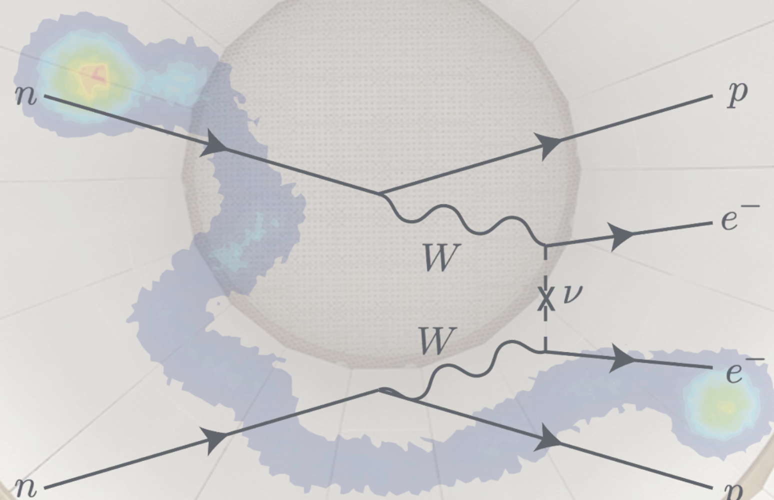
# The NEXT experiment $0\nu\beta\beta$ vision towards the tonne scale

**Krishan Mistry** on behalf of the NEXT collaboration

SNOLAB Future Projects Workshop 2025




1 May 2025

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# The NEXT Experiment

next

**N**eutrino **E**xperiment with a **X**enon **T**PC

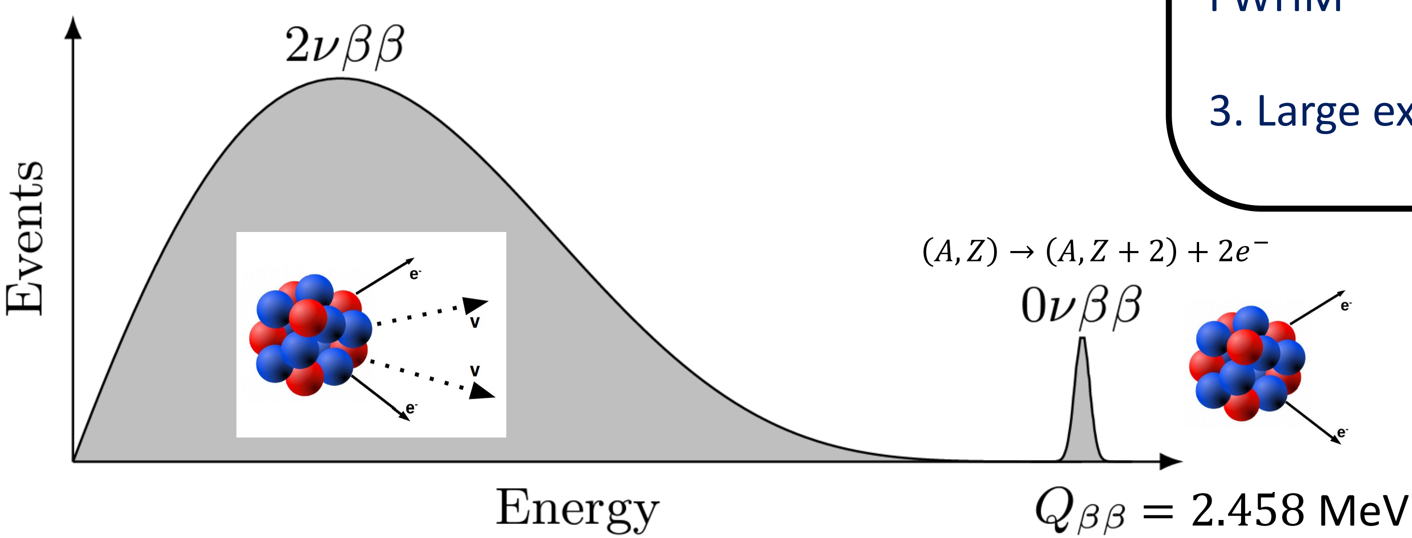
**Goal**: search for neutrinoless double beta decay $(0\nu\beta\beta)$ decay with $^{136}$Xe

A discovery will prove the neutrino is Majorana

**Requirements**

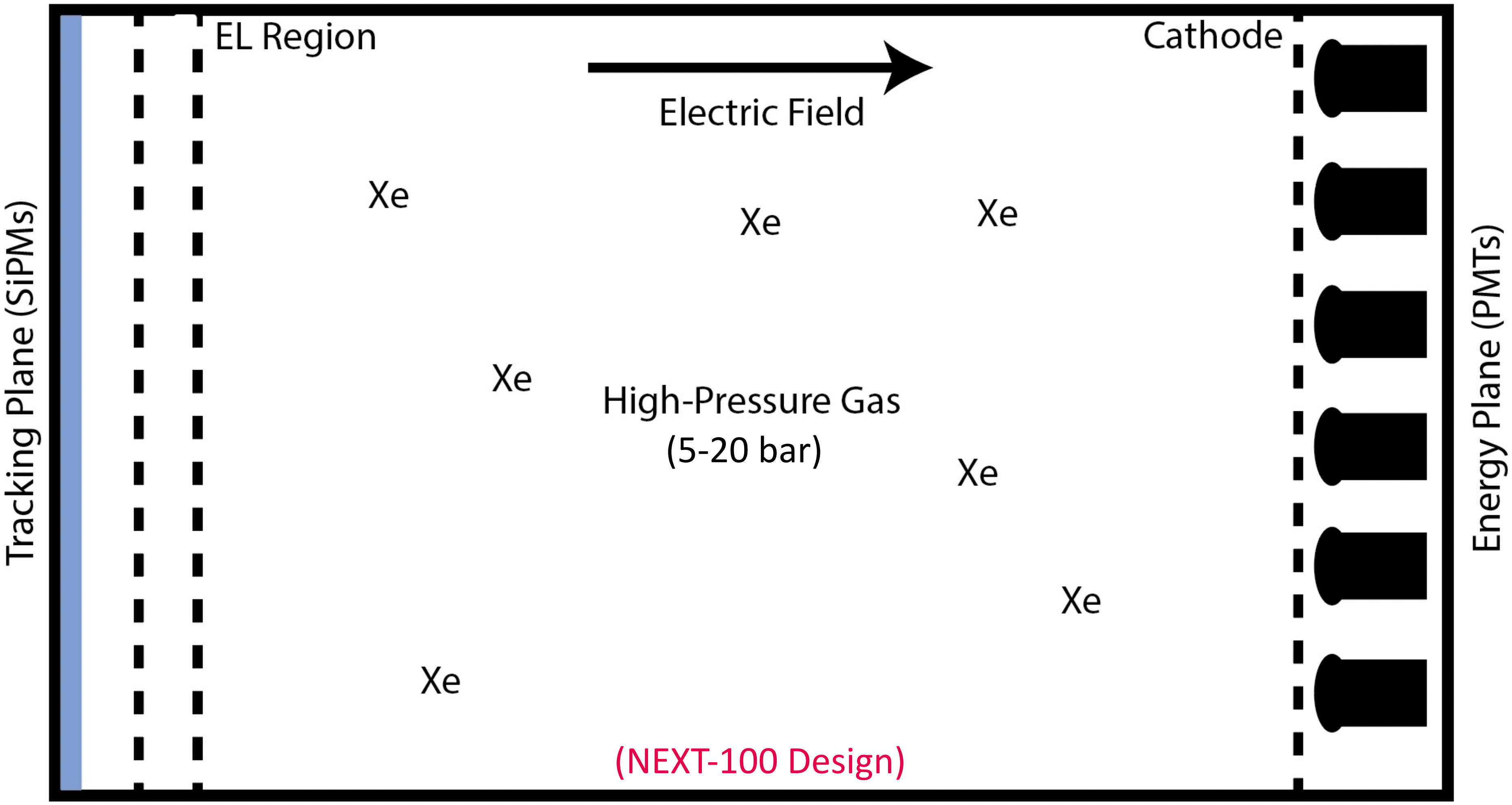
1. Background index < 1 count/(tonne year ROI)
2. Excellent energy resolution <1% FWHM
3. Large exposure mass/time

