R2D2 project overview

A.Meregaglia (LP2i Bordeaux)
On Behalf of R2D2 collaboration

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Physics case

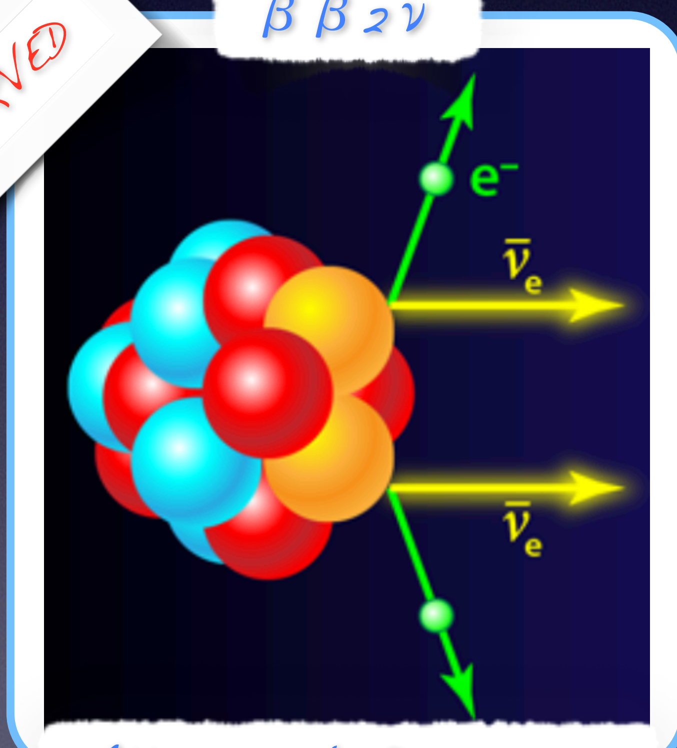
- The observation of **neutrinoless double beta decay (ββ0ν)** is fundamental to determine the nature of neutrino.

Dirac ($\nu \neq \bar{\nu}$)

Majorana ($\nu = \bar{\nu}$)

OBSERVED

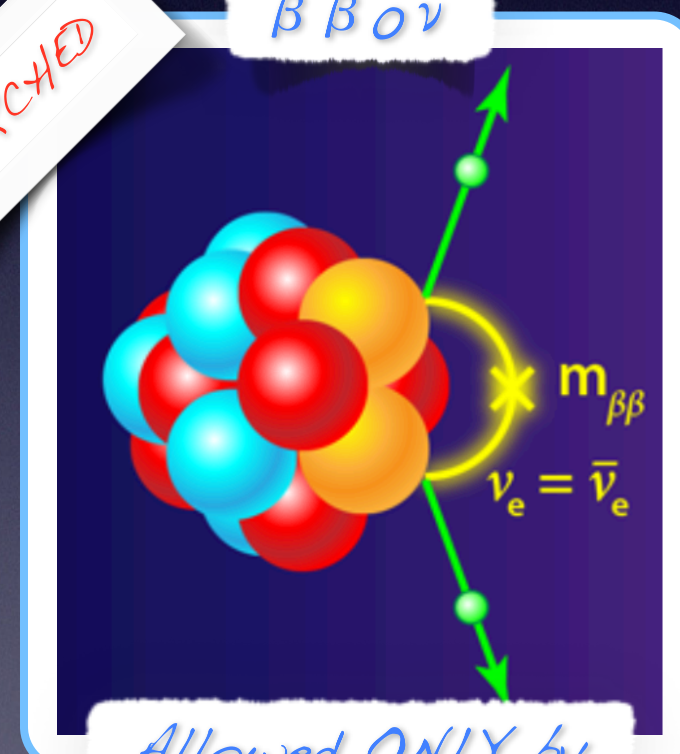
ββ2ν



Allowed by Dirac and Majorana ν

SEARCHED

ββ0ν



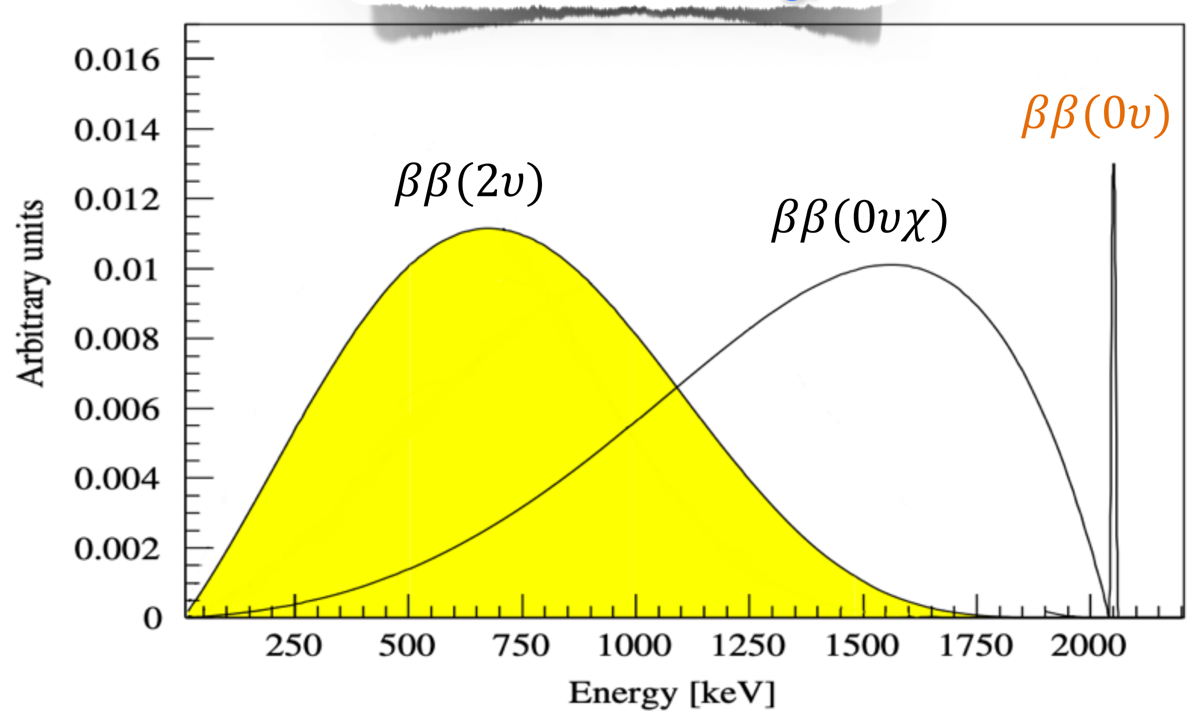
Allowed ONLY by Majorana ν

- The observation of ββ0ν decay would have **implications in particle physics** (generation of neutrino masses) and **cosmology** (leptogenesis model).

Experimental observables

- The **signature** of the decay is given by the **sum of the kinetic energy of the two emitted electrons**.

Electrons energy



Importance of energy resolution to identify the peak

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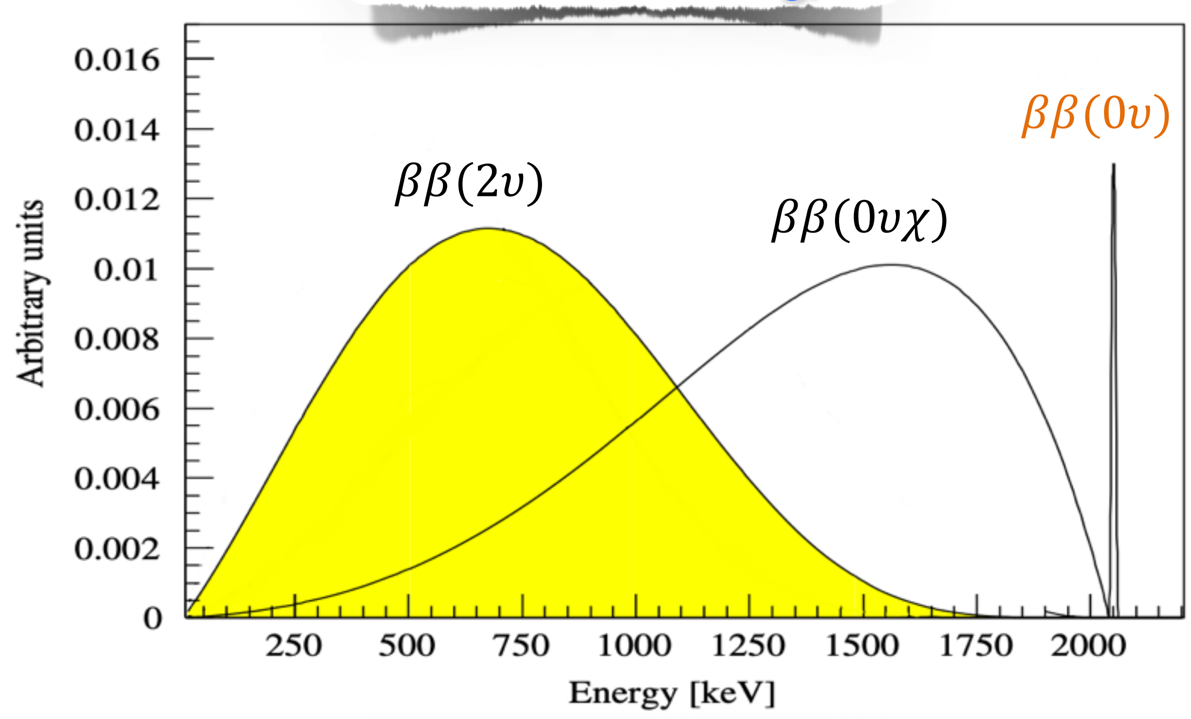
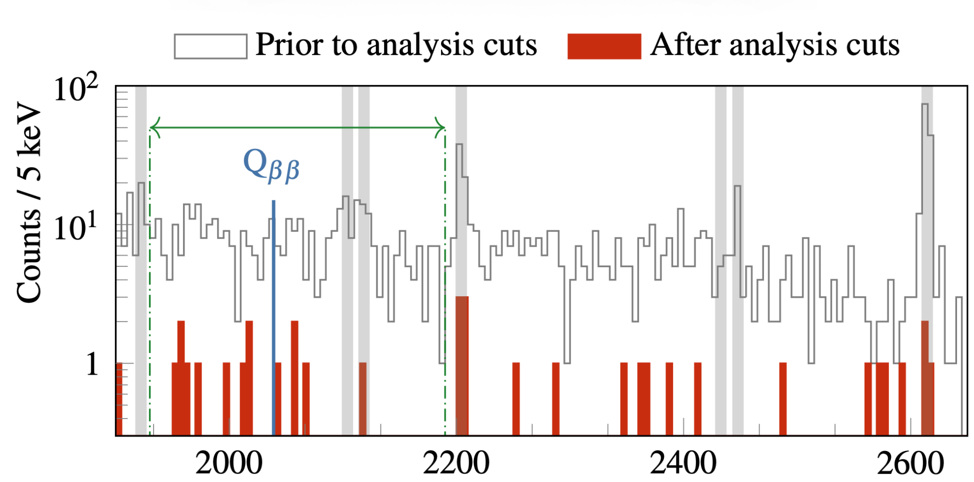


Importance of energy resolution to identify the peak

Example from GERDA



Importance of identification of two electrons if a signal is observed

Experiment sensitivity

- The experimental sensitivity can be computed in terms of a limit of the half life.

