Search for new physics with neutrinoless double beta decay

The GERDA and LEGEND experiments

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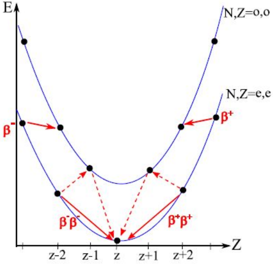
IMPRS Young Scientist Workshop at Ringberg Castle

Max-Planck-Institut
für Physik

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

GERDA

Neutrinoless double beta decay



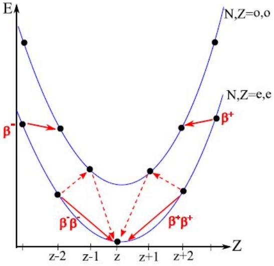
Normal beta decay is strongly suppressed for some isotopes

$\rightarrow$ Double beta decay, $2\nu\beta\beta$-Decay

[1] Fig. 1, http://www.cobra-experiment.org/double_beta_decay/

[2] Fig. 2, arXiv:1601.07512

Neutrinoless double beta decay



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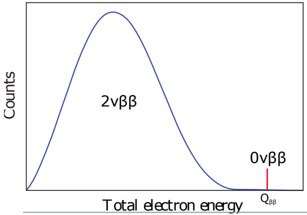

(Particle = Anti-Particle)
If neutrinos are majorana particles
→ Neutrinoless double beta decay, $0\nu\beta\beta$-Decay

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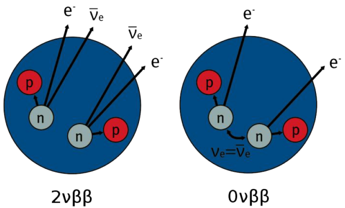
Neutrinoless double beta decay

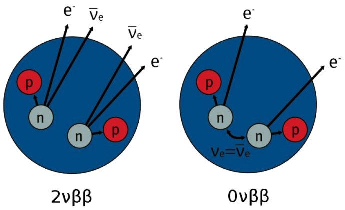


Discovery of $0\nu\beta\beta$-decay would

- demonstrate lepton number violation
- give information about the nature of neutrinos
  $\rightarrow$ Majorana or Dirac particle
- give information about absolute neutrino mass

[3] Fig. 3, AJ Zsigmond, INPA, Dec 2017
[4] M. Agostini, ICHEP 2018 – July 2018

Neutrinoless double beta decay



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The experimental limit on the $0\nu\beta\beta$-decay half-life is very long:
$> 0.9 \cdot 10^{26}$ years (for ^{76}Ge)[4]

Known double beta decay isotopes:
^{48}Ca, ^{76}Ge, ^{78}Kr, ^{82}Se, ^{86}Kr, ^{96}Zr, ^{100}Mo, ^{136}Xe, ^{130}Te, . . .

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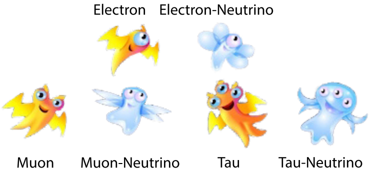
But why $0\nu\beta\beta$-decay?



What we **know** about neutrinos:

- 2nd most abundant known particles in the observable universe
- They love to oscillate
- Some neutrinos must have mass

[5] Fig. 4, http://faculty.wcas.northwestern.edu/ (11/2018)
[6] Fig. 5, minutephysics, YouTube (11/2018)

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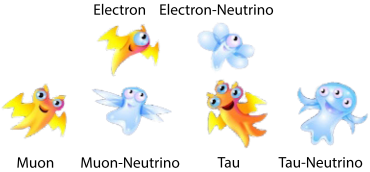

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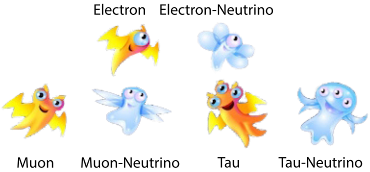

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What we **don't know** about neutrinos:

- Does the neutrino relate to matter-antimatter asymmetry?
- Absolute neutrino mass scale?
- Neutrino mass hierarchy?
- Majorana-CP/Dirac phases?
- Why is their mass tiny?

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But why $0\nu\beta\beta$-decay?

