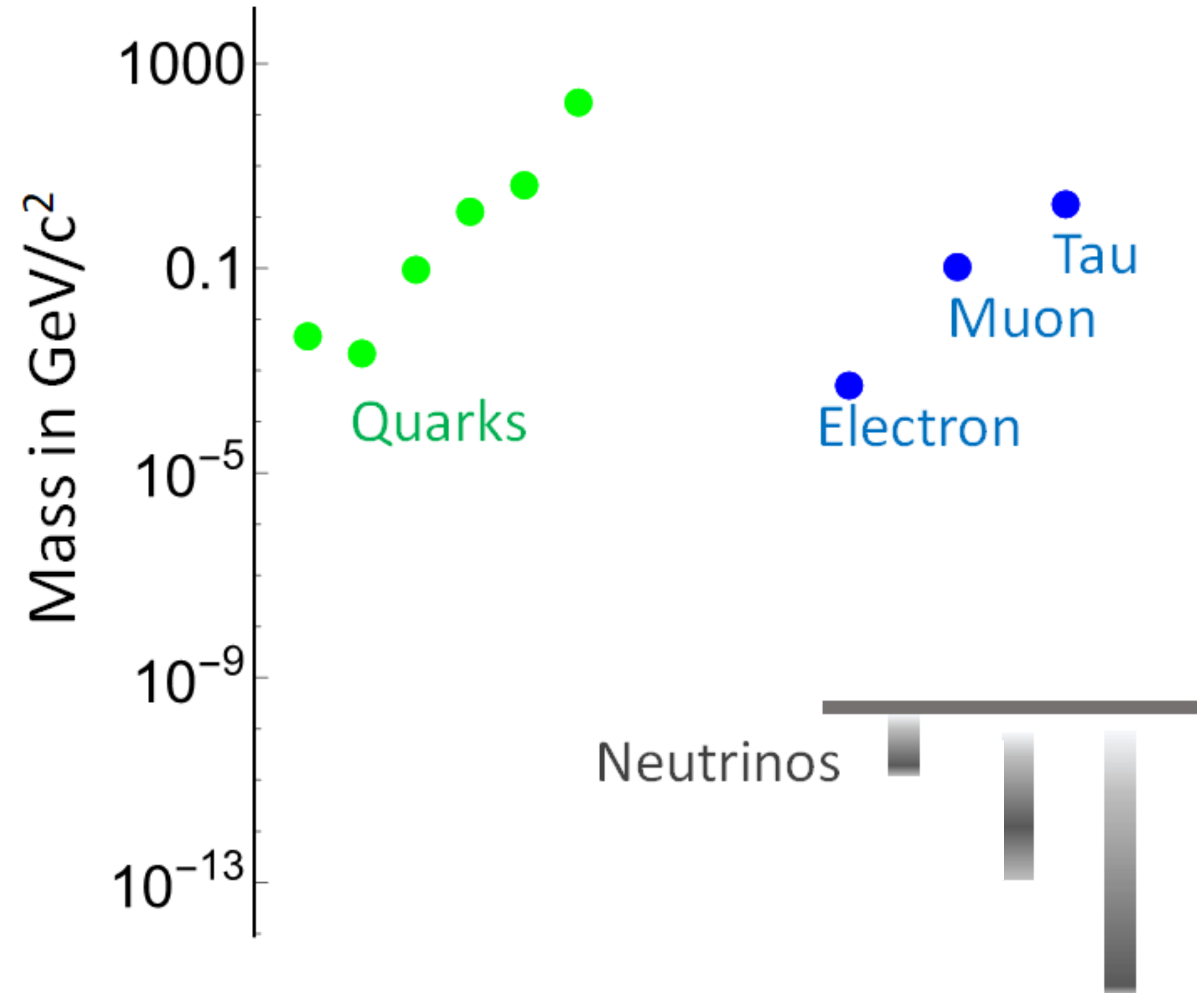


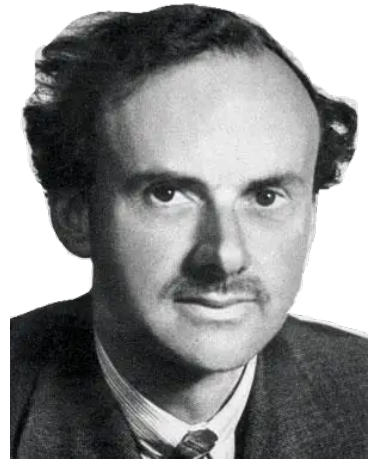
# Searching for neutrinoless double beta decay with NEXT

STEFANO ROBERTO SOLETI ON BEHALF OF THE NEXT COLLABORATION  
XESAT2023, 7 JUNE 2023

# The problem of the neutrino mass

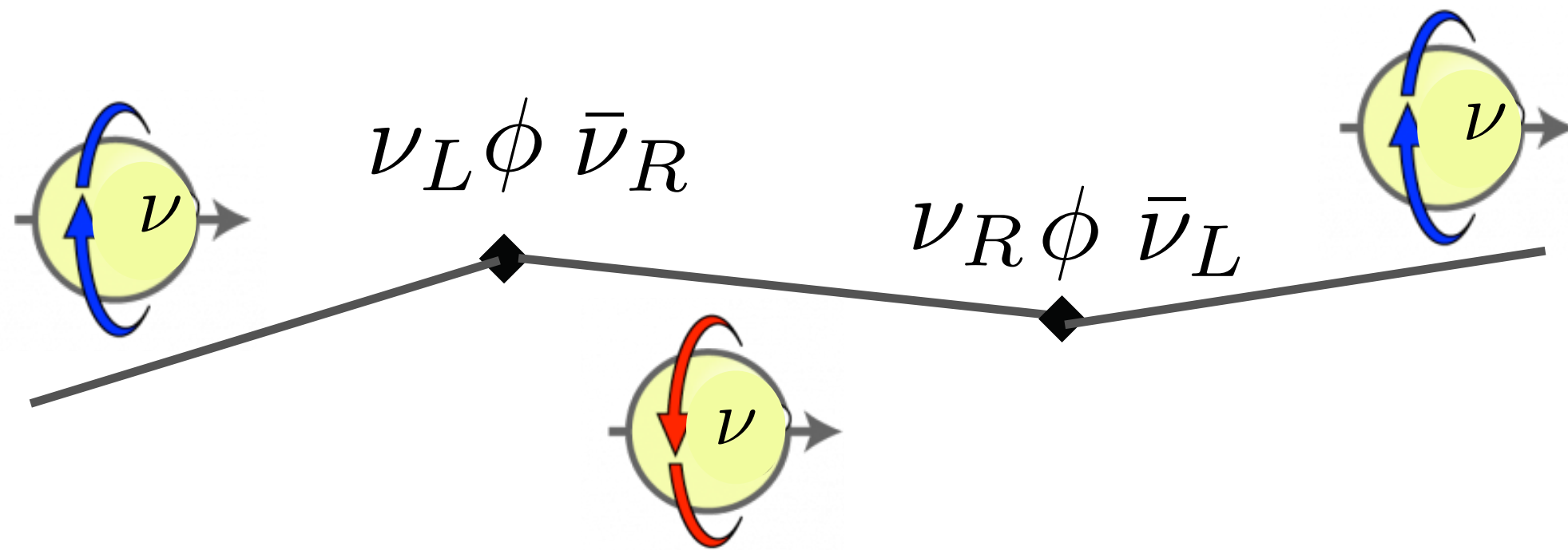
- Neutrino detection was achieved for the first time in 1956 by **Cowan and Reines**, by observing inverse beta decay from reactor antineutrinos.
- In the next decades, several experiments confirmed that **neutrinos come in three generations** of flavor, just like the charged leptons (electron, muon, tau).
- The **Standard Model does not include a mass term** for neutral leptons, so neutrinos could in principle be massless and always travel at the speed of light.
- However, several experiments in the last 30 years have confirmed that **neutrinos oscillates between different flavors** (electron, muon, tau), meaning that they must have a mass, albeit small.





# 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

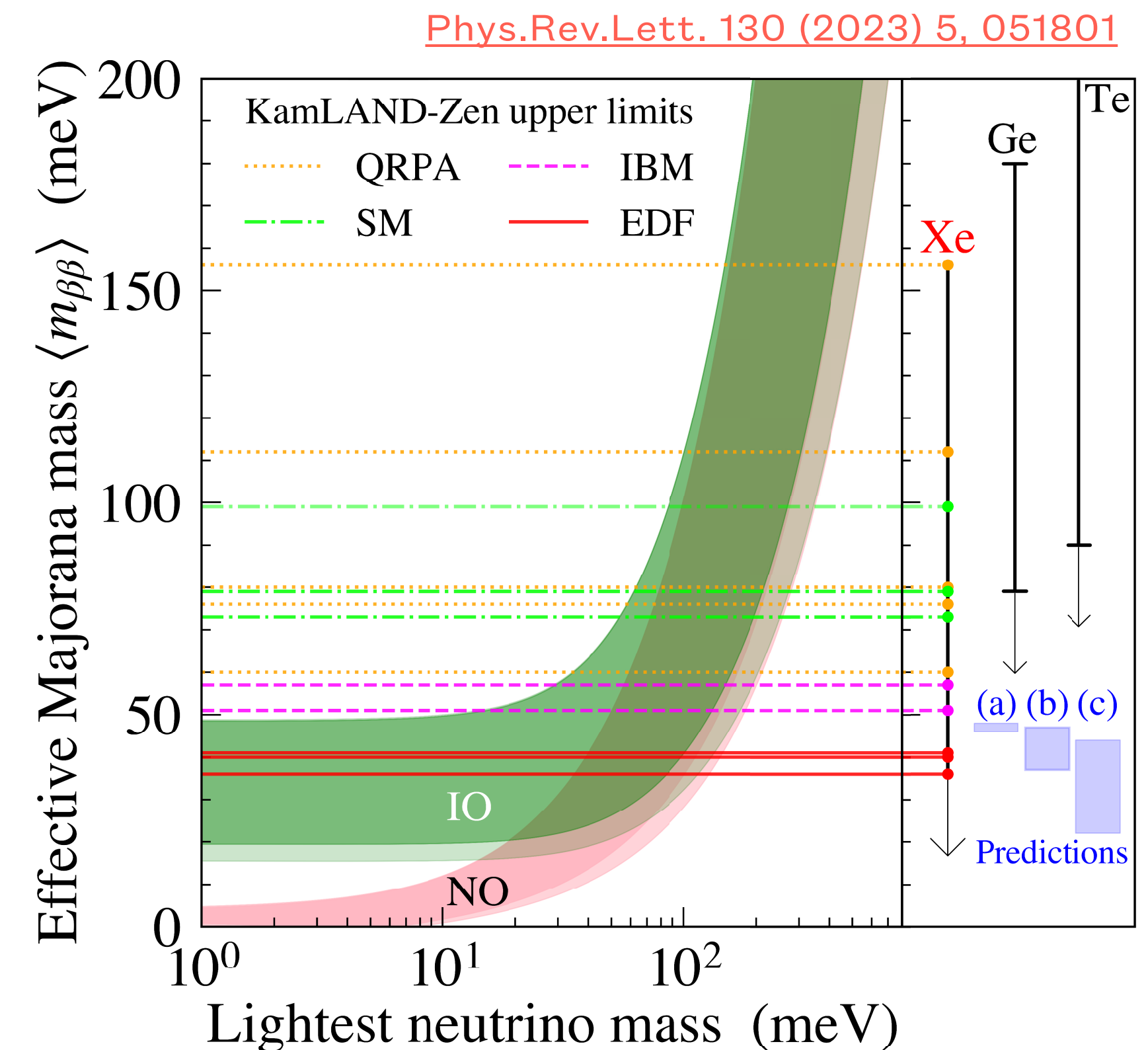
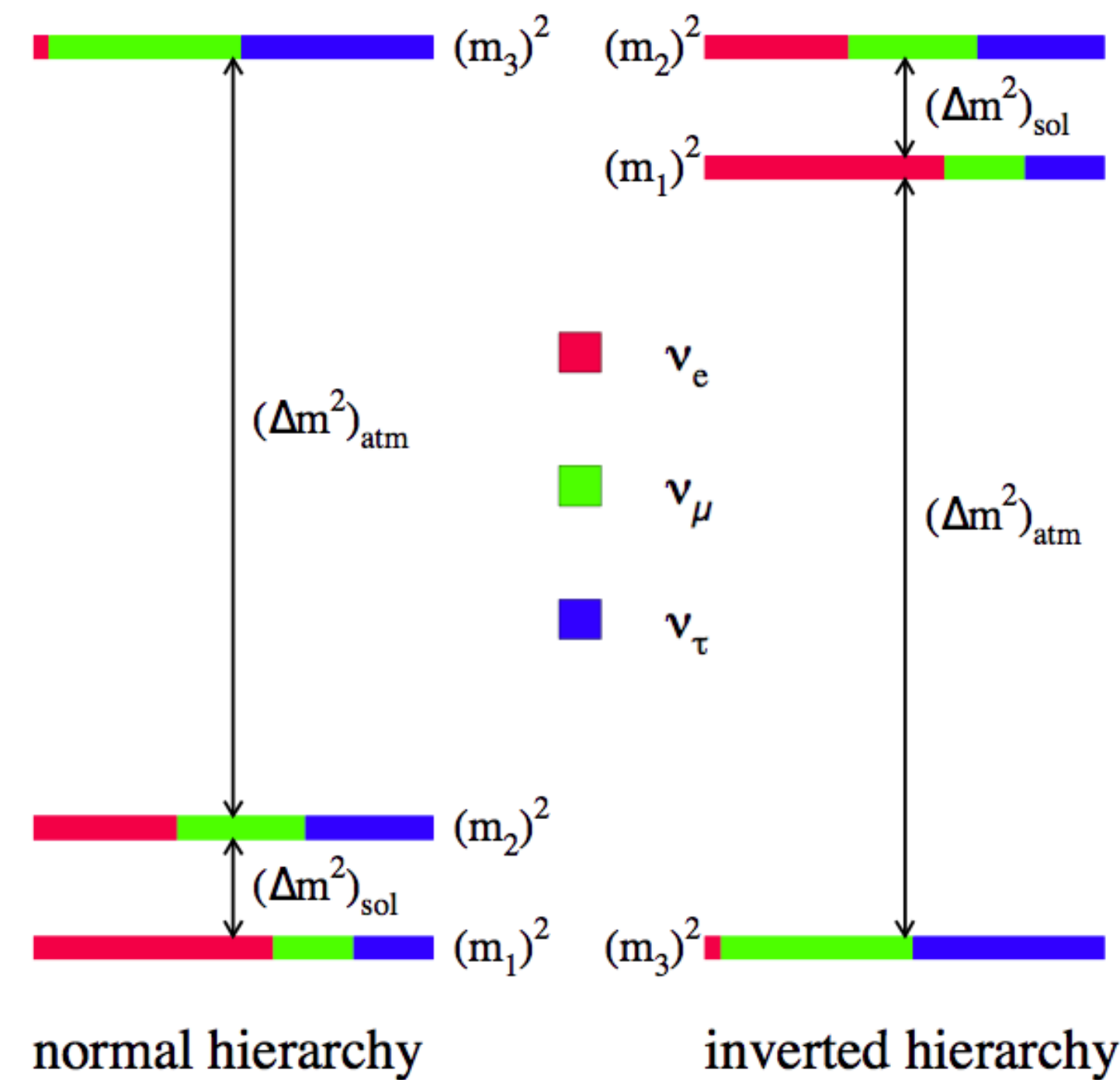


- The neutrino is a Majorana particle: the neutrino and the antineutrino are identical.
- The Lagrangian contains both Dirac mass terms and Majorana mass terms.
- The very low mass can be explained with the existence of a heavy right-handed Majorana neutrino.
- If these heavy right-handed Majorana neutrinos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

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

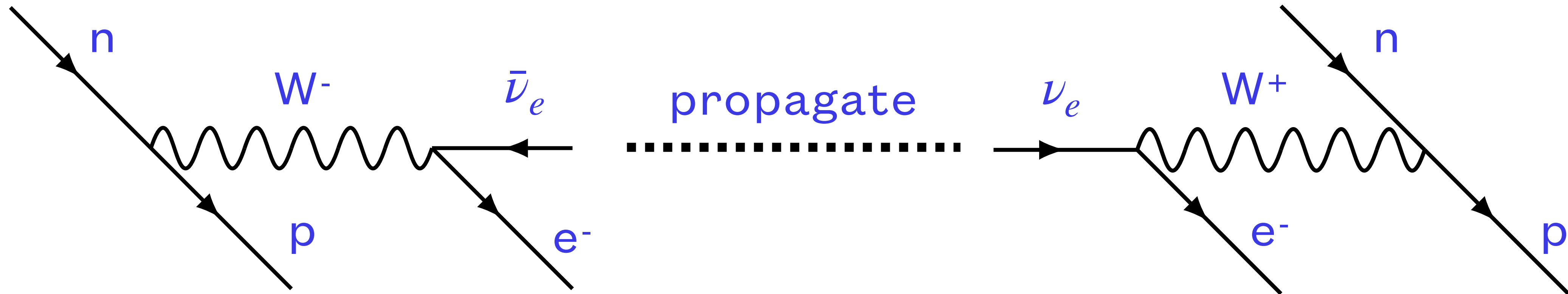
# Neutrino mass hierarchy

- 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.



# How do we choose?

- Verifying if neutrinos are their own antiparticles might sound easy: produce antineutrinos and try to detect **electrons** instead of **positrons**!



- If the neutrino is its own antiparticle, this process is possible. Small problem: the outgoing neutrino is right-chiral, while the incoming neutrino must be left-chiral.
- For massive particles chirality is not conserved, but given the extremely low mass of the neutrino, this process is suppressed **at least** by a factor of  $10^{13}$ .

# Let's ask ChatGPT...



Can you tell me what is the best way to verify if neutrinos are their own antiparticles?



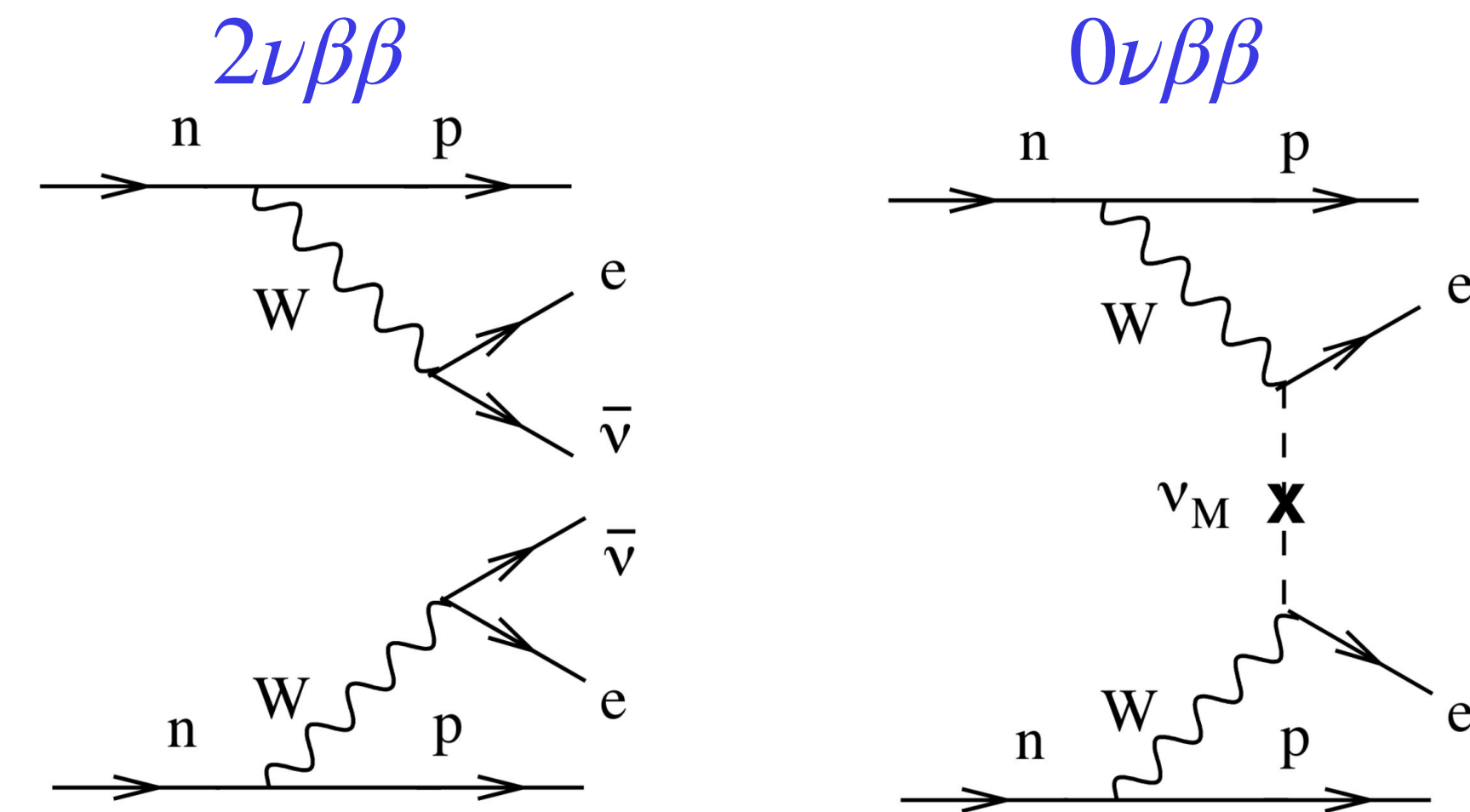
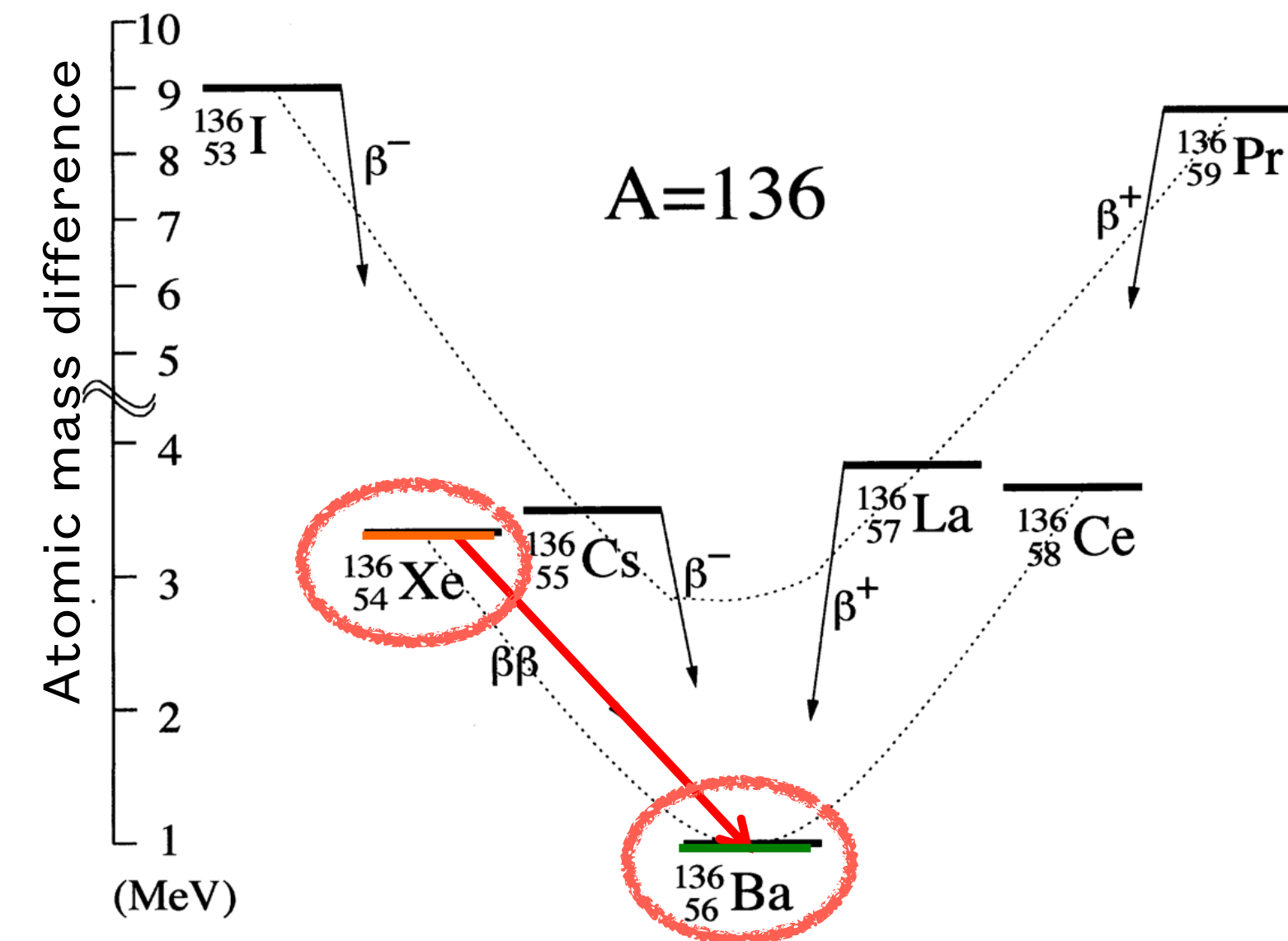
The question of whether neutrinos are their own antiparticles is an open question in physics. This property is known as "Majorana nature" of neutrinos. There are several experimental methods being developed to study this question, but none have yet provided definitive proof.

One of the most promising methods involves observing a rare form of nuclear decay known as neutrinoless double-beta decay. In this process, a nucleus decays by emitting two electrons and no neutrinos. If neutrinos are their own antiparticles, then this process can occur via the exchange of a virtual Majorana neutrino. The observation of this process would provide strong evidence for the Majorana nature of neutrinos.

Several experiments are currently searching for neutrinoless double-beta decay, including the GERDA experiment, the CUORE experiment, and the KamLAND-Zen experiment. These experiments use a variety of techniques to detect the electrons emitted in the decay, and to distinguish this rare process from other forms of double-beta decay. ■

# 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 energetically forbidden to "single" beta decay to odd-odd nuclei.
- If neutrinos are their own antiparticles, as ChatGPT says, this process can happen **without** the emission of neutrinos in the final state.
- Of course, also this process, if exists, is helicity-suppressed, so the decay time is slow...



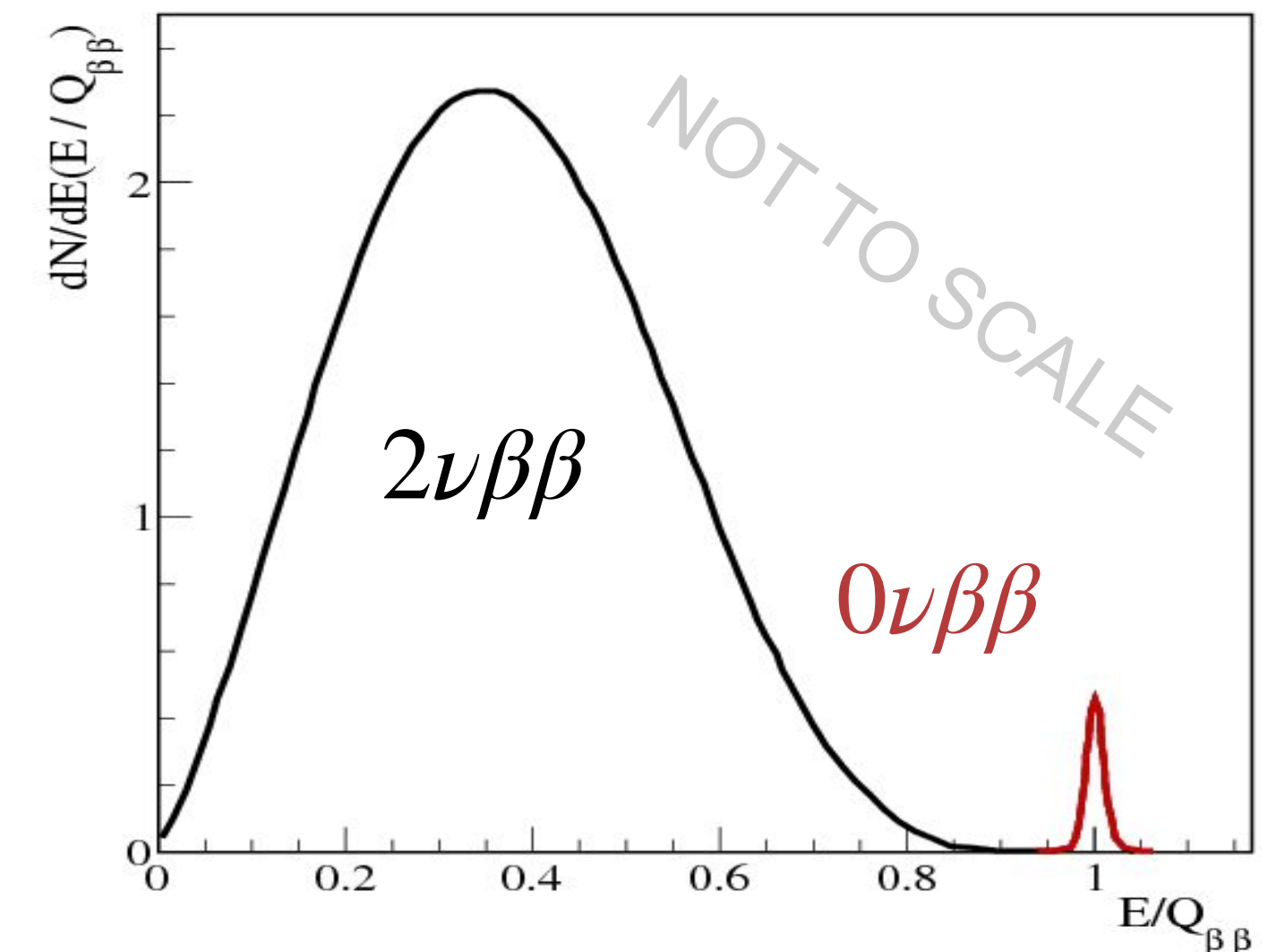
# How slow?

