The R2D2 Neutrinoless Double-Beta Decay Experiment

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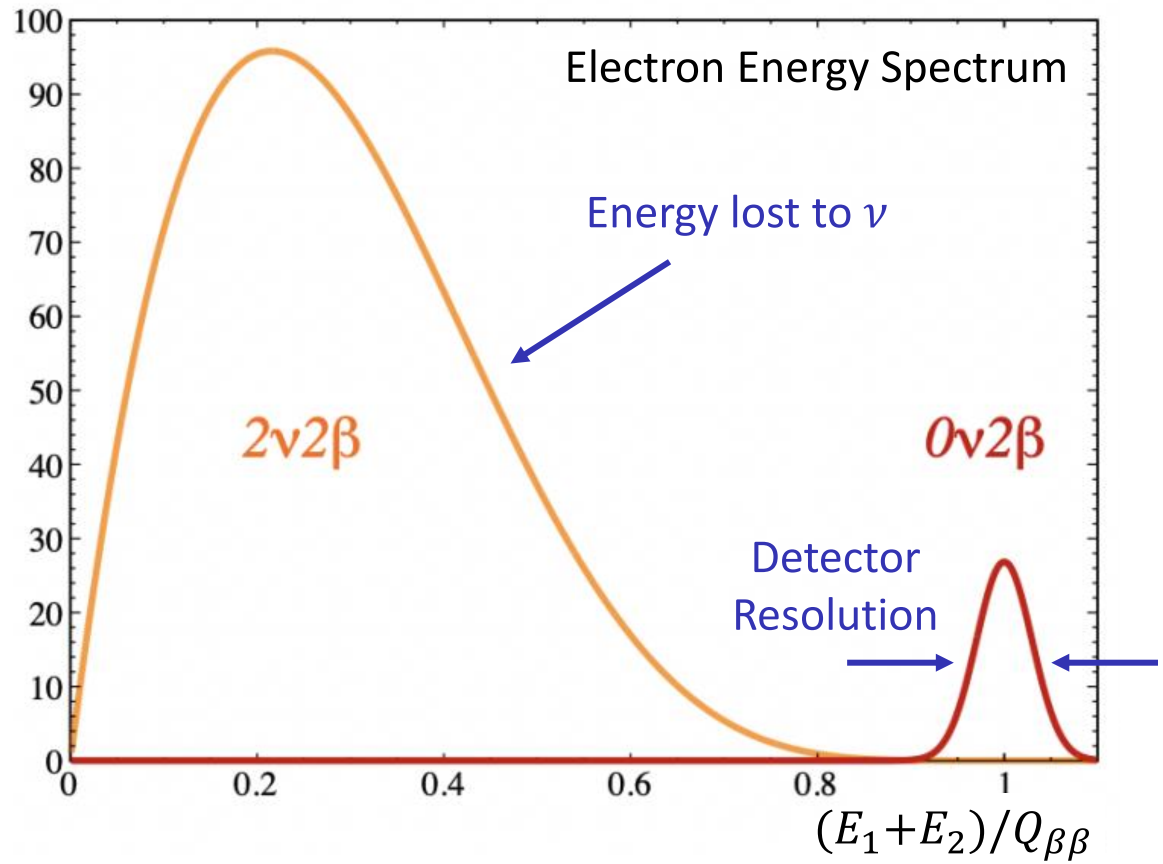
International Conference on High Energy Physics (ICHEP) 2022

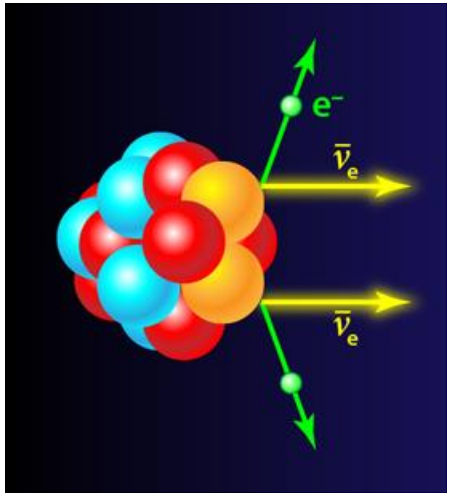
7th July 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements No 845168 (neutronSphere), No 841261 (DarkSphere) and No 101026519 (GaGARin).

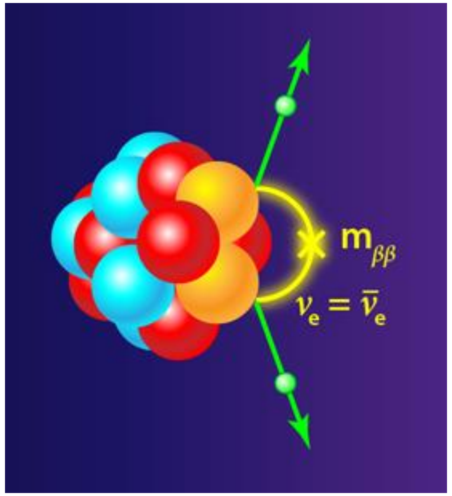
$0\nu\beta\beta$: Neutrinoless Double-Beta Decay

- Are neutrinos their own antiparticle?
  - $0\nu\beta\beta$ is the most sensitive test of the Majorana nature of the neutrino
  - Deeply linked to the ν mass mechanism – can probe question of ν mass hierarchy





$2\nu2\beta$



$0\nu2\beta$

- Requirements for sensitivity:
  - Large mass of $0\nu\beta\beta$-capable isotope
  - Good resolution at low energies
  - Low-to-zero backgrounds

R2D2: Rare Decays with a Radial Detector

- Investigate $0\nu\beta\beta$ in ^{136}Xe isotope using **spherical proportional counters**
  - Collaborative effort between IN2P3 laboratories, CEA Saclay, and the University of Birmingham

