New constrains on neutrinoless double-β decay from the GERDA experiment

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Les Rencontres de Physique de la Vallée d'Aoste
23 Feb - 01 Mar 2014

Outline

- Neutrinoless double-β decay
- The GERDA experiment
- GERDA Phase I – prior to data unblinding
- GERDA Phase I – $0\nu\beta\beta$ analysis
- Conclusions and outlook on GERDA Phase II

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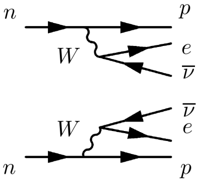
Double-β decays

Second order nuclear transitions → decay of two neutrons into two protons

2-neutrino double-β decay ($2\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z + 2) + 2e^{-} + 2\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes
- $T^{2\nu}_{1/2}$ in the range $10^{19} - 10^{24}$ yr



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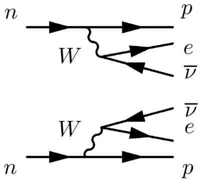

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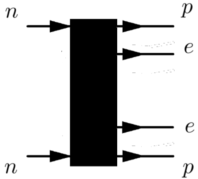
Neutrinoless double-β decay ($0\nu\beta\beta$):

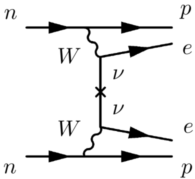


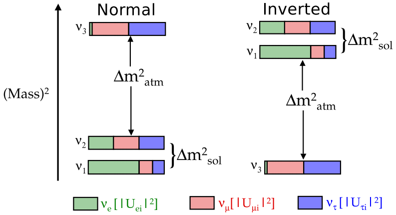
- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- lepton number violation ($\Delta L = 2$)
- physics beyond the Standard Model (e.g. light Majorana ν, R-handed weak currents, SUSY particles)
- ν Majorana mass component (Schechter-Valle theorem)
- $T^{0\nu}_{1/2}$ limits in the range $10^{21} - 10^{26}$ yr (10^{25} yr for ^{76}Ge)
- claim for a signal (subgroup of HdM experiment)

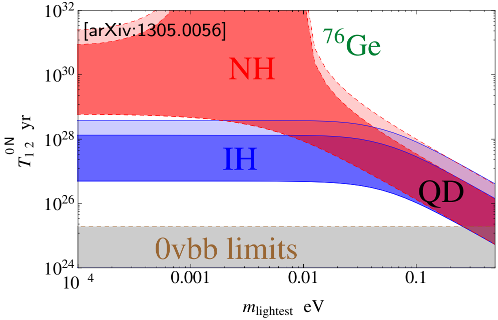
Neutrinoless double-β decay & neutrino physics

Assuming light-Majorana neutrino exchange as dominant $0\nu\beta\beta$ channel:

- $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|\mathcal{M}_{0\nu}(A, Z)|^2\langle m_{\beta\beta}\rangle^2$
- effective Majorana mass:
  $\langle m_{\beta\beta}\rangle \equiv \left|\sum_i U^2_{ei} m_i\right| = \left|c^2_{12}\, c^2_{13}\, m_1 + s^2_{12}\, c^2_{13}\, m_2\, e^{i2\alpha} + s^2_{13}\, m_3\, e^{i2\beta}\right|$
- ν mass spectrum (inverted/normal hierarchy, absolute mass scale)

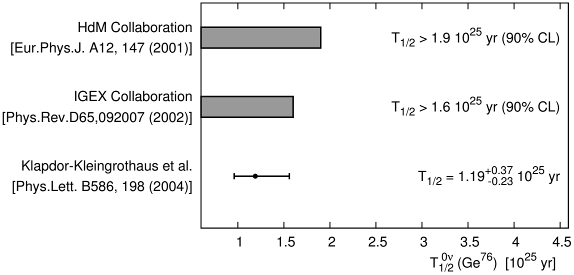


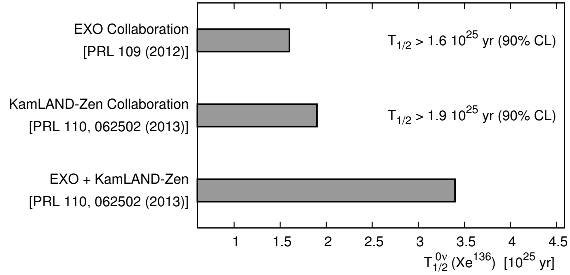




[arXiv:1305.0056]

State of the art of $0\nu\beta\beta$ search with ^{76}Ge and ^{136}Xe





KK claim 2004 [Phys.Lett. B586 198]

- ○ 71.7 kg·yr
- ○ 28.75±6.86 signal events
- ○ $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

KK claim 2006 [Mod Phys Lett A21]

Claim strengthened with pulse shape analysis but many inconsistencies in the analysis summarized in:

Ann. Phys. 525 (2013) 269

In particular:

- missing efficiency corrections
- uncertanty on signal cts smaller than Poisson error

$T^{0\nu}_{1/2}$ central value and errors incorrect

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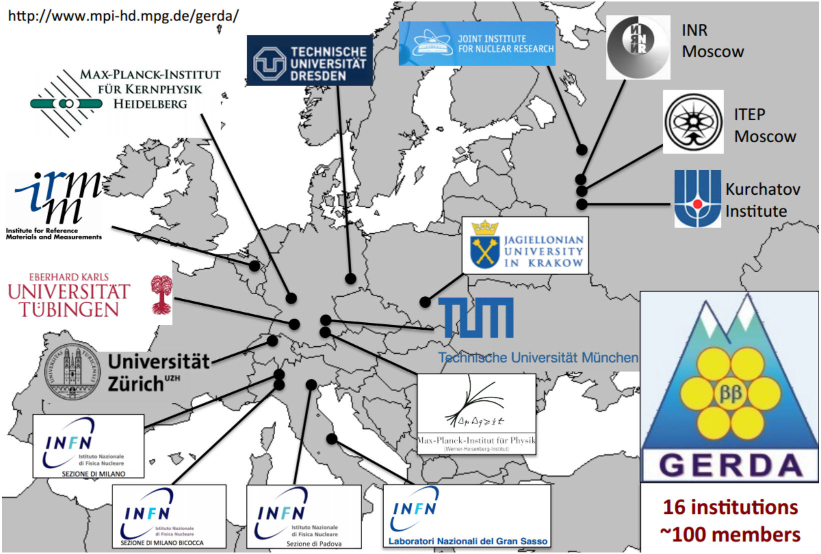
Institutions

