on behalf of the
PEN consortium

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Production of low-background poly(ethylene naphthalate) as a self-vetoing structural material for LEGEND-200

DPG Frühjahrestagung
17th March 2021
Felix Fischer

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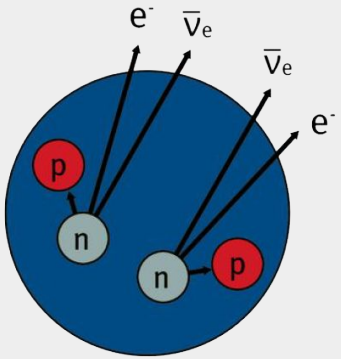
Double beta decay

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



2νββ

Fig.: AJ Zsigmond, INPA, Dec 2017

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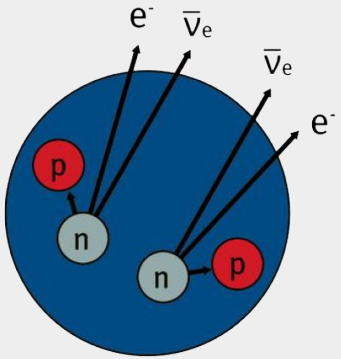
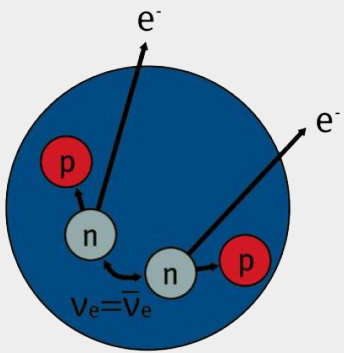


$2\nu\beta\beta$

Neutrino as majorana particle

If neutrinos are their own anti-particles
→ Neutrinoless double beta decay, $0\nu\beta\beta$-decay



$0\nu\beta\beta$

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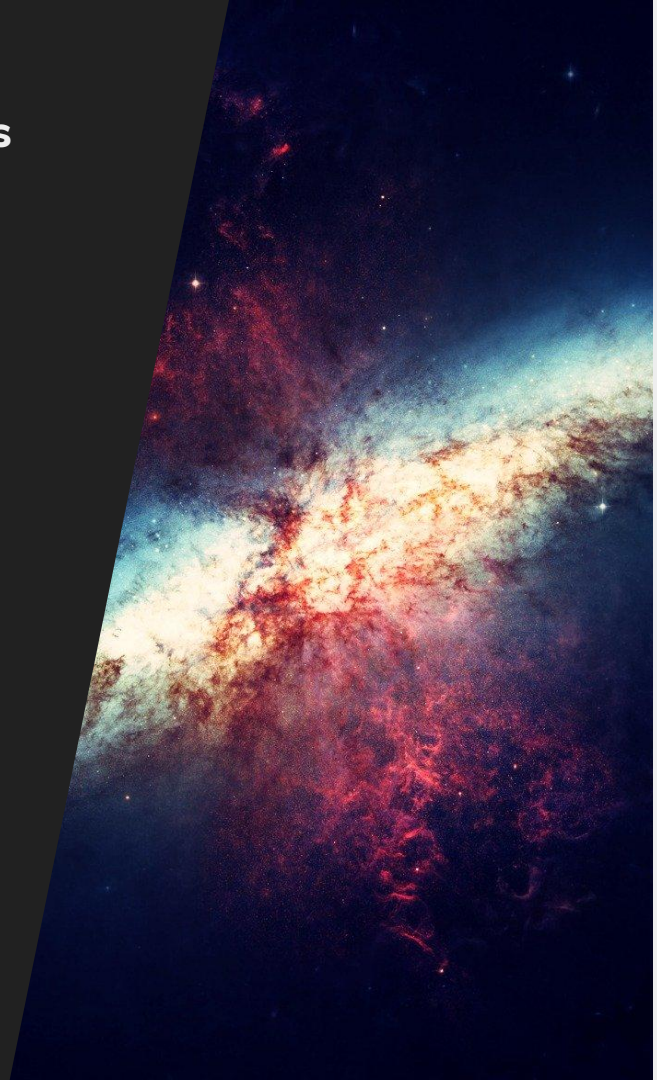
Neutrinos