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

- 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.

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

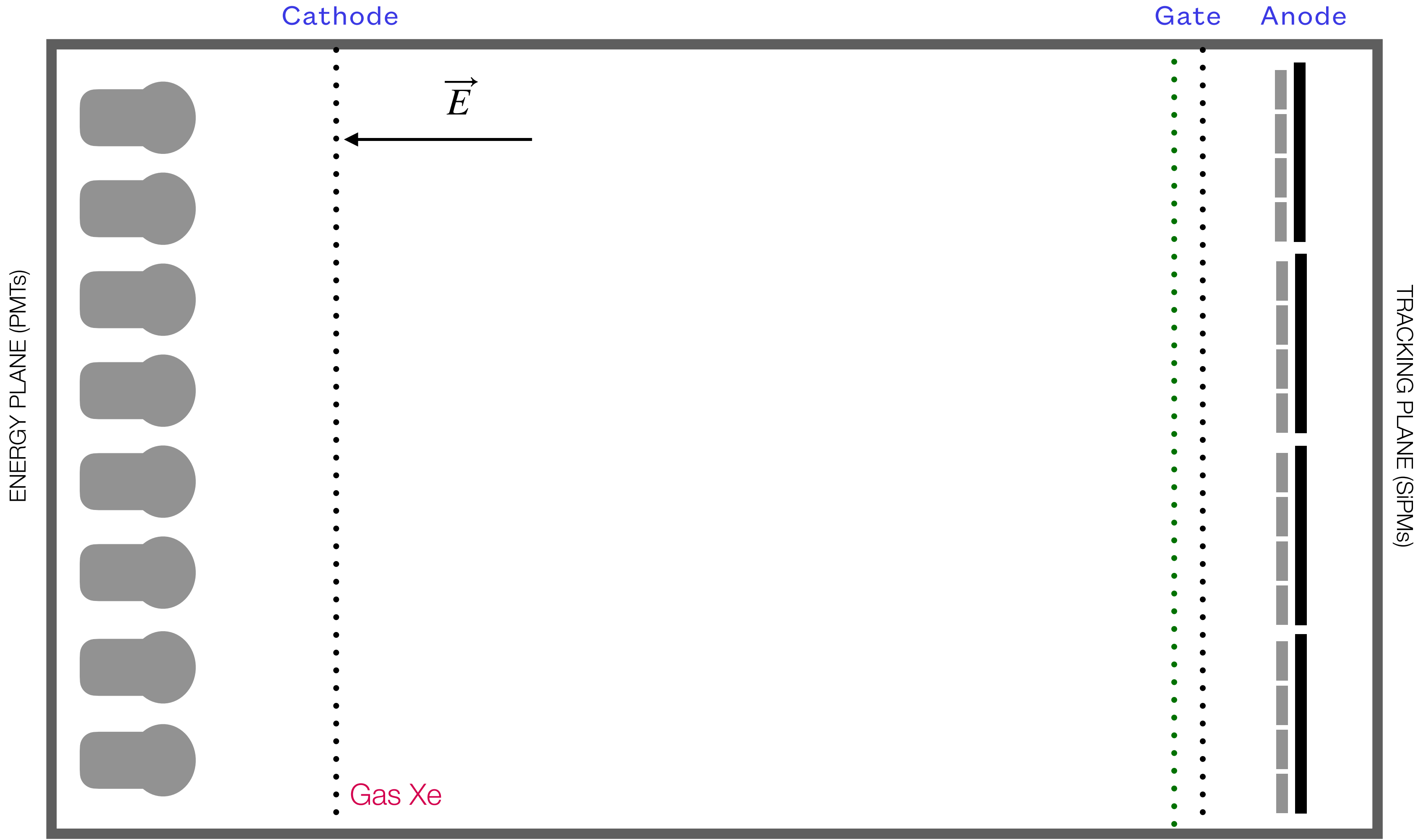




# Enters NEXT...

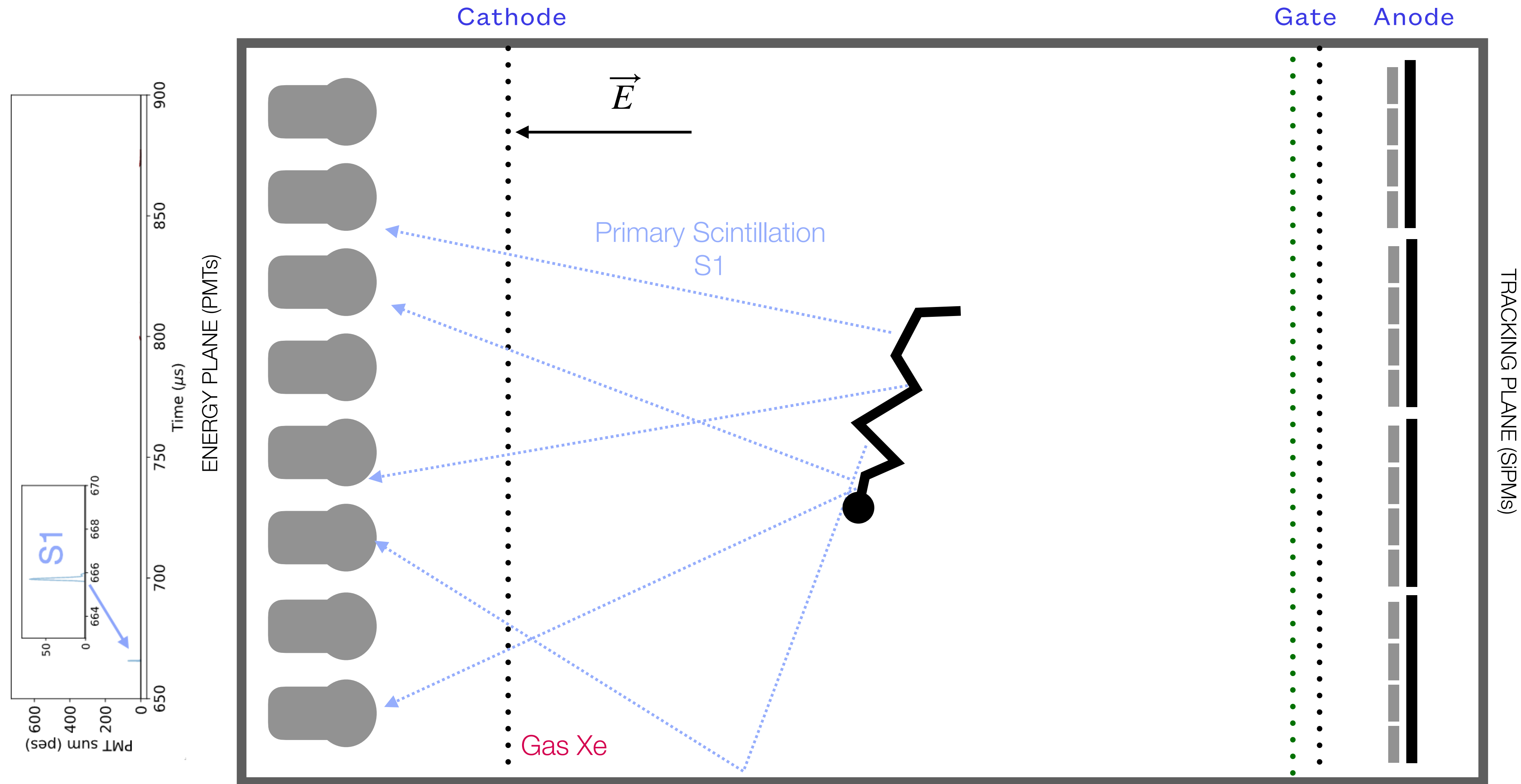


## High Pressure gaseous Xenon Time Projection Chamber



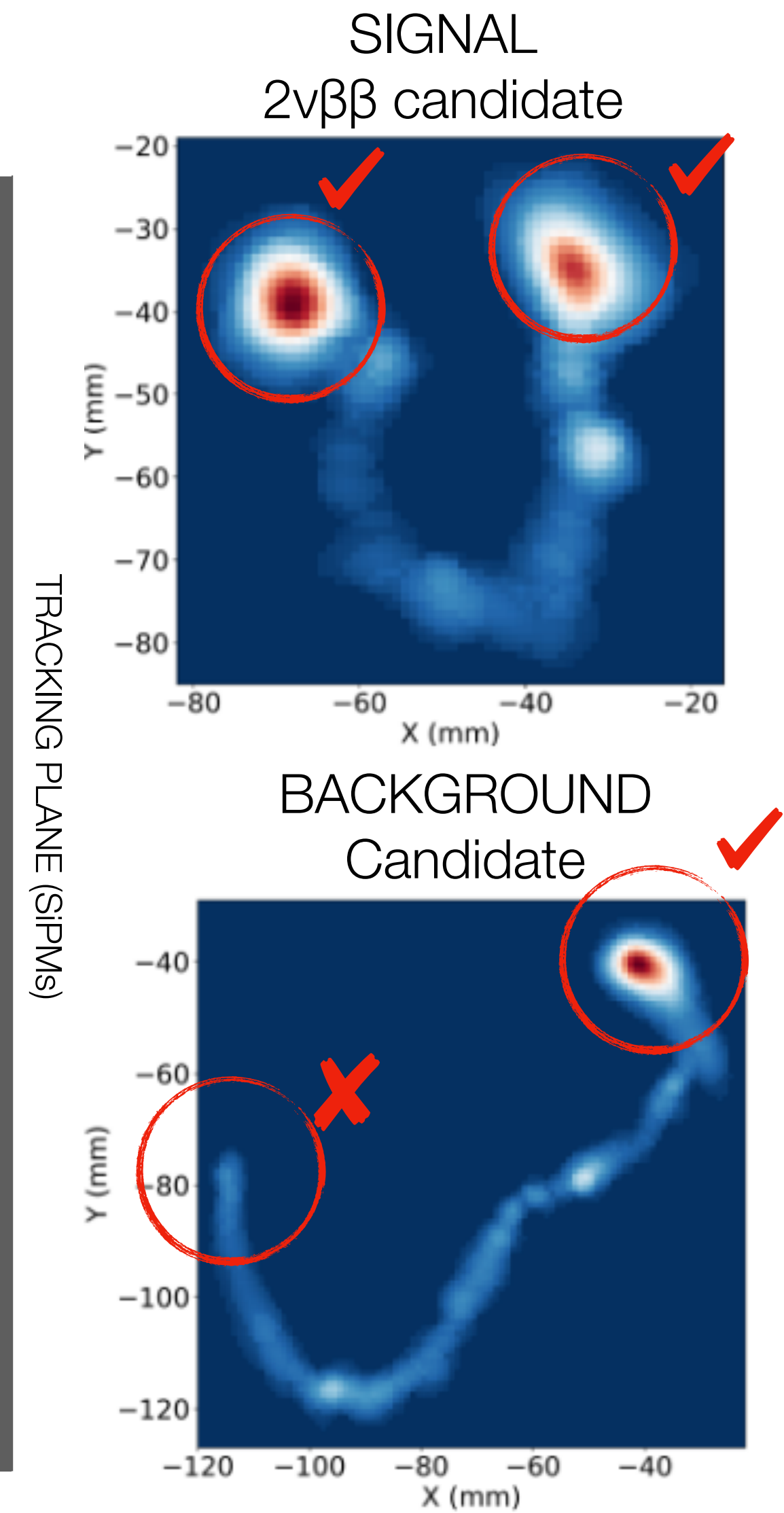
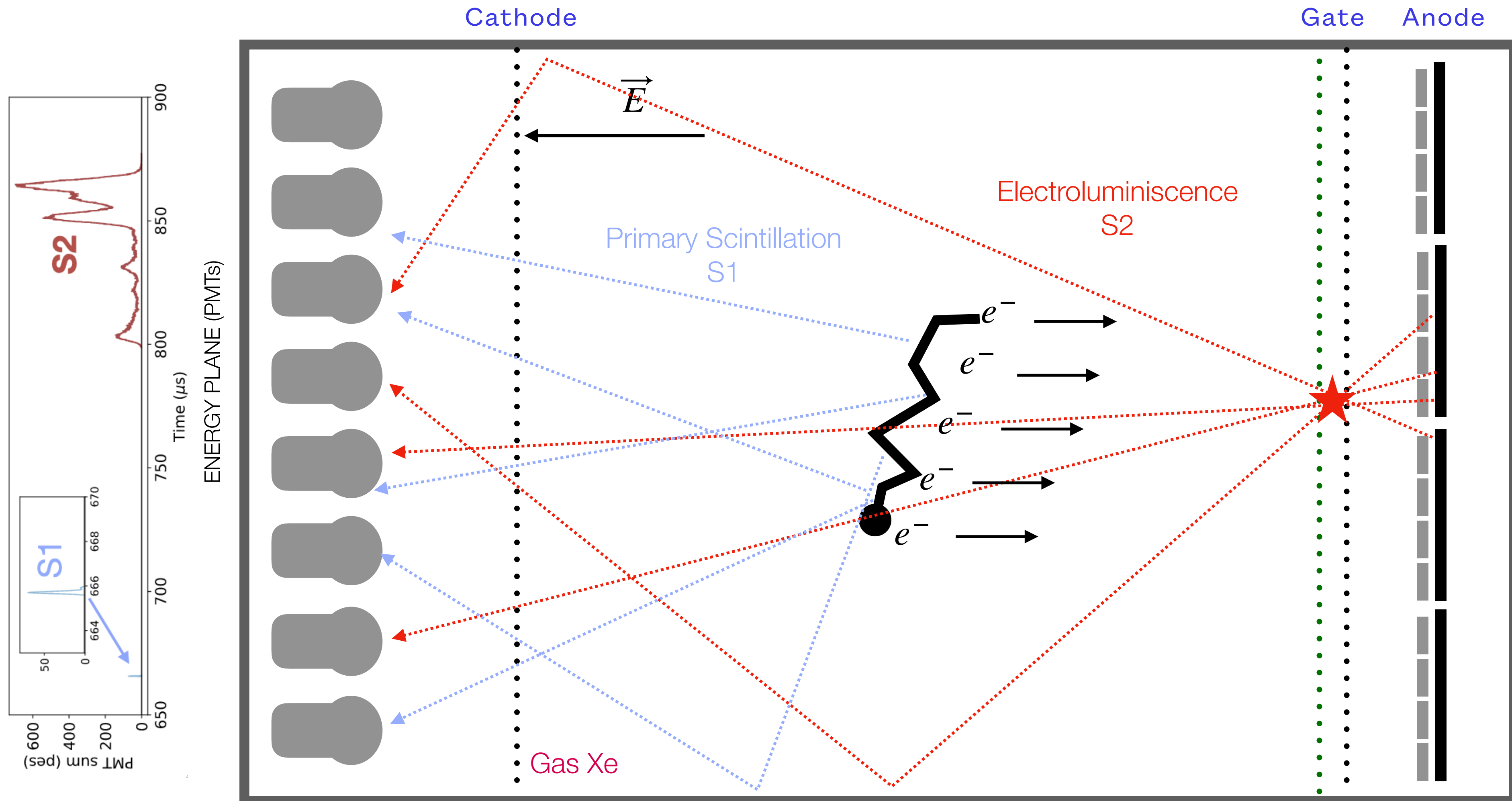
# Enters NEXT...

