CNRS IN2P3 Les deux infinis — LP2i Bordeaux — université de BORDEAUX

Feedback on

R2D2

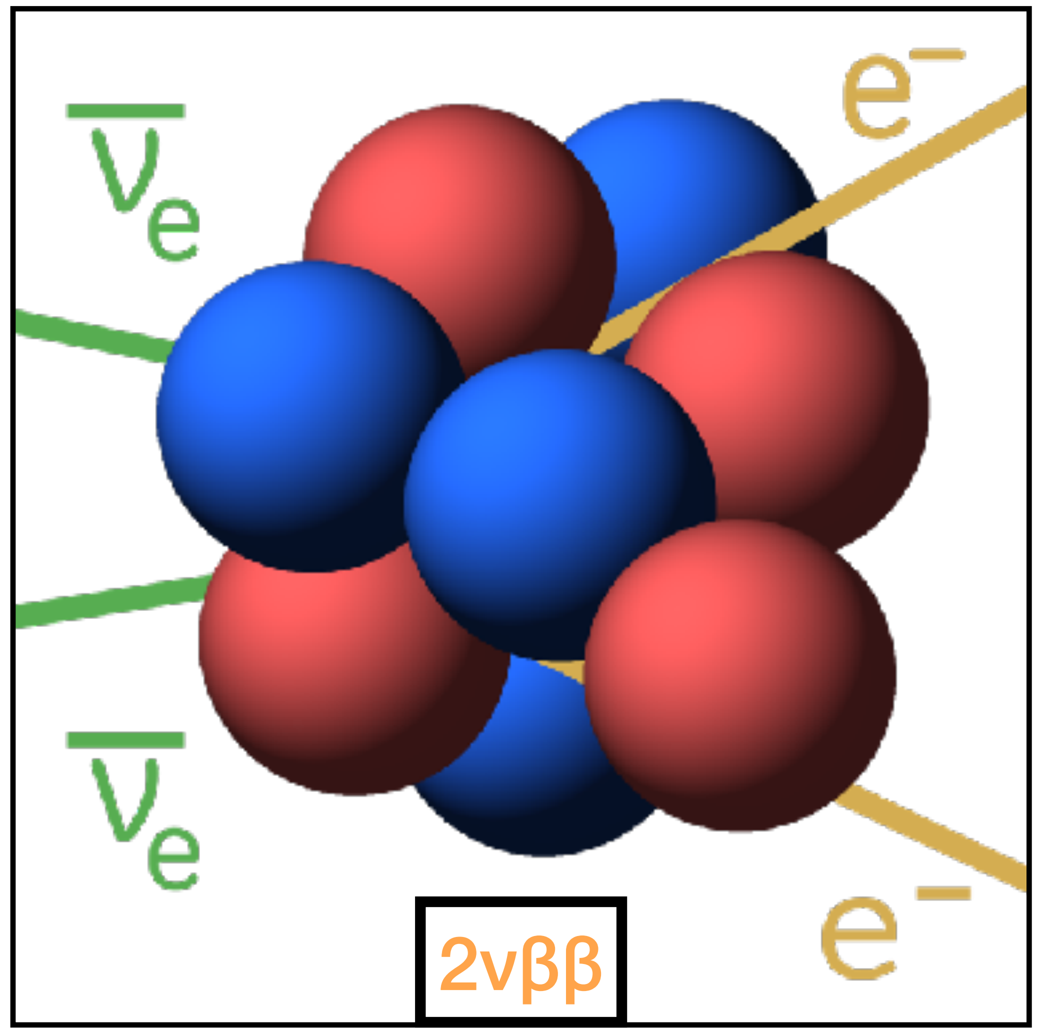
Rare Decay Radial Detector

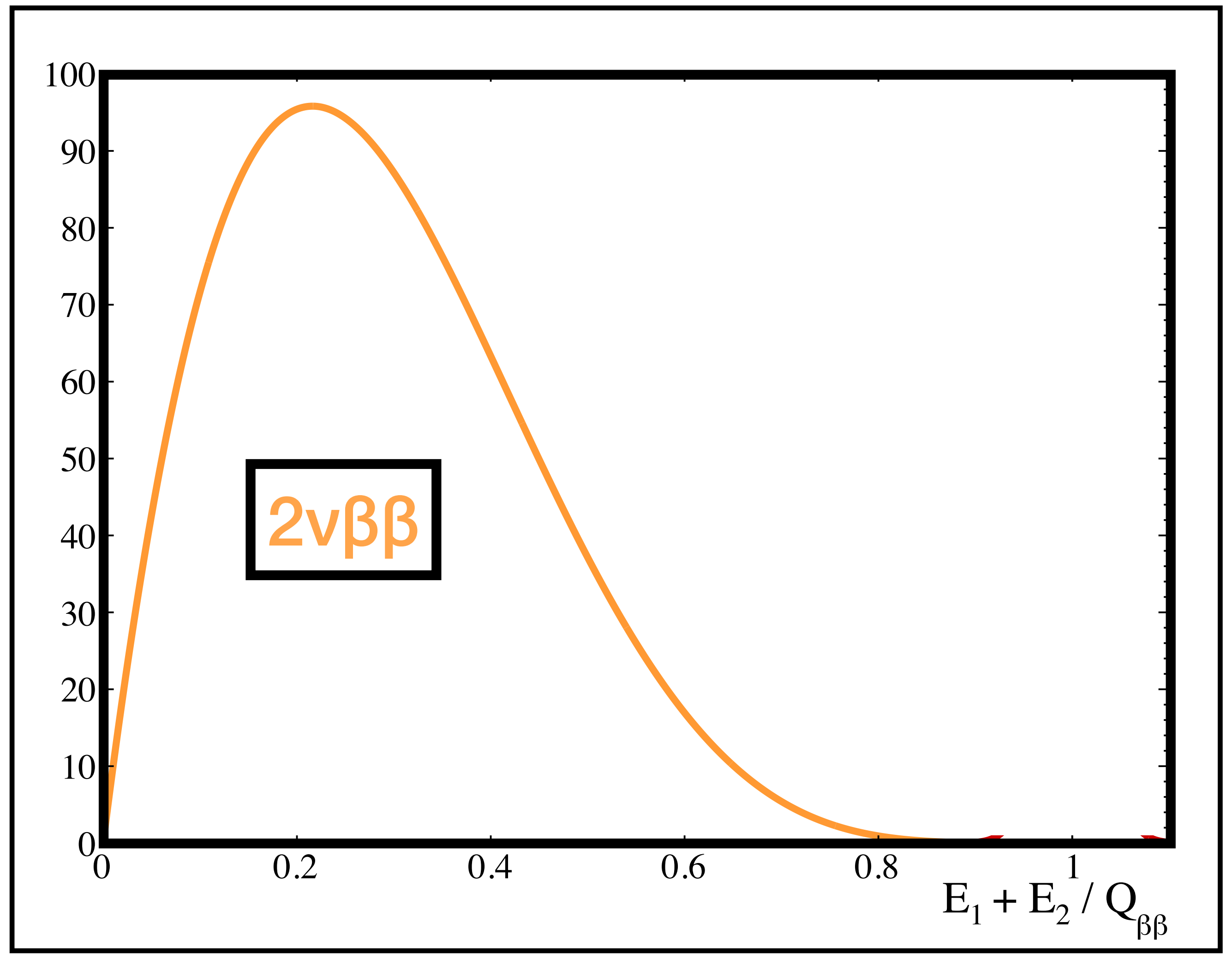
Neutrino, Majorana and ββ Decay

- Since the massive neutrino postulate, neutrino research have been one of the leading force in the exploration of outside standard model physics.

- The neutrino nature, Dirac or Majorana, mobilises global efforts and resources. The current most sensitive experimental proof of the Majorana nature of neutrino is the observation of the 0vββ decay.

  - 2vββ decay : $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}_e$ first direct observation in 1987.





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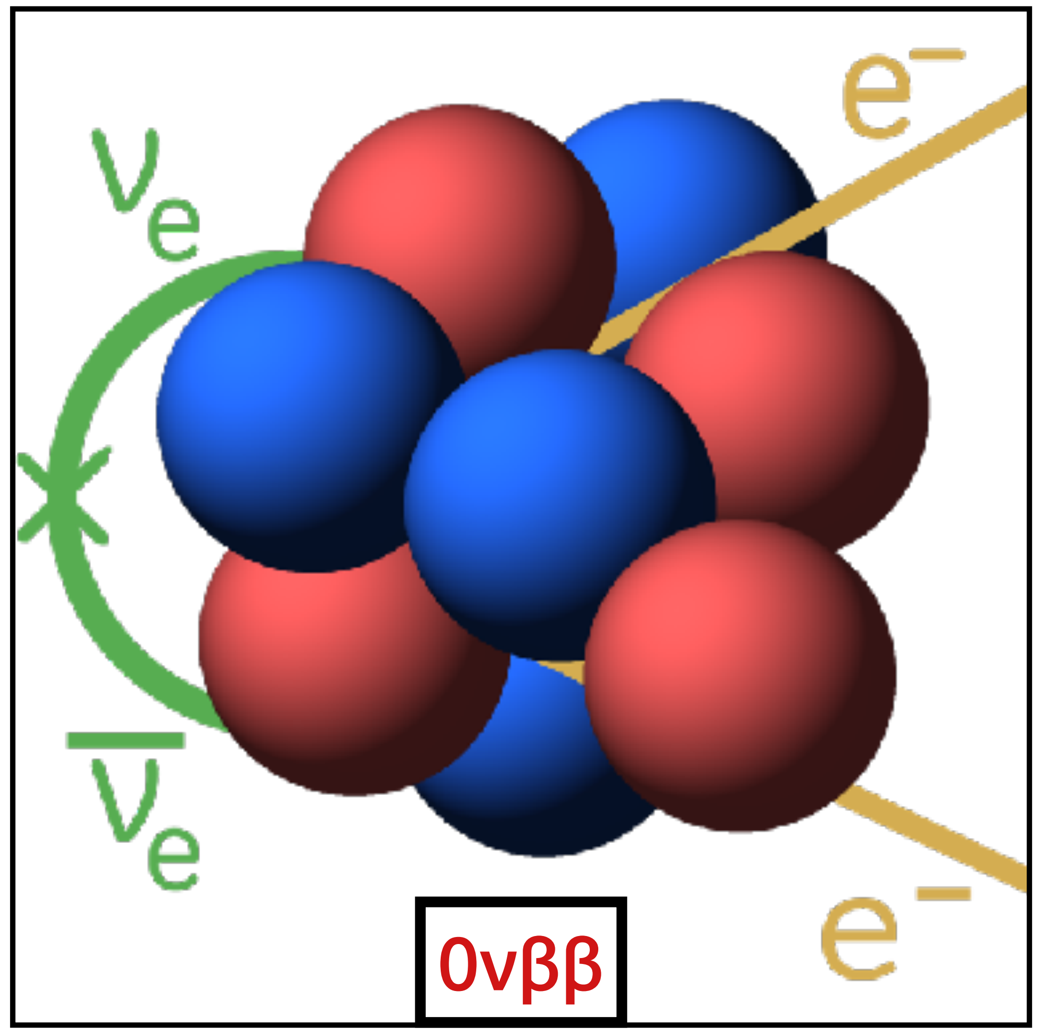
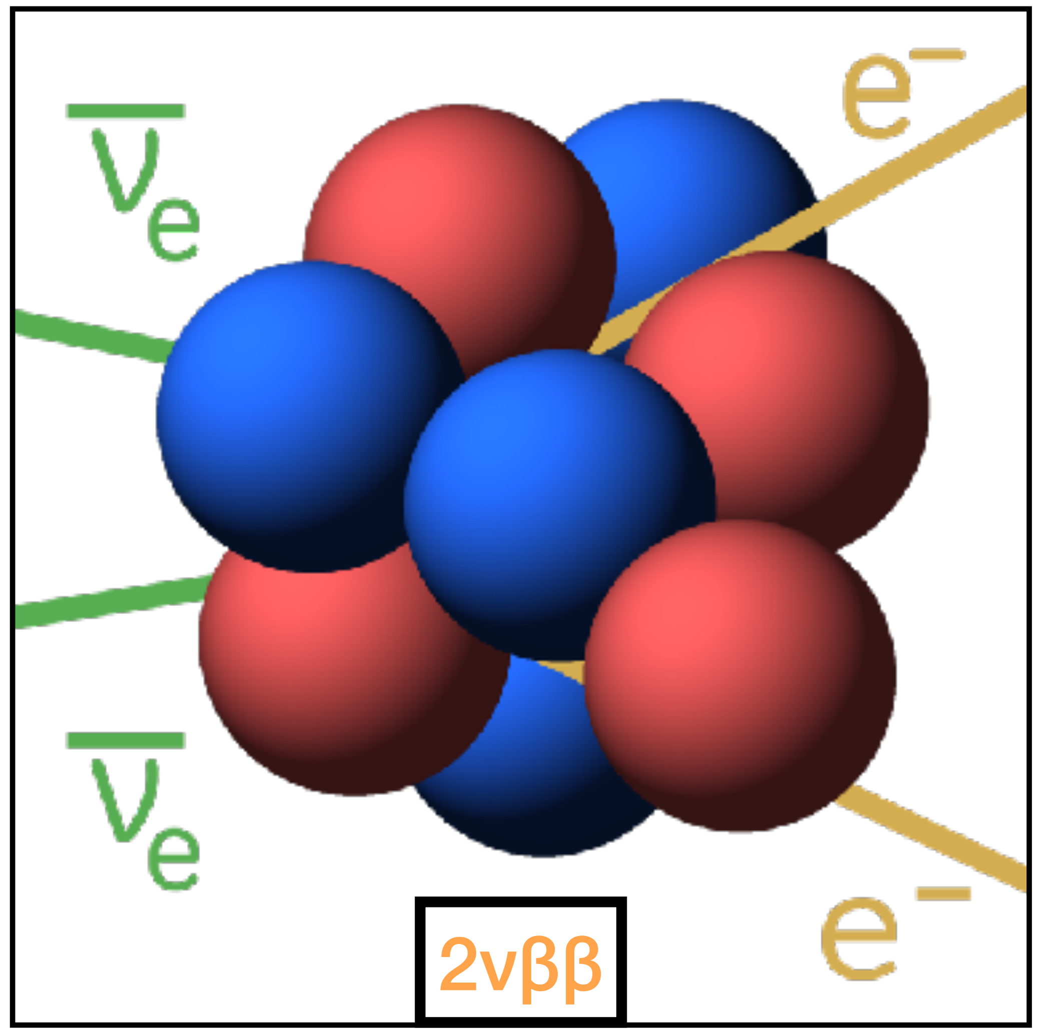
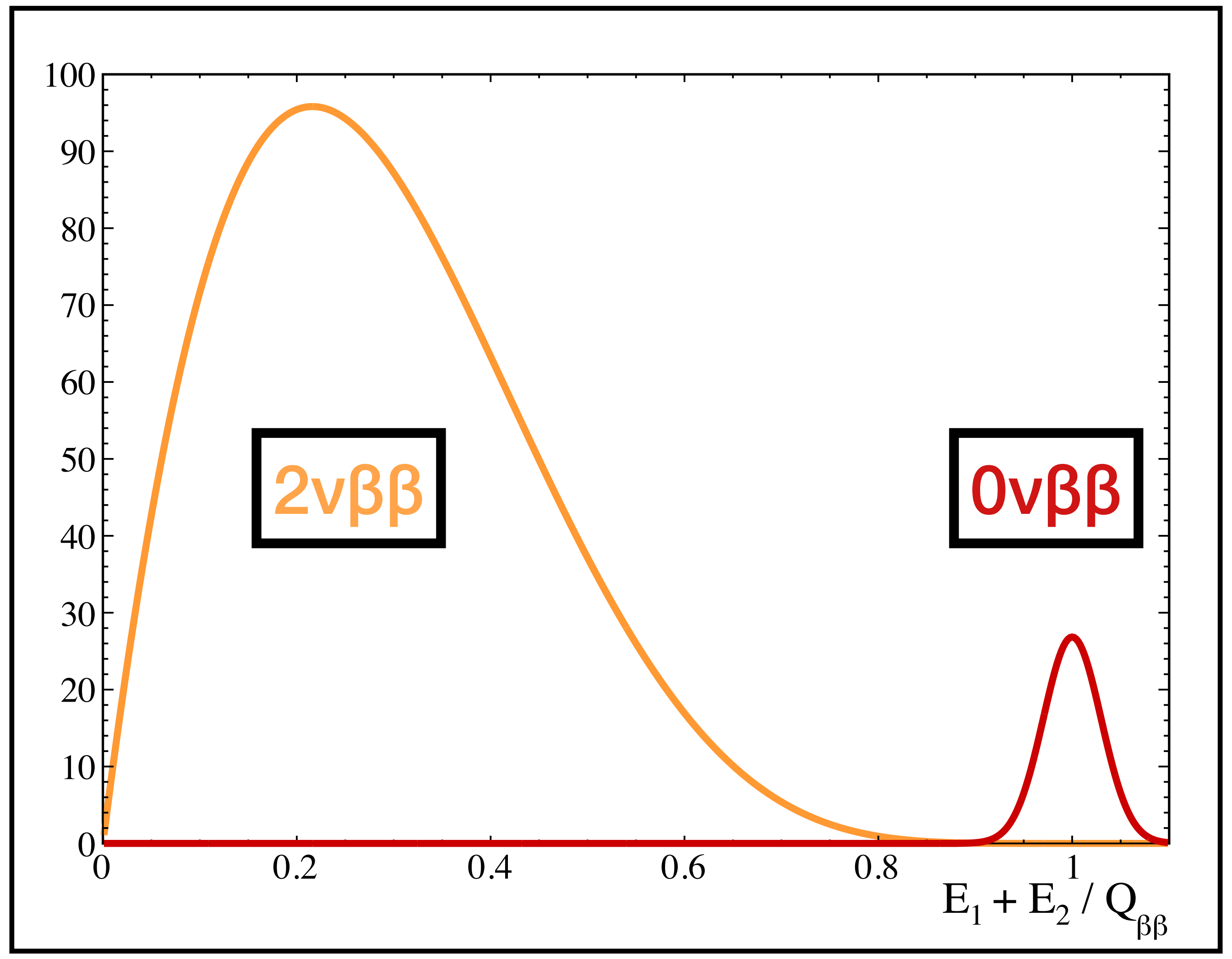
  - 2vββ decay : $(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\overline{\nu}_e$ first direct observation in 1987.
  - 0vββ decay : $(A, Z) \rightarrow (A, Z+2) + 2e^{-}$ postulated in 1939.
    - Only possible if neutrino are Majorana particles
    - Violation of total lepton number
    - Total decay energy, $Q_{\beta\beta}$, share by the two electrons.

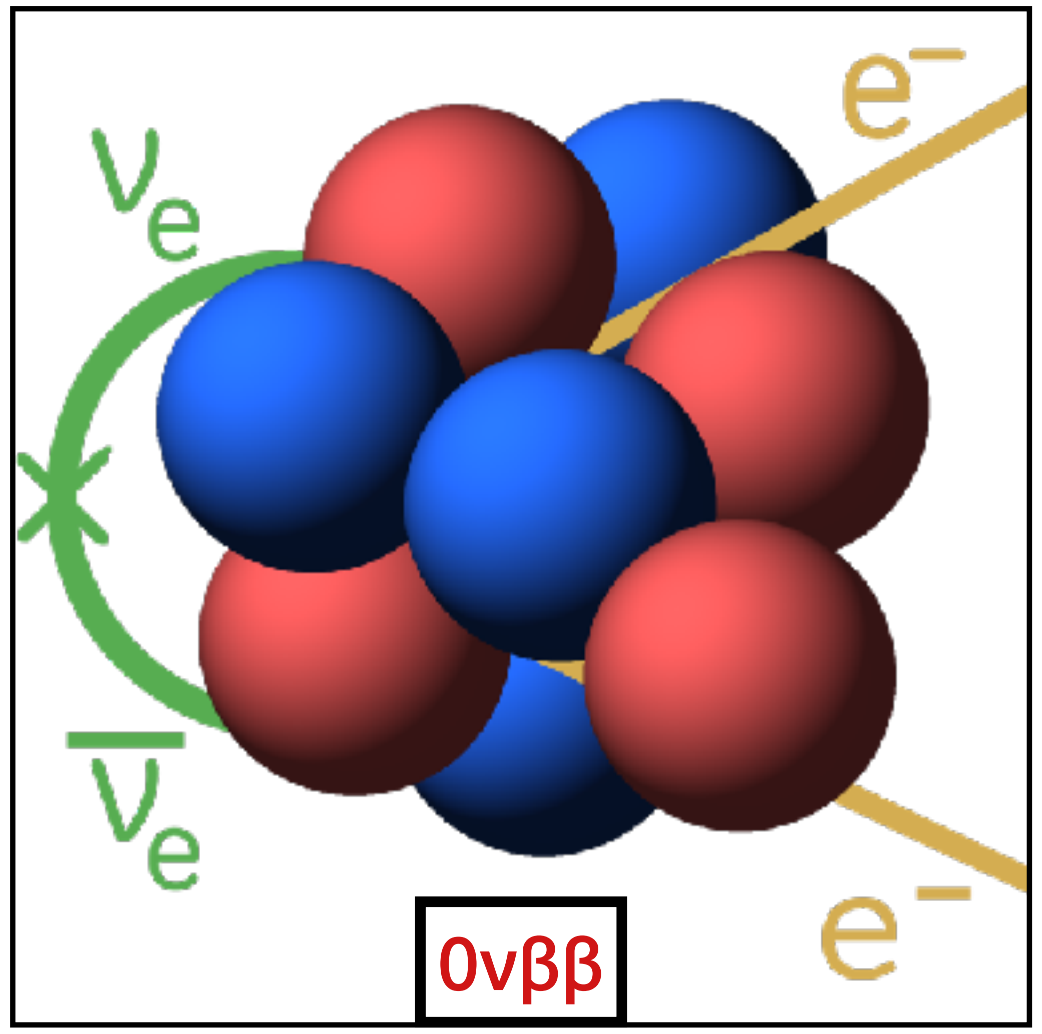


0νββ Observation

- This observation consists in the measurement of a narrow peak at the end of the two electron energy distribution, i.e the $Q_{\beta\beta}$ of the ββ decay.
- Several isotopes are ββ emitter: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{136}Xe, ^{150}Nd
  - $T^{2\nu}_{1/2} \sim 10^{18-21}$ years, $T^{0\nu}_{1/2} > 10^{21-26}$ years.







