Background modelling in GERDA

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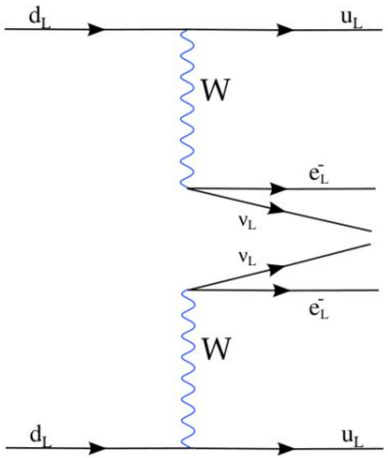
Double beta-decay

- The double beta (**2vββ**) decay can be thought as two simultaneous β-decays

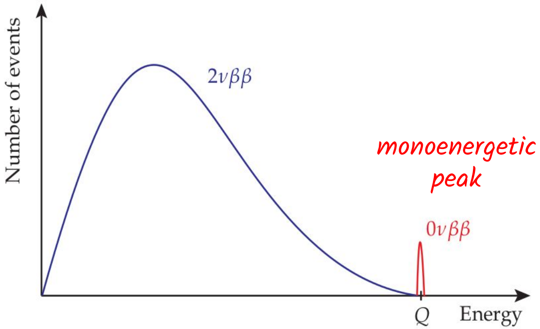
$$T^{2\nu}_{1/2} \sim 10^{21} \text{ yr in } ^{76}\text{Ge}$$

- The neutrinoless double beta (**0vββ**) double beta decay can be mediated by the exchange of two massive Majorana

$$T^{0\nu}_{1/2} > 10^{26} \text{ yr in } ^{76}\text{Ge}$$

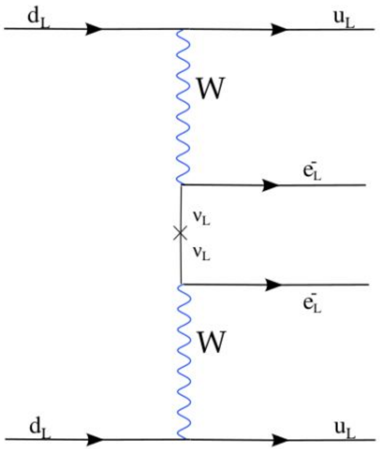


low background level and good energy resolution



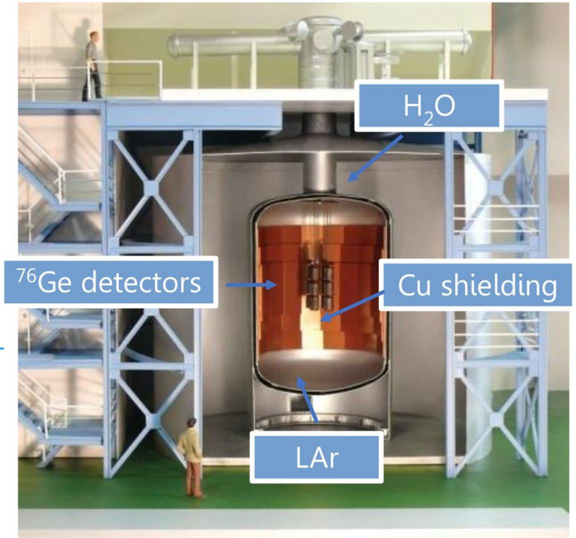
monoenergetic peak

$Q_{\beta\beta}$ = 2039 keV for ^{76}Ge

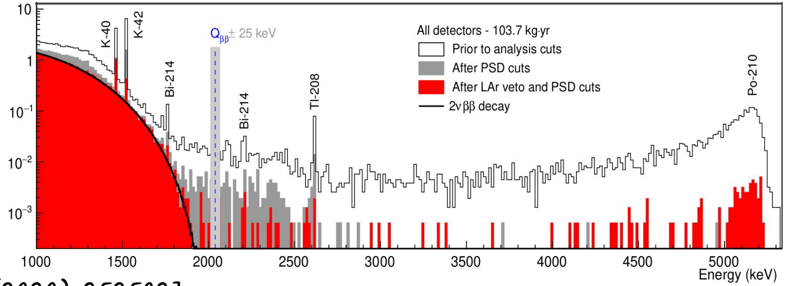


Gerda experiment

- The GERDA experiment was proposed in 2004 as a new ^{76}Ge double-beta decay experiment at LNGS (Italy).
- Up to 41 enriched ^{76}Ge detectors deployed from Dec 2015 to Dec 2019.



- The array of germanium detectors was placed in a liquid argon (LAr) cryostat.
- A tank filled with 590 m^3 pure water surrounded the cryostat.
- The water tank was equipped with PMTs detecting Cherenkov light.



[GERDA , PRL 125 (2020) 252502]

