Low background physics with HPGe detectors

Anna Julia Zsigmond
for the GERDA and LEGEND groups

MPP Project Review 2018

MAX-PLANCK-GESELLSCHAFT

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

LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

GERDA

LEGEND and GERDA people

Director:	Allen Caldwell
Group leaders:	Iris Abt, Béla Majorovits
Staff:	Chris Gooch, Xiang Liu, Oliver Schulz
Postdocs:	Anna Zsigmond, Elena Sala (until Sept), Erdem Öz
PhD students:	Felix Fischer, Lukas Hauertmann, Connor Hayward, Raphael Kneissl, Martin Schuster, Laura Vanhoefer (finished)
MSc students:	Péter Kicsiny, Thomas Krätzschmar (finished), Oliver Plaul (finished), Barbara Schweisshelm (finished), Simon Eck

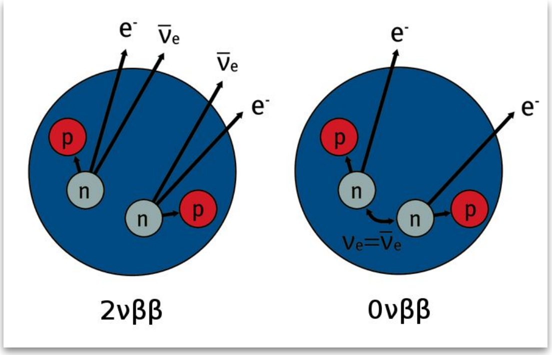
Special thanks to our colleagues
in the workshops and in the administration!

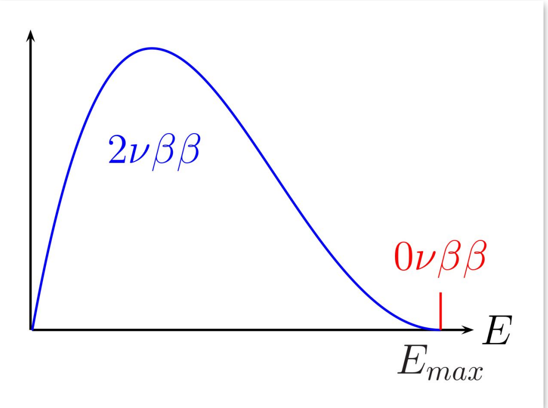
Neutrinoless double beta decay

- Double beta ($2\nu\beta\beta$) decay observed in various isotopes with a lifetime of $T^{2\nu} > 10^{19}$-10^{21} years
- If neutrino has Majorana nature
  $\rightarrow$ neutrinoless double beta ($0\nu\beta\beta$) decay
- Discovery of $0\nu\beta\beta$ decay would
  - imply lepton number violation
  - tell us about the nature of the neutrino $\rightarrow$ Majorana component
  - give information about the absolute neutrino mass through

$$T_{2\beta 0\nu}^{-1} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{NuclearM.E.}} \underbrace{\left|\sum_i \left(\tilde{U}_{\text{PMNS}}^{ei}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

in case of light Majorana neutrino exchange





Why Germanium detectors?

- Sensitivity on half-life

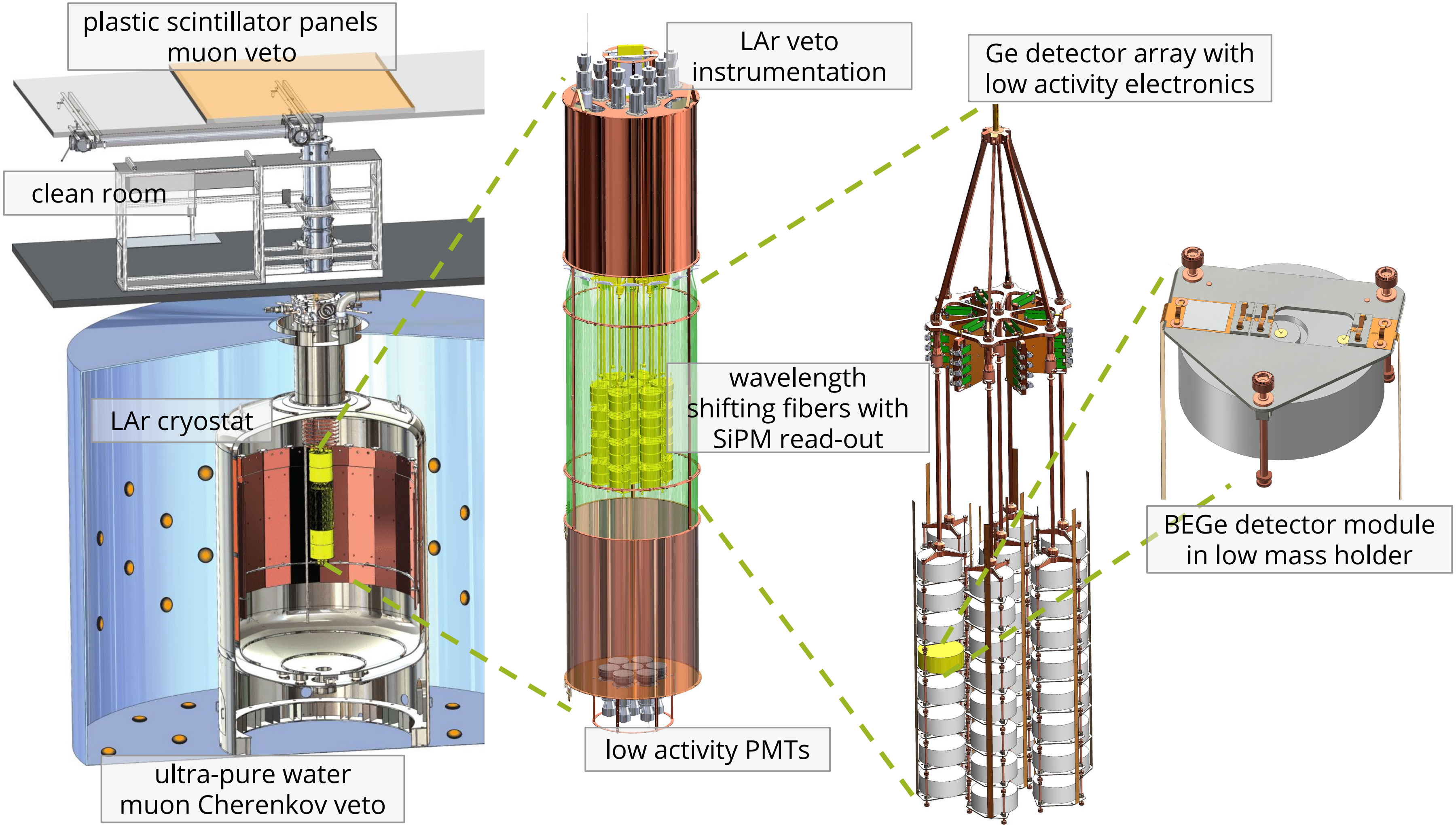
$$T^{0\nu}_{1/2} \propto \sqrt{M \cdot t / BI \cdot \Delta E}$$

- High mass and efficiency
  → isotope enrichment
- Good energy resolution
  → against intrinsic 2νββ decay
- Eliminate all backgrounds
  - Cosmic rays
    → underground
  - Environmental radioactivity
    → shielding and active veto
  - Radioactivity in setup material
    → radio-pure material selection

- Source and detector the same
  → high efficiency
- Isotope enrichment up to 90% in ^{76}Ge is established
- HPGe has excellent energy resolution
- Intrinsically pure material
- High density material
  → ββ point-like

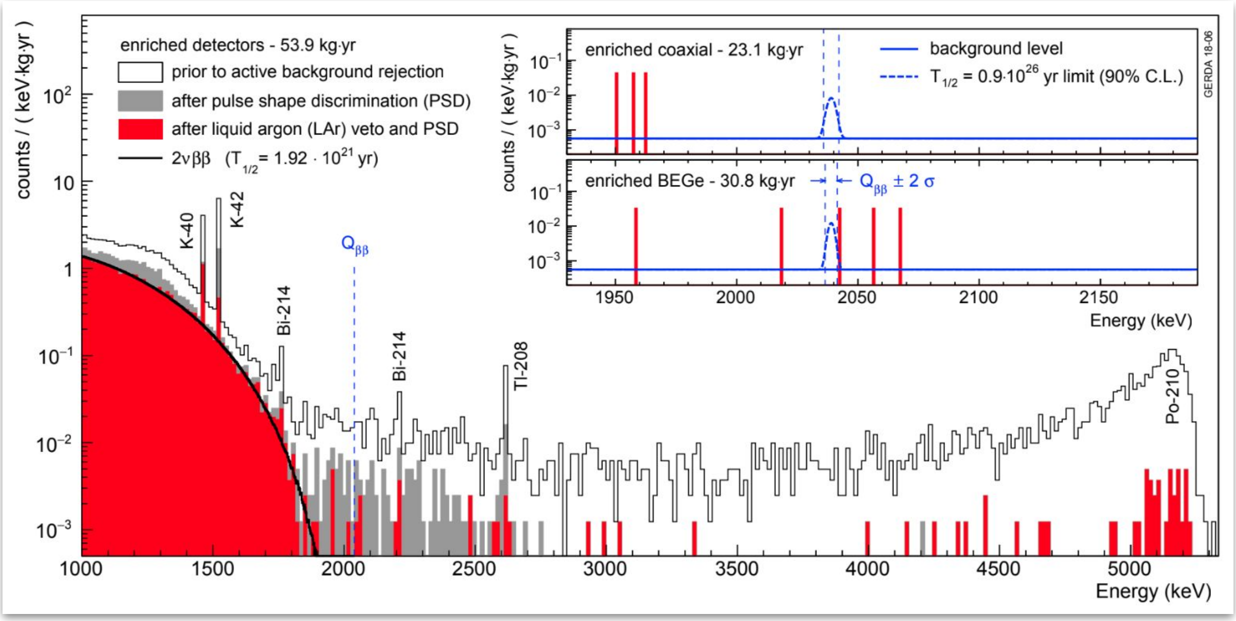
  → backgrounds can be discriminated and rejected

The present: GERDA



GERDA data release 2018

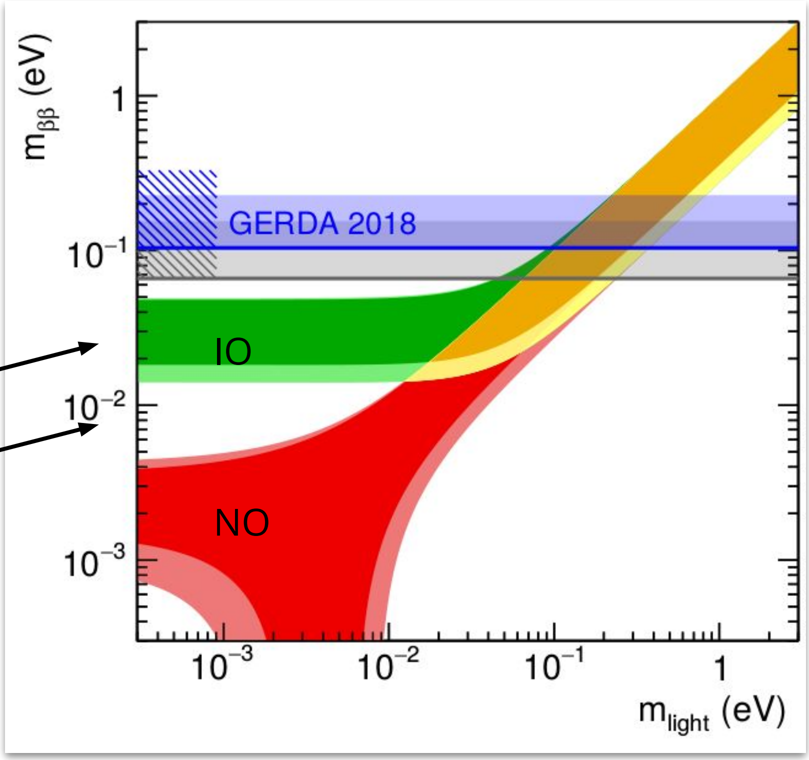
- Unblinded Phase II exposure more than doubled → **58.9 kg·yr**
- Achieved background index of **~6·10^{-4} cts/(keV·kg·yr)** for both detector types with additional PSD algorithm for coaxial detectors
- Median sensitivity for $T_{1/2}$ limit setting → **1.1·10^{26} yr** (90% C.L.)
- Best fit is for no signal
- $T_{1/2}$ > 0.9·10^{26} yr (90% C.L.)
- Limit on effective Majorana mass **< 104 - 228 meV**



The future: LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

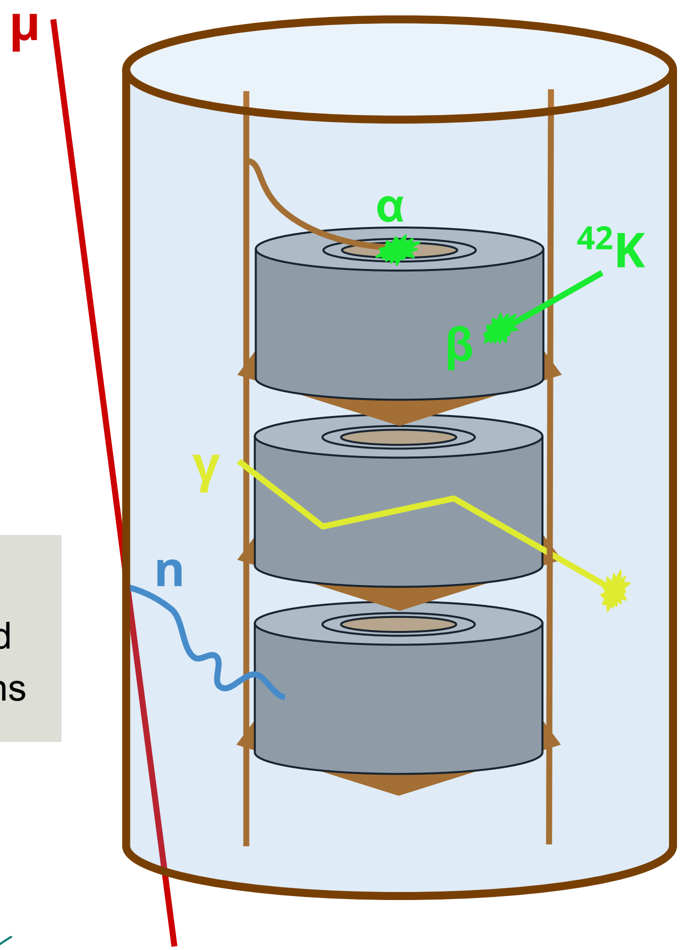
- Joint effort from Majorana and GERDA collaborations with new members for a ton-scale ^{76}Ge experiment
- Two stages
  - 200 kg in GERDA cryostat at LNGS
  - 1000 kg with improved background index
- Limit setting sensitivity
  - L200 → $1.6 \cdot 10^{27}$ yr → 28 - 61 meV
  - L1000 → $1.6 \cdot 10^{28}$ yr → 9 - 19 meV
- R&D ongoing to reach these sensitivities by reducing the backgrounds