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

Signal efficiency

Isotope active mass

Exposure in years

Signal upper limit

Isotope molar mass

Importance of large mass

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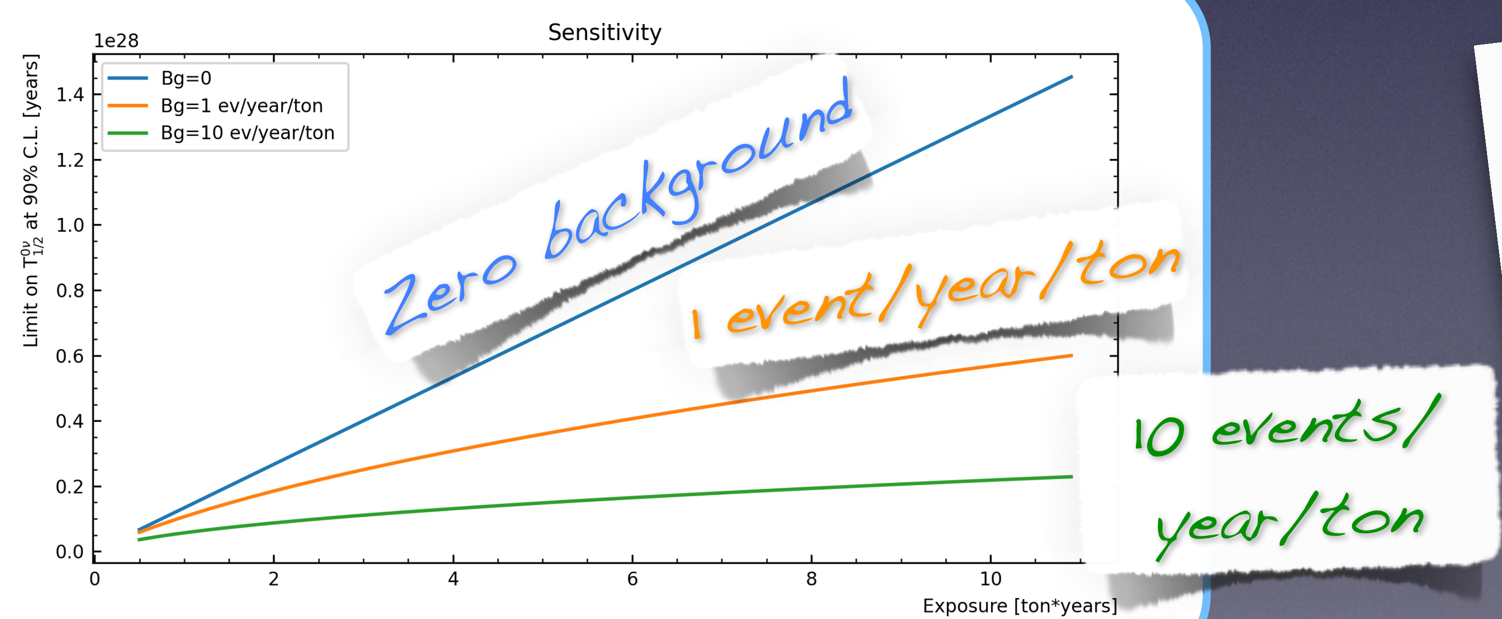
Exposure in years

Signal upper limit

Isotope molar mass

Importance of large mass

- The **signal upper limit depends** on the chosen confidence level and **on the experimental background**:



Importance of low background (the 2 electrons identification is also critical for background reduction)

Birth of R2D2

- The **main requirements** to search for 0νββ decay are:

Excellent energy resolution

Low background

Large masses of isotopes

Electron tracks identification

→ Can we meet all the requirements at the same time? → Goal of R2D2 (Rare Decays with Radial Detector)

- R2D2 is an **R&D program started 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

Standing on the shoulders of giants

R2D2

First Xe based experiments for ββ0ν

1980-2000

Experiment	Year	Volume	Pressure	Mass	Energy Resolution (FWHM @ $Q_{\beta\beta}$)	Detection Principle
Gotthard	1993	180 L	5 bar	5 kg	5.4 %	Drift + proportional
Milano (LNGS)	1992	80 L	9.5 bar	4 kg	4.2 %	Proportional
ITEP (Baksan)	1986	40 L	30 bar	8 kg	2.5 %	Ionisation
DEVIS (ITEP)	2002	13000 L	1 bar	70 kg	3 - 4 %	Proportional

Limits

- **Energy resolution** (gas purity, mode of operation e.g. wire uniformity in proportional mode, and electronics)
- **Detector design** (scaling)
- **Low background** (materials radioactivity)

Today mostly overcome thanks to the developed know-how

Standing on the shoulders of giants

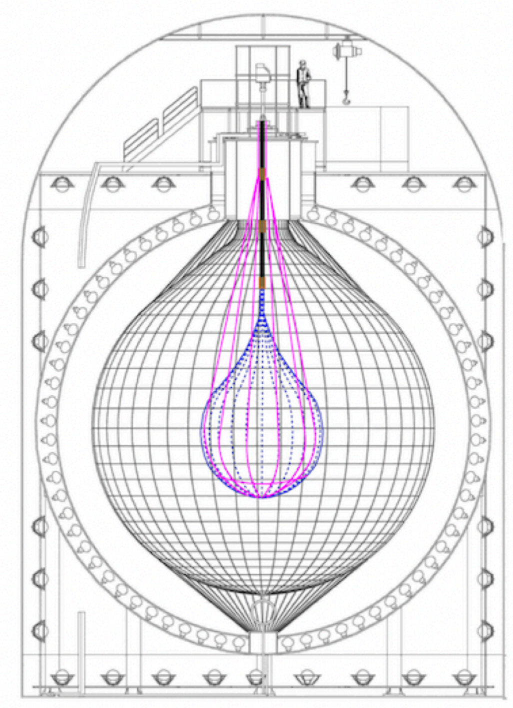
Towards Xe large mass calorimeters

2000-2025

Experiment	Year	State	Mass	Energy Resolution (FWHM @ $Q_{\beta\beta}$)	Detection Principle
EXO-200 (US)	2011	Liquid (TPC)	200 kg of ^{136}Xe	3.2 %	Scintillation + ionization
KamLAND-ZEN (JAPAN)	2011	Xe dissolved in LS	800 kg of ^{136}Xe	8%	Scintillation
NEXT (CANFRANC)	2016	High-pressure gas (10–15 bar)	100 kg of ^{136}Xe	1%	Electroluminescence (proportional light) + tracking

KamLAND-ZEN 800

The best present limit on effective neutrino mass based on pure **calorimetry**.



Possible breakthrough

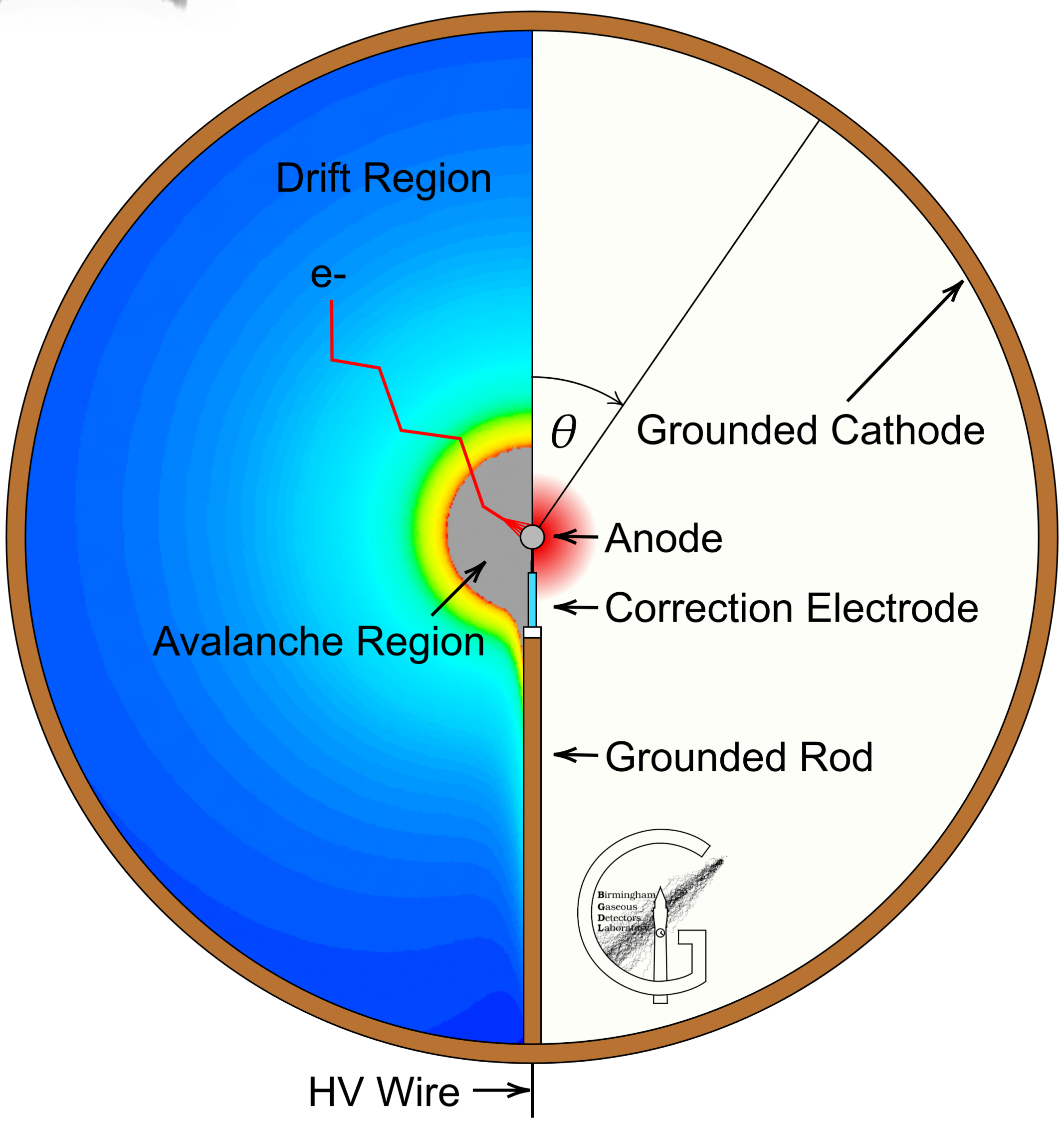
R2D2

Record energy deposits in large Xe volumes with a simple antenna, combining **calorimetry and electron identification** in a low-background environment.

Detection principle

- We started with a **spherical** Xenon gas TPC (**STPC**) as used in the NEWS-G collaboration.

STPC



Know-how achieved

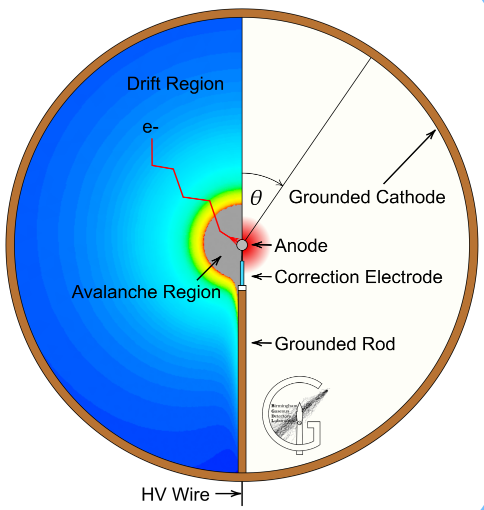
- Operation of gaseous detectors and understanding of signal formation.
- Development of DAQ and signal processing.
- Purification and recirculation system design.
- Study and mitigation of electronic noise, including HV dependence.
- Design of a low-noise preamplifier.

