Universität Zürich[UZH]

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

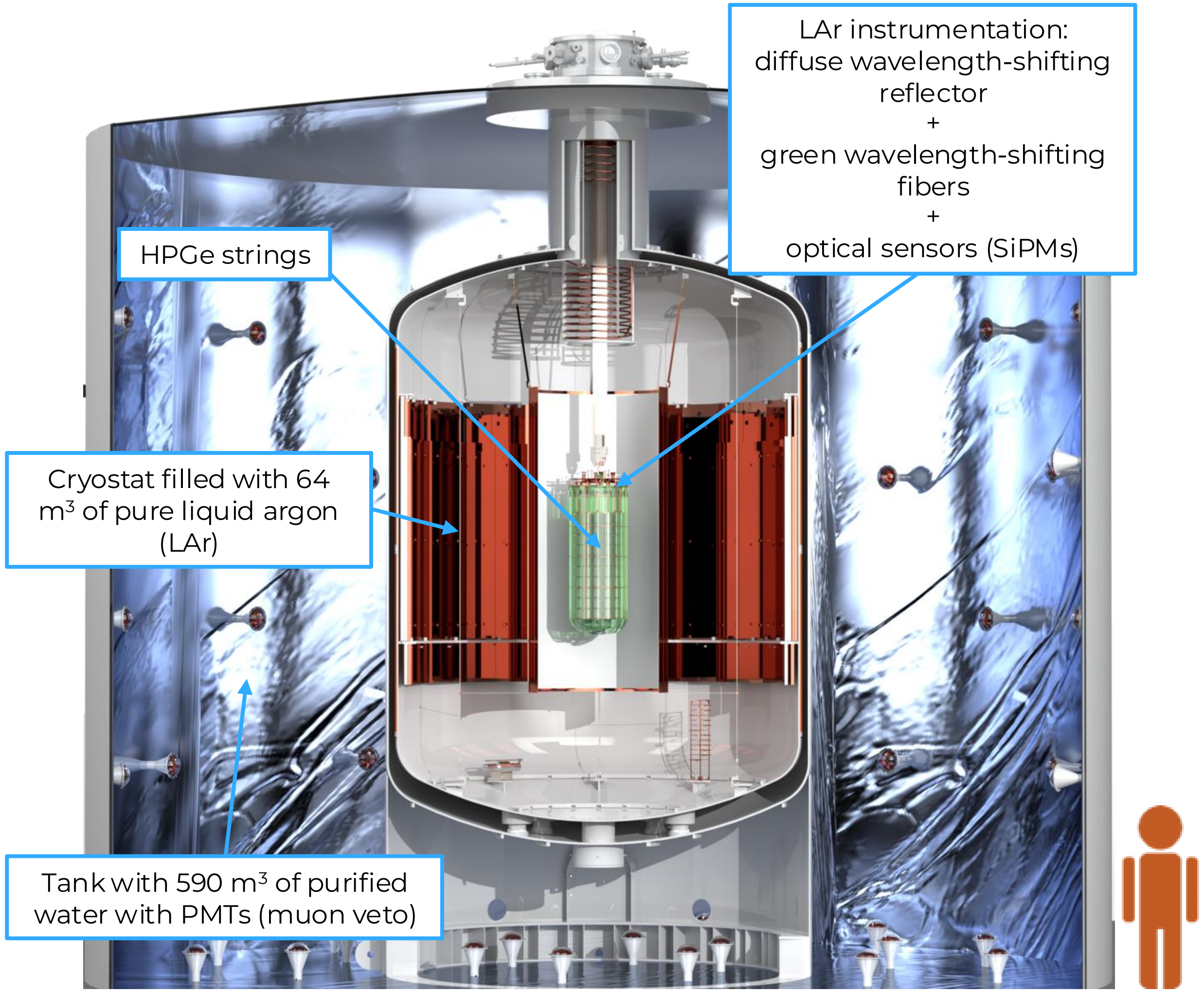
Search for the neutrinoless double electron capture of ^{36}Ar in LEGEND-200

Gloria Senatore - University of Zurich

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS -
47th Course “Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics”, Erice

21 September 2026

LEGEND: searching for $0\nu\beta\beta$



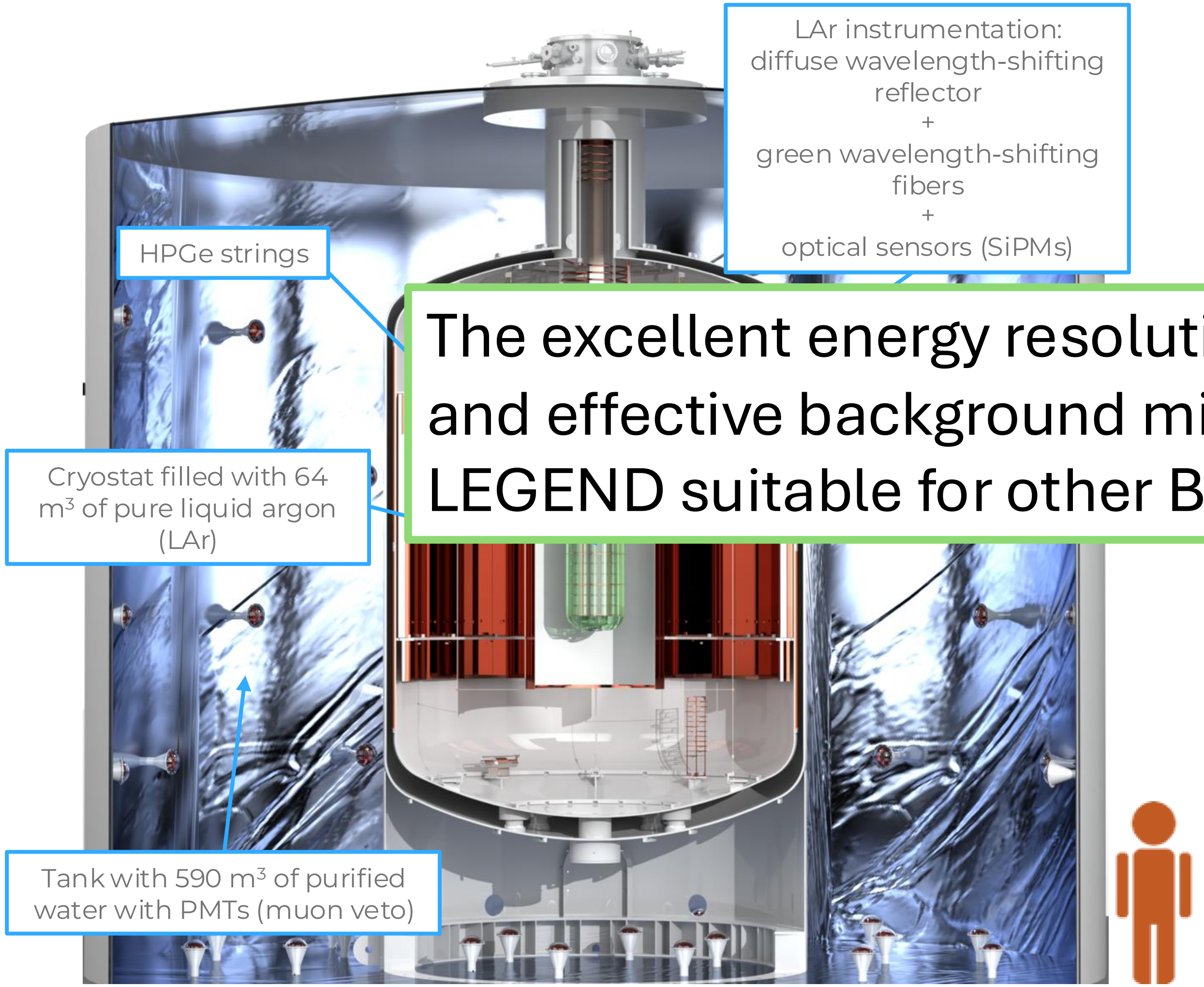
LEGEND-200. Location: Gran Sasso National Laboratory

- **Goal:** Probing the Majorana nature of neutrinos by observing the neutrinoless double beta decay in high purity germanium crystals enriched in ^{76}Ge.
- Reaction searched for:

$$\mathbf{^{76}Ge} \rightarrow \mathbf{^{76}Se} + \mathbf{2}\boldsymbol{e^{-}}$$

- Two phases:
  - LEGEND-200 with discovery sensitivity aim $T_{1/2}^{0\nu} > 10^{27}$ yr
  - LEGEND-1000 with discovery sensitivity aim $T_{1/2}^{0\nu} > 10^{28}$ yr
- Very rare event! Experimental key features:
  - High active mass
  - Excellent detector energy resolution (FWHM ~0.1% @ $Q_{\beta\beta}$)
  - Very low background environment ($2 \cdot 10^{-4}$ counts/(kg keV yr) for LEGEND-200; 20 times less for LEGEND-1000)
  - Active background reduction techniques: liquid argon veto & pulse shape discrimination.
- Results of LEGEND-200 first science run: [LEGEND Collaboration, *Phys. Rev. Lett.* **136**, 031801 (2026)].

LEGEND: searching for $0\nu\beta\beta$ → but not only!