Why ^{136}Xe?
- 9% abundance in natural Xe
- Safe and easy to enrich

Gaseous Xe allows pressure variation:
- Event containment in high pressure
- Background rejection in moderate pressure
- Good energy resolution < 0.55 g/cm^3

$$Q_{\beta\beta}(^{136}\mathrm{Xe}) = 2.458\ \mathrm{MeV}$$

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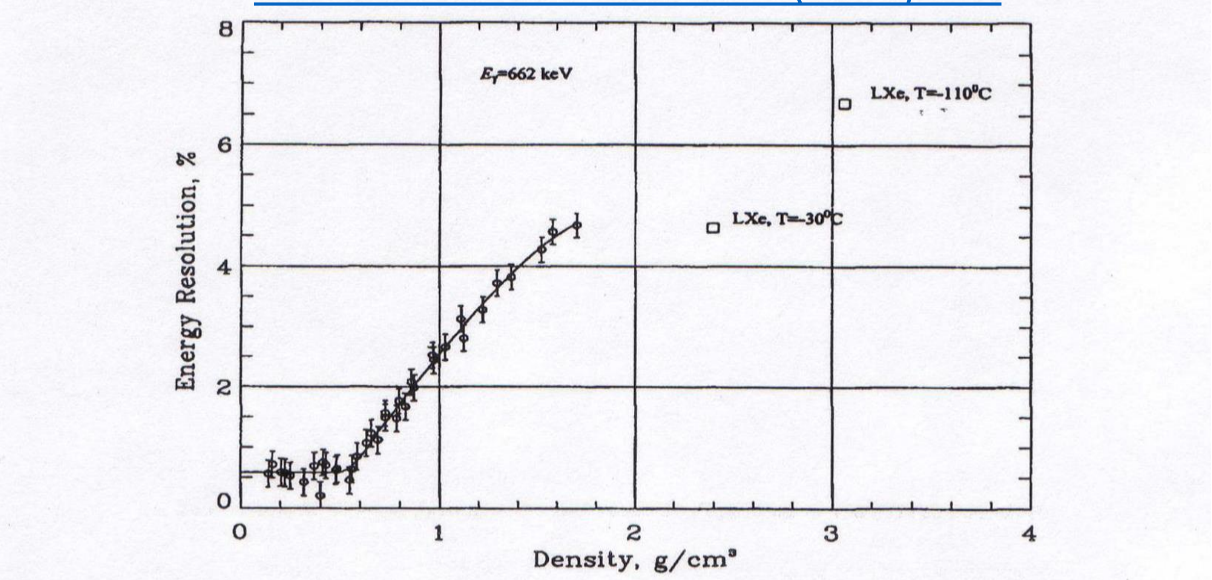
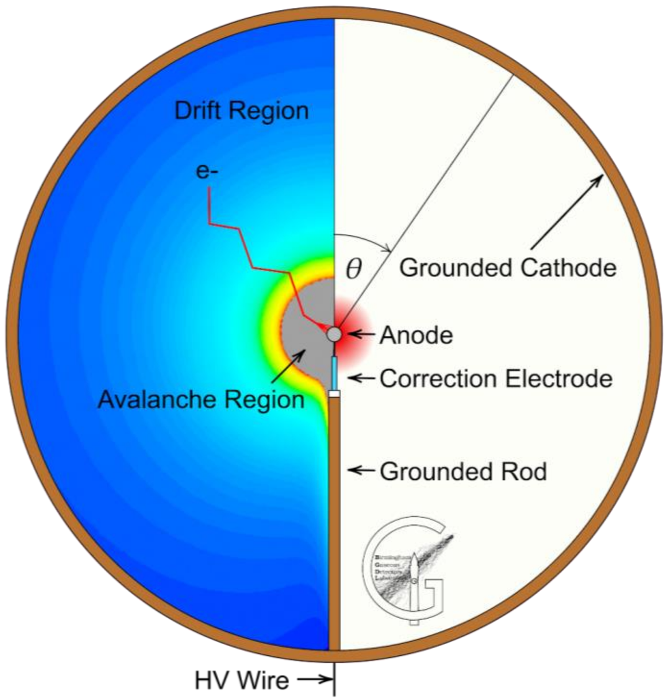


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

Spherical Proportional Counters



- Electric field $\propto 1/r^2$
  - Inherent division into 'drift' and 'amplification' regions

$$\vec{E} = \left(\frac{V_1}{r^2} \cdot \frac{r_c r_a}{r_c - r_a}\right)\hat{r} \approx \left(\frac{V_1}{r^2} r_a\right)\hat{r}$$

r_c = cathode radius
r_a = anode radius

- Capacitance independent of detector size
  - Low electronic noise

$$C = 4\pi\epsilon_0 \cdot \frac{r_c r_a}{r_c - r_a} \approx 4\pi\epsilon_0 r_a \sim 1 \text{ pF}$$

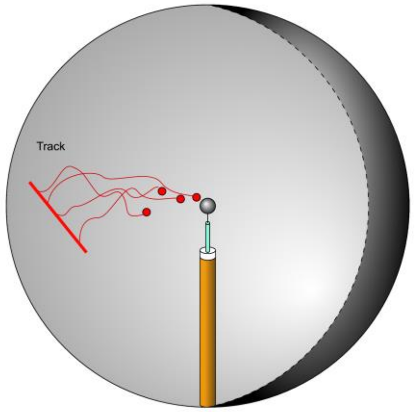
- Maximum volume-to-surface ratio
- High pressure operation
- Simple, robust design with a flexibility in target gas

See talks by K. Nikolopoulos and I. Manthos for other applications!