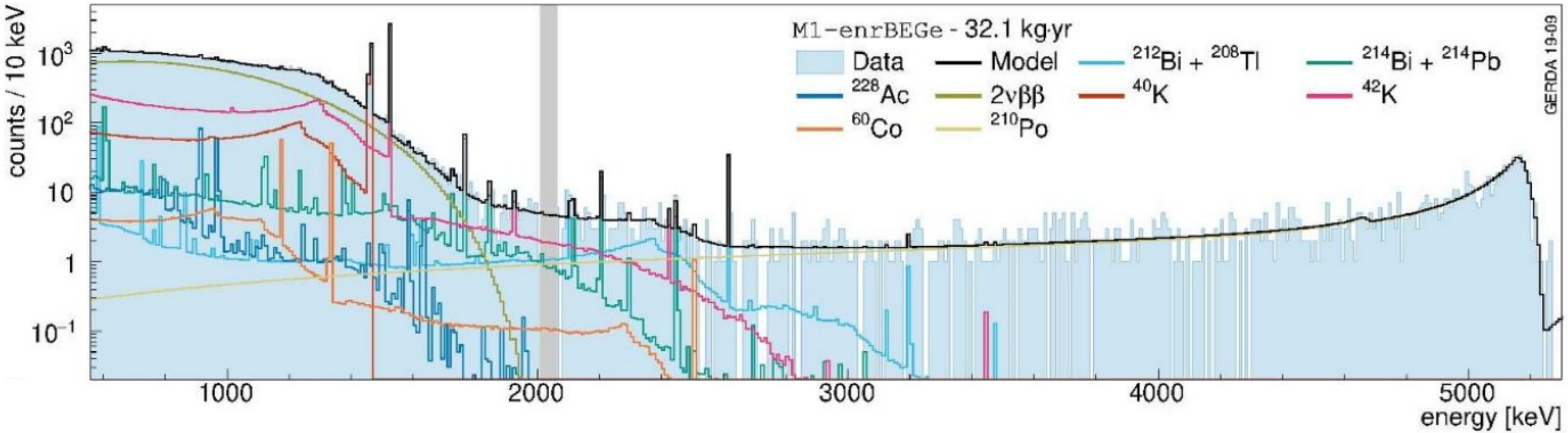
	Goals	Achievements
Background	10^{-3} cts/(keV kg yr)	$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)
Exposure	≥ 100 kg yr	103.7 kg yr phase II
Sensitivity	$T^{0\nu\beta\beta}_{1/2} \geq 10^{26}$ yr	$T^{0\nu\beta\beta}_{1/2} \geq 1.8 \cdot 10^{26}$ yr

Why modelling the background?

- A precise knowledge of background distribution and intensity in the full-range energy spectrum is fundamental to identify faint signals.
- The background model needs to predict the distribution of the events in the ROI around $Q_{\beta\beta}$. The assumption is a uniform distribution - except for known γ lines from ^{208}Tl and ^{212}Bi.
- The bkg model allows to identify 2νββ-decay events and extract a precise measurement of the half-life of the process.
- The bkg model is useful to better understand the locations of residual impurities and then, to improve future experiment design and material selection in order to further lower the background and achieve even better sensitivities.

GERDA background model

single-detector events before analysis cuts



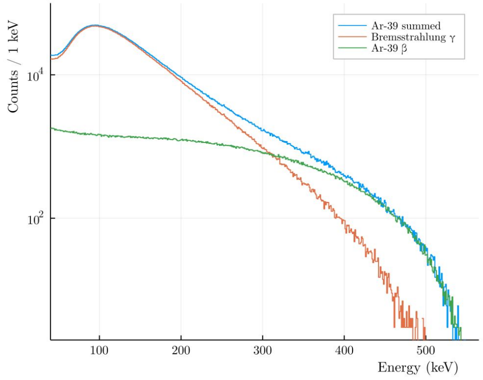
- The GERDA background model starts from <u>565 keV</u> (end-point of ^{39}Ar β^- spectrum)
    - radioactive decays depositing energy in germanium
- 2νββ decay of ^{76}Ge dominates up to 1500 keV
- αs dominate at the highest energies up to the 5.3MeV → peak structure with low energy tail
- γ-lines and Compton continuums belonging to ^{40}K, ^{42}K, ^{85}Kr, ^{208}Tl, ^{214}Bi and ^{228}Ac

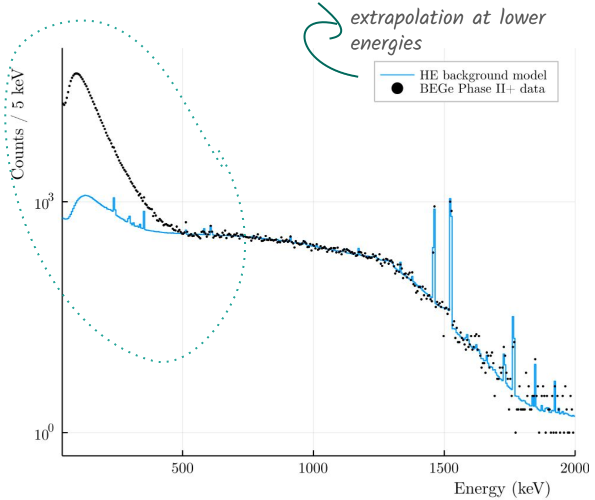
Background sources at lower energies

- Understanding the low-energy spectrum enables more sensitive signal searches.
- The next experiment LEGEND will perform new signal (from BSM particle such as dark matter WIMPS , exotic fermions and bosons, electron decay, ...) searches at low energy.

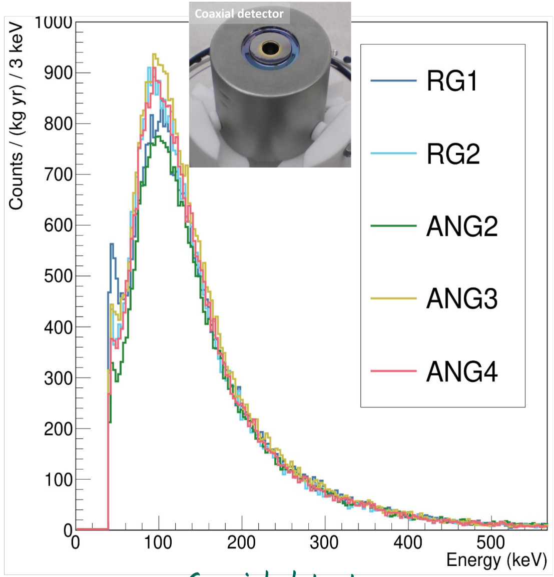
Key contributors: ^{39}Ar / ^{42}K / ^{40}K / 2νββ / ^{238}U / ^{228}Th

- Cosmogenic ^{39}Ar decay in LAr is dominant (up to 565 keV)
- Also in LAr: decay of ^{42}Ar & ^{85}Kr
  - Negligible contribution
- Other contaminants in Ge or structural materials
  - Globally at ~3% (at 100 keV)

