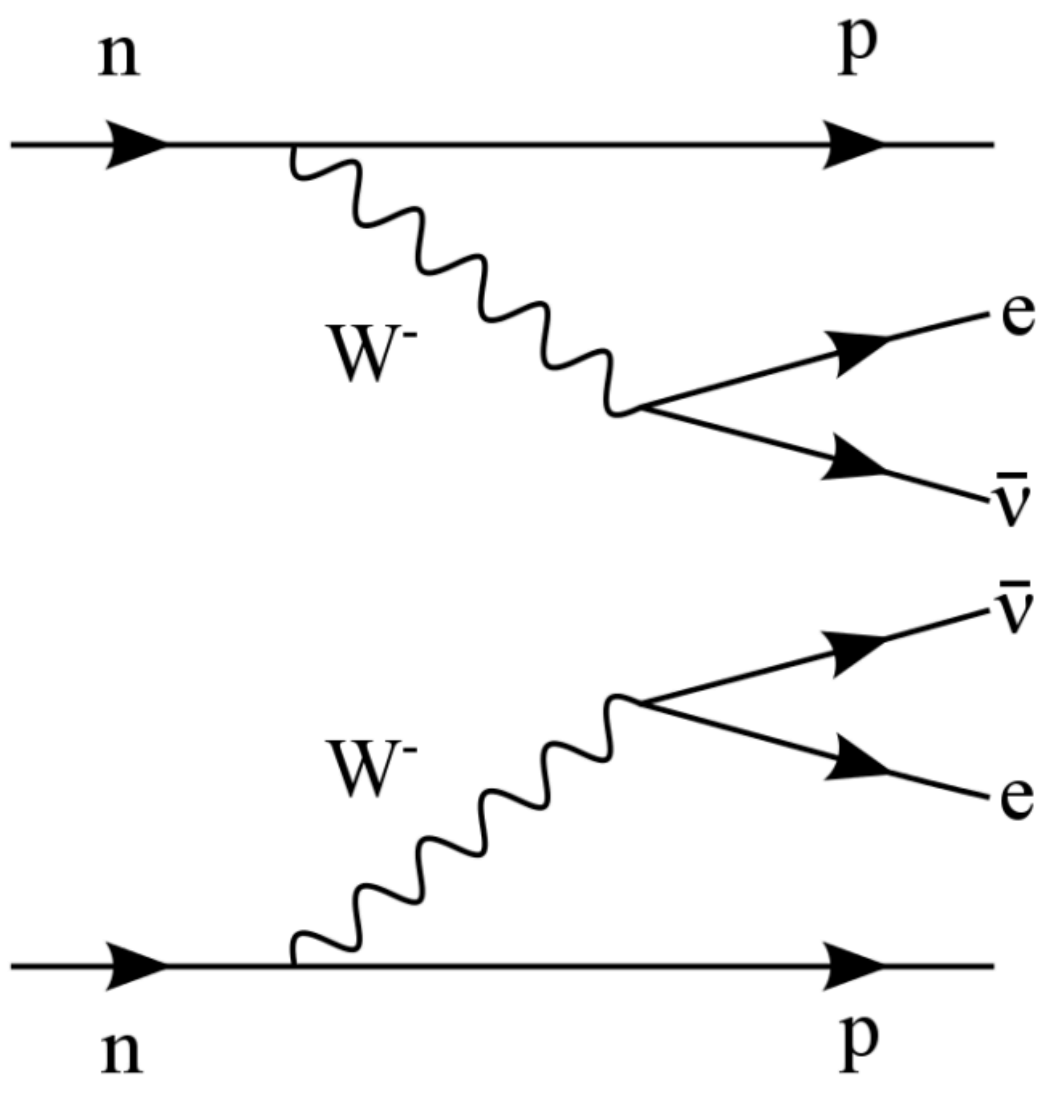
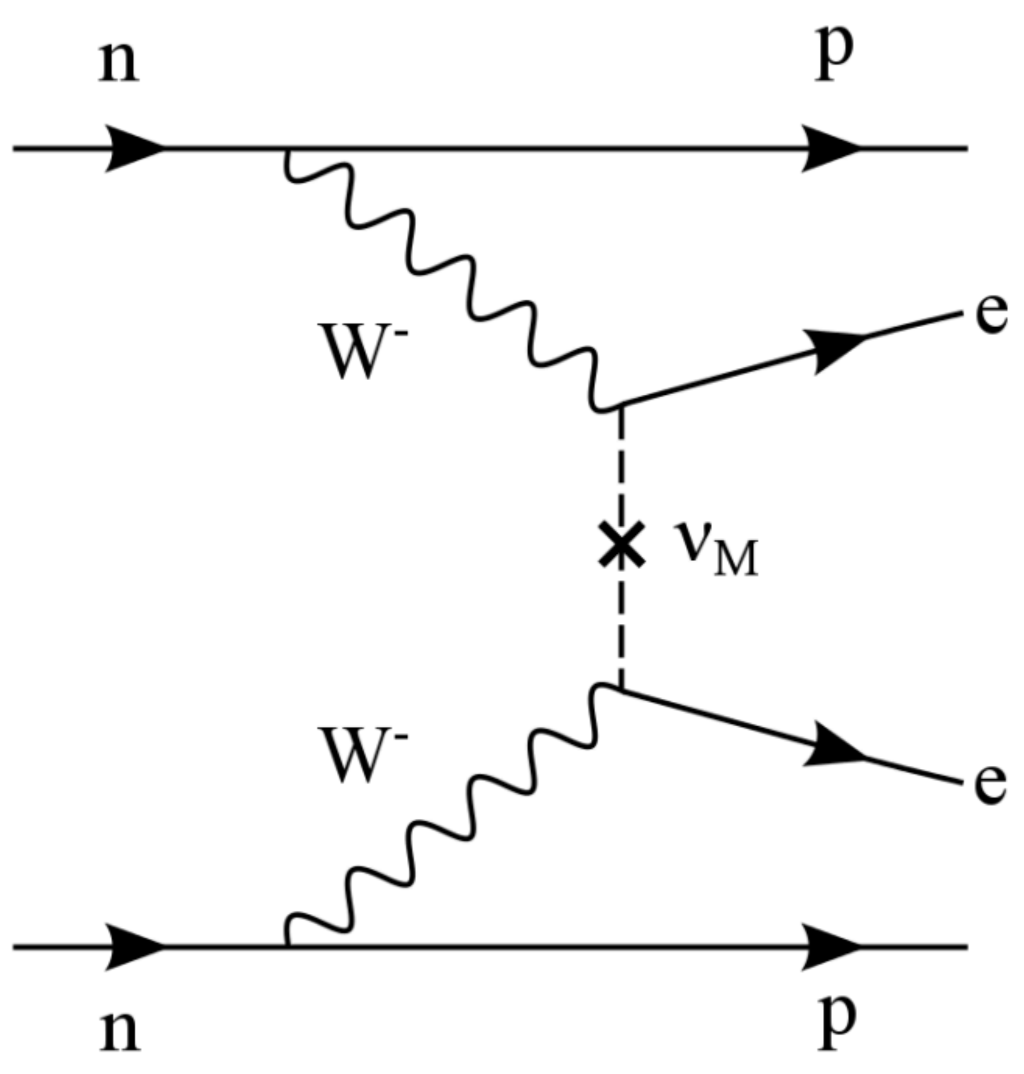
Results of the NEXT-100 detector and towards the ton-scale

S.Torelli on behalf of the NEXT collaboration

The neutrinoless double beta decay process



- Simultaneous beta decay of two neutrons of an nucleus $2\nu\beta\beta$
- Standard Model process
- Second-order weak-interaction process (strongly suppressed - high half-life)
- Observable in 44 nucleus in which single β is forbidden with $\tau = 10^{18} - 10^{24}\ yr$



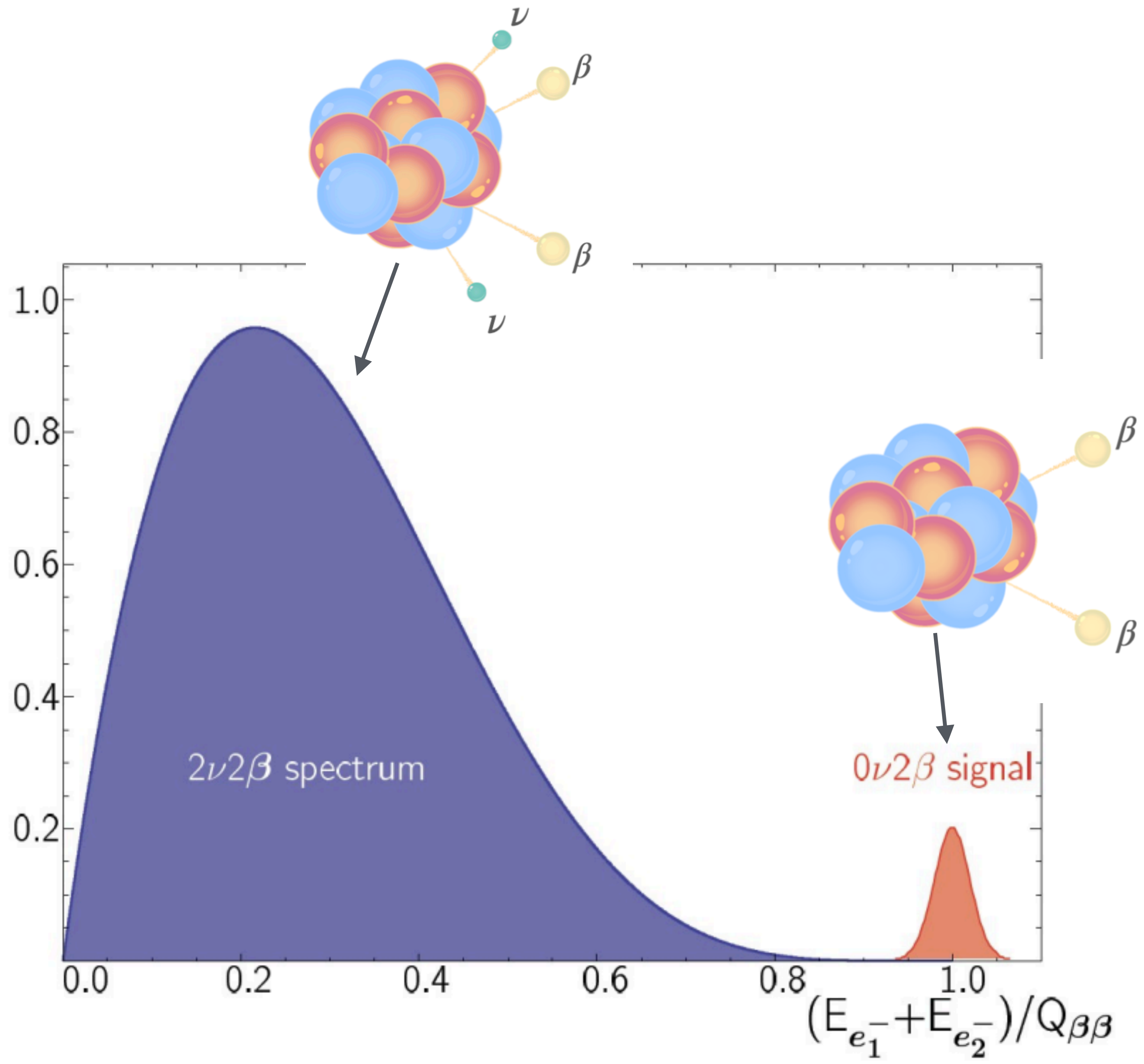
- A decay with no neutrino emission has been proposed $0\nu\beta\beta$
- This decay violates lepton number conservation as well as B-L fundamental symmetry
- Implication in matter-antimatter asymmetry, prove of the Majorana nature of neutrino $\nu = \bar{\nu}$
- Very rare event - half-life $\propto m_{\beta\beta}{}^{-2}$

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

The research in practice

- Generally detector developed for $0\nu\beta\beta$ have detection volume coinciding with the target material

- In a detector we expect to observe:
  - Continuous 2e⁻ spectrum $2\nu\beta\beta$
  - Peak at the $Q_{\beta\beta}$ value



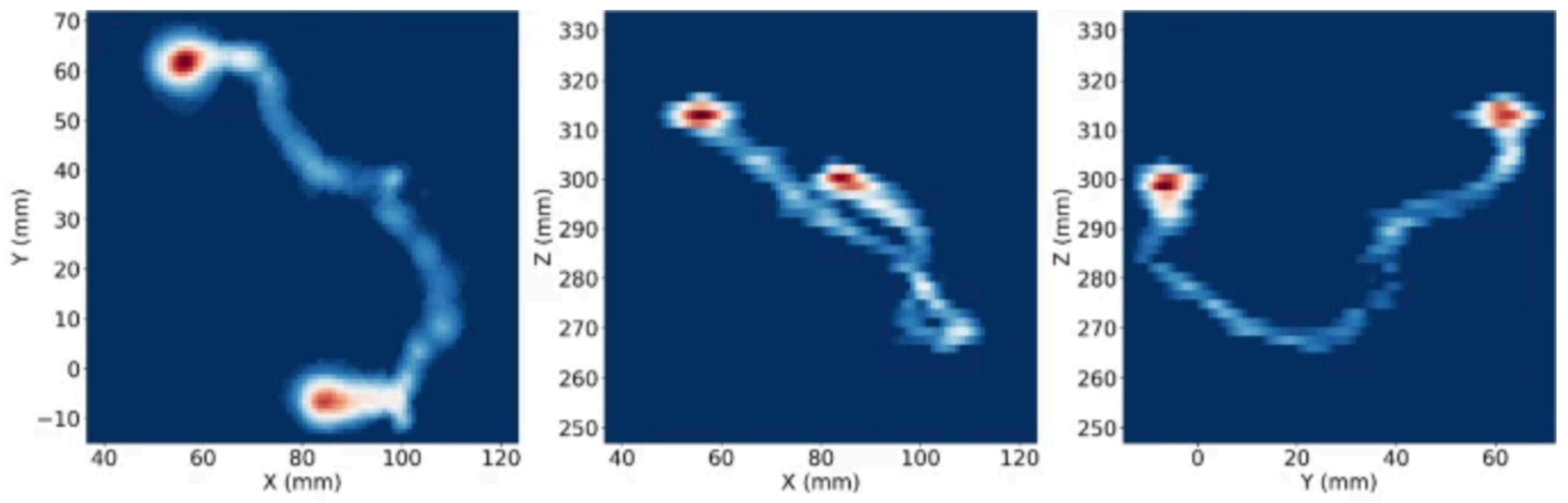
+ a very clear topological signature

- Detectors with tracking capabilities can access a unique feature of this decay

- 2 e⁻ with clear Bragg peaks at the extremities

NEXT-White data

JHEP 07 (2021) 146



$0\nu\beta\beta$ Searching strategy

Values of $m_{\beta\beta}$ explorable with detector (related also to limit on $T^{0\nu}_{1/2}$):

Background case scenario:

$$m_{\beta\beta} \propto \sqrt{1/\varepsilon}\left(\frac{c\cdot\Delta E}{M_{\beta\beta}\cdot t}\right)^{1/4}$$

Bkg counts (c); E resolution (ΔE)

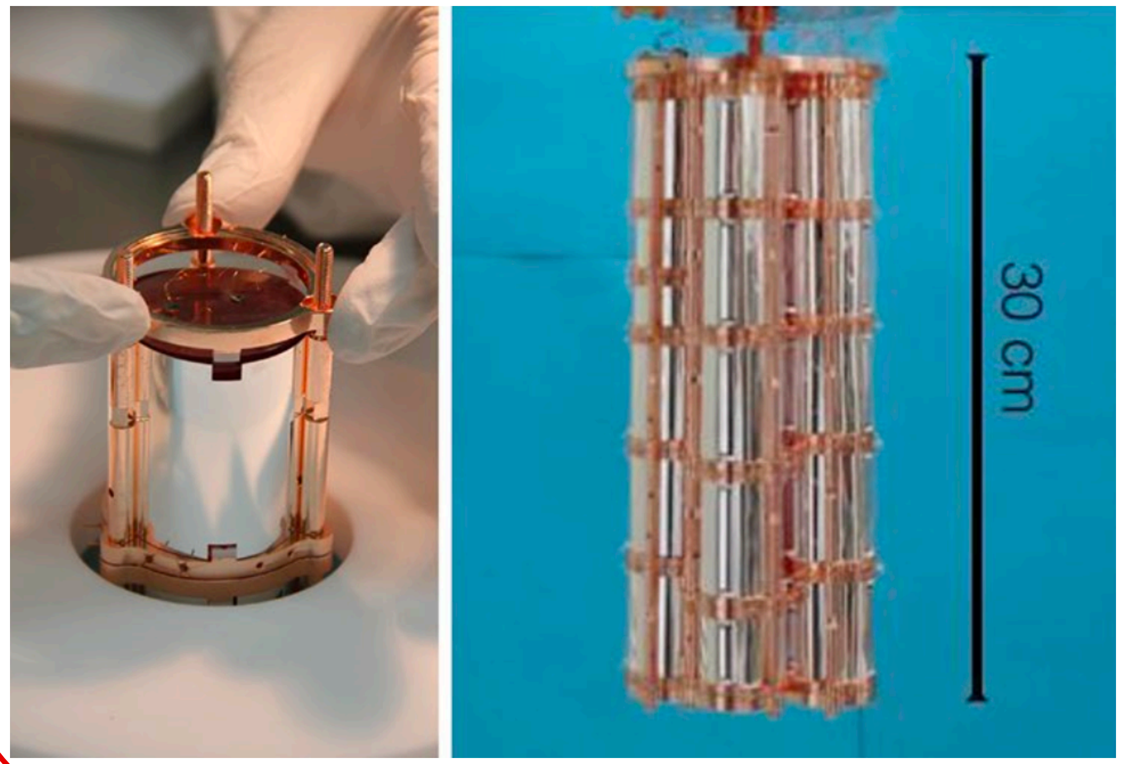
Background free limit:

$$m_{\beta\beta} \propto \sqrt{\frac{1}{\varepsilon\cdot M_{\beta\beta}\cdot t}}$$

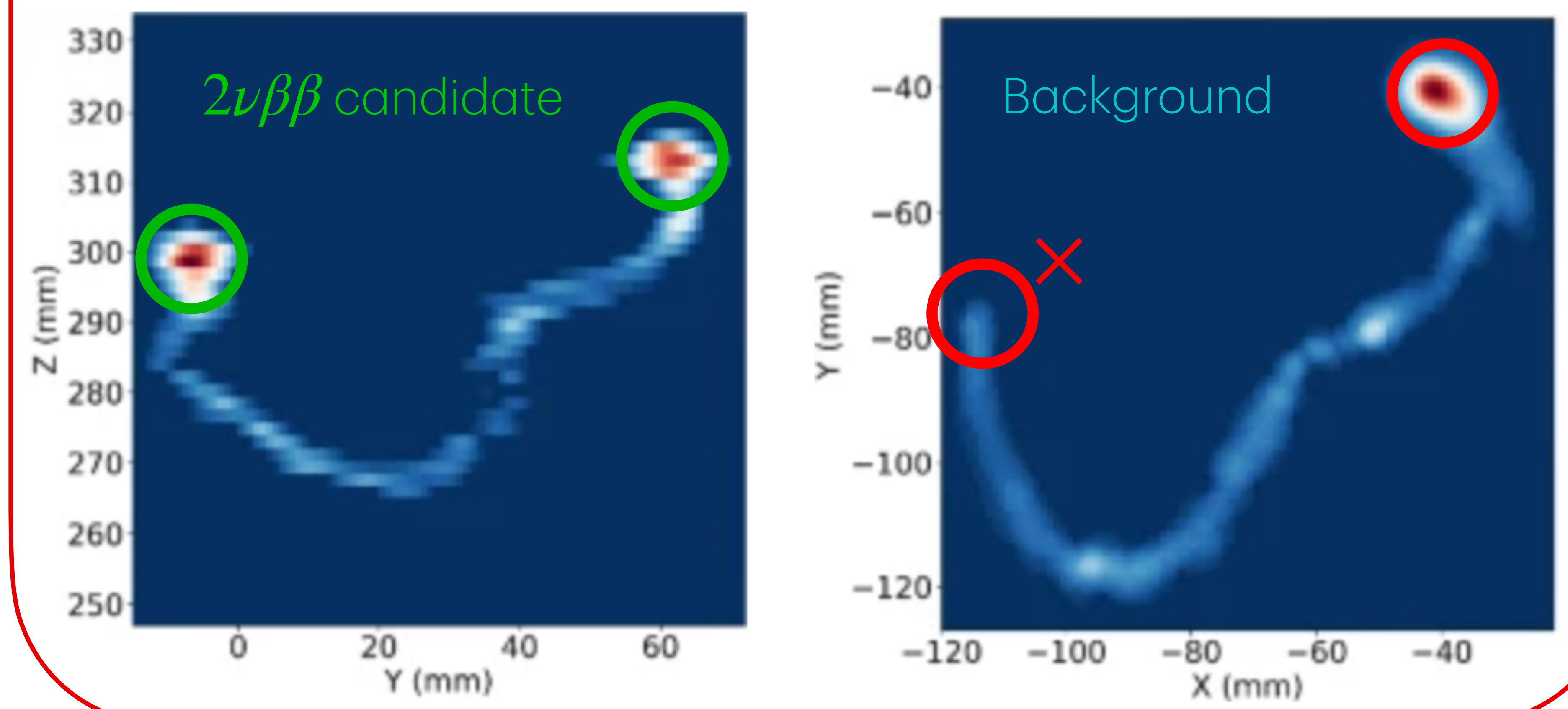
Isotope mass ($M_{\beta\beta}$); Exposure time (t); Detector efficiency (ε)

Approaches used:

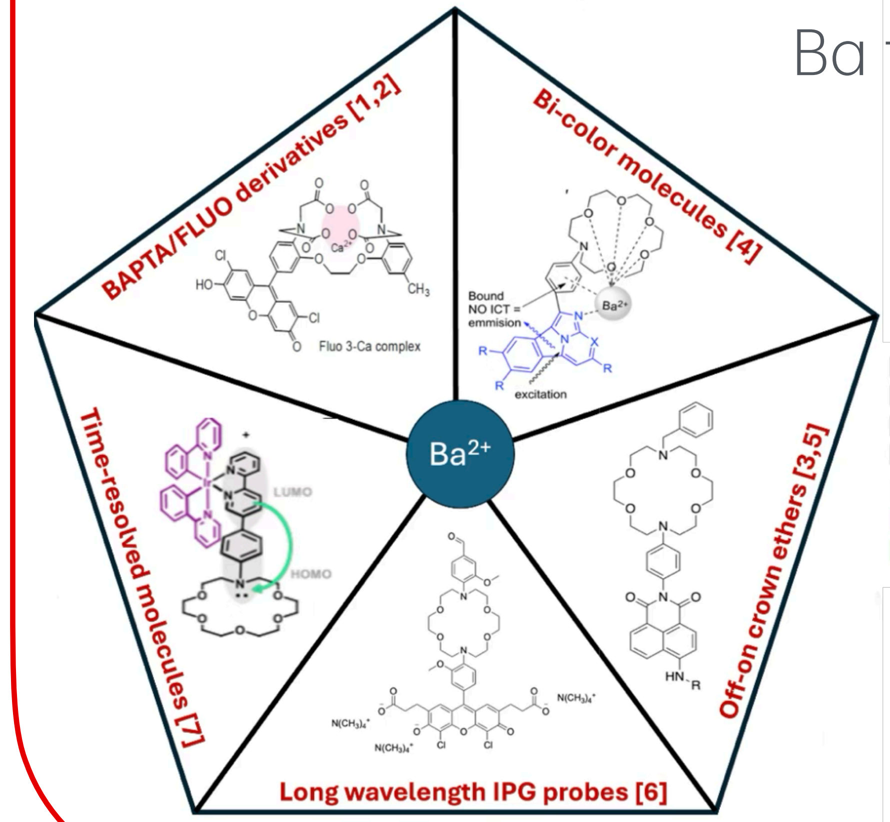
Rely on excellent E resolution and low background



