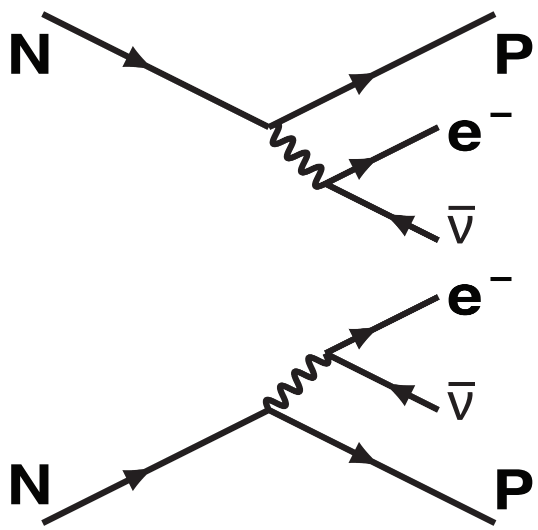
Single Ion Ba^{++} Tagging for $0\nu\beta\beta$

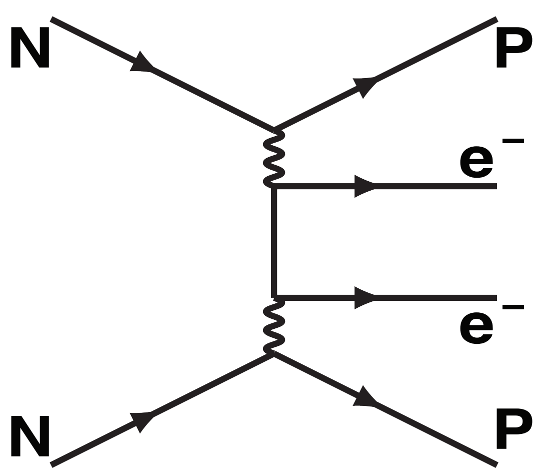
Multi-disciplinary technique in development for the NEXT experiment. Demonstration and R&D landscape.

Fernanda Psihas
For the NEXT Collaboration

Searching for the nature of neutrinos.



$$2\nu\beta\beta$$



$$0\nu\beta\beta$$

0vBB is only allowed if neutrinos are Majorana particles.

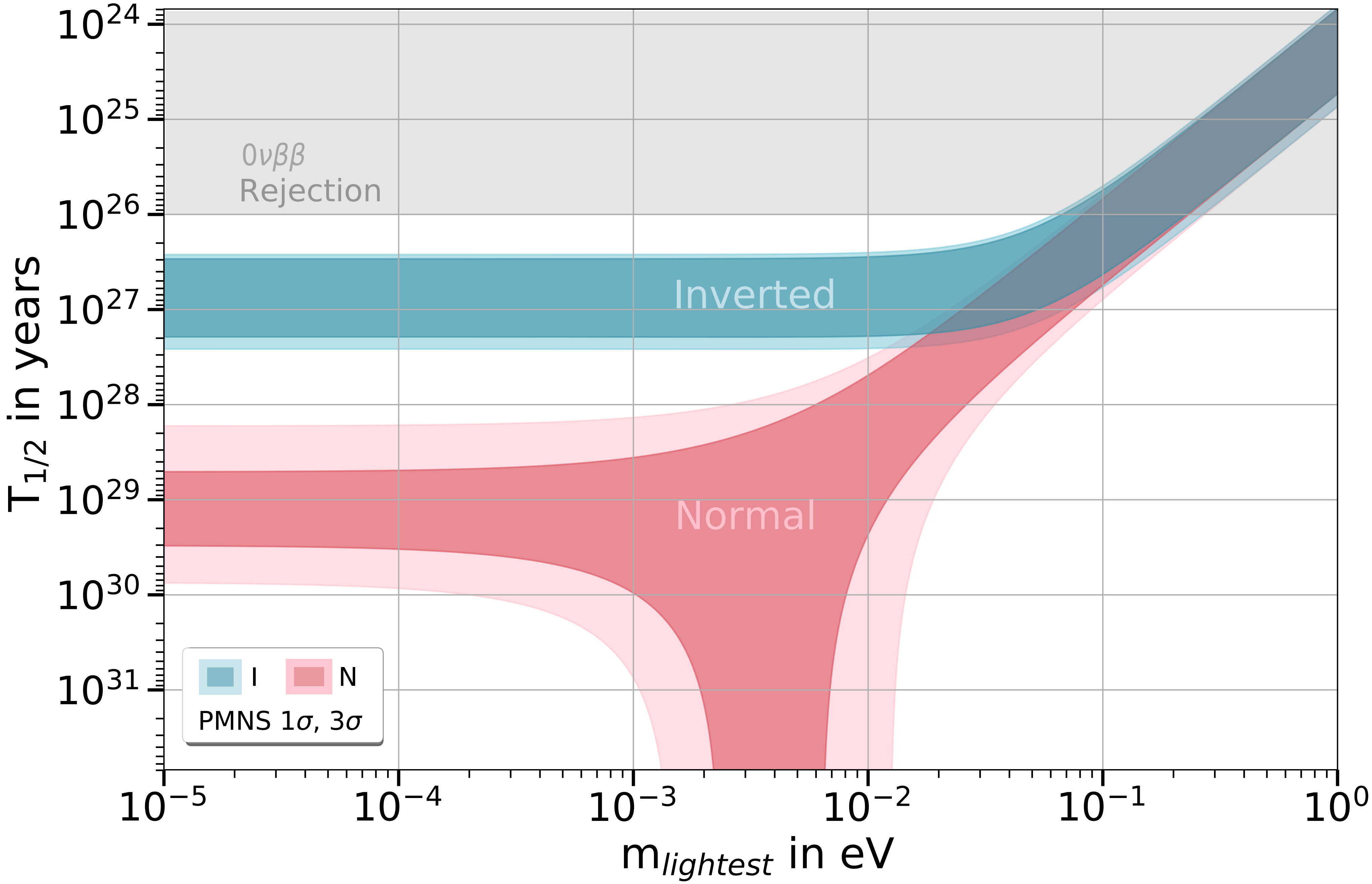
Observation of 0vBB would:

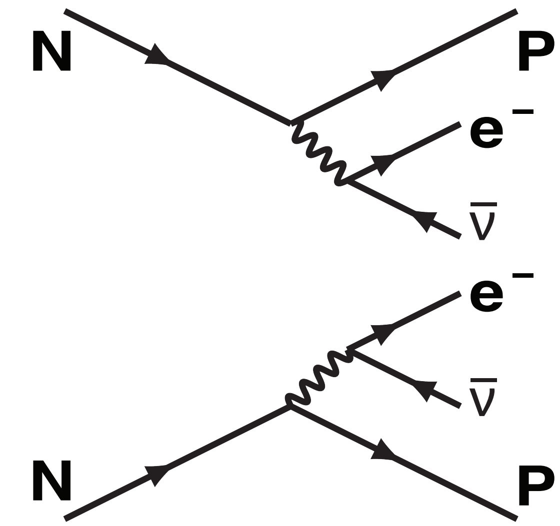
Demonstrate the existence of massive Majorana fermions.

Show that the mechanism for neutrino masses is beyond the SM Higgs coupling.

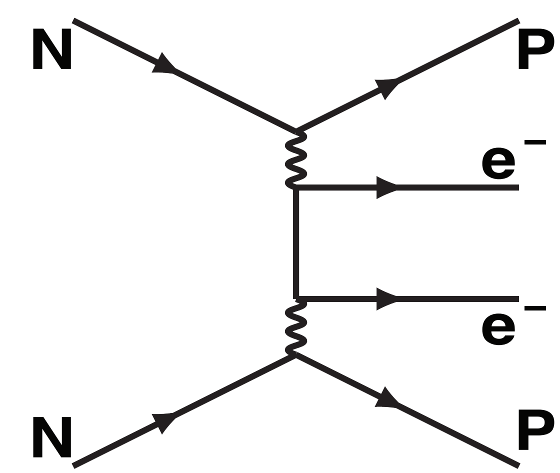
Tests one of the predictions of leptogenesis to explain matter-antimatter asymmetry.

Searching for the nature of neutrinos.





$T_{1/2} \sim 10^{18} - 10^{20}$ y



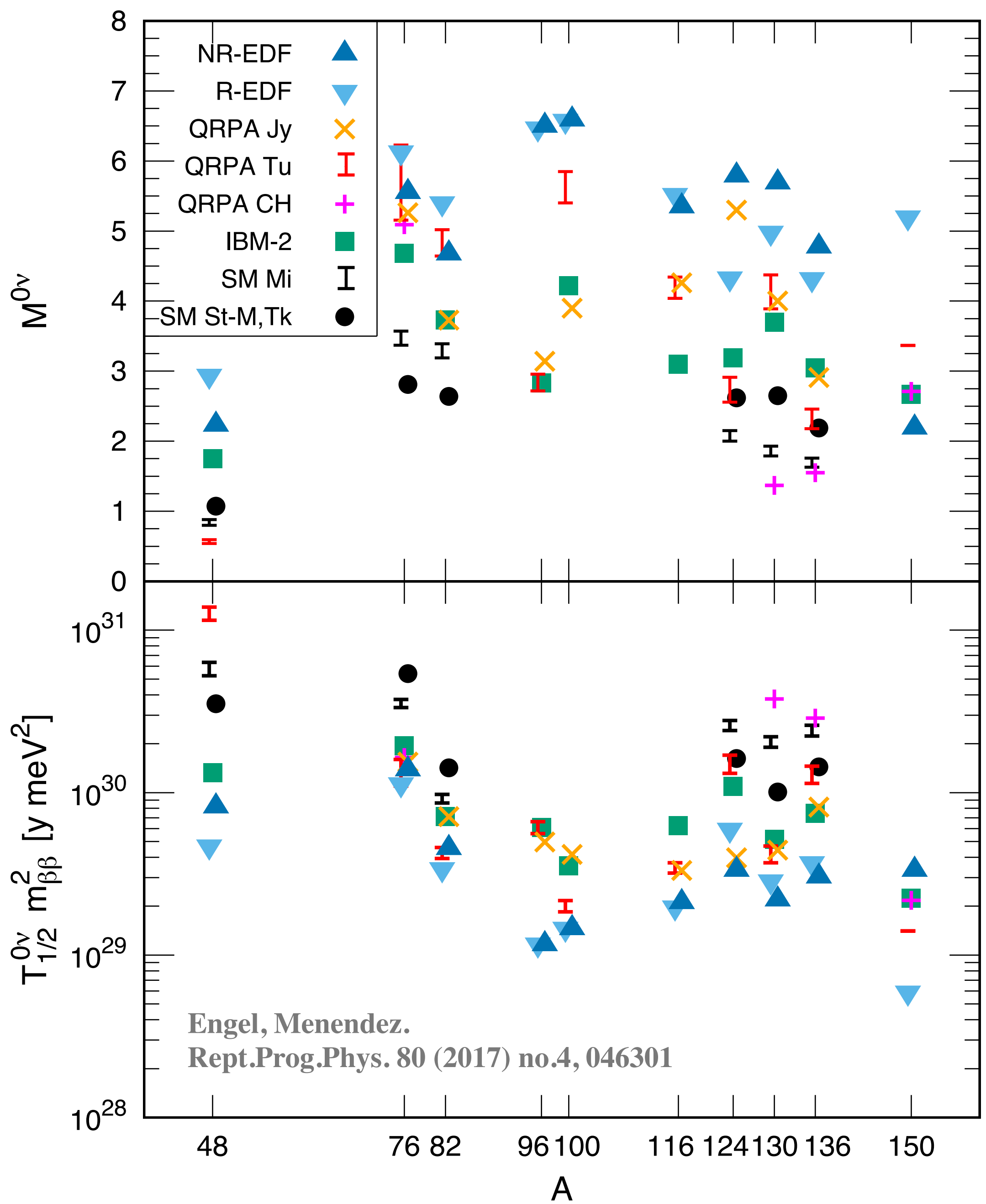
Caveat! Uncertainties from the theory

Phase space factor (PSF)

Absolute ν mass scale

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)\ |\mathcal{M}_{0\nu}|^2\ m^2_{\beta\beta}$$

Nuclear matrix element (NME)

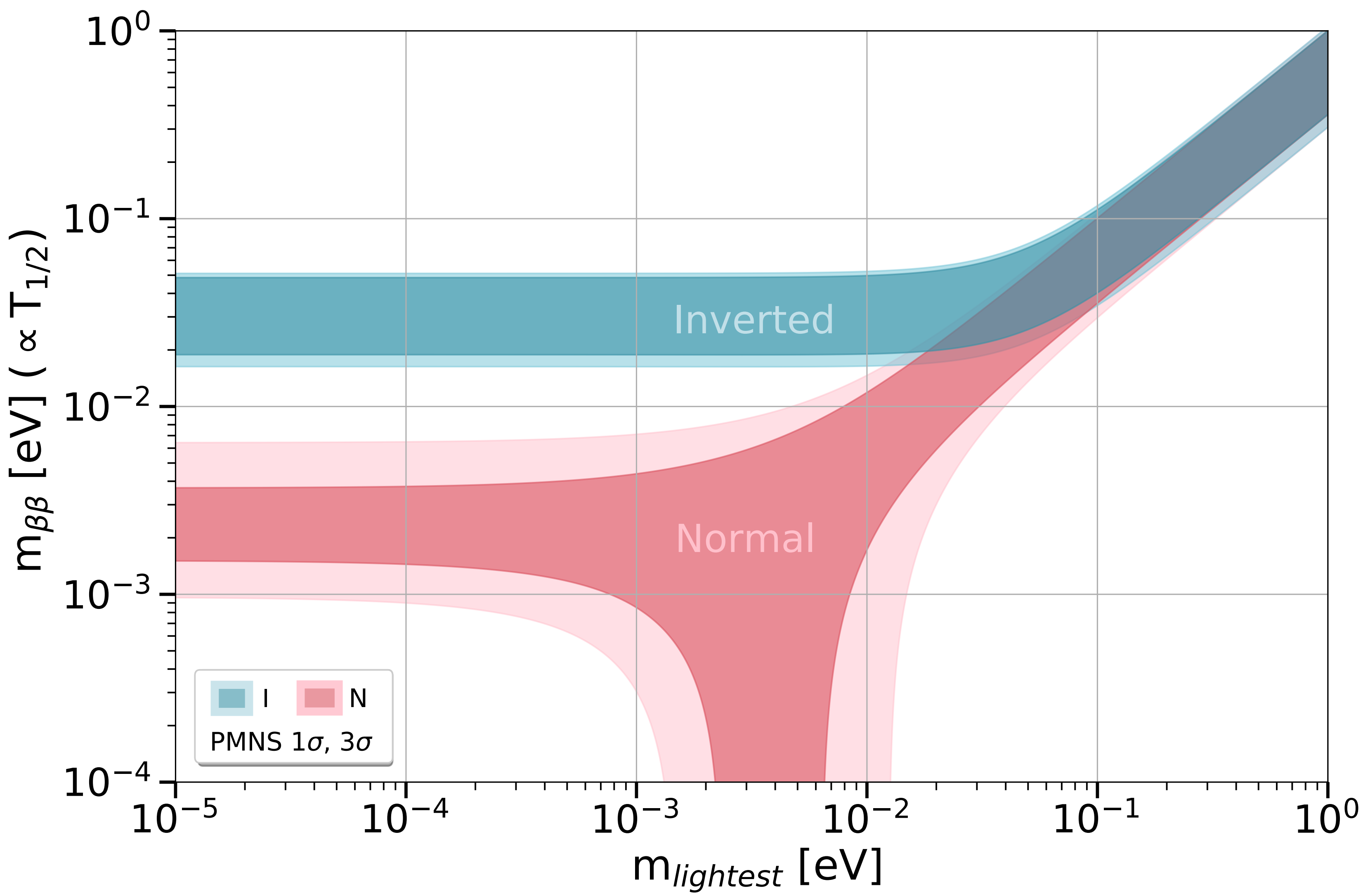


Uncertainties are large in and the nuclear matrix elements, and they which translate to order-of-magnitude differences in $T_{1/2}$.

Caveat! Allowed regions.

$$m_{\beta\beta} = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2 - \alpha_1)} + m_3 |U_{e3}|^2 e^{i(-\alpha_1 - 2\delta)} \right|$$

Dependent on oscillation parameters and neutrino masses.

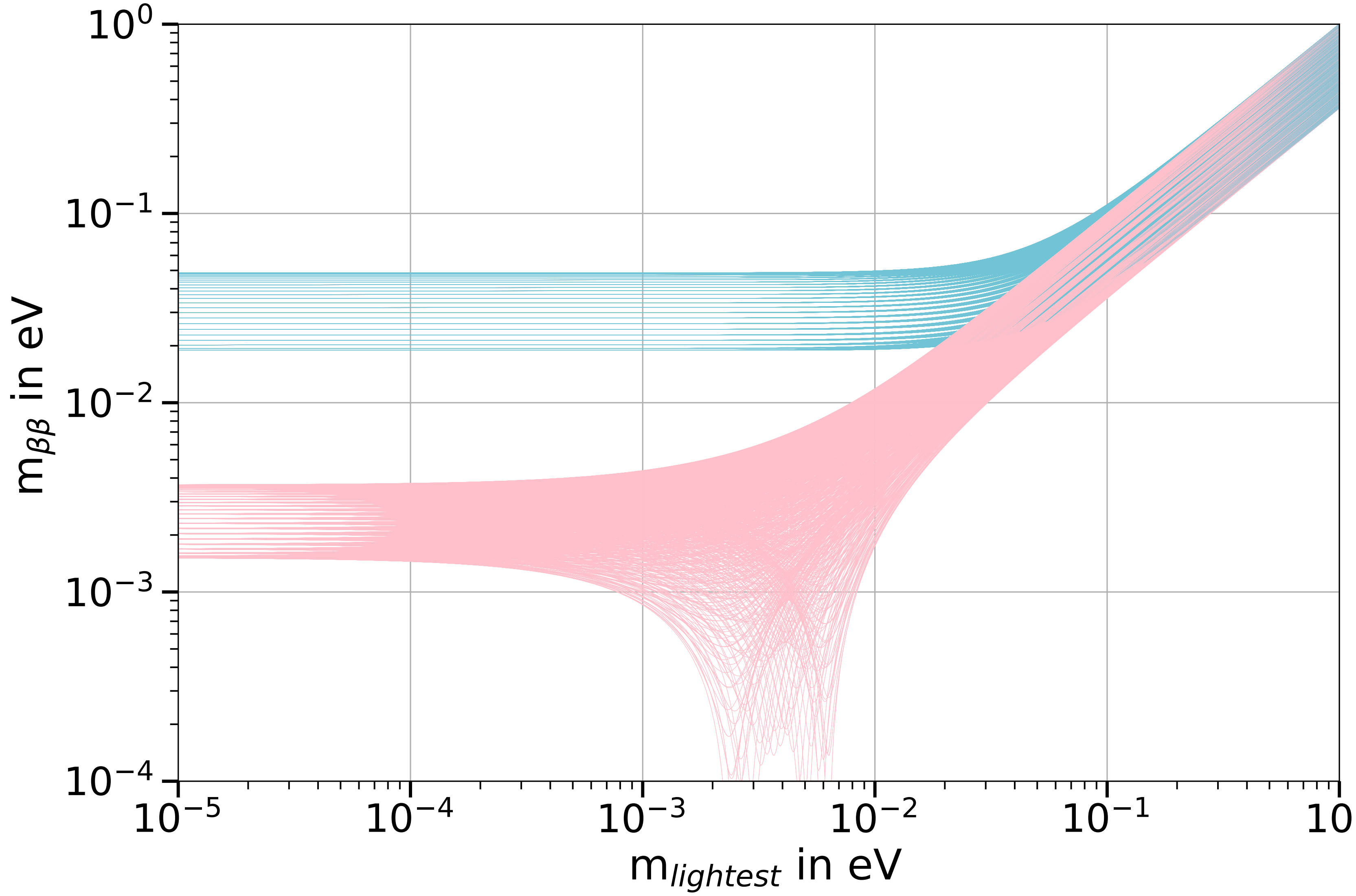


Caveat! This phase space assumes: 3 nu flavors and light Majorana neutrino exchange mechanism

Caveat! Allowed regions.

