



R2D2 project overview

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On Behalf of R2D2 collaboration

Second Workshop on Neutrinoless double beta decay search in
Xe - next-generation experiment - Manchester - 15/09/2026

Disclaimer

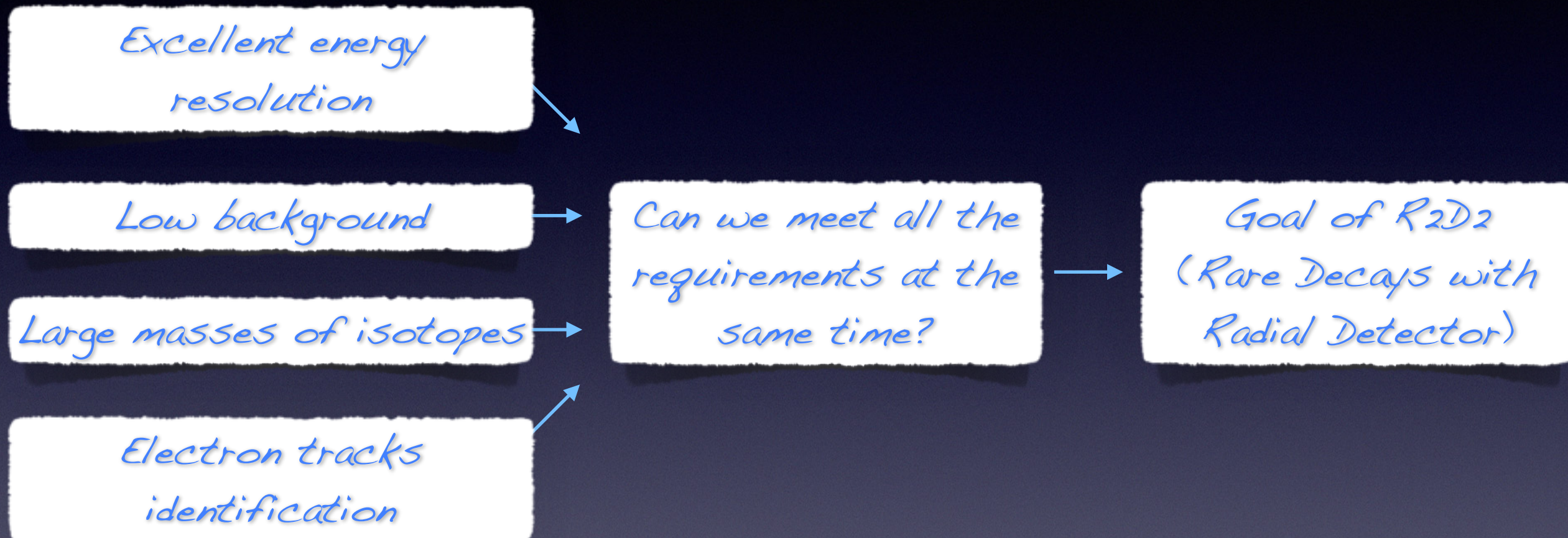


- Given the goals of this workshop and its intended audience, **this presentation deliberately does not provide a general overview of neutrinoless double beta decay** or a review of the experimental landscape.
- It assumes the importance of the search for $\beta\beta 0\nu$, the principles of its detection, and the crucial role of reconstructing the two electron tracks to achieve unambiguous signal/background discrimination.
- More complete presentations of R2D2 can be found elsewhere e.g. [Talk at ICHEP 2024](#)
- This talk focuses on the **R2D2 technology**, its current status, and its possible role within the future evolution of the field.

Birth of R2D2



- The **main requirements** to search for $\beta\beta 0\nu$ decay are:



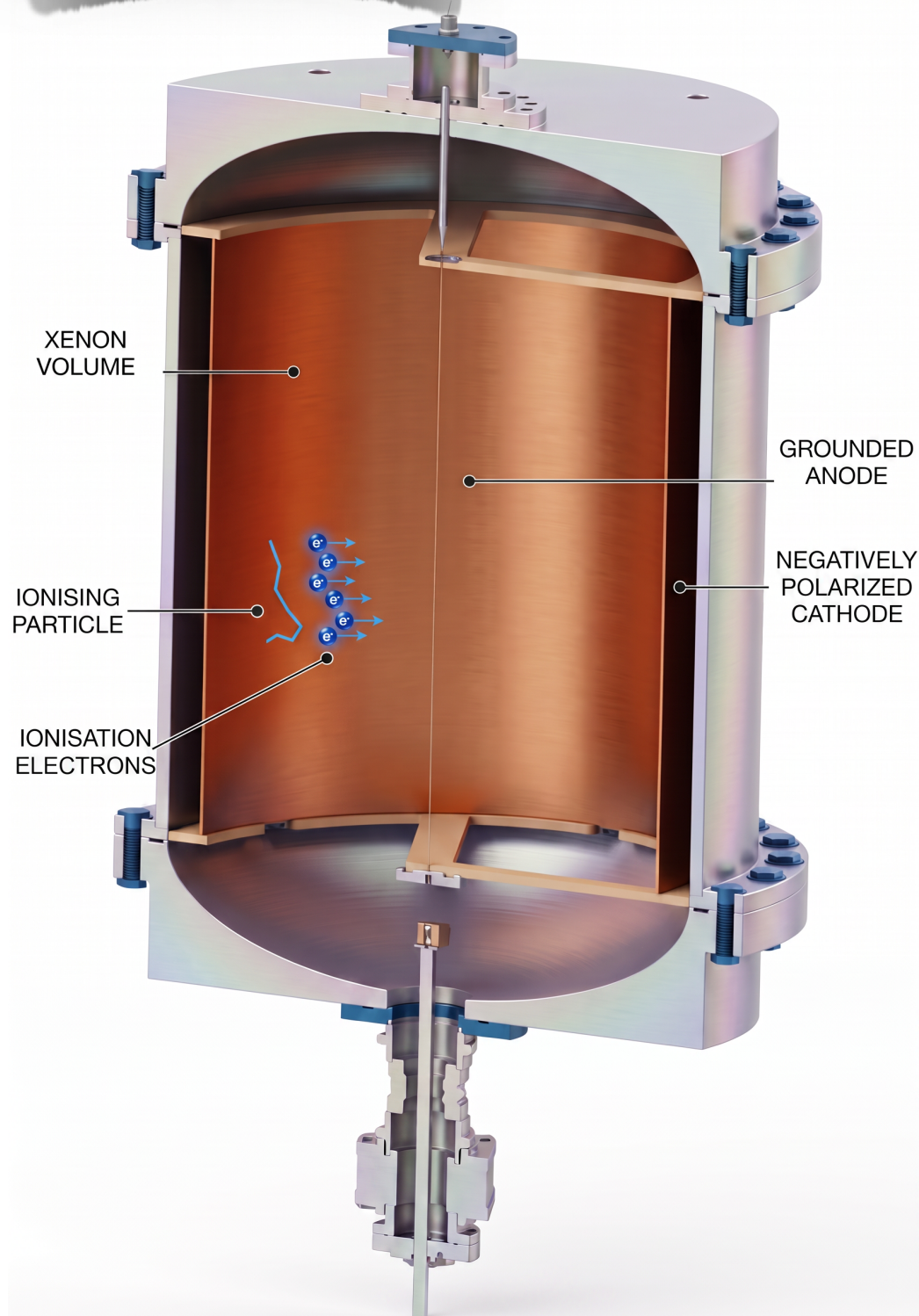
- R2D2 **started as an R&D program in 2017** aiming at the development of a **zero background ton scale detector** to search for the neutrinoless double beta decay.

