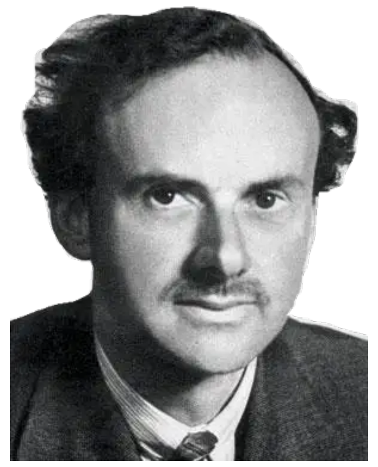
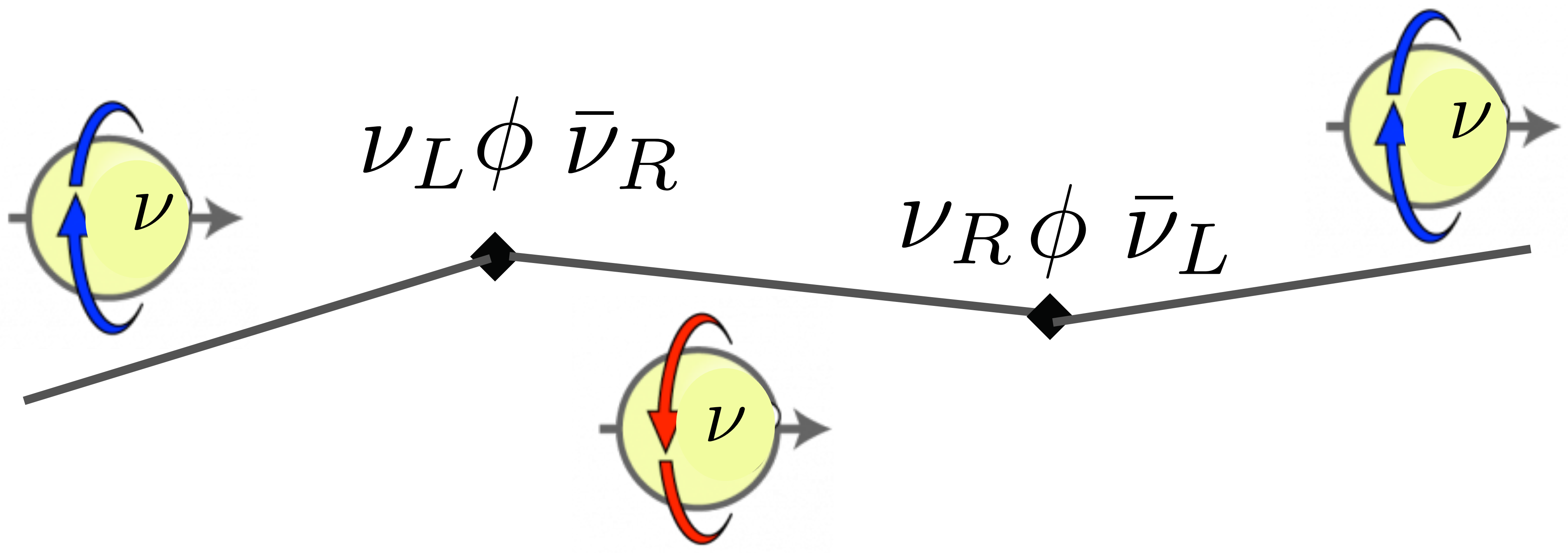
The NEXT decade for the NEXT experiment

J.J. GÓMEZ CADENAS
UGAP, MARCH, 2024



Dirac

- Higgs mass mechanism for neutrinos analogous to the one used for charged leptons.
- Left and right chiral components interacting (*very very weakly*) with the Higgs field.
- The right handed neutrinos (and the left-handed antineutrinos) are ***sterile***.
- Why the mass is so low compared with the other fundamental particles?



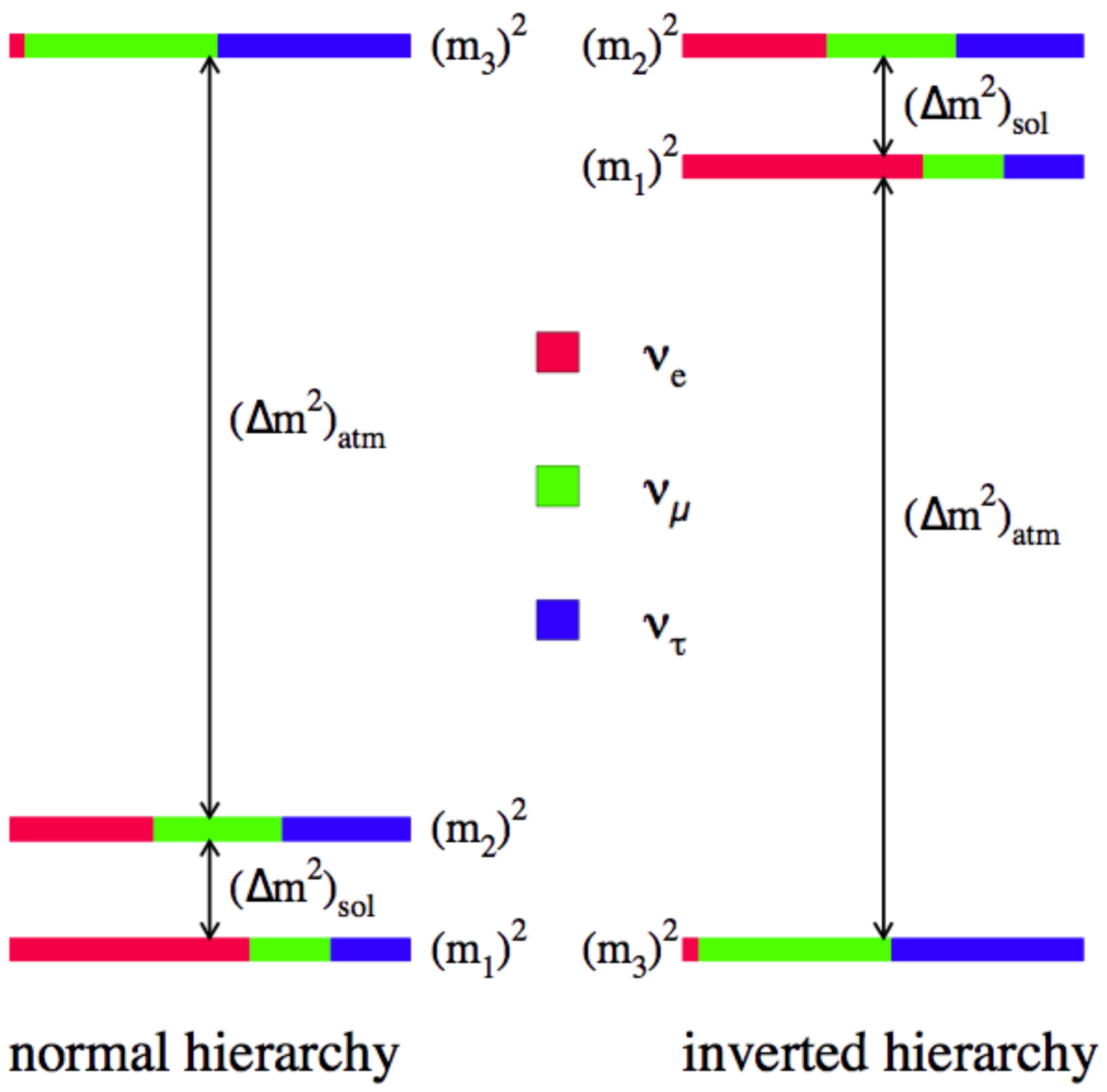
Majorana

- The neutrino is a Majorana particle: the neutrino and the antineutrino are identical.
- The Lagrangian contains both Dirac mass terms and Majorana mass terms.
- The very low mass can be explained with the existence of a heavy right-handed Majorana neutrino.
- If these heavy right-handed Majorana neutrinos exist, and if they violate CP symmetry, they could explain the matter-antimatter asymmetry in our universe (***leptogenesis***):

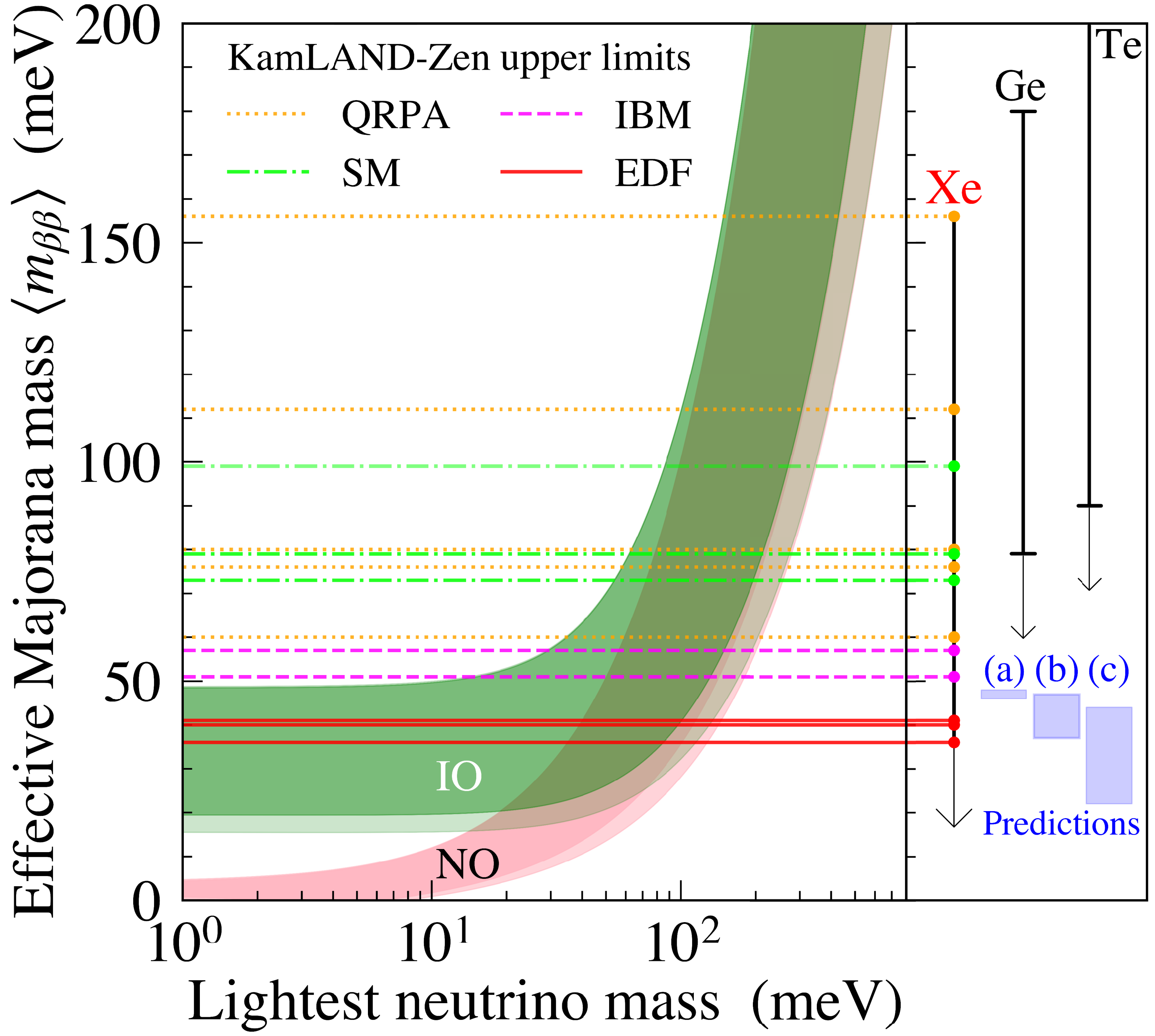
$$N \rightarrow l^- + H \neq N \rightarrow l^+ + H$$

Neutrino mass hierarchy

- Neutrino oscillations don't provide information about the order of the neutrino masses: two combinations are possible, ***normal hierarchy*** and ***inverted***.
- The effective Majorana mass and the mass of the lightest neutrino are related to the mass hierarchy.
- If **neutrinos are Majorana**, next-generation experiments might be able to **fully exclude the inverted hierarchy** phase space (depending on NME).



Phys.Rev.Lett. 130 (2023) 5, 051801

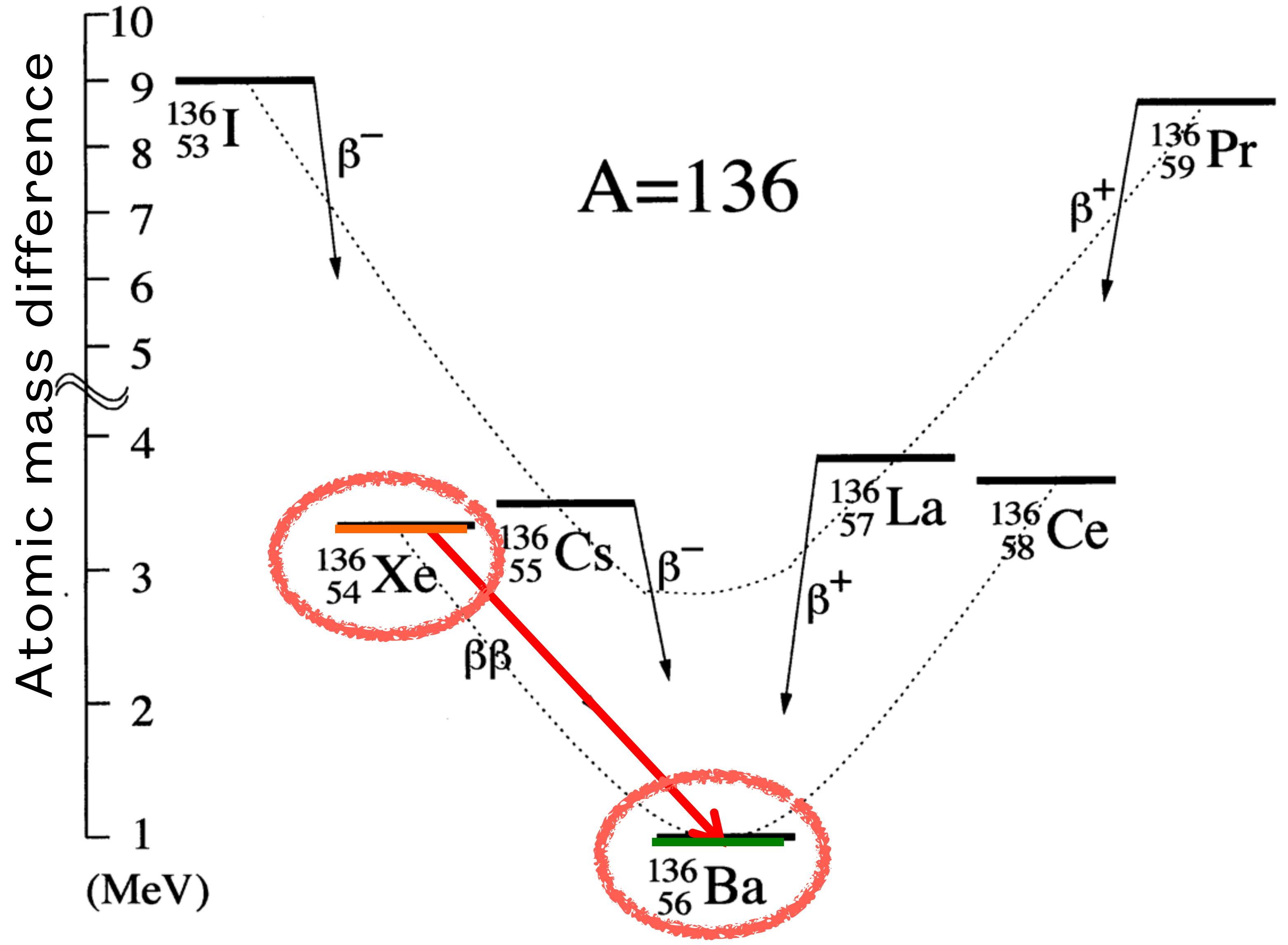


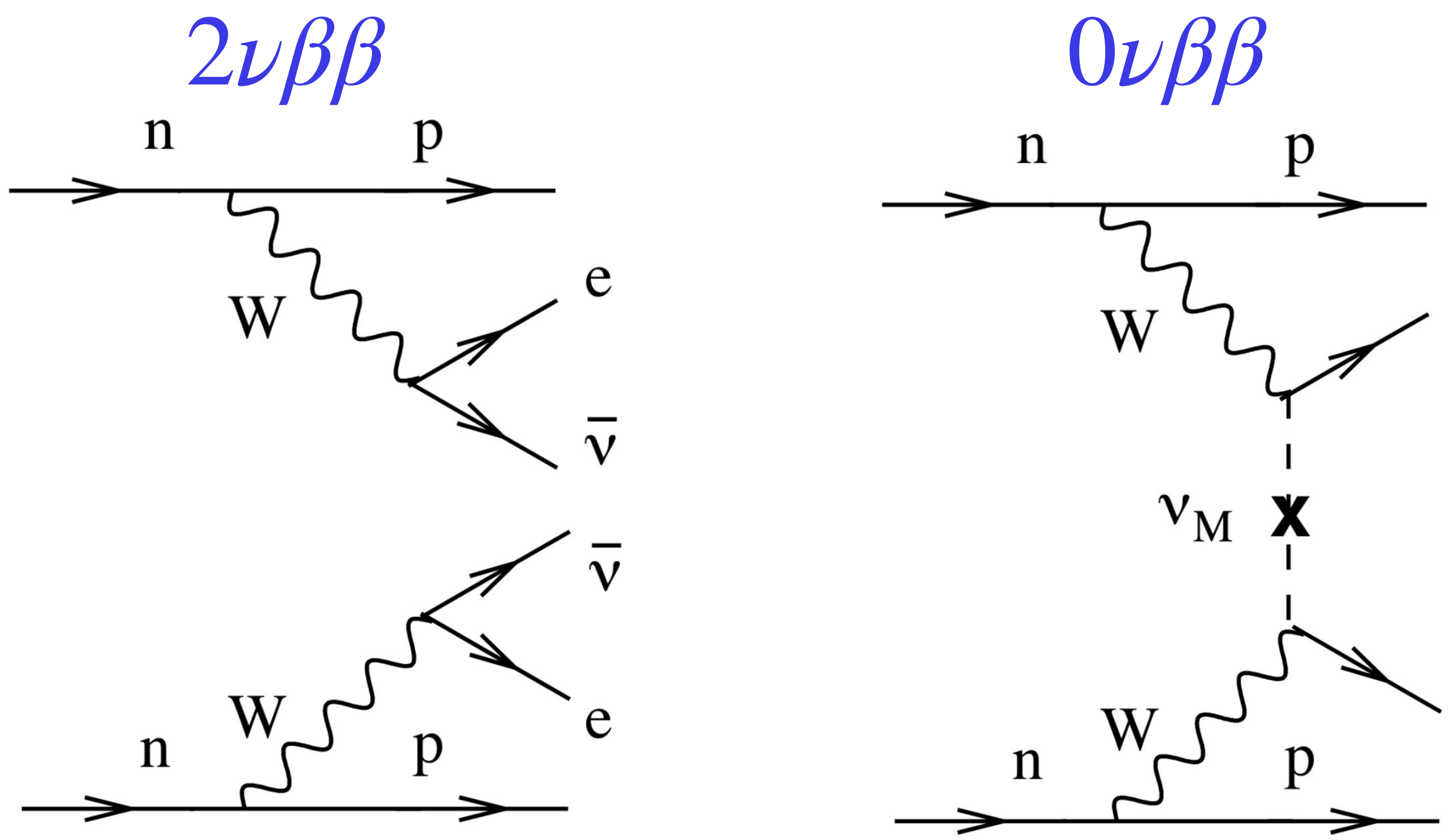
Neutrinoless double beta decay

- Nature's silver lining: some nuclei can undergo a radioactive decay with the emission of ***two electrons***.

- This is because some nuclei with even number of protons and even number of neutrons are are energetically forbidden to "single" beta decay to odd-odd nuclei.

- The process, if exists, is helicity-suppressed, so the decay time is slow…





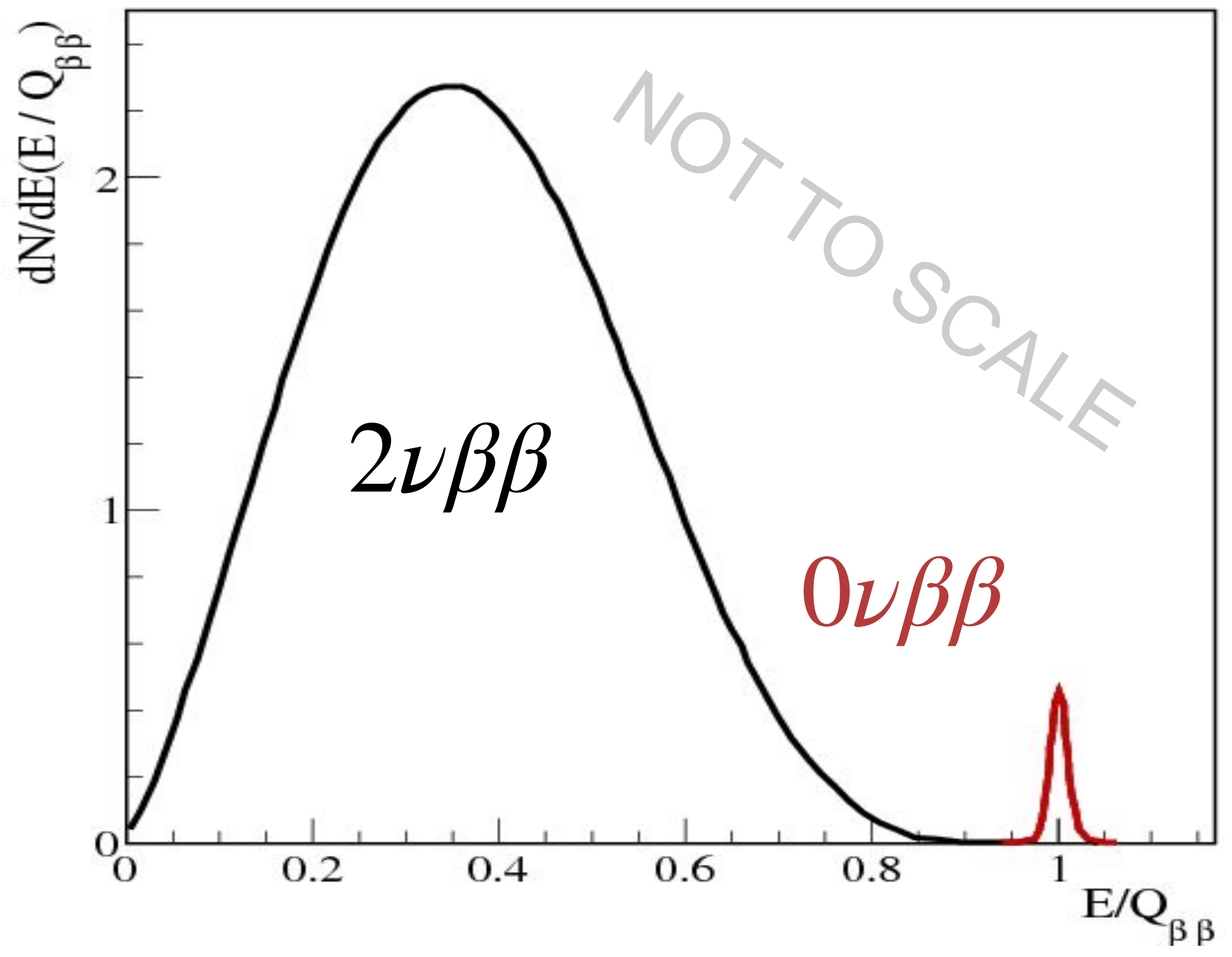
How slow?

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

Inverse of half-life | Phase-space | Nuclear matrix element | Effective Majorana mass

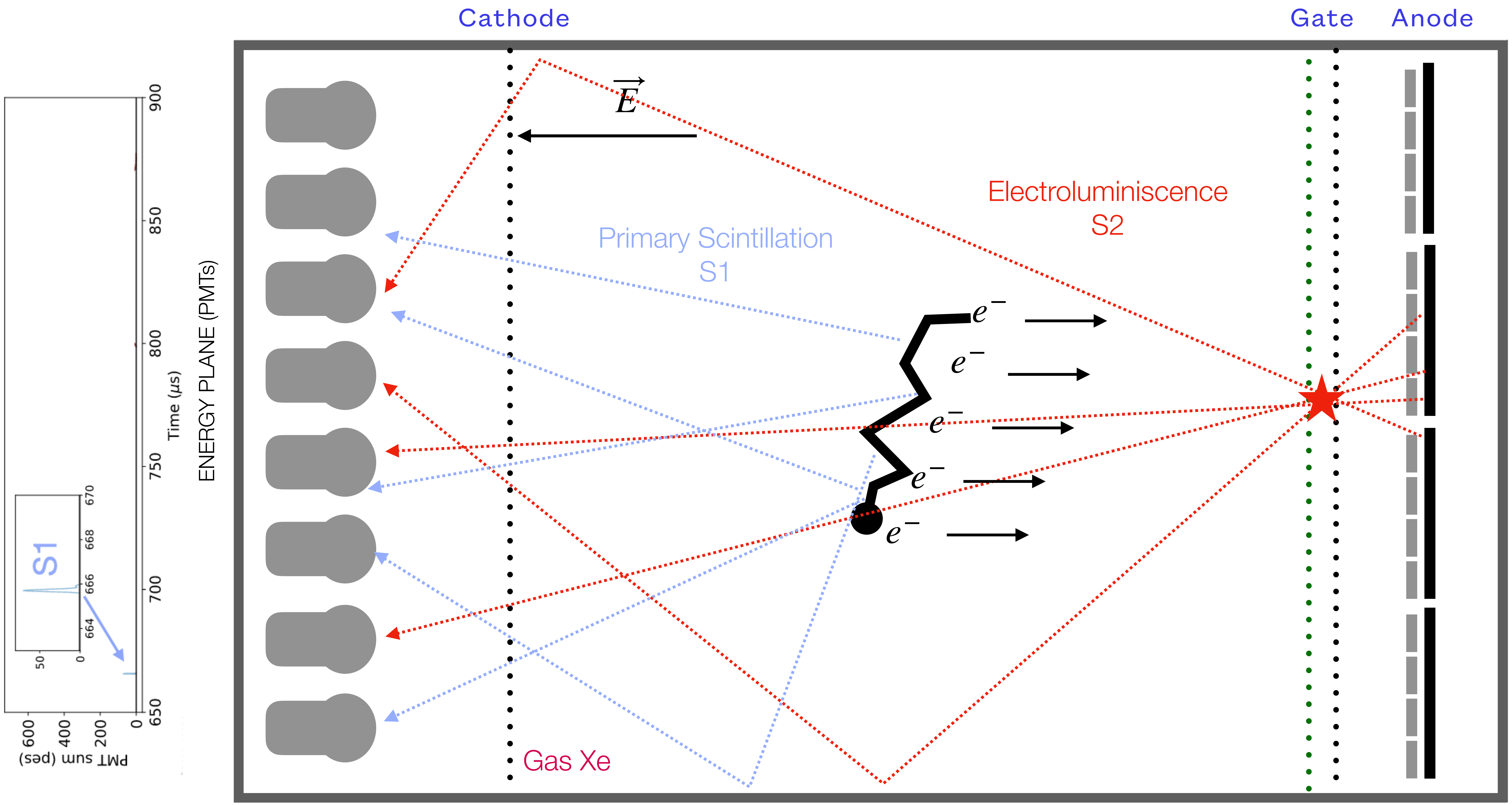
- Current best limits put the $\beta\beta 0\nu$ half-life to **at least 10^{26} years**.
- You need a lot of time… or a lot of mass.

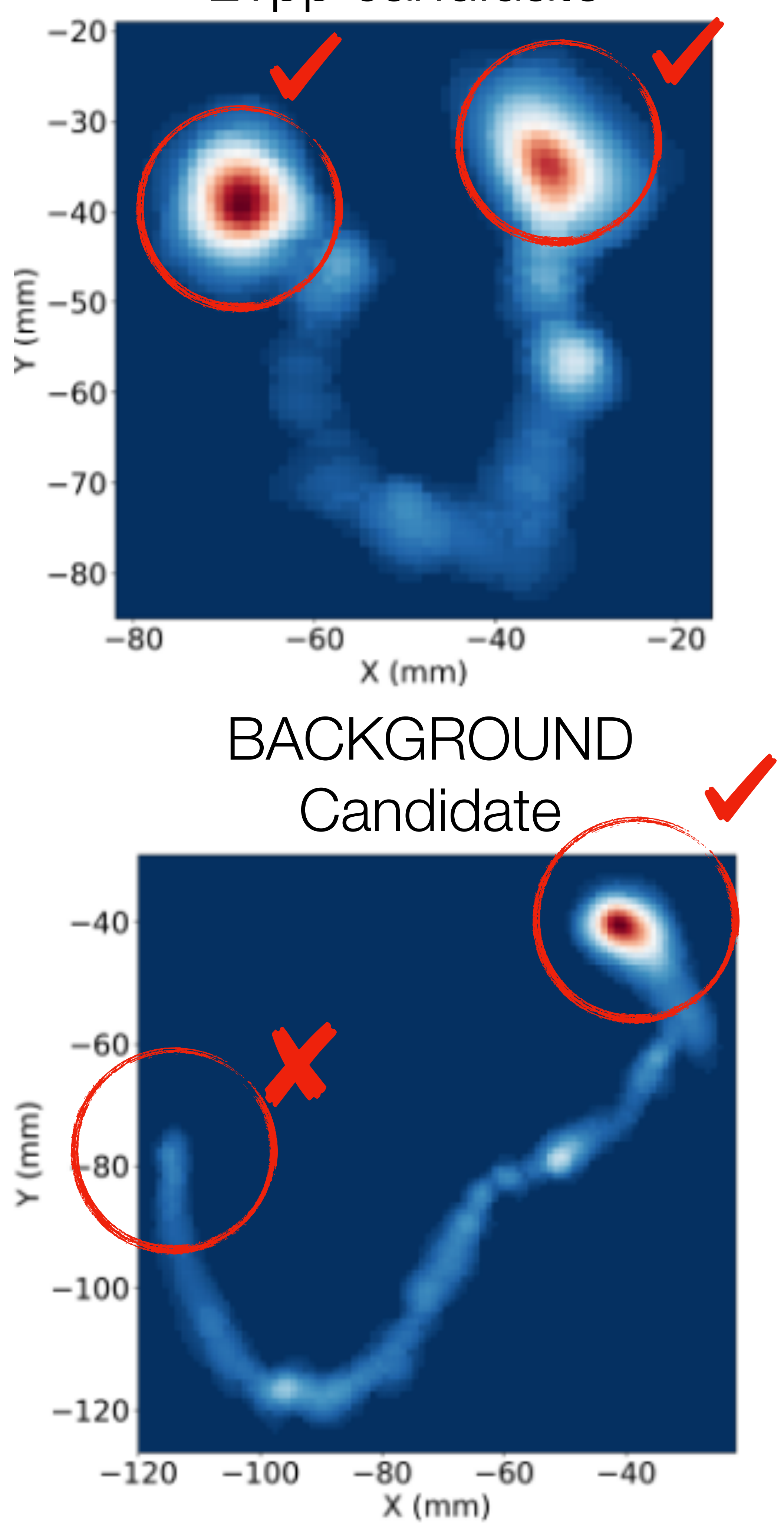
- If you measure the energy of the two electrons in the final state, the experimental signature is a **monoenergetic line.**
- It comes at a heavy price:
  - **A lot** of the isotope of interest (ton scale)
  - **Low backgrounds** in MeV range (low radioactivity)
  - Signal/background discrimination
  - **Good energy resolution**



Enters NEXT...

