The LEGEND experiment and related research activities at MPP

Felix Hagemann

November 17th 2022

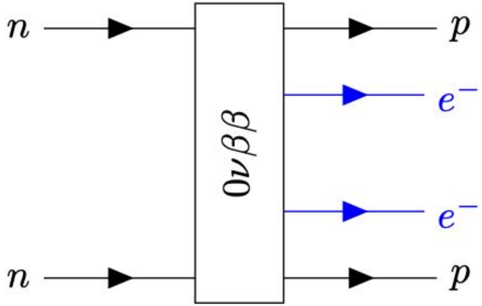
MAX-PLANCK-INSTITUT FÜR PHYSIK

The LEGEND experiment

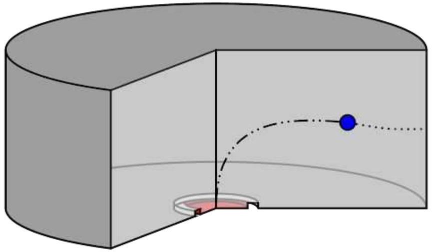
Outline

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Neutrinoless ββ Decay (0νββ)



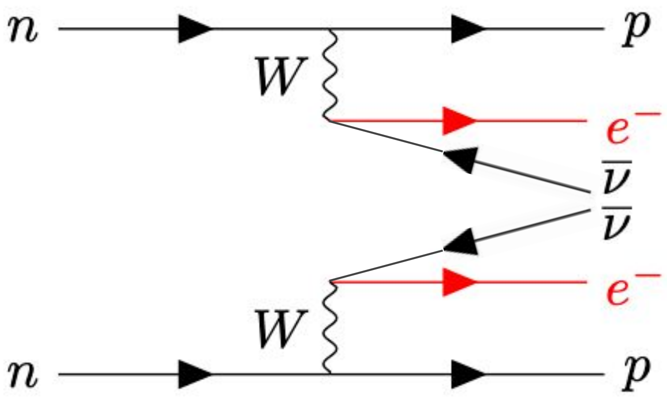
Enriched Germanium detectors

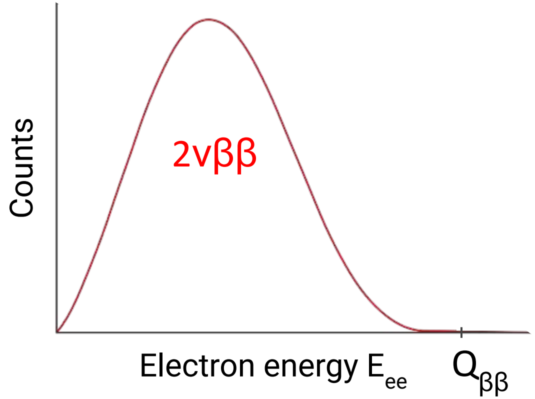


Large Experimental programs

LEGEND

Two neutrino ββ Decay (2νββ)





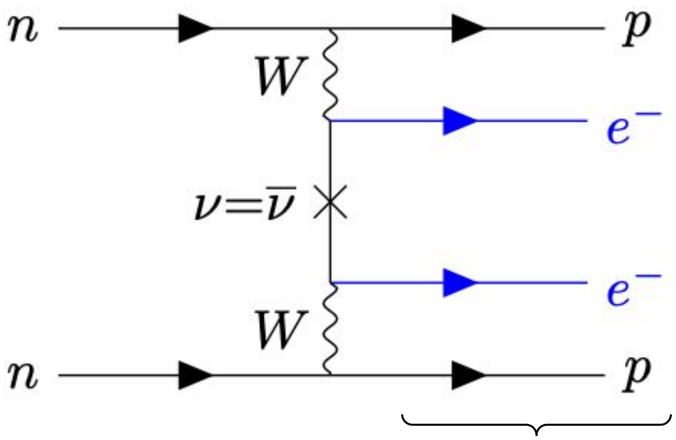
2νββ is a nuclear decay mode where two neutrons (or two protons) β-decay simultaneously

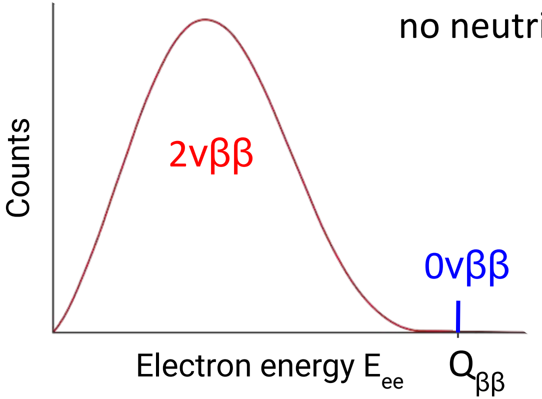
- very rare (half-lifes $T_{1/2}$ of the order 10^{19} - 10^{21} yr)
- has been observed in several isotopes, e.g.
  ^{48}Ca **^{76}Ge** ^{82}Se ^{96}Zr ^{100}Mo ^{116}Cd ^{130}Te ^{136}Xe ^{150}Nd …

In 2νββ, the released energy $\mathbf{Q_{\beta\beta}}$ is shared between the electrons and the anti-neutrinos ⇒ $E_{ee} < \mathbf{Q_{\beta\beta}}$

MAX-PLANCK-INSTITUT FÜR PHYSIK

Neutrinoless ββ Decay (0νββ)





0νββ is a hypothesized double-beta decay without emission of neutrinos → 2νββ isotopes are candidates for 0νββ

In 0νββ, the released energy $\mathbf{Q_{\beta\beta}}$ is shared amongst the two electrons ⇒ $E_{ee} = \mathbf{Q_{\beta\beta}}$

Observing 0νββ would prove that:

[Schechter and Valle, PRD 25, 2951 (1981)]

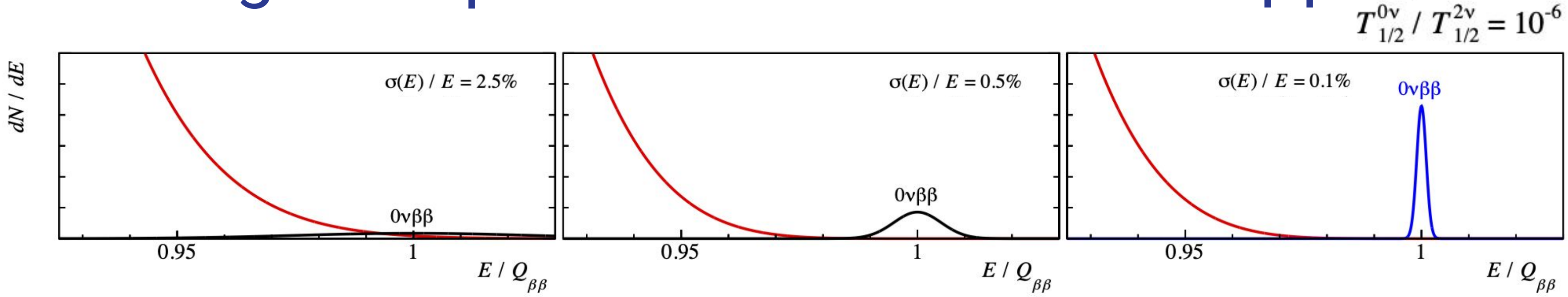
- lepton number is not conserved
- neutrinos are fundamental Majorana particles
- there is a new mass generation mechanism

If 0νββ is mediated by light Majorana neutrino exchange:

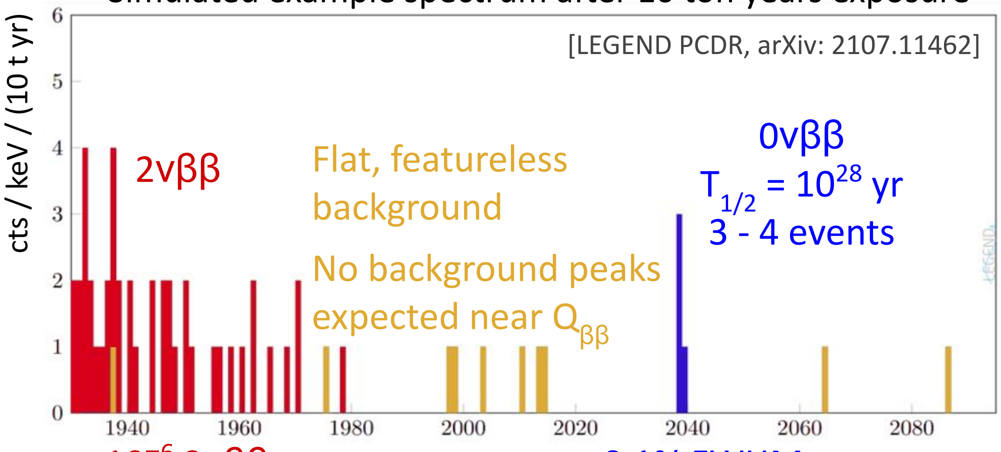
- the effective Majorana mass $m_{\beta\beta} = |\sum U_{ei}^2 m_i|$ can be determined from the decay rate: $\Gamma^{0\nu} \propto m_{\beta\beta}^2$
- For inverted ordering, $m_{\beta\beta}$ > 18.4 meV

MAX-PLANCK-INSTITUT FÜR PHYSIK

Building an Experiment to Search for 0νββ



Simulated example spectrum after 10 ton years exposure



$< 10^{-6}$ 2νββ events leak into in $Q_{\beta\beta} \pm 2\sigma$

≈ 0.1% FWHM energy resolution

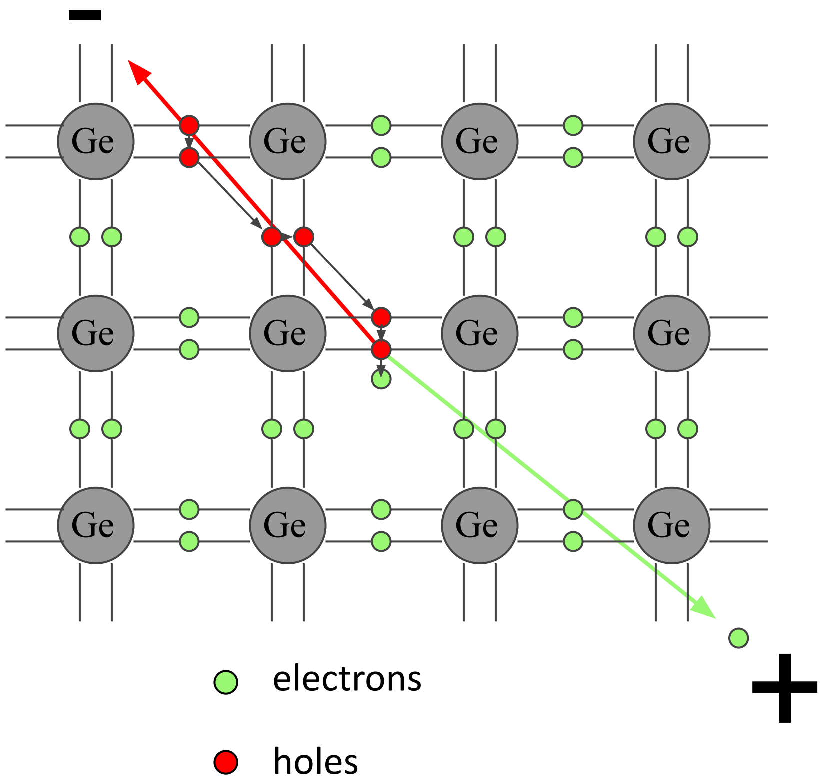
Detection of two electrons
→ high efficiency (source = detector)
→ excellent energy resolution

