GERDA and LEGEND Low-Background Physics with HPGe Detectors

Oliver Schulz

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

GERDA

LEGEND

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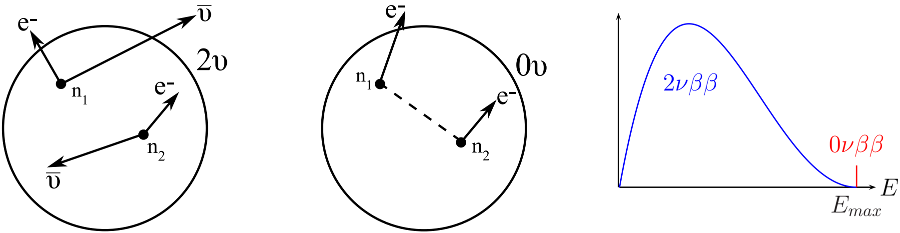
MPP Project Review, December 17, 2017

Outline

$0\nu\beta\beta$ Decay

- Single β decay not allowed for some isotopes, only double β decay
- Also $0\nu\beta\beta$ decay, due to Majorana-ν ($\nu = \bar{\nu}$)?



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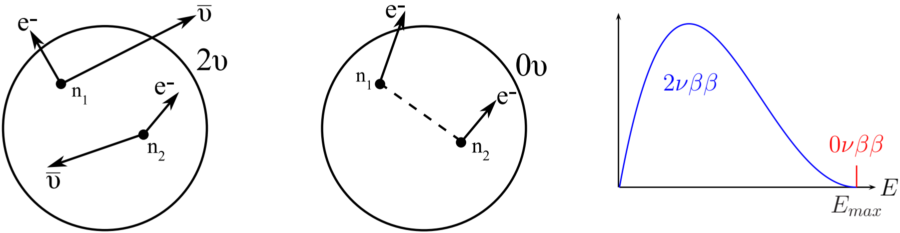

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G(Q,Z)\,|M_{\mathrm{nucl}}|^2\,\langle m_{ee}\rangle^2$$

- Discovery of $0\nu\beta\beta$ decay would
  - Imply lepton-number violation
  - Tell us about nature of ν (Majorana component?)
  - Give information about absolute Neutrino mass / hierarchy?

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Low-Background Challenge

- Expected $0\nu\beta\beta$ decay half lives very long ($\geq 10^{26}$ years): Background must be almost zero

(e.g. [Caldwell et al., Phys. Rev. D 96, 073001 (2017)])

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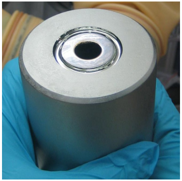
- Need high source mass
  $\rightarrow$ Isotope enrichment
- Need to get rid of radioactive background:
  - Cosmic background
    $\rightarrow$ Need underground location
  - Environmental radiation
    $\rightarrow$ Need excellent shielding
  - Radiation from materials used in setup
    $\rightarrow$ Need very radio-pure materials
  - Intrinsic $2\nu\beta\beta$ background
    $\rightarrow$ Need good energy resolution

Why use ^{76}Ge?

Advantages:

- Source = Detector
- Production of enriched detectors up to 86% well established (though expensive)



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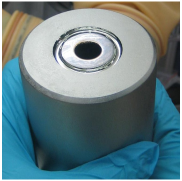

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- HPGe has excellent energy resolution, only way to reduce $2\nu\beta\beta$ decay background, also important since sensitivity is

  $T_{1/2} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$ (BG-free: $T_{1/2} \propto a \cdot \epsilon \cdot M \cdot t$)
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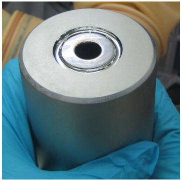

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Challenges:

- Detector operation under cryogenic conditions
- Cosmic activation of detector material ($\rightarrow$ ^{60}Co and ^{68}Ge)

The GERDA Experiment

- Search for $0\nu\beta\beta$ decay in $^{76}\mathrm{Ge}$ at $Q_{\beta\beta} = 2040 keV$
- Array of isotopically enriched HPGe detectors, suspended in liquid Argon
- Ultra-low background setup, located underground at LNGS (1400 m rock overburden, 3500 m water equivalent)

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- Phase II: Increased active mass, new detector technology lower background, additional background veto
- Phase II design goals:
  - Sensitive to half-life of $\geq 10^{26}$ yr with exposure of 100 kg $\cdot$ yr
  - Lower background: $1 \times 10^{-2} \rightarrow 1 \times 10^{-3}$ cts/(keV$\cdot$ kg$\cdot$ yr)
  - Understand whether technology is suitable for ton-scale
- Current status: Phase II data taking

Organization

- 19 Member institutes, all in Europe:
  https://www.mpi-hd.mpg.de/gerda
- GERDA at MPP:
  - Director: Allen Caldwell
  - Group leader: Bela Majorovits
  - Staff: Christopher Gooch, Oliver Schulz
  - PostDocs: Anna Zsigmond
  - PhD Students: Laura Vanhöfer
  - MSc/BSc Students: Philipp Holl (finished), Barbara Schweisshelm

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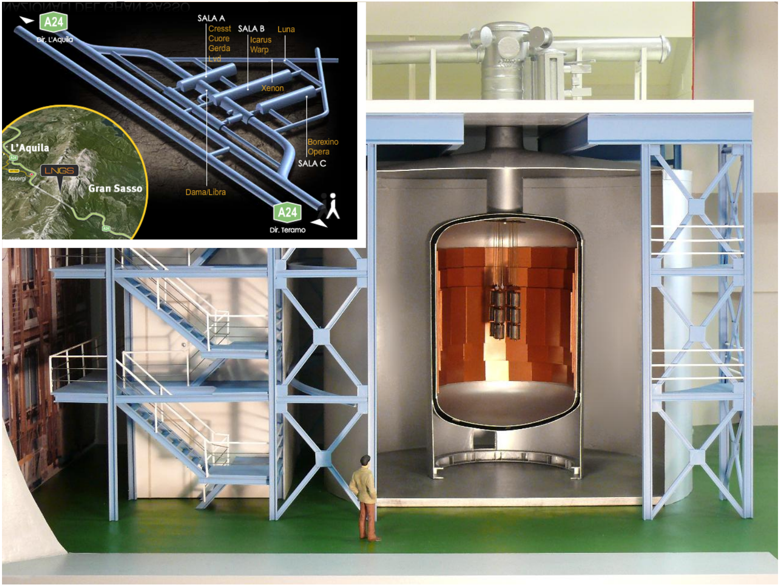
The Gerda Setup



