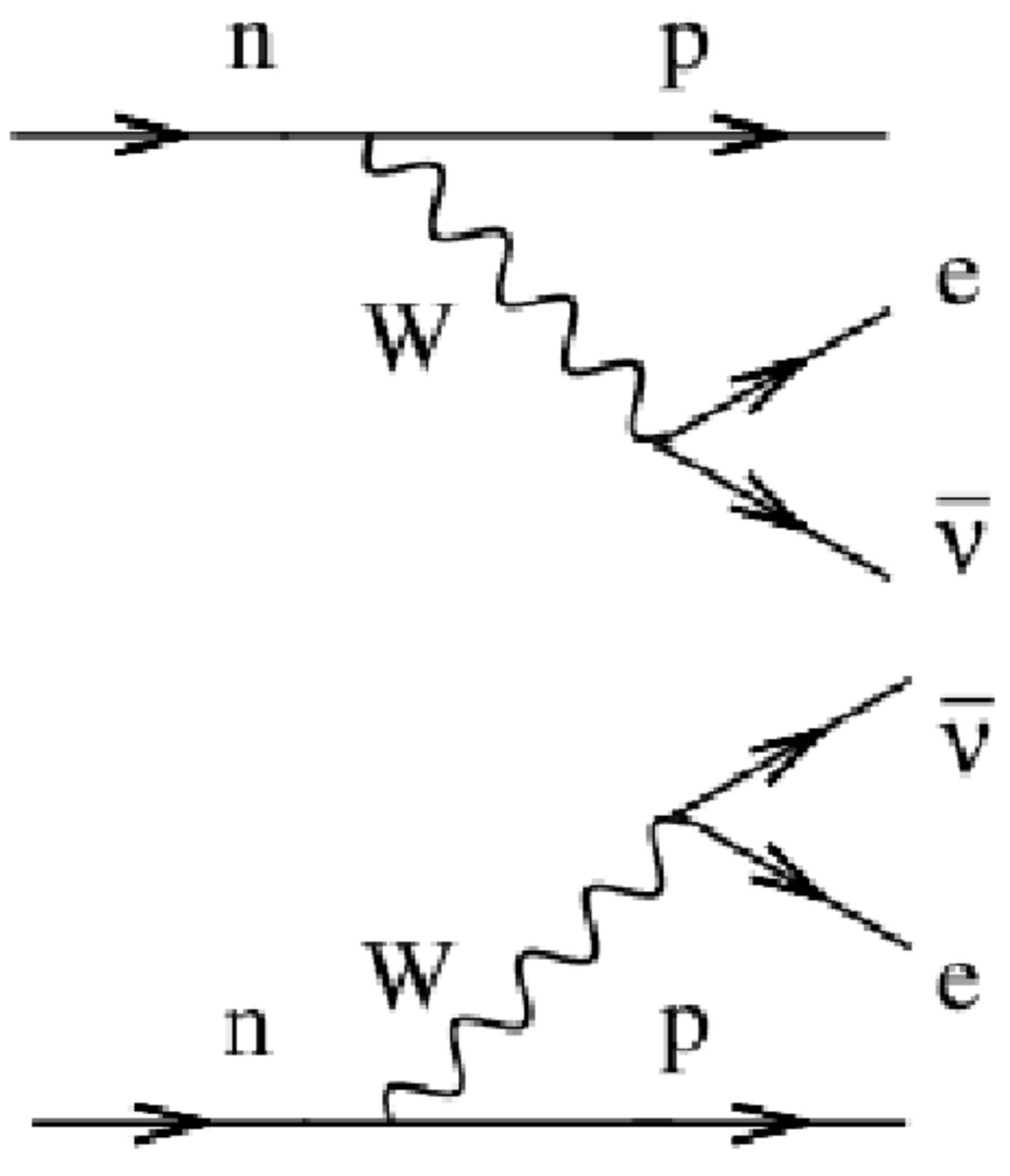
Unveiling Neutrinoless Double Beta Decay with the next Detectors: Advances, Achievements and Future Prospects

Helena Almazán, on behalf of the NEXT collaboration

MANCHESTER 1824
The University of Manchester
European Research Council
Established by the European Commission
XIII International Conference on New Frontiers in Physics
26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

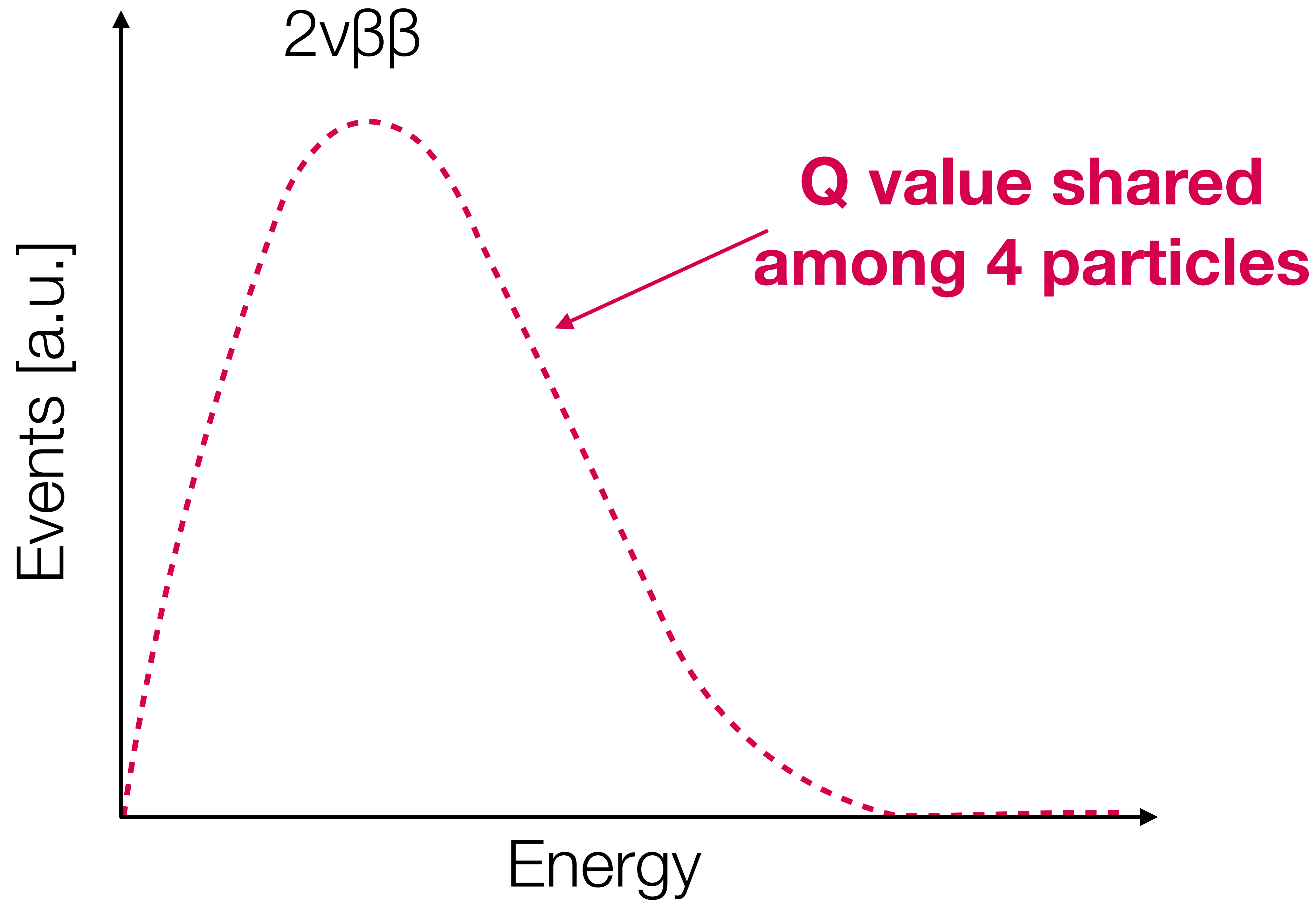
Neutrinoless Double Beta Decay

2νββ



$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+2}Y + 2e^{-} + 2\bar{\nu}_e $$

- Observed in several nuclei
- $T_{1/2} = 10^{19} - 10^{21}$ years
- $\Delta L = 0$



Isotopes capables double beta decay:

^{46}Ca, ^{48}Ca, ^{70}Zn, **^{76}Ge**, ^{80}Se, **^{82}Se**, ^{86}Kr, ^{94}Zr, ^{96}Zr, ^{98}Mo, **^{100}Mo**, ^{104}Ru, ^{110}Pd, ^{114}Cd, ^{116}Cd, ^{122}Sn, ^{124}Sn, ^{128}Te, **^{130}Te**, ^{134}Xe, **^{136}Xe**, ^{142}Ce, ^{146}Nd, ^{148}Nd, ^{150}Nd, ^{154}Sm, ^{160}Gd, ^{170}Er, ^{176}Yb, ^{186}W, ^{192}Os, ^{198}Pt, ^{204}Hg, ^{216}Po, ^{220}Rn, ^{222}Rn, ^{226}Ra, ^{232}Th, ^{238}U, ^{244}Pu, ^{248}Cm, ^{254}Cf, ^{256}Cf, and ^{260}Fm.

2νββ rate measured experimentally

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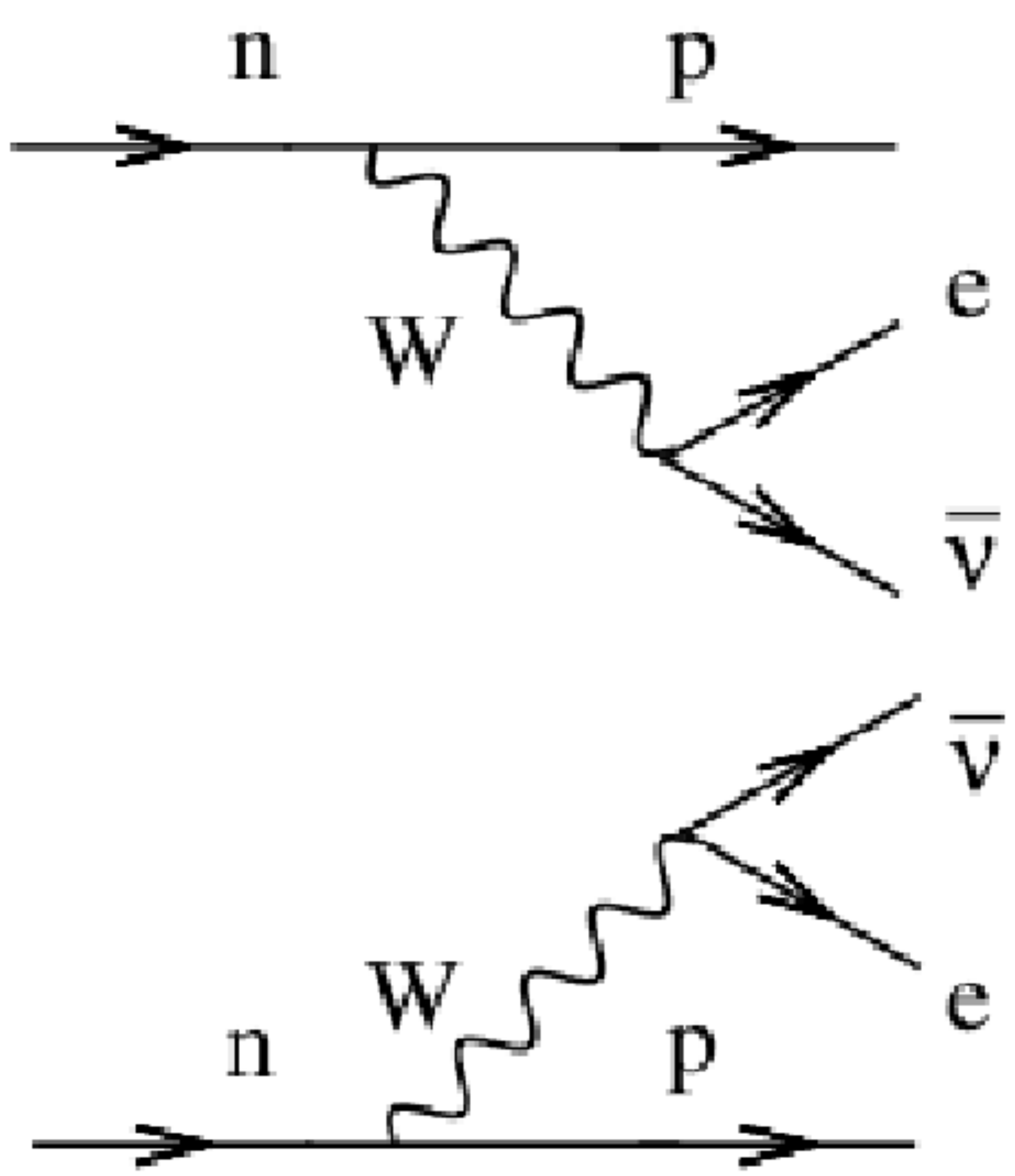
Neutrinoless Double Beta Decay

2νββ



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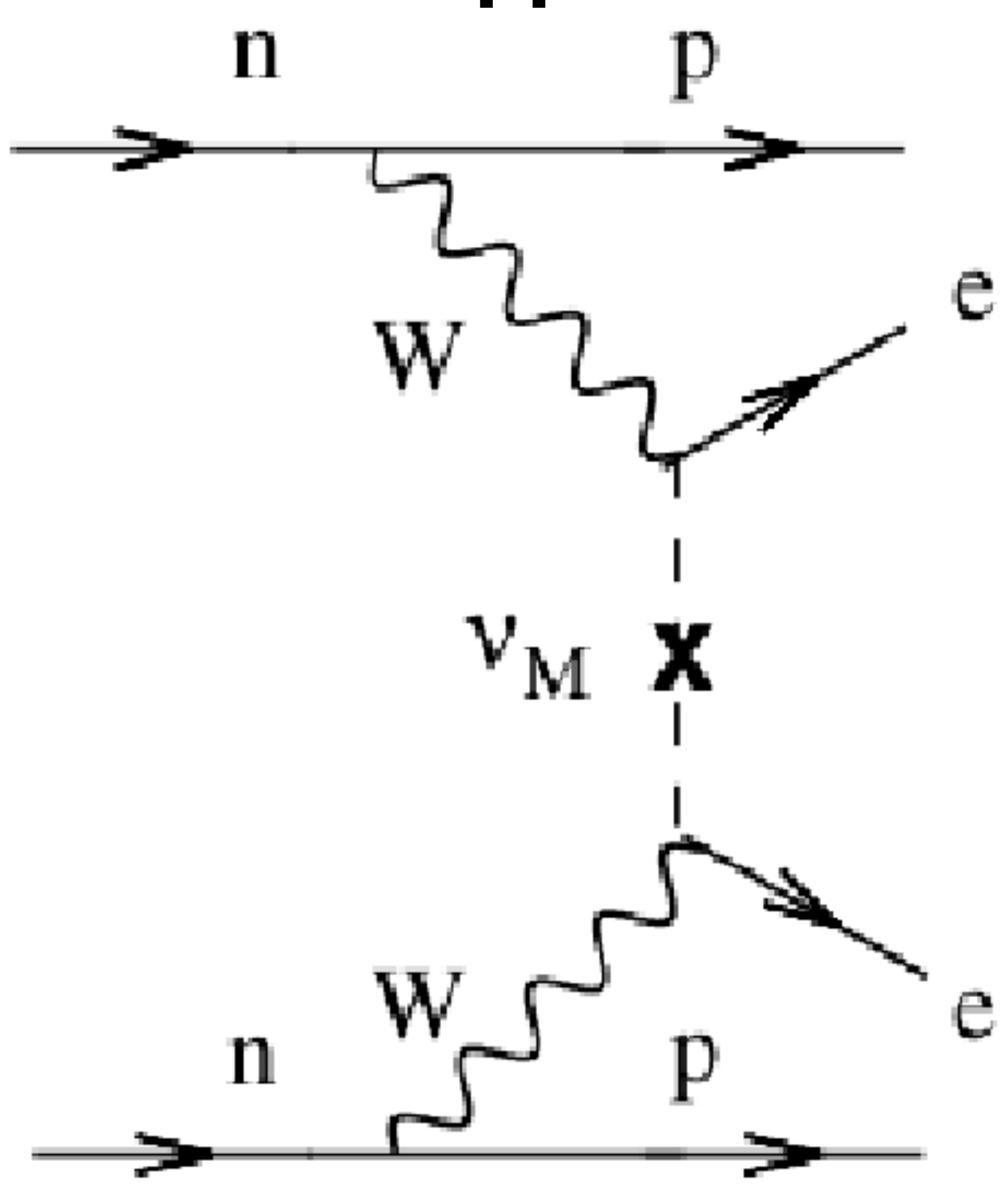
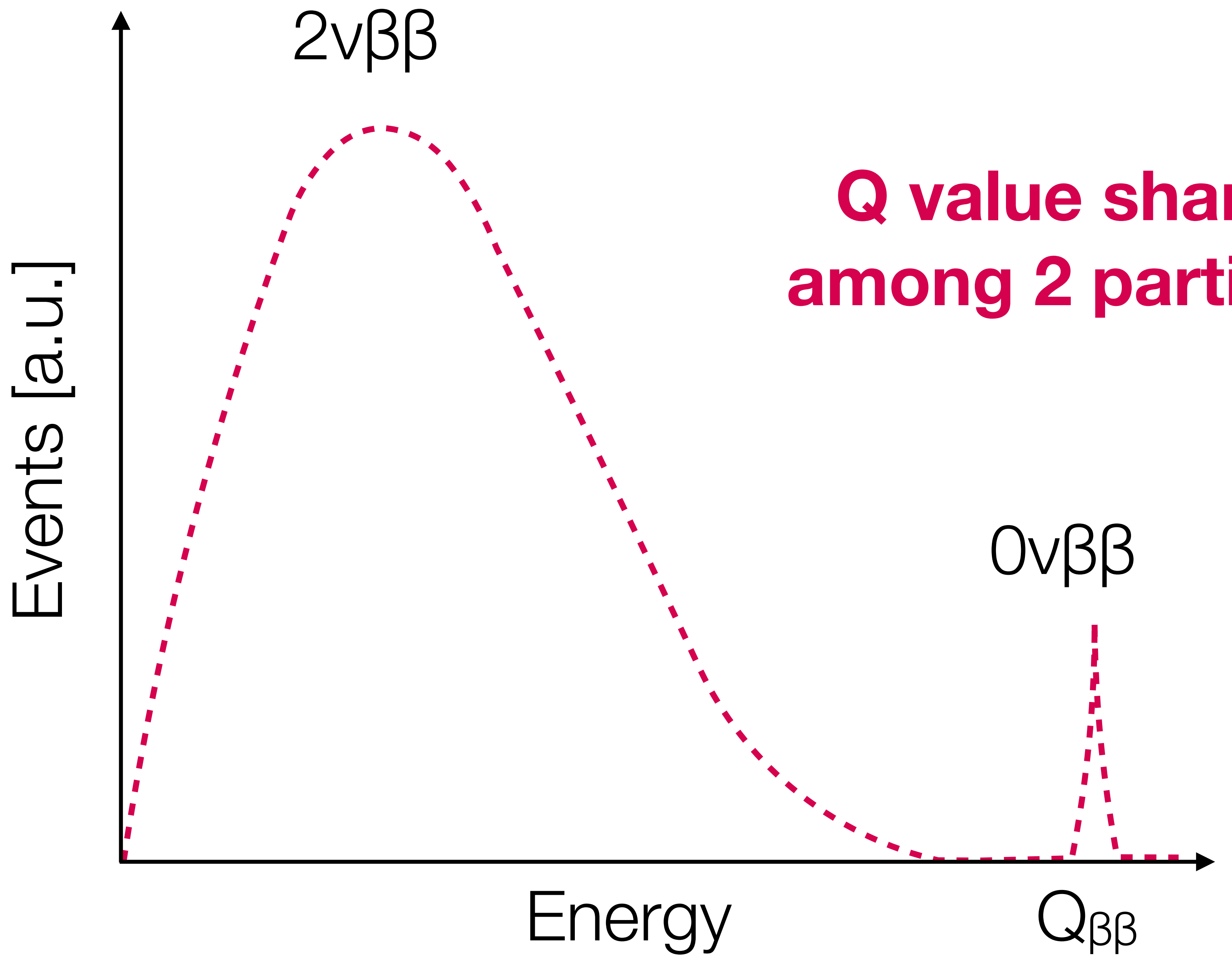
0νββ



$$^{A}_{Z}X \longrightarrow ^{A}_{Z+2}Y + 2e^{-}$$

- Unobserved
- $T_{1/2} > 10^{26}$ years
- $\Delta L = 2$



Demonstrate neutrino is a **Majorana particle** (= neutrinos are their own antiparticle) by detecting the **neutrinoless double beta decay process**

Next-generation $0\nu\beta\beta$ experiments

[arXiv: 2406.11438]

Best ***ββ0ν half-life*** experimental value (KamLAND-Zen)

$$T^{0\nu}_{1/2} > 3.8 \times 10^{26} \text{ yr } (90\ \% \text{ CL})$$

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\,|M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

effective Majorana mass

$$m_{\beta\beta} = |\sum_i U^2_{ei} \cdot m_i|$$

Next-generation $0\nu\beta\beta$ experiments

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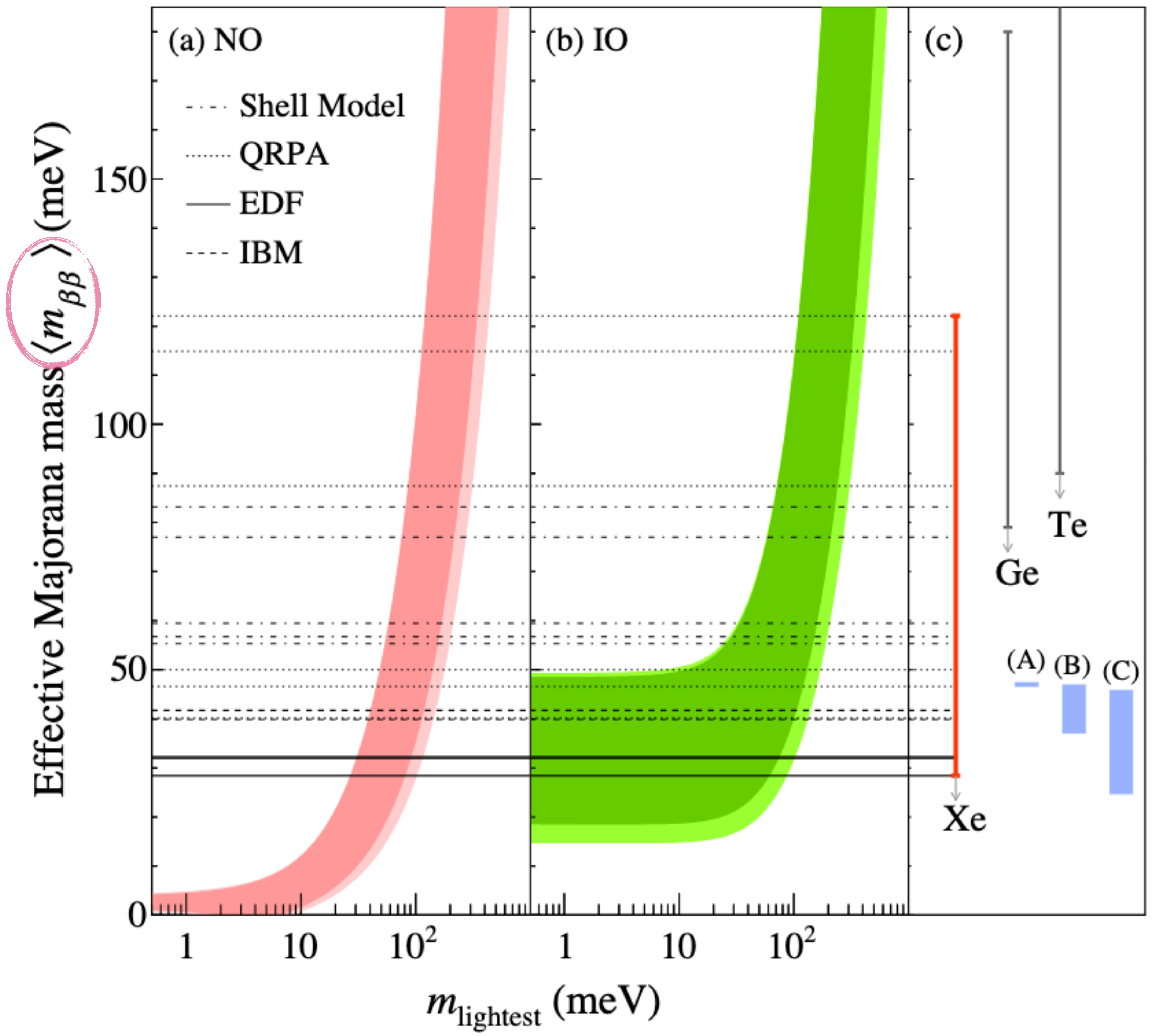
provides information about absolute neutrino mass and mass eigenstates ordering → aim to explore the **IO region**

[arXiv: 2406.11438]



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$$T^{0\nu}_{1/2} = log2\frac{N_A}{W}\frac{\epsilon M t}{N}$$

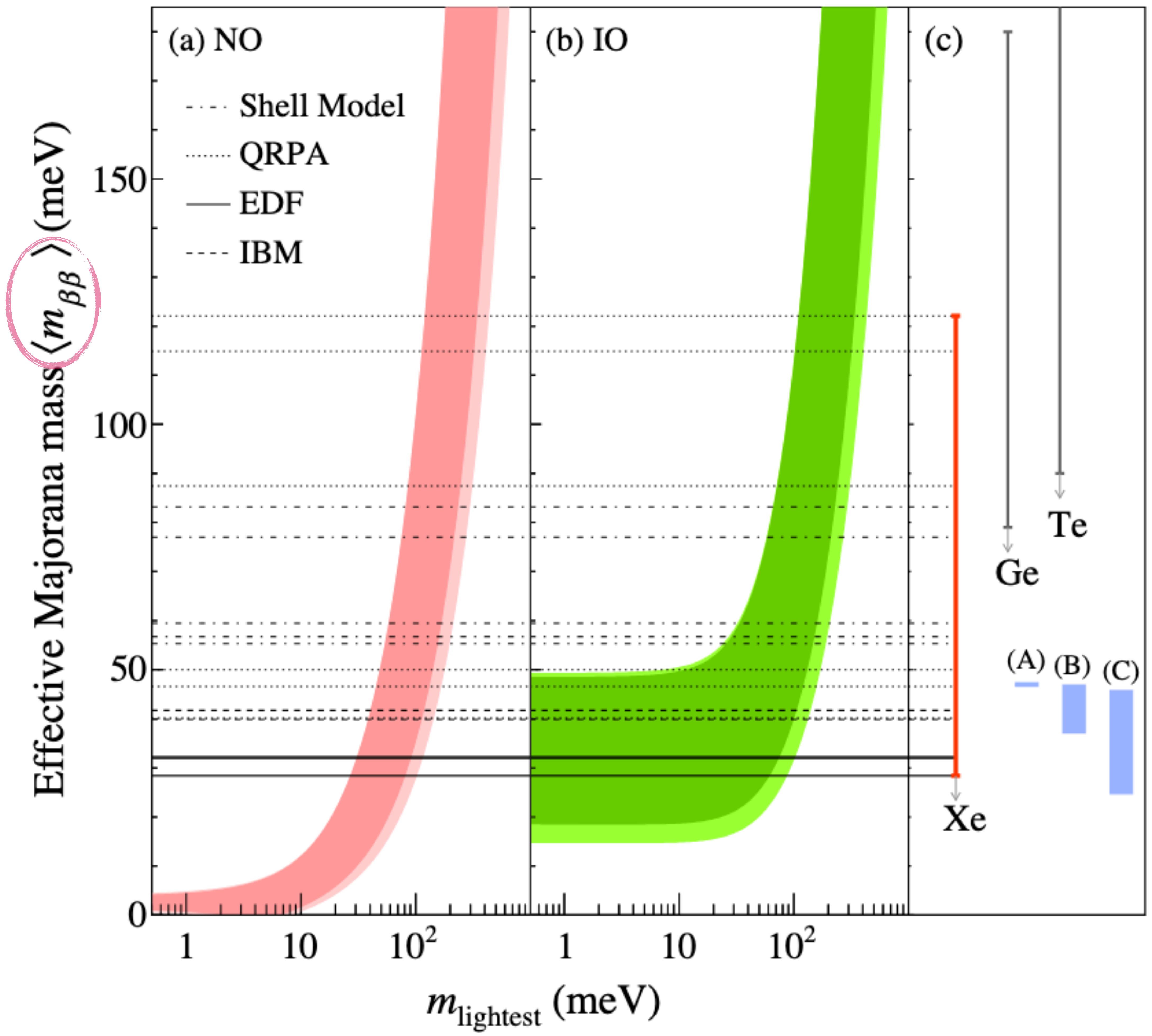
signal detection efficiency

[source mass x measuring time]

number of events

Sensitivity of **IO** region requires ***tonne-scale detectors***

[arXiv: 2406.11438]



$0\nu\beta\beta$ experiments

signal detection efficiency

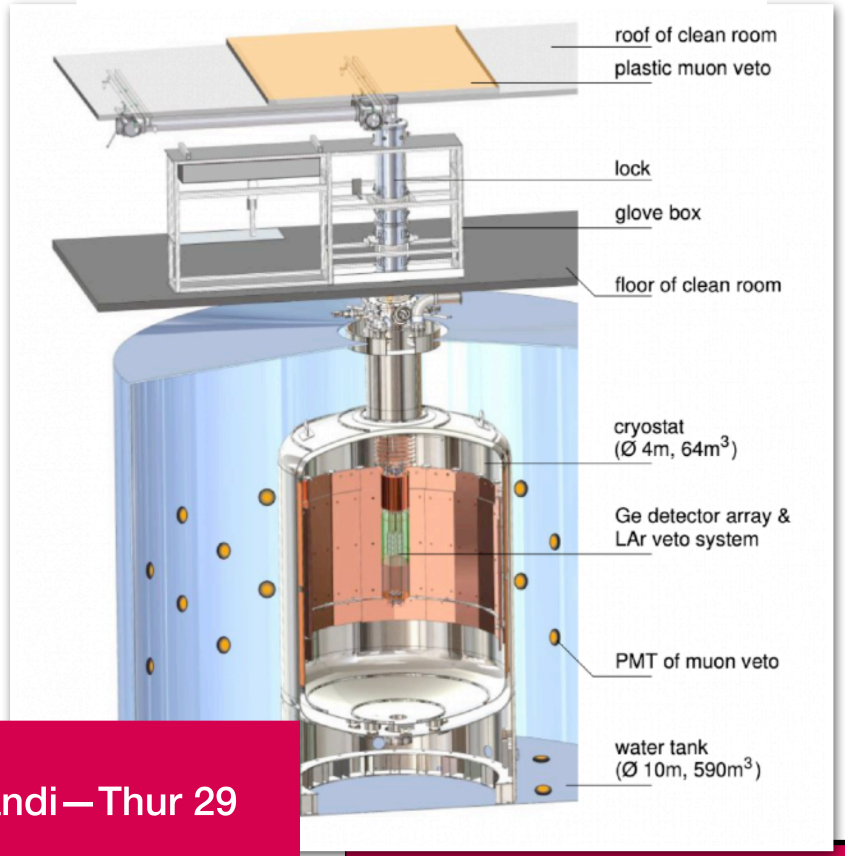
[source mass x measuring time]

$$T^{0\nu}_{1/2} = log2 \frac{N_A}{W} \frac{\epsilon M t}{N}$$

number of events

- Great **energy resolution**
- Extremely **low background**
- Scalability

$0\nu\beta\beta$ experiments



Talk by S. Ghislandi—Thur 29

$$T^{0\nu}_{1/2} = log2 \frac{N_A}{W} \frac{\epsilon M t}{N}$$

signal detection efficiency (ϵ)

[source mass x measuring time] (Mt)

number of events (N)

- Great **energy resolution**
- Extremely **low background**
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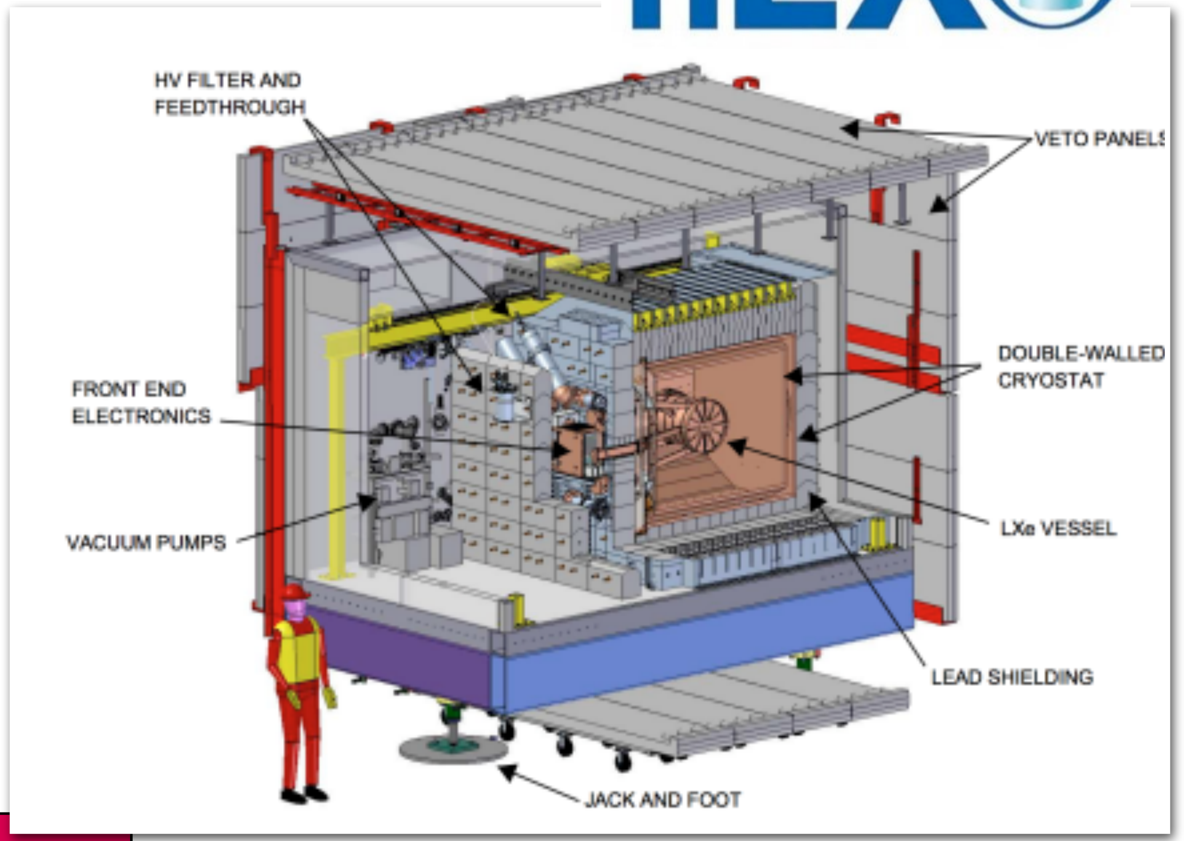
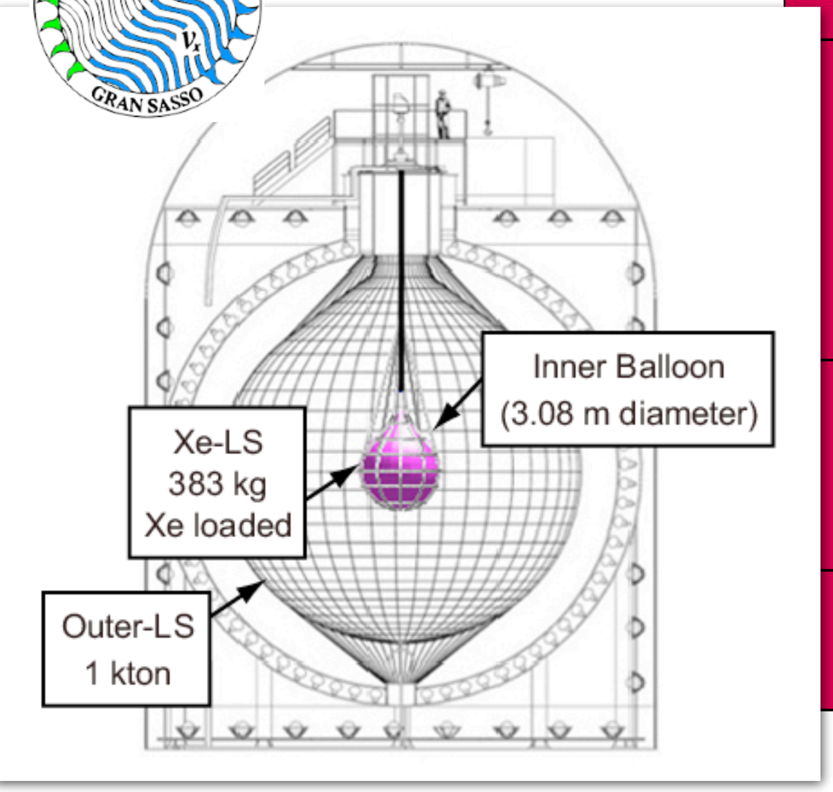
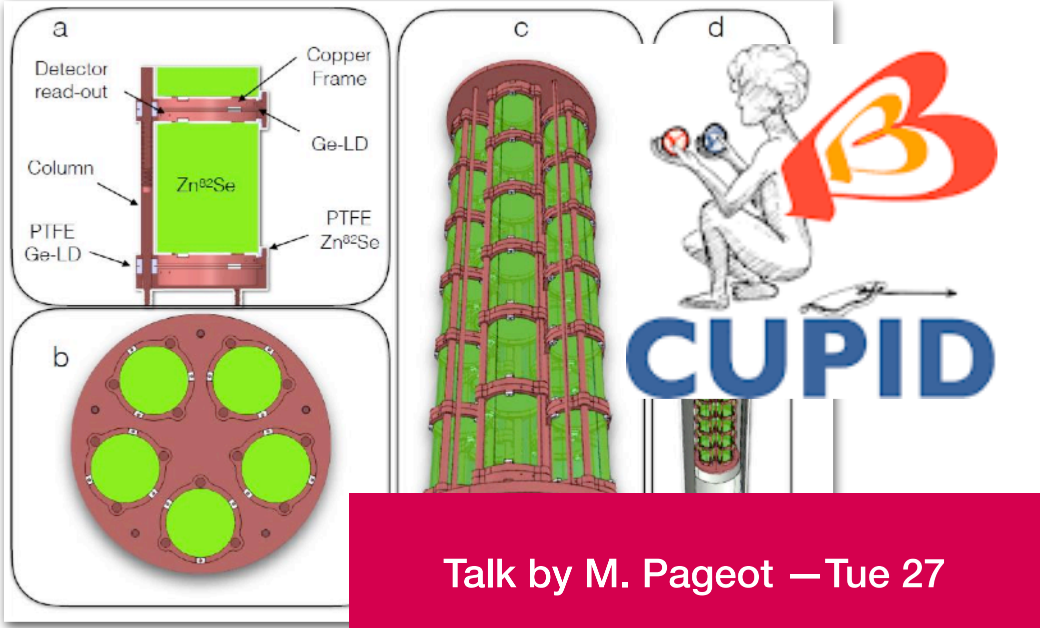


	^{76}Ge	^{136}Xe	^{130}Te	^{100}Mo
Semiconductor	GERDA-II LEGEND-200 LEGEND-1000 MAJORANA DEMOSTRATOR			
Liquid/Gas TPC		EXO-200, nEXO **NEXT-100, NEXT-HD** DARWIN, LZ PANDAX-III		
Liquid Scintillators		KamLAND-ZEN 100 KamLAND-ZEN 800 KamLAND2-ZEN	SNO+ SNO+ II	
Bolometer			CUORE	CUPID AMORE-II



Talk by E. Engelhardt —Thur 29



Talk by M. Pageot —Tue 27

The next technology

signal detection efficiency

[source mass x measuring time]

$$T^{0\nu}_{1/2} = log2\frac{N_A}{W}\frac{\epsilon M t}{N}$$

number of events

- Great **energy resolution**
- Extremely **low background**
- Scalability

next

High Pressure Gaseous Xenon Time Projection Chamber with Electroluminescent Amplification

The next technology

signal detection efficiency

[source mass x measuring time]

$$T^{0\nu}_{1/2} = log2 \frac{N_A}{W} \frac{\epsilon M t}{N}$$

number of events

- Great **energy resolution**
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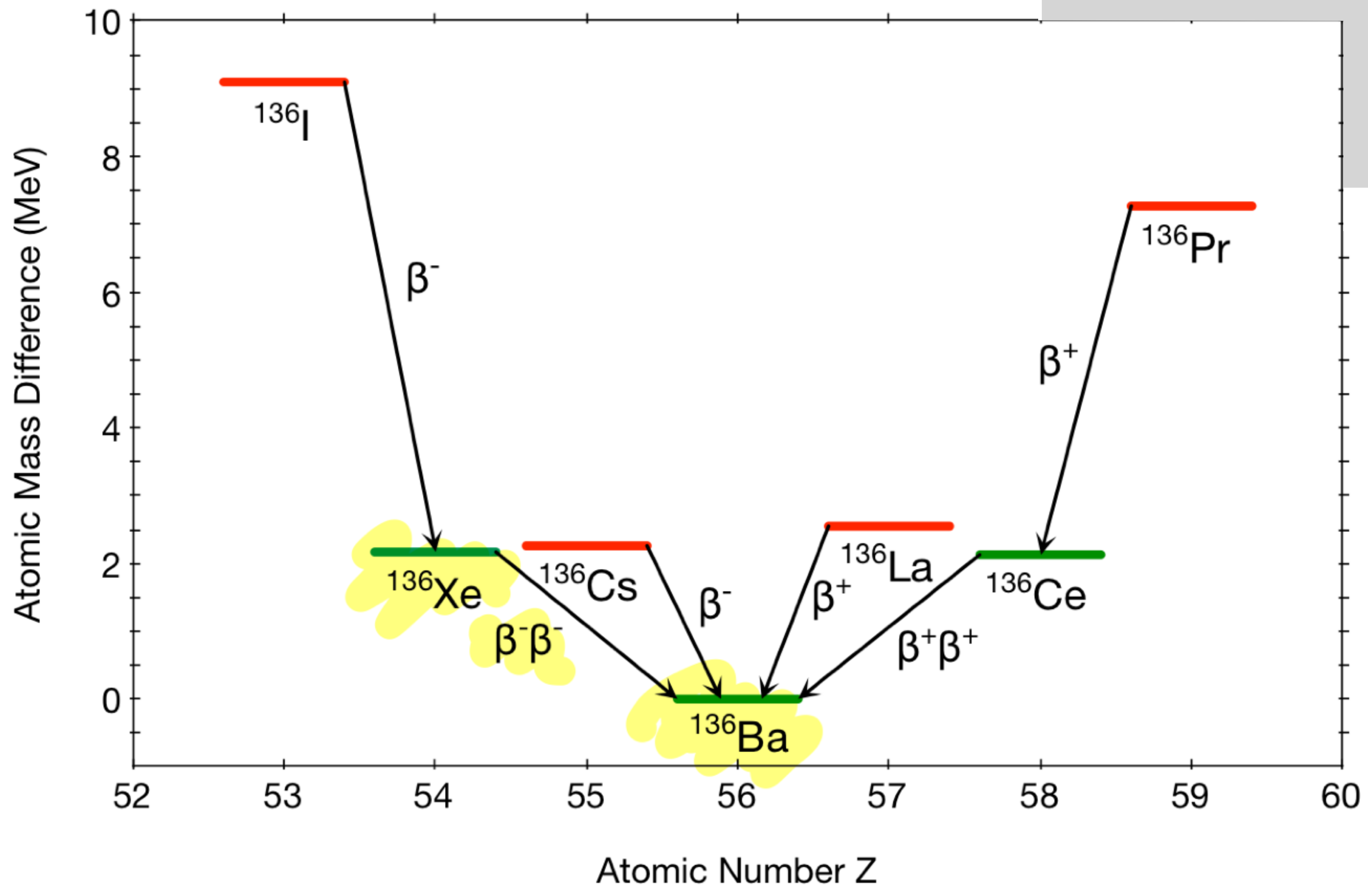
- Scalability