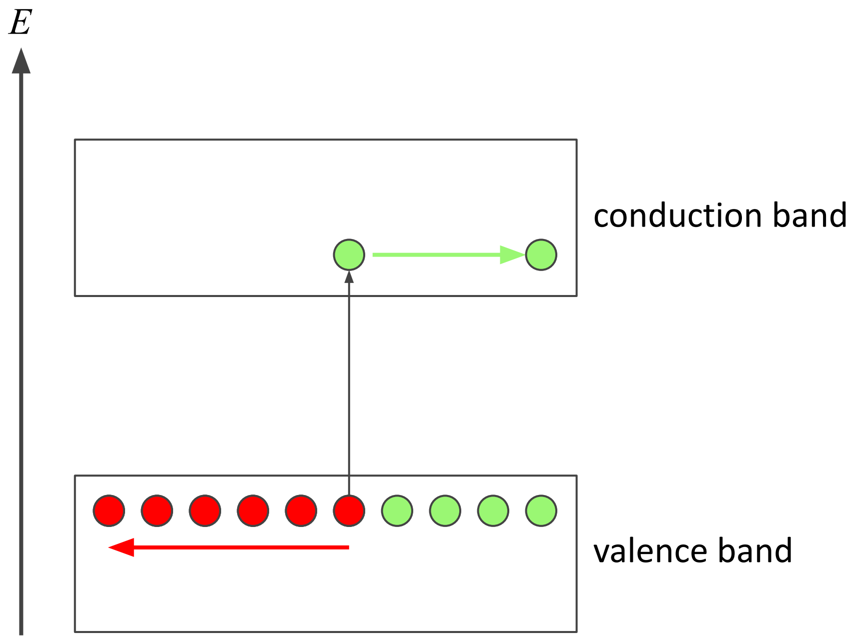
Large exposure
→ large isotope masses
→ long measurement times

Background-free measurement
→ avoid or identify background with energies around $Q_{\beta\beta}$

MAX-PLANCK-INSTITUT FÜR PHYSIK

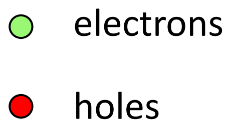
Germanium

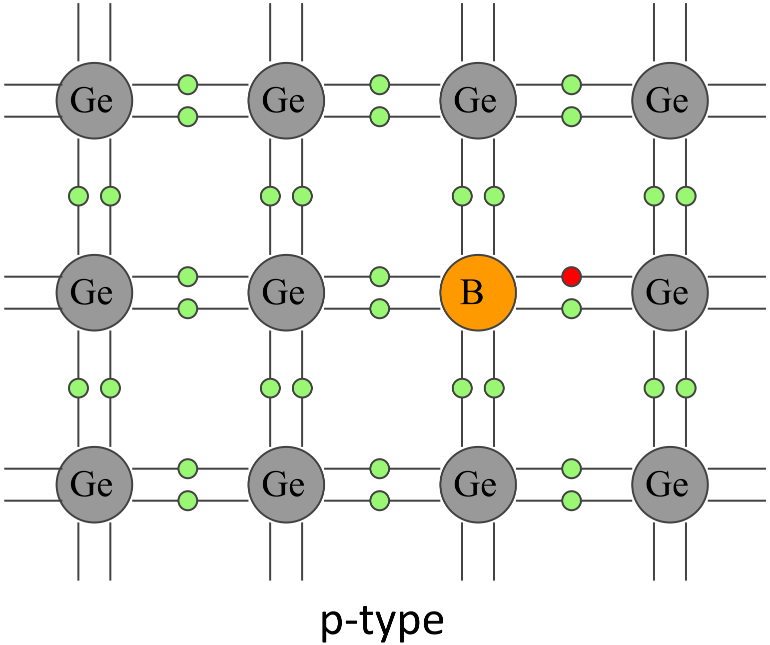


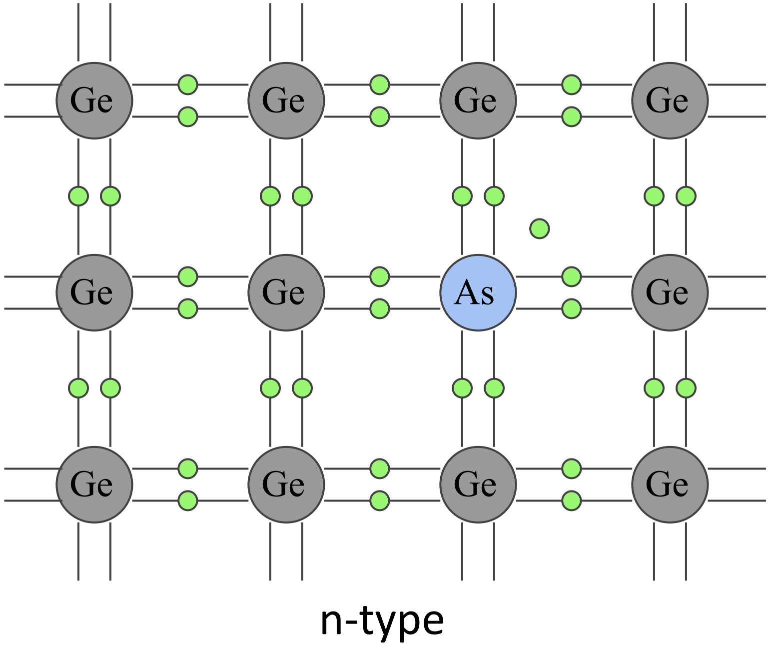


in average one electron-hole pair per 2.96 eV

Germanium

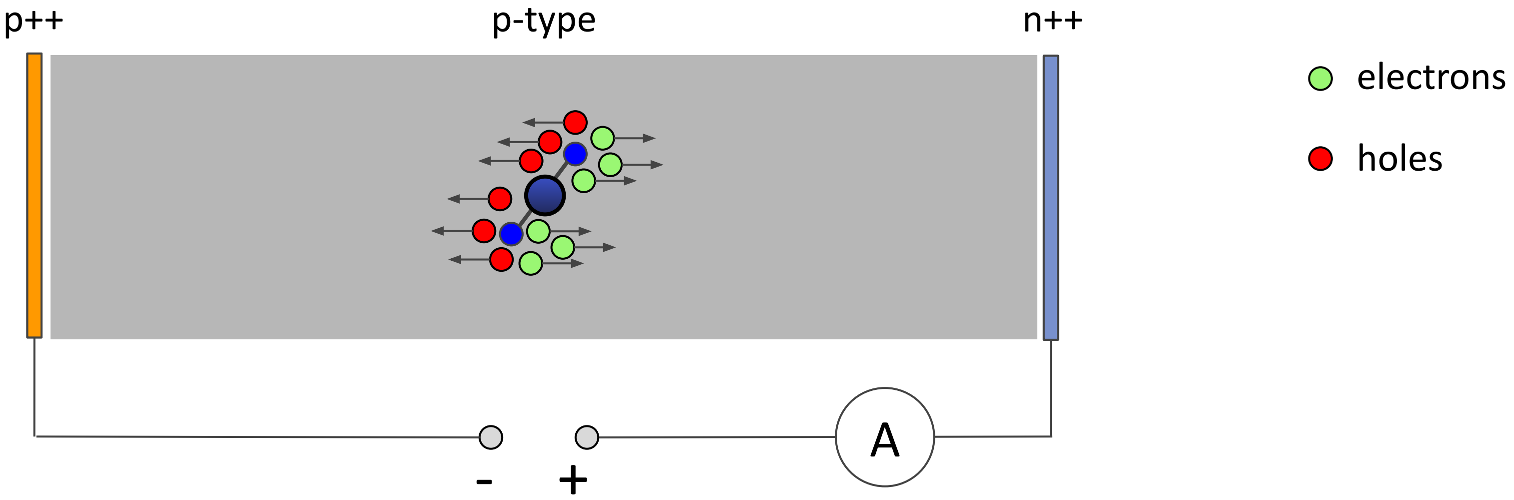






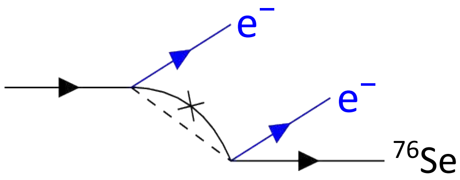
MAX-PLANCK-INSTITUT FÜR PHYSIK

Germanium Detectors



Germanium Detector Technology

HPGe detectors more than 90% enriched in ^{76}Ge



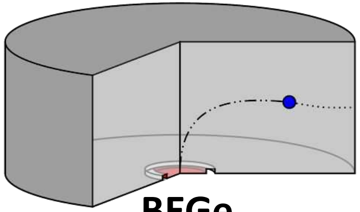
High detection efficiency (source = detector)

Best energy resolution of any 0νββ experiment (2.5 keV at $Q_{\beta\beta}$ = 2039 keV)

Modest operating voltage (< 5 kV) and cryogenic requirements (77 - 90 K)

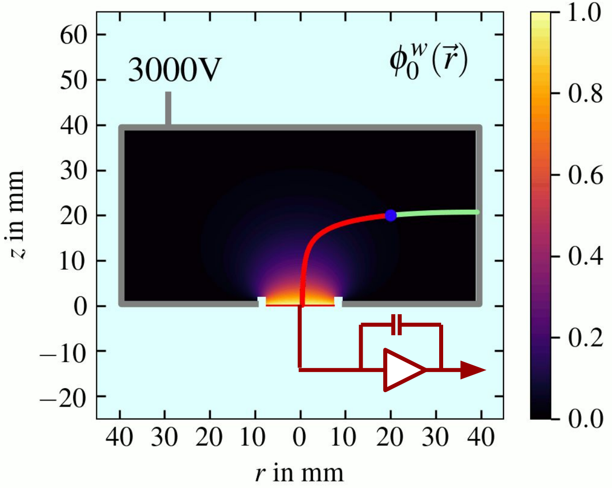
Pulse shapes used for event topology discrimination

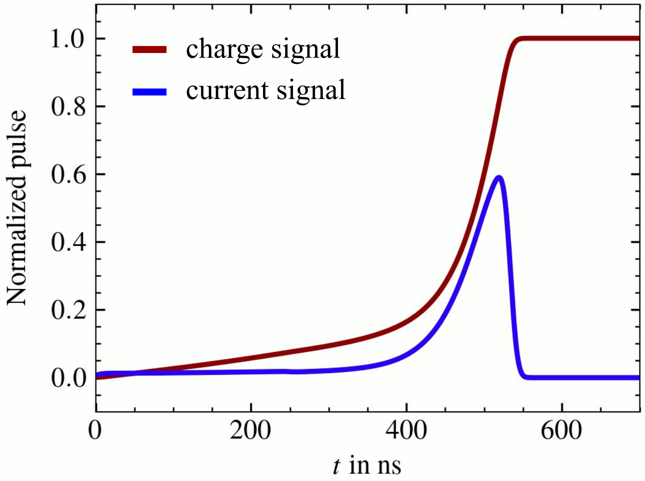
[Budjas et al., JINST 4, P10007 (2009)]
[GERDA, EPJC 79, 978 (2019)]