Two geometrical options

- The R&D and acquired know-how led to the evolution from a spherical to a **cylindrical** TPC (**CTPC**), based on the same working principle but offering easier operation and improved event topology reconstruction.

STPC

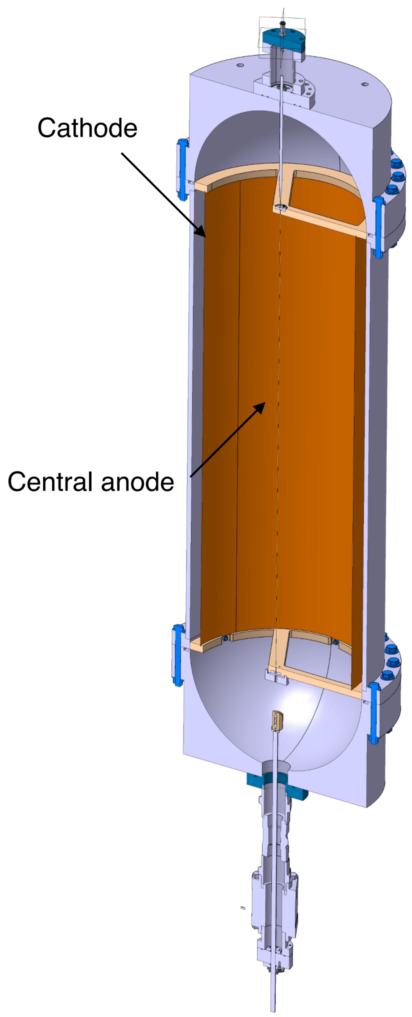
2017
Calorimetric detector
Proportional mode



7 years of R&D

CTPC

2025
Track reconstruction
Ionisation mode



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 readout channel.

Main goal of the R2D2 R&D NOW VALIDATED

Ongoing R&D with innovative materials (see later)

True by conception

Two operation modes

- The CTPC can be operated in two modes: **ionisation** (i.e. no gain) or **proportional** (i.e. avalanche near the anode with a resulting gain).
- The signal observed is a current induced according to the **Shockley-Ramo theorem**.

Proportional

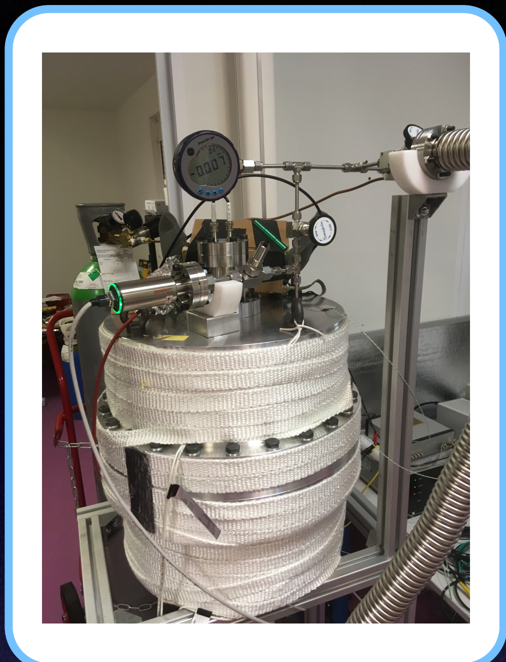
- Signal due to the **drift of the ions of the avalanche** (slower than electron signal).
- Mainly charge is reconstructed (rough position dependence based on signal risetime).
- Gas mixture needed (quenching to avoid secondary signals).
- Thin anode required.

Ionisation

- 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.
- Thick anode possible.

The ionisation mode avoids gain fluctuations and allows topological reconstruction.

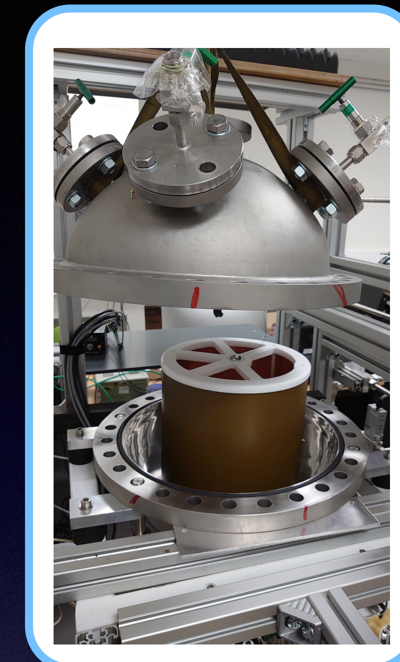
History and milestones



First STPC (no high pressure)

Second STPC (certified to 40 bar)

First CTPC (no high pressure)



Second CTPC (certified to 40 bar)

2018

2021

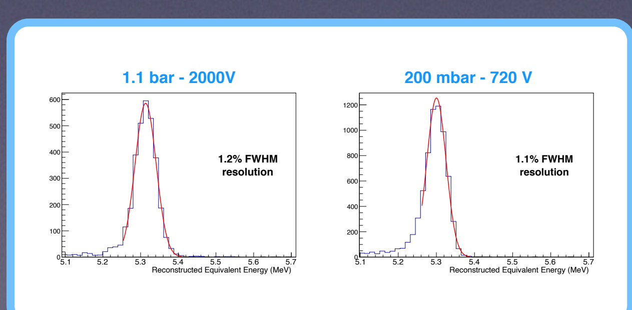
2023

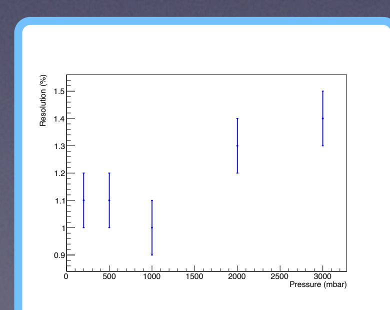
Same resolution for short and long tracks (Ar)

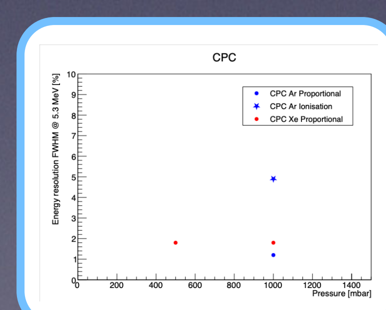
Stable resolution up to 3 bar Ar (limited by HV)

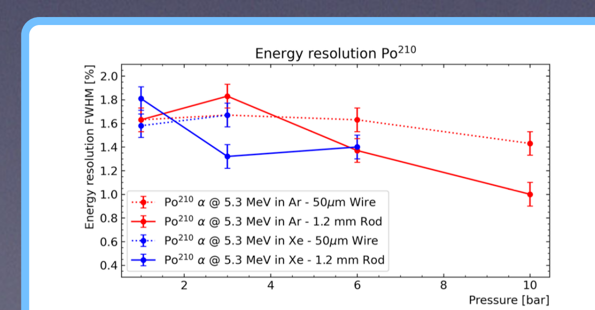
Similar resolution in Ar and Xe

Good resolution in Ar/Xe up to 10/6 bar (limited by the purification system)









JINST 16 (2021) 03, P03012

JINST 18(2023) 10, T10001

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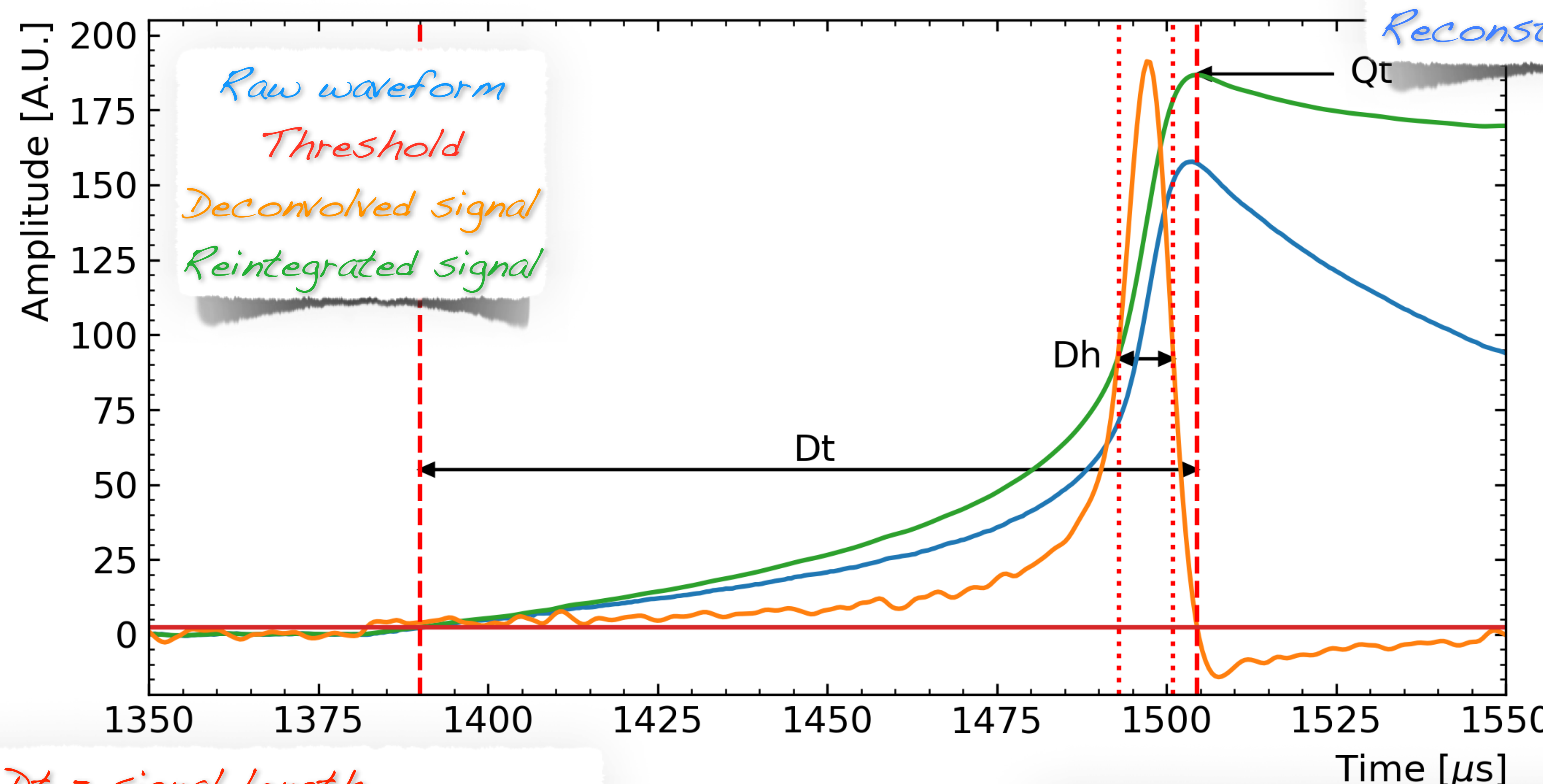
Outcomes of R&D

R2D2

Signal processing

- Signal processing is critical to extract all the information from the detector.
- A simple detector with a single readout channel could identify the two electrons, their radial position as well as their energy thanks to a dedicated signal analysis.