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$



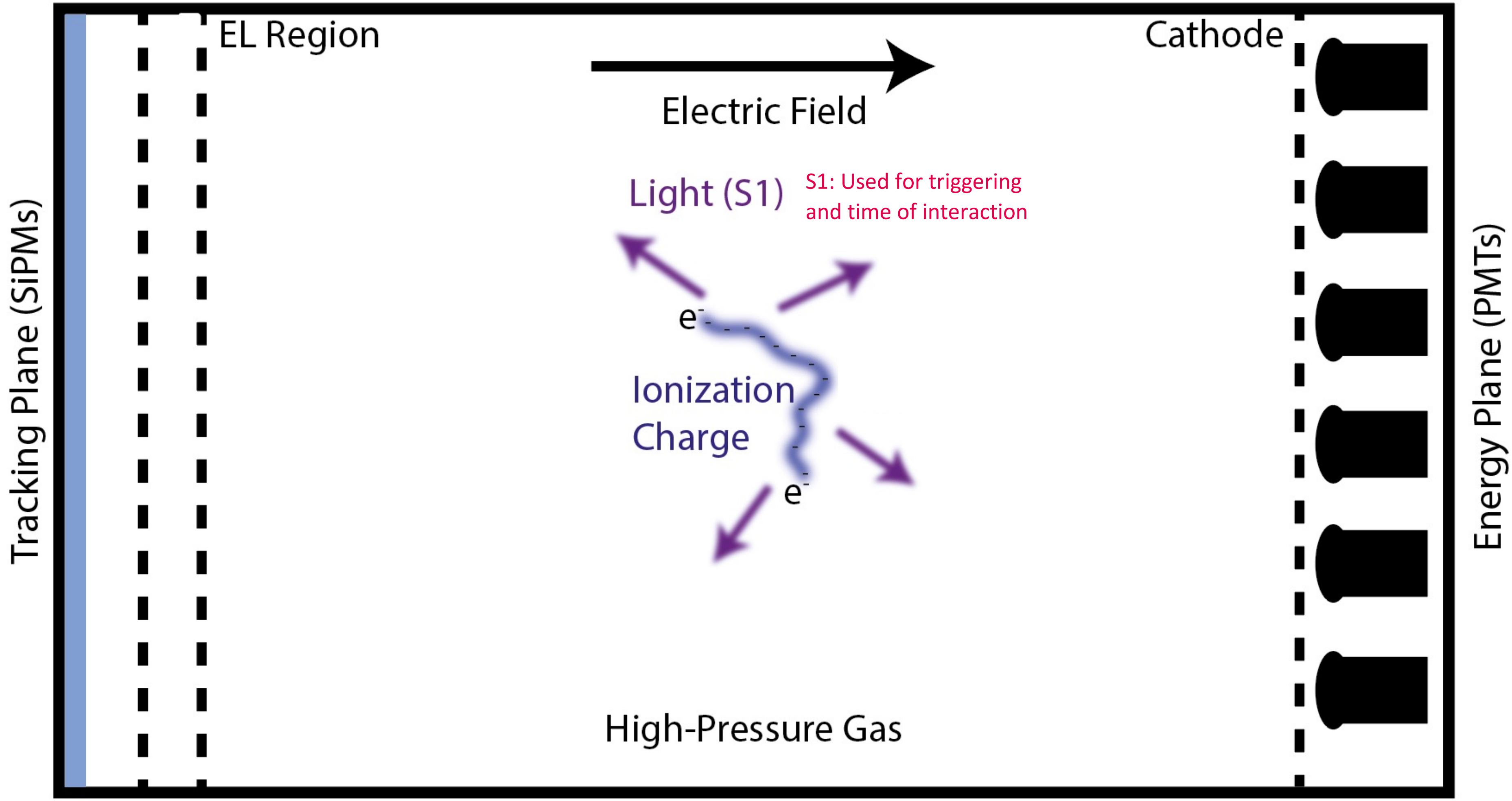
# Detector Technology

## High-Pressure Gaseous Time Projection Chamber



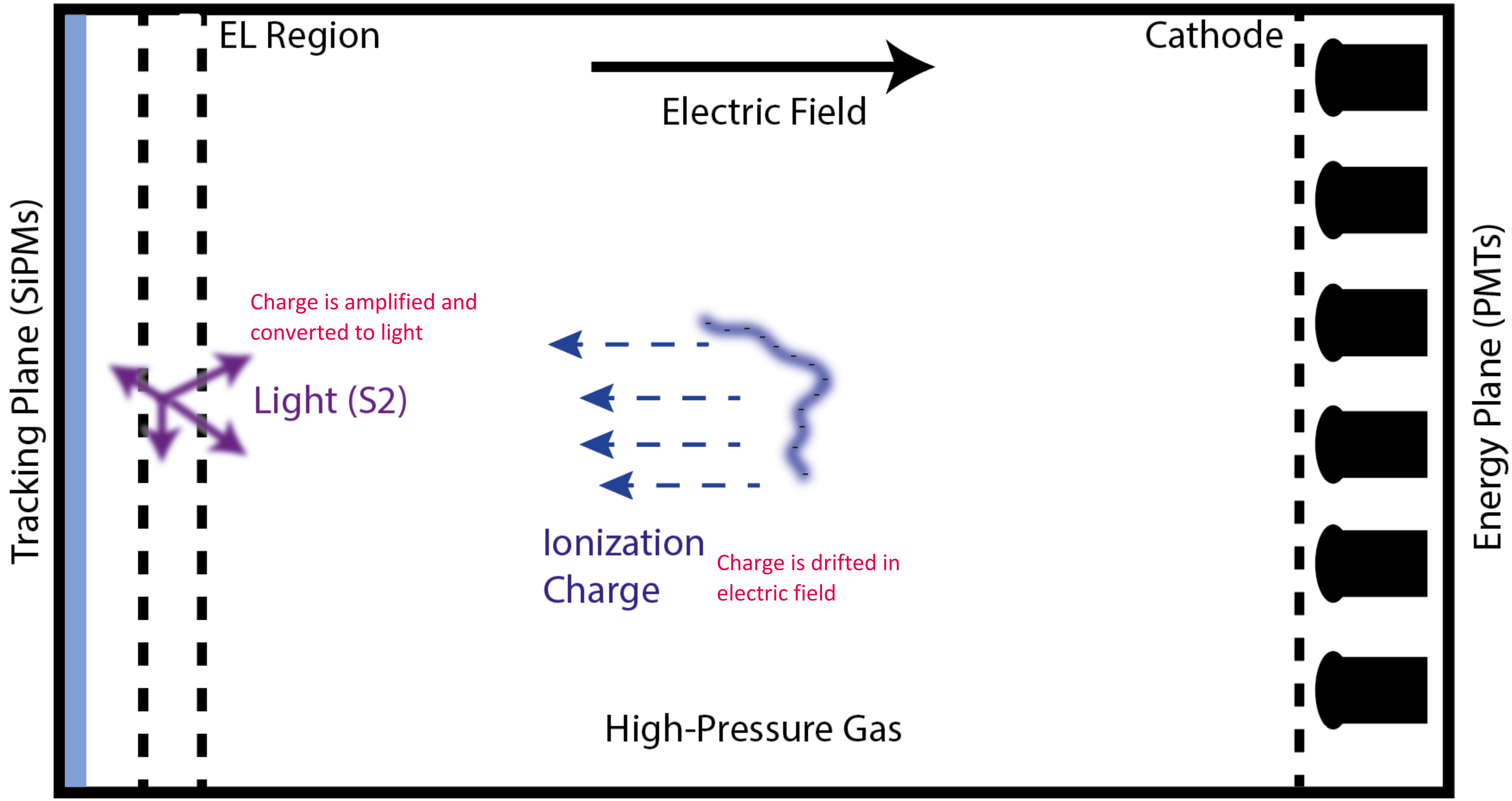
# Detector Technology

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



# Detector Technology

## Electroluminescent Amplification!

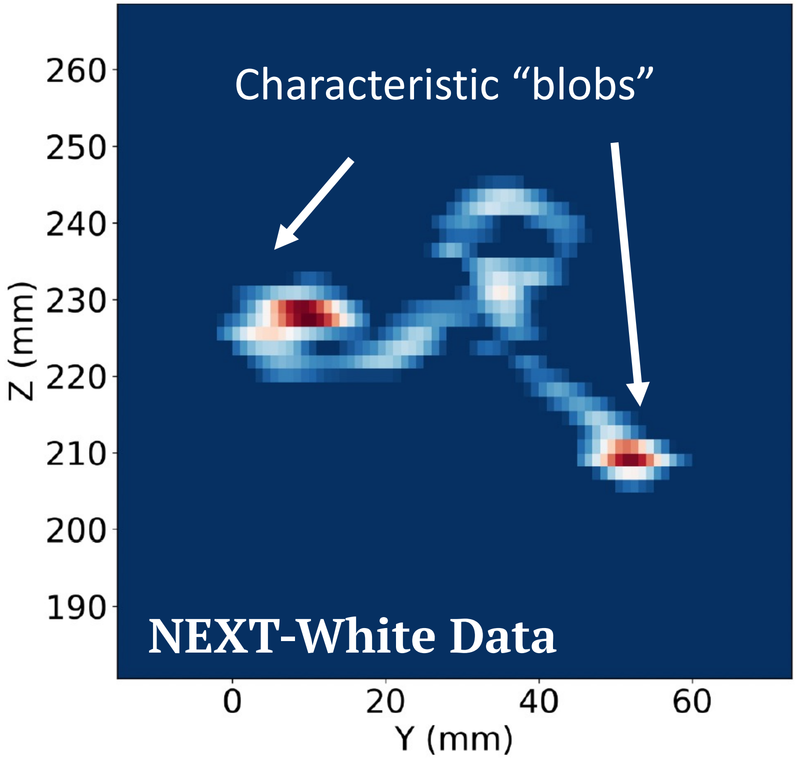


# Topology

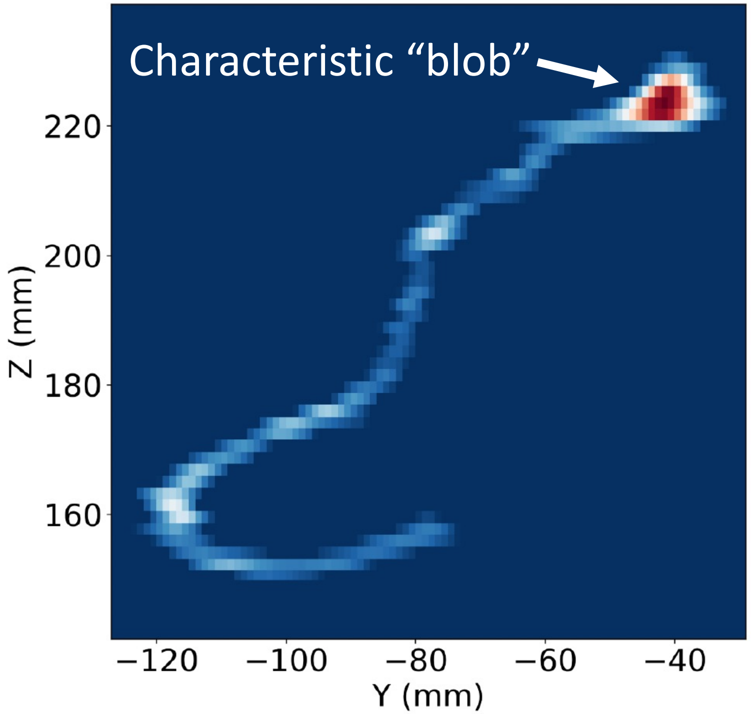
Topology: Tracks in a gas TPC have size ~20cm in 10 bar, scales inversely with pressure

→ Information about the topology of the event is effective at separation of signal (2e⁻ signatures) from background (1e⁻ signatures)

Signal-like




Background-like

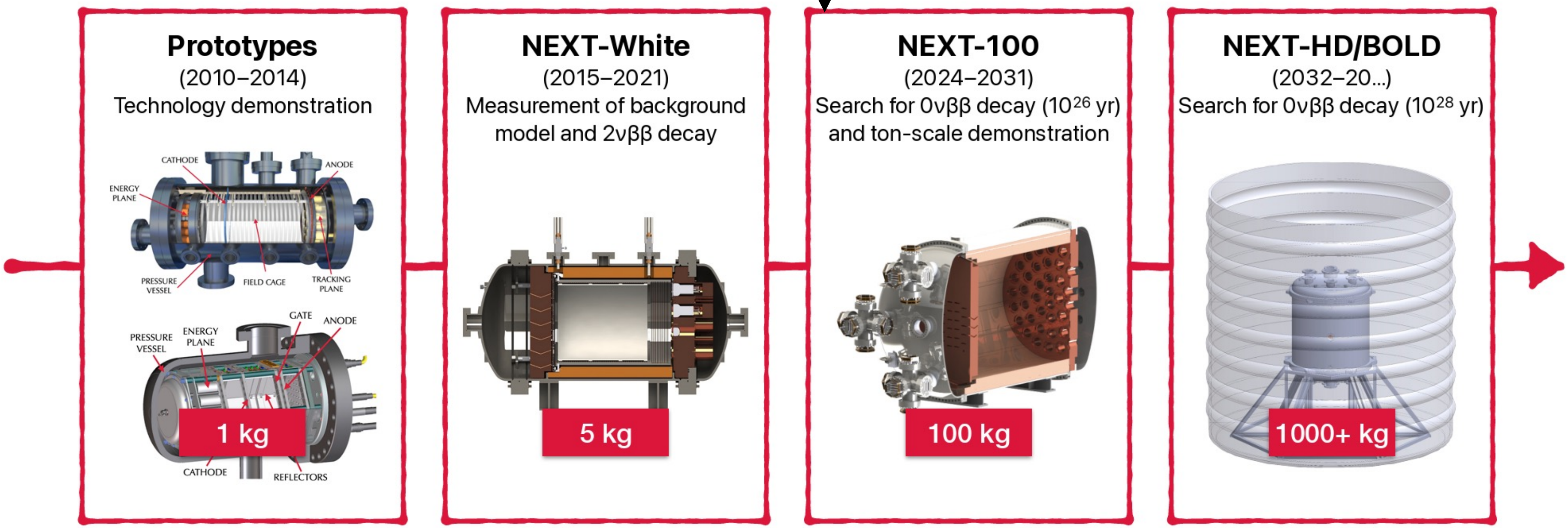


# The NEXT Program

- Series of High-Pressure Gaseous Xenon Time Projection Chambers with a rich R&D program

- NEXT-100 is the latest experiment and is taking physics data!