Very good energy resolution and high background rejection



Reach the background free limit



Ba tagging molecules (see later)

[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)

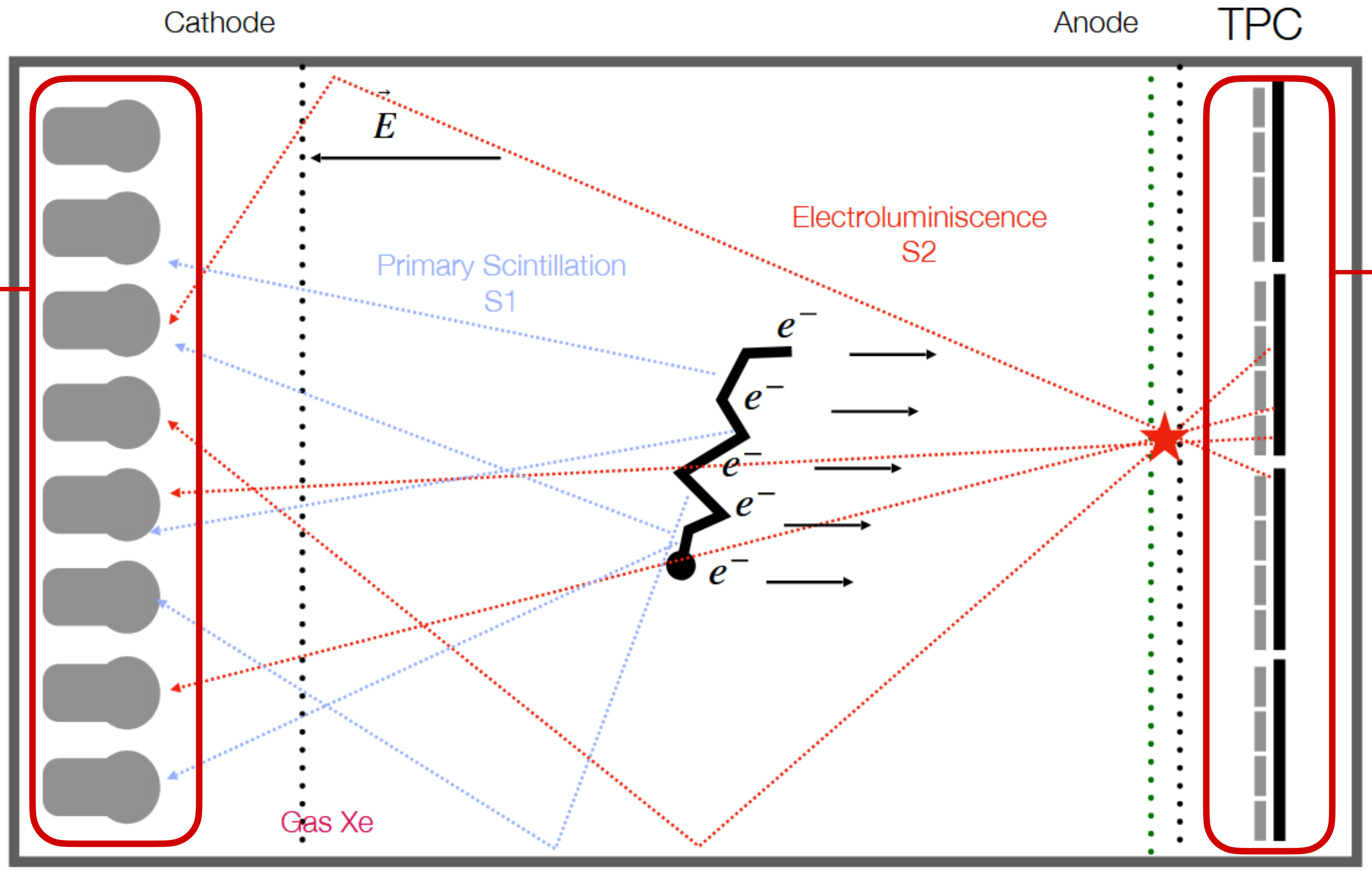
Here comes the NEXT experiment

- NEXT is a time projection chamber filled with high pressure Xe
- Pressure and Xe enrichment can be adjusted

PMTs - Energy Plane:

→precisely measure the energy via the S2 signal

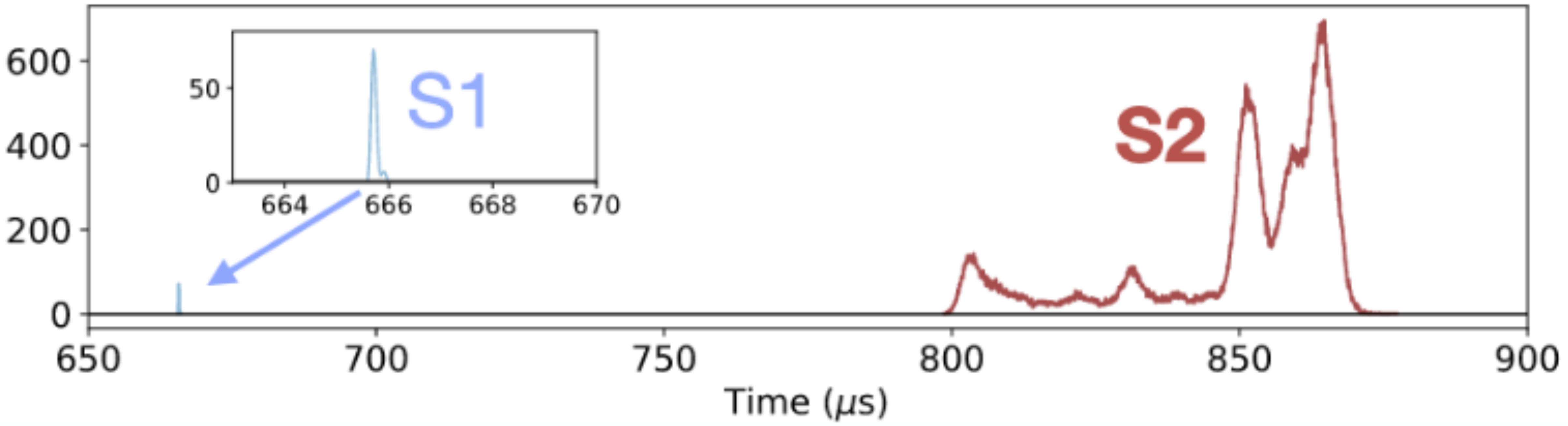
→measure the absolute z $(t_{S1} - t_{S2})$

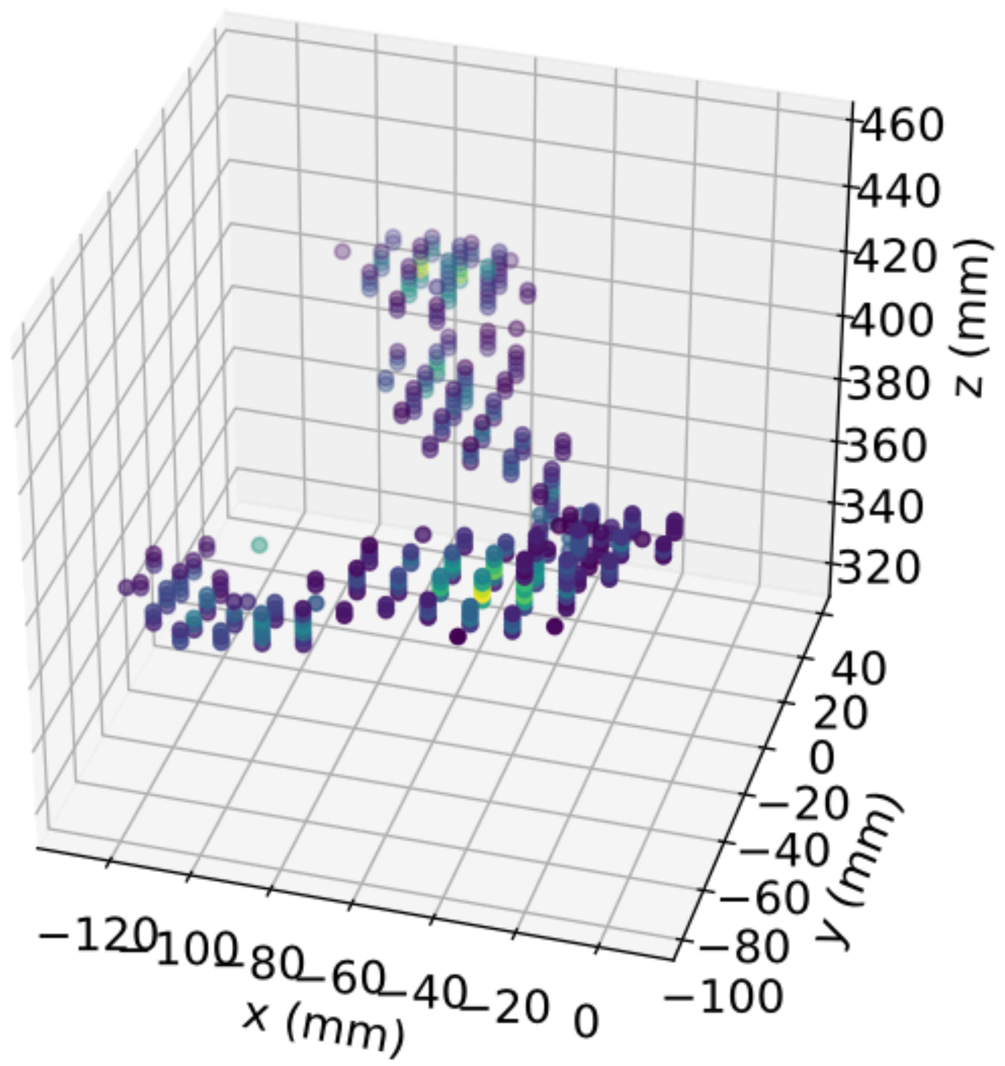


SiPMs - Tracking Plane:

Image the track in the XY and Z←

Provide local energy release ← information





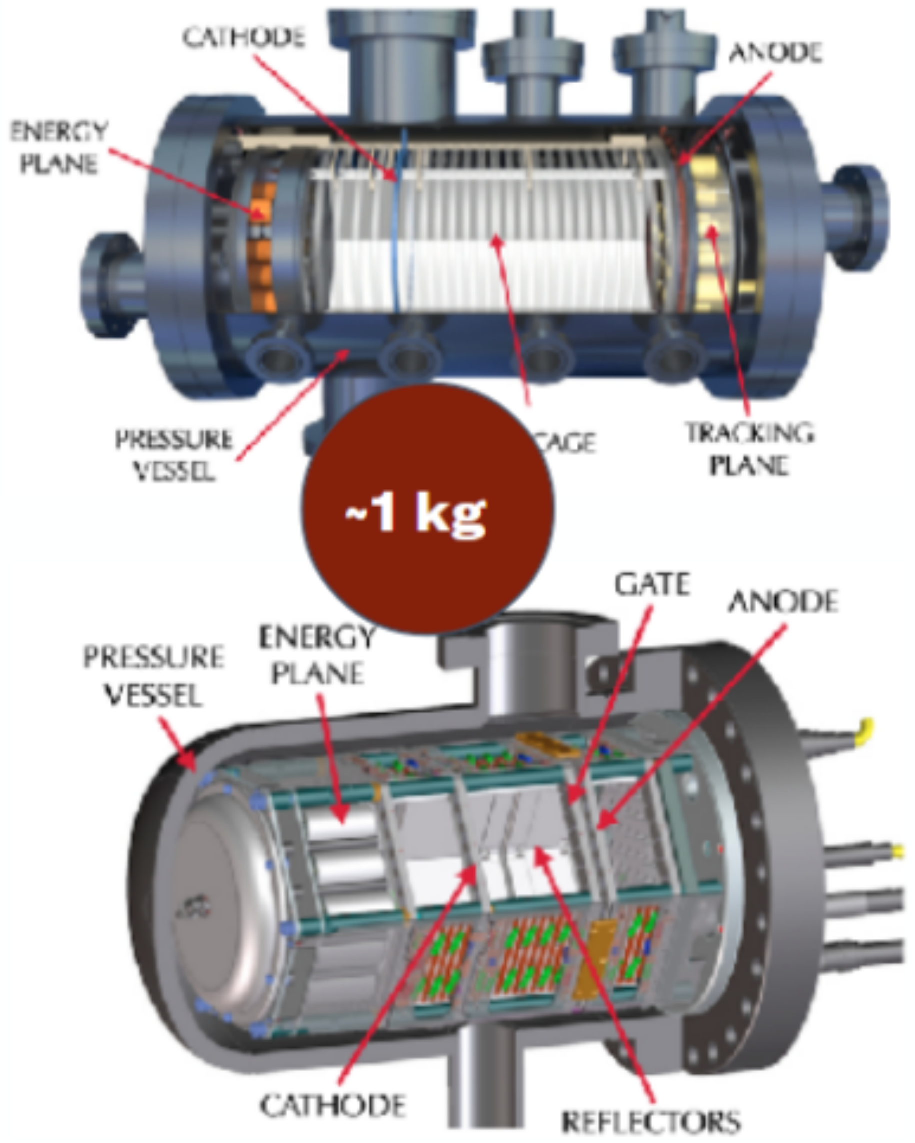
NEXT timeline

We are here

Prototypes

2010 - 2014

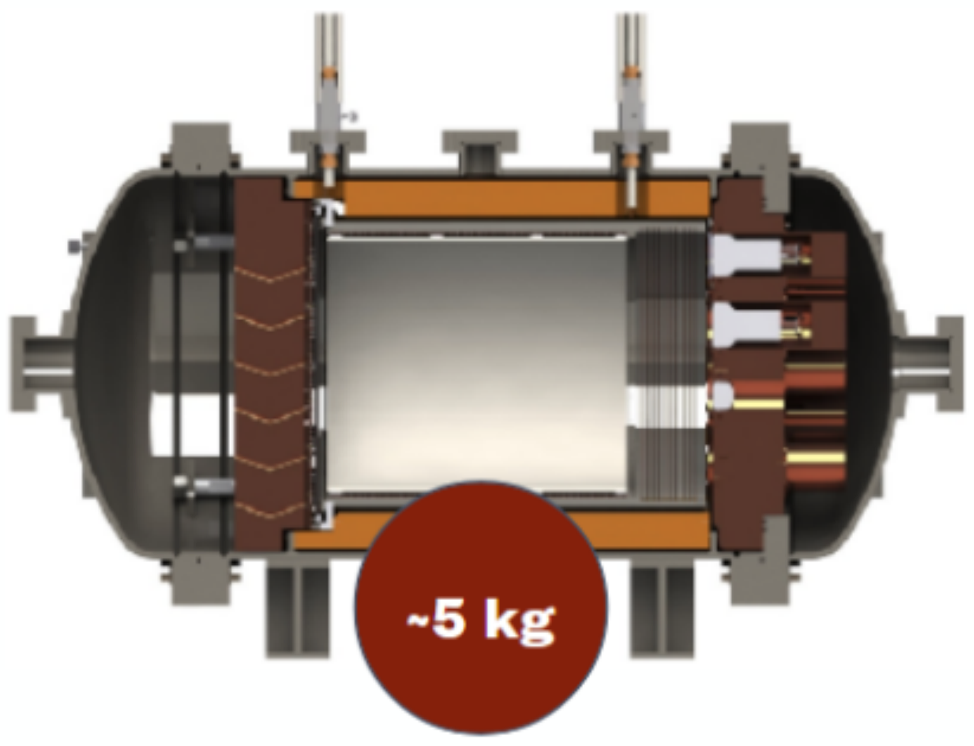
Demonstration of detector concept



NEXT-White

2015 - 2021

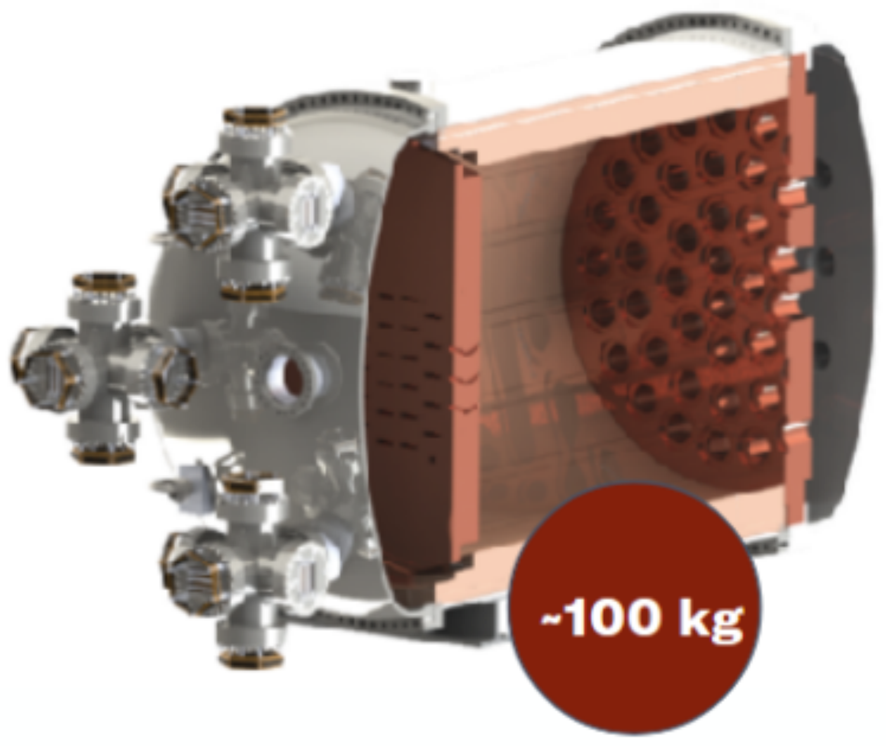
Background model assessment
$2\nu\beta\beta$ measurement for ^{136}Xe



NEXT-100

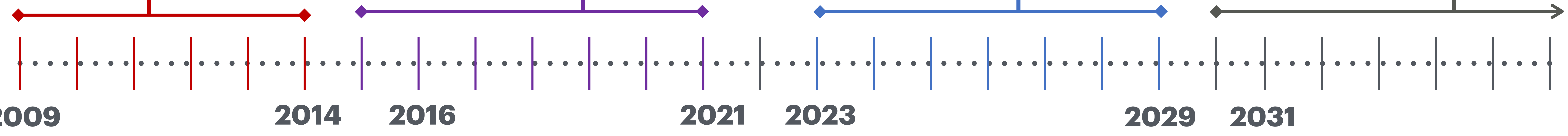
2023 - 2029

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



NEXT-HD
NEXT-BOLD

Ton-scale and barium tagging for background-free experiment in ^{136}Xe (10^{28} y)



NEXT-White results

Direct measurement of energy resolution @ $Q_{\beta\beta}$ below 1% FWHM

Background discrimination trough event topology

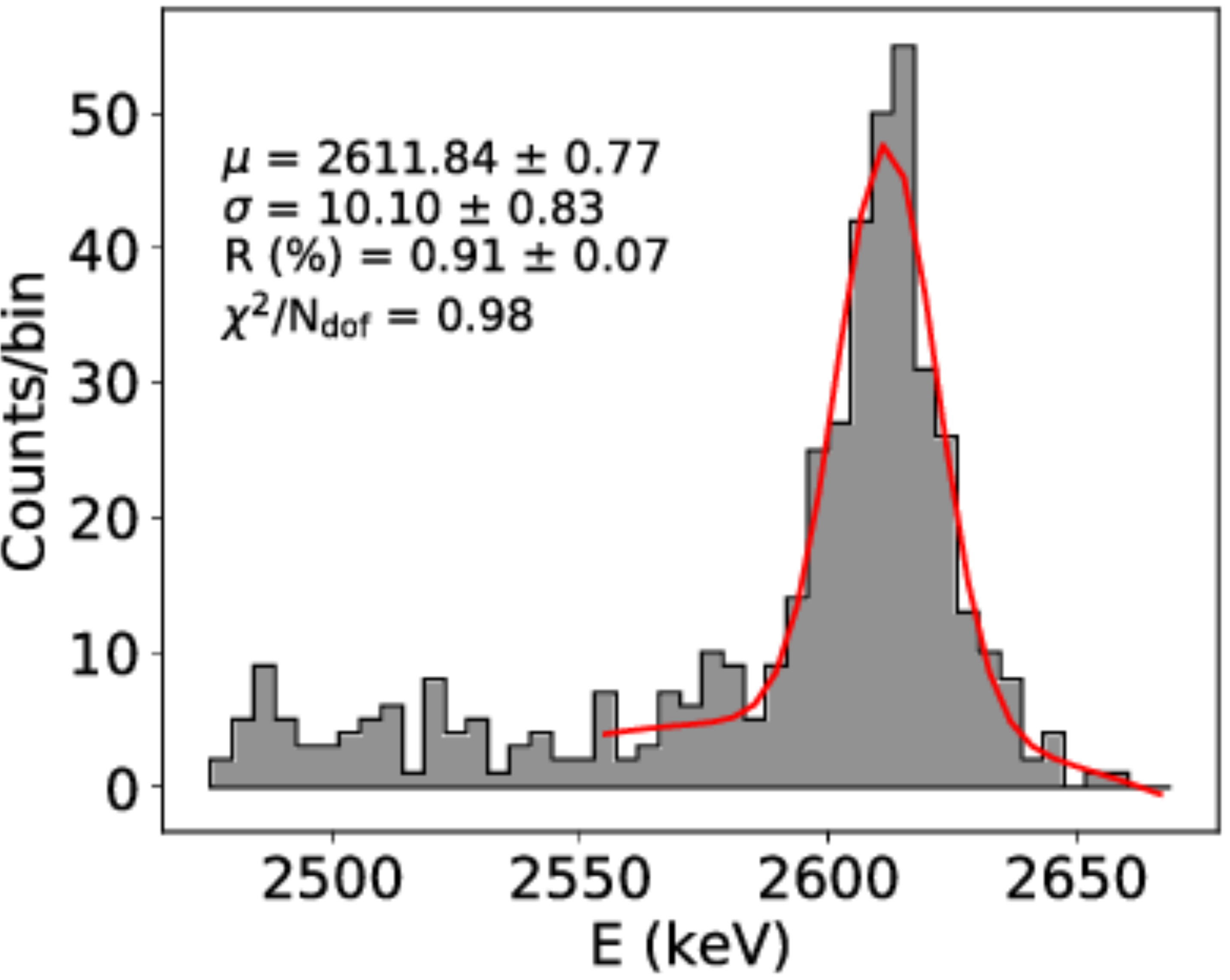
Measurement of ^{136}Xe $T_{1/2}^{2\nu\beta\beta}$ and limits on $T_{1/2}^{0\nu\beta\beta}$ with fiducial mass 3.5 kg of Xe