Neutrinoless mode of $\beta\beta$-decay would show:

- Lepton number violation
- Neutrinos must have Majorana nature
- Information of CP violating phases
- A solution to the matter/anti-matter asymmetry in the universe

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But what about the insane half-life of $> 0.9 \cdot 10^{26}$ years?

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Half-Life sensitivity

How can we measure a decay with a half-life much greater than the age of the universe?

Sensitivity on half-life:

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{m \cdot t}{BI \cdot \Delta E}} \text{ with } \begin{cases} m \cdot t & , \quad \text{exposure} \\ BI & , \quad \text{background index} \\ \Delta E & , \quad \text{energy resolution} \end{cases}$$

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$$\begin{aligned} \Delta E \quad &\rightarrow \quad \text{is limited by the detectors} \\ m \cdot t \quad &\rightarrow \quad \text{is limited by funding} \end{aligned}$$

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$$\begin{array}{ccc} \Delta E & \rightarrow & \text{is limited by the detectors} \\ m \cdot t & \rightarrow & \text{is limited by funding} \\ BI & \rightarrow & \text{can be improved!} \end{array}$$

Germanium Detector Array (GERDA)

$$^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- \text{ with } Q_{\beta\beta} = 2039 \text{ keV}$$

[8] Fig. 8-11, Eur. Phys. J. C 78 (2018) 388

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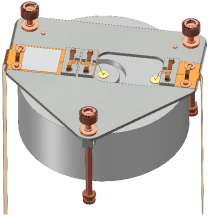

- Energy resolution $\Delta E_{Q_{\beta\beta}} < 0.1\%$

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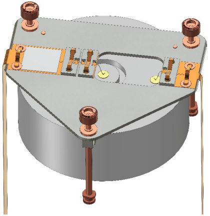

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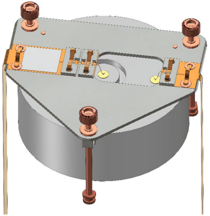

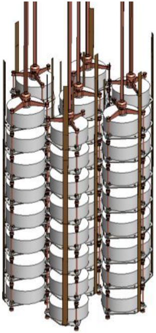

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→ Next step: increase exposure $m \cdot t$

- 40 detectors (35.6 kg enriched Germanium)

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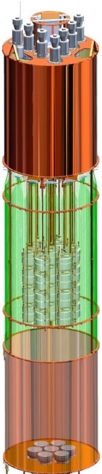
The GERDA-Experiment

Then reduce/reject the background:



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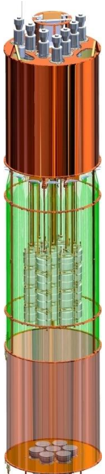
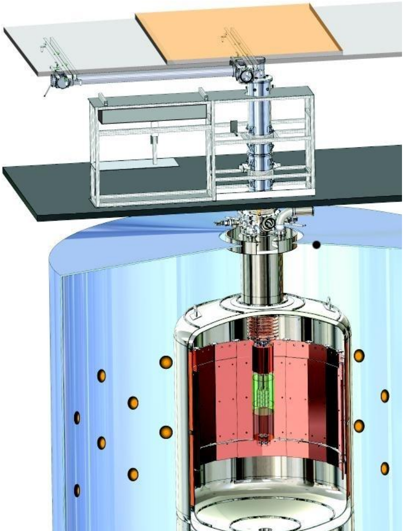
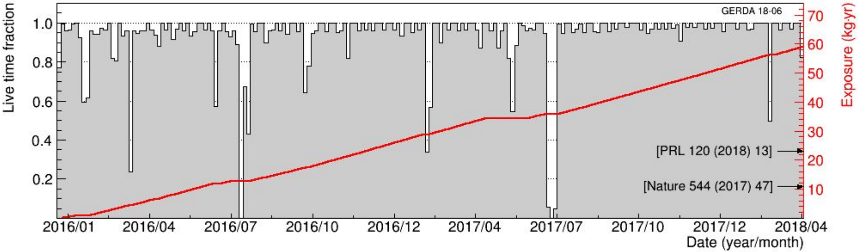