We are here!

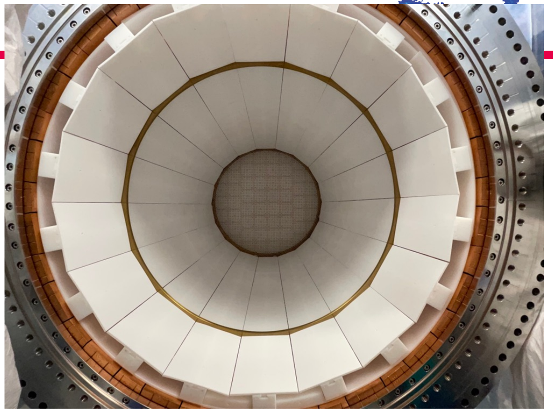


# NEXT-100 Assembly

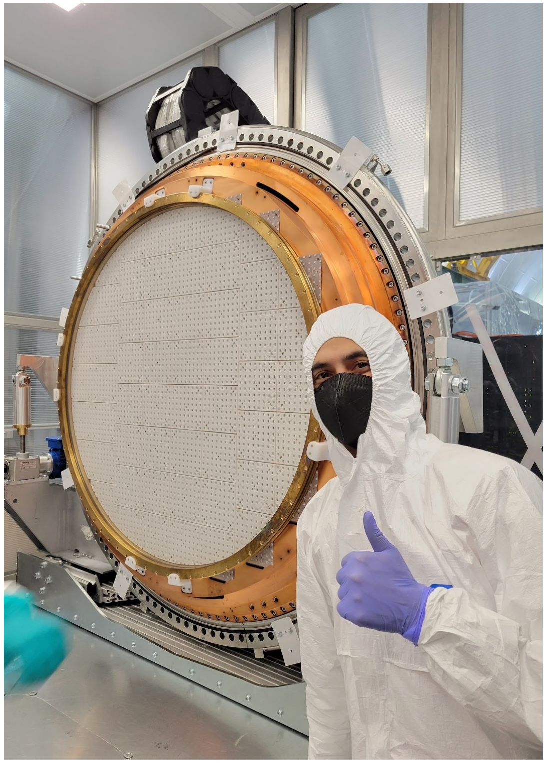
## High-Pressure Vessel

## Lead Castle

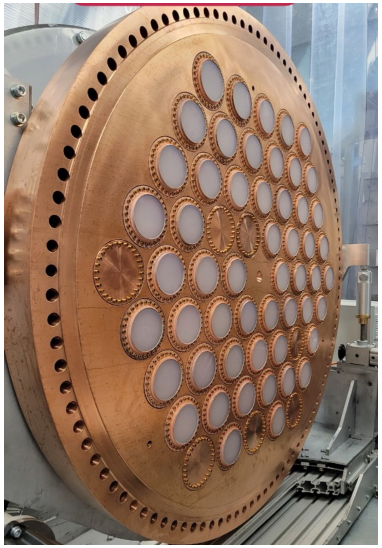
## Teflon Reflector Panels



## Tracking Plane + EL Region



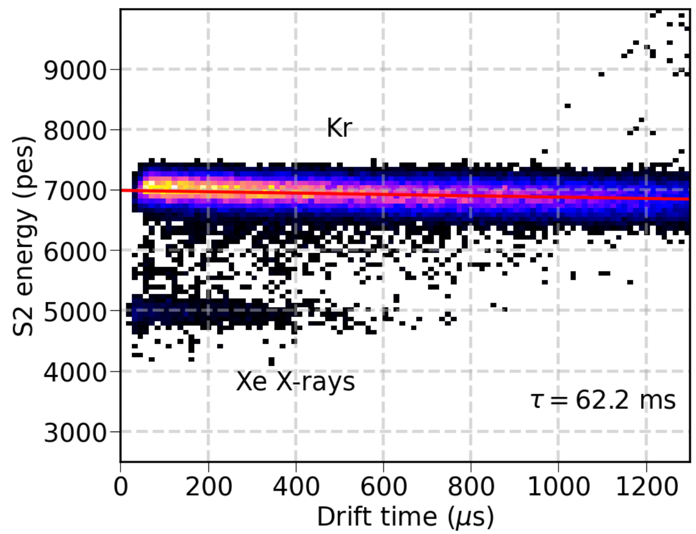
## Energy Plane (PMTs)



