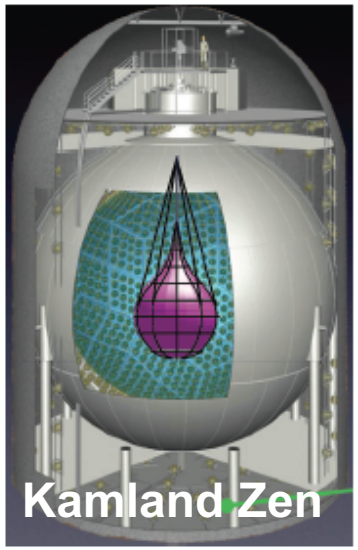
$$\frac{1}{T_{\frac{1}{2}}} = G \times \|\mathbf{M}\|^2 \times m_{\bar{\nu}}{}^2$$

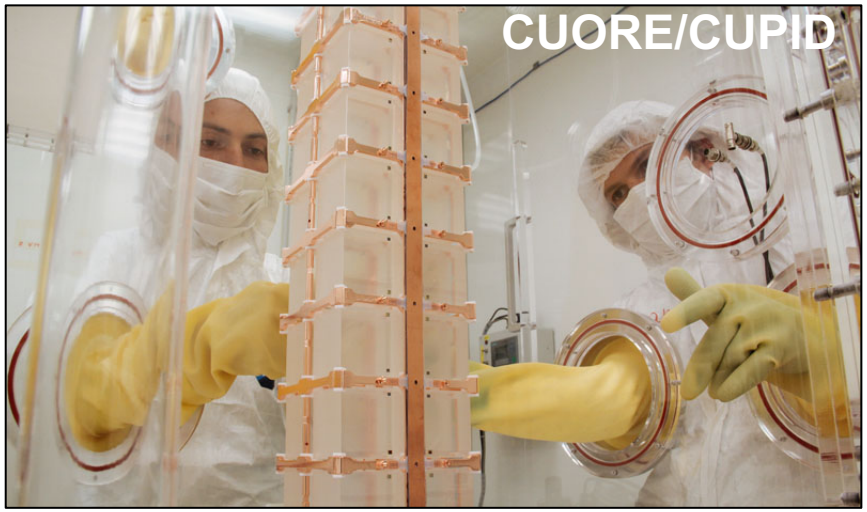
$$T_{1/2}^{0\nu} > 10^{26}$$

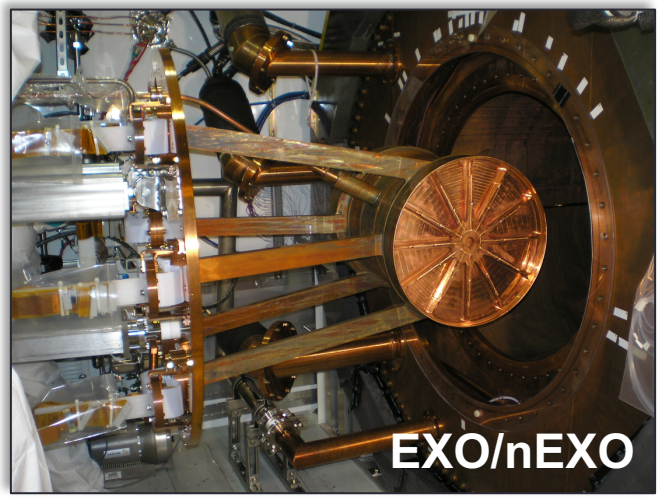




Neutrinoless Double Beta Decay Searches







Various technologies
Various isotopes
Various challenges
Same goal

Quite an impressive number of developments!

The NEXT Program

- **Sequence of HPGXe TPCs, focused on achieving big, very low background xenon 0νββ detector**

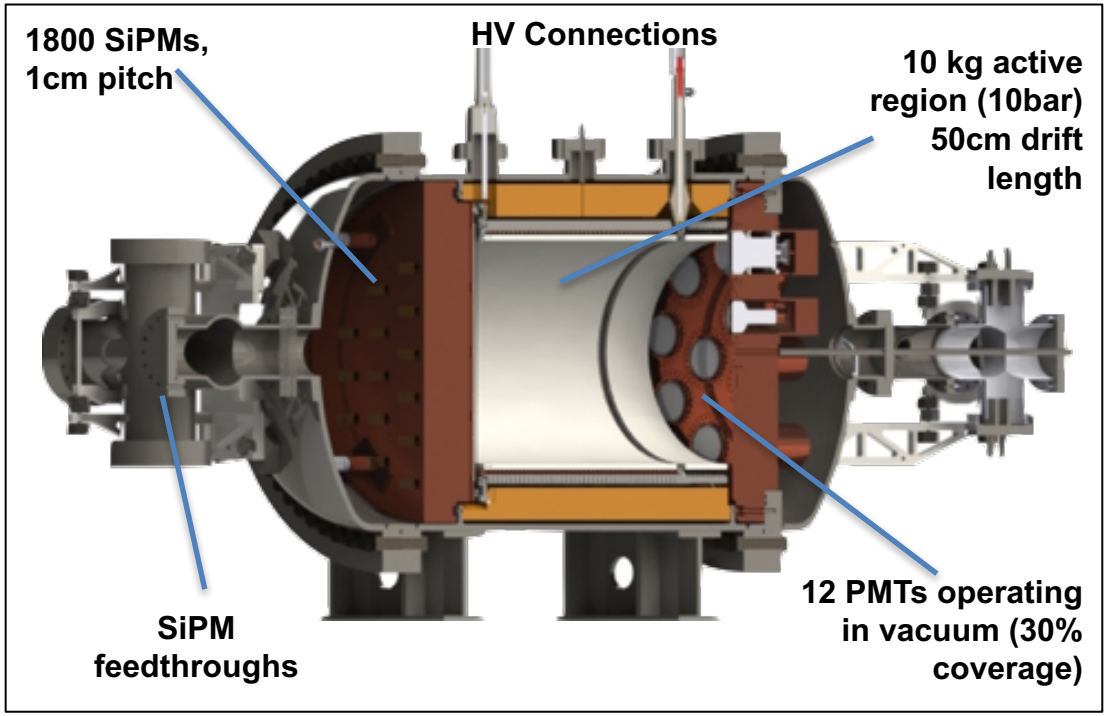
→ NEXT-DBDM
(Berkeley, US)

→ NEXT-DEMO
(Valencia, Spain)

→ **NEXT-White**
(Canfranc, Spain)

→ NEXT-100
(Canfranc, Spain)

→ NEXT-Ton
???



NEXT-White operating now
Full underground technology demonstrator @10kg scale

The NEXT Program

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→ NEXT-100
(Canfranc, Spain)

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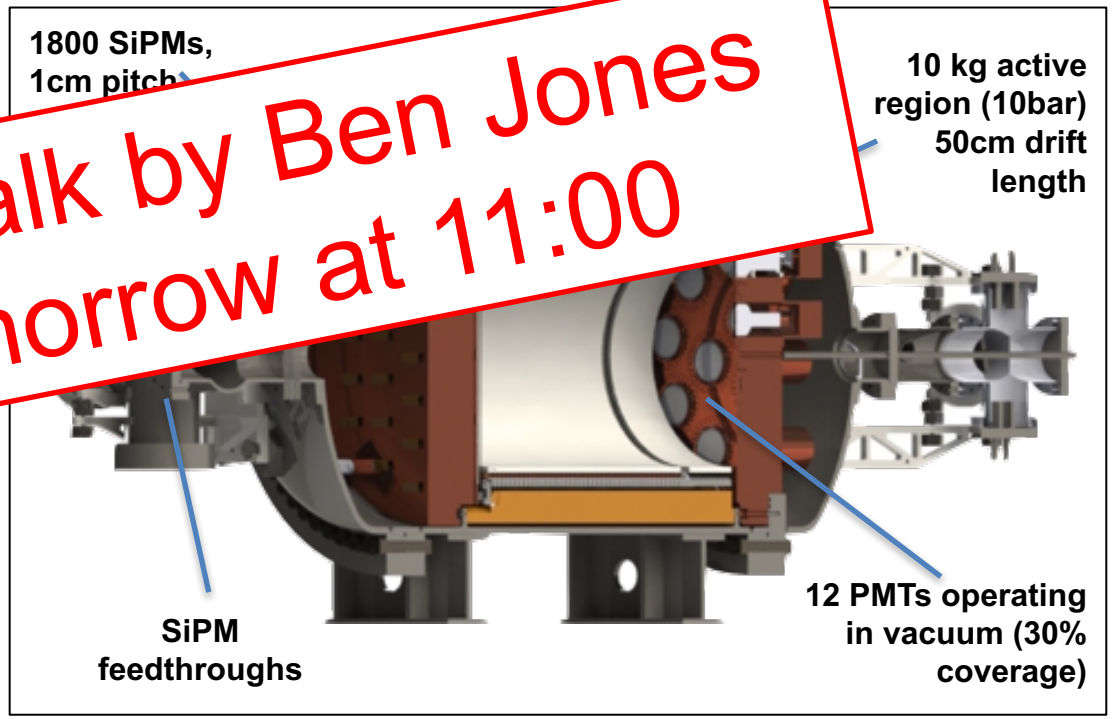
???

See Talk by Ben Jones Tomorrow at 11:00



NEXT-White operating now
Full underground technology demonstrator @10kg scale

- **Obtaining background indices in the tens of counts/(ROI Ton yr) is a tremendous feat of detector radio-purity, development, and design.**

- **However reaching a new scale of background [0.1->0.01 counts/(ROI Ton yr)] will likely require a non-traditional solution**

Daughter Identification

Xenon double beta decays into barium

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

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

Identifying the daughter atom unambiguously proves the event was xenon double beta decay

Coupled with energy resolution better than 2% FWHM would be able to provide a background free ROI

"Barium tagging" has been discussed since 1991

Moe, M. K. "Detection of neutrinoless double-beta decay." Physical Review C 44.3 (1991): R931.

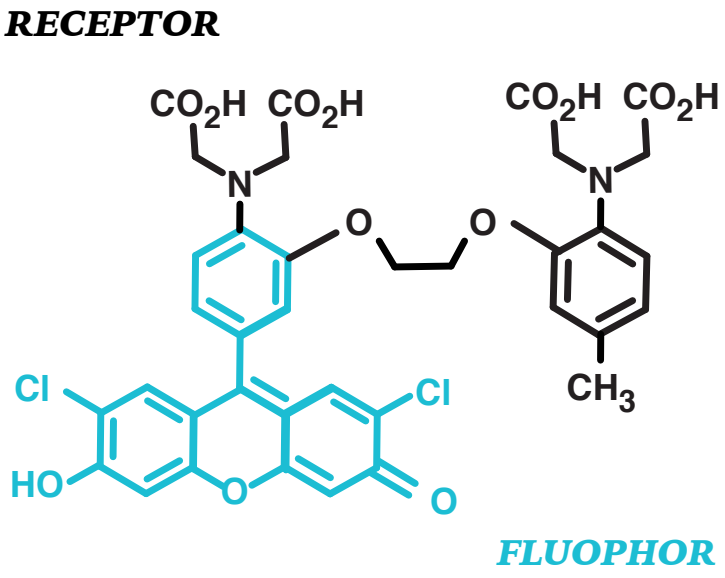
Adapting Single Molecule Imaging to work in high pressure xenon gas may be a solution.

