The NEXT project

J.J. Gomez Cadenas on behalf of the NEXT collaboration, May, 2021

The NEXT Collaboration

co-spokespersons:
David Nygren
JJ Gomez Cadenas

LSC
Laboratorio Subterráneo Canfranc

USA

University of Texas Arlington
Argonne National Laboratory
Harvard
Fermilab
A&M
Iowa State University
Pacific Northwest National Laboratory

Spain

DIPC
IFIC Institut de Física Corpuscular
Universitat de Girona
USC Universidade de Santiago de Compostela
Universidad de Zaragoza
Universitat Politècnica de València

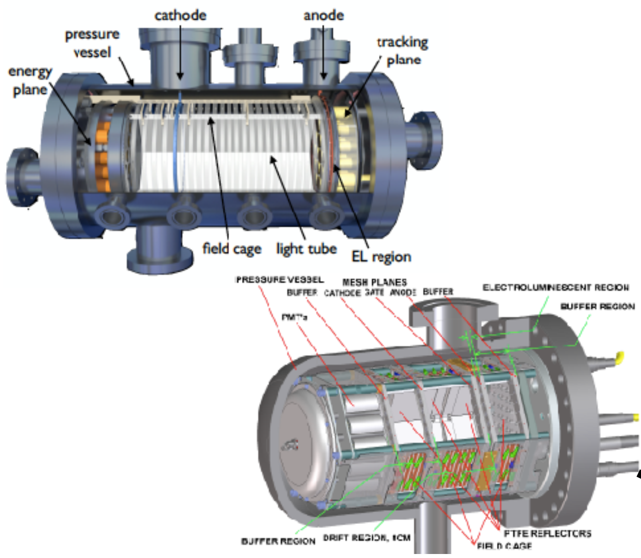
Portugal, Israel, Russia, Columbia

U C
Ben-Gurion University of the Negev
UAN Universidad Antonio Nariño
JINR Dubna
universidade de aveiro

Germany

Justus-Liebig-Universität Giessen

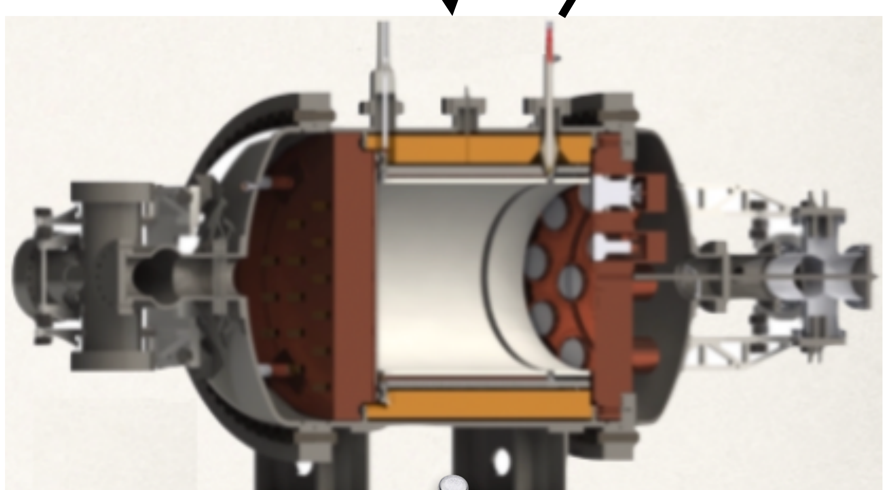
The NEXT program



Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept

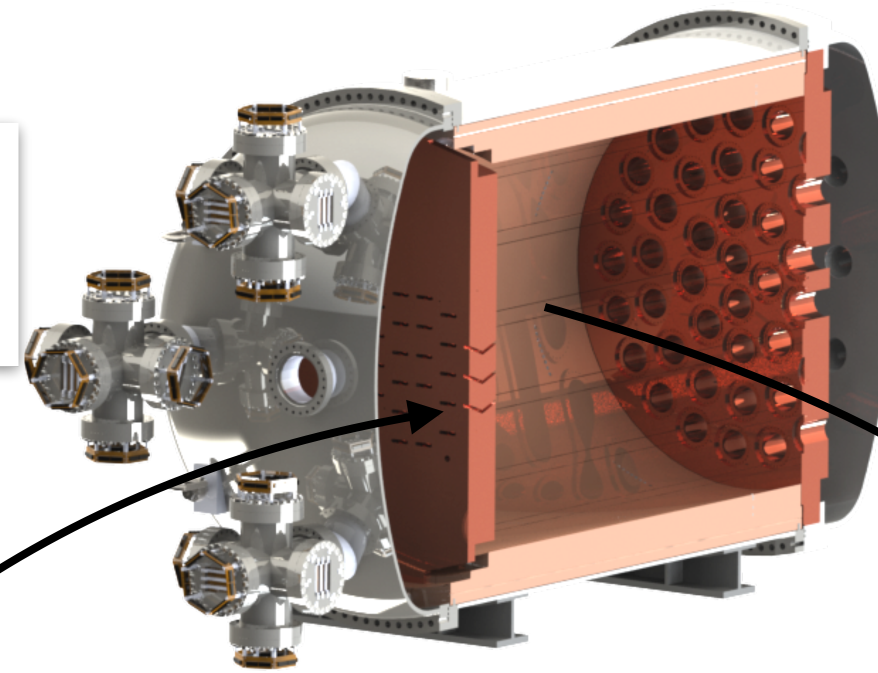
NEXT-White (~5 kg)
[2015 - 2018]



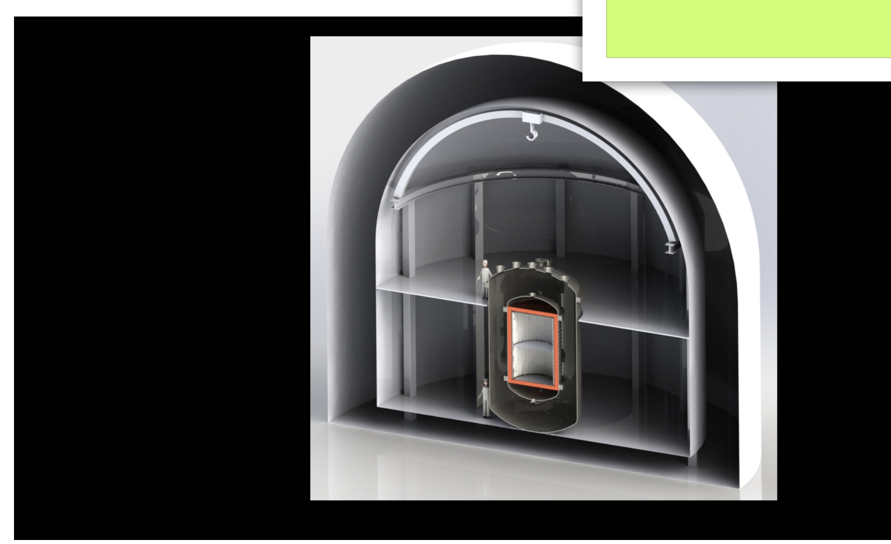
Underground and radio-pure operations, background, ββ2ν

NEXT-100 (~100 kg)
[2020 - 2024]

ββ0ν searches (10^{26} y)
Show extrapolation to ton scale

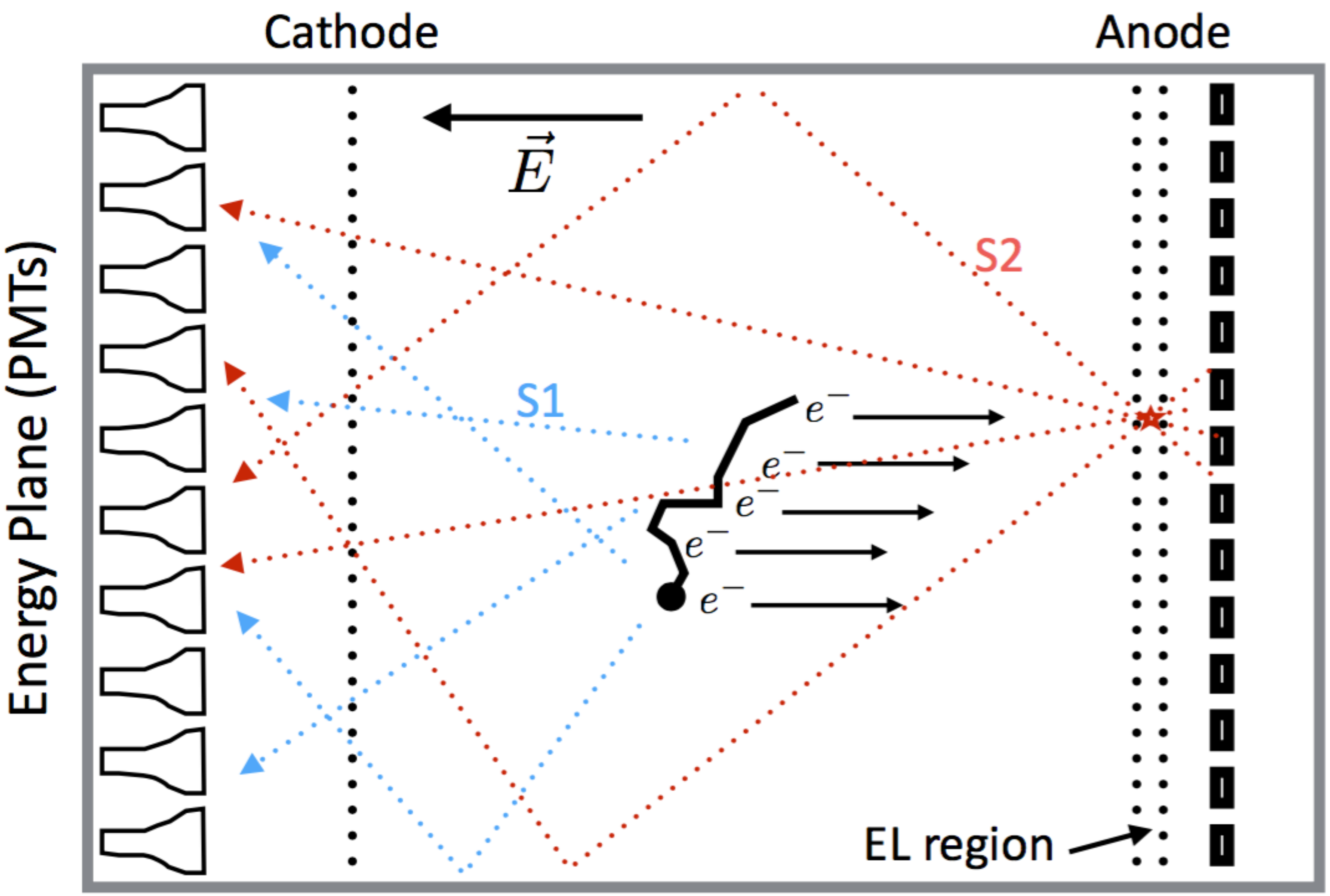


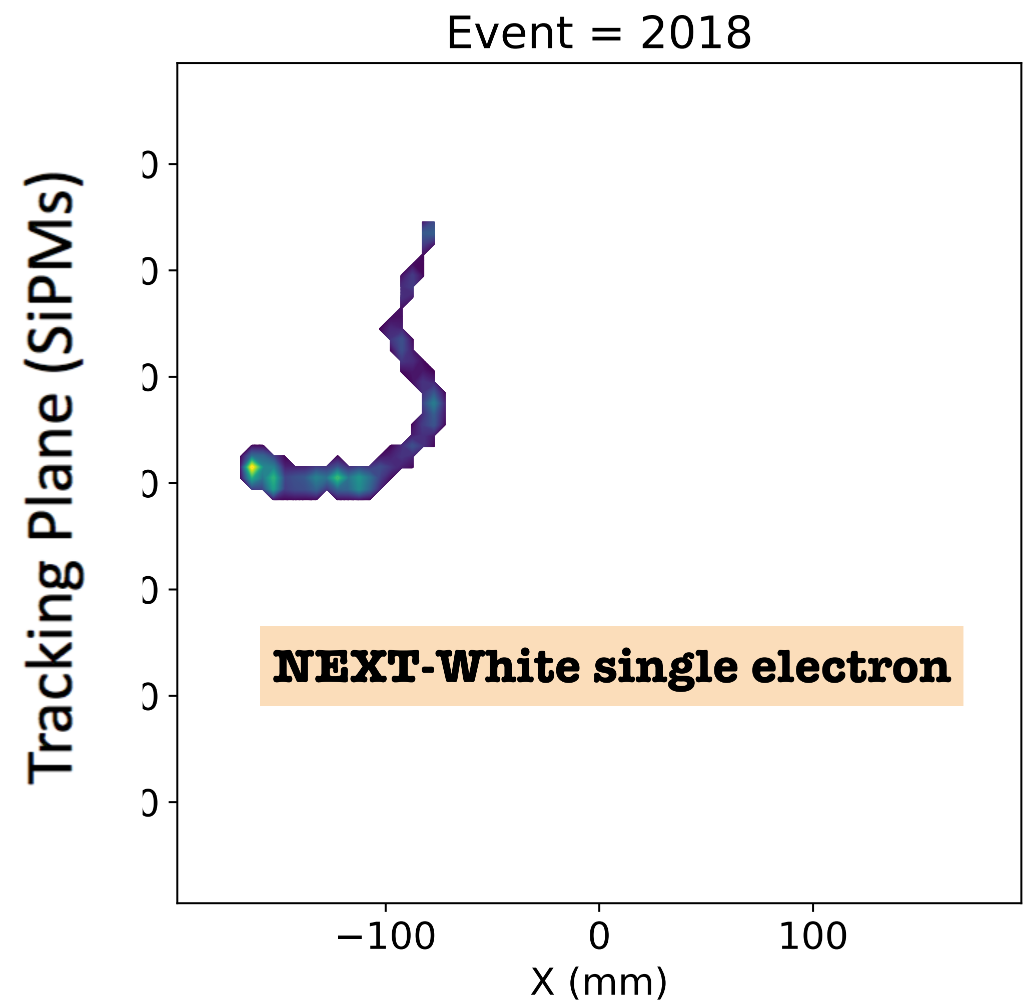
NEXT-HD/BOLD
[2025-2035…]

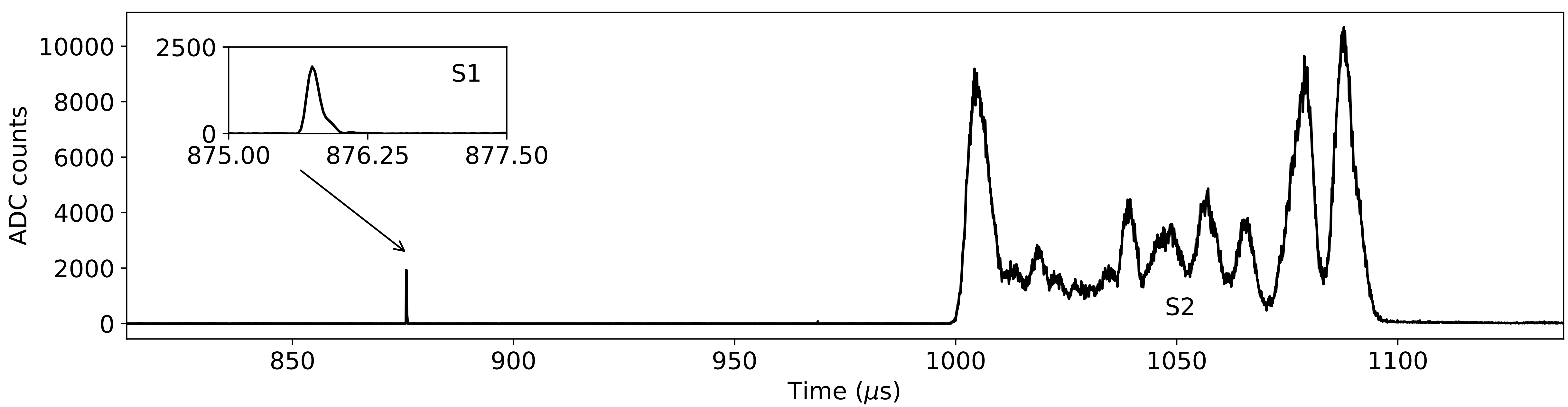


ββ0ν searches (ββ0ν searches (10^{27}- 10^{28} y)

