Status of the GERDA experiment

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INFN & Univ. of Padova

Les Rencontres de Physique de la Valle D'Aoste
La Thuile 2016, March 7 – 12, 2016

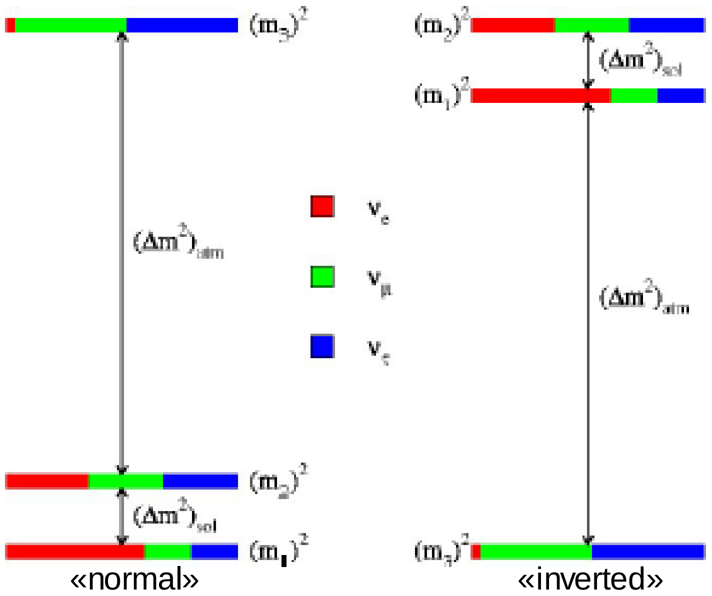
OUTLINE

- how we can test neutrino nature:
  - $\beta\beta$ decay types, signal
- the GERDA experiment:
  - collaboration, site, experimental set-up
- Phase-I results:
  - background model
  - $2\nu\beta\beta$ decay
  - $0\nu\beta\beta$ decay signal
- Phase-II status:
  - ^{76}Ge detectors deploiment
  - LAr veto
  - first commissioning results
- summary

Neutrino physics

- $2\nu\beta\beta$ is a 2nd order weak decay
- is there a Lepton number violation?
- extension to the Standard Model?
- are Majorana ($\nu \equiv \overline{\nu}$) or Dirac particles?
- is the mass hierarchy «normal» or «inverted»?
- which are their absolute masses?

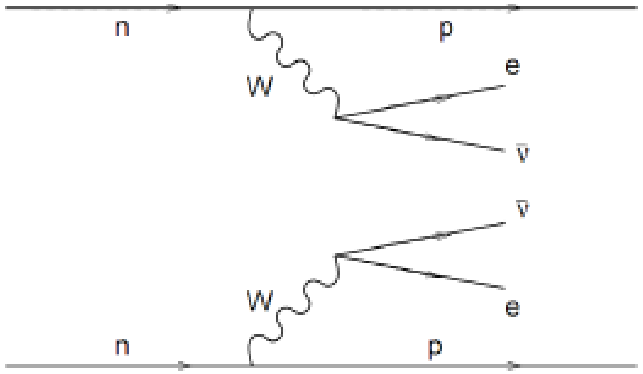
mass hierarchy



ββ decay types

$2\nu\beta\beta$

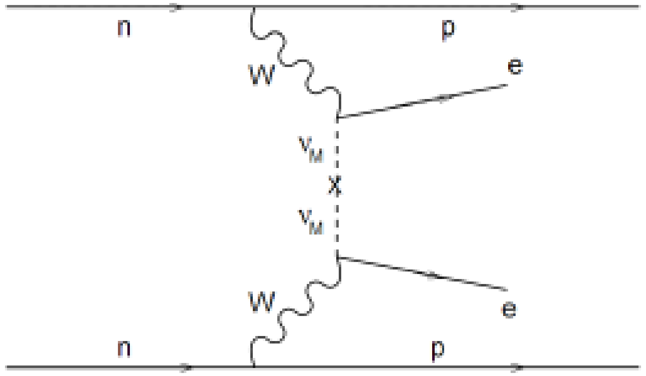
$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\overline{\nu_e}$$