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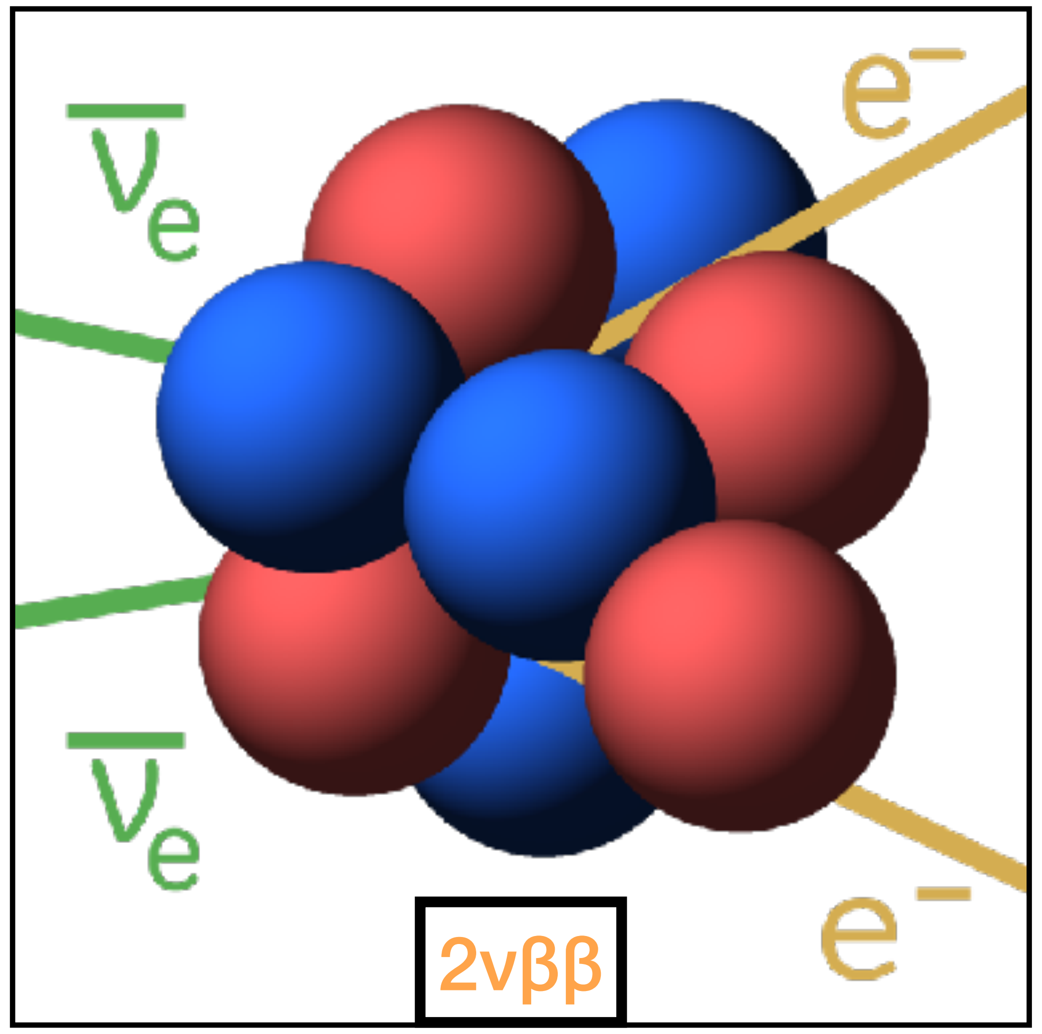
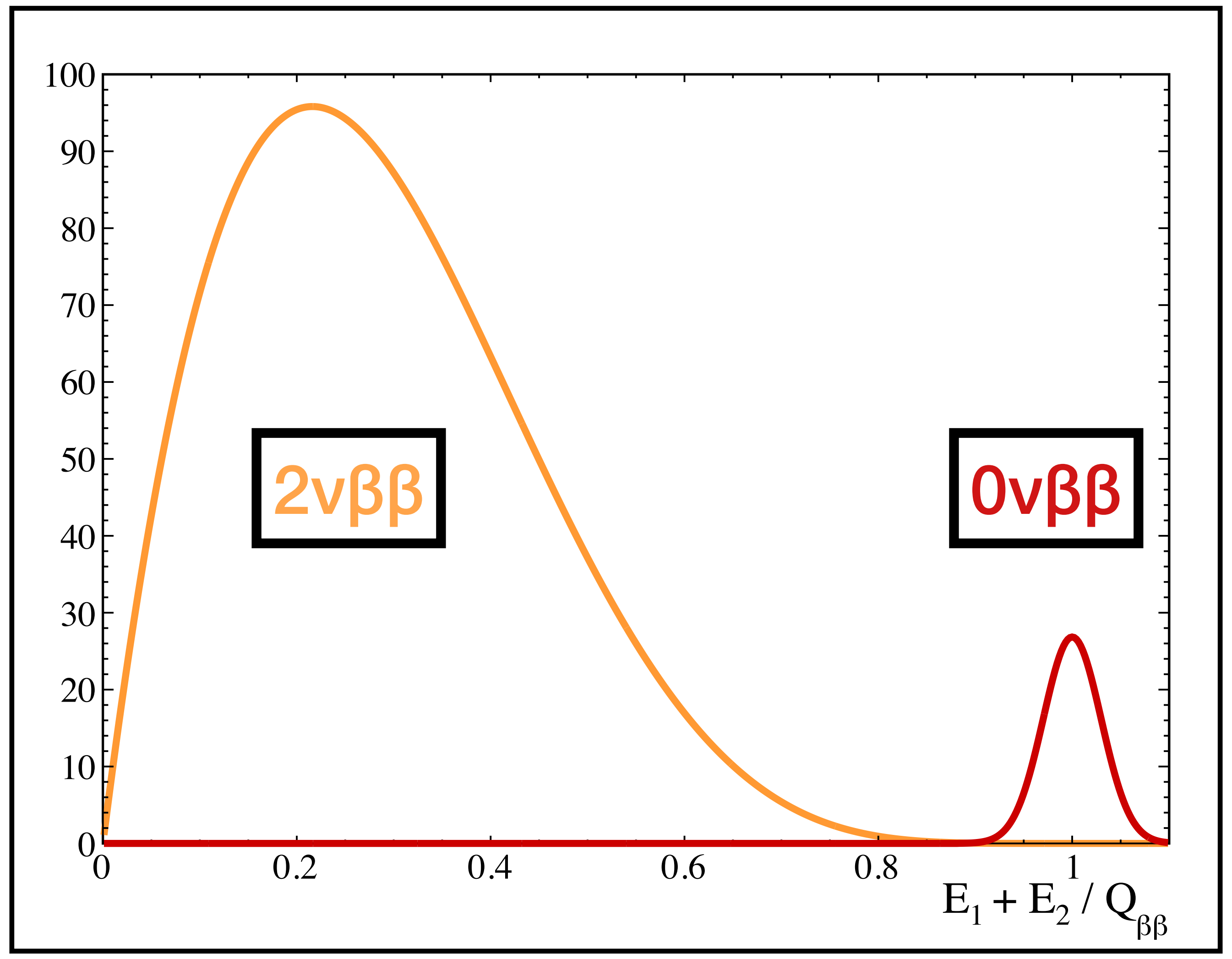
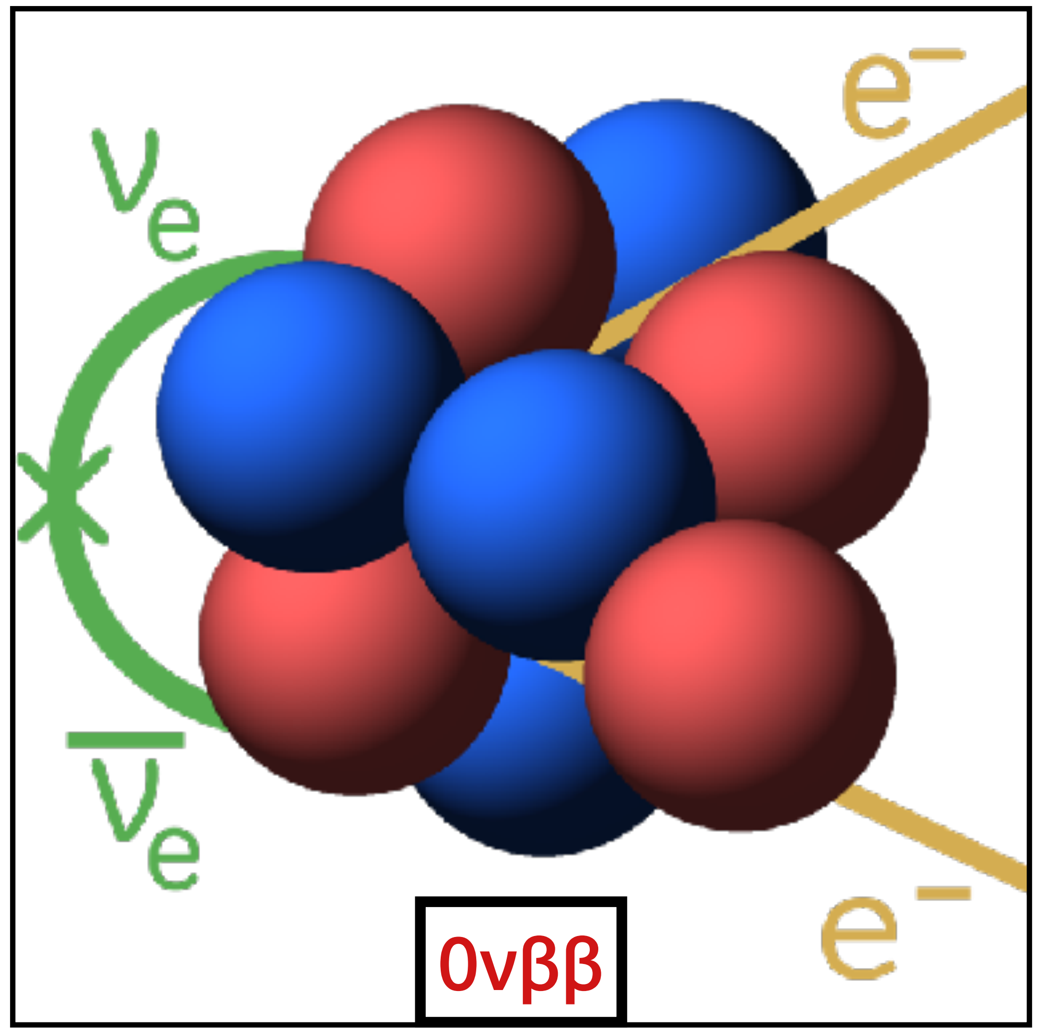
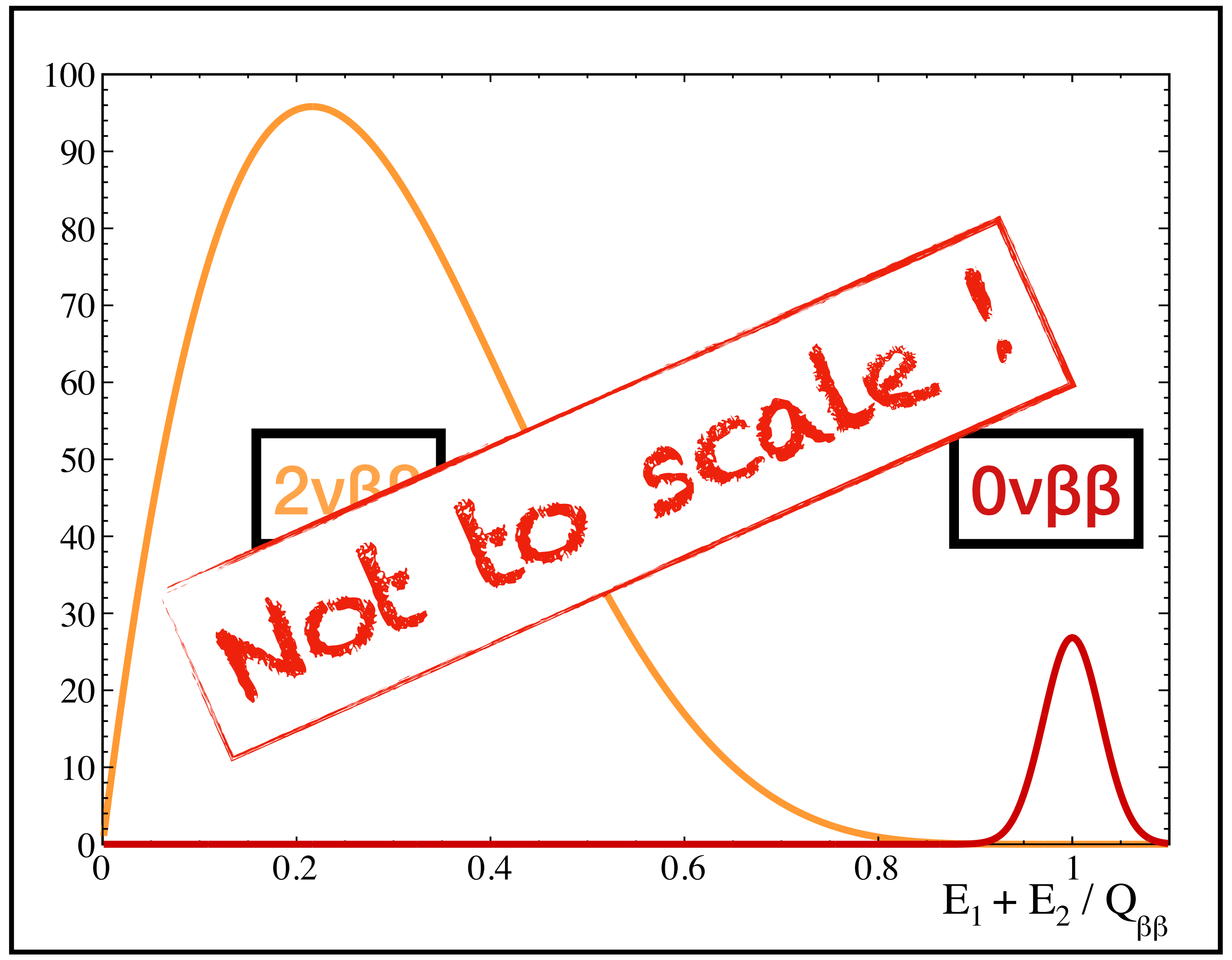
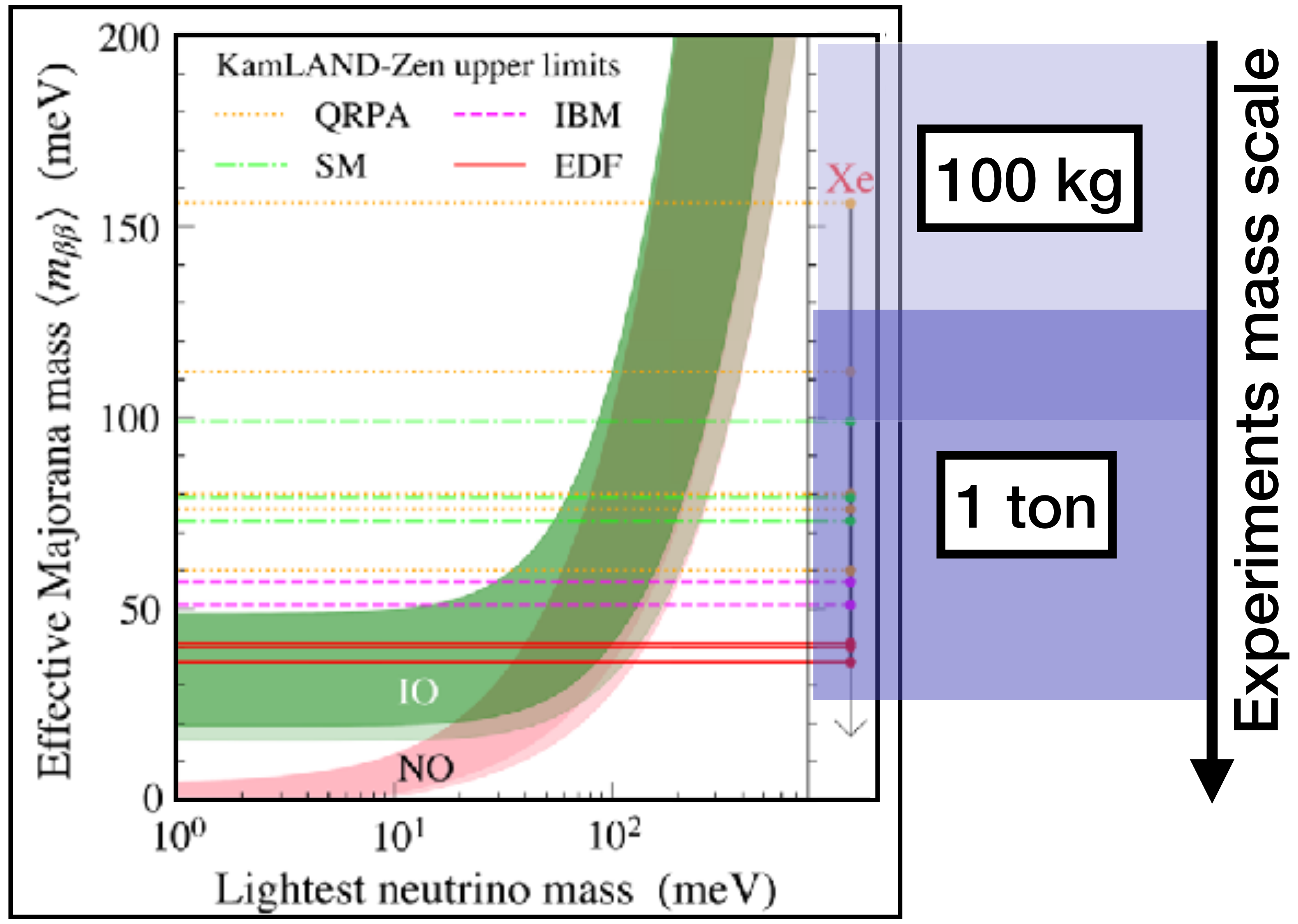






Requirements





- Excellent energy resolution
  - Factor >10^5 years between 2νββ and 0νββ half-life.
- Low (zero) background.
  - The region of interest is surrounded by natural radioactivity. Ex: ^{136}Xe $Q_{\beta\beta}$ is 2.458 MeV and ^{208}Tl gamma is at 2.615 MeV
- Ton scale experiment.
  - ton scale experiment is required to fully cover the inverse mass hierarchy region.
  - $\left(T_{1/2}^{0\nu}\right)^{-1} \propto \left| m_{\beta\beta} \right|^2$

Curent Status

	Energy resolution	Low background	Large isotope masses
Solid state detectors	Extremely good (0.1% at Q value)	Extremely low (zero background)	Large number of crystals/ electronics channels Difficult scalability to large masses
Liquid Xenon experiments	Order of 4% at Q value	Far from zero background	Ton scale easily achievable
Gaseous Xenon experiments	Order of 1% at Q value	Far from zero background	Complex detector Feasible at ton scale?

^{136}Xe assets:

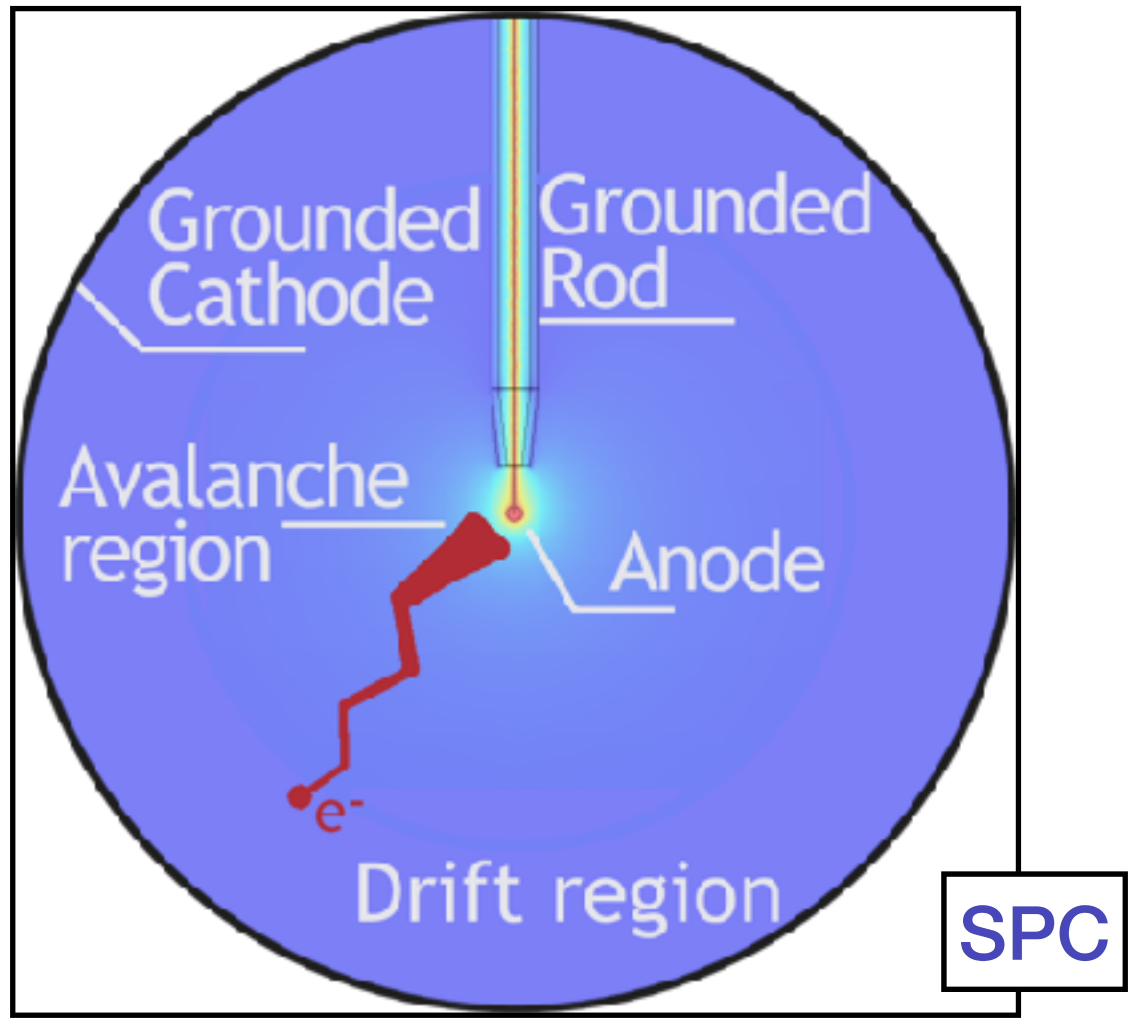
- $T^{2\nu}_{1/2} = 2.16 \pm .02 \cdot 10^{21}$ years.
- $T^{0\nu}_{1/2} > 2.3 \pm .02 \cdot 10^{26}$ years.
- One of the most abundant, 8.86 %, and easiest to enrich.

R2D2 is an R&D that explores a single anode HP-TPC[1] solution for 0νββ search.

- R2D2 Goals :
  - Meet all those requirements.
  - While also being able to perform tracking.