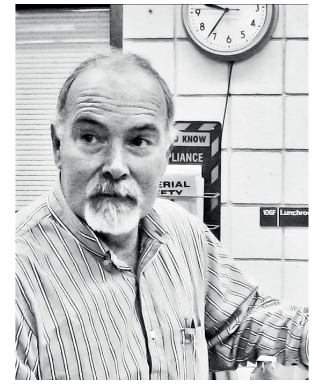
Principle of operation

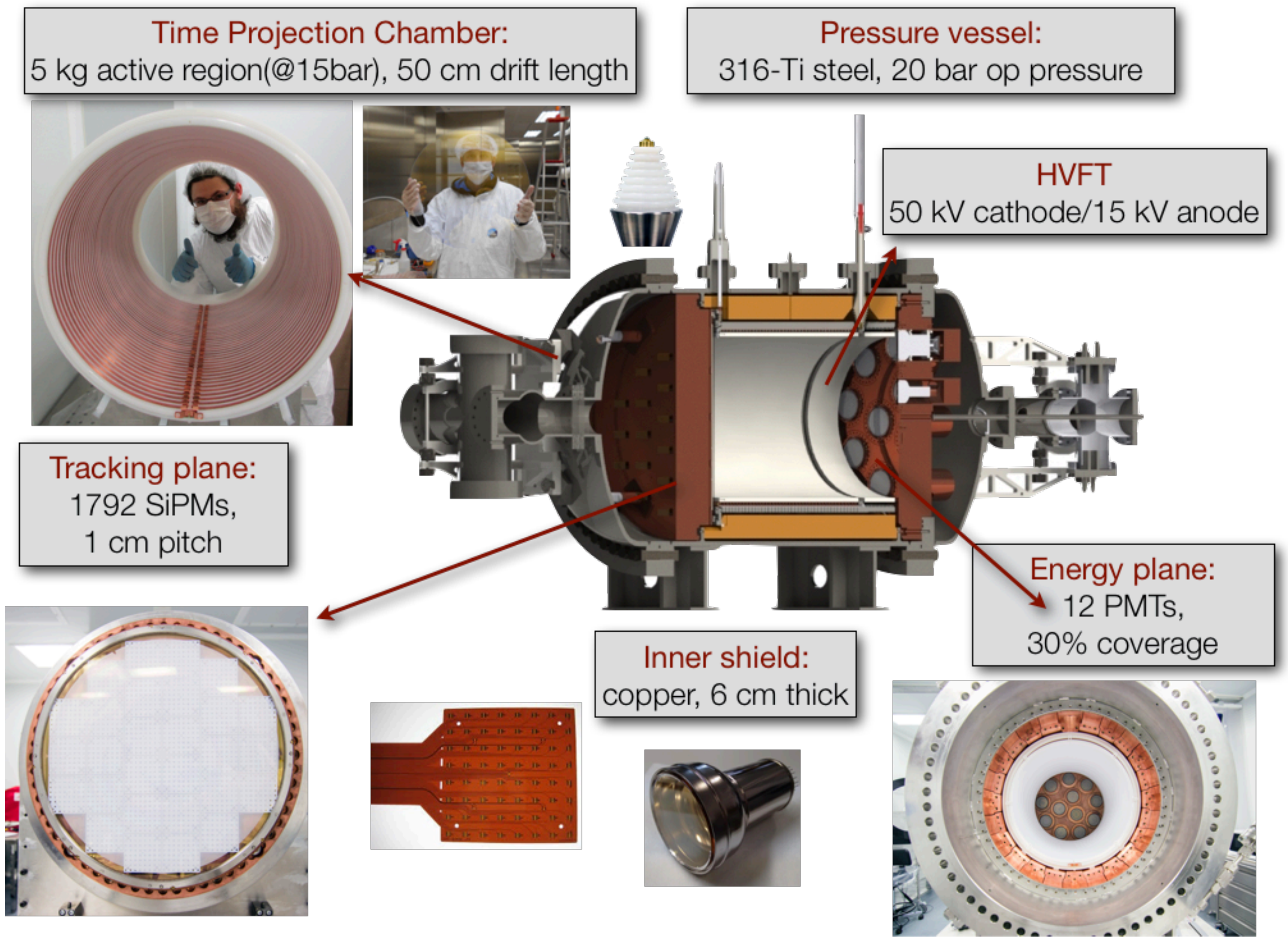






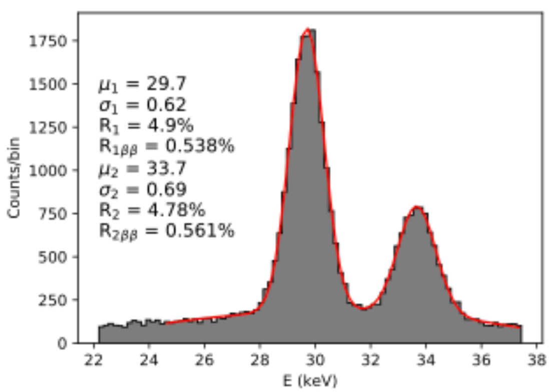
NEXT-White

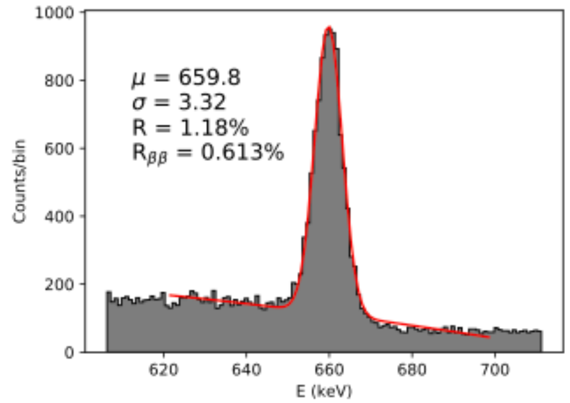


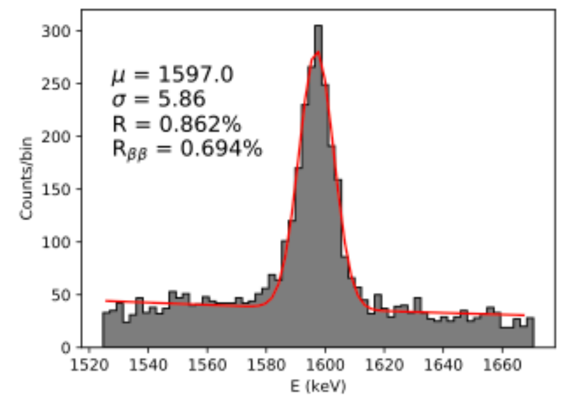


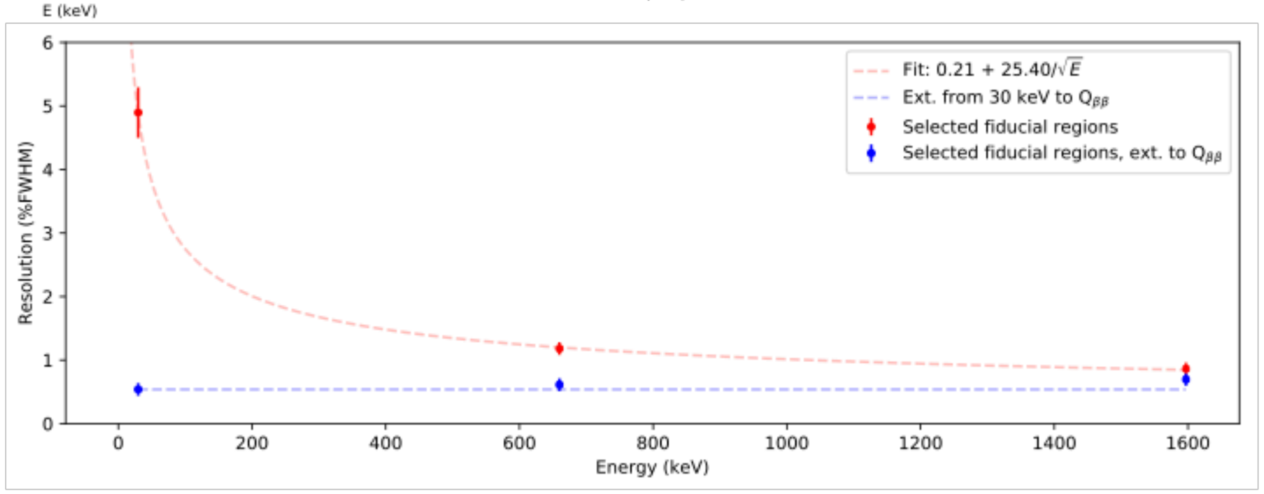
- A full scale demonstrator of the NEXT technology (started in 2016)
- Energy resolution, topology, lifetime, measured $\beta\beta 2\nu$ mode

NEXT: Resolution

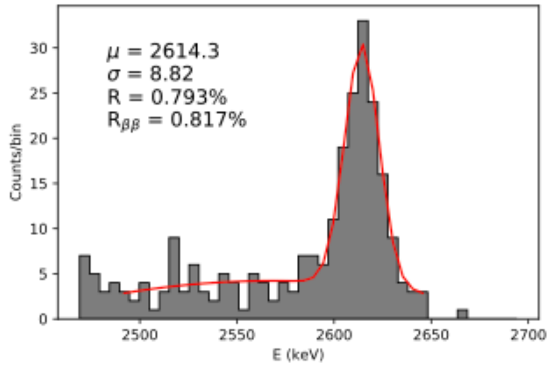








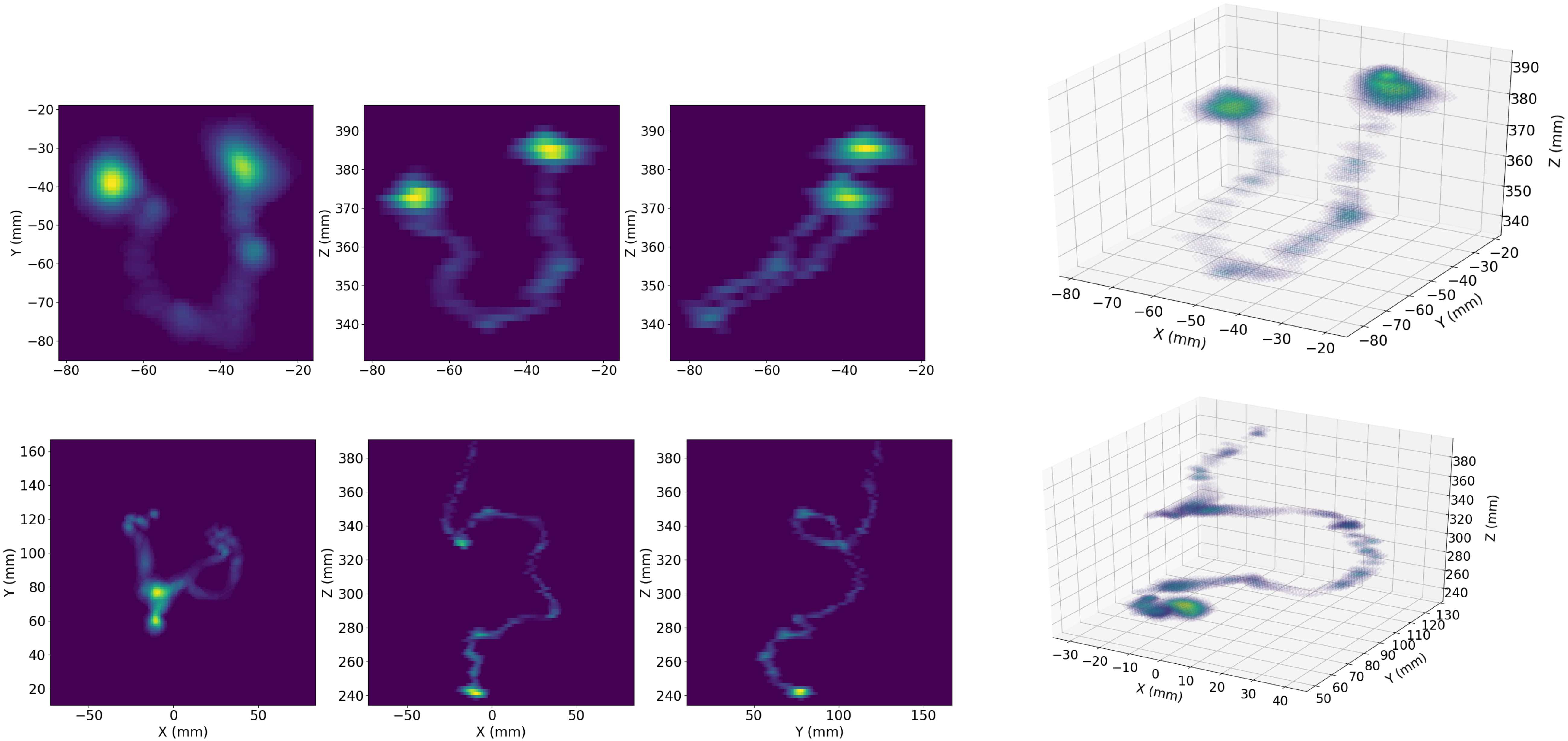
Energy resolution



Energy resolution at $Q_{\beta\beta} \sim 0.8\,\%\,FWHM$ dominated by track corrections (0.5 % FWHM por point-like tracks). Room for improvement.

Topological signature

Single and double electrons from $\beta\beta2\nu$ analysis with energies near $Q_{\beta\beta}$

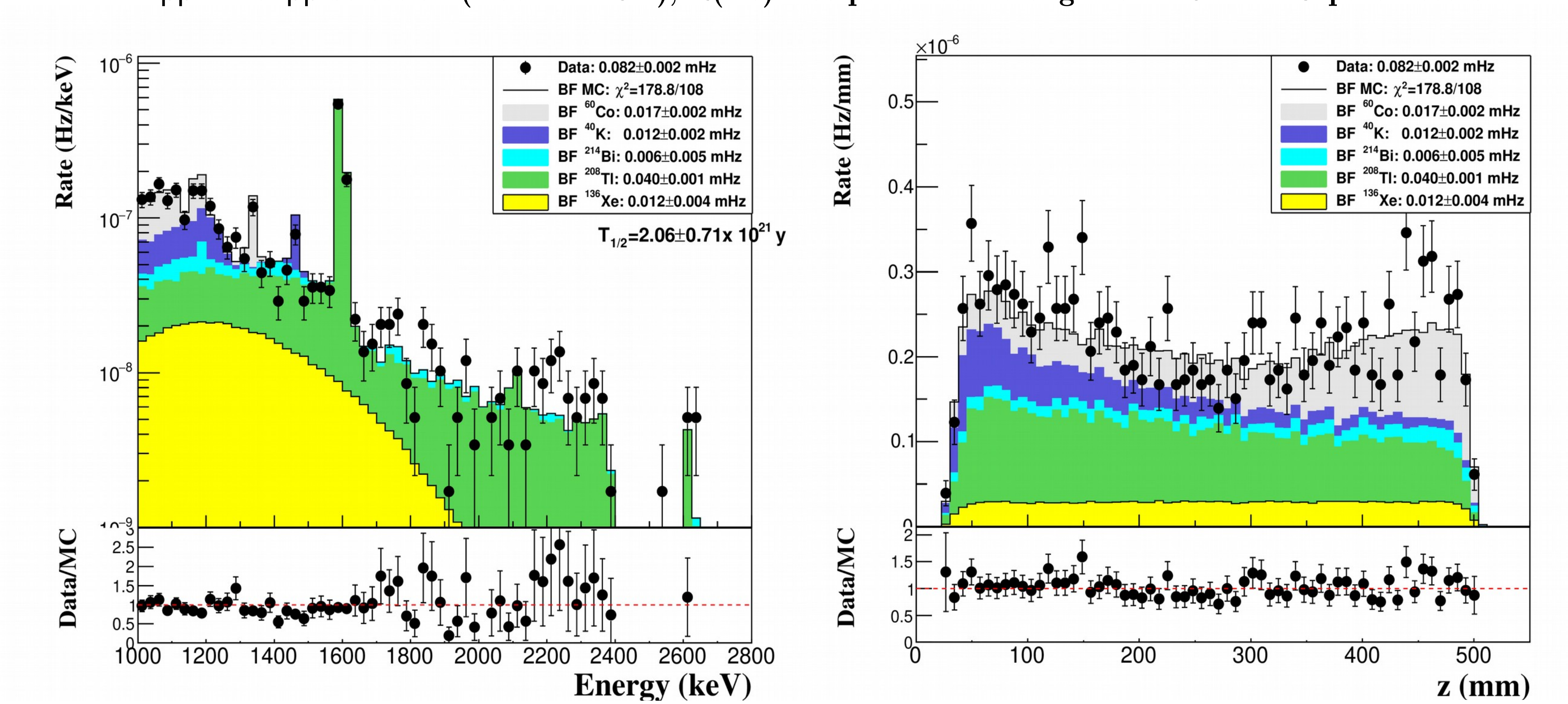


Measurement of $\beta\beta2\nu$ mode

- Run-V: enriched xenon: signal + backgrounds

ββ EZ Fit: Run-V

- ββ2ν fit: ββ selection (DocDB 1182), R(Xe) free parameter along with 4x3=12 BG parameters