## Field Cage

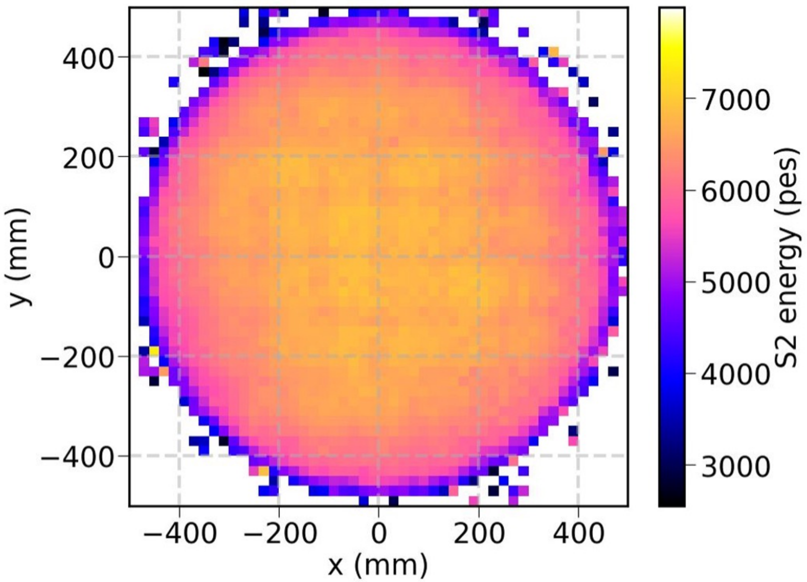
# NEXT-100 $^{83m}$Kr Calibrations

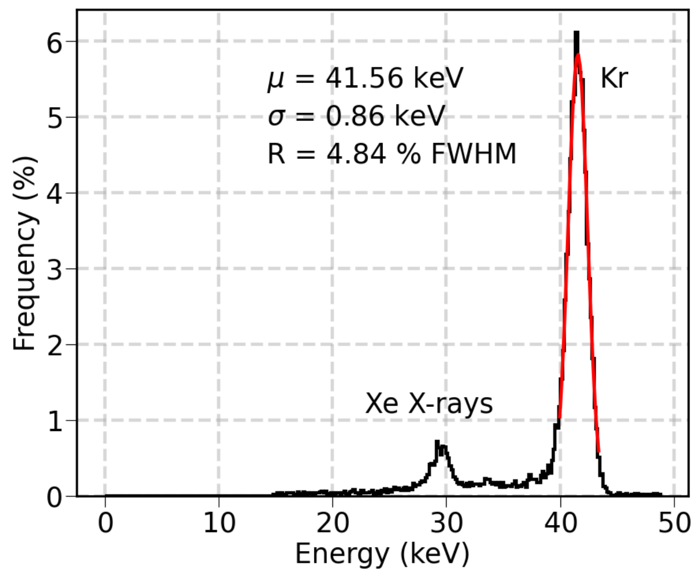
- Excellent Lifetime achieved of ~60 ms



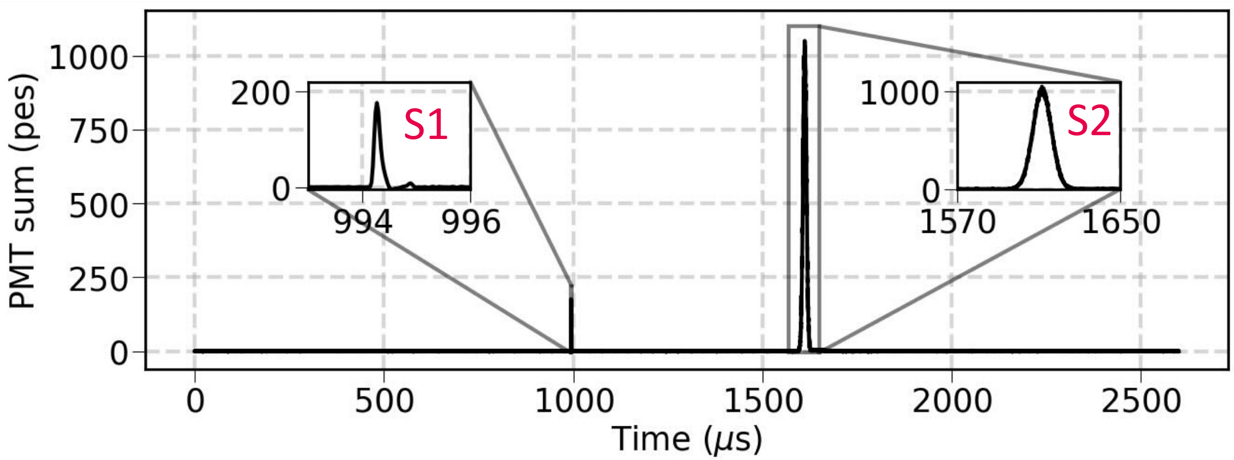

- Reconstruct 40 keV Kr peak with 5% FWHM energy resolution

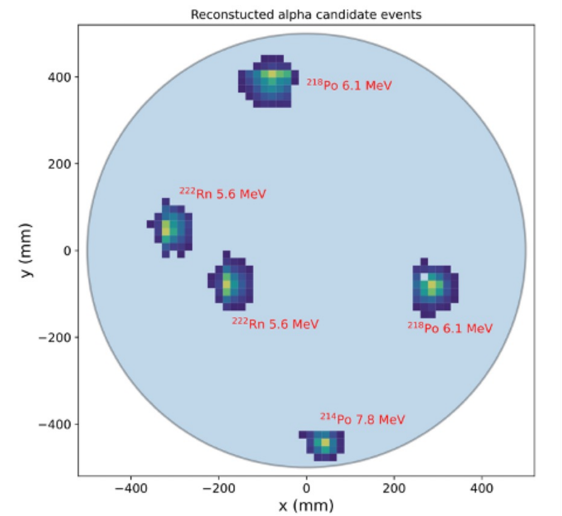
- Uniform Energy maps



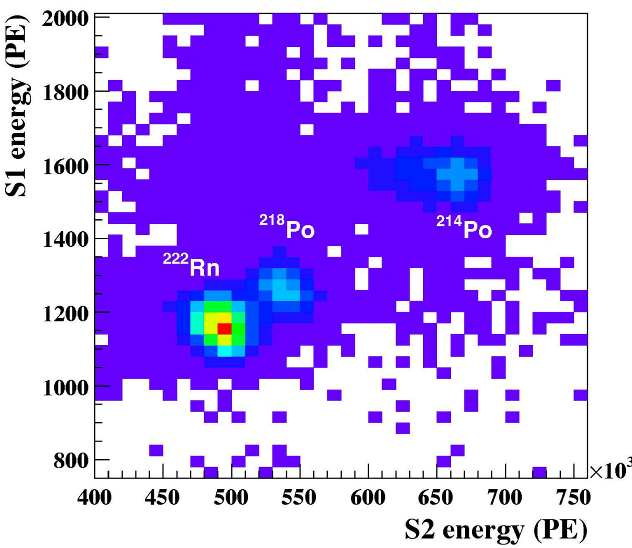



# Alpha Waveforms and Signals




Waveform of alpha particle in NEXT-100 showing primary scintillation (S1) and EL signal (S2)

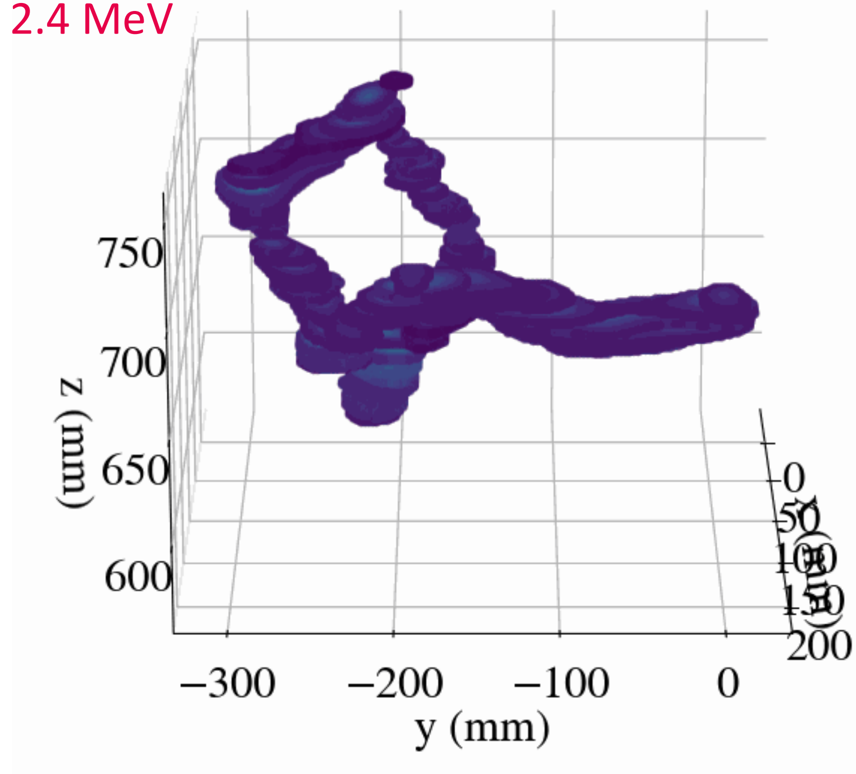



S1 v S2 signals showing clearly the alphas produced in the $^{222}$Rn chain.

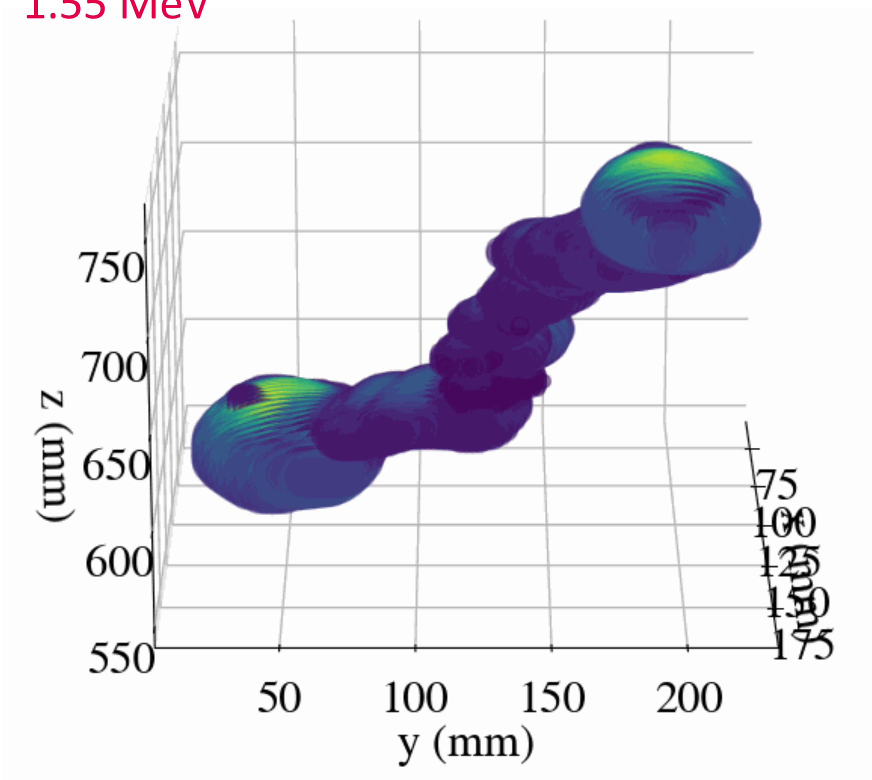
# NEXT-100 High Energy Calibrations

- **New data this month**: high energy tracks from $^{208}Tl$ calibration source

Single electron candidate
2.4 MeV




Double electron candidate
1.55 MeV




**Steady State Operation:**

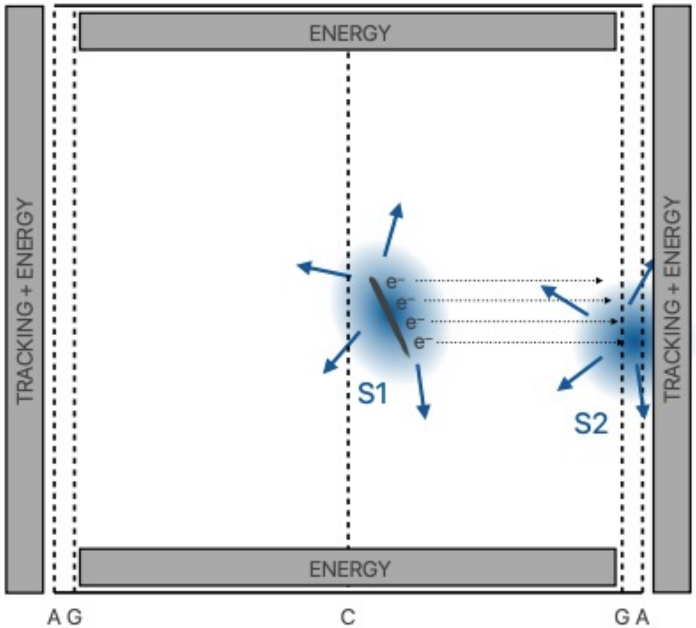
- Current operations of NEXT-100 has been very smooth
- We typically require two on-site shifters
- Minimal interventions required

# Towards the tonne scale

Tonne-scale detector required to reach target sensitivities towards $\boldsymbol{T_{1/2}} \sim 10^{28}$ 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 implementation of barium tagging

Symmetric TPC design



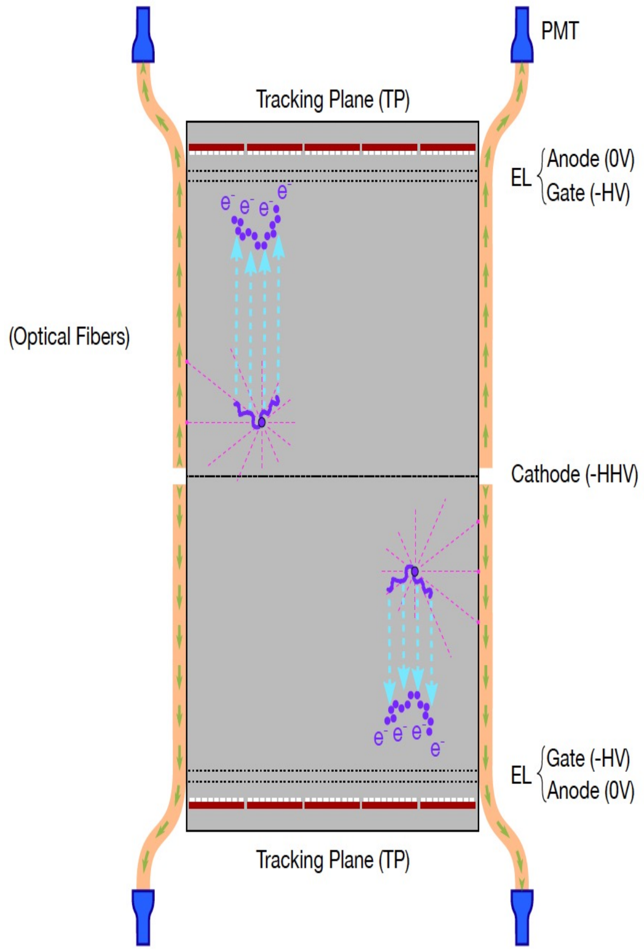

J. High Energ. Phys. 2021, 164 (2021)

# 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

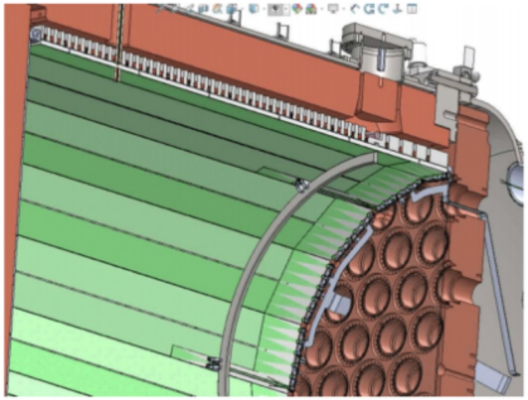
- Potential use of additives (e.g. $^4$He) to reduce diffusion