The GERDA-Experiment

9 Fig. 12, Paolo Zavarise, 1st June 2012, VULCANO Workshop

Phase II data taking

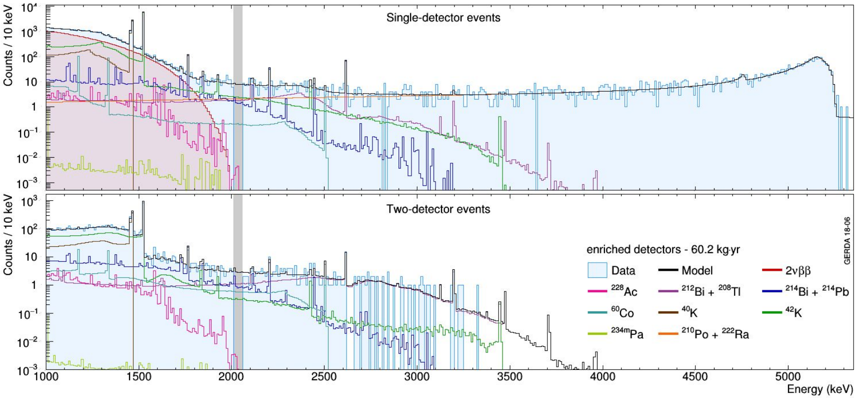


- Dec 2015 → Apr 2018 (835 days live time)
- 93% duty cycle

- Phase II: $m \cdot t = 59$ kg·yr
- Phase I + II: $m \cdot t = 82$ kg·yr

[10] Fig. 13, M. Agostini, ICHEP 2018 – July 2018

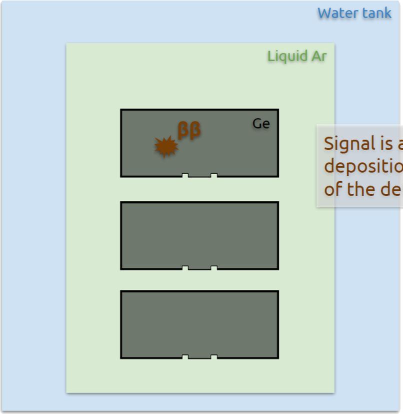
Background before analysis cuts



Background at $Q_{\beta\beta}$: α from ^{210}Po, γ from ^{208}Ti/^{214}Bi and β from ^{42}K

[11] Fig. 14, M. Agostini, ICHEP 2018 – July 2018

The low background challenge



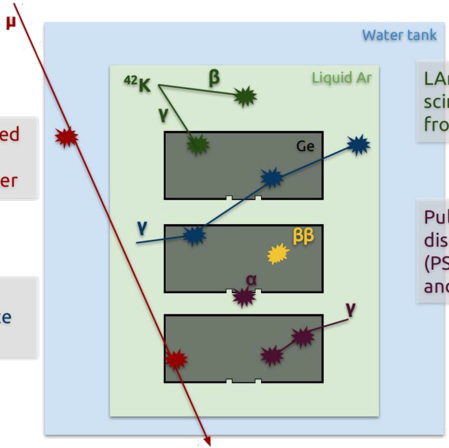
Signal is a single energy deposition within ~1 mm^3 of the detector volume

12 Fig. 15, AJ Zsigmond, INPA, Dec 2017

The low background challenge

Muon veto based on Cherenkov photons in water

Detector anti-coincidence of the array

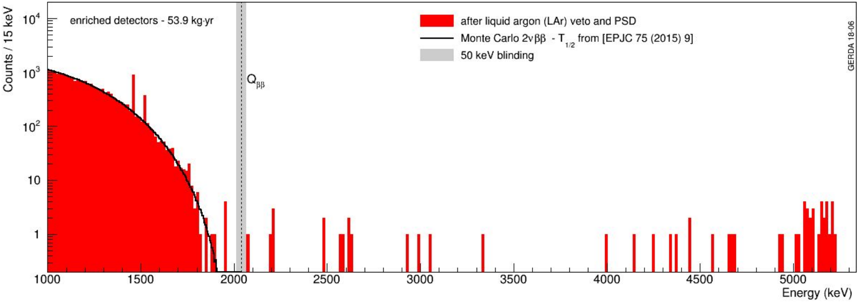


LAr veto based on scintillation light from γs and βs

Pulse shape discrimination (PSD) for multi-site and surface events

[12] Fig. 15, AJ Zsigmond, INPA, Dec 2017

Active background suppression - PSD LAr veto

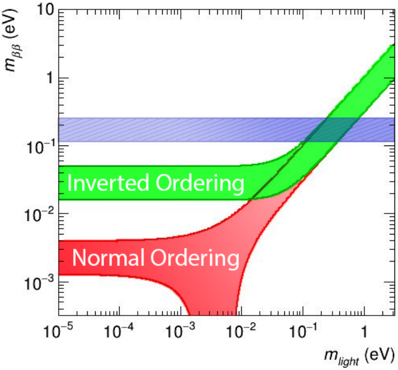


Background in the ROI:

$$BI \approx 5.6 \cdot 10^{-4} \frac{\text{cts}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}$$

[13] Fig. 16, M. Agostini, ICHEP 2018 – July 2018

Implications for neutrino physics



- $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26} yr$ (90% C.L.)

$\rightarrow$ $m_{\beta\beta} < (0.11 - 0.25)$ eV

- Next target: inverted ordering band

[14] Fig. 17, M. Agostini, ICHEP 2018 – July 2018

Outlook: LEGEND

MAJORANA and GERDA merge to form the LEGEND collaboration

- Increase exposure $m \cdot t$ in steps:
  1. LEGEND-200 with 200 kg of enriched germanium
  - Add detectors to existing GERDA environment
  - In preparation to reach $T_{1/2}^{0\nu}$ above 10^{27} yr (starting in 2021)

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

[12] AIP Conference Proceedings 1894, 020027 (2017); https://doi.org/10.1063/1.5007652

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  2. LEGEND-1000 with 1 ton of enriched germanium
- Decrease the background index BI[12]
  - Bigger detectors in order to reduce the number of cables and supports
  - Deep learning for event selection
  - Transparent, scintillating holding structures made of PEN

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Backup

Why Germanium?

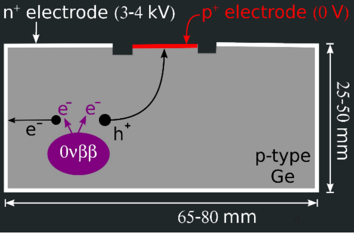
- ✓ Source can be used as a detector
  - → High signal detection efficiency
- ✓ Detector material is very pure
  - → Very low intrinsic internal background
- ✓ Very good energy resolution
  - → Background due to $0\nu\beta\beta$-decay is negligible
- ✓ Pulse shape discrimination is possible
  - → Powerful tool to identify background
- ✓ Considerable experience
  - → Industrial production, improvements possible
- X Natural abundance is just 7.8
  - → Enrichment necessary
- X Individual detector mass 1 kg
  - → Ton scale needs around 1000 detectors

The Ge Detectors

HPGe detector signals:

- ➢ signal induced by drift of electron-hole clusters
- ➢ time-projection chamber
- ➢ identification of events with multiple energy depositions
- ➢ identification of events on the surface

Signal/Background Discrimination!



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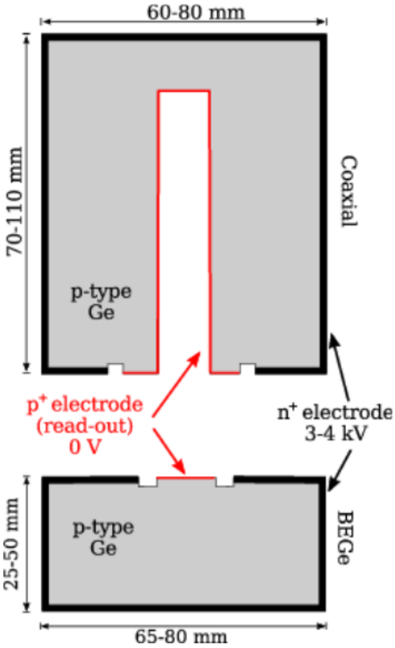
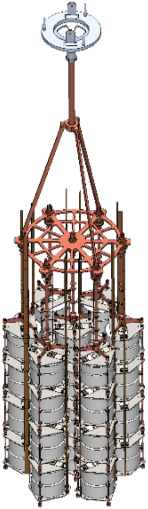
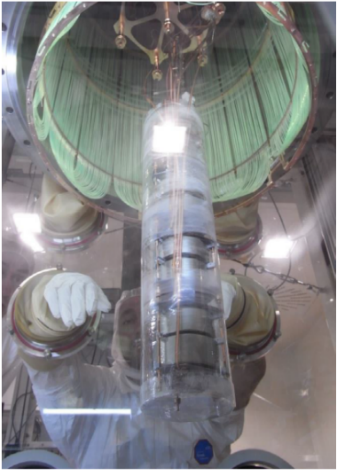
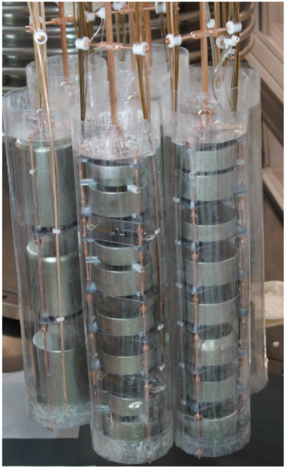