- ΔL = 0
- allowed in the SM
- $T_{1/2} \sim 10^{(18\div24)}$ yr

$0\nu\beta\beta$

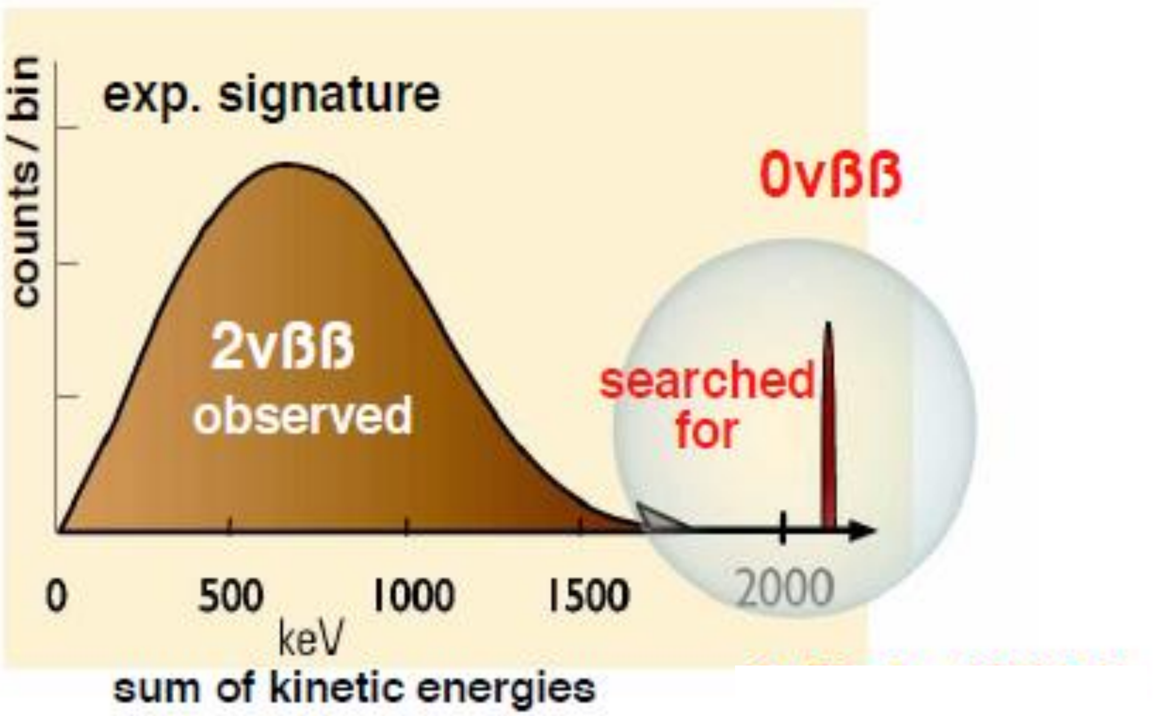
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$



- ΔL = 2
- not allowed in the SM
- $T_{1/2} > 10^{25}$ yr

$0\nu\beta\beta$ decay signal

GERDA (Germanium Detector Array)
search for $0\nu\beta\beta$ decay of ^{76}Ge



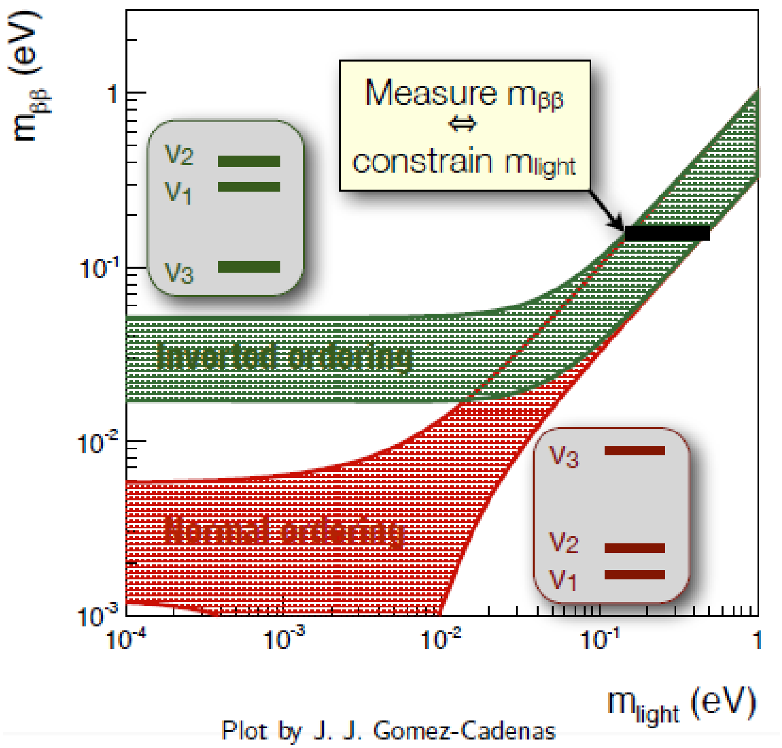
- monochromatic line at ^{76}Ge $Q_{\beta\beta} = 2039\ keV$
- extremelly low background required
- derive the half-life of the process
  $T_{1/2} > 10^{25}$ yr, *i.e.* << 0.1 event/(keV kg yr)

$$1/T_{1/2} = G(Q,Z)\ |M_{nucl}|^2 <m_{ee}>^2$$

0νββ decay rate — Phase space factor — Matrix element — Effective Majorana neutrino mass