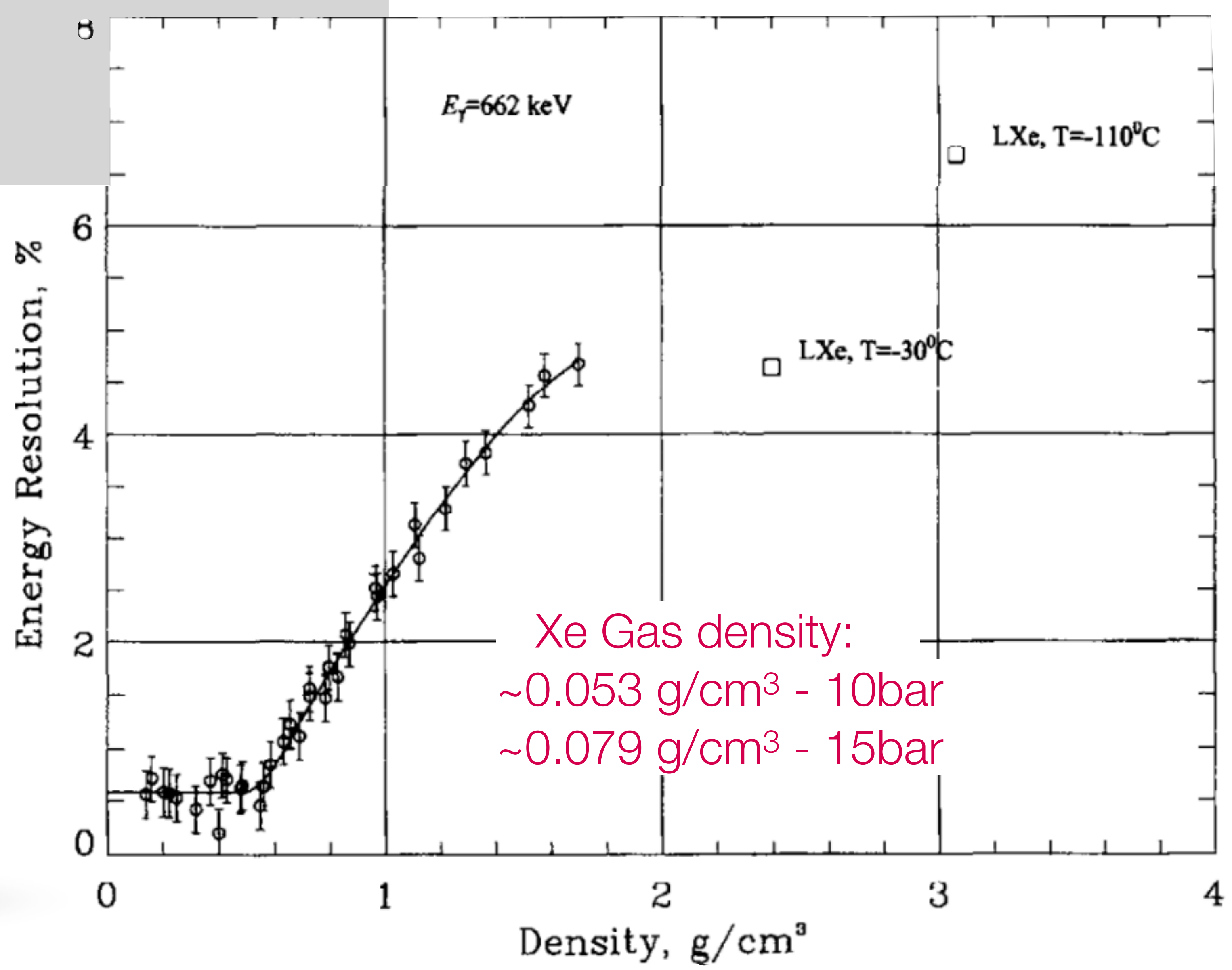


^{136}Xe Isotope:
high enough abundance
$Q_{\beta\beta}$ = 2.5 MeV
Noble gas → ideally suited to detection technology (TPC)

next
High Pressure Gaseous Xenon
Time Projection Chamber with Electroluminescent Amplification

More isotope in the same volume

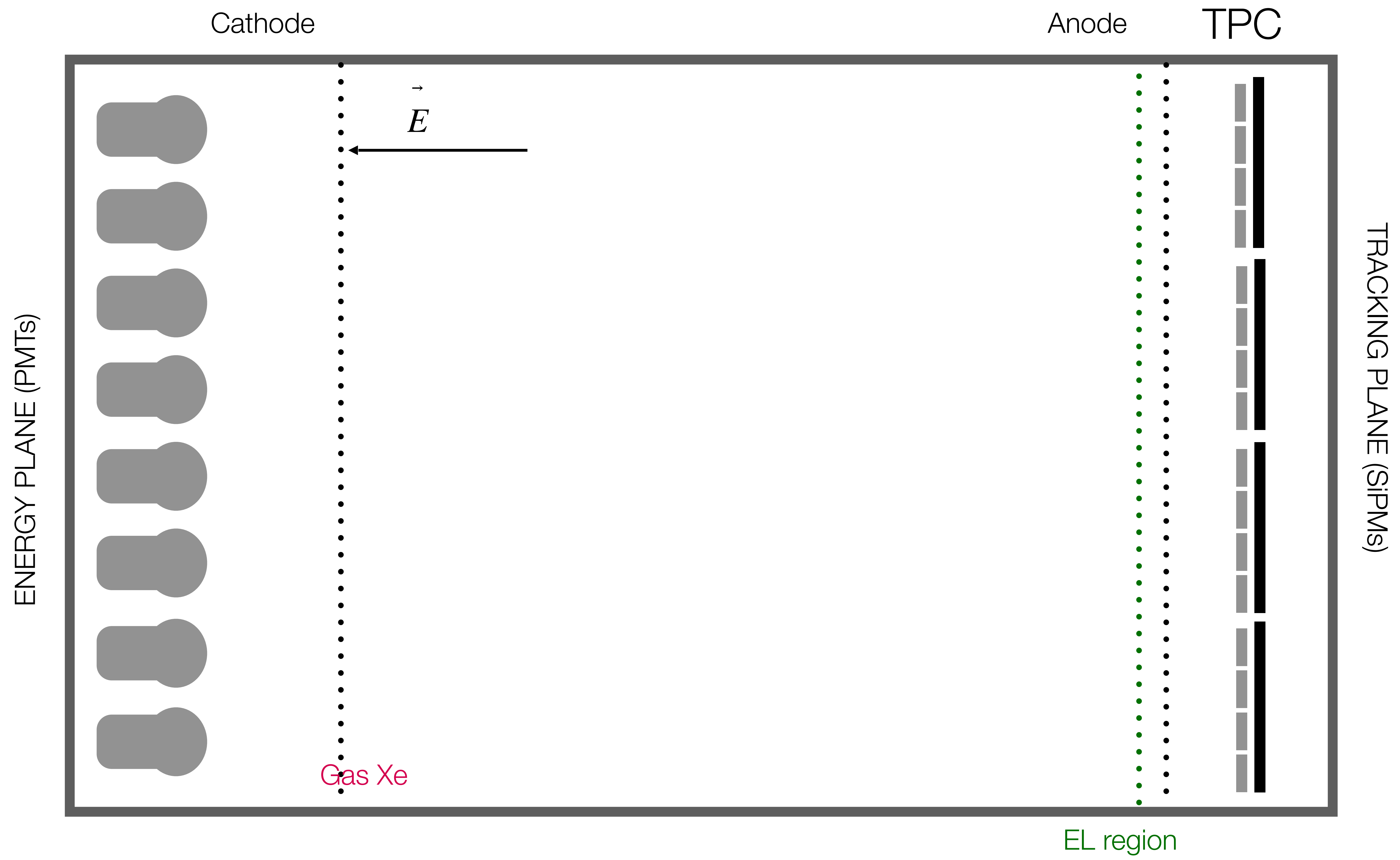
Bolotnikov and Ramsey, NIM A 396 (1997) 360



Fully active and homogenous detector → source = detector
Great intrinsic energy resolution in gas

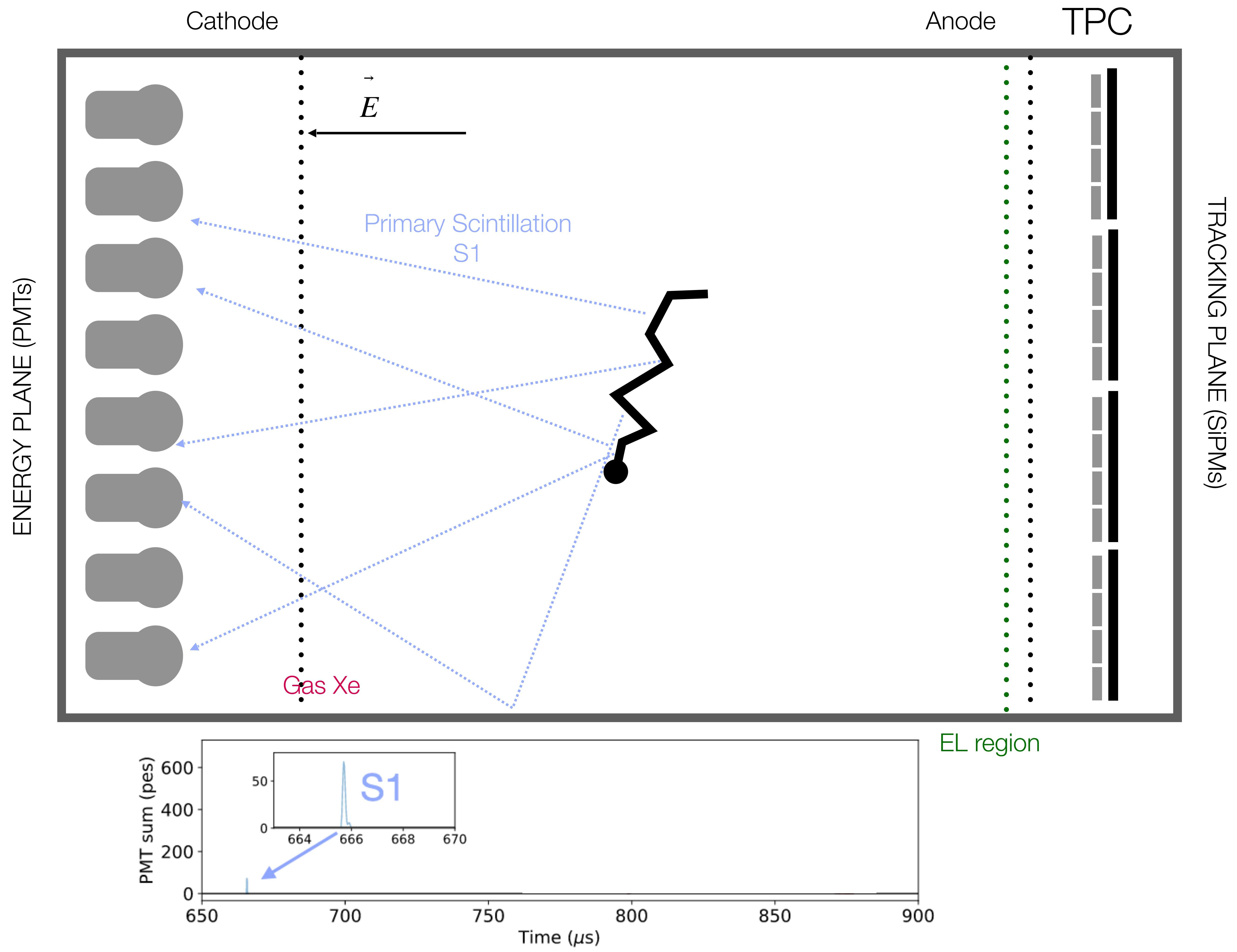
The @next technology

High Pressure Gaseous Xenon
Time Projection Chamber with Electroluminescent Amplification



The @next technology

High Pressure Gaseous Xenon
Time Projection Chamber with Electroluminescent Amplification



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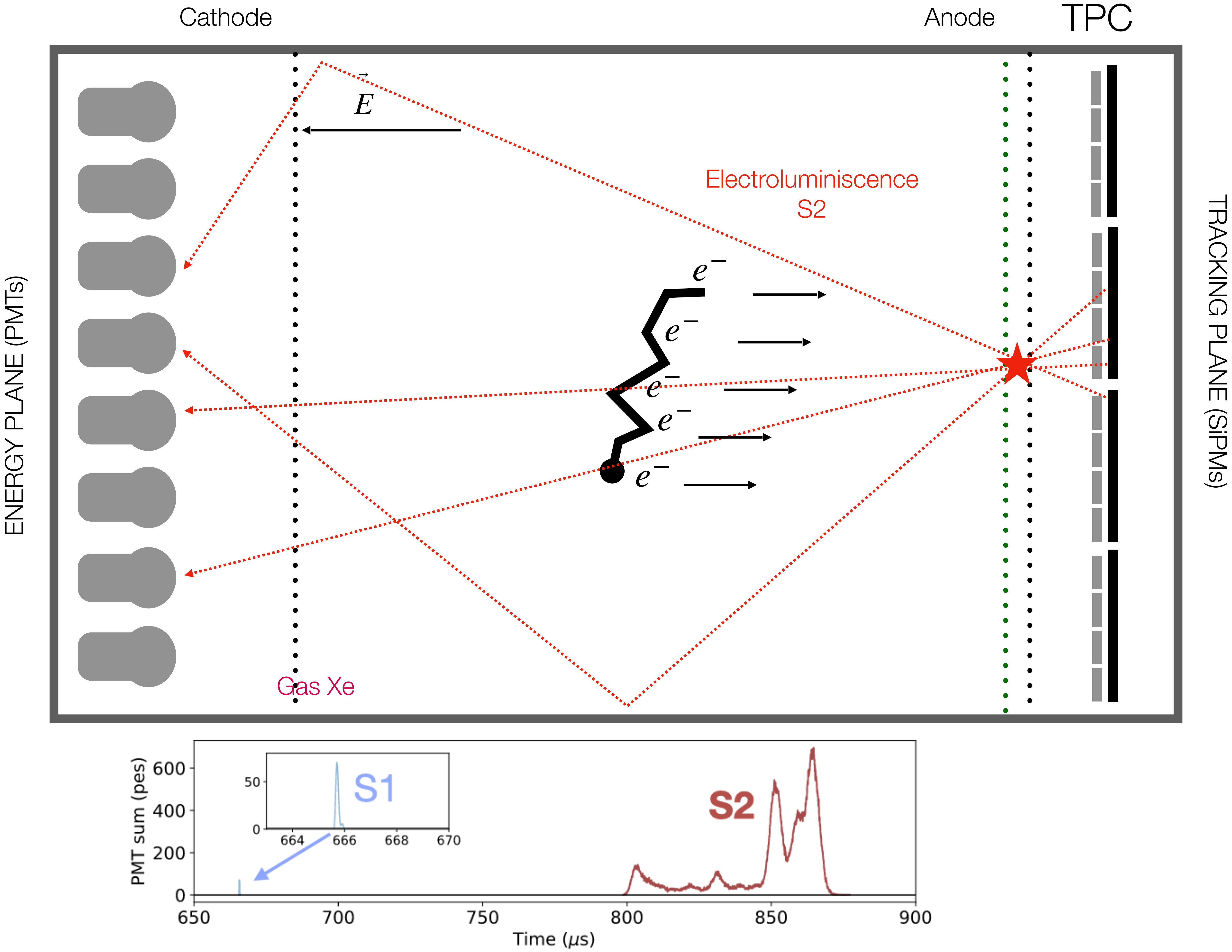
The next technology

High Pressure Gaseous Xenon
Time Projection Chamber with Electroluminescent Amplification



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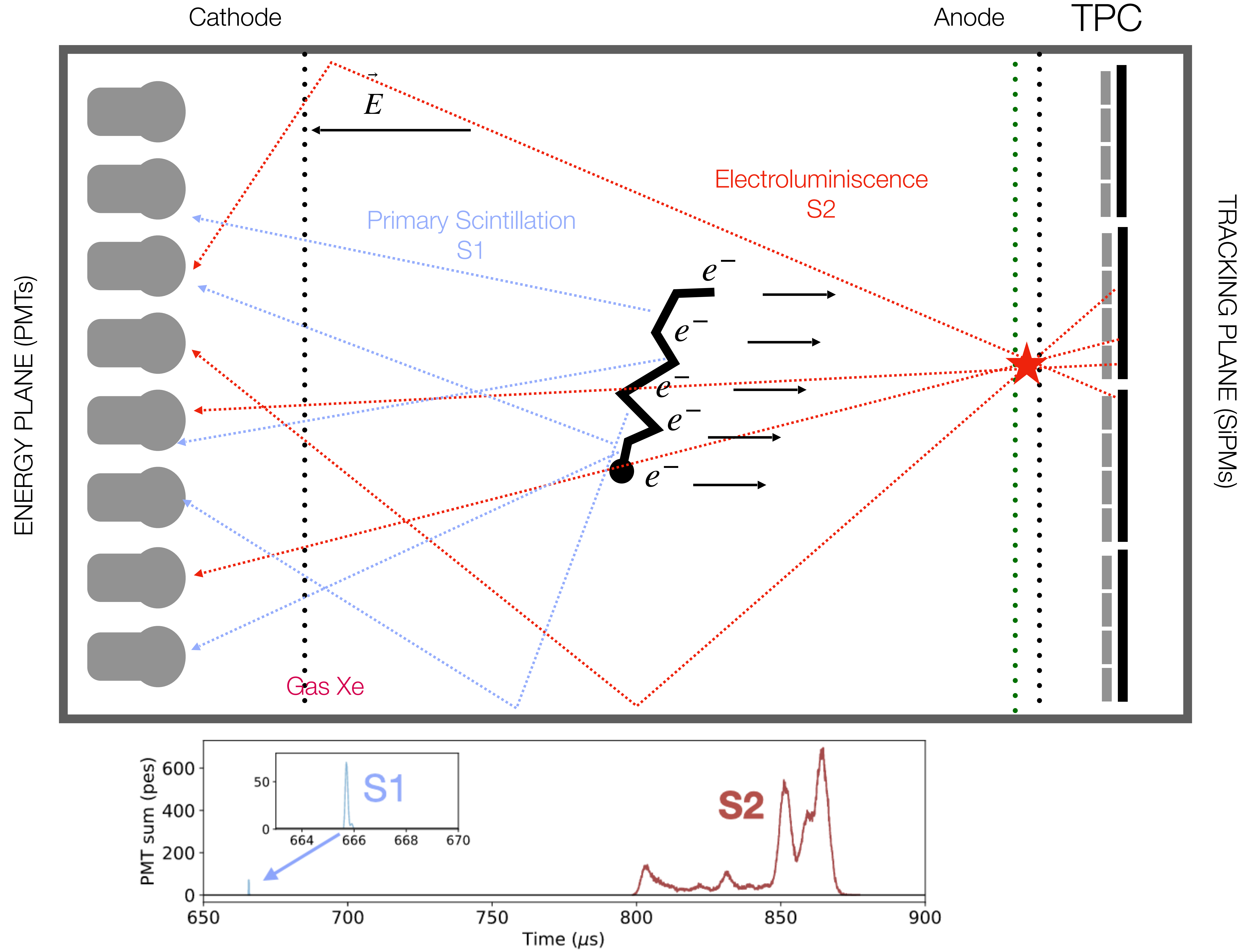
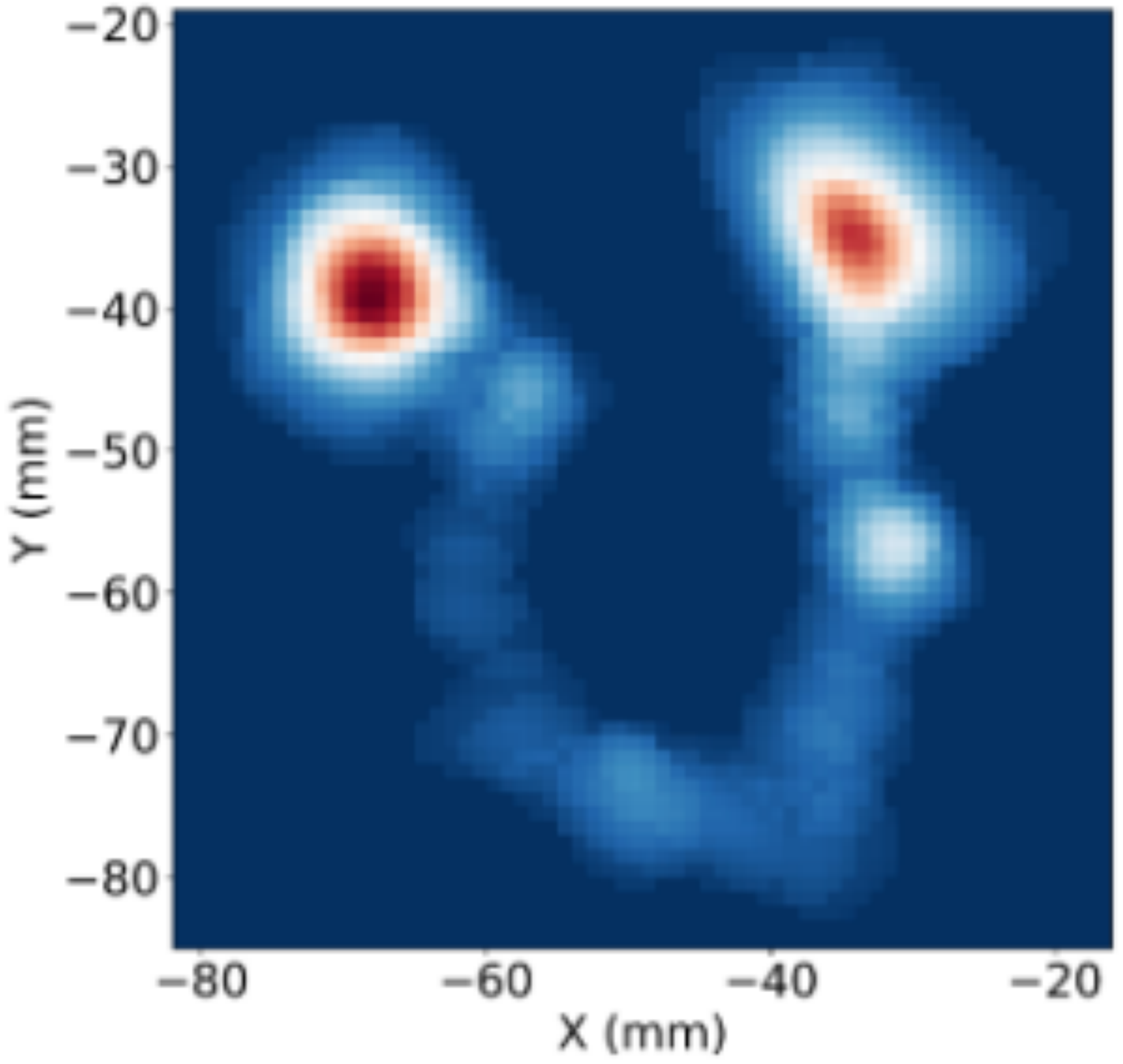
The @next technology

High Pressure Gaseous Xenon
Time Projection Chamber with Electroluminescent Amplification



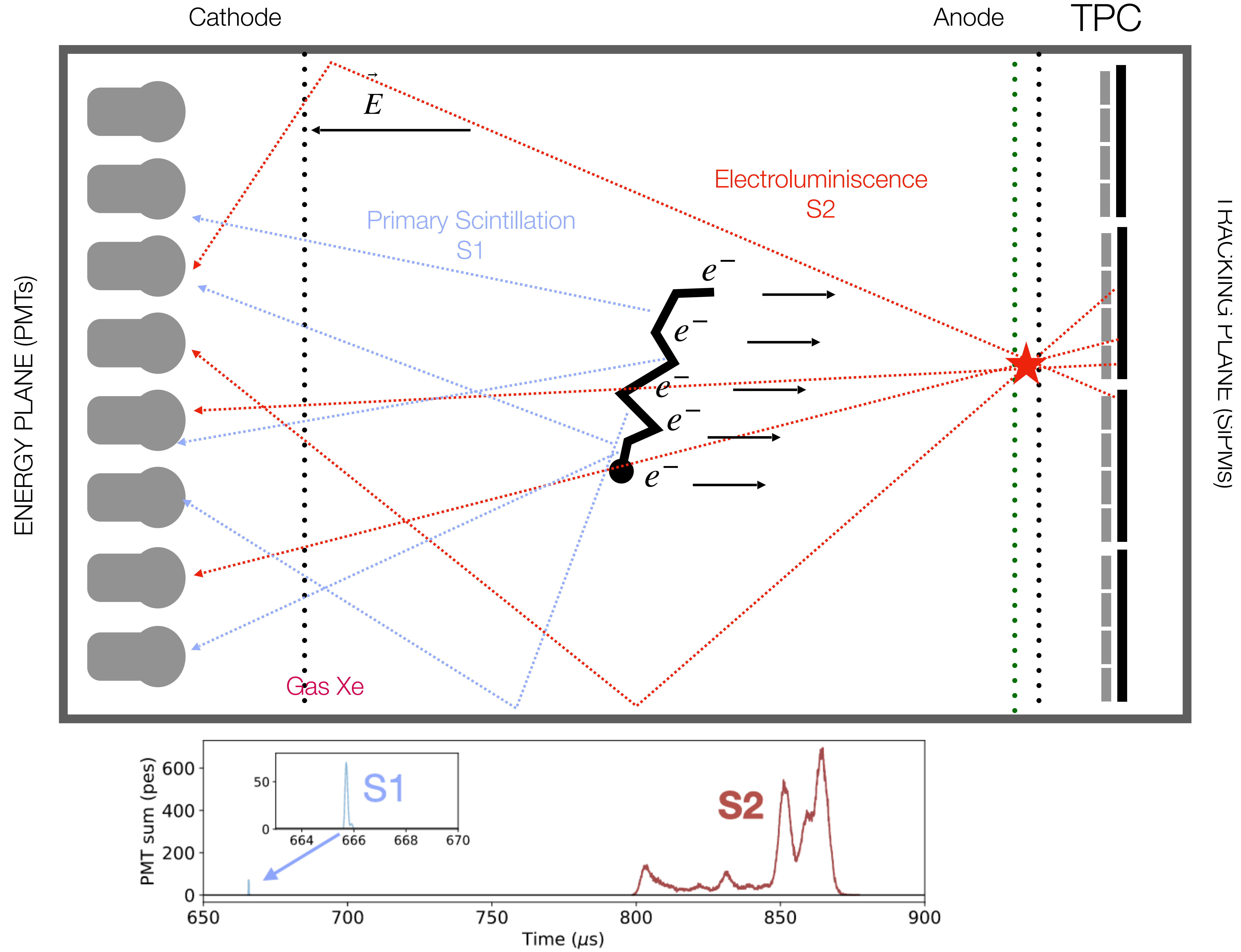
SIGNAL
$2\nu\beta\beta$ candidate

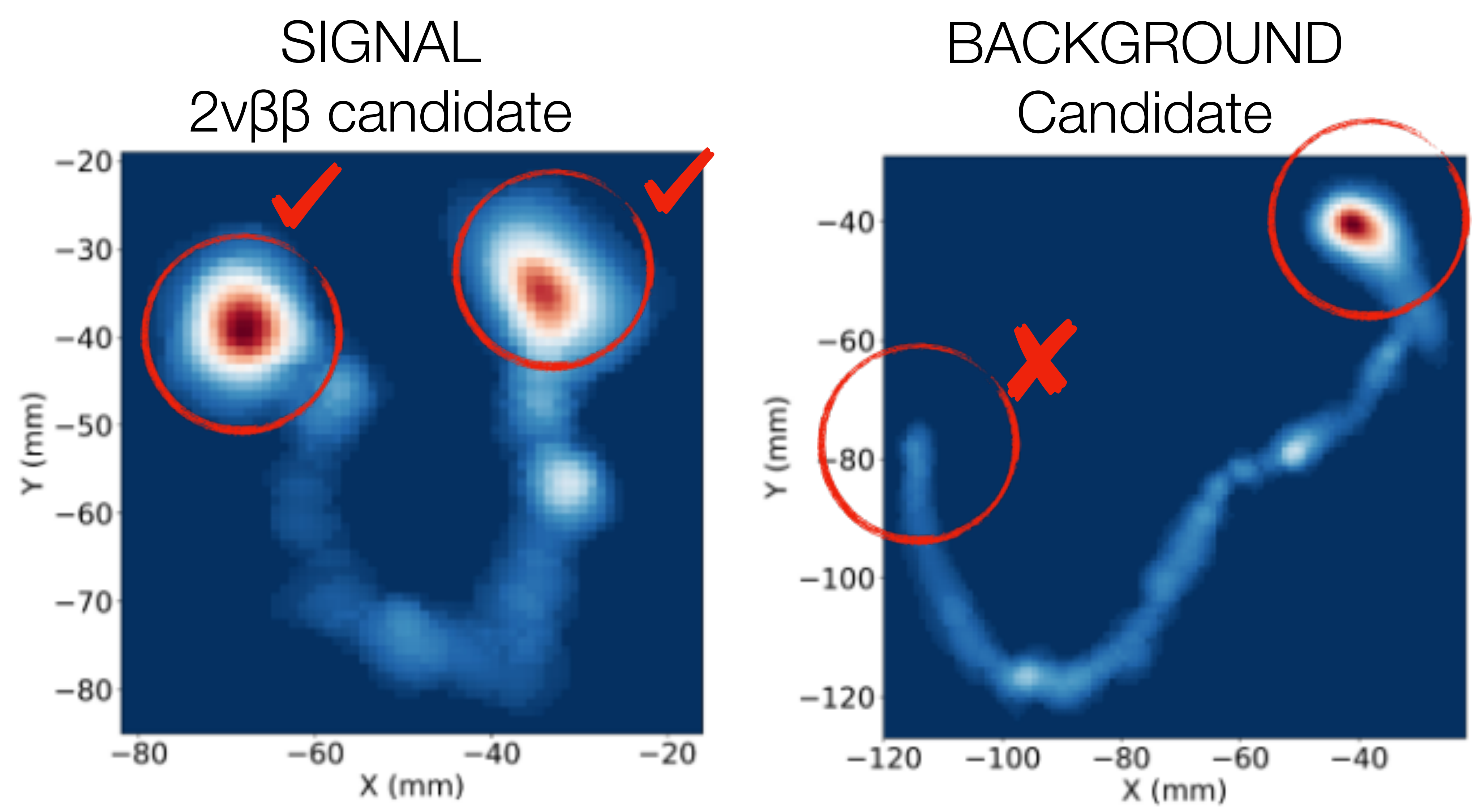


The @next technology

High Pressure Gaseous Xenon

Time Projection Chamber with Electroluminescent Amplification

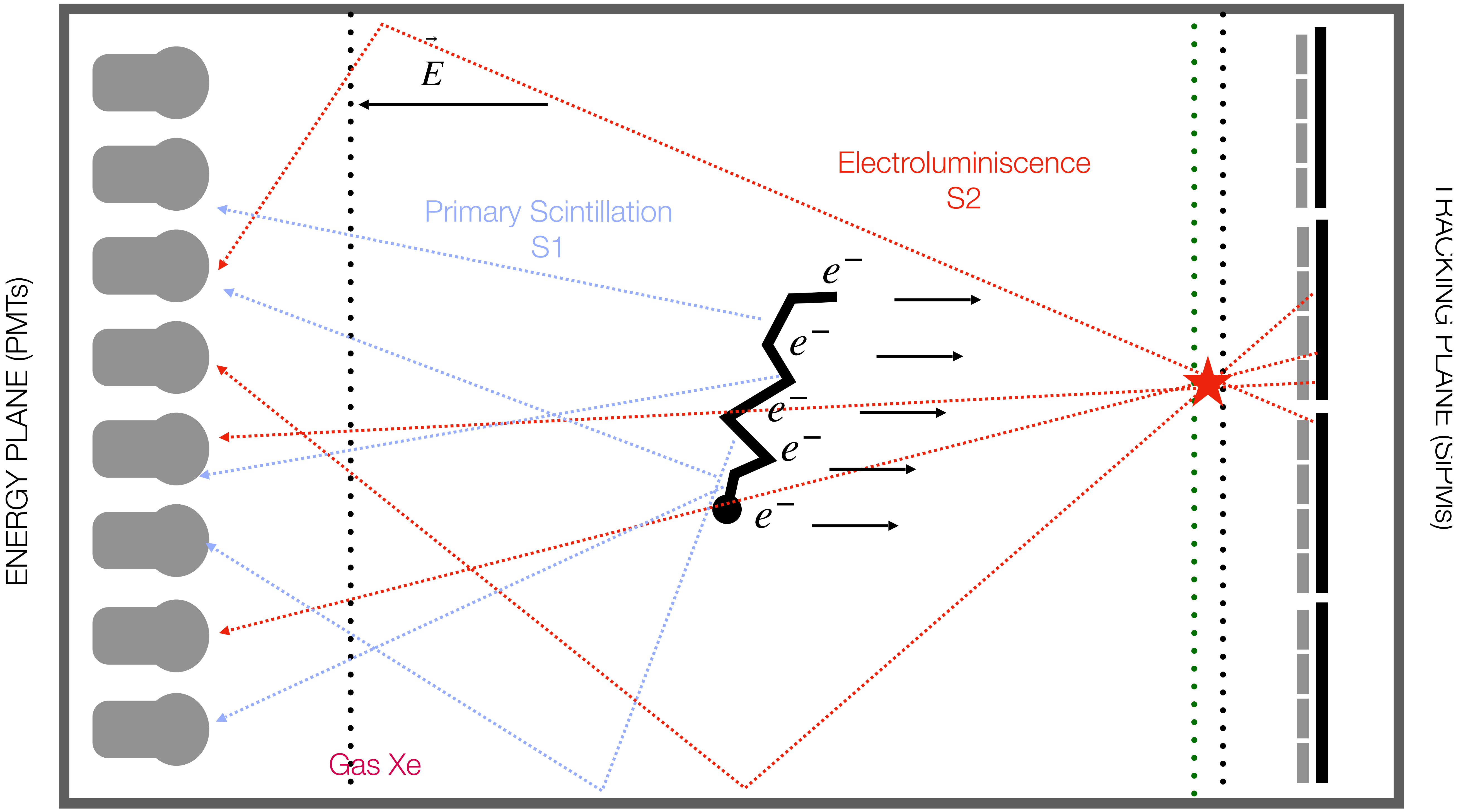


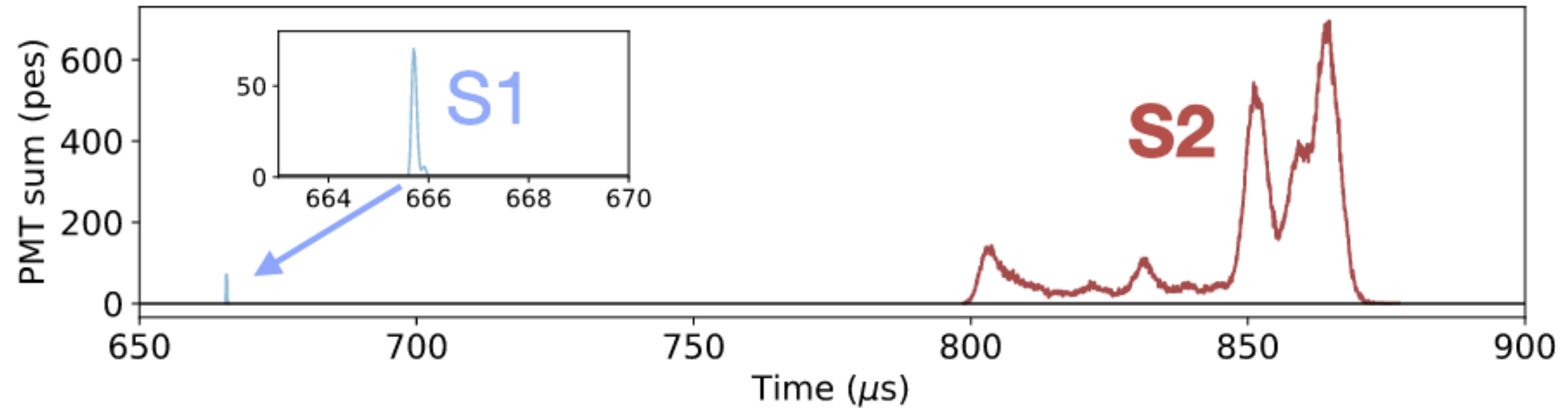


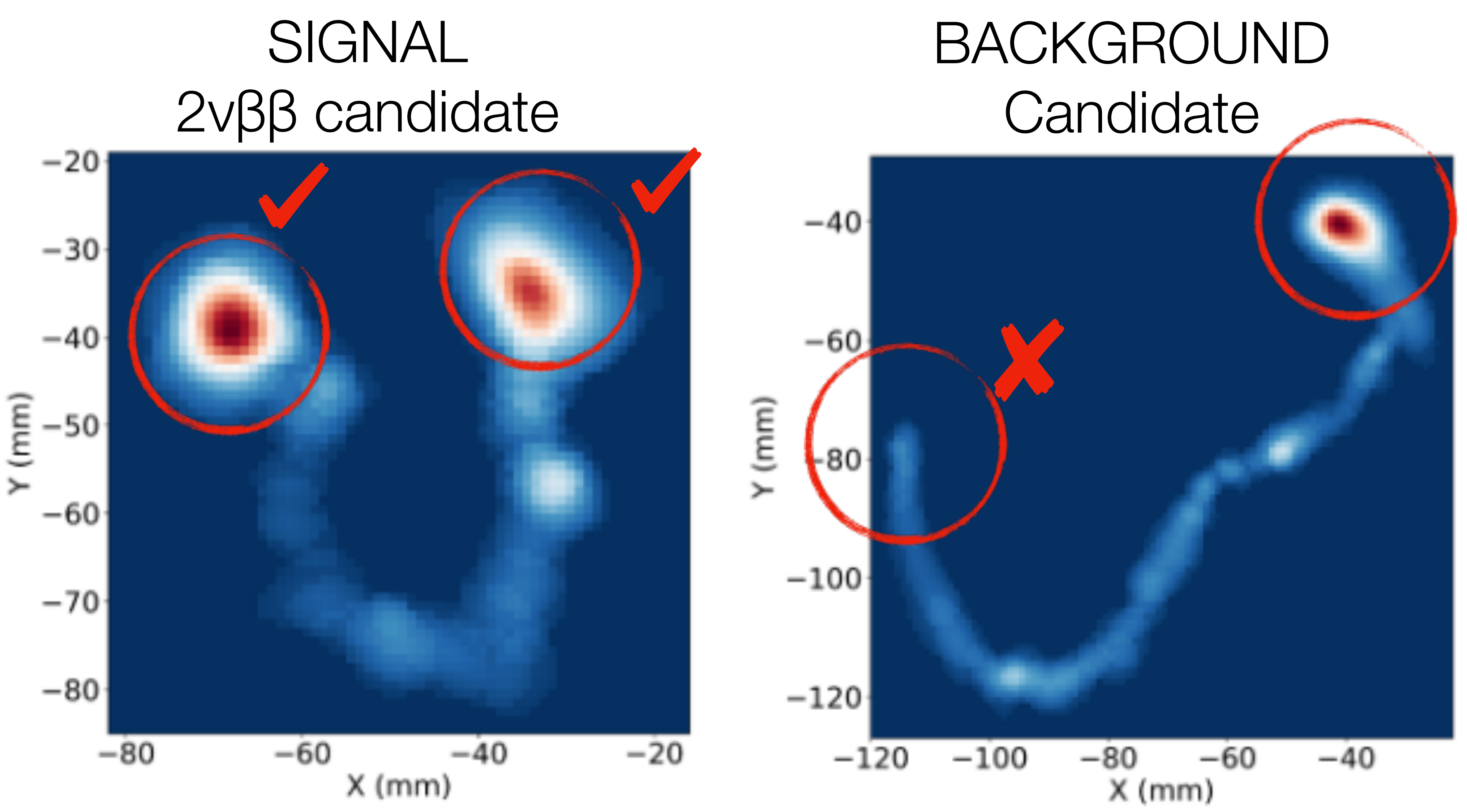
TPC allows 3D event reconstruction → improvement signal over background

The next technology

High Pressure Gaseous Xenon
Time Projection Chamber with Electroluminescent Amplification







TPC allows 3D event reconstruction → improvement signal over background

Search for 0νββ requires:

- Great **energy resolution** ✓
- Extremely **low background** ✓
- Scalability ✓

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The NEXT collaboration

NEXT

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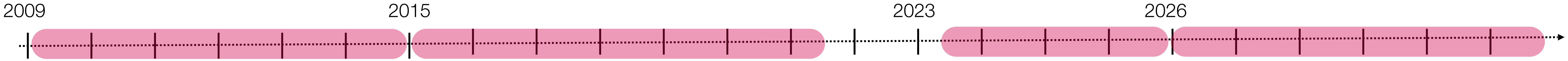
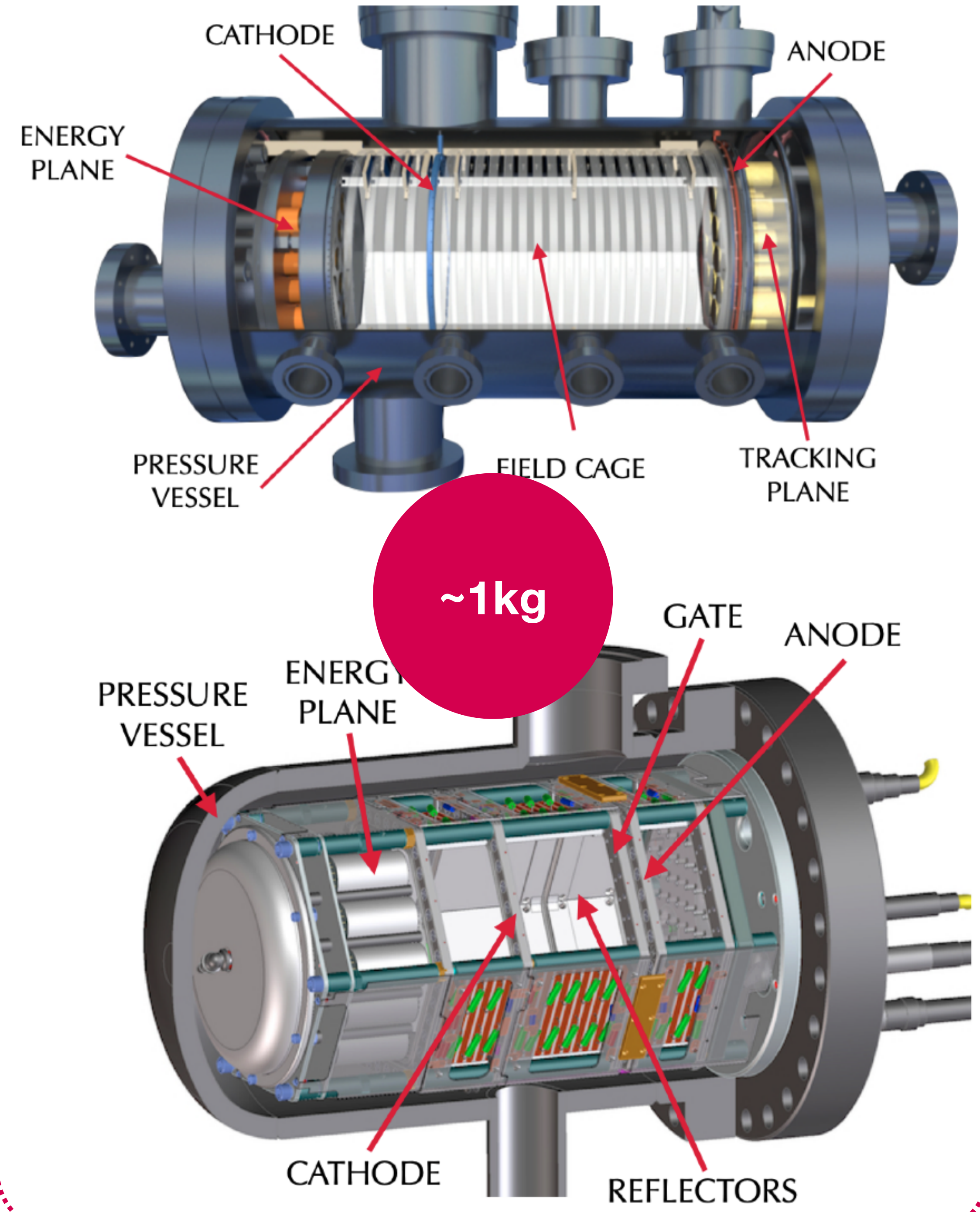
The @next programme

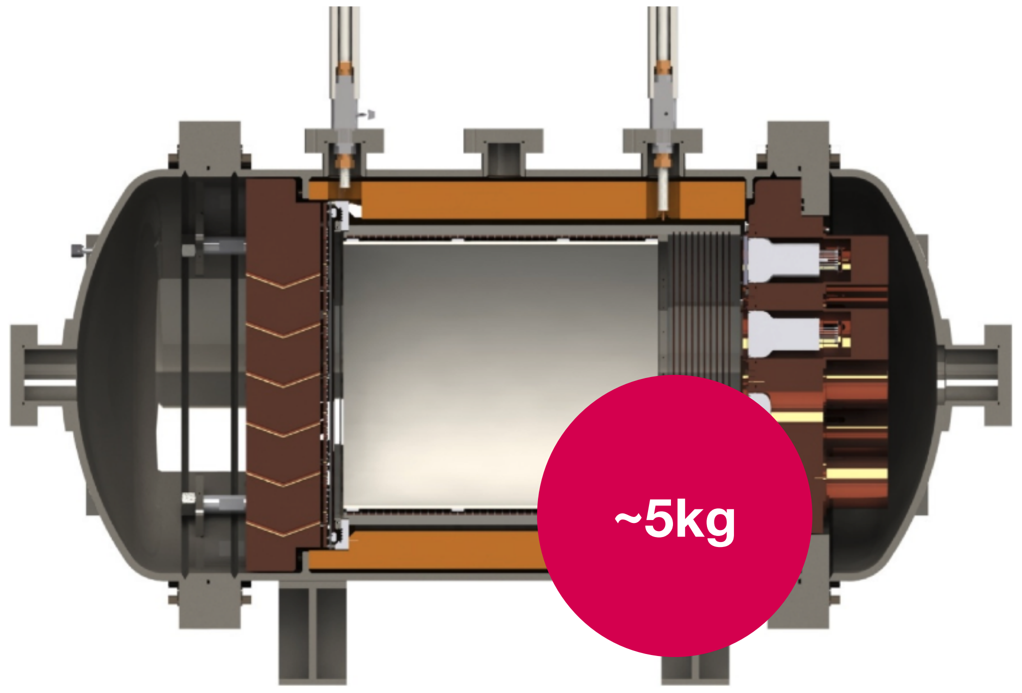


PROTOTYPES
2009/2014



NEXT-WHITE (NEW)
2015/2021

Laboratorio Subterráneo de Canfranc



NEXT-100
2023/2027

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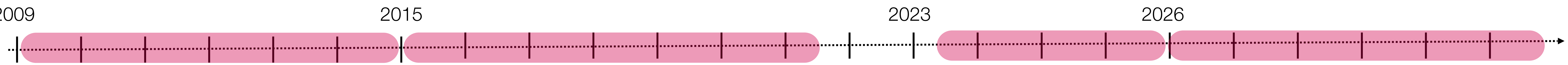
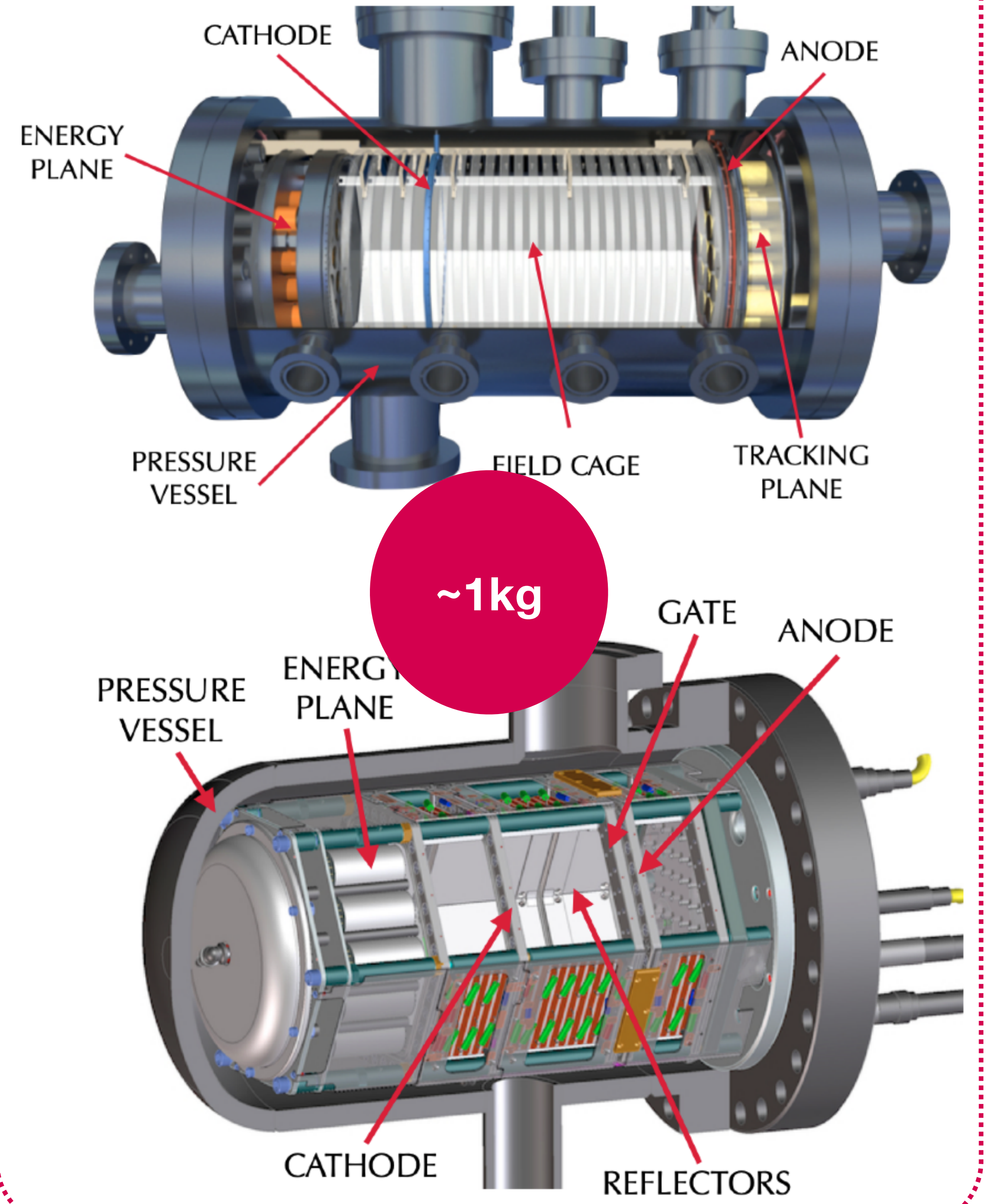
NEXT-HD
2027?

