R2D2: a xenon TPC for neutrinoless double beta decay search

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on behalf of
the R2D2 collaboration

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Introduction

- To demonstrate the Majorana nature of neutrino the most sensitive experimental way is an observation of the so called **$0\nu\beta\beta$ decay**.
- The three **main requirements** to search for such a rare phenomenon are:

Excellent energy resolution

Low background

Large masses of isotopes

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

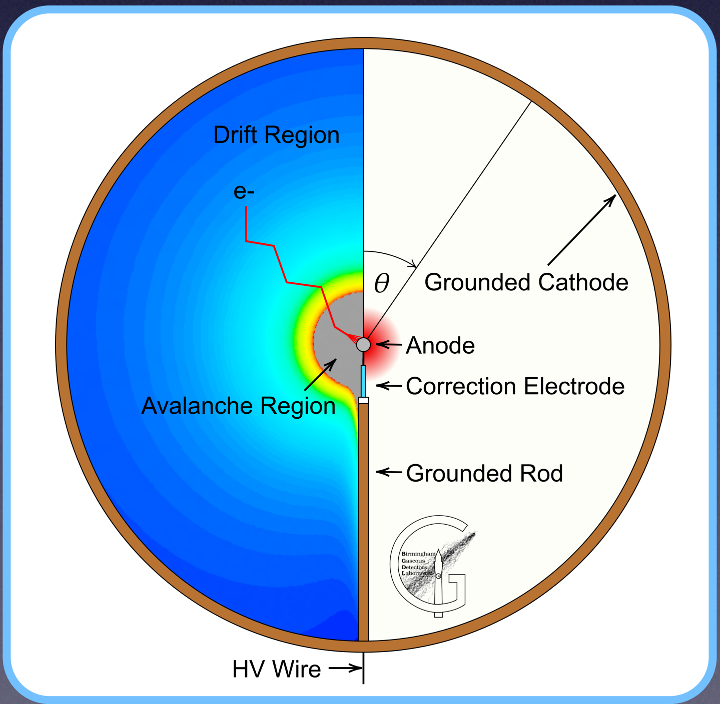
- R2D2 is an **R&D program started in 2017** aiming at the development of a **zero background ton scale detector** to search for the neutrinoless double beta decay.

→ **How?** → **Using a radial high pressure xenon TPC**

Two geometrical options

- **Two options** were considered in the R&D: a **spherical** Xenon gas proportional counter (**SPC**) as proposed by Giomataris et al. and used today in the NEWS-G collaboration for the search of dark matter, and a **cylindrical** proportional counter (**CPC**).
- The working principle is the same and both geometries have the needed detector features.

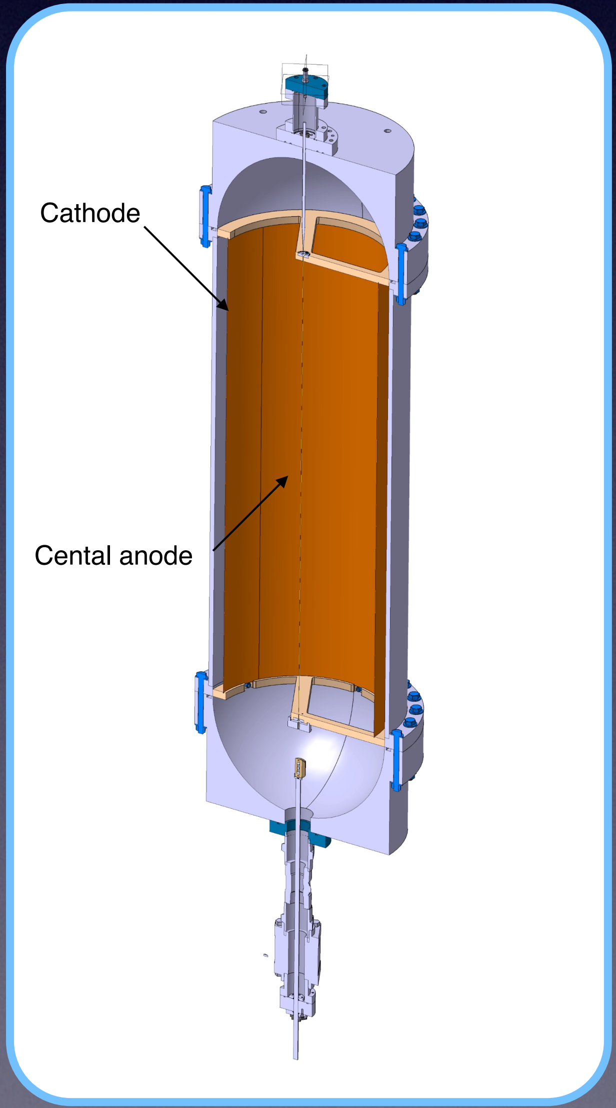
Main goal of R2D2 R&D



SPC

Detector features

- High 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.