Nygren, David R. "Detection of the barium daughter in 136Xe→ 136Ba+ 2e− by in situ single-molecule fluorescence imaging." NIM:A 824 (2016): 2-5.

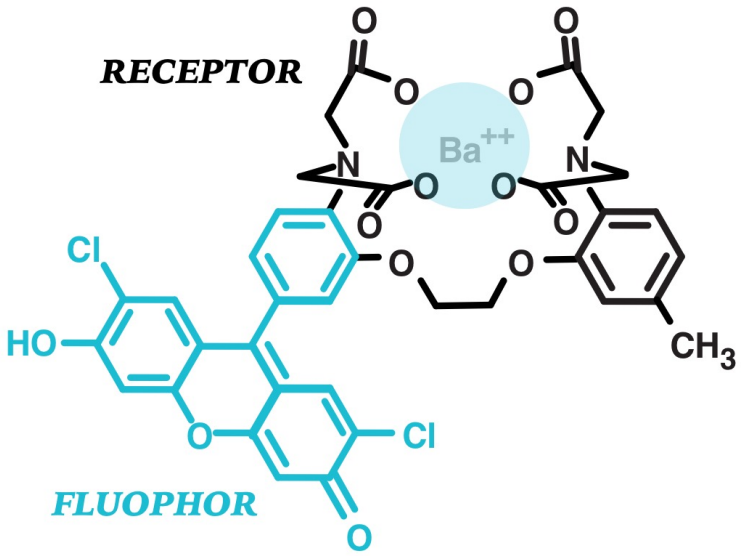
Single Molecule Imaging

Molecules become fluorescent after capturing Ba++

Non-fluorescent

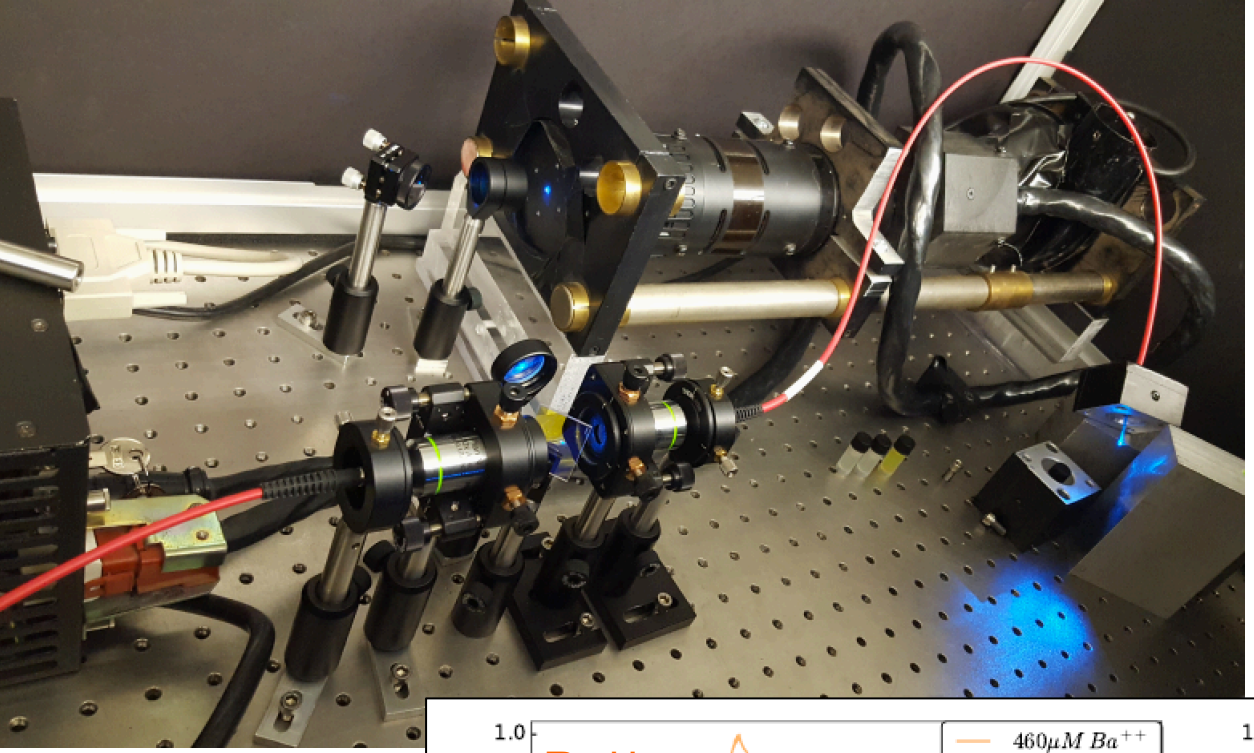


Fluorescent



Test commercial molecules for a fluorescence response when in the presence of barium.

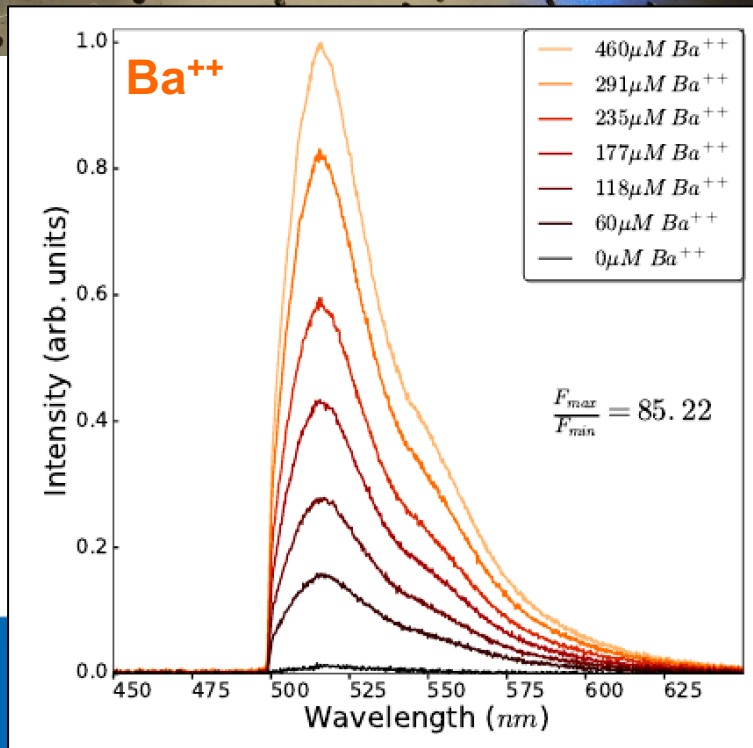
Various molecules exist for fluorescence detection

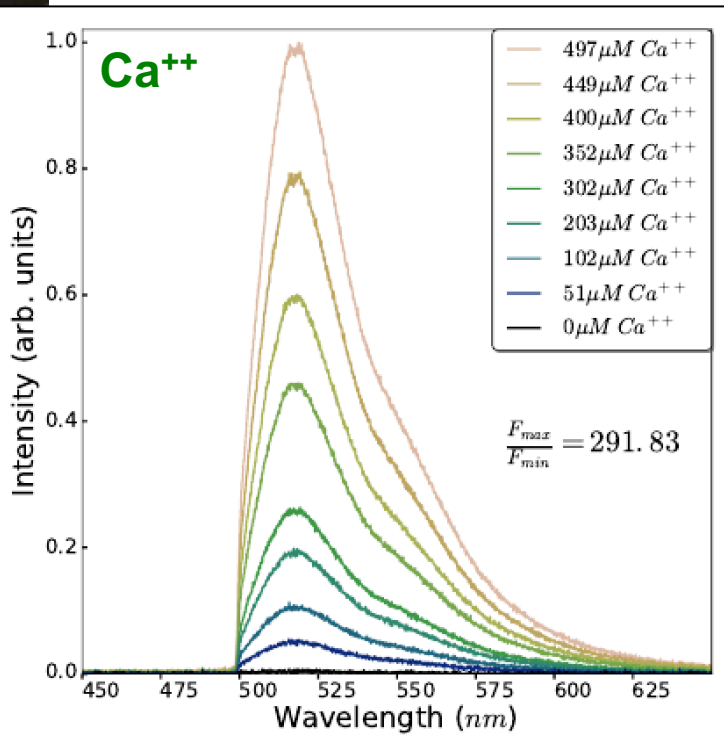


← First dabbling - developed a bespoke fluorescence sensor to study barium production at the end of a fiber.

