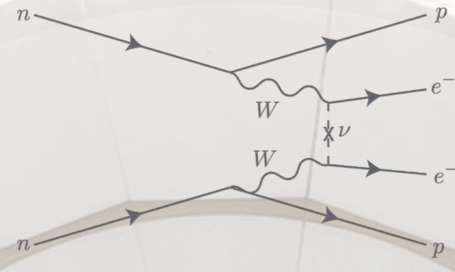


Status and prospect of the NEXT experimental program

Krishan Mistry on behalf of the NEXT collaboration

2nd December 2023

DBD 2023, Waikoloa Village, Hawaii

krishan.mistry@uta.edu

Neutrino Experiment with a Xenon TPC (NEXT)

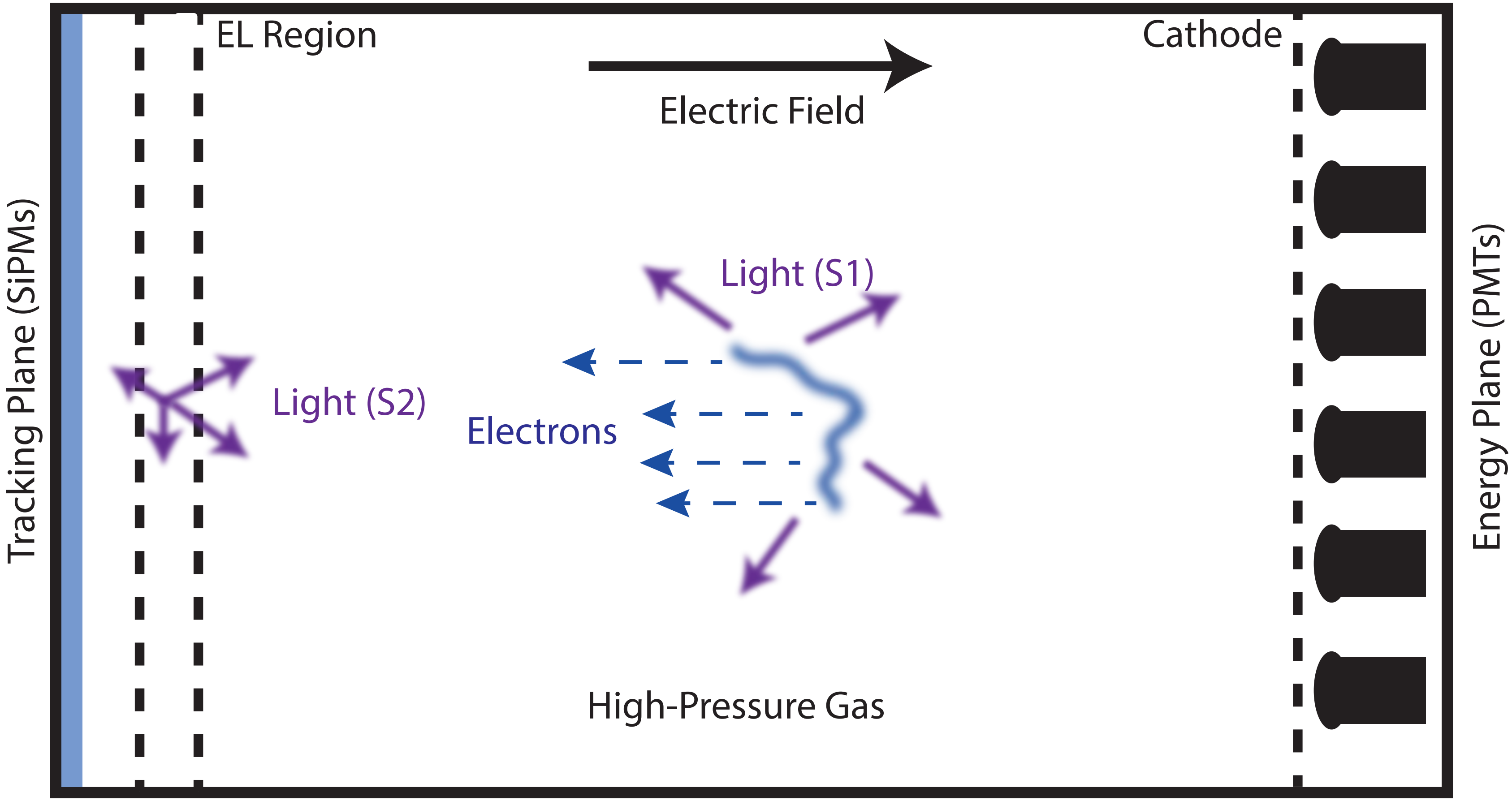
0νββ experiment with a high-pressure gaseous TPC using
$^{136}Xe \rightarrow {}^{136}Ba^{2+} + 2e^{-}$ (2.5 MeV)

NEXT is an international collaboration

The experiment is being hosted at the Canfranc Underground Lab in the Spanish Pyrenees

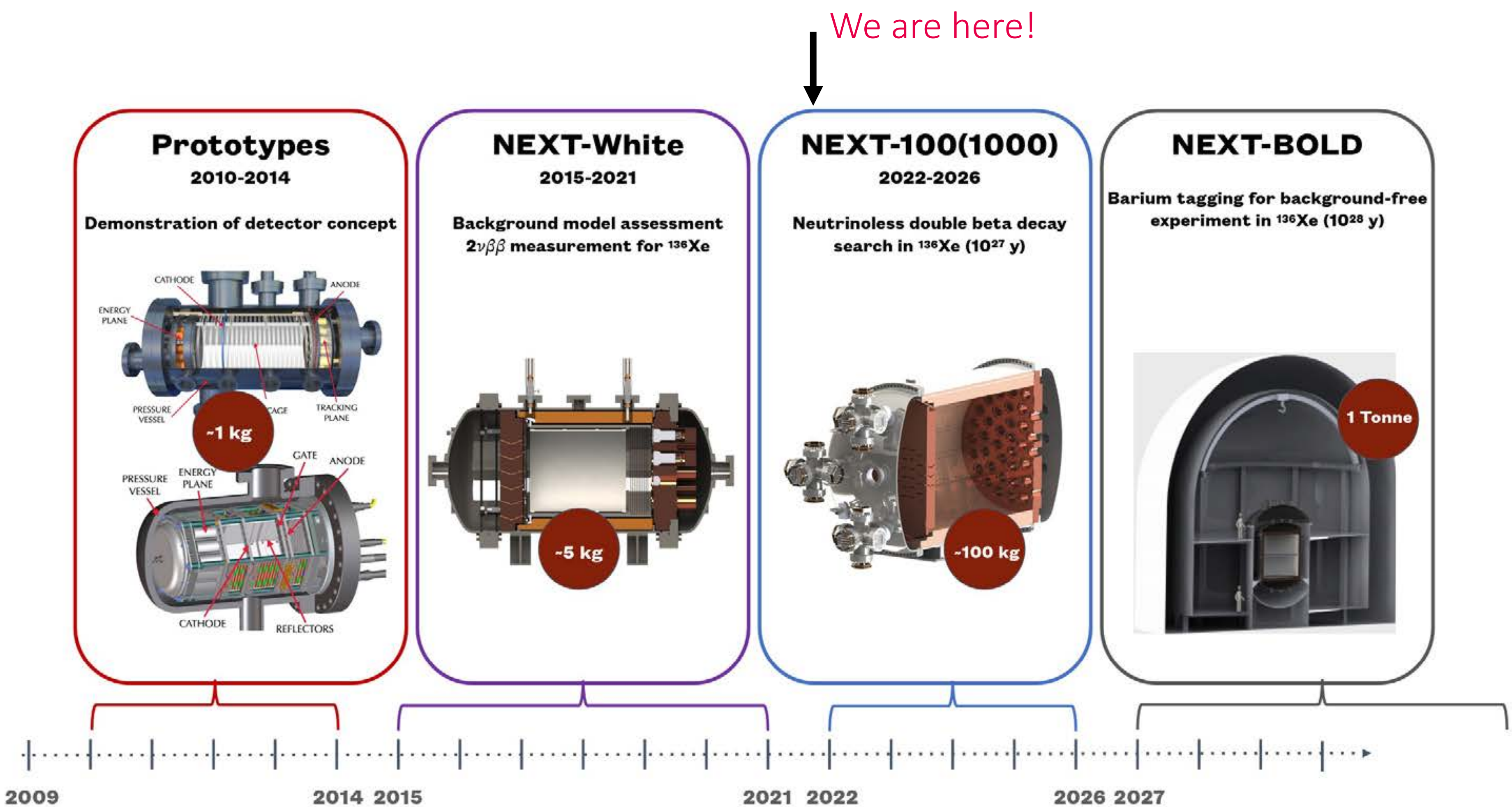
The Detector Concept

- High-pressure gas TPC with electroluminescent amplification
  - Sub-percent energy resolution
  - $0\nu\beta\beta$ tracks are about 20 cm long in 10 bar → Tracking!



The NEXT Program

- Series of High Pressure Gaseous Xenon Time Projection Chambers with a rich R&D program
  - NEXT-100 is the latest experiment and is in the final stages of construction!



The NEXT-White Experiment

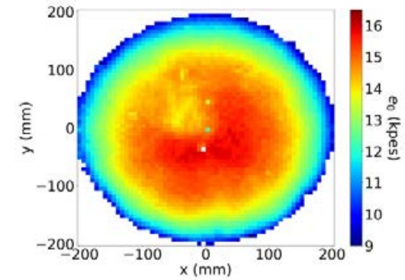
JINST 13 P12010 (2018)

Calibration in NEXT

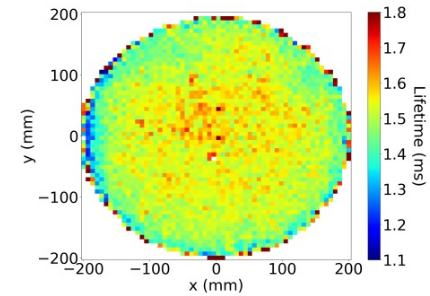
- NEXT uses several radioactive sources to calibrate the detector

- Low energy: ^{83m}Kr (short half-life ~1hr)
  - Point-like depositions (41.5 keV) uniformly distributed throughout the active volume
  - Calibration maps generated for geometrical and lifetime corrections
  - Continuous monitoring of detector conditions

Geometric Corrections

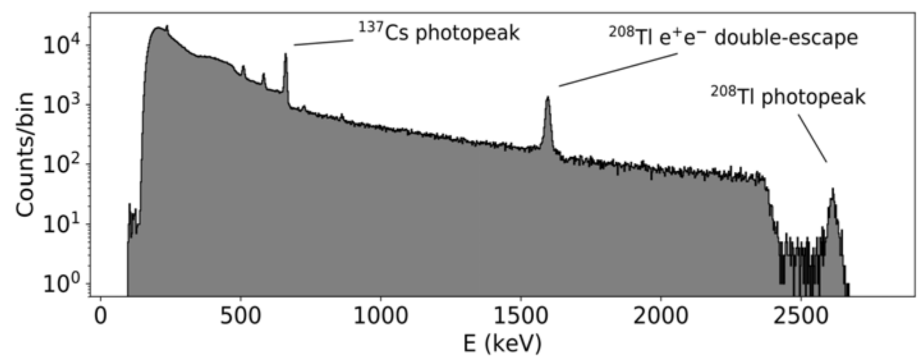


Lifetime Corrections



JINST 13 (2018) no.10, P10014

- High energy: ^{208}Tl (2615 keV) and ^{136}Cs (662 keV):
  - Energy resolution at Q value
  - Energy scale
  - Energy resolution vs E



