BETTER 0NUBB THROUGH BIOCHEMISTRY

SEARCHING FOR MAJORANA NEUTRINOS IN XENON GAS WITH SINGLE MOLECULE FLUORESCENCE IMAGING

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- Q: "What gives you hope that we could achieve anything like what you guys achieved in constructing the Standard Model today?"

- A. "The obvious answer is neutrino masses, which I think clearly take us beyond the standard model, and clearly represent something coming down from a very high energy scale."

Stephen Weinberg at the SLAC Summer Institute this year

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac12\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac12\partial_\mu H\partial_\mu H - \\
&\tfrac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
&W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac18 g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^- +4H^2\phi^+\phi^- +2(\phi^0)^2H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac14 g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
&\tfrac14 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
&\bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\tfrac43 s_w^2 - \\
&1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+ \\
&\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \\
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)] + \tfrac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1- \\
&\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \tfrac g2\tfrac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \\
&\tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- - \\
&\partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y - \\
&\partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) + igs_wA_\mu(\partial_\mu\bar X^+ X^+ - \\
&\partial_\mu\bar X^- X^-) - \tfrac12 gM[\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H] + \\
&\tfrac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \\
&igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \tfrac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]
\end{aligned}
$$

← The standard model Lagrangian we all know and love

Write down all terms that are:

1) Consistent with the symmetries groups of the SM

Gauge invariance:

$$SU(3) \times SU(2)_L \times U(1)_Y$$

+ Lorentz invariance

2) Renormalizible

If SM is a low energy effective theory:

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \ldots$$

All that stuff

Dimension-5 terms

Dimension-6 terms

Etc…

E_{new} > 10 TeV — **Seems likely (LHC)**

E_{new} ~ 10^{13} TeV — **Maybe? (GUT scale)**

If SM is a low energy effective theory:

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \ldots$$

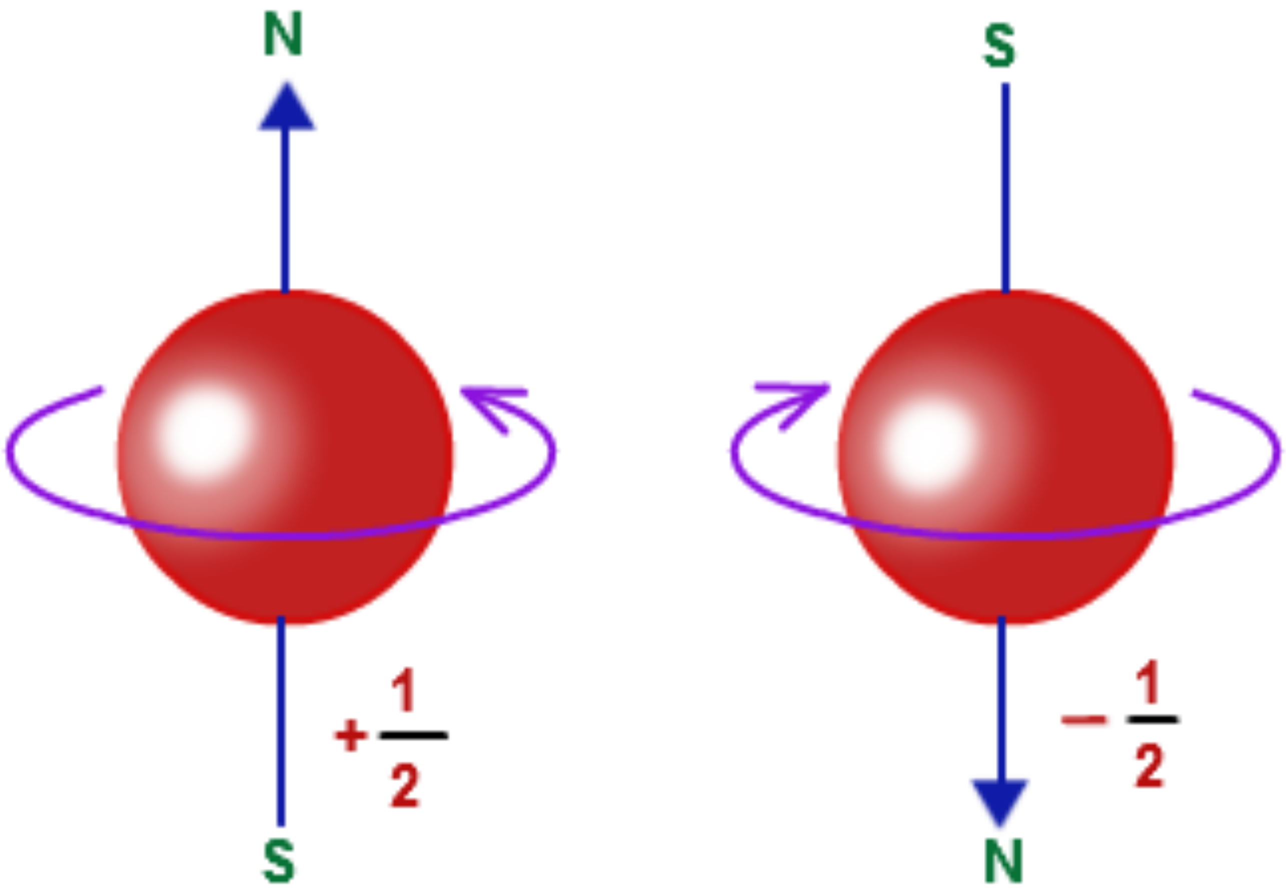
- The only dimension-5 operator one can add obeying SM gauge symmetry:

$$\boxed{\frac{L_1}{E_{new}} = y_{ij} \frac{\nu^i H \nu^j H}{E_{new}}}$$

Weinberg 1979.

- This term does an important thing - it makes neutrinos Majorana particles, with mass suppressed by the new physics scale.
- And it makes the theory non-renormalizible – implying there must be something else at high scale (see also: Seasaw)

The Weirdness of Majorana Fermions



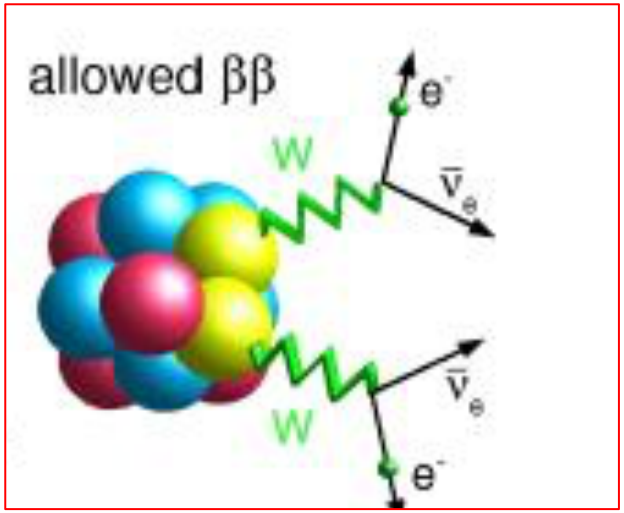
Behaves like matter **Behaves like antimatter**

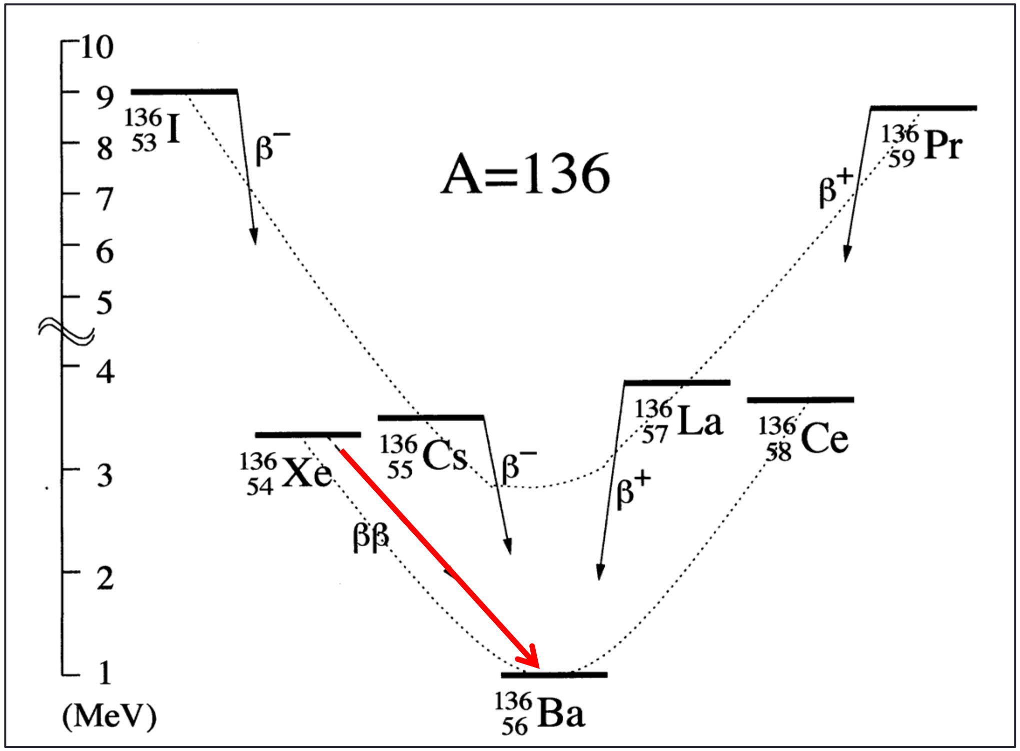
Double-Beta Decay

A rare radioactive process, energetically allowed for some even-even nuclei where $m_{Z+1} > m_Z > m_{Z+2}$

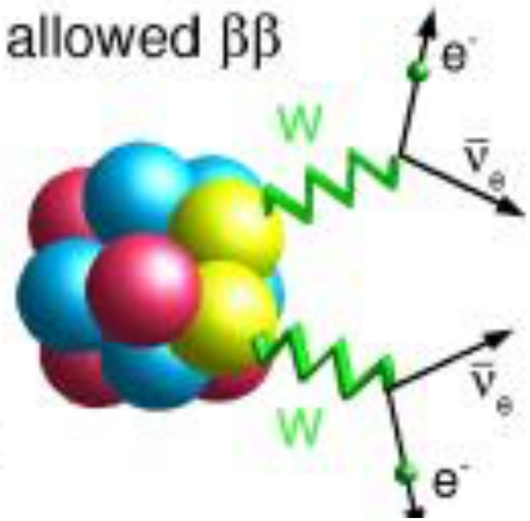
- $(Z,A) \rightarrow (Z+2,A) + e^-_1 + \underline{\nu}_1 + e^-_2 + \underline{\nu}_2$

Discovered in 1987 in ^{82}Se and now seen in multiple isotopes





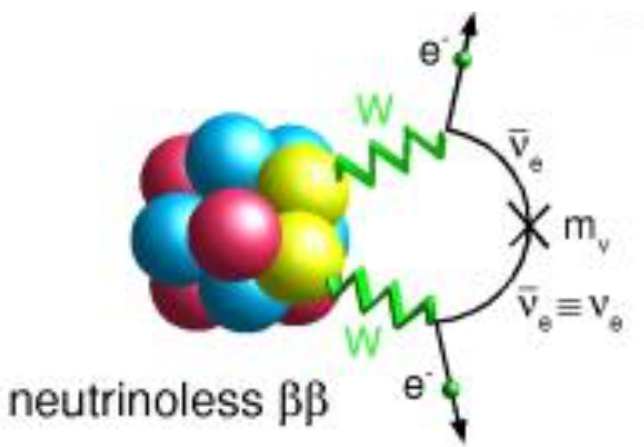
Types of double beta decay



A known standard model process and an important calibration tool

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

Final state: $e^- e^- \nu_e \nu_e$



Observation would prove that the neutrino is a Majorana fermion

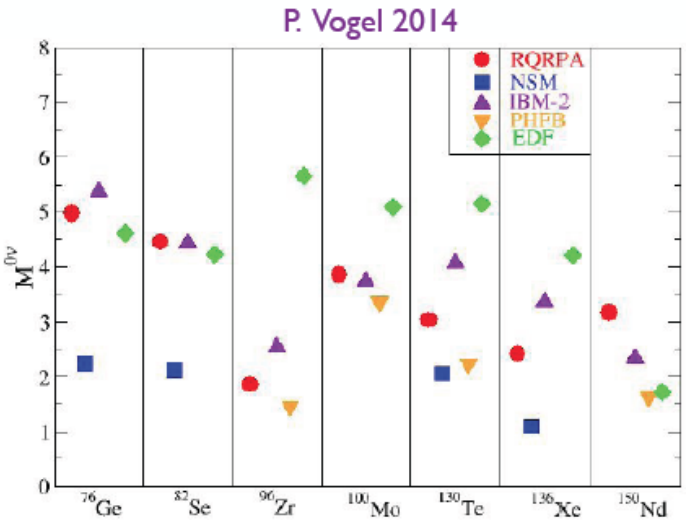
$$T_{\frac{1}{2}} \approx \boxed{????}$$

Final state: $e^- e^-$

Tale as old
AS TIME.
Song as old
AS RHYME.

1. This formula →

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

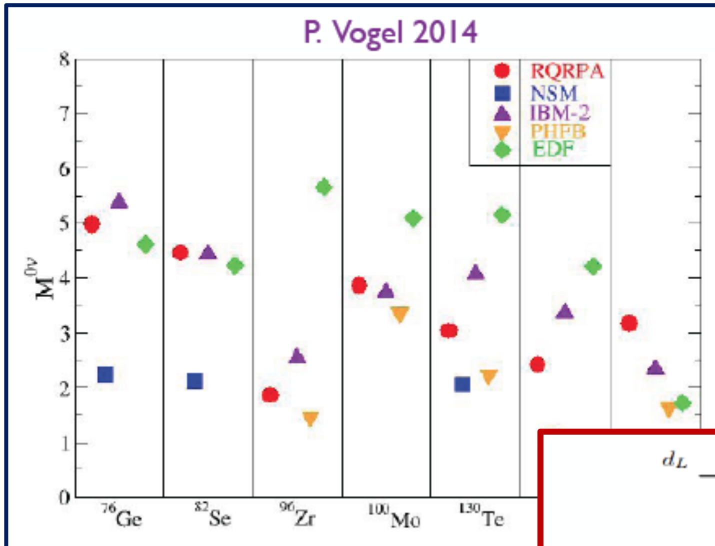


Matrix elements for "standard mechanism"

1. This formula →

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

← 2. Nuclear matrix elements



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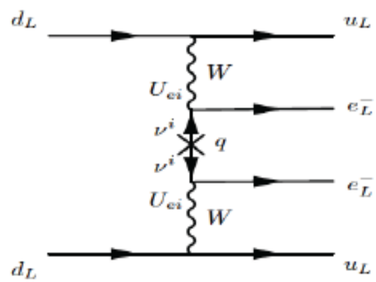
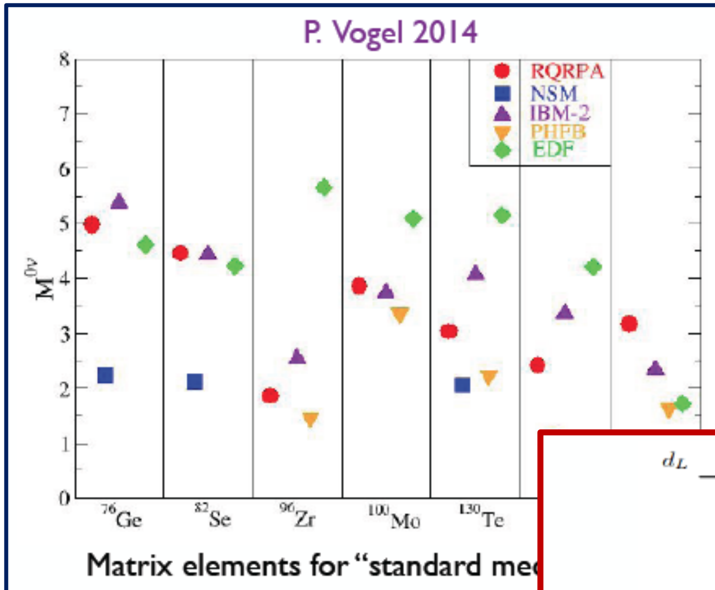


$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} g_A^4 \left|M^{(0\nu)}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$

$$\boxed{\langle m_{\beta\beta}\rangle^2 = |\cos^2\theta_{12}\cos^2\theta_{13} m_1 + \exp^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + \exp^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13} m_3|^2}$$

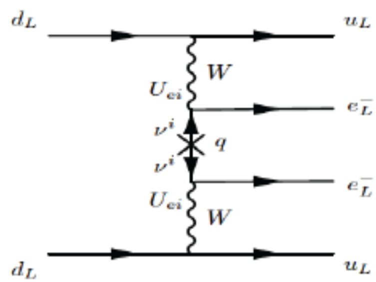
3. Effective nu mass ^



1. This formula →

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

← 2. Nuclear matrix elements



$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} g_A^4 \left| M^{(0\nu)} \right|^2 \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle^2 = \left| \sum U_{ei}^2 m_{\nu i} \right|^2$$

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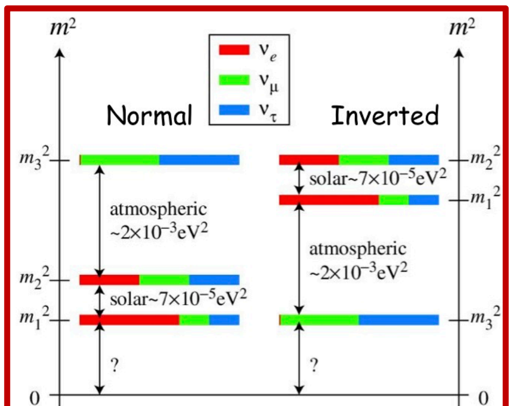
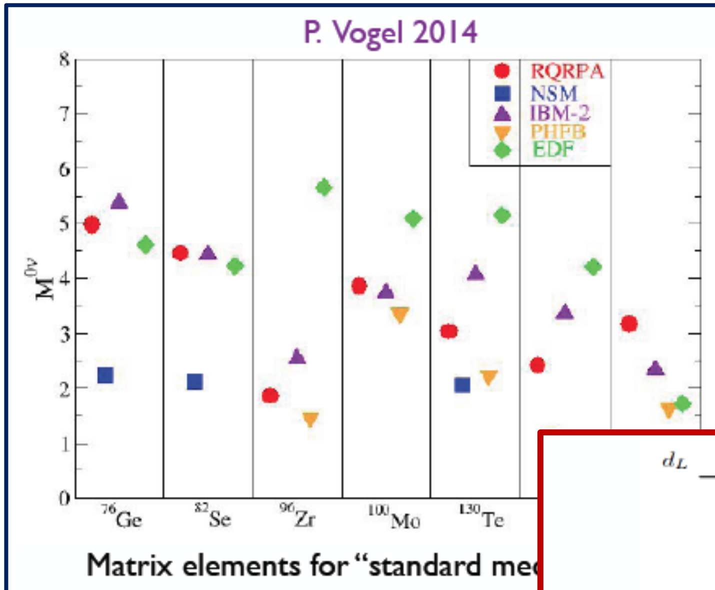
3. Effective nu mass ^



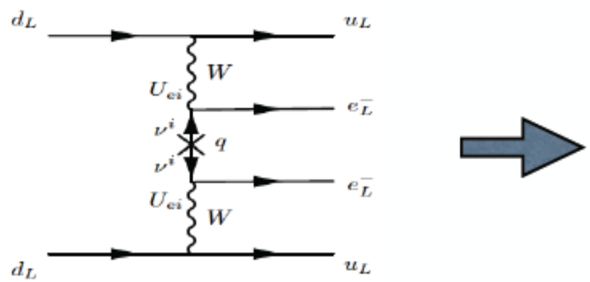
← Special bonus: connect it to this



1. This formula →

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

← 2. Nuclear matrix elements

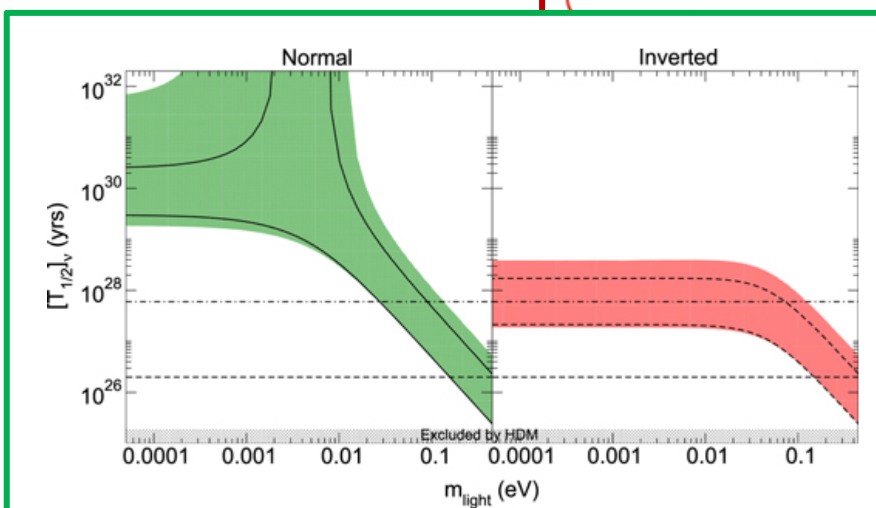


$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} g_A^4 \left|M^{(0\nu)}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$

$$\langle m_{\beta\beta}\rangle^2 = |\cos^2\theta_{12}\cos^2\theta_{13} m_1 + \exp^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + \exp^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13} m_3|^2$$

3. Effective nu mass ^



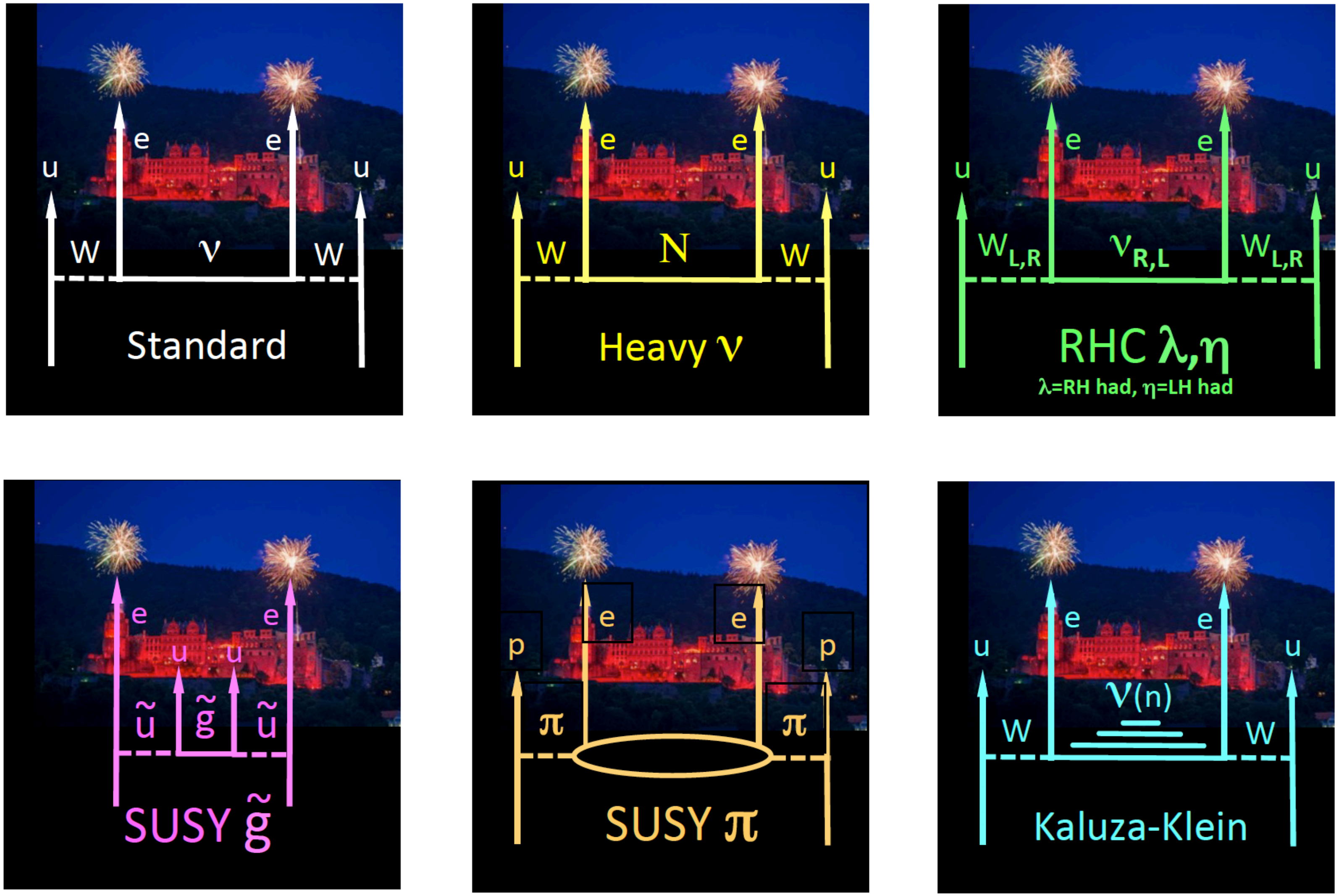
← 4. End up at this plot

Cute story, but…

- Strength of weak interaction is quenched in nuclear medium
  - Rate depends on 4th power of g_A
  - Nobody really knows where the “NH” and ”IH” bands are.

- All those plots assume light Majorana neutrino exchange mechanism.
  - *Motivated by seesaw models.*
  - *But Majorana neutrinos imply generically new high-scale physics, and generically new physics can produce generic 0nubb rates.*

Warning: **don't stick to $m_{\beta\beta}$ metric, just go on with $T_{1/2}$!** Variety of $0\nu\beta\beta$ mechanisms:



$0\nu\beta\beta$ from any mechanism → **Majorana nature of ν would be established anyway**

Slide from The Mid and Long Term Future of Neutrinoless Double Beta Decay, Andrea Giuliani, Neutrinno2018, https://doi.org/10.5281/zenodo.1286915

A robust observation of 0nubb would tell us 6 things about nature before breakfast:

1) Lepton number conservation is violated.

2) Massive fermions exist that are neither matter or antimatter but something else (Majorana fermions)

3) The SM with the Majorana term is non-renomalizible → SM is definitely a low energy effective theory.

4) There are other mass generating mechanisms in nature beyond the Higgs mechanism.

5) Like G_F tells us the weak scale and ultimately leads to W and Z mass predictions, m_ν tells us the next scale.

6) Majorana neutrinos are a prediction of the theory of Leptogenesis that may generate observed matter/anti-matter asymmetry of the Universe (given enough CPV – see also: DUNE)

So how about we all agree to:

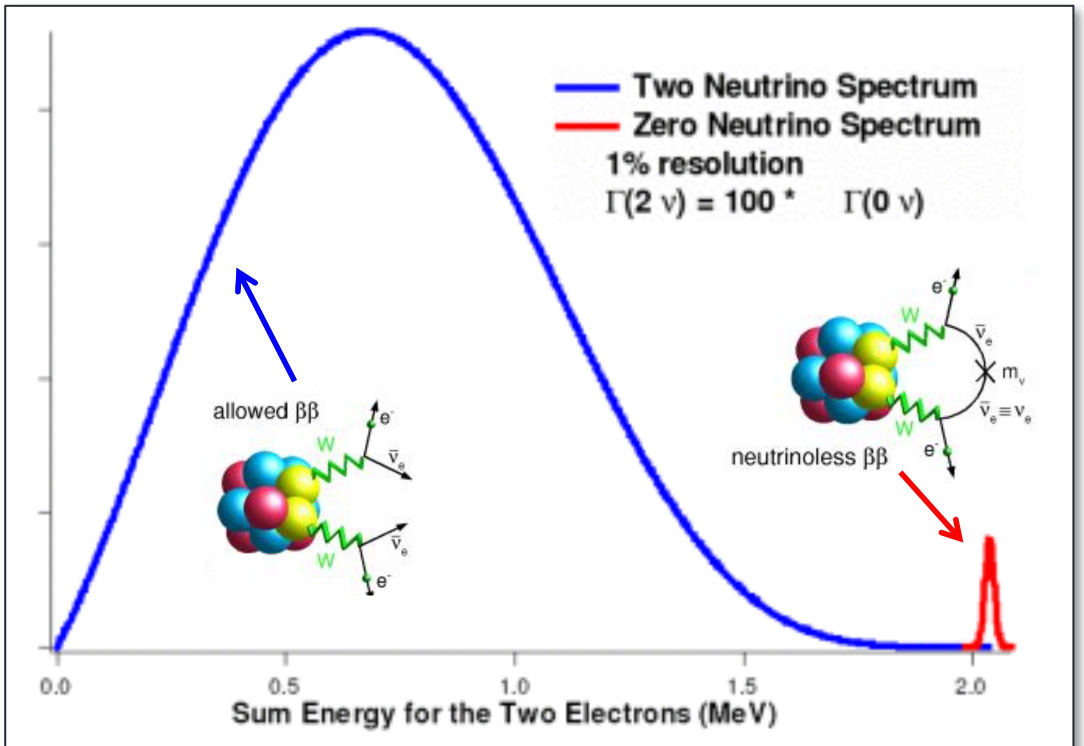
Be as sensitive as possible

(get out logarithmically into unexplored parameter space)

Build experiments that can make discoveries, not just set limits

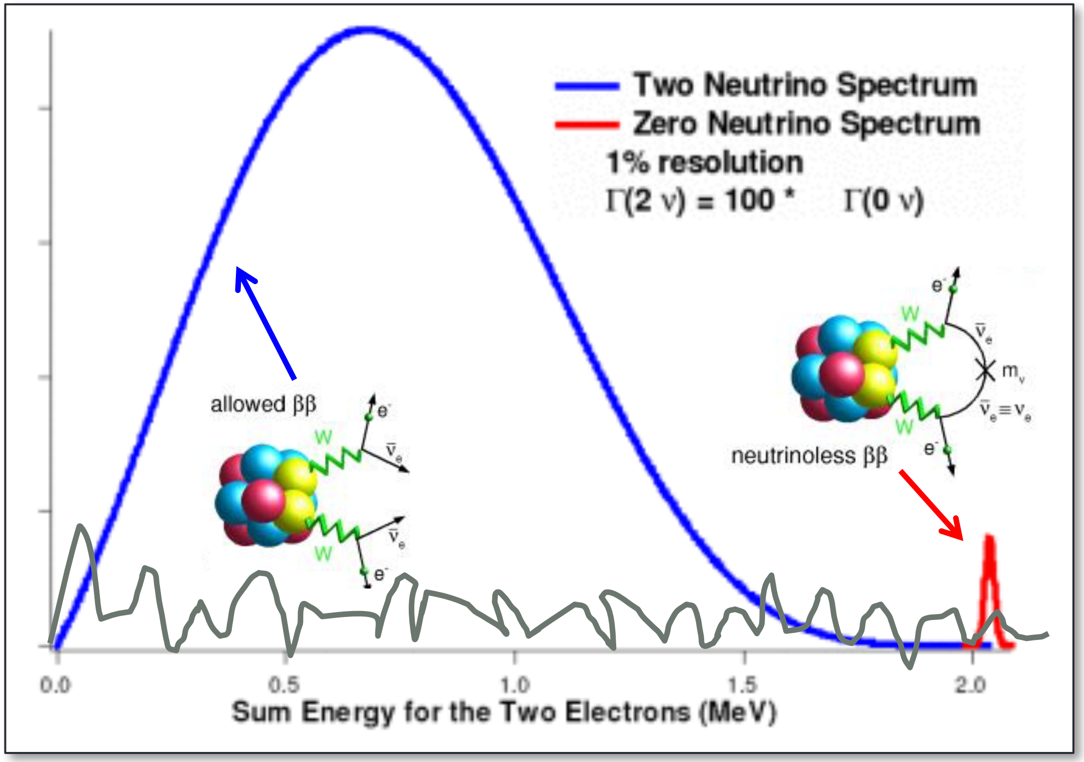
(well understood detectors with clear, positive signal criteria)

The ideal experiment:

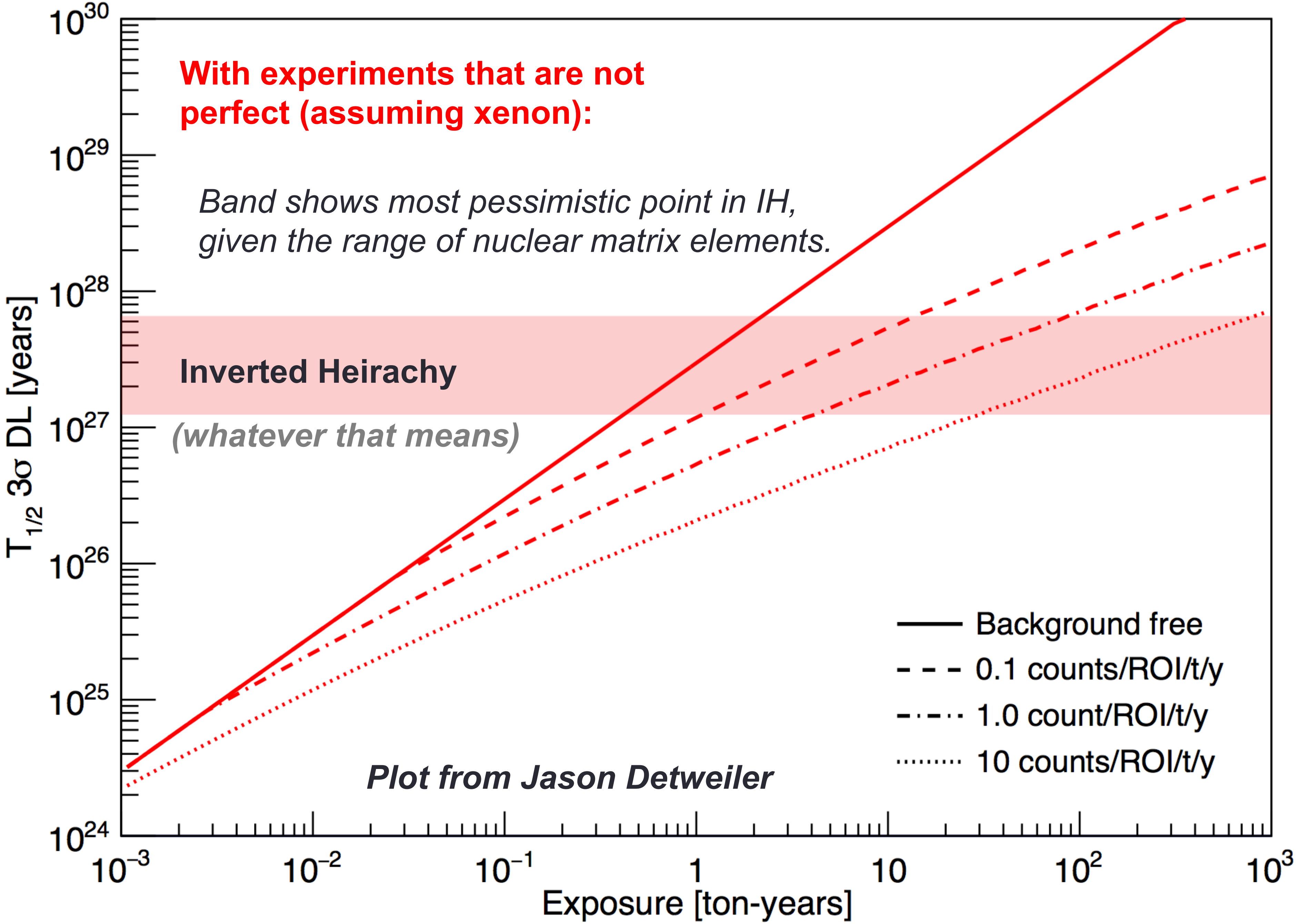


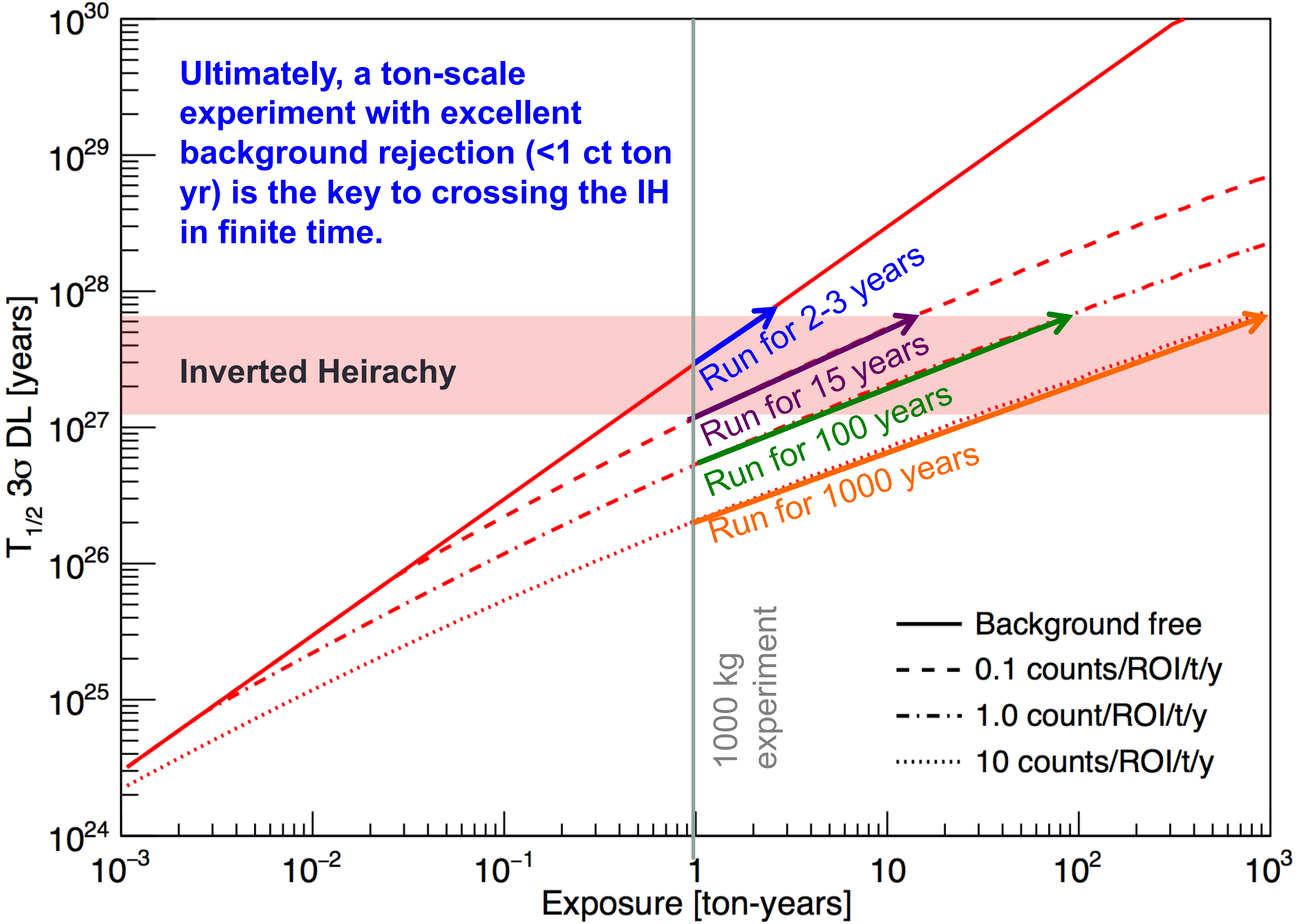
- ***MANDATORY:***
  - Resolution better than ~2% FWHM to fully reject two-neutrino mode
- ***Then just watch and wait…***

The non-ideal experiment:

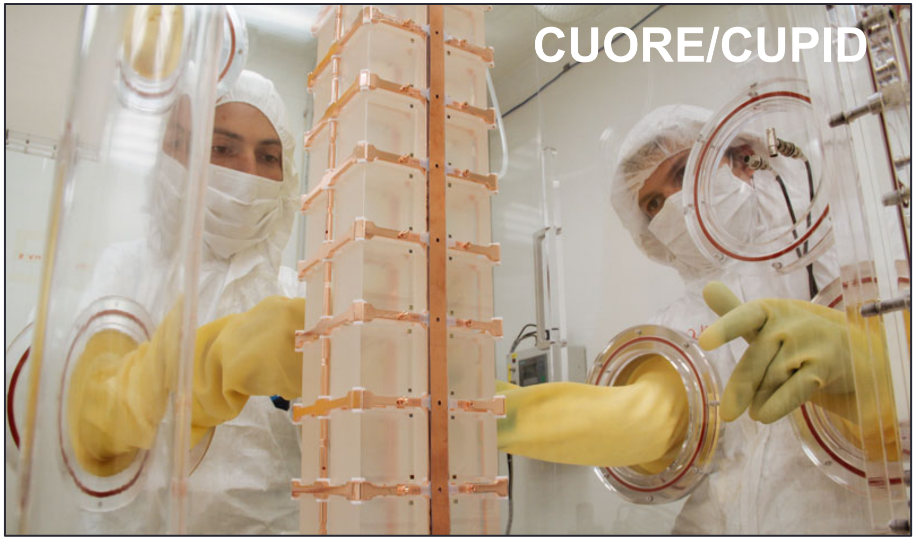


- ***MANDATORY:***
  - Resolution better than ~2% FWHM to fully reject two-neutrino mode
- ***Ideally:***
  - Would have zero other backgrounds
- ***Then just watch and wait…***

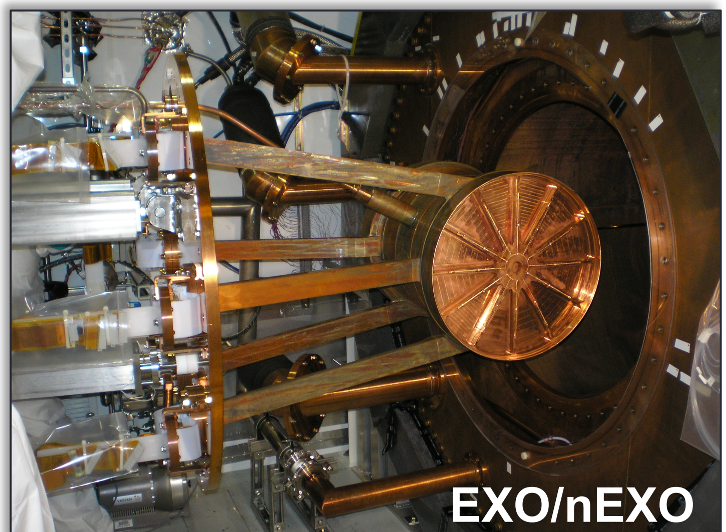

With experiments that are not perfect (assuming xenon):
Band shows most pessimistic point in IH, given the range of nuclear matrix elements.
Inverted Heirachy
(whatever that means)
Plot from Jason Detweiler
Background free
0.1 counts/ROI/t/y
1.0 count/ROI/t/y
10 counts/ROI/t/y
$T_{1/2}$ 3σ DL [years]
Exposure [ton-years]
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{30}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}

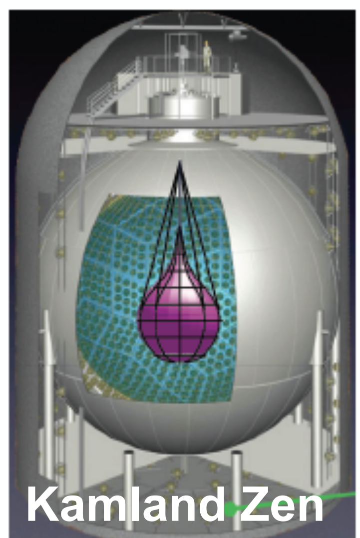

Ultimately, a ton-scale experiment with excellent background rejection (<1 ct ton yr) is the key to crossing the IH in finite time.
Inverted Heirachy
Run for 2-3 years
Run for 15 years
Run for 100 years
Run for 1000 years
1000 kg experiment
Background free
0.1 counts/ROI/t/y
1.0 count/ROI/t/y
10 counts/ROI/t/y
$T_{1/2}$ 3σ DL [years]
Exposure [ton-years]
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{30}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}

Neutrinoless Double Beta Decay Searches

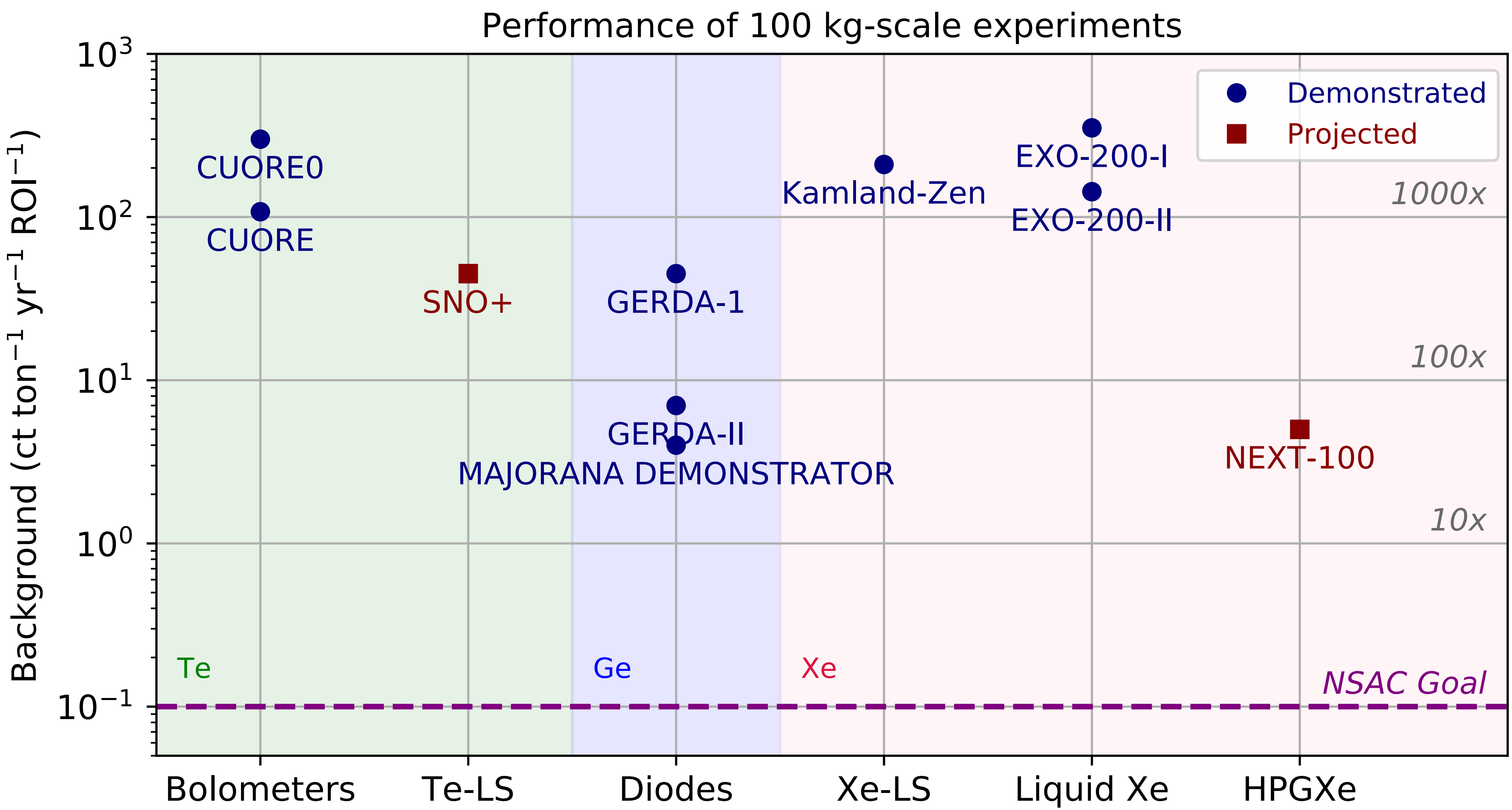


Many completely different technologies…



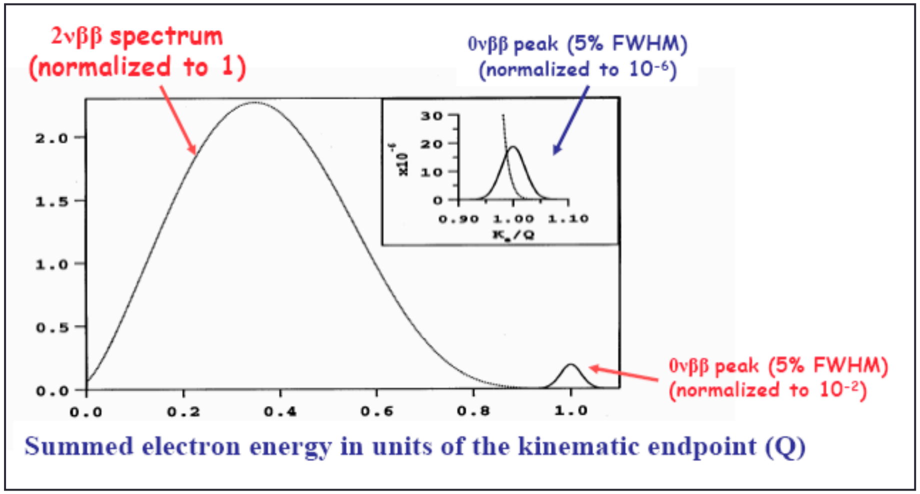


100kg-class experiments:



Methods to achieve lower background

- Reject 2νββ tail:
  - Energy resolution is only handle
    - ~2% FWHM reaches 0.1 ct ton yr.