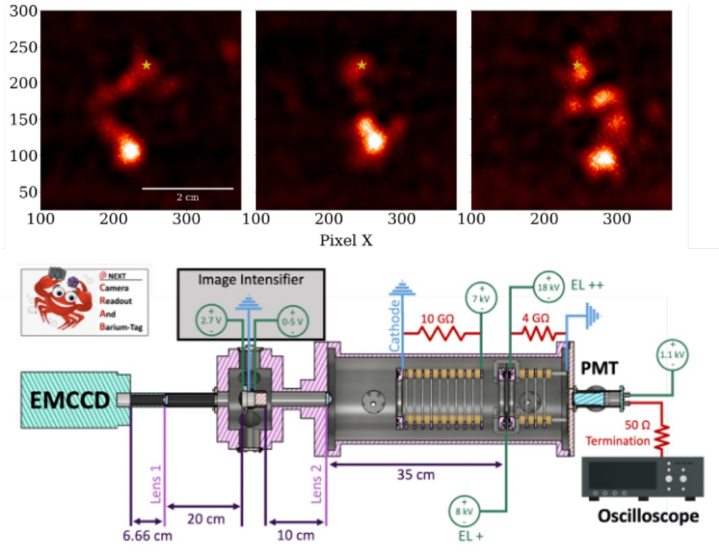

NIMA A 905 (2018); JHEP 01 (2019) 027;
JINST 14 (2019) P08009; JHEP 04 (2020) 034

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

# NEXT Tonne Scale Technologies

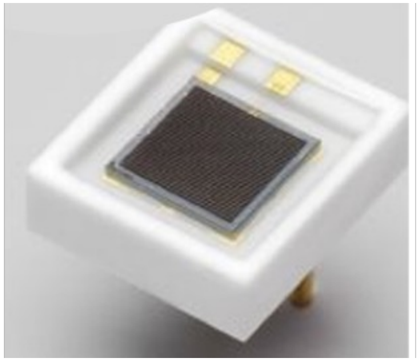


Barrel Fibre detector readout for energy readout




Camera Readout and Barium Tag Demonstrator

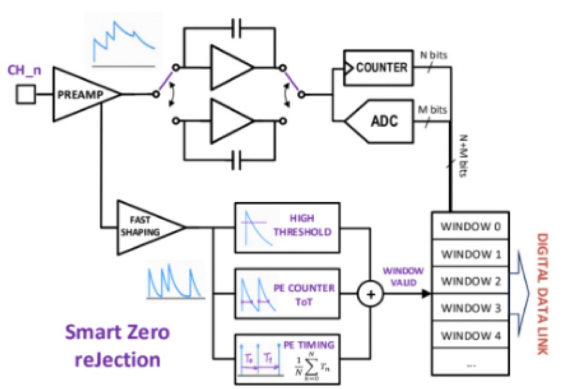
JINST 18 P08006

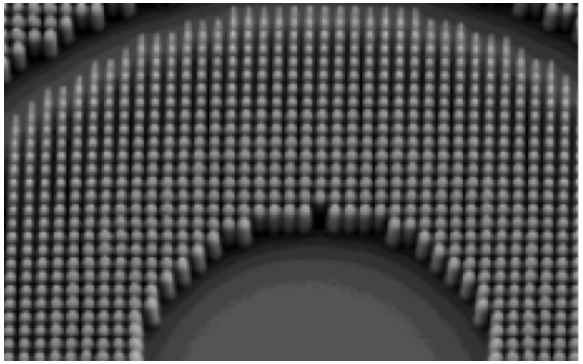


Dense tracking plane for high granularity readout

JHEP 09 (2024) 112

New ASIC designs



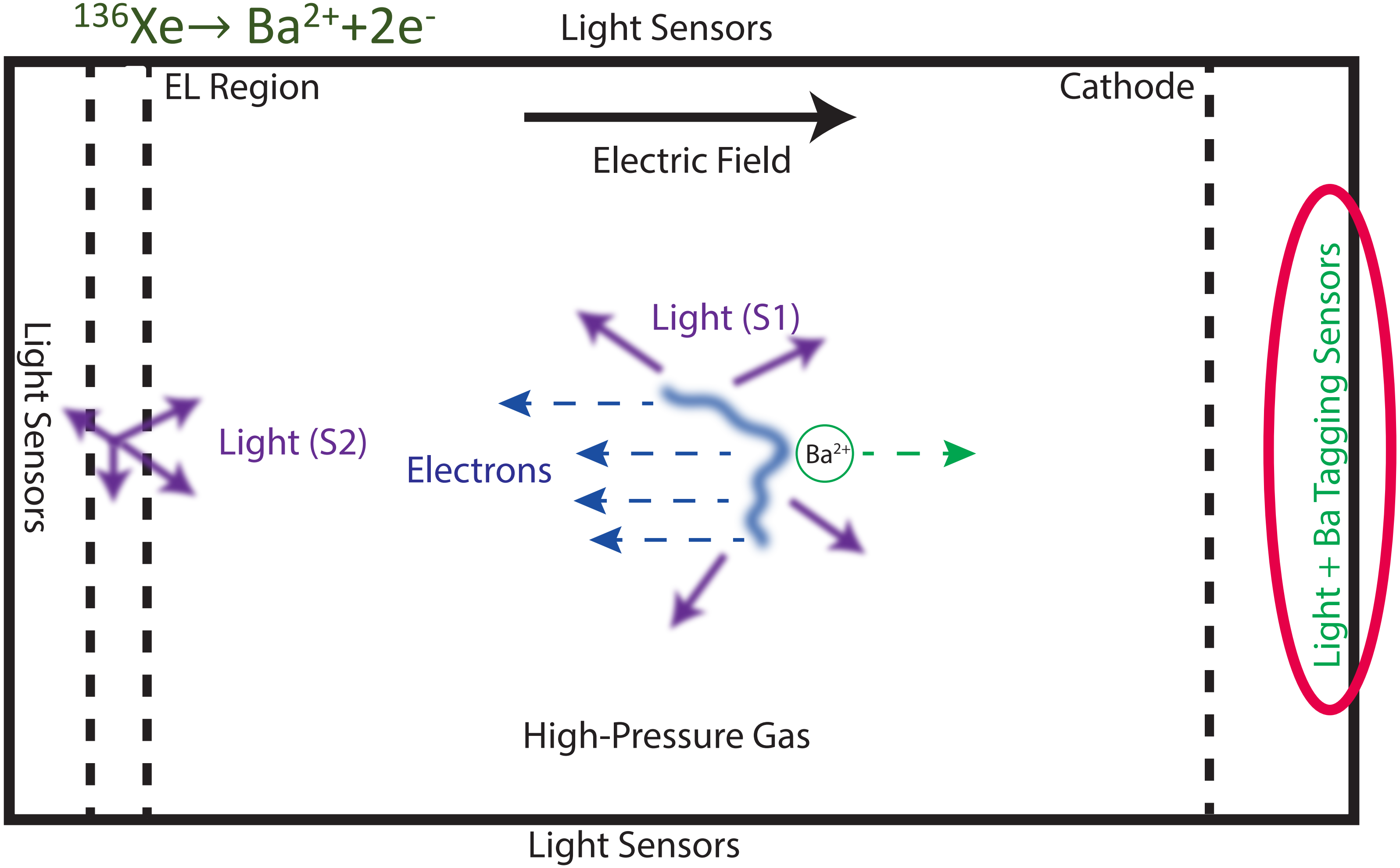



Metalens development for increasing light collection

# NEXT-BOLD: Second Tonne Scale Module

Background severely impacts your sensitivity → Tag the $Ba^{2+}$ with two electrons is a way to get a background free experiment!

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



# Single Molecule Fluorescent Imaging (SMFI)

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

Not-Fluorescent

↓

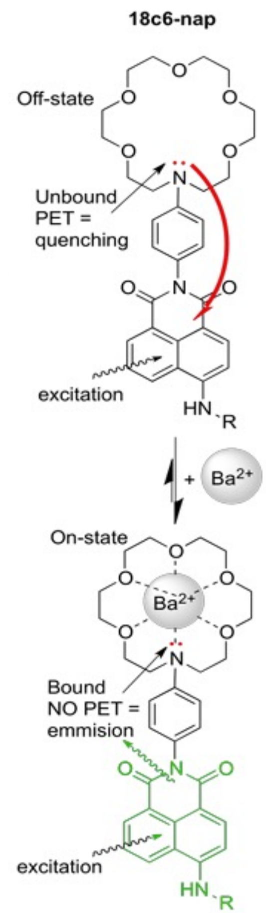
Add $Ba^{2+}$

↓

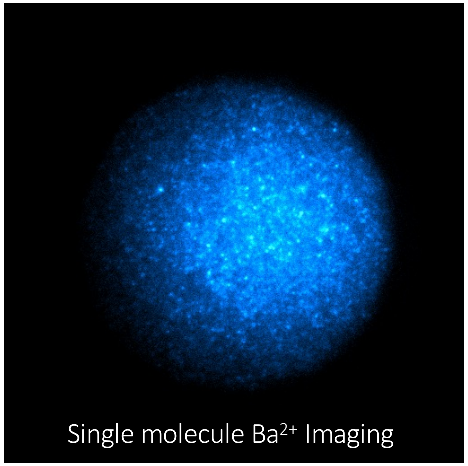
Fluorescent!