→ How? →

Using a radial high pressure xenon TPC

Detection concept

Cylindrical TPC



Detector features

- Excellent energy resolution (goal of 1% FWHM at ^{136}Xe $Q_{\beta\beta}$).
- Extremely low background due to the very low material budget.
- Scalability to large isotope masses.
- Simplicity of the detector readout with only one/two readout channels.
- Two electrons Vs one electron discrimination.

Main goal of the
R2D2 IN_2P_3 R&D
NOW VALIDATED

Ongoing R&D with
composite materials

True by conception

True by conception

To be demonstrated in
the prototype
(ongoing)

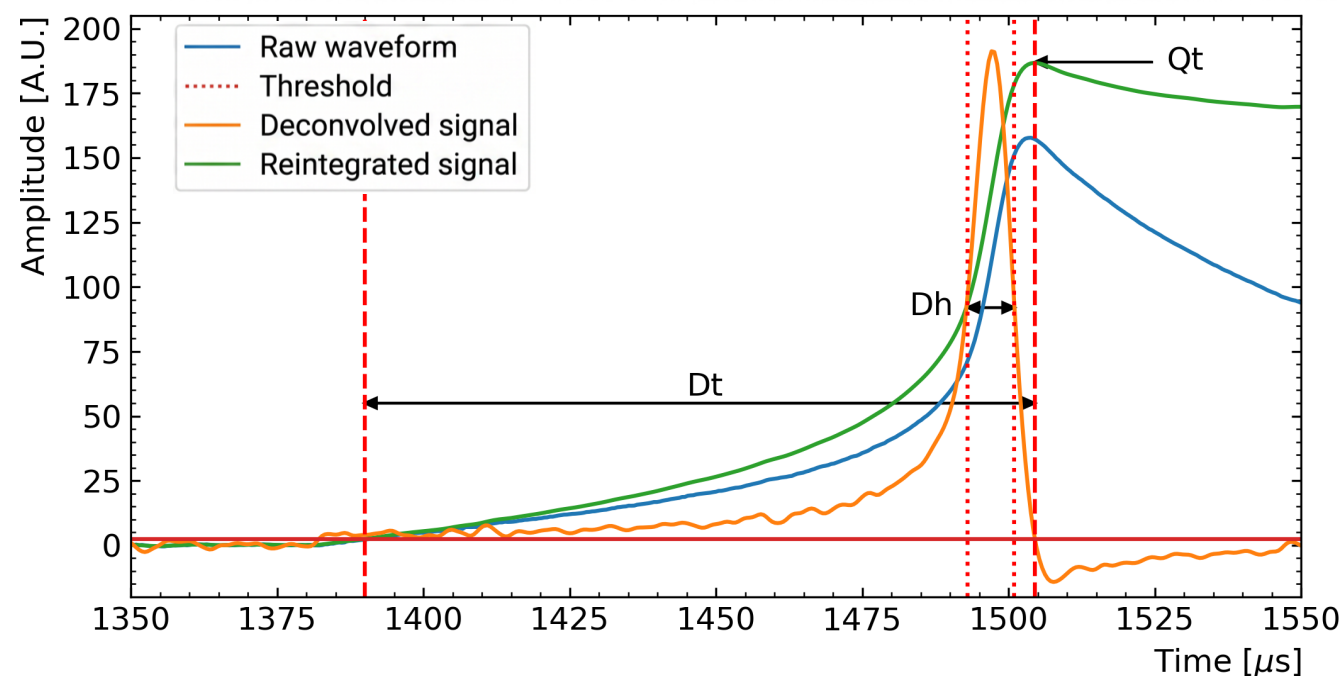
Operation mode

- The selected optimal choice for the CTPC operation is **ionisation** (i.e. no gain).
- The signal observed is a current induced according to the **Shockley-Ramo theorem** which includes the **full topology of the event**.

Advantages

- Signal due to the **drift of the electrons** and **directly related to the radial position of the energy deposit**.
- The topology of the event can be reconstructed.
- Avoid gain fluctuations.
- Thick anode possible.

Waveform and reconstructed observables



Qt
Total Charge
Reconstructed Energy

Dh
Signal Width at
Half Maximum
Radial Extent of
the Track

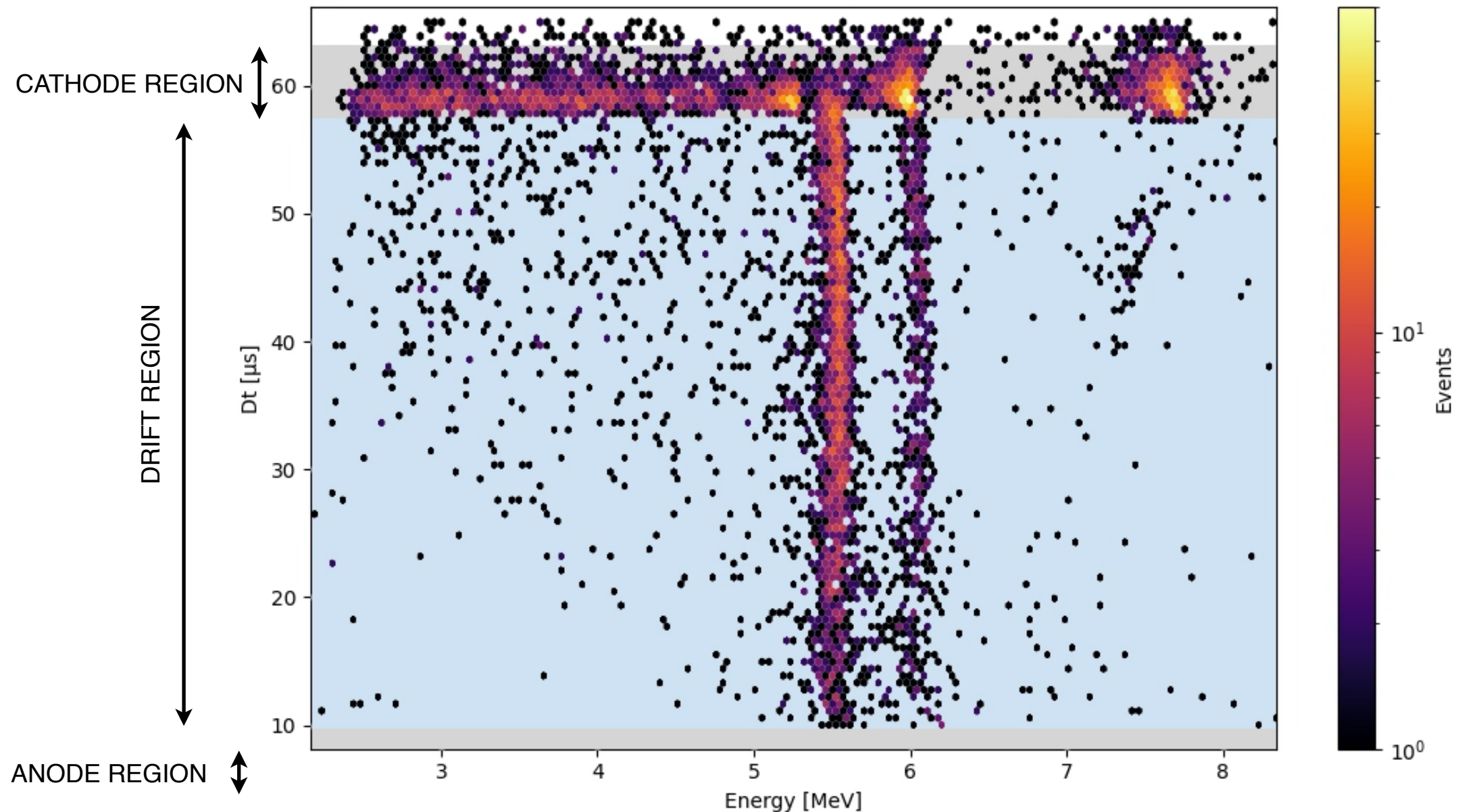
Dt
Signal Length
Maximal Radial
Radial Distance
from the Anode

Detector performance

- The **observables extracted from the signal processing** were used to select the events, namely the Po or the Rn issued alphas showing the detector performances in identifying energy and position of the events.

