A Pulse Shape Simulation for the GERDA Experiment

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GERDA

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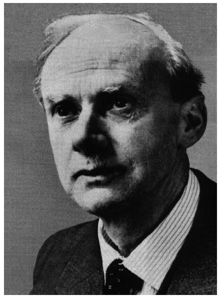
Outline:

- Motivation for Search for $0\nu\beta\beta$
- Double Beta Decay and Experimental Signatures
- GERDA Goals and Concept
- Pulse Shape Simulation
- Summary

Motivation

- **GER**manium **D**etector **A**rray (GERDA) experiment built to search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{76}Ge

- $0\nu\beta\beta$ is the only way to unveil the nature of neutrinos



Dirac

$\nu \neq \bar{\nu}$

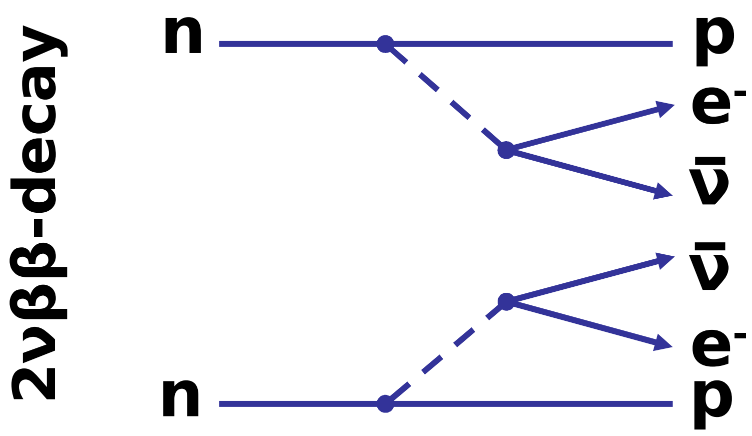
or

Majorana

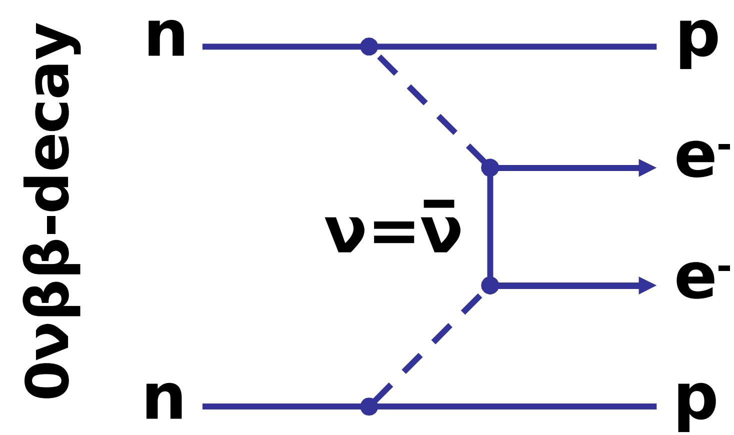
$\nu = \bar{\nu}$

- If $0\nu\beta\beta$ observed:
  - neutrino is Majorana type **Schechter-Valle theorem** (Phys. Rev. D (1982) 25, 2951)
  - lepton number violation $\Delta L = 2$
  - type I seesaw mechanism $m_\nu = \frac{m_D^2}{M_R} << m_D$
  - possible to determine absolute neutrino mass scale
  - possible to determine neutrino hierarchy

What is $\beta\beta$ Decay



- allowed process
- observed for several isotopes
- $T_{1/2} \sim O(10^{20})$ y

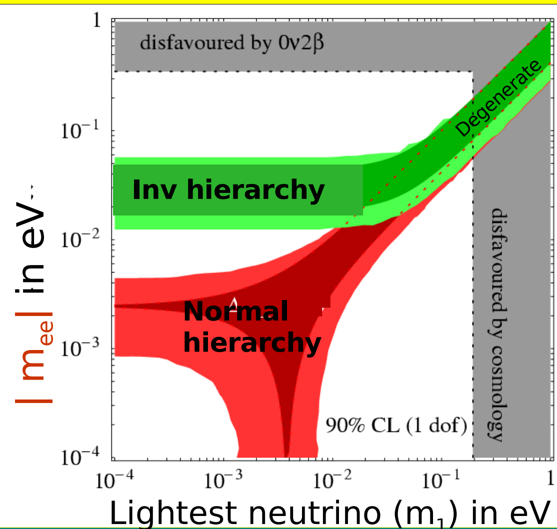


- forbidden process in SM, needs Majorana neutrino
- $T_{1/2}(^{76}Ge) \geq 1.9 \cdot 10^{25}$ y (90% C.L.)
  Eur. Phys. J. A12, 147-154 (2001)
- claim of signal from parts of HdM
  NIM A 522 (2004) 371-406

effective Majorana neutrino mass:

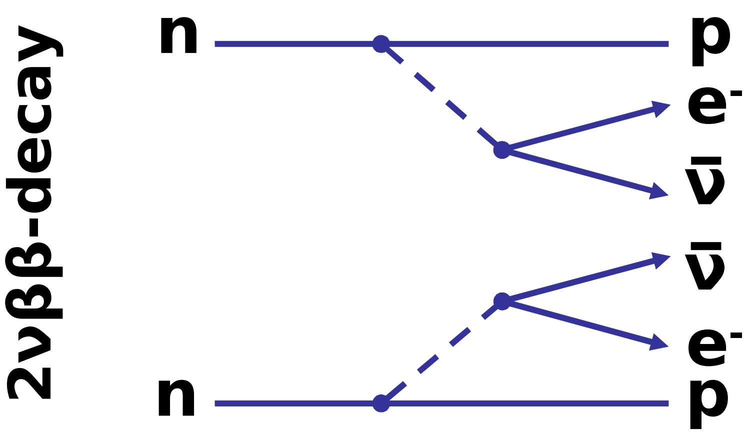
$$|m_{ee}| = |\sum_j m_j U_{ej}^2|$$

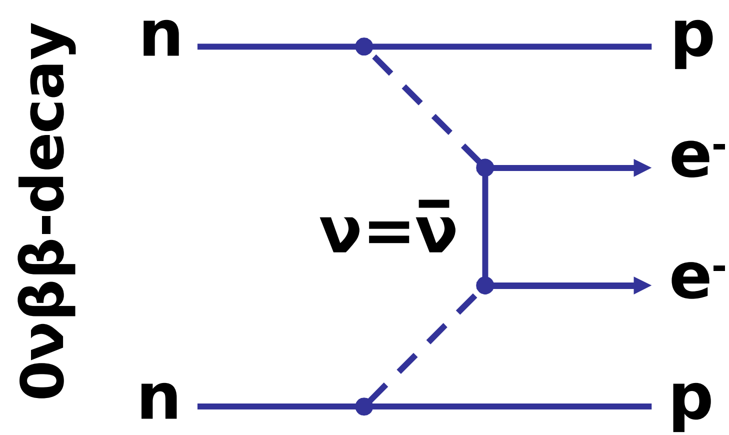
$$T_{1/2} \propto |m_{ee}|^{-2}$$



F. Feruglio, A. Strumia, F. Vissani, NPB 637

Experimental Signature





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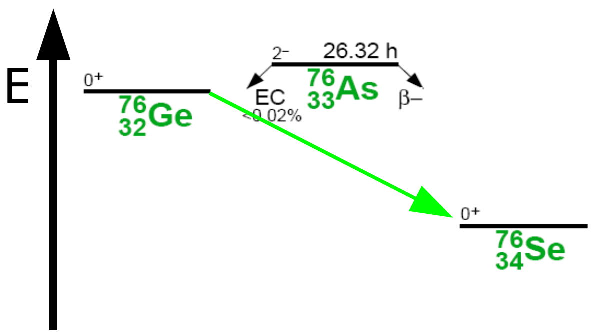
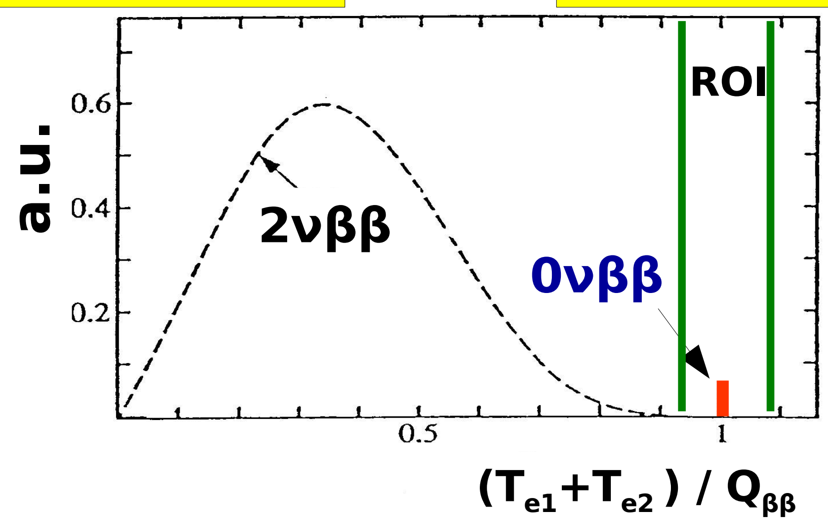
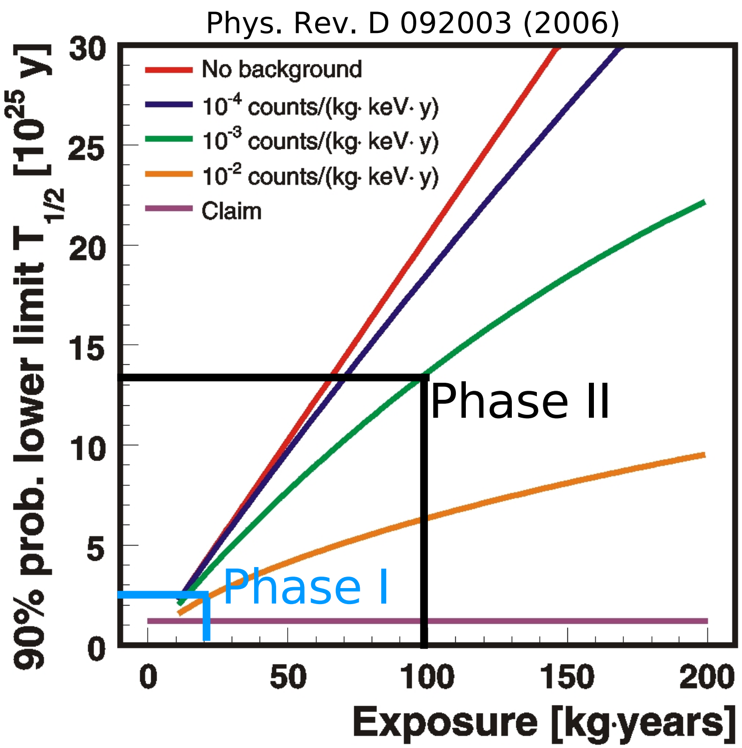
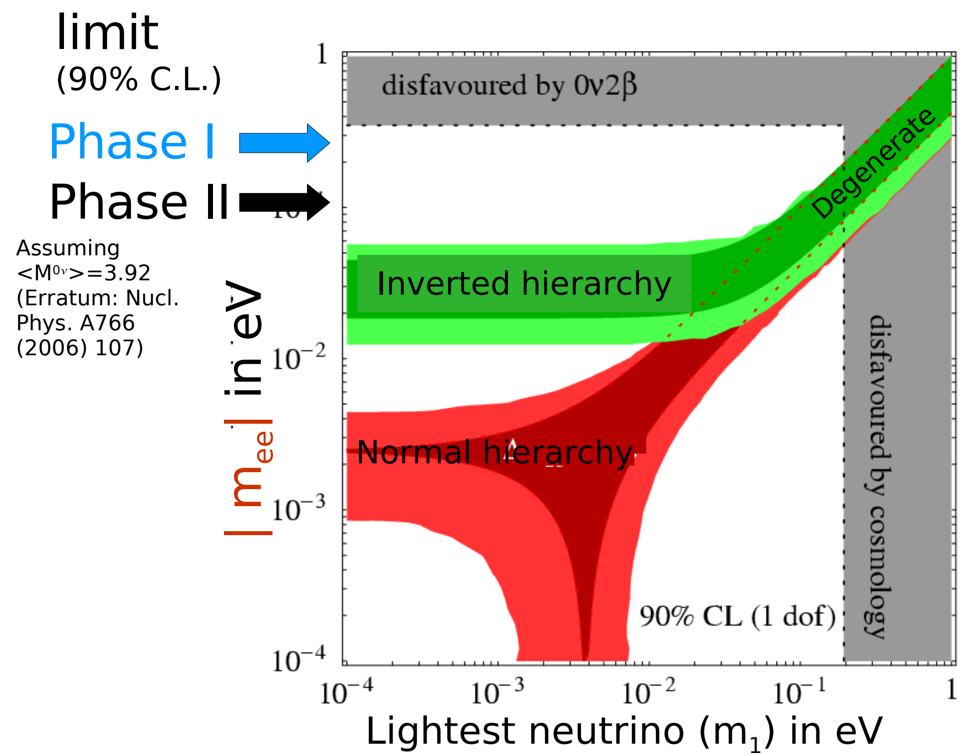