**Single-ion sensitivity!**

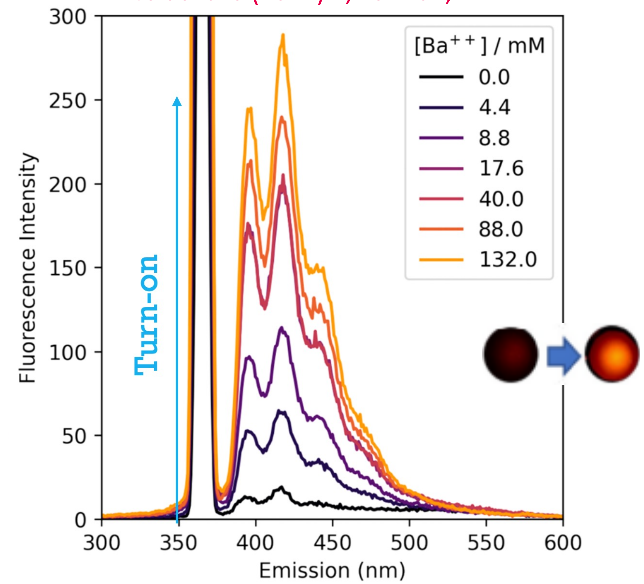
Several other types being developed including bi-color and phosphorescent




Dry-phase-sensor



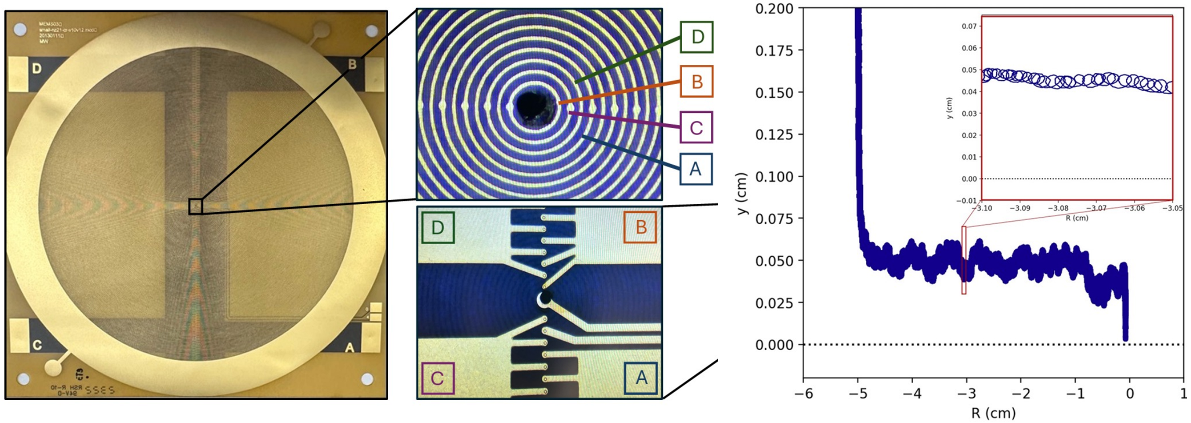

Phys. Rev. Lett. 120 (2018) 13, 132504;
ACS Sens. 6 (2021) 1, 192202;




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

# Latest Barium Tagging Technologies

Four-phased RF Carpet arxiv: 2501.18690




## RF Carpets

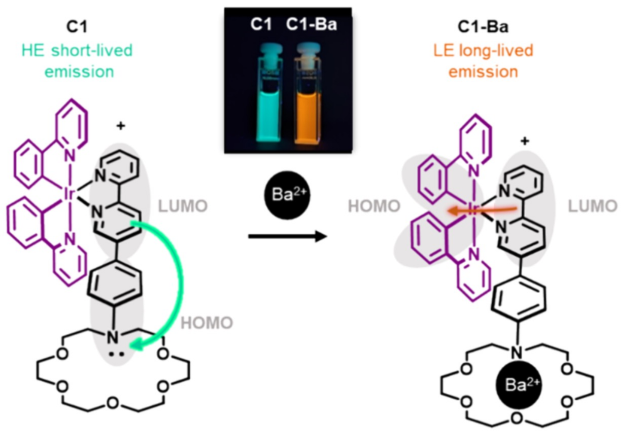
To transport barium ions to SMFI sensors

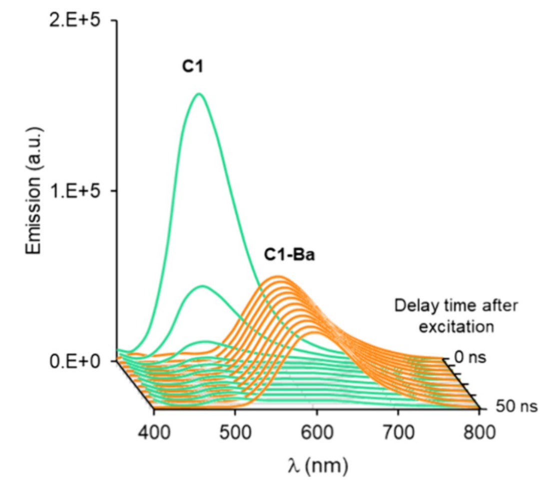
Demonstrated for the first time lateral transport of heavy ions in moderate-pressure gas (600 mbar)

## Time resolved sensors

Iridium compounds with dual fluorescent and phosphorescent emission

Phosphorescence is enhanced with addition of barium

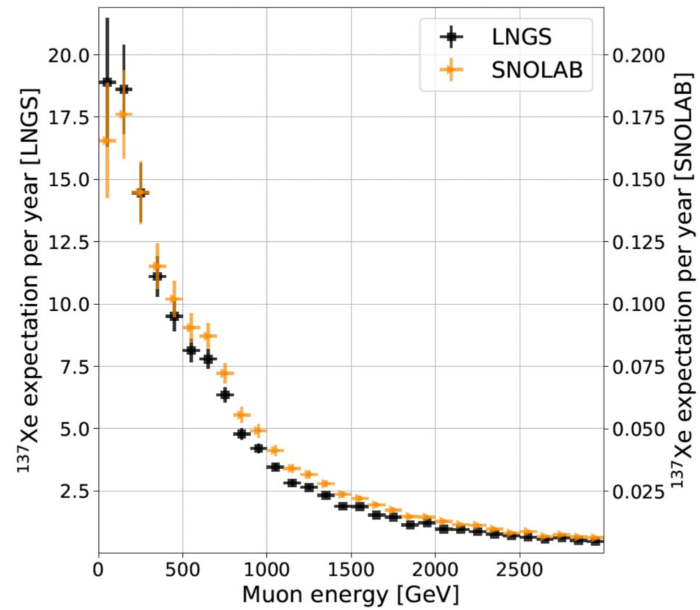



https://doi.org/10.1021/acssensors.4c01892

# NEXT-Tonne Scale Program

- Multi module system
  - LSC is enthusiastic to host NEXT-HD but this has not been fixed, we are open!
  - NEXT-HD/BOLD have different designs, so can deploy multiple modules at different sites with growing international effort e.g. LSC, SNOLAB
  - Enriched and depleted runs for background subtraction
- **Project Timescale:** estimated 2032 begin (well-suited to a 15 year plan)
- **SNOLAB is excellent for hosting a NEXT-tonne module**:
  - Deeper is better for cosmogenic backgrounds that induce 4 MeV $^{137}$Xe beta decays
  - Large caverns and world class facilities to support a 1 tonne module



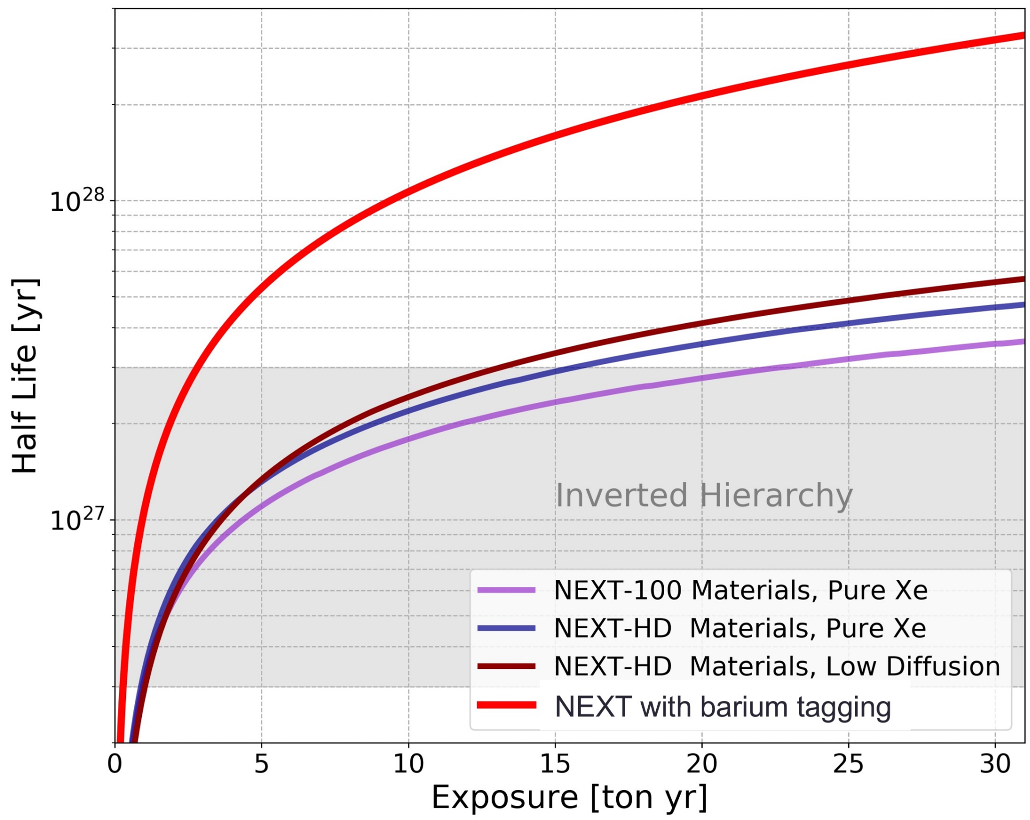

| Det. system | Acceptance $[10^{-8}]$ $^{208}$Tl | $^{214}$Bi | Background index $[\text{tonne}^{-1}\ \text{yr}^{-1}\ \text{ROI}^{-1}]$ |
|---|---|---|---|
| Field cage | 6.80(90) | 6.30(80) | $4.25 \times 10^{-3}$ |
| Readout planes | 6.80(90) | 7.80(80) | $1.36 \times 10^{-3}$ |
| Inner shielding | 4.50(70) | 1.20(70) | $37.23 \times 10^{-3}$ |
| Radon (cathode) | — | 0.10(10) | $2.72 \times 10^{-3}$ |
| $^{137}$Xe LNGS | 5.68(17) | | $6.73 \times 10^{-3}$ |
| $^{137}$Xe SNOLAB | | | $0.07 \times 10^{-3}$ |

$^{137}$Xe will be a sub-dominant background at SNOLAB

# Sensitivities

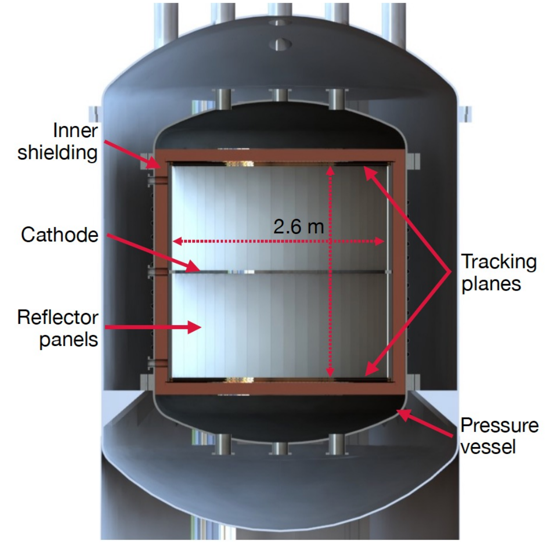
- Tonne scale sensitivities will be able to reach $10^{27}$ yr with a NEXT-HD module