http://www.mpi-hd.mpg.de/gerda/



16 institutions
~100 members

Sensitivity and background goals

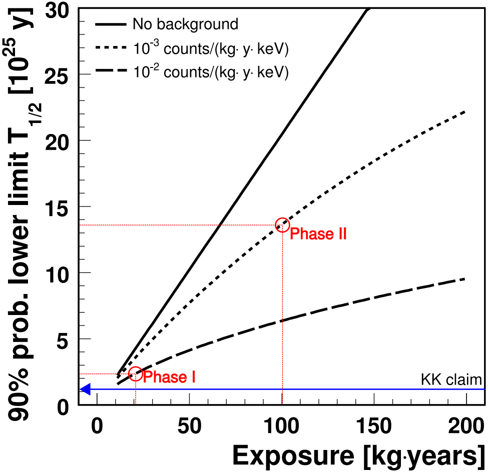
Phase I (Nov 2011 - May 2013):

- 15 – 20 kg of target mass (87% ^{76}Ge)
- bkg $\sim 10^{-2}$ cts/(keV$\cdot$ kg$\cdot$ yr) at $Q_{\beta\beta}$
- exposure 21.6 kg$\cdot$yr
- sensitivity to scrutinize KK claim

Phase II (migration ongoing):

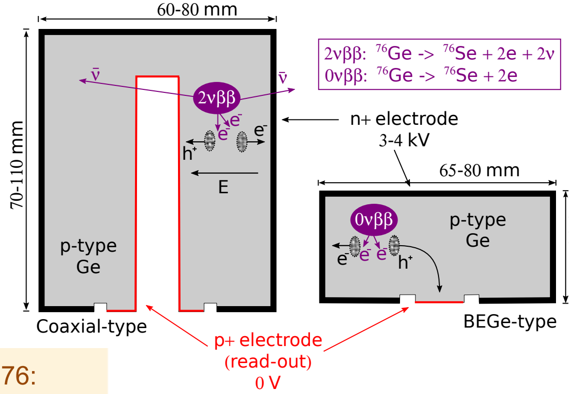
- new custom-produced BEGe detectors (additional 20 kg, 87% ^{76}Ge)
- bkg $\lesssim 10^{-3}$ cts/(keV$\cdot$ kg$\cdot$ yr) at $Q_{\beta\beta}$ (active techniques for bkg suppression)
- exposure $\gtrsim$ 100 kg$\cdot$yr
- start exploring $T^{0\nu}_{1/2}$ in the 10^{26} yr range

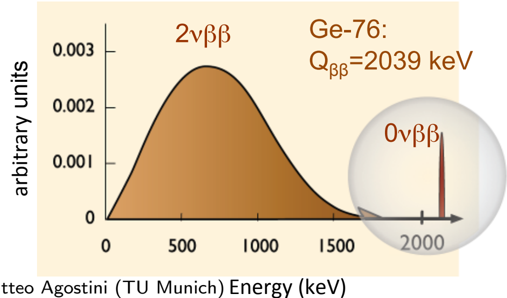
[Phys.Rev.D75, 092003 (2006)]



Detectors

- HPGe detectors from material enriched in ^{76}Ge ($\sim$87%)
- detectors well established technology
- optimal spectroscopy performance:
  - long-term stability
  - $\Delta E \approx 0.1\%$ at $Q_{\beta\beta}$
  - radio purity



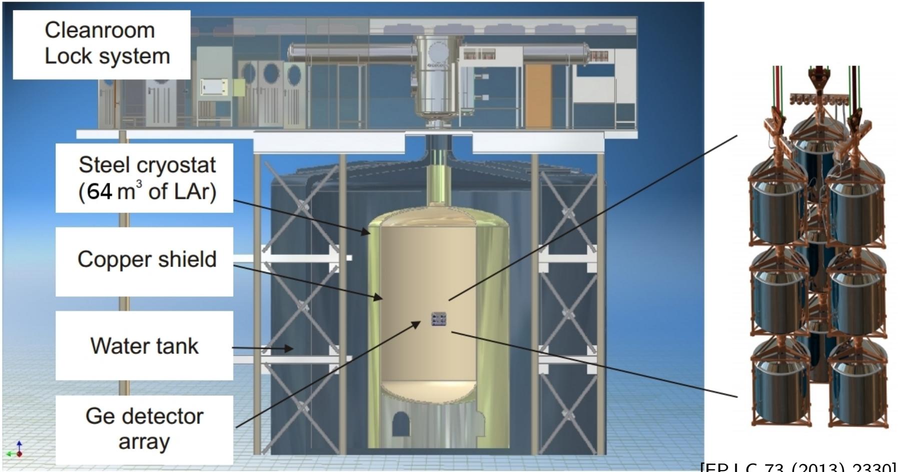


Calorimeter detectors:

- source=detector
- high detection efficiency
- peak at Q-value ($Q_{\beta\beta}$)

Shielding strategy and apparatus

- bare Ge detectors in liquid Argon (LAr)
- shield: high-purity LAr/H_2O
- radio-pure material selection
- deep underground (LNGS, 3800 m.w.e.)



[EPJ C 73 (2013) 2330]

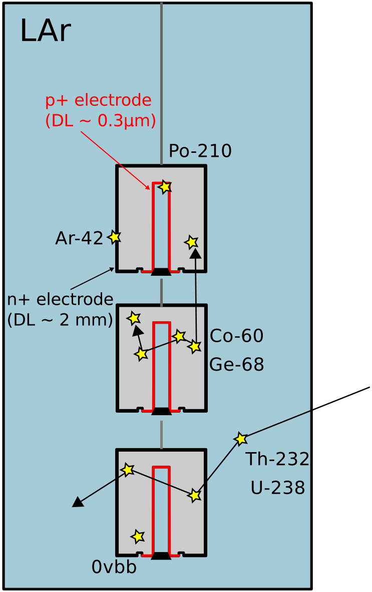
Backgrounds and mitigation techniques

Background sources:

- natural radioactivity (^{232}Th and ^{238}U chains):
  - γ-rays (e.g. ^{208}Tl, ^{214}Bi)
  - α-emitting isotopes from surface contamination (e.g. ^{210}Po) or ^{222}Rn in LAr
- cosmogenic isotopes in Ge decaying inside the detectors (^{68}Ge, ^{60}Co)
- long-lived cosmogenic Ar isotopes (^{39}Ar,^{42}Ar)