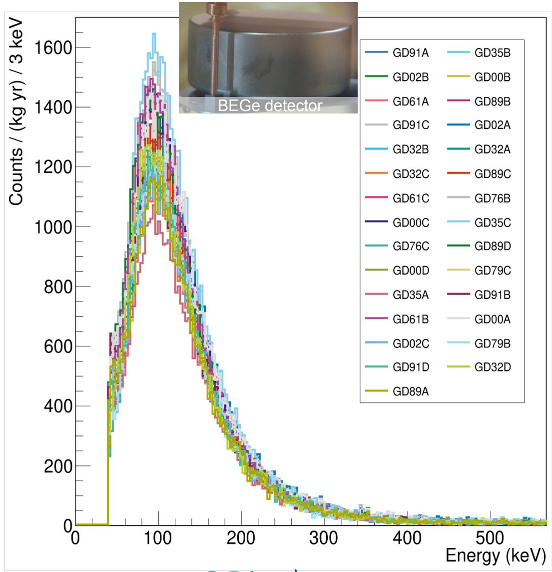




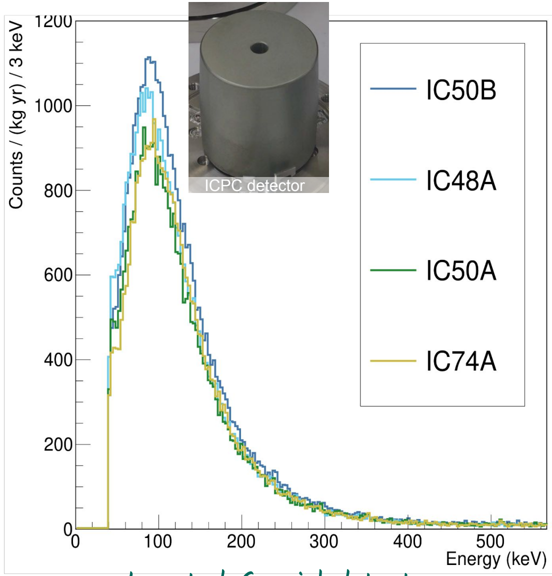
The low-energy GERDA data



Coaxial detectors



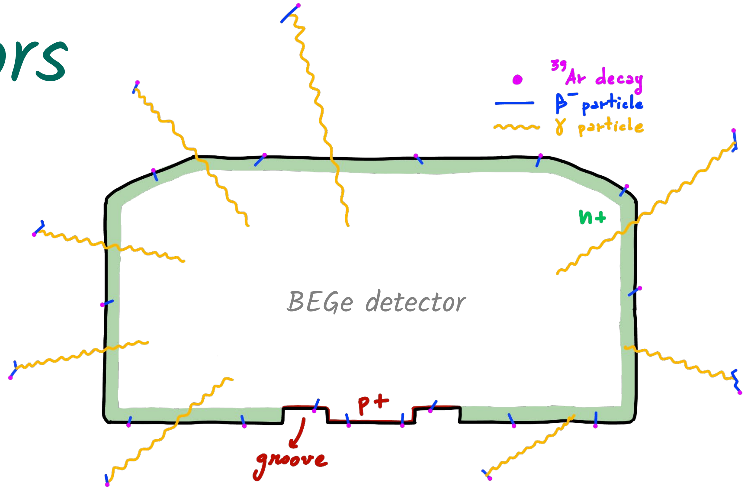
BEGe detectors



Inverted-Coaxial detectors

- Low-energy-threshold (~40 keV) data acquired with three different detector types
  - Between July 2018 and November 2019
- Differences are due to HPGe active volume.

Active volume of HPGe detectors

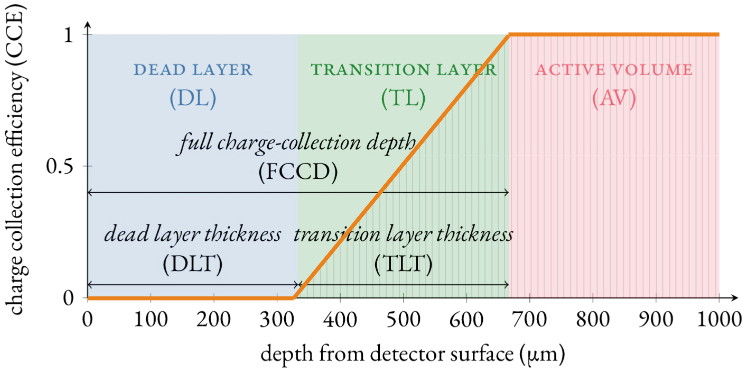


<u>An HPGe detector is made of:</u>

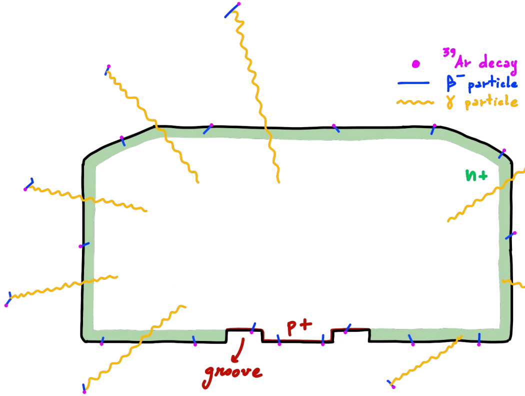
- Lithium-diffused HV contact (n+)
  - ~ 1 mm thick
  - hole-electron pairs partially lost
- High purity germanium bulk
  - full collection efficiency
- Boron-implanted readout contact (p+)
  - ~ 100 μm thick -> negligible effect