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$$^{76}\mathbf{Ge} \rightarrow {}^{76}\mathbf{Se} + 2e^{-}$$

The excellent energy resolution, ultra-pure environment and effective background mitigation techniques make LEGEND suitable for other BSM searches!

n $T_{1/2}^{0\nu}$> 10^{27} yr

im $T_{1/2}^{0\nu}$ > 10^{28} yr

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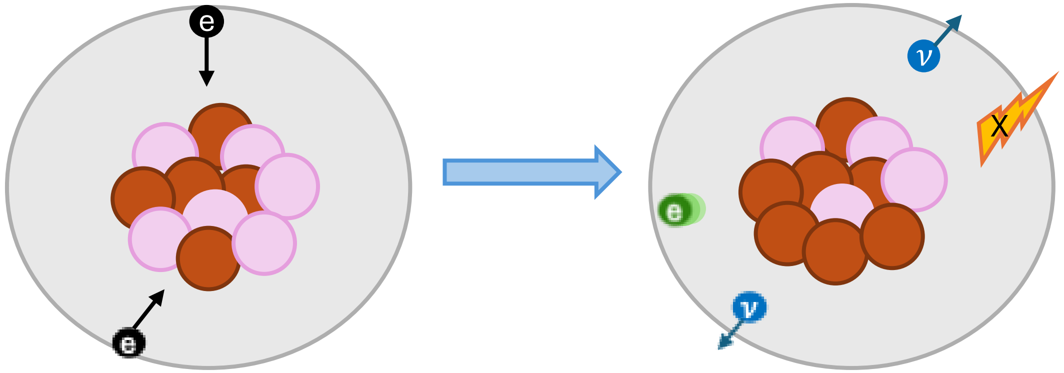
2νDEC



Electron capture

Neutrino emission & atomic relaxation

- Standard Model process.
- Much harder to observe than $2\nu\beta\beta$ because smaller phase space and low-energy observable signature.
- First direct observation in 2018 by XENON1T with ^{124}Xe [XENON Collaboration, *Nature* **568**, 532–535 (2019)].
- So far not observed in ^{36}Ar (small X-rays energy).

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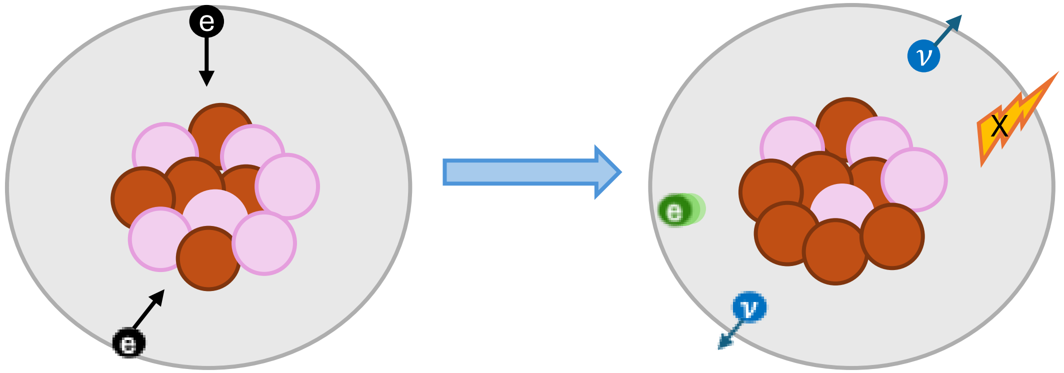

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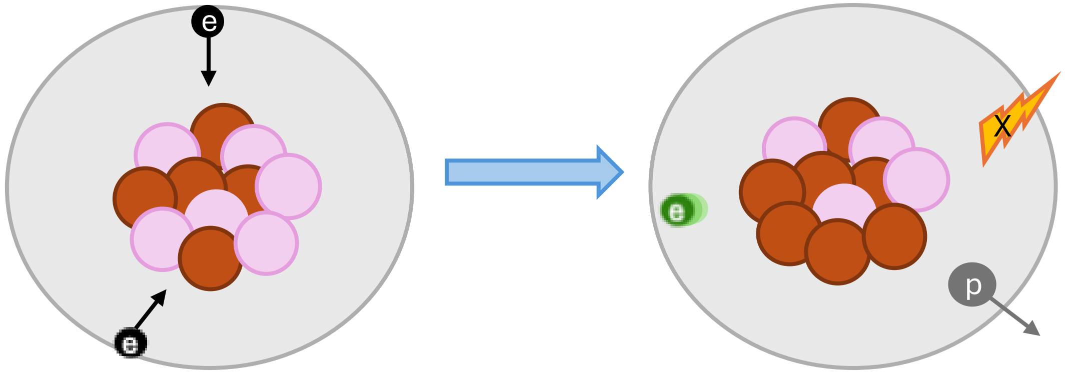
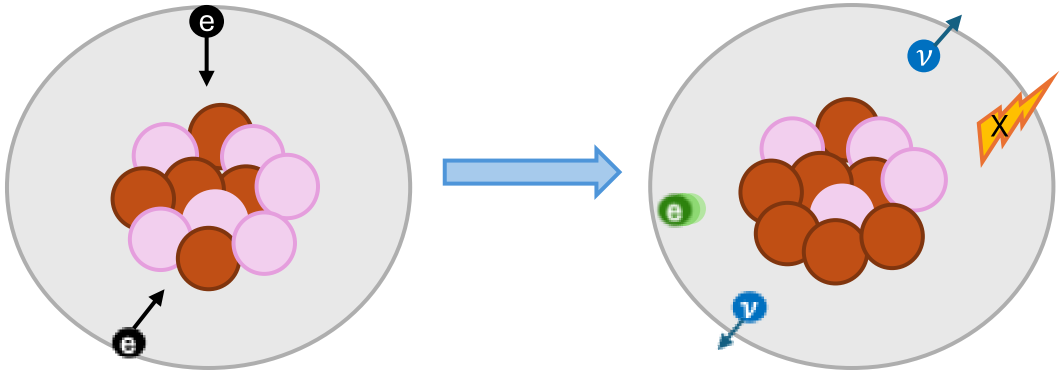


Electron capture

~~Neutrino emission~~
Atomic relaxation & additional particle emission

- Beyond Standard Model process.
- Observation would imply lepton-number violation and the Majorana nature of neutrinos.

2νDEC



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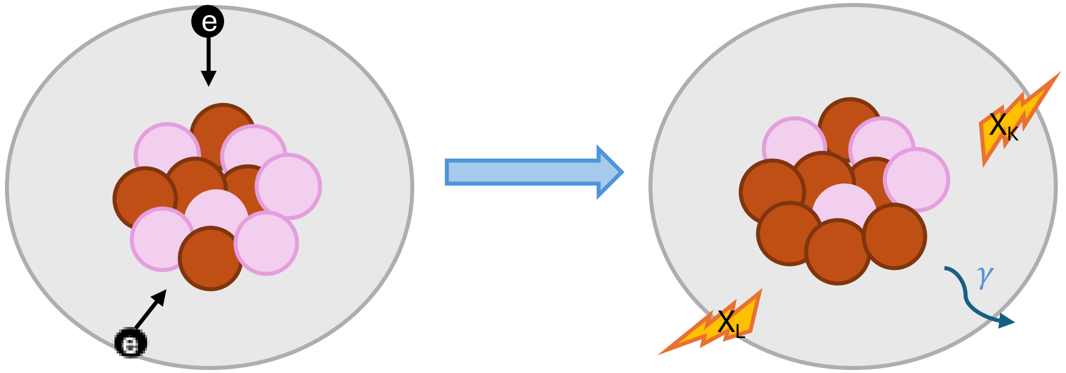
0νDEC ^{36}Ar (radiative mode)



Electron capture

~~Neutrino emission~~
Atomic relaxation & gamma emission

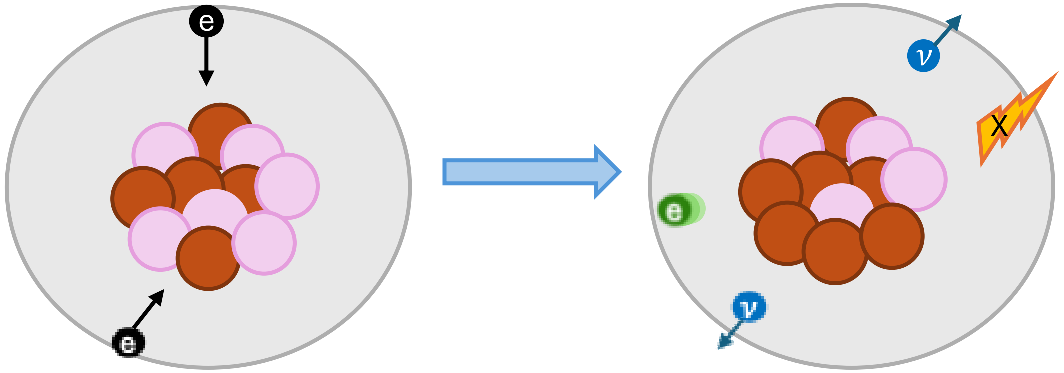
- Beyond Standard Model process.
- Observation would imply lepton-number violation and the Majorana nature of neutrinos.
- We consider the process (^{36}Ar natural abundance 0.33%):

$$^{36}\mathrm{Ar} + 2\mathrm{e}^- \longrightarrow {}^{36}\mathrm{S} + \gamma + \mathrm{X_K} + \mathrm{X_L}$$

$\boldsymbol{E_\gamma}$ = (**429.88** ± 0.19) **keV**, E_K = 2.47 keV, E_L = 0.23 keV

- GERDA found no signal and 90% C.L. half-life lower limit $1.5 \cdot 10^{22}$ yr [GERDA Collaboration, *Eur. Phys. J. C* **84**, 34 (2024)].