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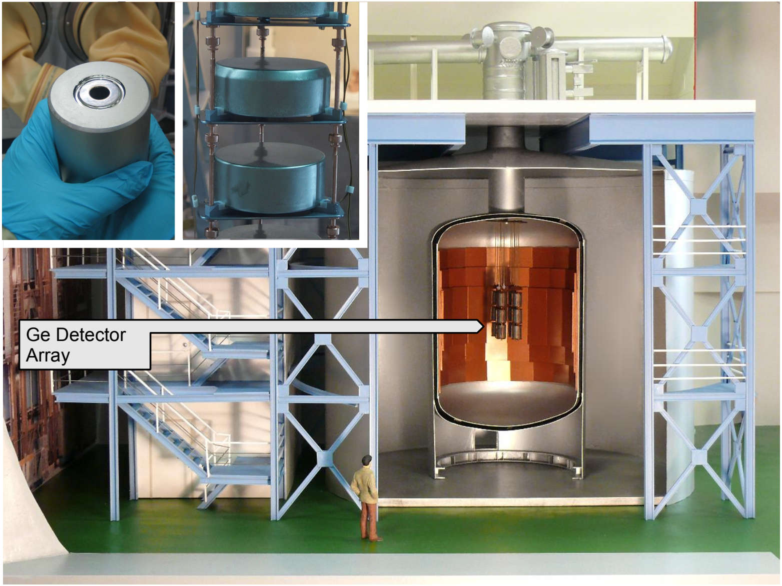

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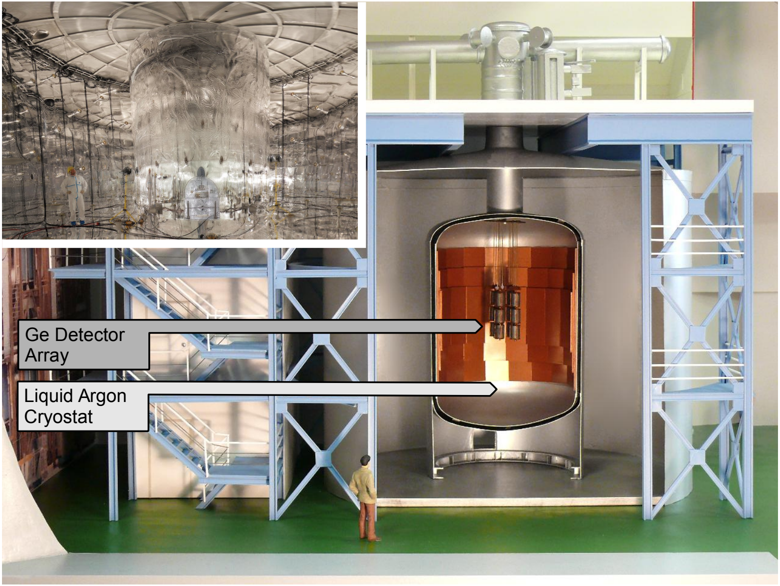

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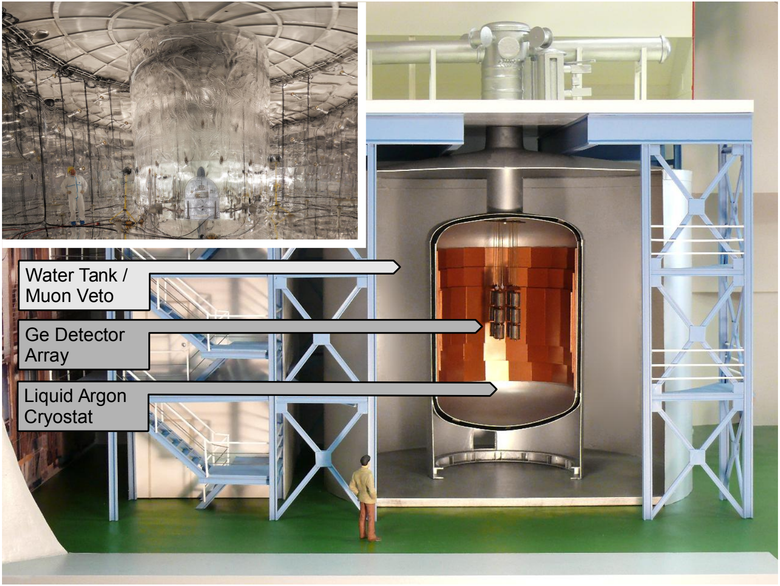

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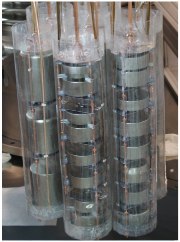
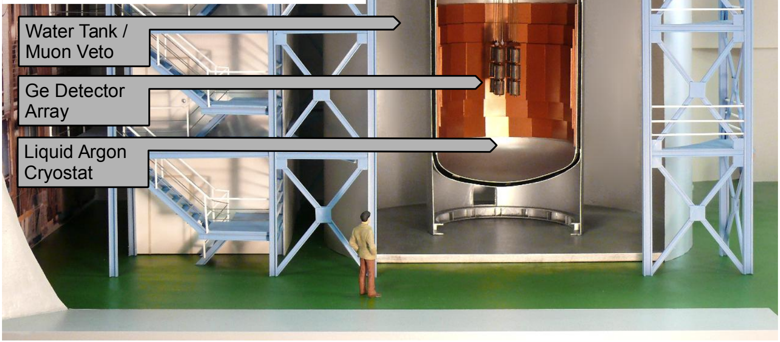
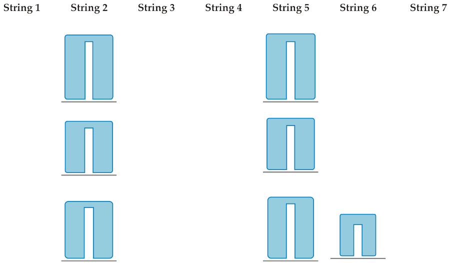




