The NEXT experiment for ββ0ν searches: status and perspectives

next

CSIC
Consejo Superior de Investigaciones Científicas

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Institut de Física Corpuscular

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on behalf of the NEXT Collaboration

XeSAT2022 - International Workshop on Applications of Noble Gas Xenon to Science and Technology

Neutrinoless double beta decay

- 2 n simultaneously transformed into 2 p
- **Very rare** process, only 33 isotopes
- Two-neutrino ($2\nu\beta\beta$) mode allowed by SM, understood & measured for several nuclides

$$T_{1/2}^{2\nu} \sim 10^{21} yr$$

- **BUT**, If neutrinos are Majorana fermions:

$$\nu_e = \bar{\nu}_e$$

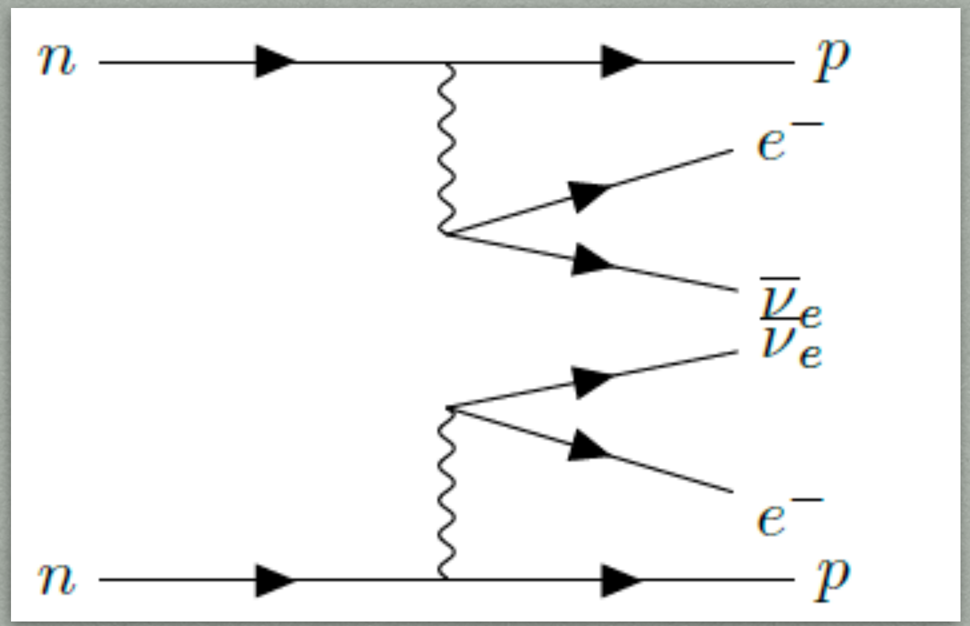
Neutrinoless double beta decay ($0\nu\beta\beta$)

- **Beyond SM** physics → $|\Delta L| = 2$
- Very important information about ν nature
- **Not measured yet** → limits:

$$T_{1/2}^{0\nu} \gg T_{1/2}^{2\nu}$$

$2\nu\beta\beta$

$$N(A,Z) \rightarrow N(A,Z+2) + 2e^- + 2\bar{\nu}_e$$



$0\nu\beta\beta$

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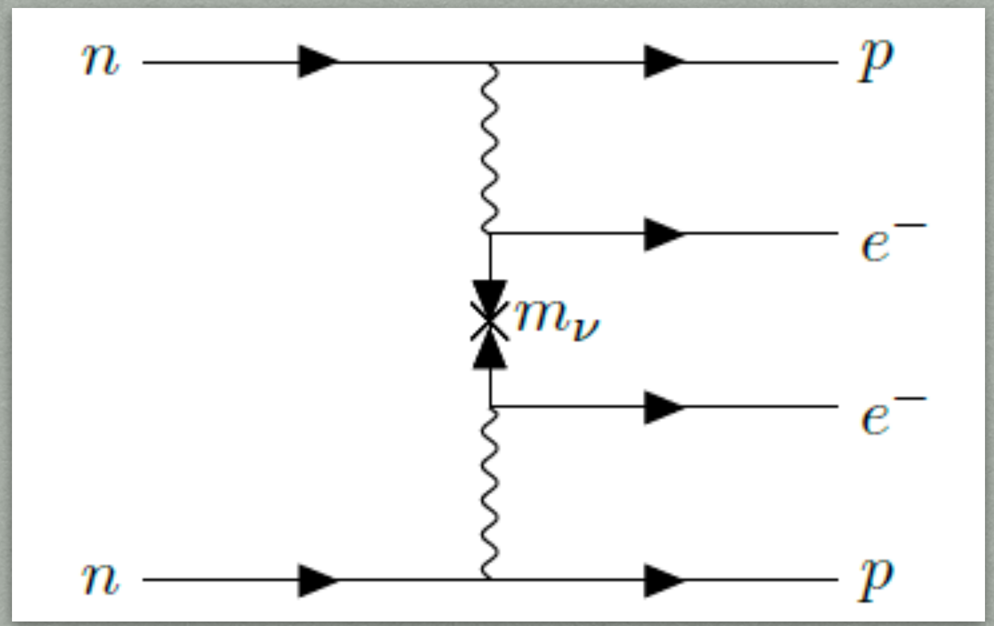
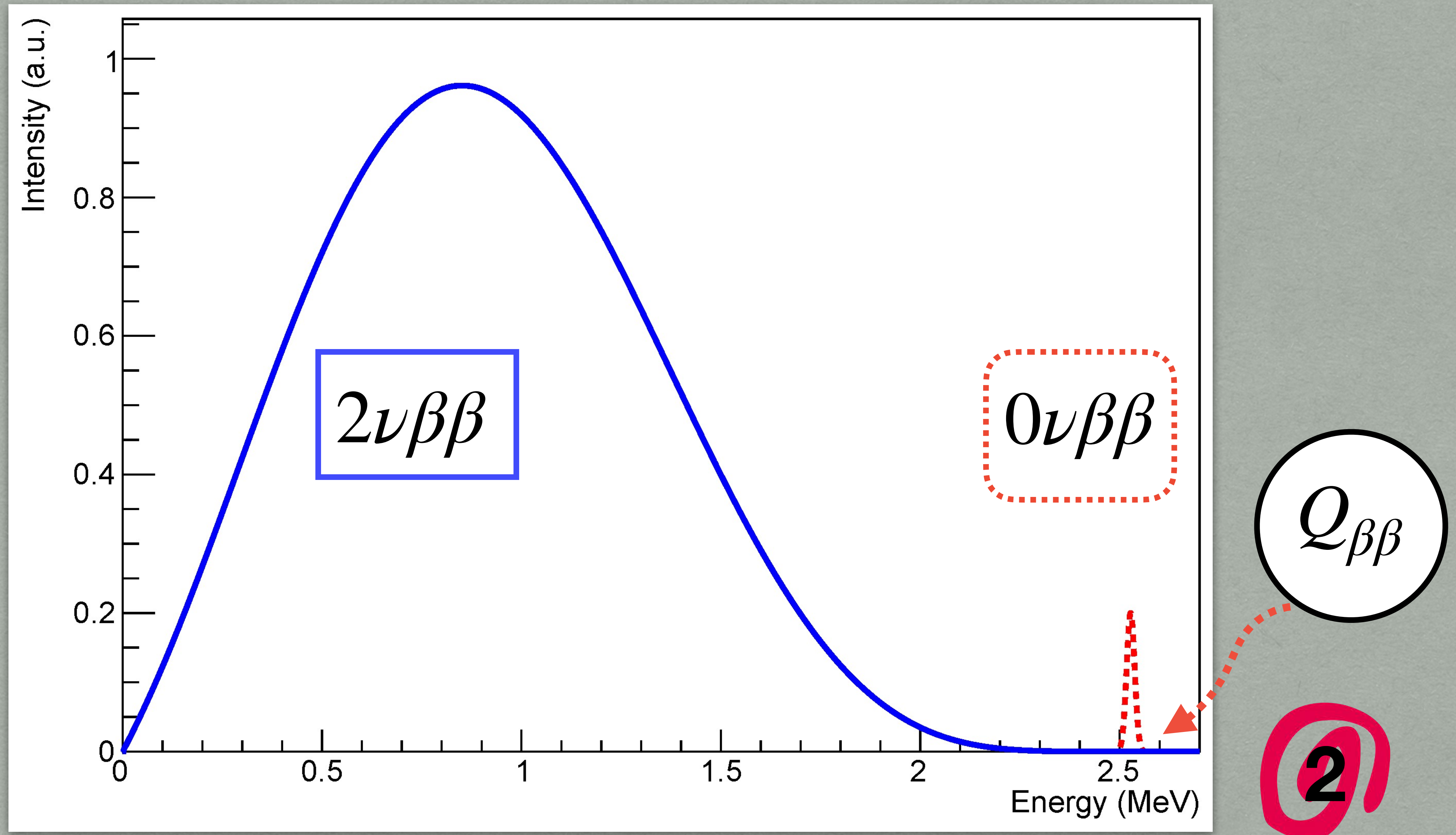
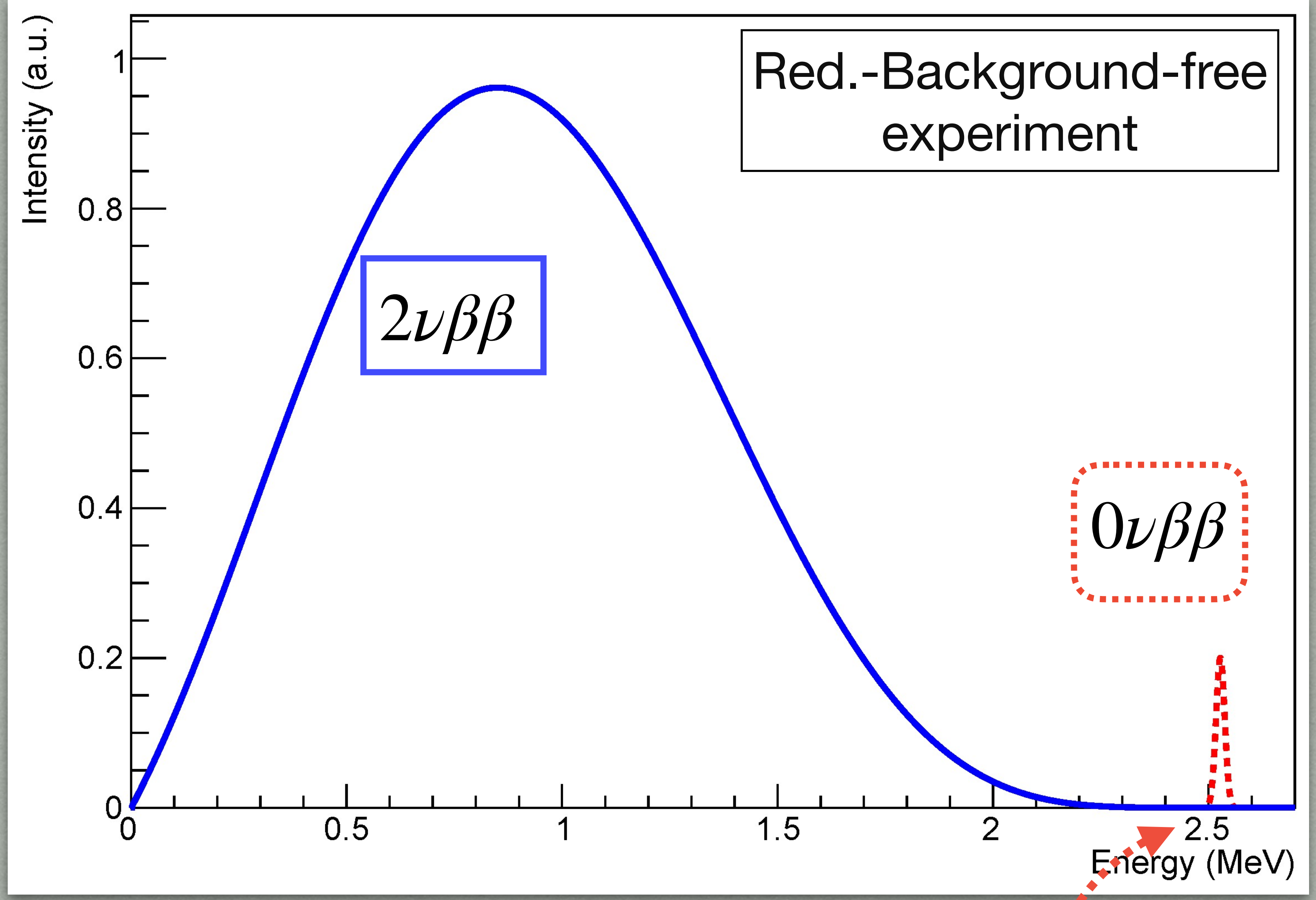




Neutrinoless double beta decay



$$Q_{\beta\beta} = M_P - M_D$$

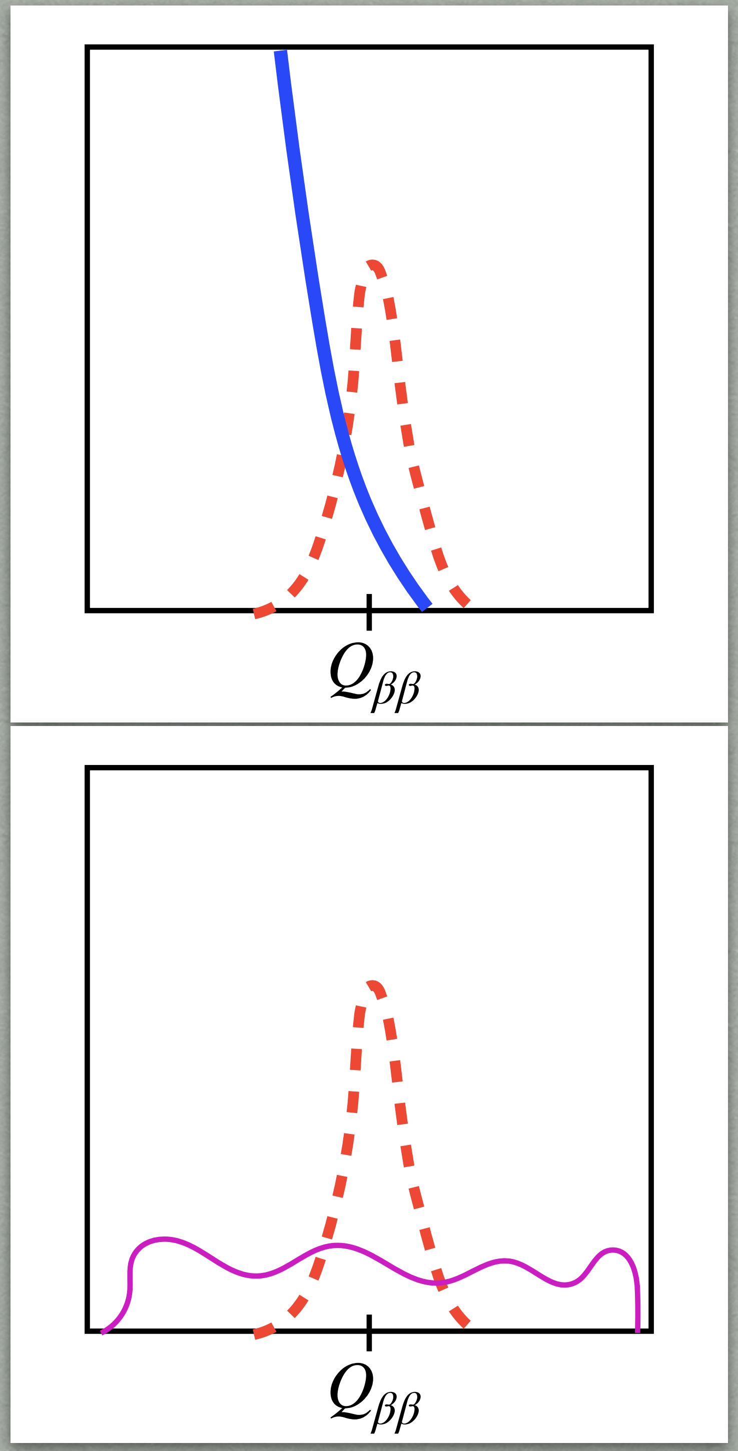
Does not look really complicated, but…

- **Not measured yet** → limits:

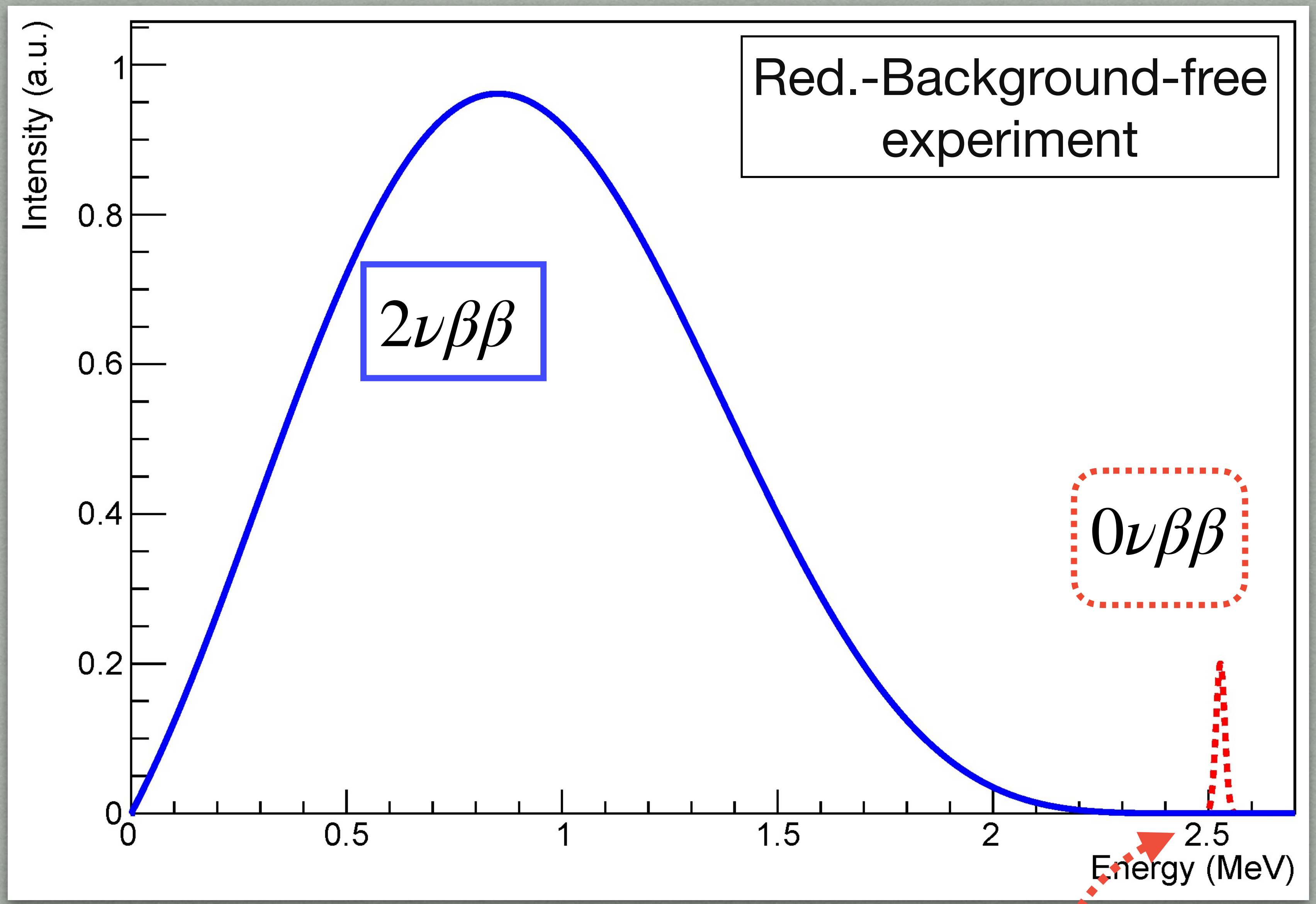
$$T^{0\nu}_{1/2} > 10^{26} yr \quad (^{136}Xe)$$

- Huge half-life → large effect of backgrounds:

1. Irreducible → **2νββ**
2. Reducible:
   A. Radiogenic
   B. Cosmogenic



Neutrinoless double beta decay



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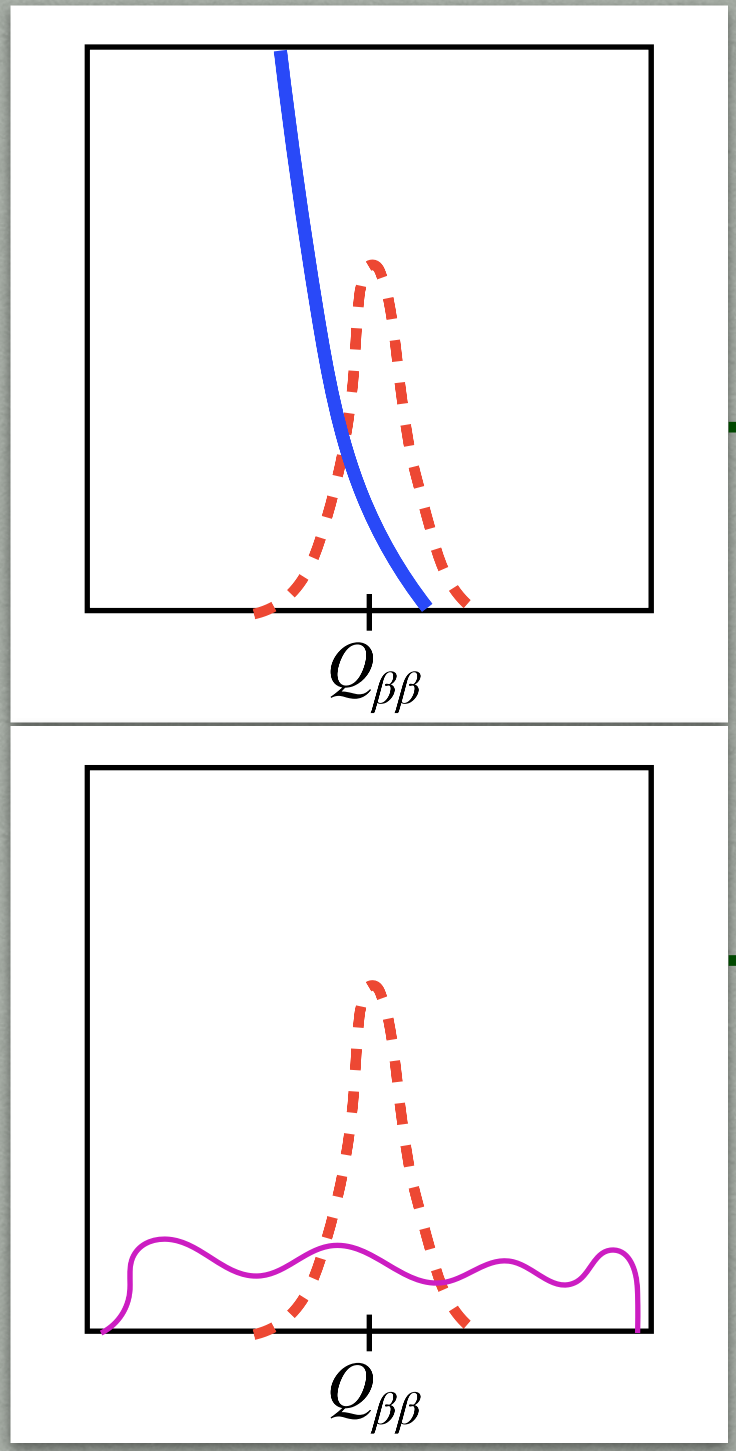


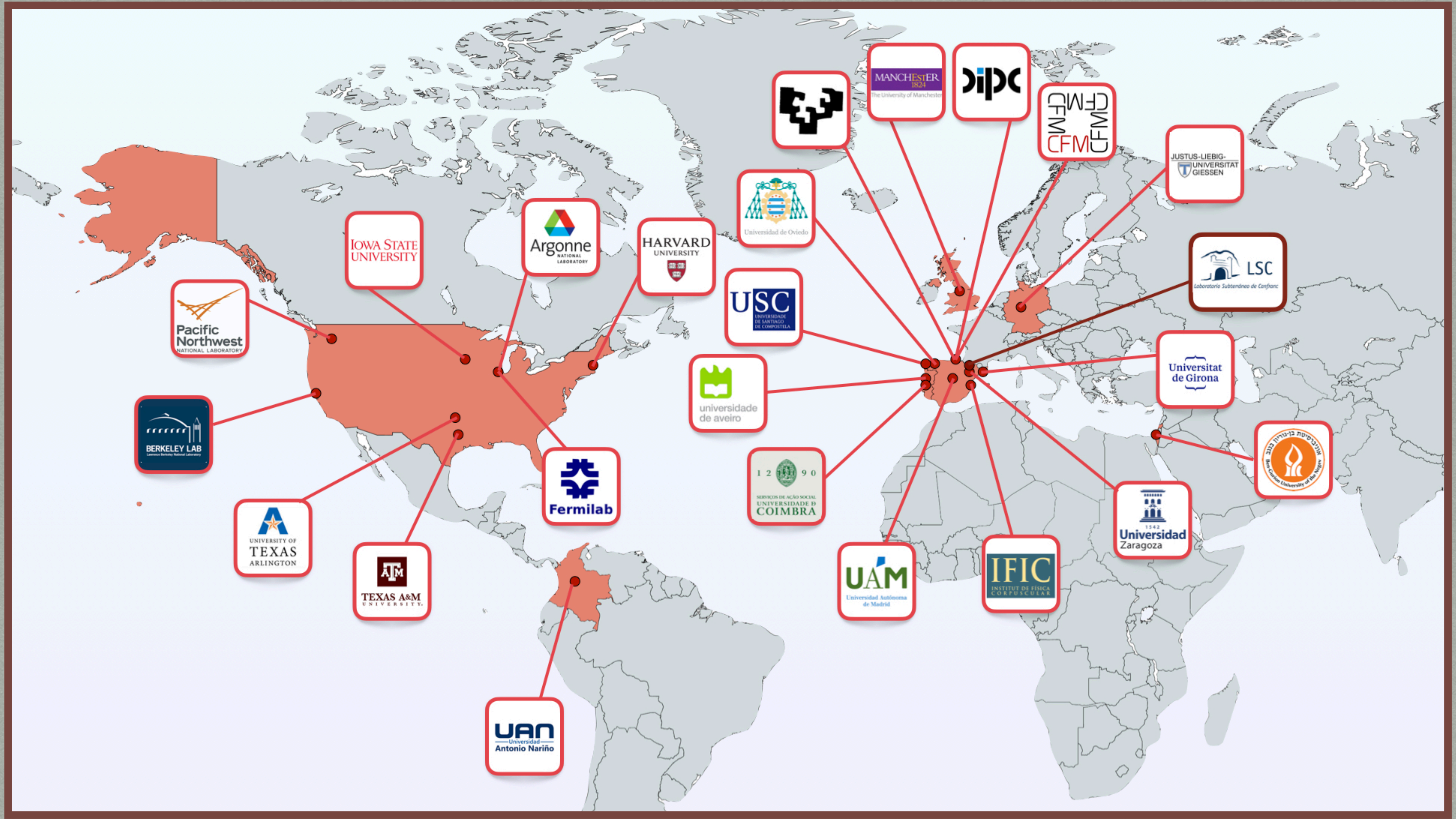
Mitigation

Energy resolution @$Q_{\beta\beta}$

Signal vs bkg discrimination strategies

The NEXT Experiment (Neutrino Experiment with a Xenon TPC)

- Time Projection Chamber with **Xenon gas** (source & detector) at **high pressure**
- **Electroluminescence** (EL) region to amplify the ionization signal
- Main goal: neutrinoless double beta decay (**ββ0ν**) processes in **^{136}Xe**



Social media:
the_next_experiment
The NEXT Experiment
@NEXT100Exp

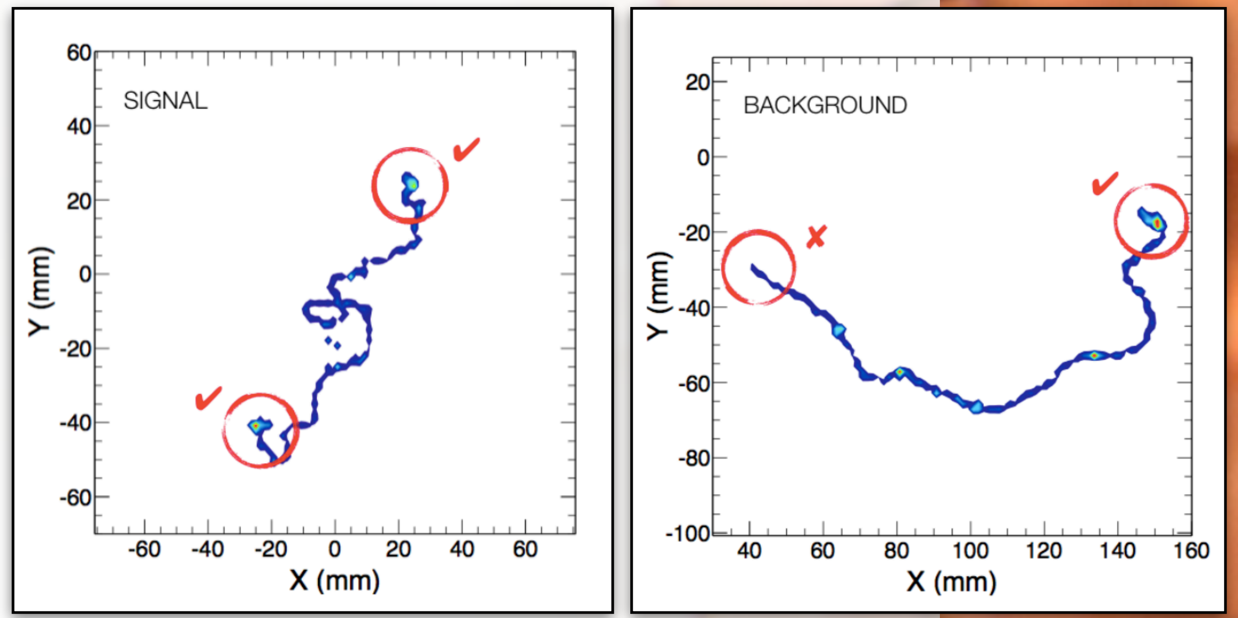
Funded by: erc, FCT Fundação para a Ciência e a Tecnologia, Gobierno de España – Ministerio de Ciencia e Innovación, Generalitat Valenciana, Agencia Estatal de Investigación, U.S. Department of Energy

Strengths of the NEXT technology

1. **Xenon**: Cheap and easy to enrich, possibility of **Barium Tagging**

2. **Gaseous TPC** detector: Fully active and homogeneous detector

   3D Tracking reconstruction → Signal vs background topological discrimination



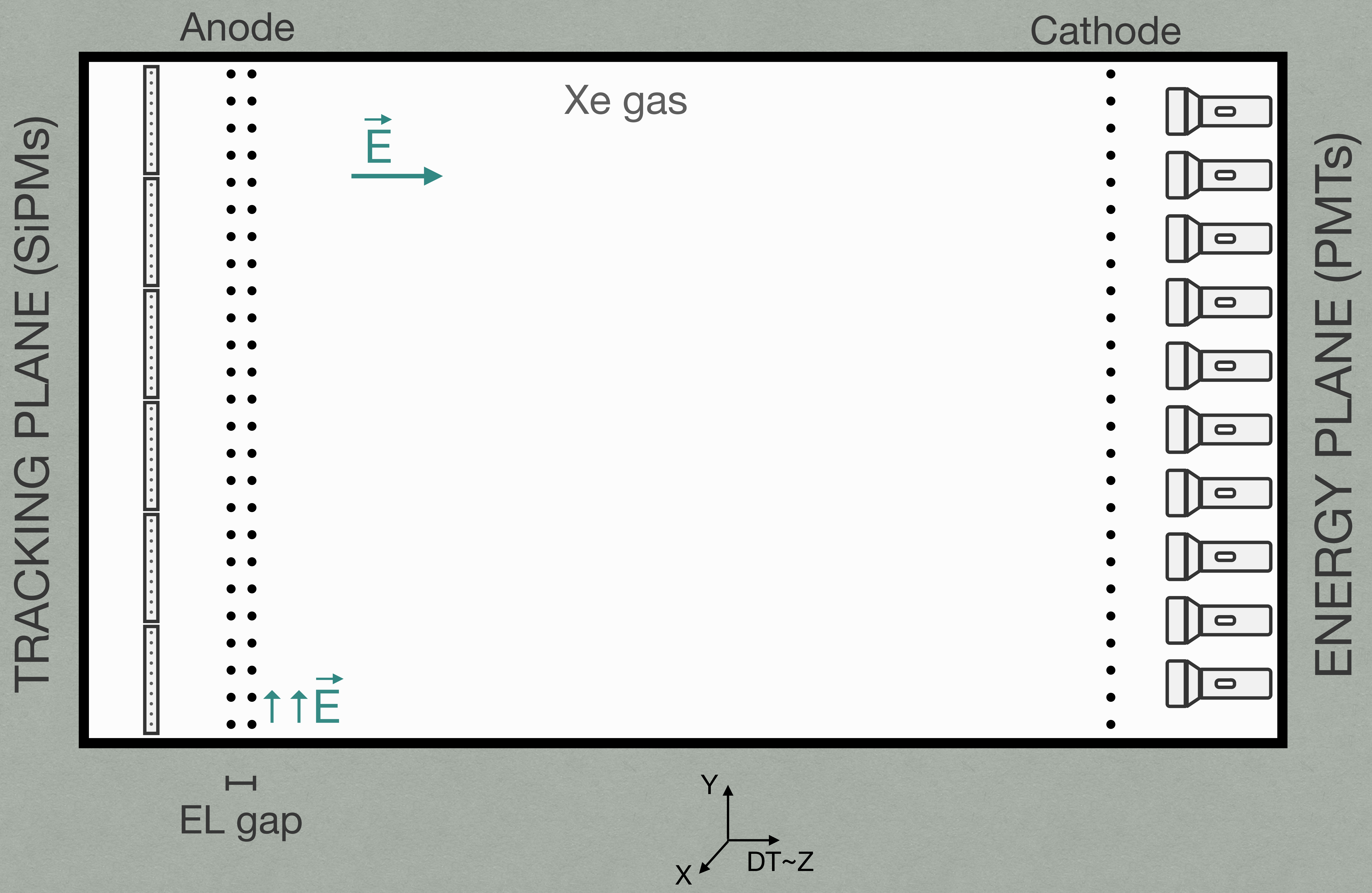
3. **High-pressure** → **compact** detectors, events **fully contained** in fiducial volume

4. **Electroluminescence** (+ low Fano factor due to GXe) → **Excellent energy resolution at $Q_{\beta\beta}$**

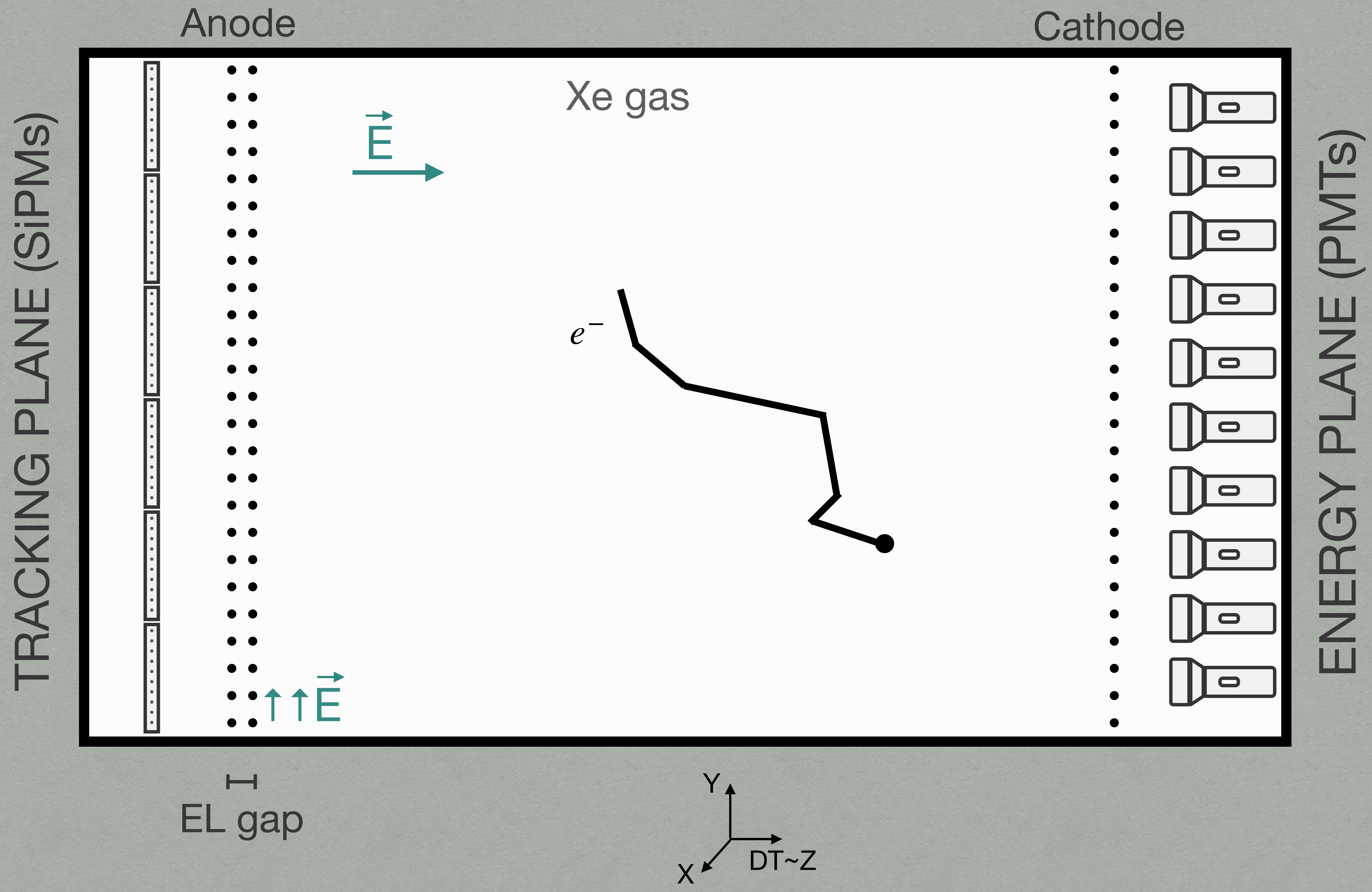
5. **Scalability** lo larger masses

6. Good **shielding** against external backgrounds

The NEXT TPC Concept



The NEXT TPC Concept



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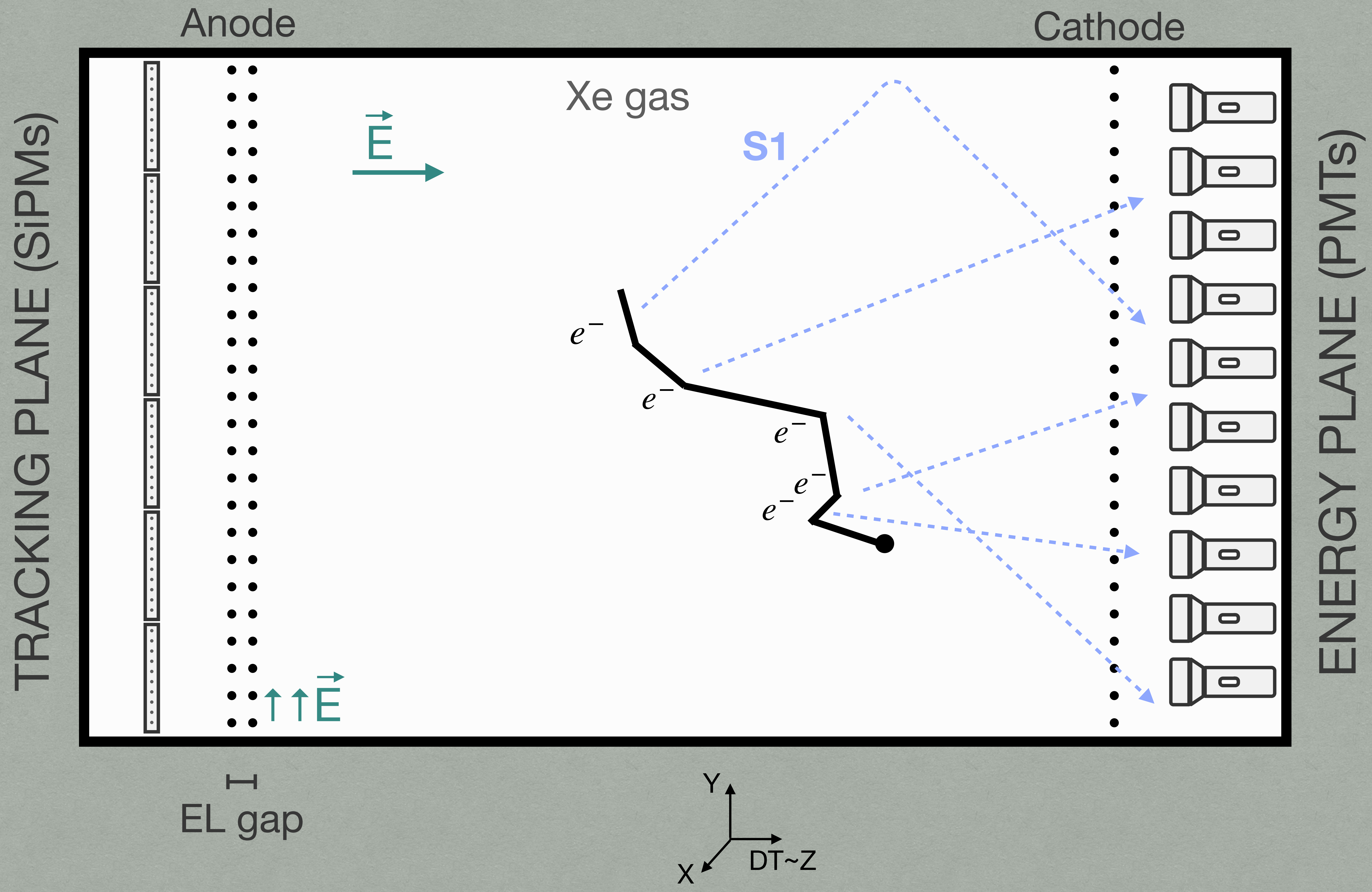
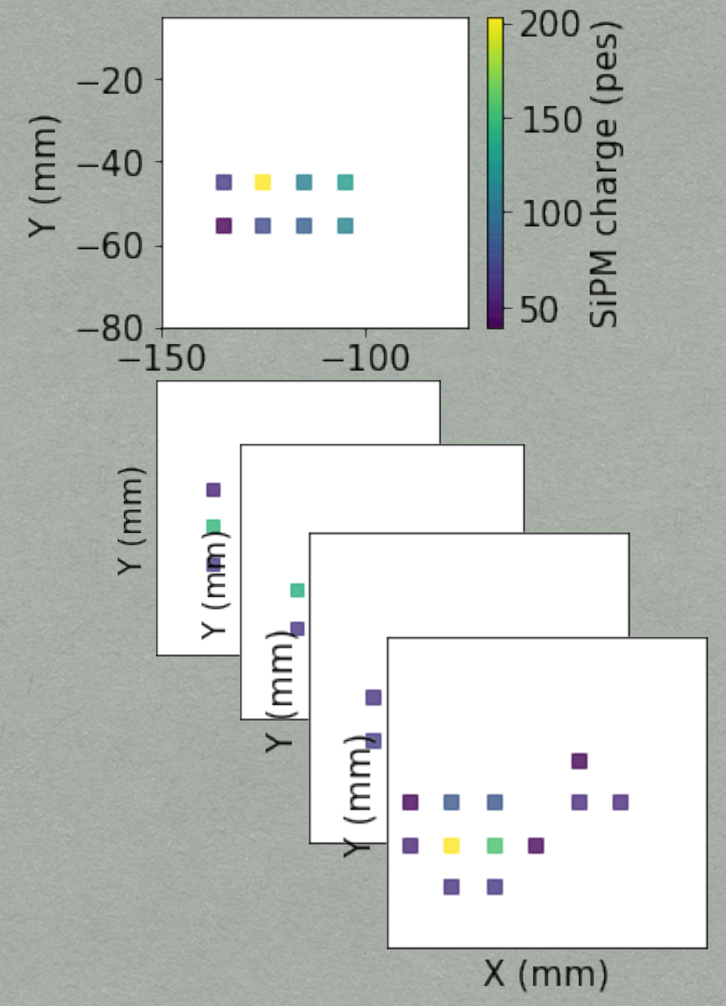
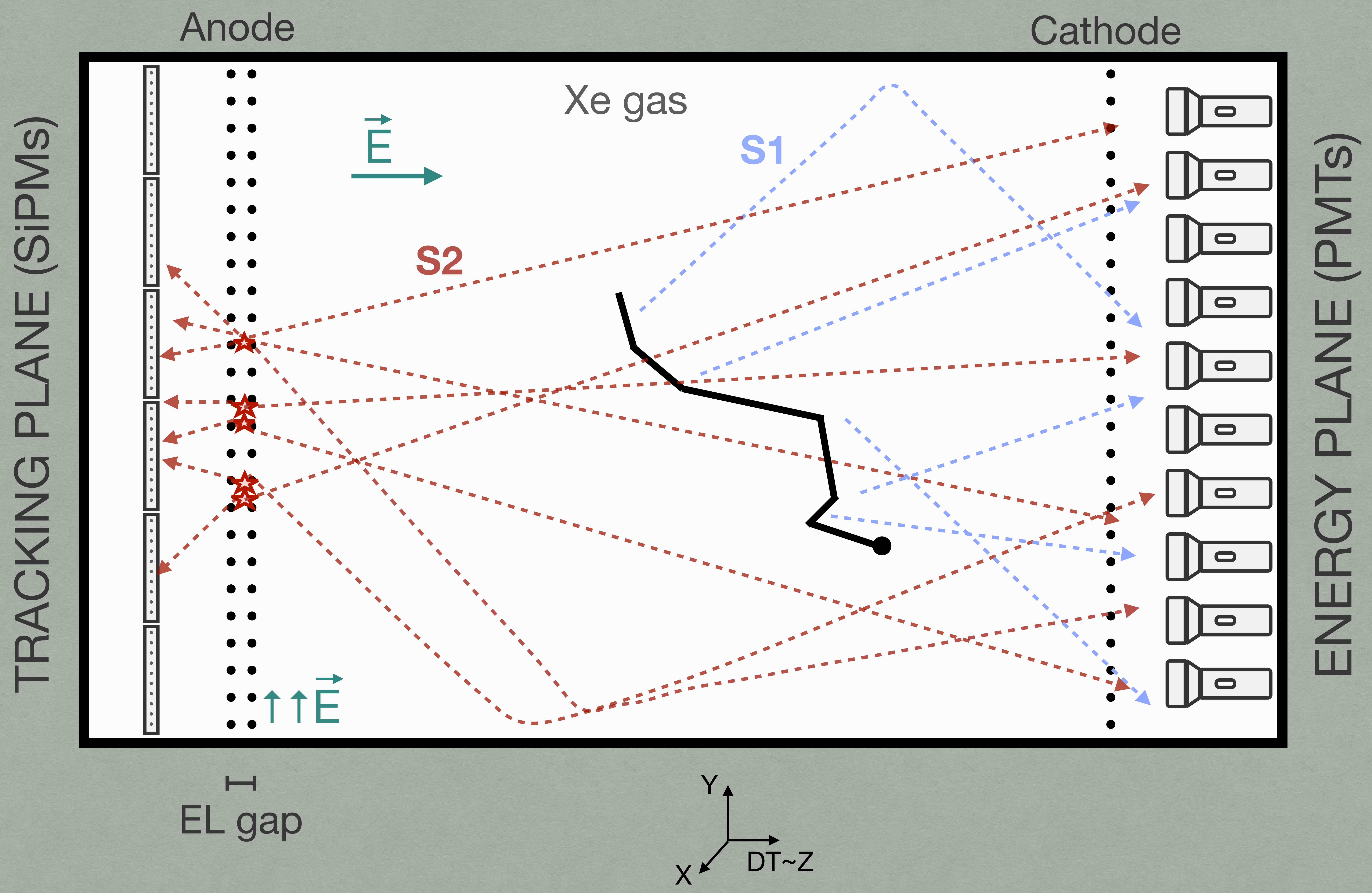