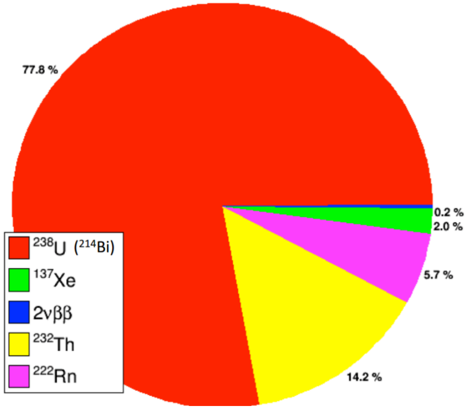


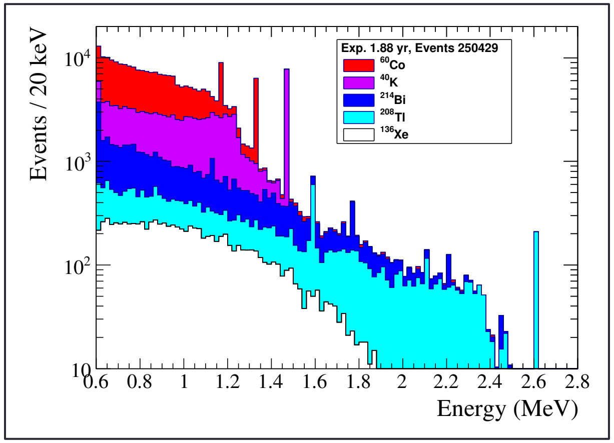
For cartoon purposes only

- Reject radioactive backgrounds

Typically ^{214}Bi, ^{208}Th from uranium and thorium chains respectively:

  - Shielding / radiopurity
  - Energy resolution
  - Topological signature
  - Daughter tag





nEXO (left) and NEXT-100 (right) background models

The NEXT Program

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

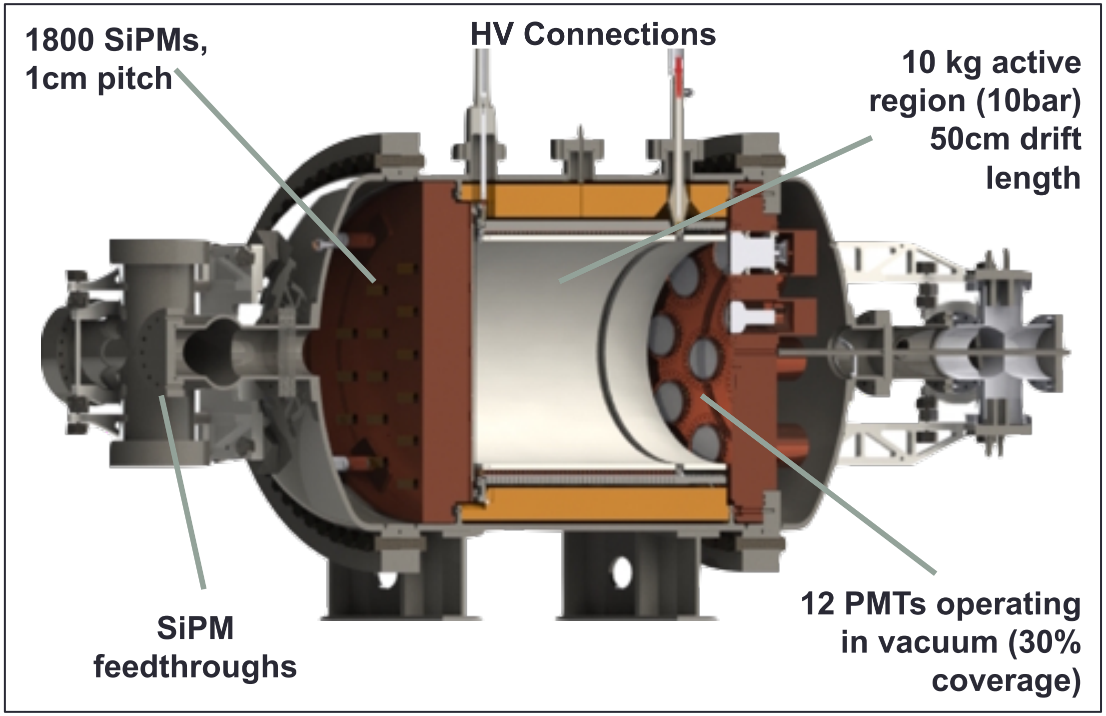
→ NEXT-DBDM
(Berkeley, US)

→ NEXT-DEMO
(Valencia, Spain)

→ NEXT-White
(Canfranc, Spain)

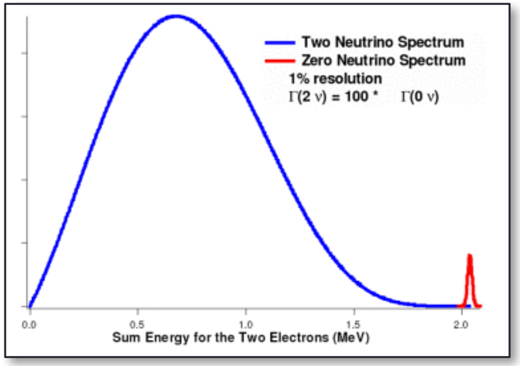
→ NEXT-100
(Canfranc, Spain)

→ NEXT-XXX
???

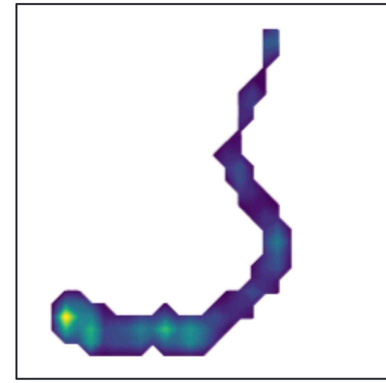


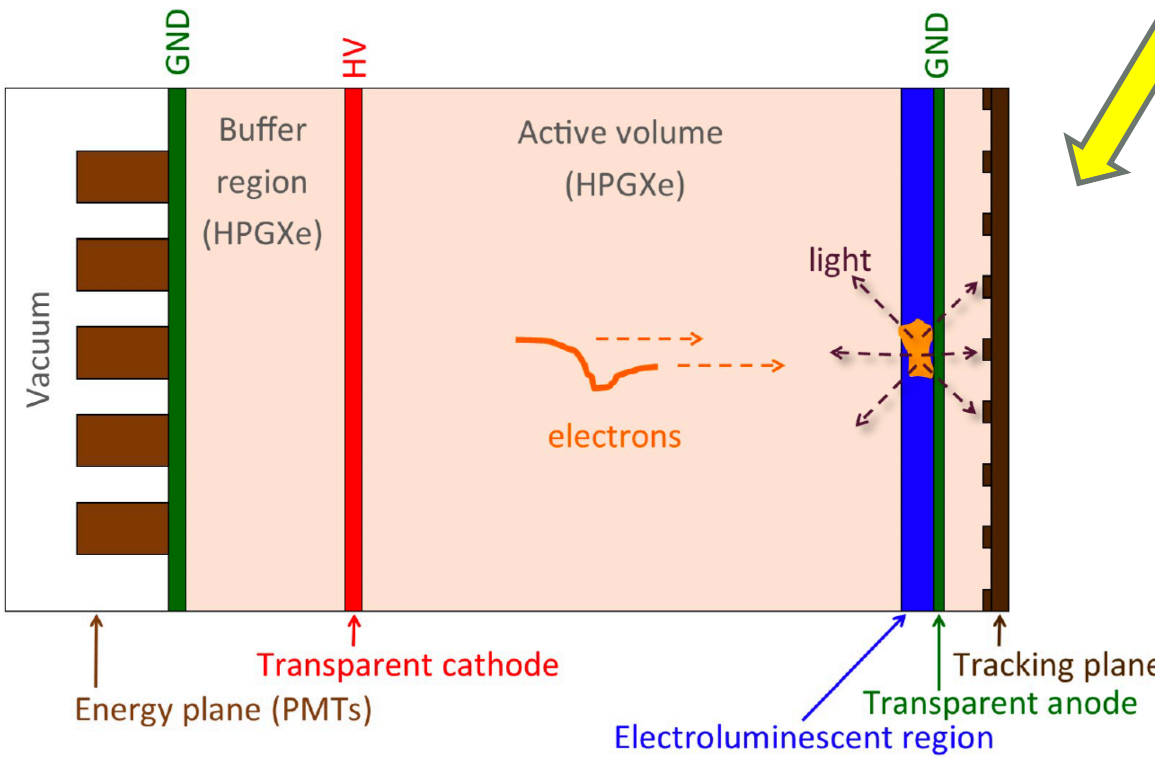
NEXT-White operating now
Full underground technology demonstrator @10kg scale

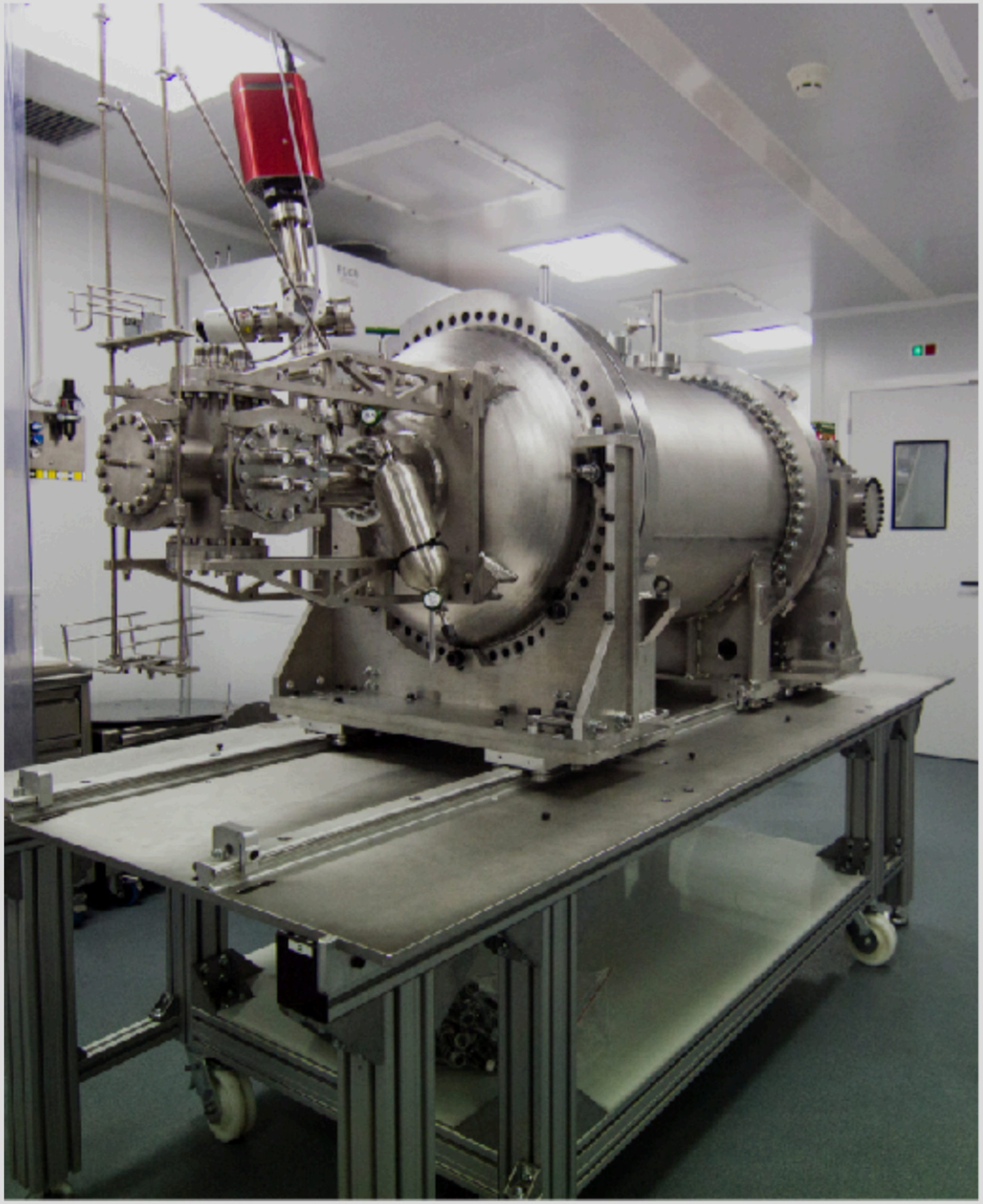
Measure energy this end

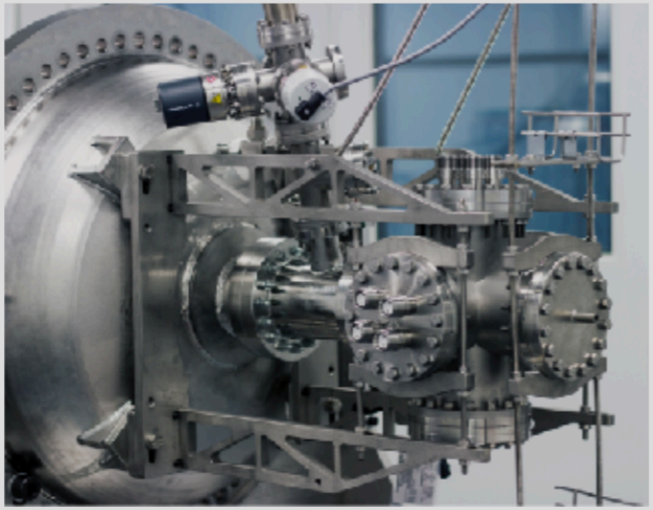


Measure topology this end

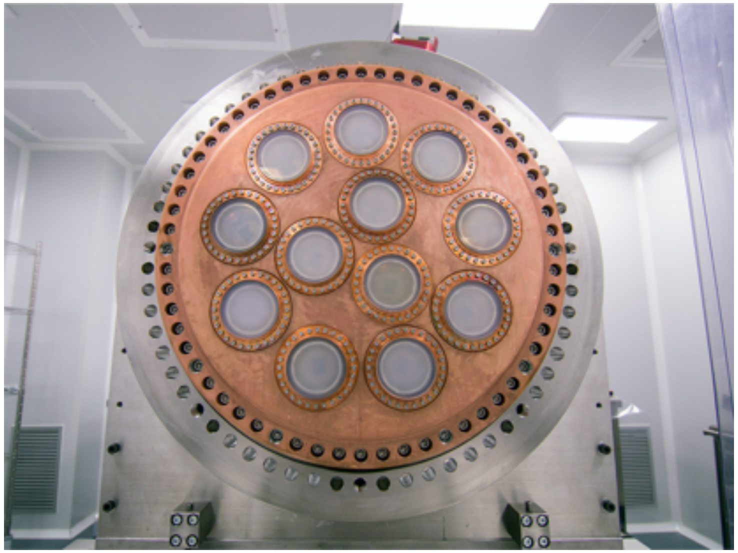




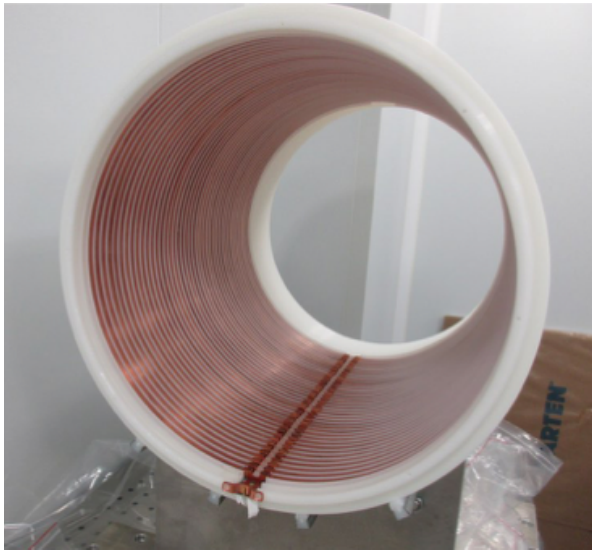




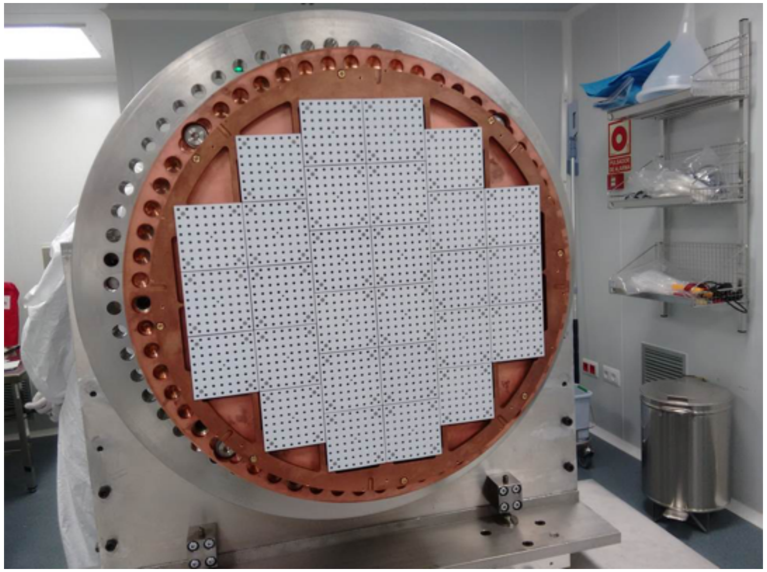
Energy Plane



Field Cage



Tracking Plane



Anode

The Next White (NEW) Detector

F. Monrabal et. al. arXiv:1804.02409

SUPPORTED BY:
U.S. DEPARTMENT OF ENERGY

The NEXT Program

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

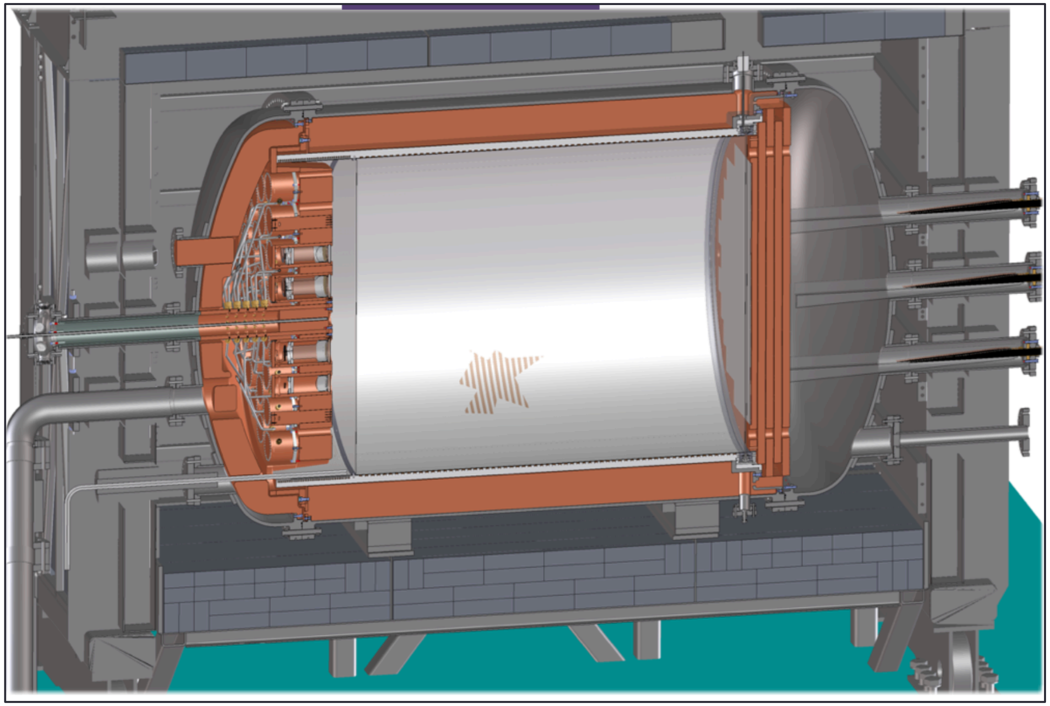
→ NEXT-DBDM

→ NEXT-DEMO

→ NEXT-NEW

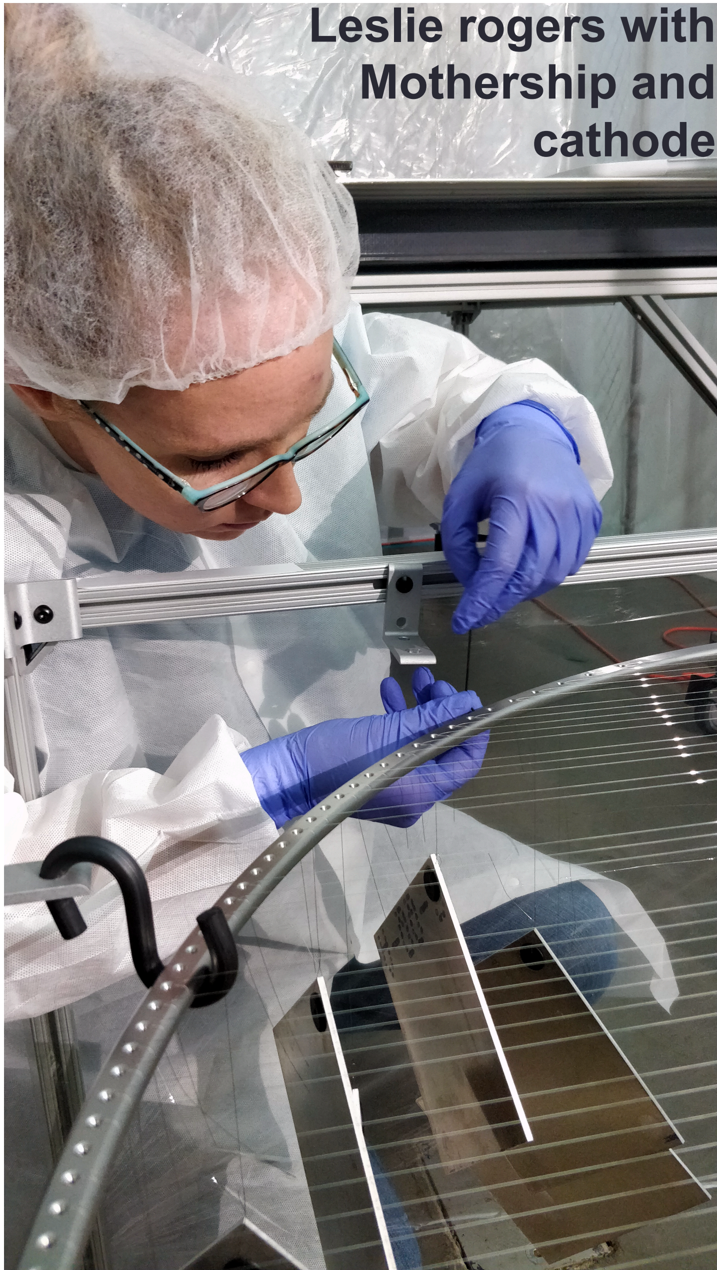
→ **NEXT-100**

→ NEXT-XXX



100 kg scale neutrinoless double beta decay search and background-study for ton-scale

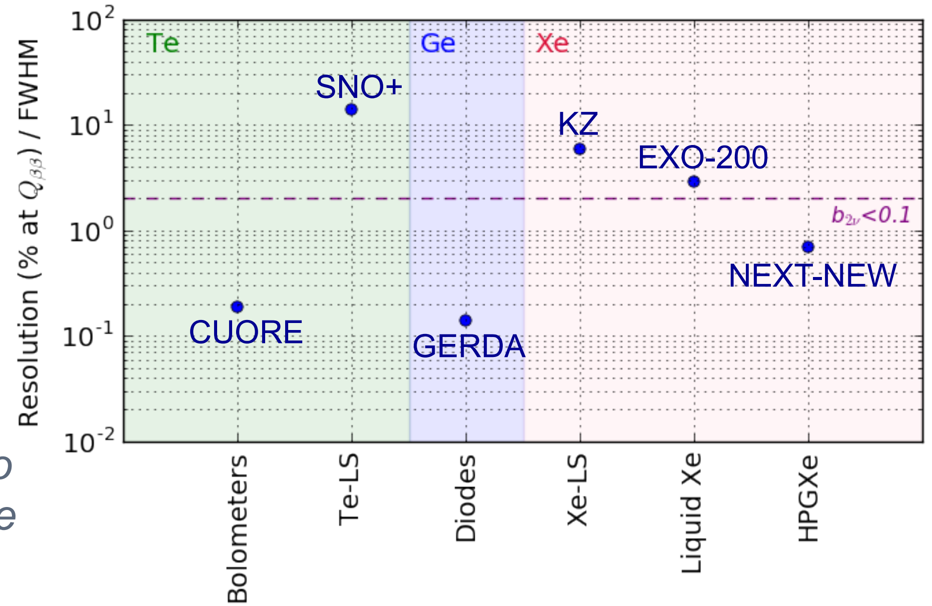
NEXT-100 cathode and electroluminescence regions built and tested at UTA



Why Xenon Gas?

- 1) Energy resolution
- 2) Topology
- 3) Practicality at ton-scale

Why Xenon Gas?

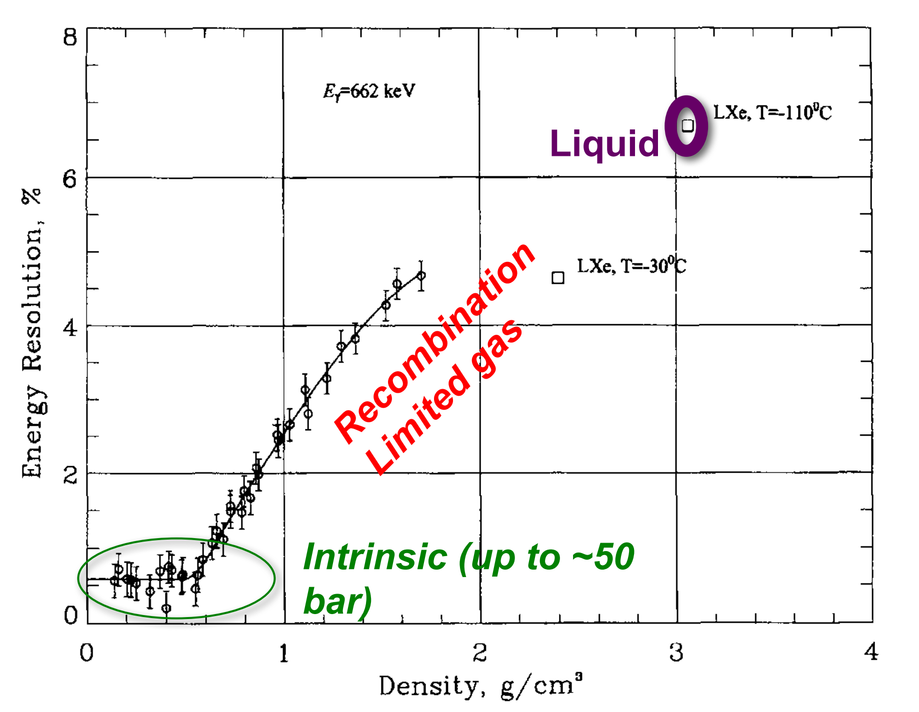


- **1) Energy resolution**

  Fluctuation-less EL gain and low Fano factor produces resolution comparable with solid-state technologies in a monolithic TPC experiment

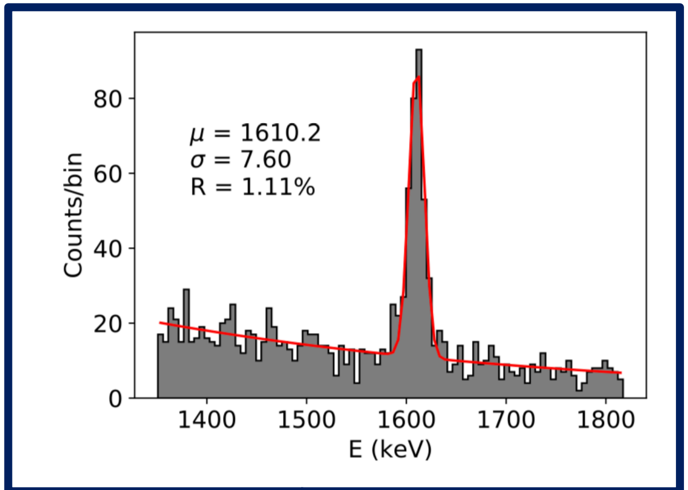
- 2) Topology

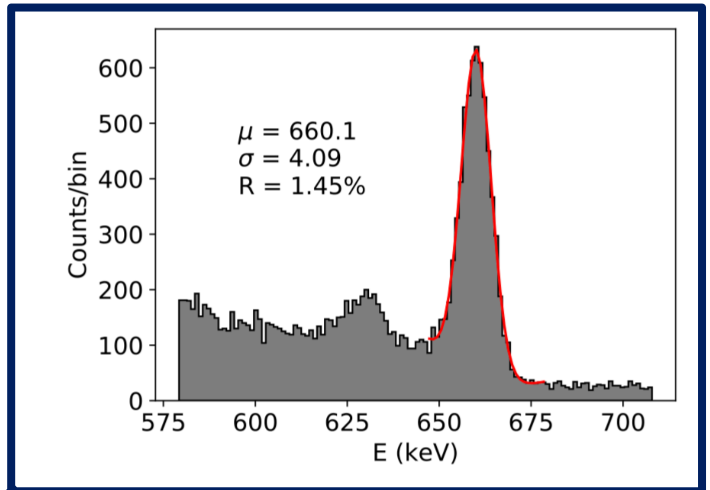
- 3) Practicality at ton-scale



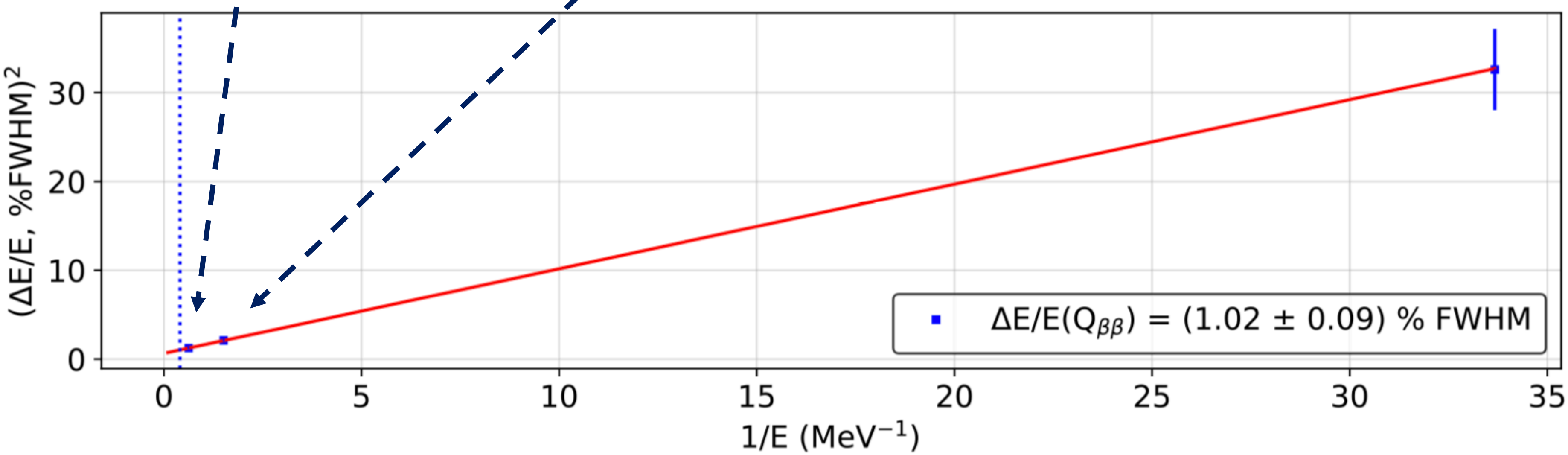
Bolotnikov and Ramsey. "The spectroscopic properties of high-pressure xenon."NIM *A* 396.3 (1997): 360-370

Initial results on energy resolution of the NEXT-White detector
J. Renner et al, arXiv 1808:01804





Energy calibrations and stability still improving: presently sit at ~1% at Q_{bb}



Why Xenon Gas?

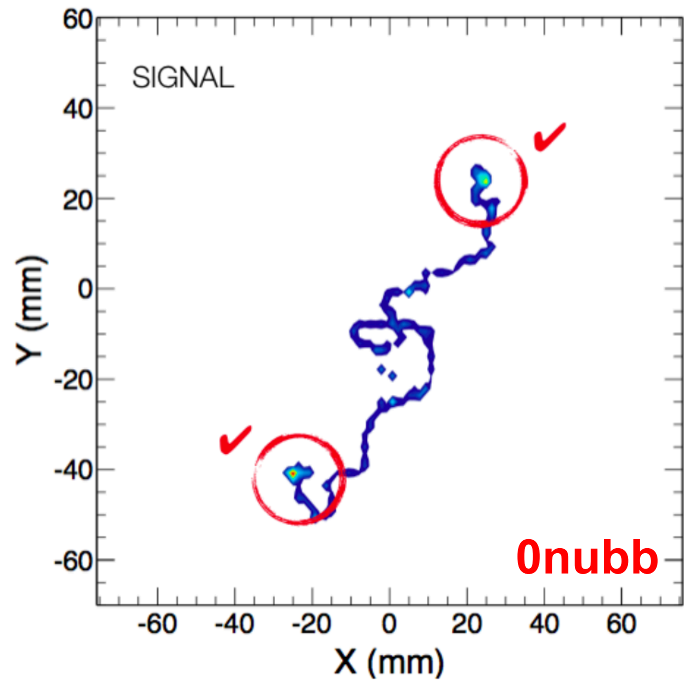
- 1) Energy resolution

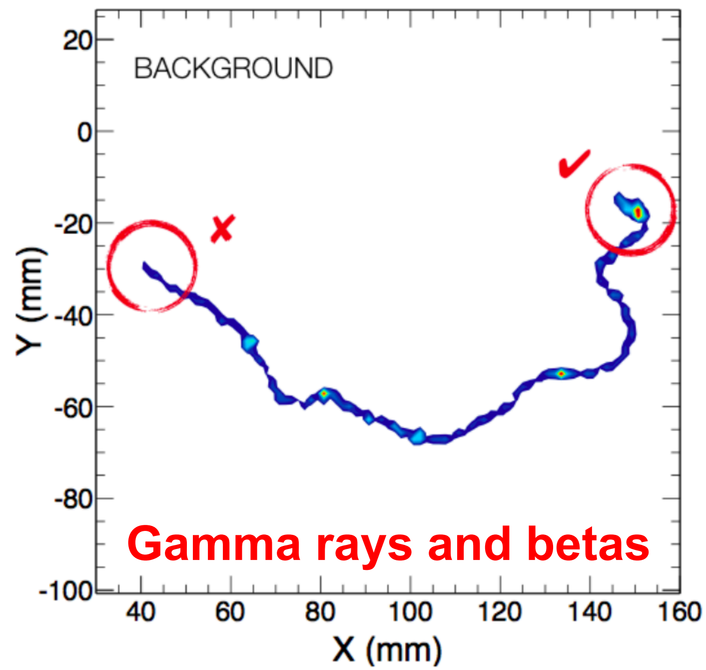
  Fluctuation-less EL gain produces resolution comparable with solid-state technologies in a monolithic TPC experiment

- **2) Topology**

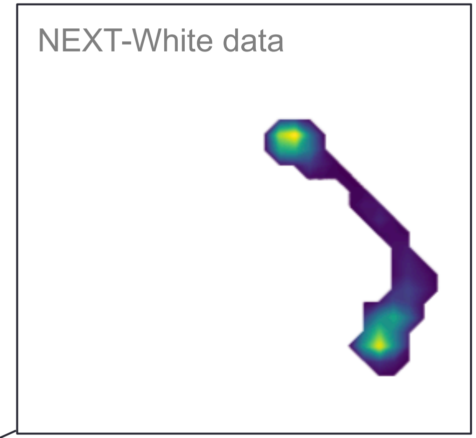
  Lower density allows powerful single-vs-multi electron and single-vs-multi-site topological background rejection

- 3) Practicality at ton-scale

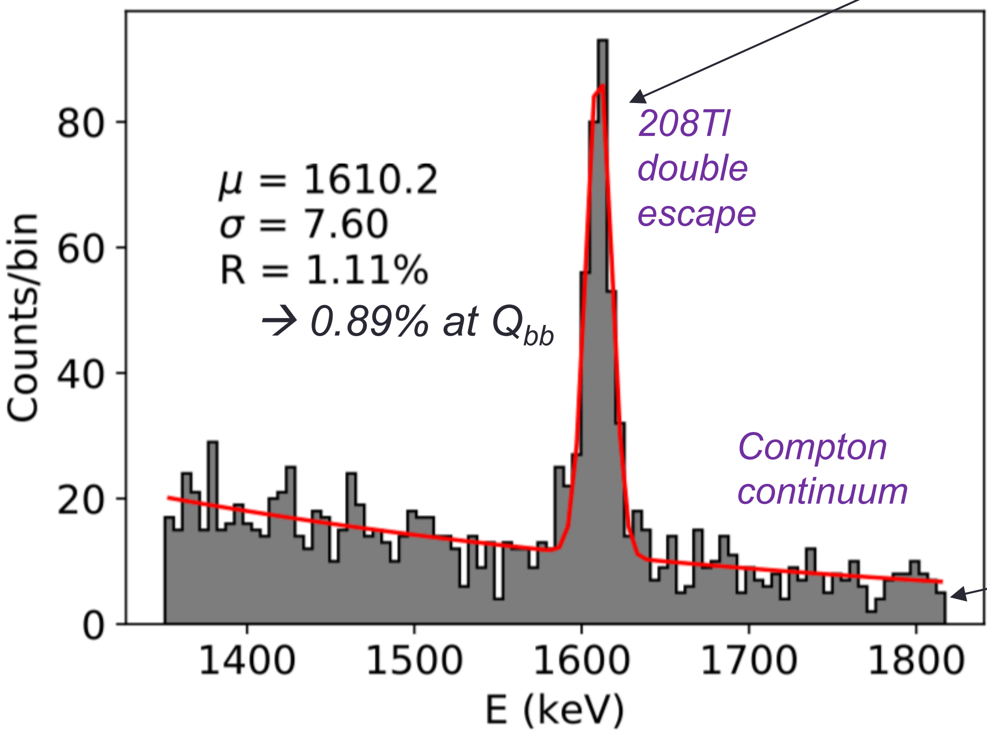


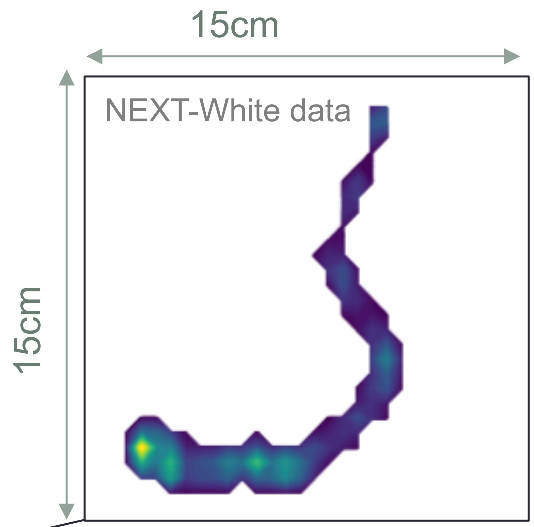


Topological Reco with Double Escape Peaks



On double escape peak





Off double escape peak

Why Xenon Gas?

- 1) Energy resolution

  Fluctuation-less EL gain produces resolution comparable with solid-state technologies in a monolithic TPC experiment

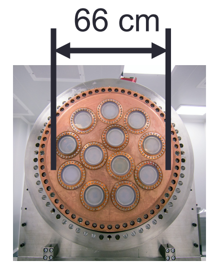
- 2) Topology

  Lower density allows powerful single-vs-multi electron and single-vs-multi-site topological background rejection

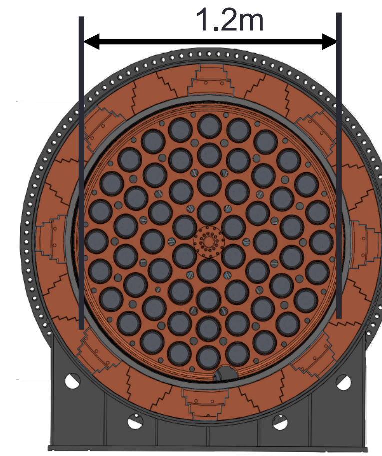
- **3) Practicality at ton-scale**

  Reliance on active background rejection rather than self shielding means program uses isotope efficiently and can be phased

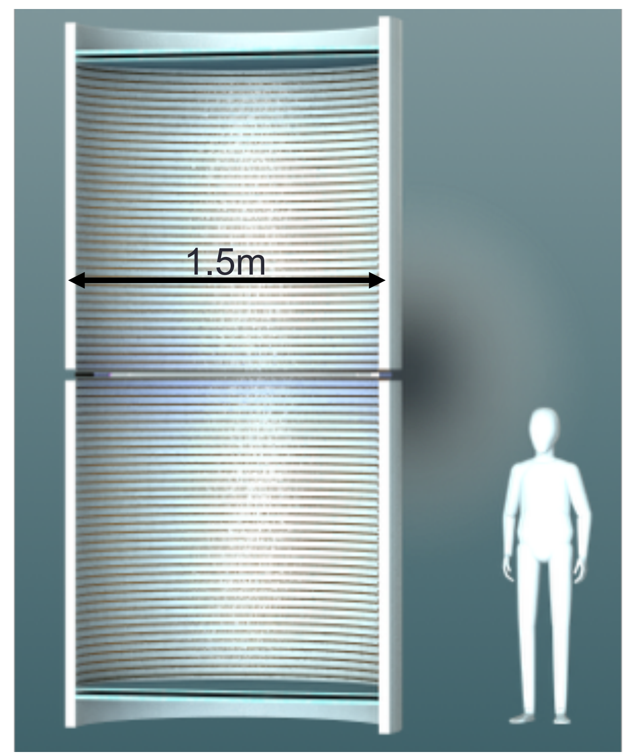
NEXT-NEW
Running



NEXT-100
2019



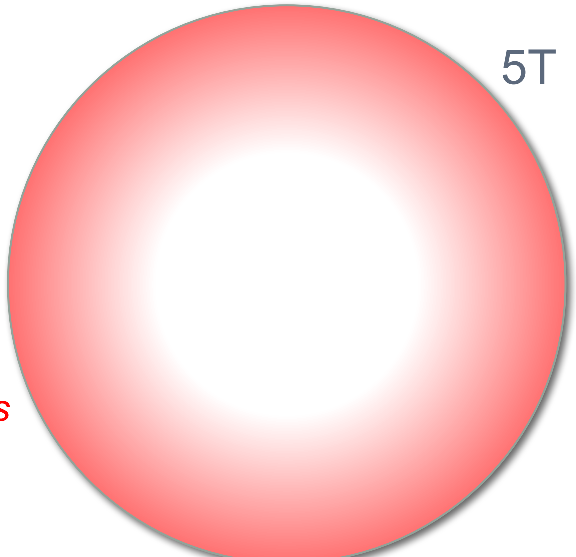
NEXT-XXX: *202?*



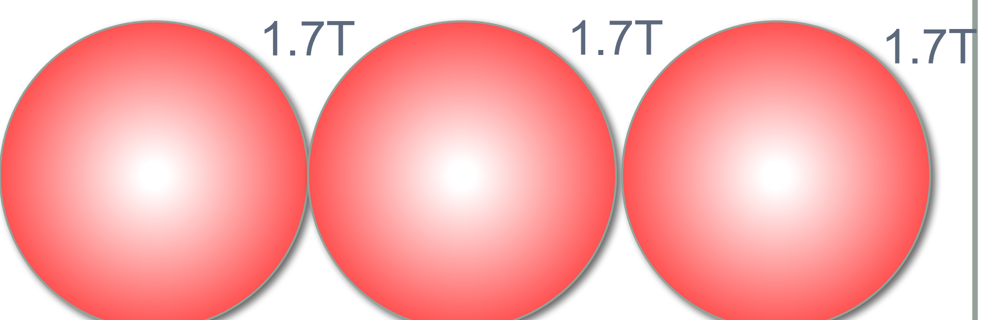
Self-shielding based
(KamlandZen, nEXO, etc)

Several tons of isotope for each clean ton

External gamma ray backgrounds absorbed in outer layers



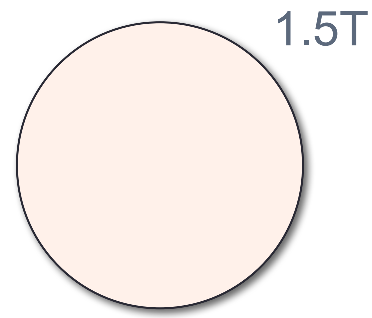
Cannot be phased into smaller modules
have to build it all at once



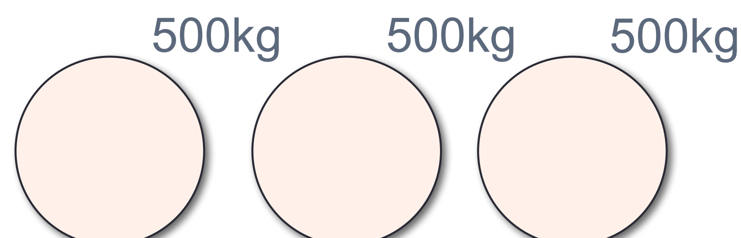
Active background rejection based
(CUORE, MAJORANA/GERDA, NEXT, etc)

1 ton of isotope for each clean ton.