Qt = total charge
Reconstructed energy



Dt = signal length
Maximal radial distance from the anode

Dh = signal width at half maximum
Radial extent of the track

Outcomes of R&D

Signal processing

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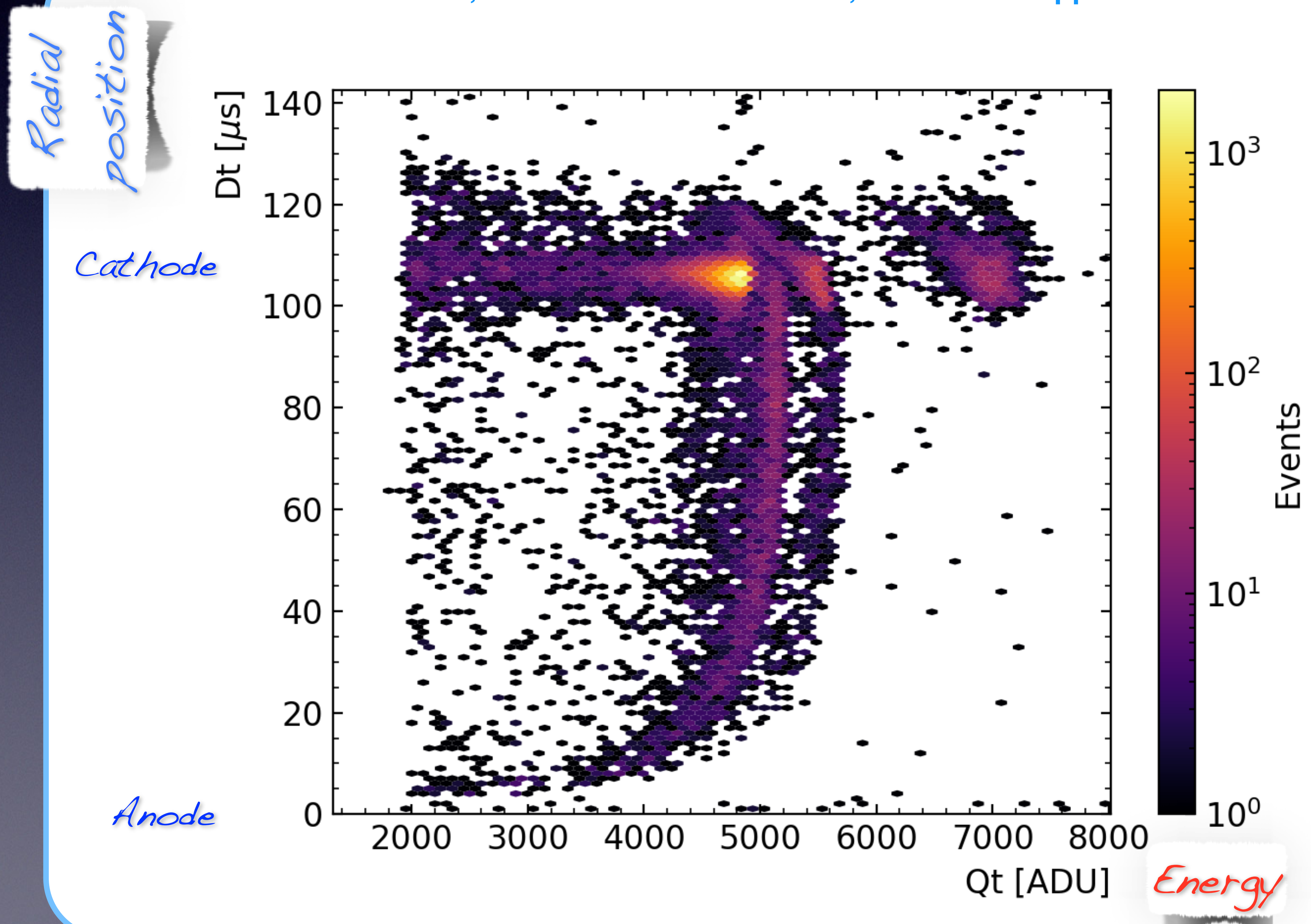
- The observables were used to select the events, namely the Po or the Rn issued alphas showing the detector performances in identifying energy and position of the events.

Data for xenon at 3 bar, anode of 1.2 mm diameter, and -3000 V applied to the cathode



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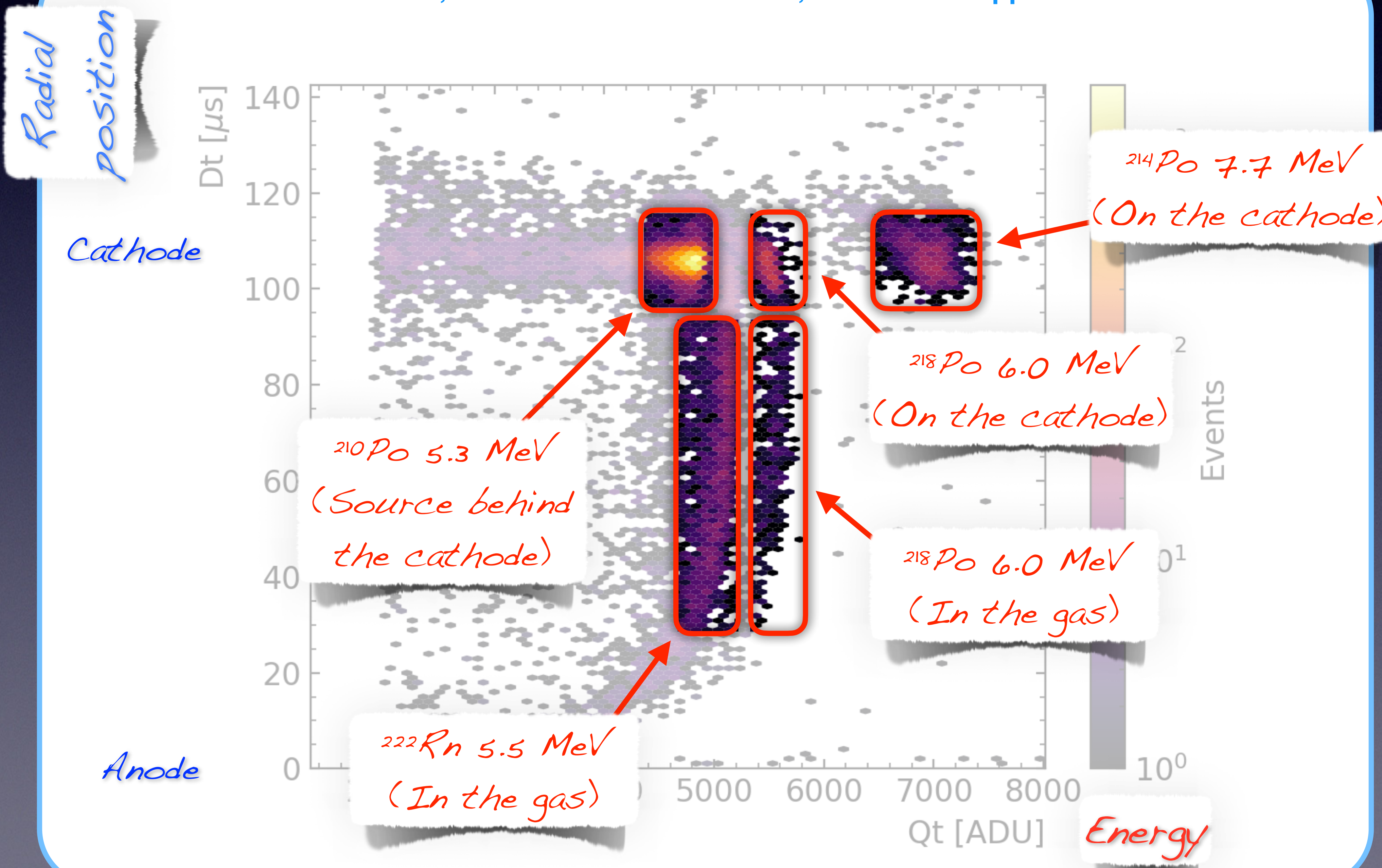

Outcomes of R&D

Energy resolution

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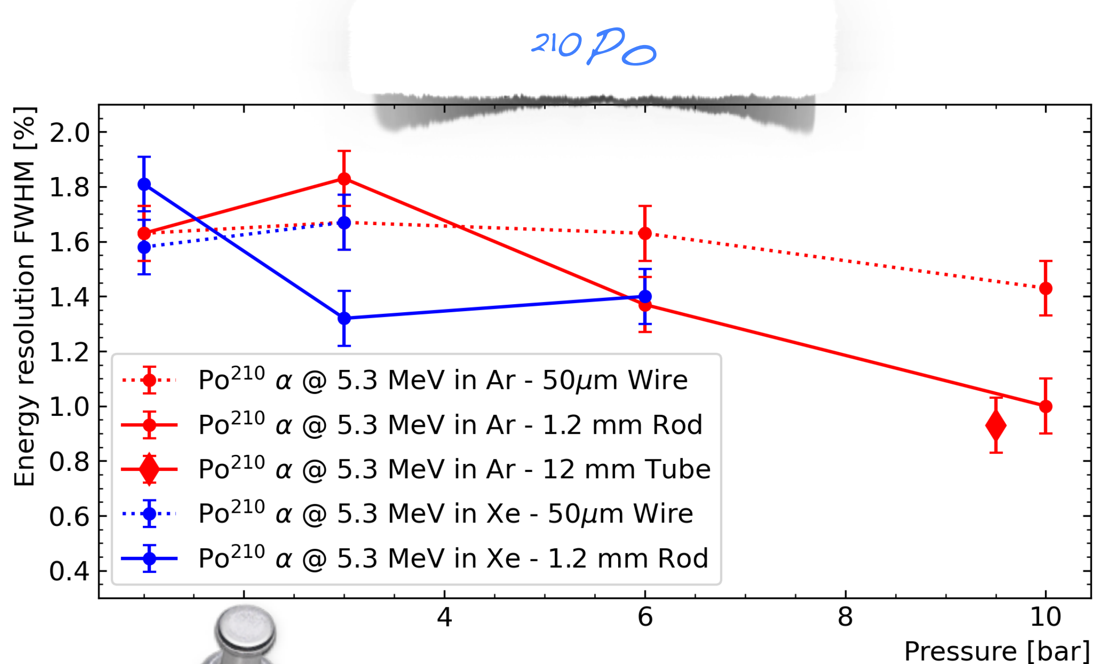
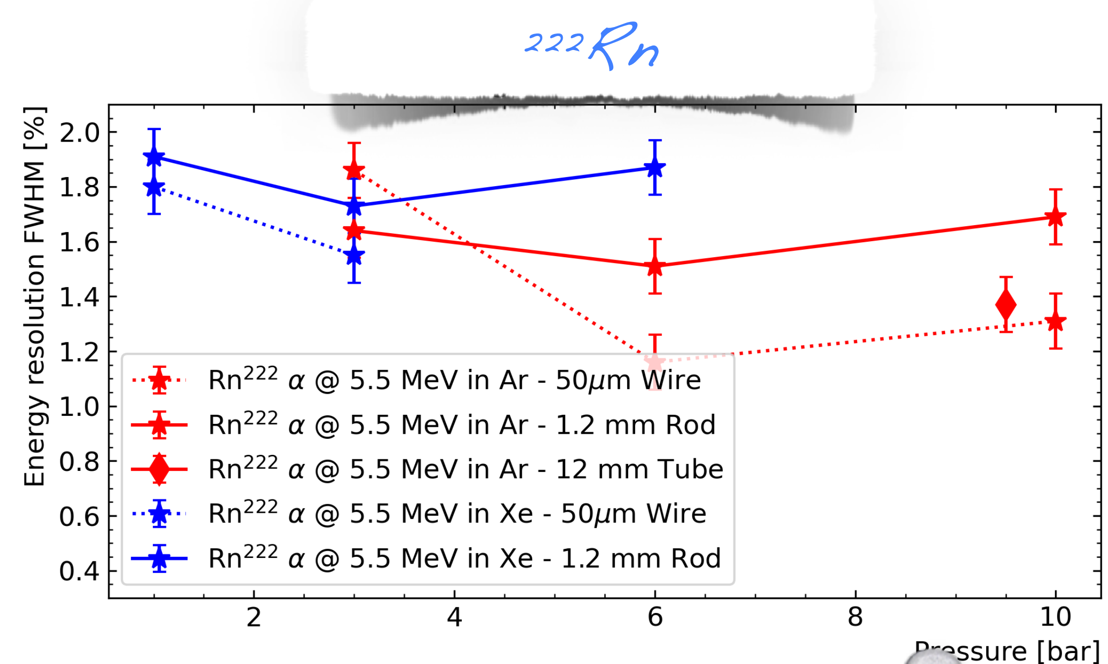
- The main goal of the R&D was to **establish the energy resolution** at the level of 1% at the ^{136}Xe $Q_{\beta\beta}$ of 2.458 MeV.