Backgrounds and how to reject them

Cosmic rays

Muon induced neutrons



Natural radioactivity

γs from surroundings (cables, holders)

Active veto scintillation light

GERDA LAr veto

Active construction materials: PEN

Pulse shape discrimination

Pulse shape simulation

αs and βs on the detector surface

Test stands and segmented detectors

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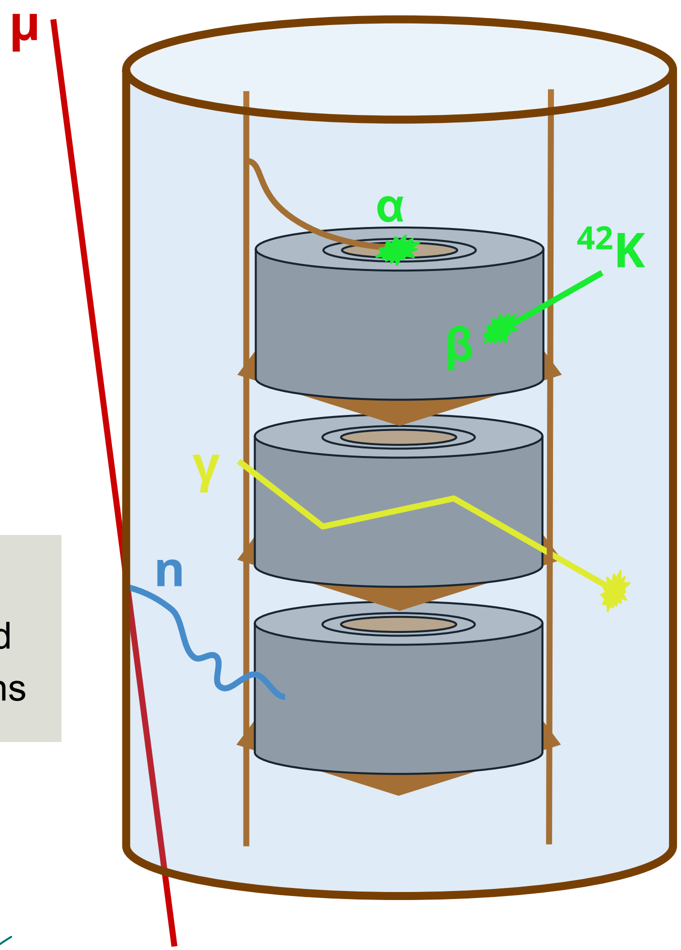

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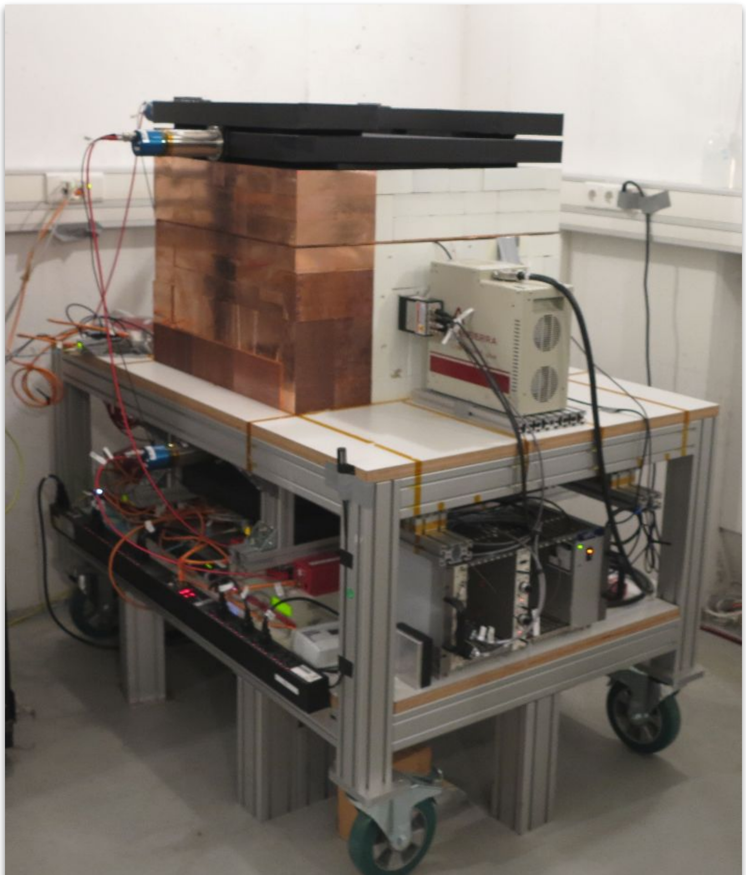
MINIDEX: muon induced neutrons



Astropart. Phys. **90** (2017) 1

Astropart. Phys. **102** (2018) 12

- Shallow underground experiment at the University of Tübingen
- Identify muon induced neutrons with
  - muon signal in scintillators
  - γ from neutron capture in water with germanium detectors
- Run 2: both target walls lead
  Run 3: one target wall to copper
- All data reanalyzed: agreement with Geant4 simulation for neutrons from lead, slight discrepancy for copper
- Differences between Geant4 and Fluka in photo-disintegration are significant

R. Kneissl et al., *to be submitted to Astropart. Phys.*

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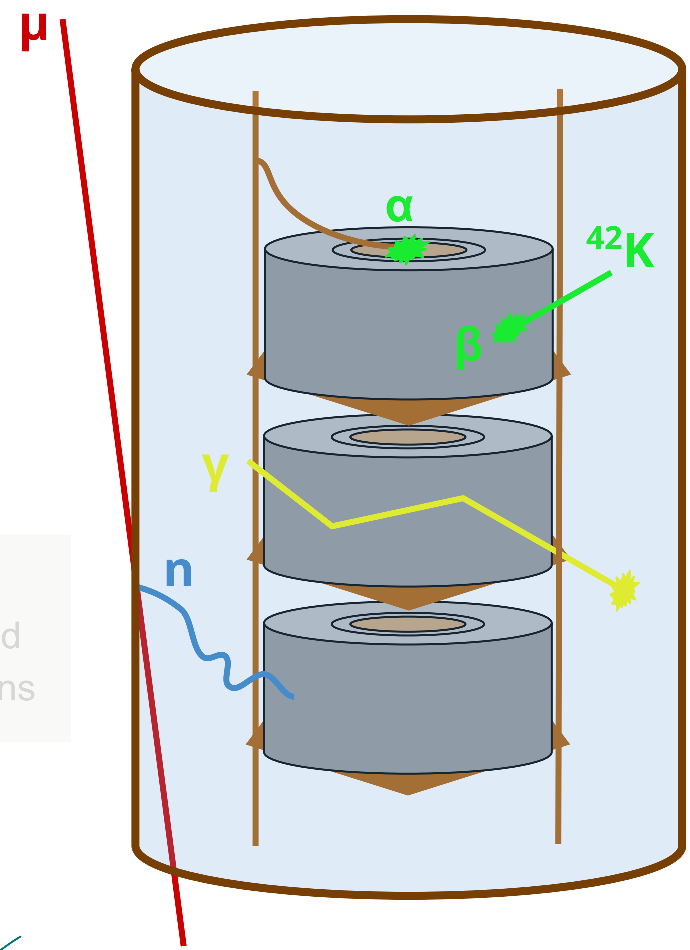

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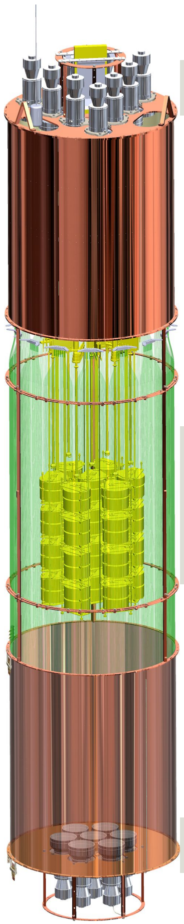
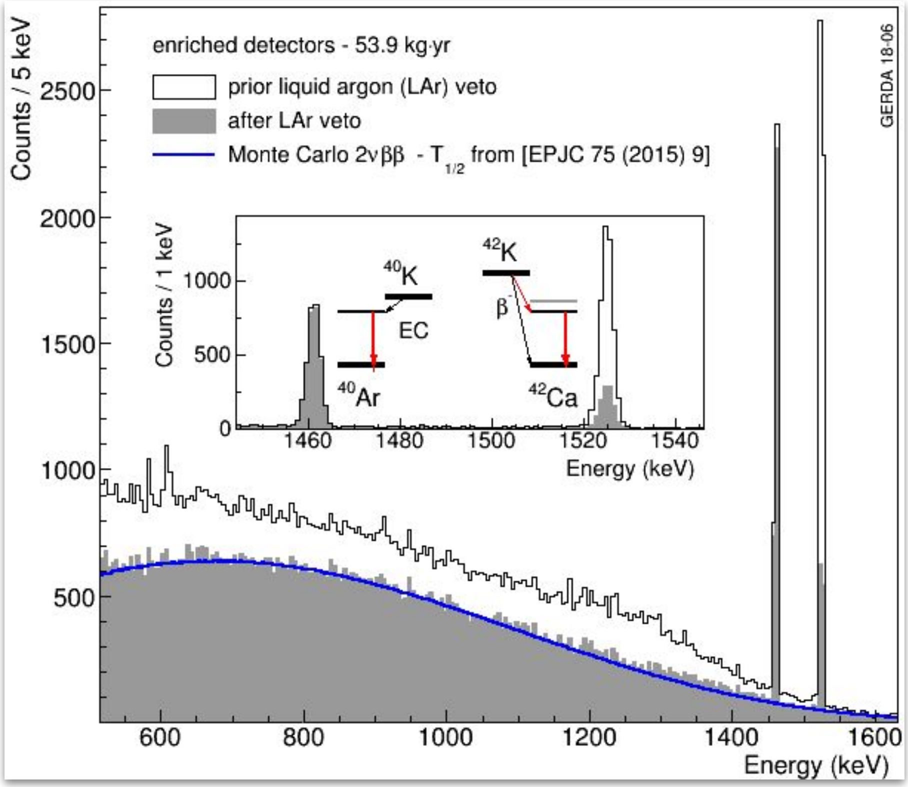
Test stands and segmented detectors

GERDA Liquid Argon veto

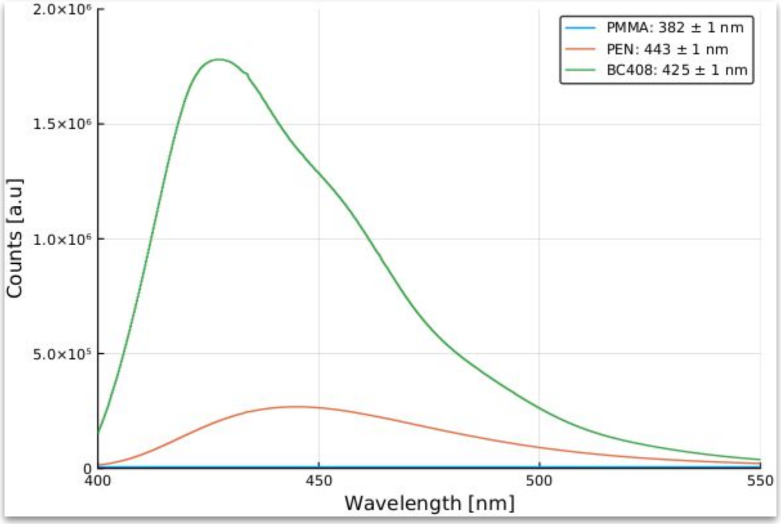




- Vetoing on the scintillation light from the LAr, an almost pure 2νββ spectrum remains
- Introduced dead time < 3%

Active construction material: PEN

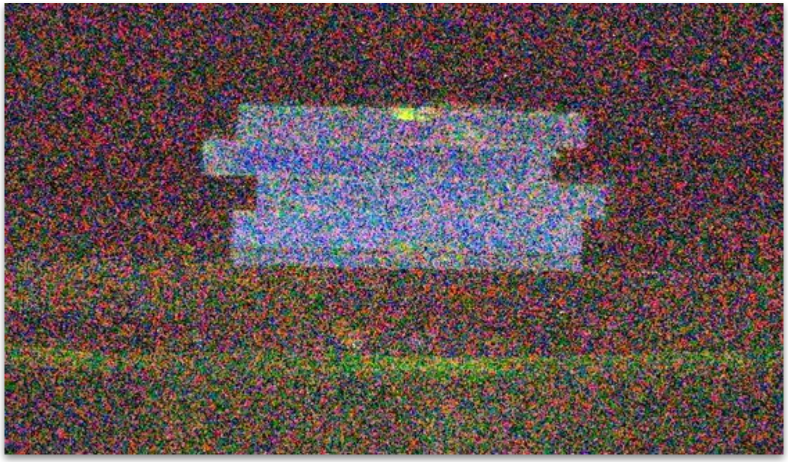
- PEN scintillates around 440 nm → directly accessible by PMTs and SiPMs, no need for wavelength shifter
- Mechanical properties have been studied → promising as holder or encapsulation for the HPGe detectors
- Radiopurity measurements are promising → other groups are working on synthesis in controlled environment to improve
- Consortium with
  - ORNL
  - Lancaster University
  - TU Dortmund
  - Czech Technical University in Prague
  - University of Tennessee
  - Nuvia a.s.