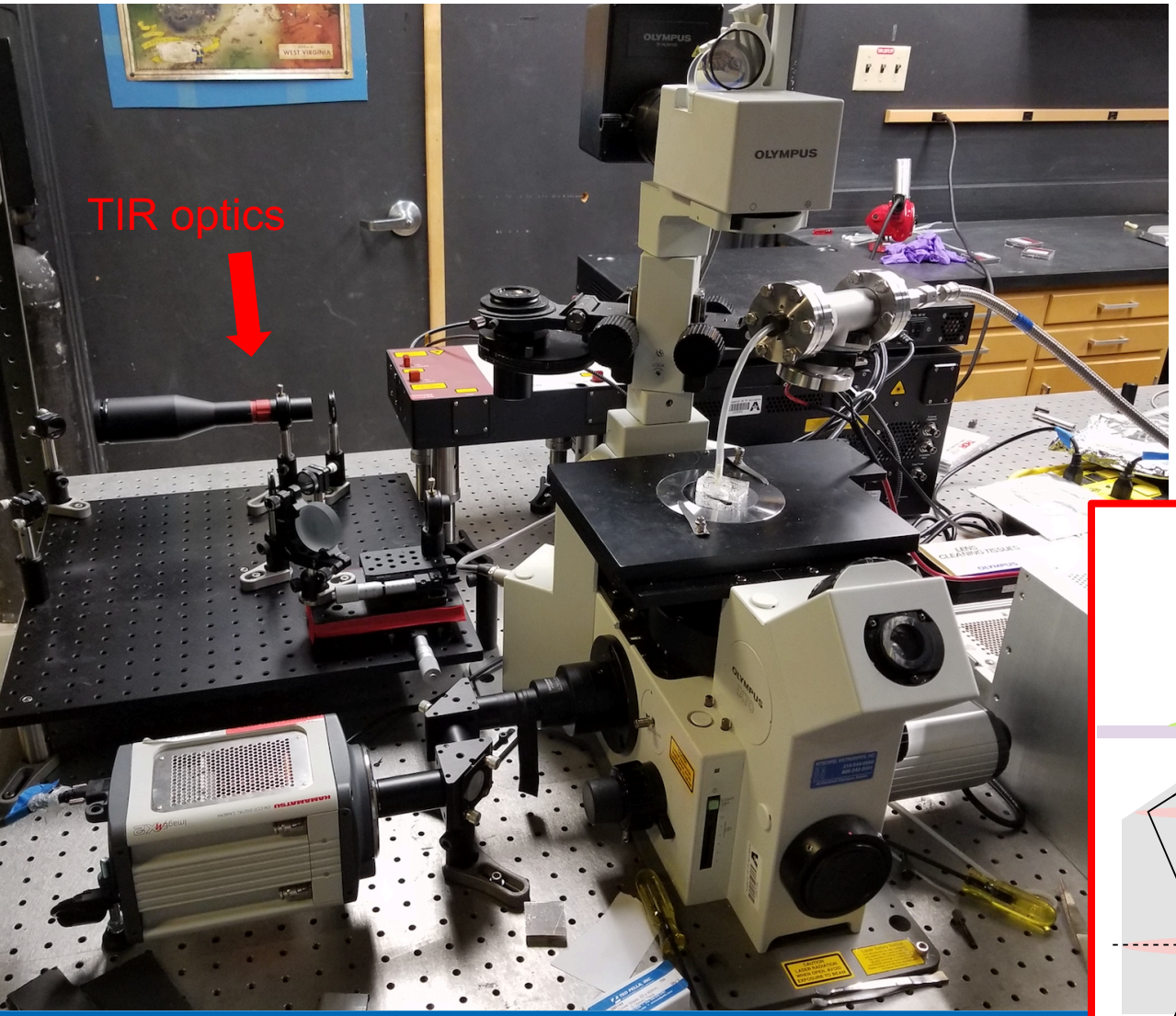
Single molecule fluorescence imaging as a technique for barium tagging in neutrinoless double beta decay
Jones, McDonald, Nygren, JINST (2016) 11 P12011

We find strong fluorescence from Fluo3 and Fluo4 under chelation with Ba^{++} ions →

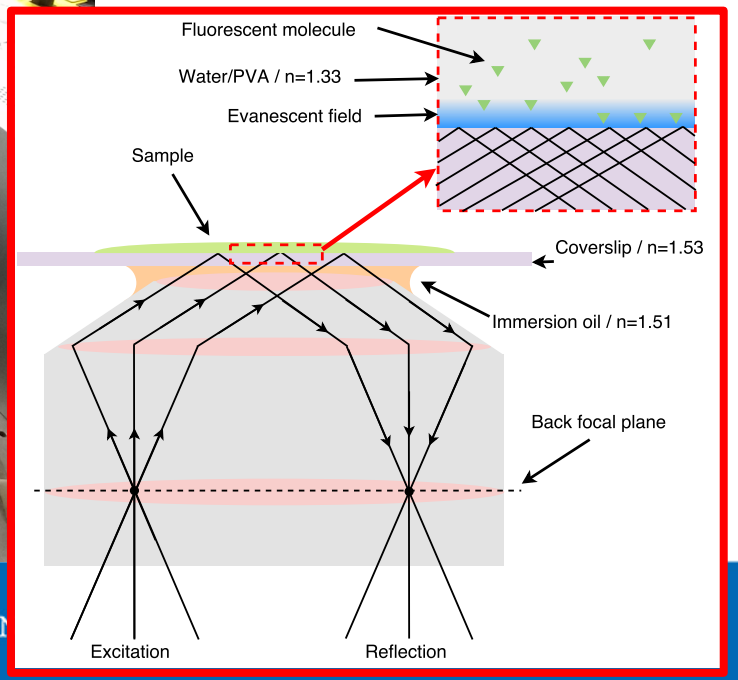


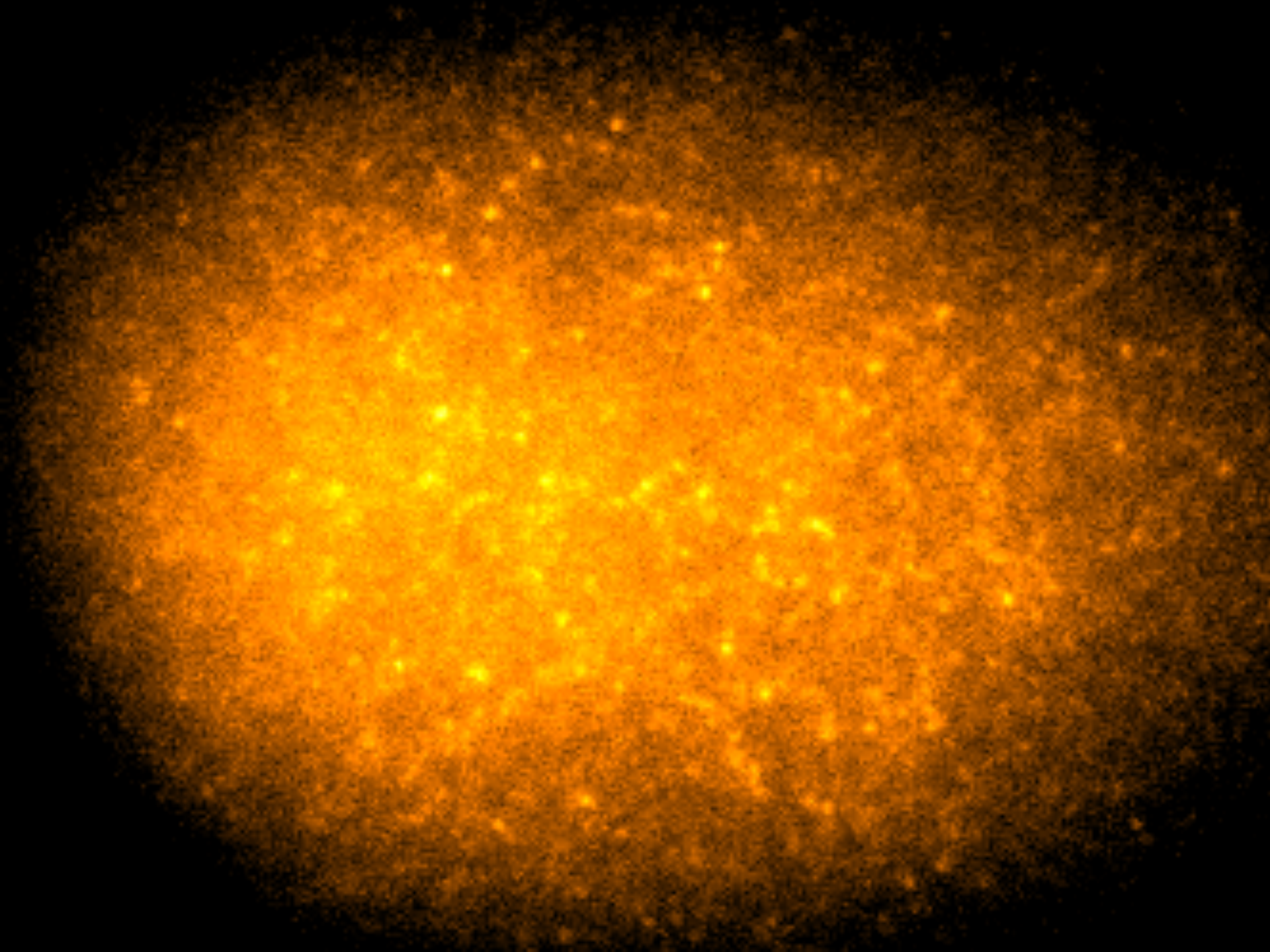


TIRF [Training wheels]



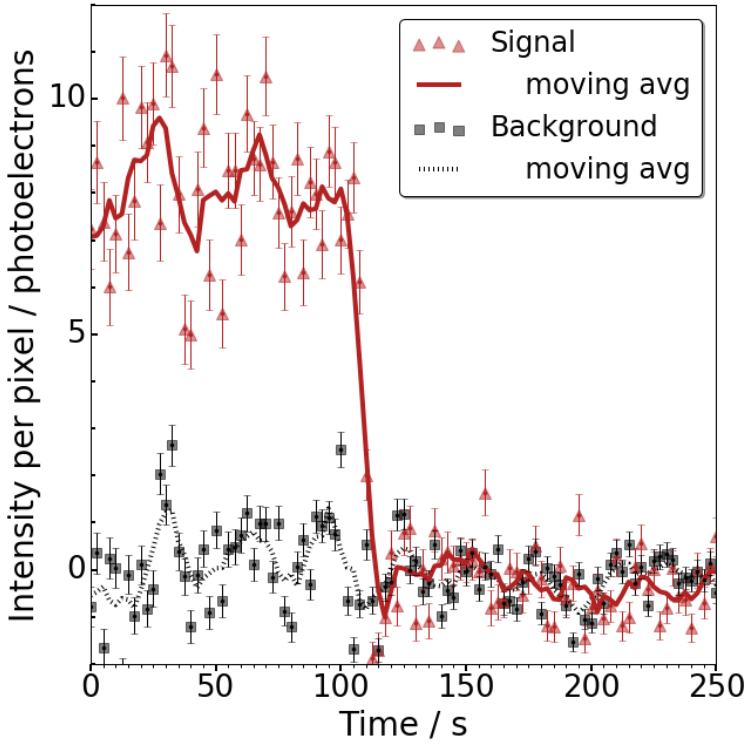
Olympus IX-70 with total internal reflection optical setup and a Hamamatsu imagEM X2 Electron Multiplying-CCD camera and supercontinuum laser