NEXT-BOLD

The @next programme



PROTOTYPES
2009/2014



NEXT-WHITE (NEW)
2015/2021

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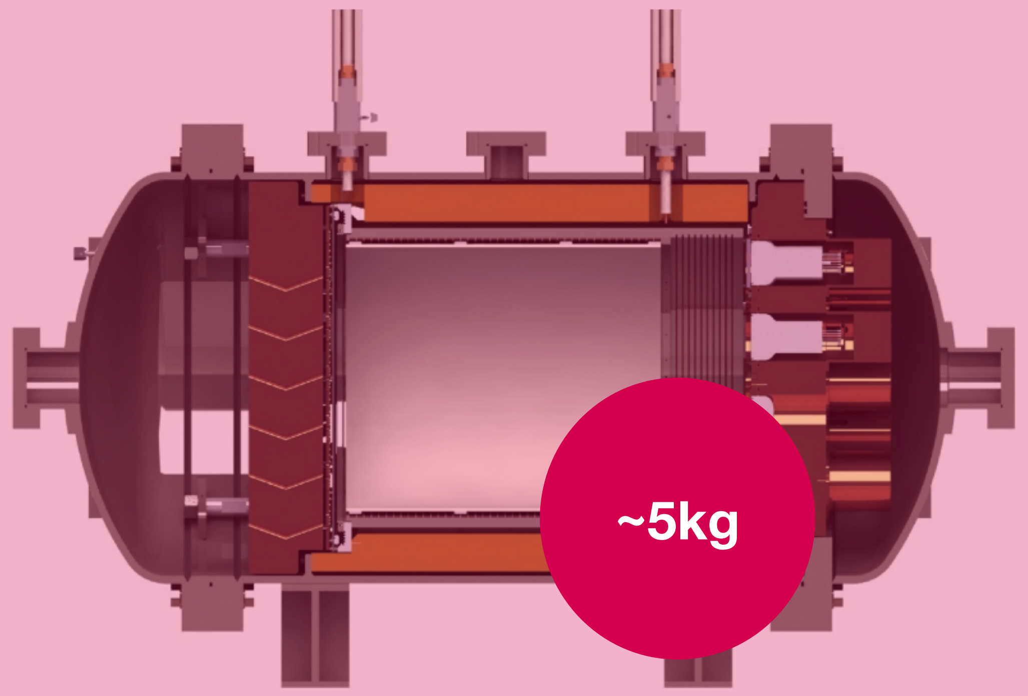

NEXT-100
2023/2027

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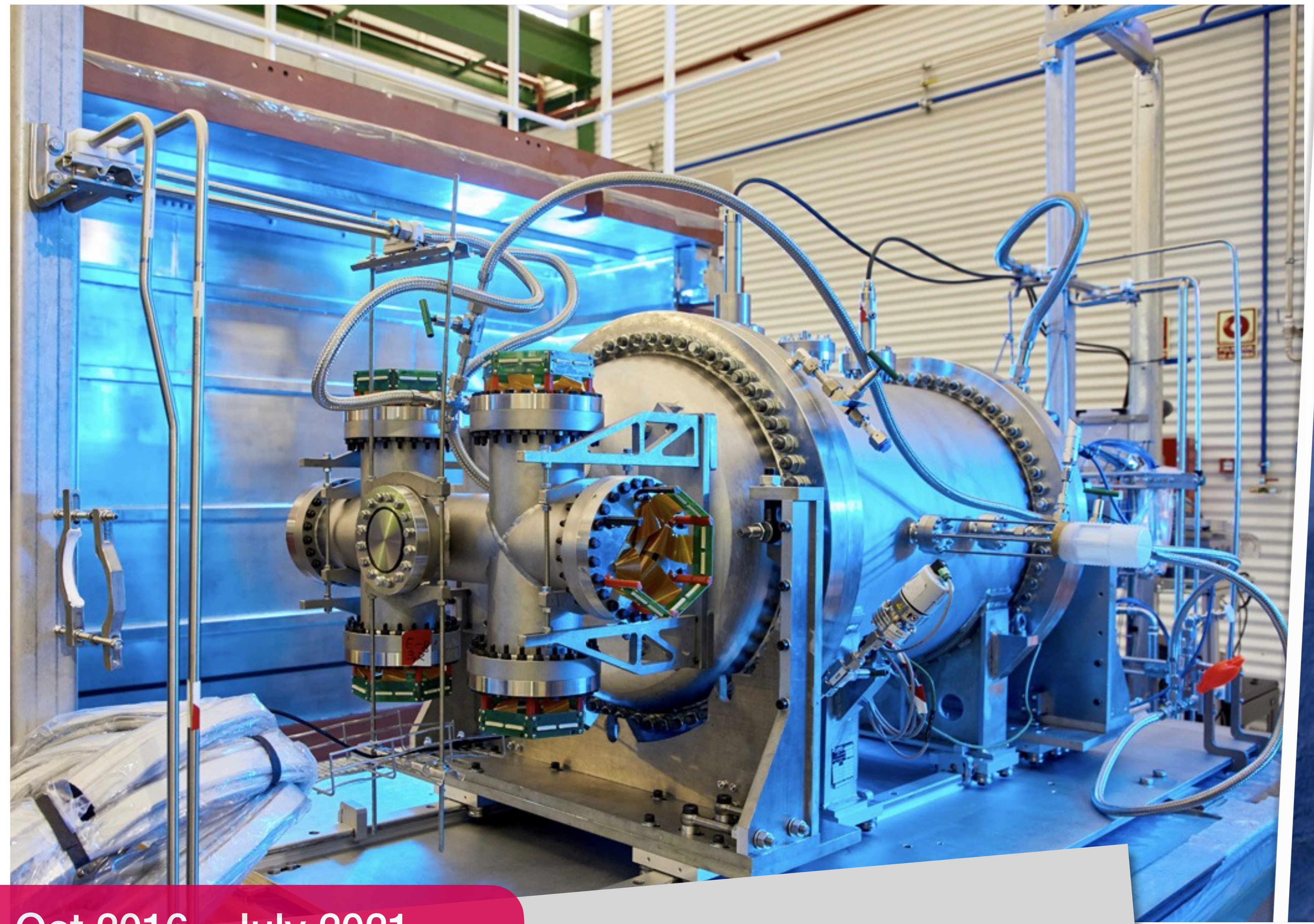
NEXT-HD
2027?

NEXT-BOLD

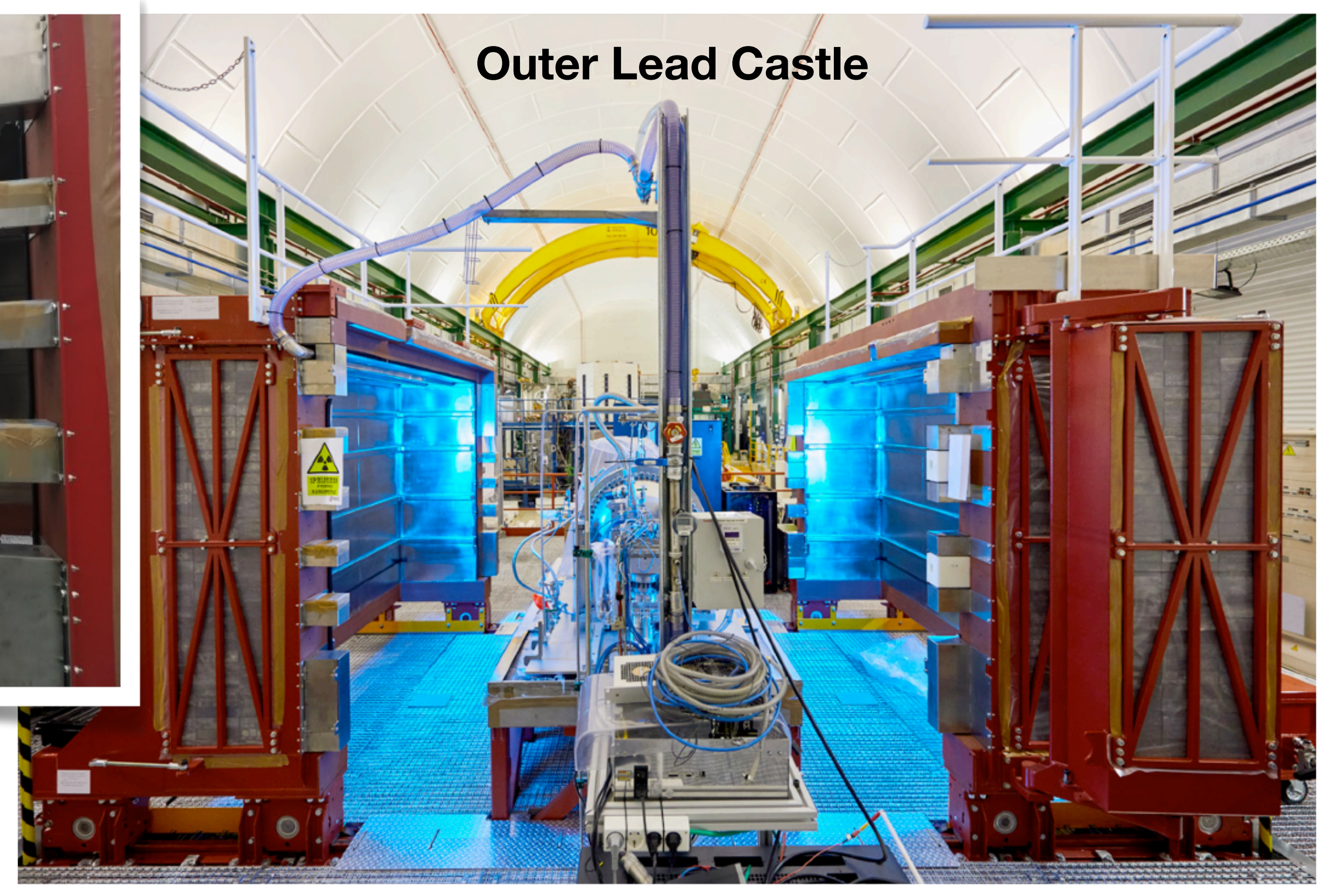
The next-white (NEW) detector



Oct 2016 - July 2021

NEW detector:

- Validate **technology** with a large-scale **radio pure detector**
- **Background** model assessment
- Demonstrate excellent **energy resolution**
- Achieve efficient **discrimination** between **single and double electron** tracks
- Measurement **2νββ** of **136Xe**



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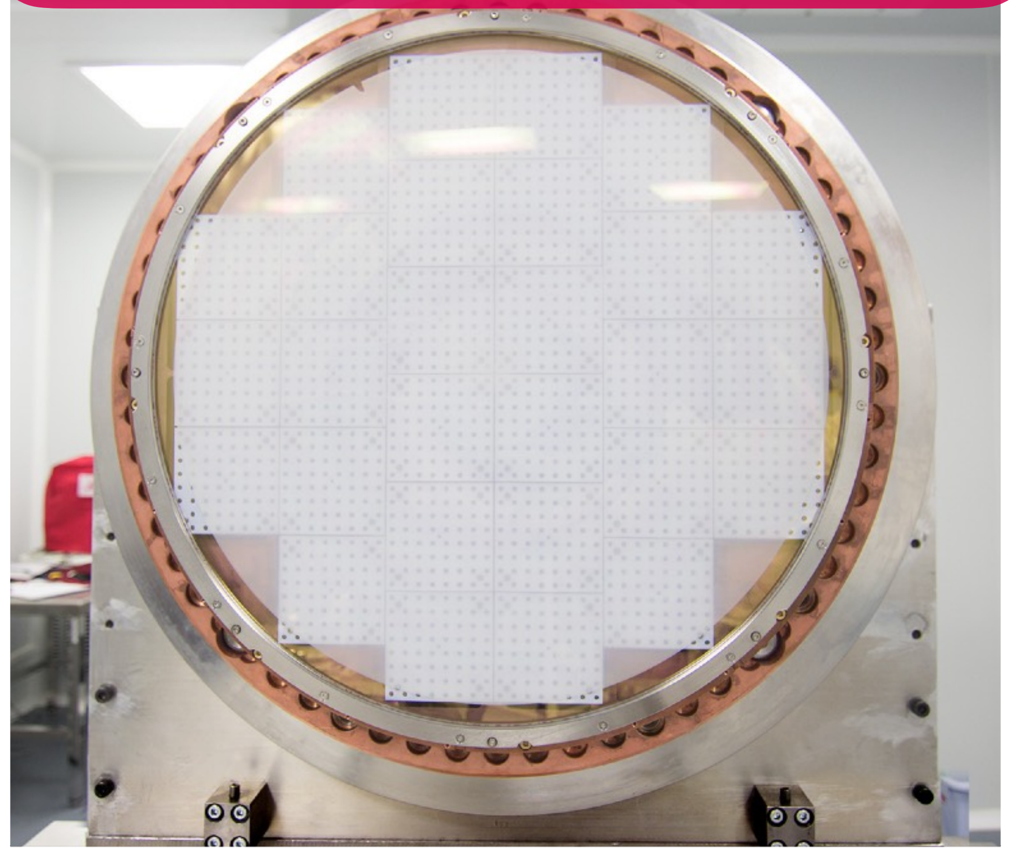
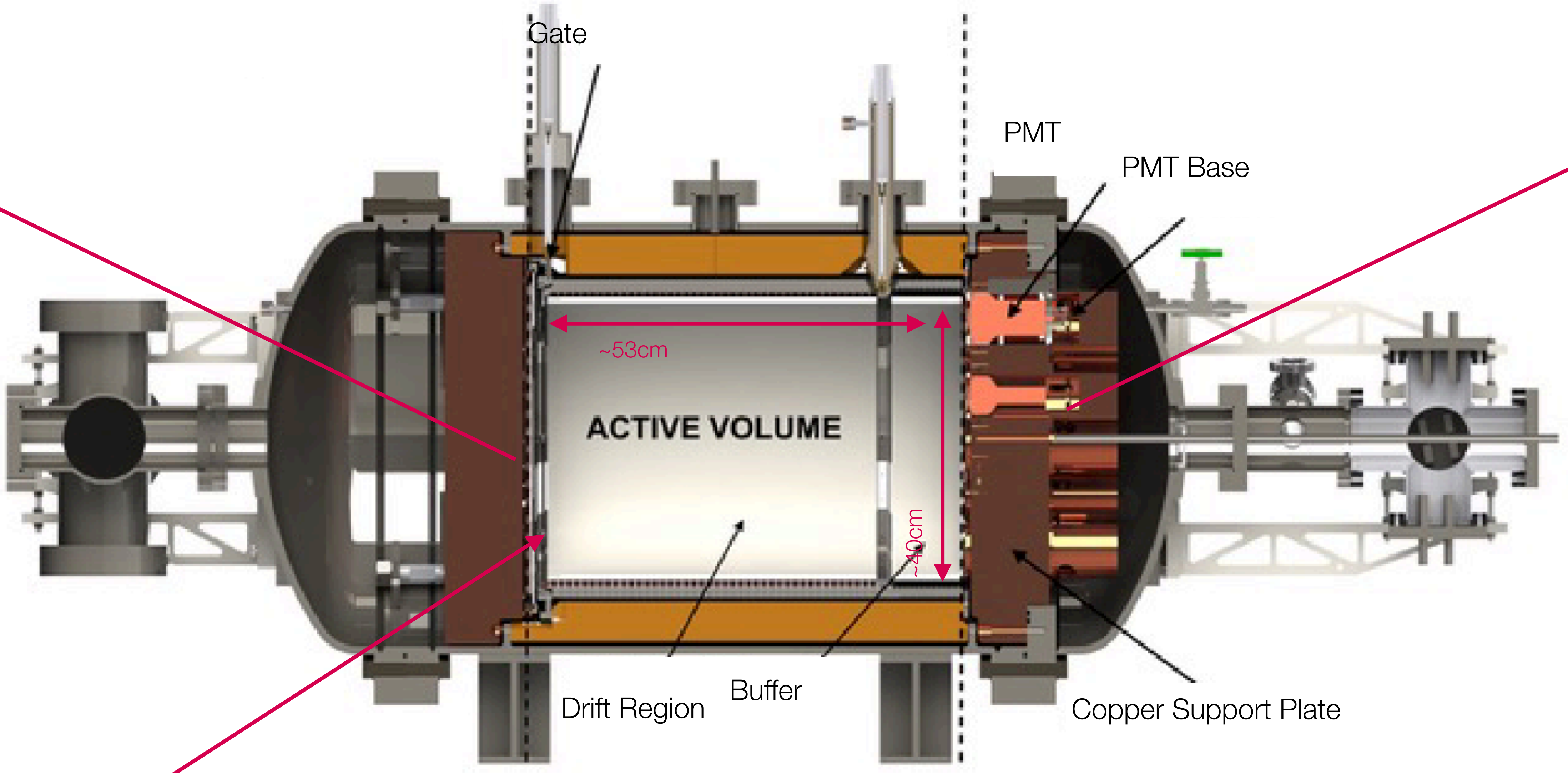
The @next-white (NEW) detector

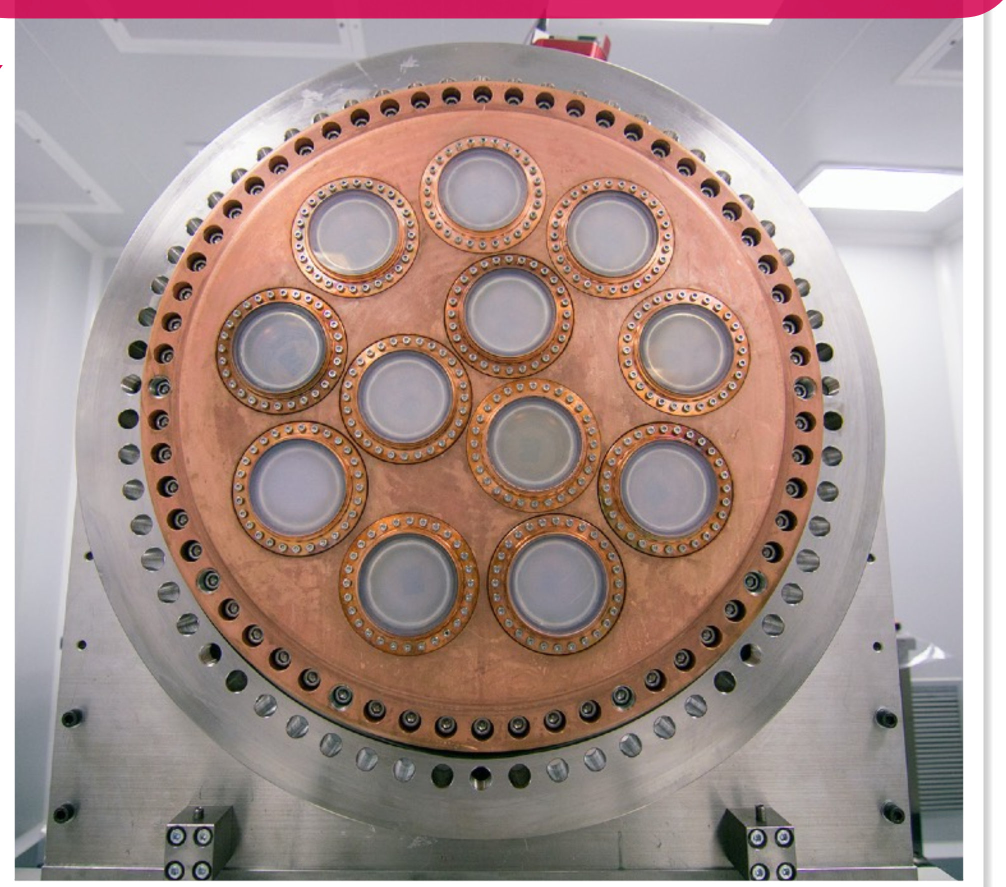
Tracking plane



1792 SENSL SiPMs
1x1 mm2 - 10 mm



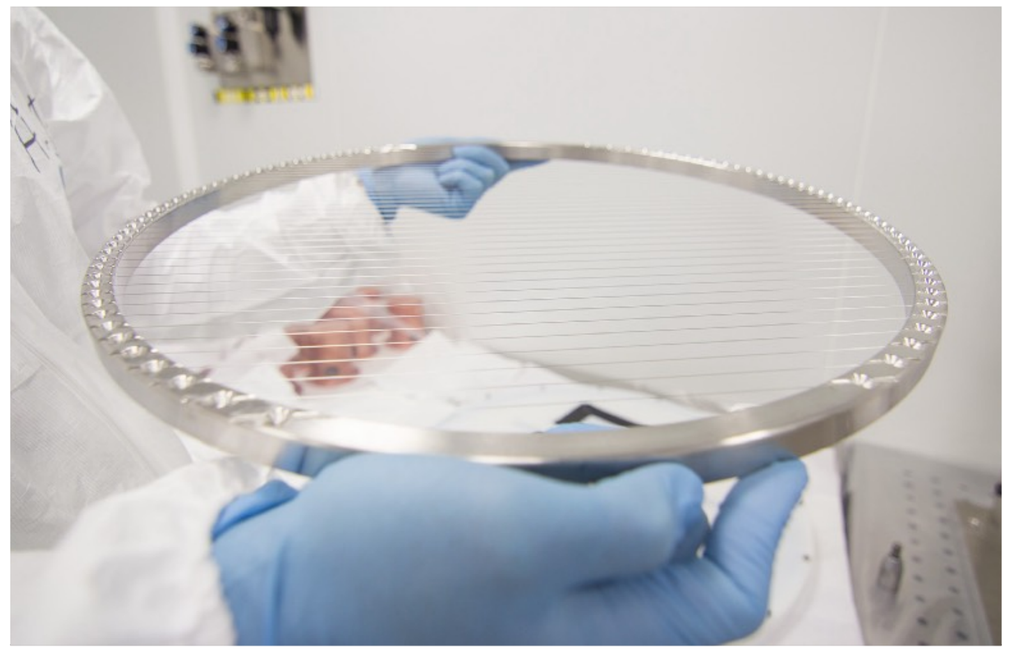
Energy plane

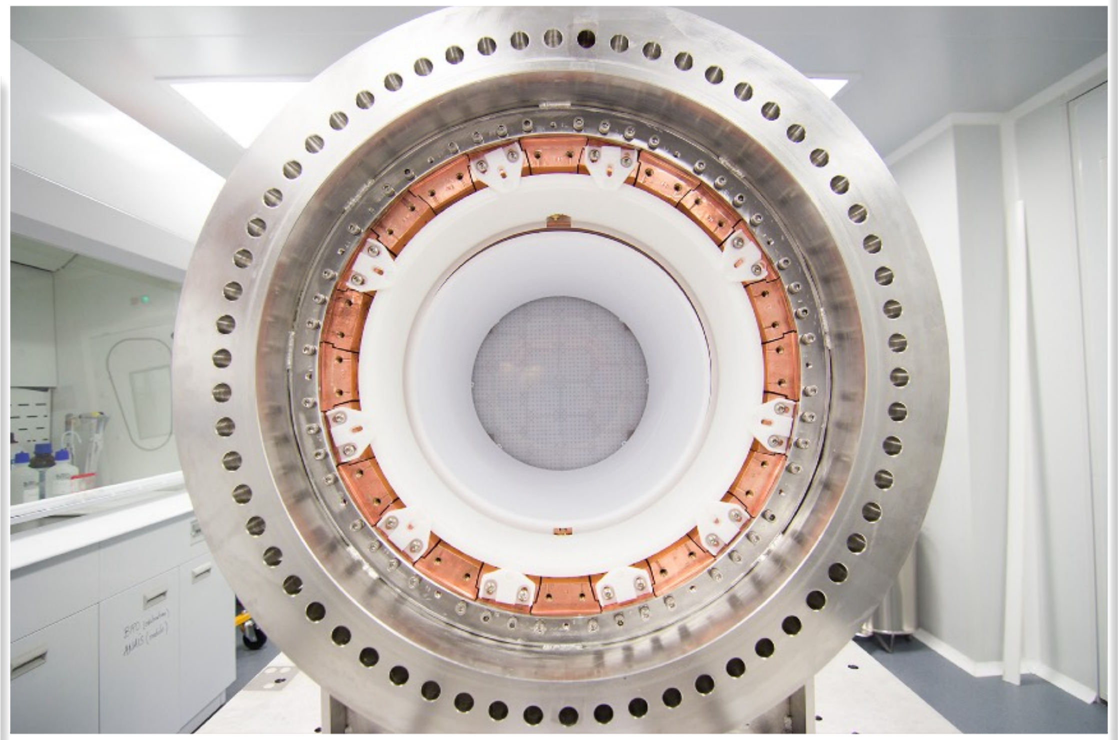


12 PMTs
Hamamatsu

Anode ITO surface coated over a silica plate

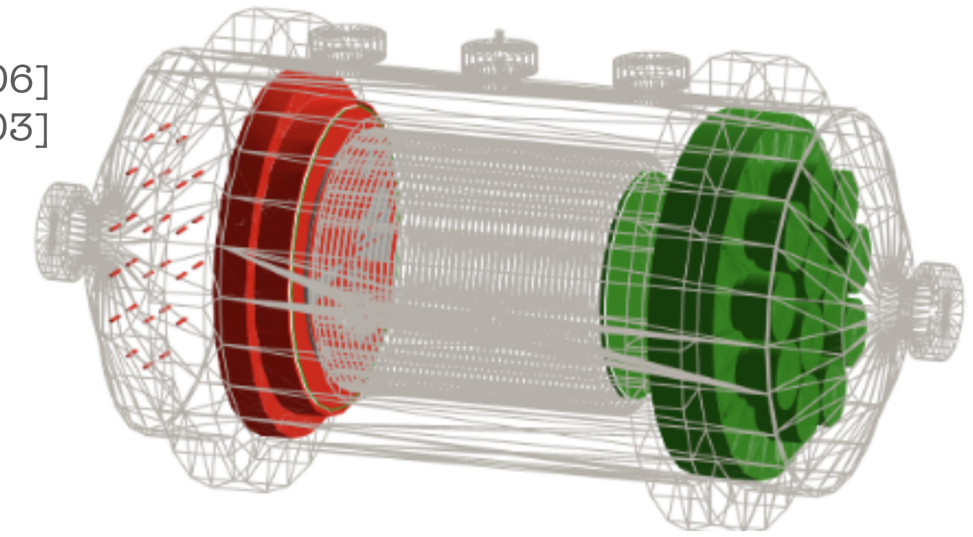
Cathode and EL grids



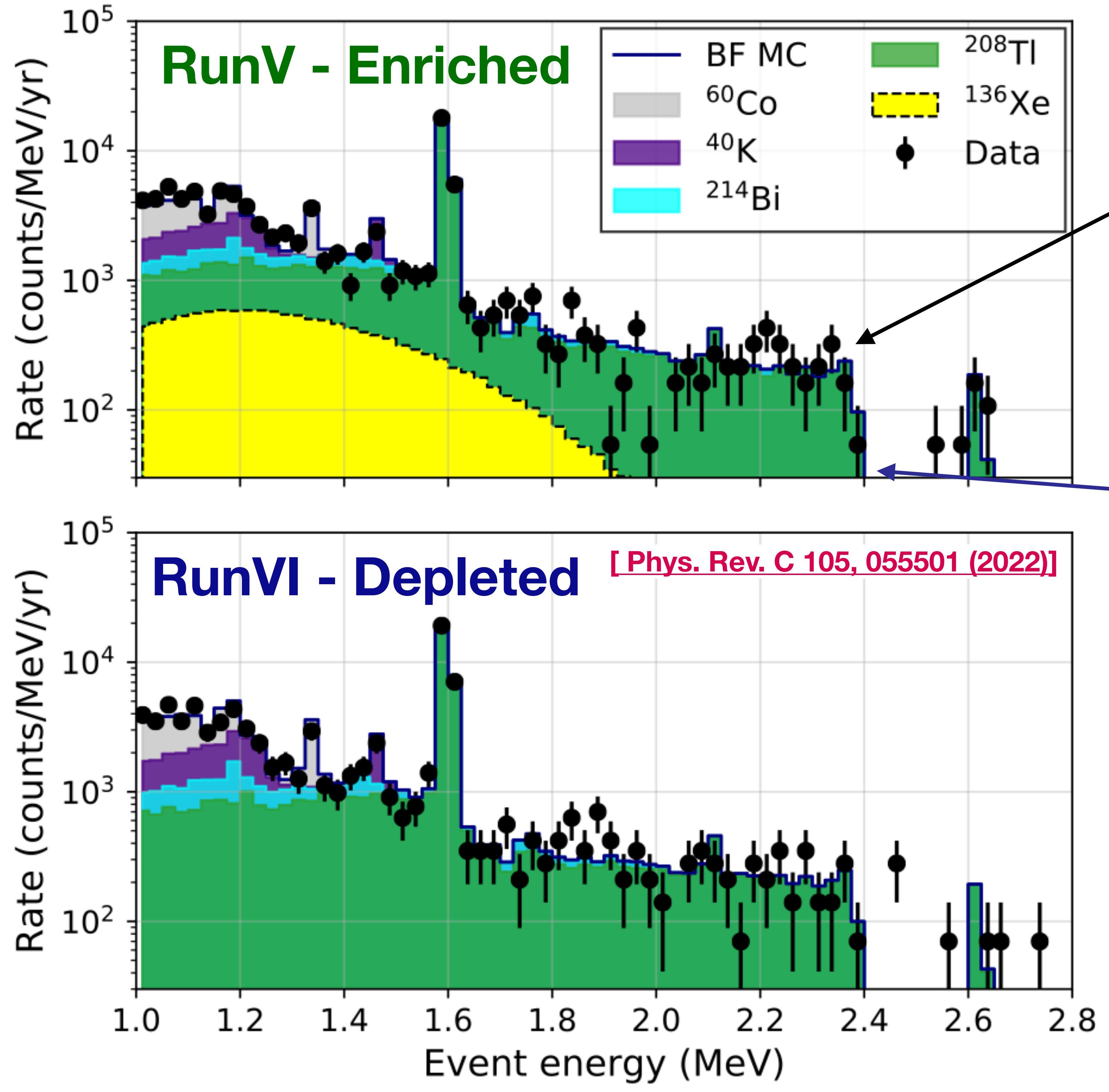


$\beta\beta$ measurement in NEW

[JINST 8 (2013) T01002]
[JINST 10 (2015) 05, P05006]
[JINST 12 (2017) 08, T08003]



2νββ Background Model Dependent



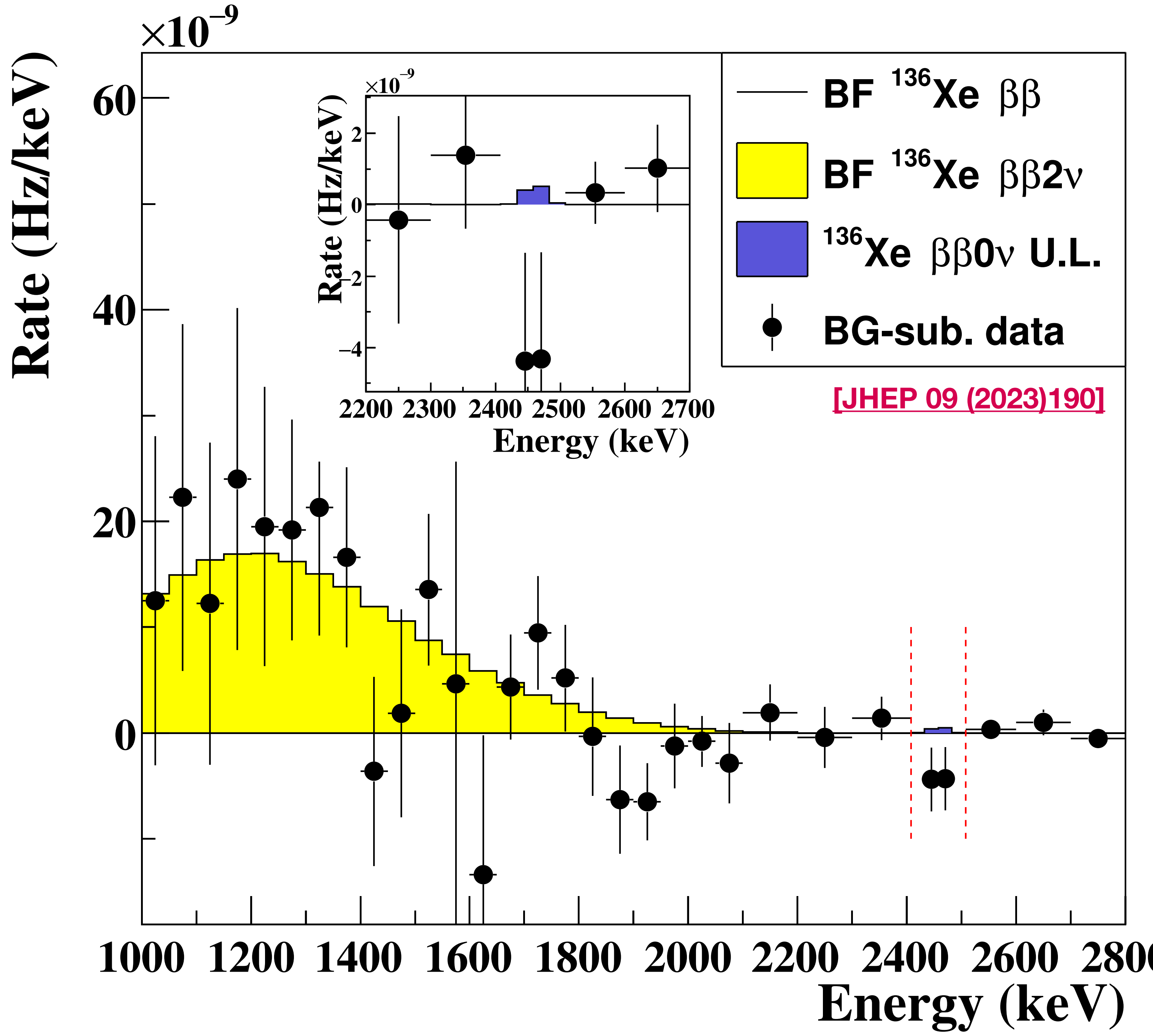
ββ-like event rates (after track selection using RL deconvolution)

Best-fit MC (accounting for each background contribution)

Joint fit → good precision by constraining the backgrounds

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

0νββ Almost Background Model Independent



Bkg Subtracted distribution fitted to 0νββ expectation

$$T_{1/2}^{0\nu} > 1.3 \cdot 10^{24}\ \text{yr (90\% CL)}$$

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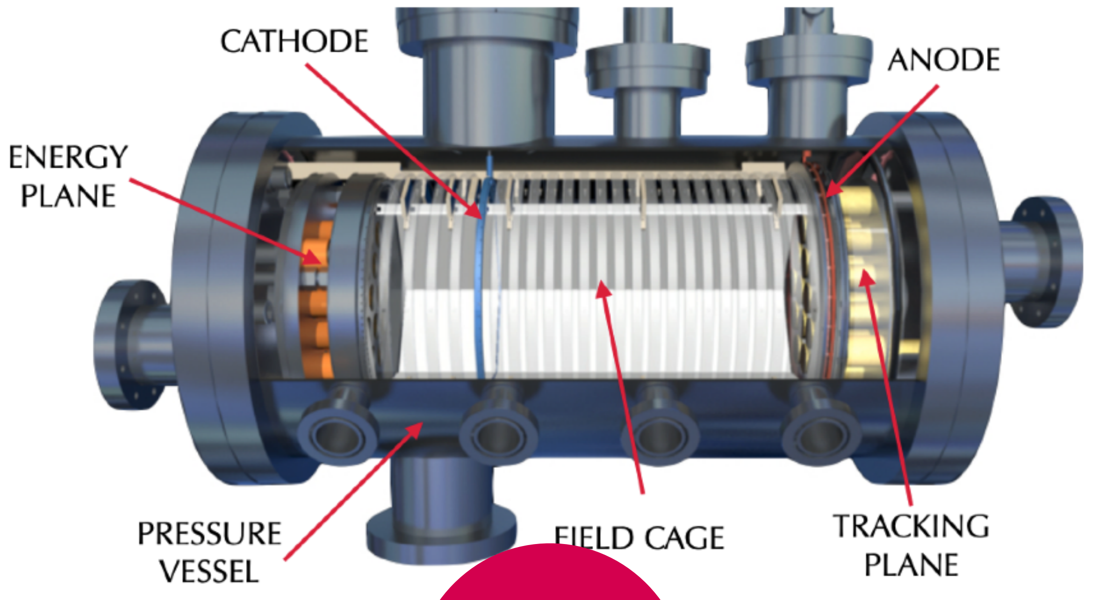
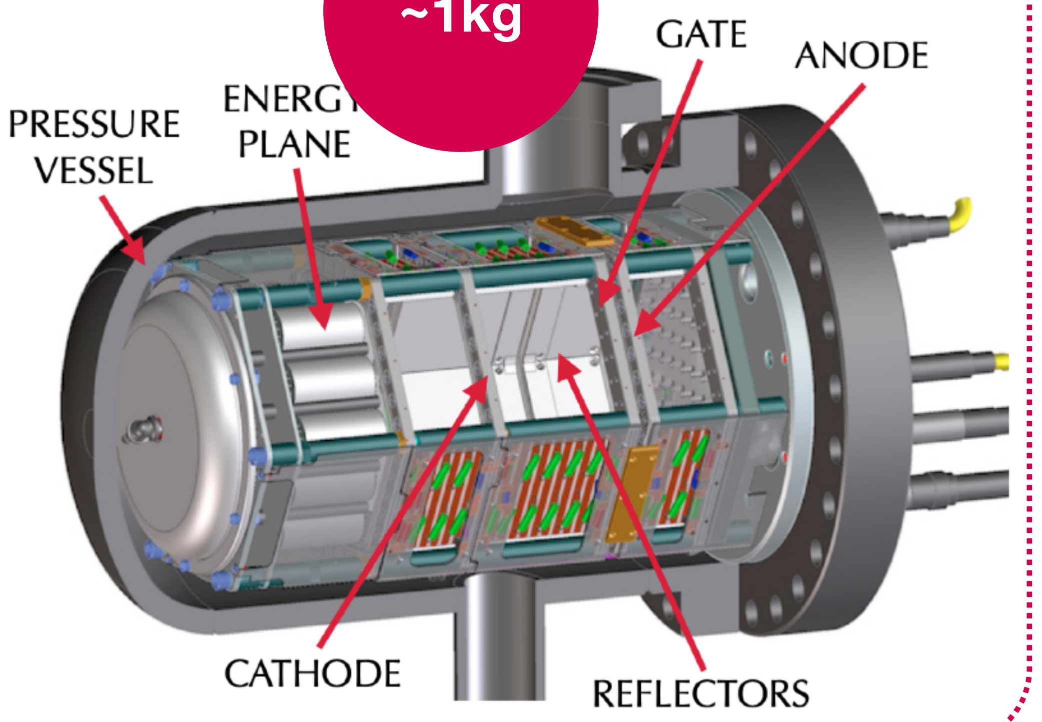
The @next programme

2009 | 2015 | 2023 | 2026

PROTOTYPES
2009/2014





NEXT-WHITE (NEW)
2015/2021

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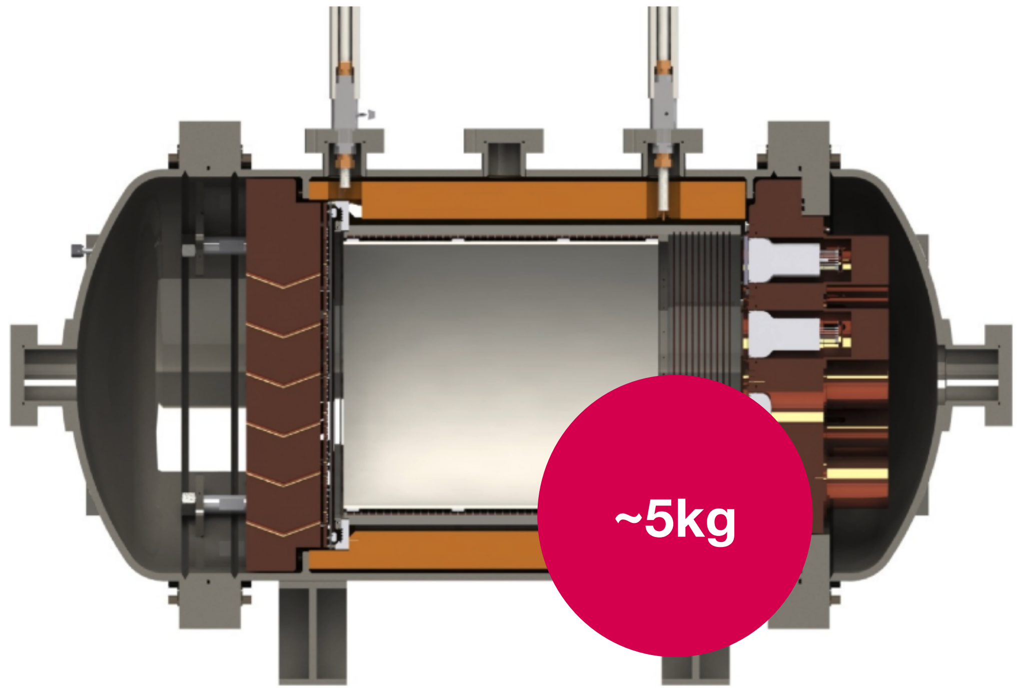

NEXT-100
2023/2027

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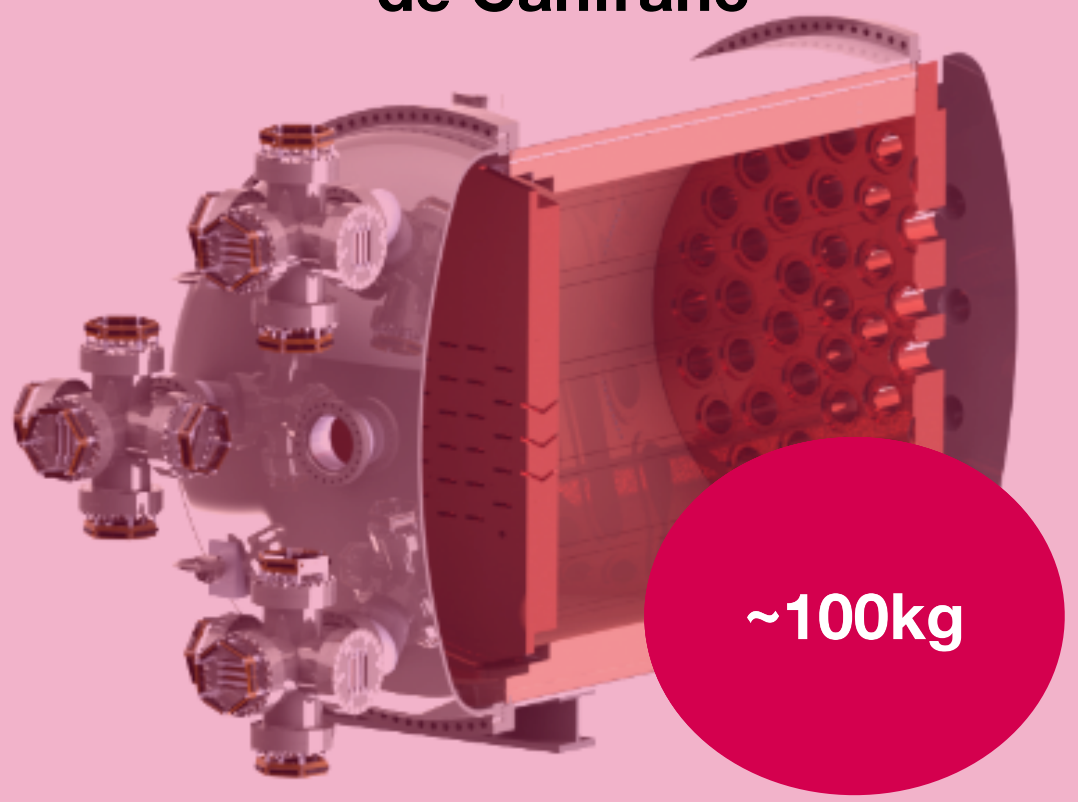

NEXT-HD
2027?