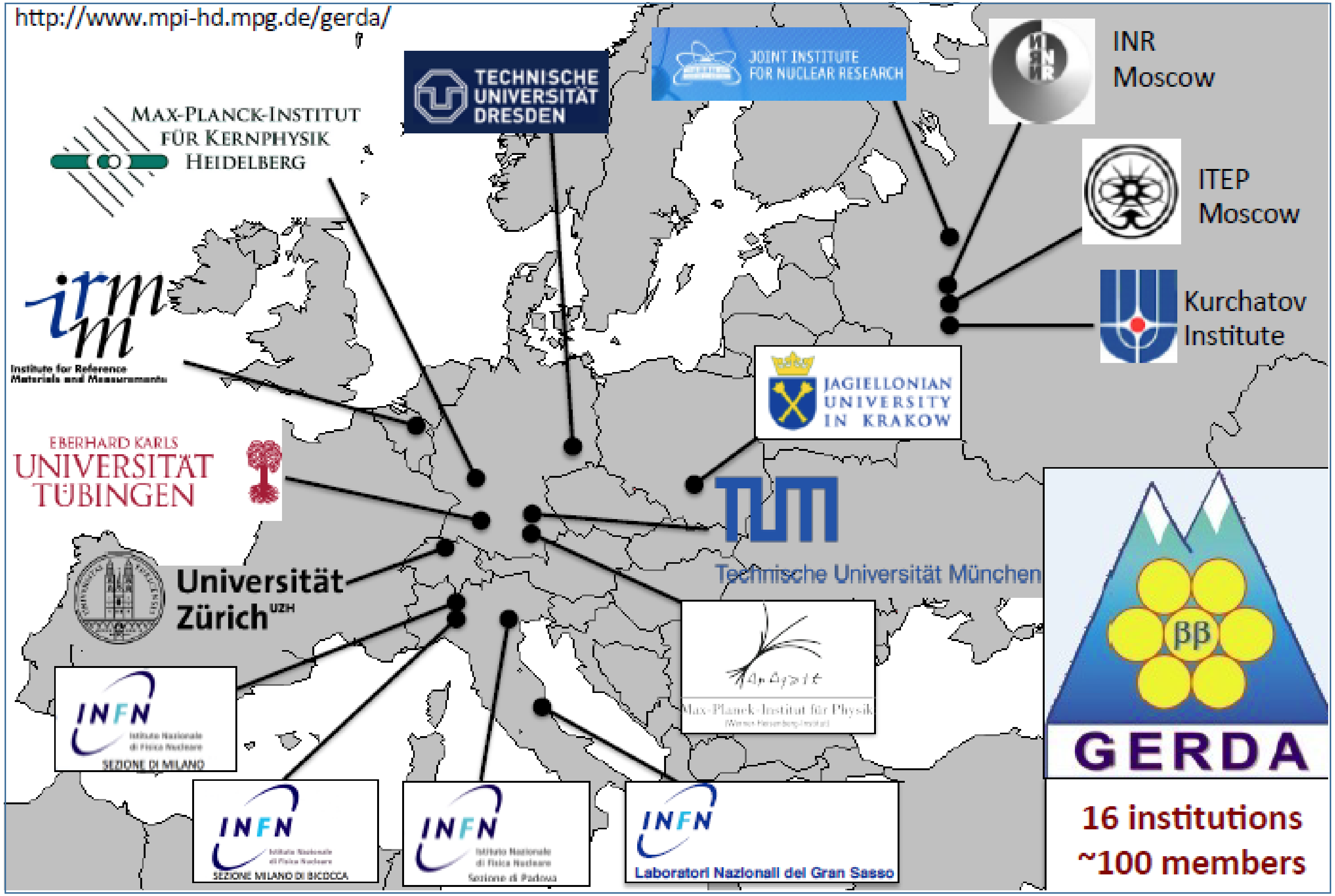
$\Updownarrow$

$|\Sigma_i U_{ei}^2 m_i|$



Plot by J. J. Gomez-Cadenas
see also Strumia,Vissani (arXiv:0606054)