GERDA Phase-II Detector Array



- 7 string, 40 detectors in total:
  - 7 enriched Coax-type (15.8 kg)

[arXiv:1711.01452]

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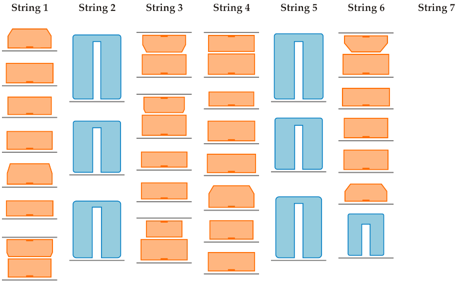

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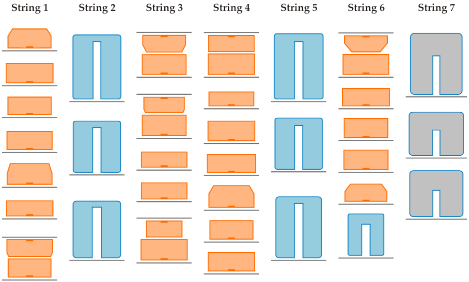

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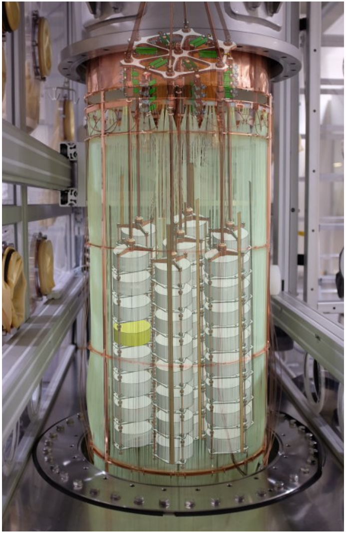

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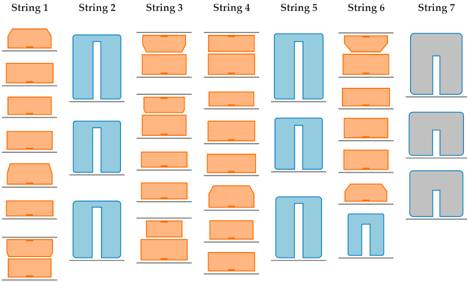

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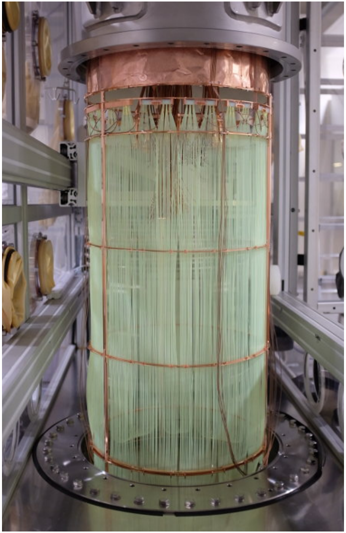

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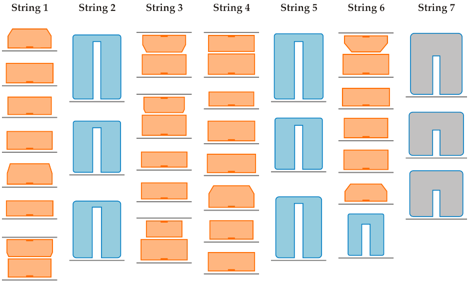

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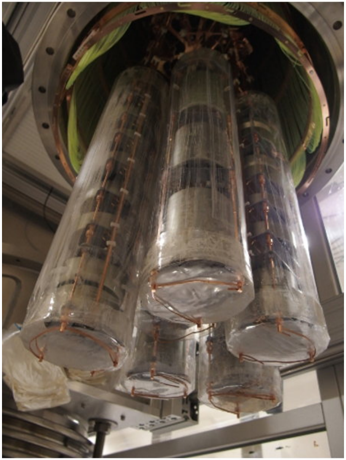

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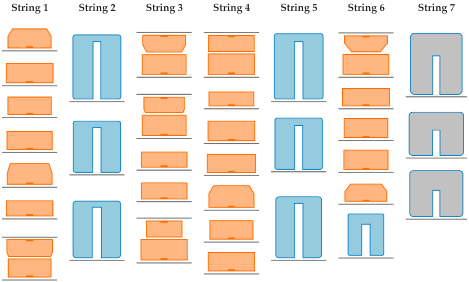

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- Array enclosed by LAr veto
- Operational since Dec. 2015

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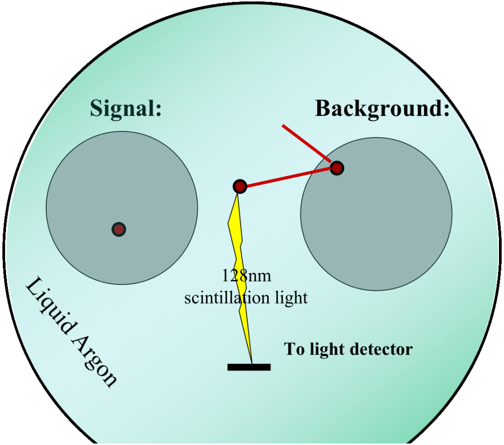
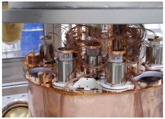
LAr Scintillation as Background Veto

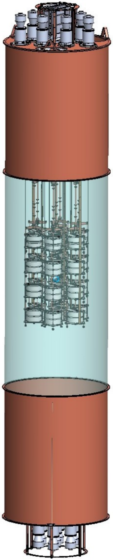


- Liquid Argon scintillates: High potential for for background reduction (esp. γ)