The resolution is mostly independent on the gas nature.

The resolution is mostly independent on the gas pressure.

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

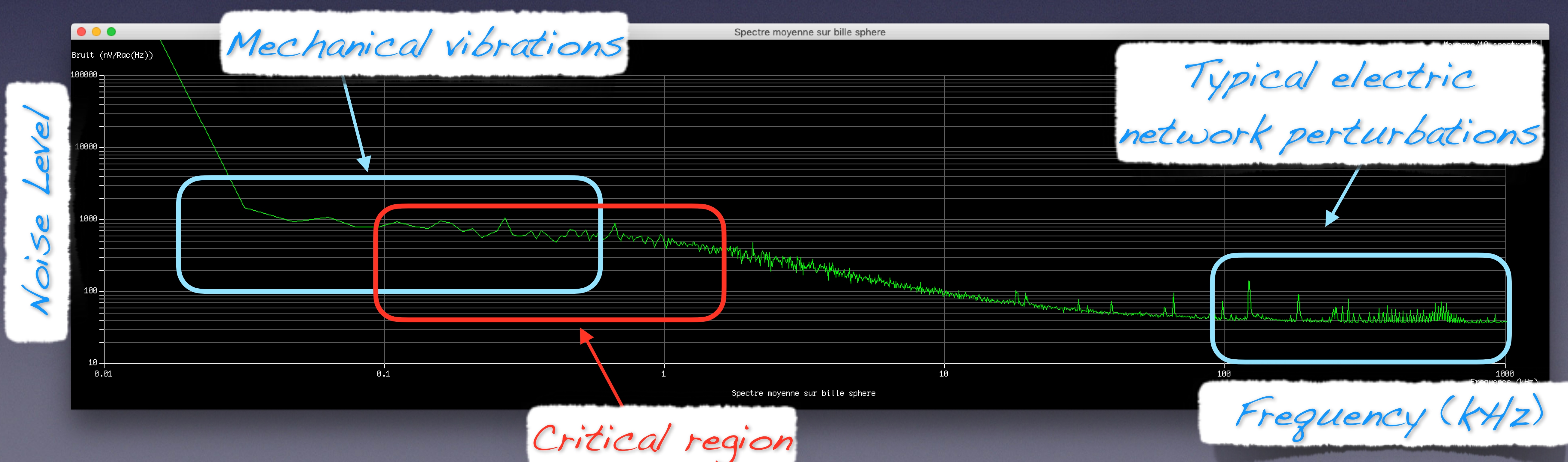
Conservative results due to several identified constraints (see next)

Constraints

Noise

- A huge effort was done to have a readout signal with the lowest noise although the **detector was not operated in a dedicated environment** (neutrino experimental hall at LP2i with other experiences and users).
- Two sources of noise were identified: electronic and vibrational.
- A low noise front end preamplifier was developed (for proportional mode) but a standard ORTEC was used for ionisation.

➡ Additional ideas for noise reduction are under investigation such as operation on battery.

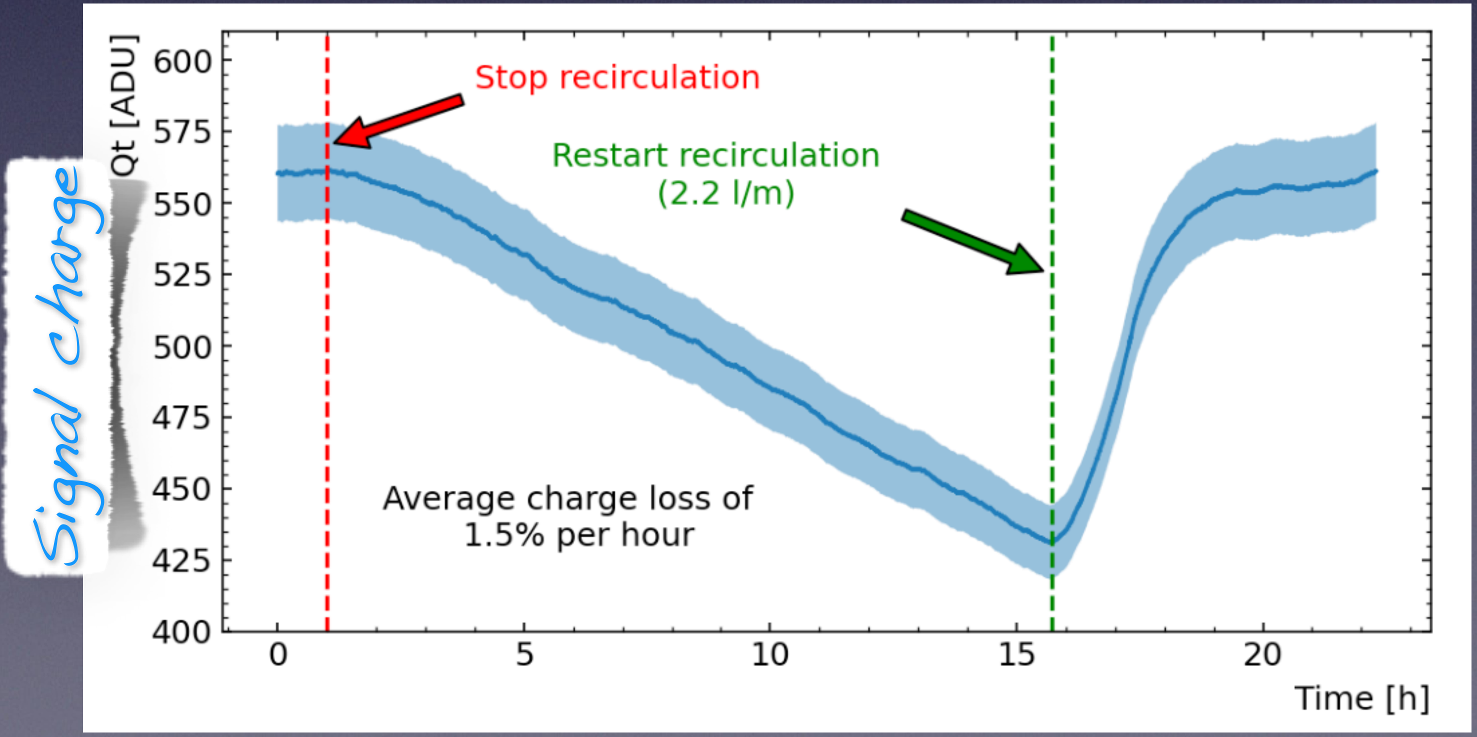


Constraints

Gas purification

- Reduction of electronegative impurities is required.
- A Recirculation and purification system with cold/hot getters was commissioned (limit at 10 bar), and a new spark-chamber-based system is under development for operation up to 40 bar.
- **Electron lifetime** of ~2 ms achieved (**one order of magnitude worse than noble liquid detectors**).

➡ Purification solutions from the xenon community are available.

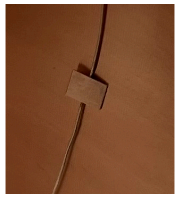


Constraints

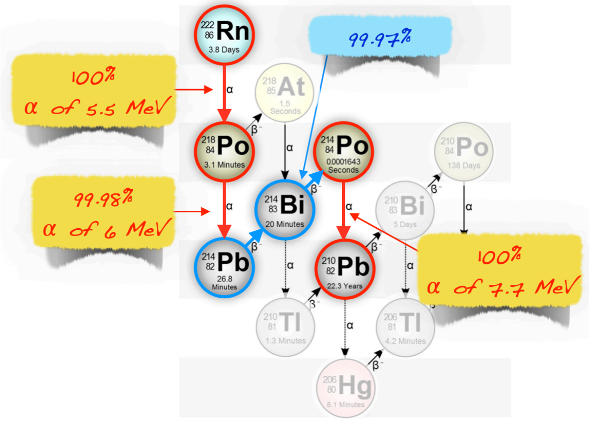
Source

- For the R&D we used ^{210}Po and ^{222}Rn alpha sources.

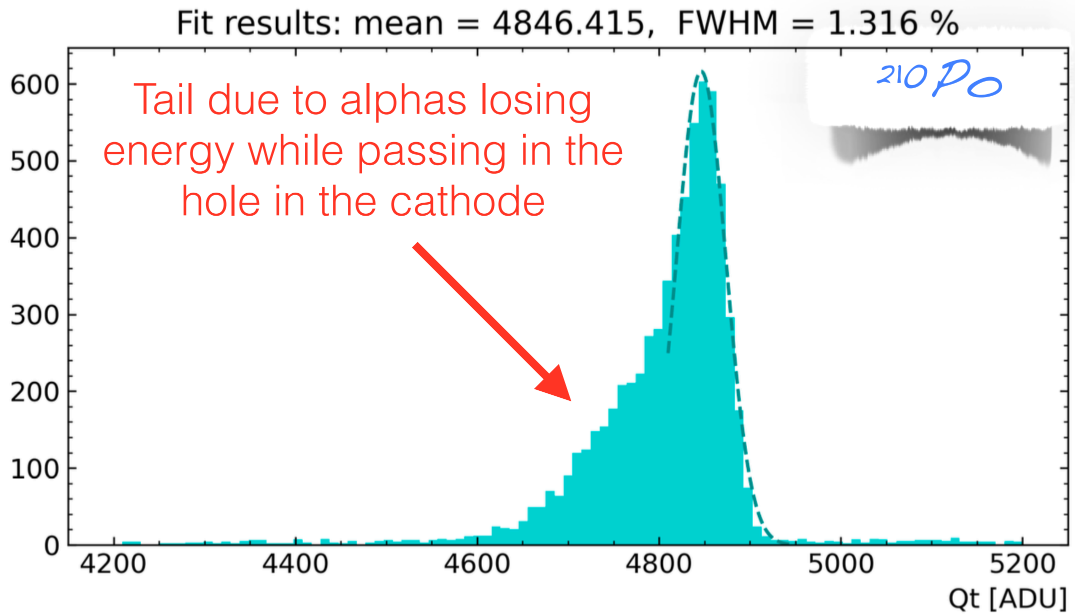
➡ A thorough calibration strategy for the full scale detector has yet to be finalized.