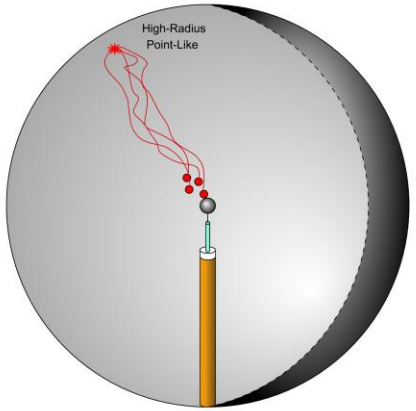
G. Charpak, I. Giomataris; CEA Saclay

Pulse-Shape Discrimination

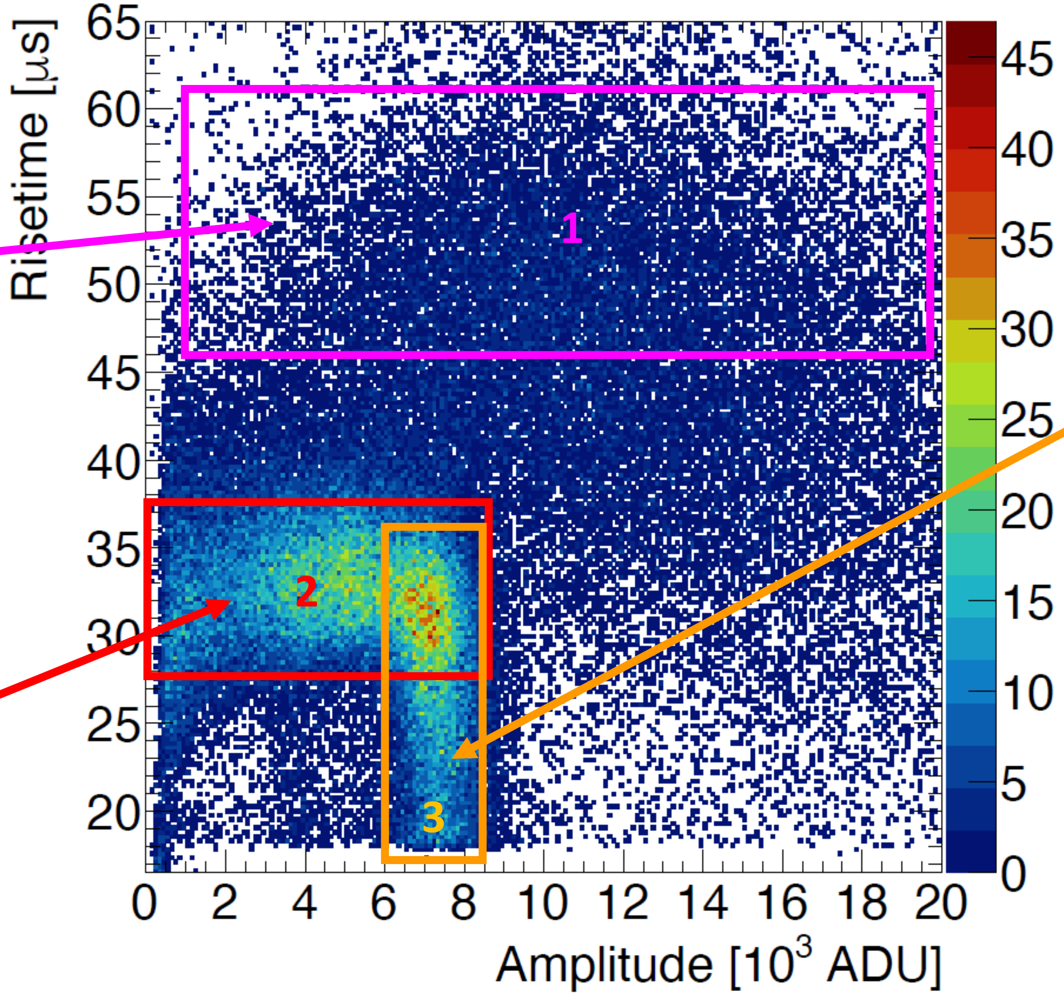
- Determine interaction properties from pulse-shape analysis
  - Detector fiducialisation and background rejection capabilities

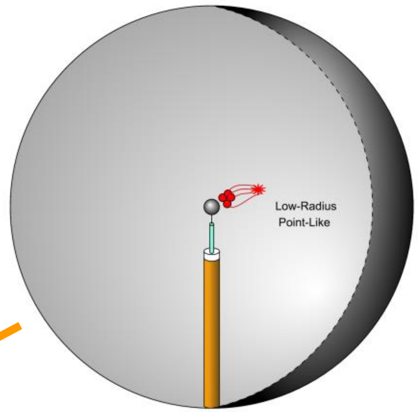


Muon-Like Events



Surface-Like Events





Signal-Like Events

- Ø30 cm detector
- 1.3 bar $He:Ar:CH_4$ $(51.7: 46\%: 2.3\%)$
- ^{55}Fe source inside detector (5.9 keV X-rays)

R2D2: Roadmap

➢ Goal for demonstrator: limit of $T^{1/2}_{0\nu\beta\beta}(^{136}\mathrm{Xe}) > 2.5 \times 10^{25}$ yr with 1 year of data taking

Prototype Stage

Demonstrate 1% resolution:

- Ø40 cm detector
- Up to 10 kg (40 bar) Xe
- No requirements on radiopurity

Current Stage

Demonstrator Stage

Demonstrate zero background:

- Ø74 cm detector
- 50 kg (40 bar) of Xe
- Liquid scintillator veto
- Radiopure

Explore $m_{\beta\beta} < 160 - 330$ meV

Demonstrator requirements:

➢ Cu vessel activity $< 10\ \mu$Bq/kg

➢ Energy resolution of 1% at $Q_{\beta\beta}(^{136}\mathrm{Xe}) = 2.458$ MeV

➢ Interaction position reconstruction

Experiment Stage

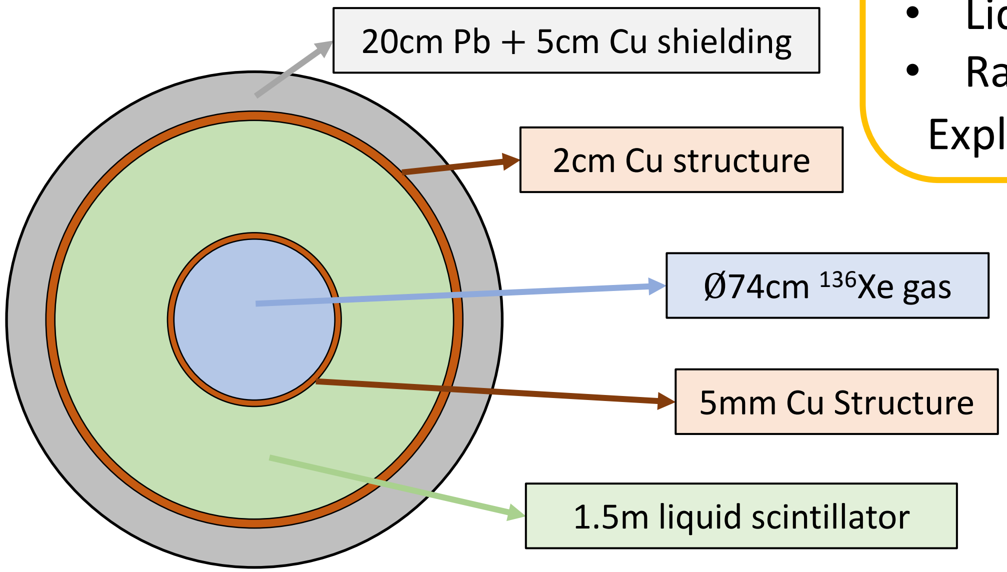
Full scale detector:

- Tonne-scale Xe target (40 bar)

$T^{1/2}_{0\nu\beta\beta}(^{136}\mathrm{Xe}) > 10^{27}$

Explore $m_{\beta\beta} < 10$ meV

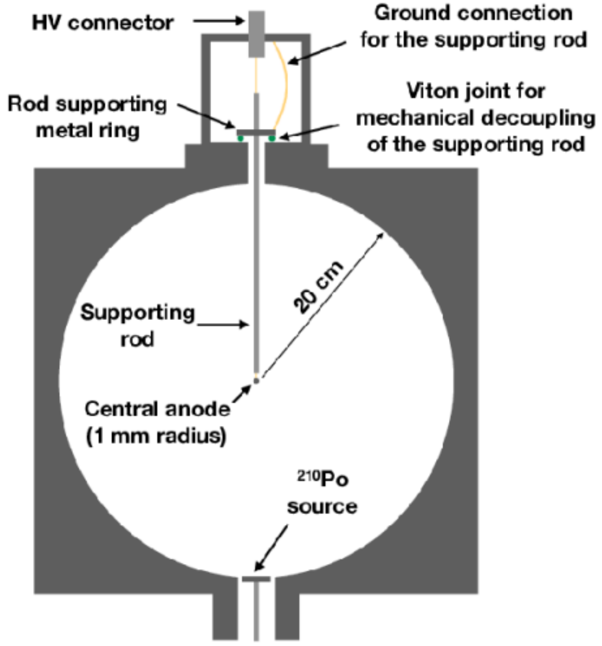
Cover inverted hierarchy



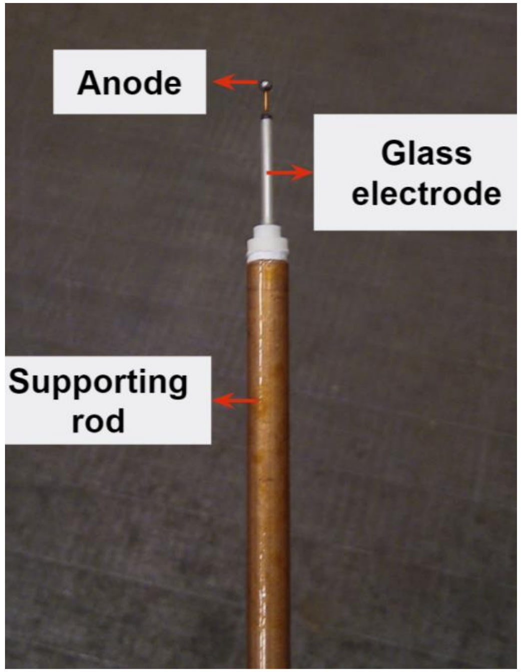
JINST (2018) 13 P01009

Energy Resolution: Overview

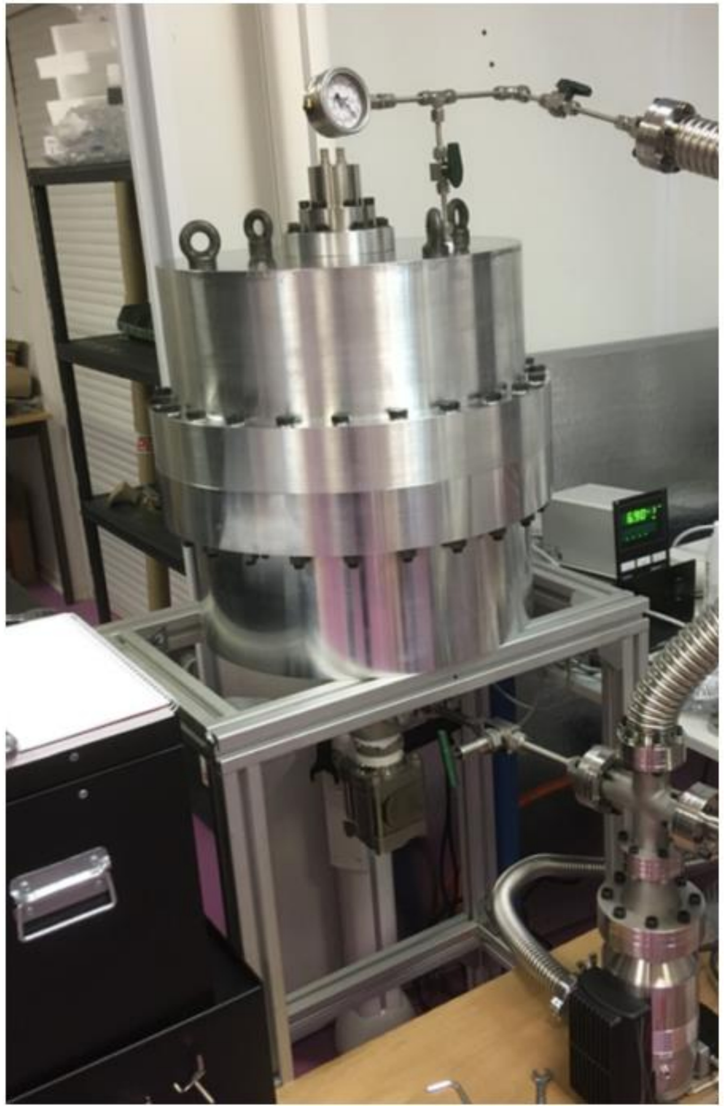
- First goal: demonstrate energy resolution
  - Ø40 cm Al detector in low-noise facility in Bordeaux
  - Custom-made electronics: OWEN project
  - Ar:CH_4 $(98\%: 2\%)$ at 0.2 bar and at 1.1 bar
  - $^{210}\mathrm{Po}$ source → 5.3 MeV α-particles - near $Q_{\beta\beta} = 2.458$ MeV