Mitigation strategy:

- detector anti-coincidence
- time-coincidence (Bi-Po or ^{68}Ge)
- pulse shape analysis (bulk localized energy deposition)
- LAr-scintillation (in Phase II)



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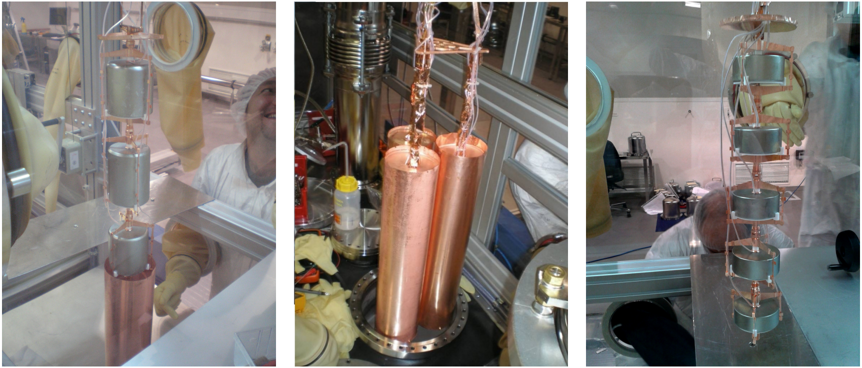
Detector array assembly

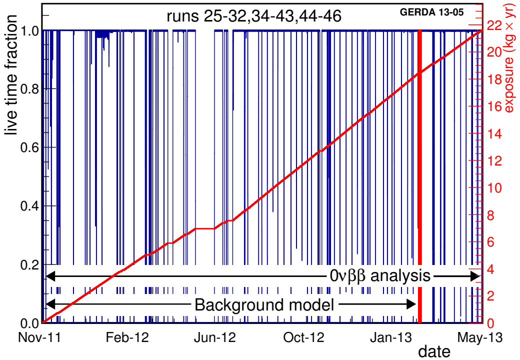


- 3 + 1 strings
- 8 $^{\mathrm{enr}}$Ge coaxial detectors (2 not considered in the analysis)
- 5 $^{\mathrm{enr}}$Ge BEGe detectors (1 not considered in the analysis)
- 1 $^{\mathrm{nat}}$Ge coaxial detectors

$^{\mathrm{enr}}$Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)

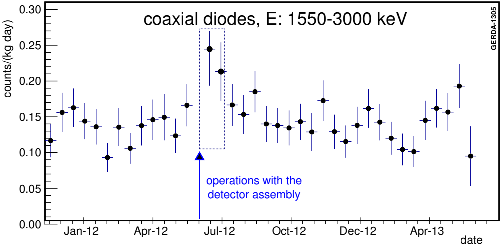
Overview of the data taking

- data taking Nov11 - May13 (492 d)
- average duty cycle 88%
- total exposure 21.6 kg·yr
- (bi)weekly calibration with Th-228 (blue spikes)



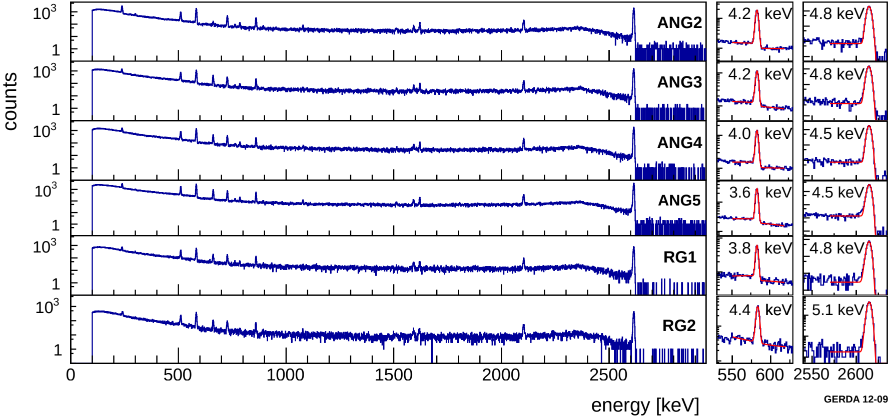
- BEGe detectors from Jul12
- 3 data sets:

dataset	exposure
coaxial (golden)	17.9 kg·yr
coaxial (silver)	1.3 kg·yr
BEGe	2.4 kg·yr



GERDA Phase I – prior to data unblinding

Calibration of the energy scale (^{228}Th)



Energy resolution at 2.6 MeV (FWHM):

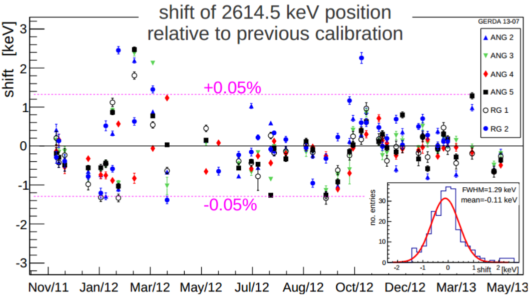
- ▶ 4 – 5 keV for coaxial data sets
- ▶ ∼ 3 keV for BEGe data set

GERDA Phase I – prior to data unblinding

Stability of the energy scale and resolution

Calibration runs:

- calibration every one/two weeks
- off-line energy reconstruction (semi-Gaussian filter)
- energy resolution stable
- energy shift between successive calibrations $\lesssim 1$ keV @ $Q_{\beta\beta}$

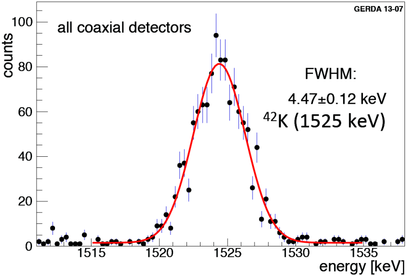


$0\nu\beta\beta$ data set:

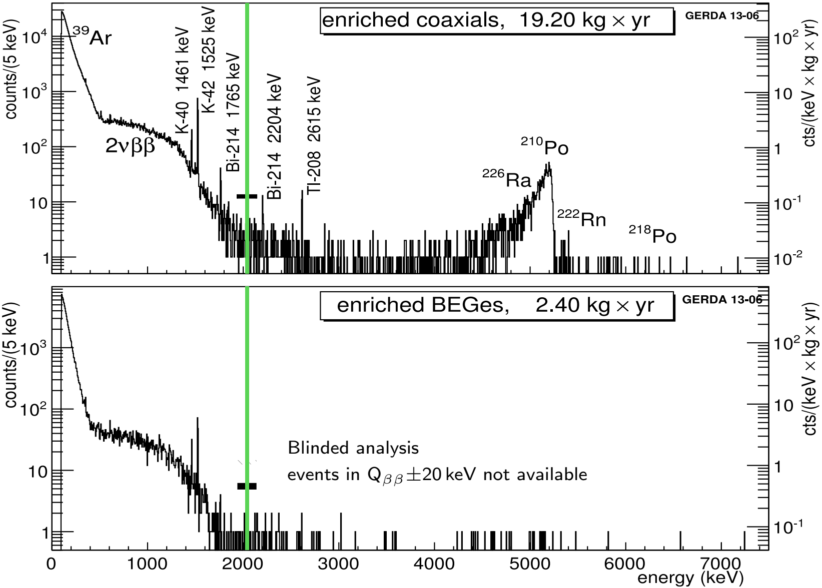
- peak position within 0.3 keV at correct position
- resolution 4% larger than in calibration runs
- mean FWHM at $Q_{\beta\beta}$ (mass/exposure weighted):

  coax —> 4.8±0.2 keV

  BEGe —> 3.2±0.2 keV



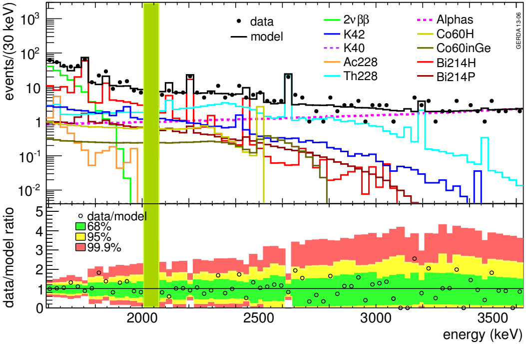
Prominent structures in the energy spectrum



Blinded analysis
events in $Q_{\beta\beta} \pm 20$ keV not available

GERDA Phase I – prior to data unblinding

Background modeling

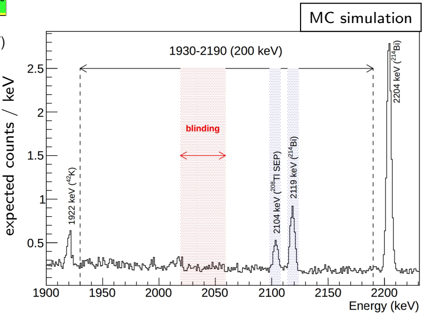


Contribution at $Q_{\beta\beta}$:

- γ-rays (close sources): Bi-214, Tl-208, K-42
- α- and β-rays (surface decays): Ra-226 daugheter, Po-210, K-42

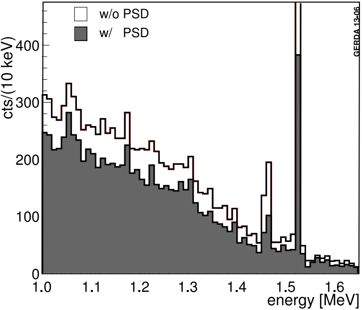
more details in [arXiv:1306.5084]

- no line expected in the blinded window
- background flat between 1930-2190 keV (excluding peaks at 2104 and 2119 keV)
- extrapolated background at $Q_{\beta\beta}$ before pulse shape analysis in units of 10^{-2} cts/(keV· kg· yr):
  - coaxial (golden): $1.75^{+0.26}_{-0.24}$
  - BEGe: $3.6^{+1.3}_{-1.0}$



GERDA Phase I – prior to data unblinding

Pulse shape discrimination

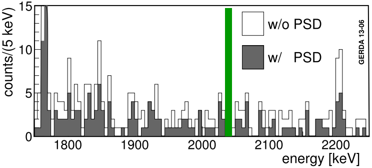


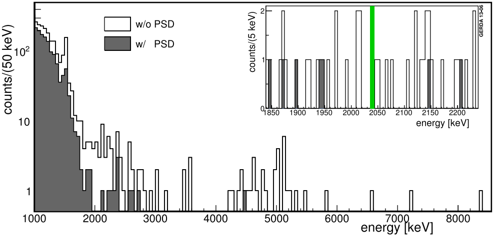
Coaxial detectors:

- artificial neural network TMlpANN
- cut defined using ^{228}Th calibration data
  cut fixed to 90% acceptance of 2.6 MeV DEP
- cross checks:
  - $2\nu\beta\beta$ acc. = (85±2)%
  - 2.6 MeV γ-line compton-edge acc. = 85-94%
  - Co-56 DEP (1576 & 2231 keV) acc. = 83-95%

$\boxed{0\nu\beta\beta \text{ acceptance} = 90^{+5}_{-9}\%}$

$\boxed{\text{background acc at } Q_{\beta\beta} = \sim 45\%}$





BEGe detectors:

- A/E method (mono-parametric PSD)
- $0\nu\beta\beta$ acc (DEP and simulations) (92±2)%
- $2\nu\beta\beta$ acc (91±5)%
- background acc at $Q_{\beta\beta} \leq$20%

more details in [Eur.Phys.J C73 (2013) 2583]

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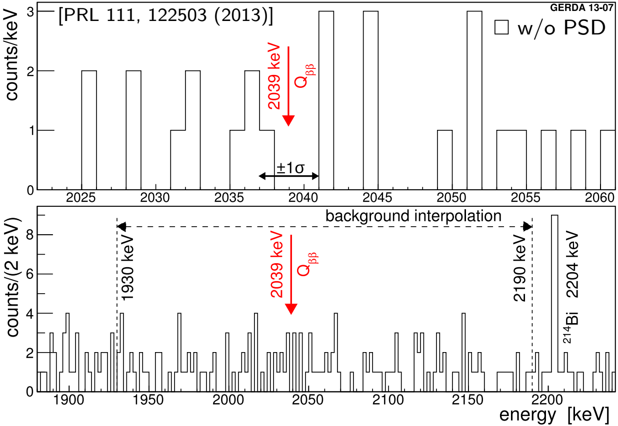
Energy spectrum around $Q_{\beta\beta}$



Analysis cuts applied:

1) signals quality cuts
2) detector anti-coincidence
3) muon-veto anti-coincidence
4) single-detectors time coincidence (BiPo cut)
5) PSD

