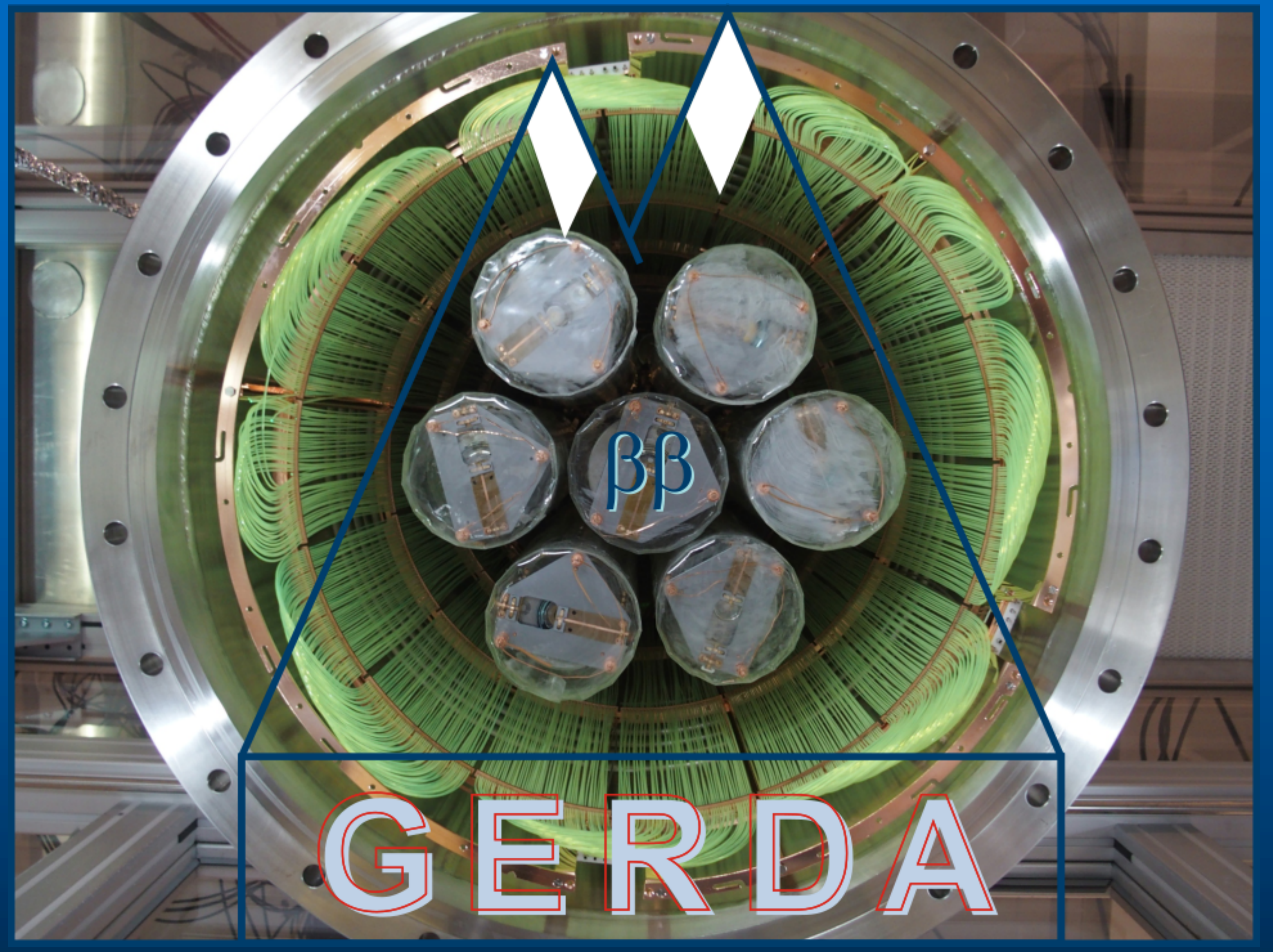
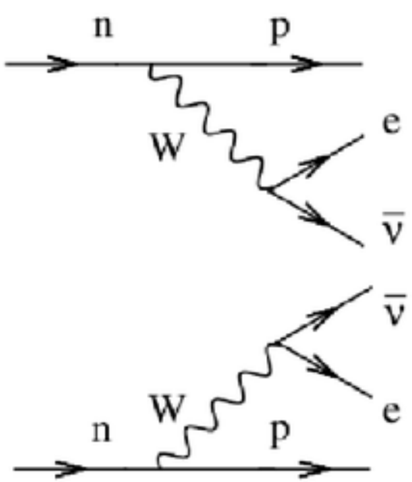

ββ
GERDA

The GERDA neutrinoless double beta decay experiment:
First data from Phase II

Tobias Bode
for the GERDA collaboration
Technische Universität München

Basics: double β-decay

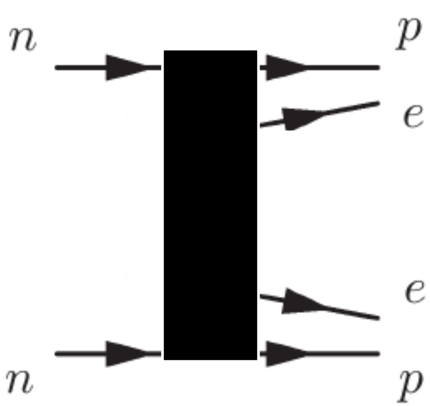


<u>2-neutrino double β-decay (2νββ)</u>

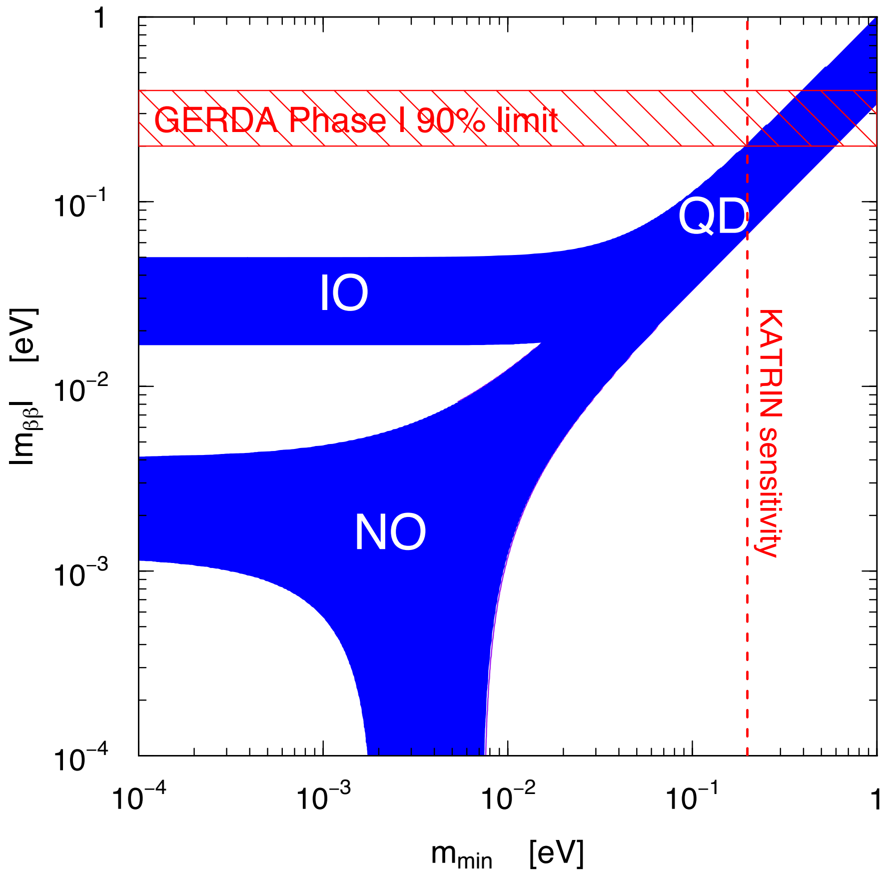
- $(\mathrm{A},\mathrm{Z}) \rightarrow (\mathrm{A},\mathrm{Z}+2) + 2\mathrm{e}^{-} + 2\bar{\nu}_{\mathrm{e}}$
- Allowed in SM
- Measured in several isotopes with $\mathrm{T}_{1/2}^{2\nu}$ in range of $10^{18} - 10^{24}$ yr

<u>neutrinoless double β-decay (0νββ)</u>

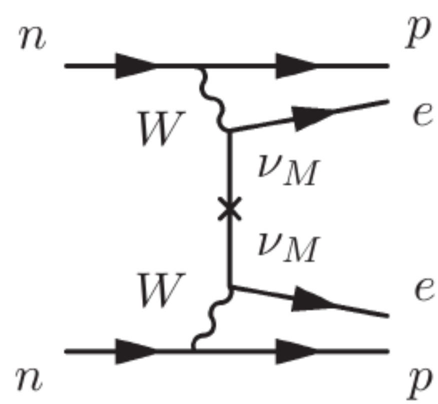
- Hypothetical process
- $(\mathrm{A},\mathrm{Z}) \rightarrow (\mathrm{A},\mathrm{Z}+2) + 2\mathrm{e}^{-}$
- Lepton number violation (ΔL=2)
- Possible mediators: light Majorana neutrino, right-handed weak currents, Majorons, etc → Physics beyond SM



Basics: 0νββ & neutrino properties



Adopted from arXiv:1411.4791 (Bilenky, Giunti)



- Schechter-Valle theorem: Neutrino Majorana mass component if observed
- Assuming light Majorana ν_M exchange dominant channel
- Effective Majorana mass $\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$

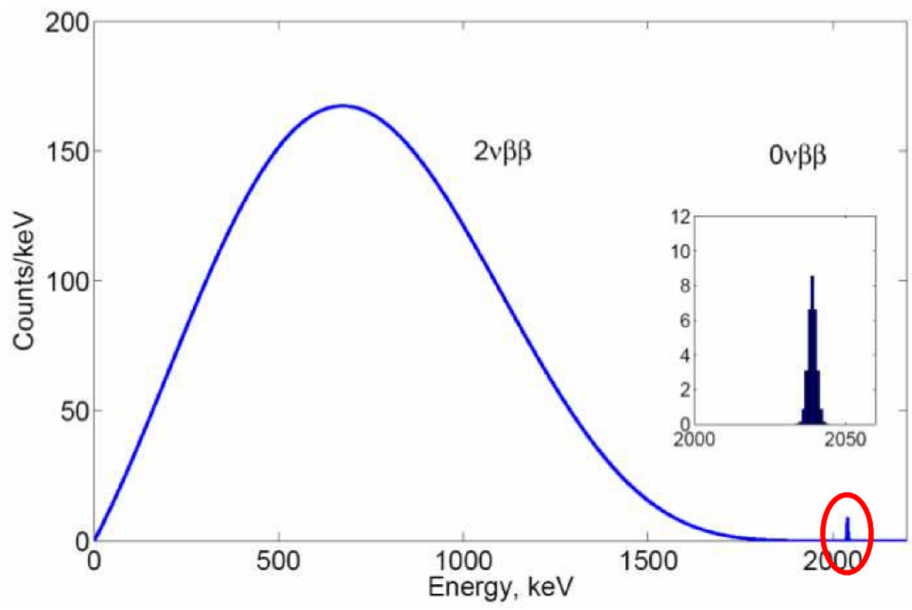
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Phase space factor