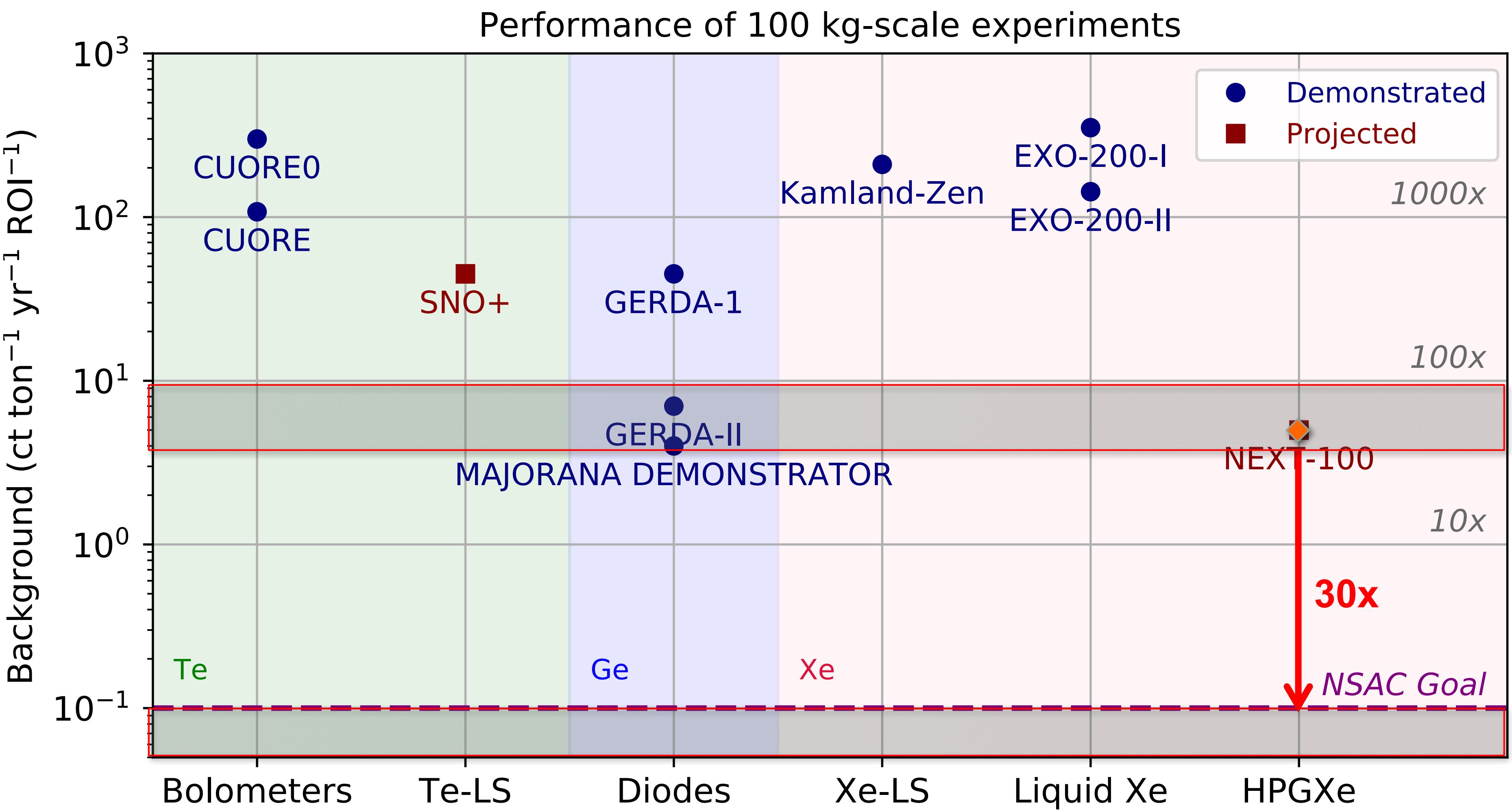
Nearly uniform background throughout



Phase-able deployment possible
Low-risk, reliable, cost effective approach to hitting background targets



NEXT-100 in 2019 will be comfortably world leading in xenon, and competitive with world leaders in other isotopes.

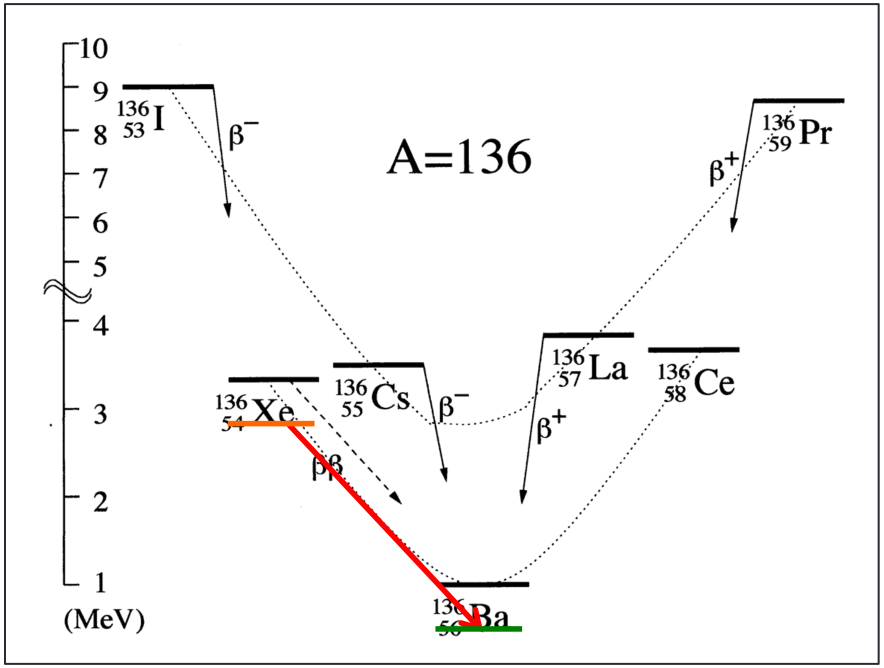


BUT WORLD-LEADING IS NOT ENOUGH!

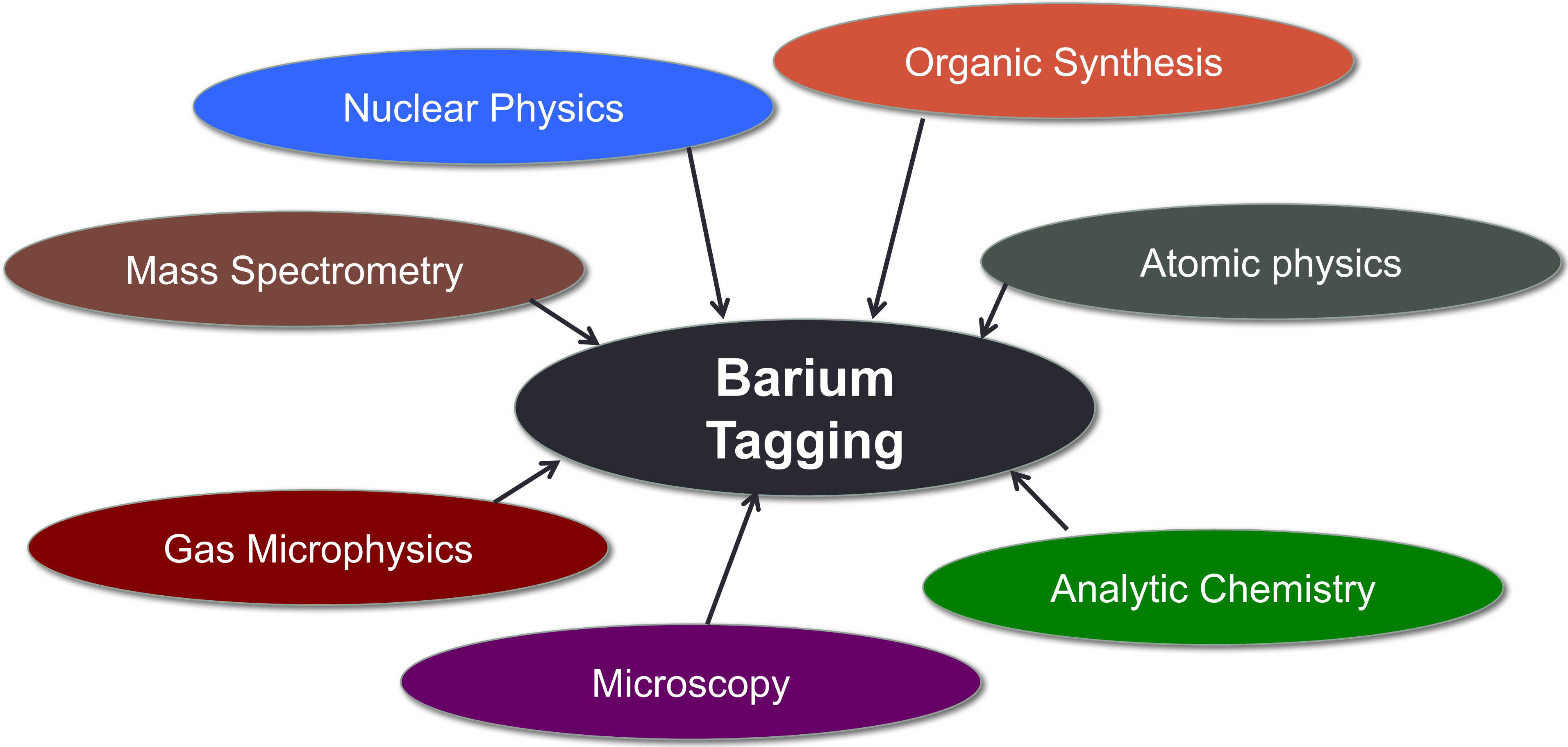
Barium Tagging

- 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 material?***

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



Barium tagging for 0nubb has been actively explored in liquid and gas xenon for >15 years, with the holy grail is a scalable single ion sensitive technology.

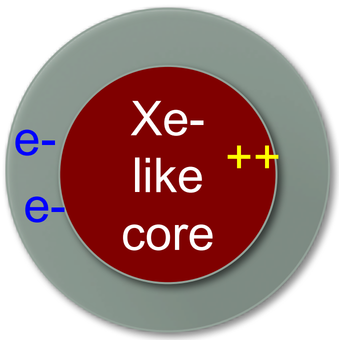

Organic Synthesis
Nuclear Physics
Atomic physics
Mass Spectrometry
Barium Tagging
Gas Microphysics
Analytic Chemistry
Microscopy

Basics - Barium Atoms and Ions

- Barium is born in a high charge state as emerging beta electrons disrupt the atom
- Quickly captures electrons from xenon to reach the Ba^{++} state
- In gas, it ~stops there. In liquid, further recombination happens.

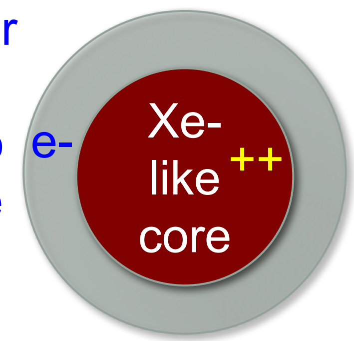
Structure of the **Ba** atom

Two outer electrons bound to +ve core



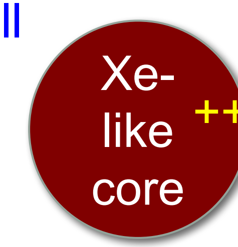
Structure of the **Ba+** ion

One outer electron bound to +ve core



Structure of the **Ba^{++}** ion

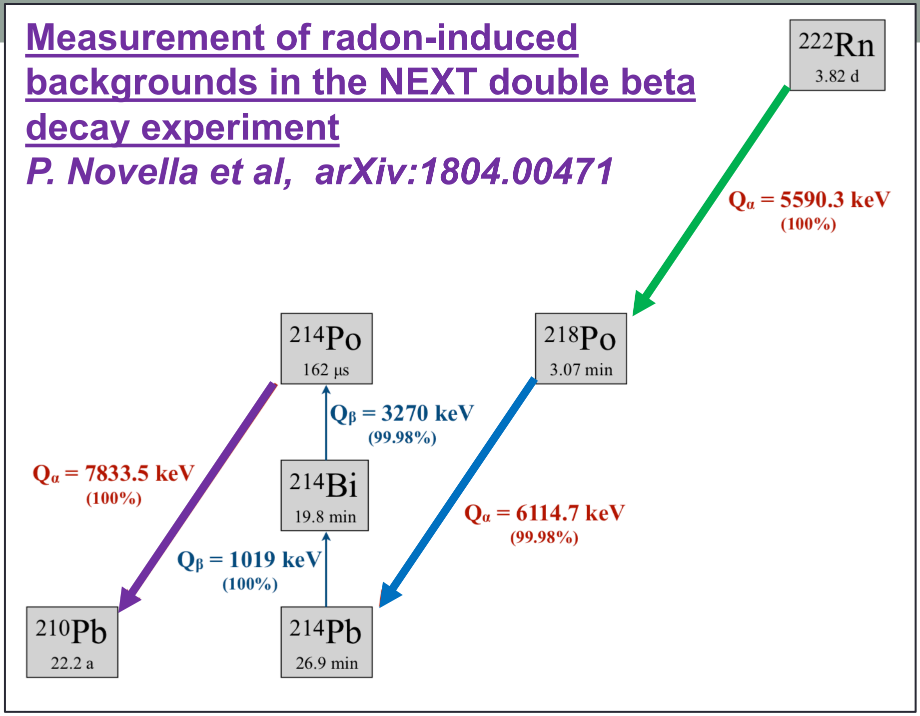
Noble-like electron shell

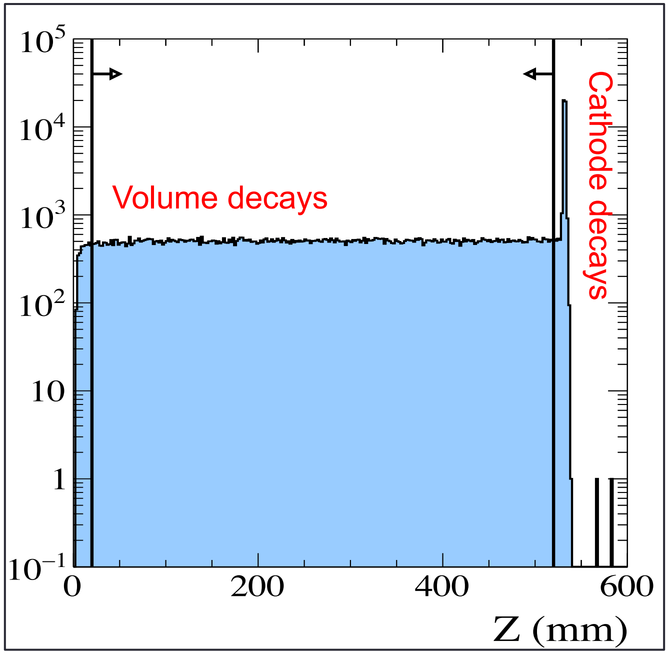


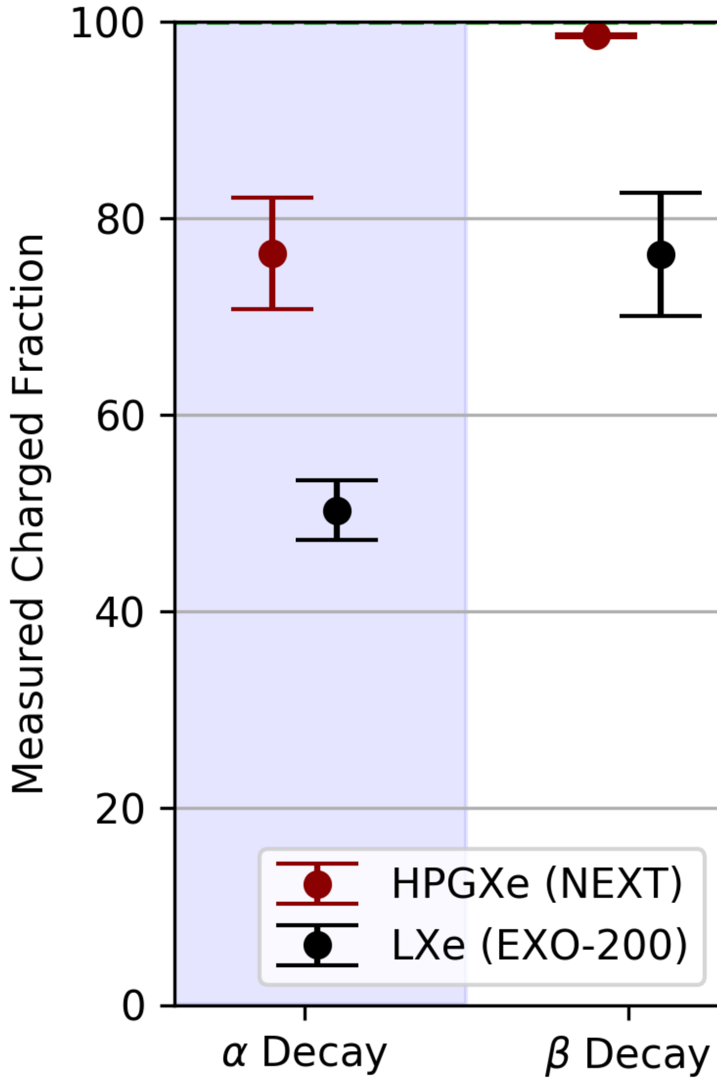
Liquid –
Some distribution

Gas –
Mostly this

Ionic Charge State in Liquid and Gas



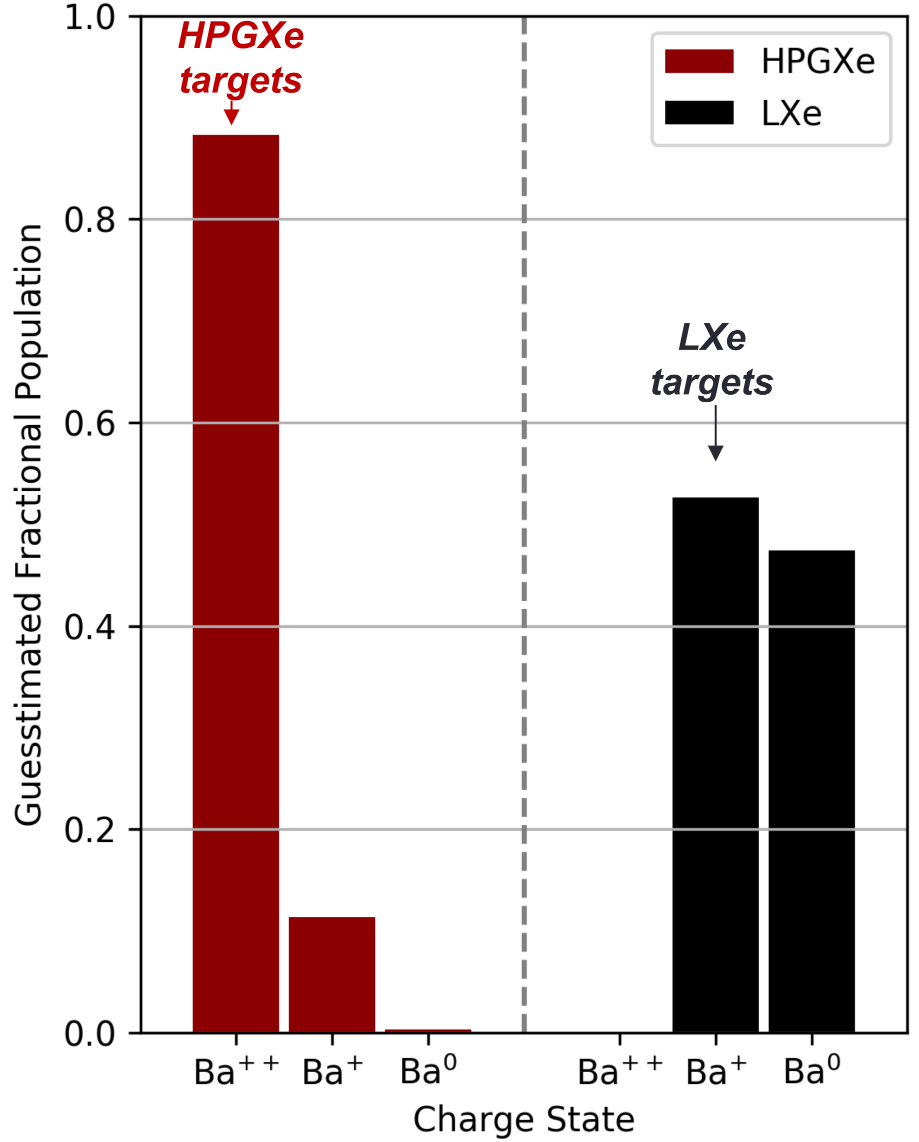




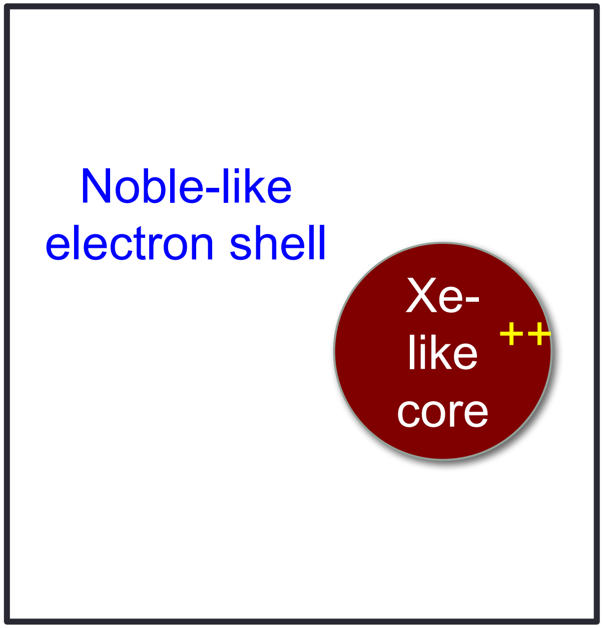
Charge States

- "Best guess" assumptions:
  - Ba++ has 2x larger Onsager radius than Ba+, so expect 4x larger capture cross section for recombination.
  - In double beta decay, two emerging tracks at nucleus, so 2x recombination of single decay.
- Guesstimate Ba charged fractions in double beta decay →

My back-of-envelope extrapolations (your mileage may vary)



Q: How do you make Ba^{++} shine?

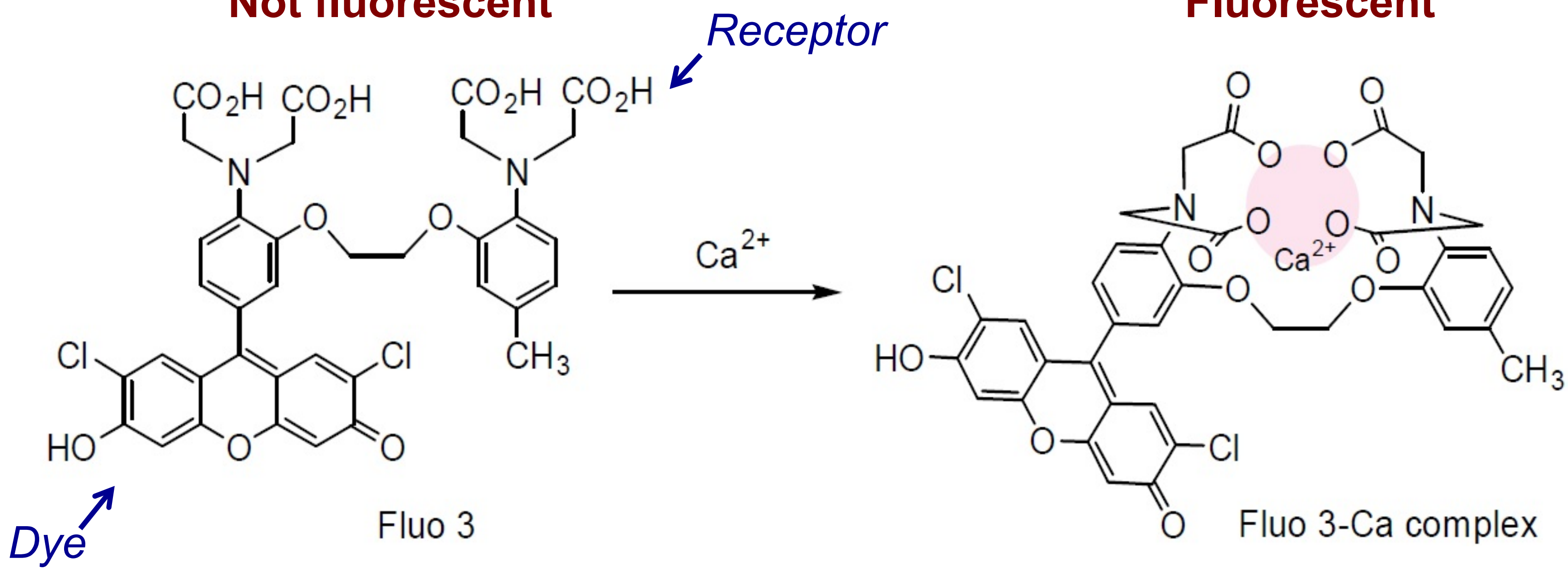


Concept to adapt SMFI for Ba tagging:
D.R. Nygren, **J.Phys.Conf.Ser. 650 (2015) no.1, 012002**

SMFI:

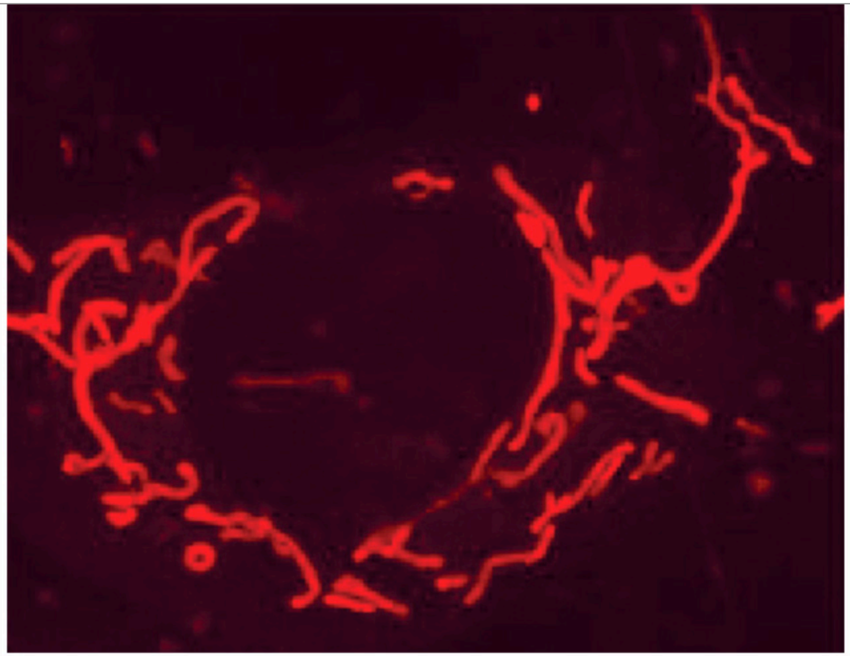
- A non-fluorescent molecule becomes fluorescent (or vice versa) upon chelation with an incident ion.

Not fluorescent **Fluorescent**



Calcium and barium are congeners – many dyes developed for calcium are also expected to respond to barium

SMFI is a technique from biochemistry with demonstrated single-ion resolution.

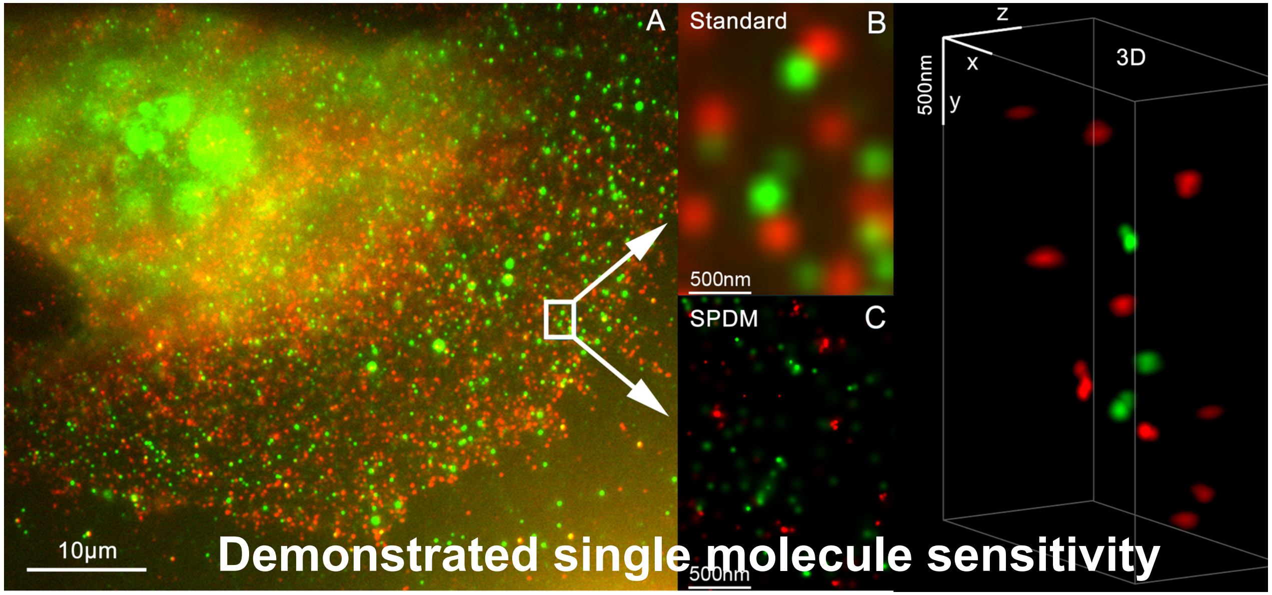


← Rhod-2 sensing Ca^{++} production in rat astrocyte cells

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

J Cell Biol 145, 795 (1999).

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



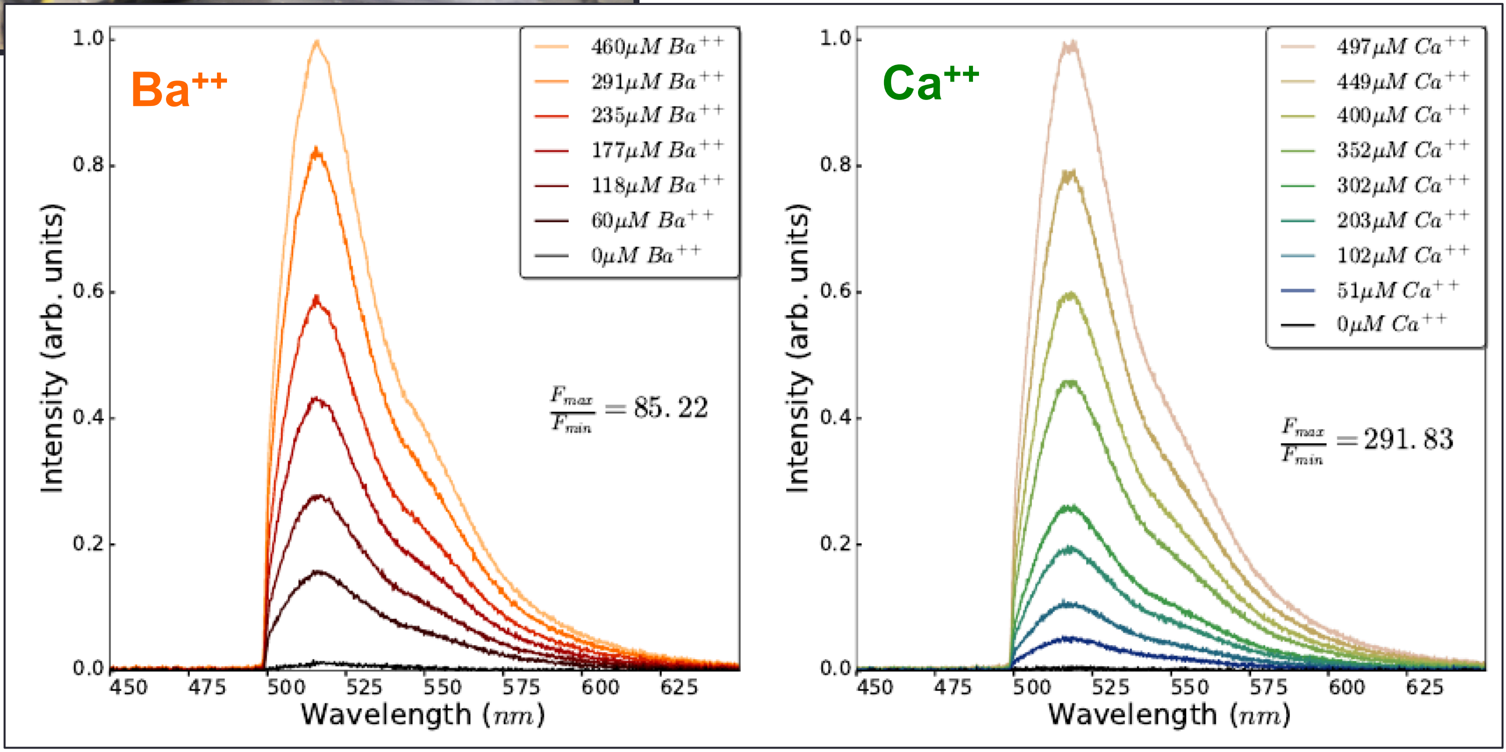
These methods won the Nobel Prize in chemistry in 2014.

Austin McDonald, with “frickin laser beam”

← 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 →



Microscope objectives:

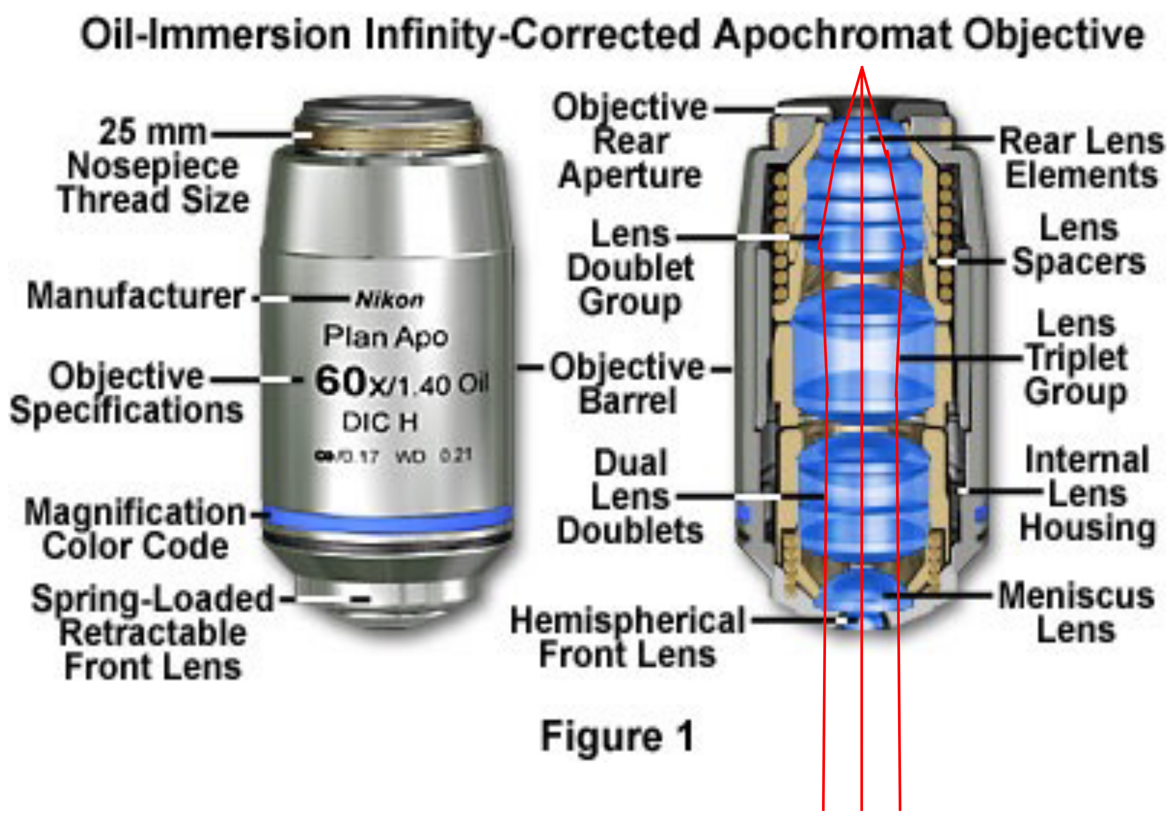
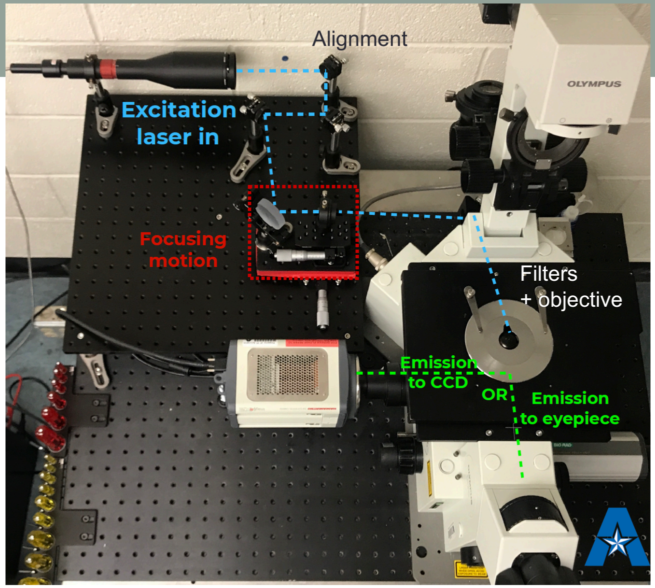
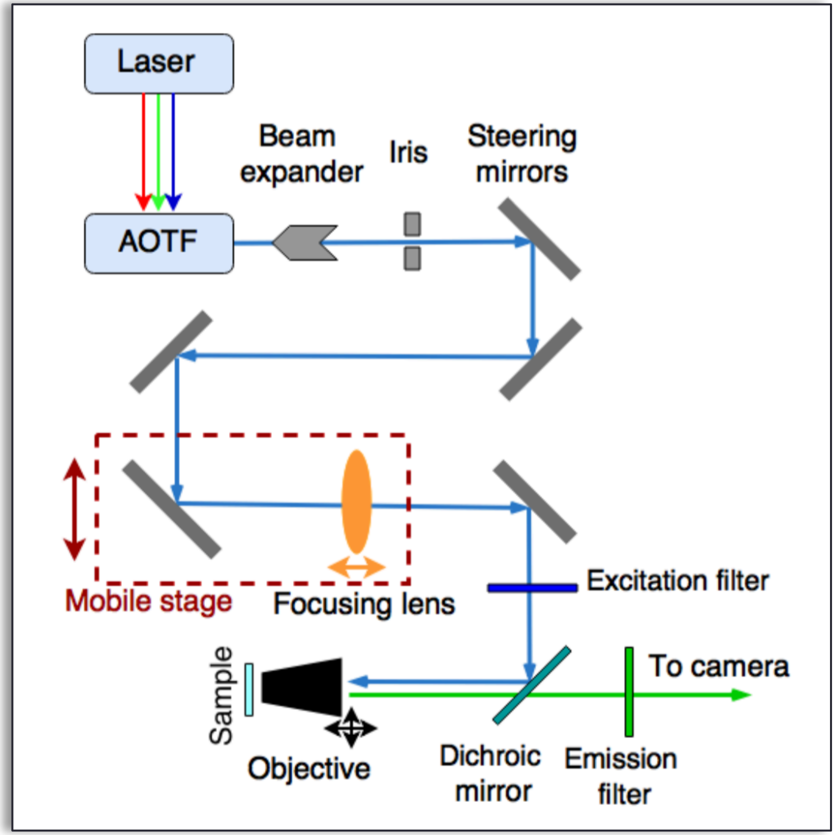
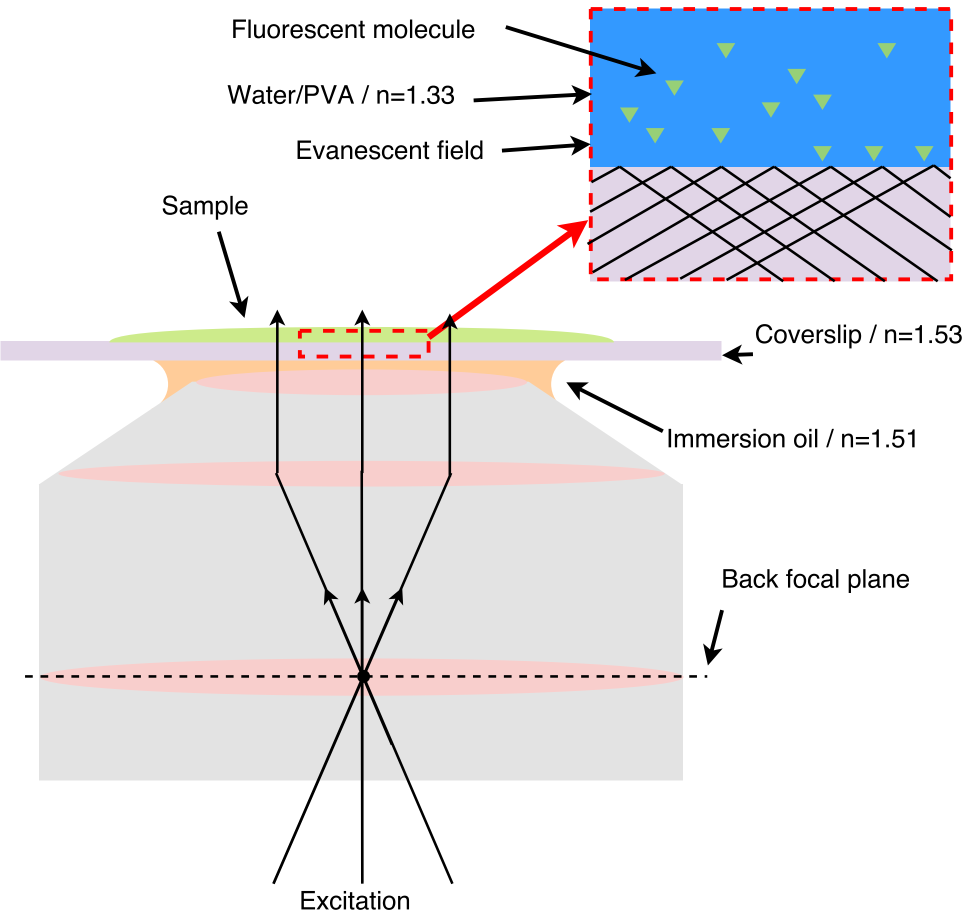


Figure 1

Goal in life: Do its darnedest to turn point sources into parallel rays - and vice versa.