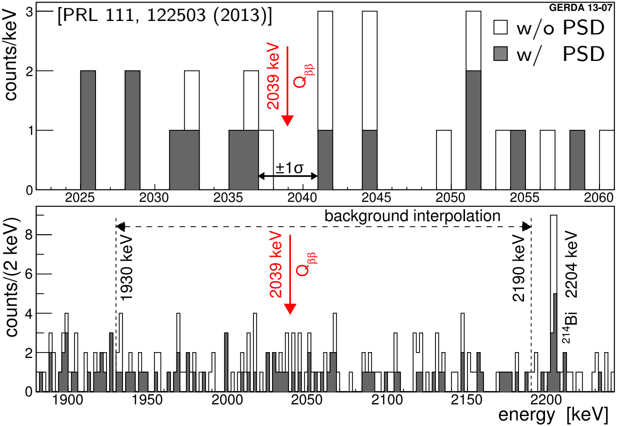
Survival fraction at $Q_{\beta\beta}$:	
1	∼99%
2+3	∼60%
4	∼100%
5	∼50%

w/o PSD

w/ PSD

data set	exposure [kg·yr]	background 10^{-2} cts/(keV· kg· yr)	expected cts ($Q_{\beta\beta}$±5 keV)	observed cts ($Q_{\beta\beta}$±5 keV)
golden	17.3	1.8	3.3	5
silver	1.3	6.3	0.8	1
BEGe	2.4	4.2	1.0	1

Energy spectrum around $Q_{\beta\beta}$



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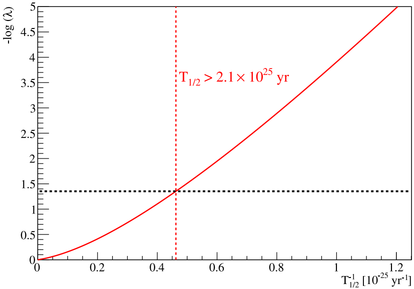
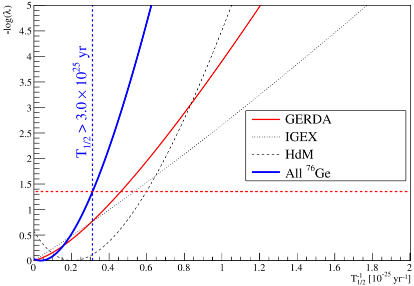
silver	1.3	6.3	3.0	0.8	0.4	1	1
BEGe	2.4	4.2	0.5	1.0	0.1	1	0

Statistical analysis





Baseline analysis (profile likelihood):

- maximum likelihood spectral fit (constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $T^{0\nu}_{1/2}$)
- $T^{0\nu}_{1/2} \geq 0$ (coverage tested)
- systematic uncertainties in the fit

Results (GERDA only):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $N_{0\nu\beta\beta} < 3.5$ cts at 90% C.L.
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal): $T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

Results (GERDA + IGEX [1] + HdM [2]):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

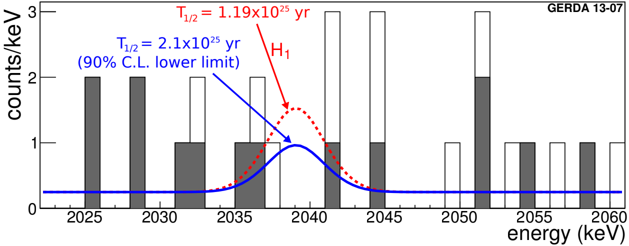
Comparison with Phys.Lett. B586 198 (2004)

Hypothesis test: H_0 (bkg only) vs H_1 ($T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr + bkg)

In $Q_{\beta\beta} \pm 2\sigma_E$ (after PSD):

- expected 2.0±0.3 bkg cts
- expected 5.9±1.4 signal cts (assuming H1)
- observed 3 cts

[PRL 111, 122503 (2013)]



GERDA only:

- ▶ Frequentist p-value $(N_{0\nu\beta\beta} = 0 | H_1) = 0.01$
- ▶ Bayes factor $P(H_1)/P(H_0) = 2.4 \cdot 10^{-2}$

GERDA + IGEX + HdM:

- ▶ Bayes factor $P(H_1)/P(H_0) = 2 \cdot 10^{-4}$

Long standing claim strongly disfavoured!

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Conclusions

- GERDA Phase I collected 21.6 kg·yr of exposure
- background order of magnitude lower than previous Ge experiments:

  ~0.01 cts/(keV· kg· yr) at $Q_{\beta\beta}$ (after PSD)
- blind analysis —> no positive $0\nu\beta\beta$ signal:

  $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L. (GERDA only)

  $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr at 90% C.L. (GERDA+IGEX+HdM)
- Long standing claim excluded at 99% C.L. (model-independent result)

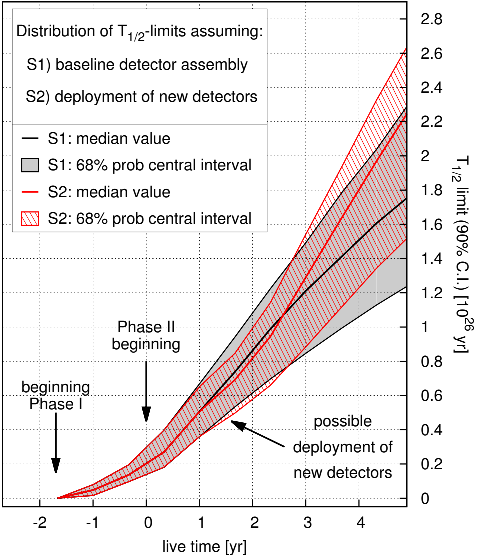
Outlook on Phase II

Transition to Phase II ongoing. Major upgrade of many components:

- increase of target mass (+20 kg)
- new hardware to detect the LAr scintillation light (anti-coincidence veto)
- new custom made BEGe detectors providing enhanced pulse shape discrimination performance

Expectations:

- ~35 kg of Ge detectors
- background $\lesssim 10^{-3}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$
- start the exploration of $T_{1/2}^{0\nu}$ values in the 10^{26} yr range