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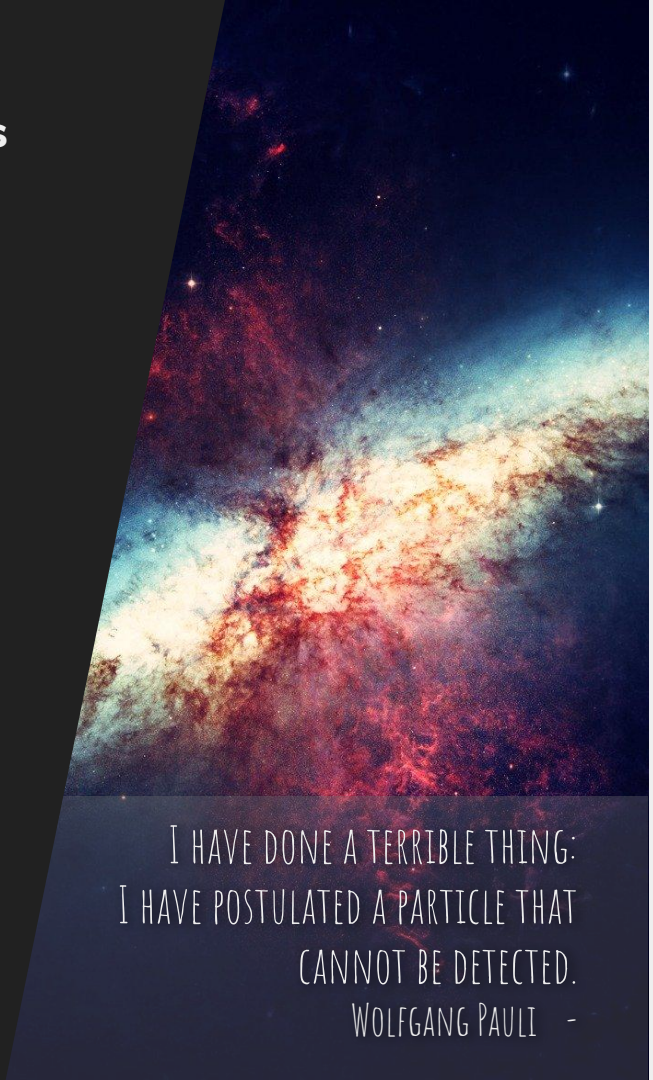
What **do we know** about neutrinos?

- 2nd most abundant known particles in the observable universe
- They love to oscillate
- At least 2 neutrino species must have mass
- They are generators for Nobel prizes

Neutrinos



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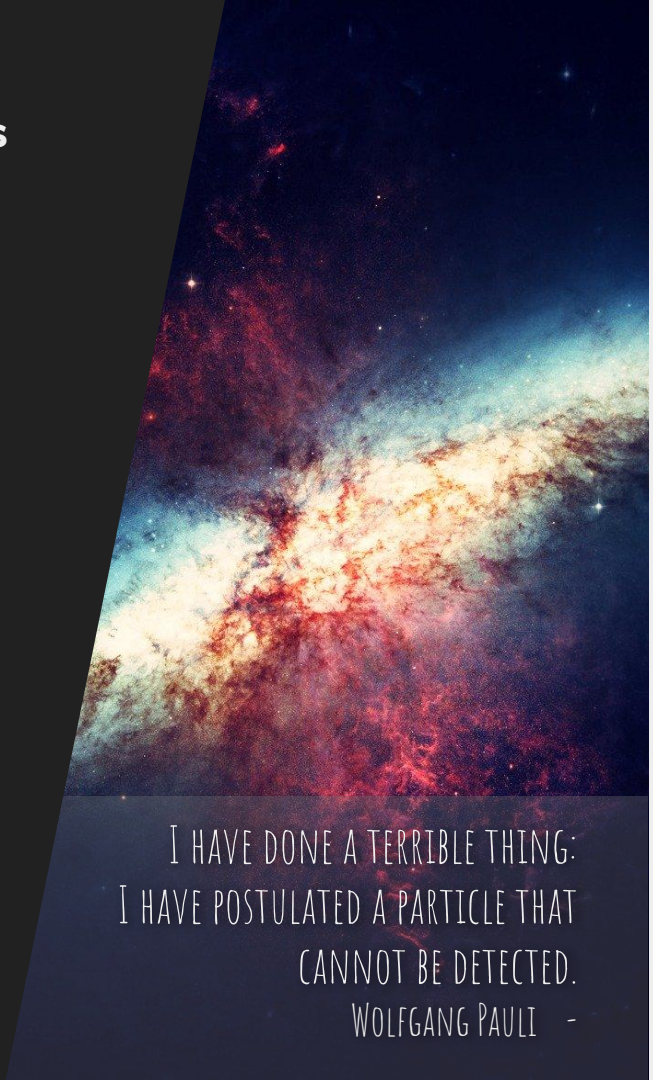
What we **don't know** about neutrinos:

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

Neutrinos



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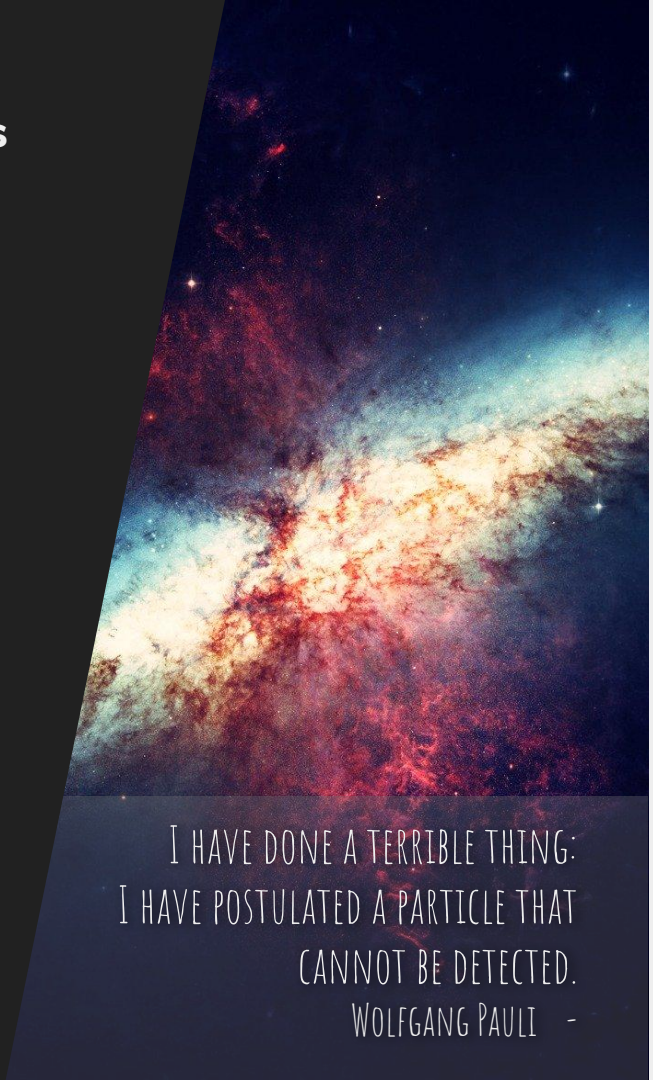
Detecting the $0\nu\beta\beta$-decay would imply:

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

Neutrinos



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So… let's get some isotope and start?

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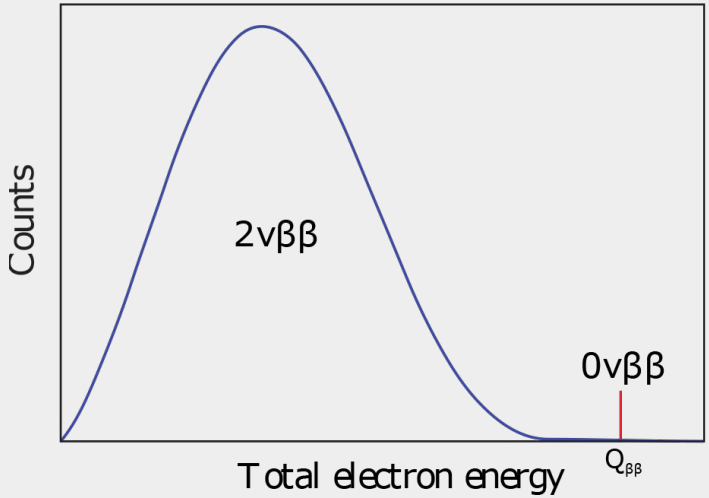
0$\nu\beta\beta$-Signal

Peak at Q-value of decay



$\beta\beta$-decay spectrum

Fig. left: arXiv:1601.07512
Fig. right: http://faculty.wcas.northwestern.edu/ (11/2018)

Let’s create an experiment!