Nuclear matrix element

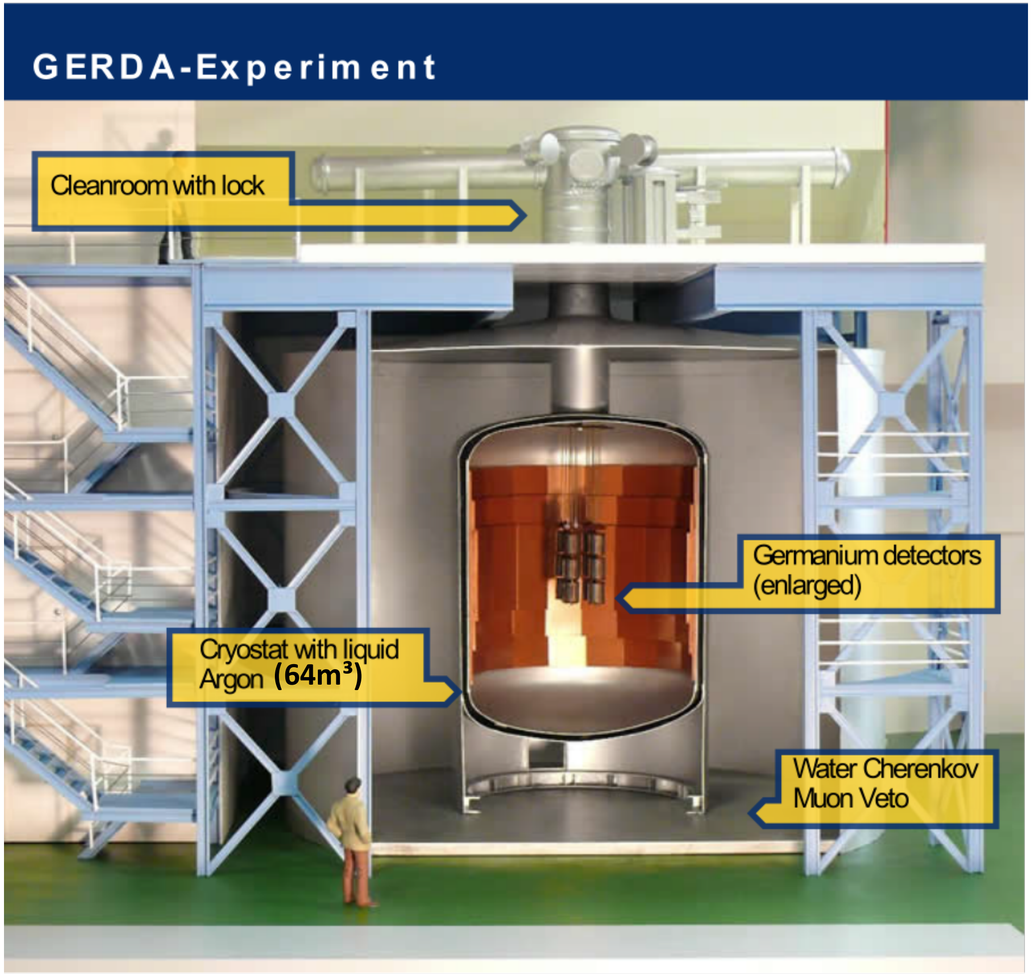
Experimental signature

- Sum-energy spectrum of 2 emitted electrons
- $2\nu\beta\beta$: continuous spectrum due to escaping ν
- $0\nu\beta\beta$: peak at Q-value ($Q_{\beta\beta}$) only with very good energy resolution



DBD sumenergy-spectrum of ^{76}Ge

The GERDA experiment



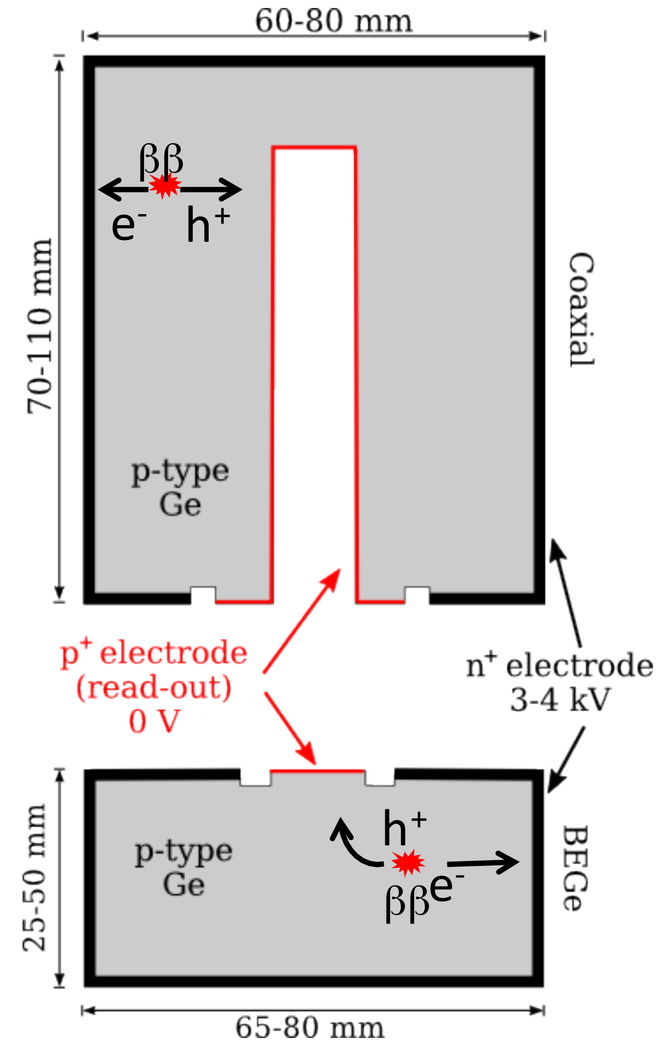
- Bare Ge detectors operated in liquid argon
- Rock, water & LAr as shield against external radiation (muon, neutrons and γ)
- Located at LNGS (3600 m.w.e)

Detectors:

Technische Universität München

- **H**igh **P**urity **Ge**rmanium (HPGe) detectors enriched (87%) in ββ isotope ^{76}Ge
  - Excellent energy resolution (≈ 0.2% FWHM at ROI/ $Q_{\beta\beta}$)
  - Long-term stability
  - Mature technology
  - Radio-purity

- Source = detector
  - High detection effiency
  - Peak at $Q_{\beta\beta}$



Phase I

GERDA Phase I

- Physics data taking Nov '11- May '13
- ^{enr}Ge mass for physics analysis: 17.6 kg
- Total exposure: 21.6 kg·yr
- Duty cycle: 88%
- $\Delta E@Q_{\beta\beta}$: **4.1 keV** (coax); **2.8keV** (BEGe) advanced filtering (Eur. J. Phys. C 75 (2015) 255))
- Background index after pulse shape discrimination (PSD) cut:

Coax: 10^{-2} cts/(keV·kg·yr)

BEGe: 5 x 10^{-3} cts/(keV·kg·yr)

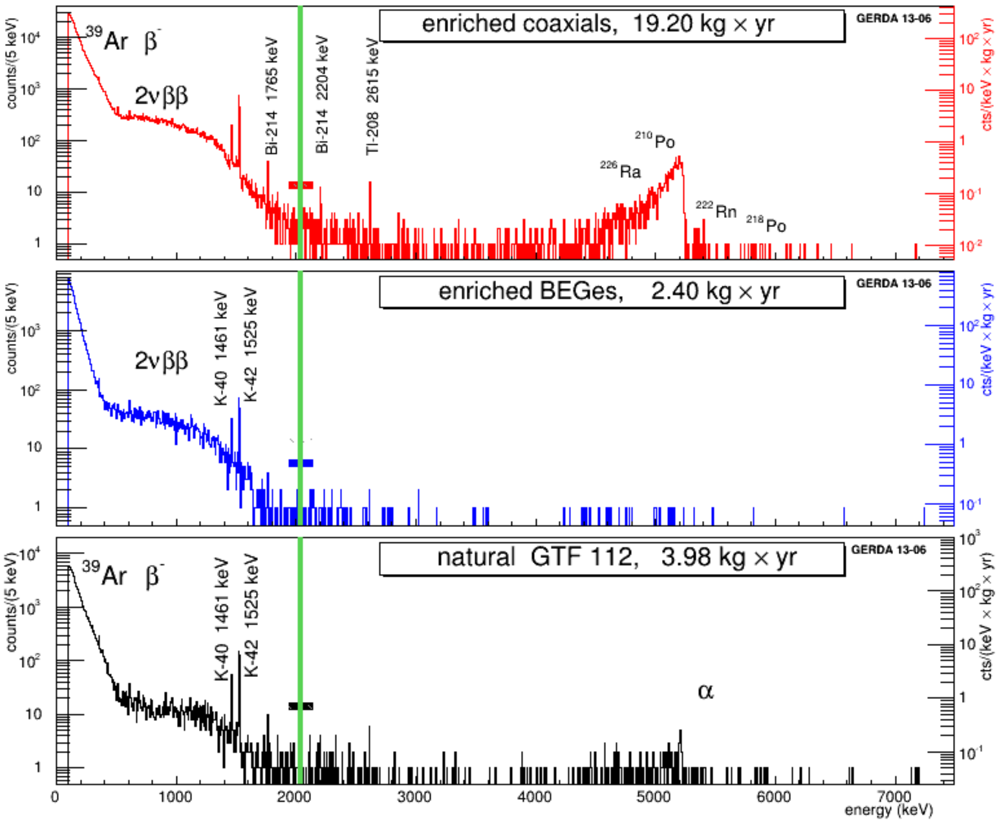
8 ^{enr}Ge +1 ^{nat}Ge coaxial detectors

5 ^{enr}Ge BEGe detectors

Cu shrouds to prevent ^{42}K ion migration to detectors

0νββ half-life limit analysis

Bkg spectra before pulse shape discrimination



Blind analysis:

Expected counts in $Q_{\beta\beta} \pm 5$keV after PSD:

2±0.3

Observed:

3cts

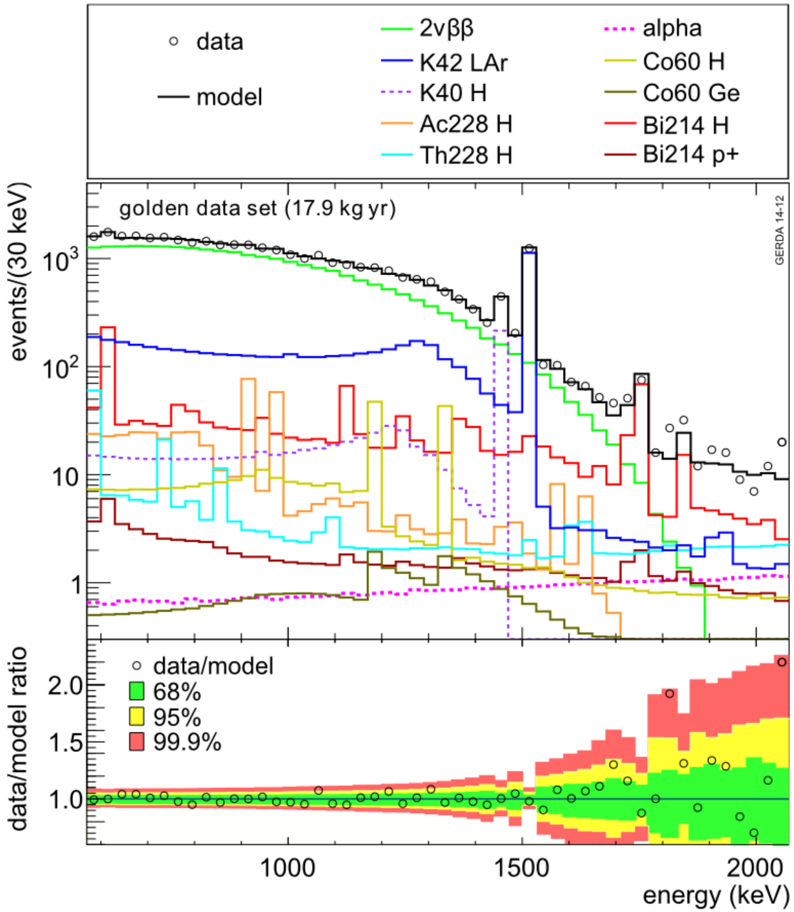
Best fit value $\mathbf{N_{0\nu\beta\beta}=0}$