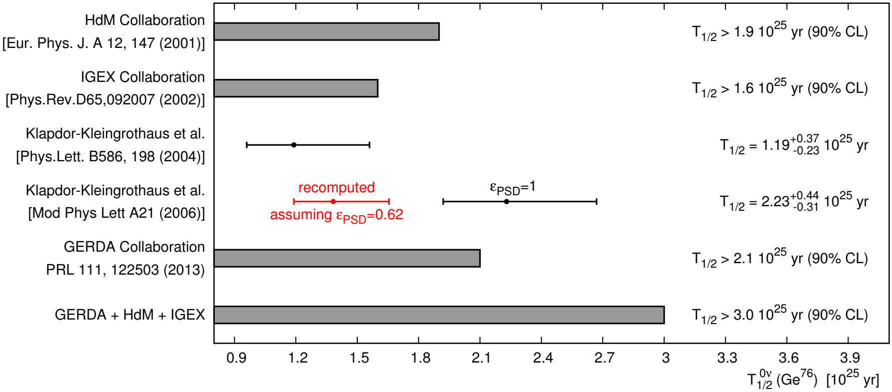


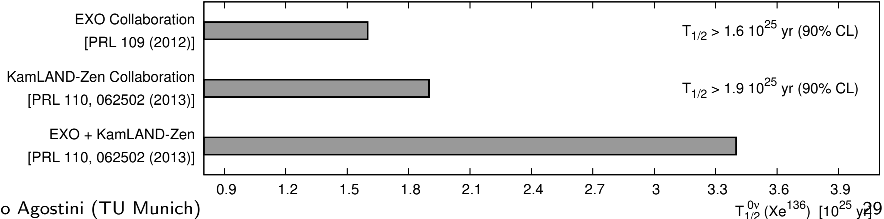
Collaboration

$\sim$100 members, 16 institutions, 6 countries

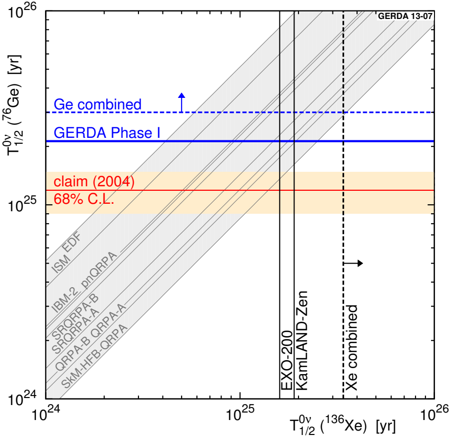
backup slides

State of the art of $0\nu\beta\beta$ search with ^{76}Ge and ^{136}Xe





Comparison between ^{76}Ge and ^{136}Xe experiments



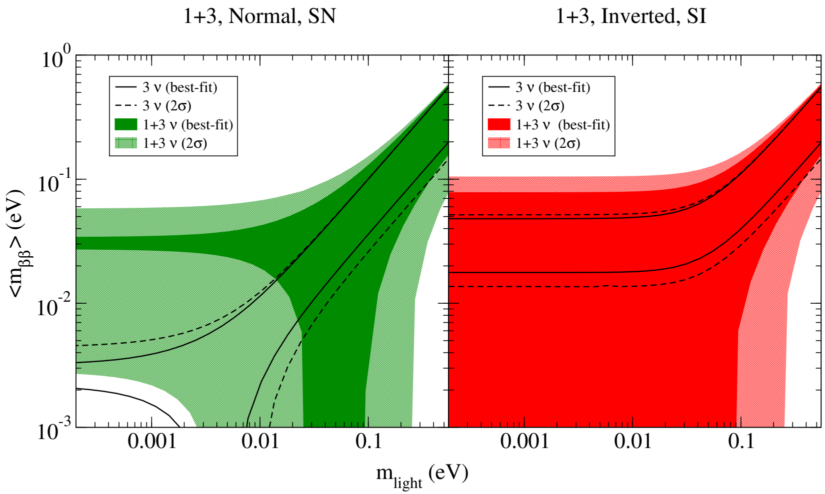
- GERDA provides a model-independent test of the signal claim
- comparison with ^{136}Xe experiments possible only through:
  - ○ assumptions on the leading channel (e.g. exchange of light Majorana neutrinos)
  - ○ matrix element computations (selection used in the plot is taken from arXiv:1305.0056)

GERDA+EXO+KamLAND-Zen:

Bayes factor $P(H_1)/P(H_0) = 2.2 \cdot 10^{-3}$

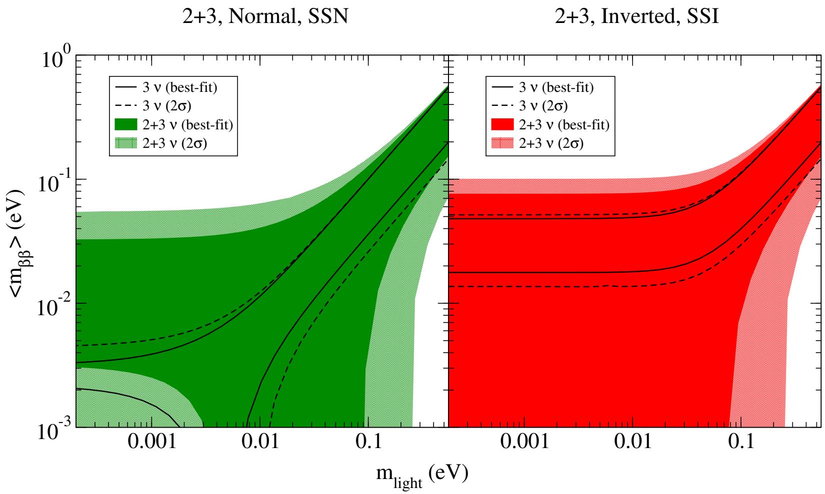
(computed for the smallest NME ratio Xe/Ge)

Sterile ν: 3 + 1



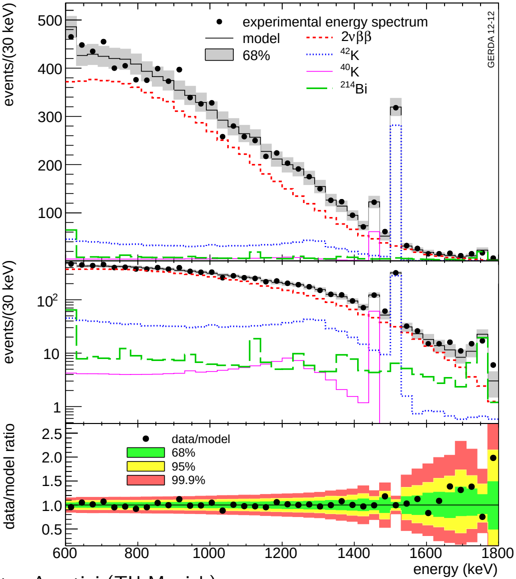
[arXiv:1106.1334]