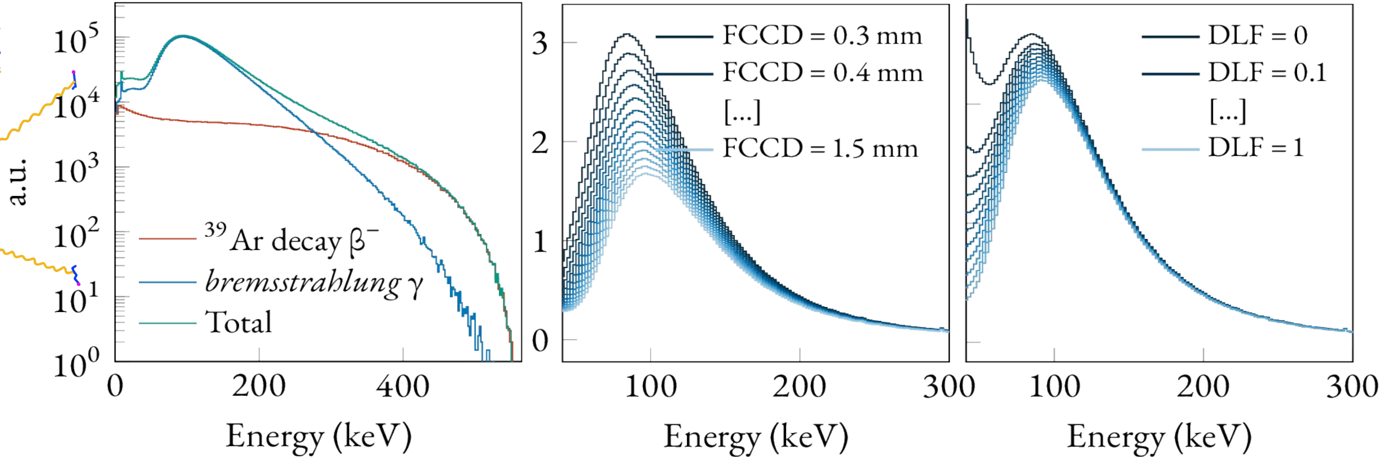
<u>How we simulate it:</u>

- Assume *linearly-increasing charge-collection profile* on the n+



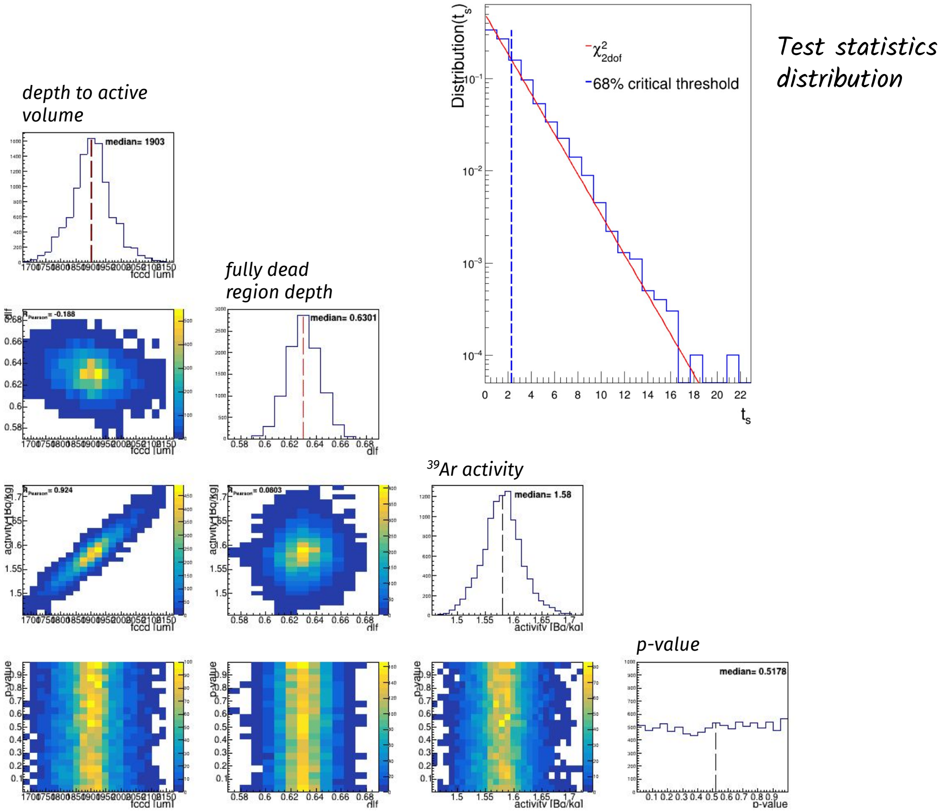
^{39}Ar and active volume





- We use GEANT4 to determine the ^{39}Ar pdf wrt. charge collection parameters
- The vast majority of ^{39}Ar events is due to *bremsstrahlung* from the β in LAr
- The β (Q_b~ 565 keV) is detected only through the p+ contact [range < 1 mm in LAr / < 0.2 mm in Ge]

Analysis

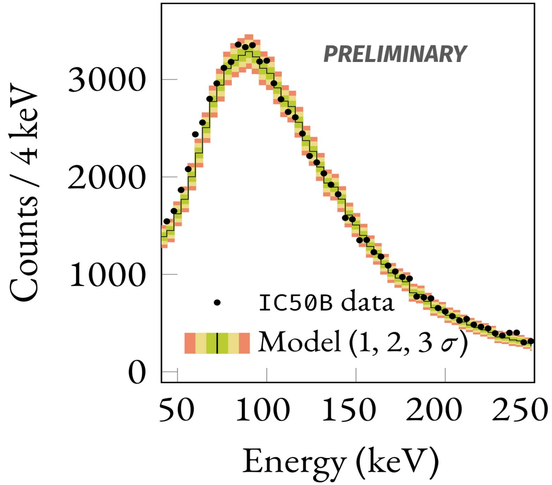


- Build MC expected pdfs, 2D discrete grid varying FCCD x DLF
- Match data and predictions around 100 keV to determine the best-fit active volume model for each HPGe separately (Likelihood profile)
- Set-up pseudo-data to evaluate performance and impact of uncertainties