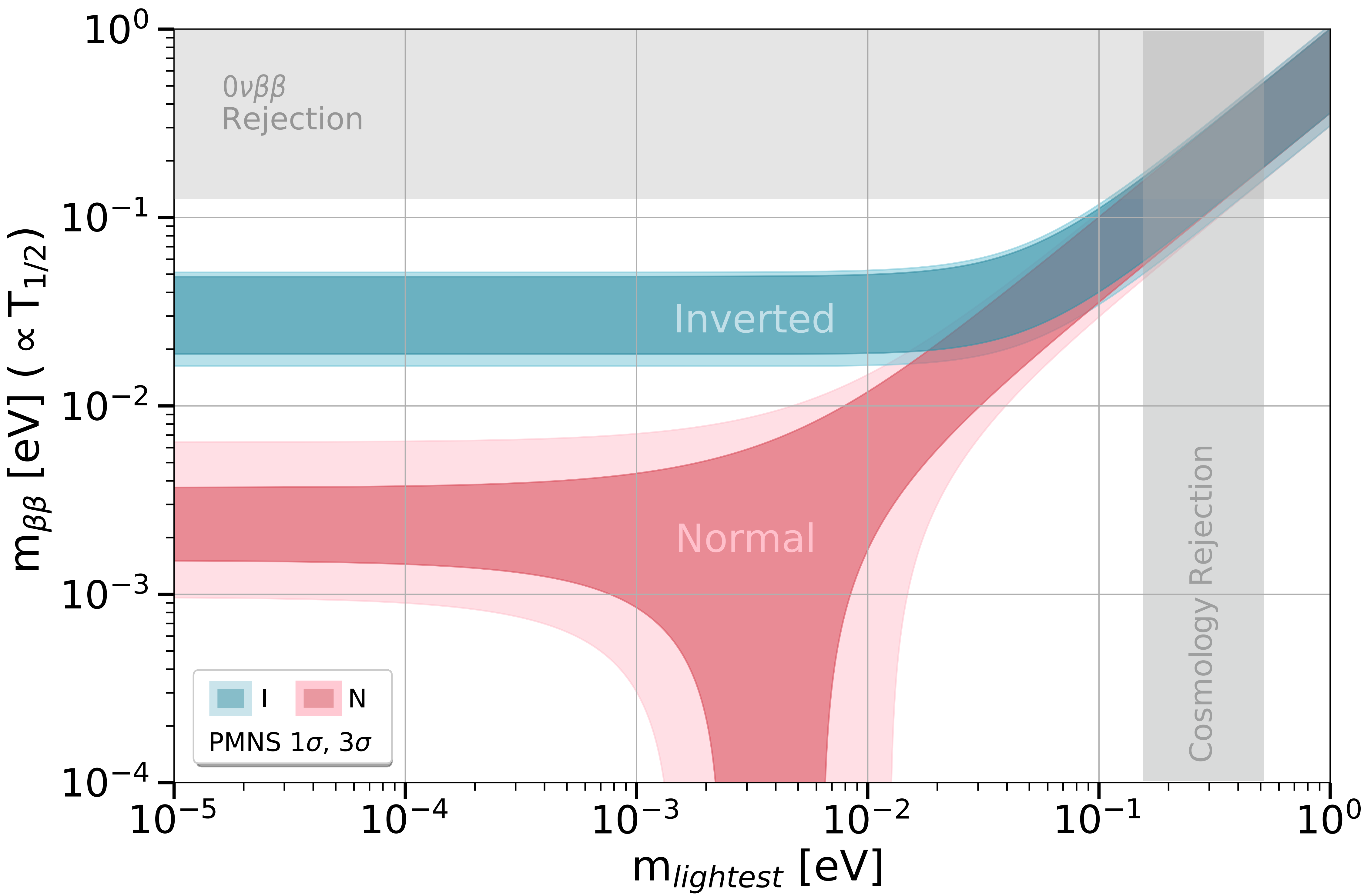
$$m_{\beta\beta} = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2 - \alpha_1)} + m_3 |U_{e3}|^2 e^{i(-\alpha_1 - 2\delta)} \right|$$

Shaded regions from all available values of the Majorana phases.

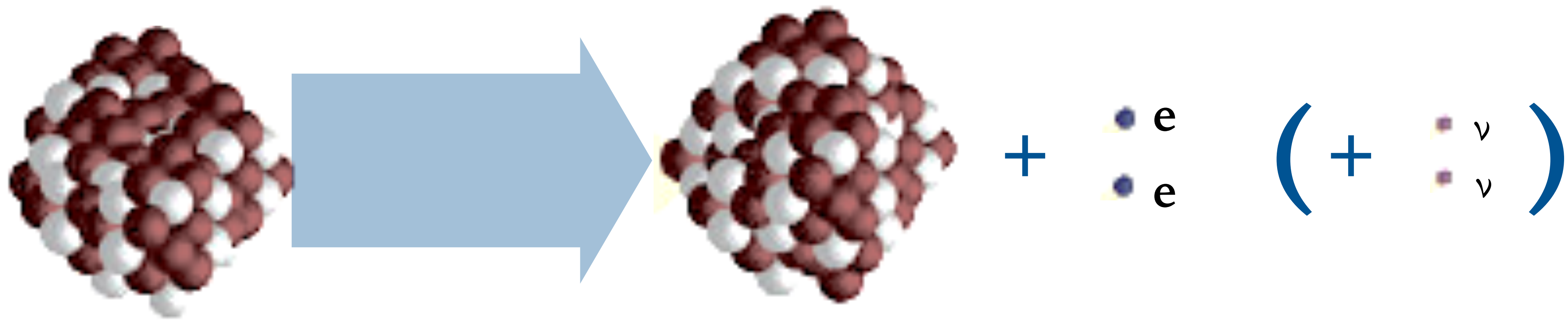


Caveat! Across all values of the Majorana phases, all regions are not equally probable.

$$m_{\beta\beta}^2 = ||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3|$$



NEXT program - Searching for $0\nu\beta\beta$



^{136}Xe ^{136}Ba

next:

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HARVARD

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Universidad de Zaragoza

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Argonne NATIONAL LABORATORY

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JINR DUBNA

Fermilab

A&M

אוניברסיטת בן-גוריון בנגב
Ben-Gurion University of the Negev

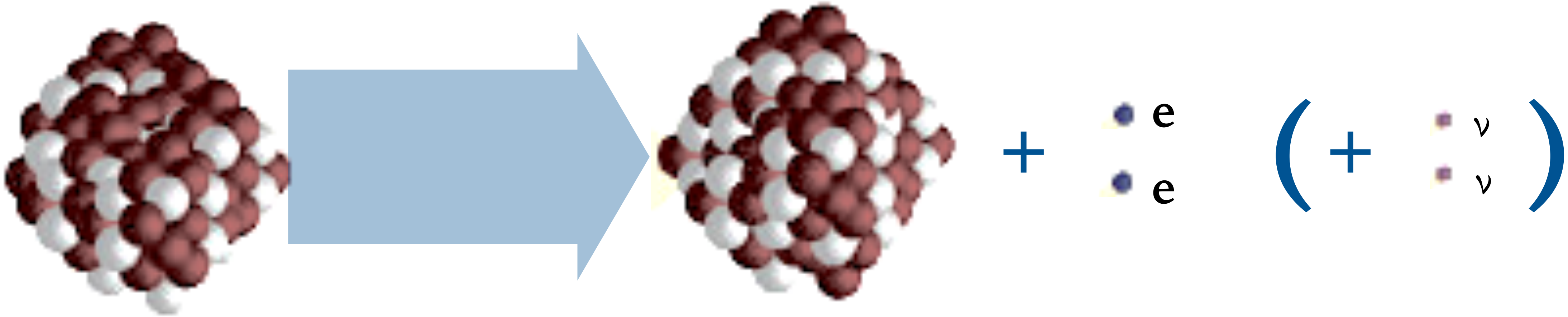
UAN UNIVERSIDAD ANTONIO NARIÑO

universidade de aveiro

THE OHIO STATE UNIVERSITY

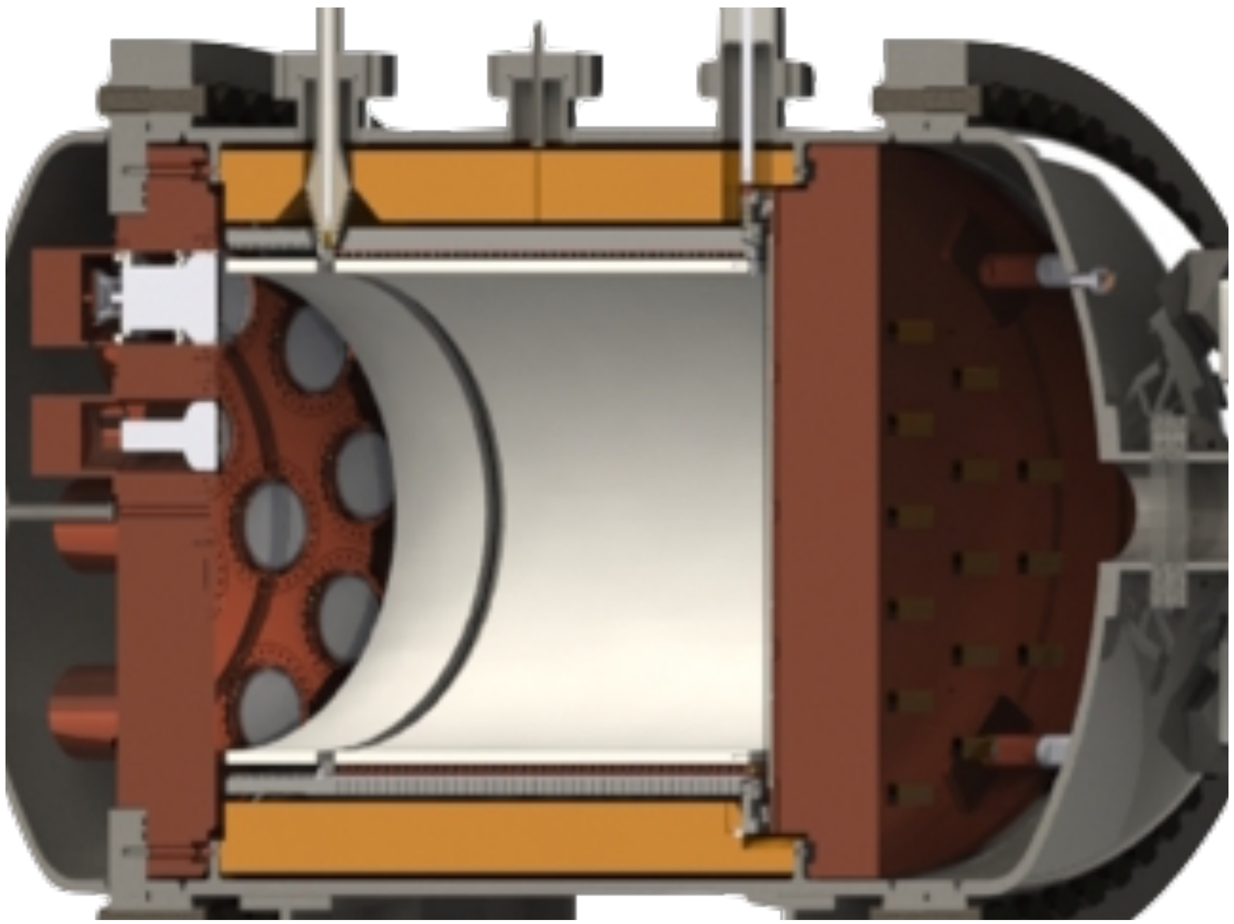
U C

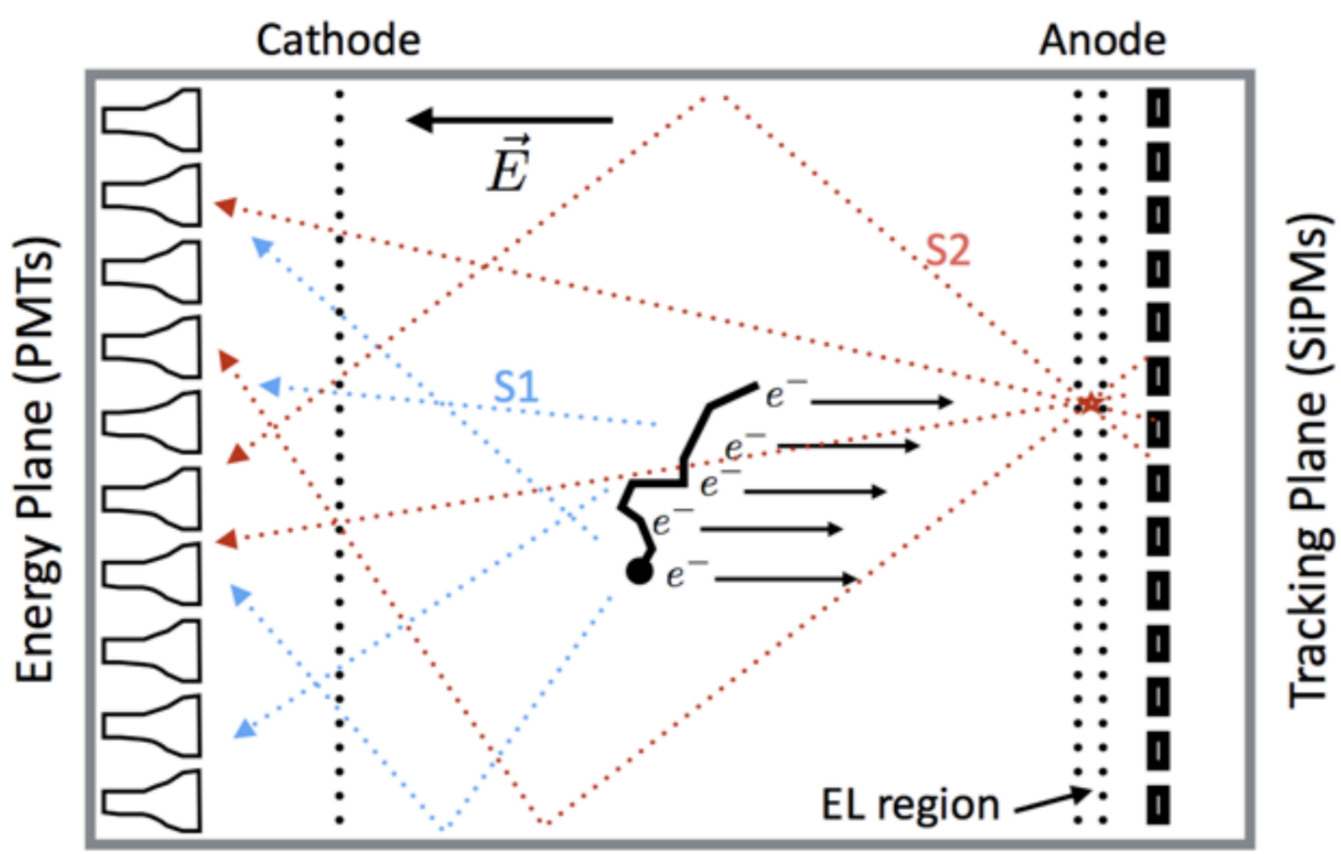
NEXT program - Searching for 0νββ



^{136}Xe

^{136}Ba





High pressure ^{136}Xe gas Electro-luminescence TPC

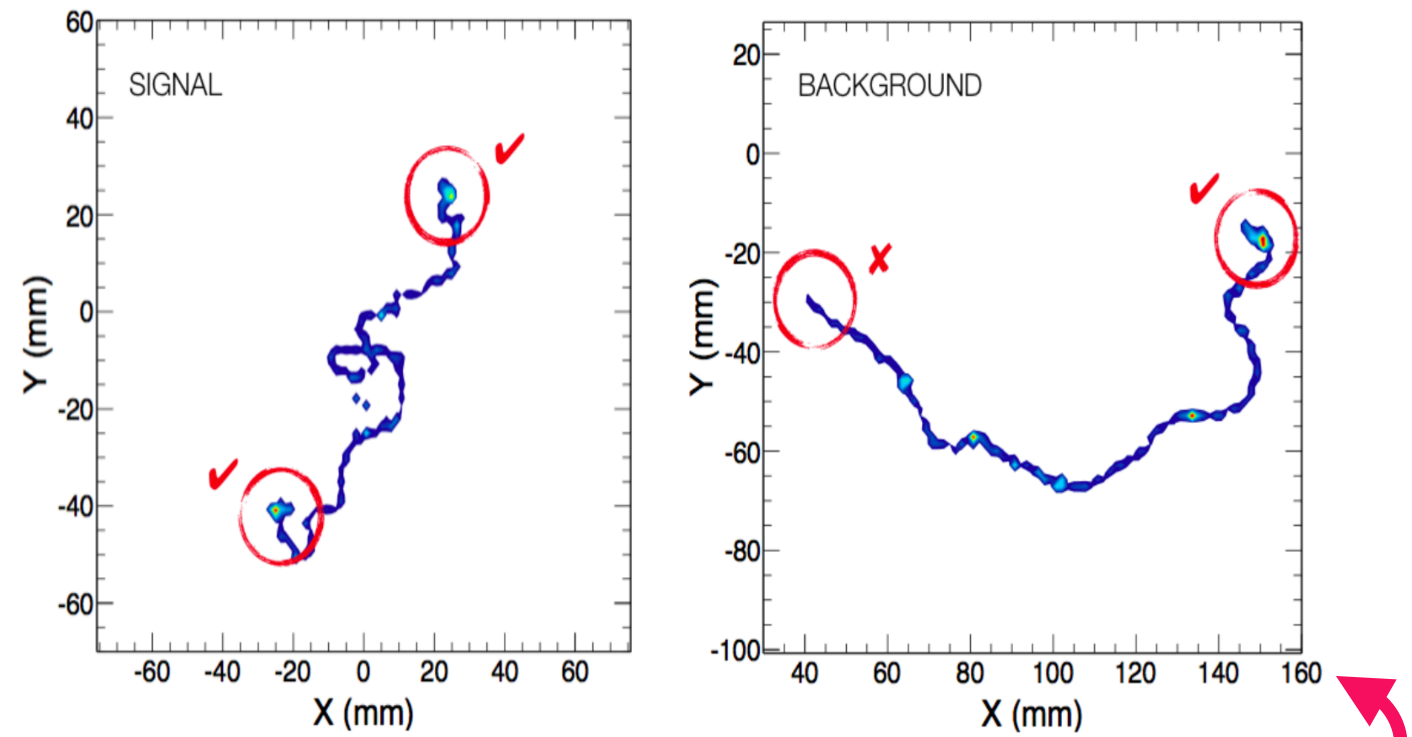
NEXT program - Searching for 0νββ

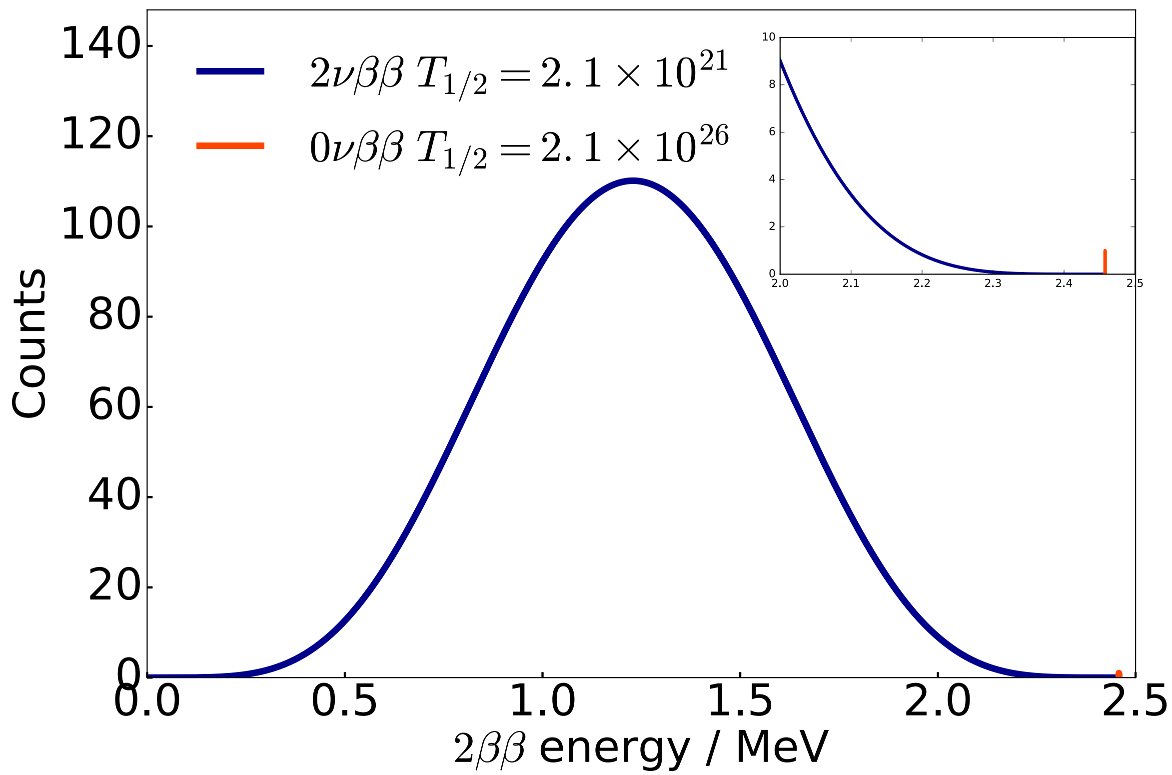
Topology is used for background rejection.