The NEXT TPC Concept





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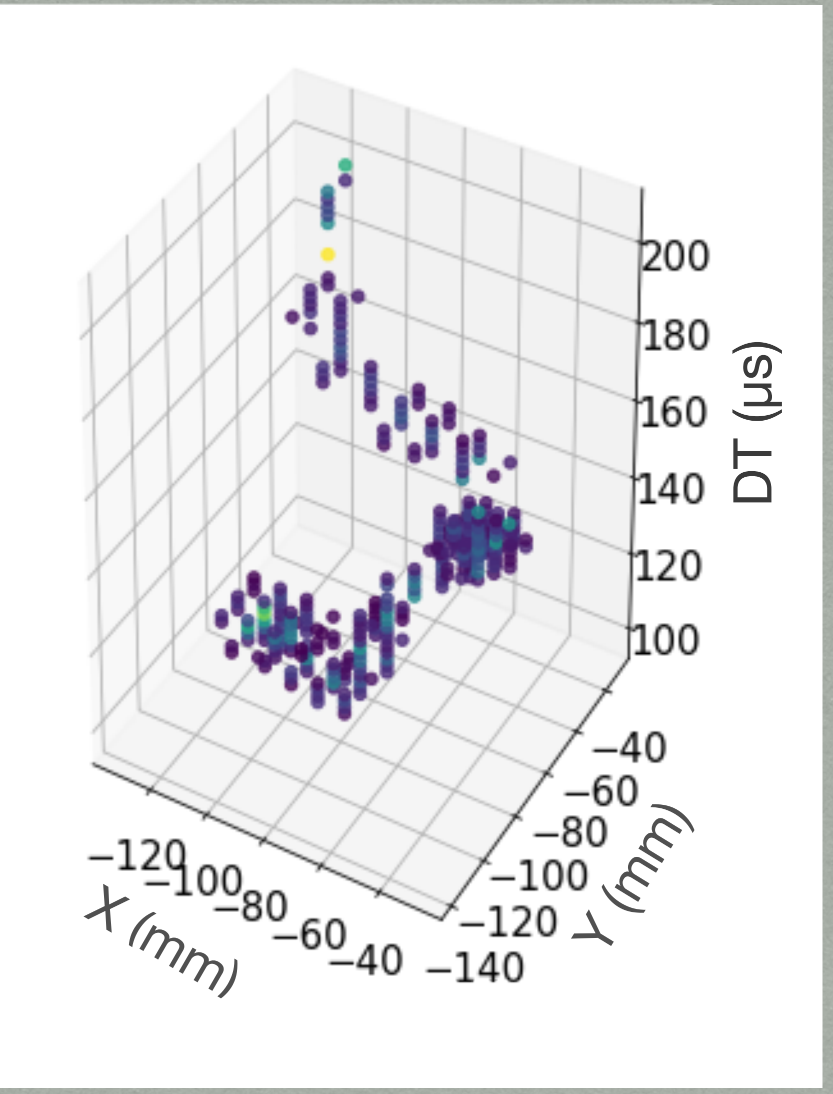

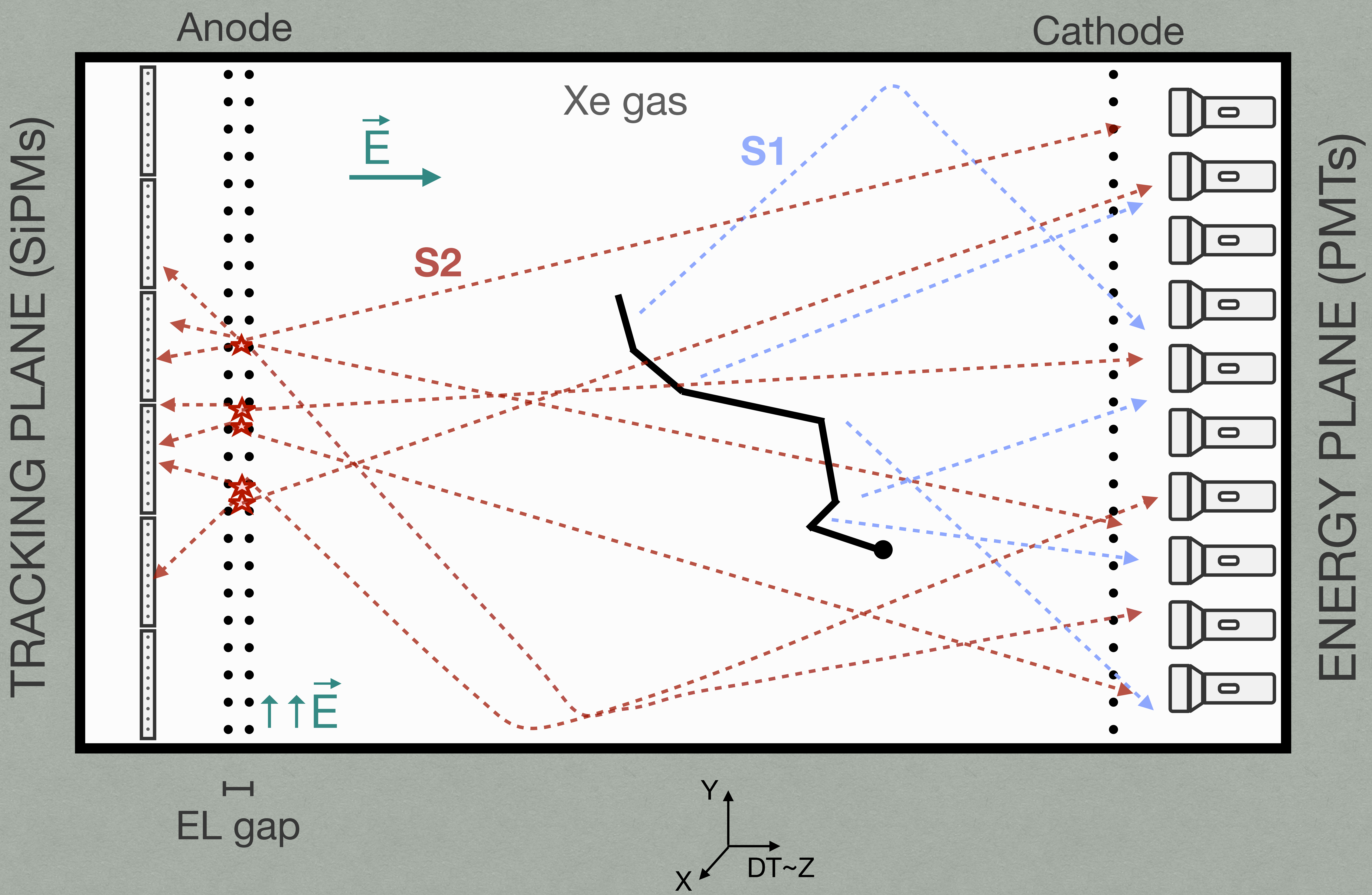

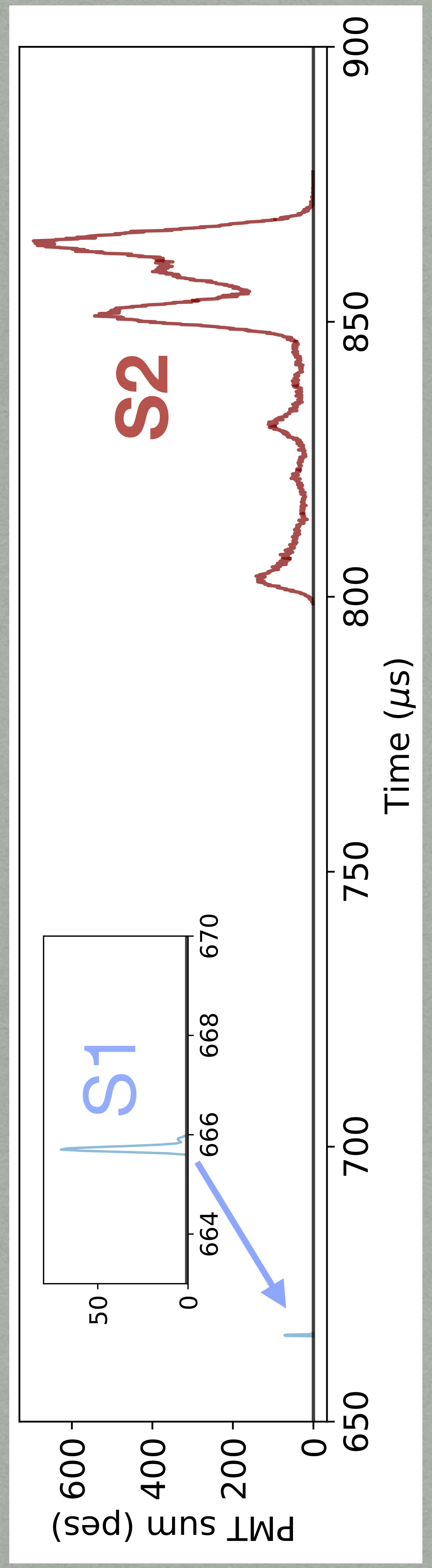

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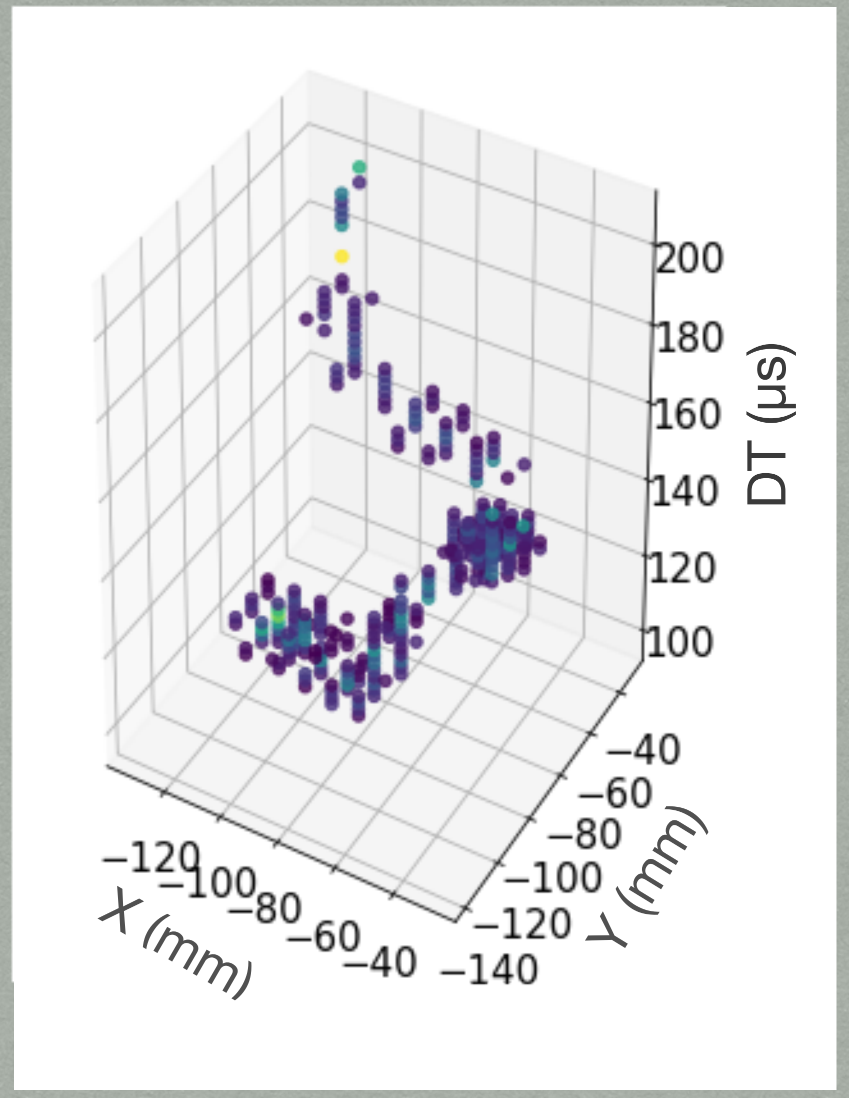
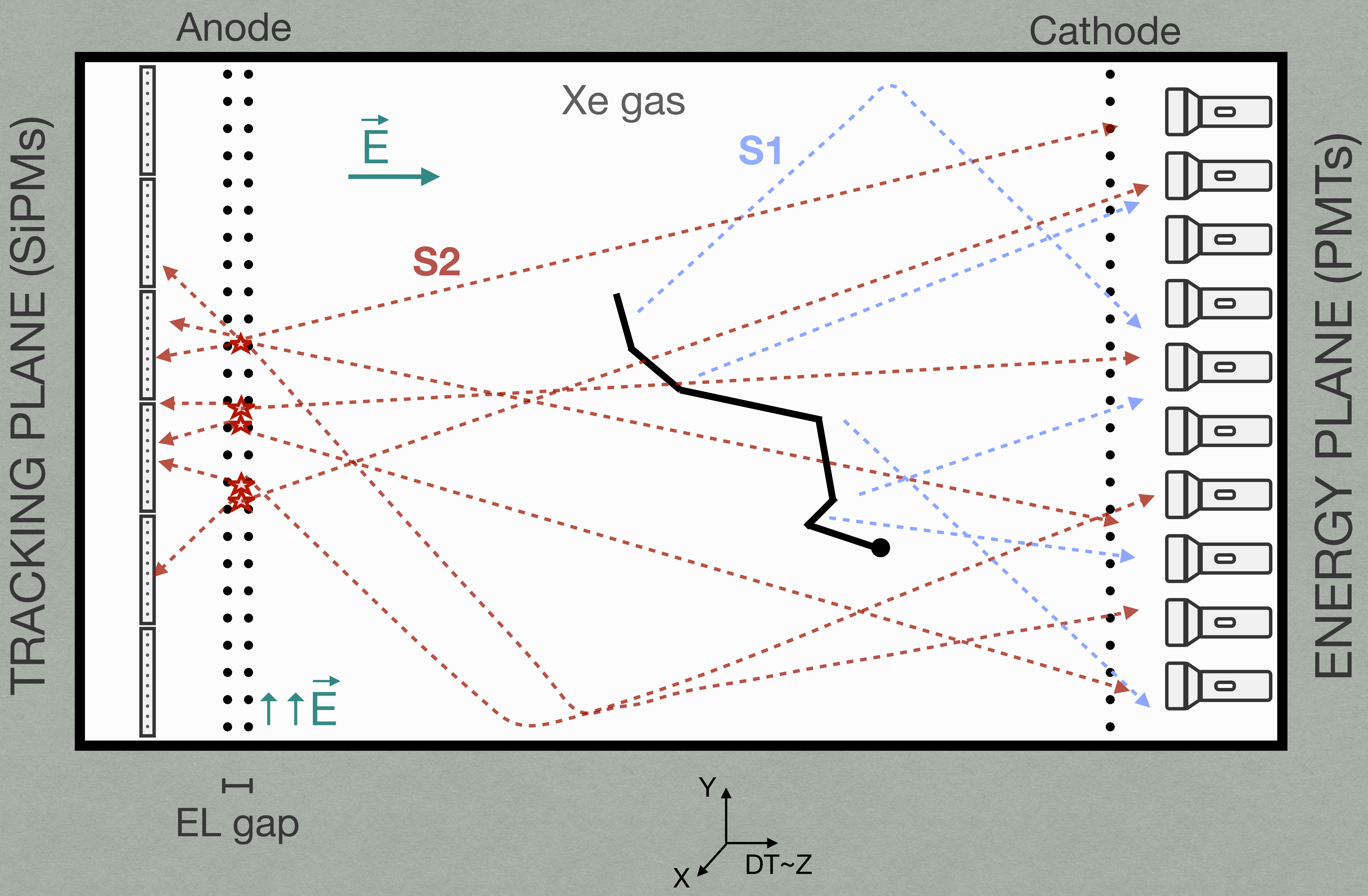
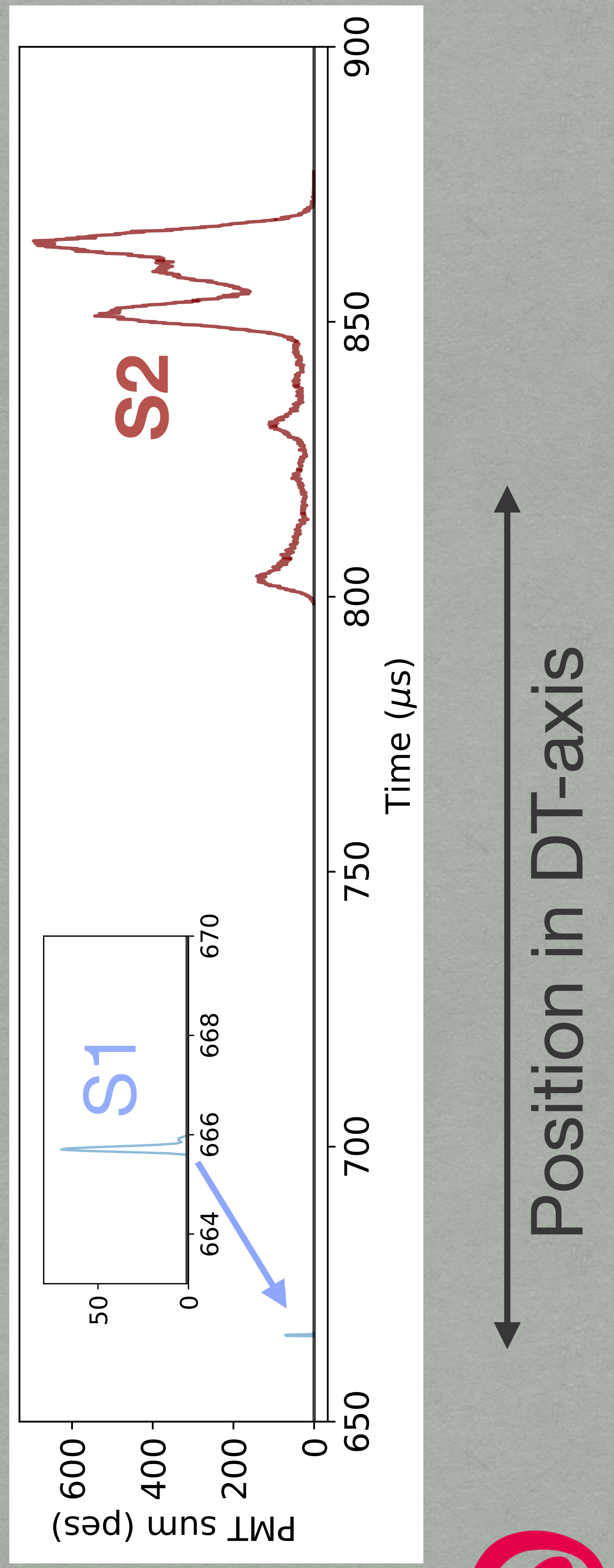
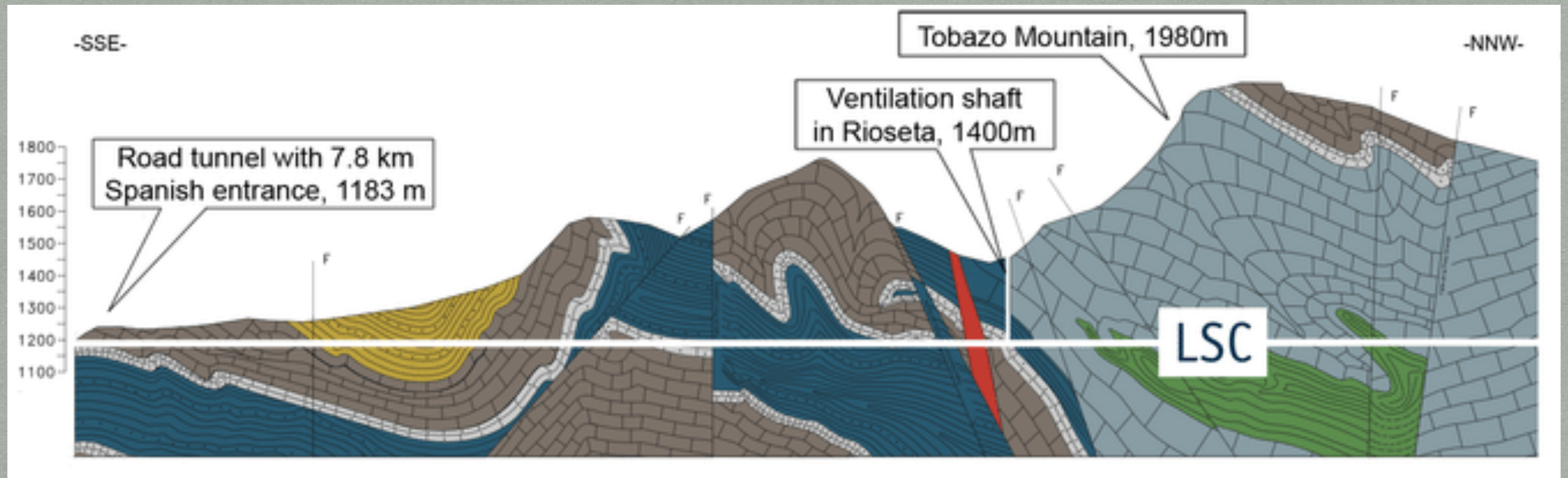
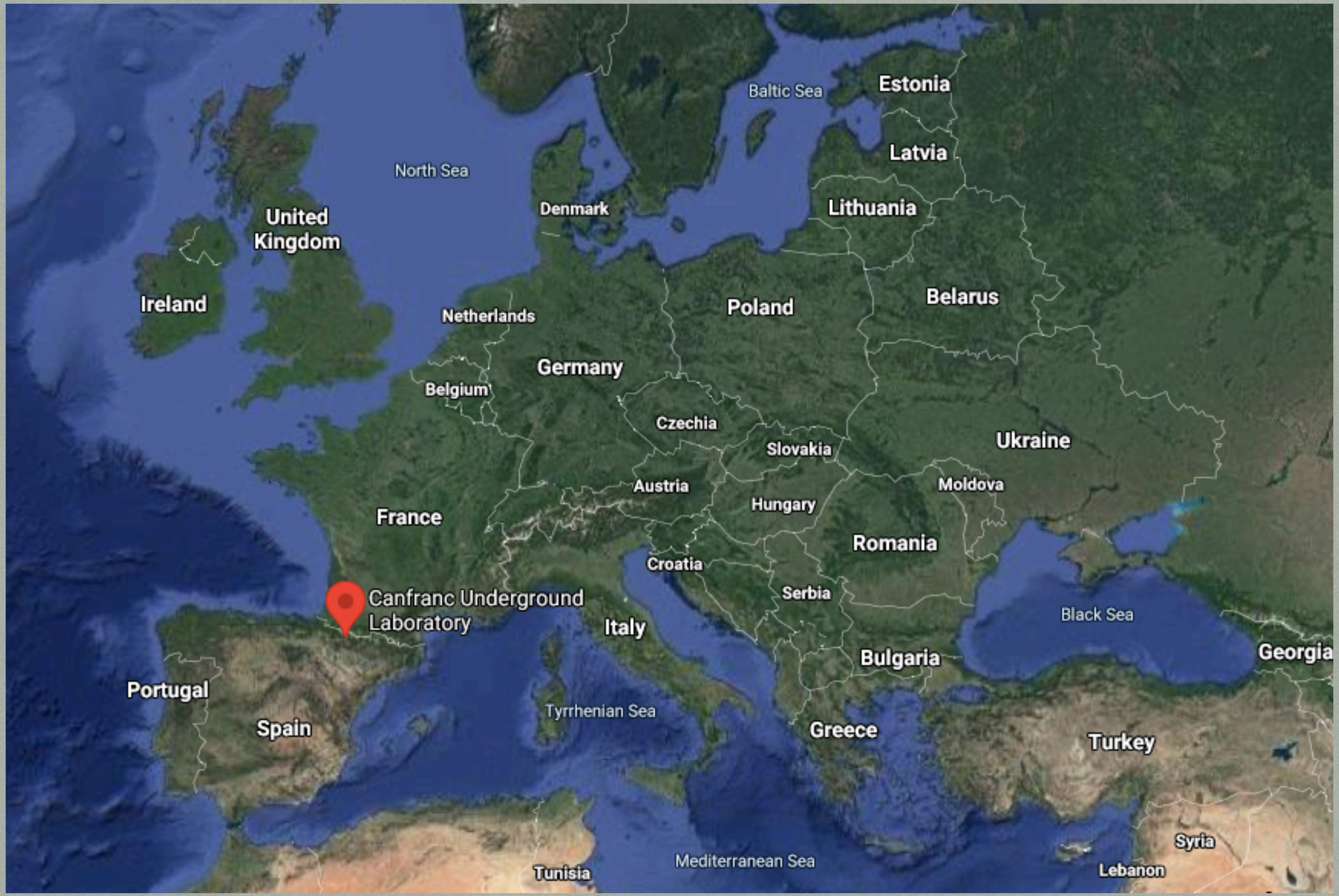






Laboratorio Subterráneo de Canfranc (LSC)





Laboratorio Subterráneo de Canfranc (LSC)

LSC
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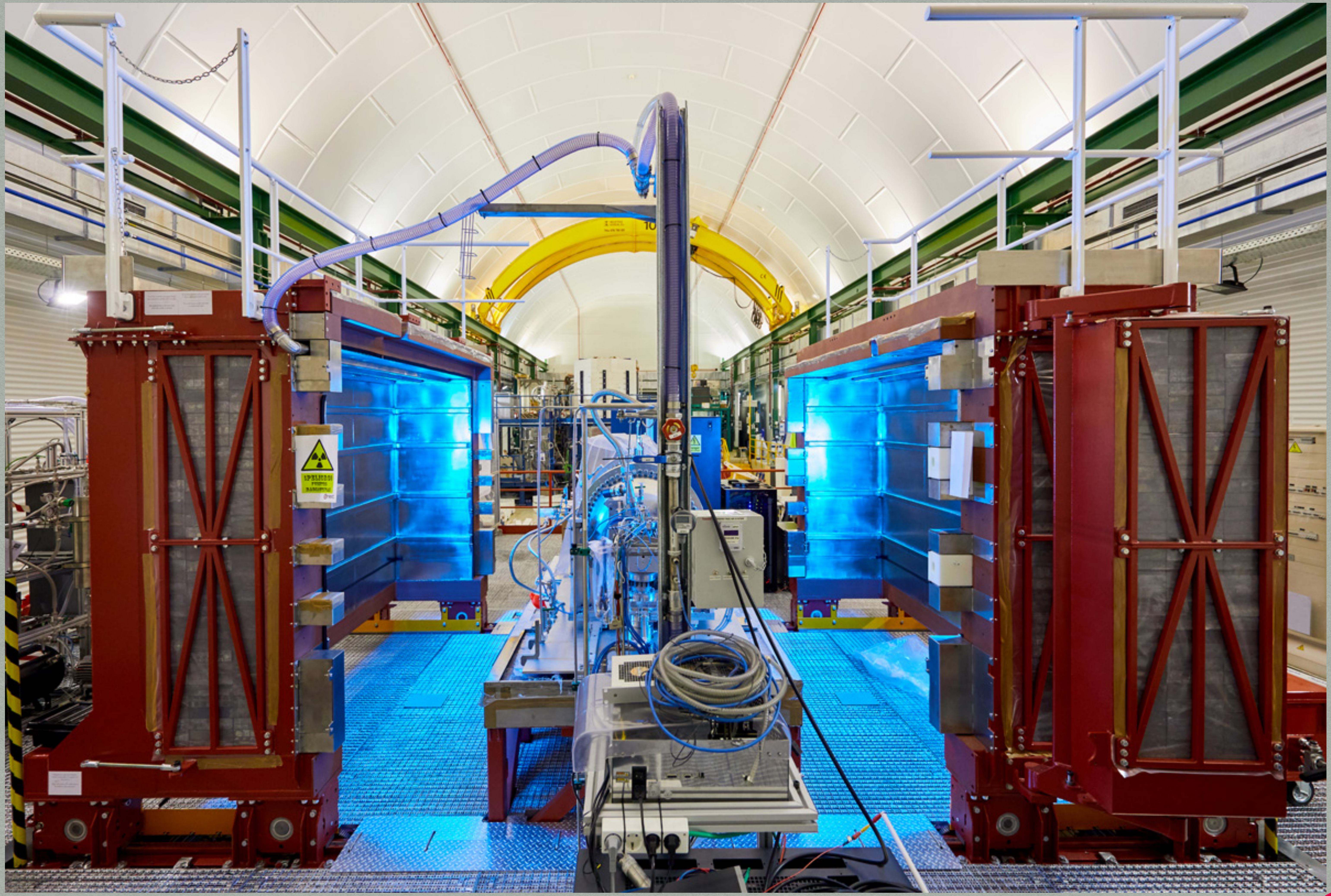
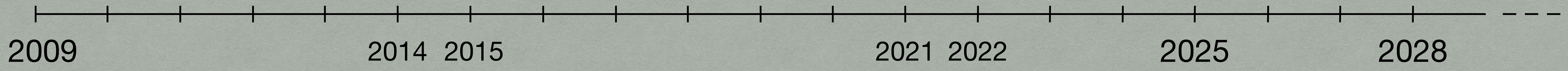


The NEXT Program

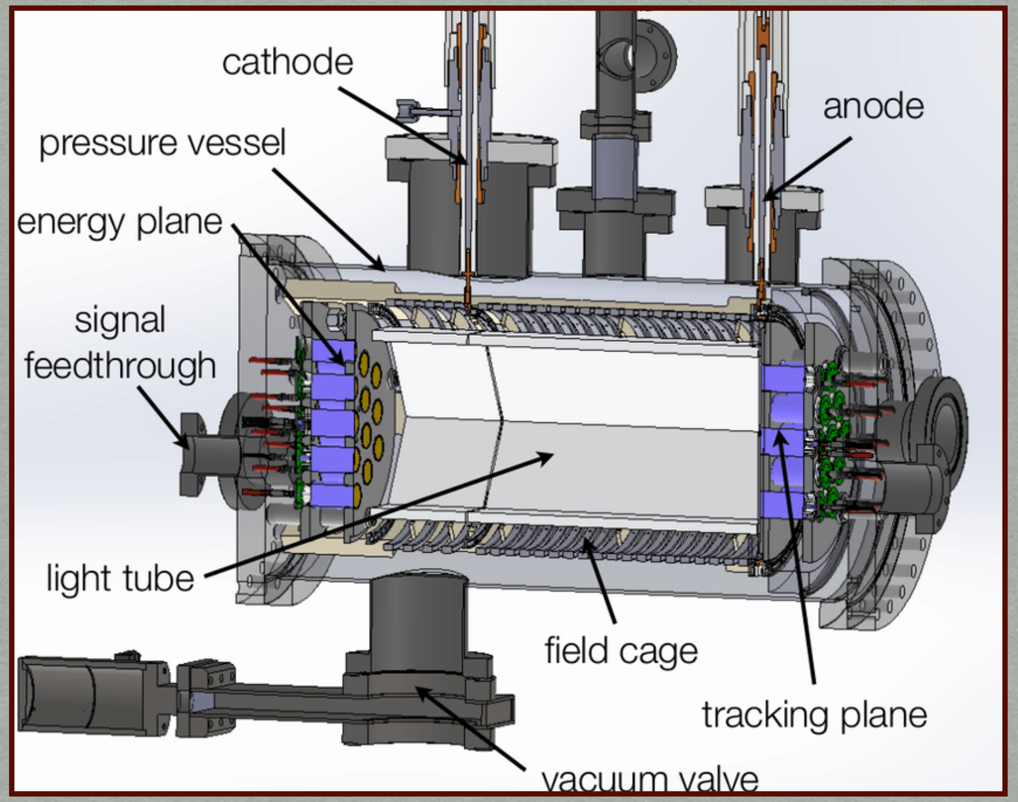


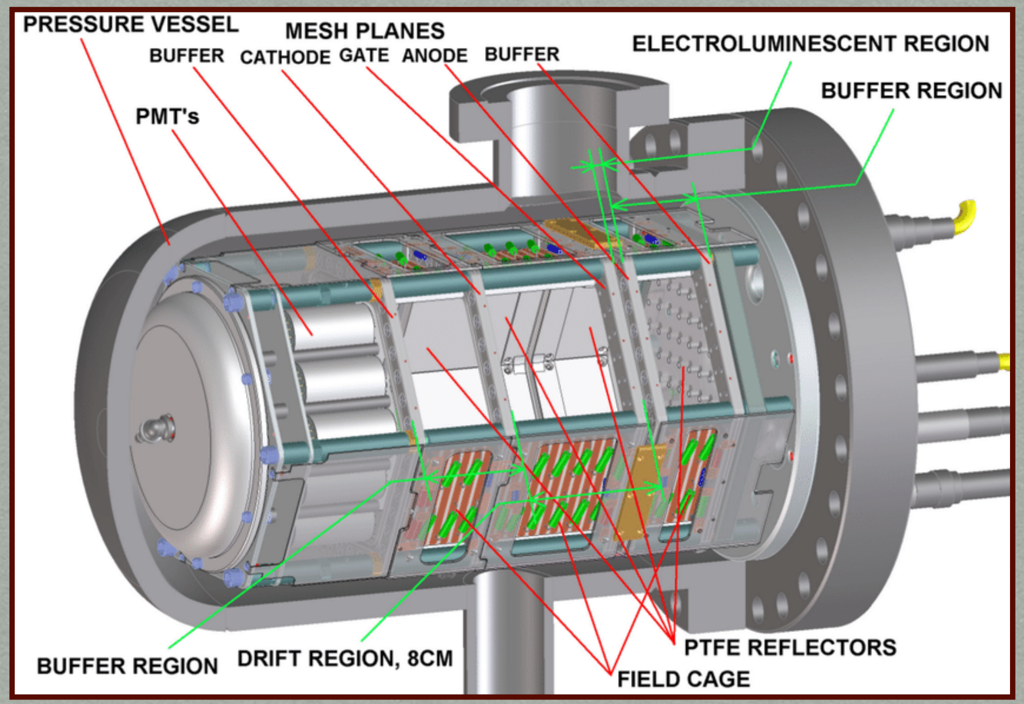
The NEXT Program

2009 2014 2015 2021 2022 2025 2028

Prototypes | ~1kg

➡ Proof of concept





The NEXT Program

2009 — 2014 2015 — 2021 2022 — 2025 — 2028 - - -

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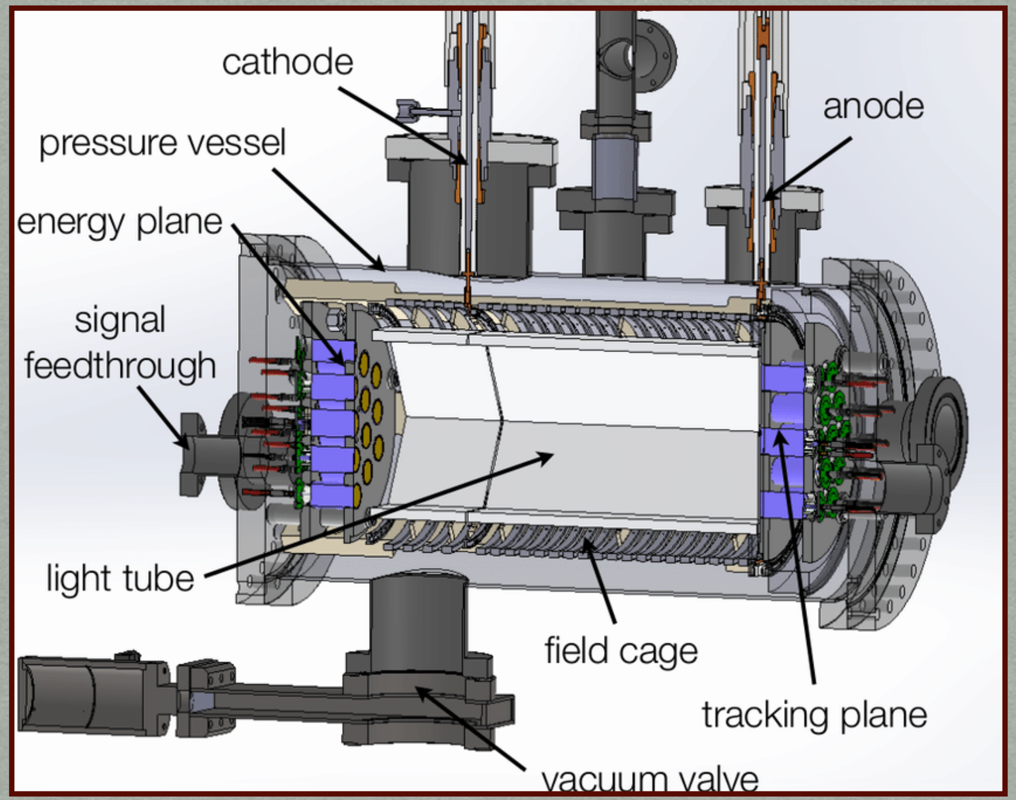
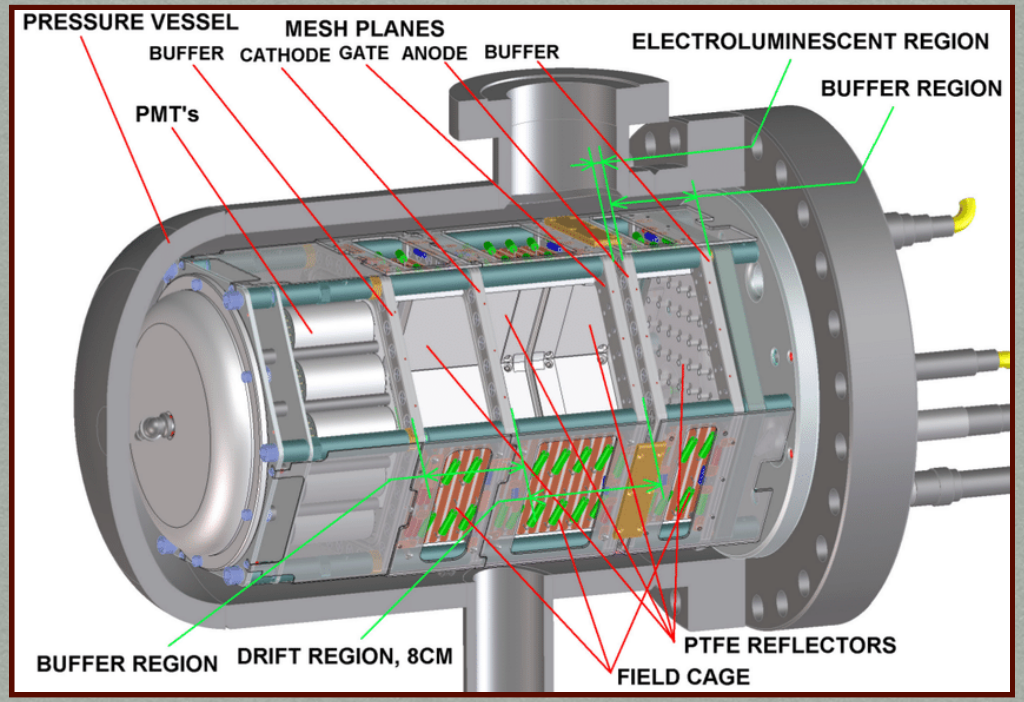
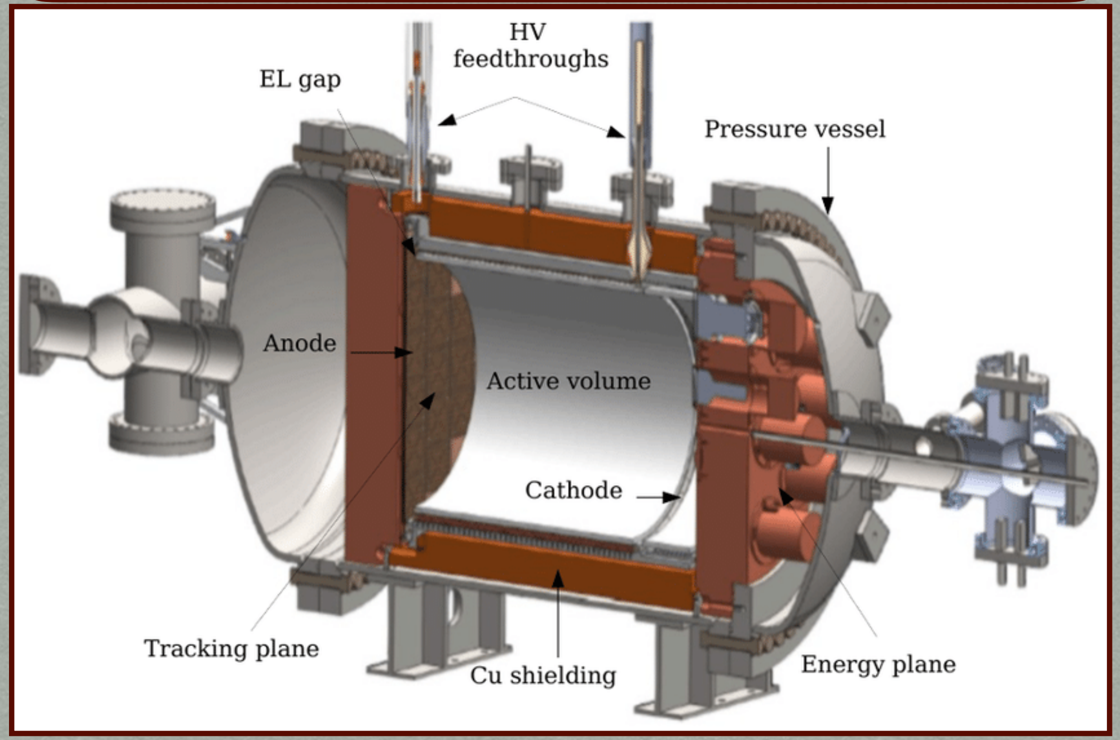