NEXT-BOLD

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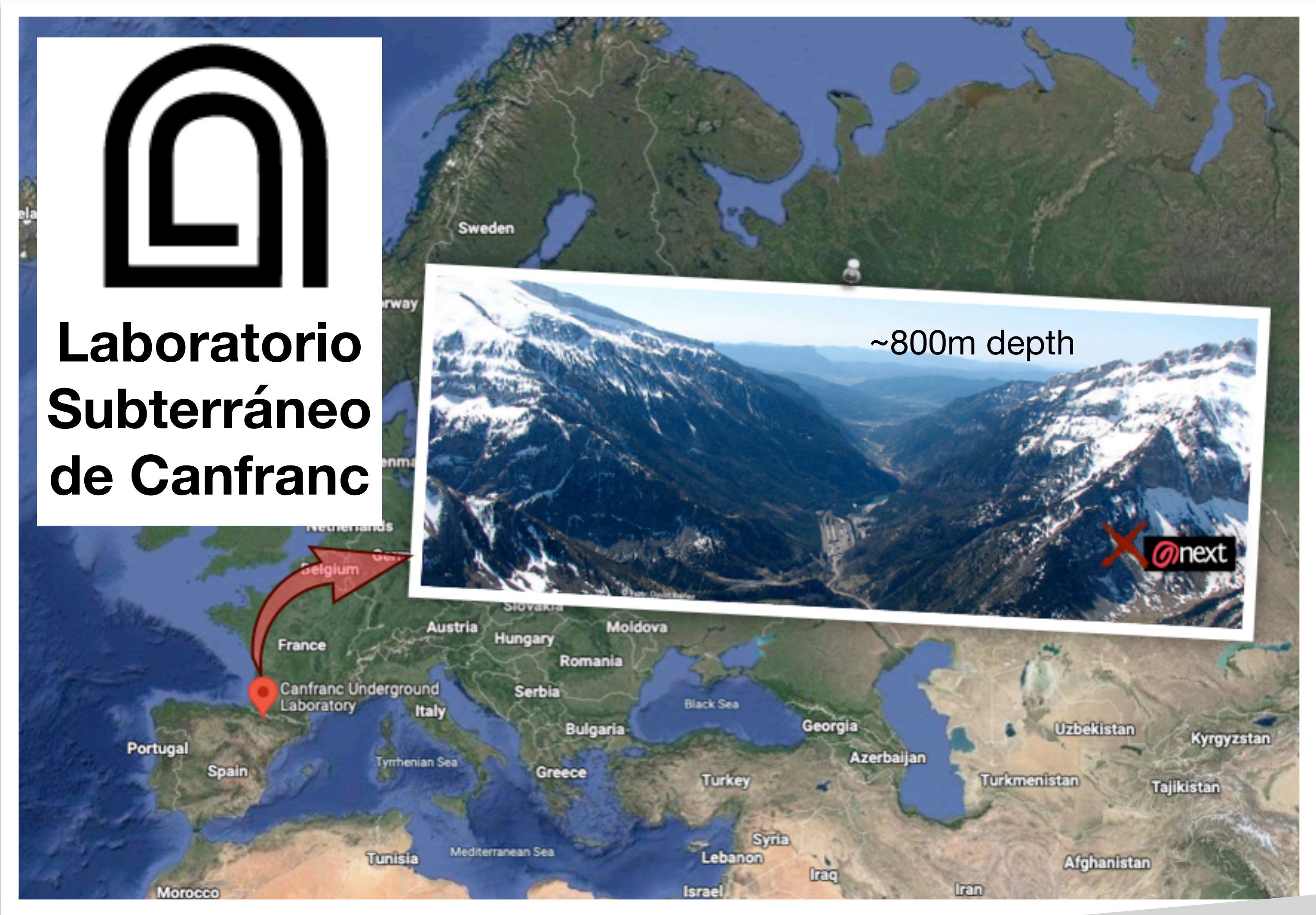
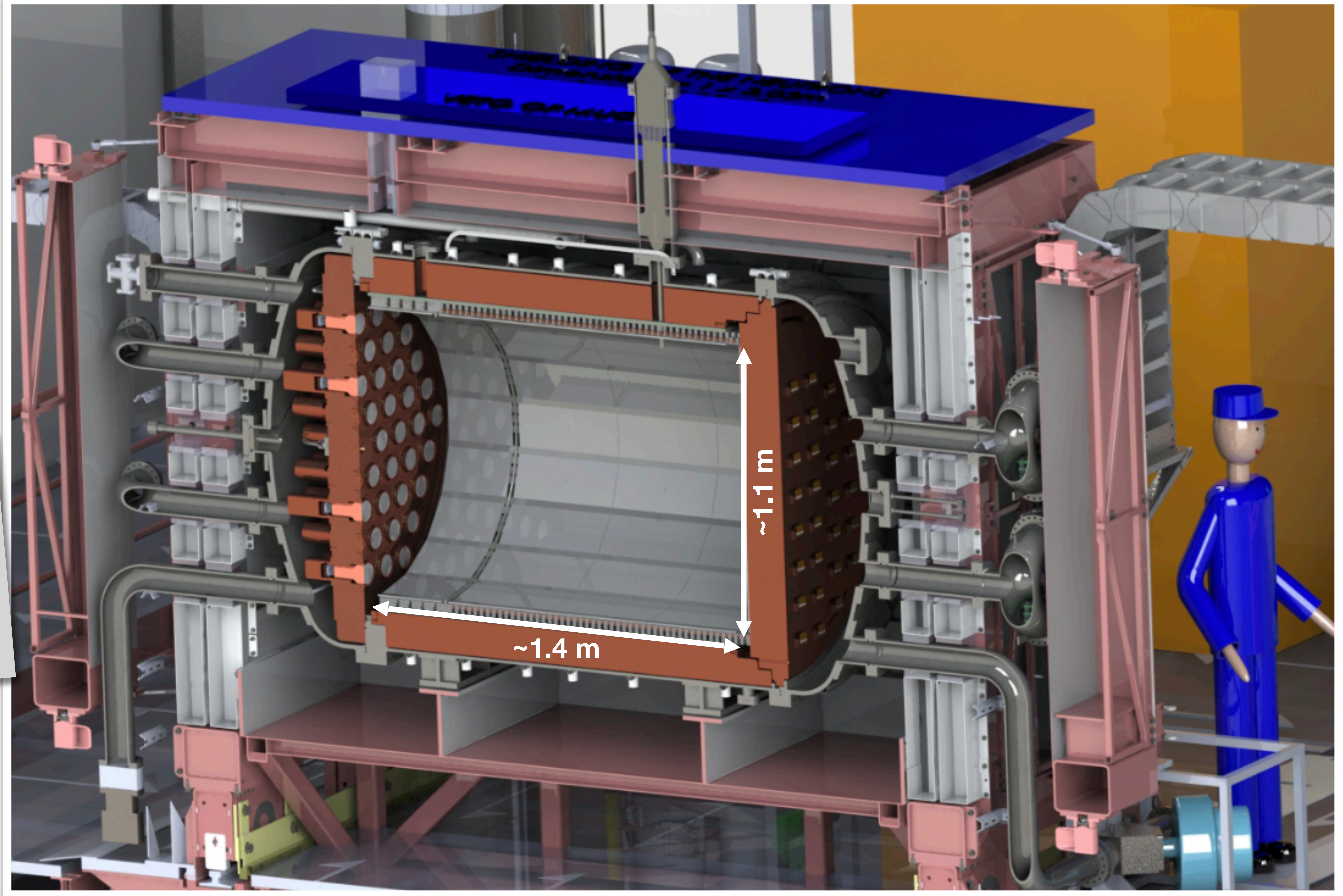
The next-100 detector



NEXT-100 detector:

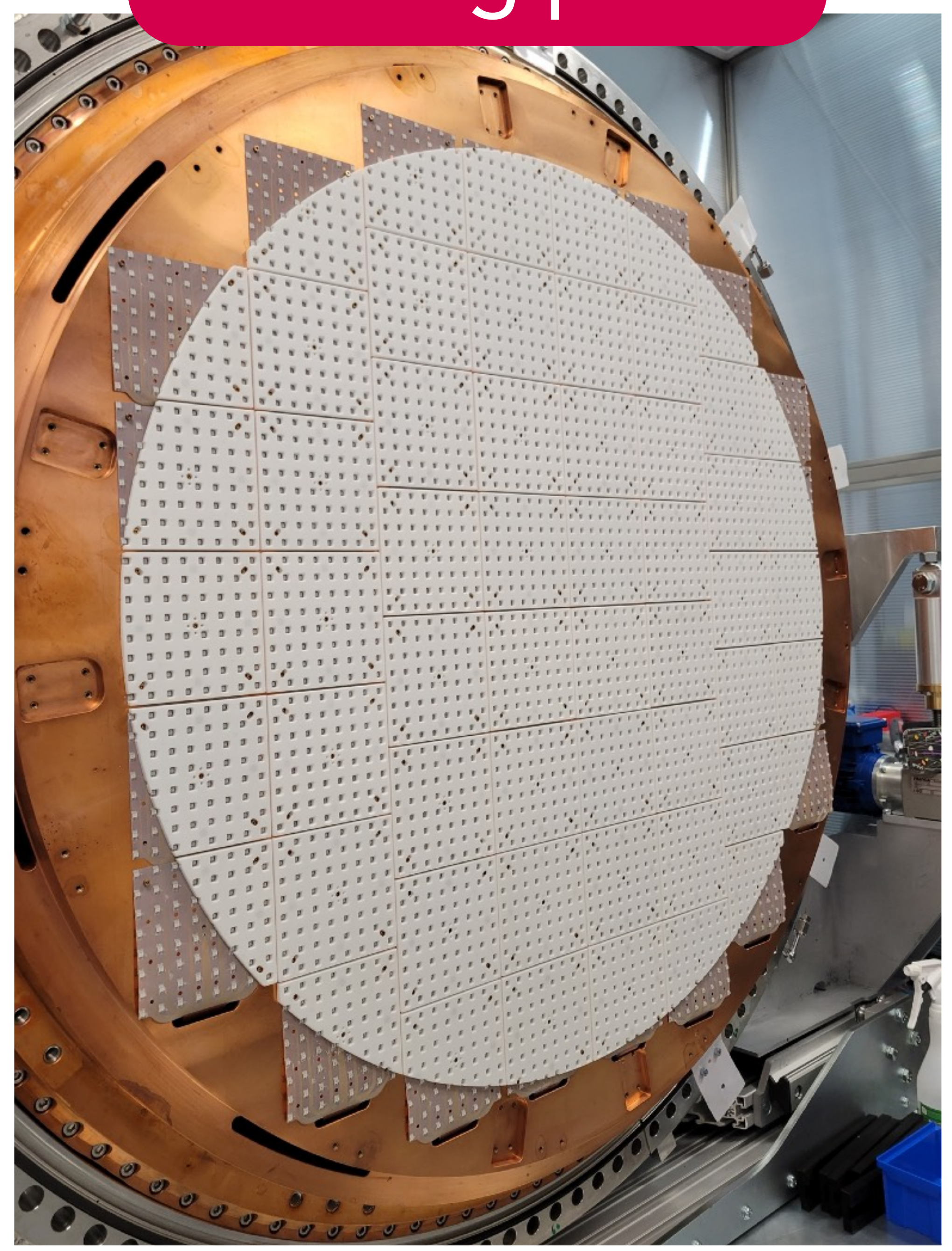
- **Energy resolution <1% at Qbb**
- Improve **radioactive** budget
- Competitive search of **0νββ**
- Prepare for the tonne-scale

- **Currently**: commissioning since May 2024

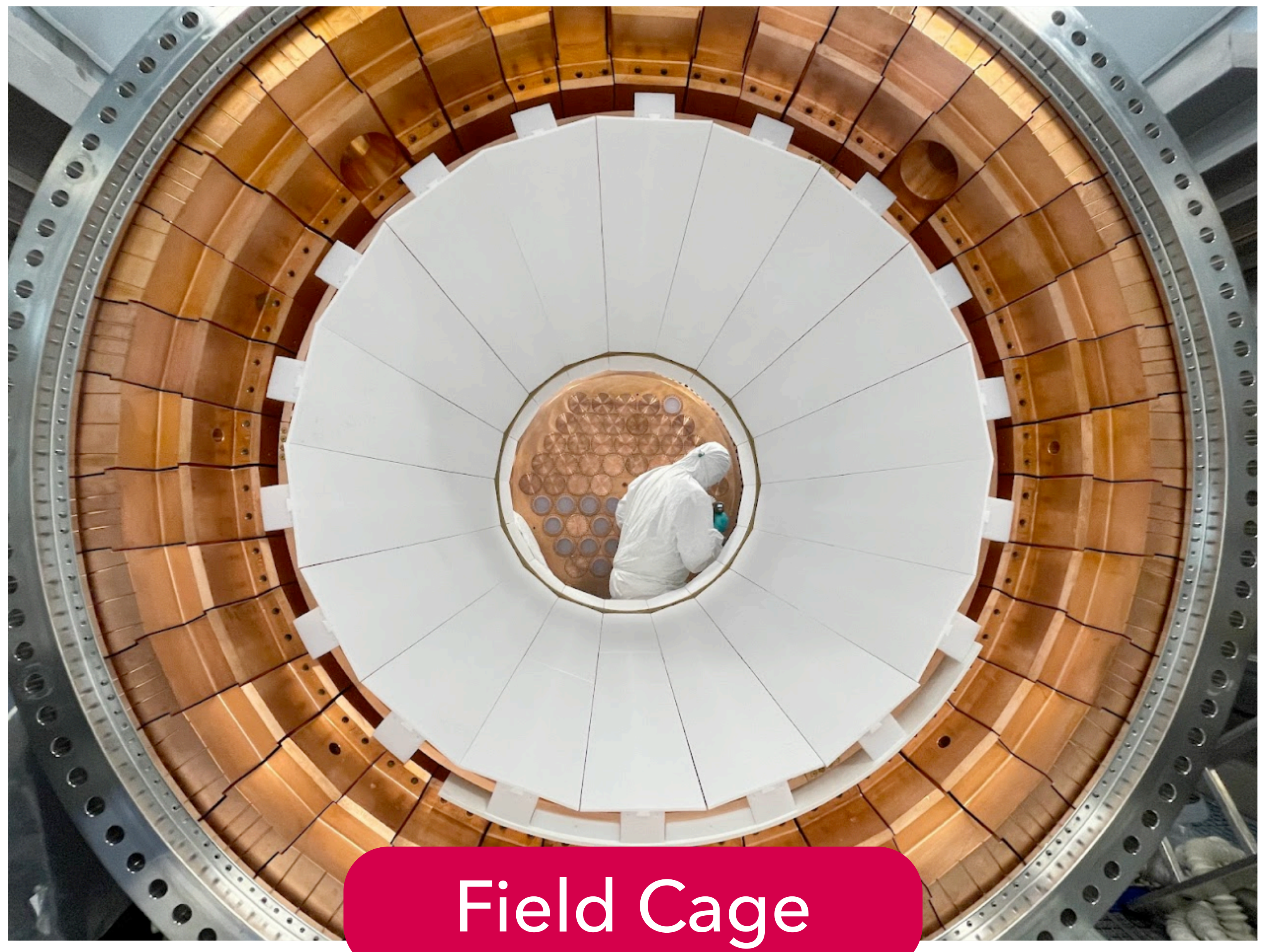


The next-100 detector

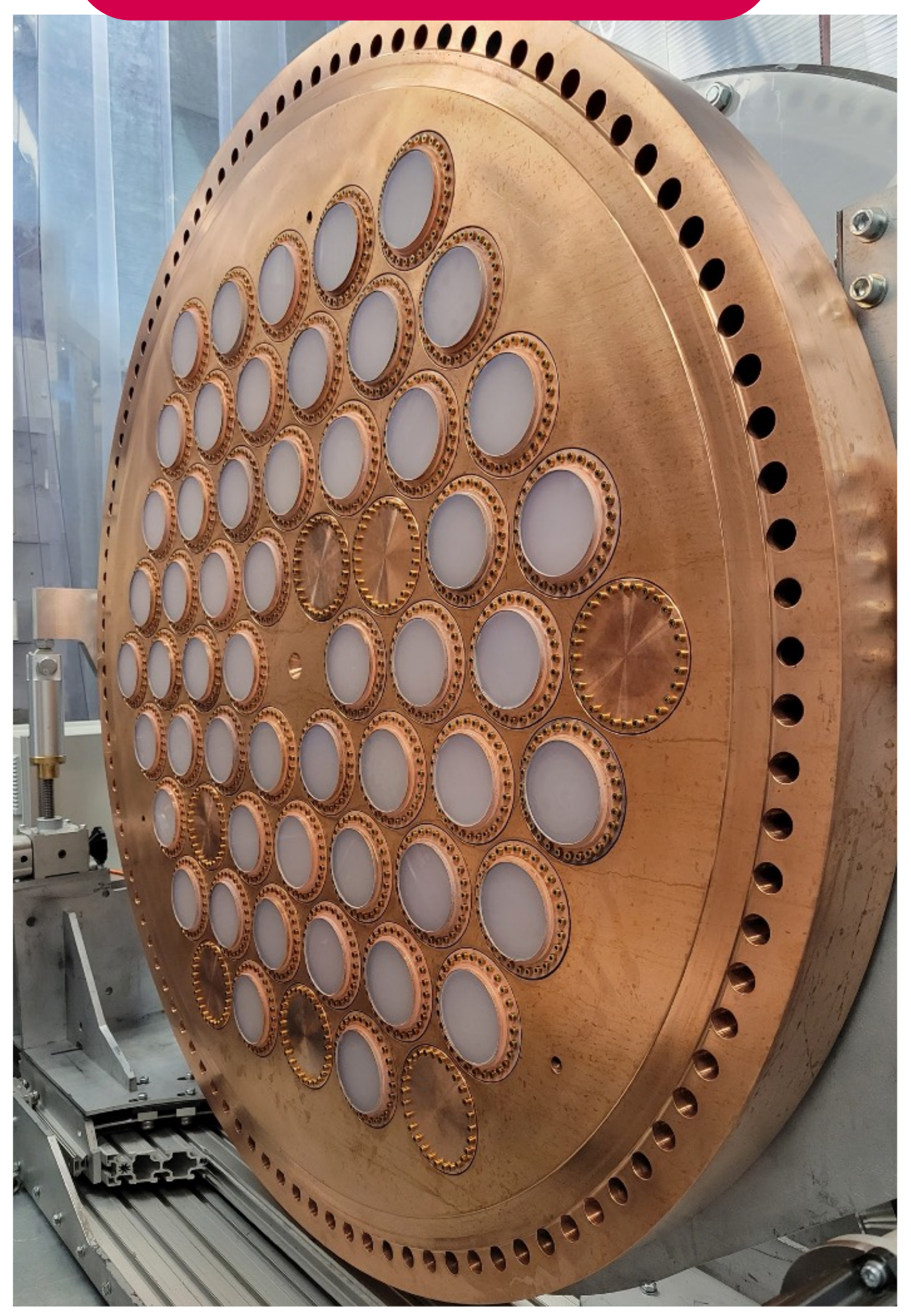
Tracking plane

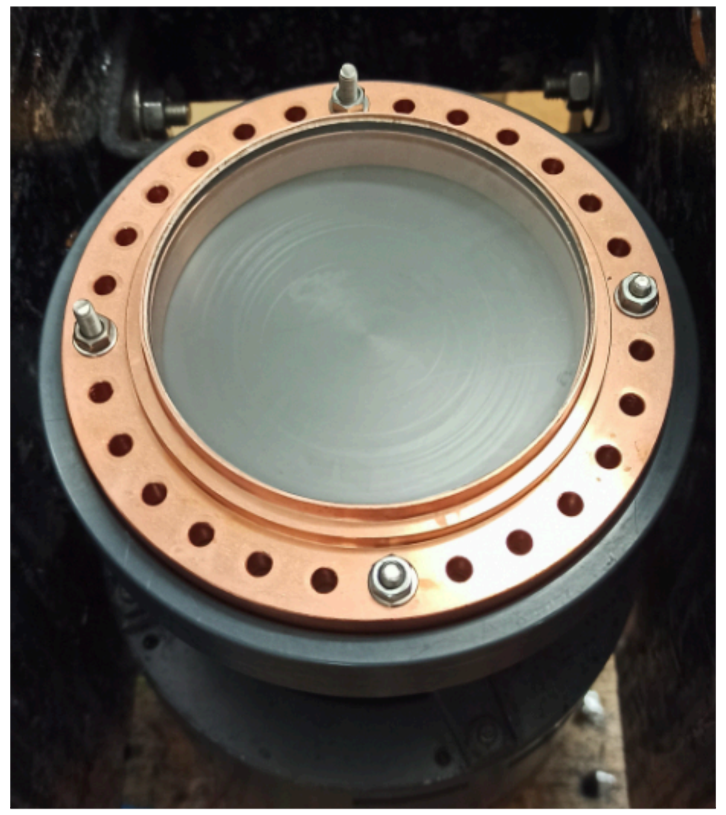


Field Cage



Energy plane





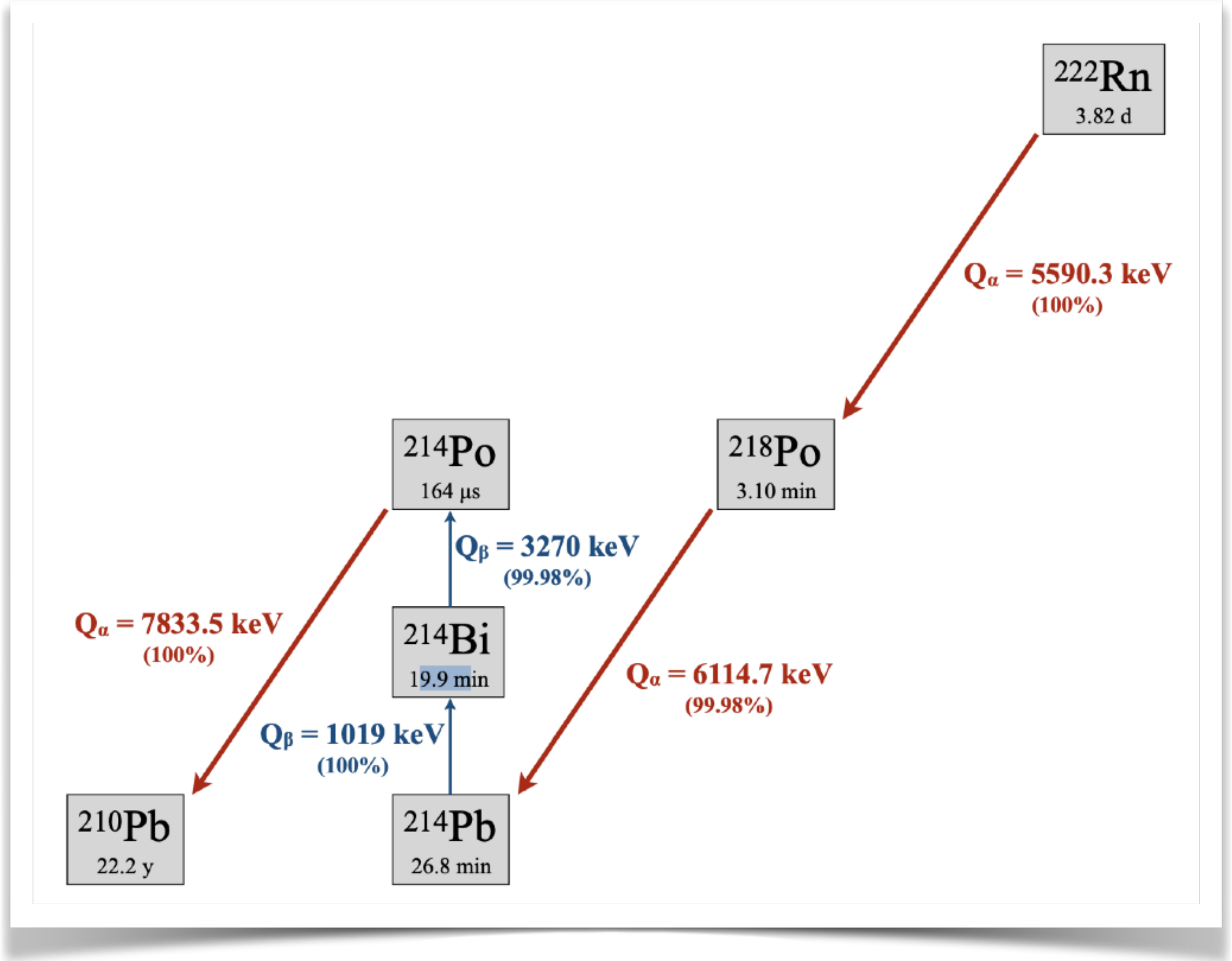
EL meshes

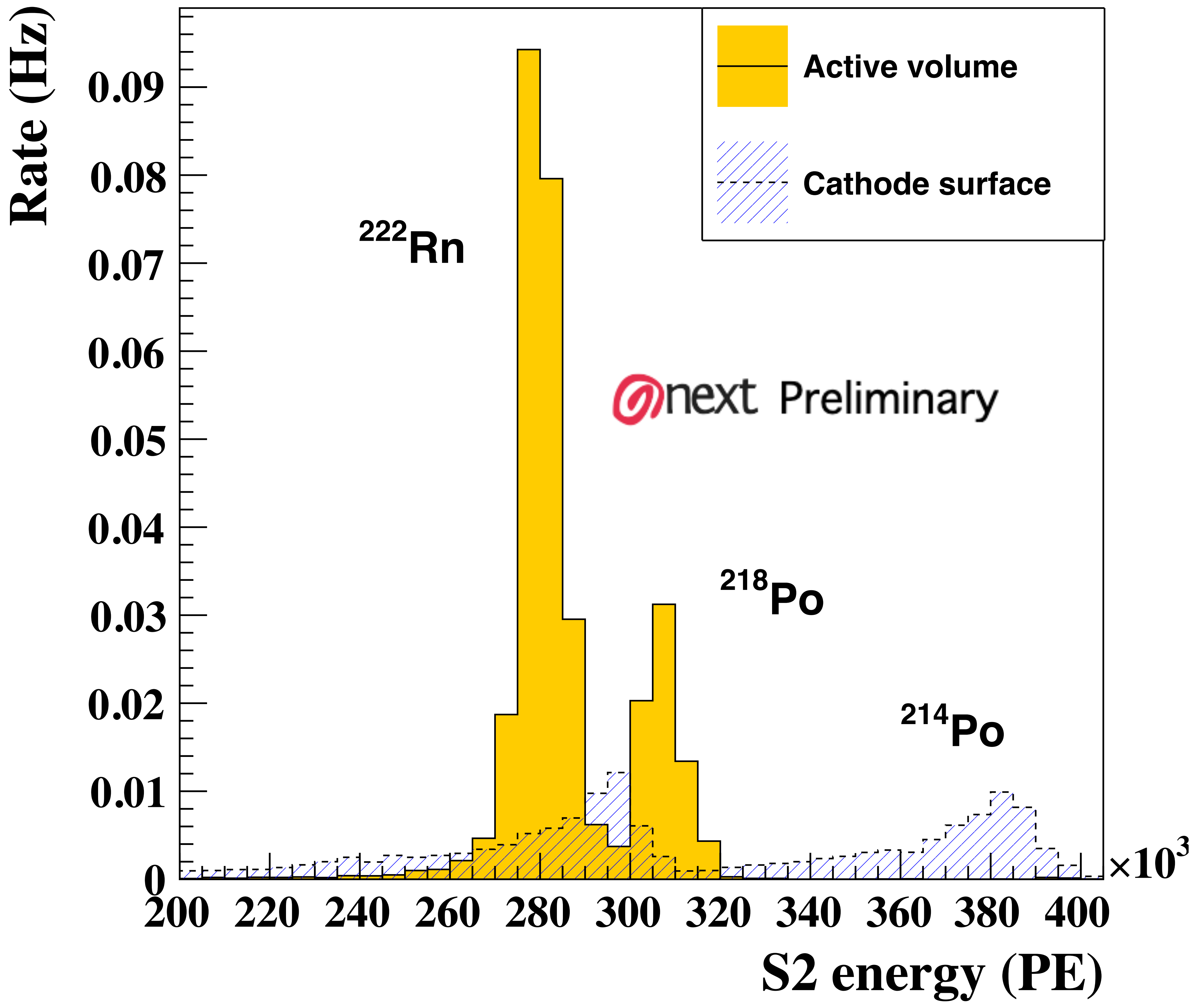
[JINST 19 (2024) 02, P02007]

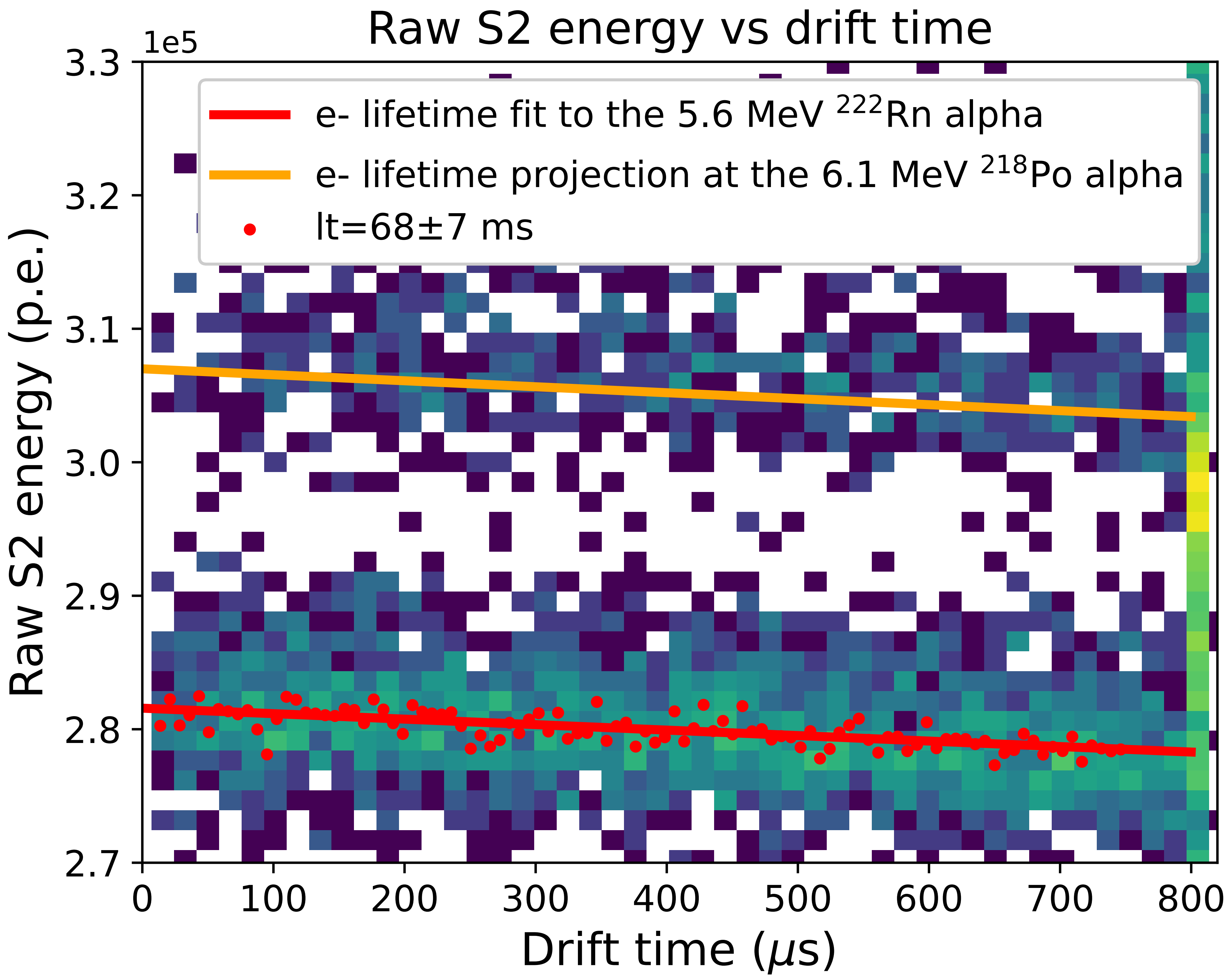
The University of Manchester

The next-100 detector

- Detector ready for **operation** in **May 2024**. It is in **stable operation** filled with **Argon** at **4.3 bar**, drift field of ~67 V/cm and EL field of ~6.9 kV/cm.
- Detector being characterised with **point-like events** = **alpha** particles from **^{222}Rn**.
- First Xenon run to be started soon. Keep tuned!

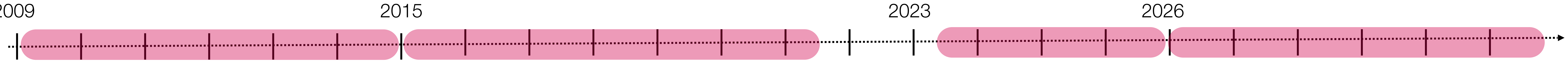




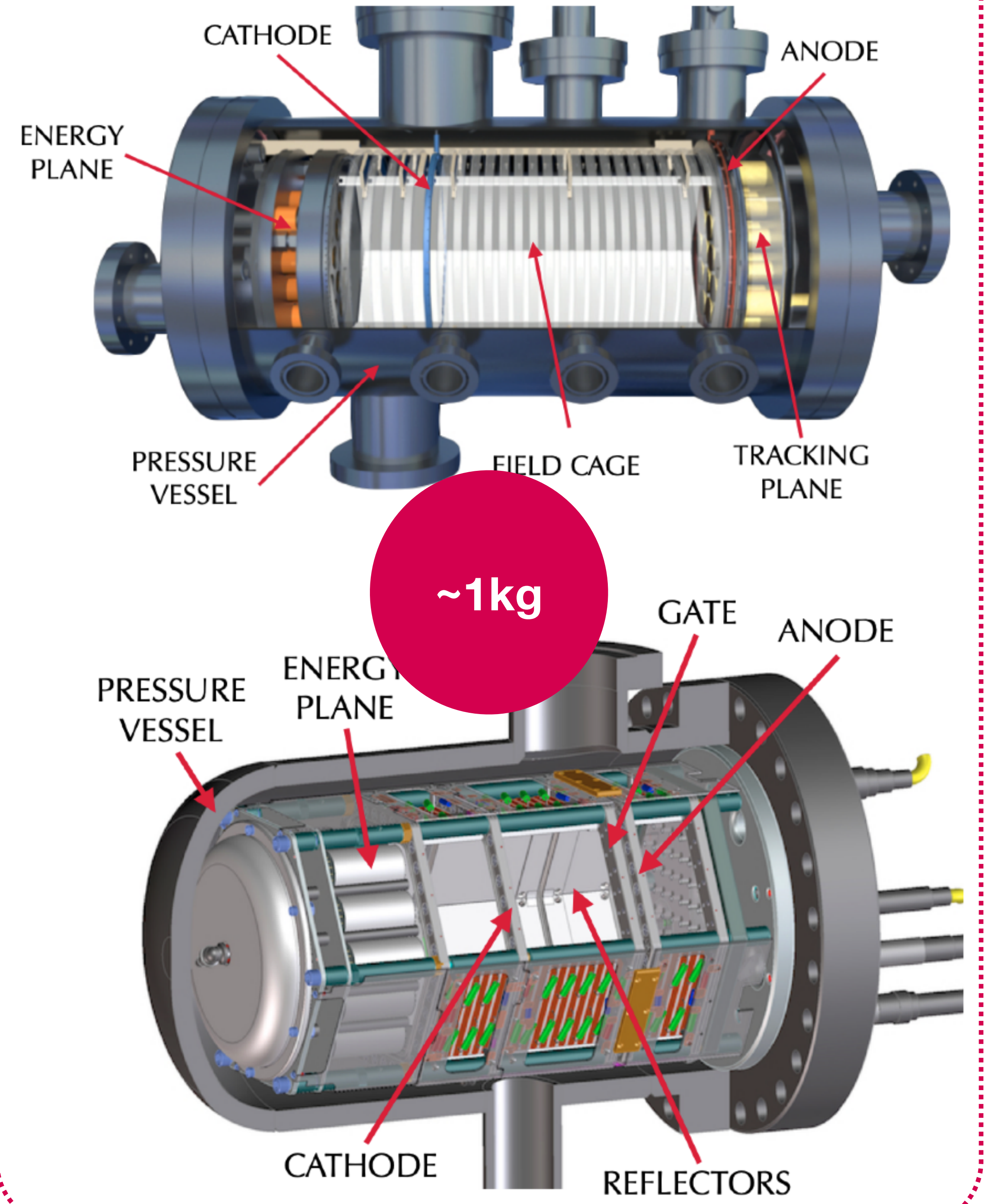


Helena Almazán

The @next programme

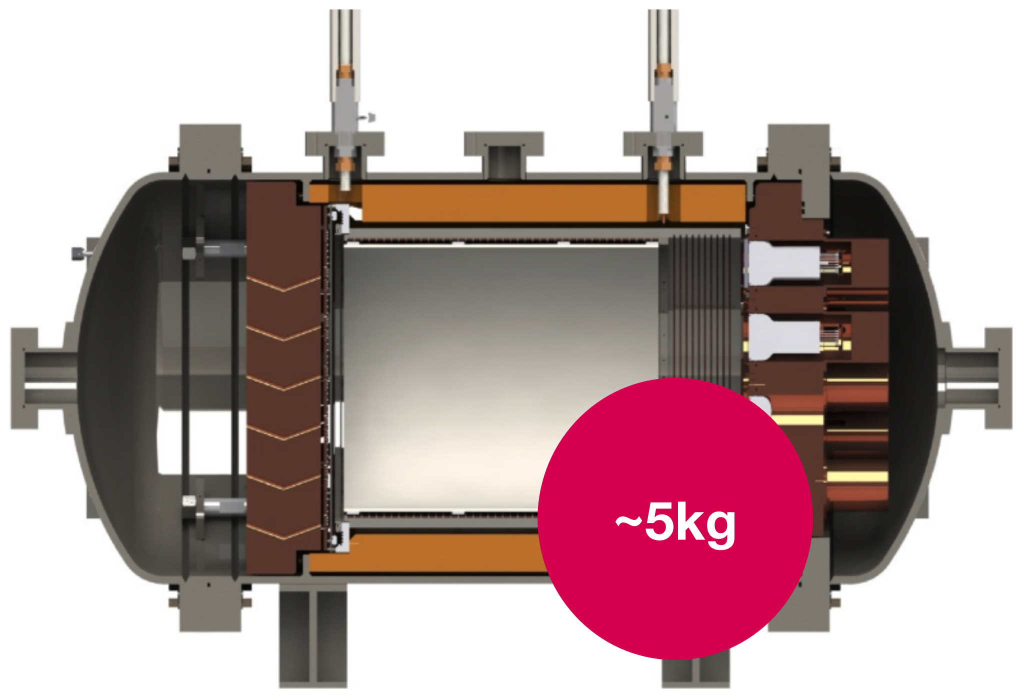


PROTOTYPES
2009/2014



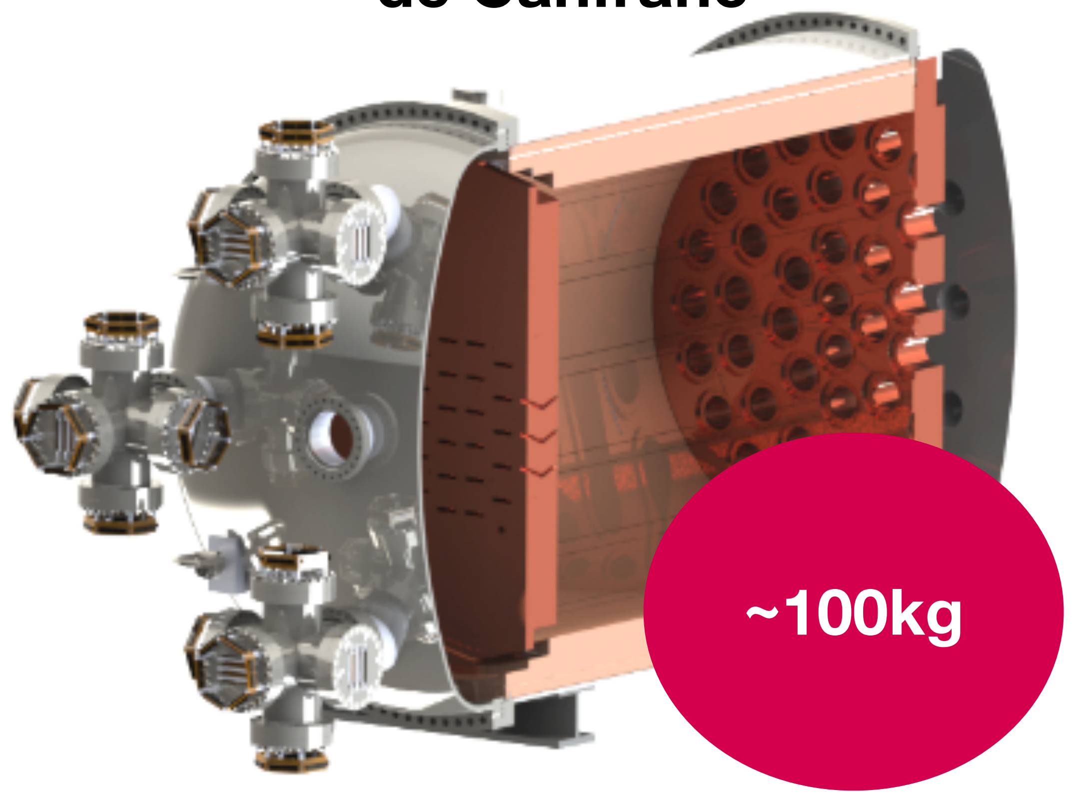
NEXT-WHITE (NEW)
2015/2021

Laboratorio Subterráneo de Canfranc



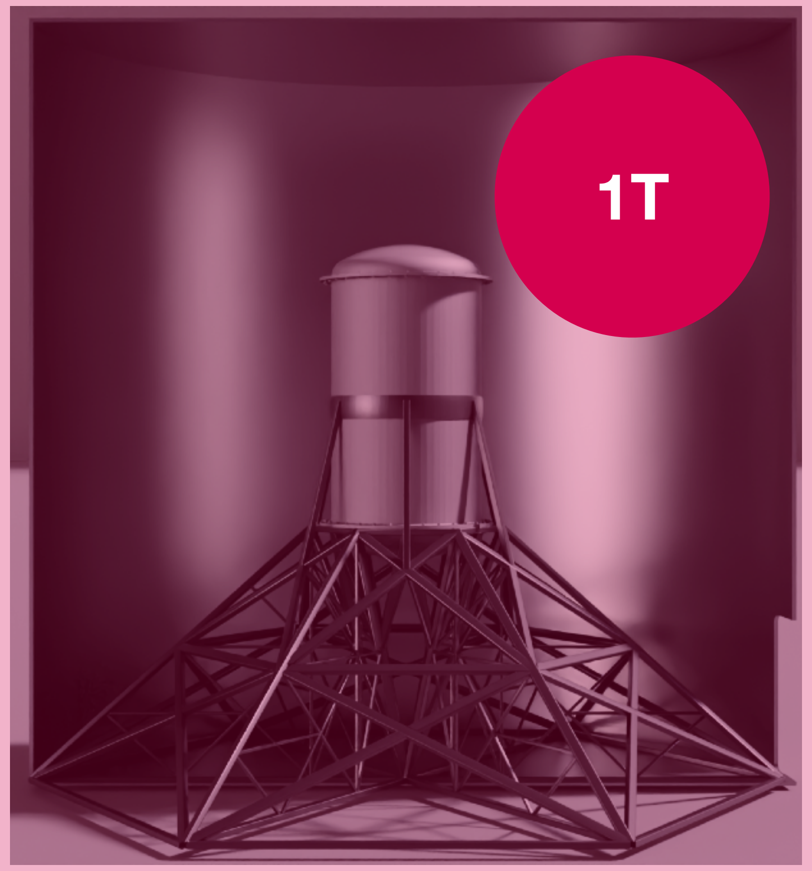
NEXT-100
2023/2027

Laboratorio Subterráneo de Canfranc



NEXT-HD
2027?