JINST (2021) 16 P03012



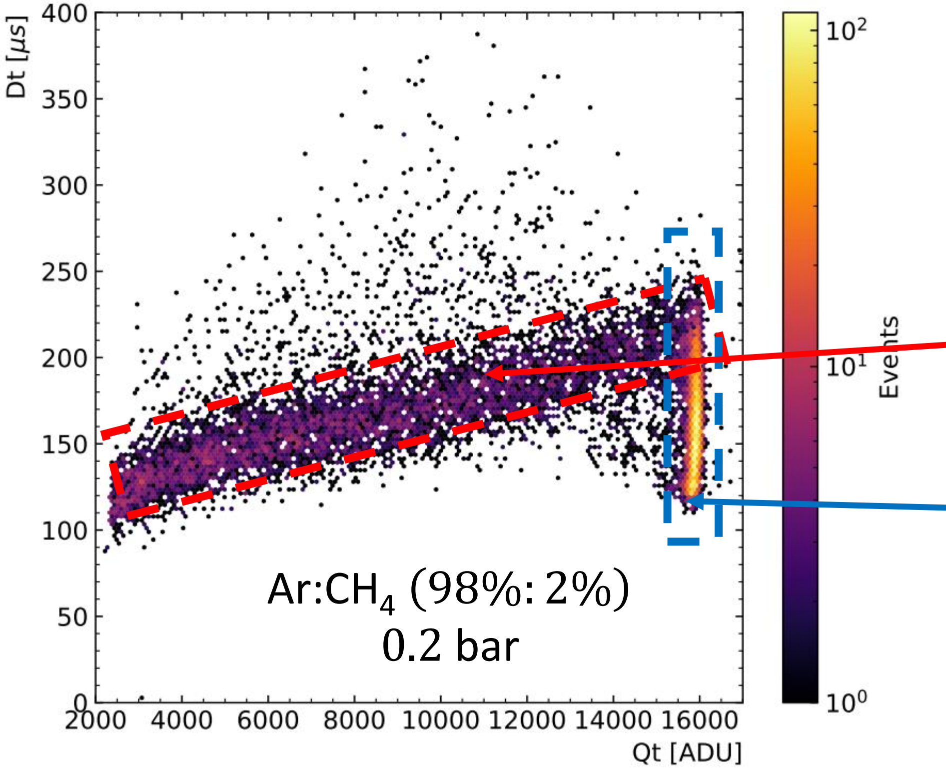
JINST (2018) 13 P11006

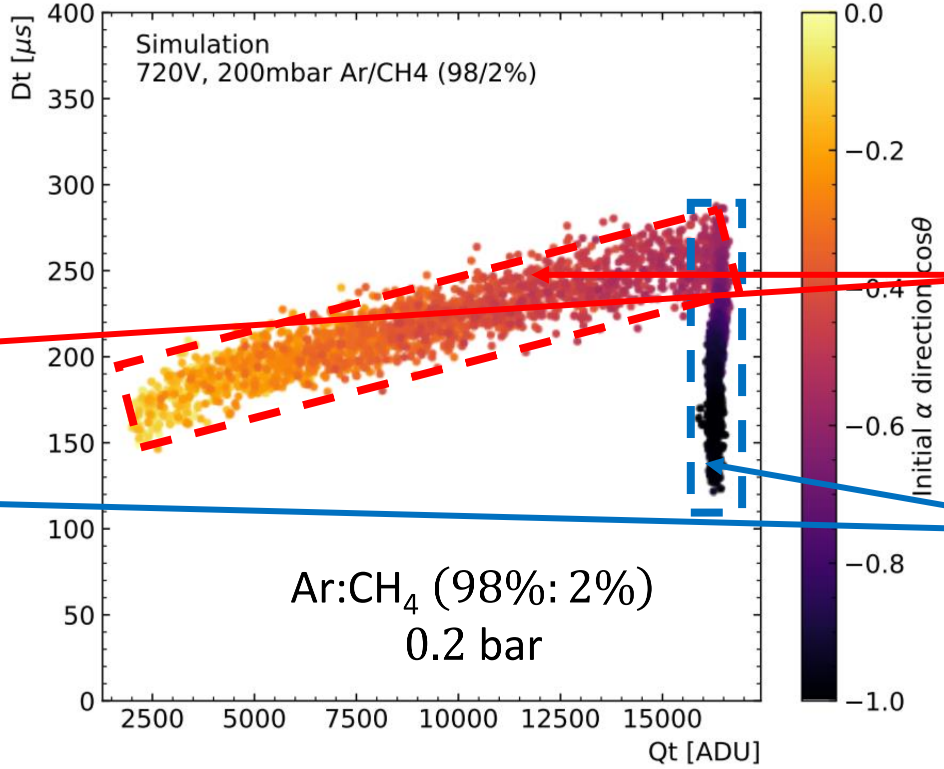


Energy Resolution: Data vs Simulation

- Reconstruct observables such as total charge, Qt, and signal duration, Dt, for the pulses
- Use **dedicated simulation** to understand experimental detector response

JINST (2020) 15 C06013





5.3 MeV α-particle range in 0.2 bar ~ 22 cm

Partial Energy Deposit (Wall effect)

Full signals differ in duration due to diffusion effects

JINST (2021) 16 P03012

Energy Resolution: Results

- 1.1% resolution at 5.3 MeV → 1.6% at 2.458 MeV
  - Resolution $\propto \sqrt{E}$
- Resolution independent of track length
  - Same resolution at 1.1 bar ($\sim 3-4$ cm) and 0.2 bar (~ 22 cm)
- 0.5% contribution from electronics
  - 0.9% resolution without noise
- Will expand study to Xe in the future