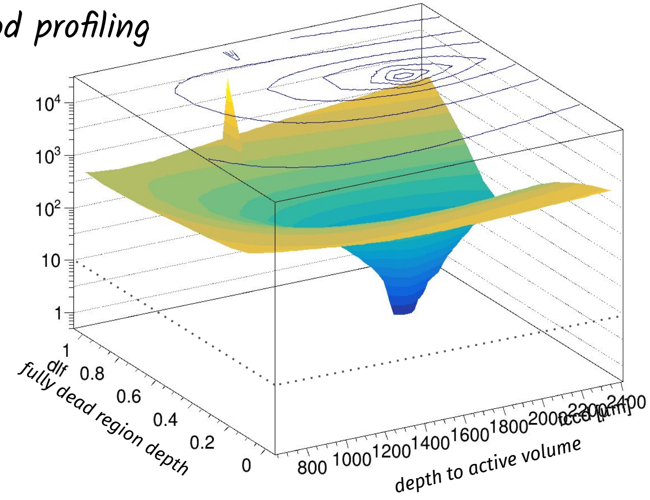
Preliminary results

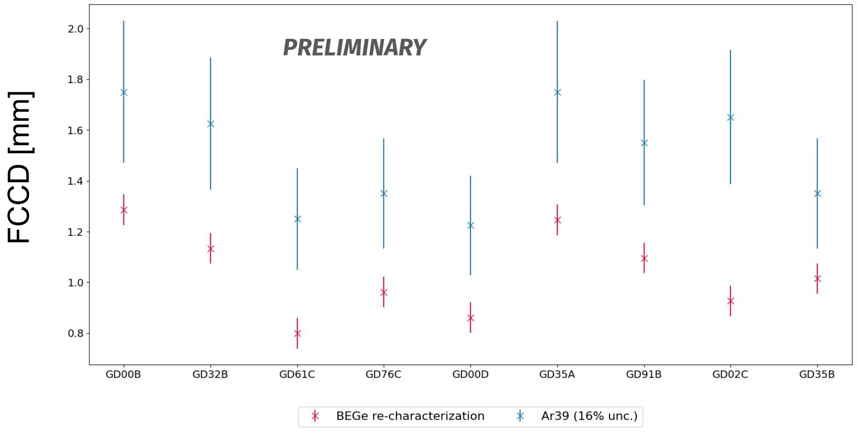
- So far, the preliminary results can reproduce the ICPC values and are consistent with the estimation of the grown* FCCD of BEGEs.

Example MC / data fit



Likelihood profiling on data





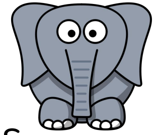
* they have stayed at room temperature for a few years

Wrapping up

- The GERDA background model is able to well describe the data
- The results are compatible with the expectations from material screening measurements
- The background event distribution in the $0\nu\beta\beta$ analysis window can be well approximated with a constant function
- ^{39}Ar is the main background contribution at lower energies
- ^{39}Ar spectrum shape is very sensible to **active volume model**, powerful way to precisely determine it

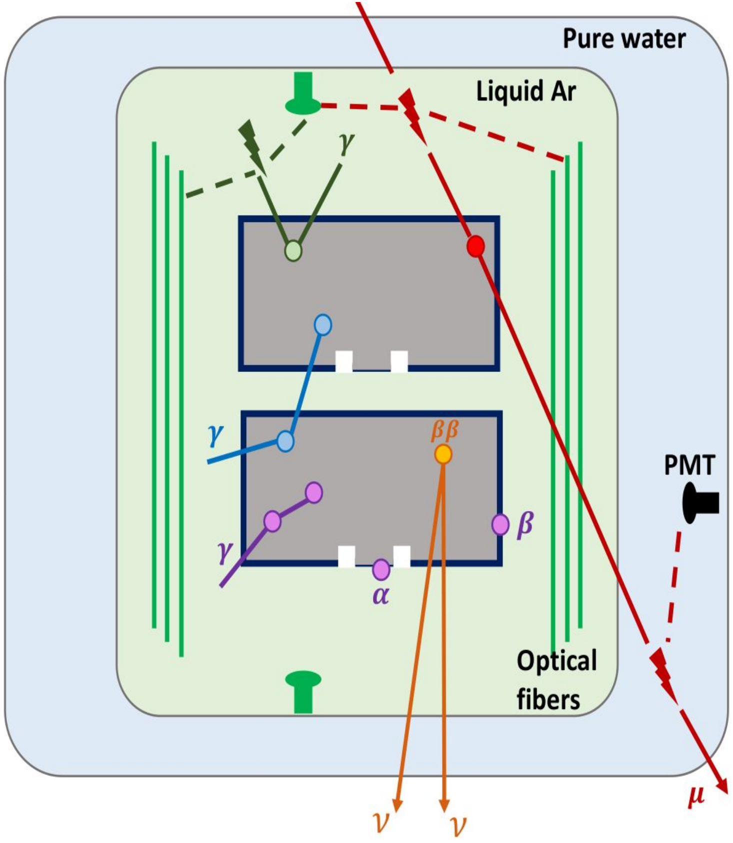
next steps

- More robust results after checking the systematics → as they have been defined now, they are dominant
- A better understanding of the offset between FCCD results from different analysis