NEXT-BOLD



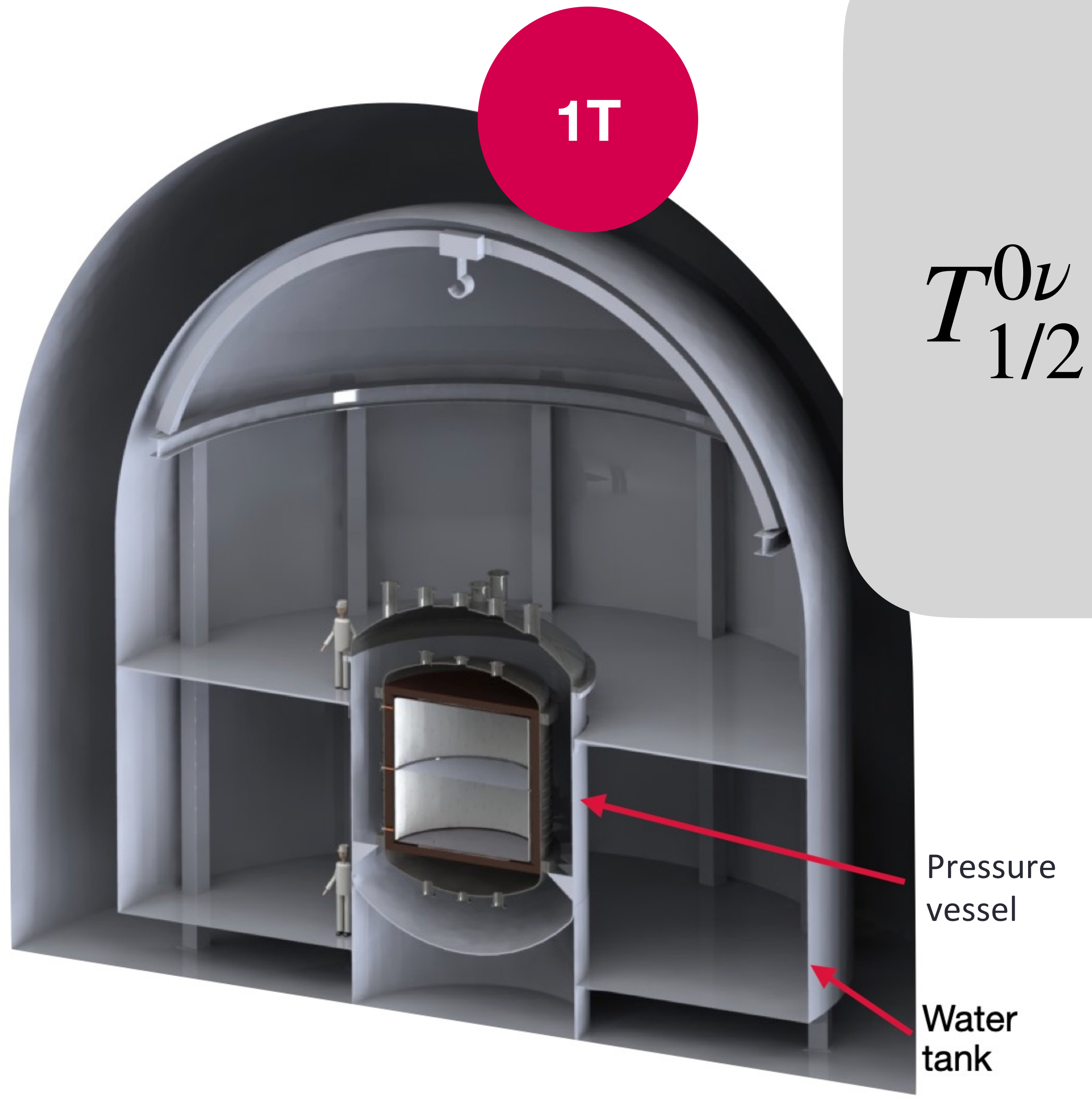
Helena Almazán

The @next-tonne scale programme

multi-module system ongoing R&D

NEXT-HD

Neutrinoless double beta decay search through inverted neutrino mass ordering



TPC containing 1 tonne of Xe

$$T^{0\nu}_{1/2} = log2 \frac{N_A}{W} \frac{\epsilon M t}{N}$$

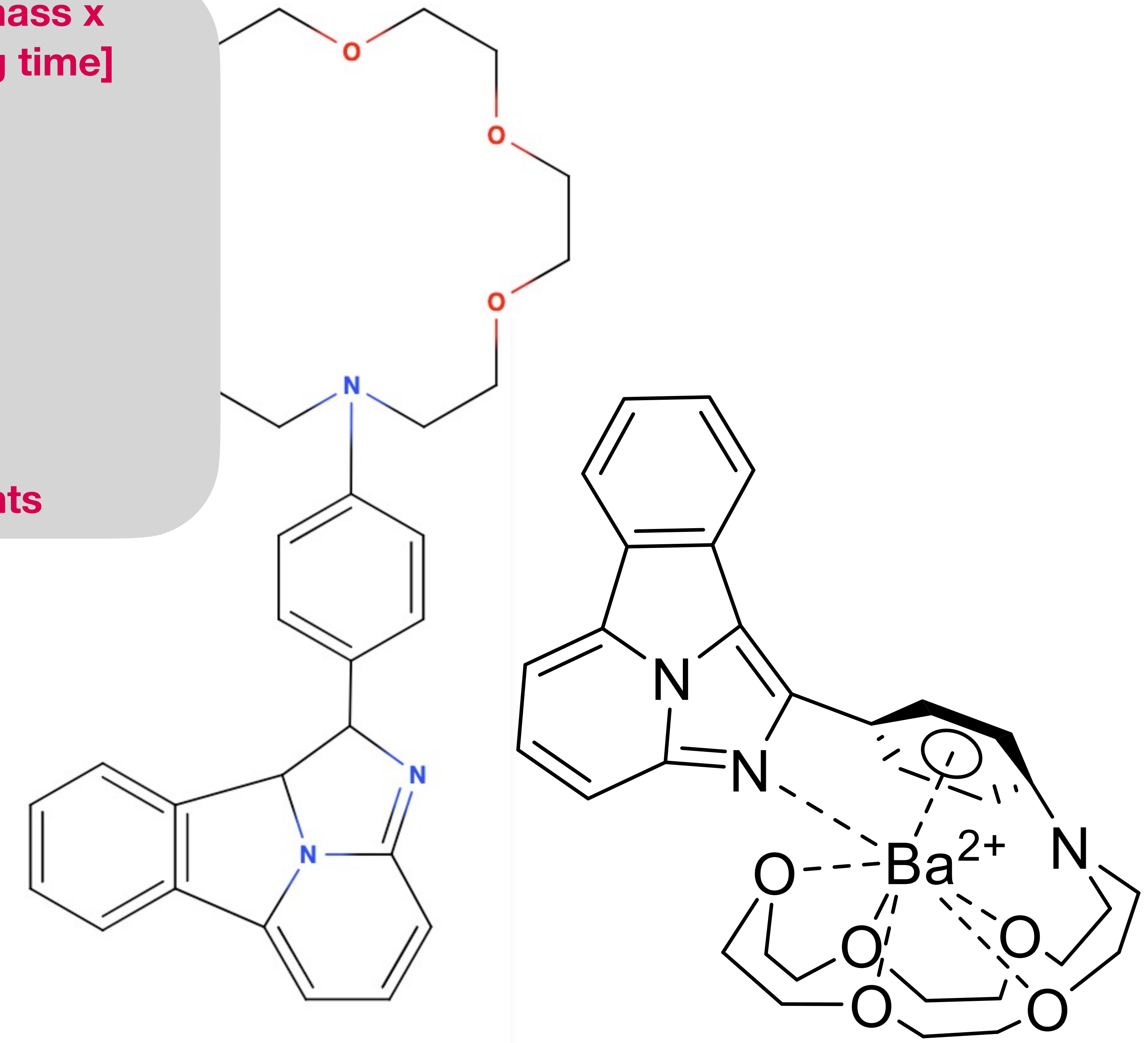
signal detection efficiency

[source mass x measuring time]

number of events

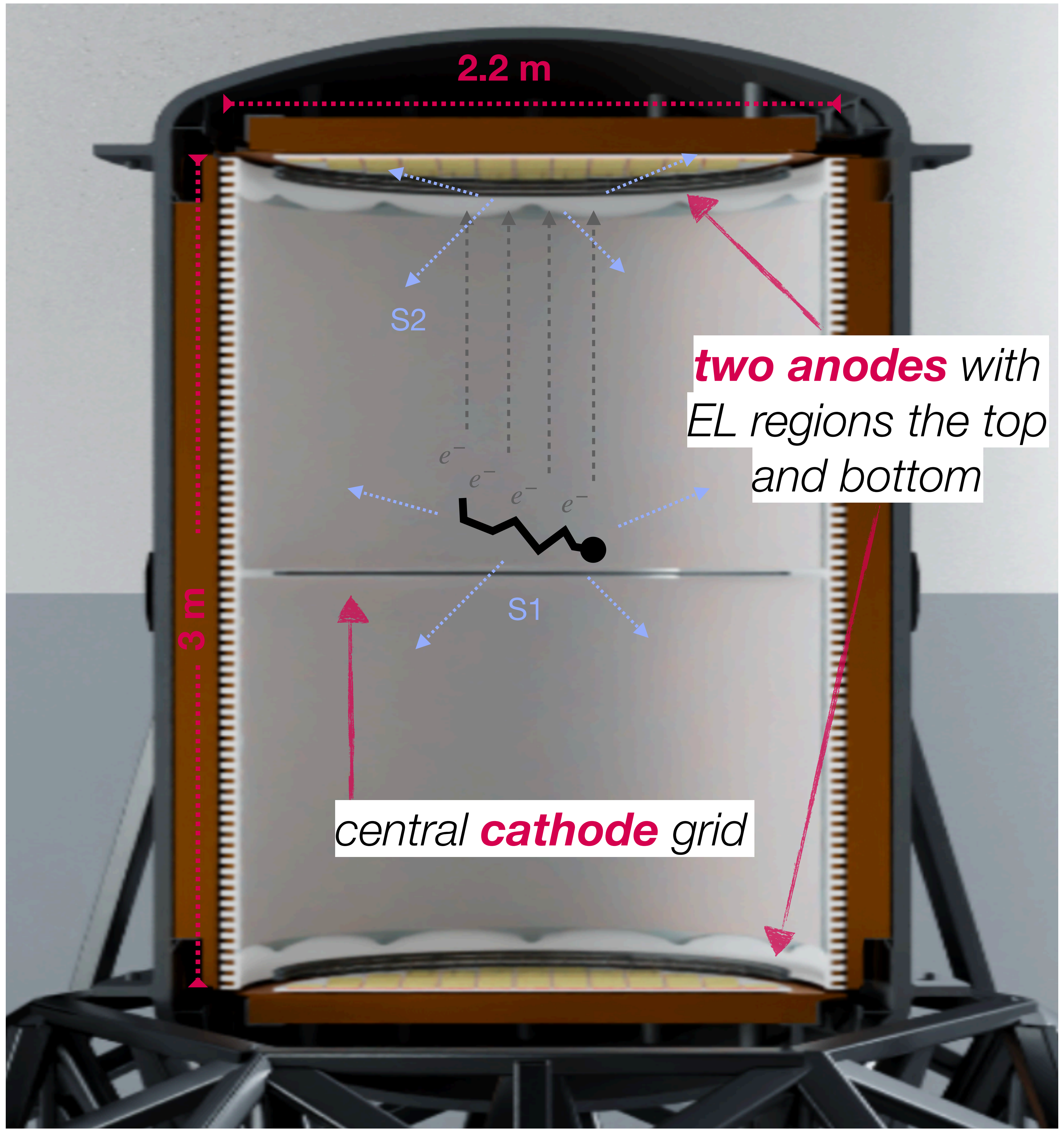
NEXT-BOLD

Barium tagging for background-free experiment inverted neutrino mass ordering



NEXT-HD Baseline Concept

symmetric vertical TPC
with two back-to-back drift regions



- Symmetric design with central cathode
- Xe/He to reduce transverse diffusion
- Barrel instrumented with fiber optics for energy and S1 measurements
- External water tank shielding

Projected for 2027

- **Mass**: ~1000 kg (at 15 bar)
- **Sensitivity**: 1.2×10^{27} y after 5 years
- **Background**: 0.01 counts$/($keV · ton · yr$)$

[JHEP 2021 (2021) 08]

NEXT with Ba-tagging

new generation of the NEXT detector with the capability to detect the barium ion, based on a ***molecular fluorescent indicator***

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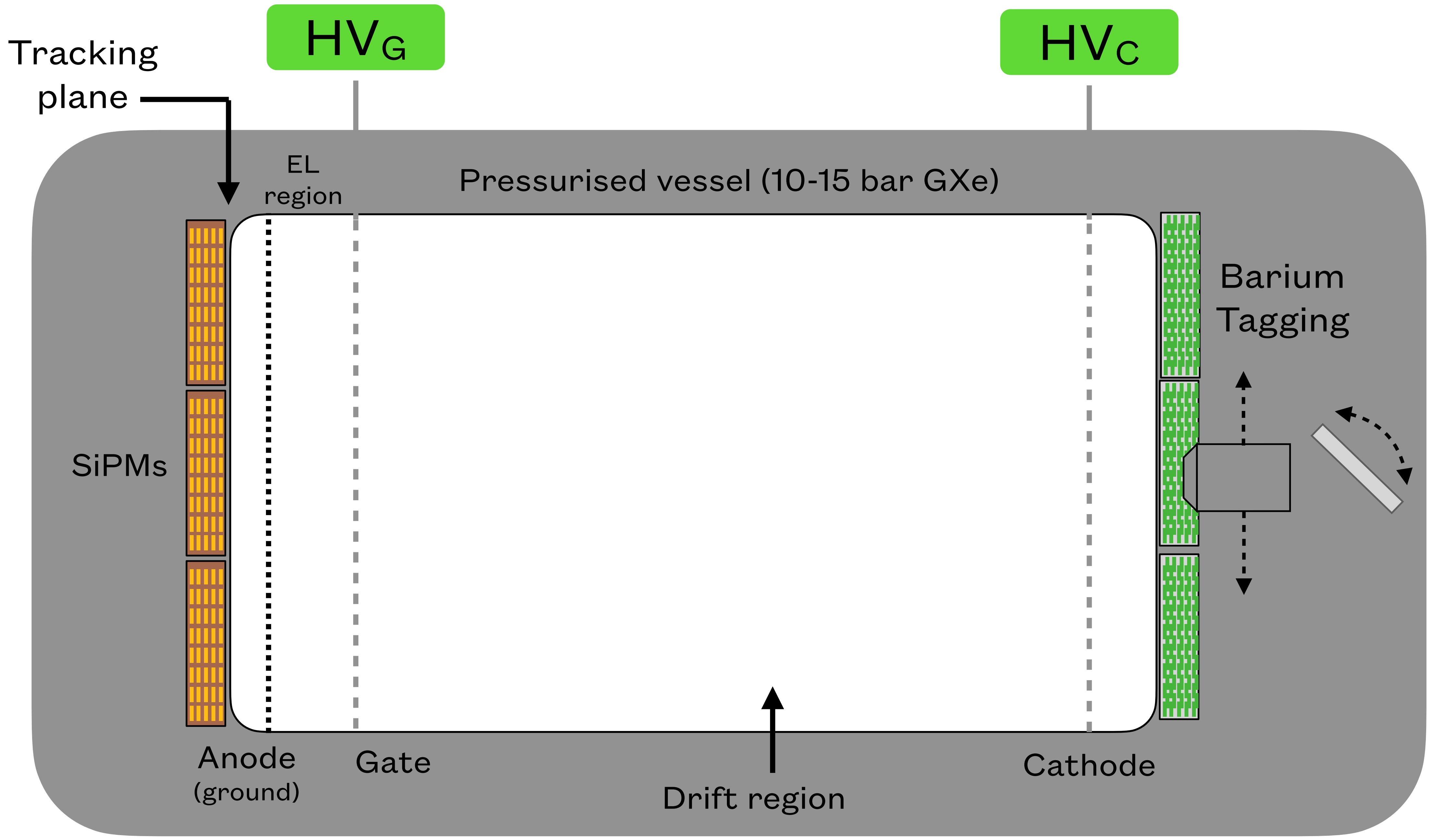
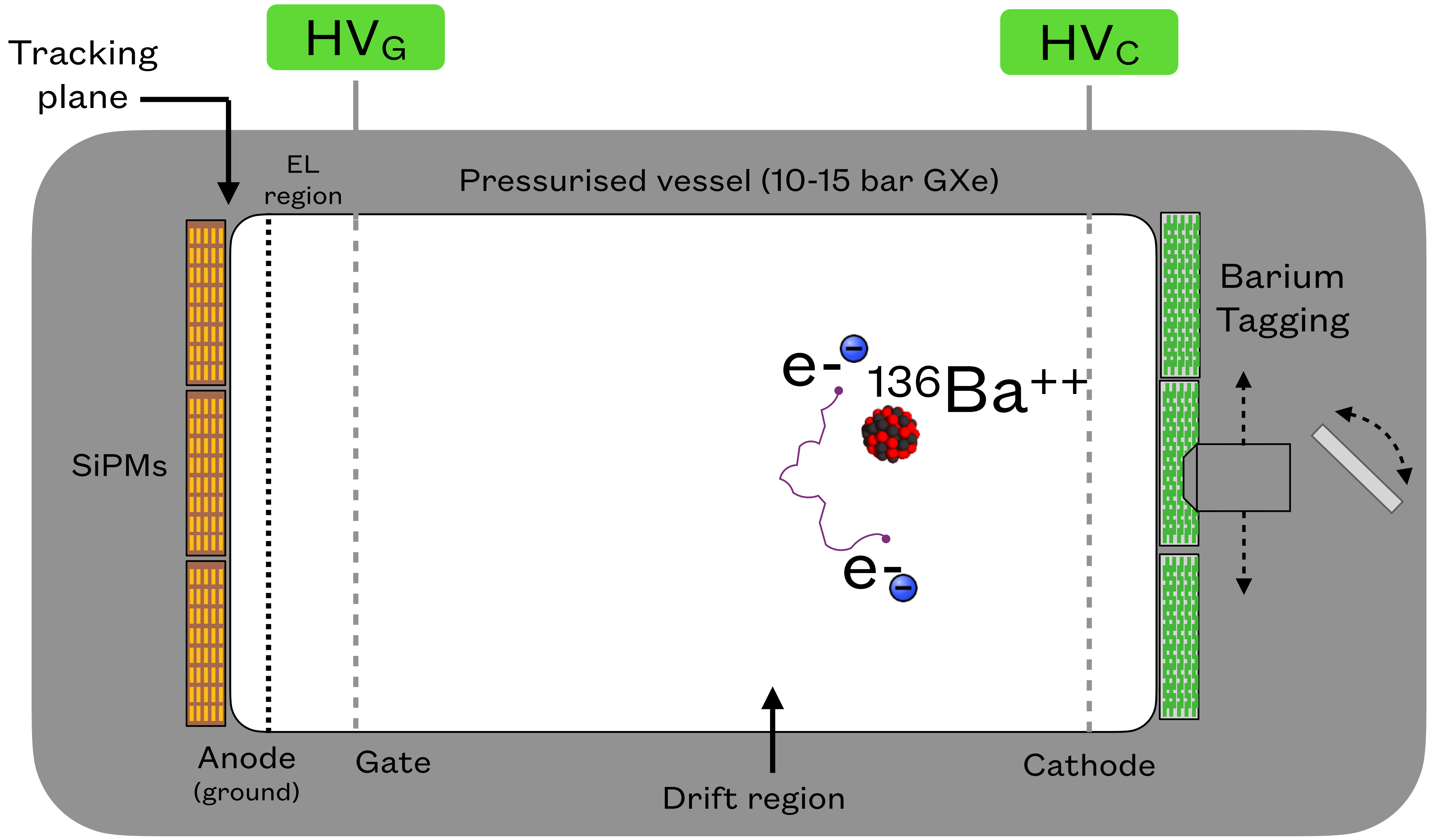


NEXT with Ba-tagging

ERC Synergy-2020 NEXT-BOLD

new generation of the NEXT detector with the capability to detect the barium ion, based on a ***molecular fluorescent indicator***



Coincidence signal:

- ^{136}**Xe** atom decays, producing: **2e-** and **Ba^{++} ion**

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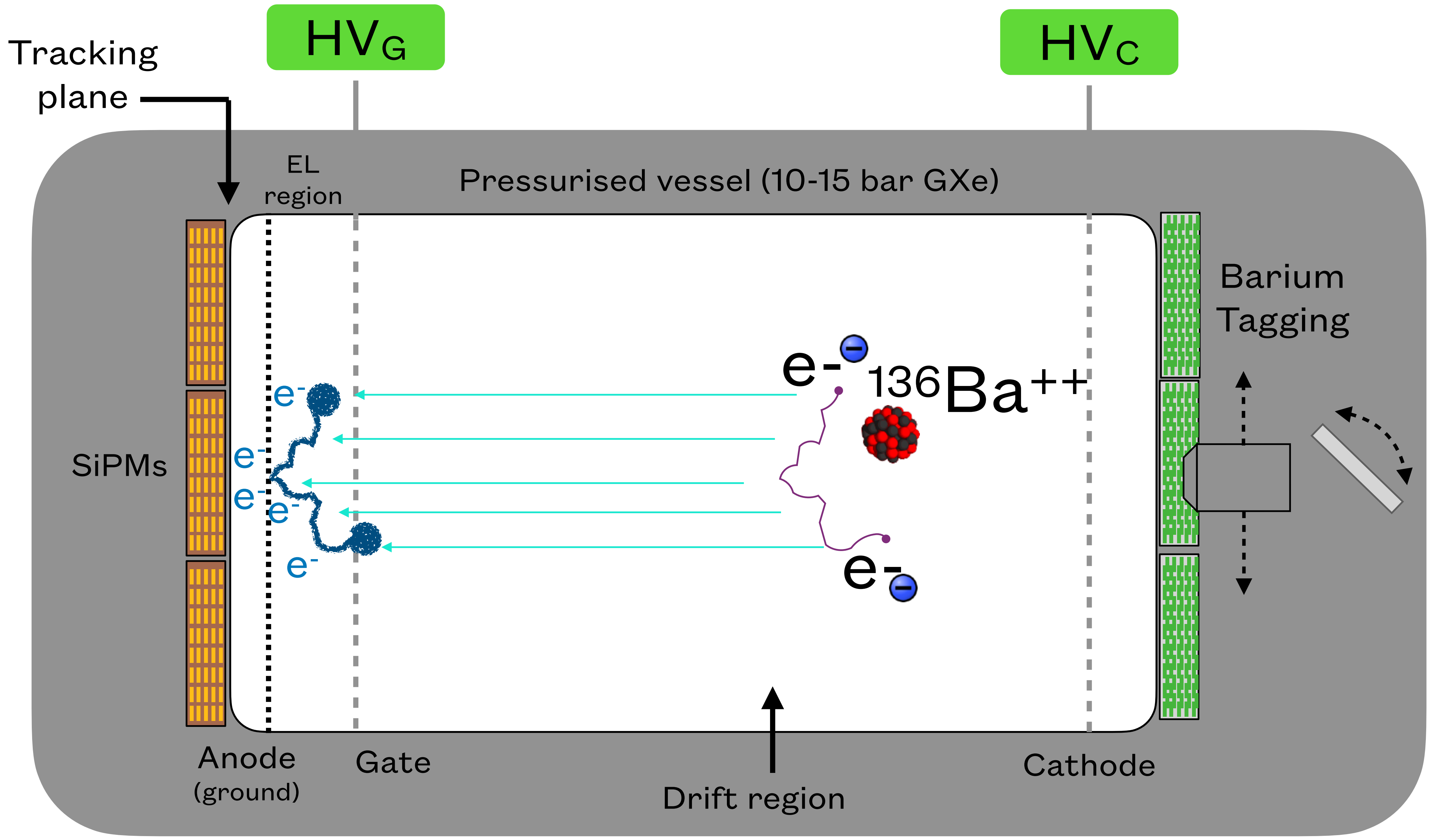

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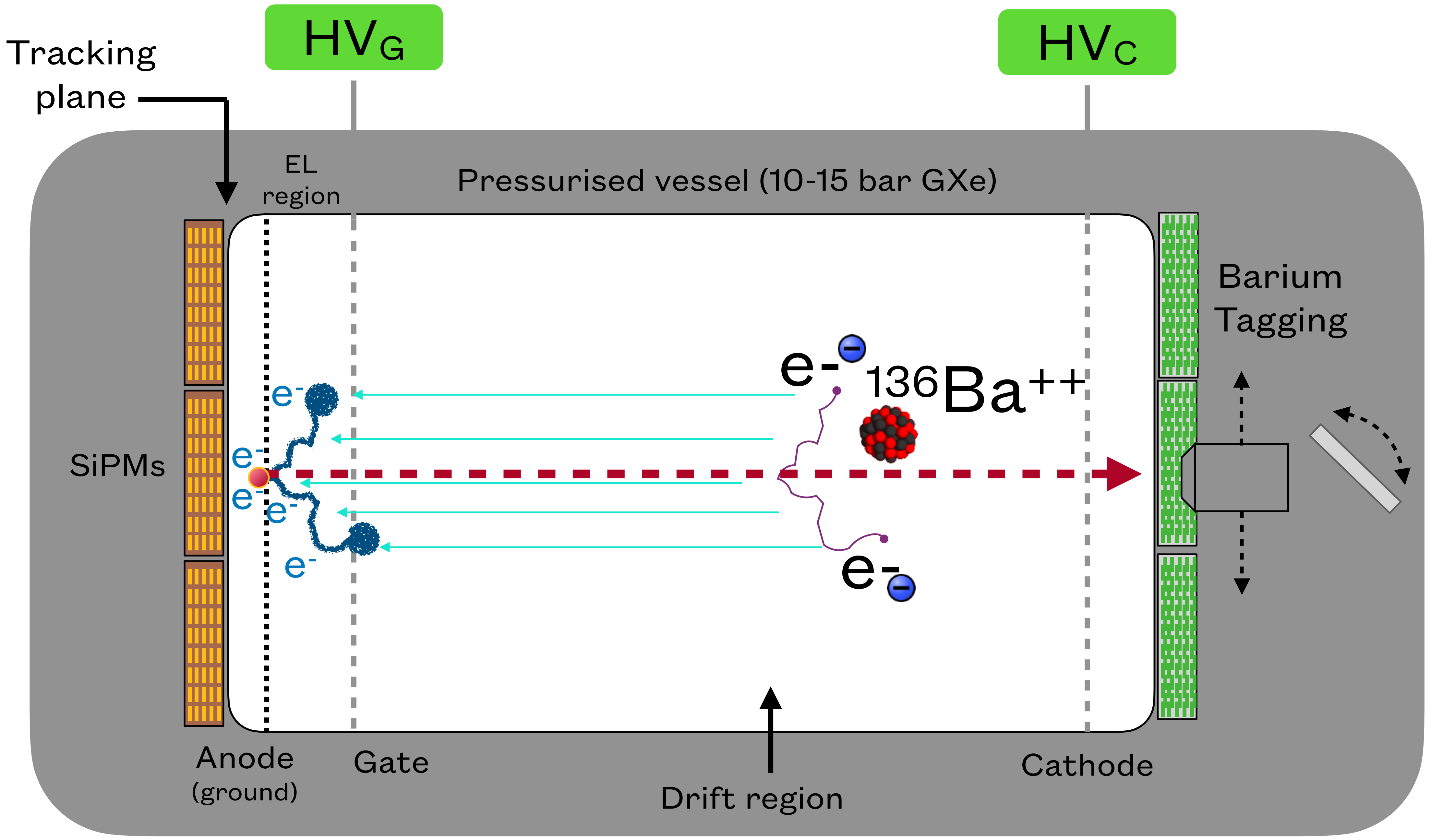

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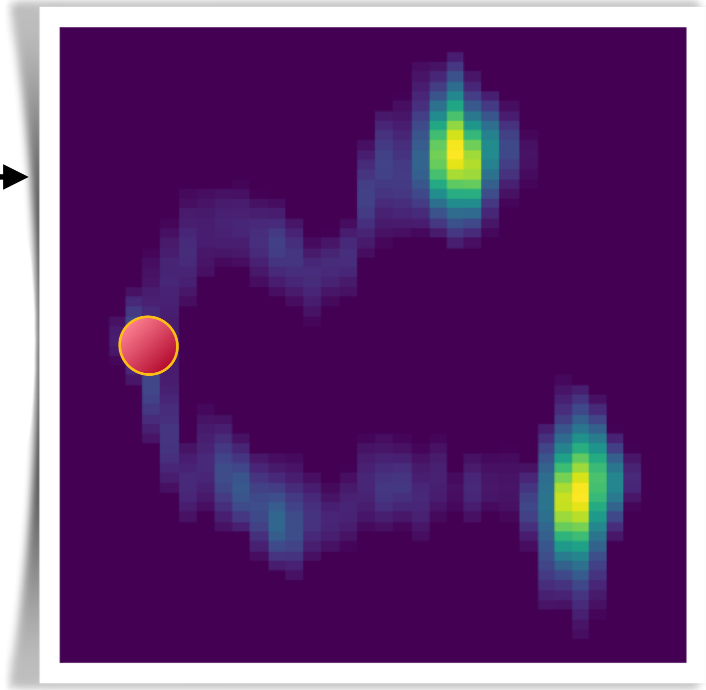
- Energy/Tracking side measures the energy of the electrons and reconstructs track ***barycentre***



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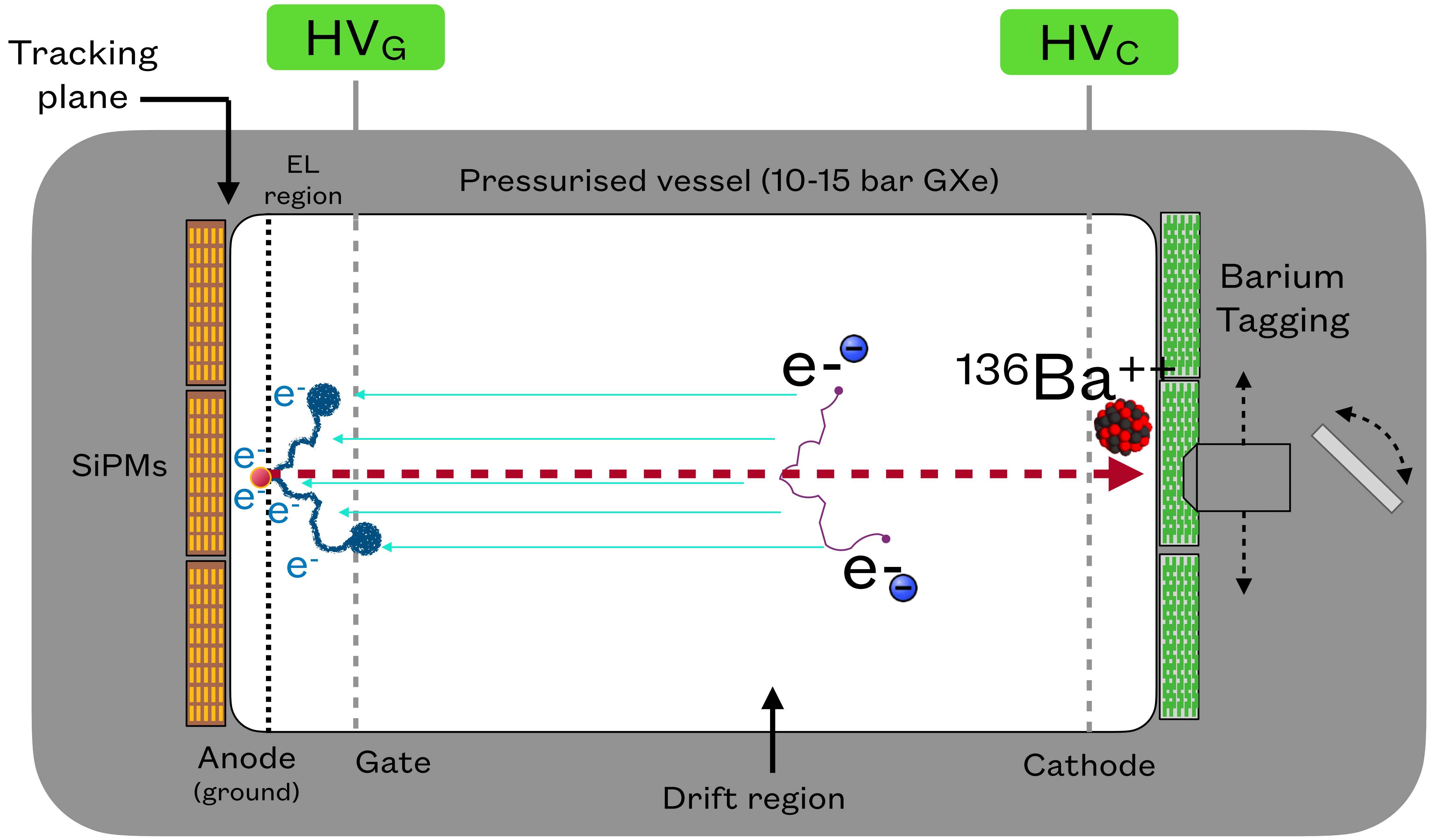

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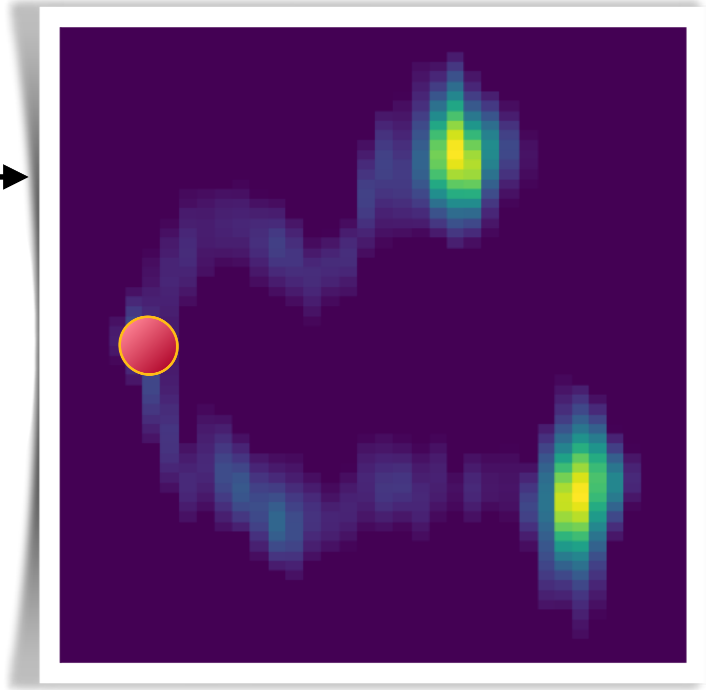

- **Ba^{++} ion** moves (*slowly*) towards cathode → detected by chemosensors

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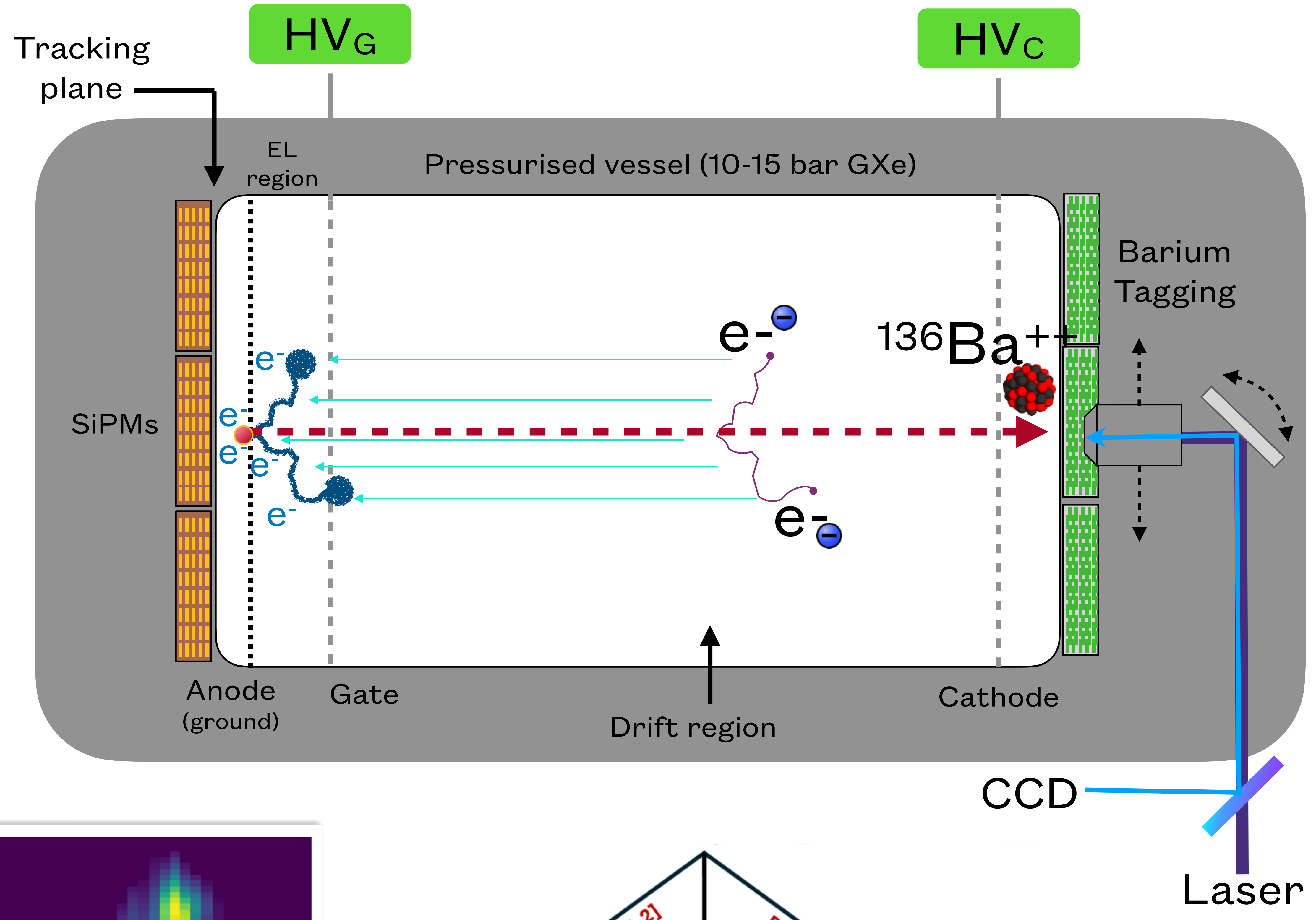

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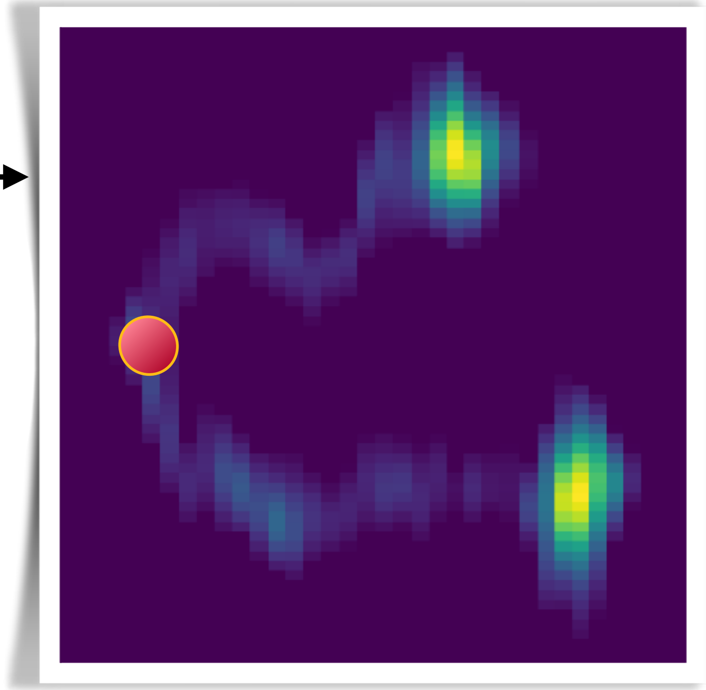

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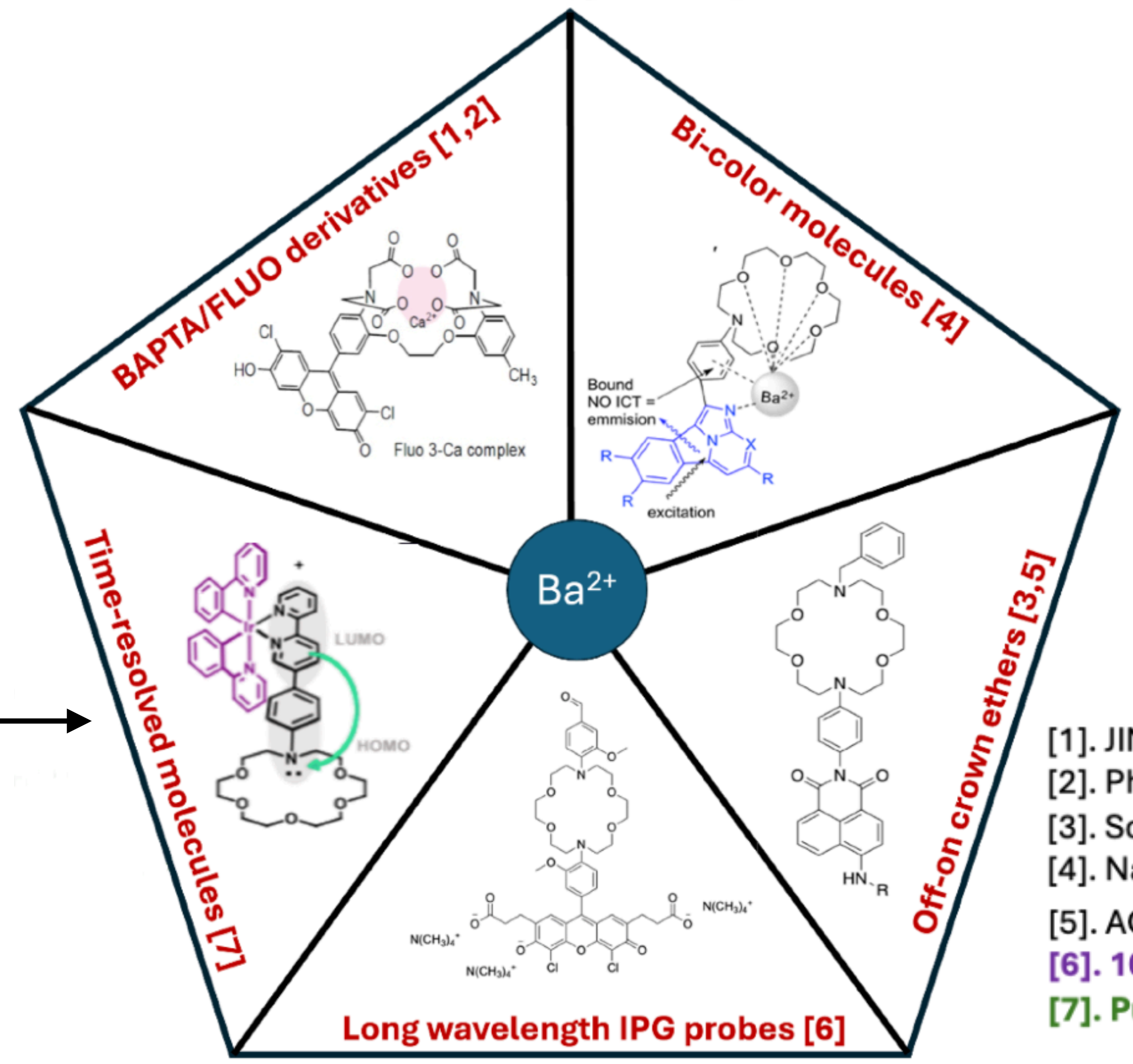
- **Ba^{++}** detection: light emission



[1]. JINST 11 P12011 (2016)
[2]. Phys. Rev. Lett. 120, 132504 (2018)
[3]. Sci Rep 9: 15097 (2019)
[4]. Nature 583, 48 (2020)
[5]. ACS Sensors 6, 1, 192-20 (2021)
[6]. 10.26434/chemrxiv-2023-wxpbh (2023)
[7]. Publication in Preparation (2024)