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

$$m_{\beta\beta} < 0.2\text{-}0.4\ \text{eV}$$

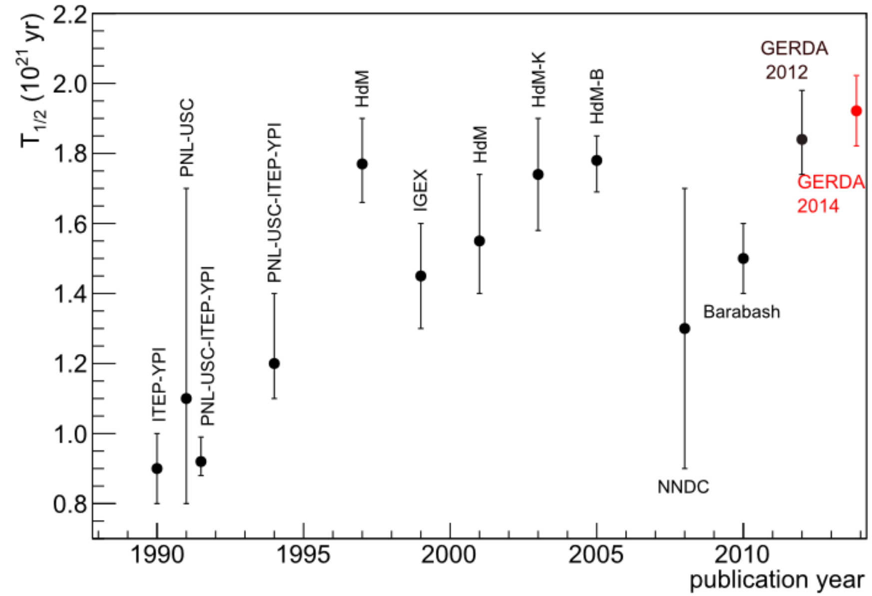
PRL 111, 122503 (2013)

2νββ half-life analysis



$$T_{1/2}^{2\nu} = (1.926 \pm 0.094) \cdot 10^{21}\ \mathrm{yr}$$

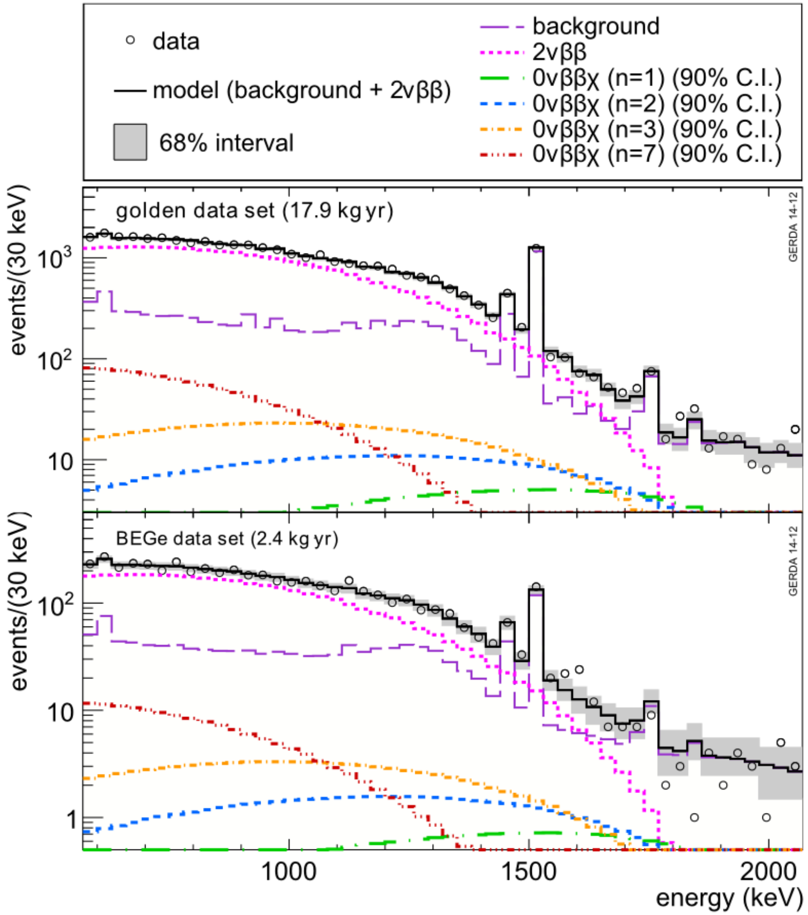
Precision better than 5 %!



Adopted from: J. Phys. G: Nucl. Part. Phys.40(2013) 035110

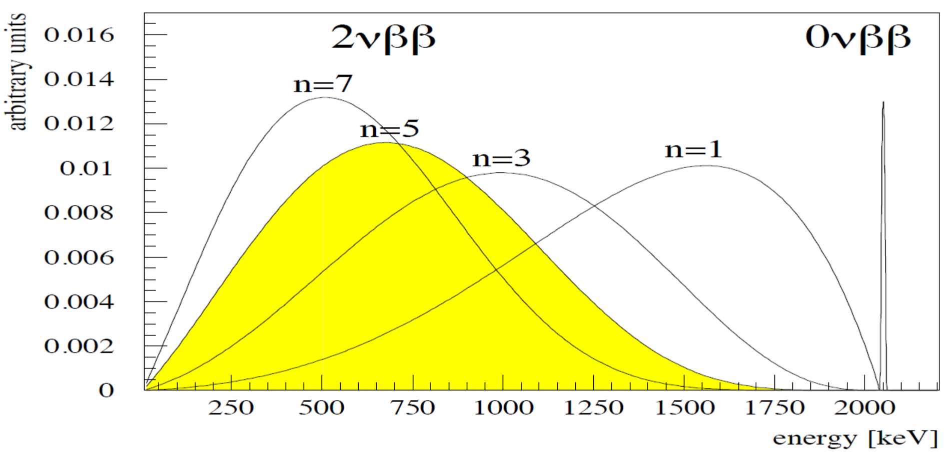
Eur. Phys. J. C 75 (2015) 416

0νββχ (Majoron) half-life limit analysis



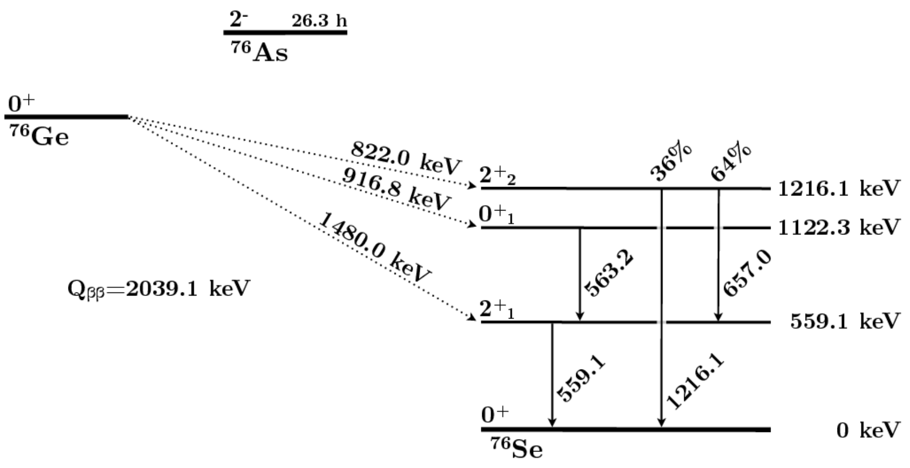
Eur. Phys. J. C 75 (2015) 416

- 0νββχ hypothetical beyond SM process possible with different spectral indices n depending on model
- $\mathbf{T_{1/2}^{0\nu\chi} > (0.3 - 4.2) \cdot 10^{23}}$ **yr** for diff. n
- Most stringent limits for ^{76}Ge yet



2νββ decay of ^{76}Ge into excited states

- Search for 2νββ decay into various excited states of ^{76}Se
- Signature: 2-detector coincidence (strong background suppression)
  - Det1: ββ energy
  - Det2: de-excitation γ full energy
- Benchmark for NME calculation methods



90 % C.L. limits:

- $T_{1/2}^{2\nu}(0_1^+) > 3.7 \cdot 10^{23}\mathrm{yr}$
- $T_{1/2}^{2\nu}(2_2^+) > 2.3 \cdot 10^{23}\mathrm{yr}$
- $T_{1/2}^{2\nu}(2_1^+) > 1.6 \cdot 10^{23}\mathrm{yr}$

→ Exludes many older NME calculations

Limits improved two orders of magnitude

J. Phys. G 42 (2015) 115201

IOP Highlight of the year 2015

Phase II

GERDA Phase II: Increase of sensitivity

Sensitivity for limit of $T_{1/2}$ of neutrinoless double beta decay

with bkg

$$T_{1/2} \propto \epsilon a \sqrt{\frac{Mt}{BI\ \Delta E}}$$

ε: detection effiency
a: abundance of ββ isotope
M: mass [kg]
t: exposure time [yr]
BI: background index [$\frac{\text{counts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}$]
Δ E: energy resolution at ROI

GERDA Phase II: Increase of sensitivity

Sensitivity for limit of $T_{1/2}$ of neutrinoless double beta decay

with bkg

$$T_{1/2} \propto \epsilon a \sqrt{\frac{Mt}{BI\ \Delta E}}$$

without bkg

$$T_{1/2} \propto \epsilon a\ Mt$$

ε: detection effiency
a: abundance of ββ isotope
M: mass [kg]
t: exposure time [yr]
BI: background index [$\frac{\text{counts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}$]
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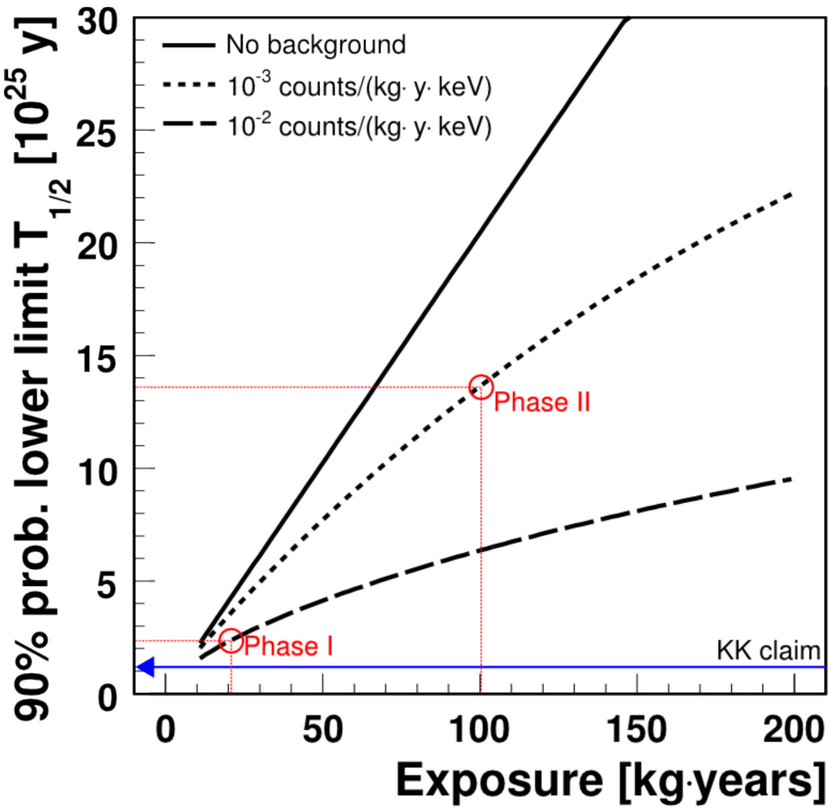