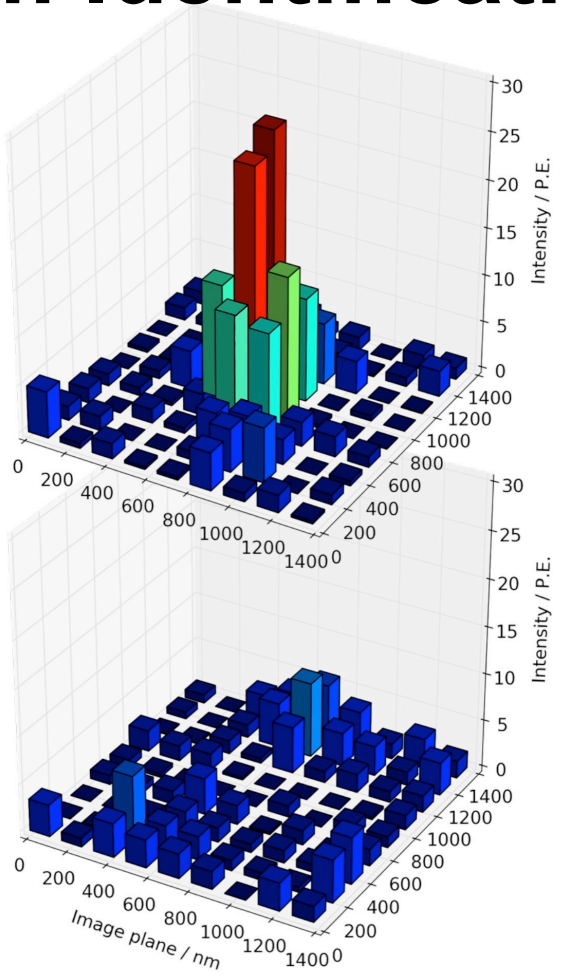




Single Barium Identification

Single step photo-bleaching confirms single molecule



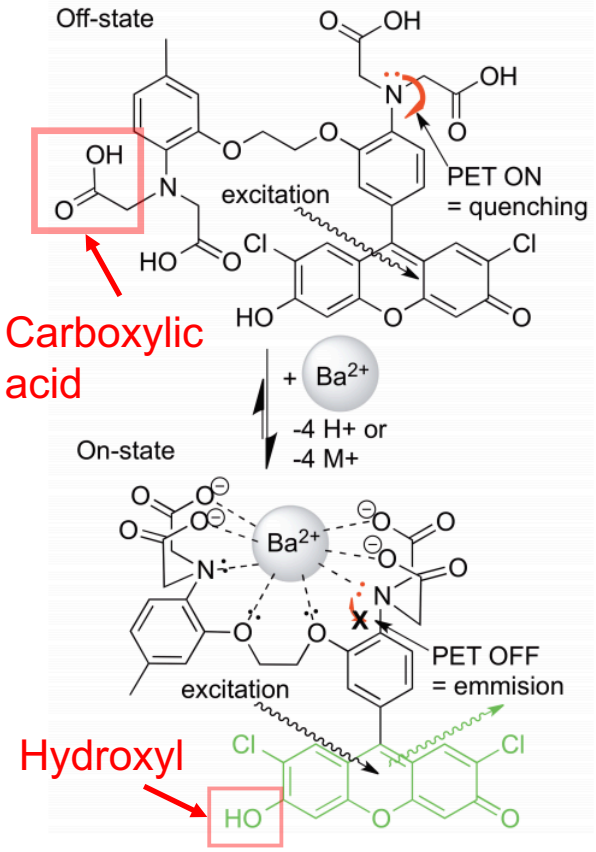


One second exposure before and after bleaching

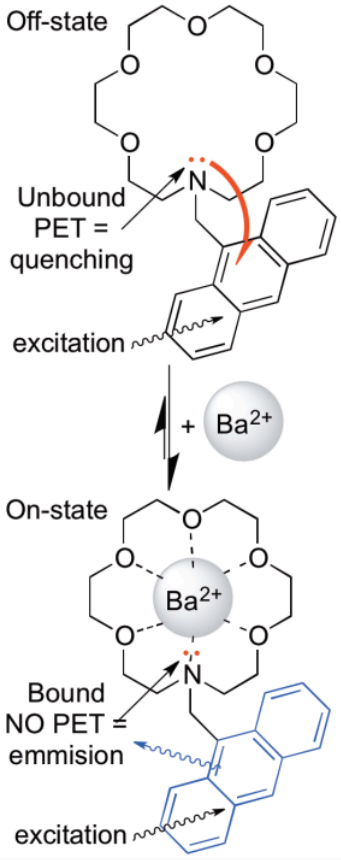
McDonald, A. D., et al. "Demonstration of Single-Barium-Ion Sensitivity for Neutrinoless Double-Beta Decay Using Single-Molecule Fluorescence Imaging." Physical review letters 120.13 (2018): 132504.

Custom Molecules

Fluo-3



18c6-an

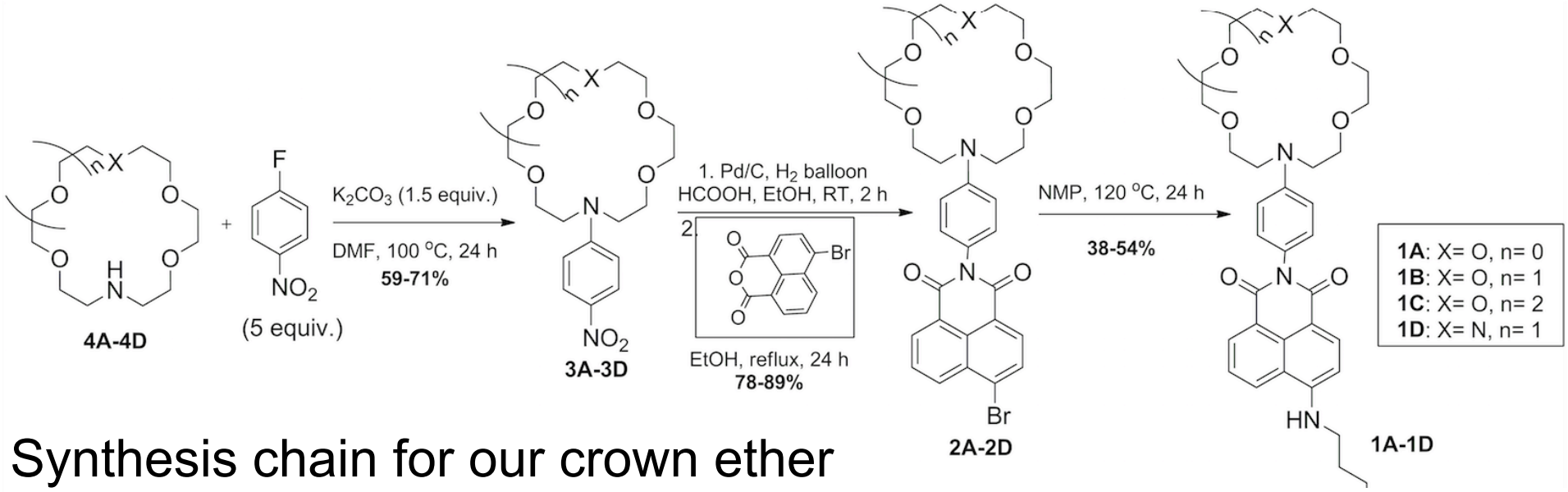


Fluo-3 relies on protonation for proper function of dye and receptor.

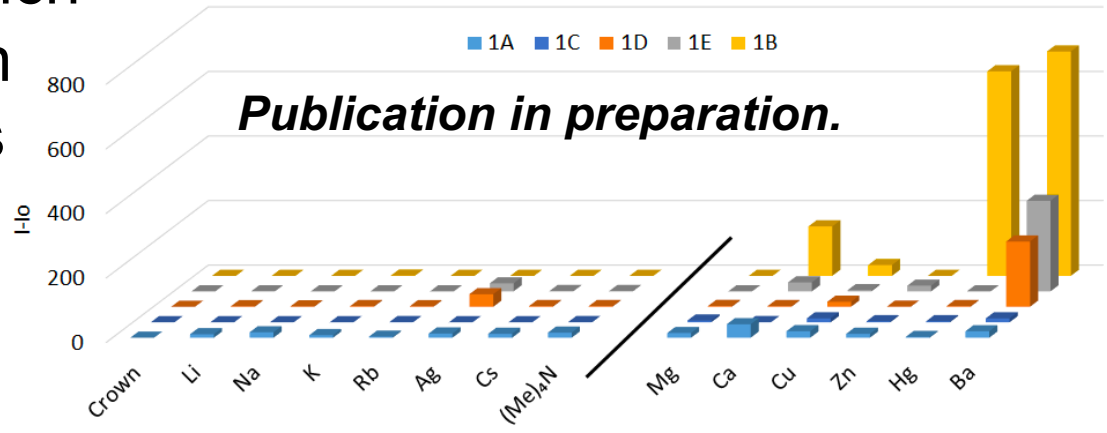
Developed custom molecules based on crown ethers that do not require protonation and as a result have robust dry state fluorescence.

Thapa, P., *et al.* Barium Chemosensors with Dry-Phase Fluorescence for Neutrinoless Double Beta Decay. *Sci Rep* **9,** 15097 (2019) doi:10.1038/s41598-019-49283-x