2νDEC



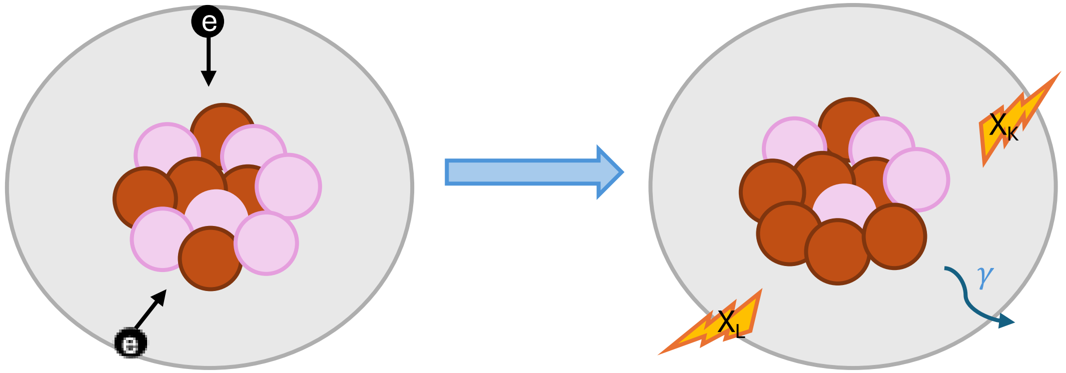
Electron capture

Neutrino emission & atomic relaxation

- Standard Model process.
- Much harder to observe than $2\nu\beta\beta$ because smaller

Compared to GERDA search, with LEGEND we benefit from:
Higher total HPGes mass (~35% more) → higher detection efficiency of 430 keV ɣ (we found ~25% more before PSD cut);
Validated PSD cuts in simulations → application of PSD cuts to real and simulated data enabled (see slide 7).

0νDEC ^{36}Ar (radiative mode)



Electron capture

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Search steps

① Detector grouping

② Physics data selection

③ γ detection efficiency estimation

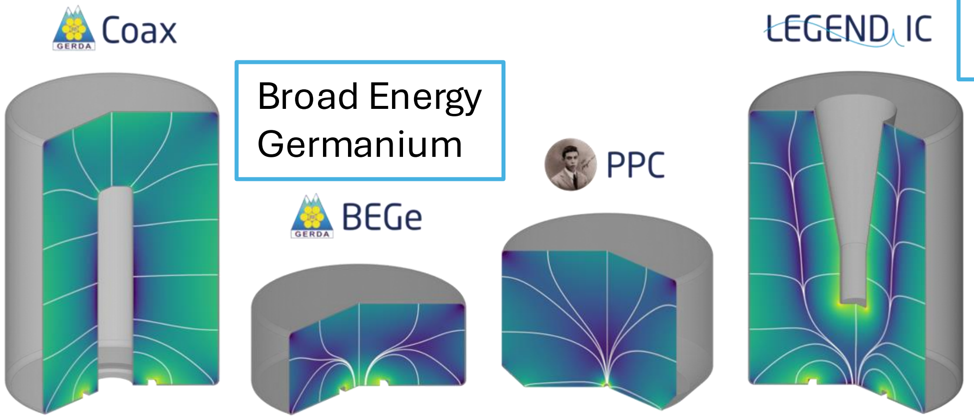
④ Pulse shape discrimination cut

⑤ Statistical analysis → signal discovery or new half-life lower limit

(in progress)

①Detector grouping

- Four detector geometries in LEGEND-200 first science run:

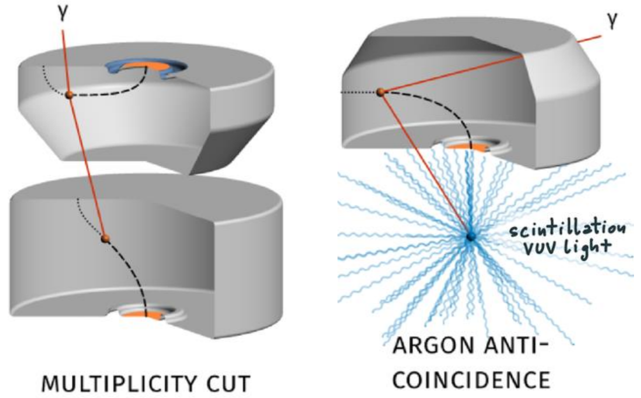


- Since they have different features and energy response, analysis is performed in five different detector groups. Each group considers detectors of the same geometry and with similar energy resolution:

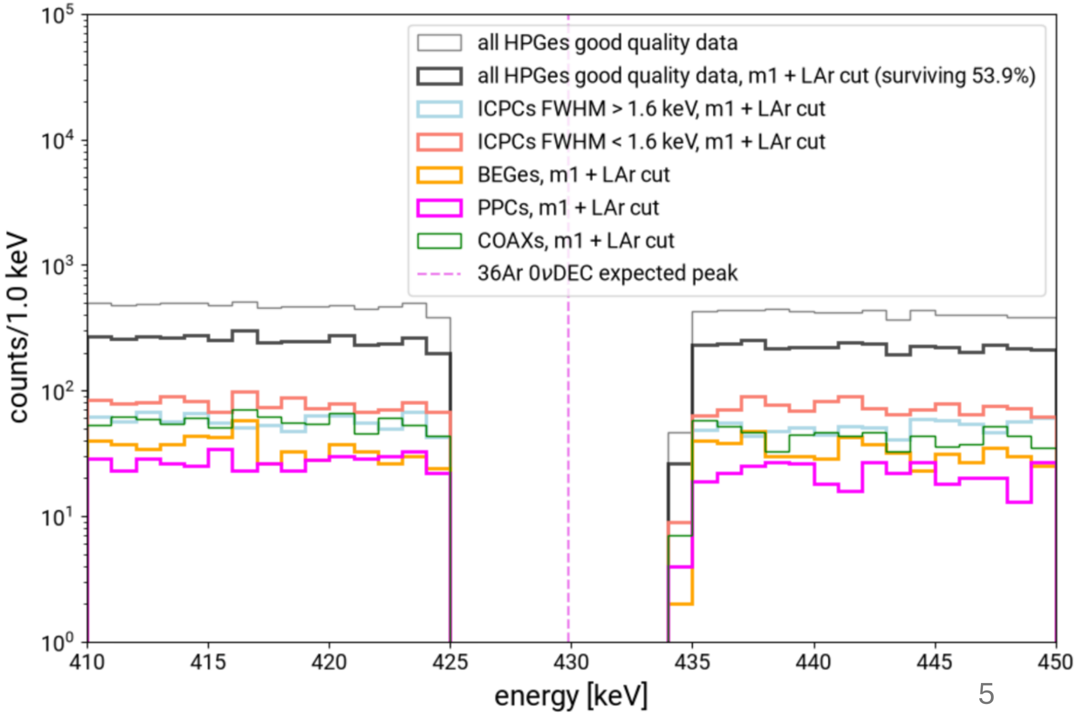
	ICPC with FWHM @ 430 keV < 1.6 keV	ICPC with FWHM @ 430 keV > 1.6 keV	BEGEs	PPCs	COAX	Total
Exposure [kg yr]	26.1	19.8	10.9	9.7	7.8	74.2
Exposure-weighted average FWHM @ 430 keV [keV]	1.38 ± 0.25	2.29 ± 0.42	1.18 ± 0.05	1.29 ± 0.11	3.92 ± 0.35	

② Physics data selection

- Research is performed on physics data acquired between March 2023 and February 2024 (LEGEND-200 first science run).
- Cuts applied:
  - Quality cuts: only physical events with good-quality waveforms are selected (no discharges, pile-up, ...)
  - Multiplicity cut: only events recorded in a single HPGe are selected, also called m1;
  - Muon cut: muon-coincident events are discarded;
  - Liquid argon anti-coincidence cut: events are rejected if there is a coincident energy deposit in LAr.



- Events in ±5 keV around the expected signal energy are hidden not to be influenced by possible presence of the signal.
- Main background events in [410, 450] keV interval: ^{39}Ar β decay and ^{76}Ge $2\nu\beta\beta$.



③ γ detection efficiency estimation

- We cannot estimate full signal efficiency: X-rays cannot reach HPGes or overcome their energy threshold. However, we can estimate the γ detection efficiency.
- Estimated by simulating 500 million 429.88 keV γ in a liquid argon cylinder surrounding the HPGe detectors considering detector statuses and livetimes in the first science run.
  Steps for γ detection efficiency estimation:

1

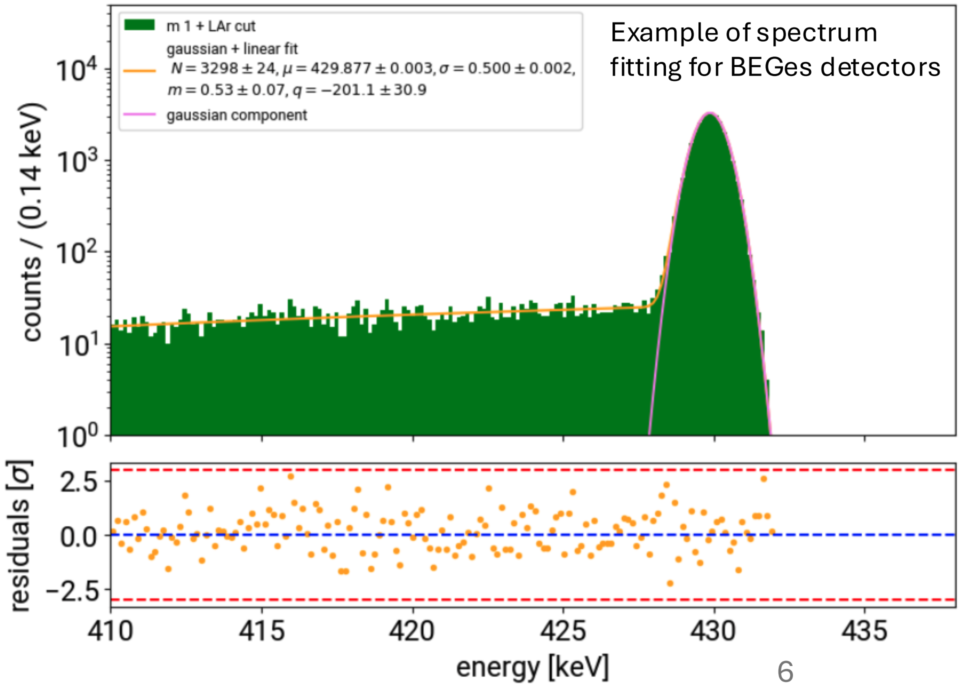
Simulation of raw events:
Sampling of γ vertices inside the LAr cylinder and transport simulation → raw energy deposition in detectors.

