

17 SEPTEMBER 2026

NEUTRINOLESS DOUBLE BETA DECAY SEARCH IN XE
NEXT-GENERATION EXPERIMENT WORKSHOP

ITACA: TPC and ion tagging

S. R. Soleti, J. J. Gómez Cadenas

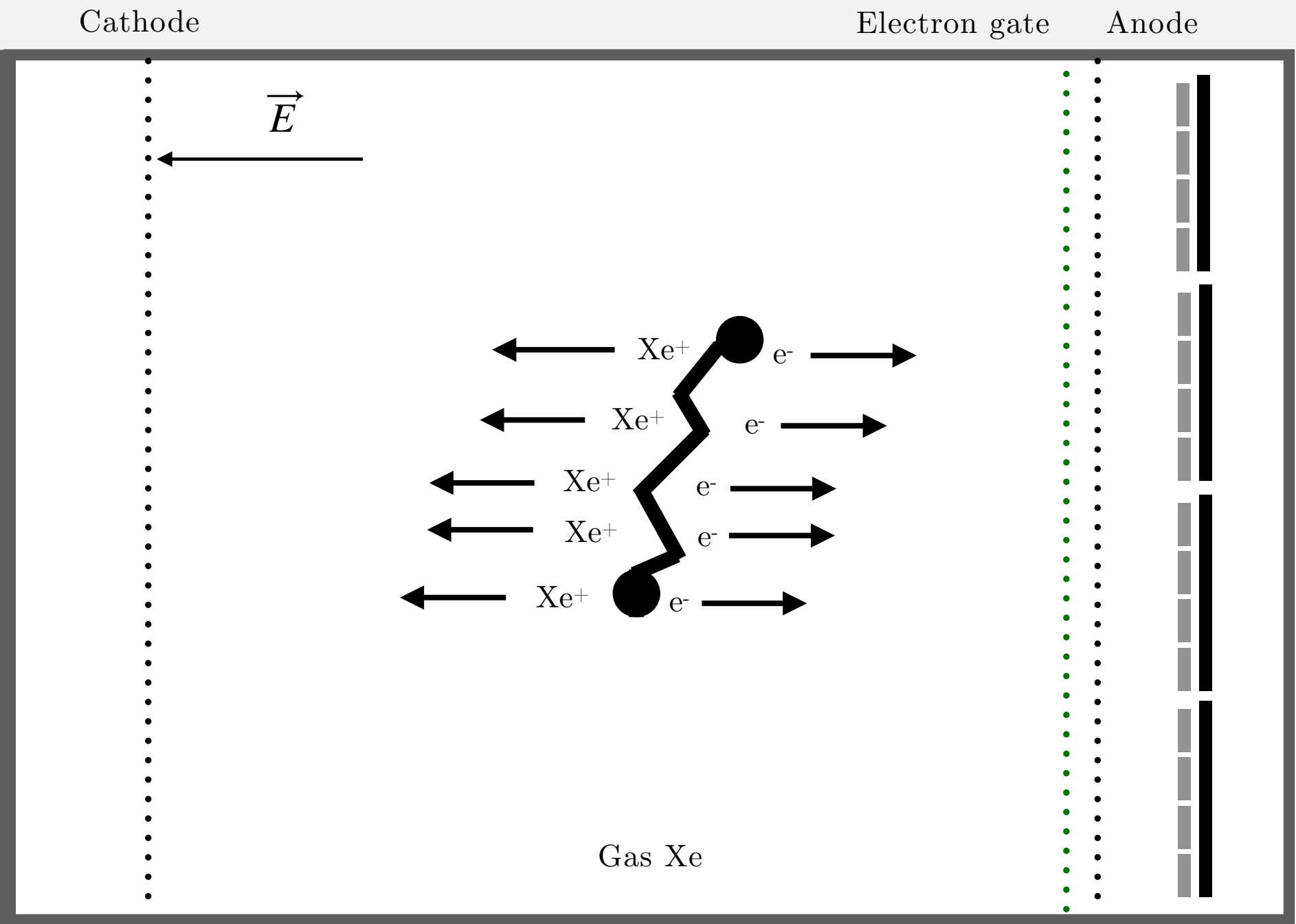
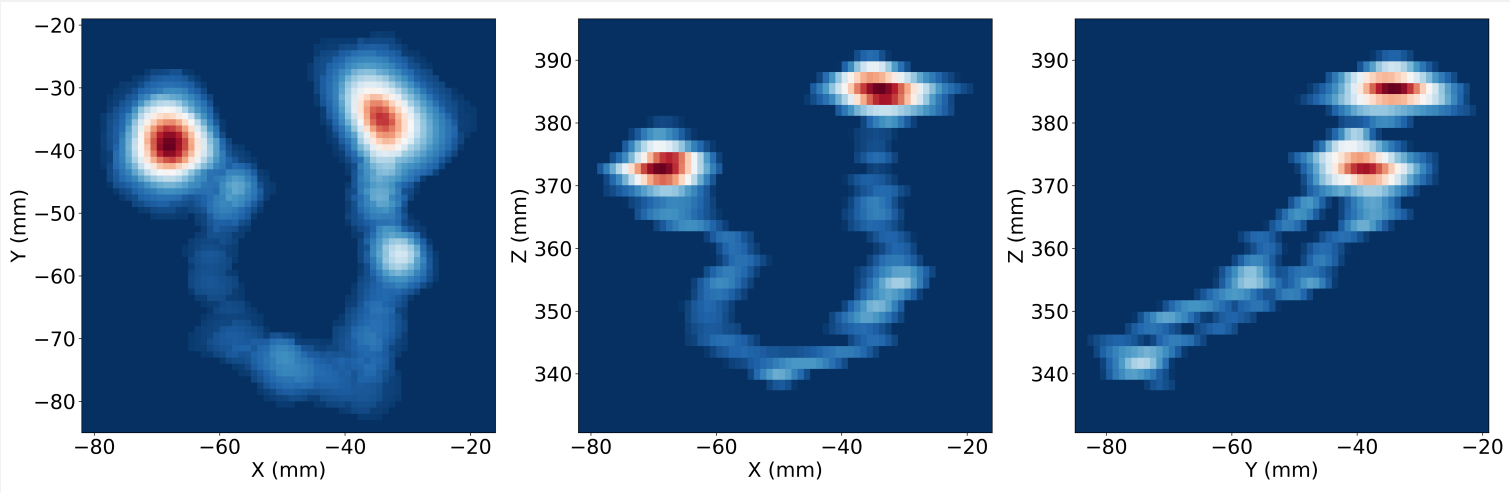
ARXIV:2512.08549 · ARXIV:2604.02443



Topological advantage in gaseous TPCs

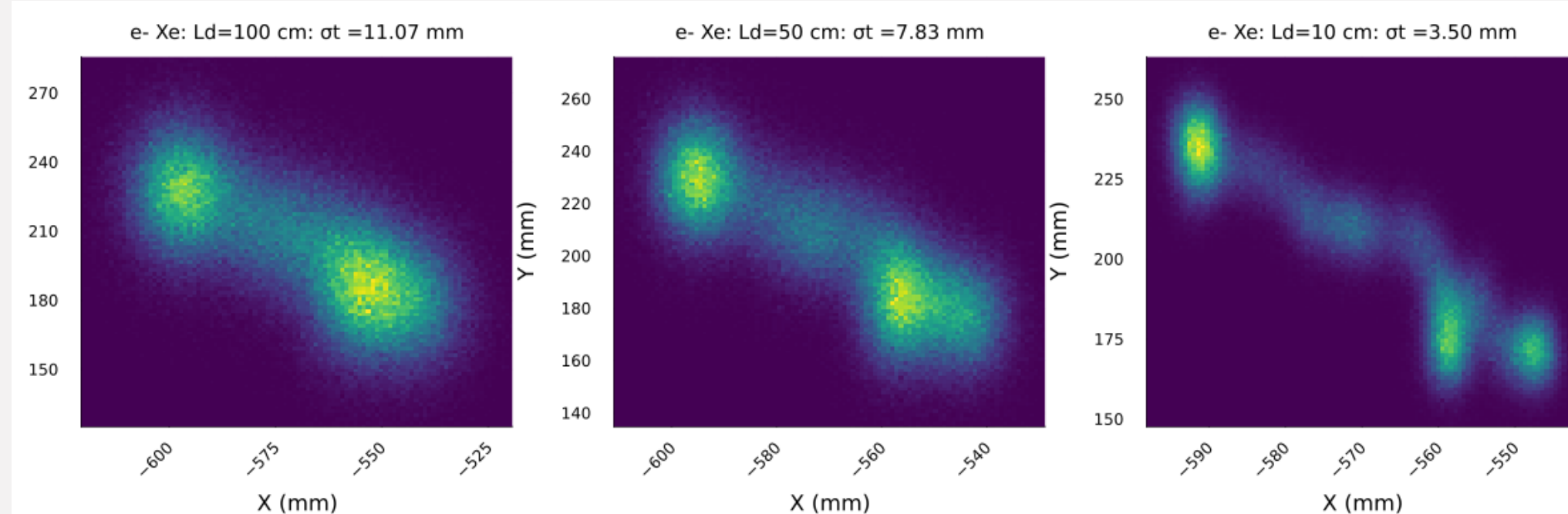
- In a HPGXeTPC the **S1** gives the t_0 and the **S2** gives the energy resolution below 1% FWHM, demonstrated by NEXT and AXEL.
- At 15 bar a $0\nu\beta\beta$ event produces a trail of ionization electrons of **O(10 cm)** , with two clear blobs at the ends.
- In NEXT this image is read by a plane of **SiPMs at the anode**, behind the electroluminescent gap.

Experimental NEXT-White $2\beta\nu\nu$ candidates

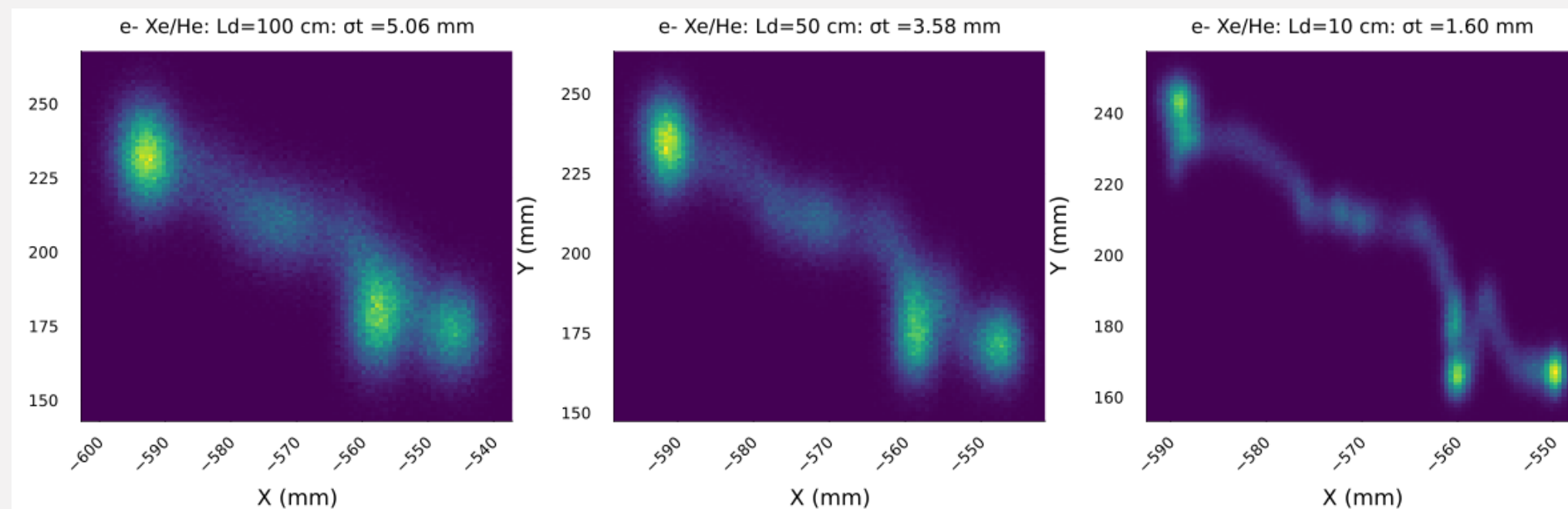


Diffusion limits the electron image

XE



XE-HE



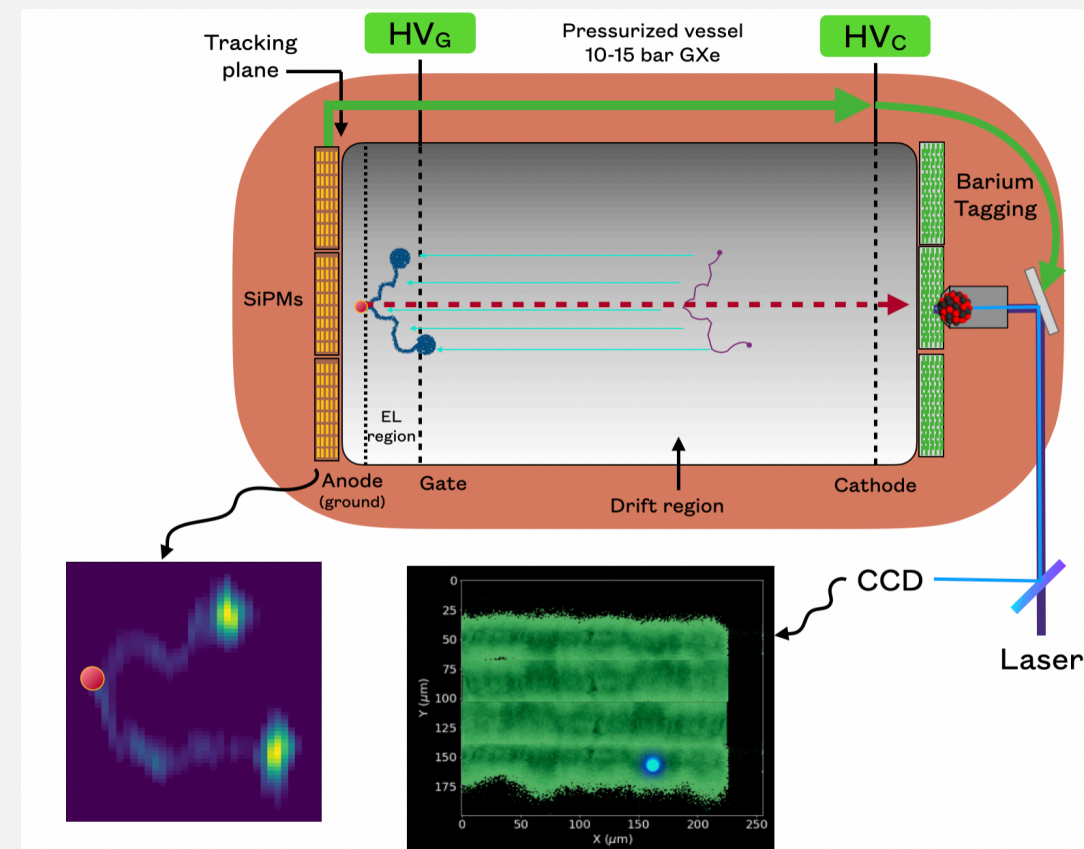
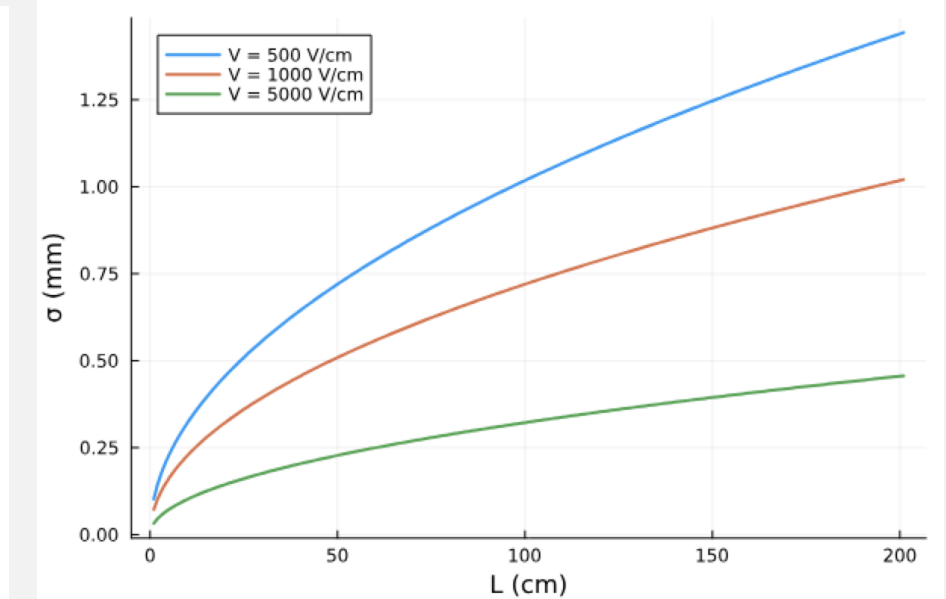
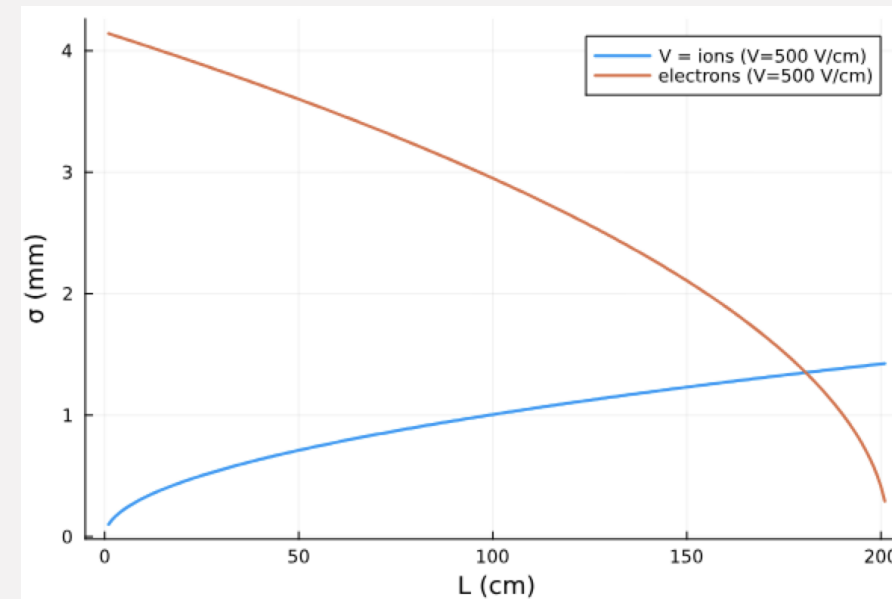
- **Xe-He mixtures** have the advantage of reducing by a factor of ~ 2 the diffusion.
- **No impact** on EL and primary scintillation.
- Currently being tested in NEXT-DEMO++ and planned for NEXT-HD.
- **Few millimeter diffusion** for tracks far from the anode.