Reconstructed observables

Data: Ar @ 16 bar, 2 cm diameter anode, HV on cathode @ -4000 V

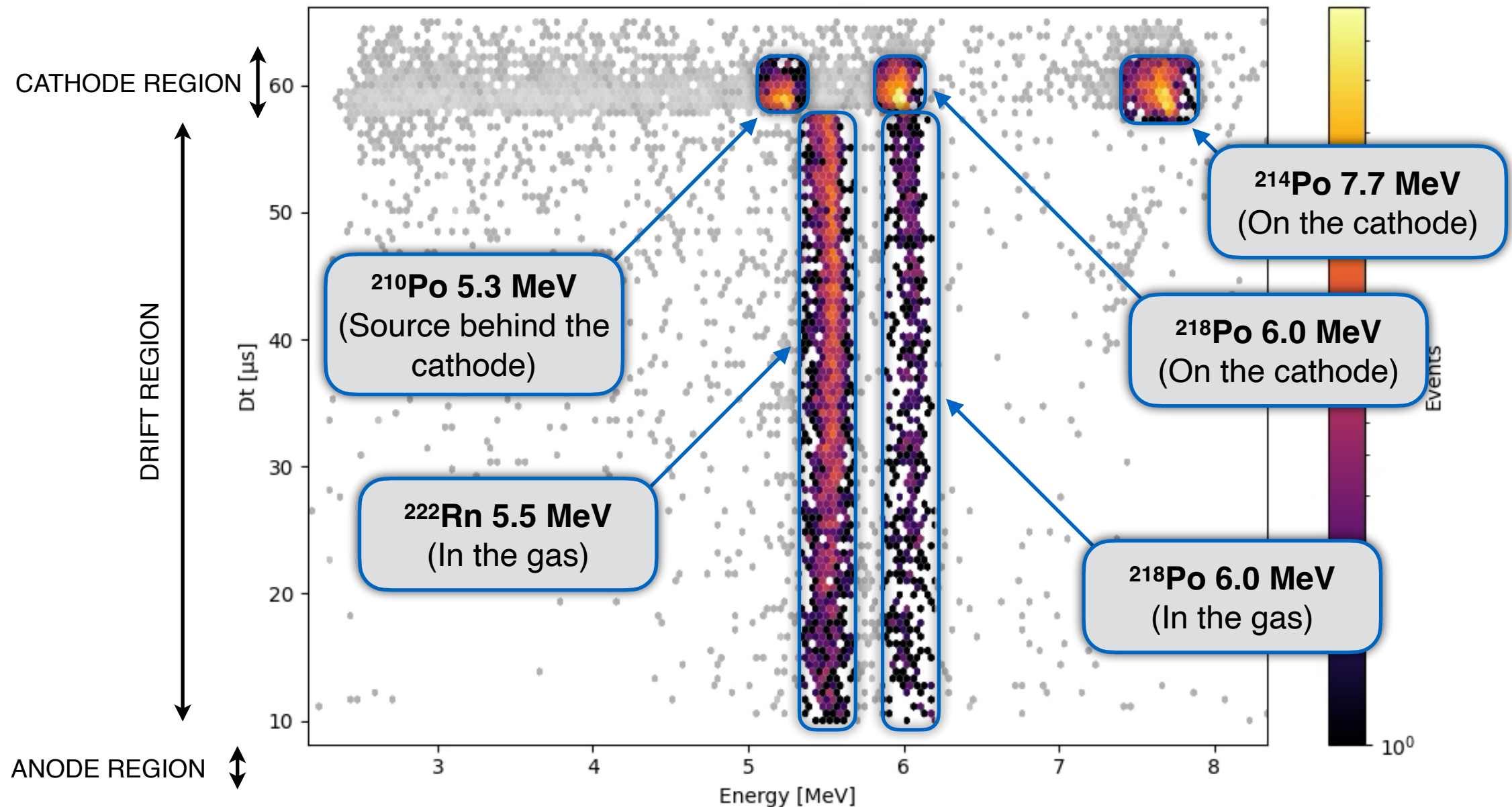


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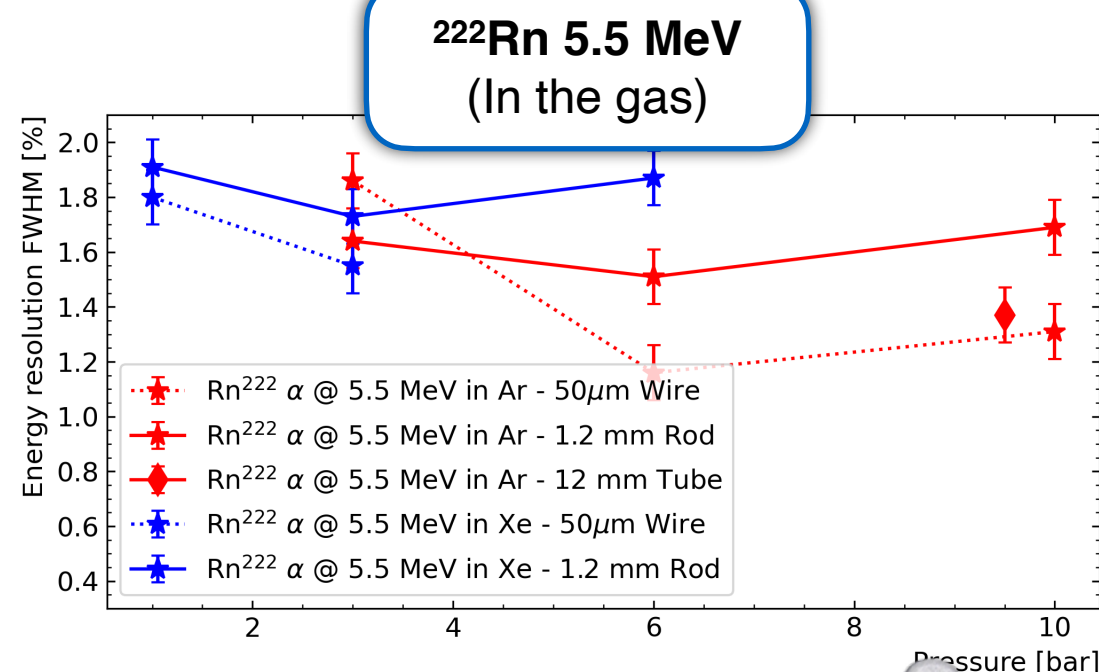
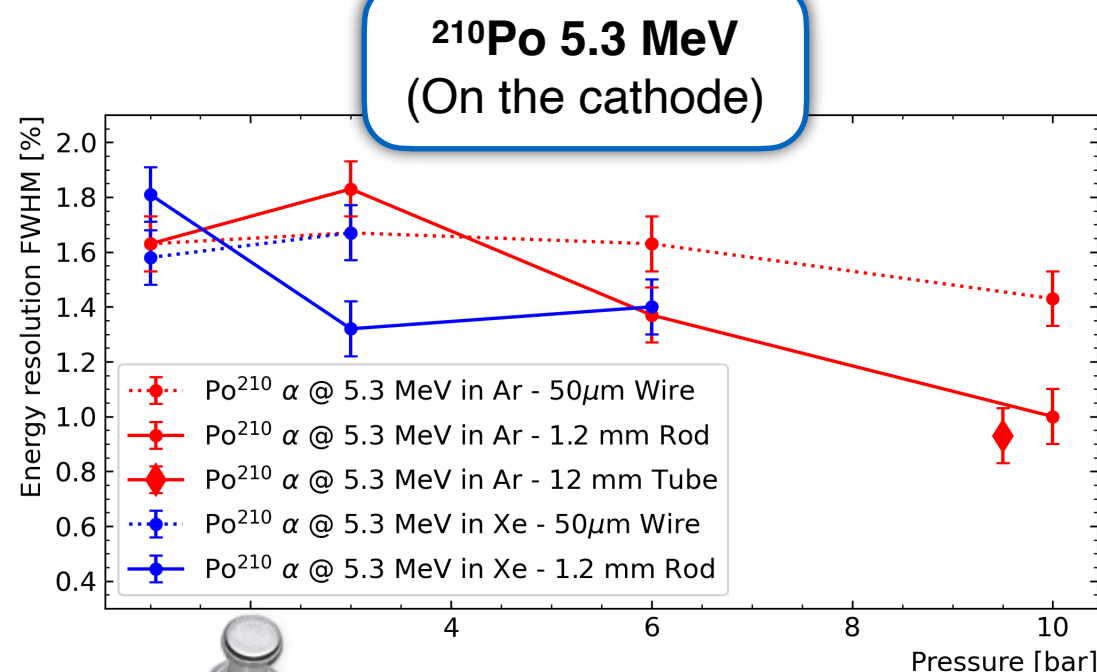
Reconstructed observables