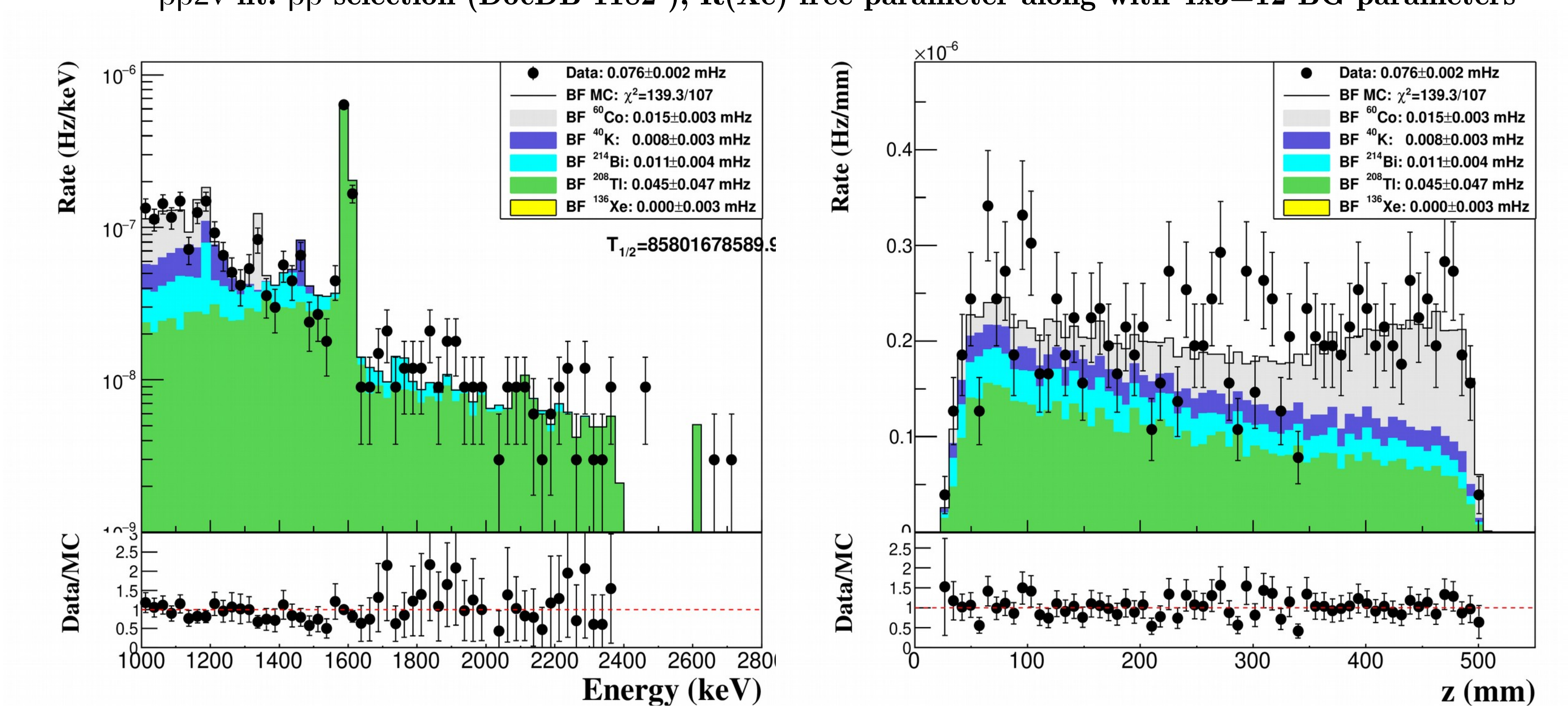
- $T_{1/2}$= (2.06±0.71) x 10^{21} year, χ^2/dof = 1.66
- Weakness: strong Bi214-Xe136 correlation and the bad χ^2 (possible bias?)

Measurement of $\beta\beta2\nu$ mode

- Run-VI: depleted xenon: only background

ββ EZ Fit: Run-VI

- ββ2ν fit: ββ selection (DocDB 1182), R(Xe) free parameter along with 4x3=12 BG parameters



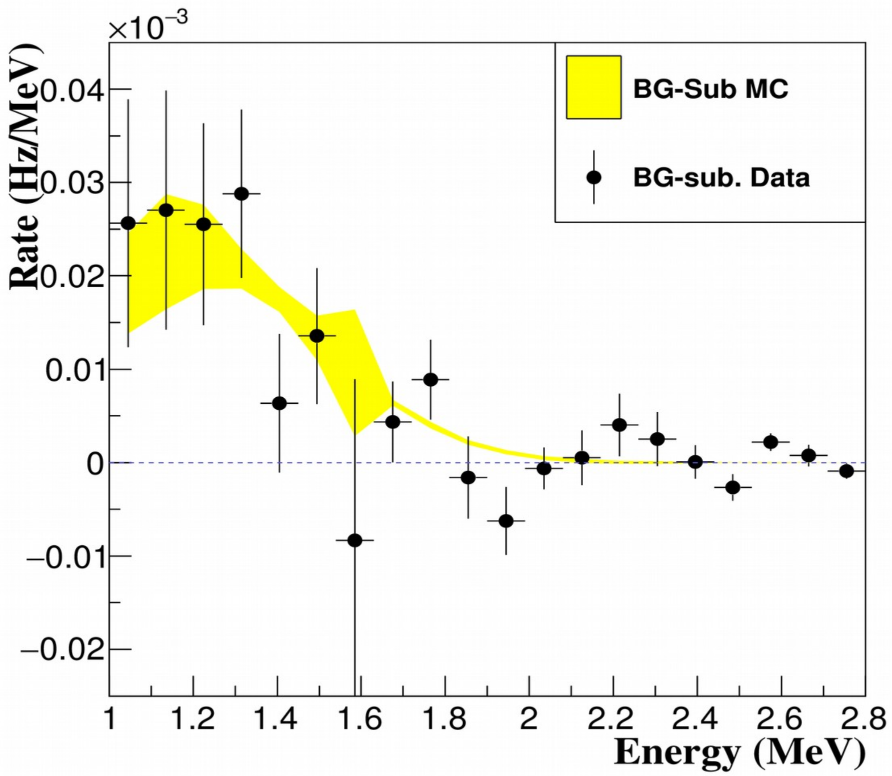
- $T_{1/2} = \infty$ (R(Xe136)=0), $\chi^2/\text{dof} = 1.30$

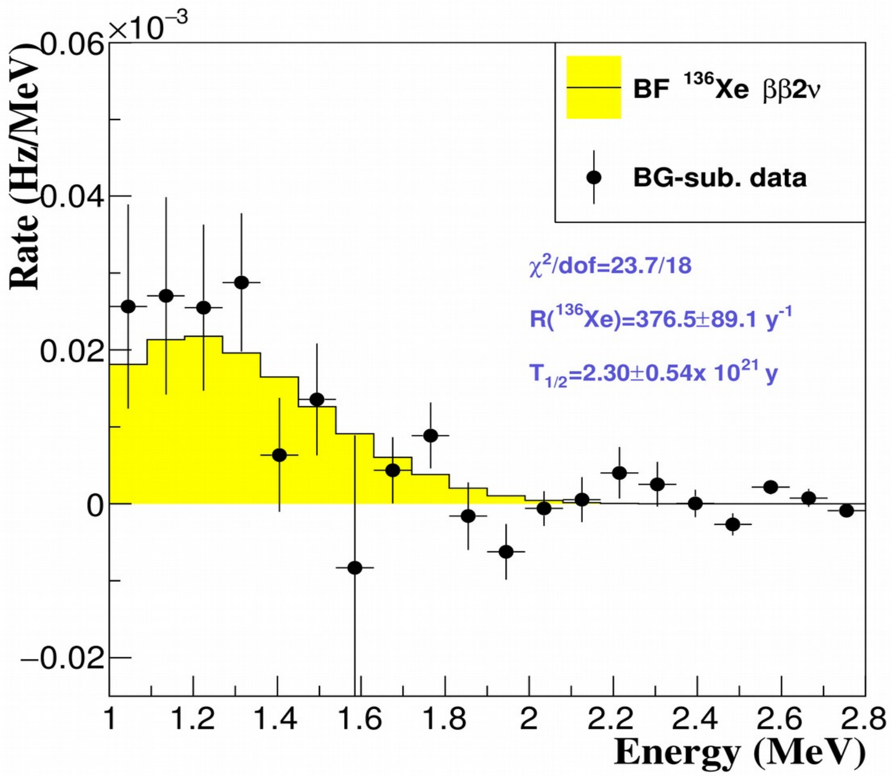
Measurement of $\beta\beta2\nu$ mode

- Combination: background model independent.

BG-Subtracted ββ2ν Spectrum

- ββ2ν rate from fit to MC, accounting for statistical uncertainty and RunV/RunVI 3.6% normalization systemati

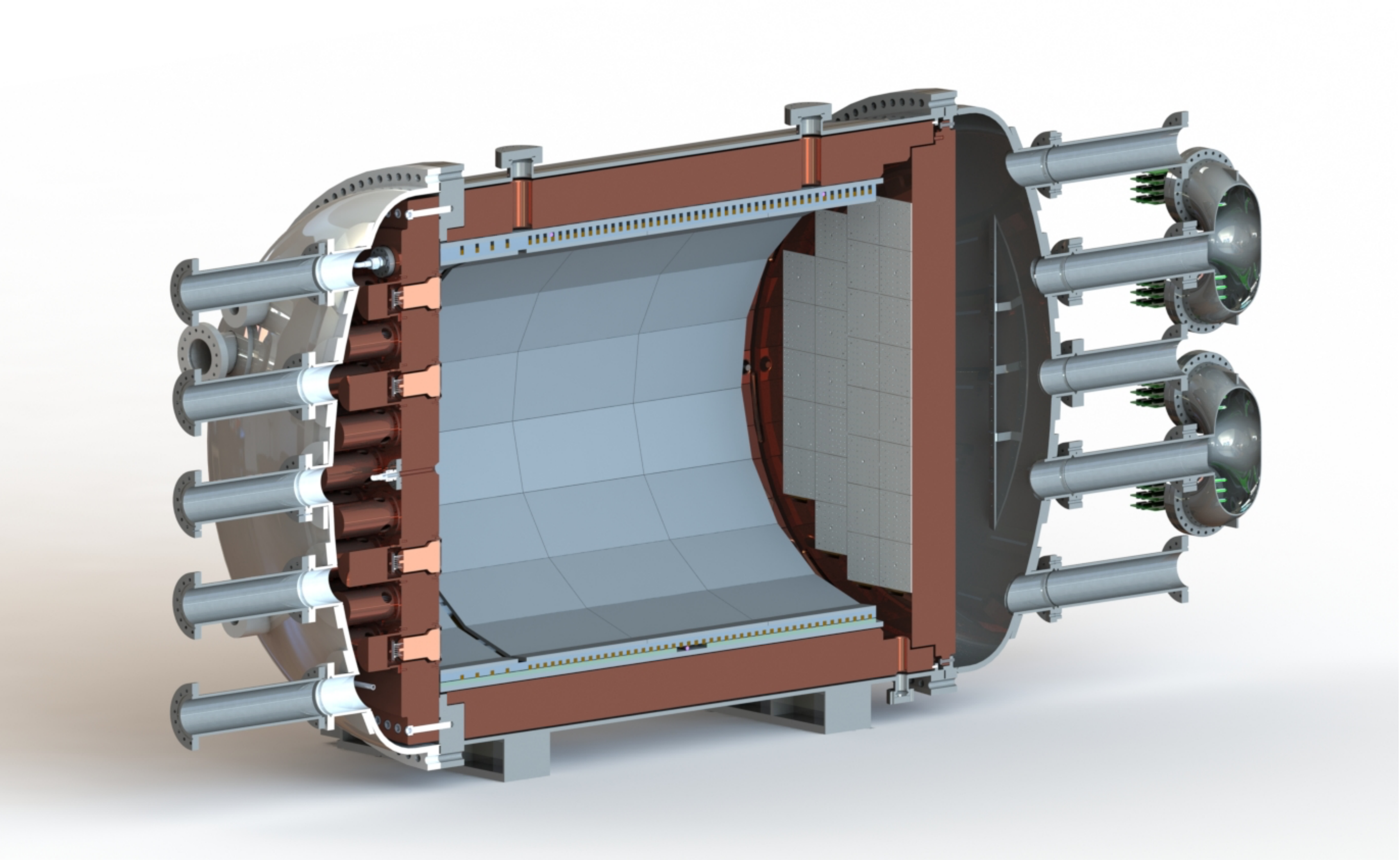


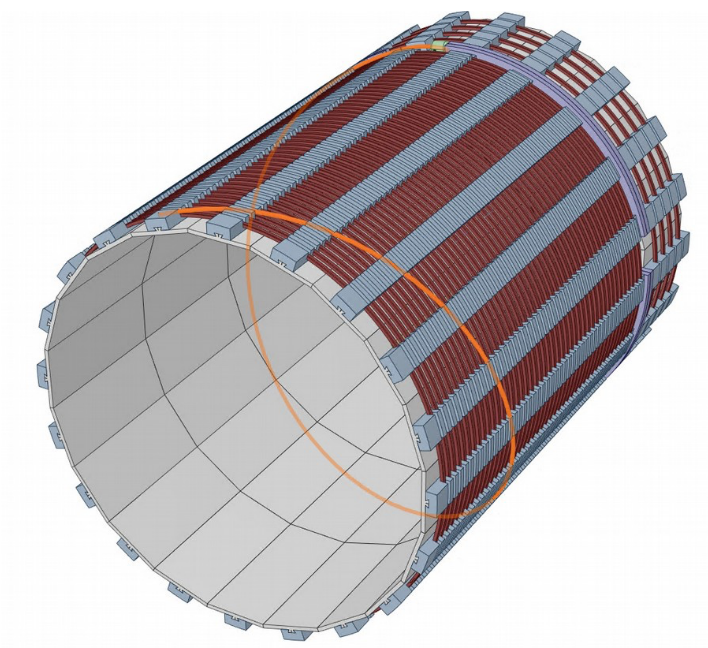


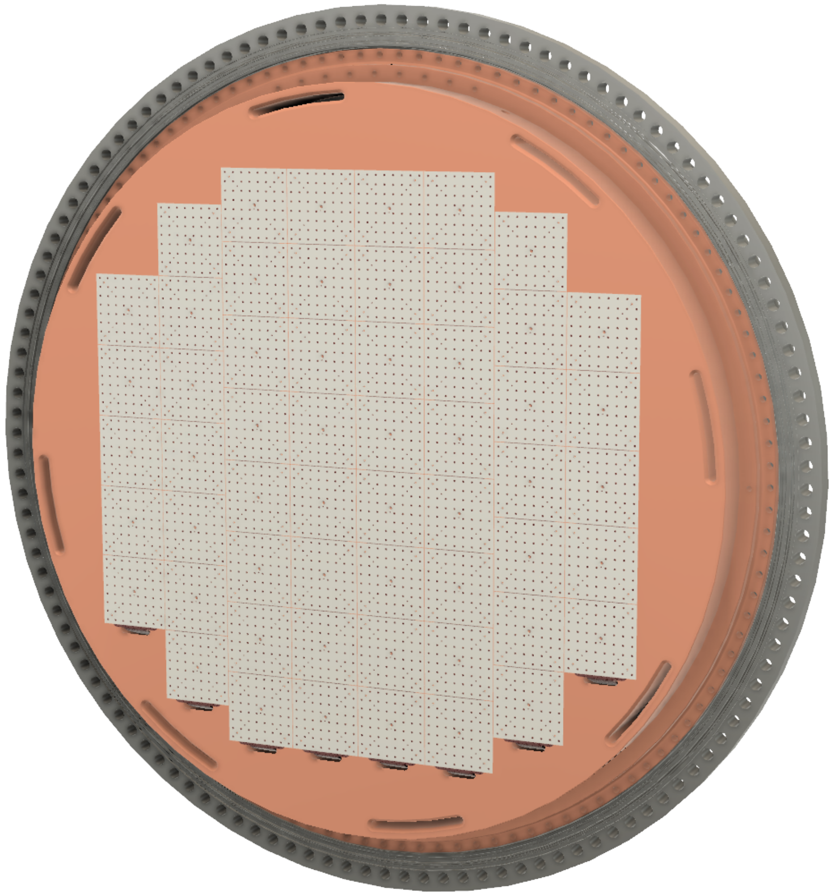
- BG-model-independent measurement: $T_{1/2} = (2.30^{+0.58}_{-0.51}) \times 10^{21}$ year, $\chi^2/\text{dof} = 1.32$ (p-value=16.5%) $\eta_{norm} = 0.99 \pm 0.03$ [input: 1±3.6%]