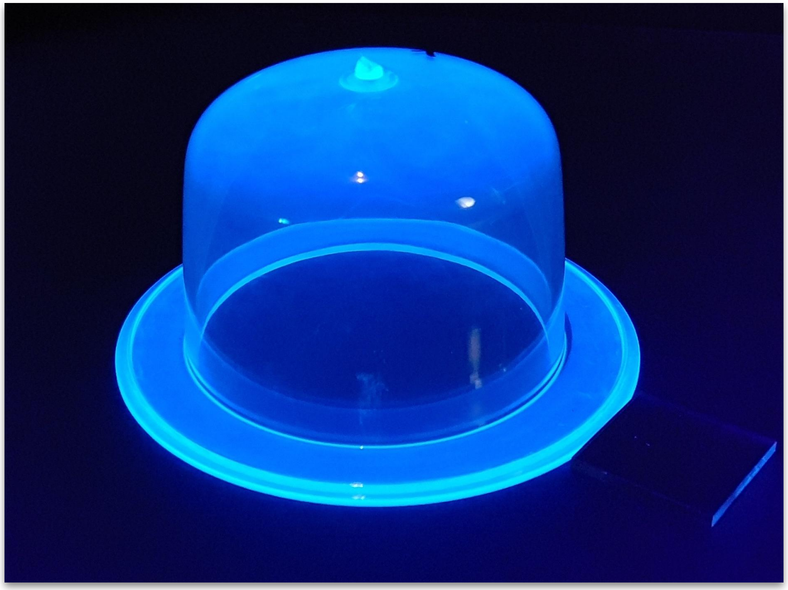


PEN scintillation

- PEN tiles excited by strong ^{137}Cs source in dark room
- Blue scintillation light visible on multi-exposure photograph

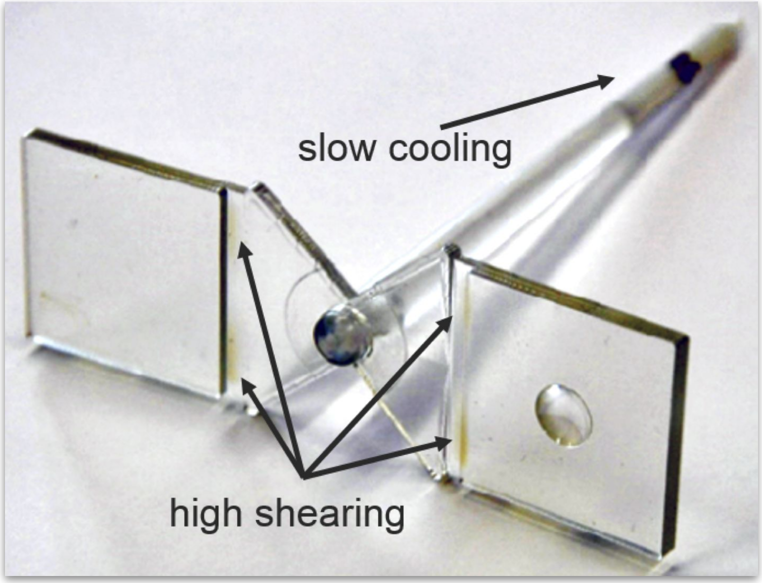
- PEN excited by UV light
- No need for wavelength shifter e.g. in LAr
- Could be used as HPGe detector encapsulation

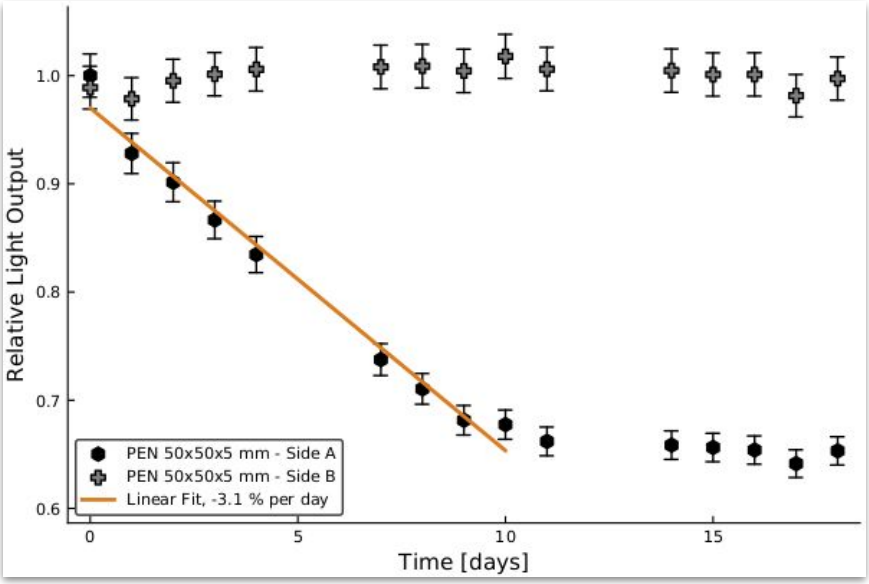




PEN molding and aging

- Large amount of tiles studied with spectrometer to optimize parameters of injection molding
- Extended exposure to UV light shows decrease of light yield of 3.1% / day and no recovery observed





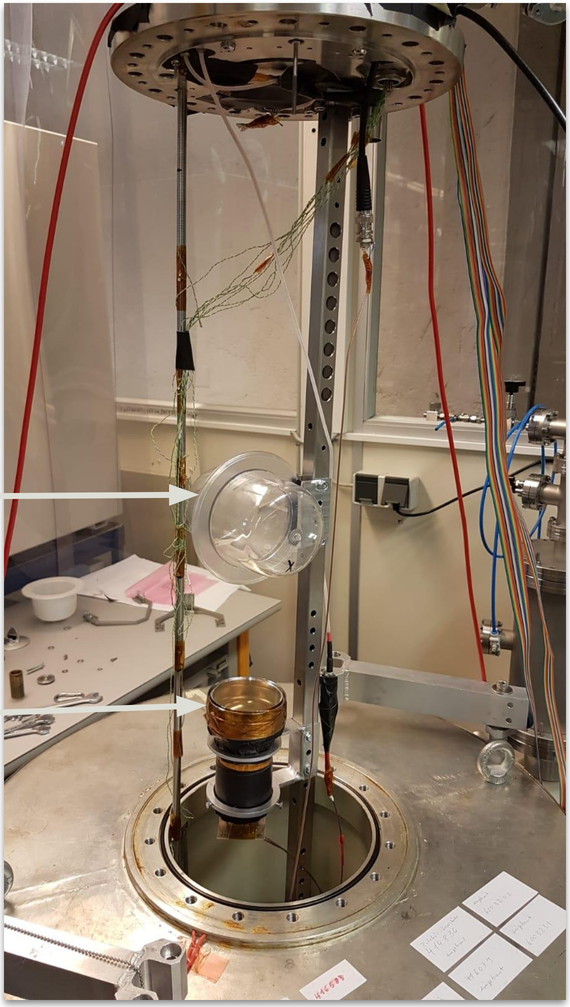
PEN scintillation at low temperatures

Gerdalinchen II test- stand revived to study PEN scintillation light in liquid nitrogen (later LAr)

^{137}Cs source outside the cryostat

PEN cup

PMT for cryogenic liquids

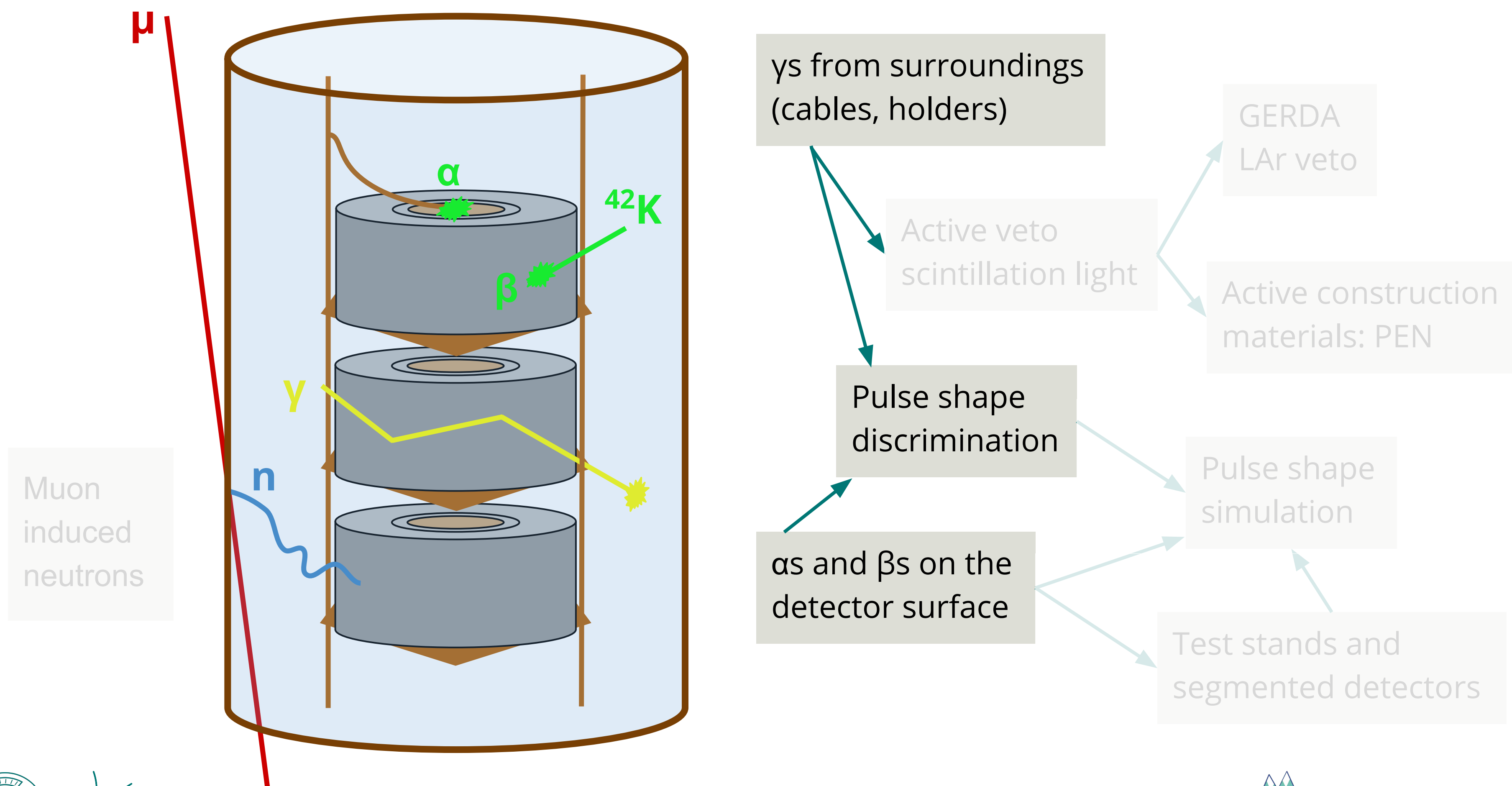


Measurements started last week!

Backgrounds and how to reject them

Cosmic rays

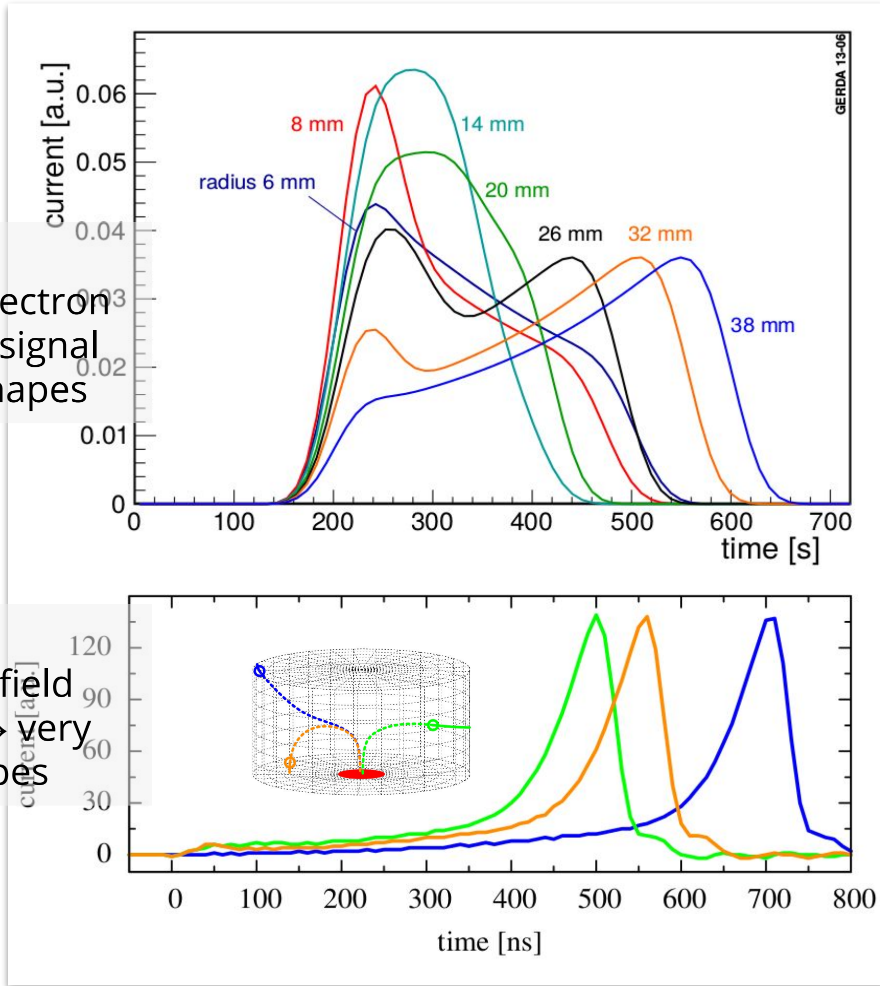
Natural radioactivity

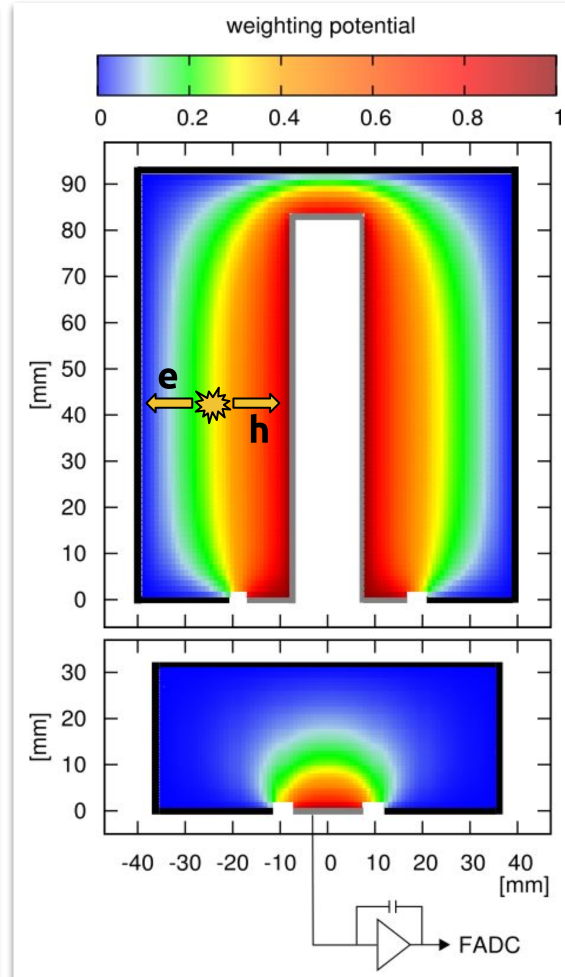


GERDA pulse shape discrimination

Coax SSEs
Both holes and electron contribute to the signal
→ complicated shapes

BEGe SSEs
Strong weighting field around contact → very similar pulse shapes

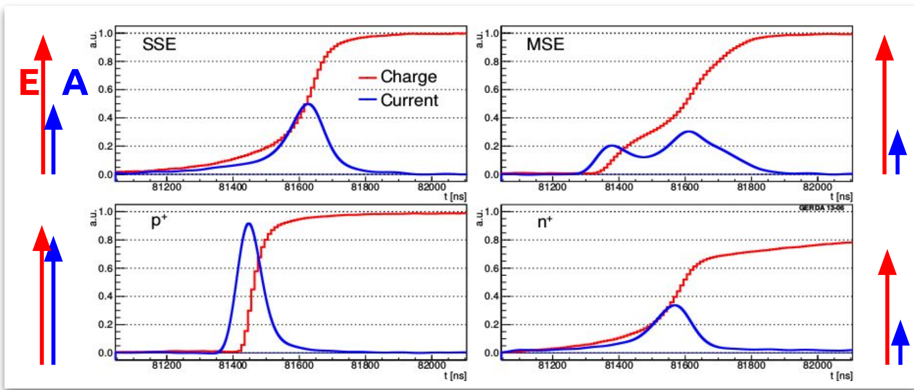




GERDA pulse shape discrimination

BEGe detectors

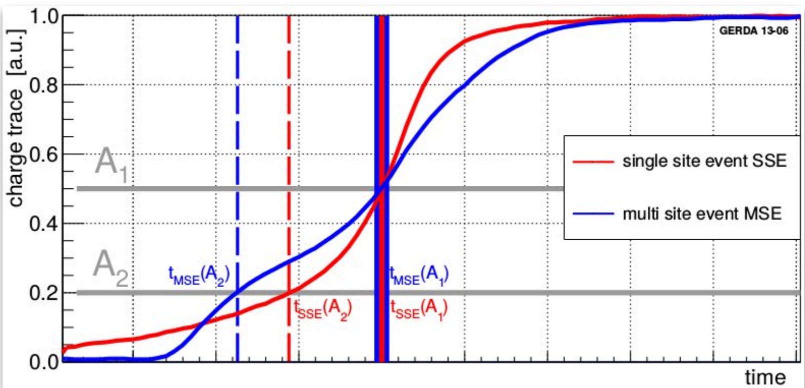
→ A/E parameter



- A = current amplitude
- E = energy
- Multi-site events have lower A/E than single-site events