High Pressure gaseous Xenon Time Projection Chamber

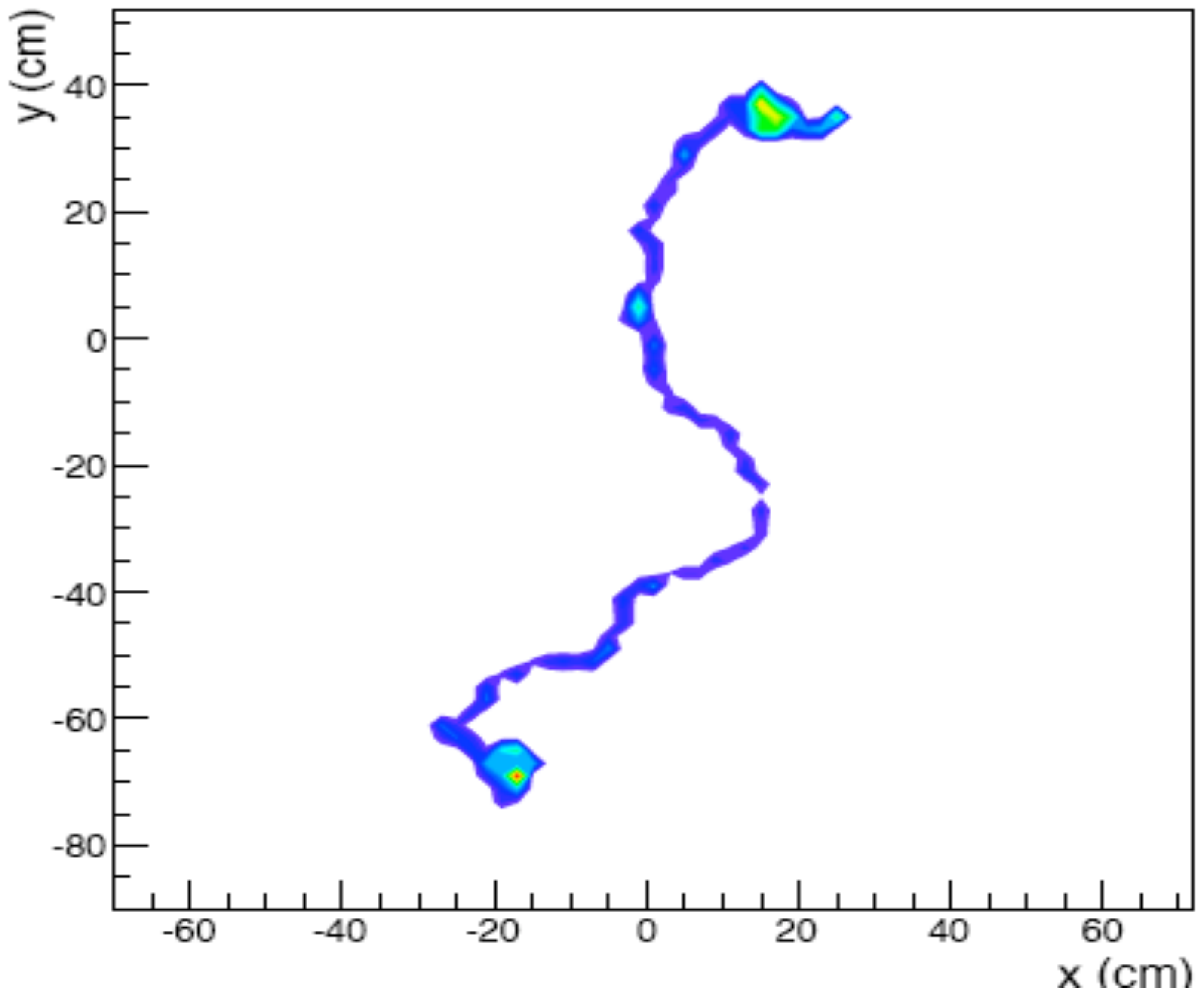




NEXT origins

Justo, JJ, James and Dave, LBNL, 2009

Topology: spaghetti, with meatballs



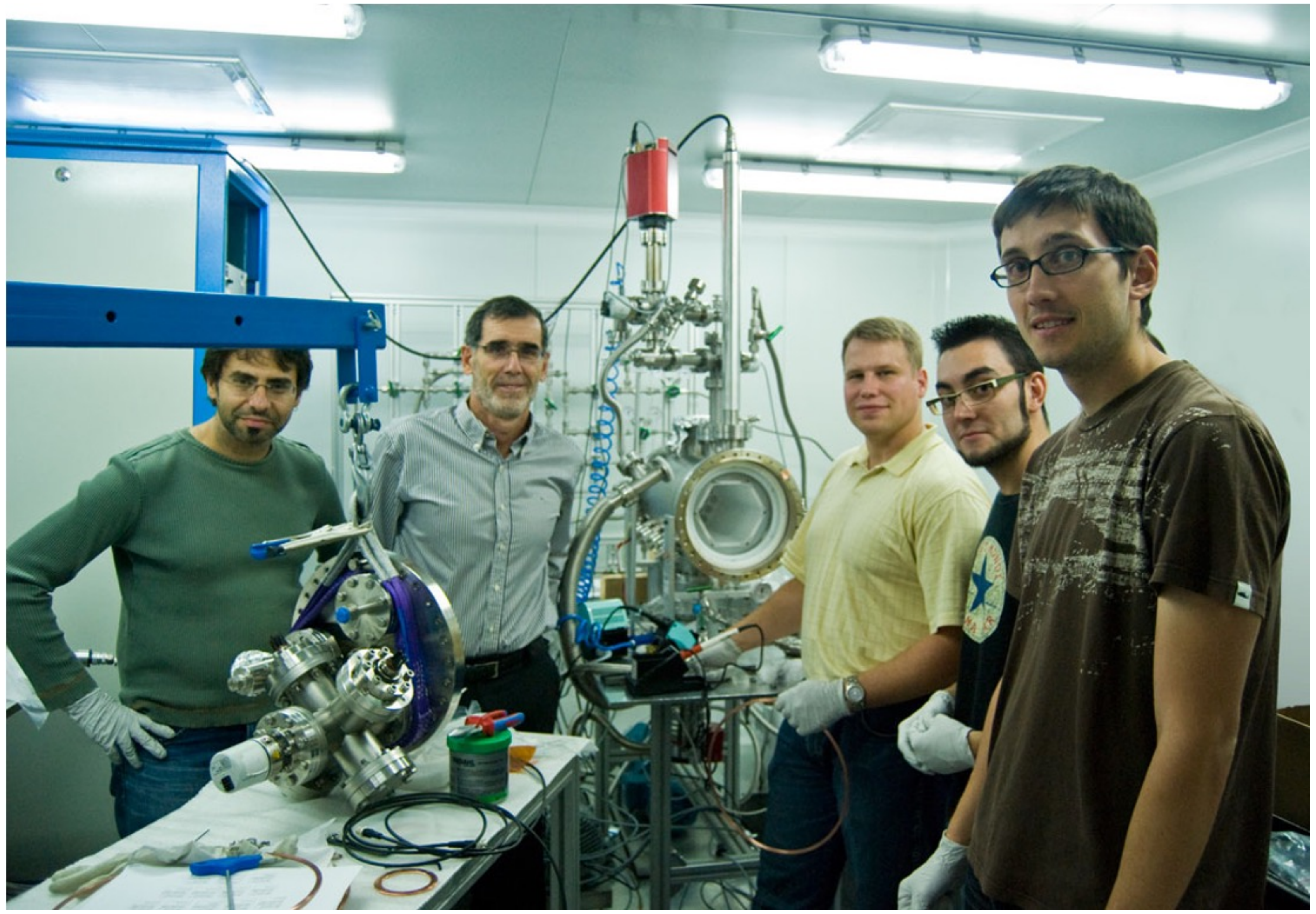
ββ events: **2**

γ events: **1**

Gotthard TPC:

~ x30 rejection

NEXT early prototypes (2011)



Near-Intrinsic Energy Resolution for 30 to 662 keV Gamma Rays in a High Pressure Xenon Electroluminescent TPC

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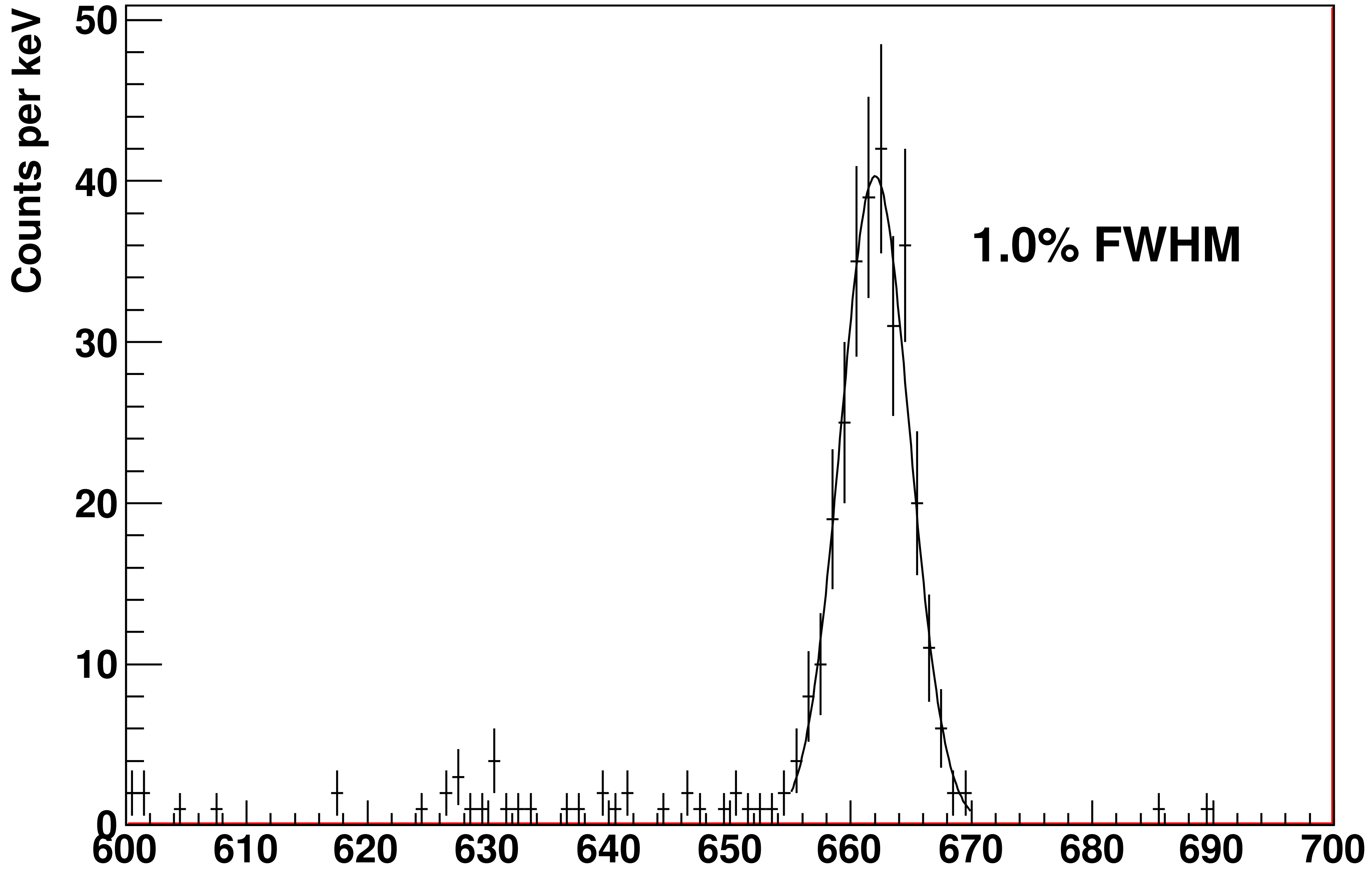
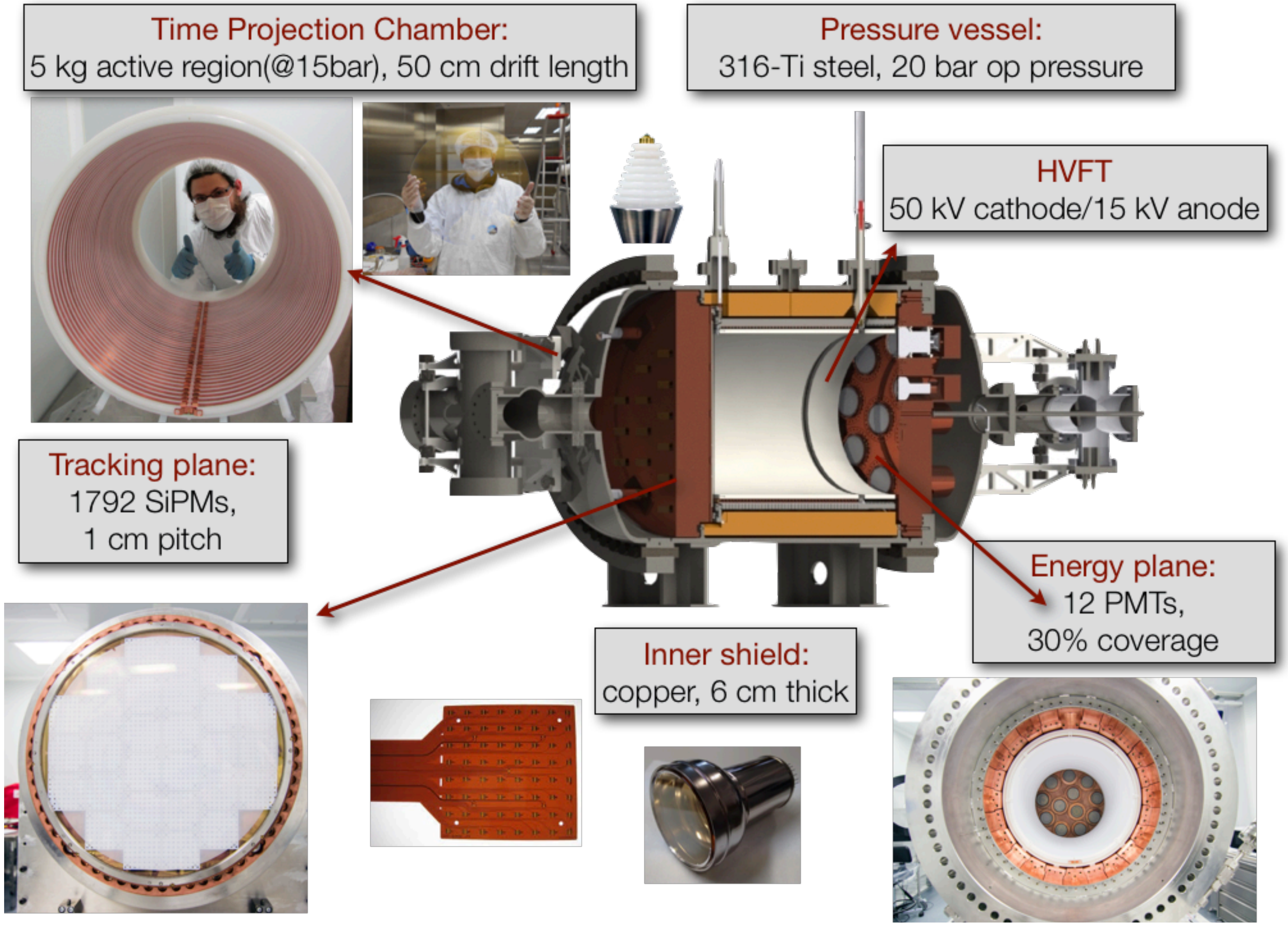
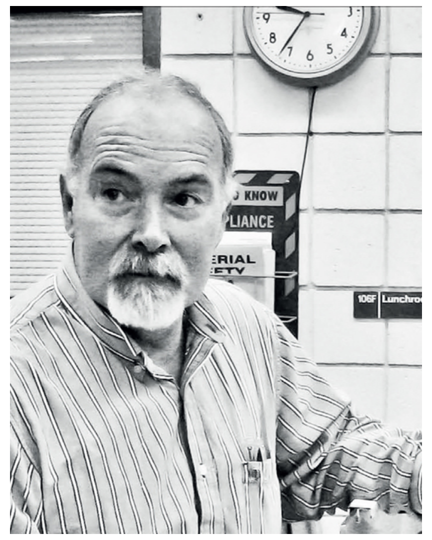


NEXT-White

The NEXT-White detector

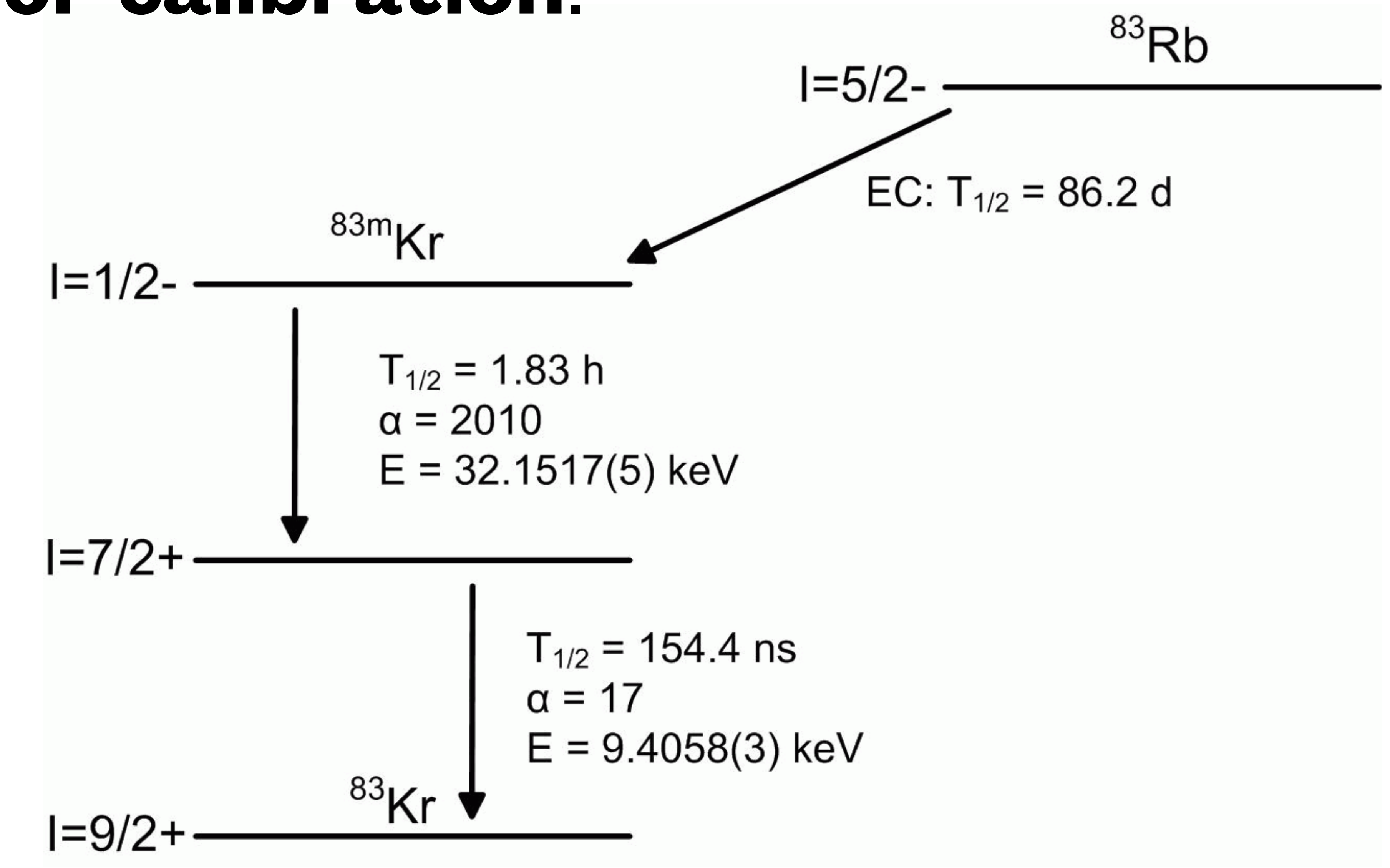


The late professor James White.
NEXT-White is named to honour
his memory.

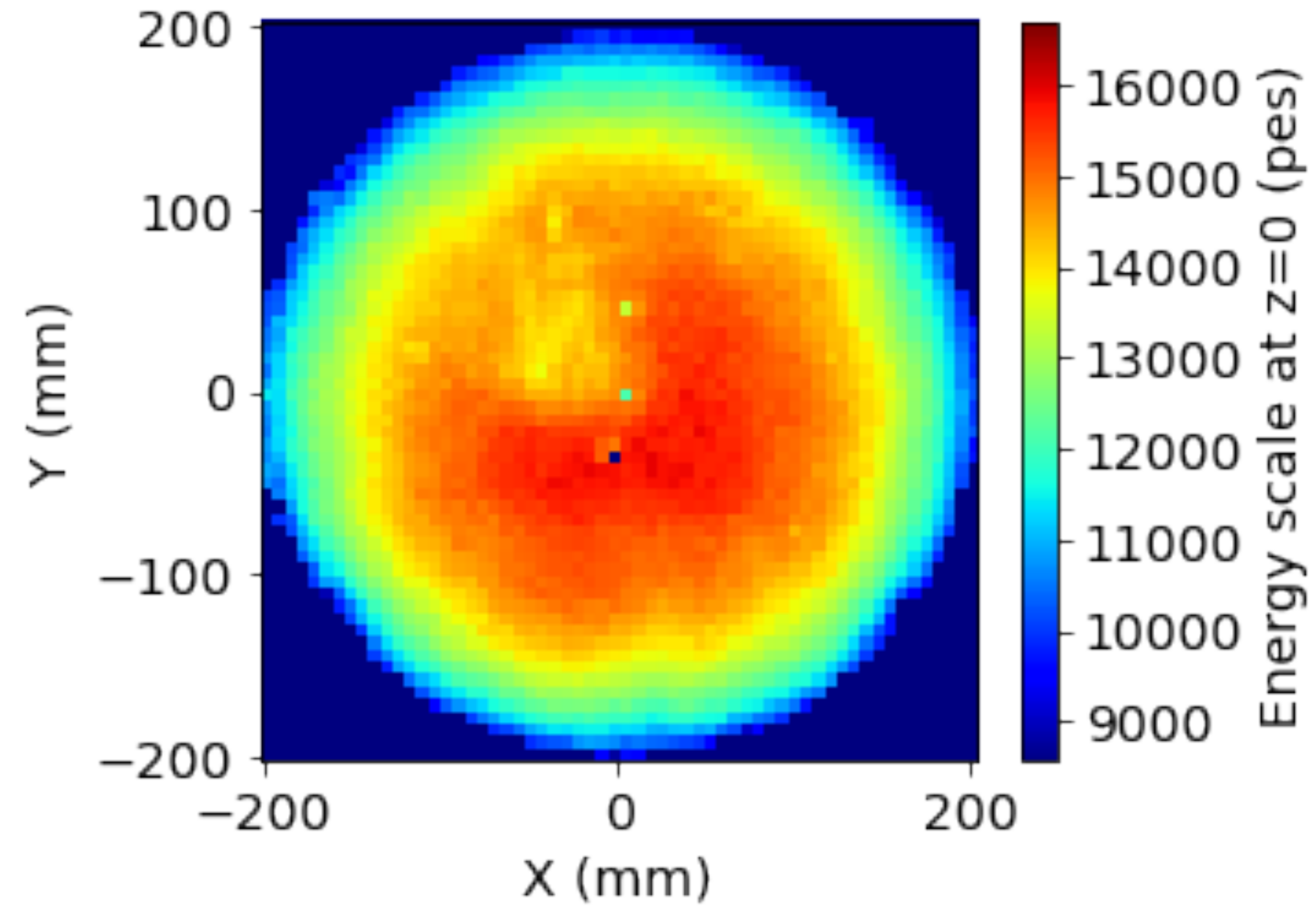


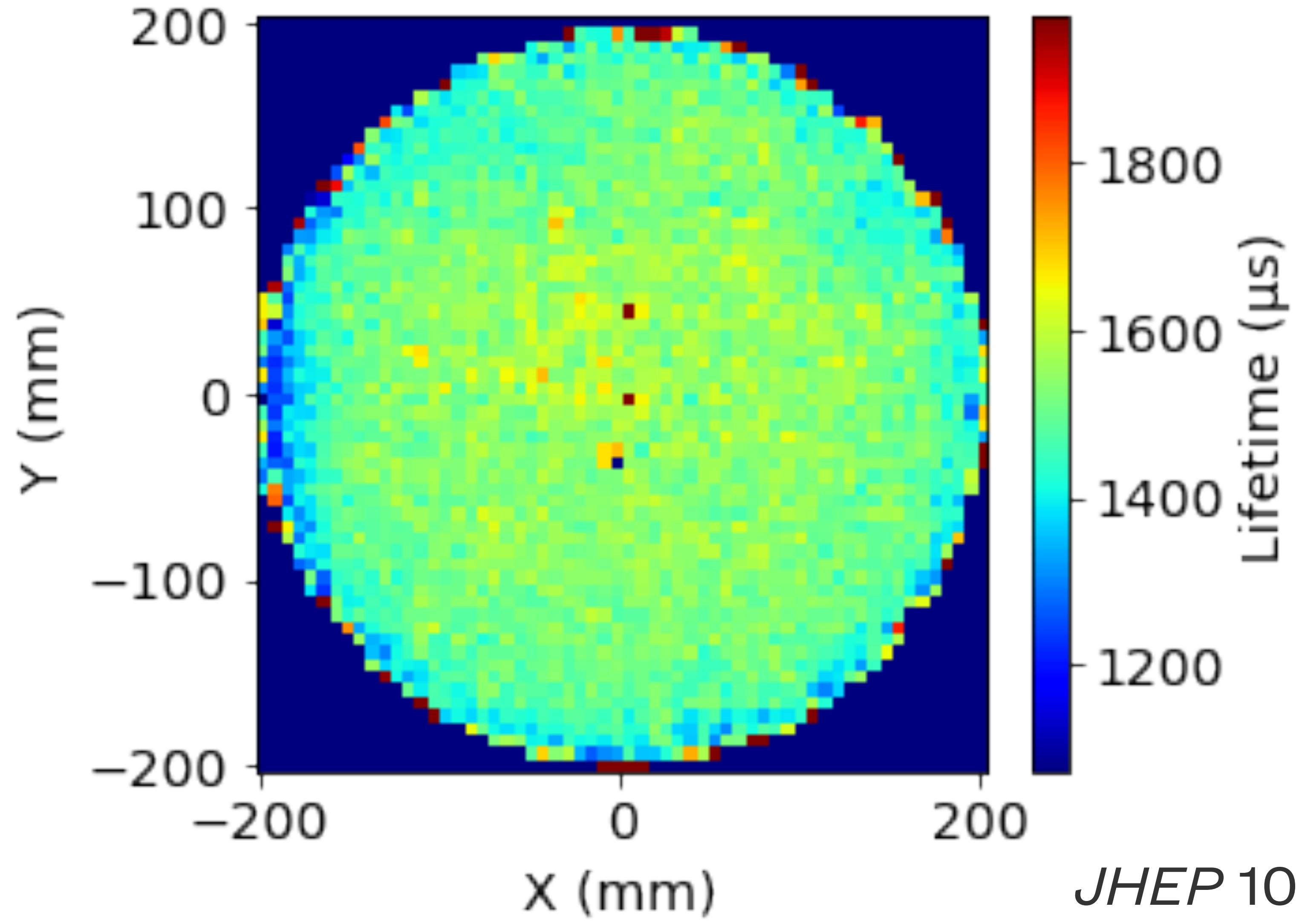
^{83}Kr calibration

- ^{83}Rb decays 75% of the time to a metastable state of ^{83}Kr through internal conversion with a half-life of 86 days.
- This metastable state decays to ground with a lifetime of 1.83 h, emitting two electrons of 32.1 and 9.4 keV.
- These **low-energy electrons** create a very short signal, **useful for calibration**.



Calibration maps for run 4845



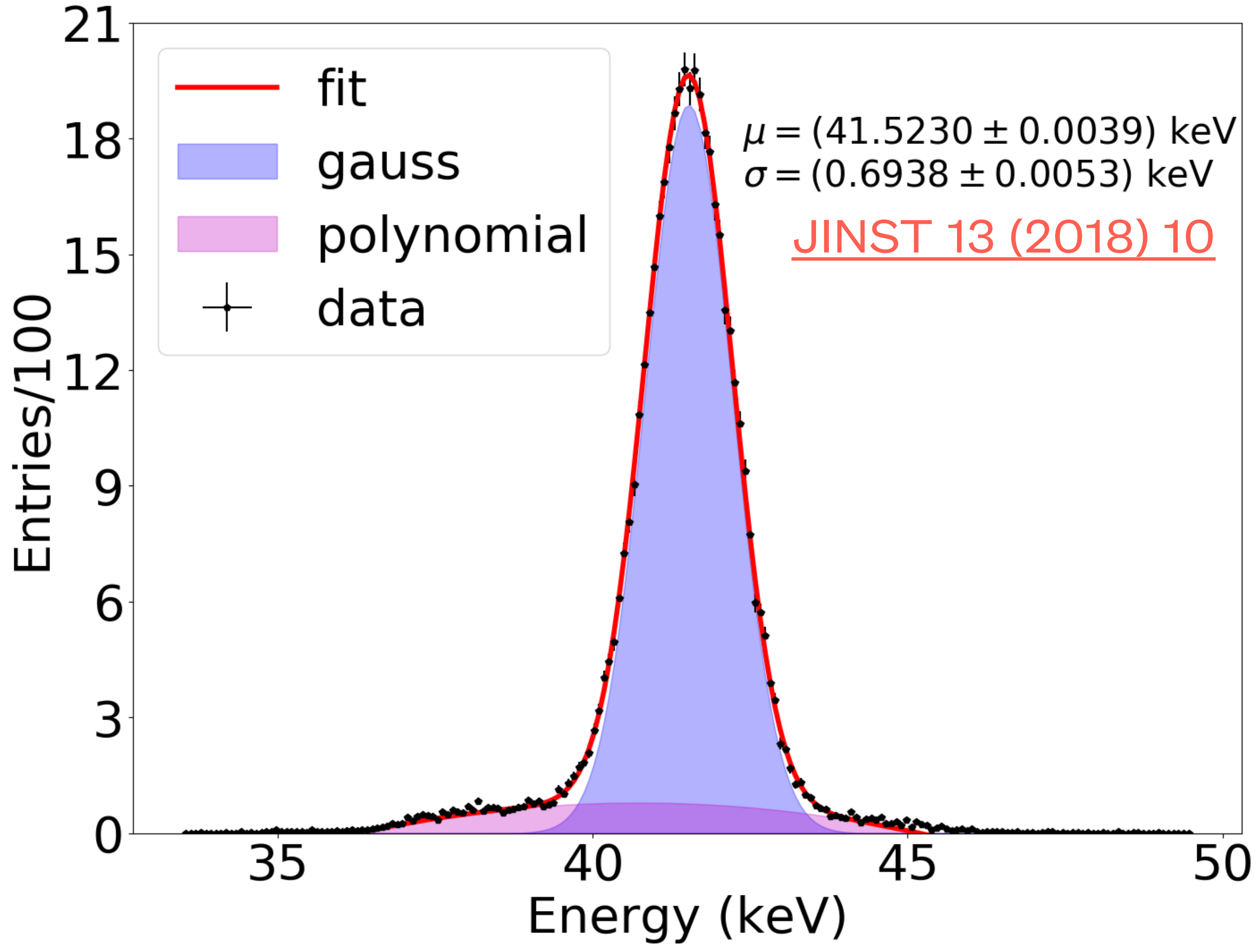


JHEP 10 (2019)

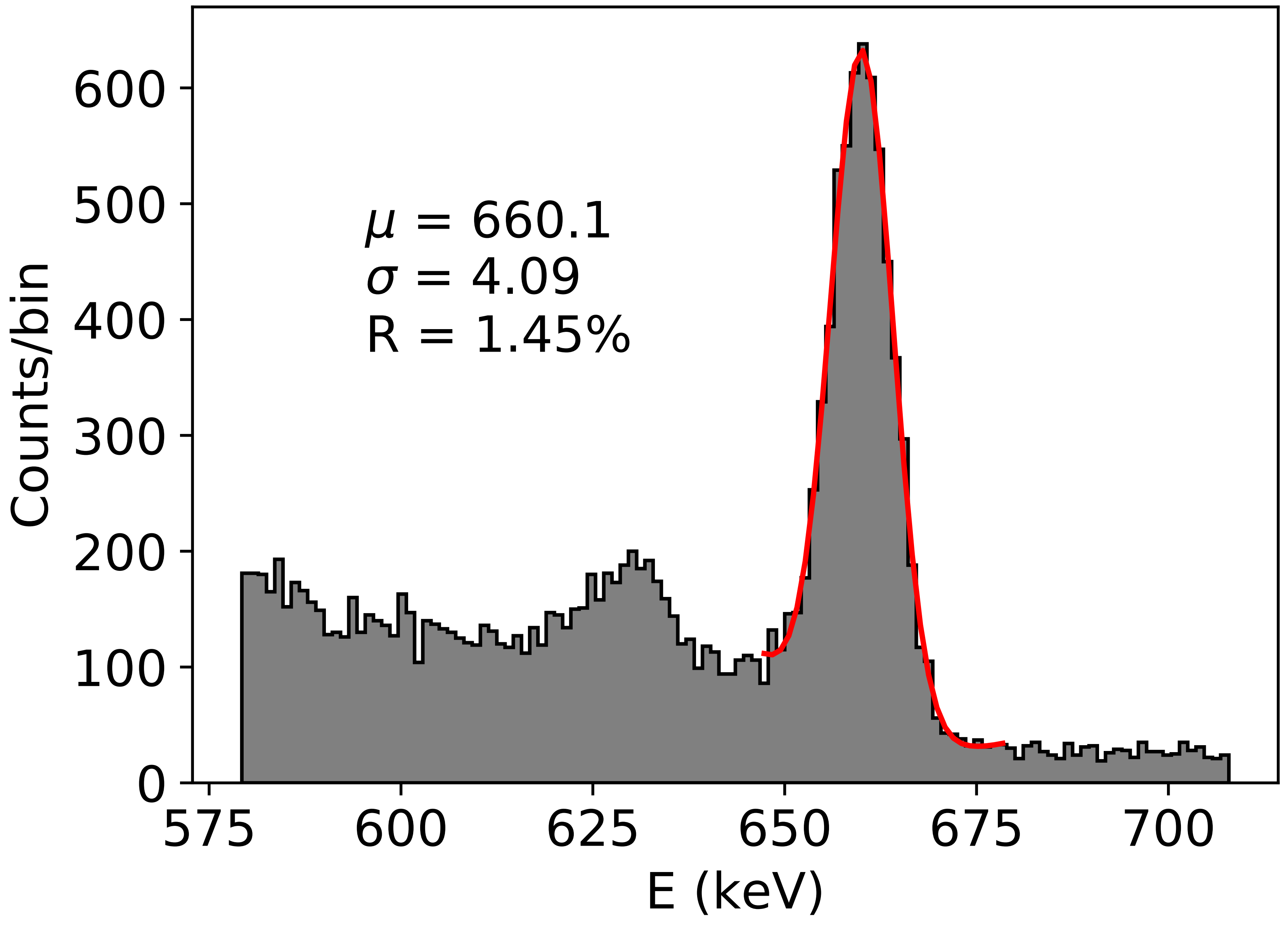
Energy resolution

- One of the main goals of NEXT-White was to measure the **energy resolution** of a high pressure xenon TPC .
- For this purpose, energy calibrations with *higher-energy radioactive sources* ^{137}Cs and ^{232}Th sources have been carried out as a part of the NEXT-White data taking.
- The energy resolution extrapolates to less than 1% FWHM at $Q_{\beta\beta}$ (0.91% at 2614 keV, ^{208}Tl photopeak).