NEXT-White | ~5kg

- Background model assessment
- Two neutrino double beta decay measurement
- Proof of concept for neutrino less double beta decay searches



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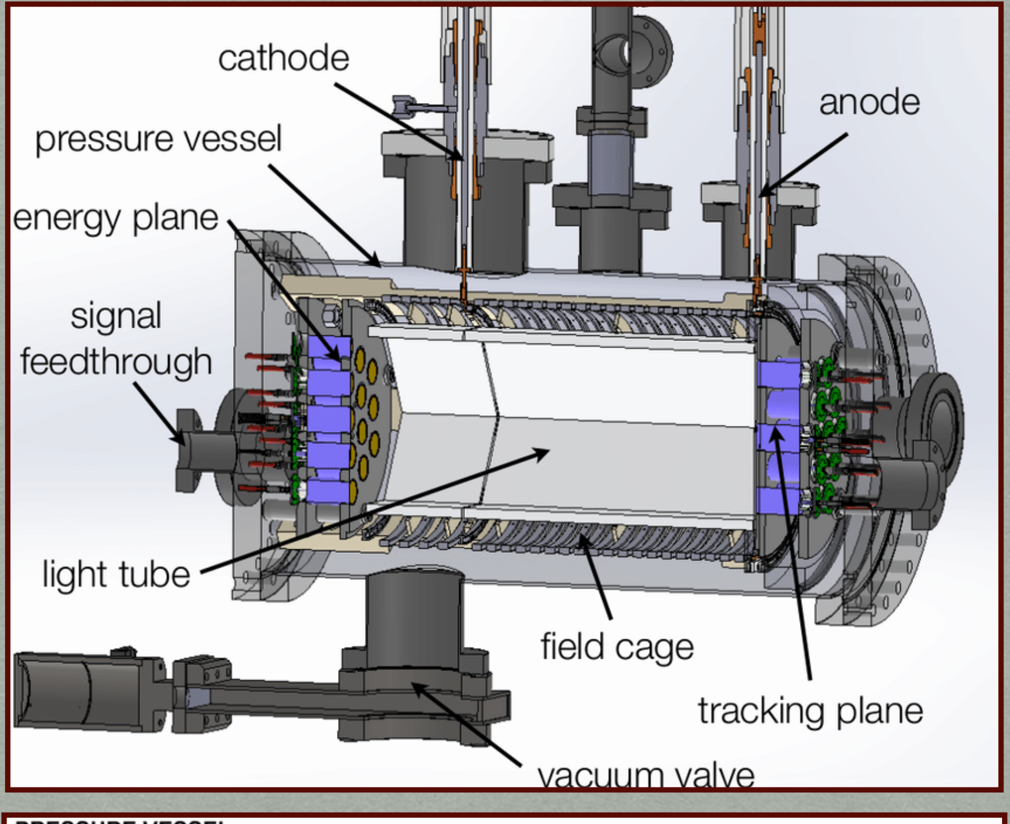
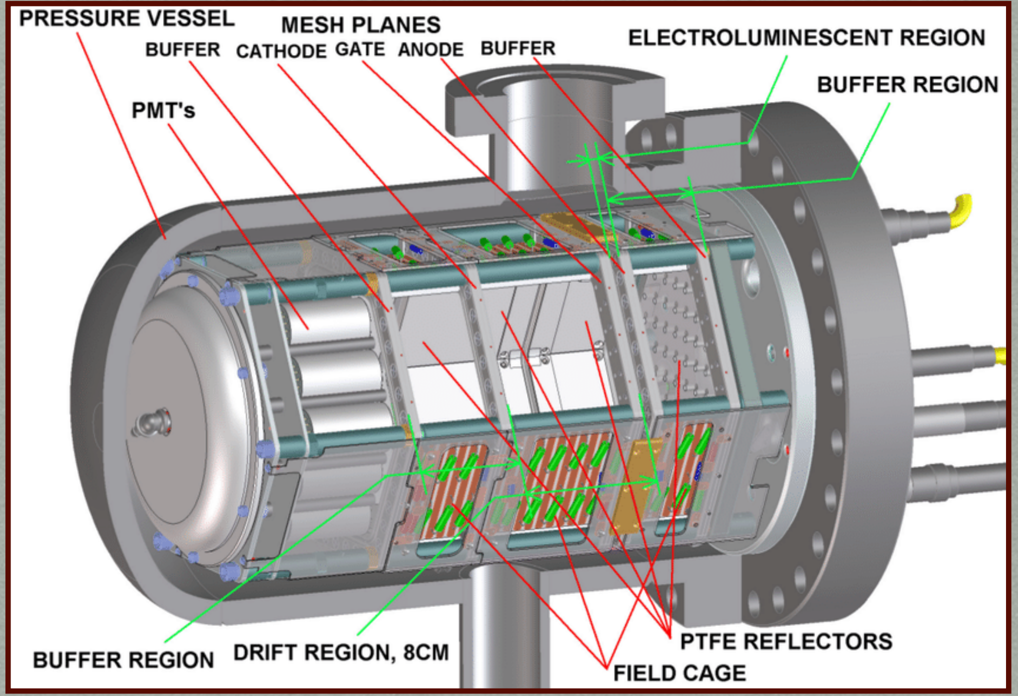
The NEXT Program

2009 — 2014 — 2015 — 2021 — 2022 — 2025 — 2028

Prototypes | **~1kg**

- Proof of concept





NEXT-White | **~5kg**

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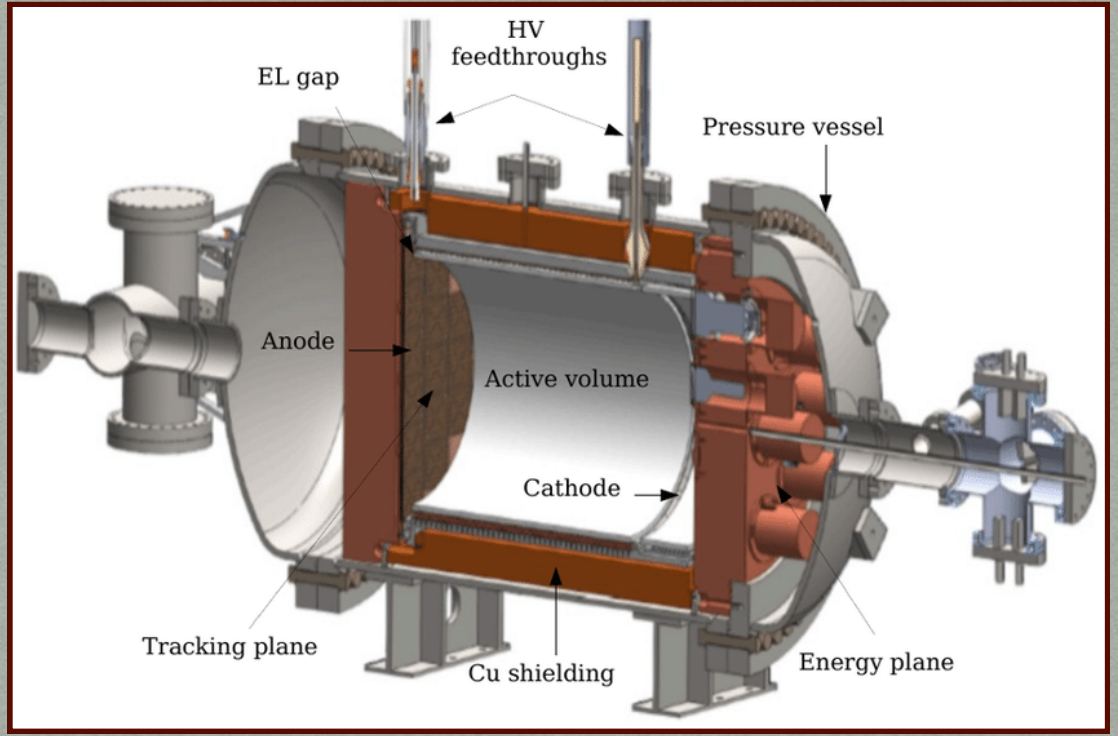

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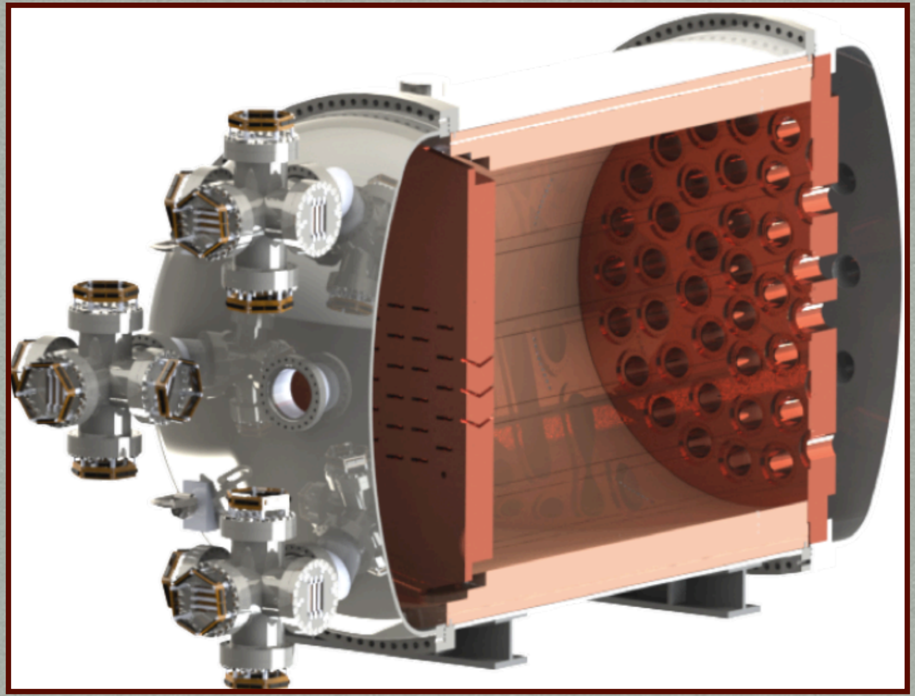
NEXT-100 | **~100kg**

- Neutrinoless double beta decay searches



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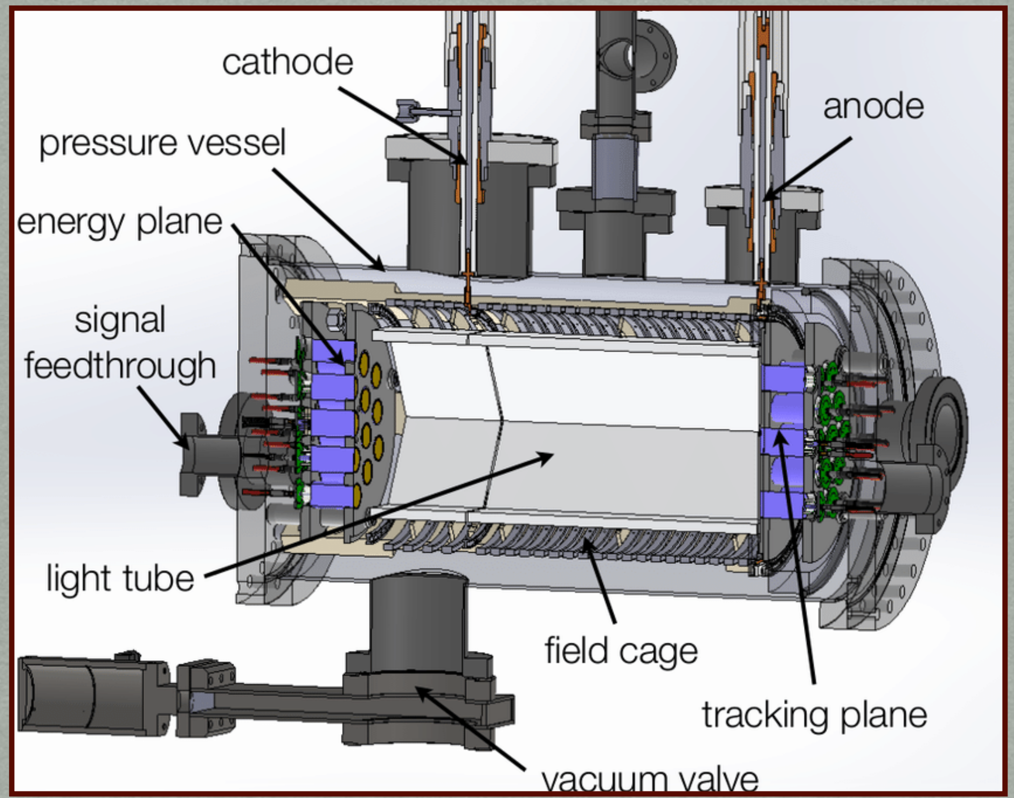
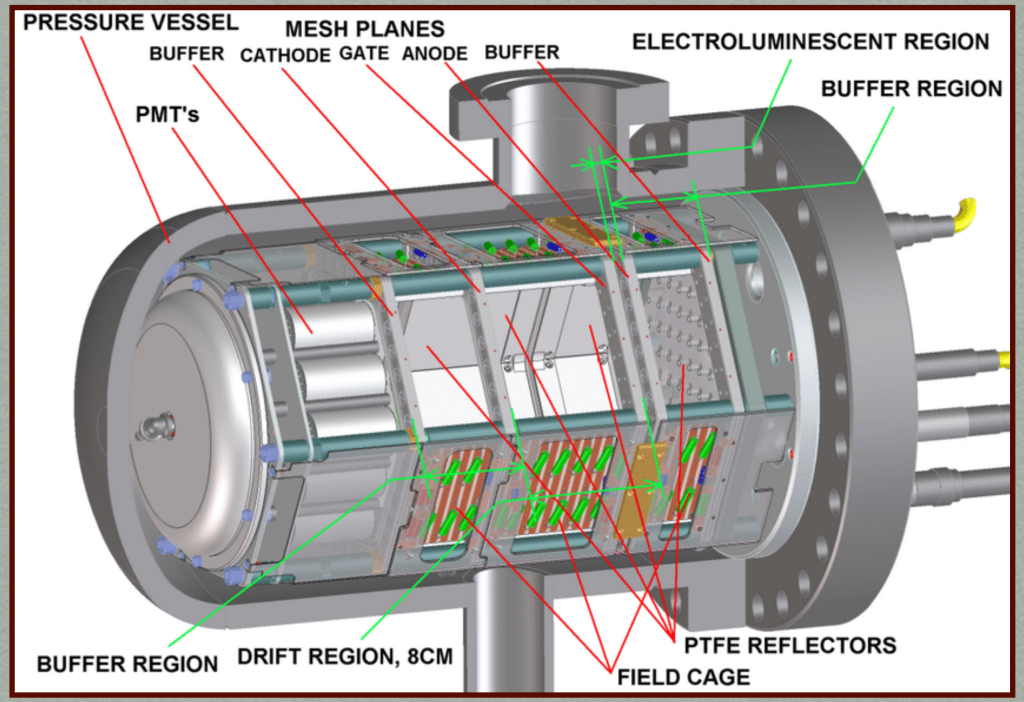
The NEXT Program

2009 2014 2015 2021 2022 2025 2028

Prototypes ~1kg

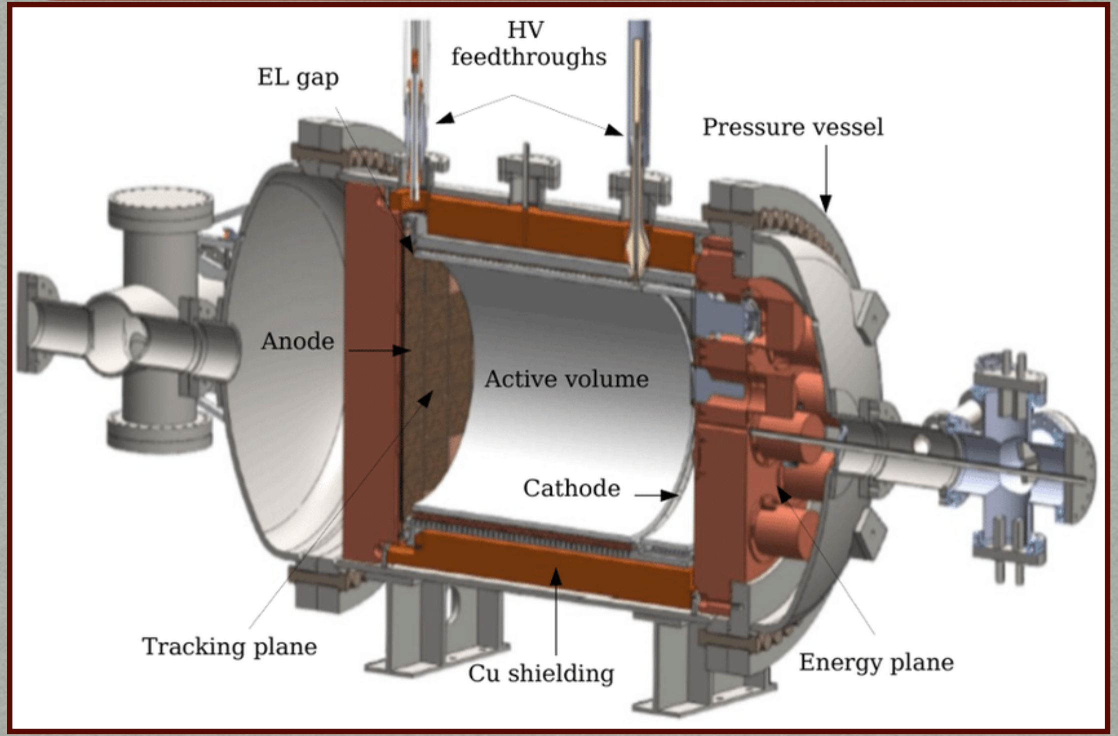
➡ Proof of concept





NEXT-White ~5kg

- ➡ Background model assessment
- ➡ Two neutrino double beta decay measurement
- ➡ Proof of concept for neutrino less double beta decay searches



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NEXT-100 ~100kg

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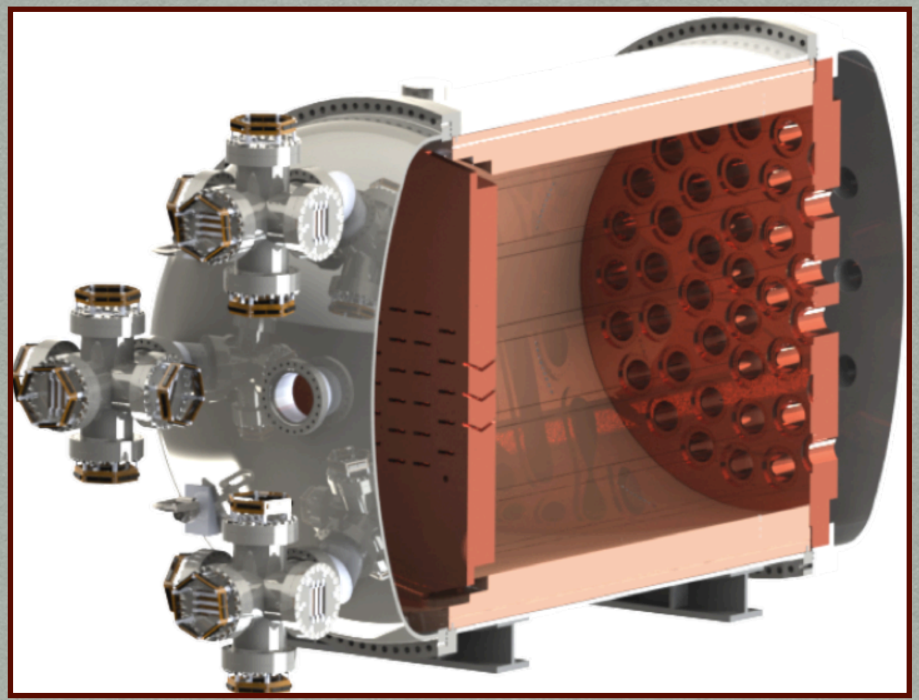

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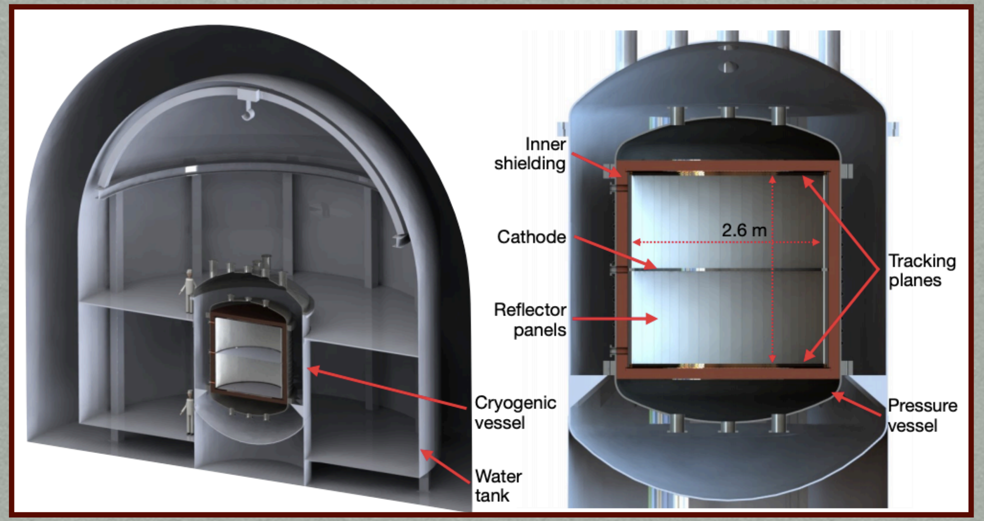
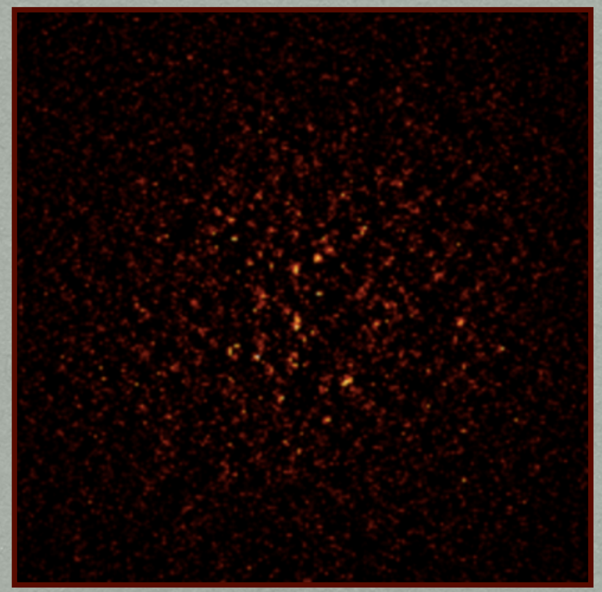
Ton-scale + Ba tagging ~1t

➡ 0νββ in the inverted ordering ν-mass region and beyond



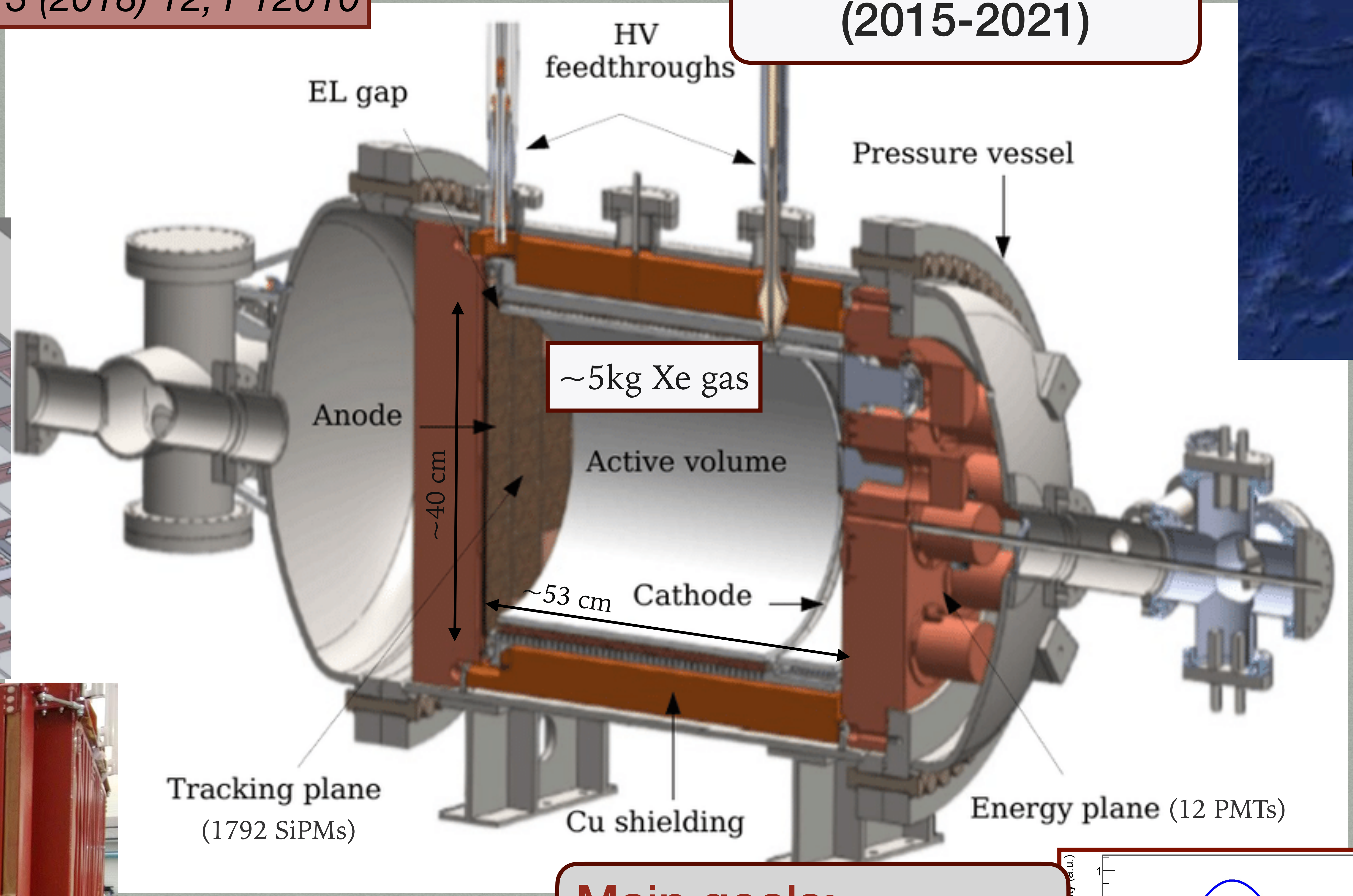


The NEXT-White detector

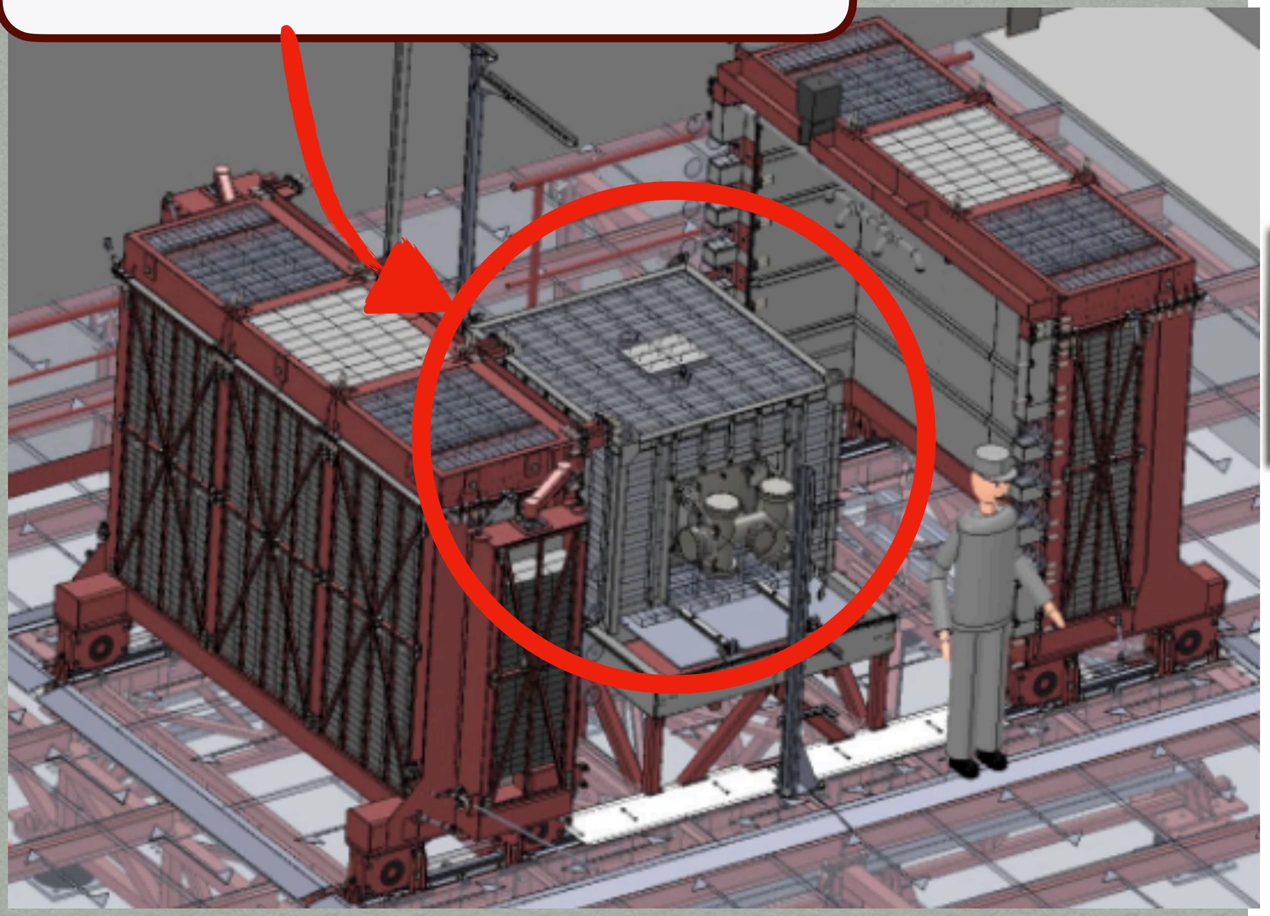
@LSC (Canfranc, Spain)
Under ~800m depth

JINST 13 (2018) 12, P12010

NEXT-White vessel
(2015-2021)



Inner Lead Castle (ILC)
Against OLC bkgs.

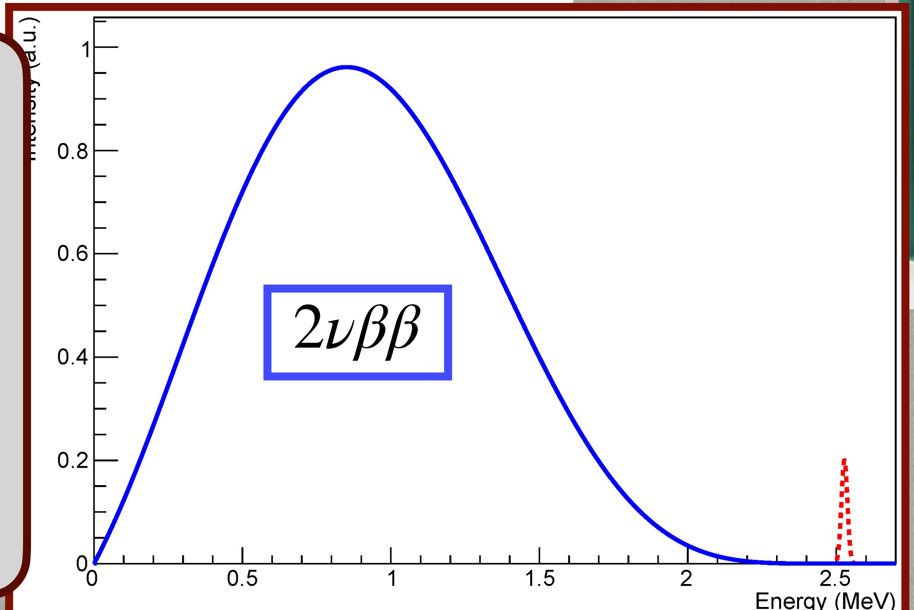


Outer Lead Castle (OLC)
Shielding external bkgs.