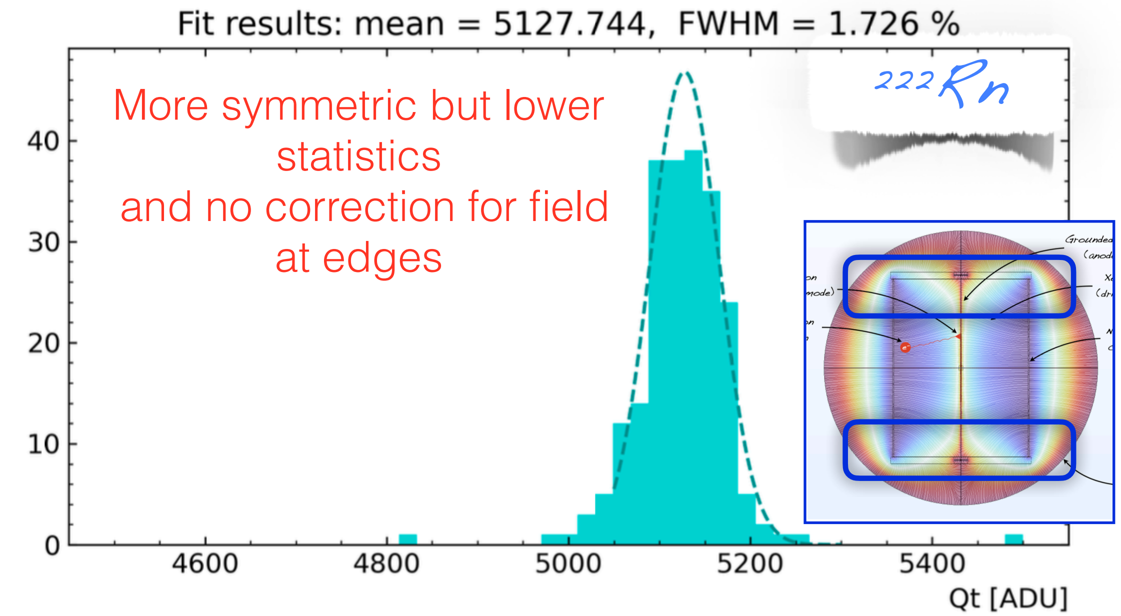


^{210}Po source (5.3 MeV alphas) located behind 2 mm diameter hole in the cathode



^{222}Rn source (and following decay chain) issued by the getter and located inside the gas





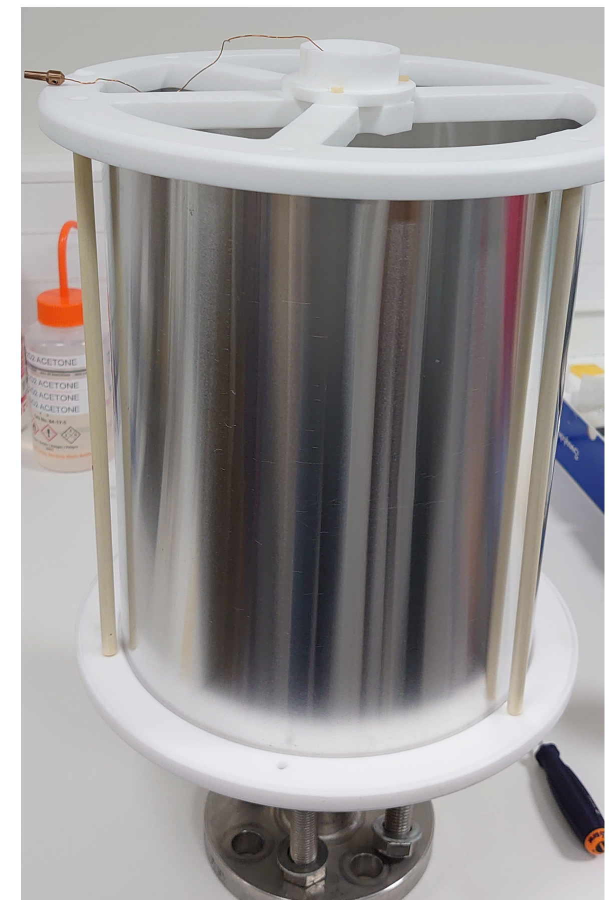
Field distortion, **energy loss** through the cathode hole.

Low statistics, and **no field correction** at the CTPC edges.

What did we learn?

A simple and light detector demonstrated

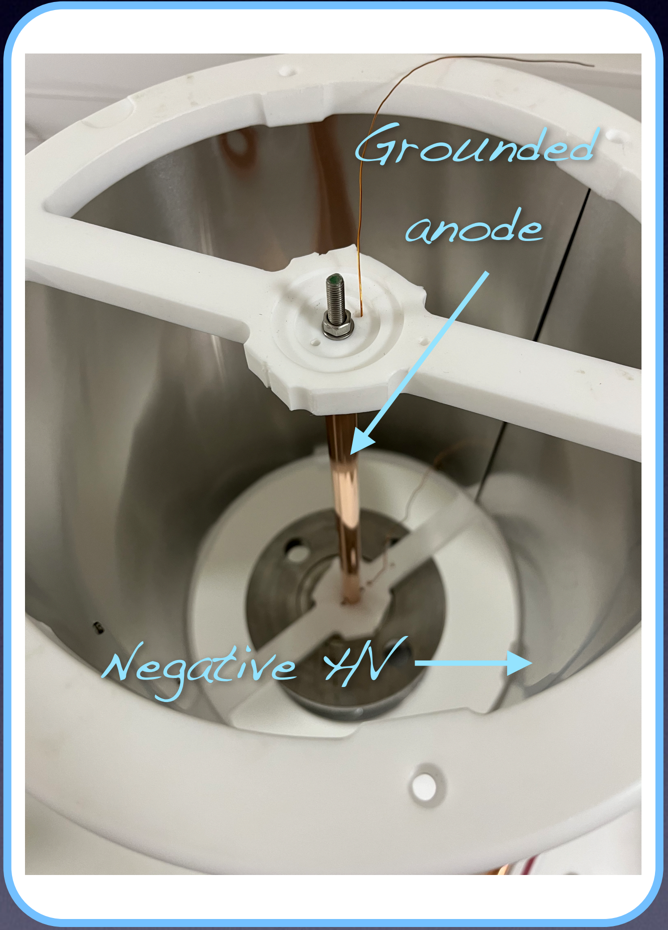
- *Geometry*: **CTPC** selected, giving strong field at the cathode (1/R dependence), uniform field through the gas volume, and electrostatic stability.
- *Anode*: **Thick tube**, more robust than a wire and providing a larger field at cathode and allowing vertical or horizontal operation.
- *Trigger*: **Autotrigger** with no need of scintillation light readout for a cheaper detector with lower radioactive contamination.
- *Read out*: Large volume read with only 1 channel, extendable to 2 for longitudinal position reconstruction. Charge preamplifier validated and ongoing tests of ASIC current preamplifier for resistive anode readout ongoing.



What did we learn?

Operation mode defined and optimised

- *Operation mode*: **Ionization** selected given no gain fluctuation and more topological info on the signal.
- *Polarisation*: Negative HV on cathode and **read out of non polarized anode** to have no HV-induced noise on the signal.
- *Gas optimisation*: Same performances in Argon and Xenon so possibility to **commission the detector in Ar**.



What did we learn?

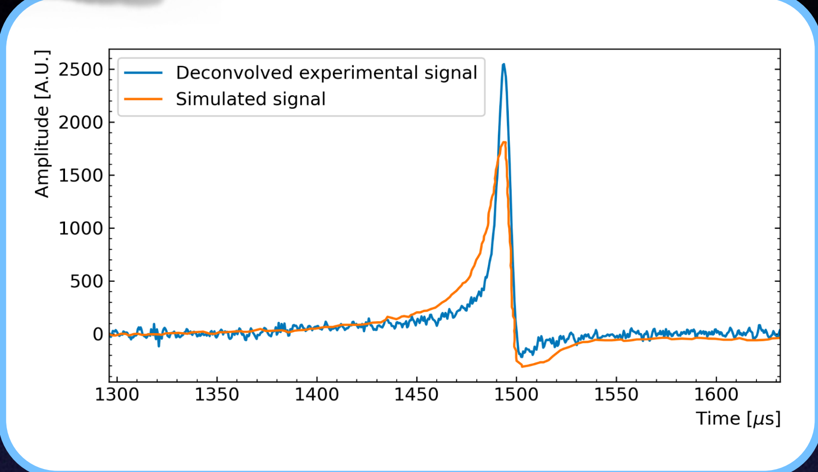
Detector capabilities proven

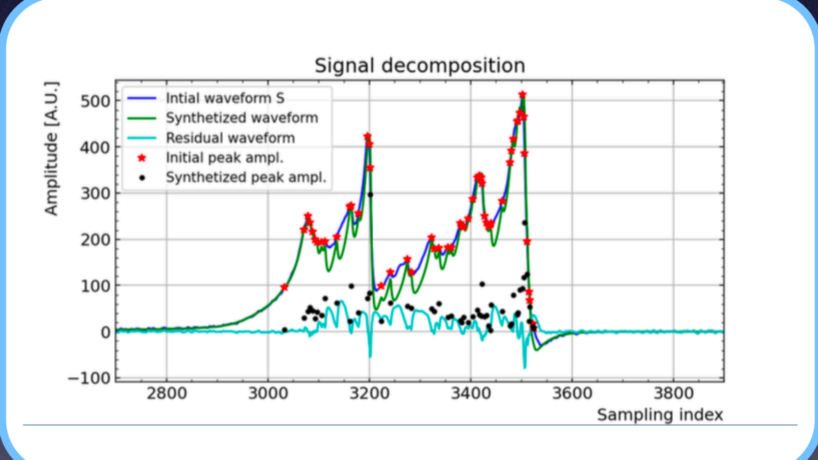
- *Signal formation*: **Clear understanding** with validation between Monte Carlo and real signals.

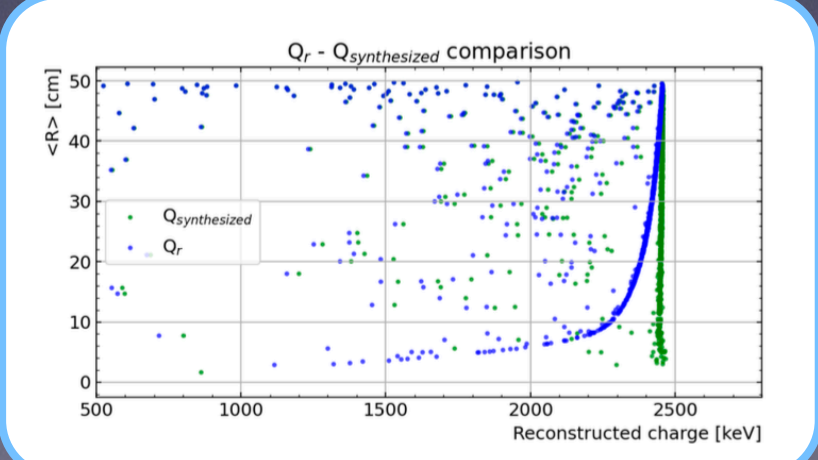
- *Signal reconstruction*: Robust detector response model, and **algorithm for 2-electron tracks and missing charge correction** validated on MC. Optimisation on data ongoing.

