The R2D2 project for $\beta\beta0\nu$ research

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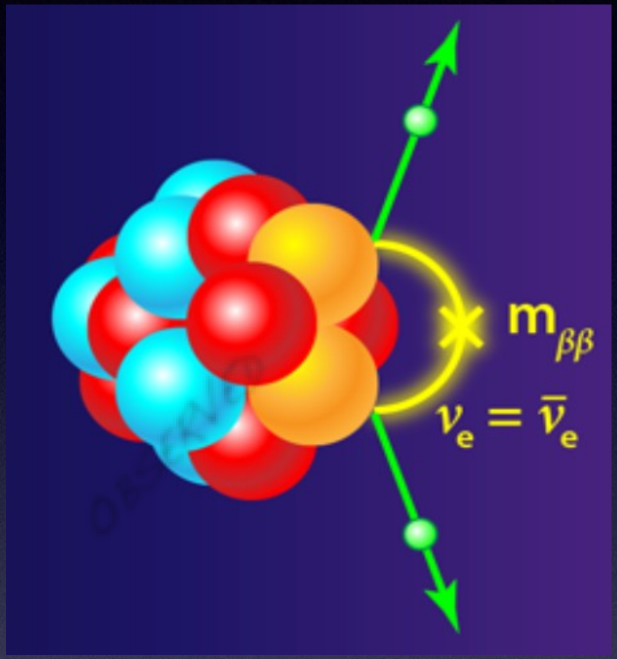
On behalf of R2D2 collaboration

Bi-National conference IN2P3-INFN on Detectors R&D, Paris, 18-20/11/2025

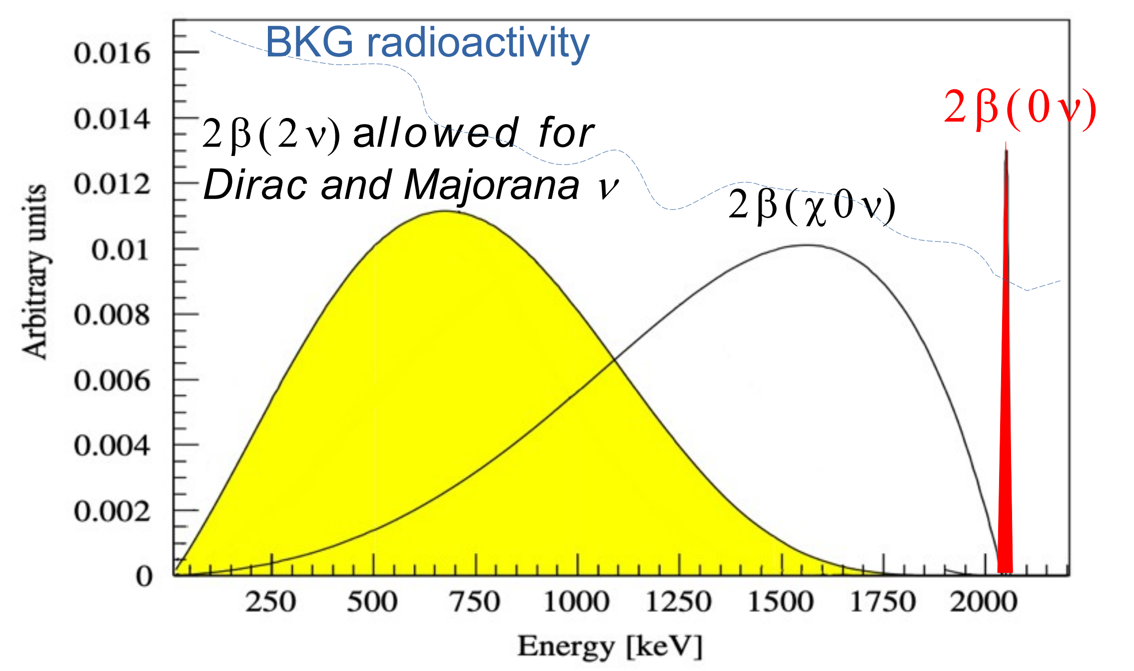
Context

The observation of **neutrinoless double beta decay (2β0ν)** is fundamental to determine the **Majorana or Dirac nature** of the neutrino.



Only allowed with Majorana ν

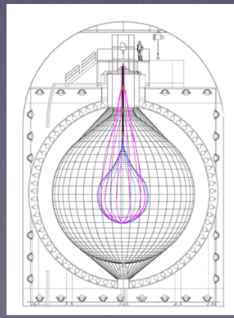
Observation of this decay would have implications in particle physics (neutrino masse generation) and cosmology (leptogenesis model).



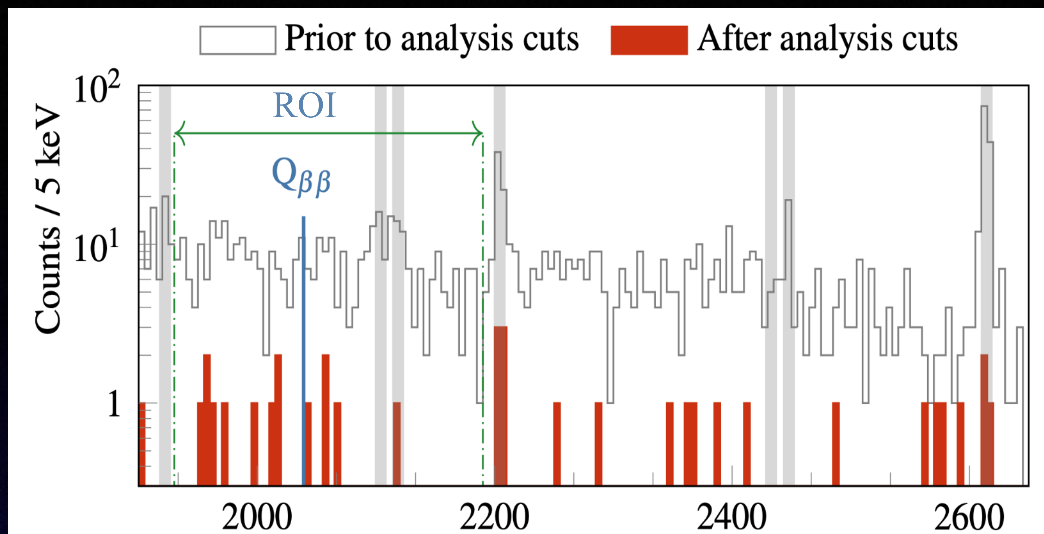
One of the signatures of this decay is given by the sum of the kinetic energy of the two emitted ē.

=> Importance of the energy resolution to identify the decay.

Best limit on effective neutrino mass obtained using pure calorimetry
=> KamLAND-ZEN 800 : $T_{1/2} > 3.8 \times 10^{26}$ y



Example from Gerda



How to disentangle the good events ?

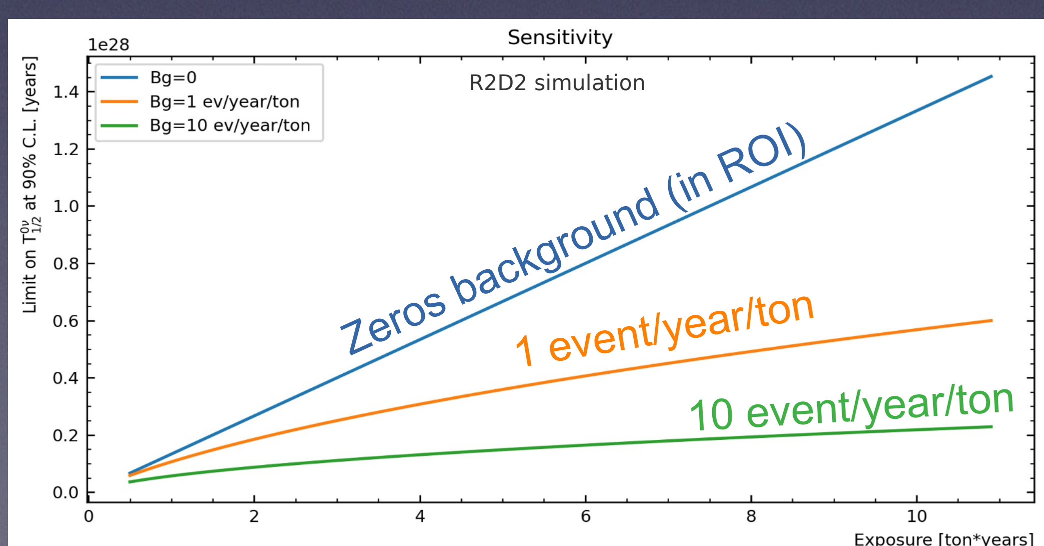
=> Importance of the 2-ē identification if few candidates are observed

Signal efficiency — isotope active mass — Exposure in years — Signal upper limit — Isotope molar mass

$$T_{1/2}^{0\nu} > \ln(2)\,\varepsilon\,\frac{N_A m}{M}\,\frac{t}{S_{up}}$$

Experimental sensitivity can be computed in terms of a limit on the half life.