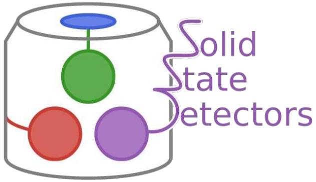


BEGe

Broad energy germanium detector







Development of open-source julia software package to simulate solid-state detectors: *SolidStateDetectors.jl*

[Abt et al., JINST 16, P08007 (2021)]

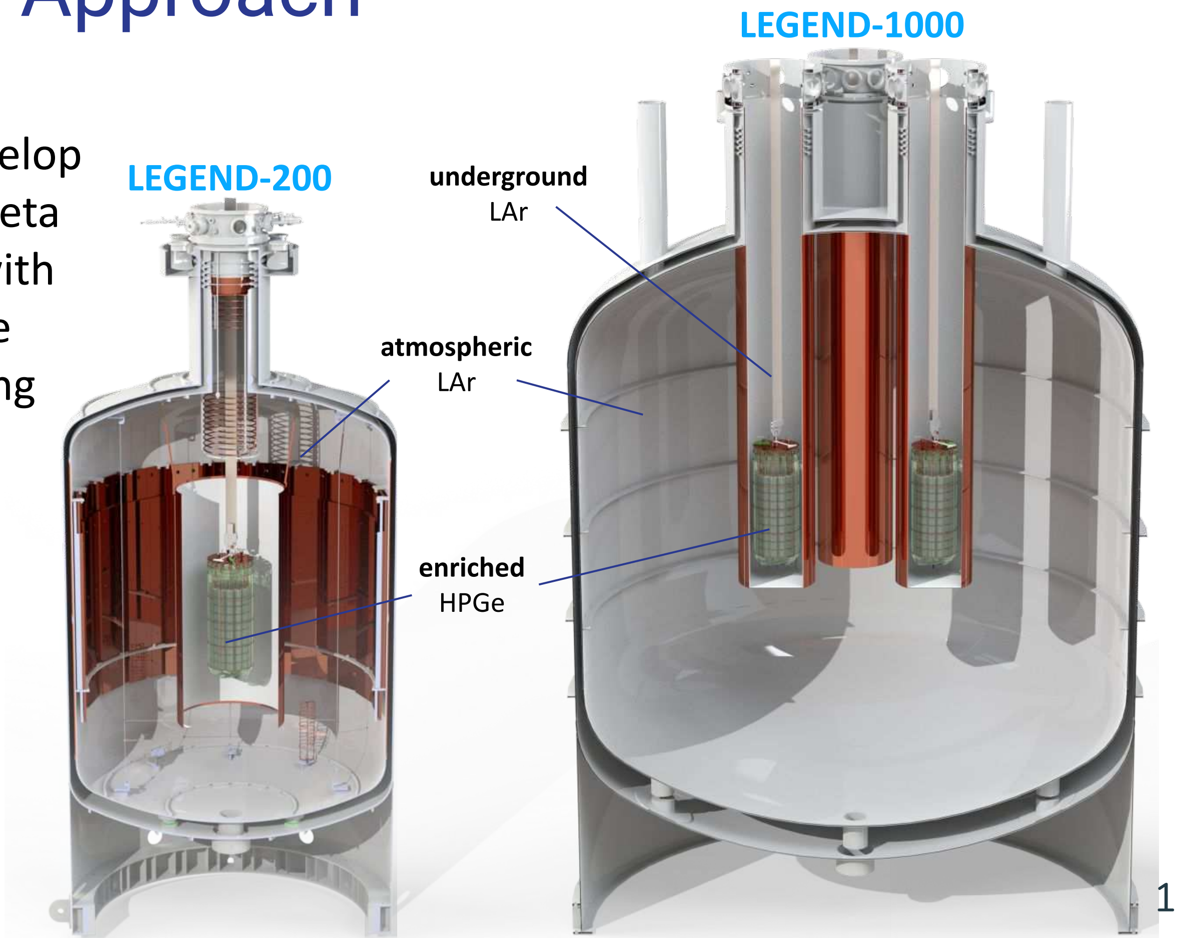
LEGEND: Phased Approach

LEGEND mission:

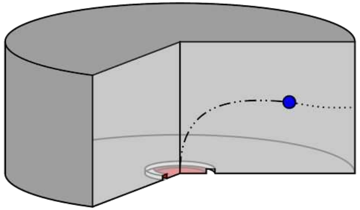
“The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results.”

About 250 members,
48 institutions, 11 countries

Preconceptual Design Report:
arXiv: 2107.11462

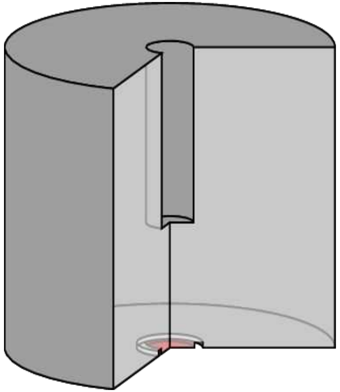


LEGEND-200



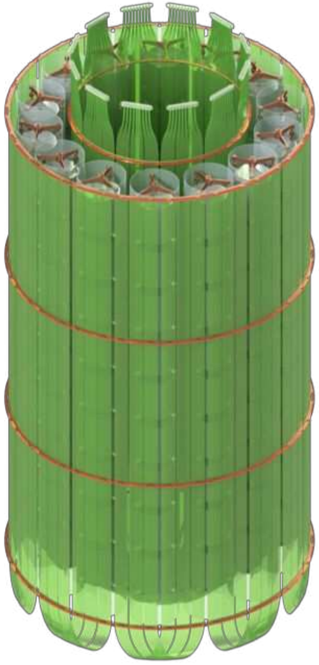
BEGe detectors

[Cooper et al., NIMA 665, 25 (2011)]

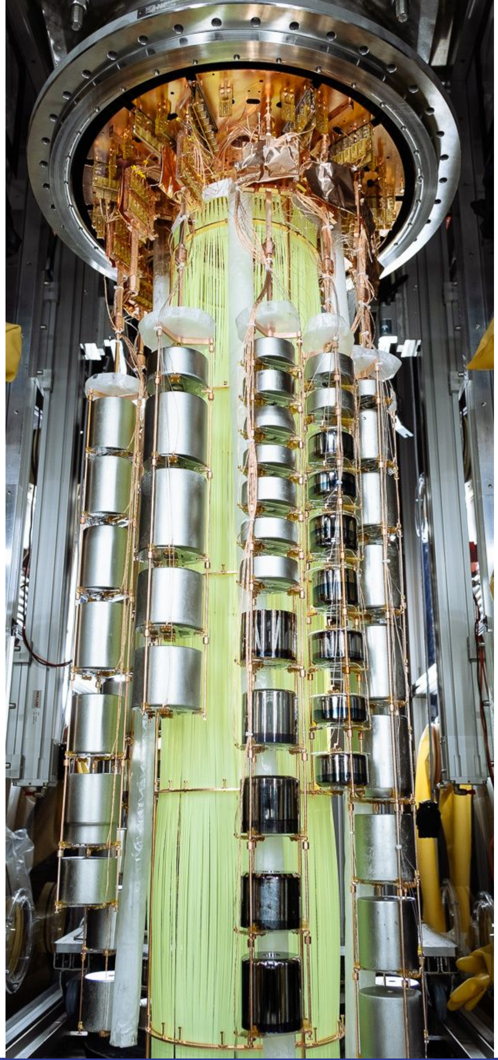


Inverted coaxial point-contact detectors

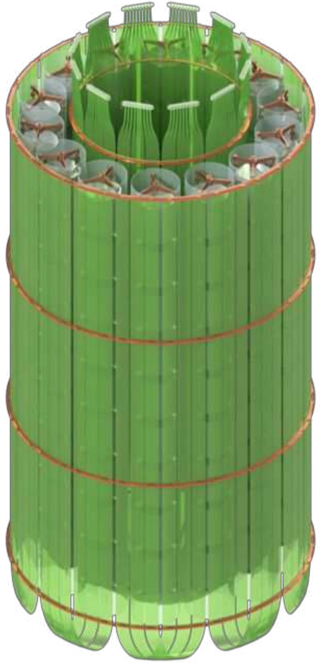
Detector arrays with copper holding structure

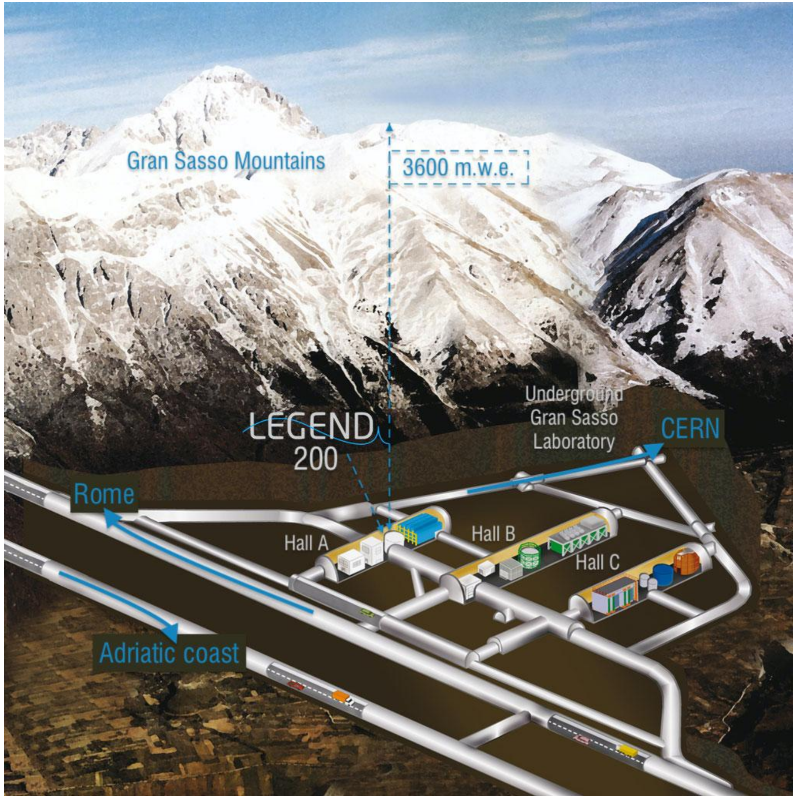


Enclosed in optical fiber shrouts



LEGEND-200



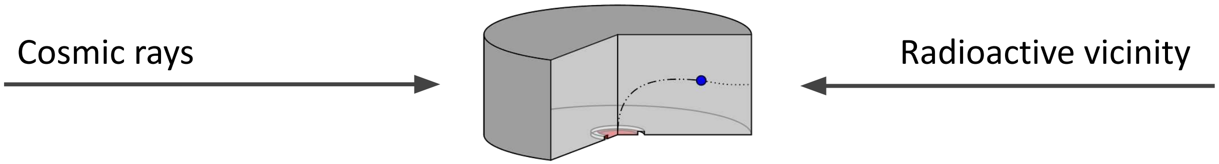


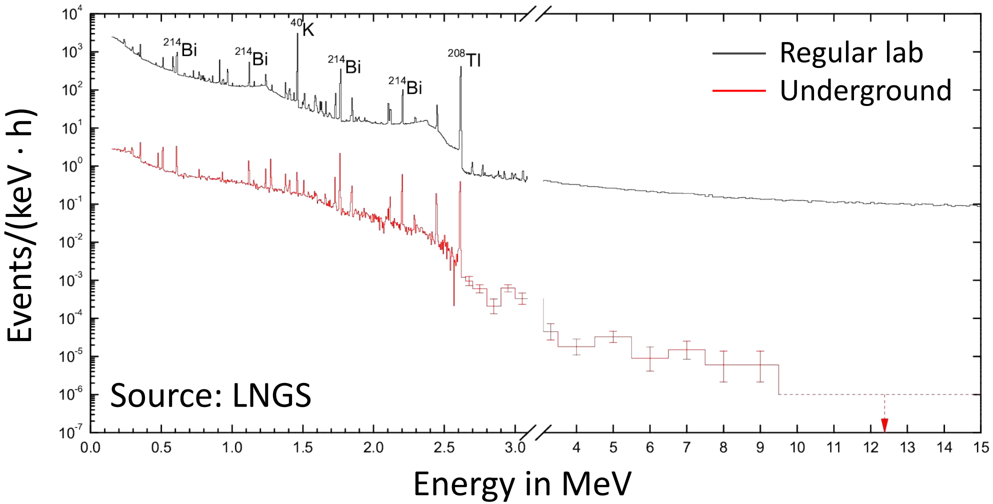
Germanium detector assembly

Liquid argon tank ($64 m^3$)
Pure water tank ($600 m^3$)

