on behalf of the
PEN consortium

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FÜR PHYSIK

Low-background *poly(ethylene naphthalate)* as active structural material for the LEGEND-200 $0\nu\beta\beta$ experiment

DPG Frühjahrestagung *Rehearsal*
16. März 2022
Felix Fischer

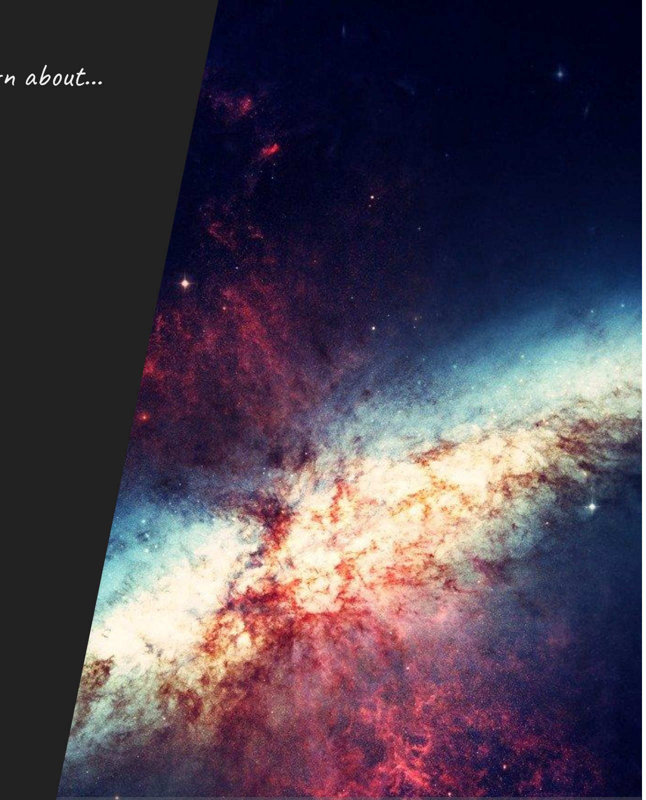
What do we want to learn about...

Neutrinos
in LEGEND

Related talks:

Tue, 14:50, T 29.3
From GERDA to LEGEND - Hunting no neutrinos
- *Christoph Wiesinger*

Wed, 16:15, T 75.1
Group Report: **Overview of LEGEND and the Commissioning Status of LEGEND-200**
- *Patrick Krause*



I HAVE DONE A TERRIBLE THING:
I HAVE POSTULATED A PARTICLE THAT
CANNOT BE DETECTED.
- WOLFGANG PAULI -

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

- Does the neutrino relate to matter-antimatter asymmetry?
  - Leptogenesis
- Absolute neutrino mass scale?
- Neutrino mass hierarchy?
- Why is their mass tiny?
- ...

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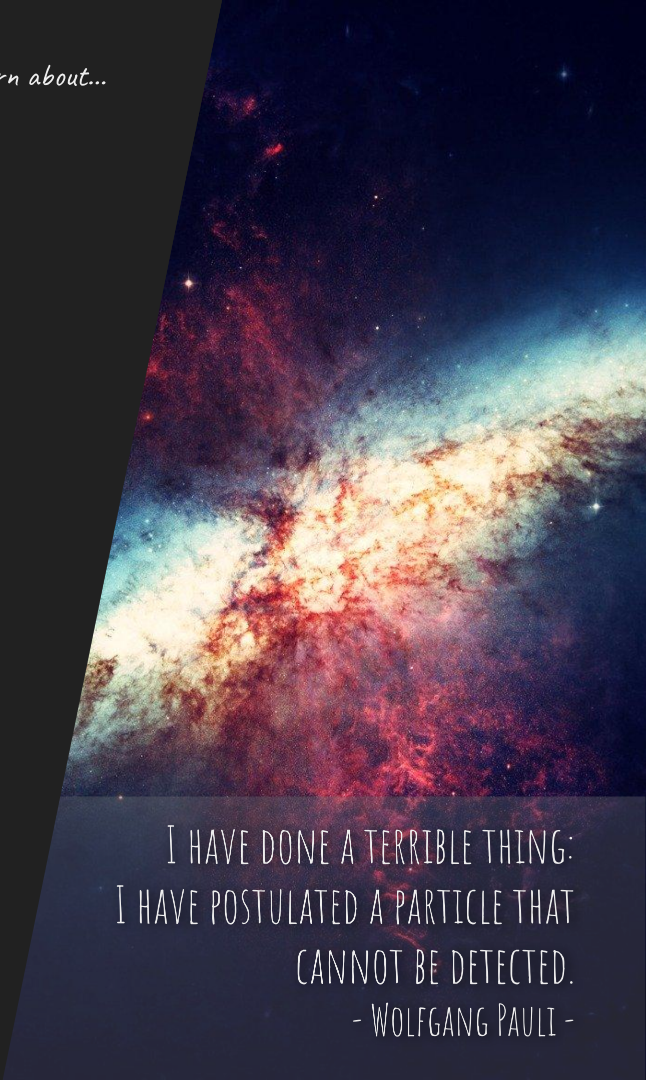

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Detecting the **neutrinoless double beta decay** ($0\nu\beta\beta$)**-decay** would imply:

- Lepton number violation
- Information about the nature of neutrinos
  - Majorana or Dirac?
- Information about absolute neutrino mass

But what's $0\nu\beta\beta$-decay?

Double beta decay

Normal beta decay is strongly suppressed for some isotopes
→ Double beta decay, $2\nu\beta\beta$-decay

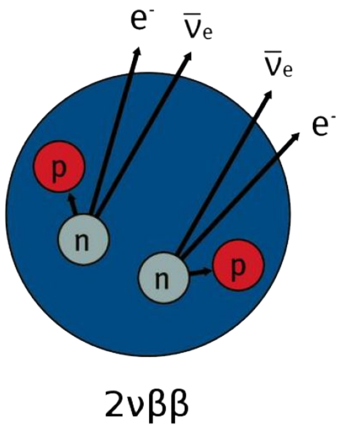

Fig.: AJ Zsigmond, INPA, Dec 2017

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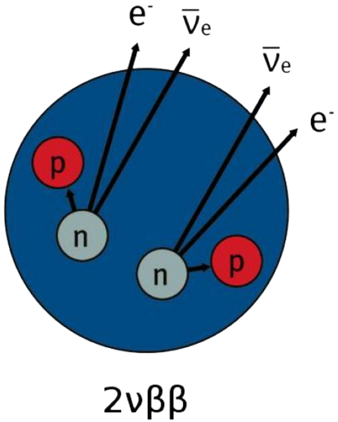
Double beta decay

Normal beta decay is strongly suppressed for some isotopes

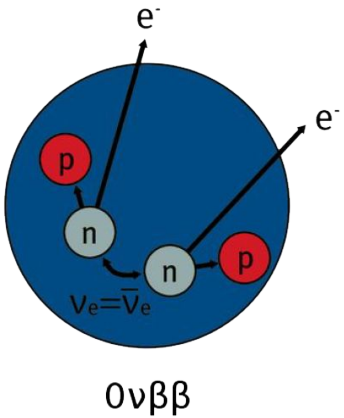
$\longrightarrow$ Double beta decay, $2\nu\beta\beta$-decay