=> Importance of large mass of isotopes



Signal upper limit depends on the chosen confidence level and on the experimental background.

=> Importance of low background

(recognition of nature of the interaction is key to background reduction).

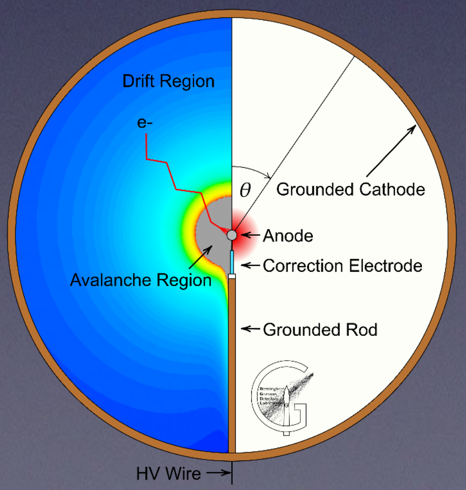
=> R2D2's motivation

Activity launched in 2017 to develop a ton-scale detector with zero background (in ROI).

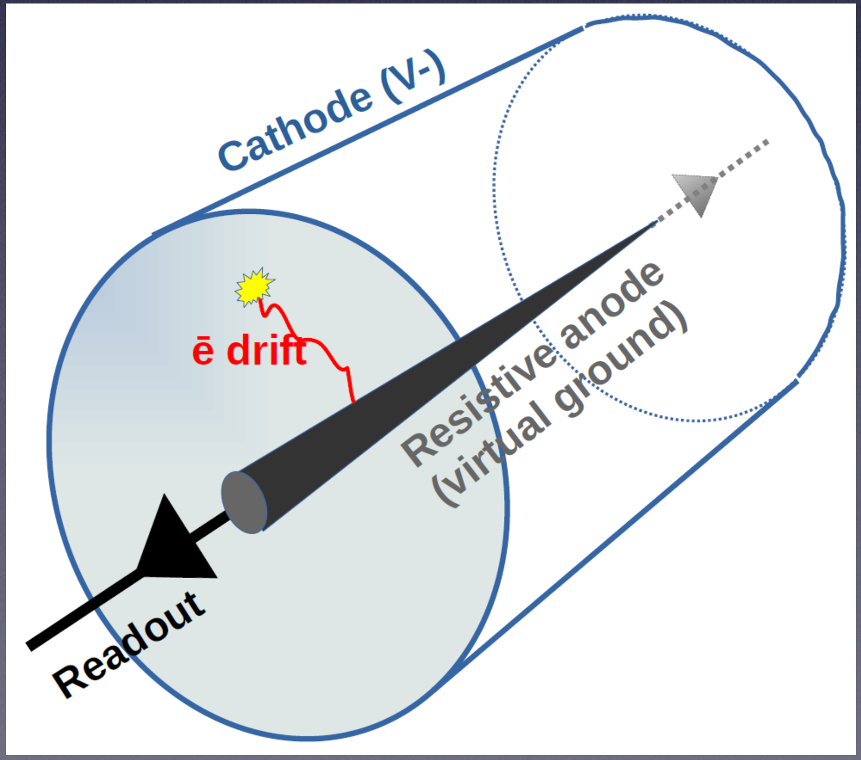
- High pressure Xe gas for 2-ē tracks identification.
- New signal treatment for energy resolution <1% FWHM.
- Scalability up to a few tons for large mass of isotopes.
- High background rejection capability combined to a low material budget

A single-anode radial-TPC filled with HP-Xe

Starting point : a spherical TPC



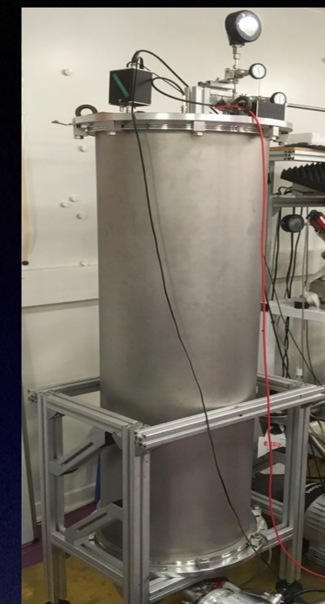
Final detector : a cylindrical TPC



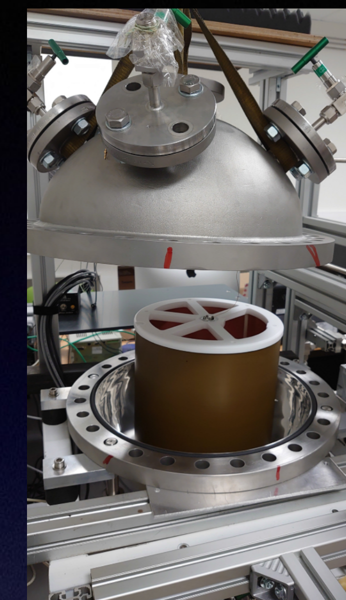
R2D2 milestones

First STPC (no high pressure)

Second STPC (certified to 40 bar)



First CTPC (no high pressure)