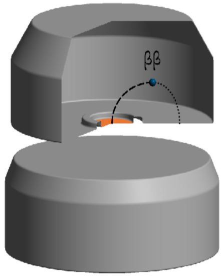


backup

Active background reduction tools



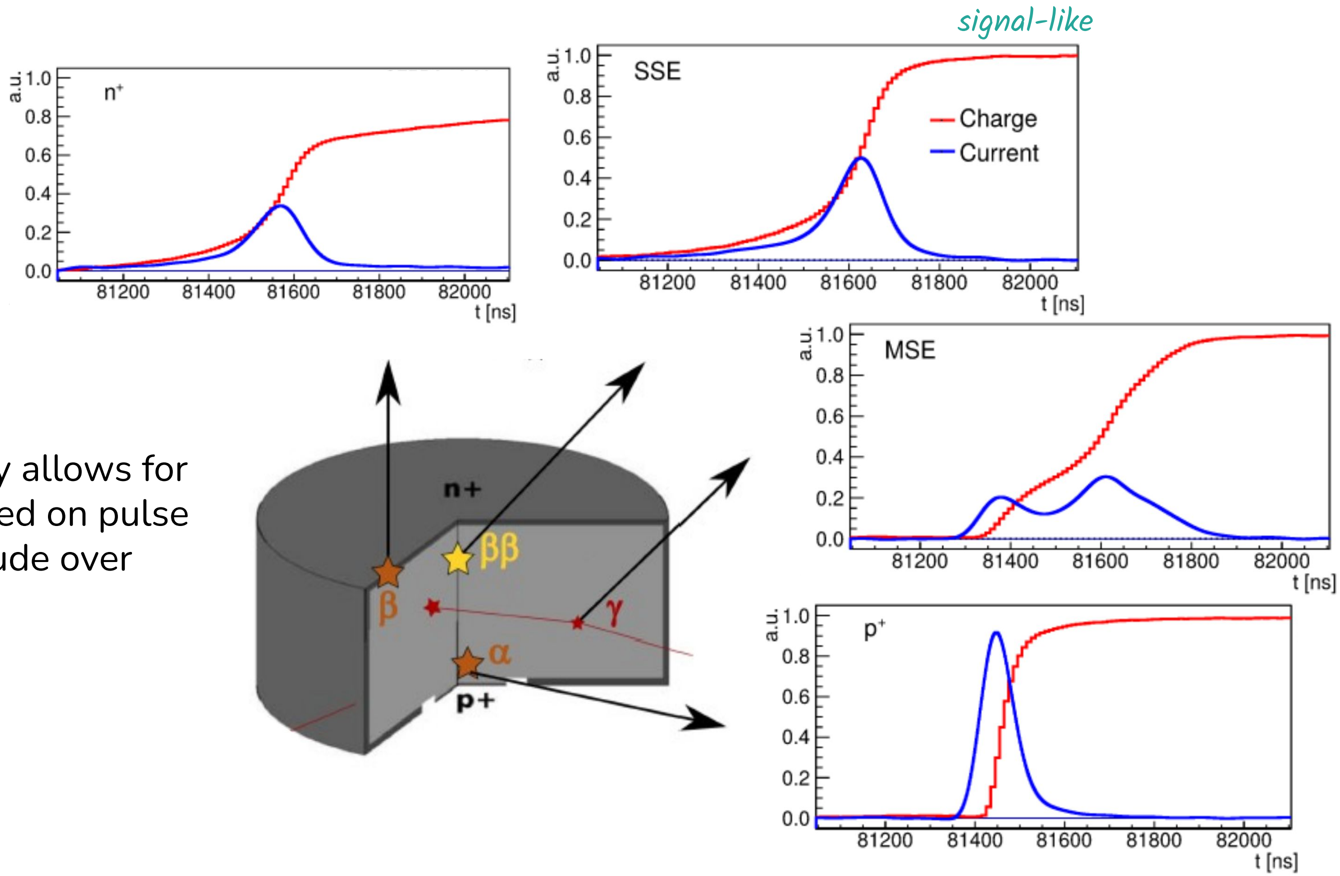
- ββ decay signal: single-site event energy deposition in a 1 mm^3 volume



- Anti-coincidence with the muon veto
- Anti-coincidence between detectors (cuts multi-site)
- Active veto using LAr scintillation (LAr Veto)
- Pulse shape discrimination (PSD)

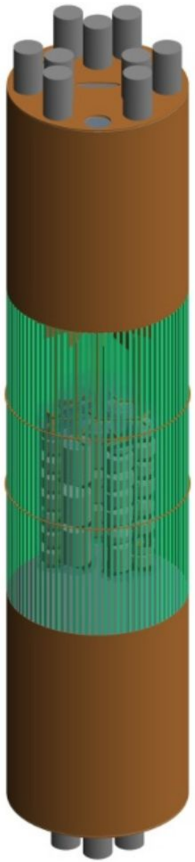
Pulse Shape Discrimination (PSD)

- Point-contact geometry allows for MS event rejection based on pulse shapes, current amplitude over energy (A/E)

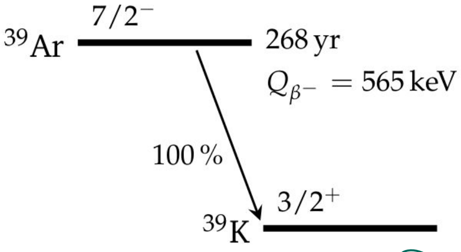


Liquid Argon veto

- The LAr scintillation-light detector acts as an active shield from any backgrounds source in the materials surrounding the array
- It suppresses background events that deposit energy in the Ar.
- It is read out via wavelength-shifting (WLS) fibers coupled to SiPMs.
- It has proven successful in GERDA and is being implemented in LEGEND-200 as two-barrel geometry.