Neutrino as Majorana particle

If neutrinos are their own anti-particles

$\longrightarrow$ Neutrinoless double beta decay, $0\nu\beta\beta$-decay



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$\beta\beta$-decay spectrum

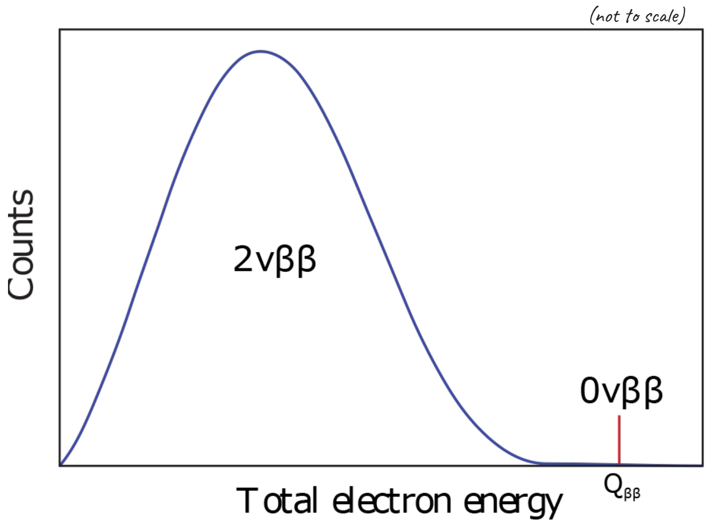
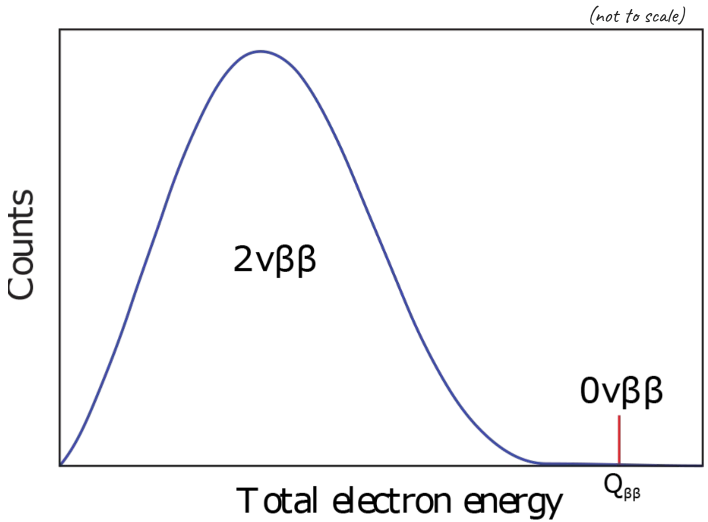


Fig.: arXiv:1601.07512

$\beta\beta$-decay spectrum



How many events do we expect?

The half-life for $0\nu\beta\beta$-decay in ^{76}Ge is

$T_{1/2} > 1.8 \cdot 10^{26}$ yr*

< 30 decays/(yr · ton)

for pure ^{76}Ge

Fig.: arXiv:1601.07512

* *Phys. Rev. Lett. 125 (2020) 252502*

Let’s build an experiment!

The **sensitivity** on $0\nu\beta\beta$-decay half-life depends on:

$$T^{0\nu}_{1/2} \propto \sqrt{\frac{m \cdot t}{BI \cdot \Delta E}}$$

Let's build an experiment!

Sensitivity: $T^{0\nu}_{1/2} \propto \sqrt{\frac{m \cdot t}{BI \cdot \Delta E}}$

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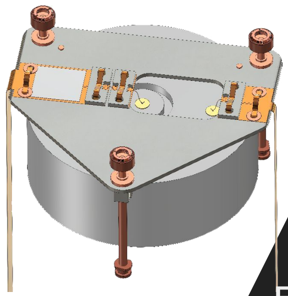
LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



HPGe Detector Energy Resolution

$$\Delta E_{Q_{\beta\beta}} \approx 0.1\%$$

at $2039 keV \Rightarrow \Delta E \approx 2.5 keV$

HPGe = High-Purity Germanium

*Figures: *Eur. Phys. J. C 78 (2018) 388*

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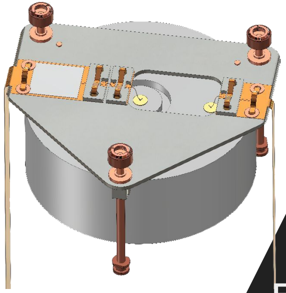
Large Enriched Germanium Experiment for Neutrinoless ββ Decay



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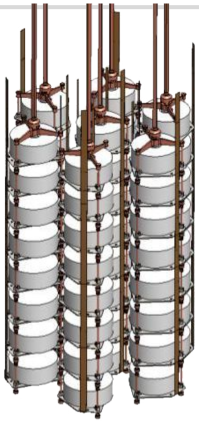
Exposure m·t

LEGEND-200 = 200 kg
LEGEND-1000 = 1 ton
of enriched material
88% ^{76}Ge



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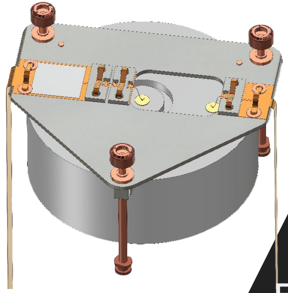

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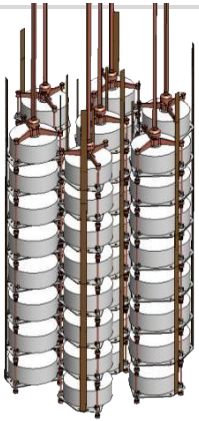
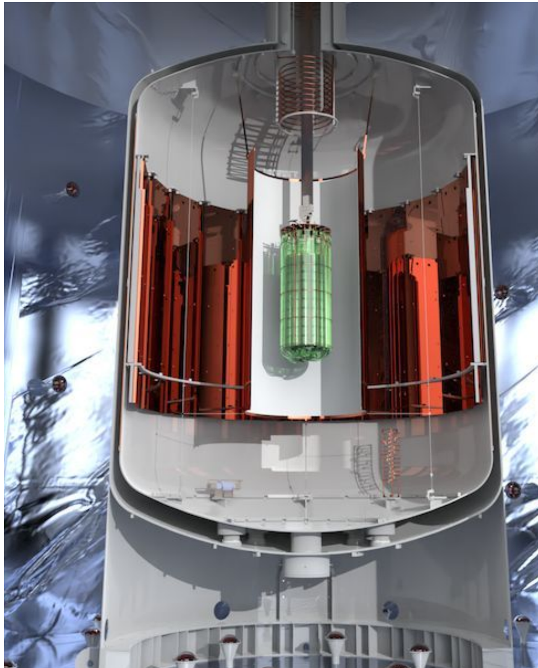


Background Index (BI)

1. Go underground
2. Radioclean materials
3. Shielding

Good enough?



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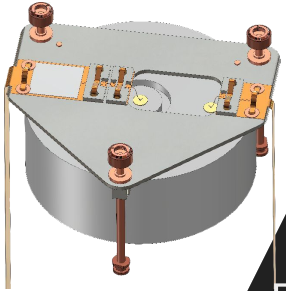

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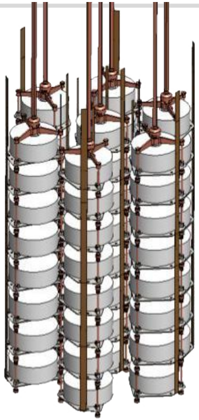

Identification & Rejection

LAr veto, Muon veto, detector anti-coincidence, Pulse-shape discrimination (PSD)

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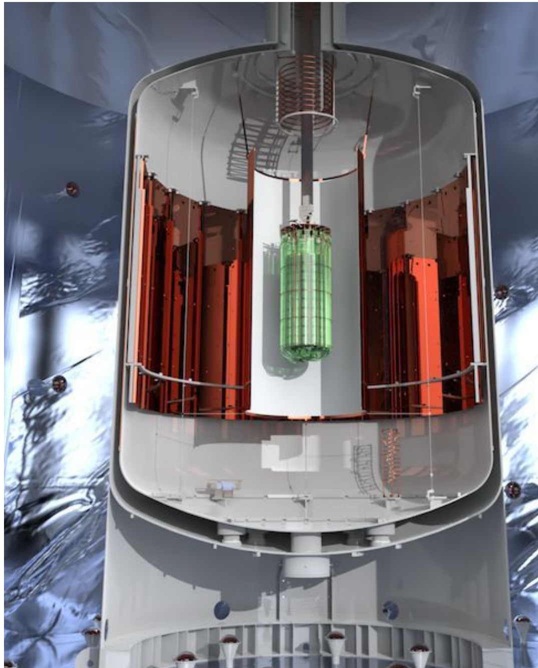