Exceptional energy resolution is needed to resolve events at the Q-value.

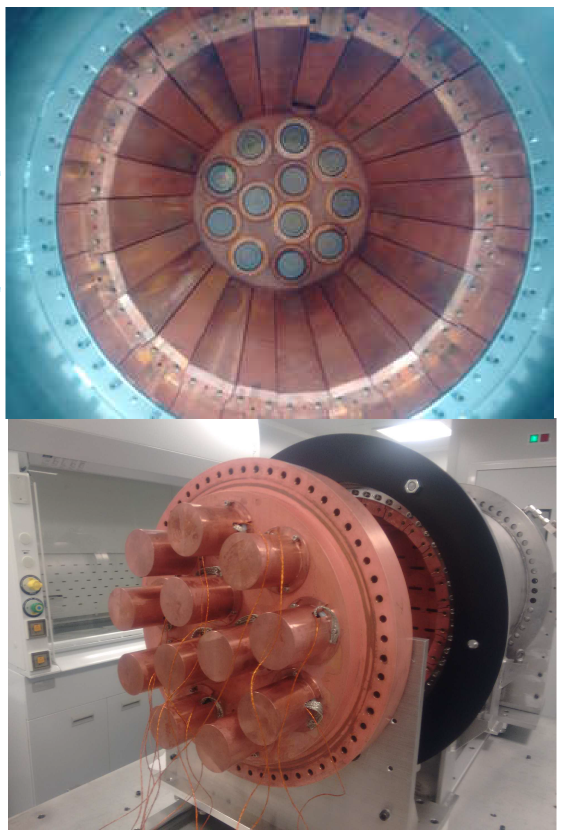
NEXT-White (10kg) has just measured

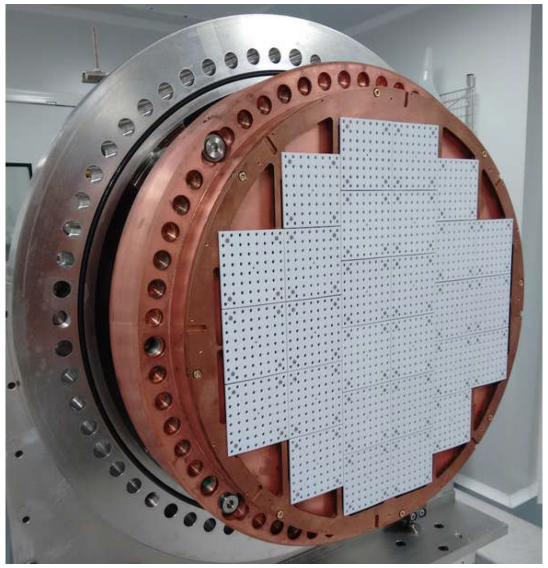
σ/E=0.43% arXiv:1808.01804





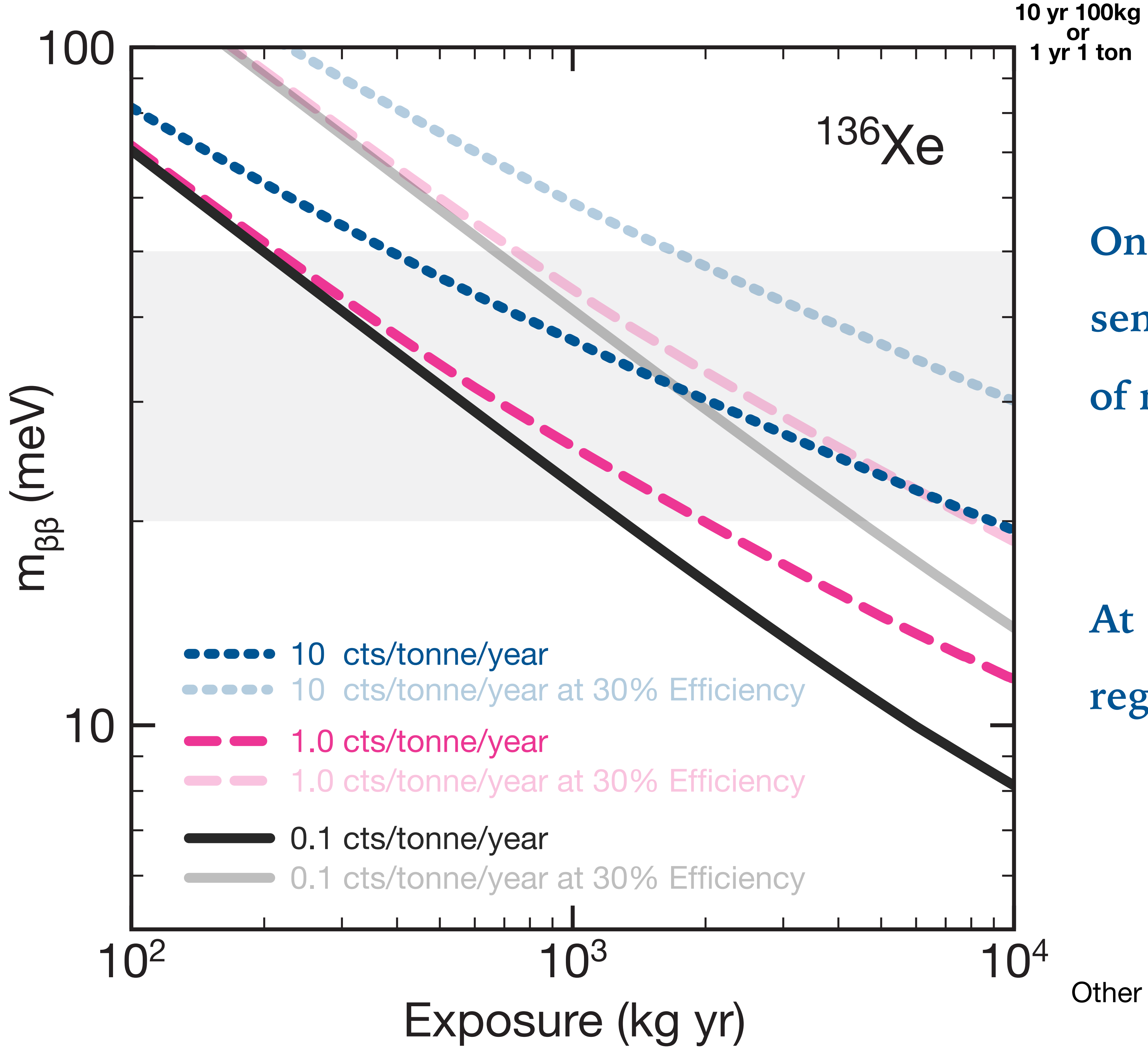
ENERGY PLANE (PMTs)





TRACKING PLANE (SiPMs)

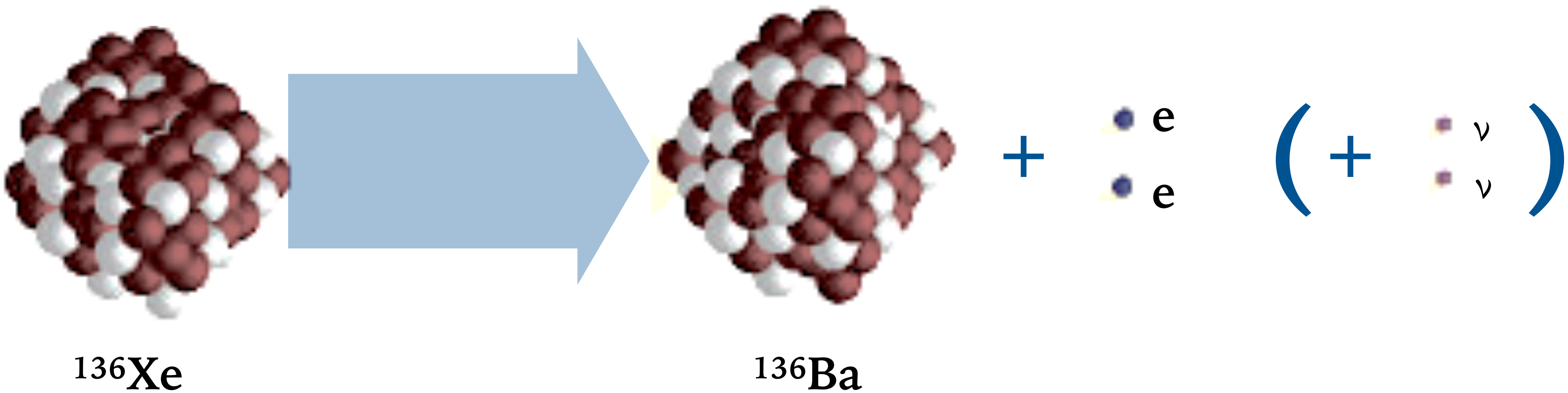
Backgrounds and Sensitivity



One order of magnitude in sensitivity requires two orders of magnitude in exposure.

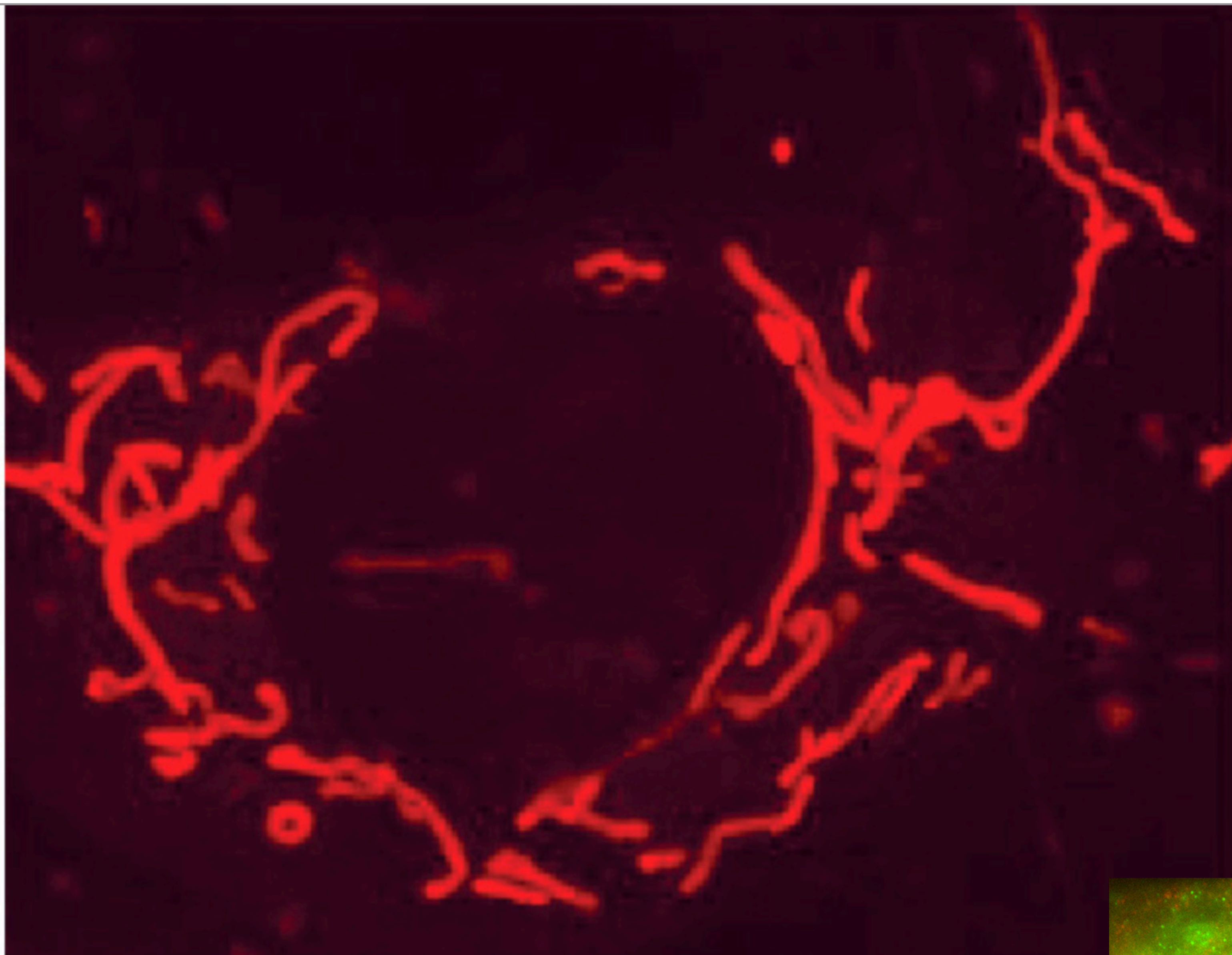
At 100% efficiency, the IH region is covered at 10^4 kg yrs

NEXT-100kg projected: 10 cts/ton/year
Other Xe best measurements: ~20 cts/ton/year



In pure Xenon, Ba is not produced by any backgrounds to ββ decay at the Q-value.

Single Molecule Fluorescence Imaging



J Cell Biol 145, 795 (1999).

Single-Molecule Spectroscopy, Imaging, and Photocontrol: Foundations for Super-Resolution Microscopy

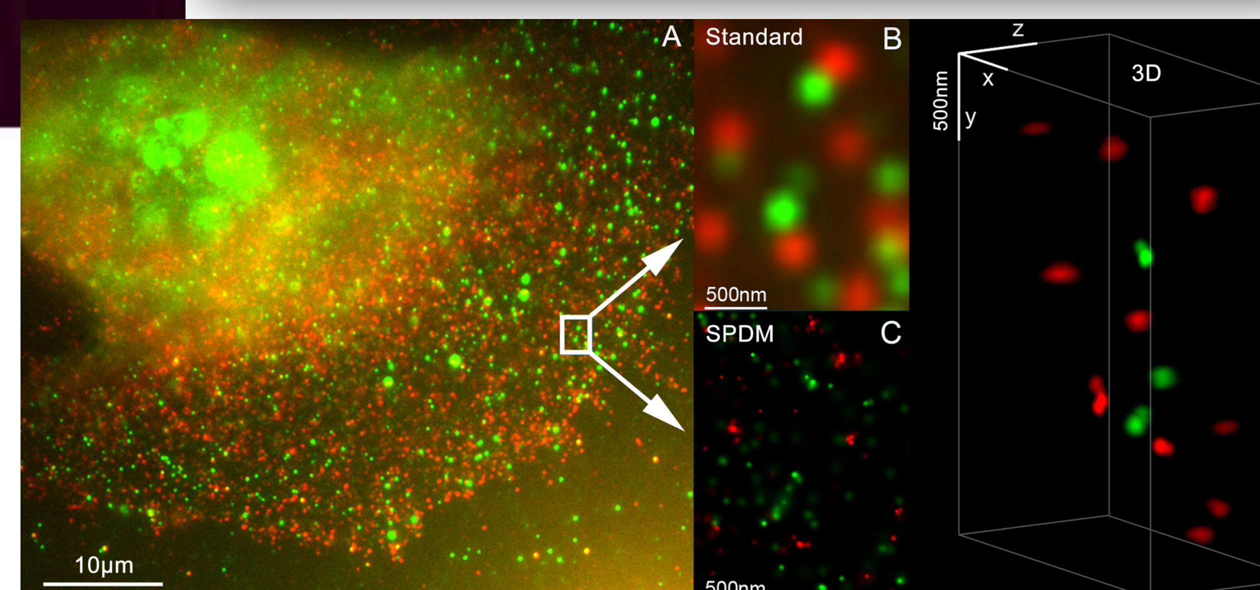
Nobel Lecture, December 8, 2014

by W. E. (William E.) Moerner

Departments of Chemistry and (by Courtesy) of Applied Physics
Stanford University, Stanford, California 94305 USA.

Calcium production tracked in rat cells.

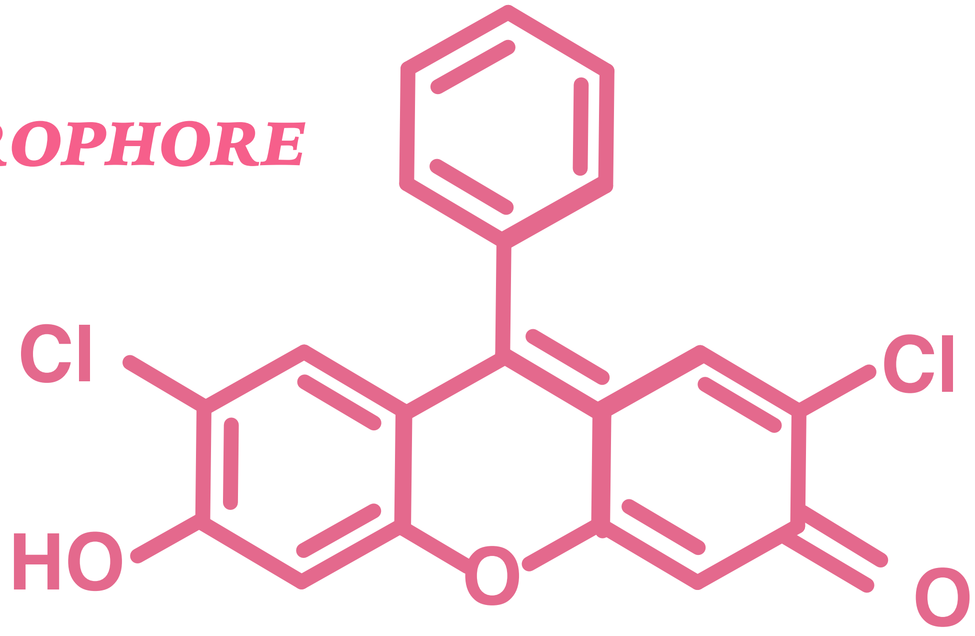
Single molecule tracking using SMFI is the basis of super-resolution microscopy