[1] HP-TPC: High Pressure Time Projection Chamber

Detectors

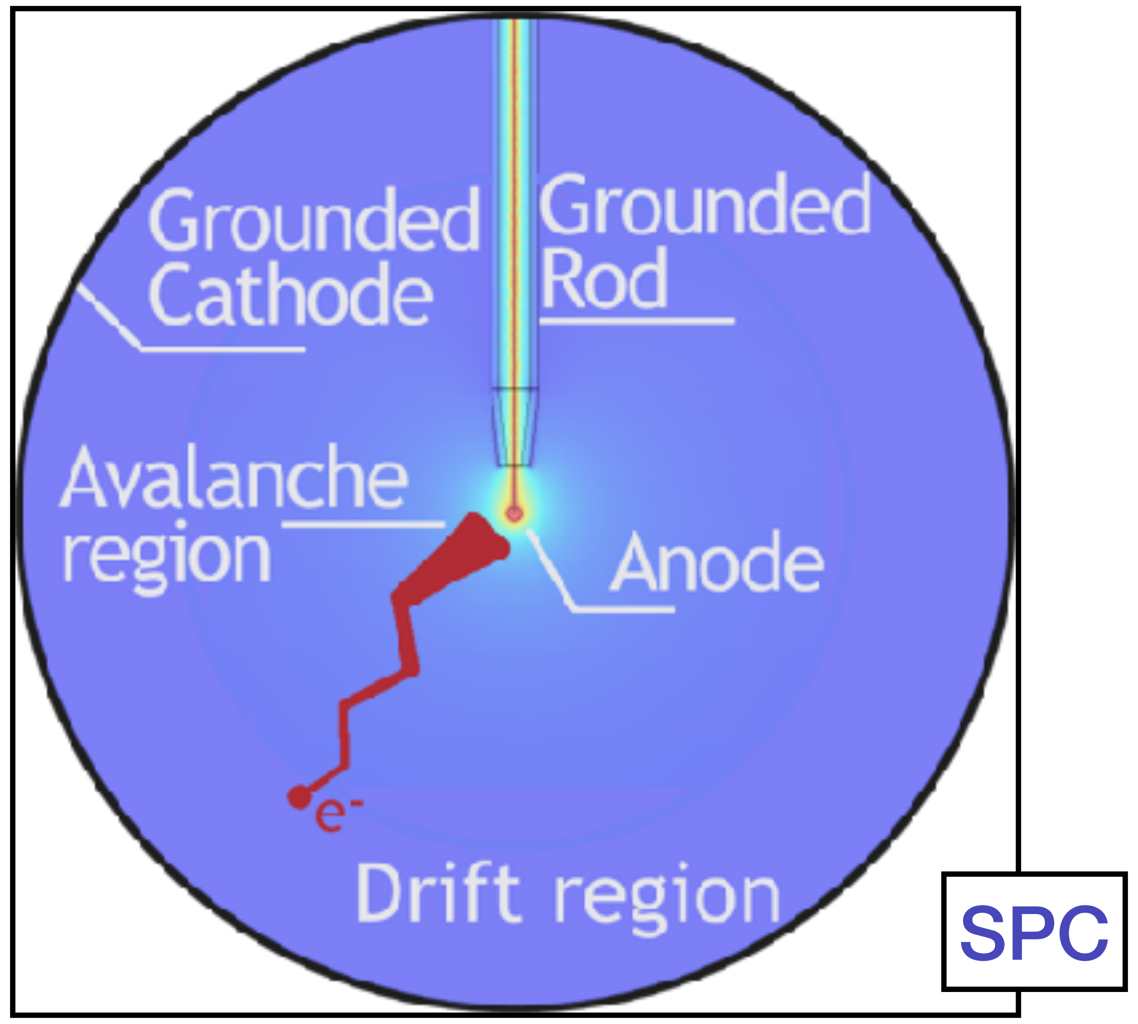


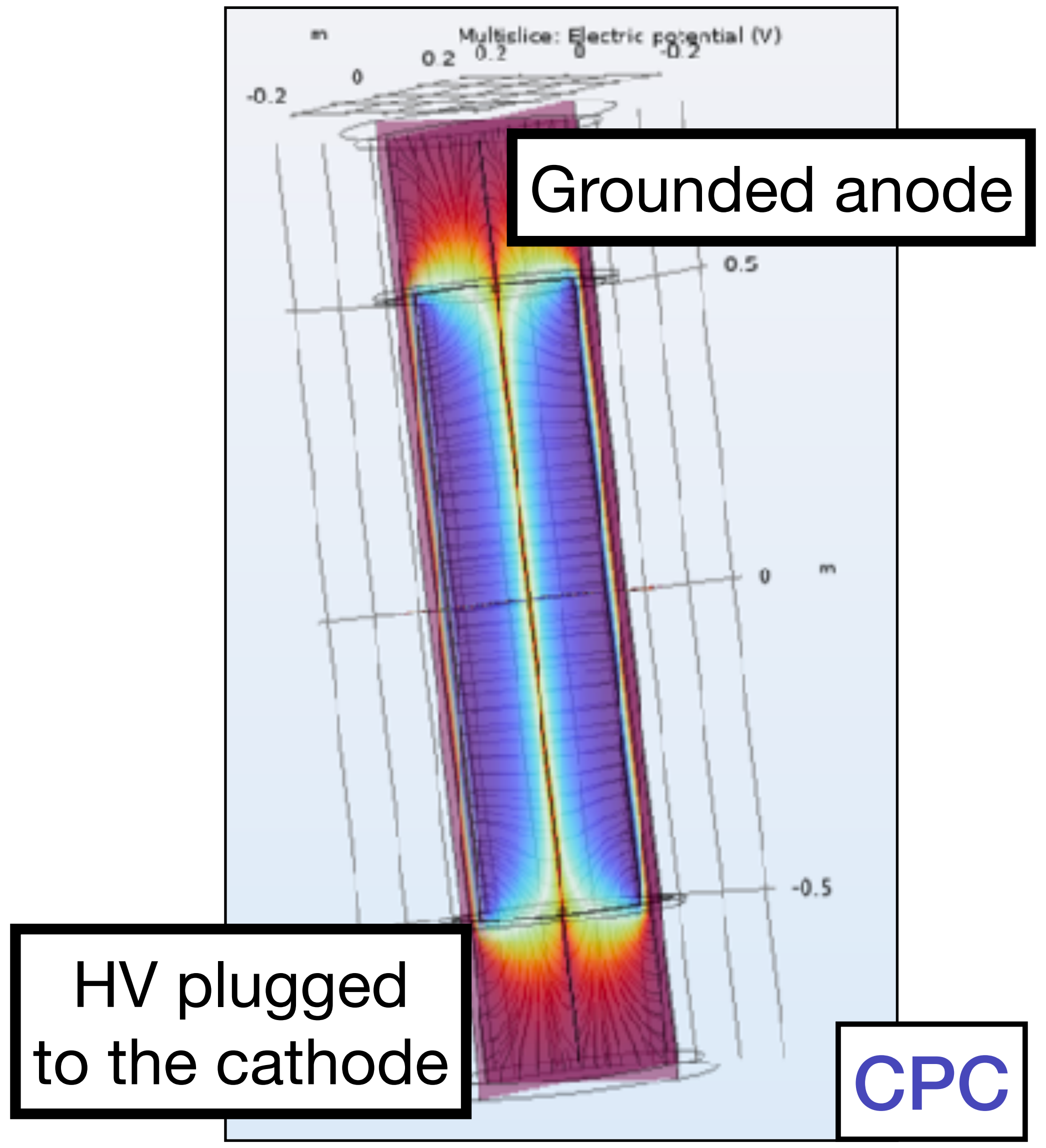
Design based on dark matter experiment

The R&D is currently considering two detectors options:

- Spherical Proportional Counter (SPC):
  - Spherical grounded cathode with a central anode.
  - Both signal and tension goes through the anode.

Detectors



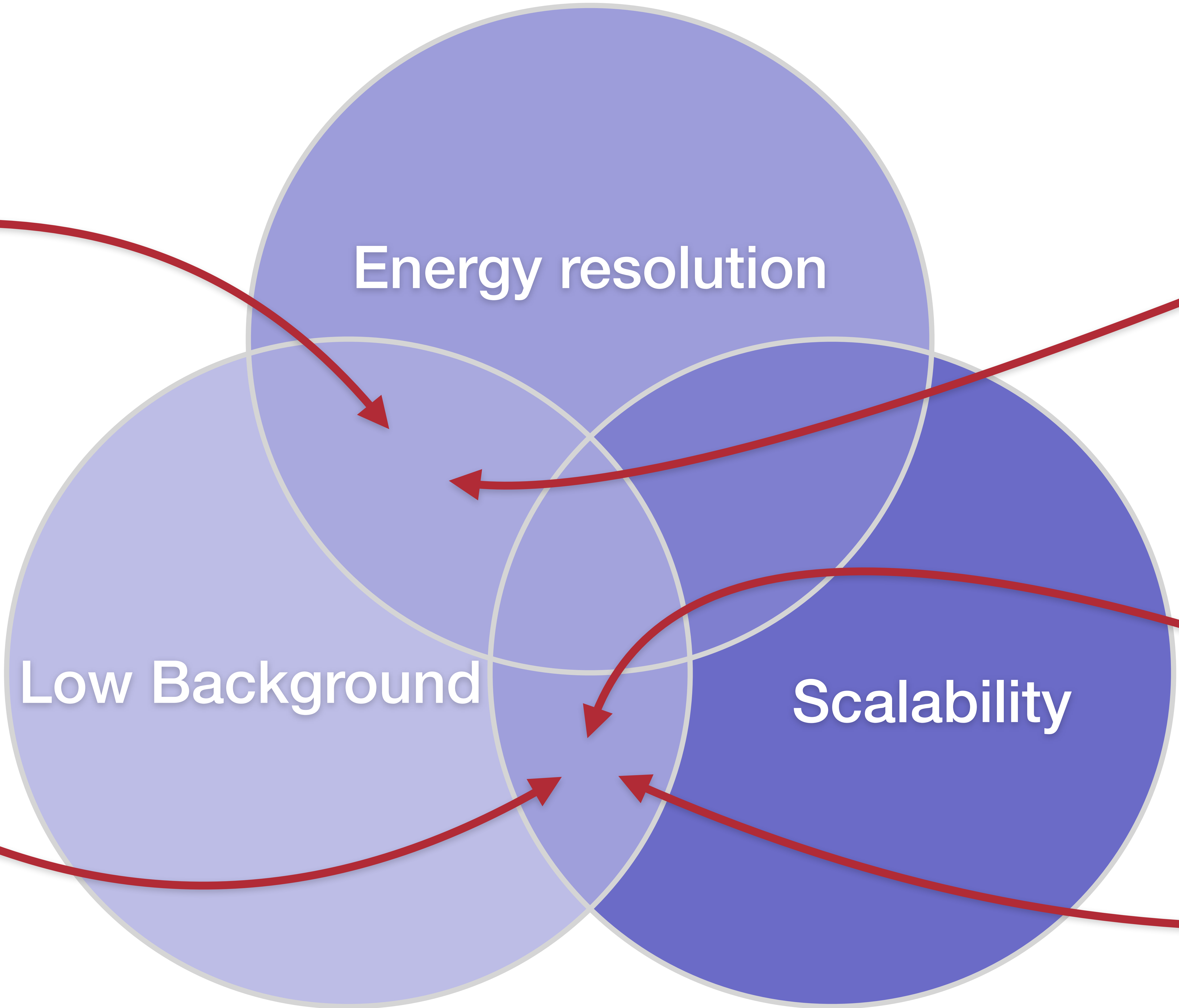


The R&D is currently considering two detectors options:

- Spherical Proportional Counter (SPC):
  - Spherical grounded cathode with a central anode.
  - Both signal and tension goes through the anode.
- Cylindrical Proportional Counter (CPC):
  - Grounded tungsten wire as the central anode of a cylindrical copper cathode.
  - Signal is red through the anode and tension with negative polarisation is applied on the cathode.

Features

- 1% FWHM at ^{136}Xe $Q_{\beta\beta}$ of 2.458 MeV.
- Excellent background rejection.



- Only one (or few in the upgraded version) readout channels.
- Low material budget.
- Simple geometry.

Current R&D Phases

Current prototype goal: Achieve 1% FWHM energy resolution at 2.458 MeV, ^{136}Xe $Q_{\beta\beta}$.

- ^{210}Po as α source.
  - Exploring ionisation and proportional mode.
  - Electronics and data acquisition.
  - Sensor characterisation and improvement.
  - Light readout[1].
  - Gas purity development.
  - Gas recirculation and recovery.

[1] Nucl.Instrum.Meth.A 1028 (2022) 166382 [arXiv:2201.12621]

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x2
First with Argon
then with Xenon

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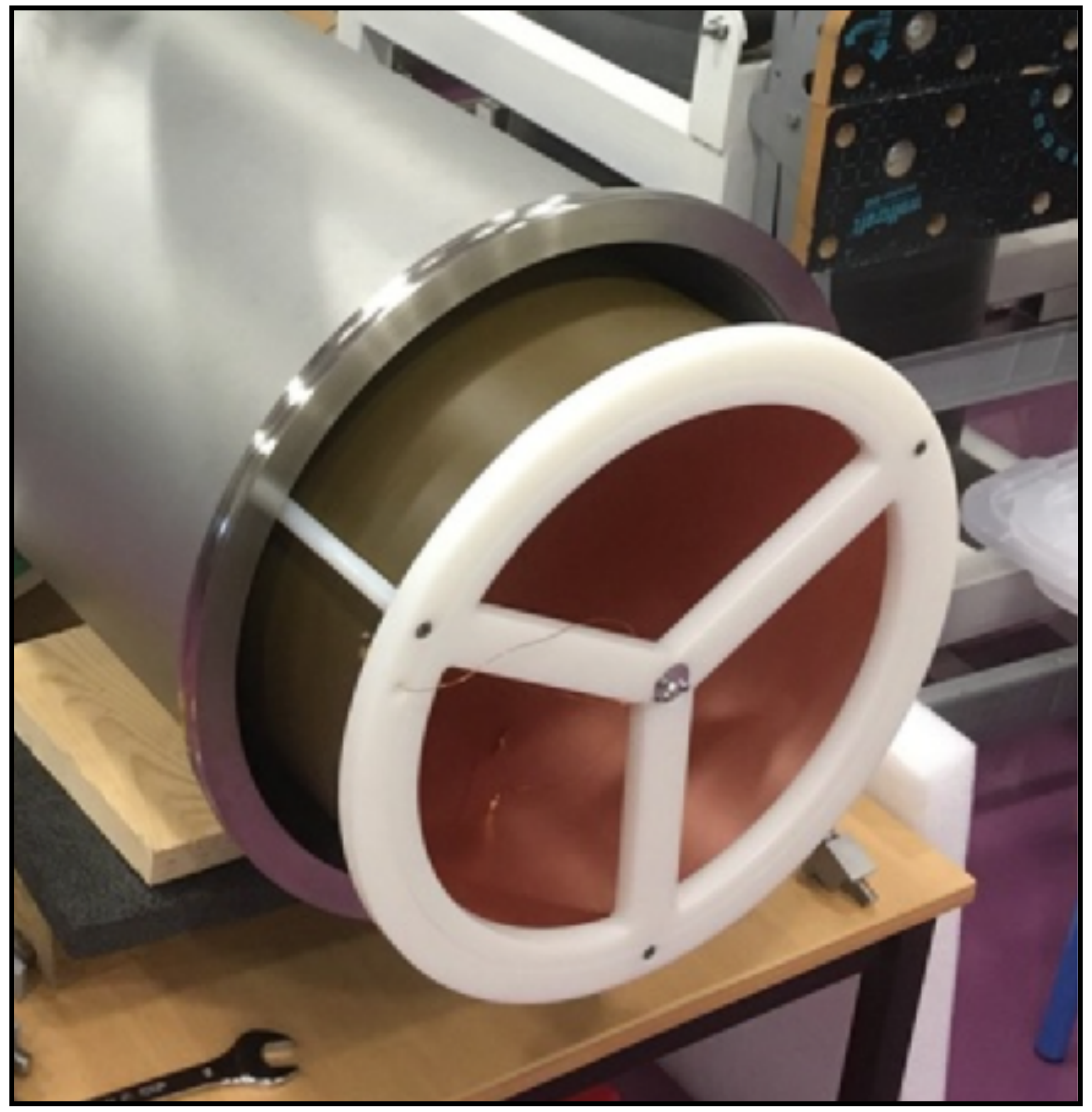
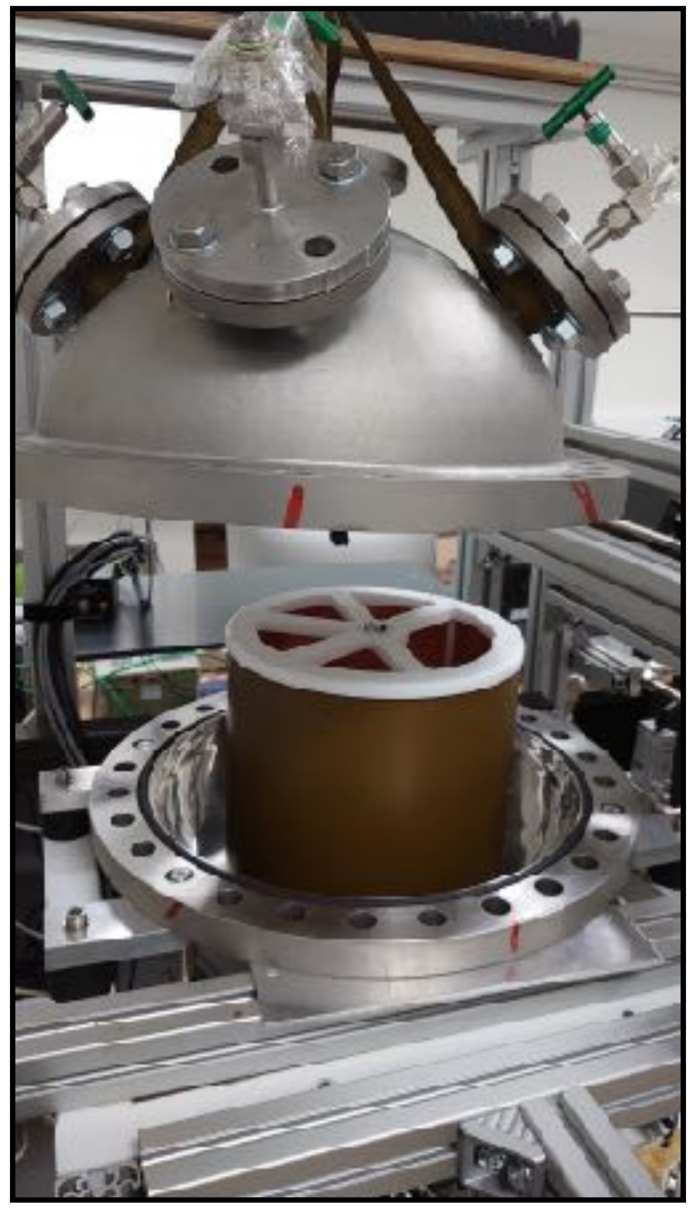
Prototype Setup Evolution At LP2I Bordeaux

SPC-1 (2018)
40 cm ⌀
Up to 1 bar[1]

SPC-2 (2021)
40 cm ⌀
Up to 40 bar[2]



CPC-1 (2022)
1m x 37 cm ⌀
Up to 1 bar[1]

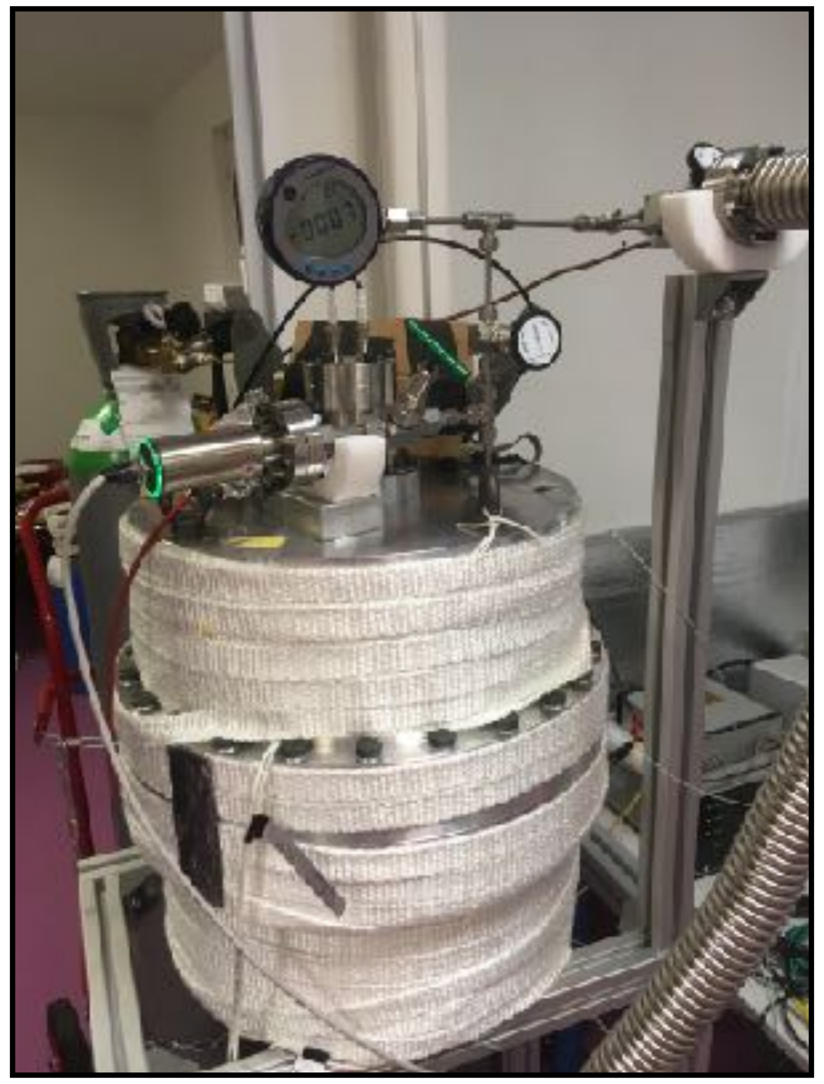


CPC-2 (2023)
27cm x 20 cm ⌀
Up to 40 bar[2]

[1] No Pressure certification
[2] Pressure certified

CPC Made at Subatech

1st SPC Prototype



- In 2018 the R2D2 was funded as R&D by the IN2P3: 1st SCP prototype was built.
- A 20 cm radius sphere made of Aluminium (i.e. no low background but much cheaper) was built at LP2IB and a custom made low noise electronics (OWEN project) was developed.
- The detector was commissioned and was operated with ArP2 at LP2IB at pressures up to 1.1 bar. First resolution results were published[1].
- A detailed simulation was setup to confirm our detector understanding: the agreement between data and simulation is very good and the detector behaviour is well understood.
- The resolution was computed at 200 mbar and 1.1 bar: we obtained a similar resolution showing no impact due to the length of the tracks (from 3-4 cm at 1.1 bar to 15-20 cm at 200 mbar).