The GERDA collaboration



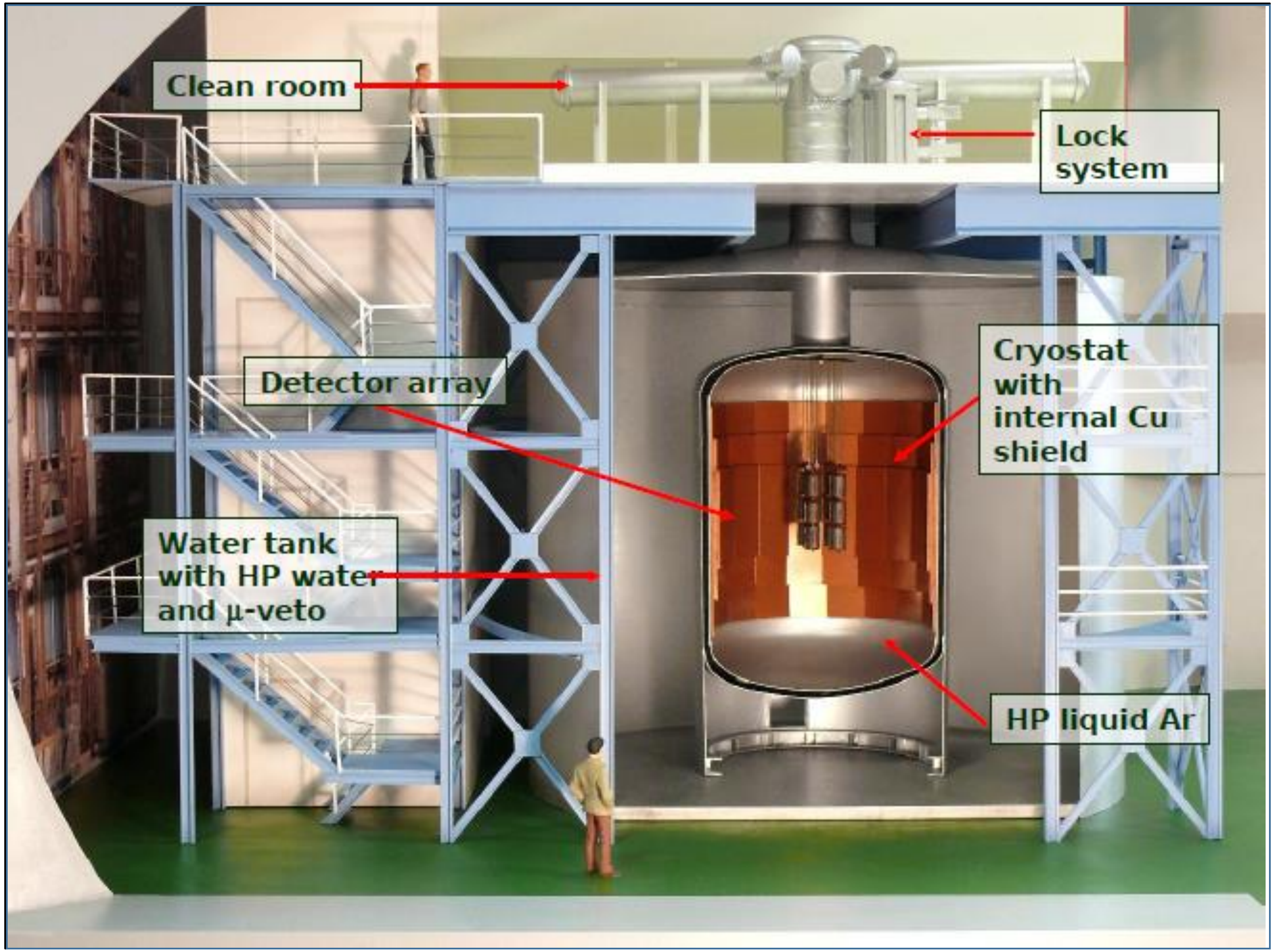
GERDA site and concept design

- **site**: INFN's national lab. of Gran Sasso, Italy
  total overburden of 3500 m.w.e.
- **concept design**: array of bare Germanium (^{76}Ge) detectors inserted in liquid Argon (LAr)
- **status**: Phase-I (2011-2013) finished and published; Phase-II started on December 2015

GERDA experimental set-up

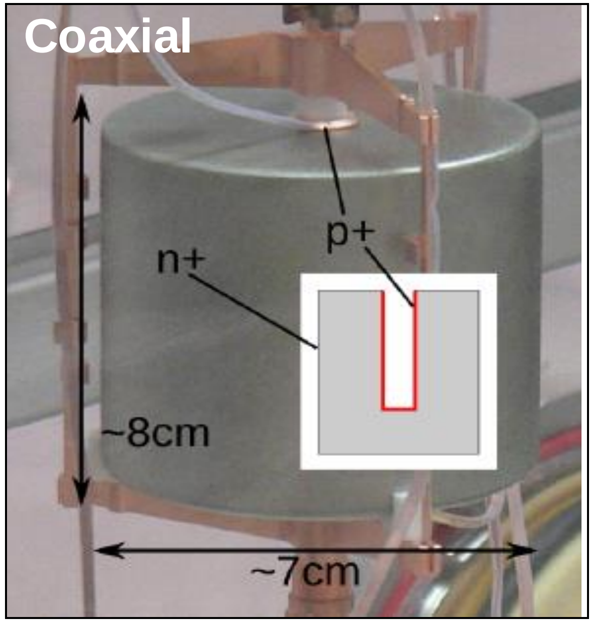
- Ge detectors, deployed from the lock system inside a clean room
- copper lined stainless steel cryostat (Phase-I), nylon (Phase-II) not shown
- 64 m^3 LAr
- 590 m^3 pure water (Cerenkov μ veto)
- plastic scintillator veto on the roof above the neck