- *Energy resolution*: **1% FWHM for 5.3 MeV alphas validated**. New synthesis algorithm reaches 0.7% (equivalent to 1% at ^{136}Xe $Q_{\beta\beta}$ of 2.458 MeV if rescaled as 1/sqrt(E)).

- *Spatial localization*: Possible reconstruction of radial and longitudinal position with **sub-cm precision**.







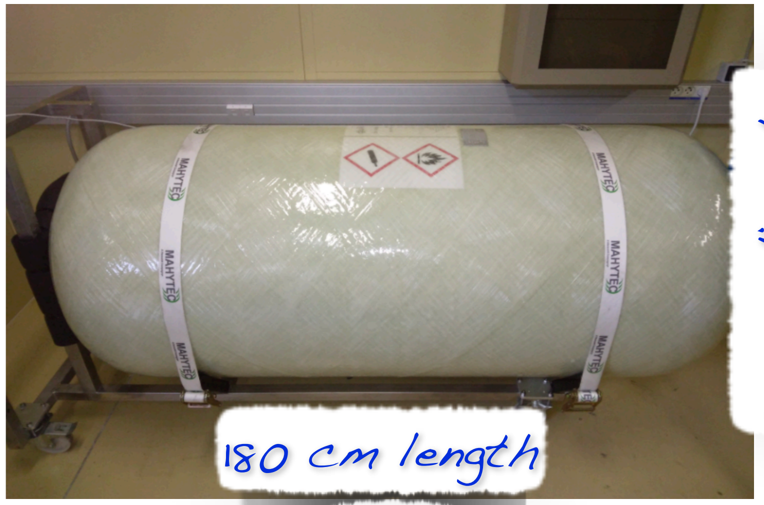
Towards a full scale demonstrator

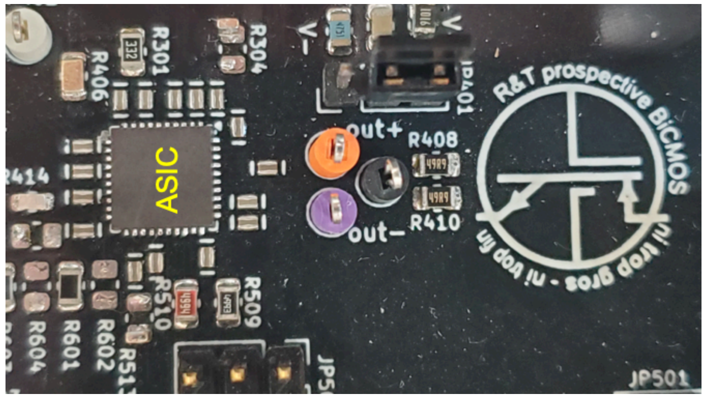
R2D2

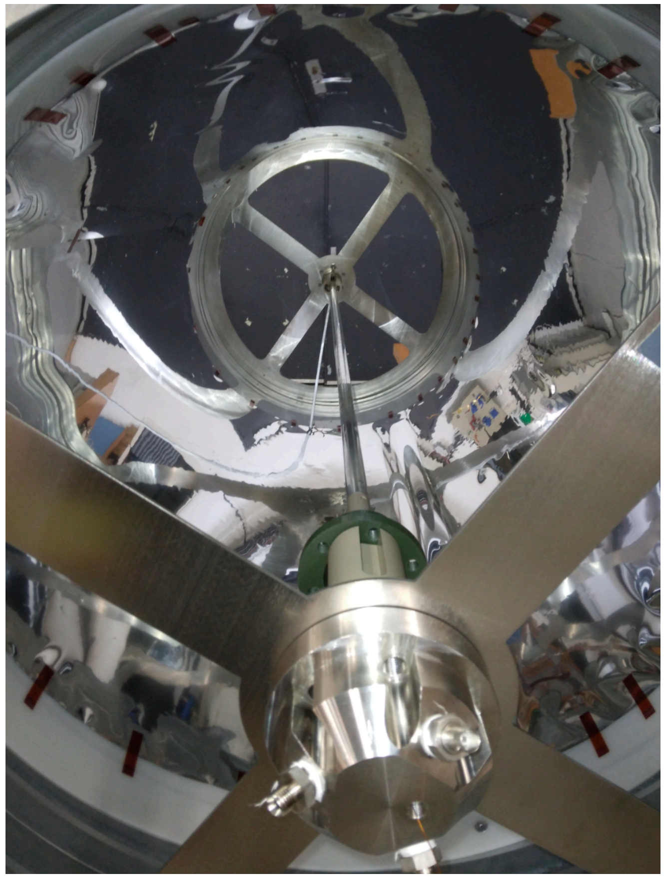
Full scale instrumentation

A composite full scale vessel from MAHYTECH has been acquired to prepare future detector instrumentation and validate critical aspects where no showstoppers are expected.

- ➡ Test detector instrumentation (cathode deployment, HV connection, and electronic noise).
- ➡ Test long drift and vertex accuracy at different pressures.
- ➡ Test resistive anode with the full ASIC electronics.
- ➡ Validate electron identification up to 40 bars.
- ➡ Validate purification principle at high pressure.







Towards a full scale demonstrator

Low background

- The **main open question** is whether a **composite vessel** can be produced with a radioactivity level of of **10 μBq/kg** (research is ongoing with industrial partner IRT Jules Verne).
- Validation of the radioactivity of other components (electronics, cables, etc.)
- Assessment and suppression of radon emanation from materials (**ANR IRENE,** P.I. J. Busto, ongoing).

Low radioactivity measurements

- Mesure with Ge detectors (LP2i, LSM, Bratislava).
- Measure by ICP-MS (Bratislava)

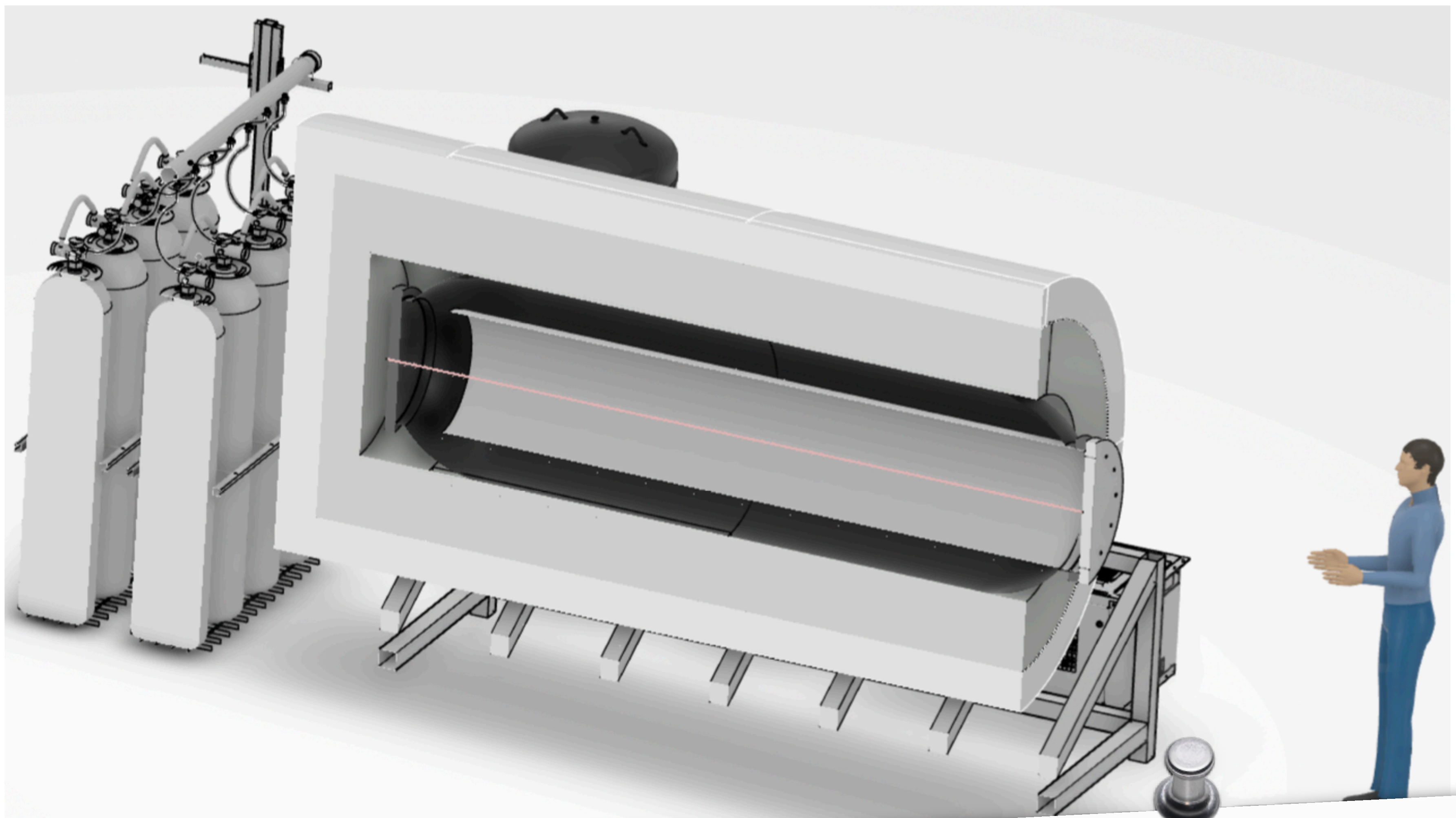
Radon measurements

- Mesure with Rn emanation chamber (LP2i, CPPM).

Only possible identified showstopper

R2D2 possible sensitivity

- Based on the know how developed in the R&D we designed a possible experiment using the R2D2 technology and computed its sensitivity.