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Energy Resolution

- The main goal of the R&D was to **establish the energy resolution** at the level of 1% at the ^{136}Xe $Q_{\beta\beta}$ of 2.458 MeV.



The resolution is mostly independent on the gas nature.

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The resolution is similar for diffuse and point-like sources.

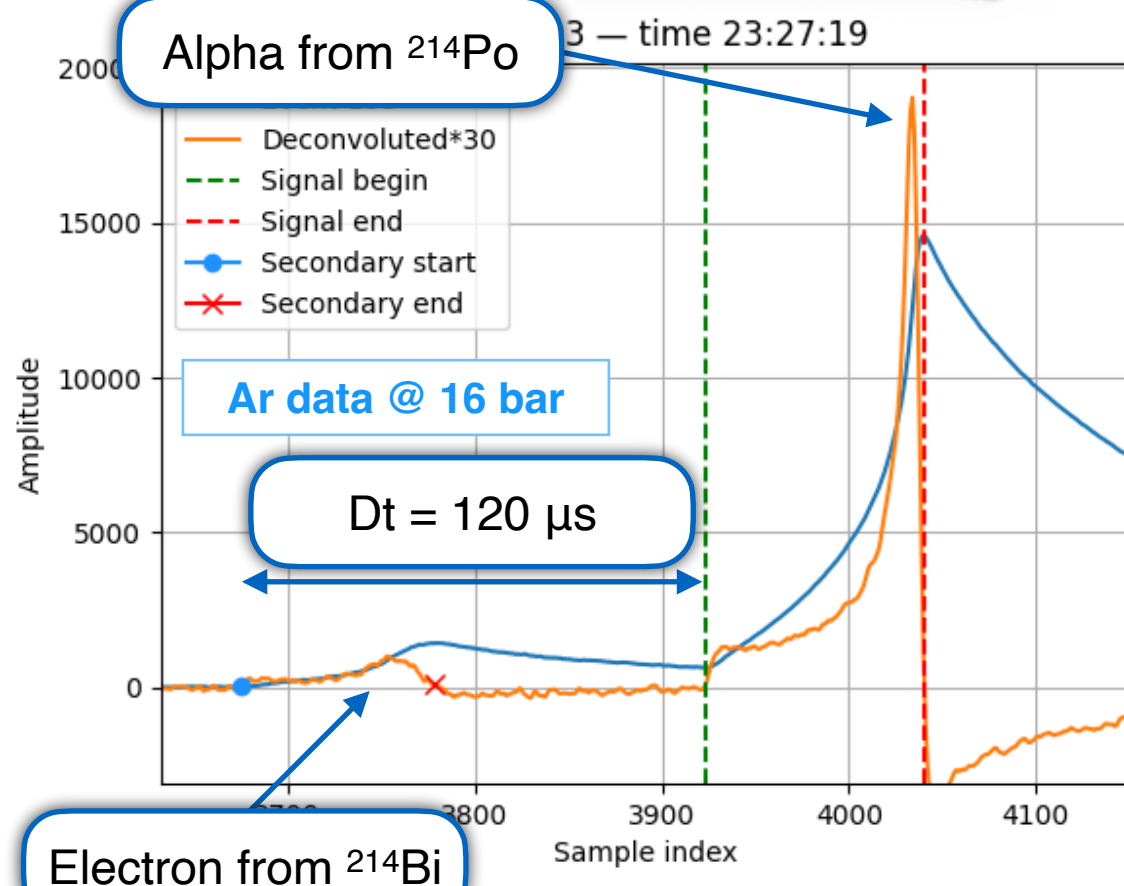
Current **results** are **conservative**: the main performance limitations have already been identified (electronics noise, gas purification, source geometry and edge-field effects).