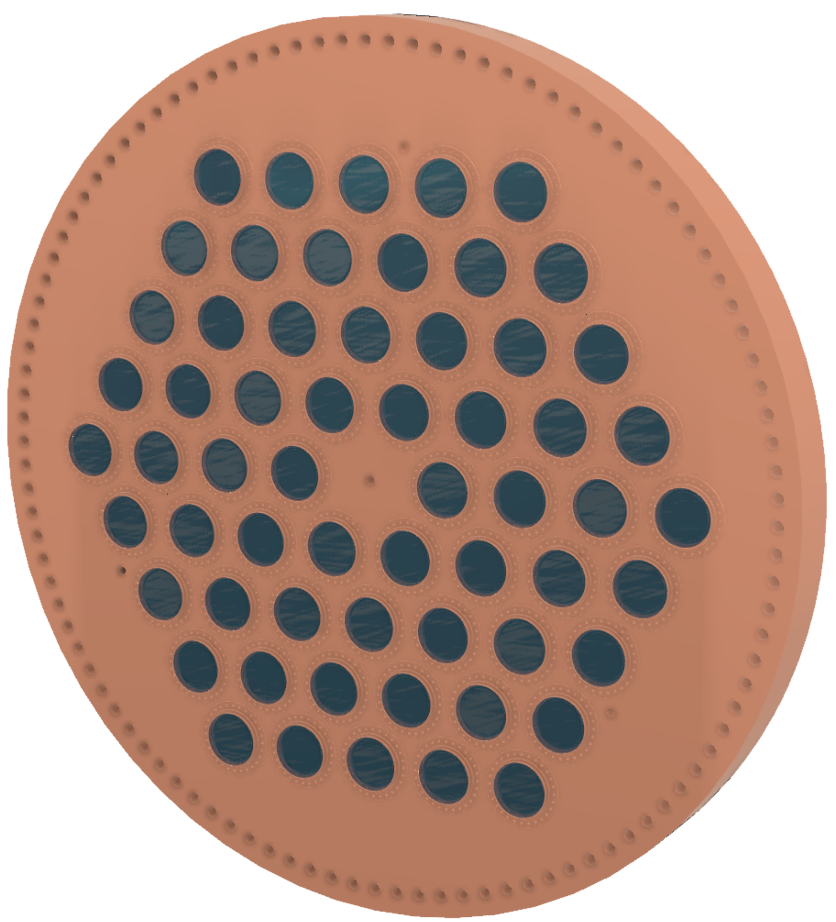
- HPXe makes feasible to measure backgrounds from the data themselves, thus reducing uncertainties associated with the background model.

NEXT-100 (construction under way)



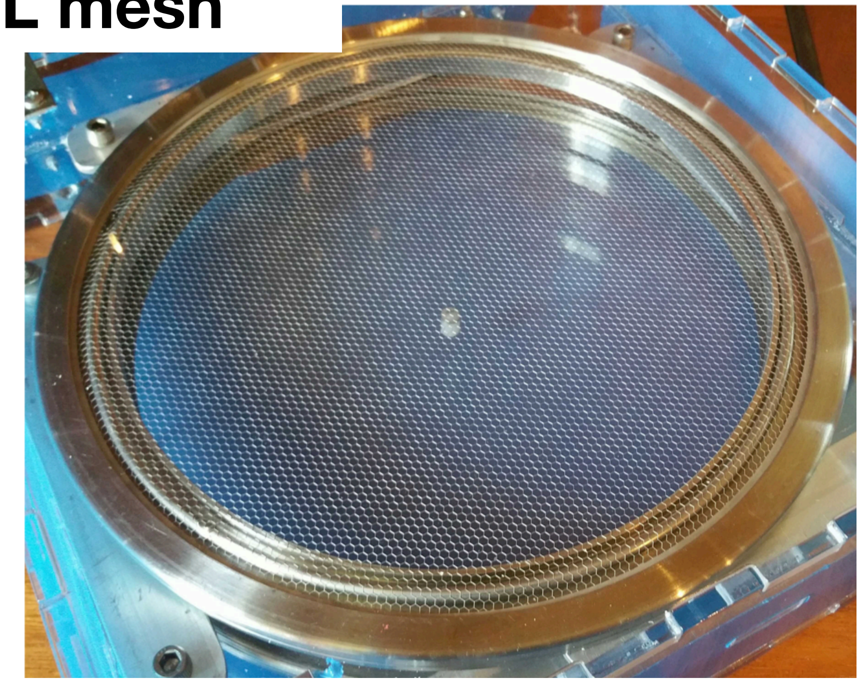




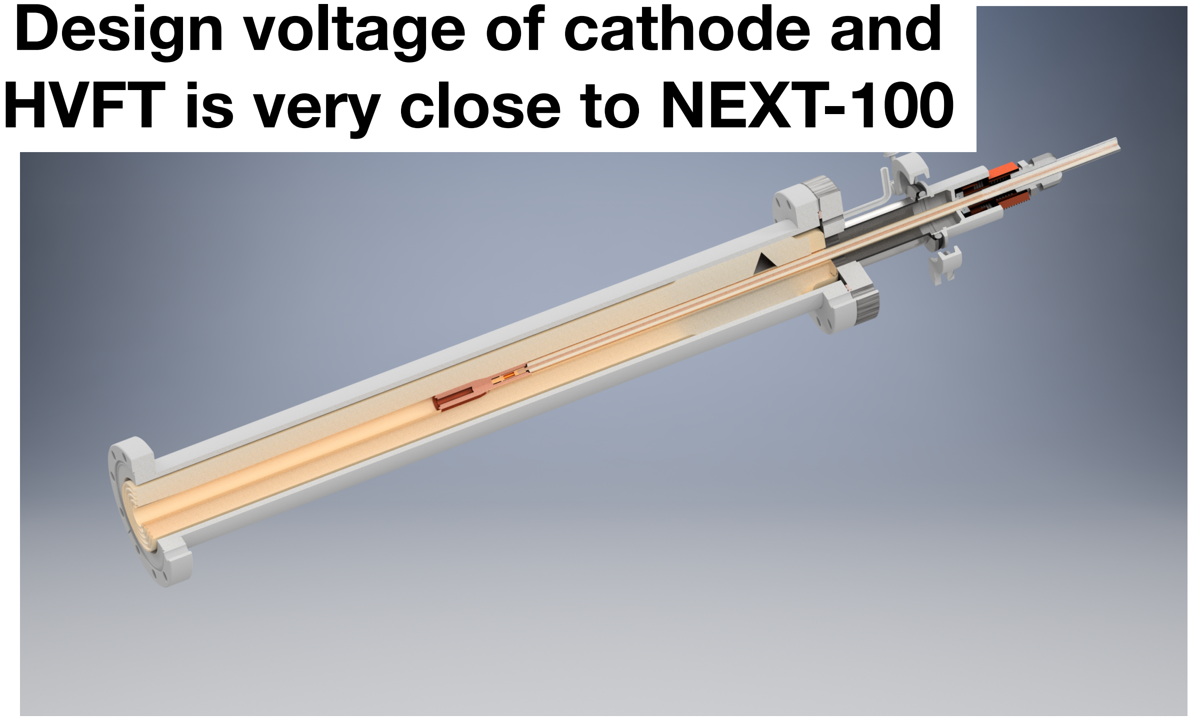


Solutions to be implemented in NEXT-100

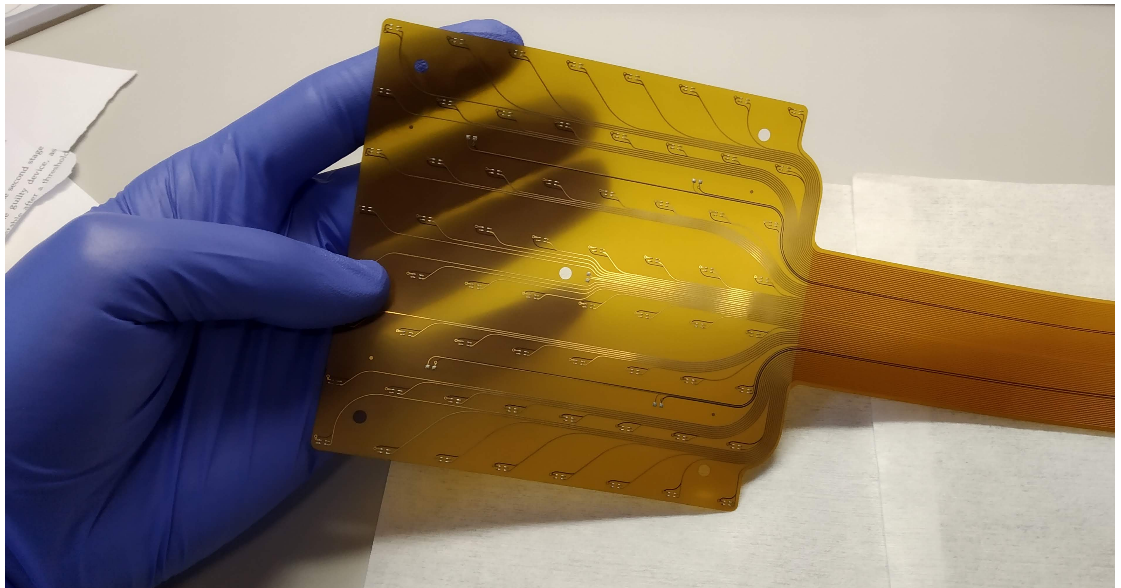
EL mesh

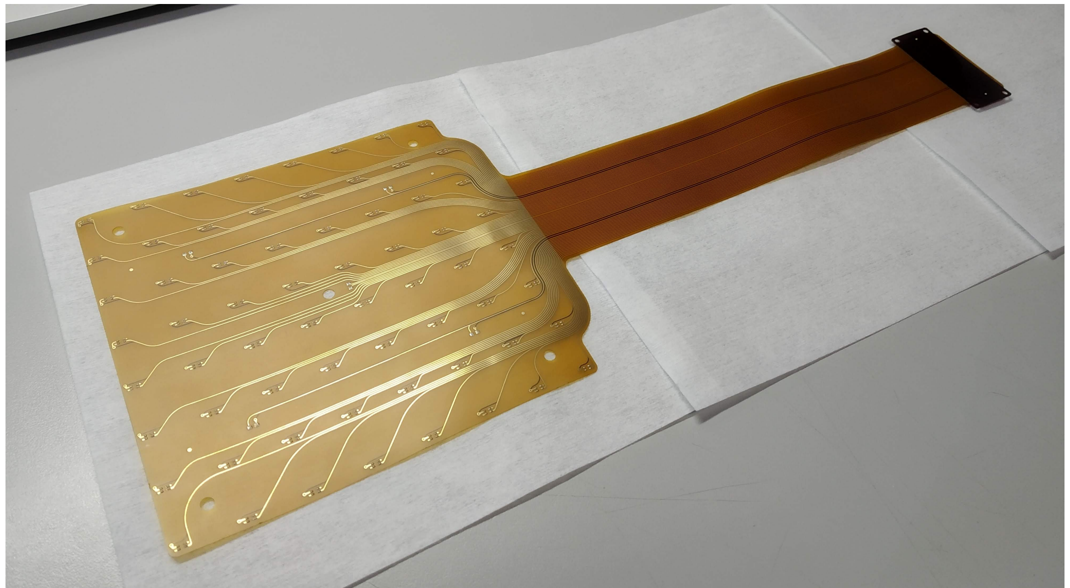


Design voltage of cathode and HVFT is very close to NEXT-100



SiPM radio-pure substrates.