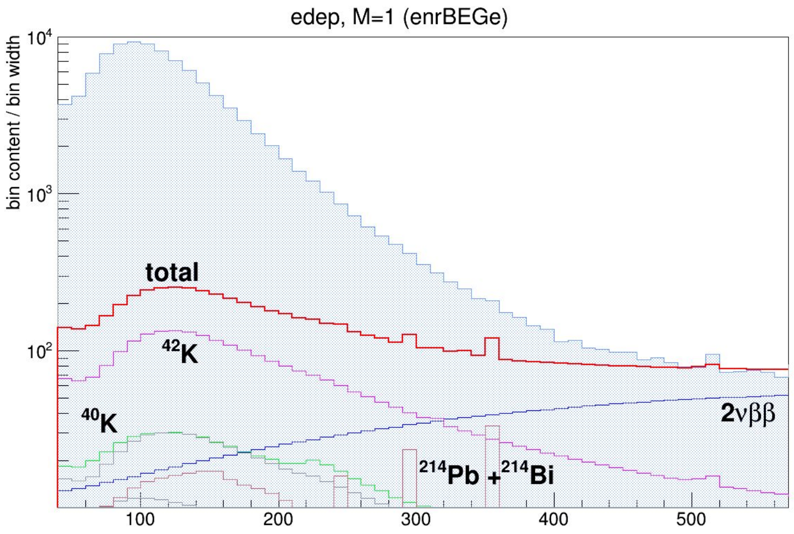
GERDA background sources



- **^{232}Th and ^{238}U decay chains**:
  - ^{232}Th decay chain → ^{228}Ac, ^{212}Bi and ^{208}Tl
  - ^{238}U decay chain → ^{214}Pb and ^{214}Bi
- **^{60}Co**: many GERDA components made of copper
- **^{40}K**: found in all screened materials, Q-value below $Q_{\beta\beta}$, γ-line at 1460.8 keV
- **^{42}K**: decay product of ^{42}Ar, a cosmogenically produced isotope in LAr. ^{42}K decays to ^{42}Ca via β-decay with Q-value above $Q_{\beta\beta}$.
- **α-emitters**: events from ^{210}Po and ^{226}Ra decay chain peaks with characteristic low-energy tails at higher energies
- **Detector bulk impurities**: ^{76}Ge decay via 2νββ as detector intrinsic background component, all other intrinsic impurities (^{68}Ge and ^{60}Co, ^{238}U and ^{232}Th) are negligible
- **Other sources**: muon, delayed decays of ^{77}Ge and ^{77m}Ge, water tank and LAr cryostat contaminations are negligible. The cosmogenically produced isotope ^{39}Ar and the anthropogenic isotope ^{85}Kr emit particles in a lower energies respect with the Phase II analysis window

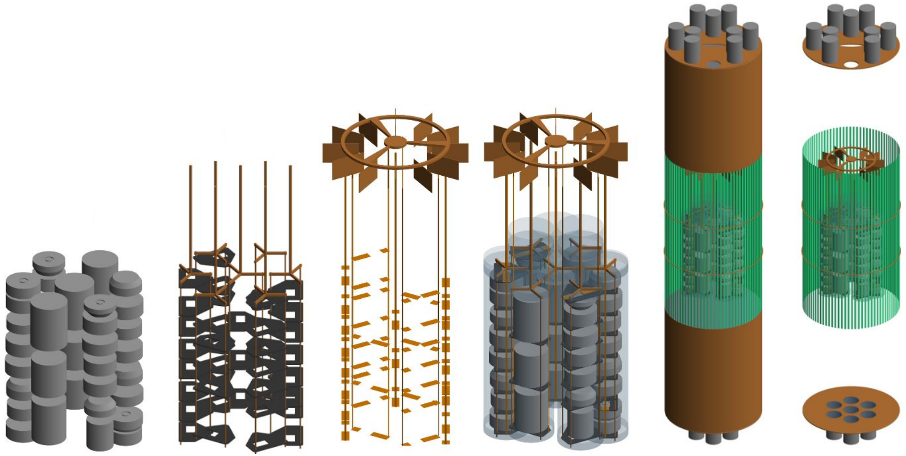
Background sources at lower energies

Counts in [45, 160] keV	**BEGe**		**SemiCoax**		**InvCoax**	
Tot data	778072	100%	326367	100%	326367	100%
Tot bkg	22484	2.9%	7562	2.3%	6733	1.2%
^{42}K	14874	1.9%	4821	1.4%	4197	1.2%
^{40}K	2732	0.4%	1052	0.3%	1042	0.3%
2nbb	1828	0.2%	855	0.3%	673	0.1%
^{214}Pb + ^{214}Bi	1553	0.2%	415	0.1%	399	0.1%
^{212}Pb + ^{212}Bi	884	0.1%	231	<0.1%	228	<0.1%
^{228}Ac	408	<0.1%	99		228	
^{85}Kr	729	0.1%	248		188	
^{42}Ar	1		1		1	



Monte Carlo simulations

- The PDFs used to model contributions to the energy spectra are obtained from Monte Carlo simulations.
- MC simulations are get using the MaGe simulation framework which contains the implementation of the GERDA detector arrays.
- $2\nu\beta\beta$ decays of ^{76}Ge in HPGe detectors and background events from radioactive contamination in all the hardware components are simulated.



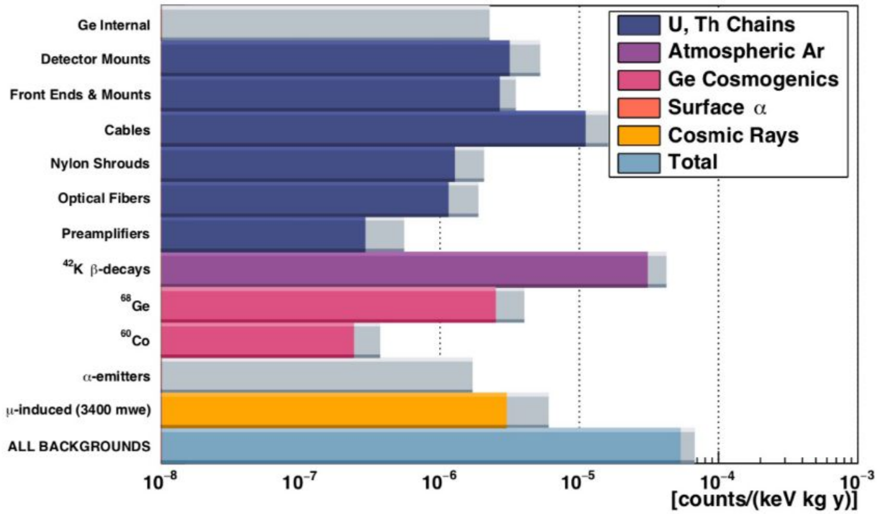
Analysis for GERDA Phase II

- The analysis is performed on the three binned data sets (bin size of 1 keV) `M1-enrBEGe`, `M1-enrCoax` and `M2-enrGe`.
- The fit range for M1 is [565-5260] keV while for M2 is [520-3600] keV
- The likelihood function combining the three datasets is