Additives and their cost

GAS	SPREAD AFTER 1 M	PRIMARY SCINTILLATION	ELECTROLUMINESCENCE
Pure Xe (e-)	~10 mm	—	—
Xe + 10% He (e-) arXiv:1710.05600	~4 mm	Unaffected	<10% decrease
Xe + CH ₄ / CO ₂ (e-) arXiv:1704.01623 · arXiv:1806.05891	~2 mm	×5–×10 quenching	30–70% decrease
Pure Xe (ions) THIS TALK	~1 mm	Unaffected	Unaffected

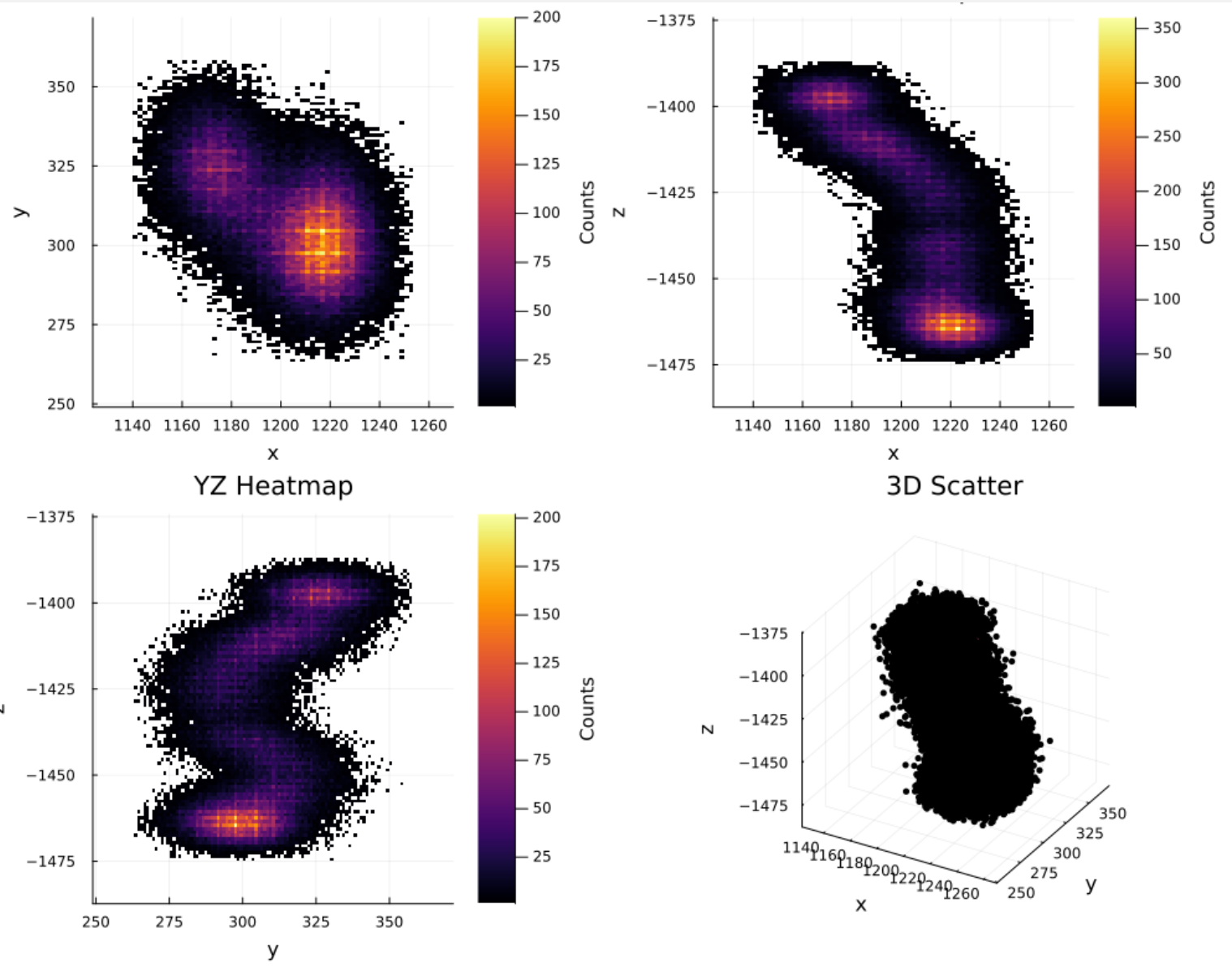
The mirror ion image

- Electron and ion diffusion are **anti-correlated**: they travel in opposite directions.
- Being far heavier, **ion diffusion is much smaller**: it sits at the thermal limit.
- The two carriers differ by **10^4 in drift speed** : seconds of latency between the arrival of the electrons and that of the ions.
- S1 gives t_0 ; the EL plane gives energy and the transverse image. The **ion sensor has seconds to get into place** at the predicted arrival position (as in the ion-to-sensor concept for Ba tagging).



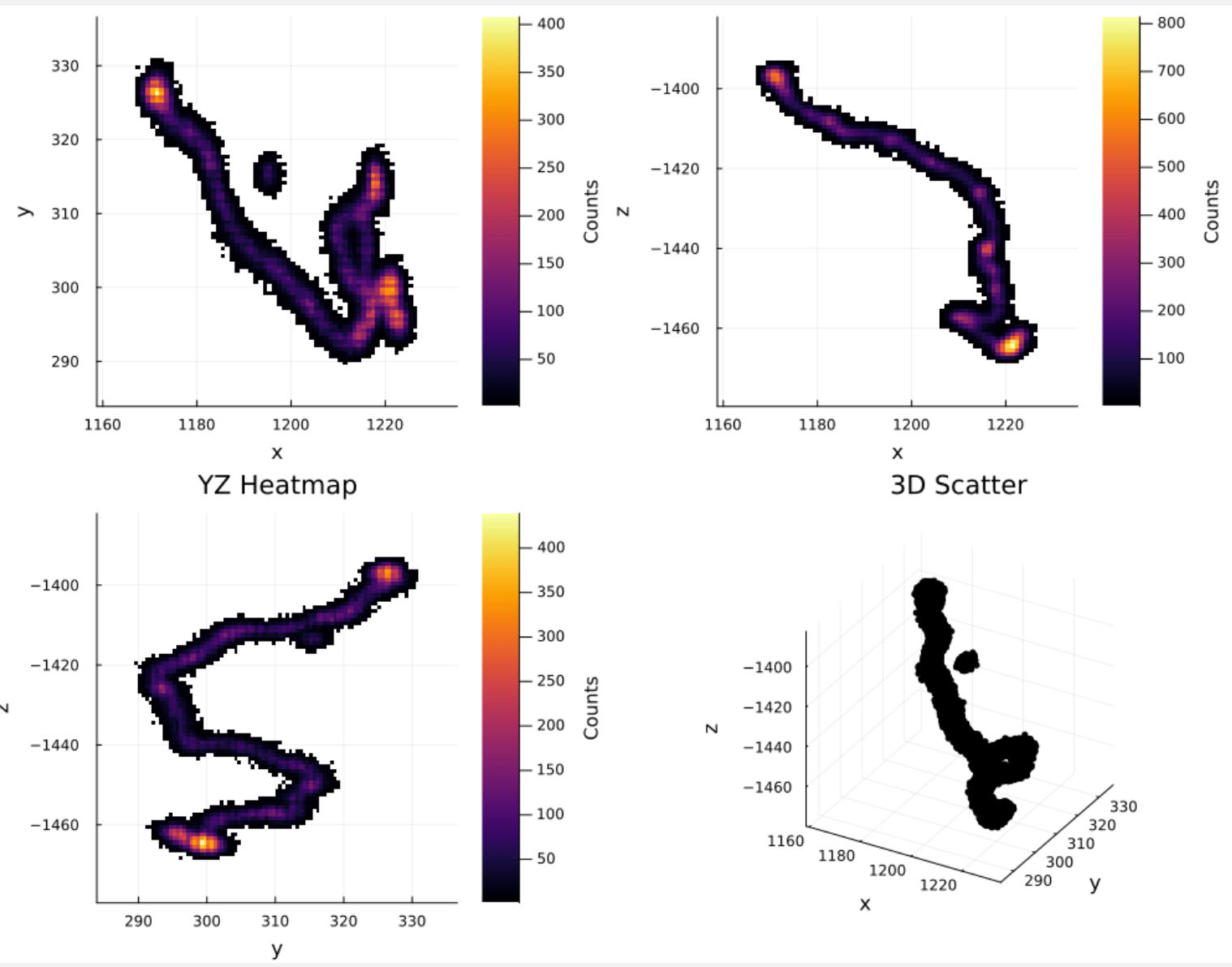
Electron image vs. ion image

Electrons in Xe-He



One cloud: blob structure and nearby X-rays are washed out.

Ions in pure Xe



Two blobs resolved; satellite deposits stay detached from the main track.

What the sharper image buys

SINGLE-TRACK CUT

×5.2

×3.1 on ^{214}Bi · ×5.9 on ^{208}Tl

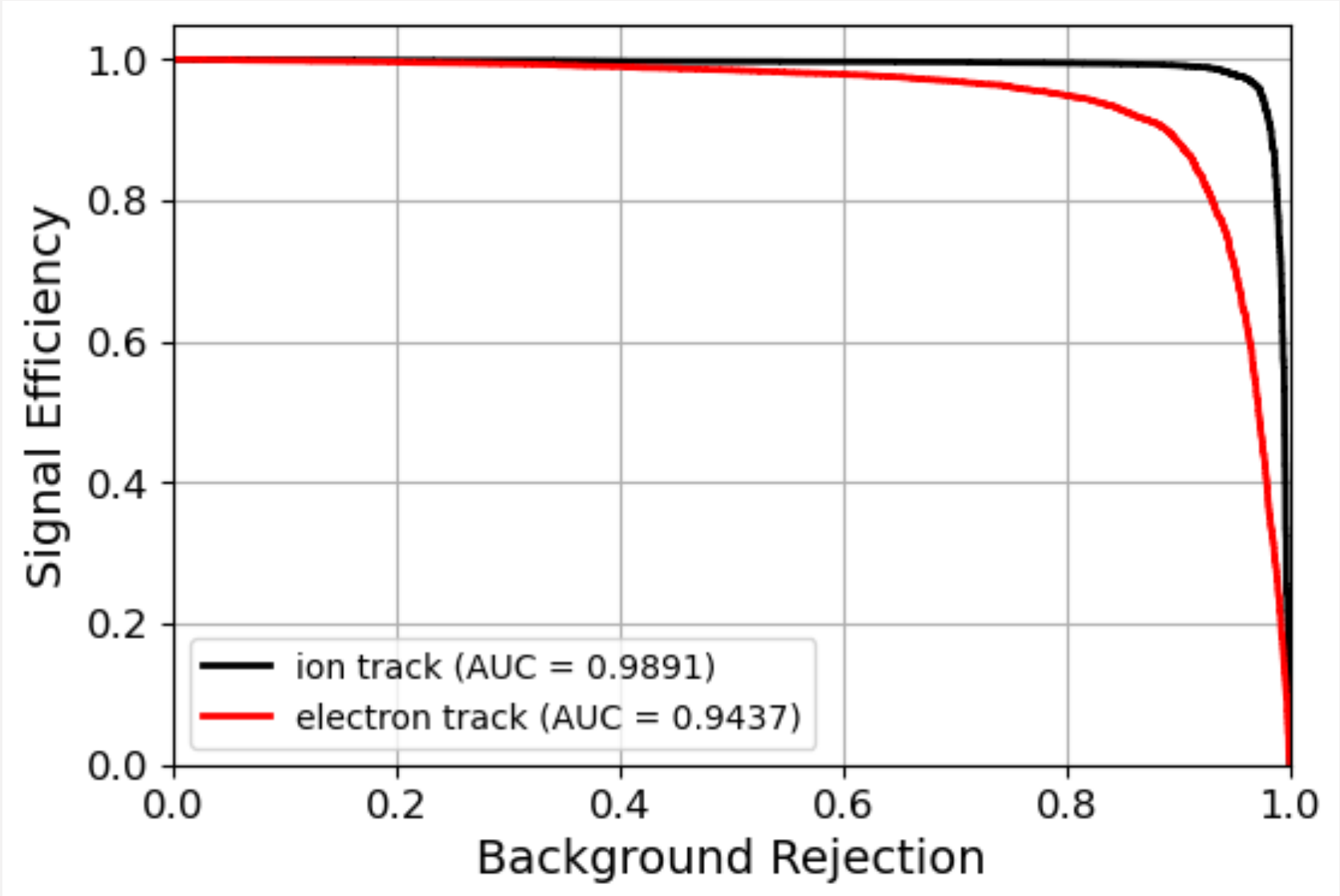
TWO-BLOB CNN

×7

At 80% signal efficiency

OVERALL REJECTION

×35 better



How do we detect the positive ions?

ROUTE A

Molecular imaging

Ion Tracking with Ammonium Cations Apparatus

NH_4^+ formed from trace ammonia, collected on a fluorescent molecular sensor and read by laser scan.

[arXiv:2512.08549](https://arxiv.org/abs/2512.08549)

ROUTE B

Direct ion detection

Ion Tracking Apparatus with CMOS ASICs

Xe_2^+ collected straight onto Topmetal pads. No additive, 10 ms CMOS frames.

[arXiv:2604.02443](https://arxiv.org/abs/2604.02443)

ROUTE A

Molecular imaging

[arXiv:2512.08549](https://arxiv.org/abs/2512.08549)

Ion Tracking with Ammonium Cations Apparatus

Ion chemistry

1 Xe_2^+ conversion

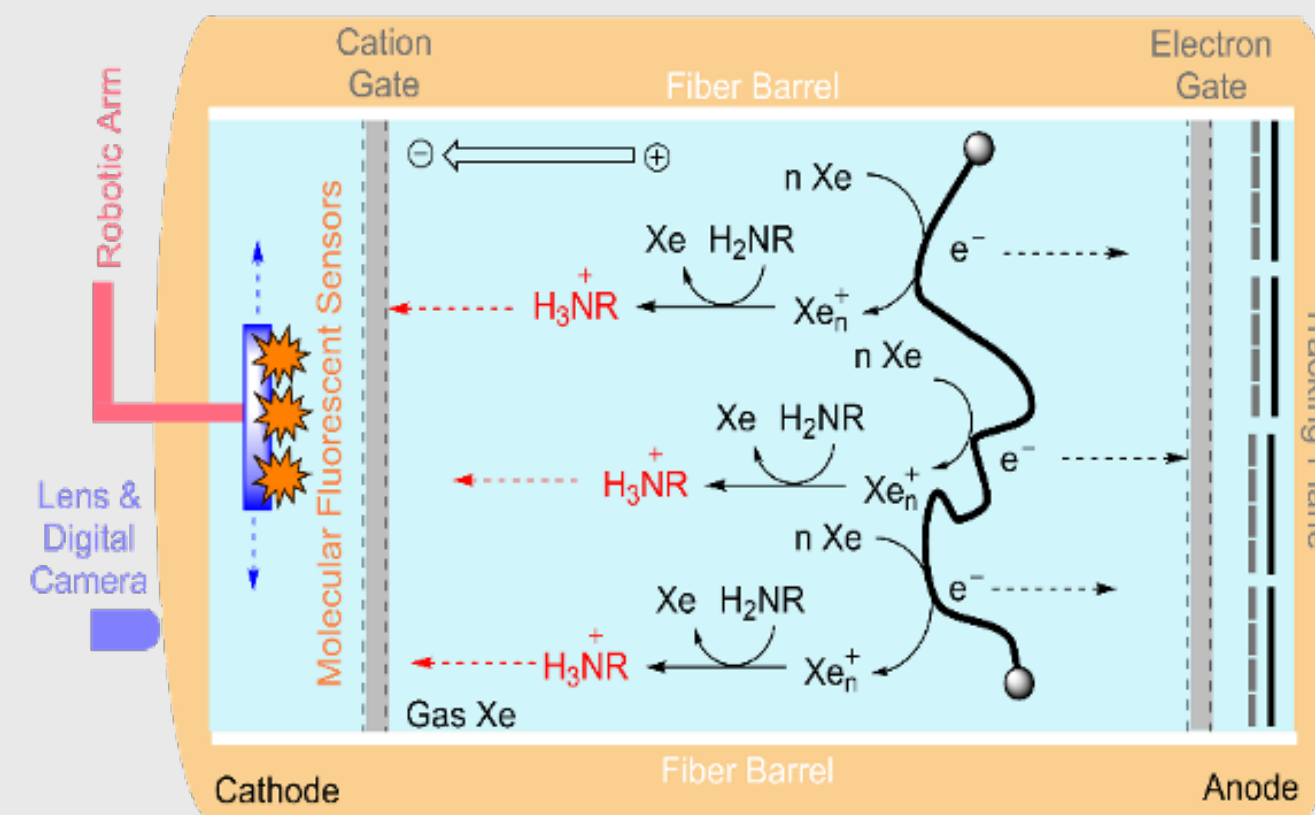
Three-body association after primary ionization.

2 Charge transfer to ammonia

Fast, exothermic, collision-limited ~ 4 ms at 1 ppb and 15 bar.

3 Proton transfer

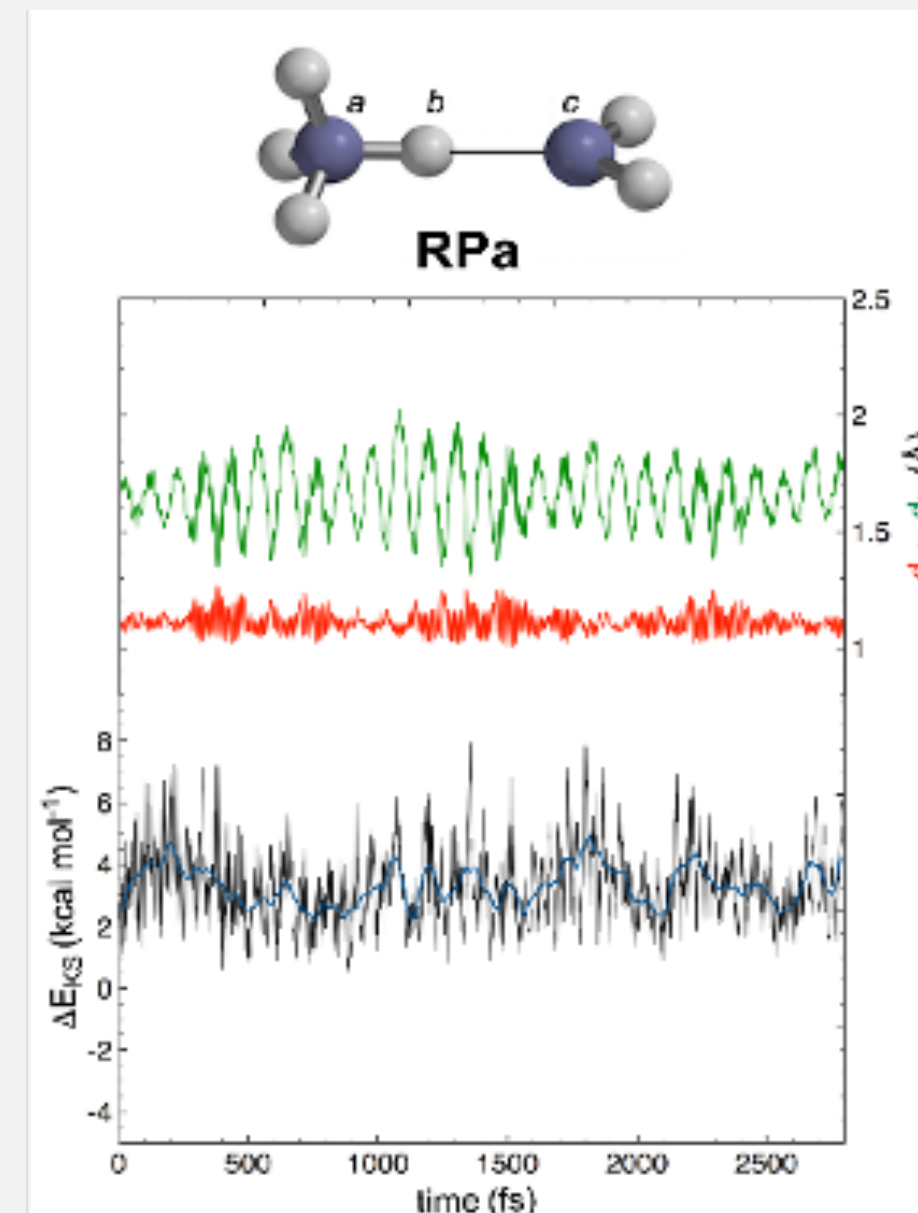
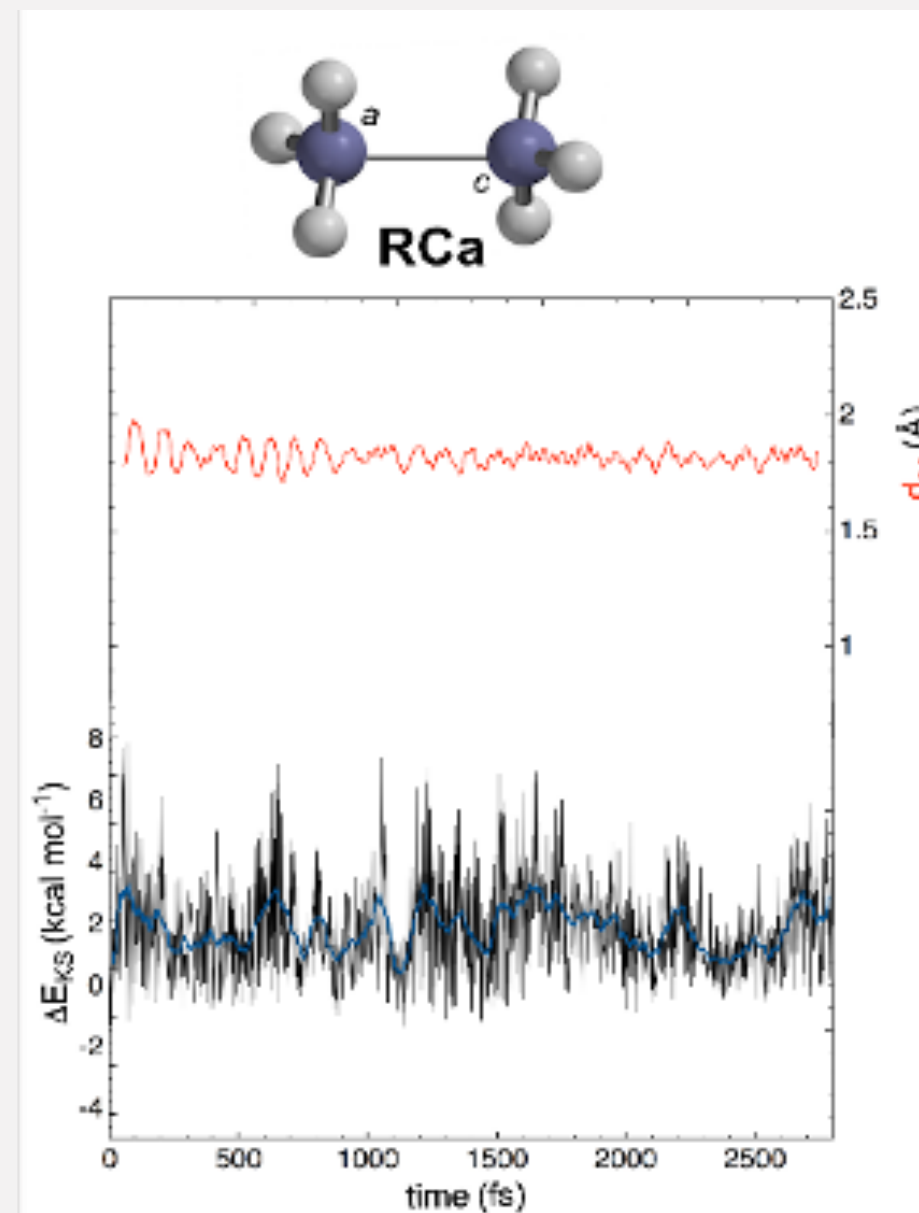
NH_3 has a very high proton affinity; ammonium forms in ~ 1.5 ms at 1 ppb.