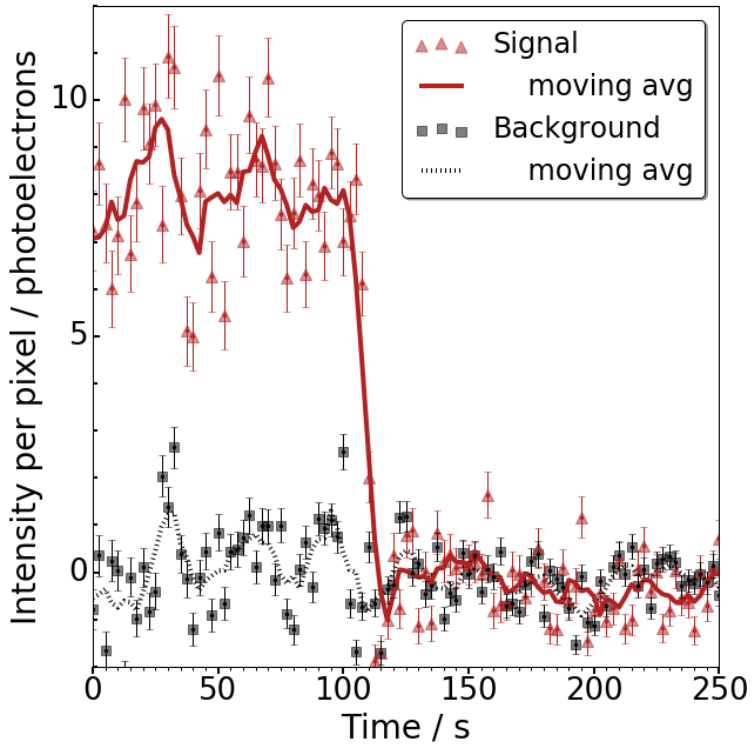
Development of Custom Molecules

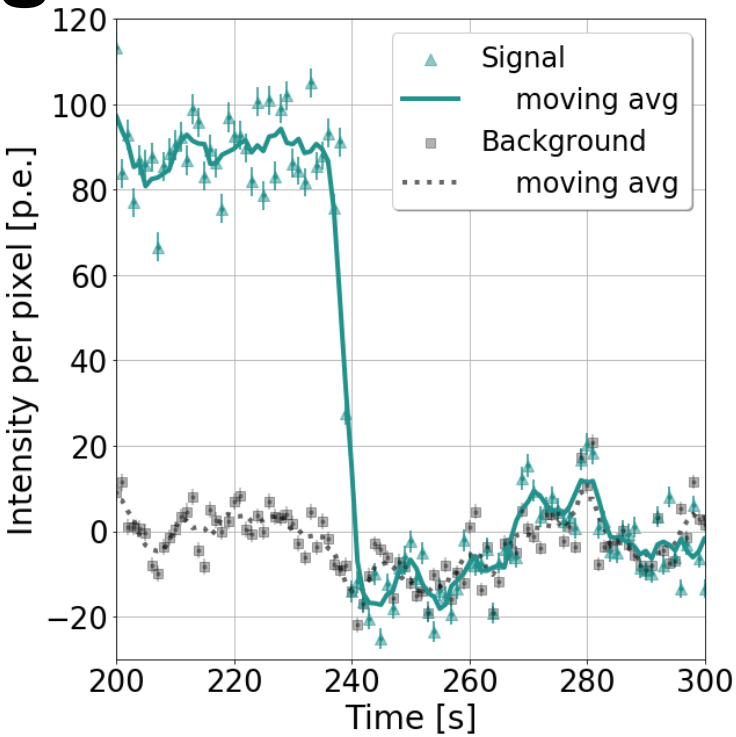


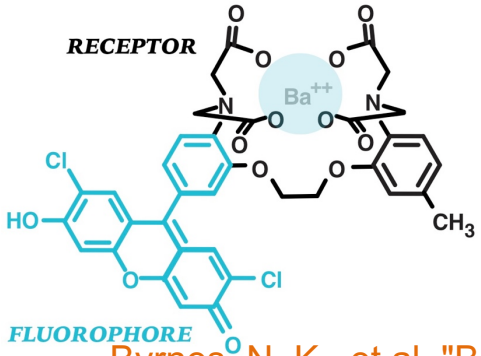
Synthesis chain for our crown ether naphthalimide molecule which has excitation and emission in the visible range and has robust **dry state fluorescence and is highly selective to barium!**



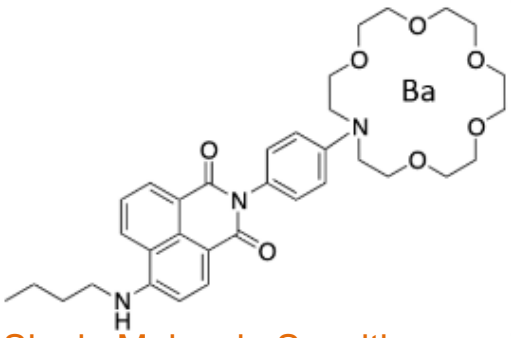
Molecule upgrade





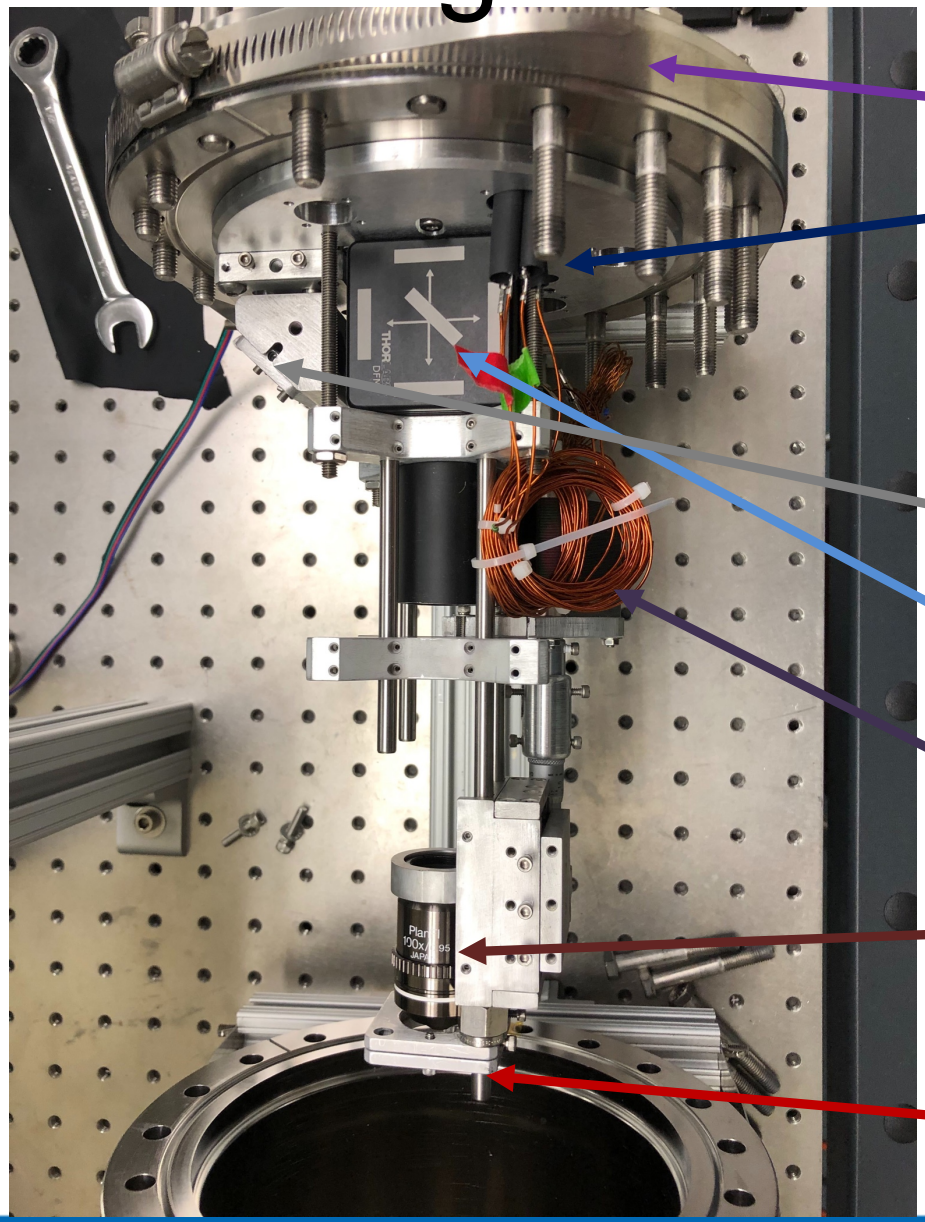


The new molecule is an order of magnitude brighter!



Byrnes, N. K., et al. "Barium Tagging with Selective, Dry-Functional, Single Molecule Sensitive On-Off Fluorophores for the NEXT Experiment." *arXiv preprint arXiv:1909.04677* (2019).

Taking off the Training Wheels



8” CF flange

Pressure-rated 10pin feedthrough

Sapphire optical windows (EM & EX) (hidden)

Internal 90-degree mirror

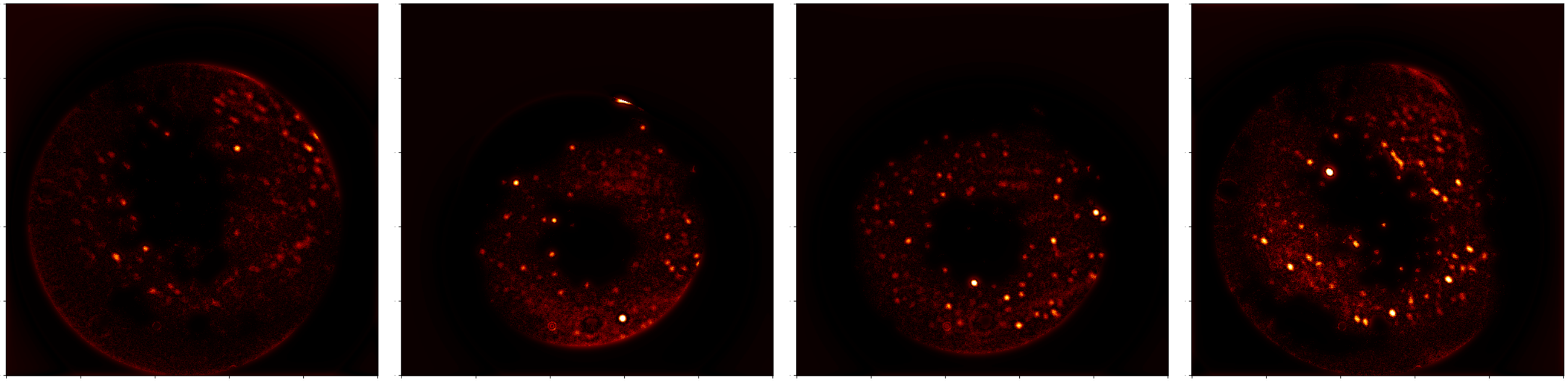
Fluorescence cube with filters

Vacuum stepper motor + micrometer screw stage

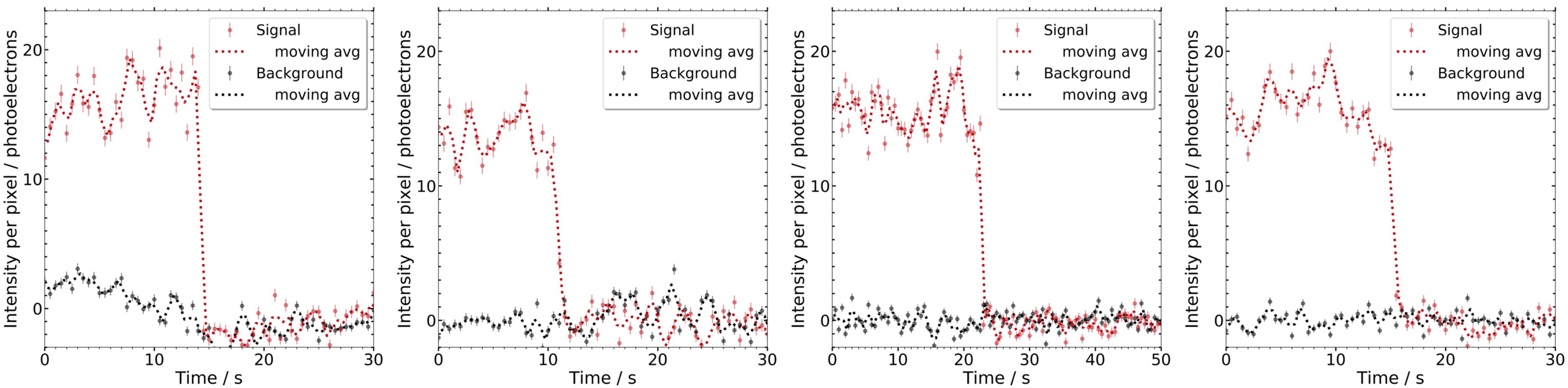
Microscope objective [modified to allow for de/pressurizing]

Slide holder

FIRST HIGH PRESSURE SINGLE MOLECULE FLOURESCENT IMAGES (ARGON GAS).