## High Pressure gaseous Xenon Time Projection Chamber



# Enters NEXT...

## High Pressure gaseous Xenon Time Projection Chamber



# The NEXT program



### Prototypes

2010-2014

Demonstration of detector concept

~1 kg

### NEXT-White

2015-2021

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

### NEXT-100(1000)

2022-2026

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

### NEXT-BOLD

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





FORÊT  
COMMUNALE  
DE BORCE

Col du Somport  
1,632 m

Col de  
1,794 m

Río Aragón

Río Estarrún

Barranco de  
Barranco de

Río Aragón

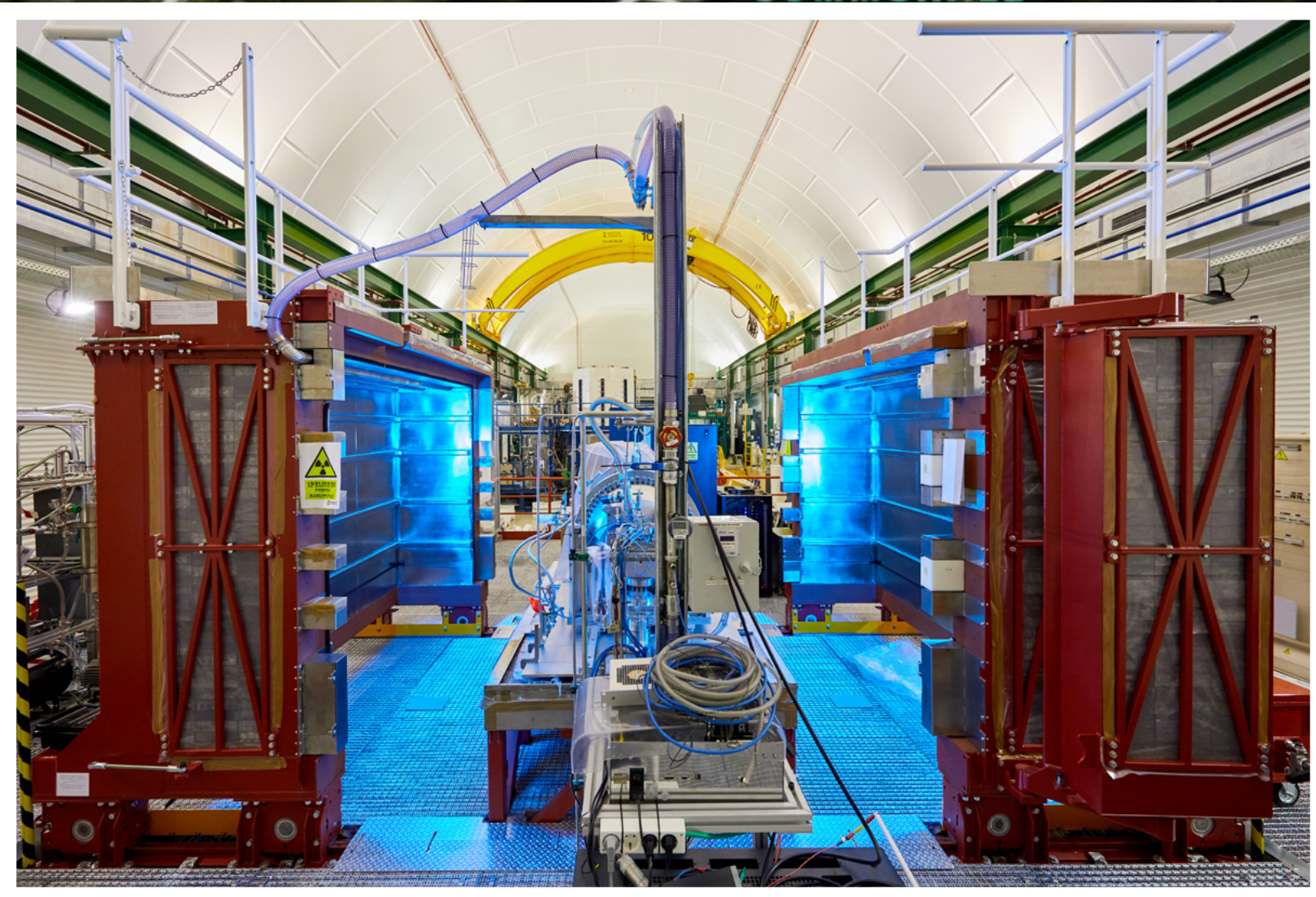
Collarada  
2,883 m





Canfranc Underground Laboratory

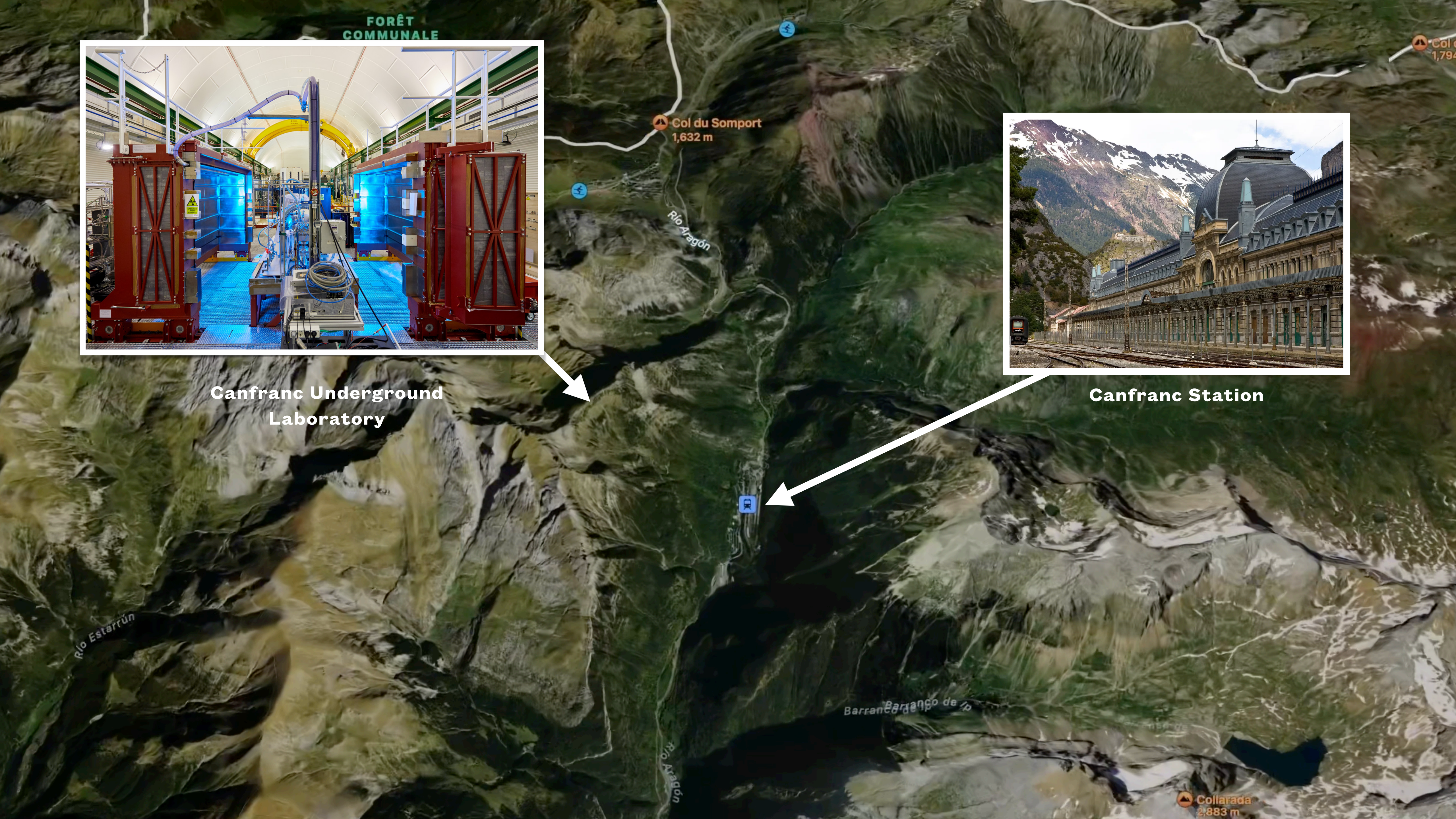




Canfranc Underground Laboratory



Canfranc Station



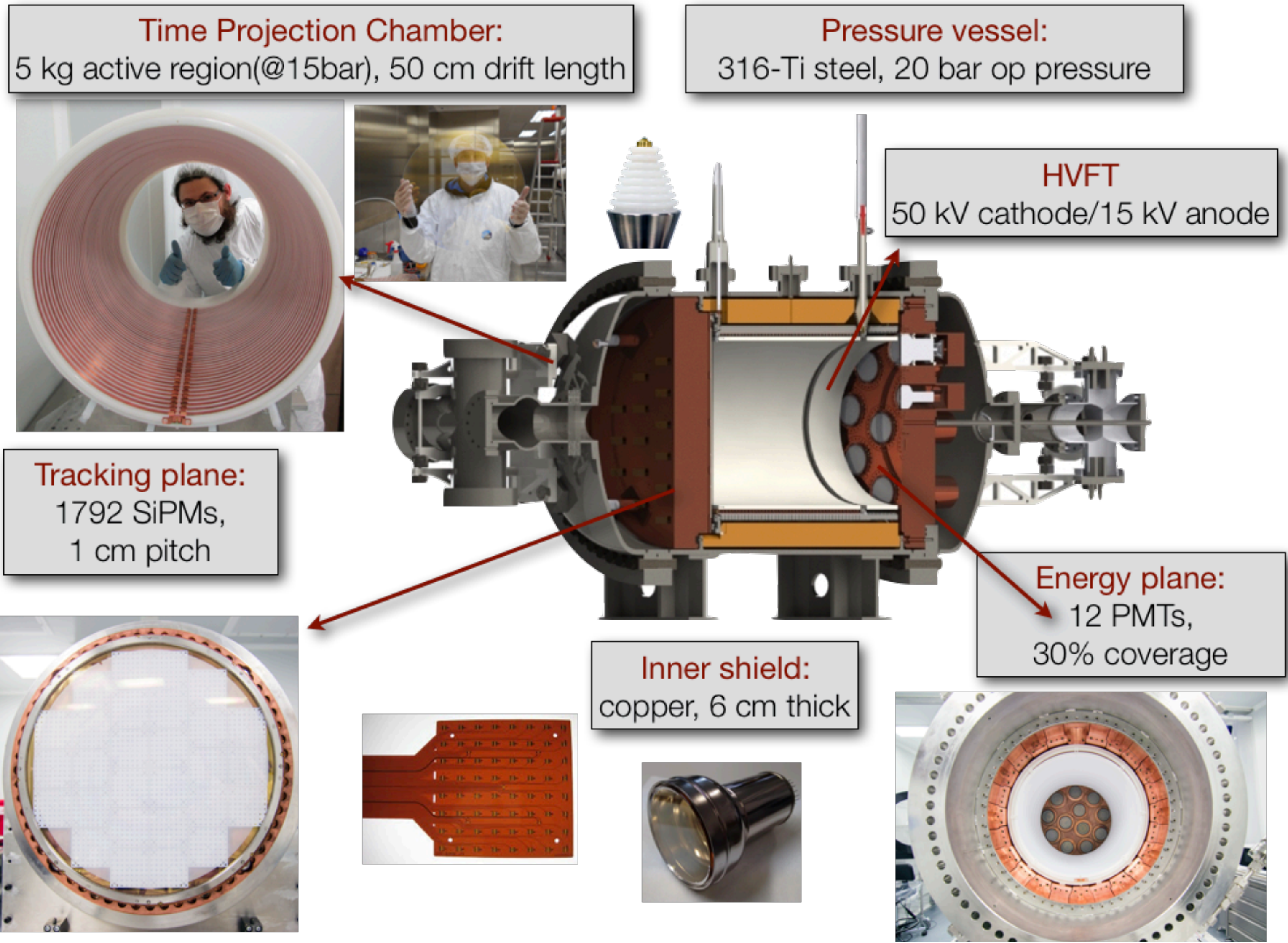




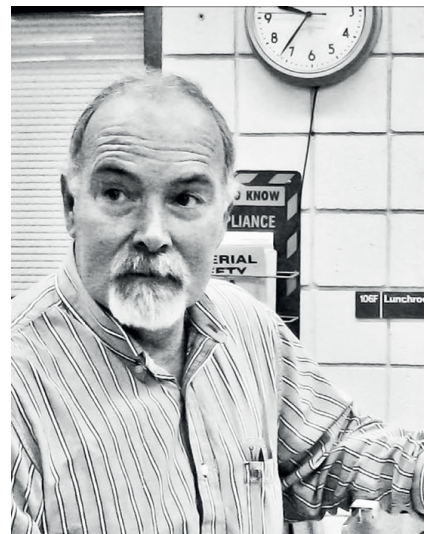
**anext**

**NEXT-White**

# The NEXT-White detector

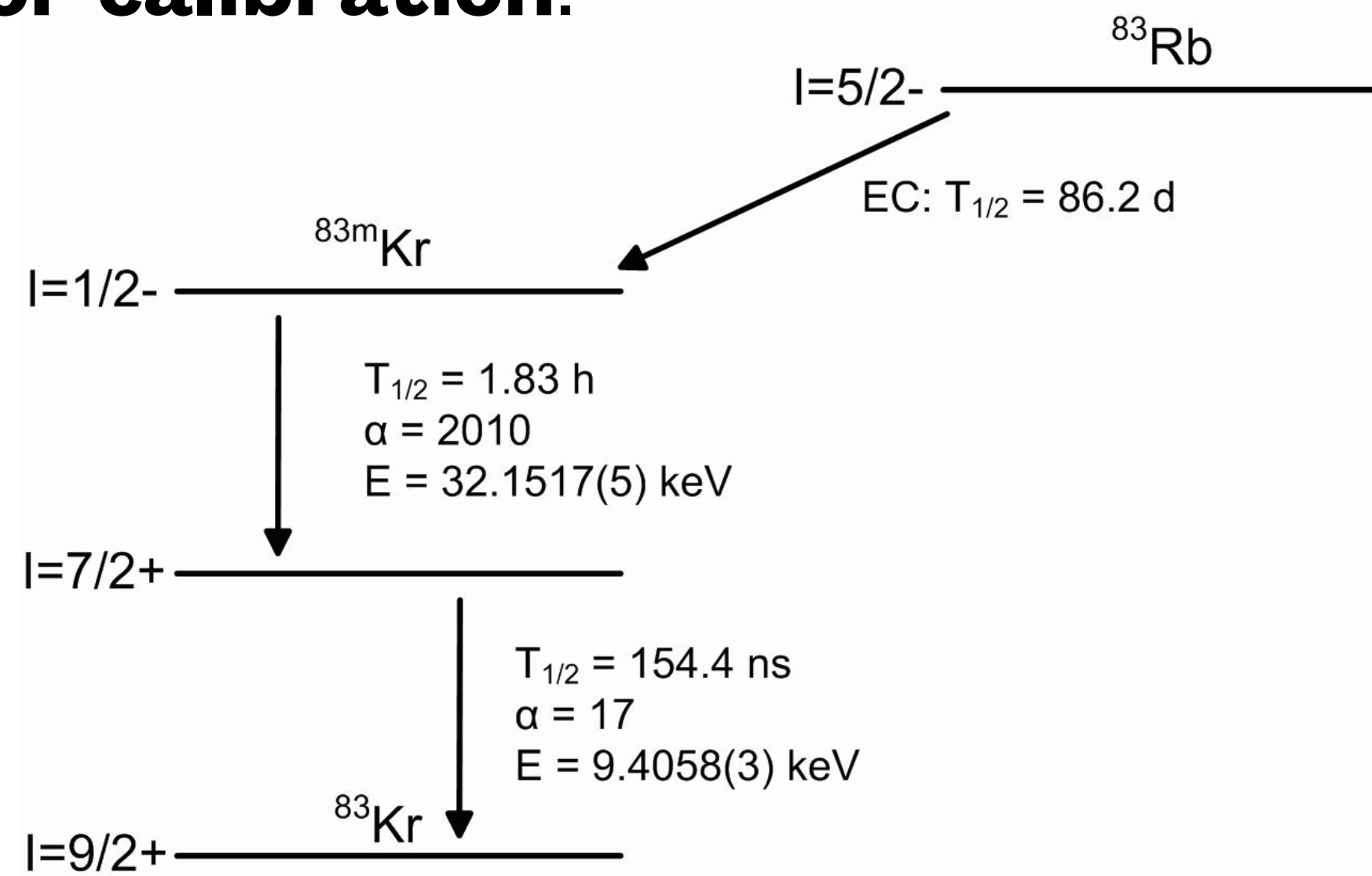


The late professor James White.  
NEXT-White is named to honour  
his memory.

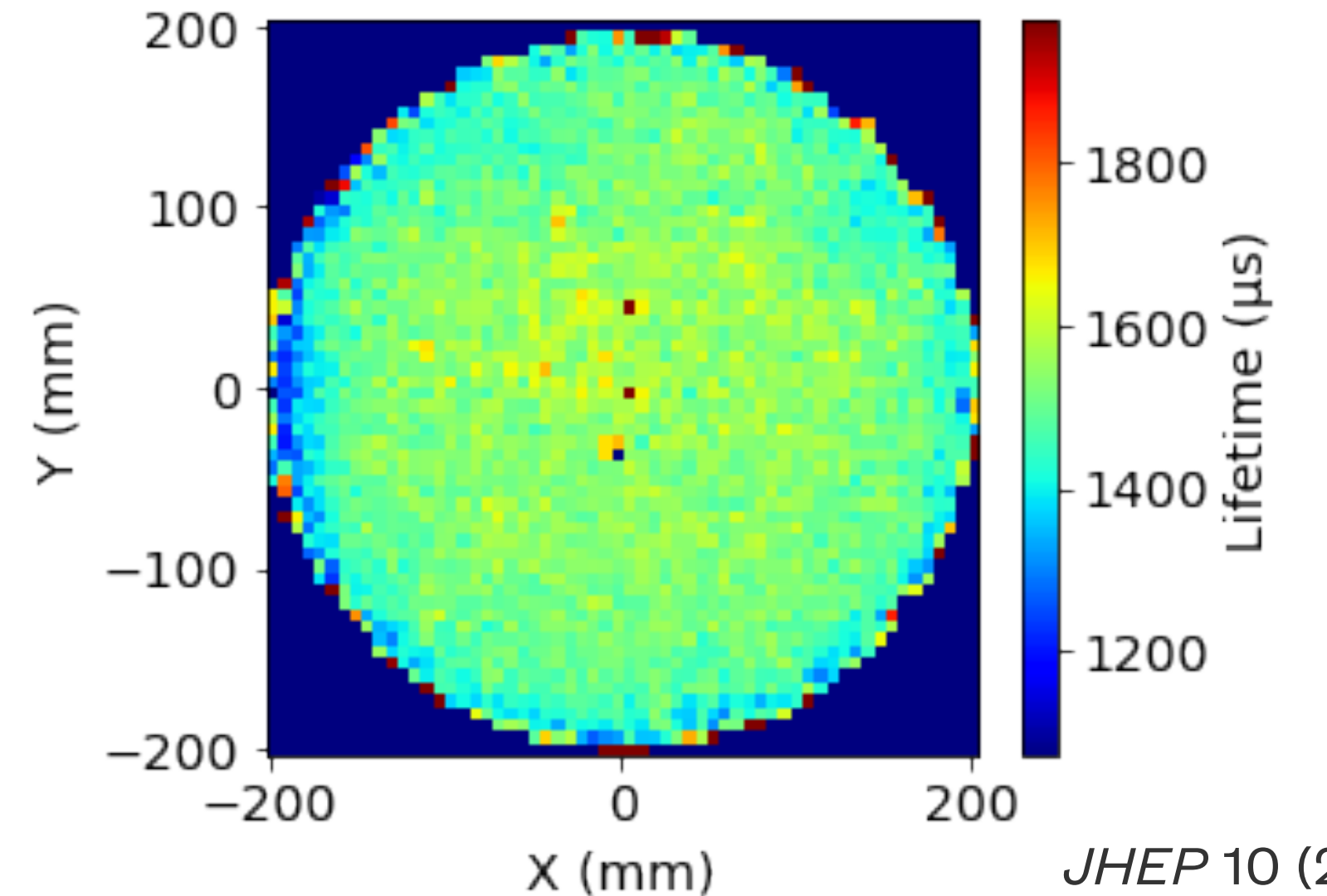
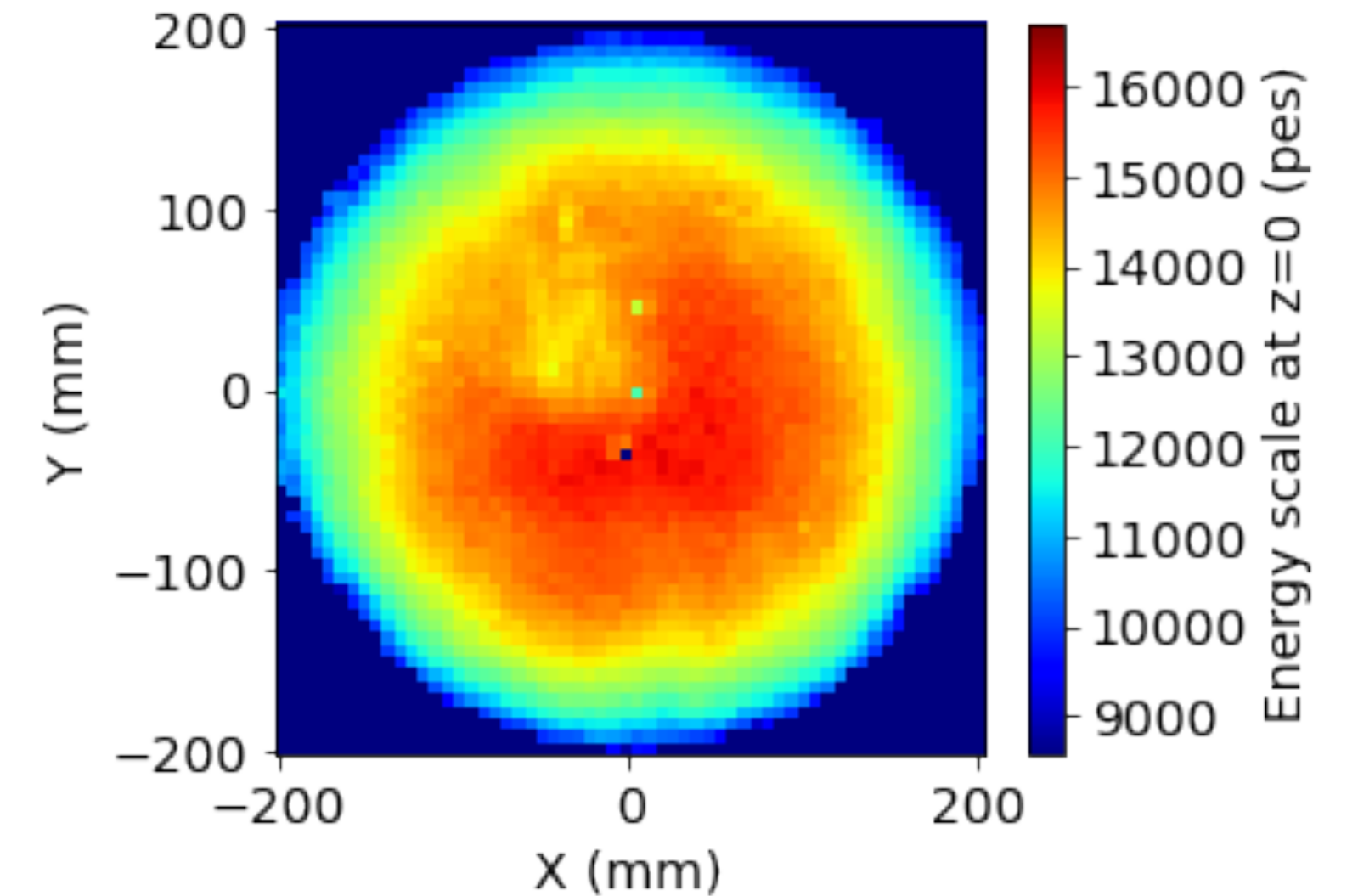


# $^{83}\text{Kr}$ calibration

- $^{83}\text{Rb}$  decays 75% of the time to a metastable state of  $^{83}\text{Kr}$  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**.



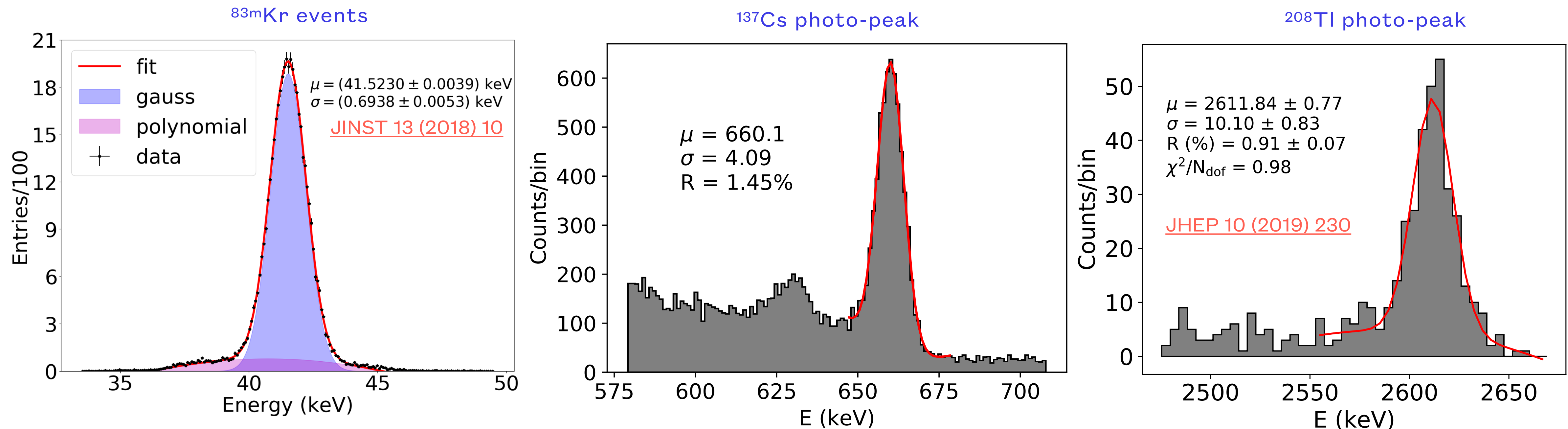
Calibration maps for run 4845



JHEP 10 (2019)

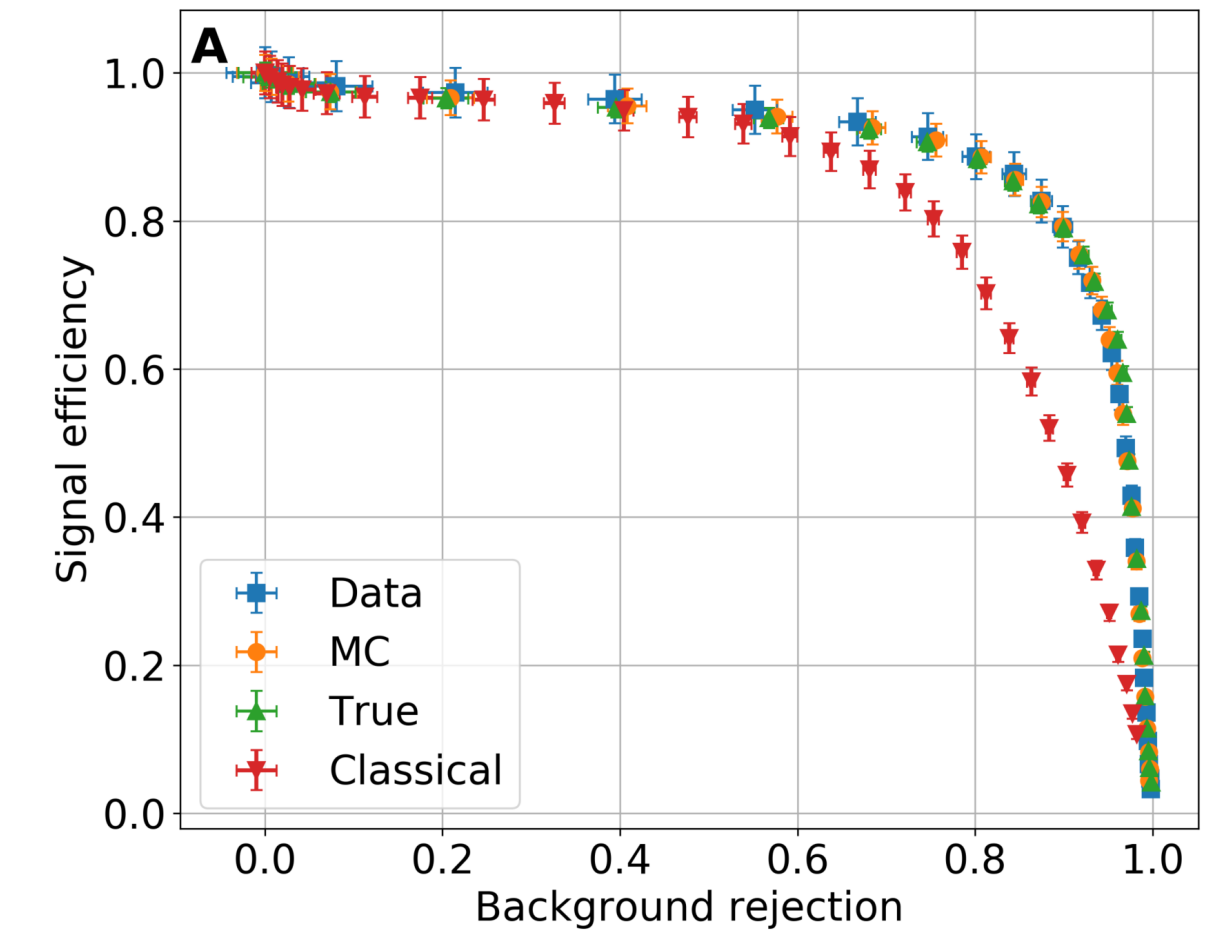
# Energy resolution

- 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*  $^{137}\text{Cs}$  and  $^{232}\text{Th}$  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,  $^{208}\text{Tl}$  photopeak).



# 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  $^{83m}\text{Kr}$  events (point-like).
- The Richardson-Lucy deconvolution uses the PSF to deconvolve the image and remove the smearing.

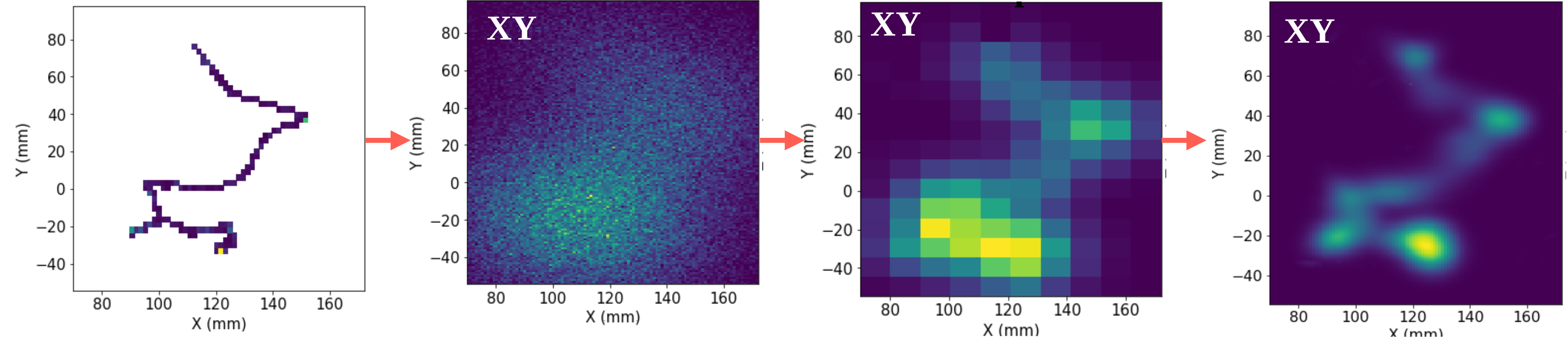


True trajectory

Diffusion effect

SiPM response

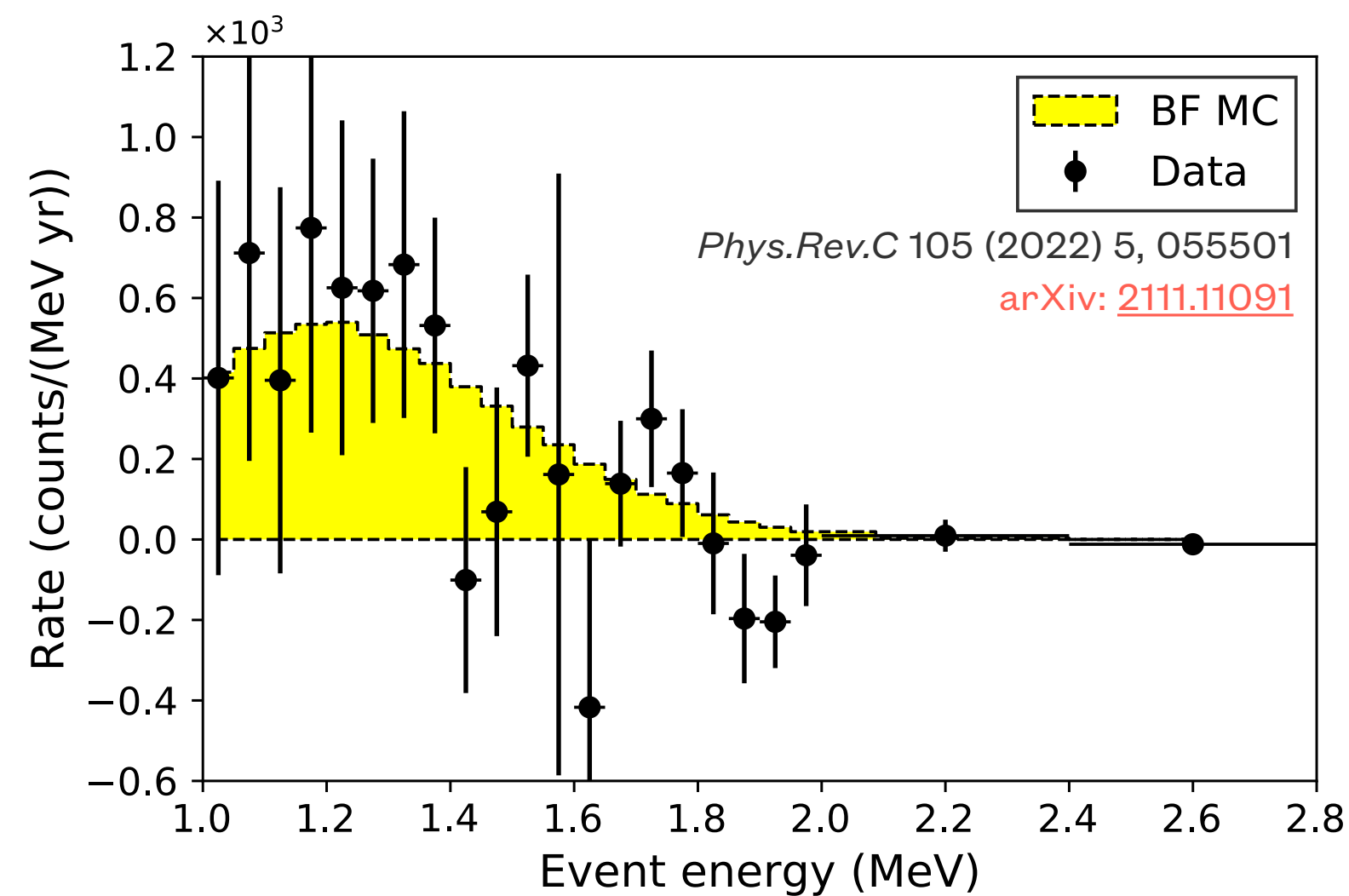
After deconvolution



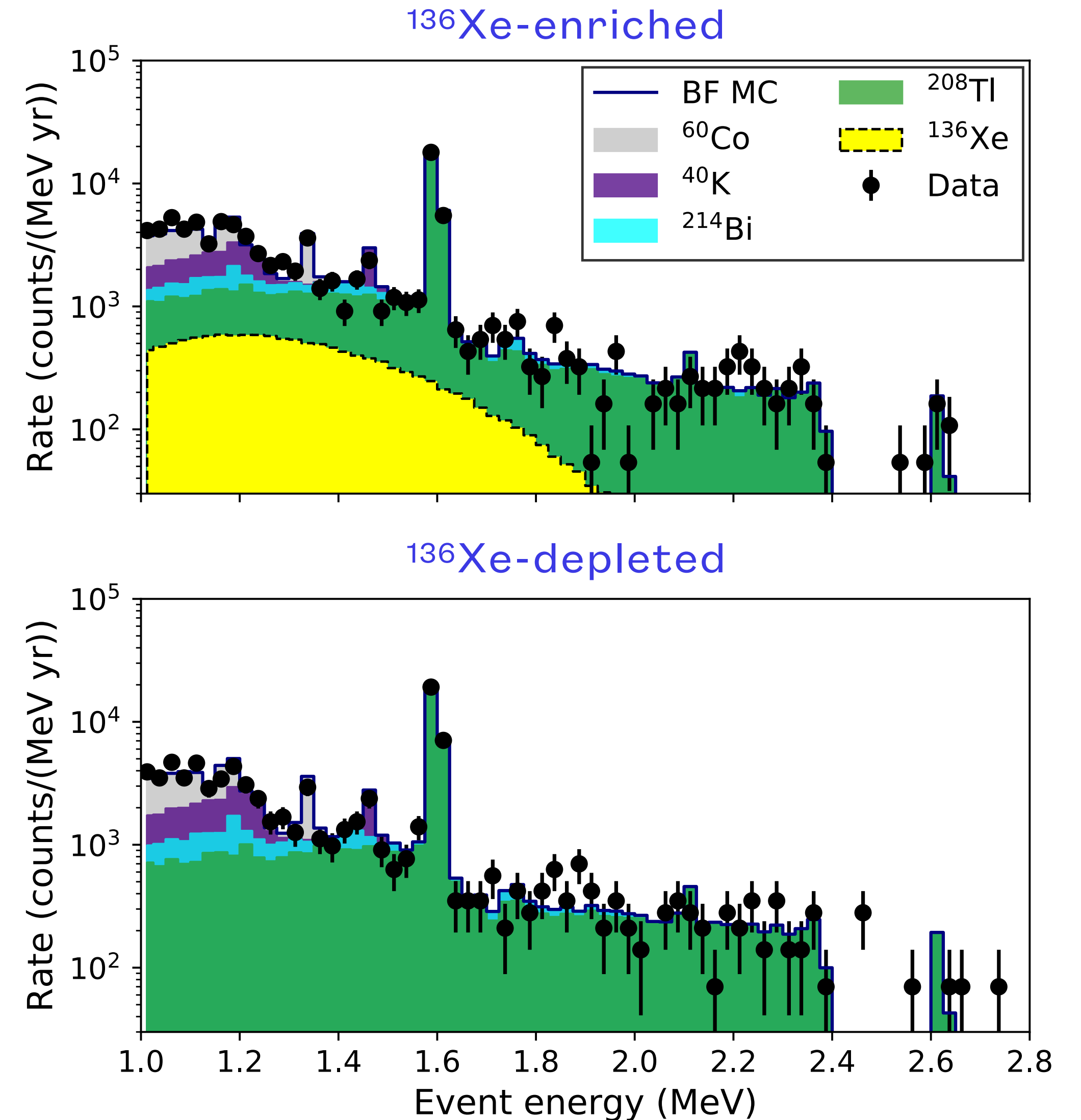
*JHEP 2021, 146 (2021)*

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

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



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



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

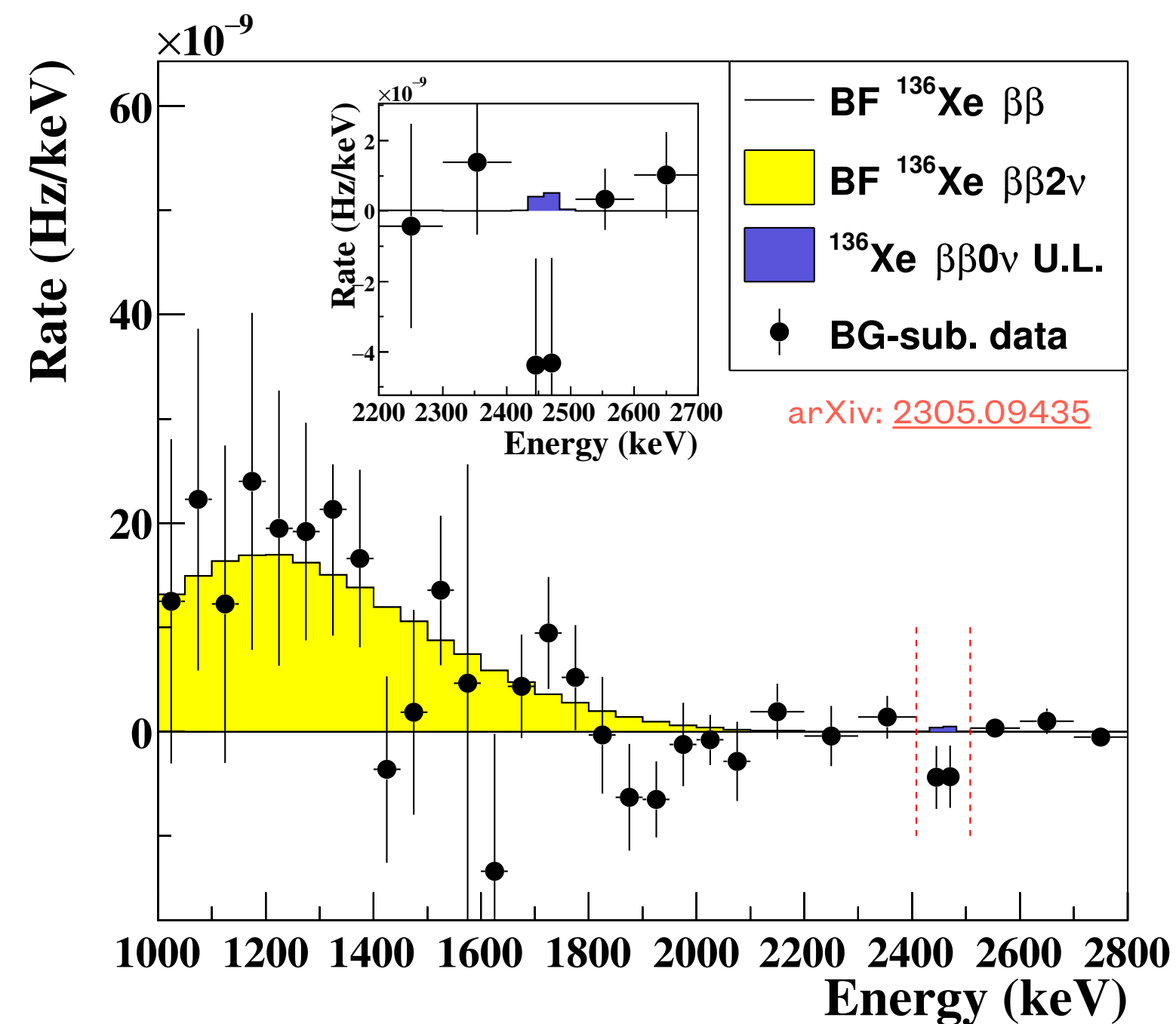
- Although originally beyond its scientific goals, the NEXT-White detector was recently exploited in order to perform a demonstration of the  $0\nu\beta\beta$  search capabilities with the NEXT technology.
- Two methods: background-model-dependent and background subtraction.
- Low mass, so result not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