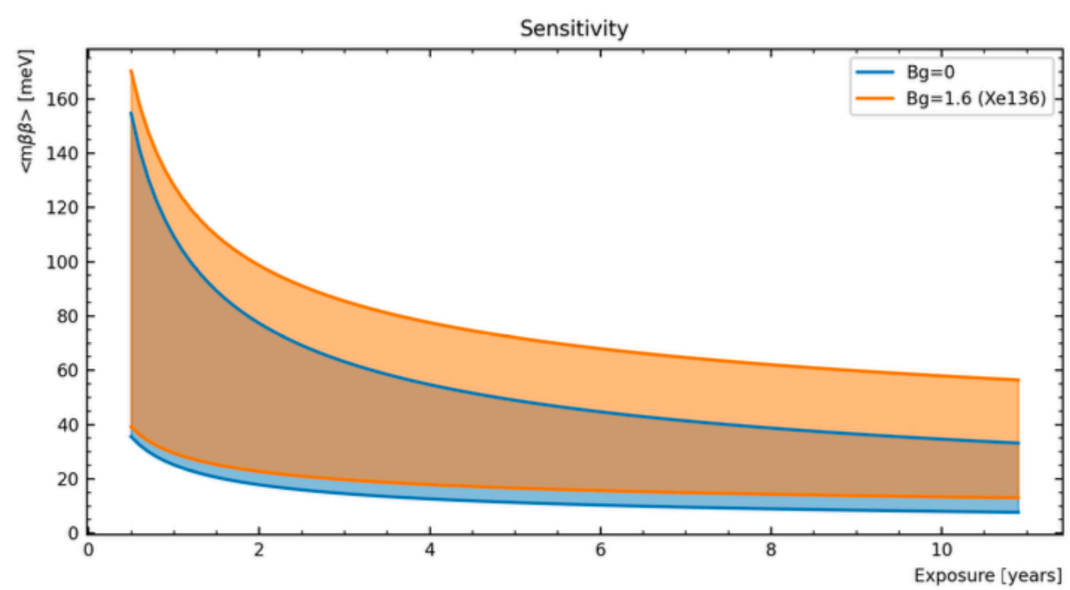
Some key numbers:

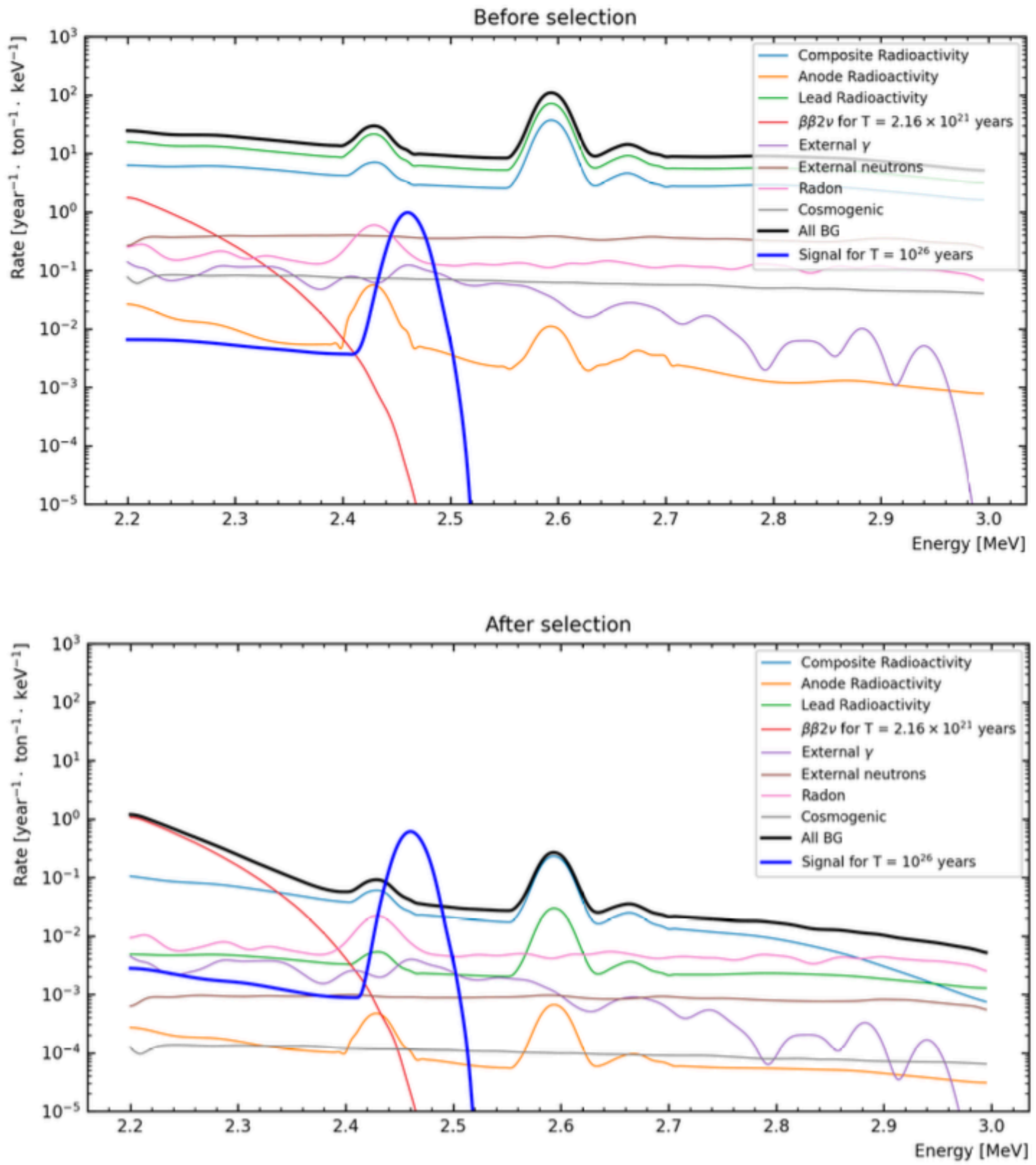
- 580 kg of active Xenon
- Footprint 50 m^2
- Detector cost (including shielding and utilities) is about 3 Millions (Enriched Xe cost excluded)

R2D2 possible sensitivity

Eur.Phys.J.C 85 (2025) 7, 732

- The sources of backgrounds were simulated and a reduction of a factor 100 is found in the ROI after selection cuts.
- The sensitivity limits at 90% CL were computed.





R2D2 in a global context

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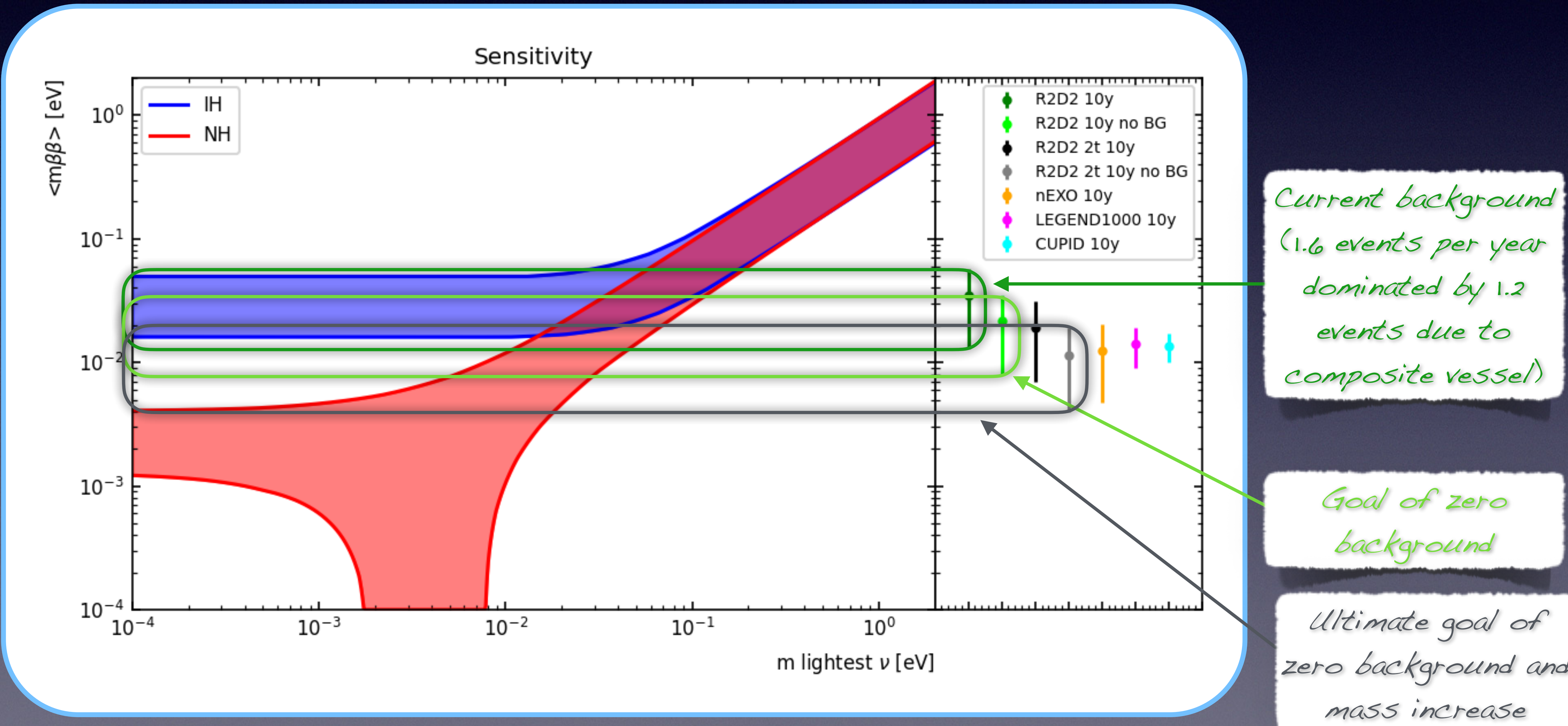
- The possible sensitivity of R2D2 is comparable with the one foreseen for other approved experiments.



Costs and timescale

Timeline	Activities	Costs
✓ 2017 – 2025	- Detector proof of principle	250 keuro for equipment 3 Meuro for salaries
2026 – 2028	- Composite development and low radioactivity assessment of vessel and other components - Validation of electronics and gas purification on MAHYTECH detector - Collaboration widening	300 keuro (mostly to collaborate with IRT Jules Verne) Our request to IN2P3 (search of funding ongoing through ANR and ERC)
2029 – 2030	- Detector construction	3 Meuro (including 500 kg of natural xenon) Possibly funded by international collaboration, ERC, ANR, RI2, regional support
2031 – 2032	- Detector commissioning (Ar / Natural Xe)	
> 2032	- Data taking with enriched xenon	10 Meuro for enriched xenon Possibly funded by International collaboration

Request to IN2P3

- The R&D phase is completed (REx on the 4th of September) **thanks to the support of IN2P3, Université de Bordeaux, IMT Atlantique, and the involved laboratories**.
- We only have one main **open question concerning the vessel radioactivity** before moving towards detector construction.
  - ➡ If **low radioactivity composite is obtained**, it will be a **major breakthrough** for all the low radioactivity experiments.
- The **next step in 2026-2028** is a transition from R&D to full-scale experiment.
- Require fundings at the level of **300 keuro** (mainly for collaboration with IRT Jules Verne) .
  - ➡ <u>Validation of the composite radioactivity</u> with IRT Jules Verne and chemical laboratories:
    - Raw material development and screening.
    - Machinery prototyping.
    - Surface treatment to avoid outgassing and vacuum compatibility (beyond state of the art in composite materials with possible industrial outcomes).
  - ➡ <u>Collaboration enlargement</u> (travel for seminars, international workshops/conferences).
  - ➡ <u>Finalisation of tests</u> on the MAHYTECH prototype.
- **We request to IN2P3 a financial support for this work in the 2026-2028 timeframe (although search for alternative fundings such as ANR and ERC is also ongoing) and manpower (PhD, PostDoc) for the project success**.

Conclusions

- R2D2 R&D proved that the **technology is mature** (electron identification and energy resolution with single anode detector) and suitable for a tonne scale neutrinoless double beta decay experiment.
- A detector based on the R2D2 technology would be competitive with current experiments and could be a breakthrough in the field.
- The simplicity of the detector and the operation at room temperature make it fully compatible with environmental sustainability requirements.
- The collaboration should be expanded, and international funding secured.
- Support from IN2P3 is requested (search for alternative funding also ongoing) to validate the low-radioactivity composite vessel and to establish the international collaboration, ensuring a smooth transition from R&D to project phase.