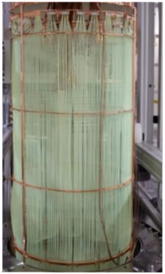
LAr Instrumentation

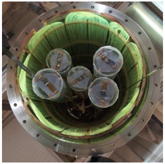
Top PMTs



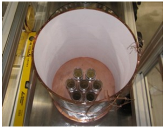


Fiber Cylinder





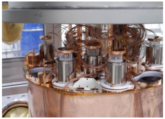
Bottom PMTs

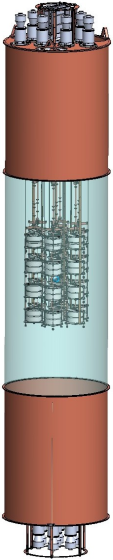


- Instrumentation of LAr volume around detectors as background veto
- 800m WLS-coated fibers, 90 SiPMs, 16 PMTs

LAr Instrumentation

Top PMTs





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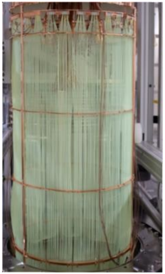

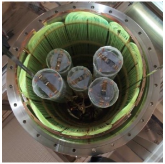

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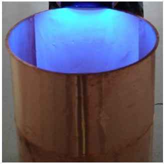

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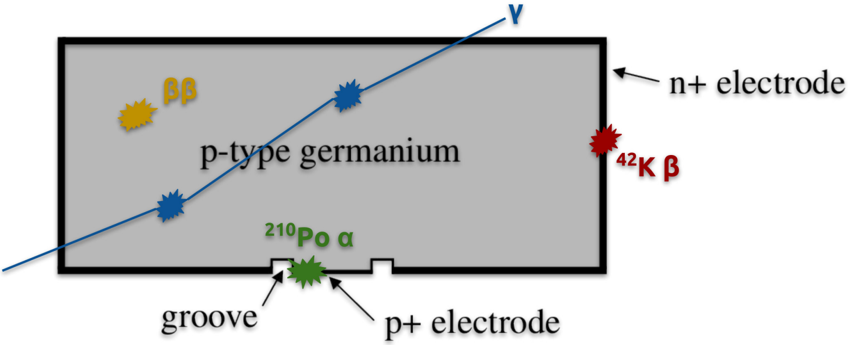
- 800m WLS-coated fibers, 90 SiPMs, 16 PMTs
- WLS-coated nylon mini-shroud around each detector string

Pulse-Shape Discrimination



- PSD: Reject multi-site and surface events based on detector signal shape

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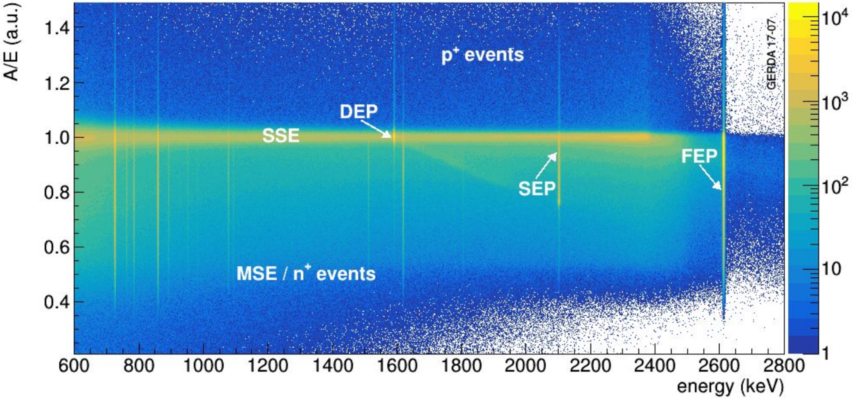

- PSD: Reject multi-site and surface events based on detector signal shape
- Methods: A/E (BEGe detectors), ANN (coaxial detectors)

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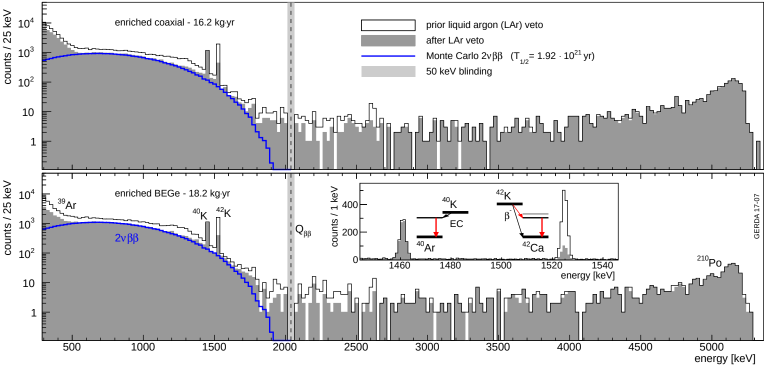
Background after Vetos and Cuts

Coax detectors

BEGe detectors



Phase II background index (1930 - 2190 keV):

- Almost pure $2\nu\beta\beta$ spectrum after LAr veto (600-1300 keV)

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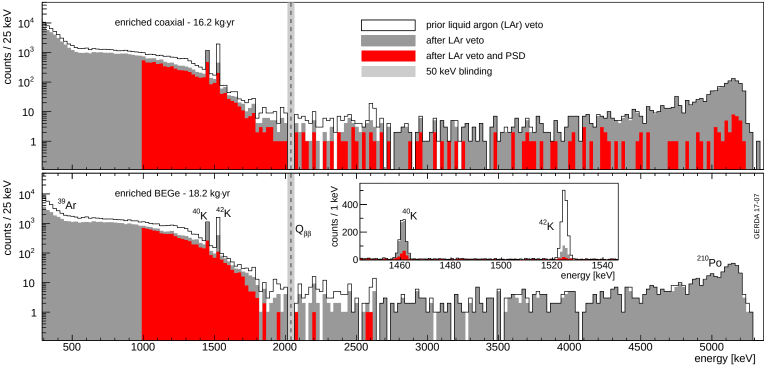

Phase II background index (1930 - 2190 keV):