JHEP 10 (2019) 230; JINST 13 (2018) no.10, P10020

Topology reconstruction

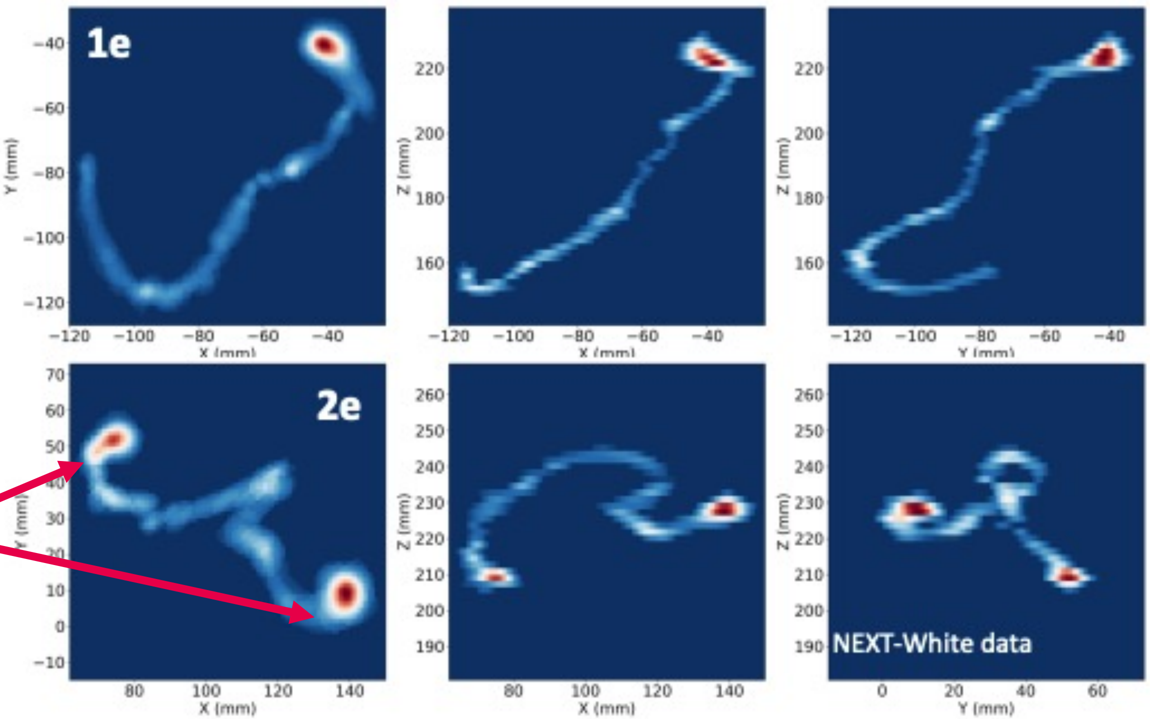
Gammas produced from natural radioactive decay chains near signal region (Q = 2.458 MeV)

- ^{208}Tl $\rightarrow \gamma$ at 2.614 MeV
- ^{214}Bi $\rightarrow \gamma$ at 2.447 MeV

Reconstruction of the topology allows for effective rejection of single electron events

- Richardson-Lucy deconvolution to improve track resolution
- "blobs" at end of tracks used to identify $2e^-$ vs $1e^-$

NEXT-White Data

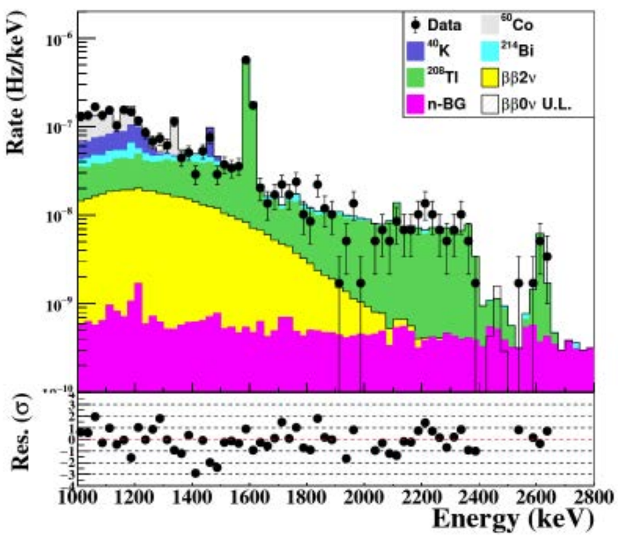


NEXT-White physics

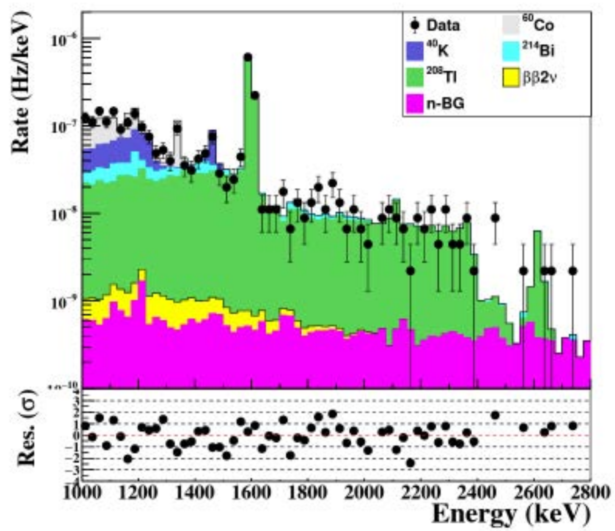
- Measurement of the $2\nu\beta\beta$ half-life Phys. Rev. C 105, 055501
- Search for $0\nu\beta\beta$ with 3.5 kg of xenon at 10 bar
- Technique employed of using depleted xenon to estimate backgrounds is novel in the field of $0\nu\beta\beta$

Background-Model Dependent

^{136}Xe Enriched



^{136}Xe Depleted

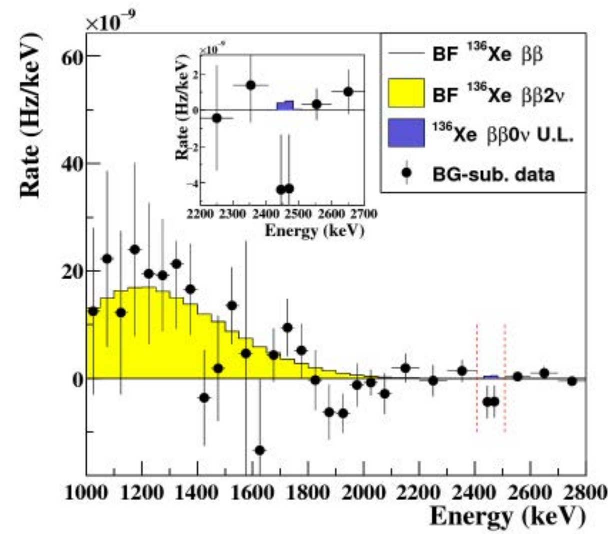


$T^{0\nu}_{1/2} > 5.5\times10^{23}$ yr

J. High Energ. Phys. 2023, 190 (2023)

90% CL

Background-Subtraction



$T^{0\nu}_{1/2} > 1.3\times10^{24}$ yr

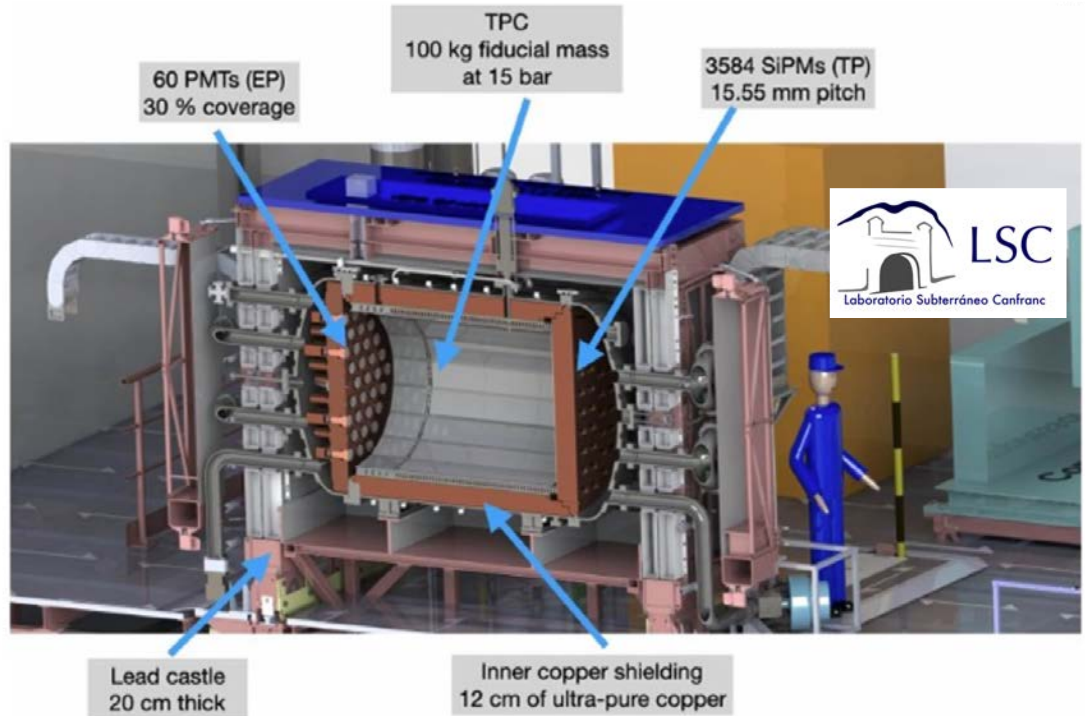
90% CL

The NEXT-100 Experiment

NEXT-100

J. High Energ. Phys. 2016, 159 (2016)

- Scales up NEXT-White by a factor of two consisting of ~100 kg xenon
- Detector 1 m diameter with 1.3m drift length
- Muon veto to reduce cosmogenics



Goals:

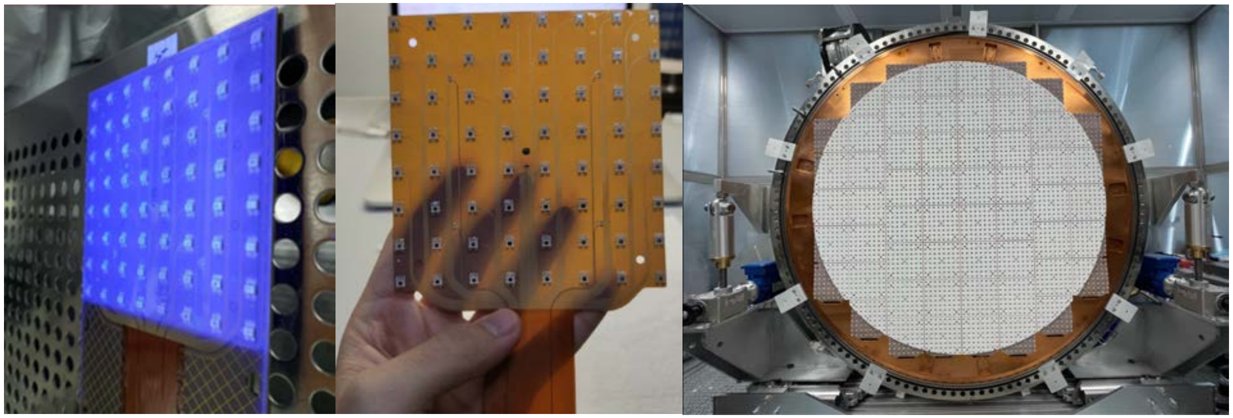
- Energy resolution <1% FWHM
- Improved radioactive budget at 1 count/yr in the ROI
- Competitive search for $0\nu\beta\beta$
- Prepare for tonne-scale

NEXT-100 Assembly

Stainless-steel pressure vessel + lead castle for shielding

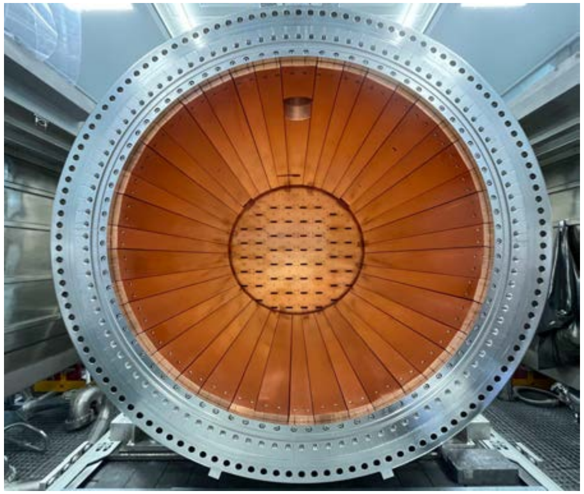
PMT energy plane installation with sapphire pressure windows in final stages

SiPM tracking plane with Teflon masks



NEXT-100 Assembly

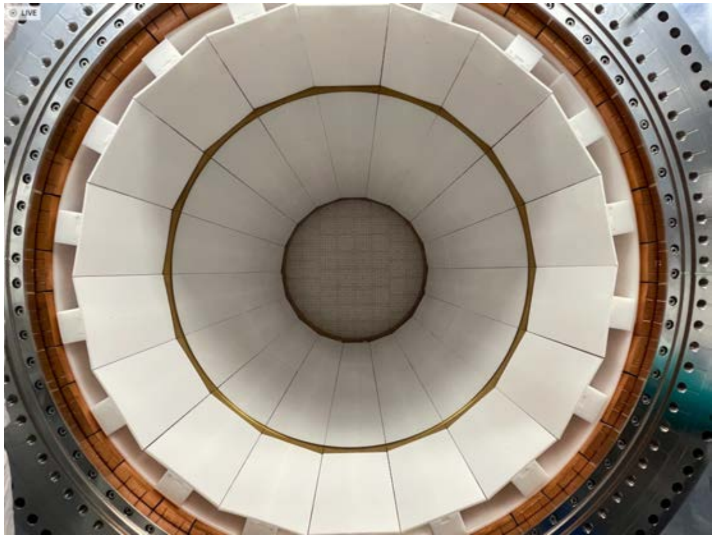
Inner copper shielding



Field cage assembled and inserted

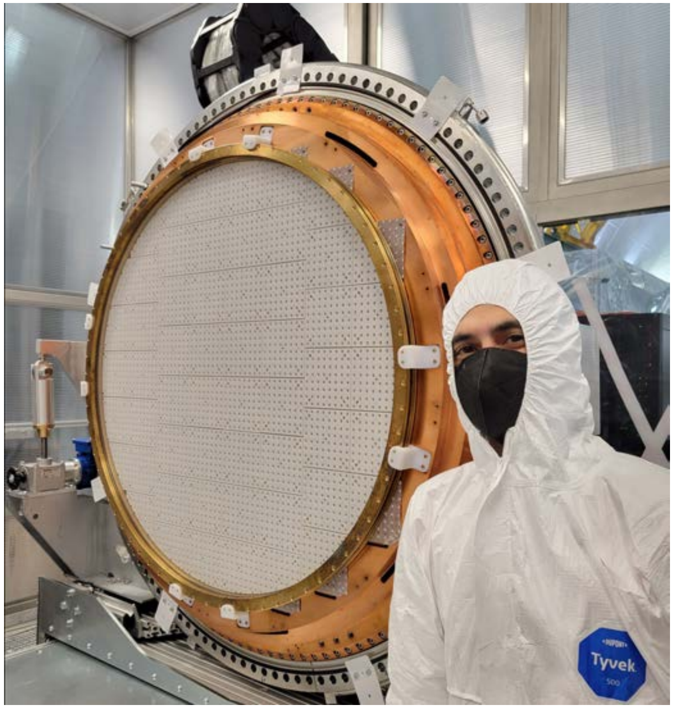
Field cage interior with transparent cathode

Teflon reflector panels with TPB



NEXT-100 Assembly

Electroluminescent region has been installed

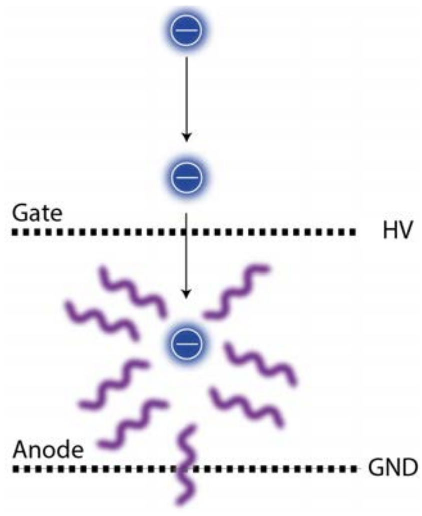


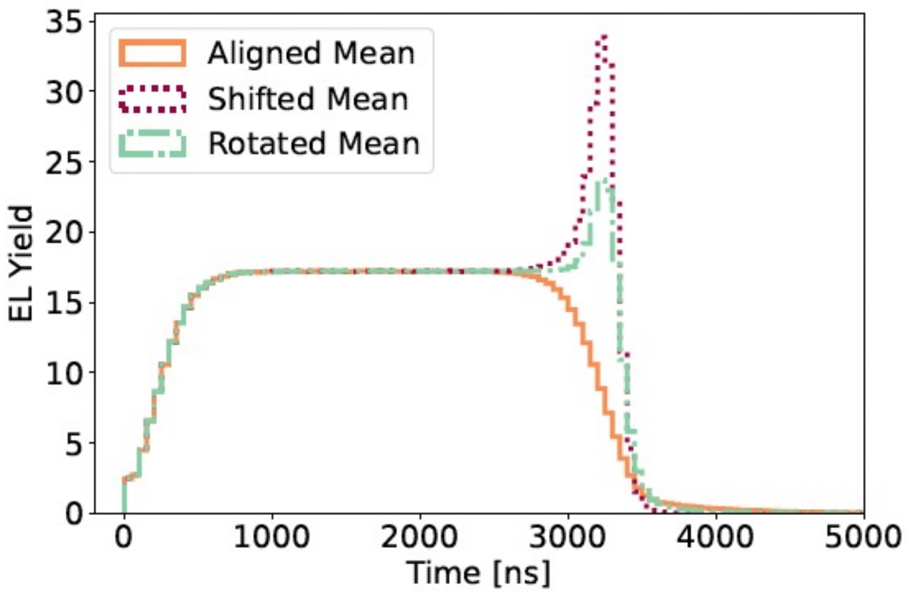
NEXT-100 is now completing the final stages of construction and will begin detector commissioning steps in 2024

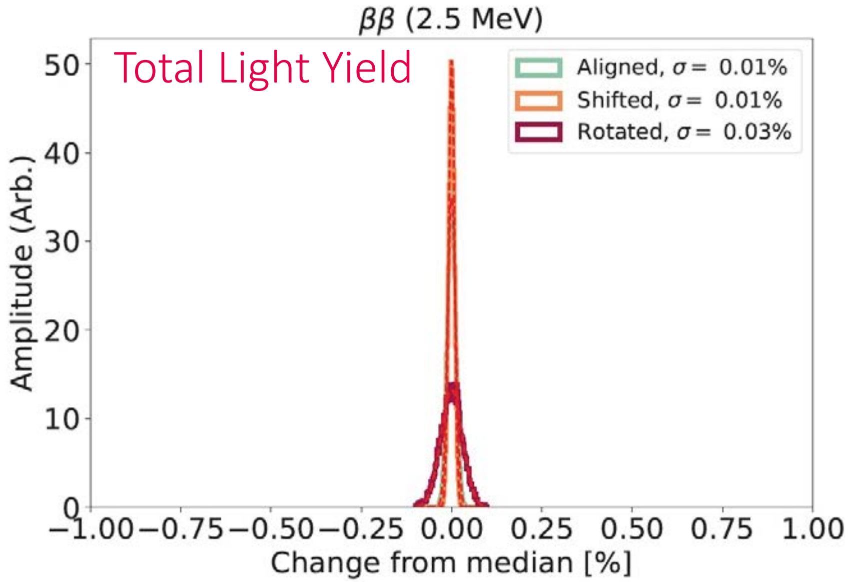
NEXT-100 EL Region

arXiv: 2311.03528

- Simulating electroluminescence accurately is important, we have improved our simulations!
  - EL emission timing profile shape is proportional to the electric field and depends on the mesh alignment
  - We find mesh alignment does not impact energy resolution significantly