- Significant improvement possible with the introduction of barium tagging



# Detector Facilities

- Dimensions
  - 3 m water shield on all sides, with possible doping to improve neutron captures
  - 2.6 m diameter/length active volume

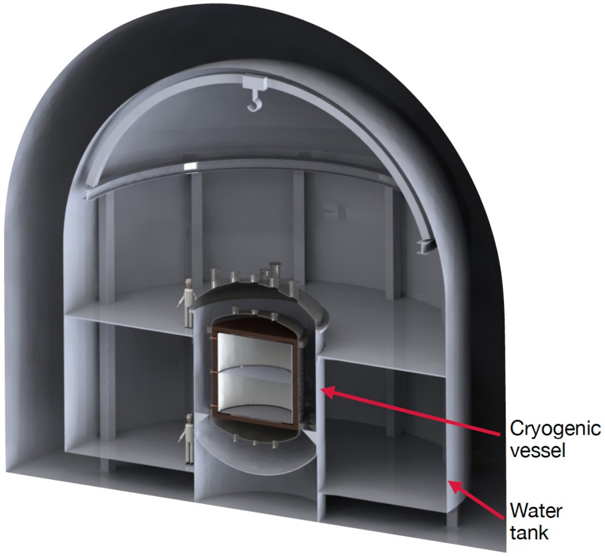



Facility Management:

- High-pressure gas management and emergency recovery
- Large volume for siting detector
- Large detector components such as end caps for supporting pressure
- Clean room entrances, equipment, and management
- Working areas underground (installation), surface (part storage), and off-site (assembly and preparation)

Personnel Support

- Radioactivity screening support for detector components
- Engineers on site for detector construction support



# Community Importance

- A discovery of $0\nu\beta\beta$ will have profound implications for our understanding of the Standard Model and particle physics
  - If discovery made, gas technology may also be able to extend physics reach such as model discrimination with topology

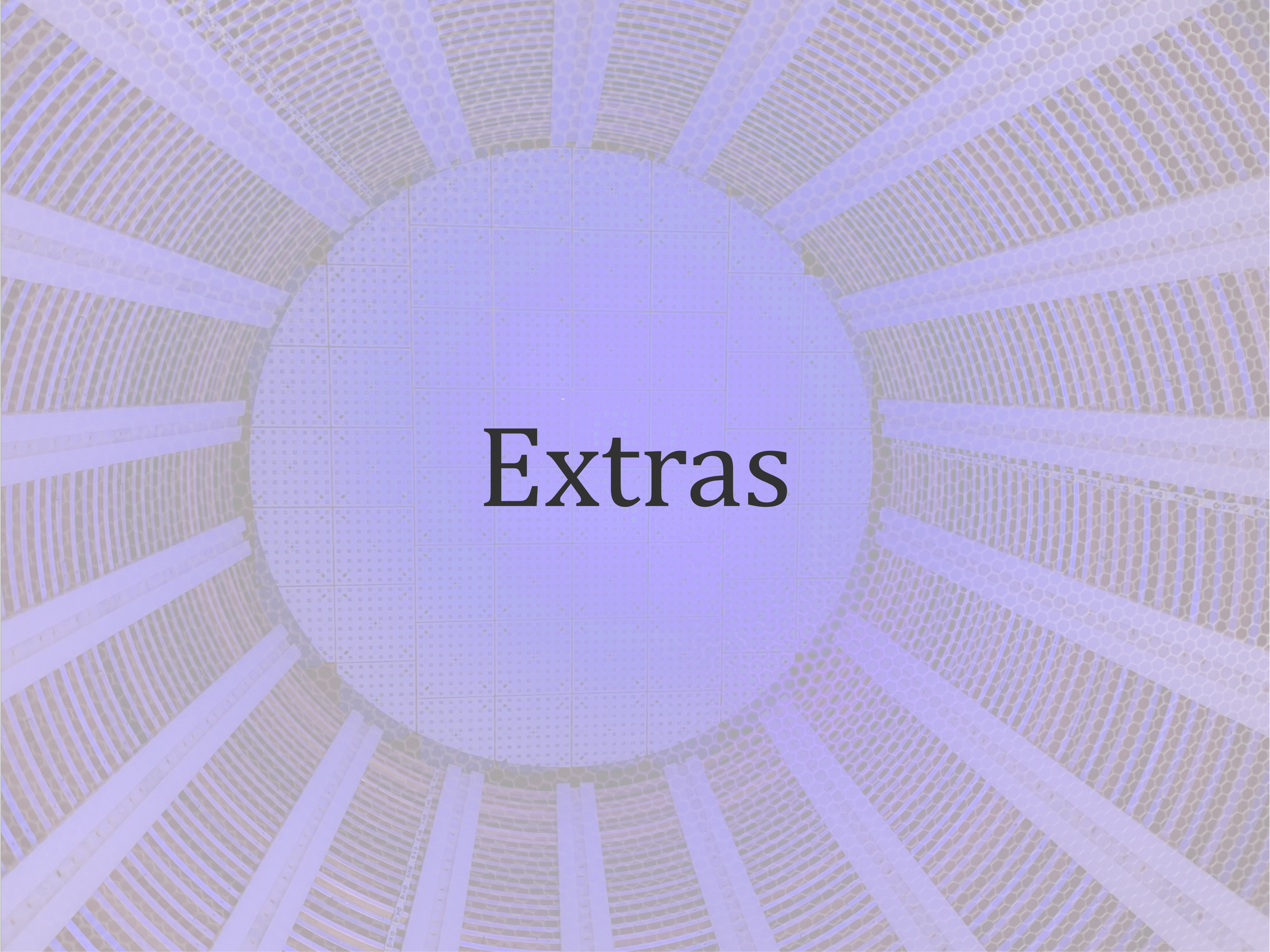
- In light of recent events, there is no longer a xenon-based $0\nu\beta\beta$ decay experiment hosted in North America
  - Great opportunity for SNOLAB to host
  - This bolsters the already huge investments in xenon-based experiments the US and Canada have already made
  - Expand the international extent of NEXT with new groups to actively contribute to NEXT detector technologies

# Summary

- The NEXT-100 experiment is currently under operation and taking physics data

- A NEXT-tonne scale detector will follow this with construction expected to begin 2032

- A NEXT-tonne module at SNOLAB is an ideal site-location:
  - Bringing a tonne scale xenon $0\nu\beta\beta$ decay experiment to North America
  - Building on existing investment in xenon detector technologies
  - Expand the NEXT international collaboration
  - Negligible backgrounds from Cosmogenics
  - World class facilities

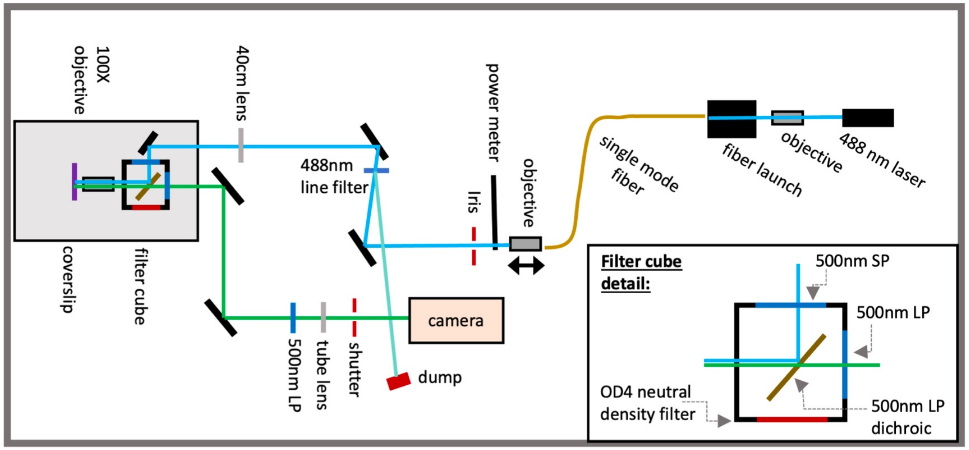


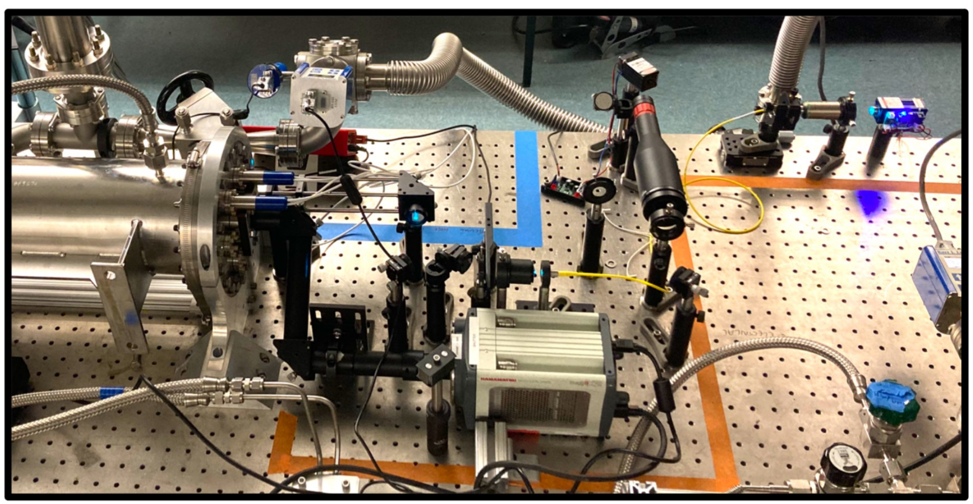
# Extras

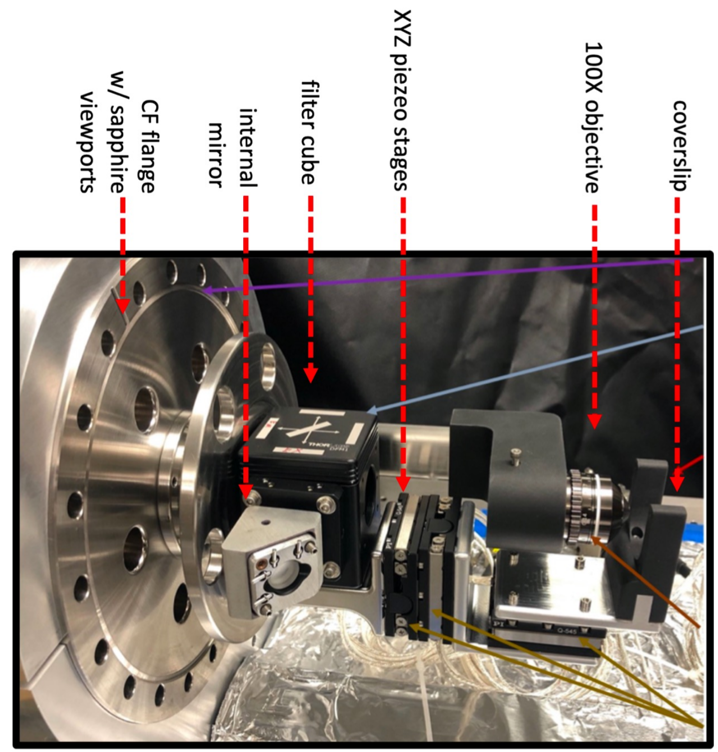
# High Pressure Microscope

*Nature Communications* **volume 15**, Article number: 10595 (2024)