Second CTPC (certified to 40 bar) => final concept

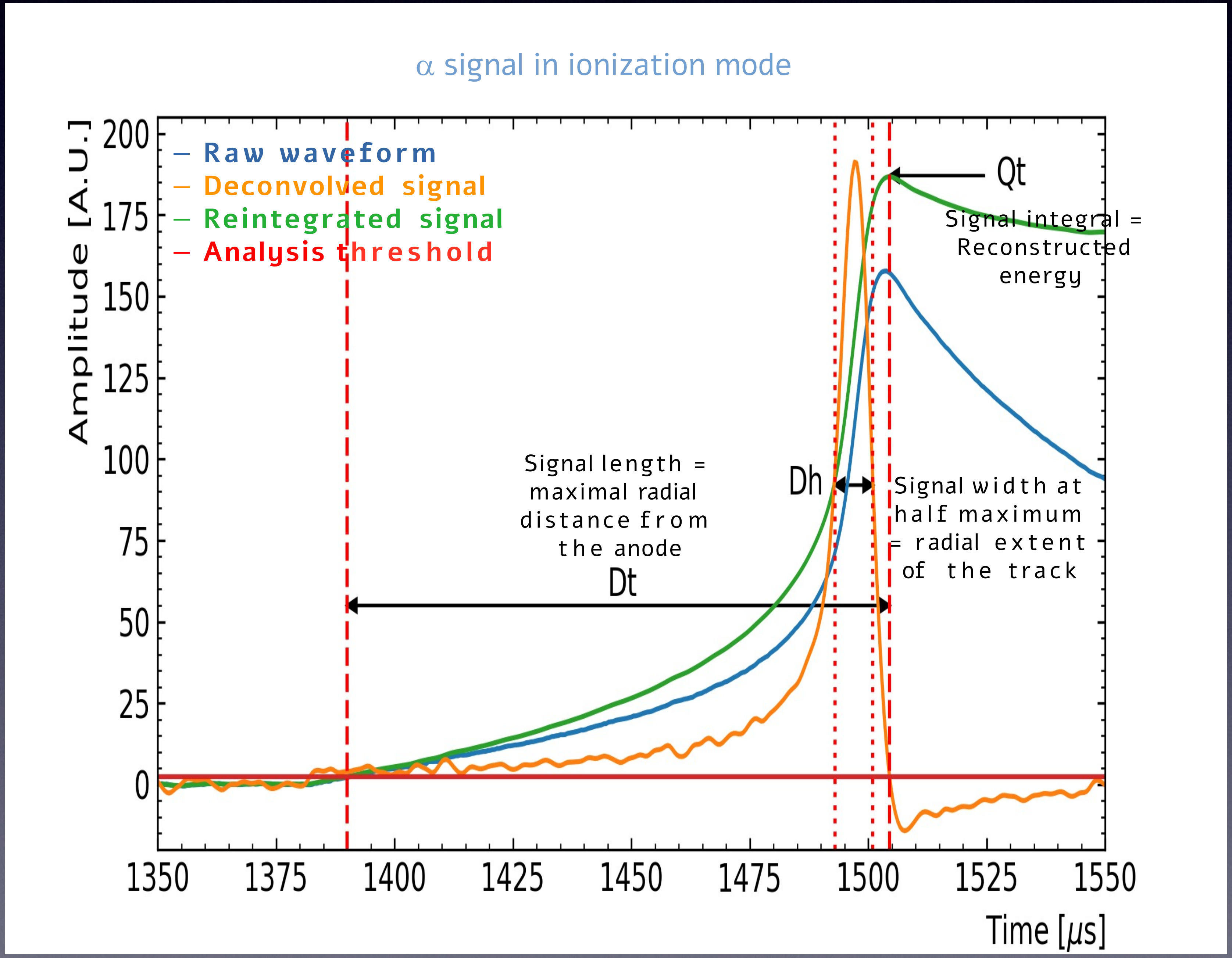
2018 — 2021 — 2022 — 2023

- Spherical TPC (Elect. field ~$1/r^2$) **=> cylindrical TPC (Elect. field ~1/r).**
- Proportional mode **=> ionization mode (no gain fluctuation, no quencher).**
- Anode polarization **=> cathode polarization.**
- Thin anode **=> thick anode.**
- Conductive anode **=> resistive anode (charge sharing).**
- Metal tank **=> Composite tank.**

JINST 16 (2021) P03012
NIM A 1028 (2022) 166382
JINST 18 (2023) 10, T10001
Eur.Phys.J.C 84 (2024) 5, 512

Signal processing

The shape of the signal allows for self-triggering (avoiding the detection of photons).
Use of a single signal => digital filtering and deconvolution (charge integrator) are essential to extract **the information contained in the induced current signal.**



- Up to 2023: Initial processing based on macro-observables for the analysis of continuous ionization tracks of alphas

- **Duration Dt => radial position R**
- **Integral Qt => energy E**

Experimental results

Alpha identification (initial processing)

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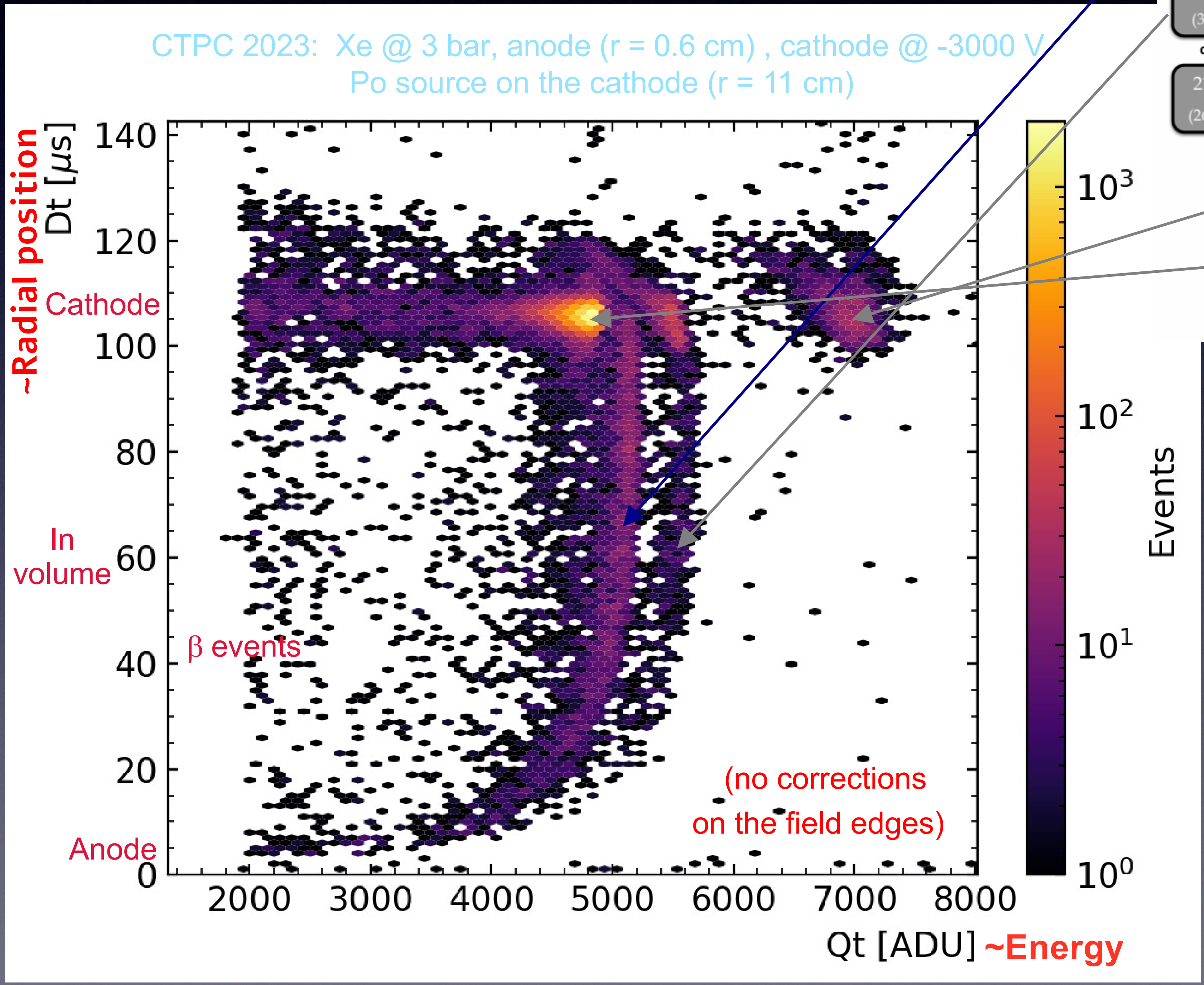
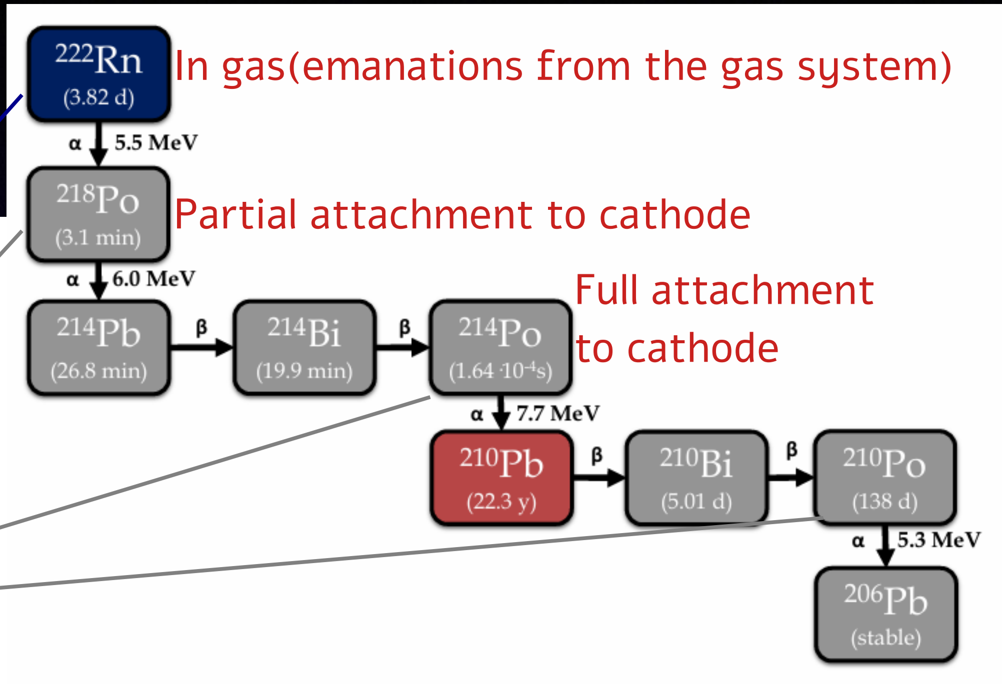
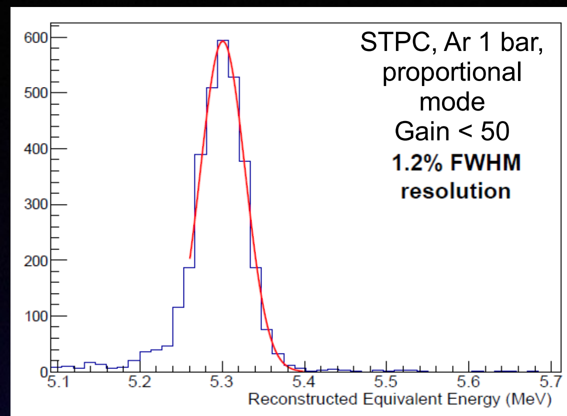
Eur.Phys.J.C 84 (2024) 5, 512
J. Phys. Conf. Ser. 2502.1 (2023), p. 012006.