REACTION CHAIN



Are the ions stable?



Both the reactive complex and the reaction products are dynamically stable.

METHOD

Car-Parrinello molecular dynamics, NVT canonical ensemble, 298 K.

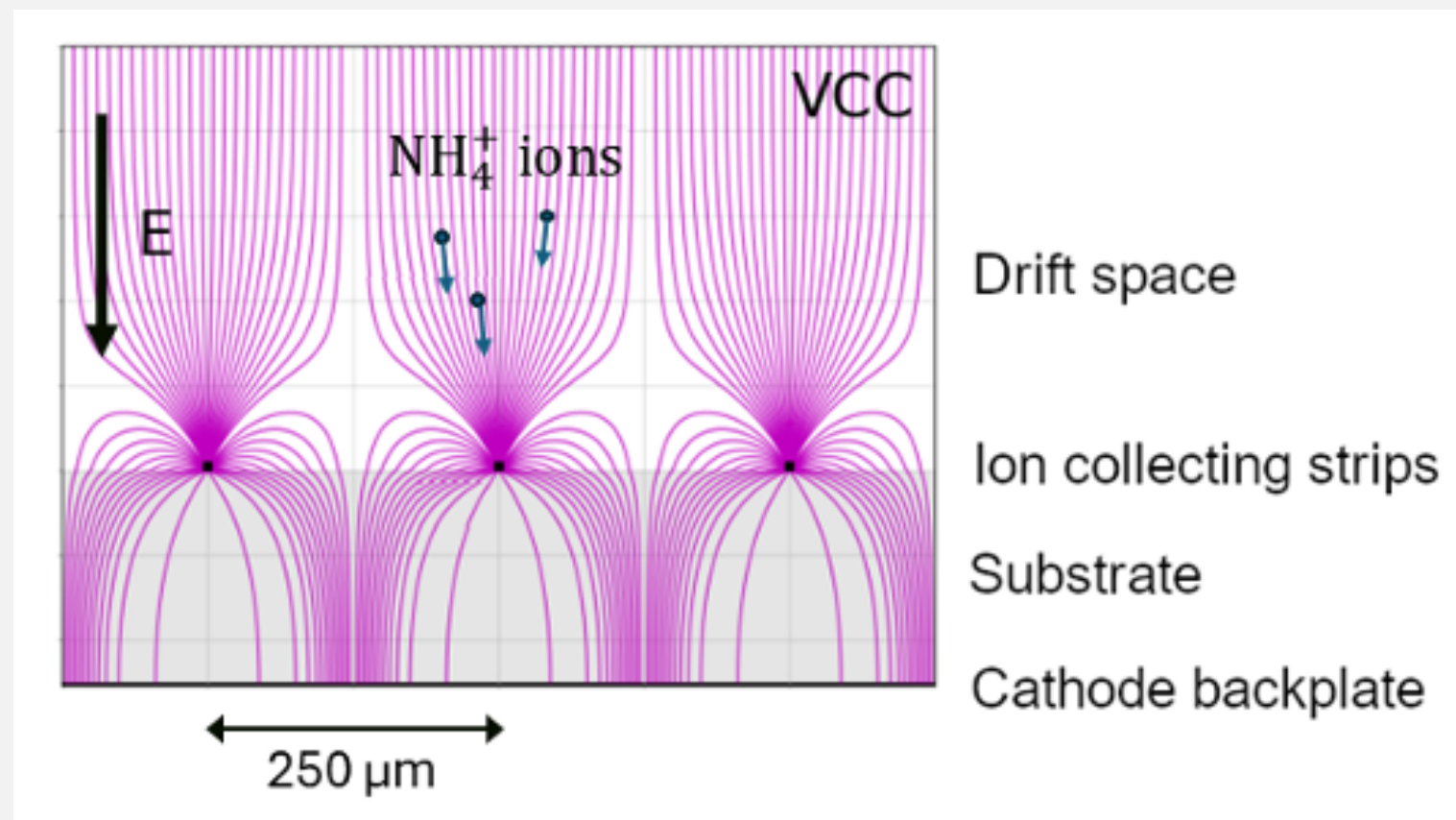
CHEMISTRY BY

Iván Rivilla, Fernando Auria-Luna, Amaia Larumbe, Virginia San Nacienceno, Óscar R. Ballesteros, Abel de Cózar, Fernando P. Cossío

Collecting and measuring the ion track

Ion collection

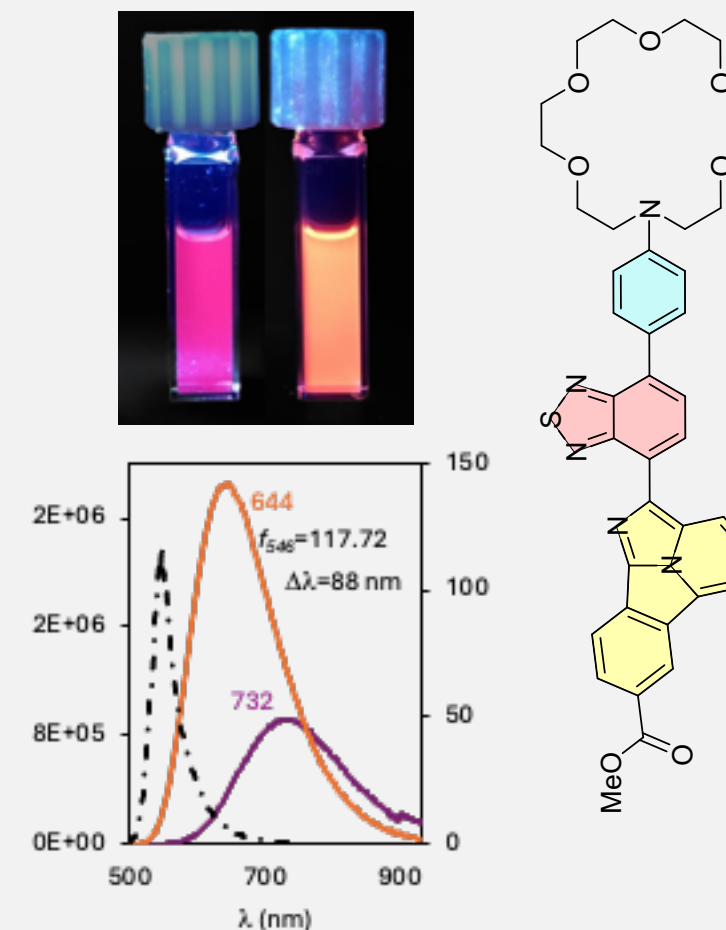
Ions are focused onto the strips of a **VCC microstructure**: 50 μm strips at 250 μm pitch. The target is moved on magnetic rails to the projected barycentre, computed from the electron track.



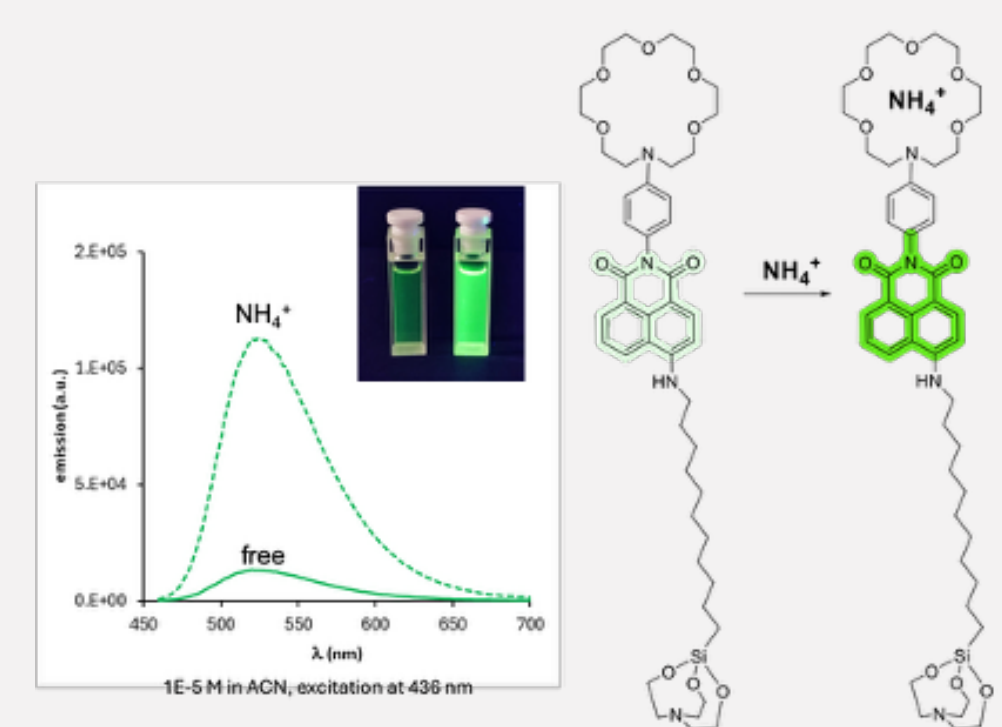
Ion sensing

The **same techniques under development for Ba^{2+} tagging** apply to NH_4^+ : a fluorescent chemical sensor on the cathode surface giving a clear luminescent response to the ion.

MONOCOLOR (FMI)

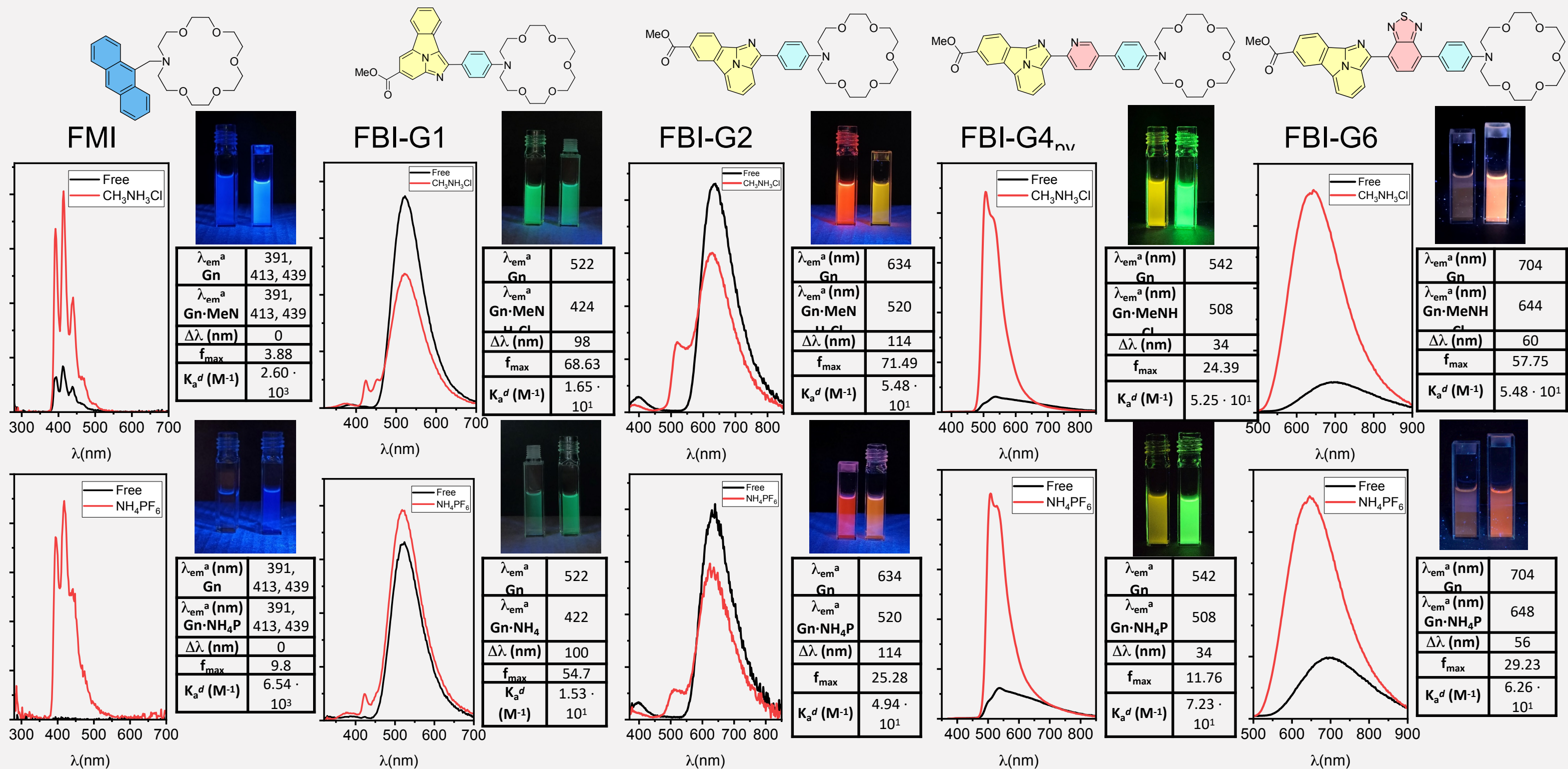


BICOLOR (FBI)



[doi:10.1088/1748-0221/17/08/P08002](https://doi.org/10.1088/1748-0221/17/08/P08002)

FMI vs. FBI: indicator survey



ROUTE B

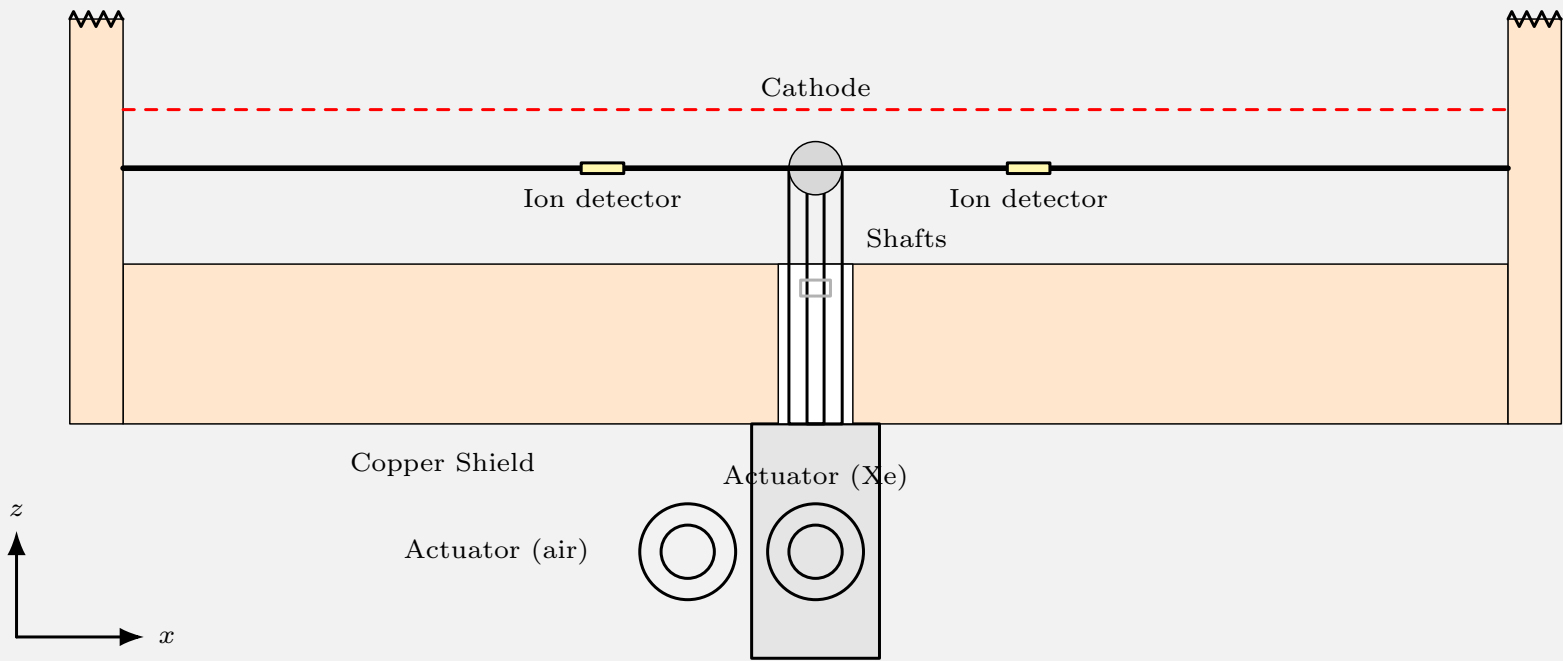
Direct ion detection

[arXiv:2604.02443](https://arxiv.org/abs/2604.02443)