Sterile ν: 3 + 2



[arXiv:1106.1334]

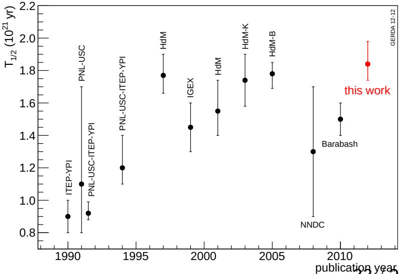
Background model – $2\nu\beta\beta$ half-life



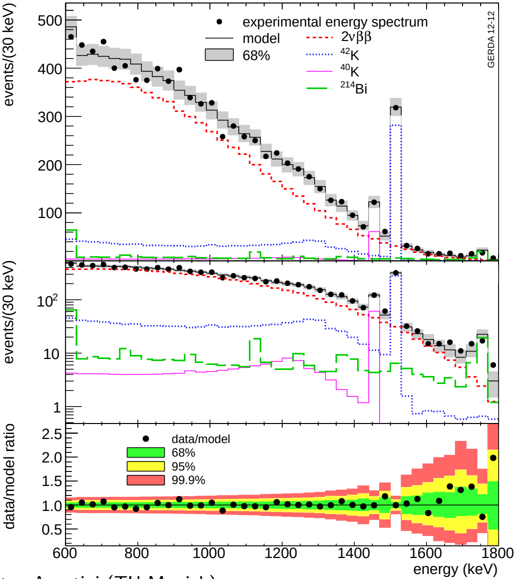
- ▶ Binned maximum likelihood (5 kg·yr)
- ▶ Nuisance parameters:
  - Active detector masses (6+1)
  - Ge-76 fractions (6)
  - Background contributions (3x6)
- ▶ $T_{1/2}^{2\nu}$ common to all detectors
- ▶ After marginalizing:

$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08}\,_{\text{fit}}\ ^{+0.11}_{-0.06}\,_{\text{syst}}) \cdot 10^{21}$$

[J.Phys.G 40 (2013) 035110]



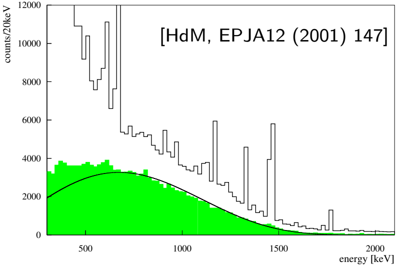
Background model – $2\nu\beta\beta$ half-life



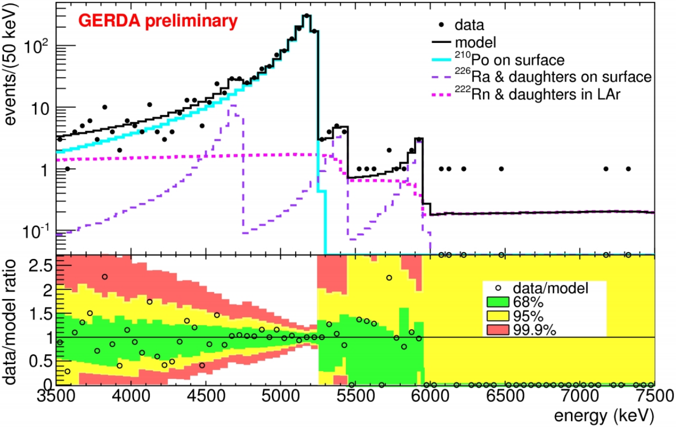
- ▶ Binned maximum likelihood (5 kg·yr)
- ▶ Nuisance parameters:
  - Active detector masses (6+1)
  - Ge-76 fractions (6)
  - Background contributions (3x6)
- ▶ $T^{2\nu}_{1/2}$ common to all detectors
- ▶ After marginalizing:

$$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08\ \text{fit}}\ {}^{+0.11}_{-0.06\ \text{syst}}) \cdot 10^{21}$$

[J.Phys.G 40 (2013) 035110]



Background model – α-emitting isotopes



- fit window 3500-7500 keV
- p-value of the fit: 0.7
- 80 bins of width 50 keV:

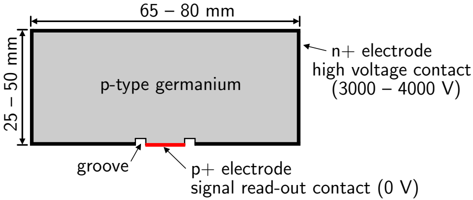
  79% in the green band

  98% in the yellow band

Colored probability intervals: [R. Aggarwal and A. Caldwell, Eur. Phys. J. Plus 127 24 (2012)]

Phase II detector design and performance

- Broad Energy Ge (BEGe) detectors:
  - ▷ commercial product (Canberra)
  - ▷ excellent spectroscopic performance (resolution, low threshold, low noise)
  - ▷ pulse shape discrimination (PSD)
- >30 BEGe detectors produced and tested



65 – 80 mm

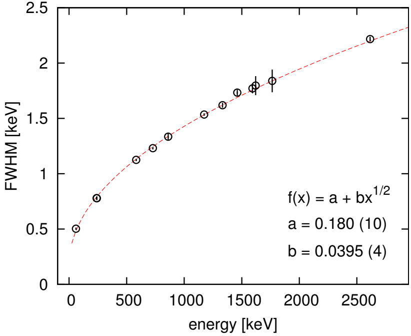
25 – 50 mm

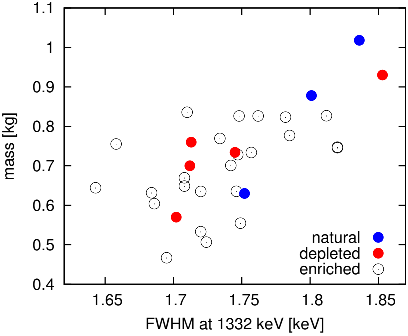
p-type germanium

n+ electrode
high voltage contact
(3000 – 4000 V)

groove

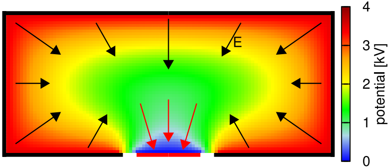
p+ electrode
signal read-out contact (0 V)