Coaxial detectors

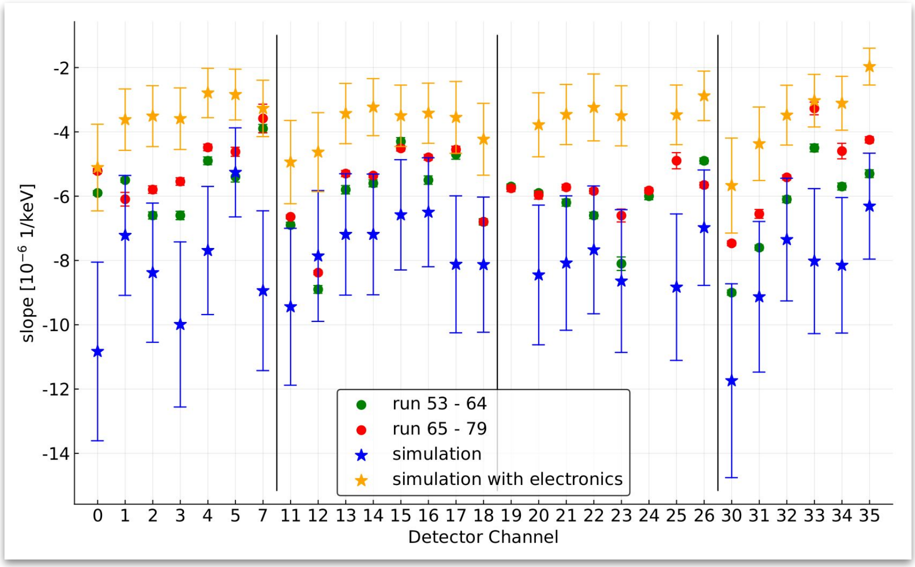
→ Neural Network (ANN)

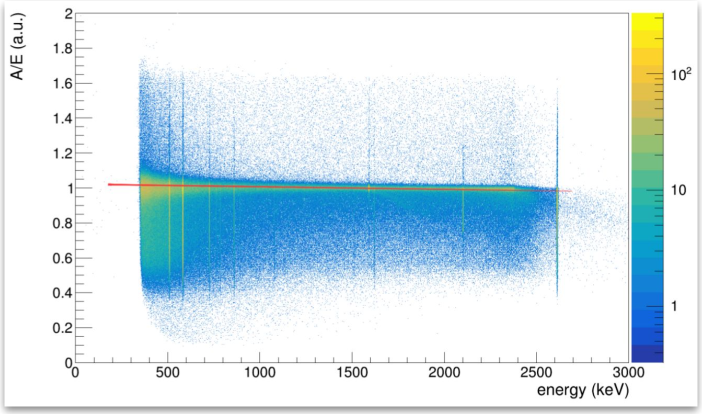


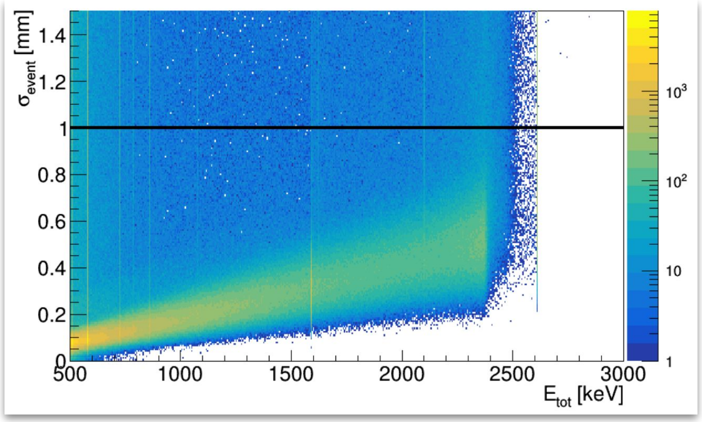
- Input variables: times when the pulse reaches a given relative height (1% … 99%)
- Trained on calibration data

Understanding A/E with simulations

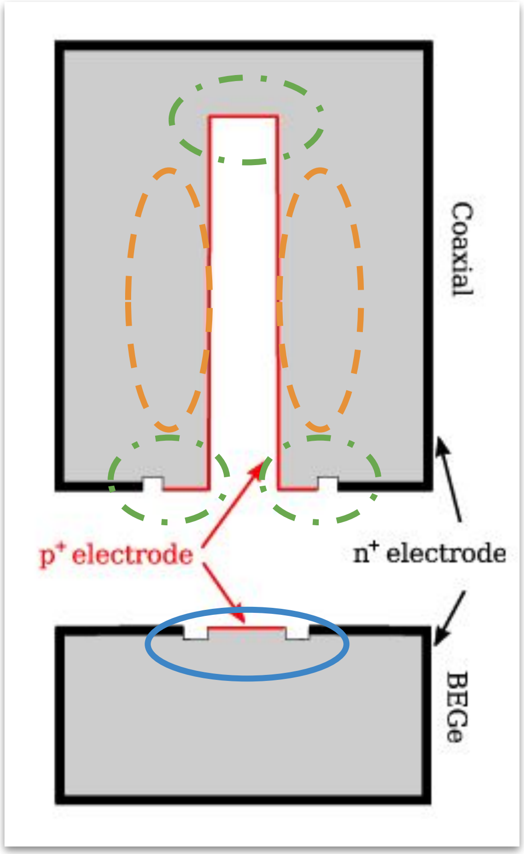
- Pulse shape simulation studies showed that the **slope of A/E** as a function of energy is **due to the increase of the charge cloud size** with energy and diffusion
- Taking these effects into account we get good agreement with the data







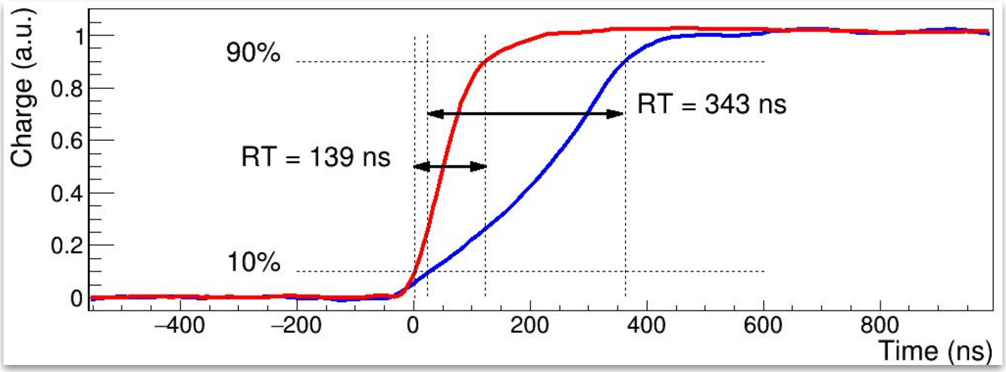
GERDA pulse shape discrimination



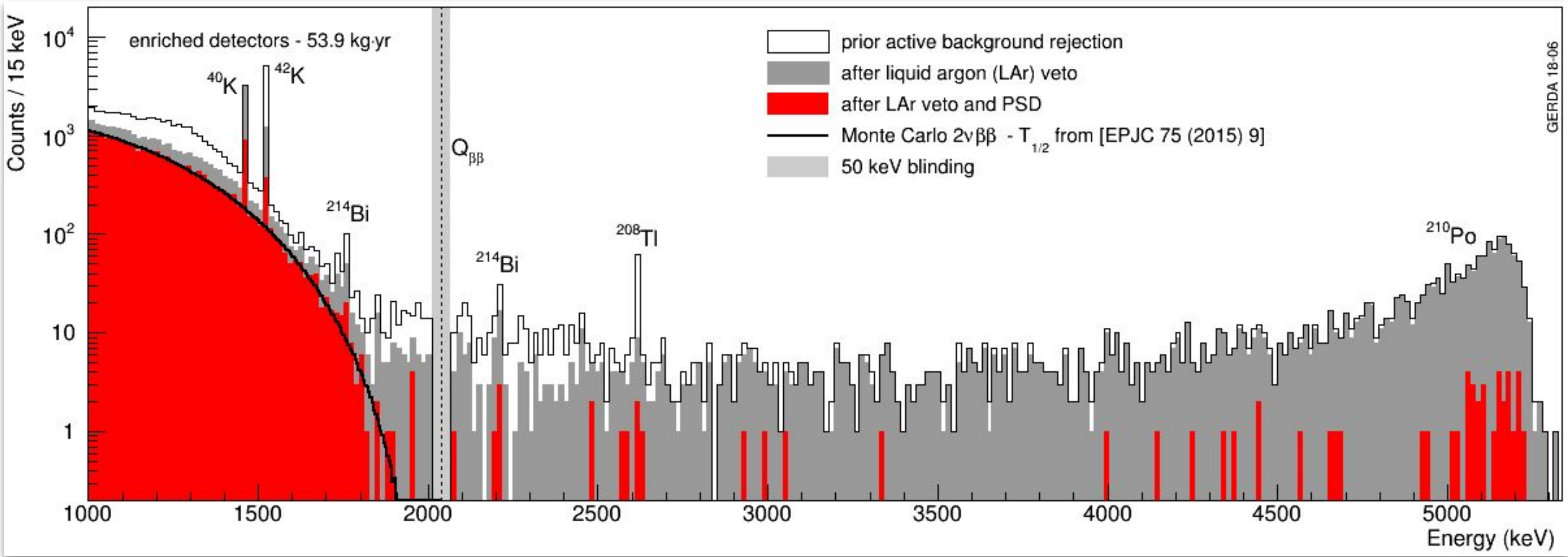
Specific regions of the detector volume have to be rejected due to α surface contamination

- High A/E values are rejected in BEGe
- ANN rejects events around the bore-hole of coaxial detectors
- **Cut on the charge collection time (10-90%) rejects fast surface events**

New



GERDA pulse shape discrimination



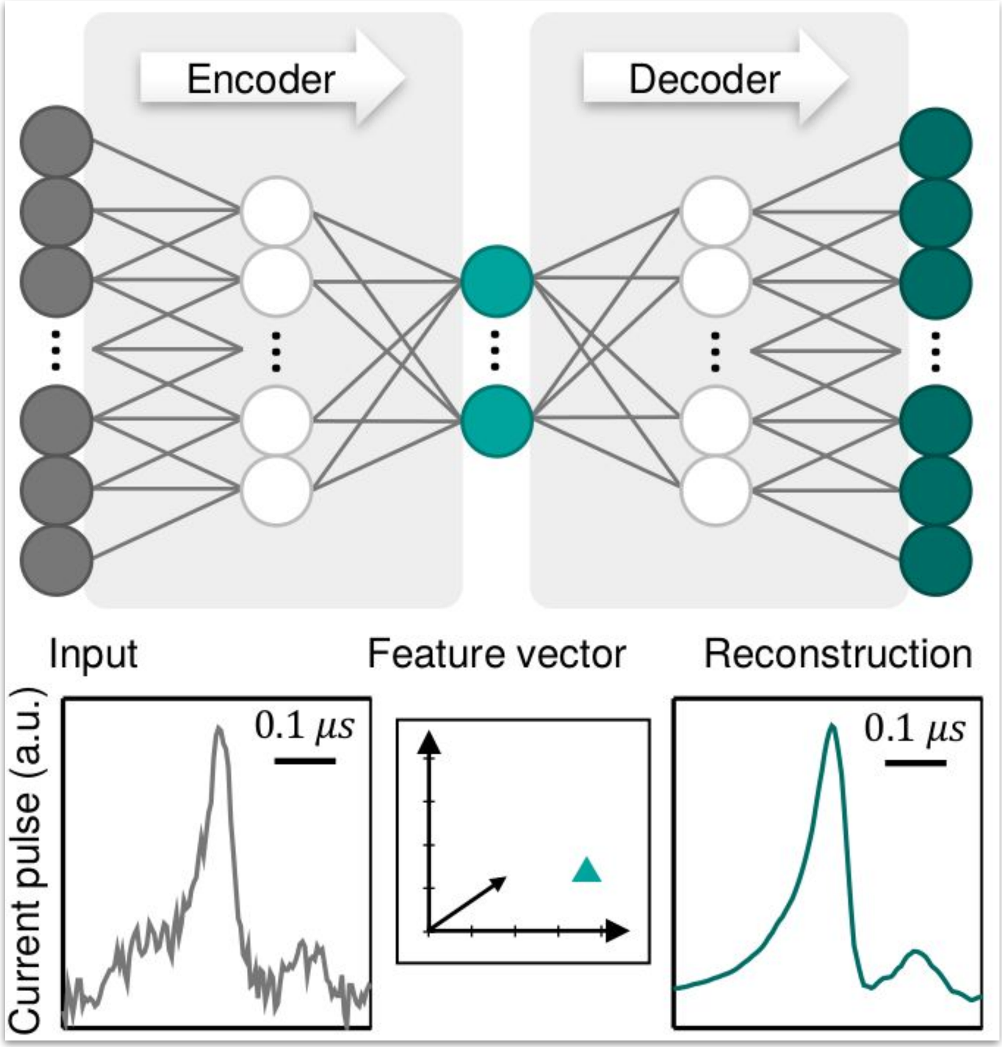
- Both K lines and high energy α events strongly suppressed, while keeping high $0\nu\beta\beta$ signal efficiency