2

Post-processing of raw events:
- Energy resolution smearing;
- Correction for HPGe dead- and transition layers, where charge collection is not possible or inefficient.

3

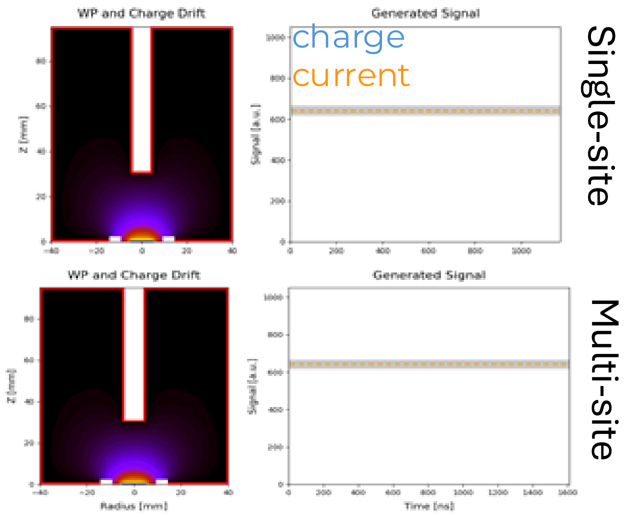
Analysis of post-processed events:
- Only events with no coincident energy deposition > 10 keV in another HPGe and no energy deposition in LAr are selected;
- Fitting of energy spectra with gaussian + linear model;
- Estimation of detection efficiency as $\frac{Area\ under\ gaussian\ fit}{Total\ number\ of\ simulated\ events}$



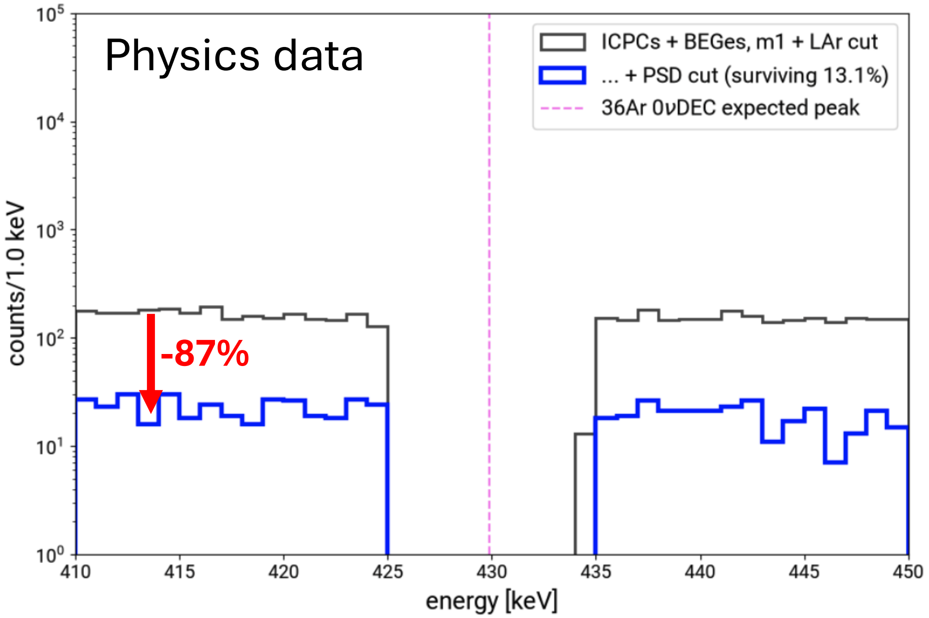
Example of spectrum fitting for BEGes detectors

Steps 1 & 2 performed with *legend-simflow* package
Documentation: https://legend-simflow.readthedocs.io/en/latest/

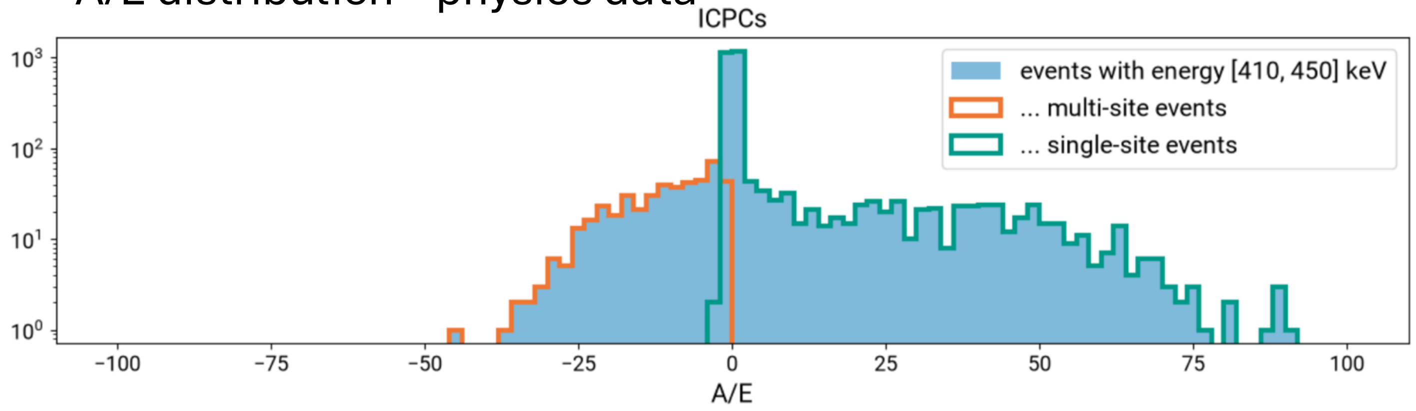
④Pulse shape discrimination cut



- Events in HPGe can be single-site, multi-site or surface events (βs, αs).
  Pulse shape discrimination (PSD) cuts are developed to discriminate among these types.
  An important PSD figure of merit: A/E (max event current / charge collected).
- 430 keV γ in HPGe give rise to a mixture of multi-site and single-site events, depending on the interaction type (Compton scattering or photoelectric effect).
- Compared to GERDA, we now benefit from thoroughly studied PSD cuts via special detectors characterization runs, that enabled the implementation and validation of PSD modelling in simulation.
- Dominant backgrounds are mainly single-site → investigated if it's advantageous to apply a PSD cut (A/E) to **select only multi-site events**.
- A/E cut applied to **both simulated and real events** recorded by ICPCs and BEGes (geometries for which special characterization runs were acquired, and PSD modelling was developed and validated).



A/E distribution – physics data



④ Pulse shape discrimination cut: impact on the sensitivity

		ICPC with FWHM @ 430 keV < 1.6 keV	ICPC with FWHM @ 430 keV > 1.6 keV	BEGEs	PPCs	COAX
Physics data	Bkg events in [410, 450] keV **before** PSD	2080	1311	1030	741	1511
		-86%	-87%	-87%		
	Bkg events in [410, 450] keV **after** PSD	282	166	129	cut not applied	cut not applied
Simulated signal	γ detection efficiency **before** PSD	16.3e-5	11.8e-5	5.9e-5	5.9e-5	4.1e-5
		-30%	-46%	-55%		
	γ detection efficiency **after** PSD	11.4e-5	6.4e-5	2.6e-5	cut not applied	cut not applied
	Estimated impact on half-life sensitivity	**+87%**	**+50%**	**+25%**		