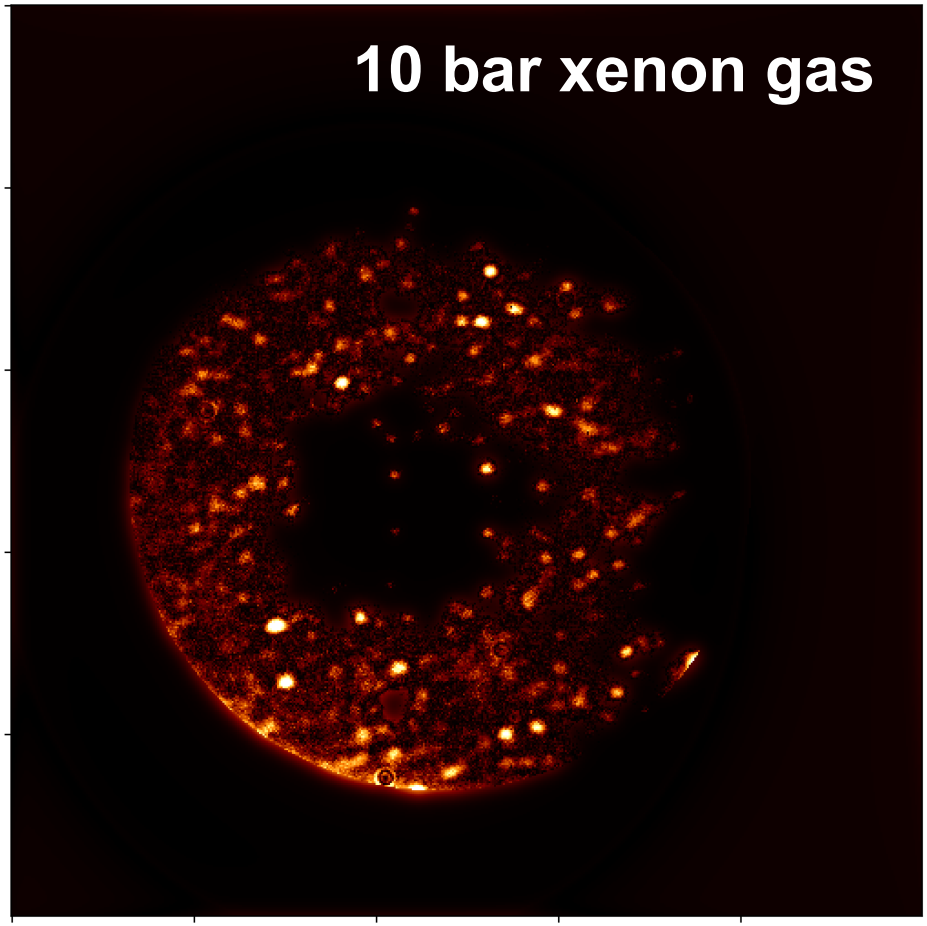
1 bar **3 bar** **7 bar** **10 bar**

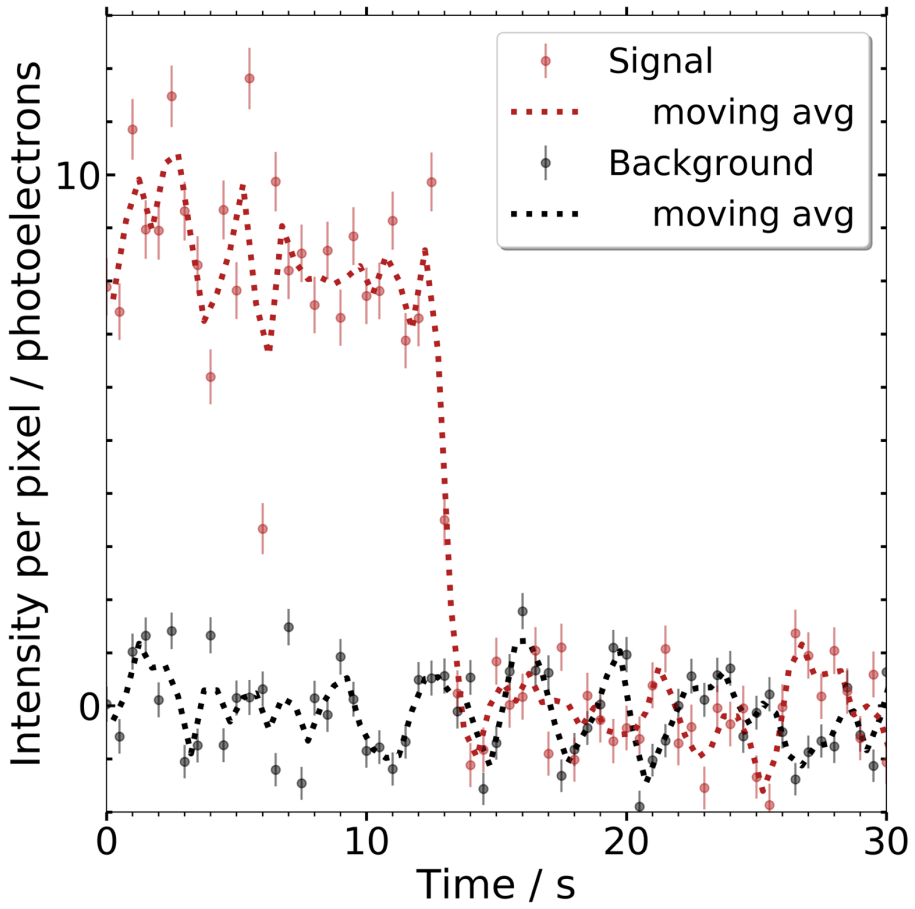


54 $4d^{10}5s^25p^6$
Xe
Xenon
131.29

And in Xenon

The first time an ion has been imaged in a bb0nu like detector medium!

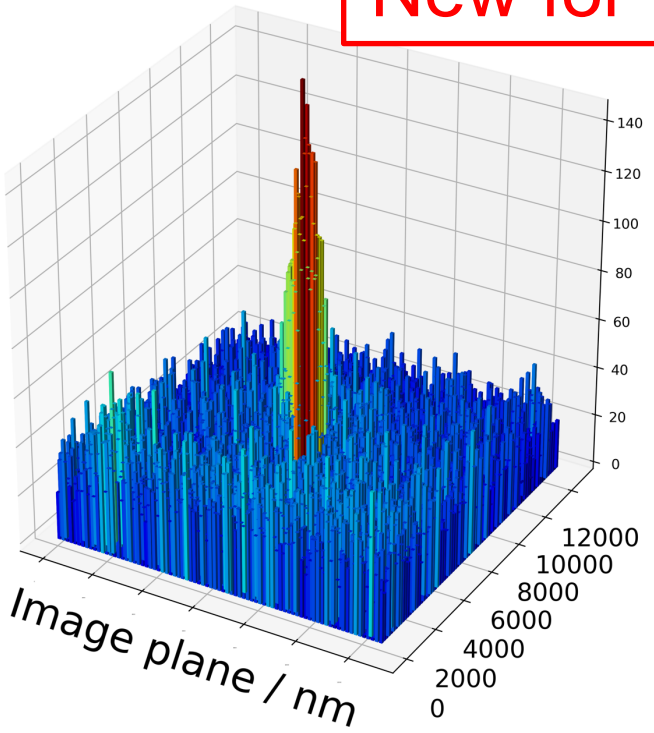




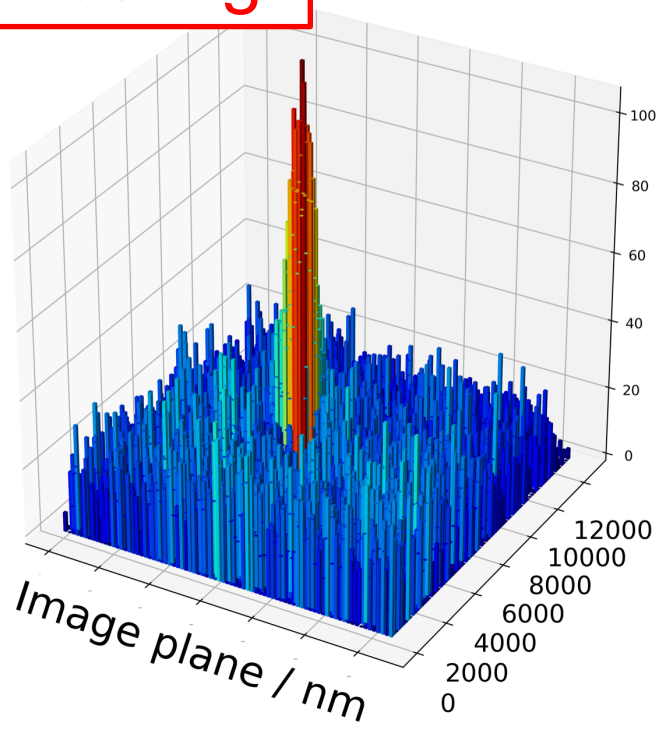
First ever single molecule images in high pressure gas

single Barium ions in 10 bar argon and xenon

New for this meeting!