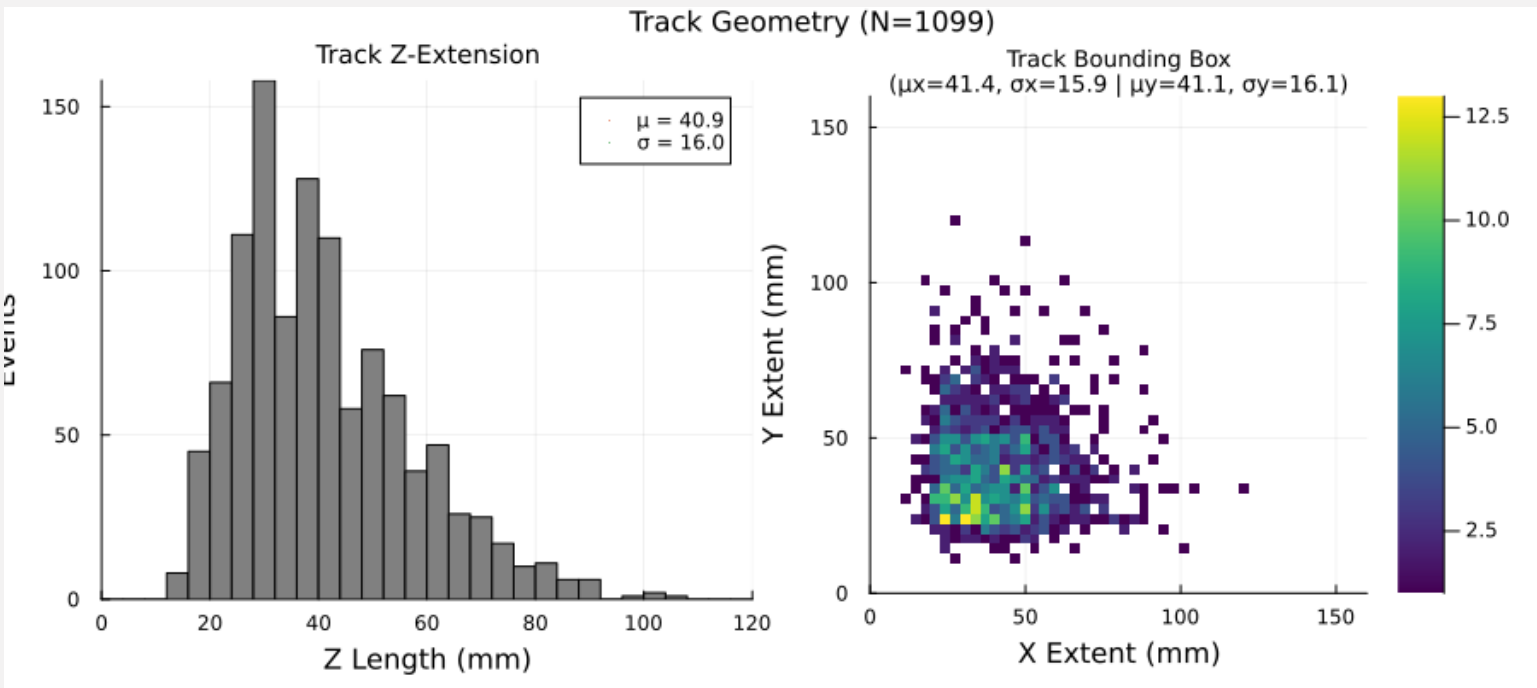
Ion Tracking Apparatus with CMOS ASICs

MARS — magnetically activated rotor system

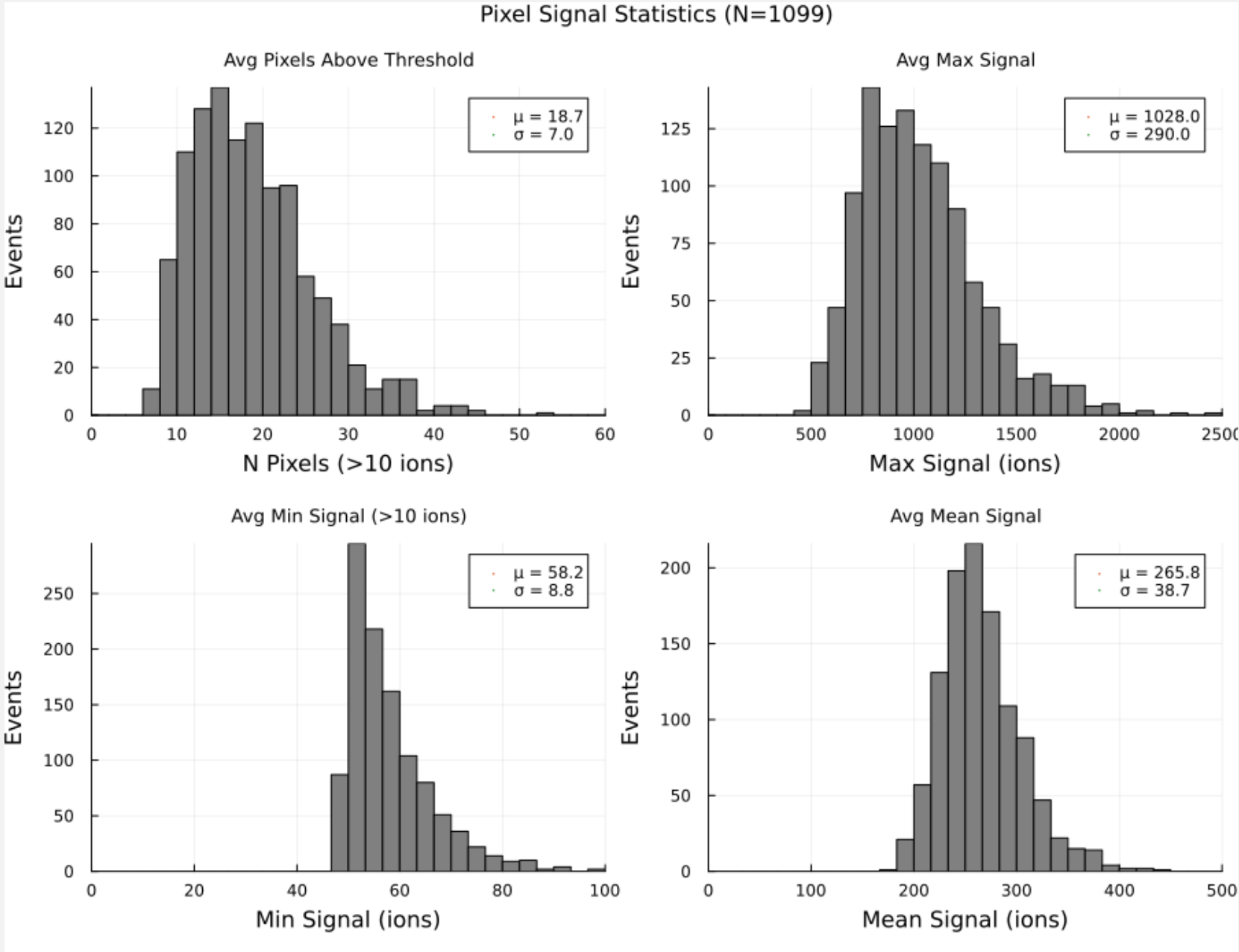
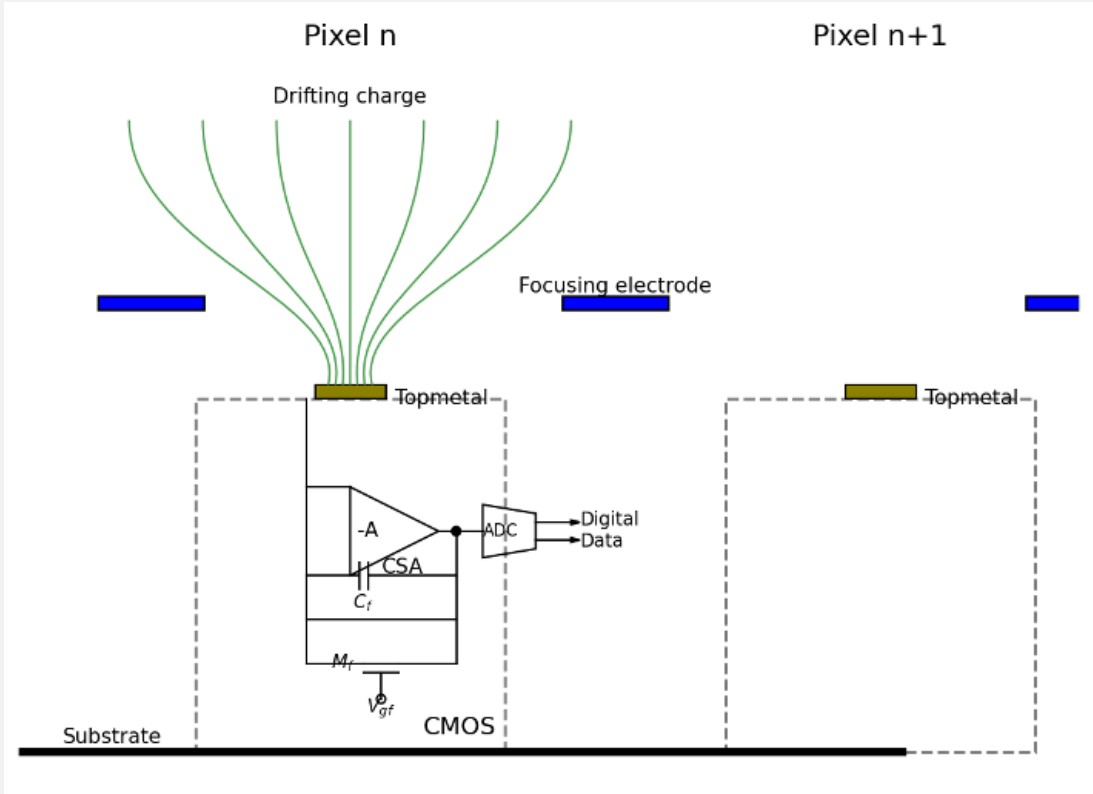
- Collecting drifting ions on charge-sensitive pads is **not a new idea**: proposed for SeF_6 in [arXiv:1801.04513](#) and [arXiv:2010.09226](#).
Electrostatic focusing onto small electrodes gives high efficiency at low capacitance.
- But those approaches instrument **large areas**: over 2 million channels for a ton-scale TPC. In a HPGXeTPC the ion track position is **predicted within milliseconds** from the fast electron track, so only a small region needs instrumenting.



$t \approx 1 \text{ ms}$	Electrons reach the EL plane: energy, topology, barycentre. The arm only moves for candidates.
$1 \text{ ms} - 1 \text{ s}$	MARS drives the plate to the predicted landing point while the ions are still in flight.
$t \approx \text{few s}$	Xe_2^+ lands on a sensor already in place; 10 ms frames read it in 3D.



NAUSICA — direct ion imaging



Occupancy statistics per 10 ms frame.

- Xe_2^+ collected directly on **0.5 mm Topmetal pads** at 2 mm pitch, no additive.
- **80 × 80 pixels** over **16 × 16 cm** ; 10 ms frames give 0.5 mm along z.
- A $0\nu\beta\beta$ event produces **10^5 ions** spread over about 20 pixels per frame.

IONS / PIXEL / FRAME	AGAINST 50 E- ENC
~260	S/N > 5
	12-bit range

The two routes, side by side

	Molecular imaging ROUTE A	CMOS ROUTE B
ION READ	NH_4^+ , after 100 ppb of NH_3	Xe_2^+ , no additive
SENSOR	Fluorescent molecular indicators	Topmetal pads
READ-OUT	Laser scan of the target	100 Hz CMOS frames
POSITIONING	Moving rails	Moving rails
R&D NEEDED	NH_4^+ recognition chemistry, in-gas mechanics	ASIC integration, in-gas mechanics

Where this leaves us

- Topology in HPGXeTPCs is **limited by electron diffusion, not by the read-out** and gas additives quench primary scintillation.
- Ions carry a **mirror image** of the electron track with $\times 10$ smaller diffusion, arriving seconds later.
- That buys roughly **$\times 35$ in background rejection**.
- Tiling the entire cathode is unfeasible: a **small-area sensor must be placed** at the expected arrival position.

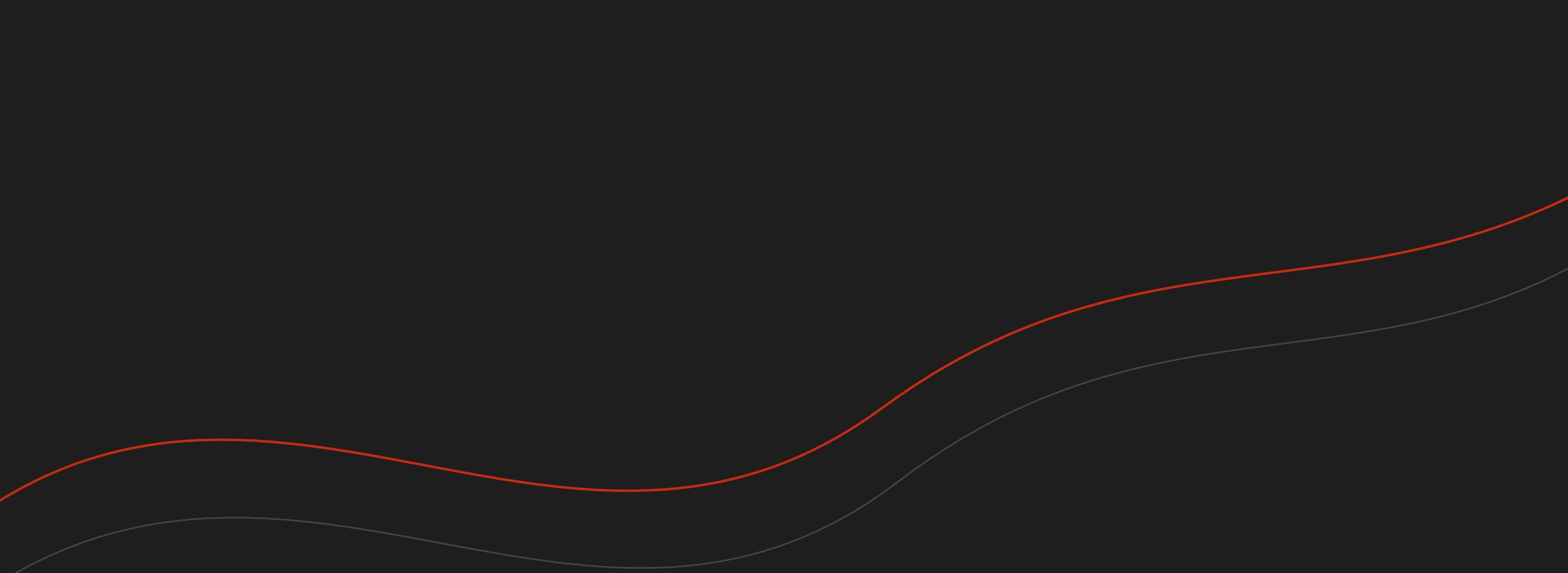
ROUTE A

Needs **better NH_4^+ recognition chemistry**, but builds on the Ba^+ tagging R&D.

ROUTE B

Needs a **large-area Topmetal ASIC** with low ENC.

Both routes need a moving arm in high-pressure xenon — that is the shared engineering problem.