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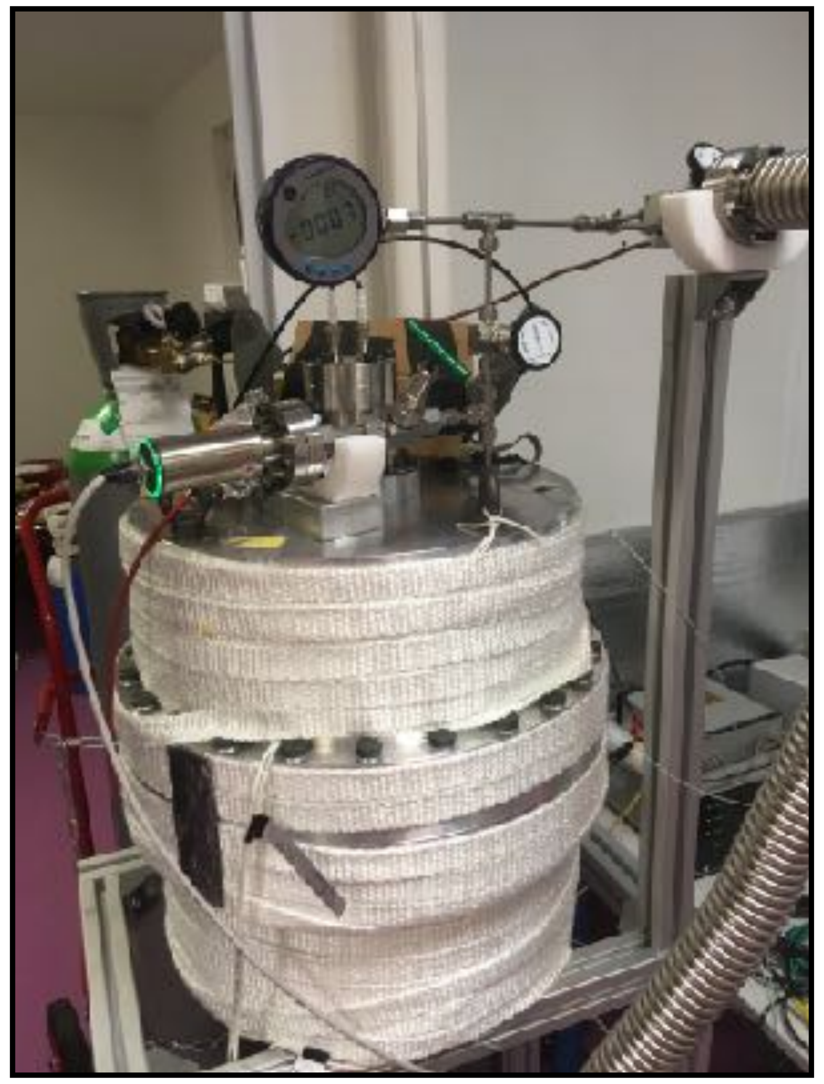

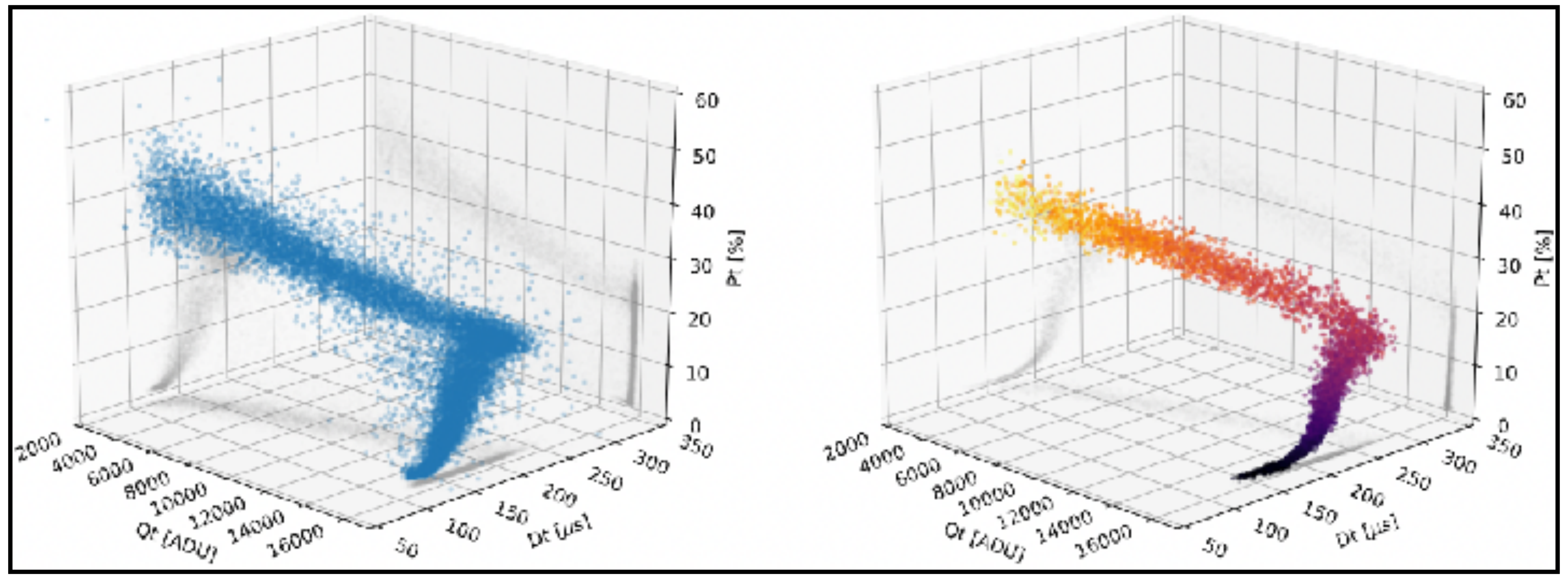

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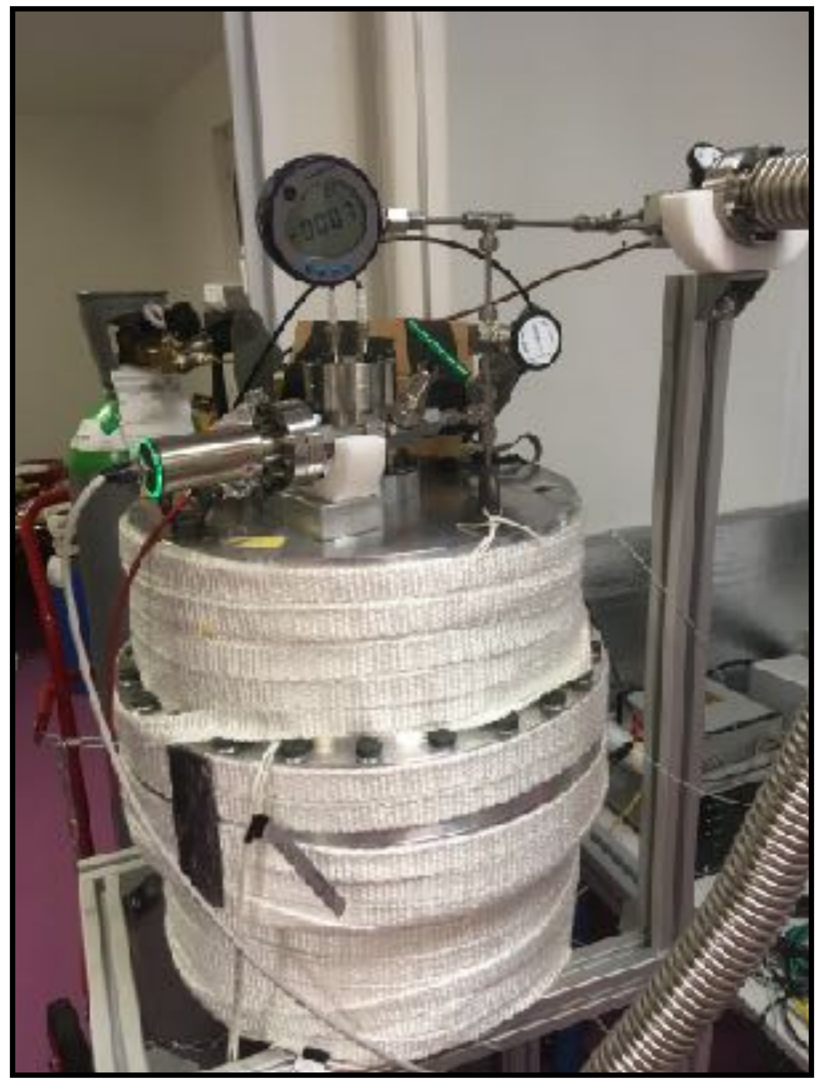

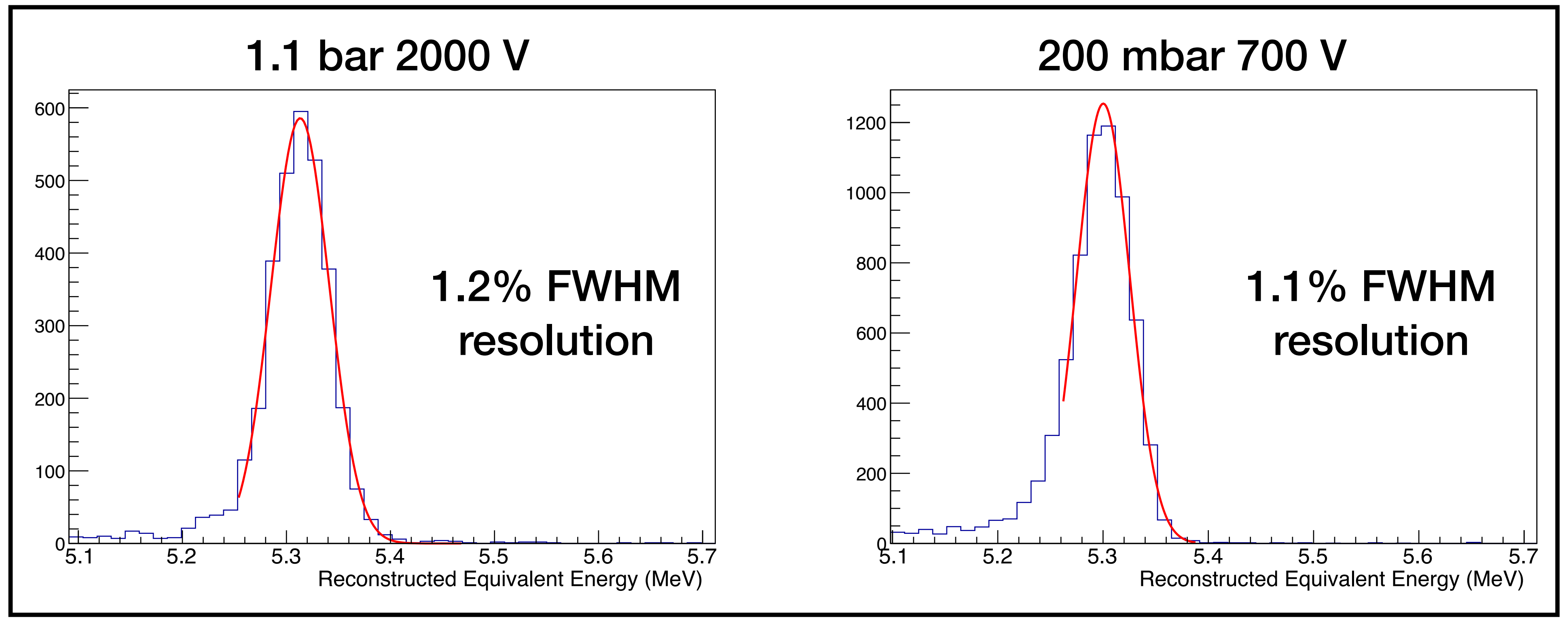

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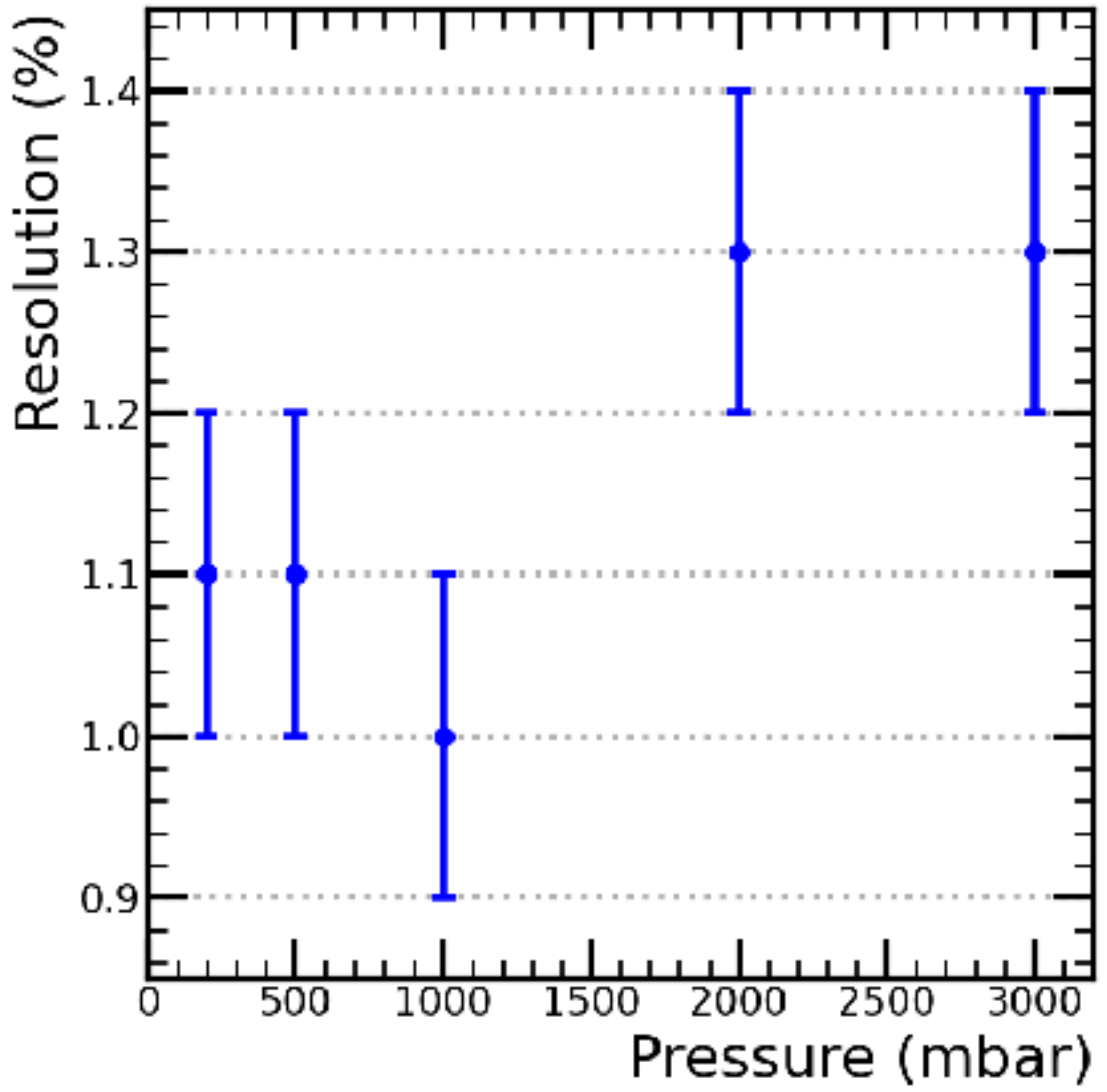
2nd SPC Prototype



- In 2021 the second SPC prototype, certified to be operated up to 40 bar, was built by RAVANAT company.

- In the meantime the xenon recirculation and recuperation system was finalized and commissioned.

- In 2022 the detector was operated with ArP2 with pressures up to 3 bar. A set of measurement was carried out with a resolution below 1.4% up to 3 bar.

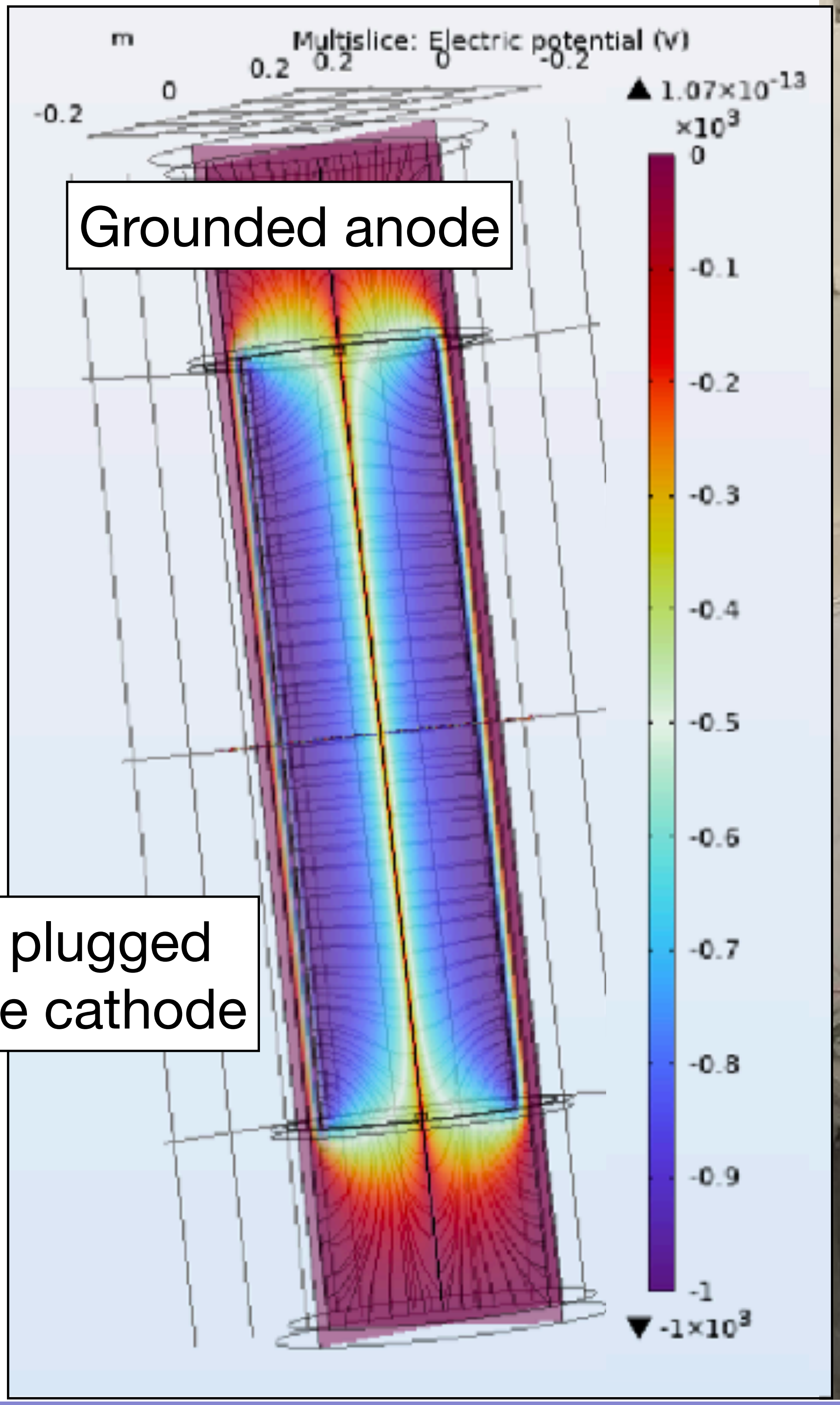
1st CPC Prototype

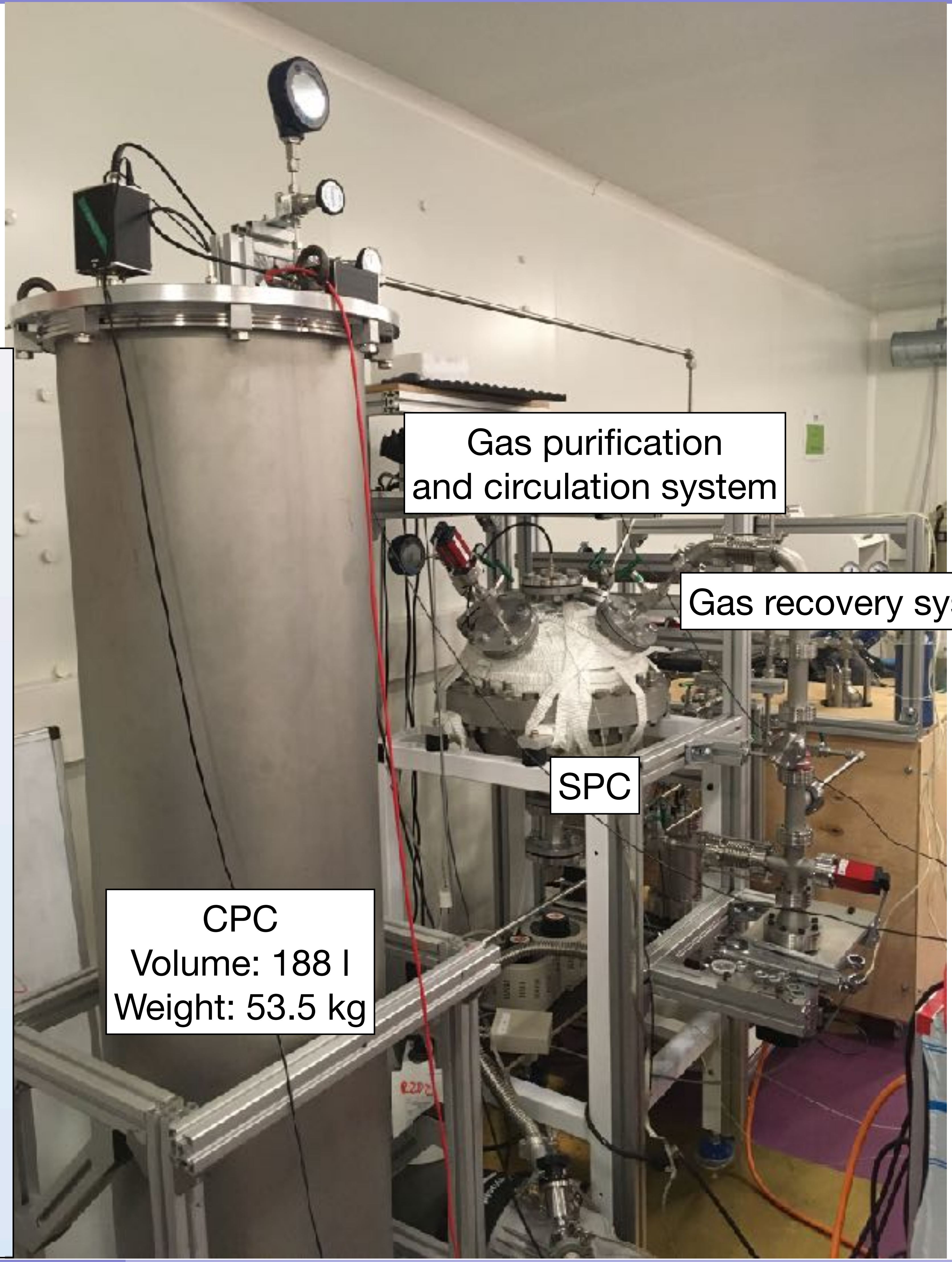
Since May 2022 a new prototype is under study. A CPC exploiting the existing electronic chain, pumping and gas management system. First validation in ArP2 showed a resolution comparable with SPC (1.2% at 1 bar) at lower voltage.

- Inox Tube: 1m50 x 40cm ⌀.
- Copper cathode: 1m x 35 cm ⌀.
- Tungsten anode: 50 µm ⌀.
- ^{210}Po source.