$Q_{\beta\beta}(^{76}Ge) = 2039$keV

GERDA Goals





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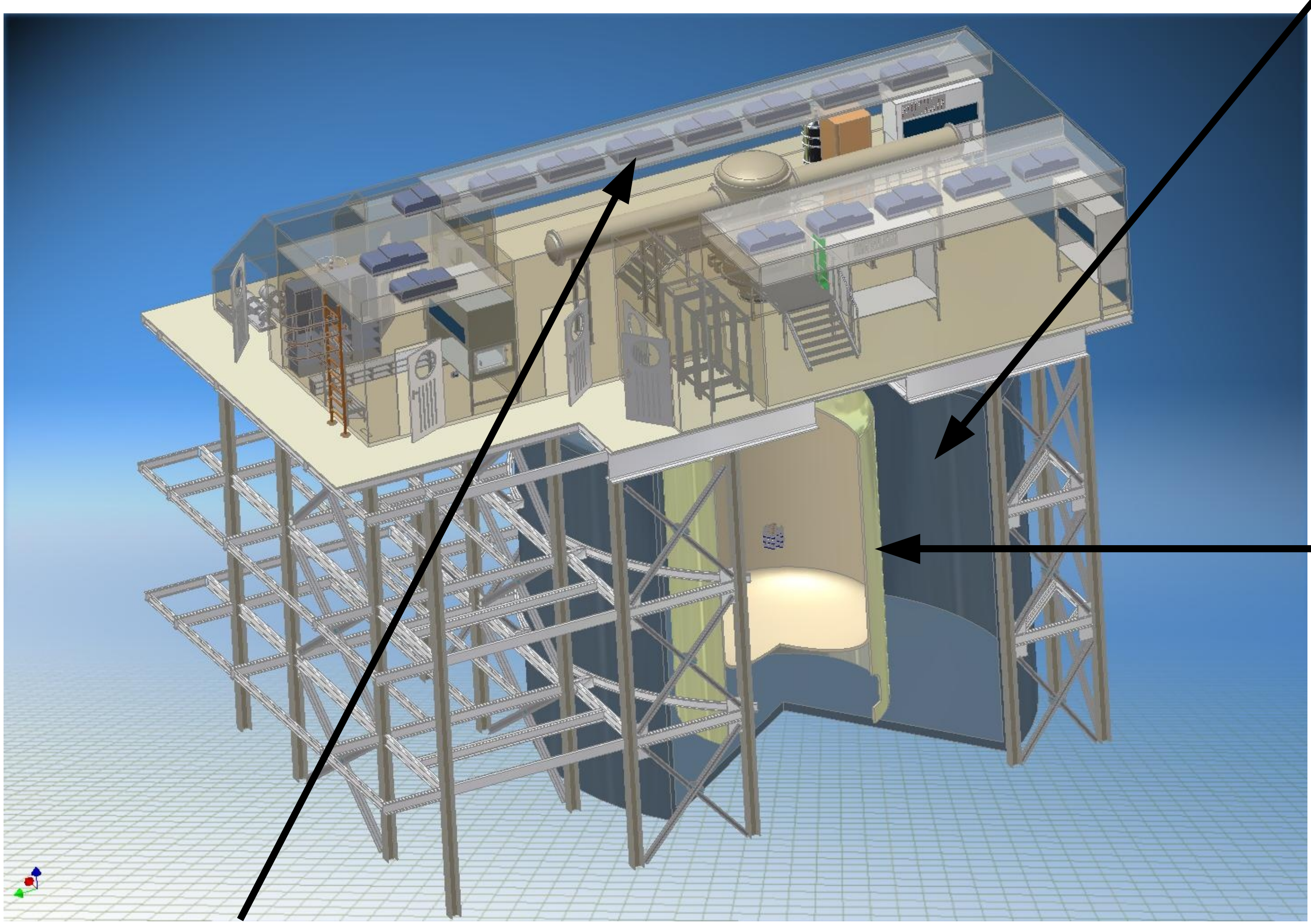
Phase I:
- operate existing ^{76}Ge detectors from HdM and IGEX + natGe Diodes
- reach background of 10^{-2} cts/(keV kg y)
- exposure of ~ 15kg y, **check claim**

Phase II:
- operate **new segmented** ^{76}Ge detectors
- reach background of 10^{-3} cts/(keV kg y)
- exposure of ~100kg y ⇒ $T_{1/2} \geq 1.35 \cdot 10^{26}$ y

Key issue:
low background rate
Phase I: O(10^{1}) < HdM

GERDA Concept

LNGS: **3800 m. w. e. rock above**



Plastic scintillators on top as muon veto

Watertank:

r = 5m, h = 9.0m

590m³ ultra-pure **water**

acts as:

- n moderator
- μ cherenkov veto

Cryostat: (copper-lining)