  (71.2 ± 4.3)% for Coax and (87.6 ± 2.5)% for BEGe detectors

- Lowest background level in the field achieved: 6×10^{-4} cts/(keV·kg·yr)

Deep Learning for PSD

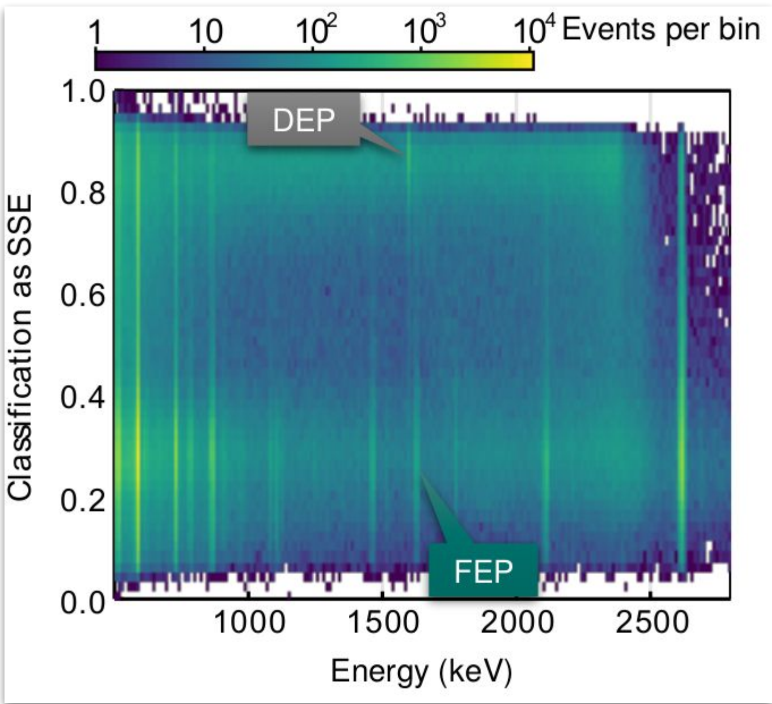
- New method for SSE / MSE classification using two neural networks
- The autoencoder provides a representation of the signals with a small number of parameters without the need for labeled data

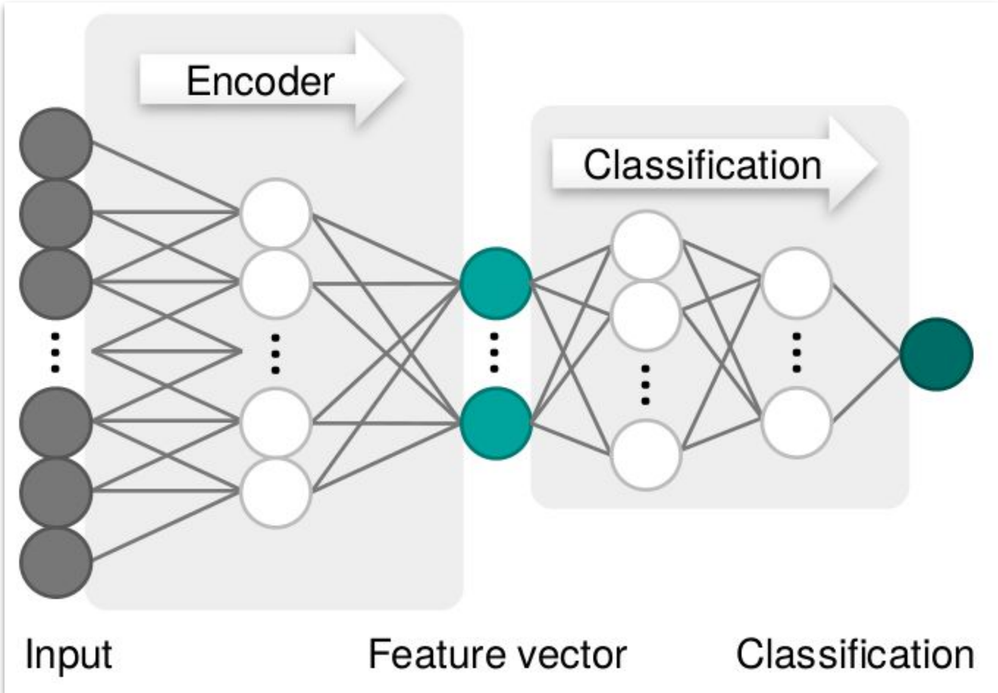


P. Holl, *publication in progress*

Deep Learning for PSD

- Classification based on the few parameters using labeled data





- Performance as good as A/E method
- But more robust without the need for time and energy dependent corrections

P. Holl, *publication in progress*

Backgrounds and how to reject them

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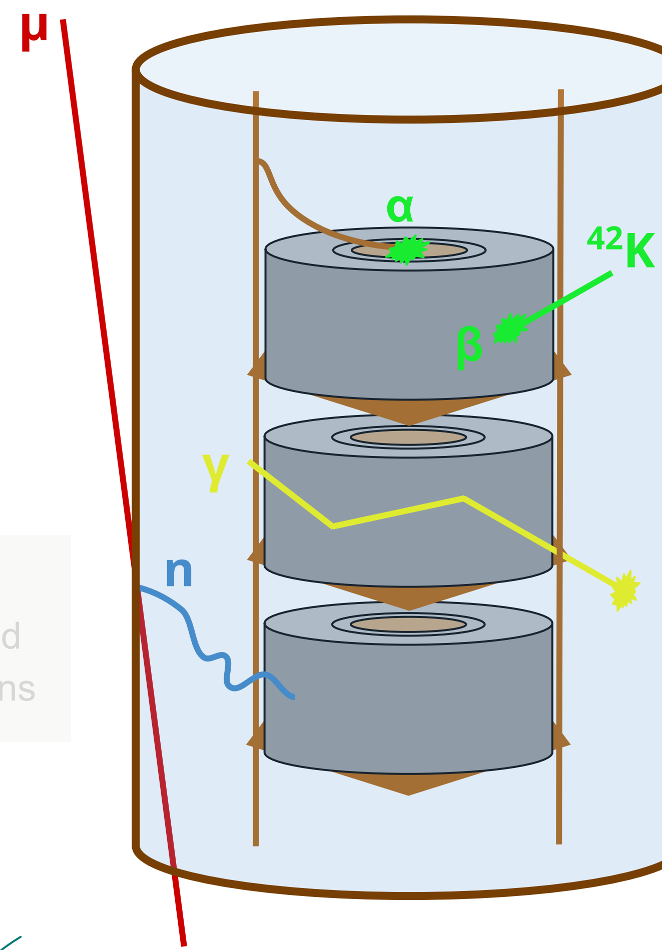

Muon induced neutrons

γs from surroundings (cables, holders)

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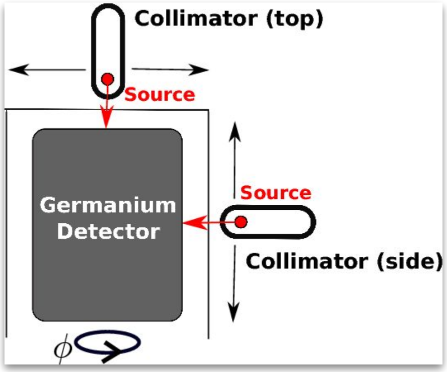
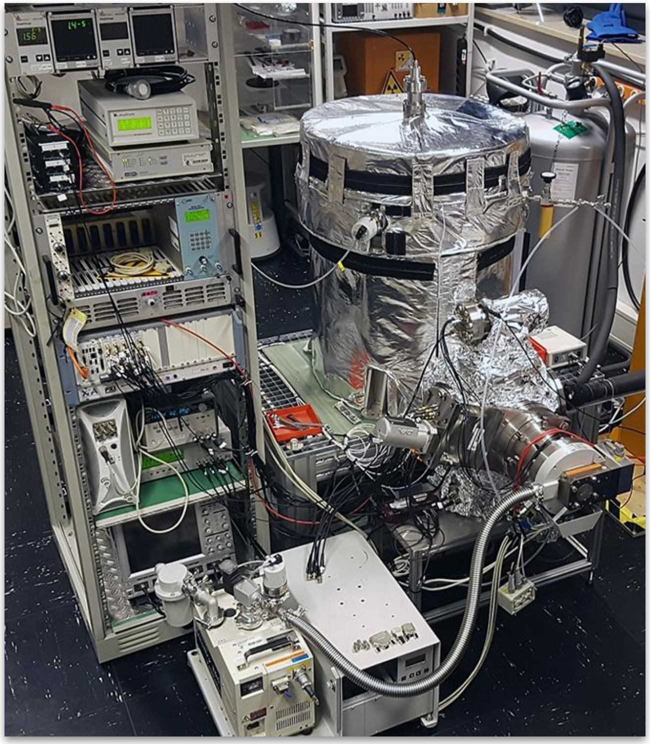
αs and βs on the detector surface

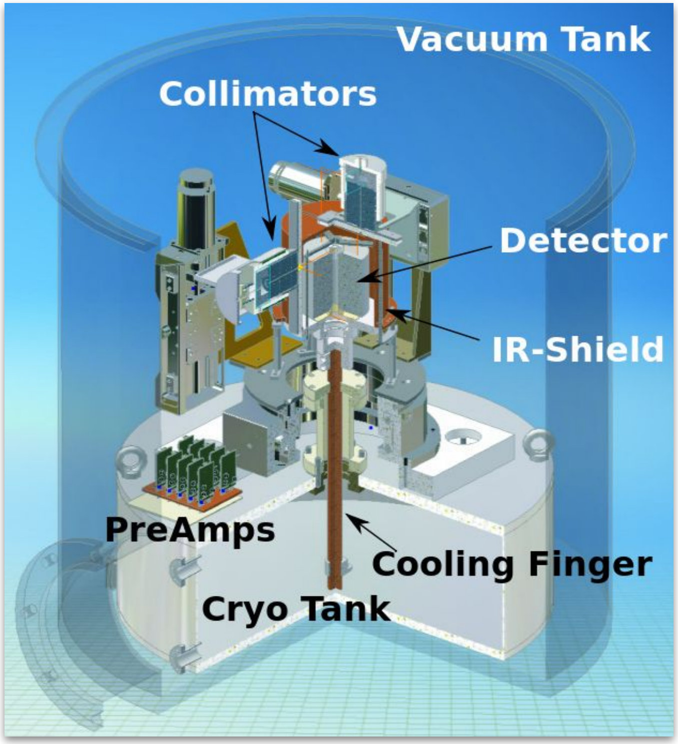
Test stands and segmented detectors

GALATEA

- Facility to scan detector surface directly with α and β sources
- New open ^{241}Am sources in both collimators



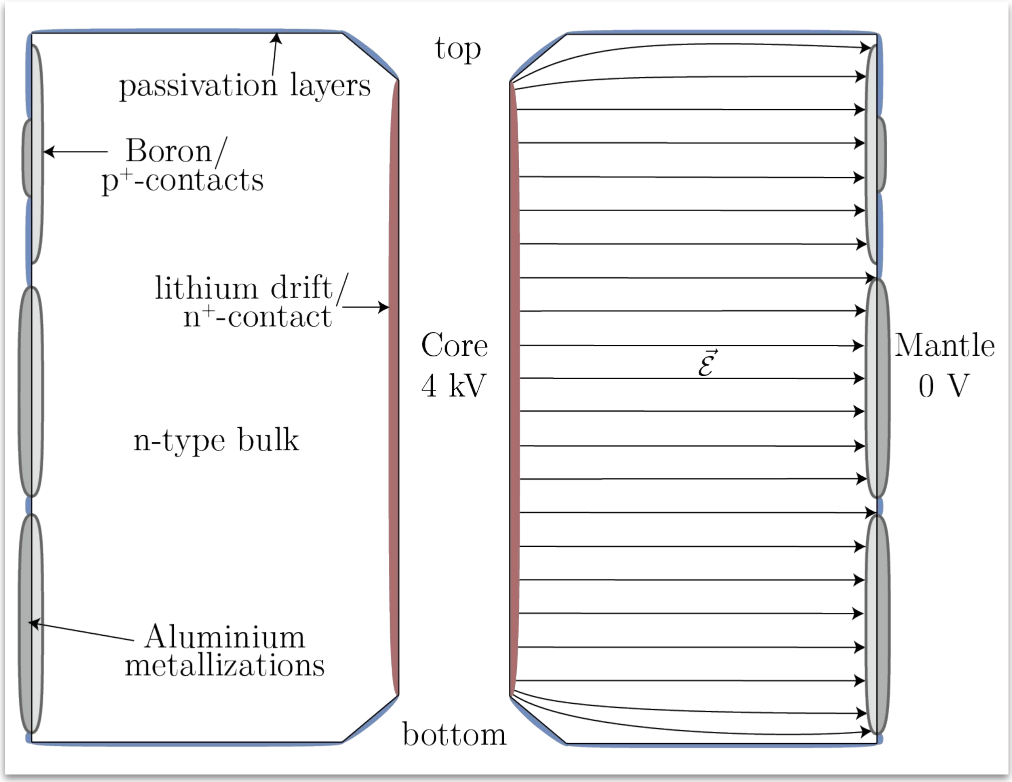


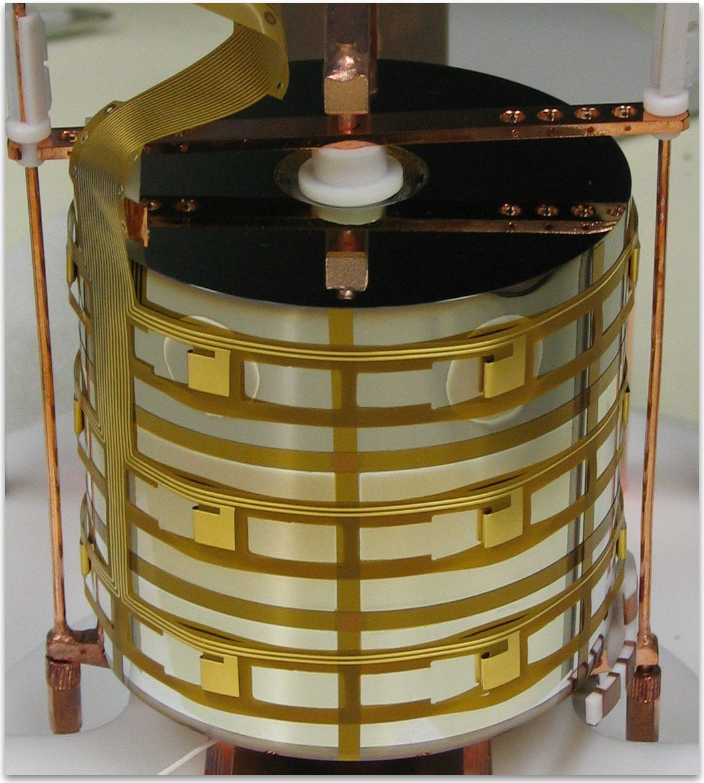


Nucl.Instrum.Meth. A **782** (2015) 56

Siegfried III

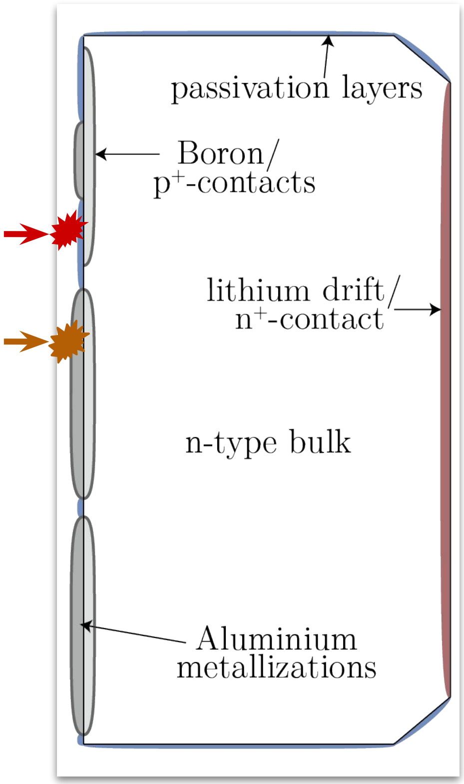
- 18-fold segmented, n-type detector with true coaxial geometry
- Study effects of passivation and metallization on the surface