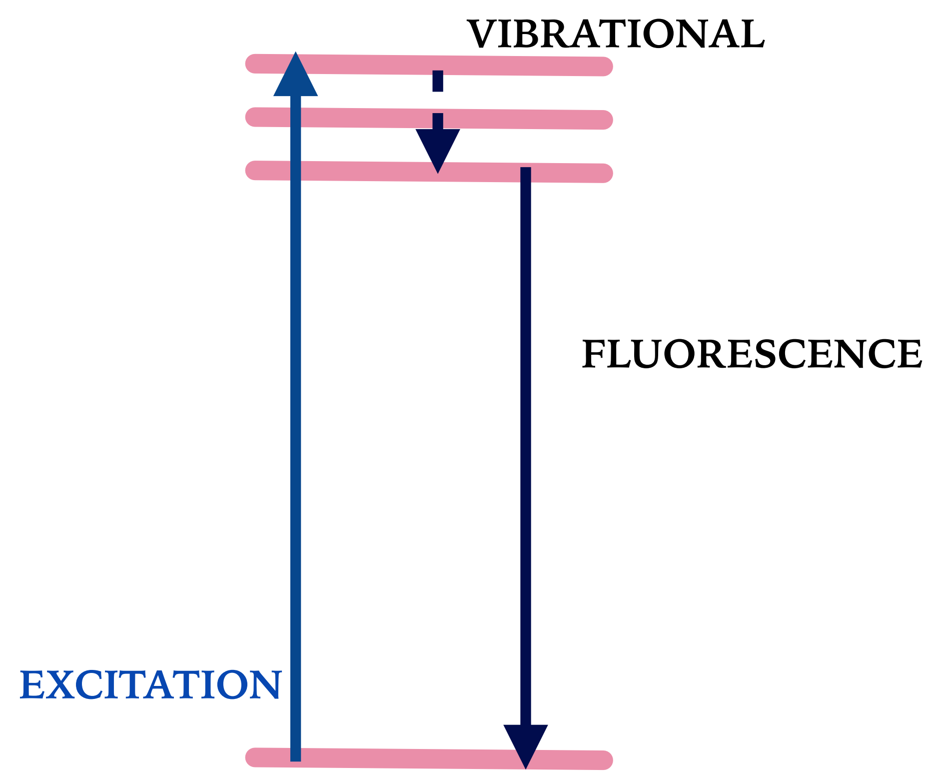
J Microsc. 2011 Apr;242(1):46-54

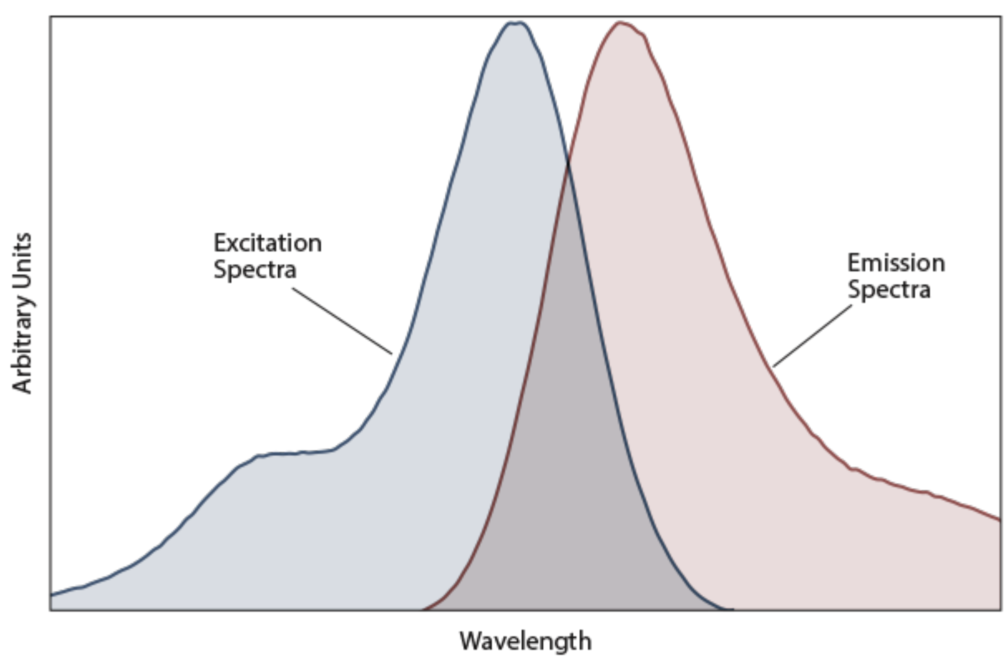
Single Molecule Fluorescence Imaging

FLUOROPHORE

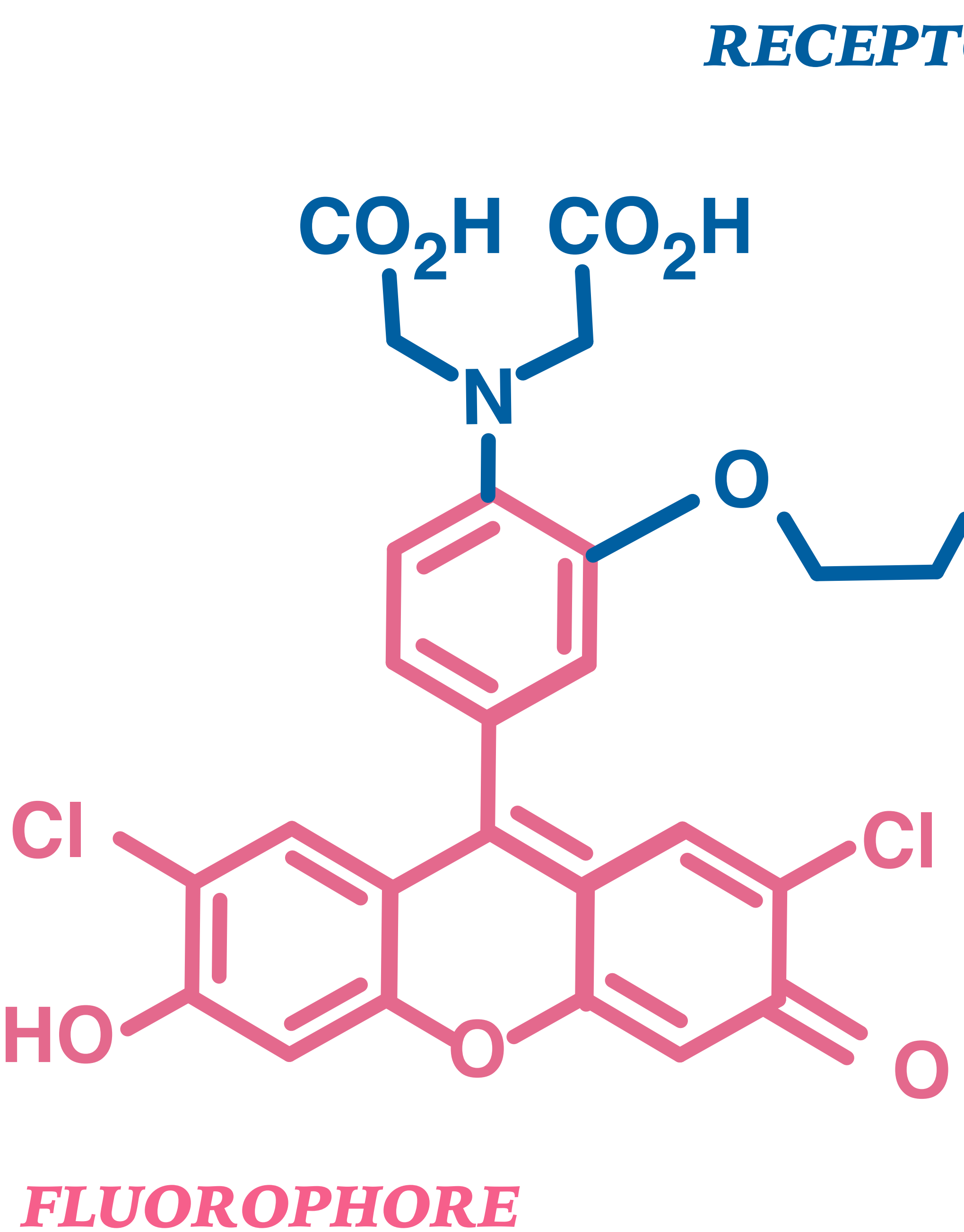


Molecule de-excites via fluorescence

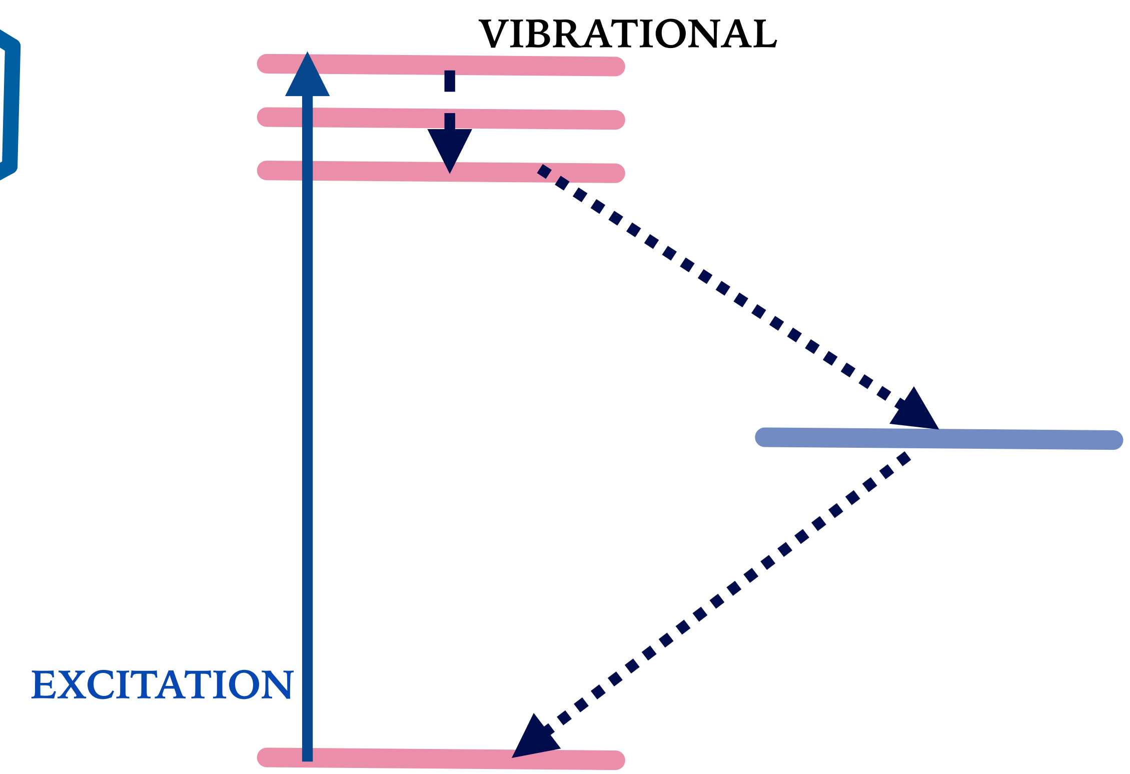




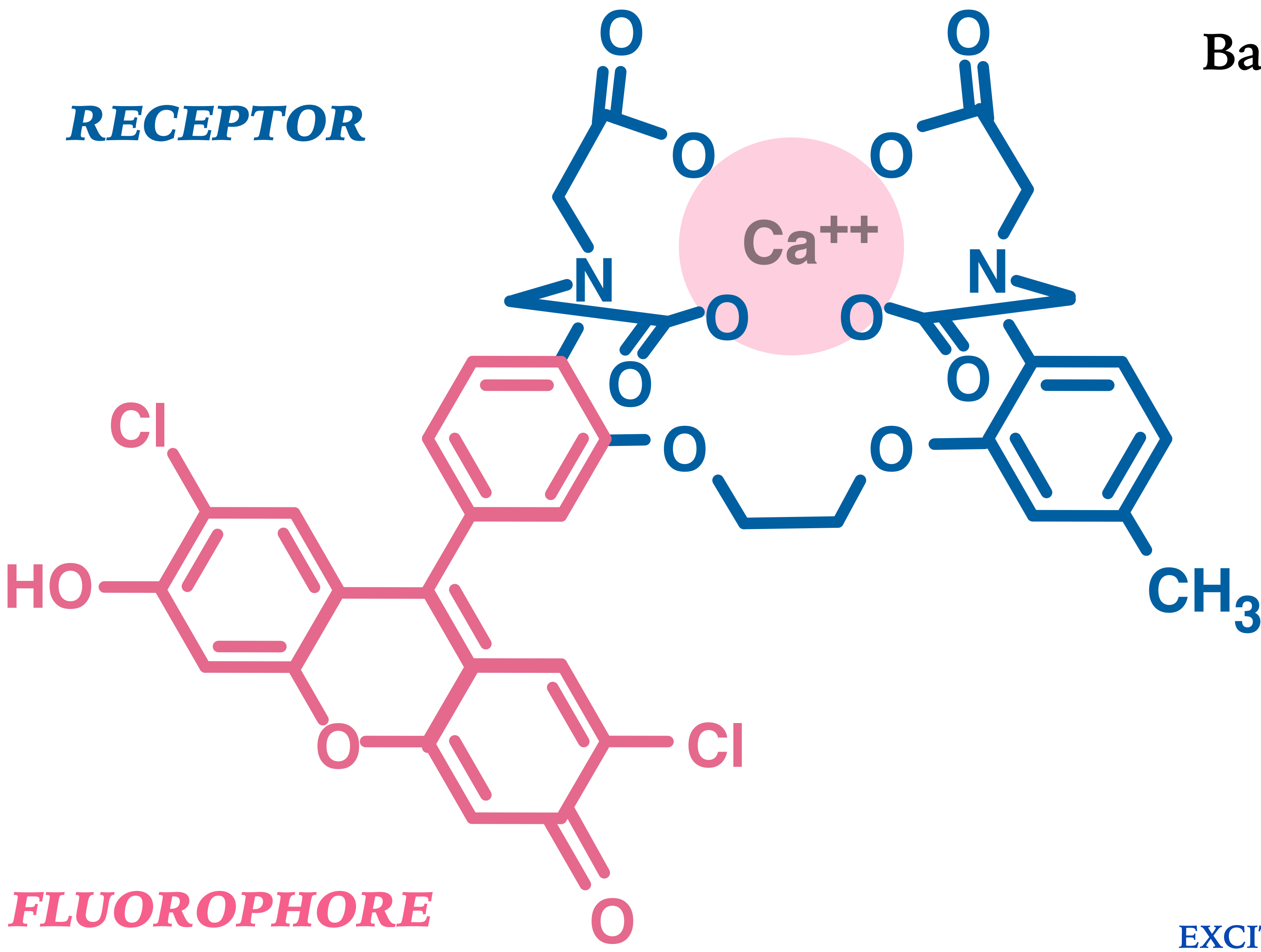
Single Molecule Fluorescence Imaging



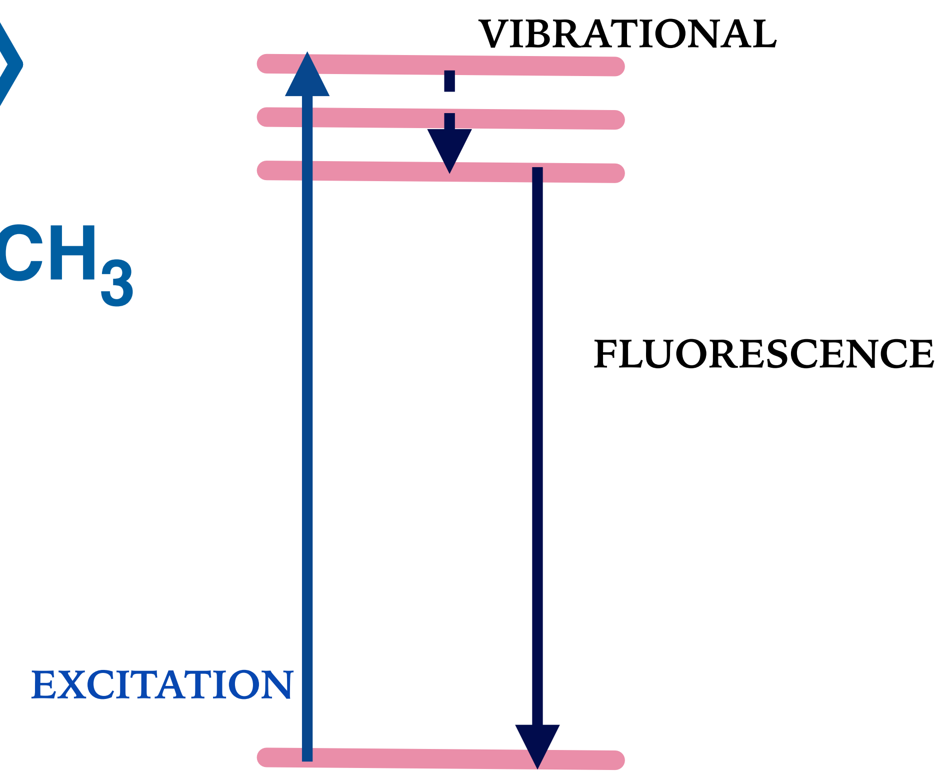
Molecular form inhibits fluorescence



Single Molecule Fluorescence Imaging

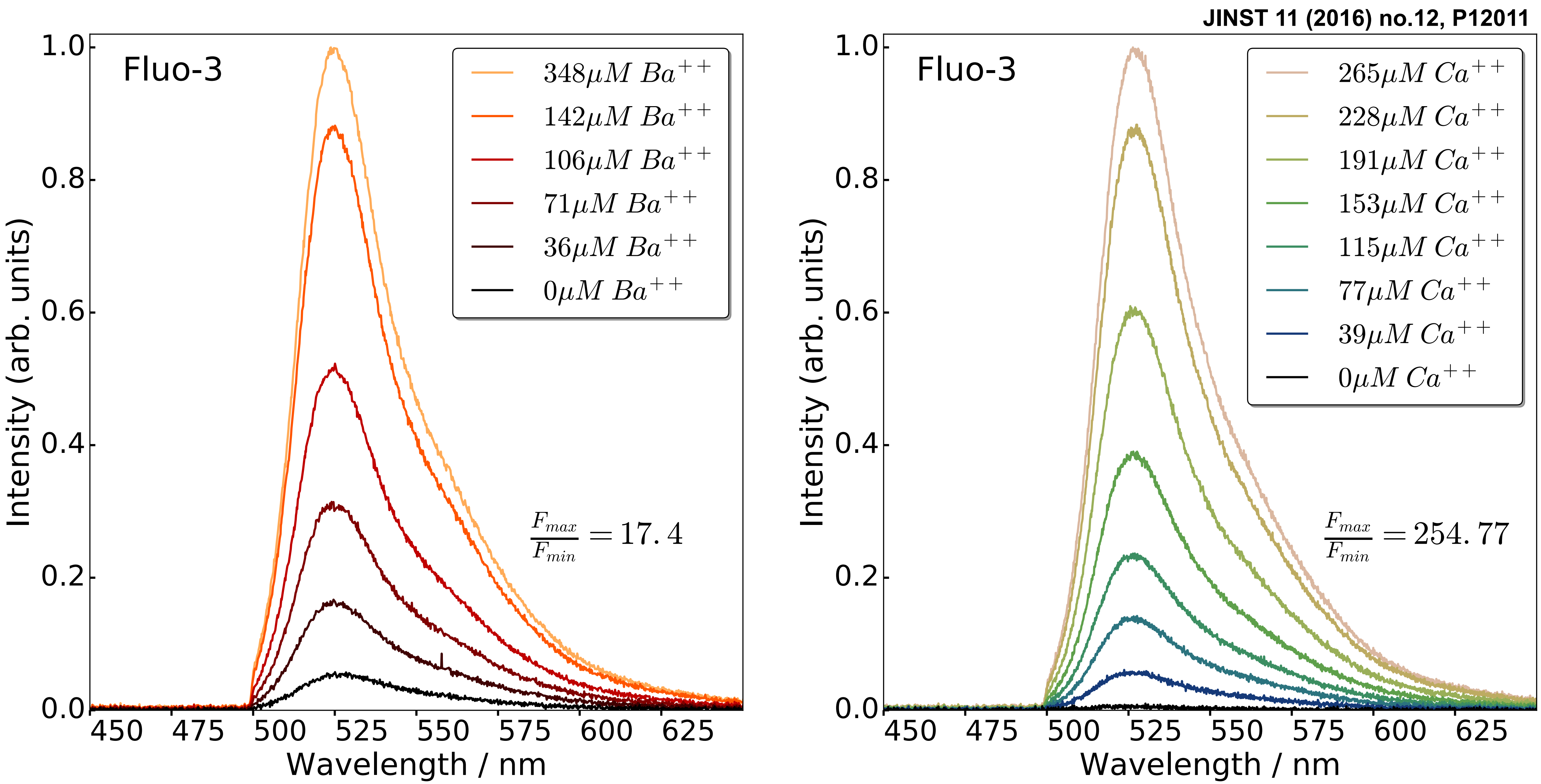


Barium trapping makes de-excitation via fluorescence available.