- Almost pure $2\nu\beta\beta$ spectrum after LAr veto (600-1300 keV)
- Coax detectors: $2.7^{+0.8}_{-1.0} \times 10^{-3}$ cts/(keV·kg·yr)
- BEGe detectors: $1.0^{+0.4}_{-0.6} \times 10^{-3}$ cts/(keV·kg·yr)
- Background-free up to design exposure 100 kg · yr

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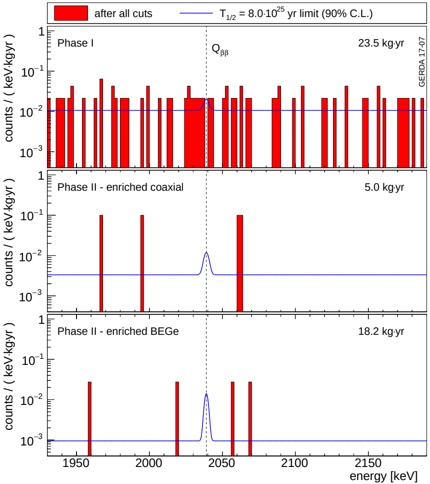
Current Combined Phase I and II Result



All limits: 90% CL/CI

- Phase I:
  $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr
- Phase-II:
  - First 10.8 kg·yr unblinded June 2016

    [Nature 554 (2017) 47]
  - Additional 12.4 kg·yr unblinded June 2017

    [arXiv:1710.07776]

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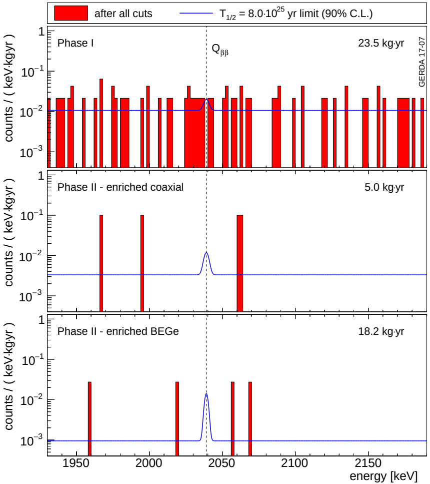

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    [Nature 554 (2017) 47]
  - Additional 12.4 kg·yr unblinded June 2017

    [arXiv:1710.07776]
- Phase I plus Phase II:
  - $T_{1/2}^{0\nu} > 8.0 \times 10^{25}$ yr (Profile likelihood)
  - $T_{1/2}^{0\nu} > 5.1 \times 10^{25}$ yr (Bayesian)

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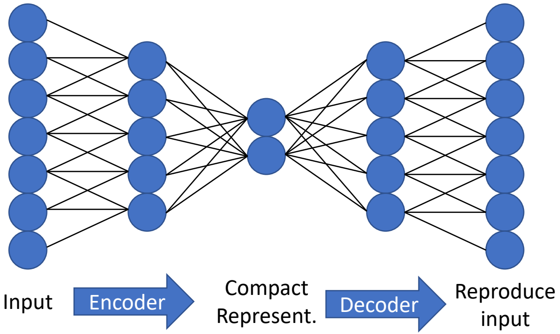
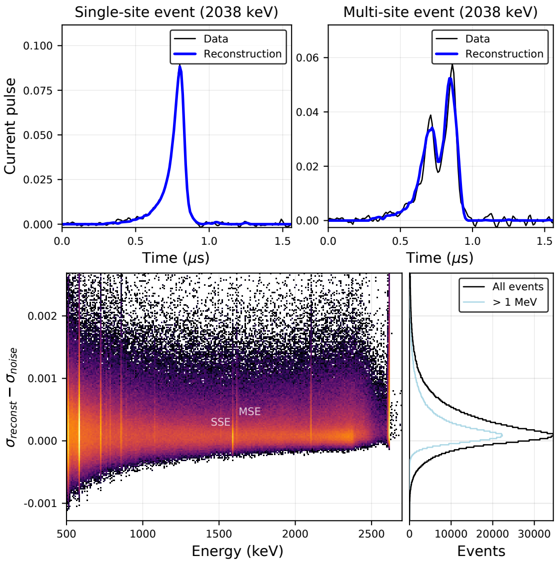
Novel PSD Techniques: Deep-Learning



- Problem: Low volume of tagged data
- Step 1: Dimensionality reduction via auto-encoder ANN

[P. Holl, MSc thesis, MPP, 2017]

Auto-Encoder Pulse-Reconstruction



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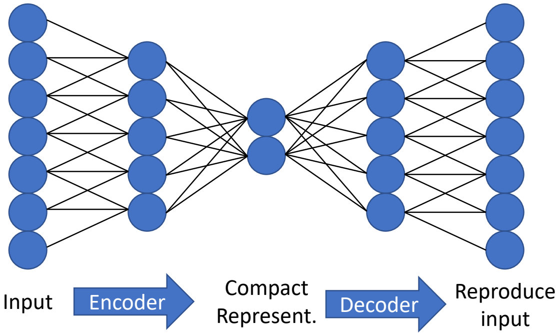

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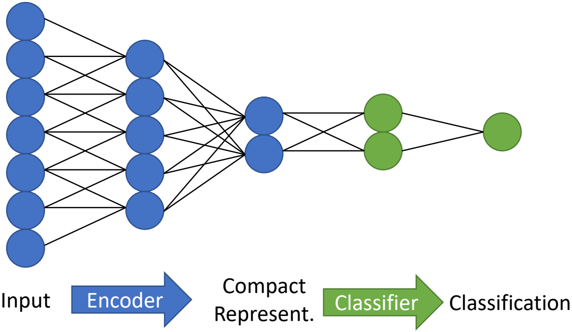