CPC

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	SPC	CPC
Field uniformity	Field issues around the supporting rod	More homogeneous field around the anodic wire
Field strength	Weak at cathode ($1/R^2$)	Stronger at cathode ($1/R$)
Xenon volume	Optimal	Volume over surface not maximized
Noise	HV dependent (HV on anode)	HV independent with grounded wire

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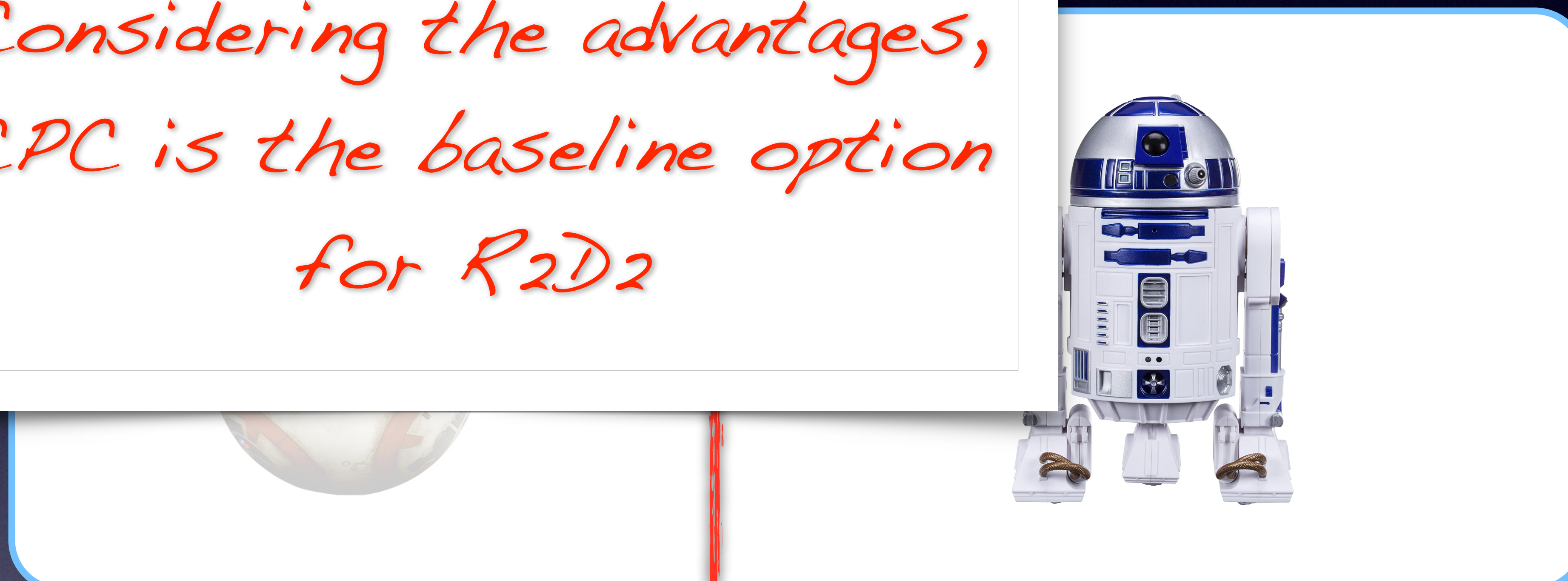
- The working p ... eeded detector features

Considering the advantages, CPC is the baseline option for R2D2



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Two operation modes

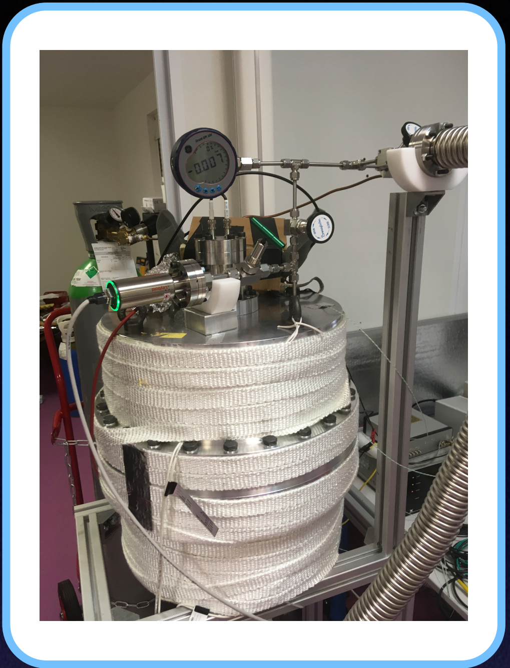
- The CPC can be operated in two modes: **ionisation** (i.e. no gain) or **proportional** (i.e. avalanche near the anode with a resulting gain).

- The **ionisation mode was selected** for the following reasons:

Detector operated in ionisation mode

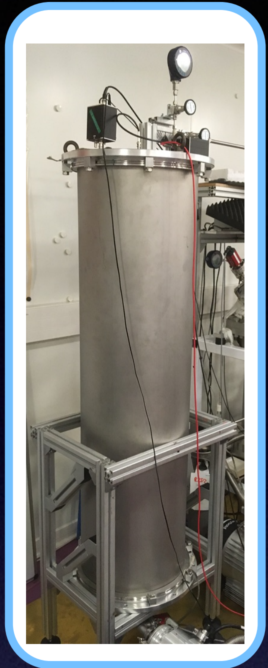
  - ➡ Provided that the signal-to-noise ratio is sufficient, ionisation mode yields the best possible energy resolution avoiding any stochastic fluctuation on the collected charge due to the avalanche process.
  - ➡ Tiny inhomogeneities of the wire diameter have no impact in ionisation mode, whereas in proportional mode they result in different gains as a function of the position impacting energy resolution.
  - ➡ In the ionisation regime the signal is mostly given by the electrons drift, on the other hand, the proportional signal is mainly due to the drift of ions produced in the avalanche. Given the low ion mobility in xenon, electronegative impurities become much more critical.
  - ➡ The ionisation regime allows to use thick wires as anode and less demanding HV for the same drift field at the cathode position.