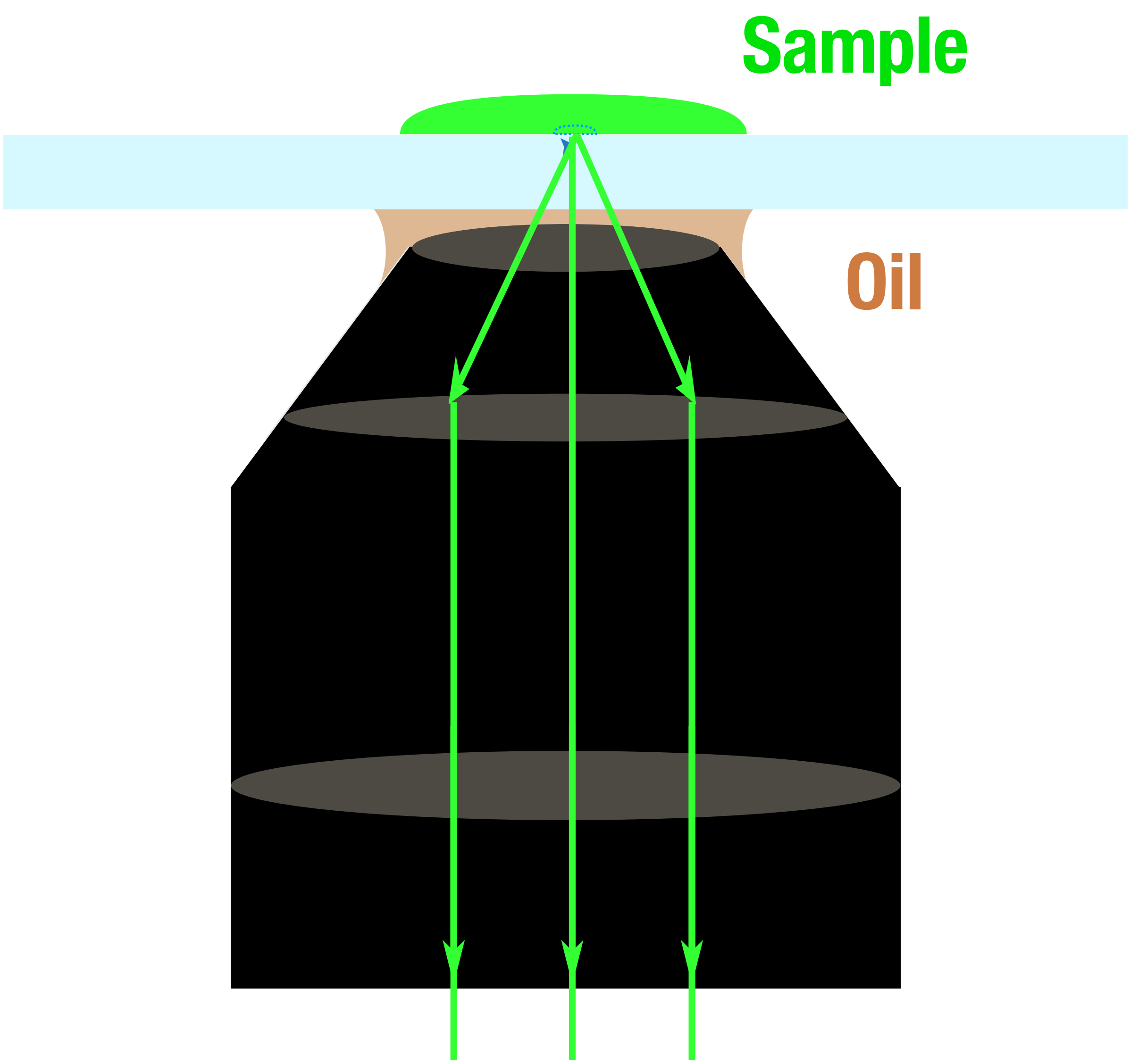


Fluorescent dyes used with Ba^{++}

Demonstrations of comercial dyes in bulk for barium fluorescence.



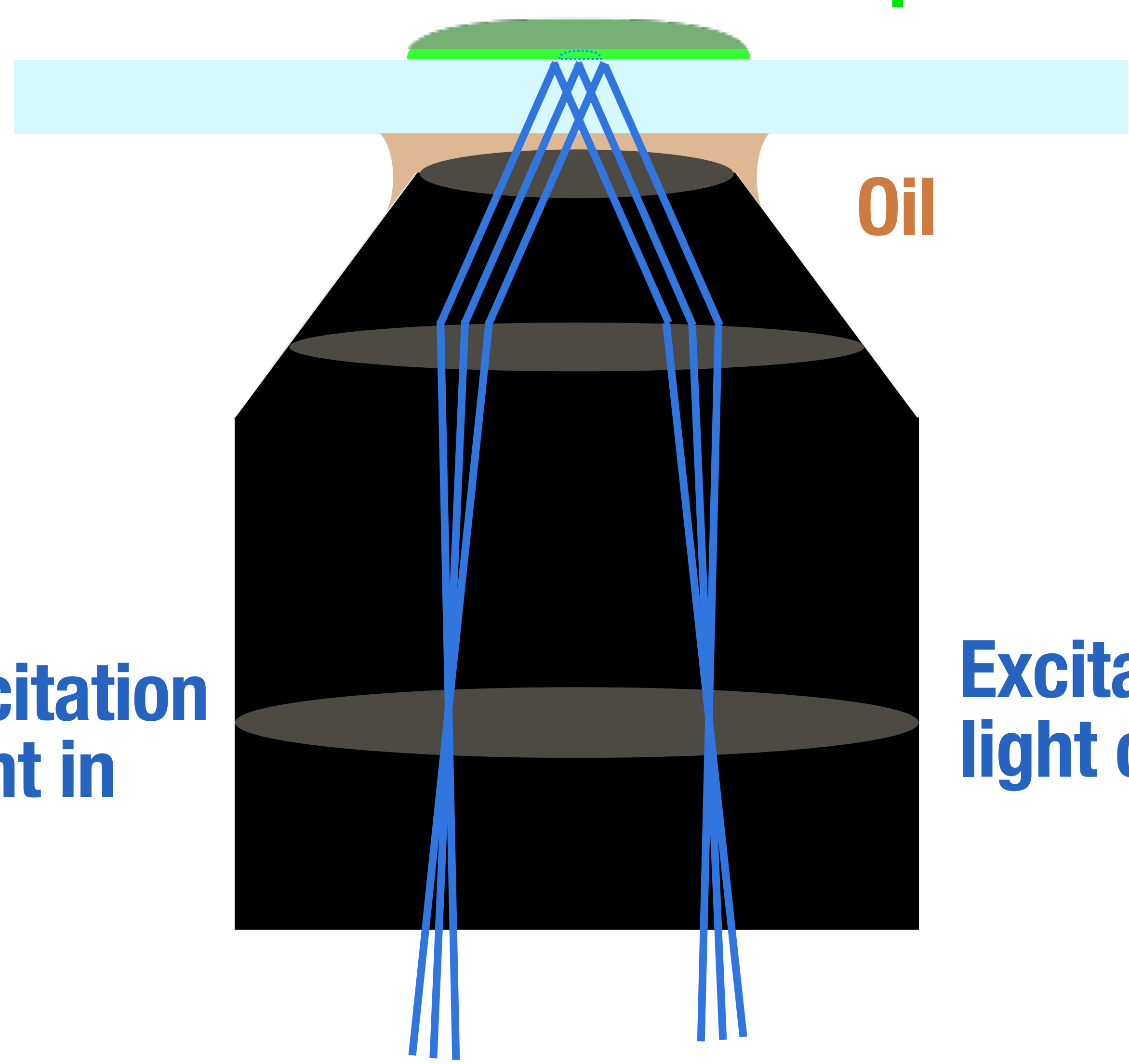
Microscopy for SMFI



Total internal reflection microscopy (TIRF) is used to image the surface of the sample.

Microscope objectives delivers the excitation light.

TIRF Microscopy



Total internal reflection microscopy (TIRF) is used to image the surface of the sample.

Microscope objectives delivers the excitation light.

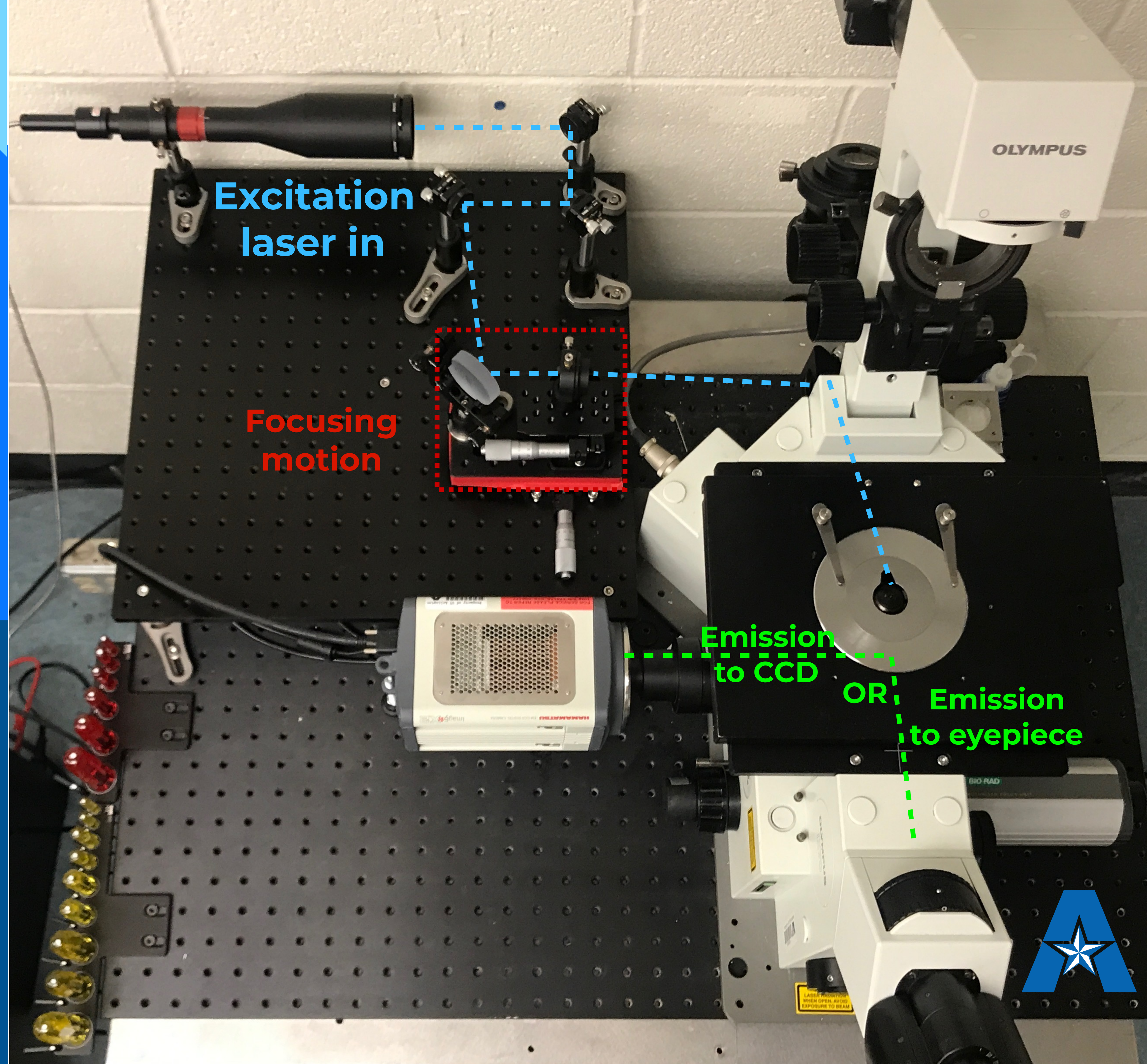
Immersion oil with high, known refractive index prevents the excitation light from deviating between the objective and the sample.

Laser Source

Laser alignment and focusing

TIRF microscopy and imaging

Ba++ SMFI



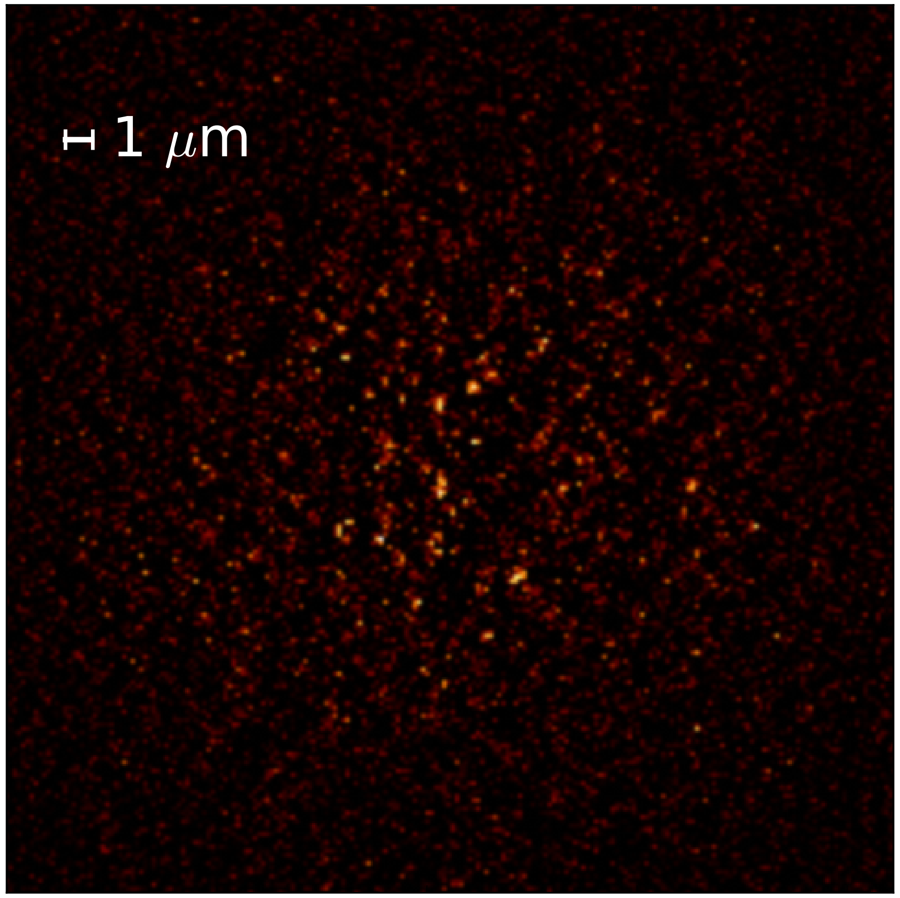
Microscope array at UTA (Generation 1 sensor).

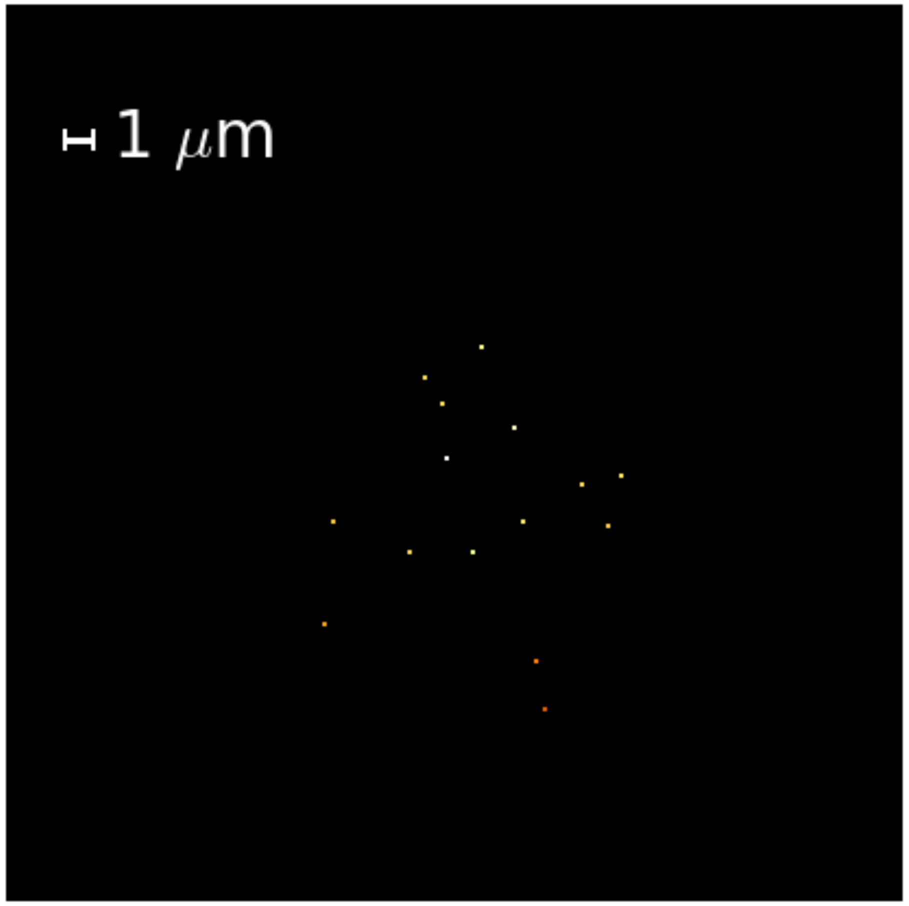
Ba^{++} SMFI images

From the images, we construct a 2D intensity profile

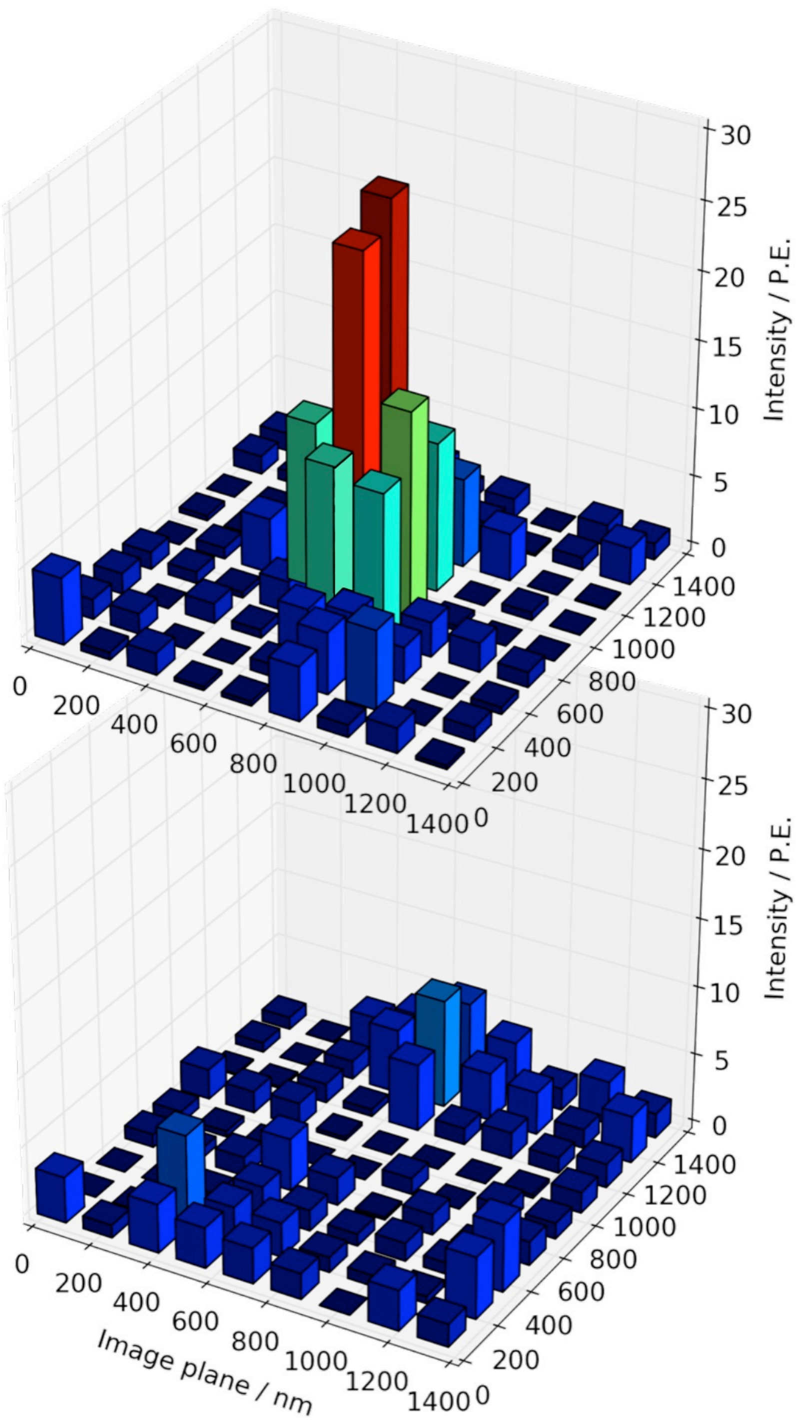
The uncertainty is ~2nm.