Bi-Po detection

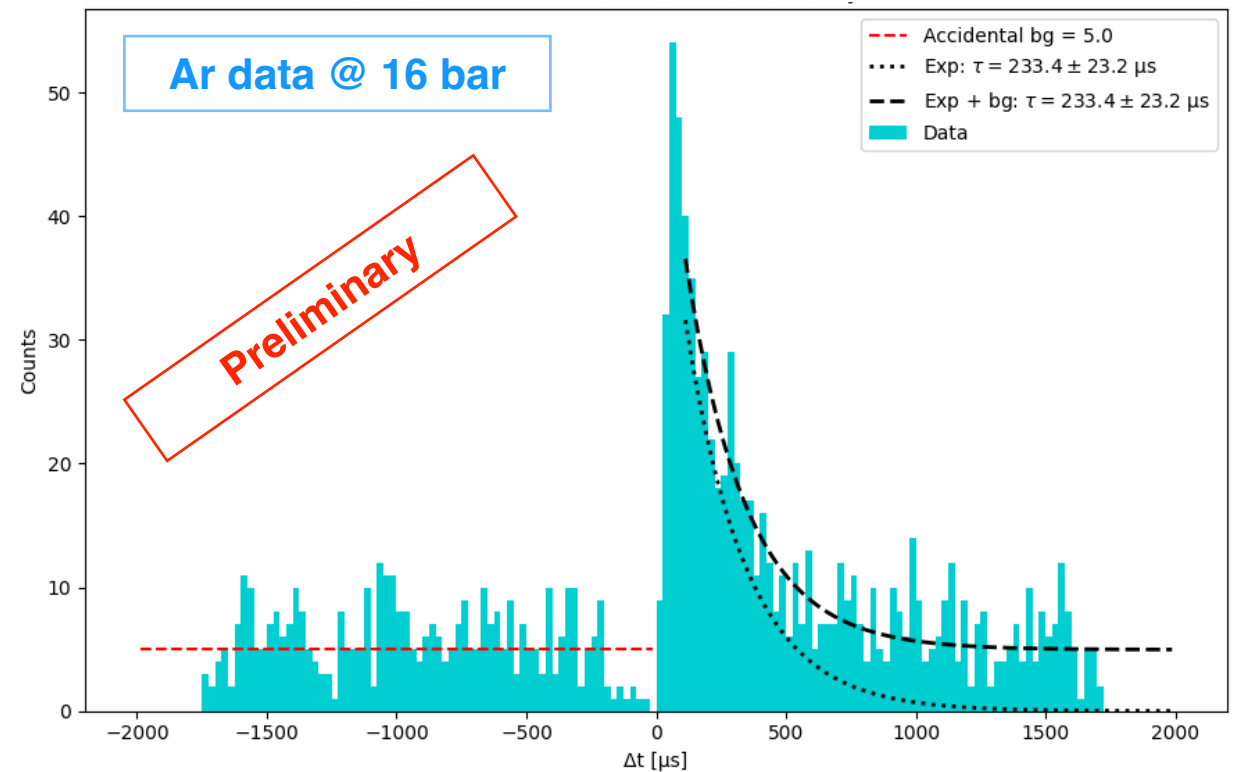


- The ^{214}Bi - ^{214}Po decay sequence (half life of $164\text{ }\mu\text{s}$ or tau of $234\text{ }\mu\text{s}$) can be fully observed within the 3 ms acquisition window. It provides a realistic benchmark to demonstrate:
 - ➔ **Reconstruction of two independent energy deposits** in the same event.
 - ➔ Accurate **reconstruction** of the Bi-Po **time delay**.
 - ➔ **Different waveform** for **point-like** (α 's) and **track-like** (electrons) energy deposits.