r = 2.1m, h = 5m

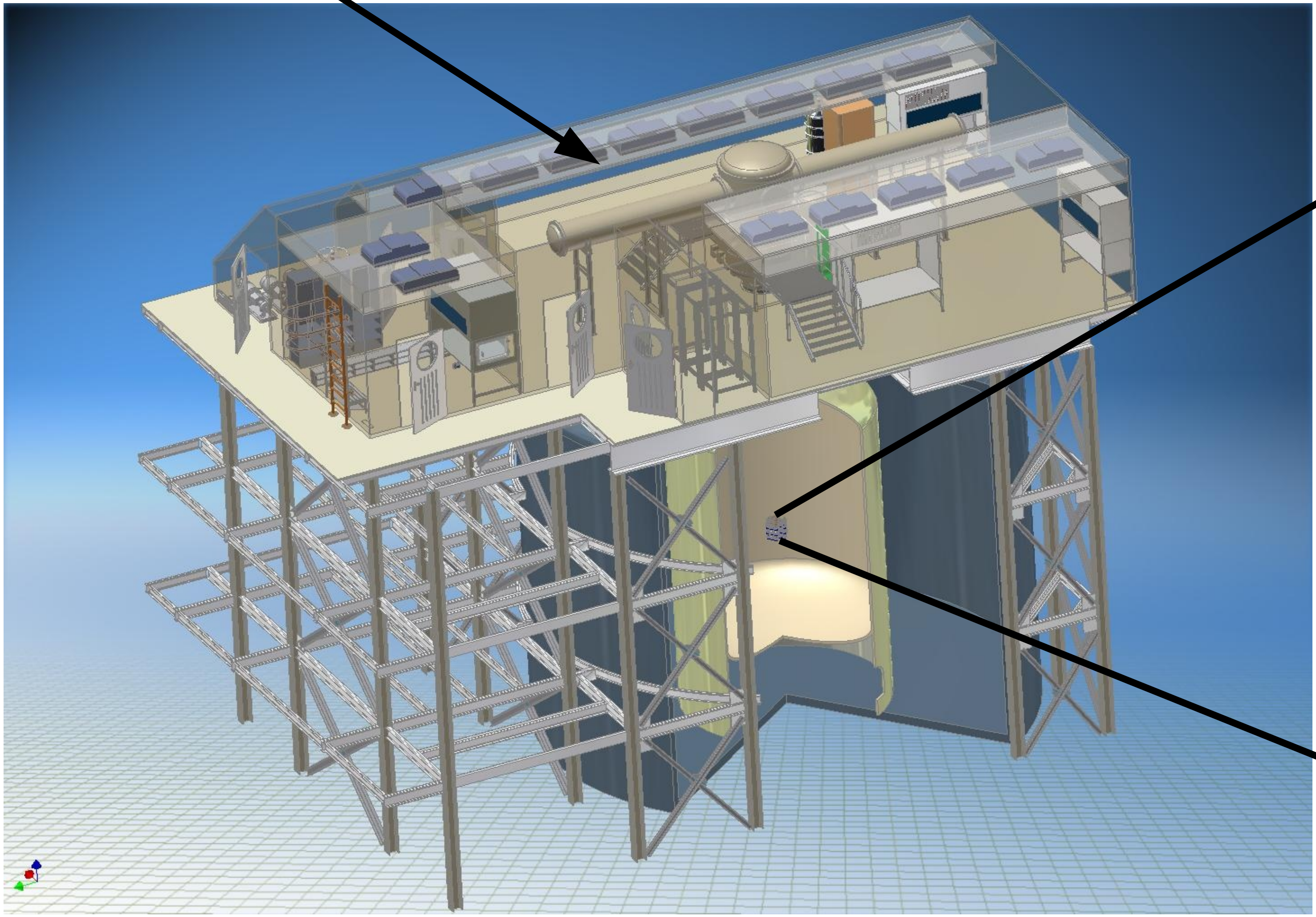
70m³ **liquid Argon**

acts as:

- shielding medium
- cooling medium

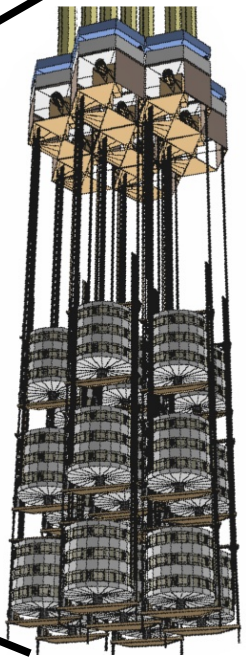
GERDA Concept

Clean room: Class 10.000



Detector array:

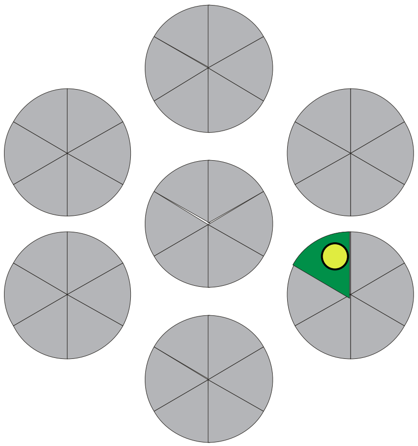
- 3 detectors per string
- up to 16 strings



- little (high-Z) material close to detectors

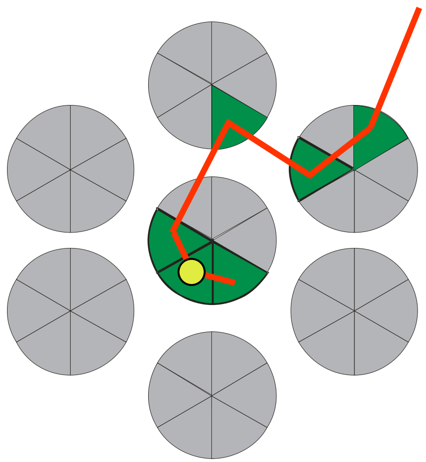
Anti-Coincidences:

Signal:



Single Site Event (SSE)

Background:

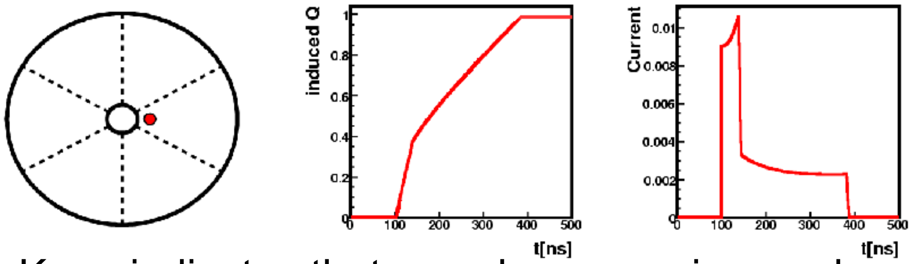


Multi Site Event (MSE)

- crystal and segment anti-coincidence possible

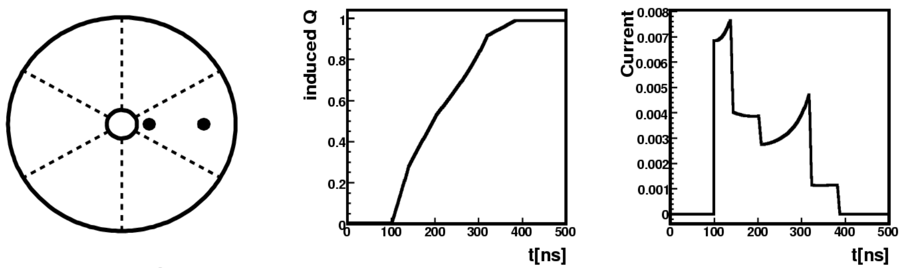
Pulse Shape Analysis:
(PSA)

Single Site Event (SSE):



Knee indicates that one charge carrier reaches electrode and stops drifting

Multi Site Event (MSE):



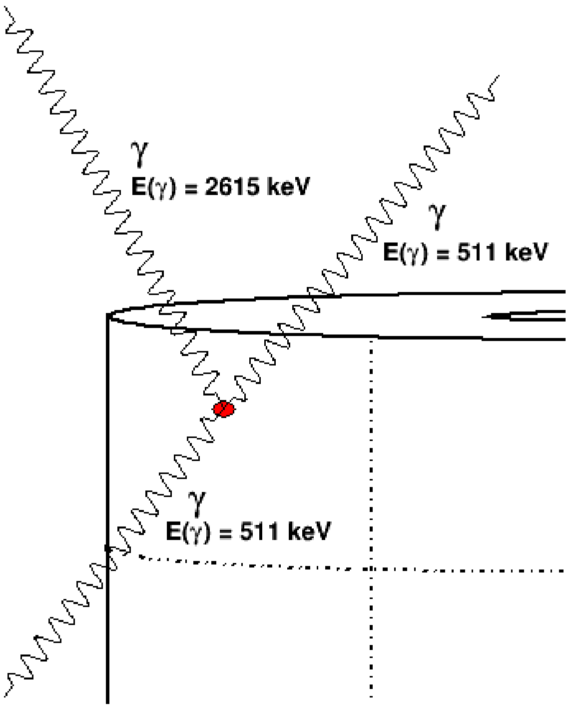
MSE tends to have more complicated pulse structures.

- up to factor 2 better background recognition for certain backgrounds

Pulse Shape Simulation - Why?