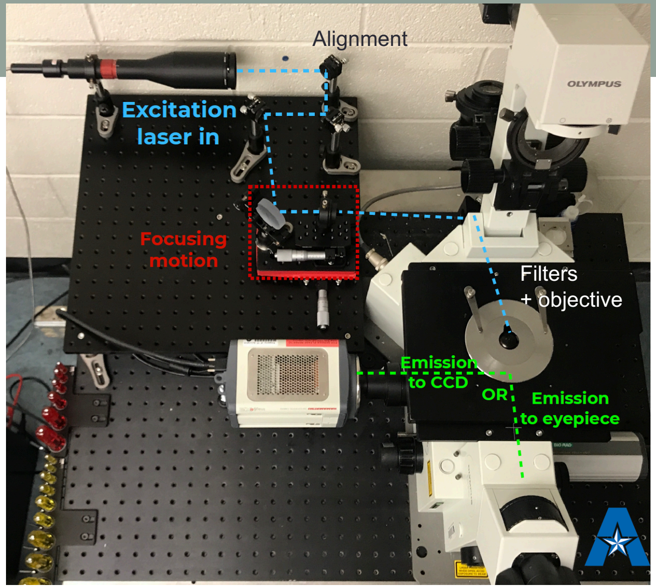


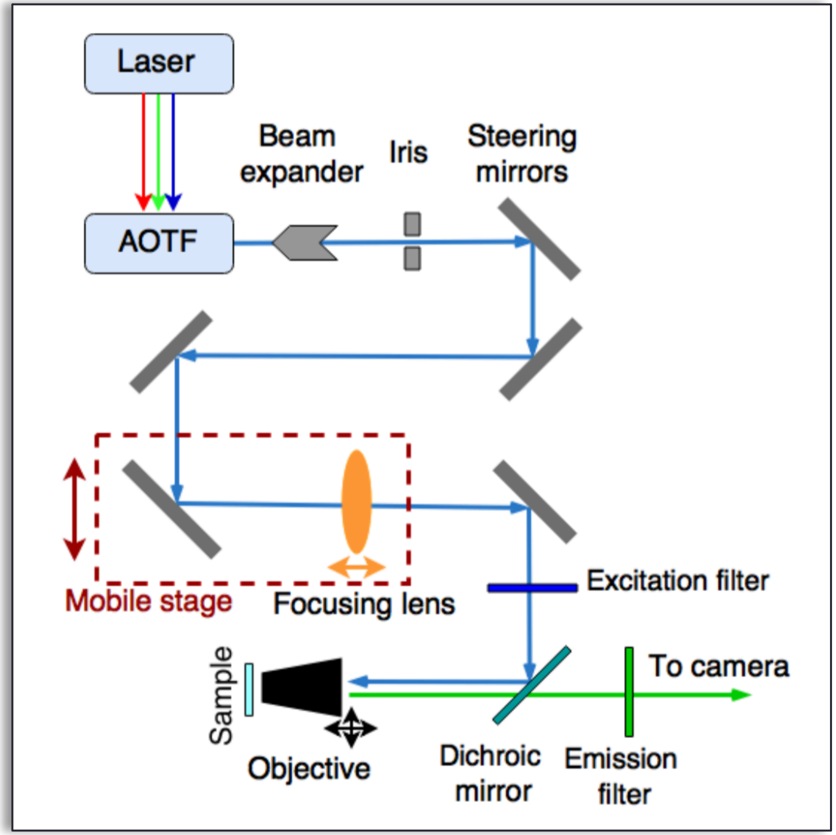


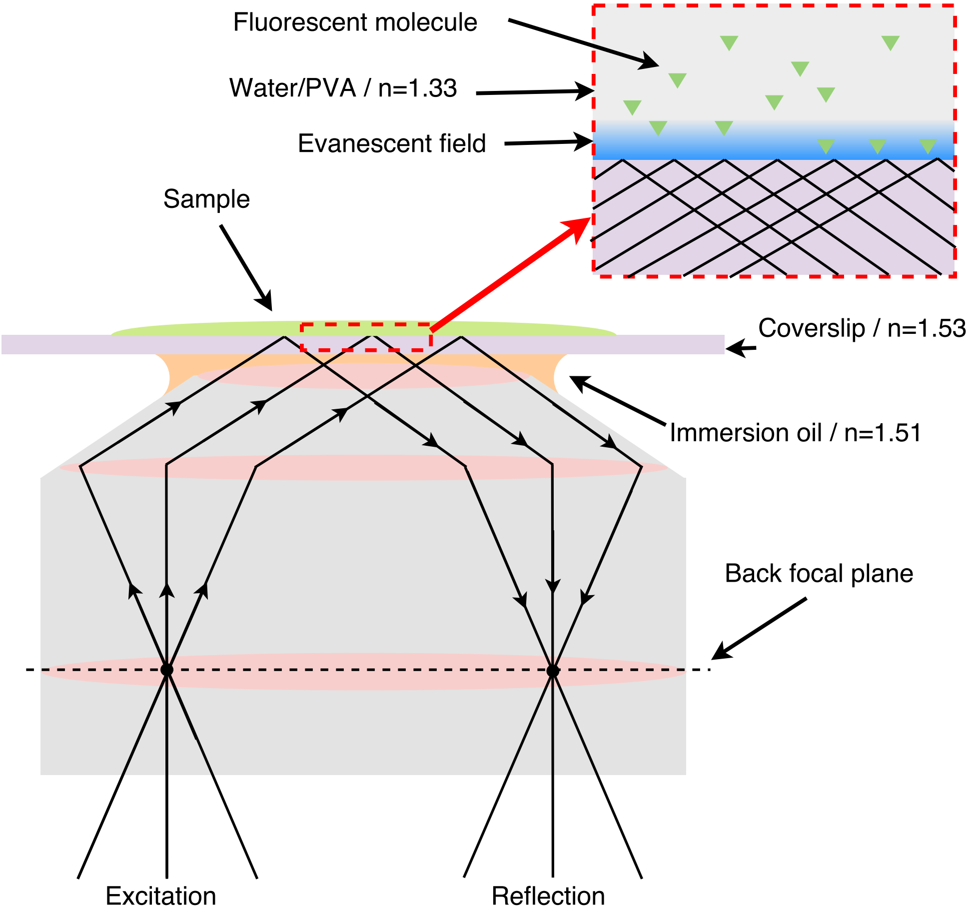


TIRF

Total Internal Reflection Fluorescence microscopy



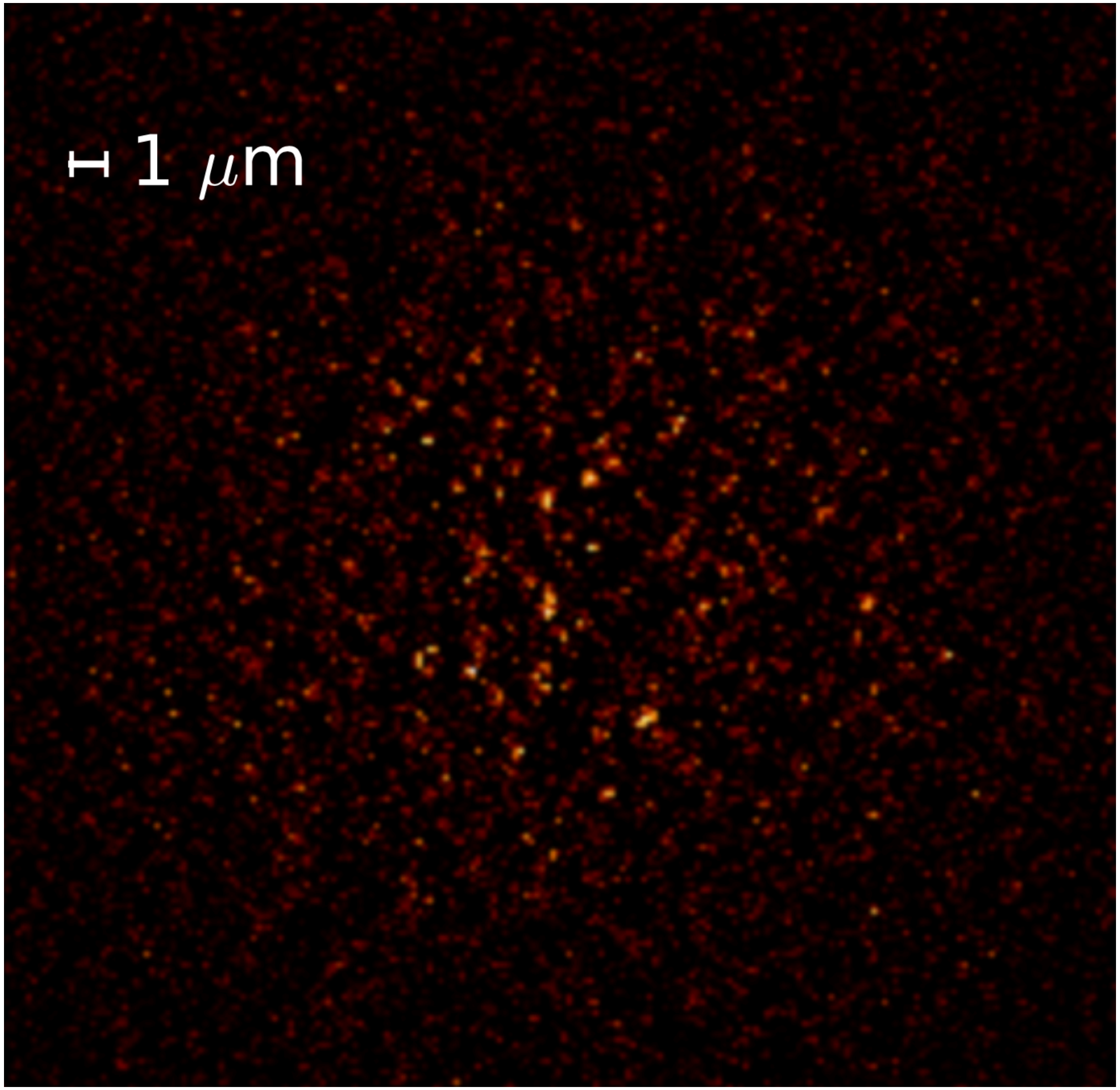




TIRF

Total Internal Reflection Fluorescence microscopy

Single Ba^{++} TIRF images from our lab at UTA

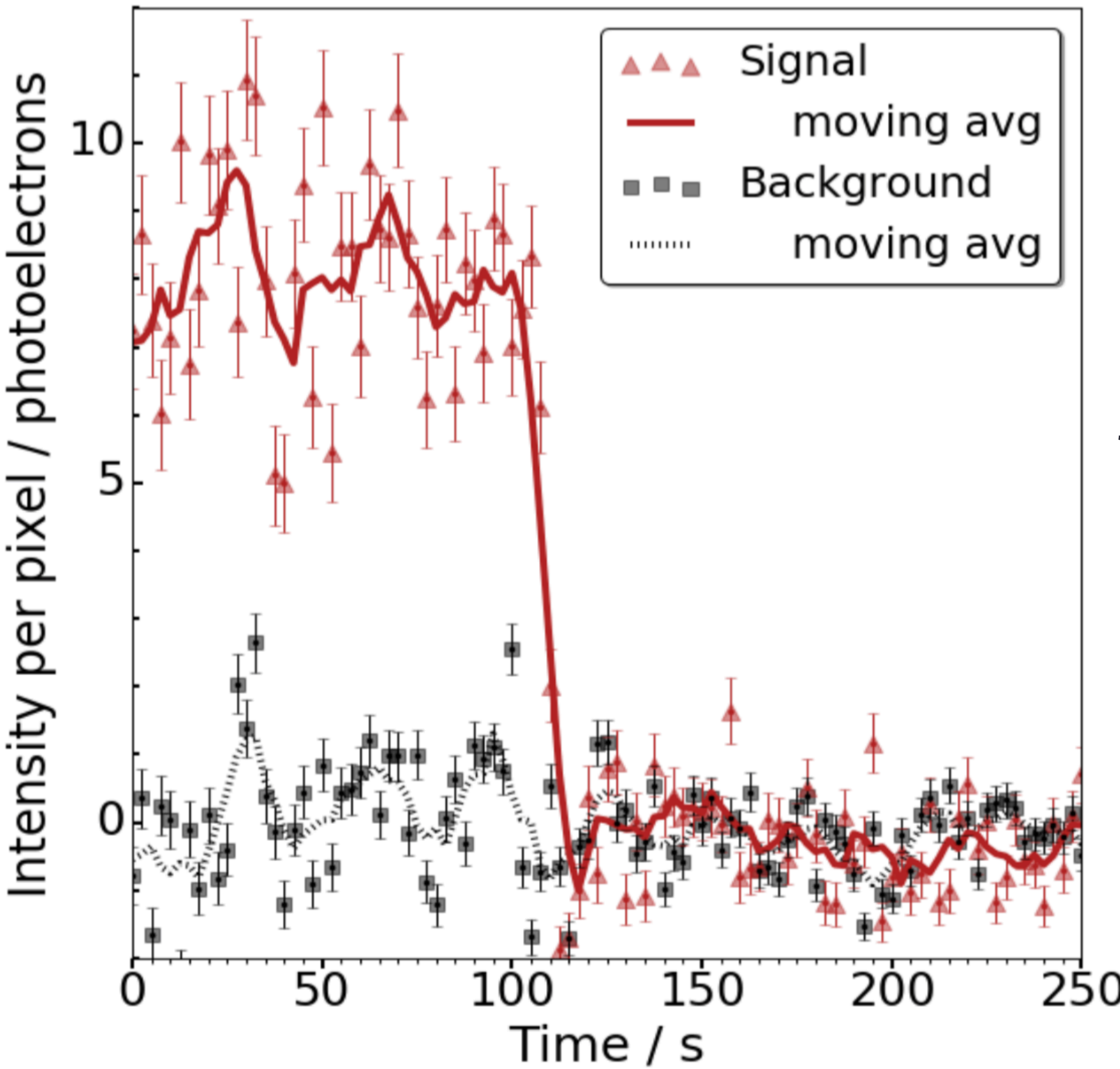


← **This image shows a weak solution of barium perchlorate salt on our sensor.**

Each spot is a **single barium ion.**

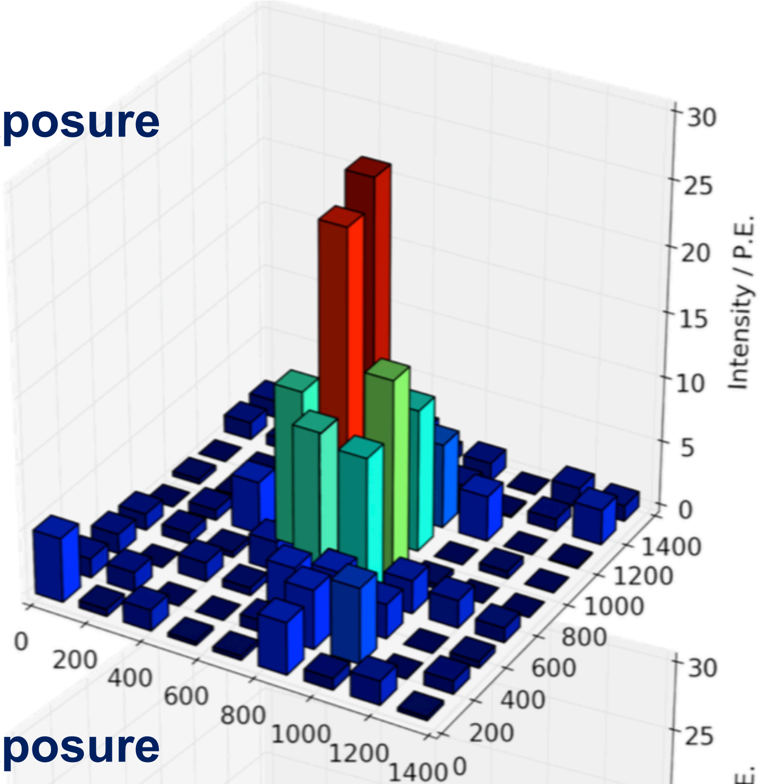
Brighter spots are near the TIRF surface, dimmer ones are deeper in the sample.

In a xenon detector, dye deposited as a monolayer and only brightest spots at constant depth expected.

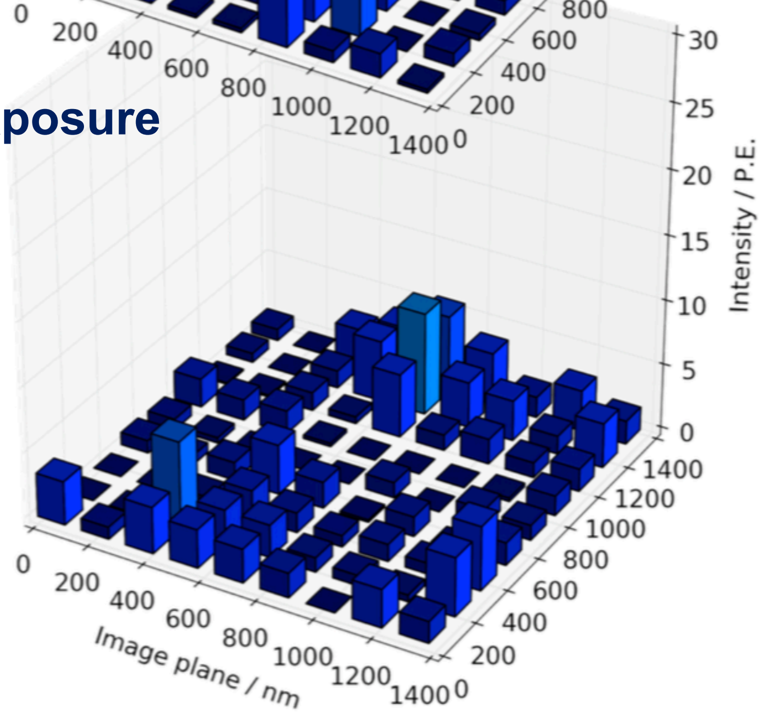


This "step" is how you know it is exactly one ion.

0.5s exposure before:

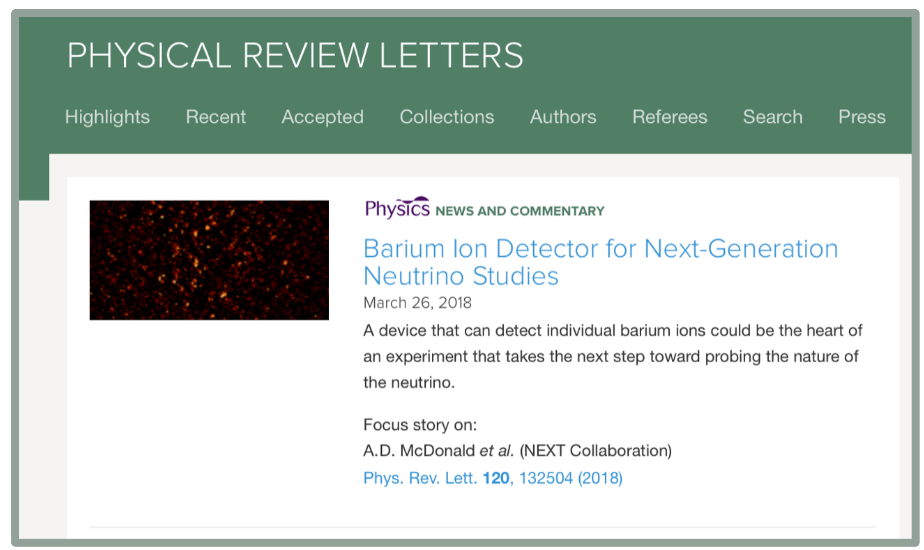


0.5s exposure after:



Single ions barium resolved with 2nm super-resolution and 12.9 sigma stat. significance.

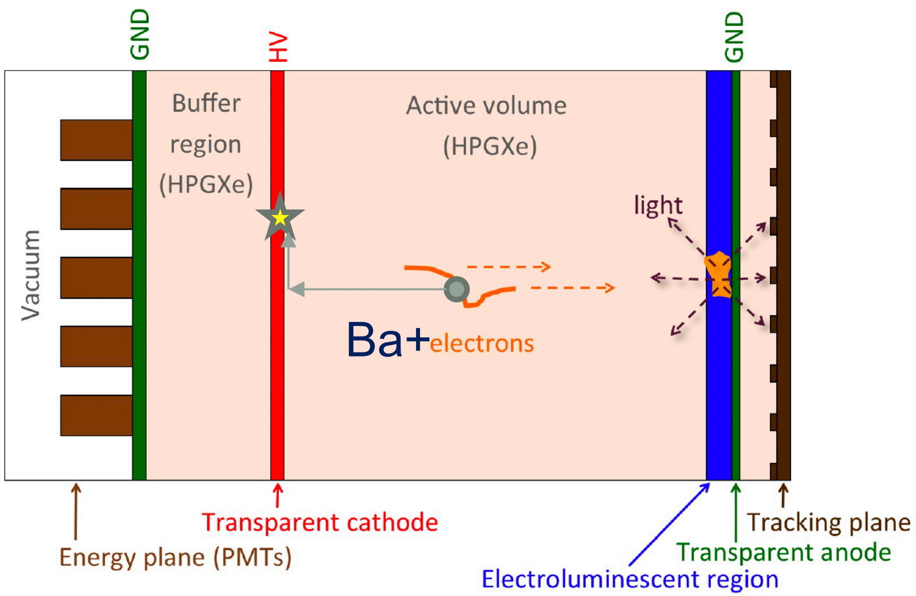
Phys.Rev.Lett. 120 (2018) no.13, 132504



First demonstration of single Ba++ ion resolution.

Next steps: Making it work in gas

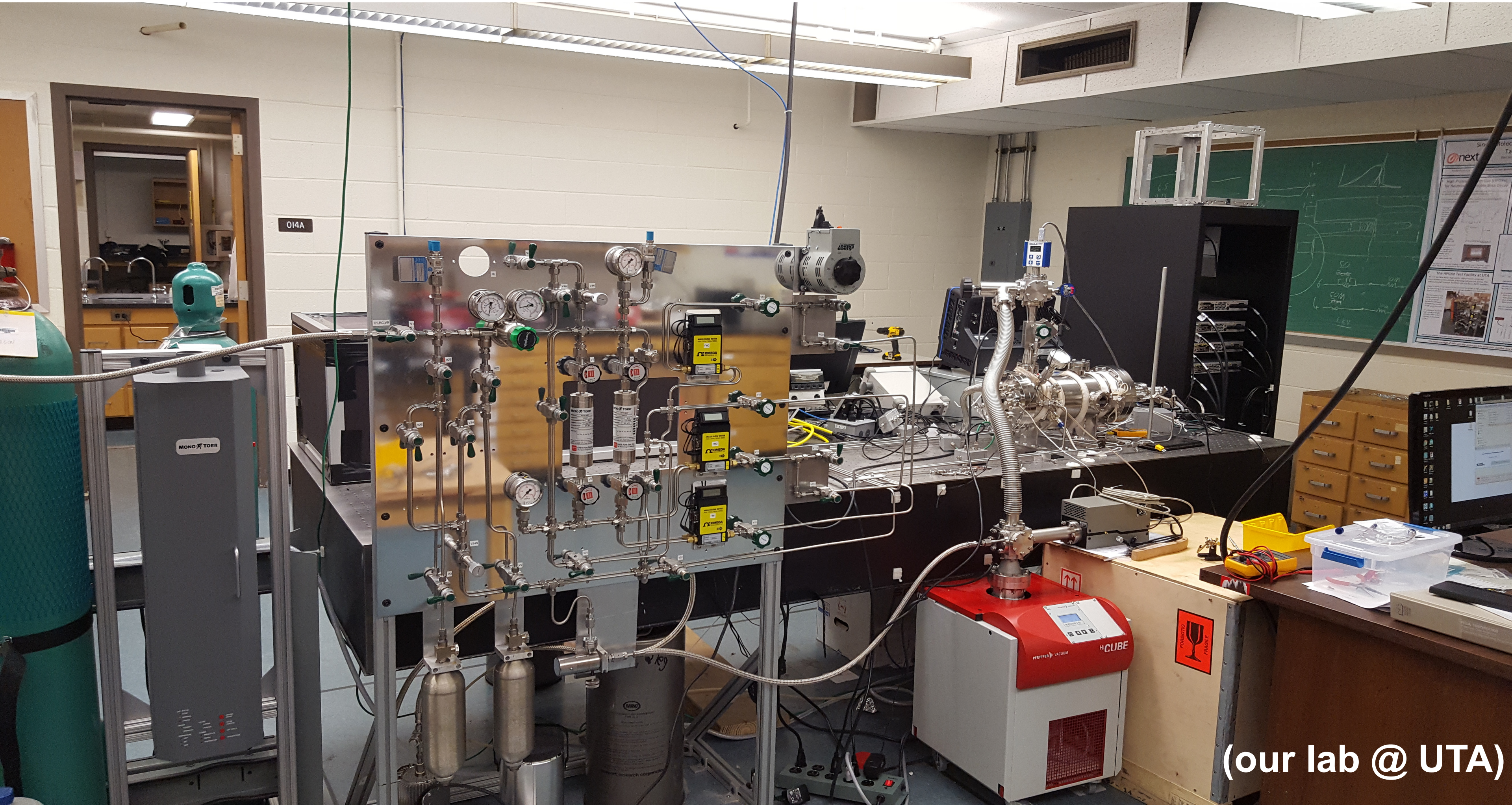
- 1. Barium ion test beam
- 2. Barium drift characterization
- 3. Dry phase microscopy
- 4. Ion concentration to sensors
- 5. Dry SMFI molecule design
- 6. Combine into a working sensor for NEXT prototype

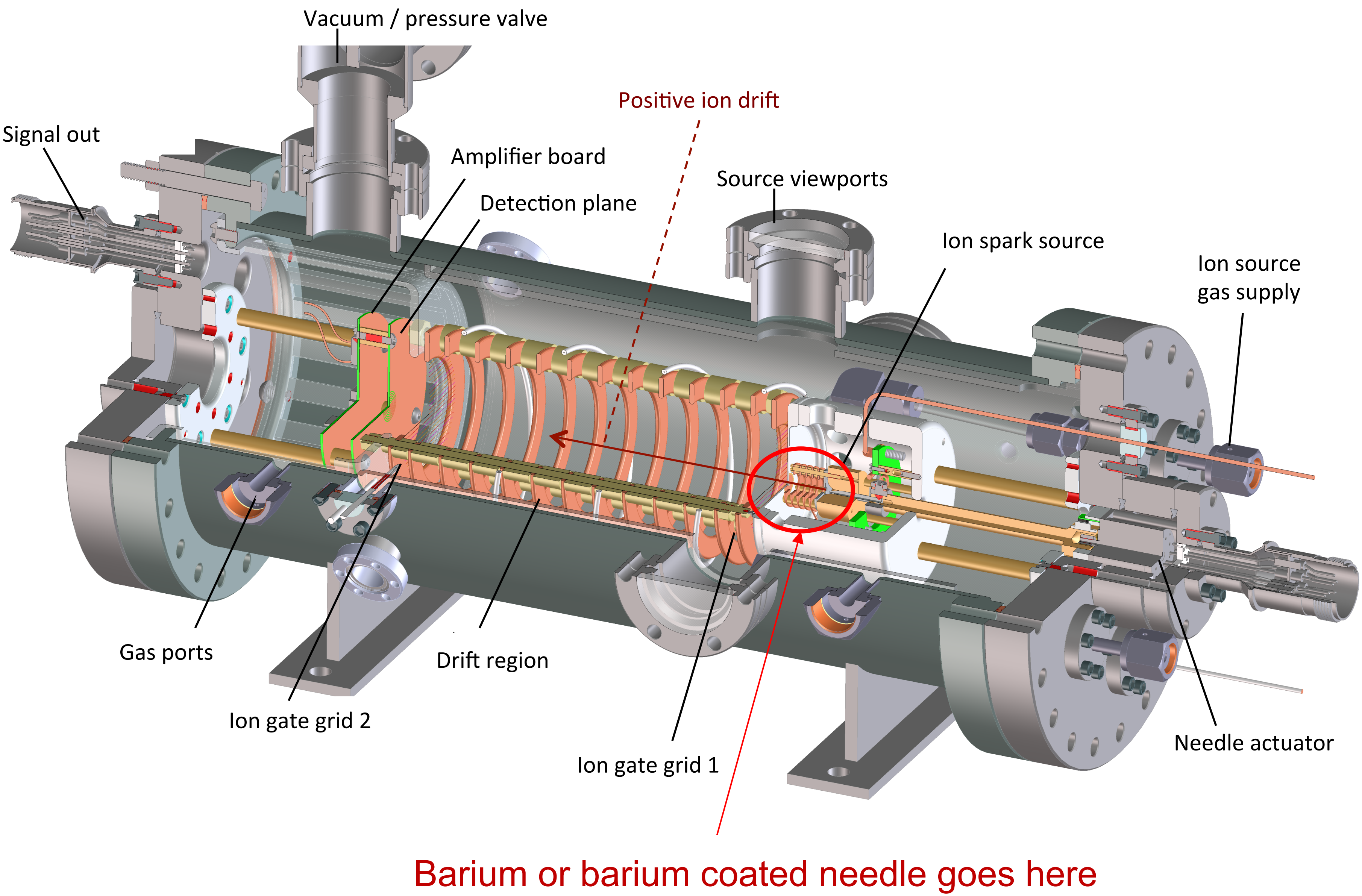


SUPPORTED BY:
U.S. DEPARTMENT OF ENERGY

The barium beam

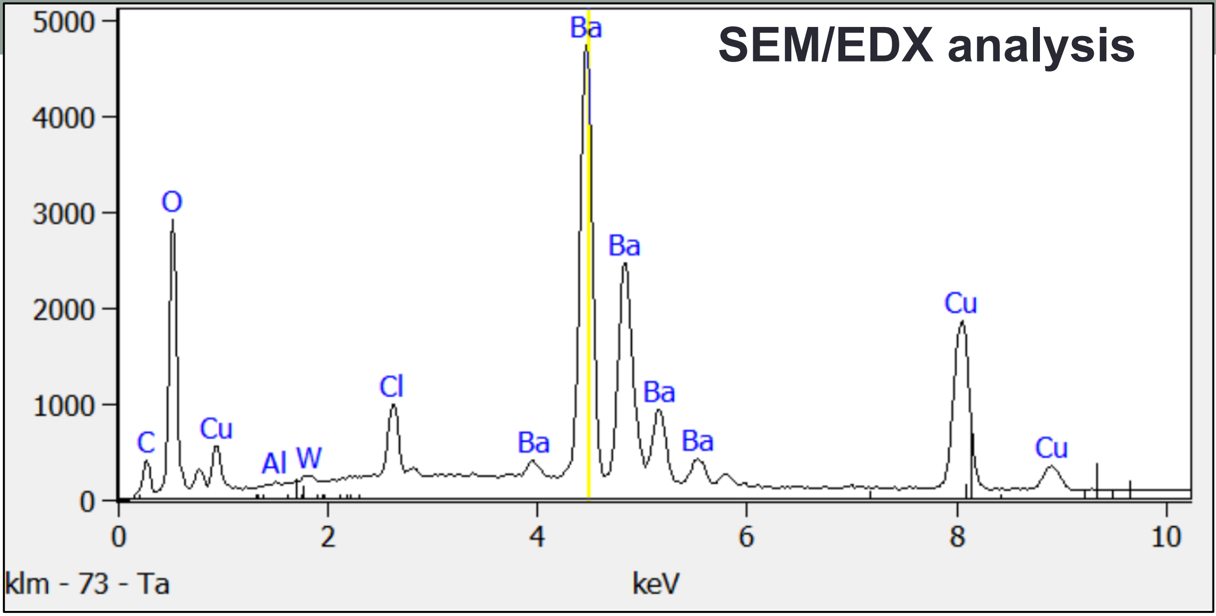
- The next major step is to test barium sensing dyes in HPGXe environment
- Expect better performance than in solution from both energetics and reactivity considerations



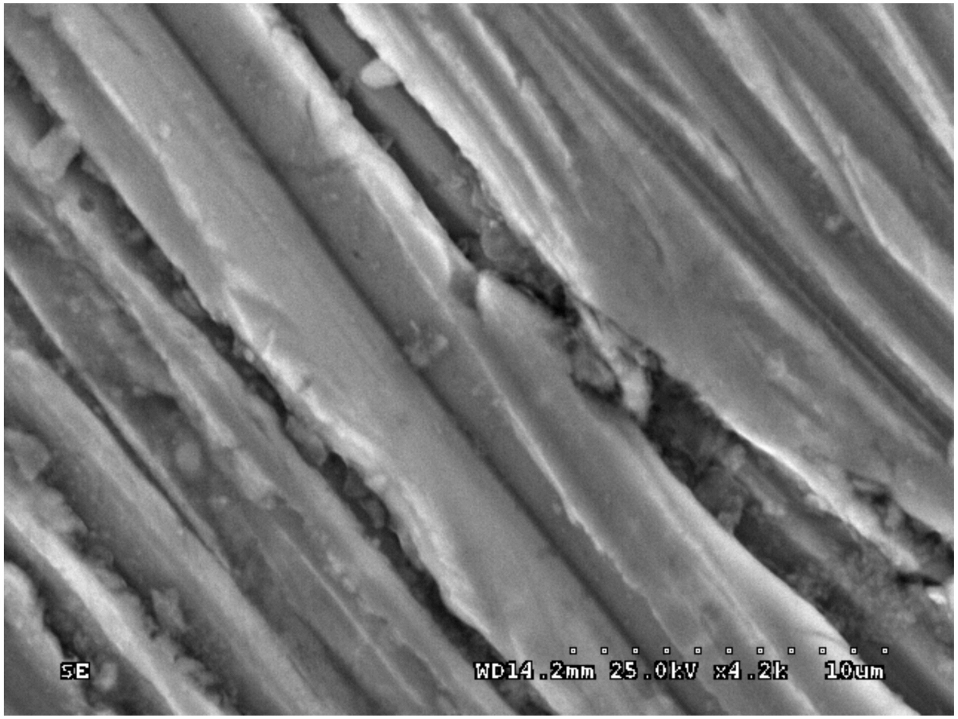

Vacuum / pressure valve
Positive ion drift
Signal out
Amplifier board
Source viewports
Detection plane
Ion spark source
Ion source
gas supply
Gas ports
Drift region
Ion gate grid 2
Ion gate grid 1
Needle actuator
Barium or barium coated needle goes here

We have developed a custom electroplating method to deposit a stable barium-rich coating onto copper for spark source from methanol.

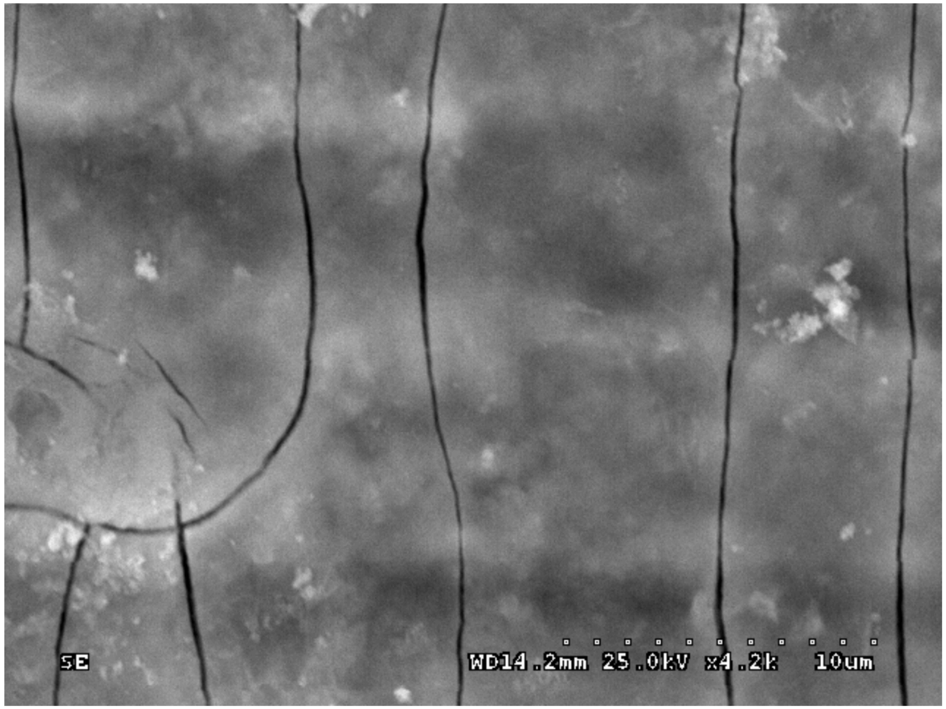
Removes difficulty of barium metal handling.



Bare copper



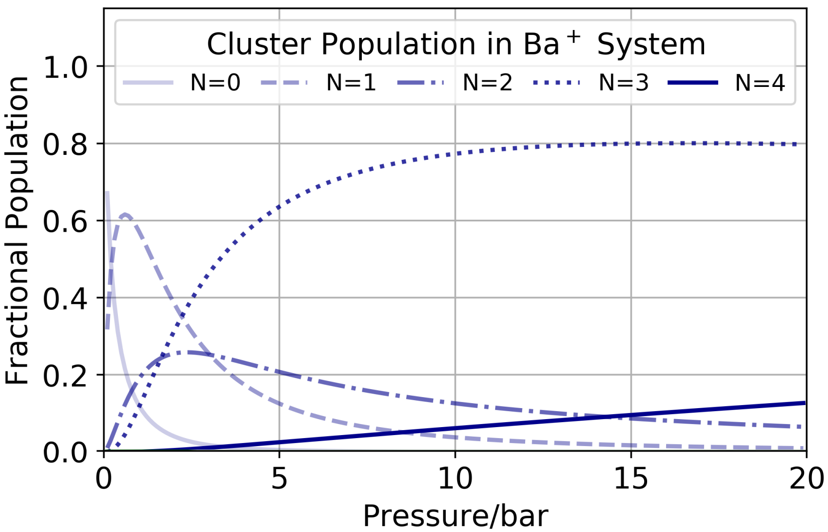
Barium electroplated copper



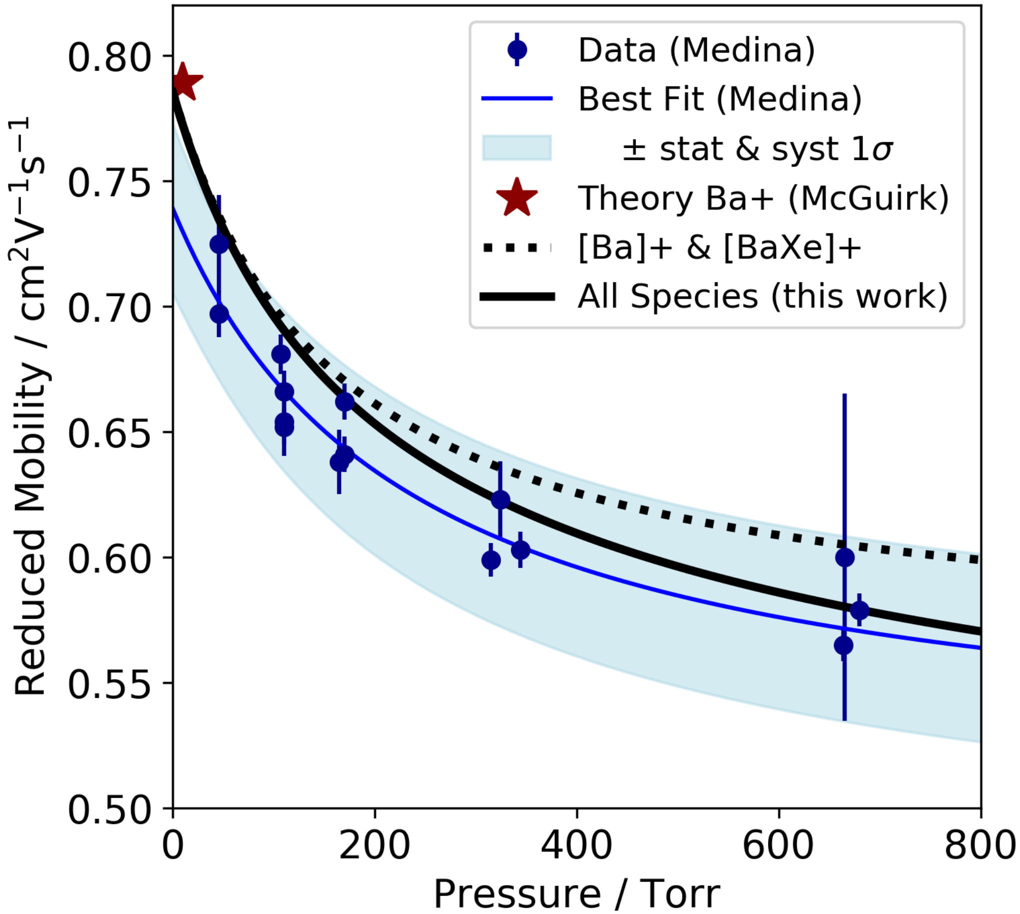
Barium mobility in gas – in theory:

Not a single ion drifting!

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

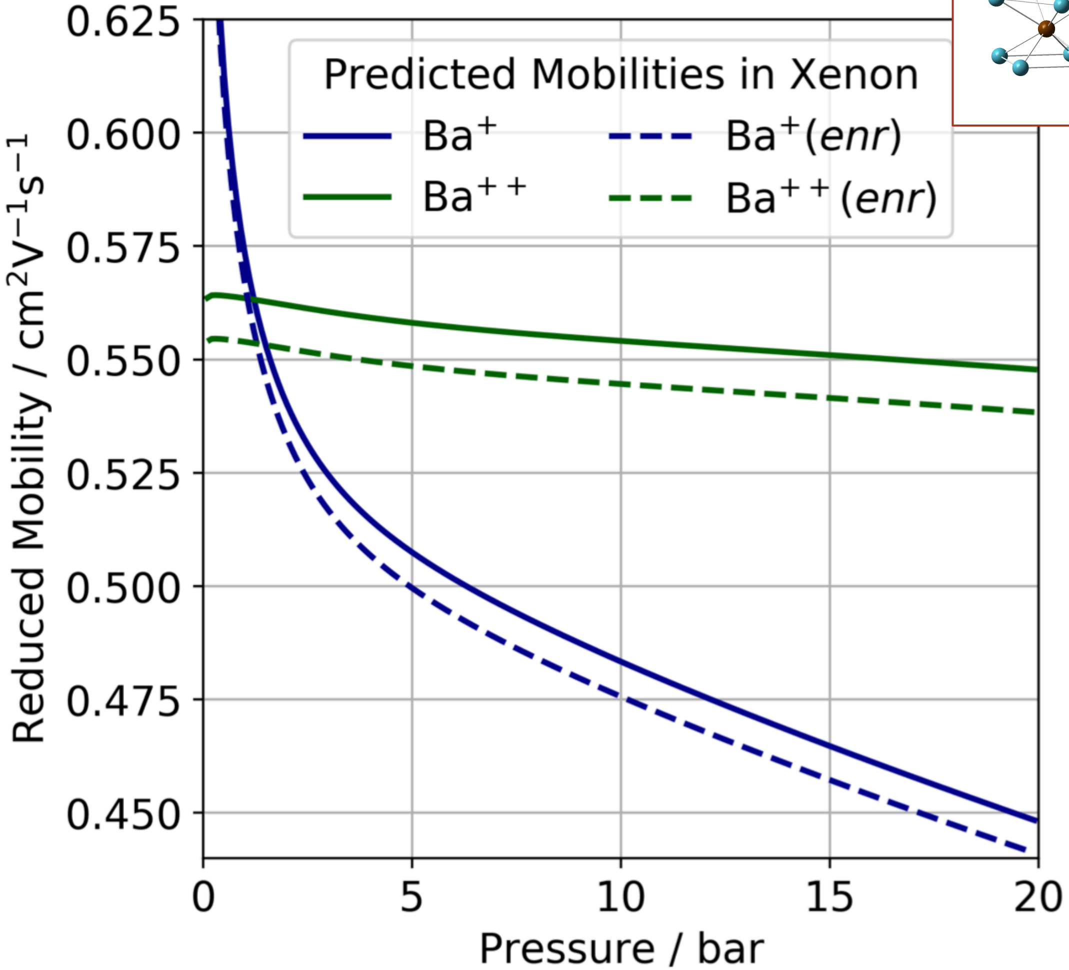


Excellent agreement with data for Ba+

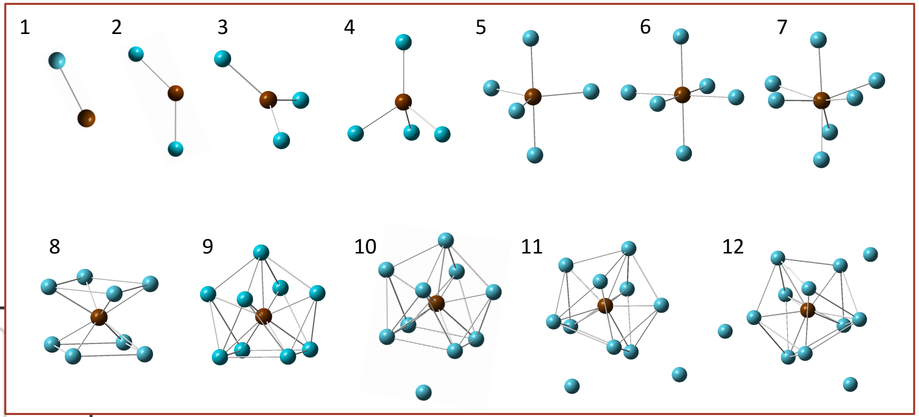


[**Mobility and Clustering of Barium Ions and Dications in High Pressure Xenon Gas**]
E. Bainglass, B.J. P. Jones, et. al. Phys.Rev. A97 (2018) no.6, 062509

For Ba++ things get more complicated.