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

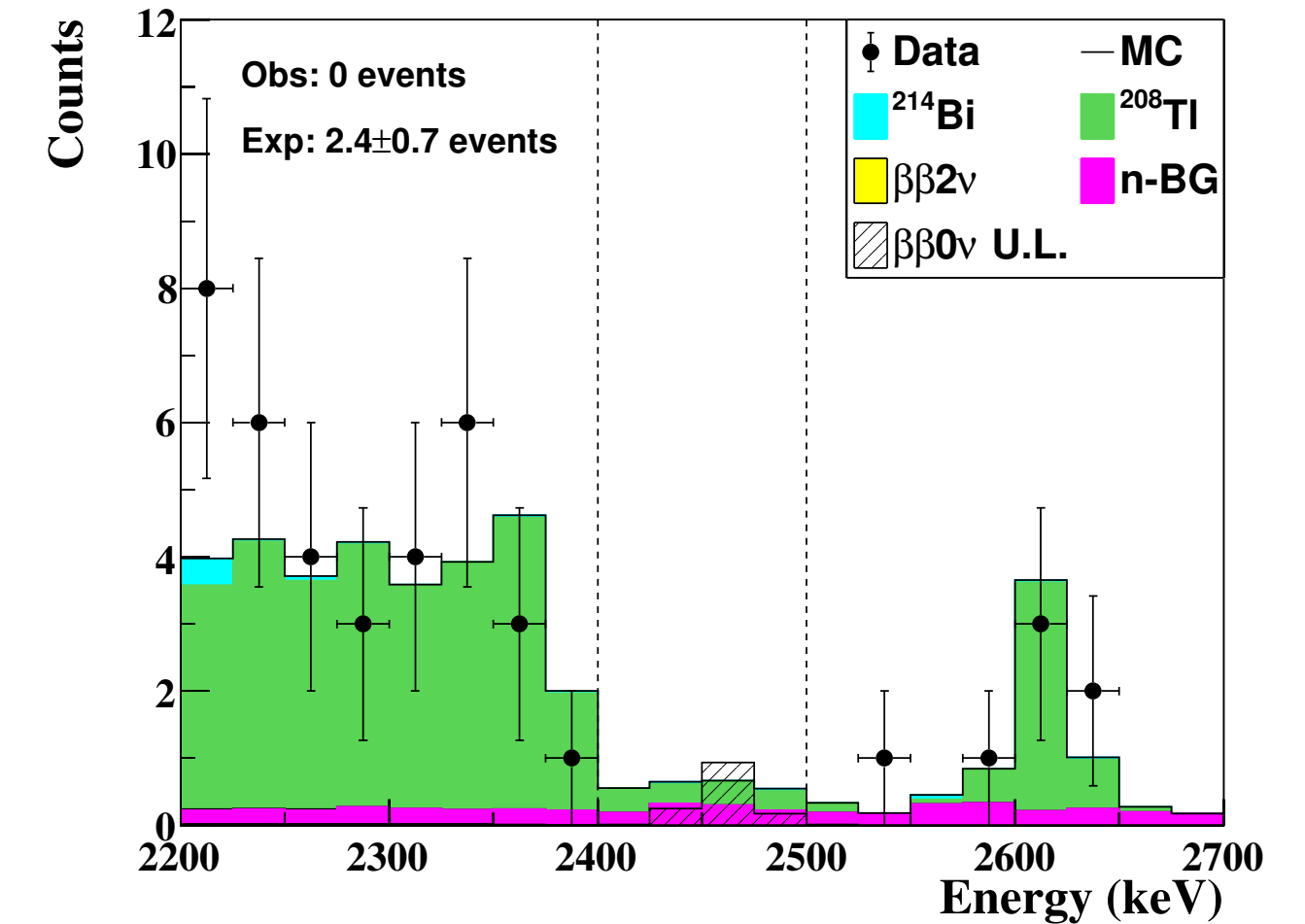
Background subtraction

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

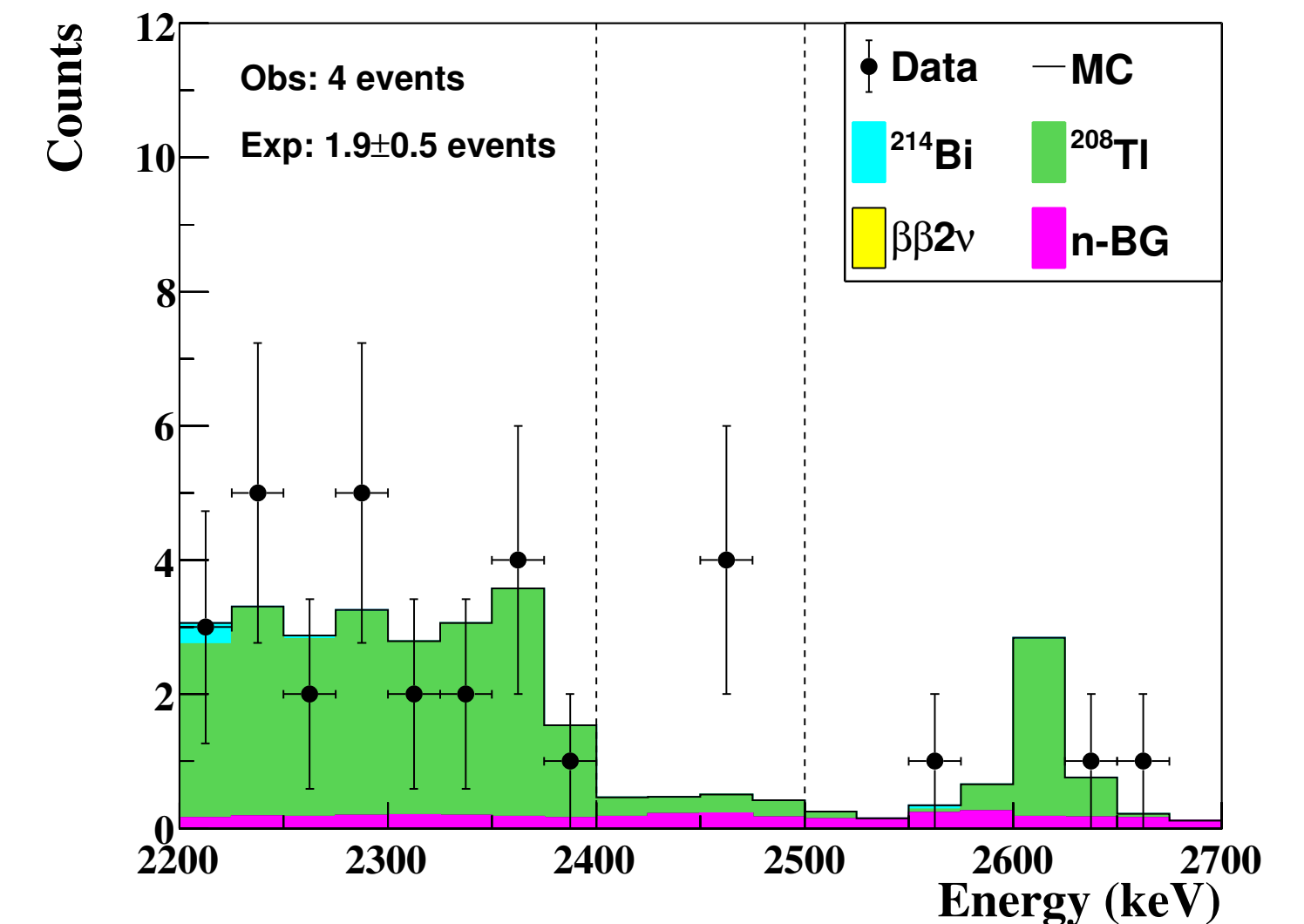
Background-model-dependent



$^{136}\text{Xe}$ -enriched



$^{136}\text{Xe}$ -depleted

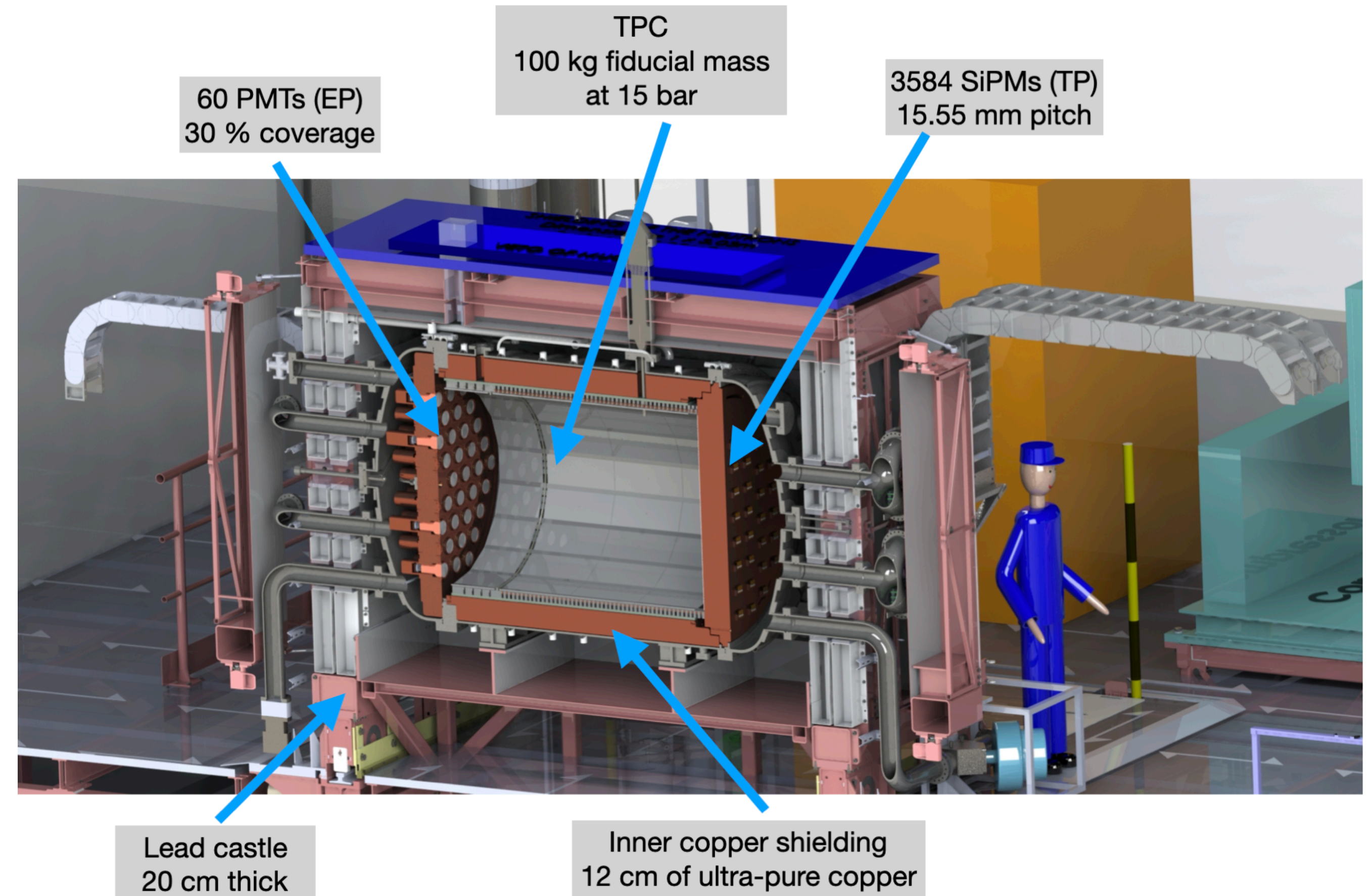


## Plans

- 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  $5 \times 10^{-4}$  counts/(keV·kg·yr) or **1 count/(ROI·yr)**.

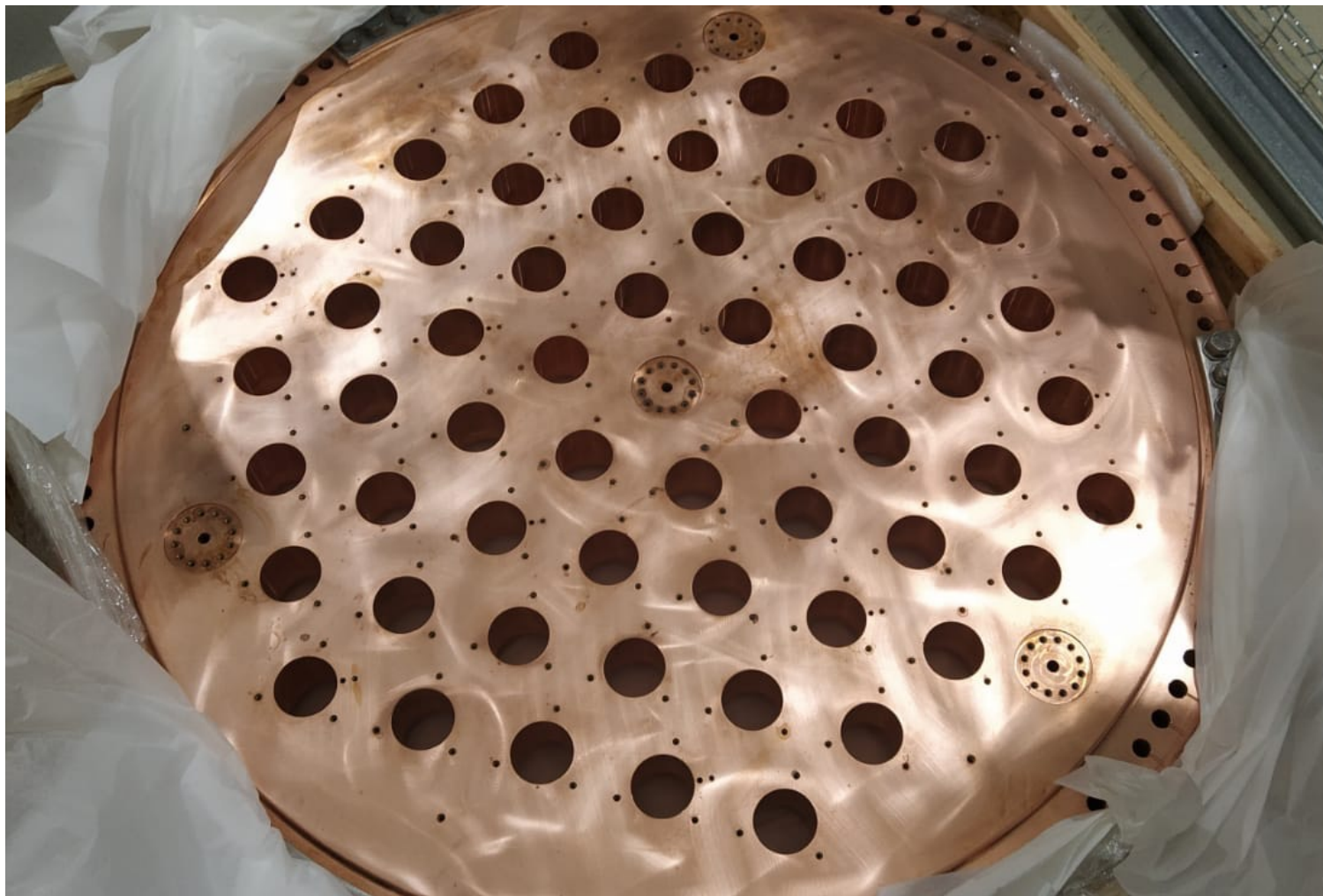
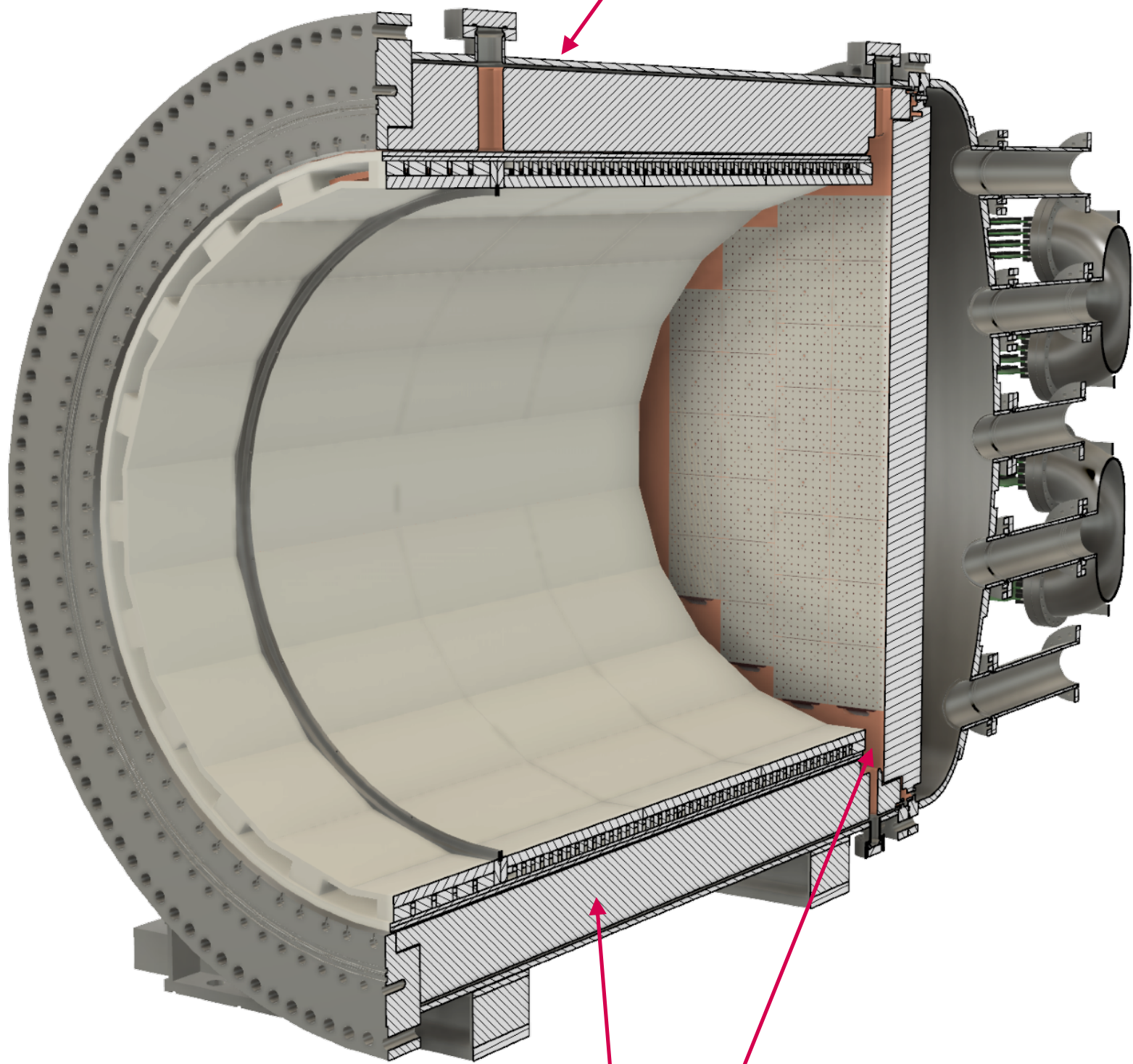