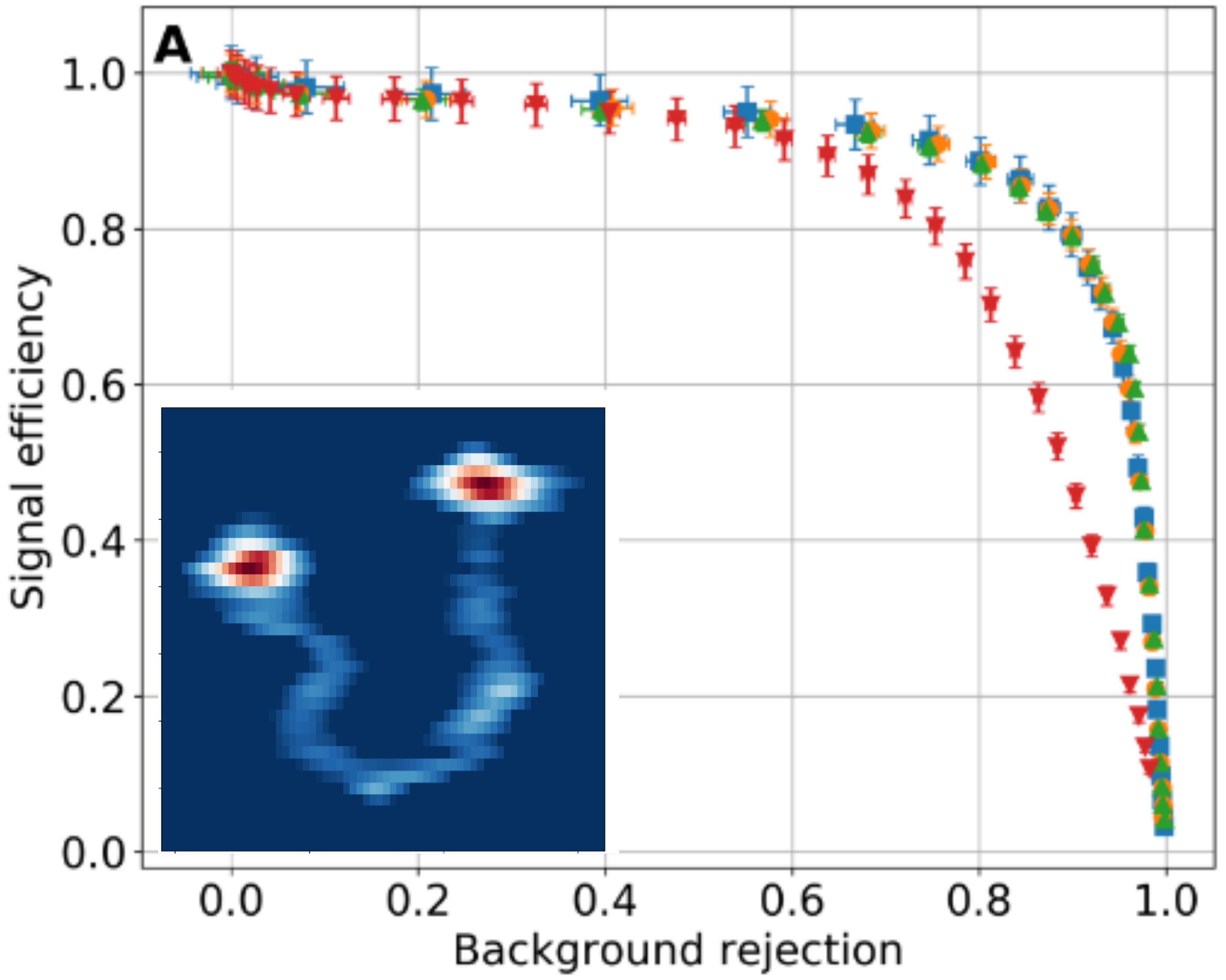
$T_{1/2}^{2\nu\beta\beta} = 2.34^{+0.85}_{-0.49} \cdot 10^{21}\ y$ $T_{1/2}^{0\nu\beta\beta} > 1.3 \cdot 10^{24}\ y$

JHEP 2019, 230

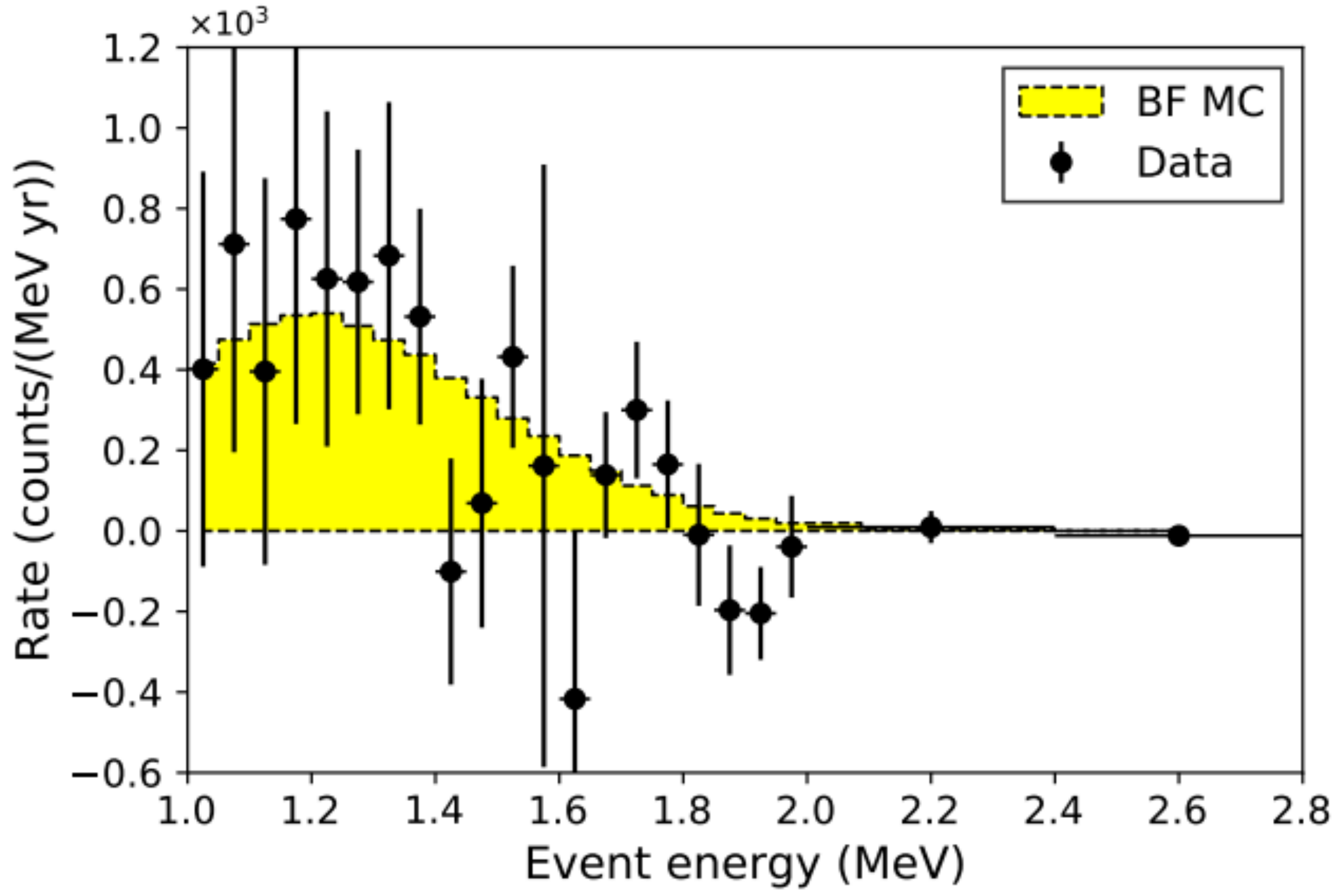
JHEP 2019, 52 JHEP 2021, 189 JHEP 2021, 146

Phys. Rev. C 105, 055501 JHEP 2023, 190





Background subtracted enriched - depleted spectrum



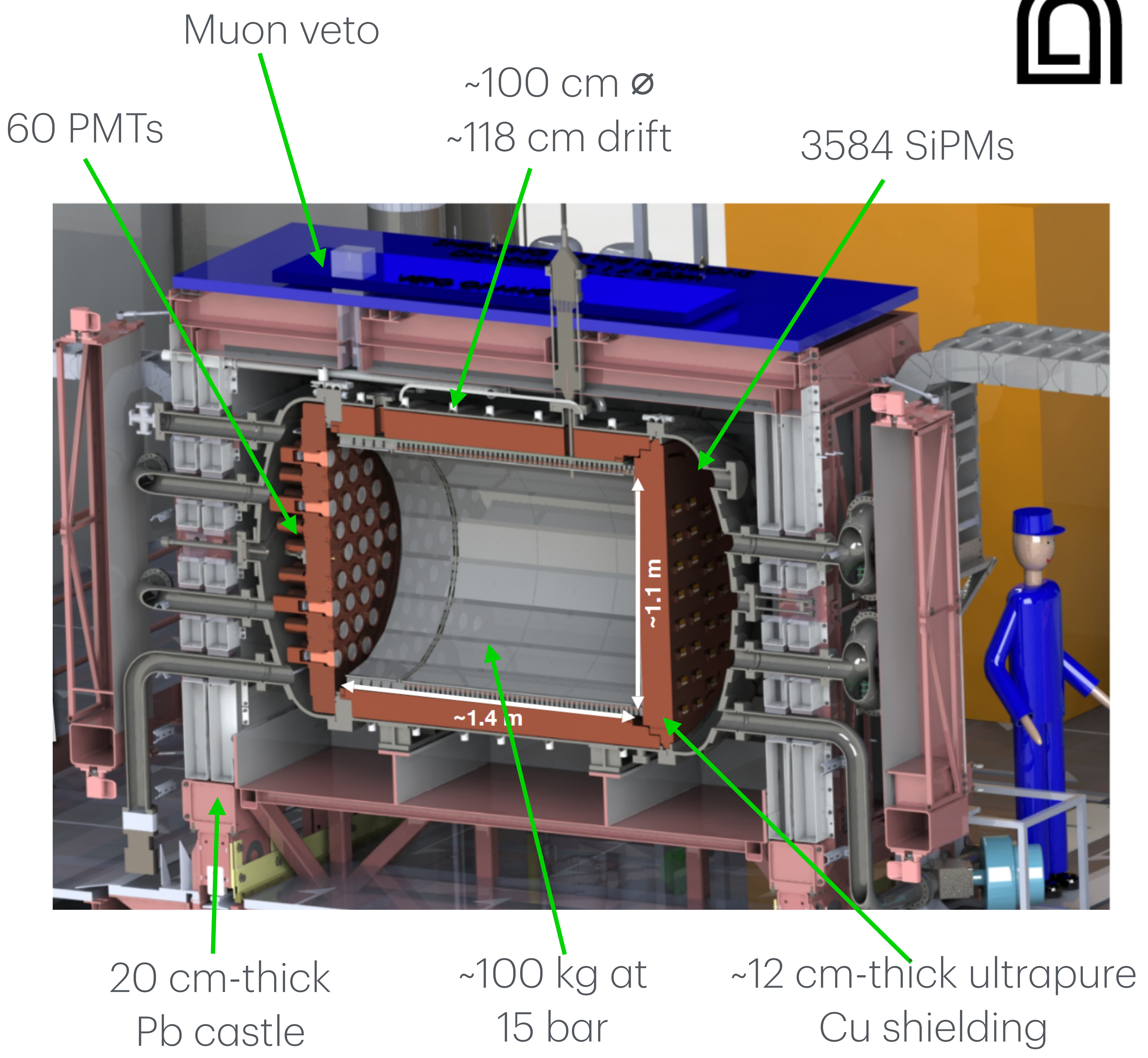
The NEXT-100 detector

Status:

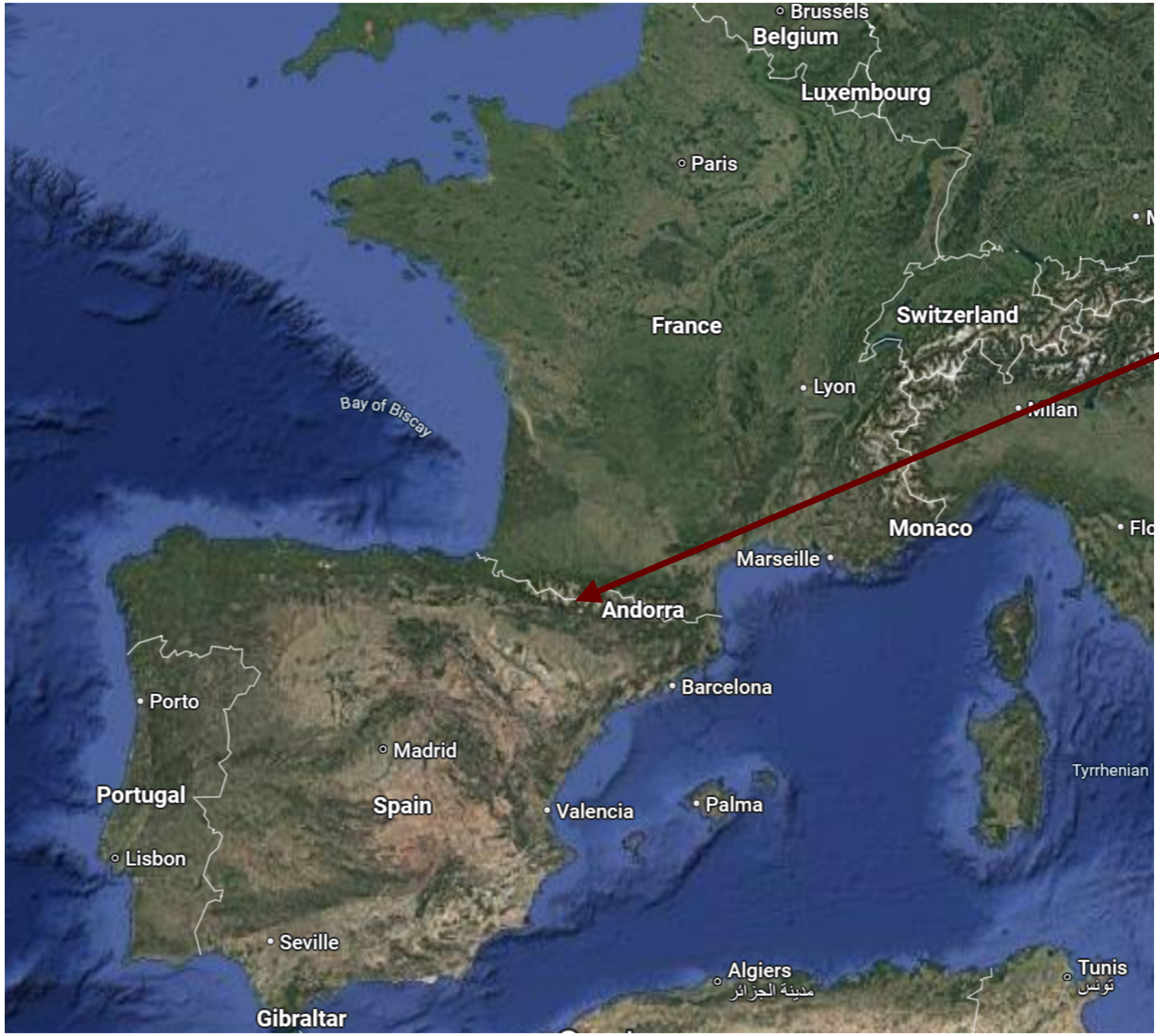
- Operation started in May 2024 @ 4 bar
- Commissioning and calibration run concluded
- Low-background run @ 4 bar in progress
- Operations at 10 bar for $0\nu\beta\beta$ search expected by 2026

Goals:

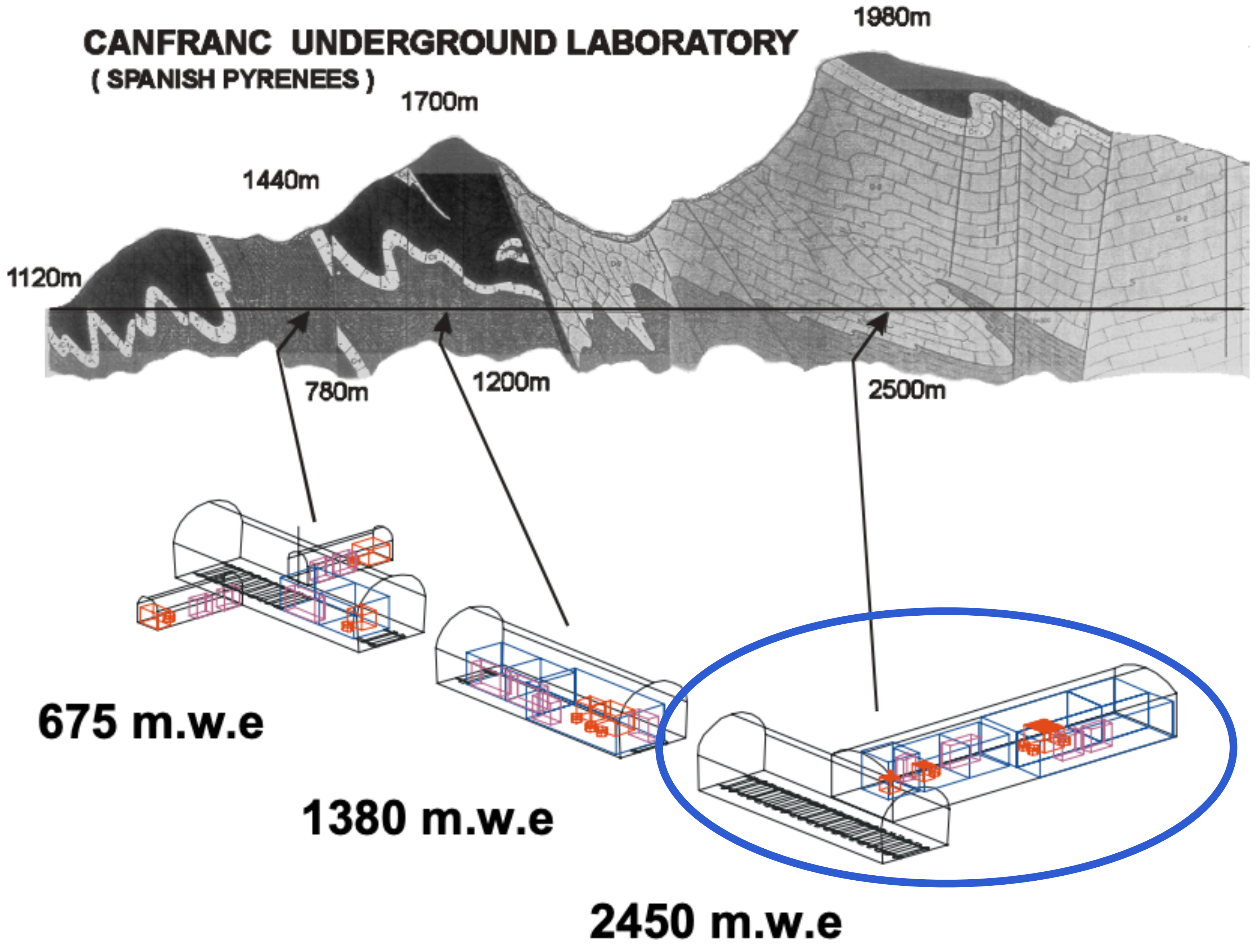
- Keep the resolution below 1% at $Q_{\beta\beta}$
- Improve the precision on $T_{1/2}^{2\nu\beta\beta}$
- competitive search of $0\nu\beta\beta$ decay within the current generation of experiments (exp. O(10^{26}) sensitivity @ 90% C.L. after 3 years)
- Demonstrate scalability towards ton-scale



@ Canfranc underground laboratories



NEXT-100 is hosted @ **L**aboratorio **S**ubterráneo de **C**anfranc (LSC)