	W [eV]	Fano
Ar	~26	~0.16
Xe	~22	0.13-0.17

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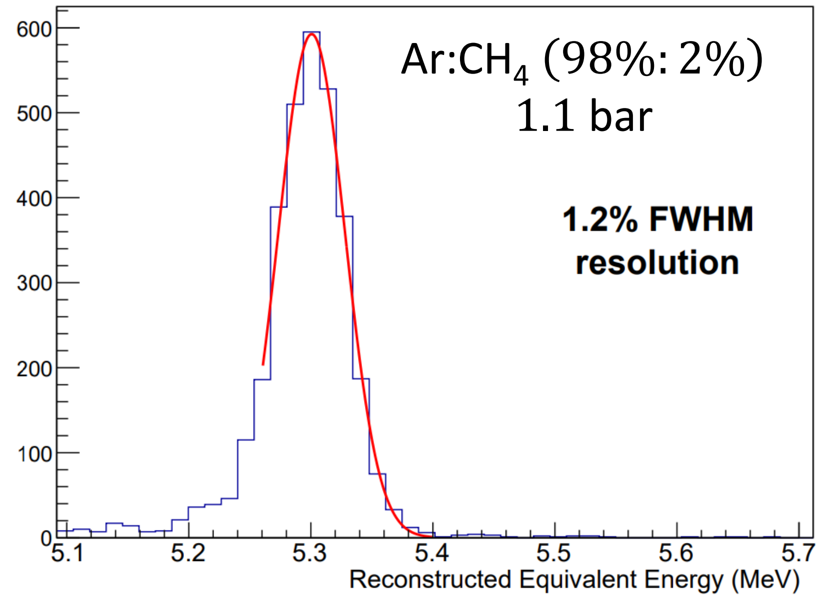
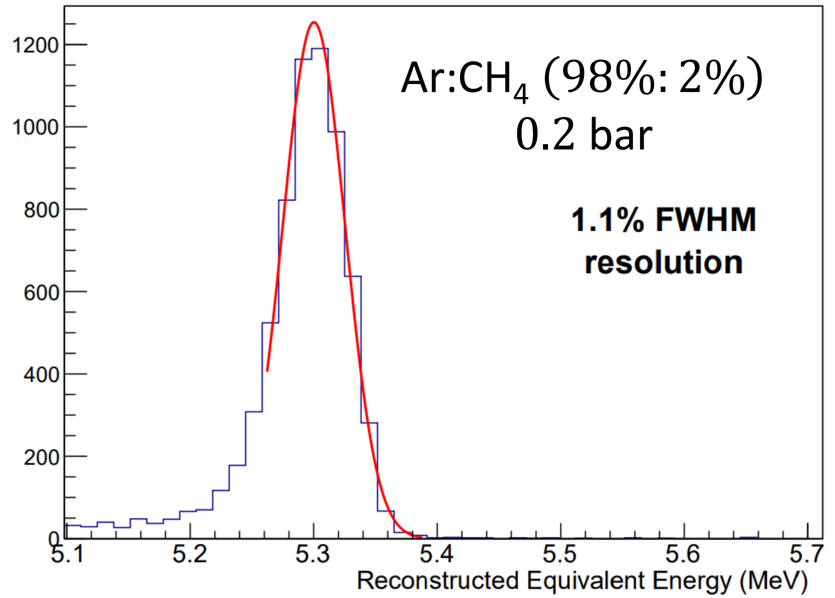
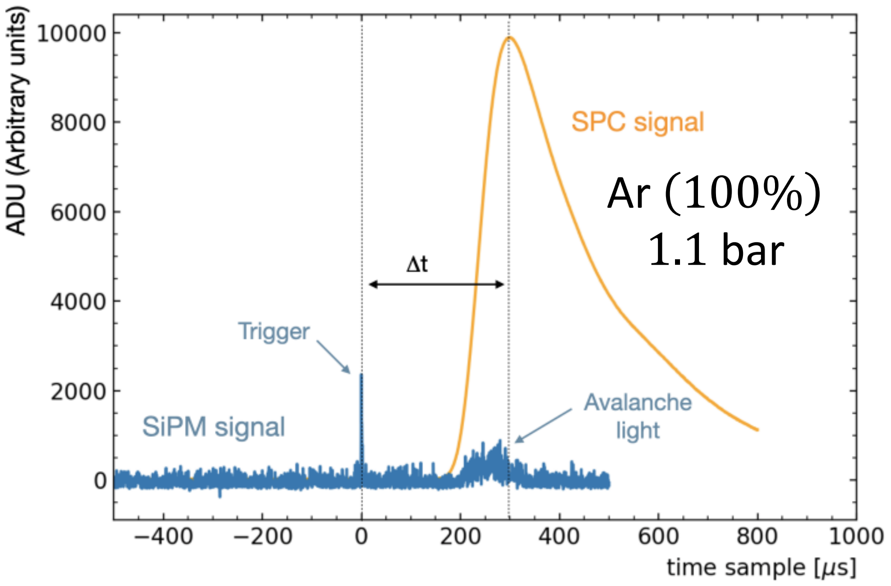
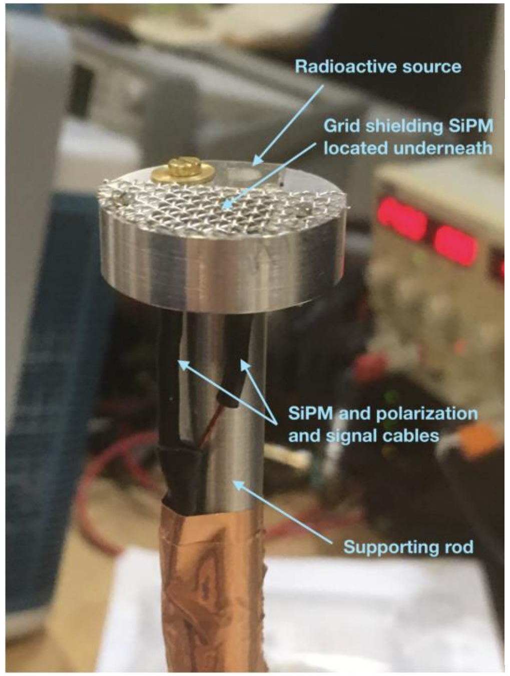