Located underground at the Laboratori Nazionali del Gran Sasso

Background Sources





+

Reduction of background sources

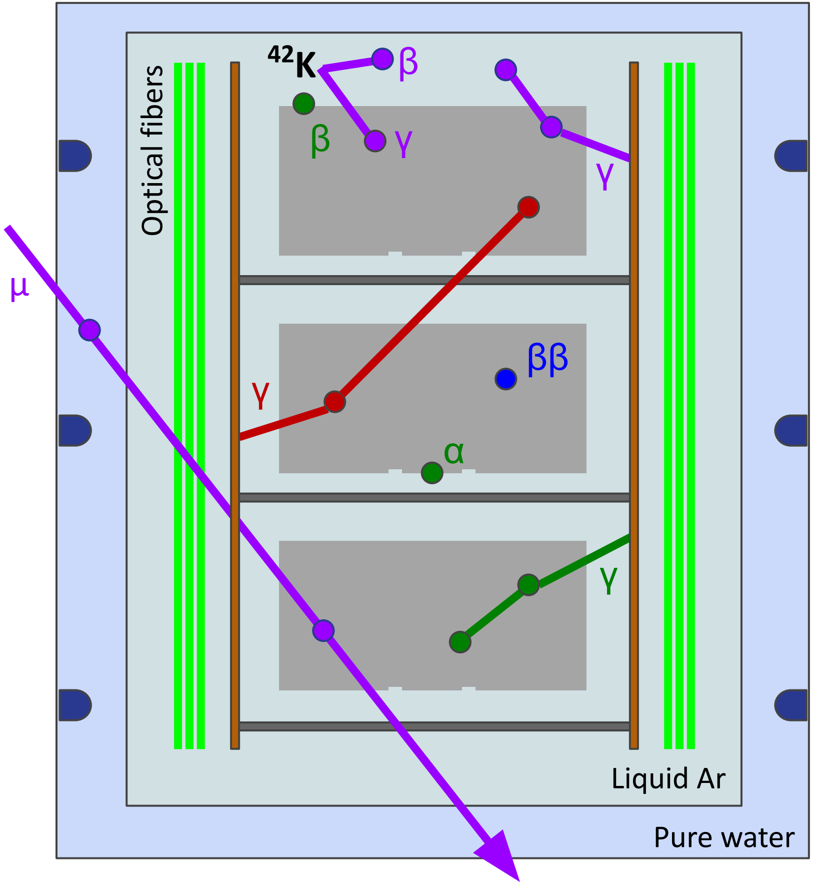
Passive shielding

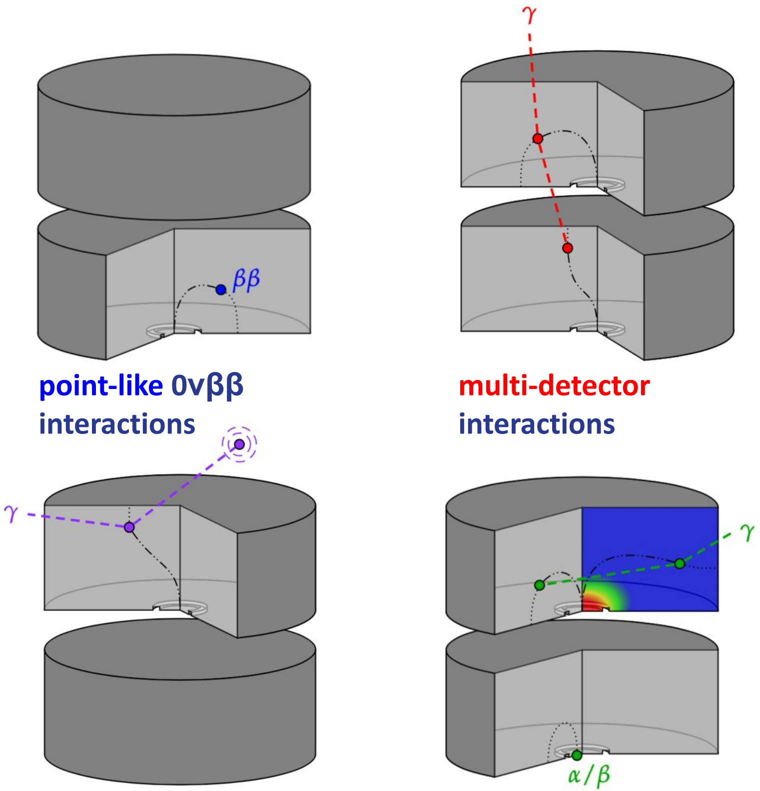
Active vetos

Pulse shape analysis

MAX-PLANCK-INSTITUT FÜR PHYSIK

Background Rejection: Active Vetos





point-like 0νββ interactions

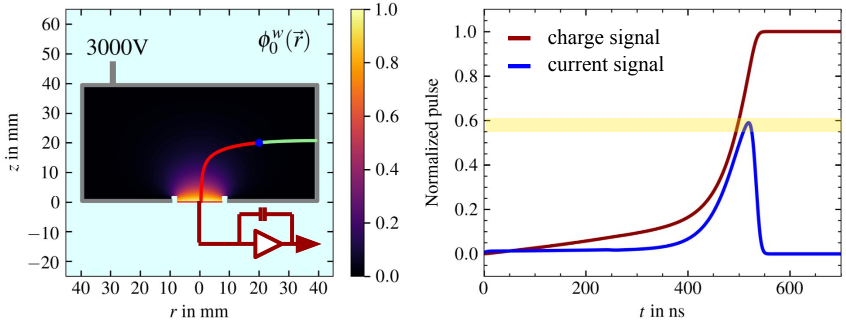
multi-detector interactions

interactions with partial energy deposition

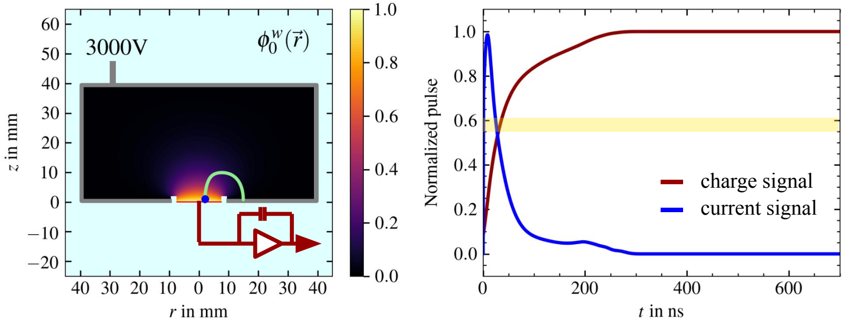
multi-site/surface interactions

Background Rejection: Pulse Shape Analysis

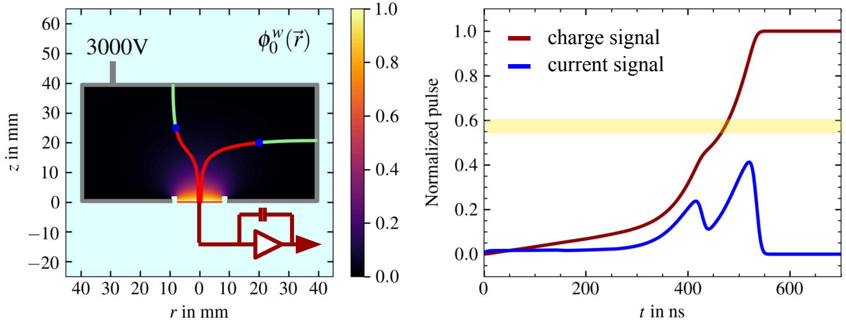
Single-site events



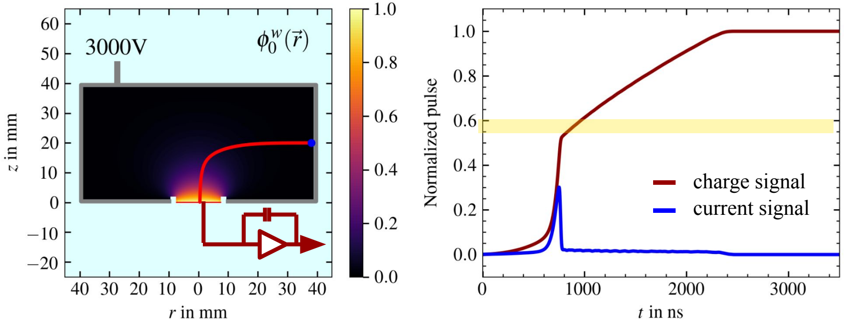
α surface events



Multi-site events



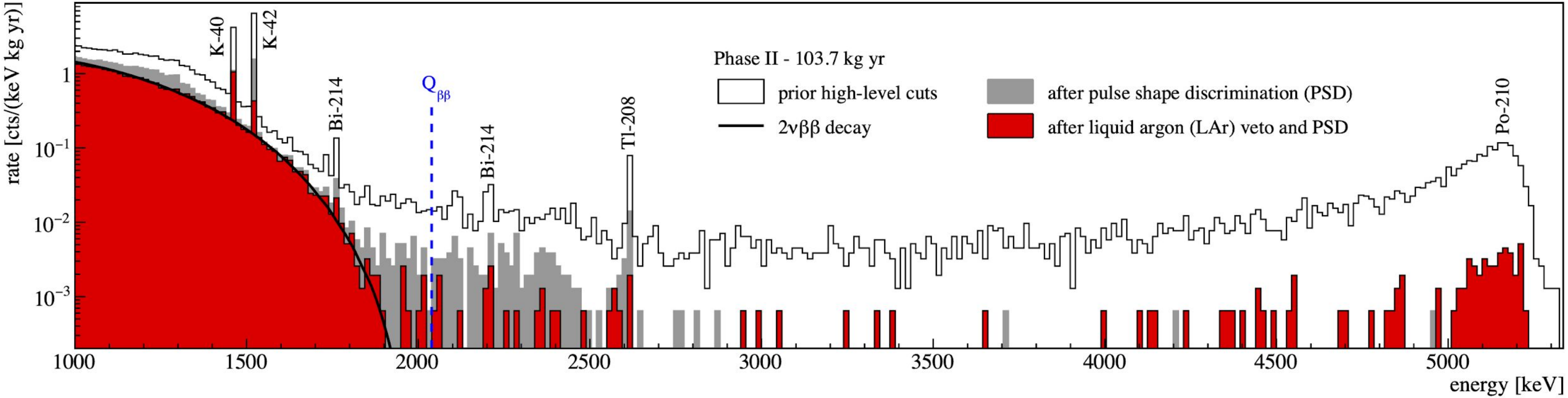
β surface events



Pulse shape discrimination based on A/E = max. of current pulse / max. of charge pulse