Isotope

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

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Decay channel

Can we detect the decay?

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

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

Let’s create an experiment!

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Isotope

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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

Let's create an experiment!

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, **^{76}Ge**, ^{78}Kr, ^{82}Se, ^{86}Kr, ^{96}Zr, ^{100}Mo, ^{136}Xe, ^{130}Te, ...

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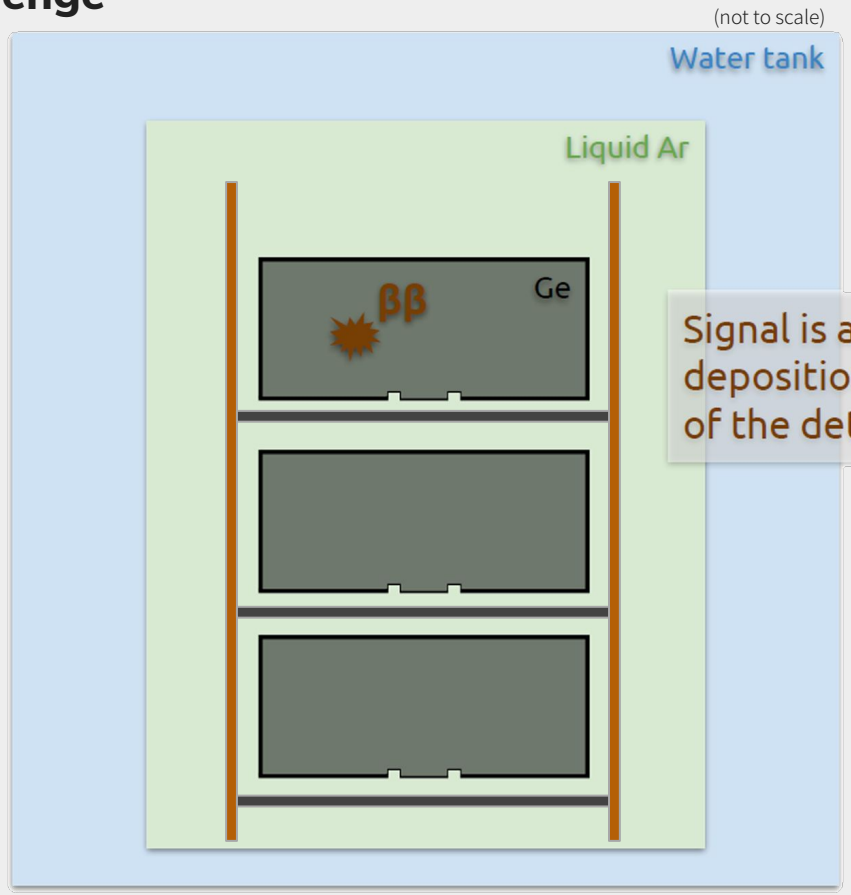
**GERDA, MAJORANA and LEGEND towards a background-free ton-scale Ge-76 experiment*, Neutrino 2020, Yoann Kermaidic