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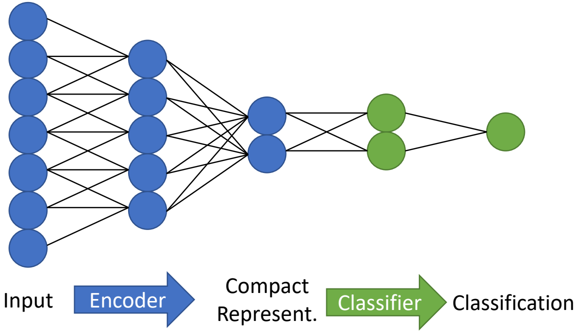
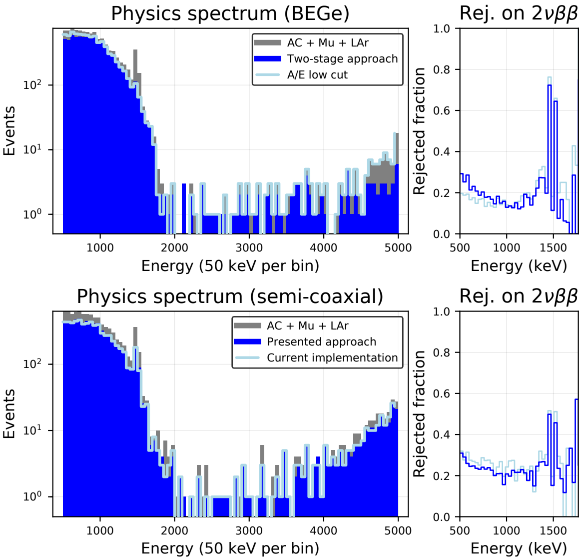


- Problem: Low volume of tagged data
- Step 1: Dimensionality reduction via auto-encoder ANN
- Step 2: Classifier ANN
- Advantages: Little bias, no classifier calibration

[P. Holl, MSc thesis, MPP, 2017]

Deep-Learning PSD Performance



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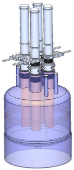
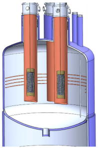
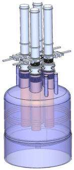
The next step: LEGEND

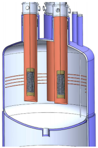




- Gerda Phase-II sensitivity will scratch inverted hierarchy
- But: Need about 1 ton of enriched $^{76}\mathrm{Ge}$ to cover it

The next step: LEGEND





- Gerda Phase-II sensitivity will scratch inverted hierarchy
- But: Need about 1 ton of enriched $^{76}\mathrm{Ge}$ to cover it
- Large fractions of GERDA and MAJORANA plus new (and old) players in the field: New LEGEND collaboration [http://legend-exp.org/] 46 institutes (Europe, USA, China)
- Two Phases:
  - LEGEND-200: In GERDA cryostat
  - LEGEND-1000: Host-lab search ongoing

[arXiv:1709.01980]

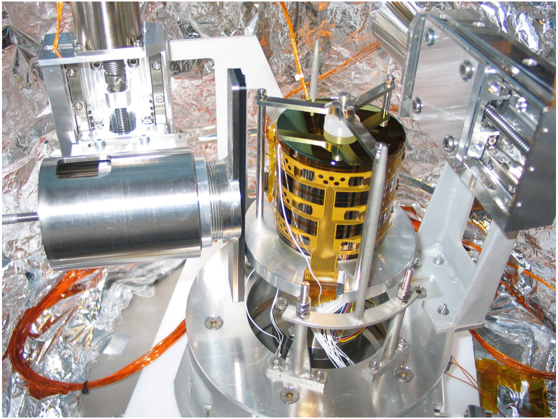
LEGEND at MPP

- Director: Allen Caldwell, group leader: Iris Abt
- Activities:
  - HPGe detector research (GeDet): I. Abt
    - Staff: Christopher Gooch, Xiang Liu, Oliver Schulz
    - PostDocs: Anna Zsigmond
    - PhD students: Lukas Hauertmann, Martin Schuster
    - MSc/BSc students: Daniel Wolfrum
    - Guest Students 2017: Jinglu Ma, Qiang Du
  - Cosmogenic Backgrounds (MINIDEX): B. Majorivits
    - Staff: Anton Empl, Christopher Gooch, Oliver Schulz
    - PhD students: Raphael Kneissl
    - MSc/BSc students: Oliver Plaul
  - Novel Active Construction Materials (PEN): B. Majorivits
    - Staff: Christopher Gooch, Oliver Schulz
    - PostDocs: Elena Sala
    - PhD students: Connor Hayward
    - MSc/BSc students: Simon Eck, Felix Fischer, Thomas Kraetzschmar

GeDet: HPGe Detector Research at MPP

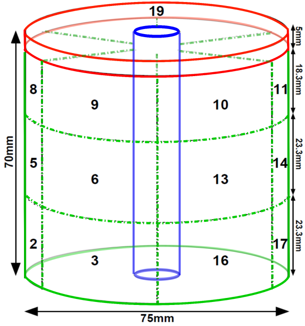
- Main focus: Gain better understanding of detector surface effects and detector pulse shapes in general
- Years of experience with segmented HPGe detectors: ideal tool to study detector properties
- Now part of MPPs involvement in LEGEND

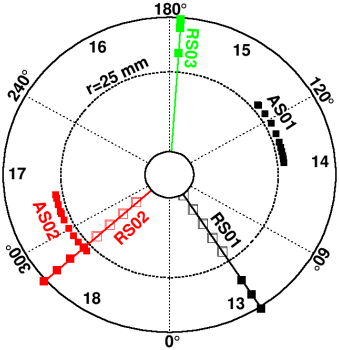
Test-Stand Galatea



- Facility for scans of detector surfaces with α and β radiation and laser
- Important improvements in 2017

α Radiation Effect at Passivated Surfaces





- α-scans of top segment of true-coax detector
- Surprise - effective dead layer very thin: $10\mu\mathrm{m}$ for electrons, $12\mu\mathrm{m}$ for holes

[L. Garbini, Phd thesis, MPP] [NIM-A 858 (2017) 80]