Bi-Po waveform

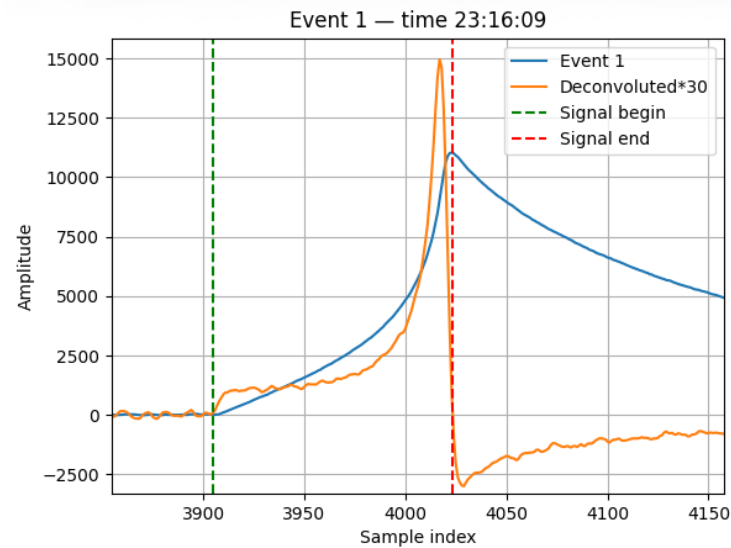


Bi-Po Δt distribution

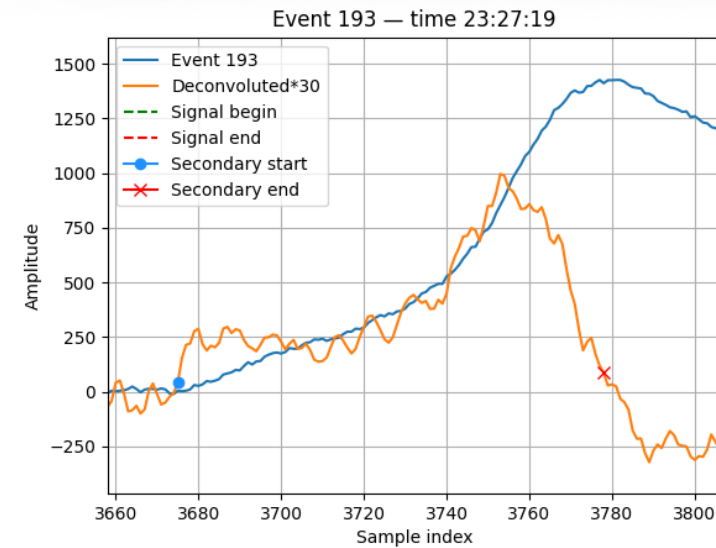


Bi-Po detection

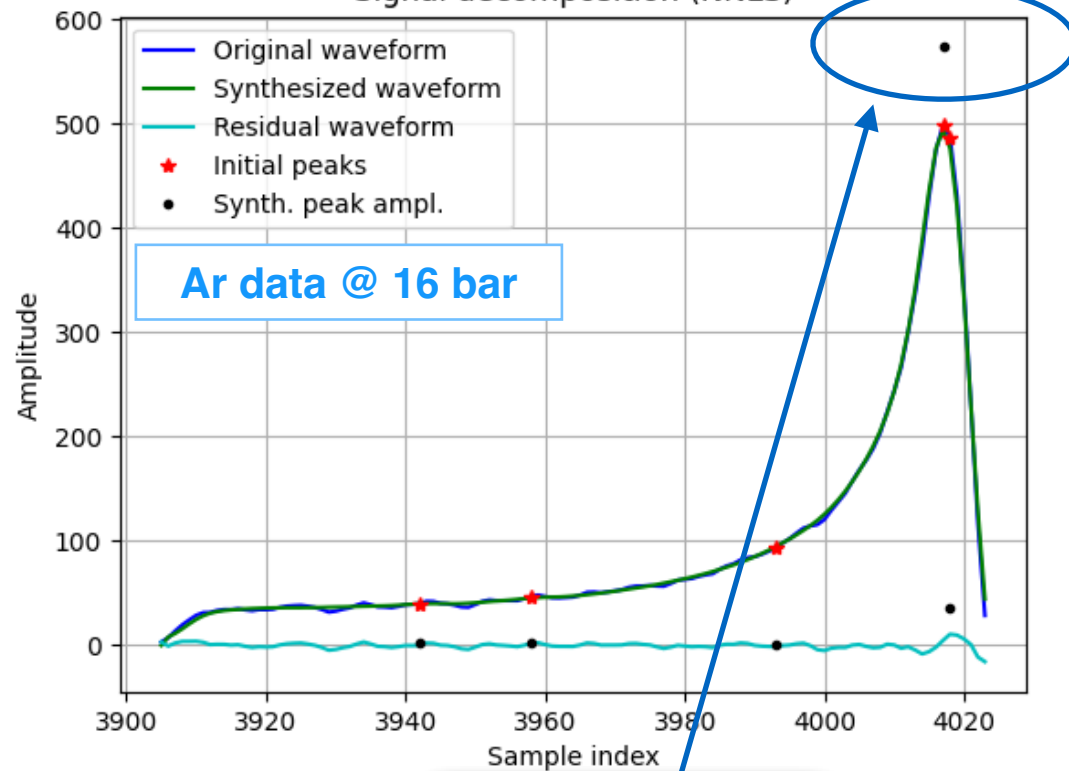
α waveform



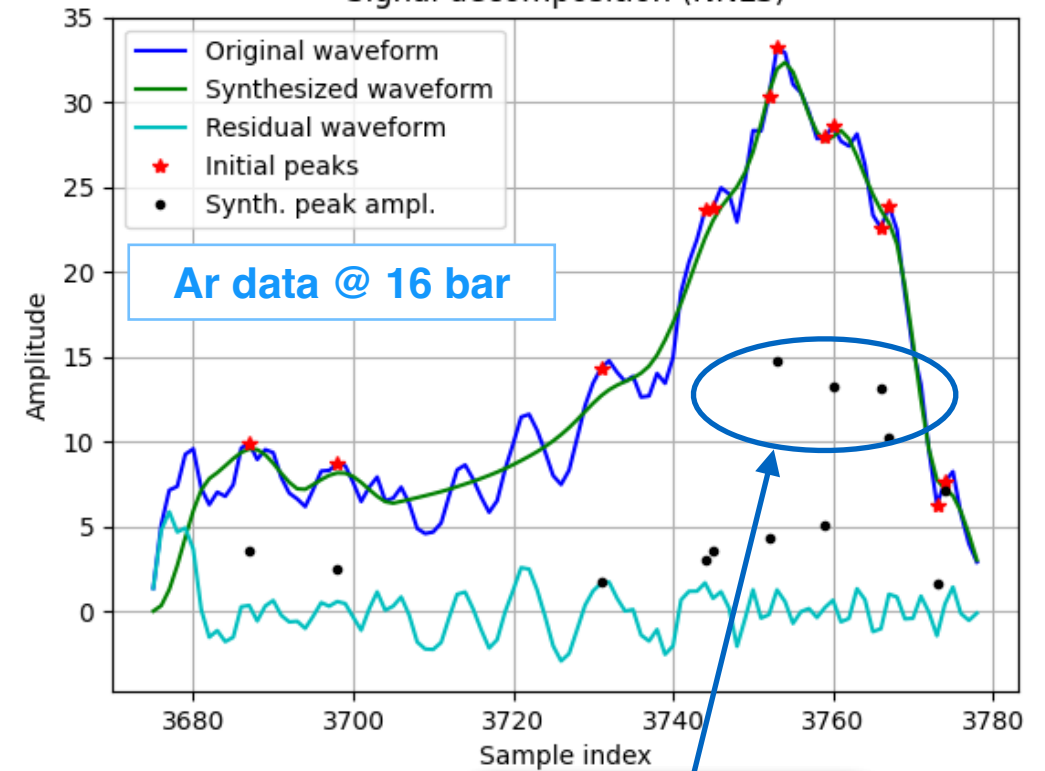
e^- waveform



Signal decomposition (NNLS)



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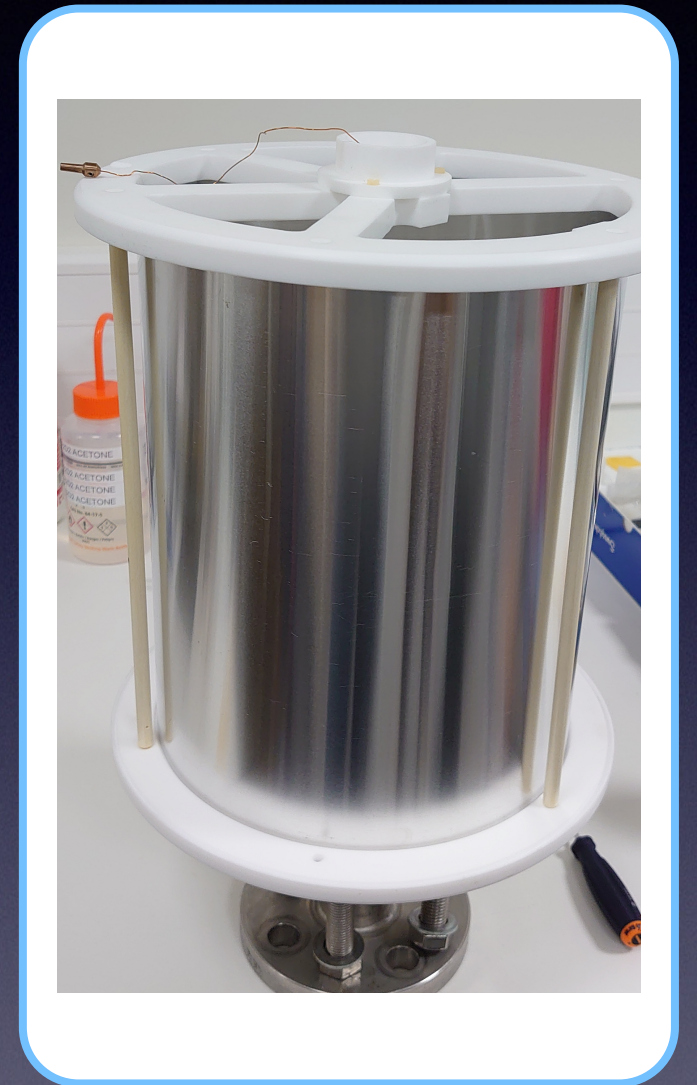


What did we learn?



A simple detector architecture is viable

- A *cylindrical geometry* provides a **uniform and electrostatically stable electric field**, while naturally enhancing the field at the cathode ($1/R$ dependence).
- A *thick anode* **preserves detector performance** while simplifying construction and enabling both vertical and horizontal operation.
- A *Single-channel readout* is **sufficient to reconstruct the relevant observables** (a second channel is only required for longitudinal position reconstruction and tests are ongoing).
- *Scintillation light readout* **is not required** enabling a simpler, lower-cost detector with reduced radioactive material.

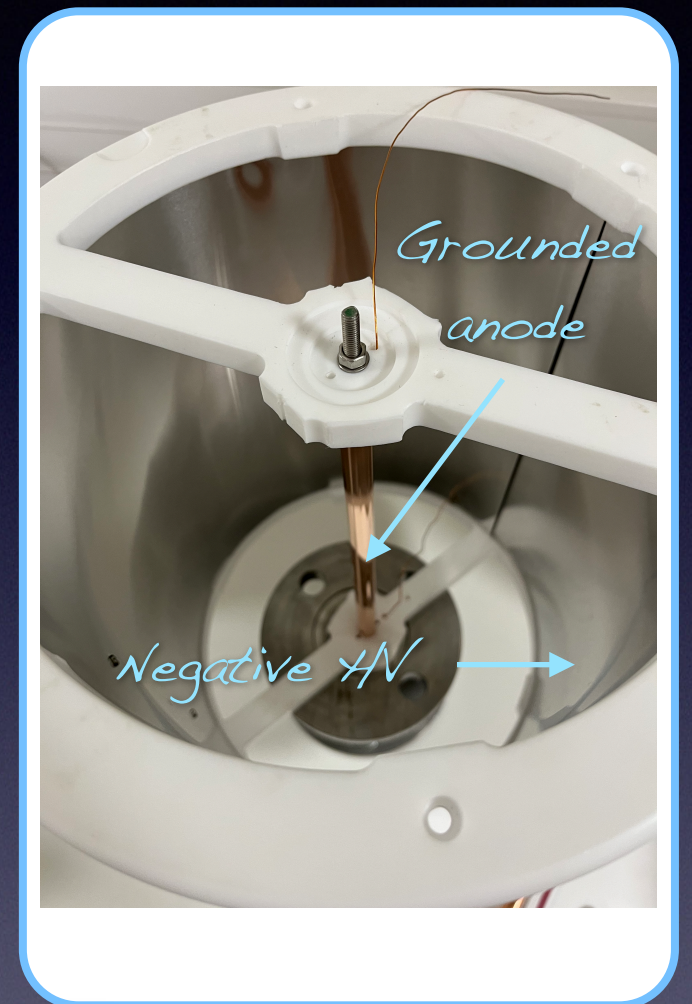


The R&D converged toward a simpler and more robust detector.