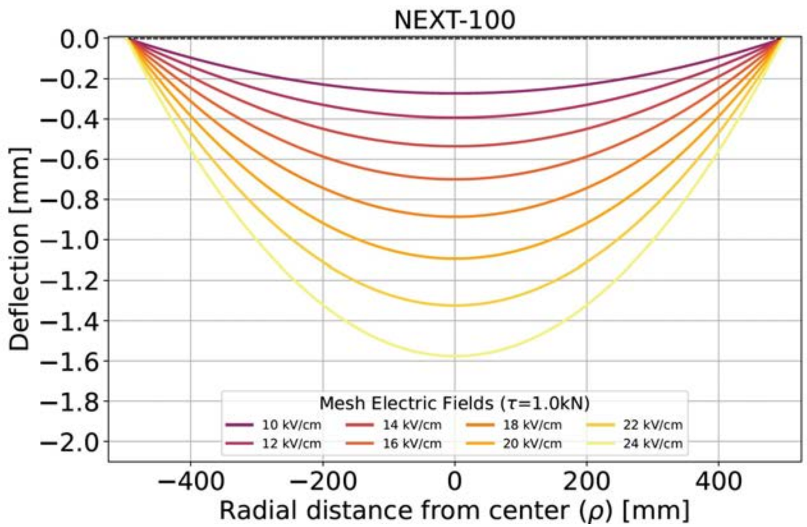


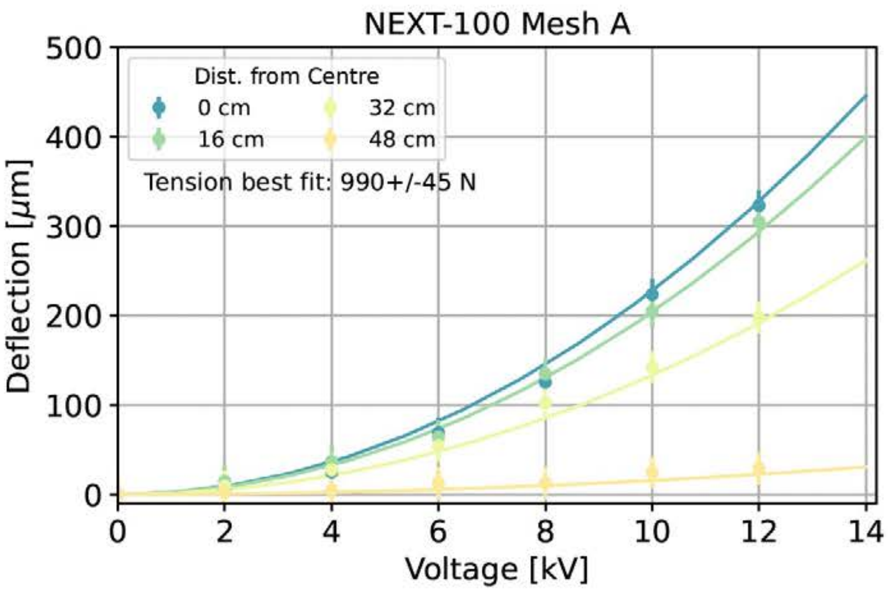


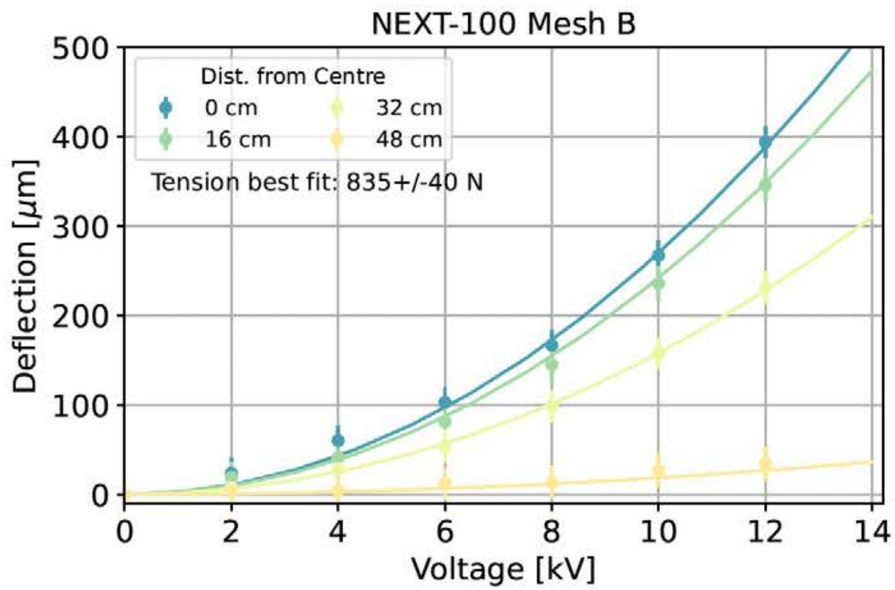
Electrostatic Deflection of EL

arXiv: 2311.03528

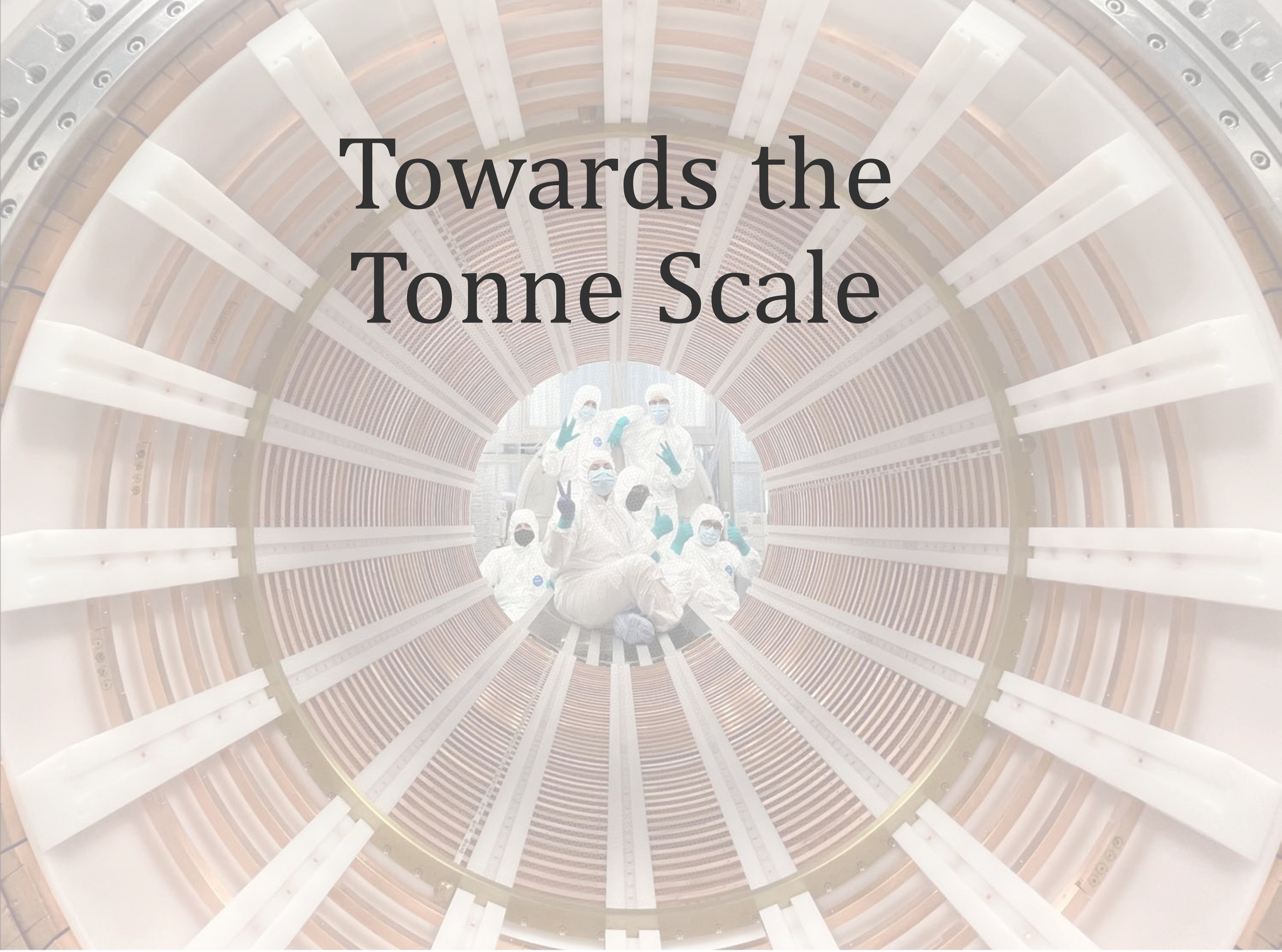
- Measurements of the electrostatic deflection NEXT-100 EL region just before installation were taken
- Handle of the expected deflection as a function of the field strength
  - Energy resolution is not expected to be impacted significantly for NEXT-100







Towards the Tonne Scale



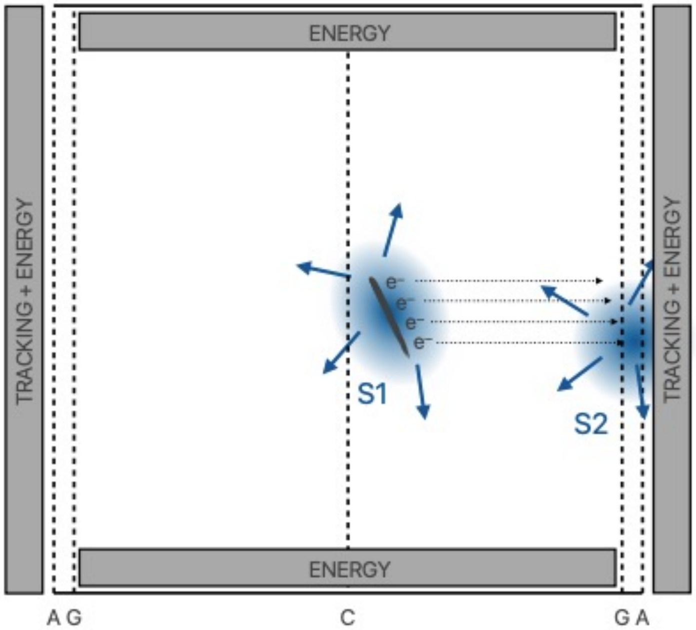
Towards the tonne scale

arXiv: 2005.06467

Tonne-scale detector required to reach target sensitivities towards $T_{1/2} \sim 10^{28}$ yr and cross the inverted hierarchy region

- Minimal background acceptance requirements
  - Estimated background 0.09 to 0.27 count/(tonne year ROI)
- Modify TPC: symmetric design helps reduce drift time (→ reduce diffusion)
- NEXT-tonne will be a multi-module system with ongoing R&D for future modules including barium tagging

Symmetric TPC design

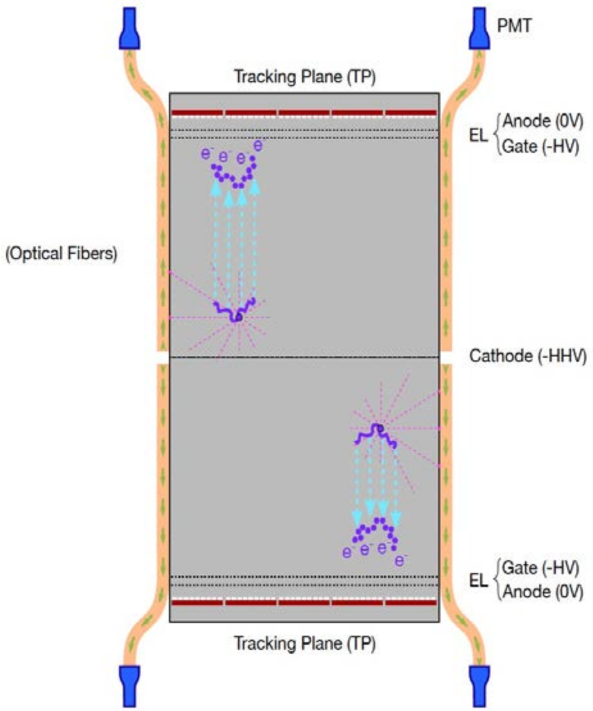


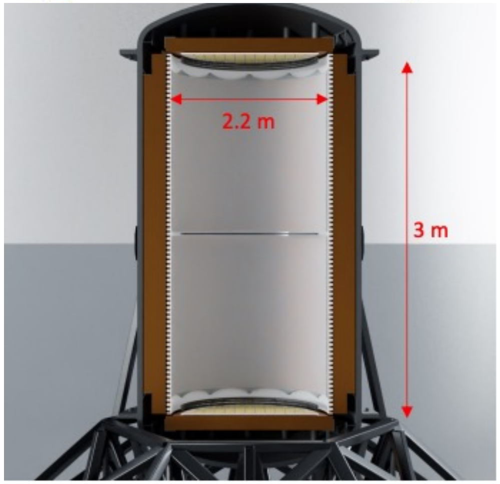
NEXT-HD: first tonne scale module

- Optical fibres around barrel of the TPC for energy measurement
  - Detection via SiPM removing the use of PMTs which are a significant source of radioactivity