GERDA Phase II: Increase of sensitivity

Sensitivity for limit of $T_{1/2}$ of neutrinoless double beta decay

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ε: detection effiency
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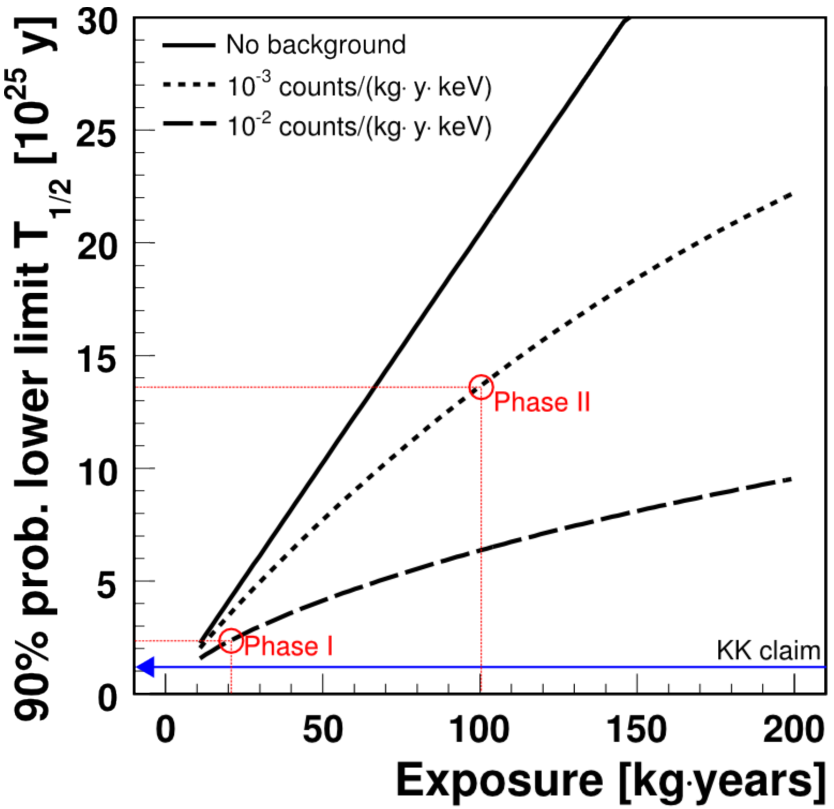
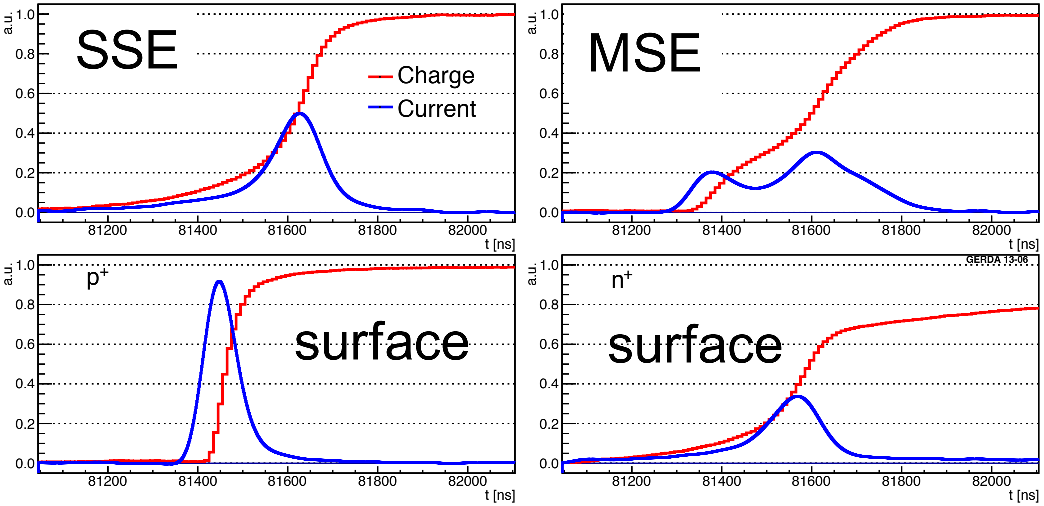


- GERDA Phase II goal: 10^{26} yr half-life sensitivity within 3 yr of data taking ($m_{\beta\beta}$<0.1 eV)
- Within three years background free (expect ≲1 cts in ROI)

GERDA Phase II: Improvements

- New custom-made detectors (BEGe) of ~20 kg total mass (15kg -> 35kg enriched Ge)
- Improvements:
  - Energy resolution ~3 - 4 keV FWHM @ $Q_{\beta\beta}$
  - Pulse shape discrimination signal (bulk single site) vs bkg (surface & multiple site)



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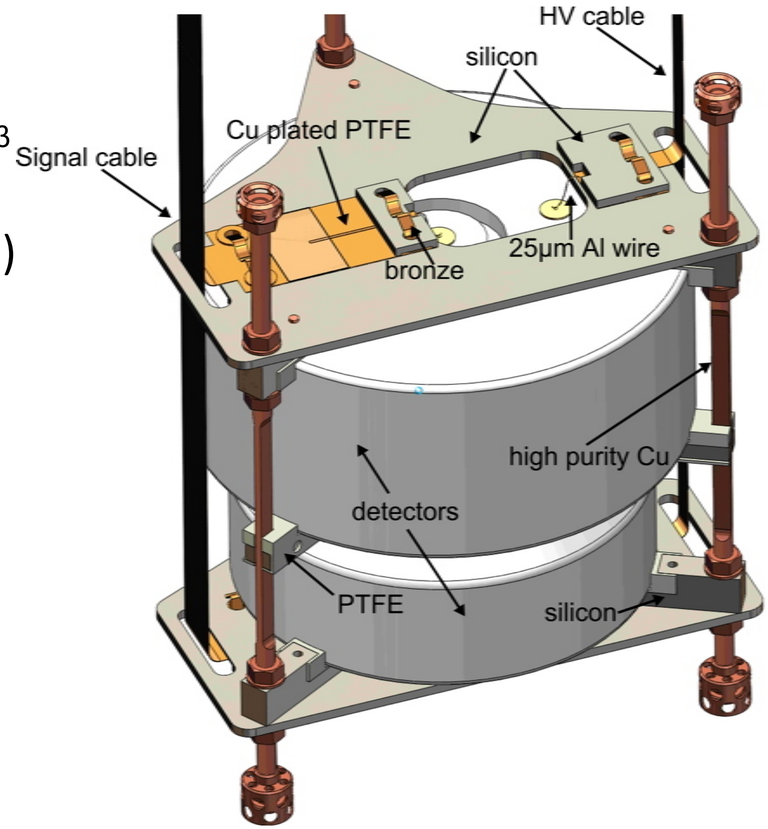
- New detector holder & contacting (bonded)



GERDA Phase II: Improvements

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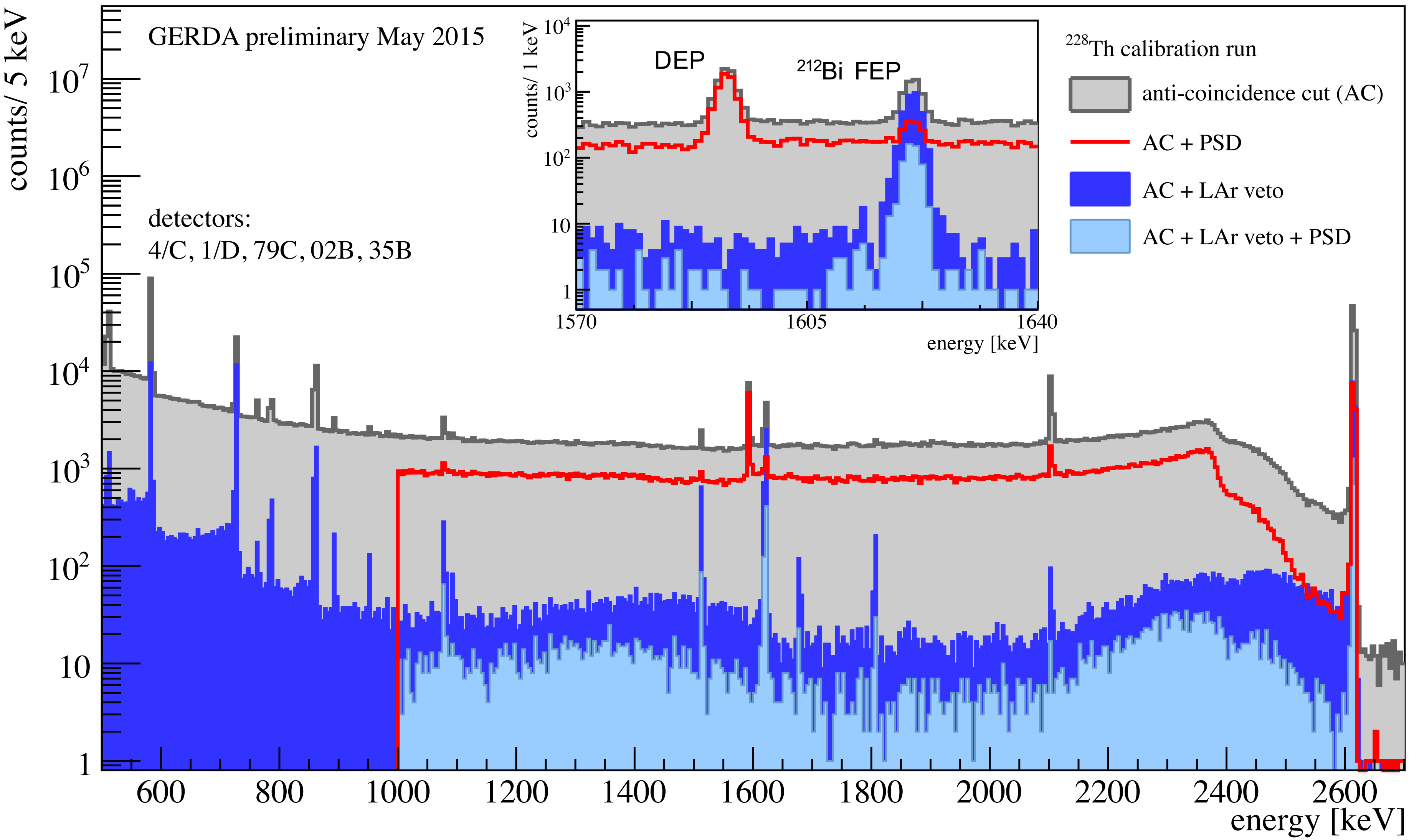
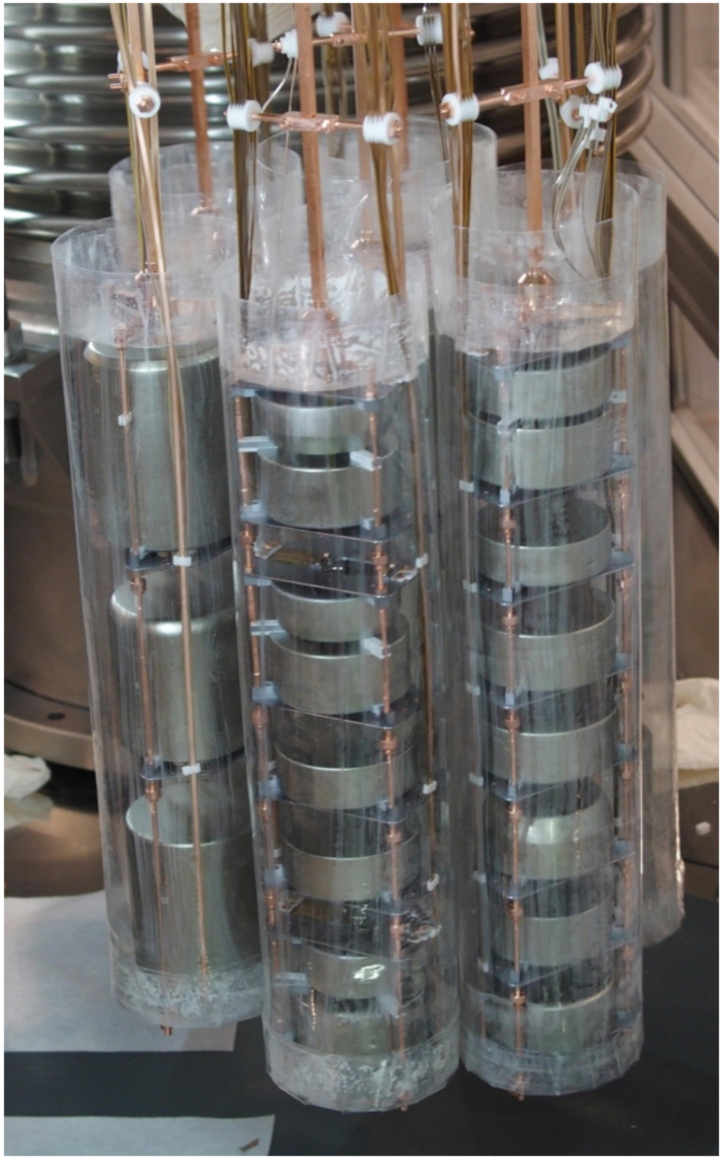
- Improvements:
  - Energy resolution ~3 - 4 keV FWHM @ $Q_{\beta\beta}$
  - Pulse shape discrimination signal (bulk single site) vs bkg (surface & multiple site)
- New detector holder & contacting (bonded)
- Additional active reduction of background
  - Instrumented liquid argon volume (LAr scintillation light veto)
  - Higher number & dense packing of detectors: better anti-coincidence cut