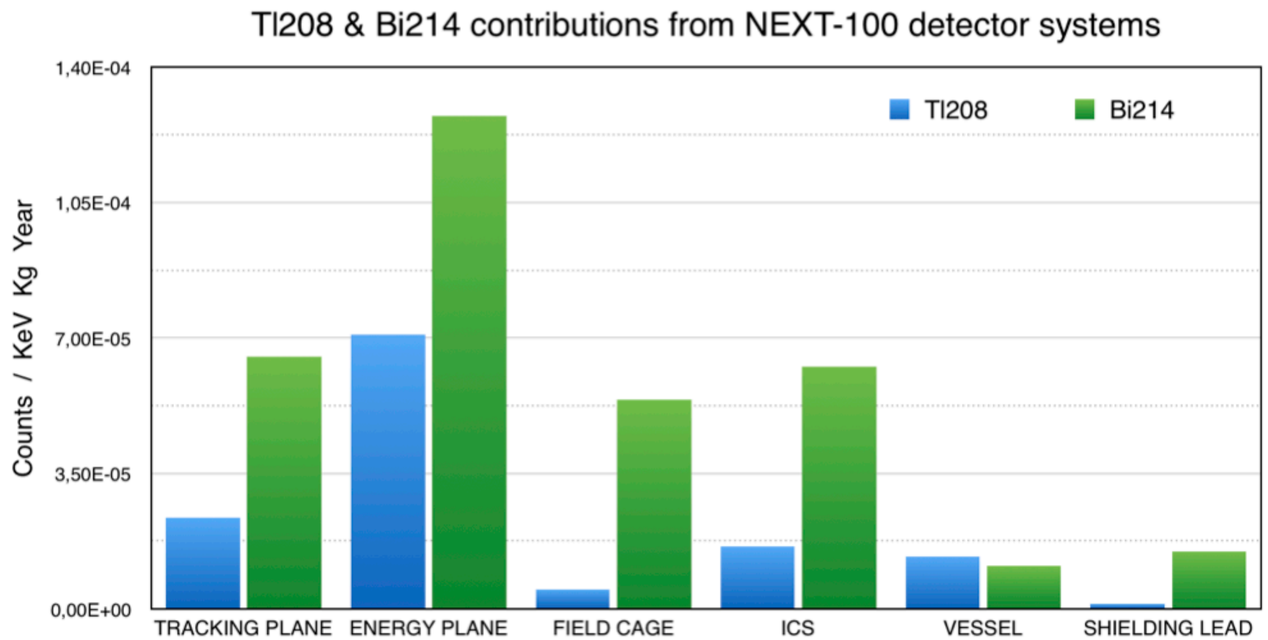


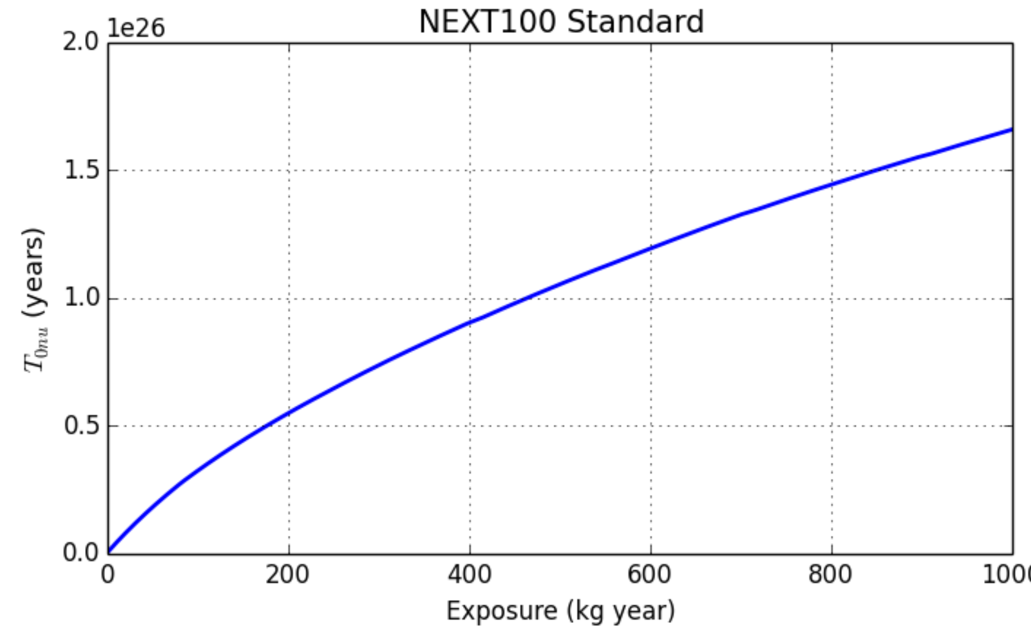
NEXT-100 goals

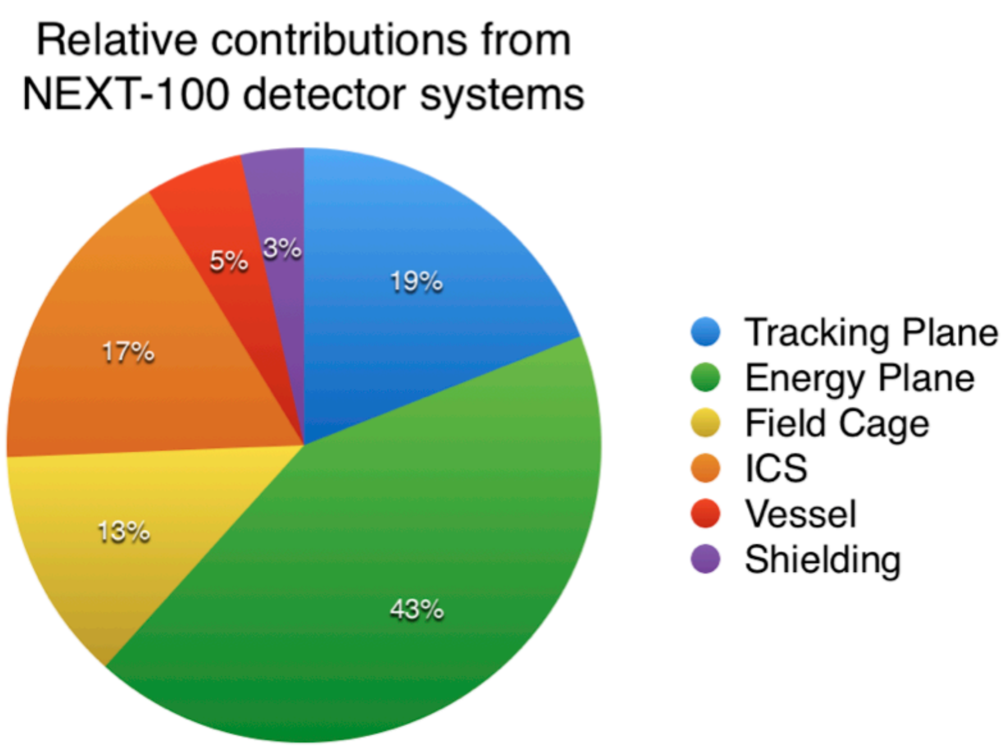
- Improve energy resolution to better than 1 % FWHM (replacing the anode plate by two etched meshes to improve uniformity)
- Improve radioactive budget (thinner SiPMs boards, lighter TPC).
- Demonstrate low background budget (thus background rate). Measure the background from the data themselves.
- Prepare ton scale.

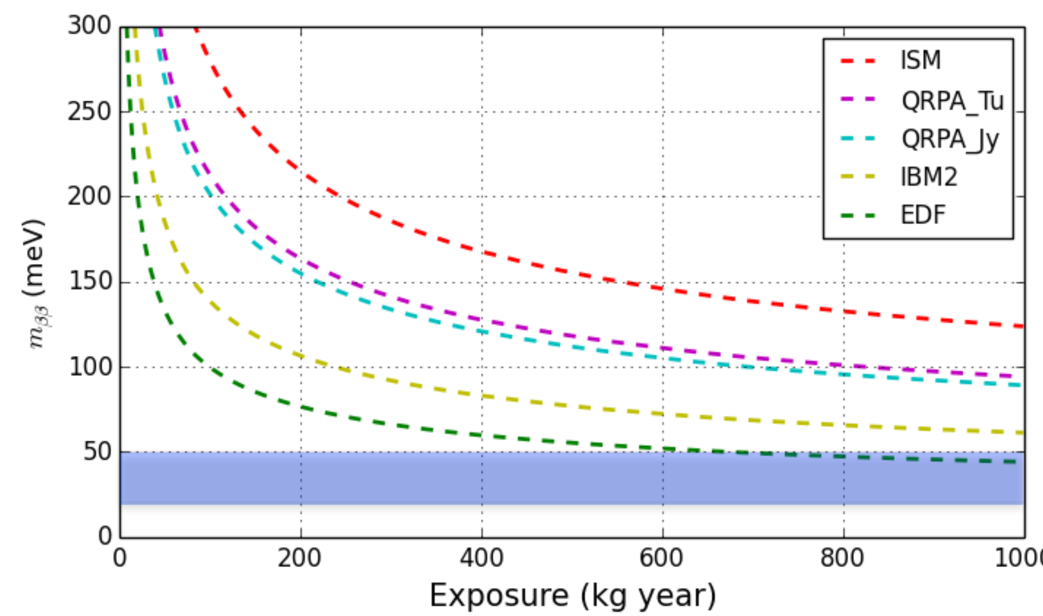
NEXT-100 Background model

1. Natural decay series: < 4.09 x 10^{-4} cts / keV kg year



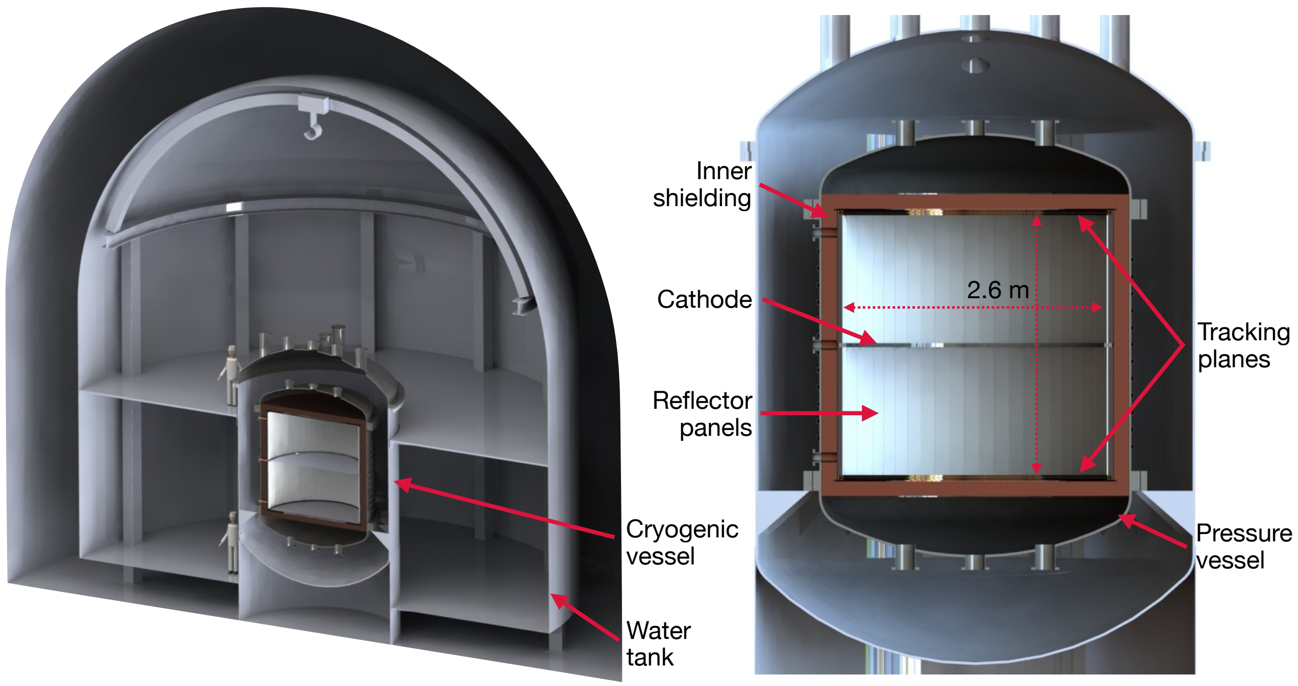






NEXT-HD

https://arxiv.org/pdf/2005.06467.pdf

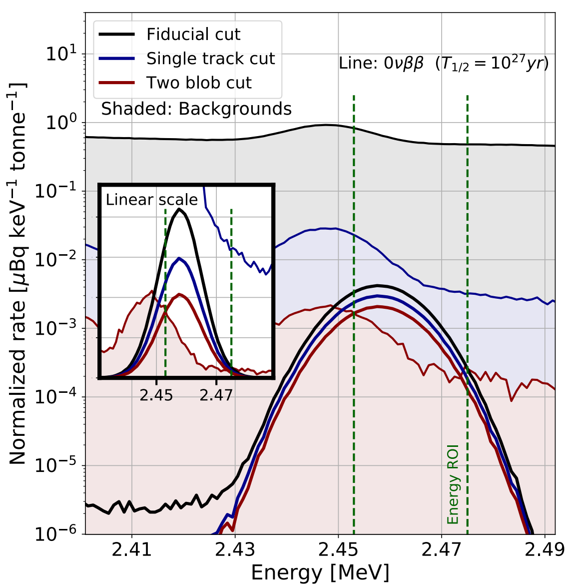


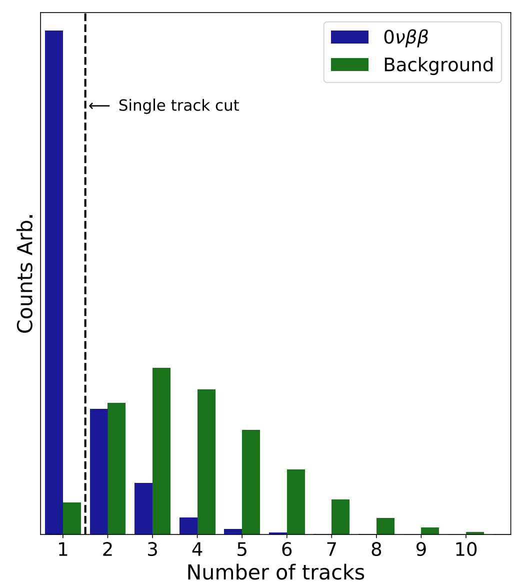
- **A detector of 2.6 m diameter and 2.6 m length deploys at mass of 1 ton at 15 bar.**

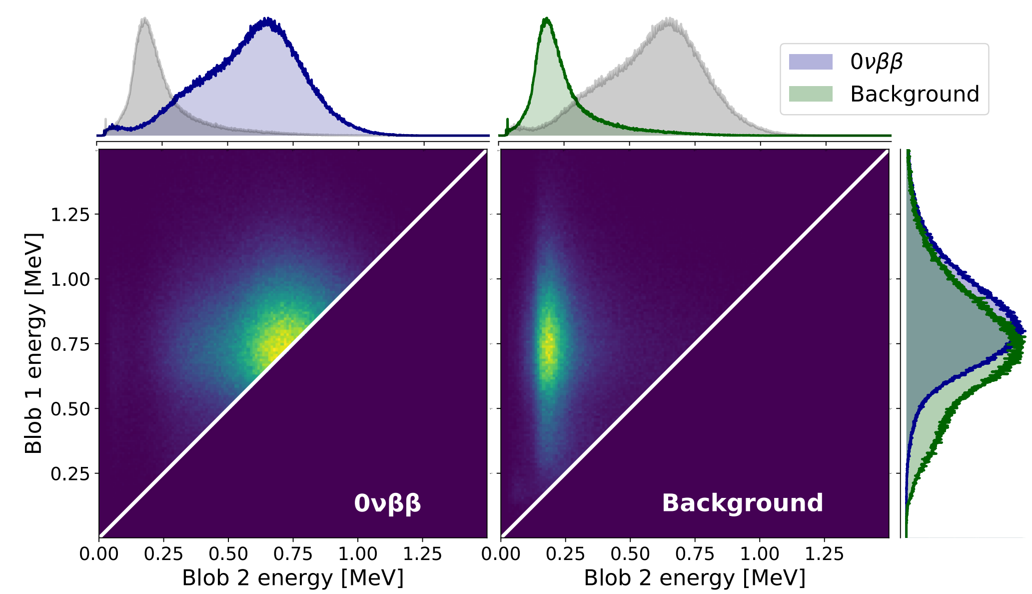
- NEXT-HD (“High Definition”) is a detector improving incrementally the technique developed by NEXT-White and NEXT-100.
- Background rate reduced to a fraction of event per ton and year in the ROI by improving topological signature (including the potential use of Xe-He to reduce diffusion) and reducing background budget (no PMTs, ultra-pure SiPM substrates).
- Symmetric design with a central cathode and two readout planes with SiPMs.
- Energy readout in a Barrel Energy Detector (double-clad fibres)

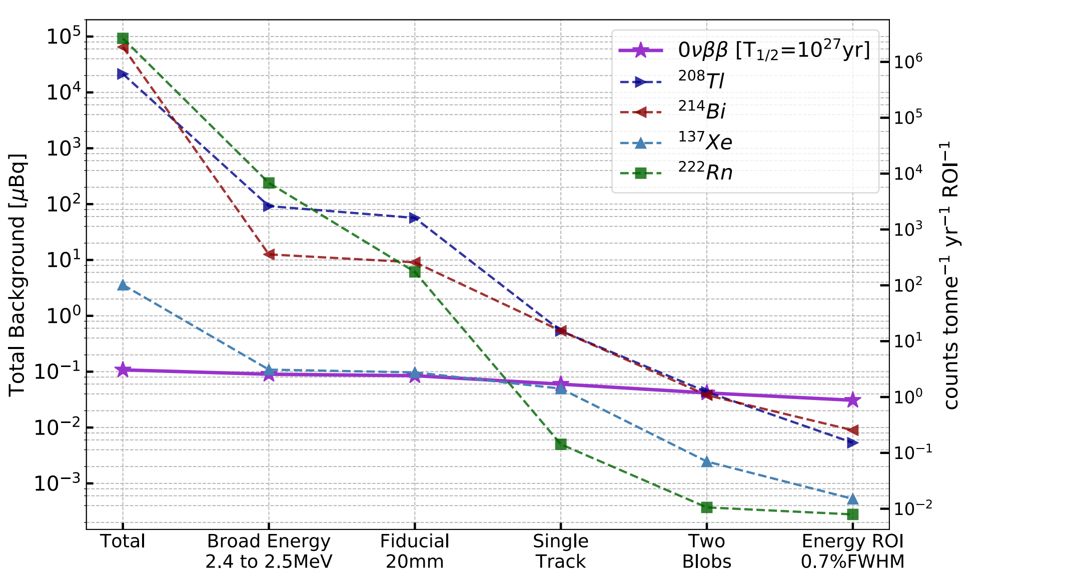
NEXT-HD

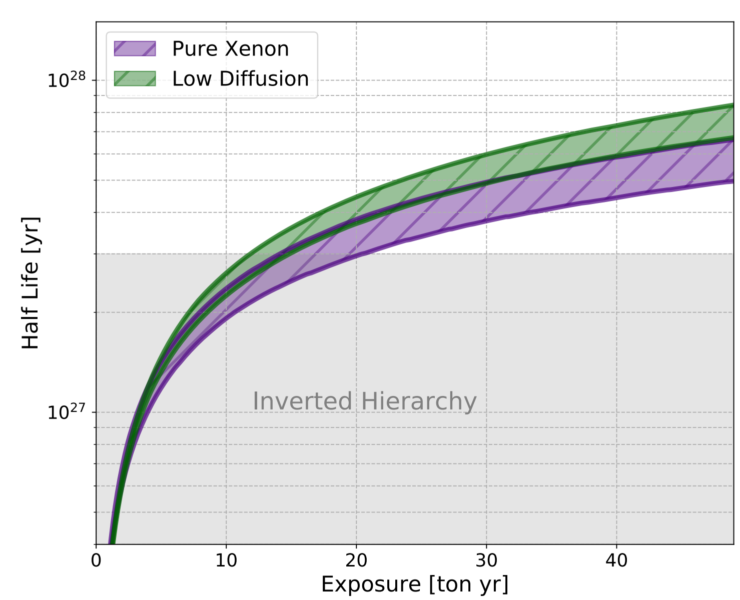
Reach: T $\sim 10^{27}$ year for 3 ton $\cdot$ year