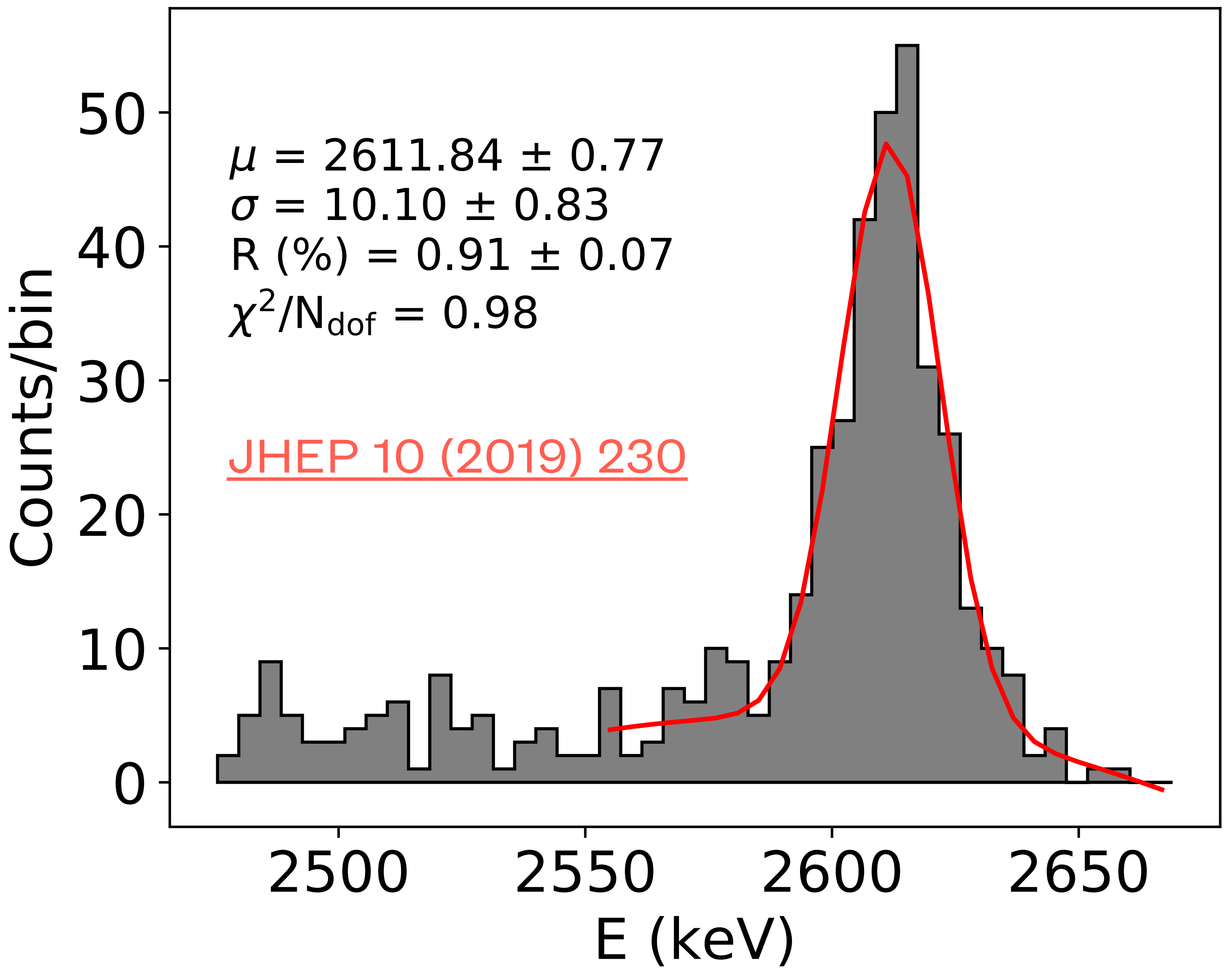
^{83m}Kr events



^{137}Cs photo-peak



^{208}Tl photo-peak



Energy calibration of the NEXT-White detector with 1% resolution near $Q_{\beta\beta}$ of ^{136}Xe

NEXT collaboration

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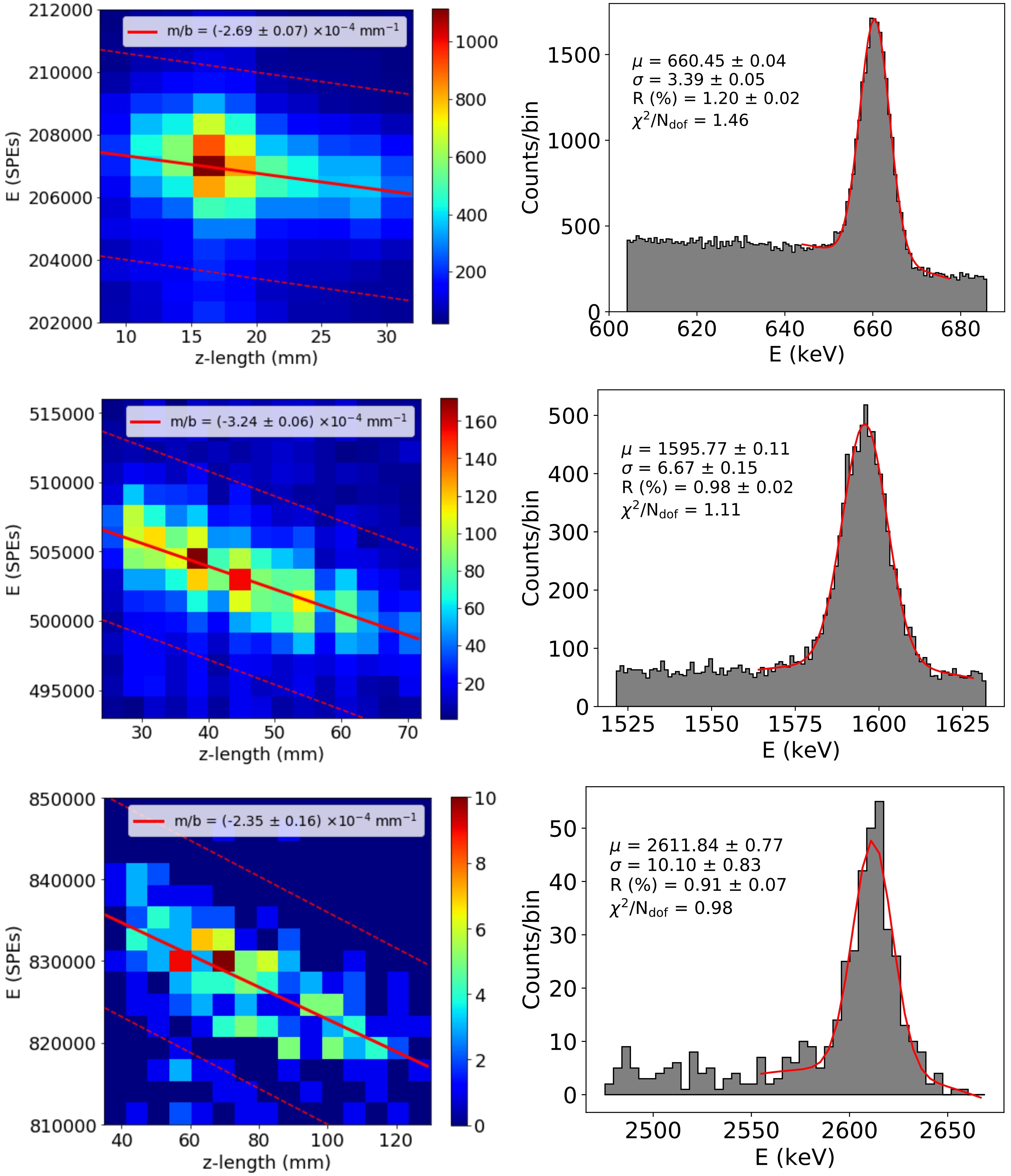
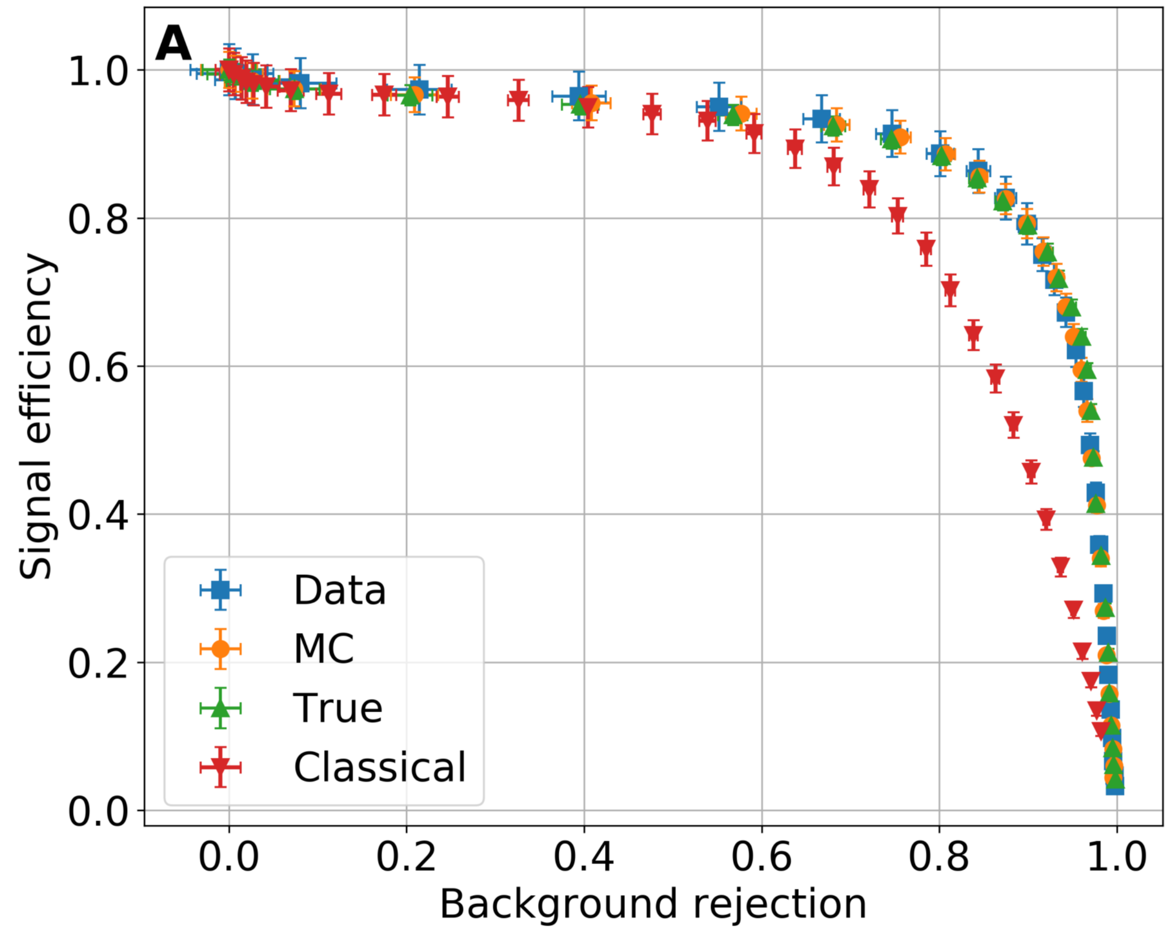
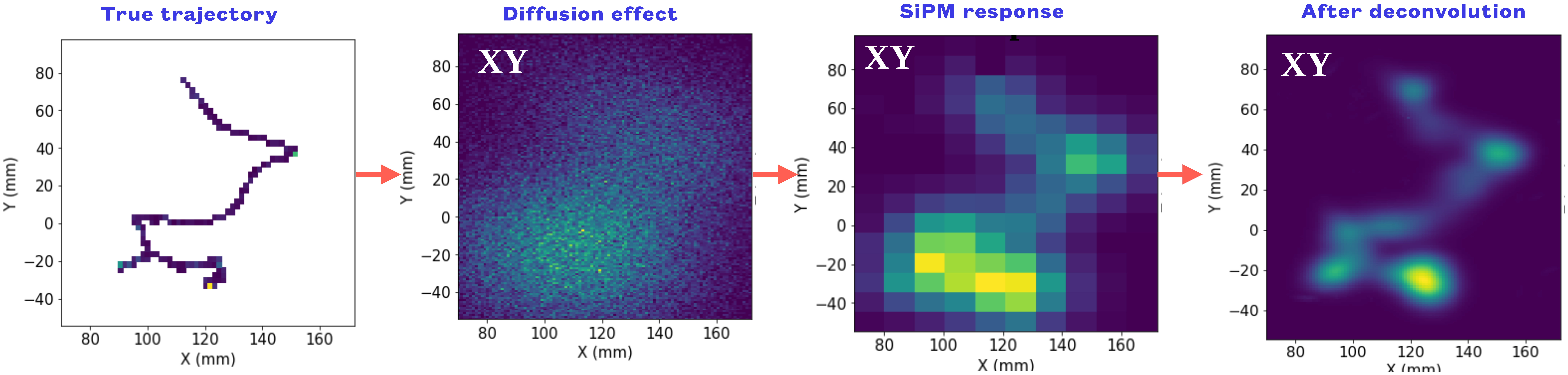
[g] On leave from Soreq Nuclear Research Center, Yavneh, Israel.
[h] Deceased.



Richardson-Lucy deconvolution

- Topological information about the event is given by **SiPMs position + time**
- Electrons **diffuse while drifting**, smearing the image.
- The smearing is described by a kernel — a *point spread function* (PSF).
- The PSF can be obtained with ^{83m}Kr events (point-like).
- The Richardson-Lucy deconvolution uses the PSF to deconvolve the image and remove the smearing.





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Demonstration of the event identification capabilities of the NEXT-White detector

The NEXT Collaboration

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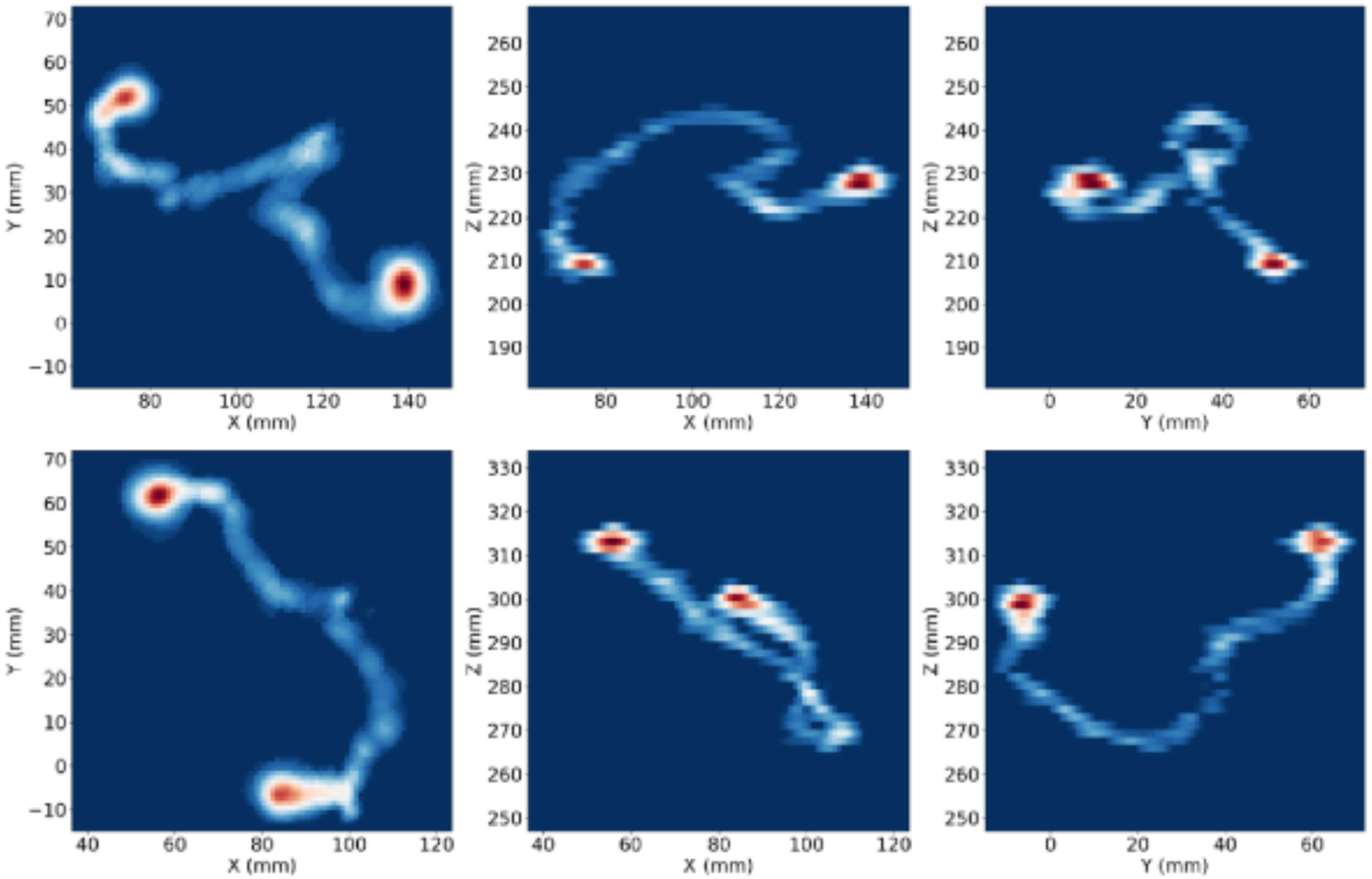
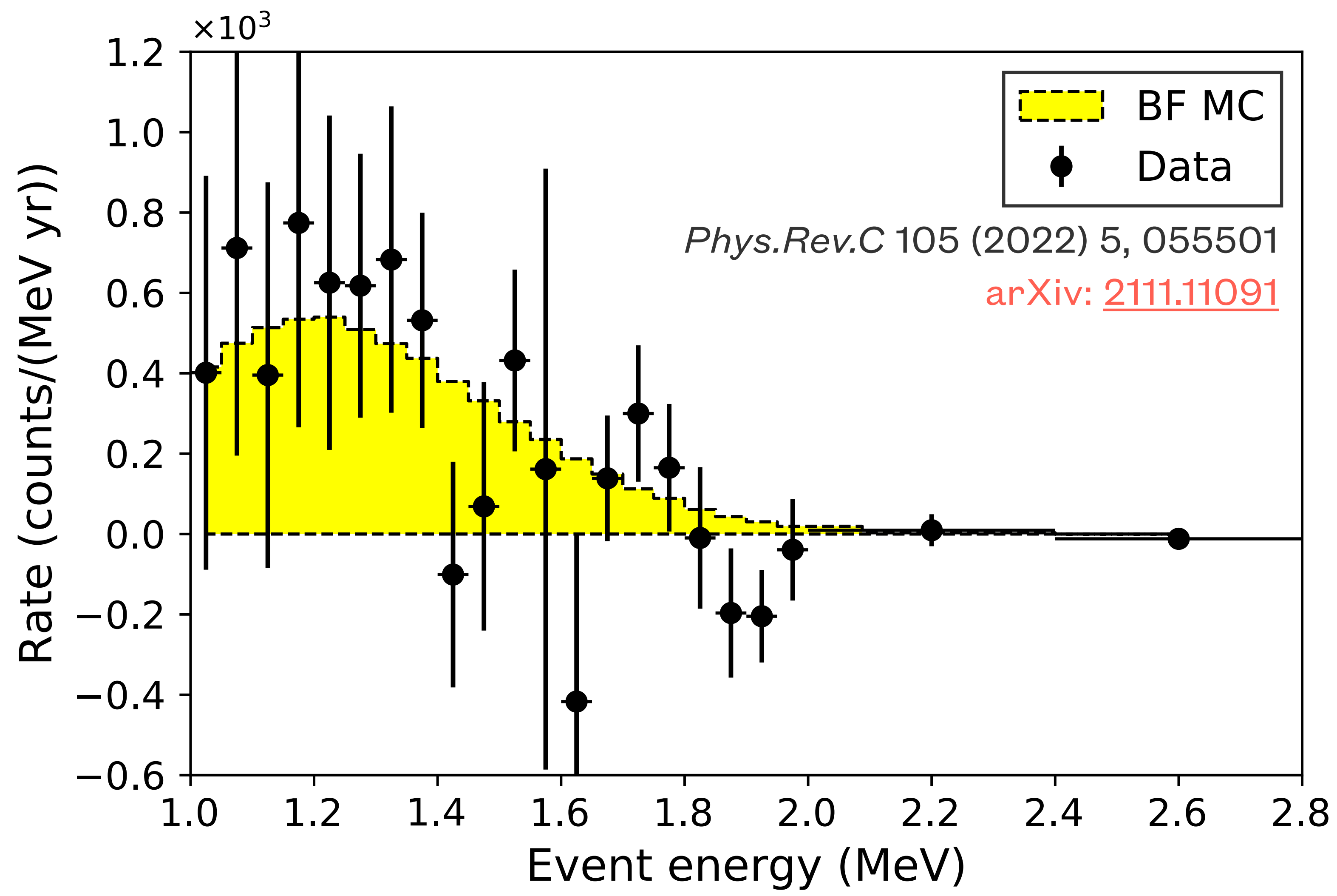
[g] On leave from Soreq Nuclear Research Center, Yavneh, Israel.

[h] Deceased.

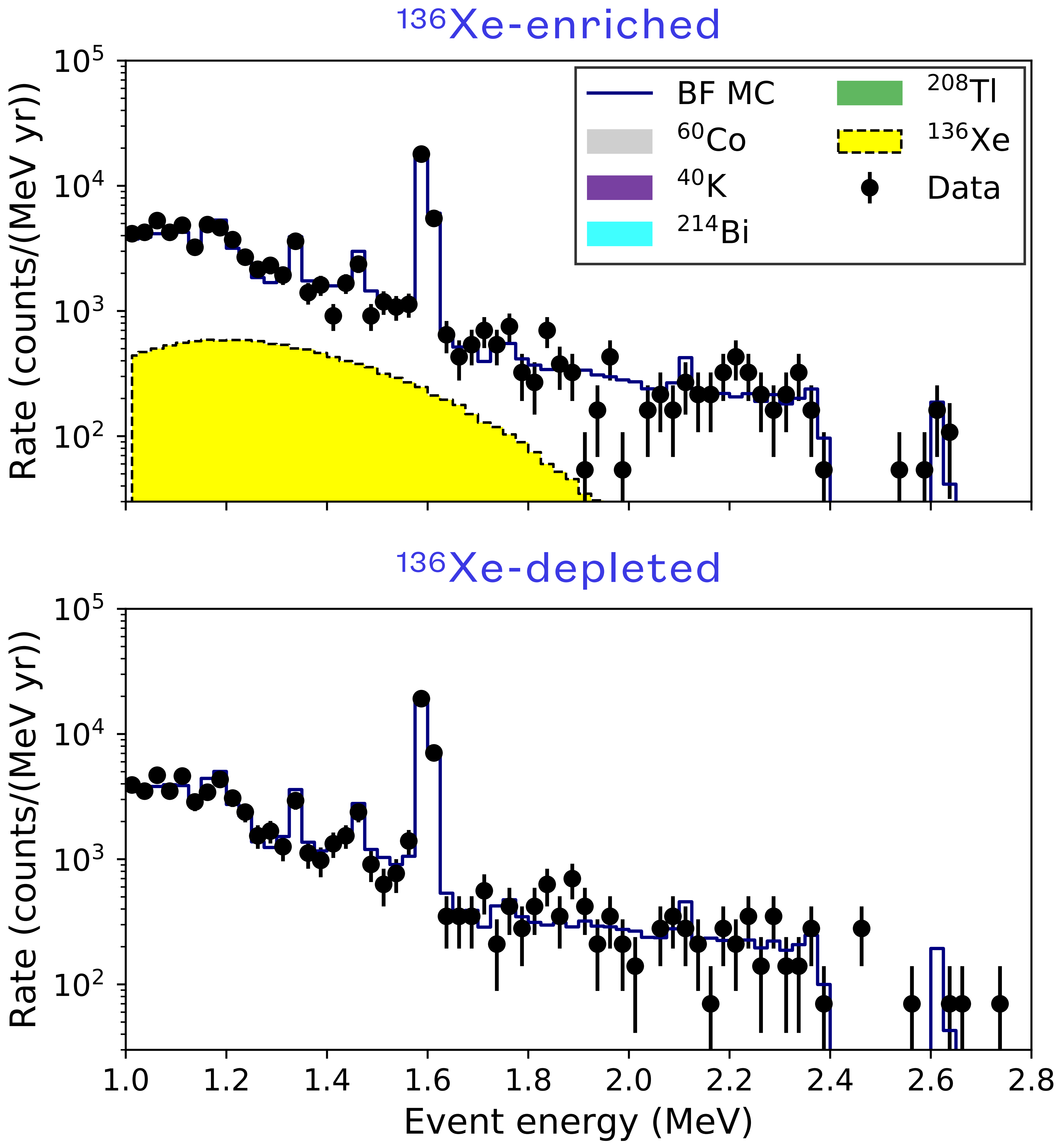


$2\nu\beta\beta$ measurement in NEXT-White

- The NEXT-White experiment was able to measure the **half-life of the $2\nu\beta\beta$ decay in ^{136}Xe** (a continuous spectrum).
- Two analysis methods: background-model dependent and model-independent
- Model-independent analysis: difference between ^{136}Xe-enriched spectrum and ^{136}Xe-depleted spectrum.



$$T_{1/2} = 2.34^{+0.80}_{-0.46}\ \text{(stat)}\ ^{+0.30}_{-0.17}\ \text{(sys)} \times 10^{21}\ \text{yr}$$



$0\nu\beta\beta$ measurement in NEXT-White

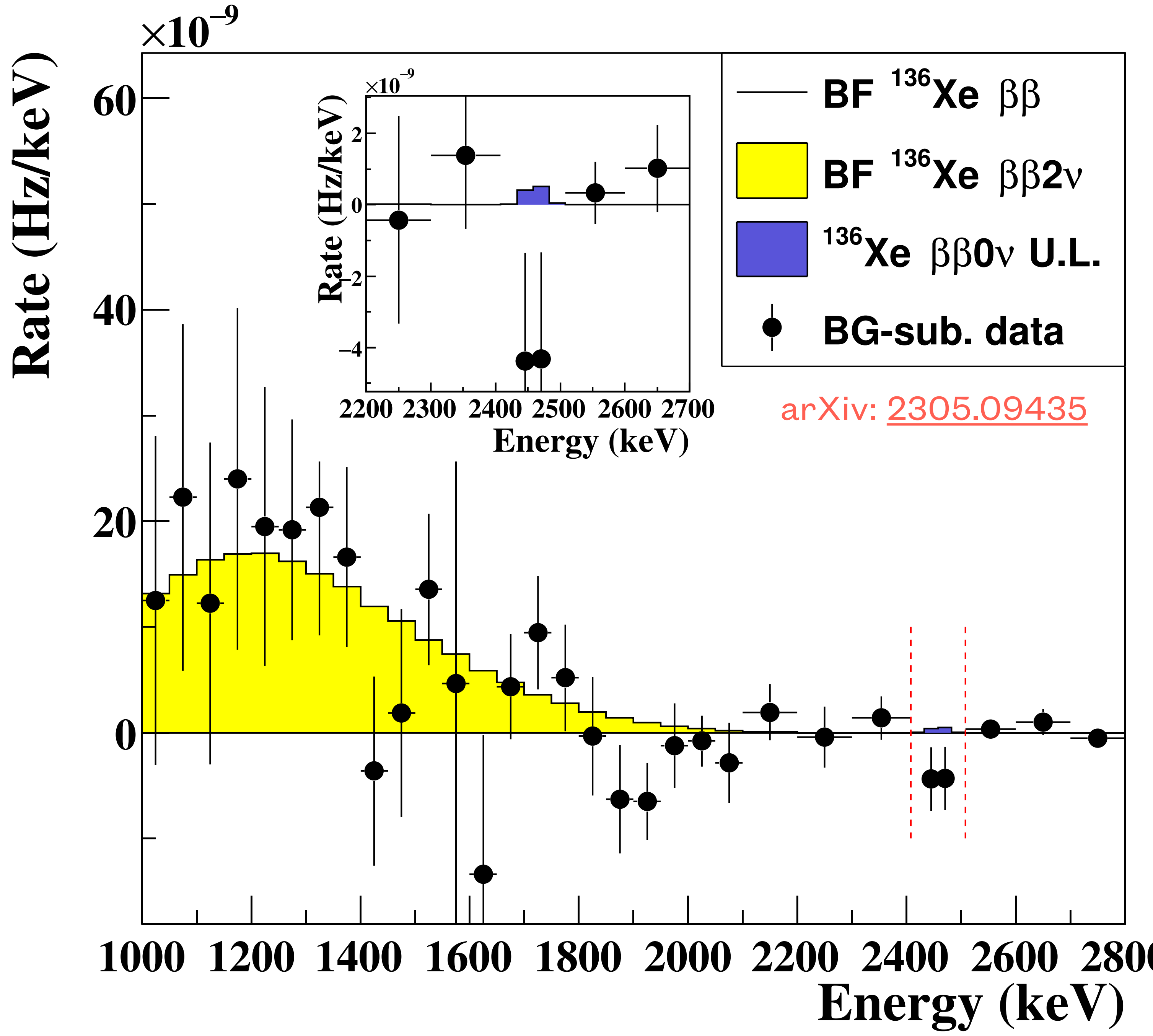
- Although originally beyond its scientific goals, the NEXT-White detector was recently exploited in order to perform a demonstration of the $0\nu\beta\beta$ search capabilities with the NEXT technology.
- Two methods: background-model-dependent and background subtraction.
- Low mass, so result not competitive with world's best limit, but **proof-of-principle analysis**