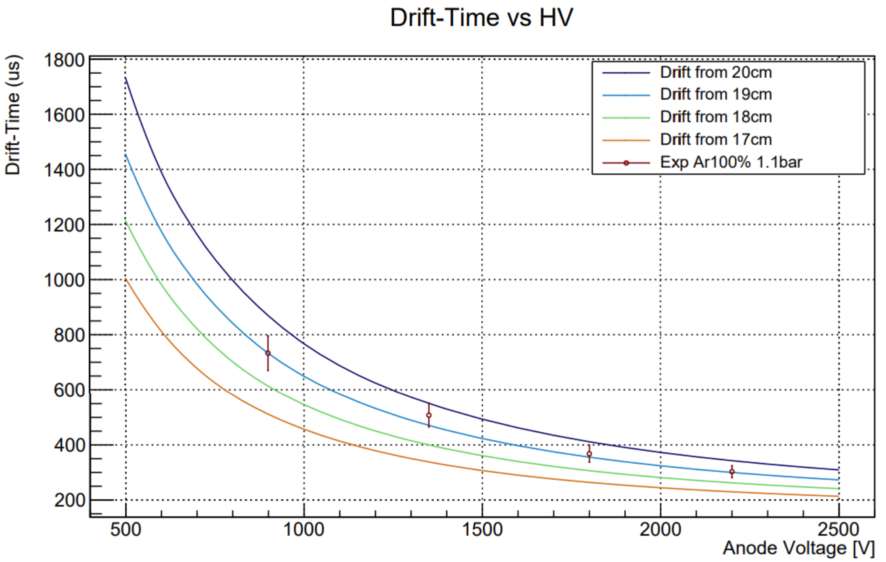


Scintillation Signal

- Operate SPC in pure Argon and use scintillation light as a trigger
  - First measurements performed with a 6×6 mm^2 Hamamatsu SiPM
- Primary interaction produces scintillation
  - Prompt signal, s_1
- Avalanche produces electroluminescence
  - Delayed signal, s_2
- Time difference, Δt, between s_1 and s_2 allows electron drift time to be measured
  - Excellent agreement between data and simulation for α-particles







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

Next-Steps

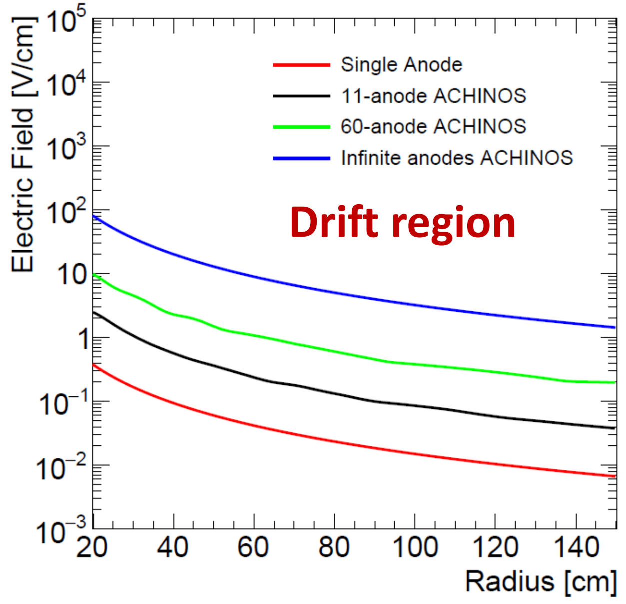
- New, higher pressure detector is commissioned
  - Enables 40 bar gas
- Perform studies with 5 bar of Ar
  - New results soon!
- Xe gas filling
  - Implementing recovery and circulation system
- Implement gas purification system to remove electronegative impurities
- Calibrate with different radioactive sources
  - $^{207}\mathrm{Bi} \rightarrow \beta$-particles
  - Gaseous Rn source→ α-particles
- Optimise sensor technologies

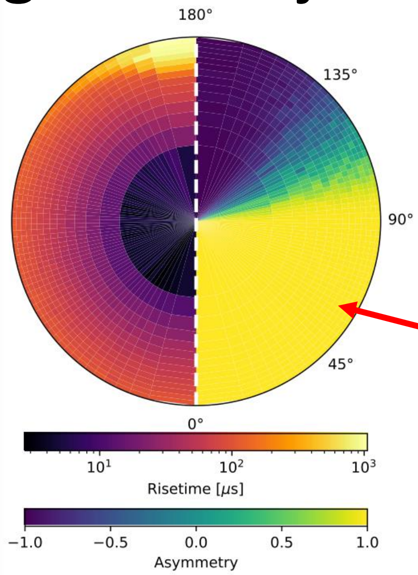
ACHINOS: Multi-Anode Sensor

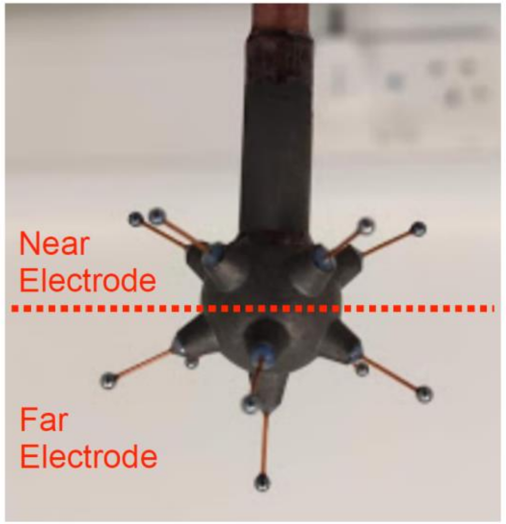
- Multiple anodes equidistant from the centre
  - Decouples drift and amplification regions
    - Larger volume detectors
    - Higher gas pressures
    - Smaller anodes (< Ø1 mm)
- Multi-channel readout allows further detector fiducialisation and background rejection