Calculated Ba++ clusters:

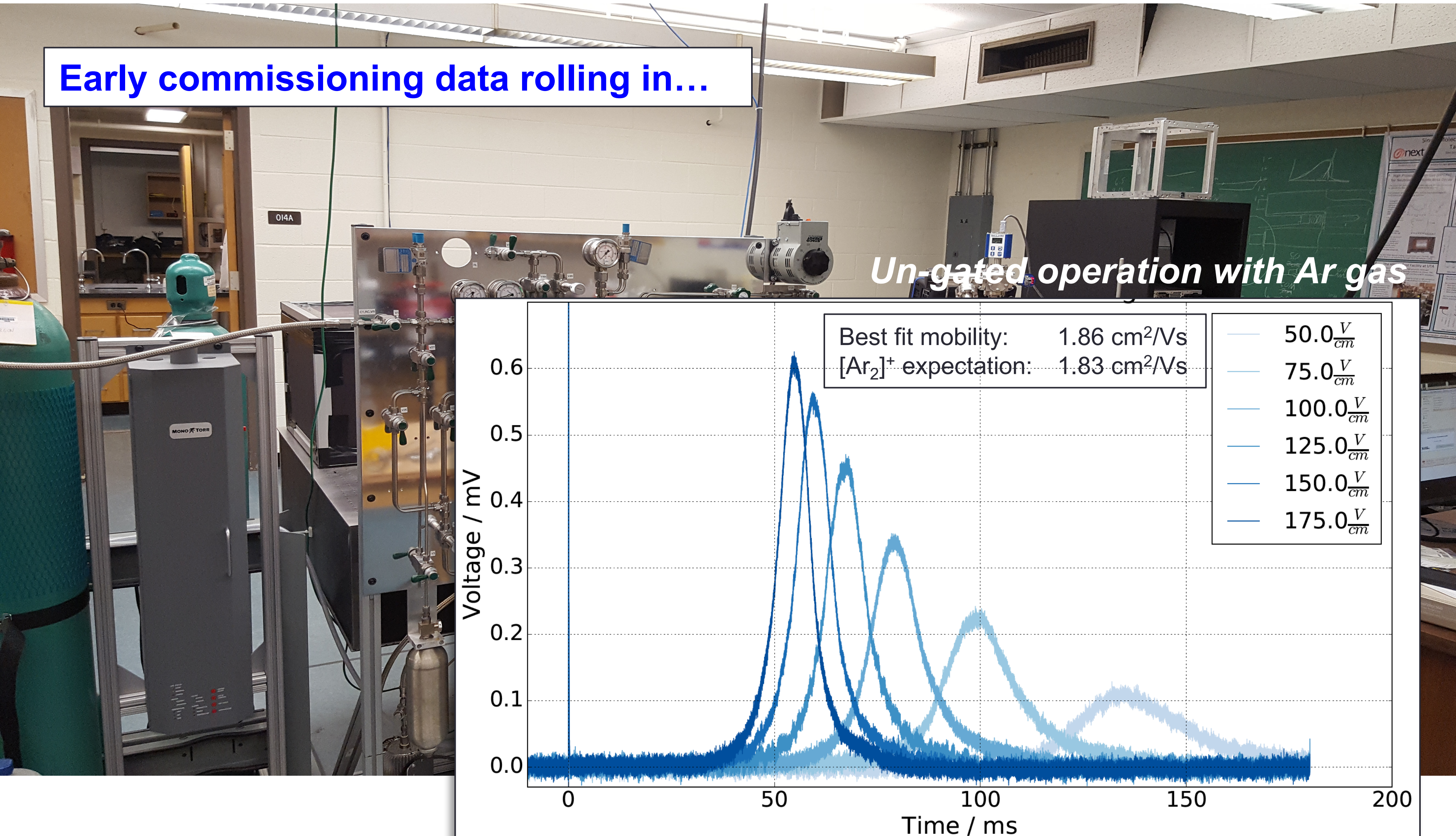


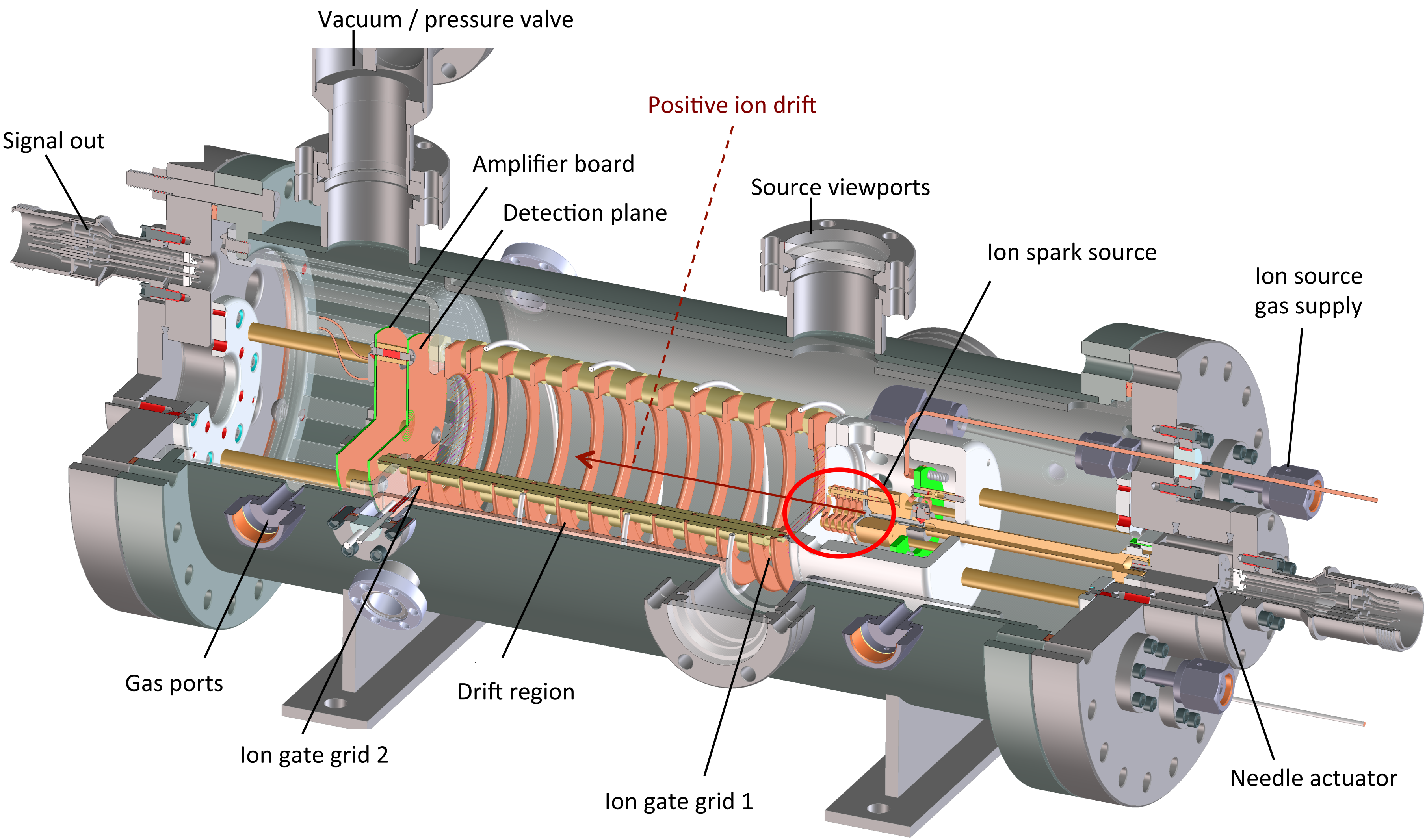
Bigger clusters more similar to each other, so less pressure dependence in Ba++ than Ba+

Isotopic composition changes scattering kinematics, so %-level differences with enriched xenon

We will test this with experimental data soon!

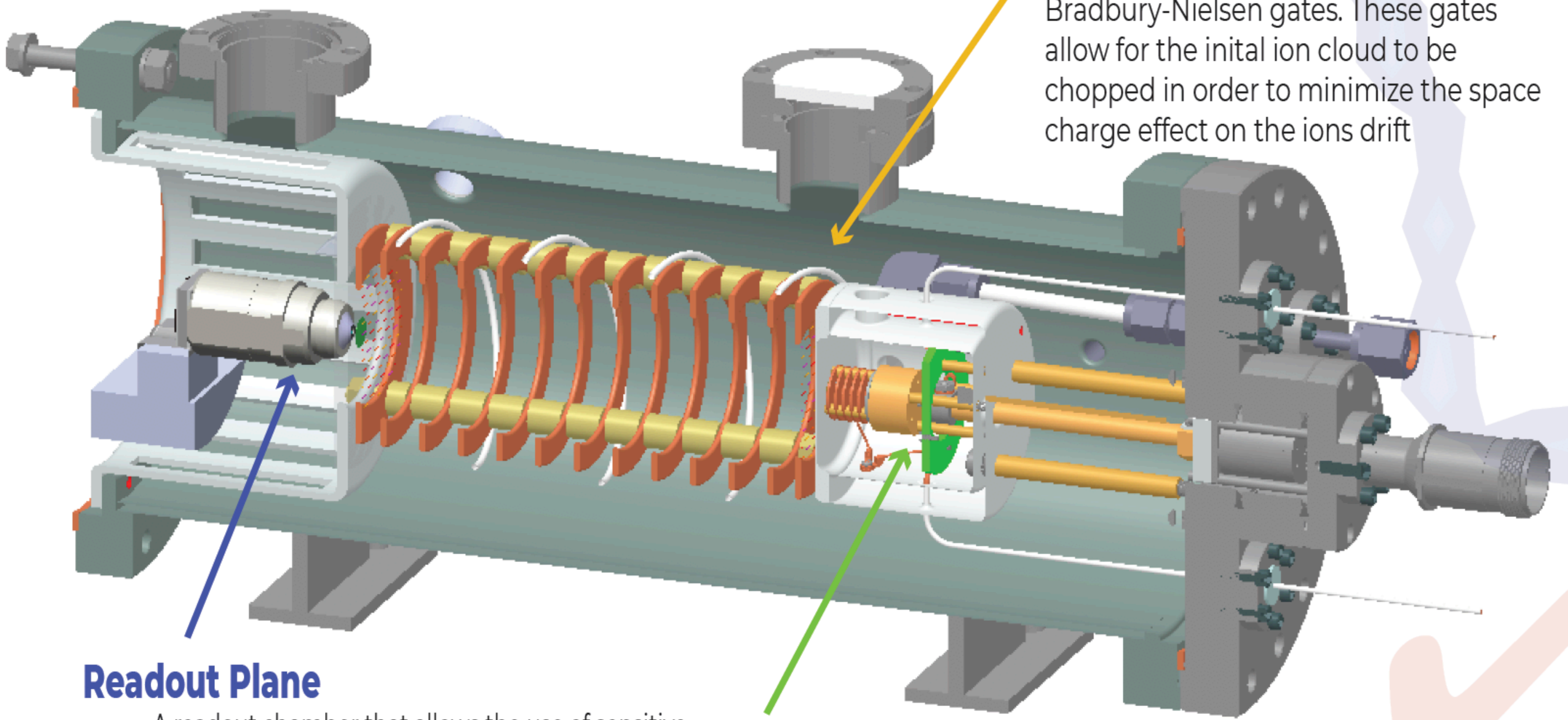
The ion beam is coming…




Vacuum / pressure valve
Positive ion drift
Signal out
Amplifier board
Detection plane
Source viewports
Ion spark source
Ion source
gas supply
Gas ports
Drift region
Ion gate grid 2
Ion gate grid 1
Needle actuator

Gated Drift Region

20cm uniform drift region that utilized Bradbury-Nielsen gates. These gates allow for the inital ion cloud to be chopped in order to minimize the space charge effect on the ions drift



Readout Plane

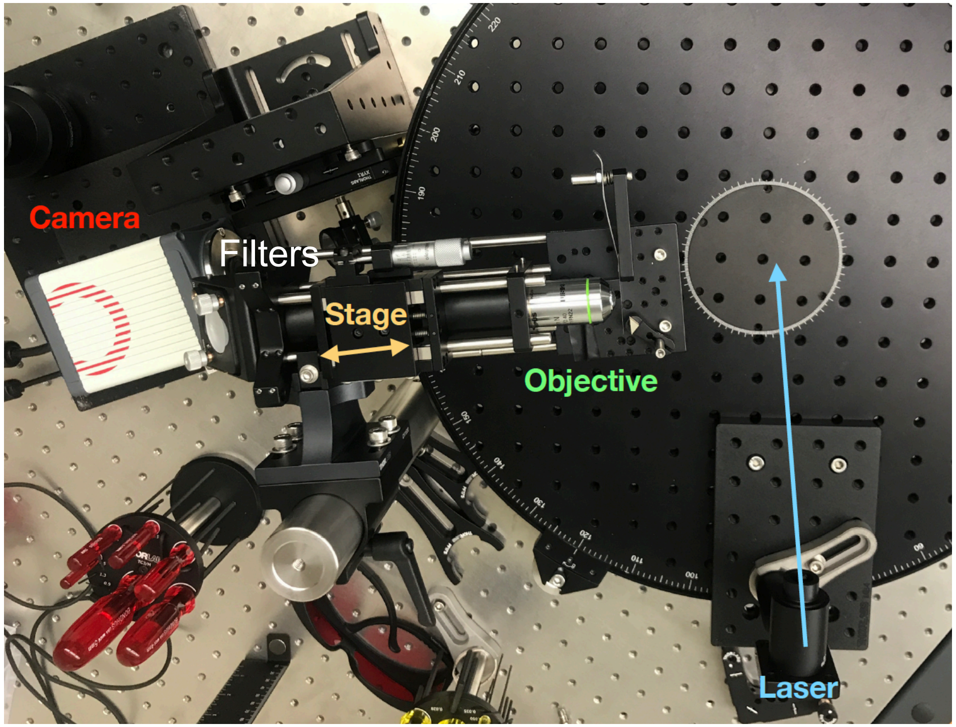
A readout chamber that allows the use of sensitive eletrical amplifier or optical readout. The ions are guided here via an eletric field.

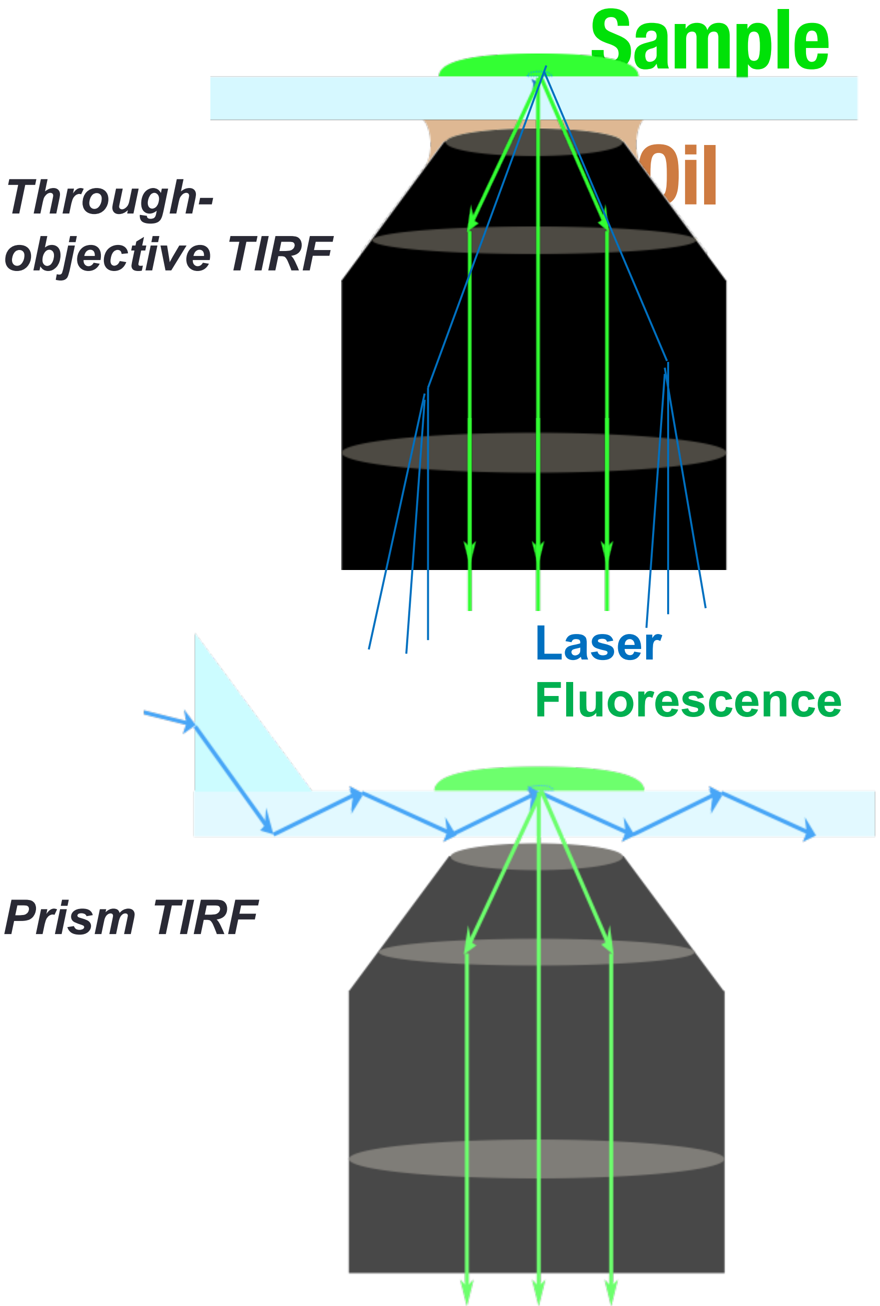
Ion Source

A needle and ring electrode that is adjustable allowing for an adjustable spark gap to acomadate Various pulse and pressure conditions.

Dry Microscopy

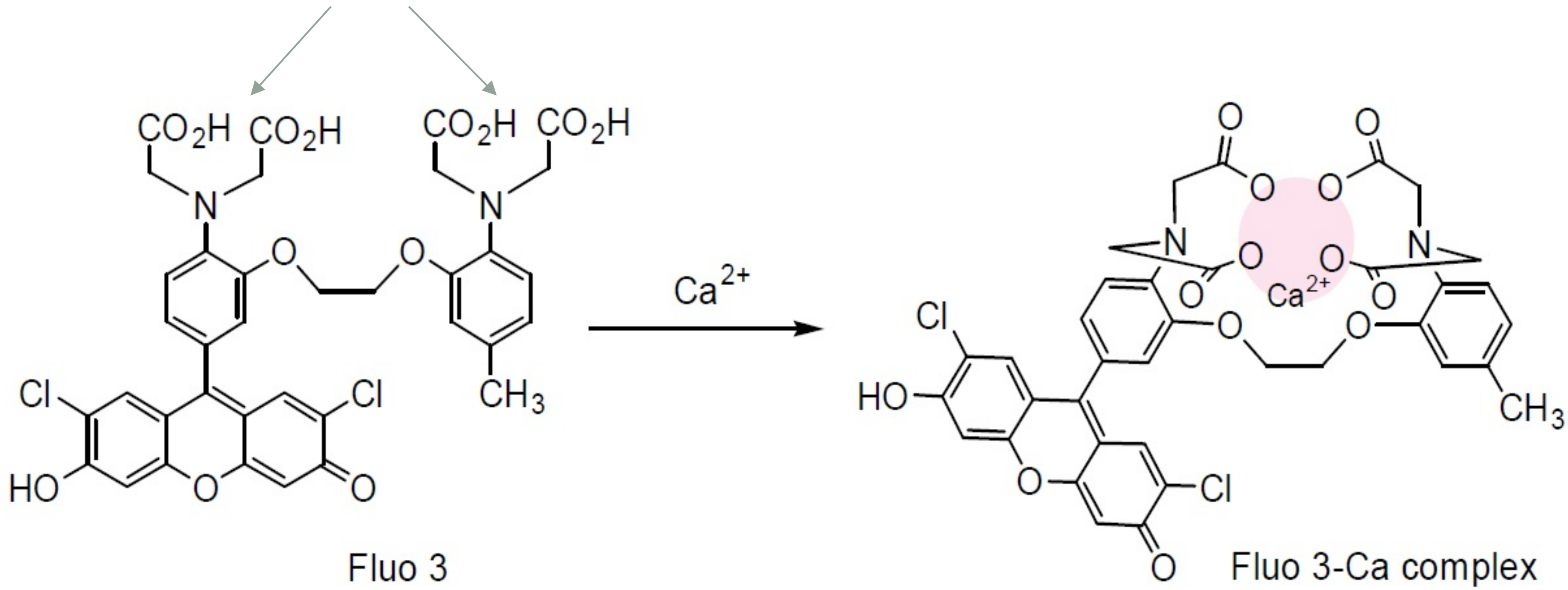
- To remove microscope oil (incompatible with HPGXe) we need to deliver excitation transversely.
- This is achieved through prism TIRF-decouples the motion of the objective and the TIRF source.
- We are building up a prism TIRF array at UTA for operation in gas



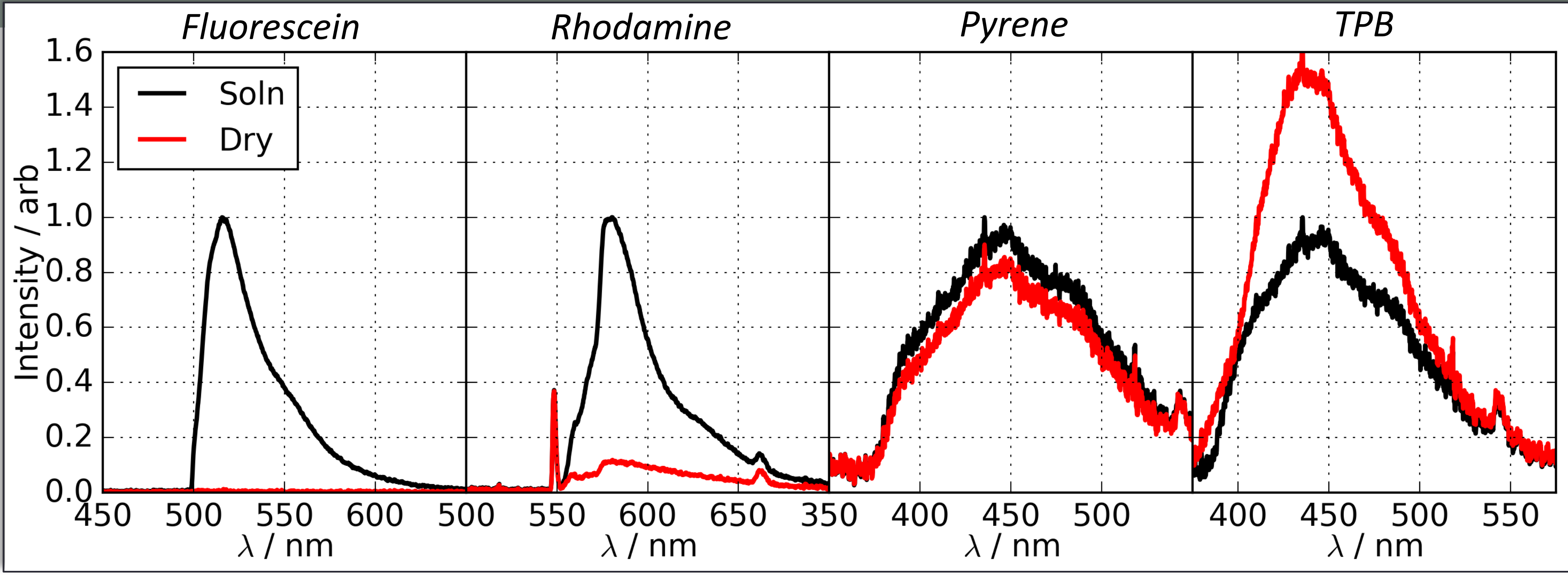


Dry Phase Receptor

Deprotonation of carboxylic acids is required to accept the ion –
we observe the characteristic pH dependence of this in solution

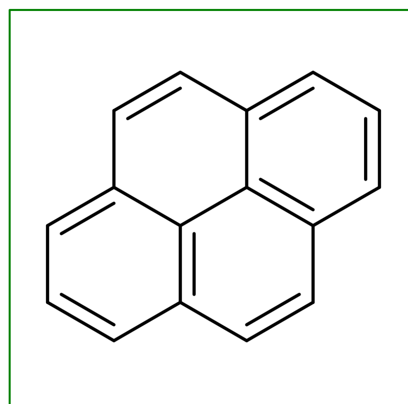


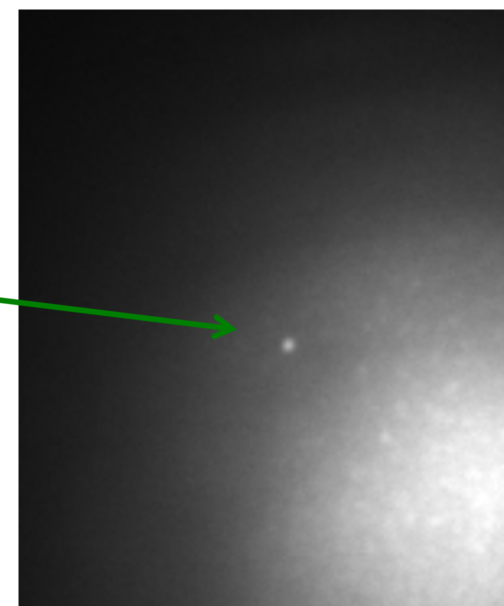
It is unclear if deprotonation will occur in solid phase but we suspect perhaps not. This motivated us to start building “dry-taylored” molecules even before we have a dry system to test in.



Fluo-3 may not be ideal for HPGXe, since fluorescein dye is not bright in dry phase.

But pyrene works. We can resolve single molecules of it too.



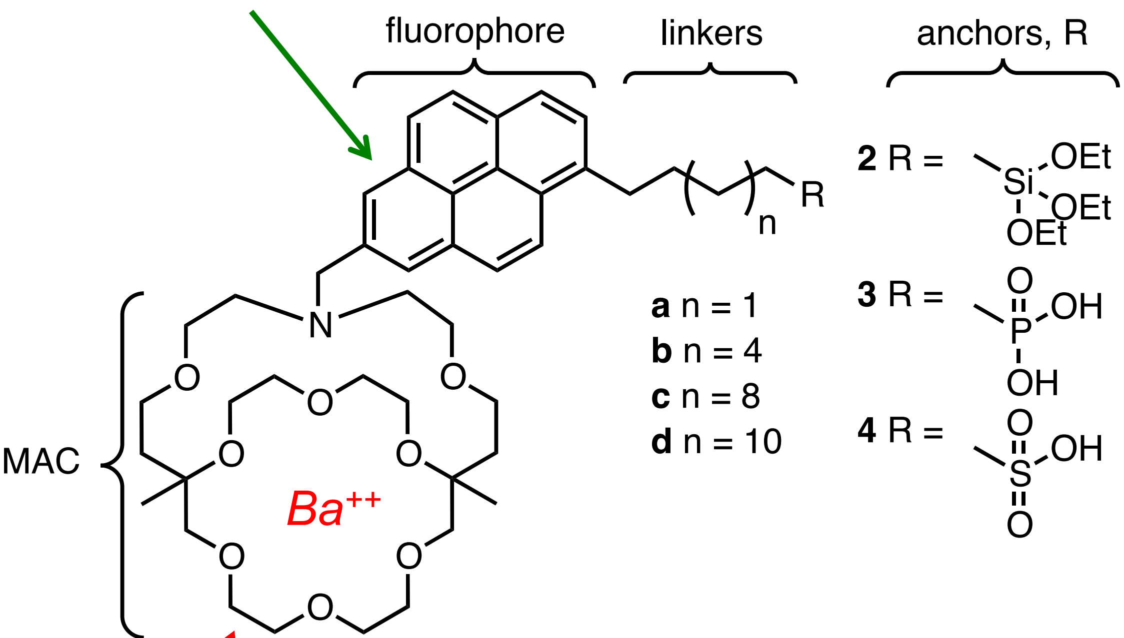


The Dream Molecule?

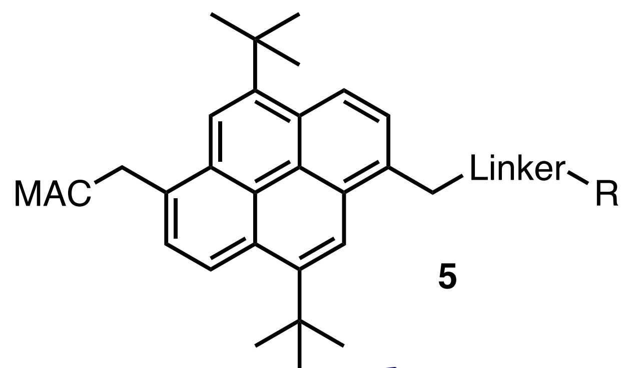
Tethered pyrene substituted monoazocryptand (tPSMA)

Our first batch is being synthesized right now by Foss lab at UTA.

Pyrene
(bright in dry phase)



Monoazocryptand
(hyper Ba^{++} specific)



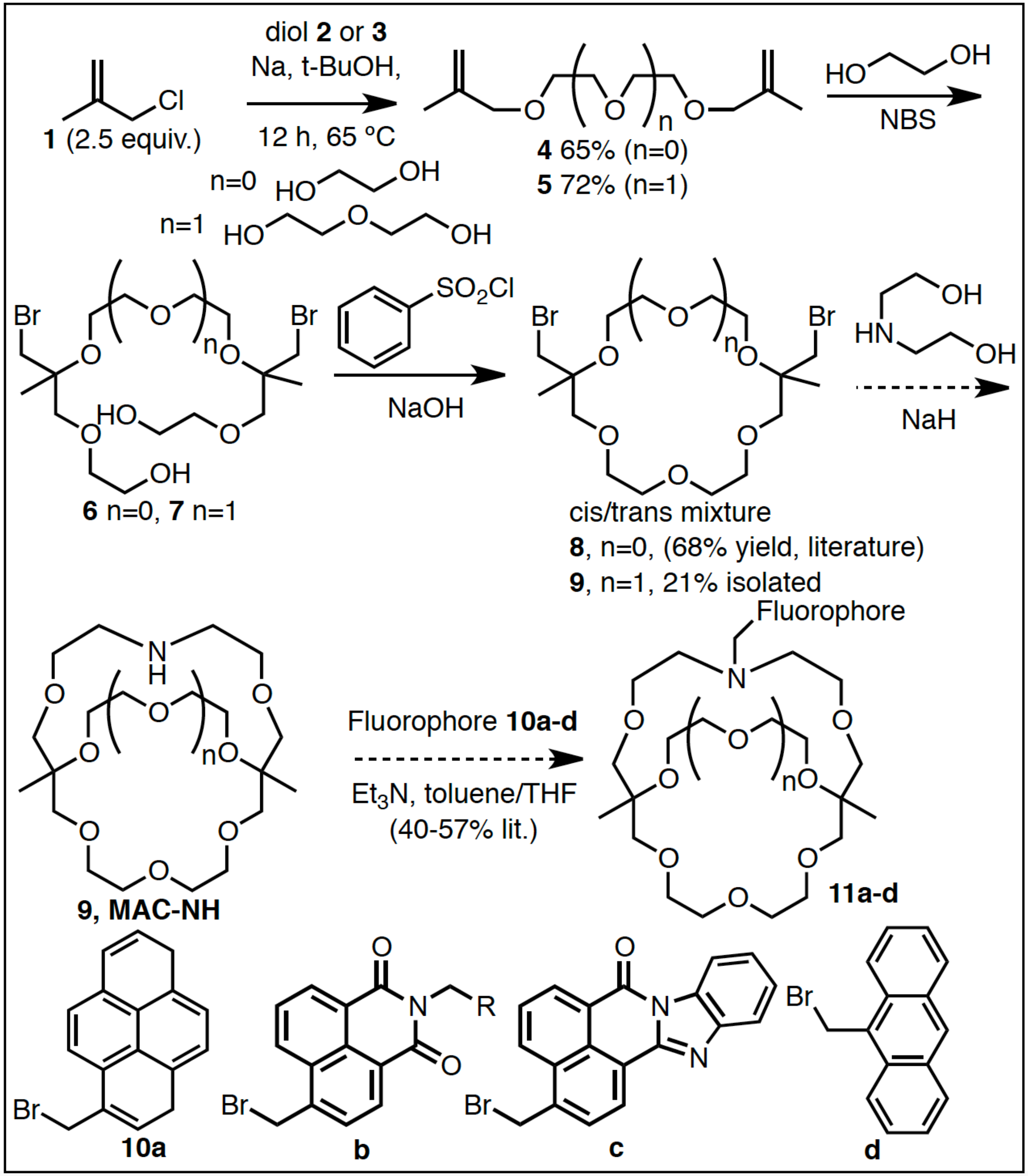
5

Possible “arms” inhibit surface quenching of fluor

Diner, C., Scott, D. E., Tykwinski, R. R., Gray, M. R., & Stryker, J. M. Scalable, Chromatography-Free Synthesis of Alkyl-Tethered Pyrene-Based Materials. Application to First-Generation “Archipelago Model” Asphaltene Compounds. *J. Org. Chem.* **2015**, *80*(3), 1719–1726.

Synthesis of PSMA and its relatives

The story so far…

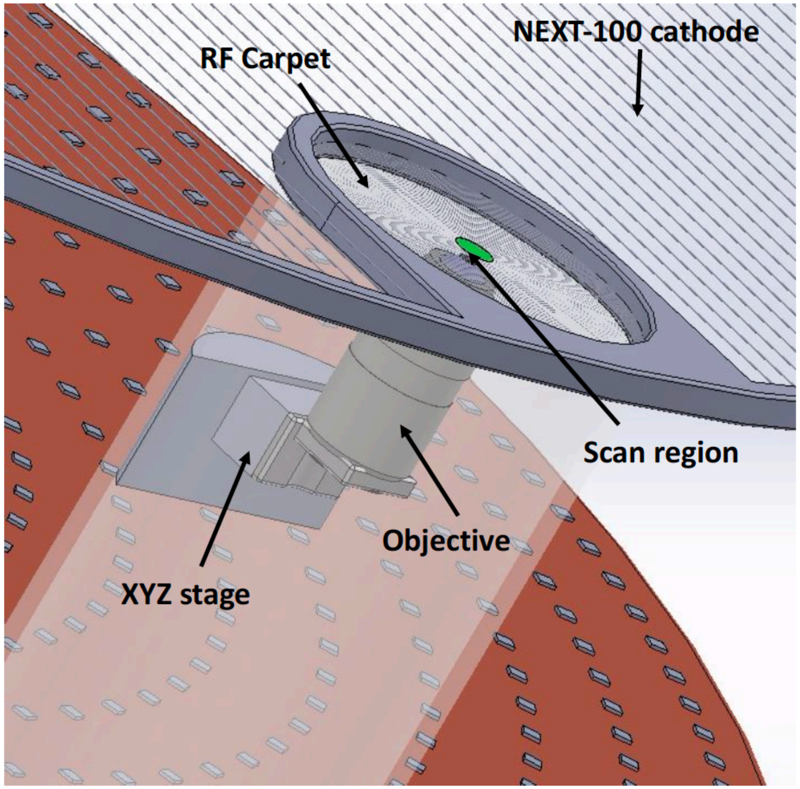


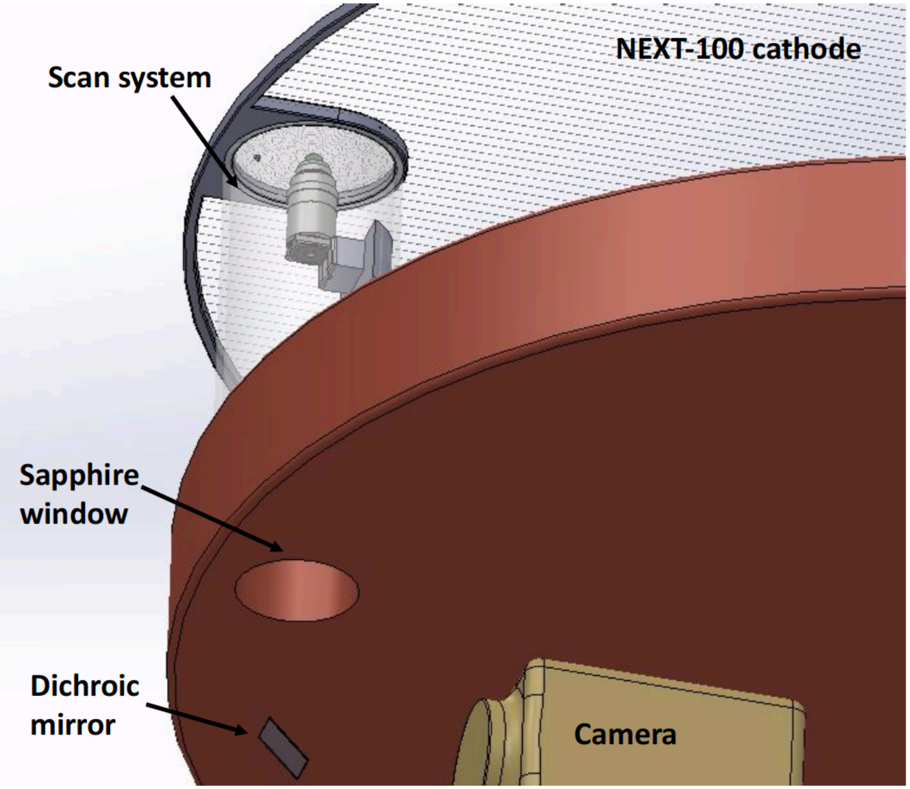
First batch of custom dry fluorophores coming off production line now.

Watch this space!

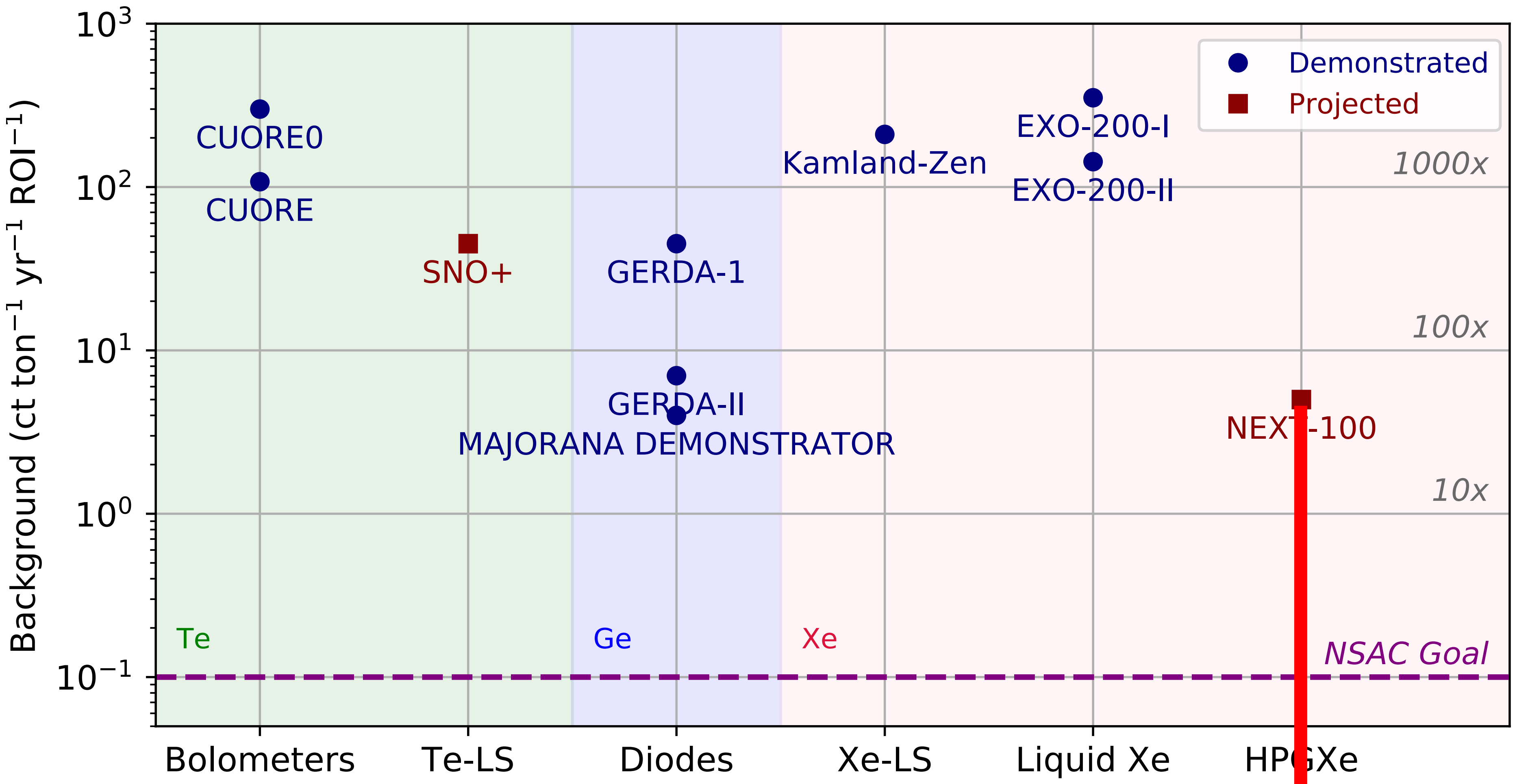
Implementation in NEXT

- The NEXT collaboration is exploring implementation of a prototype barium tagging sensor in a near-future phase of NEXT.
- Our R&D plan aims to converge on an end-to-end barium tagging scheme by 2022-2023. Optimistic, but looks possible from where we stand now.
- **A ton-scale barium tagging HPGXeTPC may be what we need to uncover the Majorana nature of the neutrino, and open the window to the next energy scale.**





THIS QUESTION OF NEUTRINO MASS IS TOO IMPORTANT NOT TO ANSWER, OR TO ANSWER AMBIGUOUSLY.



LETS DO IT!

Thanks!

on behalf of…

Th… tion

USA *(co-spokesperso…*

UNIVERSITY OF TEXAS ARLINGTON

Argon… NAT…

…A STATE …VERSITY

A&M

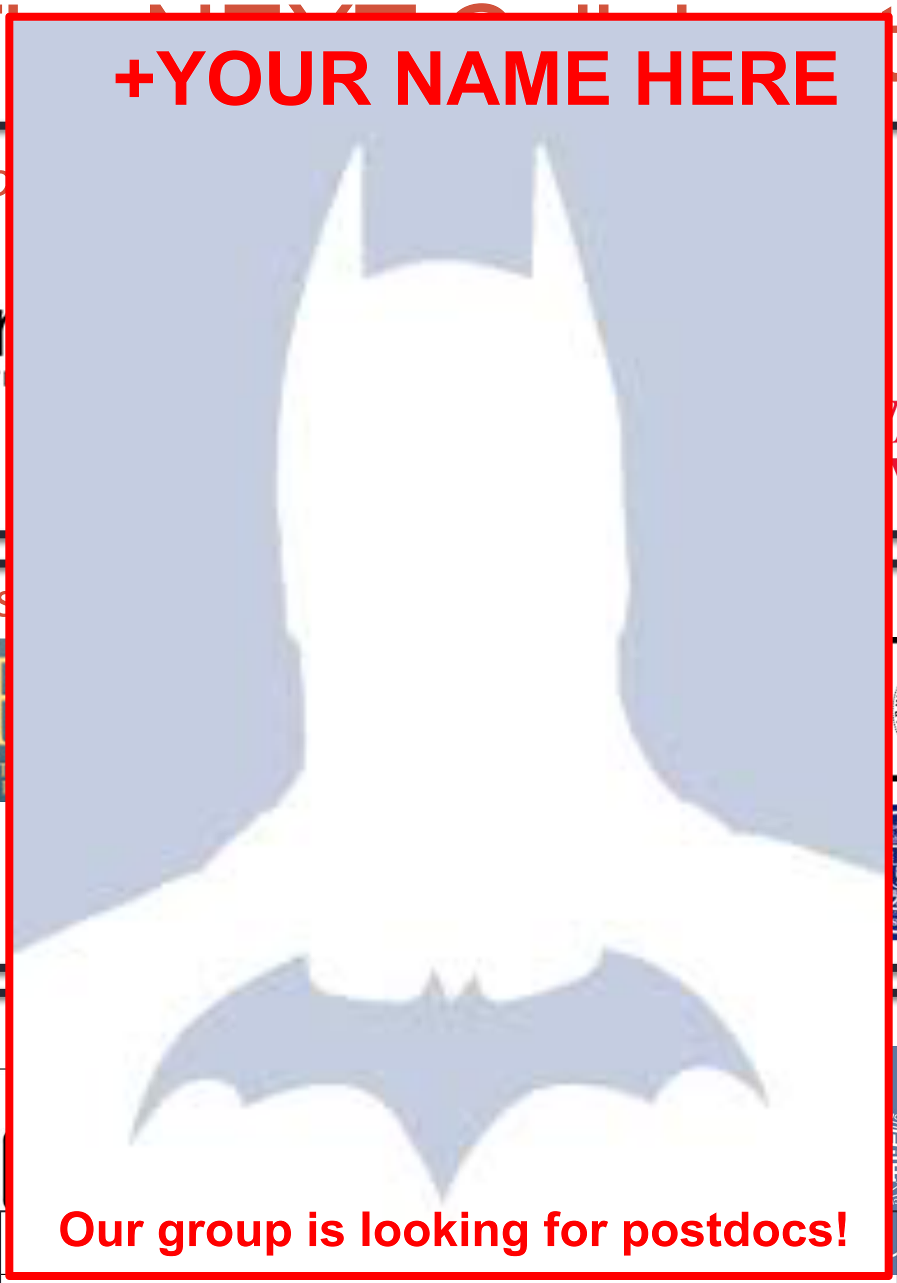
Spain *(co-spokespers…*

DIPC

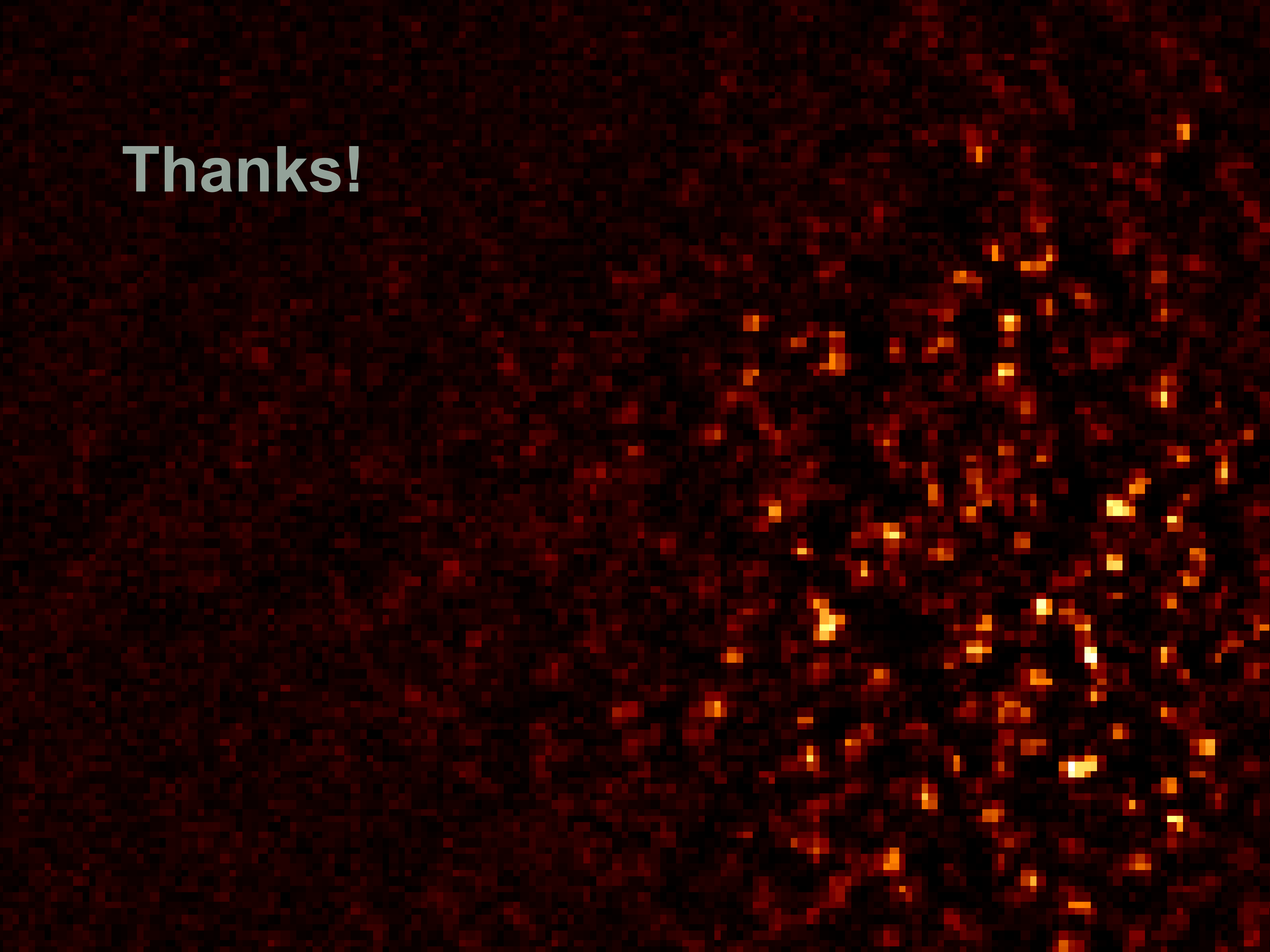
Universidad de Zaragoza

Others

UAN UNIVERSIDAD ANTONIO NARIÑO

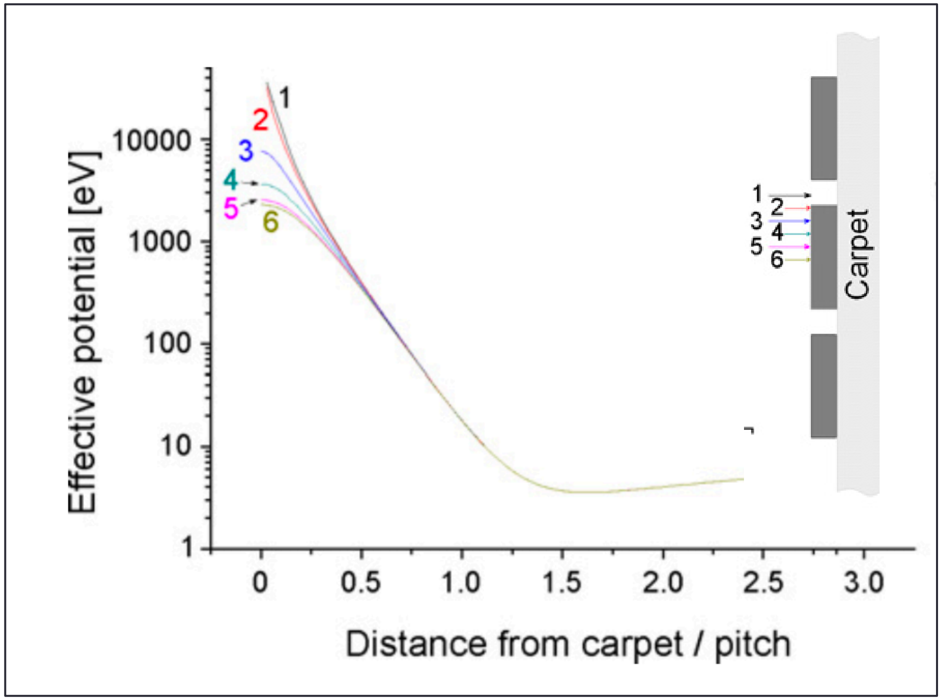


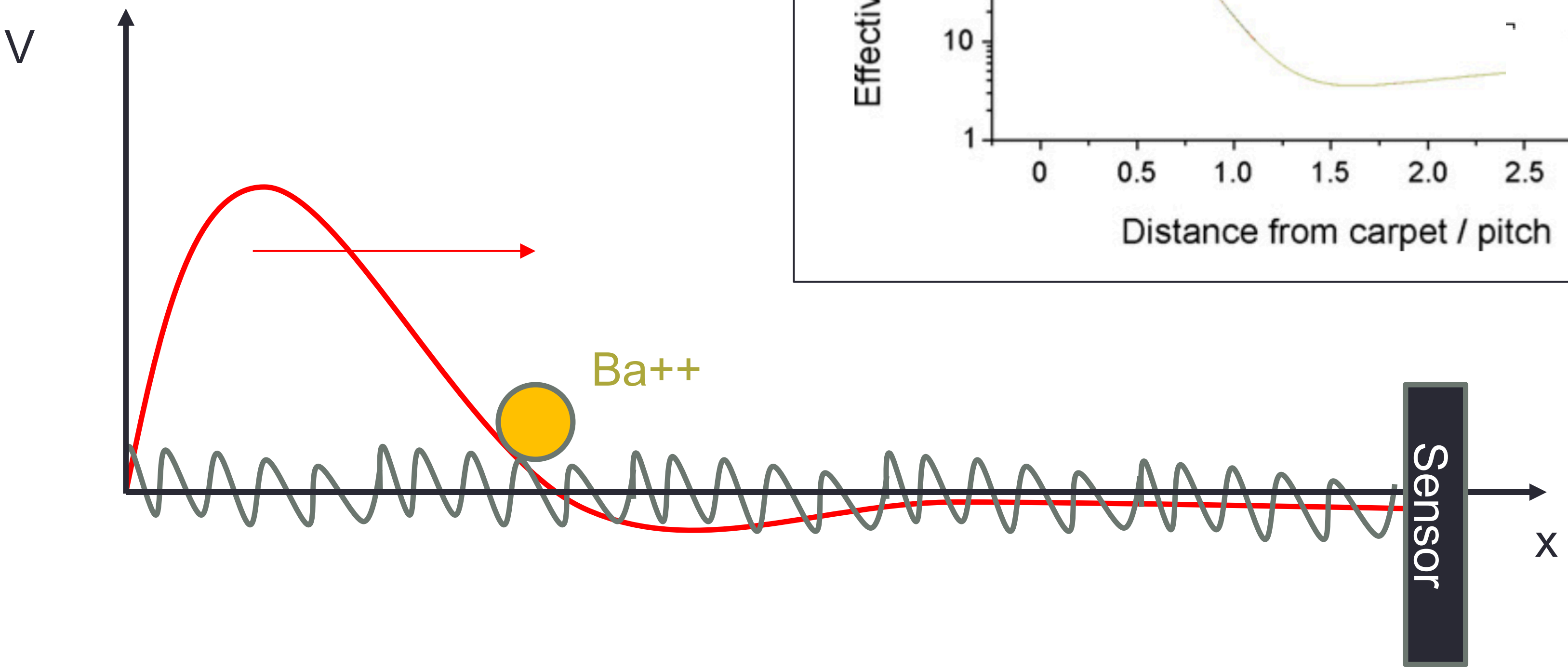
Thanks!