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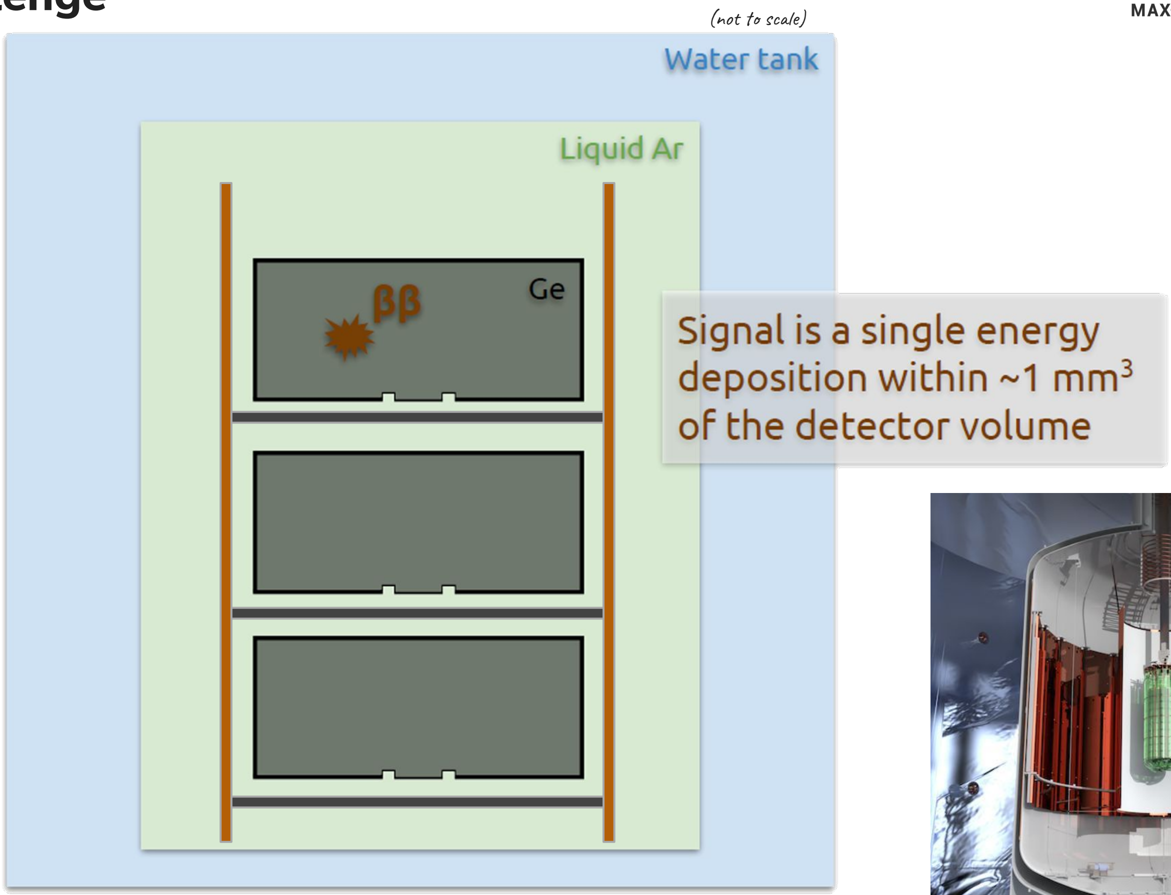
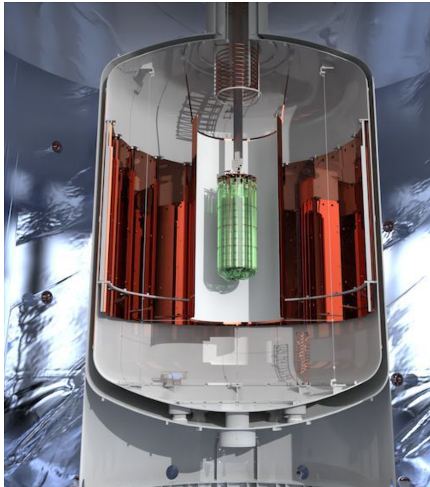
Low-background challenge





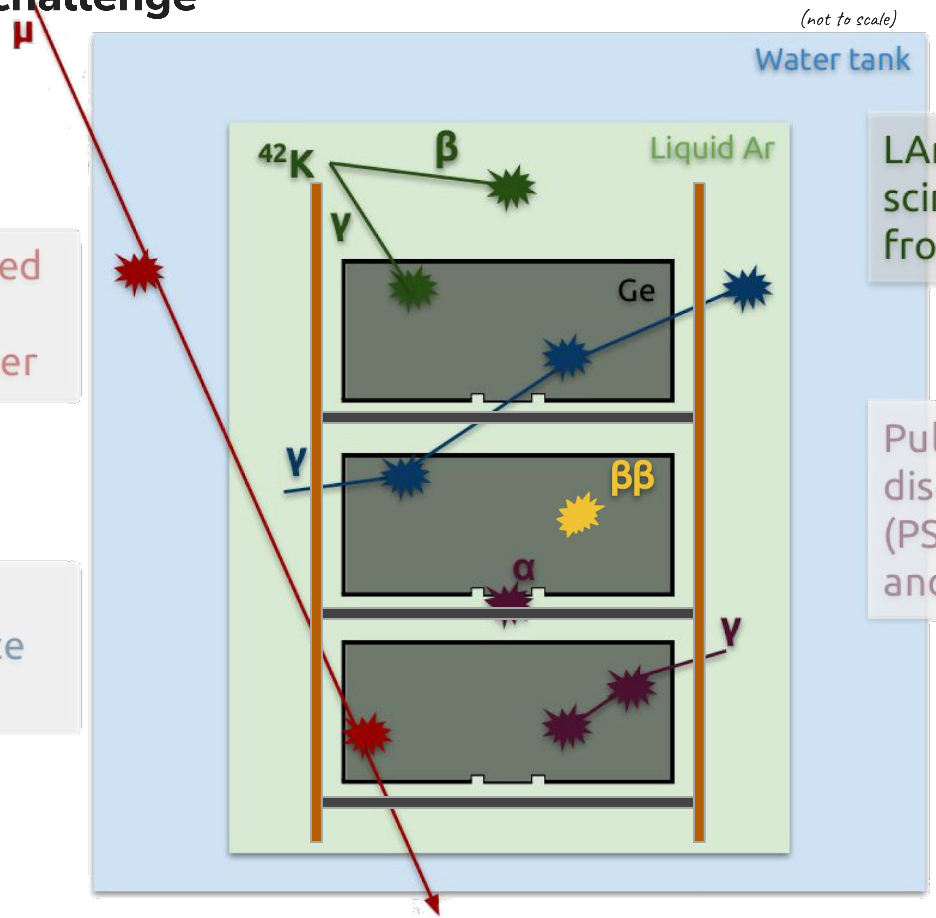
Tue, 14:50, T 29.3
From GERDA to LEGEND - Hunting no neutrinos
- Christoph Wiesinger

Illustration adapted from AJ Zsigmond

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

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PEN
Poly(ethylene 2,6-naphthalate)