PSD and LAr veto on ^{228}Th spectrum



Phase II data taking – Performance

- Status:
  - Phase II started Dec 20, 2015
  - 7 strings – 40 detectors
    - 30 enr. BEGe (20 kg)
    - 7 enr. Coax (15 kg)
    - 3 nat. coax (7 kg)



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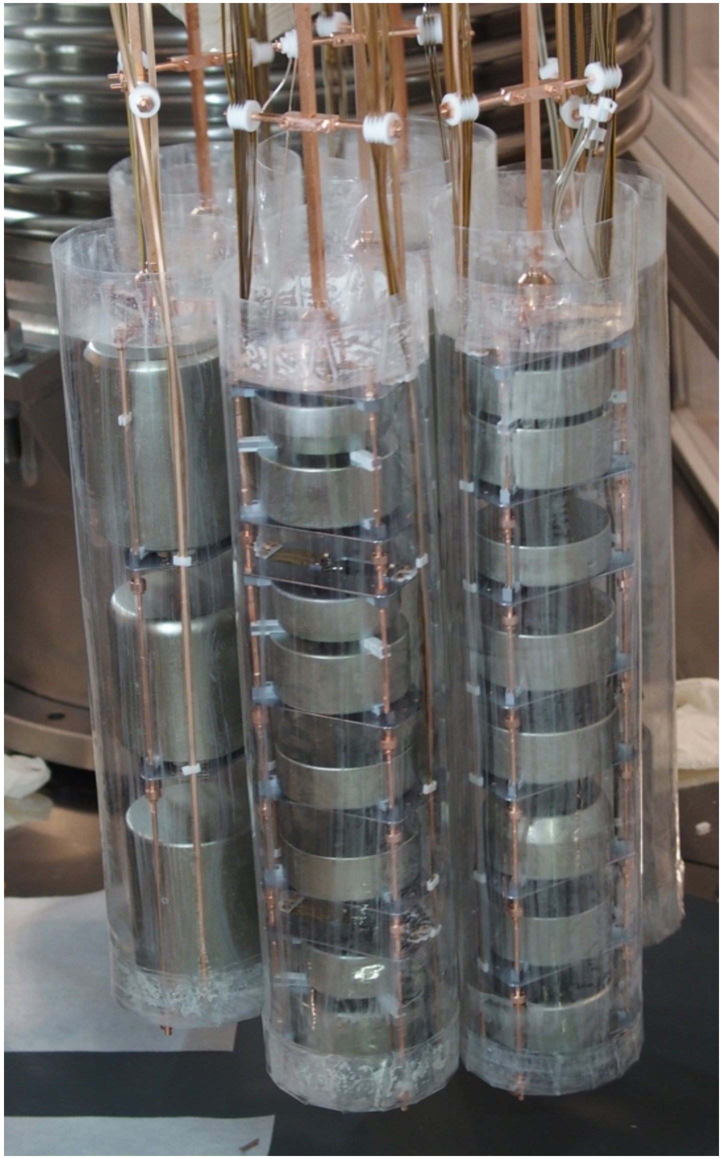
  - Phase II started Dec 20, 2015
  - 7 strings – 40 detectors
    - 30 enr. BEGe (20 kg)
    - 7 enr. Coax (15 kg)
    - 3 nat. coax (7 kg)
- Energy resolution:

FWHM @ 2.6 MeV

  - BEGe: ~3.4 keV
  - Coax : ~4.0 keV

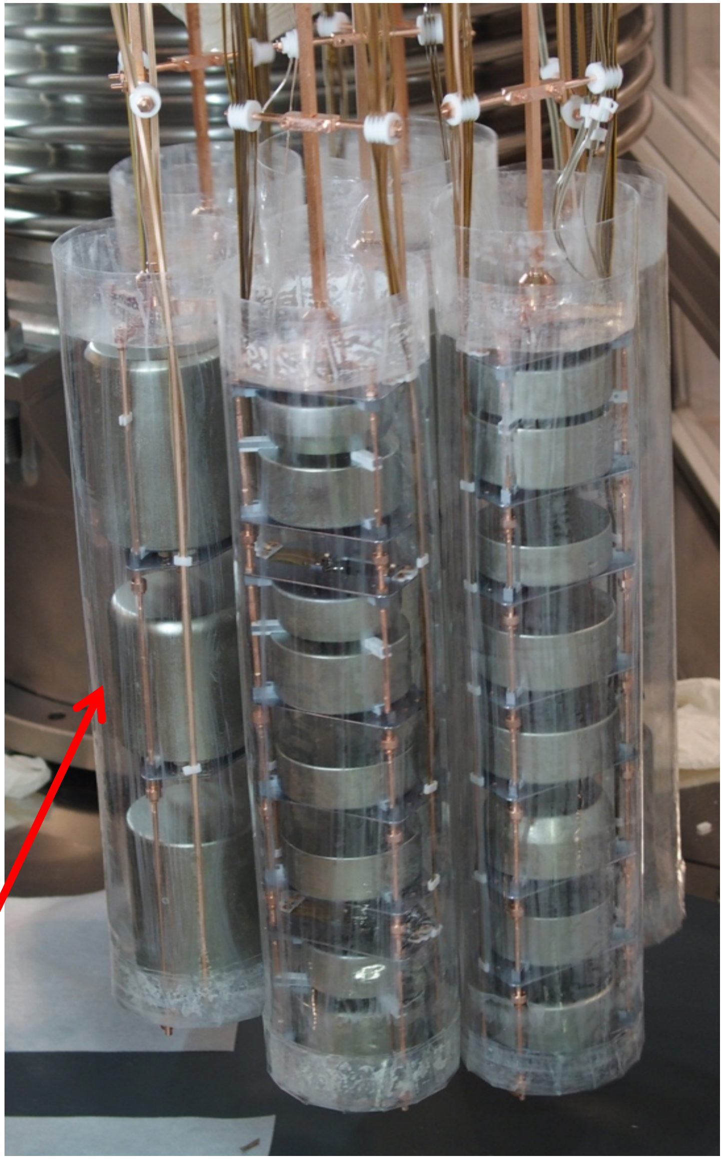


Phase II data taking – Performance

- Status:
  - Phase II started Dec 20, 2015
  - 7 strings – 40 detectors
    - 30 enr. BEGe (20 kg)
    - 7 enr. Coax (16 kg)
    - 3 nat. coax (8 kg)
- Energy resolution:

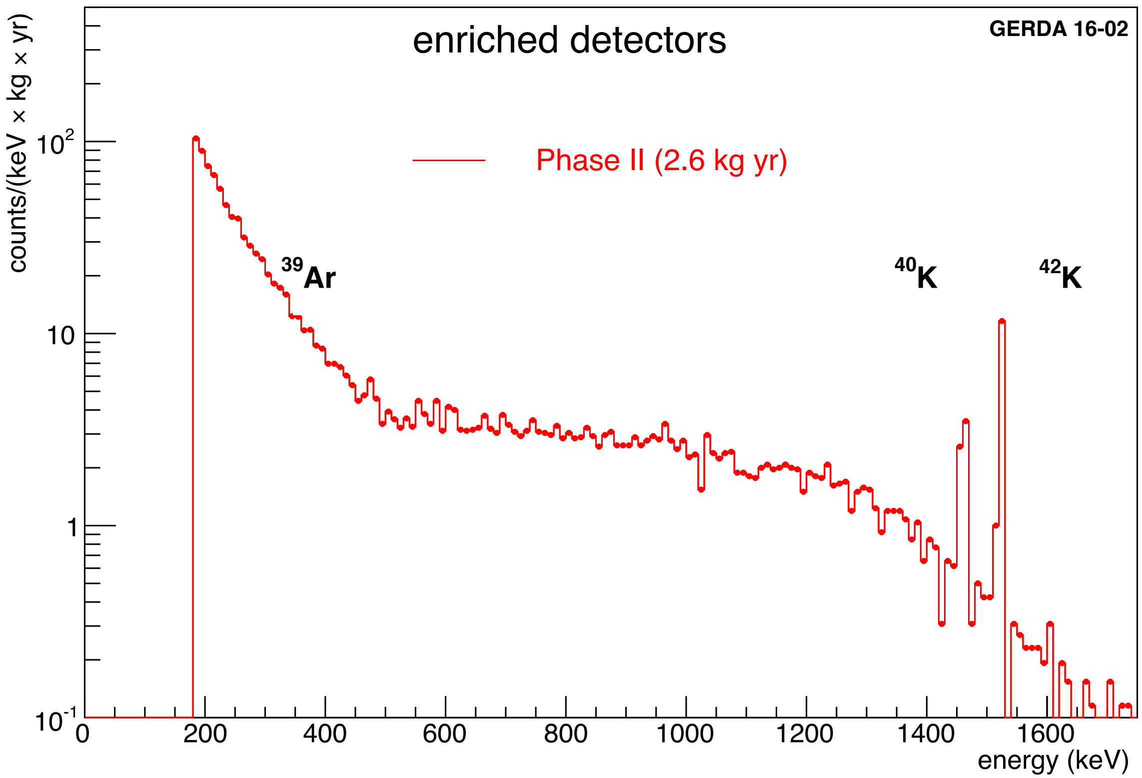
FWHM @ 2.6 MeV

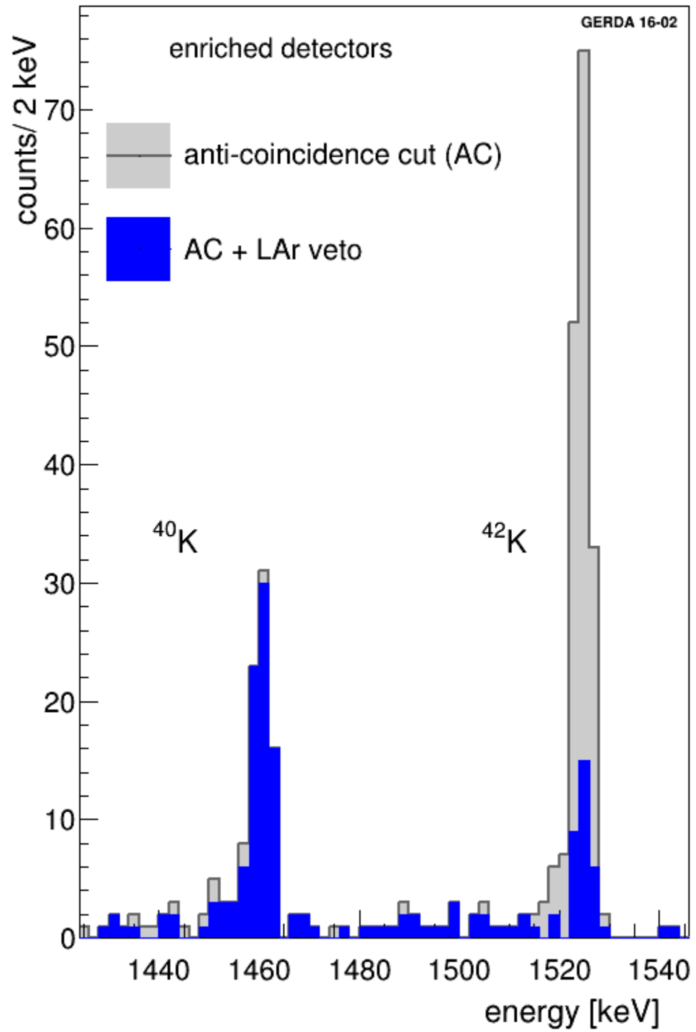
  - BEGe: ~3.4 keV
  - Coax : ~4.0 keV



Plastic shrouds to prevent ^{42}K ion migration to detectors

First background spectrum until 1.7 MeV

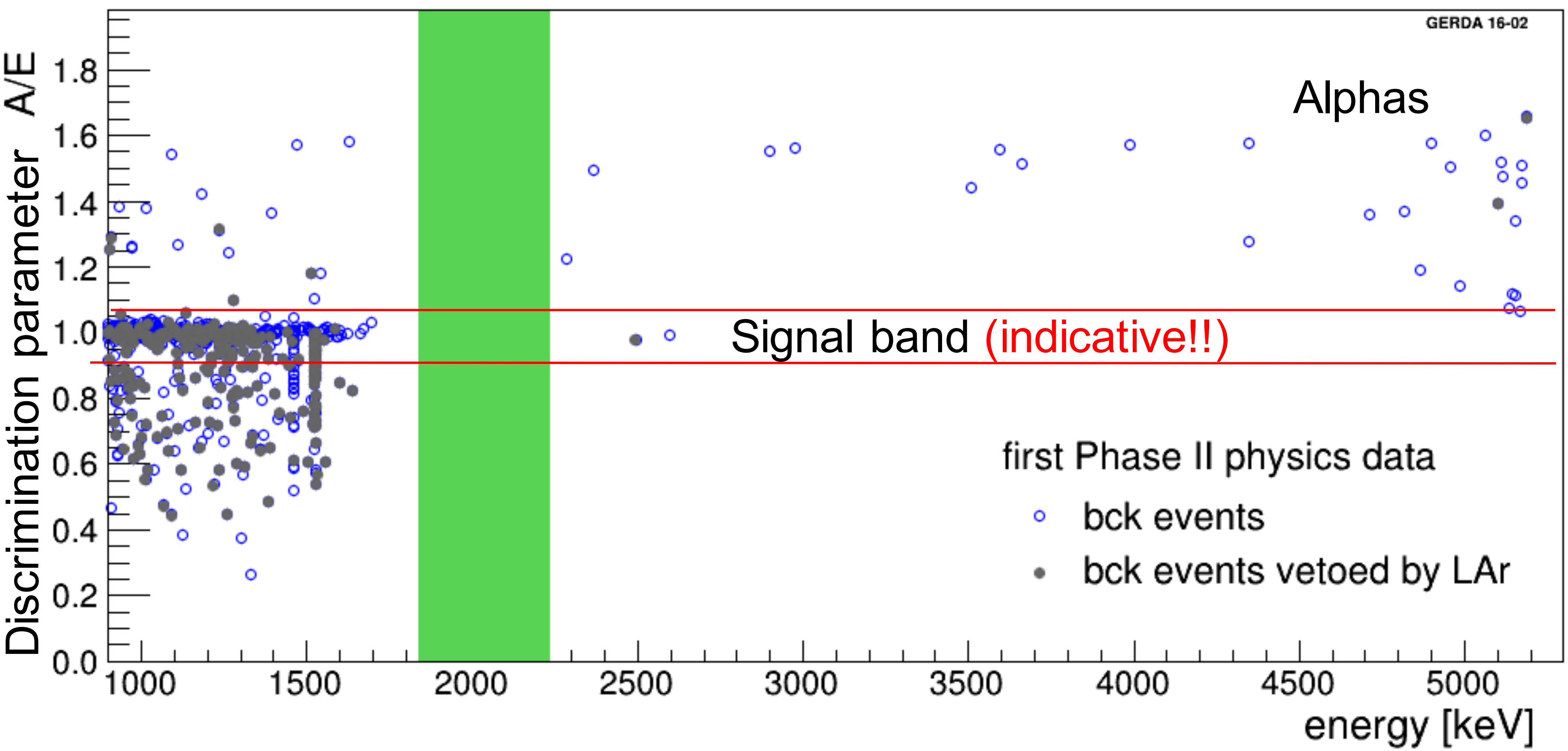




Survival prob.

- ^{40}K (98 ±4) % (single γ detected in Ge)
- ^{42}K (18 ±4) % (β seen by LAr veto & γ det. in Ge)

BEGe Pulse Shape Discrimination



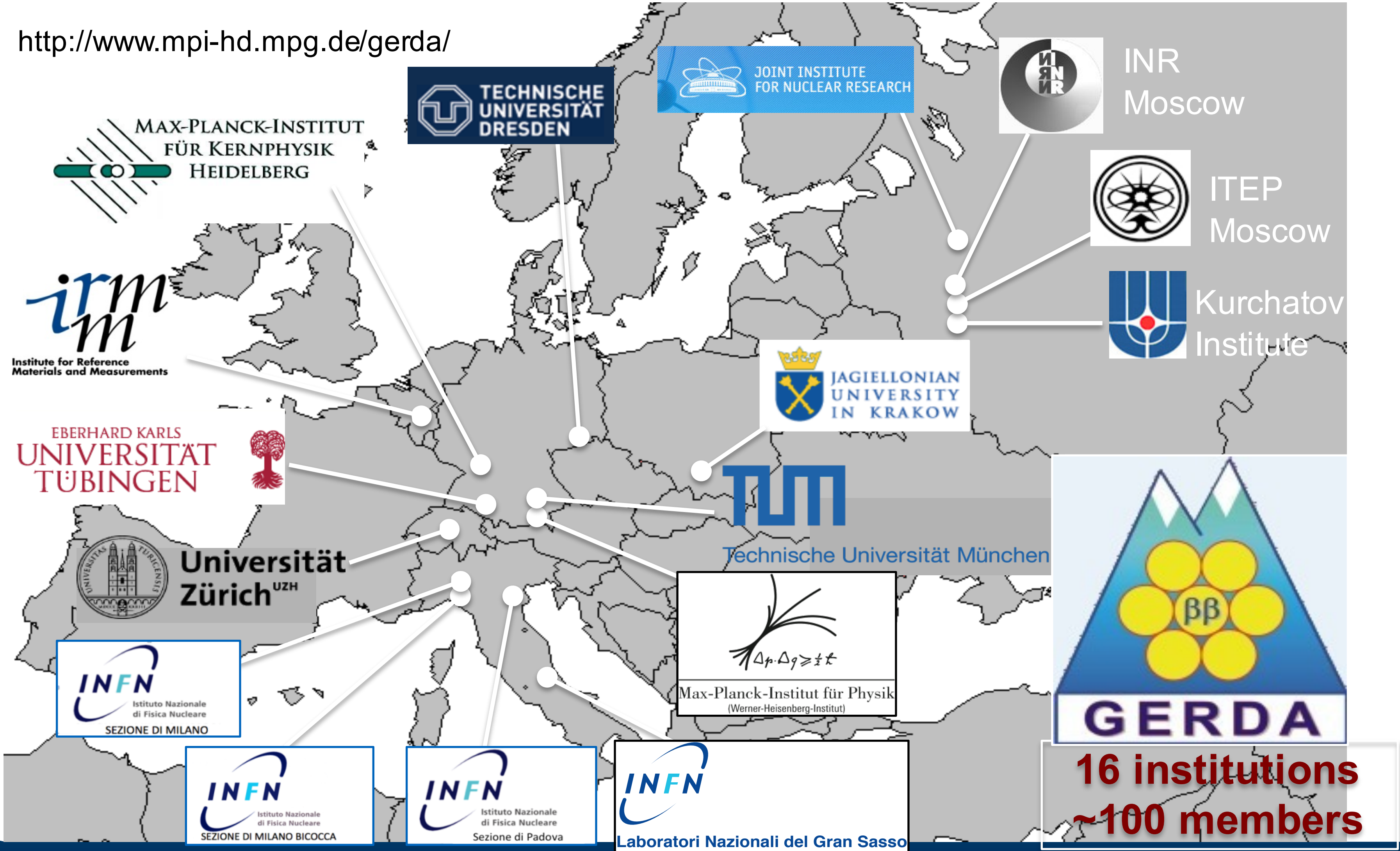
Summary and outlook

- Phase I successfully completed
  - Additional analyses carried out (2νββ & 0νββχ, 2νββ excited states)
- Phase II goals:
  - Increase half life sensitivity to 10^{26} yr
    - Double active mass compared to Phase I
    - Reduce background to 10^{-3} cts/(keV kg yr)
      - Better PSD, liquid argon veto, new holder structure
- Present status: Phase II running!
  - Data taking since December 2015
  - 40 HPGe detectors (working) with ~35 kg of ^{enr}Ge (3 – 4 keV FWHM @ 2.6MeV)
  - LAr veto operational
  - ~2.6 kg·yr exposure until Feb 2016 (now more)
  - No background surprises
- Stay tuned, data release soon

Thank you for your attention

GERDA: the Collaboration

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



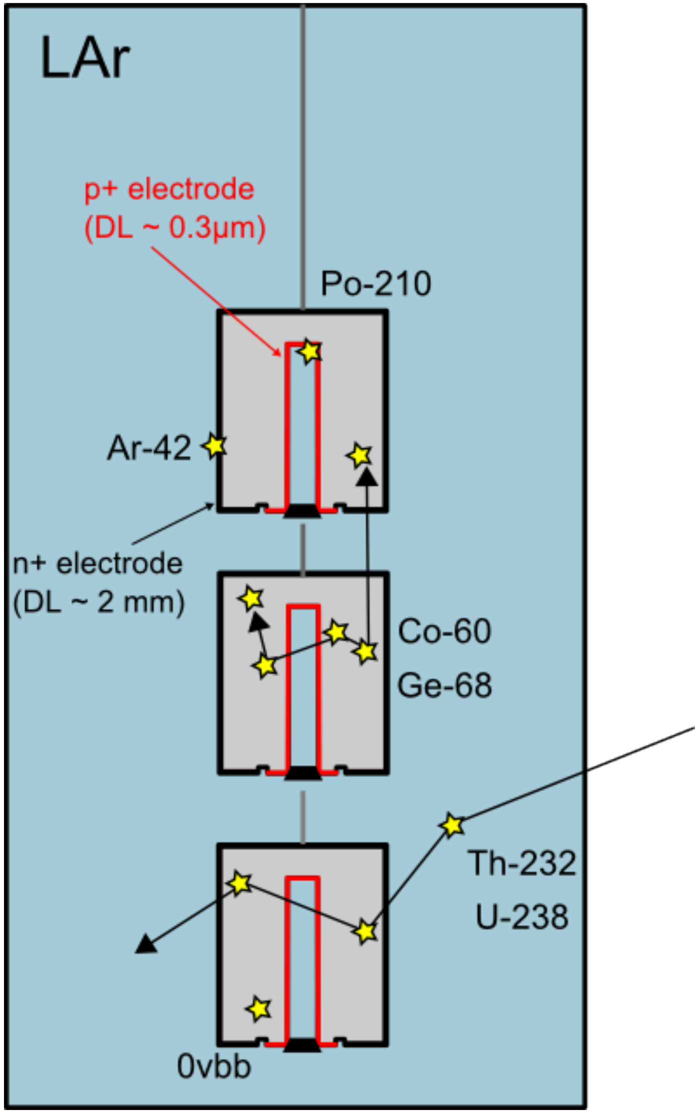
Bonus slides

Background events in GERDA

- Natural radioactivity (^{232}Th & ^{238}U chains)
  - γ's (e.g. ^{208}Tl & ^{214}Bi)
  - α's (e.g. ^{210}Po from surfaces, ^{222}Rn in LAr)
- Cosmogenic activated isotopes in Ge(^{68}Ge, ^{60}Co)
- Long lived cosmogenic isotopes in LAr (^{39}Ar, ^{42}Ar)