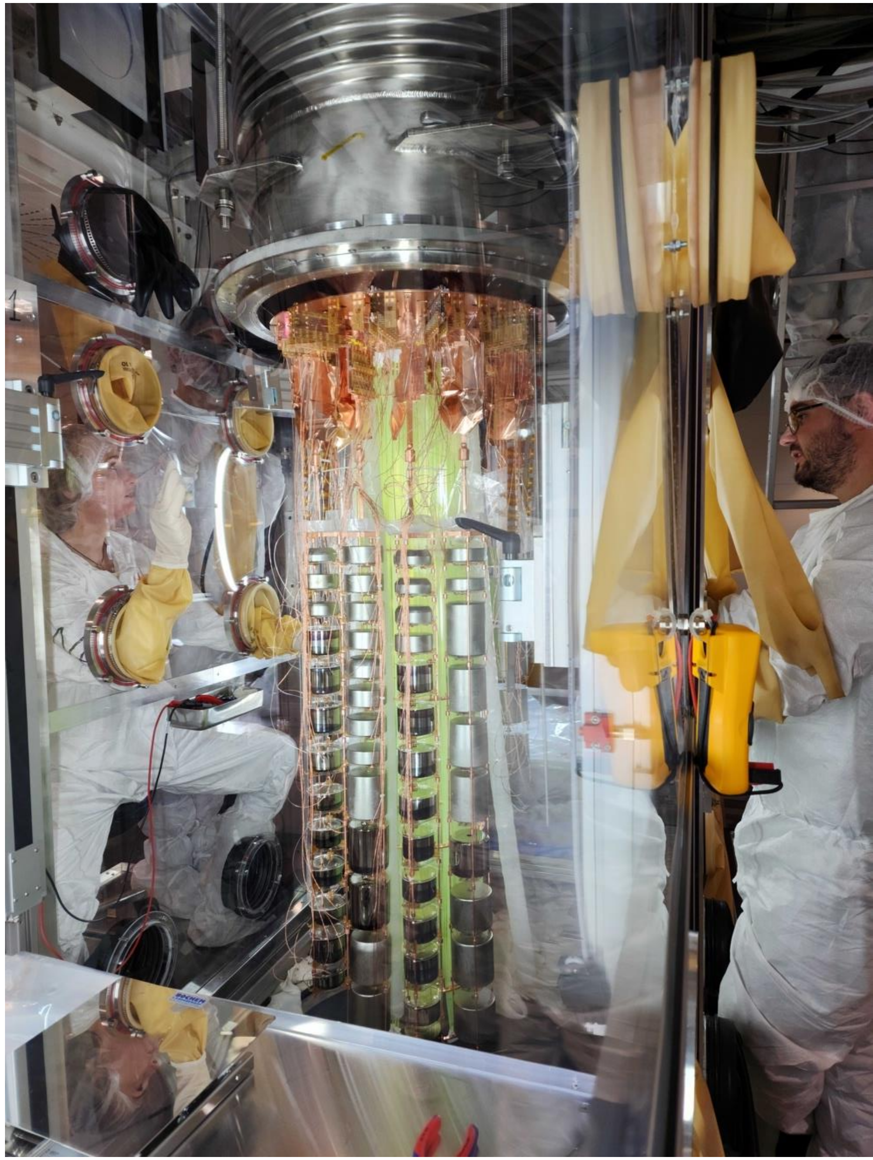
- Considering that the experimental sensitivity to the decay half-life scales as $\frac{detection\ efficiency}{\sqrt{background\ events}}$.
- Based on these results, it seems advantageous to apply PSD cut discarding single-site events collected by ICPCs and BEGes detectors.

Summary & next steps

- We are designing a search for the 0νDEC of ^{36}Ar in LEGEND-200 with data from the first science run.
- Detector grouping, physics data selection, γ detection efficiency estimation steps are completed.
- We studied whether the application of a PSD cut discarding single-site events has a positive impact on the half-life experimental sensitivity. Results are that the loss in signal efficiency seems to be overcome by the gain in background rejection.

Next steps:

- The A/E cut was optimized at high energies (for the ^{76}Ge $0\nu\beta\beta$ search @ $\sim$2 MeV) → validation at low energies is needed.
- Systematics estimation: we expect dominant syst. to be caused by HPGes dead-layers (impacting the γ detection efficiency by 5%–10%).
- Performing the statistical analysis. Planned analysis strategy: simultaneous bayesian binned likelihood fit of the physics data energy spectra of the five detector groups, by modelling the expected signal as a gaussian peak and the background as a linear function in the interval [410, 450] keV.



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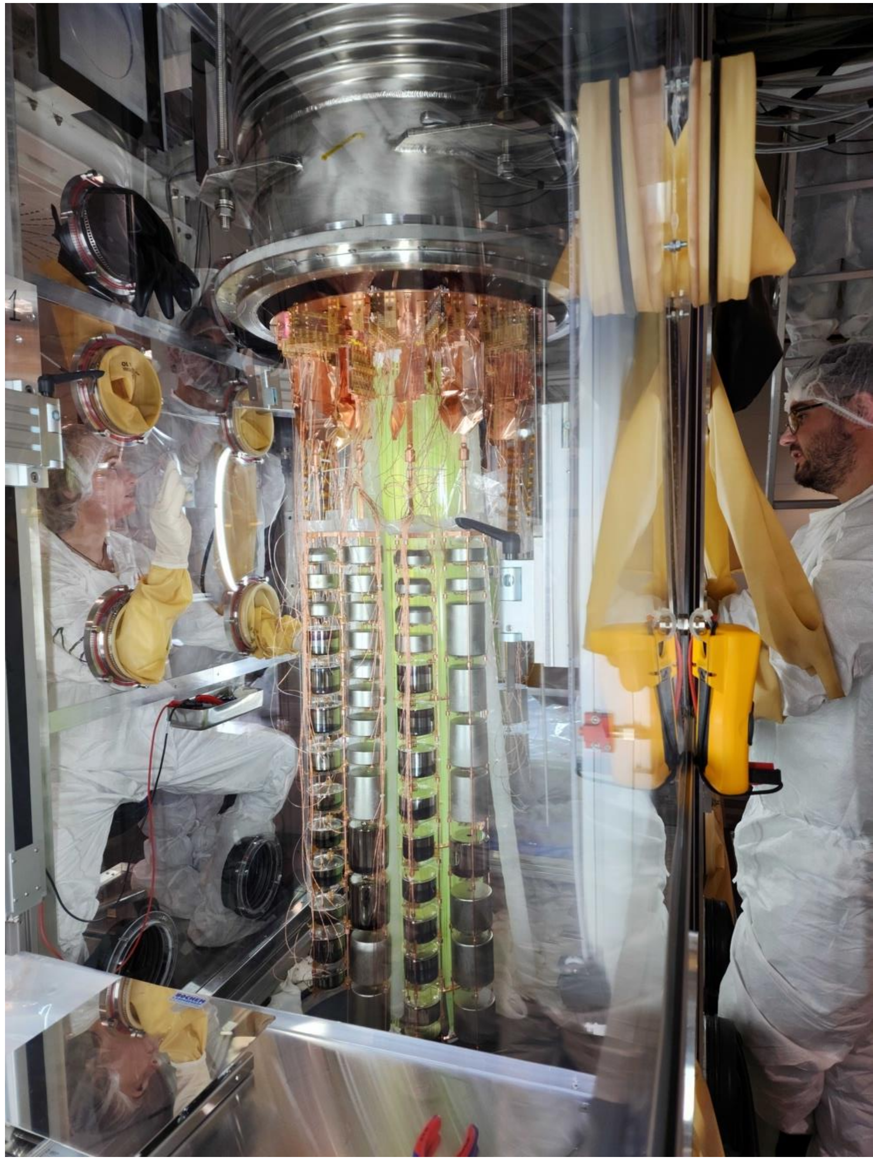

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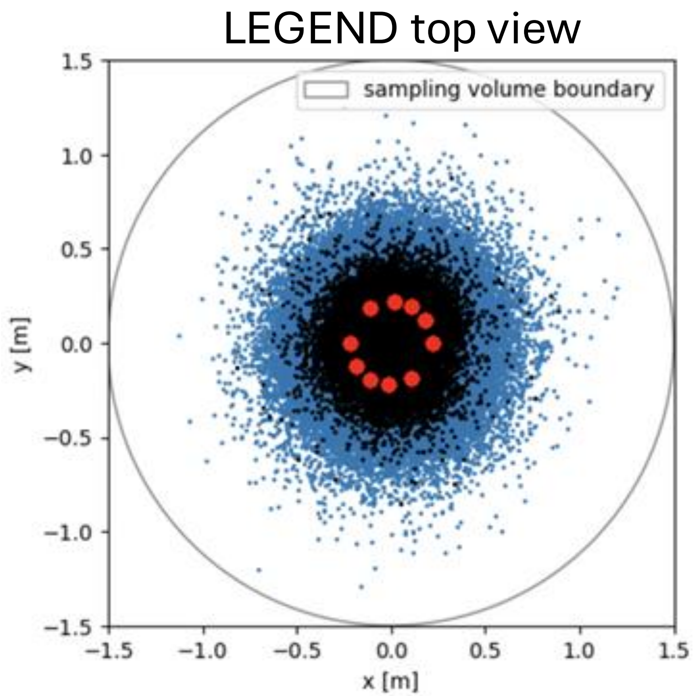
Thank you very much!

Backup

More about γ simulation

- Reconstructed γ efficiency estimated by simulating 500 million 429.88 keV γ in a liquid argon cylinder surrounding the HPGe detectors.
- The sampling cylinder dimensions (1.5 m radius, 2.5 m height) are chosen such that vertices of gammas depositing all their energy in a single HPGe are completely contained.