# The NEXT-100 detector

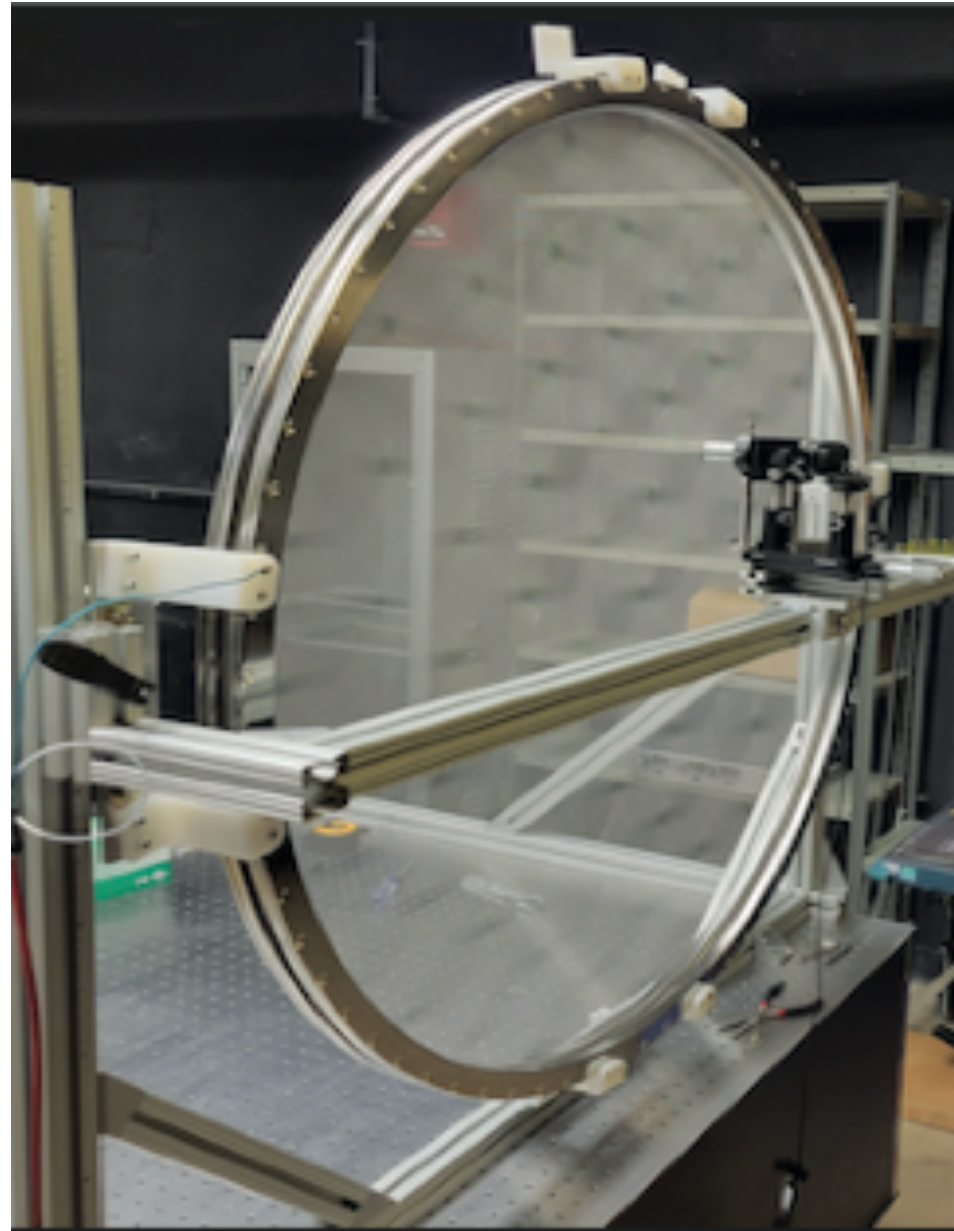


**Pressure Vessel**  
100kg fiducial mass @  
~15bar

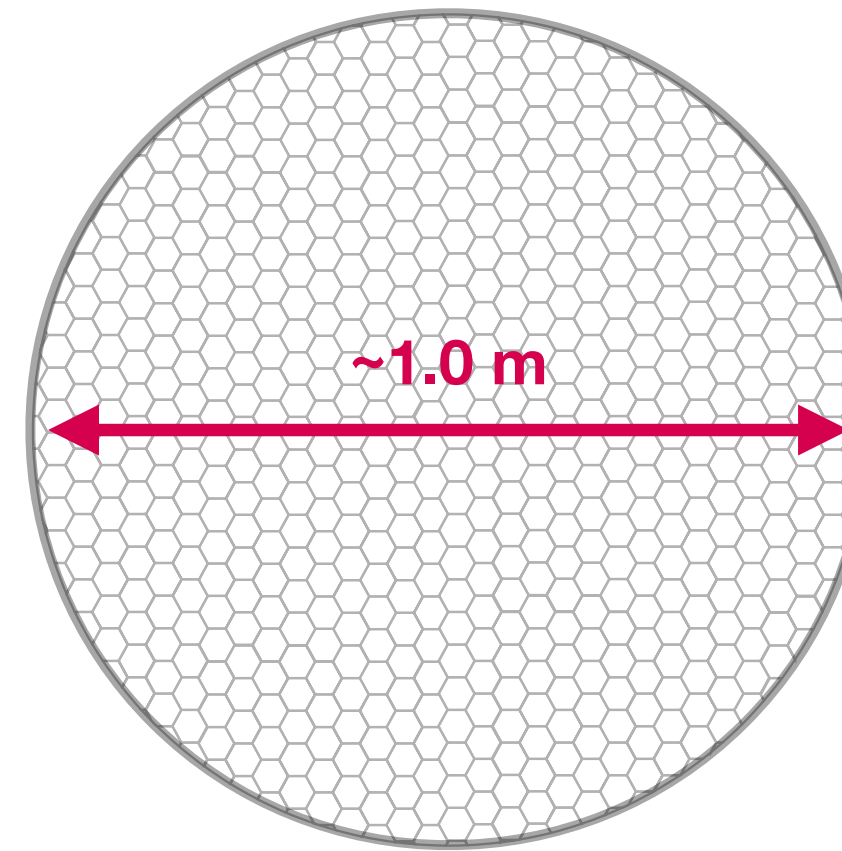


**Copper Shielding**  
Thicker (12cm) ultra-pure copper shielding  
Big machinery for production

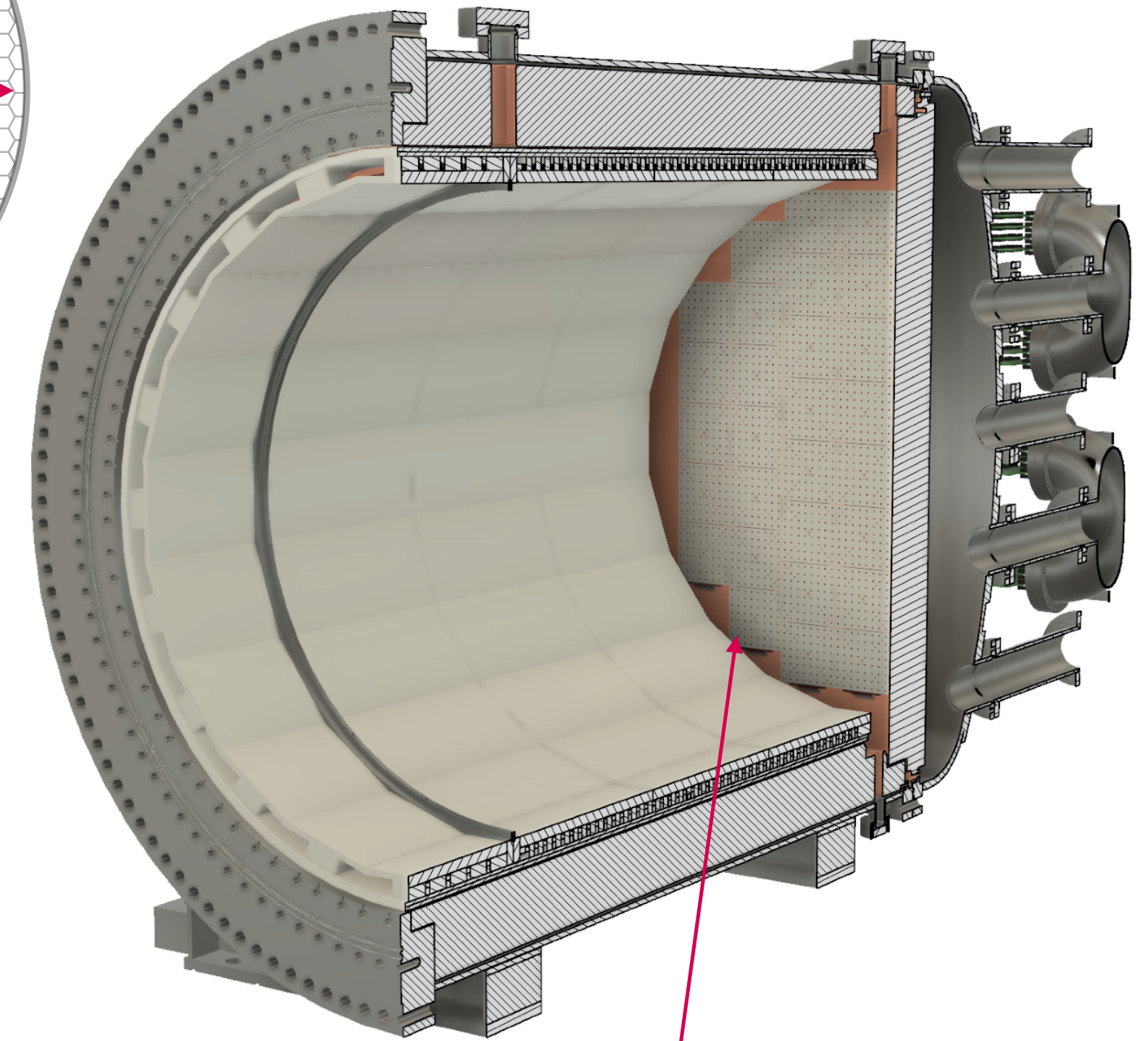
# The NEXT-100 detector



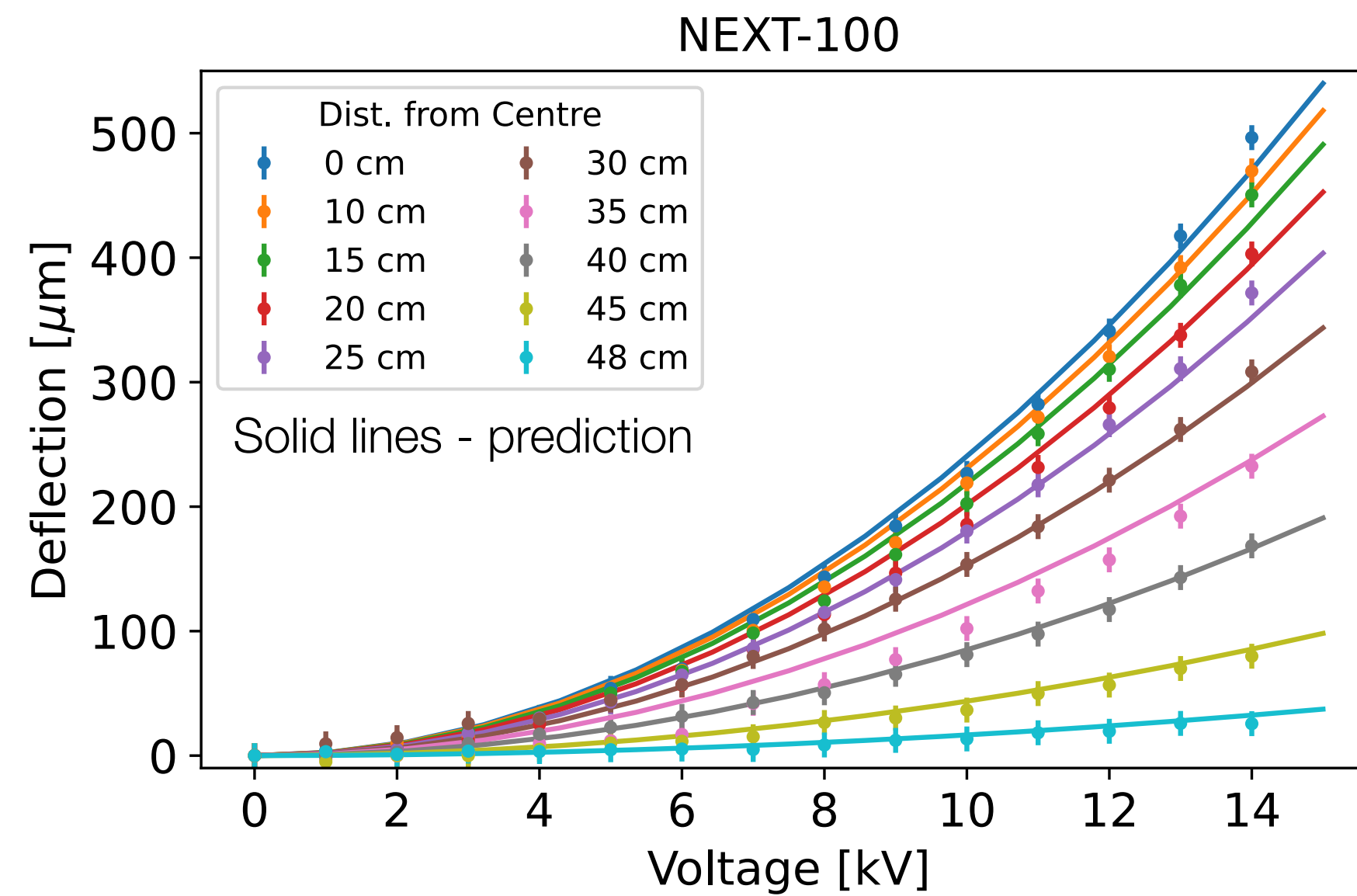
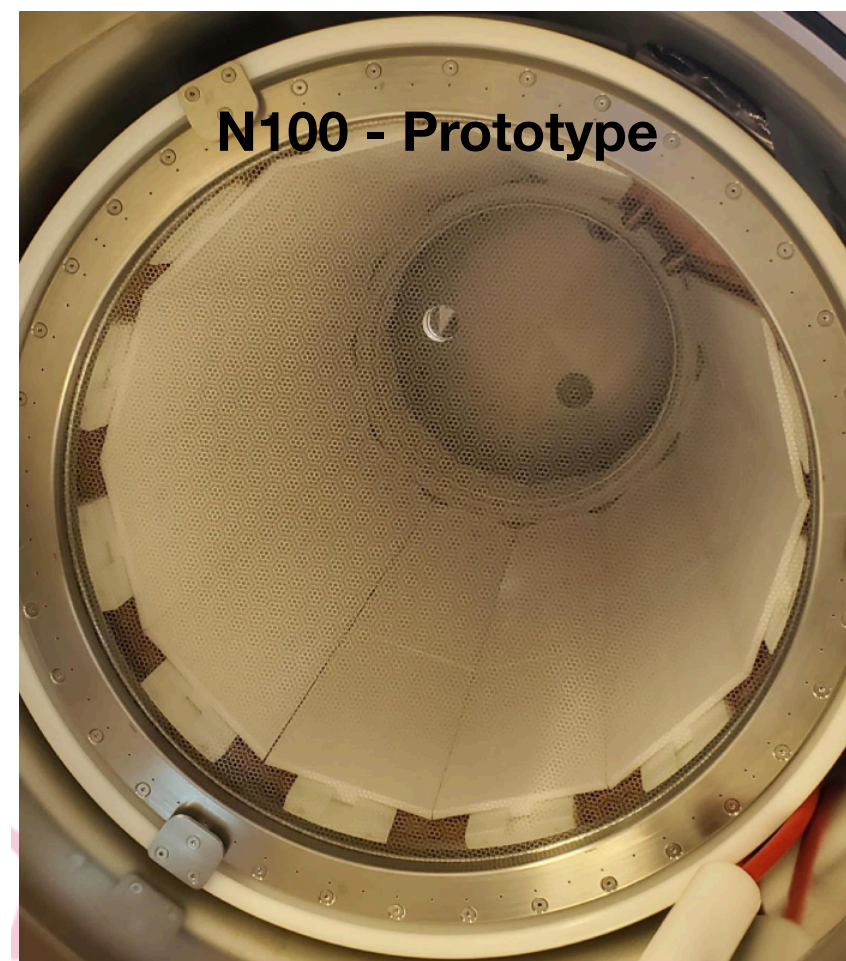
EL and cathode constructed from tensioned hexagonal meshes (~100  $\mu\text{m}$  thickness)



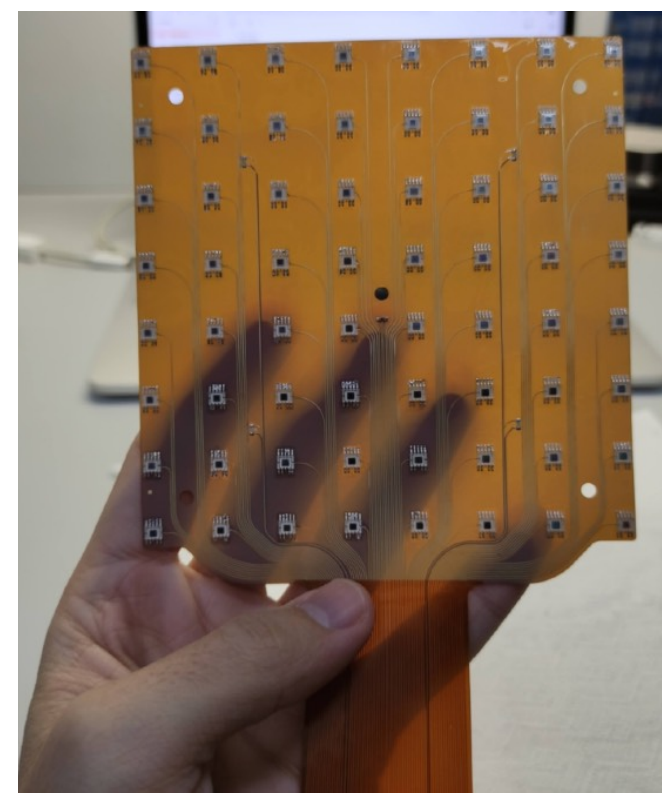
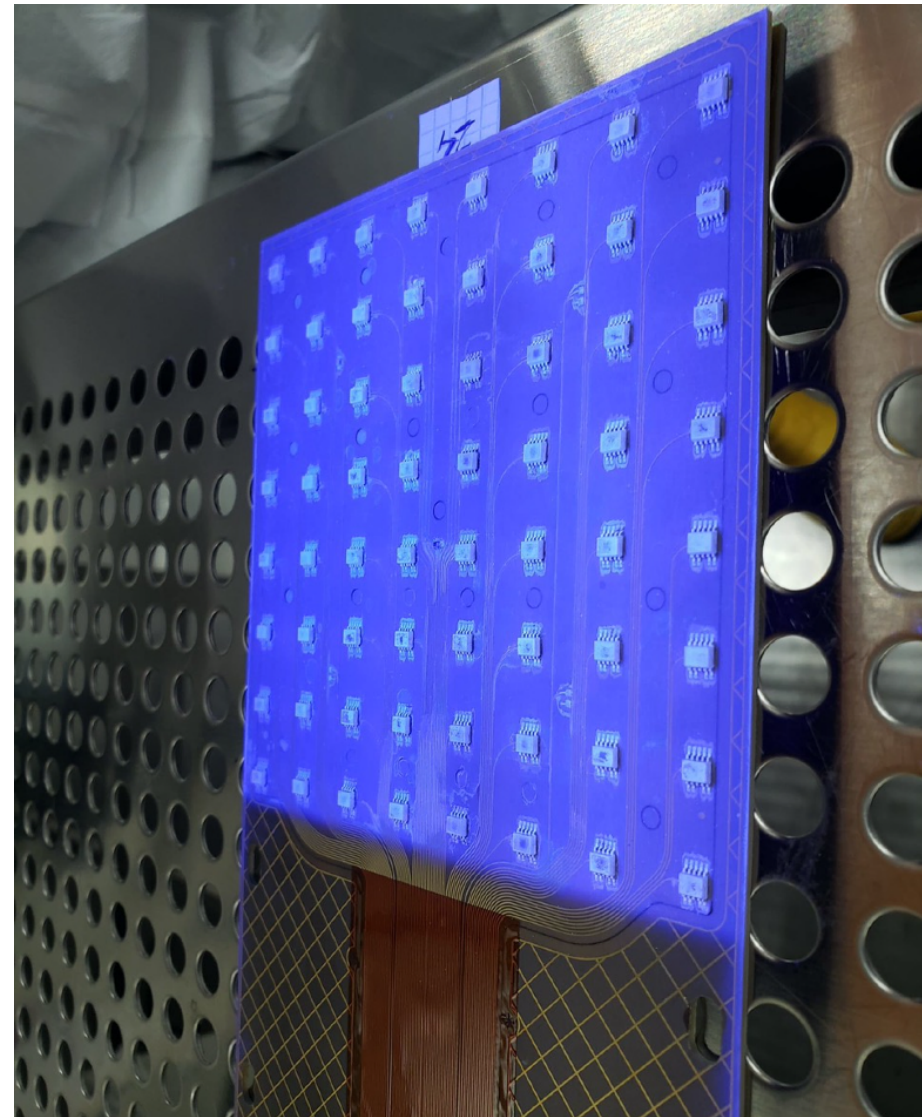
Electrostatic deflection of the EL measured (important for energy resolution)



Anode-EL region using meshes



# The NEXT-100 detector



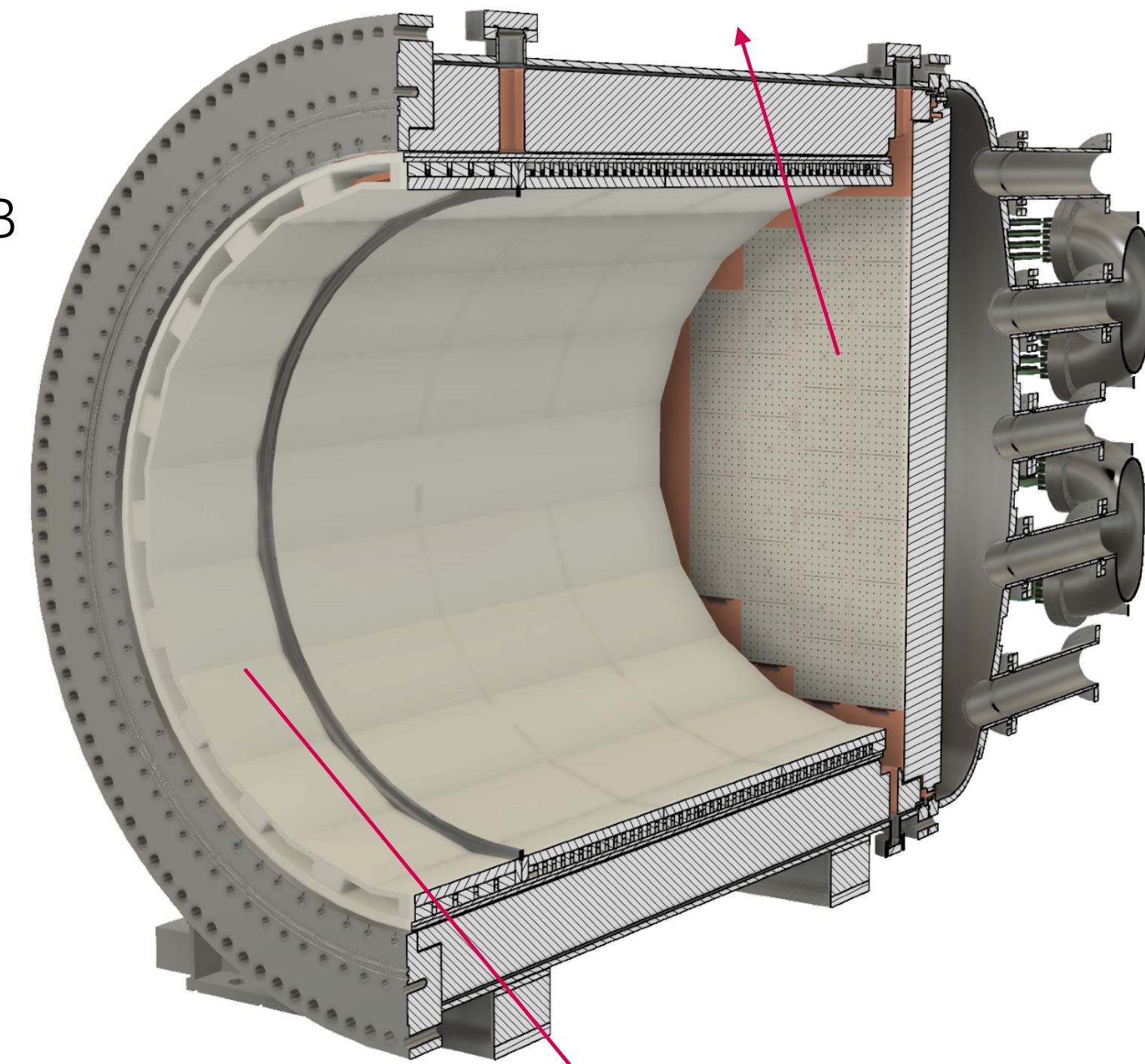
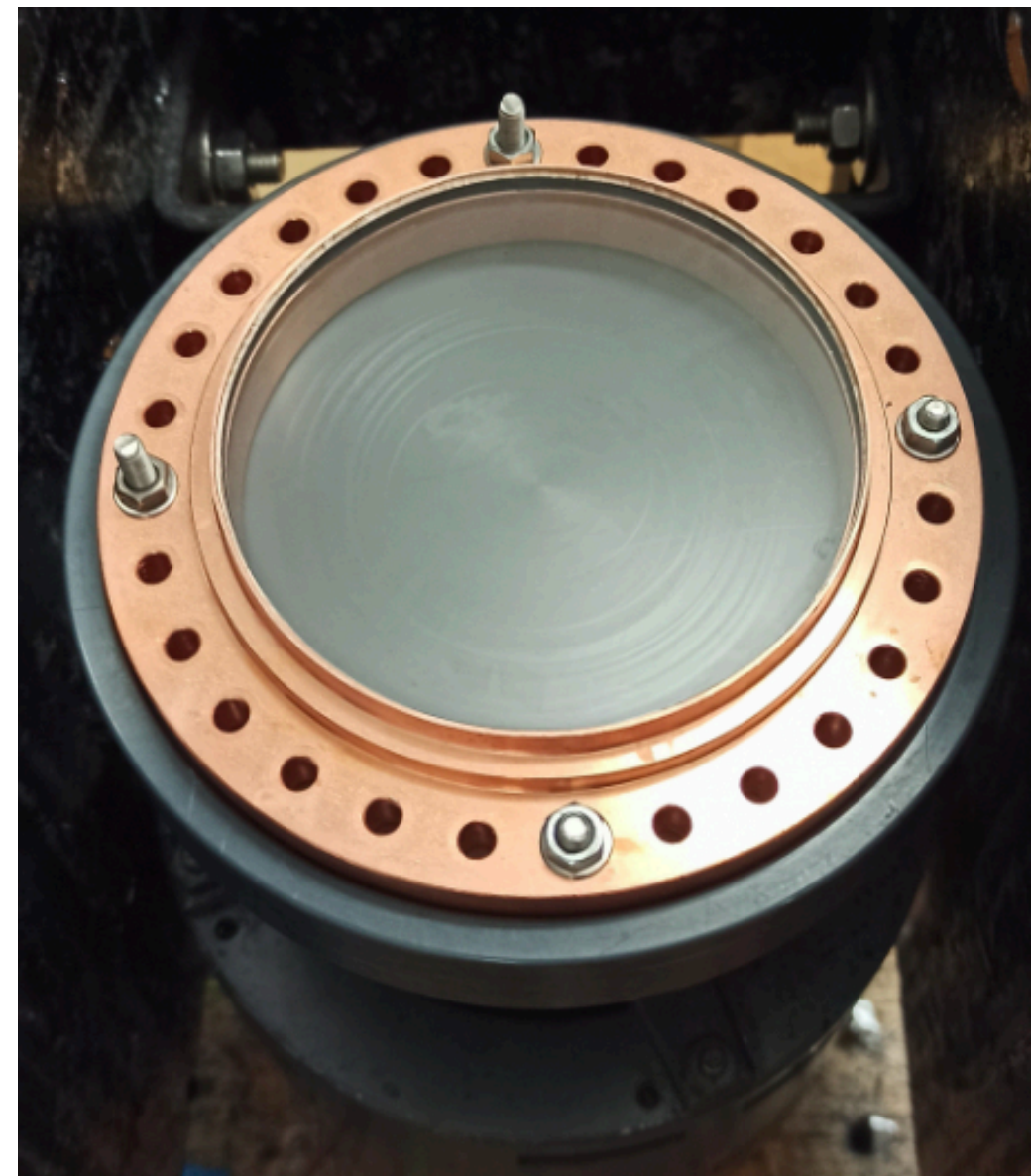
Hamamatsu SiPMs:  
easier to mount,  
more robust,  
larger area.  
Better for  
dynamic range

Coated with TPB  
for better light  
detection

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



Windows are  
coated with PEDOT



## Tracking Plane

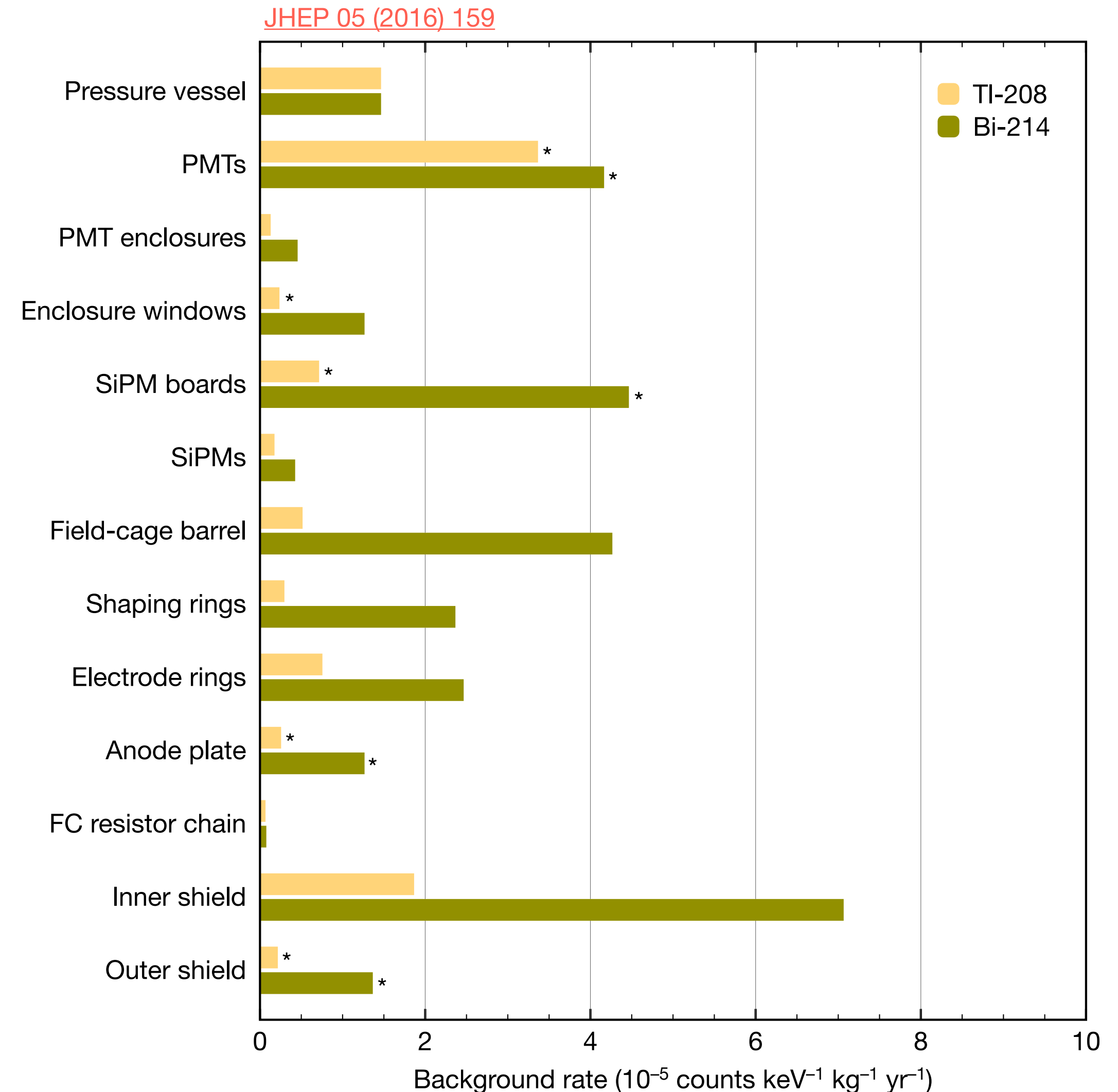
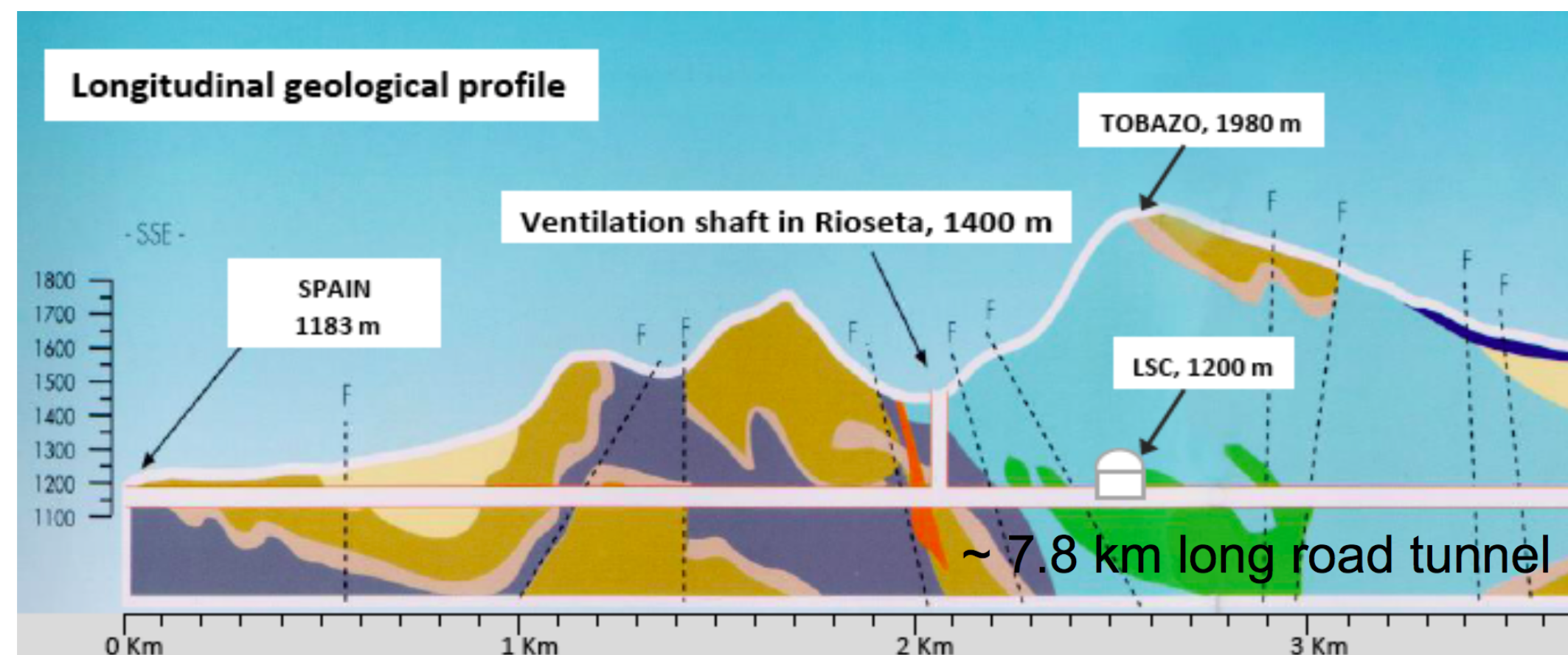
3584 Hamamatsu SiPMs  
1.3x1.3 mm<sup>2</sup> - 15.55 mm pitch  
(60% more photons)