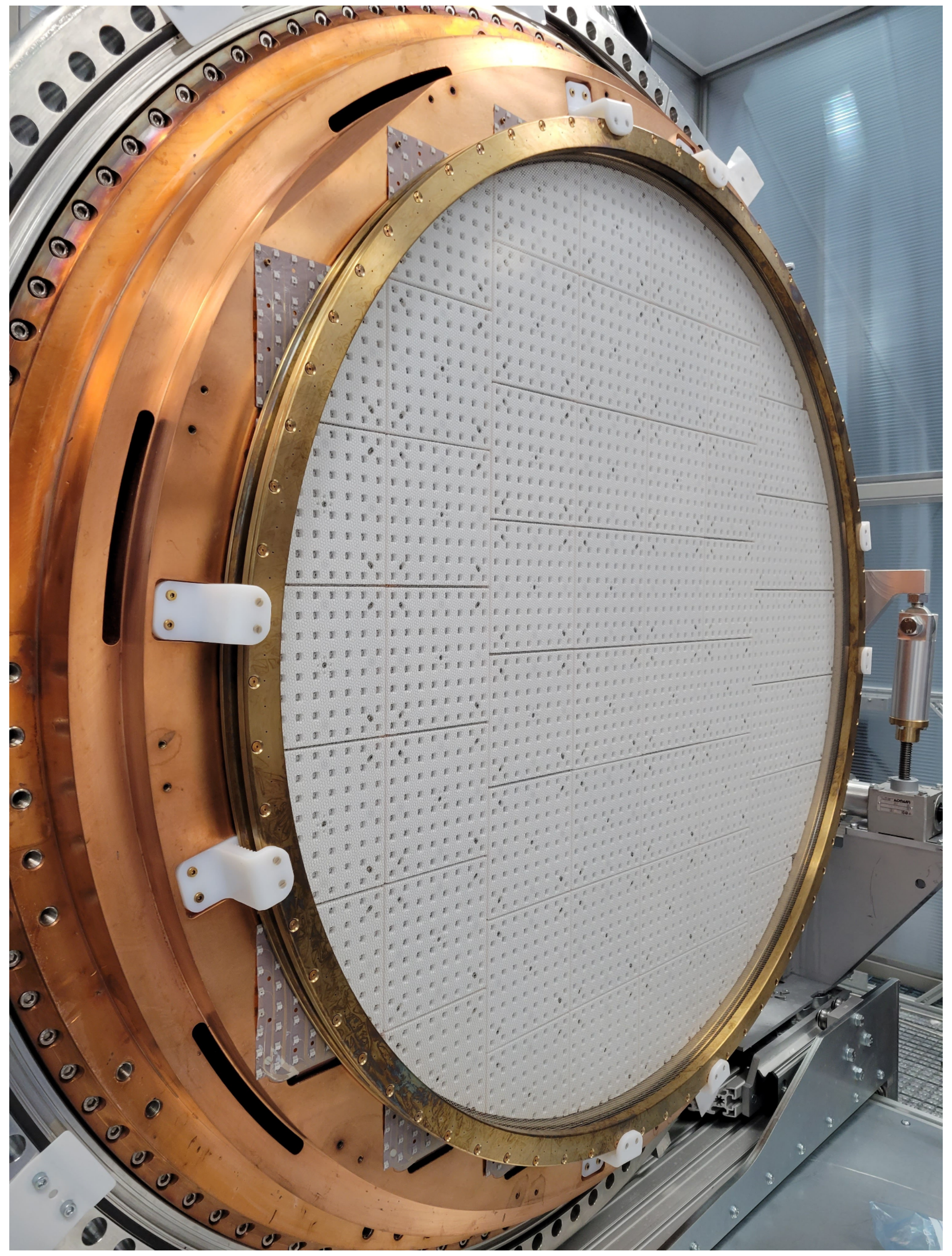


Detector Vessel

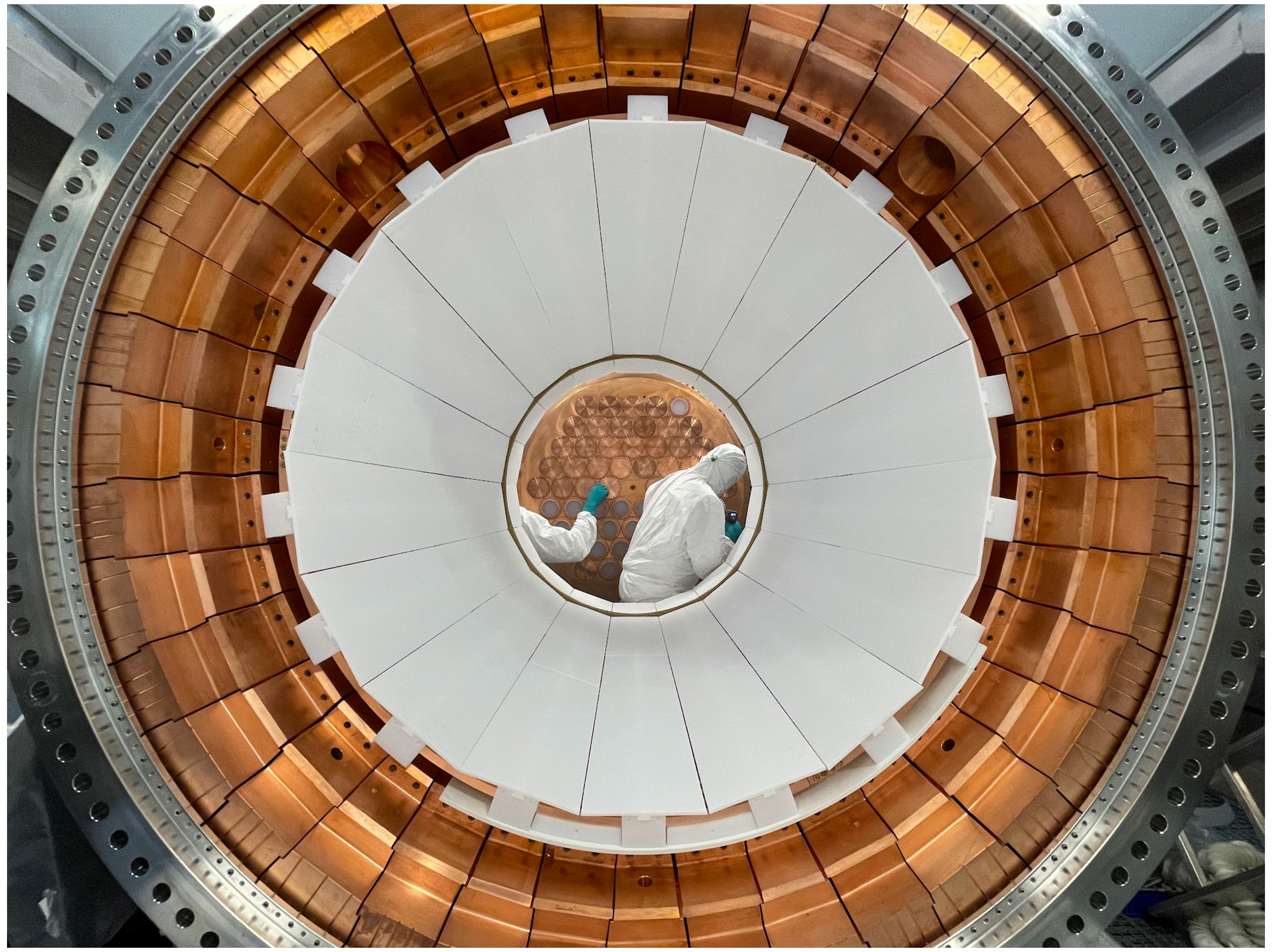
Detector field cage

arXiv.2505.17848

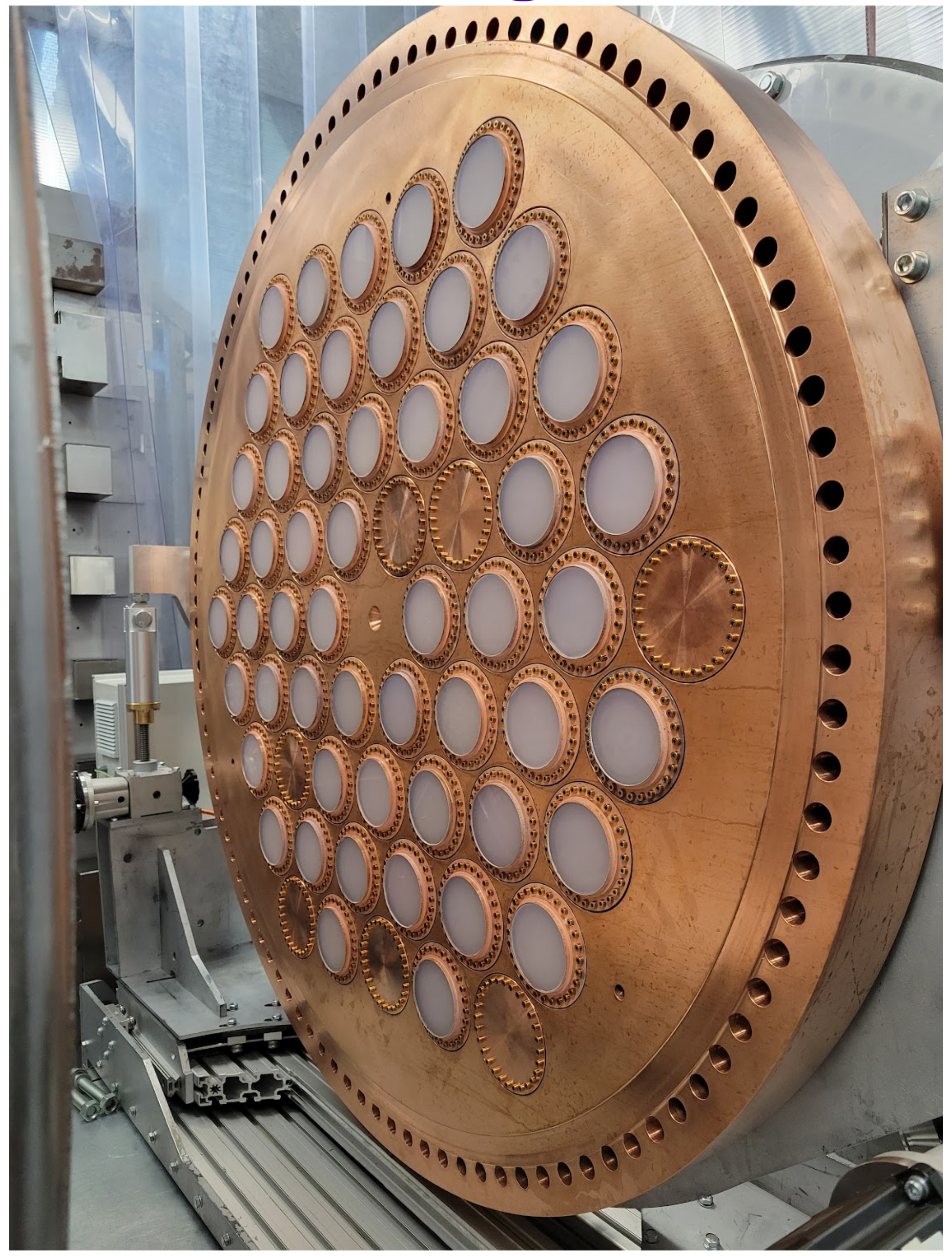
SiPM Tracking plane



Inner part of the field cage



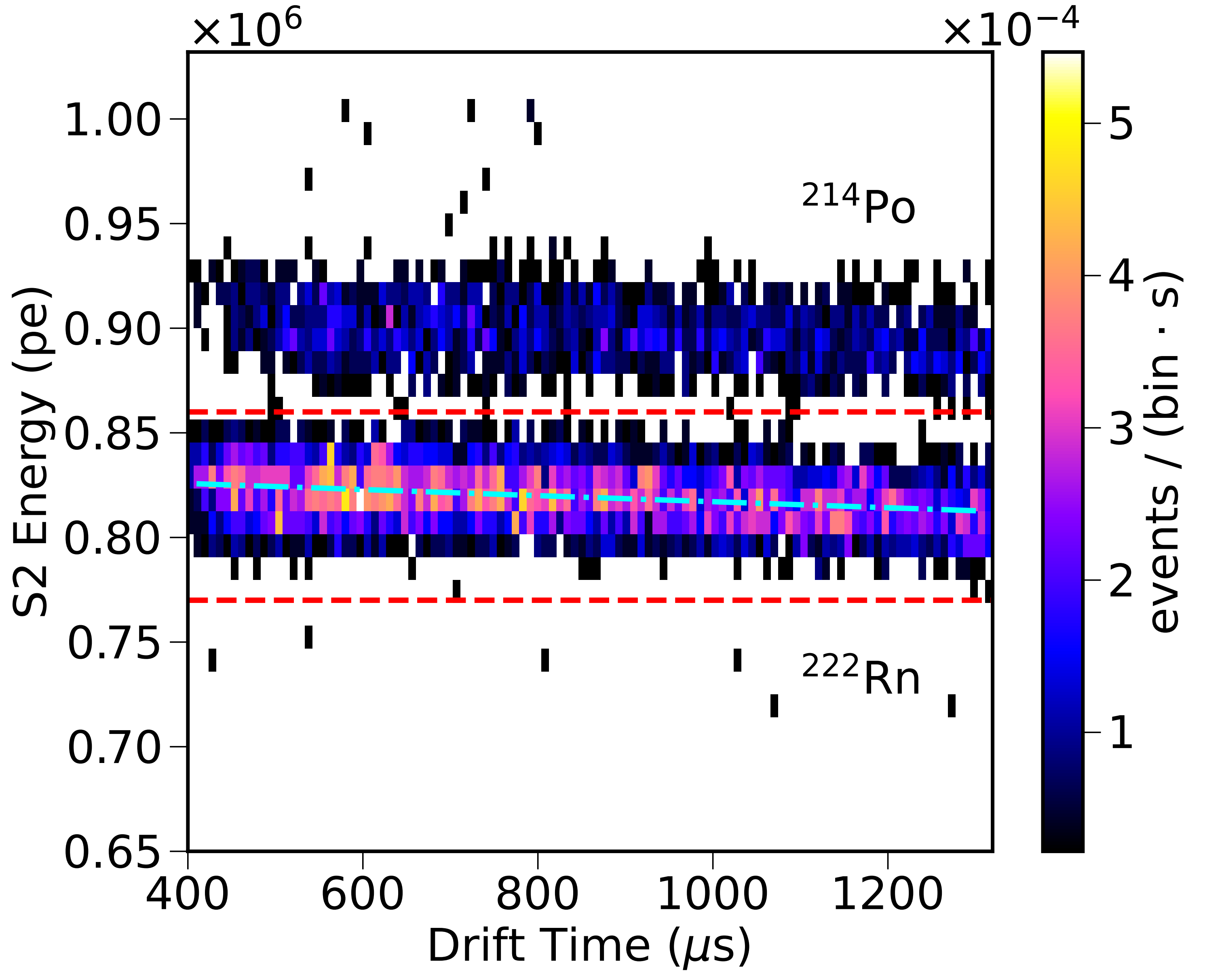
PMT energy plane



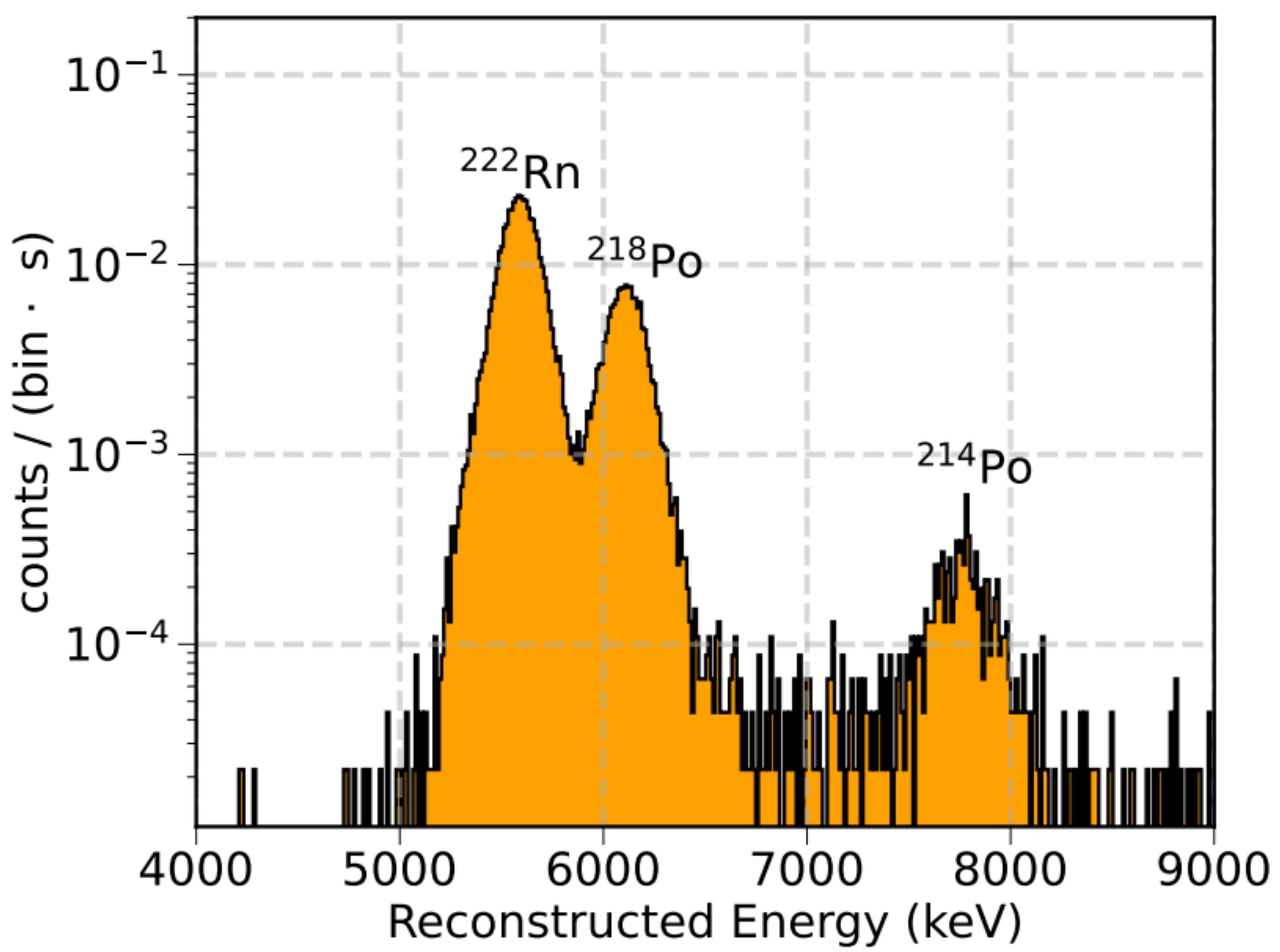
Detector commissioning with alpha particles in Xe

arXiv.2505.17848

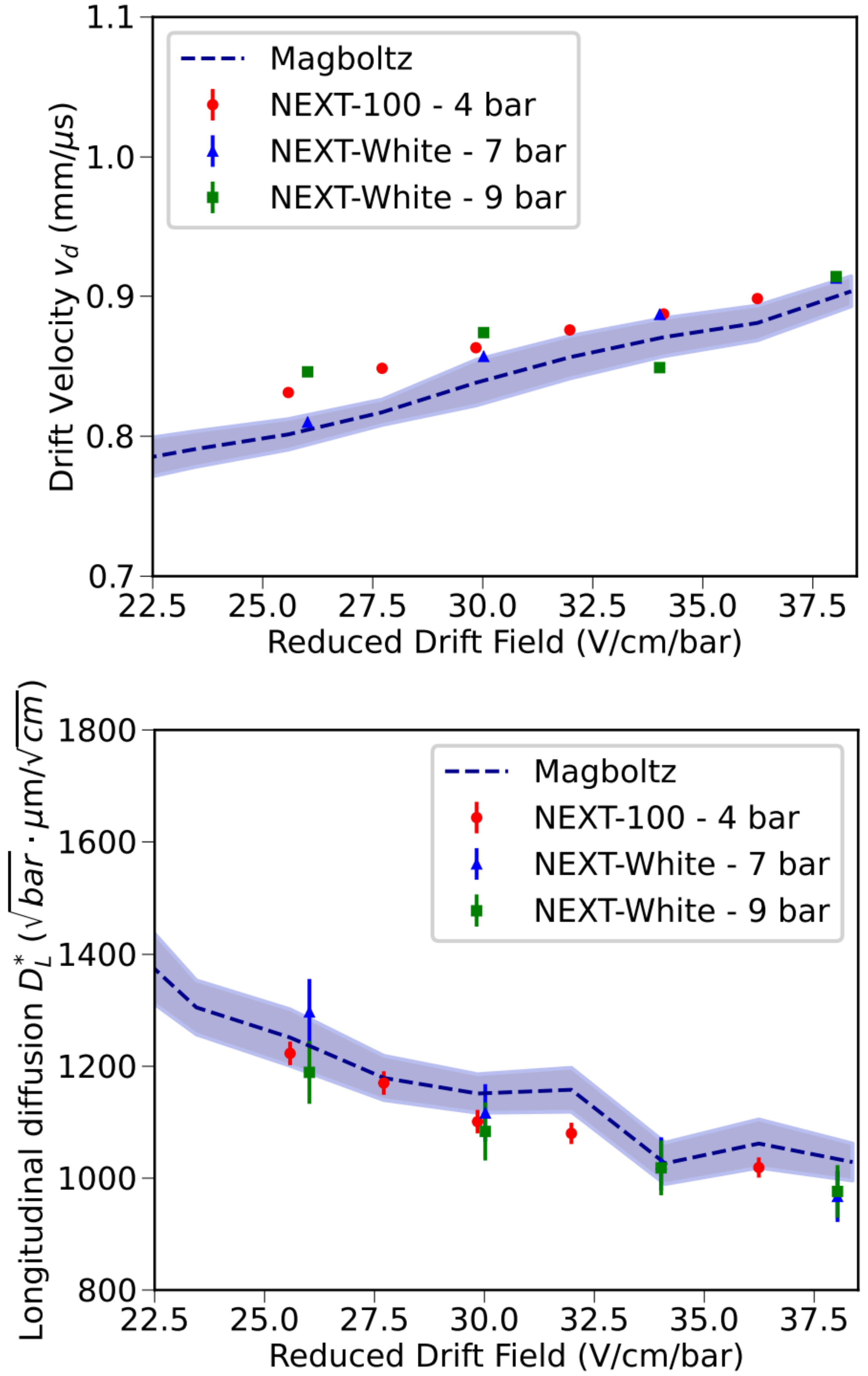
- Data taken with Xe depleted in ^{136}Xe at 4 bar of pressure
- Alphas analyzed to monitor electron lifetime, light yield and drift properties
- Excellent electron timelife measured τ = O(40ms) measured >> max drift time (1ms)



- Rn-induced background characterized: ^{222}Rn, ^{218}Po & ^{214}Po peaks visible in the energy distribution
- <1% light variation observed in 24 h
- <10% light variation observed in 1 week



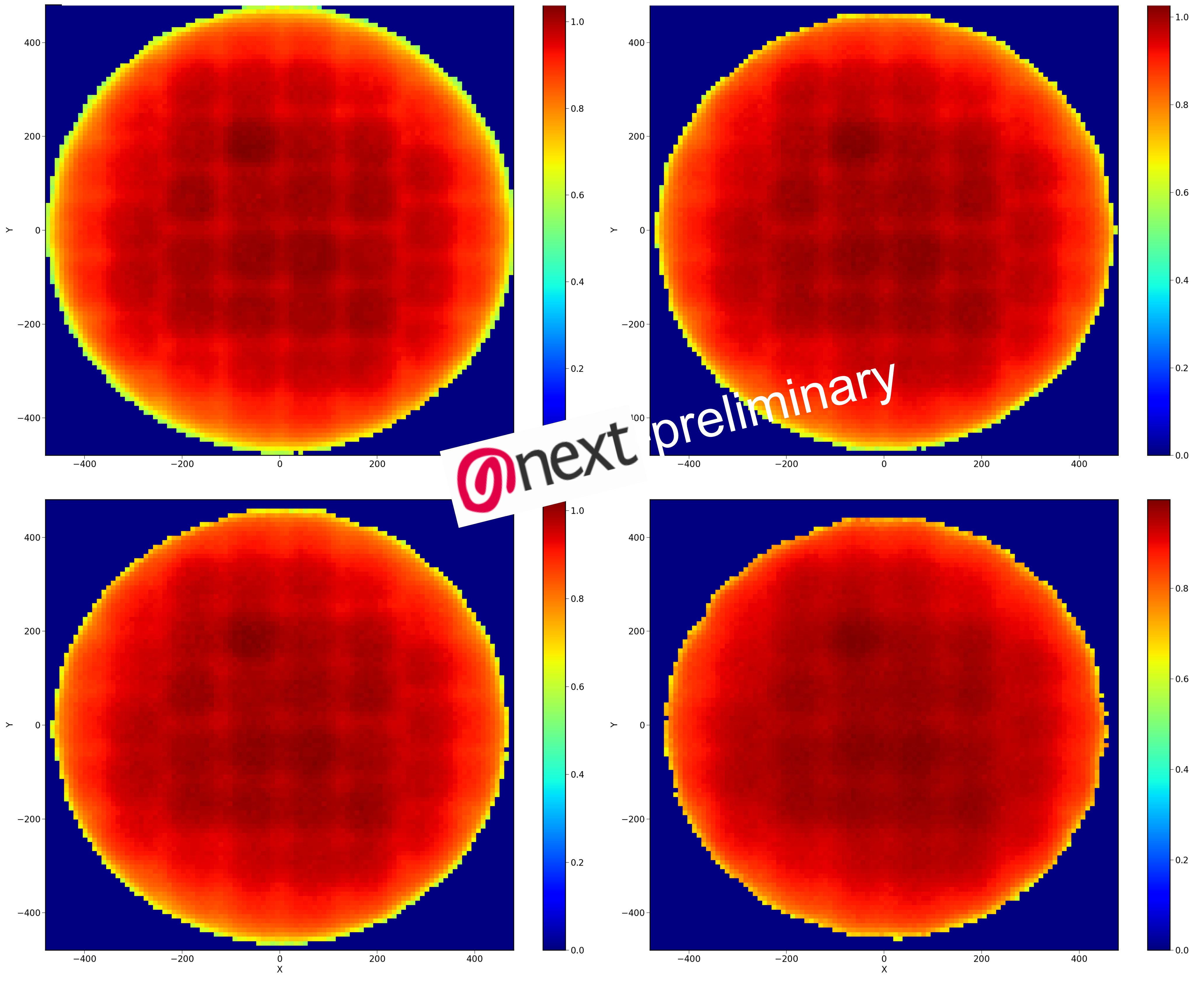
- Drift velocity and Long diffusion compatible with Magboltz and previous measurements