Eur.Phys.J. C73 (2013)2330



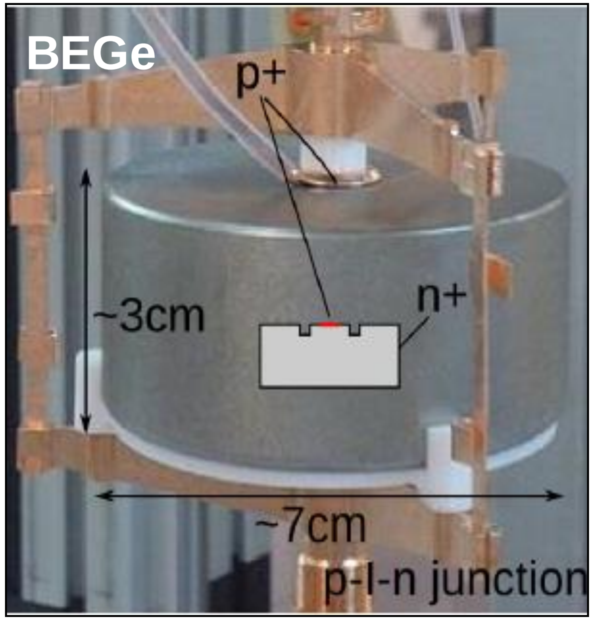
HPGe detectors

- detector-grade germanium is a high purity material ⇒ low background enriched 86% in ^{76}Ge
- established detector technology ⇒ industrial support
- very good energy resolution $\sim$ 0.1% at $Q_{\beta\beta}$
- high detector efficiency, source = detector



Coaxial detectors (from HdM, IGEX)

- total mass 17 kg
- reprocessed by Canberra
- energy resolution (average FWHM) = 4.8 keV at $Q_{\beta\beta}$



new Phase II BEGe detectors

- total mass 20 kg
- better pulse shape discrimination capability and energy resolution (Phase I = 3.2 keV at $Q_{\beta\beta}$)