Ba^{++} ion / 10 bar xenon

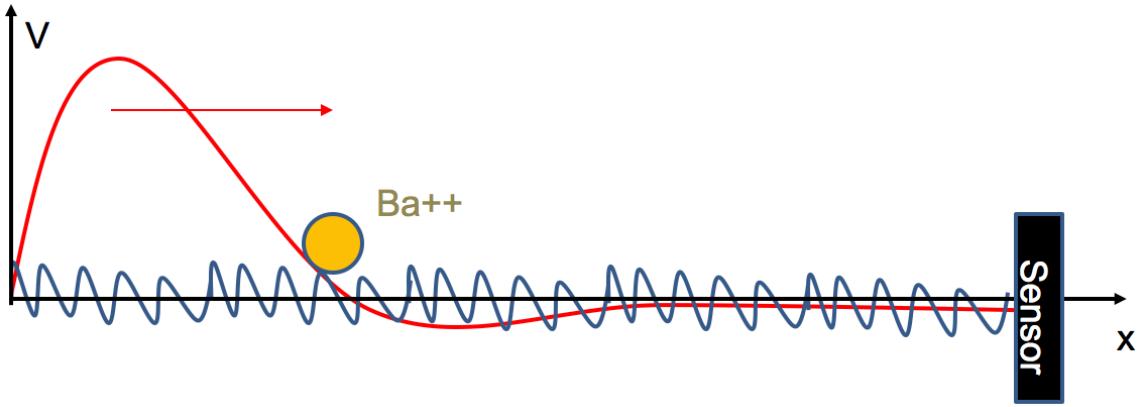


Ba^{++} ion / 10 bar argon

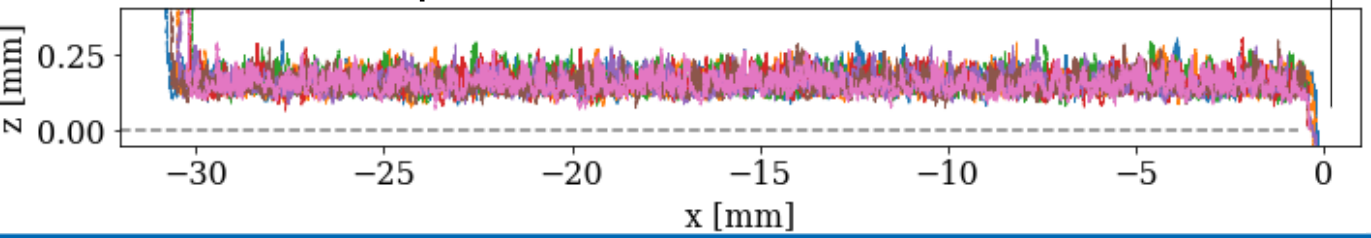
Up Next - Ion Delivery

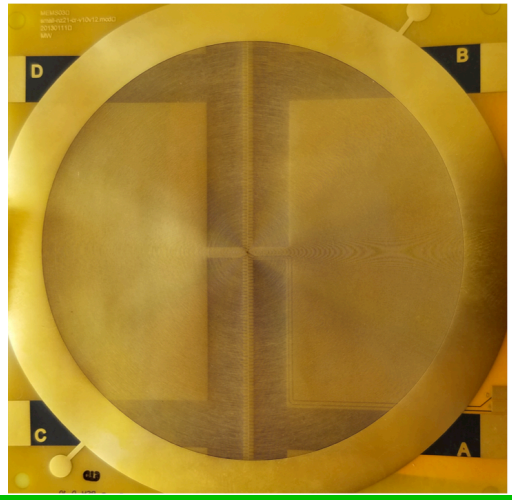
Developing high pressure RF carpet to readout a large area with a small sensor

The RF field “levitates” the ions and then they are “swept” to a sensor

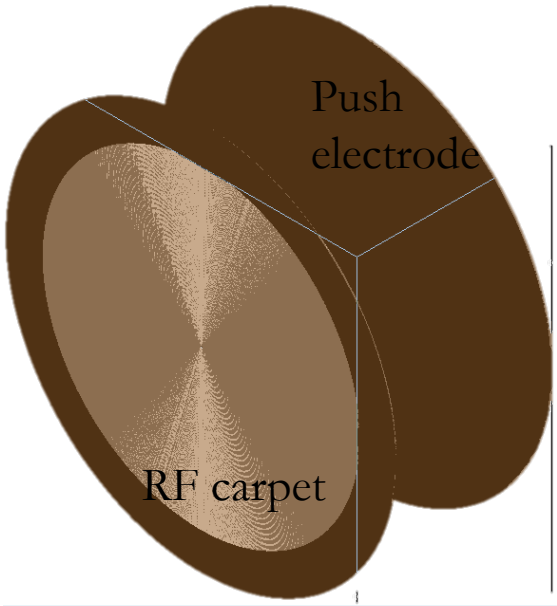


SIMION RF carpet simulations of Ba^{++} in 10 bar Xe





SIMION®

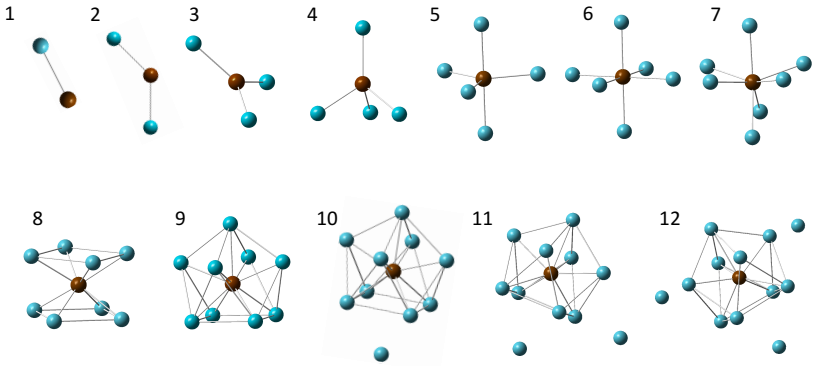


Understanding Ion Transport in Xenon

- Ions are a mostly overlooked channel for TPC experiments - much remains to be understood about their drift and survival.
- **Ion transport / concentration is the next experimental hurdle for barium tagging!**

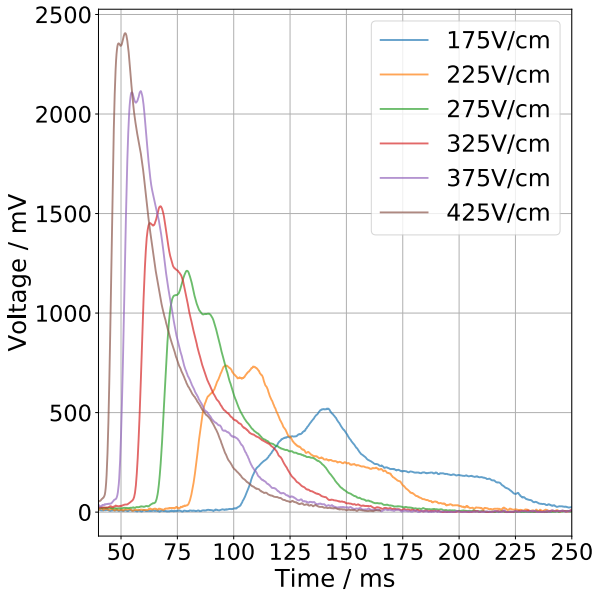
Theoretical work on ion clustering

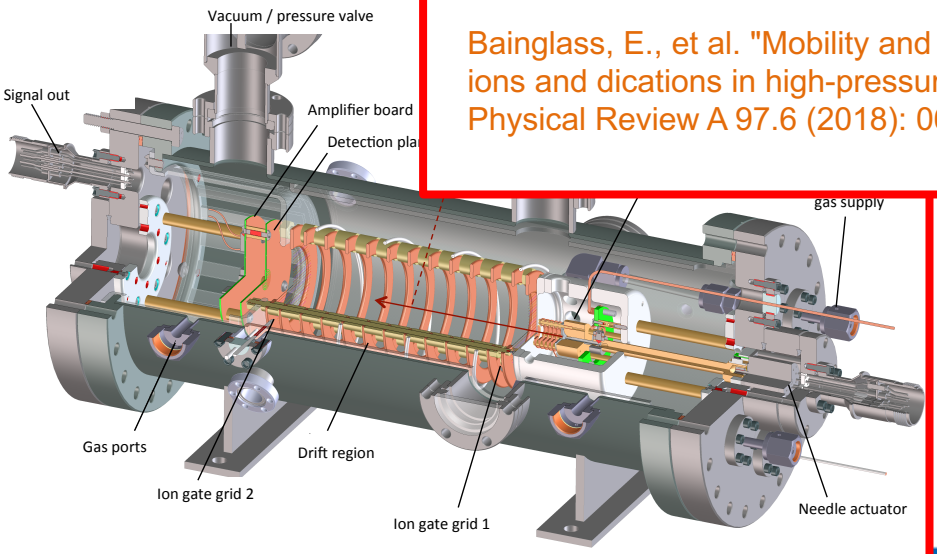
$$[BaXe_{N-1}]^{++} + Xe \leftrightarrow [BaXe_N]^{++}$$



Bainglass, E., et al. "Mobility and clustering of barium ions and dications in high-pressure xenon gas." Physical Review A 97.6 (2018): 062509.