➡ samples of SSE and MSE are needed to understand efficiencies of PSA

- MSE can be easily extracted from data (MeV photon peaks)
- SSE can be also be extracted from data (Double Escape Peak)

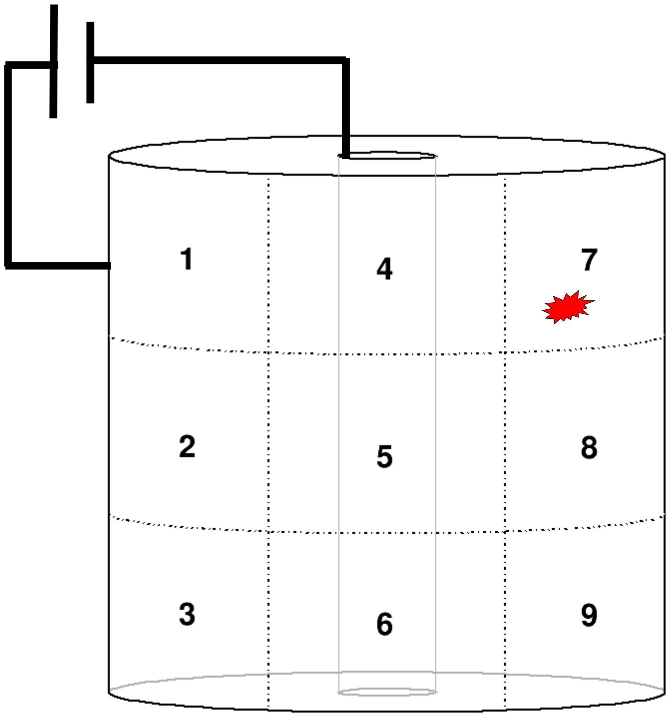


BUT:
- samples are not pure SSE or MSE
- events are not homogeniously distributed throughout the detector

can be overcome

BUT takes long time to record samples

- Data should be supplemented by simulated pulses
- PSS can give insights into crystal properties
- helps reconstructing interaction positions



- **energy deposit** ⇒ electrons holes created
- charges **drift** under influence of external **E-Field**
- drifting charges **induce pulses** on electrodes

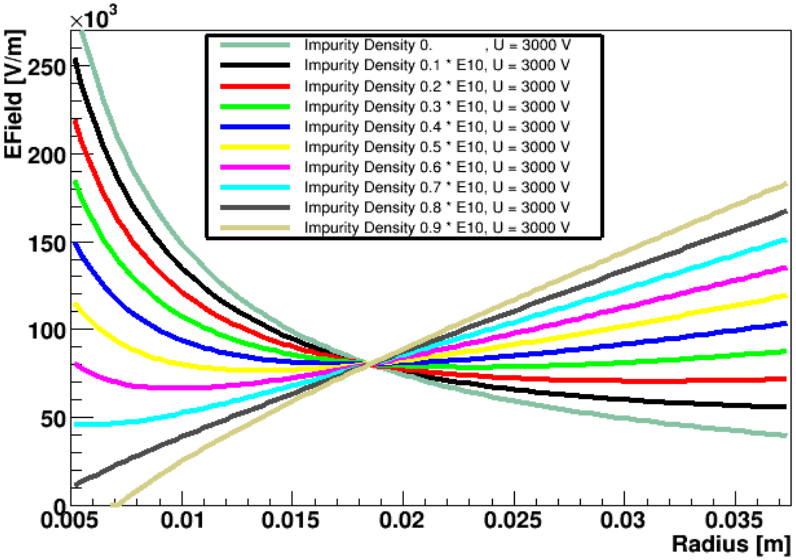
1. simulate energy deposit using MaGe
2. group hits according to position bandwidth and sampling frequency
3. determine number of electron hole pairs
4. **calculate E-Field** inside detector
5. **calculate drift** of charge carriers
   ⇒ **calculate induced charges** using **weighting potentials**
6. take into account electronics effect, i.e noise, bandwidth...

Solve Poisson-equation: $\nabla^2 \varphi(\vec{r}) = \frac{1}{(\epsilon_0 \cdot \epsilon_R)} \cdot \rho(\vec{r})$

numerical procedure: **Successive Overrelaxation (SOR)**

agreement
numerical and analytical solution
better than 1%

numerical calculation works

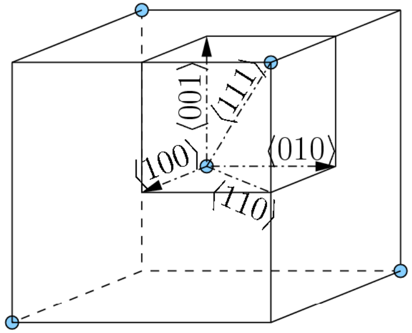


- impurity density ρ dominates the electric field
- ρ changes with radius, height and also in azimuthal angle ϕ

Drift:

$$\vec{v}(\vec{r}) = \mu_{e,h}\vec{E}(\vec{r})$$

with $\mu_{e,h}$ depends on temperature, electric Field and **structure** of **germanium crystal**



- in direction
  ⟨100⟩, ⟨110⟩ and ⟨111⟩
  $\mu_{e,h}$ **parallel** to E-Field
  otherwise not!

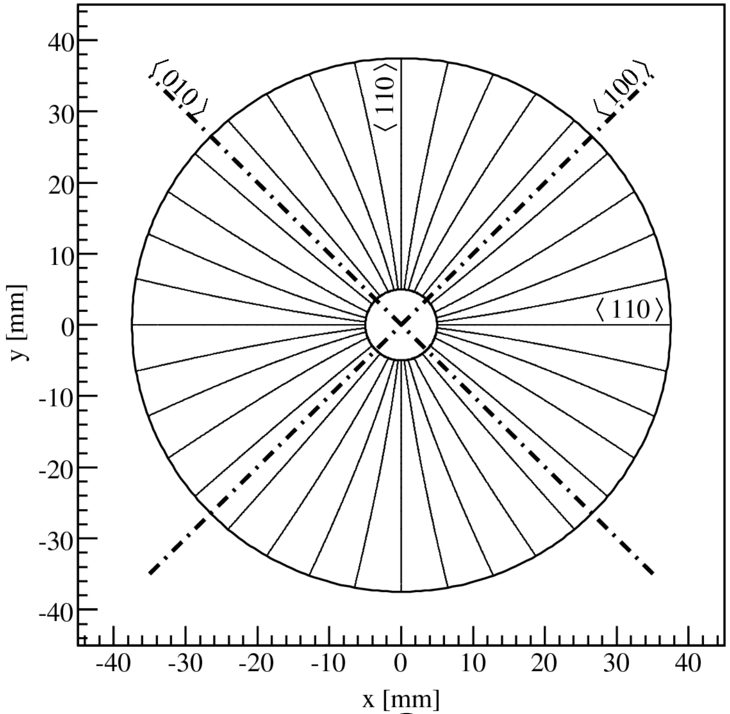
- experimental data along axes exists
  ⇒ mobility can extracted along axes

$$v = \frac{\mu_0 E}{\left[1 + \left(\frac{E}{E_0}\right)^{\beta}\right]^{1/\beta}} - \mu_n E$$