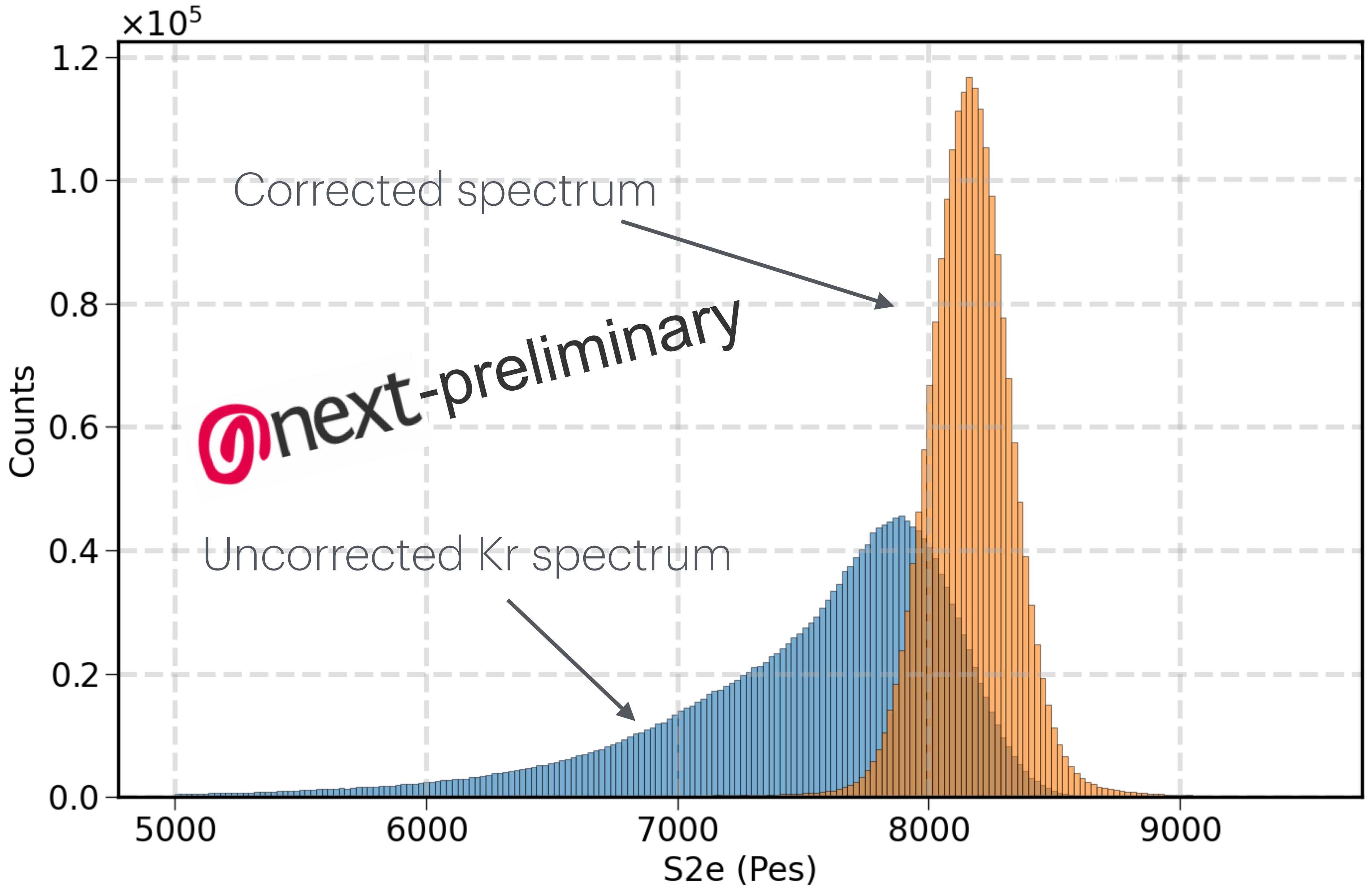


Low energy calibration with ^{83m}Kr

- ^{83}Rb decays into ^{83m}Kr which propagates into the full detector volume producing a point-like energy deposits of 41.5 keV
- Can be used to map the local detector response, correct geometrical effects, and monitor and correct for lifetime

3D map of Kr response





- Resolution of 4.2% FWHM @ 41.5 keV full volume and 3.8% FWHM @ 41.5 keV fiducial volume R < 200 mm z < 200 μs
- Approximate resolution extrapolated at $Q_{\beta\beta}$ = 0.56 - 0.49% FWHM (full volume - fiducial volume)

next-preliminary

High energy calibration with ^{232}Th source

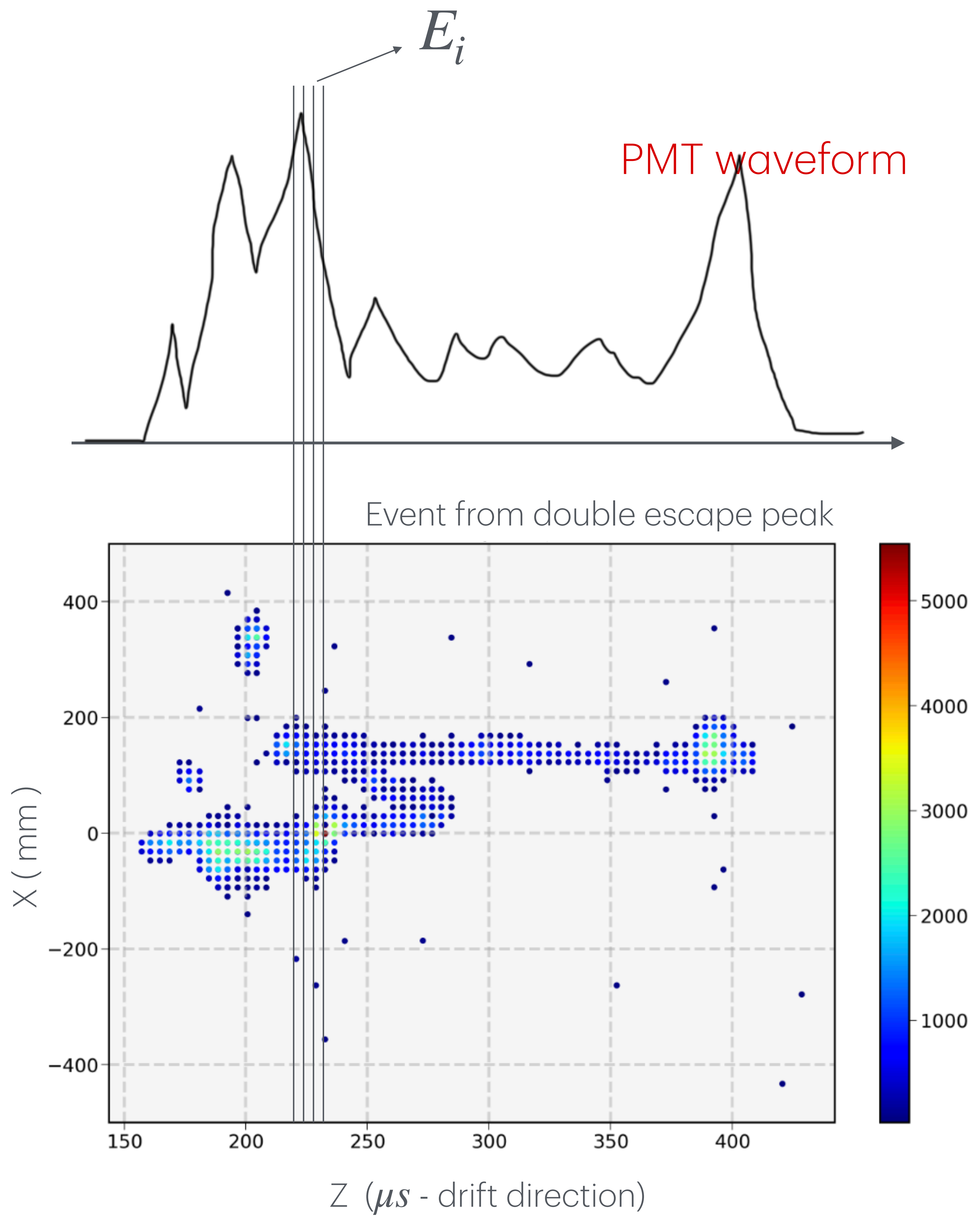
- With high energy tracks the track is corrected at hit level using the kr map
- Energy of each slice of the wf is divided proportionally to the charge seen by the SIPM

E in the slice — SiPM charge in the voxel

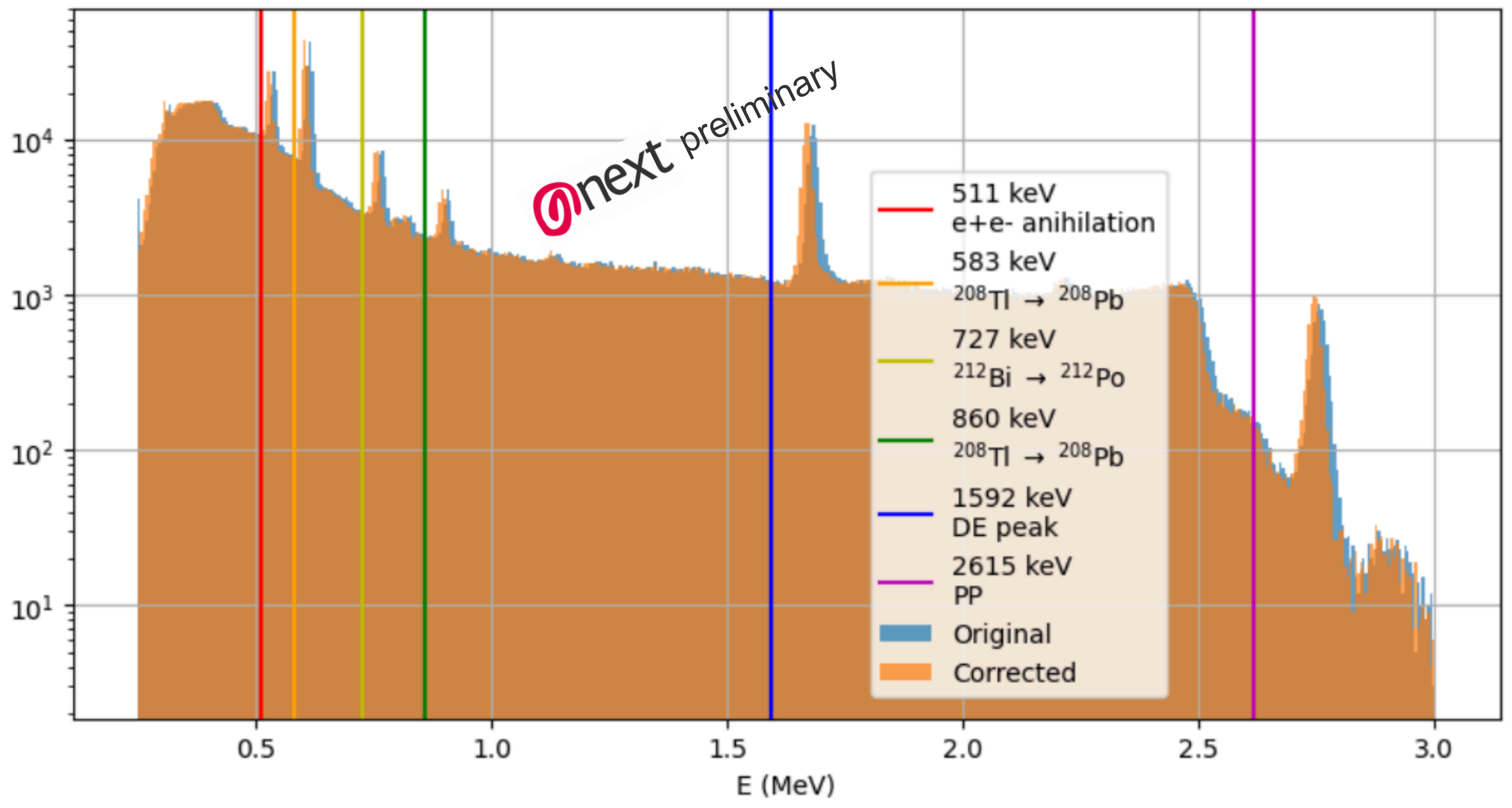
$$E_v = E_i \cdot \frac{Q_k}{Q_{tot}}$$

E associated to the voxel — Total SiPM charge in the slice

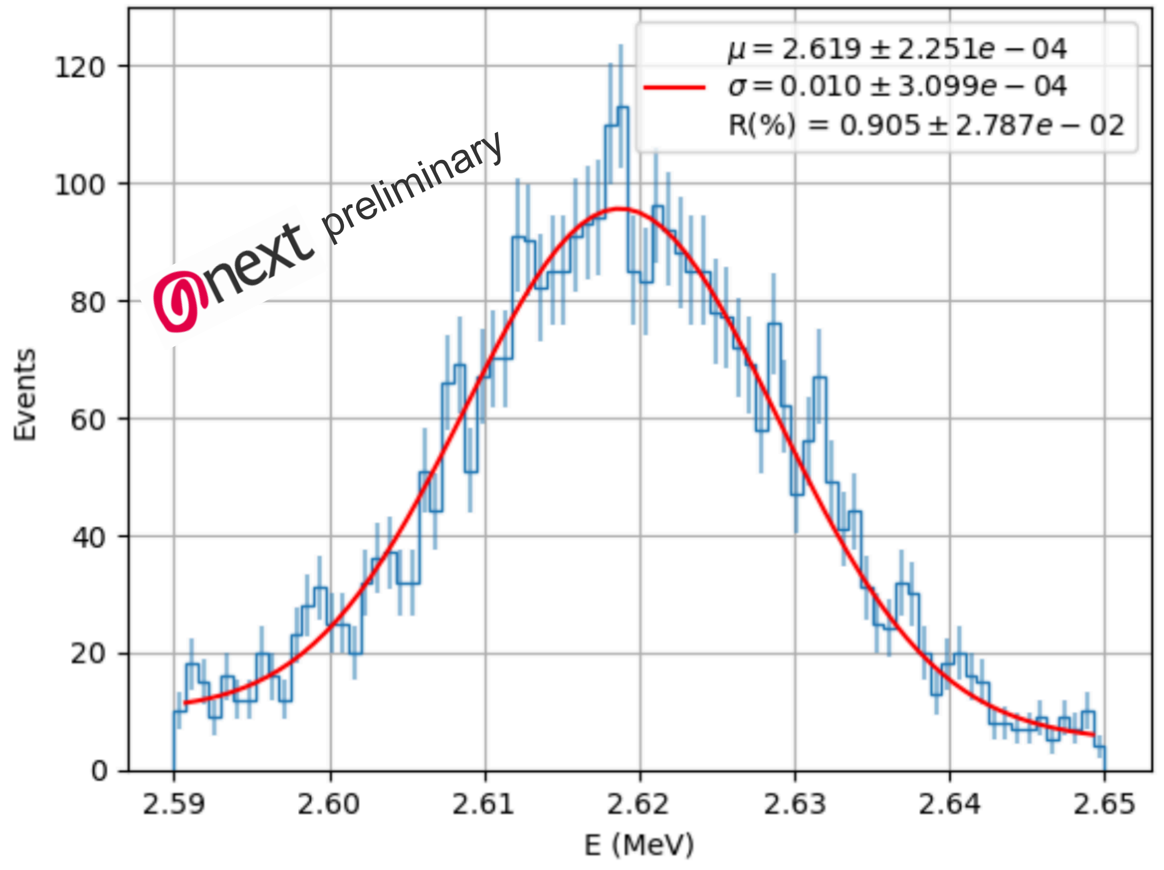
- Energy of the individual voxel in (X,Y,Z) is corrected with the Kr map



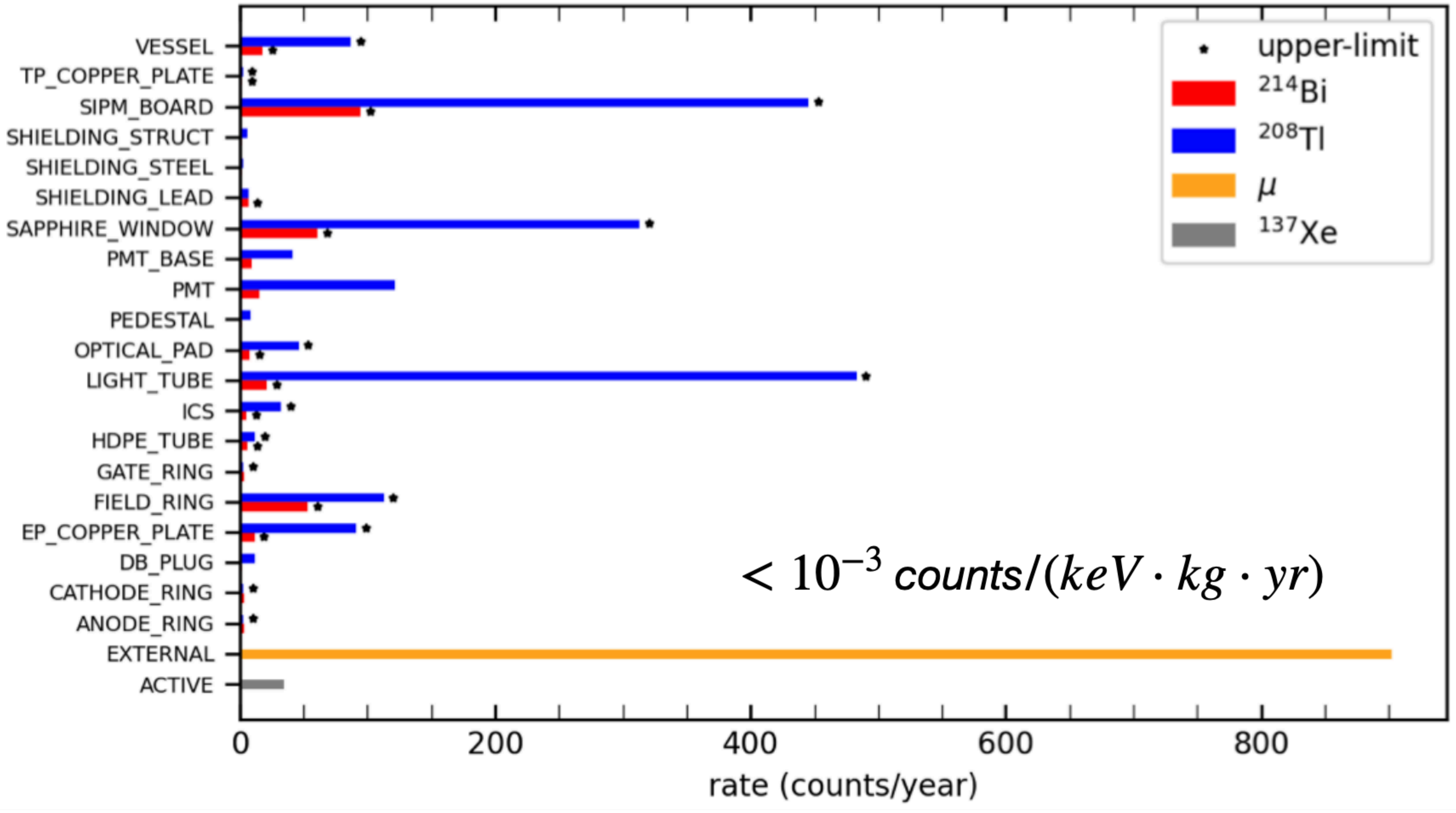
Energy spectrum with ^{208}Tl source (corrected)