## Energy Plane

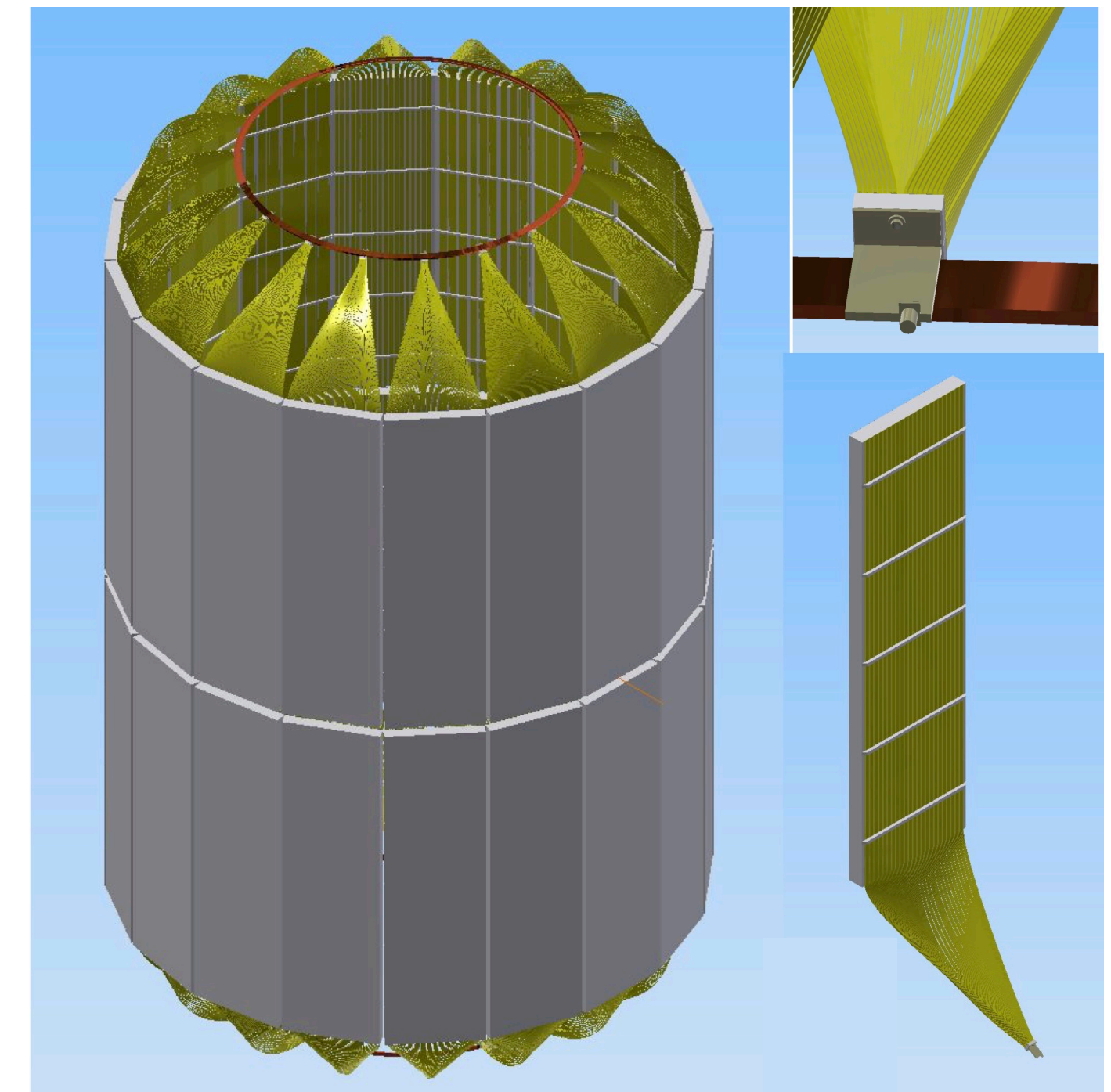
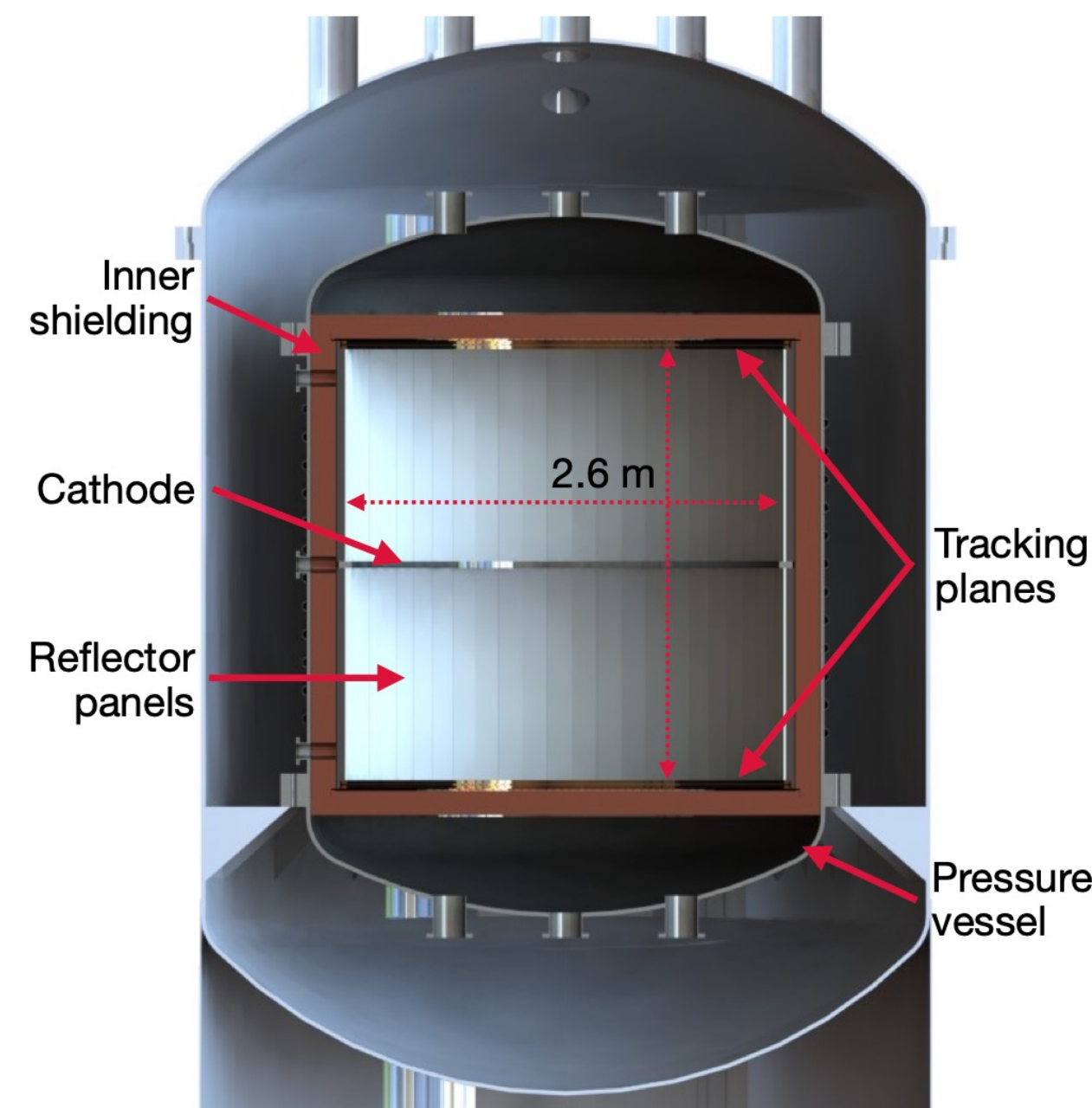
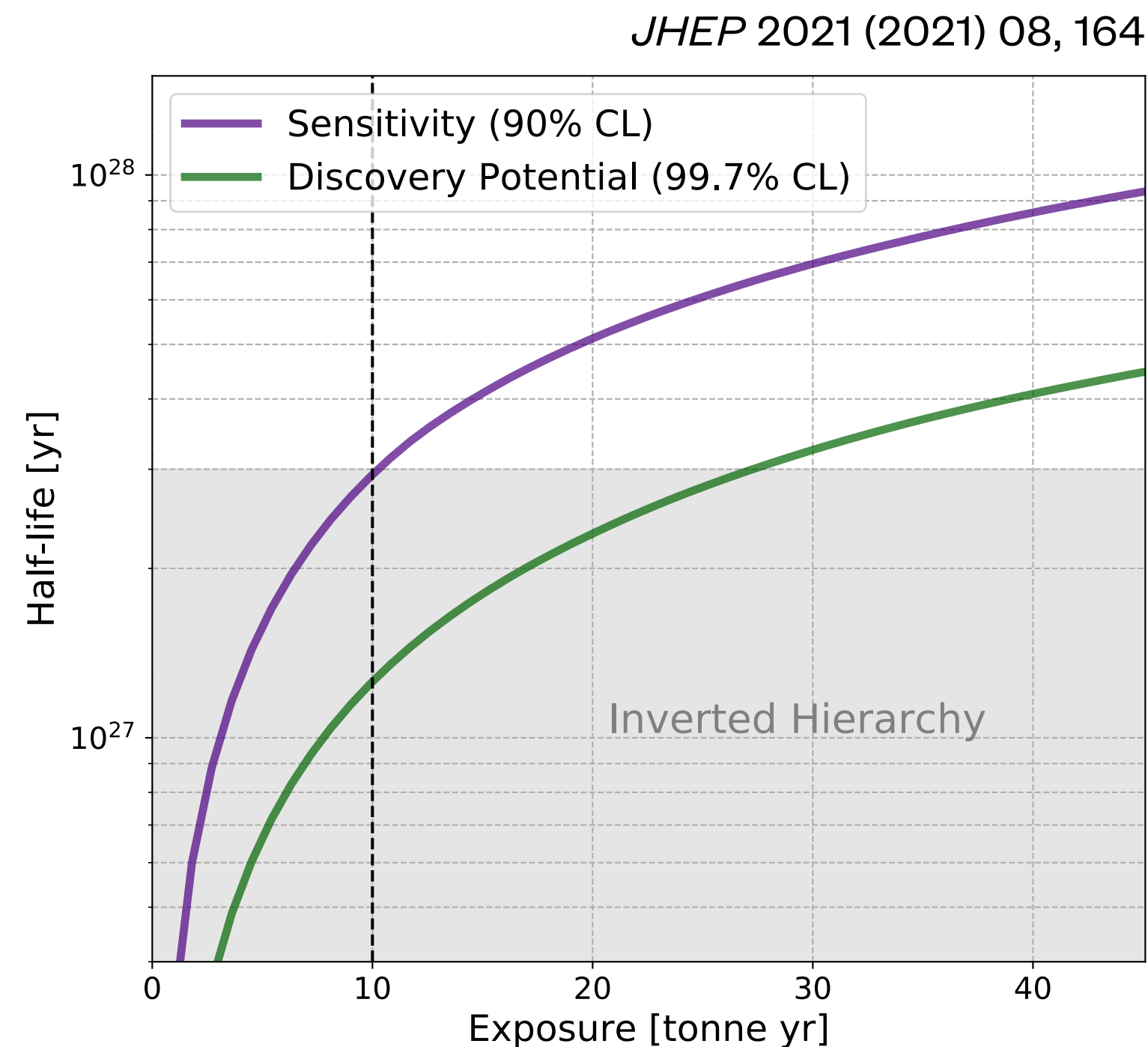
60 Hamamatsu PMTs  
R11410-10 - Same NEW  
(30% coverage)

# NEXT-100 background budget

- The main background in NEXT is represented by natural decay series (U, Th) producing  $^{214}\text{Bi}$  and  $^{208}\text{Tl}$ .
- The Canfranc Underground Laboratory provides a radiopurity facility to assess 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.

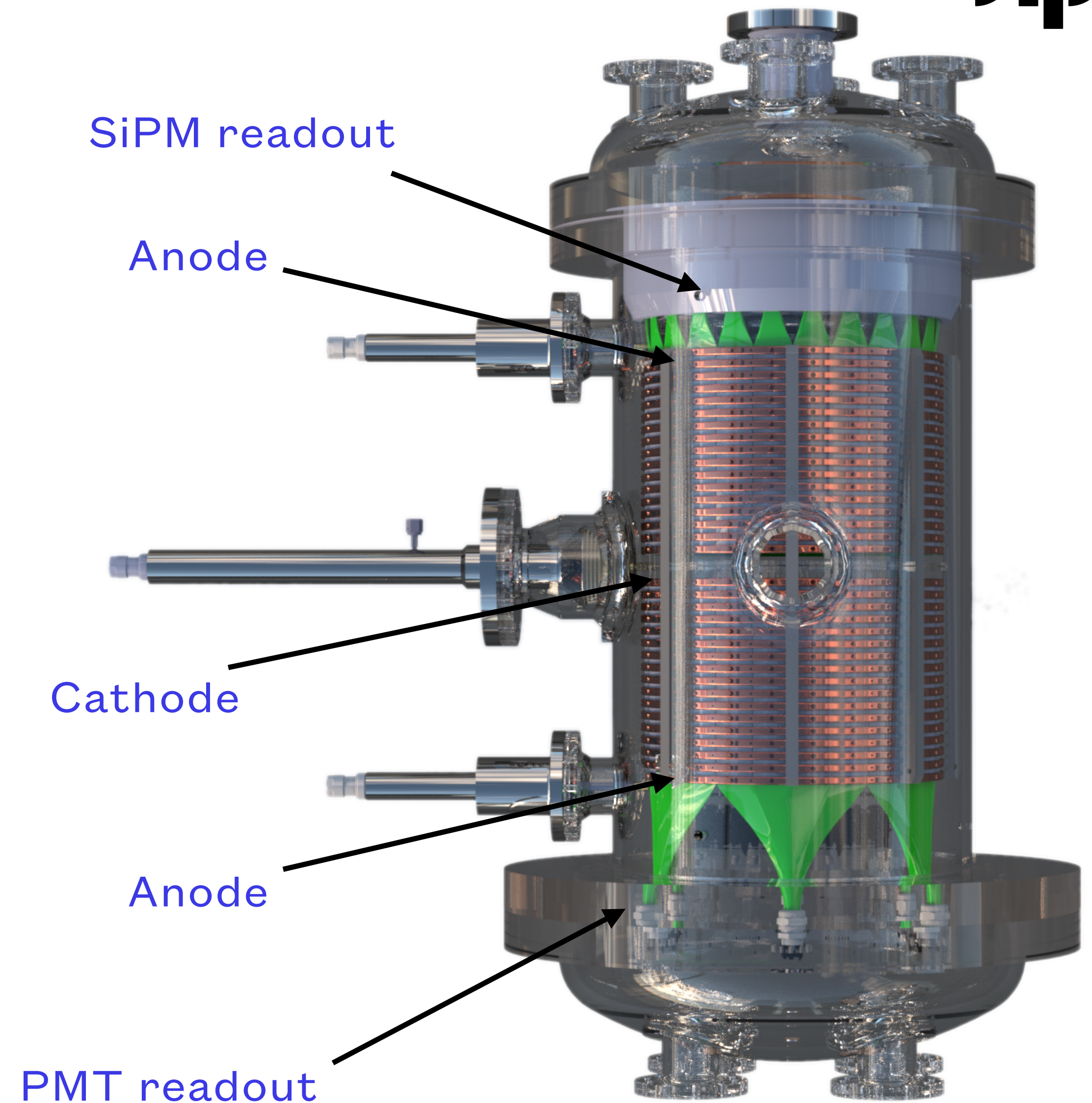


- If we want to explore the inverted hierarchy region with the NEXT technology, we need a **bigger detector**, NEXT-HD:
  - Order of magnitude more Xe than NEXT-100, **~1 tonne** at 15 bar.
  - **Symmetric design** with a central cathode and two readout planes with SiPMs (no *energy plane* with PMTs).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



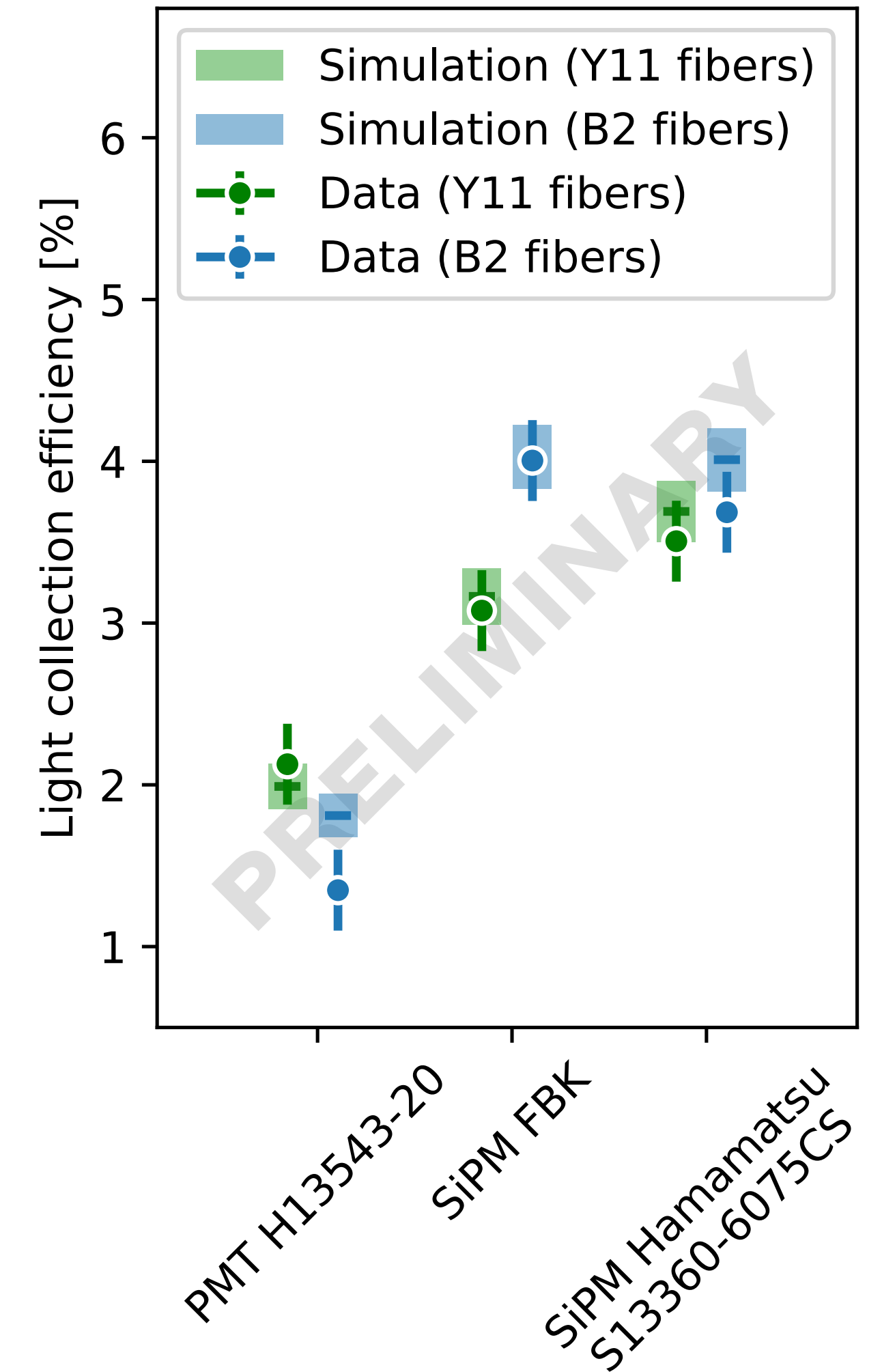
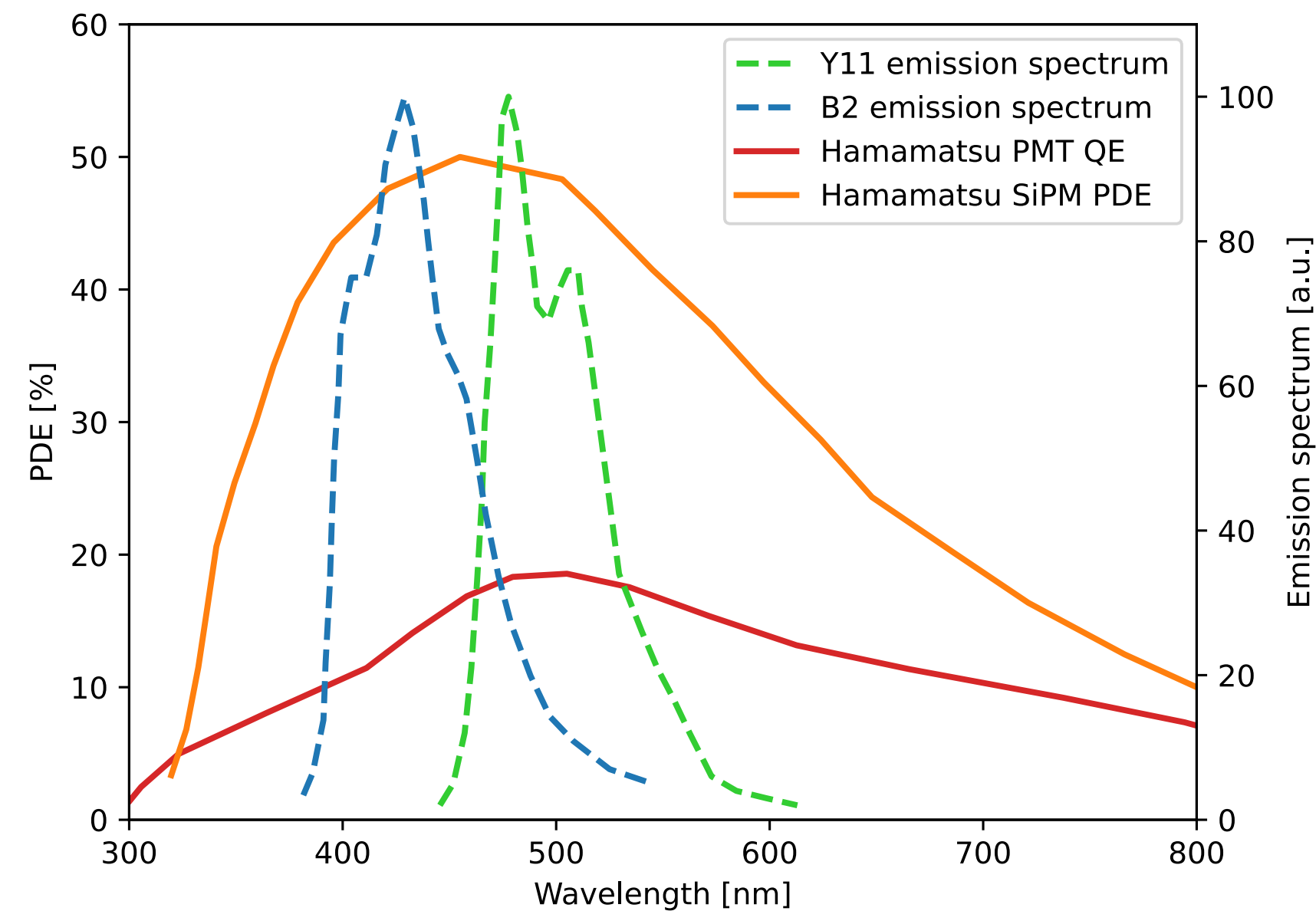
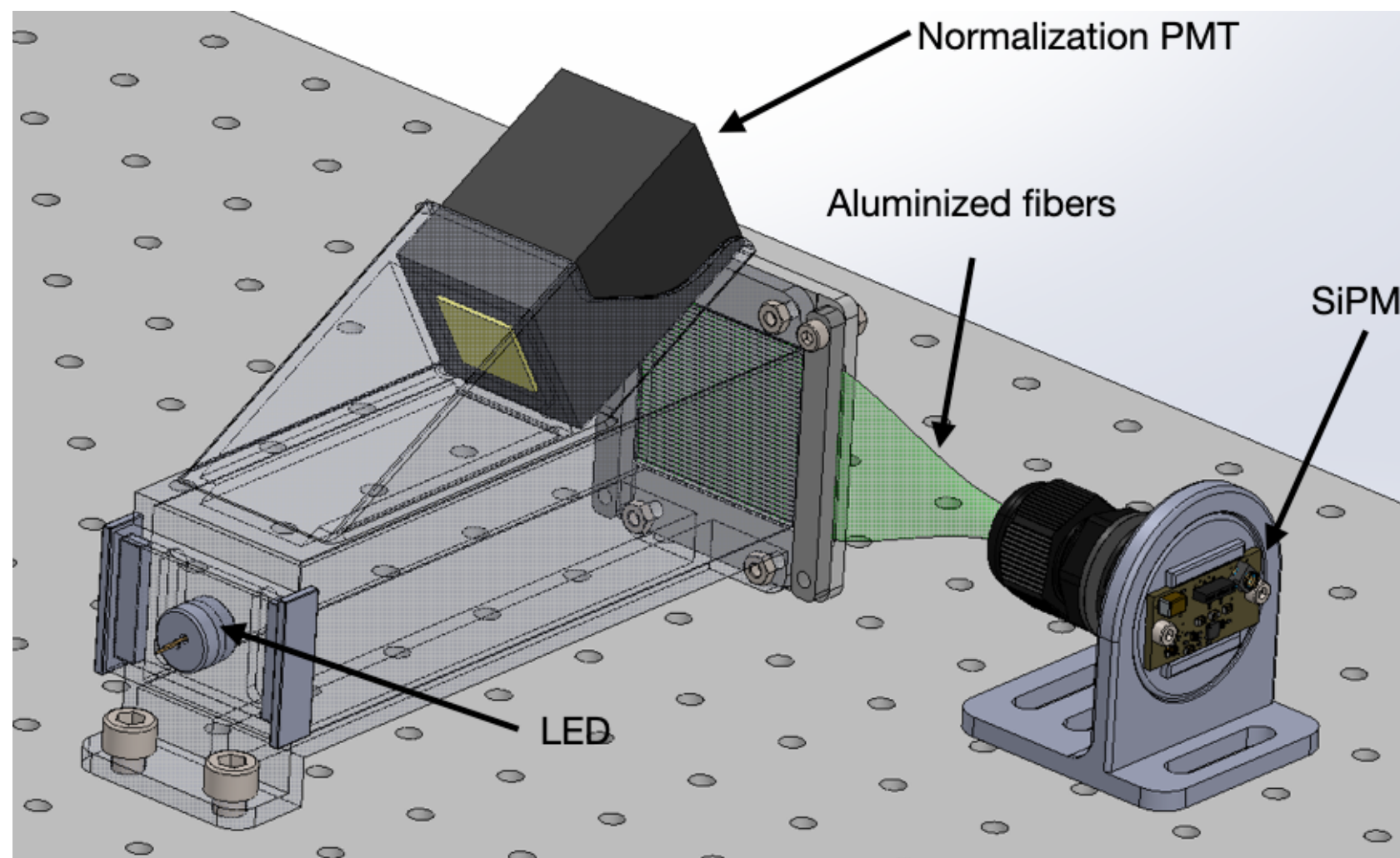
# HD-DEMO

- 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 DIPAC

- 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.