What did we learn?

A stable operating mode was established

- *Ionisation mode* was selected to **avoid gain fluctuations** and preserve the **full topological information** contained in the induced-current signal.
- The *HV configuration* was optimised with a **negative cathode** and a non-polarised anode, minimising HV-induced noise on the signal.
- *Gas operation* was validated with similar performances in argon and xenon, **enabling detector commissioning and optimisation in argon**.



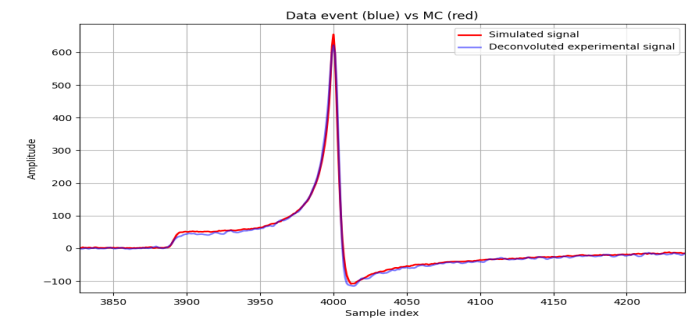
The R&D identified a stable and low-complexity operating regime.

What did we learn?



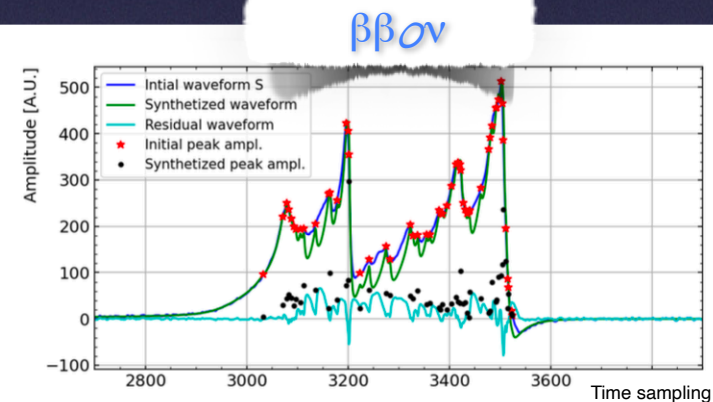
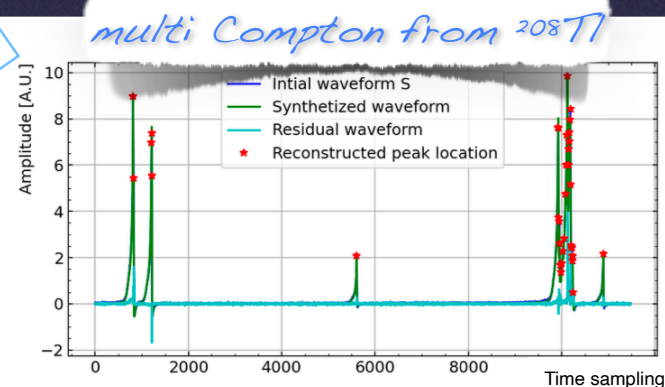
Detector response validated

- Signal formation* is quantitatively reproduced by Monte Carlo, providing a **validated detector response model**.

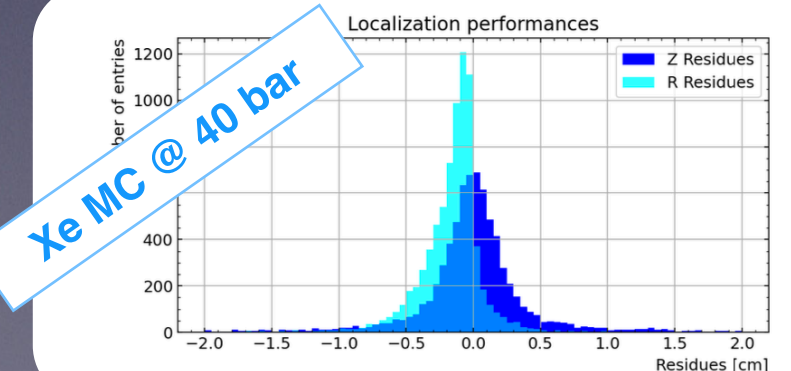


- Signal reconstruction* algorithms have been validated on Monte Carlo for **two-electron and Compton-like** event topologies (experimental validation is ongoing).

Xe MC @ 40 bar



- Spatial localization* provides **sub-cm precision**, allowing reconstruction of both radial and longitudinal event positions.



From prototype to demonstrator



Remaining validation milestones

- *Signal Multi-site and topology identification*: validation of gamma-induced events vs electron tracks discrimination and 1 or 2 electron topology reconstruction.
 - ➔ **40 bar Ar prototype with external ^{208}Tl source** to identify γ interactions and double escape peak (2 electrons with total electron energy deposit at 1.59 MeV).
- *Longitudinal position reconstruction*: validation of ASIC current preamplifier and resistive anode readout.
 - ➔ **Components already available** and ready for integration.
- *High-pressure gas purification*: validation of the purification strategy under detector operating conditions.
 - ➔ **Titanium spark-based purification setup under test.**
- *Scale-up*: validation of electron drift over longer distances.
 - ➔ **40 cm drift prototype already available.**



From prototype to demonstrator



Low-radioactivity detector implementation

- Following the **R2D2 design philosophy**, the objective is to minimise intrinsic background by **reducing the detector material budget**.
- A composite pressure vessel is being developed to withstand 40 bar operation with a few-mm material thickness.
- The target is a **composite vessel** with a radiopurity of **10 $\mu\text{Bq/kg}$** , developed in collaboration with IRT Jules Verne.
 - ➔ *Component screening*: HPGe measurements and ICP-MS analyses of epoxy and carbon fibres ongoing.
 - ➔ *Material qualification*: final composite material to be measured before vessel production.
 - ➔ *Background validation*: radon emanation measurements and underground validation with the final prototype.