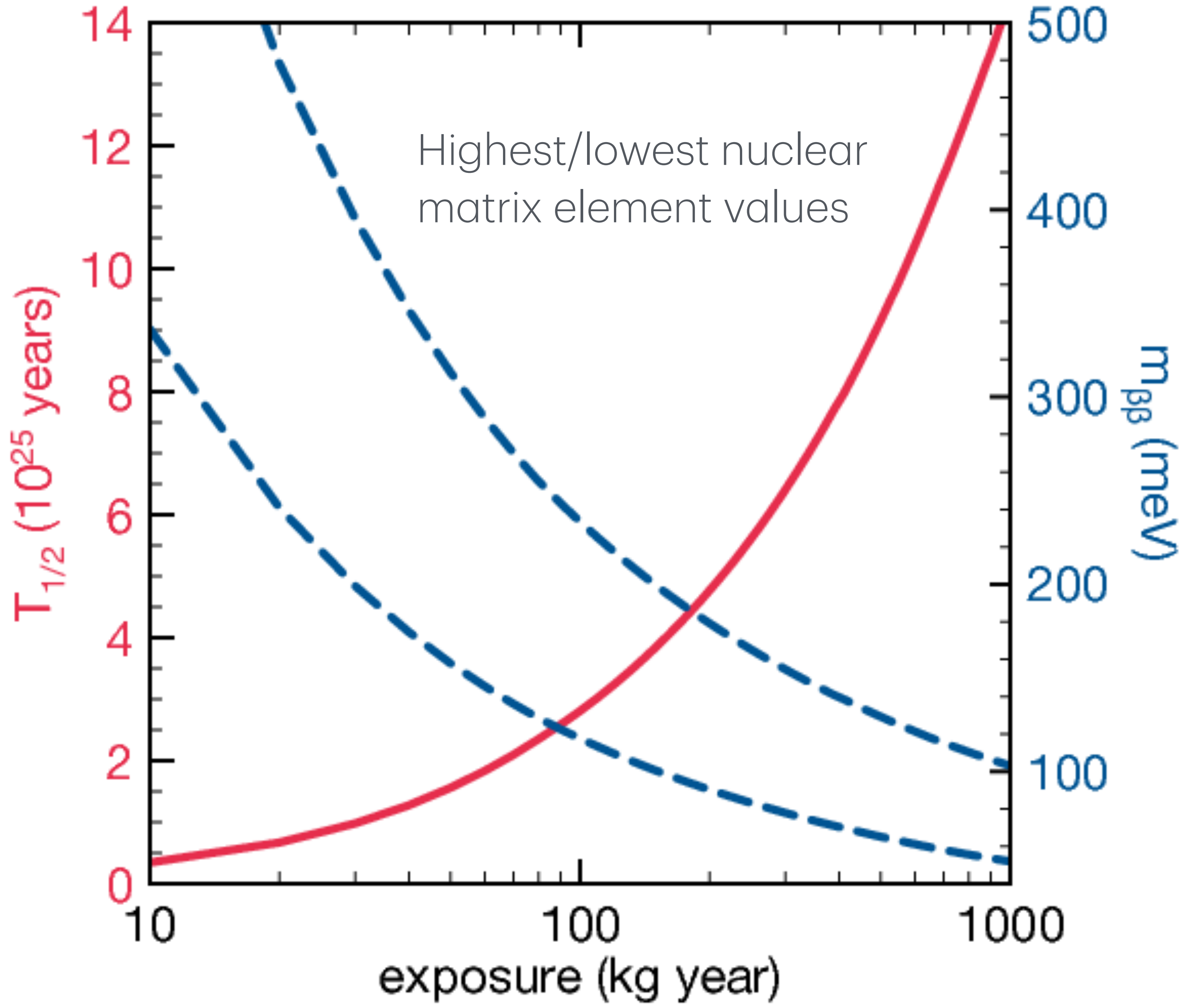
$E_{res}(2.61 MeV) = 0.90\,\%$



Future steps for NEXT-100



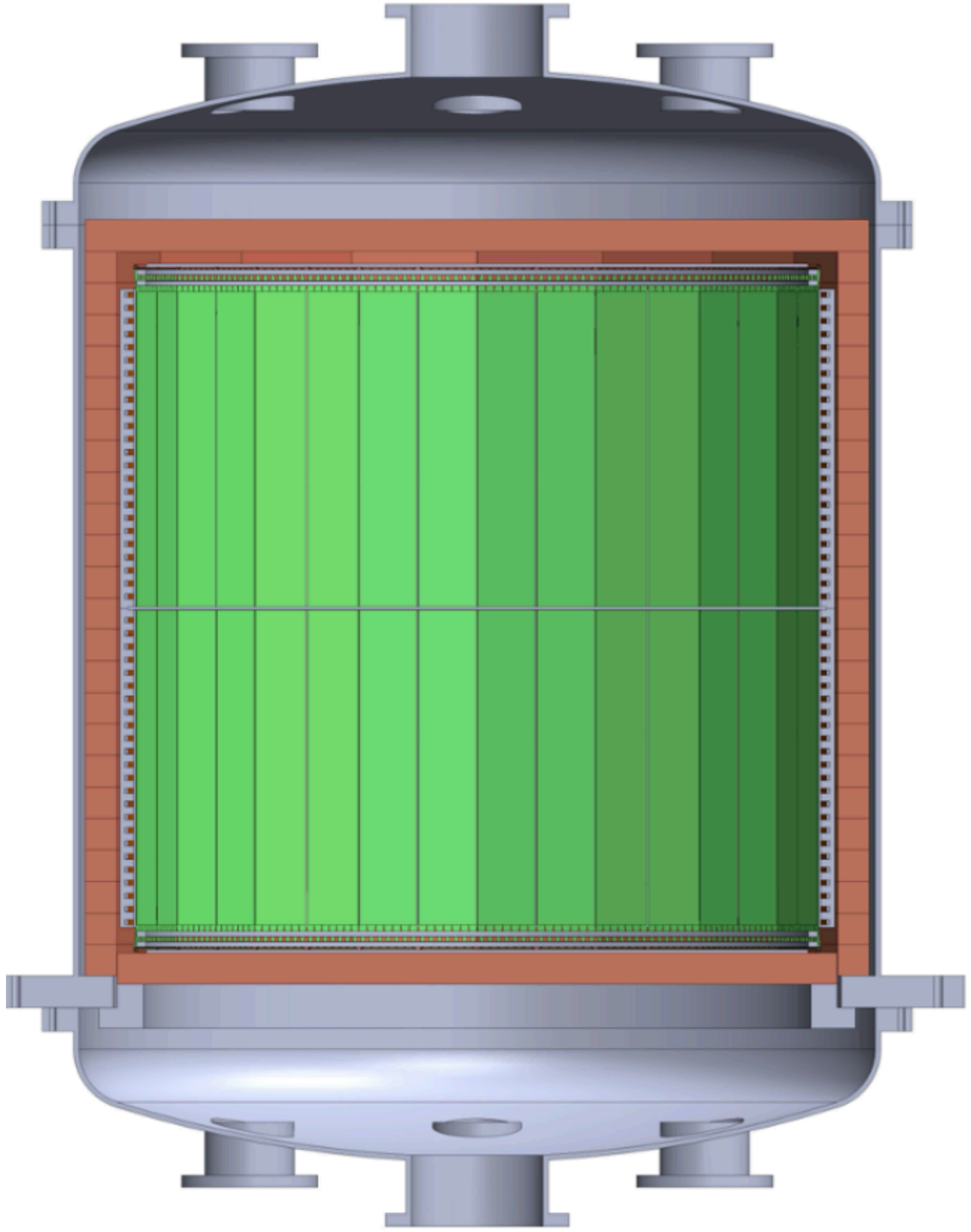
- Background characterization at 4 bar (ongoing)
- Start operations at 10 bar
  - Repeat full detector calibration at higher pressure
- Preciser measurement of the $2\nu\beta\beta$
- Search for $0\nu\beta\beta$ decay
  - Sensitivity (3 yr) ≈ $4 \cdot 10^{25}$ yr @ 90% C.L.



JHEP 2016, 159

Ton-scale NEXT detectors: NEXT-HD

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



Projected for ~2030

Mass: ~1000 kg (at 15 bar)

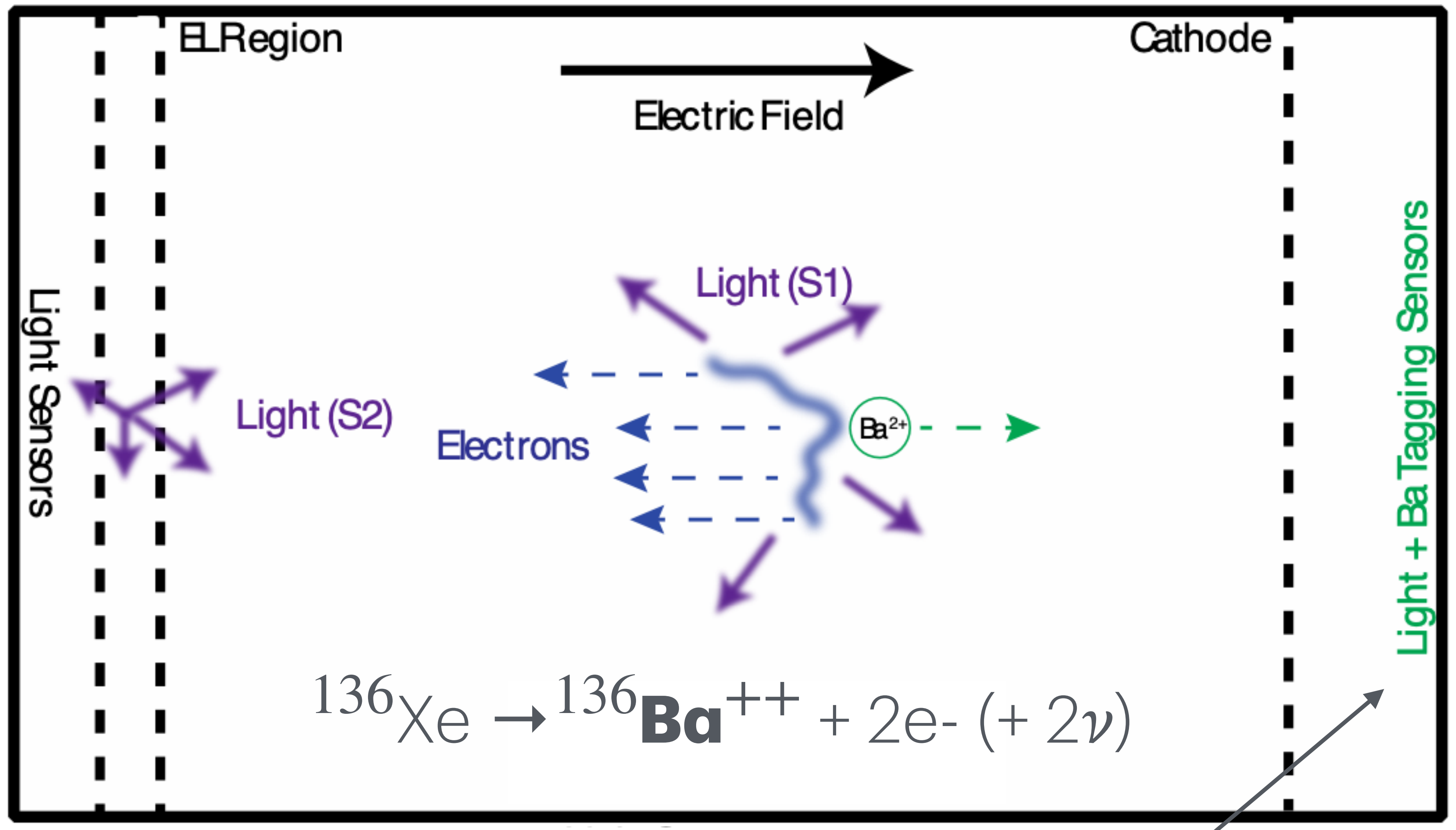
Sensitivity: O(10^{27}) y after 5 years

Background: 0.01 counts/(keV ton y)

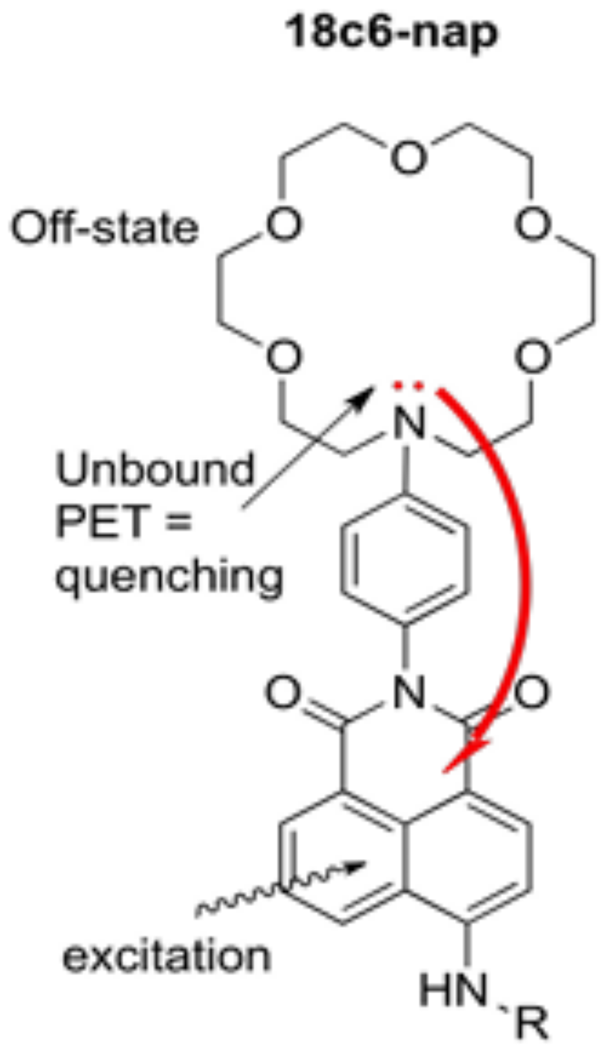
JHEP 2021, 164

Barium tagging: Single Molecule Fluorescent Imaging (SMFI)

- Free $^{136}Ba^{2+}$ might be detected in coincidence with $0\nu\beta\beta$ candidate with single Molecule Fluorescence Indicators
- This would lead to an experiment virtually background free as no background can mimic the signal

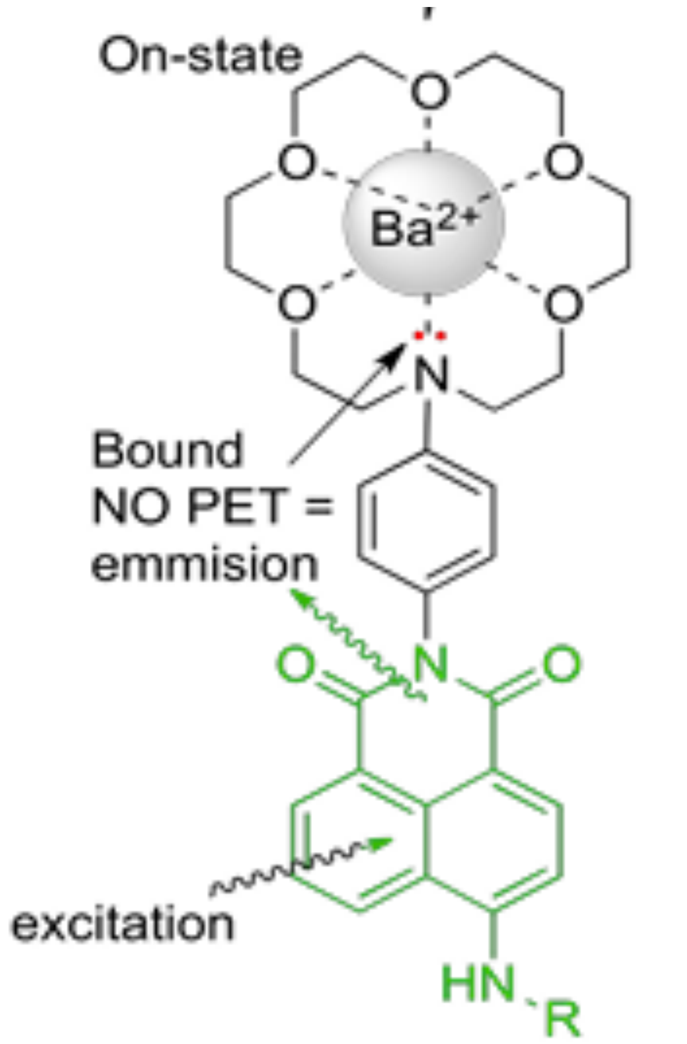


Non fluorescent molecule



Capture of a single Ba^{++}

Fluorescence



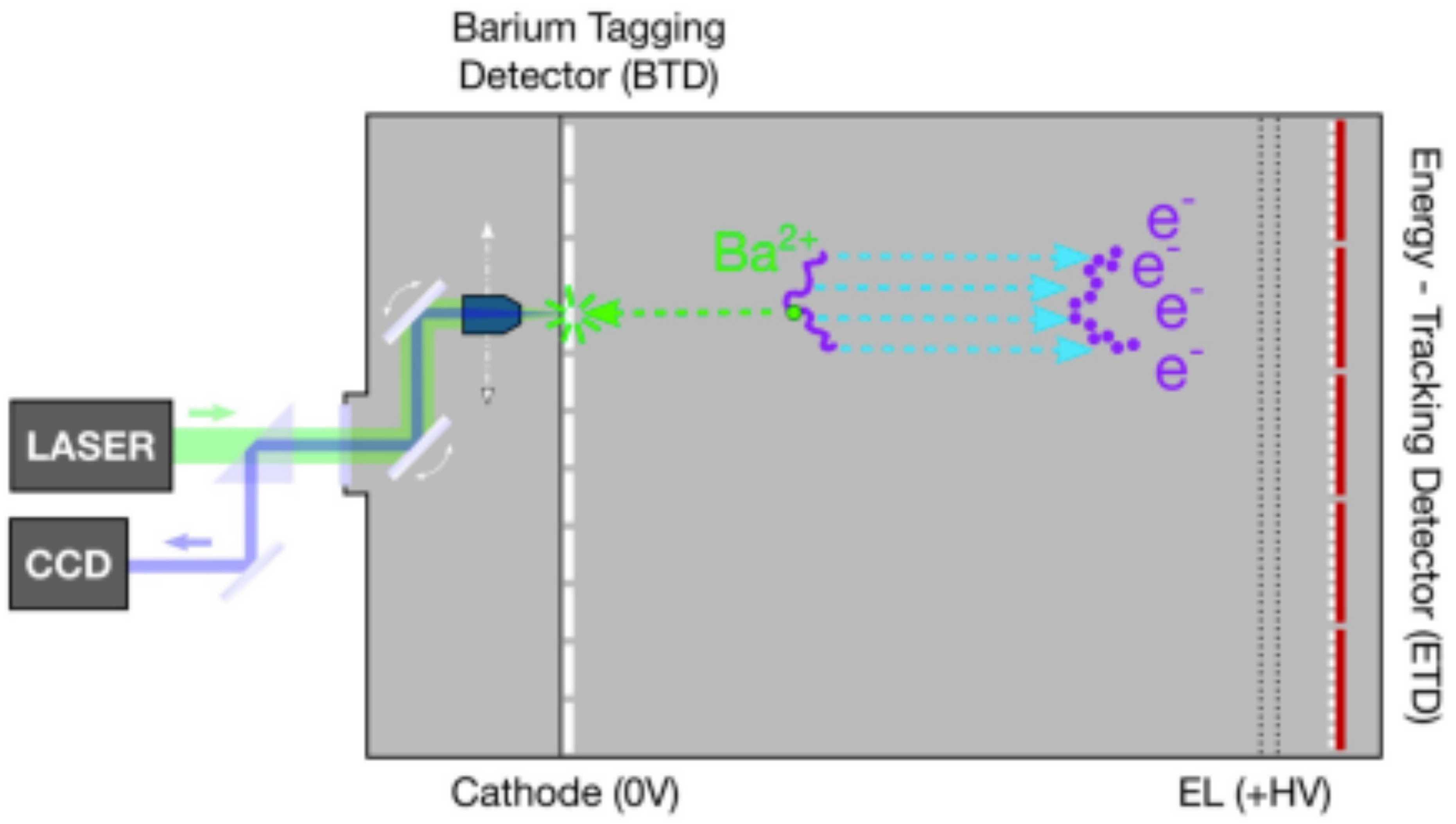
Challenge: detect a single Ba^{++} ion over a ton of material

Barium tagging: Demonstration phase

- Demonstrator phase under intensive R&D over a 2-3 ys timescale. Two approaches are being tested

- Sensor to Ion approach

Bring the sensor to the single ion expected location

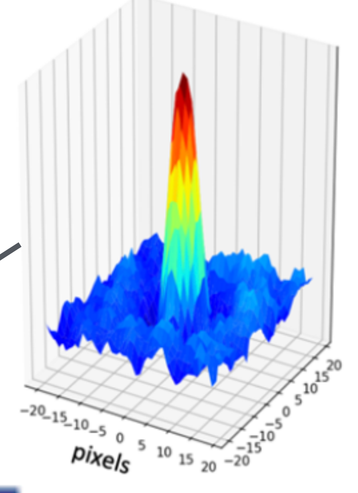


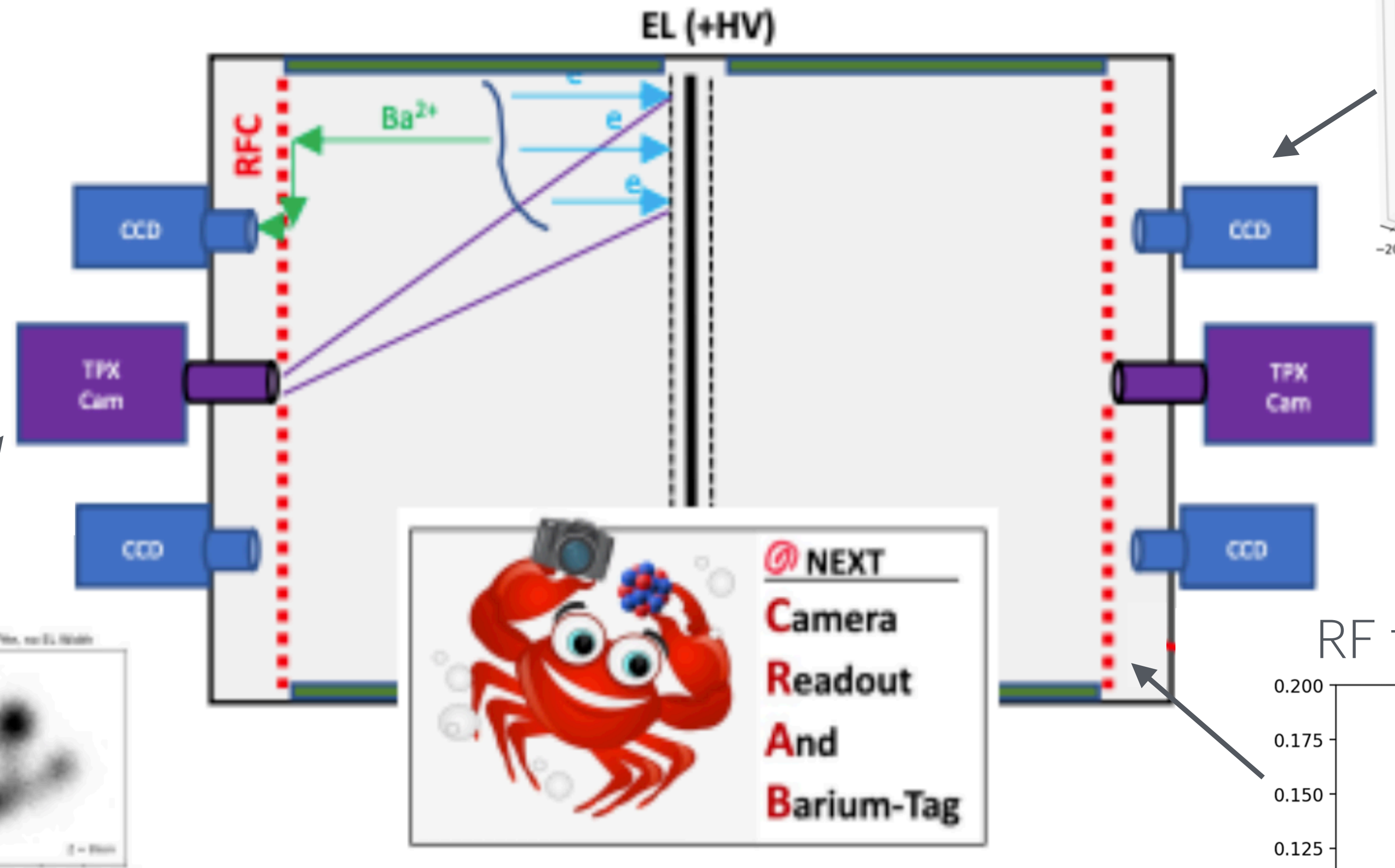
- Ion to sensor approach

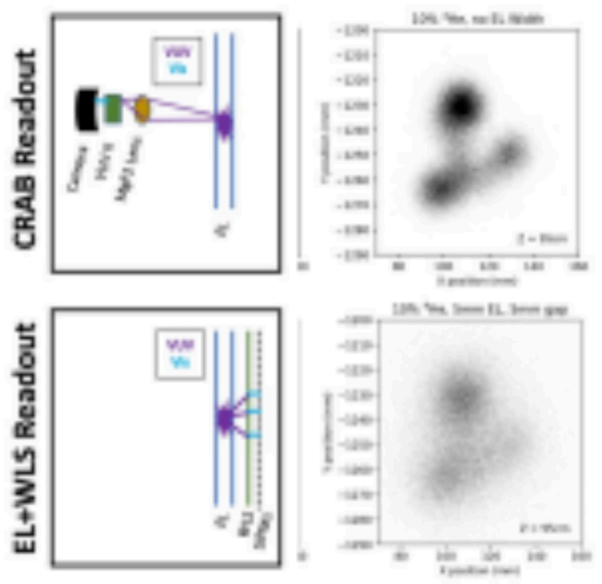
Transportation of the ions to the detection location