Electric Field:

- SPC: $\propto \frac{1}{r^2}$
- CPC: $\propto \frac{1}{r}$ (far from the edges)





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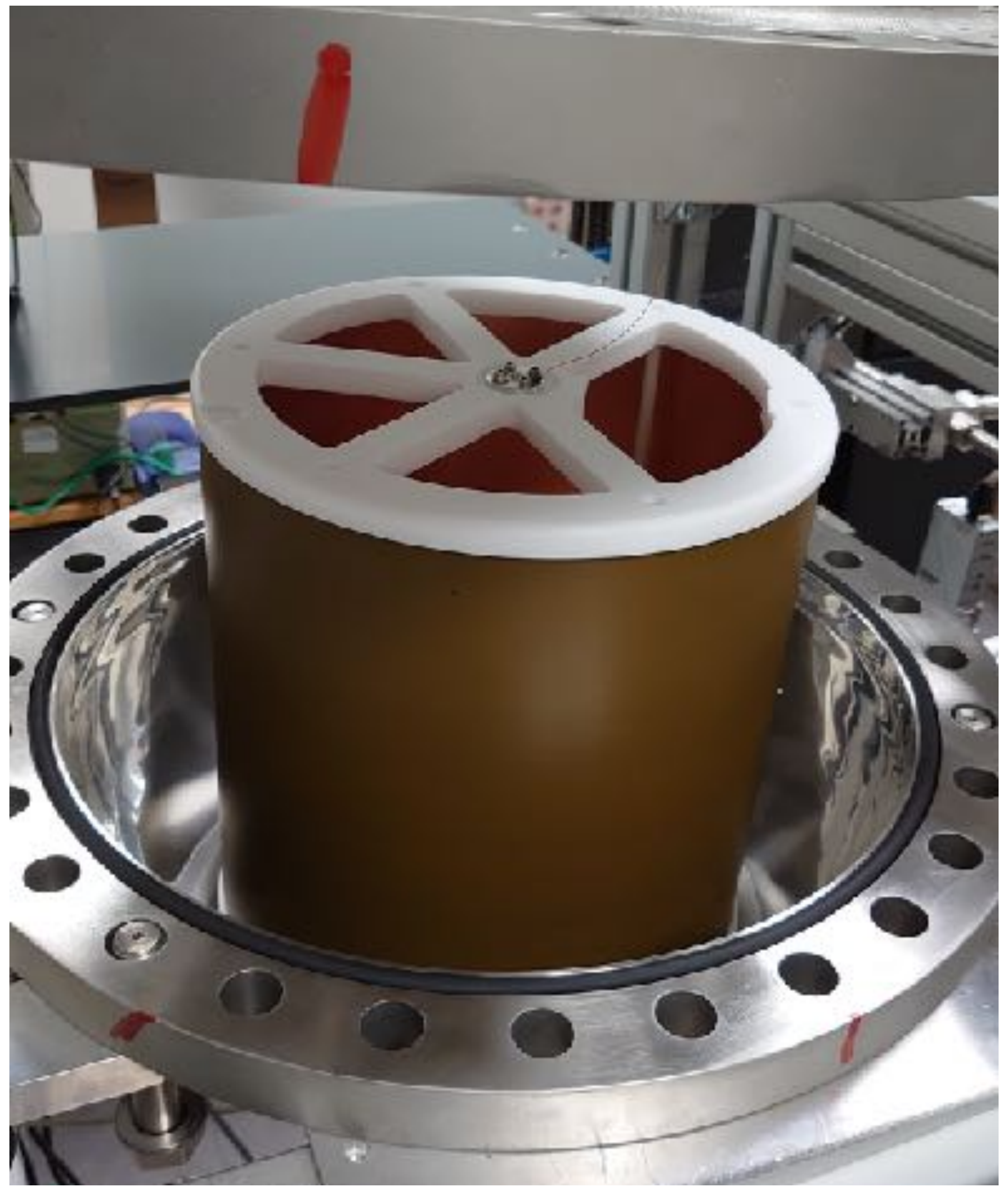
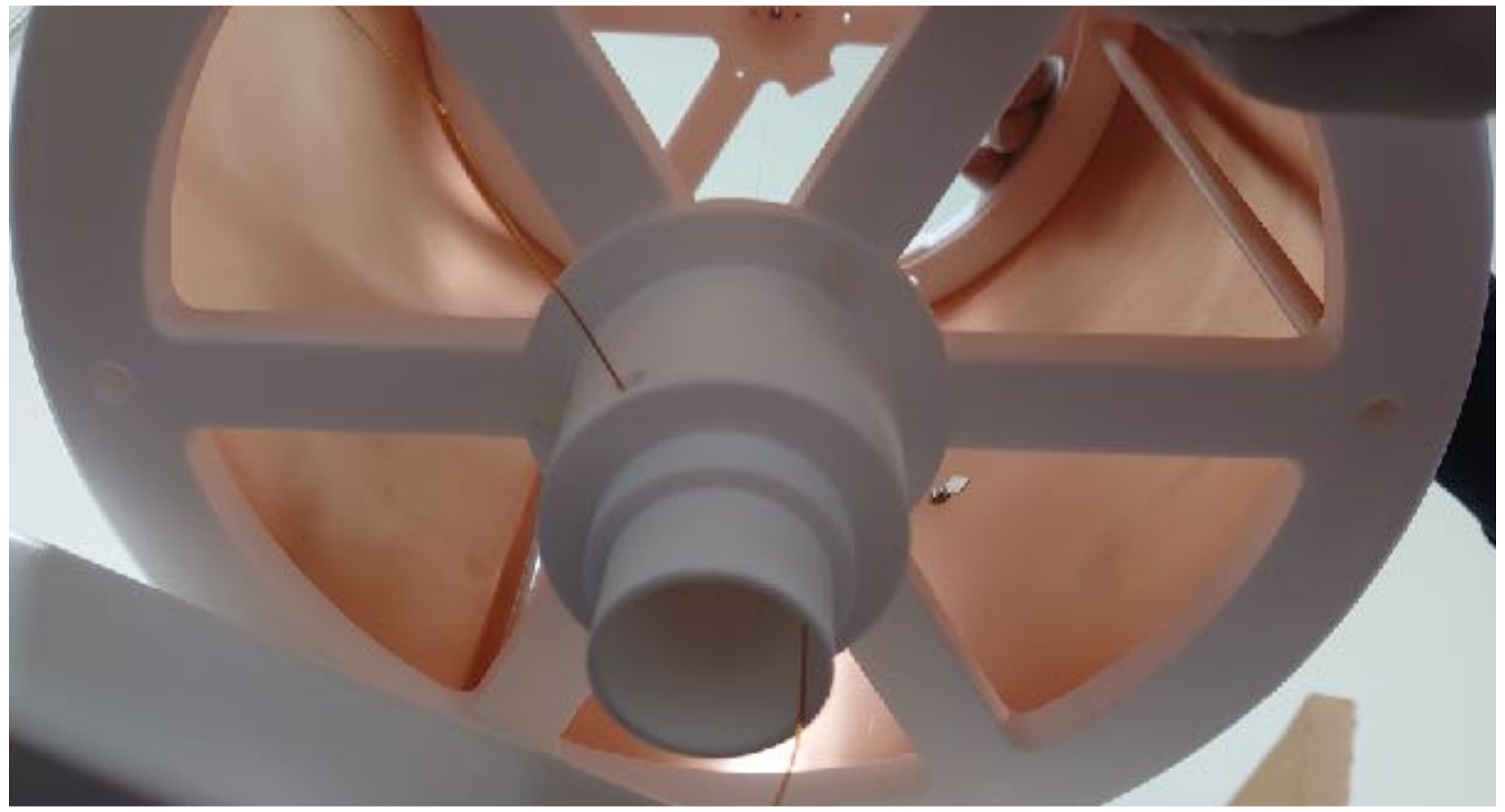
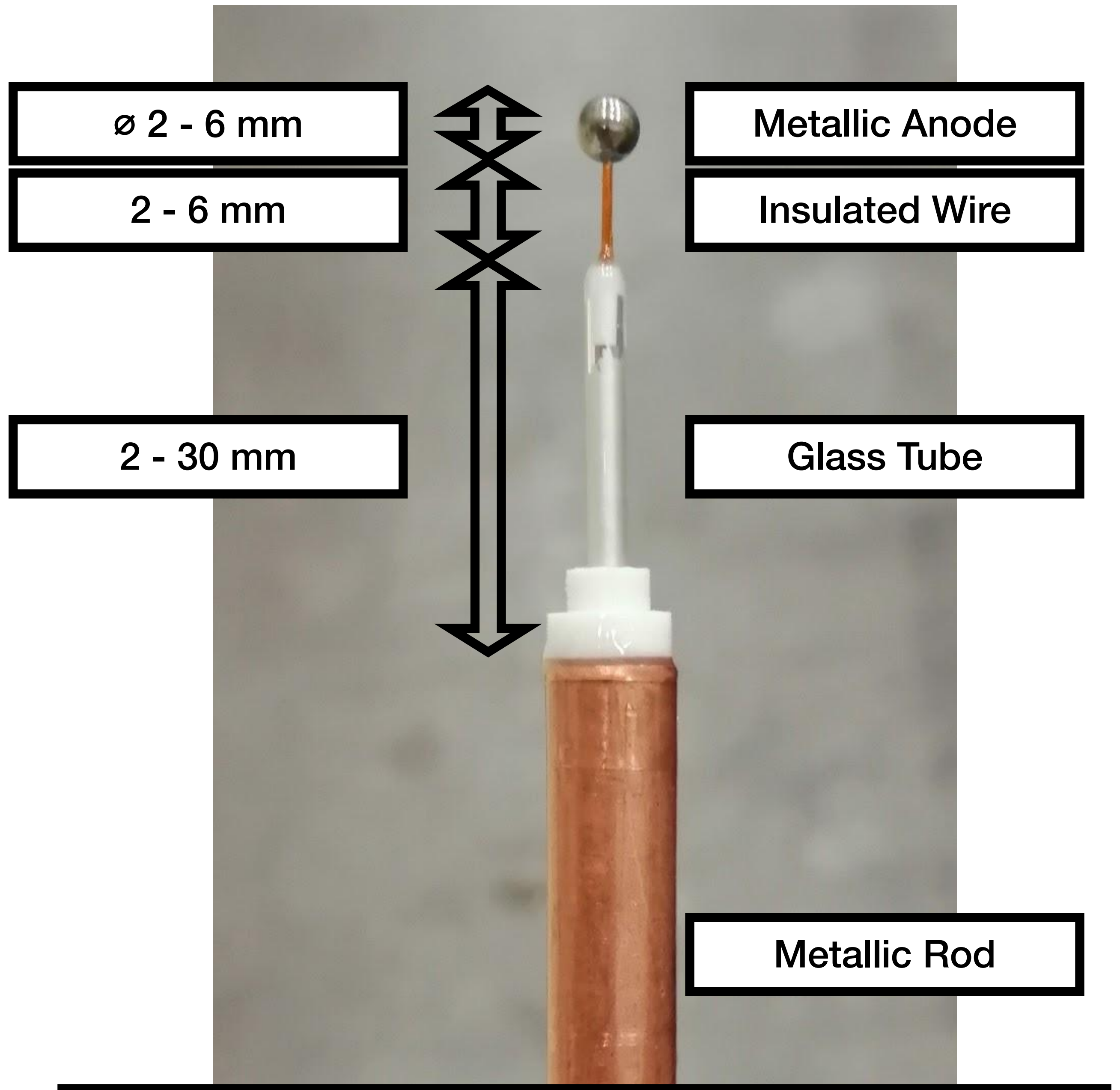




- Early 2023 the second prototype for CPC was conceived and built at Subatech.
- The CPC is designed to be operated inside the sphere (SPC 2nd prototype) in order to test the detector at high pressure.
- First test in ArP2 showed a good behavior of the CPC up to 15 bars. Tests in xenon were carried out up to 3 bars as well.
- The limiting factor is still the gas purity. The hot getter was received in May 2023 and tests are in progress.

SPC Sensor

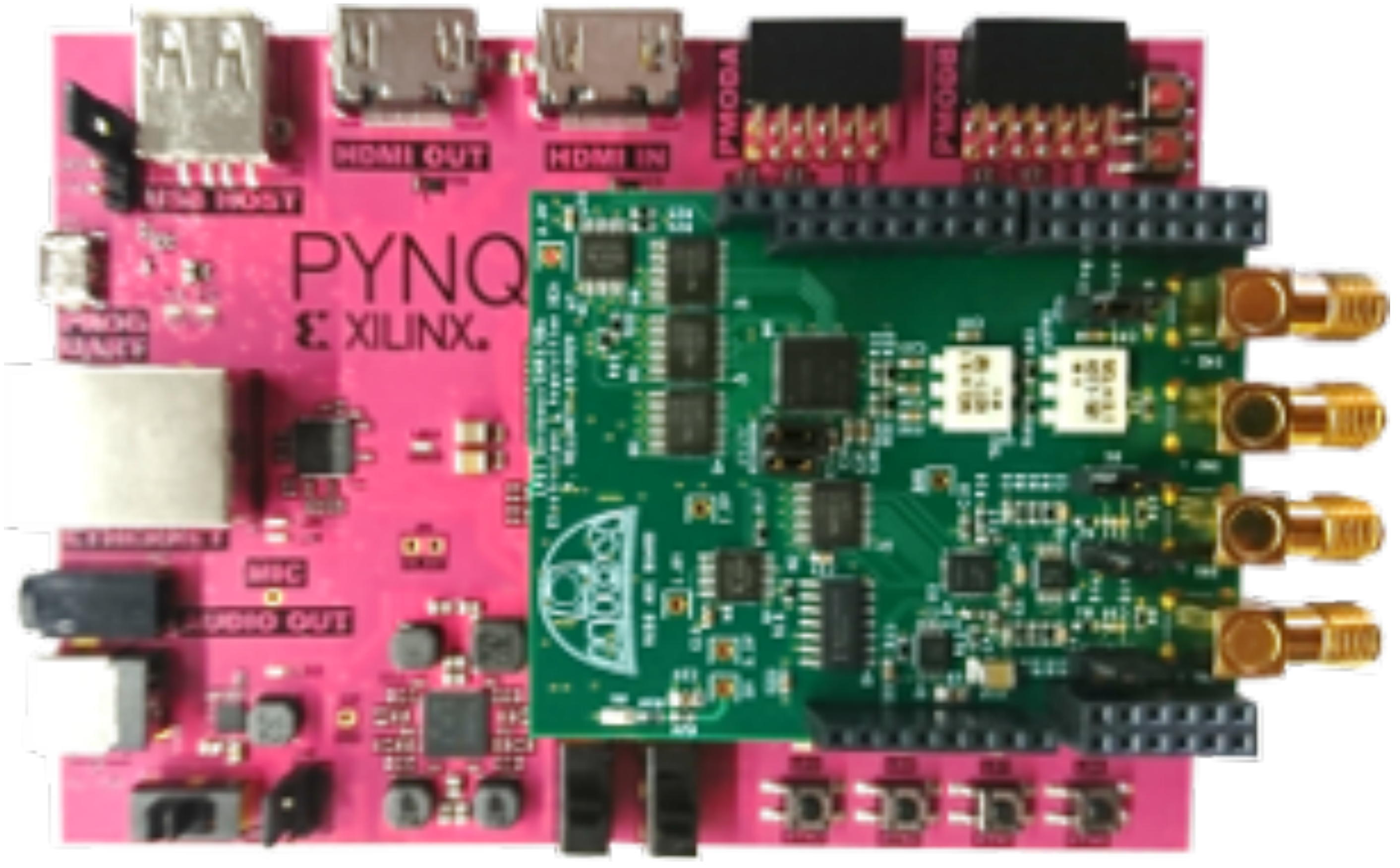


J. Instrum. 13 (2018), (11):P11006
[arXiv: 1809.03270]

Achinos by cea

- The sensor is the key point of the SPC detector.
- With the ongoing R&D we learned a lot from the detector functioning and we tested different option modifying the distance between the anode and the supporting rod.
- The anode soldering to the wire is still a critical point since any imperfection results into a field distortion. We are in discussion with AXON to perform micro soldering without drilling the anode and compromise its sphericity.
- Multi channel sensor (Achinos) was also tested but channel equalisation is currently an issue for resolution.

Electronics and DAQ



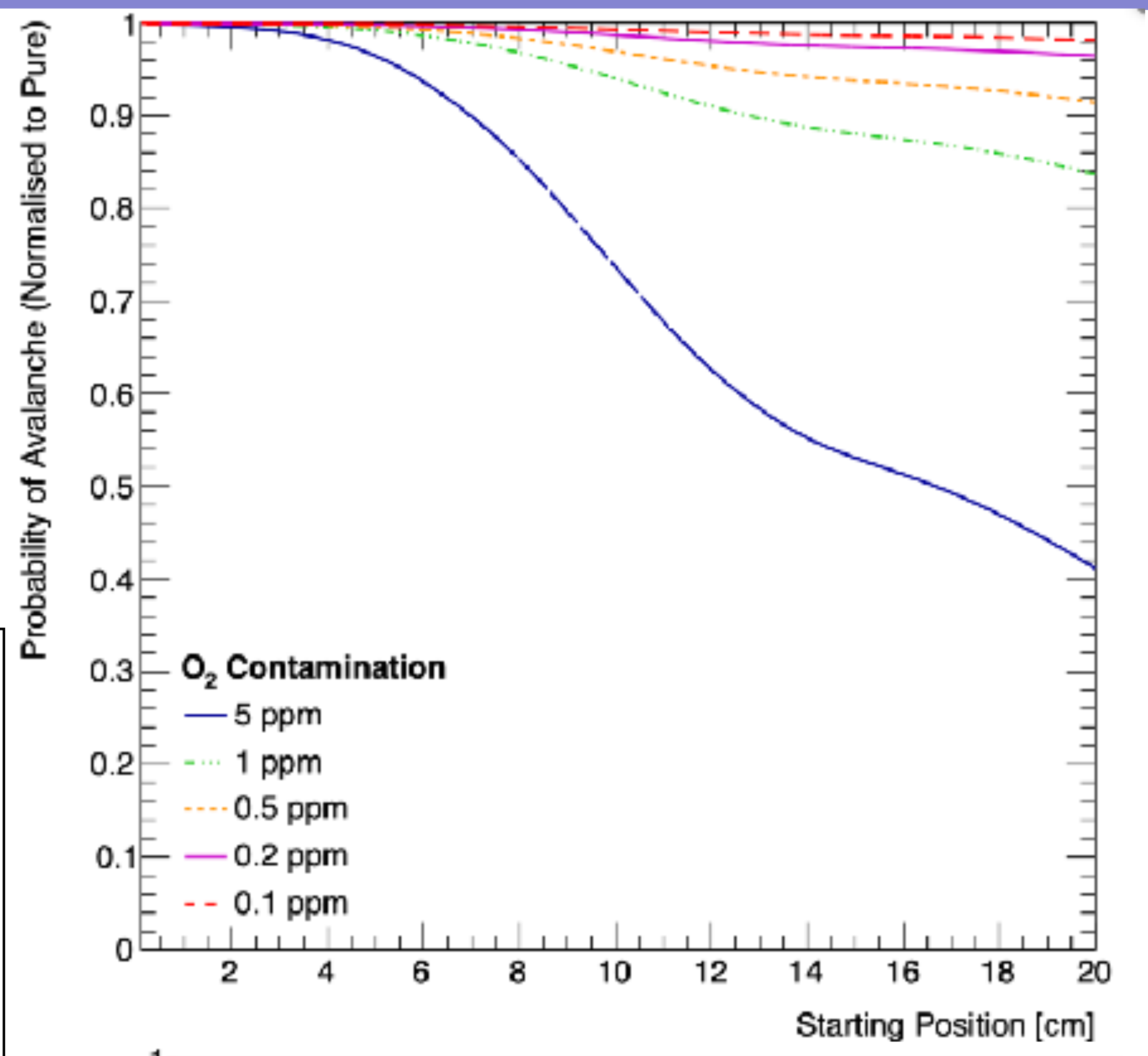
Optimal Waveform recognition Electronic Node

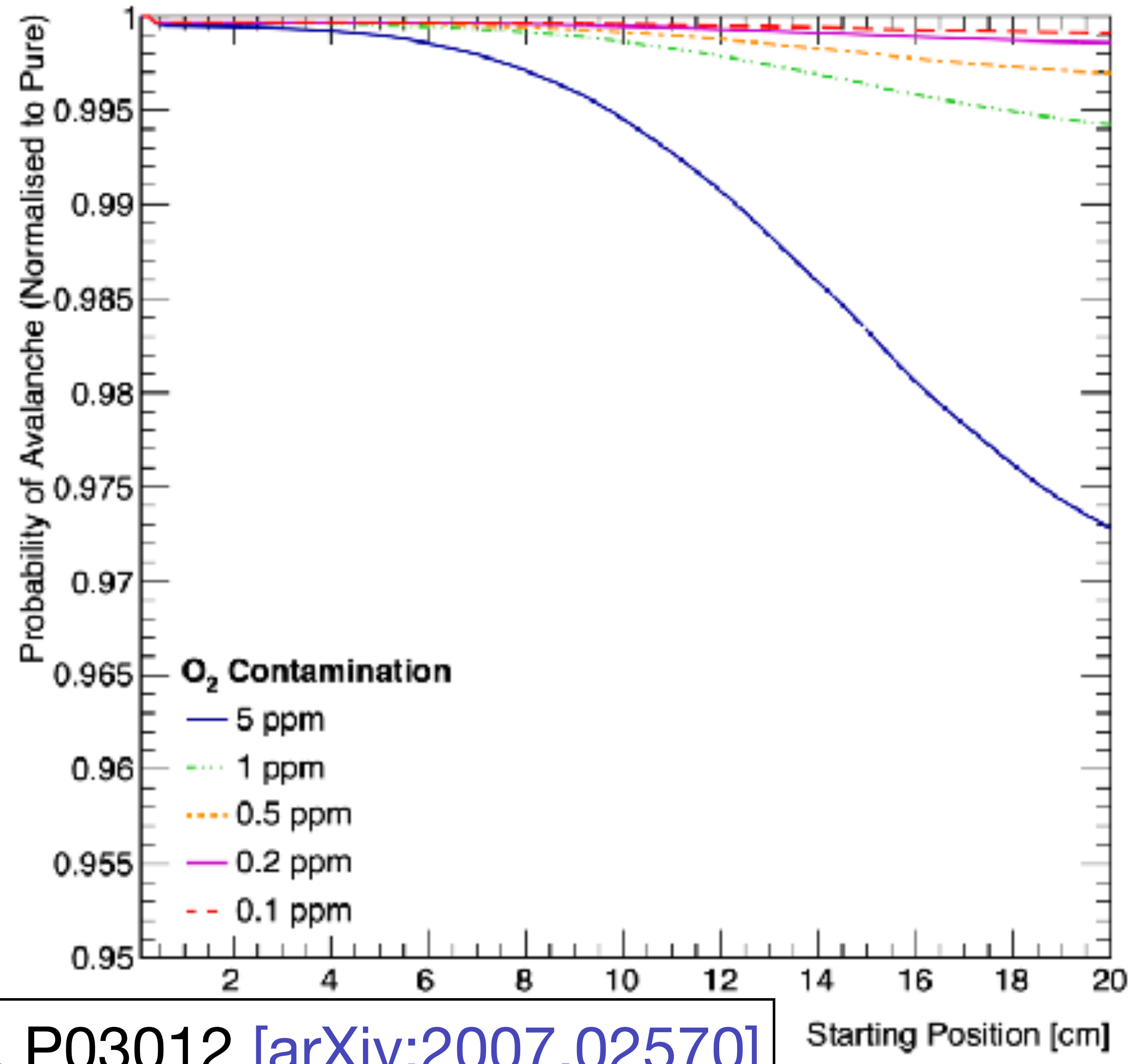
- To achieve the energy resolution requirement, a dedicated low noise electronics chain is essential.
- A low noise preamplifier was developed and a DAQ chain is under development (foreseen for end-2023) while we use in the meantime the CALI card developed for EDELWEISS and used today in NEWS-G.
- This work is carried out in the framework of the OWEN project (IdEX Emergence Université Bordeaux) which includes a dedicated development of onboard technology for a fast data processing.
- A specific work related to Artificial Intelligence is also ongoing in synergy with the THINK project of IN2P3 both for the final onboard technology and for the offline waveform processing in order to analyse signal and possibly reconstruct two-electrons tracks signature in the signal.

Gas Purity And Recirculation

- Purification:
  - High purity is a strong requirement.
  - Circulation inside getters.
- Recirculation:
  - Recirculation system.
  - Controlled flow.
- Recovery: First design by
  - Creation of a cryopumping system.
  - Pressure controlled valve.