Radon Abatement System
Flushing Rn-free air

Main goals:

- 2νββ meas.
- demonstration of technology in “large”-scale detector

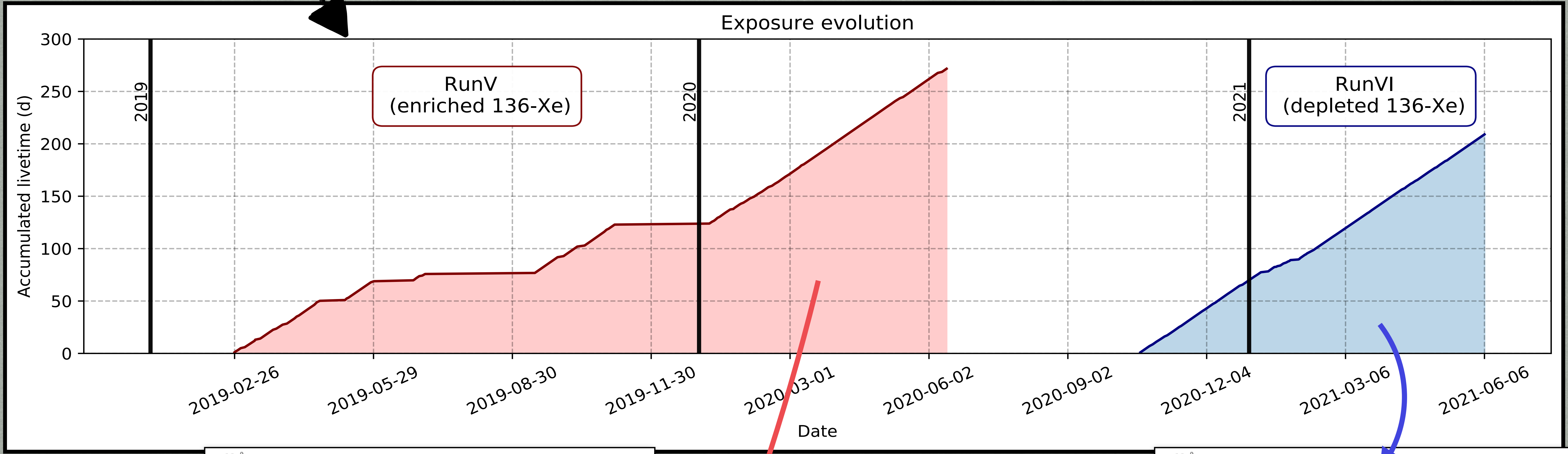


The Next-White Detector Operation

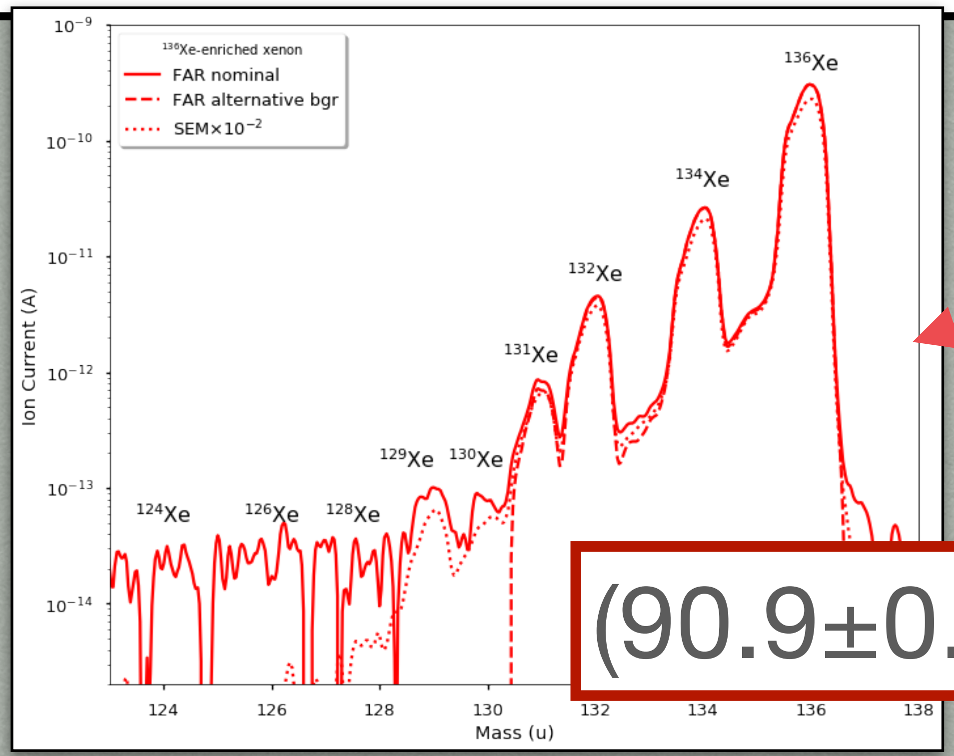
- **2017-2018**: **Calibration** campaign
- **2018-2019**: **Background** meas. + demonstration of technology: ^{136}Xe-depleted Xe
- **2019-2021: ββ2v measurement**: 2 periods: (^{136}Xe-enriched & ^{136}Xe-depleted) gas
  - (Calibration runs previous to each sub period)

Inner lead castle

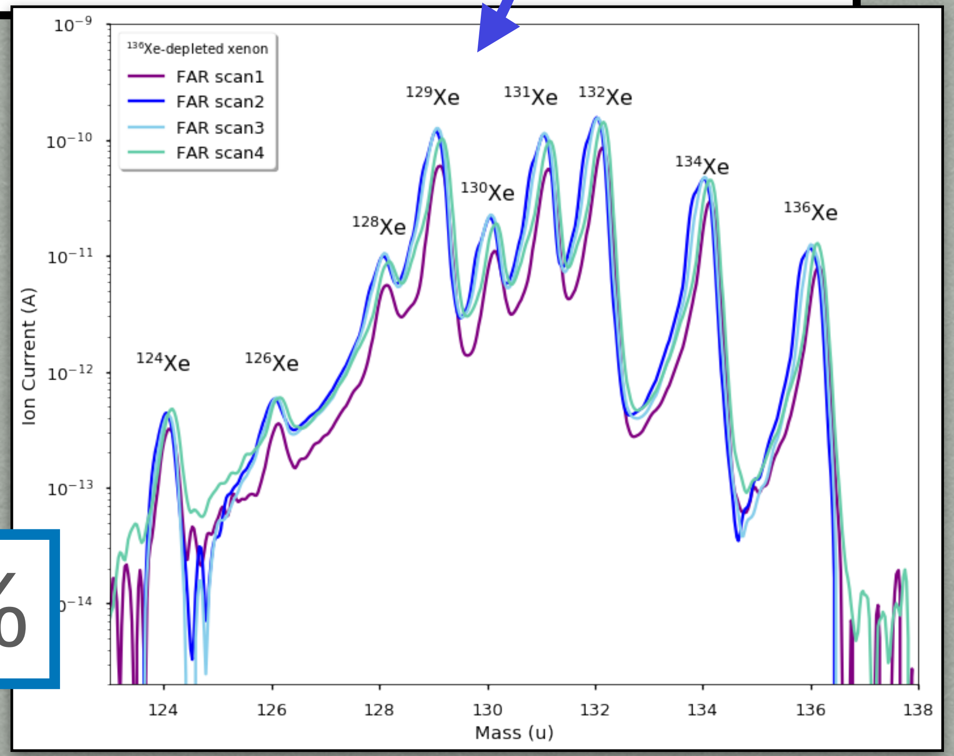
Radon abatement system



	Run-V	**Run-VI**
^{136}Xe	Enriched	Depleted
Start date	25/02/2019	20/10/2020
Run time (d)	271.6	208.9
# Triggers	2,147,899	1,646,501

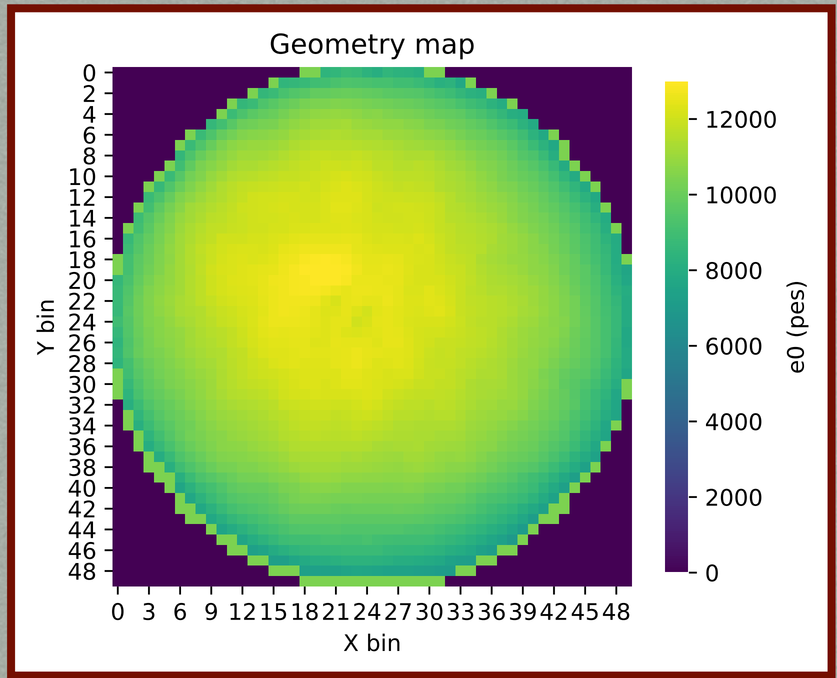


(90.9±0.4)%

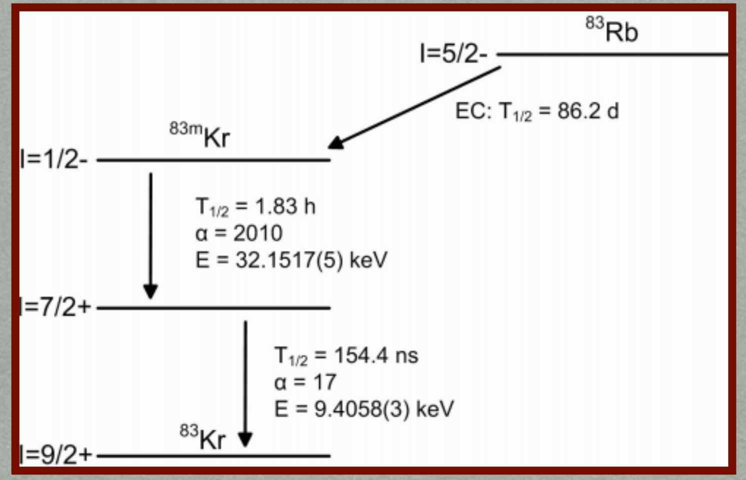


(2.6±0.2)%

NEXT-White Results



- Great **stability** → studied on a daily basis thanks to **dual trigger scheme**:



tr1: homogeneous ^{83m}Kr (41.5 keV)
+
tr2: high energy trigger (>0.4 MeV)

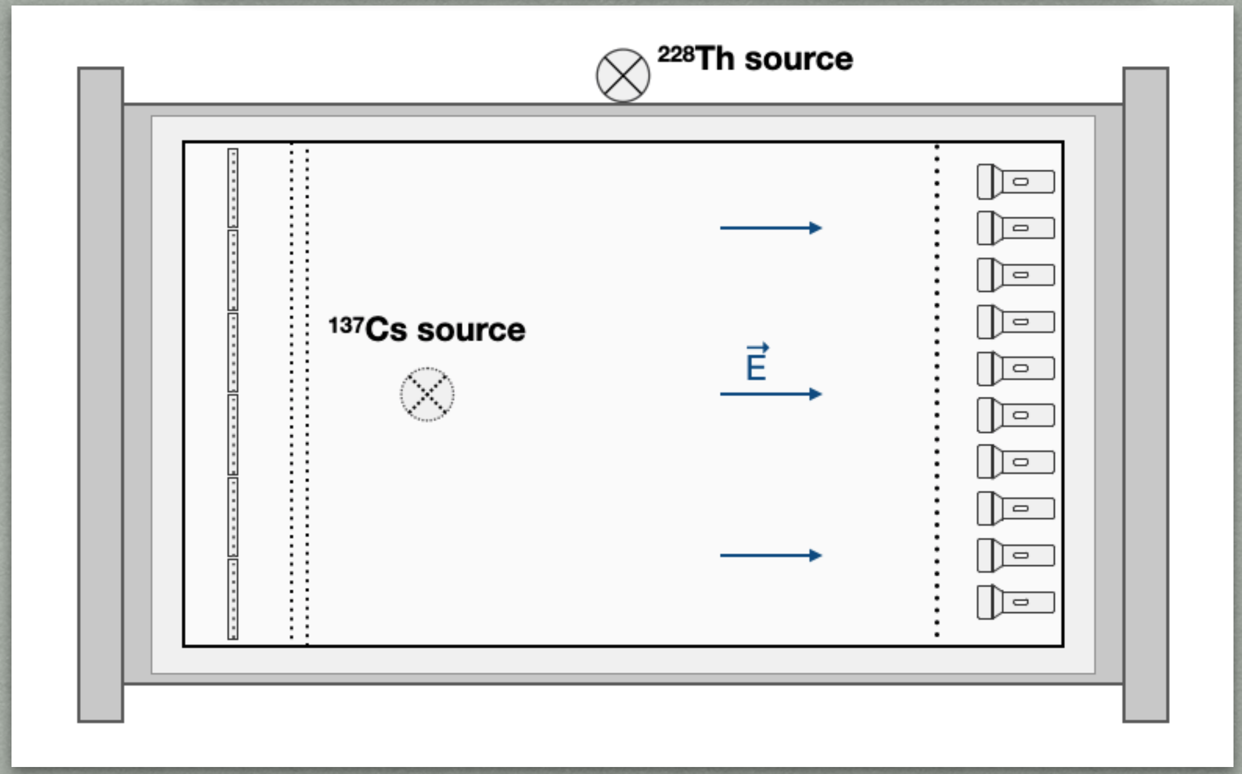
→ Continuous detector monitoring

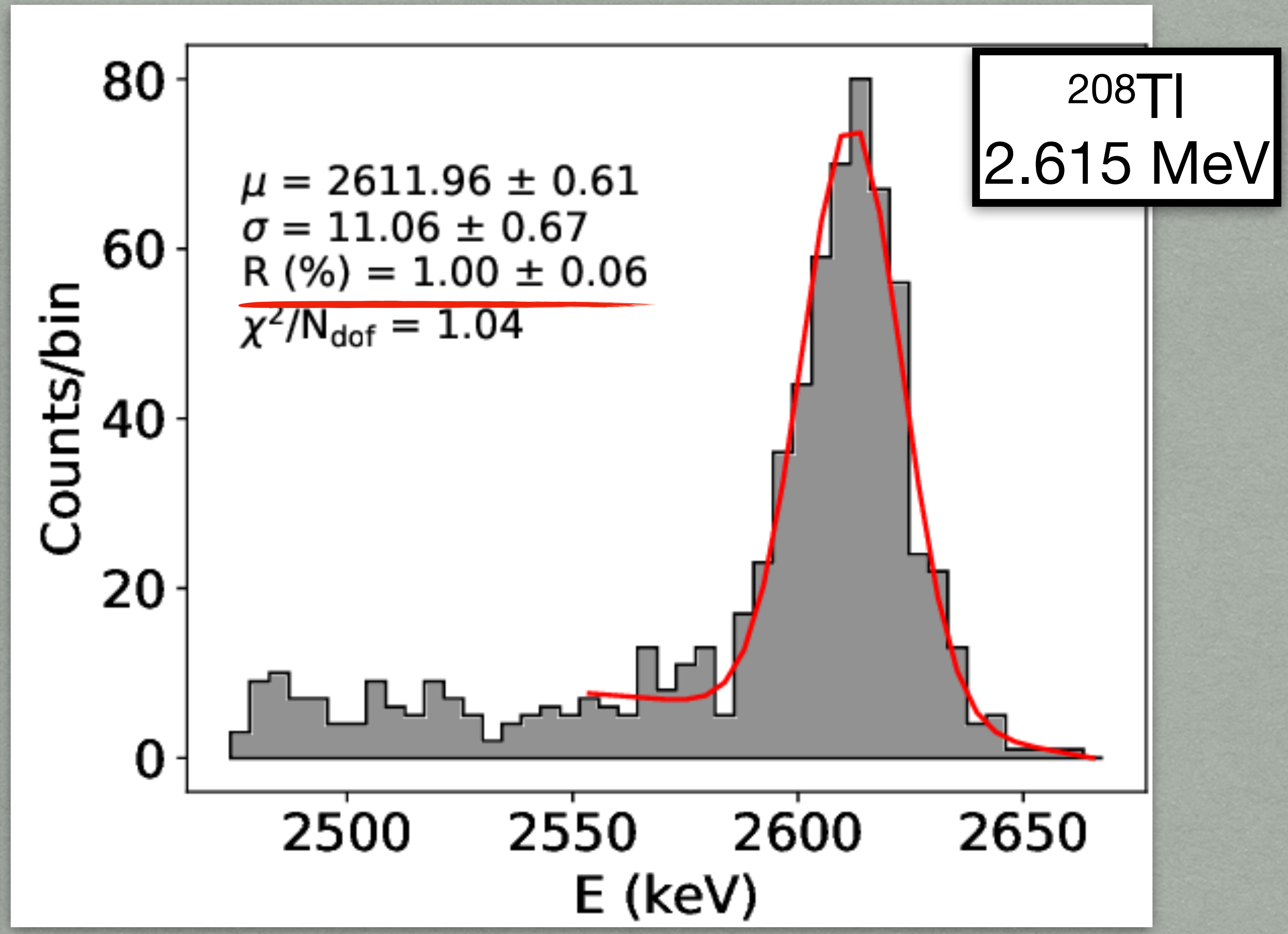
→ Correction XY maps → Geometry effects; Drift e⁻ attachment

JINST 13 (2018) P10014

- **All physics goals of NEXT-White achieved successfully:**

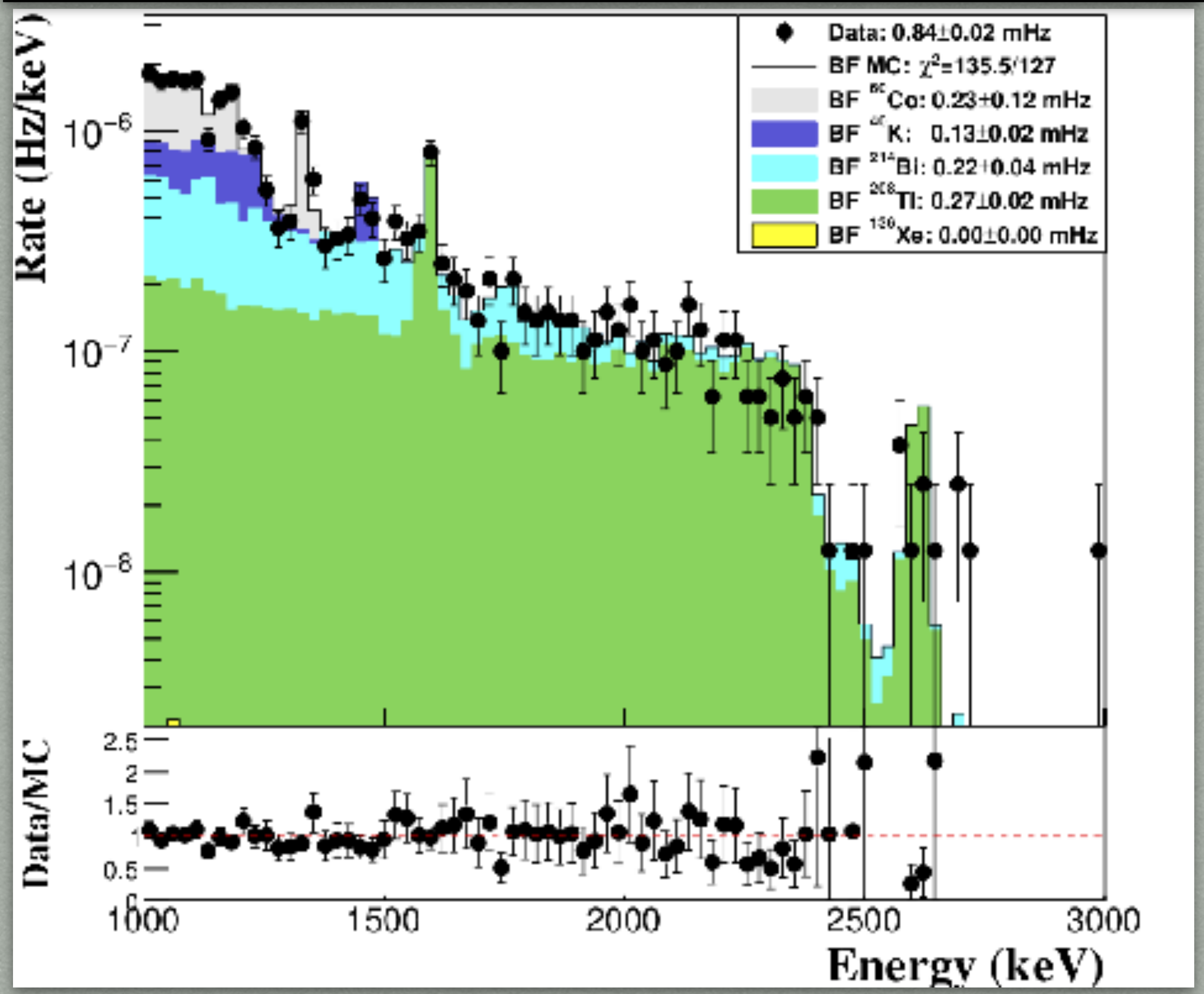
Energy resolution
< 1% FWHM @$Q_{\beta\beta}$





JHEP 10 (2019) 230

Background measurement



JHEP 10 (2019) 051 *JHEP 10 (2018) 112*

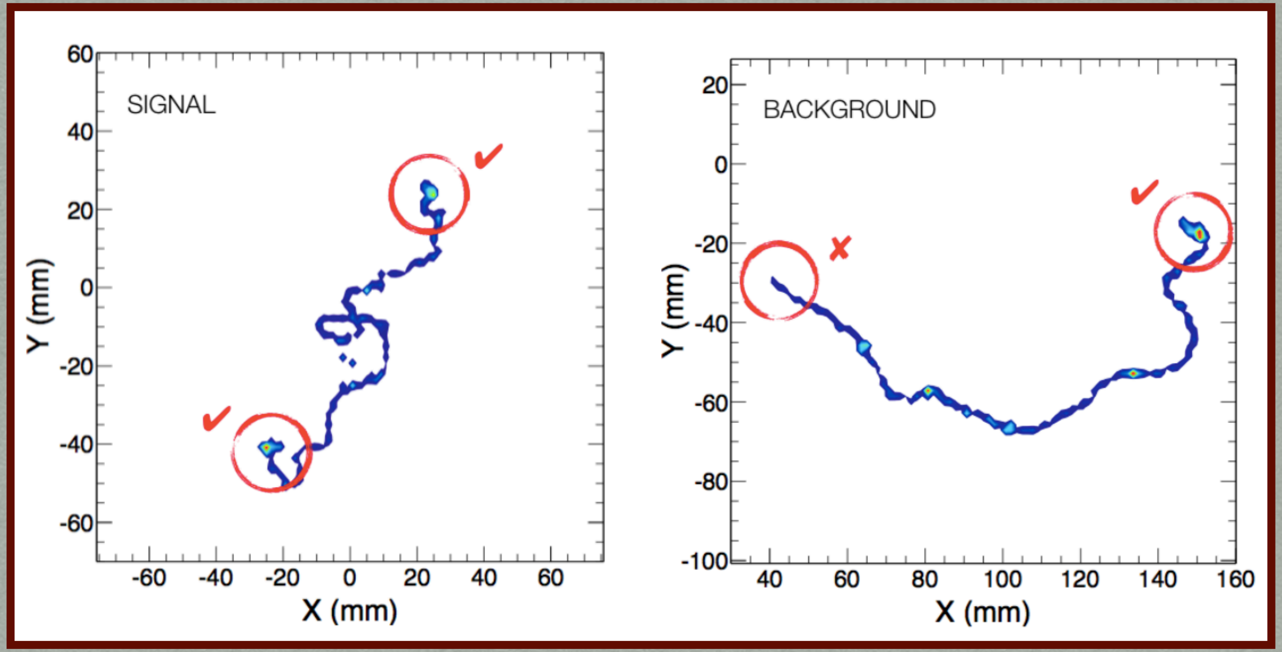
More results…

NEXT-White Results: topological signature

- ββ2ν **topological** analysis: **distinct feature** to separate signal from background

JHEP 10 (2019) 052

JHEP 01 (2021) 189 (CNN)

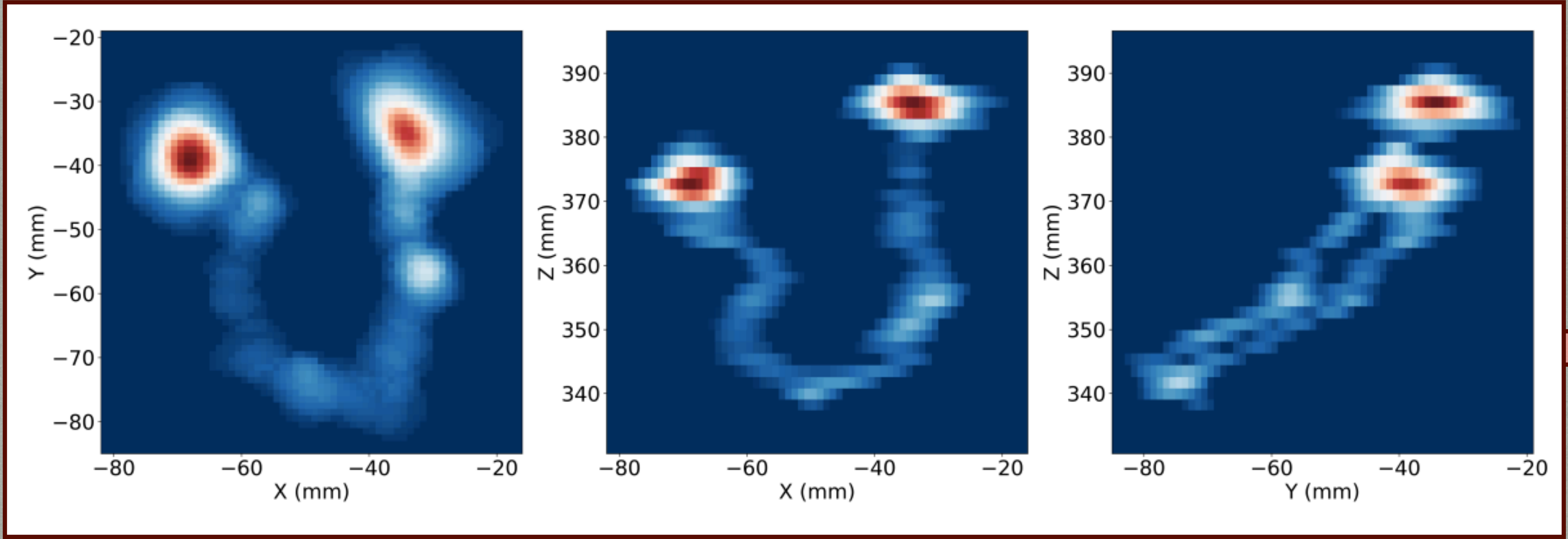


Energy loss for a charged particle in the gas **~1/v²**
Low energy → rapid energy deposition → **Bragg peak**

- Background: 1 Bragg peak
- Signal: 2 Bragg peaks

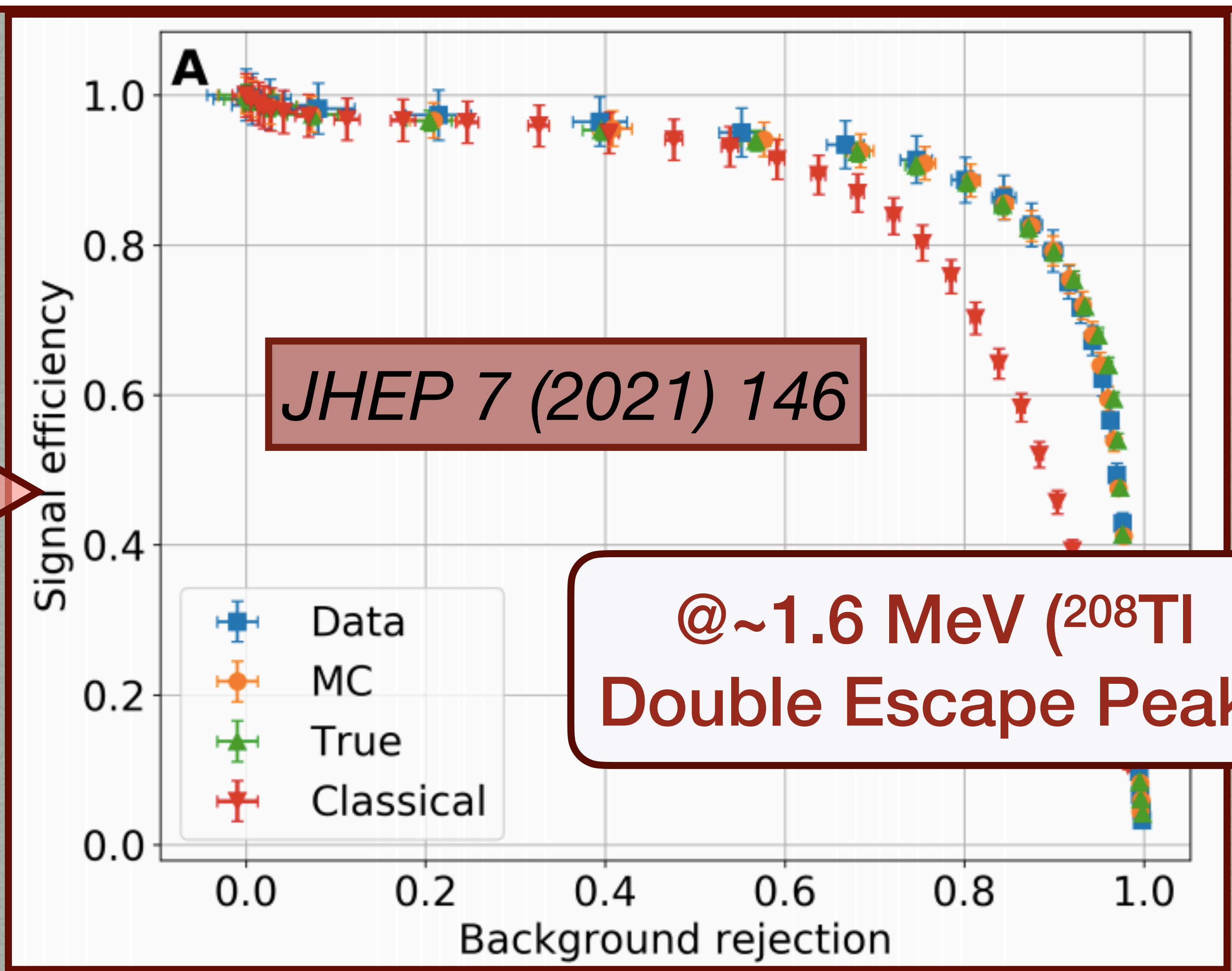
- **Richardson-Lucy** deconvolution (iterative) algorithm to counteract blurring effects (Drift process / EL amplification) in tracks

XYZ projections for real 2 MeV 2νββ candidate



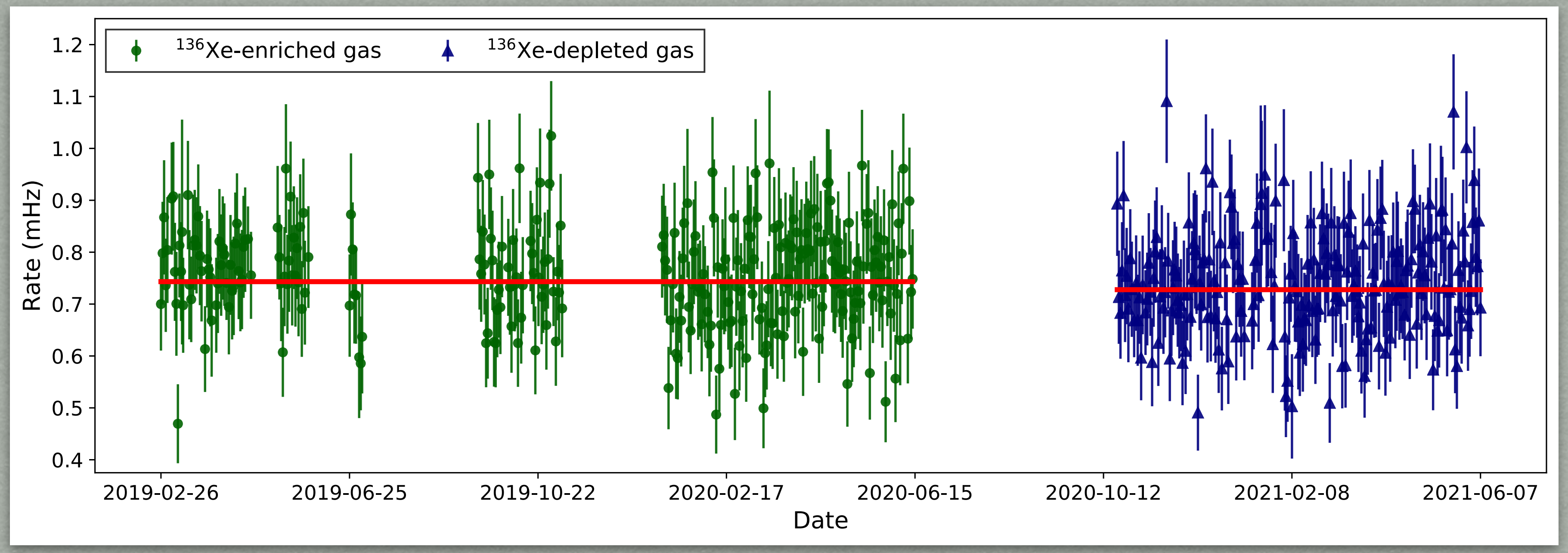
@~1.6 MeV (^{208}Tl Double Escape Peak)

bkg. acceptance = (3.7±0.7)%
signal efficiency = (56.6±2.2)%



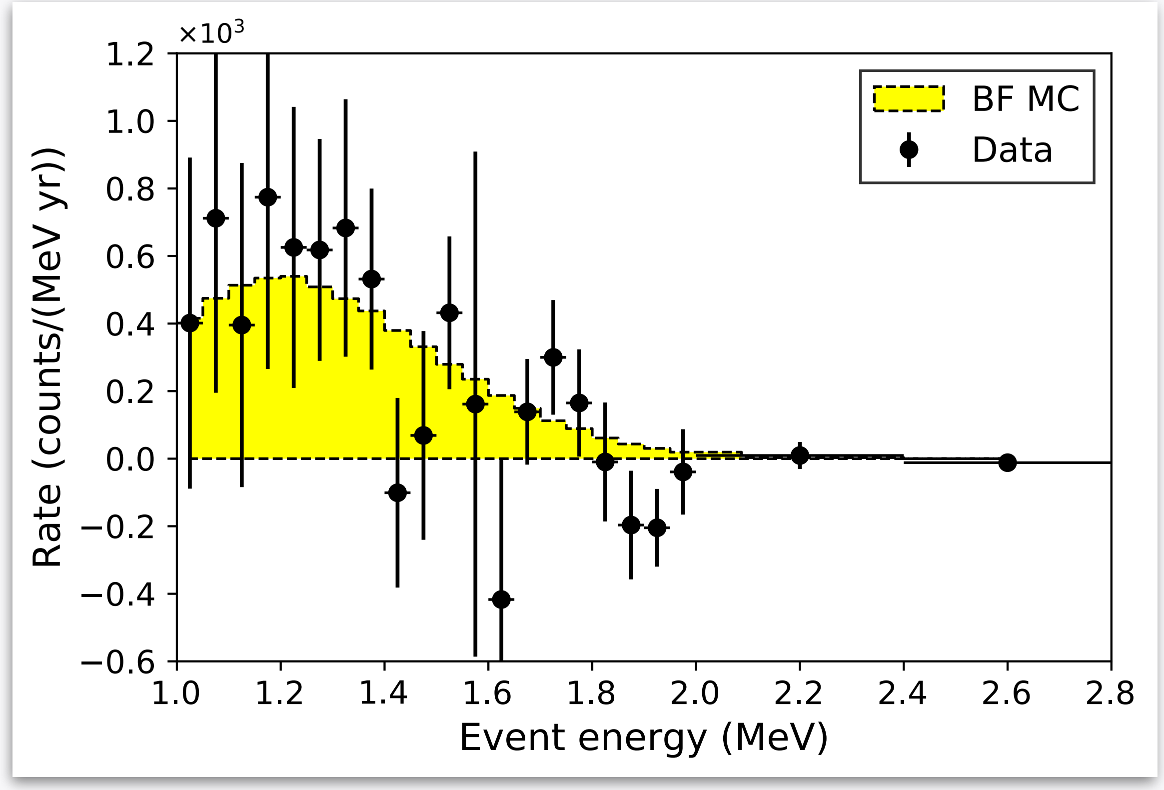
NEXT-White Results: 2νββ meas. & 0νββ searches

- Rely on **event energy** spectrum of ββ candidates
- Backgrounds demonstrated to be **stable** in time →
- **Two independent** approaches:



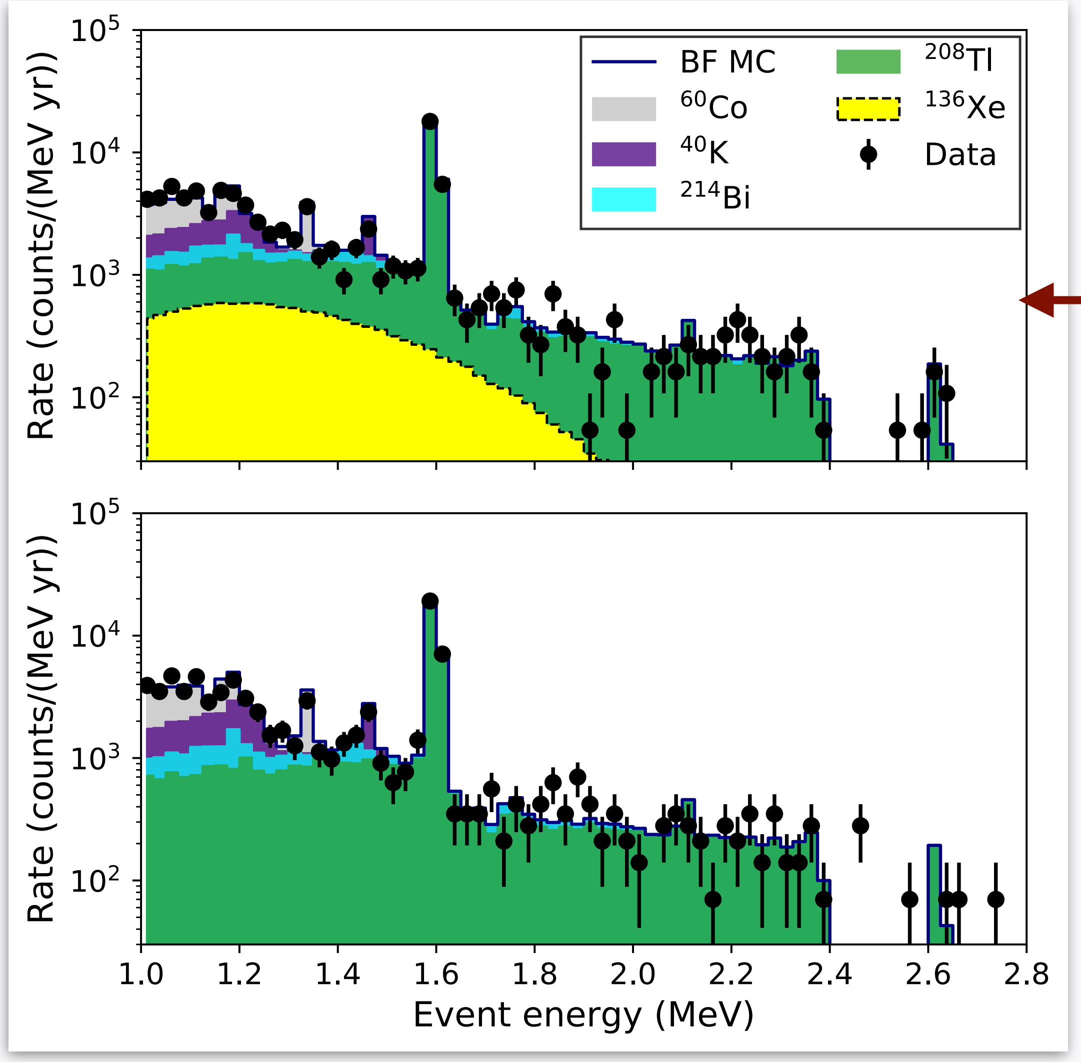
Bkg-Subtraction fit

- ➡ (^{136}Xe-enriched energy spectrum)
  - (^{136}Xe-depleted energy spectrum)
  → fit to ββ dst.
- ➡ Small dependence with Bkg-Model (only ^{137}Xe) → Interesting for current- & future-generation exps.