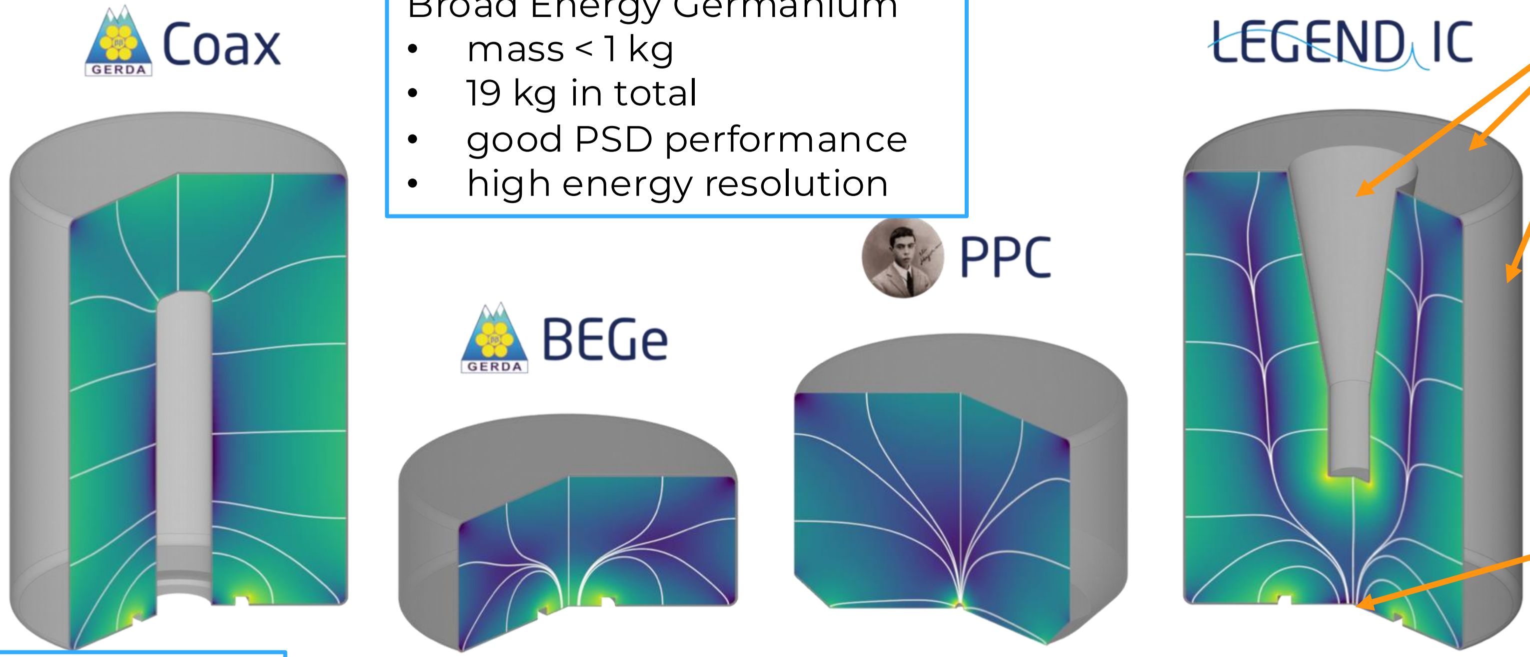
- Detector centres
- Vertices of gammas depositing some energy in the Ge
- Vertices of gammas depositing all their energy in a single Ge (black points superimposed on the blue points)

Mean free path of 430 keV ɣ in LAr ~10 cm

LEGEND-200 detectors during first science run

Broad Energy Germanium
- mass < 1 kg
- 19 kg in total
- good PSD performance
- high energy resolution

n+ high voltage contact (lithium layer)



p+ readout contact (boron implantation)

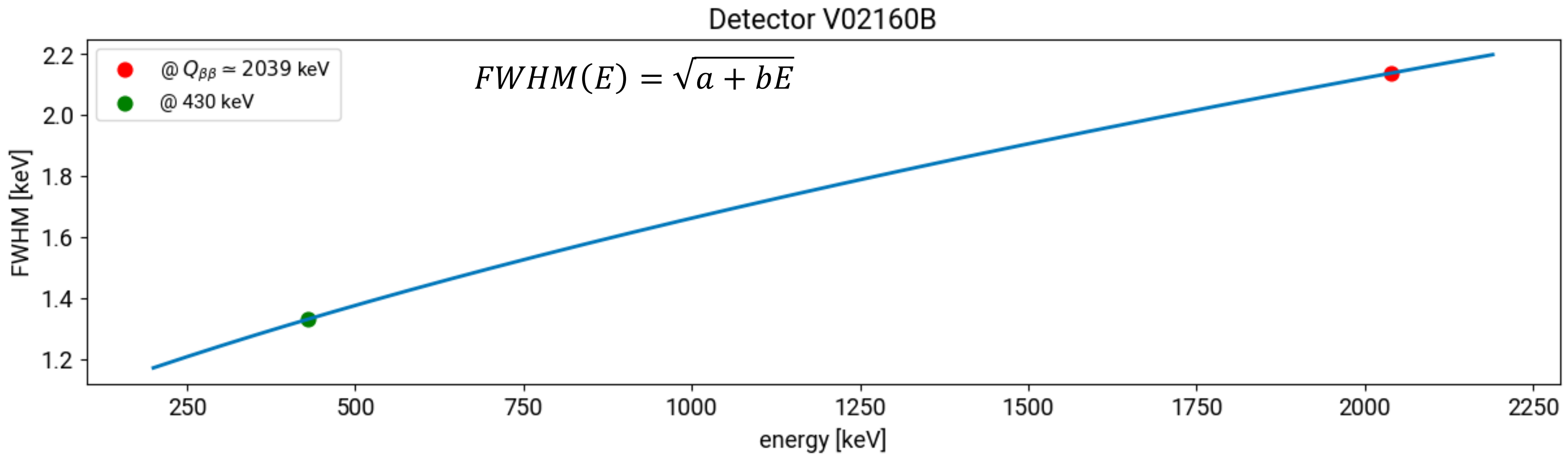
Semi-coaxial:
- mass < 3 kg
- 14.7 kg in total
- not extremely good PSD performance
- quite high energy resolution

P-type Point Contact:
- mass < 1 kg
- 22.1 kg in total
- high energy resolution

Inverted Coaxial Point Contact:
- large mass (2-4 kg)
- 86.7 kg in total
- excellent PSD performance
- high energy resolution

Energy resolution estimation

- We estimated the energy resolution of our detector groups by extrapolating the resolution @ photo-peak of each detector from its energy resolution curve and then combining energy resolutions of detectors in the same group with an exposure-weighted average.



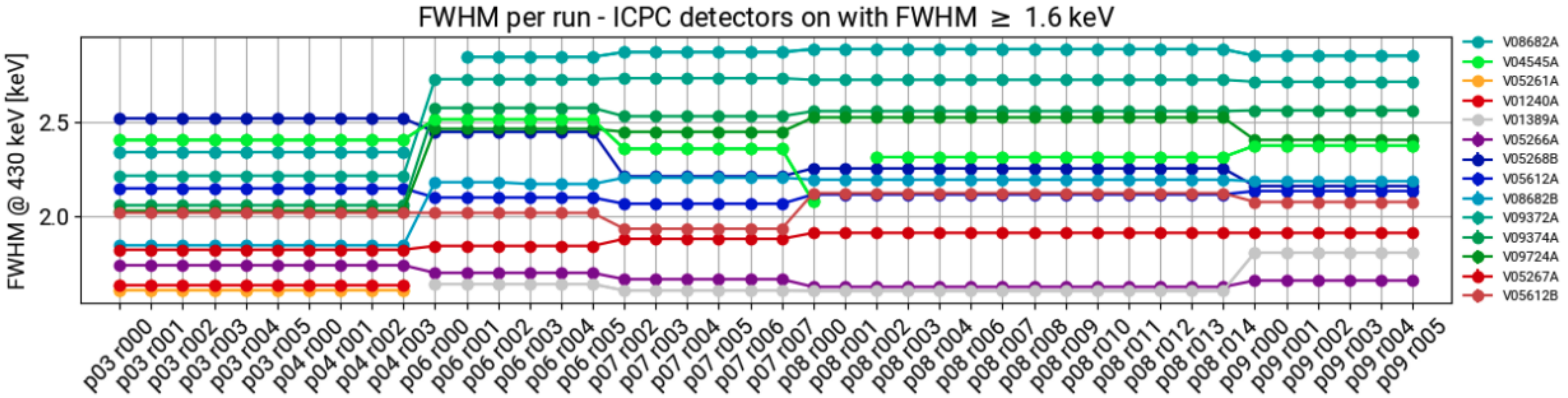
Example of energy resolution curve

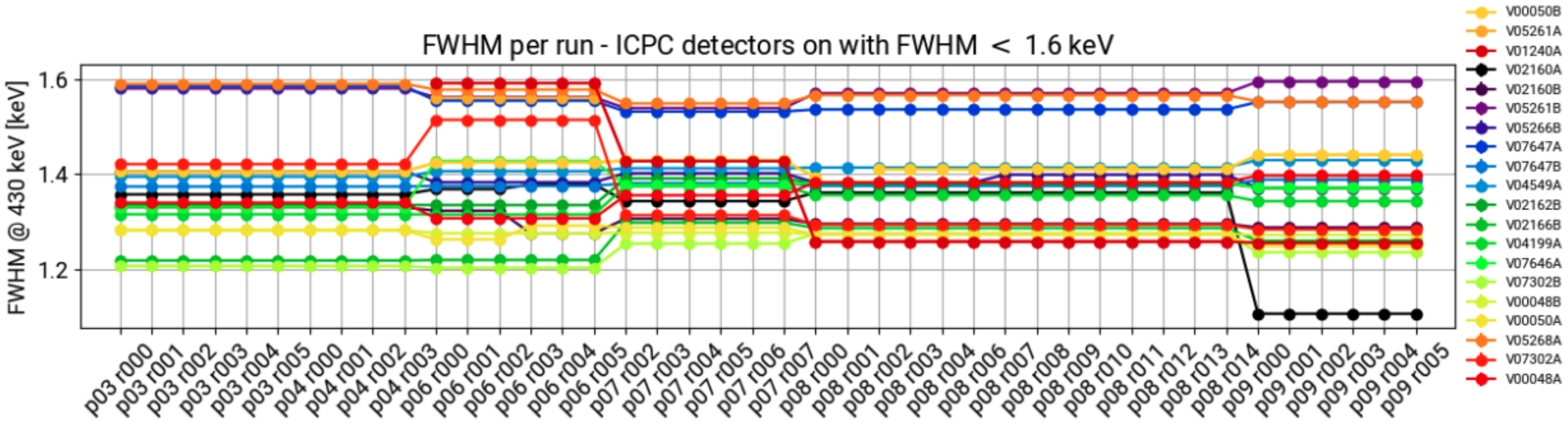
@ 430 keV	ICPC FWHM > 1.6 keV	ICPC FWHM < 1.6 keV	BEGE	PPC	COAX
FWHM [keV]	2.29	1.38	1.18	1.29	3.92