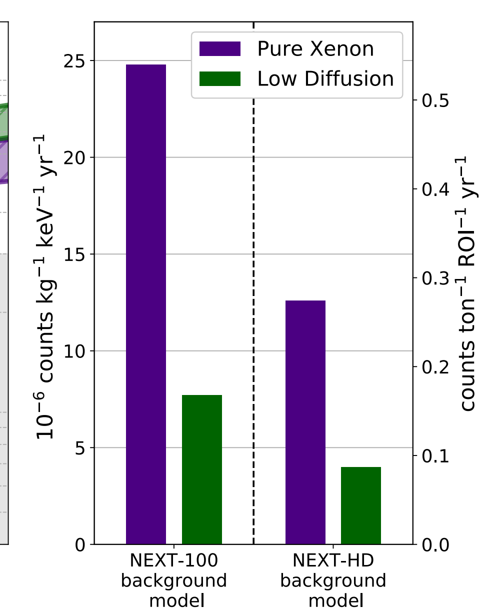




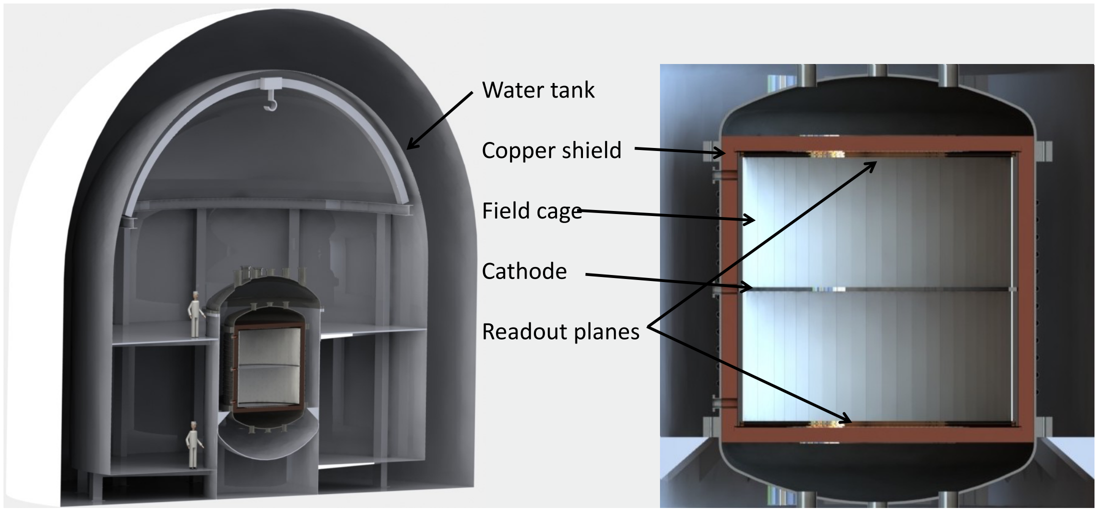






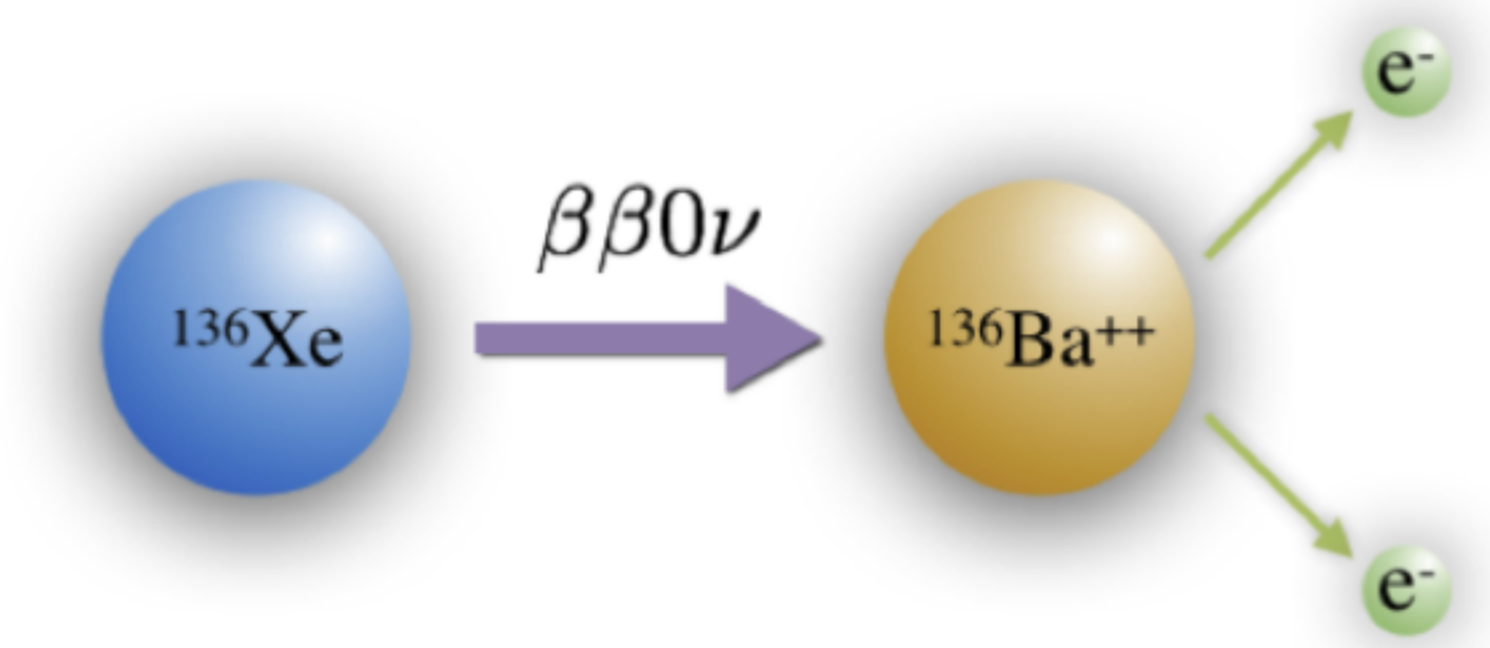


R&D for NEXT-HD



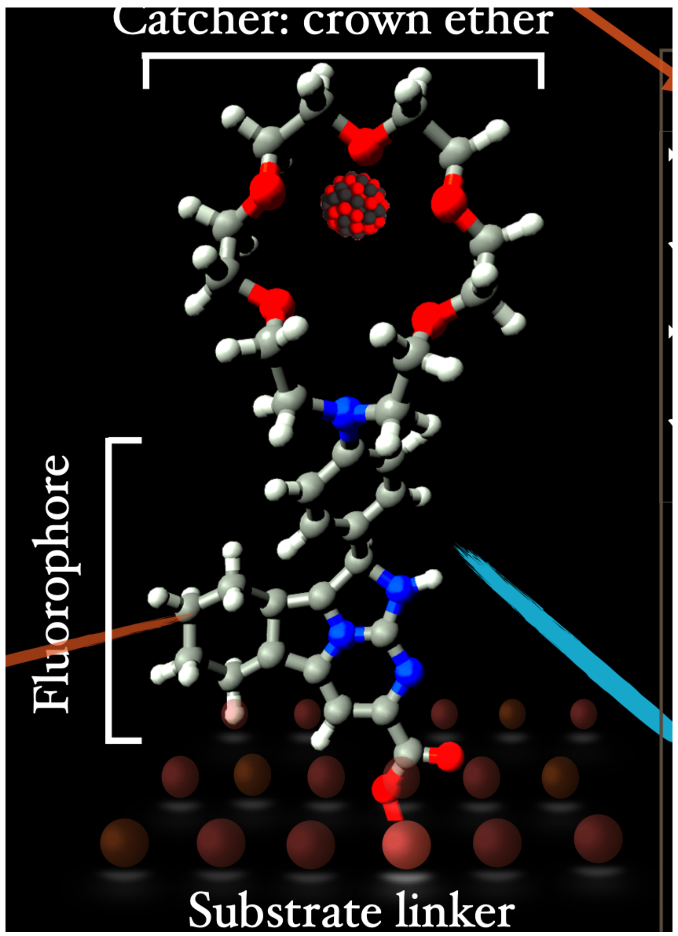
- EL amplification for large diameter grids.
- Barrel Energy Detector based on double-clad fibres (coated with TPB).
- Improve topological signature (low diffusion, deconvolution methods).
- Handle dense tracking plane signals (ASIC for the tracking plane)
- Reduce radioactive budget further w.r.t. NEXT-100 (no PMTs, ultra low radioactivity substrates)

NEXT-BOLD



Detecting “tagging” the Ba++ signaling a ββ0v process has been a long sought holy grail of xenon chambers.

Ba2+ detection using molecular indicators



D. Nygren , J.Phys.Conf.Ser. 650 (2015) no.1, 012002
A.D. McDonald *et al.* (NEXT Collaboration) Phys. Rev. Lett. 120, 132504 (2017)
Nature Sci Rep 9, 15097 (2019)
Nature 583, 48–54 (2020)
ACS Sens. 2021, 6, 1, 192–202 (2021)
JINST 11 (2016) no.12, P12011

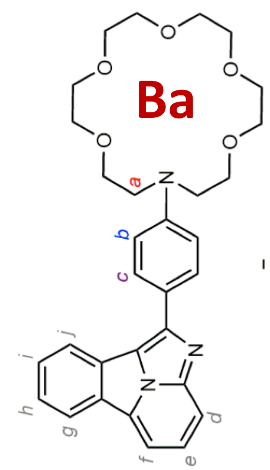
- **Idea (Nygren)**: Exploit single molecule fluorescent imaging (SFMF) to visualise ("tag") a single Ba2+ ion as it arrives at the TPC cathode
- **Ba2+ sensor**: Based on molecular indicators, able to change luminous response after chelating Ba2+ cations.
- **Apparatus**: Must be able to detect in delayed coincidence the electron signal (in anode) and the cation signal in cathode.
- **Crucial bonus** : delayed coincidence pushes estimated background (and error) to very small numbers (ultimately limited by $\beta\beta 2\nu$ at levels near 10^{-9} ckky). Efficiency of delayed coincidence can be measured (calibration with Ra2+ source and/or $\beta\beta 2\nu$).

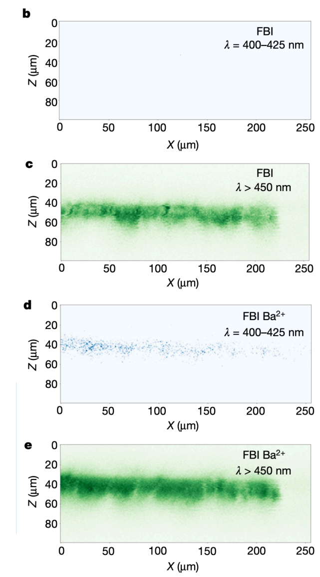
New Chemistry

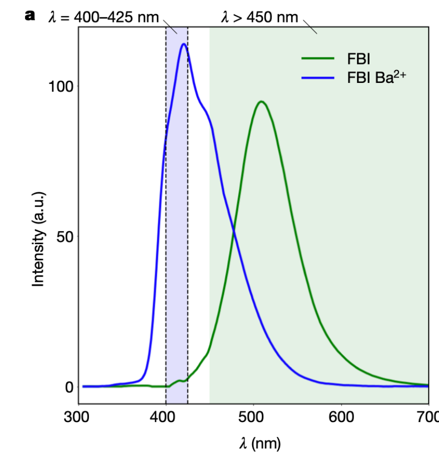
- Conventional ion chemosensors are not suitable for solventless (dry) imaging.
- NEXT has developed selective, dry-phase imaging of barium ions using crown ether derivatives.
- Ring receptor can be tuned to bind efficiently and selectively to barium.
- Computational chemistry is predictive for molecular fluorescence and binding.
- Two types have been developed: on-off, and bi-color.

Sci Rep 9, 15097 (2019)
Nature 583, 48–54 (2020)
ACS Sens. 2021, 6, 1, 192–202 (2021)

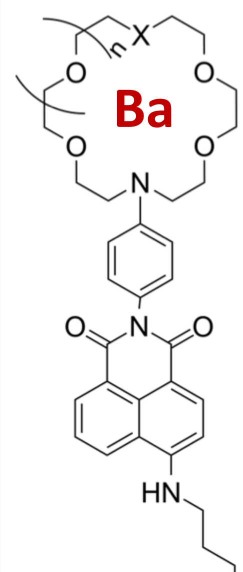
In-vacuo capture from $Ba(ClO_4)_2$ with bi-color response



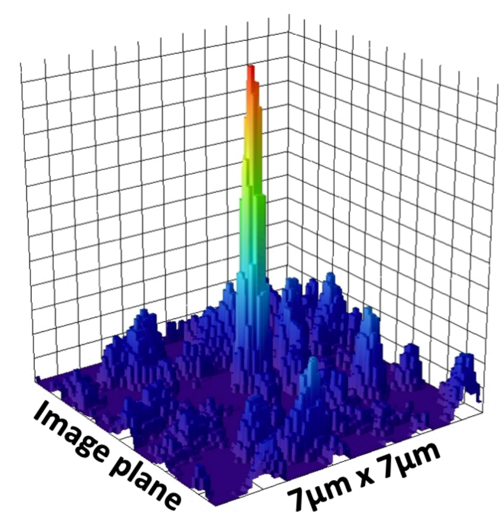


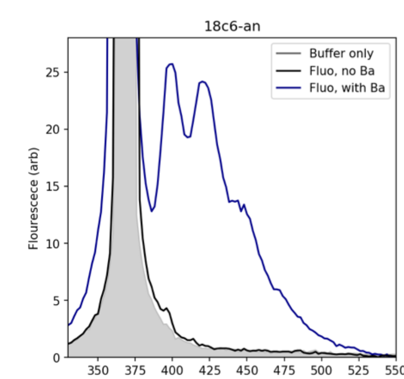


Dry single Ba^{++} ion detection with on-off fluorescence



1A-1E





Ba2+ expected to chelated indicators in high pressure gas

Nature 583, 48–54 (2020)

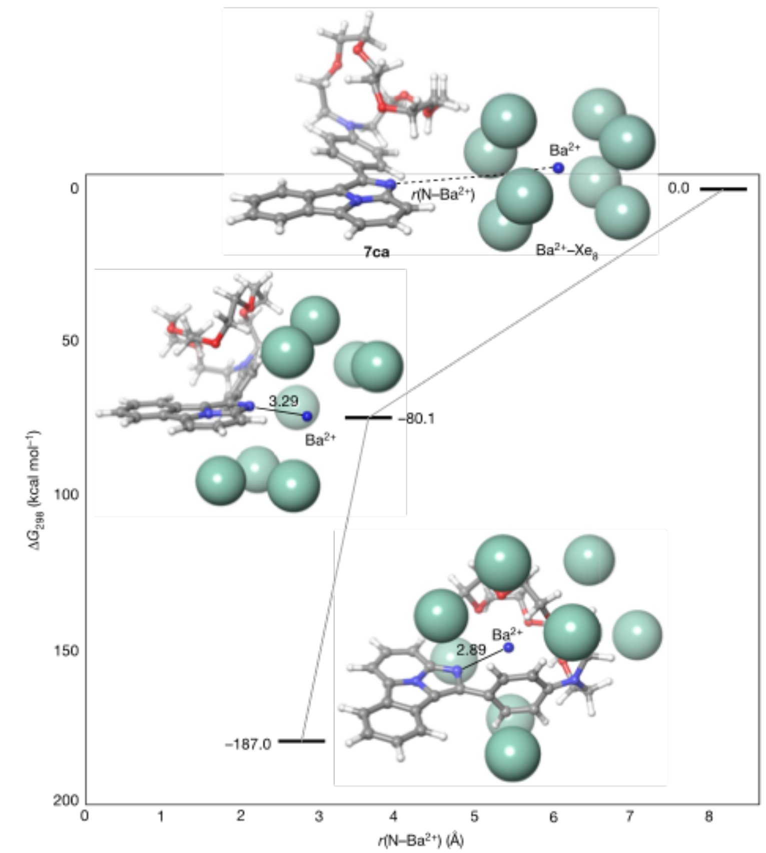
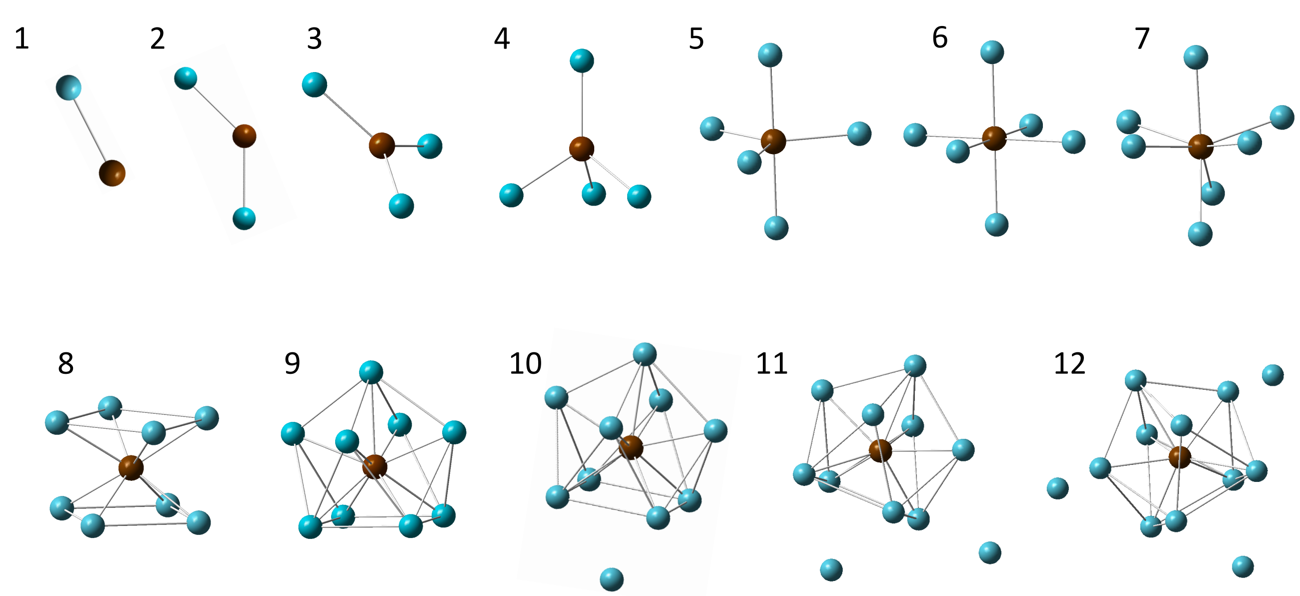
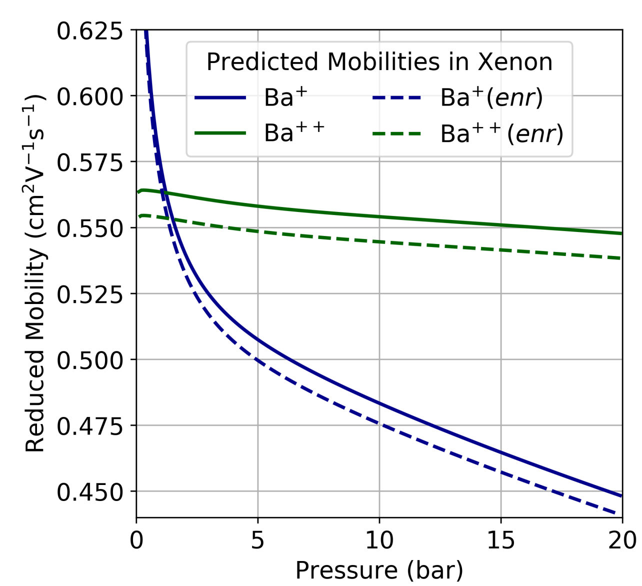