60-80 mm
70-110 mm
Coaxial
p-type
Ge
p+ electrode
(read-out)
0 V
n+ electrode
3-4 kV
25-50 mm
p-type
Ge
BEGe
65-80 mm

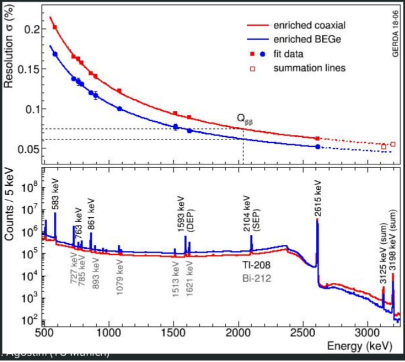




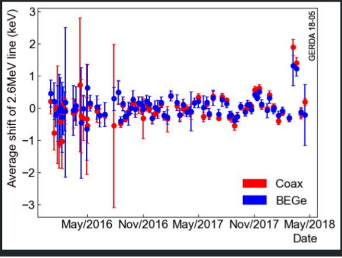
with TPB COATED
nylon mini-shroud



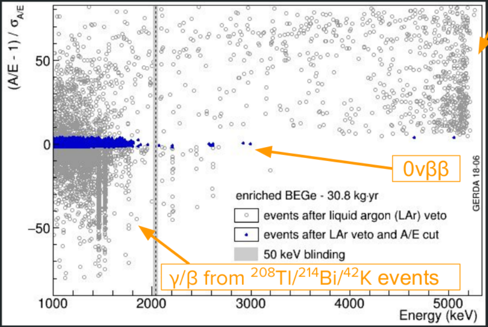
Energy Scale

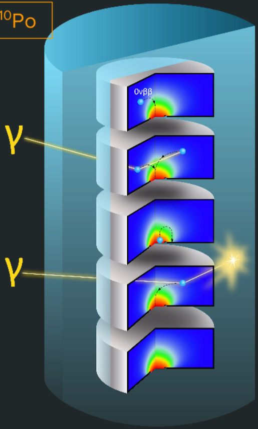


- ➢ Weekly calibration with Th-228 sources
- ➢ Fluctuations between calibrations <1 keV
- ➢ Resolution at Qbb better than 0.1%
  (3-4 keV FWHM)



Pulse shape discrimination





0νββ efficiency → ε_{BEGe}= (87.6+2.5)% ε_{coax}= (71.2+4.3)%

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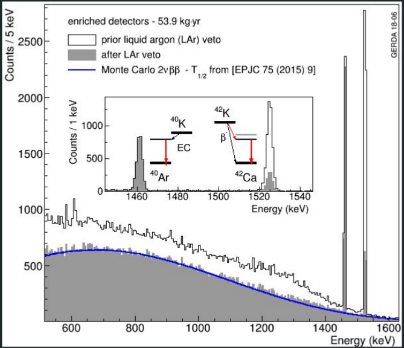
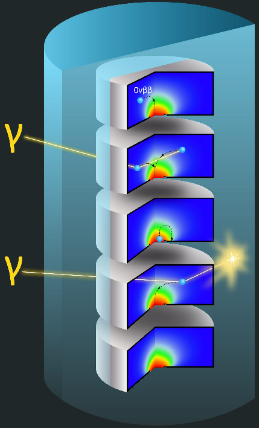
LAr scintillation anti-coincidence



Dead time

~2%



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