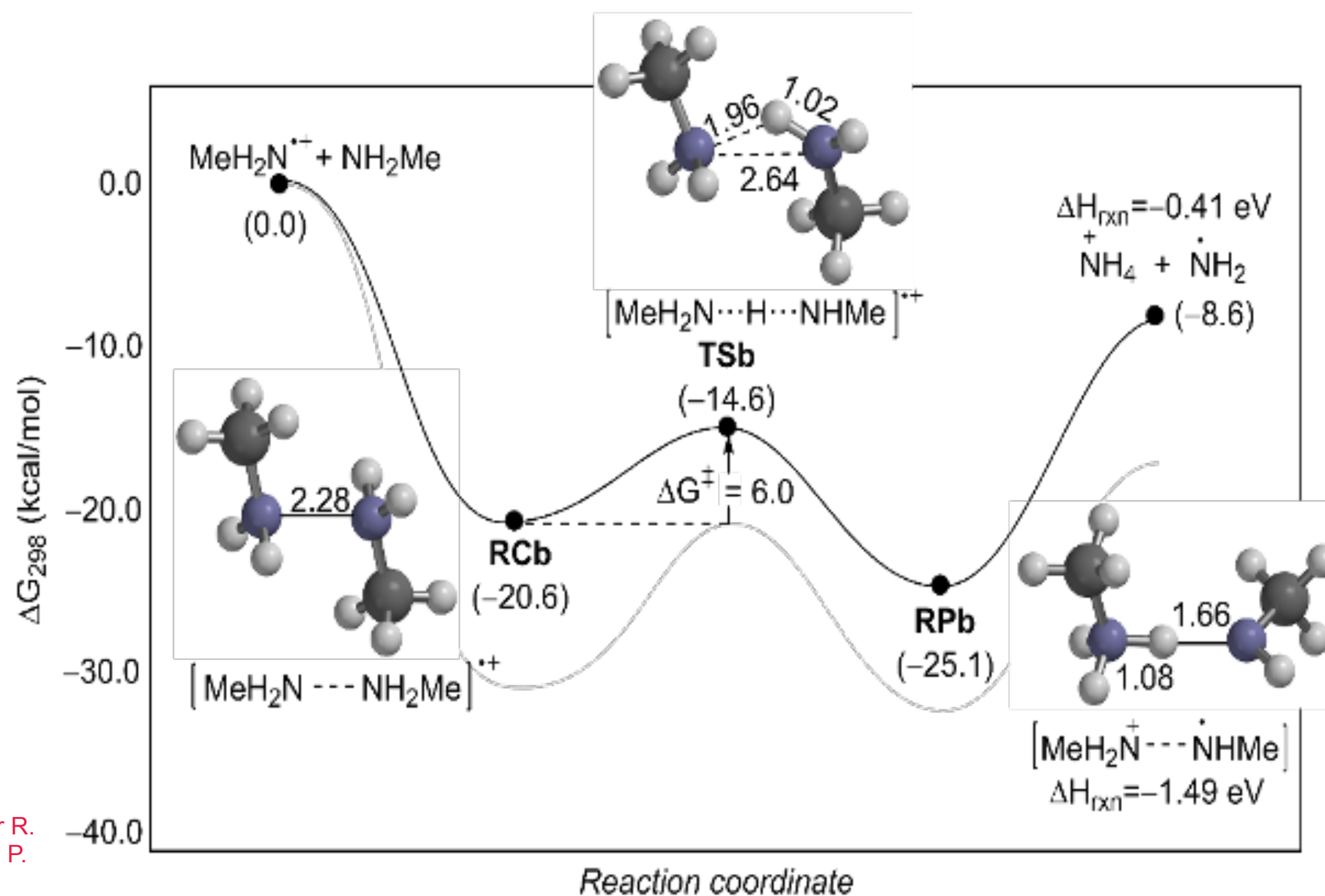


APPENDIX

Backup

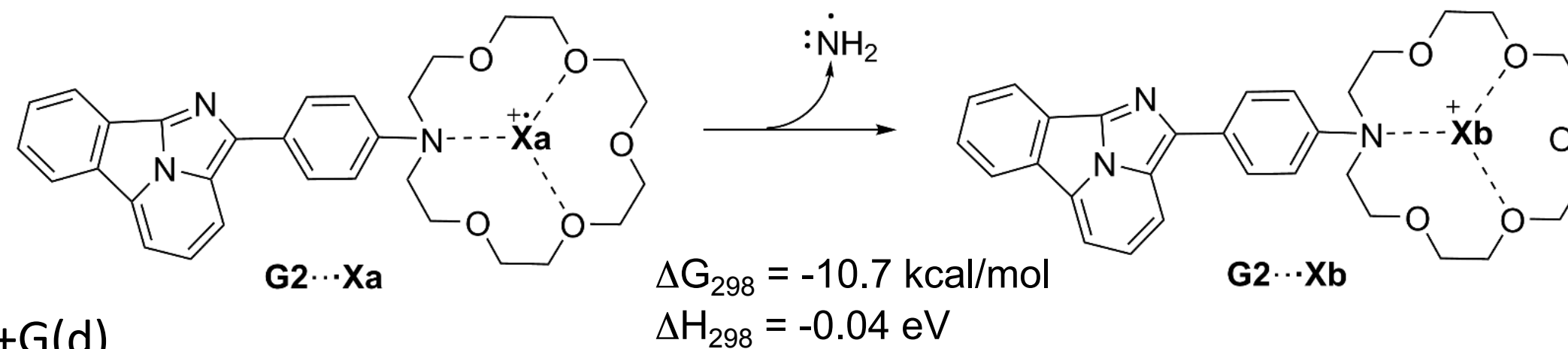
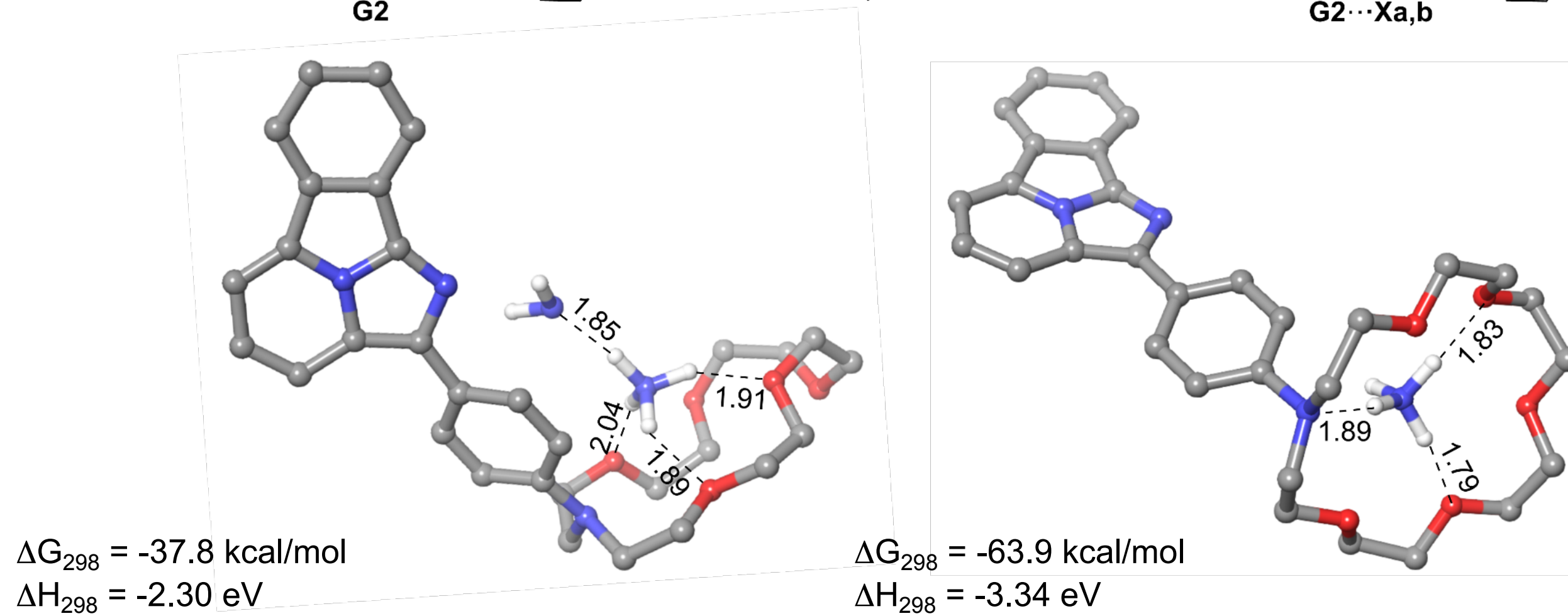
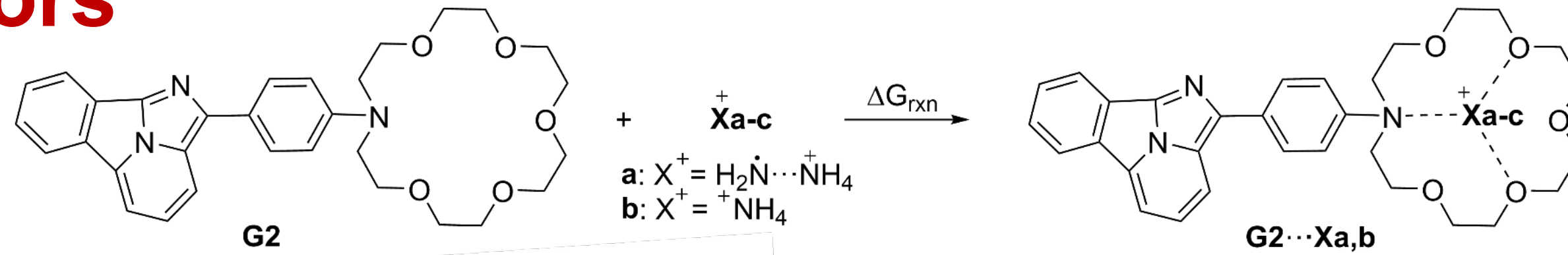
Chemistry, thermodynamics and synthesis behind the molecular route.

CH₃-NH₄⁺ as reagent



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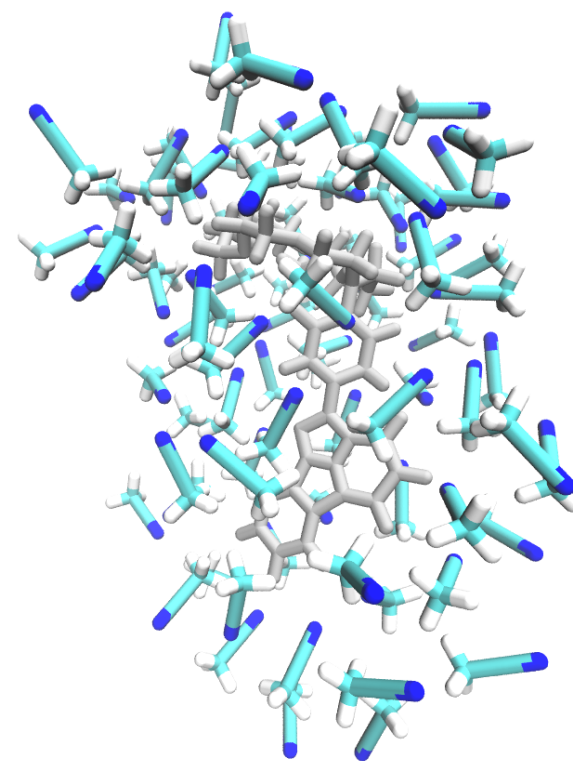
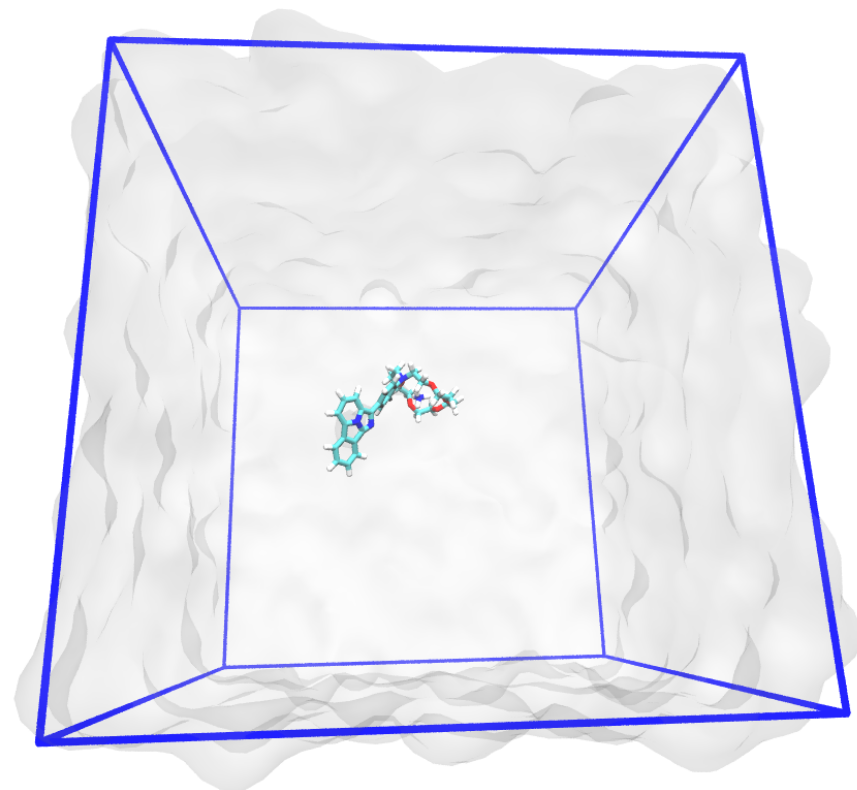
Fluorescent Bicolor Indicators as ITACA Sensors



$\omega\text{b97XD(SCRF, ACE)}/6\text{-}311\text{++G(d)}$

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 Cossío

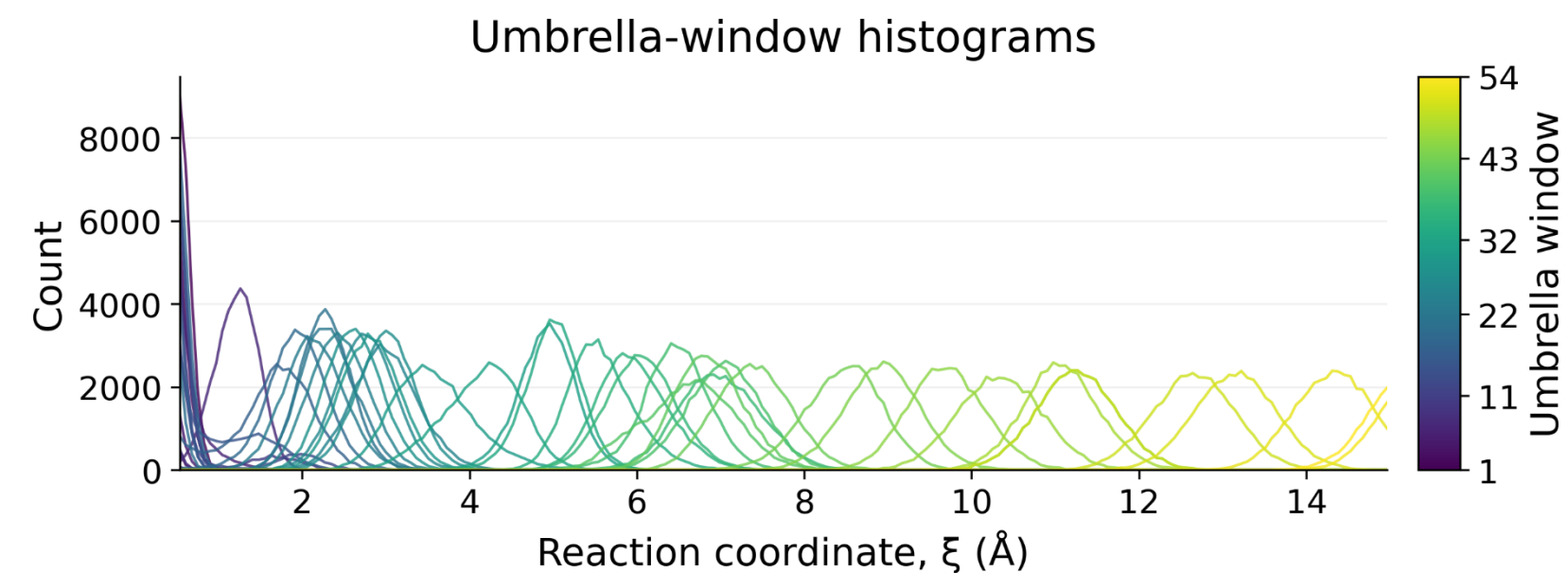
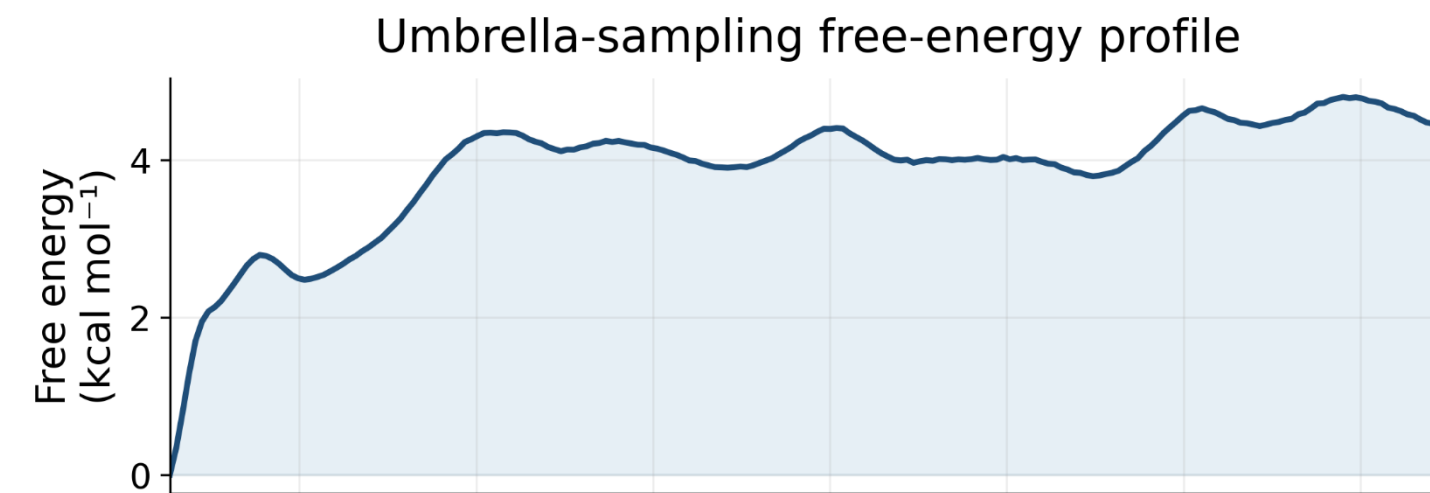
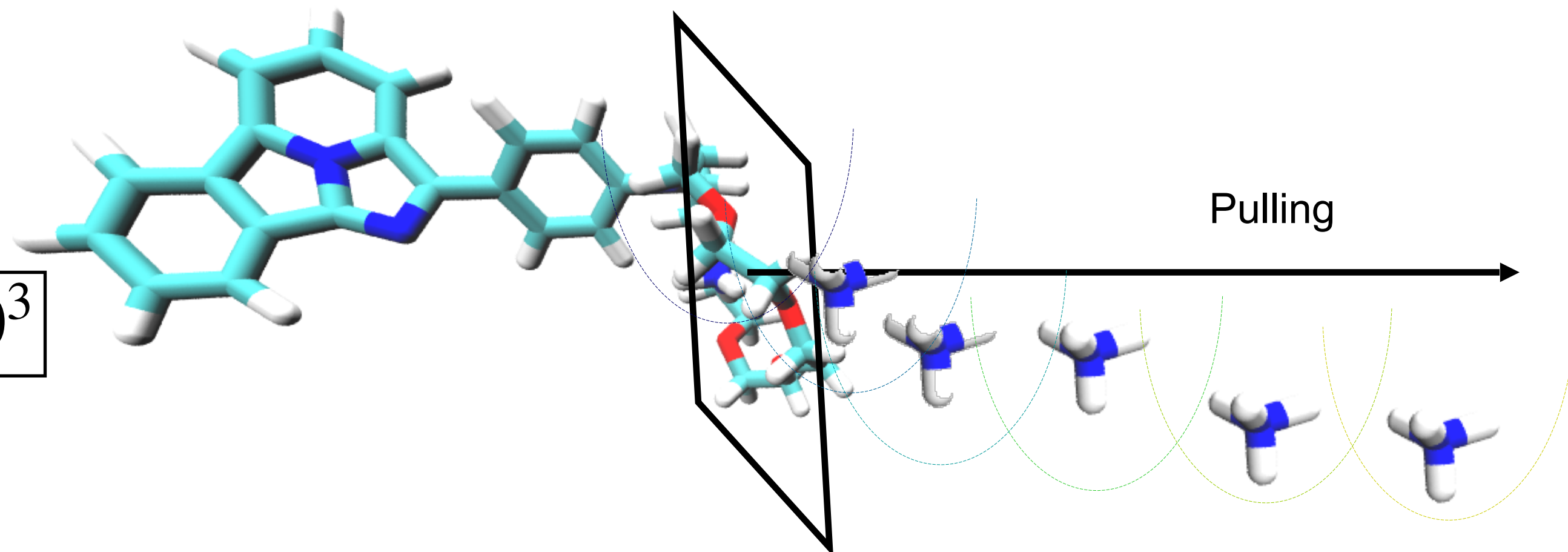
Umbrella Sampling simulations



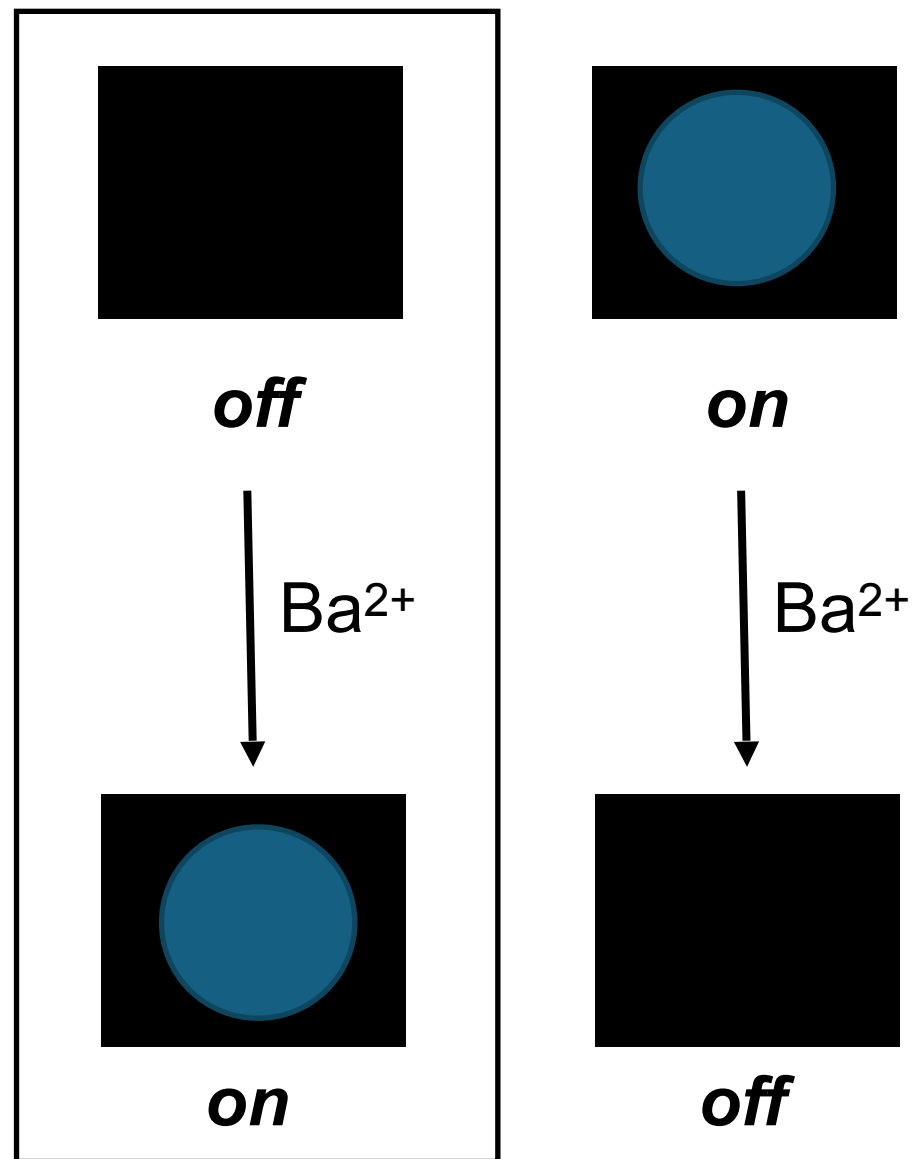
Simulated system

- G2 & NH_4^+ : GAFF + MK charges wb97xd/6-311++g(d,p)
- ACN: GAFF
- PF_6^- : OPLSAA