=> An efficient tool for characterizing the in-situ radioactive background

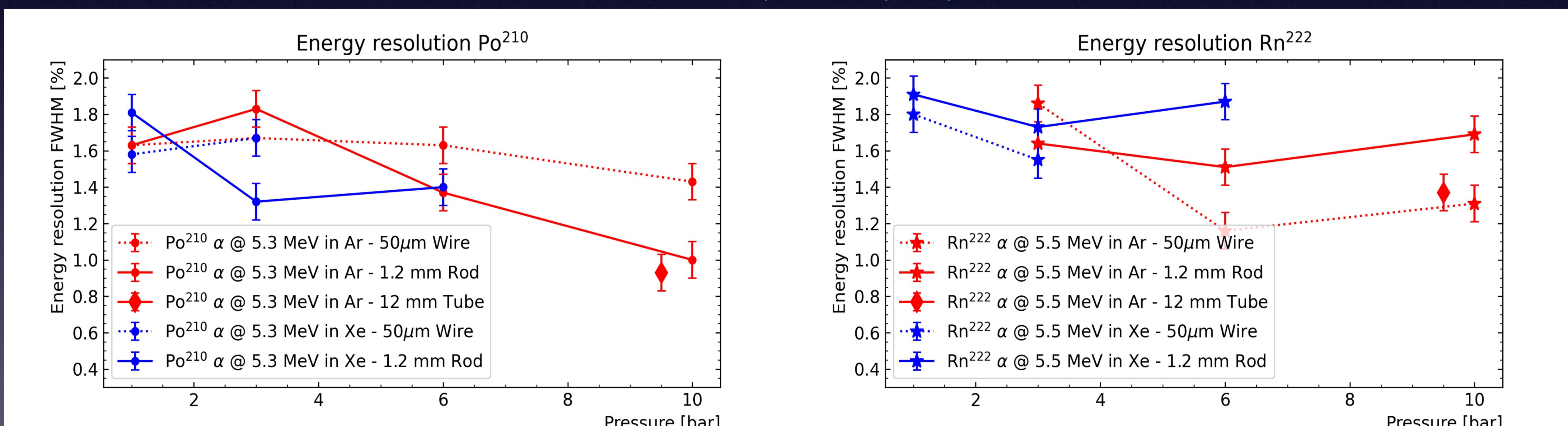
Energy resolution with alphas (initial processing)



First results in proportional mode indicated that the desired energy resolution would be achievable.

JINST 16 (2021) 03, P03012

CTPC 2023 - Eur.Phys.J.C 84 (2024) 5, 512



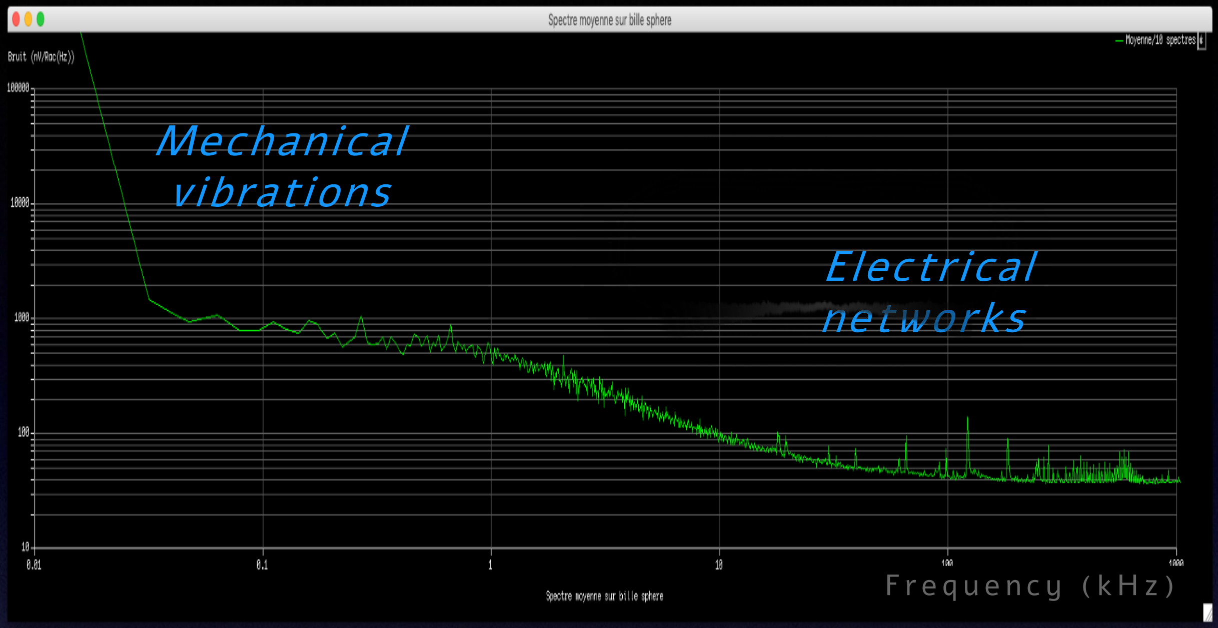
- Similar resolution for diffuse and point-like source
  - Resolution independent on the gas pressure
    - Resolution independent on the gas nature

=> Possibility to commission the detector with Ar

Other developments

No **dedicated environment** (contiguity of other experiences in the room)
+ use of a conventional charge amplifier.
=> Noise was dominant.

=> Use of batteries is considered.



- Commissioning of a simple circulation/purification system with cold/hot getters **=> but limited to 10 bar.**
- **Electron lifetime of ~2 ms achieved** (one order of magnitude worse than noble liquid detectors).

=> Spark-chamber under development for operation up to 40 bar.

=> The detector appears robust to disturbances.

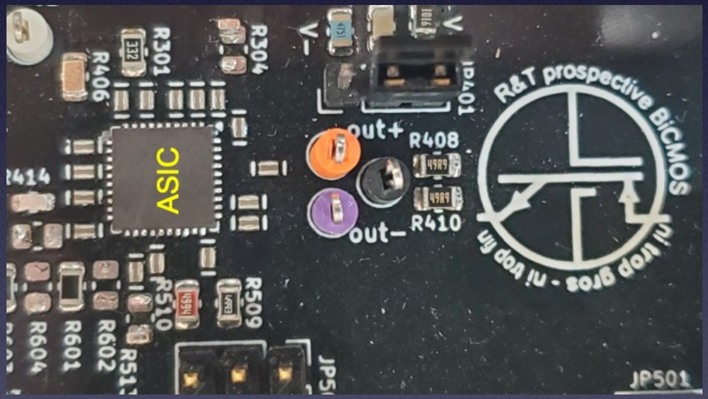
2024-2028: Test of a full scale demonstrator

2024-2025: Instrumentation of a composite (epoxy-fiberglass) full scale tank (produced by MAHYTEC SAS).