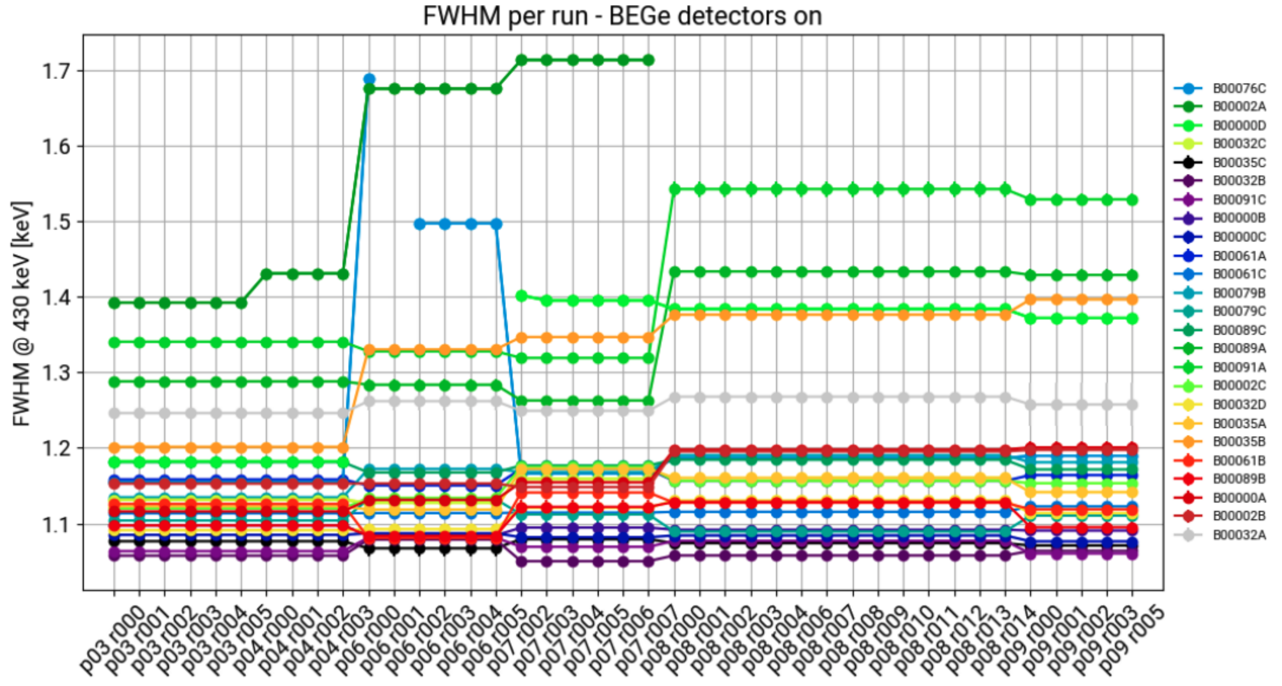
FWHM @ $Q_{\beta\beta}$ reported in the LEGEND paper [The LEGEND Collaboration et al. (2026), arXiv:2605.22479]:

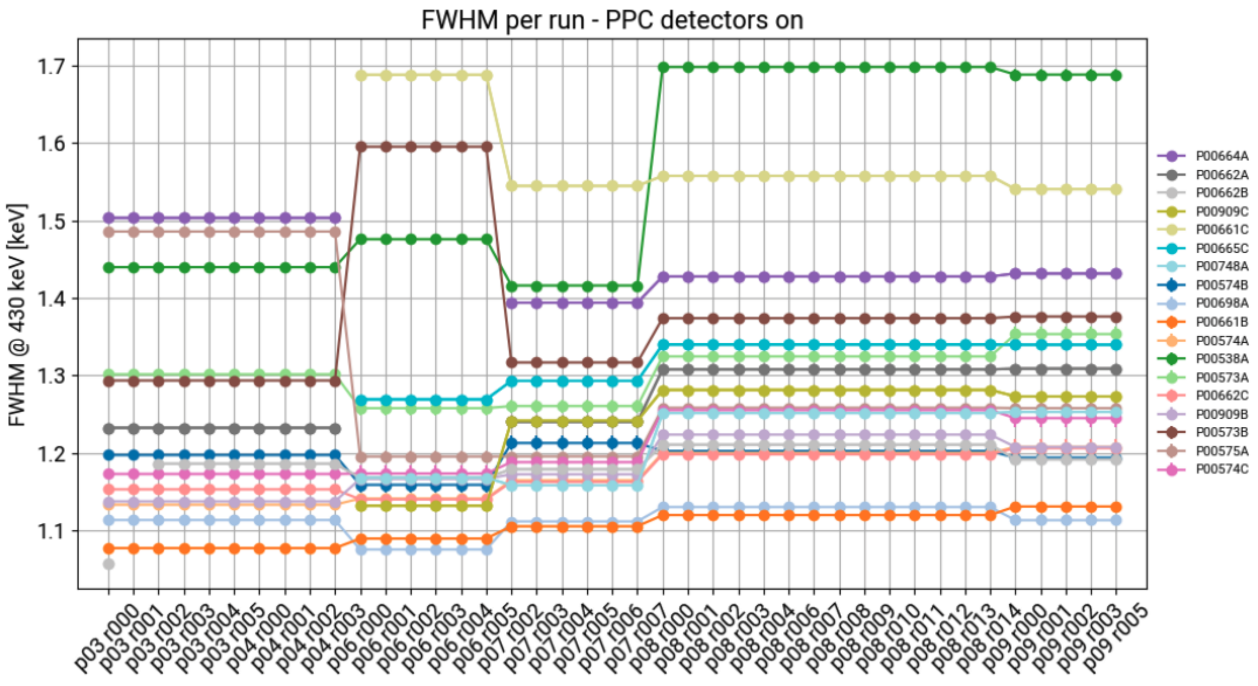
@ $Q_{\beta\beta}$	ICPC	BEGE	PPC	COAX
FWHM [keV]	2.63	2.09	2.55	4.42