$$T^{0\nu}_{1/2} > 1.3 \times 10^{24}\ \text{yr}$$

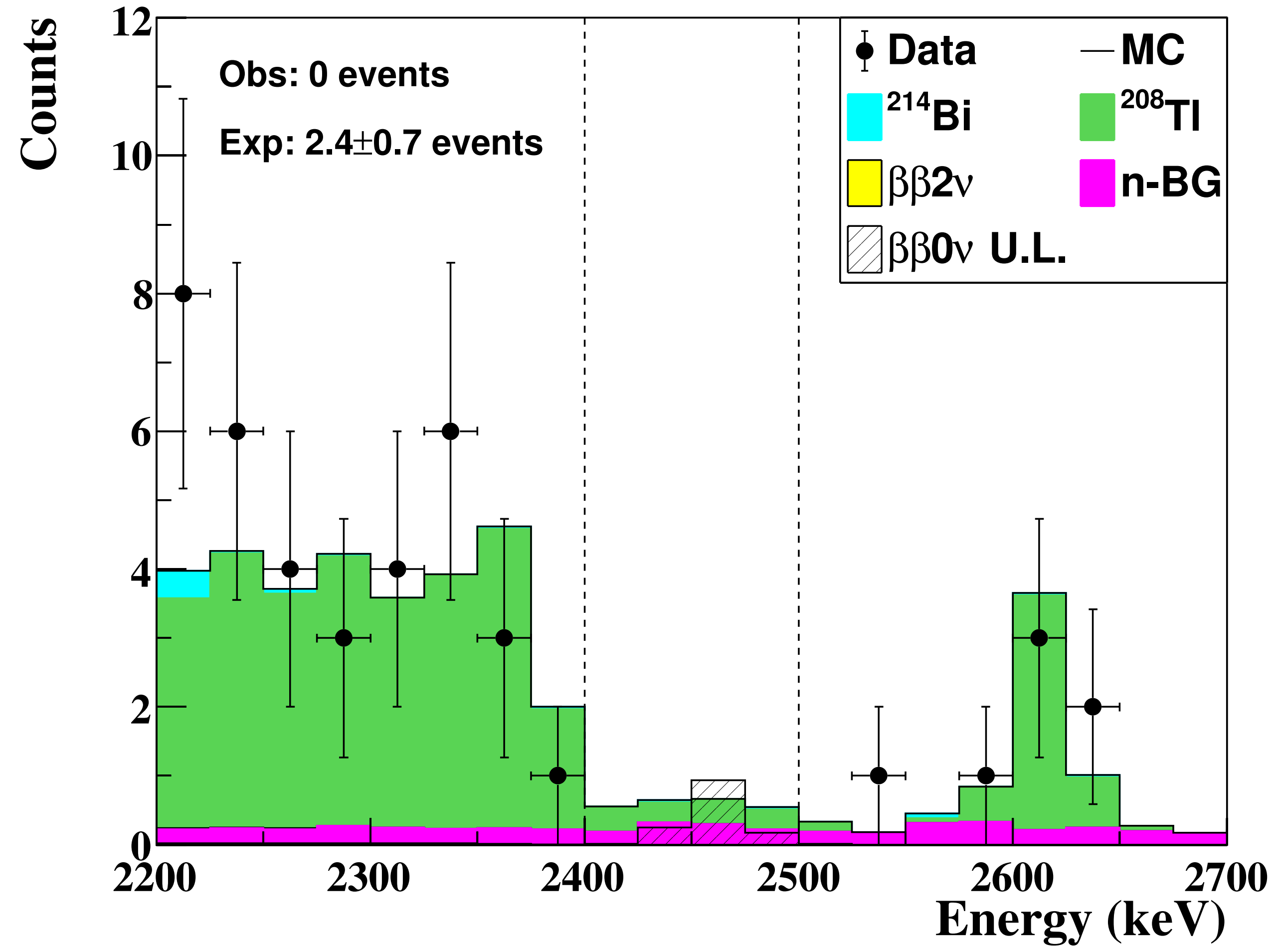
Background subtraction

$$T^{0\nu}_{1/2} > 5.5 \times 10^{23}\ \text{yr}$$

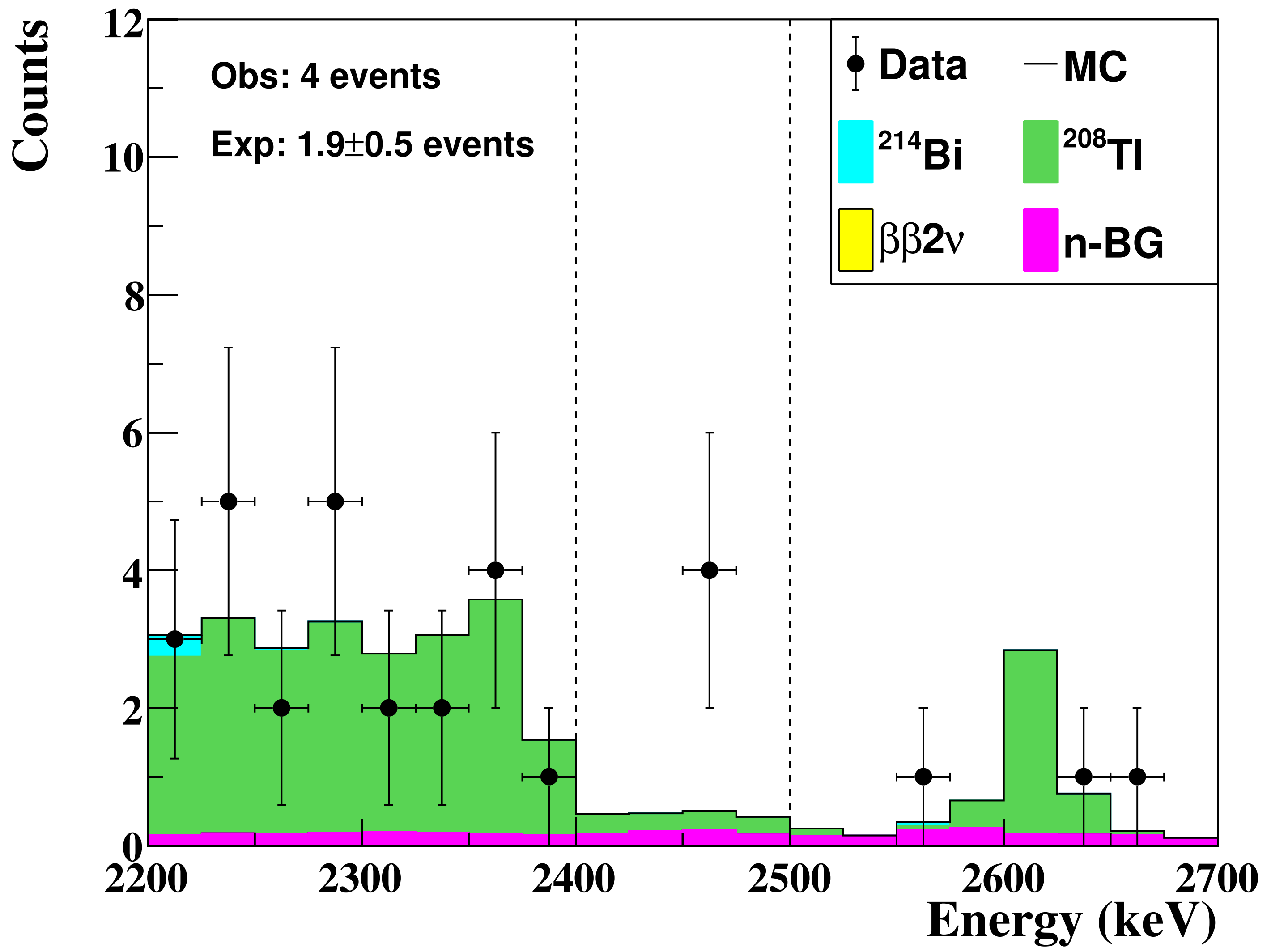
Background-model-dependent



136Xe-enriched



136Xe-depleted



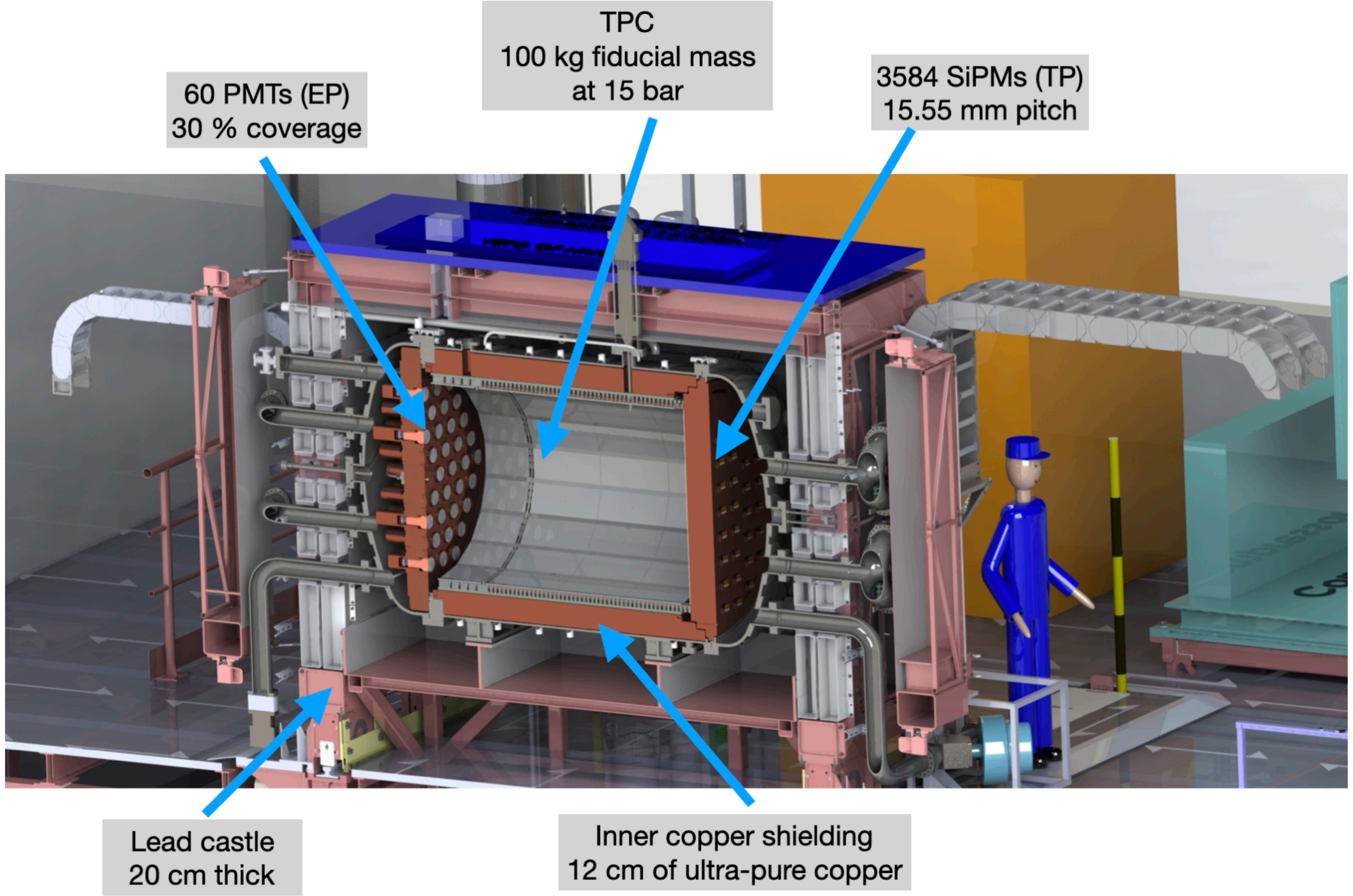
NEXT-100

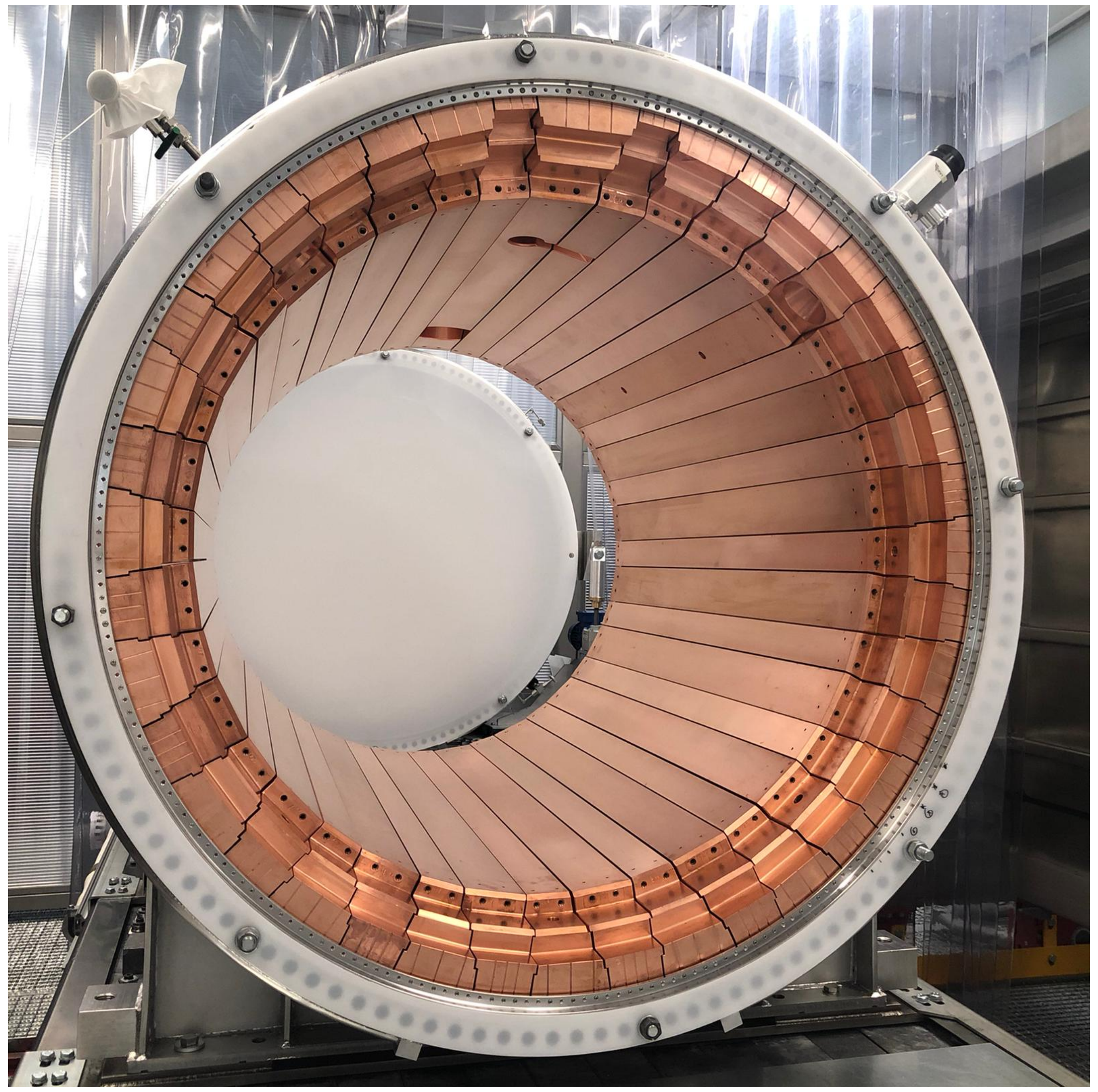
Plans

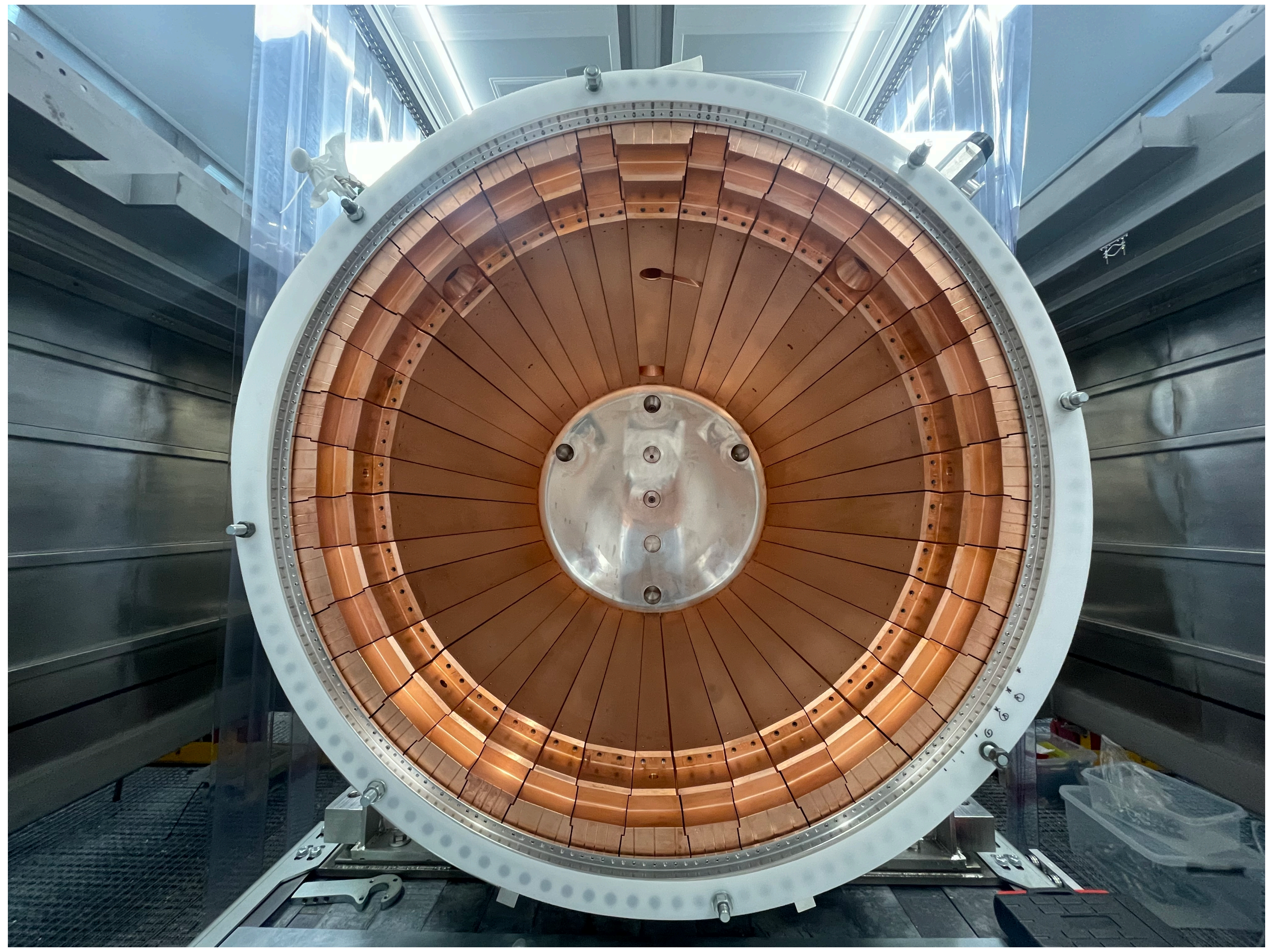
- Scales up NEXT-White ~2:1 in dimensions
- 1st half of 2023 → **Construction completed & assembling**
- 2nd half of 2023 → **Commissioning & calibration**

Goals

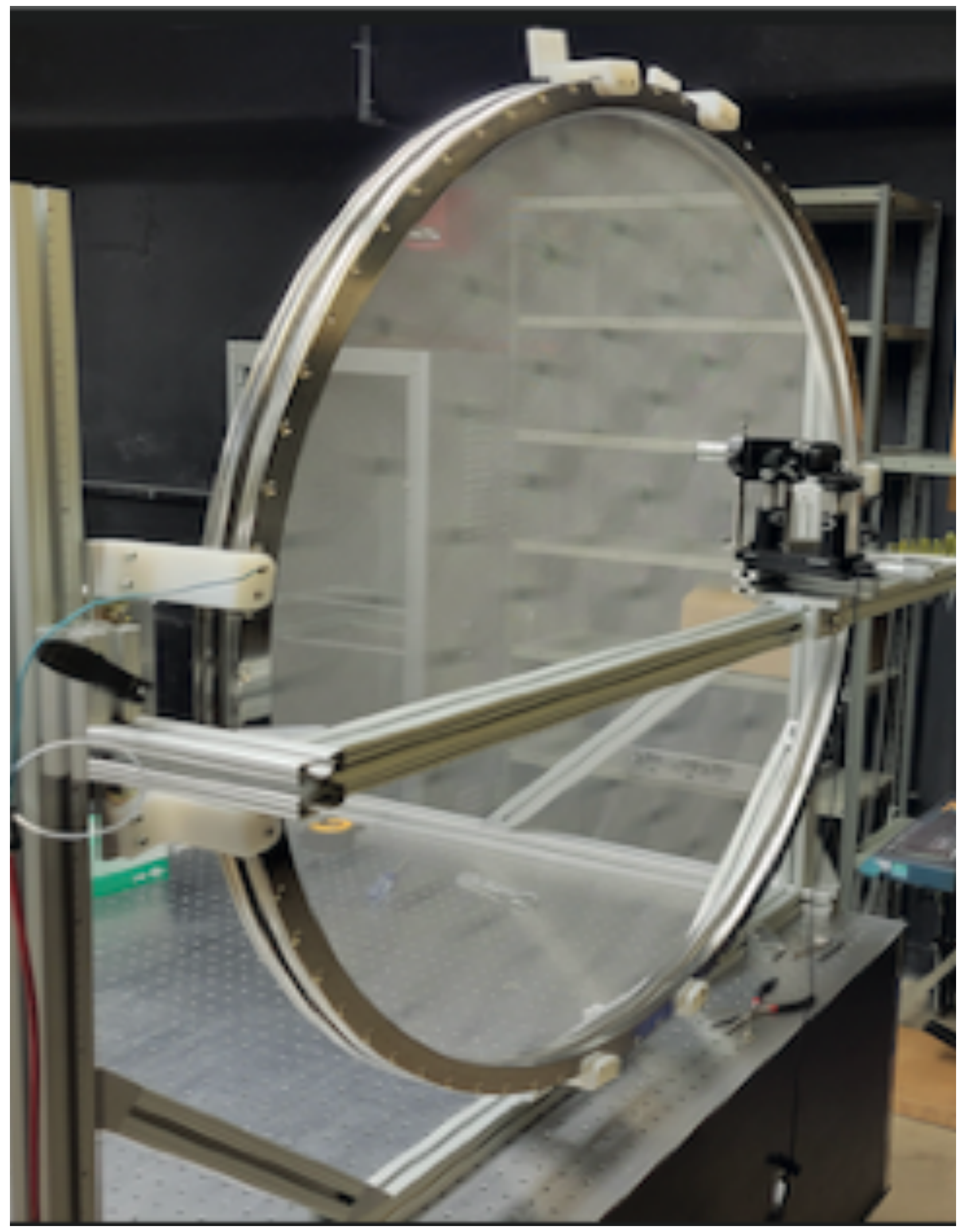
- Keep energy resolution <1% FWHM
- Improve radioactive budget
- Prepare for the tonne-scale
- Target background rate of 5×10^{-4} counts/(keV·kg·yr) or **1 count/(ROI·yr).**

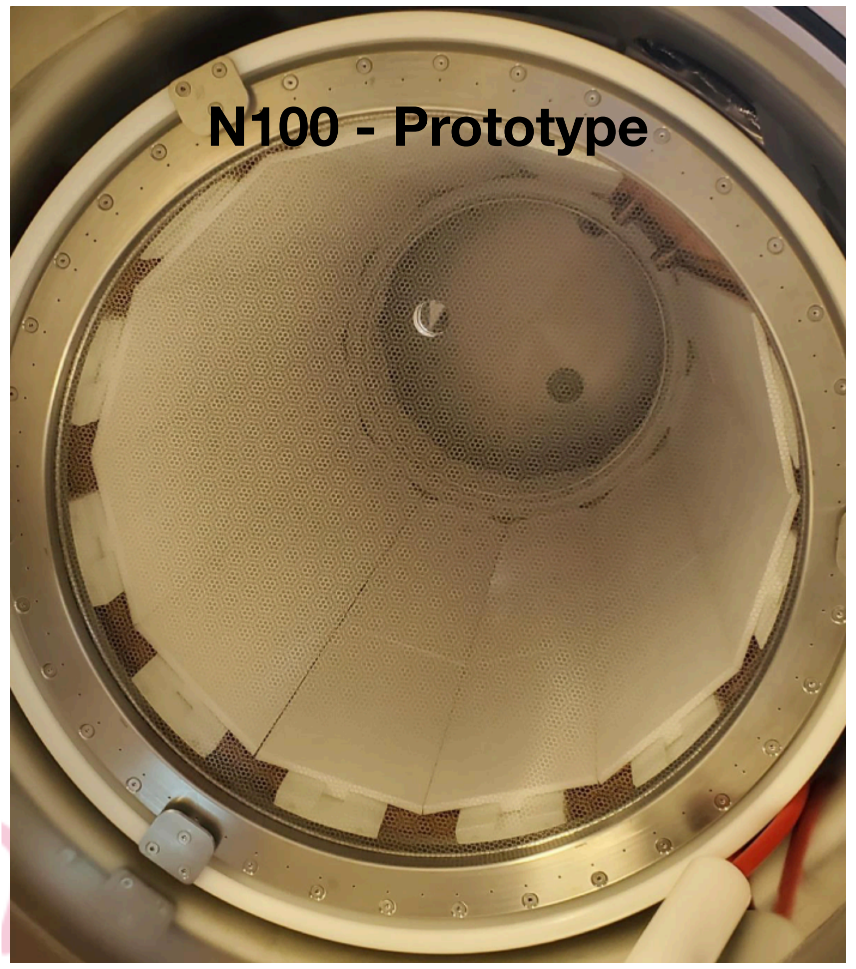




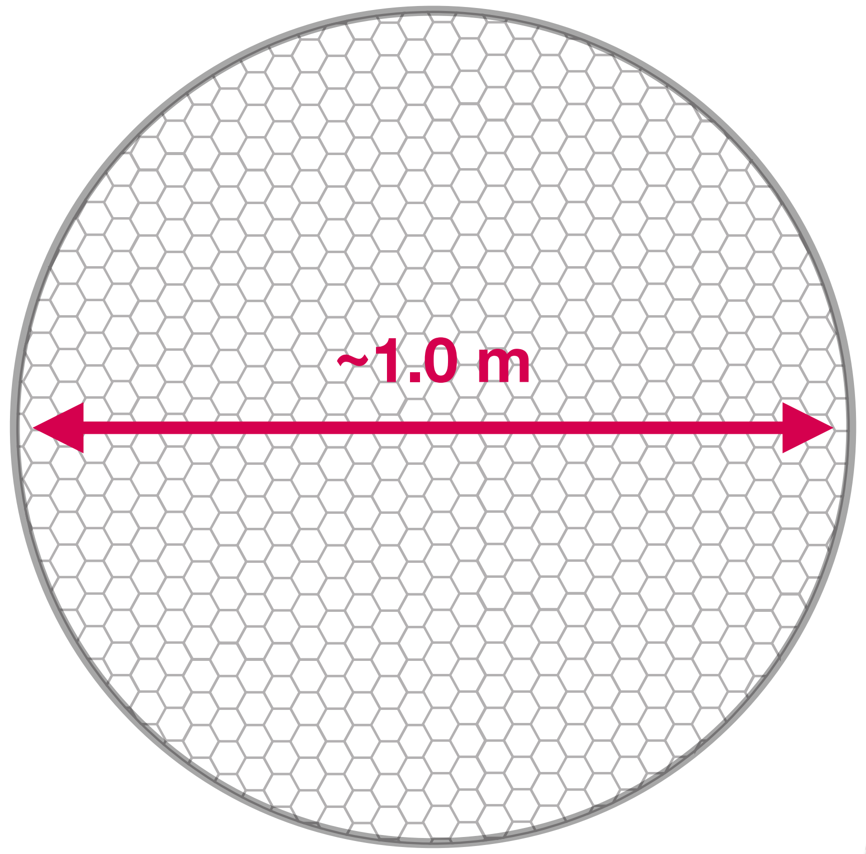


The NEXT-100 detector

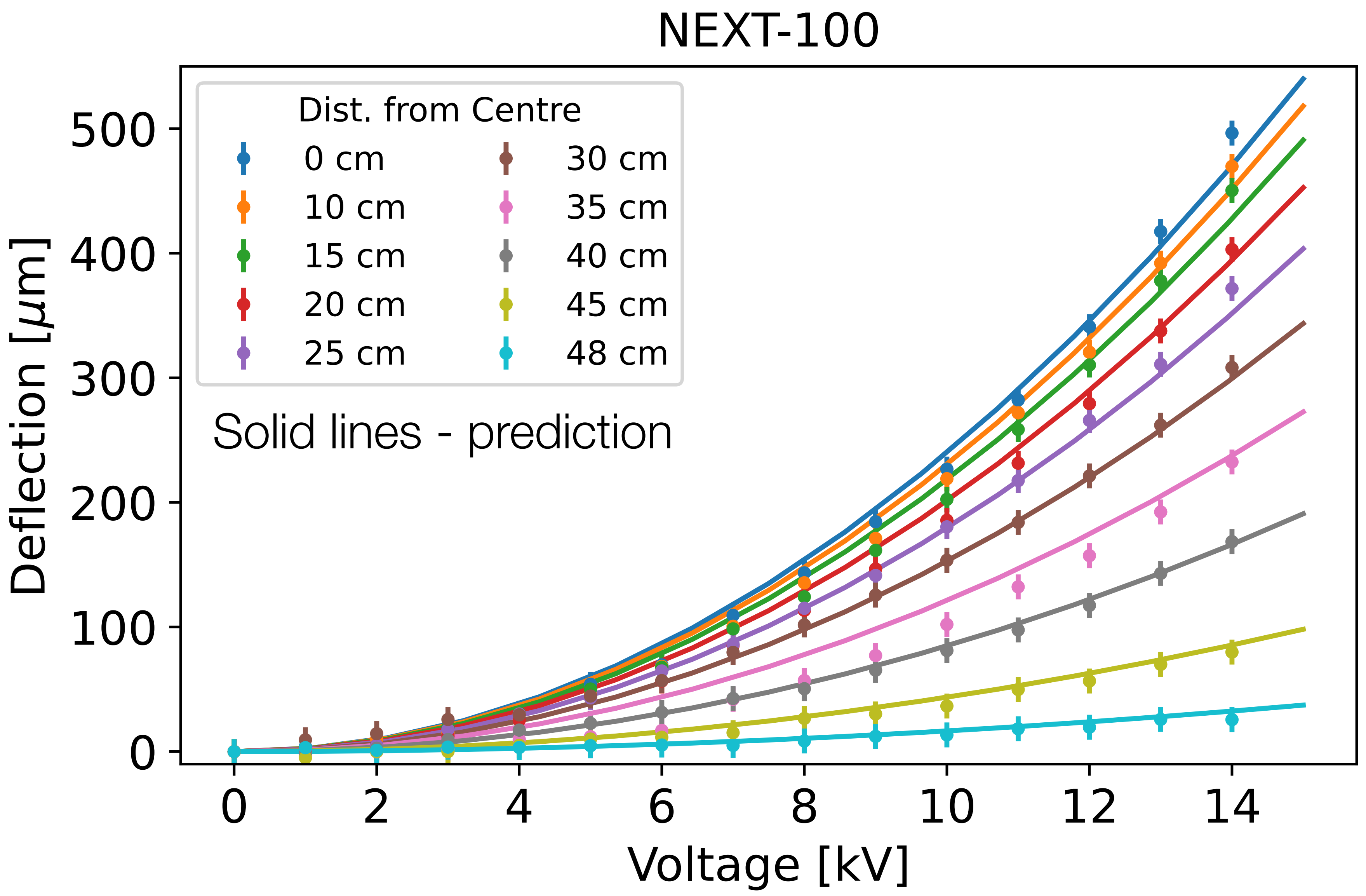


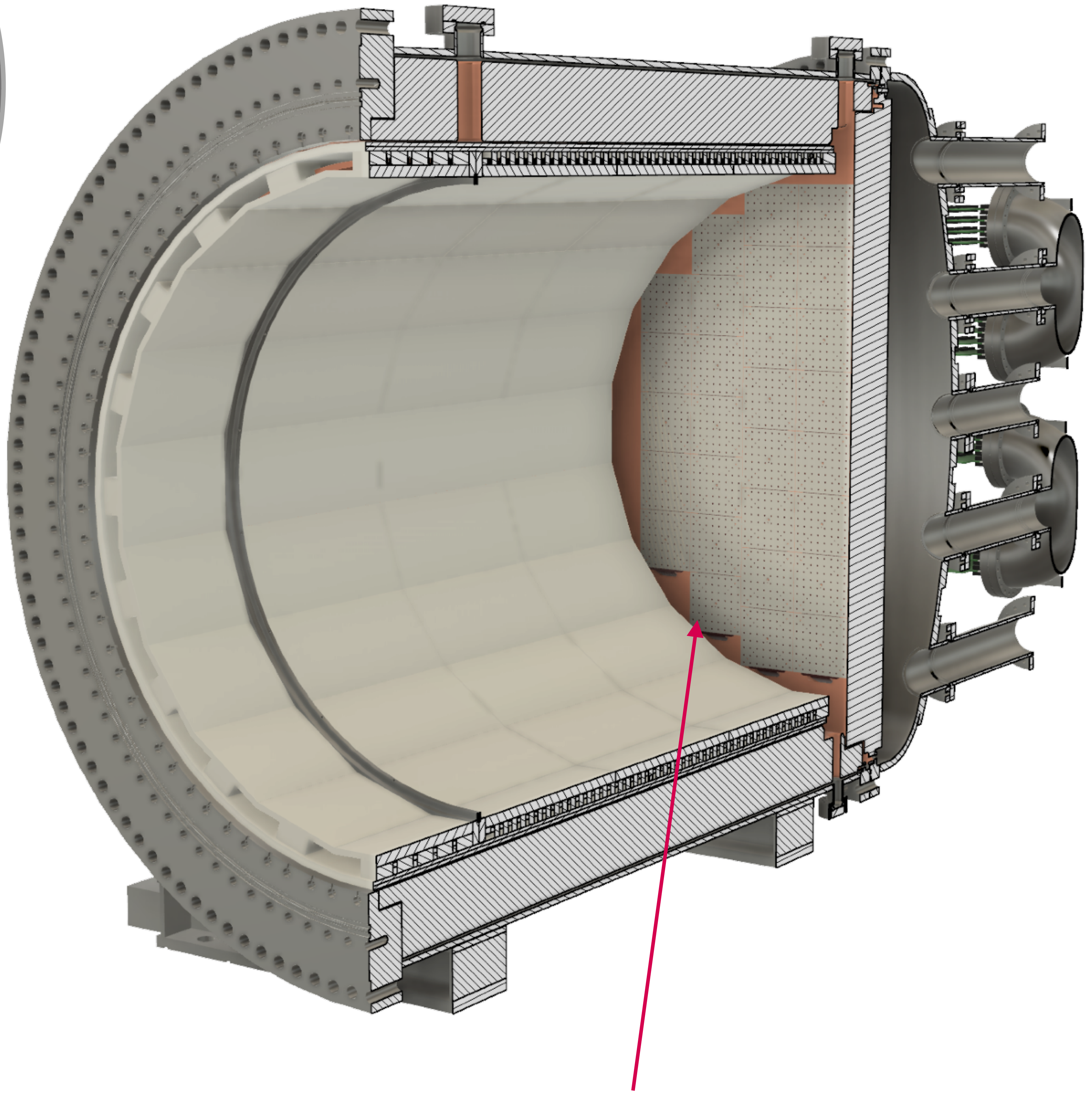


EL and cathode constructed from tensioned hexagonal meshes (~100 μm thickness)



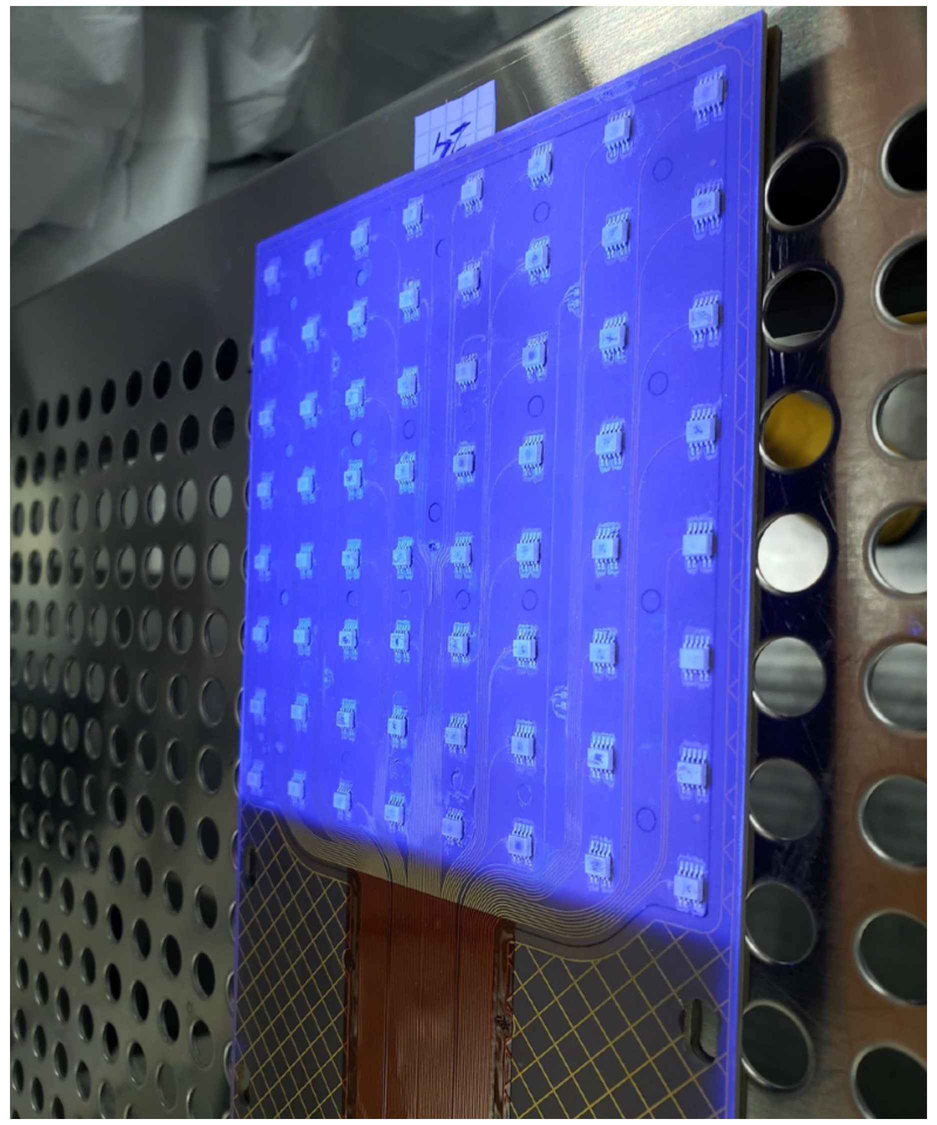
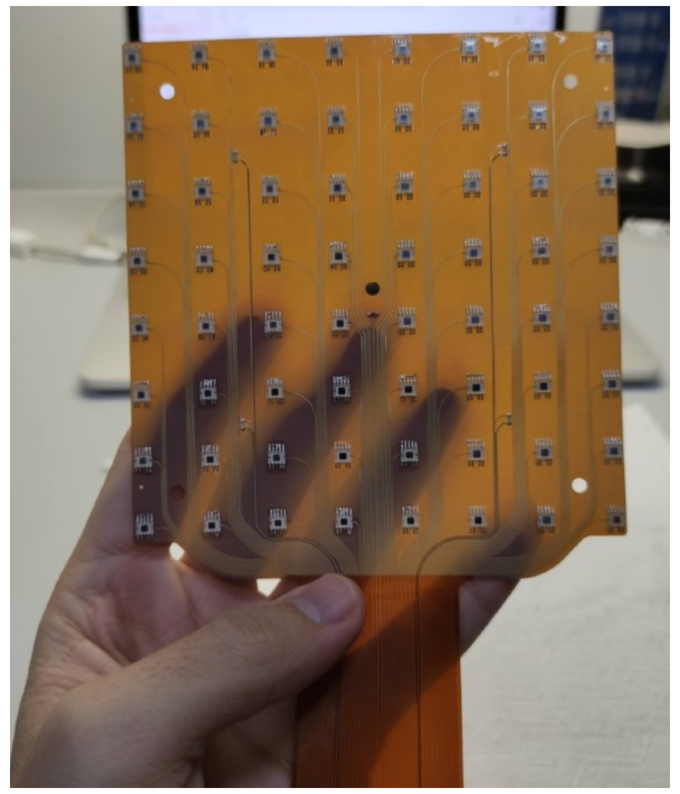
Electrostatic deflection of the EL measured (important for energy resolution)