Final **GERDA** Results

[GERDA, PRL 125, 252502 (2020)]

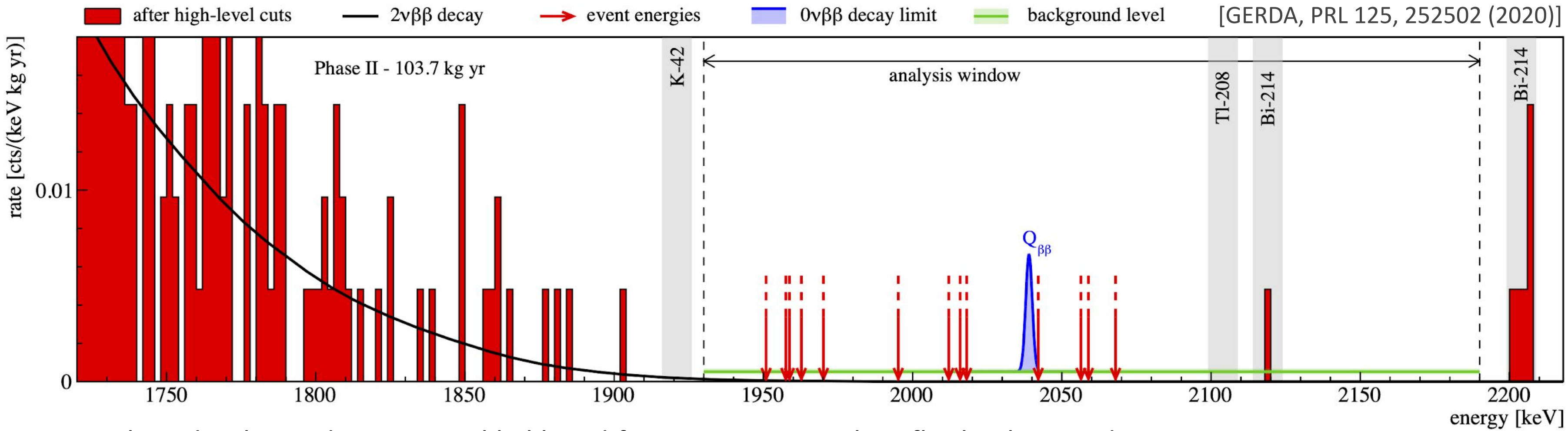


almost pure 2νββ continuum → precision studies, new physics searches (e.g. 0νββ decay with Majoron emission)

sparse single counts in the region of interest around $Q_{\beta\beta}$ = 2039 keV

Final **GERDA** Results

13 events, closest event at 2.4 σ



[GERDA, PRL 125, 252502 (2020)]

combined unbinned maximum likelihood fit, Gaussian signal on flat background, individual efficiencies/resolution (mean FWHM of 2.6 keV)

best fit: no signal $N^{0\nu} = 0$, background index $(5.2 \pm^{1.6}_{1.3}) \cdot 10^{-4}$ cts/(keV kg yr)
⟶ if normalized by the energy resolution: lowest background in the field

Frequentist $T_{1/2} > 1.8 \cdot 10^{26}$ yr (median sensitivity) at 90% C.L. ⇒ $m_{\beta\beta} < (79 - 180)$ meV

Current and Future $0\nu\beta\beta$ Experiments using ^{76}Ge

	GERDA [GERDA, PRL 125, 252502 (2020)]	LEGEND-200 [LEGEND, arXiv: 1709.01980]	LEGEND-1000 [LEGEND PCDR, arXiv: 2107.11462]
Detector mass	44.2 kg	up to 200 kg	1000 kg (payloads)
Background index [cts/(keV kg yr)]	$(5.2 \pm^{1.6}_{1.3}) \cdot 10^{-4}$	$< 2 \cdot 10^{-4}$	$< 1 \cdot 10^{-5}$
Energy resolution (FWHM)	(2.6 ± 0.2) keV	< 2.5 keV	< 2.5 keV
Experimental site	LNGS	LNGS	LNGS or SNOLAB
Discovery (90% CL)	$1.8 \cdot 10^{26}$ yr	$> 10^{27}$ yr	$> 10^{28}$ yr

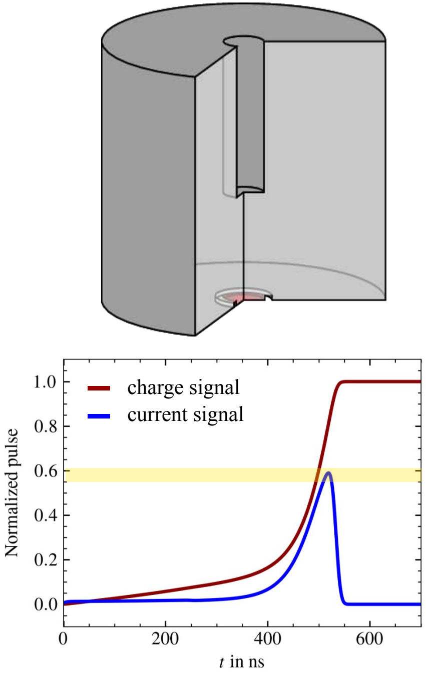
GERDA:
very low back-
ground index

LEGEND:
learn from the experience of **GERDA**
improve sensitivity by reducing background

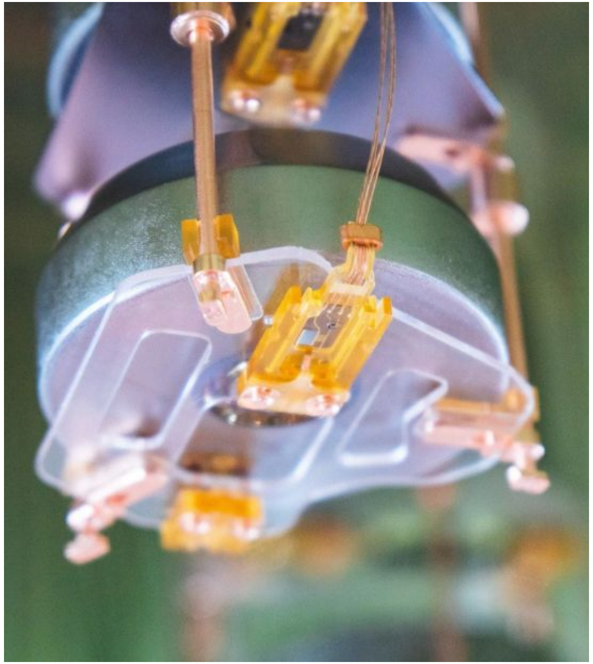
MAX-PLANCK-INSTITUT
FÜR PHYSIK

LEGEND: Research and Development

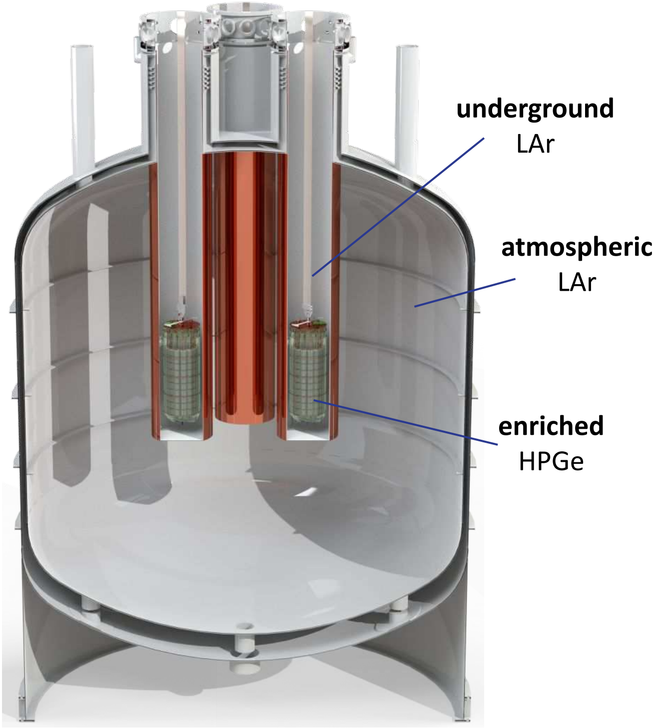
[LEGEND PCDR, arXiv: 2107.11462]



Increase pulse shape discrimination efficiency



Improve material selection and scintillation light read-out



Optimize cryostat design for **LEGEND-1000**

LEGEND related research activities at MPP

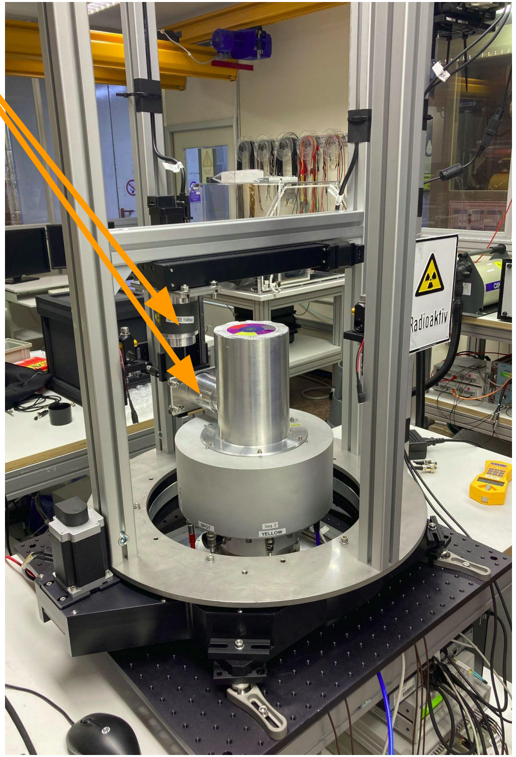
^{133}Ba Surface Scanner

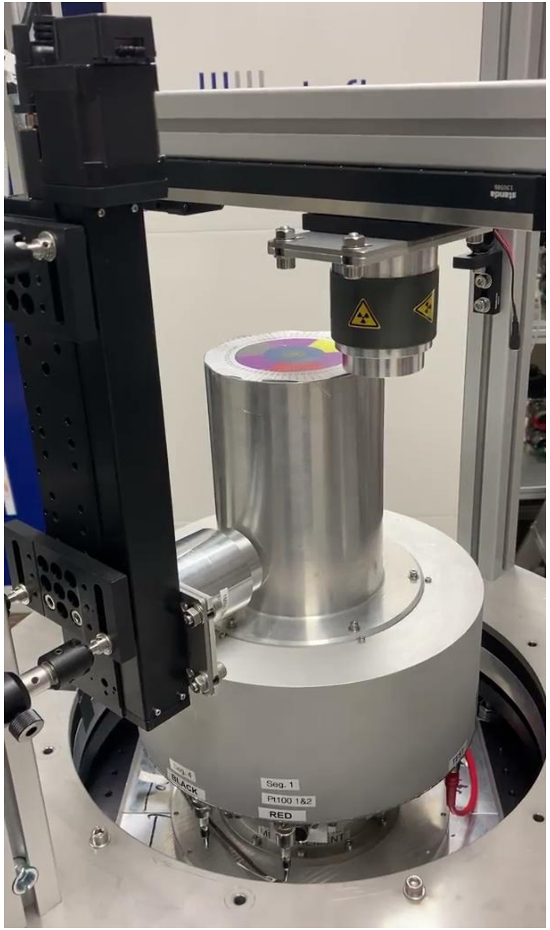
Two ^{133}Ba sources (each 1 MBq)
→ 30.973 keV photon
→ 80.997 keV photon
→ 276.398 keV photon
→ 302.853 keV photon
→ 356.017 keV photon
→ 383.851 keV photon