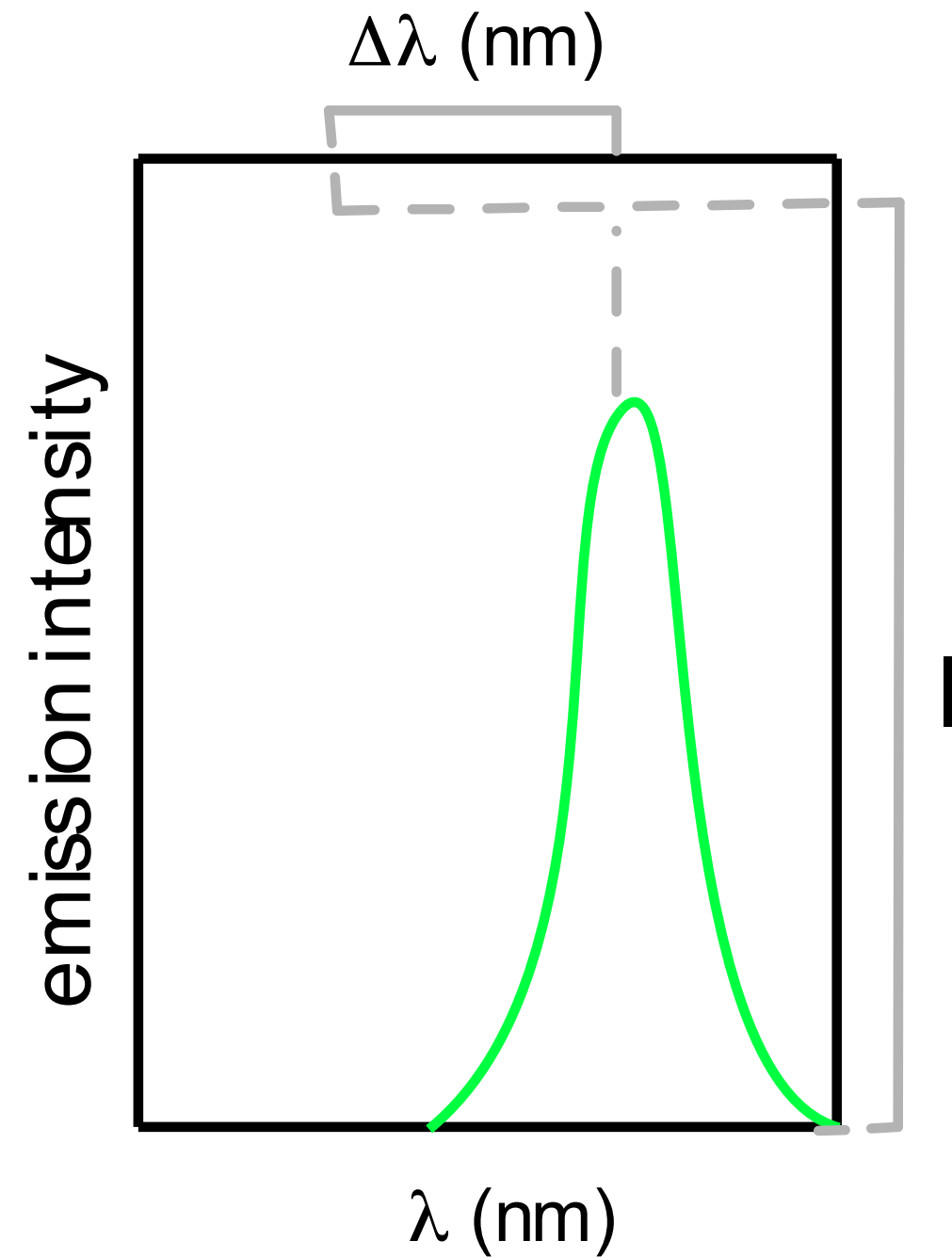
$$K = e^{\Delta G/RT} \approx 1.2 \cdot 10^3$$



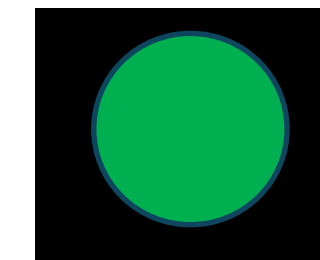
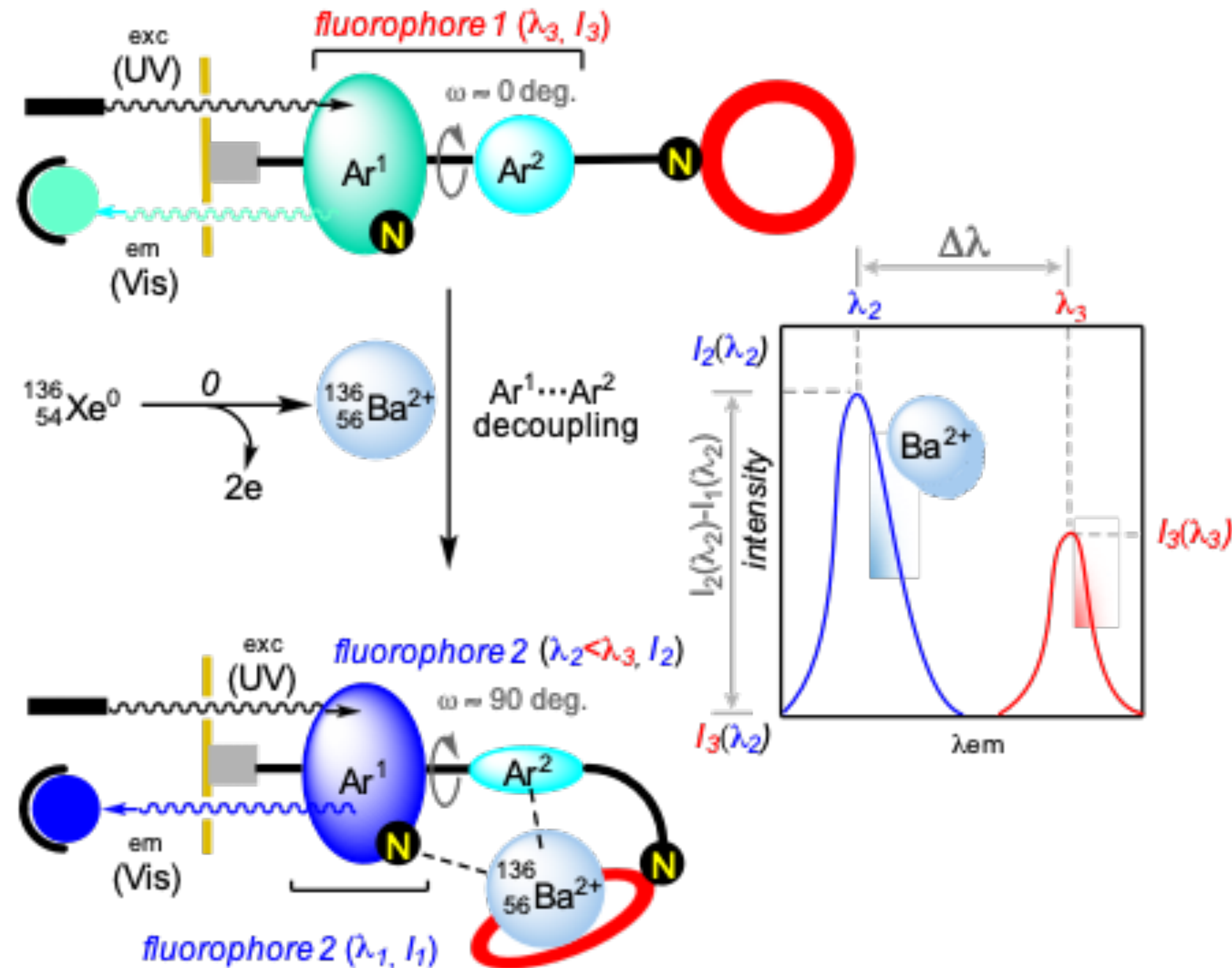
FMI (Fluorescent Monocolor Indicators) vs FBI (Fluorescent Bicolor Indicators)



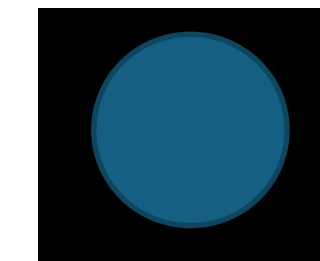
FMIs



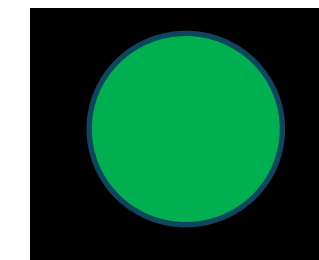
FMI (Fluorescent Monocolor Indicators) vs FBI (Fluorescent Bicolor Indicators)



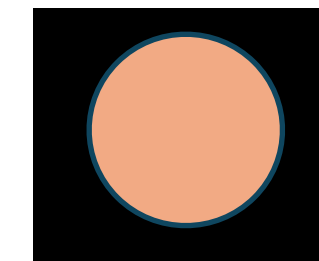
on



on'
(blue shift)



on



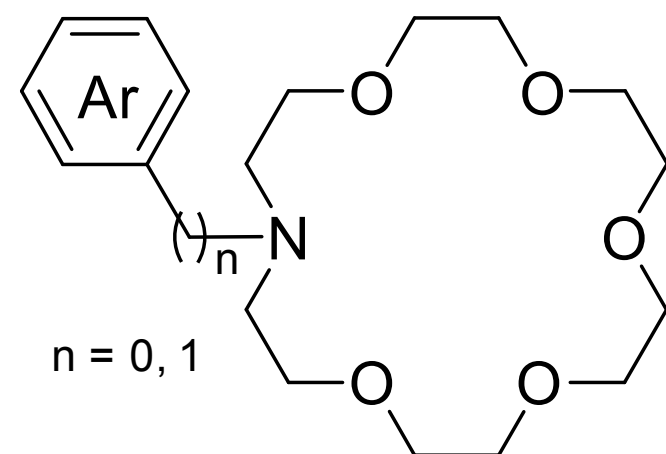
on'
(red shift)

FBIs

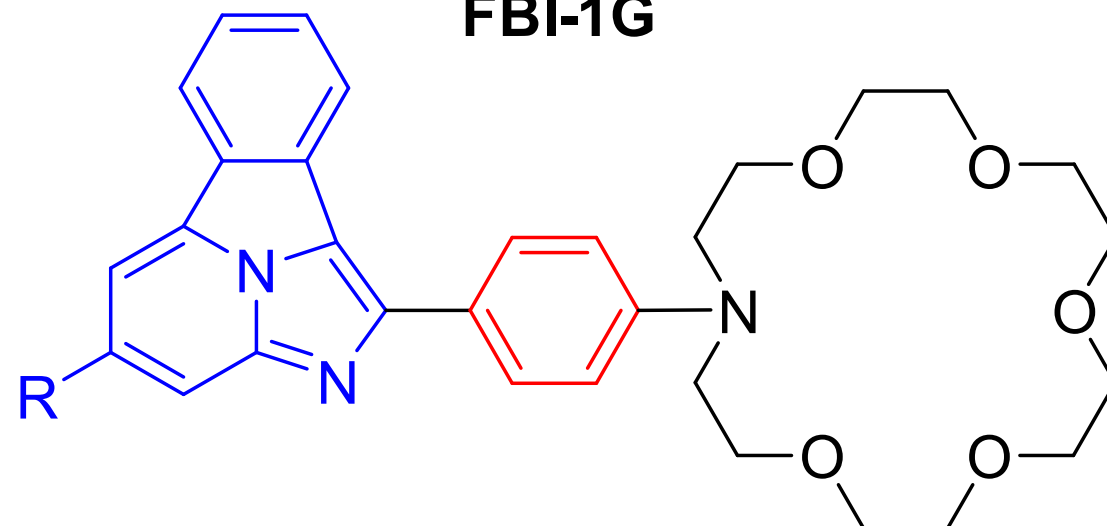
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FMI/FBI Series

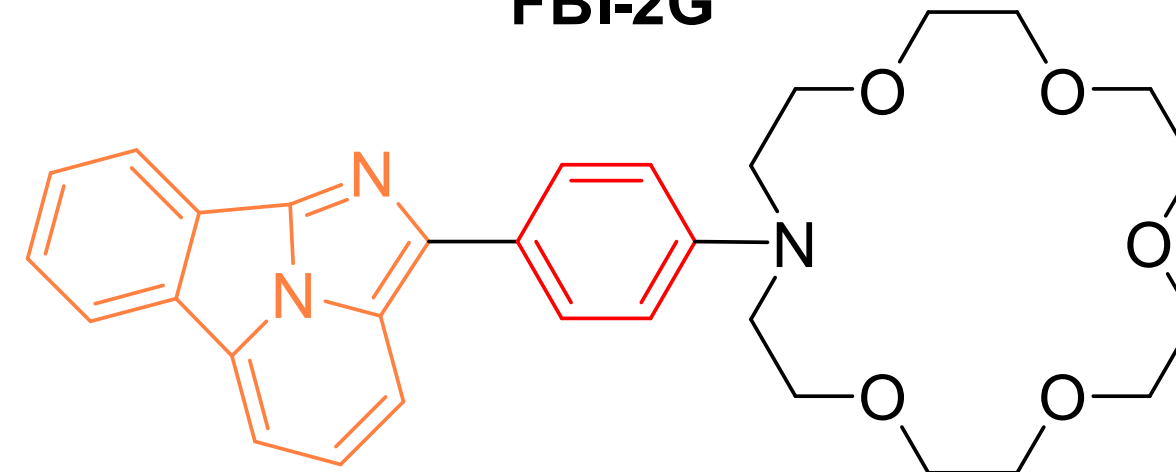
FMI



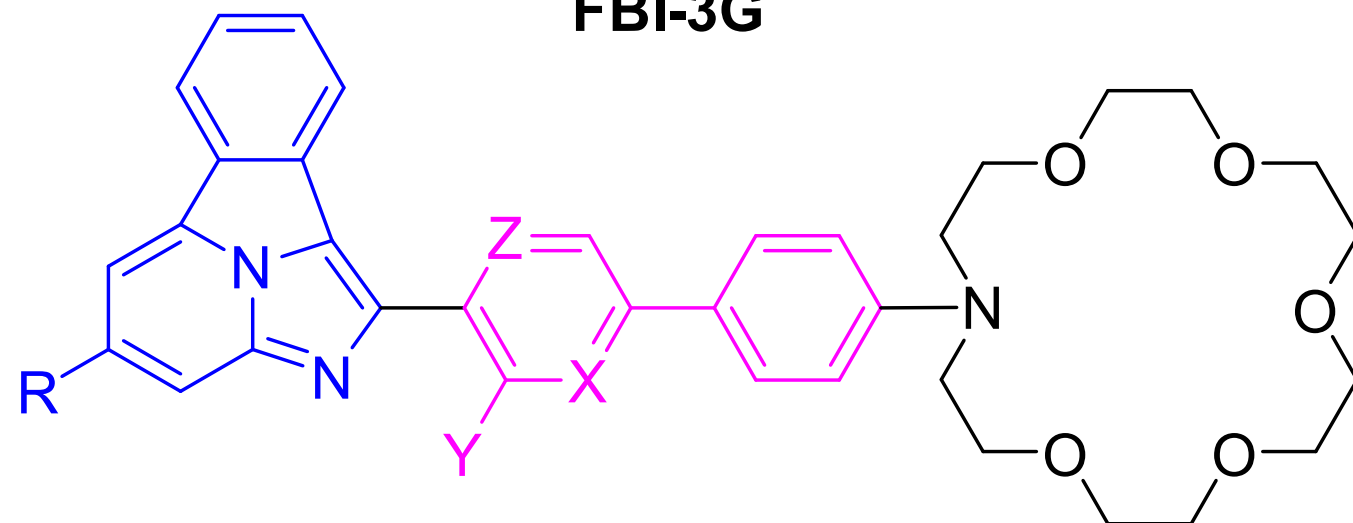
FBI-1G



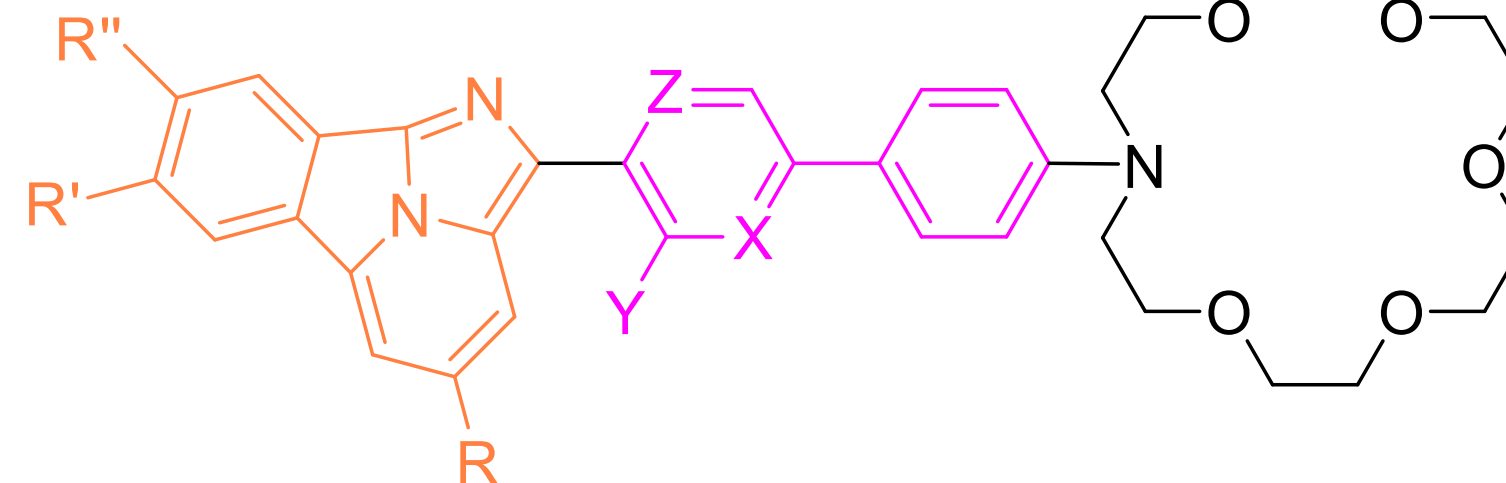
FBI-2G



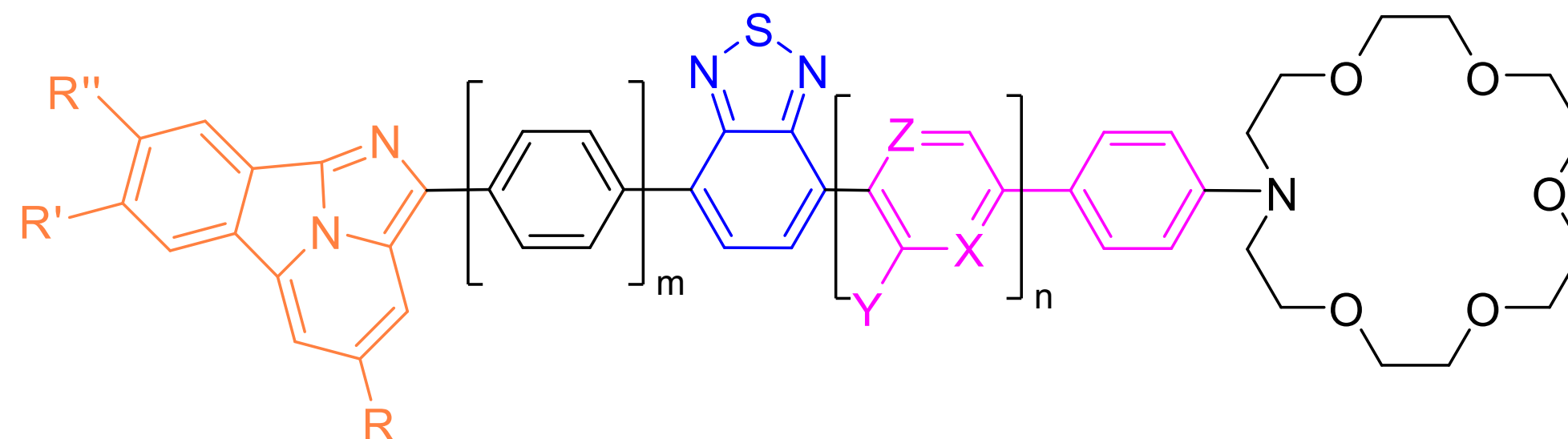
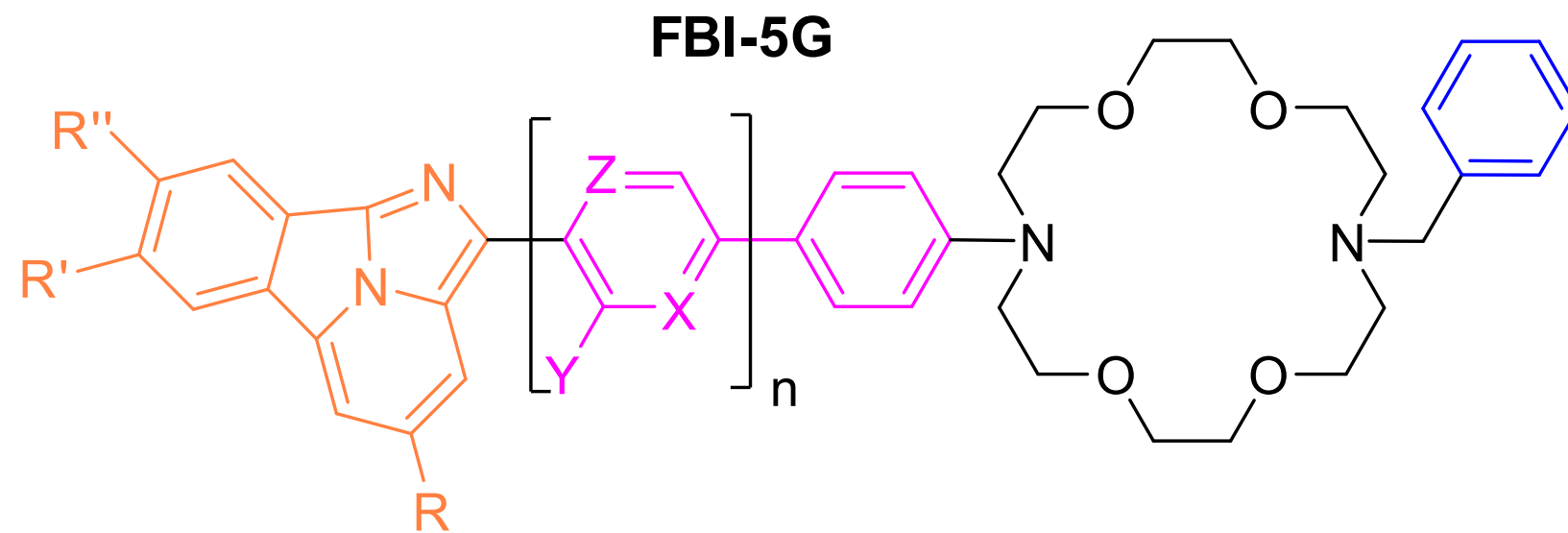
FBI-3G