Anode-EL region using meshes

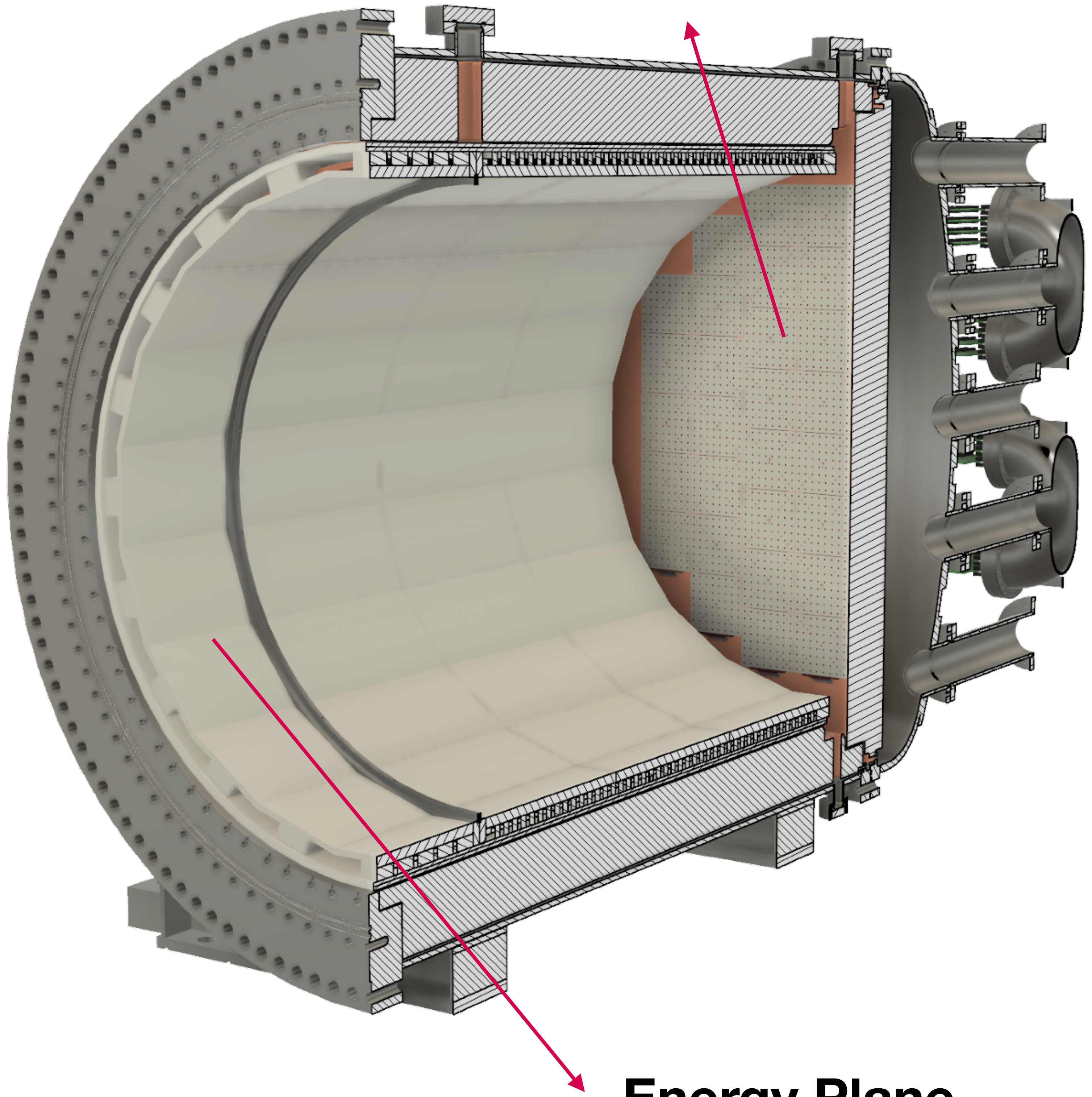
The NEXT-100 detector

Hamamatsu SiPMs:
easier to mount,
more robust,
larger area.
Better for
dynamic range

Coated with TPB
for better light
detection

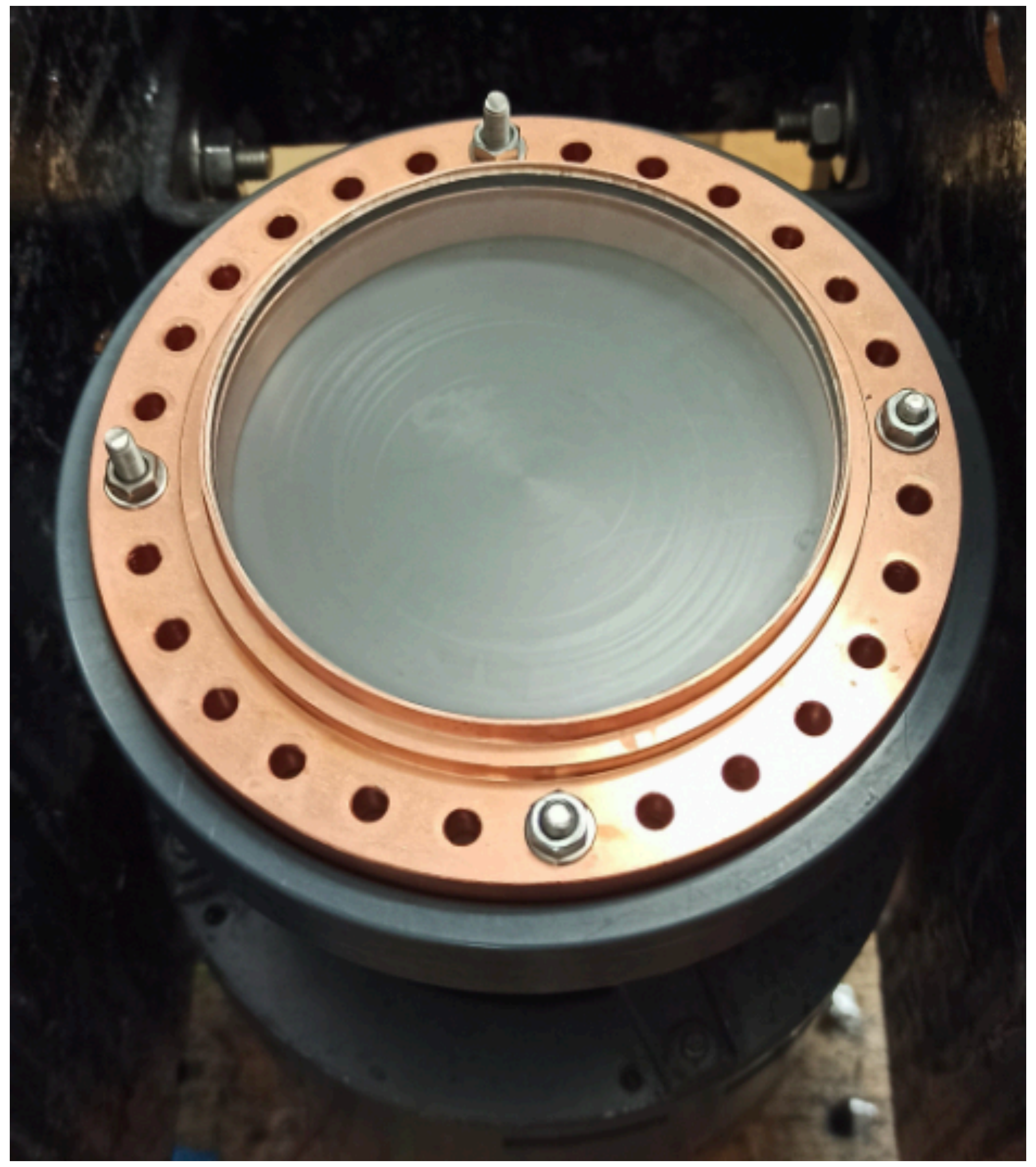
Tracking Plane
3584 Hamamatsu SiPMs
1.3x1.3 mm2 - 15.55 mm pitch
(60% more photons)

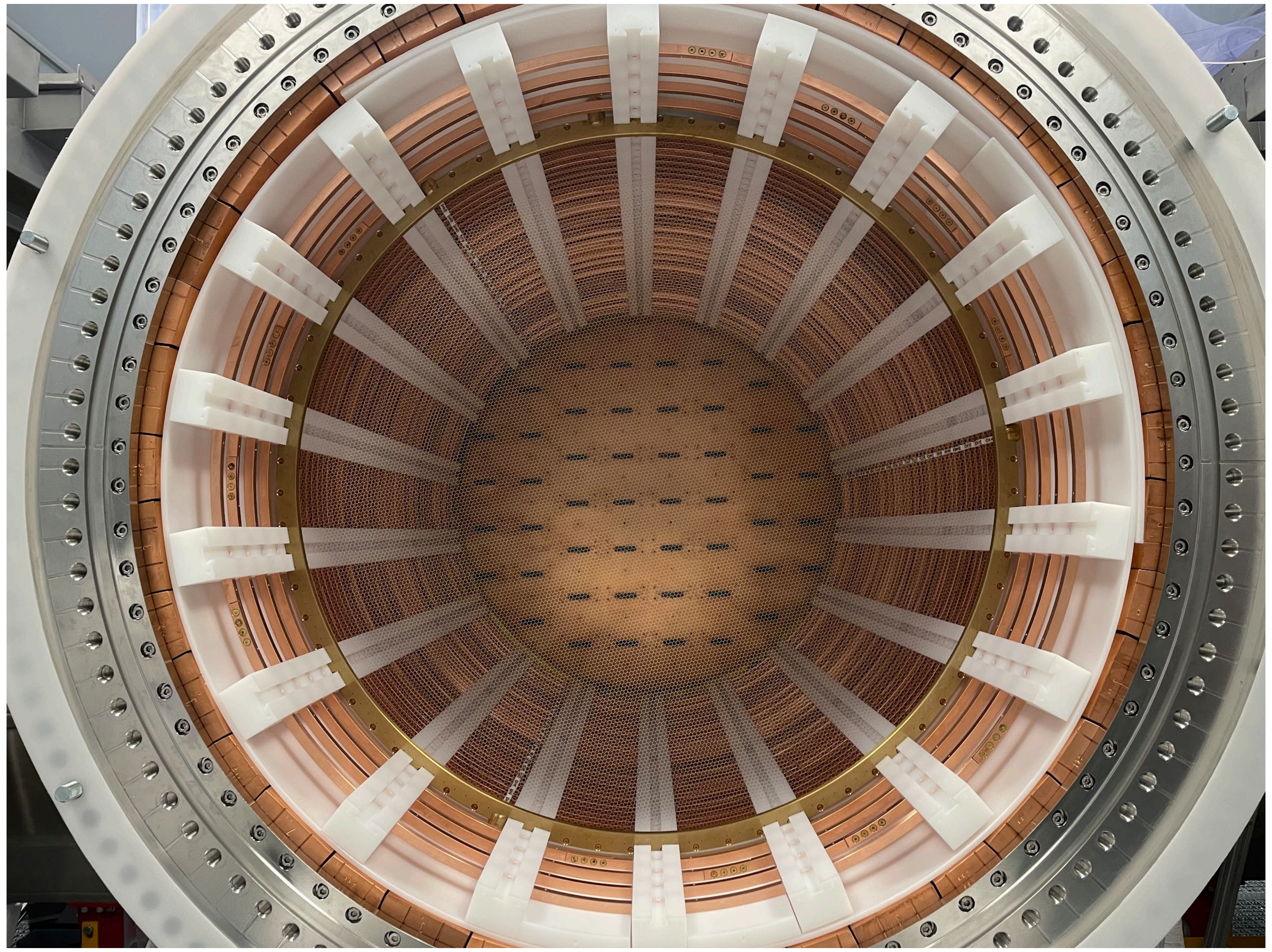
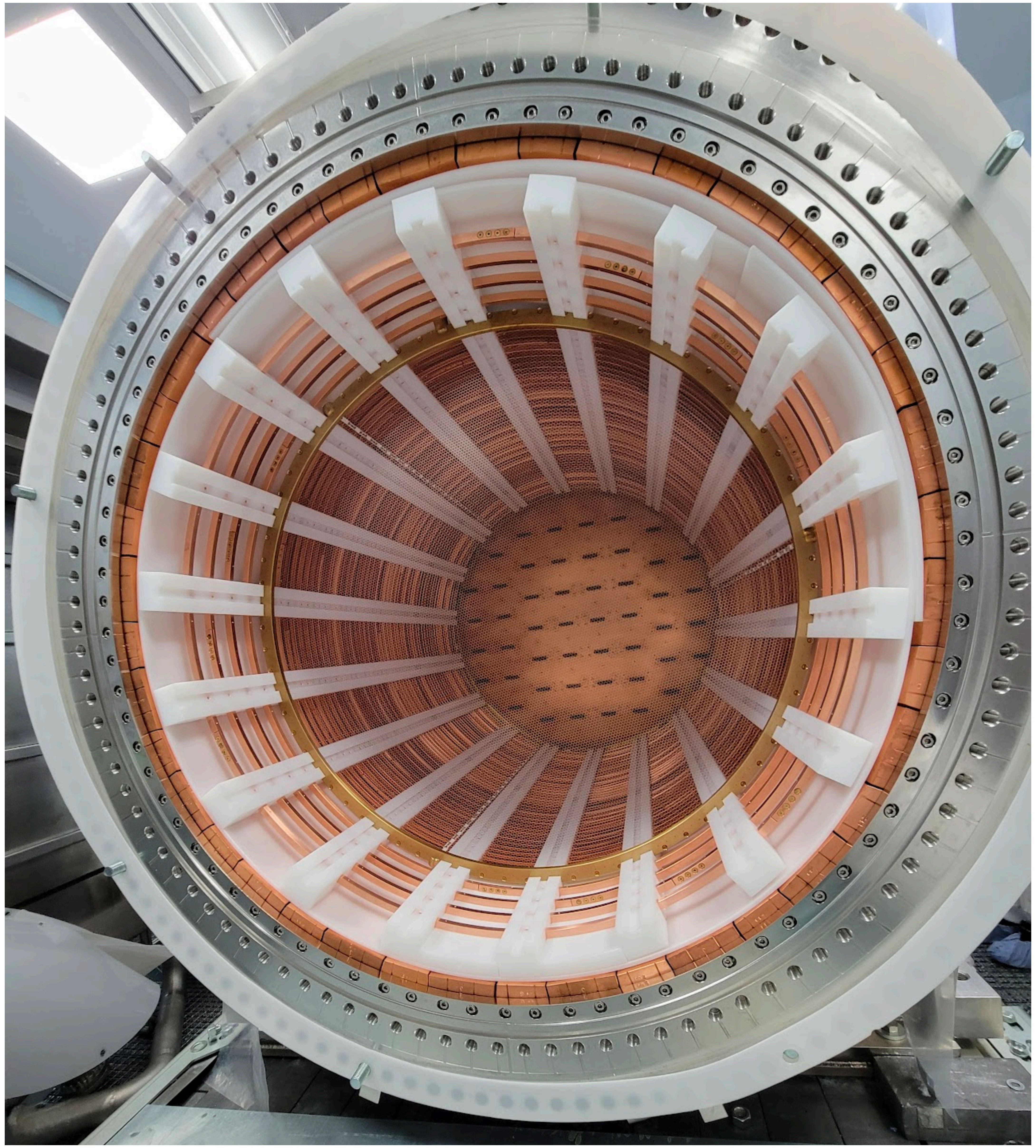


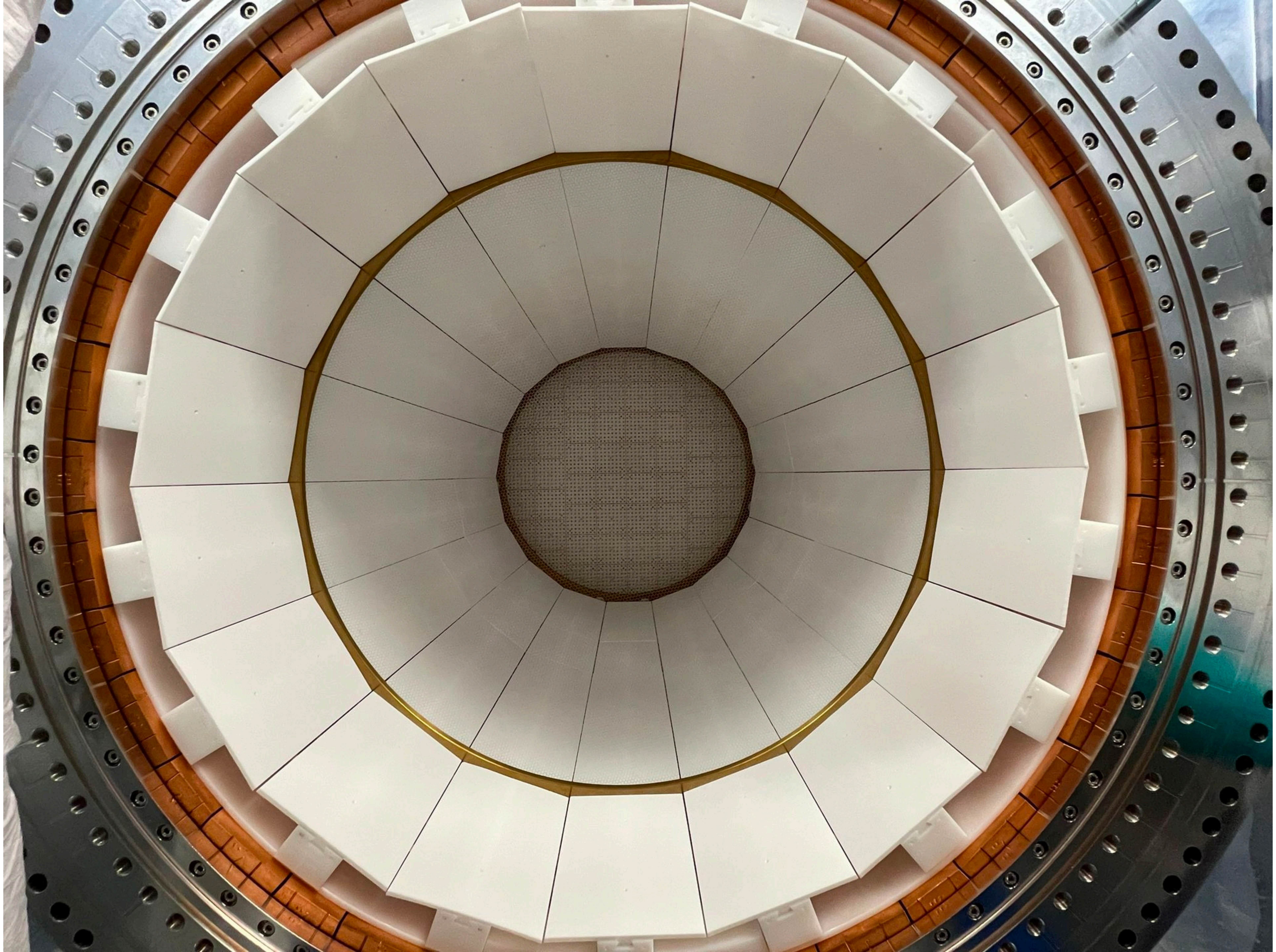
Energy Plane
60 Hamamatsu PMTs
R11410-10 - Same NEW
(30% coverage)

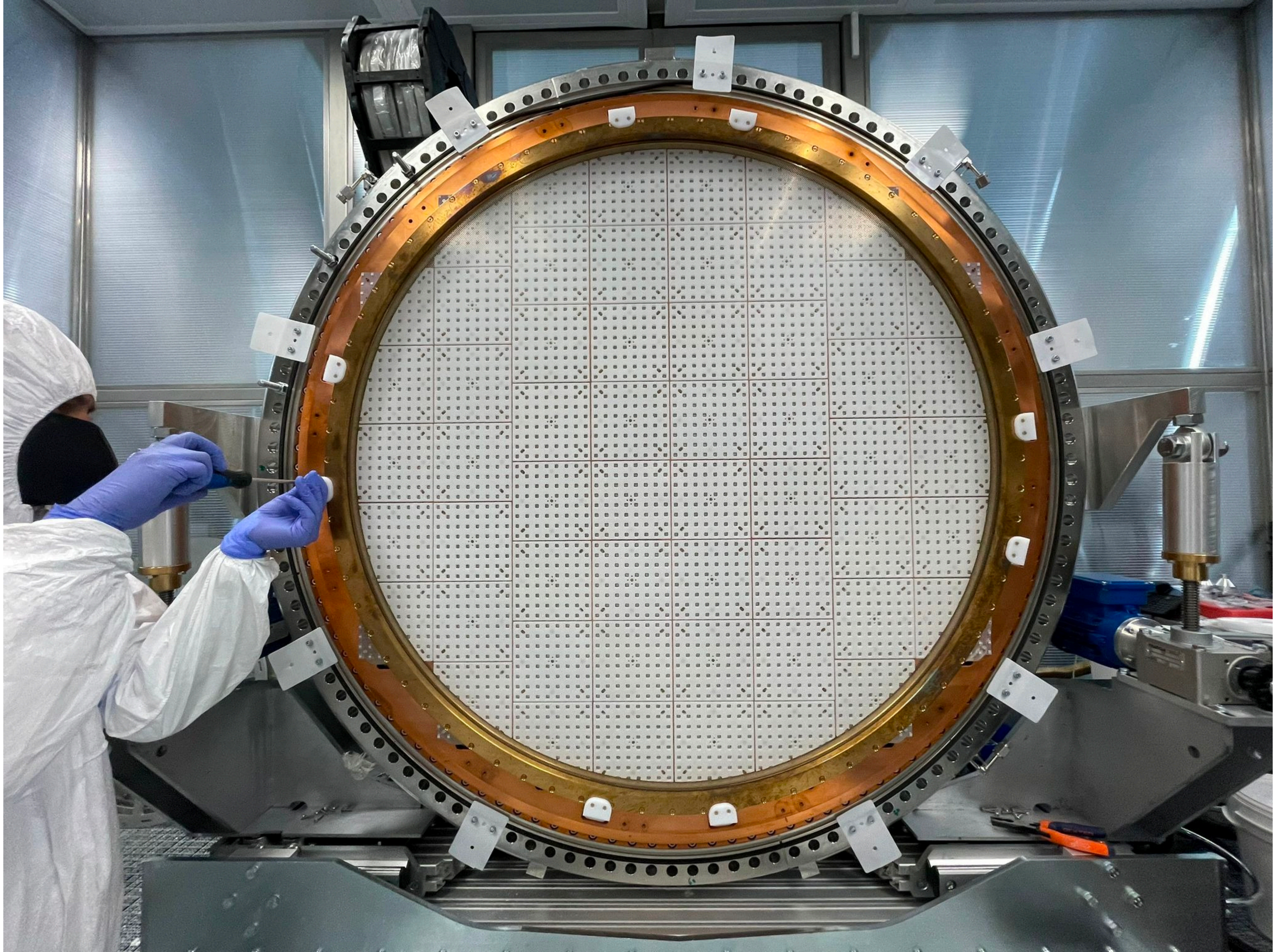
PMTs coupled
to xenon gas
through
sapphire
windows
welded to a
radio pure
copper frame

Windows are
coated with PEDOT



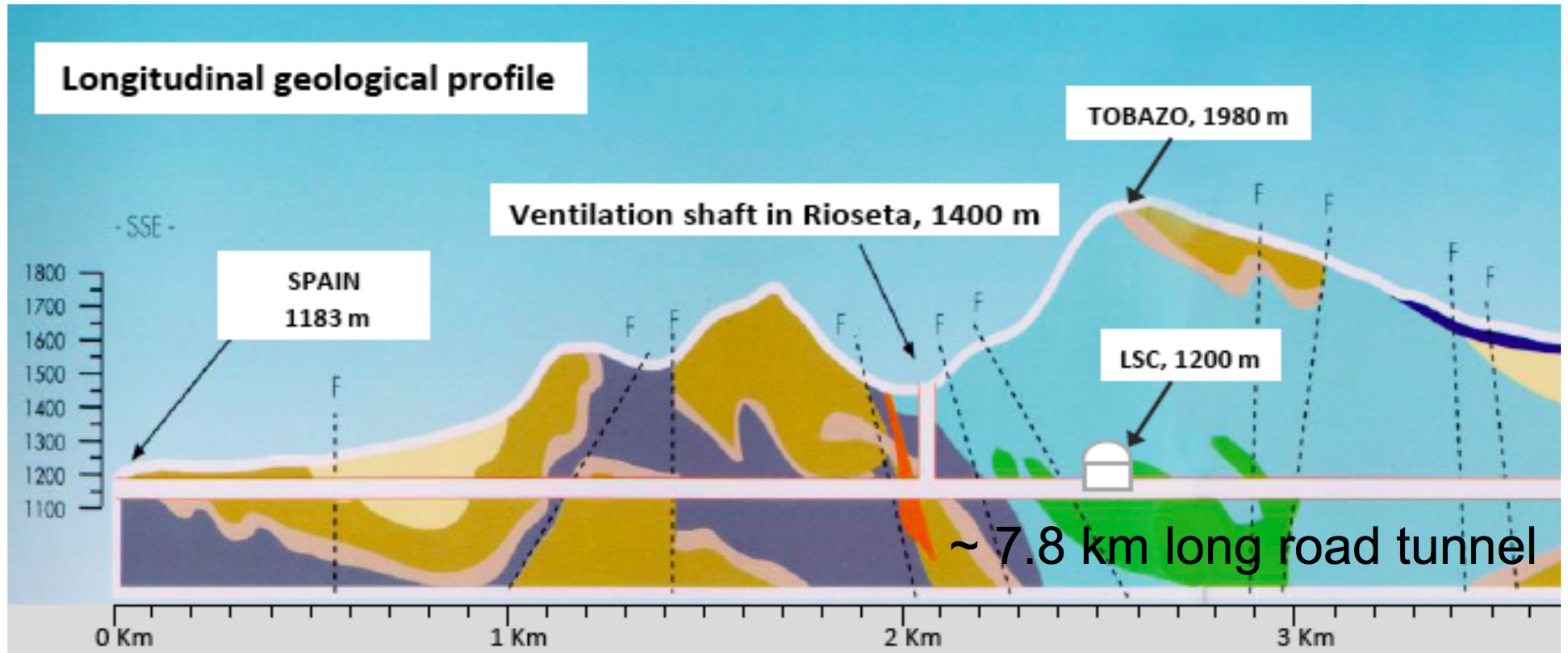







NEXT-100 background budget

- The main background in NEXT is represented by natural decay series (U, Th) producing ^{214}**Bi** and ^{208}**Tl**.
- The Canfranc Underground Laboratory provides a radiopurity facility to asses the radioactivity of the detector materials (copper, PMTs, boards…)
- Detector will operate in an airborne-radon-depleted environment thanks to the radon-abatement system provided by the LSC.
- **Spallation neutrons** produced by cosmic rays: flux reduced by rock above the detector. Main source are those originating in the detector shielding: muon veto being considered.