History and milestones



First SPC
(no high pressure)

Second SPC
(certified to 40 bar)



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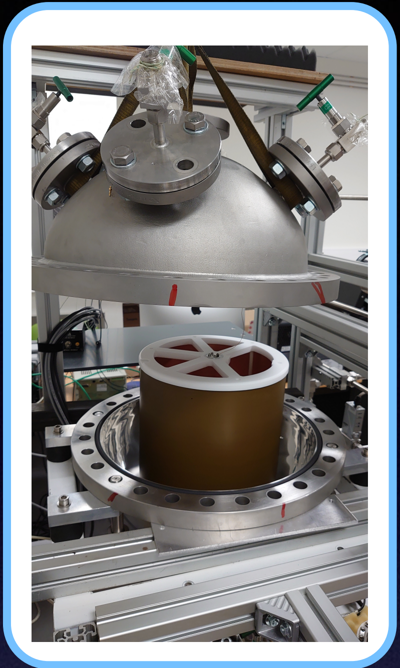
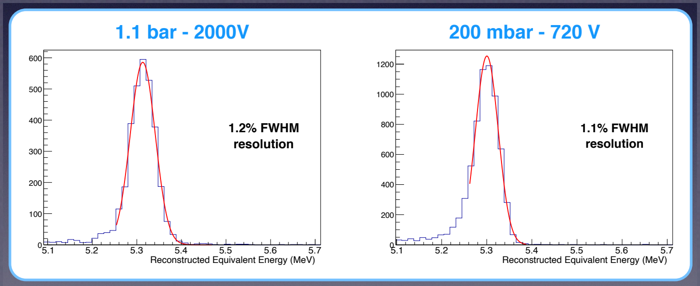


Second CPC
(certified to 40 bar)

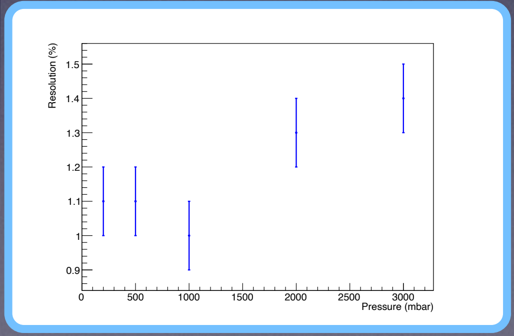
2018 — 2021 — 2023

Same resolution for short and long tracks (Ar)

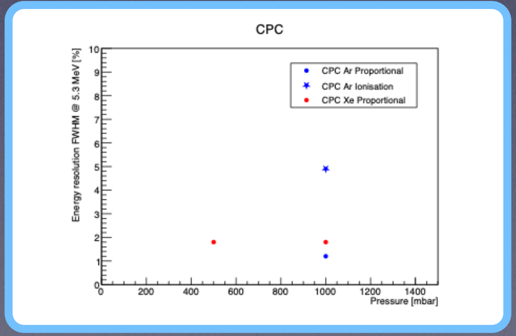


JINST 16 (2021) 03, P03012

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



Similar resolution in Ar and Xe



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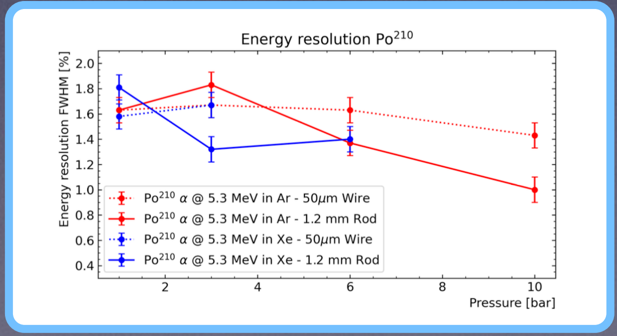
Good resolution in Ar/Xe up to 10/6 bar



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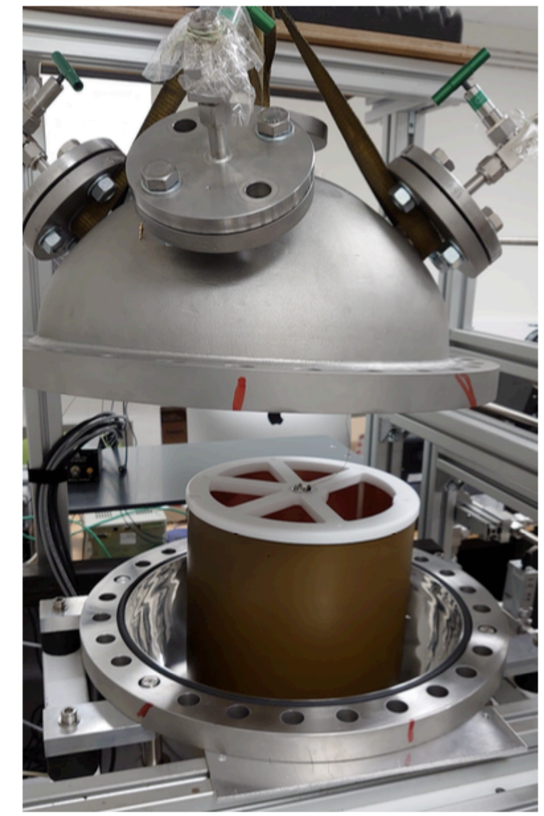
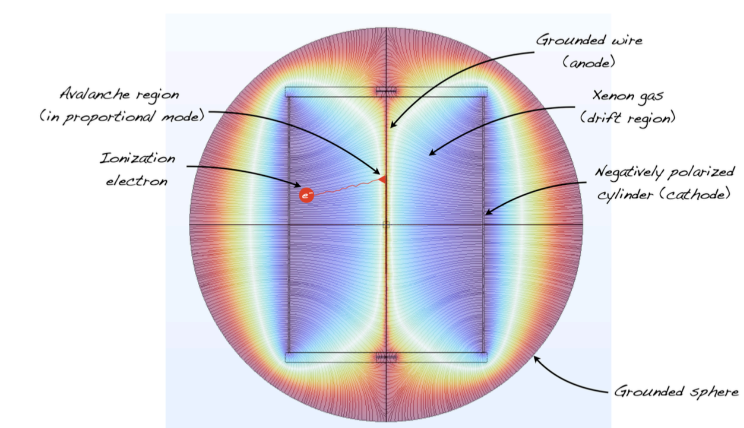
Current prototype design