Single molecule sensitivity is shown from the time-profile of 5x5 pixels in the image

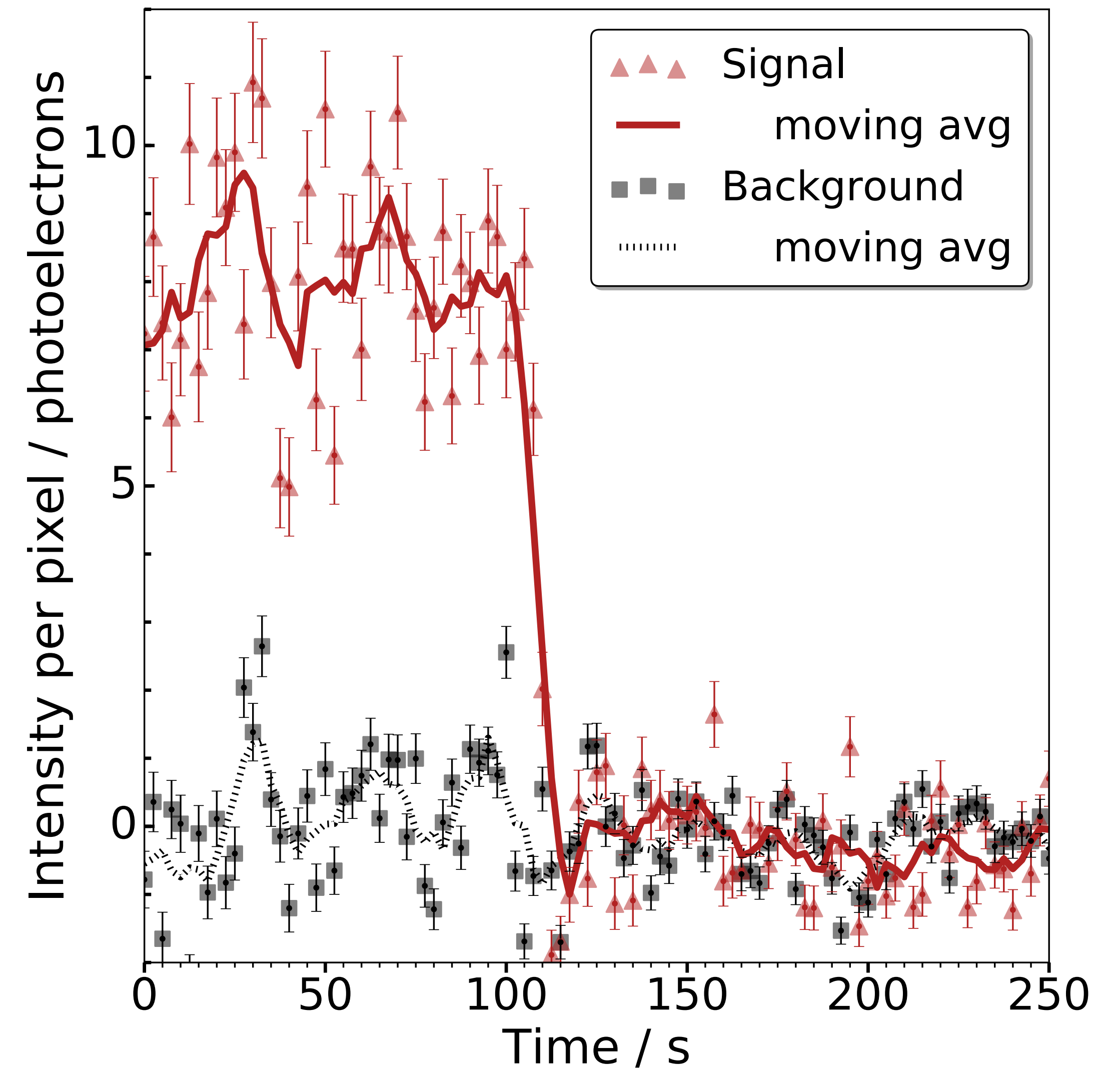




Single Ion Sensitivity



Photobleaching:
Degradation of the fluorescence of the dye. This is the characteristic single-molecule signal.

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Physics NEWS AND COMMENTARY

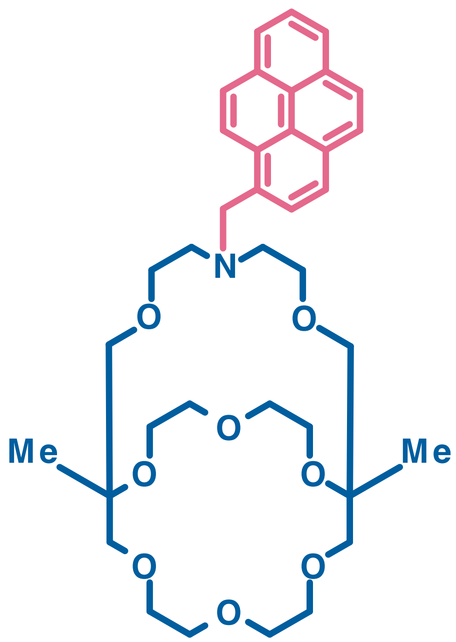
Barium Ion Detector for Next-Generation Neutrino Studies

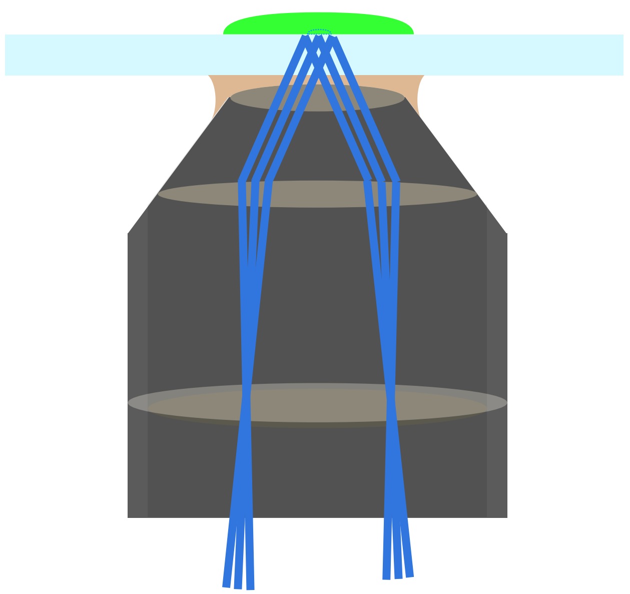
March 26, 2018

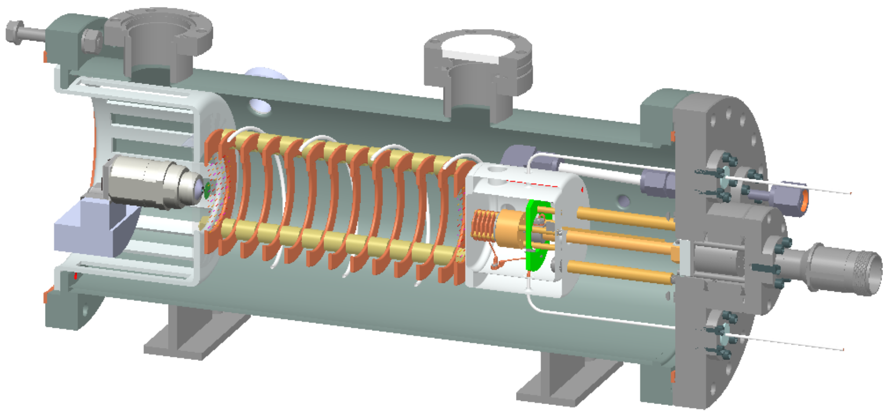
A device that can detect individual barium ions could be the heart of an experiment that takes the next step toward probing the nature of the neutrino.

Focus story on:
A.D. McDonald *et al.* (NEXT Collaboration)
Phys. Rev. Lett. **120**, 132504 (2018)

Can Ba SMFI work in HPXe Gas?







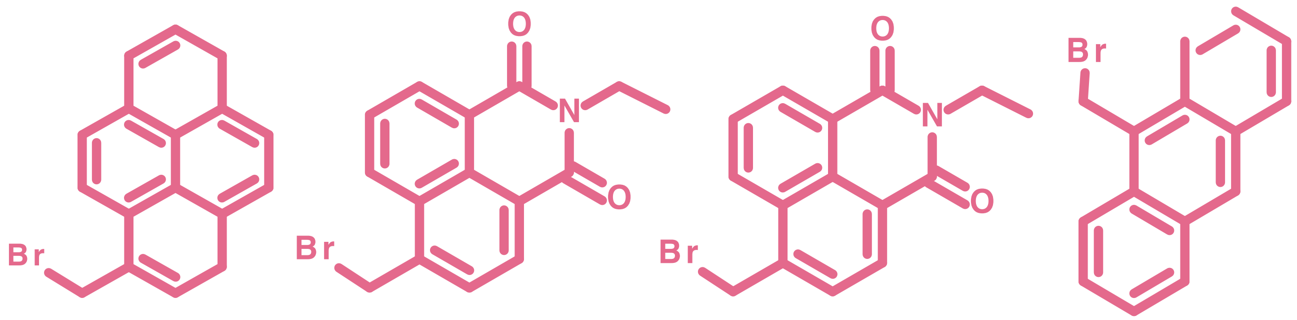
Chemistry and performance of the dye

High Pressure Microscopy

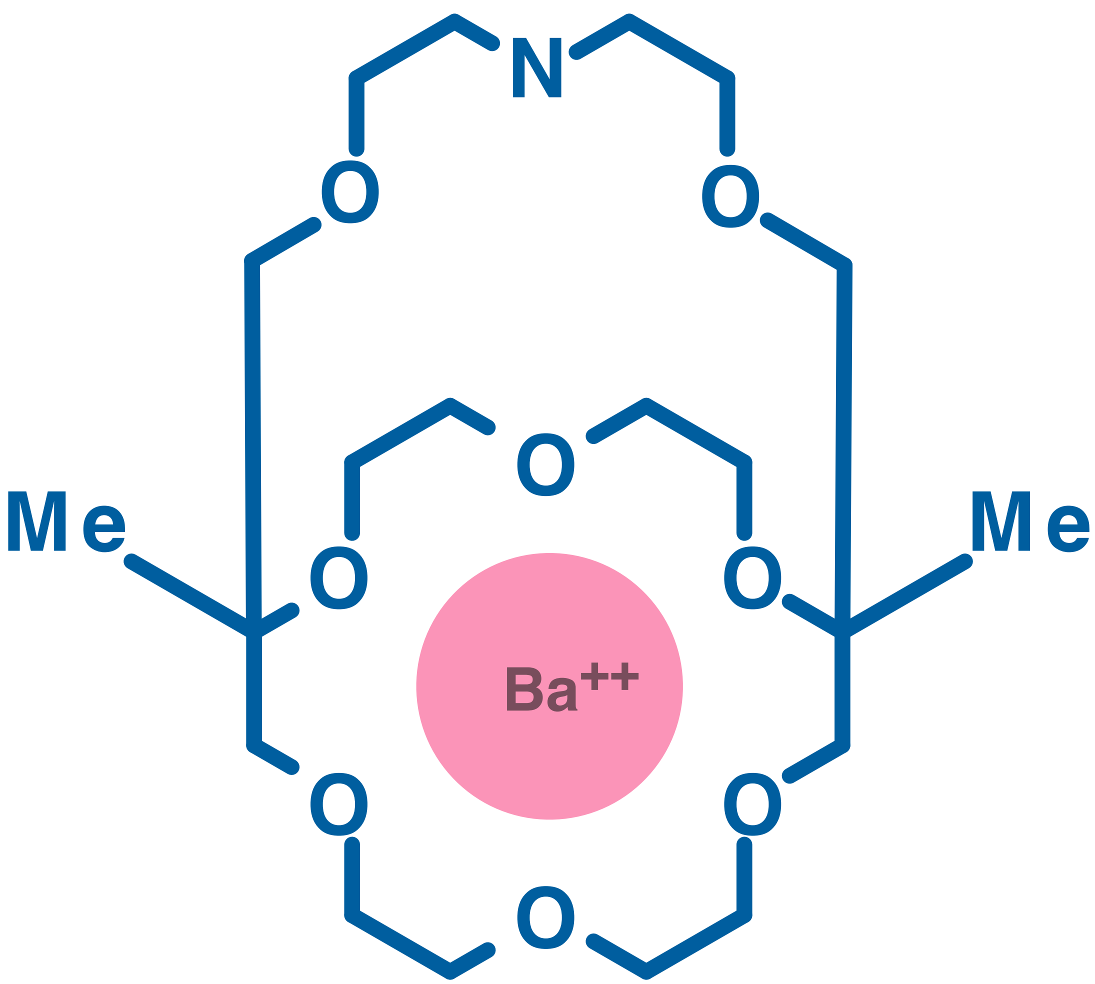
Sensitivity in detector conditions

Developing a Custom Dye

FLUOPHORE



RECEPTOR



Pyrene substituted Monoacytcryptand (MAC)

High sensitivity to Barium.

Selectivity to Barium (from the size of the molecule).

Can be tethered to a substrate by chemical binding.

Can be produced with different fluophores

Producing custom dyes allows for tuning of response to barium.

Ongoing: Benchmarks and characterization of commercial dyes.

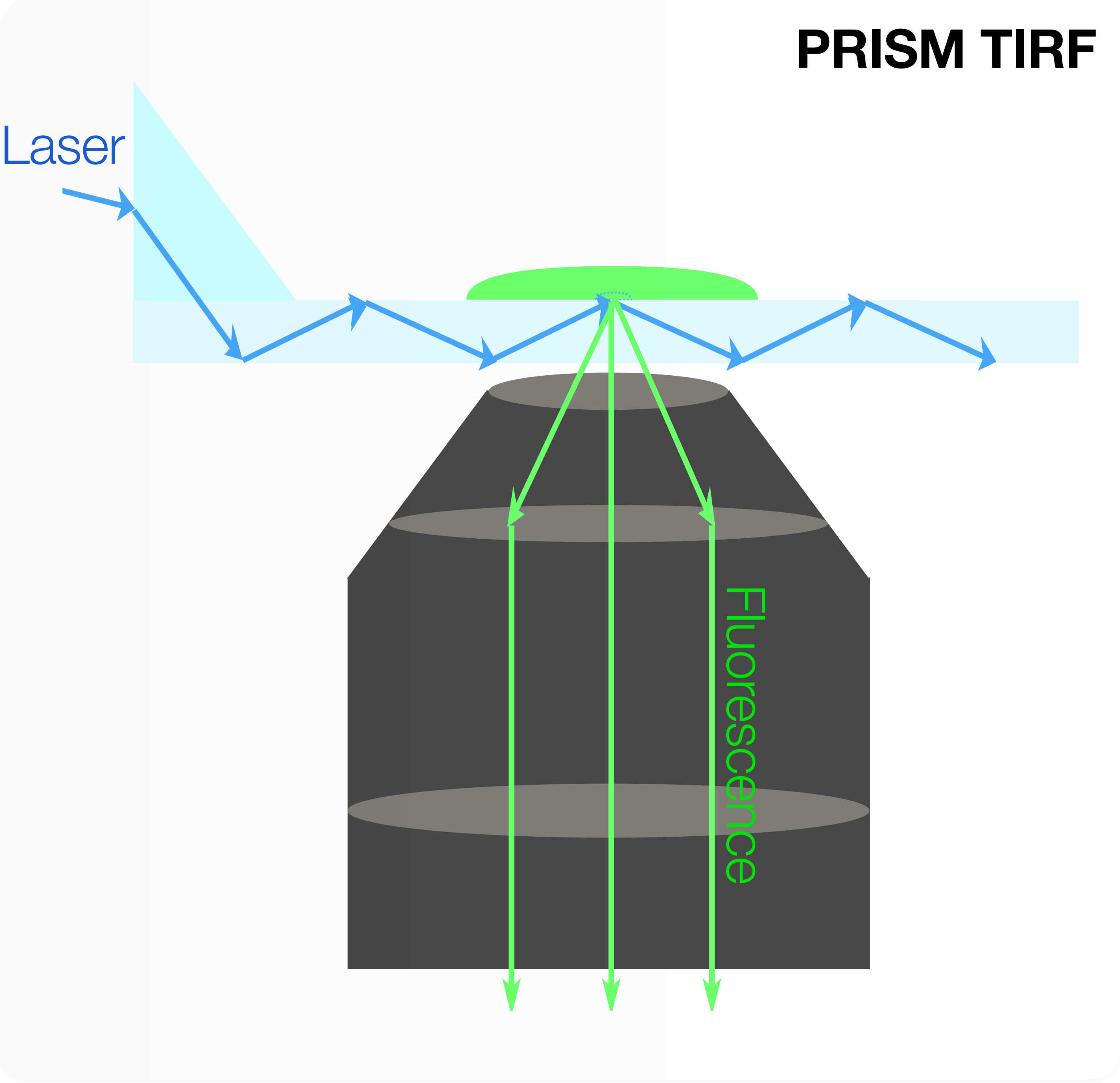
Generation 2 Ba Sensor

Prism TIRF: Delivers the excitation light to the sample without the need for an additional medium.

It also decouples the motion of the objective and the TIRF source:

The **objective** collects the fluorescence light.
The prism delivers the excitation light.

The new sensor requires a new optical array.



Generation 2 Ba Sensor

Requirements:

Remove oil from TIRF array.

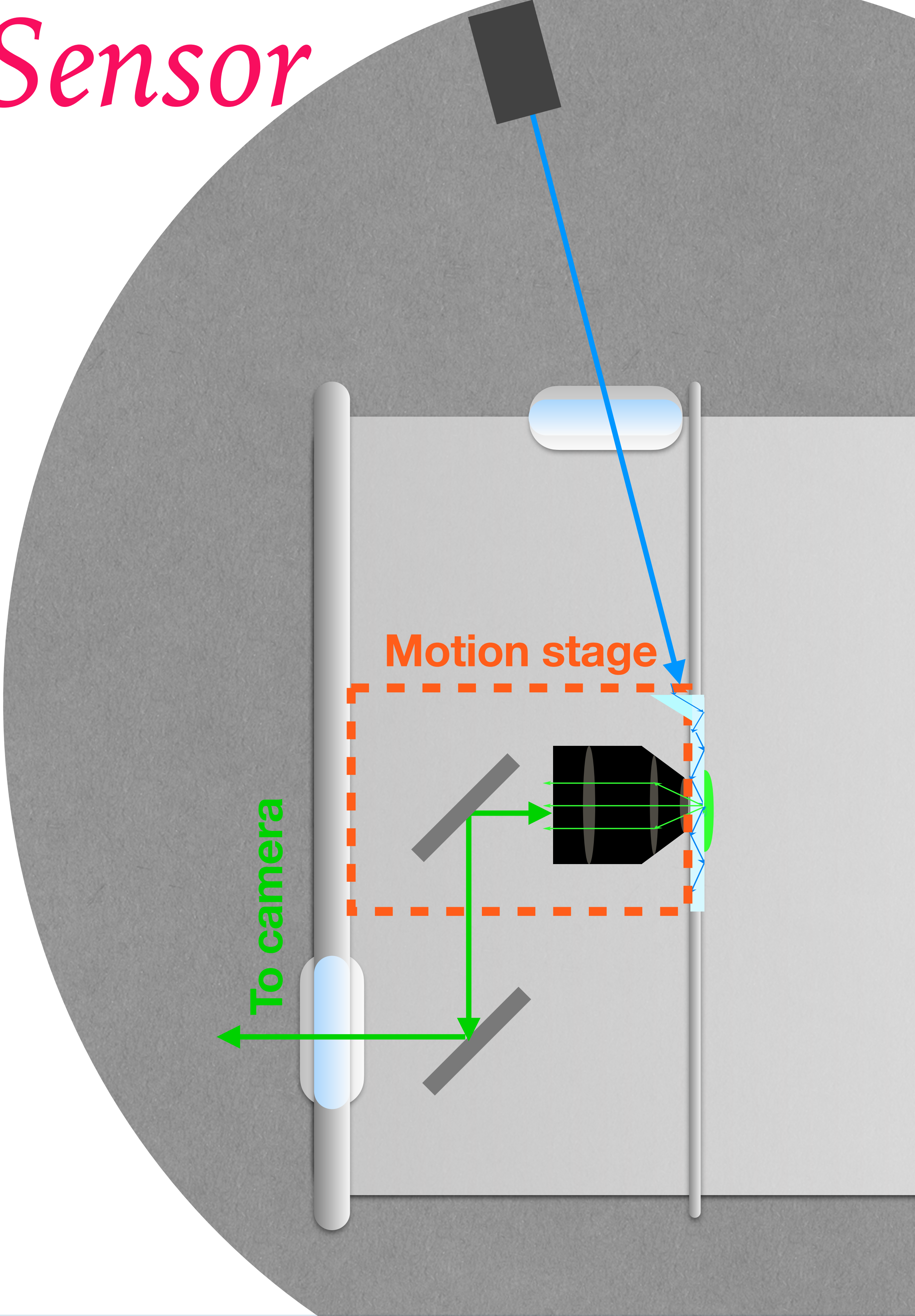
Optical array must operate in HPGXe.