4cm tungsten collimator
with ø 1.5mm borehole

Energy is deposited close to the
surface via the photoelectric effect

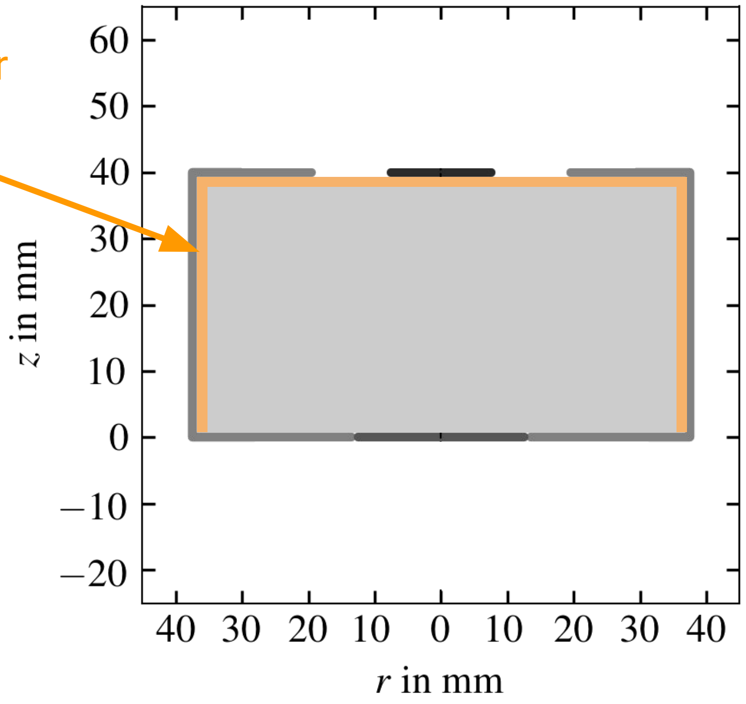
Fully automated setup





Experimental test stands

^{133}Ba Surface Scanner



^{137}Cs Compton Scanner

[Abt et al., EPJC 82, 936 (2022)]

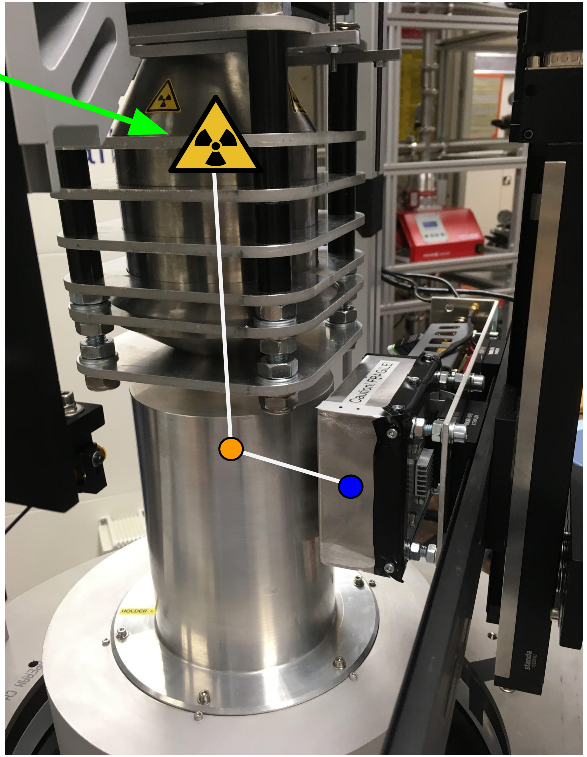
^{137}Cs source (740 MBq)
→ 661.66 keV gammas

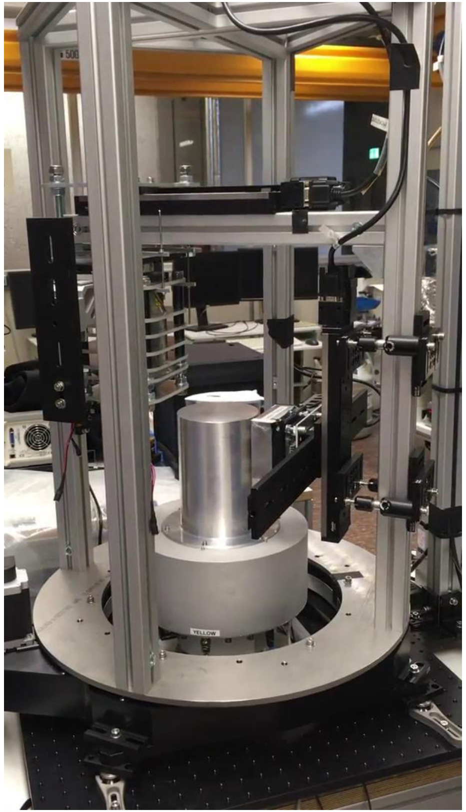
10cm tungsten collimator with ø 0.9mm borehole

Pixelated CdZnTe camera at the side of the detector

Energy is deposited in the bulk of the detector via Compton scattering → the Compton scattered gammas are detected in the camera

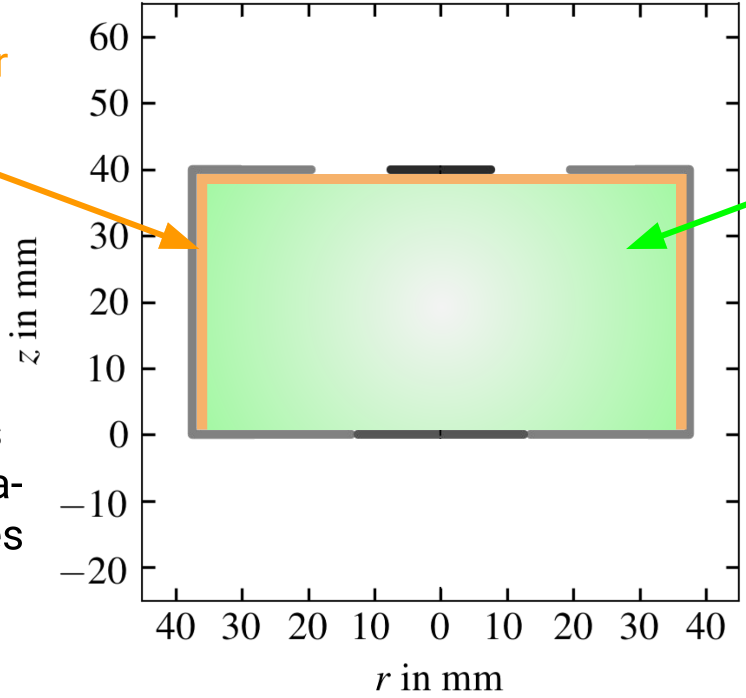
Fully automated setup





Experimental test stands

^{133}Ba Surface Scanner



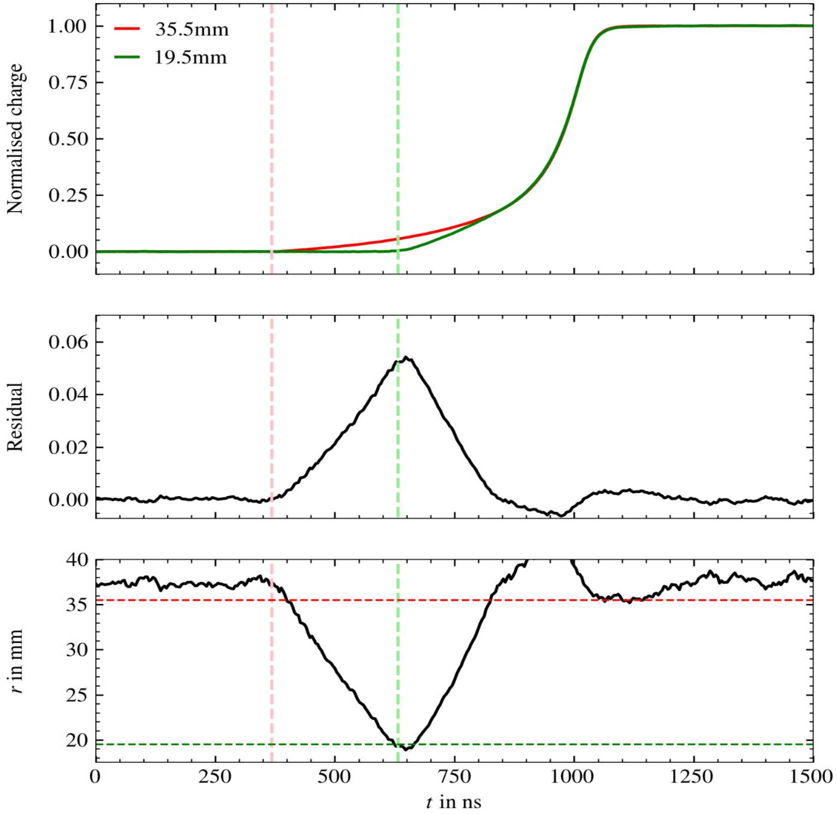
^{137}Cs Compton Scanner

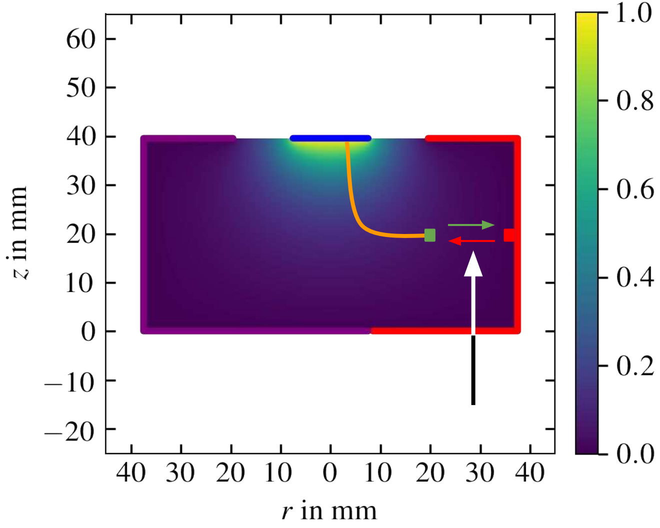
Pulse shape libraries at different bias voltages and temperatures