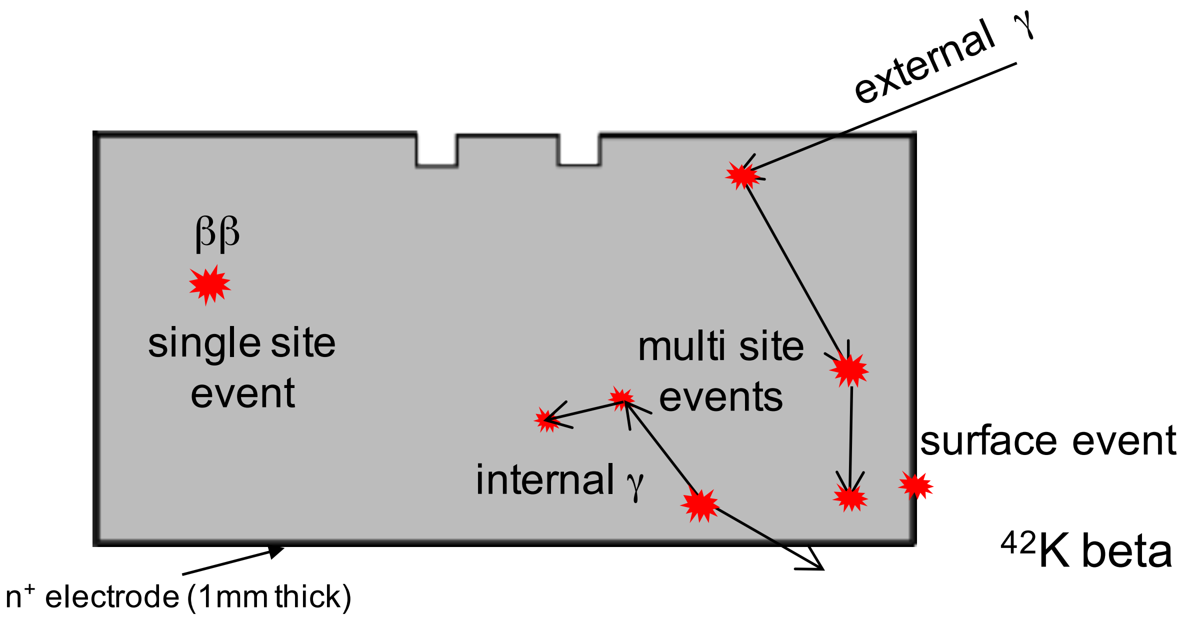
Supression strategies:

- Detector anti-coincidence (AC)
- Pulse-shape descrimination (PSD)
- Liquid argon scintillation light veto
- Time-coincidence (Bi-Po)



Pulse shapes discrimination (PSD) in BEGe detectors

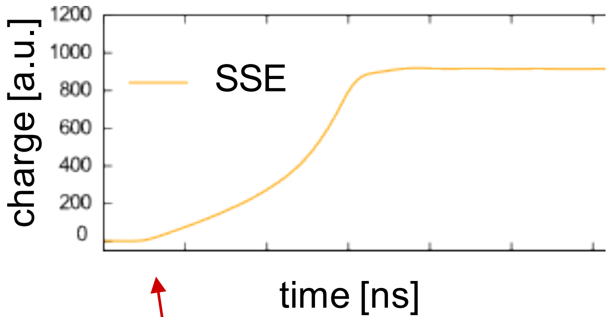
- Broad Energy Germanium Detectors (BEGe)
- Small read-out electrode -> low noise
- PSD enhanced by characteristic electric field in detector

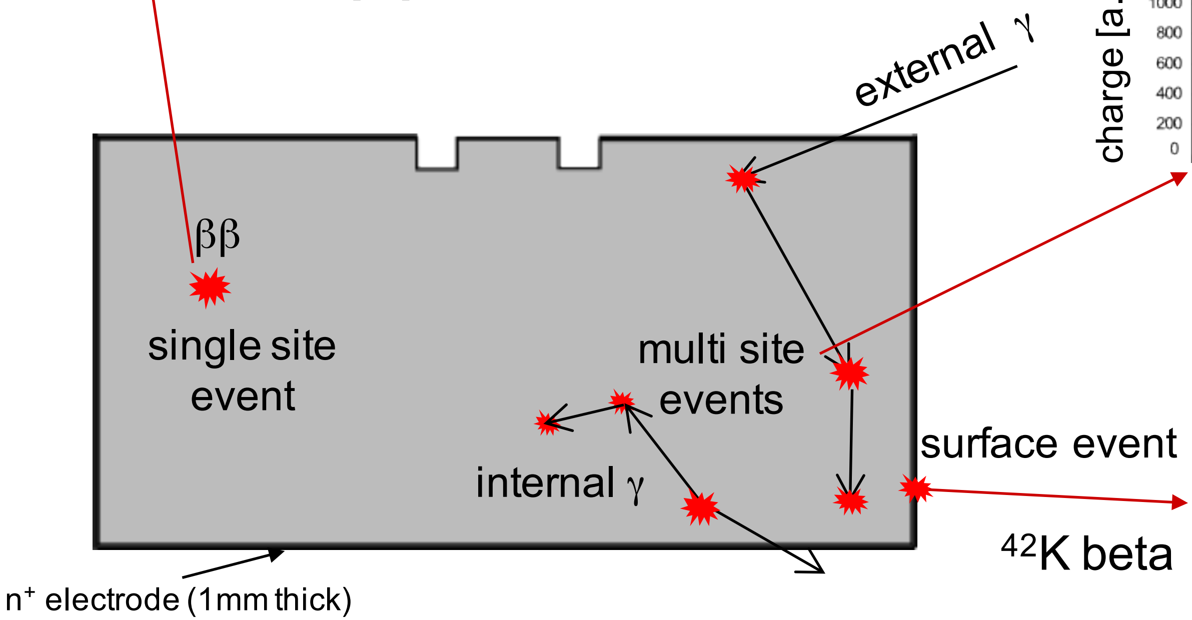


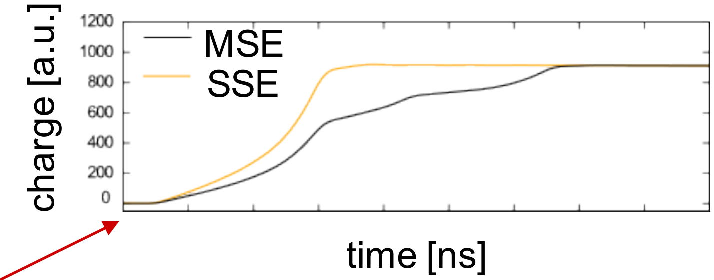
Pulse shapes discrimination (PSD) in BEGe detectors

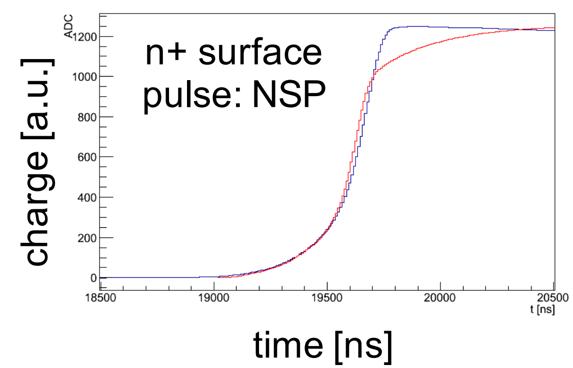
JINST, 4 (2009) P10007, JINST, 6 (2011) P03005,
Eur.Phys.J C73 (2013) 2583

Signal acceptance: 90%
Bkg acc. @$Q_{\beta\beta}$: <20% (Phase I)

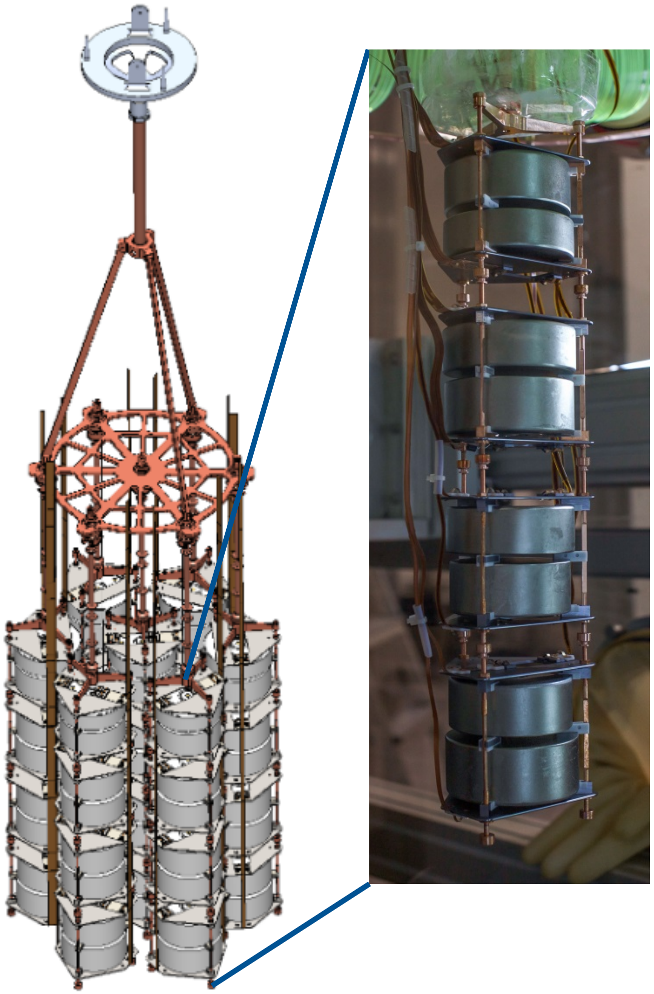






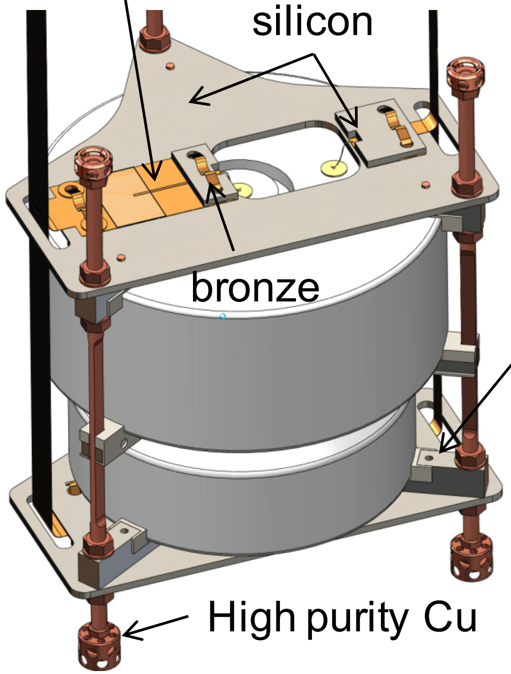


Phase II detector array & assembly



- 7 strings of detectors
- 15 pairs of ^{enr}Ge BEGe detectors mounted back-to-back
- 10 semi-coaxial detectors(7 ^{enr}Ge & 3 ^{nat}Ge)