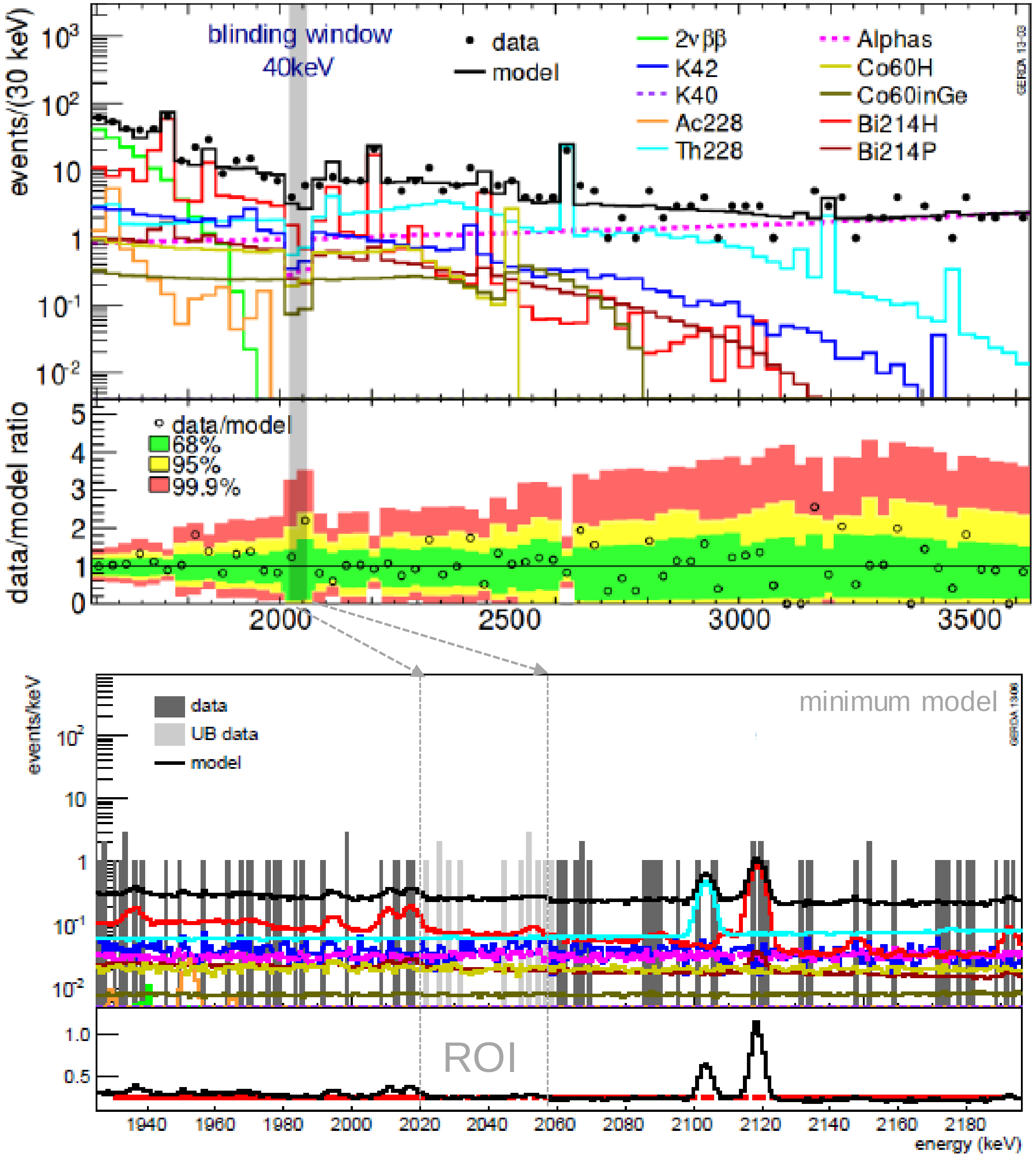
GERDA Phase-I

- data blinding at $Q_{\beta\beta}$ (2039) $\pm$ 40 keV $\equiv$ ROI
- November 2011 – May 2013 with 88% duty cycle
- weekly ^{228}Th calibration and constant monitoring with test pulser
- total exposure 21.6 kg yr (M =14.6 kg Coaxial + 6.0 kg BEGe (3kg natural, 3 kg enriched))

data selection:

- quality – unphysical events < 0.1 % misidentification
- muon veto – 99.1% rejection efficiency
- anti-coincidences – (signal in more than one detector) negligible random coincidences
- eliminate BiPo – cascade of low energy ^{214}Bi and high energy α ^{214}Po ~ 50% efficiency