Simulation
Cathode: 20 cm radius
Anode: 1 mm radius; 2000V
ArP2: 1.1 bar ↑
Anode: 1 mm radius; 720V
ArP2: 200 mbar ↓





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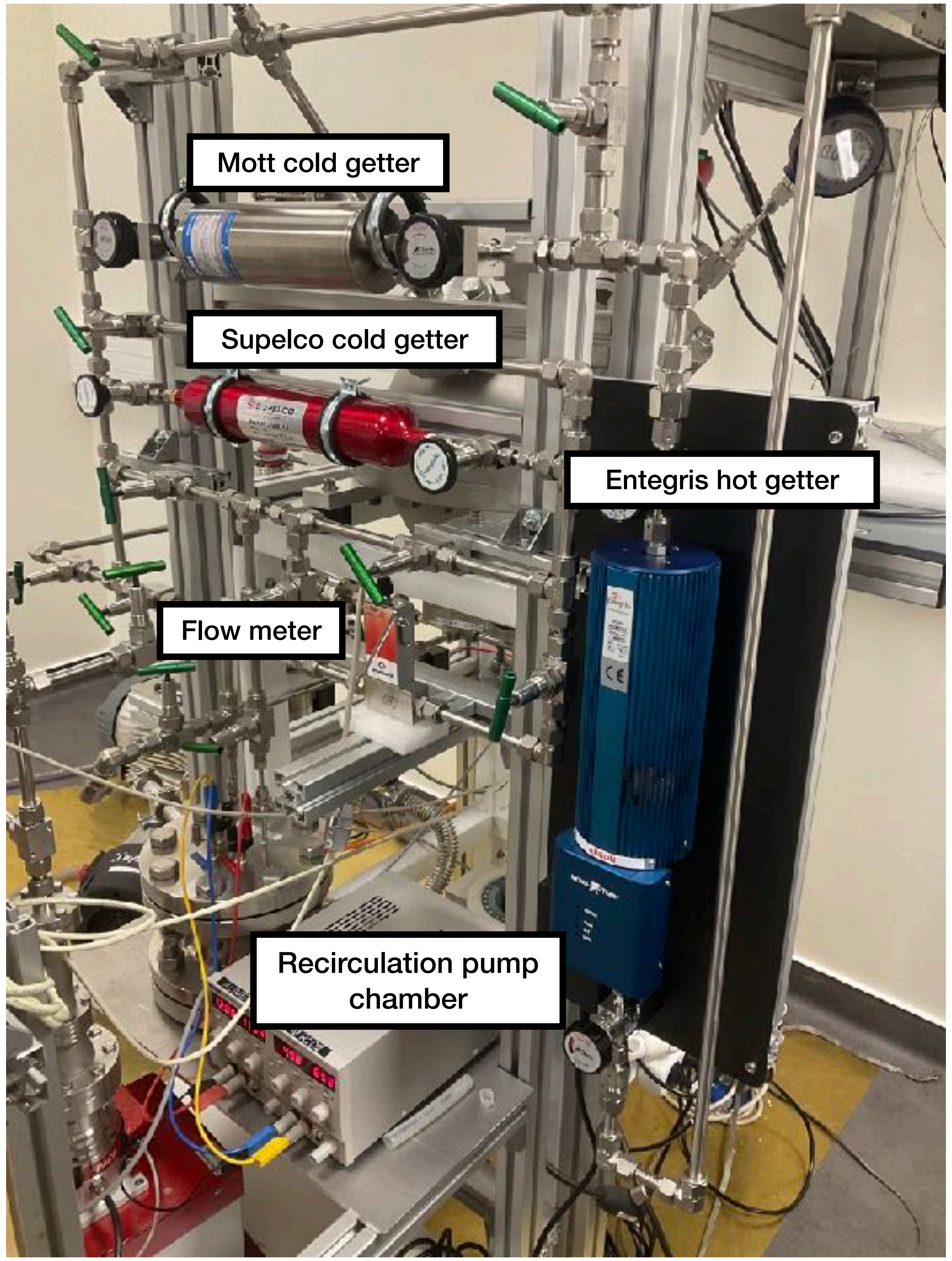

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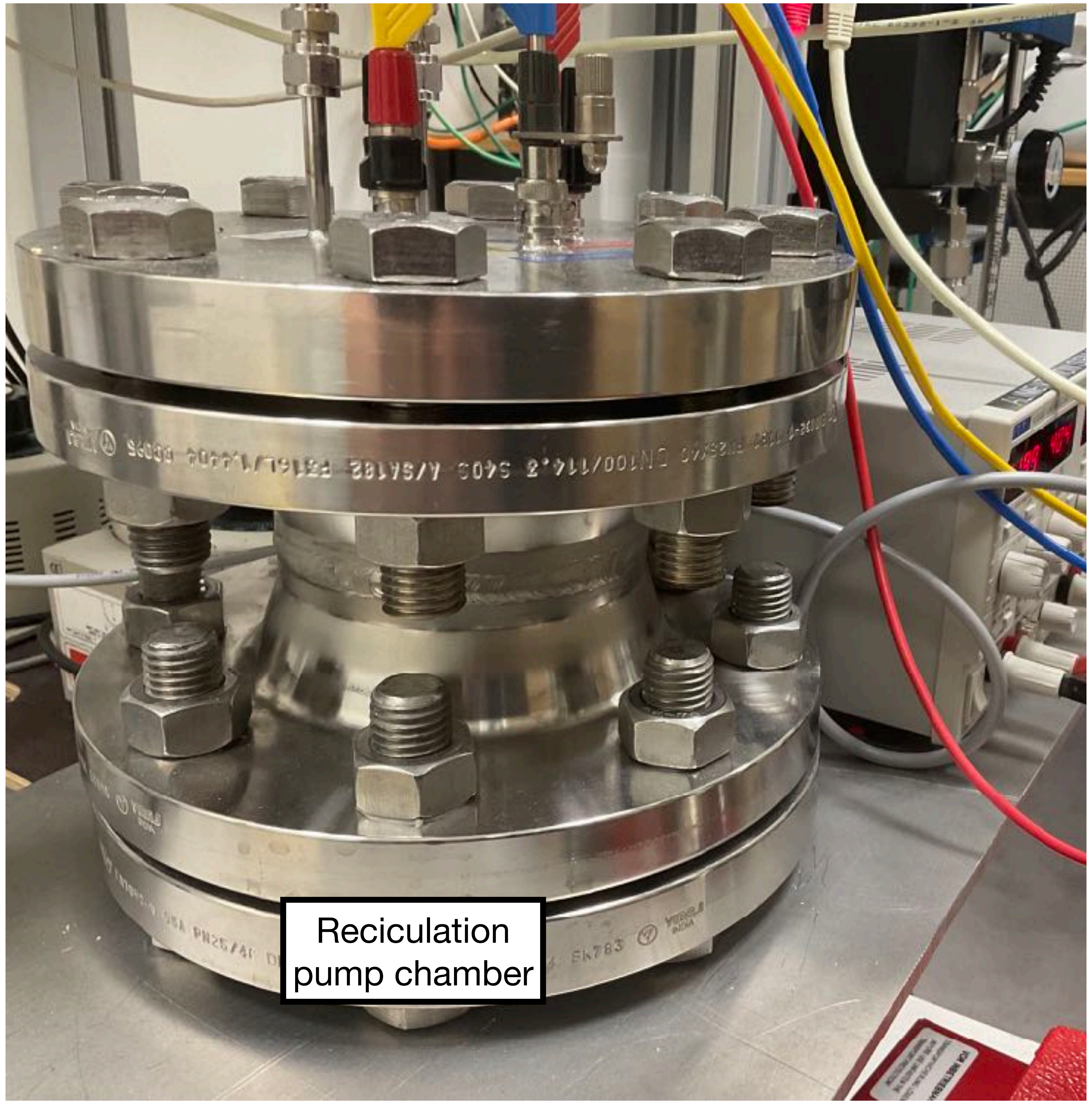

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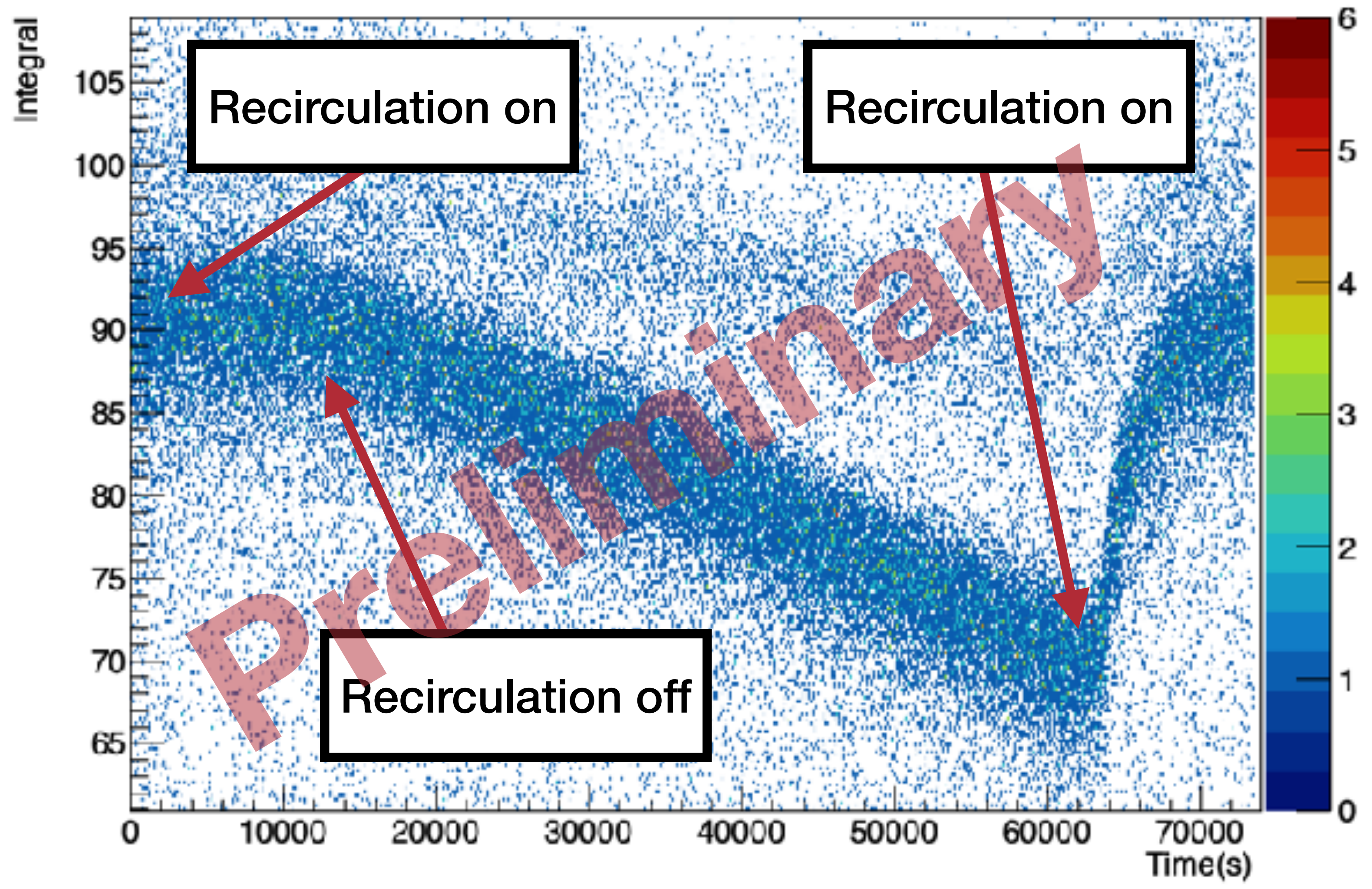

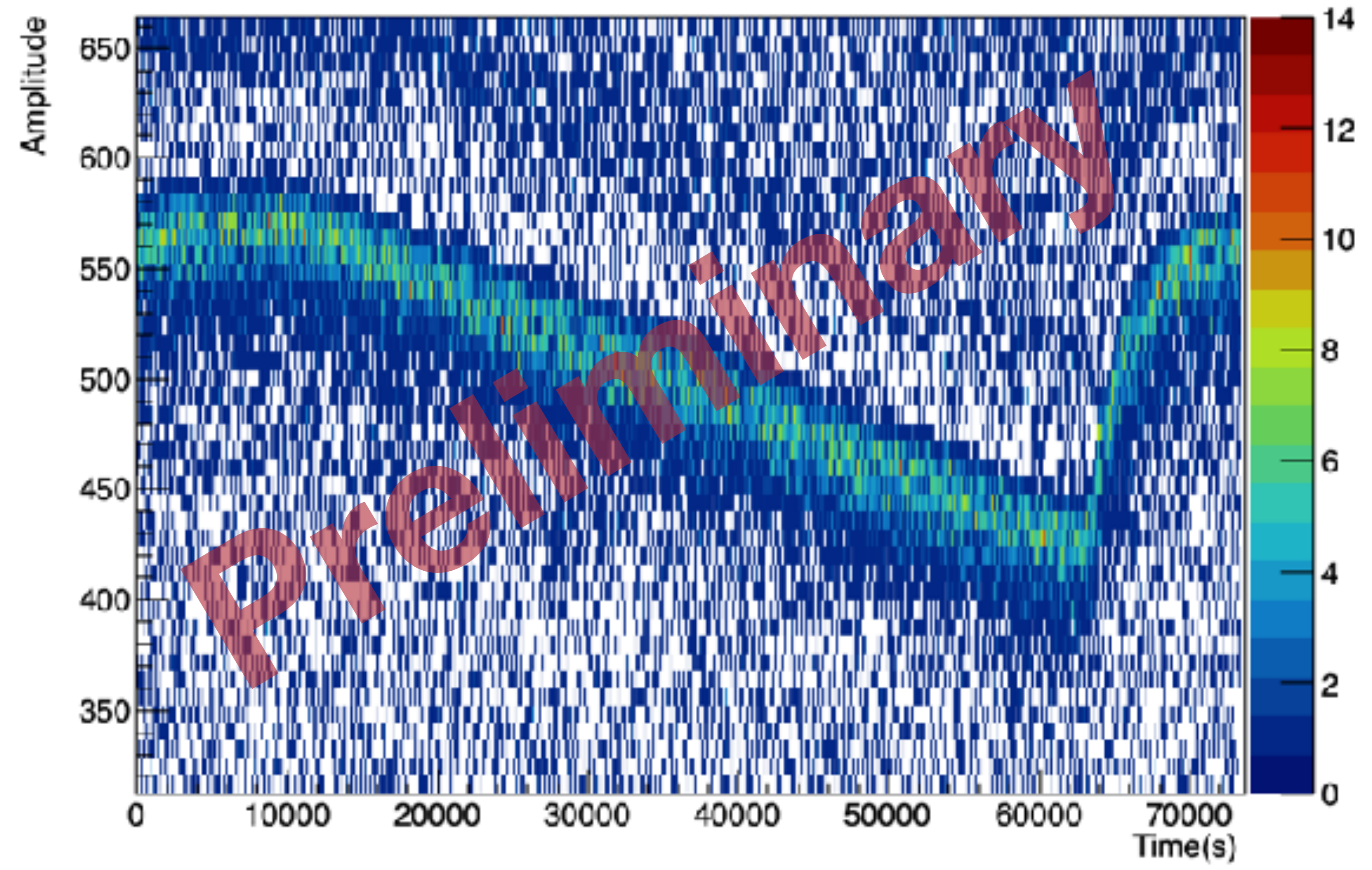

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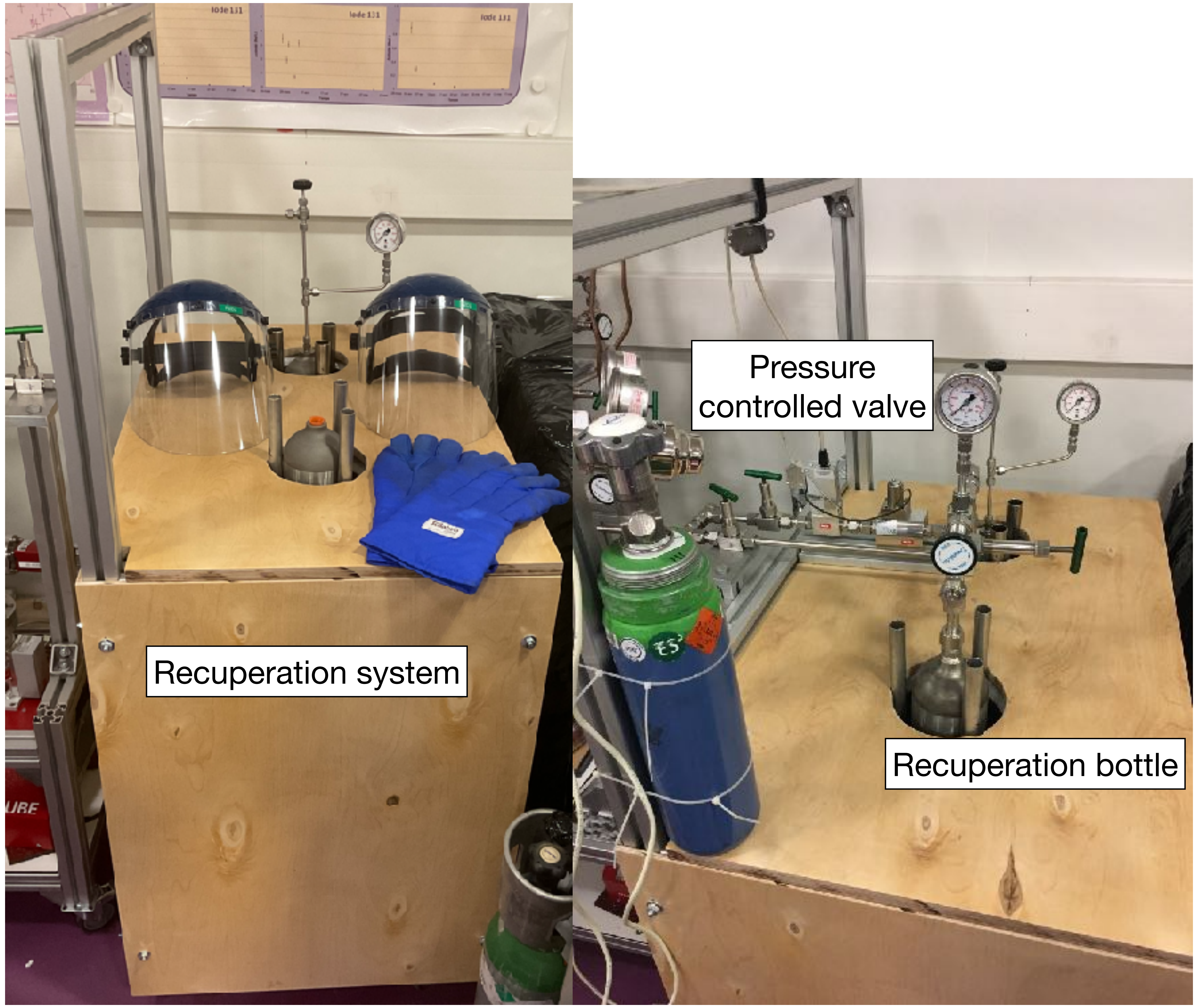

Results

Gas	Detector	Anode (radius)	Pressure (mbar)	HV (V)	Noise (ADU)	Gain	Resolution (%)
ArP2	SPC	1 mm	200	800	4.3	45	1.1
			500	1300	4.1	34	1.1
			1000	1900	4.2	30	0.9
			2000	2700	4.5	10	1.3
			3000	3900	4.8	10	1.3
		3 mm	1000	700	4.4	1	8.2
	CPC	10 µm	1000	200	3.6	1	4.9
			1000	900	3.9	9	1.2
Xe	SPC	3 mm	250	1300	4.5	1.3	3.8
			900	1300	4.4	1	7.2
	CPC	10 µm	500	900	3.8	20	1.8
			1000	1200	3.9	14	1.8

- SPC in proportional mode is limited at HV since noise increases with HV. In ionization mode the limit is given by the electronic noise.
- Noise in the CPC is smaller (independent on the HV) and resolution in ionization mode is better.
- CPC in proportional mode requires smaller HV and resolution is good enough. At high pressure the limit is given by the gas purity.

Conclusion

- The R2D2, R&D proud of its 6 years of experience, has achieved a specific knowledge of the detector.
- Those efforts yield to a validation of the detector up to 15 bar in ArP2 and up to 3 bar in xenon.
- The current gas purity limits are expected to be improved with new equipment.
- CPC is easier to operate and achieved better results. Therefore, it will be the design baseline for future steps.
- A dedicated low noise electronics has to be developed in particular to work in ionisation mode and to read the sensor at both ends to reconstruct longitudinal position.

The End

Backups

R2D2 collaboration

- A proto-collaboration has been formed (Czech colleagues from Prague joined R2D2 in April 2023).
- R2D2 is today approved as IN2P3 R&D to assess in particular the possibility to reach the desired energy resolution which is the major showstopper.

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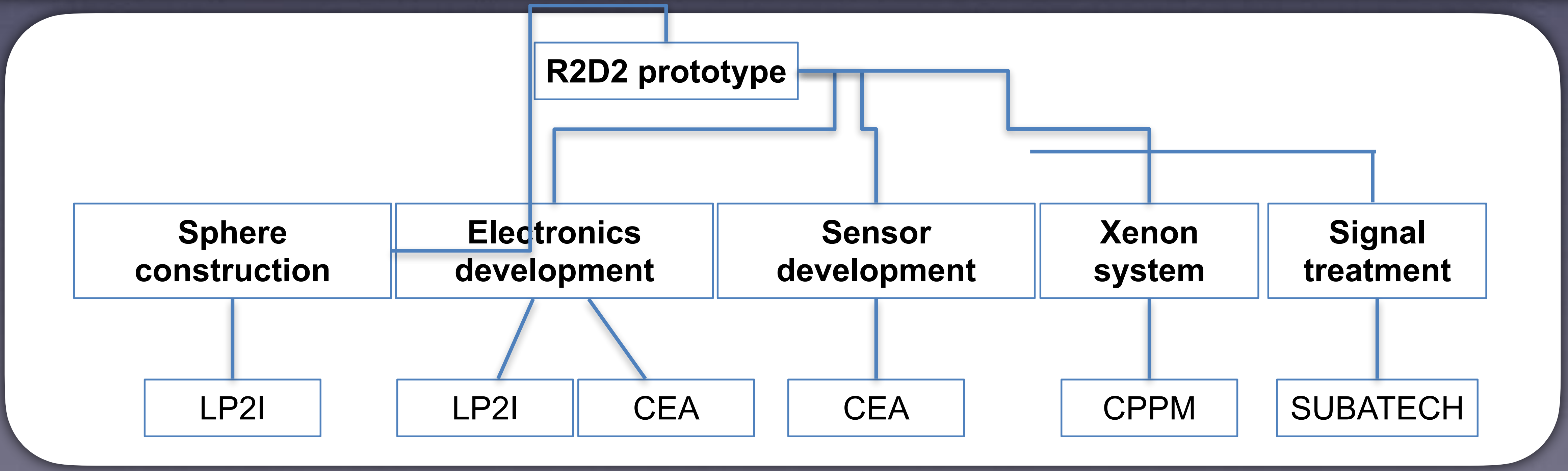


Sensitivity studies

- A **full Monte Carlo simulation** was developed to assess our capability to reject background and to evaluate the possible sensitivity on the searched signal.
- We considered a geometry including active and passive veto and a small mass of 50 kg of xenon corresponding to the foreseen prototype.

Xenon active volume

Mass of 50 kg

Radius of 37 cm

Pressure of 40 bar

This choice, based on the results of a pressure and radius scan, is driven by the need of containing at least 80% of the $\beta\beta0\nu$ electrons.