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

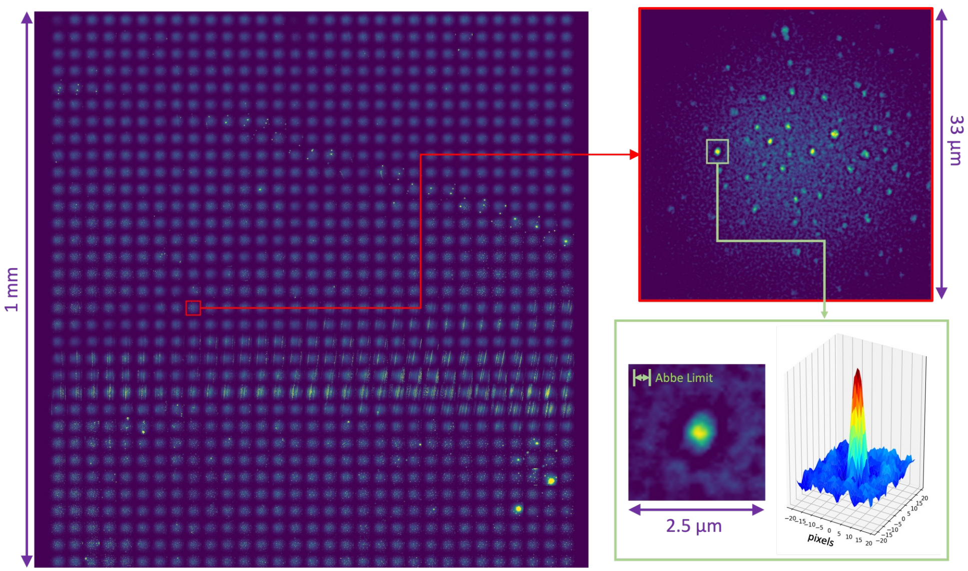





Microscope has a 5x5mm$^2$ scan area with 1x1mm$^2$ scan area demonstrated at pressure

# Microscope scanning and focus

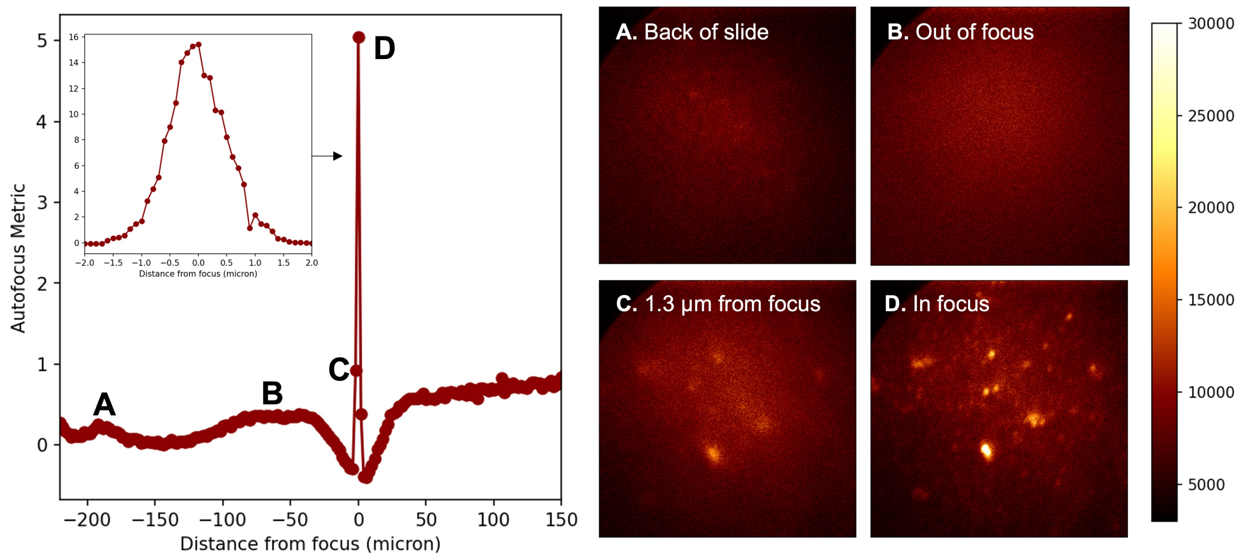



*Nature Communications* **volume 15**, Article number: 10595 (2024)

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

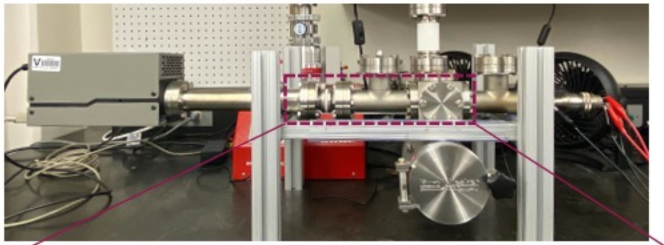
Maintains the focal plane with 1um precision across 1mm, at 150um working distance

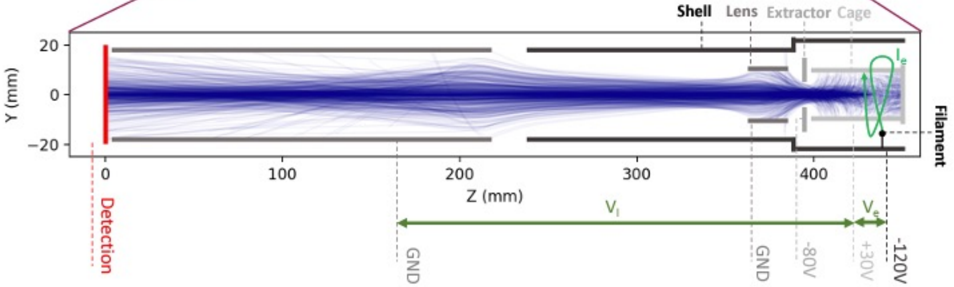


# Characterizing the sensors

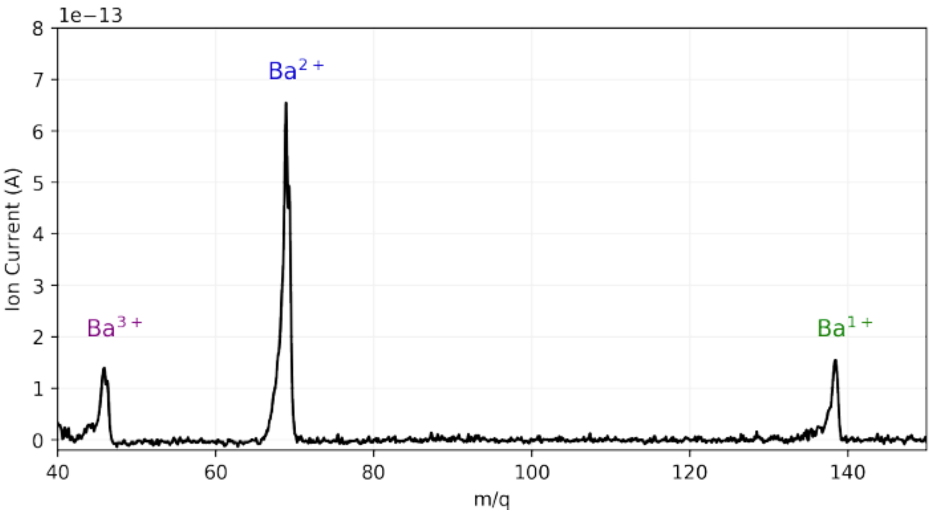
Navarro et al JINST 18 P07044 (2023)

- Demonstrating capture and fluorescence requires a controlled $Ba^{2+}$ beam in xenon gas
  - ⇥ Not trivial!





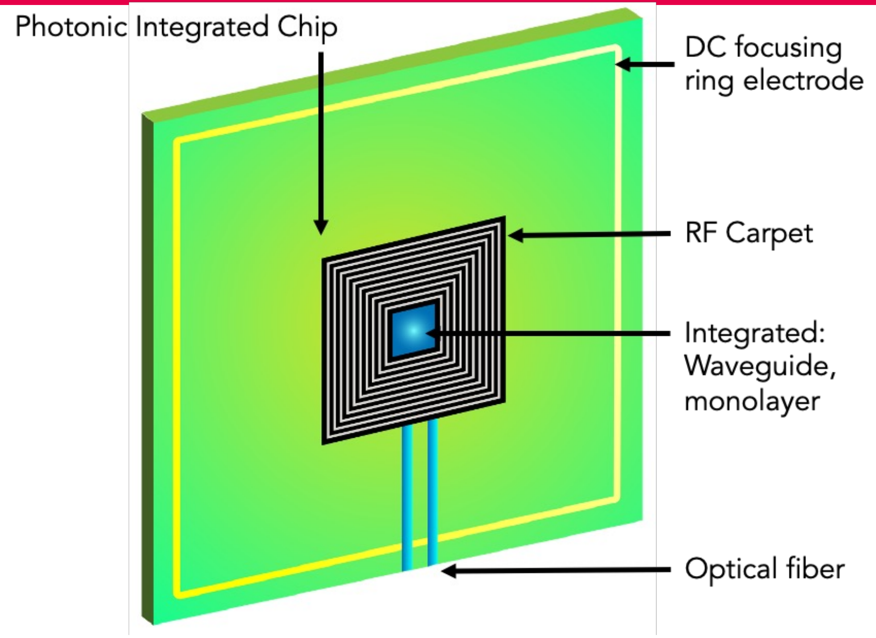

- We have developed a tuneable metal ion beam in a bench-top sized system




- 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
- Integrated light-guides
  - Similar techniques employed in trapped ion qubits
- Tile the readout plane with these chips




First prototype RF chips!