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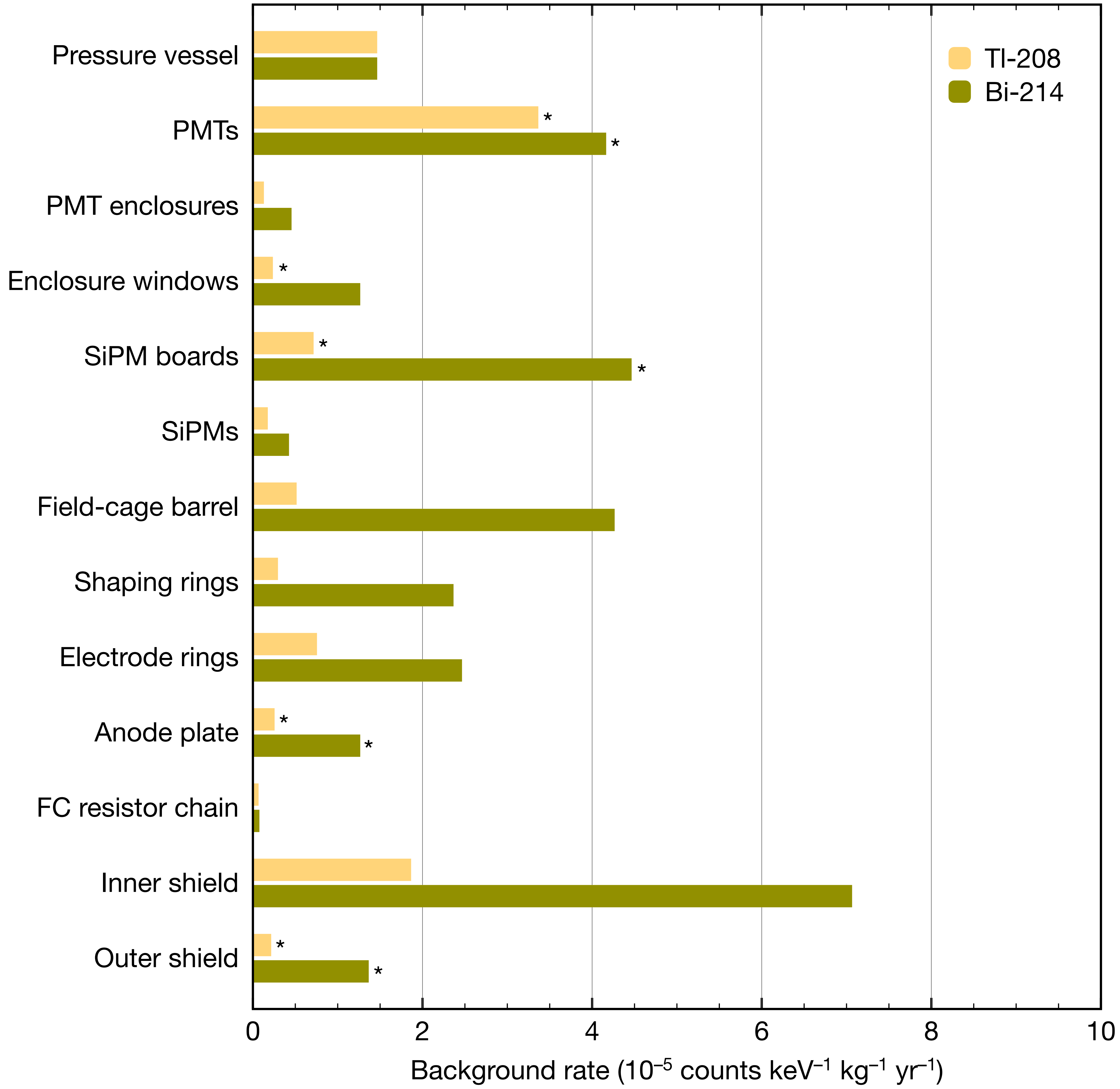
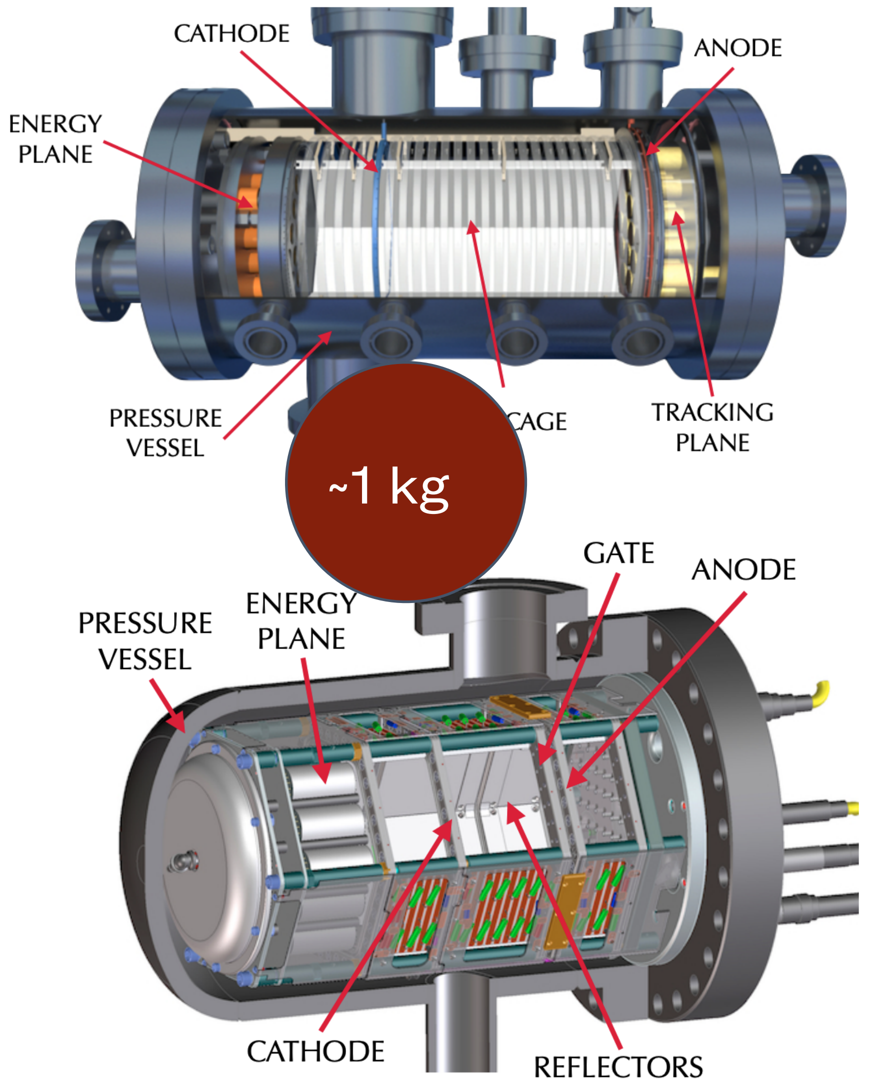


The NEXT program

Prototypes

2010-2014

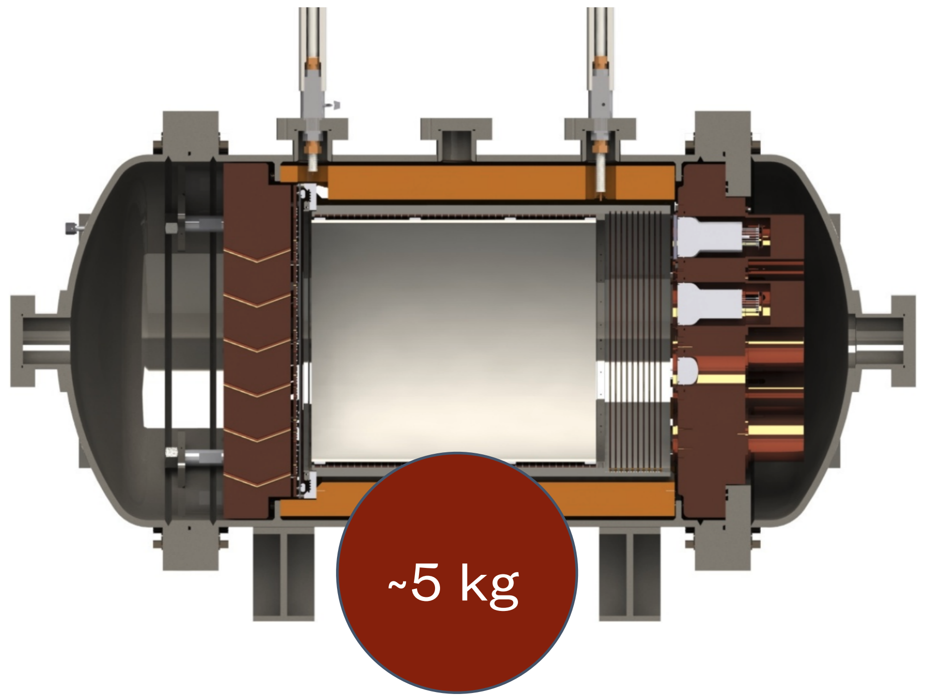
Demonstration of detector concept



NEXT-White

2015-2021

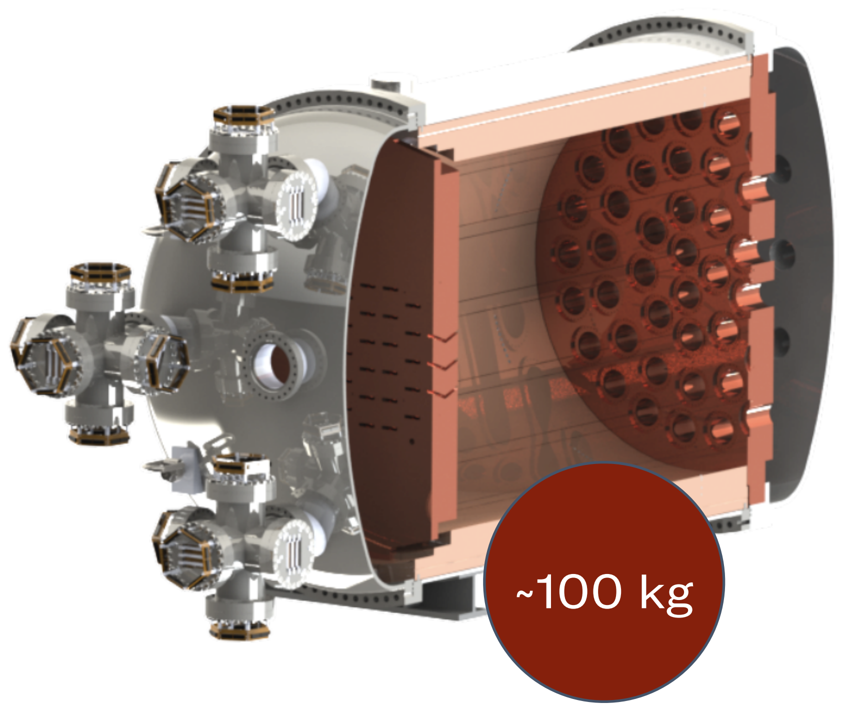
Background model assessment
$2\nu\beta\beta$ measurement for ^{136}Xe



NEXT-100(1000)

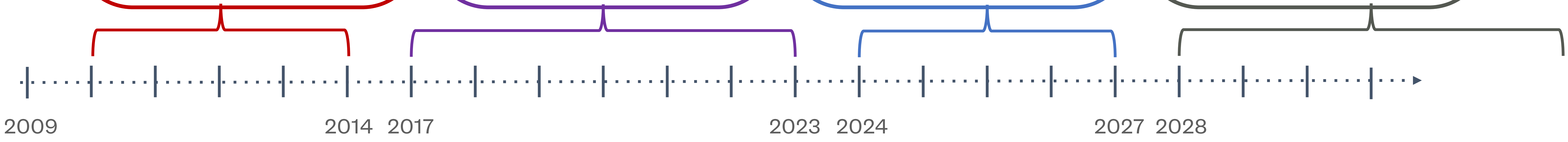
2022-2026

Neutrinoless double beta decay search in ^{136}Xe (10^{27} y)



NEXT-HD/BOLD

Barium tagging for background-free experiment in ^{136}Xe (10^{28} y)



MANCHESTER 1824
The University of Manchester
DIPC
CFM
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
Universidad de Oviedo
LSC
Laboratorio Subterráneo de Canfranc
IOWA STATE UNIVERSITY
Argonne NATIONAL LABORATORY
HARVARD UNIVERSITY
USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
Pacific Northwest NATIONAL LABORATORY
universidade de aveiro
Universitat de Girona
BERKELEY LAB
Fermilab
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TEXAS A&M UNIVERSITY
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Universidad Autónoma de Madrid
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Universidad Zaragoza
THE HEBREW UNIVERSITY OF JERUSALEM
UAN
Universidad
Antonio Nariño

NEXT-HD

- If we want to explore the inverted hierarchy region with the NEXT technology, we need a **bigger detector**, NEXT-HD:
  - Order of magnitude more Xe than NEXT-100, **~1 tonne** at 15 bar.
  - **Symmetric design** with a central cathode and two readout planes with SiPMs (no *energy plane* with PMTs).
  - Energy readout by a **Barrel Energy Detector** (double-clad fibers read out by SiPMs).

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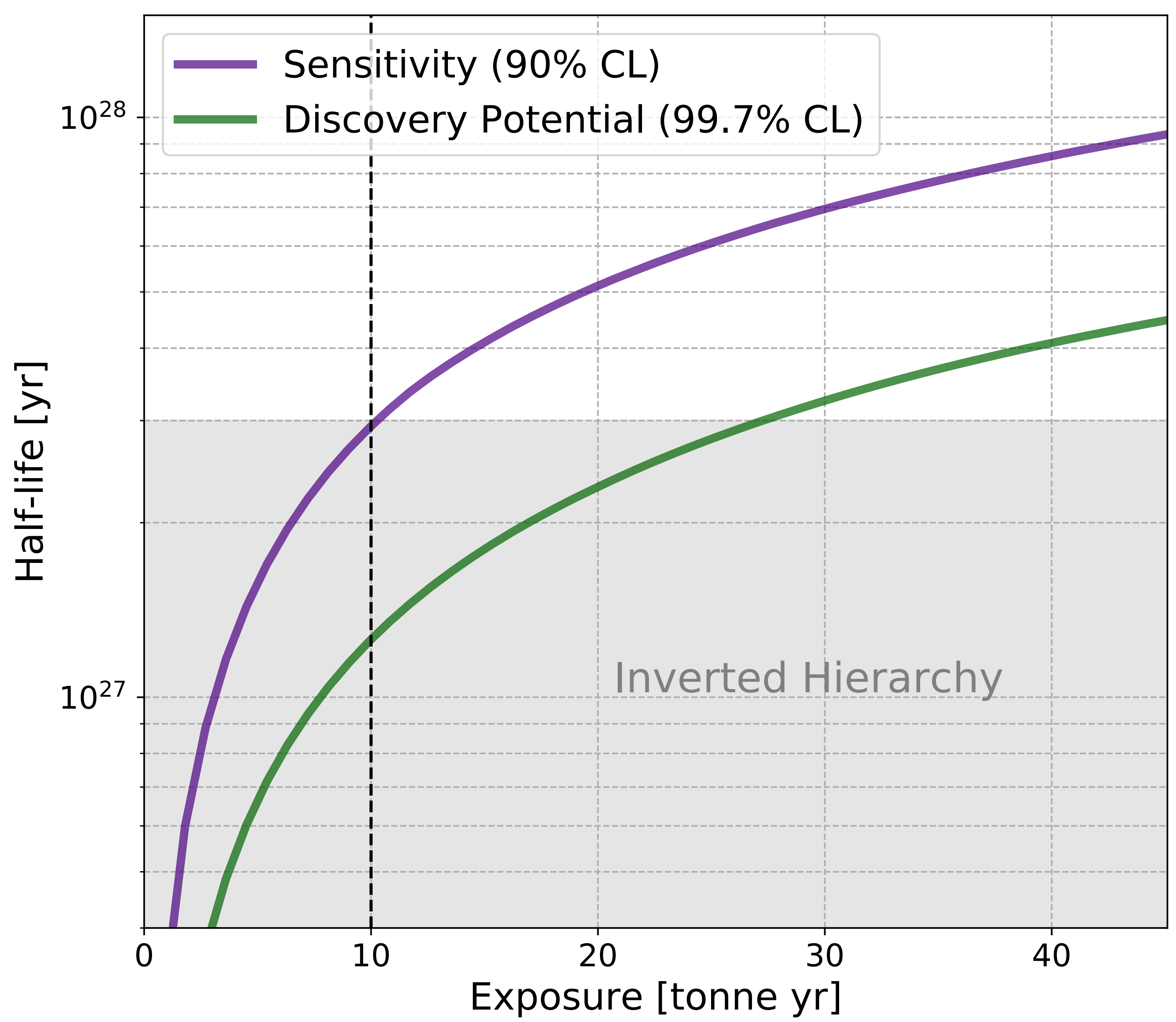
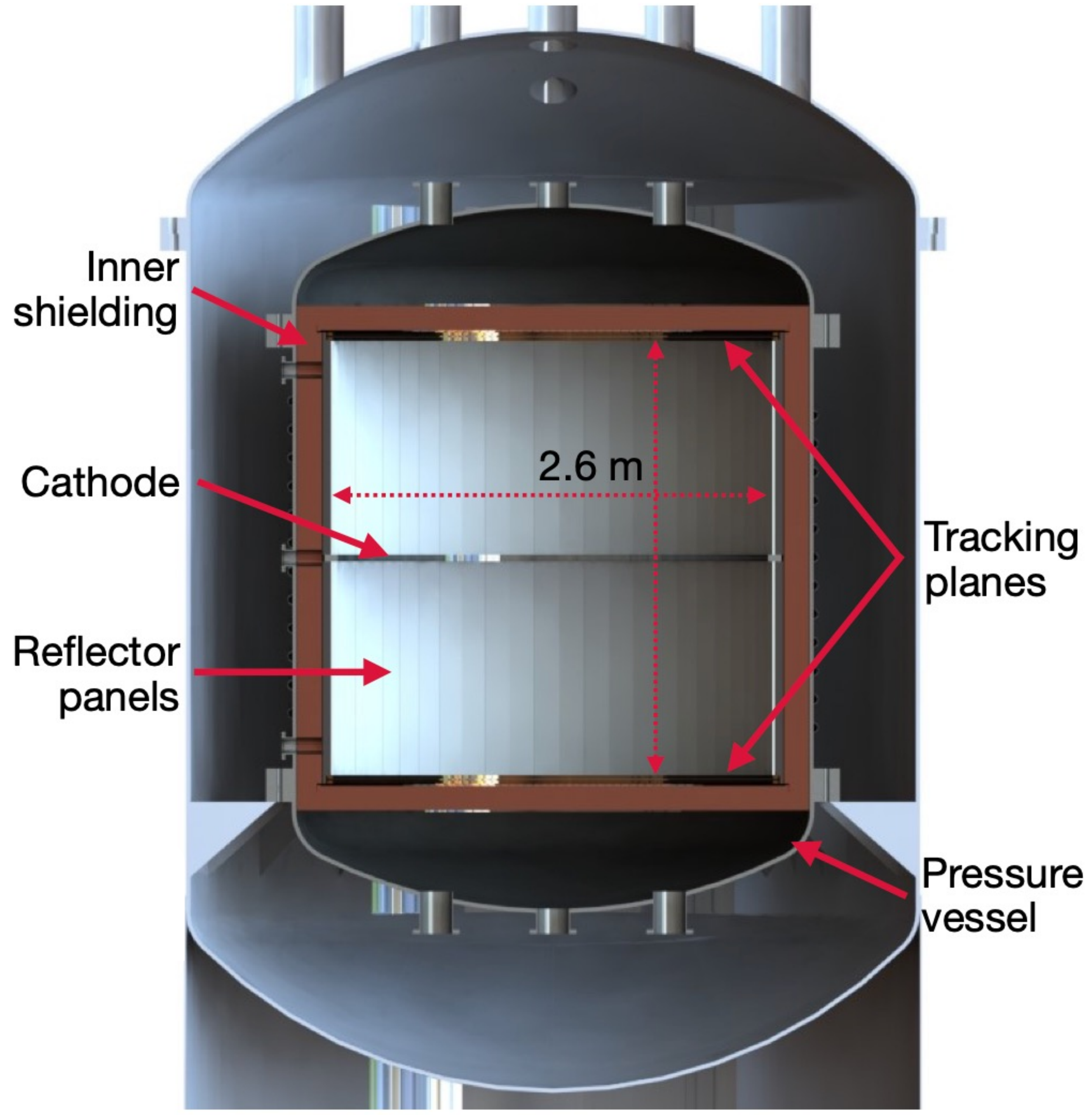
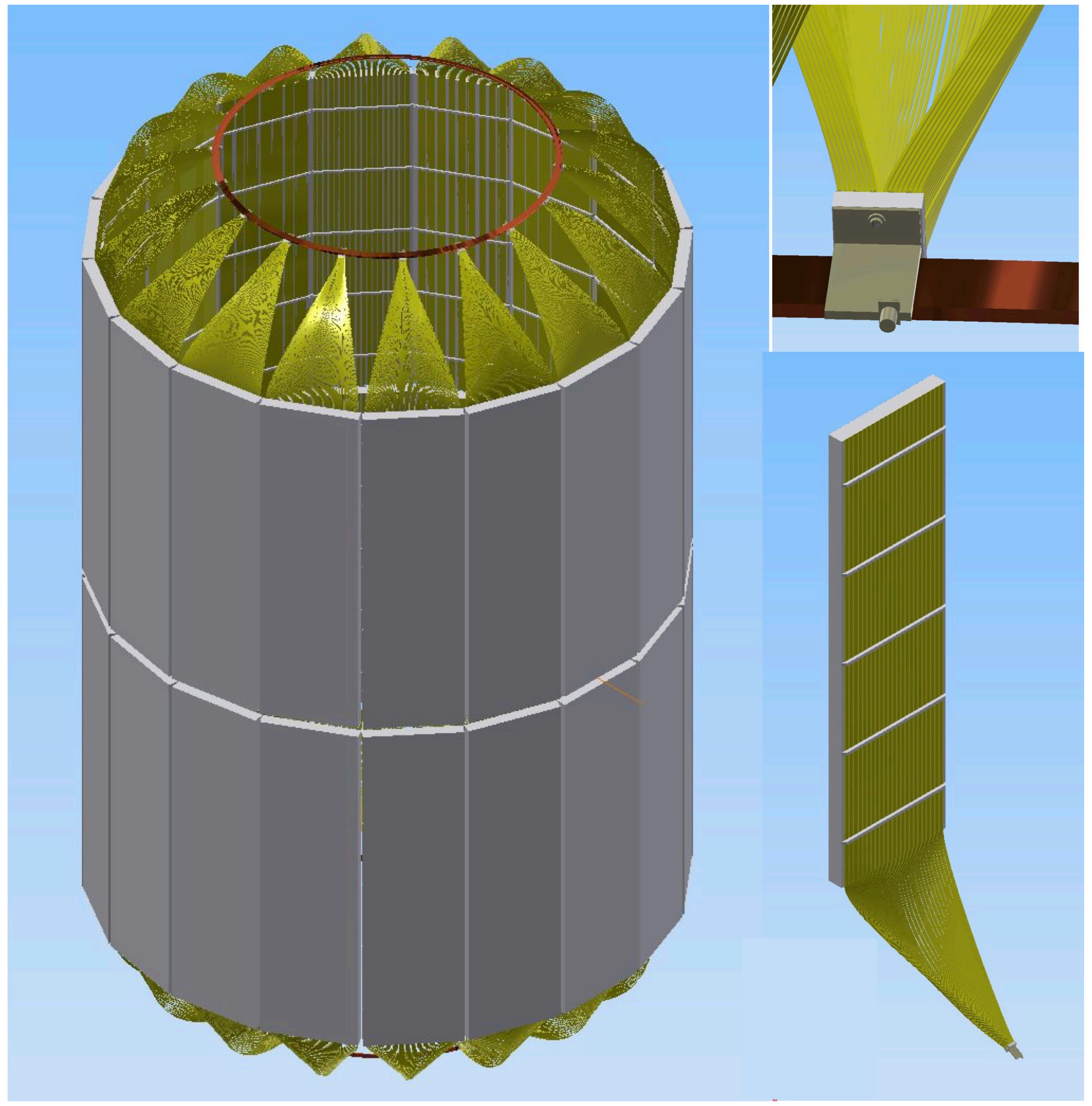
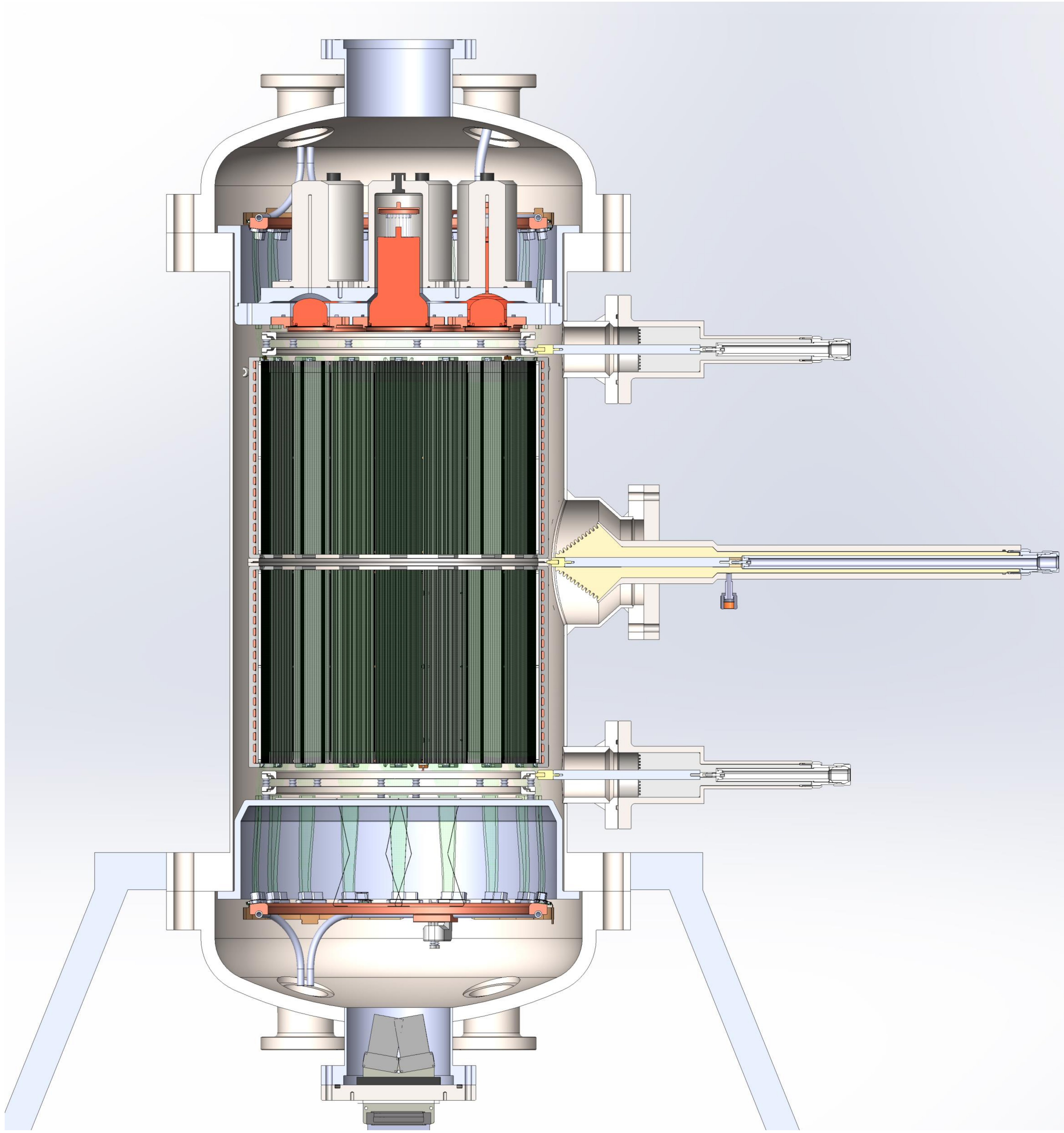






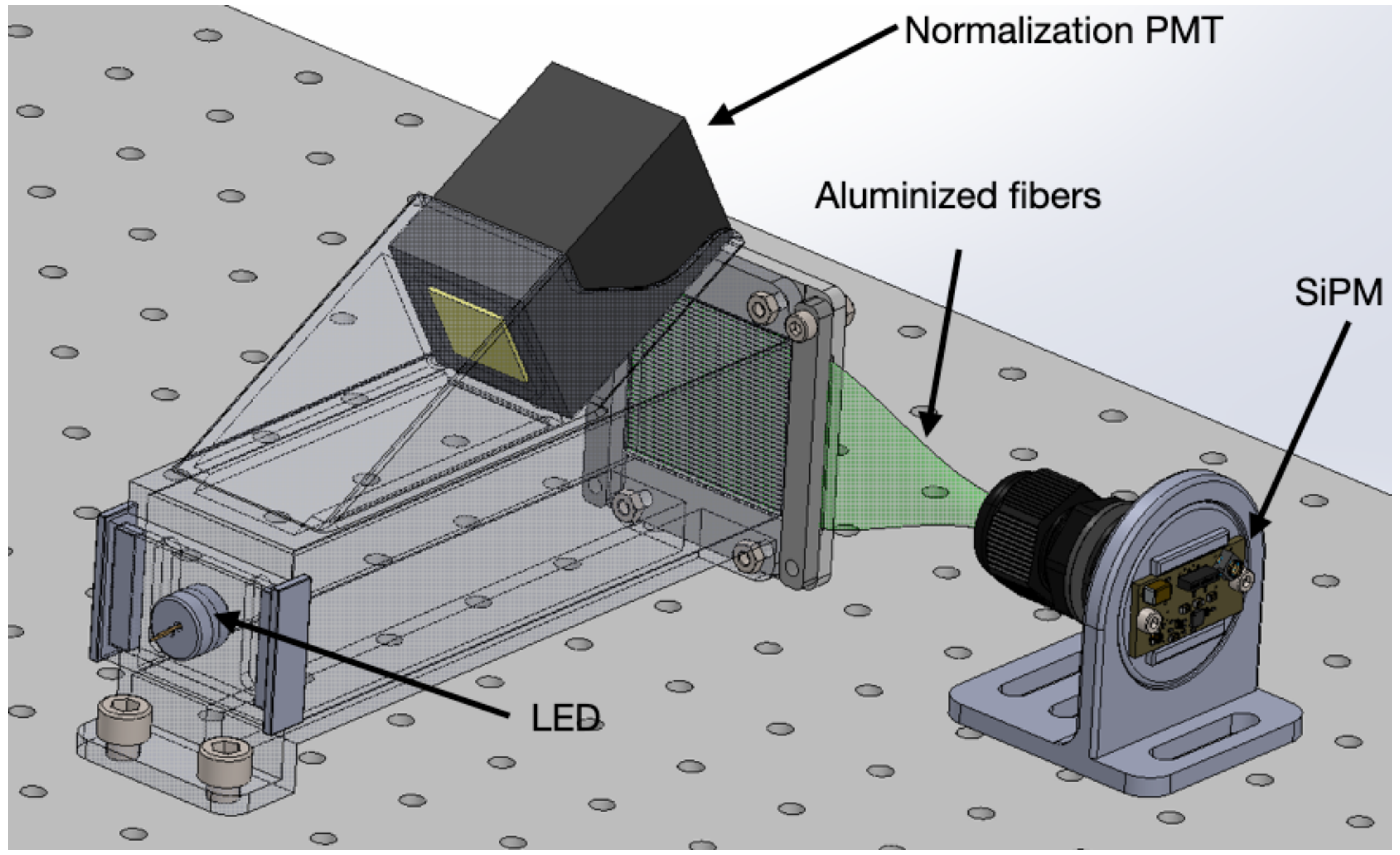
HD-DEMO

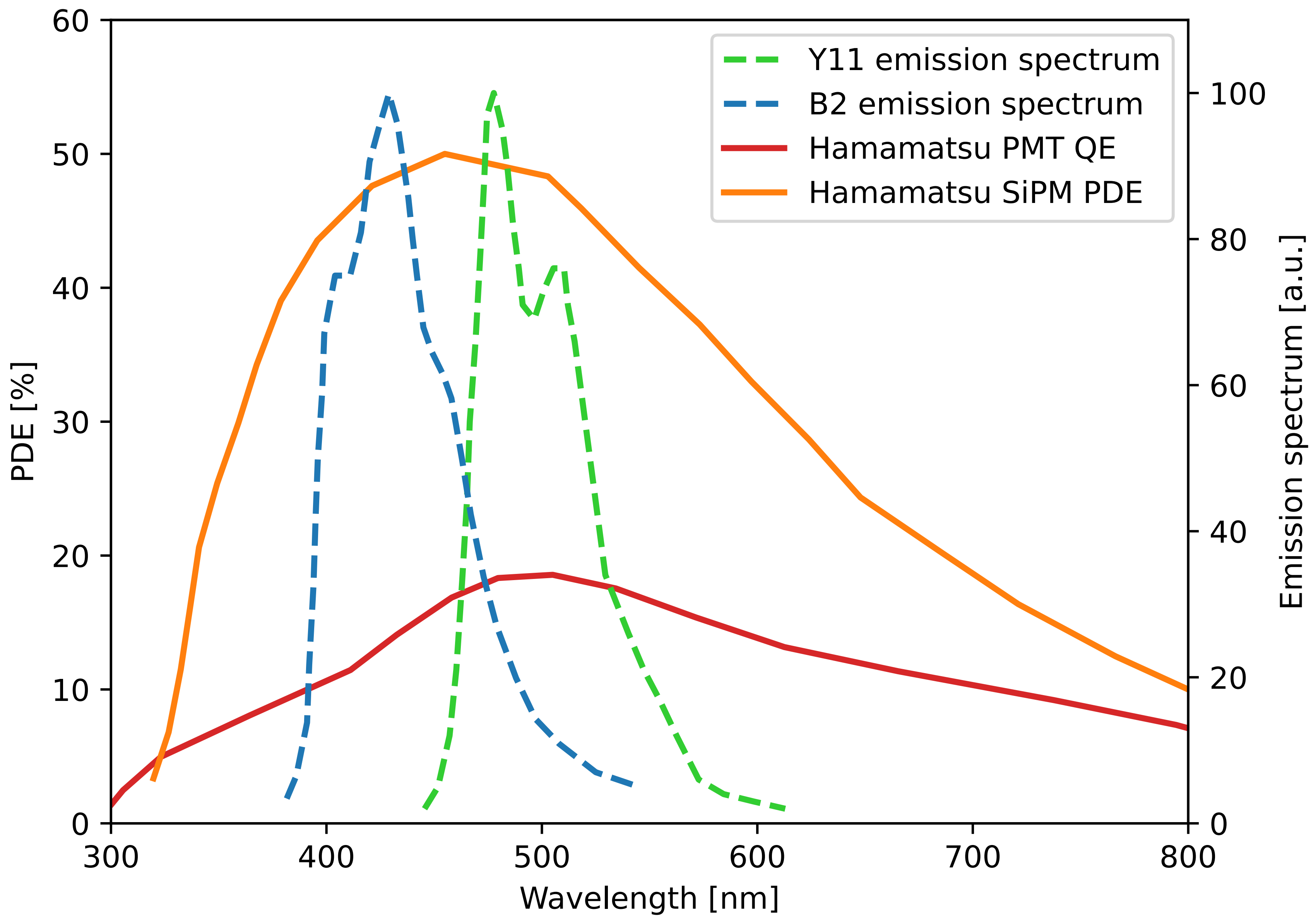
- Before scaling to 1 t we need to validate the technology choice: HD-DEMO.
- **A barrel of WLS fibers** will cover the surface of the cylinder in order to detect Xe scintillation light (175 nm).
- **Symmetric design**: cathode in the middle, two anodes
- PMT readout on one side, cooled SiPM readout on the other side.
- Different options being explored:
  - Green-to-blue fibers coated with TPB.
  - UV-to-blue fibers coated with p-terphenyl.

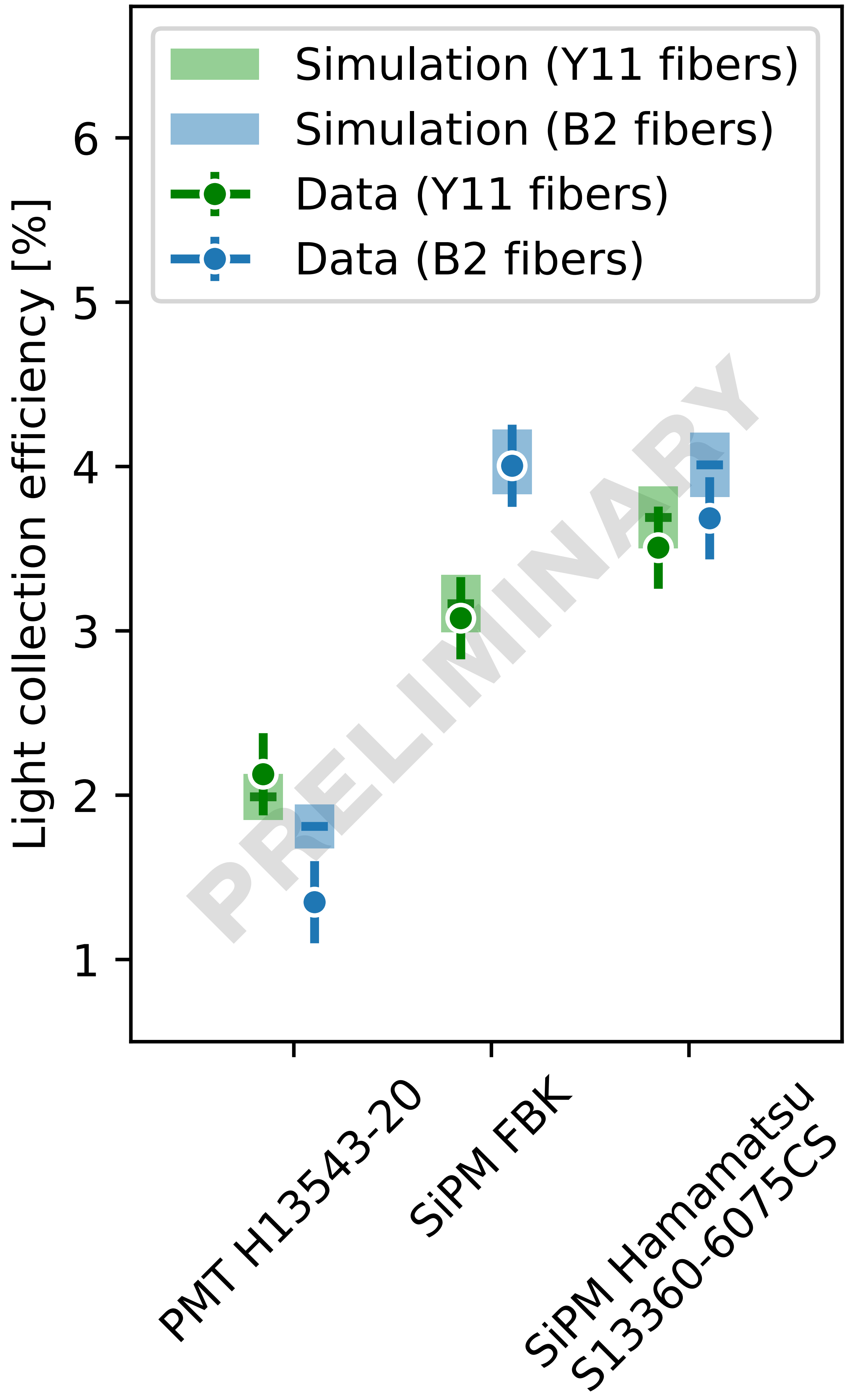


Fiber R&D at DIPC

- Illuminate **different fibers** with LED and read out with **different photosensors** (PMT, SiPMs).
- Measure light collection efficiency of the system in two steps:
  - Measure the light emitted by the LED by placing the photosensor in front.
  - Measure the light re-emitted by WLS fibers, illuminated by the same LED.
- LED light output is monitored by a dedicated PMT.