Bkg-Model-Dependent fit

- ➡ Once NEXT bkg. model is verified
- ➡ It fits 2νββ, 0νββ and every bkg. contribution using ^{136}Xe-depleted & ^{136}Xe-enriched samples



PRC 105 (2022) 055501

	Bkg-Sub	Bkg-Model
$T^{2\nu}_{1/2} \times 10^{21}$ (yr)	$2.34^{+0.80}_{-0.46}(\text{stat})^{+0.30}_{-0.17}(\text{sys})$	$2.14^{+0.65}_{-0.38}(\text{stat})^{+0.46}_{-0.26}(\text{sys})$
$T^{0\nu}_{1/2}$ limit (yr)	1.3×10^{24}	5.5×10^{23}
$\langle m_{\beta\beta} \rangle$ (meV)	$541 - 1068$	$832 - 1641$

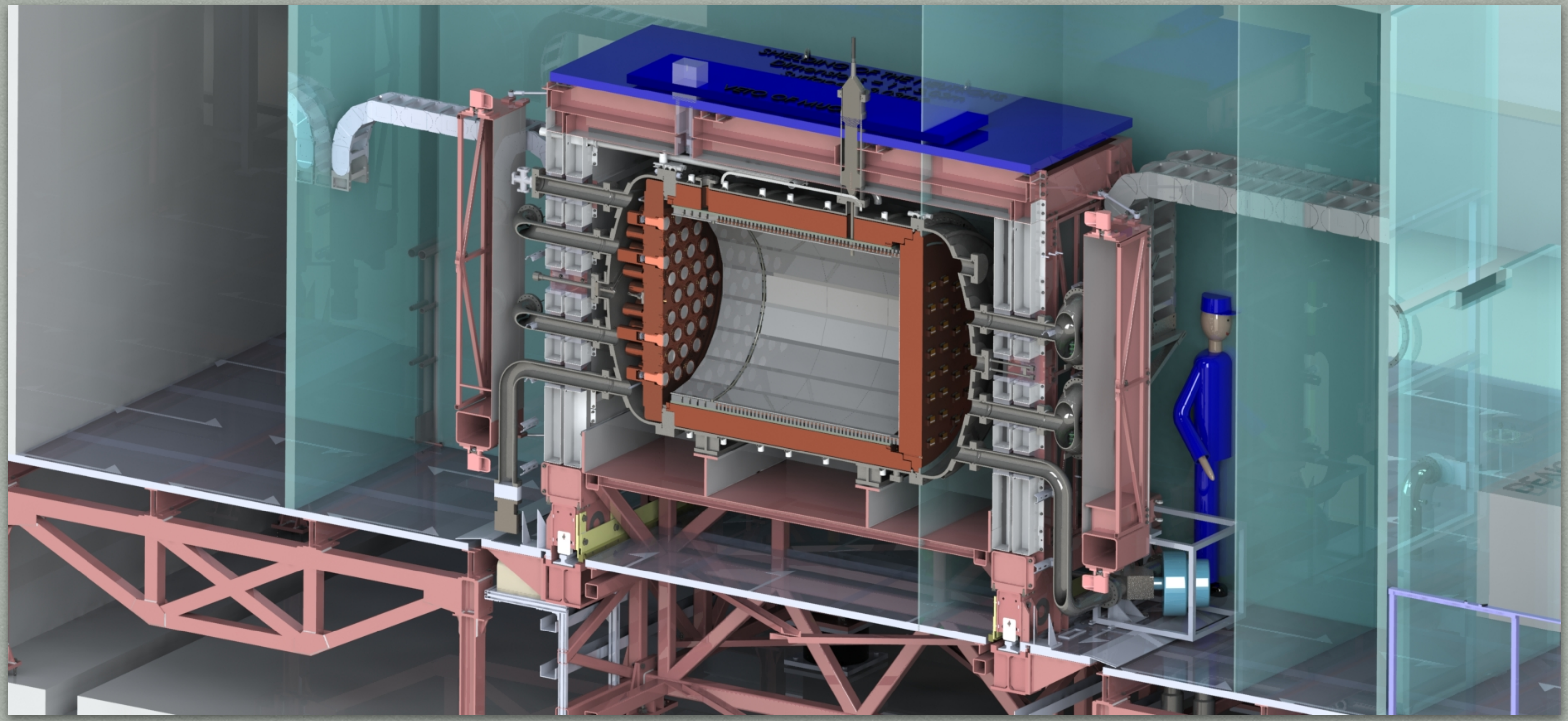
Preliminary

0νββ paper in preparation

- ➡ Good agreement between independent fit strategies
- ➡ Consistency with other experiments
- ➡ Very low amount of ββ source (3.5 kg)

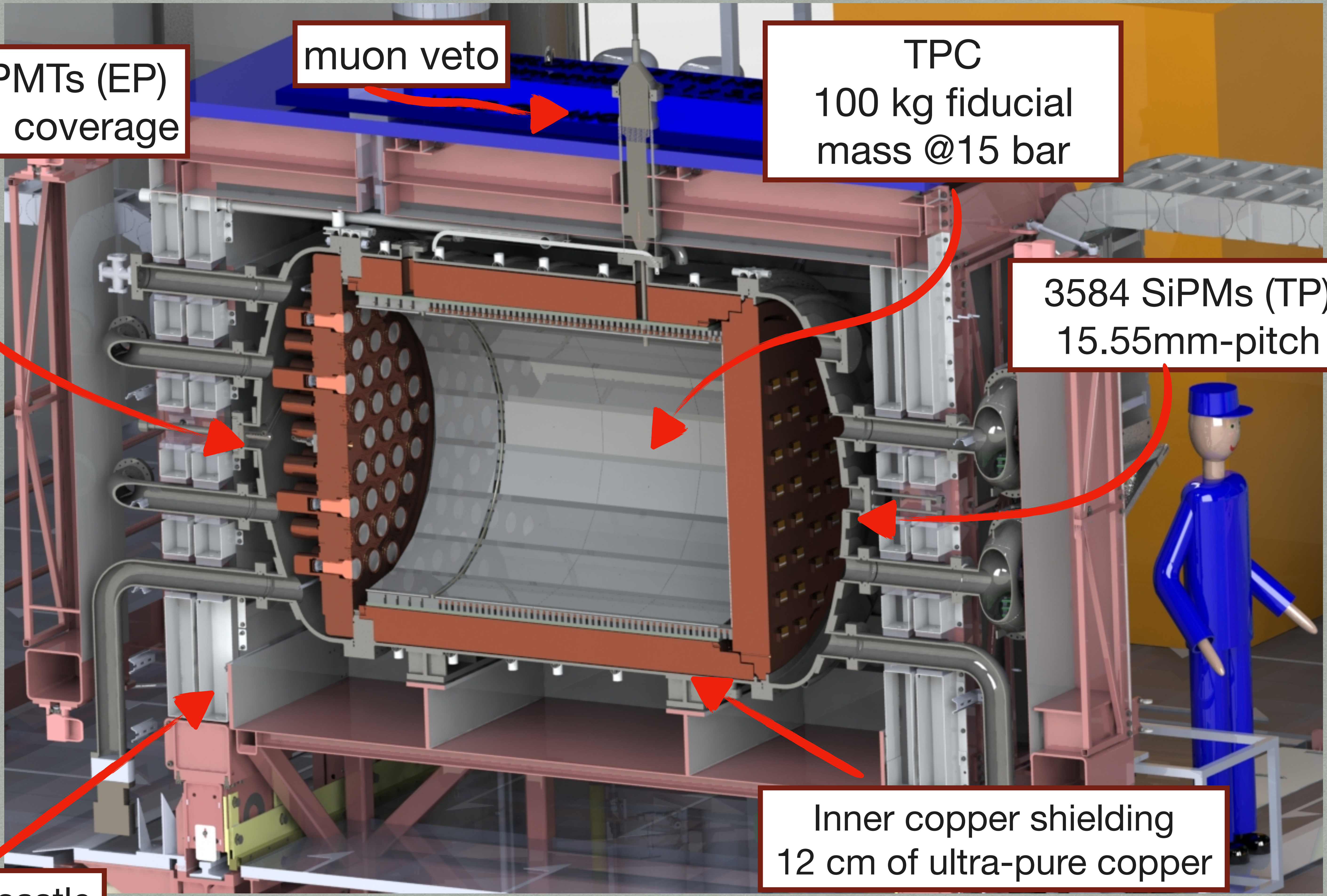
The NEXT-100 detector

- Once NEXT-White detector life is over, we are now constructing the **NEXT-100** detector
- Main goal: first competitive 0νββ search with NEXT technology
- And test-bench for tonne-scale detector
    1. Understand technical solutions at larger scale
    2. Validate Bkg-Model in a more radiopure and better shielded scenario
    3. Understand further energy resolution, topological signature, direct bkg-subtraction

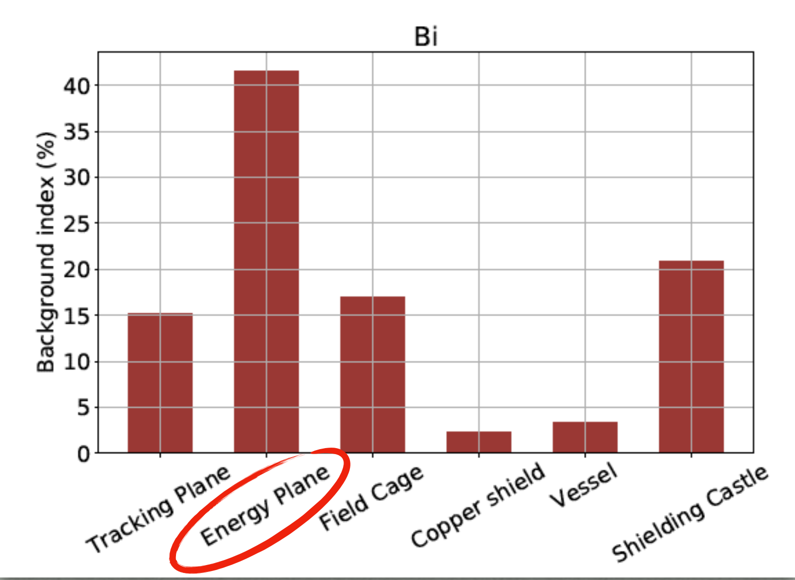


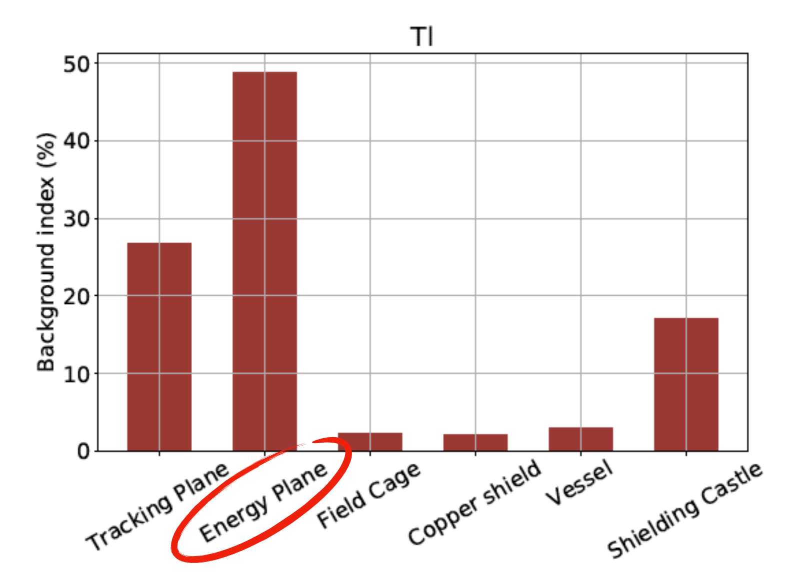
The NEXT-100 detector

- Larger but similar structure (~2:1) as in NEXT-White (asymmetric TPC):



https://roderic.uv.es/handle/10550/76715

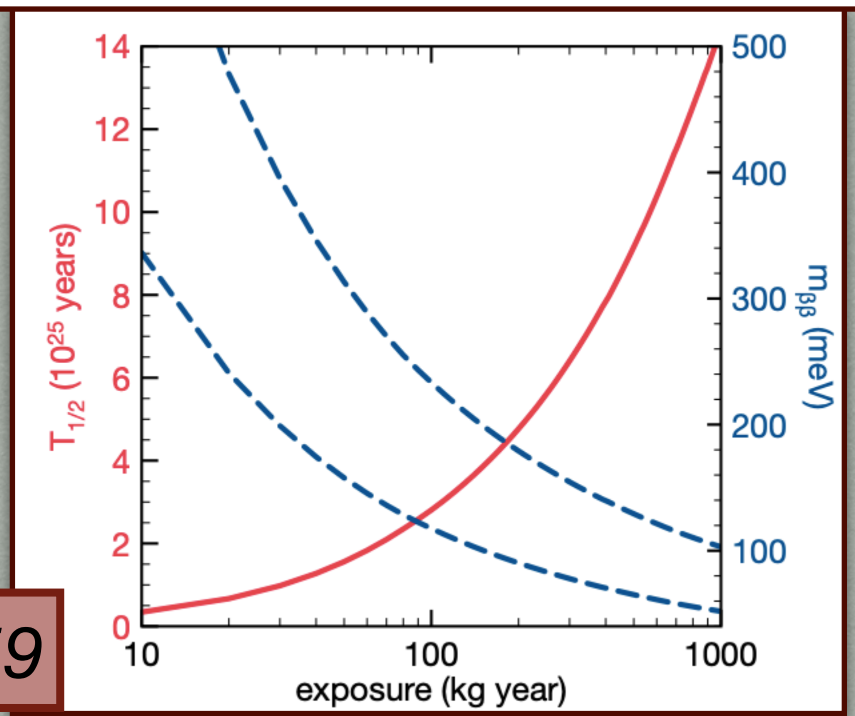




- Also located at LSC Laboratorio Subterráneo de Canfranc
- Expected to start operation in 2022/23

Expected results:

- After validating BG model with NEXT-White → **Bkg. index = 4.29 × 10^{-4} counts/keV/kg/yr**
- Majority of the background coming from **PMTs**
- **$m_{\beta\beta}$ < 70-130 meV** @ 90% CL (5 yr of data)

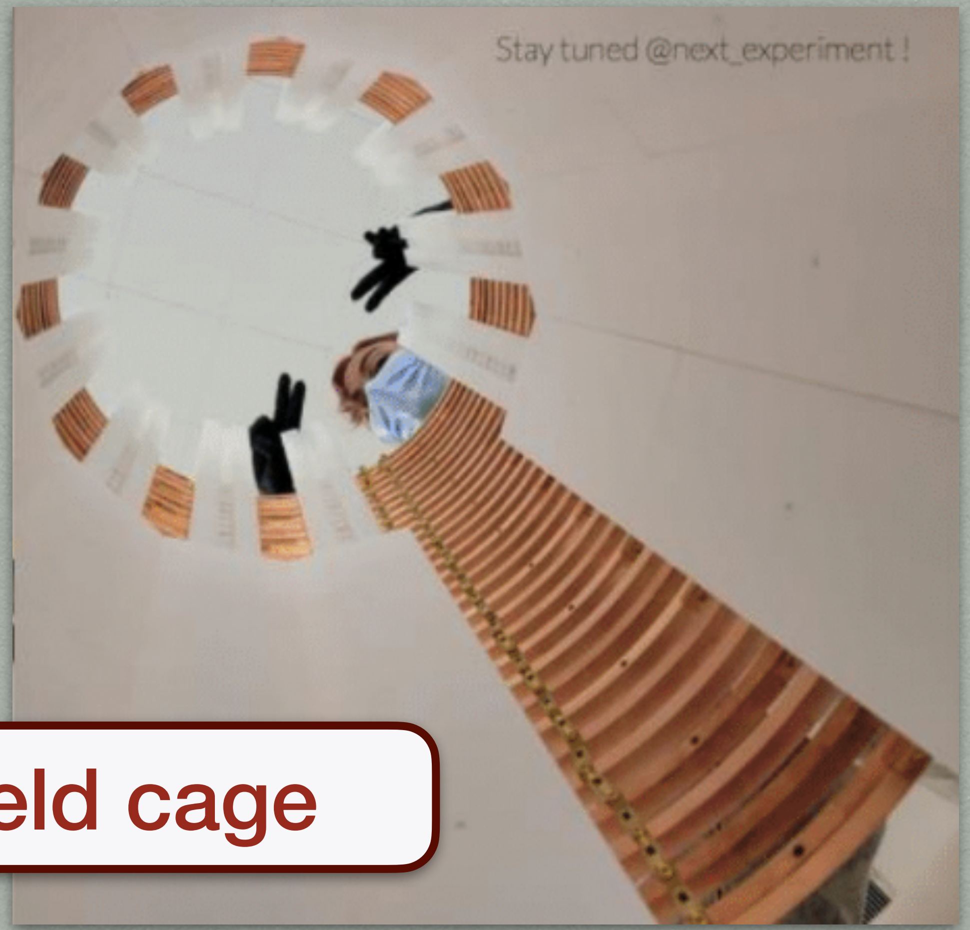


JHEP 1605 (2016) 159

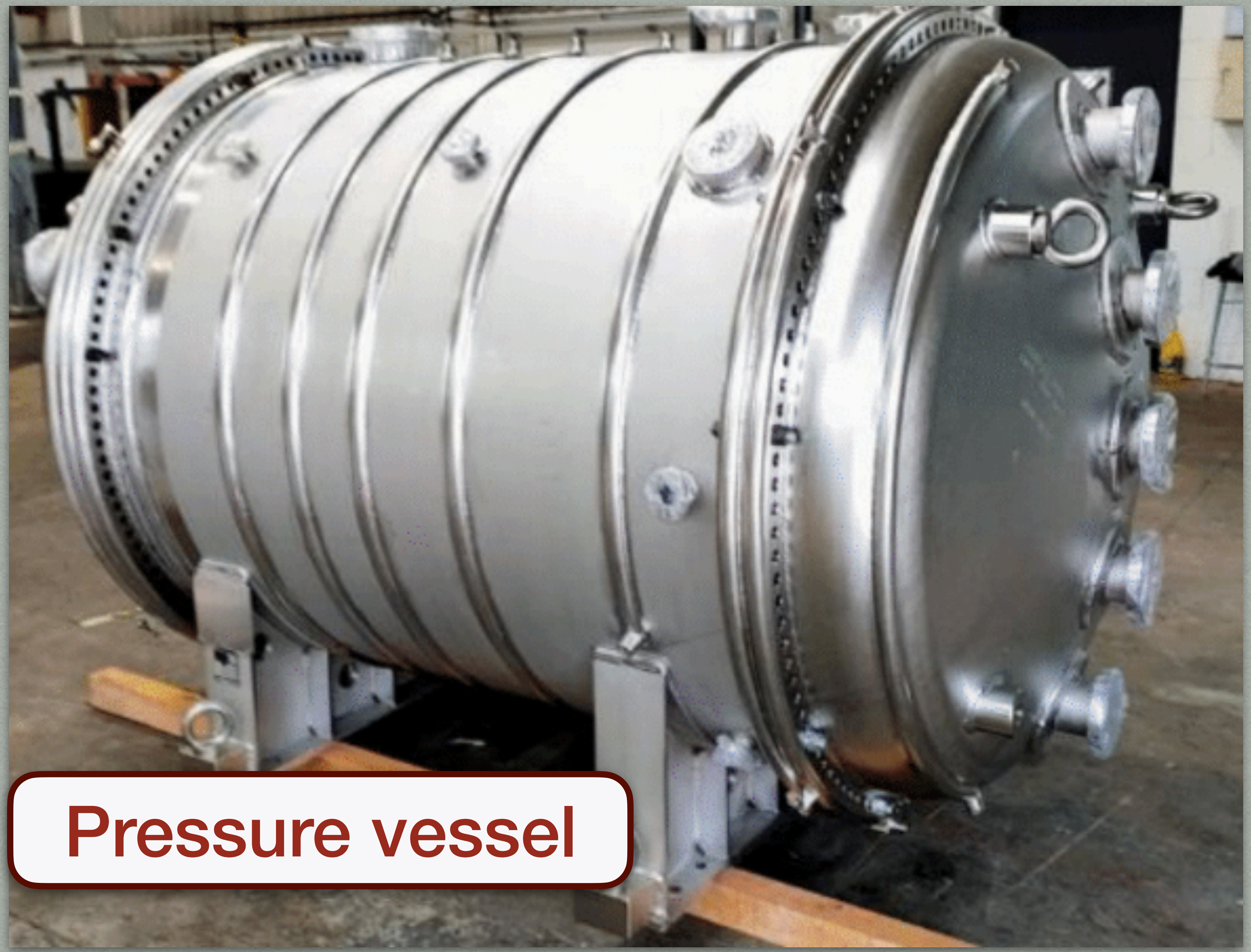
The NEXT-100 detector

- Currently → Final part of construction
- Assembly in LSC → Soon

Lead castle (repainted)

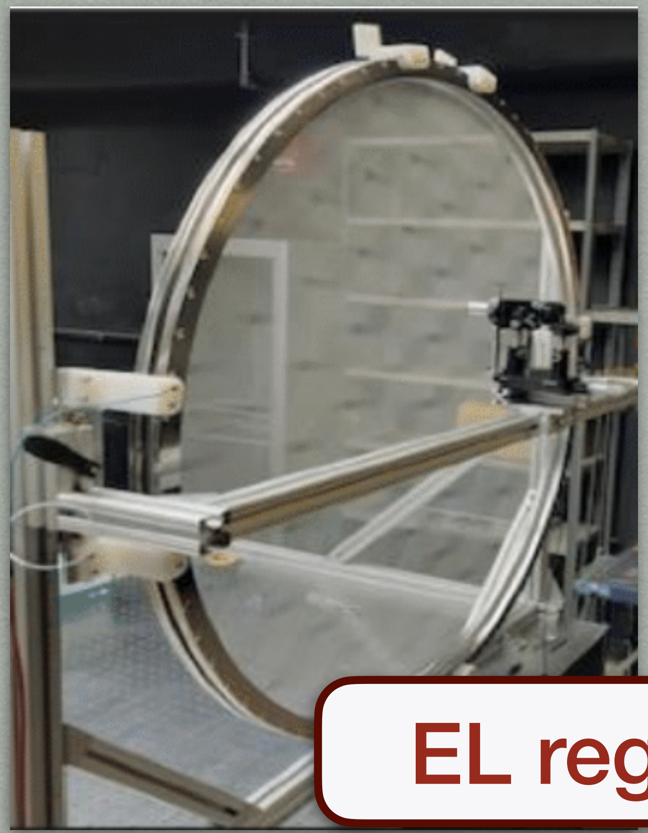


Field cage

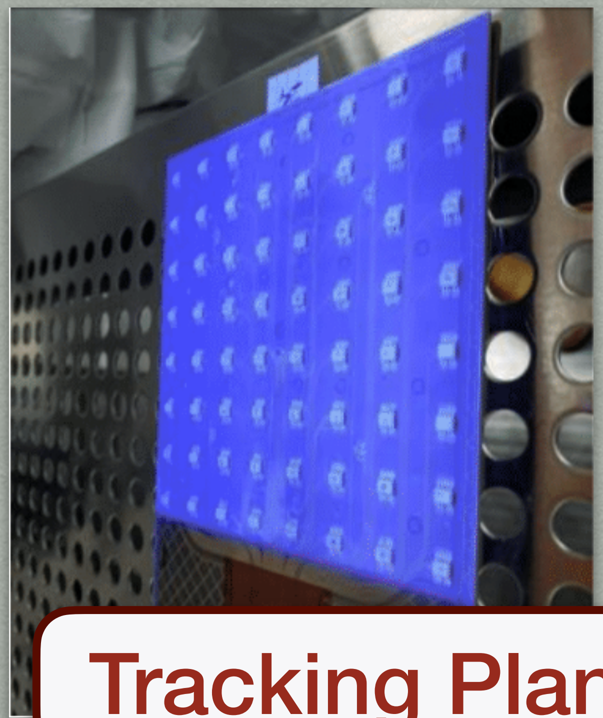


Pressure vessel

Copper shield



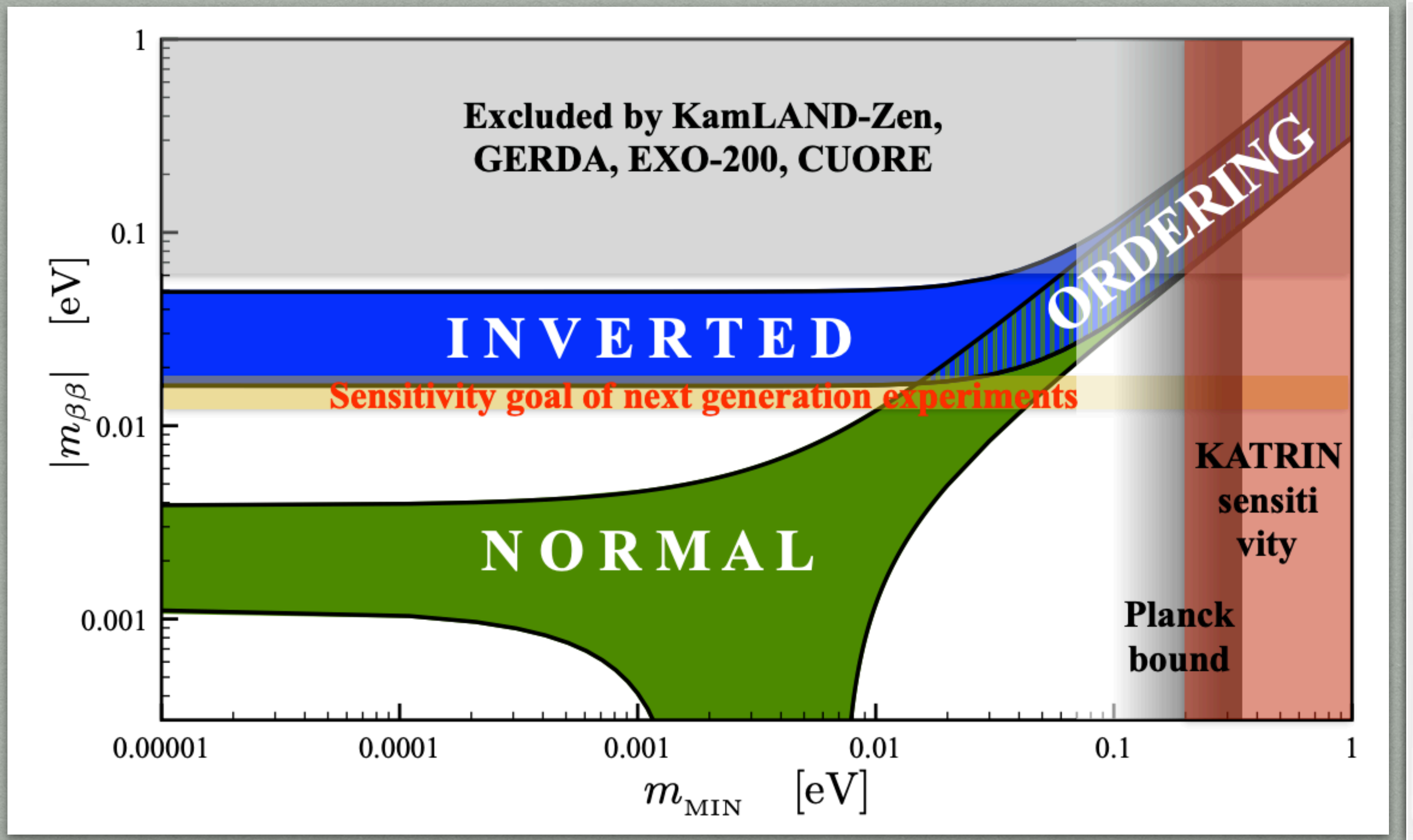
EL regions

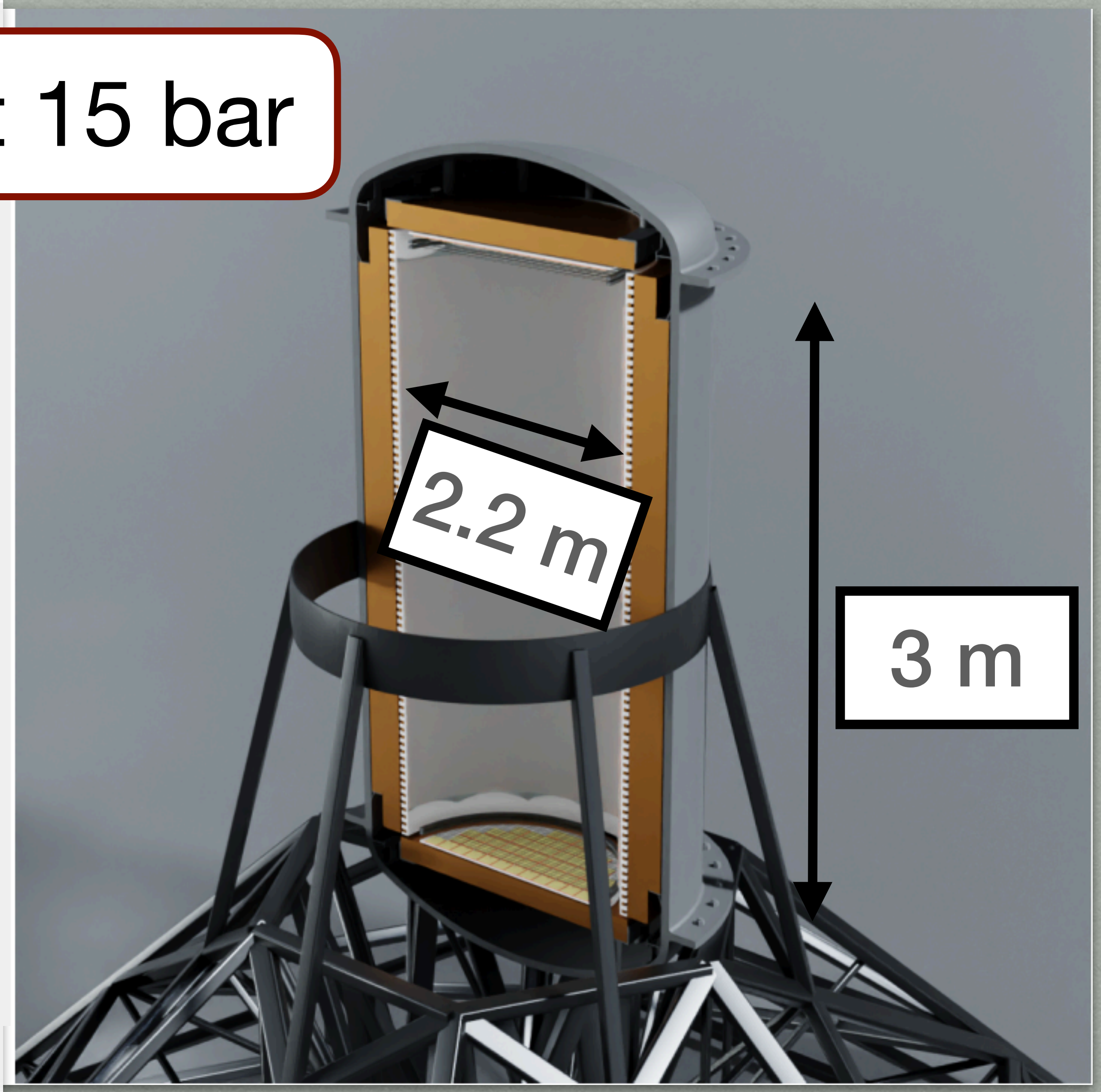


Tracking Plane board

Towards the Tonne-scale: NEXT-HD

- **Goal**: fully explore the IH region
- Such large $T^{0\nu}_{1/2}$ values require tonne-scale source material
- Here → NEXT-HD ≡ NEXT-1t @LSC → HD ≡ High Definition ≡ High Density
- Several modules at different locations are considered to be exploited.



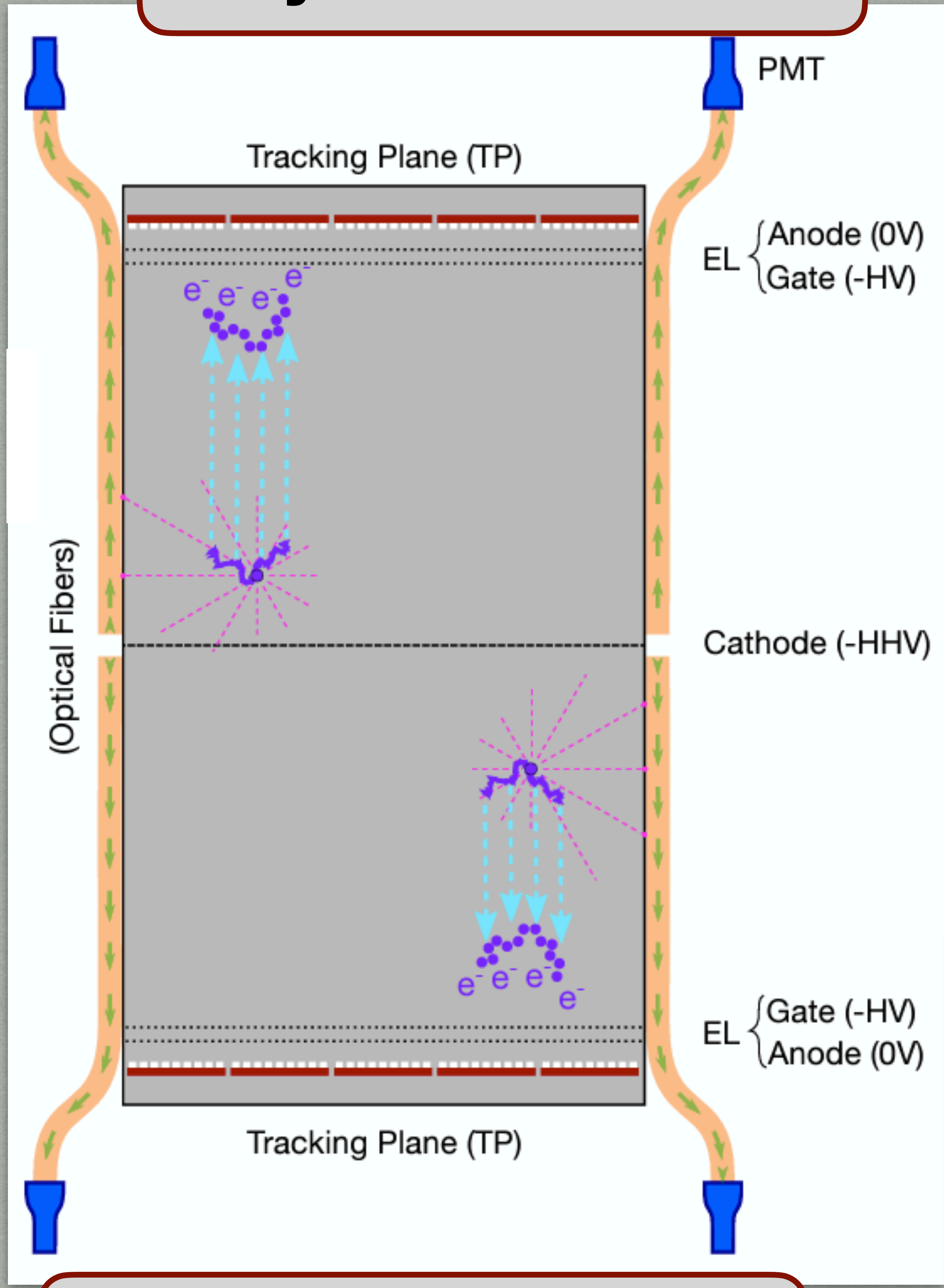


NEXT-HD

- Significant differences with NEXT-White & NEXT-100:

Better E resolution | Better Tracking

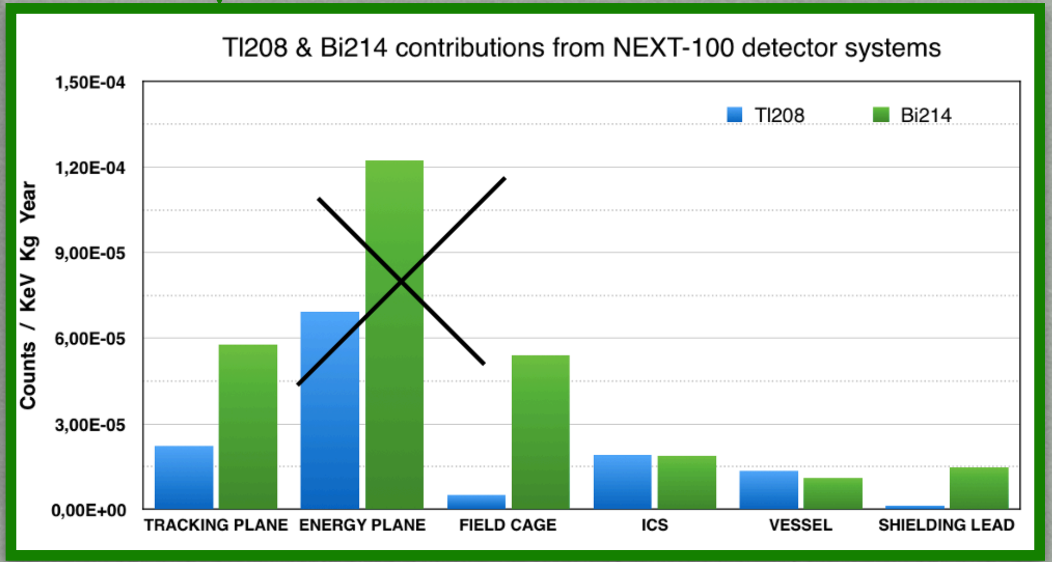
Symmetric TPC → Shorter drift length → Lower diffusion



Water tank surrounding

- 2 dense SiPM planes
- No PMTs close to active volume
- Double-clad scintillating optical fibres coupled to external PMTs (or SiPMs)

Optical det. eff: 1.2% → ~3%



Operation at cooler temperatures

Lower SiPM dark-count-rate: ΔT=-30K → DCR×0.1

Gas mixtures

Xe-He Lower Diffusion

JHEP 04 (2020) 034

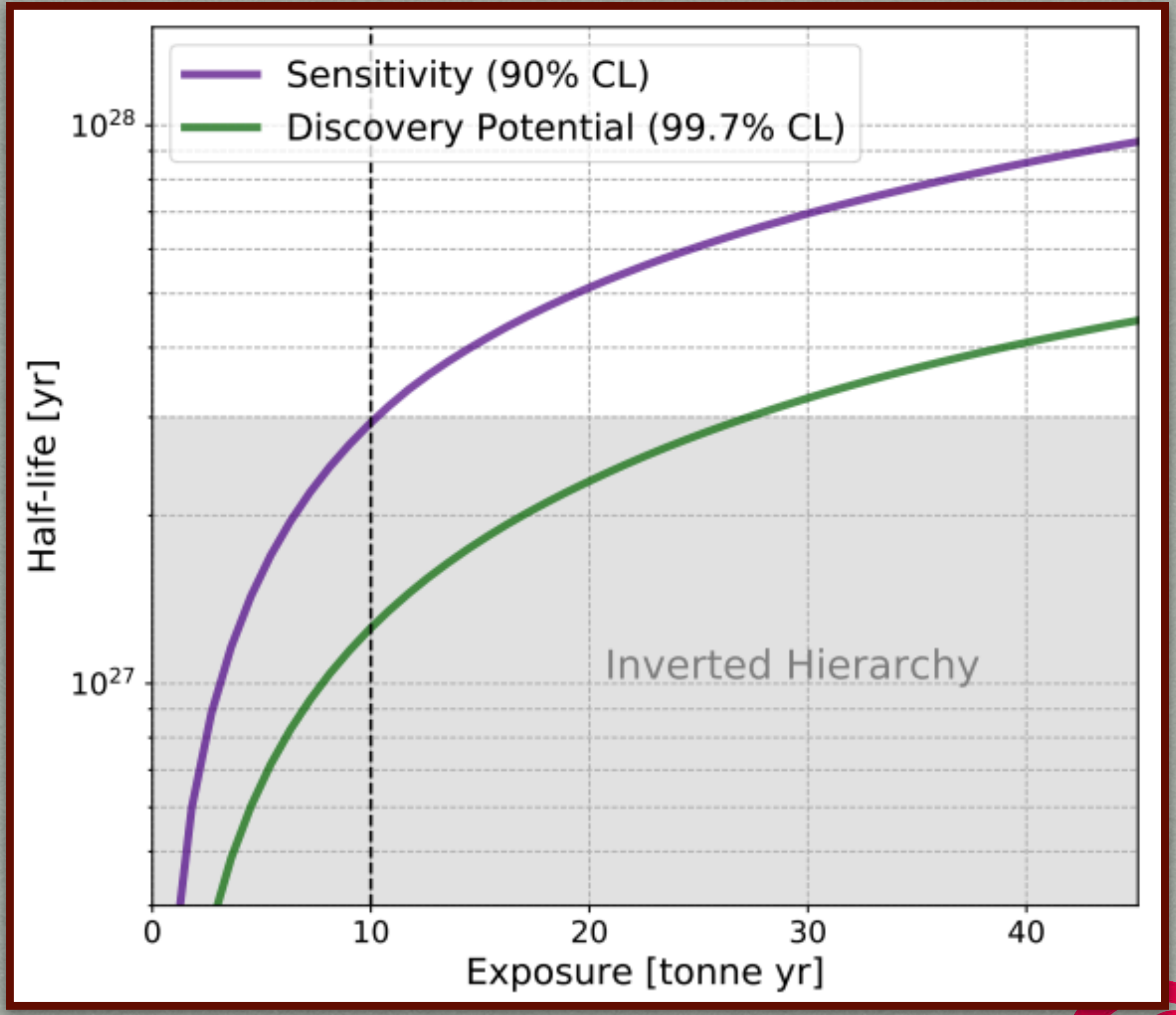
^{3}He mitigates cosmogenic bkgs.