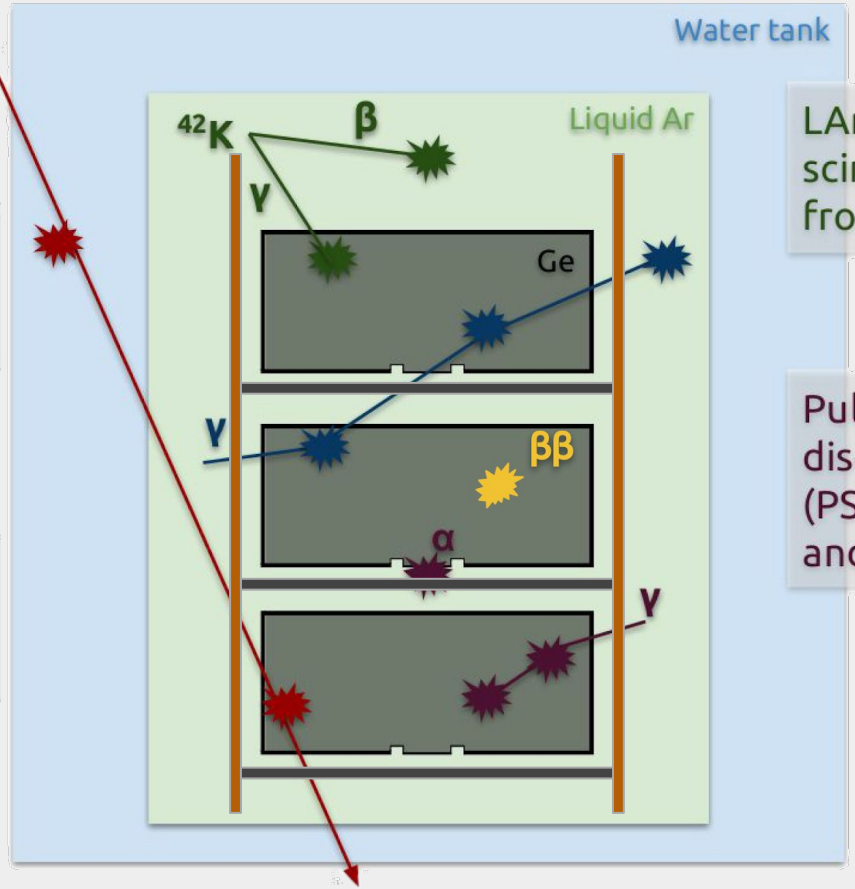
Low-background challenge



T 68.1: **LEGEND Group Report**
Wednesday, March 17, 2021,
16:00–16:20

Illustration: 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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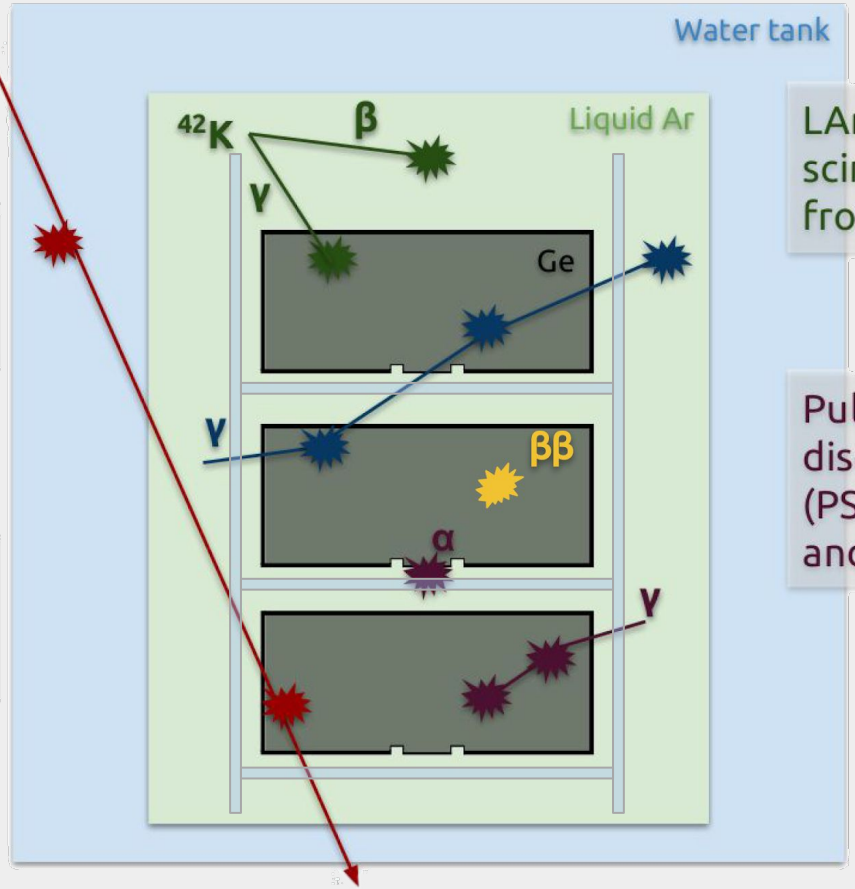