Charge carrier drift in **any** direction can be computed using mobilities along ⟨100⟩ and ⟨111⟩ directions

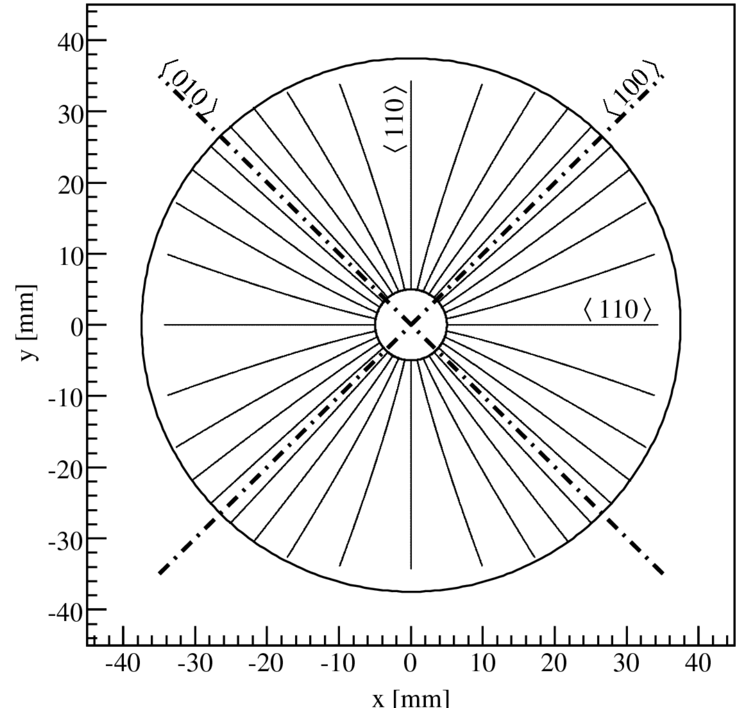
Pulse Shape Simulation - Drift

- drift charges in **fixed time intervall** Δt
- start position **equally spaced** on outer/inner surface



e⁻

drift from outside in



h⁺

drift from inside out

- holes drift slower than electrons
- drift along ⟨100⟩ axis faster than ⟨110⟩

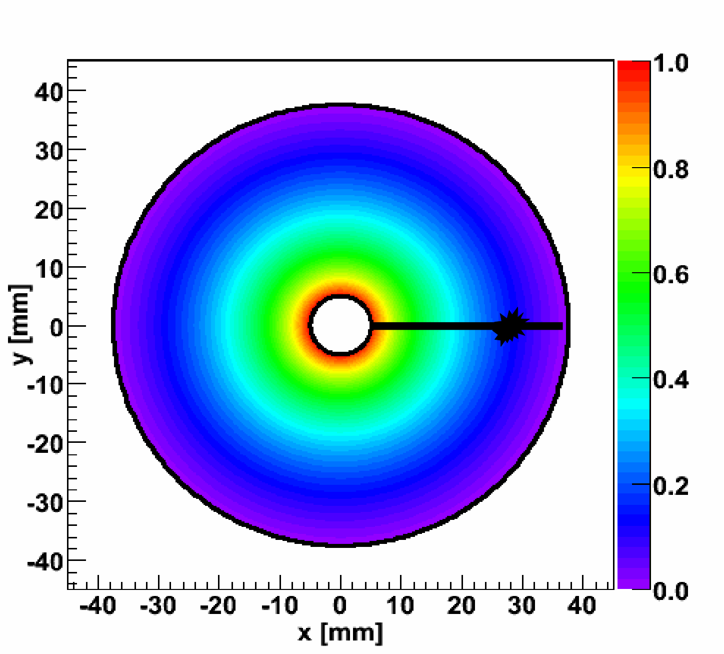
Shockley-Ramos Theorem:

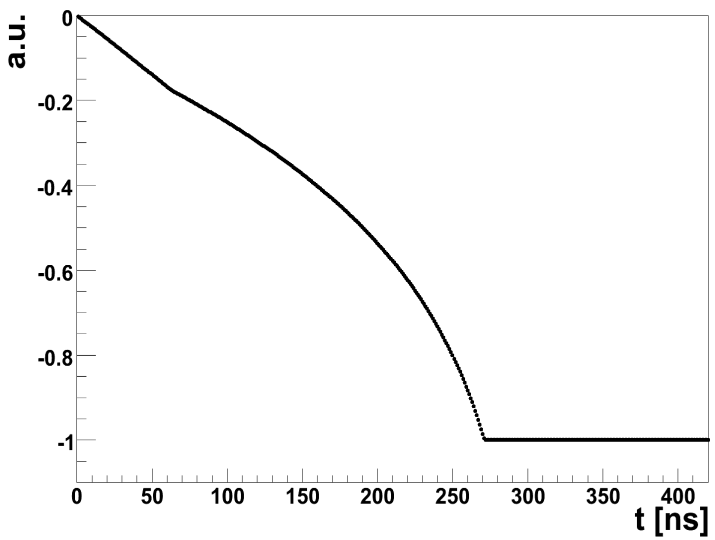
$$Q^{i}_{induced}(t) = q_e \cdot \phi^{i}_{W}(\vec{r}(t)) + q_h \cdot \phi^{i}_{W}(\vec{r}\,'(t))$$

Weighting Potential: **no** analytical solution in 3D for 18 segments

calculated solving Laplace equation
BC WP on electrode 1, otherwise 0

Need numerical calculation (SOR)