J.Phys.G: Nucl.Part.Phys. 47 075001

Expected results:

JHEP 08 (2021) 164

Source mass (^{136}Xe)	1109 kg
Signal efficiency	24.6%
Background rate	0.004 keV^{-1} t^{-1} yr^{-1}
	0.061 ROI^{-1} t^{-1} yr^{-1}
Energy resolution	0.5% FWHM at 2458 keV
$\overline{T}_{1/2}$ (5 t yr)	1.4×10^{27} yr at 90% CL
$\overline{T}_{1/2}$ (10 t yr)	2.7×10^{27} yr at 90% CL



NEXT-Bold

- To explore **NH** region → higher background rejection and efficiency
- Break-through option: $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}(+2\bar{\nu}_e)$ **Barium Tagging**

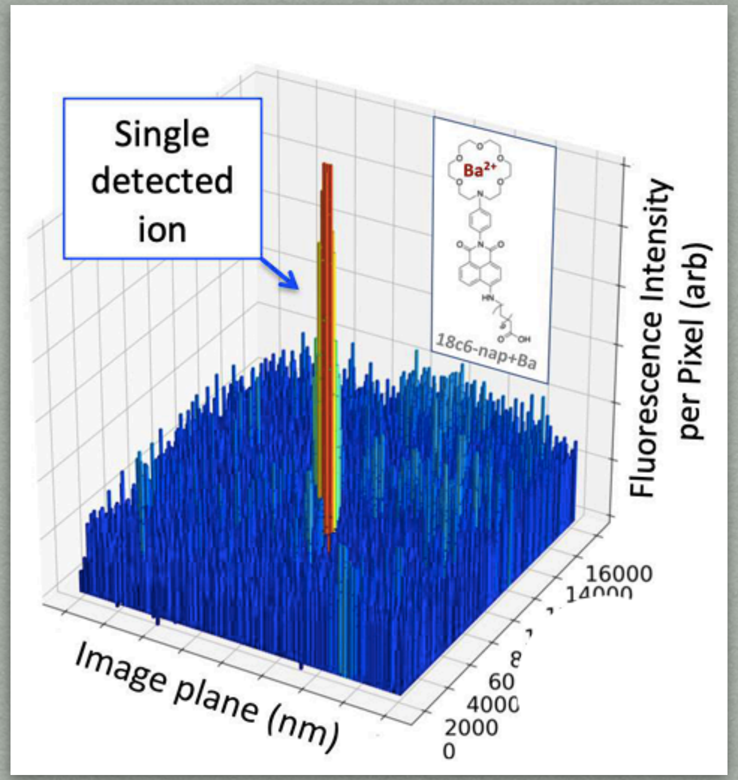
  If detected → (Reducible background)-free experiment

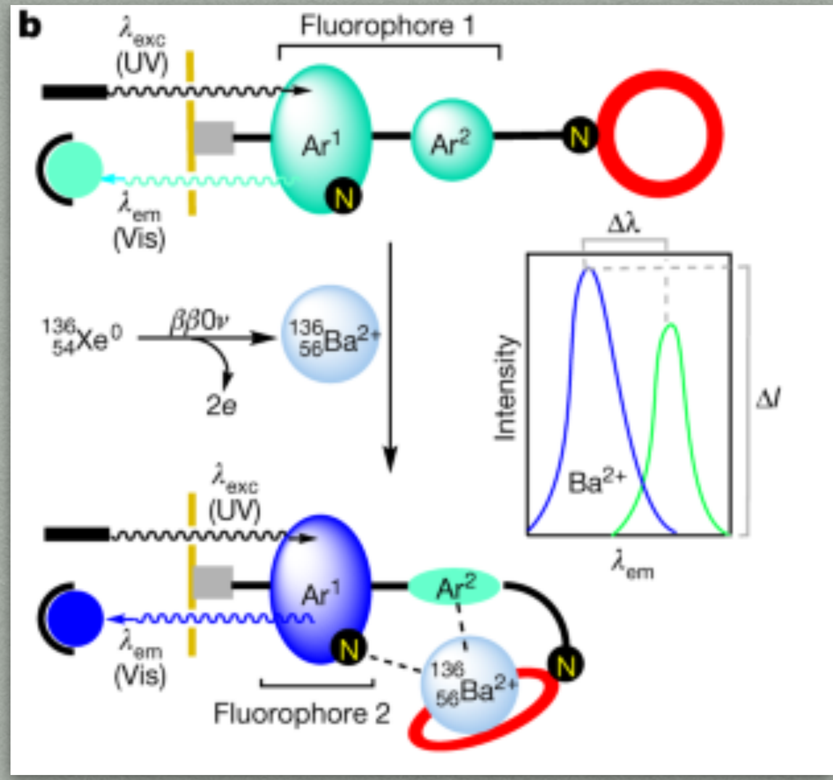
I. Rivilla talk

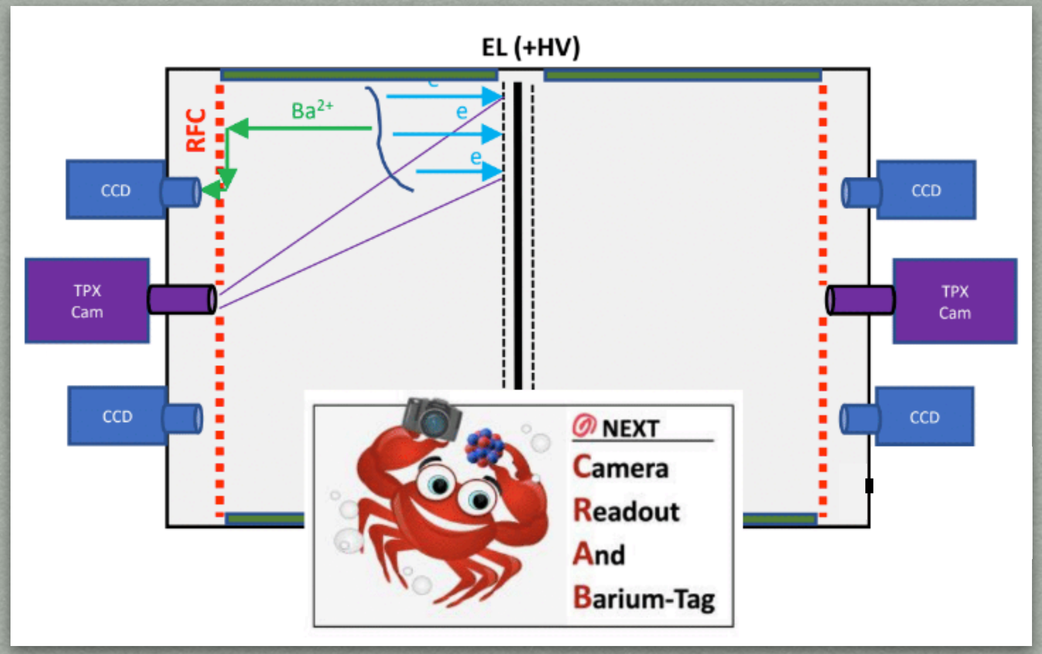
Nature 583, 48-54 (2020)

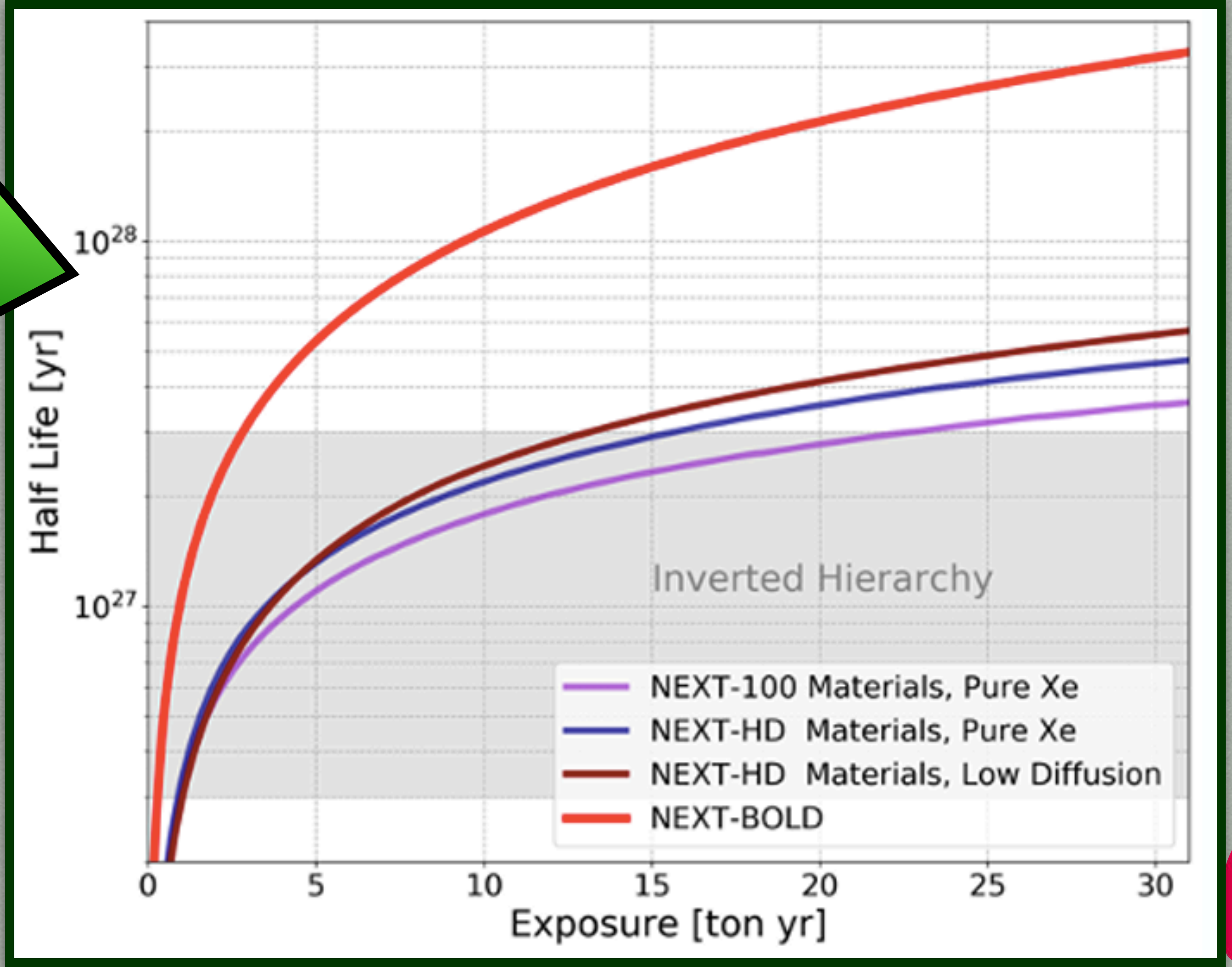
PRL 120 (2018) 132504

- Background contribution reduced to **2νββ**
- Idea: Exploiting **single molecule fluorescent imaging** (SMFI) to *tag* single Ba^{++} ions
- Delayed coincidences: electron signal S2 (anode) & cation signal (cathode)
- Intense R&D for ion concentration & collection in parallel:
  - Sensor-to-ion (BTD concept)
  - Ion-to-sensor (CRAB concept)









Summary

- NEXT final goal: 0νββ searches with HPGXe TPCs
- Relevant features already demonstrated with the NEXT-White detector:
  - Very good **energy resolution** at Q-value (<1% FWHM)
  - Excellent **tracking capabilities** to discriminate backgrounds from signal
- NEXT-White was capable of measuring $T_{1/2}^{2\nu}$ with really **low fiducial mass** (3.5 kg!)
- It also demonstrated **Direct Background-Subtraction** method for 0νββ searches novel in field
- **NEXT-100** will start commissioning by the end of 2022 → Competitive 0νββ limits with current experiments
- **Intense R&D** program already conducted towards NEXT-HD: tonne-scale + barium tagging

→ Almost-free background experiment → NH region

That's all for the moment...

Thanks for your attention!

Backup

Energy resolution

- Intrinsic energy resolution (lower limit):

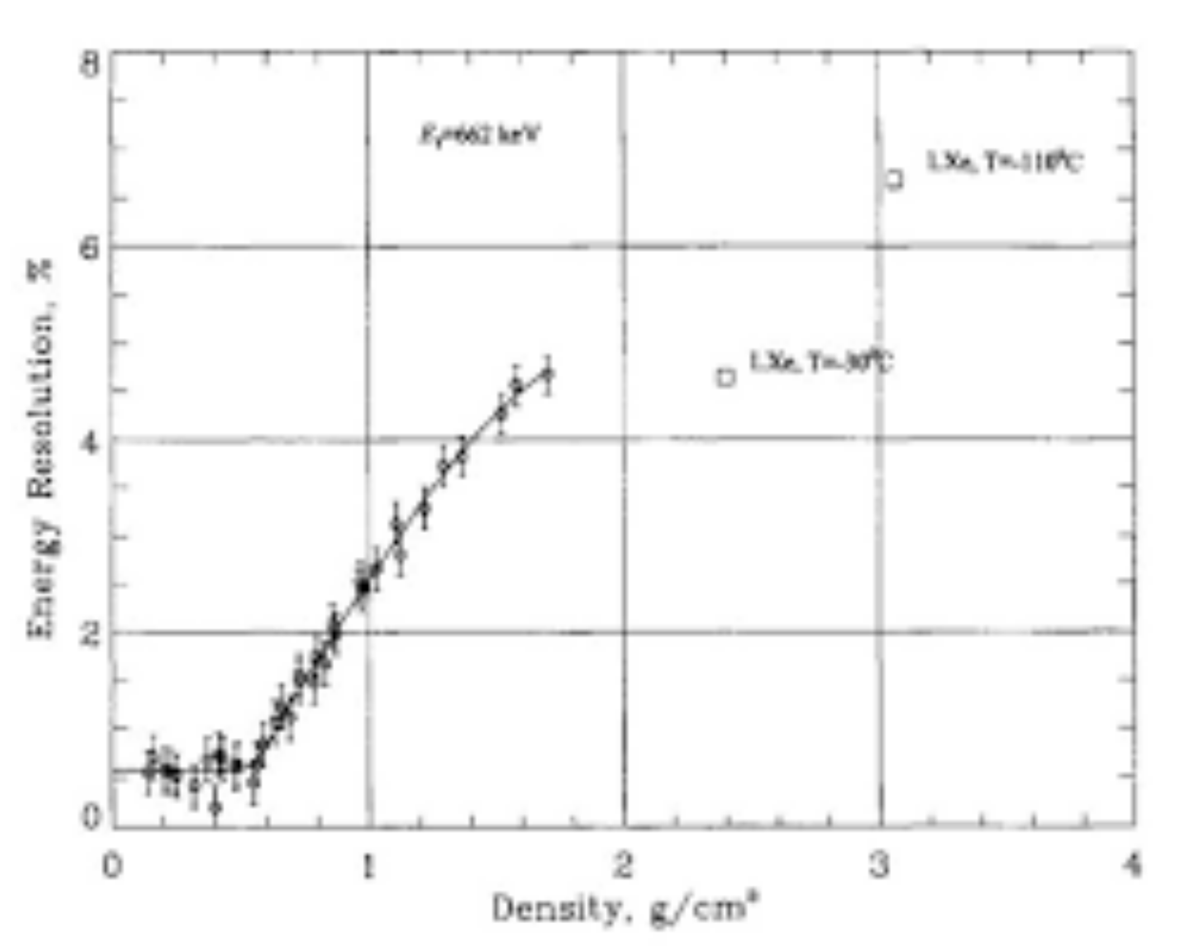
$$\sigma_i^2 = F \cdot N_i = F \cdot \frac{E}{W_i}$$

<energy> to produce ionization e-

$$\frac{\delta E}{E} = \frac{\delta N_i}{N_i} = 2.35 \cdot \frac{W_i \cdot \sigma_i}{E} = 2.35 \cdot \sqrt{\frac{F \cdot W_i}{E}}$$

- F(GXe) ~ (0.13-0.17)
- F(LXe) >20

$$\left.\frac{\delta E}{E}\right|_{Q_{\beta\beta}} \simeq 0.3\,\%\ \text{FWHM}$$



- Although in practice:

$$\frac{\delta E}{E} = 2.35 \cdot \sqrt{\frac{F + G + L + n^2/(m \cdot N_i)}{N_i \cdot \epsilon^2}}$$

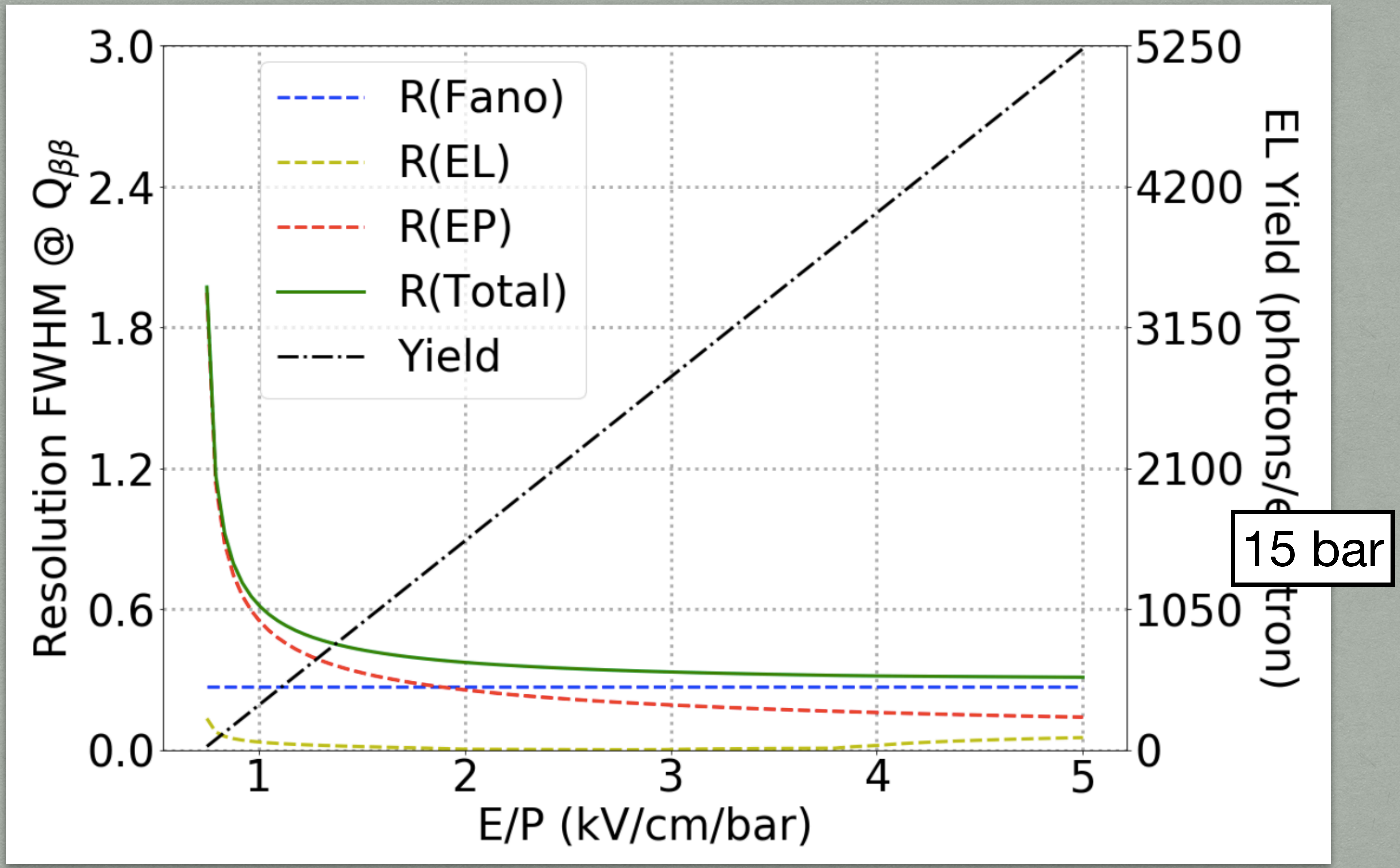
e- collection eff.

Drift e- attachment (+ recombination...) → $L = 1 - \epsilon$
Signal amplification m in PMTs → G
Intrinsic noise of calorimetric sensors → n

Electroluminscence amplification

- G small for EL amplification

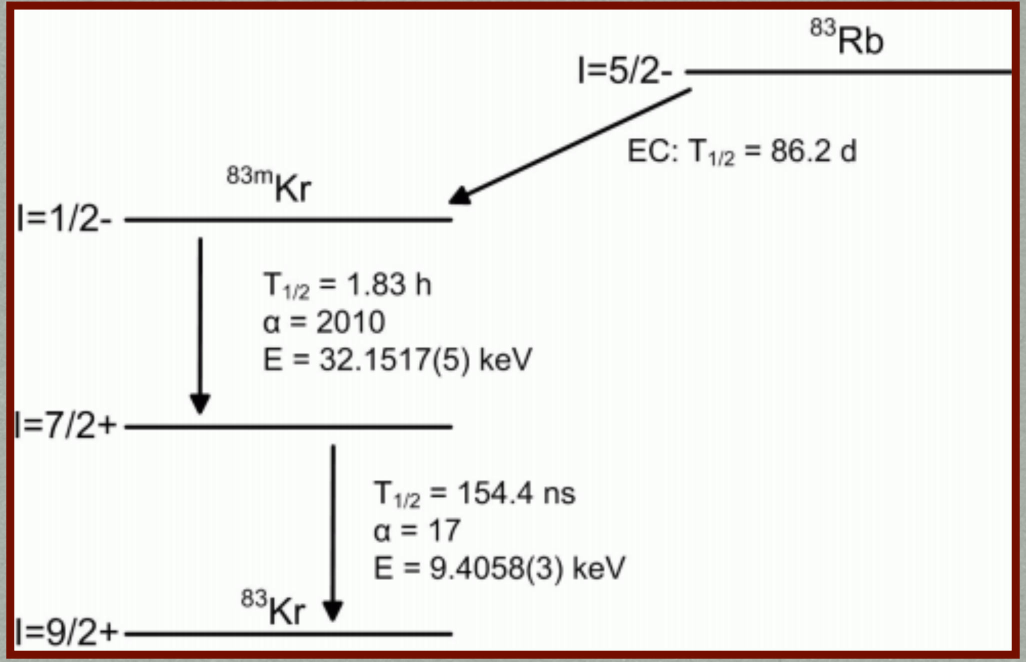
$$\frac{Y}{P\Delta x} = \left(136\frac{E}{P} - 99\right) \text{photons} \cdot \text{electron}^{-1} \cdot \text{cm}^{-1} \cdot \text{bar}^{-1}$$



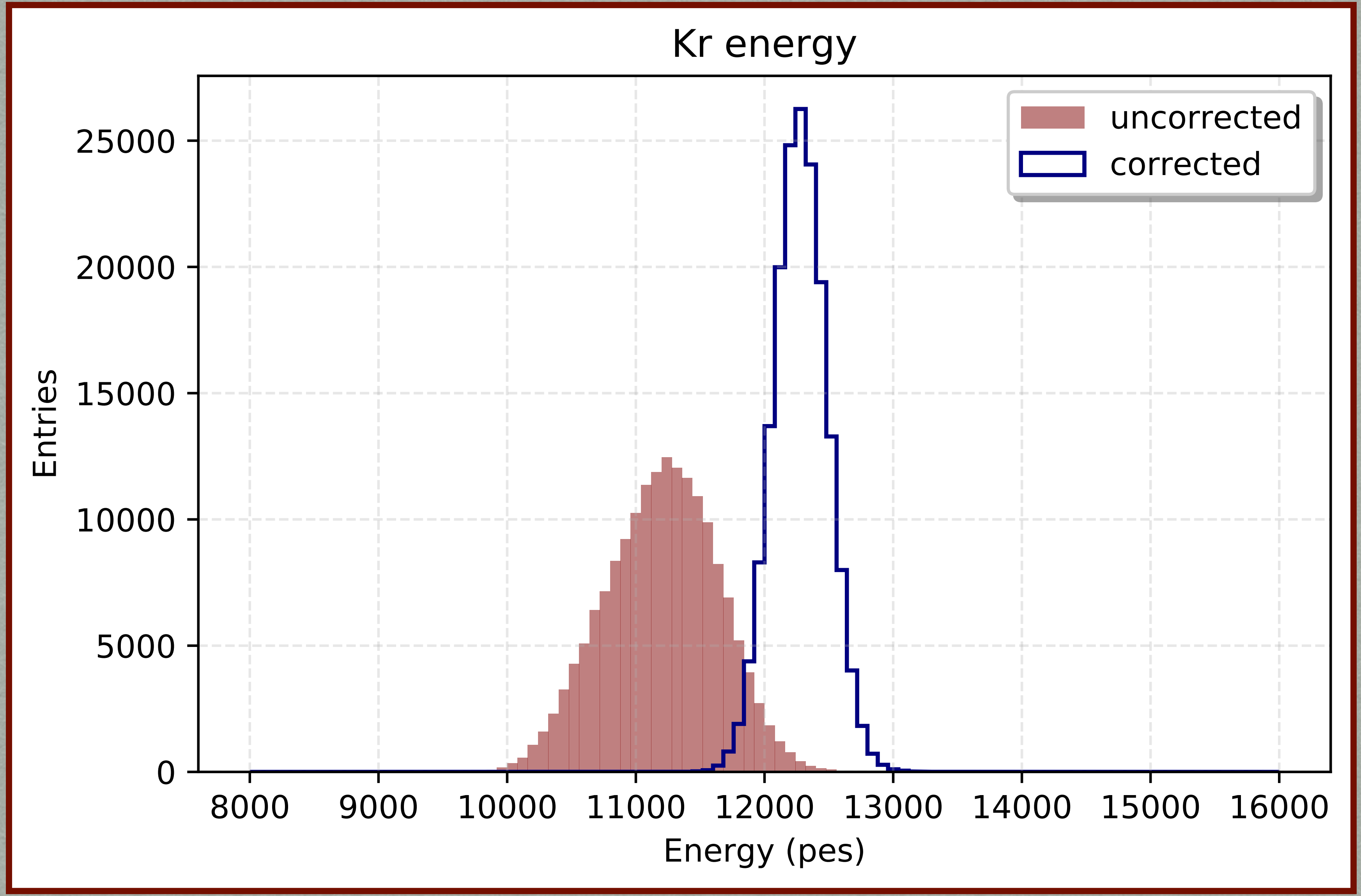
Near-intrinsic Eres achievable with moderately high $\vec{E}$

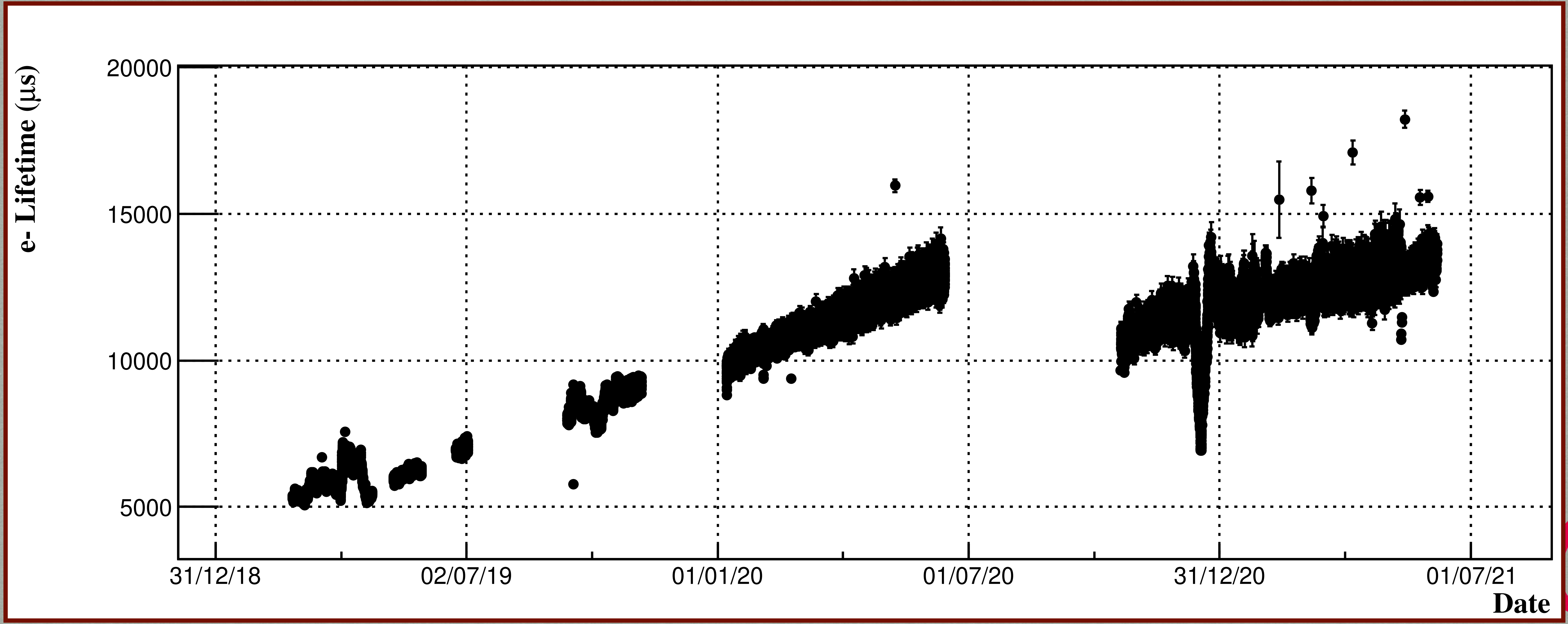
Next-White calibration: ^{83m}Kr

JINST 13 (2018) 10, P10014

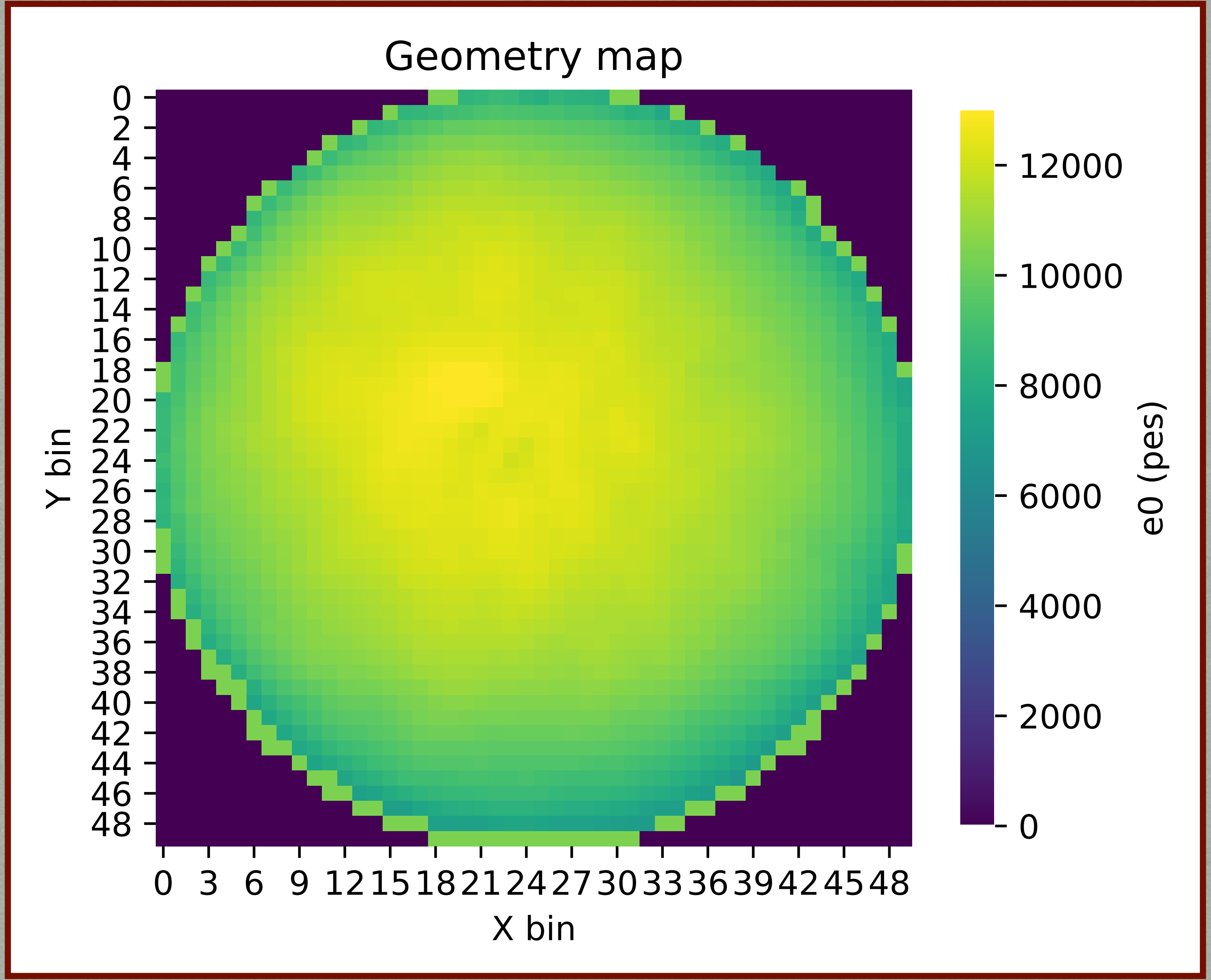


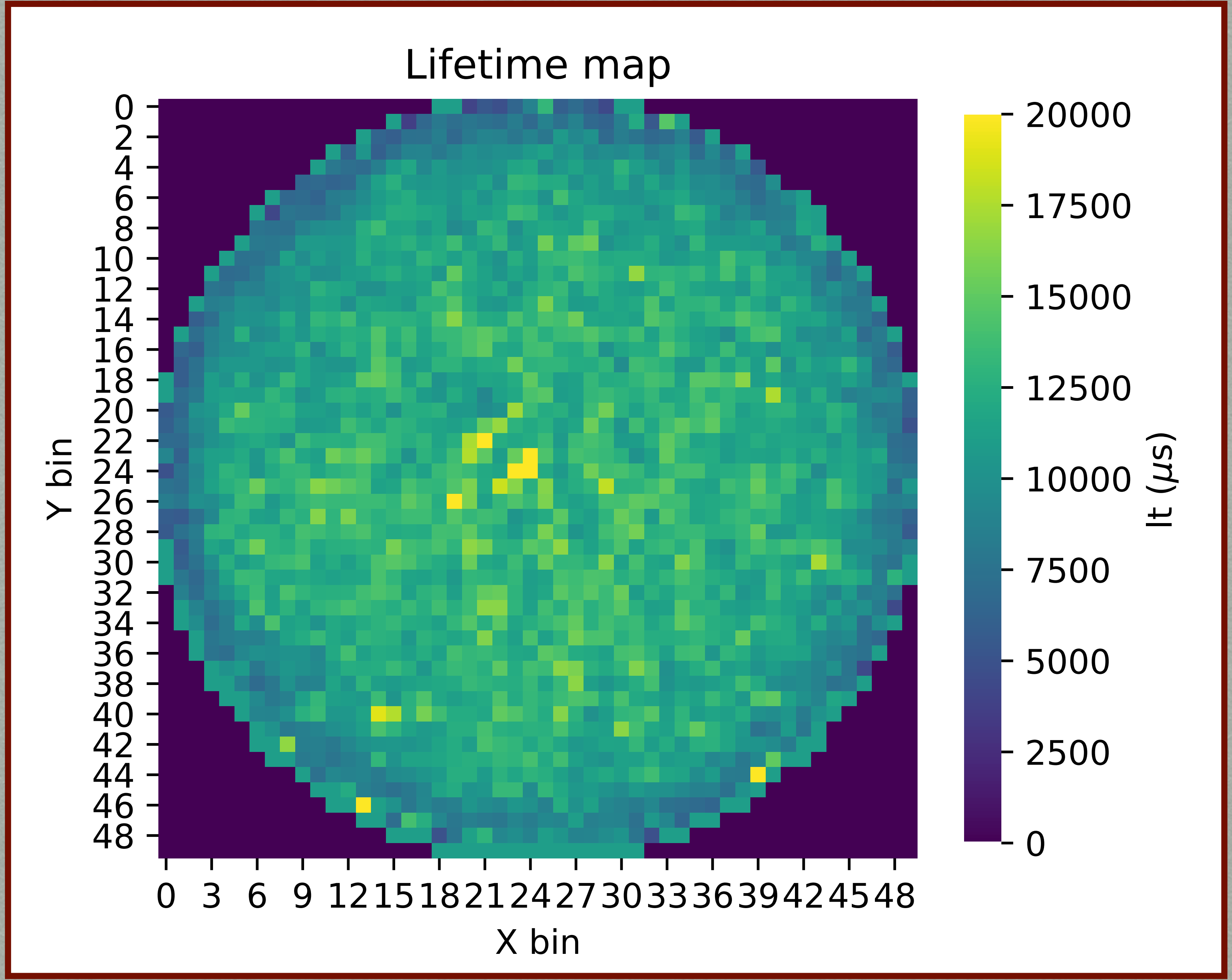
- ^{83m}Kr decays (from ^{83}Rb source) introduce XYZ uniform low-energy point-like events constantly in the chamber
- Dual trigger scheme allows acquisition of ^{83m}Kr triggers in parallel to higher-energy physics triggers
- 2 factors degrade detector response:
  1. Geometry (no homogeneous XY light collection)
  2. Attachment of ionization e- while drifting
- These events provide **energy correction** & continuous detector **monitoring**

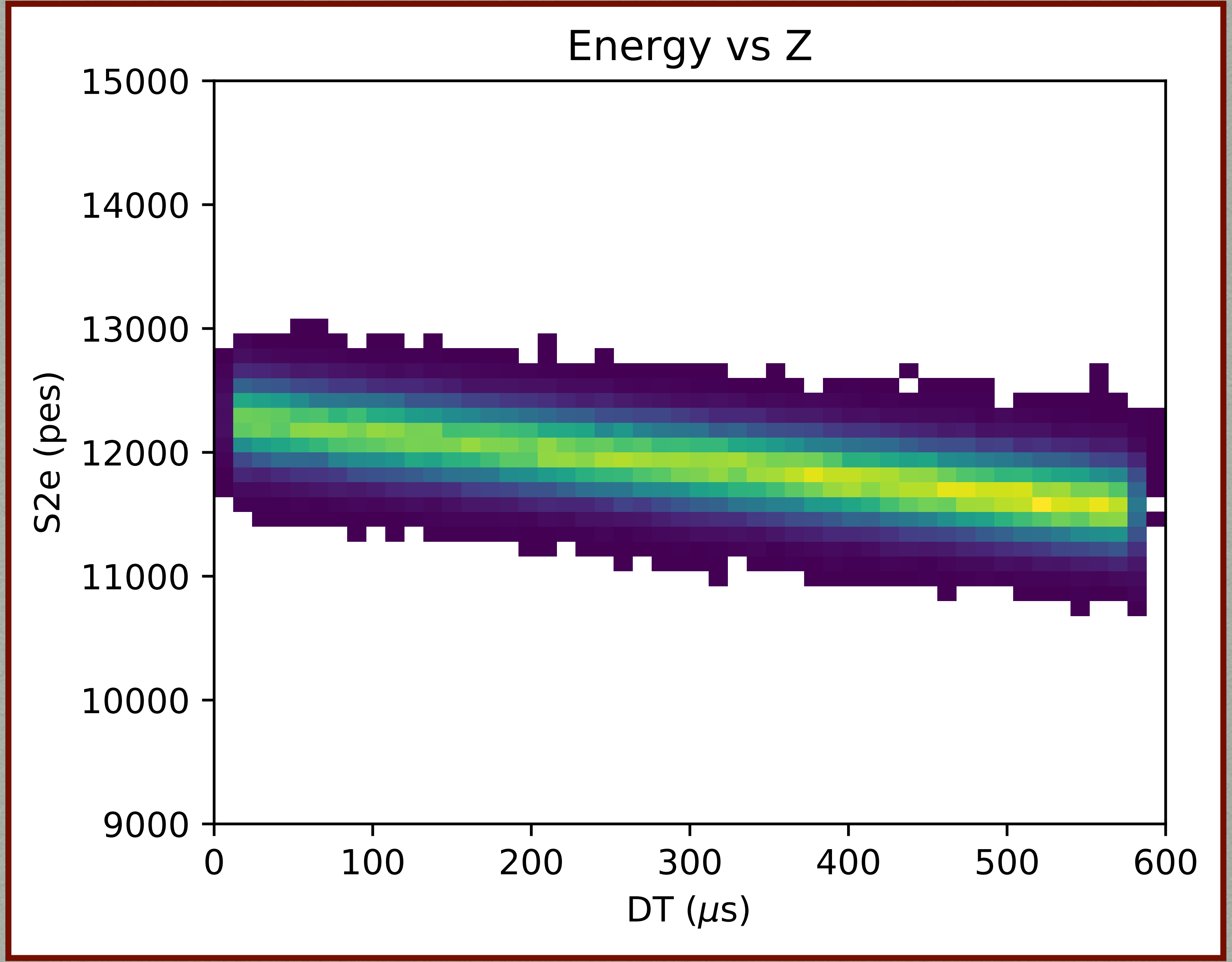




Next-White corrections: ^{83m}Kr

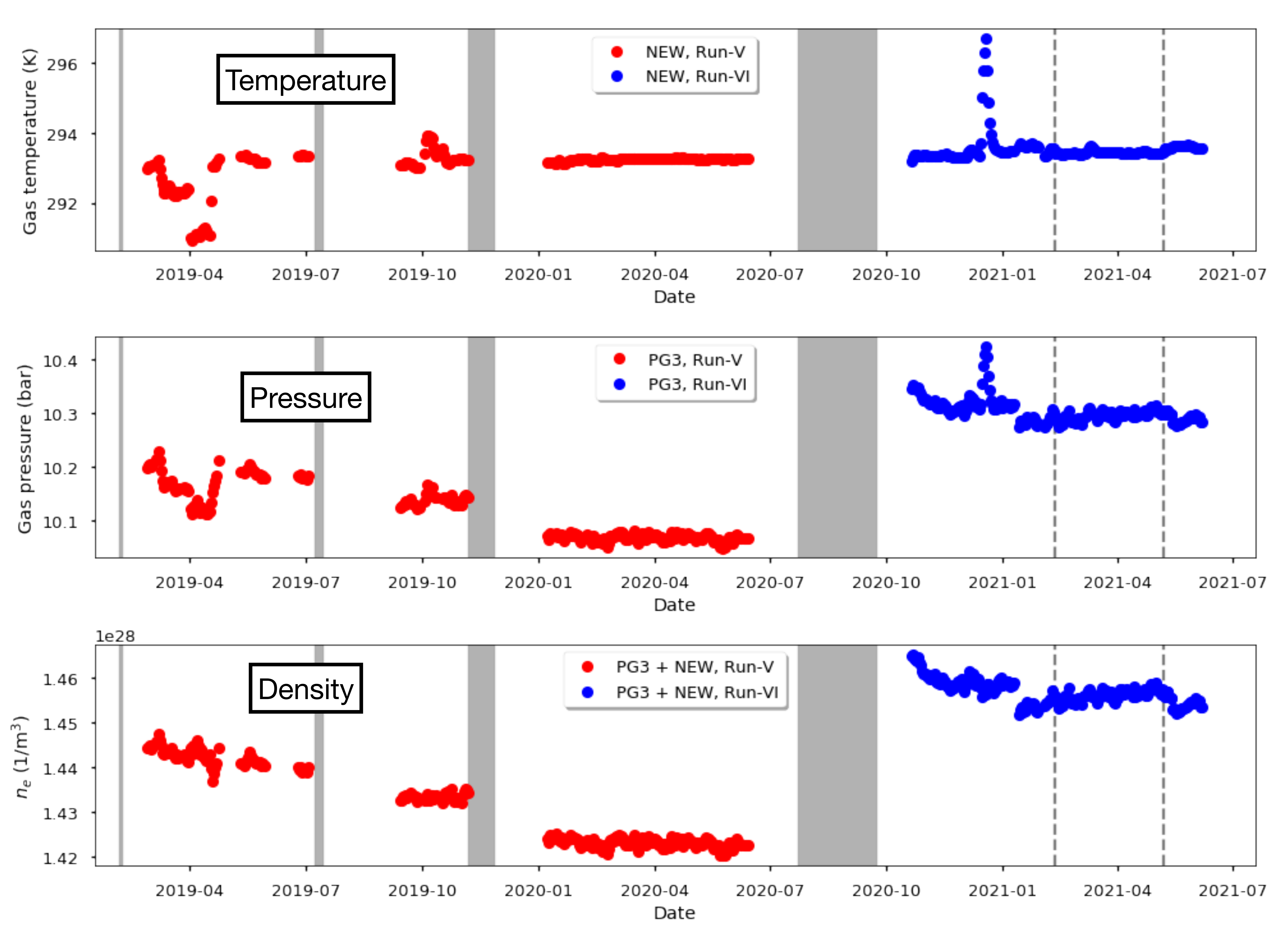






Gas density

- Density variations → variations in BG absorption length → corrected



$$n_e = \frac{Z_{\mathrm{Xe}} \cdot N_A \cdot P}{z \cdot R \cdot T}$$

Run period	n_e $(10^{28})/\mathrm{m}^3$	n_e/n_e(Run-V)	R/R(Run-V)
Run-Va	1.4422	1.0085	1.0109
Run-Vb	1.4333	1.0022	1.0028
Run-Vc	1.4230	0.9950	0.9936
Run-V	1.4301	1	1
Run-VI	1.4568	1.0187	1.0241

Selection of events

Inclusive sample → **Background sel.** → **No-overlap sel.** → **Double electron sel.**

Background sel.
- Rejects multi-track & e- from the borders
- Large statistics

→ Radiogenic background fit

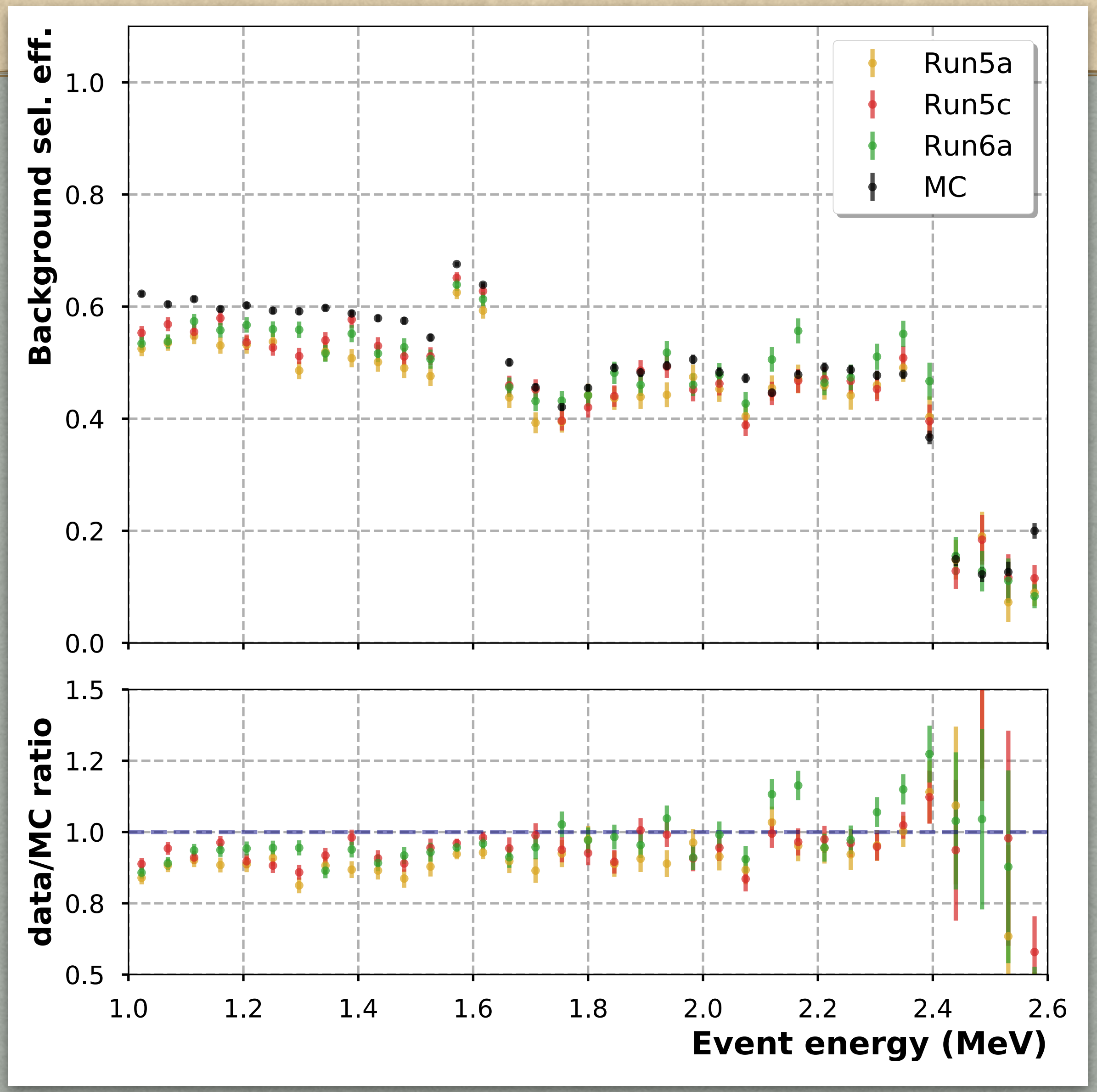
No-overlap sel.
- Rejects events where the two blobs share hits
- Lower statistics, but allows blob-related analysis