Fig. 4 | Computed structures of FBI (7ca) and a $Ba^{2+}Xe_8$ cluster at different N–Ba^{2+} distances. The geometries and energies shown were computed using DFT (see Methods for further details). Xenon atoms are represented using the Corey–Pauling–Koltun (CPK) space-filling model. The remaining atoms are represented using a ball-and-stick model and the CPK colouring code. Relative free energies (ΔG_{298}), have been computed at 25 °C (298 K).

Phys. Rev. A **97**, 062509





Ba2+ chelation in dry medium

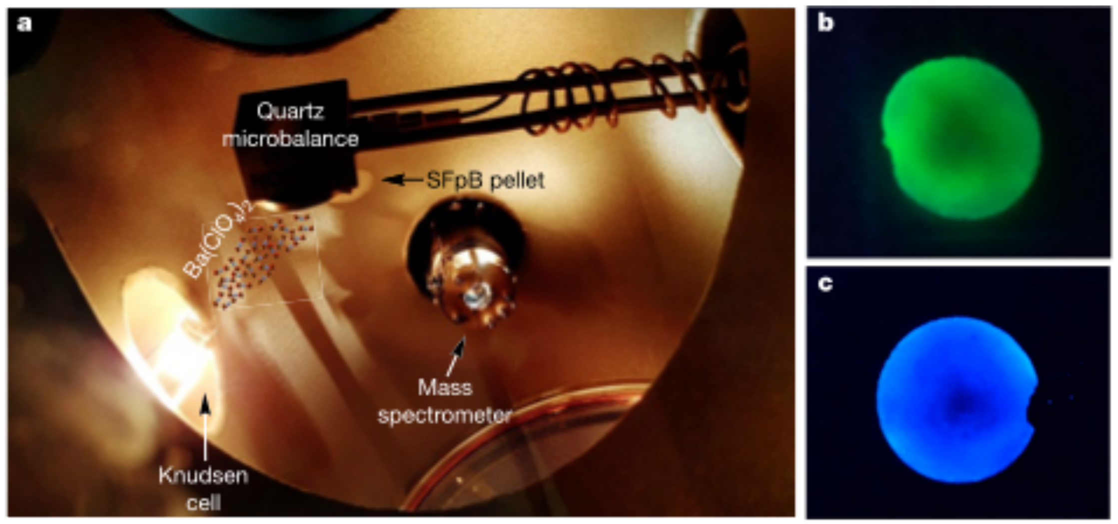
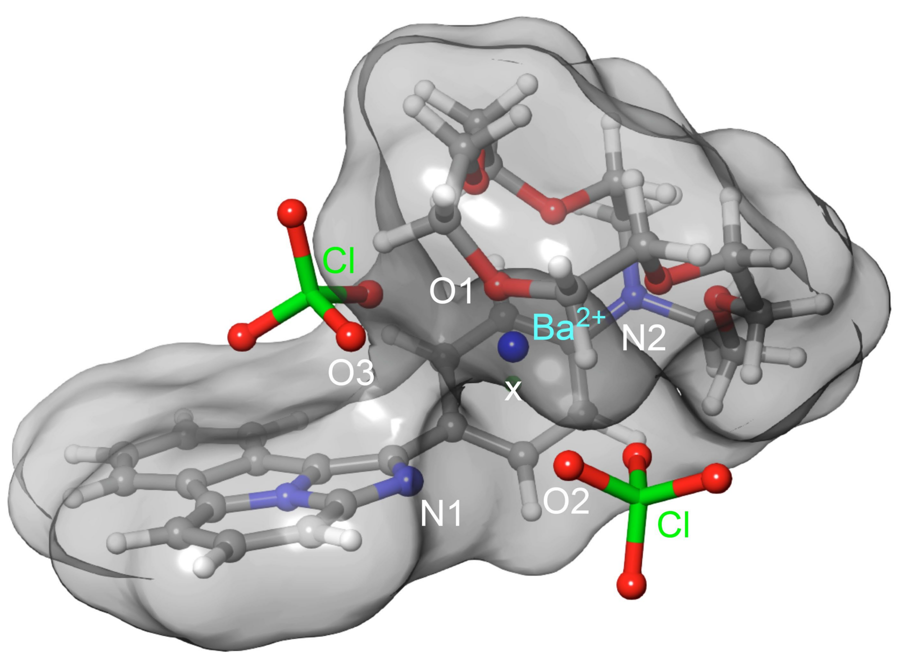


Fig. 3 | Sublimation of $Ba(ClO_4)_2$ on the FBI. a, Experimental setup. Photograph of the interior of the UHV chamber used for sublimation. The positions of the pellet, evaporator, quartz microbalance and mass spectrometer are indicated. **b**, **c**, Photographs of the pellet before (**b**) and after (**c**) the sublimation. In both cases, the excitation light is 365 nm. We note the characteristic green colour of unchelated FBI before the sublimation and the blue shift after the sublimation, which shows a large density of chelated molecules.



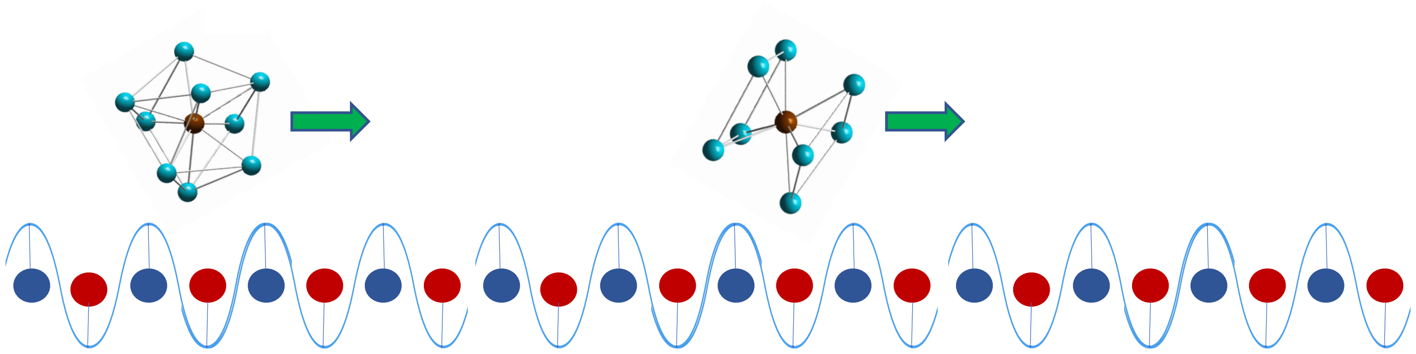
Nature 583, 48–54 (2020)

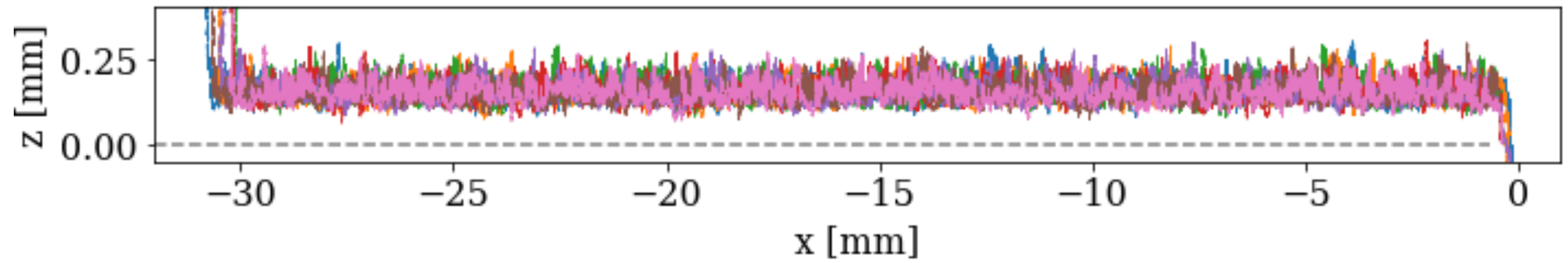
Ion Transport & Concentration

- One concept for ion collection from large volume is through concentration with RF carpets at 10 bar, onto 1mm² sensors.
- Simulations and HV tests suggest that efficient ion transport is achievable in principle at 10 bar.
- Dynamics of transport influenced by molecular ion formation with xenon – experiment is mandatory.
- Program of R&D at the CARIBU facility will test high pressure RF carpet, scheduled for 2020 (COVID permitting).

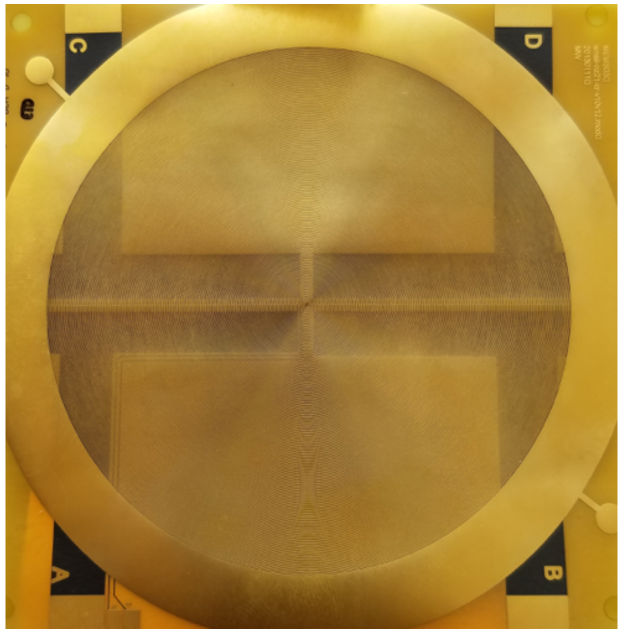
JINST 15 (2020) 04, P04022
Phys.Rev.A 97 (2018) 6, 062509

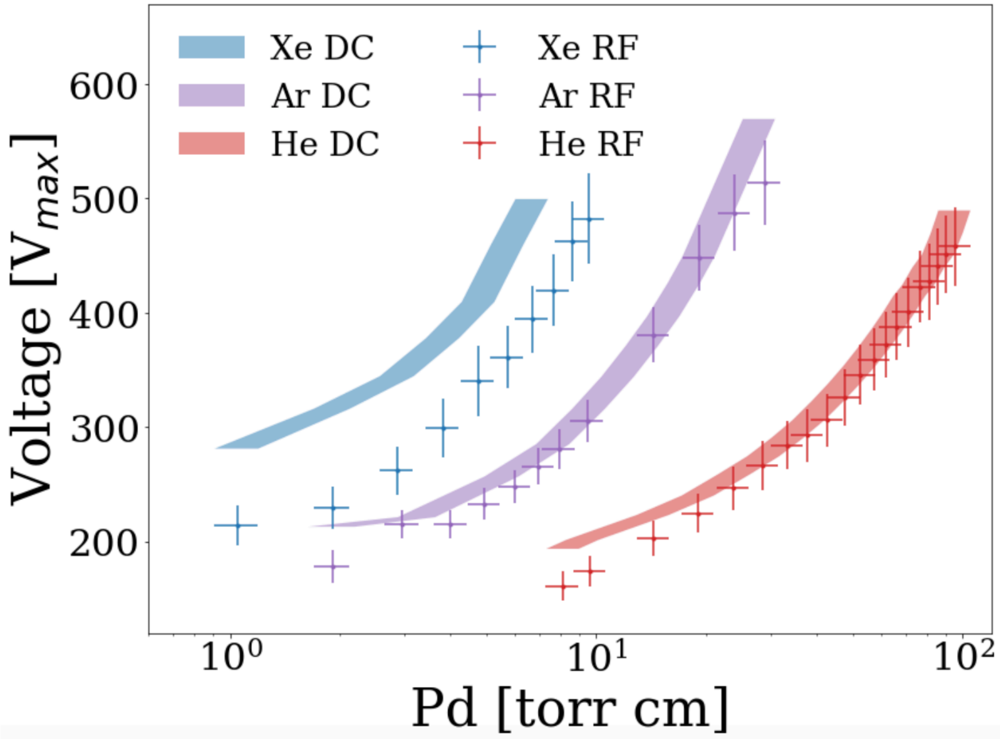
DFT calculations predict ion clustering and RF carpet simulations predict efficient transport.