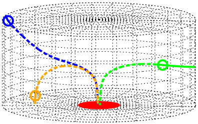


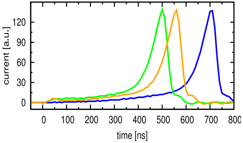
Charge collection and signal formation

- Charge collection:
  - ▷ electrons –> n+ electrode
  - ▷ holes –> detector center –> p+ electrode



- Signal formation:
  - ▷ electron contribution usually irrelevant
  - ▷ narrow current peak induced by hole drift
  - ▷ peak features independent from interaction site



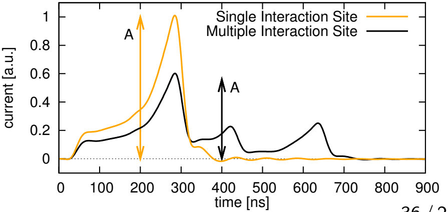


▷ single site interactions (0$\nu\beta\beta$-**like**)

▷ multiple-site interactions (typically γ-induced)

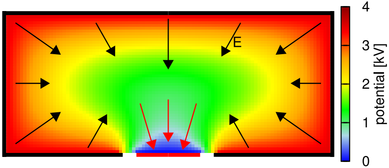
A/E method:

E: integral of the current signal (energy)
A: maximum of the current signal

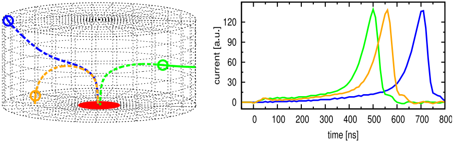


(Budjas et al. JINST 4 P10007, Agostini et al. JINST 6 P03005)

Charge collection and signal formation



- Charge collection:
  - ▷ electrons –> n+ electrode
  - ▷ holes –> detector center –> p+ electrode
- Signal formation:
  - ▷ electron contribution usually irrelevant
  - ▷ narrow current peak induced by hole drift
  - ▷ peak features independent from interaction site



▷ single site interactions ($0\nu\beta\beta$-**like**)
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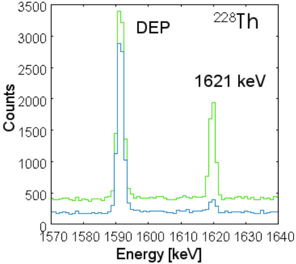
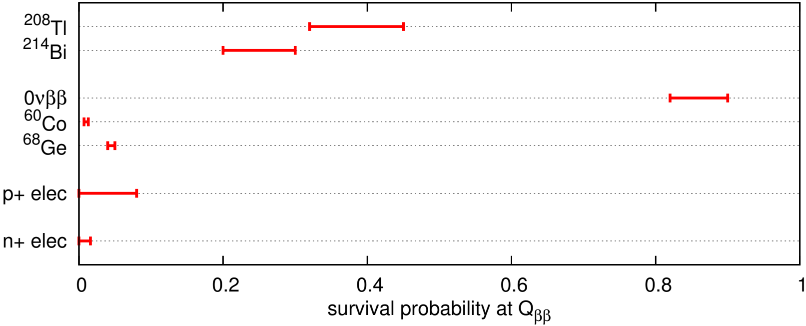


(Budjas et al. JINST 4 P10007, Agostini et al. JINST 6 P03005)

Signal identification and background reduction

Background expected in Phase II:

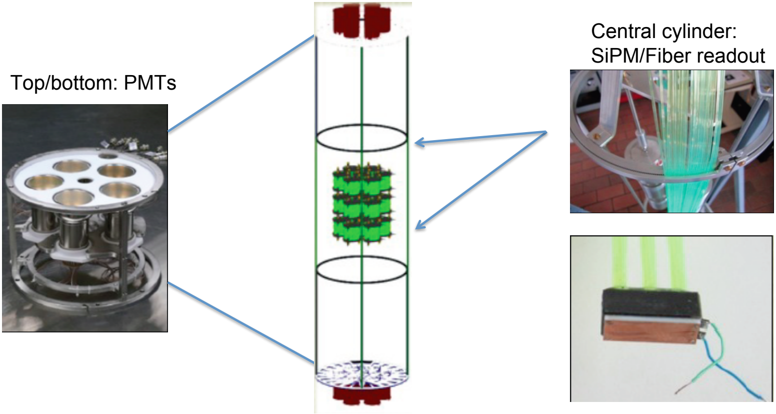
- γ-rays from ^{208}Tl and ^{214}Bi -> measured with many γ-sources
- internal decays ($0\nu\beta\beta$ and cosmogenic isotopes) -> pulse shape simulation
- α-rays on the p+ electrode -> experimental scan with collimated ^{241}Am source
- β-rays on the n+ electrode -> experimental measurements with ^{90}Sr and ^{106}Ru



Detection of LAr scintillation

LAr-scintillation (combined design):

- low-background photo-multipliers
- WLS fibers read-out with Si photo-multipliers



Top/bottom: PMTs

Central cylinder:
SiPM/Fiber readout

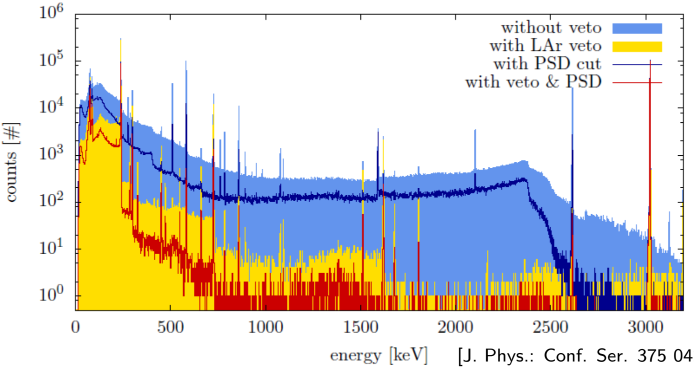
Phase II detectors and liquid argon scintillation

BEGe detectors:

- excellent energy resolution (1.6 keV @ 1.3 MeV)
- enhanced pulse shape discrimination performance
- 30 new ^{enr}Ge detectors ready at LNGS (20 kg)

LAr-scintillation (combined design):

- low-background photo-multipliers
- WLS fibers with Si photo-multipliers



[J. Phys.: Conf. Ser. 375 042009]

Pulse shape analysis combined with LAr-scintillation (in LArGe setup): measured suppression factor of $(5.2 \pm 1.3) \cdot 10^3$ at $Q_{\beta\beta}$ for close Th-228