RF Carpet fields

International Journal of Mass Spectrometry 299 (2011) 71–77



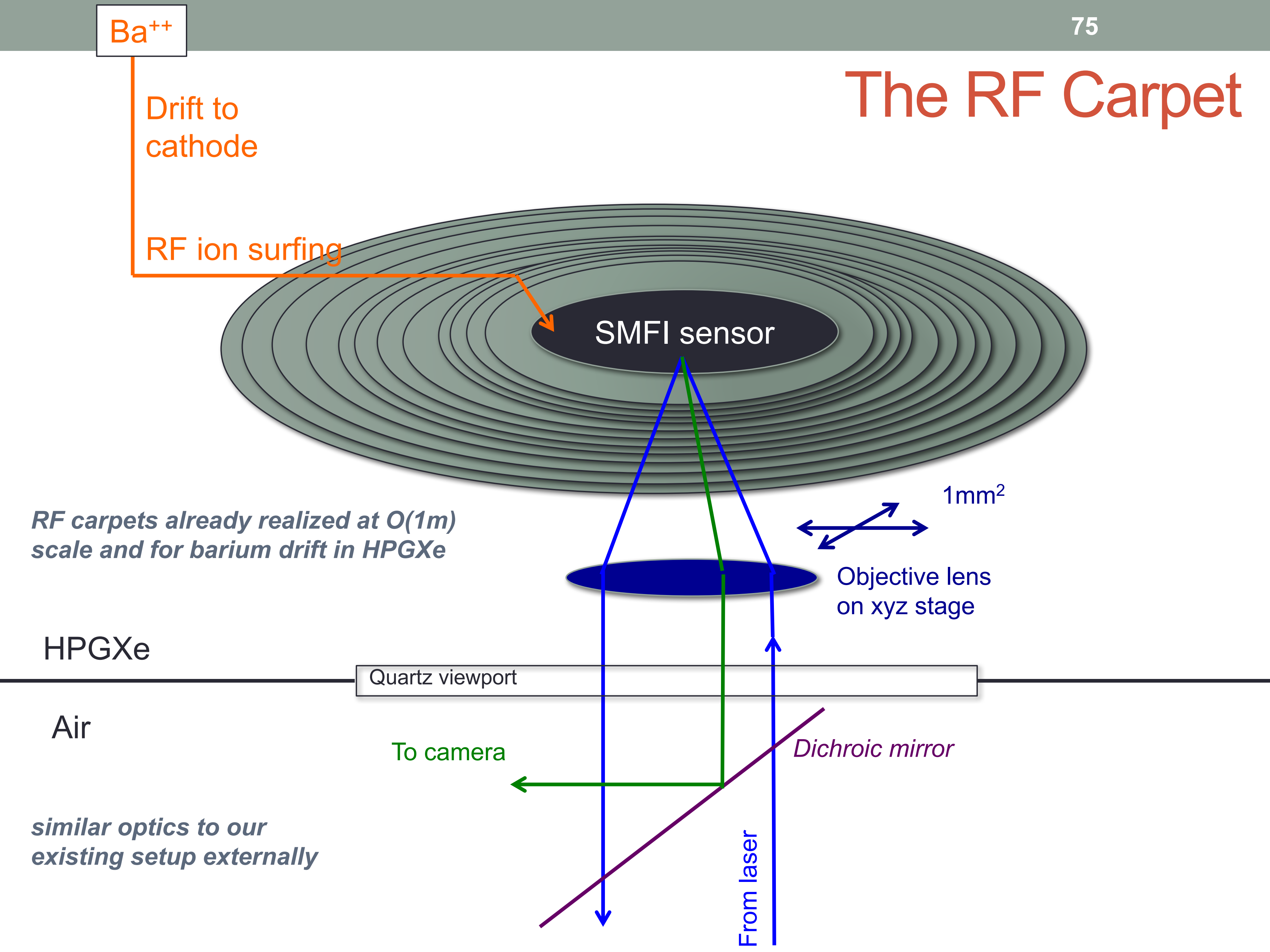


Superposed fields:

RF creates effective potential that levitates ions without neutralization

Surfing field sweeps ions to center,

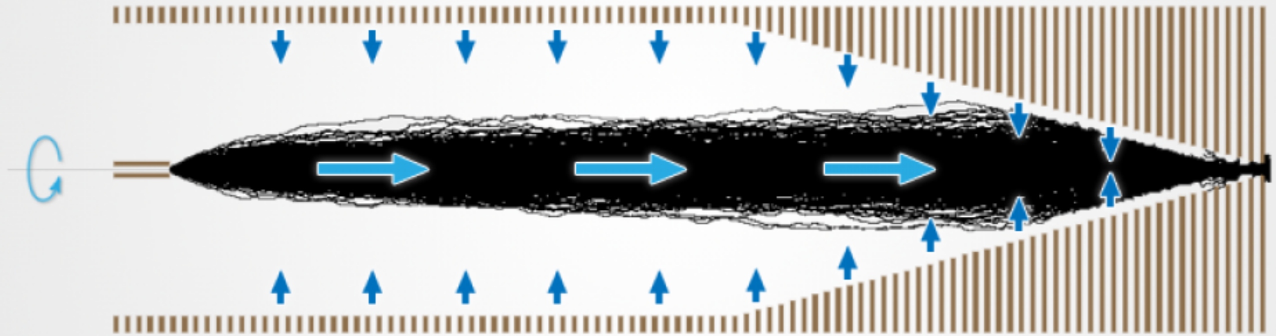
The RF Carpet



RF carpets already realized at O(1m) scale and for barium drift in HPGXe

similar optics to our existing setup externally

ION FUNNEL - FOCUSING

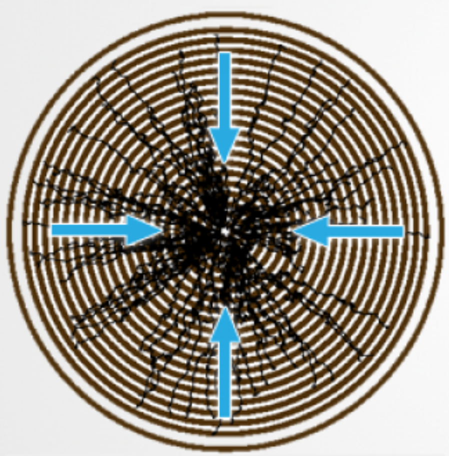


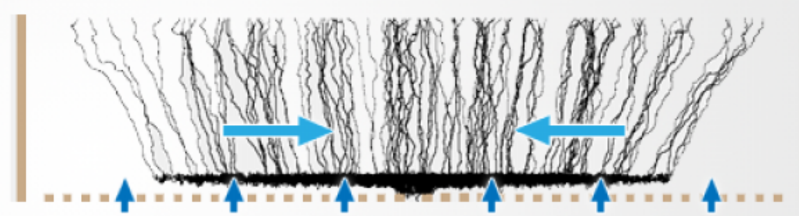
RF WAVEFORMS PROVIDE RADIAL FOCUSING, AND A DC GRADIENT PUSHES IONS AXIALLY TOWARD THE BASE.

MASS SPEC PRO

As explored by Brunner / nEXO for extraction to trap

ION CARPET - FOCUSING



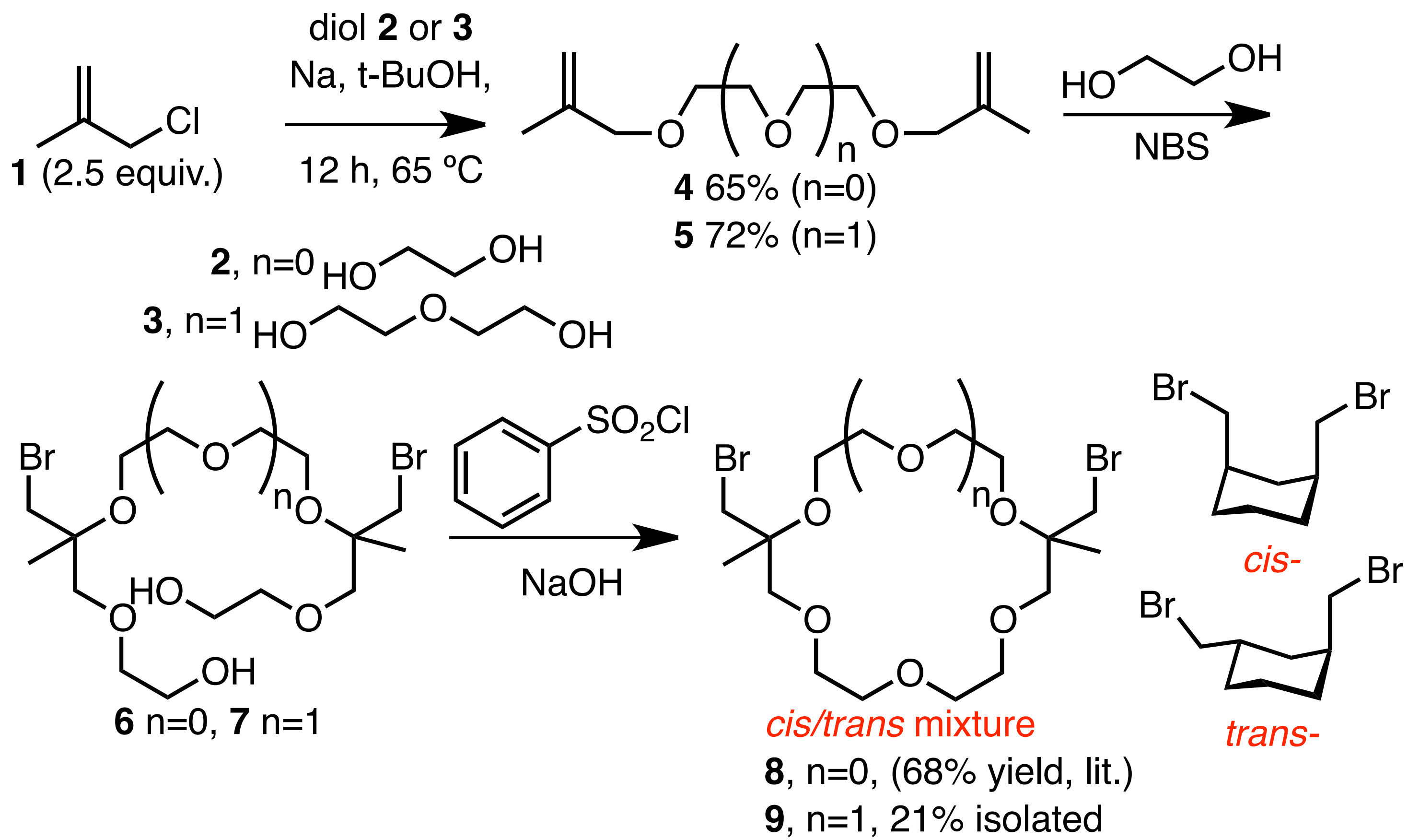


THE ALTERNATING RF PHASES ON THE STRIPS PROVIDE A SHORT-RANGE FORCE PUSHING IONS AWAY FROM THE CARPET, WHILE A DC GRADIENT PULLS THEM TOWARD THE CENTER.

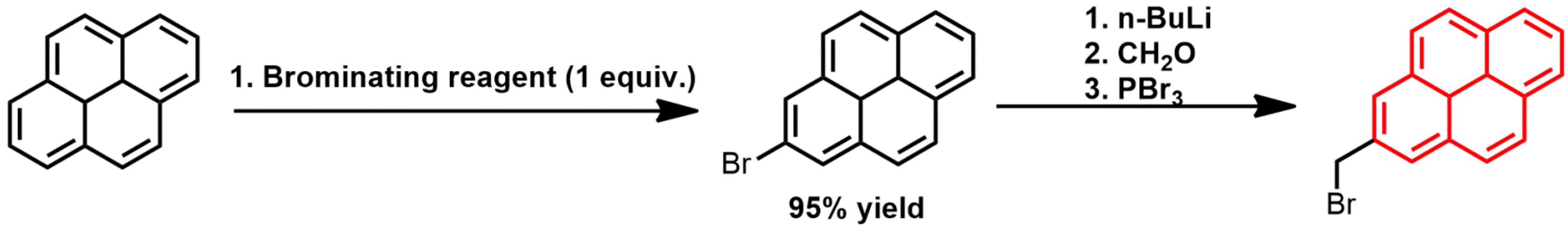
MASS SPEC PRO

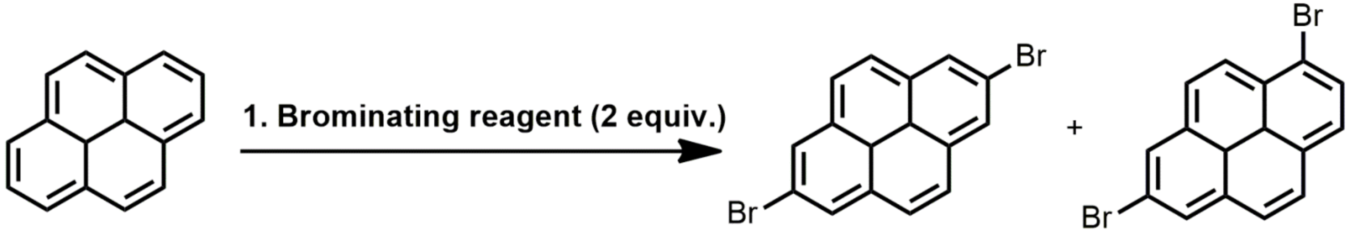
We plan to prototype and demonstrate a small (5cm) RF carpet at UTA

MAC Synthesis: *cis*-crown ether

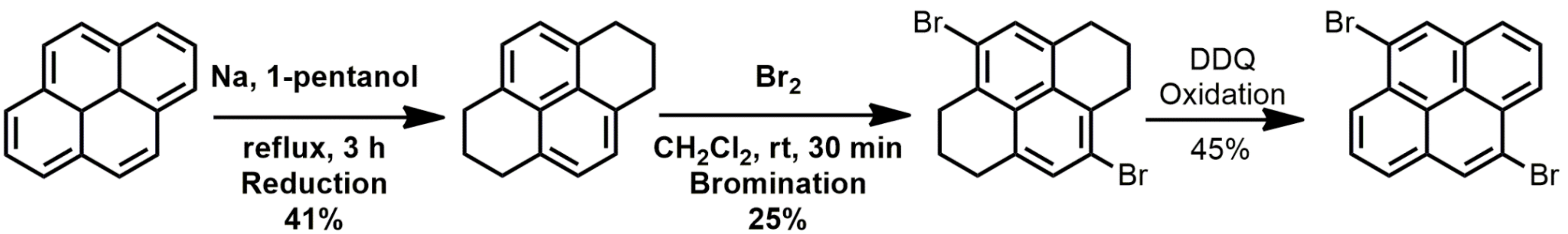


Orientation of the Pyrene Moiety





NBS and Br_2 gave similar result of mixture of isomers

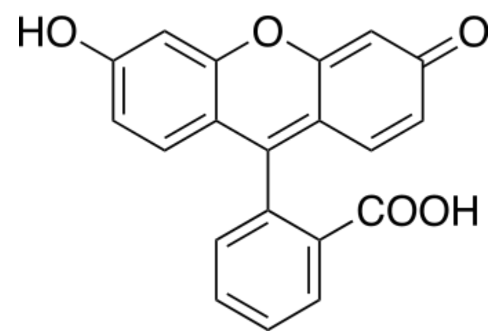


- Nakatsuji, Y.; *Bull. Chem. Soc. Jpn*. **2002**, *75*, 1765-1770.
- *Langmuir*, **2008**, *24*, 5140-5145

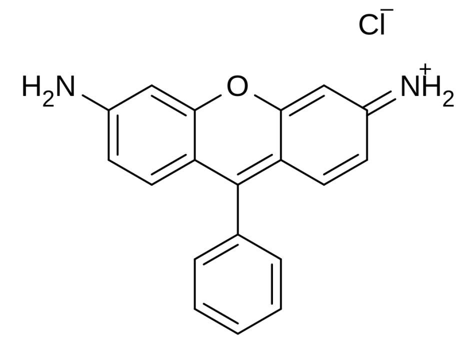
Table 4.1 Photophysical properties of some common dyes with potential for single molecule fluorescence studies

Fluorophore	λ_{ex}^{1p} (nm)	λ_{em}^{1p} (nm)	QY	ε ($cm^{-1}M^{-1}$)	SS (nm)	τ_f (ns)	λ_{ex}^{2p} (nm)	λ_{em}^{2p} (nm)	Reference
FITC	495	520	0.7	73,000	25	—	947	530	[87–89]
FAM	495	520	0.7	83,000	25	—	—	—	[88]
TMR	554	585	0.2–0.5	95,000	31	2.1	849	570	[5,90,91]
R6G	530	556	—	105,000	26	—	—	—	[92]
Cy2	489	506	—	—	17	—	905	520	[87,93]
Cy3	550	570	0.14	150,000	20	~1	1032	578	[3,87,90]
Cy5	650	670	0.15	250,000	20	~1	—	—	[3,5,90]
Cy5.5	675	694	—	250,000	19	—	—	—	[3]
Cy7	743	767	0.02	250,000	24	~0.8	—	—	[3,90,94]
ECFP	458	472	0.4	26,000	14	—	—	—	[94]
EGFP	395,470	509	0.8	30,000	39	3.2	—	—	[5,90,94]
EYFP	514	527	0.6	84,000	13	3.7	—	—	[90,94]
DsRed	532	582	0.29	22,500	50	2.8	—	—	[90]
Bodipy Fl	504	510	—	70,000	6	—	920	526	[87,88]
Bodipy R6G	528	547	—	70,000	19	—	—	—	[88]
AF488	495	520	0.5–0.9	80,000	25	—	985	530	[5,87]
AF546	554	570	—	112,000	16	—	1028	582	[87,95]
AF555	555	565	—	150,000	10	—	—	—	[3]
AF594	590	617	—	92,000	27	—	1074	619	[87,95]
AF633	632	647	—	100,000	15	3.2	—	—	[3,90]

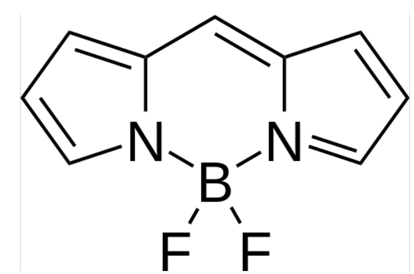
Handbook of Single Molecule Fluorescence, Gell, C. Brockwell, D. Smith, A. OUP Oxford, 2006, New York p. 168-9.



Fluoroscein: FITC + FAM

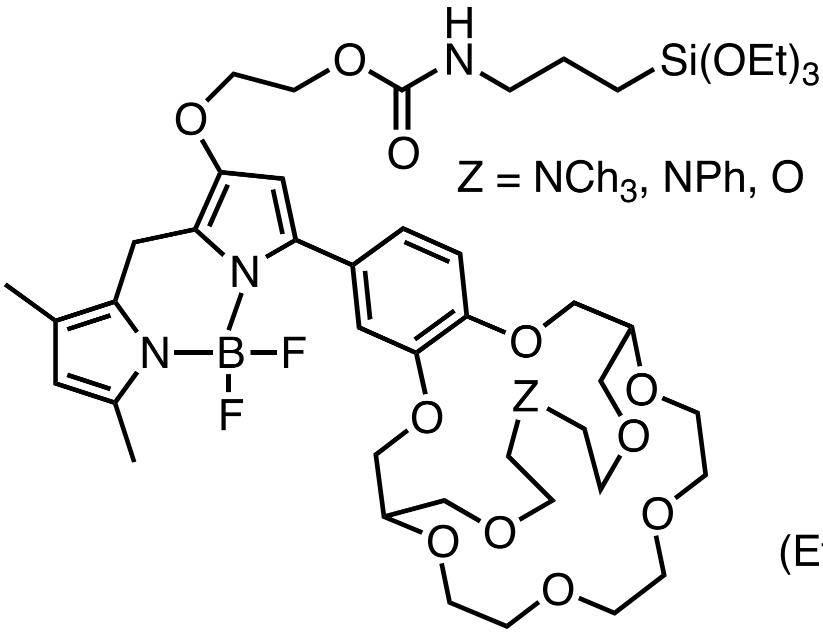


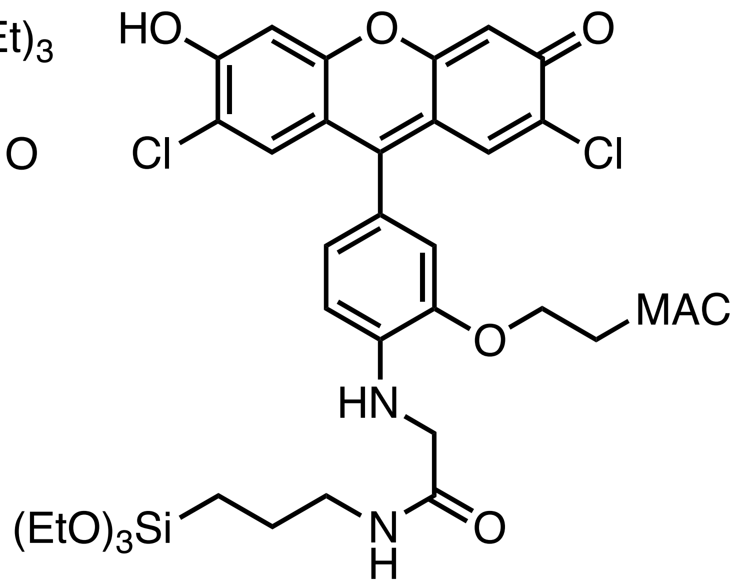
Rhodamine: TMR, R6G

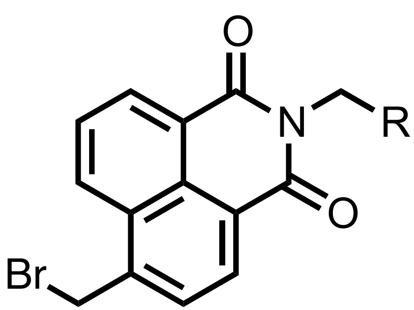


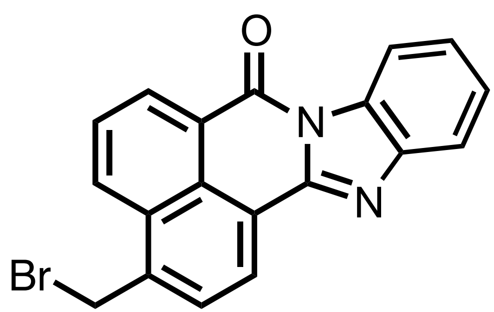
BODIPY

Alternative Fluorophores









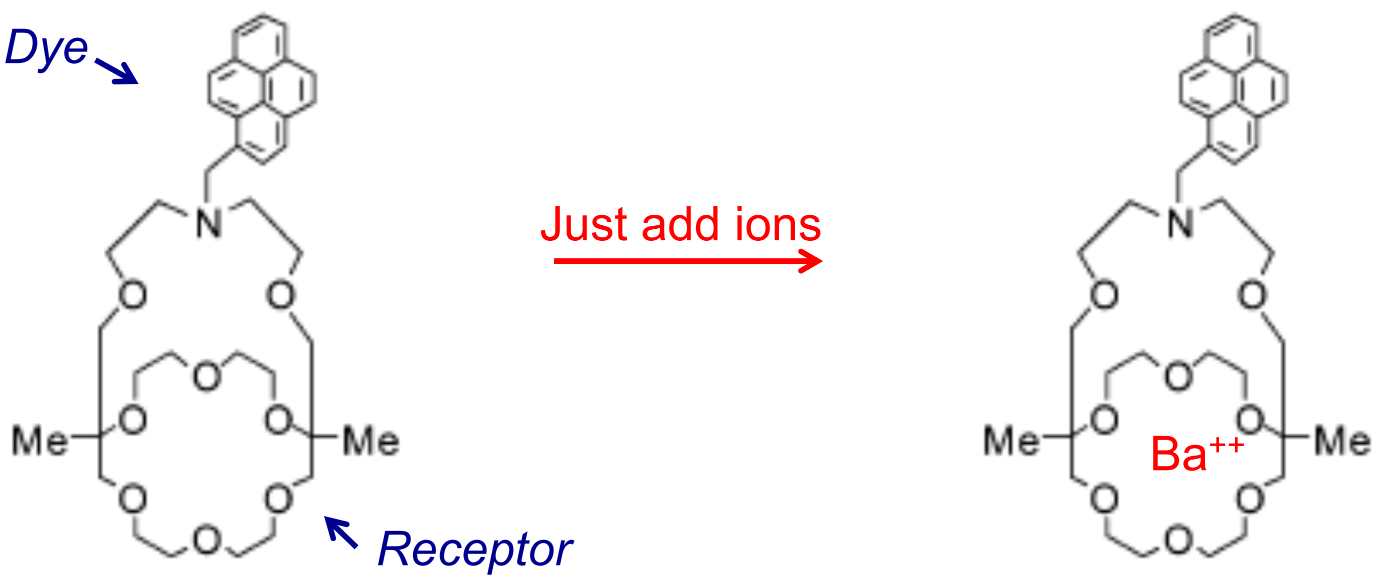
Ando, Hiruta, Citterio, Suzuki
Analyst, 2009, 134, 2314-2319

Hiruta, Sato, Takahashi, Kubobuchi, Shichi, Citterio, Suzuki
RSC Adv. 2013, 3, 6499-6506

The basic SMFI method:

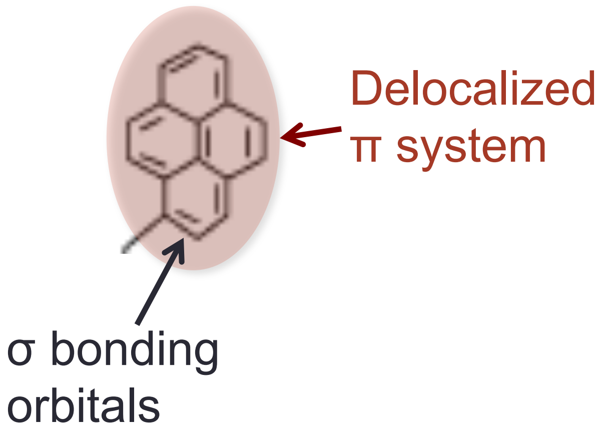
- A non-fluorescent molecule becomes fluorescent (or vice versa) upon chelation with an incident ion.

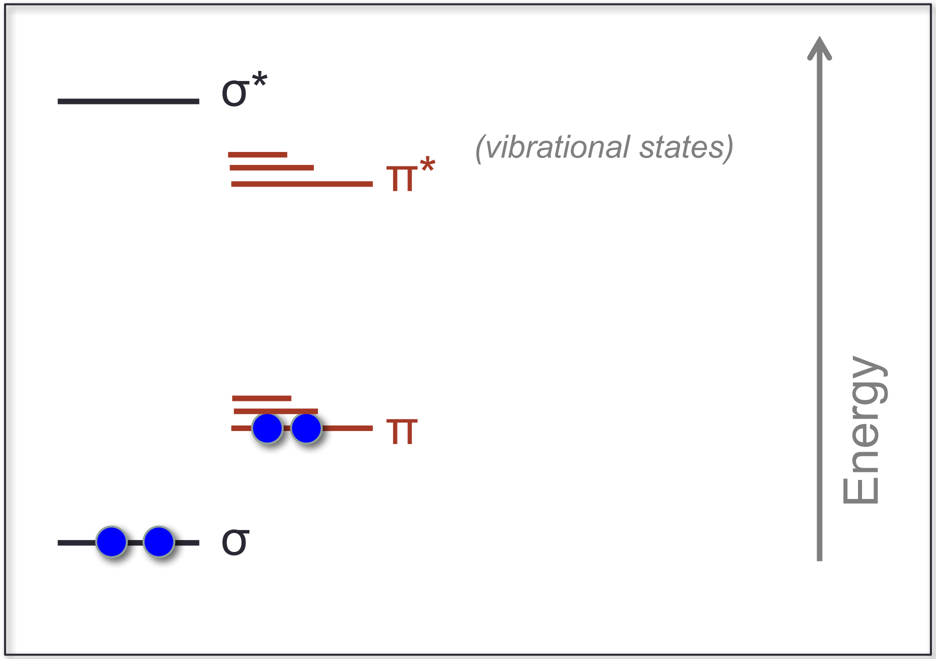
Not fluorescent **Fluorescent**



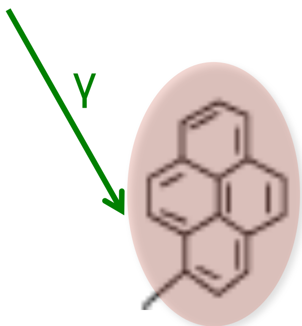
- Calcium and barium are congeners – many dyes developed for calcium are also expected to respond to barium

Fluorescence in pyrene:

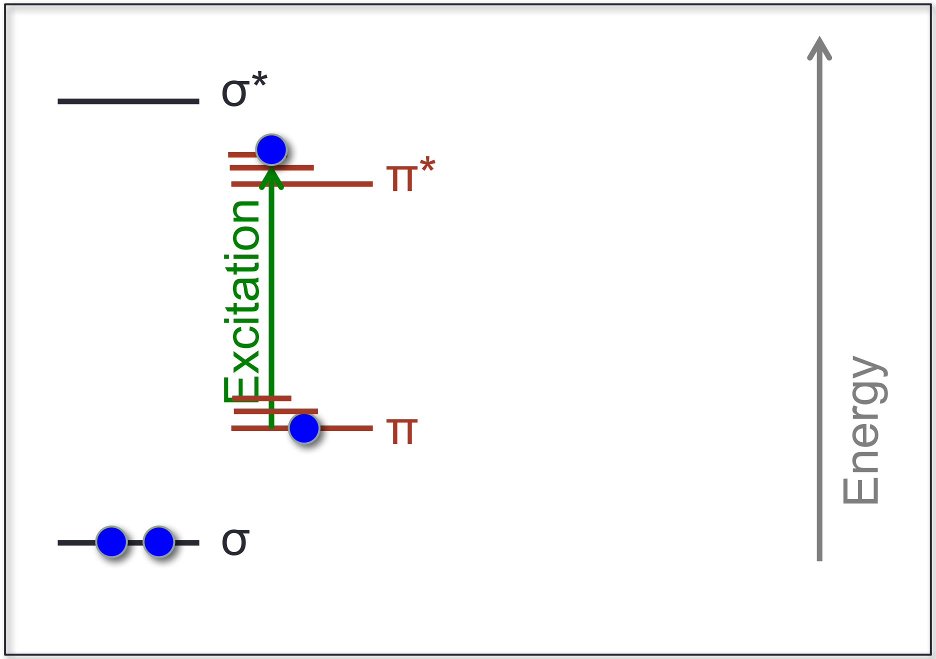




Fluorescence in pyrene:

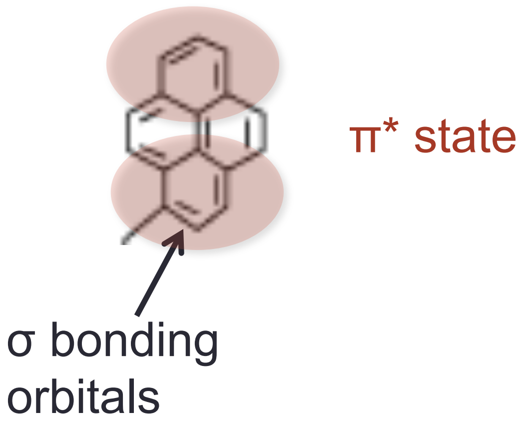


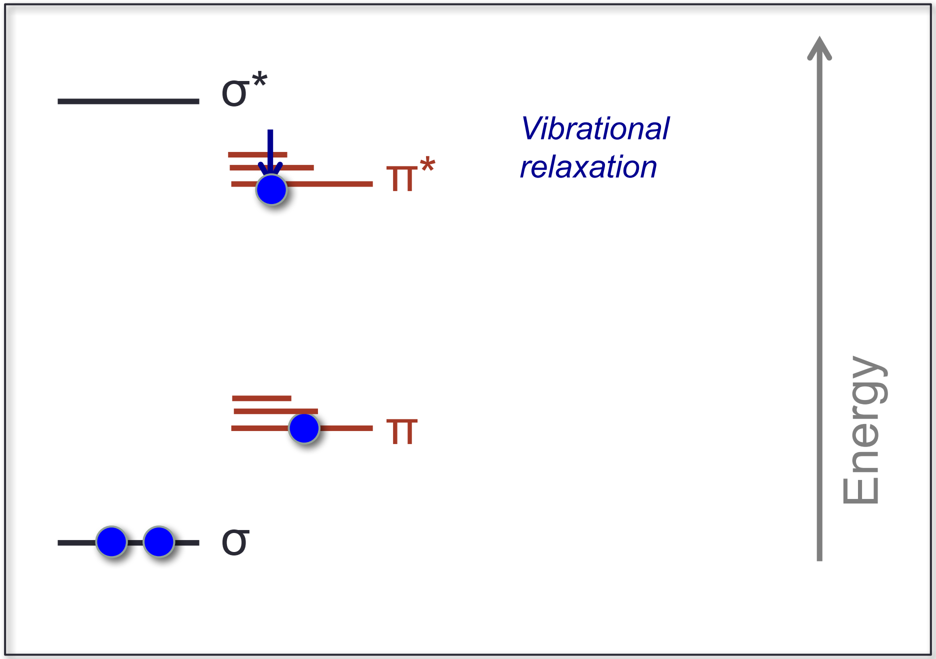
Excitation photon



Fluoresence process

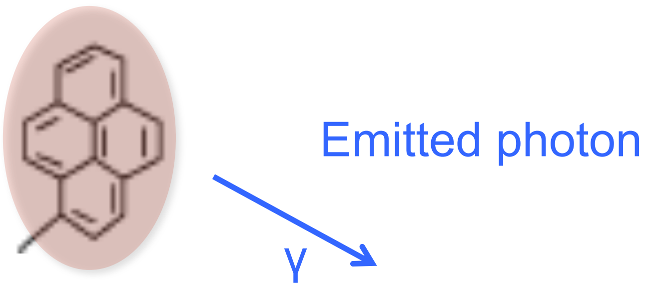
Fluorescence in pyrene:

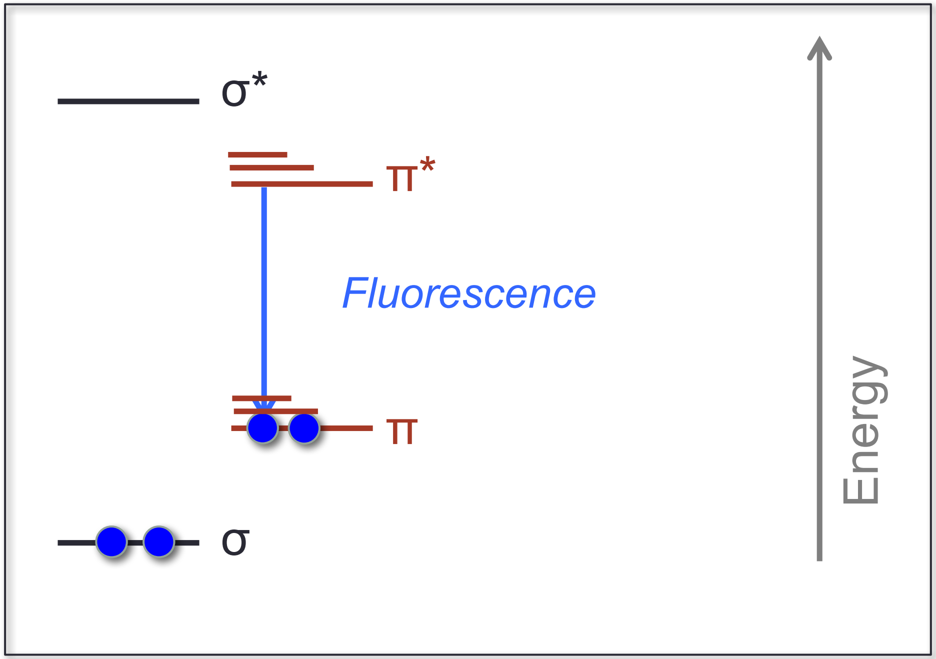




Fluoresence process

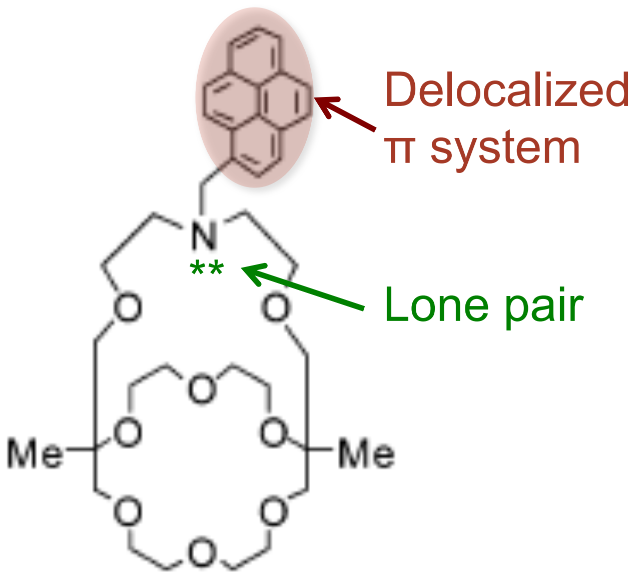
Fluorescence in pyrene:

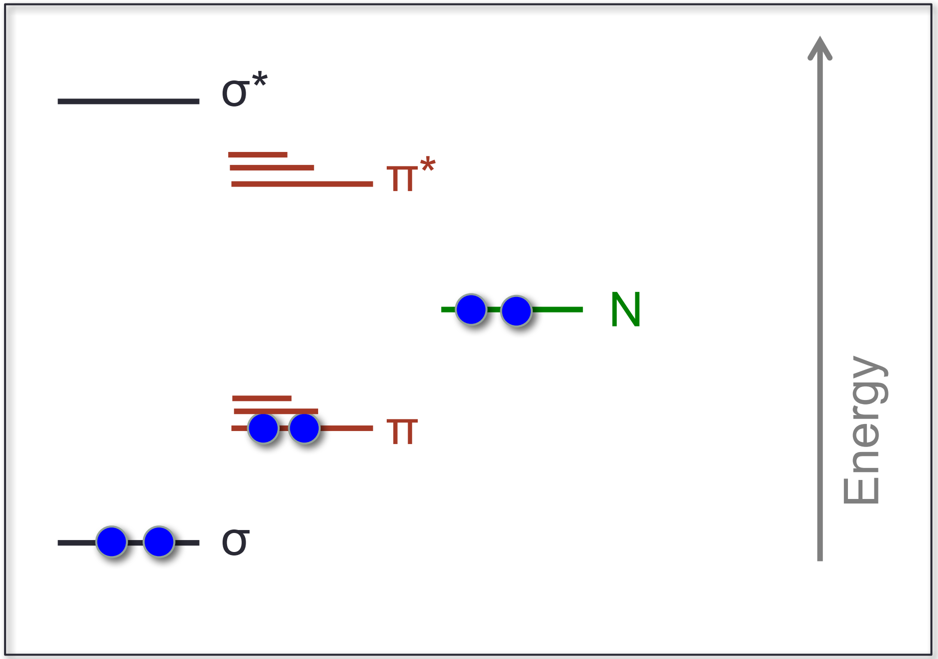




Fluoresence process

The PSMA magic:





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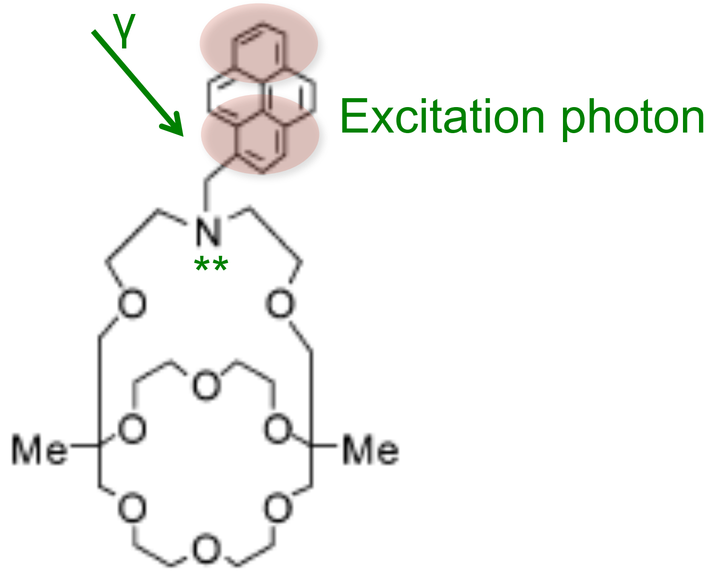