Muon veto based on Cherenkov photons in water

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Active Materials

Replace opaque materials with transparent szintillator

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Illustration: AJ Zsigmond

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

Significant improvement in the **identification efficiency** of background events close to the detector

e.g. ^{42}K

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

Particle identification

Differentiation of particles by PSD

High purity

< 1µBq per holding plate

PEN

Poly(ethylene 2,6-naphthalate)

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Wavelength shifter

Shifts 128 nm scintillation light from LAr to visible blue light

Particle identification

Differentiation of particles by PSD

High purity

< 1µBq per holding plate

Mechanical properties

Stronger than Si plates
Mechanically better in cryogenic liquids than Cu
R&D on encapsulation for L1000

(T 68.2: Wednesday, March 17, 2021, 16:20–16:35, L. Manzanillas)

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PEN
(almost) Radio-pure production

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

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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

PEN
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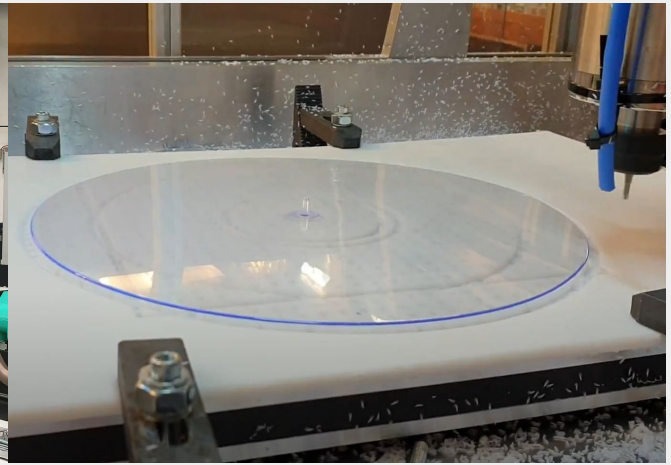
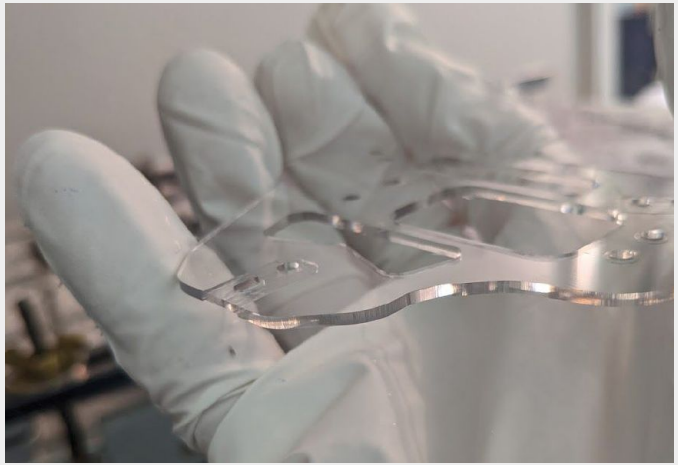


- Method: **Injection compression molding**
- All parts in contact with PEN have been acid-etched
- Complete production in class 100 clean room
- Plates have been scanned for radio-impurities for ~60 days

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

Qualification Measurements

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Processed Holders:

- Measurements ongoing
  - Attenuation length, veto efficiency, radio-purity, light yield
- First real-life tests have been performed in 2020
  - SCARF setup at TU Munich
  - Post GERDA tests (PGT)
- Detectors were not affected by leakage current

Qualification Measurements

Outlook

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Processed Holders:

- Measurements ongoing
  - Attenuation length, veto efficiency, radio-purity, light yield
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- Detectors were not affected by leakage current

LEGEND-200

- Start is expected this year
- Delayed due to the pandemic
- All PEN structures are at LNGS and will be screened until they will be integrated into the experiment