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NEXT with Ba-tagging

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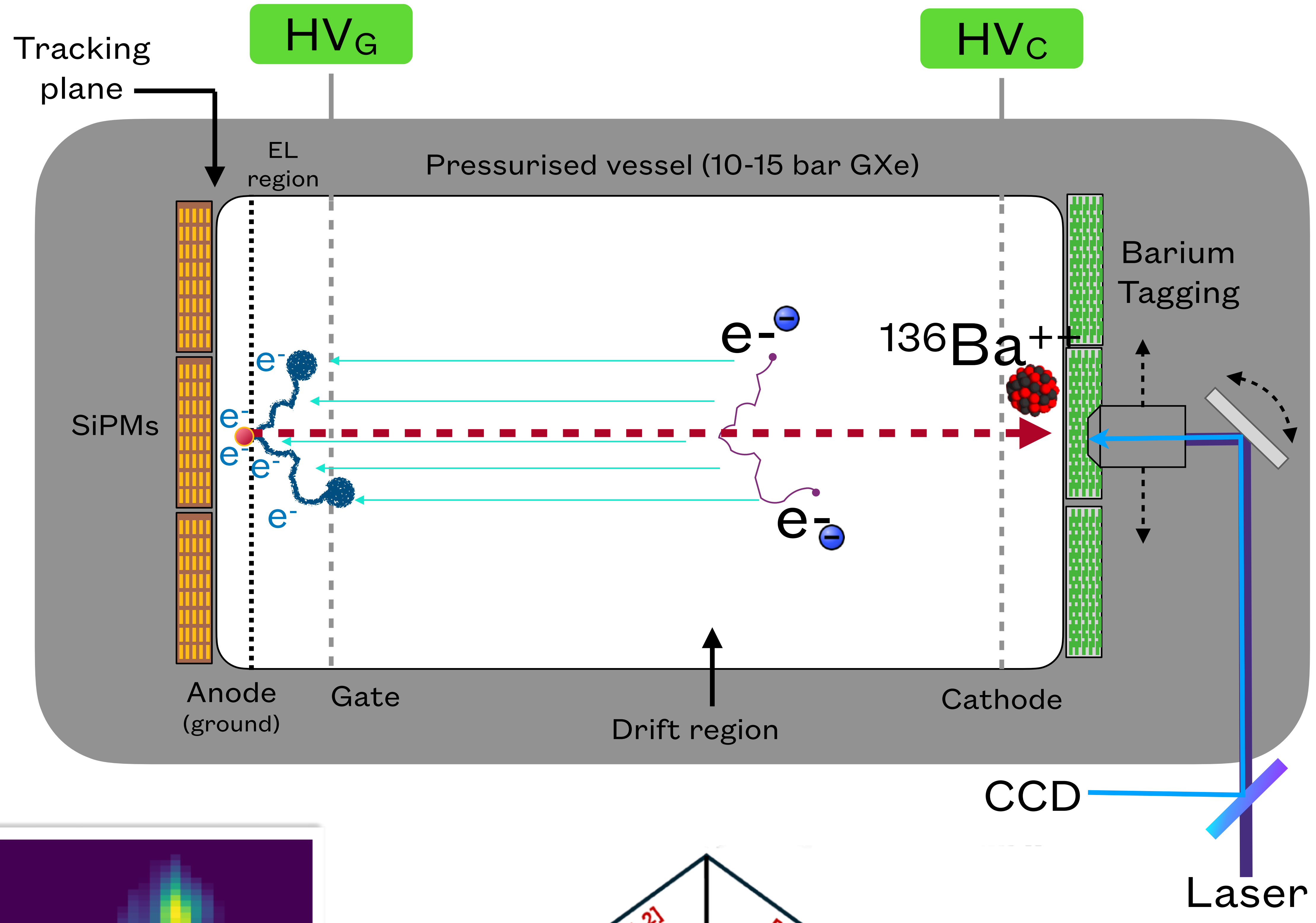

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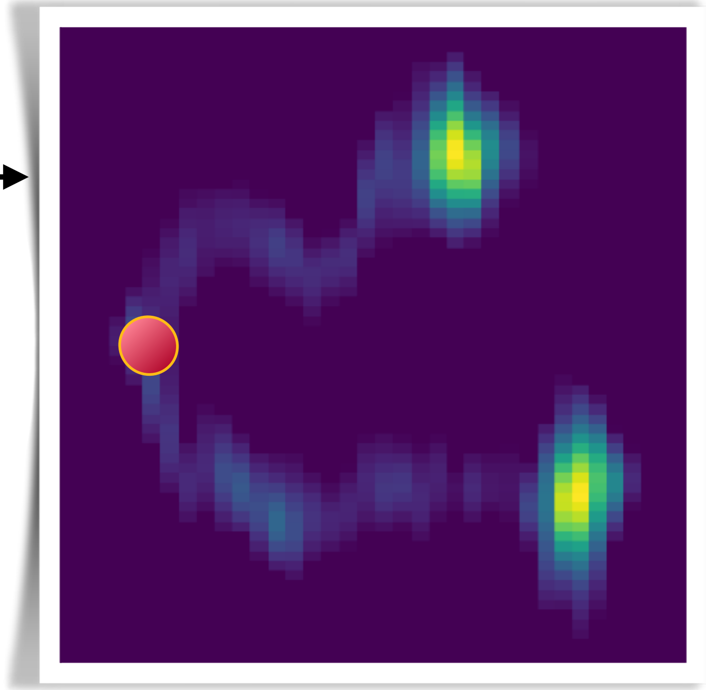

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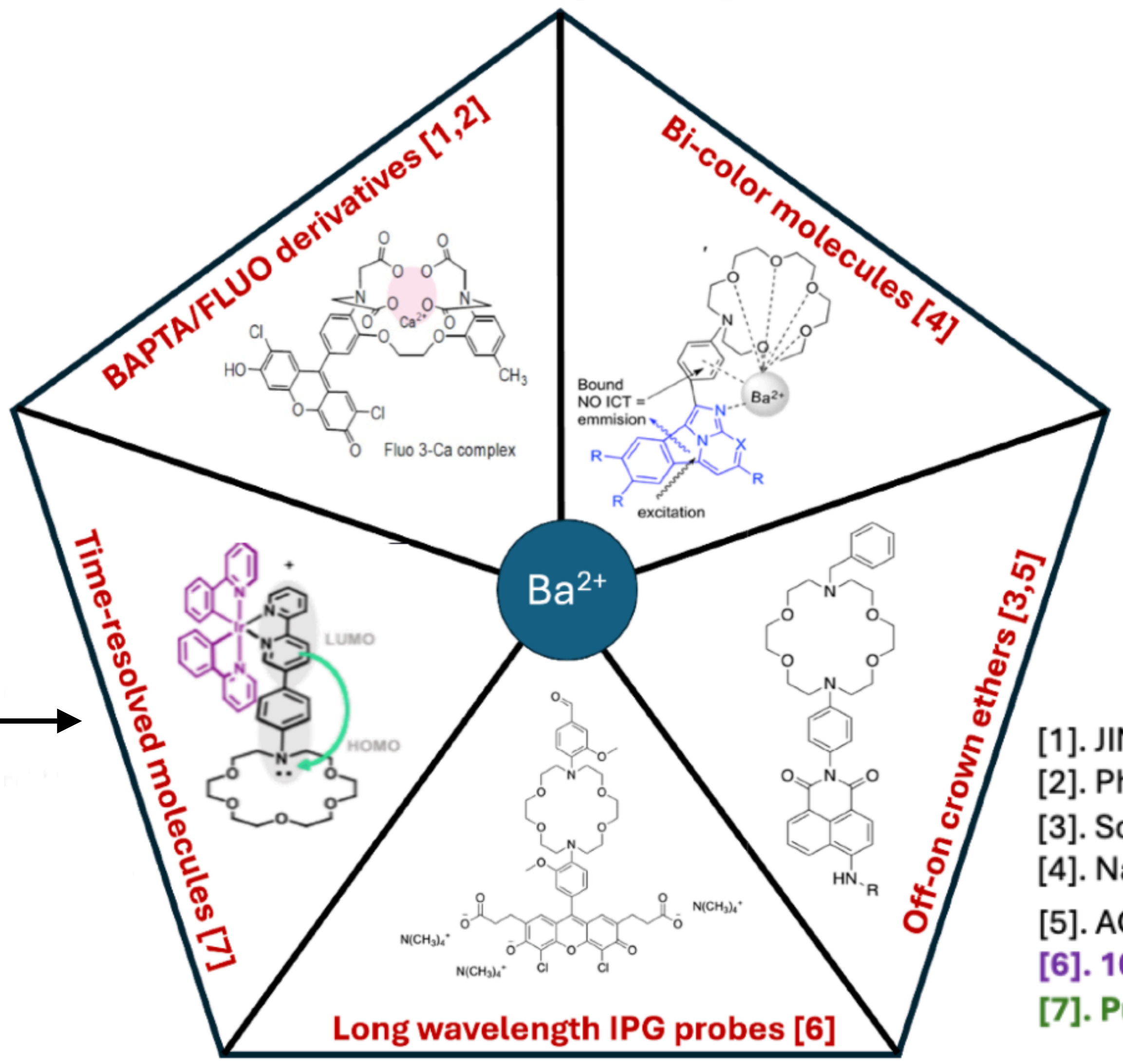

- Together with the **electron track** we obtain **delayed coincidence signal** → *Background free experiment*

[1]. JINST 11 P12011 (2016)
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Helena Almazán

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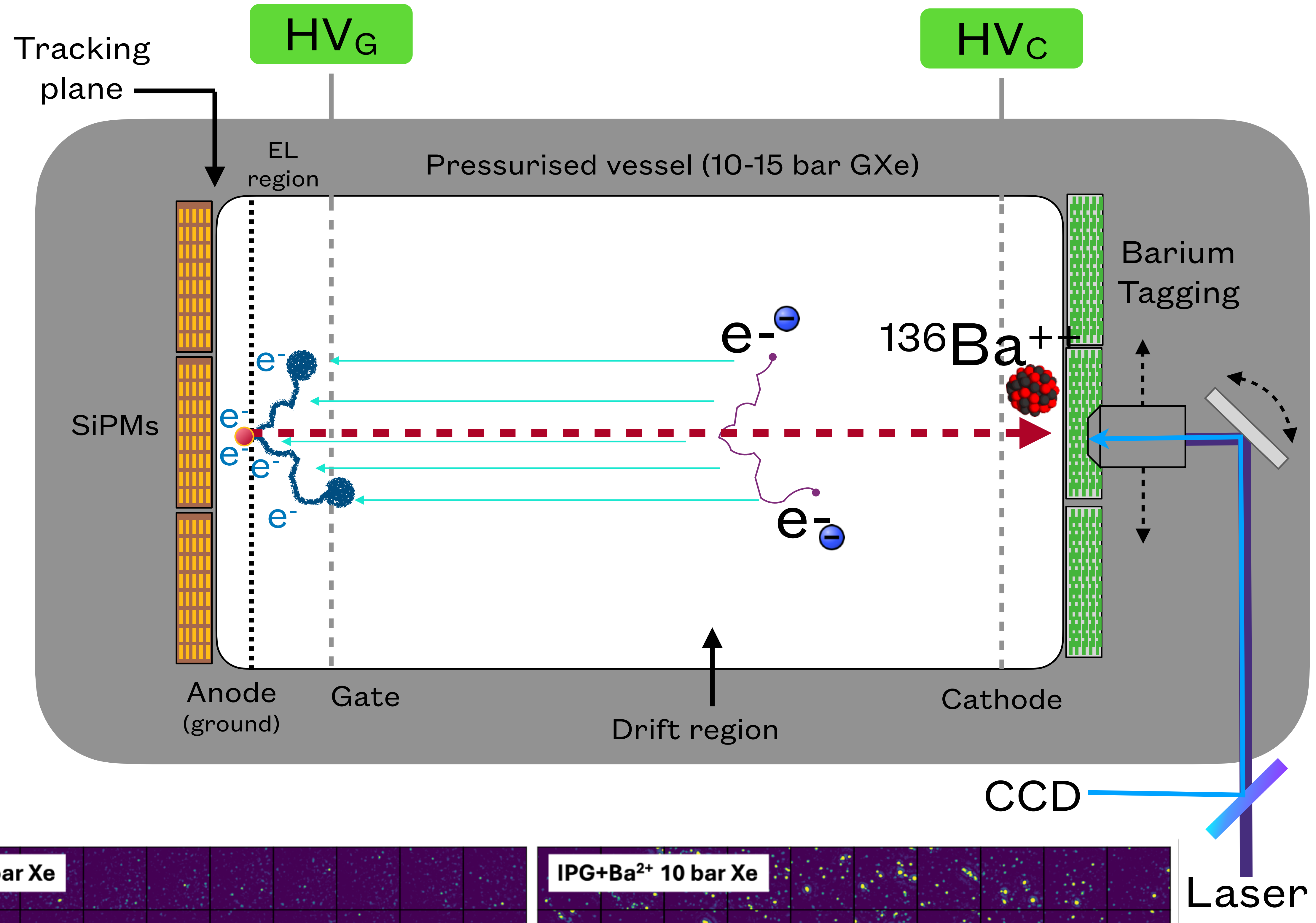

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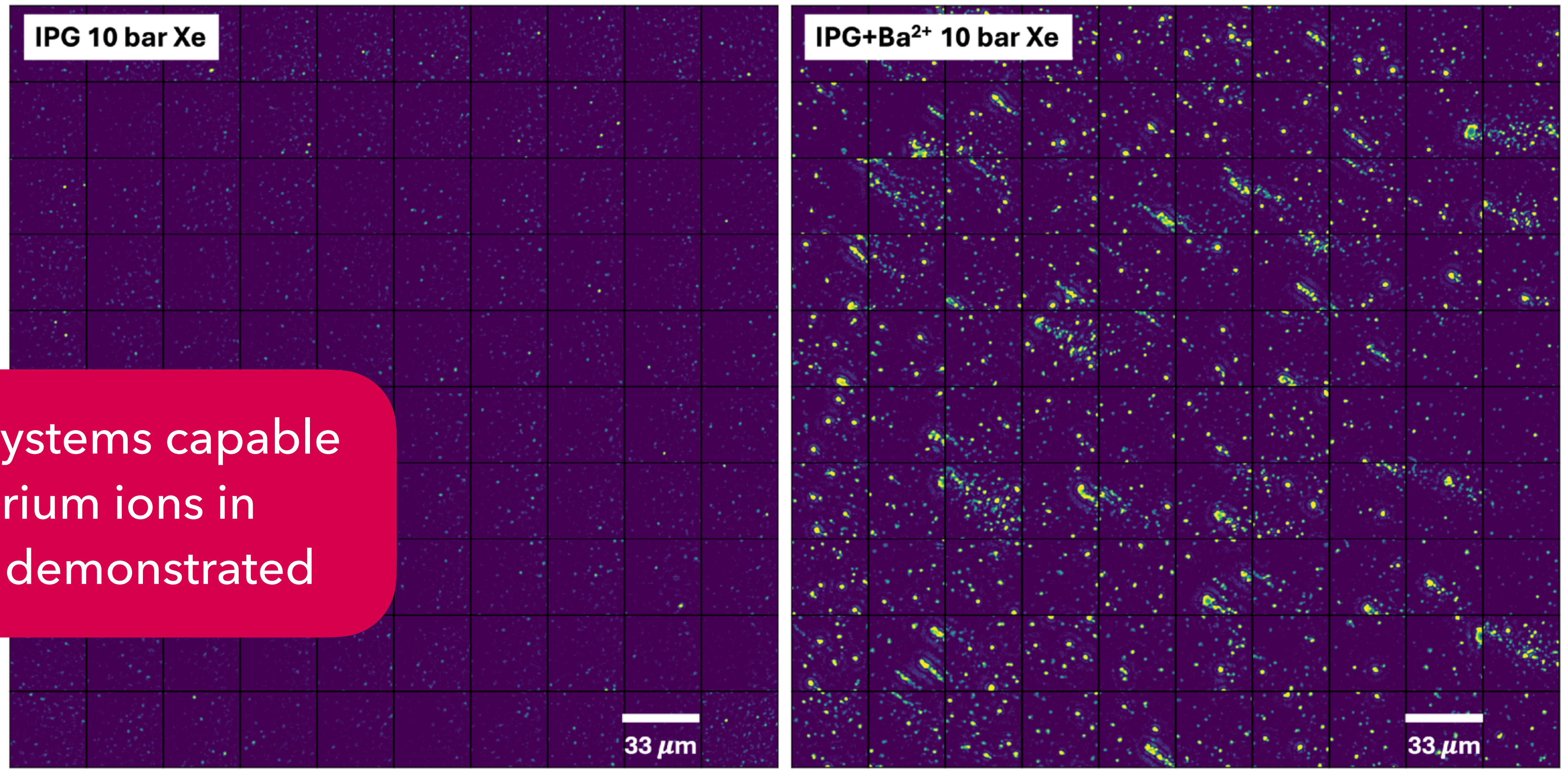
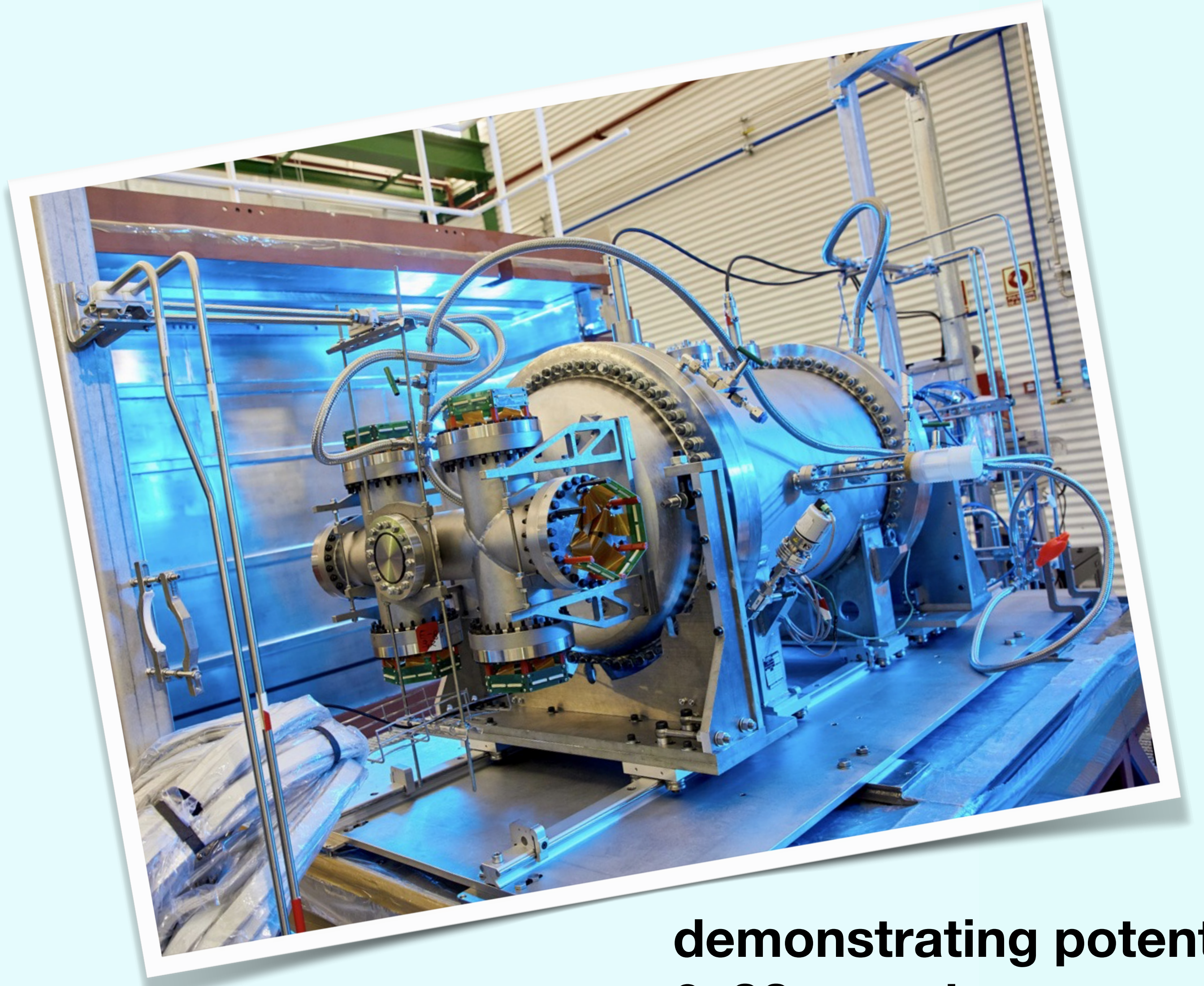


The viability of microscopy systems capable of imaging individual barium ions in high-pressure xenon gas is demonstrated

Summary

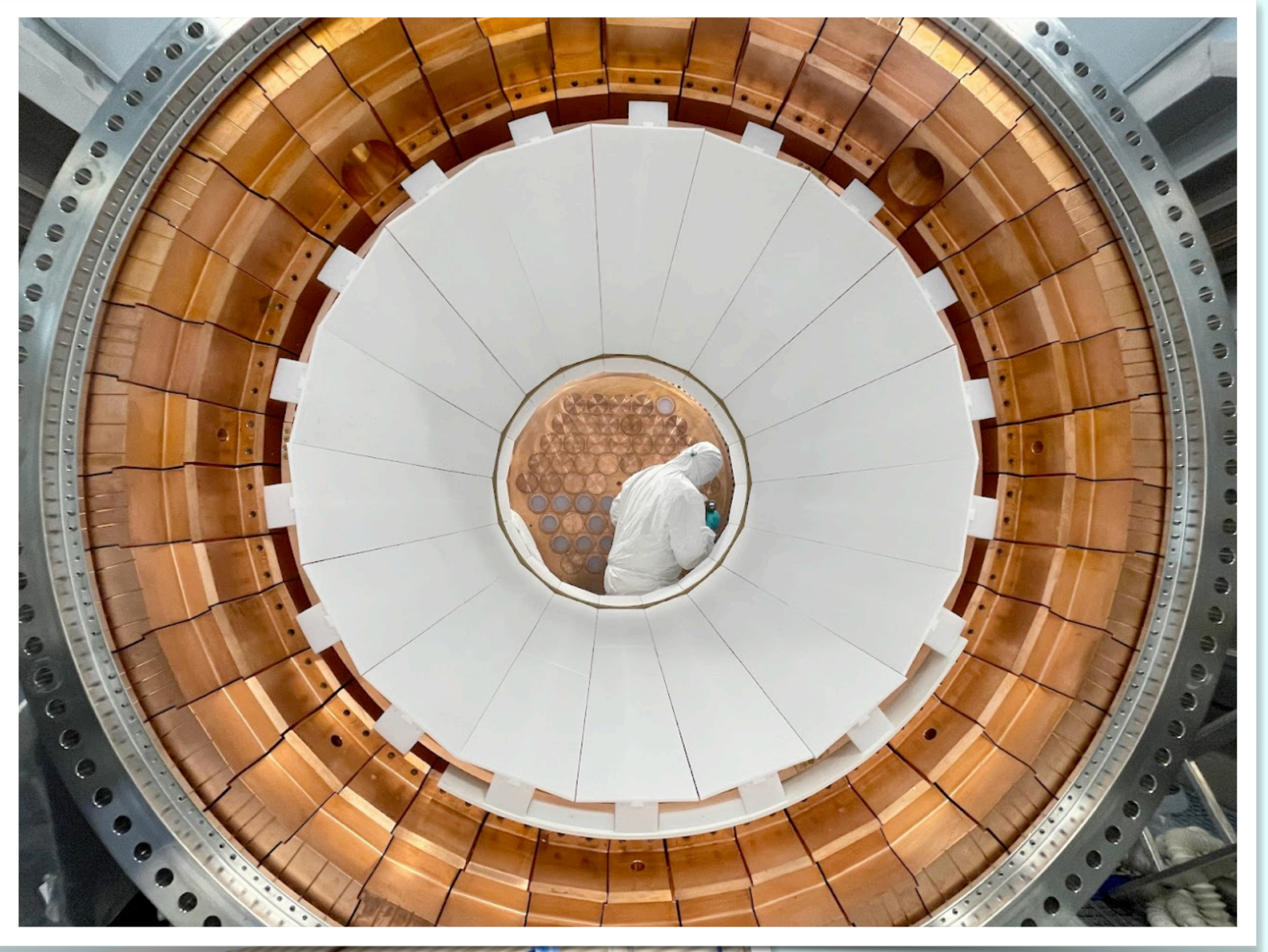


NEXT-White

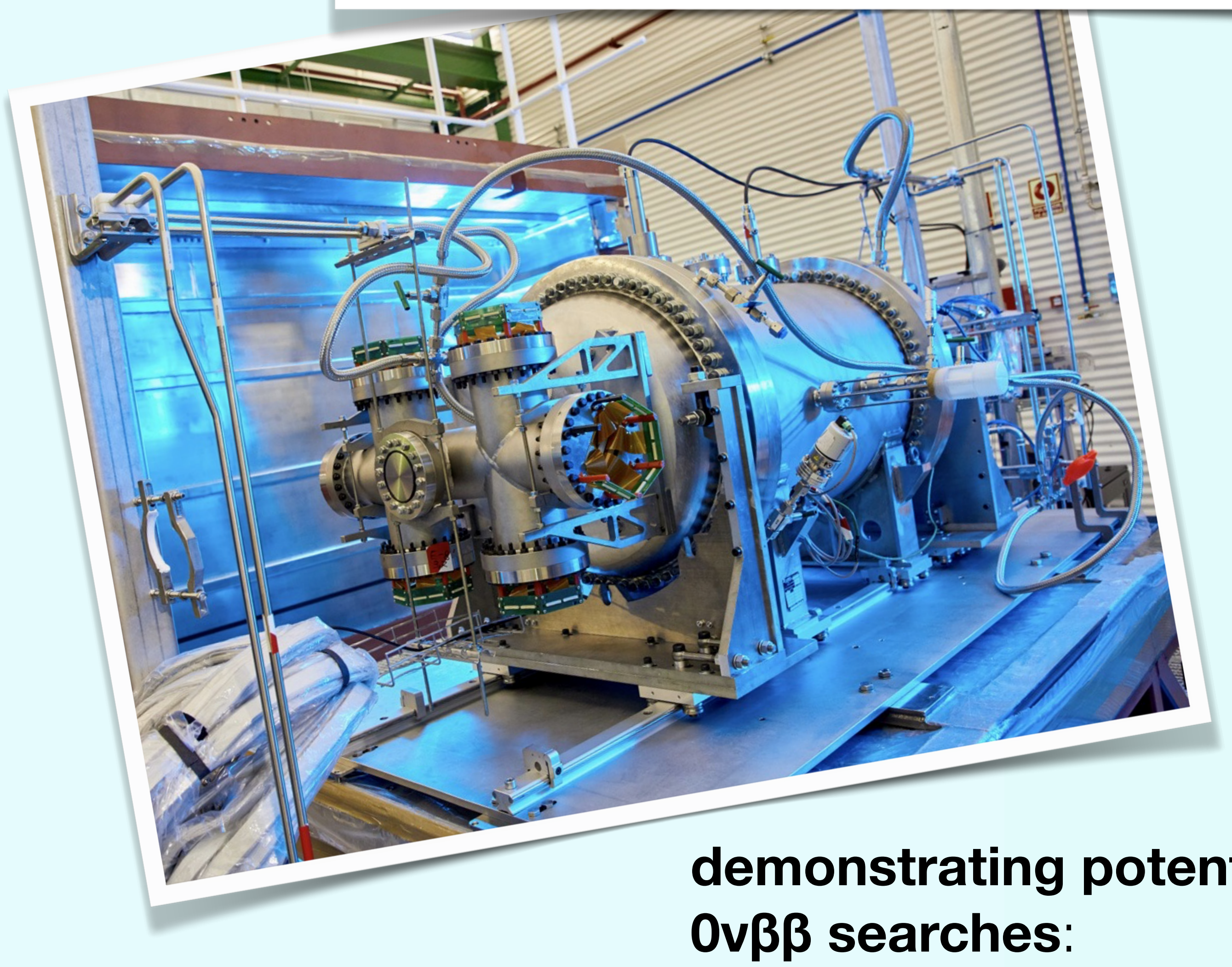
demonstrating potential of HPXe-TPC for **0νββ searches**:

- Energy resolution < 1% at $Q_{\beta\beta}$
- Topology-based background rejection and measurement of the 2νββ lifetime

Summary



Construction finished and in commissioning since May 2024, will demonstrate **low background level. Competitive search** for **0νββ.**



NEXT-White

NEXT-100

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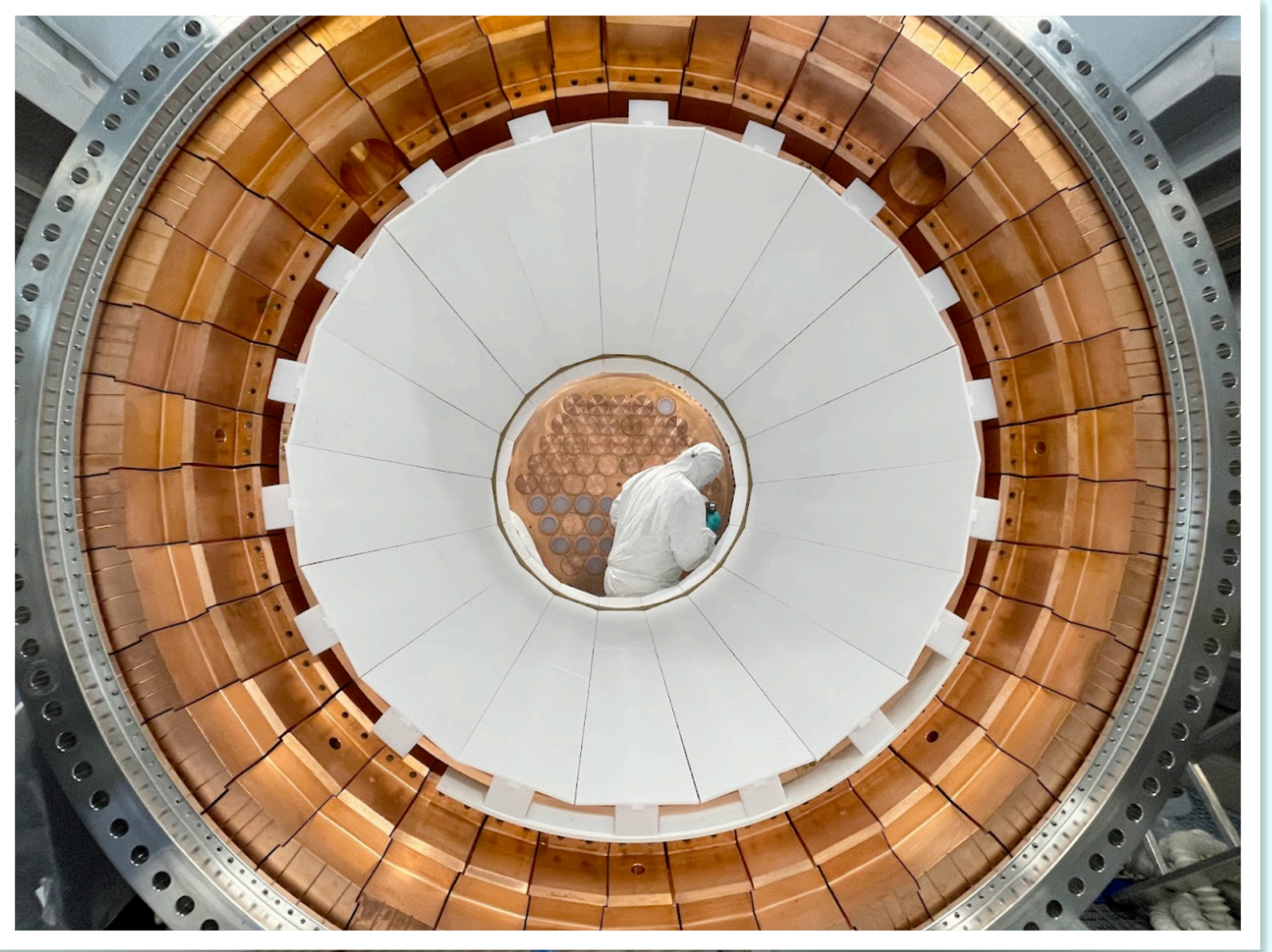

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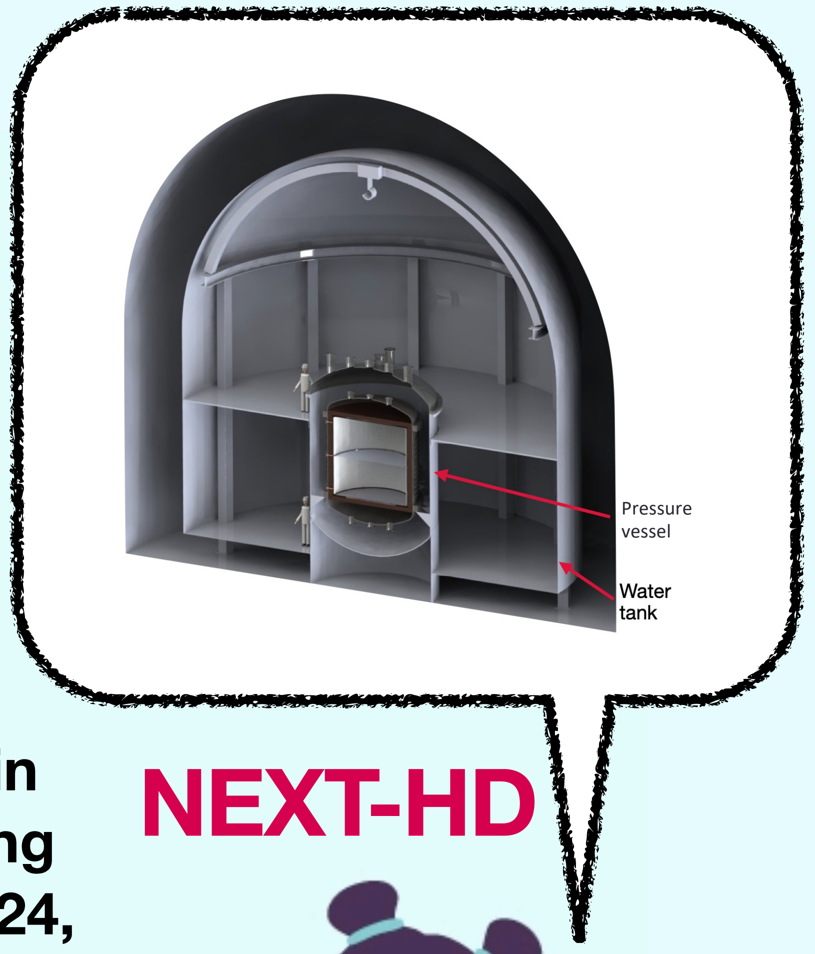
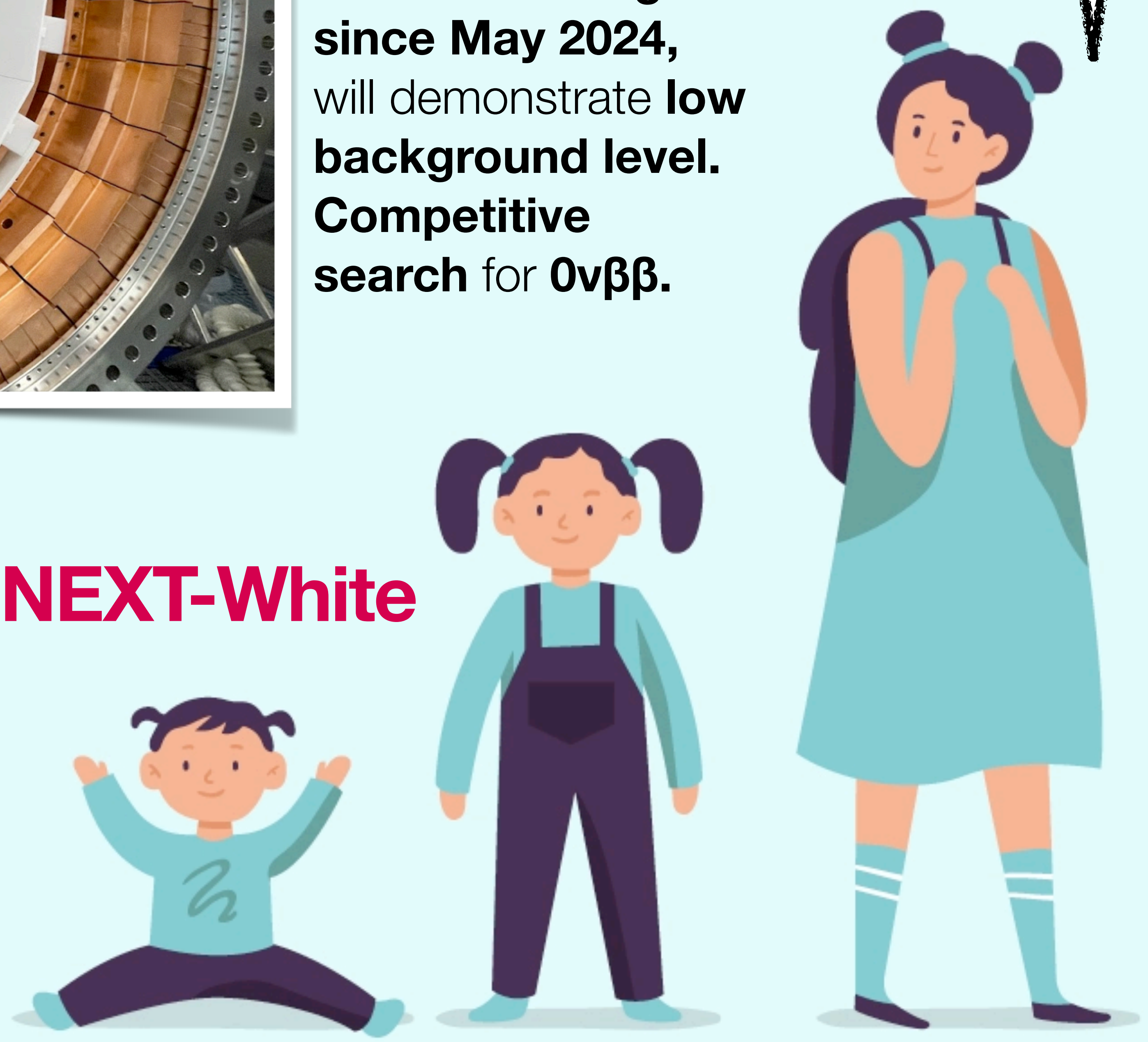
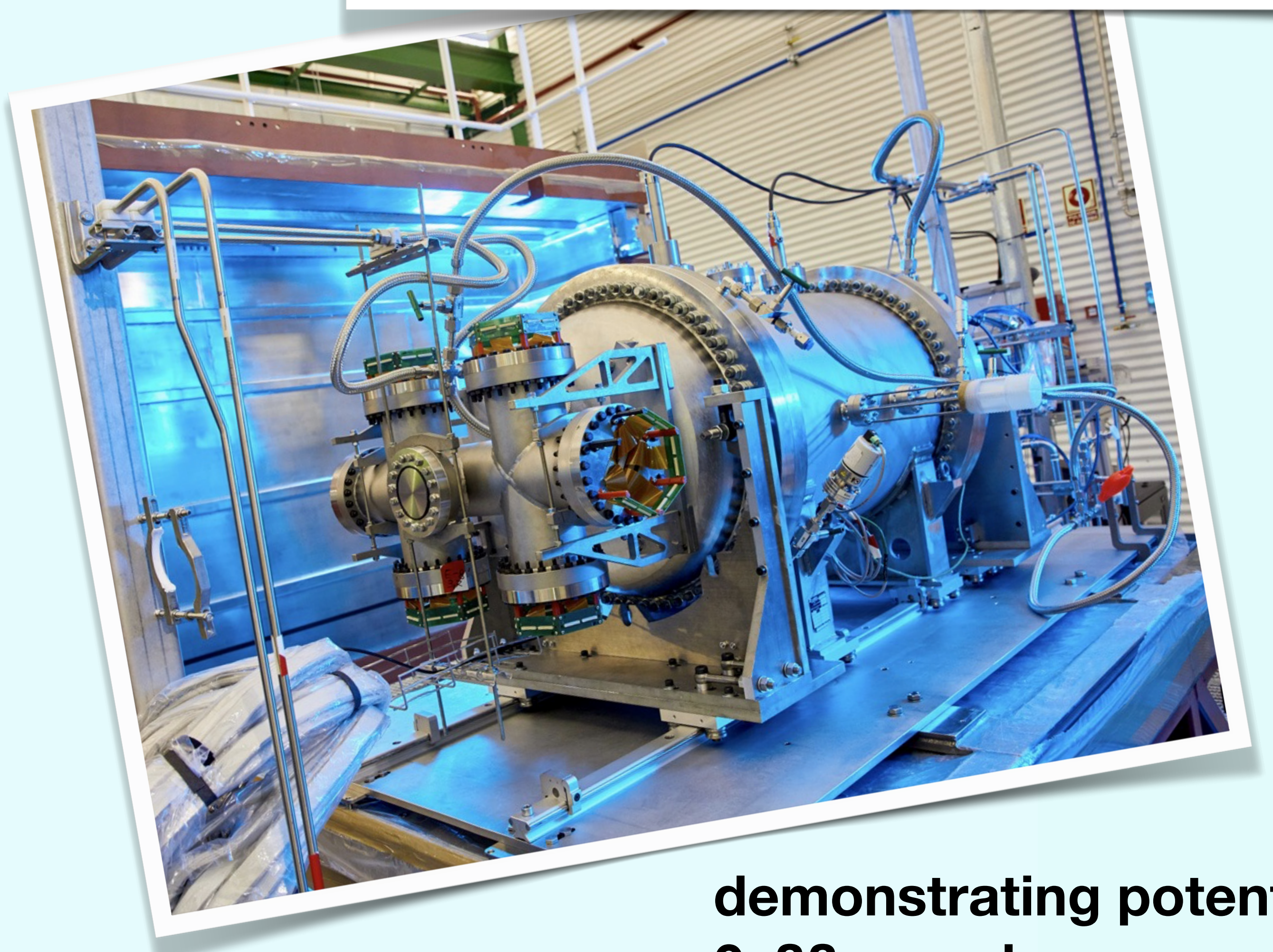


NEXT-HD



NEXT-White

NEXT-100



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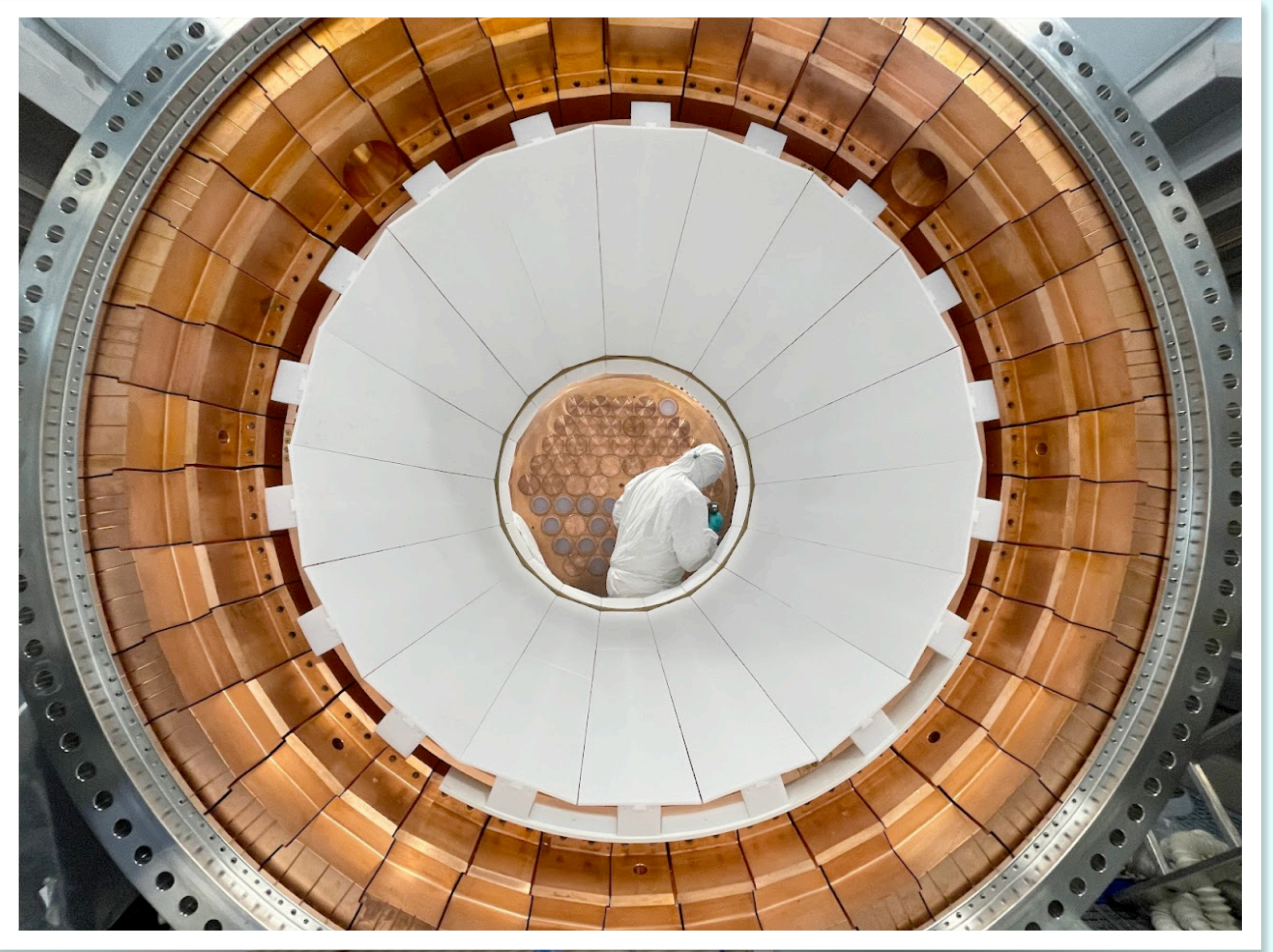
Summary