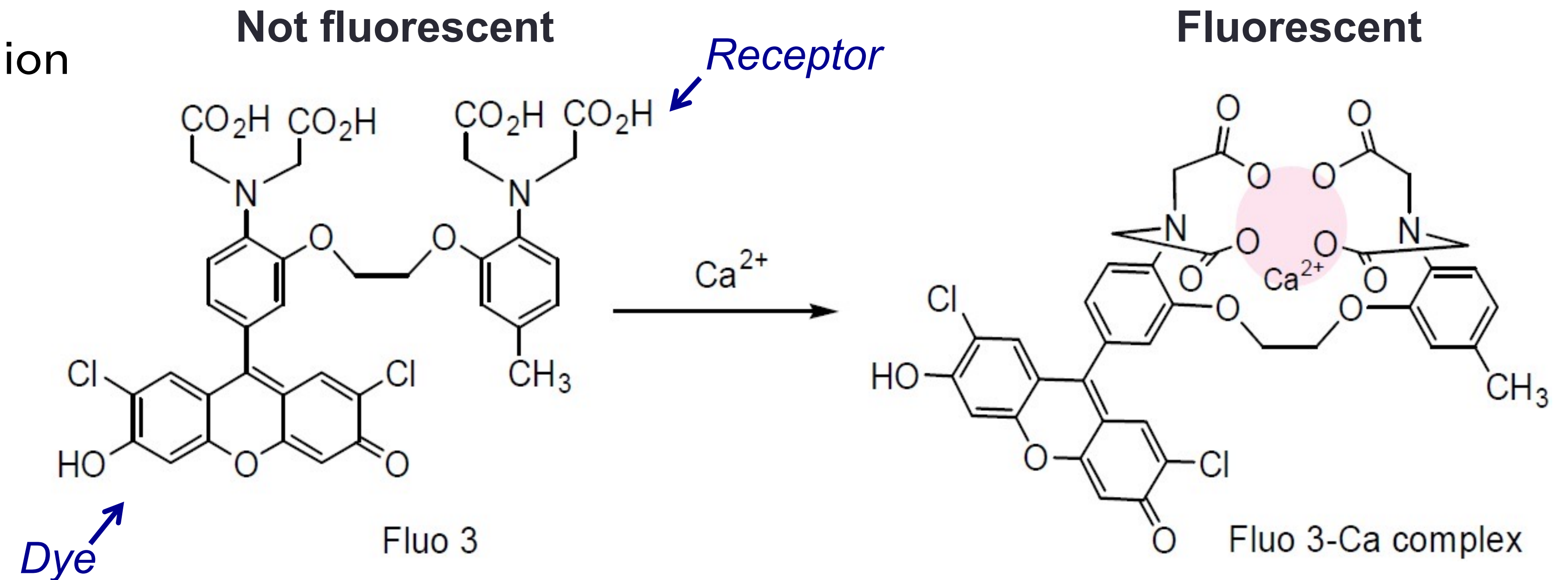


# A new hope

- Going further than the inverted hierarchy seems impossible: several tons or several decades...
- Cowan and Reines were detecting the slow neutron in delayed coincidence with the positron.
- Neutrinoless double beta decay in the final state has two electrons... and a  $^{136}\text{Ba}^{++}$  ion.

- What if we could detect the presence of this single barium ion in a ton of xenon? **Barium tagging!**

- **Single molecule fluorescent imaging:** technique borrowed from chemistry (and 2014 chemistry Nobel Prize)

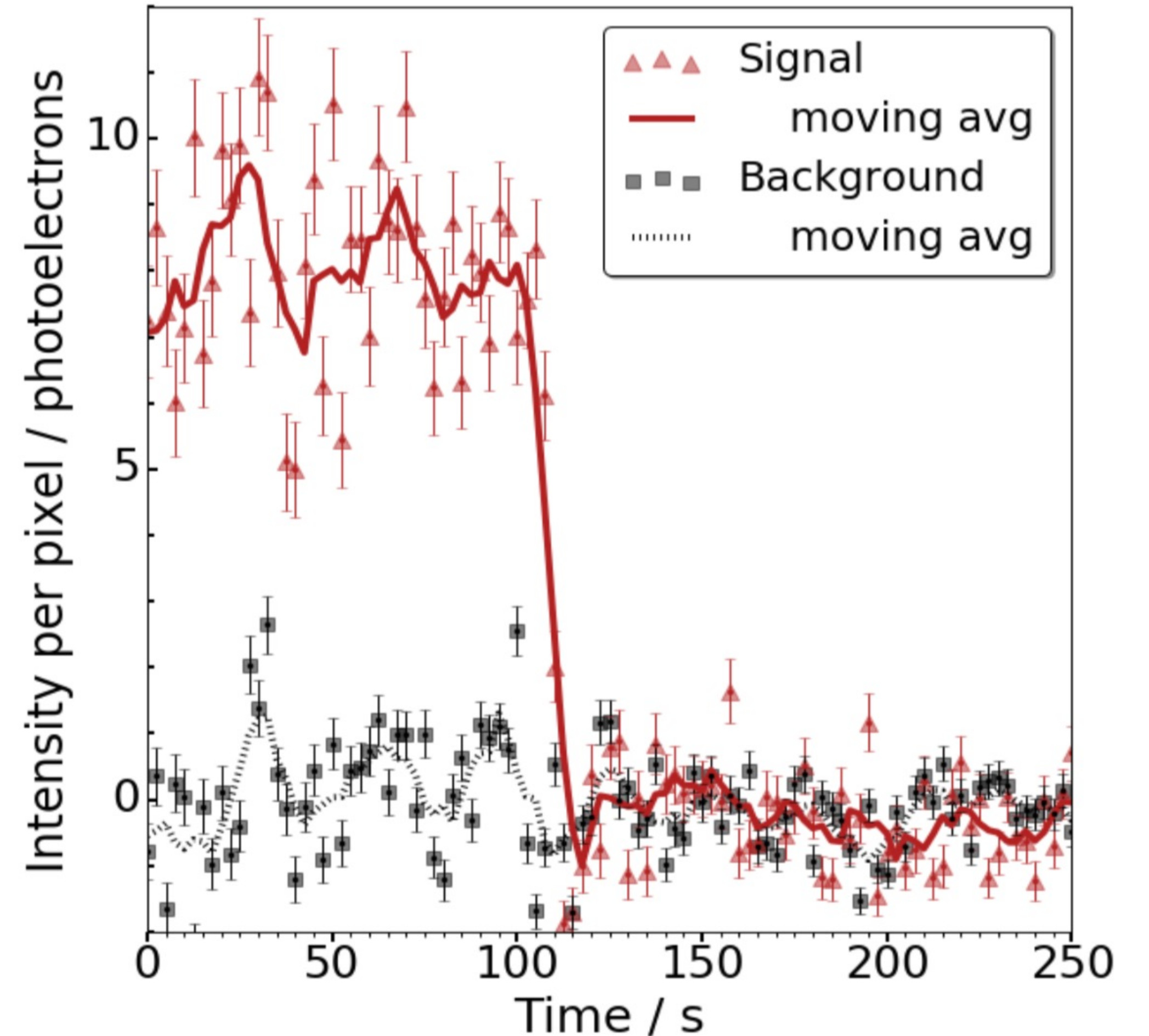
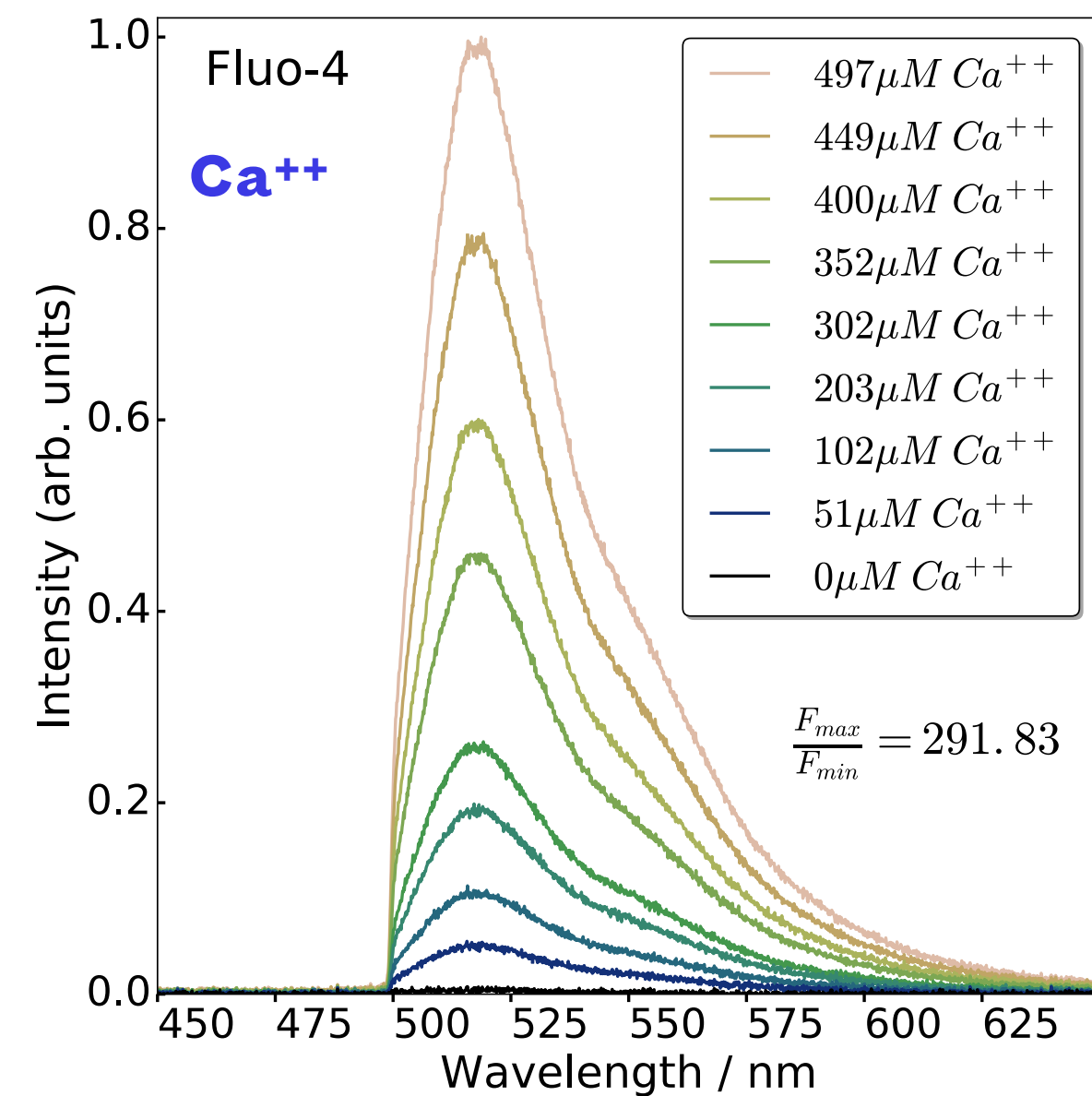
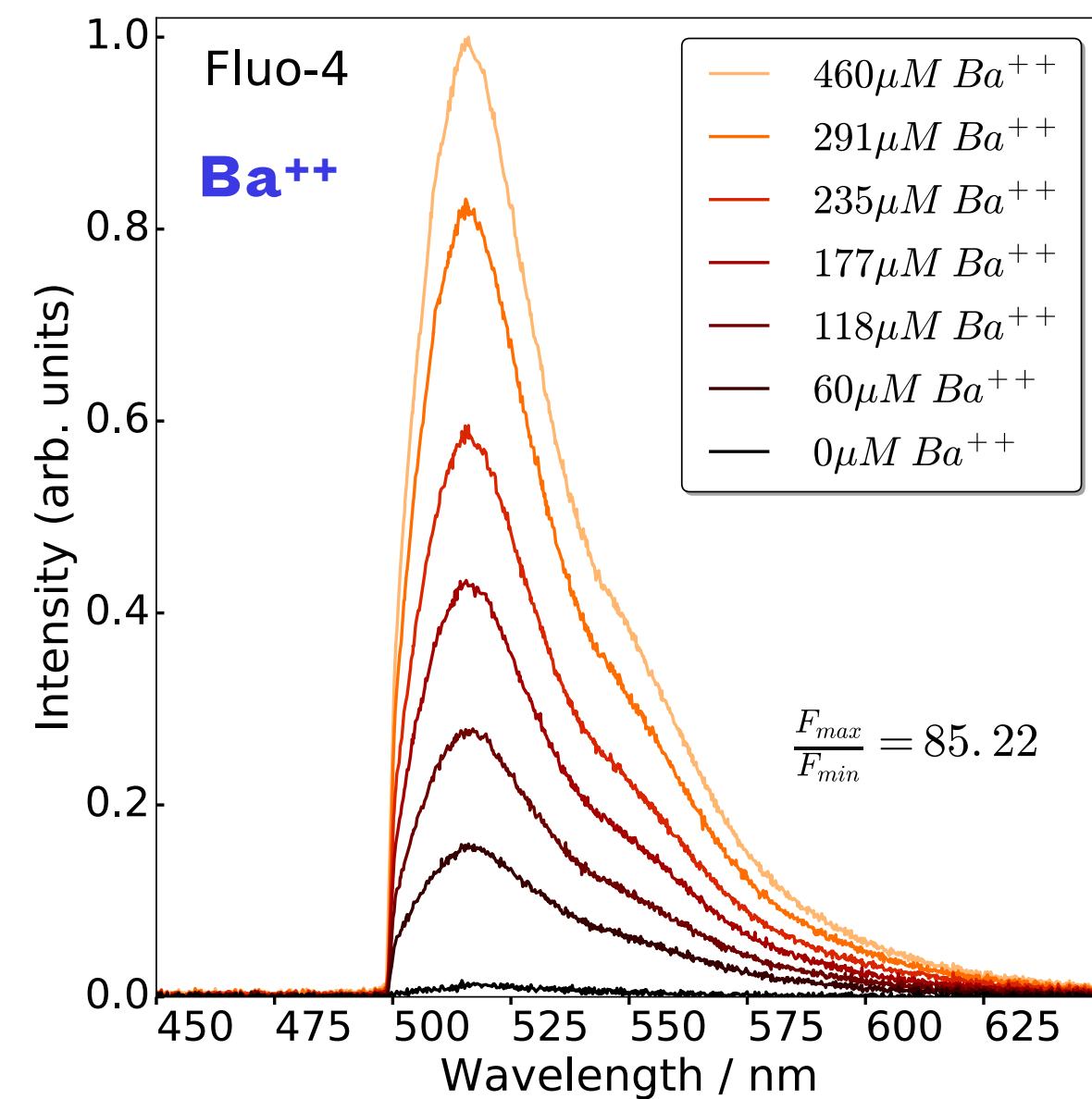


Phys.Rev.Lett. 120 (2018) no.13, 132504



# From Ca to Ba

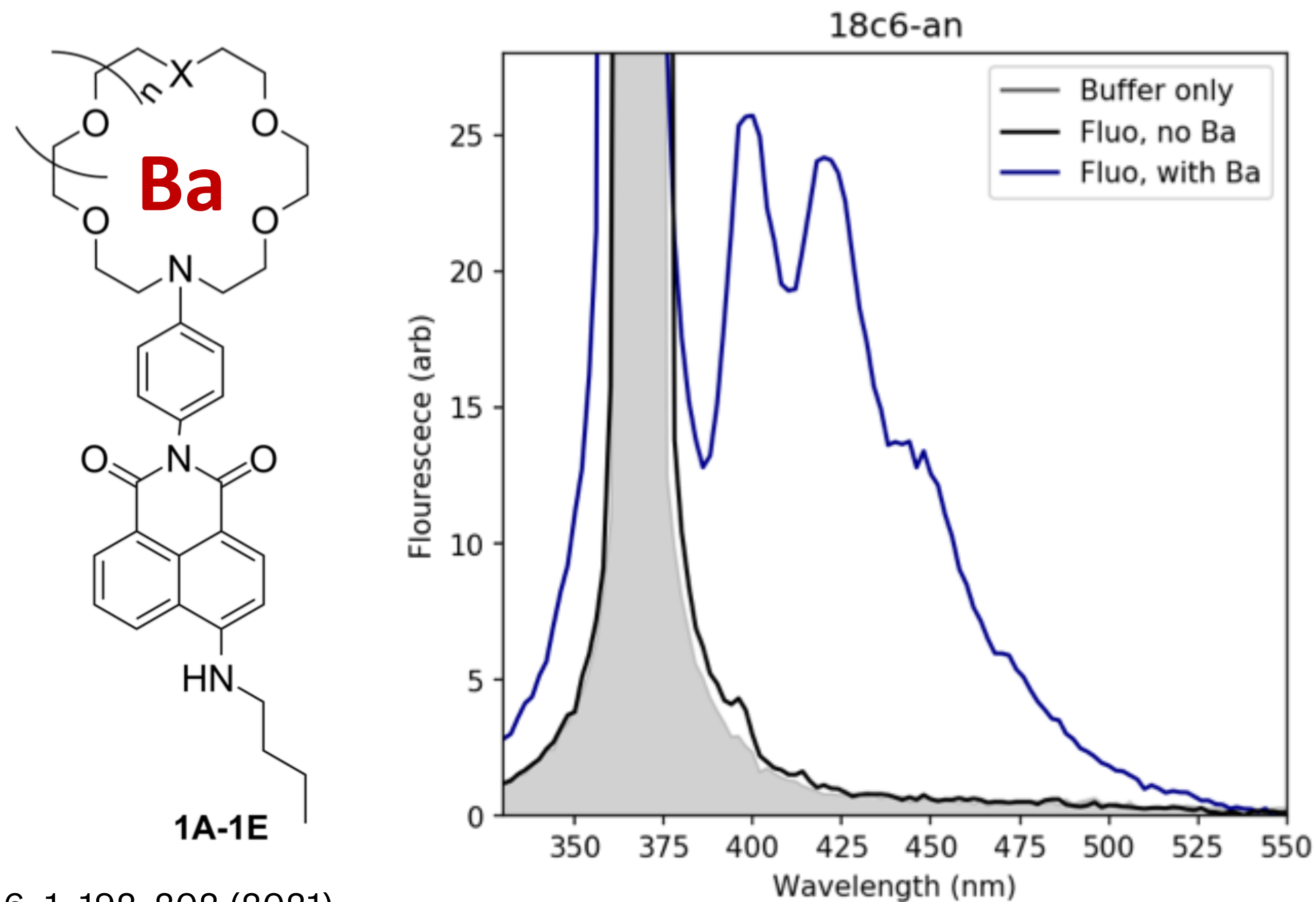
- The first step was to verify if commercially-available compounds were **able to emit light upon barium chelation**.
- Then, the sensitivity was advanced to single-ion level.
- However, these components work in **aqueous solutions**: R&D is required for high-pressure gaseous xenon.



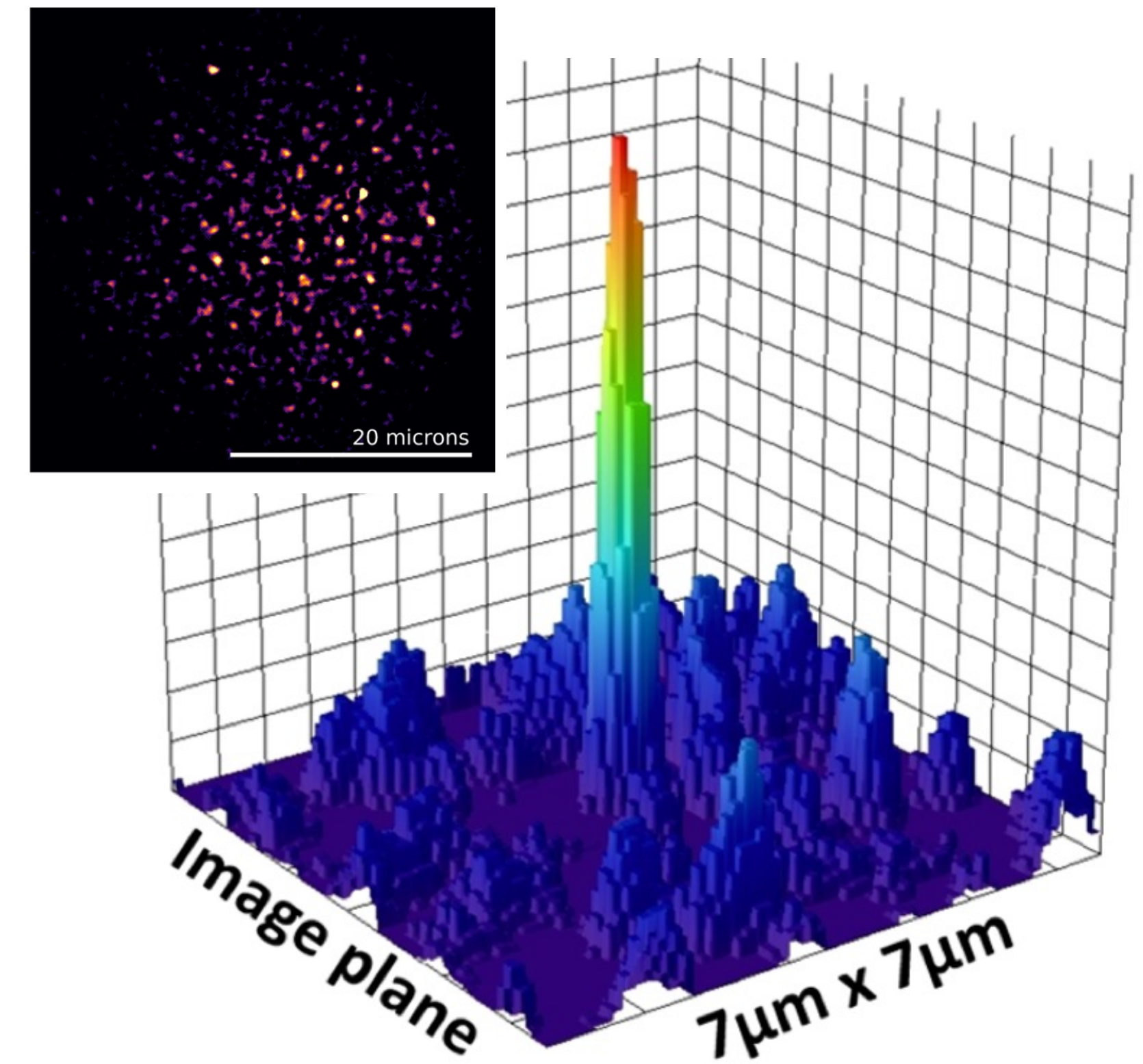
Single-step in the amount of light collected means detection of one ion

# Dry-barium sensing with on-off molecules

- Molecular design computationally tuned for selectivity and sensitivity.
- Dry single Ba<sup>++</sup> ion sensitivity demonstrated with **on-off molecules**.



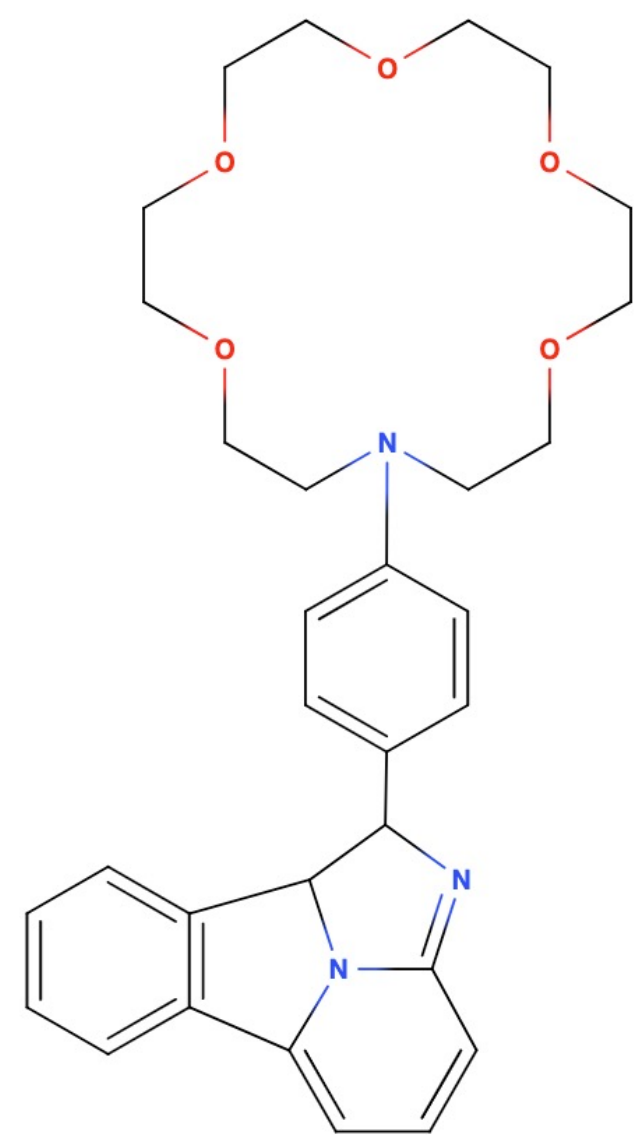
ACS Sensors 6, 1, 192–202 (2021)