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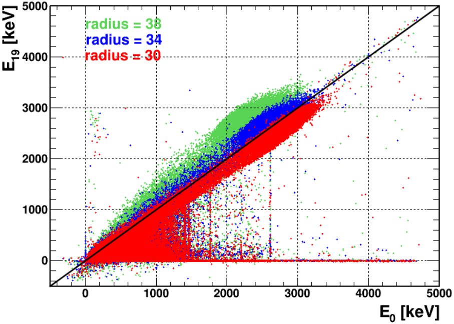
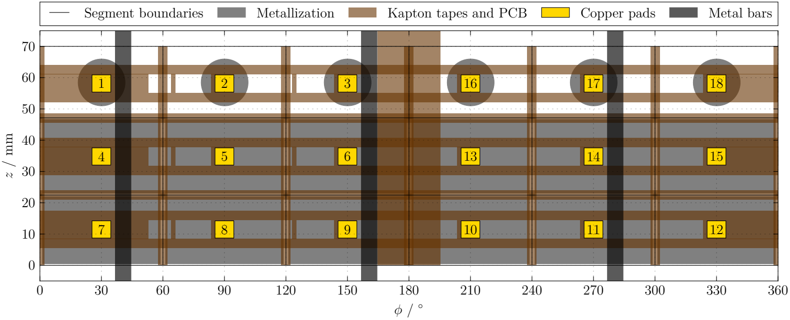


- α-scans of top segment of true-coax detector
- Surprise - effective dead layer very thin: $10\mu m$ for electrons, $12\mu m$ for holes
- Observed electron or hole, trapping dependent on radius
- Charge loss can be recovered via other segments

[L. Garbini, Phd thesis, MPP] [NIM-A 858 (2017) 80]

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

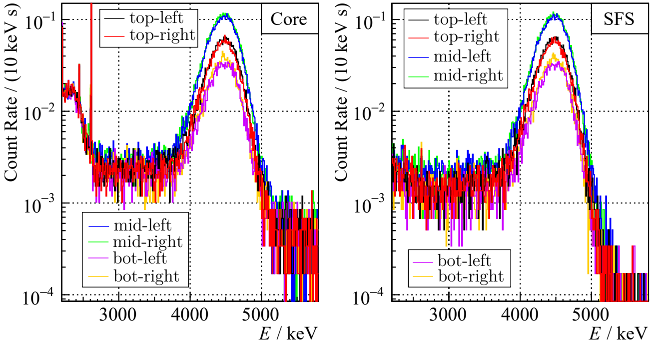
Surface-Metalization Effects



- α/γ-scans over fully and partially metalized segments

[L. Hauertmann, MSc thesis, MPP, 2017]

Surface-Metalization Effects



- α/γ-scans over fully and partially metalized segments
- Metalization scheme seems to have almost no effect
  $\rightarrow$ can build low-background detectors
  with partial metalization

[L. Hauertmann, MSc thesis, MPP, 2017]

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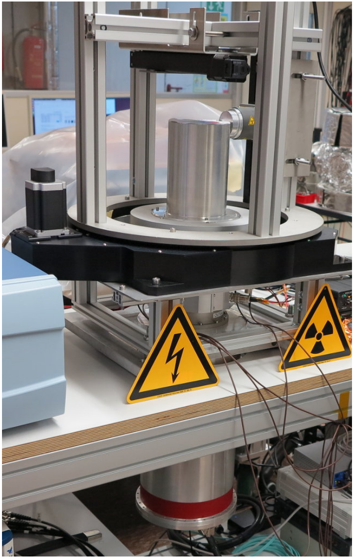
(Werner-Heisenberg-Institut)

Test-Stand K2



- Temperature-controlled cryostat
  for HPGe detectors
- 2017: Added
  automated scanning stage
  (side- and top-scans)

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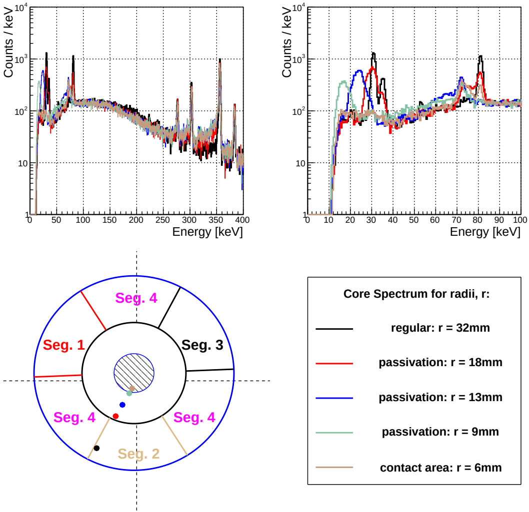
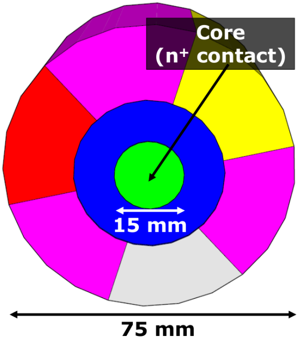
Charge Loss Beneath Surface Passivation

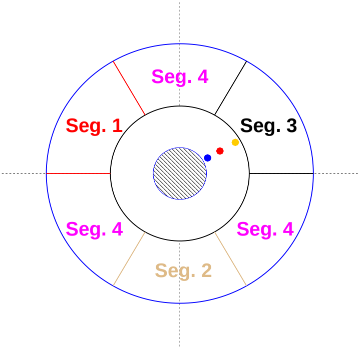


[M. Schuster, MSc thesis, MPP, 2017]

- Measurements with ^{133}Ba at passivation area of segmented BEGe-detector
- Observed charge loss at surprisingly high interaction depths
- Partial charge recovery via segment signals

Temperature Effect on Charge Loss

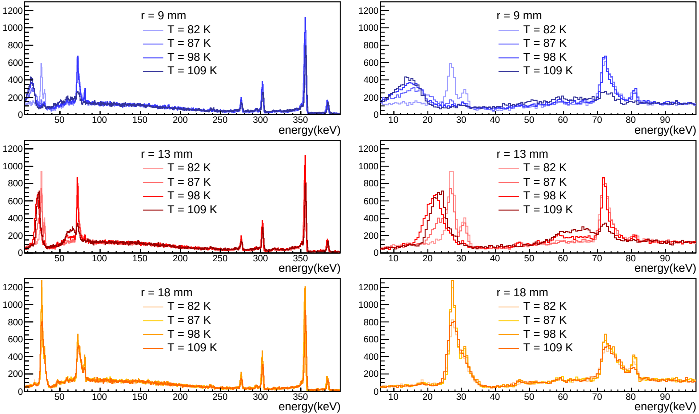




- $^{133}\mathrm{Ba}$-scans at different temperatures

[J. Ma, guest-student, MPP, 2017]