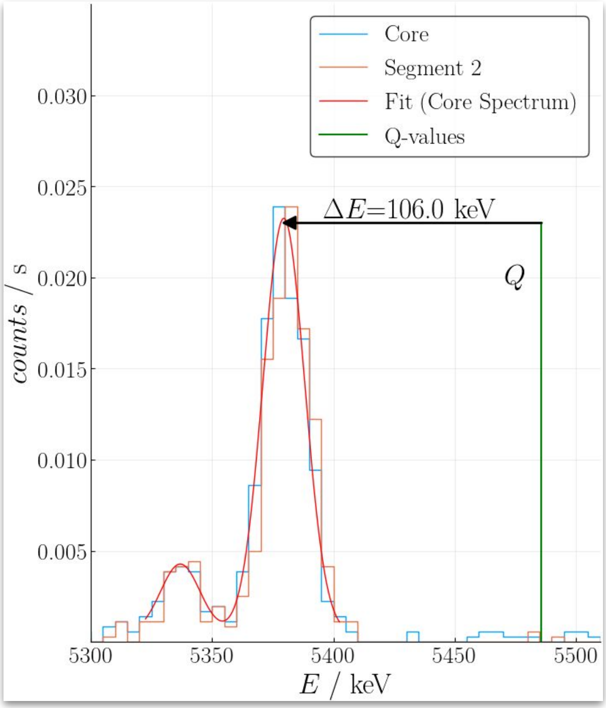


GALATEA and Siegfried III

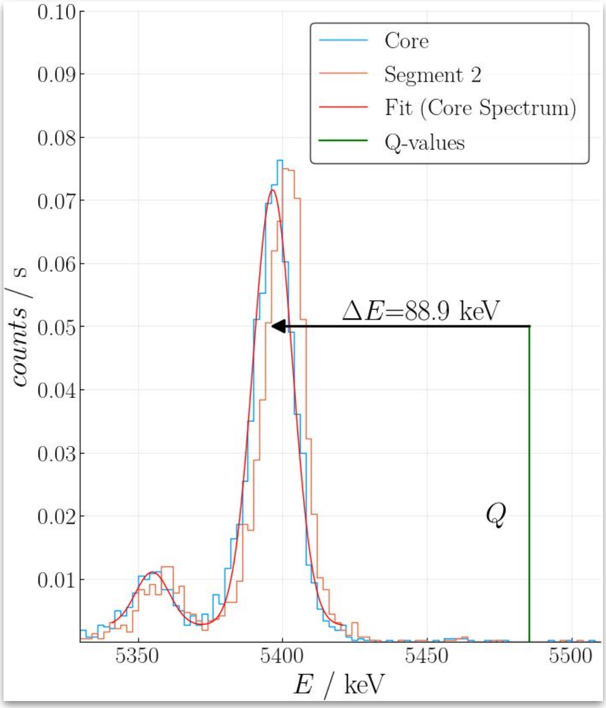
- With the new α sources the size of layers can be estimated based on the energy loss ≈ 206 keV / μm (for E ≈ 5.4 MeV)



Boron depth ≈ 0.5 μm
No passivation on the mantle



Metallization on the nm scale and has no effect

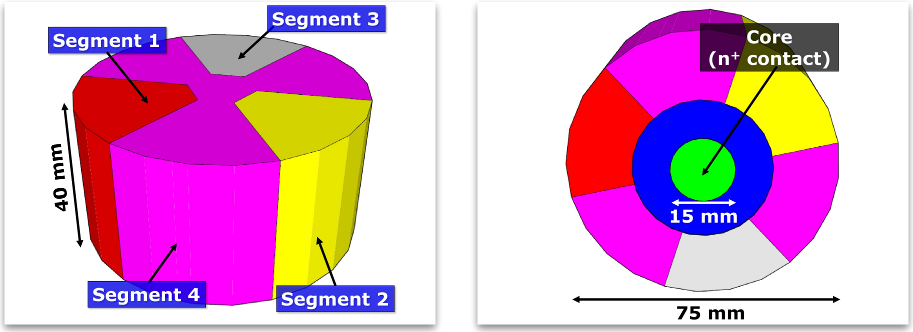


K2 and Segmented BEGe

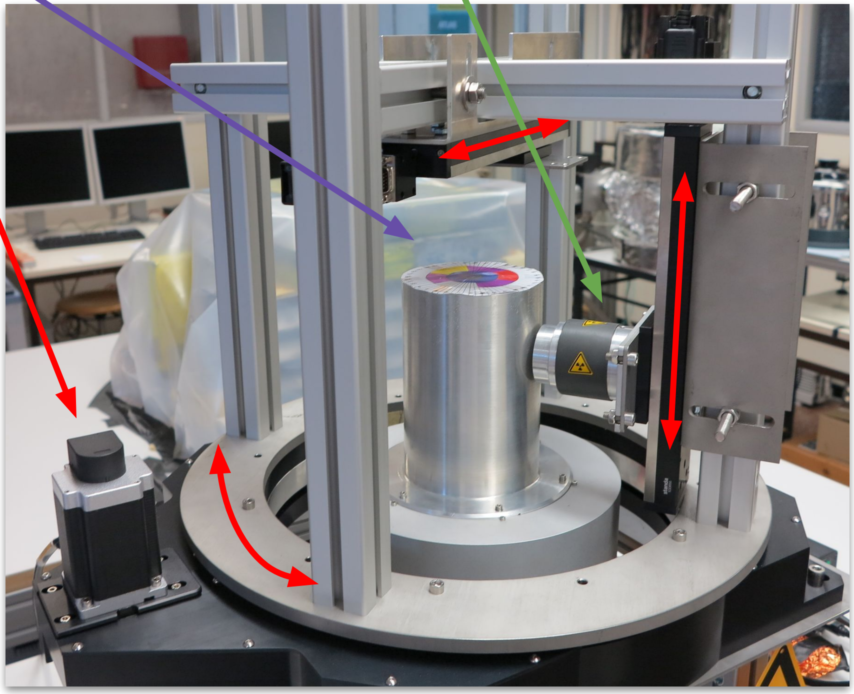
Electrically cooled cryostat
→ study temperature dependence

3-axes scanning stages

4-fold segmented n-type detector
with small (BEGe-type) core contact
→ study parts of the charge drift



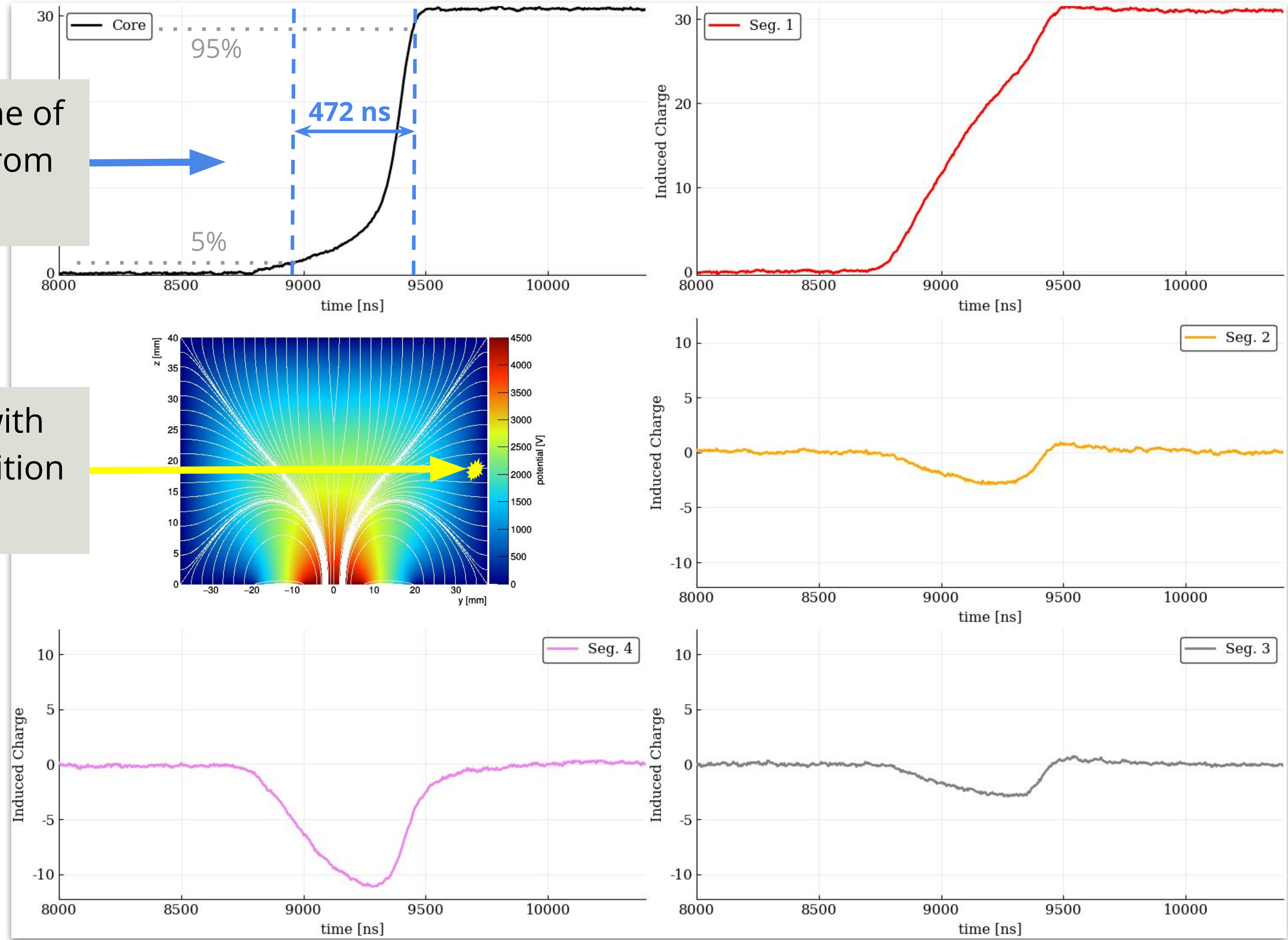
Collimated 133Ba source
→ low energy γ events close to the surface



K2 and Segmented BEGe

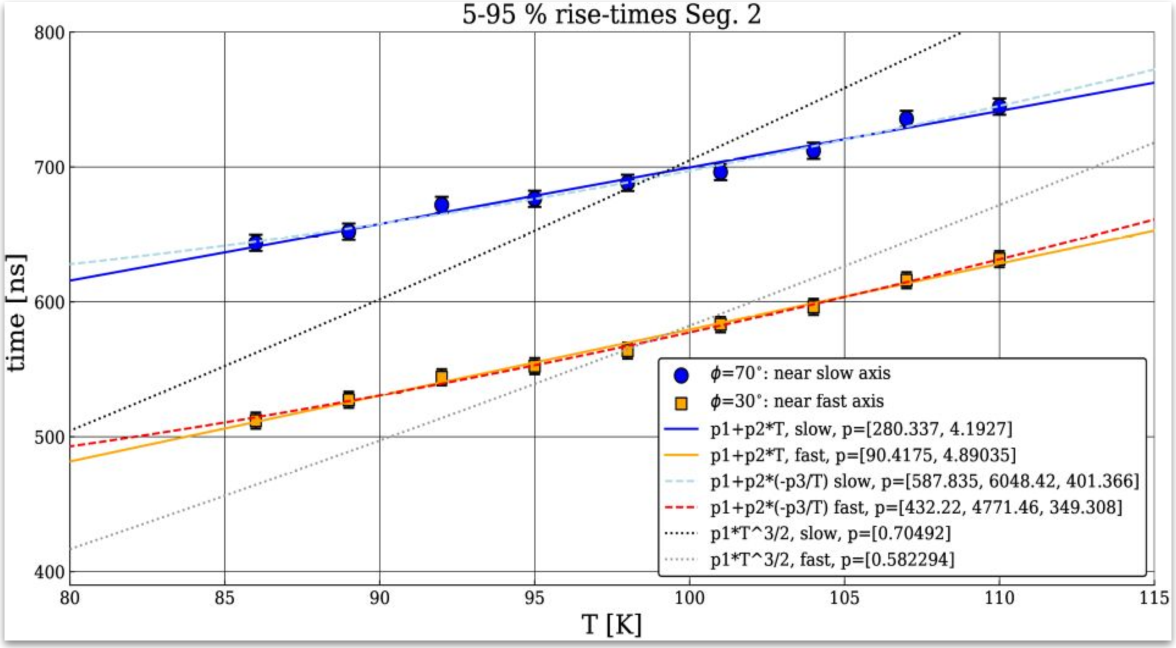
Study the rise time of the core pulses from 31 keV γ events