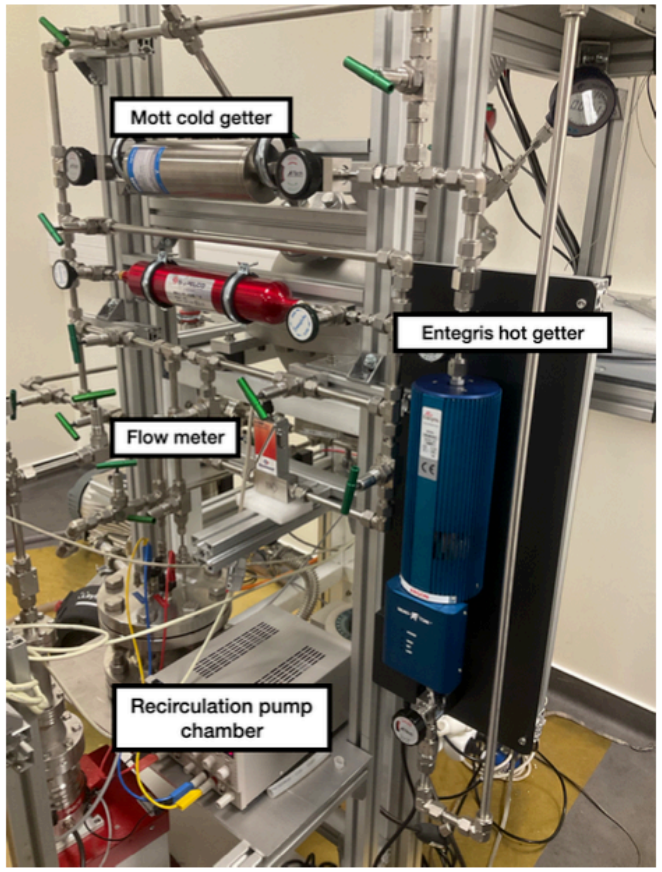
- The current prototype is a CPC of 27 cm height and 11 cm radius which is inserted in the previous SPC vessel to take measurements up to 40 bar.
- Measurements of material outgassing were made for the choice of cathode and supporting structure and we finally chose Teflon as supporting structure and a cathode made of 200 μm thick Aluminum.
- The HV was applied to the cathode up to values of 5 kV.
- Different anodes were tested from wires of 50 μm diameter, to rods of 1.2 and 12 mm diameter.
- Two calibration sources were used:
    - ➡ A ^{210}Po α source of 5.3 MeV deposited on a silver plate of 0.6 × 0.6 cm^2 , and positioned on the outside of the cathode behind a hole of 1 mm radius.
    - ➡ Diffuse ^{222}Rn in the gas emitting α of 5.5 MeV in all the volume.