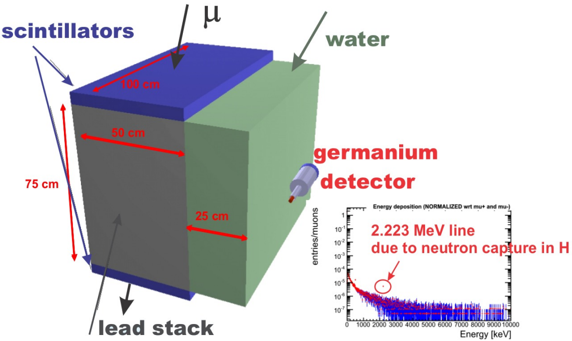
Temperature Effect on Charge Loss



- ^{133}Ba-scans at different temperatures
- Charge loss depth depends on temperature and radius

[J. Ma, guest-student, MPP, 2017]

MINIDEX: μ-Induced Neutrons



- Shallow-underground experiment MINIDEX measures μ-induced neutron production (at Uni Tübingen)

[Astropart.Phys. 90 (2017) 1-13] [Q. Du, guest-student, MPP, 2017]

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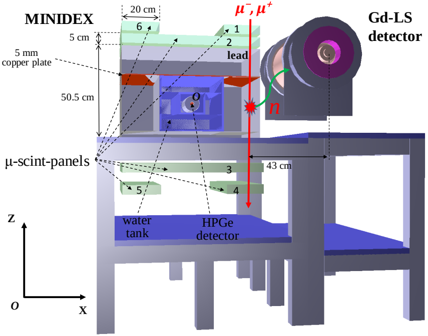

- Shallow-underground experiment MINIDEX measures μ-induced neutron production (at Uni Tübingen)
- Confirmed neutron deficit in Monte Carlo in data with additional neutron detector (cooperation with Tsinghua University)
- Good run 2017

[Astropart.Phys. 90 (2017) 1-13] [Q. Du, guest-student, MPP, 2017]

Max-Planck-Institut für Physik
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Active Construction Materials: PEN

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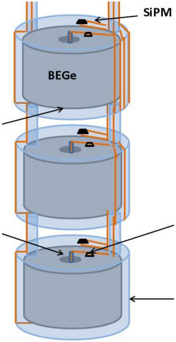

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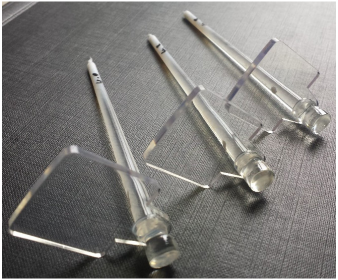
  - Originally MPP GERDA activity, now integrated in LEGEND
- Idea: Encapsulate Ge-detectors in PEN, also use pen for holder structures
- PEN-Research in cooperation with F. Simon (MPP), TU Dortmund, Uni Lancaster, ORNL and CTU Prague

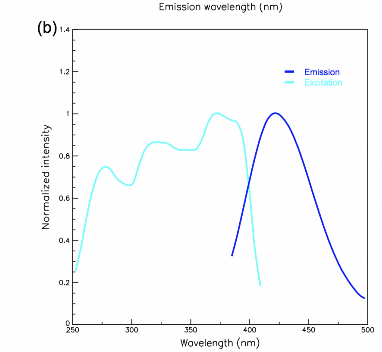
[arXiv:1708.09265]

PEN Injection Molding



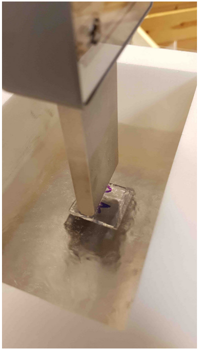
- Successfully shaped PEN via injection molding (at LKT TU Dortmund and Fraunhofer ICT)
- Currently using commercial material, but first successful PEN synthesis at ORNL and NUVIA
- Attenuation length still not a good as we'd like → systematic study

PEN Emission Spectrum



- PEN emission spectrum around 430 nm: Directly accessible with PMTs and SiPMs, needs no wavelength shifter

Mechanical Properties in Cryoliquids



- Currently measuring mechanical properties of PEN in liquid nitrogen
- PEN performs very well so far

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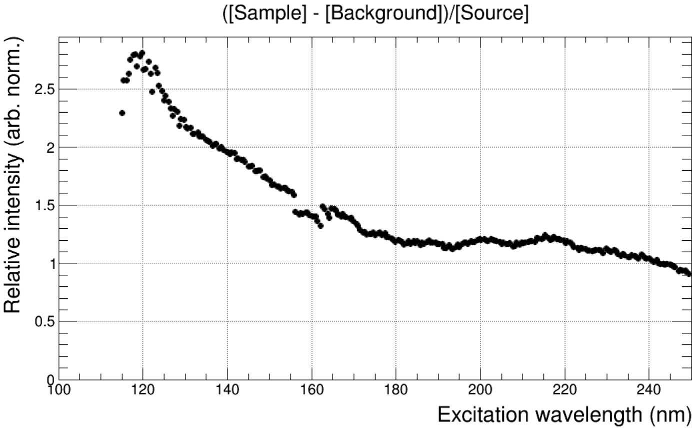
PEN Excitation at VUV Wavelengths



[M. Febbraro, ORNL]

- Preliminary: Strong excitation at VUV wavelength
  → wavelength shifter for LAr scintillation light!

Summary

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  several important studies completed in 2017,
  important upgrades to our setups
- MINIDEX operation continues as planned,
  expecting a publication and a Phd thesis in 2018
- PEN project is picking up speed,
  material looks increasingly promising,
  international partners complementary expertise