Average events with same source position to reduce noise



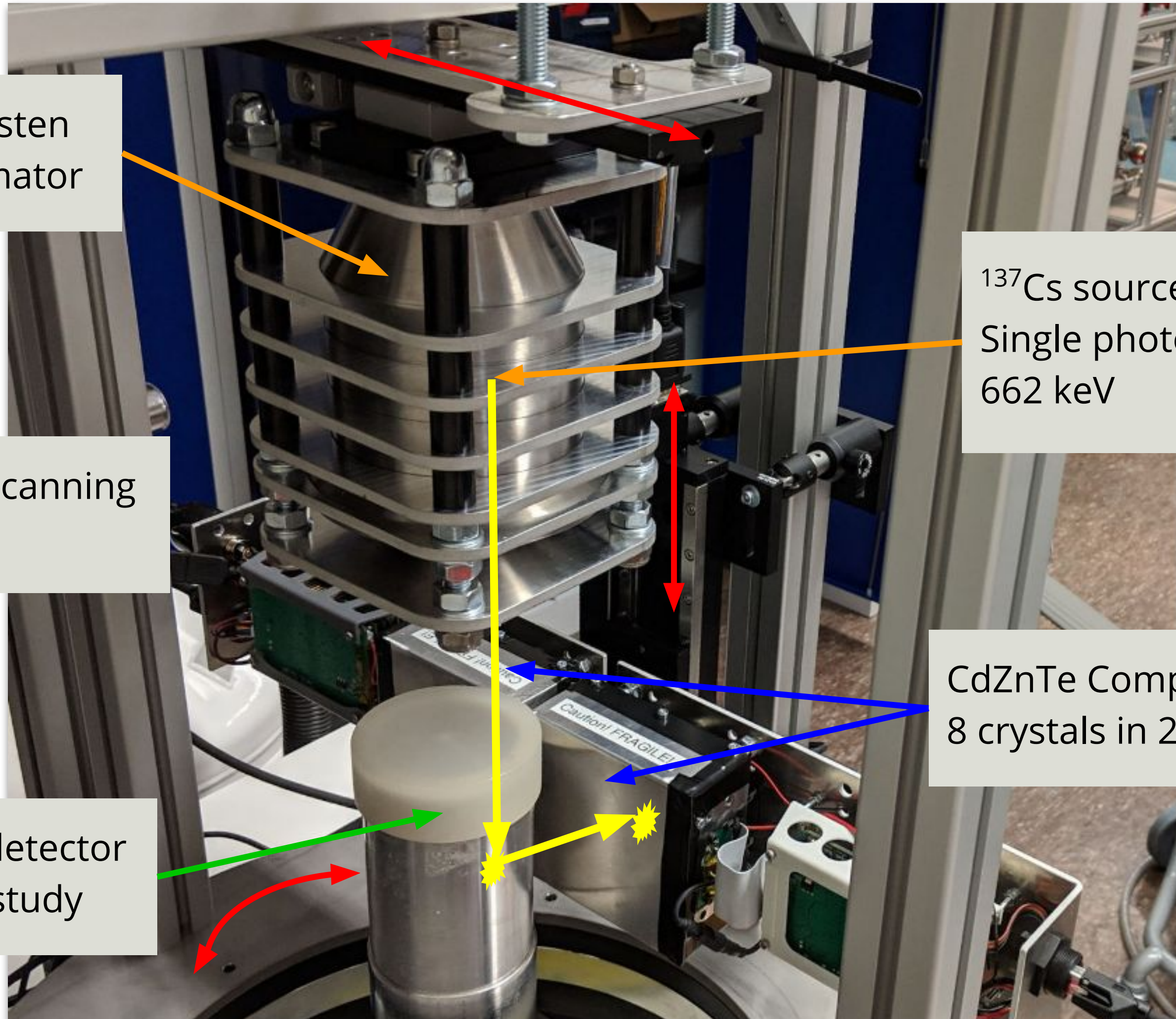
Temperature dependence

- Preliminary results confirm that the usually assumed power-law does not describe HPGe detectors at 80-120 K temperatures
- Different temperature dependence of drift times at different crystal axes



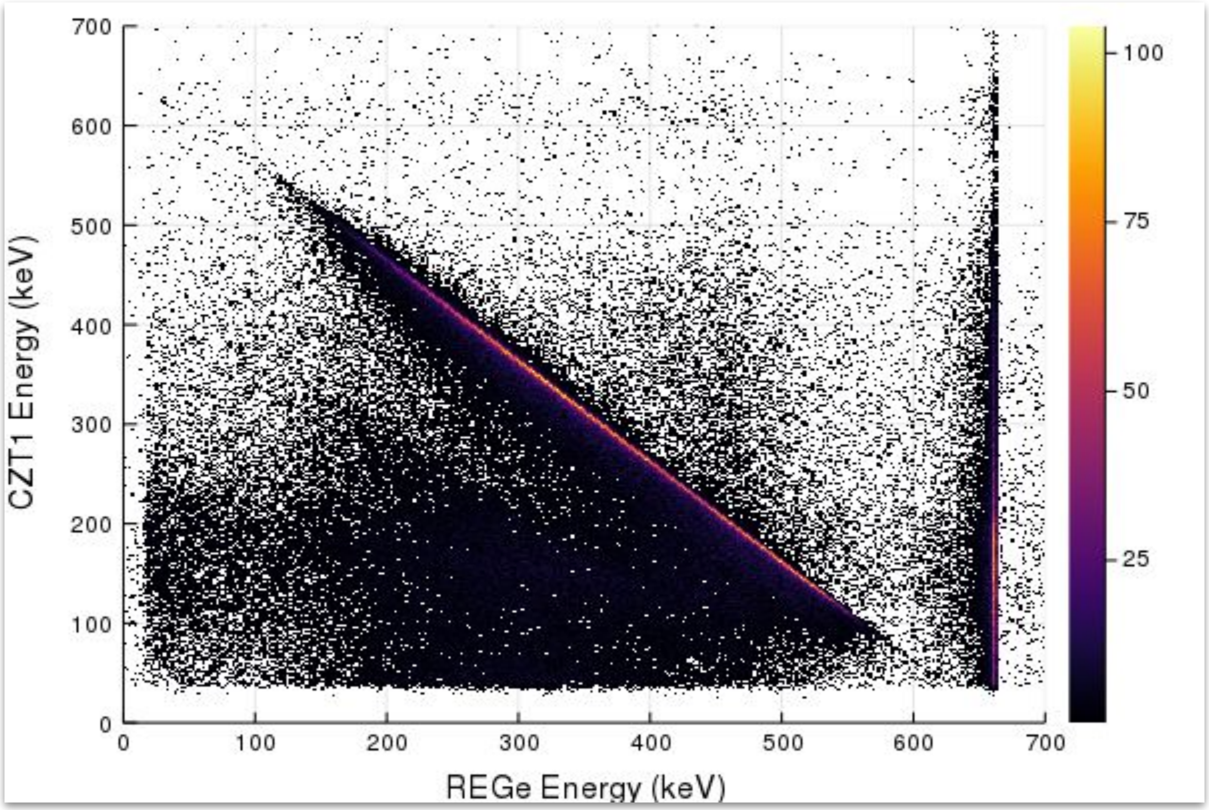
- **Large amount of data taken to be analyzed next year**

Bulk properties: Compton scanner setup



Bulk properties: Compton scanner setup

- Correlation between HPGe and CZT detectors established



- Analysis ongoing ...

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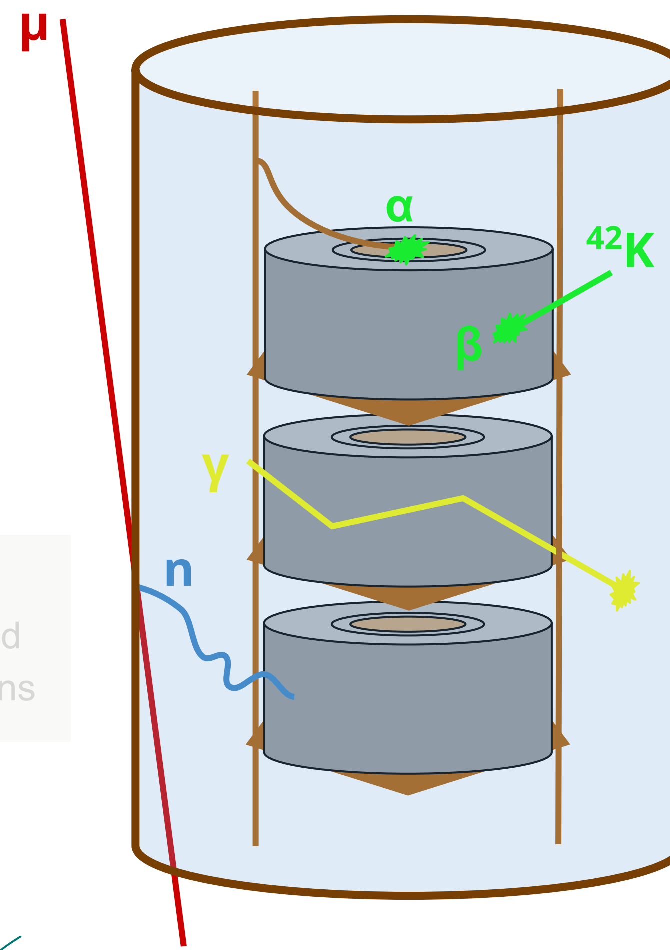

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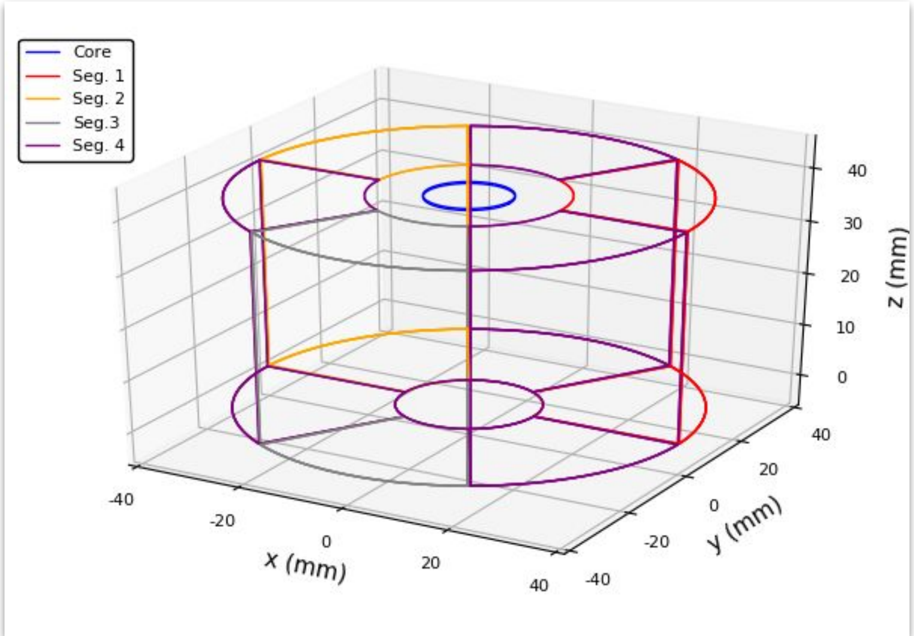
Test stands and segmented detectors

Pulse shape simulation: building blocks

- Electric field calculation
  - 2D for φ symmetric detectors
  - 3D for segmented detectors
  - Multithreading
  - Adaptive grid
  - Fast enough for detector design optimization
  - Handling of undepleted regions
- Drift velocity model
  - Same as in other Germanium simulation models but easily extendable
- Charge carrier drift
  - Clustering of energy depositions
  - Handling of floating surfaces
  - Mirror pulses in non-collecting segments
- Open source for easier development within the community