GERDA Phase-I background model



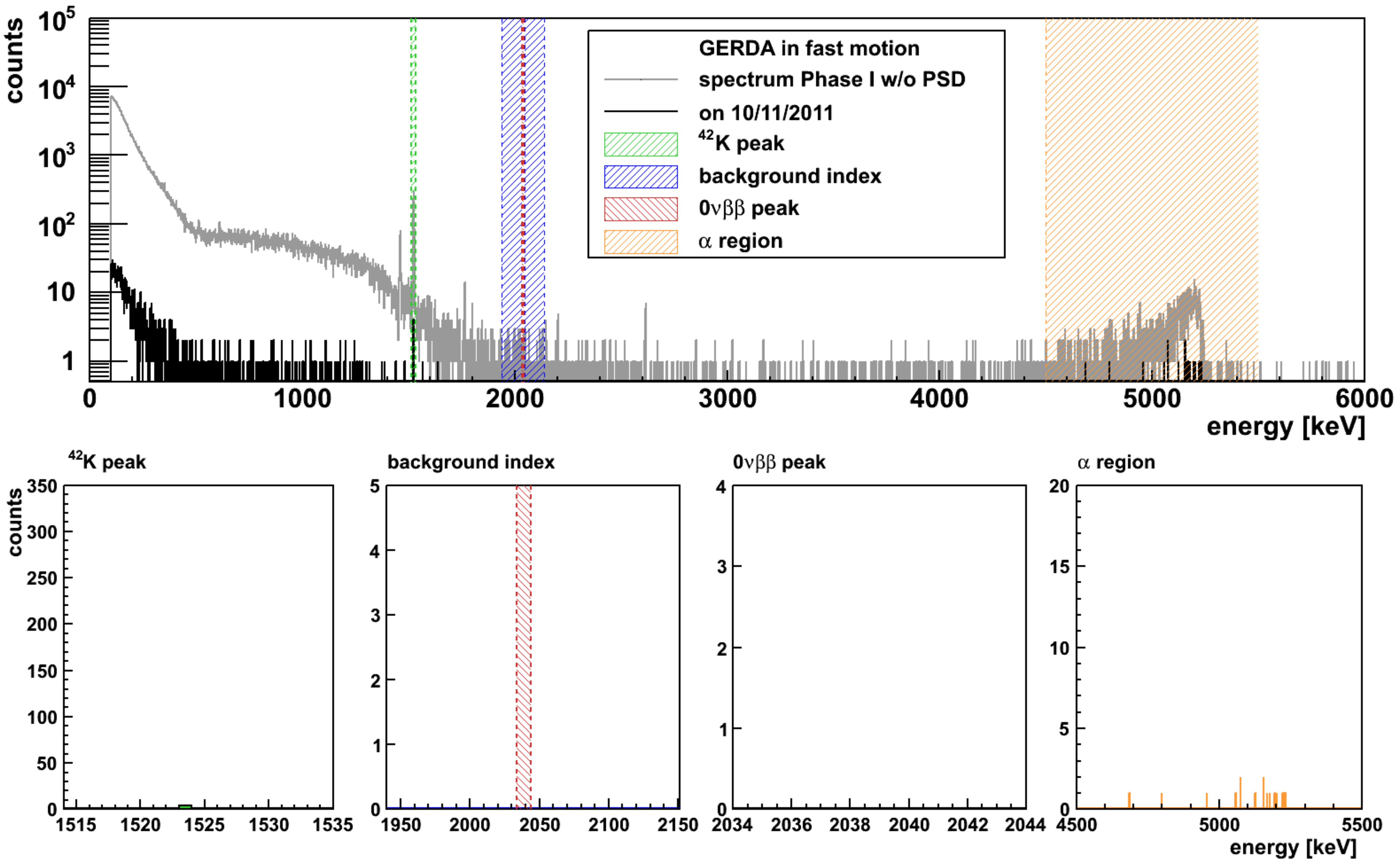
Eur.Phys. J C74 (2014) 2764

- background ~10X lower than previous Ge experiments

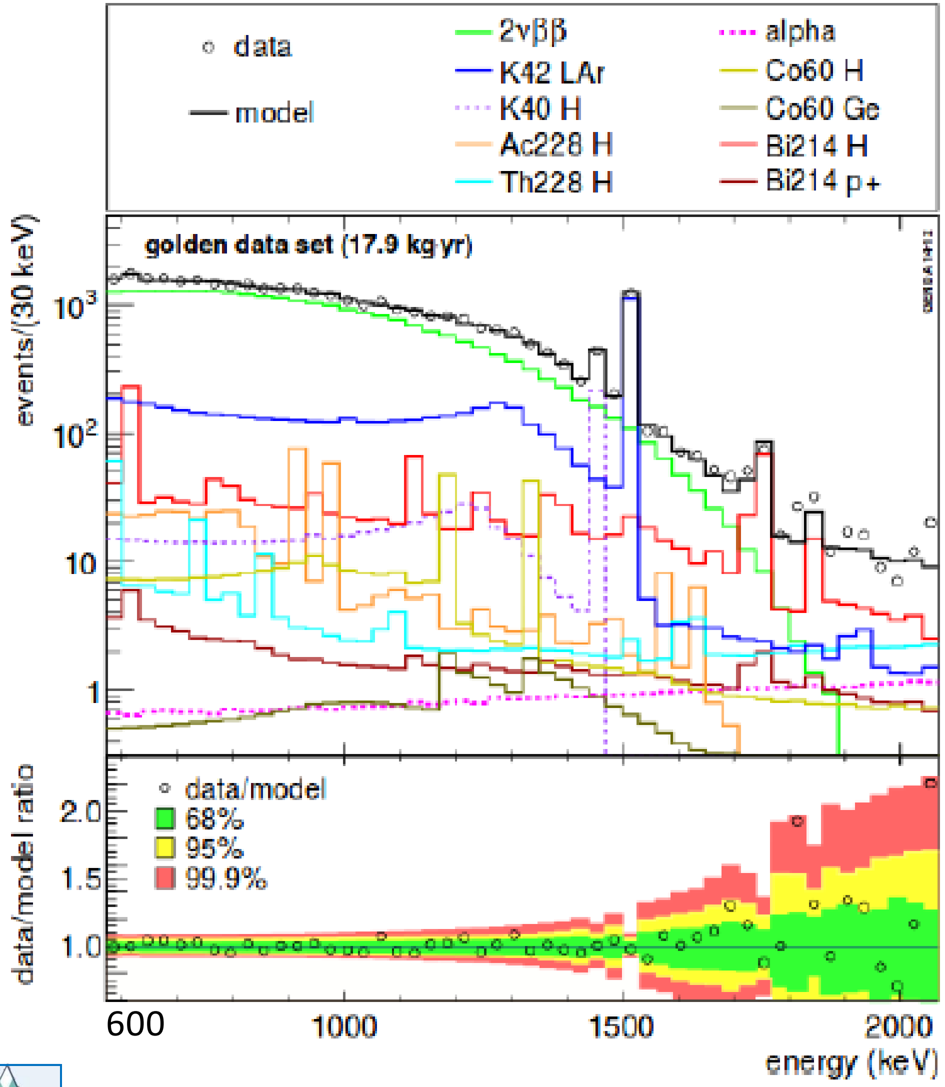
- main contributions:
  ^{228}Th and ^{226}Ra on holders,
  ^{42}Ar, and α on surface
- no line expected on ROI
  ($Q_{\beta\beta}$ = 2039 ±40 keV)
- 2014 keV ^{208}Tl and
  2119 keV ^{214}Bi excluded