Alignment controllable from outside the vessel.

Objective motion controllable from outside the vessel

Laser delivery through side port, minimizes alignment inside the vessel.

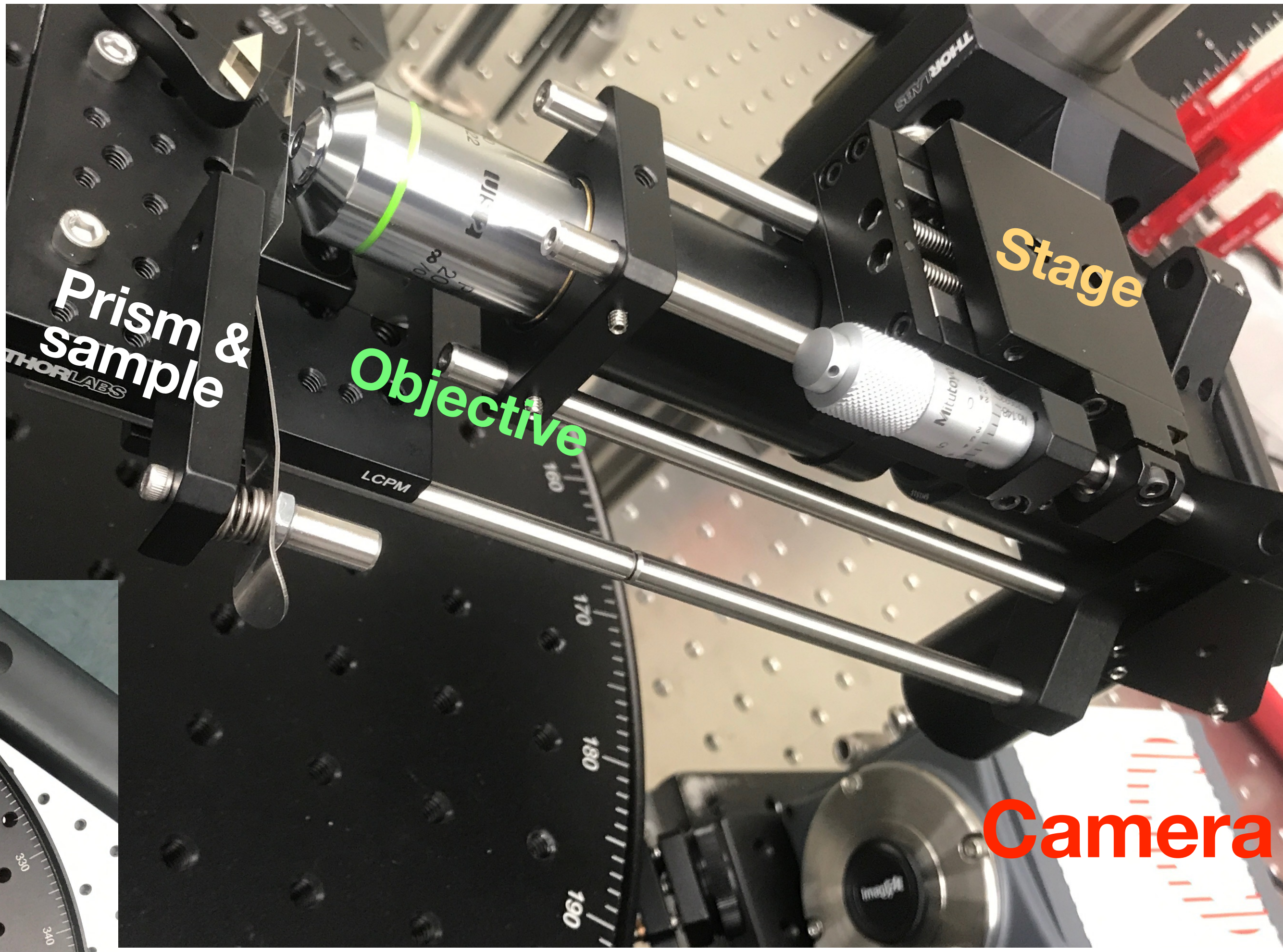
TIRF angle controllable with rotation about prism.

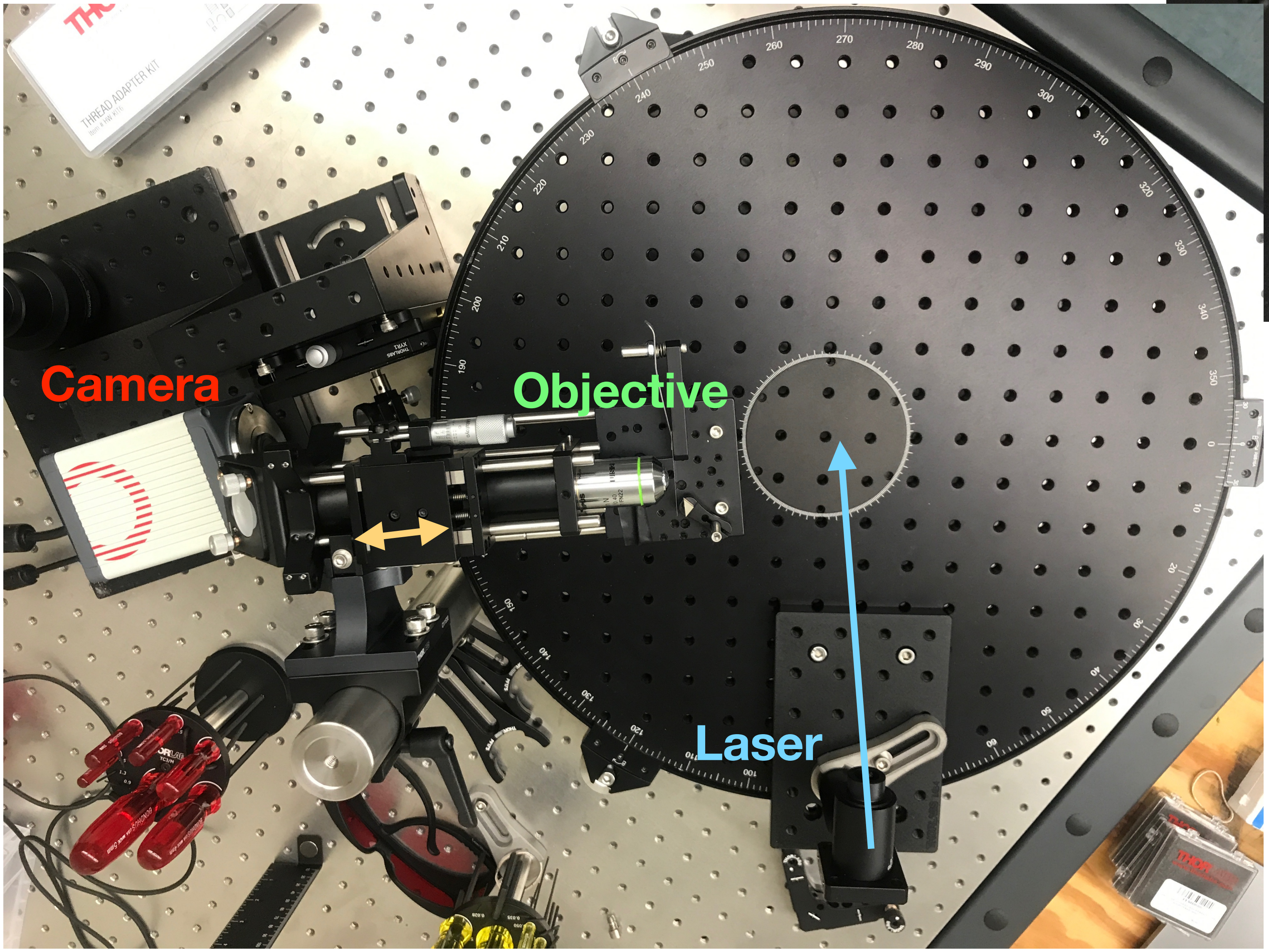


Generation 2 Ba Sensor

Test Stand at UTA is being developed.

TIRF microscopy to be tested outside pressure vessel is step 1 of R&D
First calibration images in the following months!





First calibration images in the coming months!

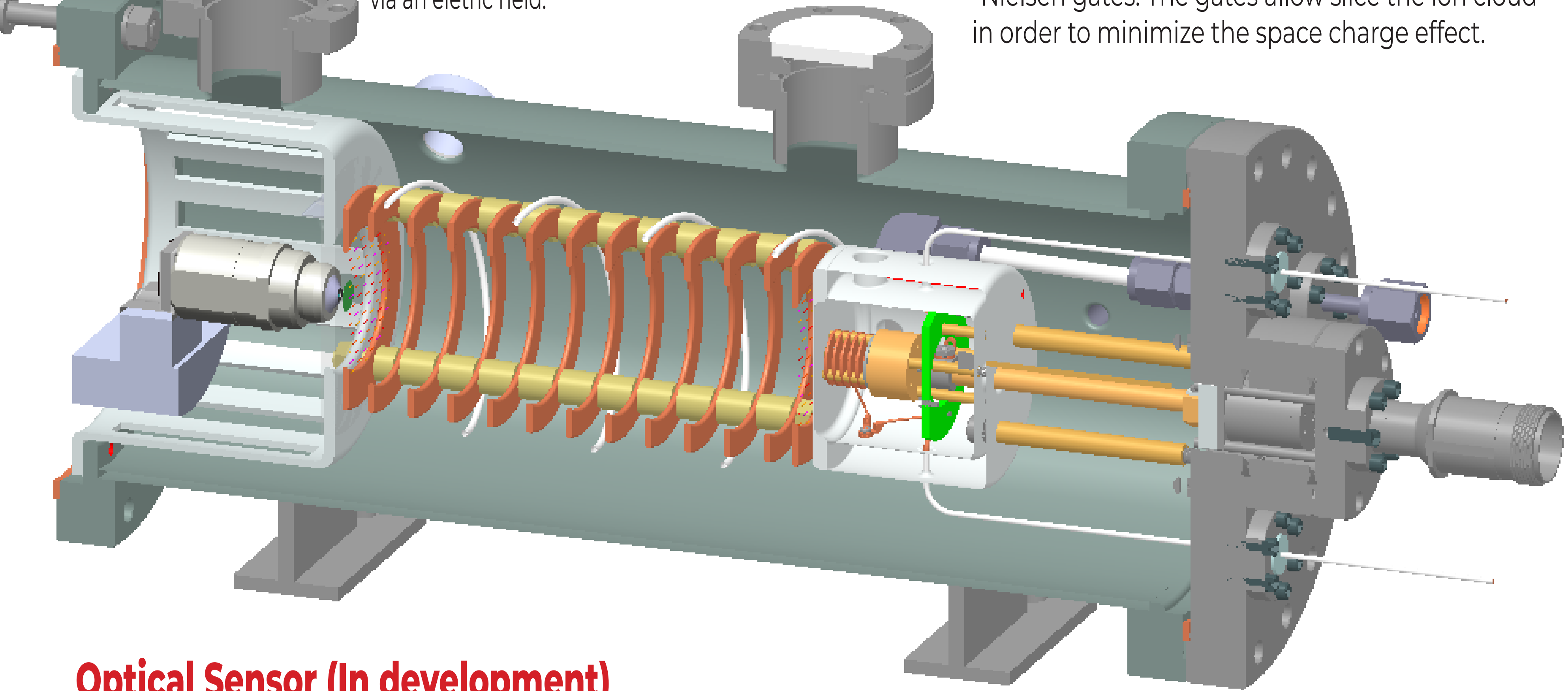
Single ion HP Xe test-stand

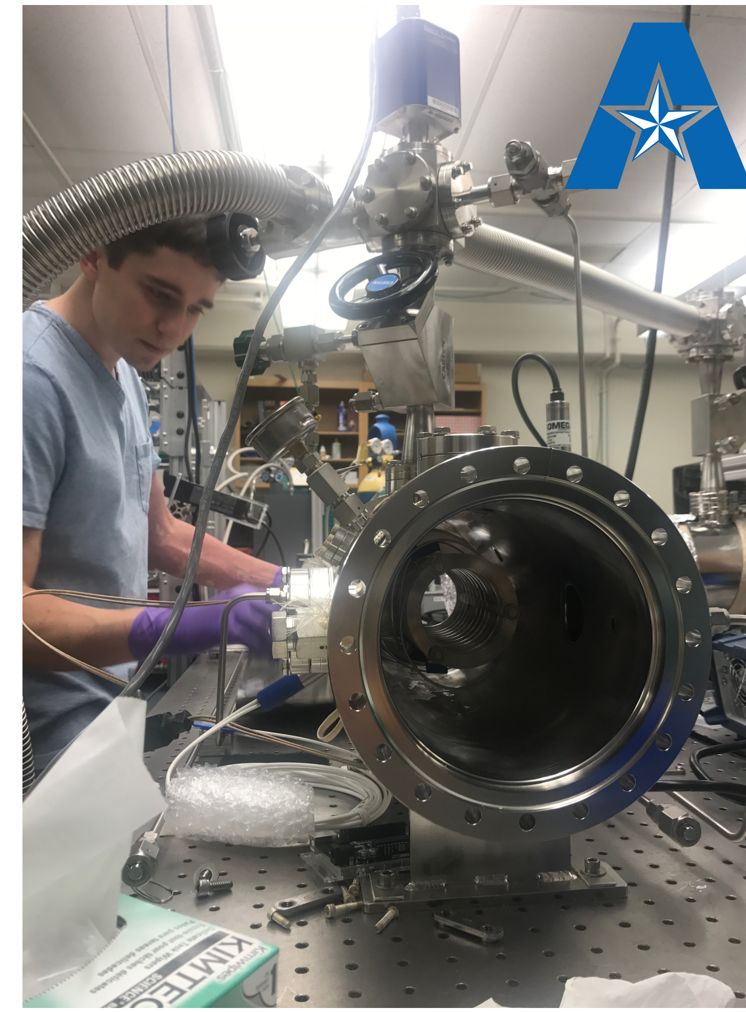
Readout Plane

Allows the use of a sensitive eletrical amplifier for optical readout. The ions are guided here via an eletric field.

Gated Drift Region

20cm uniform drift region using Bradbury -Nielsen gates. The gates allow slice the ion cloud in order to minimize the space charge effect.



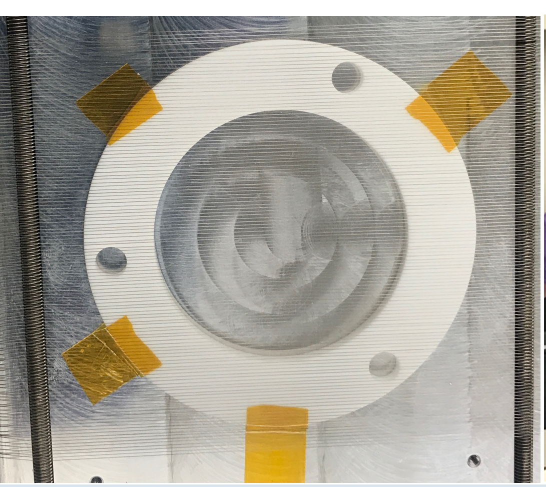


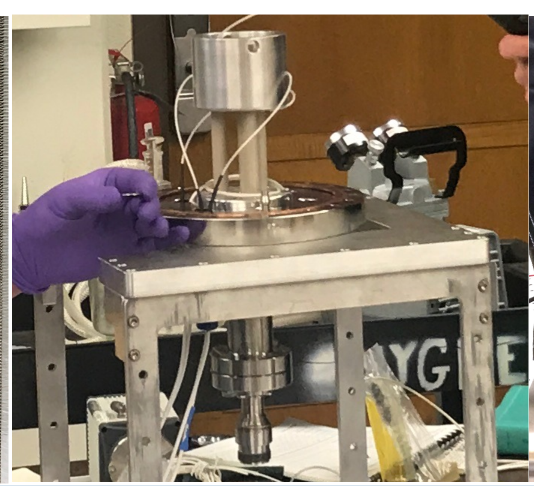
Optical Sensor (In development)

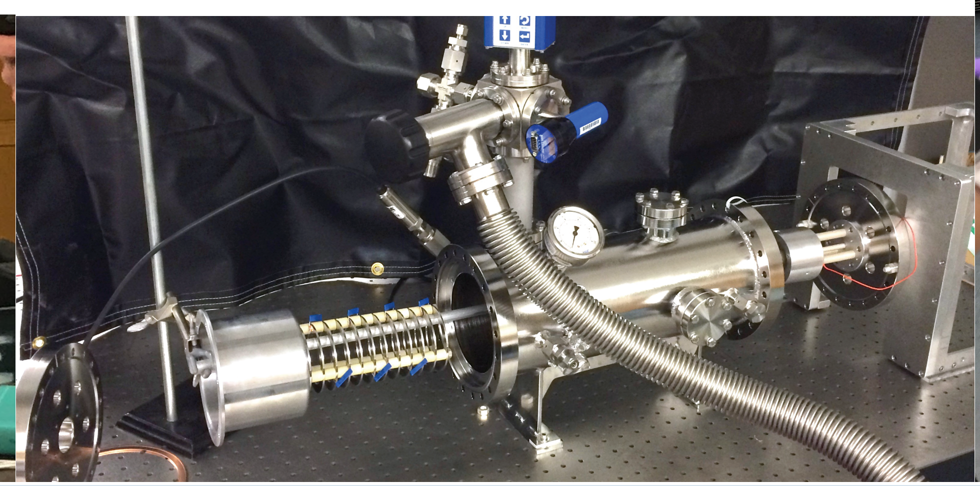
The development of a sensor which can achieve single molecule sensitivity inside a high pressure xenon gas test stand is ongoing at UTA. **This incarnation of our barium sensor will be the first single ion sensor of its kind.**

Ion Source

Adjustable, plated needle and ring electrode that accomadate various pulse and pressure conditions. Ions from the plated materal will drift in the parent gas.