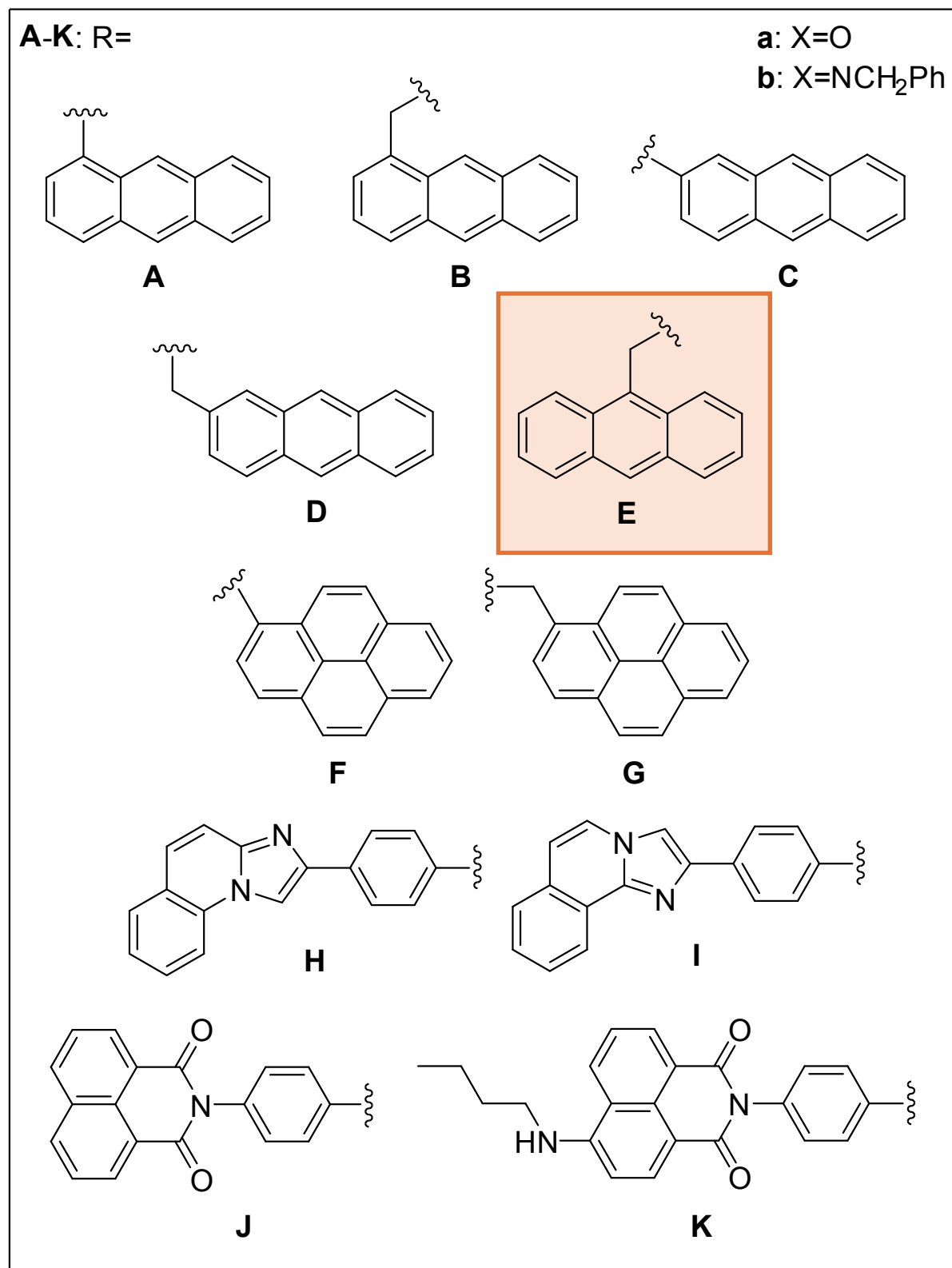
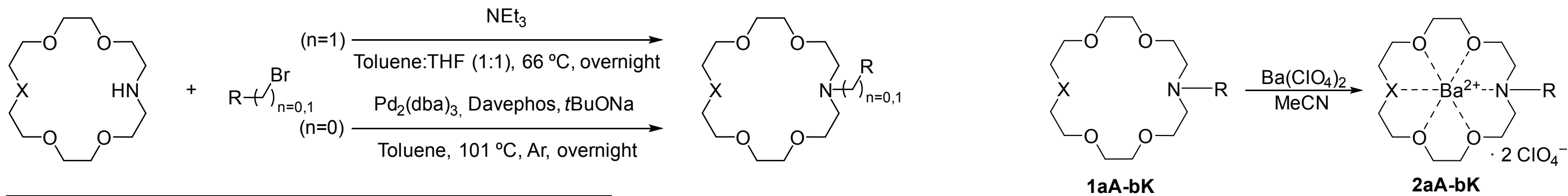
FBI-4G



FBI-6G



Chemical Synthesis of Selected FMIs

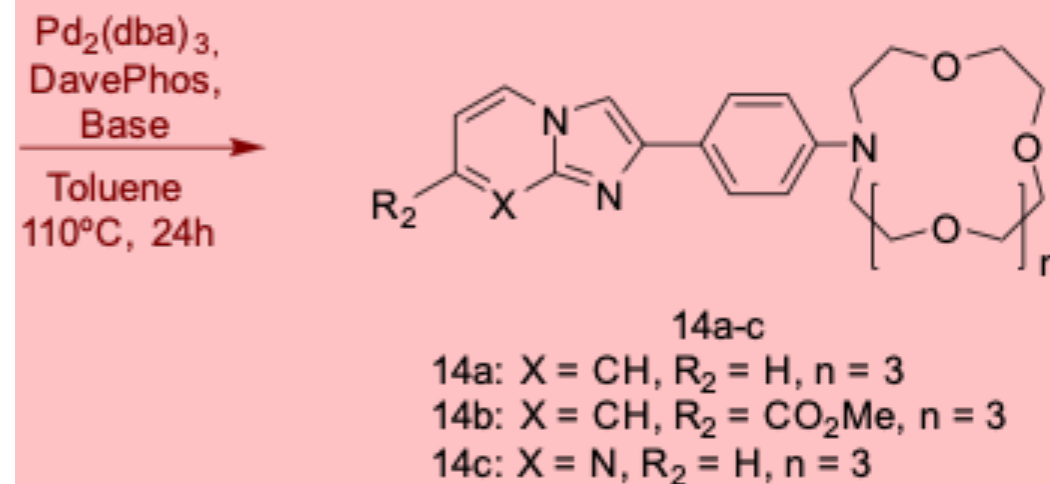


Comp.	ϕ_{lexc} (free)	ϕ_{lexc} (·Ba ²⁺)	$\lambda_{\text{exc. max}}$, (nm)	Emission max. λ (nm)	
				(free)	(·Ba ²⁺)
1aA	0.19	0.07	388	538	518
1aB	0.15	0.16	242, 262 , 386	482	482
1aC	0.16	0.21	339 , 424	510	500
1aD	0.14	0.22	270	460	450
1aE*	0.005	0.26	262 , 348, 366	391 , 413, 437	395 , 437, 413
1aF	0.57	0.23	240, 276, 342	447	429
1aG	0.007	0.05	350	387, 407	376, 396
1aH	0.21	0.14	304	532	498
1aI	0.38	0.33	250, 304	494	432

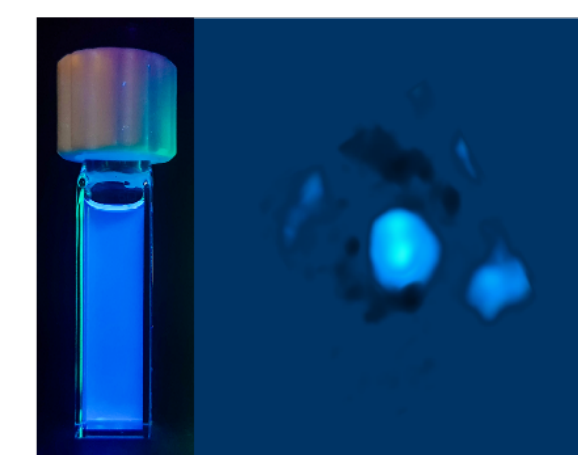
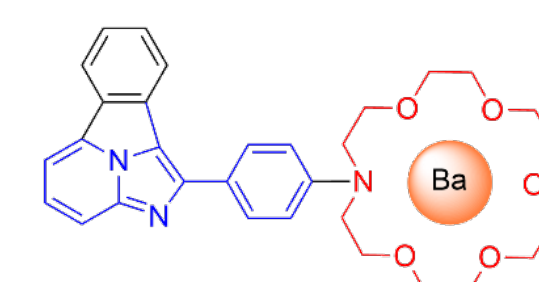
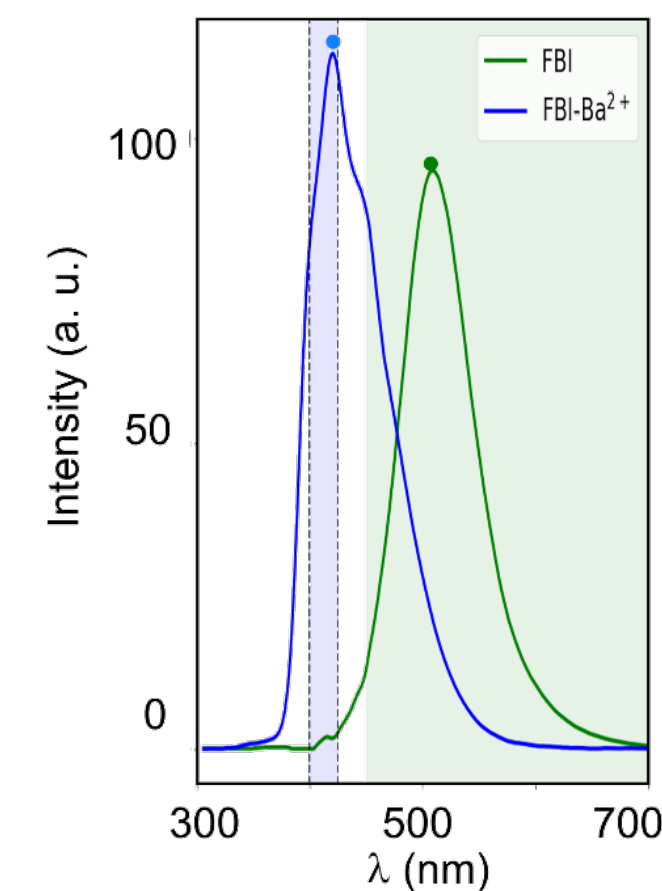
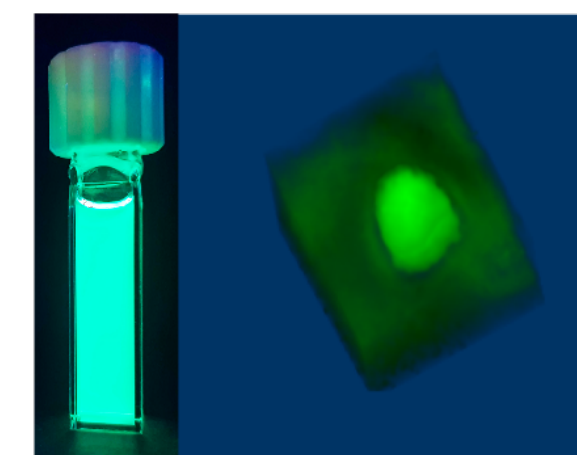
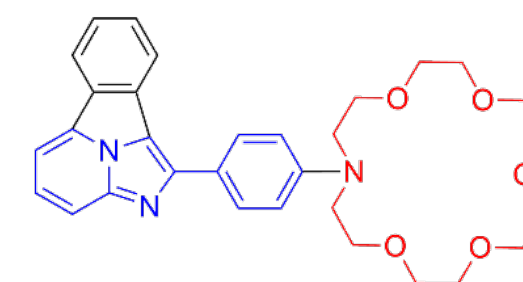
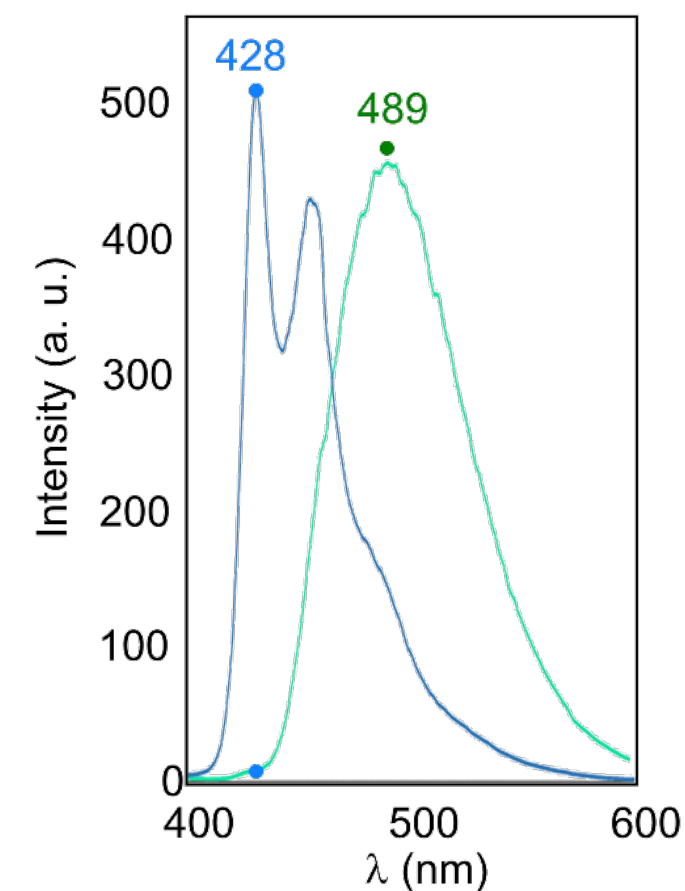
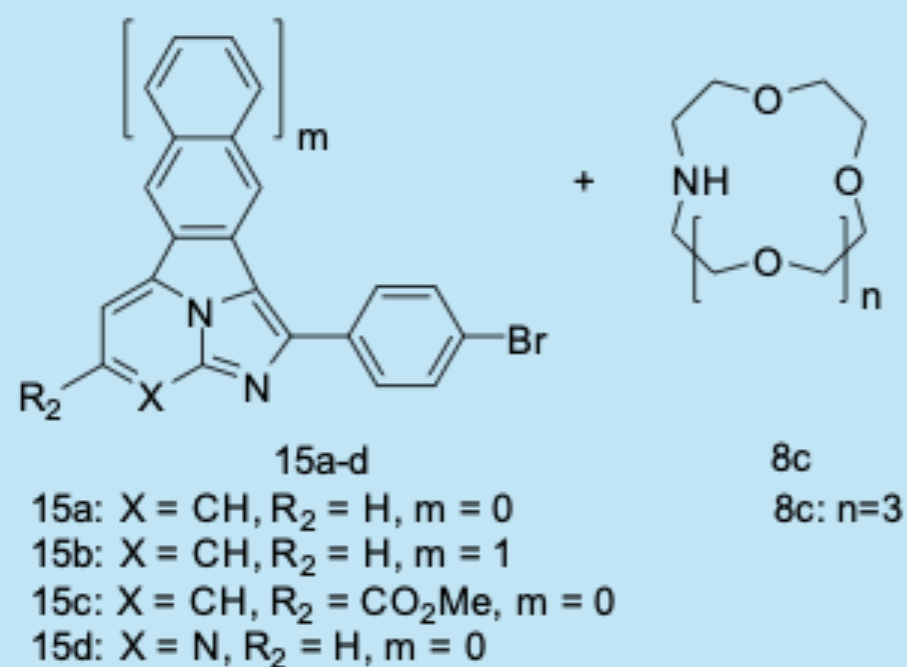
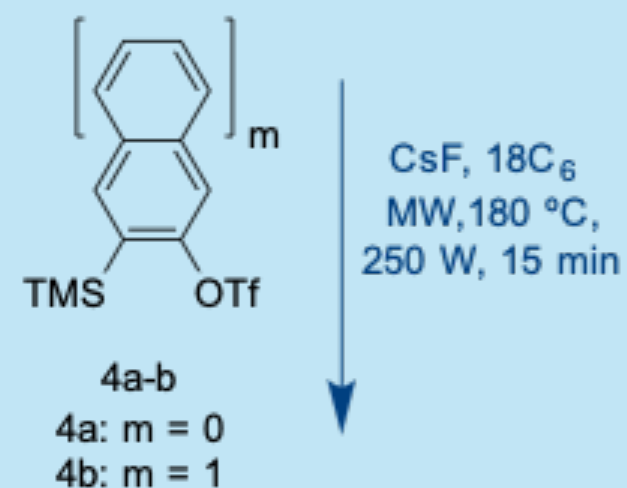
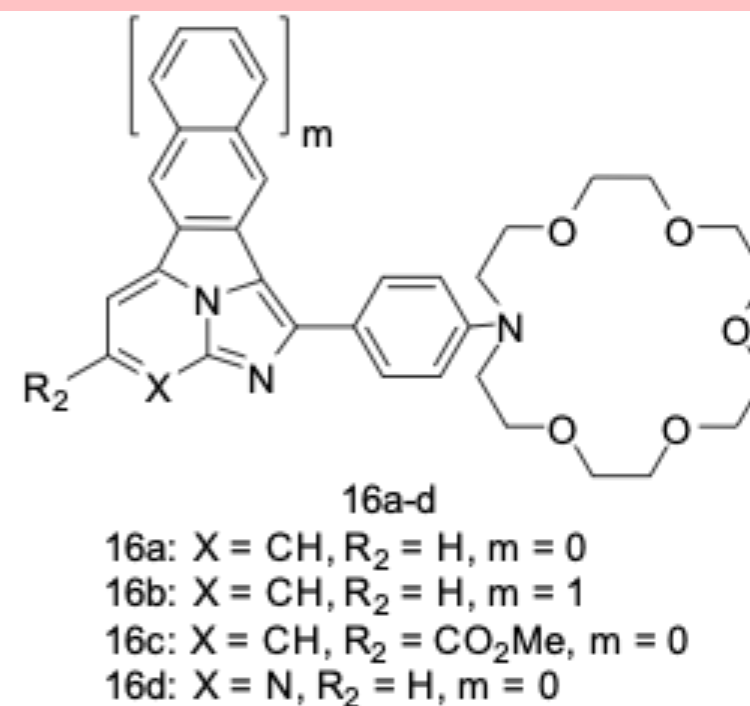
Quantum yields ϕ_{λ} , were recorded for lexc max. (*) Thapa, P. *et al.*, *Sci. Rep.* **2019**, 9, 15097. 10.1038/s41598-019-49283-x. 10.1021/acssensors.0c02104

(**) Thapa, P. *et al.*, *ACS Sensors* **2021**, 6, 192-202.