Scintillator

- Potential to veto background events

Wavelength shifter

- Shifts 128 nm scintillation light from LAr to visible blue light

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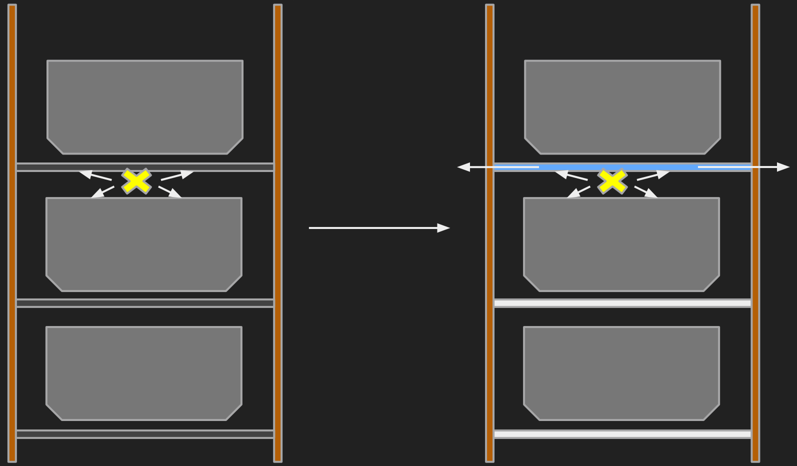

Significant improvement in the **identification efficiency** of background events close to the detector
e.g. ^{42}K

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Particle identification

- Differentiation of particles by PSD

High purity

- < 1.2 μBq per LEGEND-200 detector holding plate (~6.2g) achieved

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High purity

- < 1.2 µBq per LEGEND-200 detector holding plate (~6.2g) achieved

Mechanical properties

- Stronger than Si plates (used in GERDA)
- Mechanically better in cryogenic liquids than Cu
- Encapsulation of HPGe detectors seems possible

PEN in LEGEND-200 (L200)

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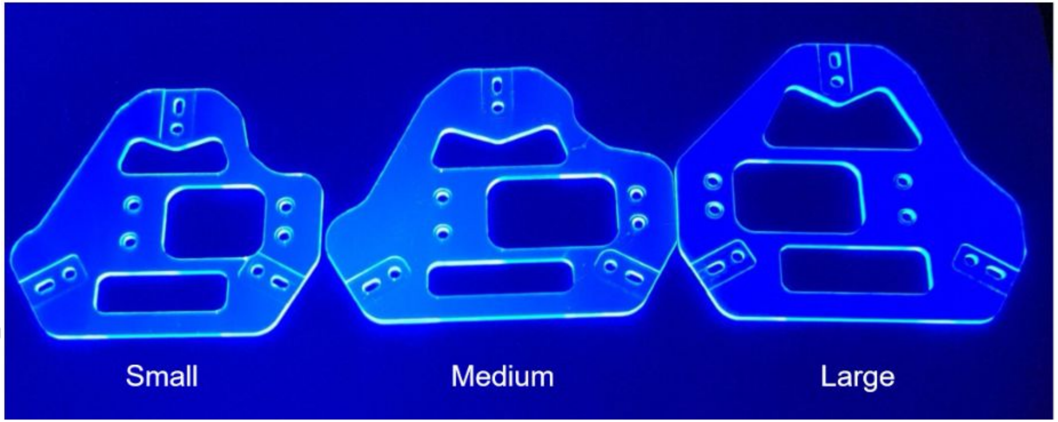
- **Three (+1) holder shapes** to fit all L200 detector types
- For prediction of LEGEND-1000 veto efficiency: **simulations required**
- Optical properties need to be investigated for simulation
  - Emission spectrum ⇒ λ_{peak}= (440 ± 3)nm
  - Surface quality
  - Attenuation length
  - Light yield



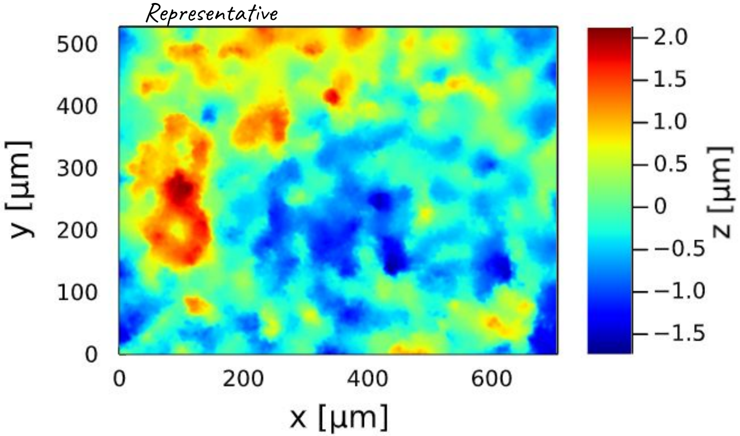
PEN in L200 - Surface Quality

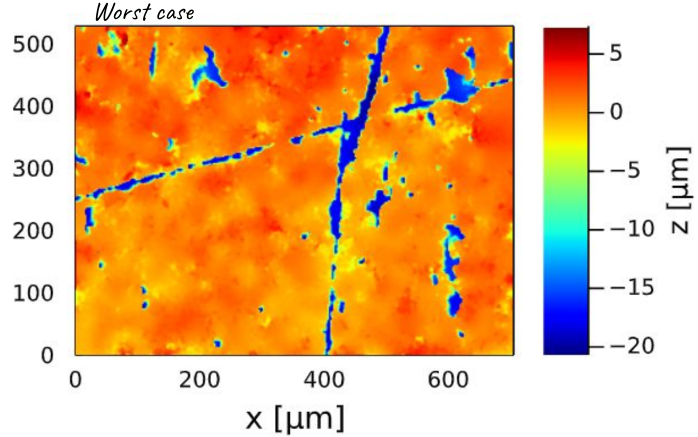
Height and angular distribution of the surface micro-facets

- Needed for light propagation simulation
- Parameters: σ_h and σ_α

Setup:

- Keyence VHX-6000 digital microscope
- Resolution in $x / y = 440$ nm
- Resolution in $z = 10$ nm





*Figures: PEN group "Optical properties of low-background PEN structural components for the LEGEND-200 experiment". In: JINST(To be submitted soon)

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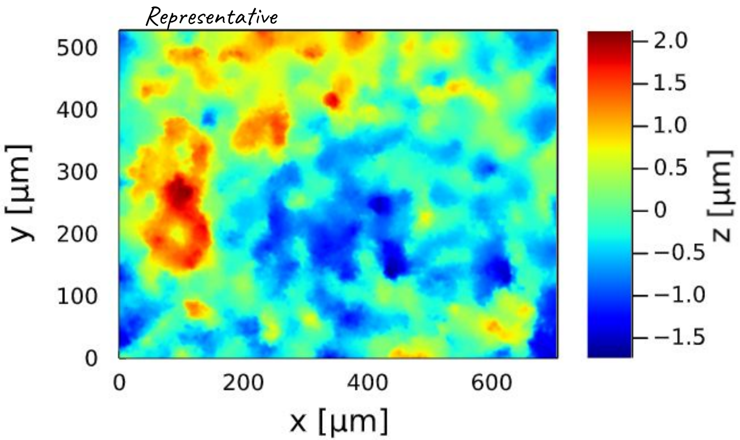
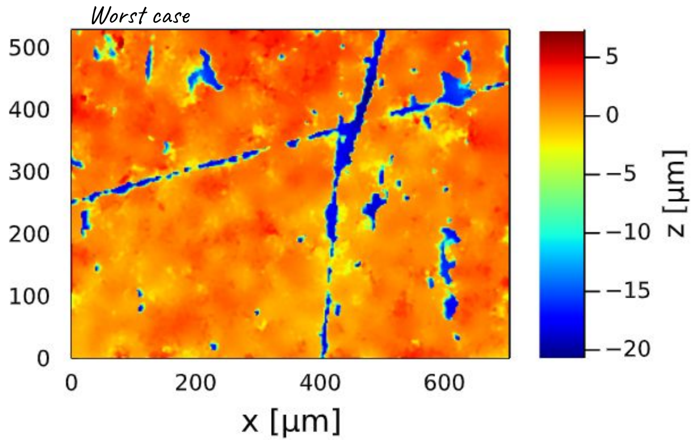
Results:

- $\sigma_{h,rep.}$ = (0.60±0.05) µm, $\sigma_{h,bad}$ = (1.02±0.02) µm
- $\sigma_{\alpha,rep.}$ = (0.95±0.11)°, $\sigma_{\alpha,bad}$ > 4° *<5° is to be classified as polished*
- Surface is to be classified as **polished**





*Figures & result: PEN group "Optical properties of low-background PEN structural components for the LEGEND-200 experiment". In: JINST(To be submitted soon)

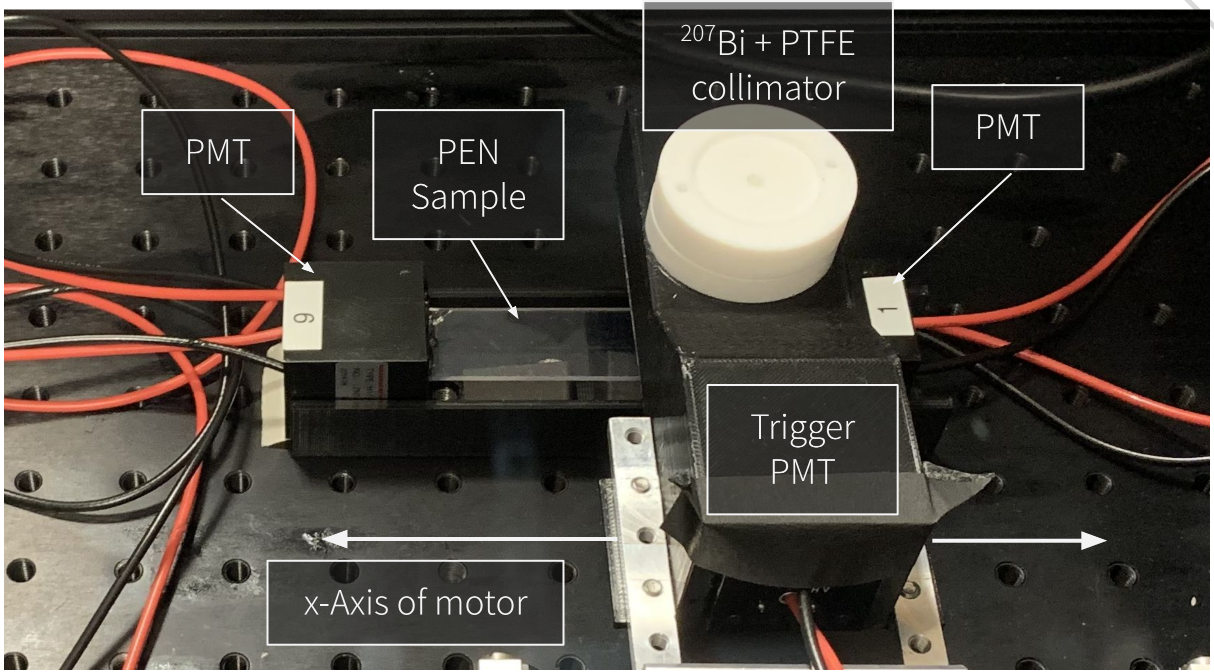
PEN in L200 - Attenuation Length

Attenuation length $\lambda_{att.}$

- Needed for light propagation simulation
- Limits size of PEN structures

Setup:

- Sample: 100×20×1.7 mm^3
- Mono-energetic electrons ~1MeV from ^{207}Bi
- 2 Photomultiplier tubes (PMTs) collect the light
- Source is moved along x



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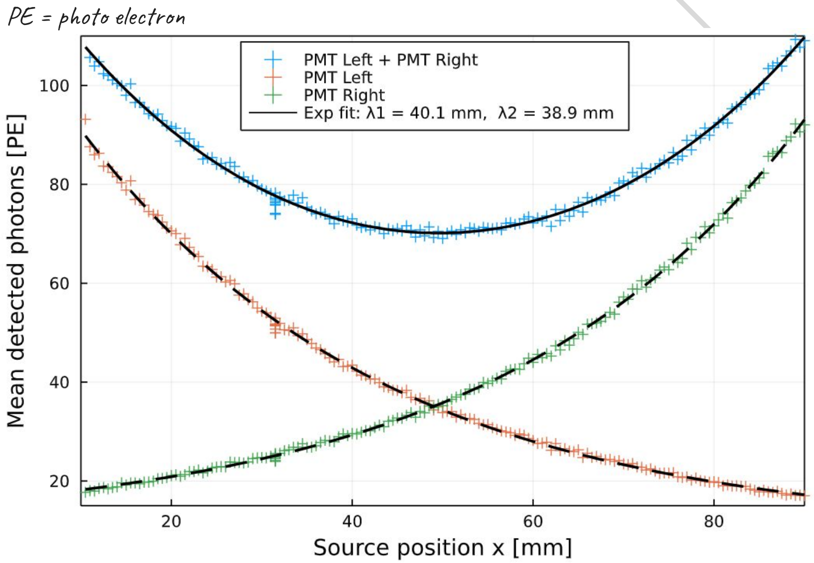
Results:

- $\lambda_{att.}$ = (39.5±1.5) mm
- Shorter than for standard plastic scintillators (> 1m)
  - Still ok for samples that are not significantly larger than the attenuation length



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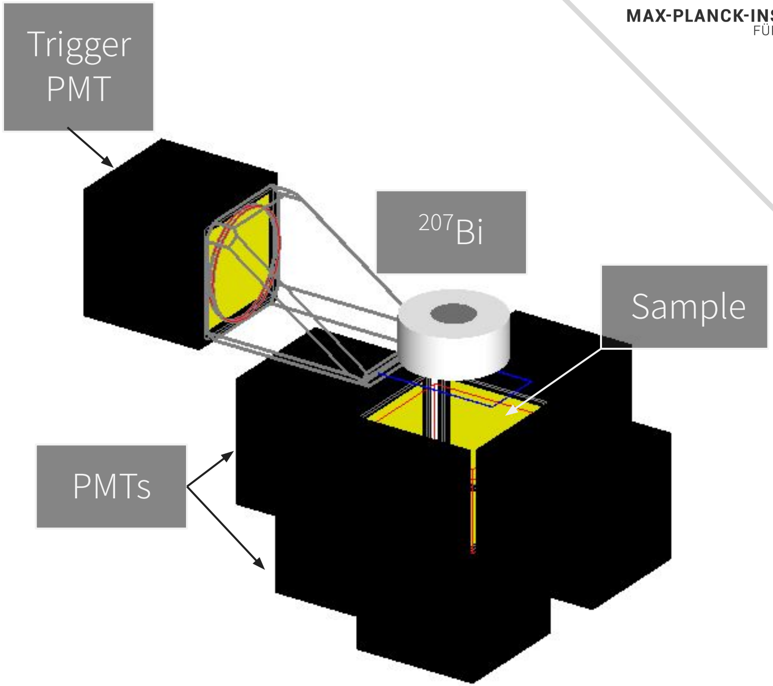
PEN in L200 - Light Yield

Light output and Yield

- Number of photons emitted per MeV energy deposition

Setup:

- Sample: 30×30×1.7 mm^3
  - 2 samples were stacked
  - Different samples: PEN, PS32, EJ-200
- Mono-energetic electrons ~1MeV from ^{207}Bi
  - Source is pointed to the center
- 5 PMTs collect the light