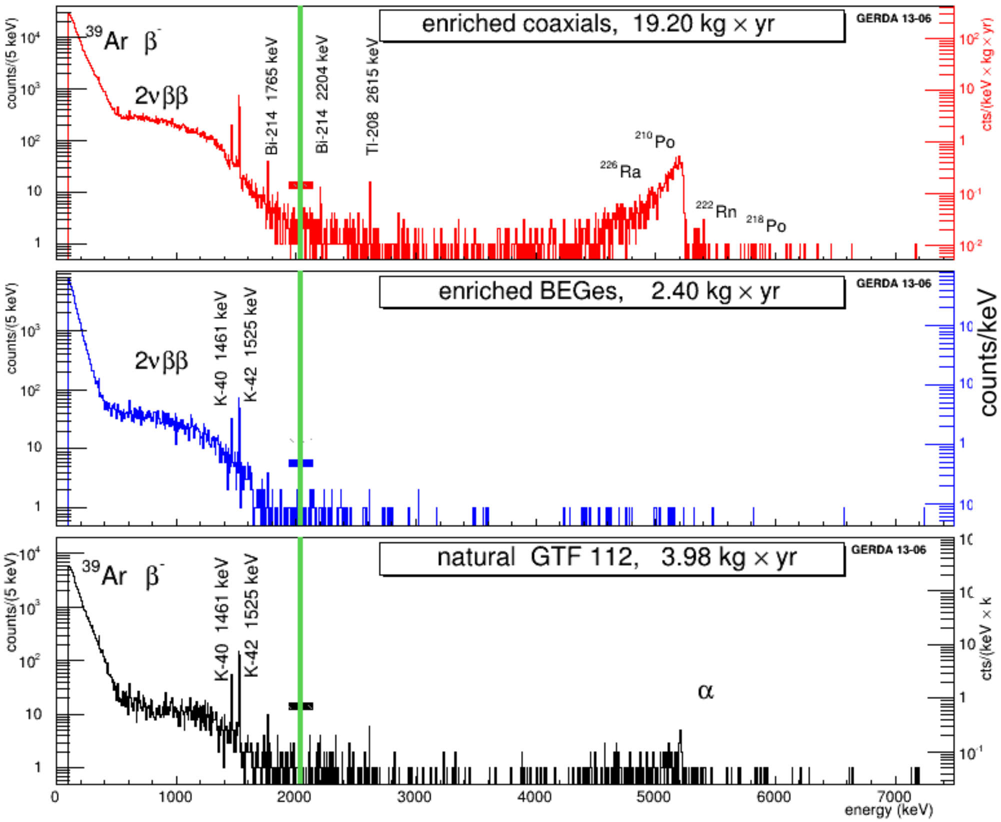
Phase II detector array & assembly



- 7 strings of detectors
- 15 pairs of ^{enr}Ge BEGe detectors mounted back-to-back
- 10 semi-coaxial detectors(7 ^{enr}Ge & 3 ^{nat}Ge)
- Reduction of material in vicinity of detectors
  - Detector mount & Front-end electronics
- ~1.5 reduction copper & PTFE mass per kg detector mass
- Replace as much copper as possible with intrinsically pure mono crystalline silicon

0νββ half-life limit analysis

Bkg spectra before PSD

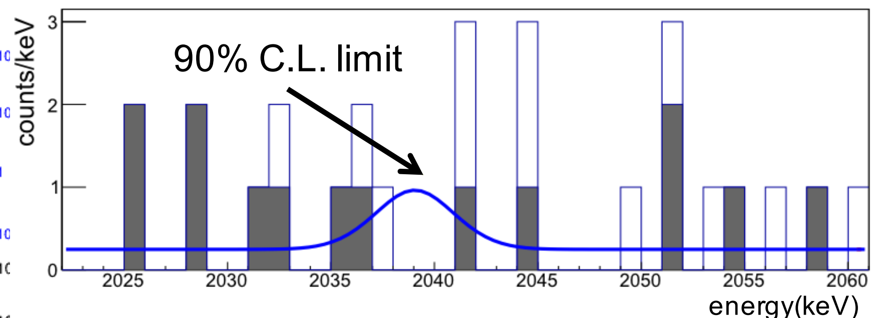


Blind analysis:

Expected counts in $Q_{\beta\beta}\pm$5keV after PSD: 2$\pm$0.3

Observed: 3cts

Best fit value $N_{0\nu\beta\beta}$=0



Open histogram before PSD; filled histogram after PSD

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

$$m_{\beta\beta}<0.2\text{-}0.4\ \text{eV}$$

PRL 111, 122503 (2013)

LAr veto

- Energy deposition by background radiation

  → Characterisitic scintillation UV light @ 127 nm

  → Anti-coincidence veto

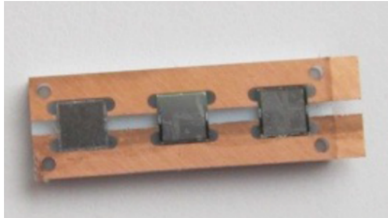
Requirements for instrumentation:

- Low induced background
- Deployment via GERDA lock
- Large instrumented volume

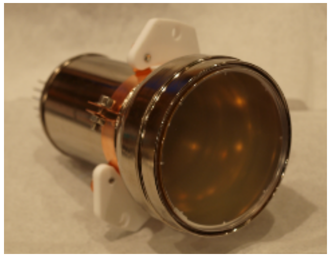
Design

- Top/bottom plate: low bkg PMTs
- Optical fiber curtain coated with wavelength shifter TPB (127nm-> 430nm)
- „In-die" SiPMs coupled to fibers

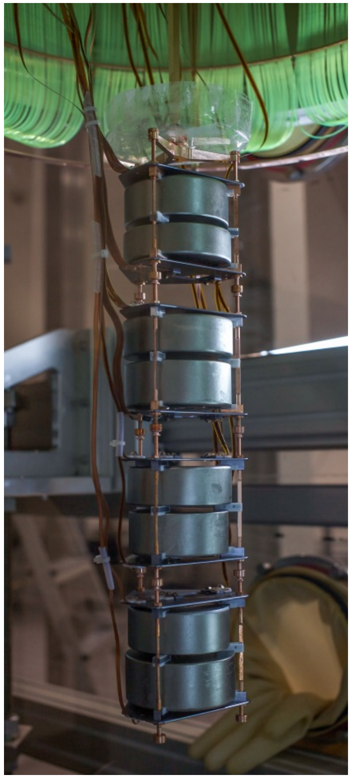
SiPM array

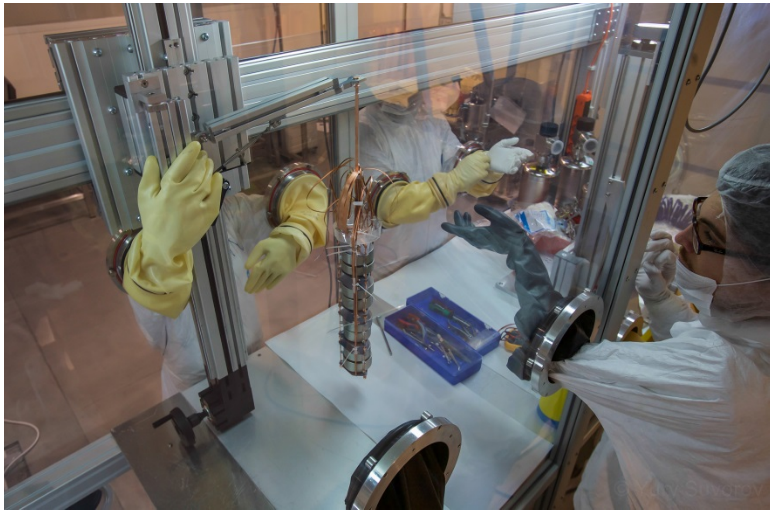


PMT



Phase II commissioning

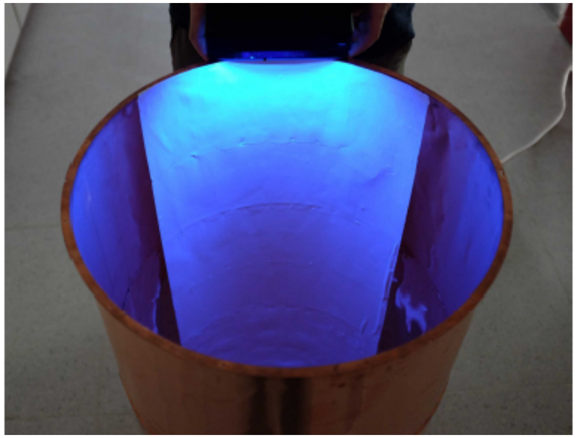


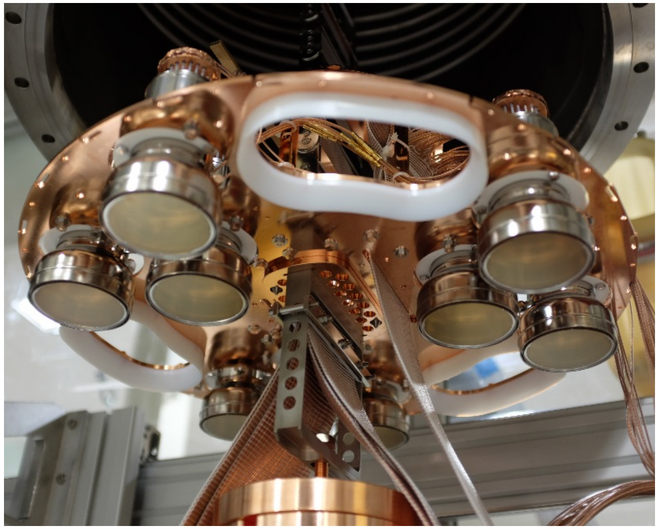


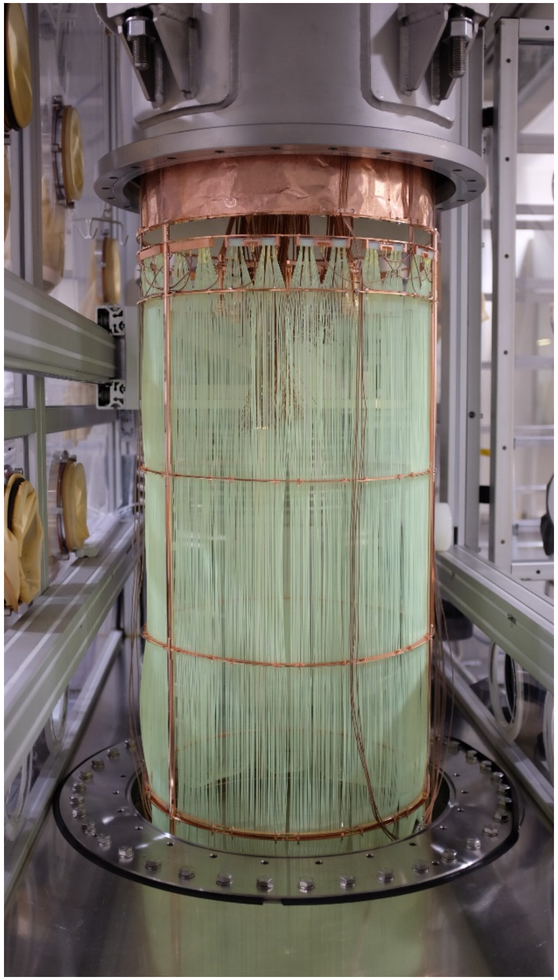
- First integration of full string
- 4 BEGe from ^{enr}Ge
- 4 BEGe from ^{dep}Ge
- Preliminary energy resolution ΔE (FWHM)@ 2.6 MeV: ≈3keV

LAr veto

Technische Universität München







The Phase II detector mount - contacting

- Ultrasonic wire bonding identified as a low-mass, reliable electrical contact between detector, amplifying electronics and HV supply
- First time large volume Germanium diode detectors contacted with wire bonding
- Deposition of Al thin film on germanium diodes to allow bonding at manufacturer's site
- All 30 BEGe's from enriched Ge modified