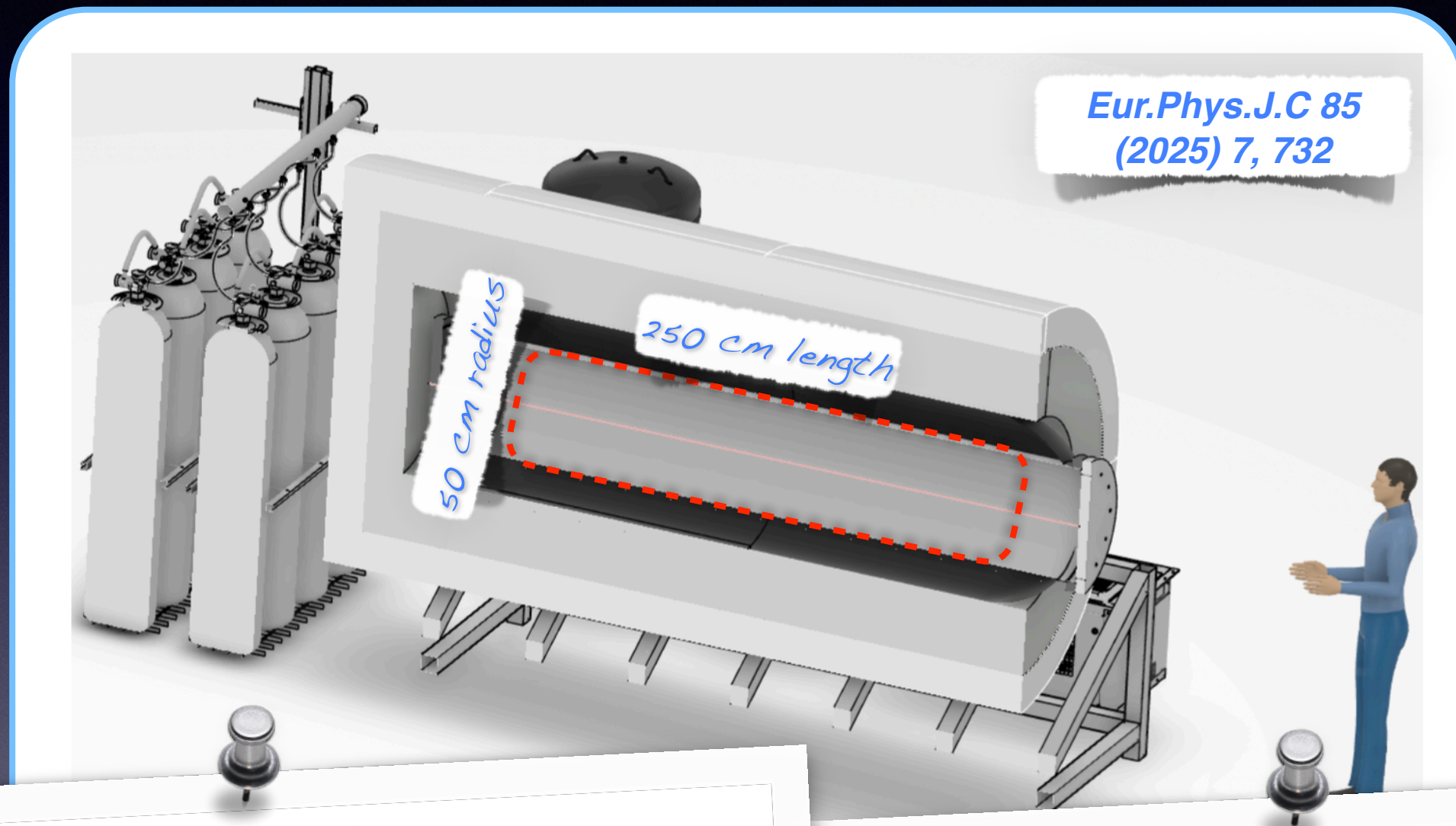


The composite vessel is an opportunity, not a risk. A backup solution based on an ultra-pure copper thick liner remains possible.

Physics reach of a possible R2D2 demonstrator



- Based on the R&D results, a possible R2D2 experiment has been designed and its physics reach evaluated.



Configuration

- 580 kg of active Xenon
- Footprint 50 m²
- Detector cost (including shielding and utilities) is about 3 Millions (Enriched Xe cost excluded)

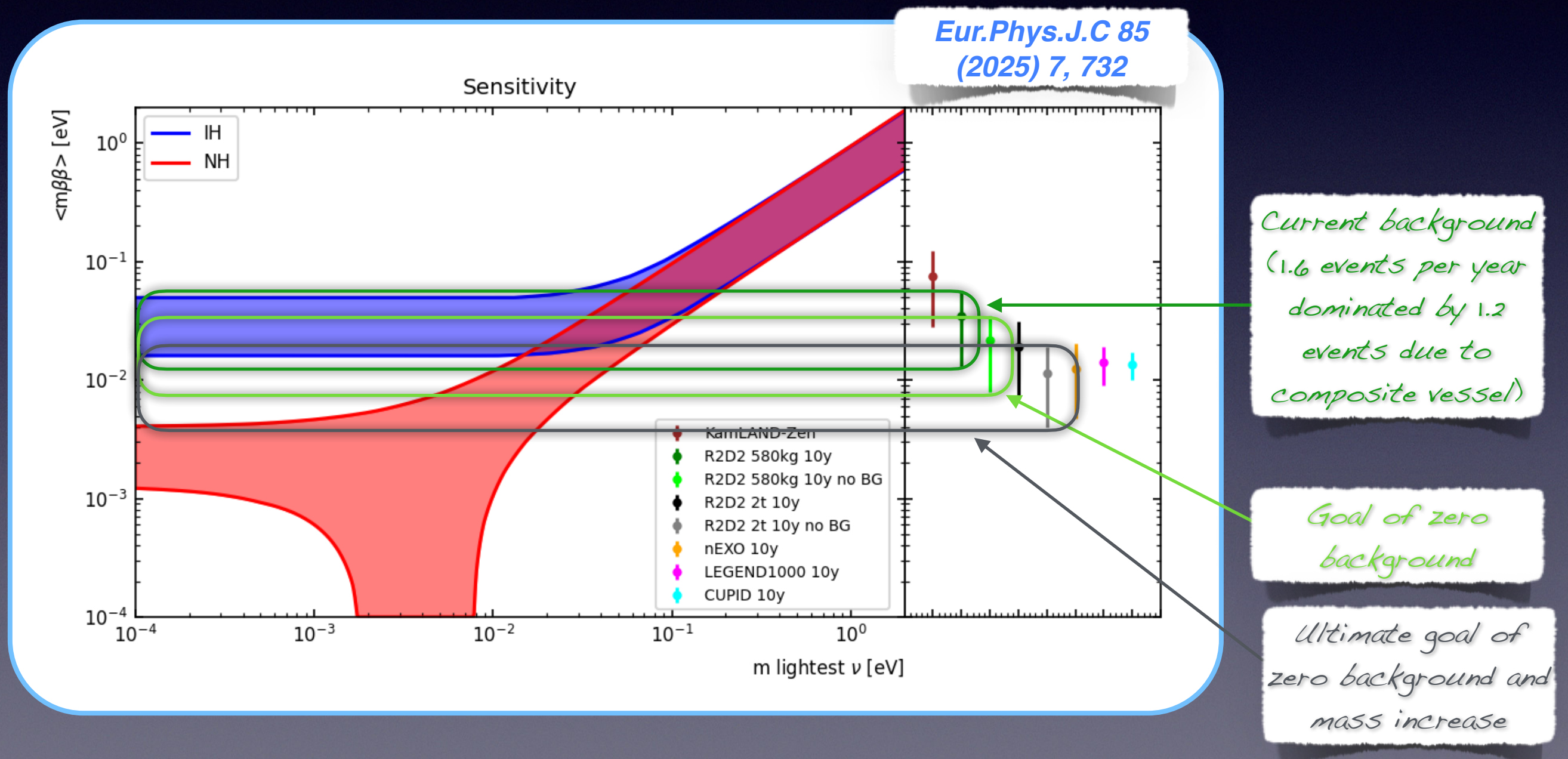
Background assumptions

- 1.6 background events/year in the ROI
- Further reduction possible with a lower-mass composite vessel

A possible role for R2D2 in the future $\beta\beta 0\nu$ landscape



- A possible R2D2 implementation could reach a sensitivity comparable to other next-generation $\beta\beta 0\nu$ experiments.



Conclusions



- R2D2 evolved **from a novel concept into a mature detector technology**.
- The detector design was simplified while preserving the required physics capabilities.
- A stable and low-complexity operation mode was established.
- The detector response is quantitatively understood and key reconstruction tools are available.
- The **remaining challenges toward a demonstrator have been identified with concrete validation paths**.
- A possible R2D2 implementation could provide a competitive approach in the future $\beta\beta 0\nu$ landscape.



The main question is no longer whether the technology works, but whether it should be considered among the possible paths for future neutrinoless double beta decay experiments.