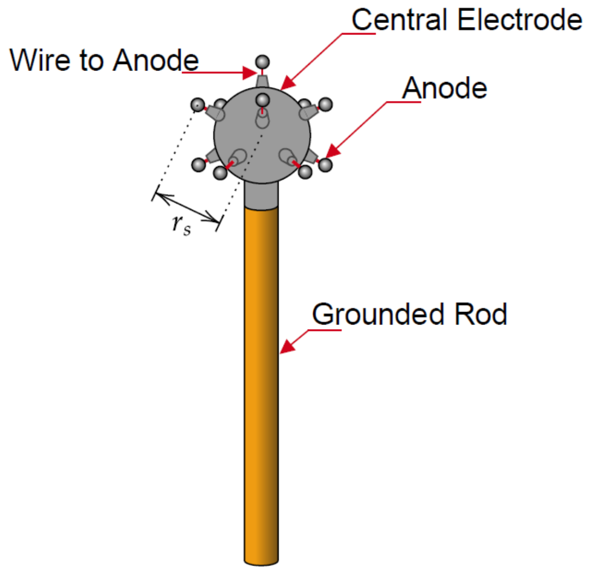
JINST (2020) 15 P11023

JINST (2017) 12 P12031



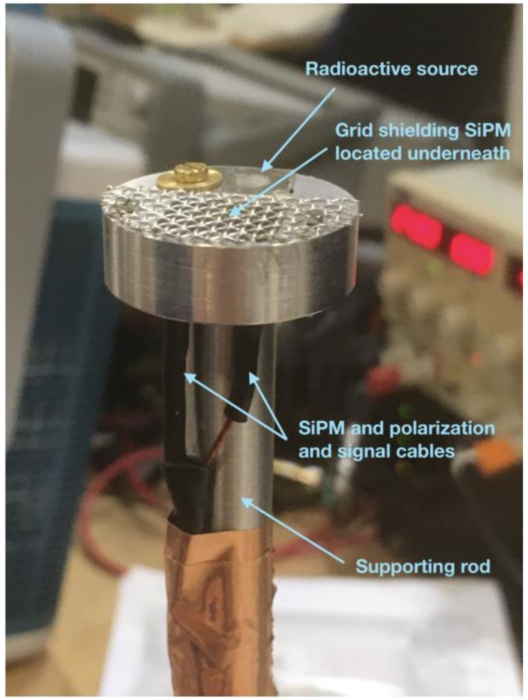


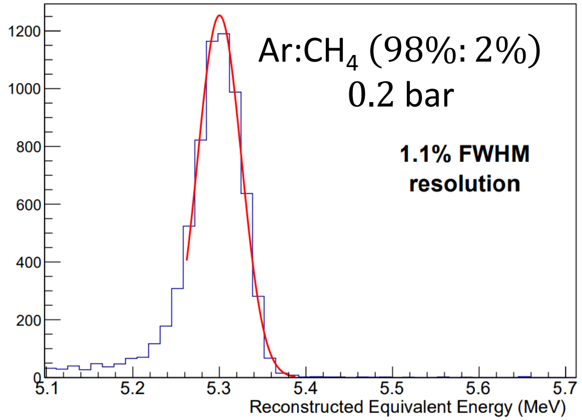


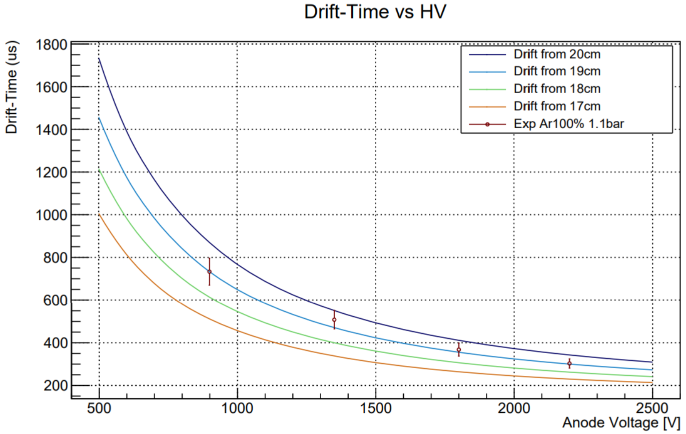


Summary

- R2D2 Collaboration aims to search for $0\nu\beta\beta$ using spherical proportional counters filled with Xe
- First results are promising!
  - 1.1% resolution at 5.3 MeV
    $\rightarrow$ 1.6% energy resolution at $Q_{\beta\beta} = 2.458$ MeV
  - Successful read out of scintillation light
- Next steps are to run with Xe and enable higher pressures
  - Set-up commissioned, data-taking to begin soon
- Closely working with other SPC developments to optimise experiment
  - ACHINOS, radiopure materials, simulation







Additional Slides

$0\nu\beta\beta$ Results

https://arxiv.org/abs/1411.4791

$\beta\beta^-$ decay	experiment	$T^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [eV]
$^{48}_{20}\mathrm{Ca} \to ^{48}_{22}\mathrm{Ti}$	ELEGANT-VI [119]	$> 1.4 \times 10^{22}$	$< 6.6 - 31$
$^{76}_{32}\mathrm{Ge} \to ^{76}_{34}\mathrm{Se}$	Heidelberg-Moscow [224]	$> 1.9 \times 10^{25}$	$< 0.23 - 0.67$
	IGEX [226]	$> 1.6 \times 10^{25}$	$< 0.25 - 0.73$
	GERDA [32]	$> 2.1 \times 10^{25}$	$< 0.22 - 0.64$
$^{82}_{34}\mathrm{Se} \to ^{82}_{36}\mathrm{Kr}$	NEMO-3 [120]	$> 1.0 \times 10^{23}$	$< 1.8 - 4.7$
$^{100}_{42}\mathrm{Mo} \to ^{100}_{44}\mathrm{Ru}$	NEMO-3 [121]	$> 2.1 \times 10^{25}$	$< 0.32 - 0.88$
$^{116}_{48}\mathrm{Cd} \to ^{116}_{50}\mathrm{Sn}$	Solotvina [234]	$> 1.7 \times 10^{23}$	$< 1.5 - 2.5$
$^{128}_{52}\mathrm{Te} \to ^{128}_{54}\mathrm{Xe}$	CUORICINO [235]	$> 1.1 \times 10^{23}$	$< 7.2 - 18$
$^{130}_{52}\mathrm{Te} \to ^{130}_{54}\mathrm{Xe}$	CUORICINO [236]	$> 2.8 \times 10^{24}$	$< 0.32 - 1.2$
$^{136}_{54}\mathrm{Xe} \to ^{136}_{56}\mathrm{Ba}$	EXO [239]	$> 1.1 \times 10^{25}$	$< 0.2 - 0.69$
	KamLAND-Zen [241]	$> 1.9 \times 10^{25}$	$< 0.15 - 0.52$
$^{150}_{60}\mathrm{Nd} \to ^{150}_{62}\mathrm{Sm}$	NEMO-3 [243]	$> 2.1 \times 10^{25}$	$< 2.6 - 10$