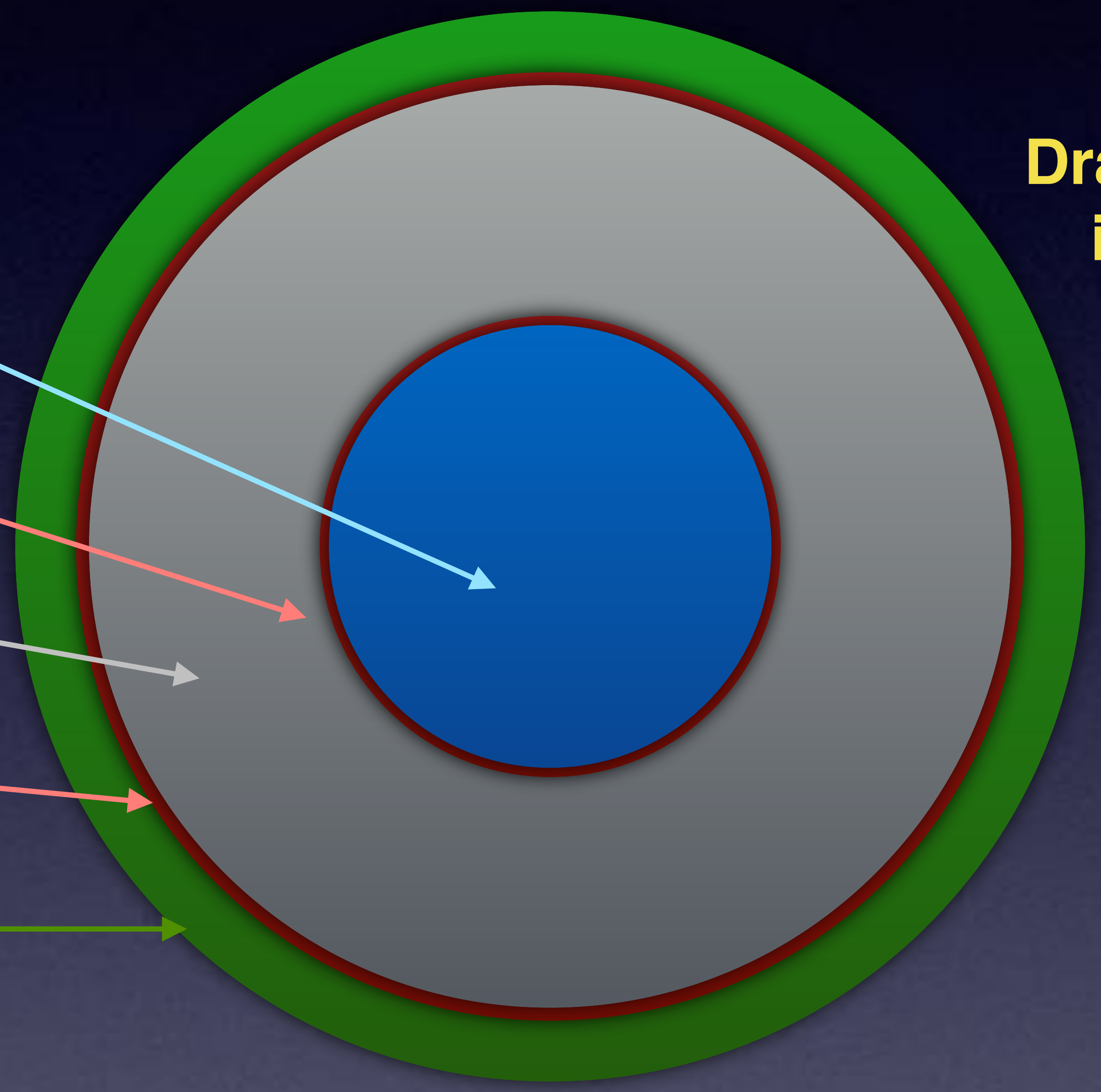
37 cm radius inner volume of Xe gas

0.5 cm thick Cu structure

1.5 m thick liquid scintillator

2 cm thick Cu structure

20 cm thick Pb + 5 cm thick Cu shielding



Drawing not in scale

Liquid scintillator volume

Thickness of 1.5 m

Assumed to be LAB

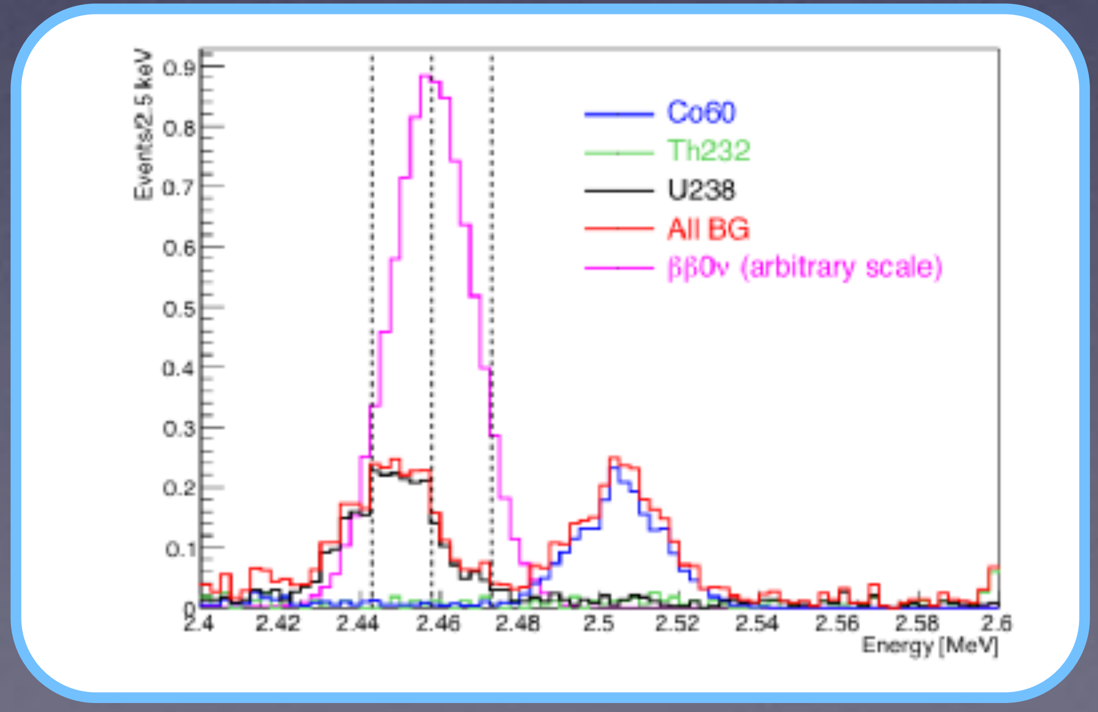
The thickness is chosen in order to have a background rate below 0.1 events per year from the ^{208}Tl contamination of the liquid scintillator vessel.

Shielding volume

20 cm Lead

5 cm Copper

The choice was made to match the shielding used in measurements performed at LSM to have a reliable and less complicated MC.



JINST 13 (2018) no.01, P01009

Released results

- We have published 4 papers and recently submitted a new one on the first results on xenon.

PAPERS

- **"Performance of a spherical high pressure gas TPC for neutrino magnetic moment measurement"** R. Bouet et al. JINST 18 (2023) 03, P03031 " [arXiv:2201.12621] ← **Sensitivity to neutrino magnetic moment**
- **"Simultaneous scintillation light and charge readout of a pure argon filled Spherical Proportional Counter"** R. Bouet et al. Nucl.Instrum.Meth.A 1028 (2022) 166382 "[arXiv:2201.12621] ← **Observation of scintillation light**
- **"R2D2 spherical TPC: first energy resolution results"** R. Bouet et al. JINST 16 (2021) 03, P03012 " [arXiv:2007.02570] ← **First results in ArP2**
- **"Study of a spherical Xenon gas TPC for neutrinoless double beta detection"** A.Meregaglia et al. JINST 13 (2018) no.01, P01009 "[arXiv:1710.04536] ← **First sensitivity studies**

- We have presented the obtained results at various international conferences.

TALKS

- **Journé Matière Sombre France 2017 - Paris - 2017:** "The R2D2 project" A.Meregaglia
- **Double Beta France workshop - Paris - 2018:** "Status of the R2D2 project" A.Meregaglia
- **GET workshop - Bordeaux - 2018:** "The R2D2 project" A.Meregaglia
- **9th Symposium on Large TPCs for low-energy rare event detection - Paris - 2018:** "A new neutrinoless double beta decay experiment: R2D2" A.Meregaglia
- **Low Radioactivity Techniques - Canfranc - 2019:** "A new neutrinoless double beta decay experiment: R2D2" A.Meregaglia
- **TAUP 2019 - Toyama - 2019:** "A new neutrinoless double beta decay experiment: R2D2" C.Jollet (Talk given by G.Gerbier)
- **ICHEP2020 - Prague - 2020:** "First results of the R2D2 project" A.Meregaglia
- **XIX International workshop on Neutrino Telescopes - Venice - 2021:** "Latest results of the R2D2 project" T.Neep
- **TIPP2021 - Virtual - 2021:** "Latest results of the R2D2 project" A.Meregaglia
- **TAUP2021 - Virtual - 2021:** "Status of the R2D2 project A future 0νββ experiment" I.Katsioulas
- **10th LTPC symposium - Paris - 2021:** "R2D2: An R&D program for the research of 2b0n decay with a SPC" P.Lautridou
- **XeSAT2022 - Coimbra - 2022:** "R2D2: a xenon TPC for neutrinoless double beta decay search" A.Meregaglia

POSTERS

- **Neutrino2020 - Chicago - 2020:** "R2D2: a spherical high pressure TPC for the neutrinoless double beta decay search" V.Cecchini
- **Neutrino2022 - Seoul Virtual - 2022:** "R2D2: a xenon TPC for the neutrinoless double beta decay search" P.Charpentier

Technical developments

High Voltage

- High voltages at the level of more than 20 kV might be needed when working at 40 bars (a possible back up option is to work in ionisation mode).
- At the moment we need however a feed through with several features:
  - Good for vacuum and high pressure
  - Good up to 10 kV (possibly more in the future)
  - Good for temperatures up to 100 degrees for detector heating.
  - Low noise
- We tested several commercial options but **each feed through has to be welded by a certified company and the behavior in terms of noise is not guarantee to be the same after and before**.
- Discussion ongoing with AXON company (already collaborating in JUNO) and prototype expected in 2023.

Leakage current

Not shielded (noise)

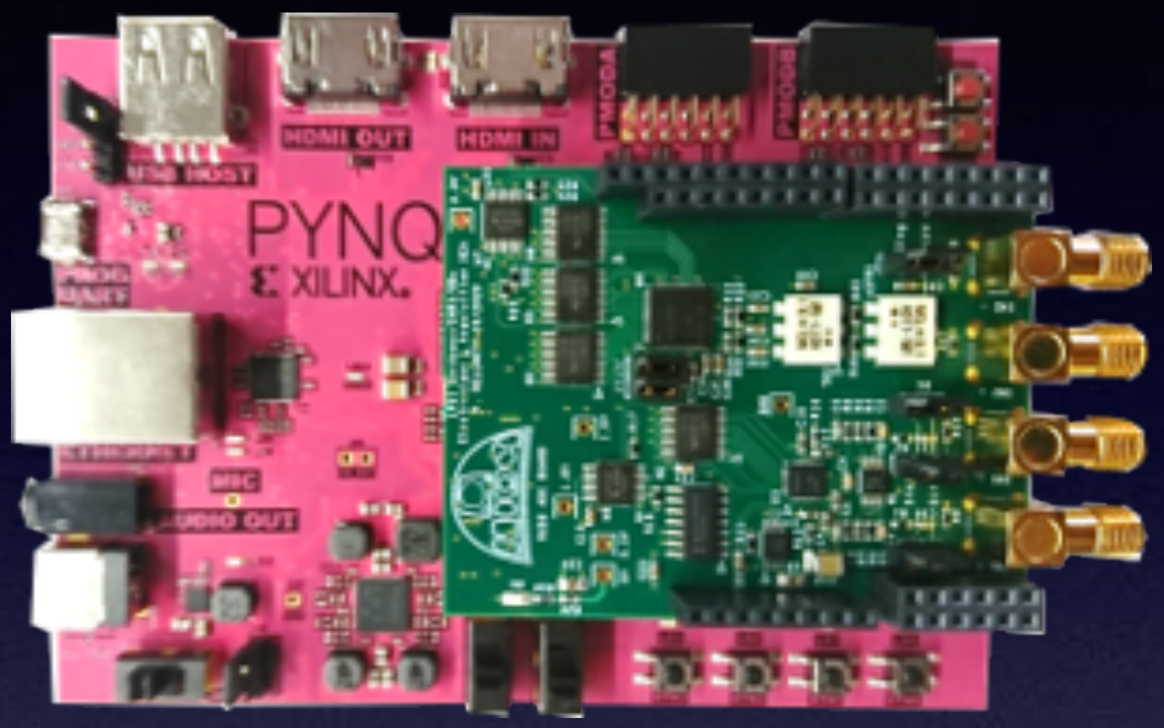
Not certified for HP

Note: This is an issue only for SPC

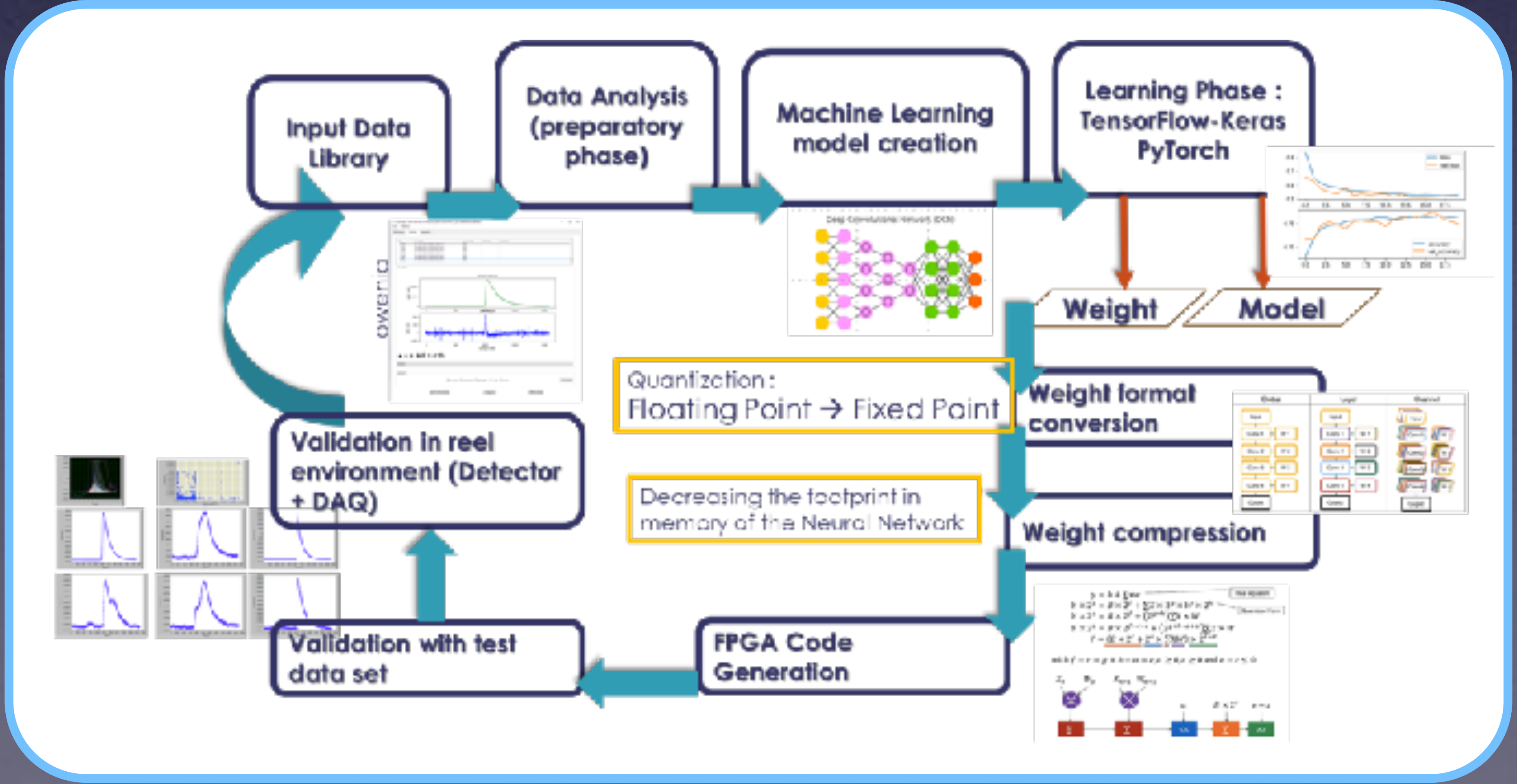
OWEN

Optimal Waveform recognition Electronic Node

- **Hardware developments**:
  - Very low noise front end
  - Optimized waveform digitization with High resolution (18 bits)
  - Embedded processor in integrated shape @ 1Gb/s



- **On-Line Embedded Artificial Intelligence:**
  - Offline classification waveform (classic AI) to possibly reconstruct two-electrons track signature
  - Research of a good neural network architecture to fulfill R2D2 needs
  - Research of a process to integrate AI algorithm in embedded system
  - Digital signal processing to tag events online (with embedded AI)

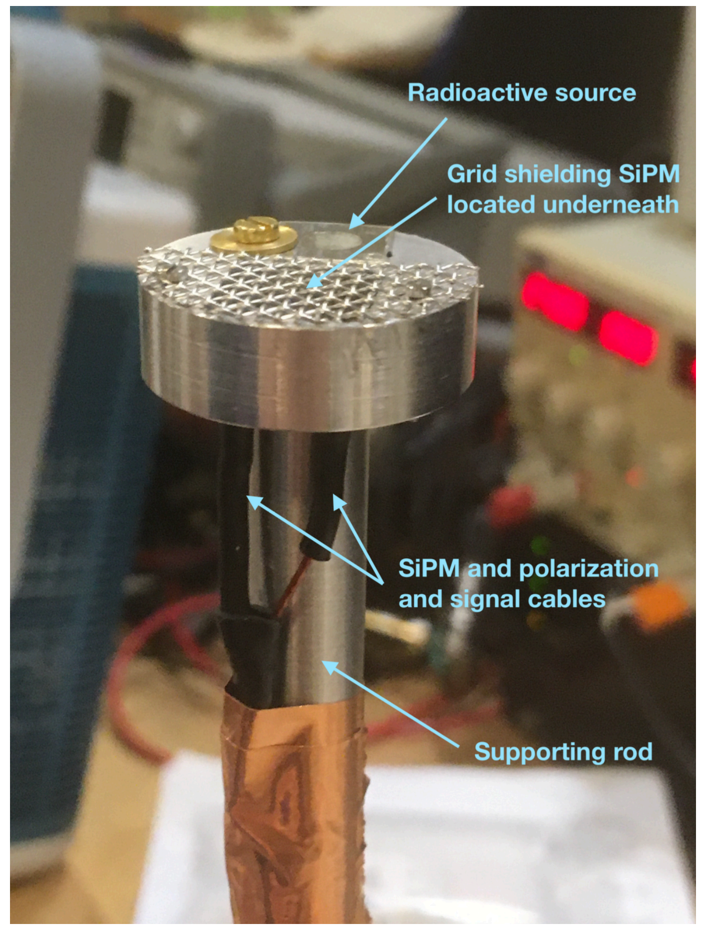


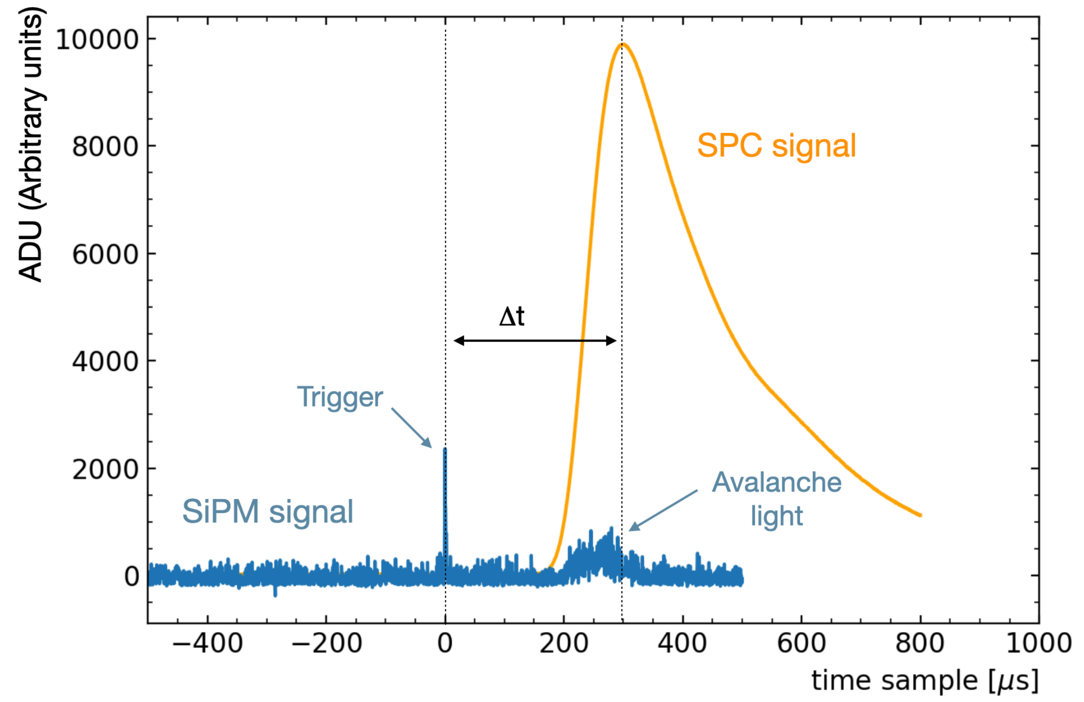
Full system expected to be ready for experiments in 2023

Technical developments

Light readout

- So far spherical TPC (NEWS-G or SEDINE detectors) used the waveform rise time to reconstruct the radial position of the deposited energy with a precision of the order of few cm.
- Having an event trigger (T_0) and knowing the drift velocity a sub-cm precision can be reached which is important for any fiducialization of the volume or to identify multiple energy depositions (electron/gamma rejection).
- We run the detector in pure argon to observe the scintillation light and use it as trigger for the first time in a SPC detector.
- We used a 6x6 mm^2 SiPM from Hamamatsu with a 15% QE at 128 nm.
- We observed two signals on the SiPM: a trigger given by the scintillation light (S1) and a second signal on time with the SPC signal due to the light emitted in the avalanche (S2).
- The time between the S1 and S2 gives the electrons drift time and can be used to validate the Garfield++ simulation. An **excellent agreement is found for alphas emitted at about 19 cm** from the anode as expected.

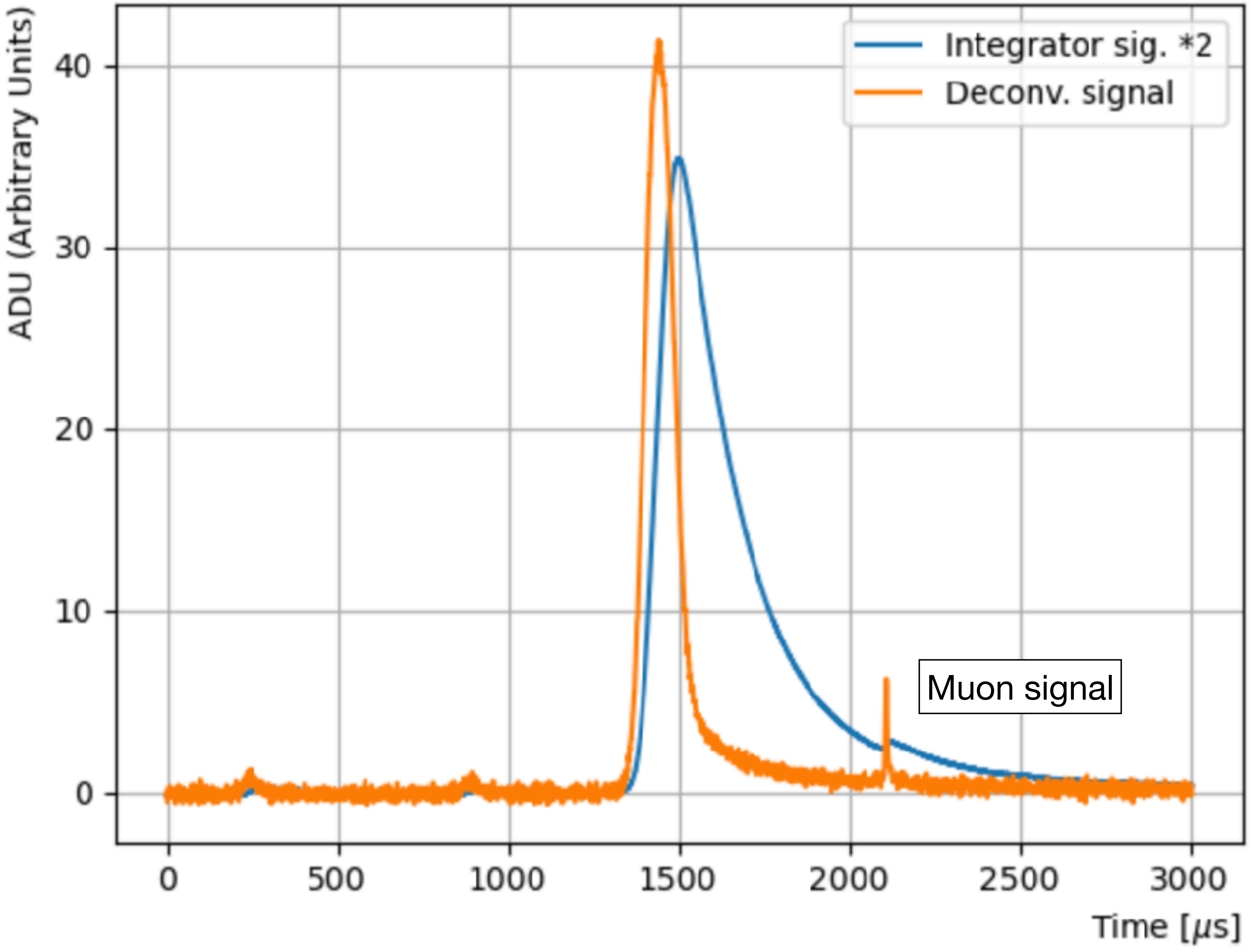




Nucl.Instrum.Meth.A 1028 (2022) 166382

CPC Xenon: Cosmic Background

- Unlike our current SPC, the geometry and orientation of our CPC prototype makes it more sensible to cosmic muons background.
- The energy deposit of a muon in Xe at 1 bar is significantly enough degrade the energy resolution of the α particles.
- This explain the right hand tail of the CPC reconstructed integral distribution.
- Nevertheless the final experiment shall take place in underground facilities, avoiding such inconveniences.