Stable temperatures in the range from 73K to 100K

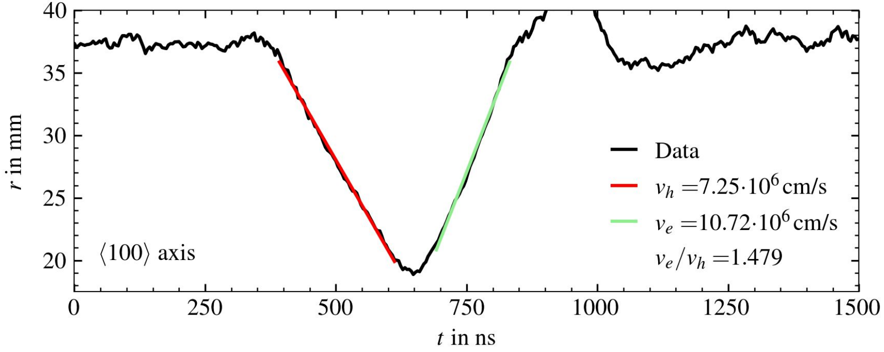
Different bias voltages (recommended: −3000V, here from −900V to −4500V)

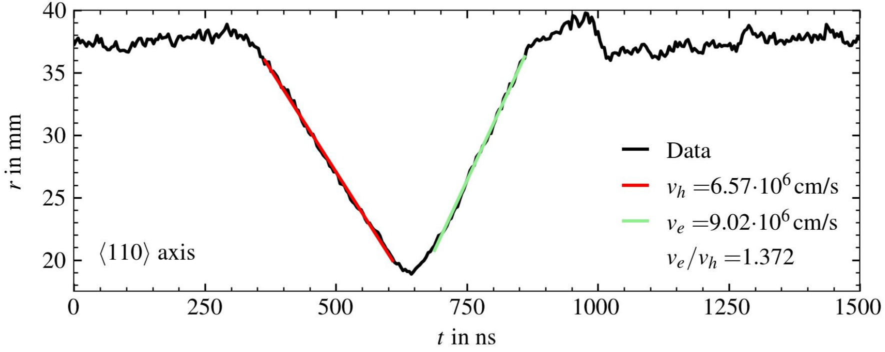
Determination of drift mobilities





Determination of drift mobilities





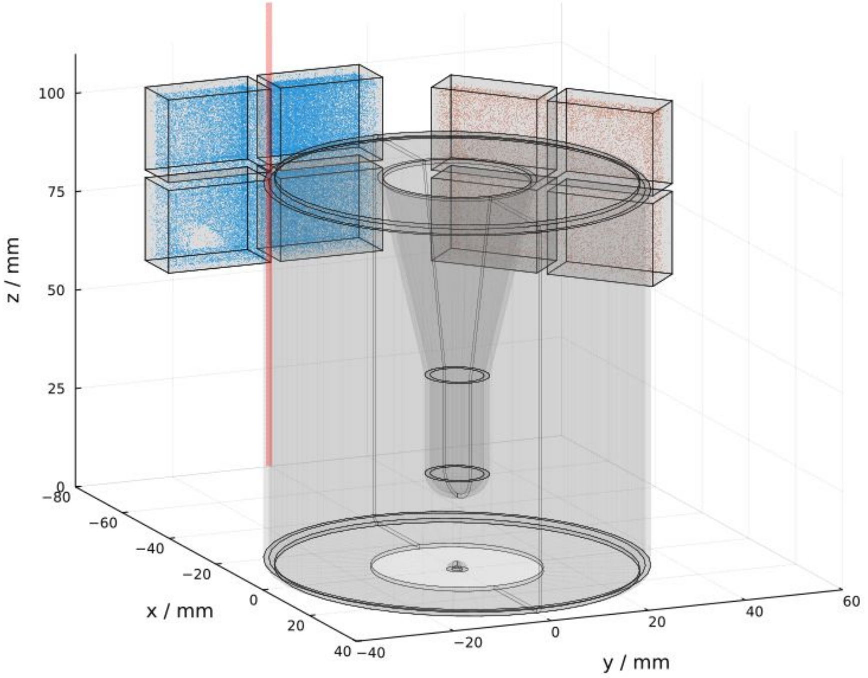
$$\nabla \left(\varepsilon_r(\vec{r}) \vec{E}(\vec{r}) \right) = \frac{\rho(\vec{r})}{\varepsilon_0}$$

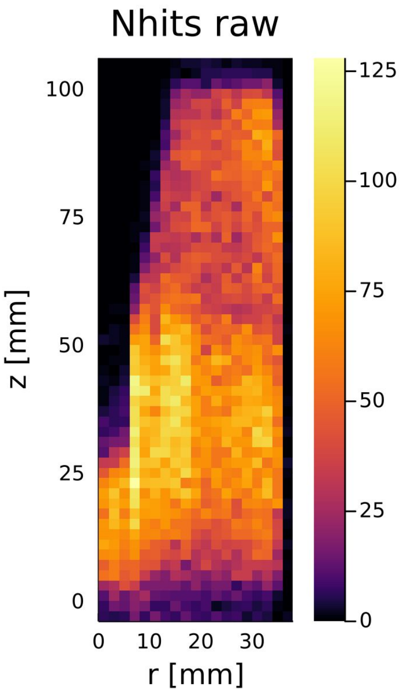
$$\vec{v}_e(\vec{r}_e) = \hat{\mu}_e \vec{E}(\vec{r}_e)$$

$$\vec{v}_h(\vec{r}_h) = \hat{\mu}_h \vec{E}(\vec{r}_h)$$

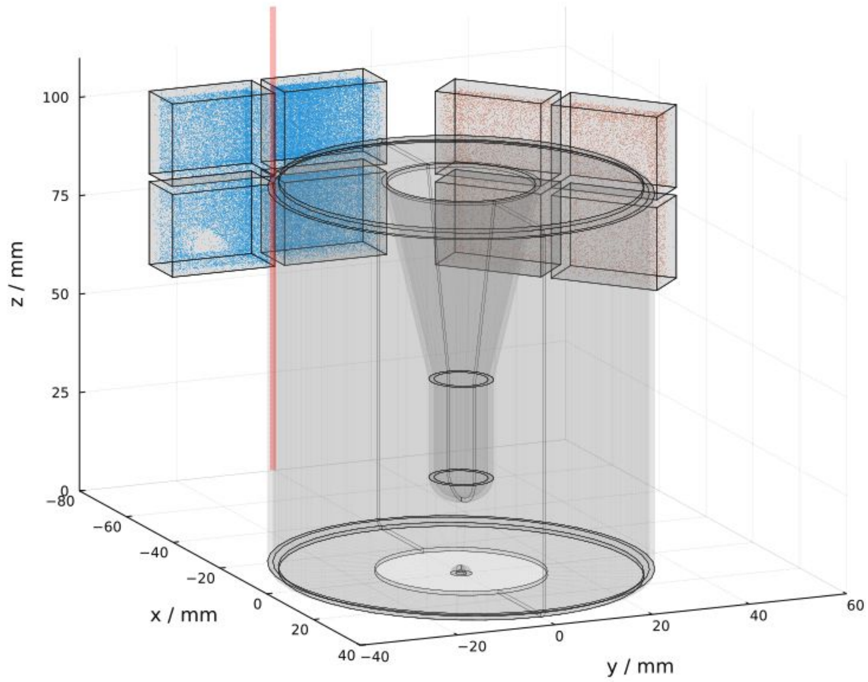
MAX-PLANCK-INSTITUT FÜR PHYSIK

ICPC detectors & Depletion bubble imaging



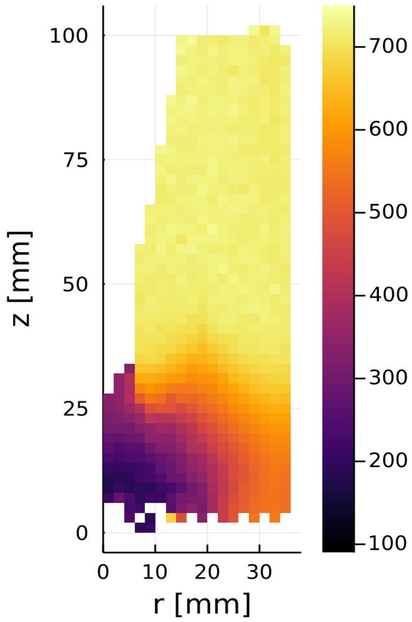


ICPC detectors & Depletion bubble imaging



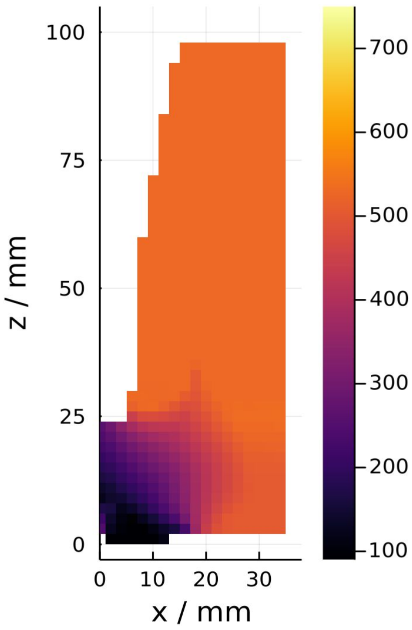
MEASURED

1 – 99% rise time in ns



SIMULATED

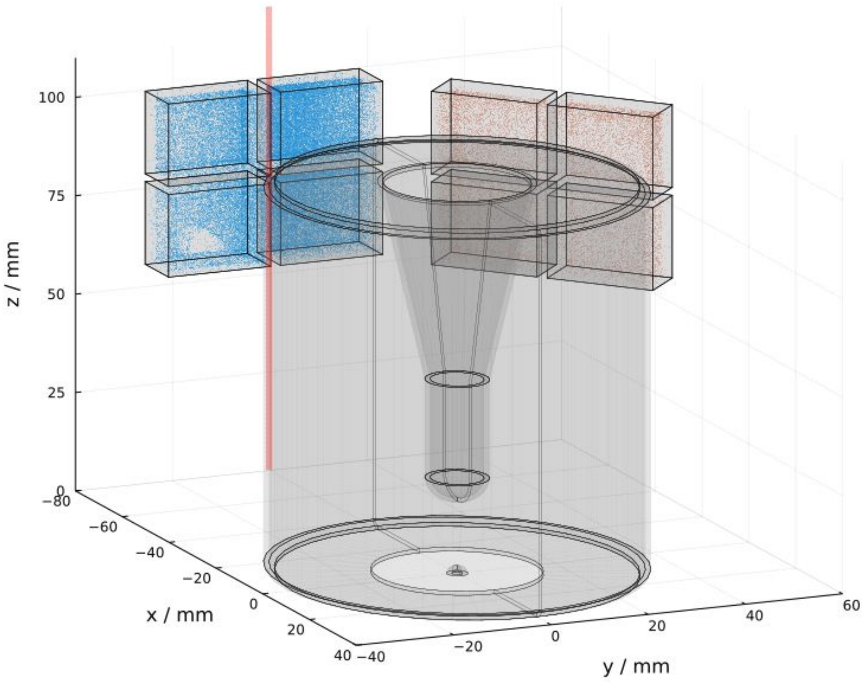
1 – 99% rise time in ns



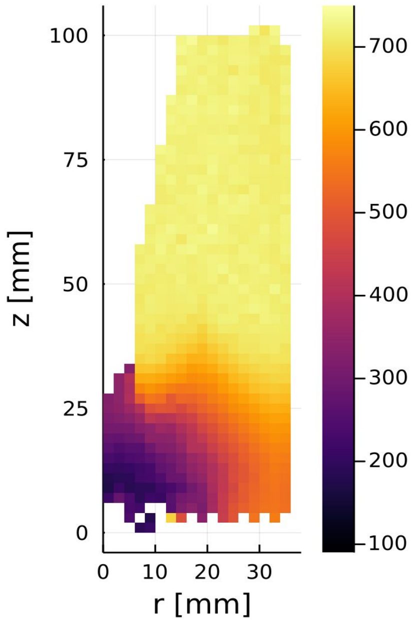
VALUES GIVEN BY THE CRYSTAL MANUFACTURER