- Dense SiPM plane readout for high resolution tracking

- Potential use of additives:
  - Use of gas additives (e.g. ^{4}He) to reduce diffusion
  - ^{3}He to reduce neutron capture on ^{136}Xe - which will be a contributing background for NEXT at this scale





NIMA A 905 (2018); JHEP 01 (2019) 027;
JINST 14 (2019) P08009; JHEP 04 (2020) 034

J. Phys. G: Nucl. Part. Phys. 47 075001

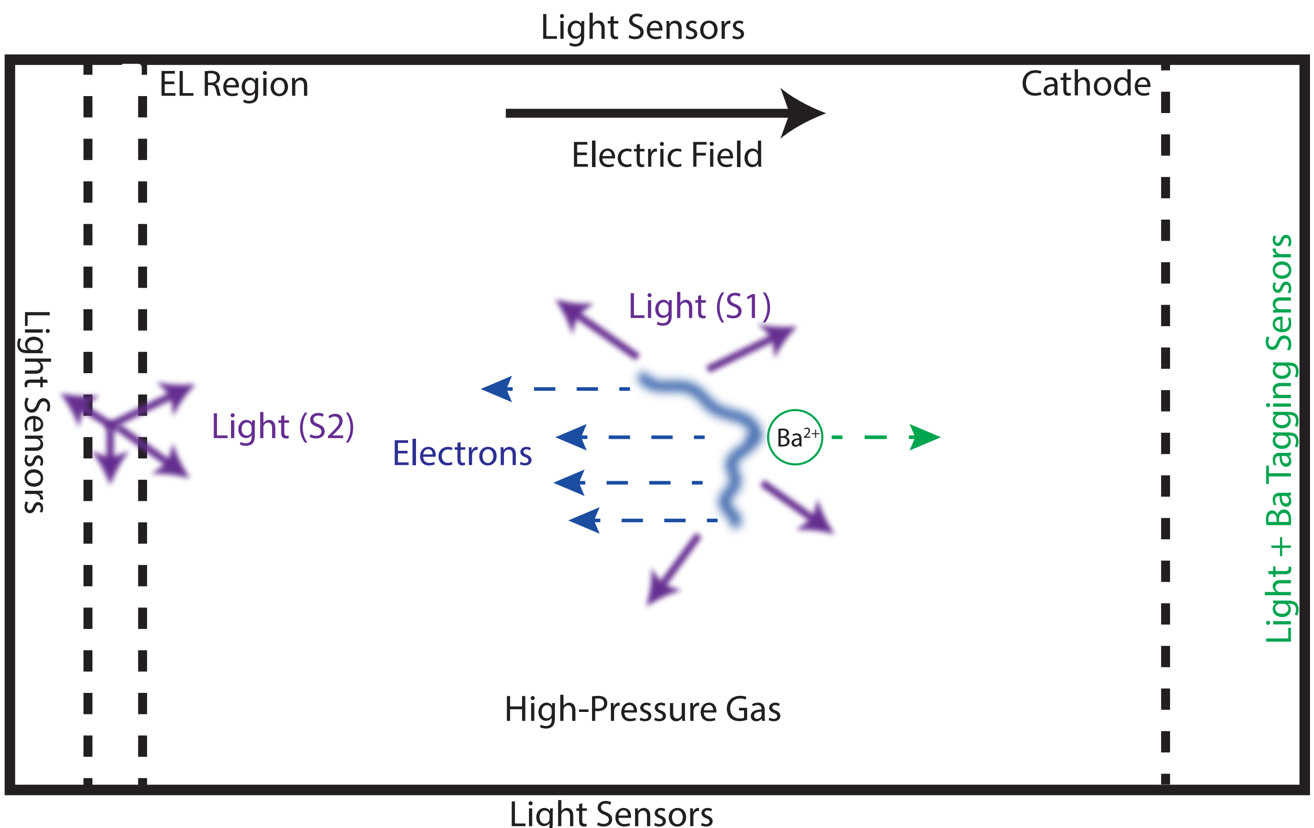
NEXT Barium Tagging Program

NEXT-BOLD: making barium shine

Barium daughter drifts in opposite direction to electrons

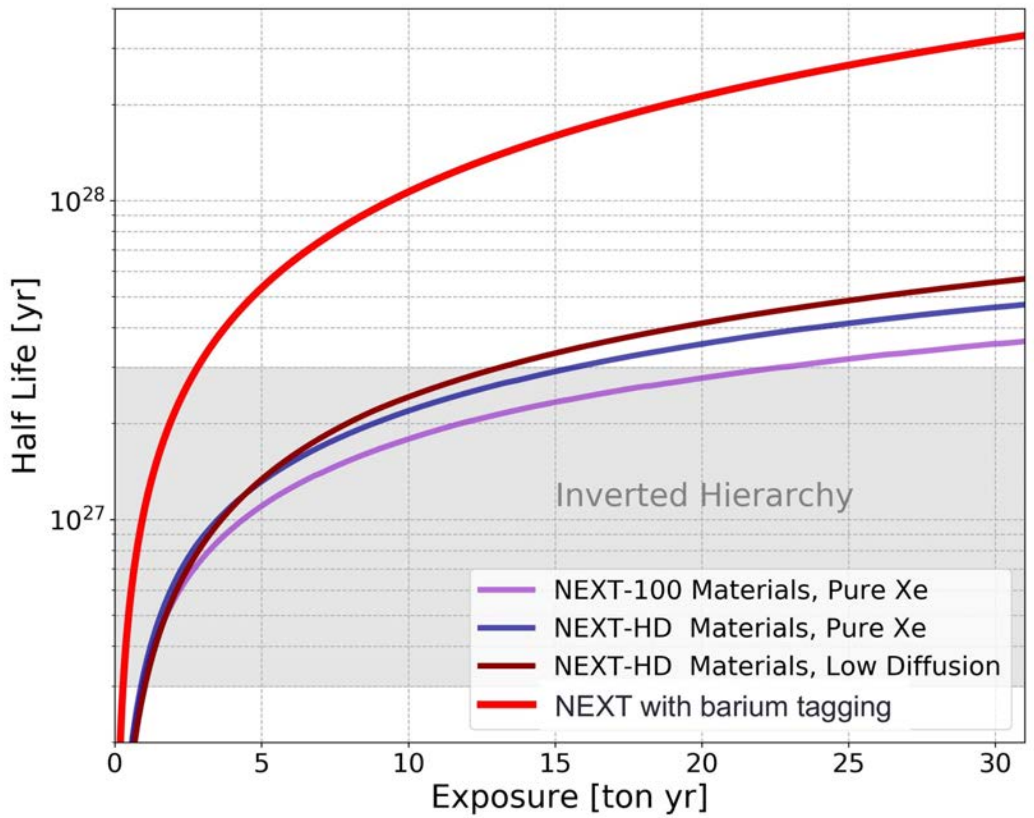
Tagging the barium ion in co-incidence with a two-electron signal in the ROI would yield a background free experiment

$^{136}Xe \rightarrow {}^{136}Ba^{2+} + 2e^{-}$ (2.5 MeV)



Sensitivity Comparisons

- Significant improvement in sensitivity possible with the introduction of barium tagging
- Much greater improvement than improving other detector designs including radiopurity and diffusion



Realizing Barium Tagging

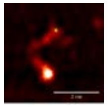
- Several milestones to realize a barium tagging system
  - Bring Ba^{2+} to sensor or sensor to the ion
  - Sensor with sensitivity to only single ions of Ba^{2+}
  - Free up space in detector plane to incorporate sensors
  - Demonstrating a functioning system with realistic conditions
  - Allowing for scaling to large scale detector to tonne scale and beyond

NEXT is attacking all these challenges on multiple fronts

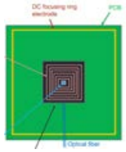
- RF carpets for bringing Ba^{2+} to sensors in high-pressure gas

- Single molecule fluorescent imaging for single ion detection

- High-speed VUV image intensified CCD cameras for large area tracking



- Underground phase with HPGTPC demonstrator system
- Integrated barium tagging sensors



See backups for more info!

Single Molecule Fluorescent Imaging (SMFI)

A non-fluorescent molecule becomes fluorescent (or vice versa) upon the introduction of a ion species such as barium

Not-Fluorescent

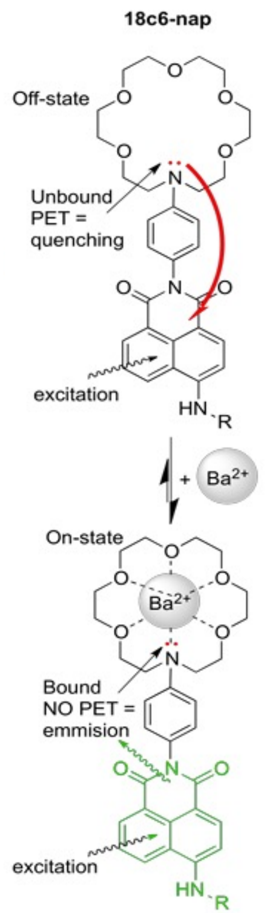
↓

Add Ba^{2+}

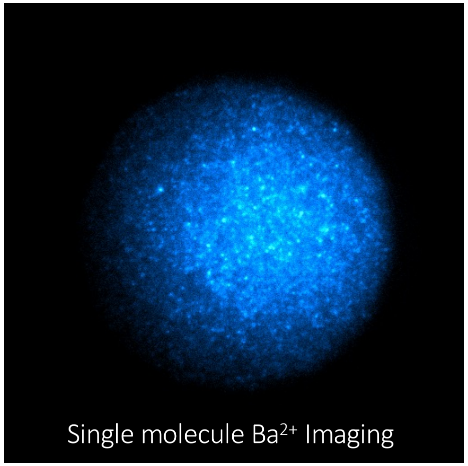
↓

Fluorescent!