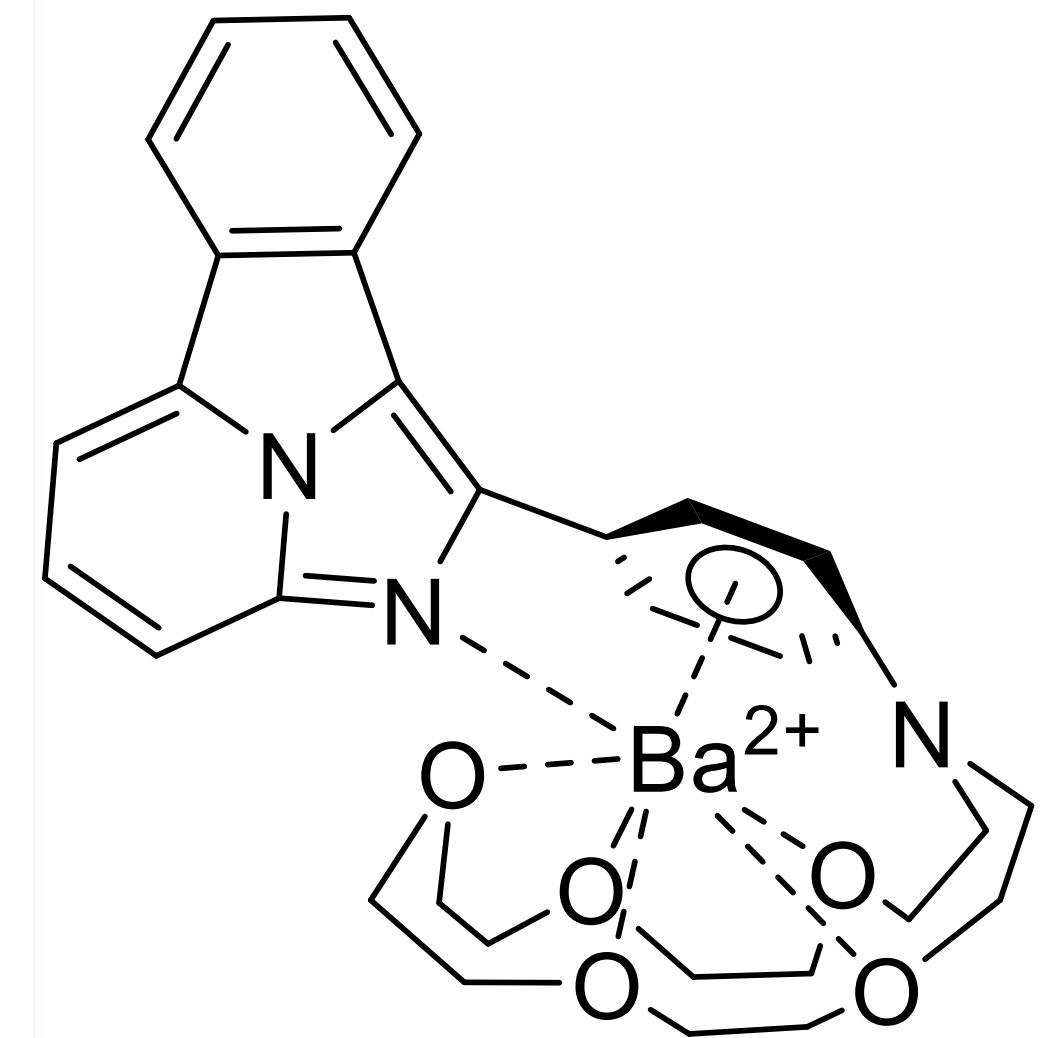
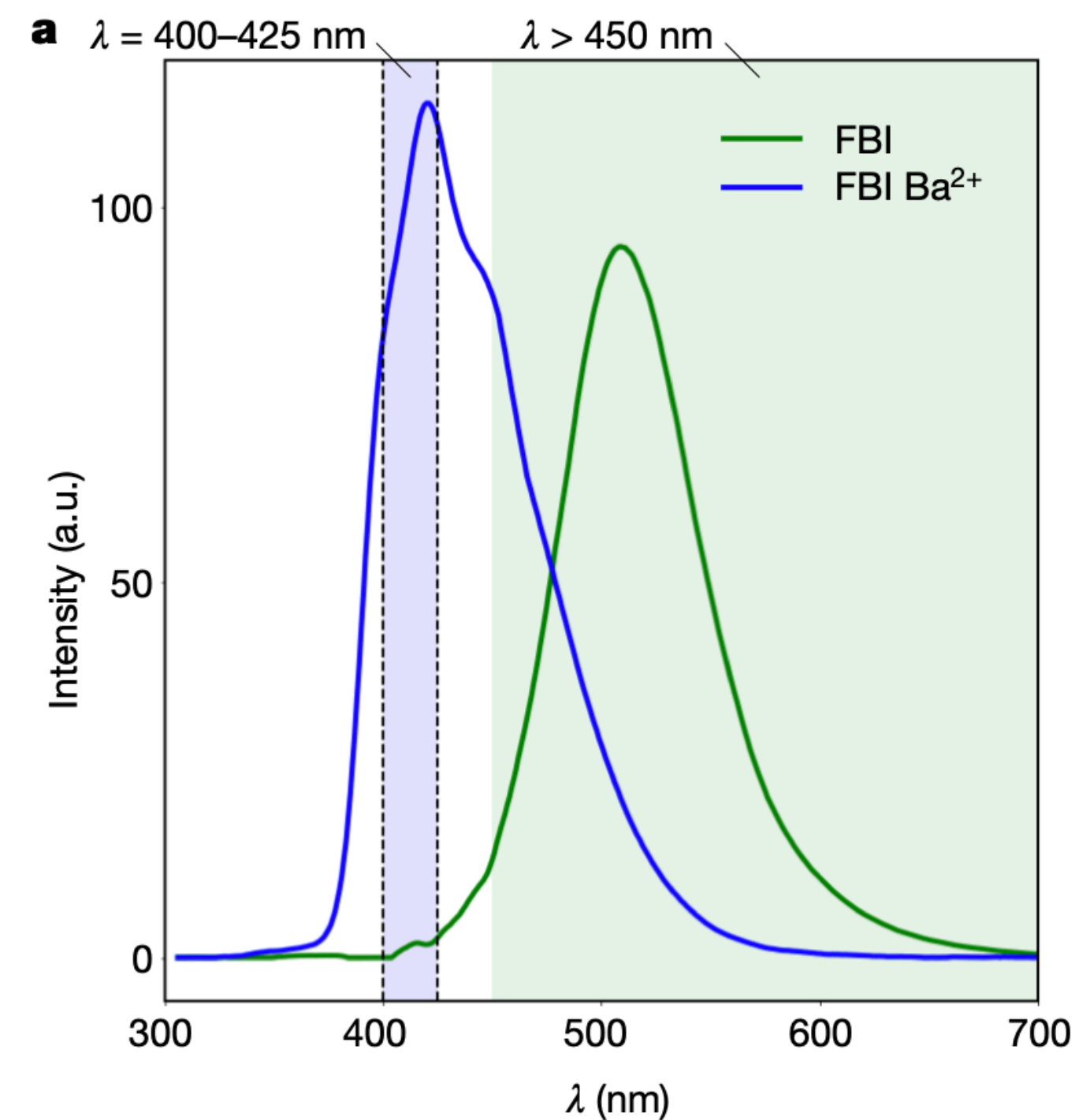
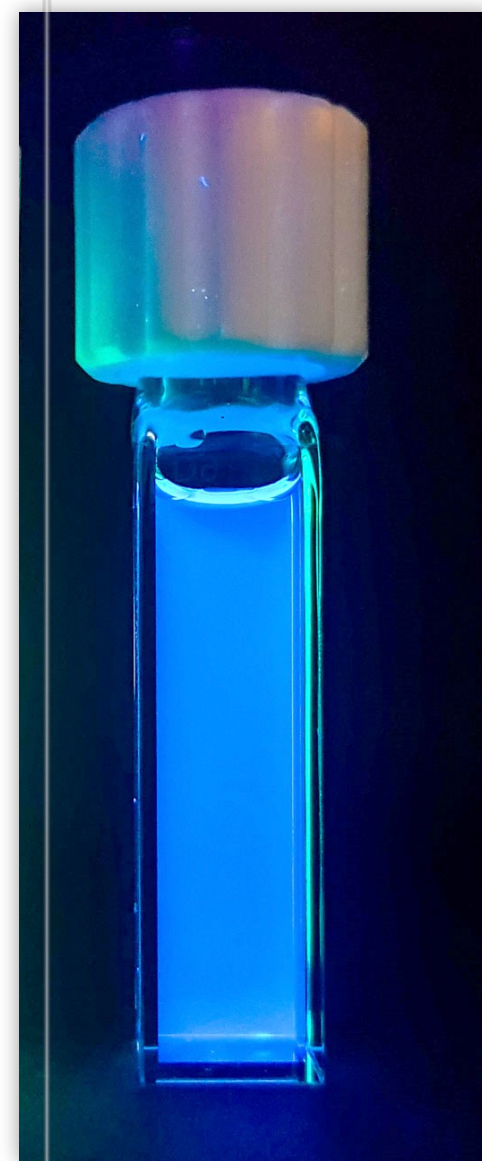
Barium-spiked sample showing fluorescent molecules (top) and a single Ba<sup>++</sup> candidate (bottom)

# Bi-color sensing

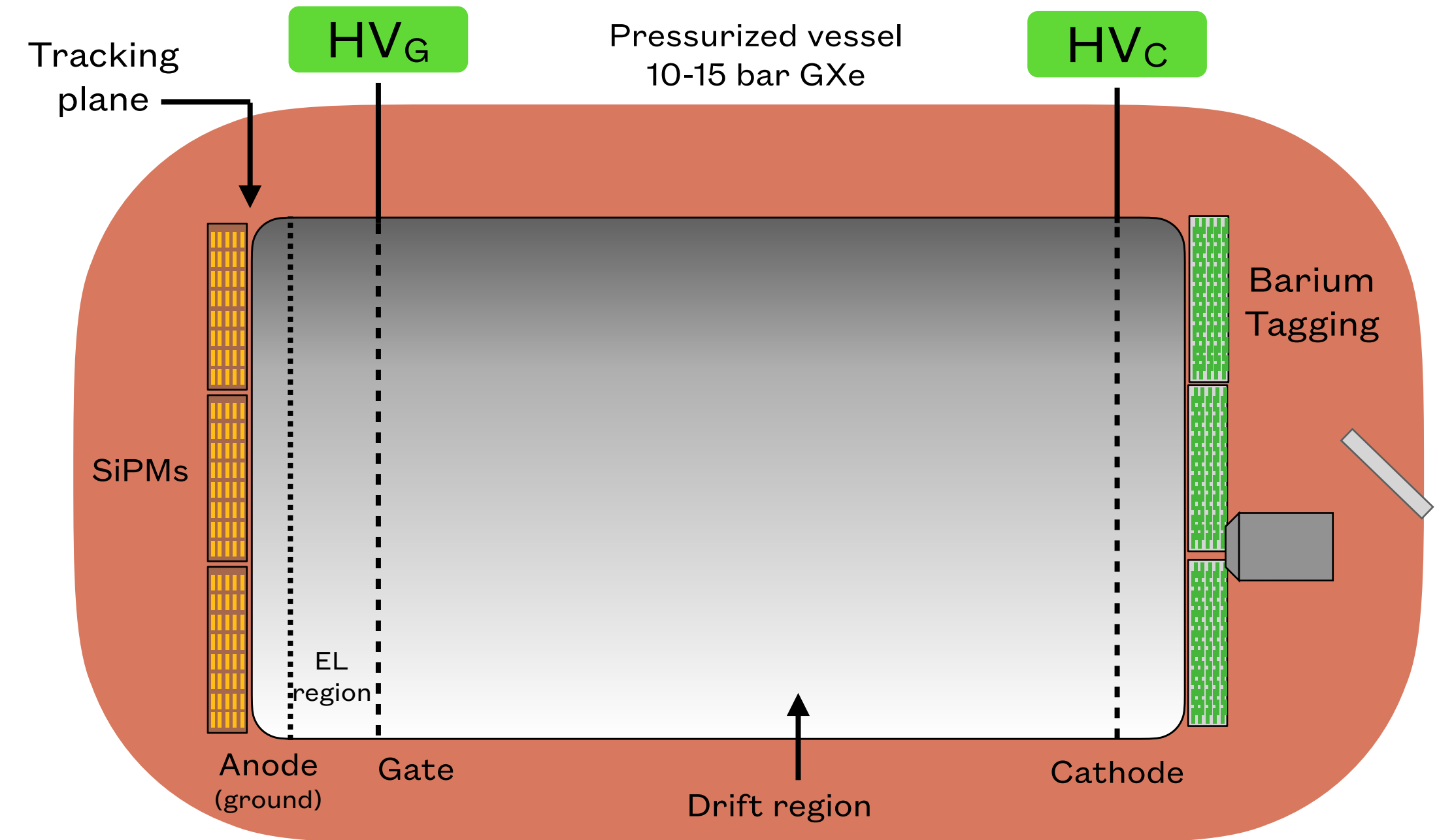
- **Variometric** rather than off-on sensing technique
- **Switches from green to blue upon chelation**; filter removes green light background allowing fluorescence separation.
- Barium interacts with nitrogen on fluorescent group on chelation, giving dual function of color-shift and fluorescence enhancement.



Nature 583, 48–54 (2020)



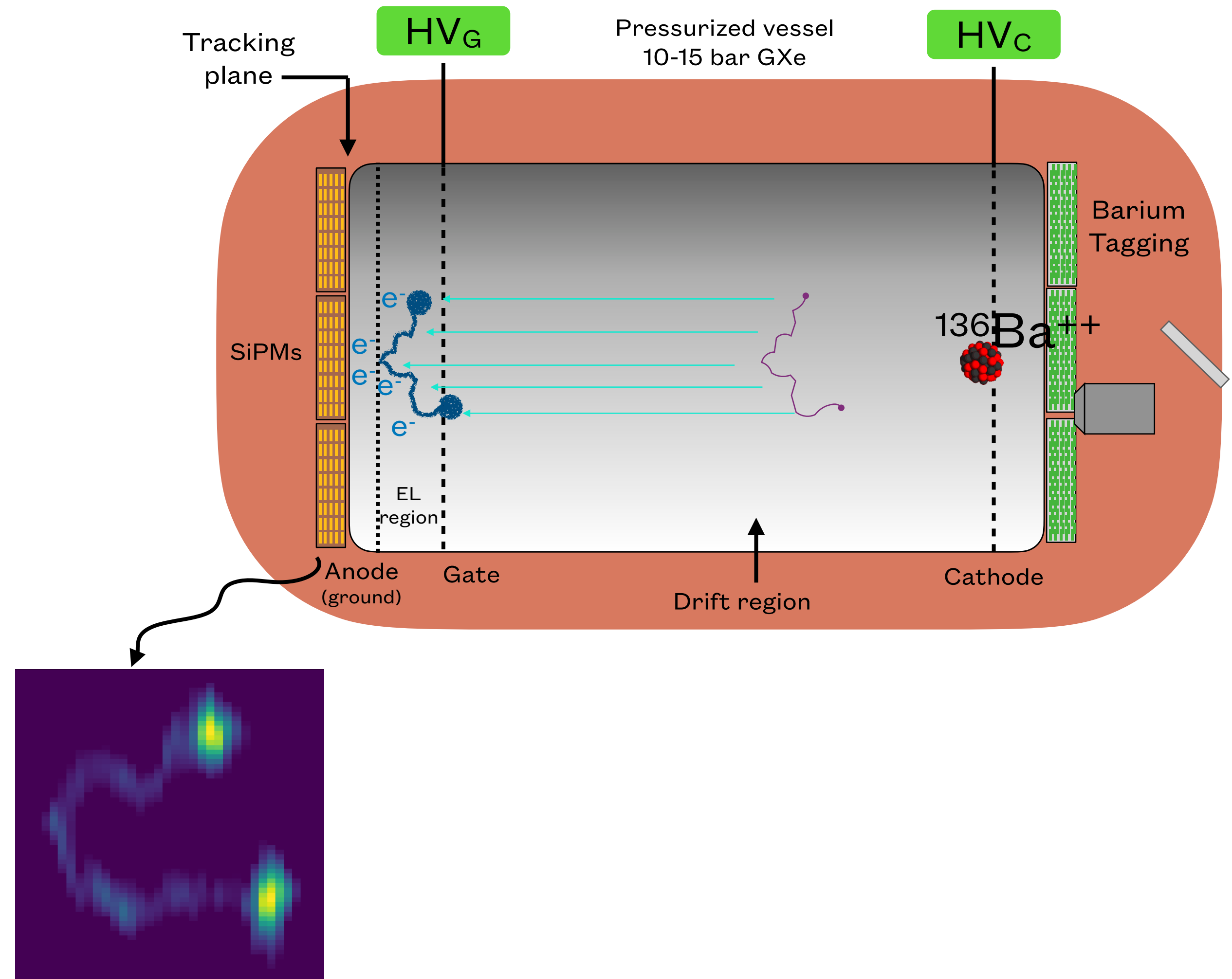
## Sensor-to-ion concept



# NEXT-BOLD

1. The  $^{136}\text{Xe}$  atom decays, producing **two electrons** and the **Ba<sup>++</sup> ion**.
2. The electrons drift towards the anode and the Ba (slowly) towards the cathode.

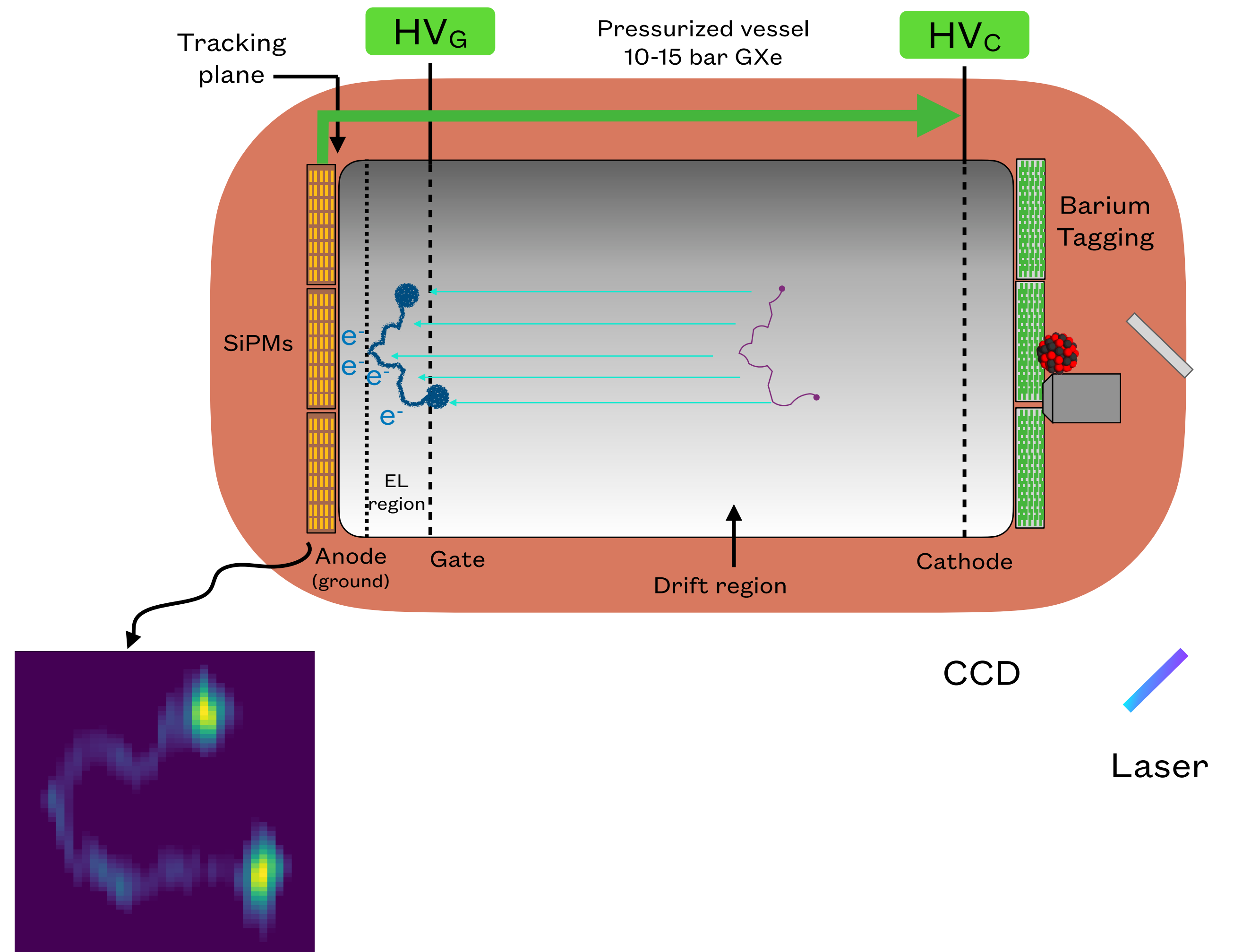
## Sensor-to-ion concept



# NEXT-BOLD

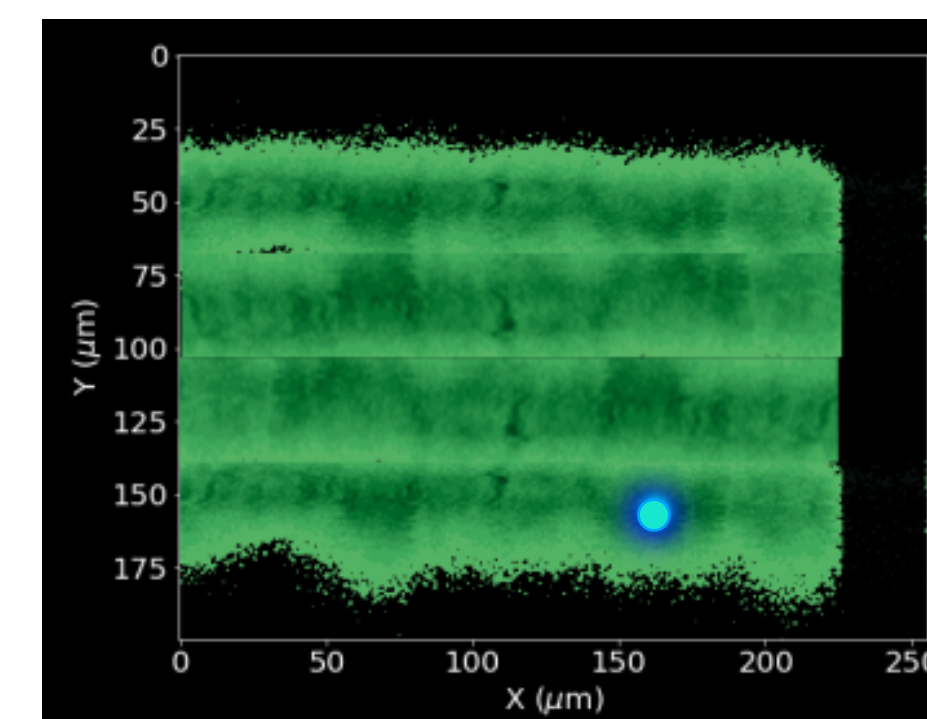
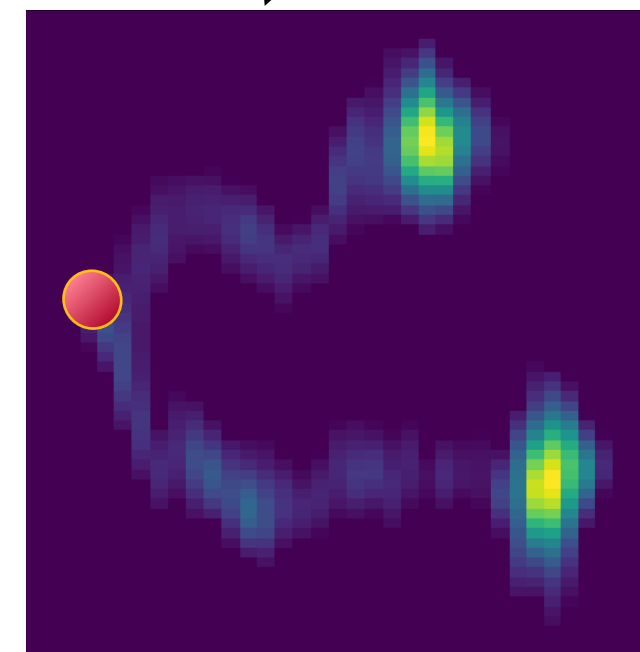
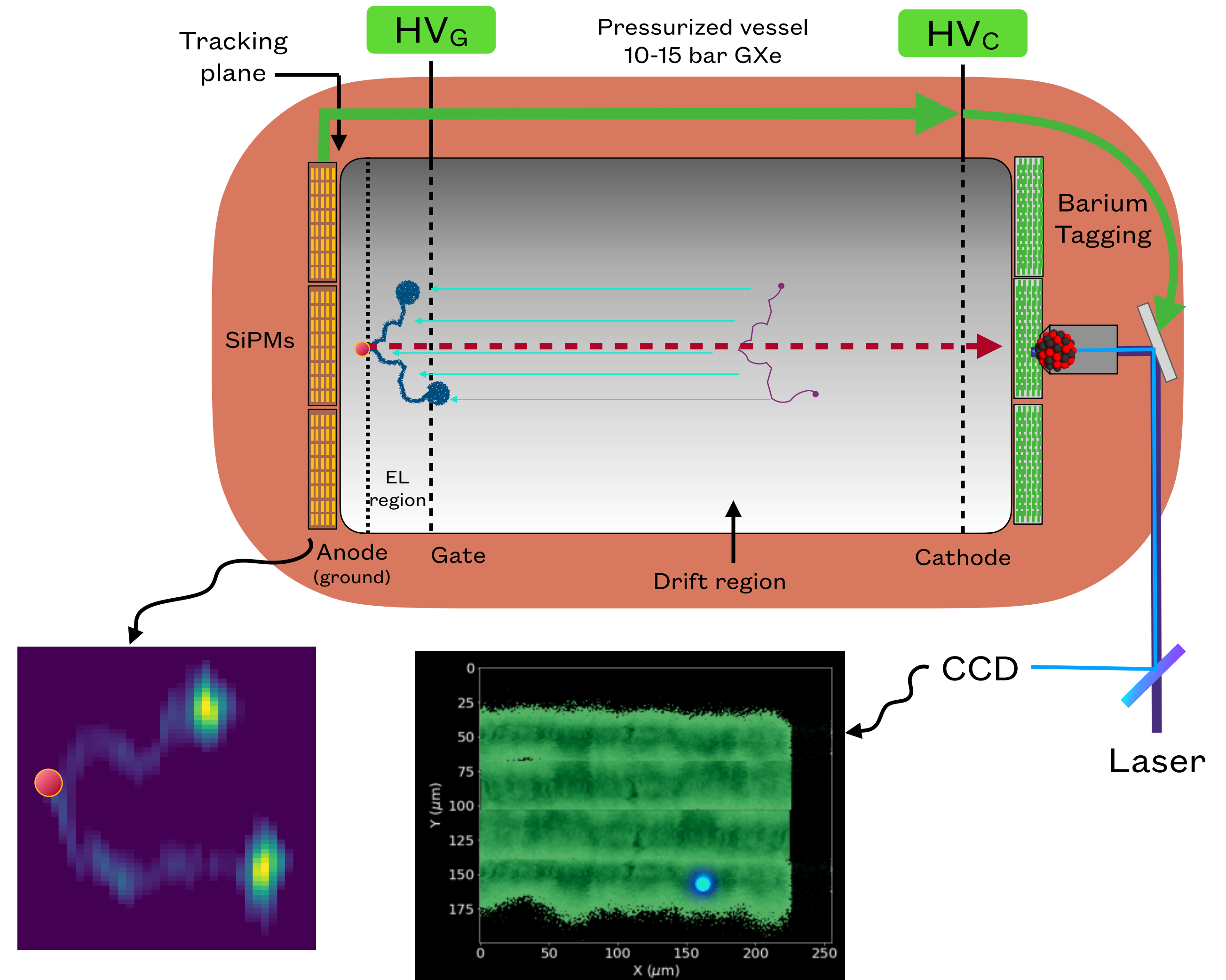
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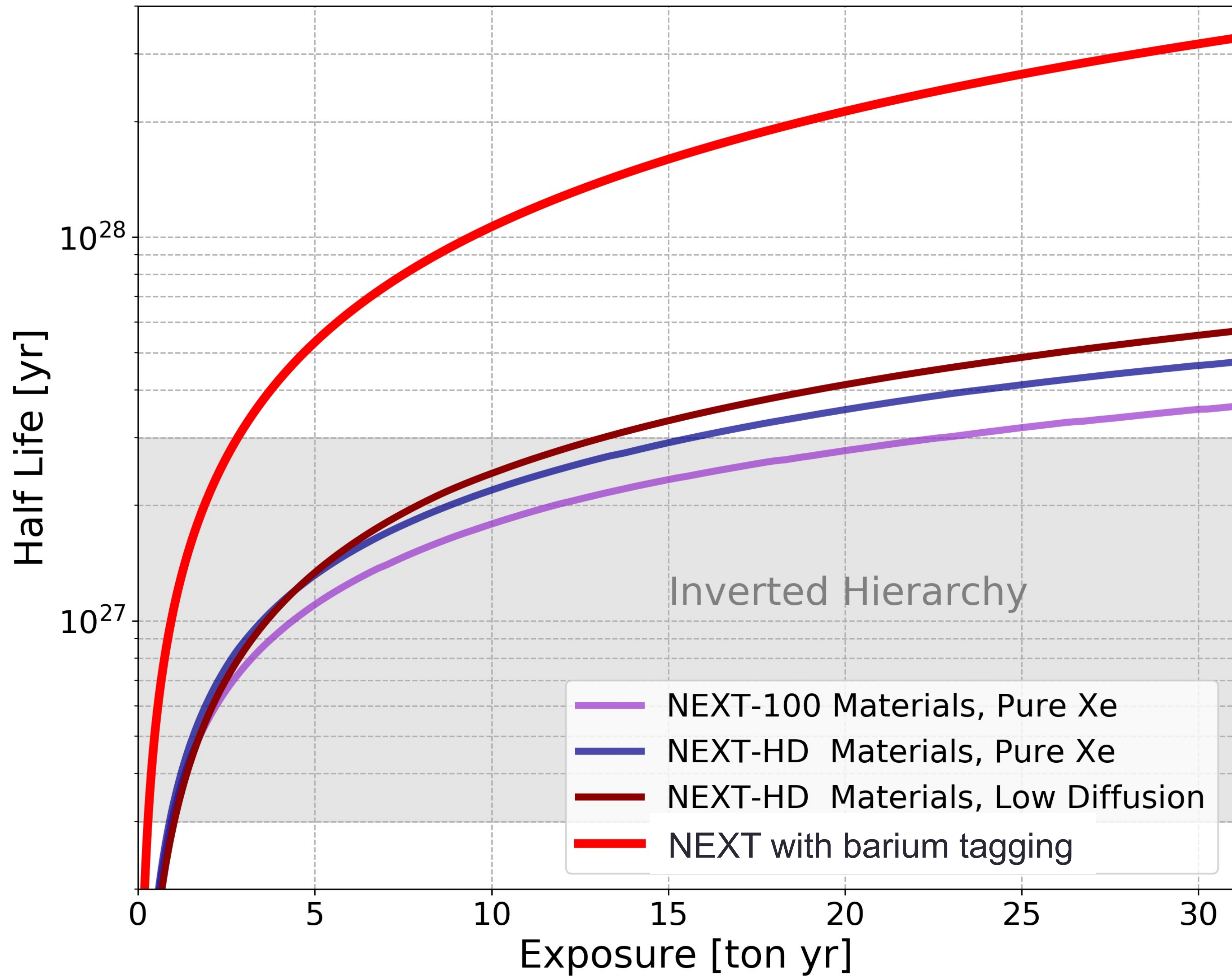
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## Sensor-to-ion concept

1. The  $^{136}\text{Xe}$  atom decays, producing **two electrons** and the **Ba<sup>++</sup> 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<sup>2+</sup>. This is the signal of Ba<sup>2+</sup> detection.
6. The sensor is **scanned repeatedly**.
7. Together with the electron track we obtain a **delayed coincidence signal**.







- The NEXT collaboration has proven that **HPXeTPC technology works**.
- The NEXT-100 is currently under construction and will be able to **provide competitive search** of  $0\nu\beta\beta$  in  $^{136}\text{Xe}$ .
- Next generation, ton-scale experiment targets to reach  $10^{27}$  years lifetime and **explore the inverted hierarchy** region. Background rates at 1 evt/tonne-year.
- Going above this limit requires a different approach, which can't be simply scaling up:
  - NEXT-BOLD with **barium tagging** may be a background free experiment.
  - In vacuo barium chelation reactions and imaging both shown to be possible.
  - Important R&D remains for ion collection / sensor manipulation.
- The challenge requires interdisciplinary science, combining particle physics, molecular chemistry, surface physics science, sophisticated microscopy, and state-of-the-art robotics.