MAX-PLANCK-INSTITUT FÜR PHYSIK

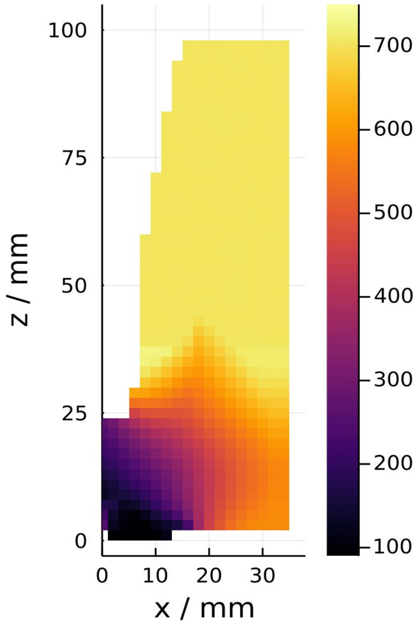
ICPC detectors & Depletion bubble imaging



MEASURED
1 – 99% rise time in ns



SIMULATED
1 – 99% rise time in ns

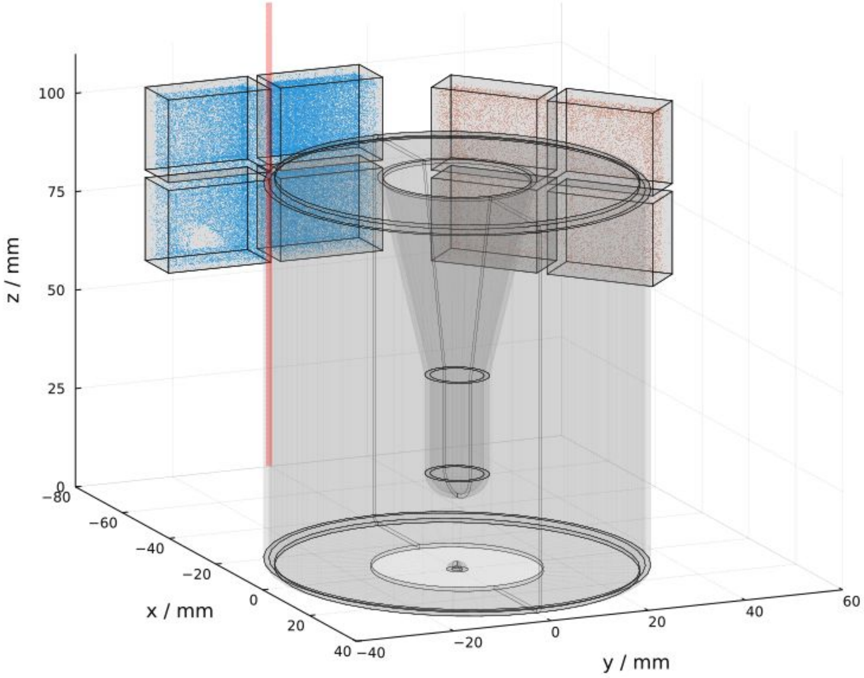


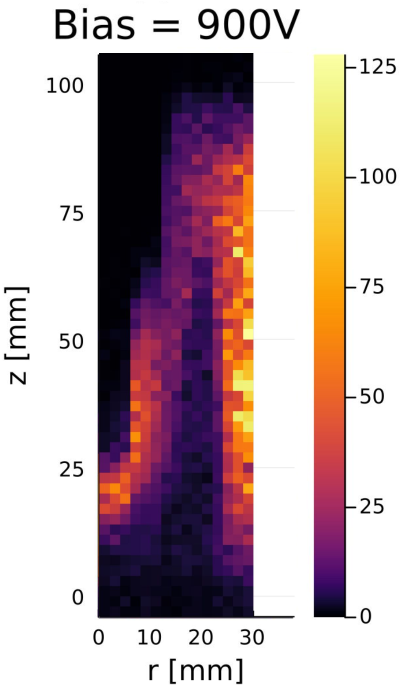
Solid State Detectors

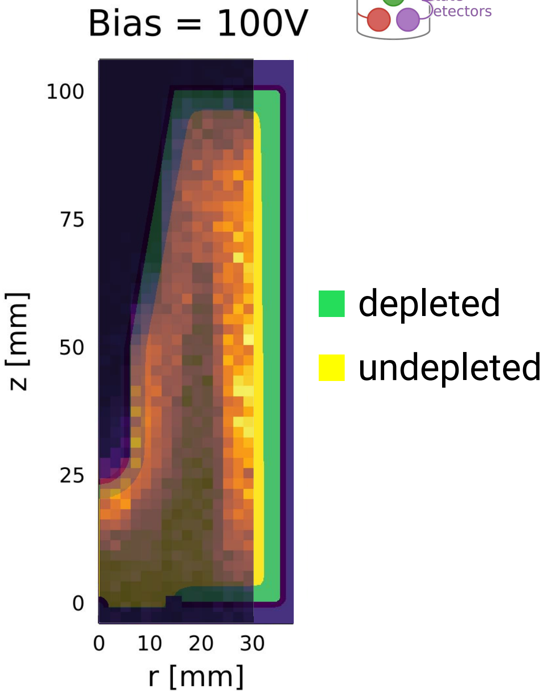
VALUES 90% OF THE IMPURITY DENSITY VALUES

MAX-PLANCK-INSTITUT FÜR PHYSIK

ICPC detectors & Depletion bubble imaging

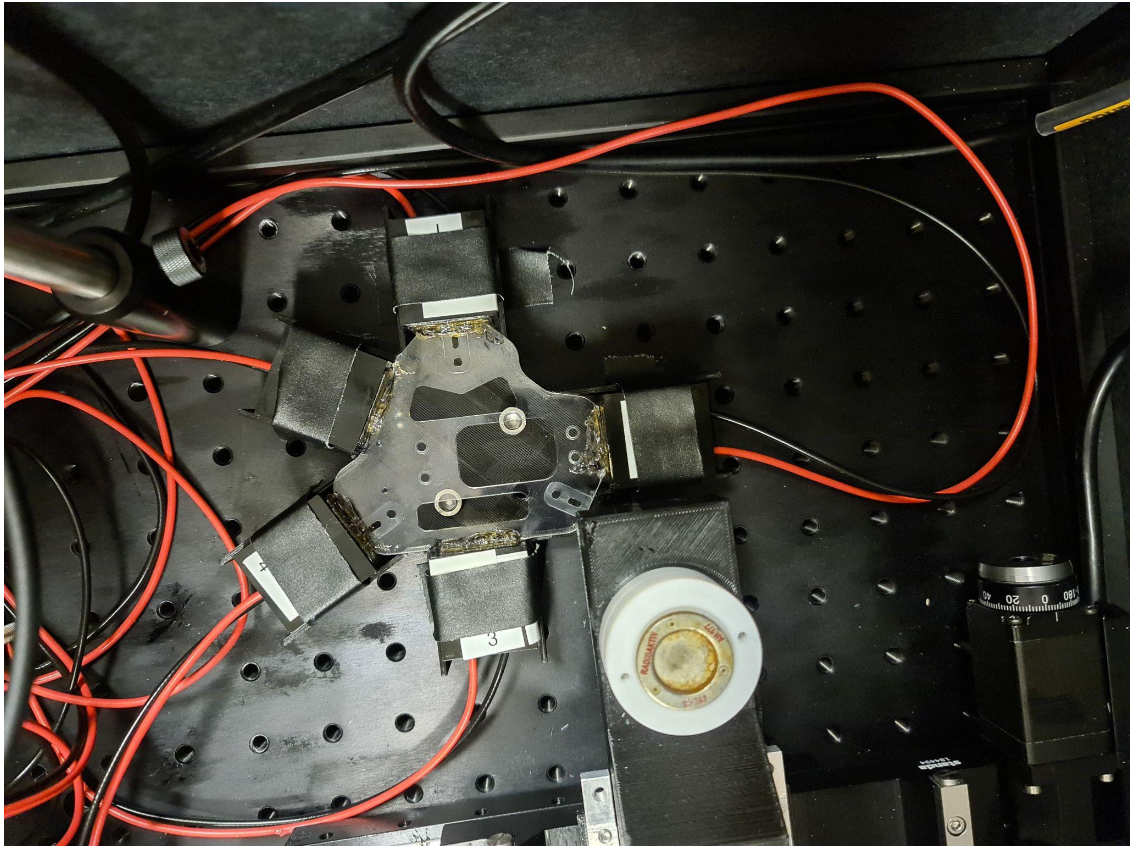


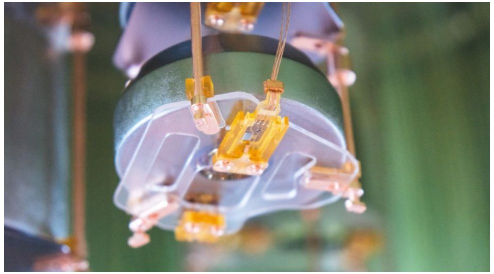




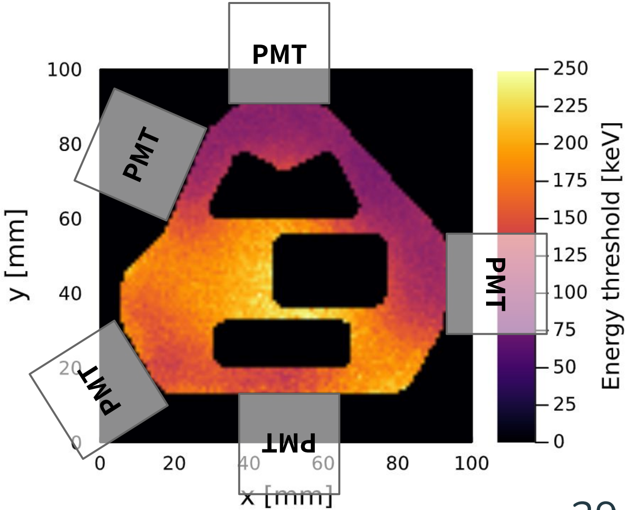
PEN Scanning Table Setup at MPP

[Efremenko et al., JINST 17, P01010 (2022)]





PEN = poly (ethylene naphthalate)



Summary

L arge

E nriched

G ermanium

E xperiment for

N eutrinoless ββ

D ecay

M easurements on germanium detectors

P ulse shape analysis / simulations

P EN research and development