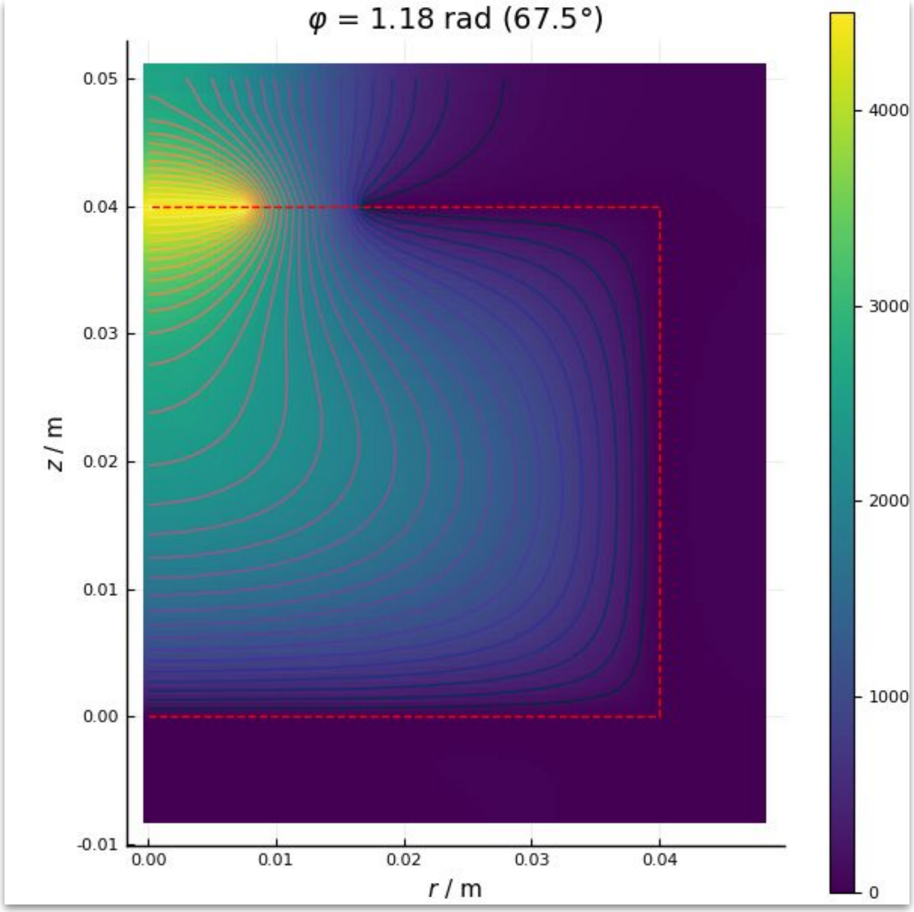
Detector geometry



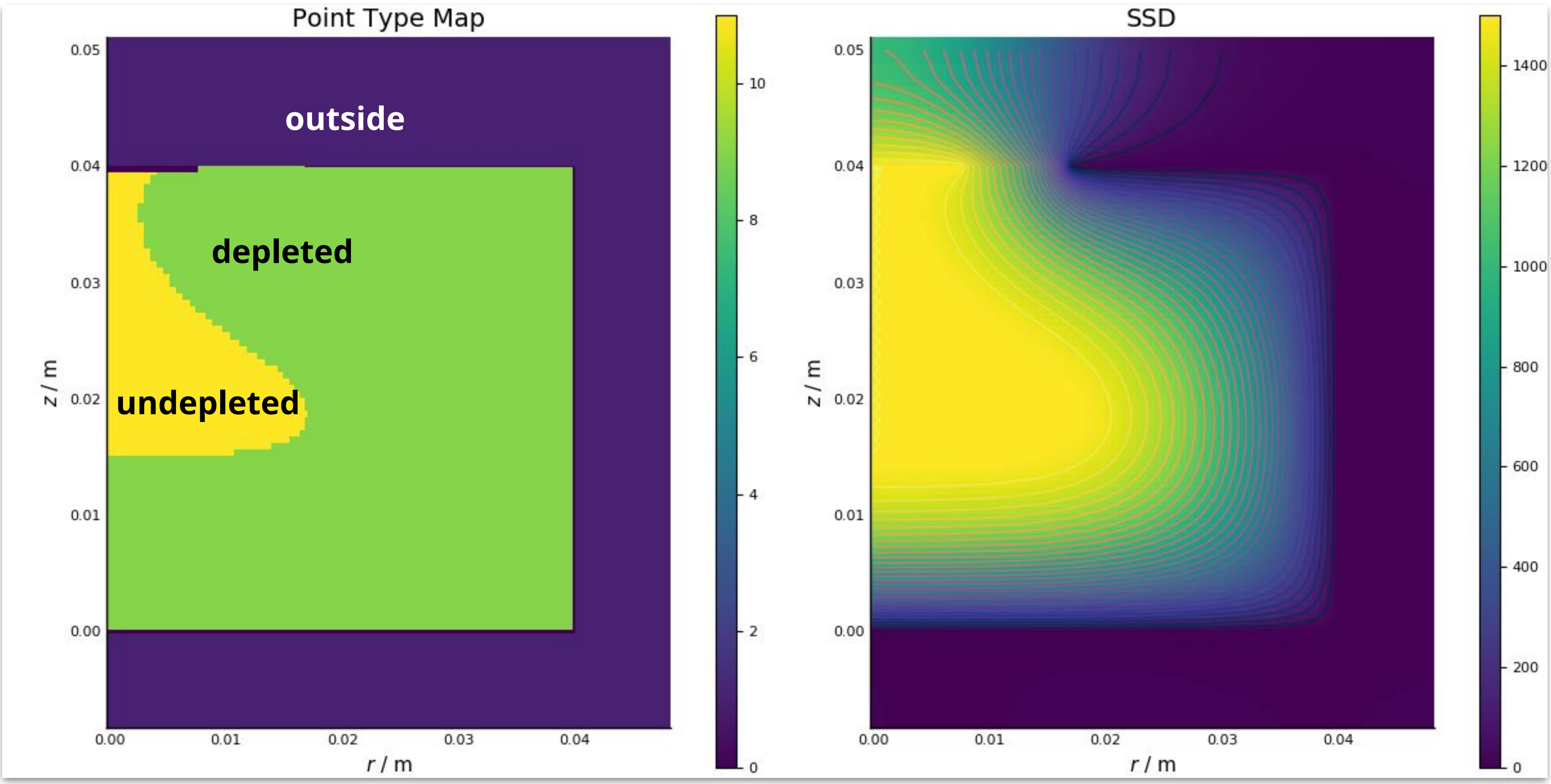
- All detector geometries at MPP and in GERDA implemented
    - True coax with segmentation
    - BEGe / PPC
    - Segmented BEGe
    - Inverted coax
- Parameters set in a human-readable json file
- Examples available within the package

Electric potential

- Solving Gauss' law with successive over-relaxation algorithm
- 2D for symmetric detectors or slower 3D for segmented detectors
- Adaptive grid: refine grid where the potential gradient is large
- Faster than other freely available software



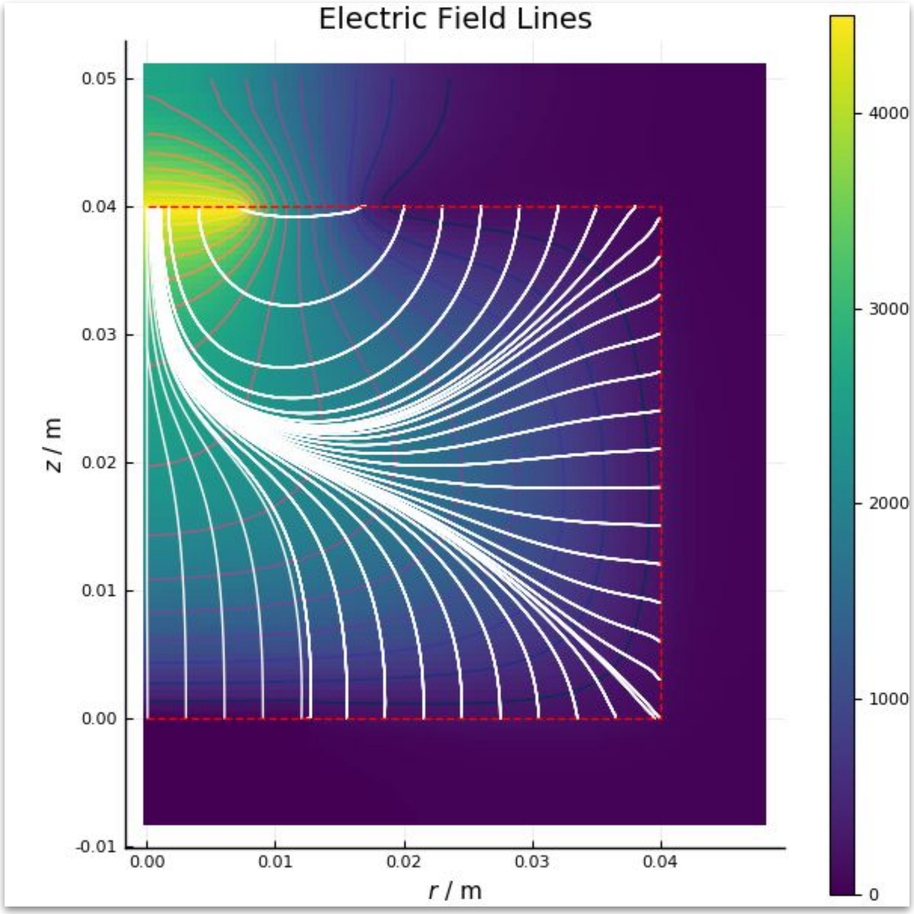
Depletion for detector design



https://github.com/JuliaHEP/SolidStateDetectors.jl

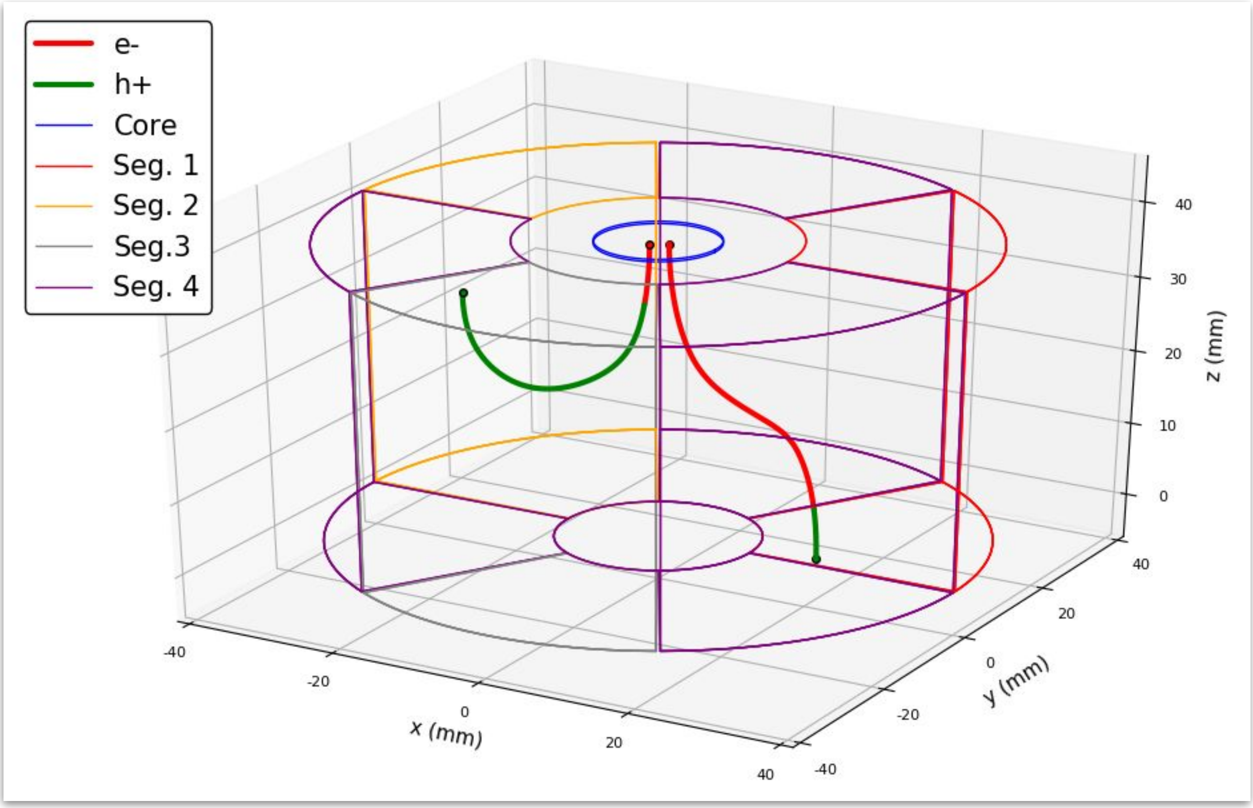
Electric field

- Electric field calculated from the potential
- Charges drift approximately along the field lines

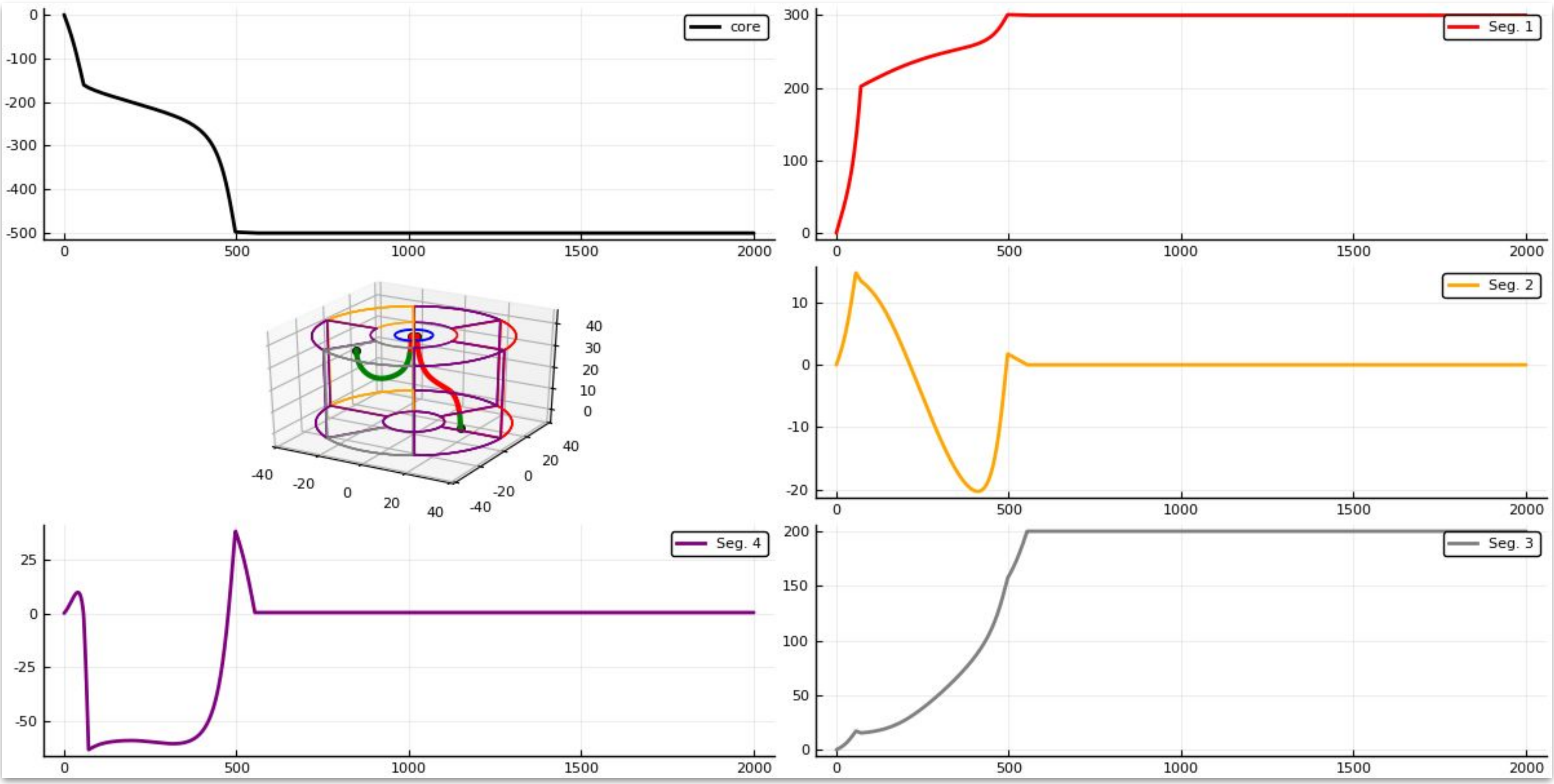


Charge drift

- Drift velocity calculated from the electric field for both holes and electrons
- The model takes into account the effect of the crystal axes



Signals


core
Seg. 1
Seg. 2
Seg. 3
Seg. 4
0
-100
-200
-300
-400
-500
500
1000
1500
2000
300
200
100
10
-10
-20
25
-25
-50
150
50
40
30
20
-40

PIRE GEMADARC

Germanium Materials and Detectors Advancement Research Consortium between institutes from USA, China and MPP

- pire.gemadarc.org

2018 Summer school and collaboration meeting in China

- pire.gemadarc.org/education/school18
- 5 lecturers and 4 students from MPP

2019 May: Summer school and collaboration meeting at MPP

- indico.mpp.mpg.de/event/6013
- Lectures and hands-on sessions on germanium detector properties and operation, undergraduate training program
- Registration open!

Summary

- GERDA reached important milestones in the $0\nu\beta\beta$ search with
  - $6{\cdot}10^{-4}$ cts/(keV·kg·yr) background index
  - $T_{1/2} > 10^{26}$ yr sensitivity for limit setting
  - $m_{\beta\beta} < 104 - 228$ meV
- LEGEND R&D is ongoing to further reduce backgrounds in $0\nu\beta\beta$ search with enriched Ge detectors
  - Active construction material PEN for veto
  - New pulse shape discrimination methods using machine learning
  - Alpha scan measurements to study surface effects
  - Measurement of the temperature dependence of drift velocities
  - New open source fast pulse shape simulation package in Julia
- Our group is making significant contributions to both experiments