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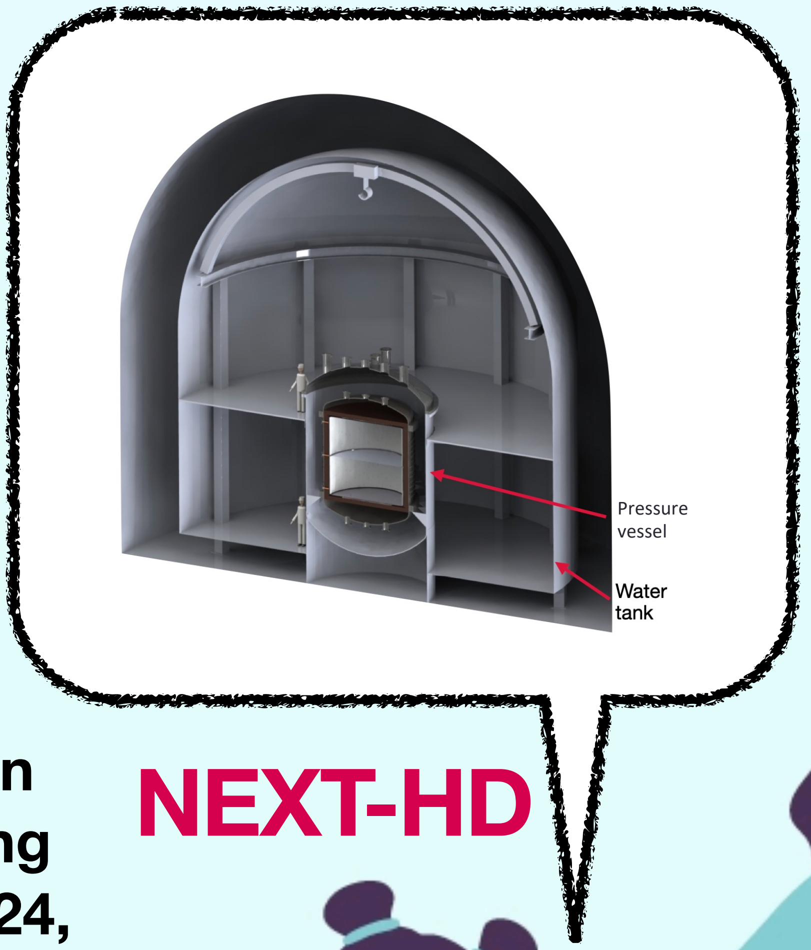
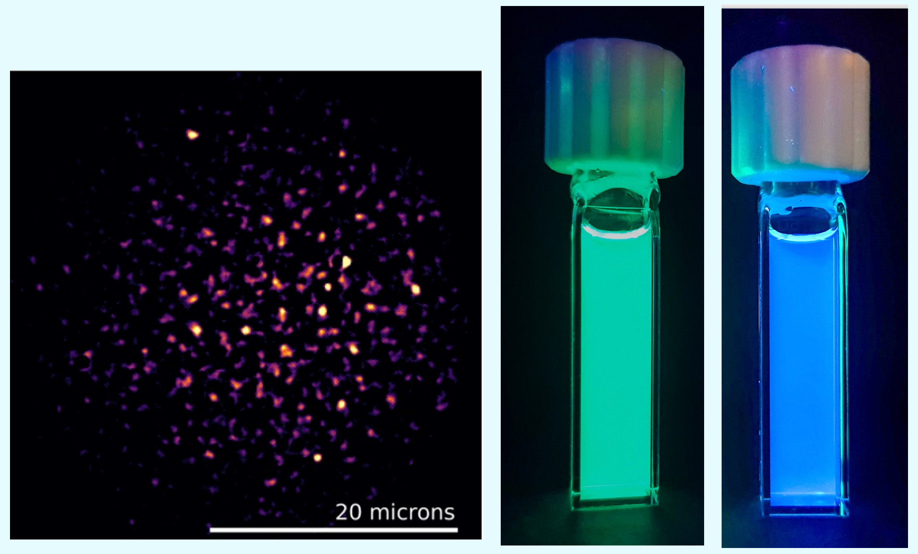
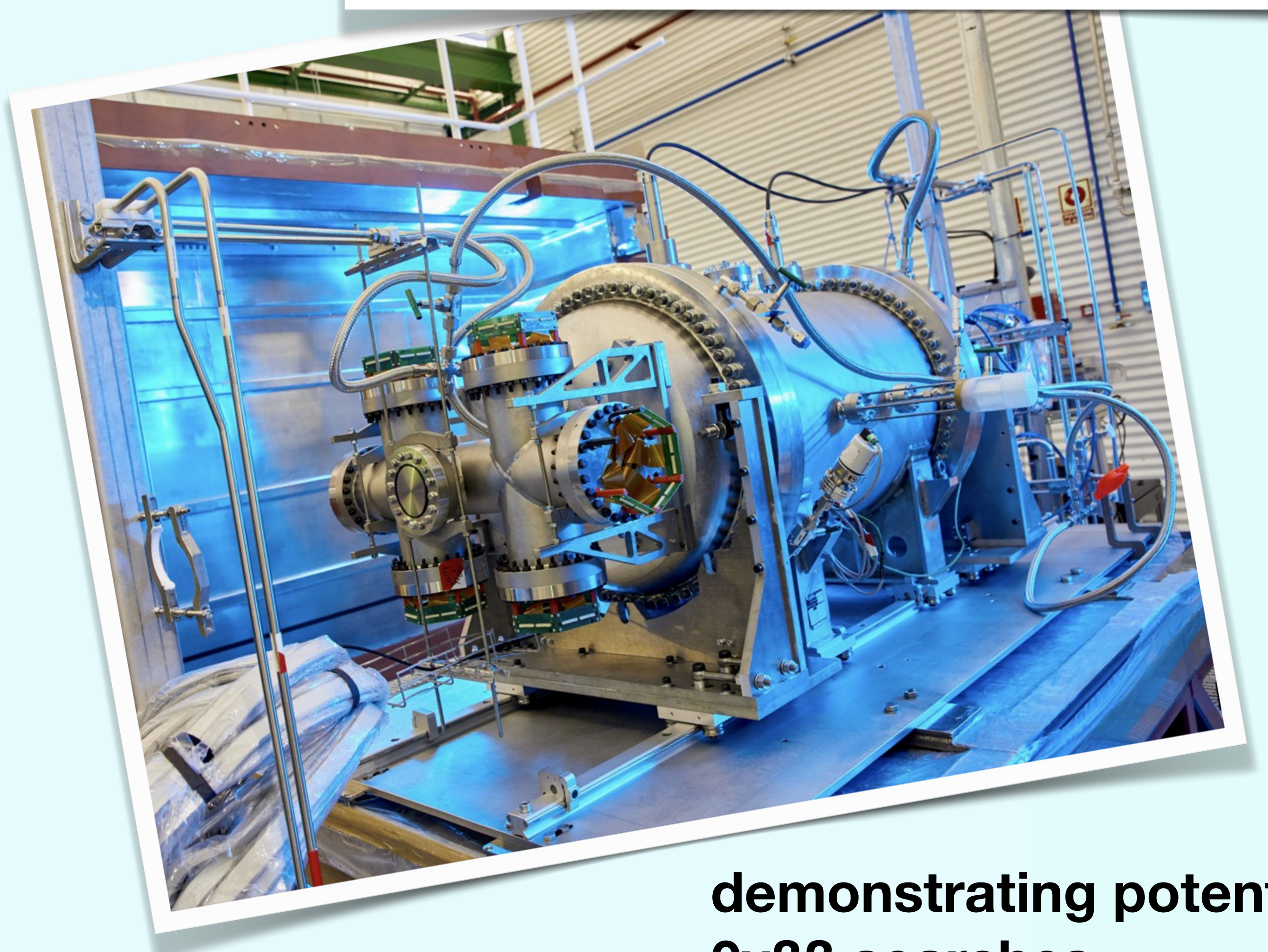
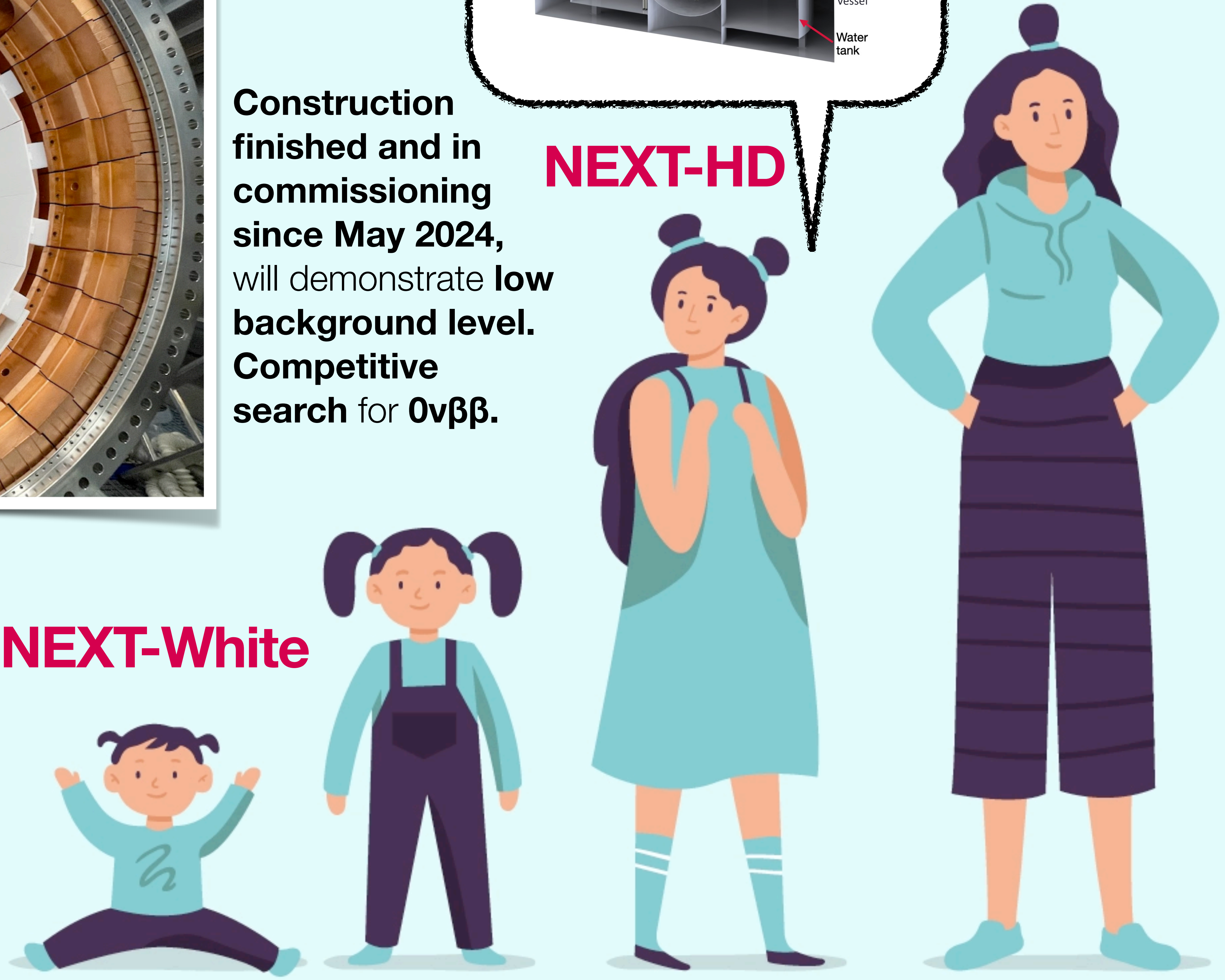


NEXT-HD

Ba-tagging







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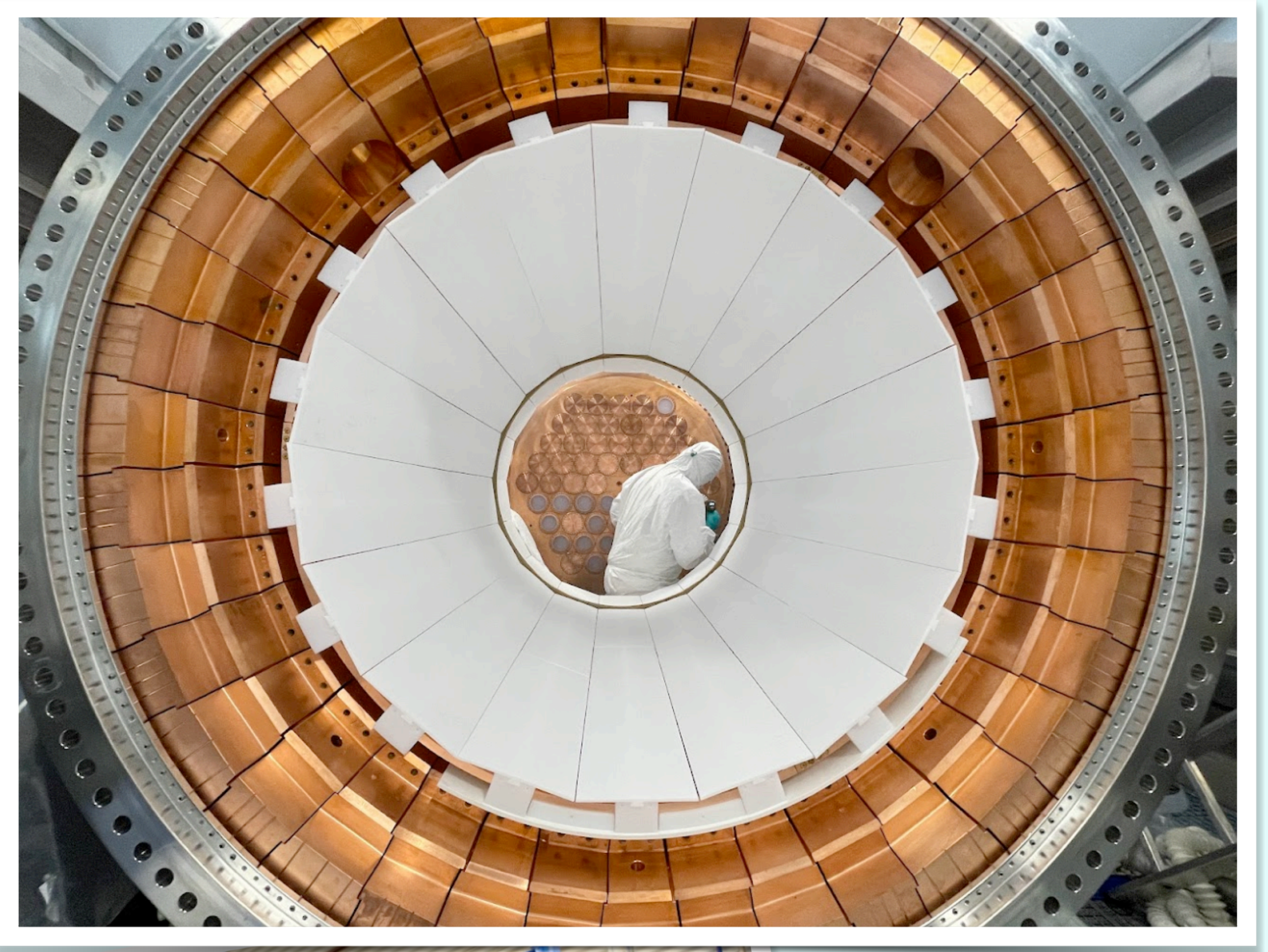
Summary



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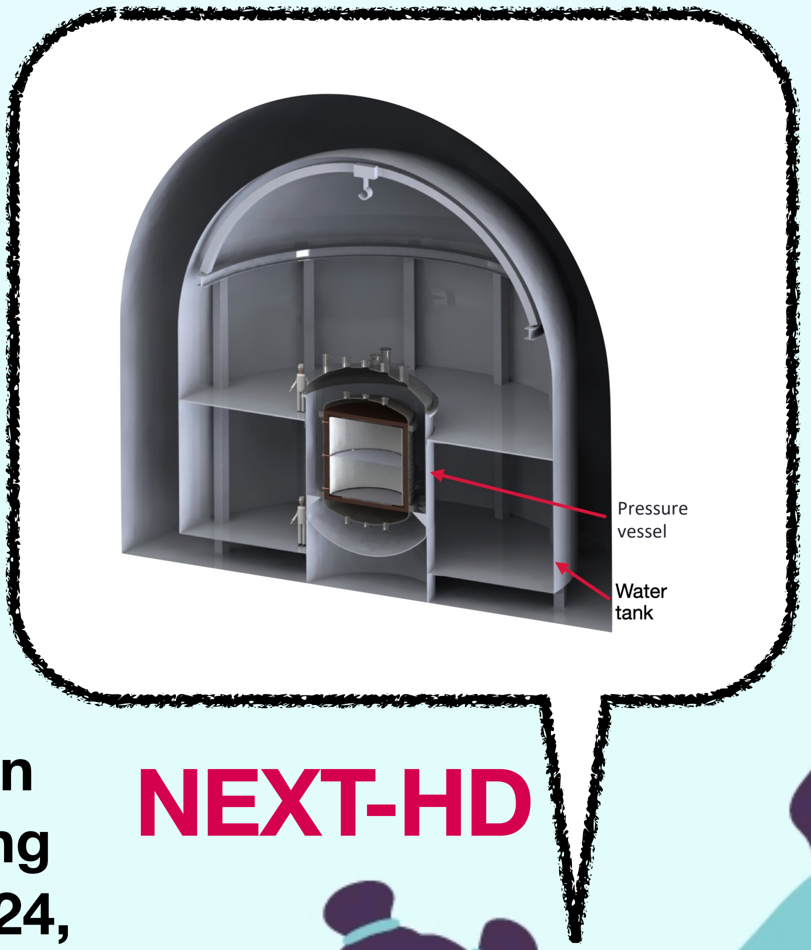
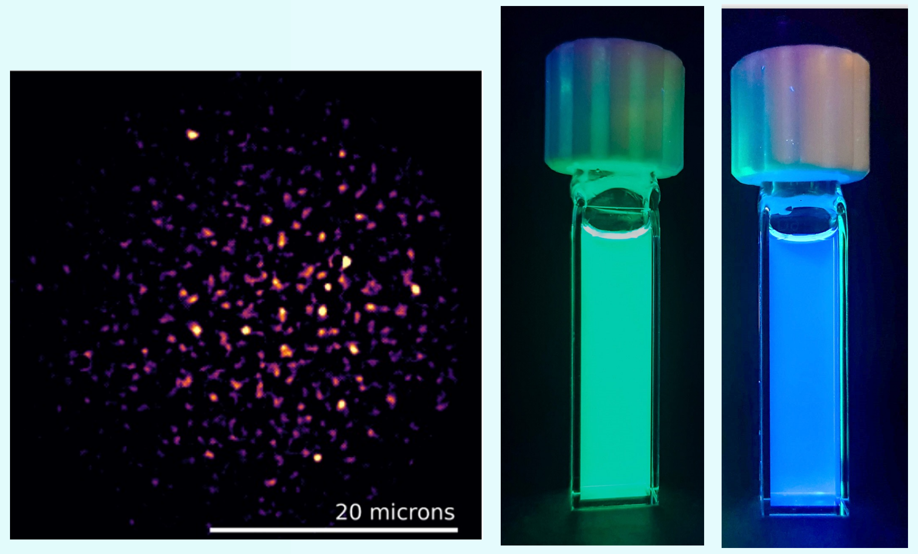


NEXT-HD

Ba-tagging



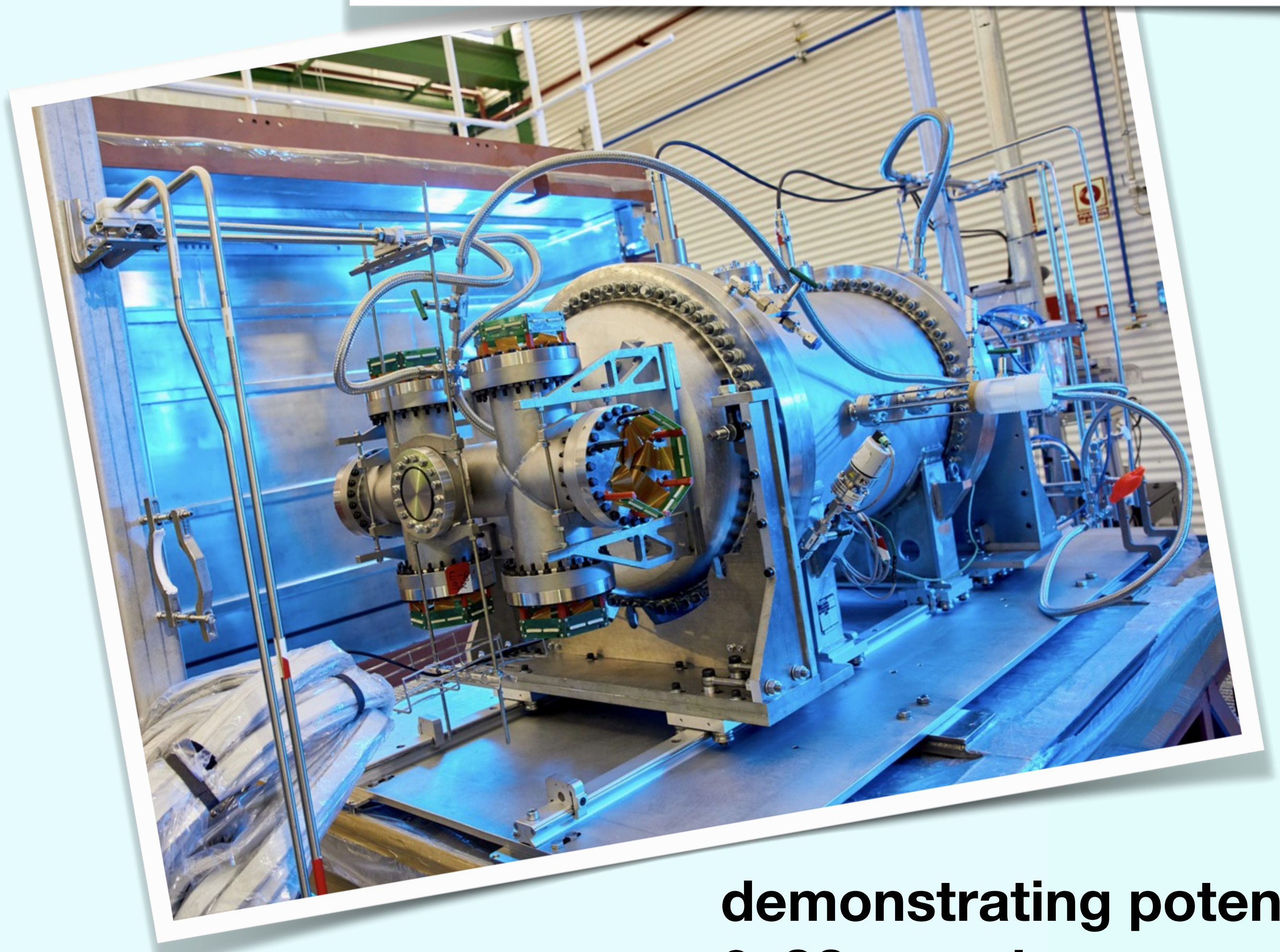
particle physics

surface physics science

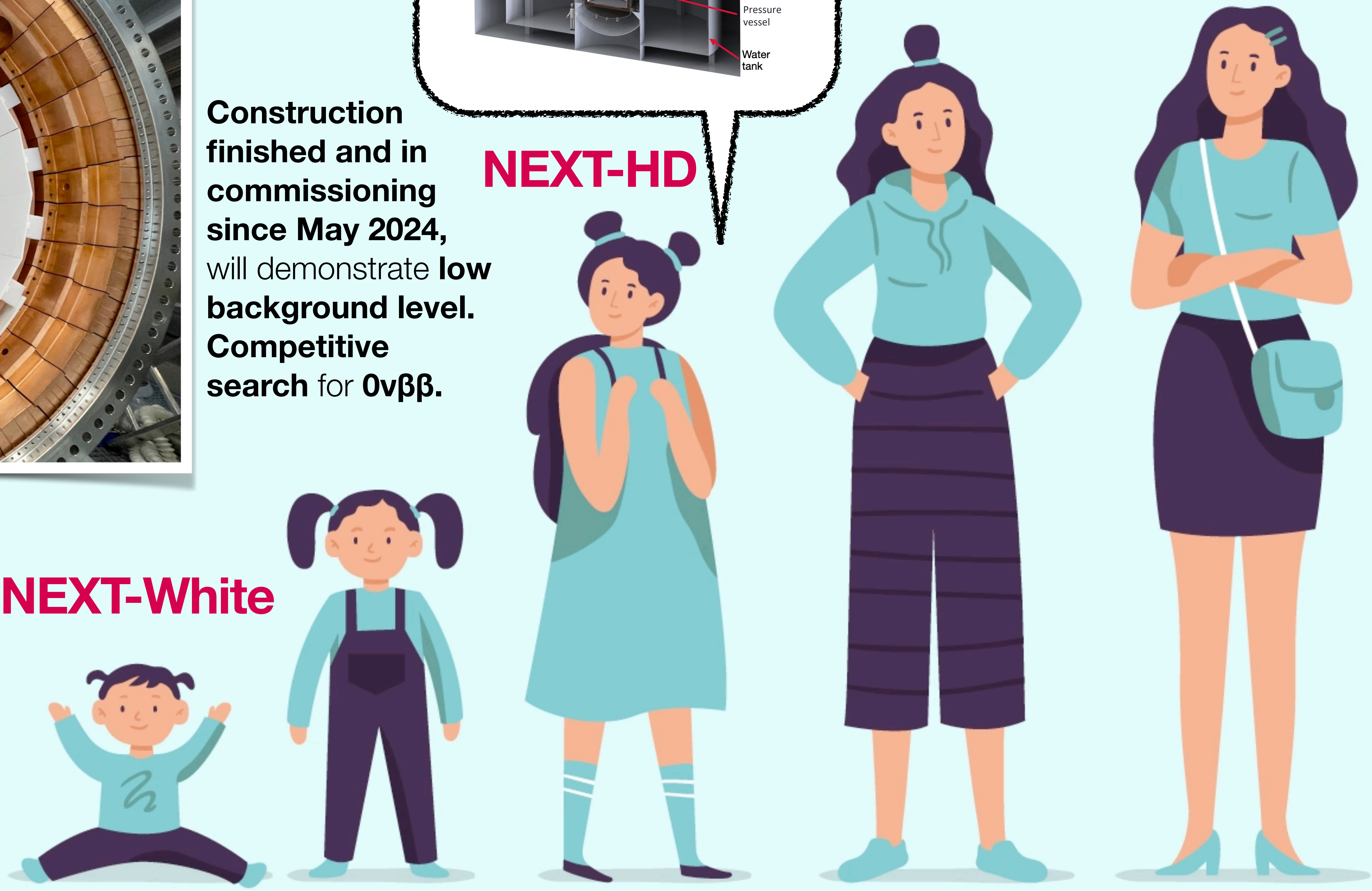
molecular chemistry

sophisticated microscopy

state-of-art robotics



NEXT-White



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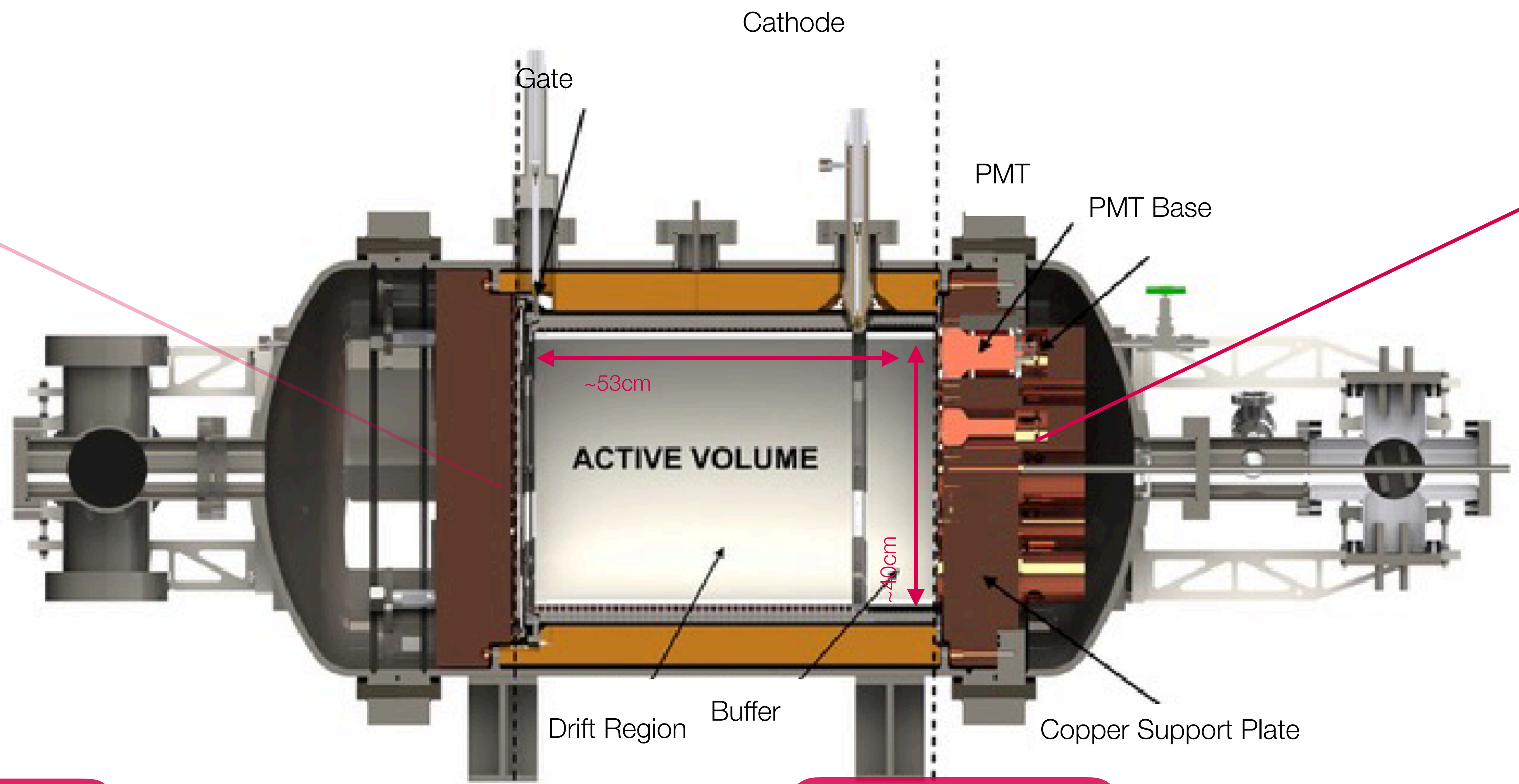
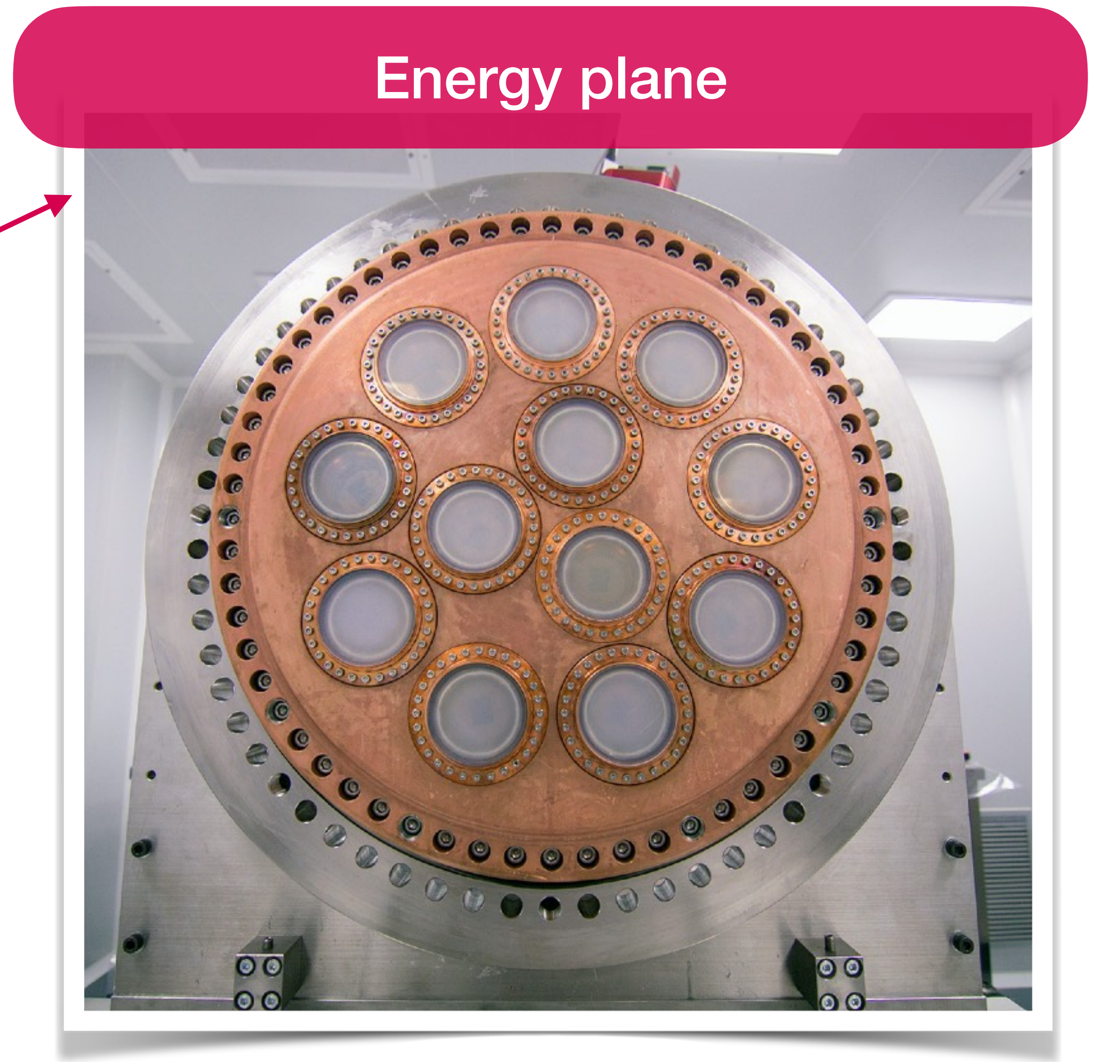
Thanks for your attention!

BACK-UP

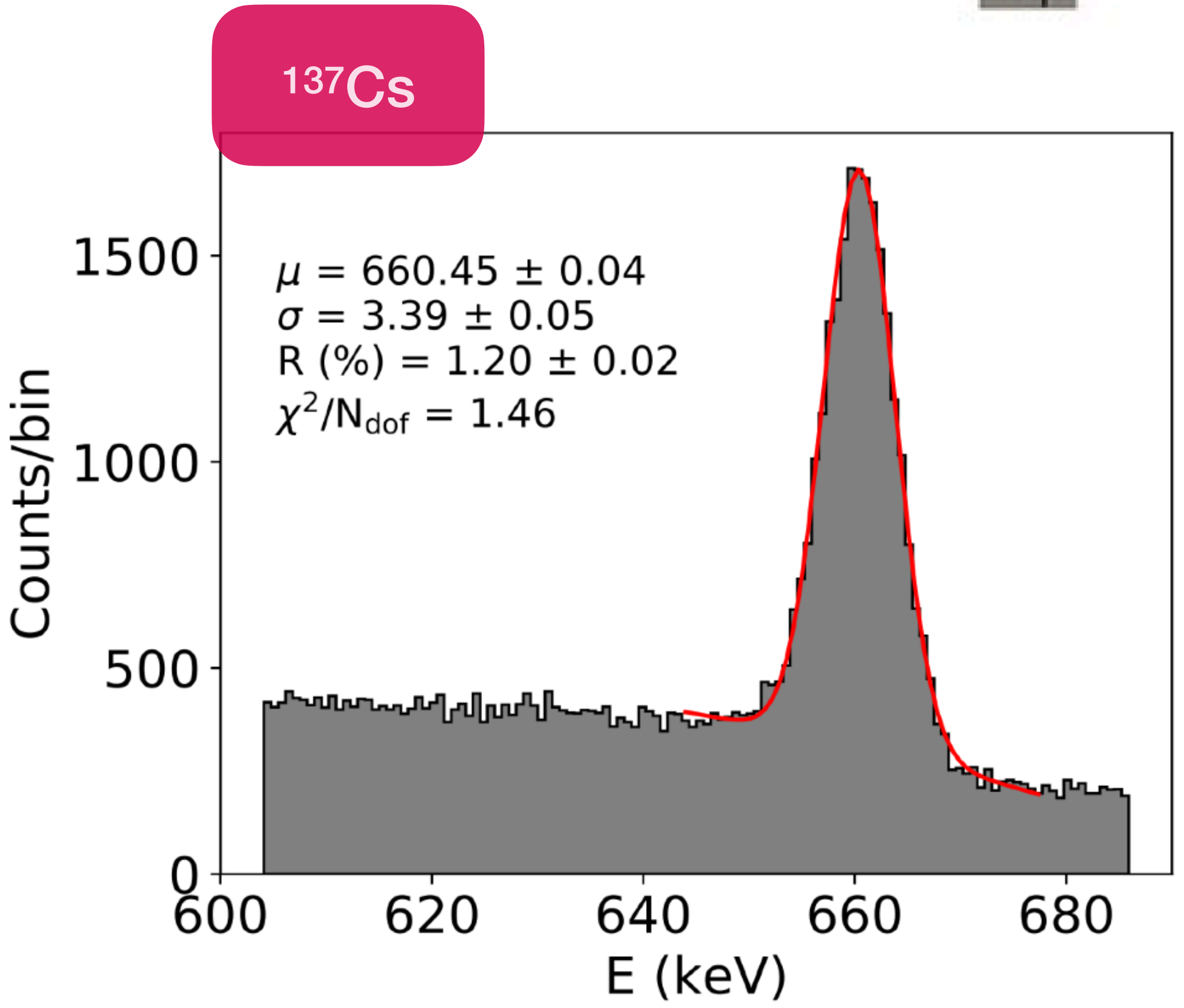
NEW Energy Resolution

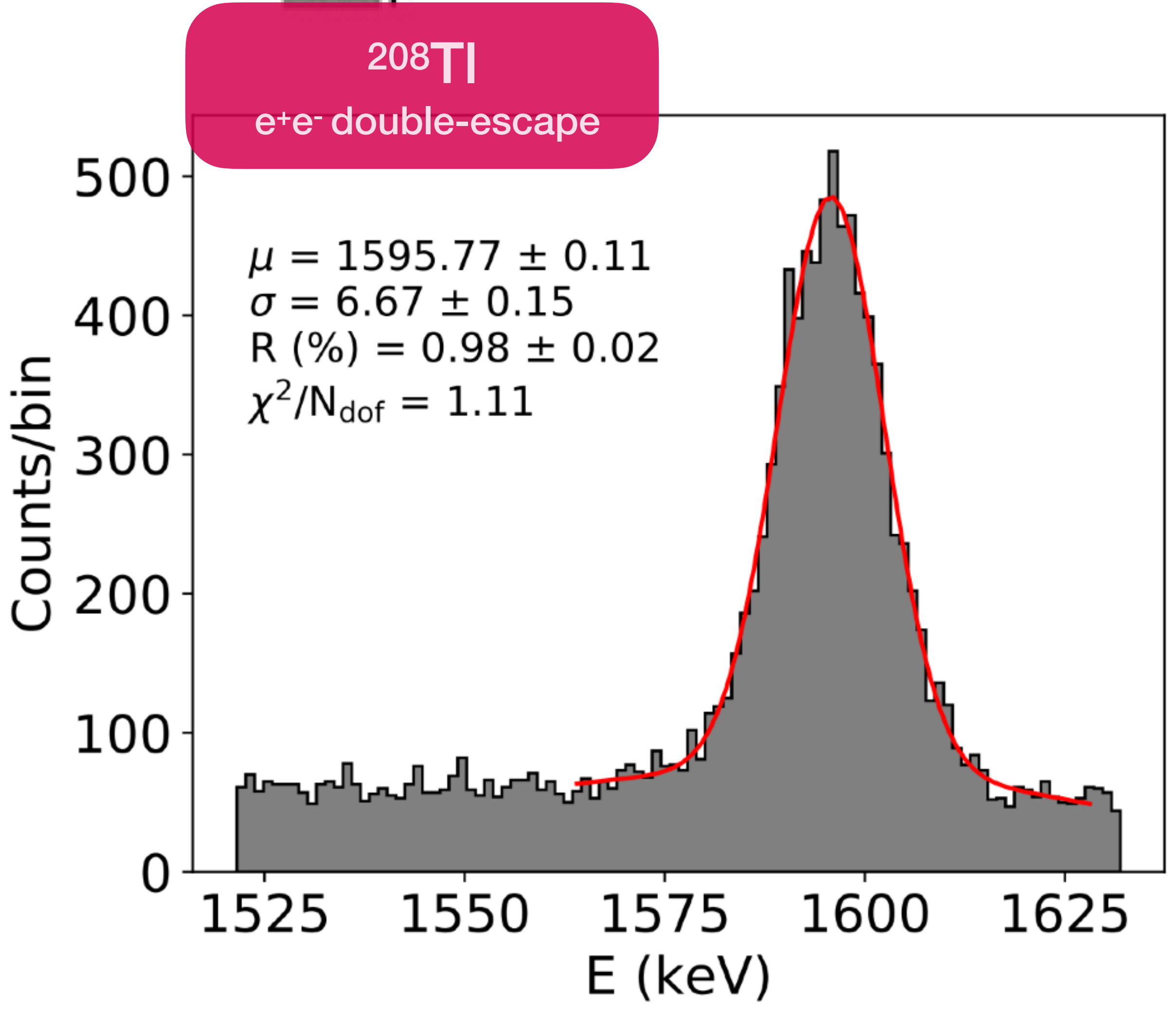


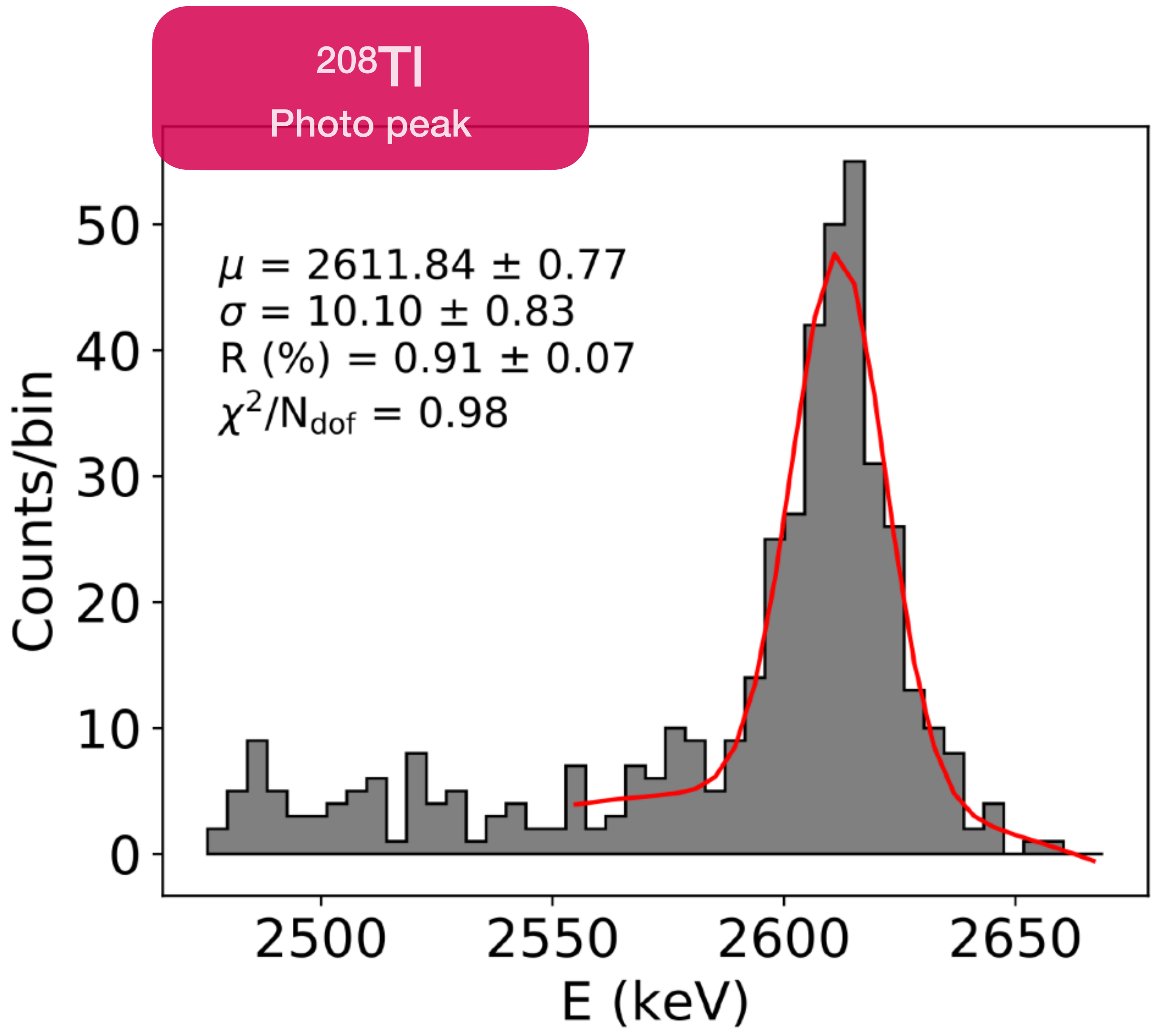


- The **energy resolution** extrapolates to **less than 1% FWHM at Q_{bb}** (0.91% at 2614 keV, ^{208}Tl photo peak).