- **In 2025:**
  Completion of the internal intrumentation (through the 6 cm openings)

- **For 2026:**
- Test of gas purification and of long drifting.
- Development of the resistive anode.
- Testing of the dedicated ASIC current amplifier is underway.

Mahytec tank (for H2 storage)
(L=1.8 m, D= 0.84 m, V=0.85 m^3, P≤60 bar, 10 k€)



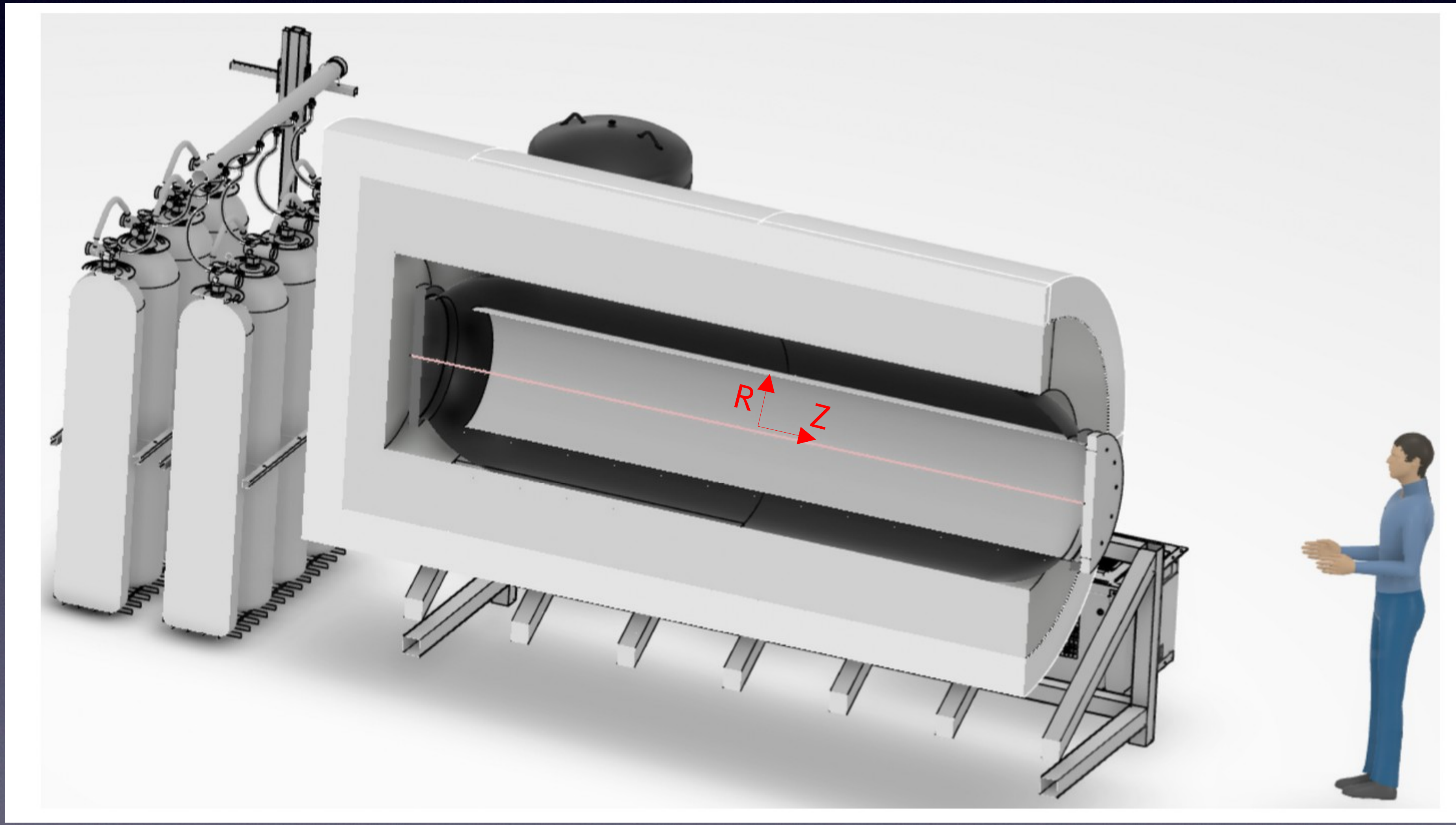
=> No showstopper expected

By 2028: Development of a low-radioactivity composite prototype (with 10 μBq/kg)

=> Selection of the epoxy resin, C-fibers, and manufacturing process is currently underway with our industrial partner IRT-Jules Verne.

Preparation for the period 2029-2032

Since 2024, based on the results obtained, we have designed a possible experiment and computed its sensitivity.

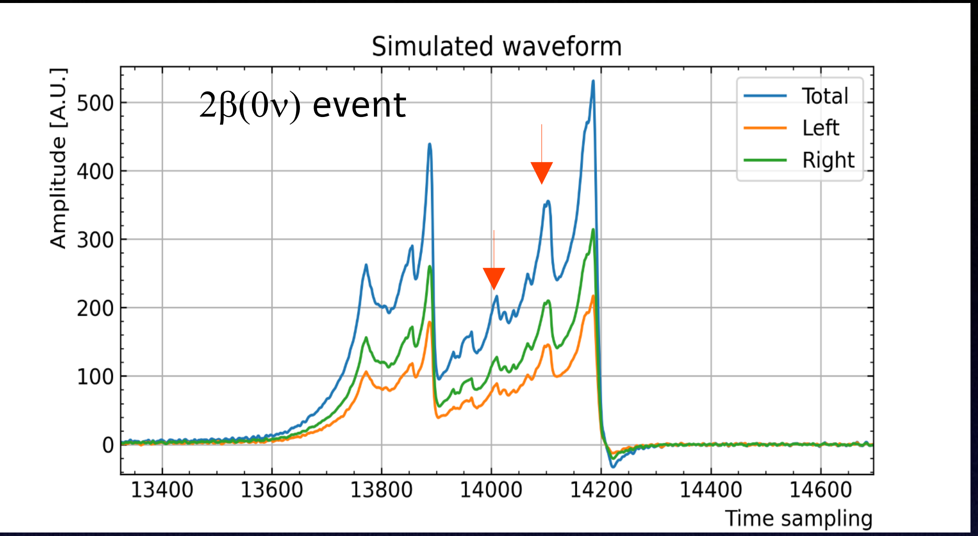


- Composite vessel L=3.5m, D=1 m, weight<50 kg, Active volume : 582 kg of Xe @ 40 bar
- Use of a resistive anode for longitudinal localization
- **Cost ~ 3 M€ (including shielding and utilities, Xe excluded)**

Currently modeled configuration with Pb main shield, but water envisaged.

Setup simulations

Signal modeling:
- For ionization regime
- With charge sharing on the anode: $W_R = W^*(Z/Z_{anode})$
  $W_L = W - W_R$
  (NIM A 492 (2002) 26–34)

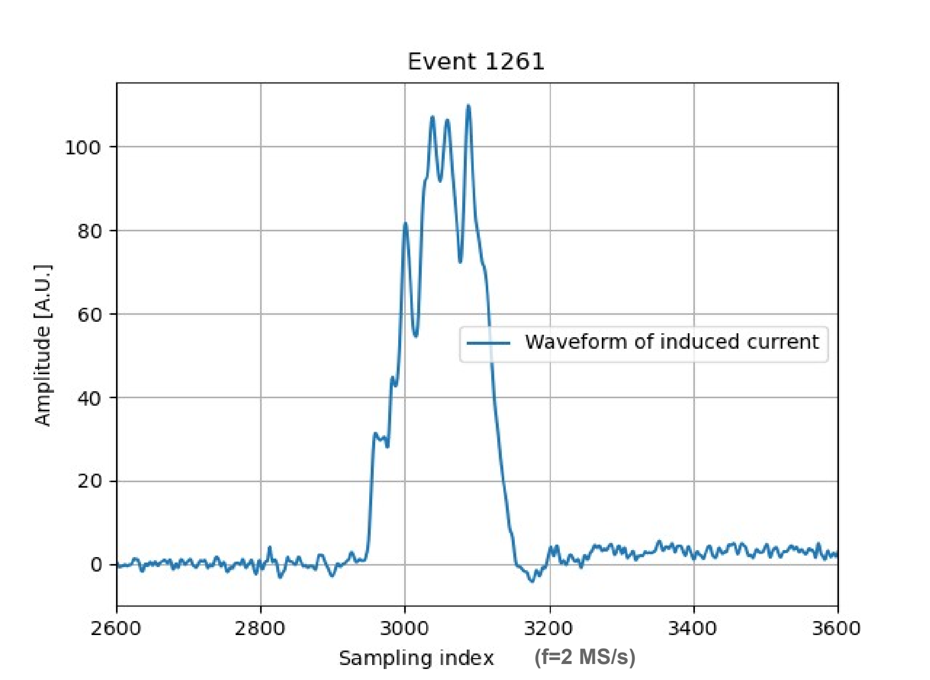


=> Unlike α's, β interactions produce spaced clusters of primaries => new methode of analysis.