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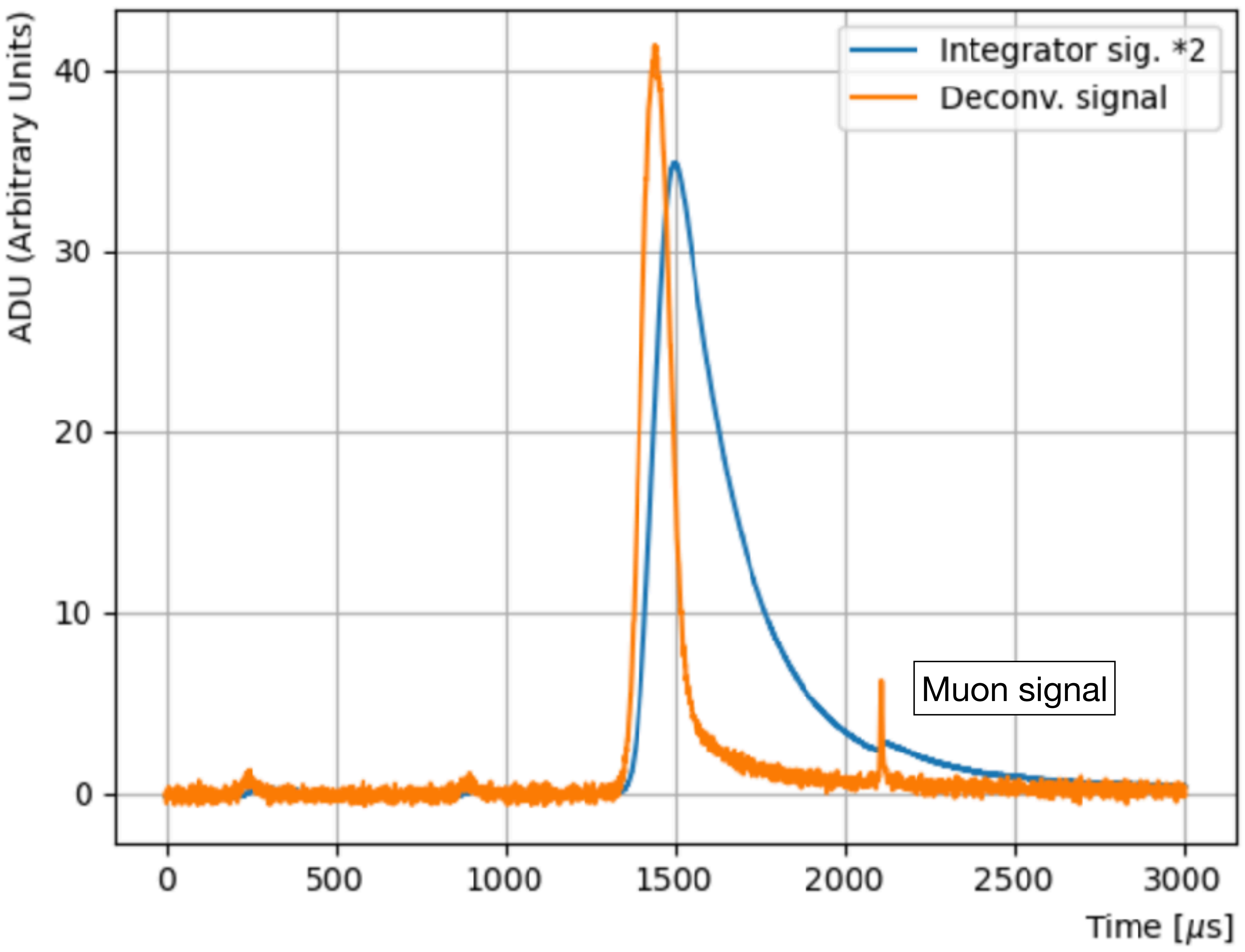

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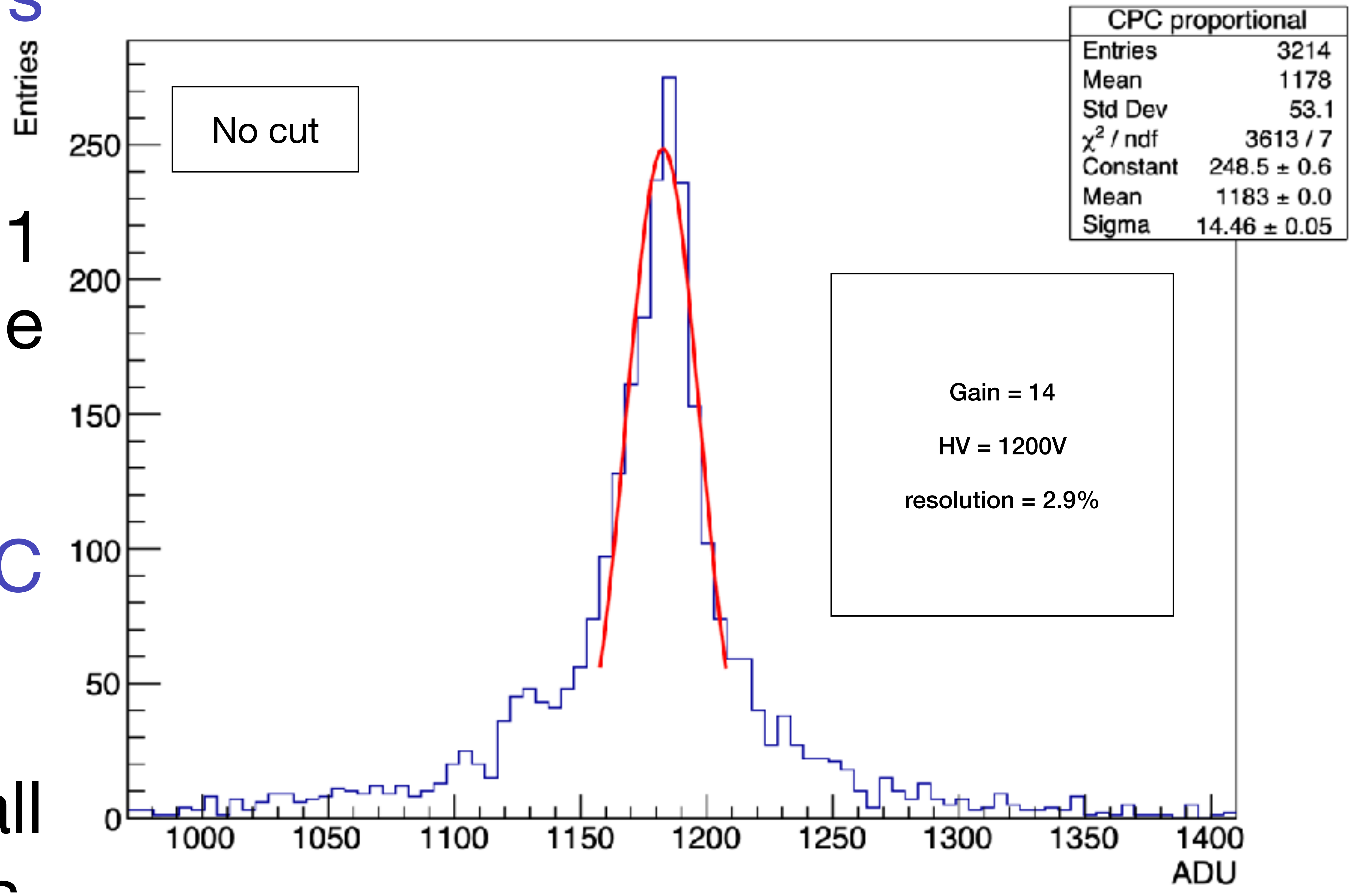
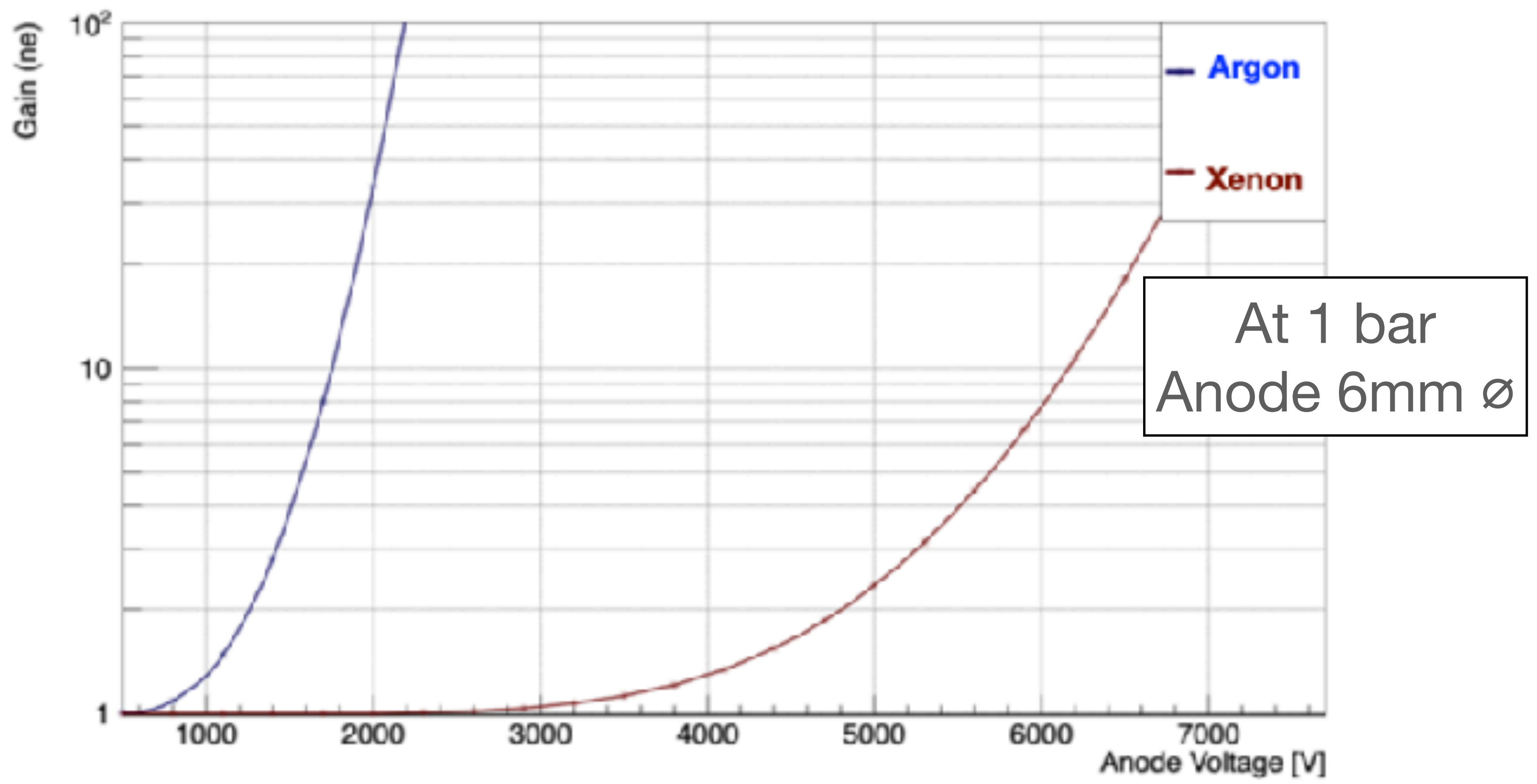
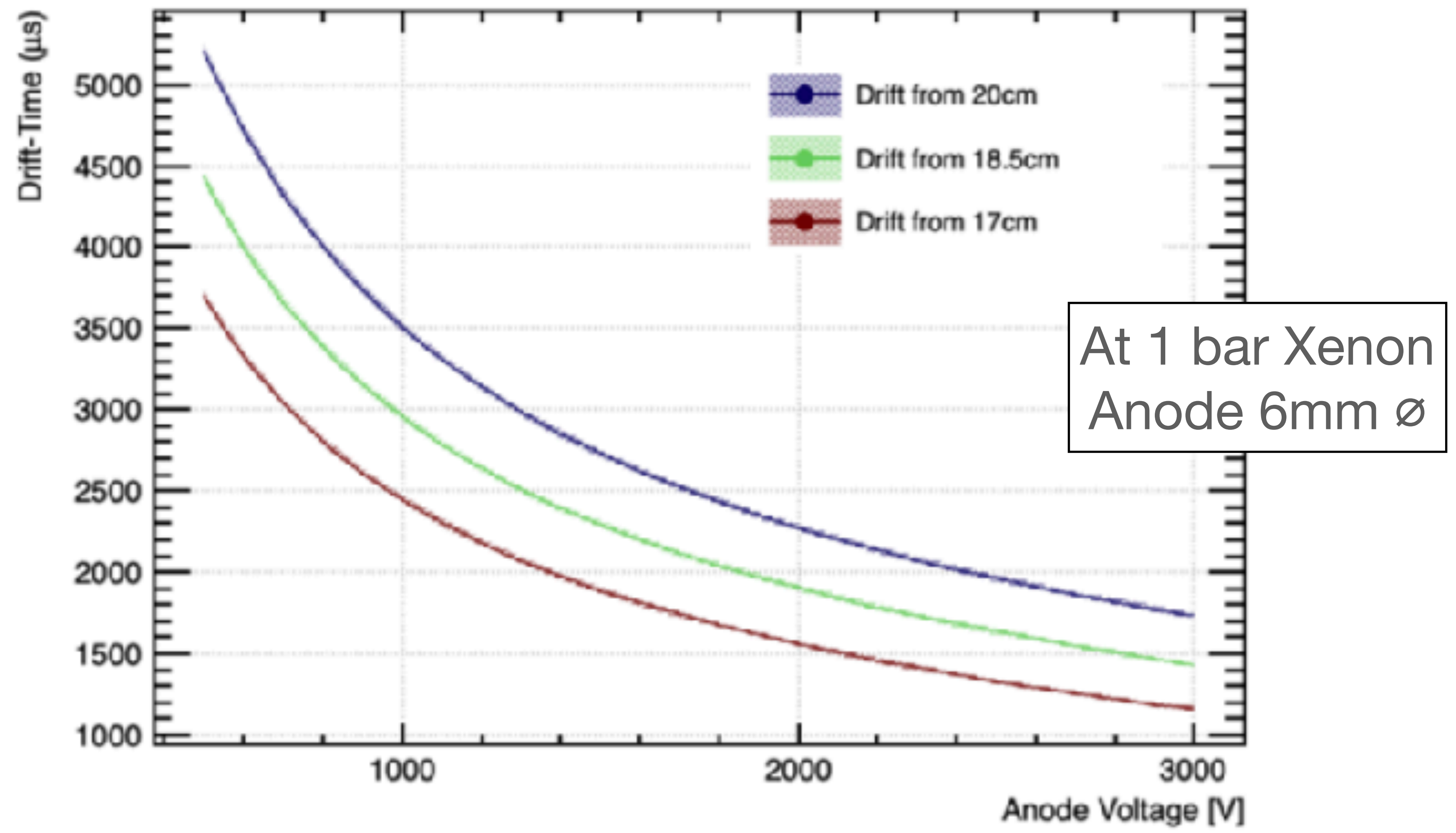


SPC Xenon: Main Difficulties

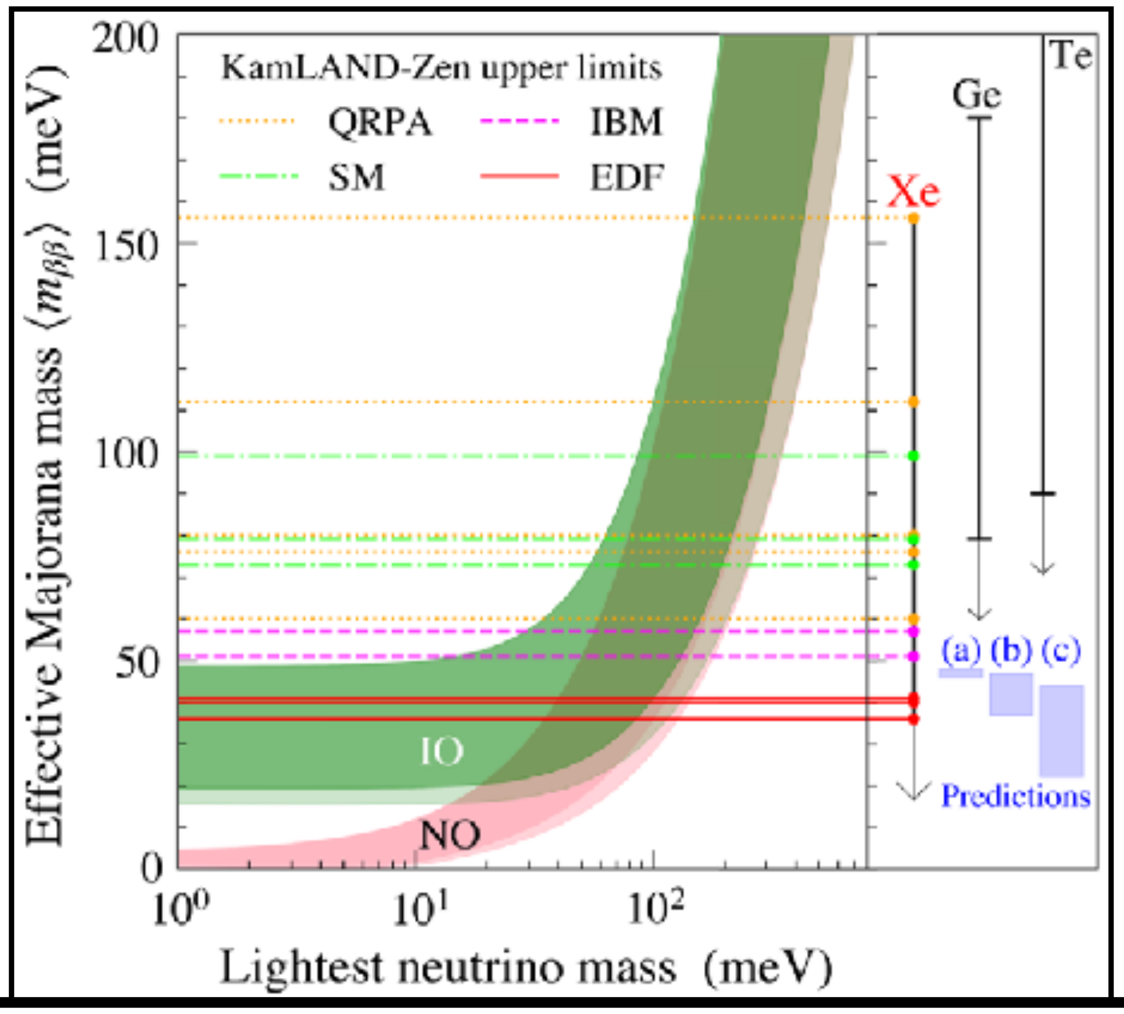
Switching from Ar to Xe implied a lot of challenges to overcome. Aside from the previously discussed technical consideration:

- Xe electrons drift time is one order of magnitude larger than Ar.
- Electronegative impurities become more critical. Purity is paramount.
- A stronger electric field is needed across the whole medium.
  - Higher HV → higher noise.
  - Larger anode → Ionisation mode only.





Références



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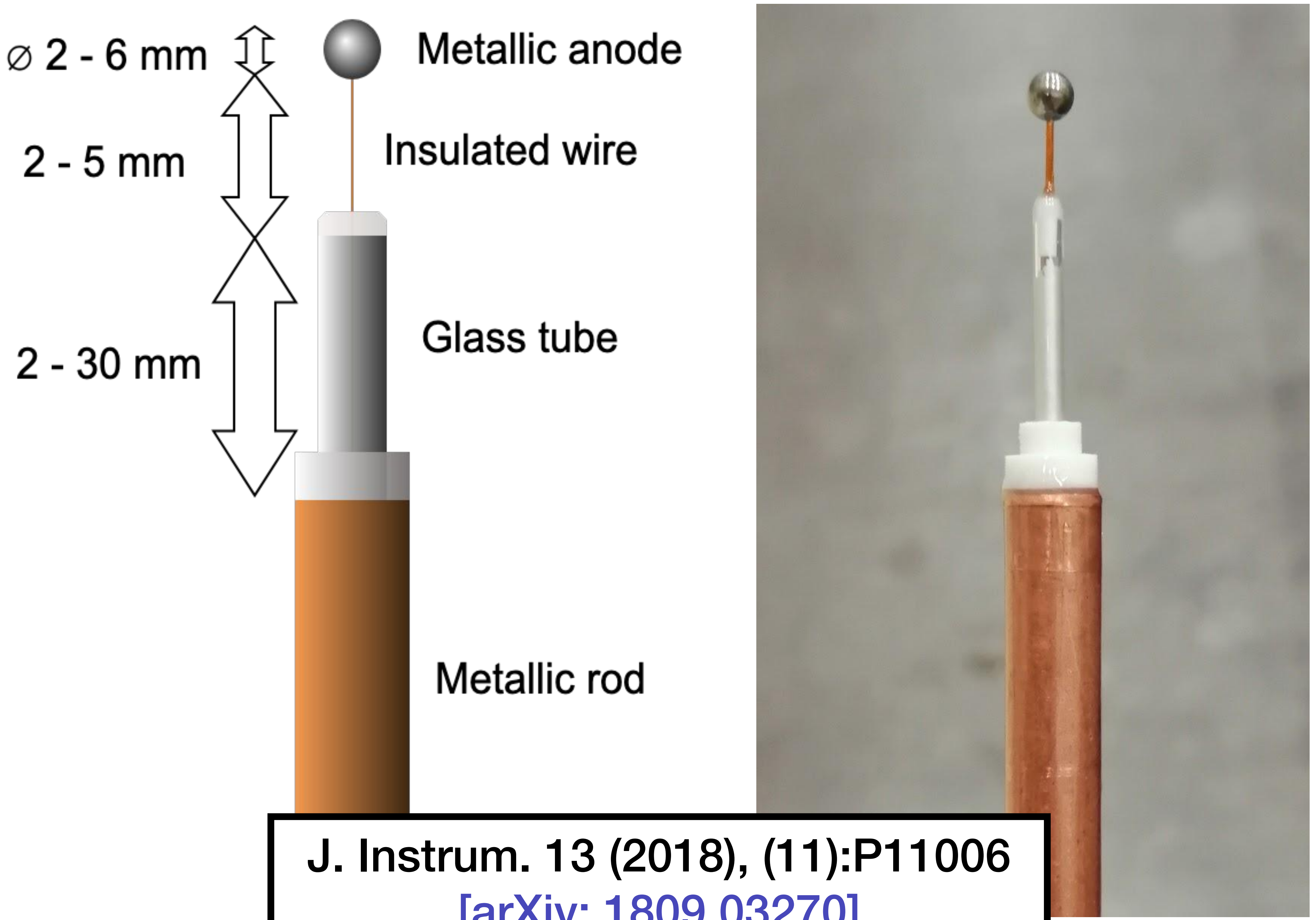

J. Instrum. 13 (2018), (11):P11006
[arXiv: 1809.03270]