*Journal of Instrumentation **13**, P10014 (2018), [arXiv:1804.01780].*
*JINST **13**, P10020 (2018), [arXiv:1808.01804].*
*JHEP **10**, 230 (2019), [arXiv:1905.13110].*

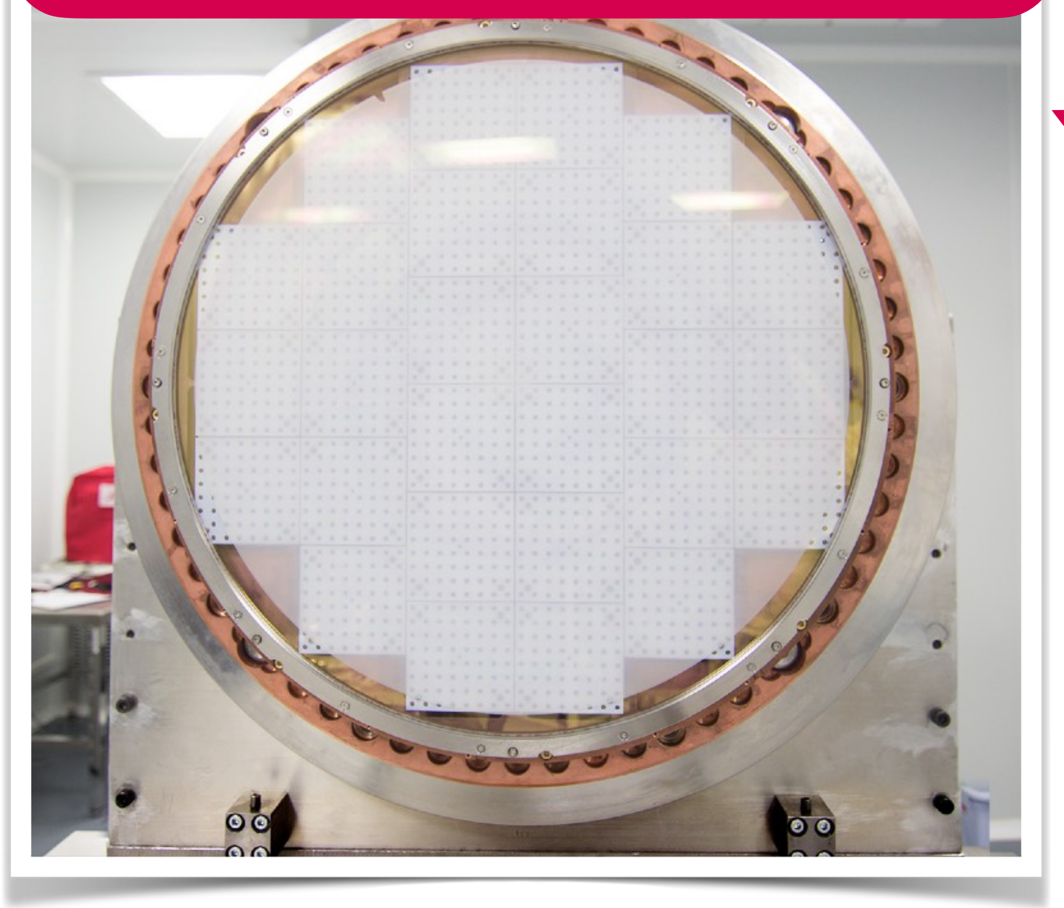


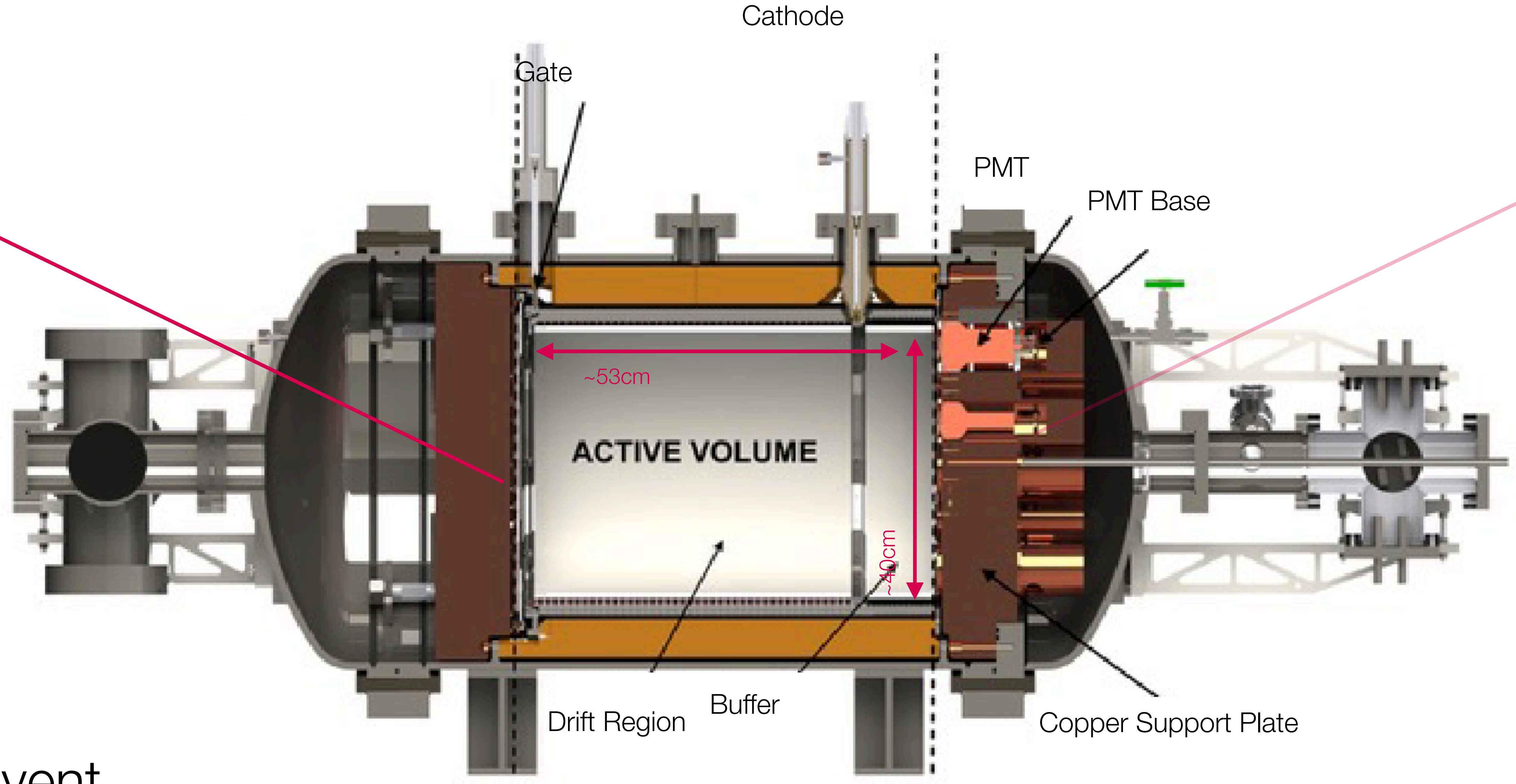




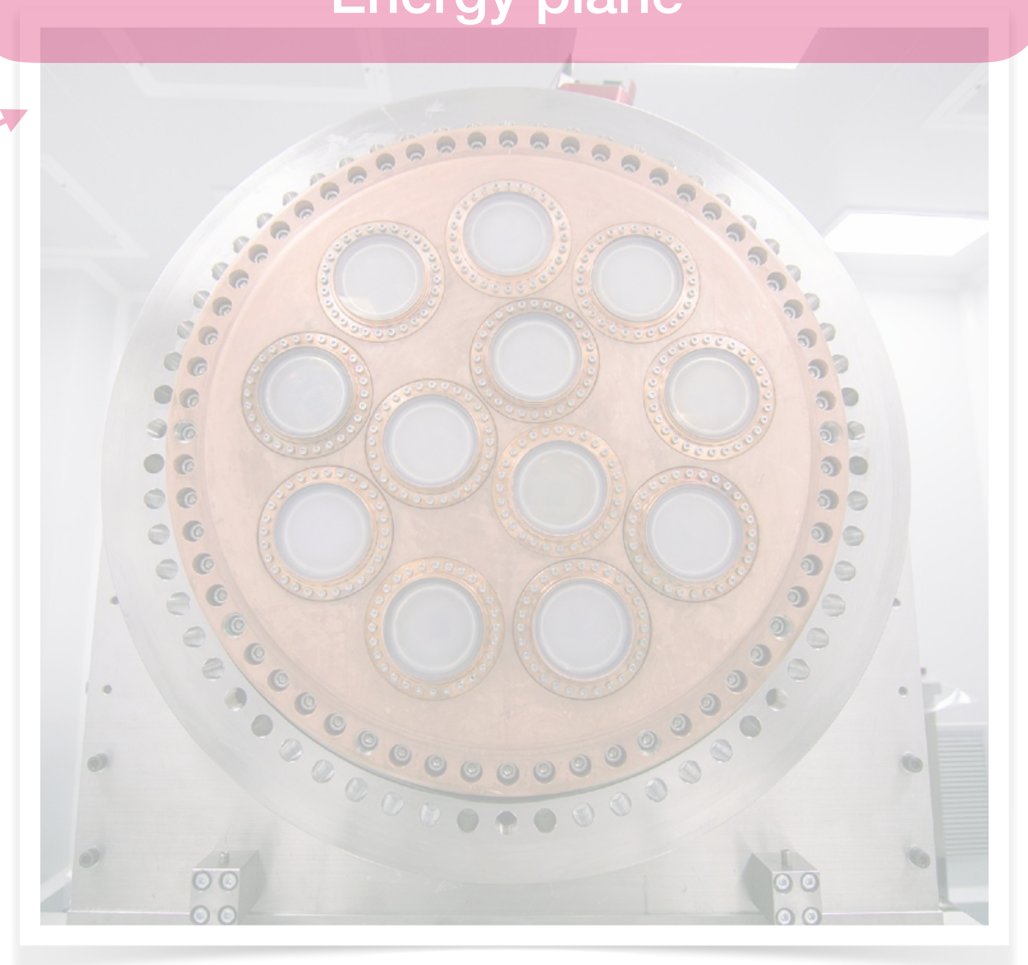
NEW Richardson-Lucy Deconvolution

Tracking plane

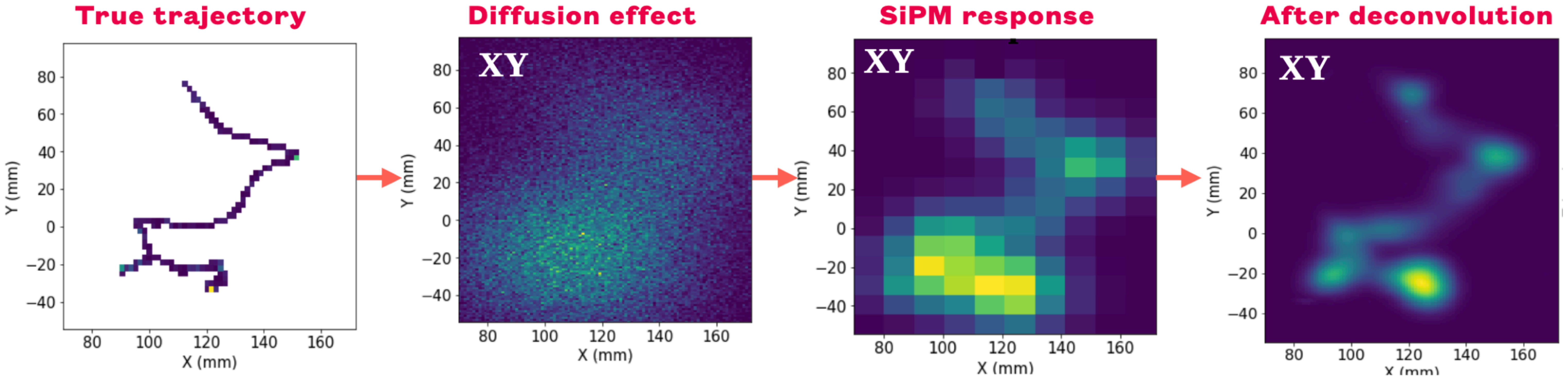




Energy plane



Topological information about the event given by SiPMs position + time



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Electrons diffuse while drifting, smearing the image

- The **smearing** can be described by a **Point Spread Function** (PSF) obtained with ^{83m}Kr events.
- The **Richardson-Lucy** deconvolution uses the PSF to deconvolve the image and remove the smearing.

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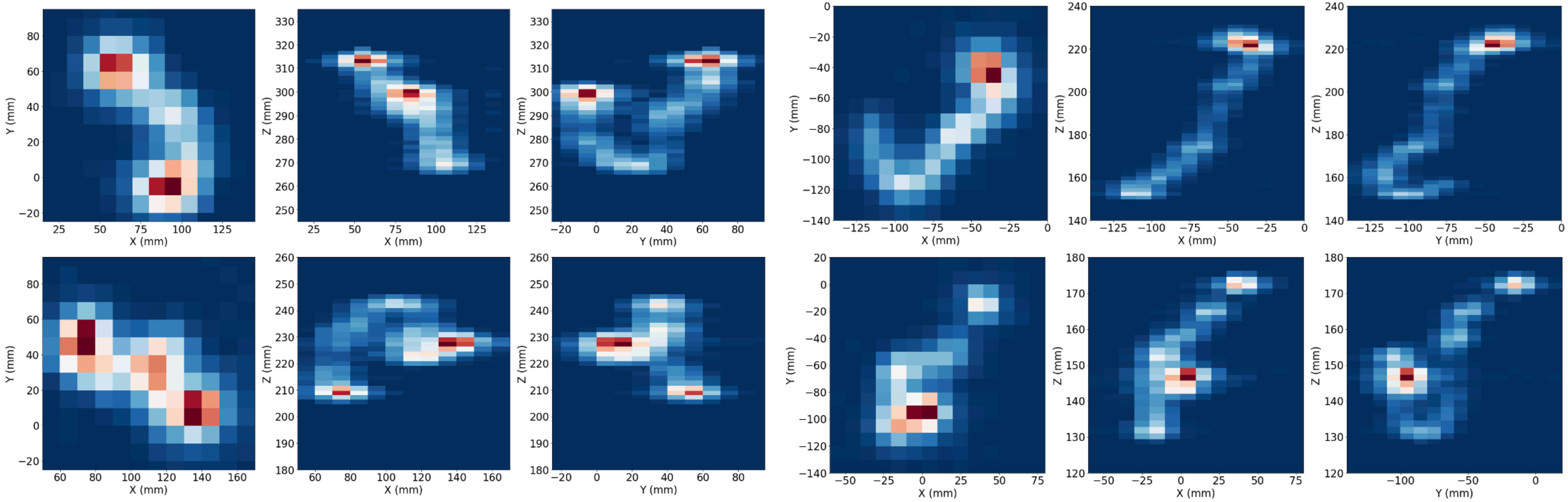
NEW Richardson-Lucy Deconvolution

Raw Signal



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Ander - LIDINE conference

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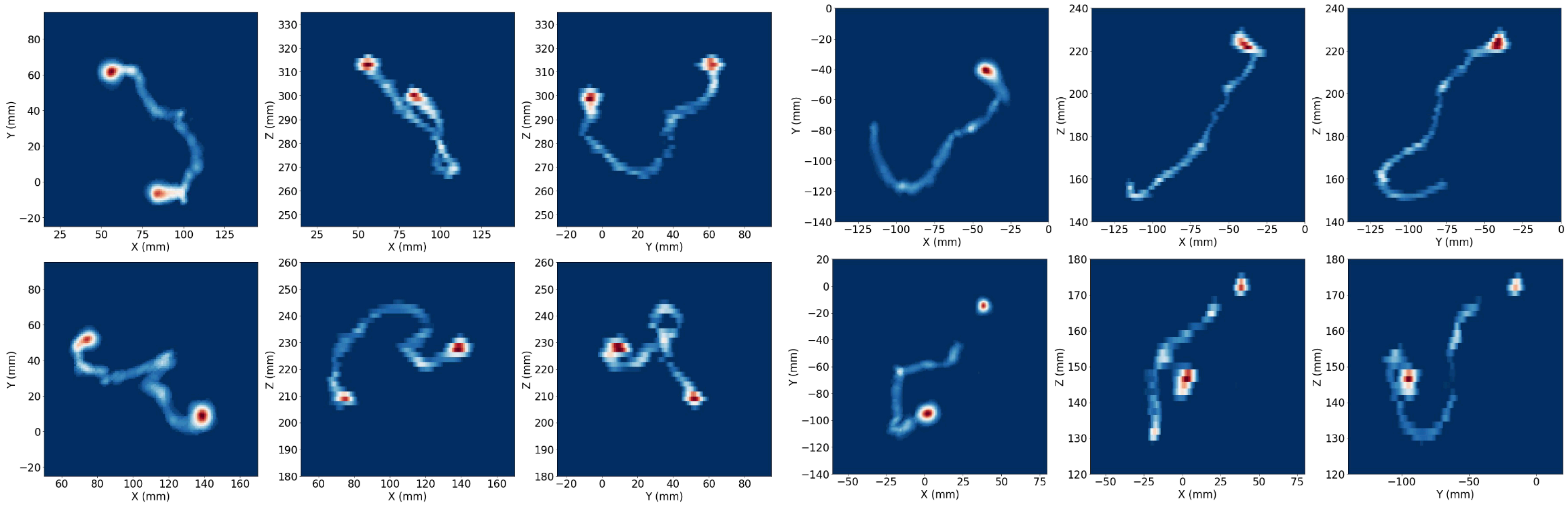
NEW Richardson-Lucy Deconvolution

RL Deconvolution



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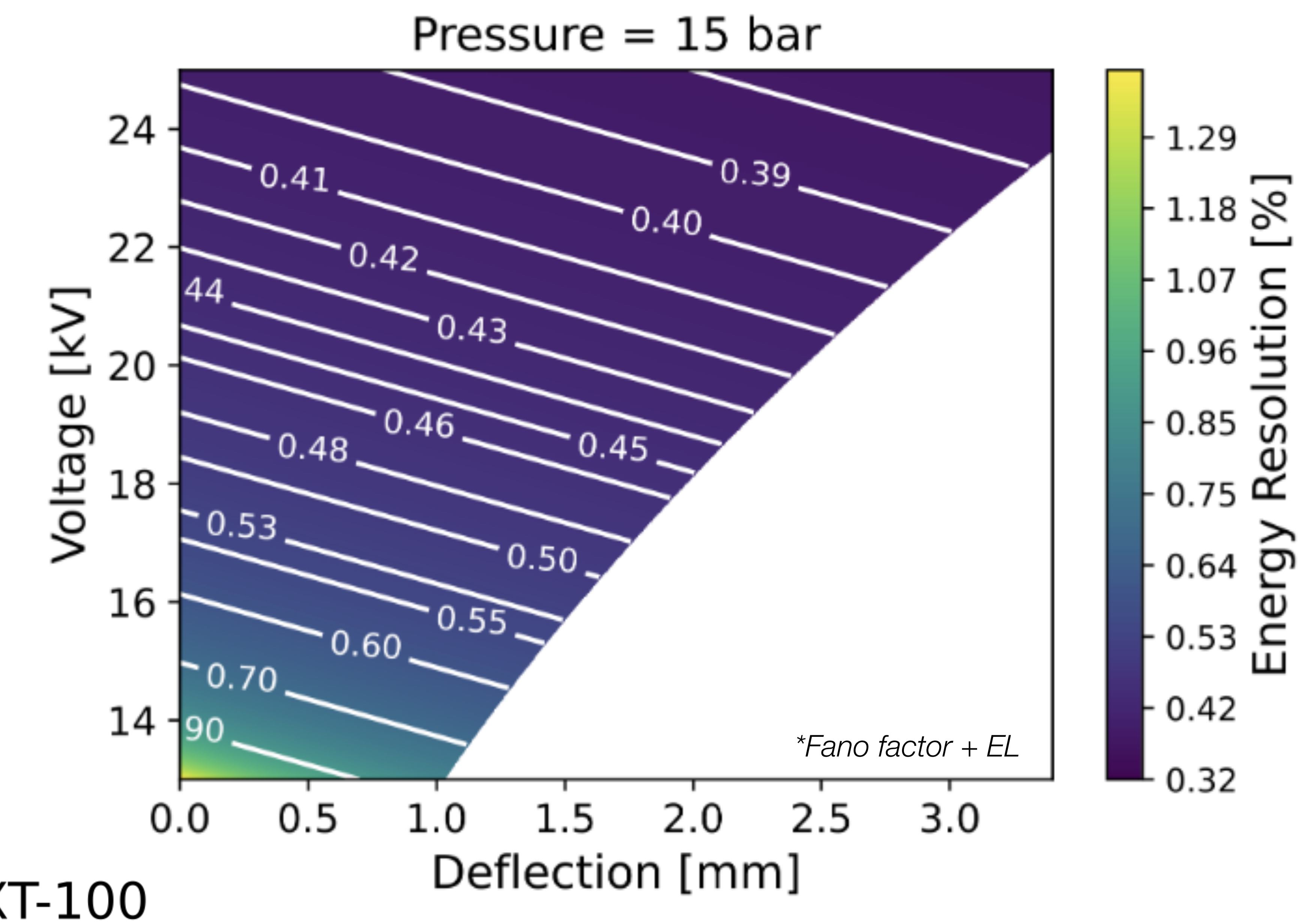
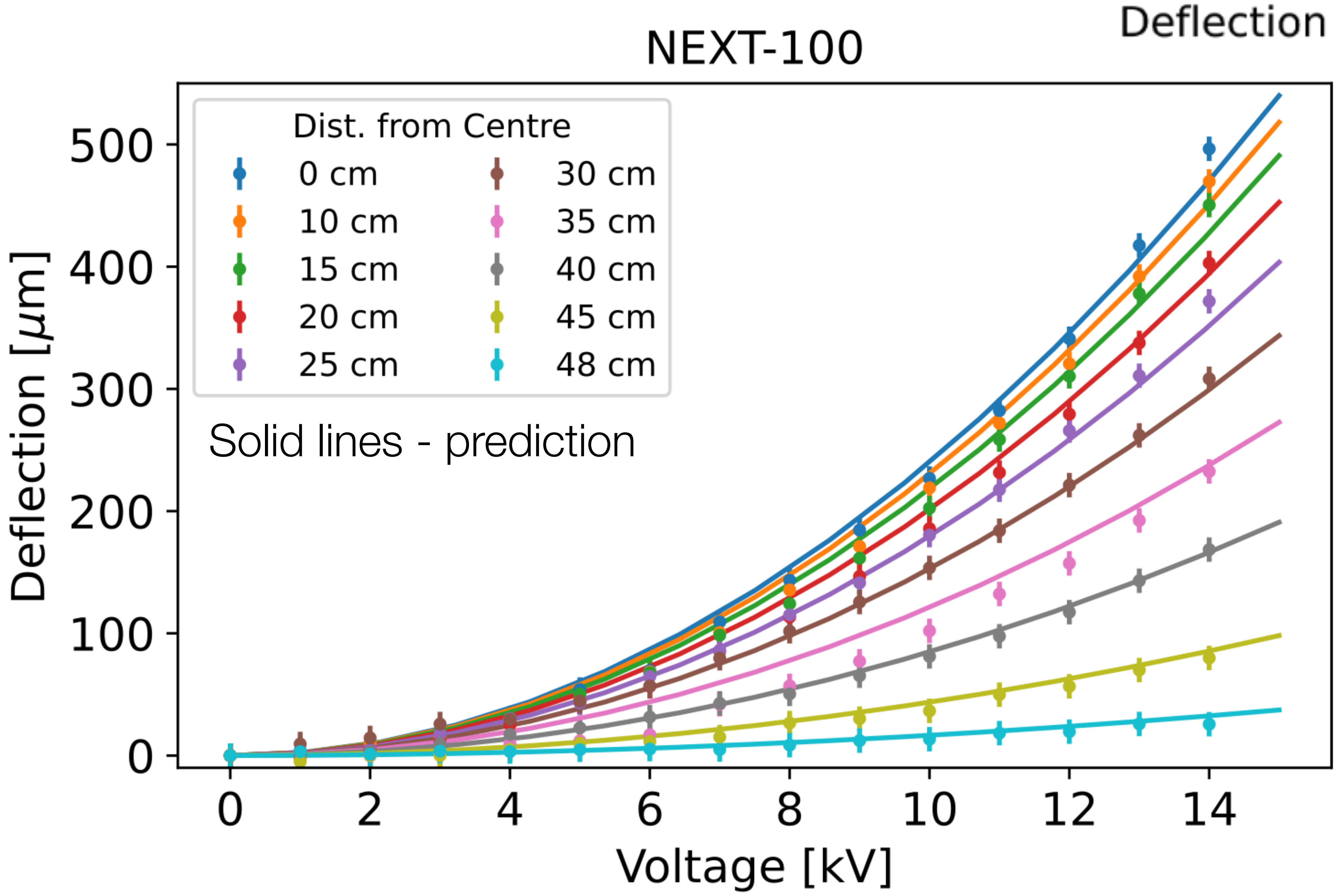
The @next-100 detector

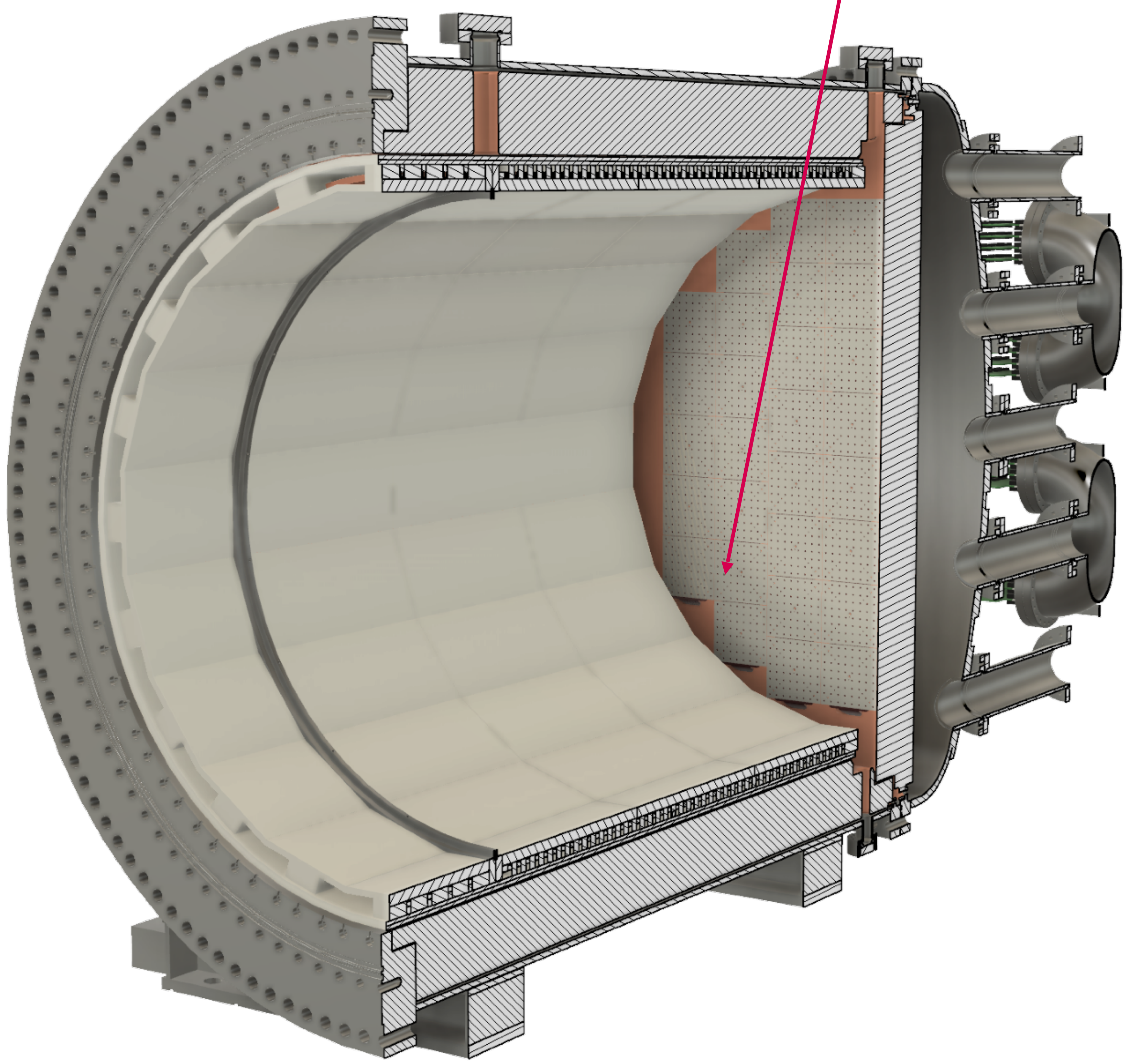
Electrostatic deflection of the EL measured (important for energy resolution)

[arXiv:2311.03528]





Cathode-EL region using meshes



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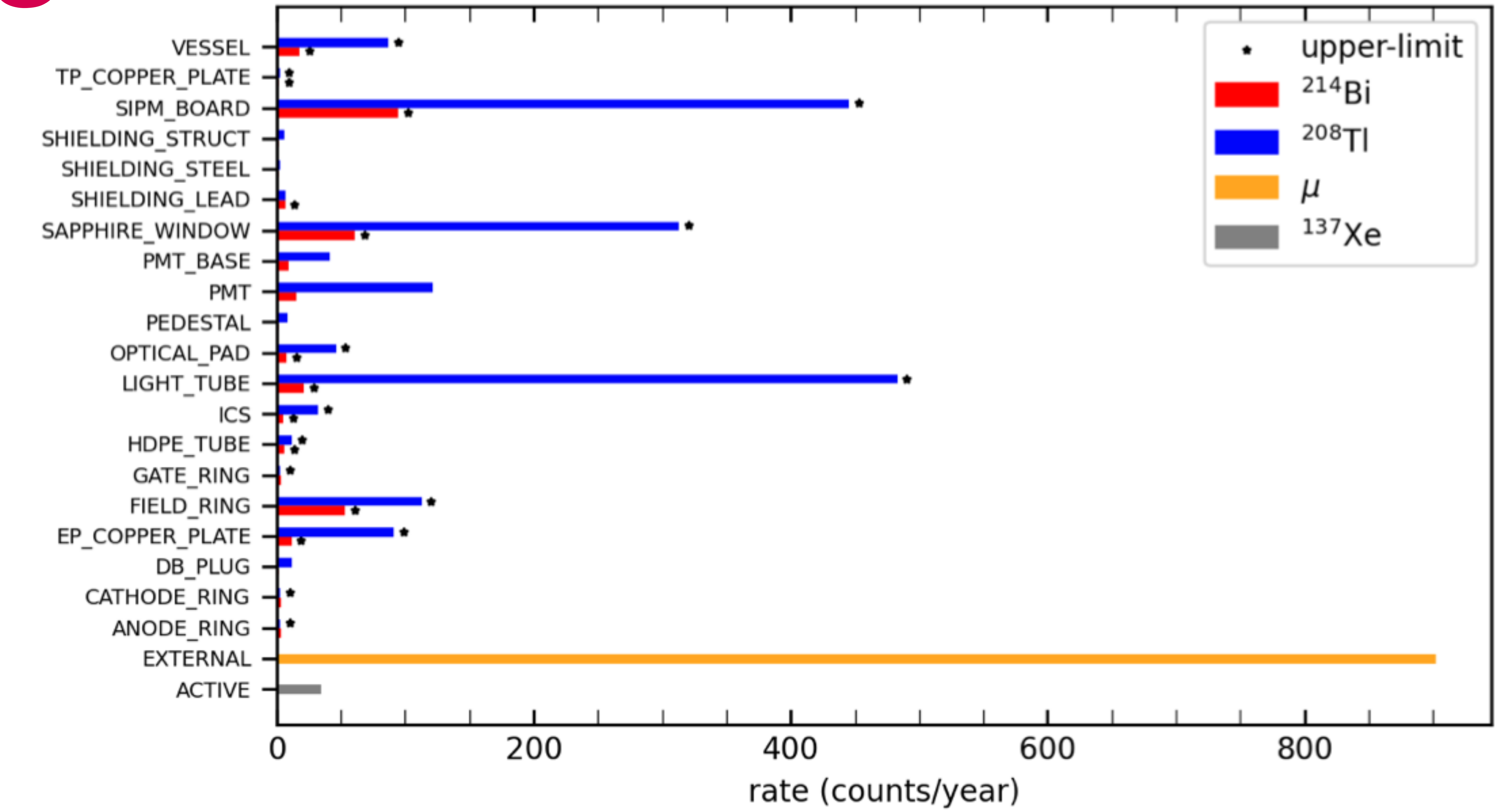
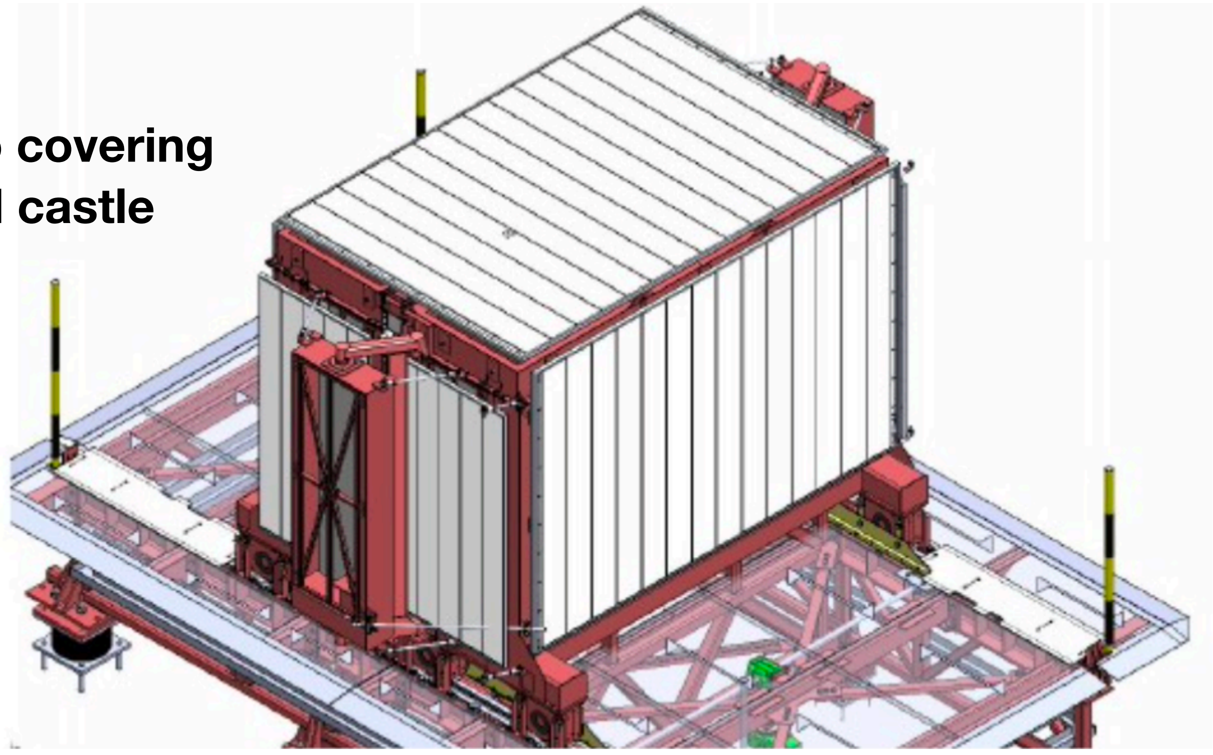
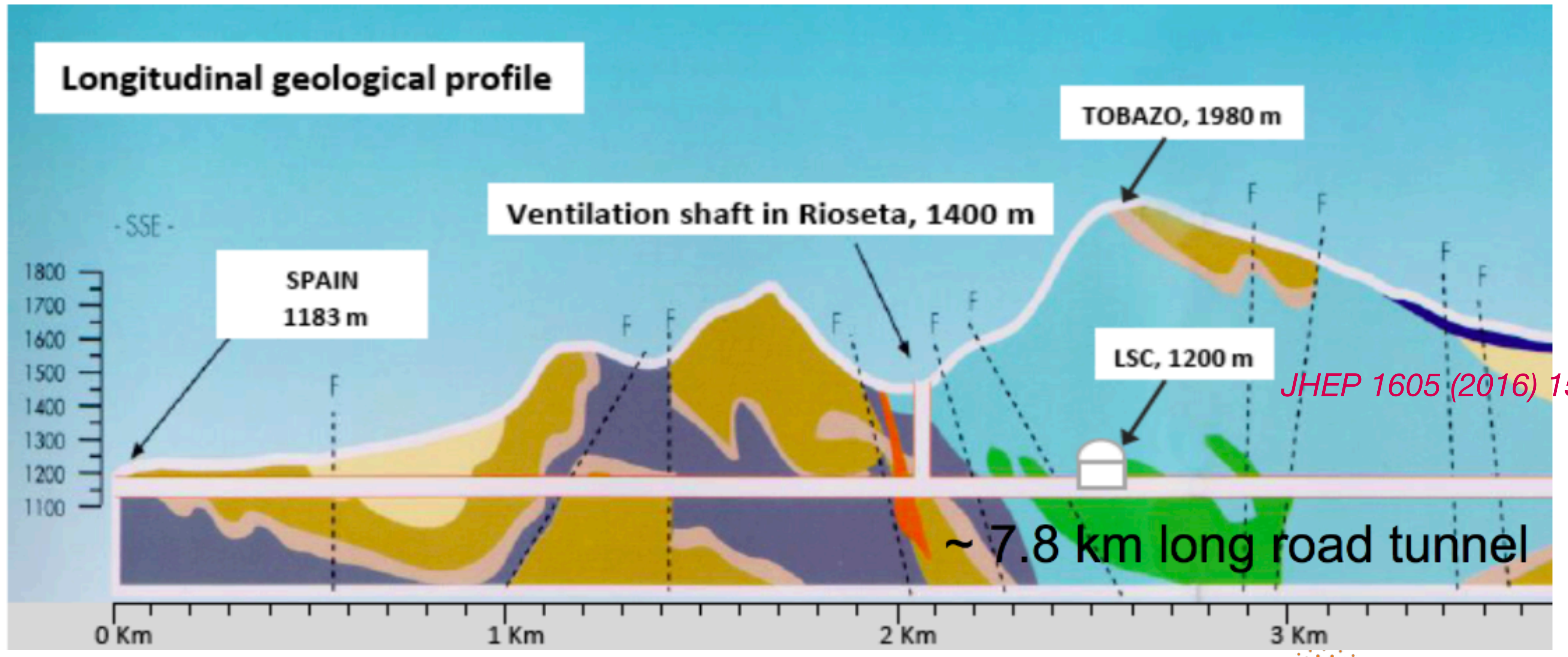
The next-100 backgrounds

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



Muon veto covering the lead castle





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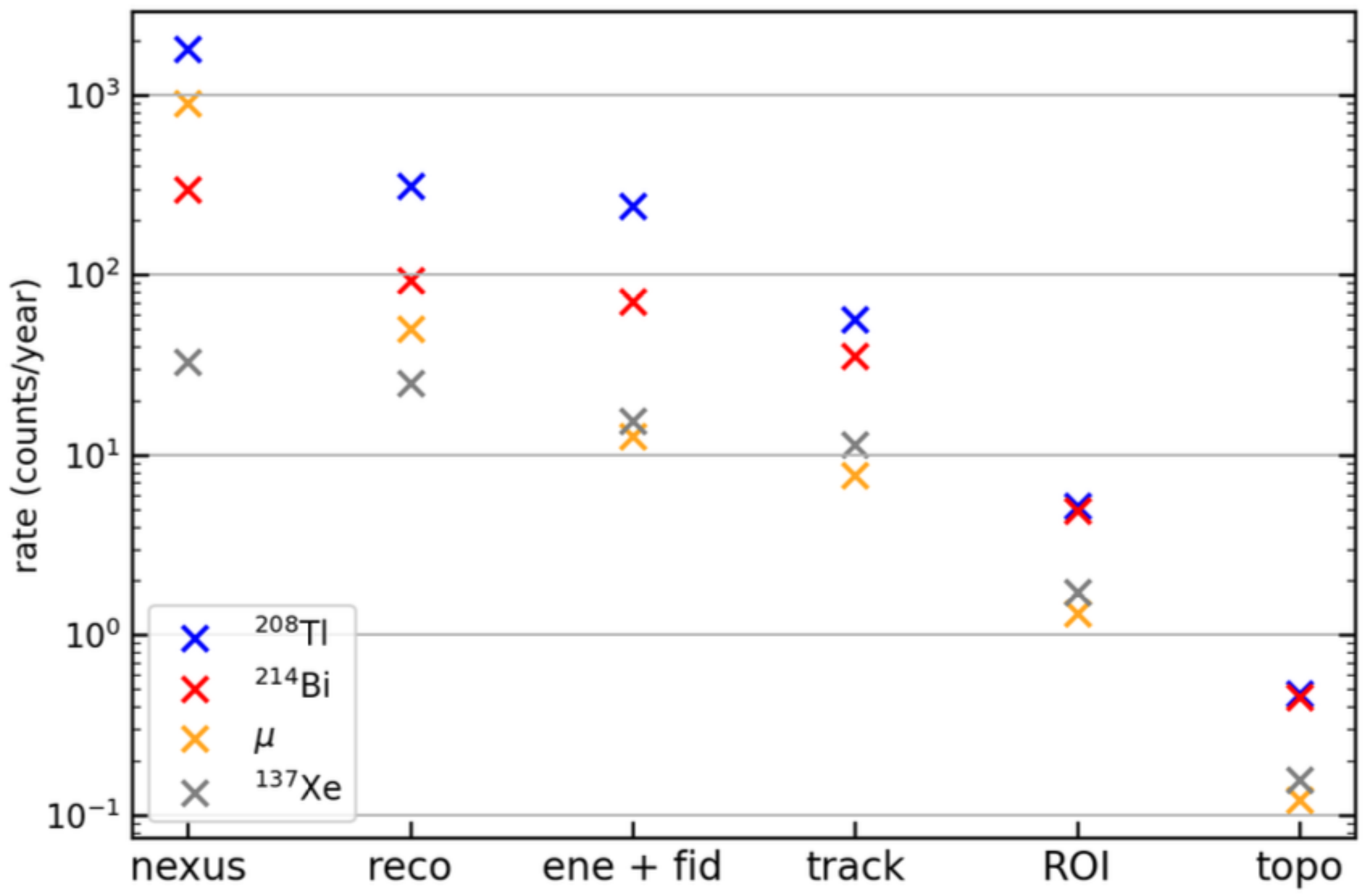
The @next-100 sensitivity

Target background rate $4 \cdot 10^{-4}$ counts/(keV · kg · yr), or ~1 count/(ROI · yr) *(majority coming from PMTs)*



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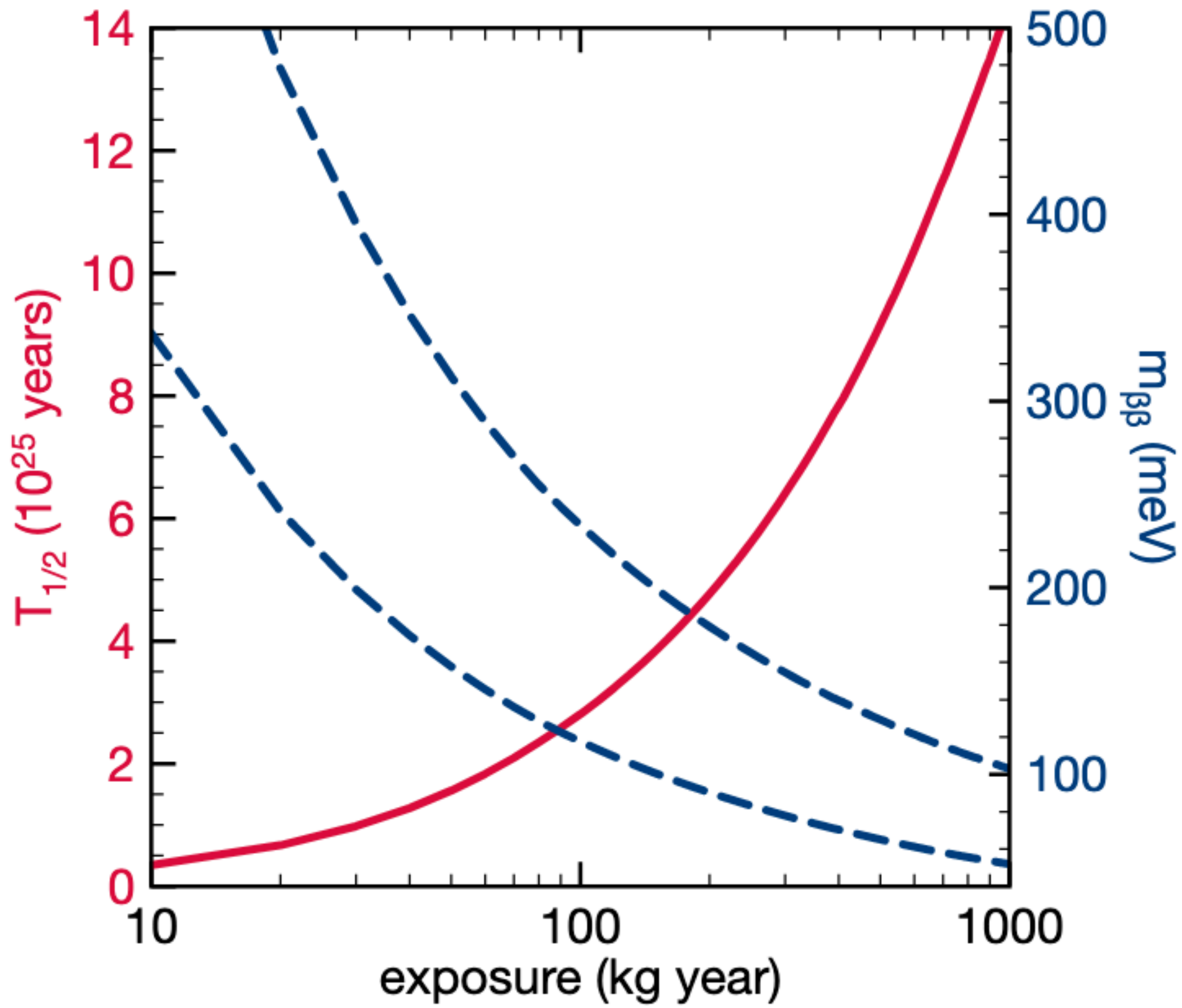

$T^{0\nu}_{1/2} = 6.0 \times 10^{25} years$ @ 90% CL
(3 years of data)

$m_{\beta\beta} < 80 - 160$ MeV @ 90% CL
(3 years of data)