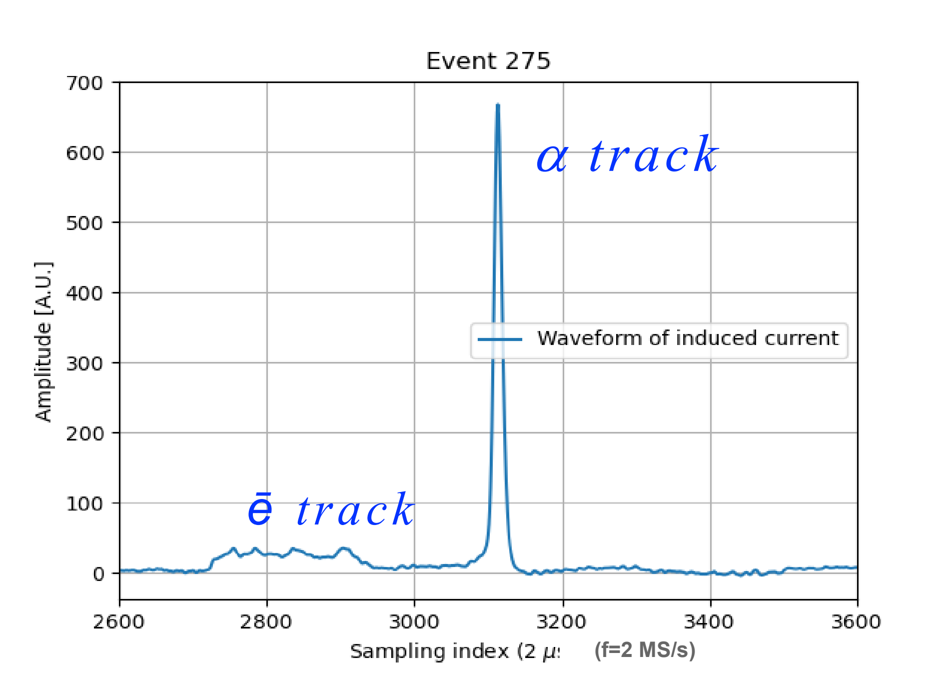
=> Comparison to real waveforms

CTPC-2023: Ar @ 10 bar, anode (r = 0.6 cm) , cathode @ -2200 V

Electron



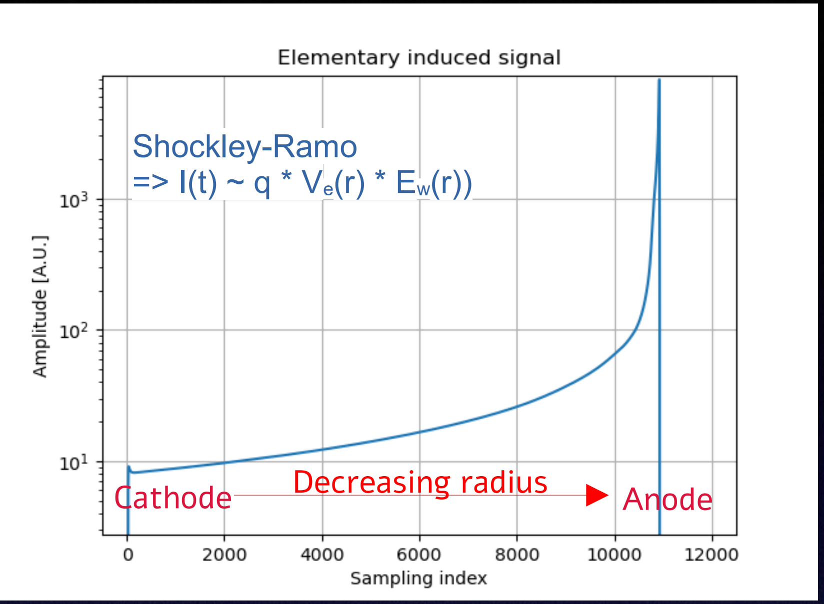
Bi-Po

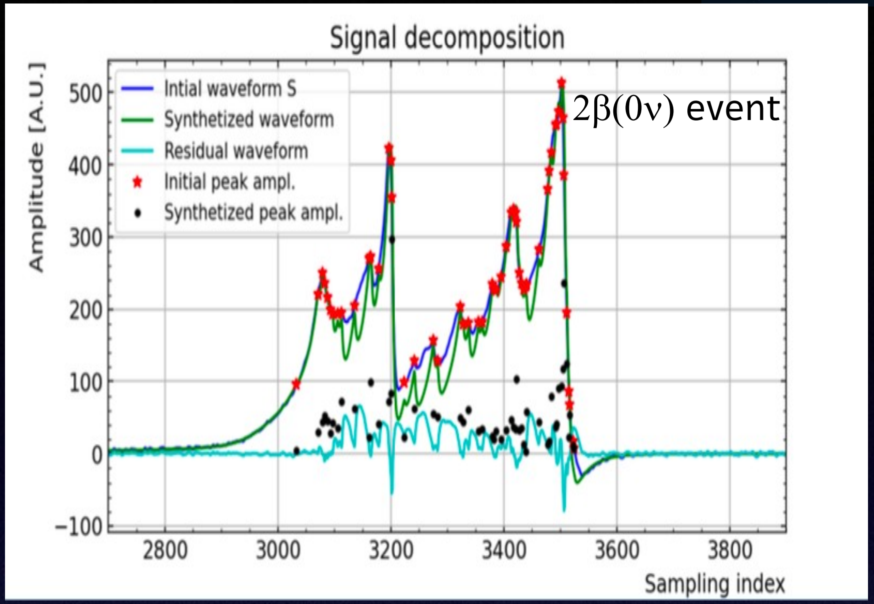


Improved processing for analysis of β tracks

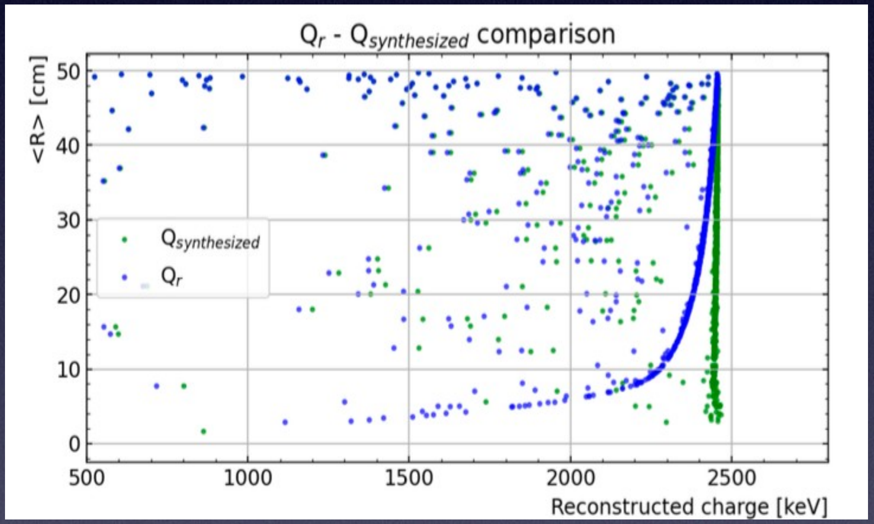
based on the elementary induction signal.

=> Decomposition/ synthesis algorithm.