→ Background subtraction fit with Eblob

Double electron sel.
- Only ββ candidates
- Ethr computed empirically (with MC)

→ Bkg-model-dependent fit

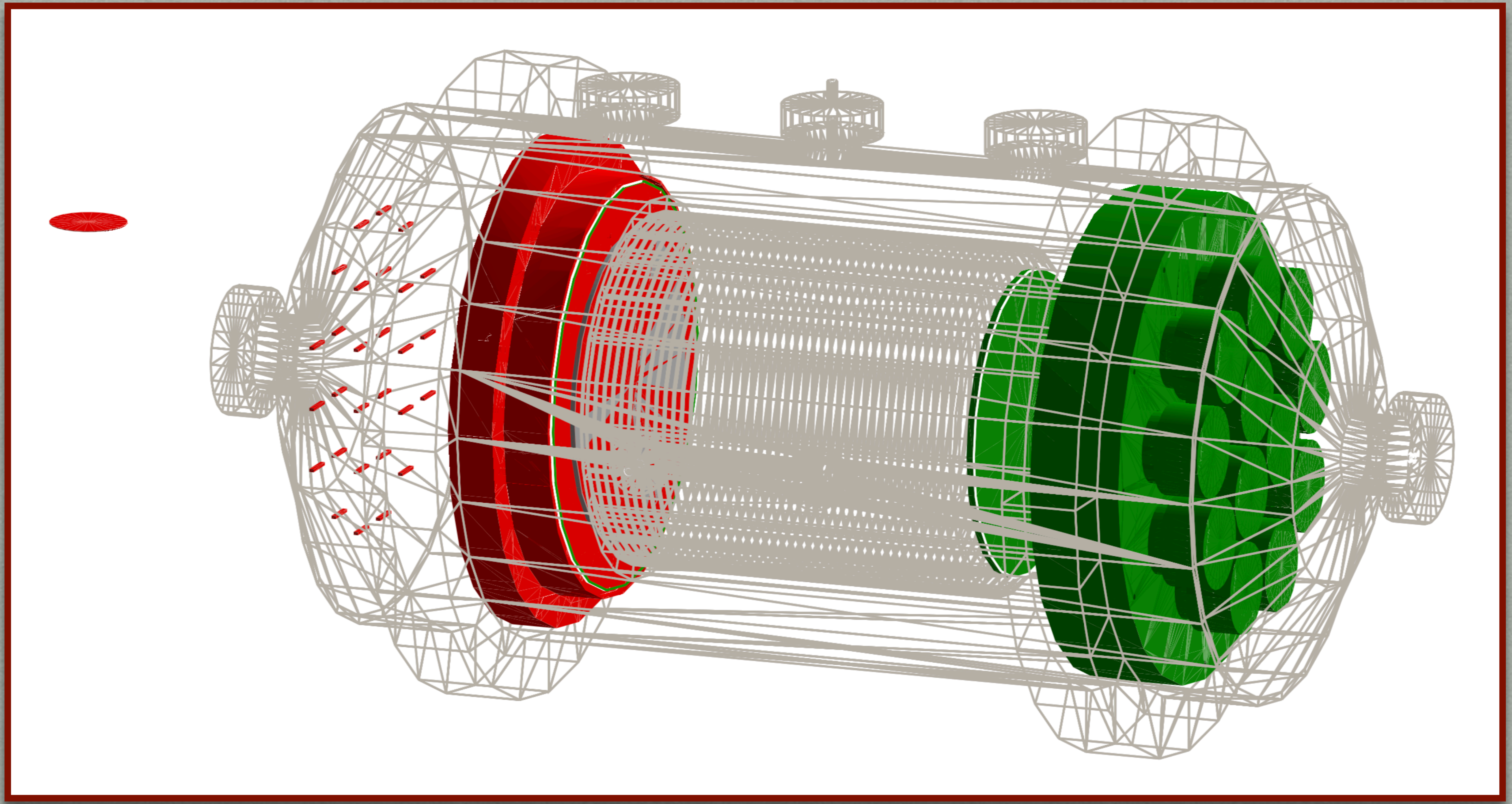
→ Background subtraction fit with Energy

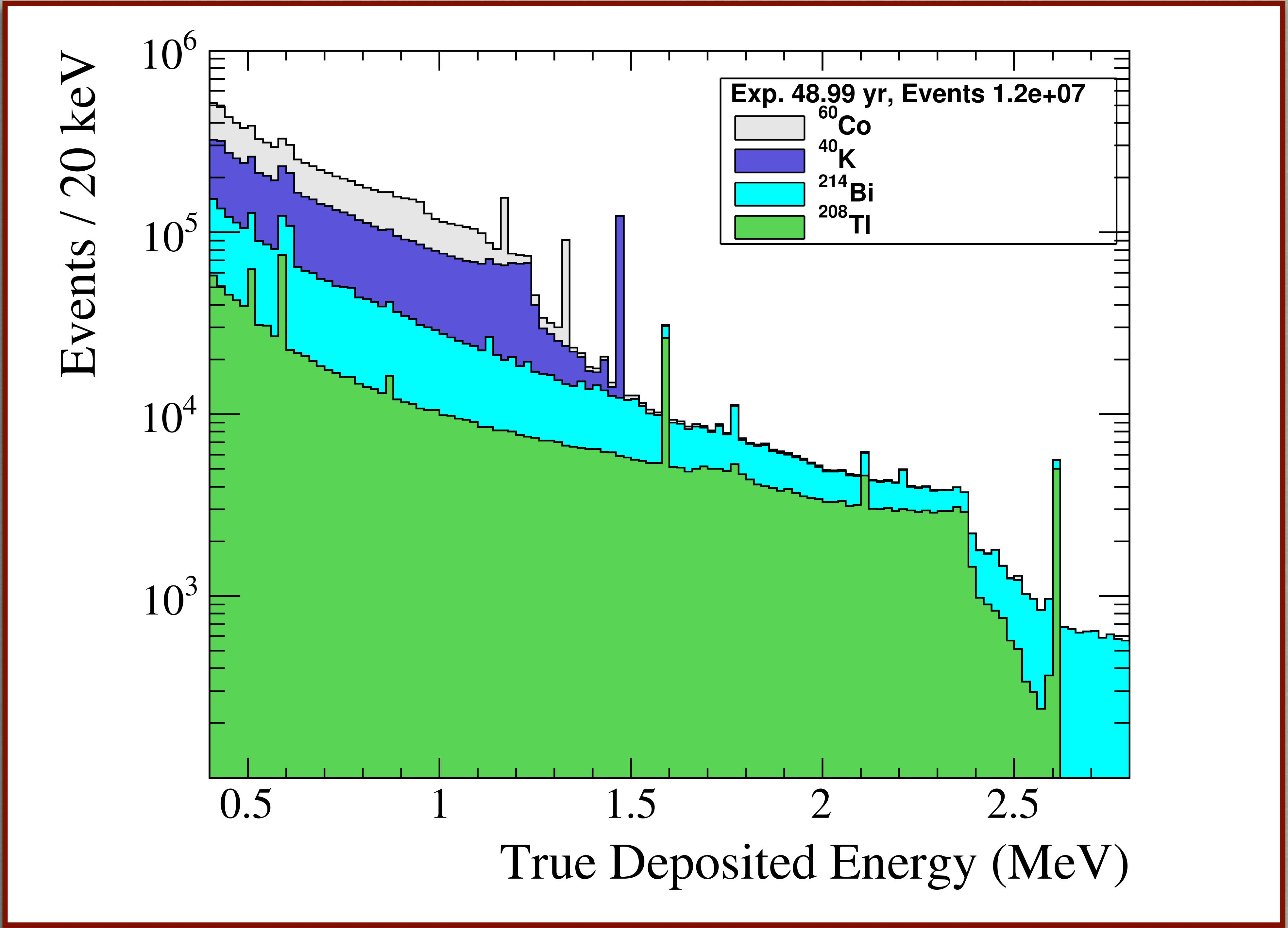


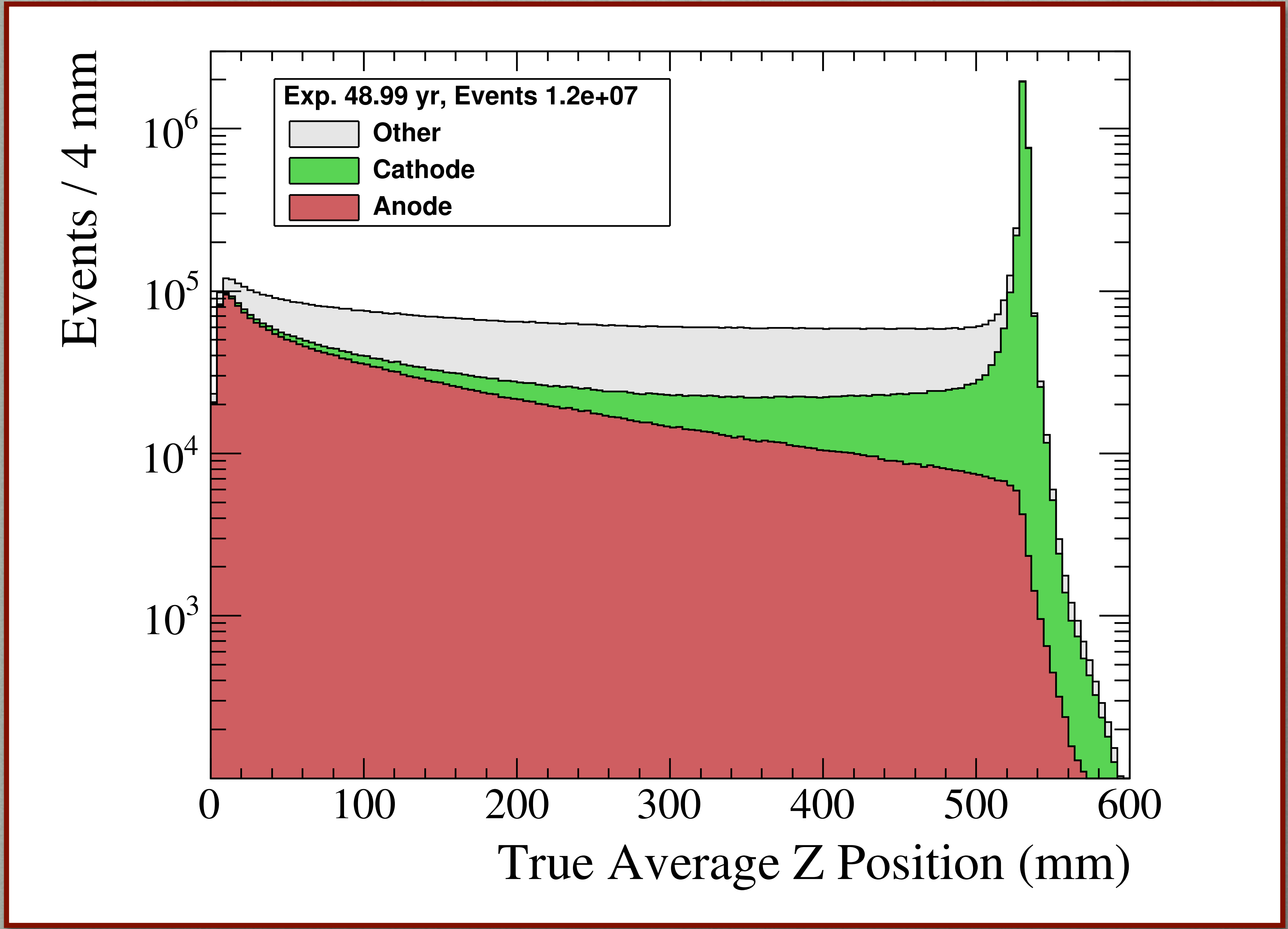
- Possible data/MC differences in event selection evaluated with independent samples (HE Calibration) and corrected

Background model

- MC background exposure: 48.99 y
  - **4 bkg isotopes** (^{208}Tl, ^{214}Bi, ^{60}Co, ^{40}K)
  - **84 sources** grouped in Cathode, Anode, Other

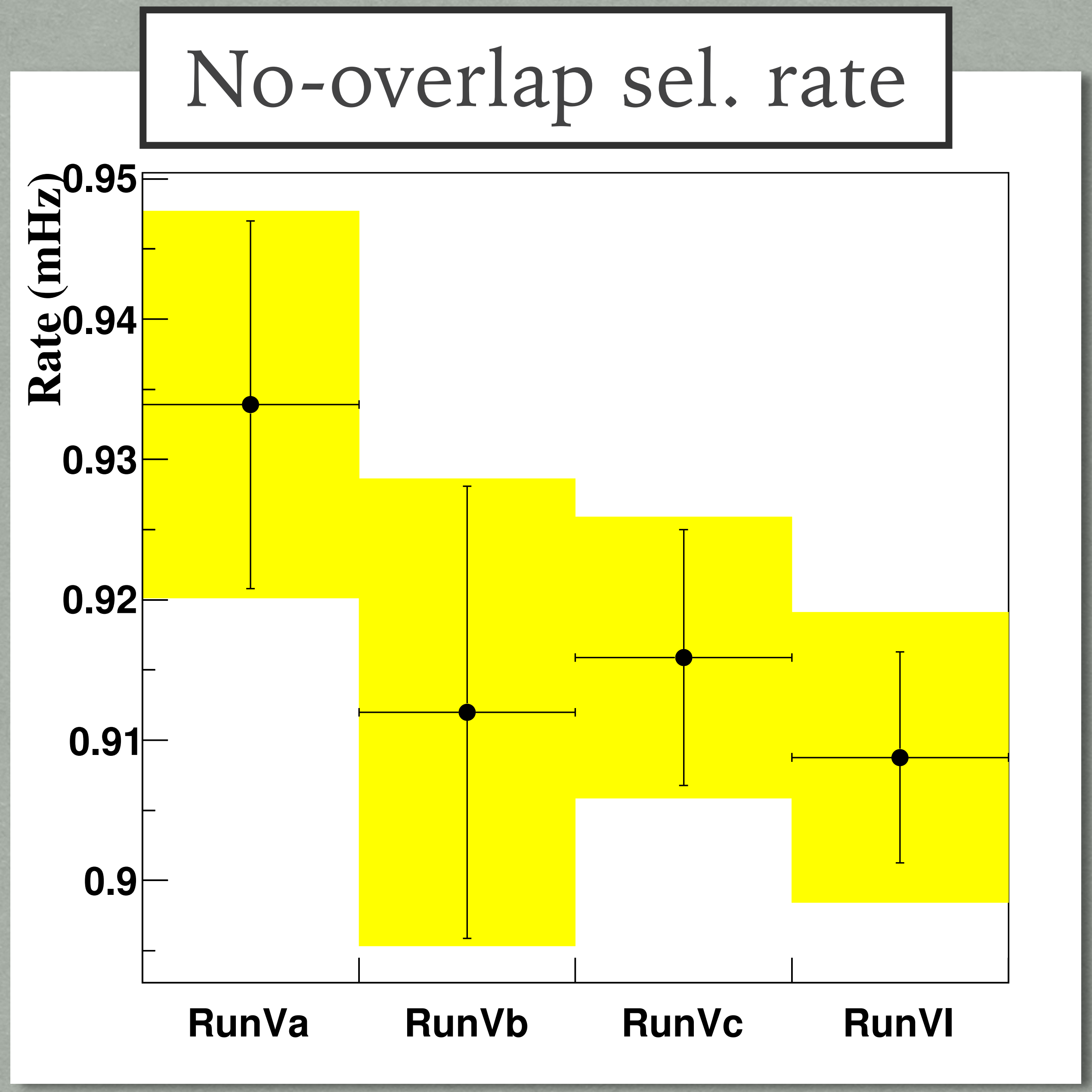


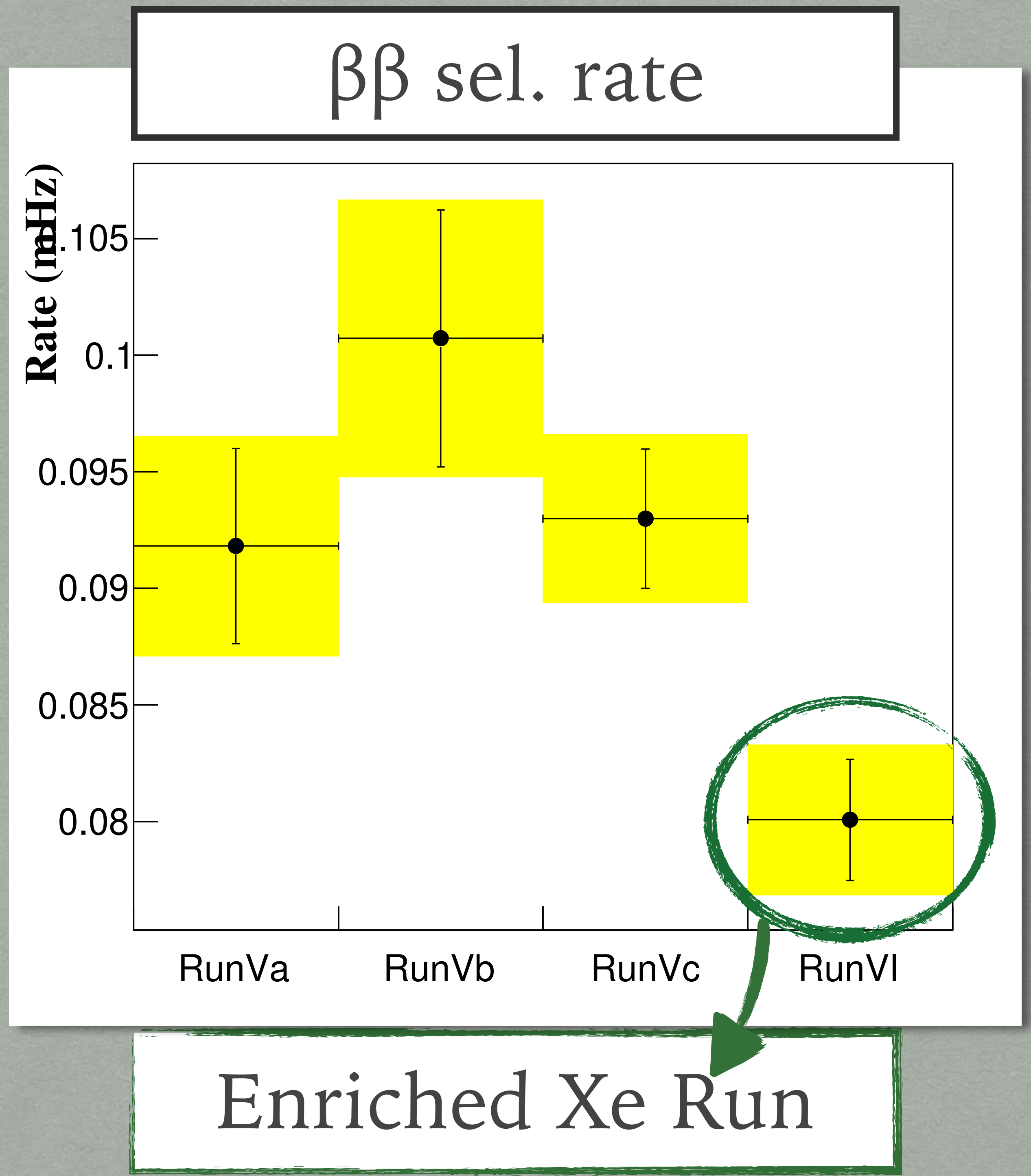




Background stability

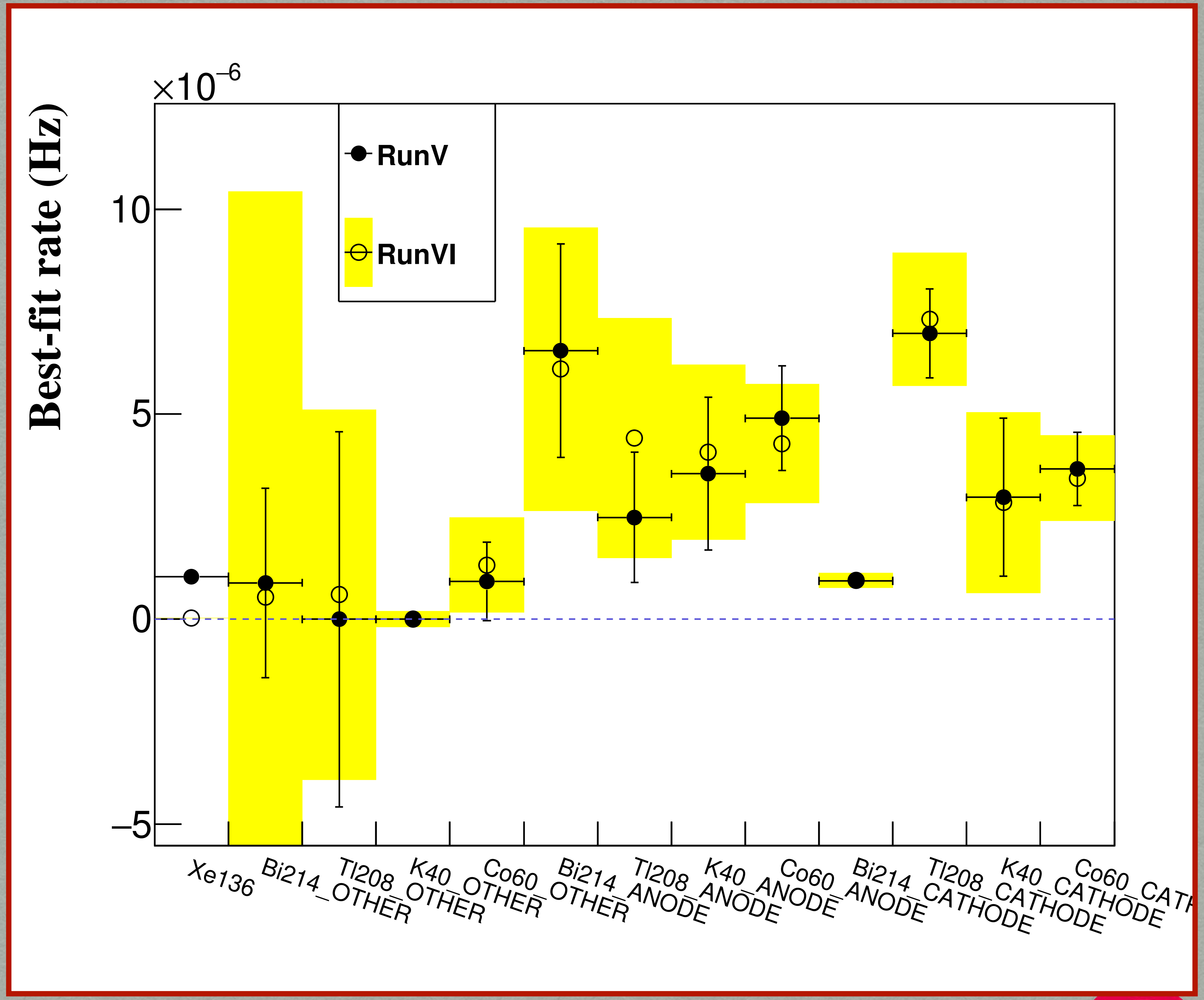
- Evolution of background & ββ-selected events rate
- Backgrounds <u>stable</u> in time
- bb events rate depends on the run (as expected)





- After fitting (E+Z) spectra:

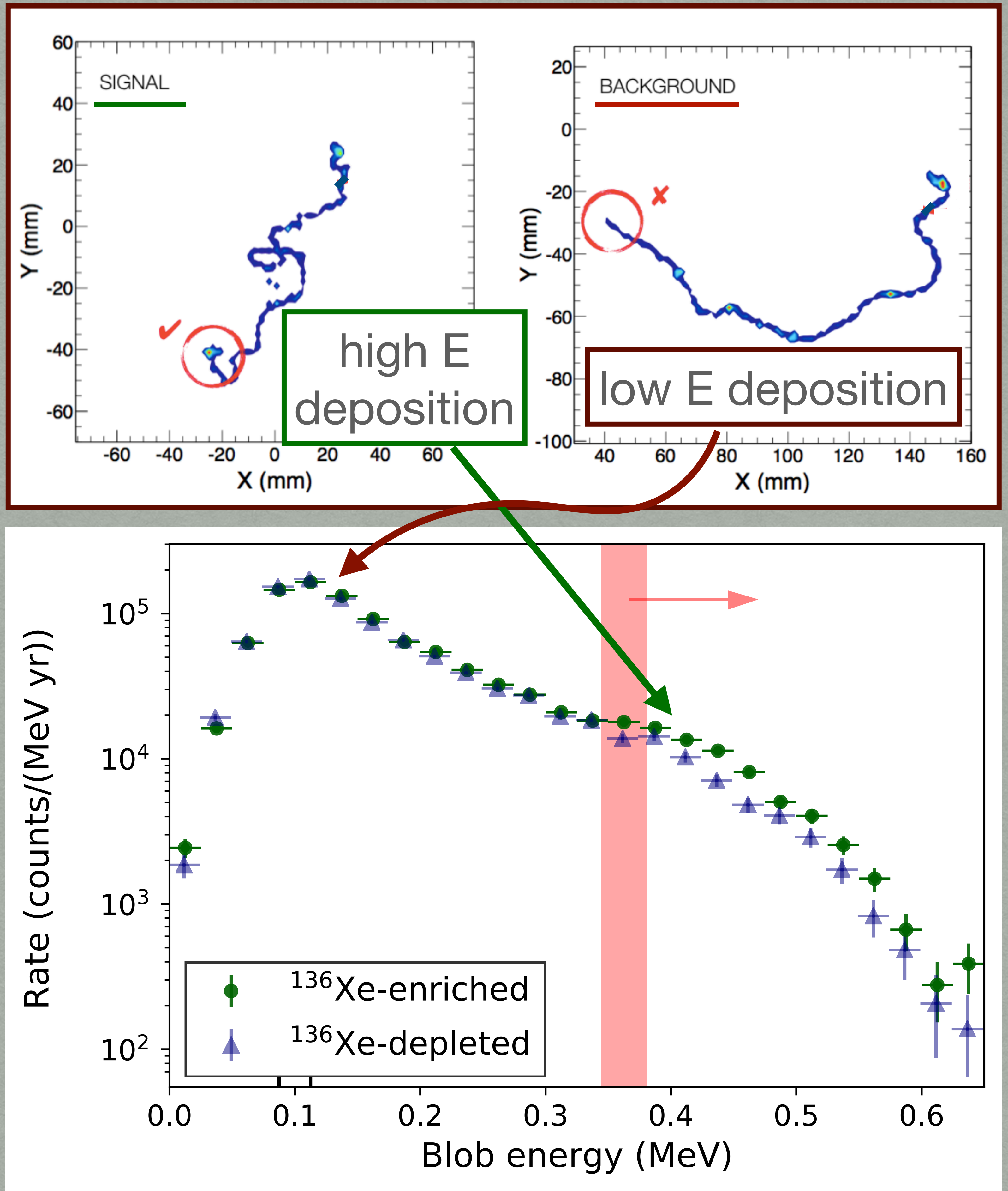
  Contribution of each isotope/location <u>consistent</u> between periods



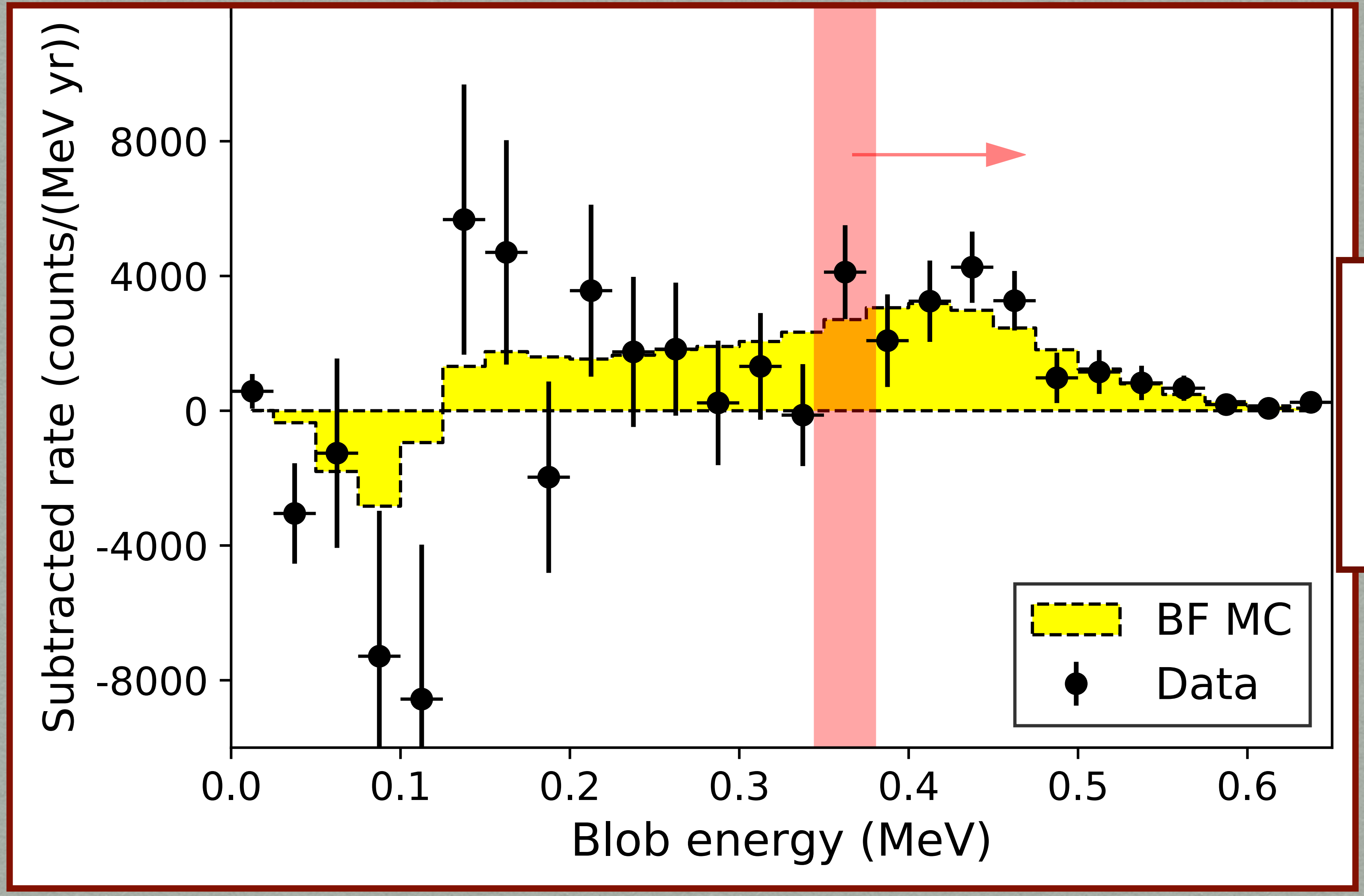
2νββ: Background subtraction fit II

- Additional strategy considered
- Analogous to the background subtraction fit presented but:

~~event energy~~ → energy around less energetic extreme ("eblob")



- Again, RunV (enriched) - RunVI (depleted), and resulting eblob distribution fitted to expected (ββ2ν)

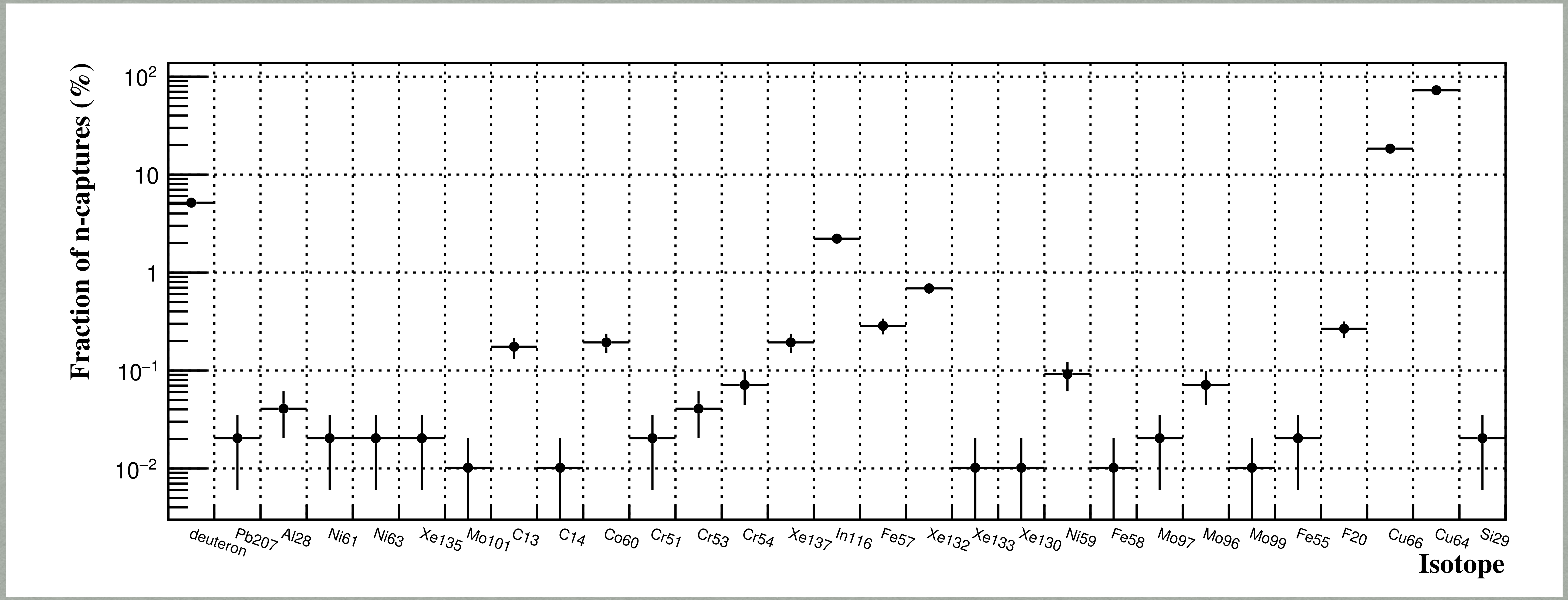


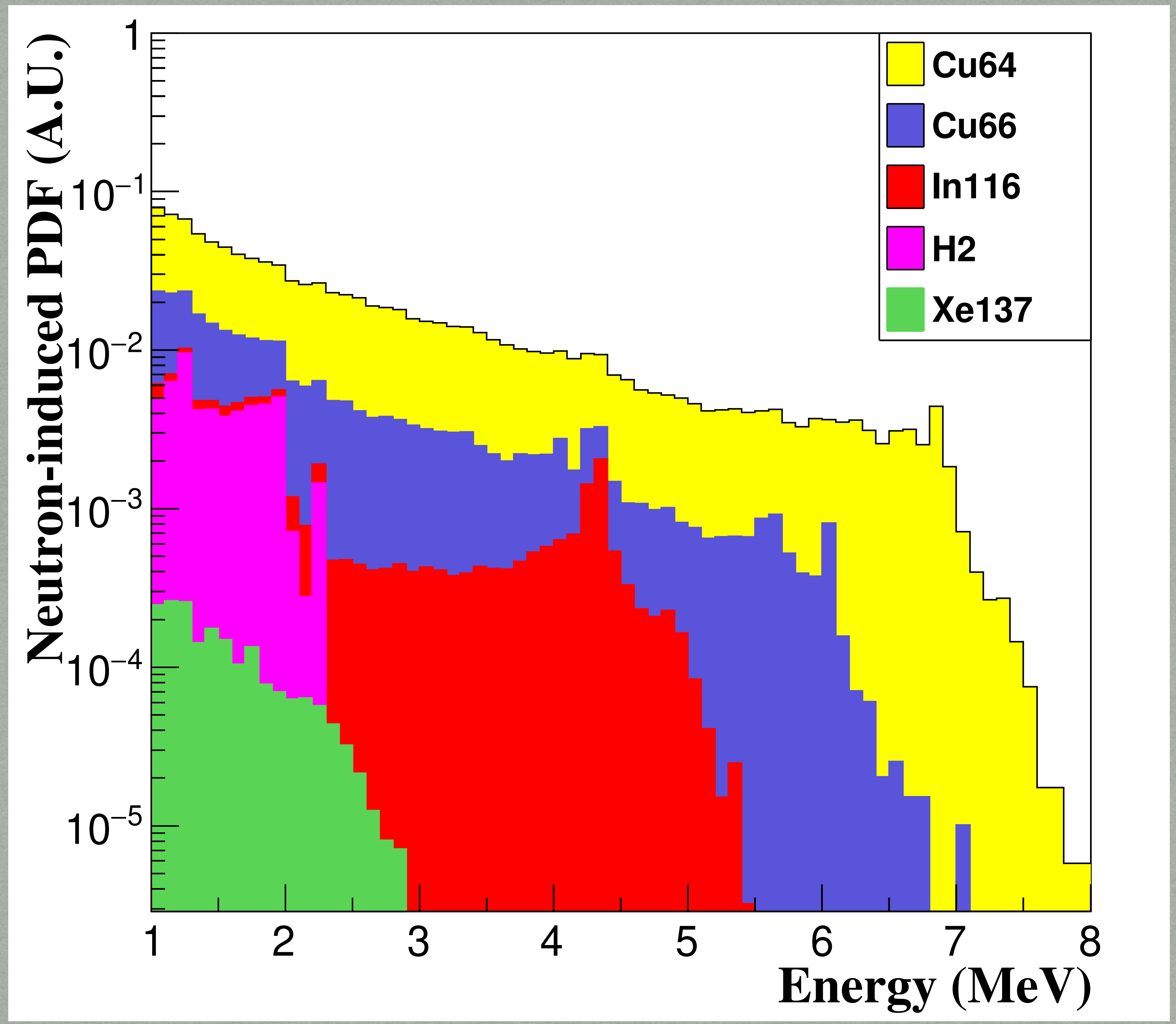
Good χ^2/dof (24.8/25)

$$T_{1/2}^{2\nu} = 1.66^{+0.29}_{-0.21}(\text{stat})^{+0.25}_{-0.25}(\text{syst}) \times 10^{21}\ \text{y}$$

Cosmogenic Backgrounds

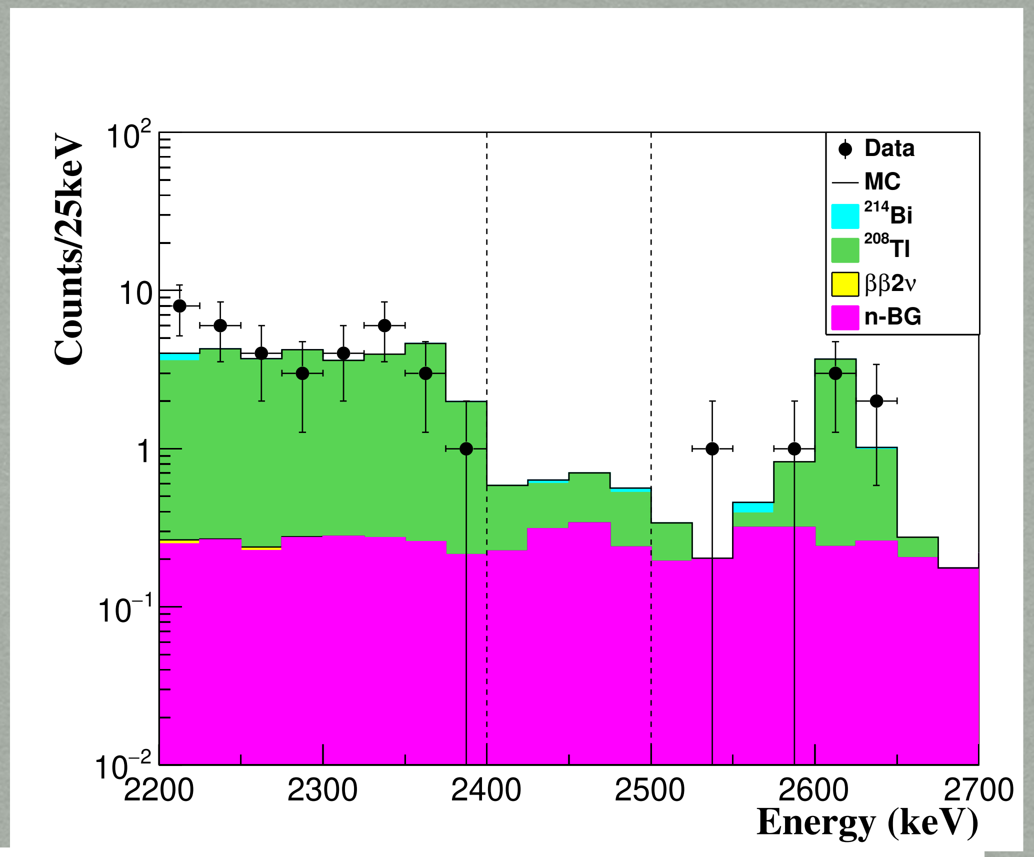
- Induced by high-energy (~TeV) muons that reach the laboratory
- They produce neutrons, that after thermalization, can activate detector materials
- Activations yield:
  - prompt deexcitation γ (mostly Cu isotopes), that can be temporal-correlated with muon
  - delayed gammas from long-lived isotopes (^{137}Xe)