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- Mono-energetic electrons ~1MeV from ^{207}Bi
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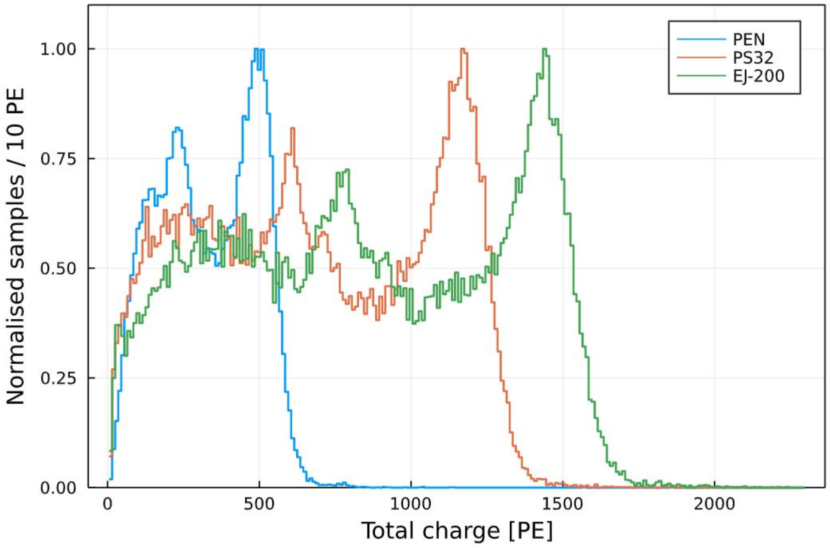
Results:

- **Light output:** ~⅓ of EJ-200
  - EJ-200 has a light yield of 10.000 ph/MeV
- **Light yield** taking the attenuation and efficiencies of the setup into account using simulations:
  - **(5460±220) ph/MeV**

PE = photo electron



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PEN in L200 - Energy Threshold

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Definition

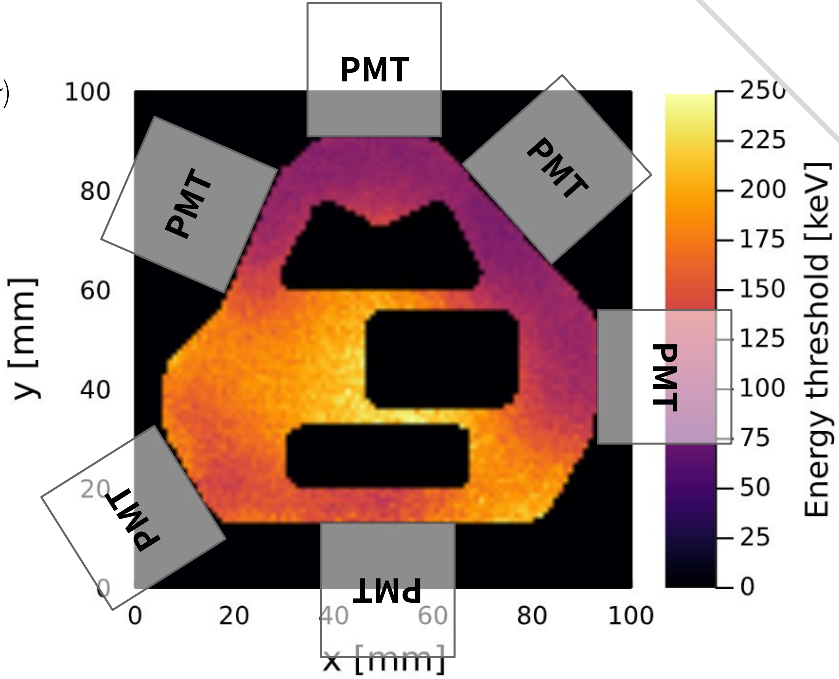
- Minimum energy deposition in the L200 holder needed to generate a signal that can be detected with 99.99994% (5σ)
  - Setup dependent
  - Signal: 2 PE detected

Setup:

- Sample: L200 holders made of PEN
  - 2 samples were stacked
- Mono-energetic electrons ~1MeV from ^{207}Bi
  - Source scanned the whole sample
- 6 PMTs collect the light

Results:

- **Energy threshold:** ~254 keV in this setup
- Measurement will be used to tune simulations



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Conclusions

PEN is a suitable scintillator to be used as active structural material in LEGEND-200

- Successful production of low-background PEN holders
- Setups for reproducible optical characterization deployed
- All optical parameters for simulation determined

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Outlook

LEGEND-200

- Start is expected late 2022
- Delayed due to the pandemic
- All PEN structures are at LNGS and ready for deployment
- All germanium detectors will be mounted using PEN holders

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Further reading:

"Use of poly(ethylene naphthalate) as a self-vetoing structural material".
In: JINST 14.07 (2019), P07006

"Production and validation of scintillating structural components from low-background Poly(ethylene naphthalate)"
In: JINST 17.01 (2022), P01010

"Optical properties of low-background PEN structural components for the LEGEND-200 experiment".
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Backup

Radio-purity measurement PEN

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	Raw TN-8065S GeMPI4	Discs GeMPI4	Discs OBELIX	L200 holders GeMPI3
Mass	-	14.315 kg	5.231 kg	1.07 kg
Time	-	68 days	79 days	68 days
Unit	mBq/kg	μBq/kg	μBq/kg	μBq/kg
^{228}Ra	< 0.15	92 ± 25	107 ± 38	< 460
^{228}Th	0.23 ± 0.05	32 ± 16	67 ± 18	< 480
^{226}Ra	0.25 ± 0.05	60 ± 15	76 ± 22	< 360
^{234}Th	< 11	< 1900	-	< 5800
^{234}Pa	< 3.4	< 1700	-	< 7000
^{235}U	< 0.066	< 56	-	< 2200
^{40}K	1600 ± 400	< 240	< 567	< 4100
^{137}Cs	< 0.057	< 0.15	-	< 91

TABLE 7.1: Radiopurity results from HPGe screening for moulded PEN discs and LEGEND-200 (L200) germanium detector holders. Two sets of moulded PEN discs were measured at LNGS (GeMPI3/4) and LSM (OBELIX) underground laboratories. A previous measurement of untreated PEN granulate [9] is listed, too. With the OBELIX setup, not all listed radionuclides were analysed. Limits are given with 90% confidence level. Results published in [80].

[9] Y. Efremenko et al. “Use of poly(ethylene naphthalate) as a self-vetoing structural material”. In: JINST14.07 (2019), P07006.
[80] Y. Efremenko et al. “Production and validation of scintillating structural components from low-background Poly(ethylene naphthalate)”. In:JINST17.01 (2022), P01010

PEN in L200 - Emission Spectrum

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Peak emission λ_{peak} gives information on:

- What kind of light sensors can be used
- Light propagation

Setup:

- Shamrock-SR-303I-A spectrometer
- Excitation light source: (340 ± 10)nm LED
- Varying the distance from excitation point to sensor

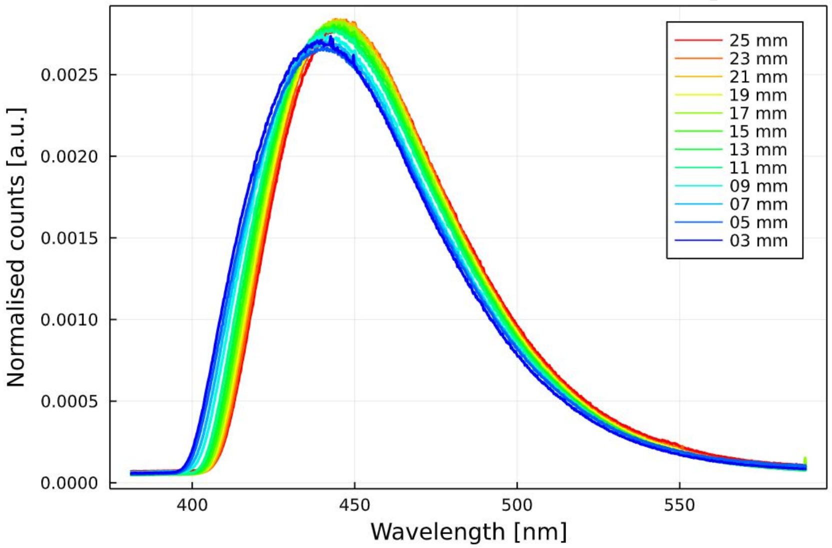

*Figure & result: PEN group "Optical properties of low-background PEN structural components for the LEGEND-200 experiment". In: JINST(To be submitted soon)

PEN in L200 - Emission Spectrum

Peak emission λ_{peak} gives information on:

- What kind of light sensors can be used
- Light propagation

Setup:

- Shamrock-SR-303I-A spectrometer
- Excitation light source: (340 ± 10)nm LED
- Varying the distance from excitation point to sensor

Results:

- λ_{peak} = (440 ± 3)nm
  - Very good for most standard light-sensors
  - Visible by eye
- Attenuation expected to be higher than in standard plastic scintillators (BC-408, EJ-200,..)