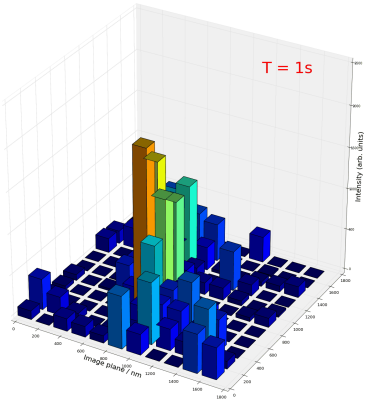
Ion attachment on impurities

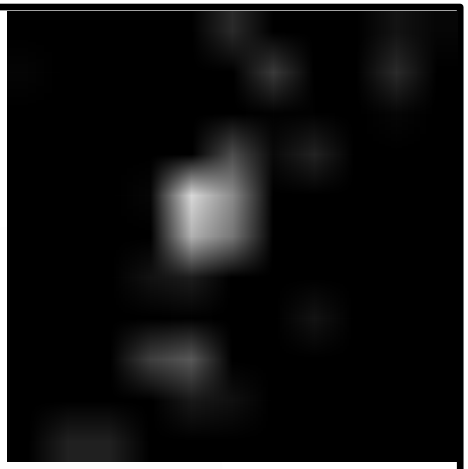


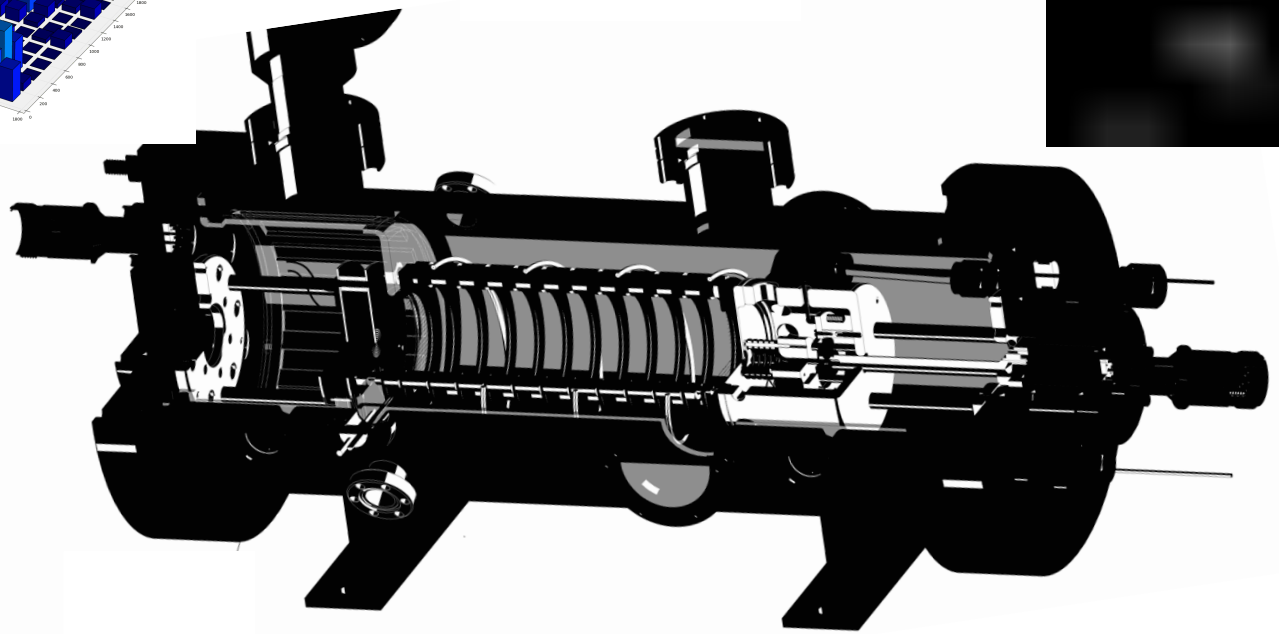


Summary

- Single molecule fluorescent imaging is a potentially transformative new technology for barium tagging.
- The first single molecule images have been taken in a high pressure Nobel gas environment.
- This is the first ever single barium identification in a working 0nubb experiment medium.
- Understanding ion transport, concentration and survival is the next key step toward realizing this technology.
- HPGXe TPC with **internal real-time fluorescent tagging of barium daughter** may offer a new way to eliminate gamma ray backgrounds in 0vbb search.





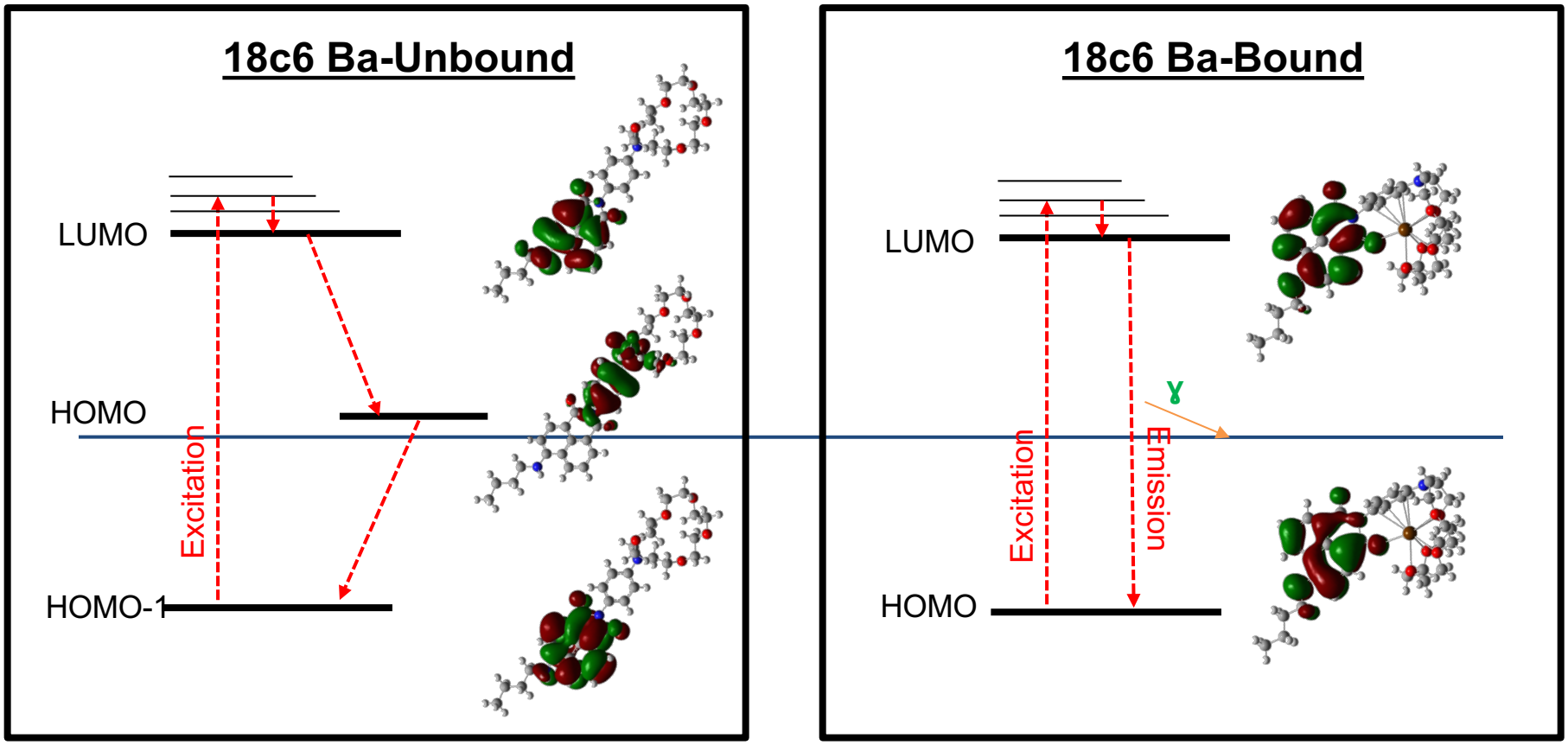


COME AND TAG IT

THE UNIVERSITY OF TEXAS AT ARLINGTON
HIGH-PRESSURE XENON GAS BARIUM TAGGING LAB

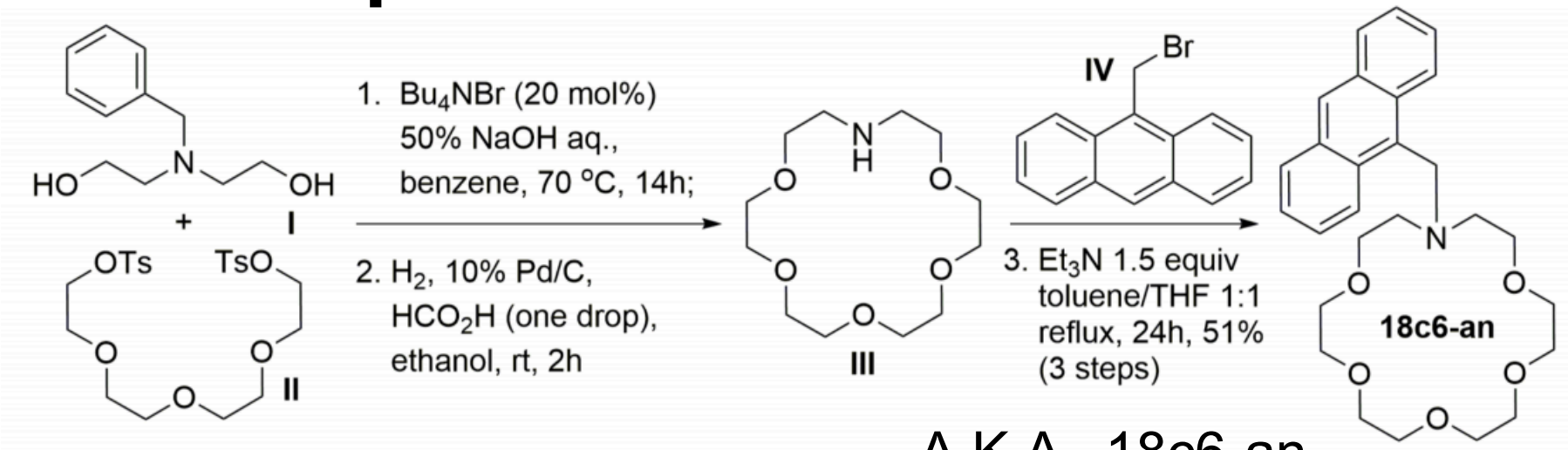
BACKUP

Development of Custom Molecules



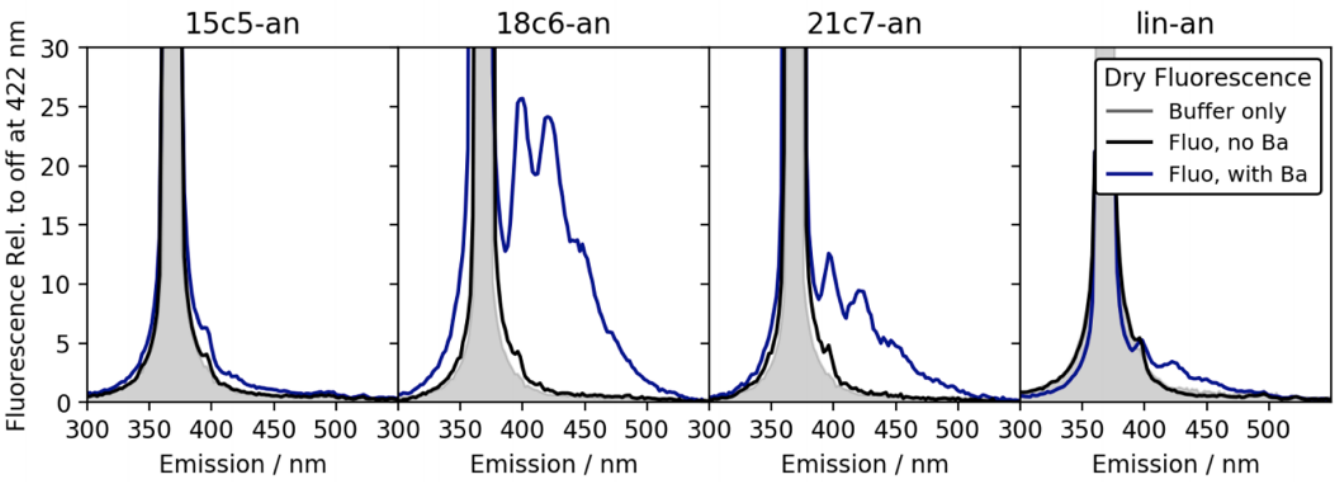
Simulations illustrate on-off mechanism in 18c6-nap:
Electron density around nitrogen lone pair pulled into bonding configuration to disable quenching transition, effectively switching on fluorescence upon binding.

Development of Custom Molecules



A.K.A 18c6-an

Synthesis chain for
1-(9-anthracenyl)methyl-1-aza-18-crown-6



Dry phase!

Thapa, P., *et al.* Barium Chemosensors with Dry-Phase Fluorescence for Neutrinoless Double Beta Decay. *Sci Rep* **9,** 15097 (2019) doi:10.1038/s41598-019-49283-x