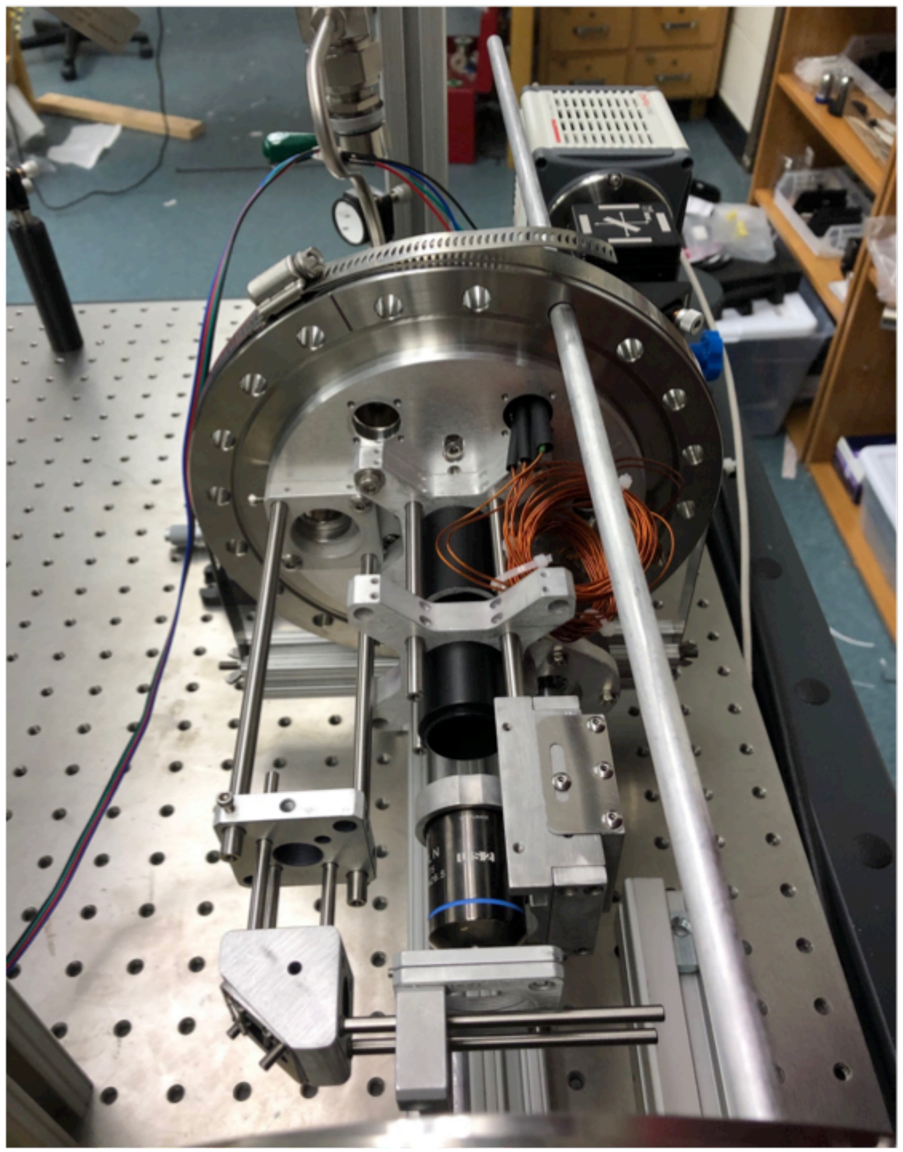


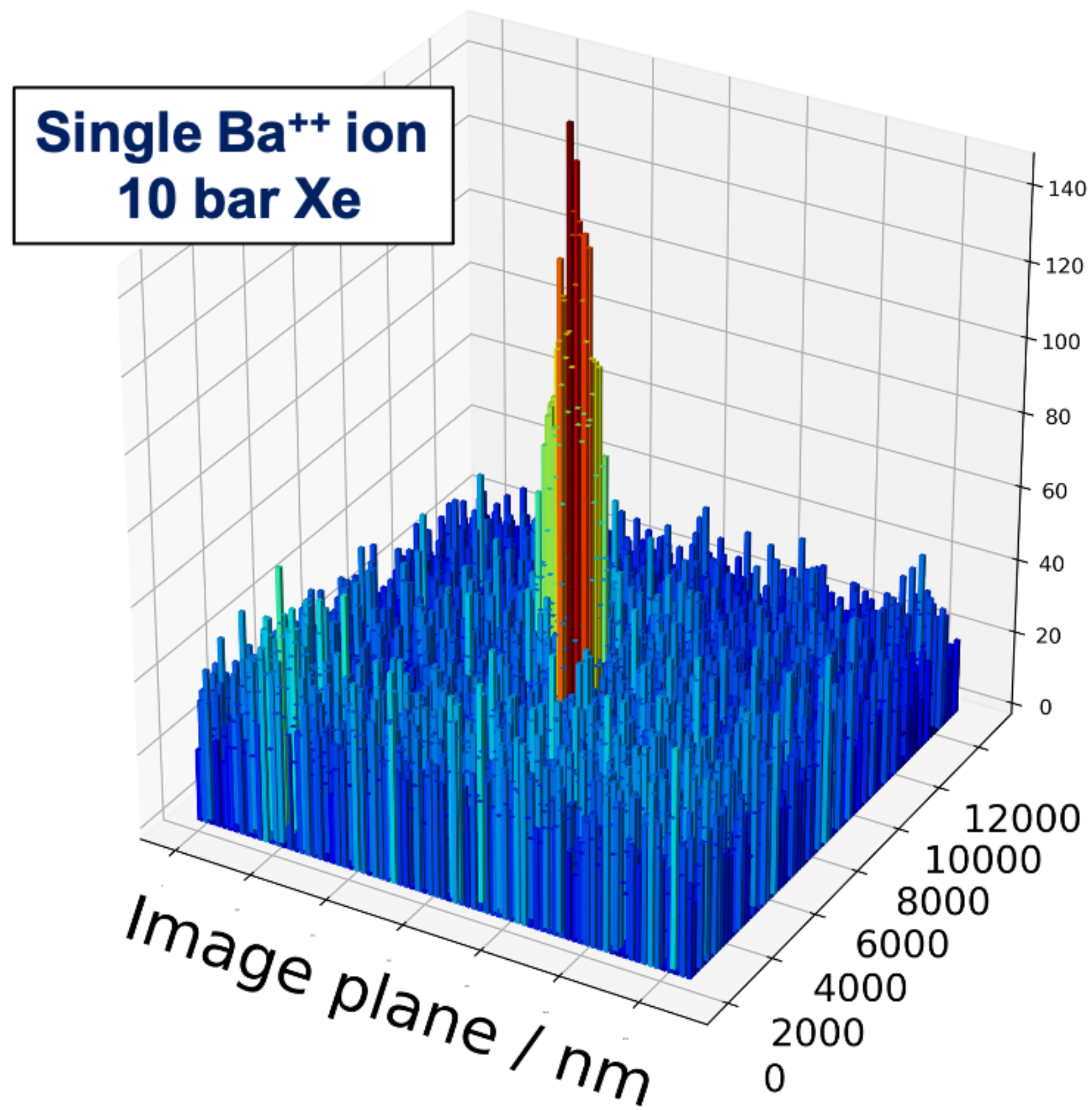
RF HV strength of Xe is sufficient for RF transport at 10bar.





High pressure microscopy

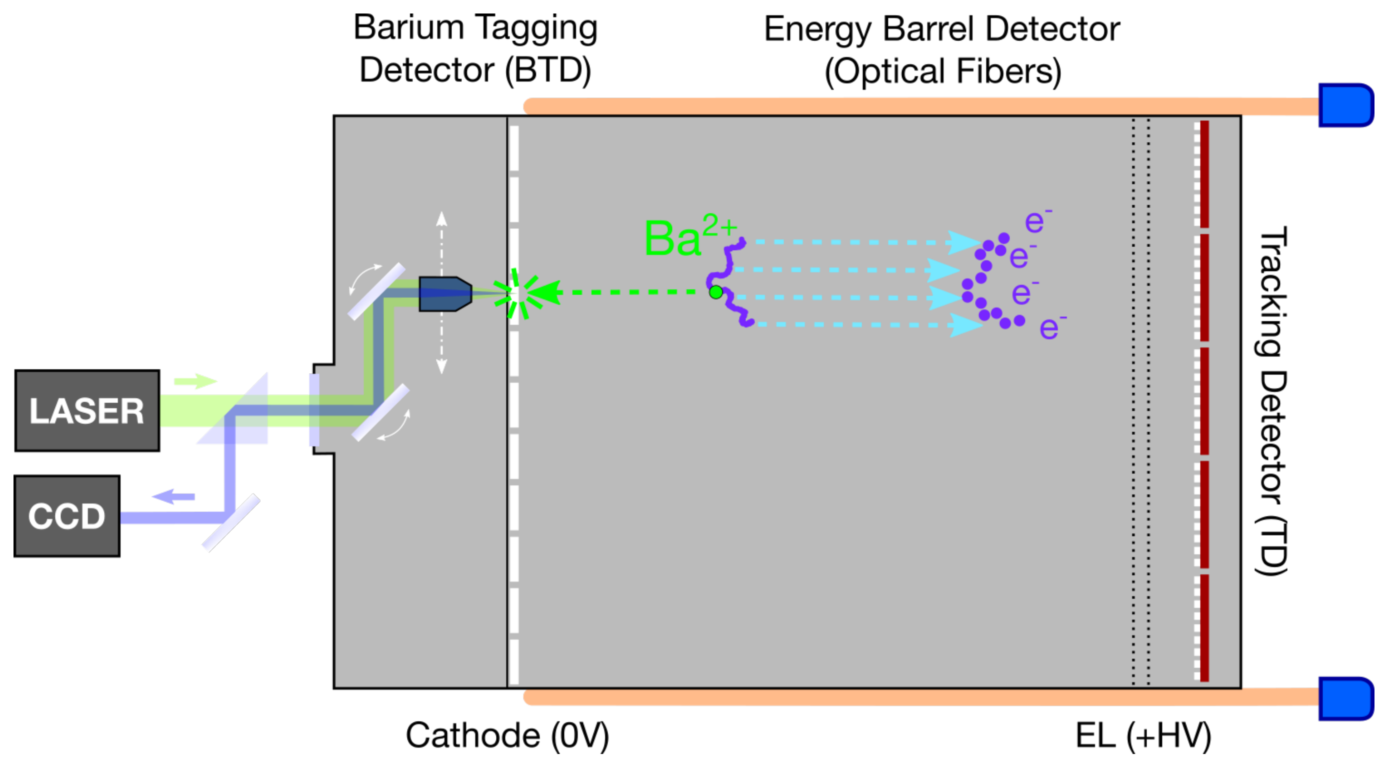




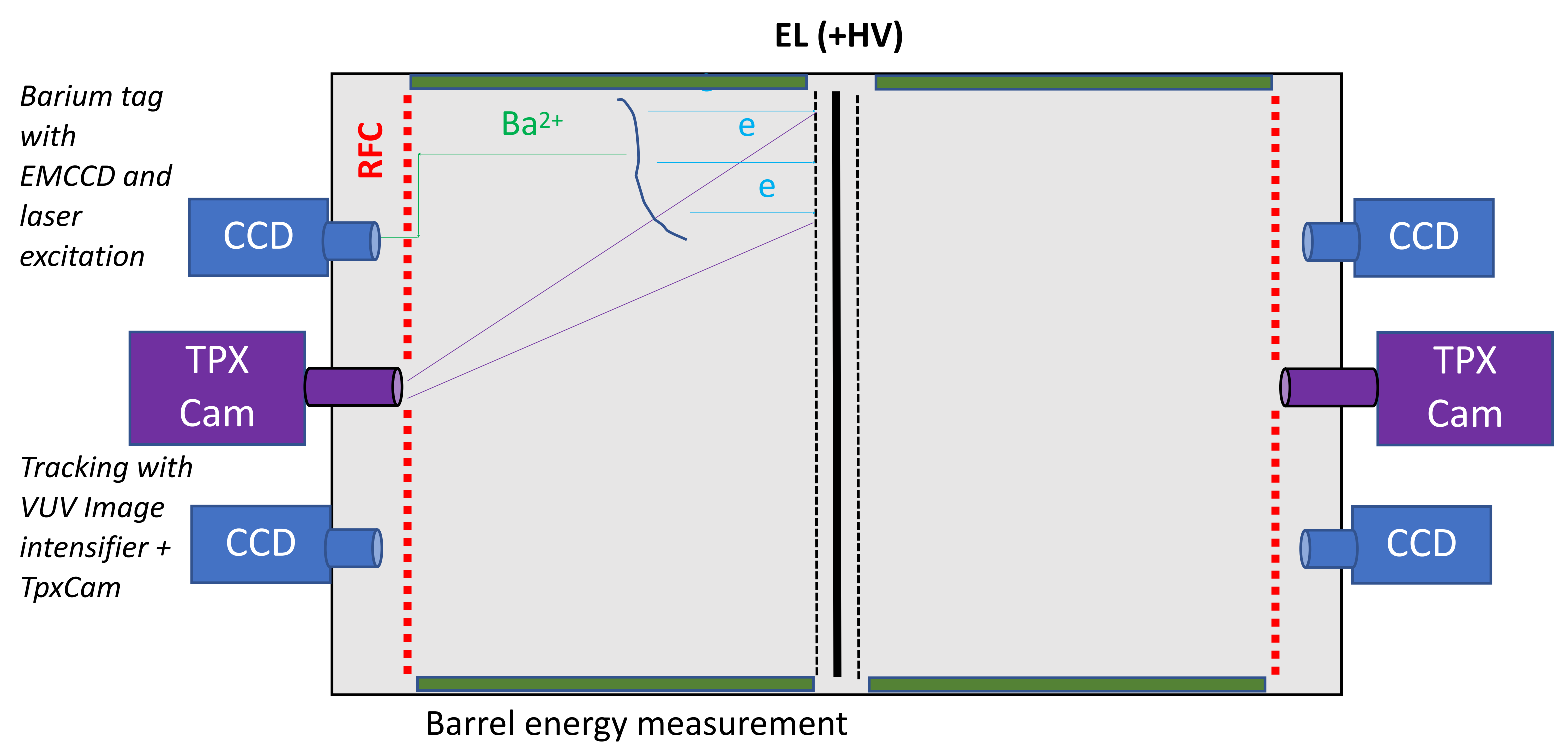
BOLD R&D

- Ion beams using $^{222}Rn^{2+}$ from thorium decay are under development for single ion test.
- Beam tests also planned at ANL CARIBU with $^{144}Ba^{2+}$ mass-selected from ^{252}Cf fission.
- The ultimate test-beam is ββ2ν !
- Demonstrator phases at 10kg-scale are being planned for ~2024-2025.
- Multiple full system concepts under exploration, to be guided by ongoing R&D.
- The program is well funded by DOE in USA and by ERC (Synergy Grant, 2020) in Europe.

"SABAT" concept with fully active cathode, SiPM-based tracking and Energy Barrel Detector



"CRAB" concept with RF carpet concentrators and camera-based topology measurement



Plans for first NEXT-ton module at LSC

- NEXT-100 will operate at the LSC from 2021-2024 with 100 kg of enriched xenon

- LSC is starting the process to procure +400 kg by 2025.

- The goal of the collaboration is to build a new detector in 2024 initially with 500 kg fiducial mass. R&D under way to determine flexibility to increase pressure, so that the same vessel could hold 500 kg at 10 bar and ~1ton at 20 bar.

- The baseline option is to build a symmetric “HD” design, with the aim to reach a sensitivity ~10^{27} y, while the R&D on “BOLD” proceeds.

- Eventually, replace “HD” by “BOLD” with a mass of ~1 ton.

Multi-ton, multi-module, multi-site approach

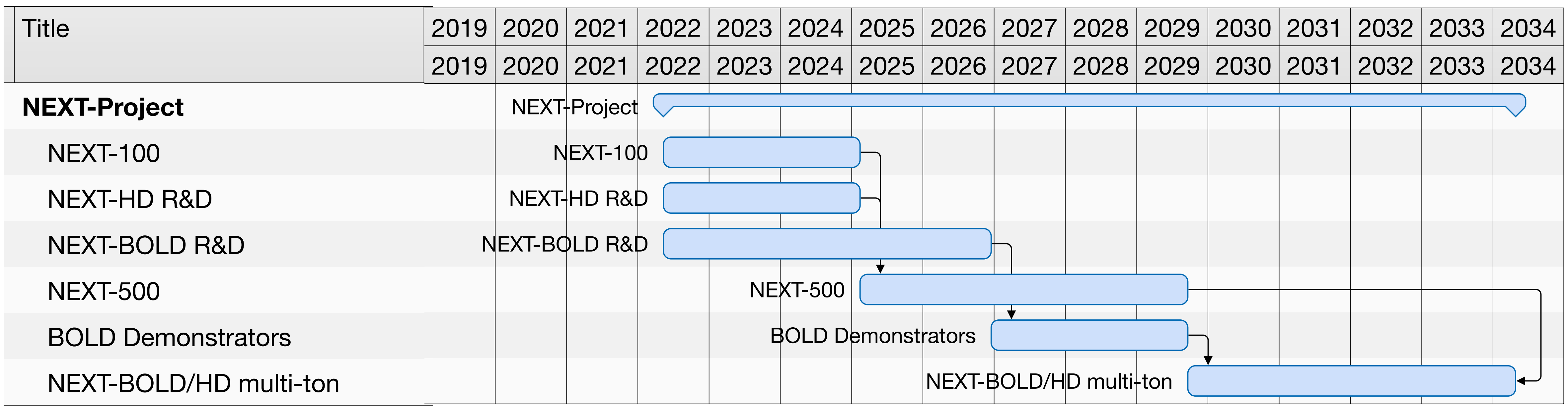
- HPXe detectors can be staged. Once the technology is mastered, duplicating modules is (relatively) straight forward. Operating at room temperatures avoids many complications associated with cryogenics.

- Thus, it is possible to build more than one module, and the modules can operate in more than one lab. We believe that modules of 1 ton can be achieved and will be demonstrated by the pilot-module at LSC.

- SNOLAB depth makes for an attractive location for one or more of those modules (given the reduced impact on cosmogenic background) and fits well with the strong NorthAmerica-Europe nature of the NEXT collaboration.

- The R&D for BOLD may involve prototypes/demonstrators operating both at LSC and at SNOLAB.

Time line


Title
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034
NEXT-Project
NEXT-100
NEXT-HD R&D
NEXT-BOLD R&D
NEXT-500
BOLD Demonstrators
NEXT-BOLD/HD multi-ton
NEXT-Project
NEXT-100
NEXT-HD R&D
NEXT-BOLD R&D
NEXT-500
BOLD Demonstrators
NEXT-BOLD/HD multi-ton