JINST 18 (2023) P08006

Single ion tagging with camera

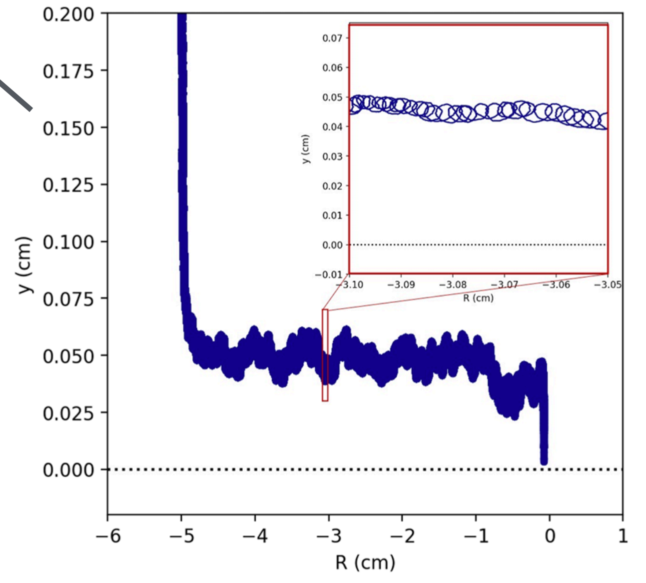






tracking with camera

RF for transportation

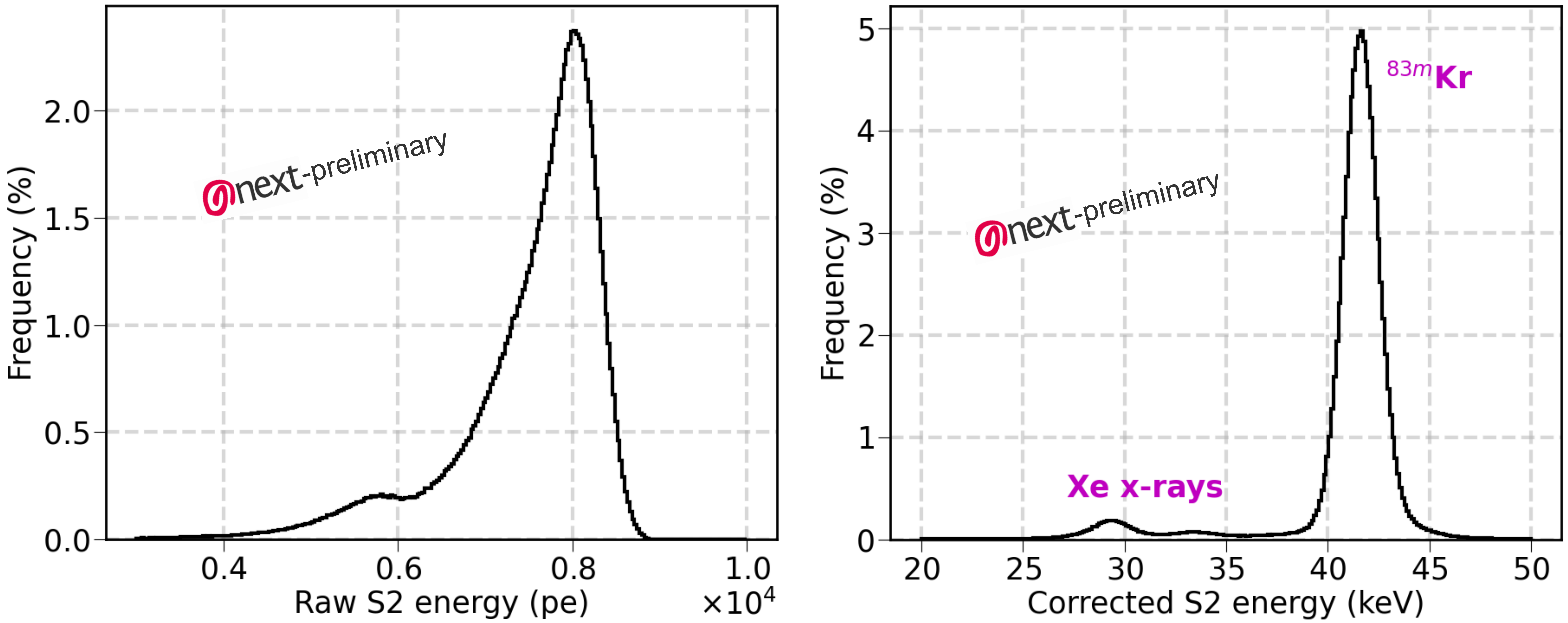


Conclusions

- The observation of the $0\nu\beta\beta$ process might have strong implications in current understanding of physics
- NEXT is contributing with a gas TPC relying on a very good energy resolution and particle discrimination strategy
- After the results of NEXT-White, the NEXT-100 detector is currently installed in **L**aboratorio **S**ubterráneo de **C**anfranc
- The commissioning phase has confirmed the stability of the detector response and a lifetime >> the maximum drift time
- The detector calibration phase is finished:
    - The low energy calibration showed the effectiveness of the Kr map correction, and a resolution @ 41.5 keV < 4.2%
    - The high energy calibration has preliminary demonstrated that a <1% energy resolution is feasible @ the $Q_{\beta\beta}$ value
- The detector is currently taking low background data @ 4 bar to characterize the different background sources
- Subsequently operations at 10 bars with $2\nu\beta\beta$ measurements and $0\nu\beta\beta$ searches will start
- For the future a O(1000 kg) NEXT detector is foreseen, and with the barium tagging technique might operate ~background free

Backup slides

X-ray data

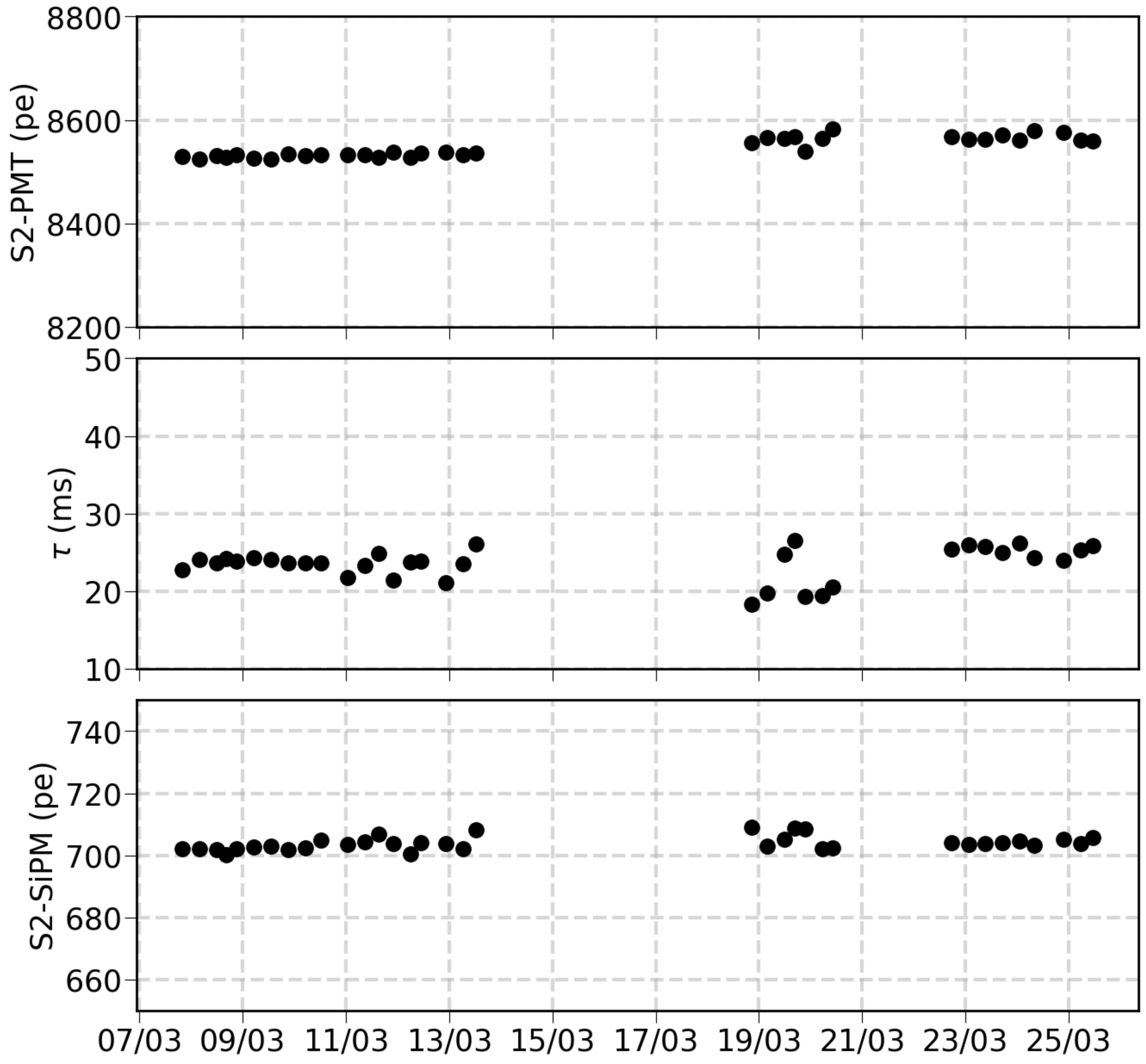


next-preliminary
Frequency (%)
2.0
1.5
1.0
0.5
0.0
0.4
0.6
0.8
1.0
Raw S2 energy (pe)
×10⁴
next-preliminary
Frequency (%)
5
4
3
2
1
0
20
25
30
35
40
45
50
Corrected S2 energy (keV)
83mKr
Xe x-rays

Detector Stability

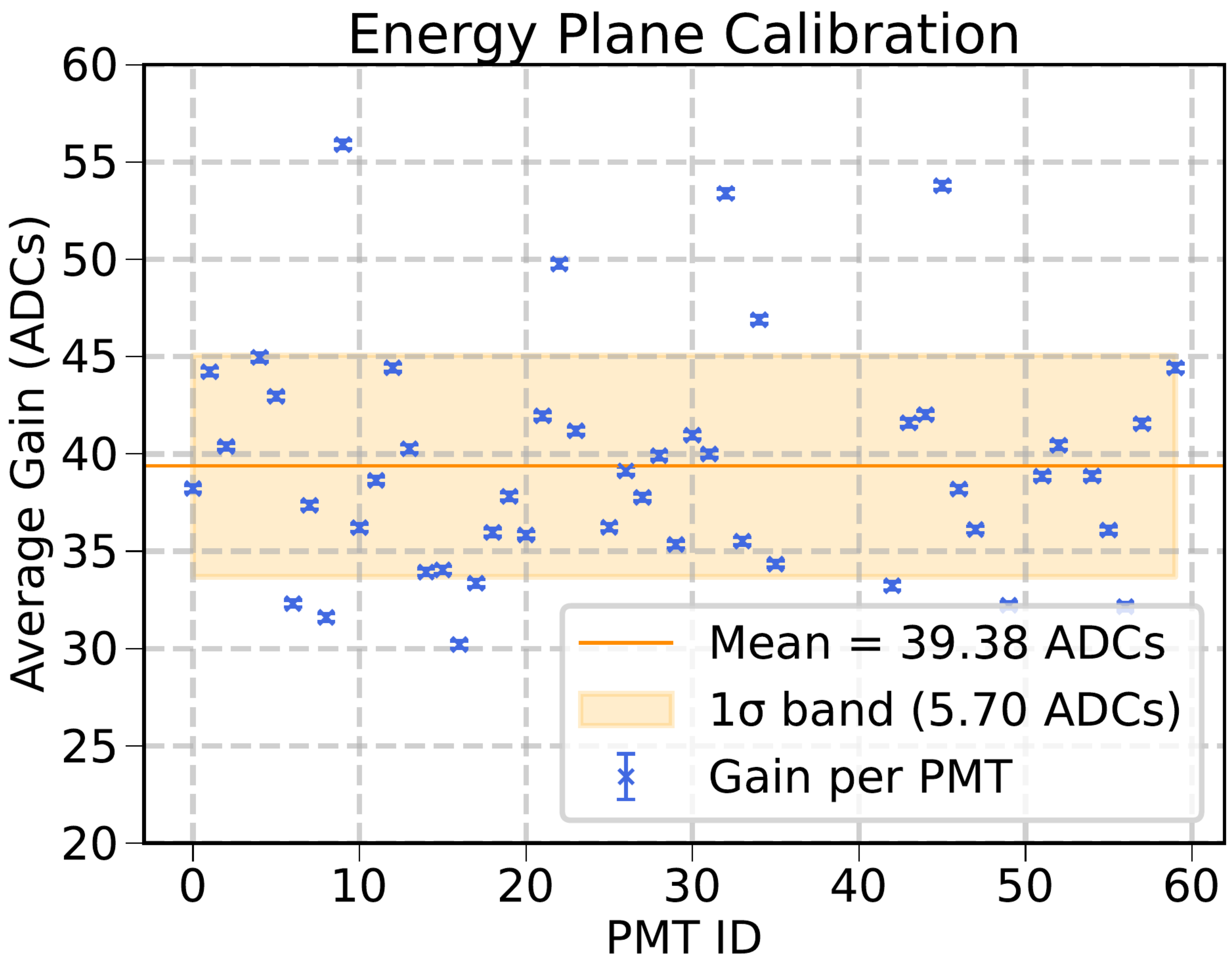
- ^{83m}Kr also used to monitor the detector
  - PMT response
  - SiPM response
  - Electron lifetime

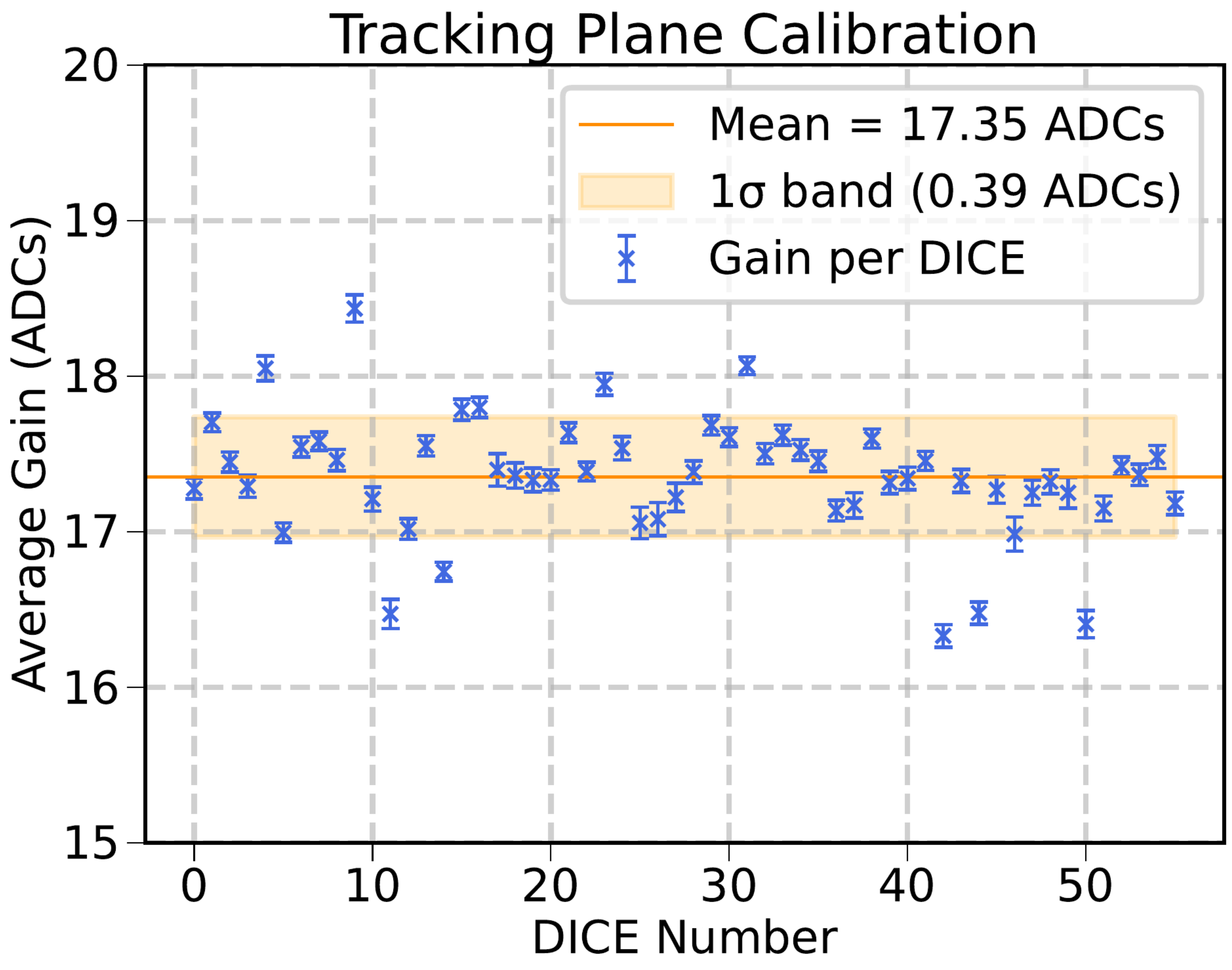
- Good stability over long periods of time
- ^{83m}Kr provides a continuous calibration of the detector!



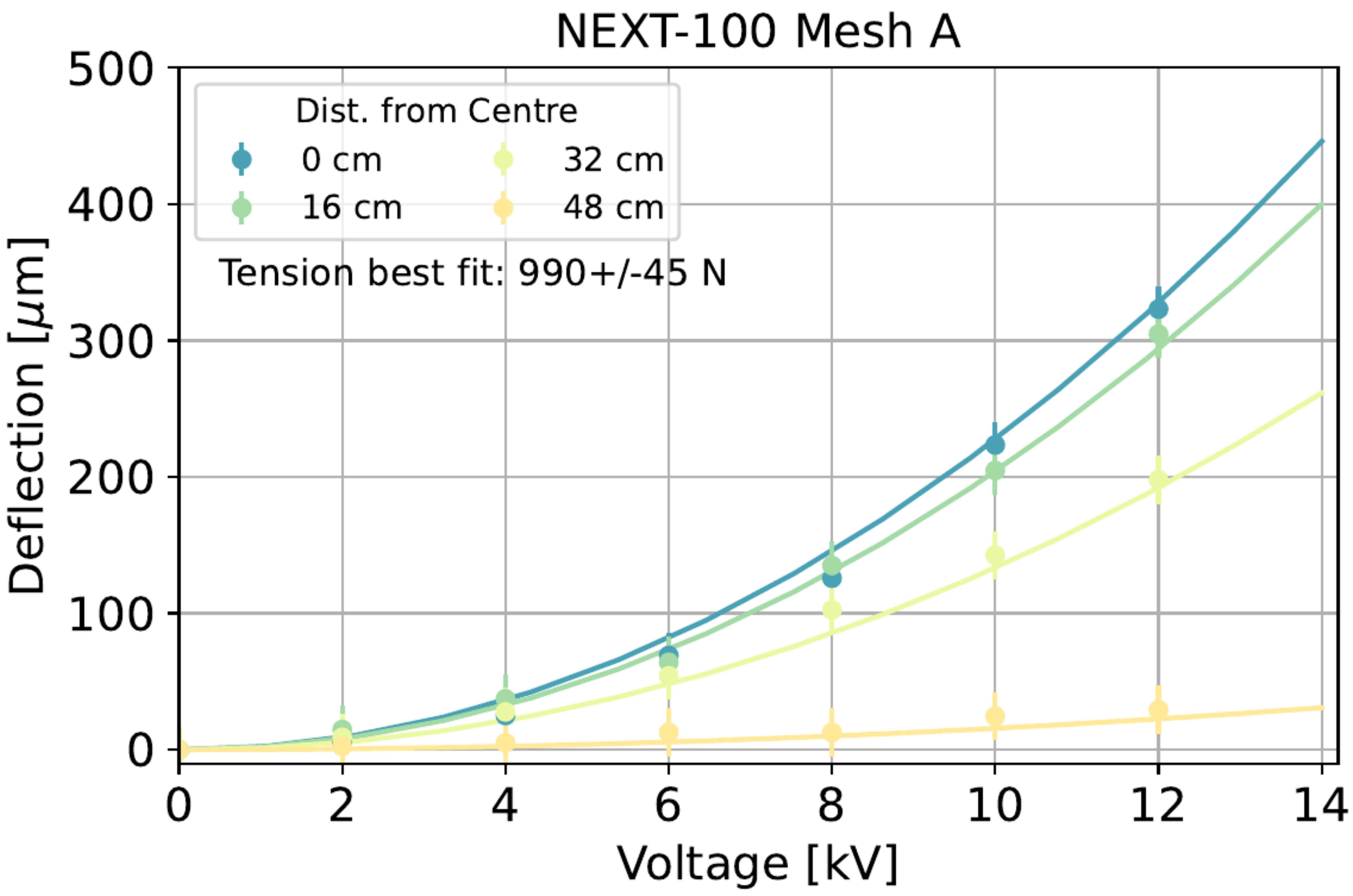
Sensor Calibration

- PMT and SiPMs calibrated with pulsed LED source
- Most sensors calibrated within 1 sigma of the average value





Mesh Deflection



NEXT-HD Sensitivity

Sensitivity (5 t · yr) ≈ $1.5 \cdot 10^{27}$ yr @ 90% CL
Sensitivity (10 t · yr) ≈ $3.0 \cdot 10^{27}$ yr @ 90% CL