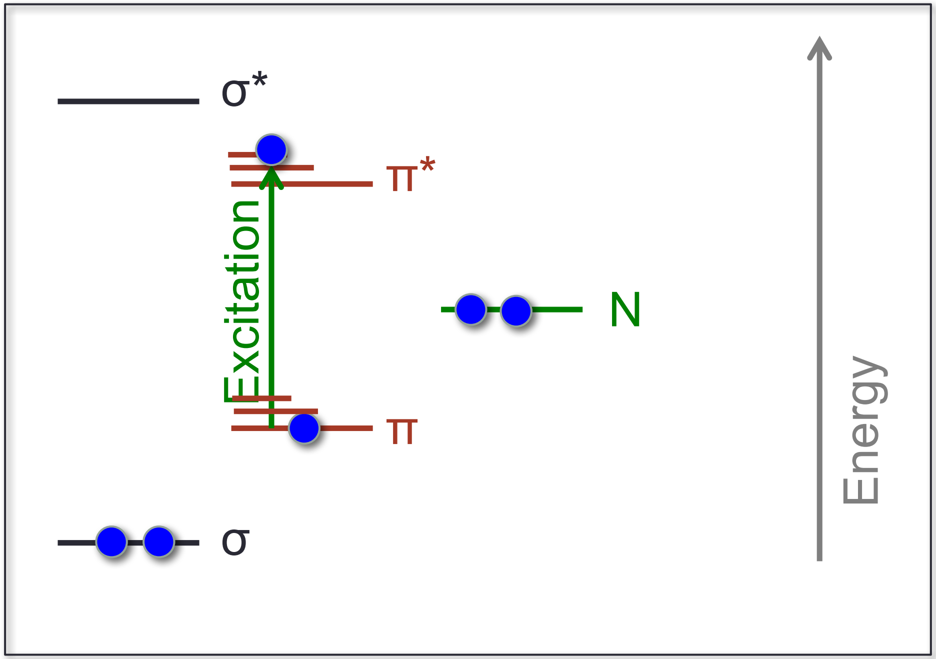

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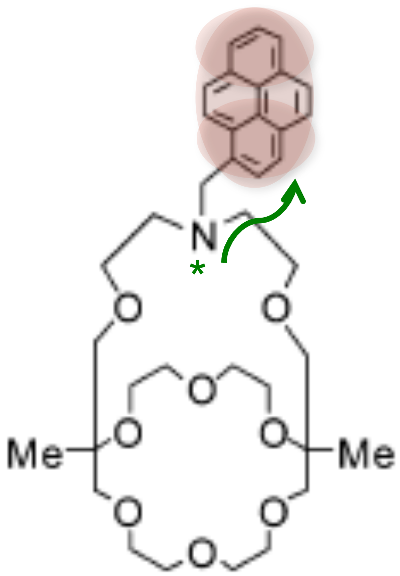

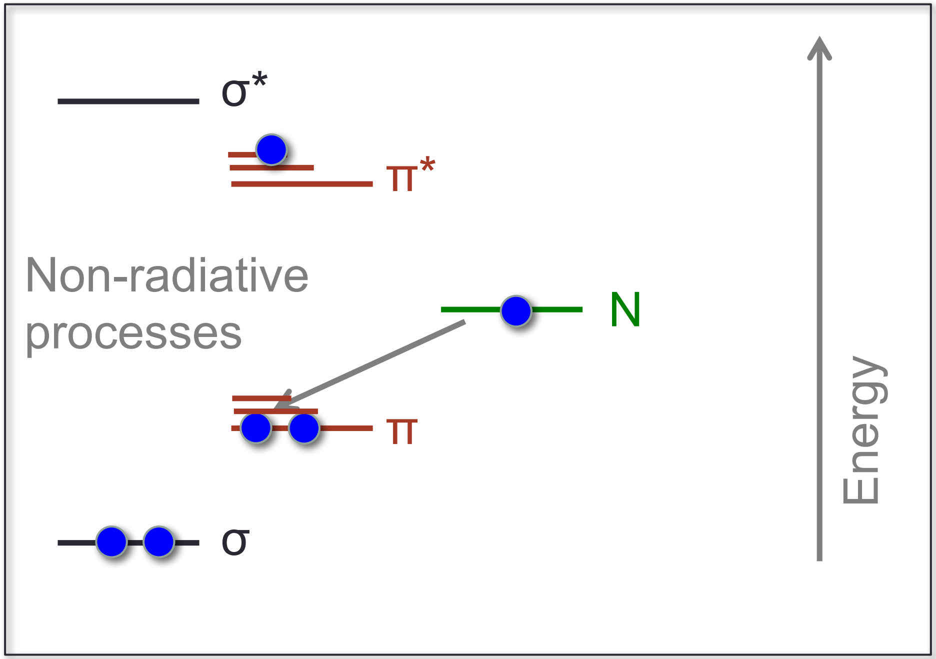

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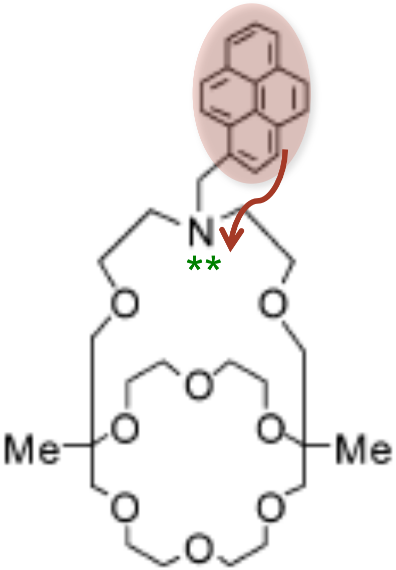
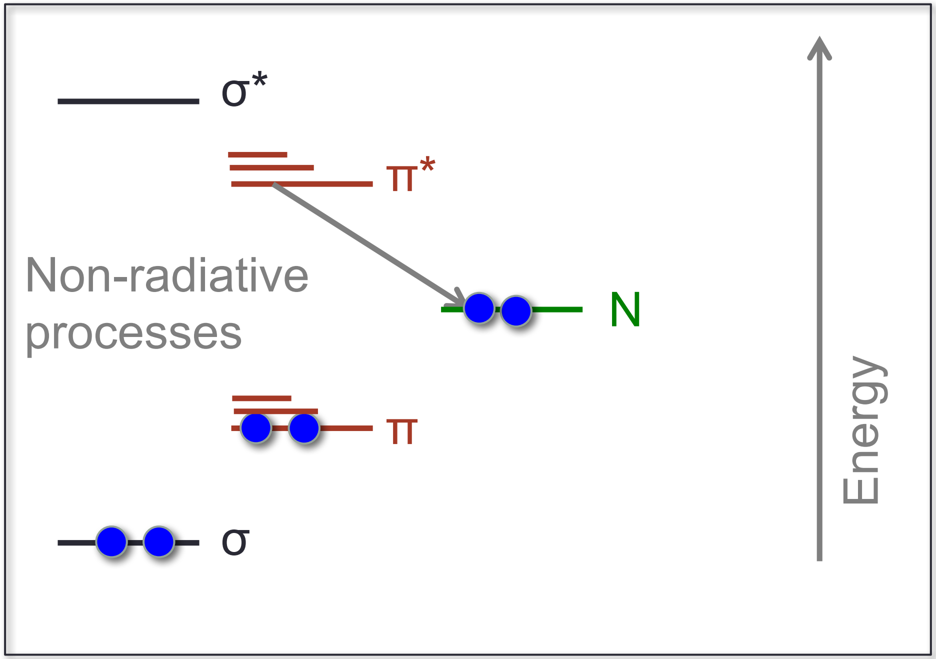
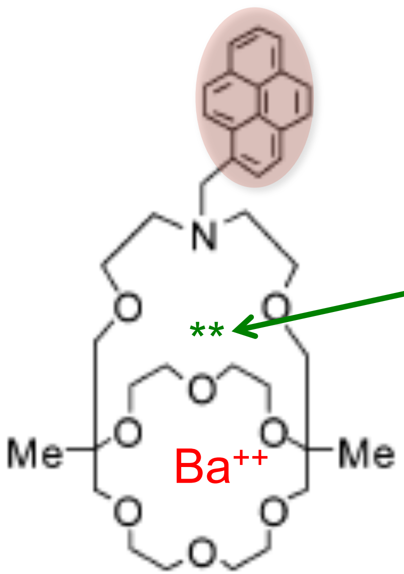


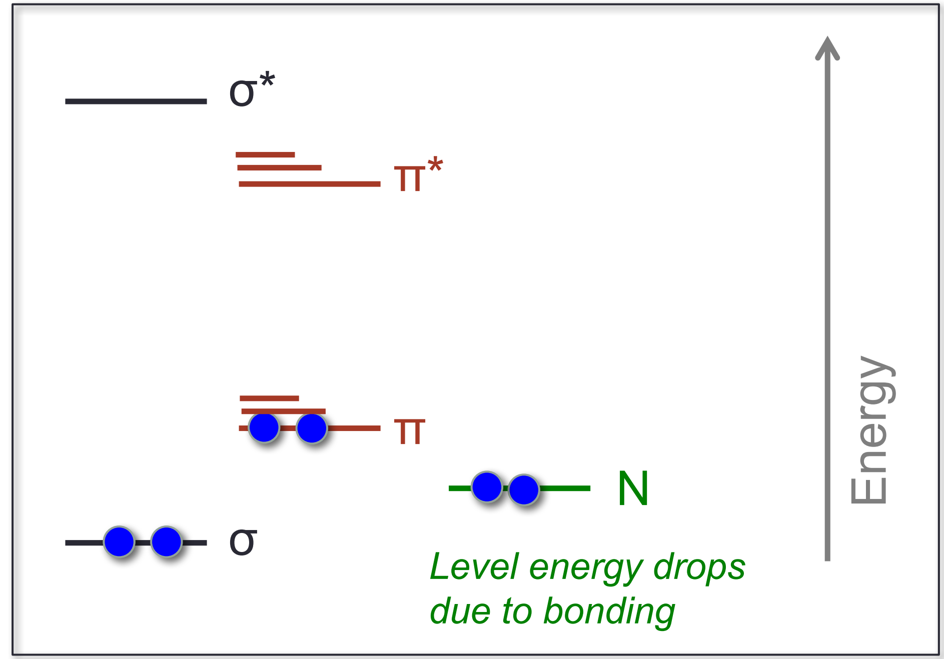


Back in the ground state with no fluorescence!

The PSMA magic:

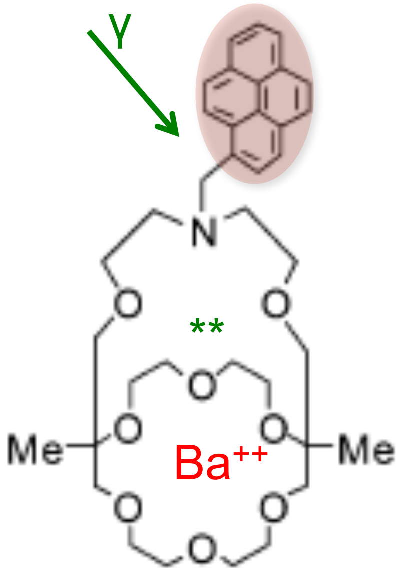


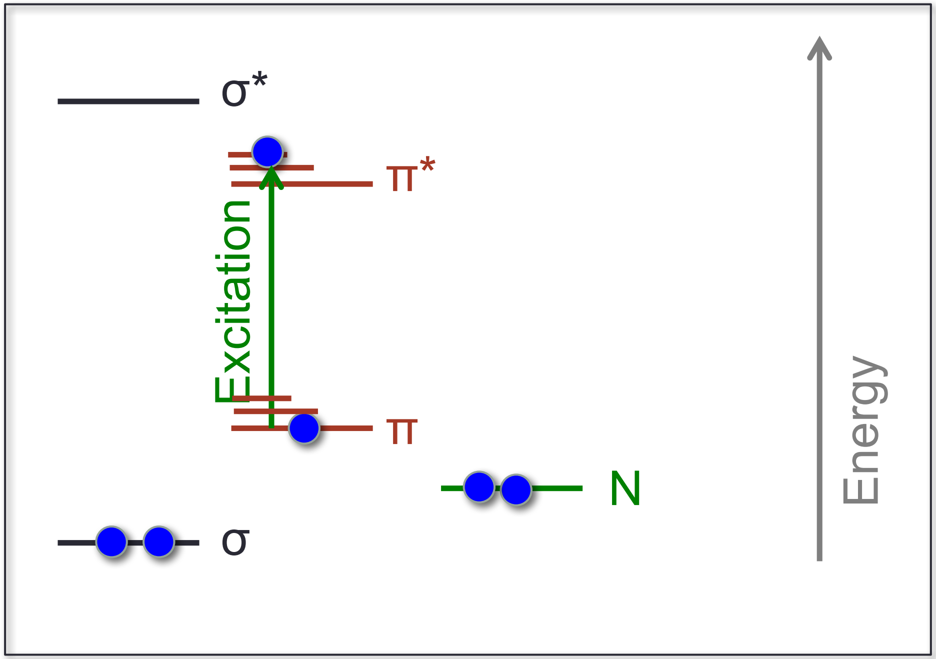
Lone pair pulled into a partial bonding configuration with barium



Now when there is a barium dication in the cage…

The PSMA magic:





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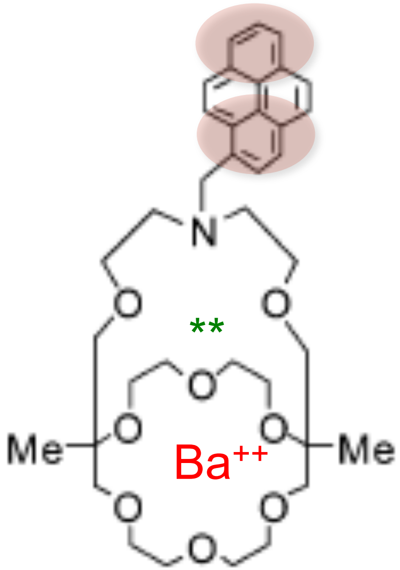

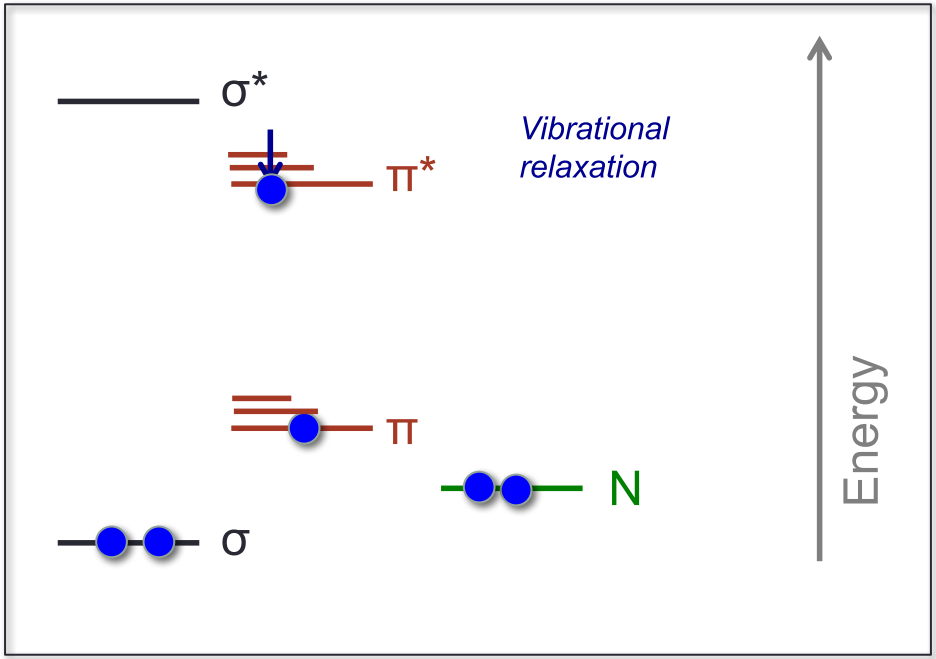

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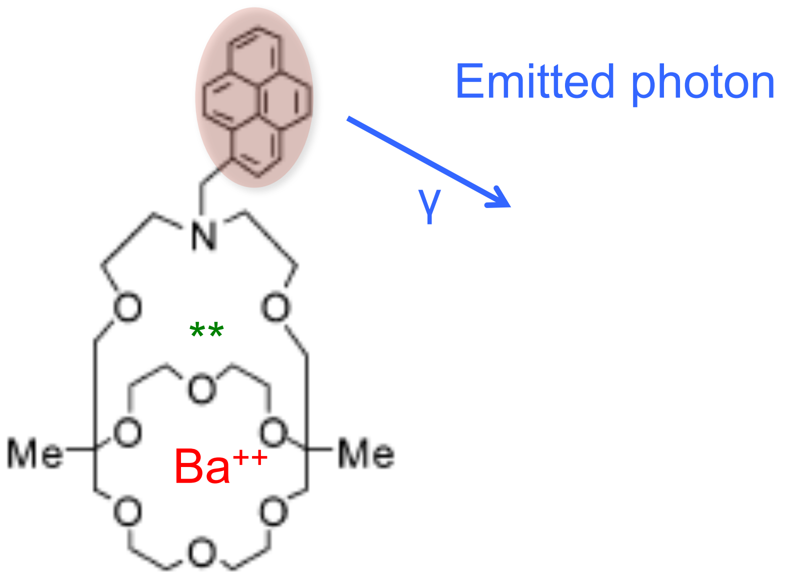
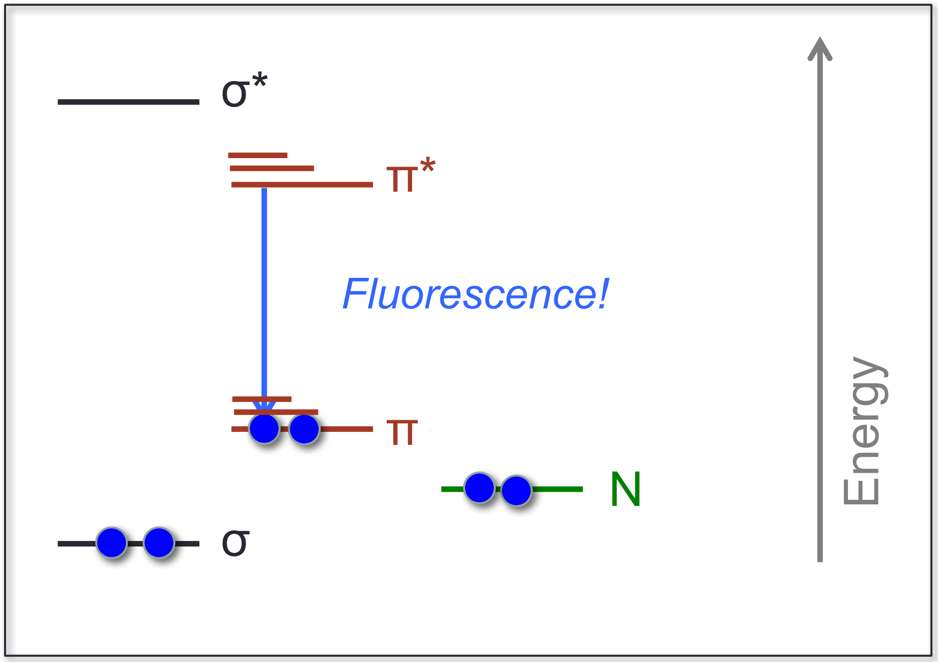
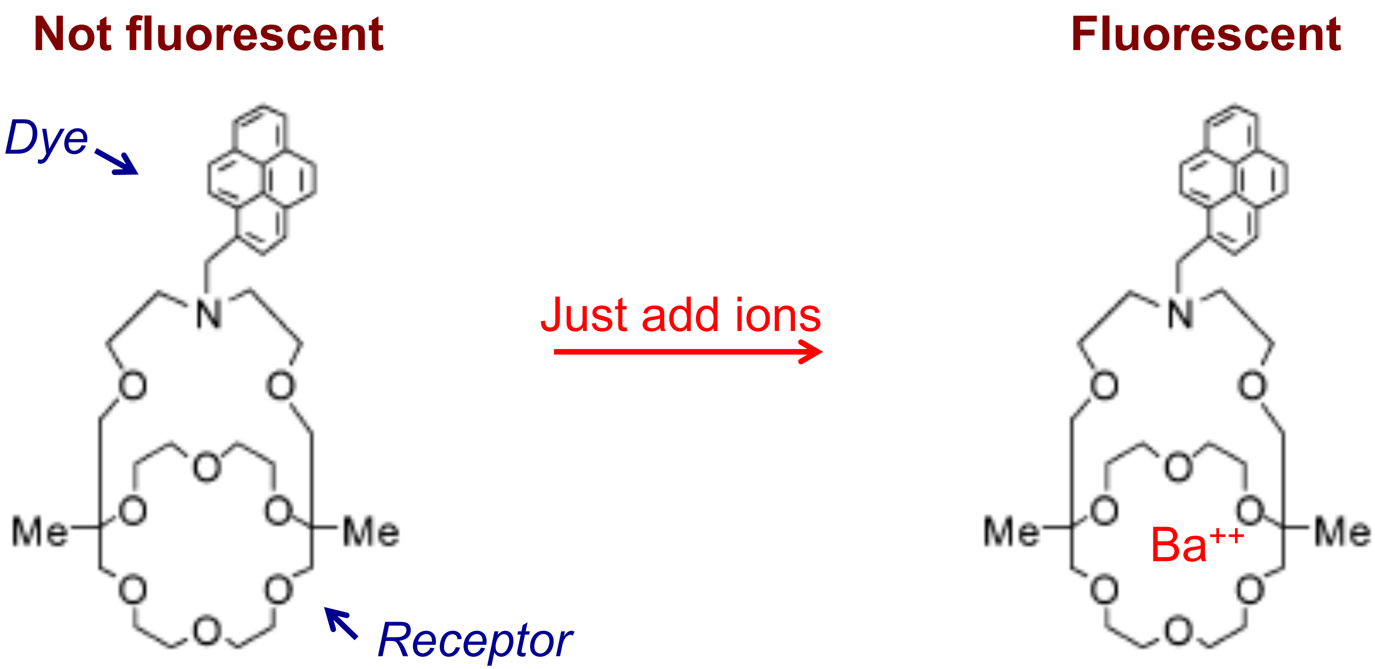




Fluorescence is switched on only when barium ion is present

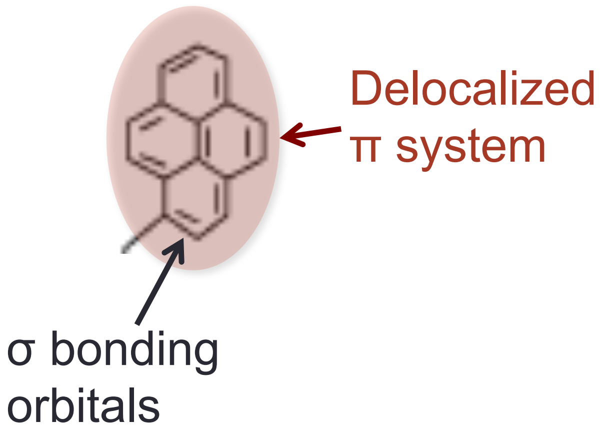
The basic SMFI method:

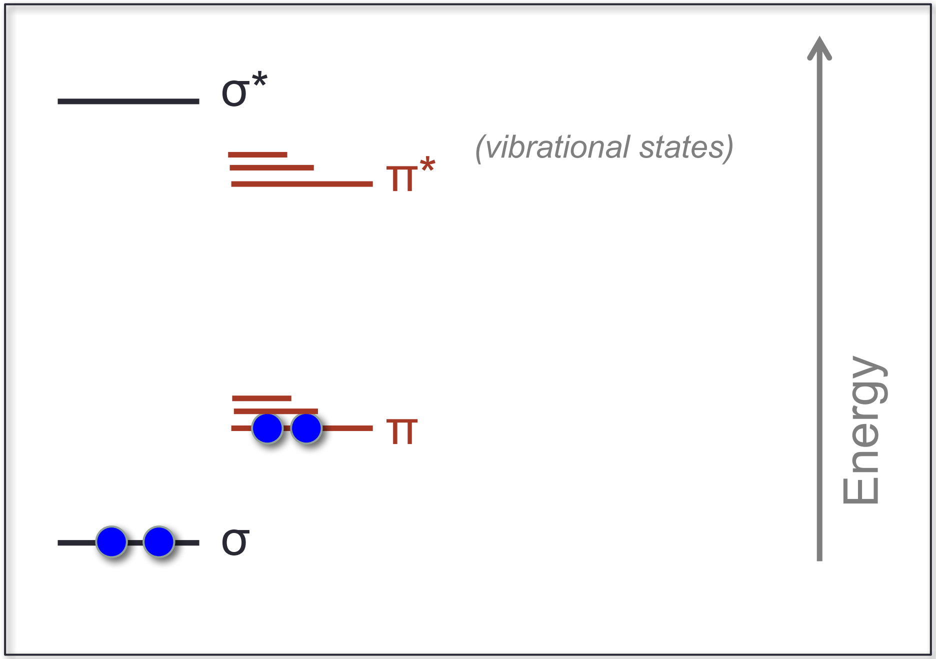
- A non-fluorescent molecule becomes fluorescent (or vice versa) upon chelation with an incident ion.



- Calcium and barium are congeners – many dyes developed for calcium are also expected to respond to barium

Fluorescence in pyrene:





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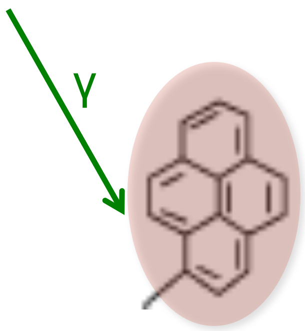
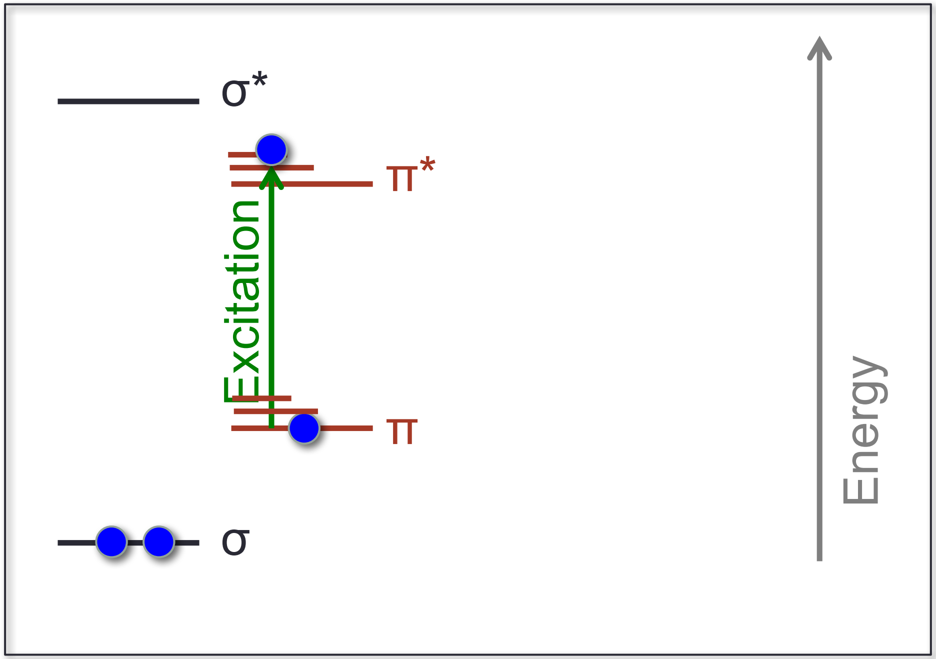
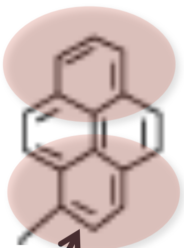


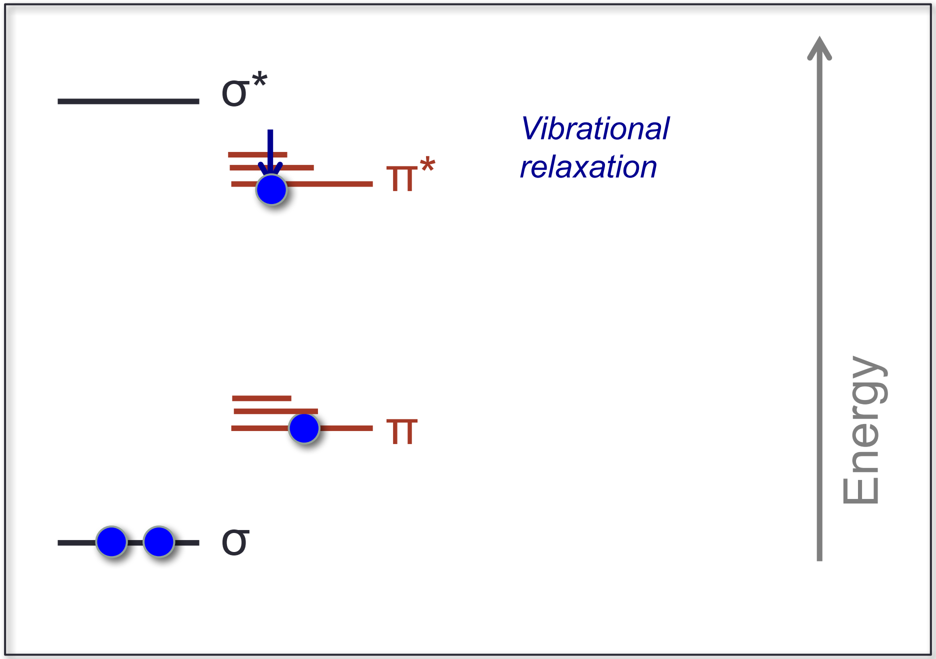
Excitation photon



Fluoresence process

Fluorescence in pyrene:





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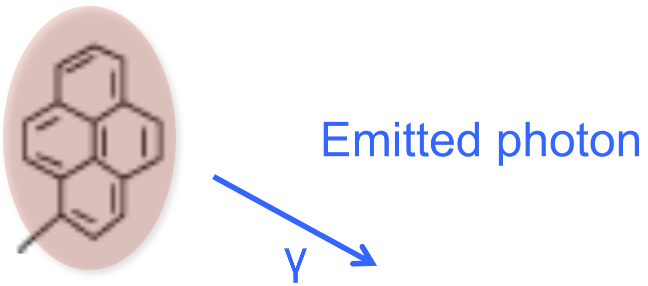
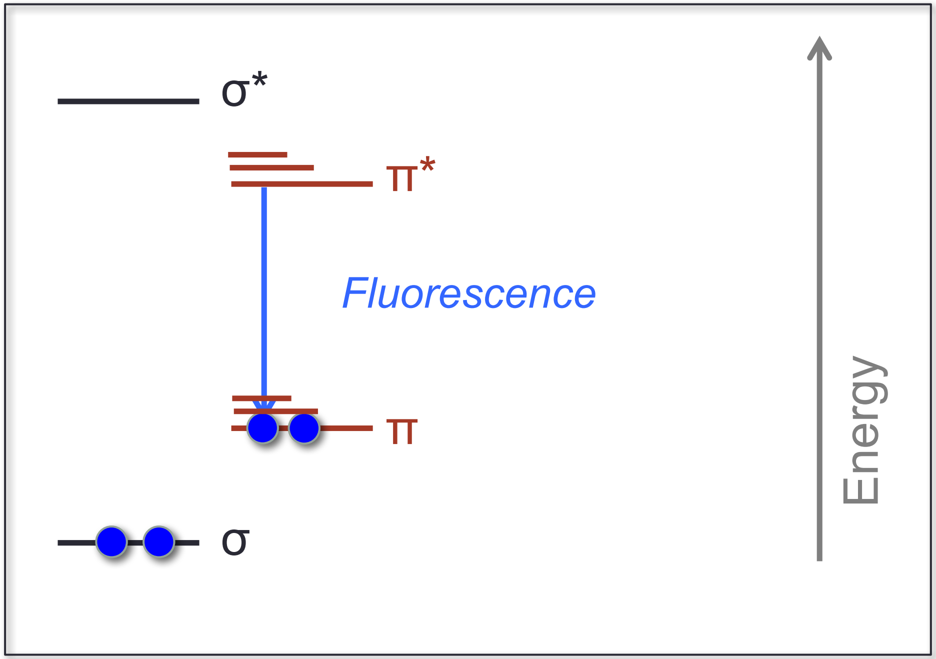
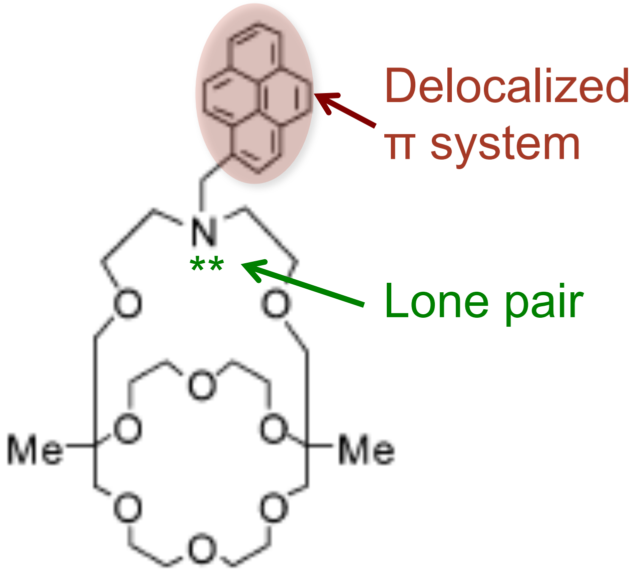
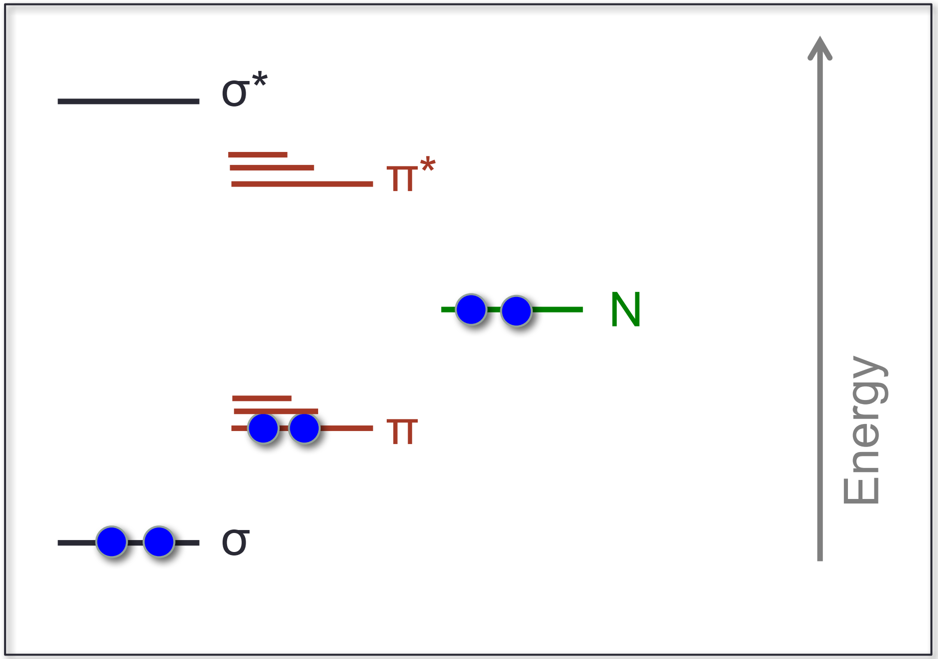




Fluoresence process

The PSMA magic:





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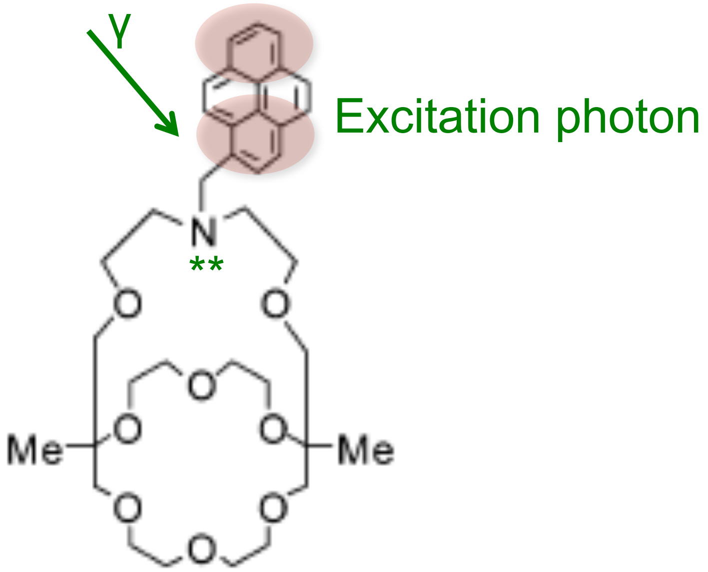

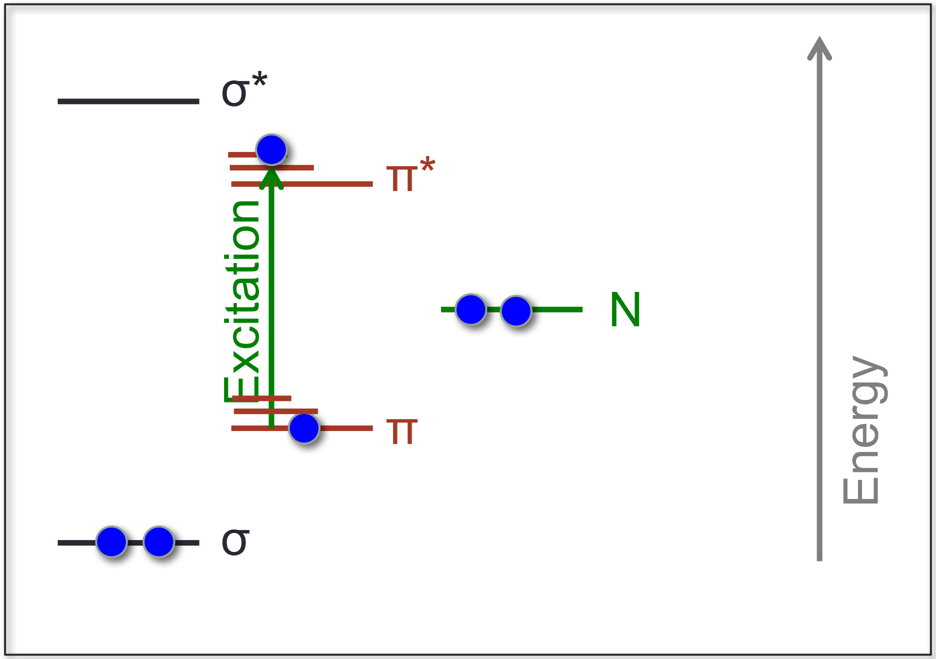

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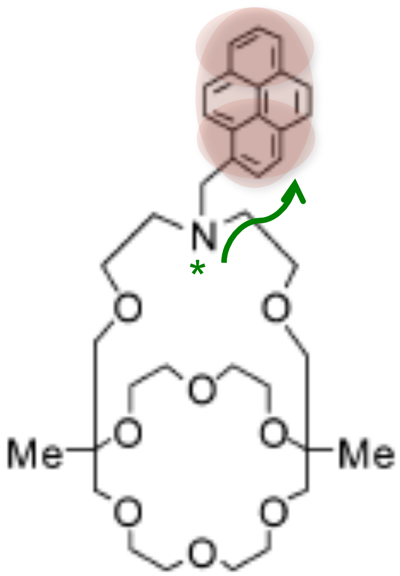

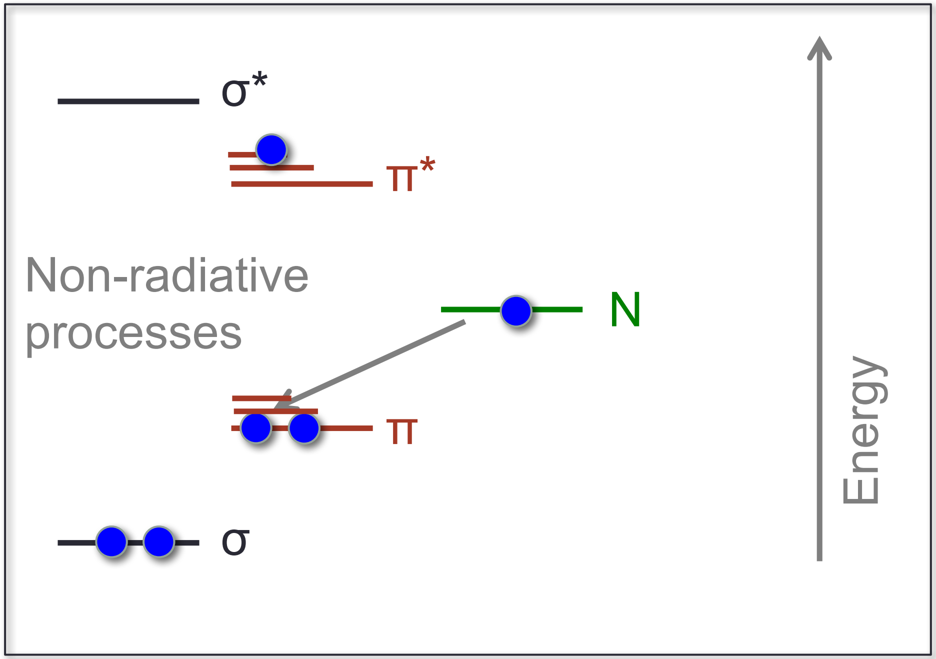

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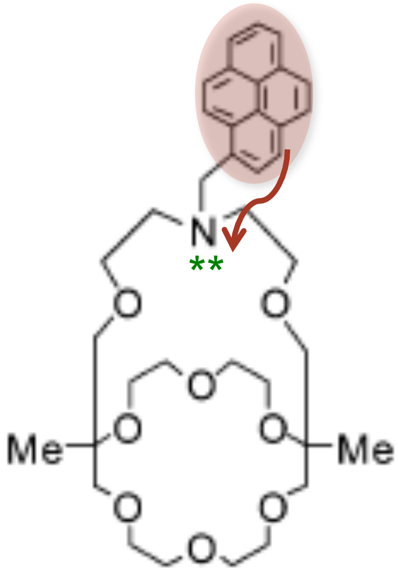

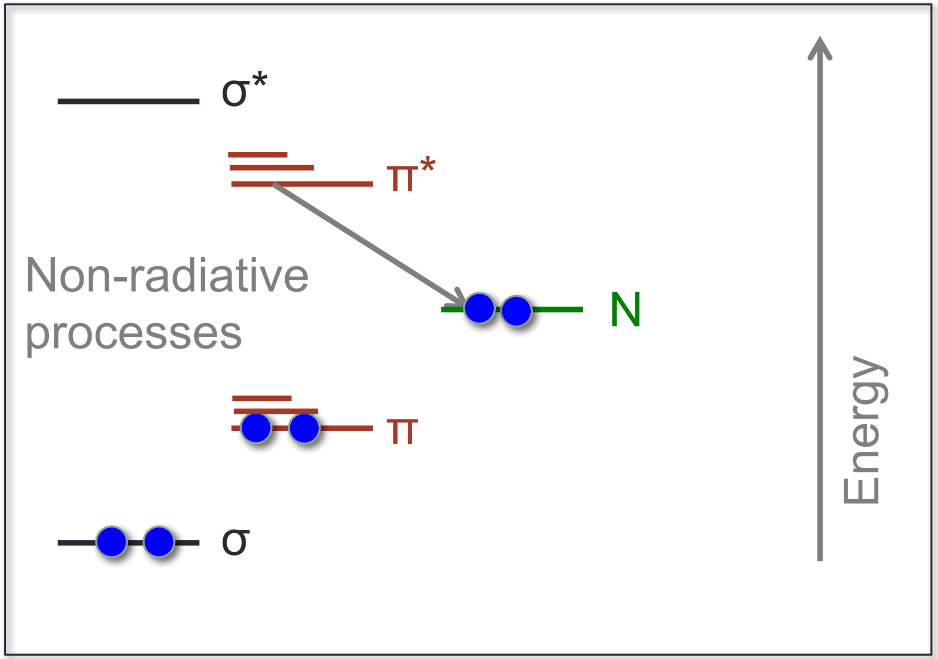

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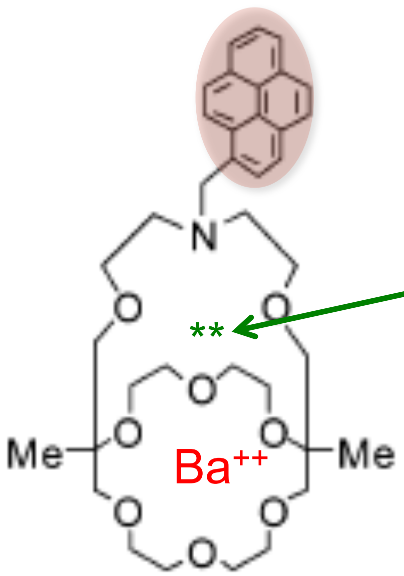
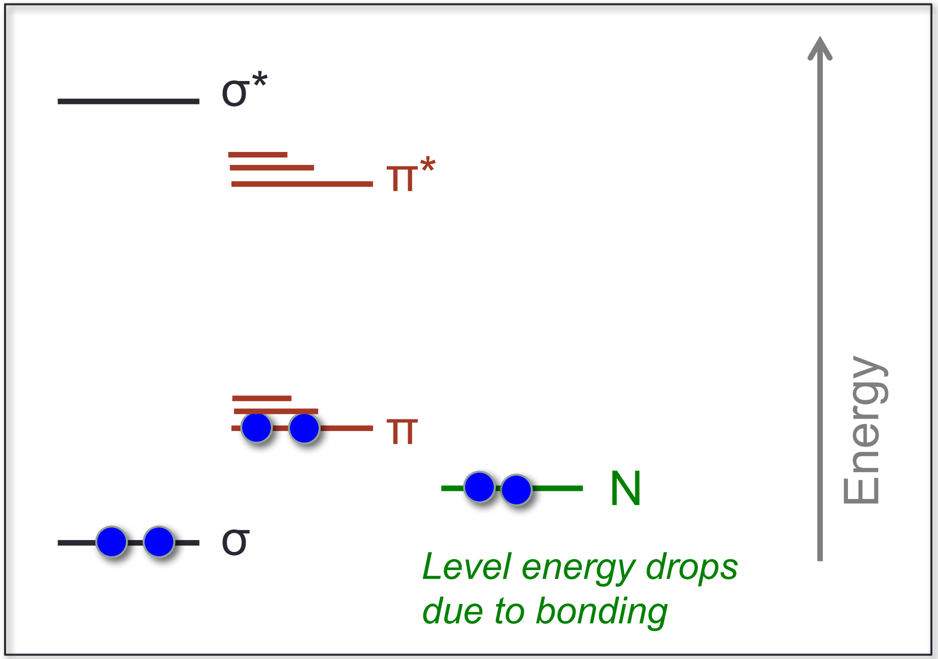


Lone pair pulled into a partial bonding configuration with barium



Now when there is a barium dication in the cage…

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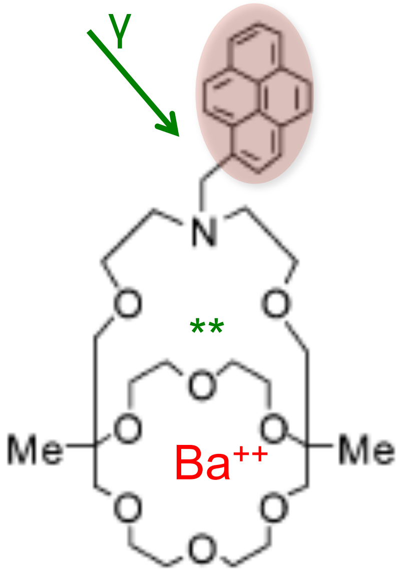