NEXT-HD backgrounds and sensitivity

- **Background sources**
  - **Natural radioactivity** in detector materials: ^{238}U and ^{232}Th result in gamma-ray lines of ^{208}Tl and ^{214}Bi
  - **Radon**: ^{220}Rn and ^{222}Rn diffuse from detector materials or gas system
    - Radon abatement system deployed at LSC makes this component subdominant
  - **Background of cosmogenic origin**: derive from neutron capture on detector materials (copper isotopes and ^{136}Xe)
    - External tank of water included in detector designs suppresses gamma radiation from laboratory walls

In less than 5 years NEXT-HD can reach a half-life sensitivity of 1.2x1027 yr (90% CL),

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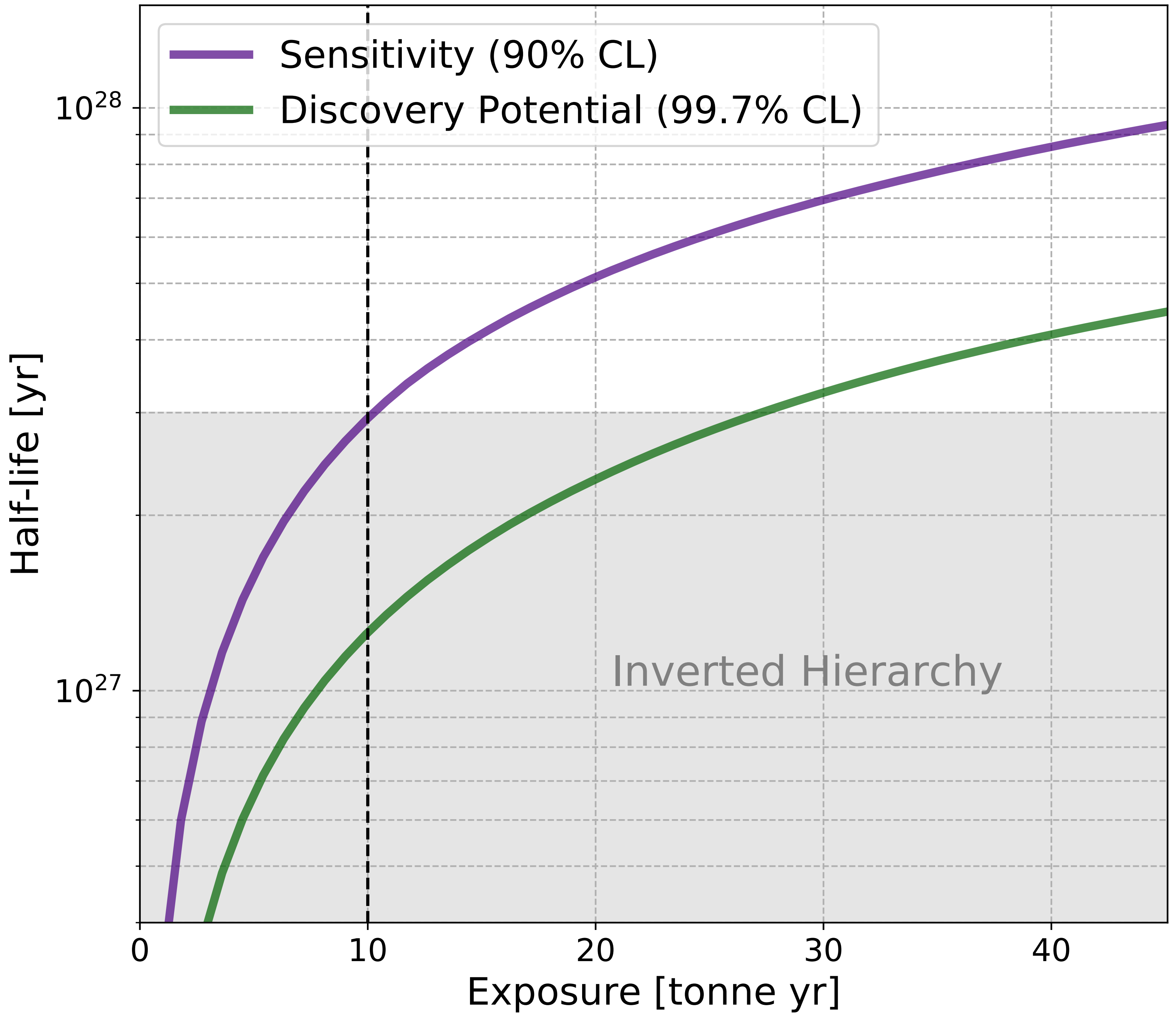

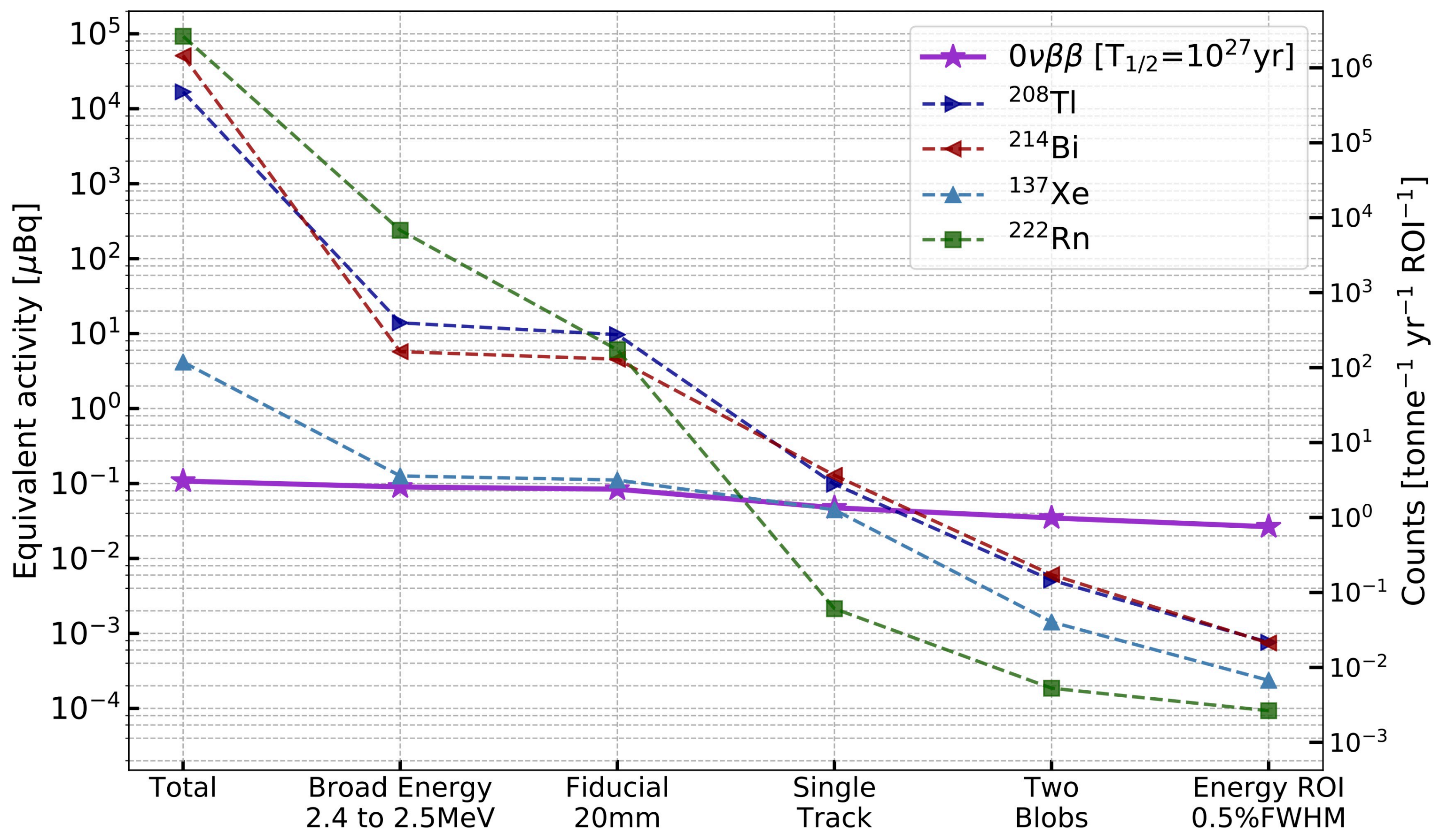

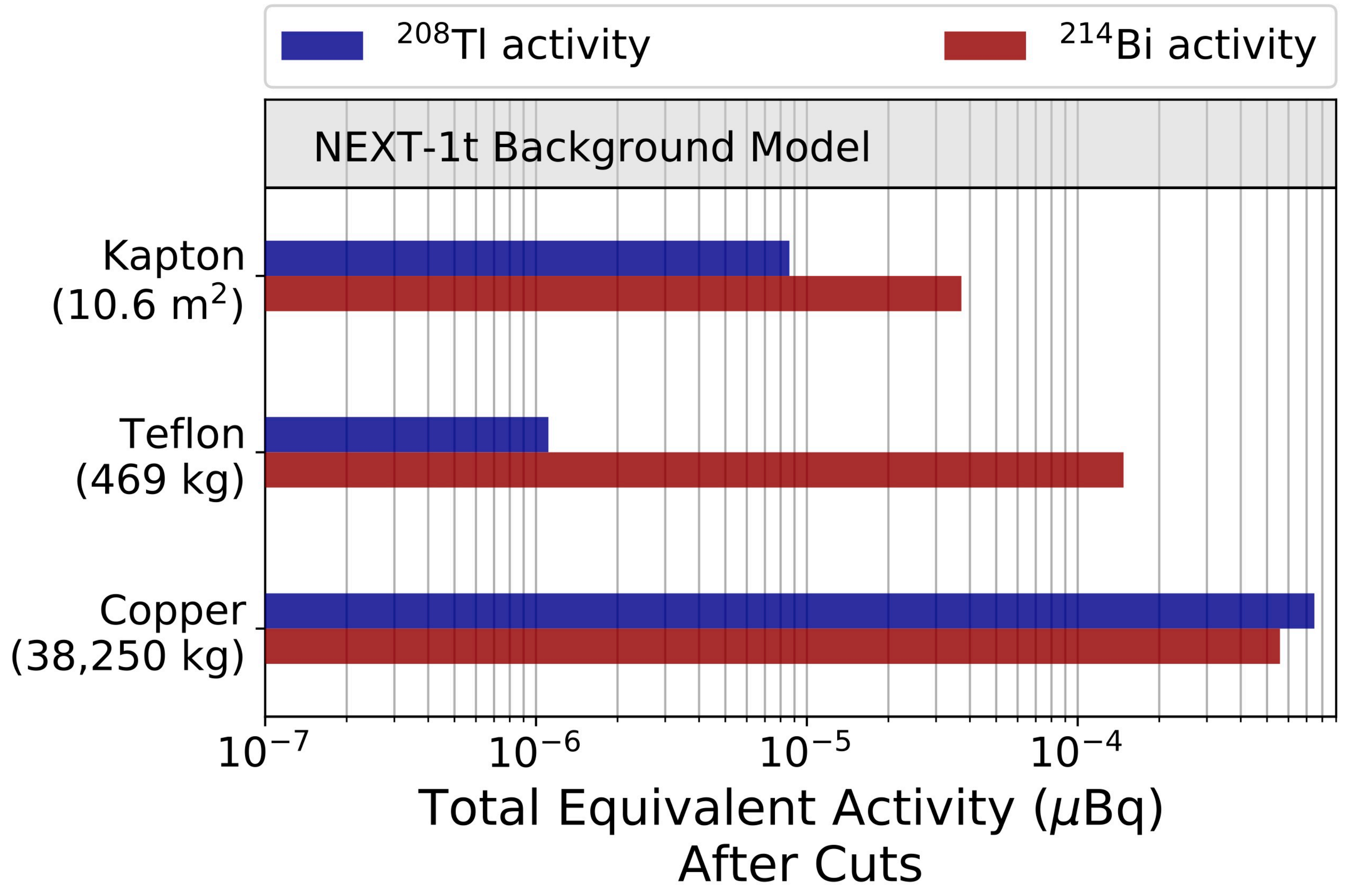

arXiv:1711.04782v3 [physics.ins-det] 6 Feb 2018

Demonstration of Single Barium Ion Sensitivity for Neutrinoless Double Beta Decay using Single Molecule Fluorescence Imaging

(The NEXT Collaboration)

A.D.McDonald,[1,*] B.J.P. Jones,[1,†] D.R.Nygren,[1,‡] C. Adams,[2] V. Álvarez,[3] C.D.R. Azevedo,[4] J.M. Benlloch-Rodríguez,[3] F.I.G.M. Borges,[5] A. Botas,[3] S. Cárcel,[3] J.V. Carrión,[3] S. Cebrián,[6] C.A.N. Conde,[5] J. Díaz,[3] M. Diesburg,[7] J. Escada,[5] R. Esteve,[8] R. Felkai,[3] L.M.P. Fernandes,[9] P. Ferrario,[3] A.L. Ferreira,[4] E.D.C. Freitas,[9] A. Goldschmidt,[10] J.J. Gómez-Cadenas,[3,‡] D. González-Díaz,[11] R.M. Gutiérrez,[12] R. Guenette,[2] K. Hafidi,[13] J. Hauptman,[14] C.A.O. Henriques,[9] A.I. Hernandez,[12] J.A. Hernando Morata,[11] V. Herrero,[8] S. Johnston,[13] L. Labarga,[15] A. Laing,[3] P. Lebrun,[7] I. Liubarsky,[3] N. López-March,[1,3] M. Losada,[12] J. Martín-Albo,[2] G. Martínez-Lema,[11] A. Martínez,[3] F. Monrabal,[1] C.M.B. Monteiro,[9] F.J. Mora,[8] L.M. Moutinho,[4] J. Muñoz Vidal,[3] M. Musti,[3] M. Nebot-Guinot,[3] P. Novella,[3] B. Palmeiro,[3] A. Para,[7] J. Pérez,[3] M. Querol,[8] J. Repond,[13] J. Renner,[3] S. Riordan,[13] L. Ripoll,[16] J. Rodríguez,[3] L. Rogers,[1] F.P. Santos,[5] J.M.F. dos Santos,[9] A. Simón,[3] C. Sofka,[3,§] M. Sorel,[3] T. Stiegler,[17] J.F. Toledo,[8] J. Torrent,[3] Z. Tsamalaidze,[18] J.F.C.A. Veloso,[4] R. Webb,[17] J.T. White,[17,¶] and N. Yahlali[3]

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[18] *Joint Institute for Nuclear Research (JINR), Joliot-Curie 6, 141980 Dubna, Russia*

(Dated: November 11, 2017)

A new method to tag the barium daughter in the double beta decay of ^{136}Xe is reported. Using the technique of single molecule fluorescent imaging (SMFI), individual barium dication (Ba^{++}) resolution at a transparent scanning surface has been demonstrated. A single-step photo-bleach confirms the single ion interpretation. Individual ions are localized with super-resolution (∼2 nm), and detected with a statistical significance of 12.9 σ over backgrounds. This lays the foundation for a new and potentially background-free neutrinoless double beta decay technology, based on SMFI coupled to high pressure xenon gas time projection chambers.

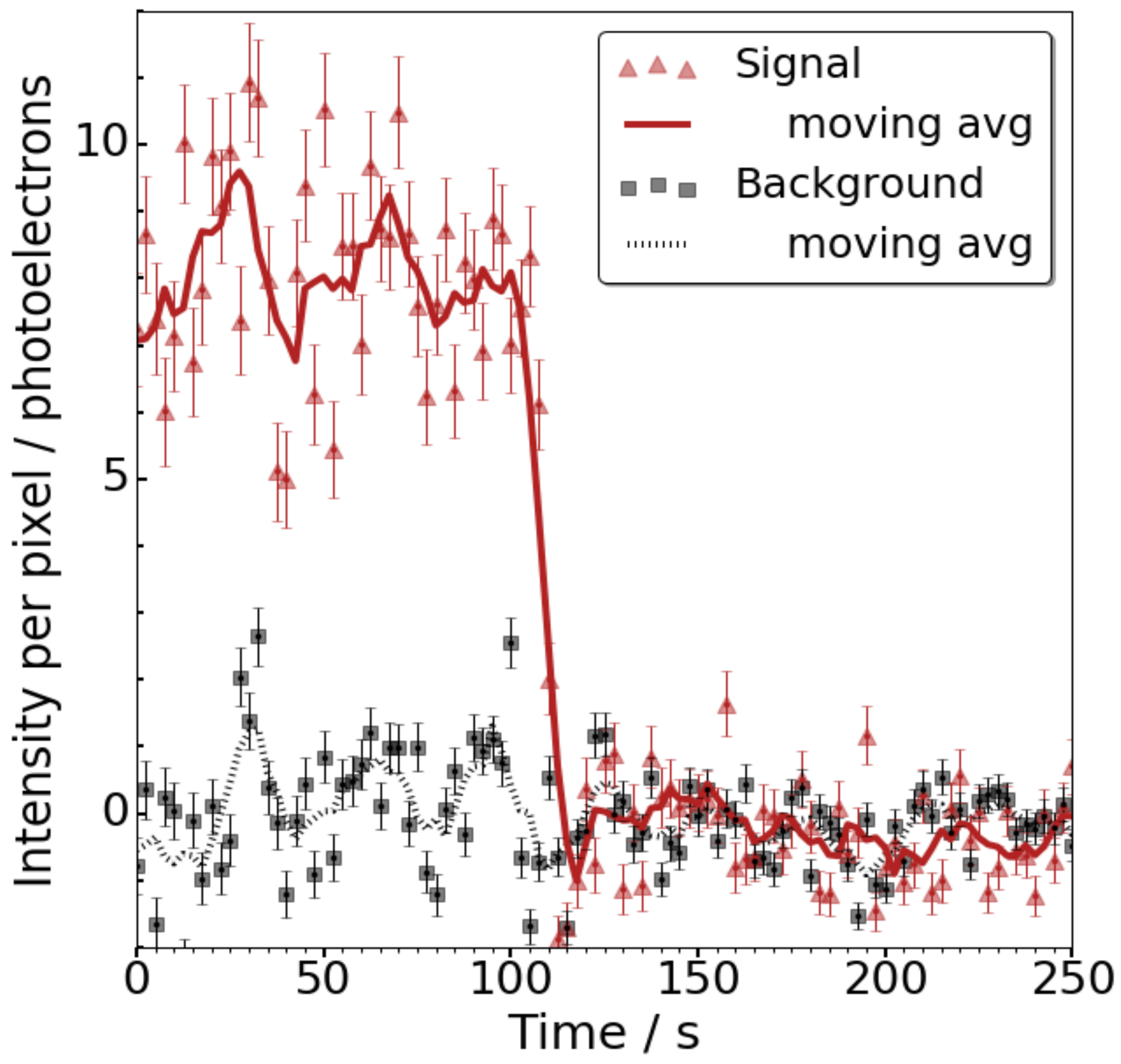
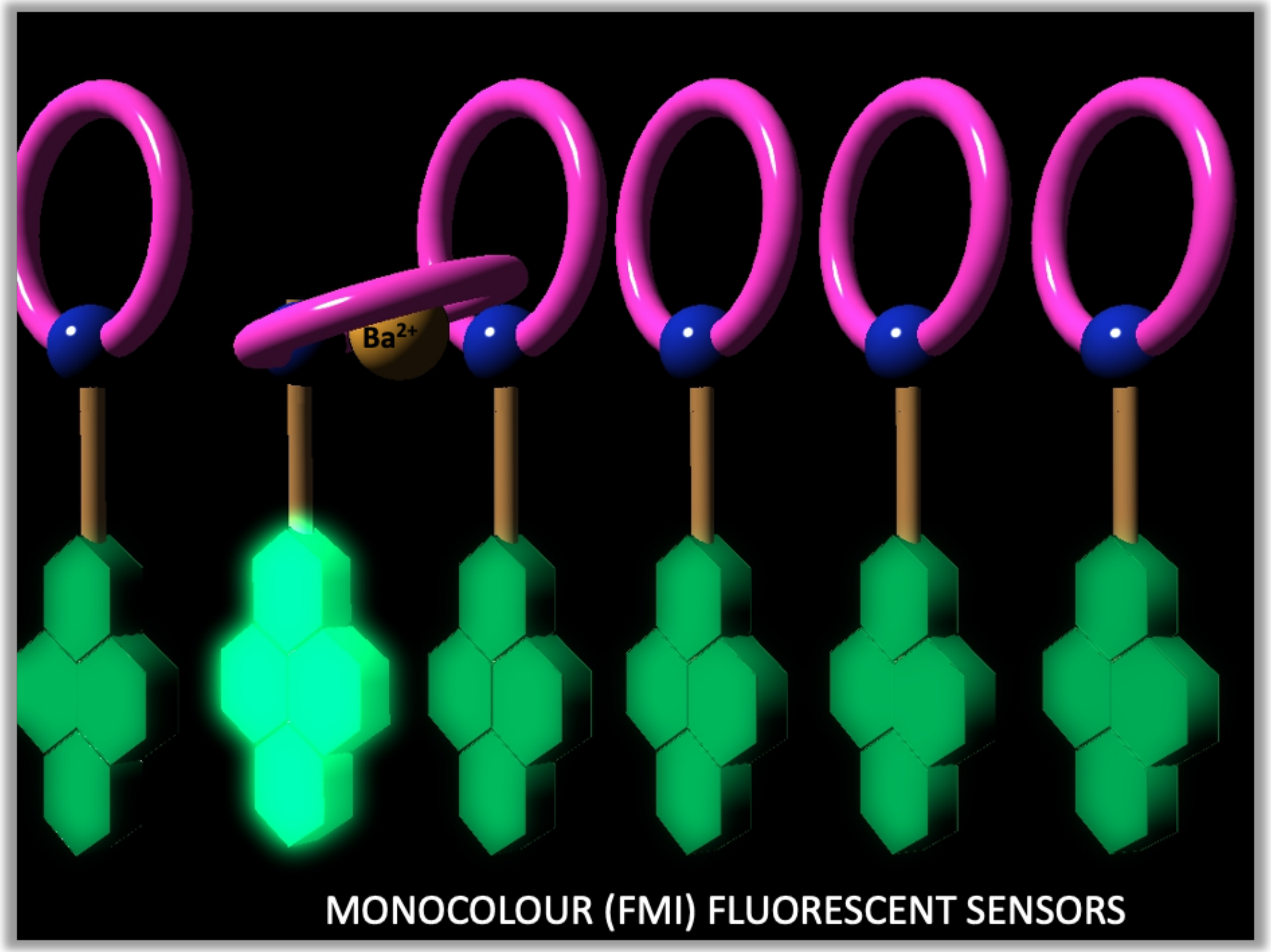
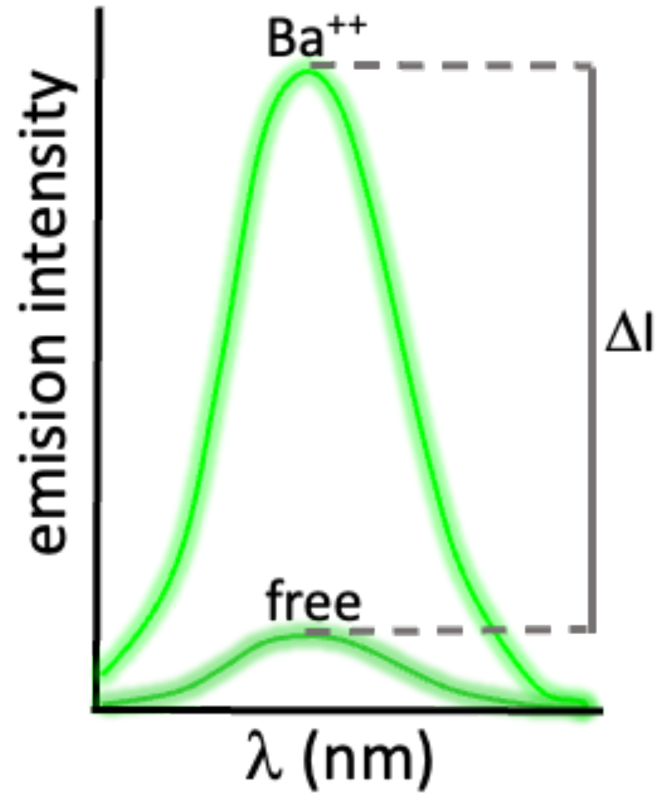


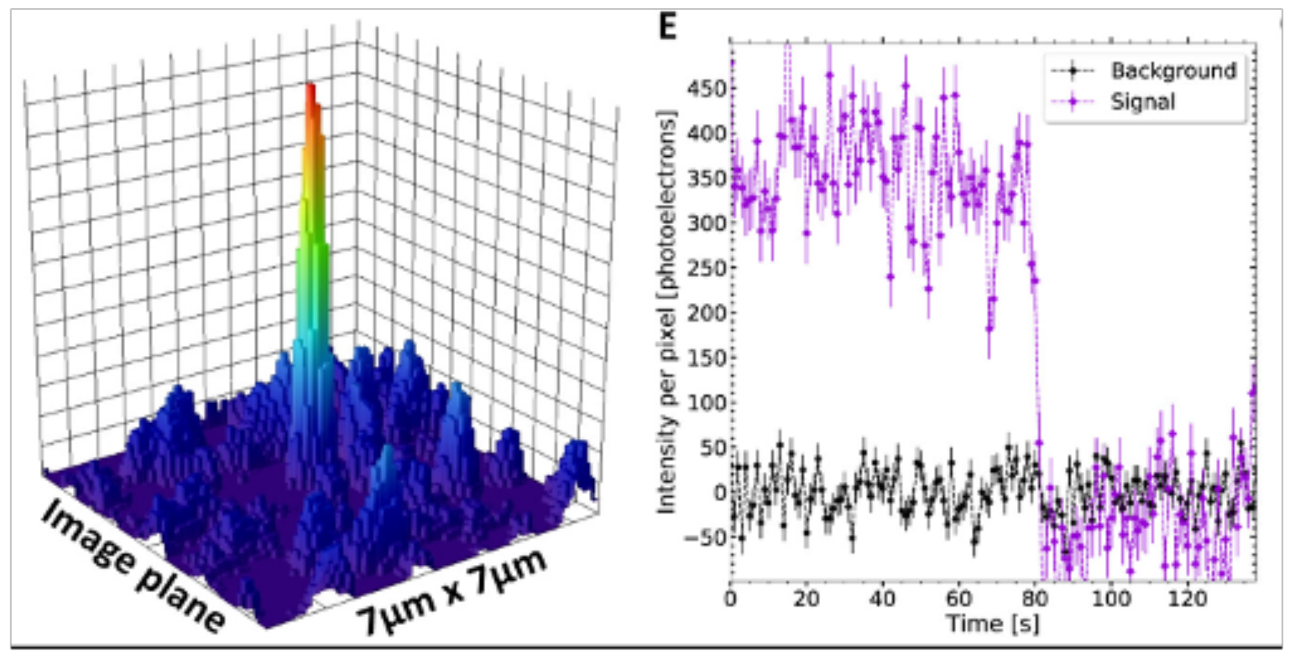
FIG. 4. Fluorescence trajectory for one candidate in a barium-spiked sample. "Signal" shows the average activity in 5x5 pixels centered on the local maximum. "Background" shows the average in the 56 surrounding. The single step photo-bleach is characteristic of single molecule fluorescence.

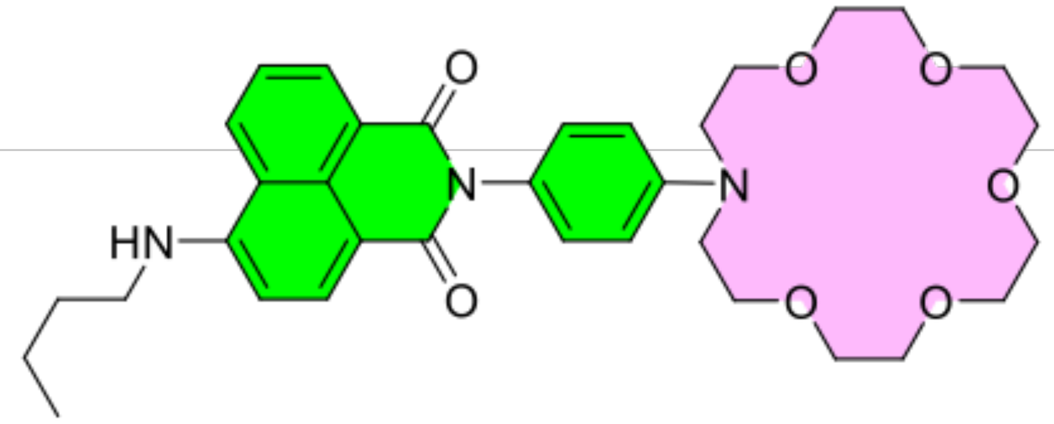
Sensors under development for single Ba^{2+} tagging@next .