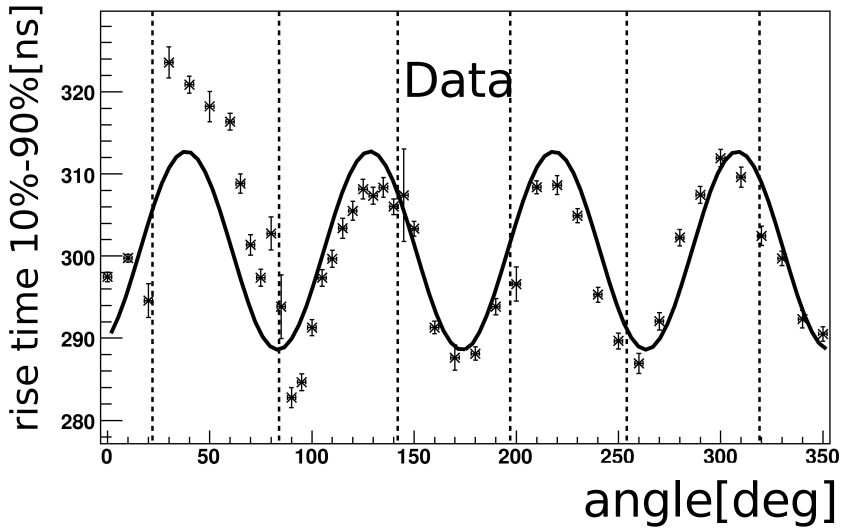


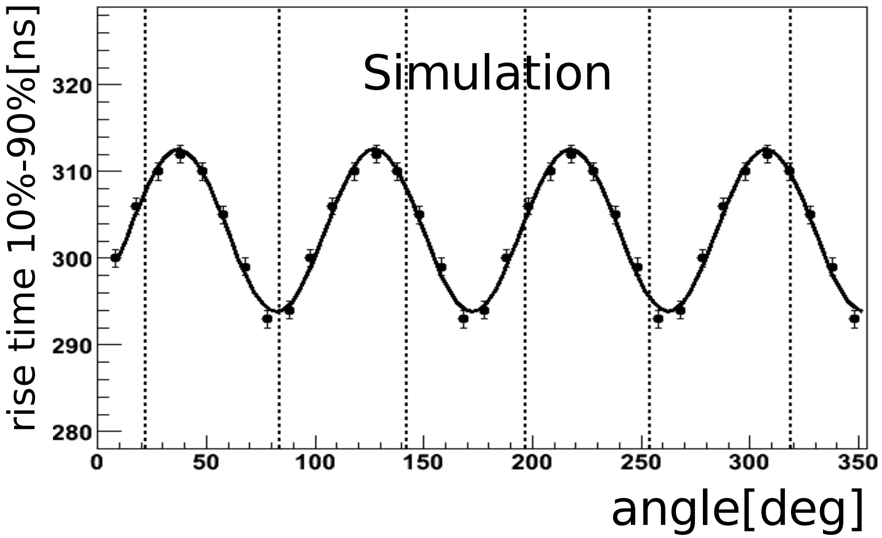


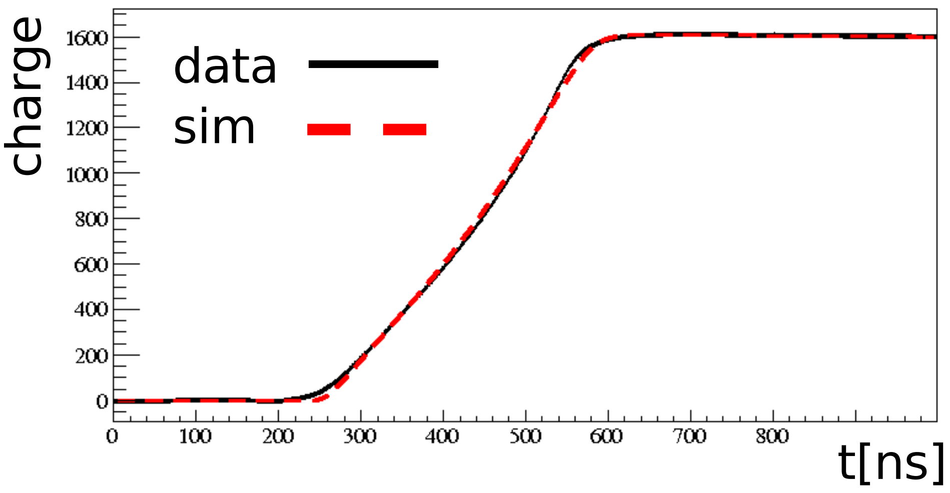
Pulse Shape Simulation - Results

- adding **electronics bandwidth** and **DAQ sampling frequency**

⇒ realistic pulse - comparable to data:







- scaling of pulse length of ~10% needed
- agreement of rise time and shape at the % level

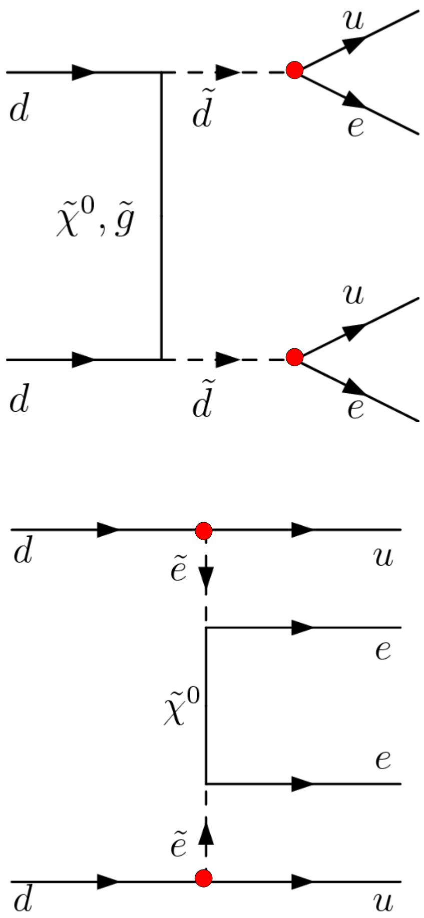
Summary

- Neutrinoless double beta decay **only way** to unveil the nature of the neutrino
- GERDA will search for $0\nu\beta\beta$ and check claim of parts of the HDM group
- Background reduction is crucial: **Anti-coincidence** and **Pulse Shape Analysis** needed to reduce background
- **Realistic** pulse shape simulation **needed** to fully **understand** PSA
- Realistic pulse shape simulation was **succesfully developed**

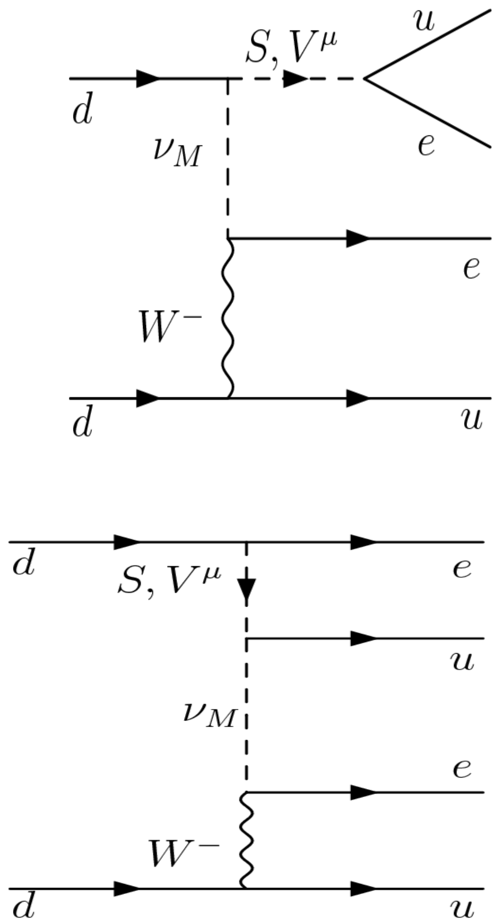
Extras

Other Possibilities of $0\nu\beta\beta$

R-Parity violation SUSY:



Leptoquarks:



Even more:

- Theories allowing for right handed currents
- Compositness
- Heavy Majorana neutrino exchange

Strongest bounds on λ'_{111} from $0\nu\beta\beta$
e.g. Physics Reports 420: 1-202, 2005

Halflife Limits

Heidelberg-Moscow experiment:

- 5 enriched Ge p-type crystals
- background index ~0.1 cts/(keV kg y)
- $T_{1/2} \geq 1.9 \cdot 10^{25}$ y (90% C.L.) 35.5 kg y

  Eur. Phys. J. A12, 147-154 (2001)
- part of collaboration claims a signal

  Mod. Phys. Lett. A16 2409-2420 (2001), NIM A 522 (2004) 371-406

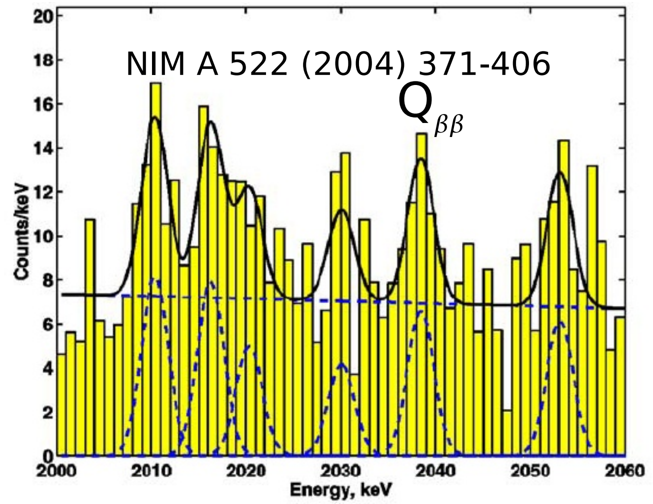
IGEX:

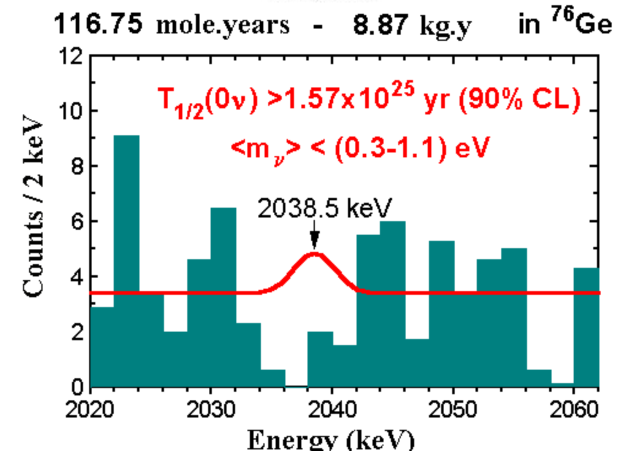
- 3 enriched Ge p-type crystals
- $T_{1/2} \geq 1.57 \cdot 10^{25}$ y (90% C.L.) 8.87 kg y

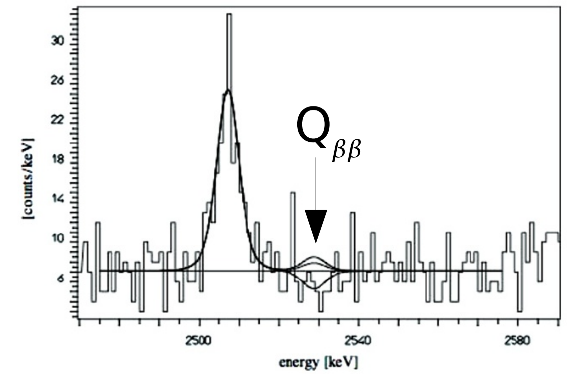
  NP B (Proc.Suppl.) 87 (2000) 278

Cuoricino: *Phys. Rev. C 78 (2008) 035502*

- 62 TeO_2 bolometers 40.7kg
- $T_{1/2} \geq 3.0 \cdot 10^{24}$ y (90% C.L.) 11.83 kg y







Experimental Considerations - Germanium Detectors

$$T_{1/2} \propto \text{const} \bullet \epsilon \bullet (M \bullet T / b \bullet \Delta E)^{1/2}$$ if background

general considerations

- high Q-value:
  - phase space scales with Q^5
  - natural radioactivity contribution reduced
- large target mass M; large natural abundance, or enrichment
- high signal effiency ϵ
- **low background rate b** in ROI **crucial**! rate := counts/(keV · kg·y)
- **good energy resolution ΔE** to seperate $0\nu\beta\beta$ from ($2\nu\beta\beta$ + other bkg)

Ge detectors

- $Q_{\beta\beta}(^{76}Ge) = 2039$ keV
- enrichement in ^{76}Ge of 86%
- source = detector
- germanium is one of the purest materials to produce
- excellent energy resolution FWHM($Q_{\beta\beta}$) < 5keV; $\Delta E/E = 0.2\%$

Background

Background: processes which cause energy deposition inside Region Of Interest

- **Decay of cosmogenically produced radioactive isotopes** ← Detector production and storage
- Cosmic muons
- Neutrons:
  - Muon induced
  - From radioactive isotopes in the rock

Depth and laboratory dependent (applies to: Cosmic muons; Neutrons; Muon induced)

- Radioactive isotopes in the surrounding:
  - Electrons/positrons
  - **Photons**
  - Alphas (surface)

Choice of material close to detectors (applies to: Electrons/positrons; Photons)

Purity of the liquid argon (applies to: Alphas (surface))

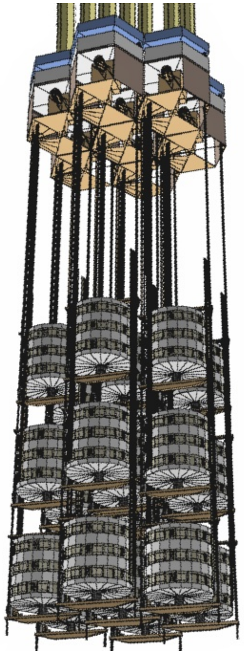
Background units:

counts / (keV·kg·y)

- keV: around $Q_{\beta\beta}$
- kg: total mass
- y: measuring time

Expected Background Phase II

- simulation of an array with 21 segmented detectors, 7 strings, each 3 detectors
- simulation carried out with **MaGe** (MajoranaGerda) GEANT4 based framework
- background including segment anti-coincidence



Part	Background contribution $[10^{-4}$ counts/(keV·kg·y)]	
Crystal	18	^{68}Ge main source
Holder	3	
Cabling	18	R&D for new cable
Electronics	5	
Muons	~ 0.1	including muon veto
Neutrons	~ 0.1	external n negligible
Total	~ 44	

PSA Example

- n-type 18-fold segmented HP Ge detector
- only core pulse used

Eur. Phys. J. C 52, 19-27 (2007)