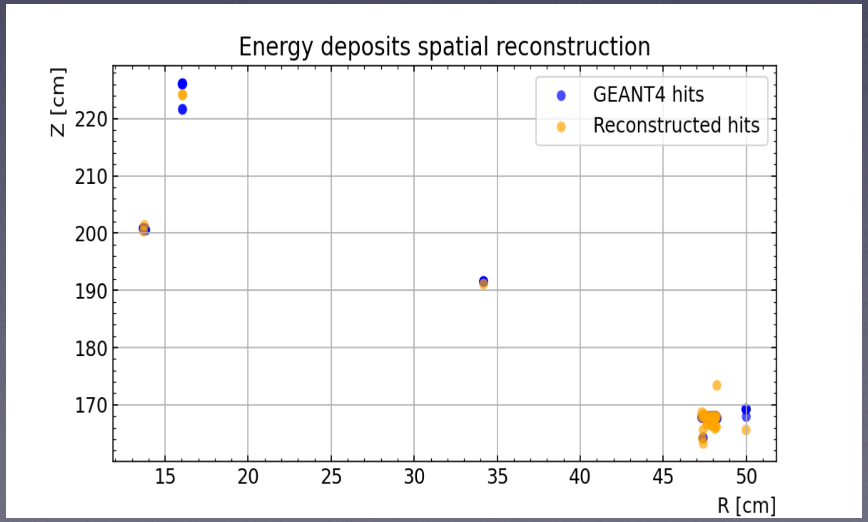




=> By using the missing charge correction, **an energy resolution < 1% FWHM was obtained at the 136Xe Qββ of 2.458 MeV** (downgraded to 1% for the subsequent simulations to maintain a safety margin).

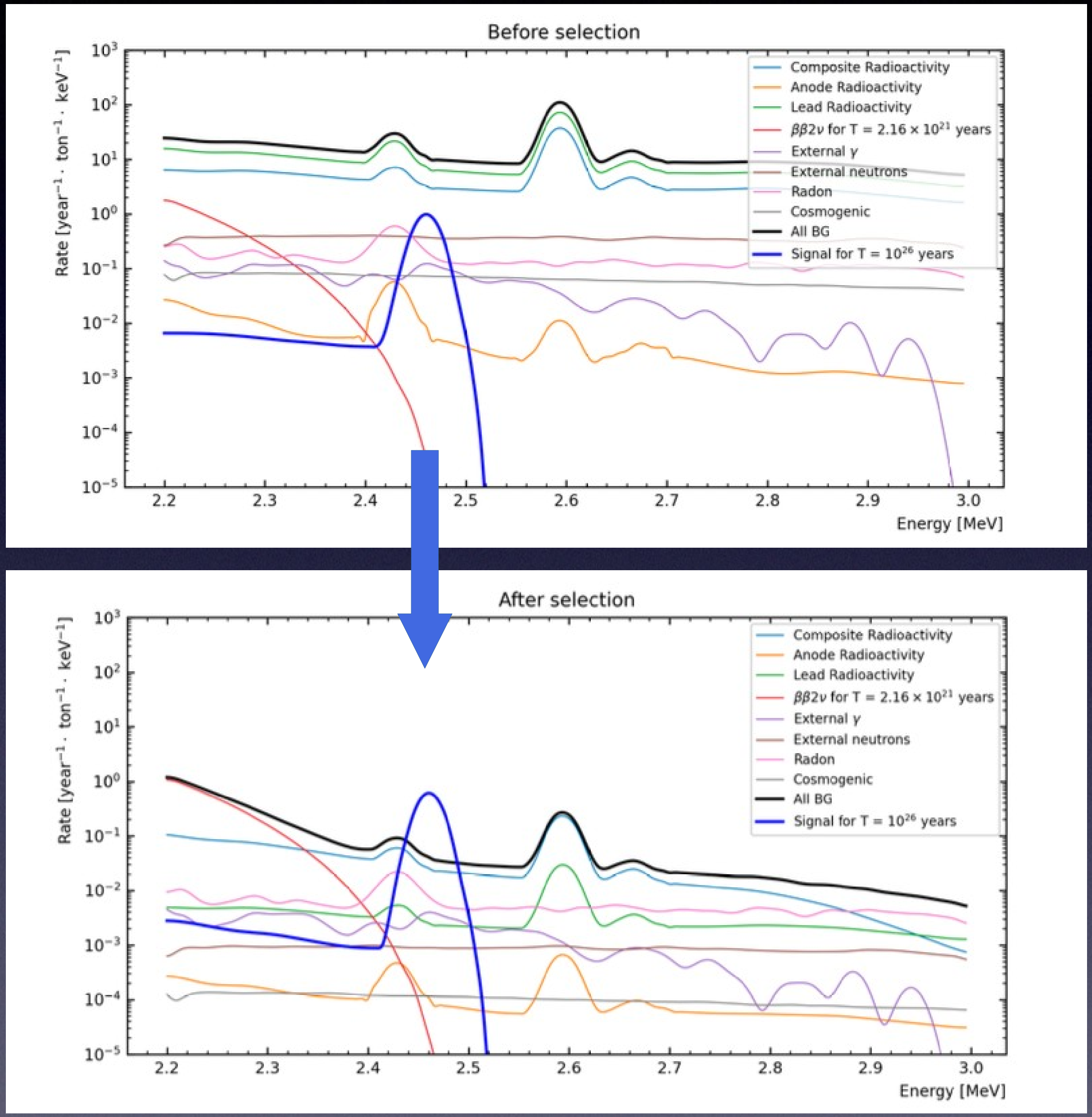


=> Reconstruction of radial and longitudinal positions with mm precision was obtained.



Sensitivity simulations

(without 2-ē tracks recognition). *Eur.Phys.J.C 85 (2025) 7, 732*

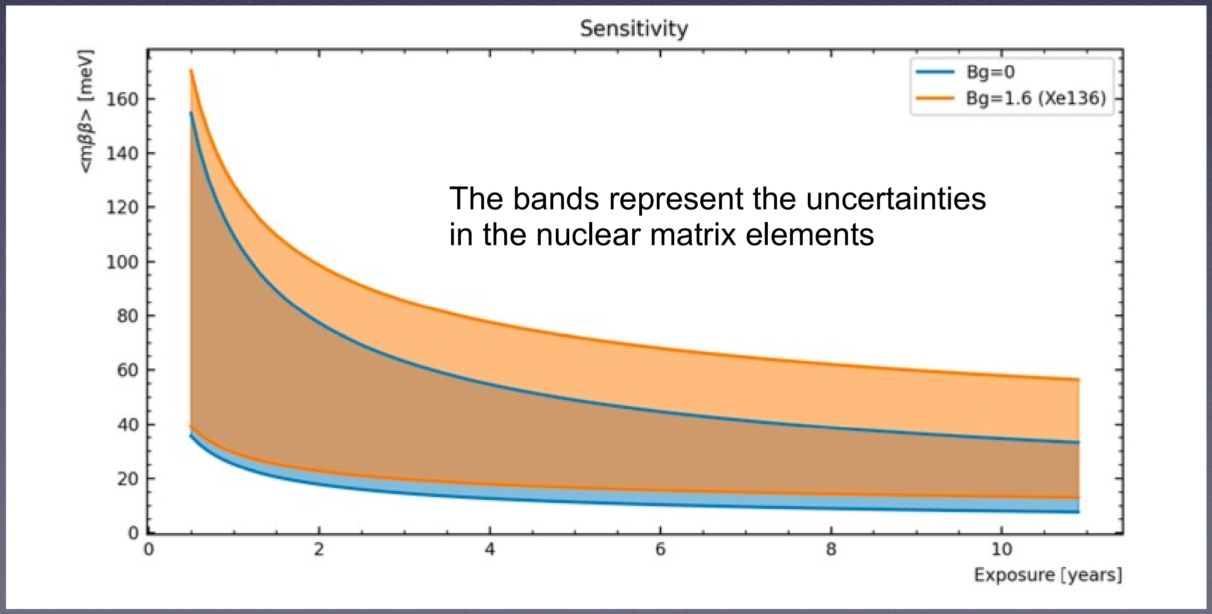


Background modeling

=> Reduction of a factor 100 was achieved in the ROI through selection criteria based on event topology.