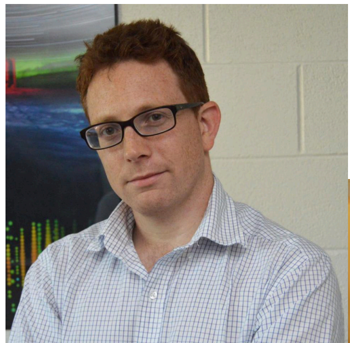




Current progress on R&D

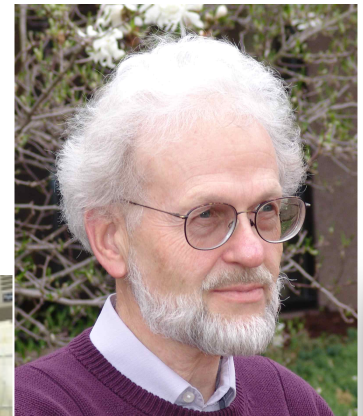
Detecting the barium daughter in ^{136}Xe 0-νββ decay using single-molecule fluorescence imaging techniques

David R. Nygren



Ben Jones

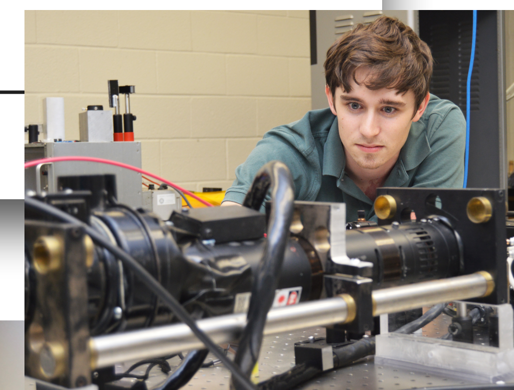
Frank Foss



David Nygren

Single Molecule Fluorescence Imaging as a Technique for Barium Tagging in Neutrinoless Double Beta Decay

B. J. P. Jones, A. D. McDonald and D. R. Nygren



Austin McDonald

Fernanda Psihas

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

E. Bainglass,[1,*] B.J.P. Jones,[1,†] F. W. Foss Jr,[2] M. N. Huda,[1] and D. R. Nygren[1]

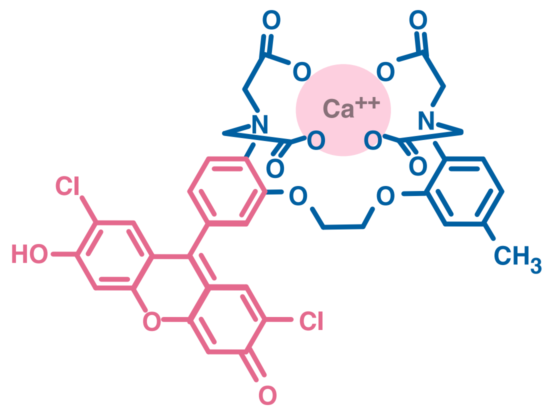
Powan

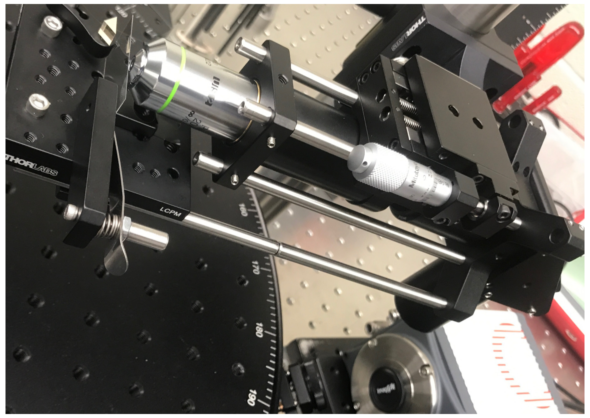
UTA Undergrads (not pictured):
Denise Huerta, Jerry Tram, Ryan Clark, Zane Miller.

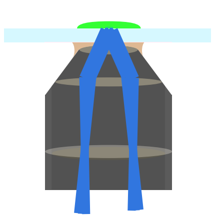
Demonstration of Single Barium Ion Sensitivity for Neutrinoless Double Beta Decay using Single Molecule Fluorescence Imaging

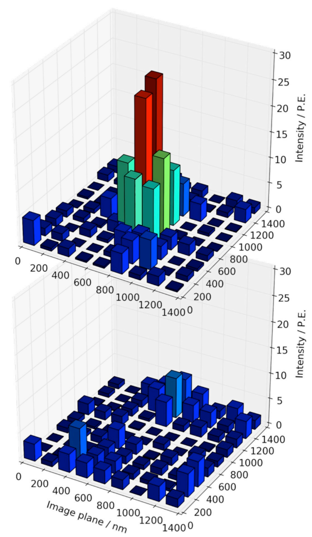
(The NEXT Collaboration)

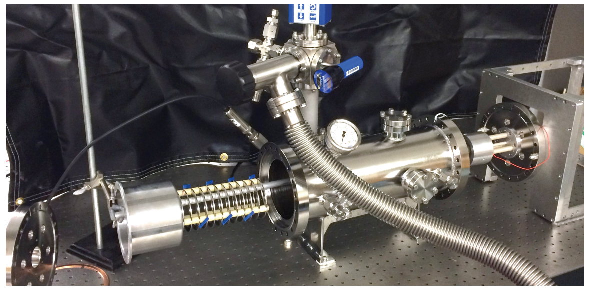
Summary









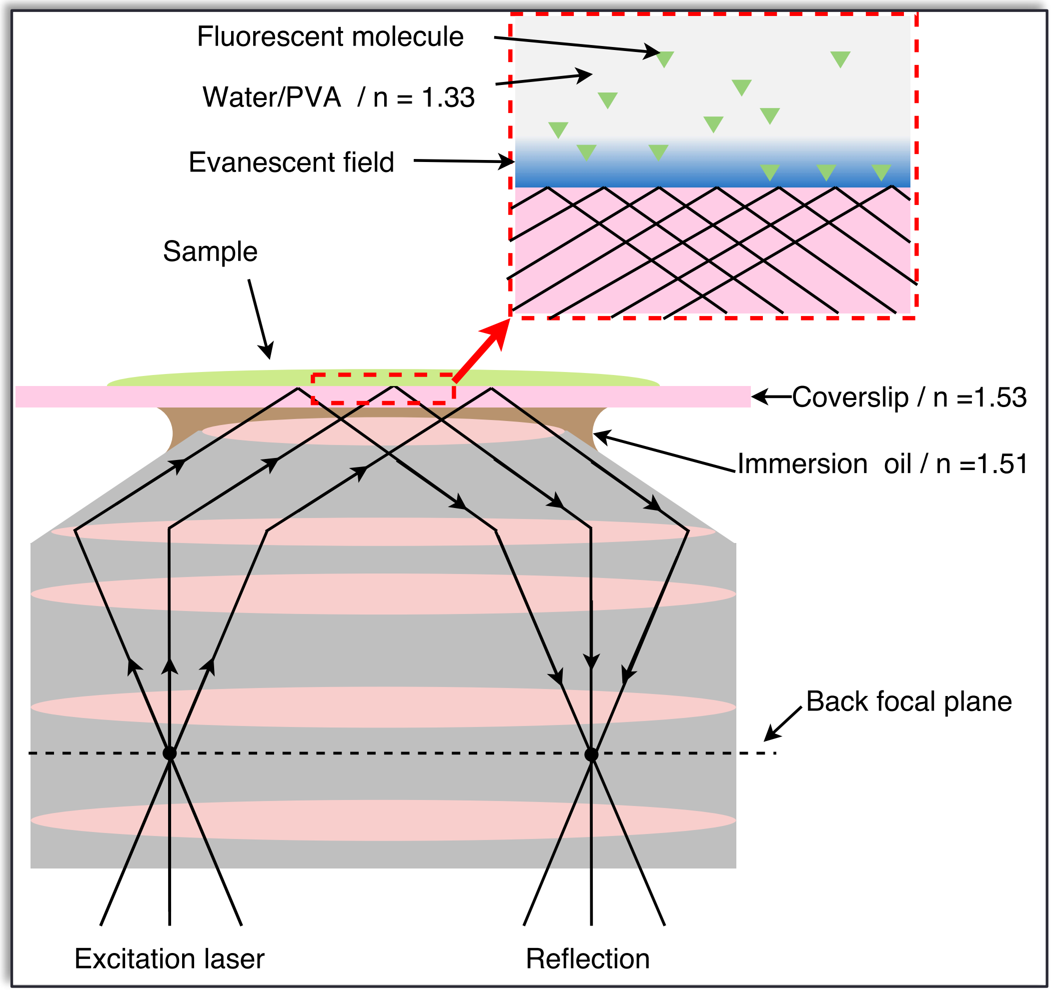


SMFI for barium tagging for 0vBB on NEXT has been demonstrated!

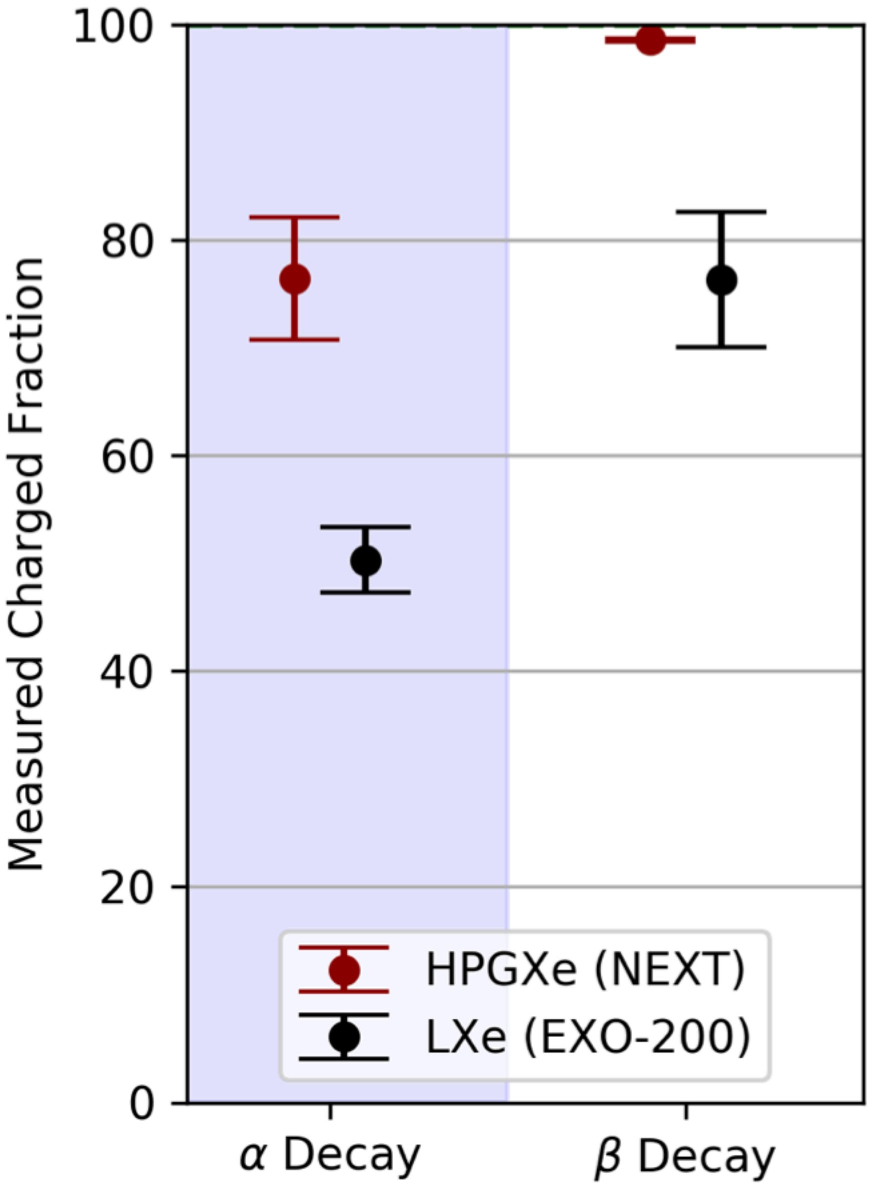
Current R&D program is focused on a demonstration of single ion sensitivity in detector-like conditions.

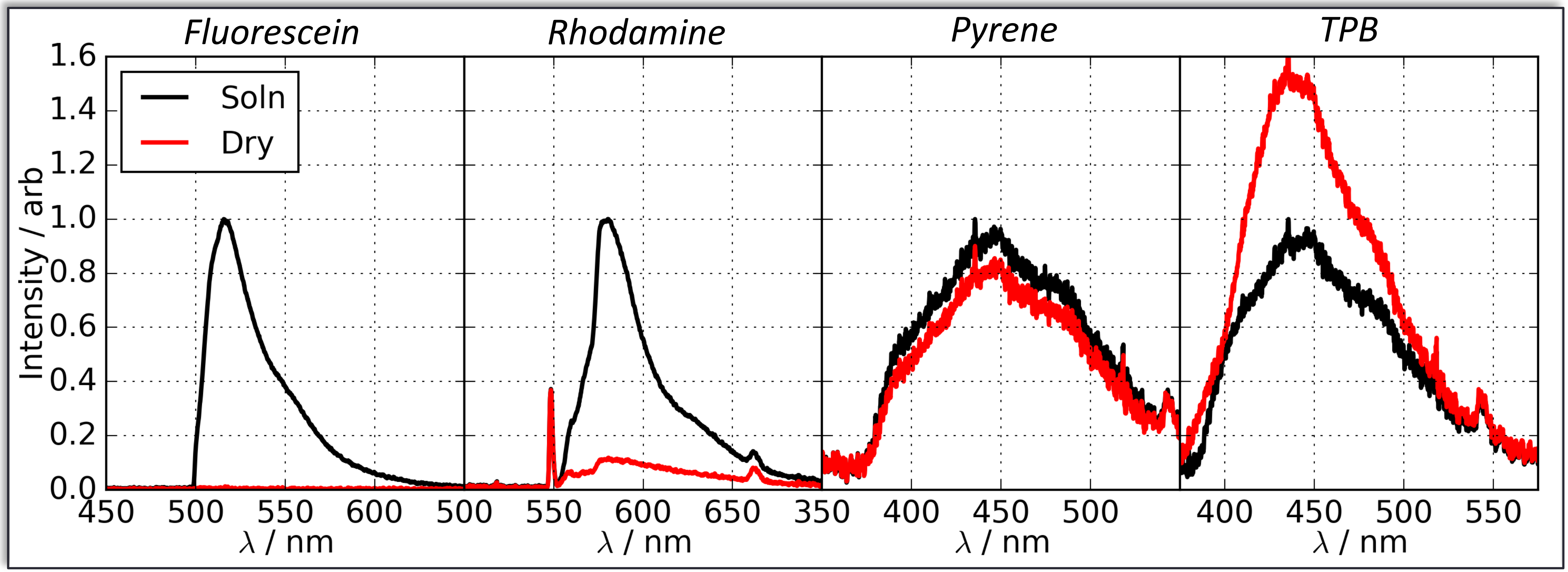
Test-stands at UTA for prism TIRF, ion mobility measurements and HPXe single molecule imaging.

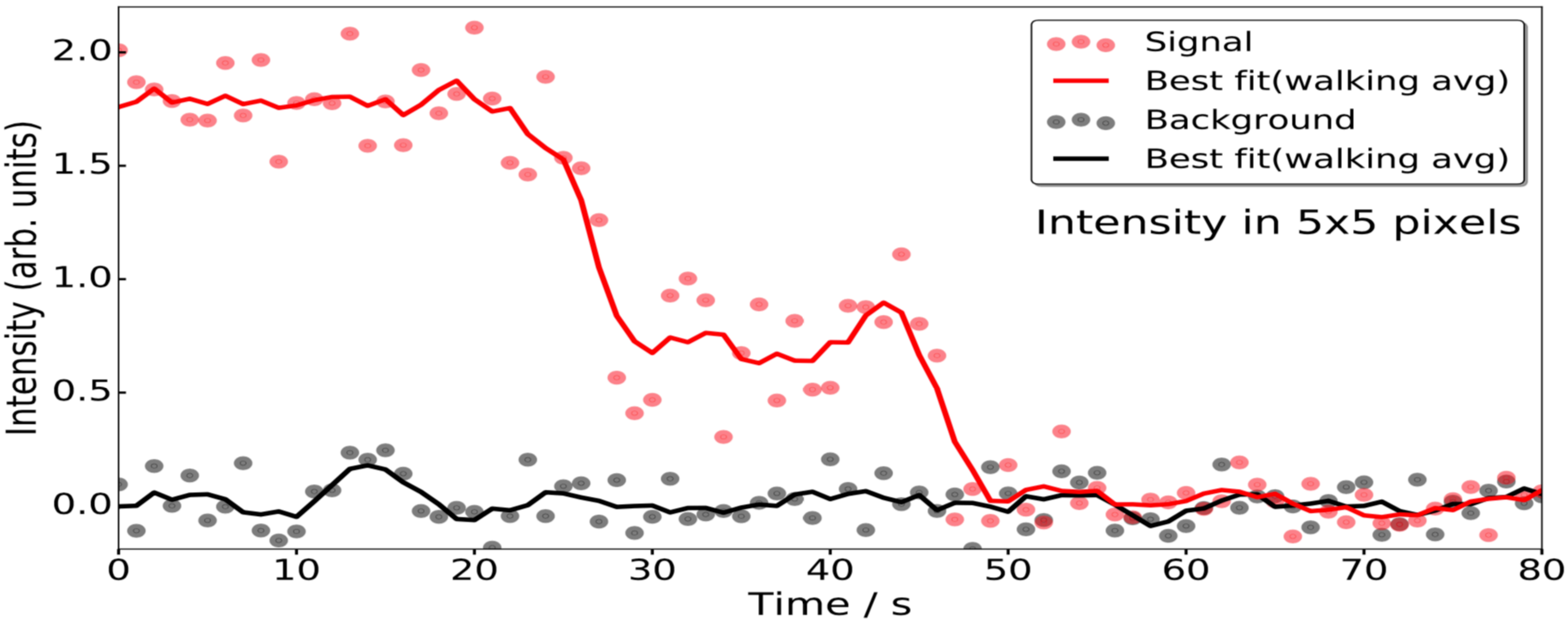
Stay tuned for next steps toward a background free technology for NEXT.

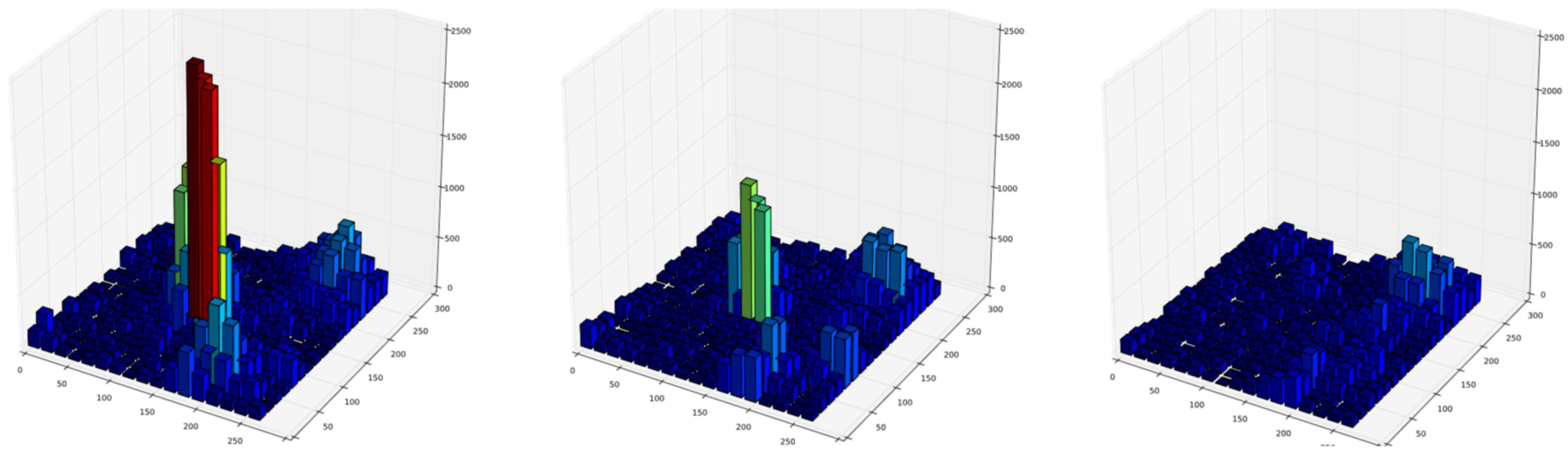


Ionic Charge State in Liquid and Gas




Fluorescein
Rhodamine
Pyrene
TPB
Soln
Dry
Intensity / arb
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
450 500 550 600
500 550 600 650
350 400 450 500
400 450 500 550
λ / nm


Signal
Best fit(walking avg)
Background
Best fit(walking avg)
Intensity in 5x5 pixels
Intensity (arb. units)
Time / s



Ion focussing