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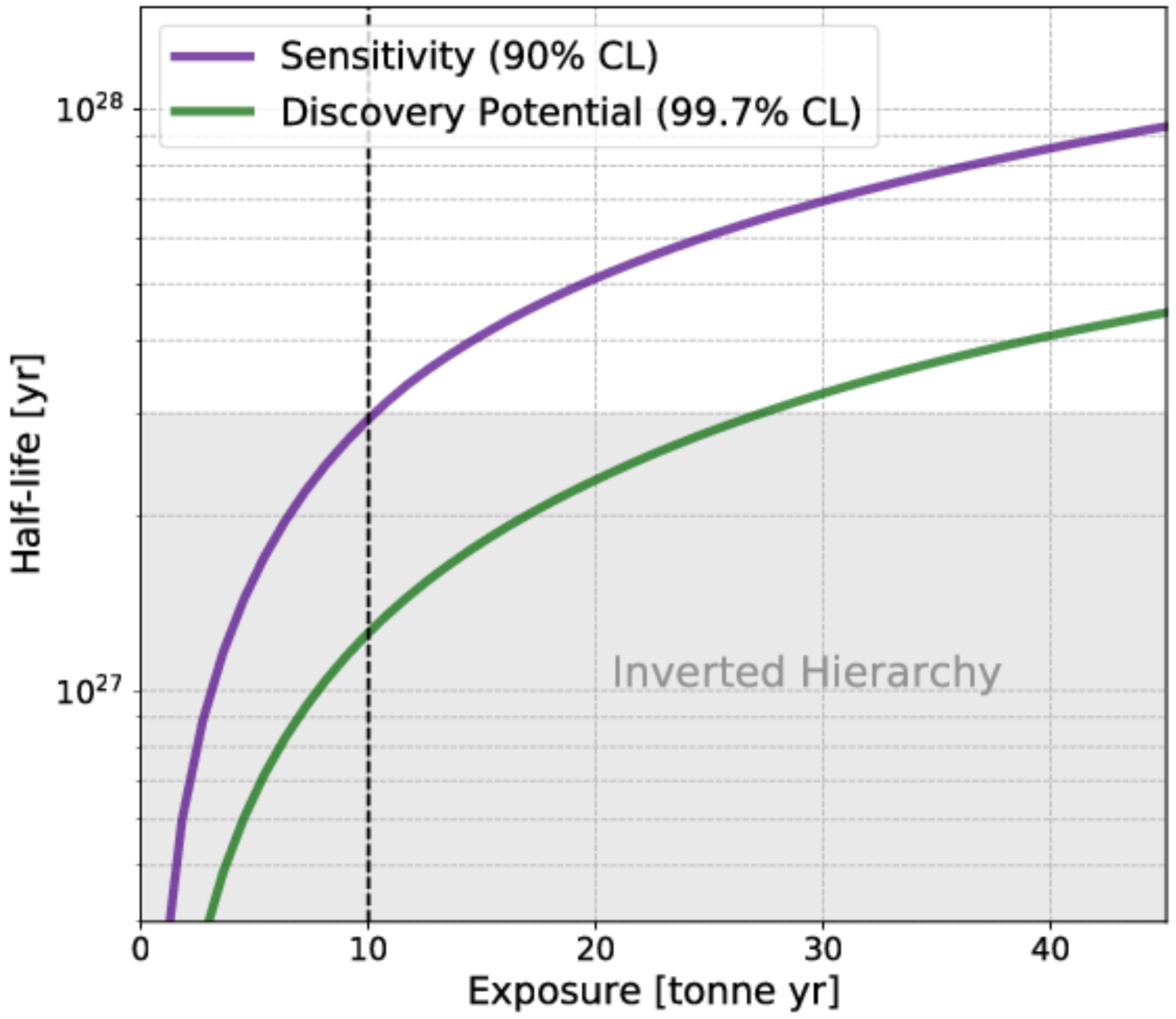
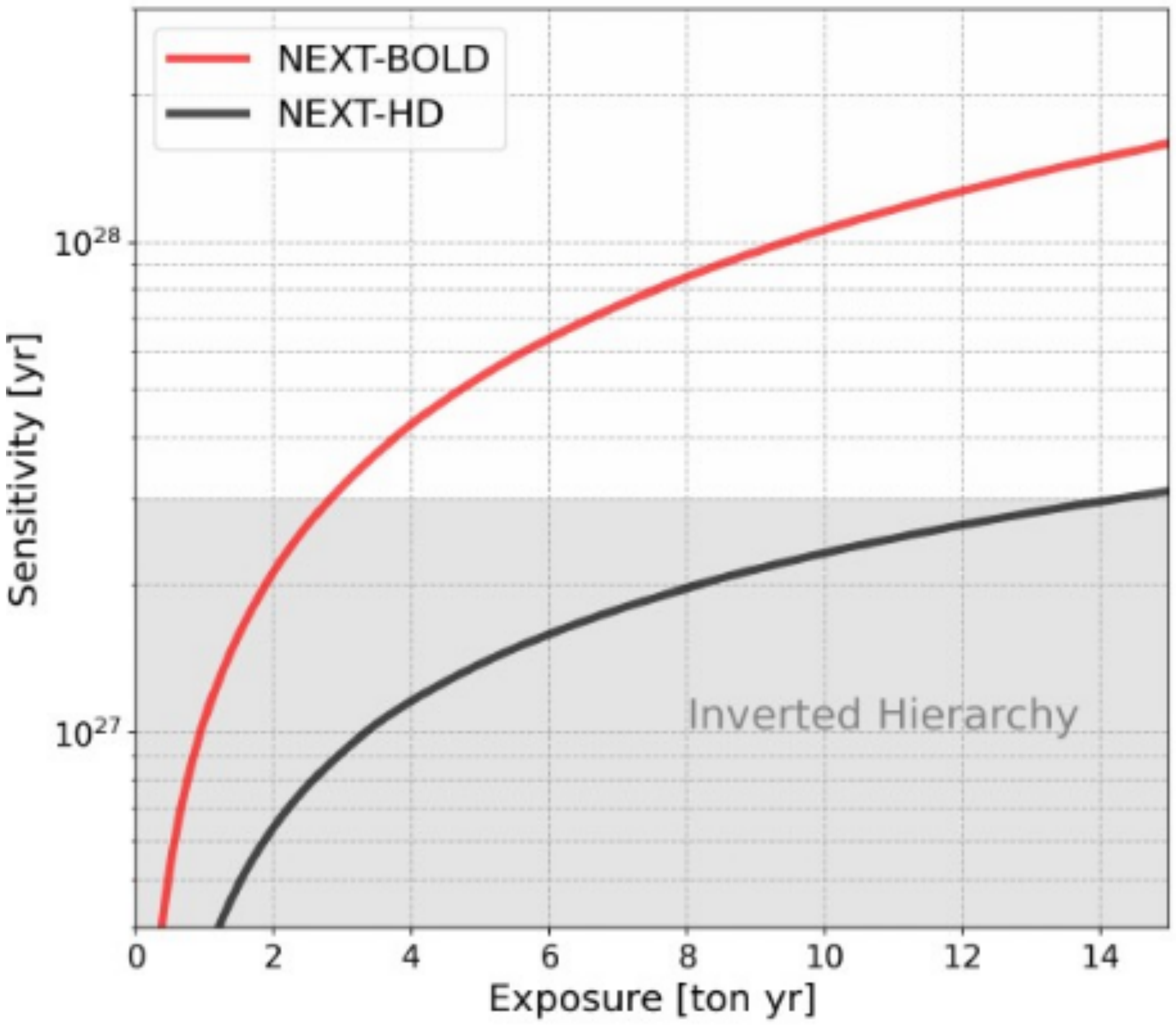


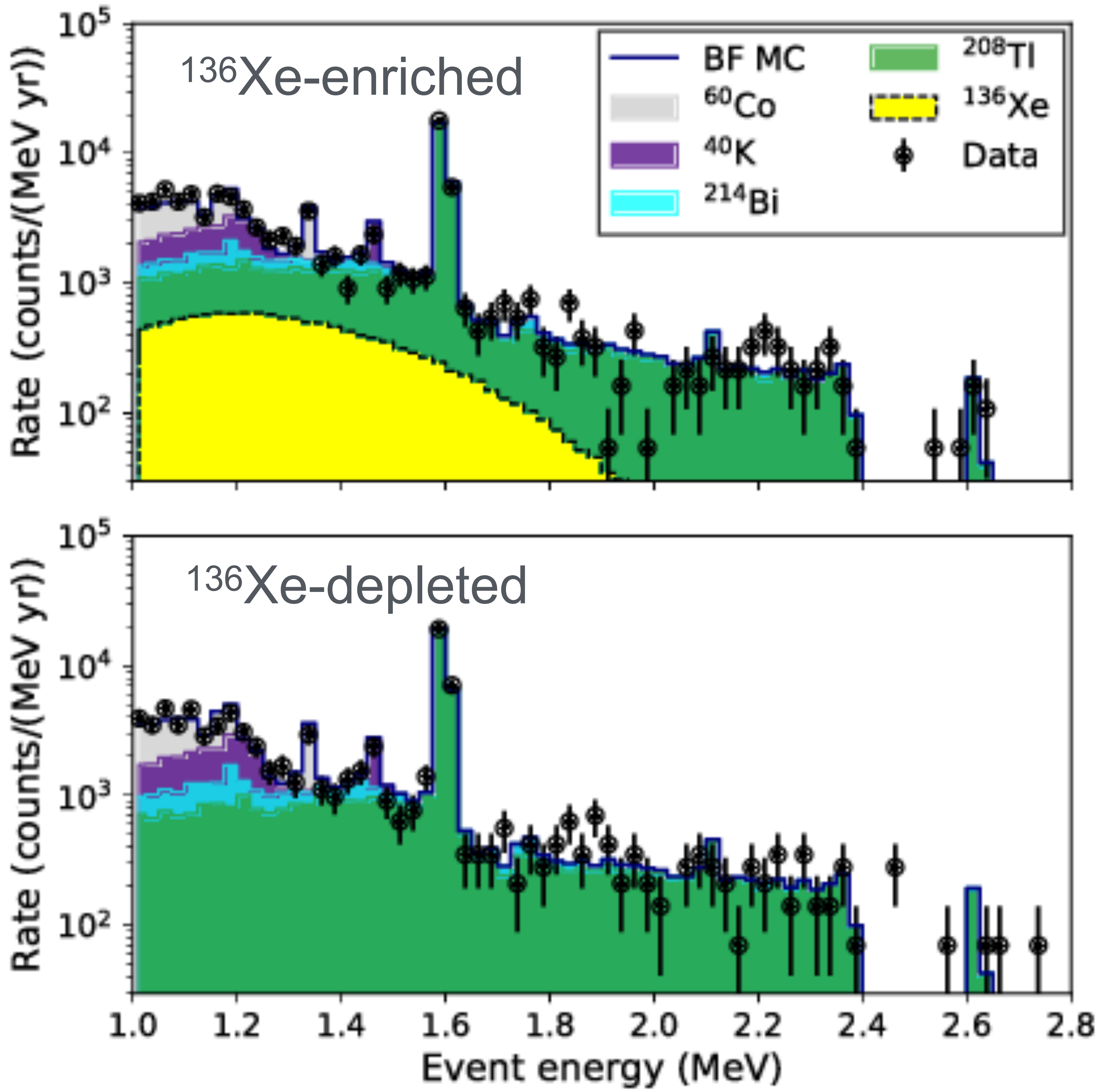
NEXT-Bold Sensitivity

Sensitivity (5 t · yr) ≈ $6 \cdot 10^{27}$ yr @ 90% CL
Sensitivity (10 t · yr) ≈ $1 \cdot 10^{28}$ yr @ 90% CL

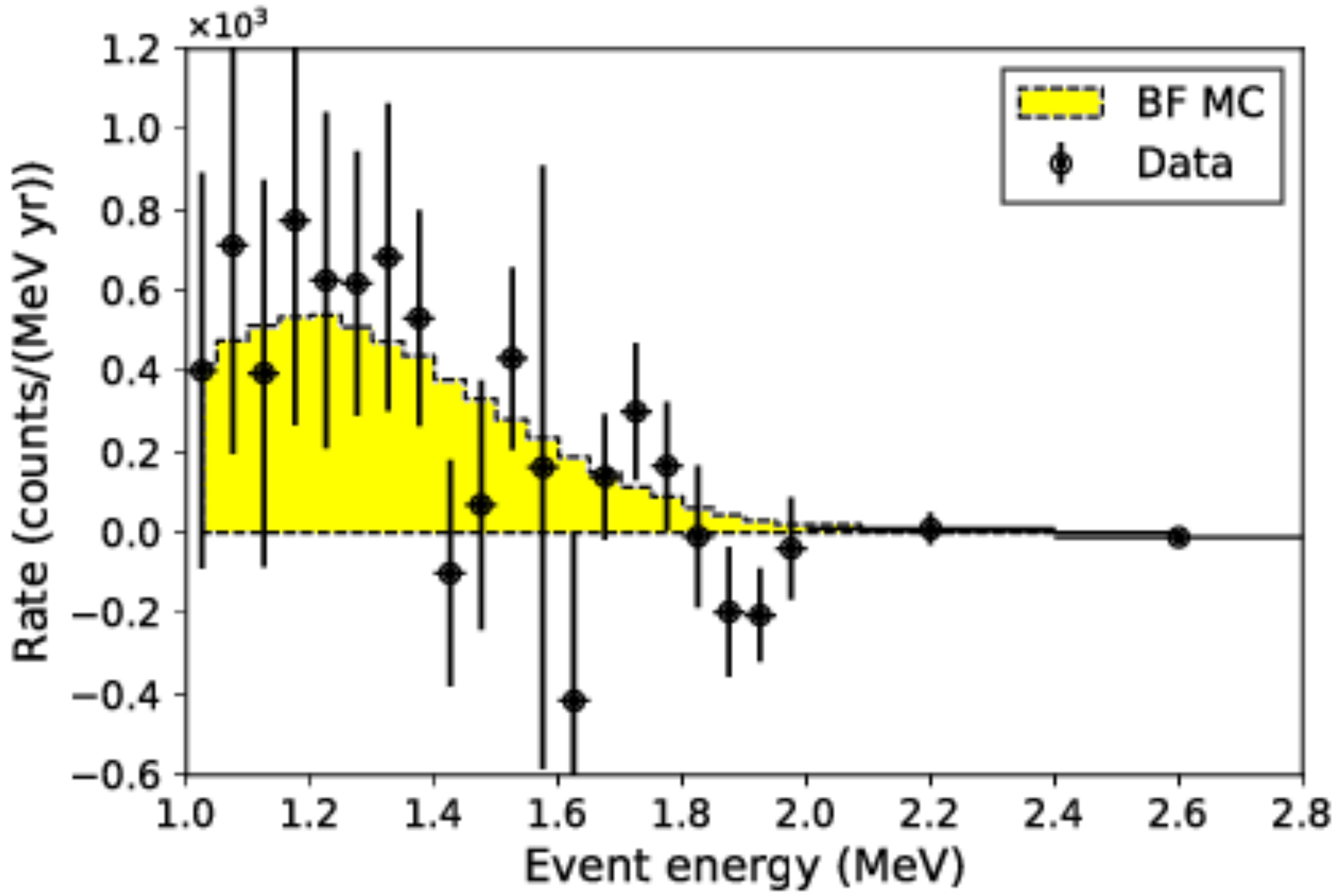


Direct background substraction: $\beta\beta 2\nu$

Phys. Rev. C 105, 055501



Subtraction



$$T_{1/2}^{2\nu\beta\beta} = 2.34^{+0.85}_{-0.49} \cdot 10^{21}\ y$$

Direct background substraction: $\beta\beta0\nu$

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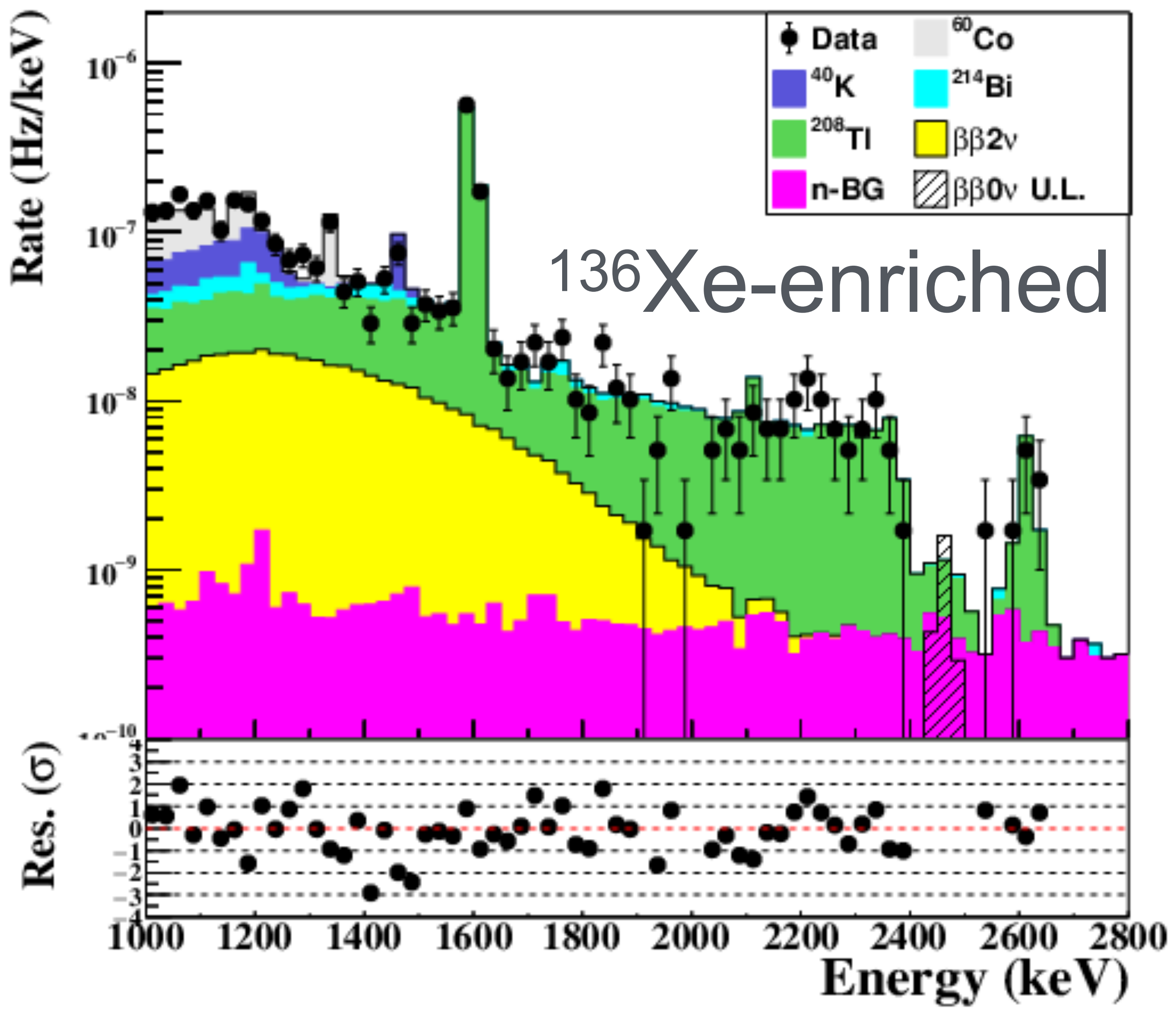
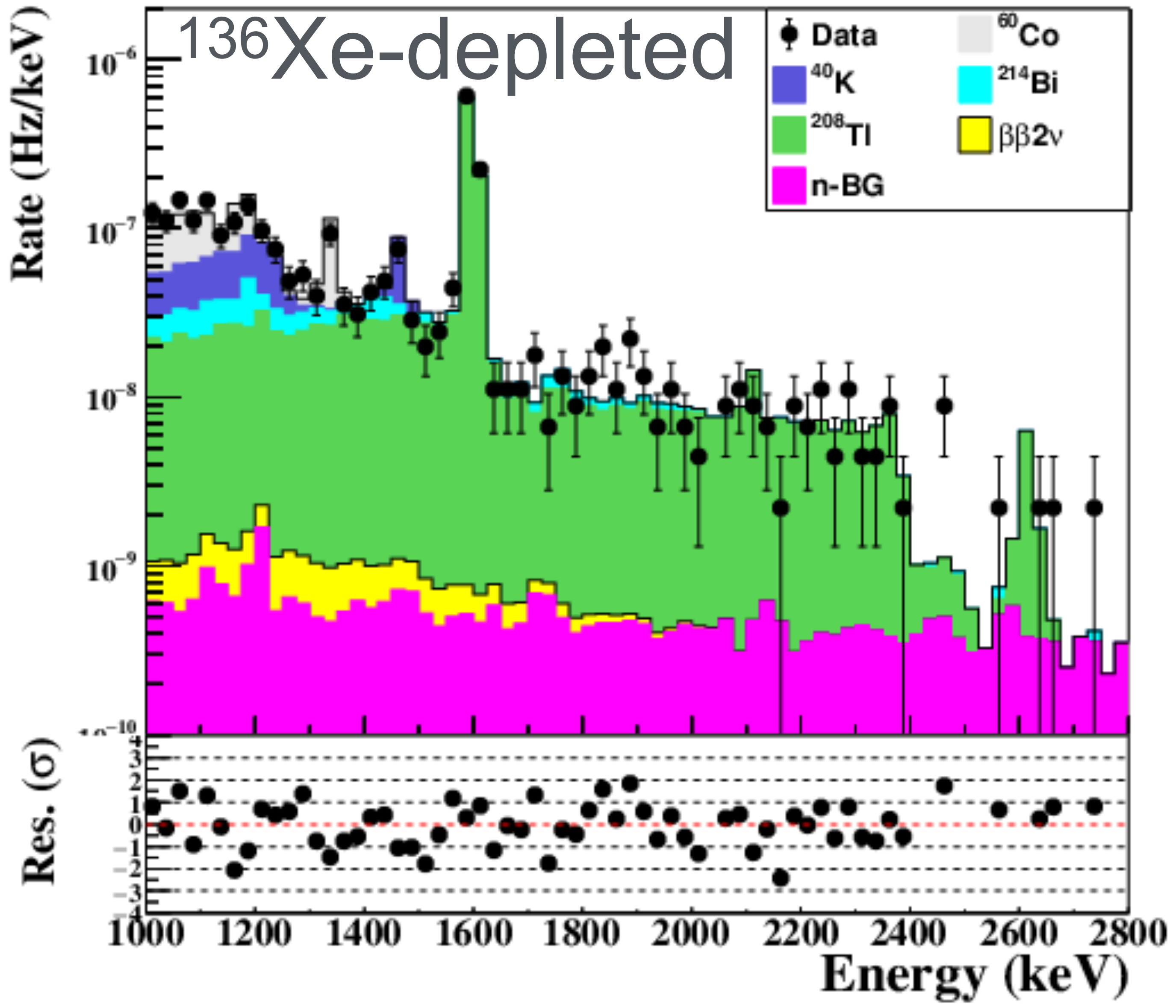
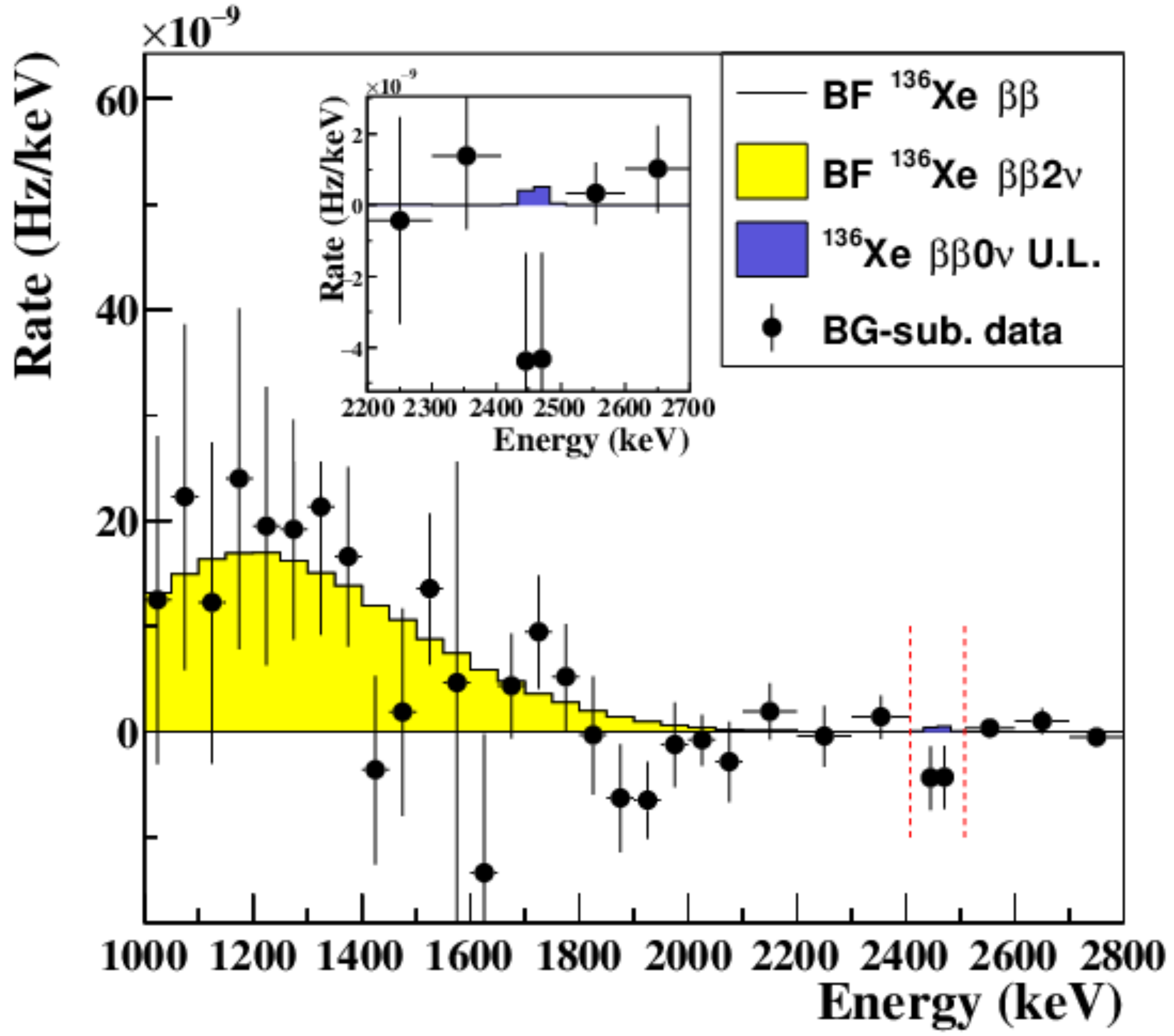




Subtraction



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