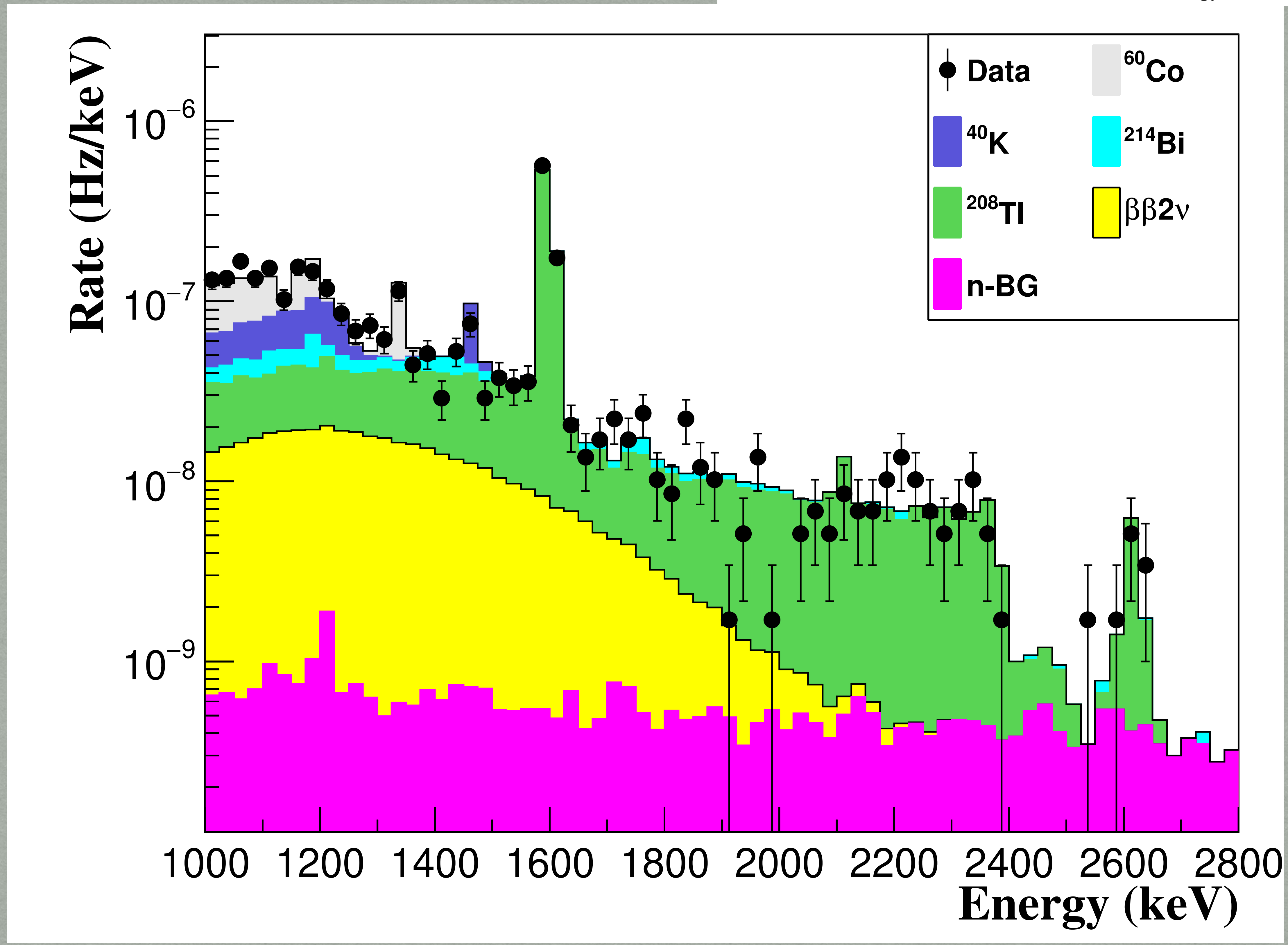




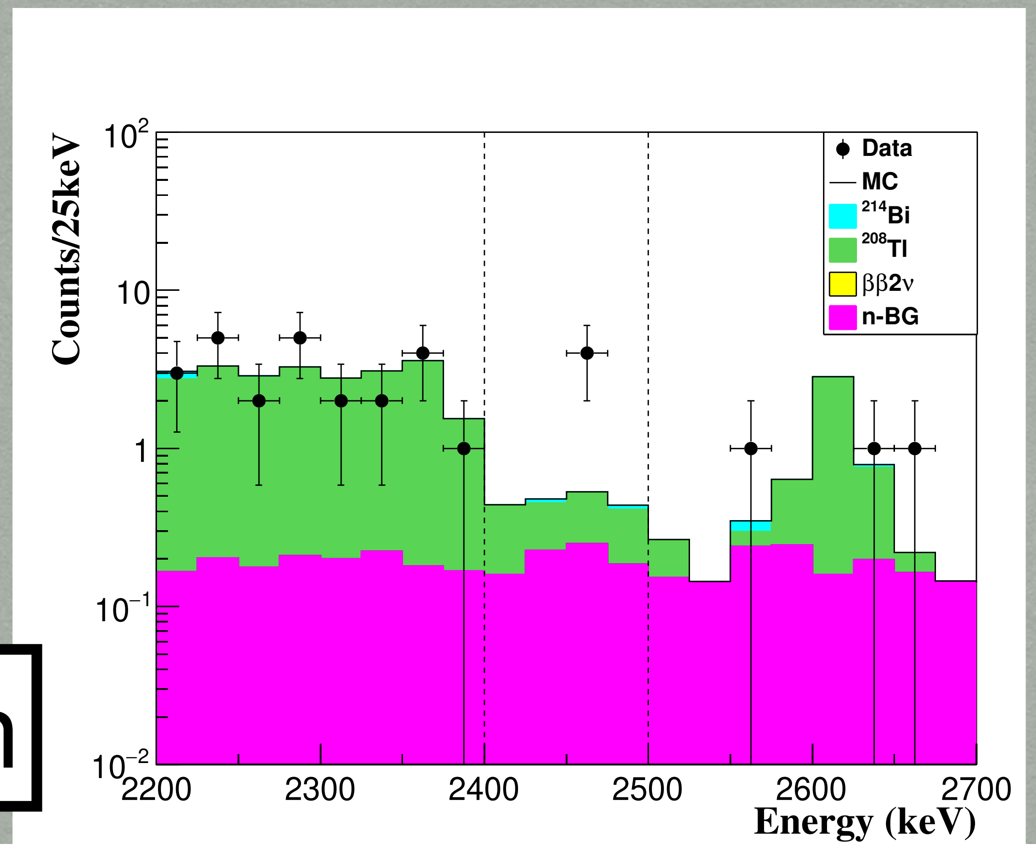
0νββ fits

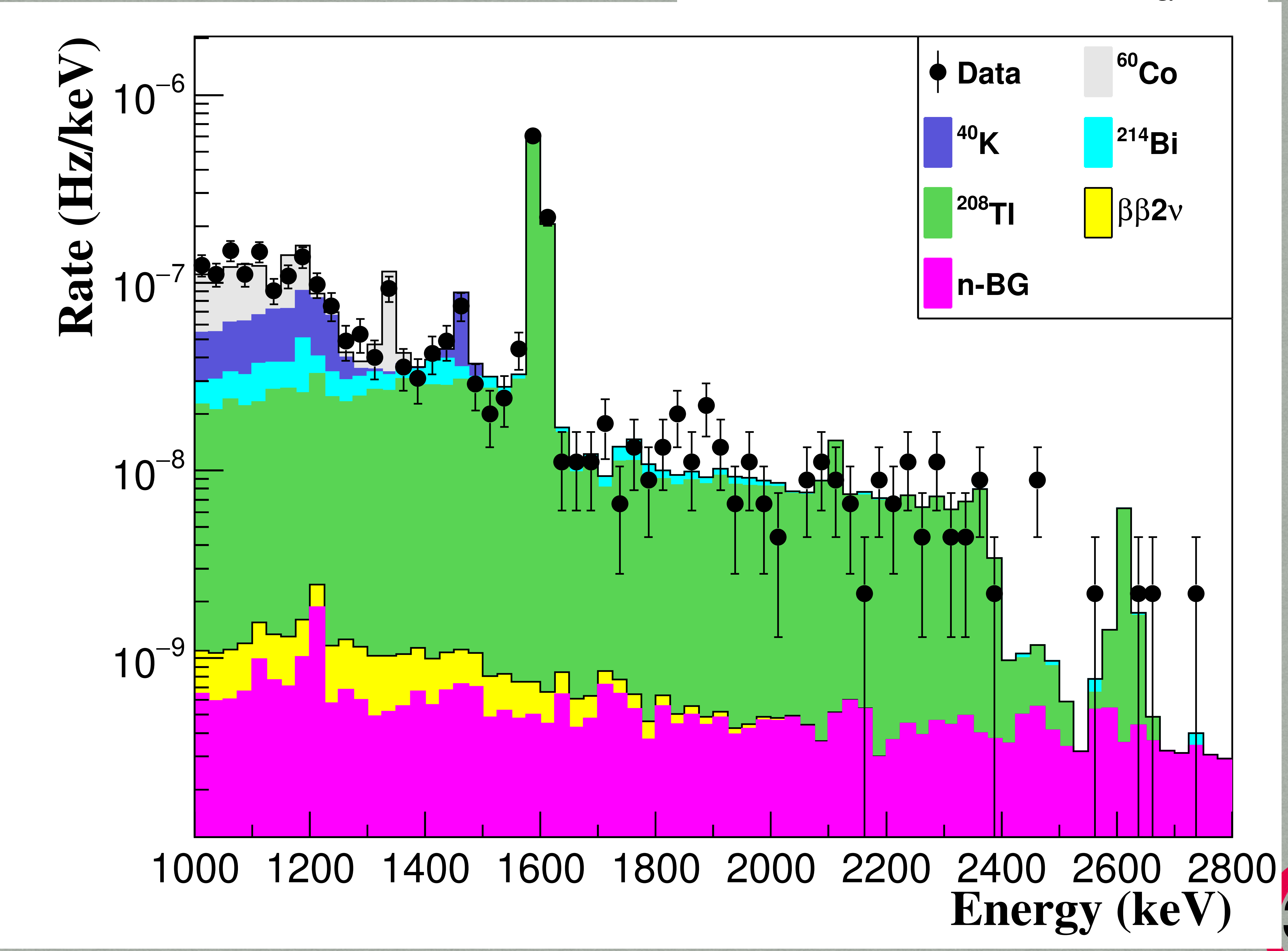
^{136}Xe-enriched Xe Run





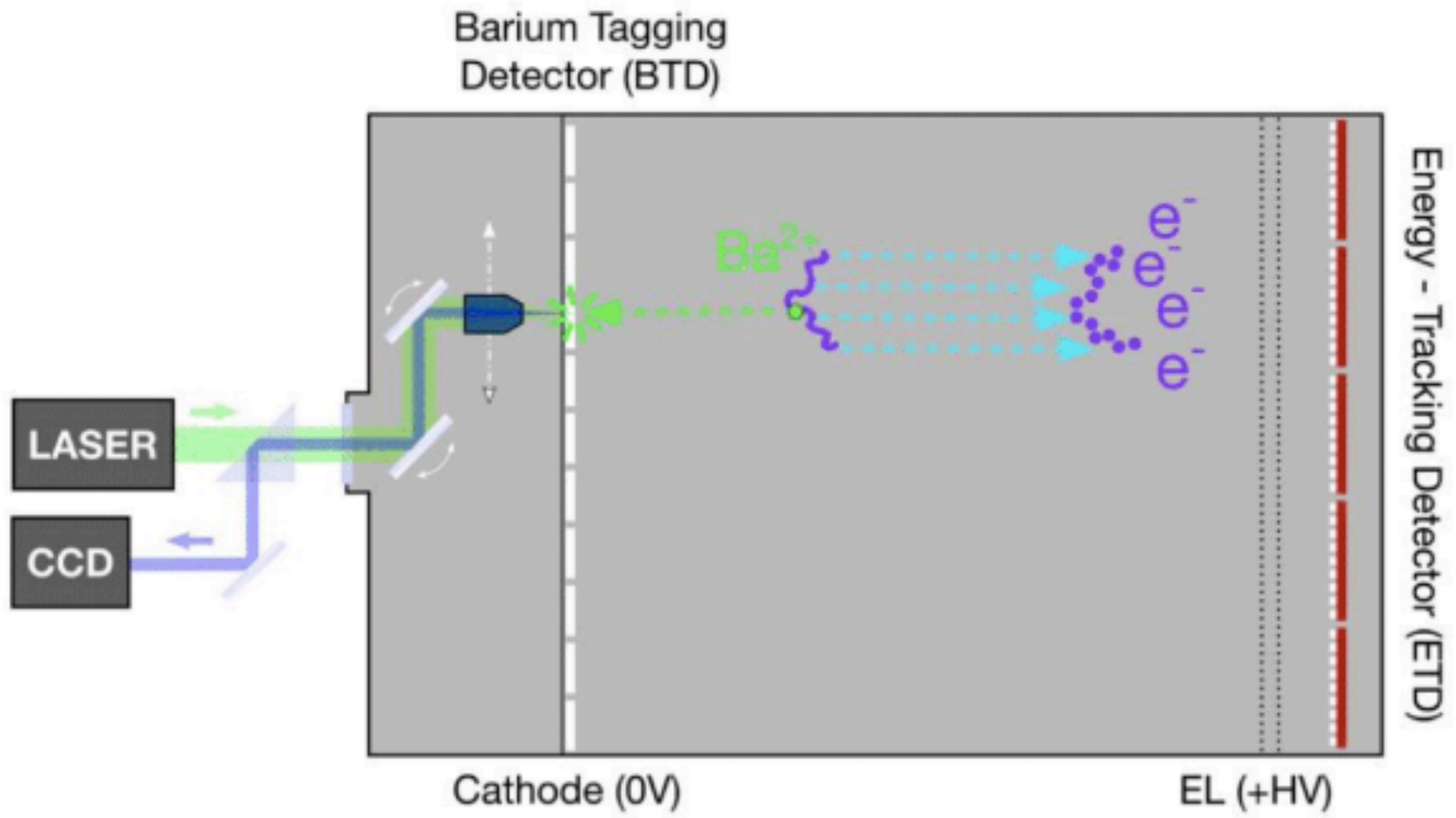
^{136}Xe-depleted Xe Run





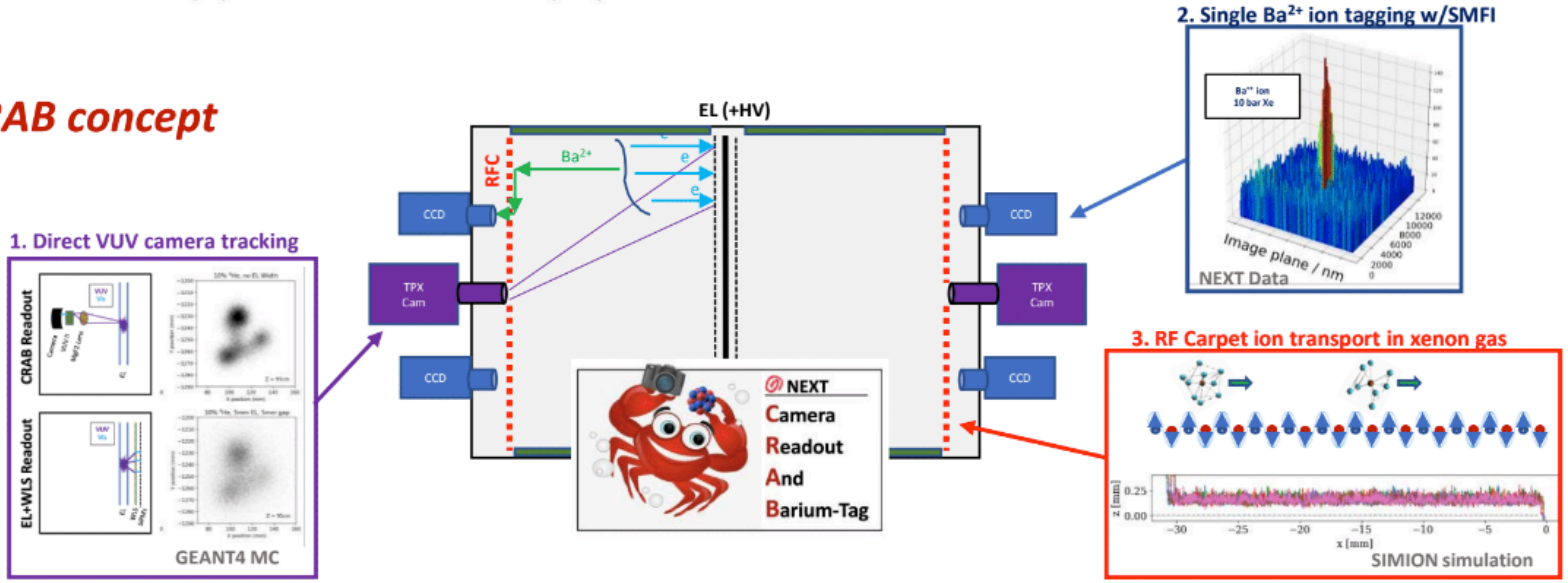
Barium tagging demonstration phases

NEXT-BTD concept



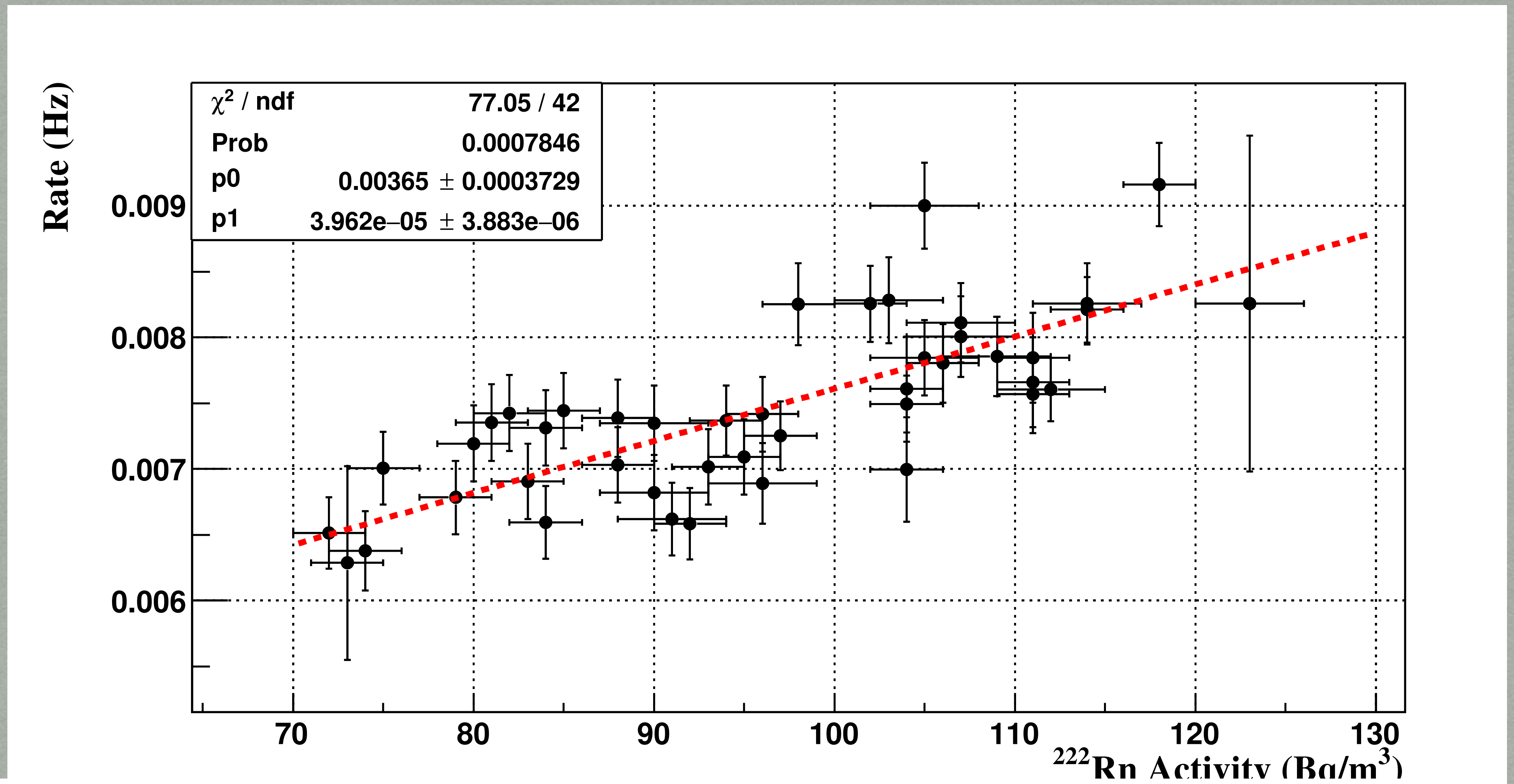
- Single ion sensor concepts are now fairly advanced
- Important R&D remains for ion concentration and collection:
  - *Sensor-to-ion (BTD concept)*
  - *Ion-to-sensor (CRAB concept)*

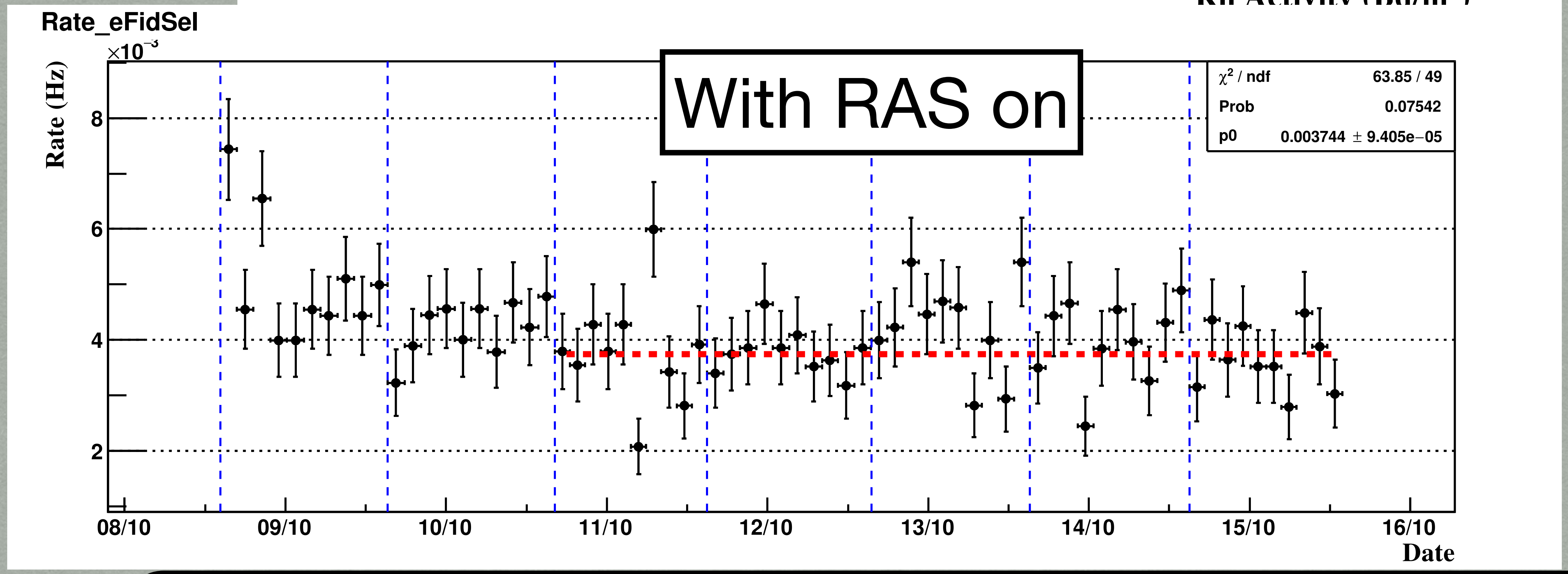
NEXT-CRAB concept



→ **Demonstrator phases under intensive development on 2-3 year timescale**

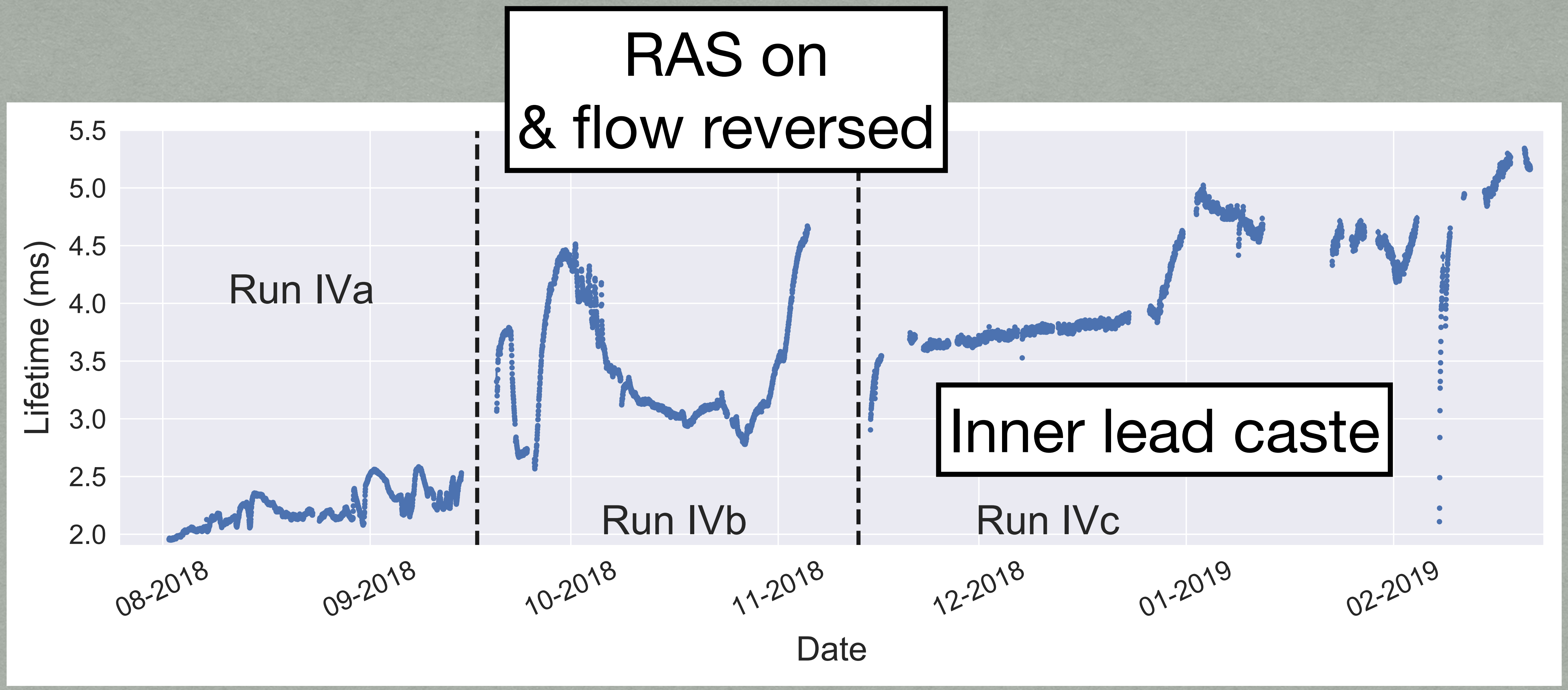
Radon Abatement System (RAS)

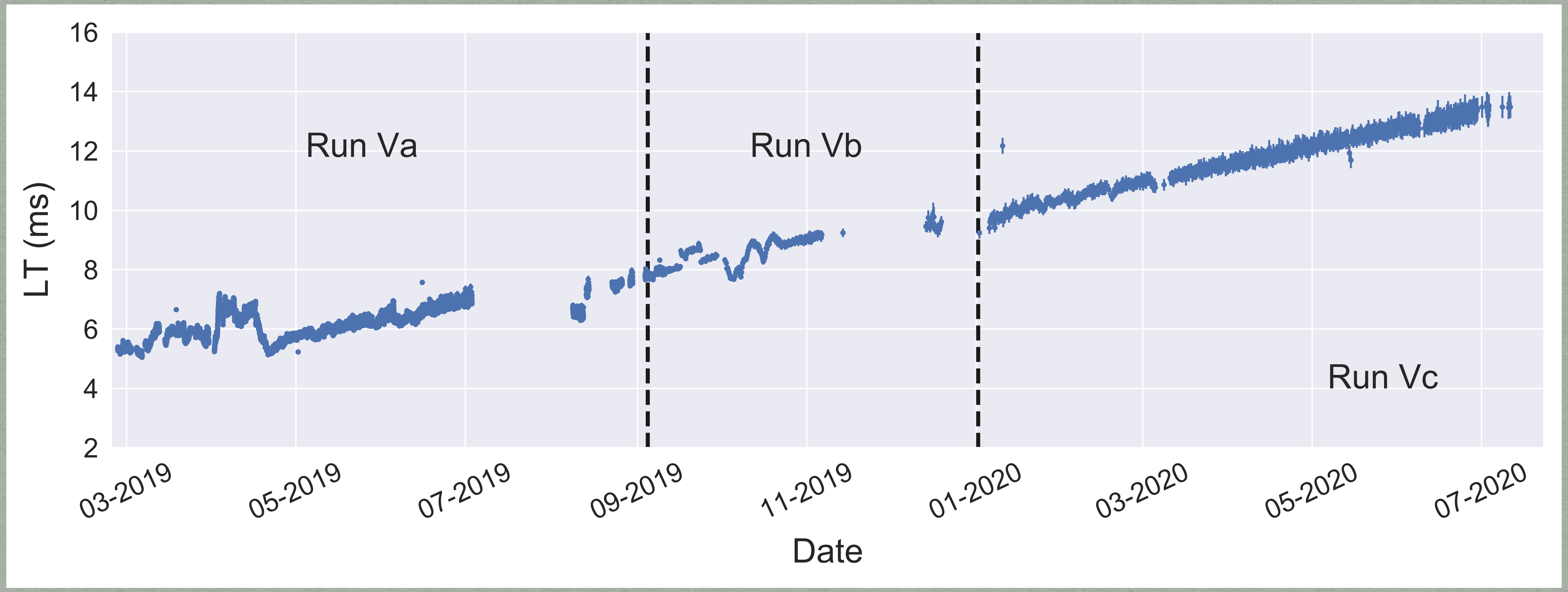


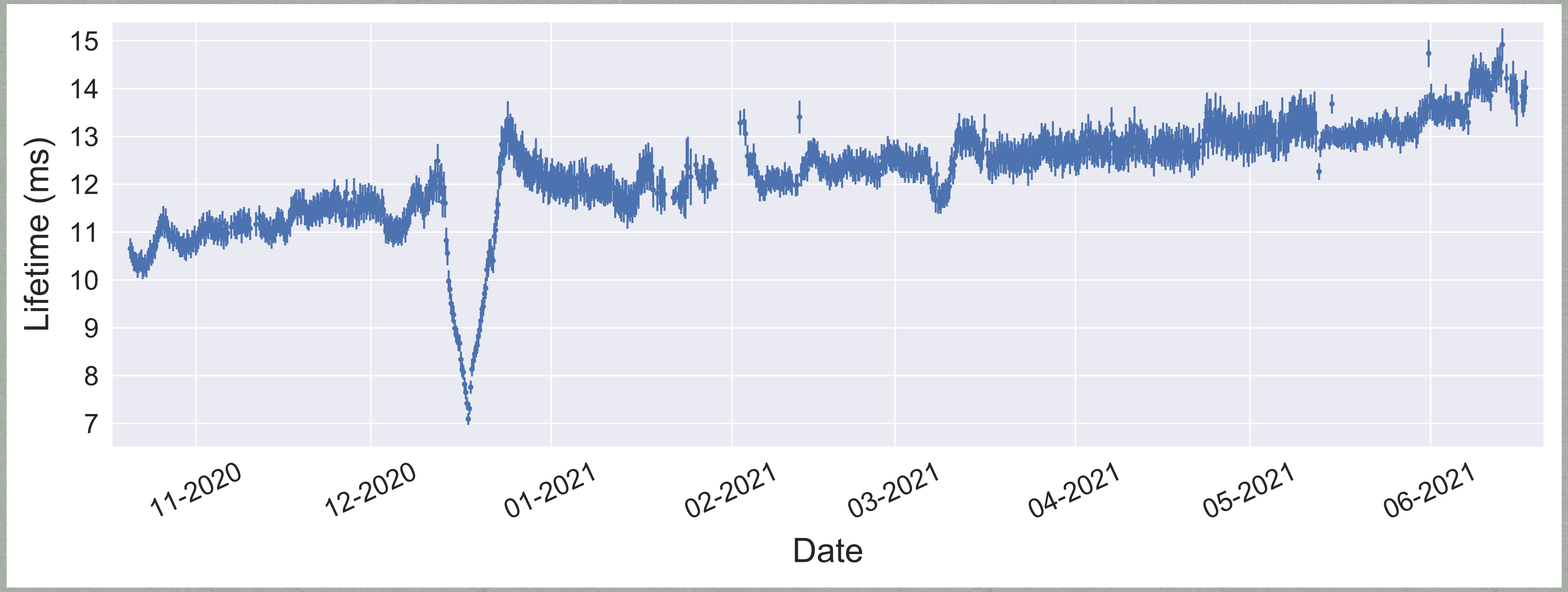


Backgrounds induced by airborne radon eliminated by providing Rn-free air to the NEXT shielding structure surrounding the vessel

Lifetime evolution

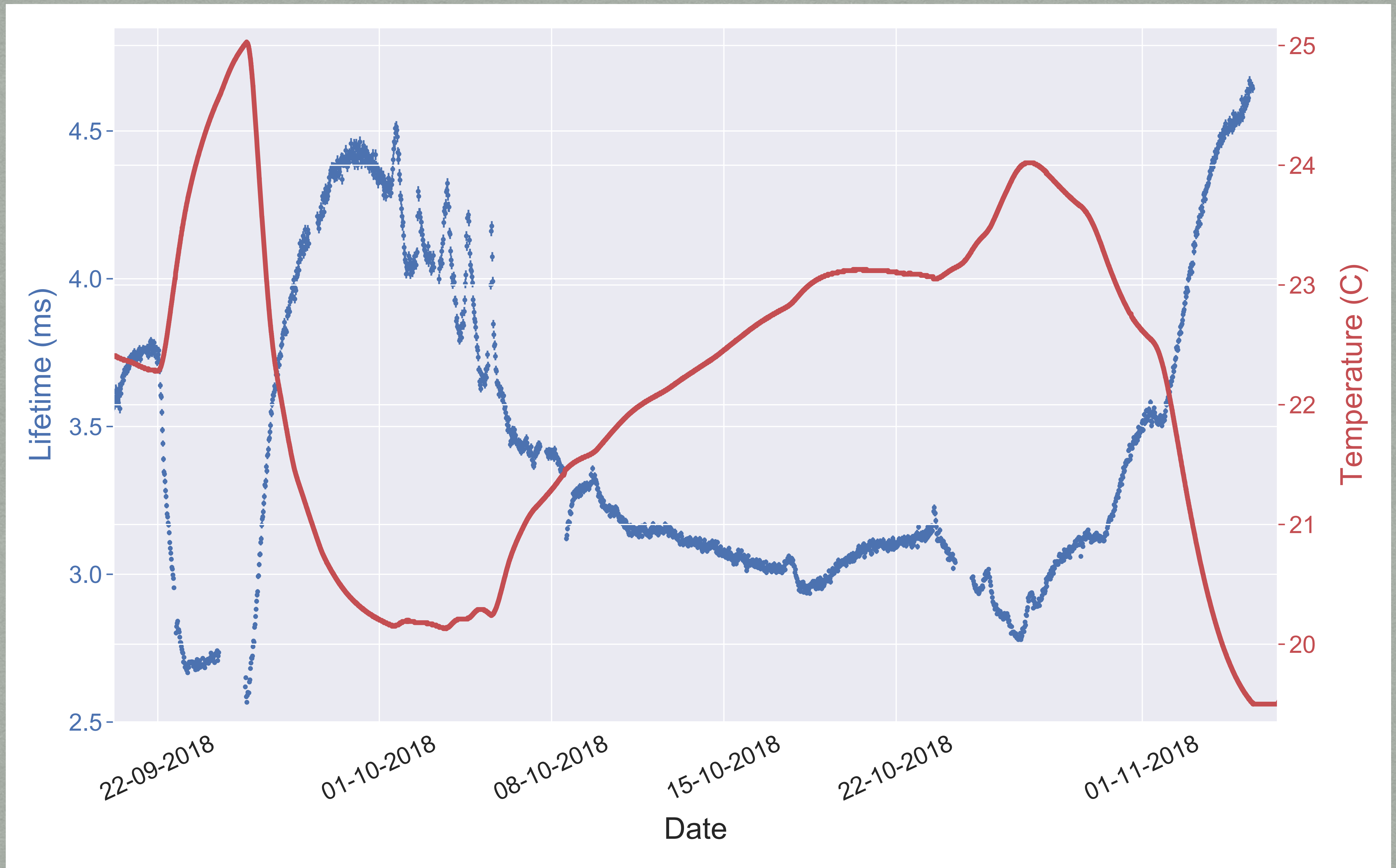


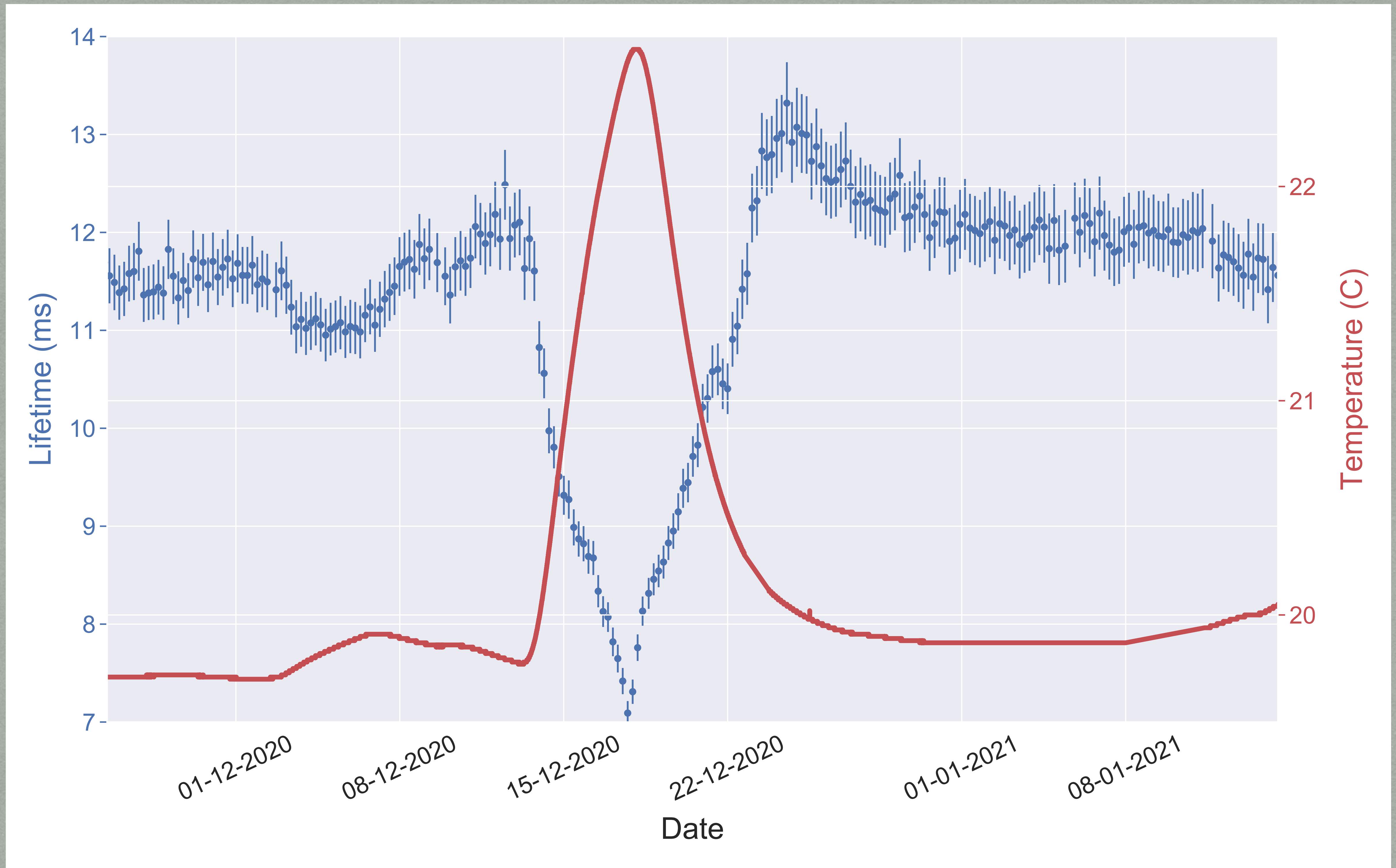




The several bumps are correlated with episodes where the temperature in the hall hosting the experiment had increased because of the air cooling system malfunctioning. In fact, it is remarkable how the variability decreased significantly after the installation of the inner castle and the radon abatement system.

Lifetime vs Temperature





The temperature variations of the gas, driven by the variations in the laboratory conditions, affect the system behaviour.

Gas system

Three main tasks:

- pressurization (and depressurization) of the system
- recirculation and cleaning of the gas
- eventual evacuation of the detector