Backup

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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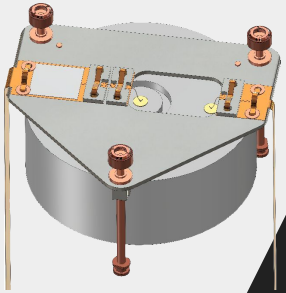


Energy Resolution

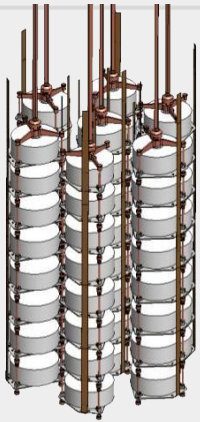
$\Delta E_{Q_{\beta\beta}} \approx 0.1\%$

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

using HPGe detectors

Exposure

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



Identification & Rejection

LAr veto, Muon veto, detector anti-coincidence, PSD, active materials,...

Background Index

1. Go underground
2. Radioclean materials
3. Shielding

Good enough?

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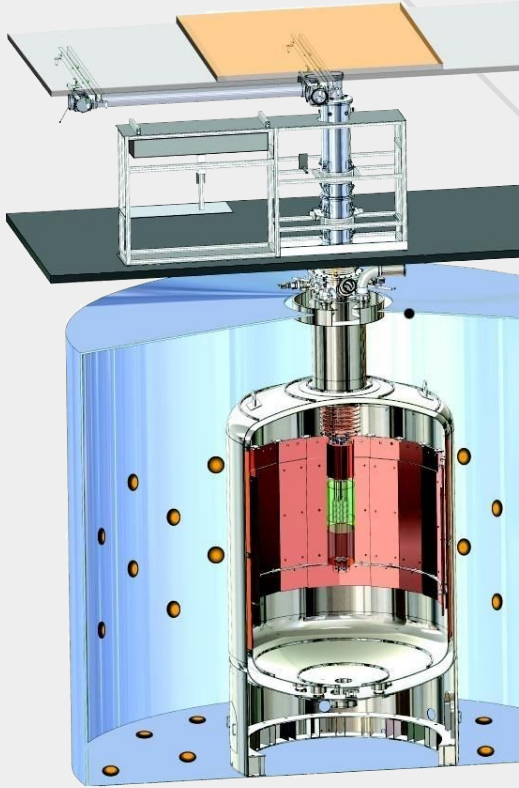

*Figures: *Eur. Phys. J. C 78 (2018) 388*

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Can we detect such decay?

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

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

Felix Fischer

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Combining the best features of MAJORANA and GERDA

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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)