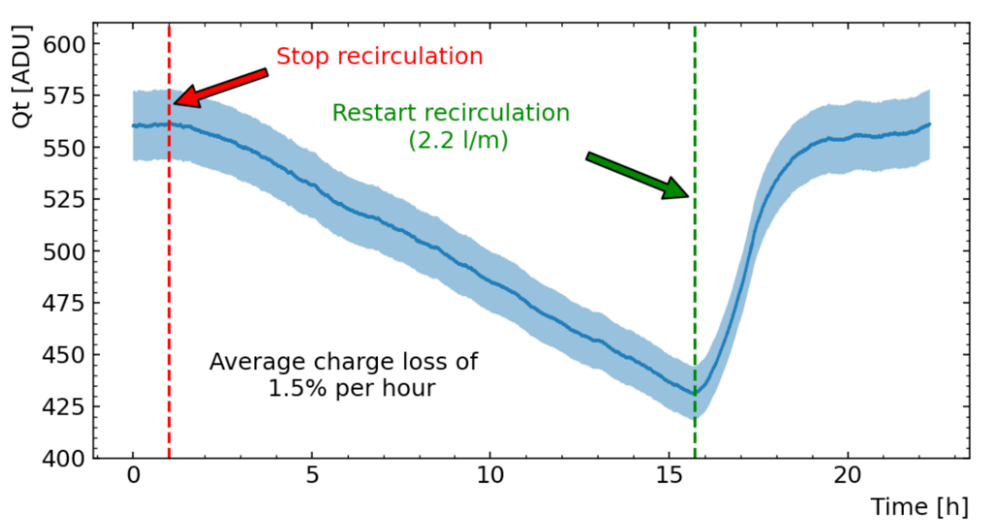


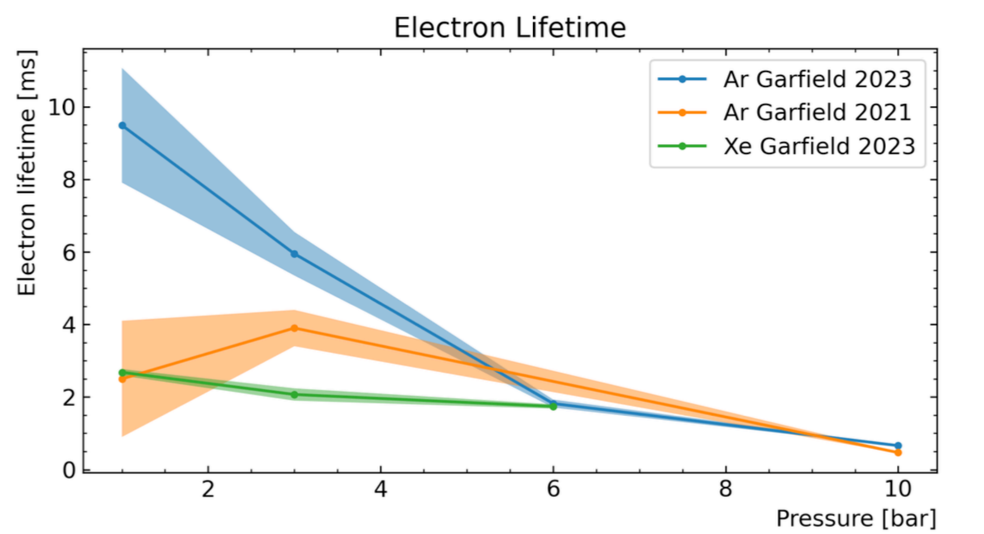


Gas purity

- Gas purity is a key issue for the operation of the CPC.
- A system based on cold and hot getter was set up granting purities up to few ppb in terms of electronegative impurities such as Oxygen.
- However, the purification system limits the operation of the detector at 10 bar.
- The gas is constantly recirculated through the getter to grant a constant purity.
- The achieved purity in tems of “electron lifetime” is good enough for the prototype but far from the values obtained in liquid argon and xenon of 20 ms and 10 ms, respectively.

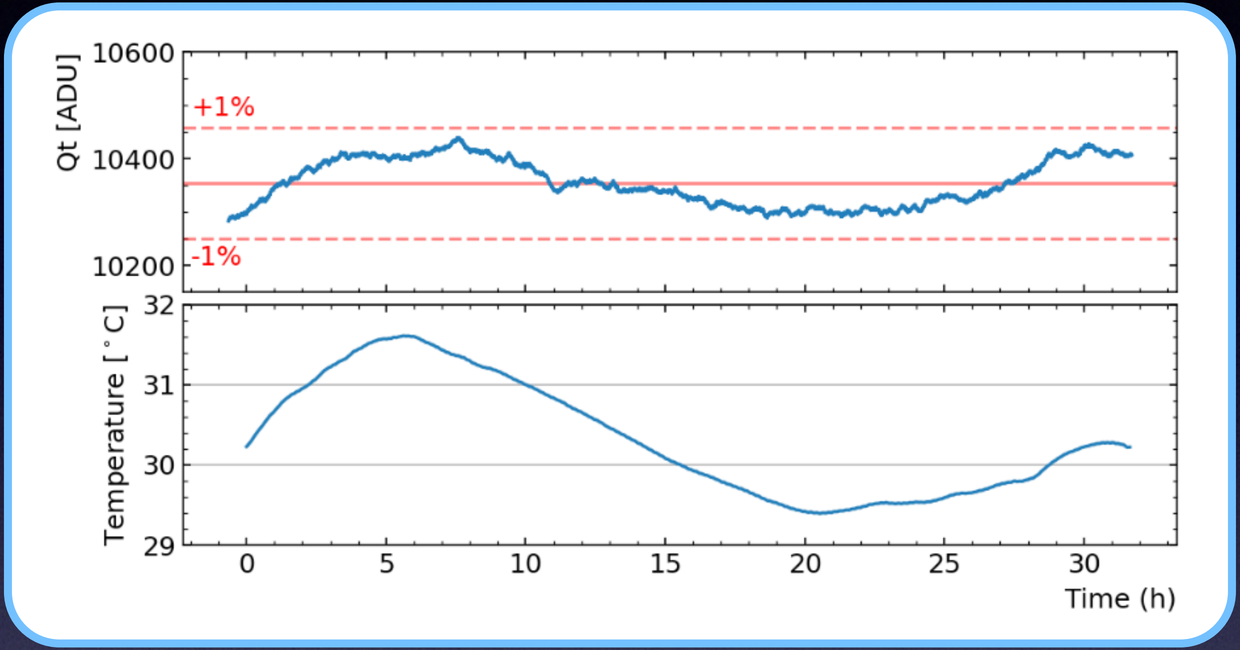






Temperature corrections

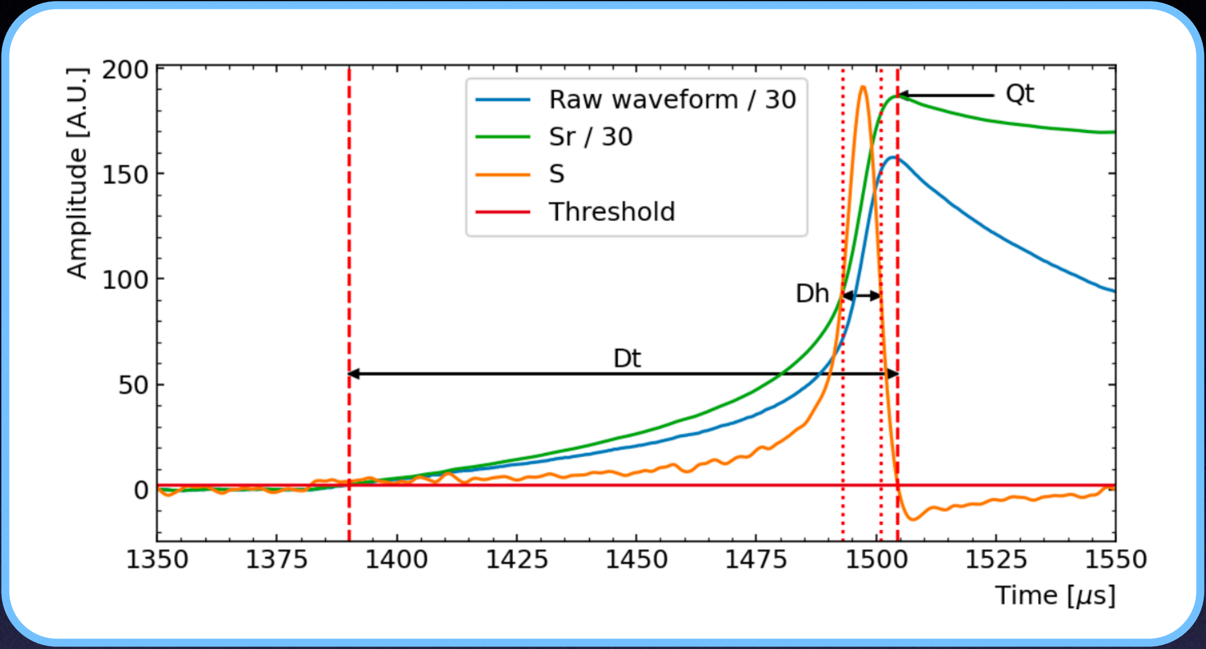
- Variations of the temperature also affect the signal integral.
- The temperature variations impact the measurements in two ways: gas temperature variations (implying pressure variations), and variations of the electronics chain response.
- To obtain a resolution at the percent level, the temperature has to be stable within 1 degree at the most, or corrections have to be applied.