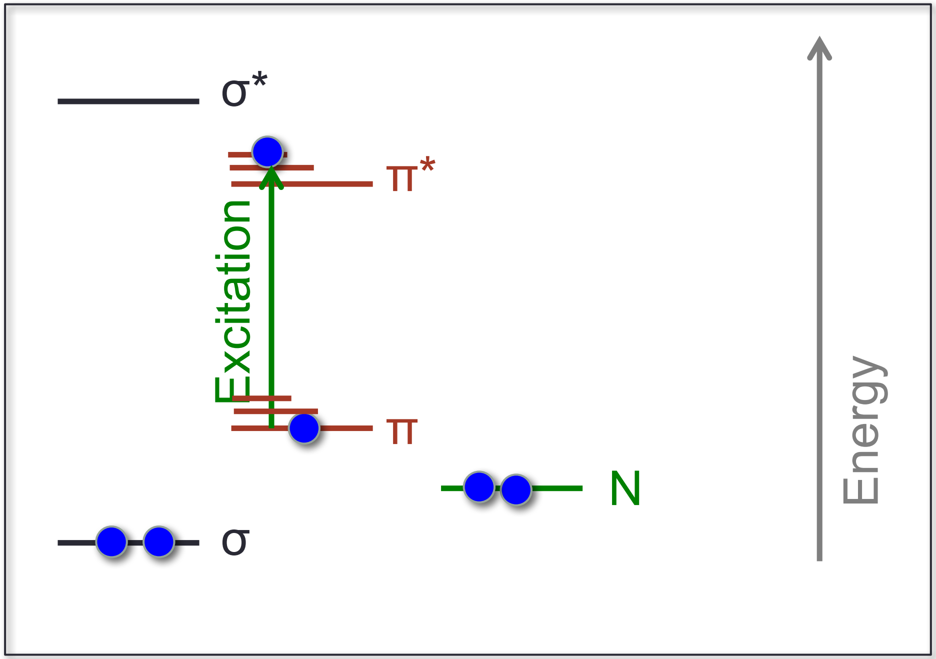

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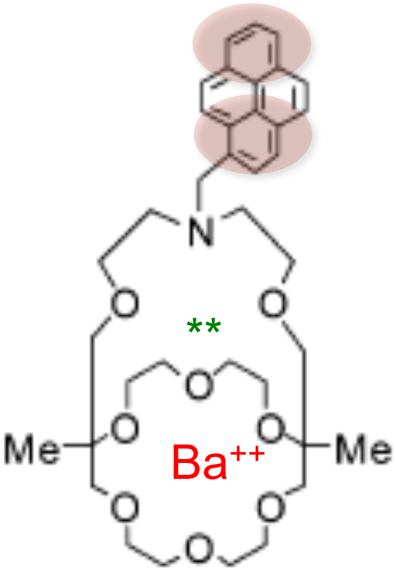

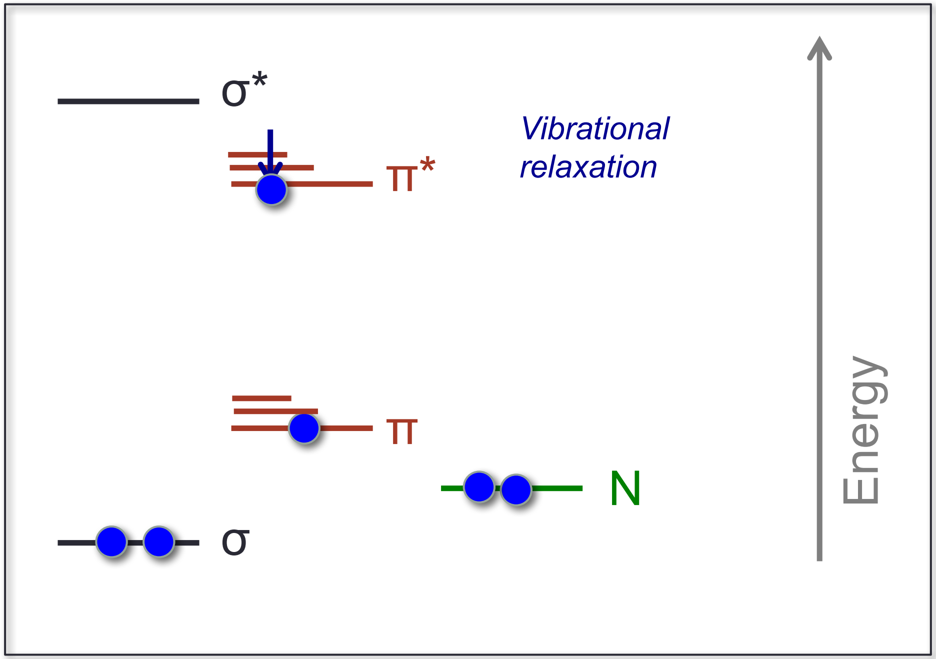

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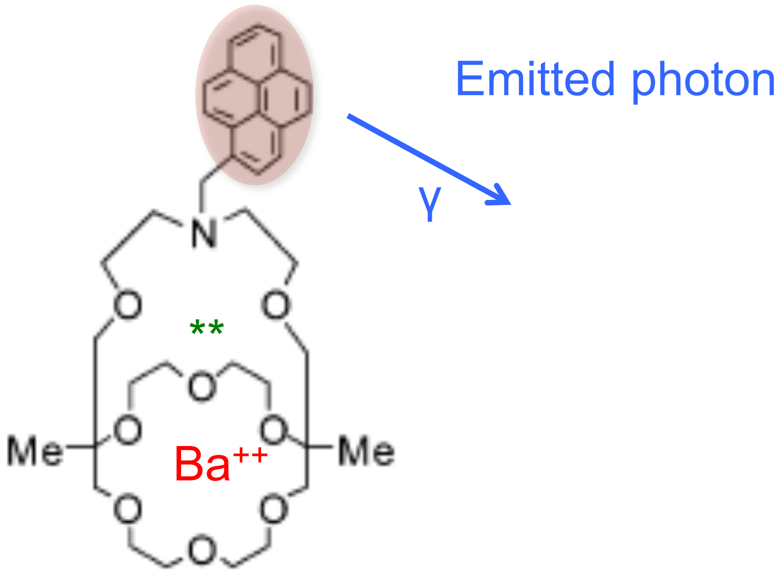
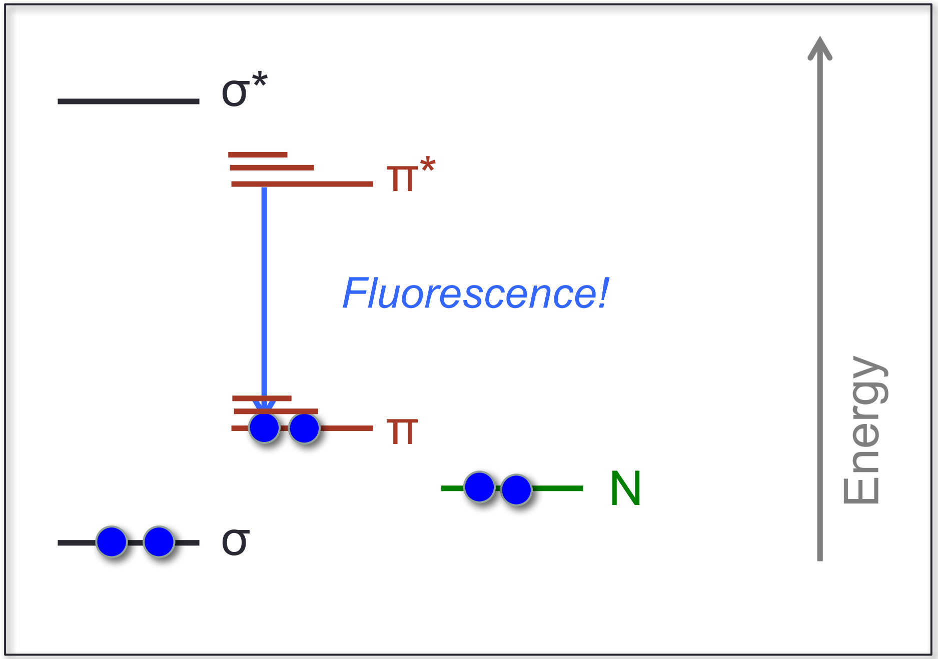
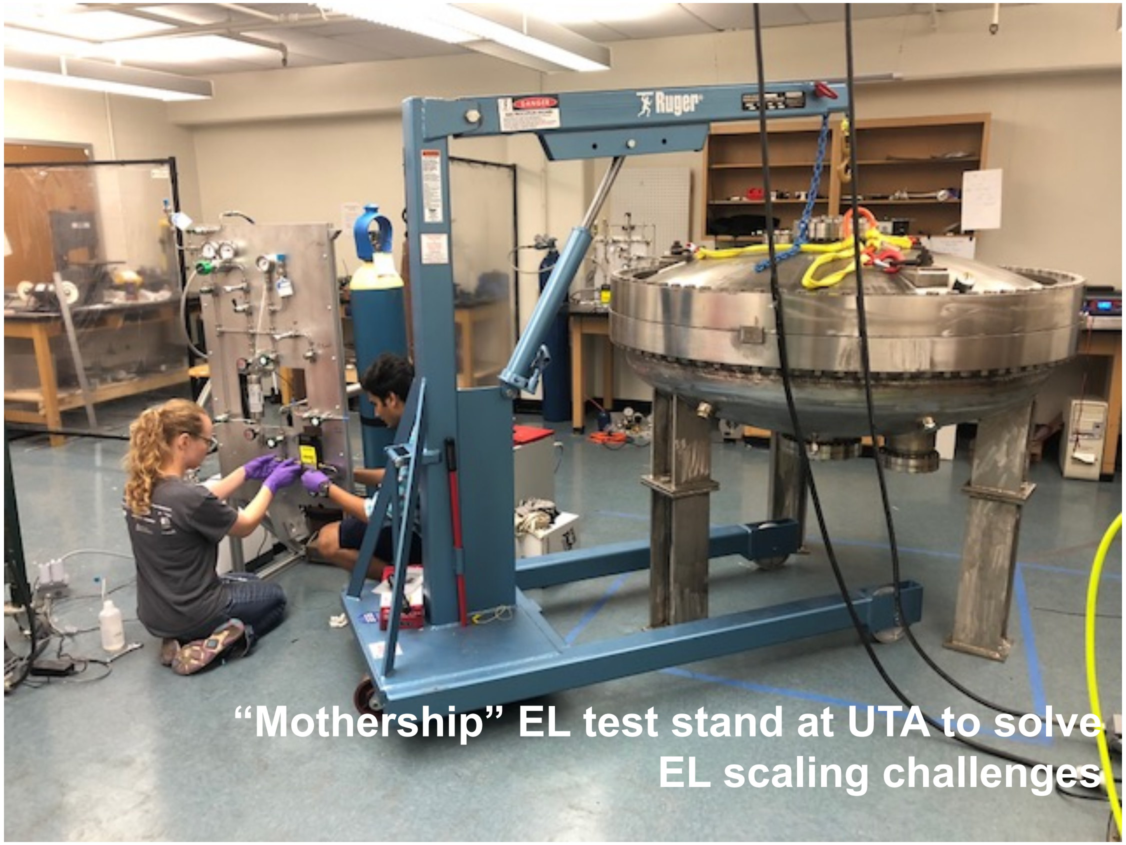




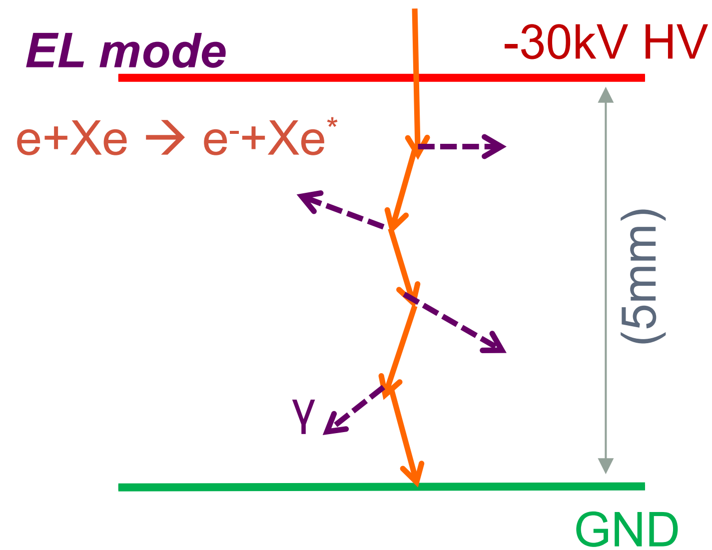
Fluorescence is switched on only when barium ion is present

A scaling challenge: EL amplification

- Ongoing work at UTA to develop large, stable, uniform EL amplification plane for NEXT-100 (D=1.2 m) and NEXT-XXX (D~1.5m)



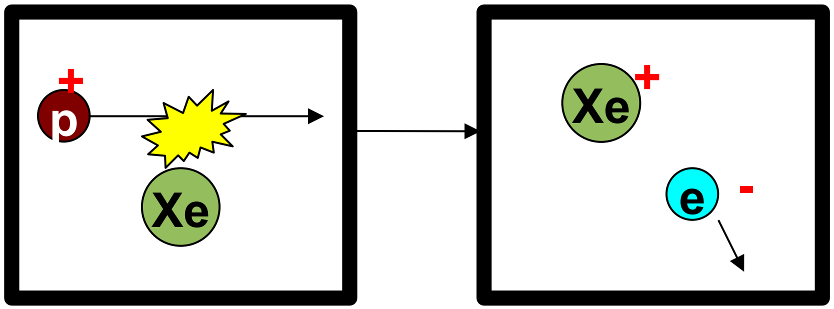
"Mothership" EL test stand at UTA to solve EL scaling challenges



High Voltage Insulation and Gas Absorption of Polymers in High Pressure Argon and Xenon Gases
arXiv:1804.04116. L.Rogers et. al.

PROUDLY SUPPORTED BY:
U.S. DEPARTMENT OF ENERGY

Energy loss through ionization



Ionization

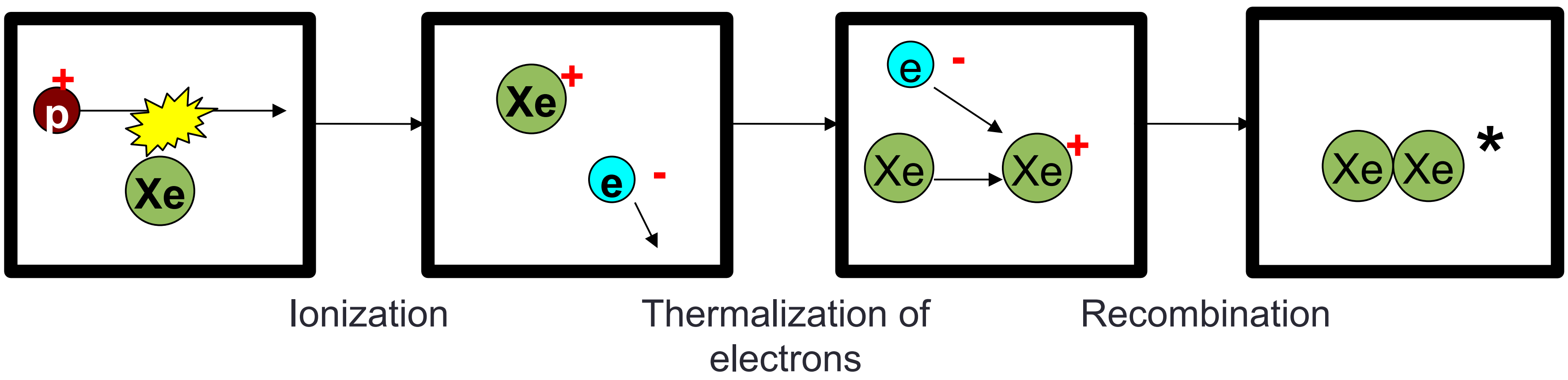
A well defined energy fraction is converted into ionization electrons

“Intrinsic” energy resolution achievable by measuring ionization at 2400MeV is around 0.3% at $Q_{\beta\beta}$

Fano Factor = 0.15

At high densities…

(gas >50 bar and liquid)

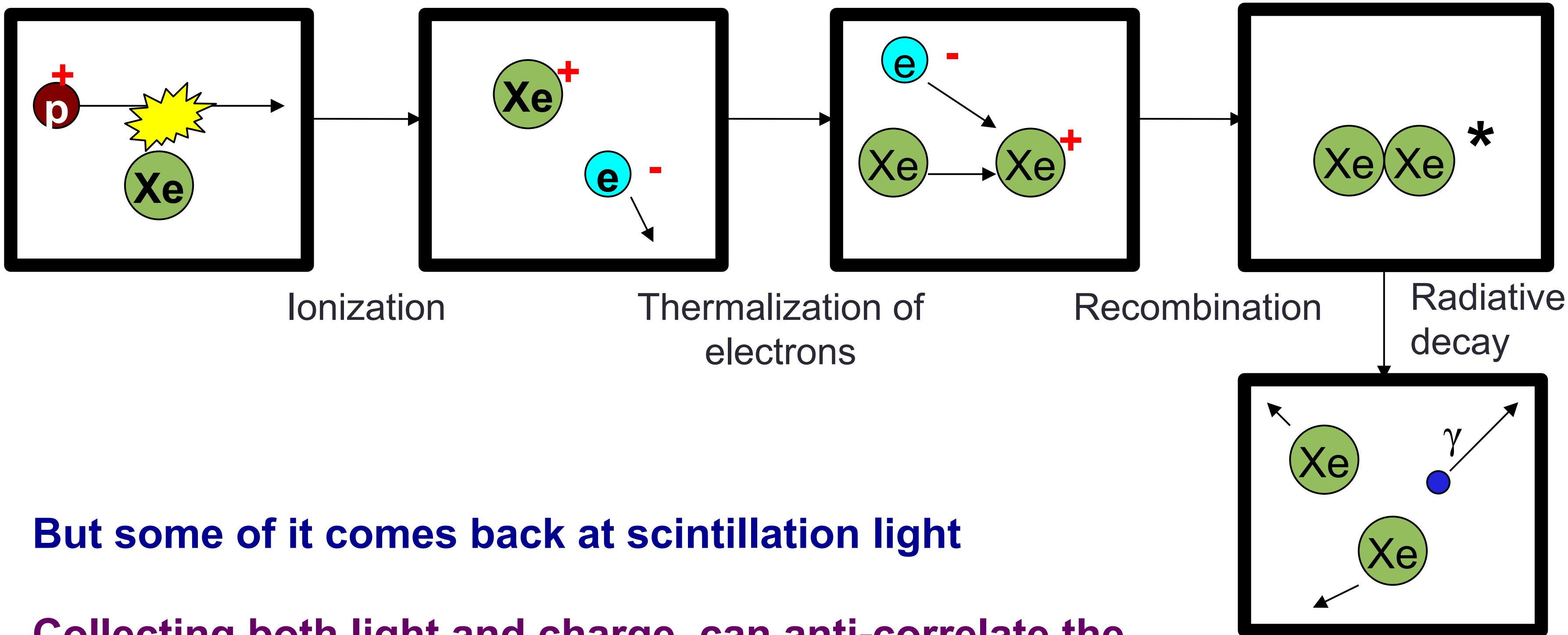


At high densities, ionization charge is lost to recombination

The recombination process is random, and this introduces fluctuations → intrinsic resolution is degraded
(ionization no longer carries a well known fraction of event energy)

At high densities…

(gas >50 bar and liquid)

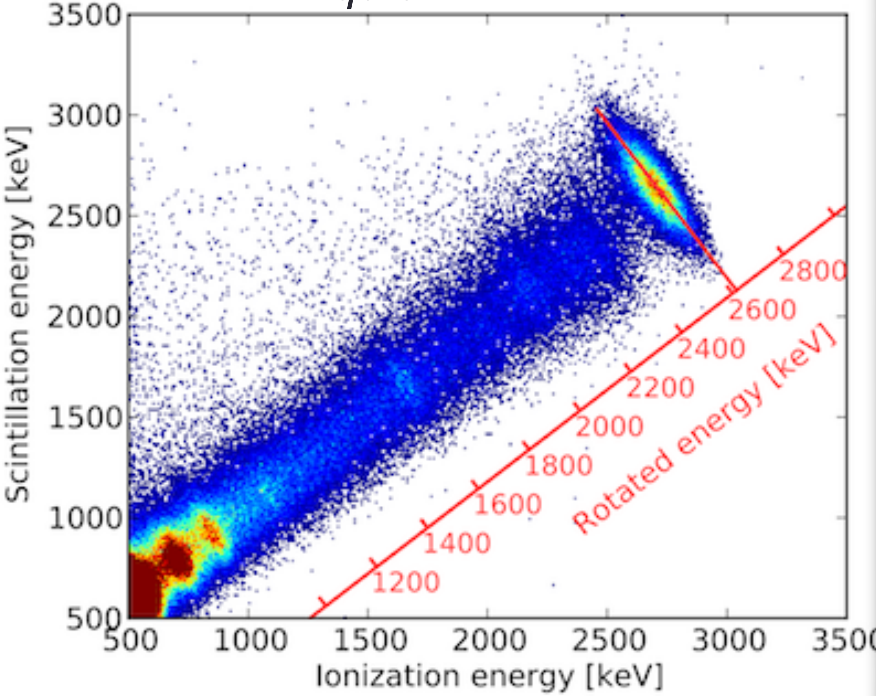


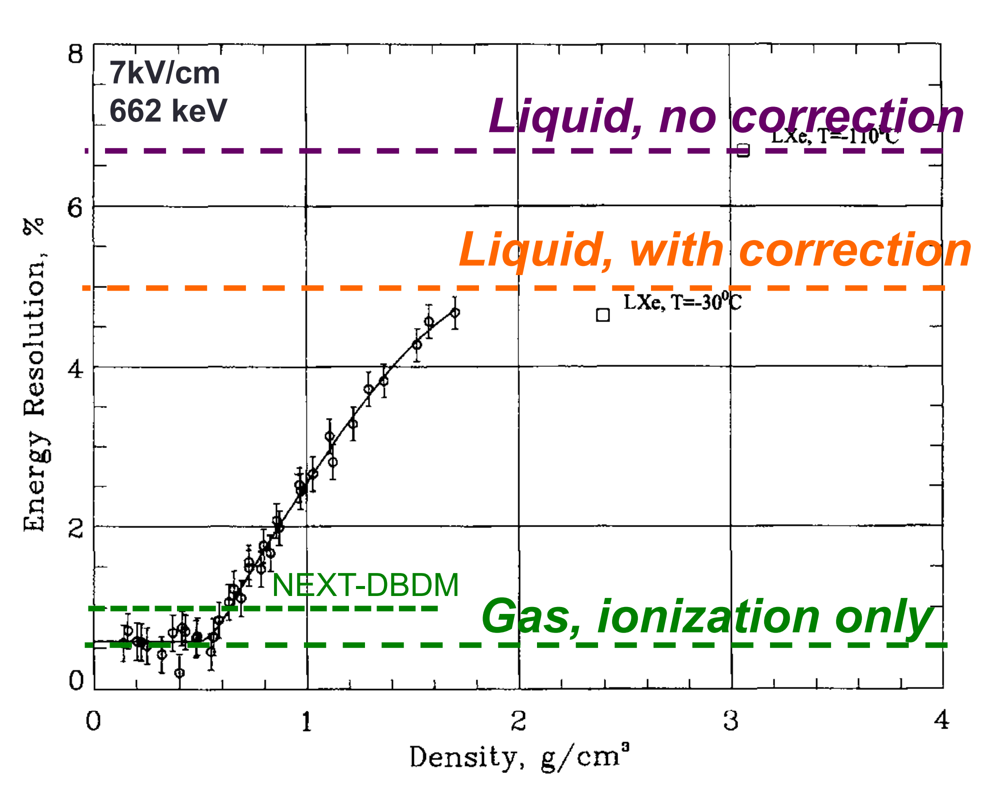
But some of it comes back at scintillation light

Collecting both light and charge, can anti-correlate the fluctuations. This is what liquid experiments do.

In gas @15 bar, no recombination and so no recombination fluctuations.

In liquid:



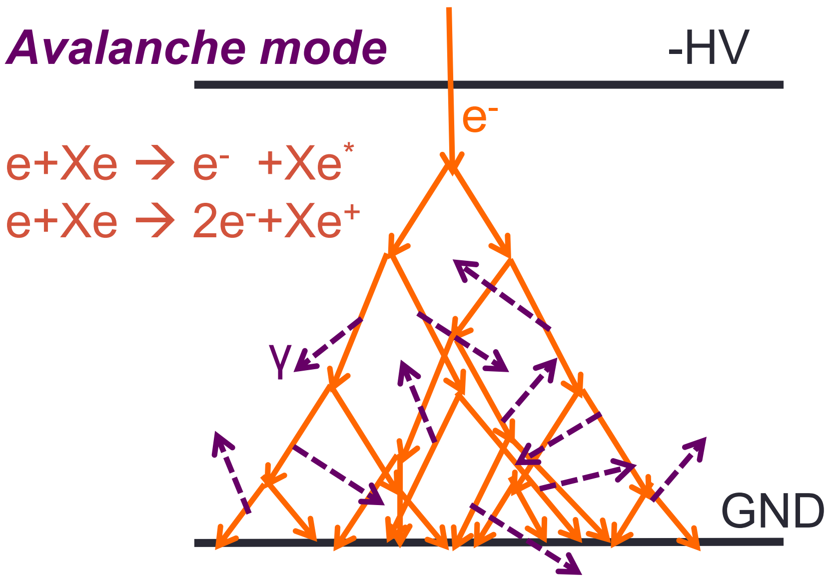


Caveat:
- *All the liquid lines are E-field dependent*
- *Gas has minimal recombination so ~no E-field dependence*

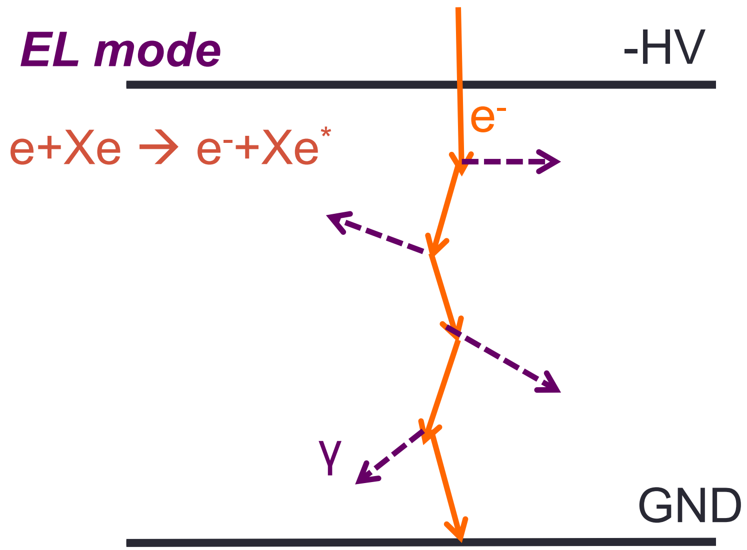
Amplifying the charge

- In high pressure gas, measuring ionization charge **alone** gives excellent energy resolution (0.3%) **in principle.**

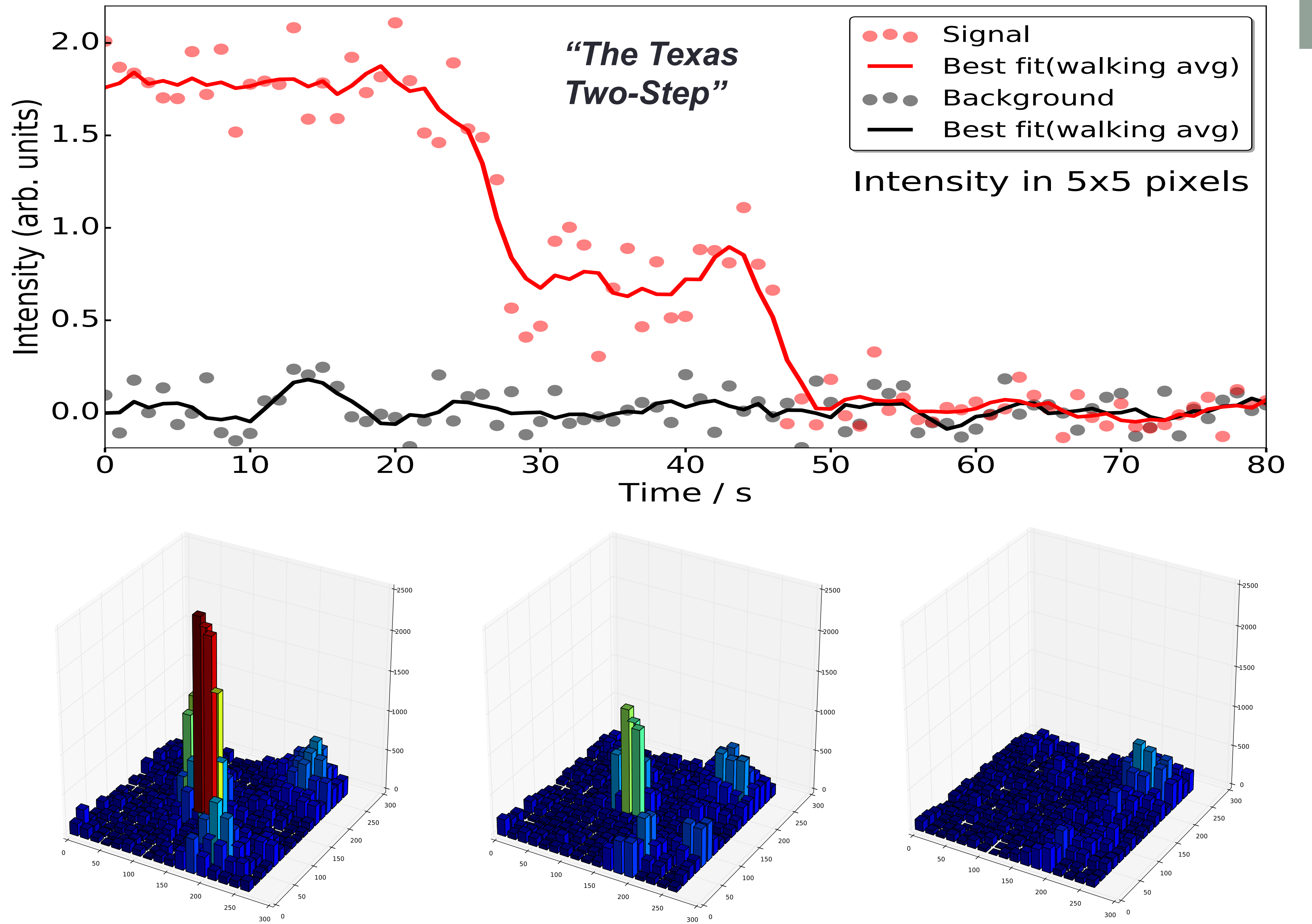
- Now the challenge is to amplify it without introducing fluctuations.
- Use electroluminescent gain mechanism:



Electrons get enough energy to ionize as well as excite Xe:
→ big fluctuations in photon yield



Only enough energy to excite Xe
→ small fluctuations in photon yield



That this can happen suggests two ions may trap in a single pore in PVA matrix (v. rare)

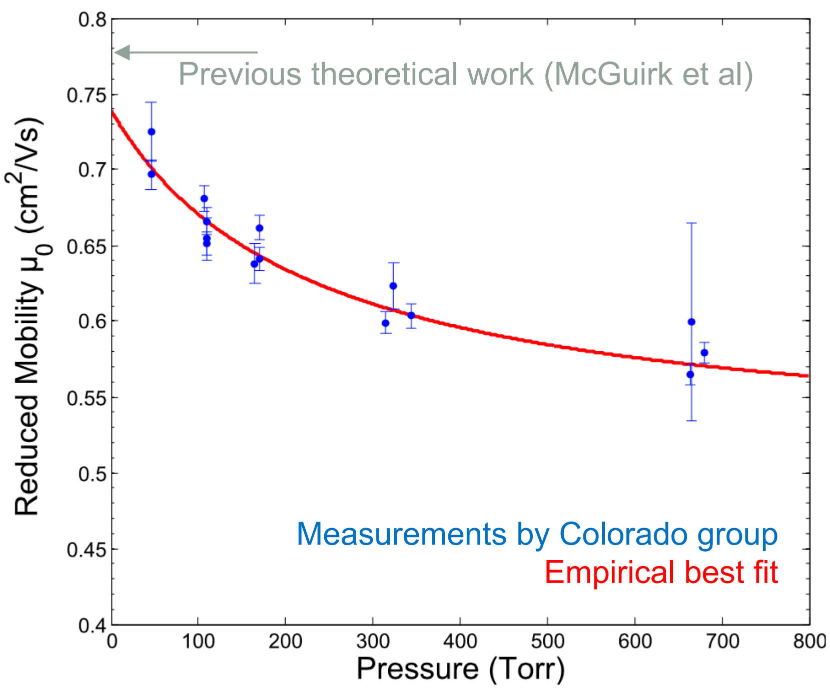
Barium ion mobility in gas

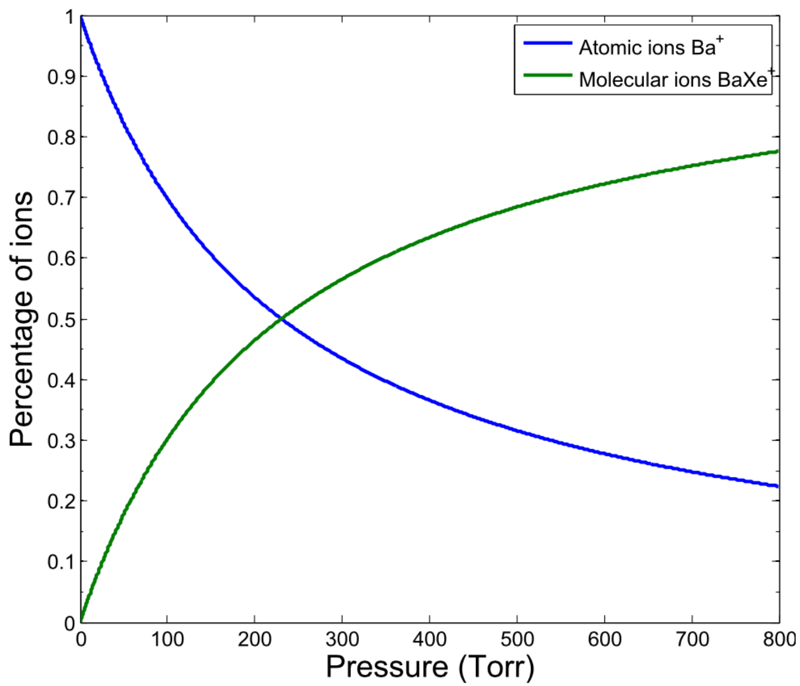
- Measurements from Medina's PhD thesis illustrate the importance of molecular ion formation.

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

- Never measured in Ba^{++} to our knowledge
- And not measured above 1 bar to our knowledge either

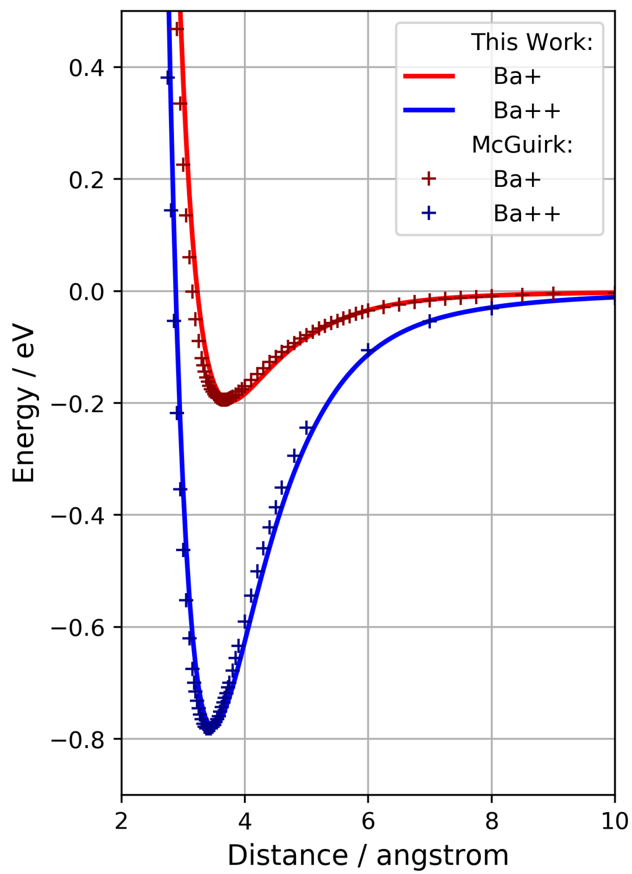
From **"Mobility and fluorescence of barium ions in xenon gas for the EXO experiment" – Julio Cesar Benitez Madina, PhD thesis, Colorado State University**





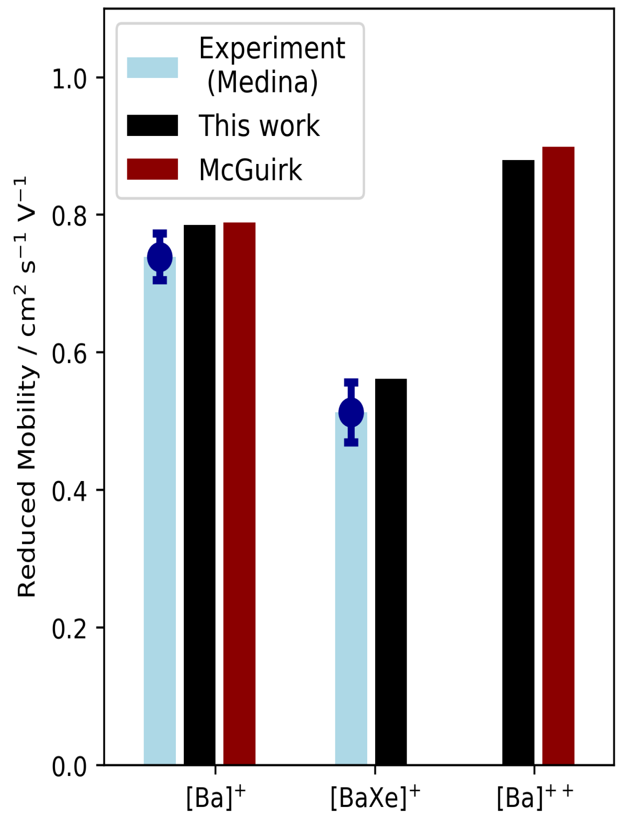
DFT vs coupled clusters

- Past published calcs used coupled cluster theory – good for bare ion ONLY.
- We calculate cluster distributions and cross sections using density functional theory then evaluate mobility.
- DFT is not expected to be as accurate. But too many atoms for coupled cluster method.
- We benchmark our DFT + ion mobility calculations for bare ions against McGuirk, and experimentally extracted data for BaXe system.



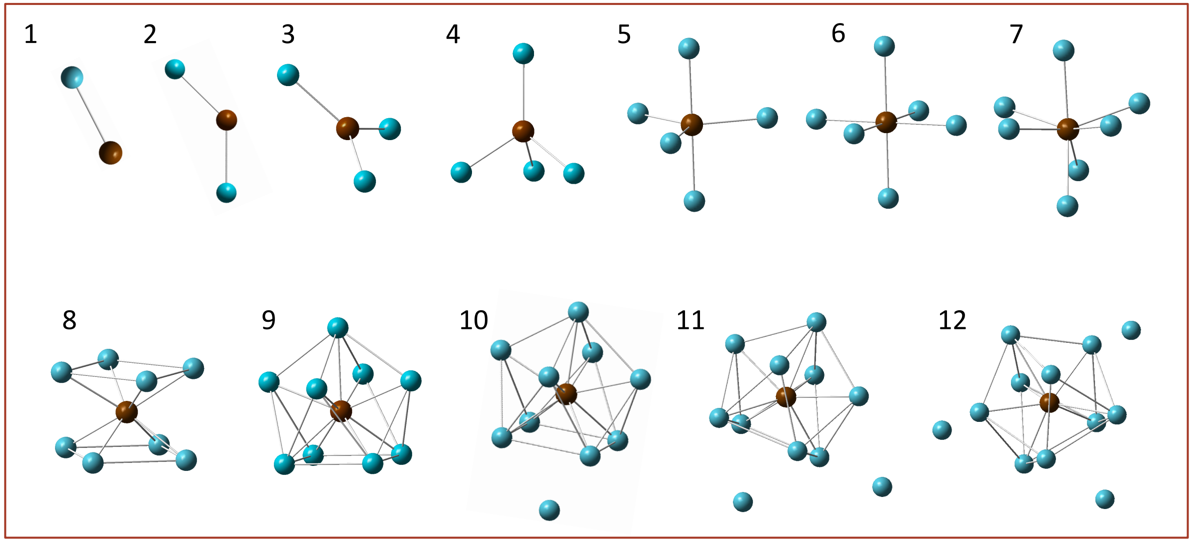
Comparison of potentials

%-level agreement



Comparison of mobilities

Ba++ clusters much more



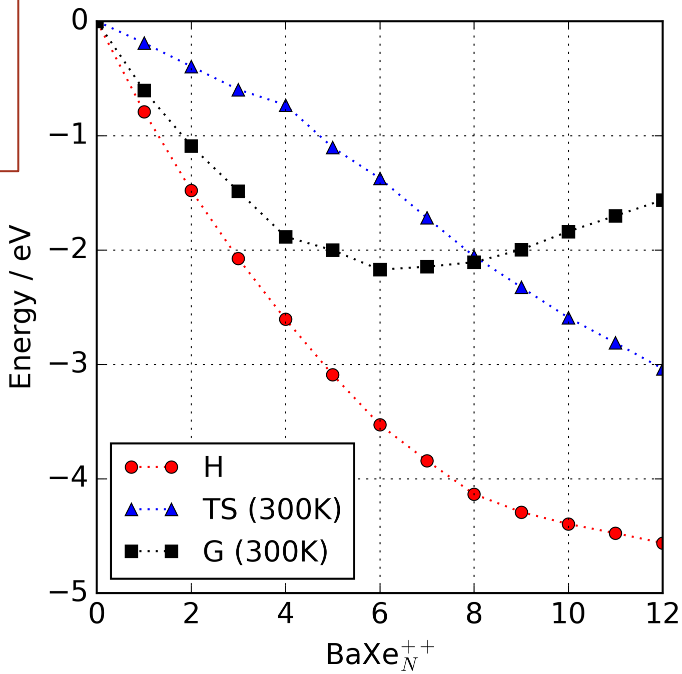
Our calculated DFT clusters

Our calculated thermo quantities

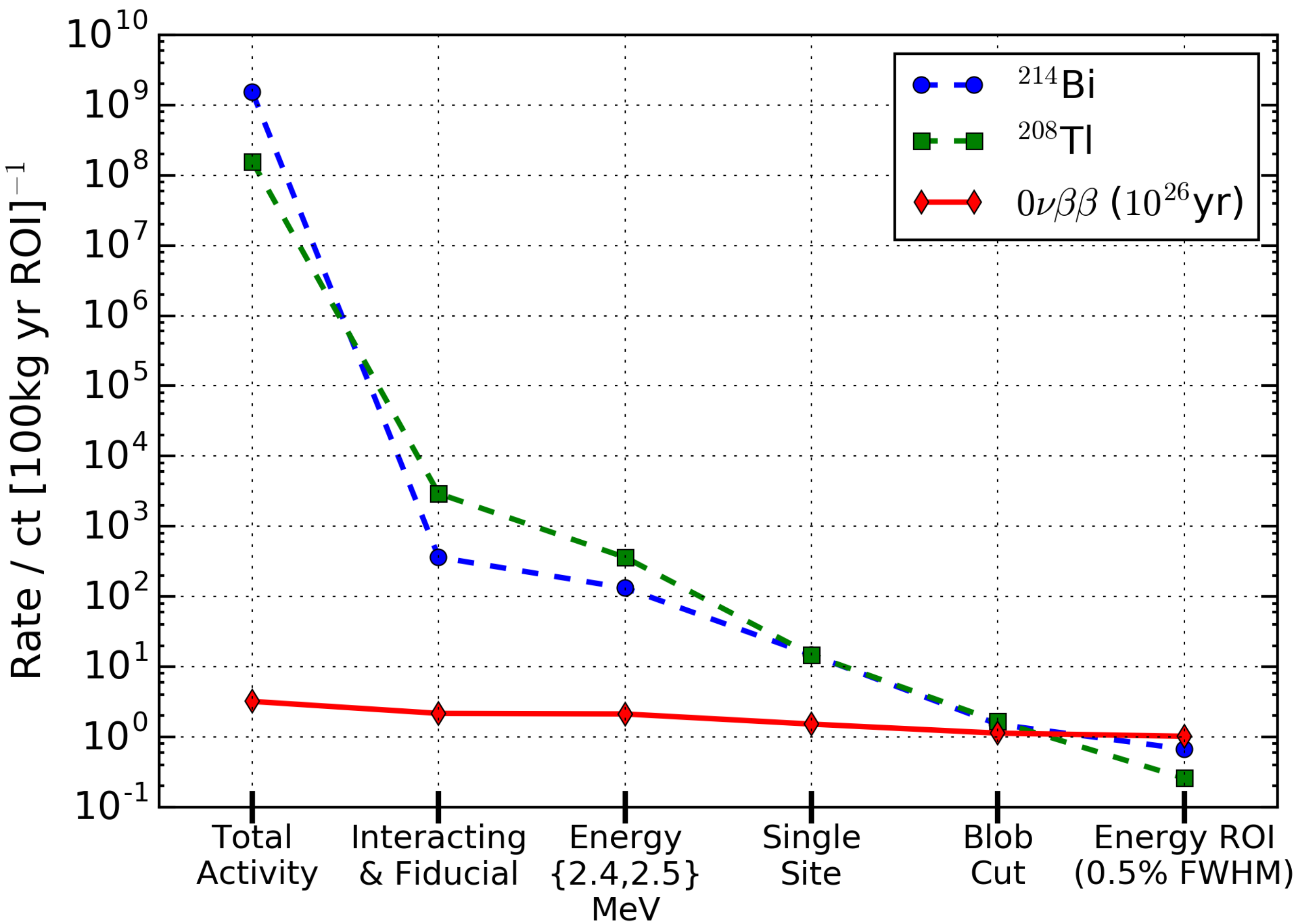
Enthalpy pushes this way

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

Entropy pushes this way



NEXT-100 projected background index performance



← Approximately Background free @ 100kg-scale

World-leading in xenon by an order of magnitude, but still ~5-7 cts/yr at ton scale

^{22}Na calibration of NEXT-NEW

- ***Preliminary results:***
- **6.75% FWHM (0.74% at $Q_{\beta\beta}$)** resolution for x-rays (29.6 keV).
- **2.35% FWHM (1.07% at $Q_{\beta\beta}$)** resolution for 511 keV γ.
- Continuing improvements from improved analysis methods and detector stability.