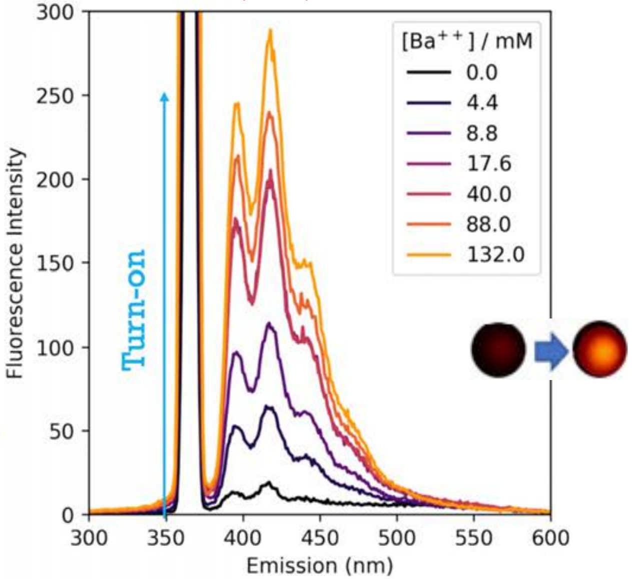
Single-ion sensitivity!



Dry-phase-sensor



Phys. Rev. Lett. 120 (2018) 13, 132504;
ACS Sens. 6 (2021) 1, 192202;



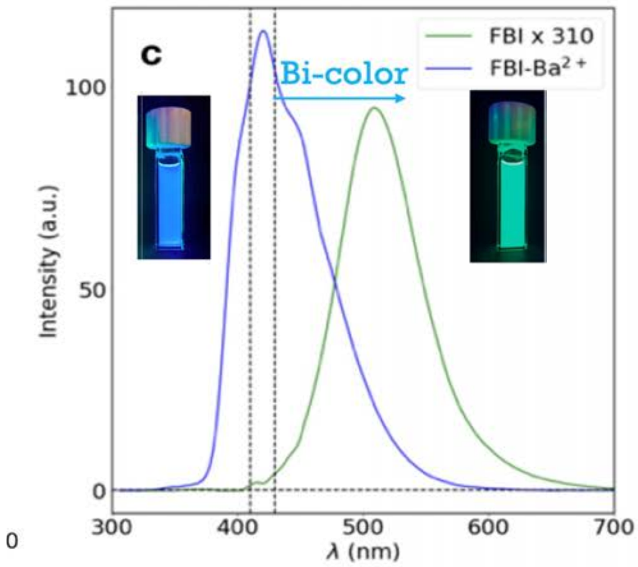
D.R. Nygren, J.Phys.Conf.Ser. 650 (2015) no.1, 012002

Additional Variants of Chemosensors

Molecule with barium has different optical properties compared to without

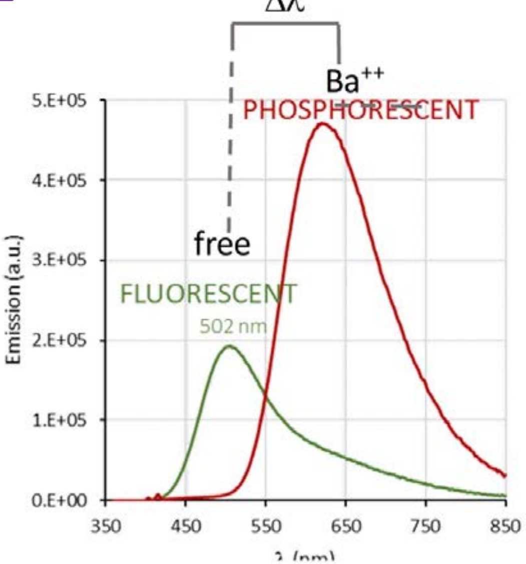
- Colour shifts
- Fluorescent to phosphorescent

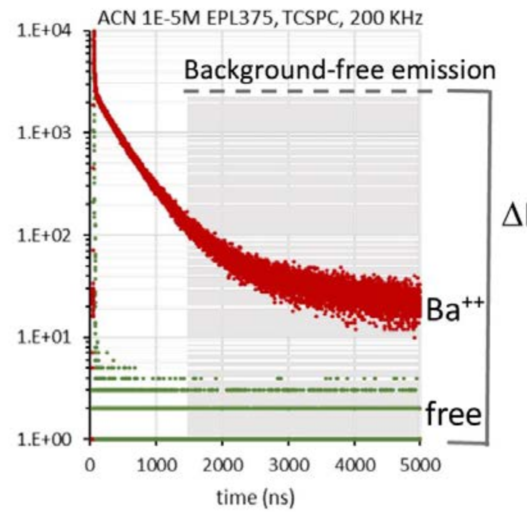
Bi-colour



Nature 583 (2020) 7814, 48–54

Fluorescent → Phosphorescent

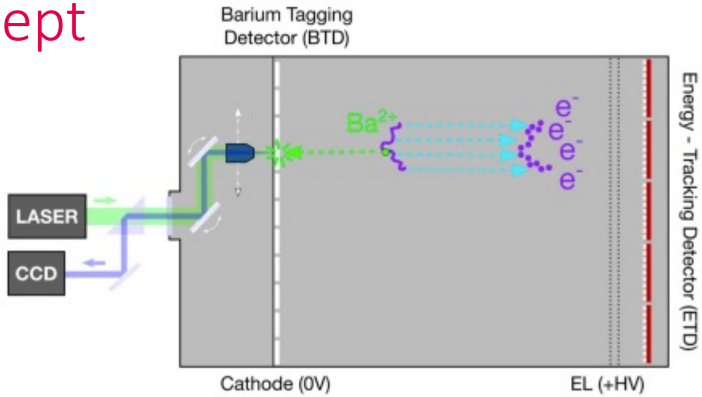




Ba tagging demonstrator phases

Demonstrator phases under intensive development under 2-3 yr time-scale

Sensor to Ion Concept

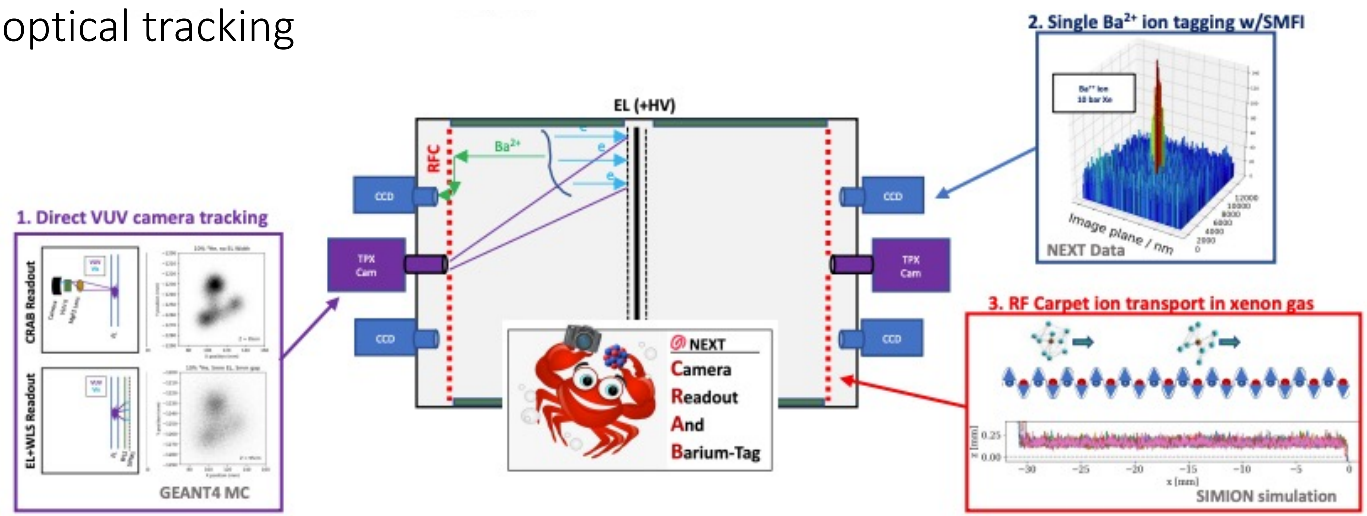


Bring the sensor to the single-ion location

Ion to Sensor (NEXT-CRAB) Concept JINST 18 (2023) P08006

- High speed cameras for optical tracking

We are currently scaling this technology and a future underground phase on the horizon which will prepare for the incorporation of Ba^{2+} tagging



JINST 15 (2020) 04, P04022

Summary

- The NEXT experiment is a high-pressure xenon TPC searching for $0\nu\beta\beta$ decay with a phased program
- NEXT-100 experiment is in the final stages of construction and will begin commissioning in the beginning of 2024 for a first competitive search
- Subsequent phases at the tonne scale are under intensive development and aim to enter the inverted hierarchy region with improved background indexes and detector hardware
- Barium tagging R&D program is making significant progress with RF carpets, single ion sensitive compounds, tracking with high-speed cameras with a future small-scale phase on the horizon the demonstrate the technology in realistic conditions