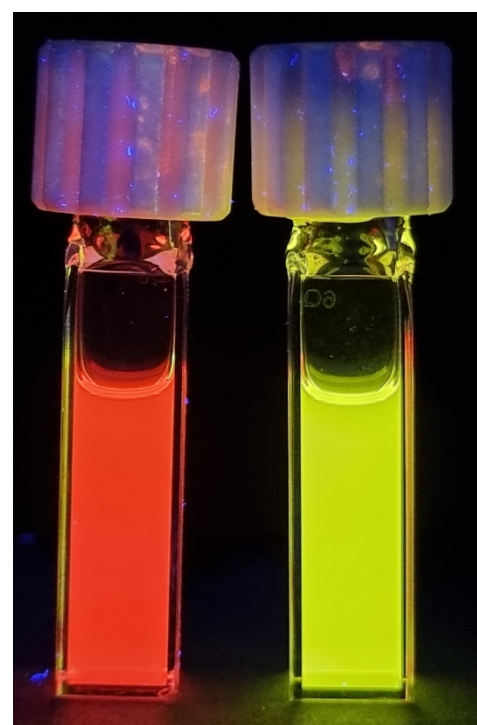
Chemical Synthesis of Selected FBIs (I)



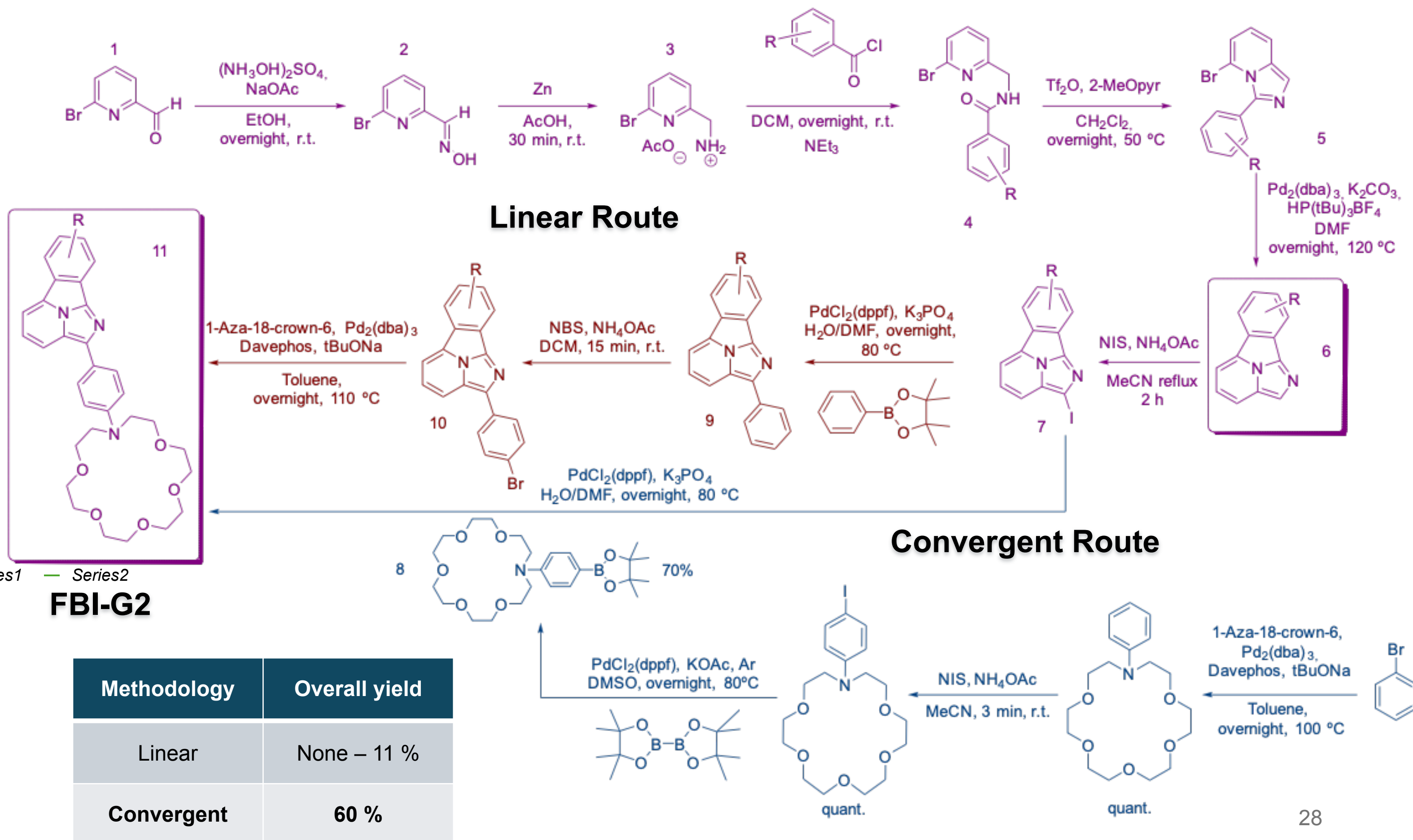
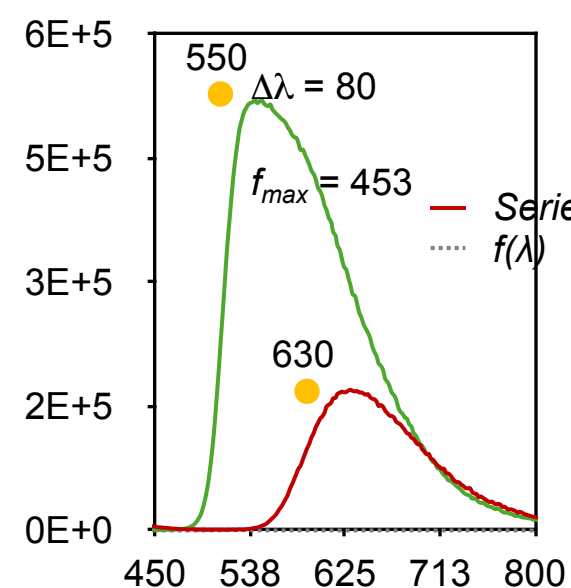
Route A



Chemical Synthesis of Selected FBIs (II)

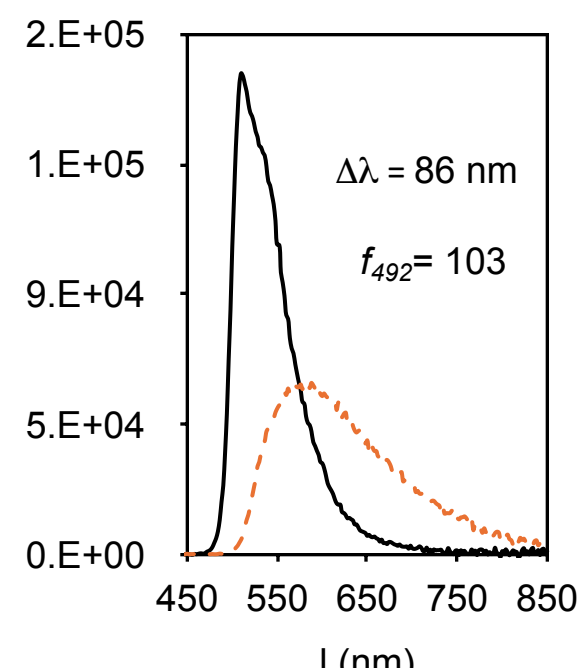
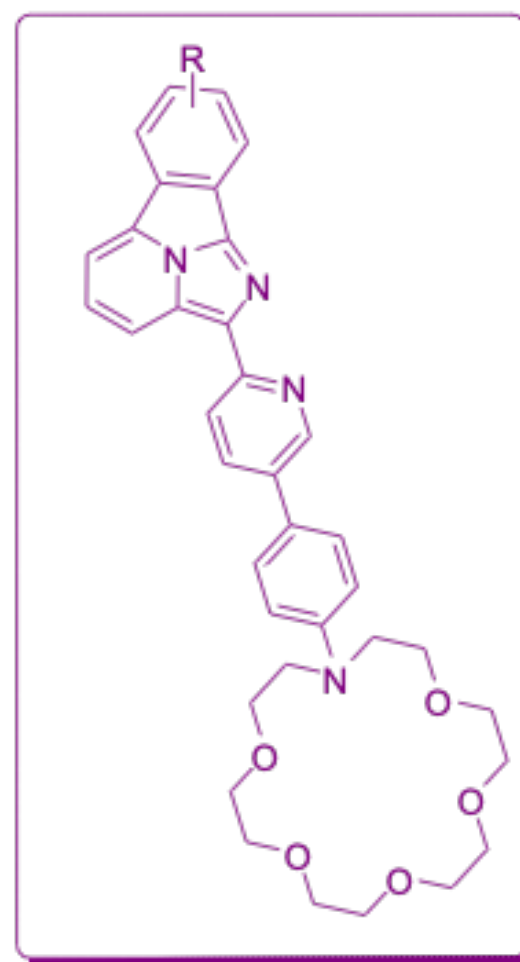


Ba²⁺
Free

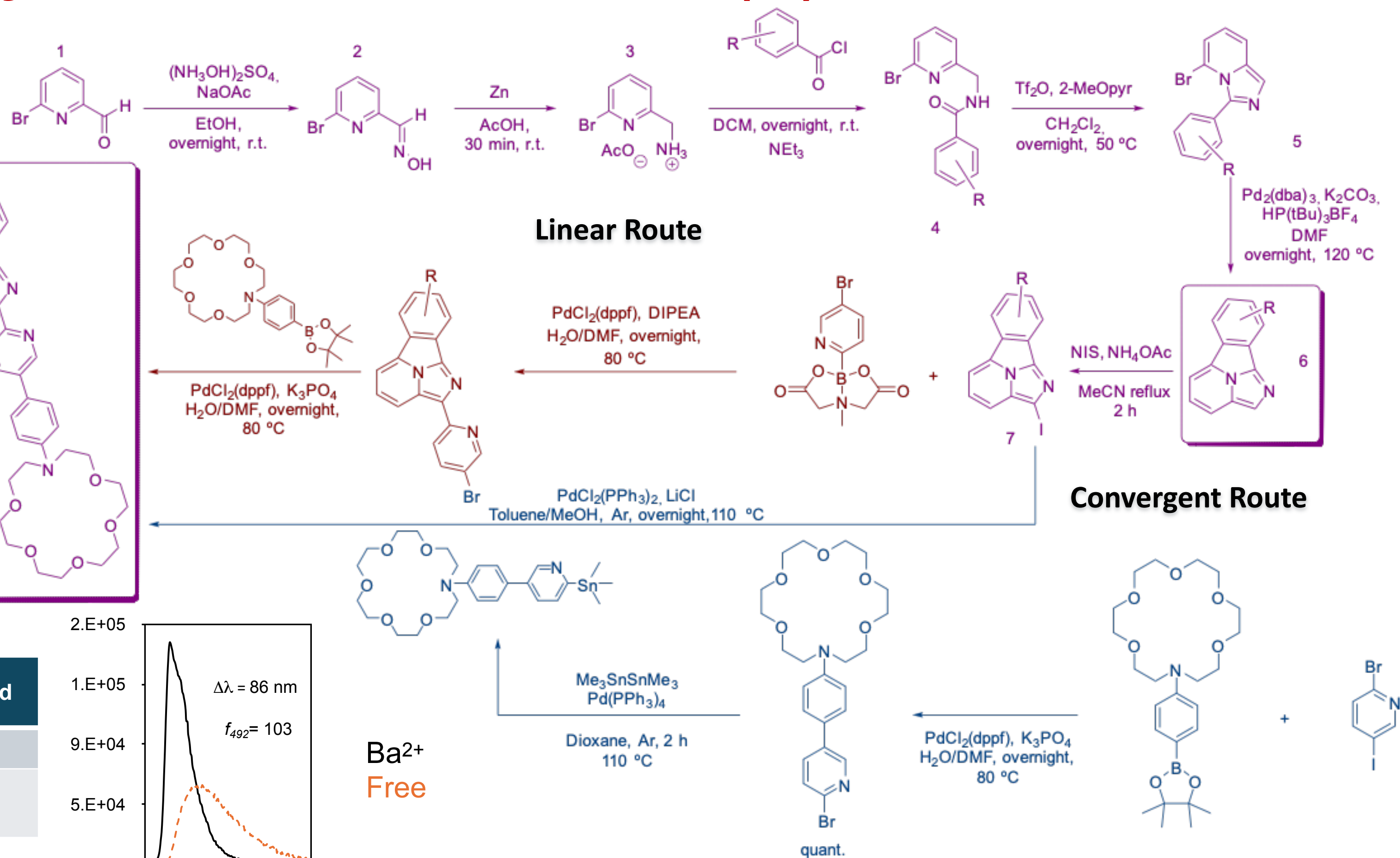


Chemical Synthesis of Selected FBIs (III)

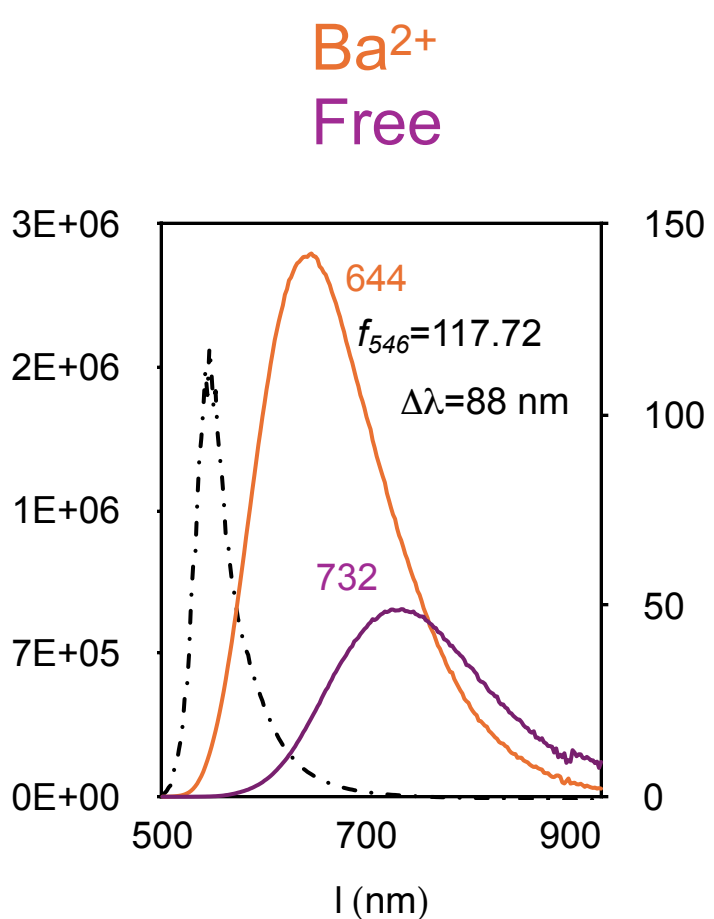
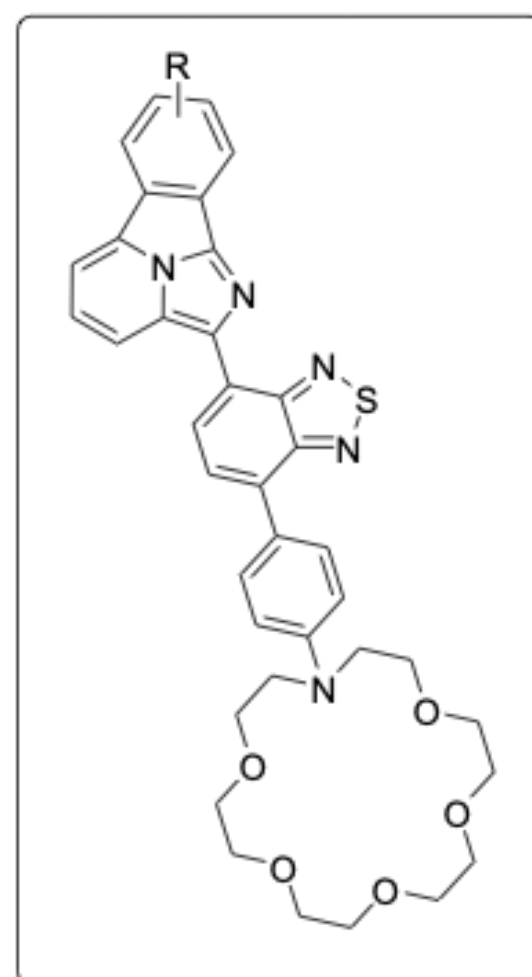
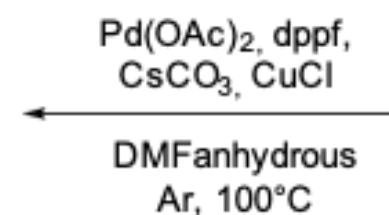
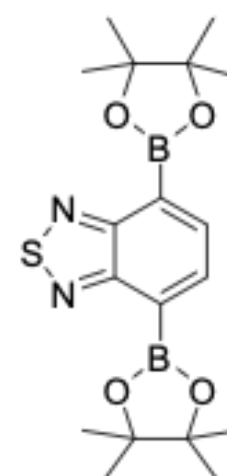
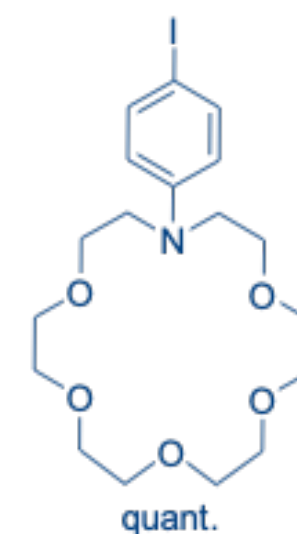
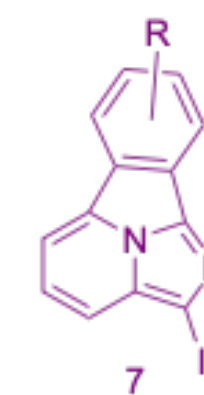
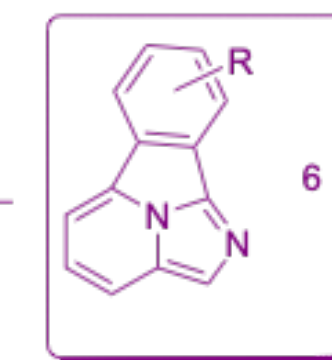
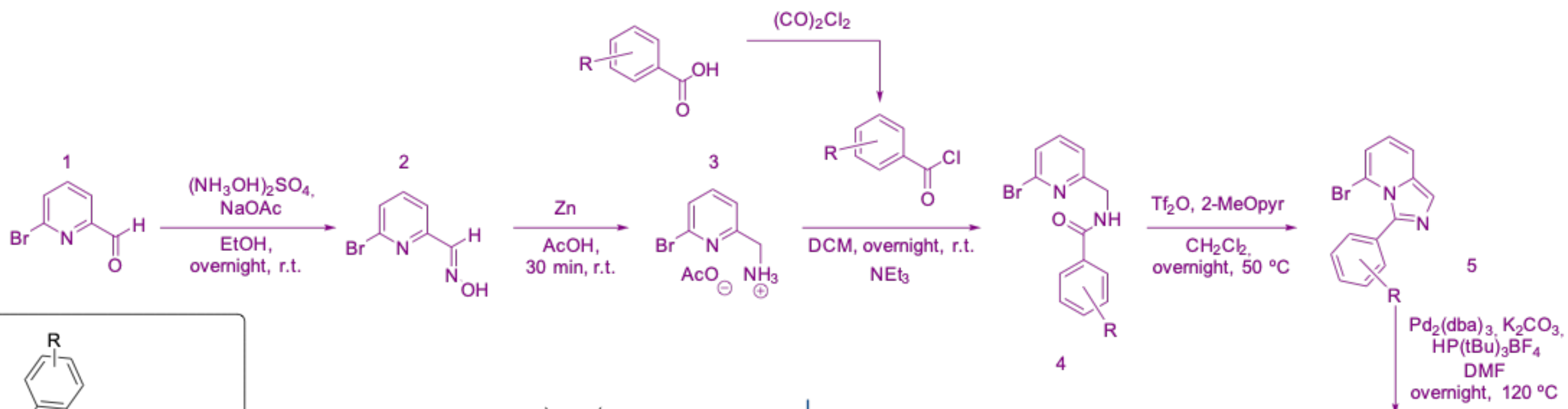
FBI-G4Py



Methodology	Overall yield
Linear	1 to 8 %
Convergent	55 to 60 %



Chemical Synthesis of Selected FBIs (IV)



Methodology	Overall yield
Convergent	40 %