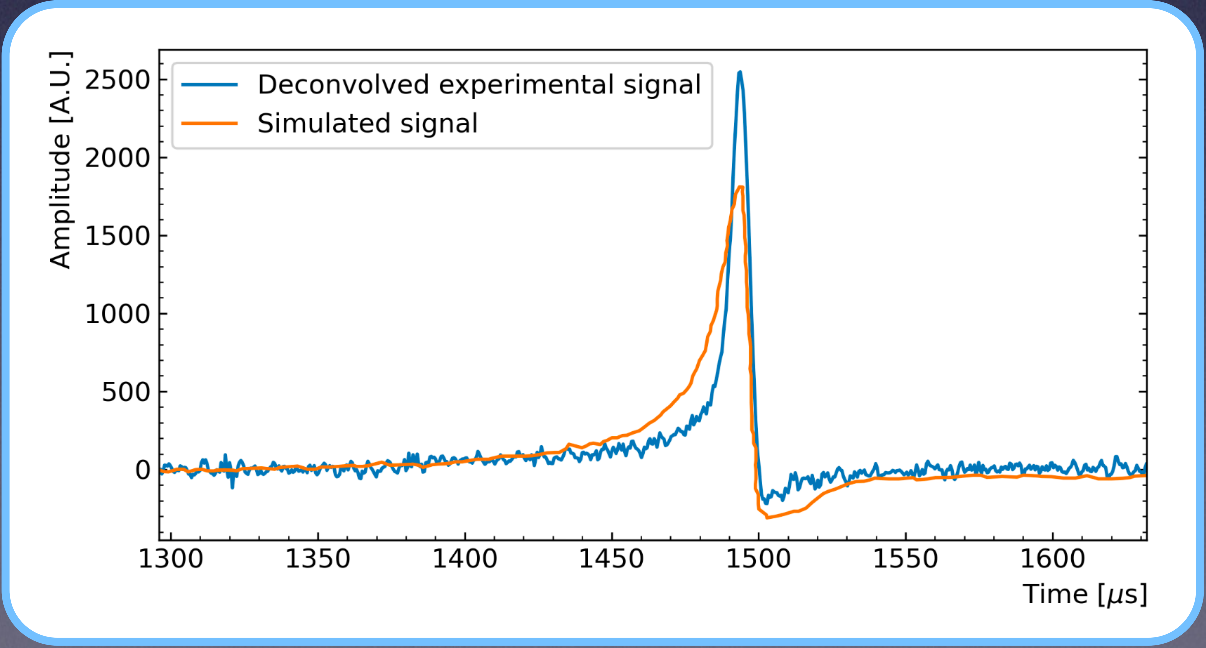
- The temperature is monitored constantly and corrections are applied to long runs lasting more than 1 hour (i.e. for run using Radon source).

Signal

- The reconstructed waveforms are used to extract observables such as the total charge of the event, its duration and the width at half height.
- Each observable is associated to a specific feature of the original signal:
  - Qt ⇒ Reconstructed energy.
  - Dt ⇒ Maximal radial distance from the anode.
  - Dh ⇒ Radial extent of the track.



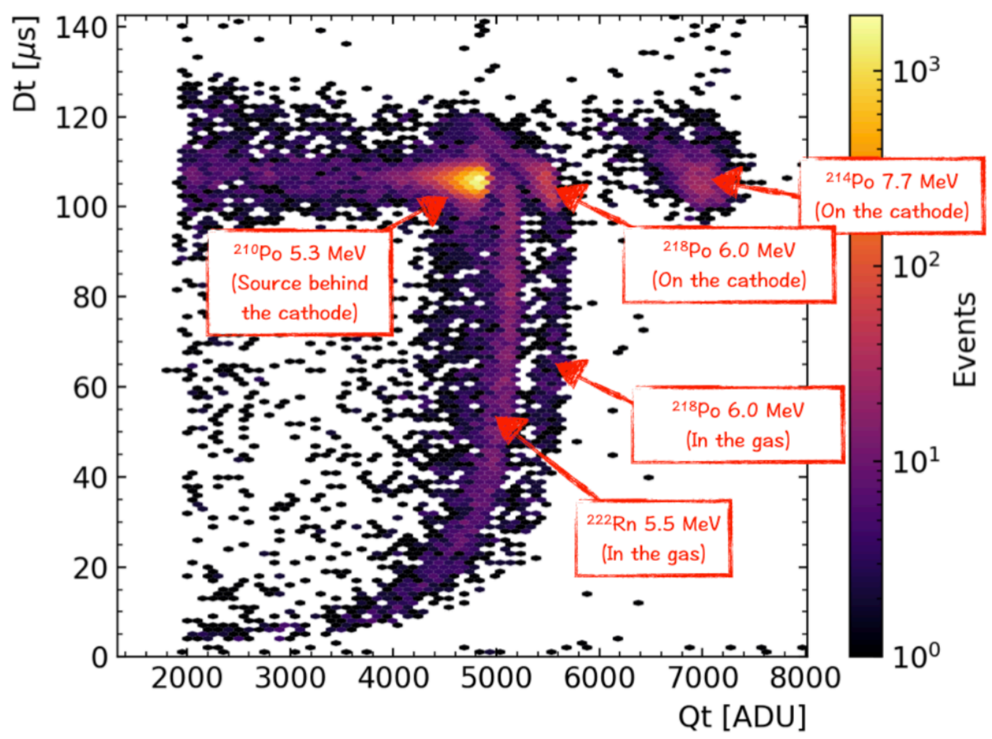
- A simulation based on the Shockley-Ramo theorem was developed and a very good agreement was found between the registered and the simulated waveforms.
- The simulation was used to confirm our understanding of the observables.