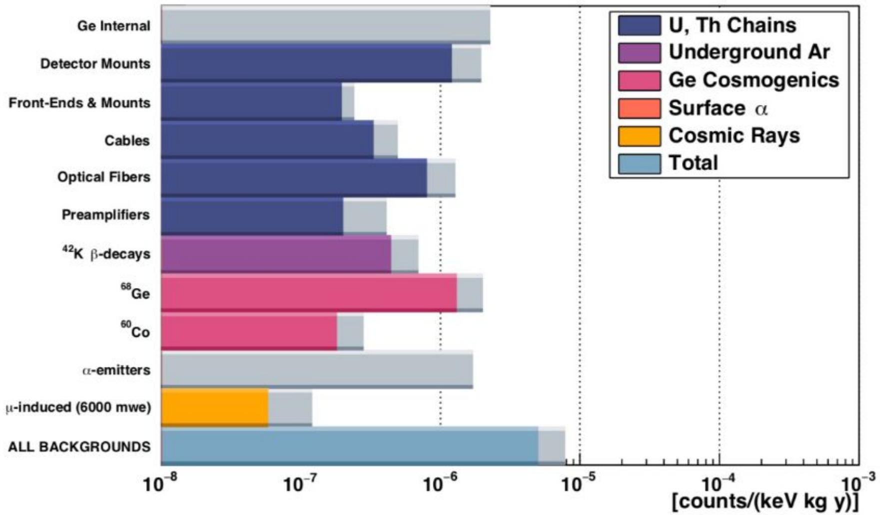
$$\mathcal{L}(\lambda_1, \ldots, \lambda_m \,|\, \text{data}) = \prod_{d=1}^{N_{\text{dat}}} \prod_{i=1}^{N_{\text{bins}}} \text{Pois}(n_{d,i}; \nu_{d,i})$$

- The statistical inference is made within a Bayesian framework.
- To obtain posterior probabilities for the free parameters of interest λ_j, the likelihood is multiplied by the prior of each background component
- The computation is performed using a Markov Chain Monte Carlo (MCMC) and is implemented using the BAT software suite
- A p-value estimate is provided as a goodness-of-fit measure

Future Backgrounds



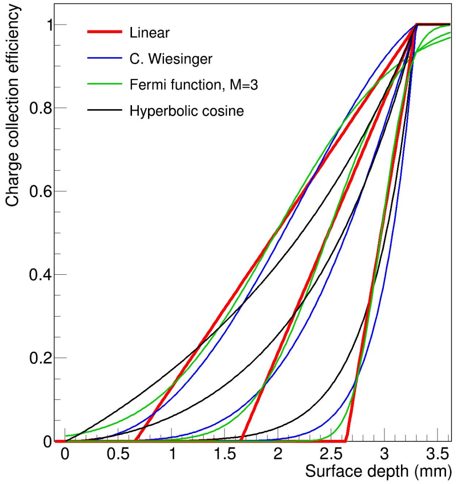
L-200 Background Summary

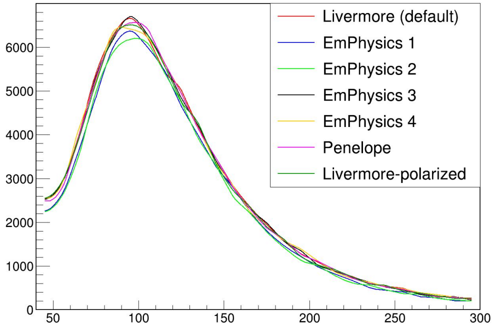


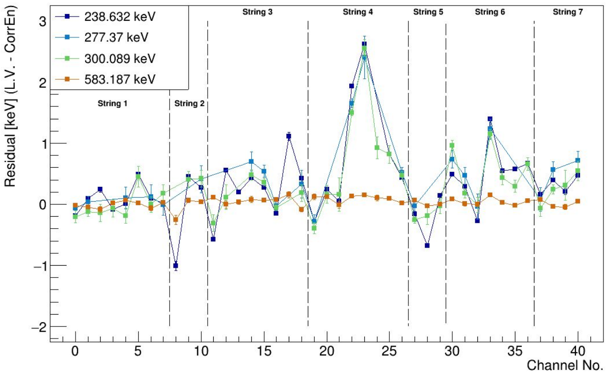
L-1000 Background Summary

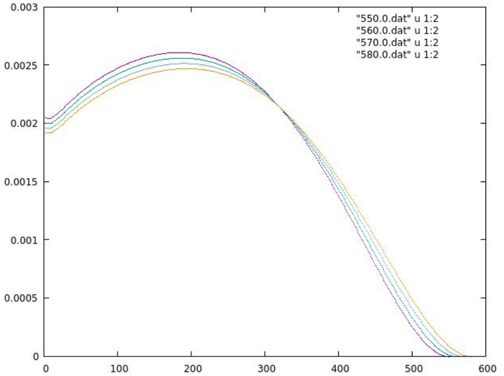
Systematics uncertainties in ^{39}Ar analysis

- Analytic model of the transition layer
- Alternative Geant4 low-energy physics lists (*bremsstrahlung* model)
- Background model (test different source positions)
- ^{39}Ar Q-value (565+-5) keV
- Low-energy scale









How systematics affects the ^{39}Ar analysis

- Profile likelihood for FCCD parameter obtained from the data
- Critical threshold (68% CL) of the t_s for systematic uncertainty
- ~ 16% systematic uncertainty