Extras

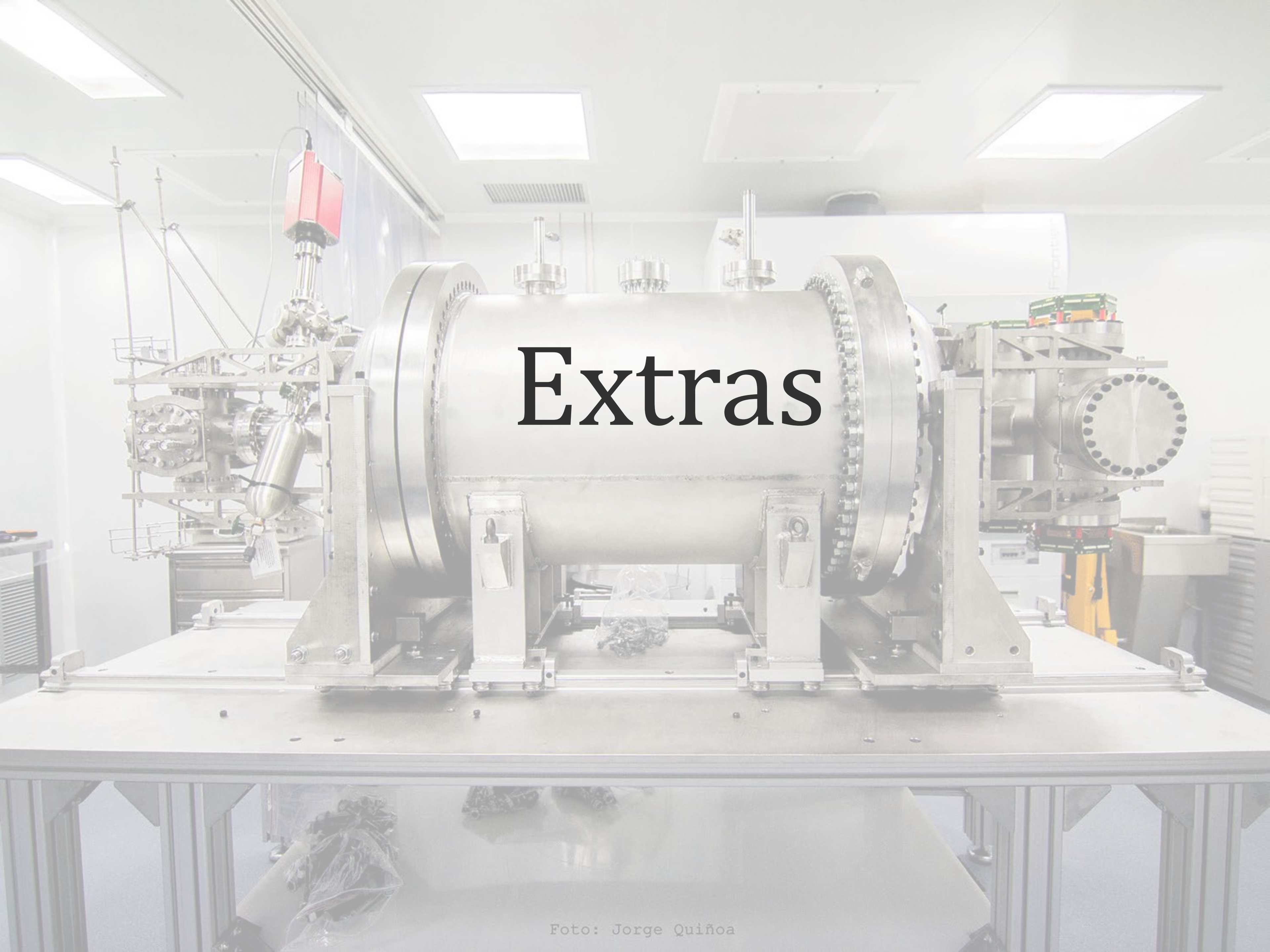
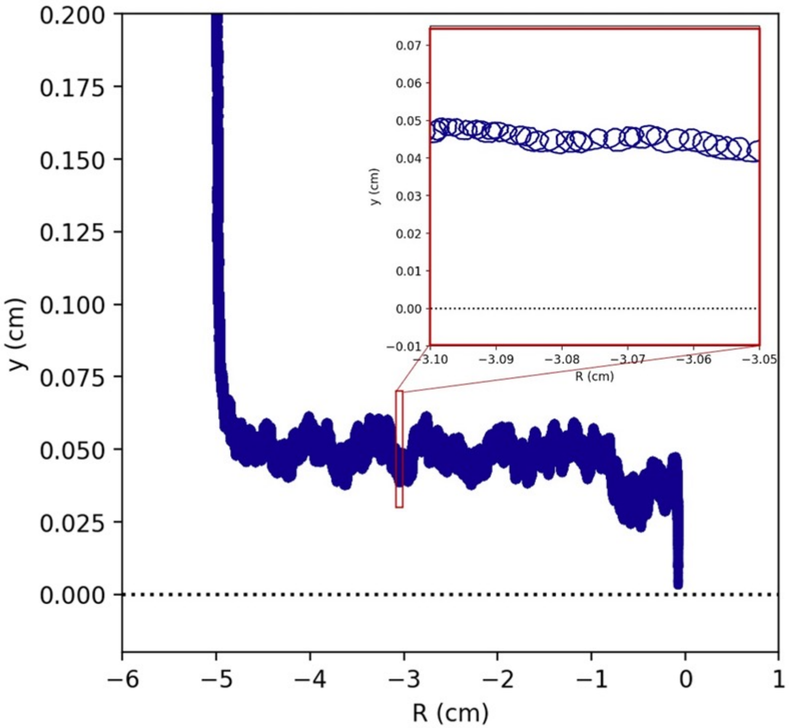


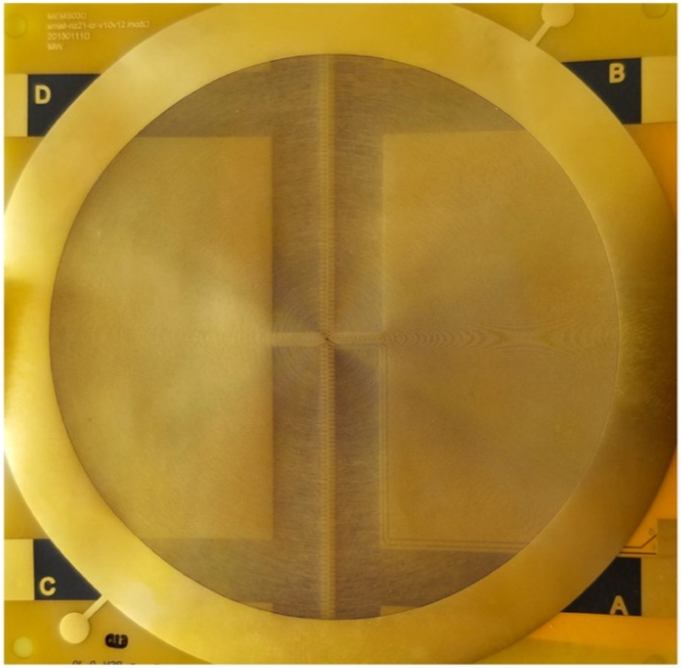
Foto: Jorge Quiñoa

Ion Transport with RF Carpets

- Once barium ion arrives in the sensor region plane, we have two options:
  - Transport the ion to the sensor
  - Bring the sensor to the ion

- RF carpets with small pitches ~100μm are being developed for use in high-pressure gas environments to bring ion to sensor





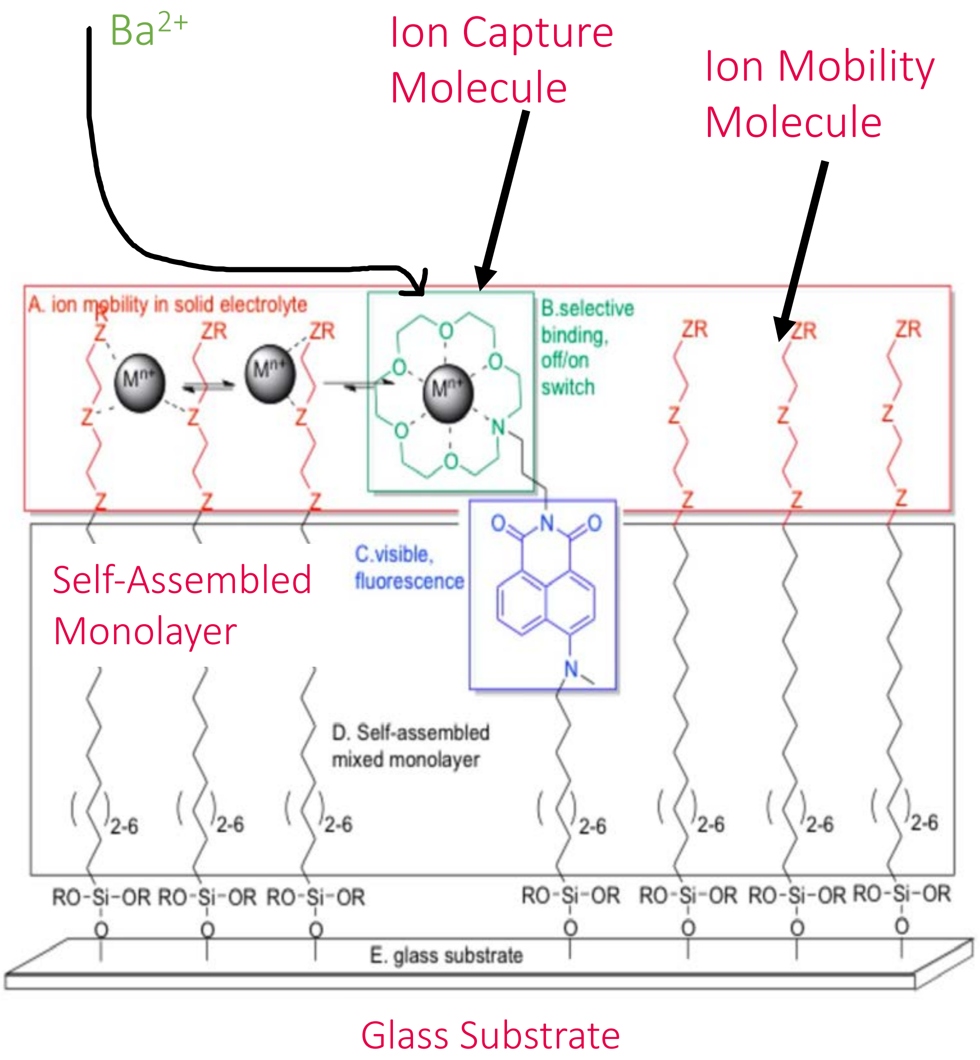
Several manufacturing methods and parameters being investigated:
- Pitch
- Shape + Size
- Frequency of potential
- Voltage

JINST 15 (2020) 04, P04022

“Meadow” Sensor Design

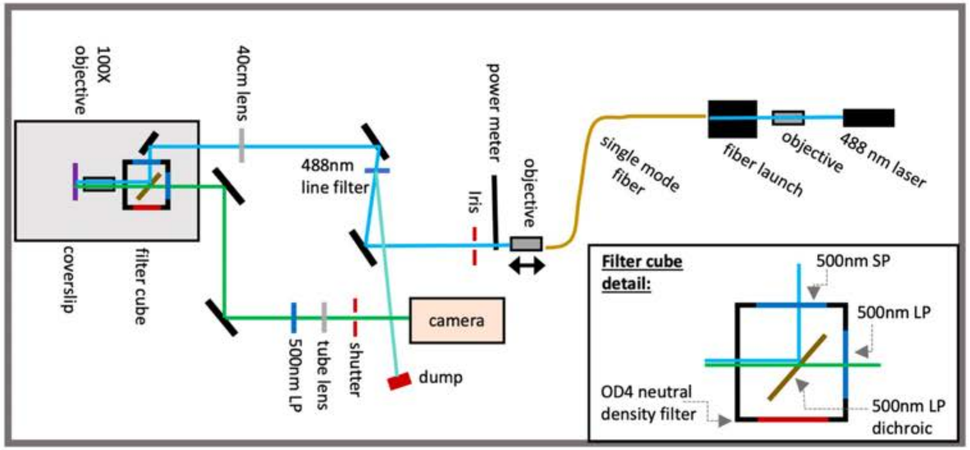
The ideal sensor

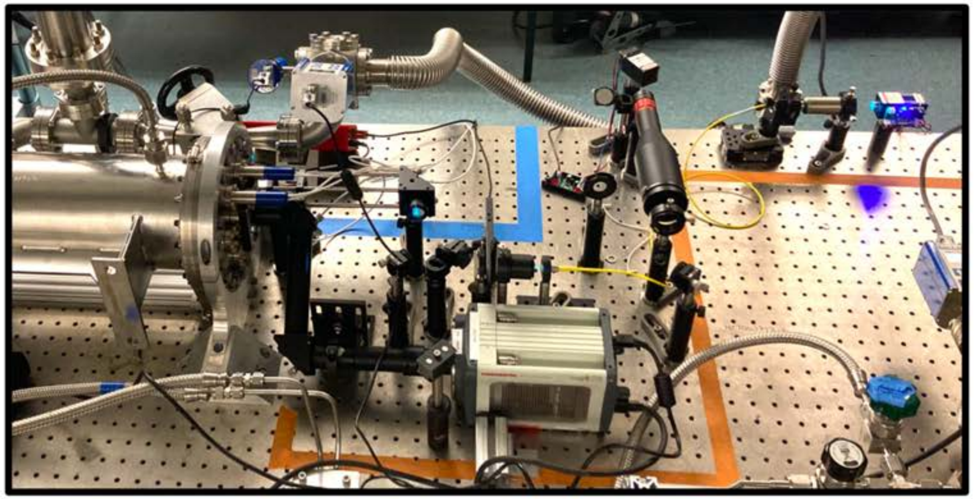
- Self-assembled monolayer interface between substrate and receptors
- Receptors close (but not too close) together
- Barium Ions survive in 2+ state while mobile on the electrolyte surface
- High efficiency and low background