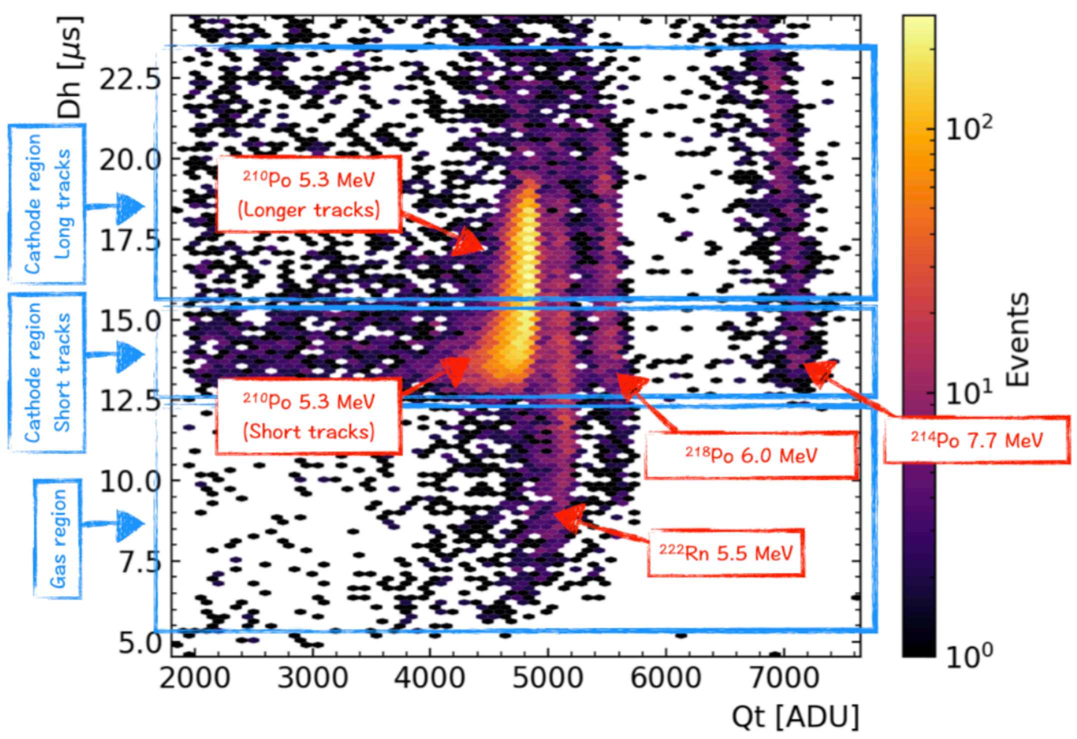


Results

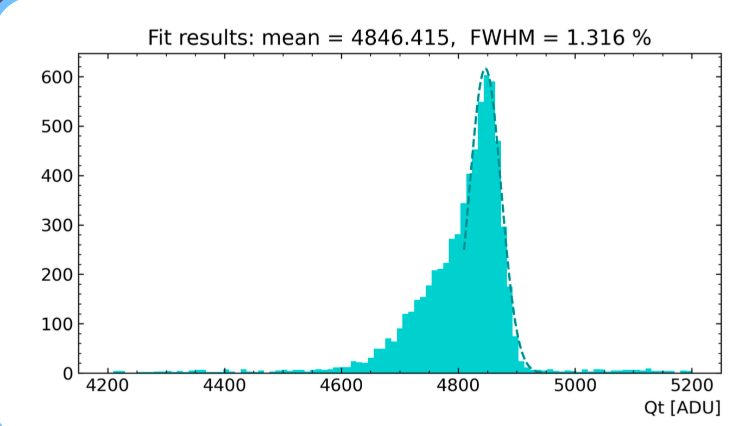
- The observables were used to select the events, namely the Po or the Rn issued alphas.
- The Qt of selected events were fitted to establish the energy resolution.