Sensitivity

=> Expected limits for < mββ > at 90% C.L.



R2D2 in a global context

(without 2-ē tracks recognition)

The simulated sensitivity of R2D2 appears comparable with those predicted for other projects.

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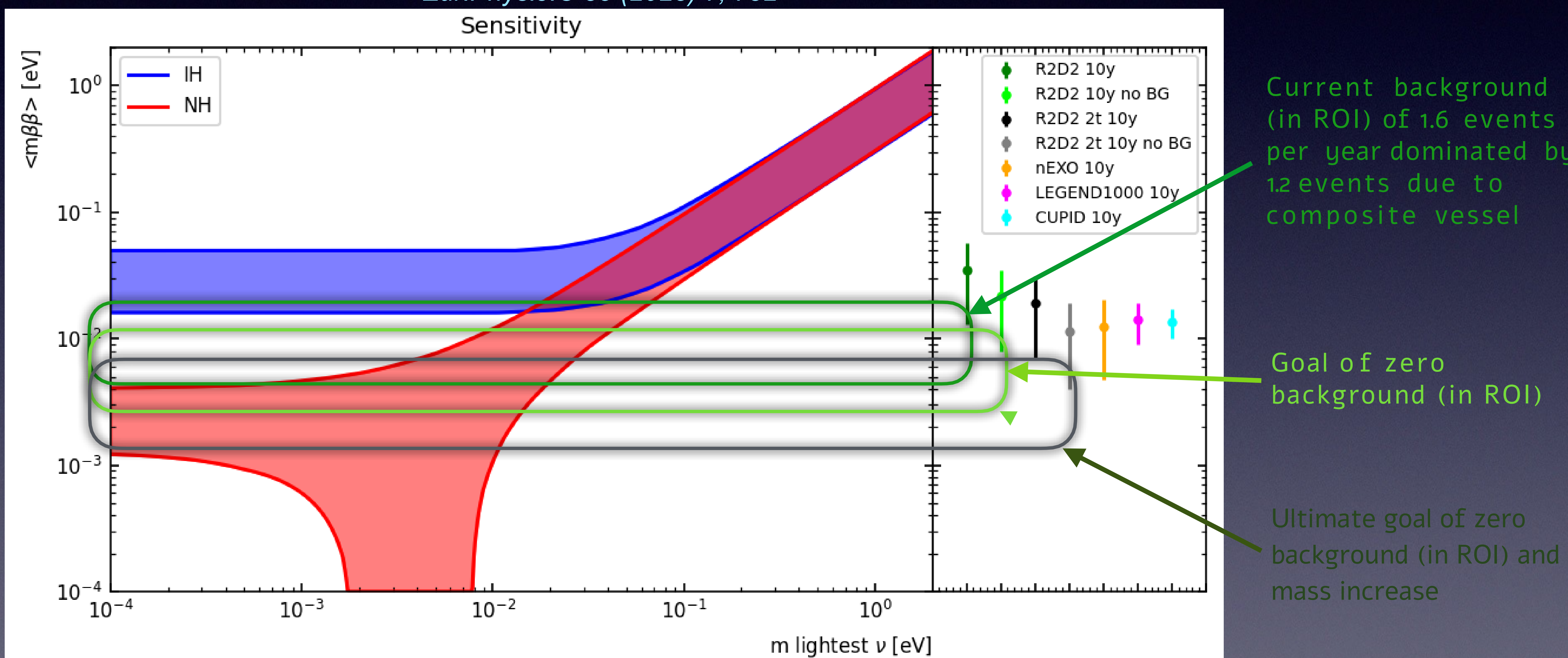
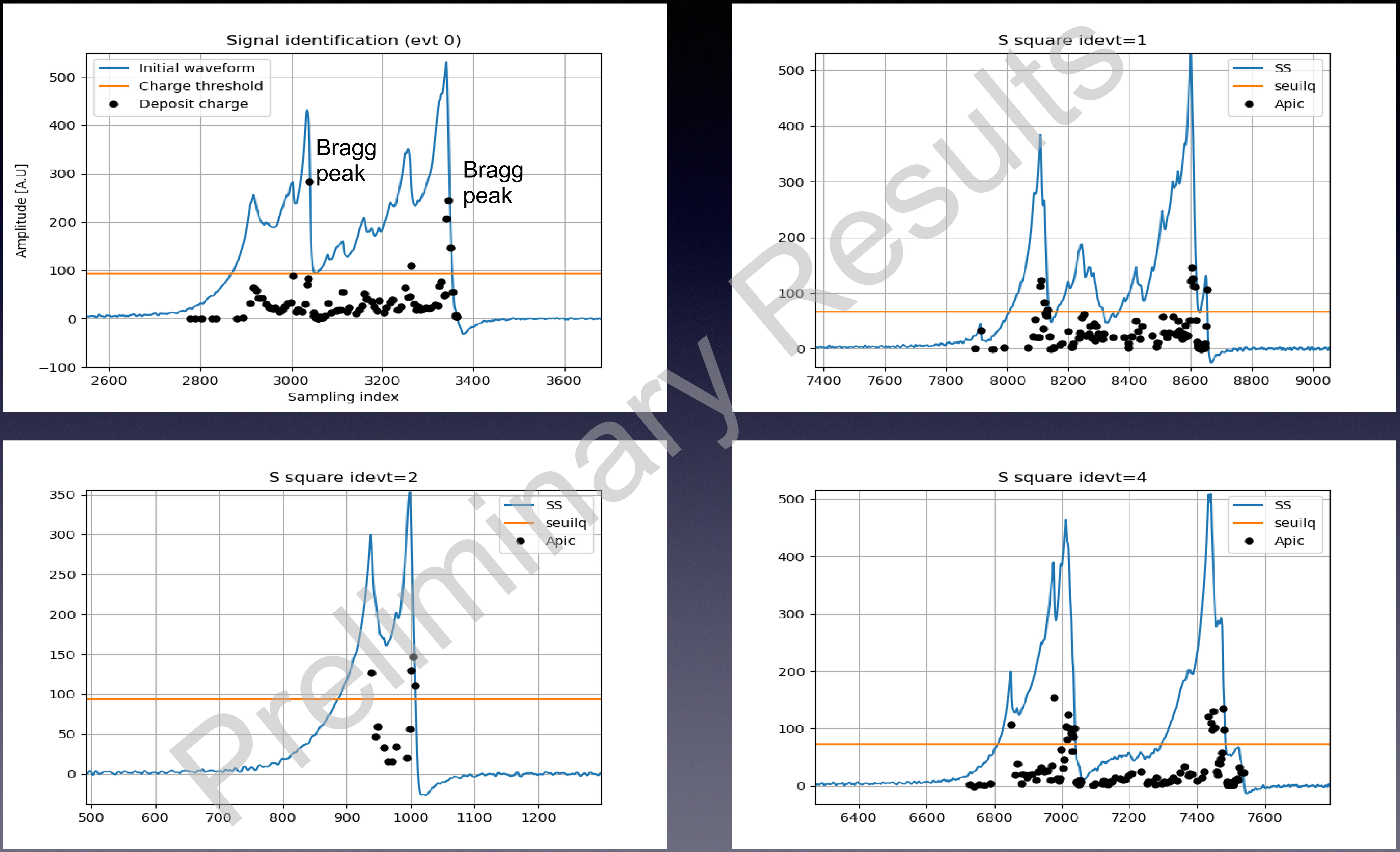


=> Preliminary 2-ē track recognition with the decomposition/synthesis method

(Simulated waveforms for 2β(0ν) events)



(Experimental validation in progress)

Conclusions

The detection principle is established (2-ē identification, energy resolution, localization...)
=> Additional expertise is now welcome to complement R&D.

- **The main concern for 2026-2028 is the completion of a low radioactivity vessel prototype,** before proceeding with the experiment construction.

If low radioactivity composite can be obtained, it will be a major breakthrough for all low radioactivity experiments.

- 2029-2030: final detector construction
- 2031-2032: commissioning (Ar/natural Xe)
- >2023: data taking with enriched Xe

This technology would be perfectly suited to parallel operations, of several tanks, on several sites, and with several actors.

Simple setup and operation at room temperature make it also fully compatible with environmental sustainability requirements.

Thank you for your attention