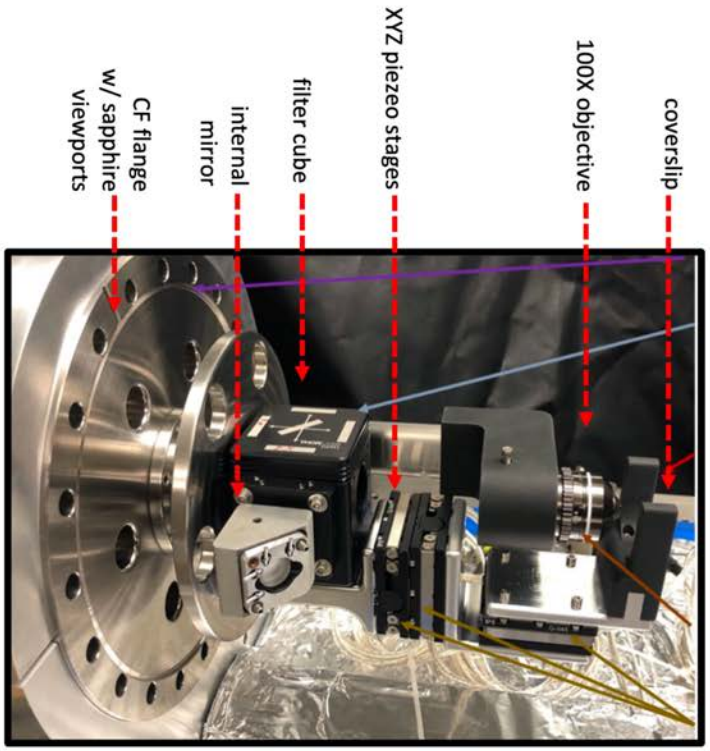


High Pressure Microscope

- We have developed a custom single-molecule sensitive microscope suitable for high-pressure xenon gas

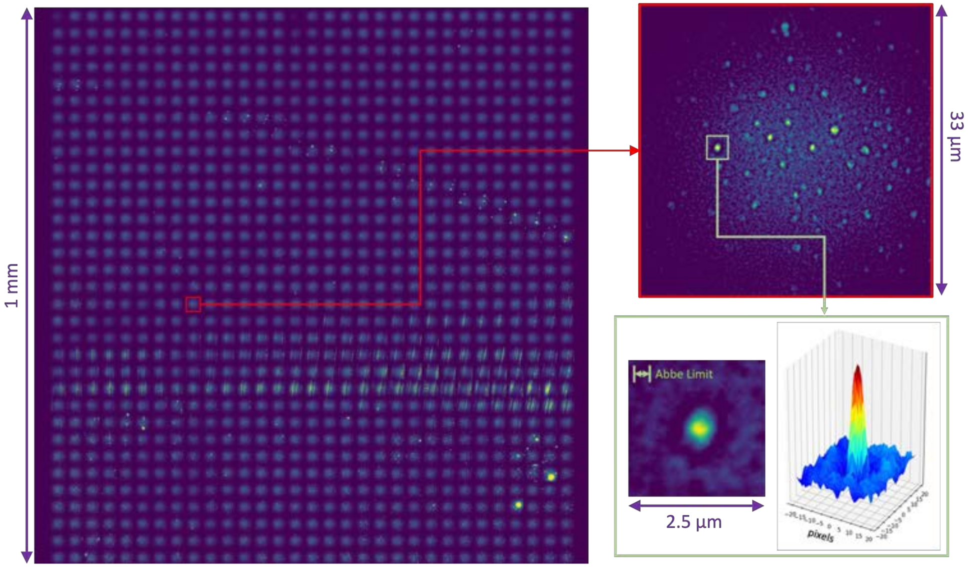






Microscope has a 5x5mm^2 scan area with 1x1mm^2 scan area demonstrated at pressure

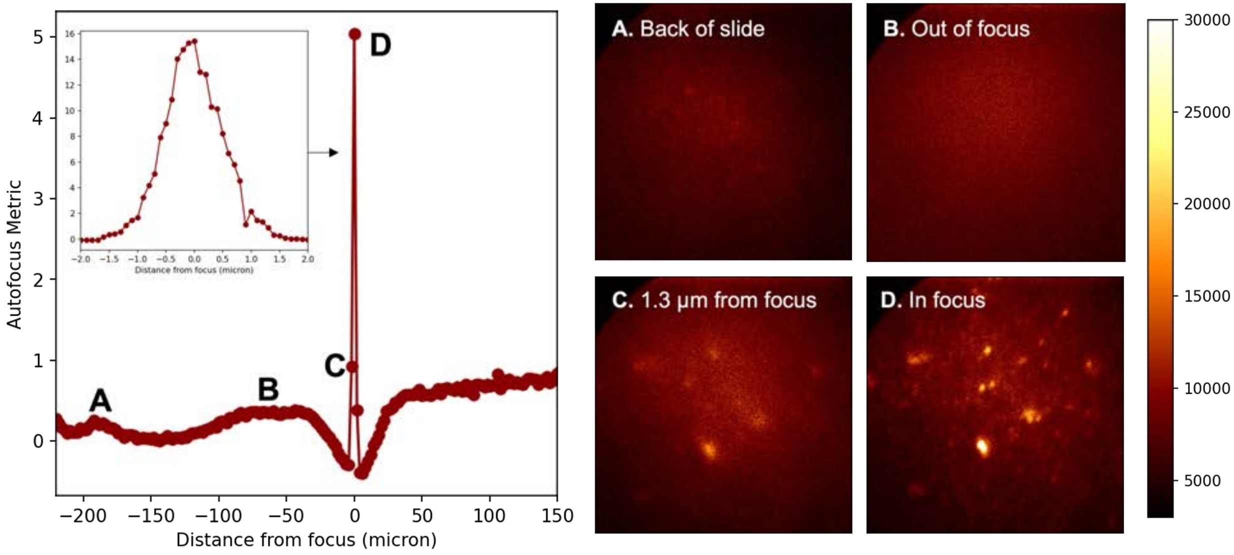
Microscope scanning and focus



Scanning a mm^2 in with single molecule sensitivity and Point Spread Function at the Abbe limit in high pressure xenon

A novel single molecule autofocus method has been developed

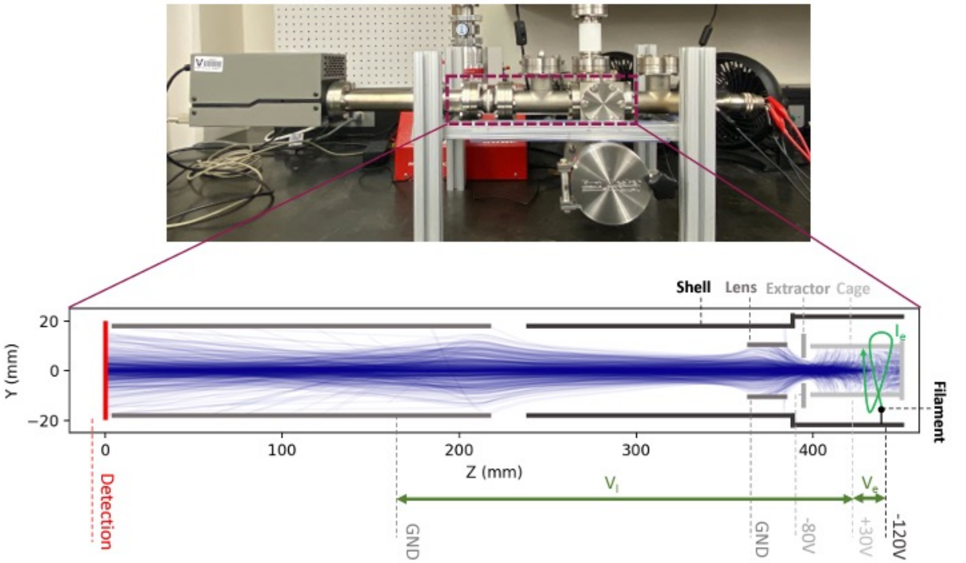
Maintains the focal plane with 1um precision across 1mm, at 150um working distance

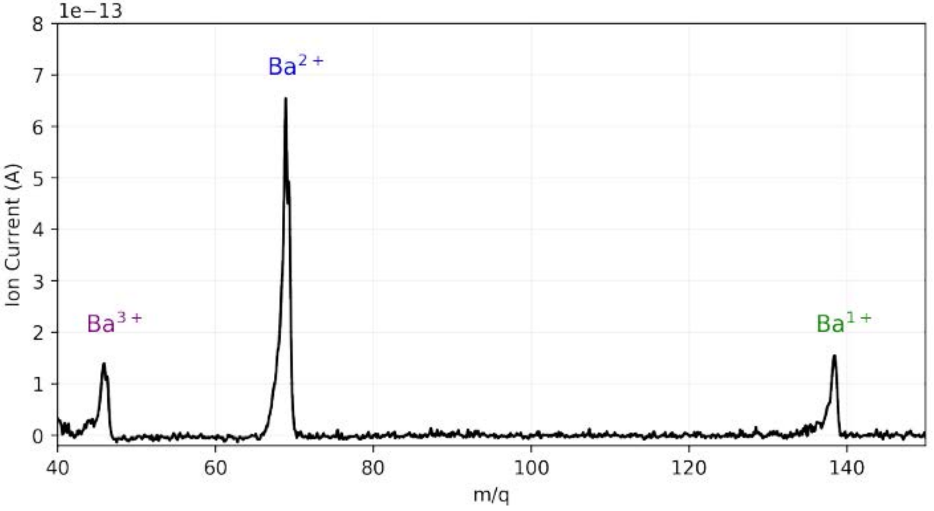


Characterizing the sensors

JINST 18 P07044 (2023)

- Demonstrating capture and fluorescence requires a controlled Ba^{2+} beam in xenon gas
  - Not trivial!
- We have developed a tuneable metal ion beam in a bench-top sized system
- Controllable currents with ion charge selectivity in the picoamp range





νBIT: Integrated Barium Sensors

- Package RF electronics and SMFI chemosensors into a single integrated chip
  - Current electrode designs have achieved a 10um pitch which is suitable for 10 bar operation

- Integrated light-guides
  - Similar to techniques employed in trapped ion qubits

- Tile the readout plane with these chips