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

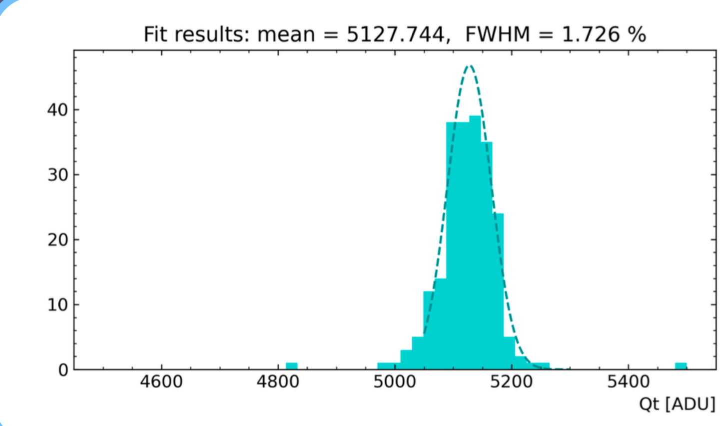




^{210}Po

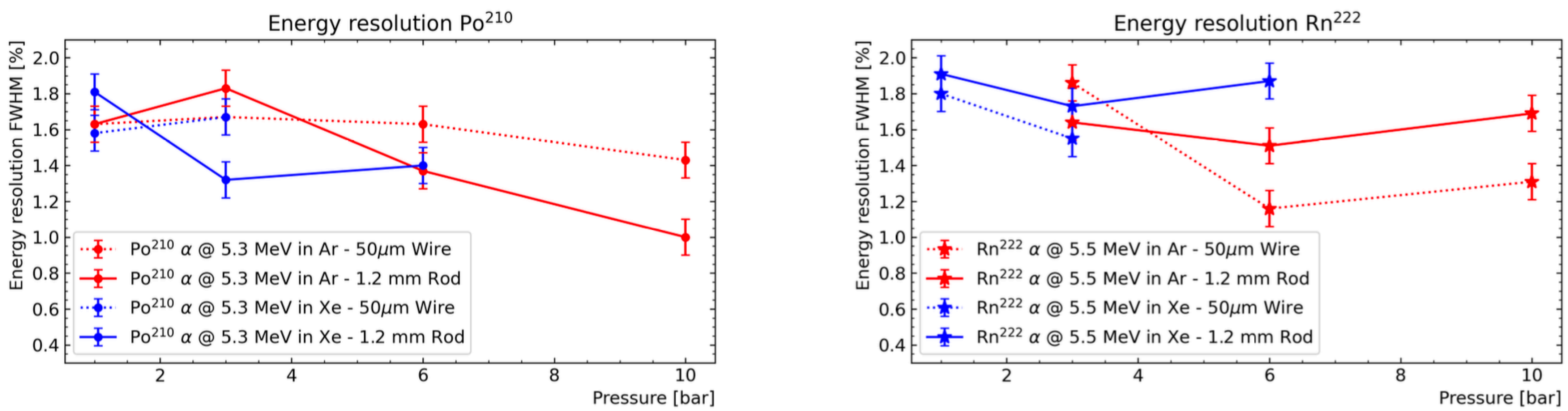


^{222}Rn



Resolution results

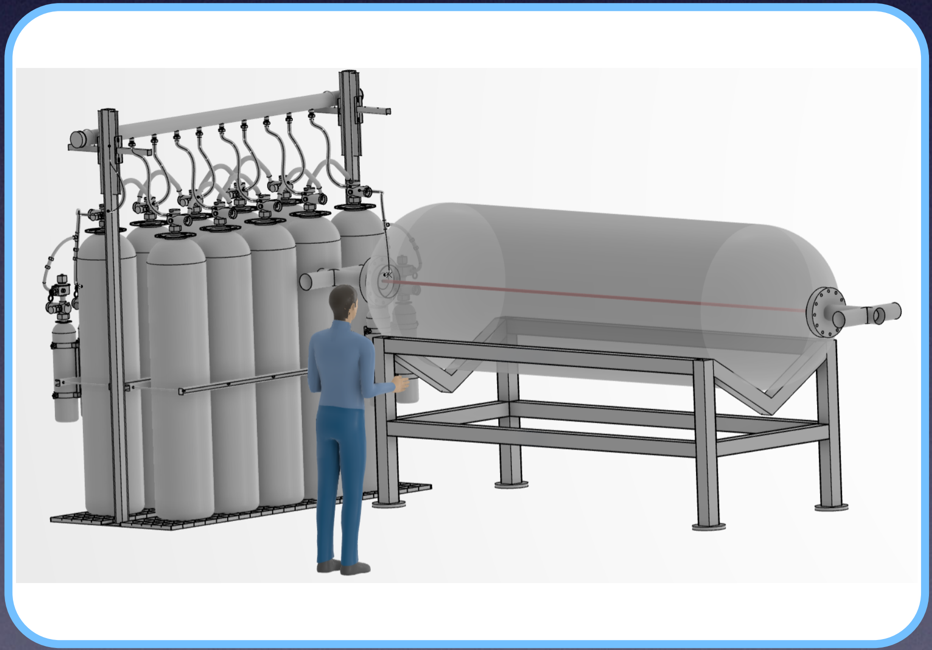
- Resolution was computed with different anodes for Ar and Xe up to 10 bar.



- *The resolution is mostly independent on the gas pressure.*
- *The resolution is mostly independent on the gas nature.*
- *The resolution is similar for diffuse and point-like sources.*

Next step

- The R2D2 R&D reached the goal of demonstrating an energy resolution at the percent level.
- A complete sensitivity study including the obtained performance of a CPC is ongoing.
- The next key step is to demonstrate that we can have a low-background composite detector reducing the mass as much as possible.
- Test on a composite detector are ongoing (40 cm drift on a 1.9 m long tank) and studies of the composite material are performed in parrallel to reduce the radioactivity.



If successfull we could have a cheap (order of few hundreds keuro not including the cost of xenon), not cryogenic, ton scale detector, with almost no background.

Conclusions

- In the R&D started in 2017 we demonstrated that a CPC can acheive an energy resolution at the level of 1% FWHM.
- We conceived a simple detector with only one readout channel and with the lowest possible material budget.
- The proposed detector is cheap and requires no cryogenic infrastructures.
- The ultimate goal is to demonstrate that such a detector can be build with low radioactivity composite material and a zero background can be achieved.
- If that is the case, the proposed detector would be a competitive solution for the neutrinoless double decay search at the ton scal to rule out the inverted mass hierarchy region.

We think we are ready to move on to a real international collaboration and interested persons are welcome to join our effort