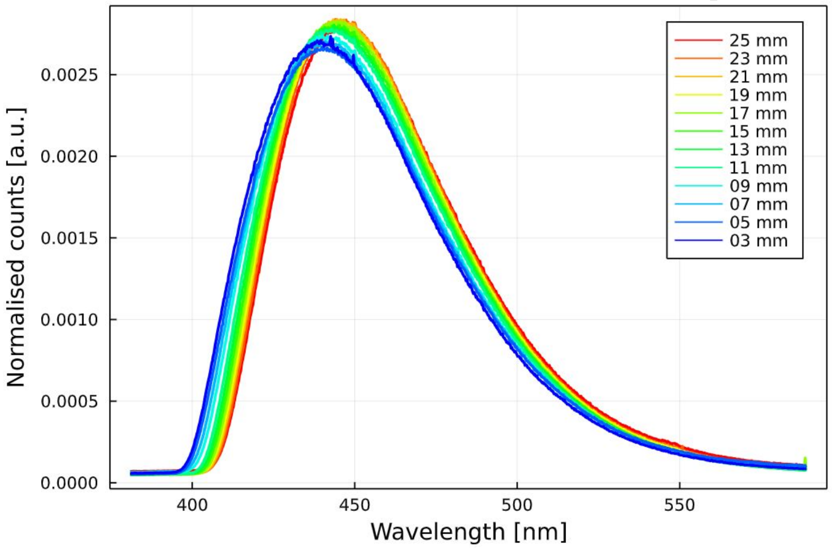

*Figure & result: PEN group "Optical properties of low-background PEN structural components for the LEGEND-200 experiment". In: JINST(To be submitted soon)

PEN in L200 - Surface Quality

Height and angular distribution of the surface micro-facets

- Needed for light propagation simulation
- Parameters: σ_h and σ_α

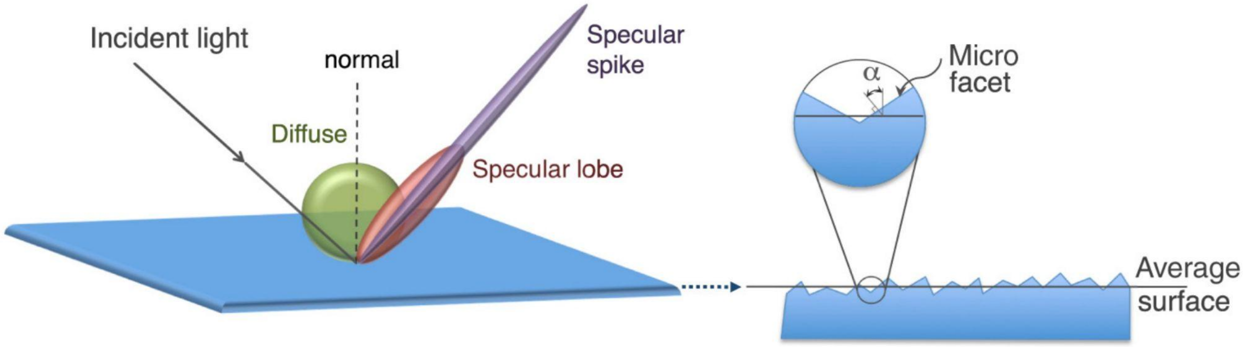

*Figure: Vesna Cuplov et al. In:Journal of biomedical optics 19 (Feb. 2014), p. 26004

PEN
(almost) Radio-pure production

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Our goal is clear, but how do we get there in a **radio-pure way**?

Let's start with the raw material:

- All parts have been **acid-etched** using high purity nitric acid
- Only **18 MOhm water** was used
- Drying was done in a **heated vacuum tank**

PEN

(almost) Radio-pure production

Our goal is clear, but how do we get there in a **radio-pure way**?

Producing PEN plates:

- Method: **Injection compression molding**
- All parts in contact with PEN have been acid-etched
- Complete production in class 100 clean room

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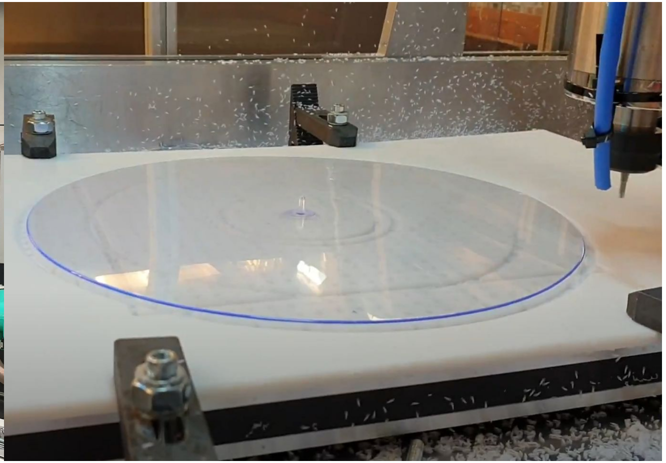
PEN
(almost) Radio-pure production

Our goal is clear, but how do we get there in a **radio-pure way**?

Producing PEN plates:



- Method: **Injection compression molding**
- All parts in contact with PEN have been acid-etched
- Complete production in class 100 clean room
- Plates have been scanned for radio-impurities for ~60 days

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PEN

(almost) Radio-pure production

Our goal is clear, but how do we get there in a **radio-pure way**?

LEGEND-200 holder production:

- Screening of plates for ~60 days
  - < 1 µBq per holder mass
- All holders needed for L200 have been produced
  - Screening ongoing

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Can we detect such decay?

Sensitivity on half-life: $T_{1/2}^{0\nu} \propto \sqrt{\frac{m \cdot t}{BI \cdot \Delta E}}$

Exposure: m · t

More mass and longer measurement
⟶ Limited by funding

Background index: BI

⟶ Can be improved!