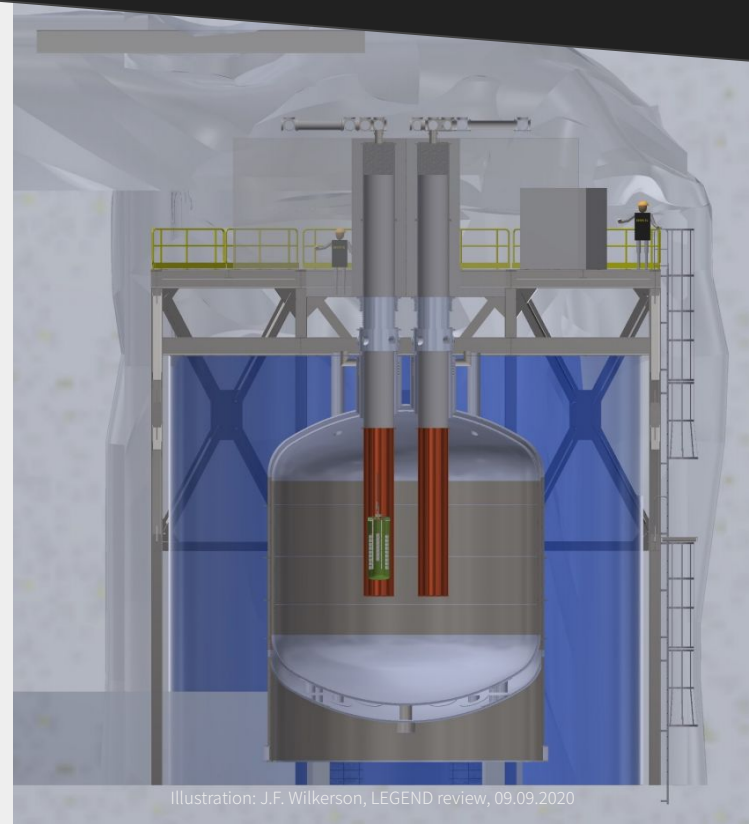
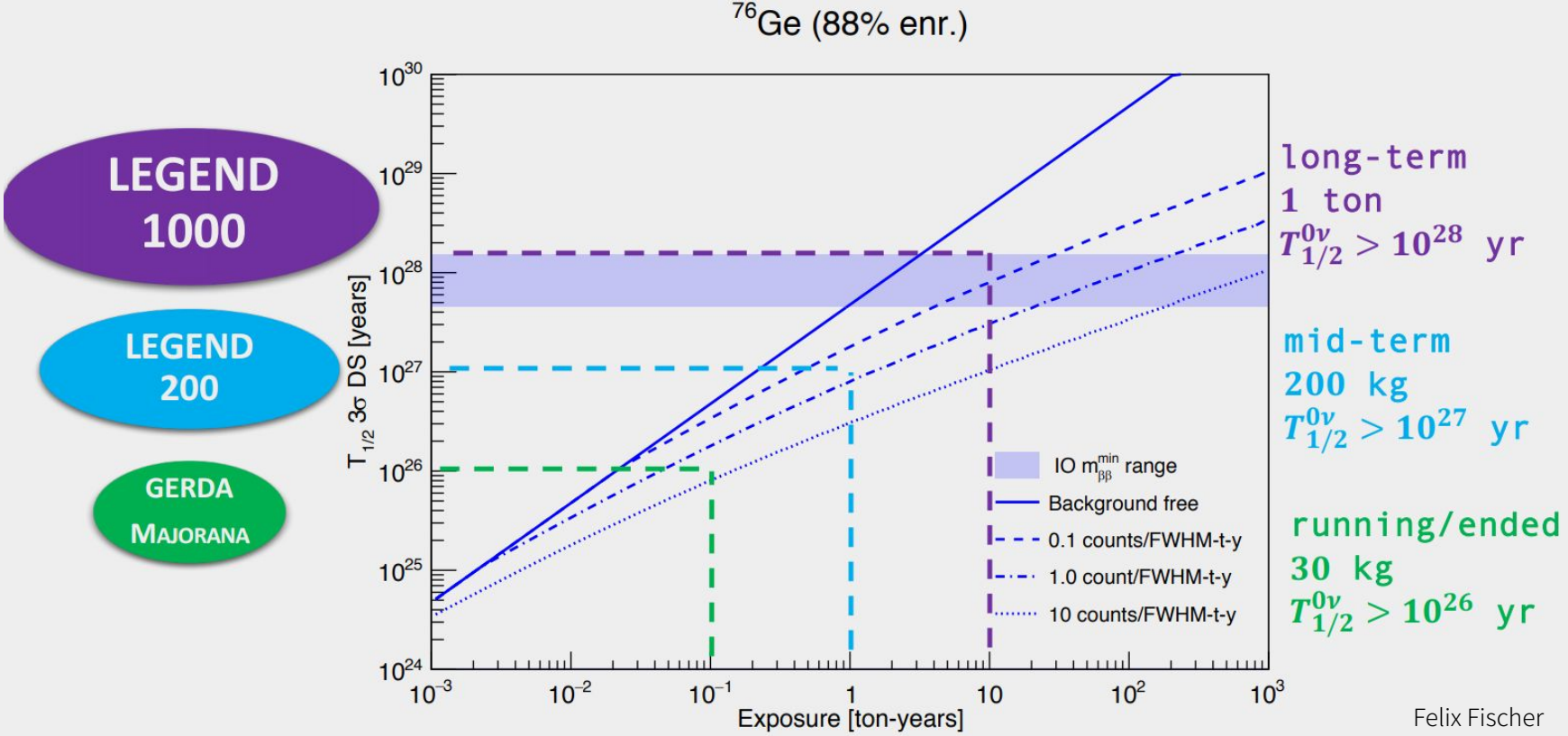


Illustration: J.F. Wilkerson, LEGEND review, 09.09.2020

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