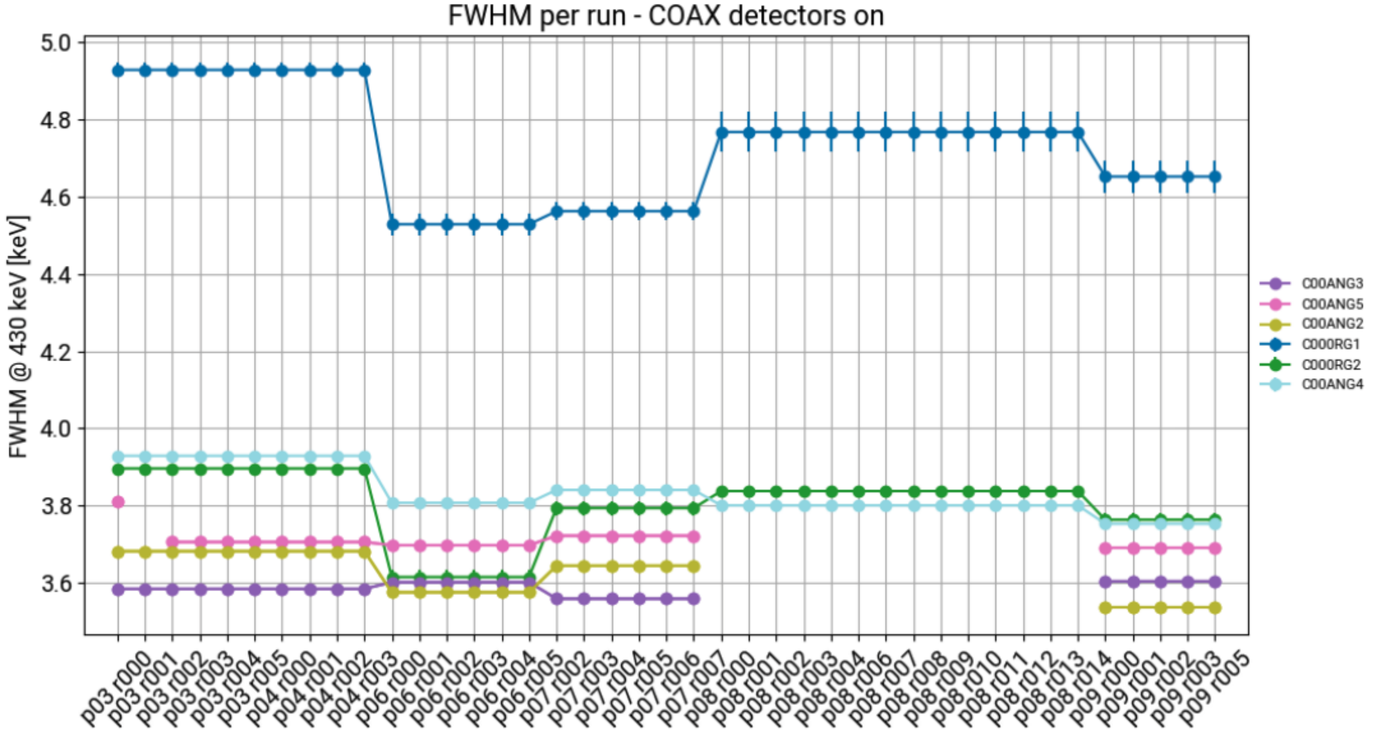
Energy resolution of detector groups





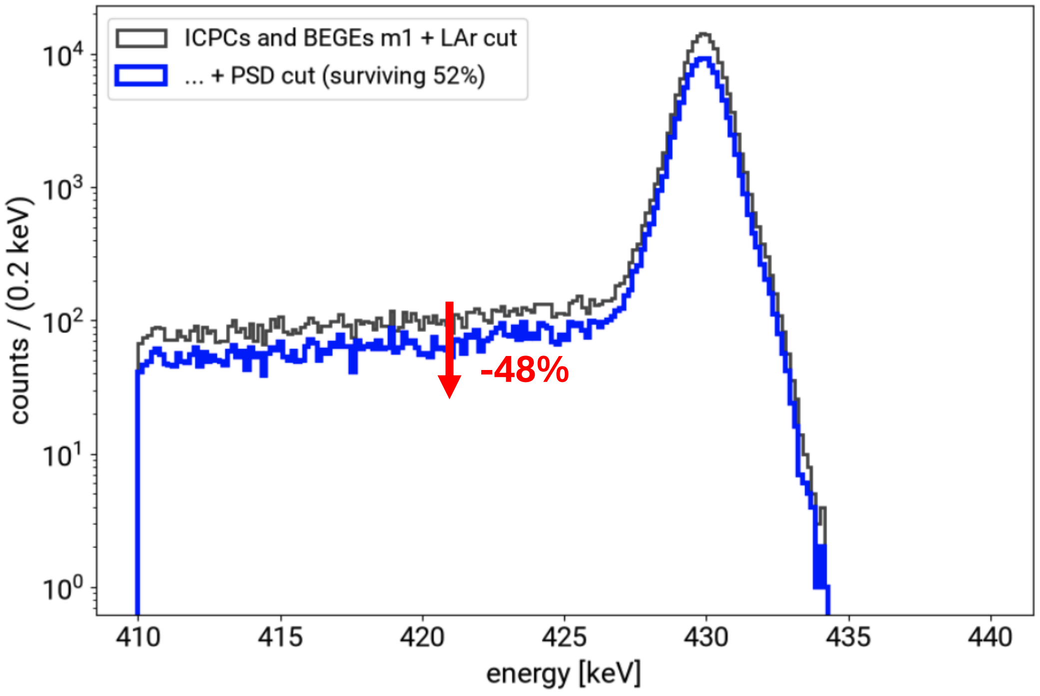

FWHM per run - BEGe detectors on
FWHM @ 430 keV [keV]
B00076C
B00002A
B00000D
B00032C
B00035C
B00032B
B00091C
B00000B
B00000C
B00061A
B00061C
B00079B
B00079C
B00089C
B00089A
B00091A
B00002C
B00032D
B00035A
B00035B
B00061B
B00089B
B00000A
B00002B
B00032A


FWHM per run - PPC detectors on
FWHM @ 430 keV [keV]
P00664A
P00662A
P00662B
P00909C
P00661C
P00665C
P00748A
P00574B
P00698A
P00661B
P00574A
P00538A
P00573A
P00662C
P00909B
P00573B
P00575A
P00574C

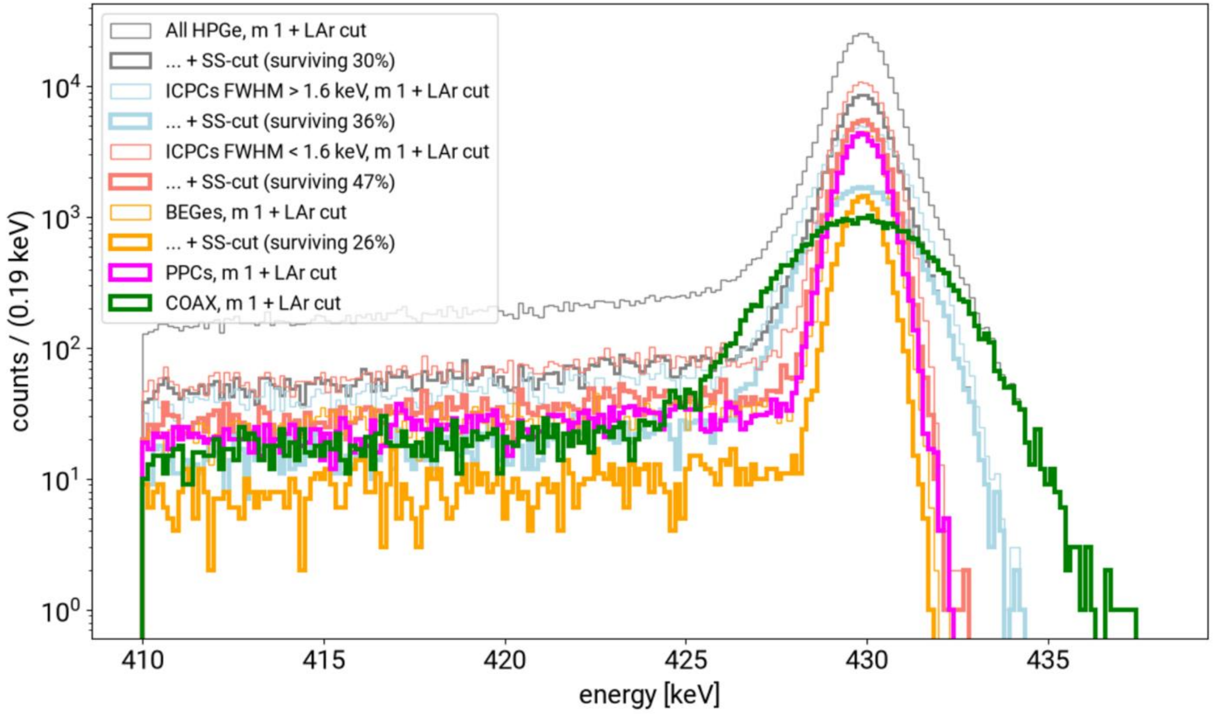

FWHM per run - COAX detectors on
FWHM @ 430 keV [keV]
C00ANG3
C00ANG5
C00ANG2
C000RG1
C000RG2
C00ANG4

More on pulse shape discrimination cut applied to sim data

- Exemplary plot of A/E cut applied to simulated data:

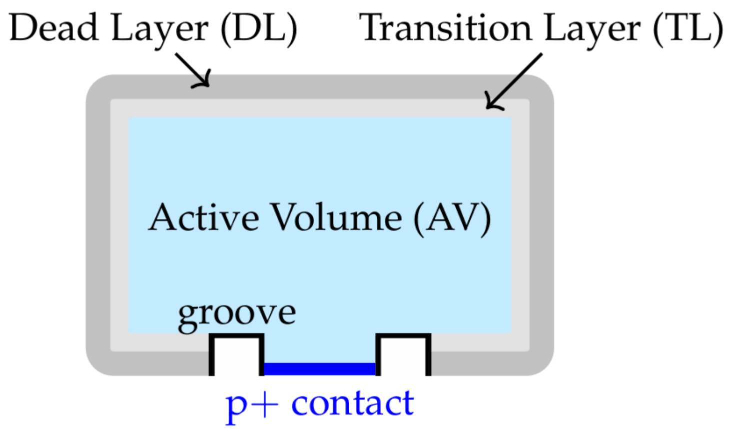


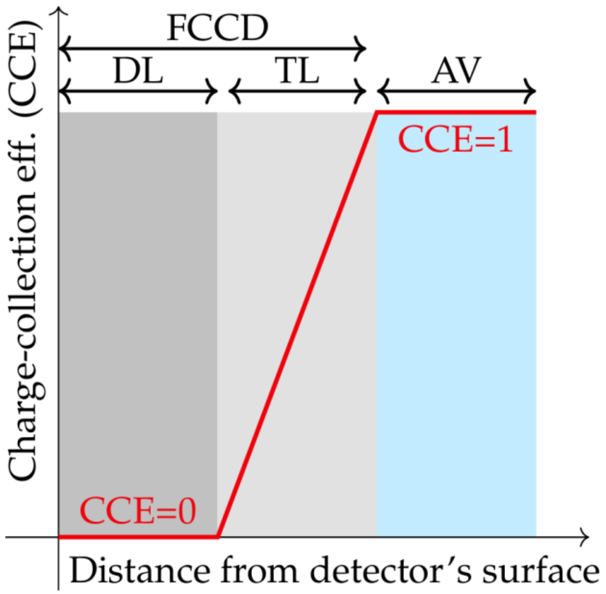
- Effect of A/E cut applied to different detector types (apart from PPCs and COAX, for which the cut is not applied):
  In the legend "SS-cut" is the PSD cut applied.



FCCD: full charge collection depth

- FCCD: thickness of the outer region of a HPGe where charge collection is incomplete or inefficient (dead layer + transition layer. In total usually ~0.5 mm – 1.5 mm thick).





X-rays detection

Mean free path of 2.7 keV X-ray in LAr ~20 μm

$$^{36}\mathrm{Ar} + 2e^- \longrightarrow {}^{36}\mathrm{S} + \gamma + X_K + X_L$$

Any chance to detect the X-rays with the Ge and/or the optical photons generated by the X-rays with the SiPMs? Useful for this search and maybe for ^{36}Ar 2νDEC search (for which no gamma is emitted, just X-rays or Auger electrons).

We simulated 5 million 2.70 keV X-rays (coming from 2.47 keV + 0.23 keV) in the same previous LAr cylinder enabling optical physics processes.

No X-rays reach the Ge and overcome the FCCD layer.

For the SiPMs, we found an efficiency (# X-rays for which at least one photon is detected by the SiPMs / # total X-rays simulated) of 2.354 ± 0.007(stat) %.

Very low photon-per-event value → this makes a 2νDEC search very difficult.

But at least, this tells us how often those X-rays would accidentally veto the 0νDEC radiative signal.