Resolution: ΔE

Germanium detectors have a great energy resolution
< 0.1% at $Q_{\beta\beta}$
⟶ Limited by the detectors

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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Combining the best features of MAJORANA and GERDA

LEGEND-200

Upgrade to 200 kg of germanium
Existing infrastructure at LNGS
Funding: granted in 2018
Data taking: 2021
Sensitivity goal: $T_{1/2} > 10^{27}$ yr
Background goal: $2 \cdot 10^{-4}$ c/(keV·kg·yr)
GERDA: $5 \cdot 10^{-4}$ c/(keV·kg·yr)

LEGEND-1000

Upgrade to 1000 kg of germanium
New lab is being discussed
Funding: in progress
Sensitivity goal: $T_{1/2} > 10^{28}$ yr
Background goal: $6 \cdot 10^{-5}$ c/(keV·kg·yr)

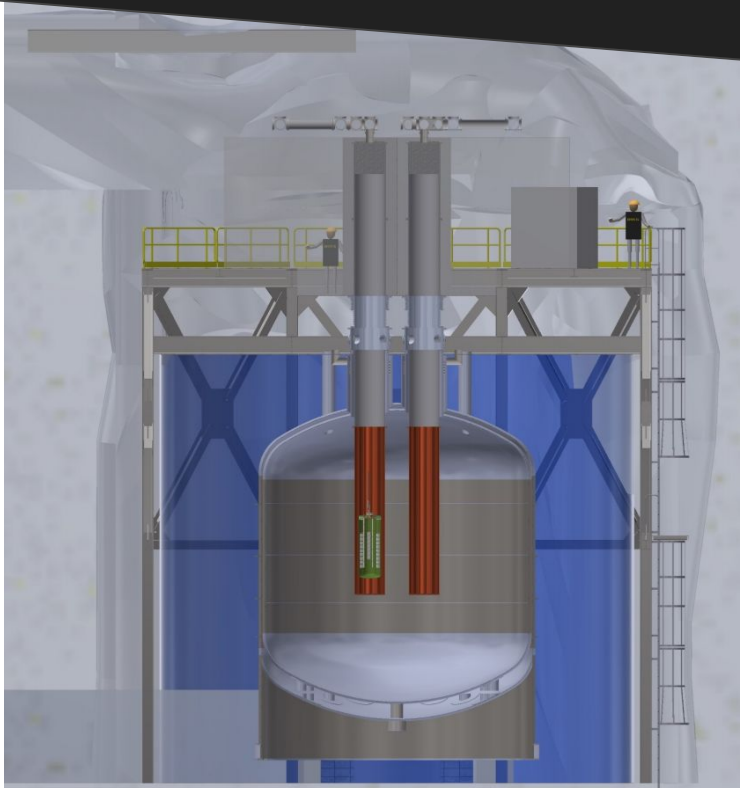
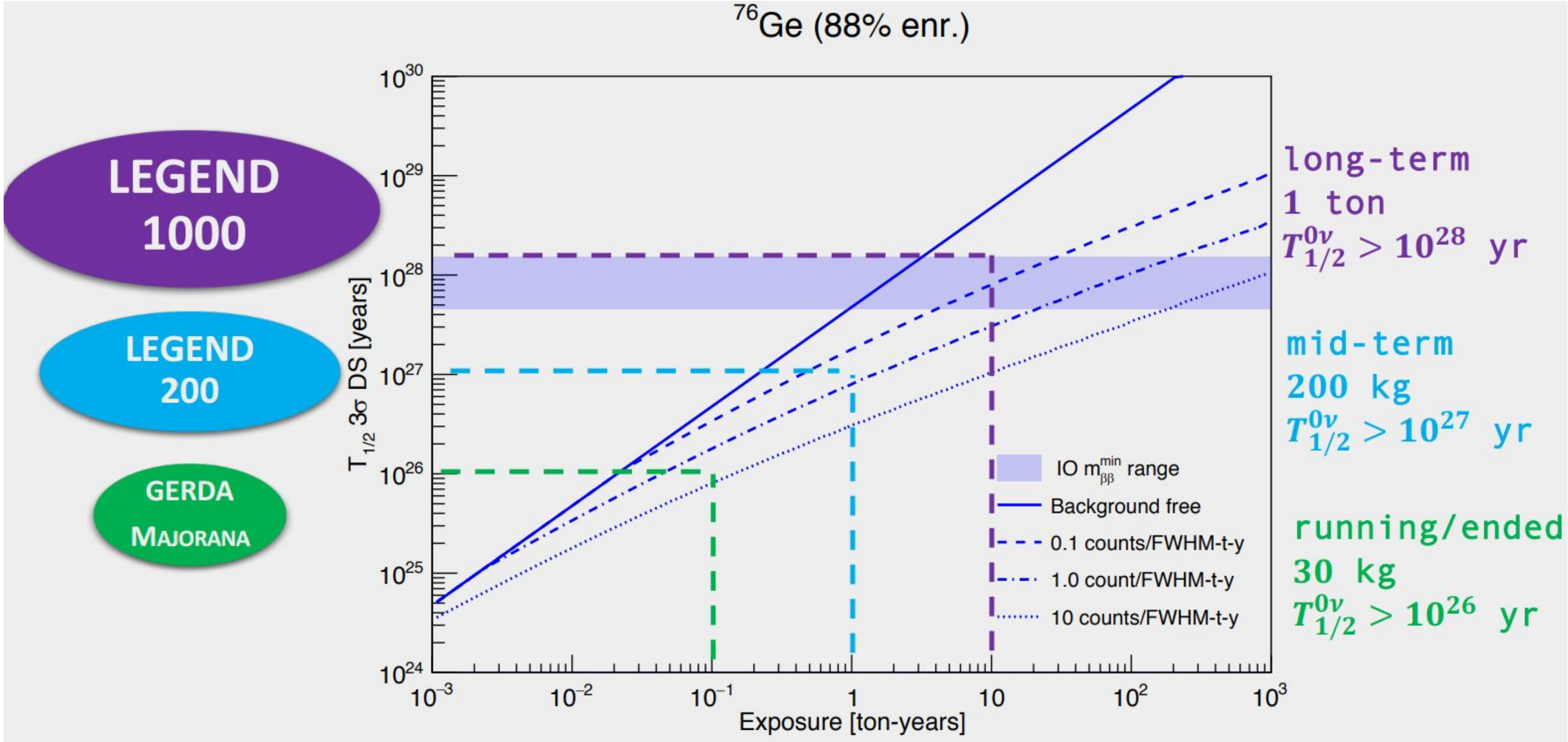


Illustration: J.F. Wilkerson, LEGEND review, 09.09.2020

Implication for neutrino physics

Target: Inverted ordering band



* *GERDA, MAJORANA and LEGEND towards a background-free ton-scale Ge-76 experiment*, Neutrino 2020, Yoann Kermaidic

Implication for neutrino mass

Considering light Majorana neutrino exchange, the $0\nu\beta\beta$-decay rate $\Gamma^{0\nu}$ is given by

$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}(0^+ \to 0^+)} = G^{0\nu}(E_0, Z)\,|\mathcal{M}_{\mathrm{nucl}}|^2\,\langle m_\nu \rangle^2 . \qquad (2.8)$$

Here, $\mathcal{M}_{\mathrm{nucl}}$ is the nuclear matrix element and $\langle m_\nu \rangle$ is the effective Majorana neutrino mass [20]. The half-life $T_{1/2}^{0\nu}$ of $0\nu\beta\beta$ is the inverse to the decay rate. Hence, it is inversely proportional to the squared effective neutrino mass $\langle m_\nu \rangle$ [19]. Observation of $0\nu\beta\beta$-decay would hence mean that the neutrino has Majorana character and that the lepton number is violated. In addition, information about the absolute neutrino mass can be deduced. There are many experimental approaches for the $0\nu\beta\beta$ search. The GERDA experiment is a promising candidate using germanium detectors enriched in the double beta emitter ^{76}Ge.

Master Thesis, Felix Fischer

Let's create an experiment!

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How many events do we expect?

The half-life for $0\nu\beta\beta$-decay in ^{76}Ge is

$T_{1/2} > 1.8 \cdot 10^{26}$ yr*

< 6 decays/yr

(for 200 kg of pure ^{76}Ge)

Isotope

^{48}Ca, $\mathbf{^{76}Ge}$, ^{78}Kr, ^{82}Se, ^{86}Kr, ^{96}Zr, ^{100}Mo, ^{136}Xe, ^{130}Te, ...

Detector

Germanium crystals make great detectors with high energy resolution

Decay channel

Can we detect the decay?

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

$Q_{\beta\beta} = 2039$ keV

* *Phys. Rev. Lett. 125 (2020) 252502*