FMI







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Article

Demonstration of Selective Single-Barium Ion Detection with Dry Diazacrown Ether Naphthalimide Turn-on Chemosensors

Pawan Thapa,* Nicholas K. Byrnes,* Alena A. Denisenko, James X. Mao, Austin D. McDonald, Charleston A. Newhouse, Thanh T. Vuong, Katherine Woodruff, Kwangho Nam, David R. Nygren, Benjamin J. P. Jones,* and Frank W. Foss, Jr.*

Cite This: ACS Sens. 2021, 6, 192−202
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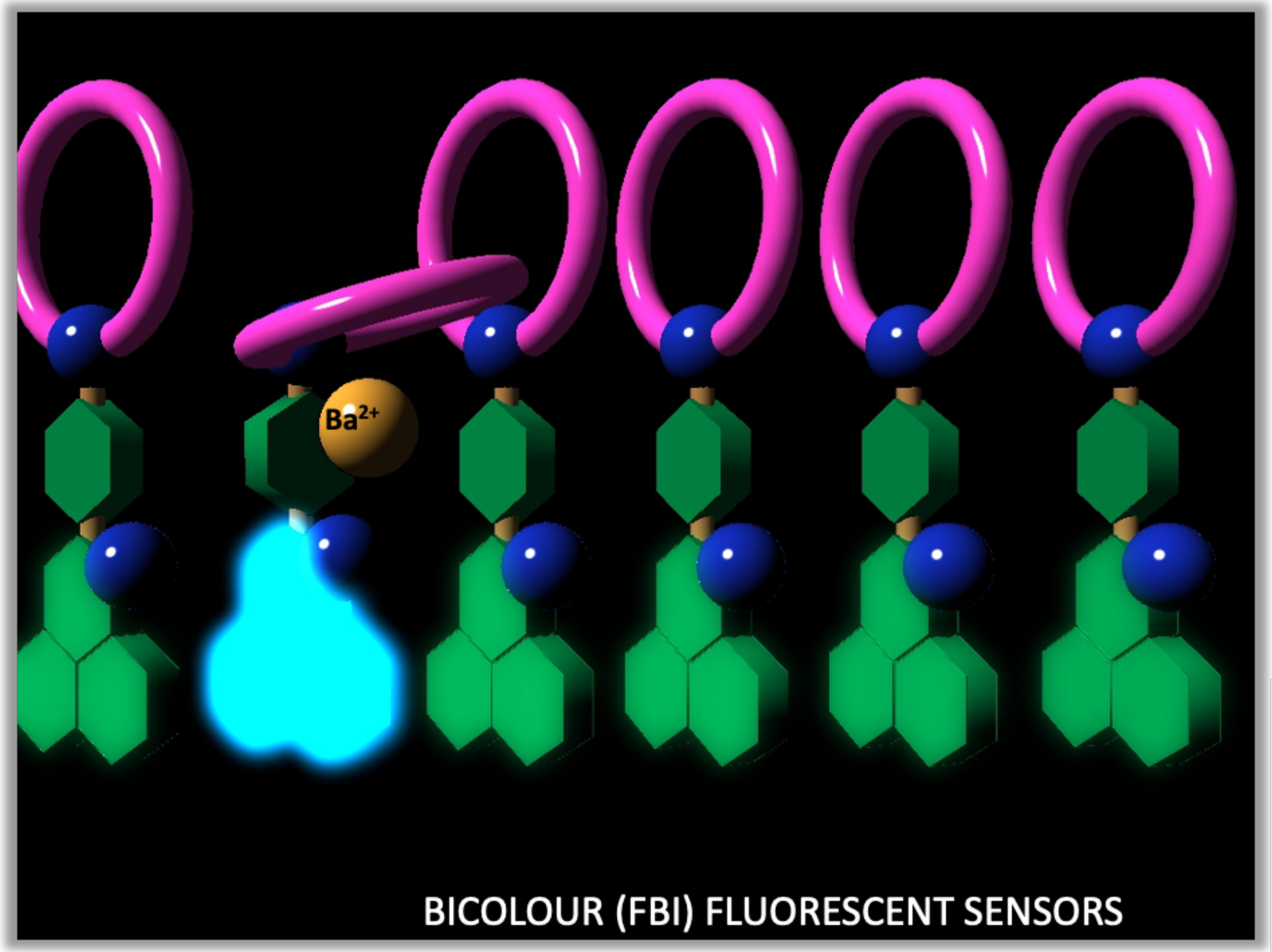
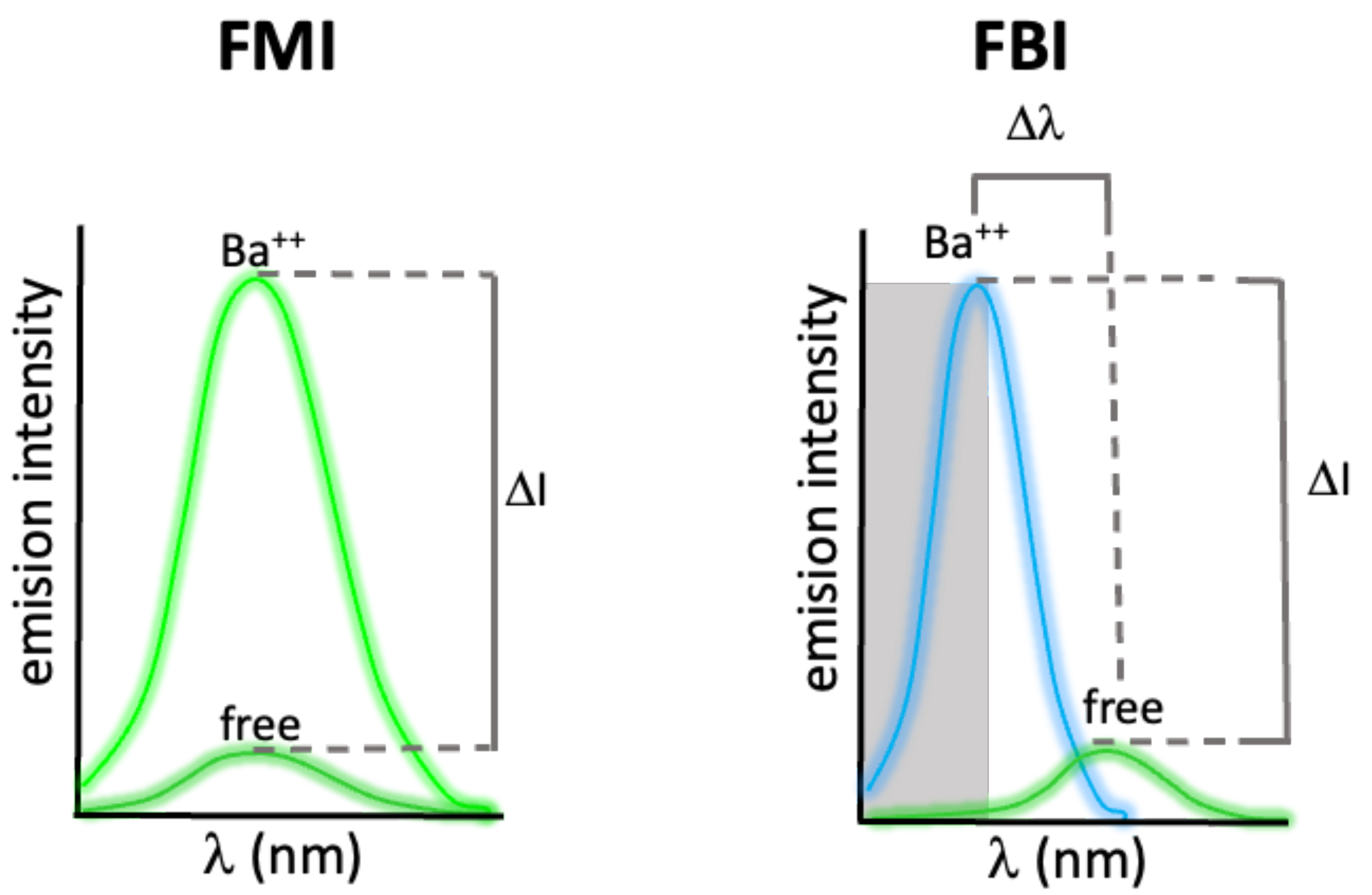
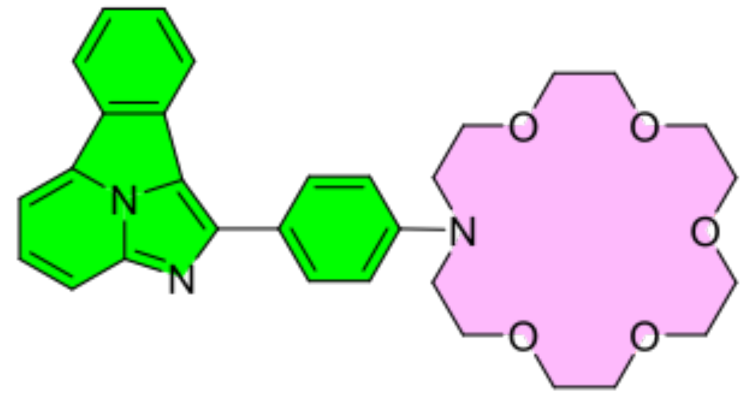
Sensors under development for single Ba^{2+} tagging@next .







Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments

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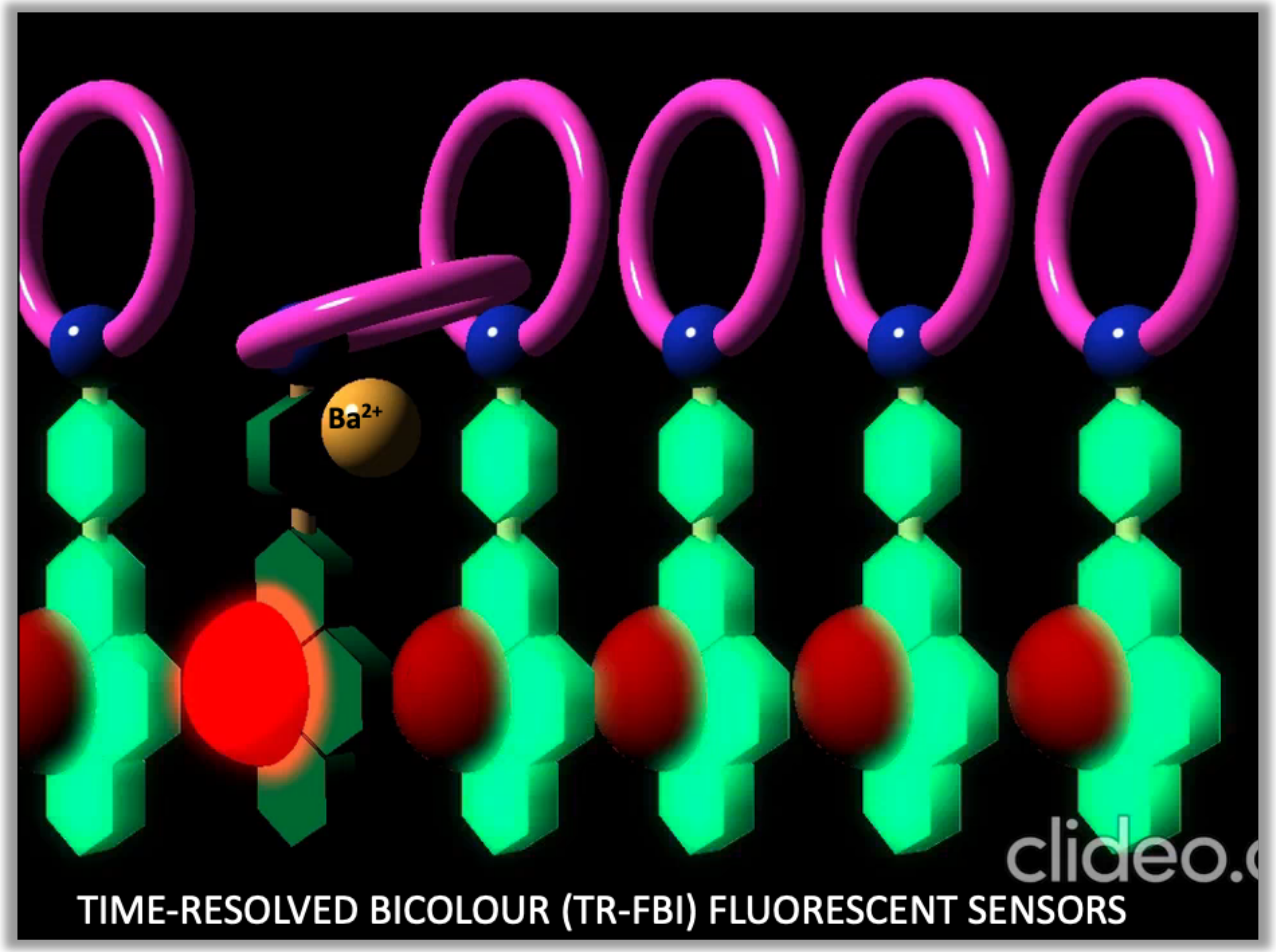
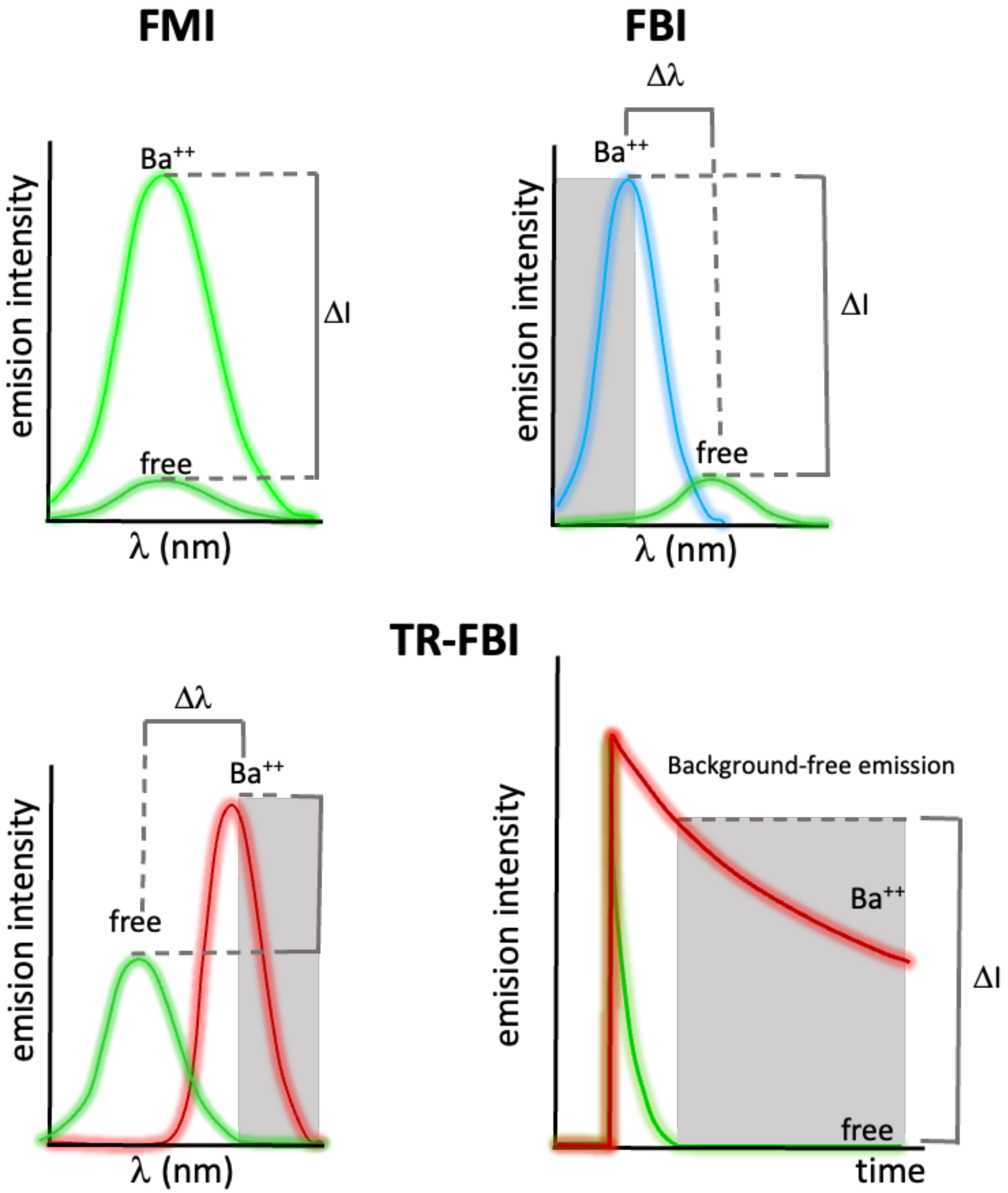
Published online: 22 June 2020

Iván Rivilla[1], Borja Aparicio[2], Juan M. Bueno[3], David Casanova[1,4], Claire Tonnelé[1], Zoraida Freixa[4,5], Pablo Herrero[1], Celia Rogero[1,6], José I. Miranda[7], Rosa M. Martínez-Ojeda[3], Francesc Monrabal[1,4], Beñat Olave[8], Thomas Schäfer[4,8], Pablo Artal[3], David Nygren[9], Fernando P. Cossío[1,2] & Juan J. Gómez-Cadenas[1,4]

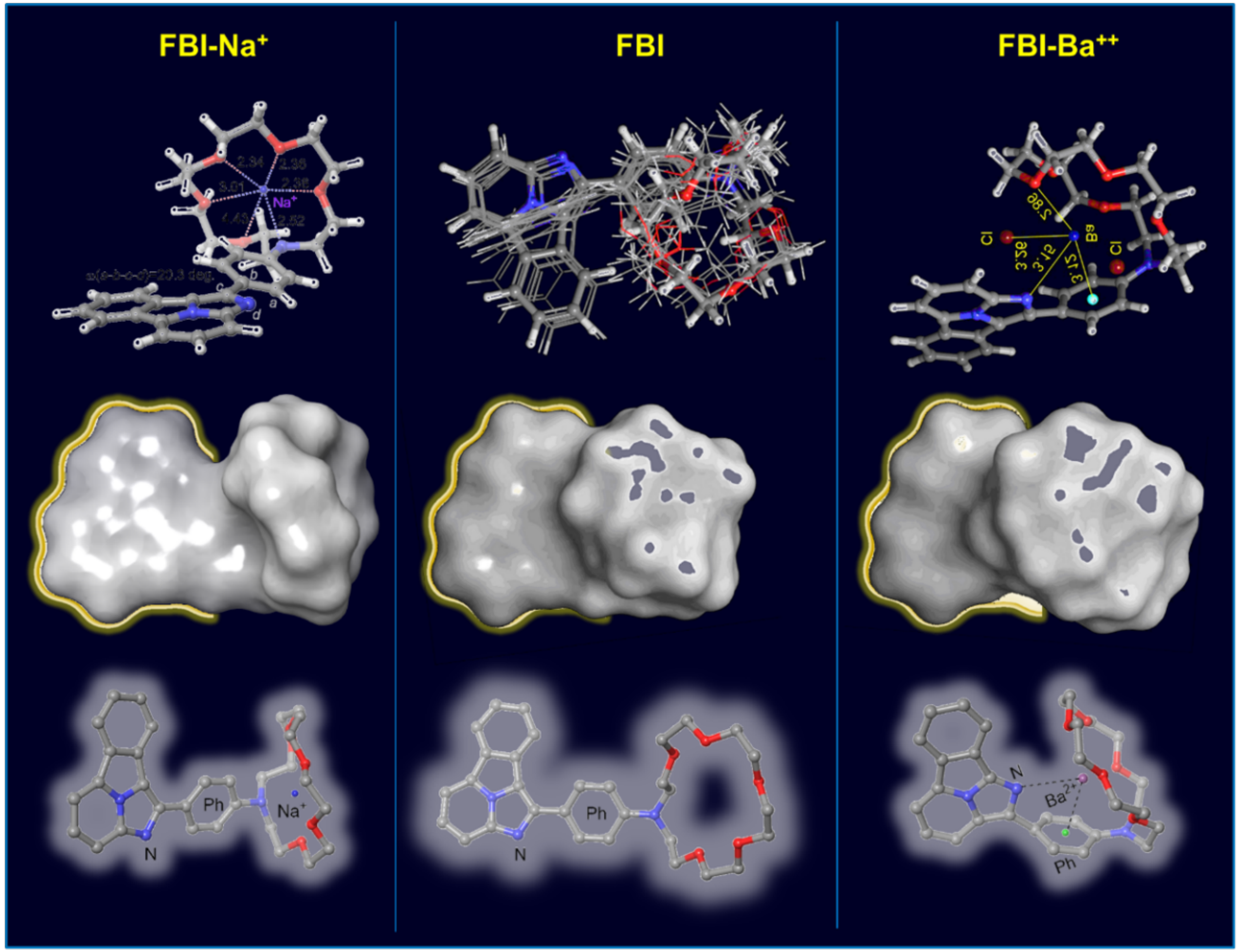
nature
International journal of science

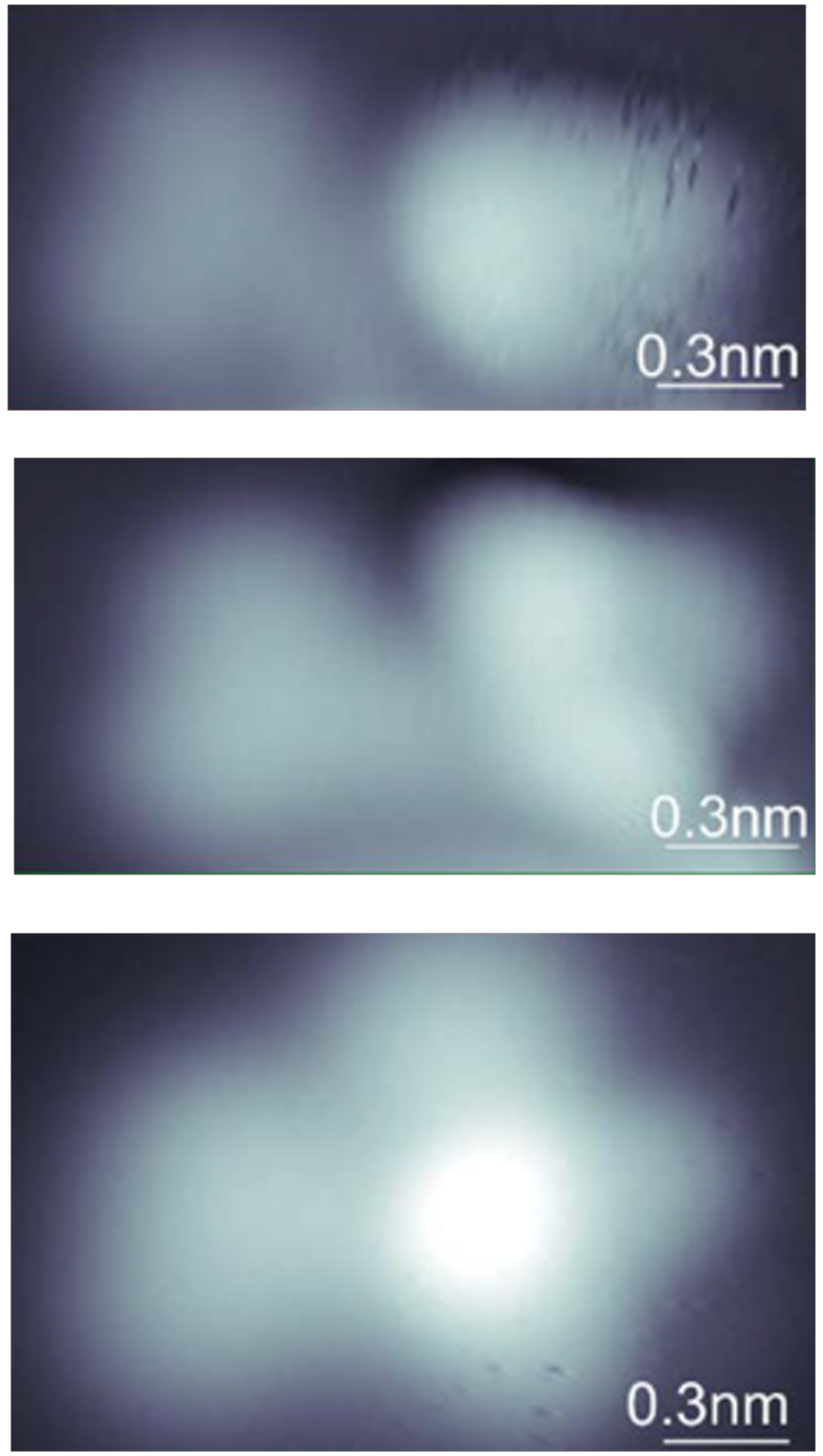
Sensors under development for single Ba^{2+} tagging@next .





Interaction of FBI-G1 with cations





Nat. Commun. **2022**, *13,* 7741 (*Highlighted paper*)

NEXT-BOLD

1. The ^{136}Xe atom decays, producing **two electrons** and the **Ba^{++} ion**.

2. The electrons drift towards the anode and the Ba (slowly) towards the cathode.

3. The Energy-Tracking Device measures the energy of the electrons and **reconstructs the barycentre** of the track.

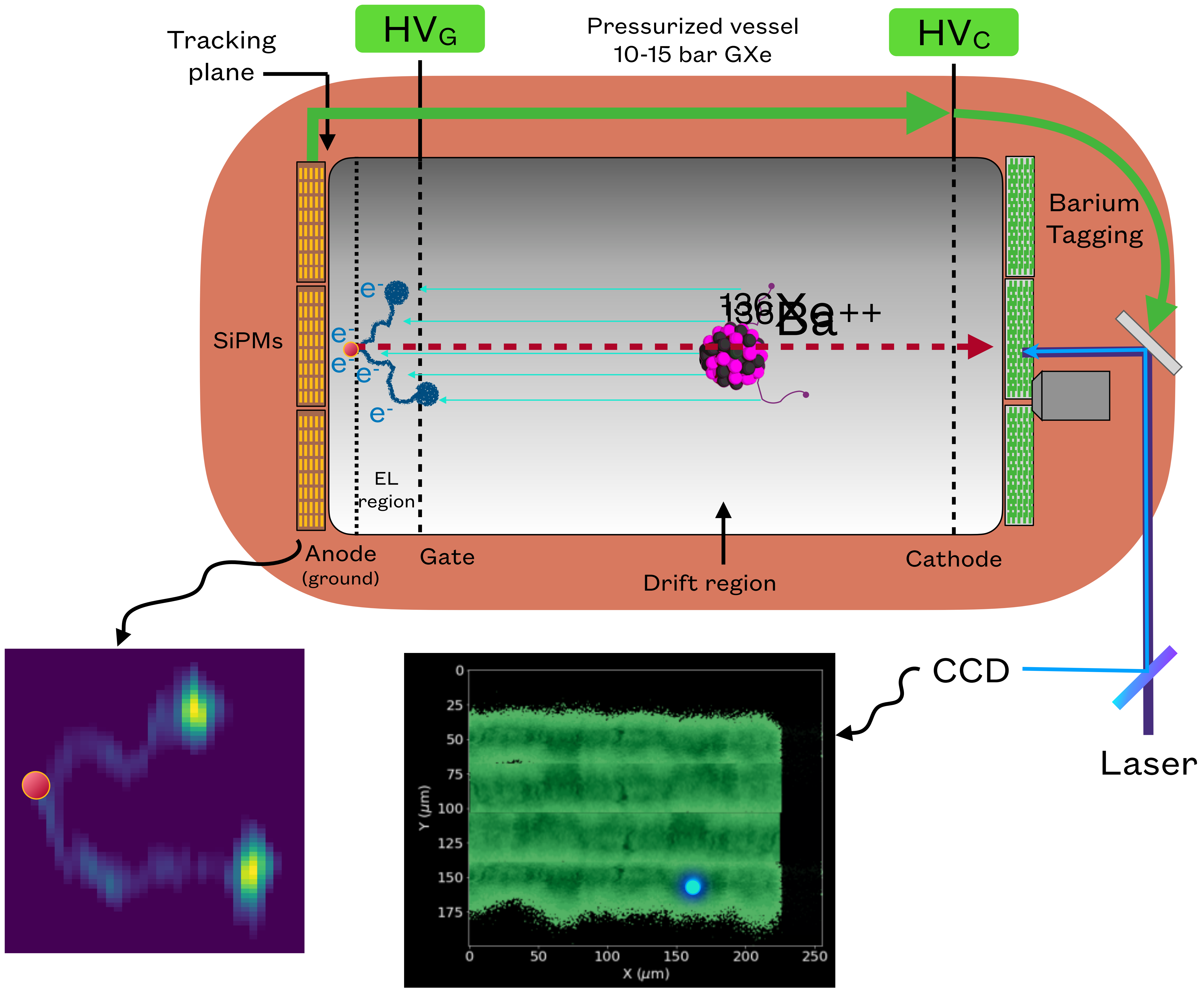
4. This **triggers the sensor** while drifts towards the cathode where a ML of organic molecules catches it.

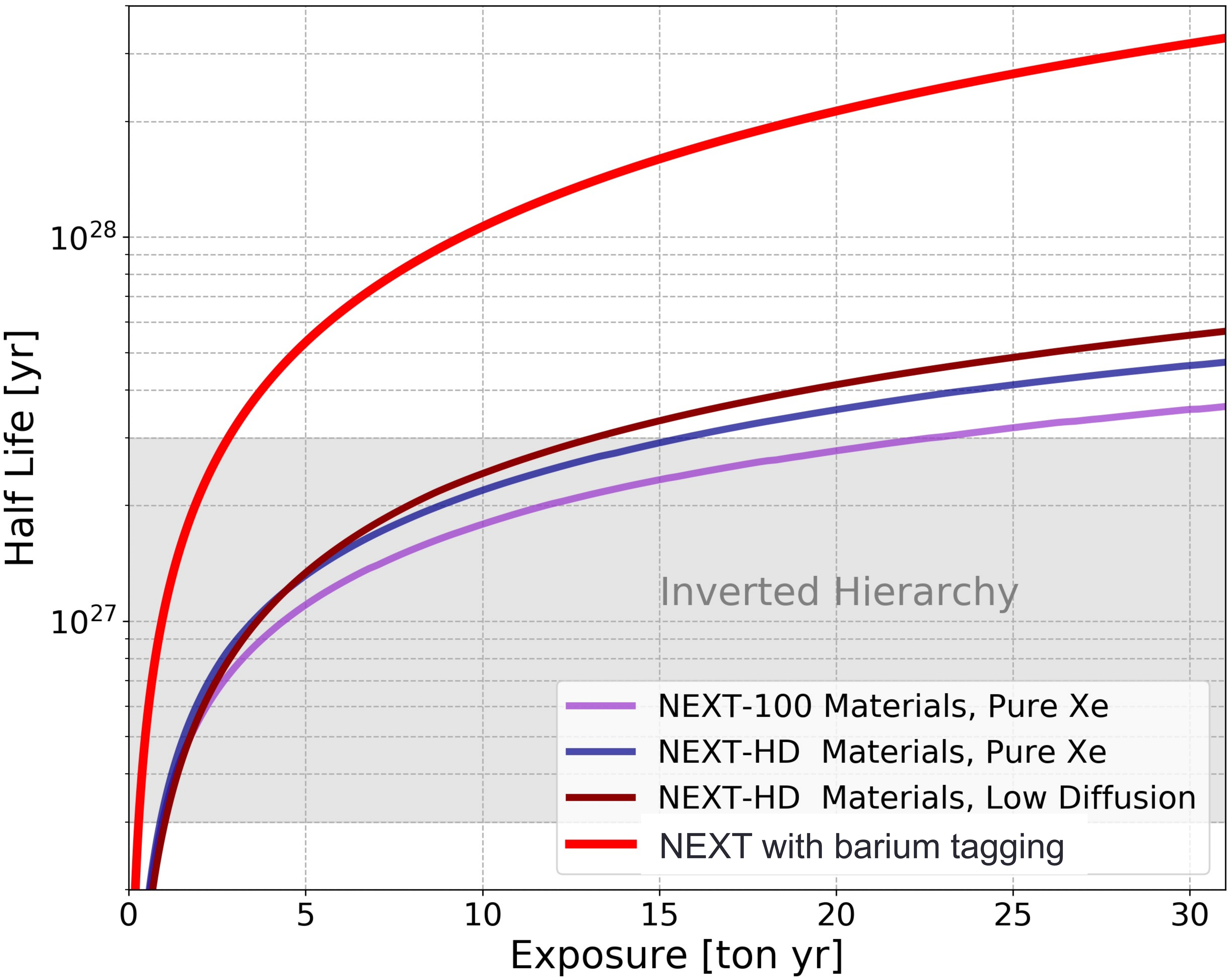
5. These molecules work as **Fluorescent Bicolor Indicators** (FBI), as their light emission shifts upon chelation with Ba^{2+}. This is the signal of Ba^{2+} detection.

6. The sensor is **scanned repeatedly**.

7. Together with the electron track we obtain a **delayed coincidence signal.**

Sensor-to-ion concept





Half Life [yr]
10^28
10^27
Exposure [ton yr]
0
5
10
15
20
25
30
Inverted Hierarchy
NEXT-100 Materials, Pure Xe
NEXT-HD Materials, Pure Xe
NEXT-HD Materials, Low Diffusion
NEXT with barium tagging

Evolution of NEXT-100: Towards a demonstrator of HD/BOLD

1. After its initial run, NEXT-100 will be upgraded to become a true demonstrator of HD/BOLD technology.

2. PMTs will be replaced by a BFD (Barrel Fiber Detector).

3. SiPMs in the tracking plane will be readout by in-house developed ASICs, thus making it possible to scale to larger tracking planes.

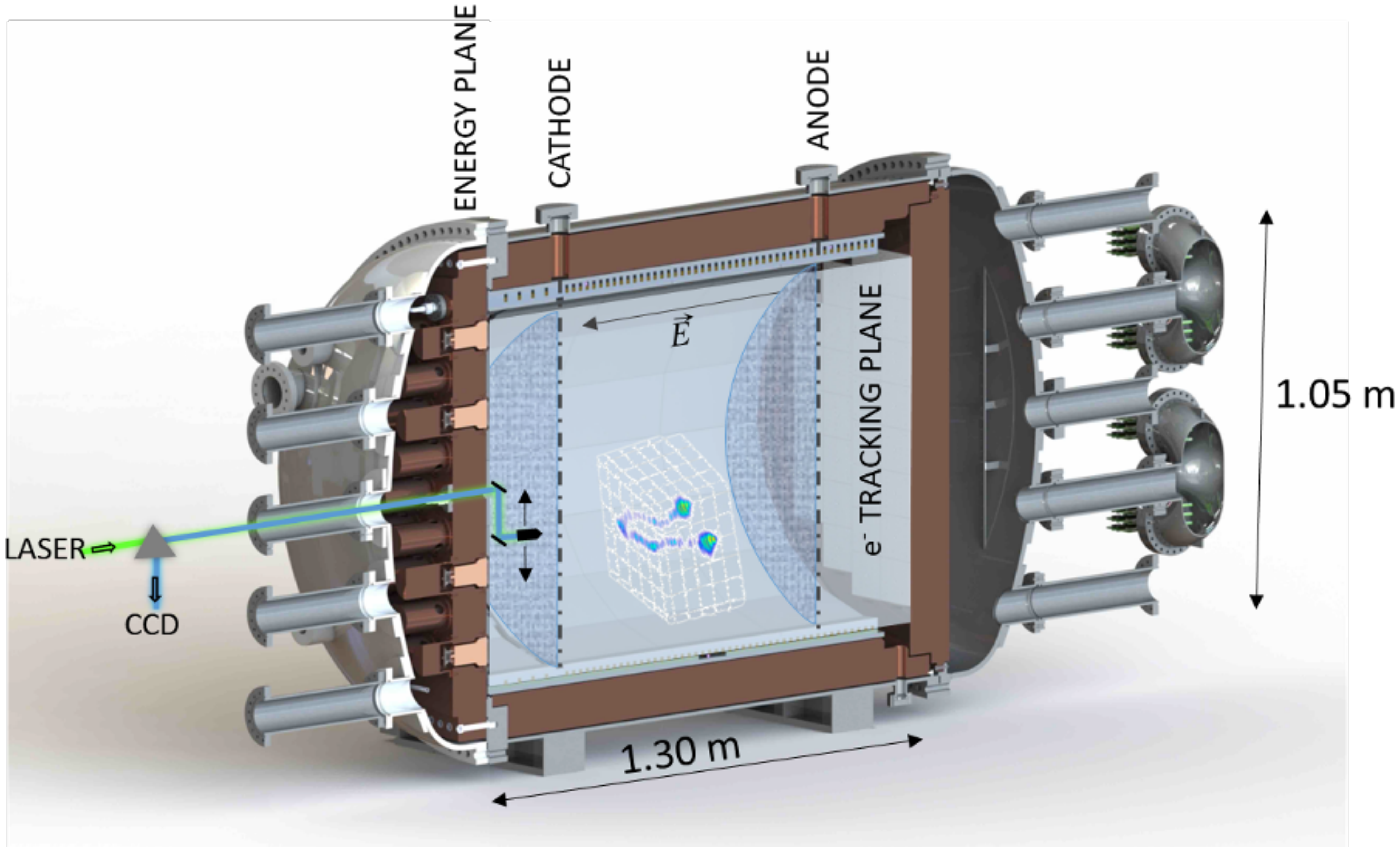
4. Possibility to upgrading tracking plane itself (e.g, improving the optics, “Axel-style”. Great opportunity for collaboration.

5. 5% Helium will reduce diffusion improve performance.

6. A prototype of BOLD detecting system can be installed in cathode (no PMTs).

7. Upgrade + data taking: 2027/2029

8. HD/BOLD could start in 2030.



The NEXT project

- The operation of NEXT-White and now NEXT-100 (HD-DEMO) has established the HPXE-EL technology and will allow us to optimise its design, both from the point of view of improving the technology (e.g, replacing PMTs with optical fibers), and from the point of view of reducing backgrounds.

- A ton-scale project can consist of one or more modules with masses around 1 ton.

- R&D on Barium Tagging (NEXT-BOLD) could result in a breakthrough.

- NEXT-100 physics program will take ~5-6 years. One could start building first module(s) of NEXT-HD circa 2030.

- NEXT-HD could explore the inverted hierarchy with competitive results by 2030. NEXT-BOLD could reach the normal hierarchy.