- expected events
  - 8.6 minimum model
  - 10.3 maximum model

GERDA spectrum Phase-I



Phase-I: $2\nu\beta\beta$ results



- «golden dataset ≡17.9 kg yr Coaxial» used for the analysis
- binned Maximum Likelihood approach
- $2\nu\beta\beta$ half-life useful for understanding $0\nu\beta\beta$ (e.g. nuclear matrix element)

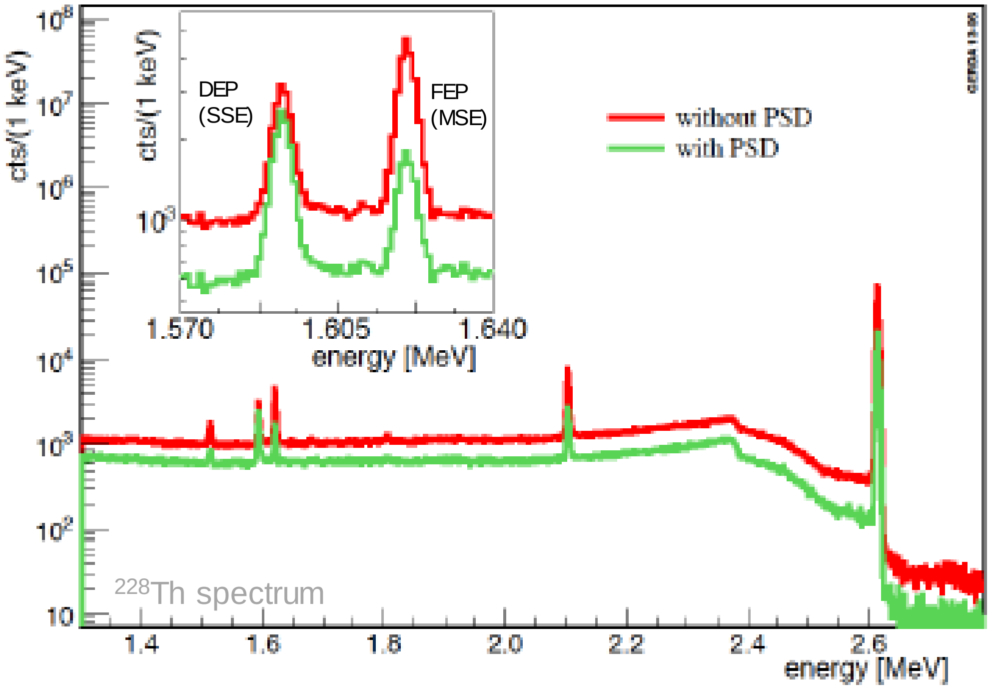
$$T_{1/2}^{2\nu\beta\beta} = (1.926 \pm 0.0095) \cdot 10^{21}\ \mathrm{yr}$$

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

Phase-I: Pulse Shape Discrimination

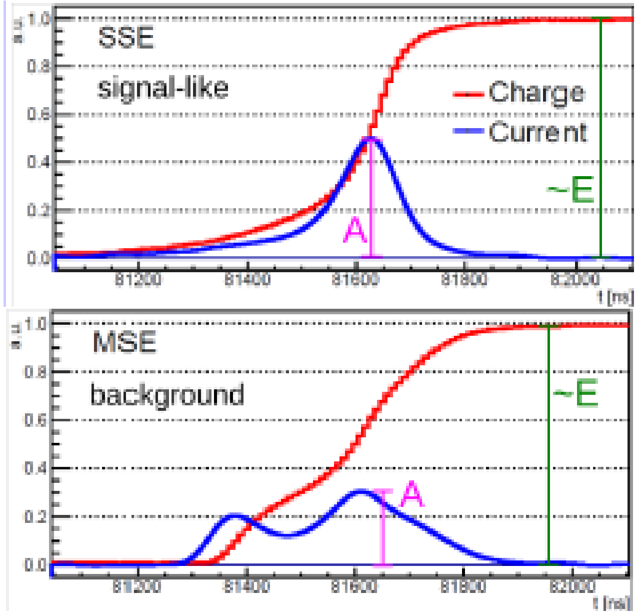
Coaxial: Artificial Neural Network

- SSE training with signal-like ^{208}Tl (e^-like signal)
- MSE training with background-like ^{212}Bi (γ like signal)
- cut adjusted for each detector to have $90^{+5}_{-9}\%$ survival probability on DEP



BEGe: A/E

- A = amplitude of current pulse
- E = energy
- high capability of distinguishing SSE from MSE, superficial events (p^+(fast) and n^+(low E))



acceptance: $0\nu\beta\beta: 92 \pm 2$ %
$2\nu\beta\beta: 91 \pm 5$ %

JINST 4(2009) 10007; JINST 3(2011)3005; EPJ C 73(2013)2583

Phase-I: $0\nu\beta\beta$ results

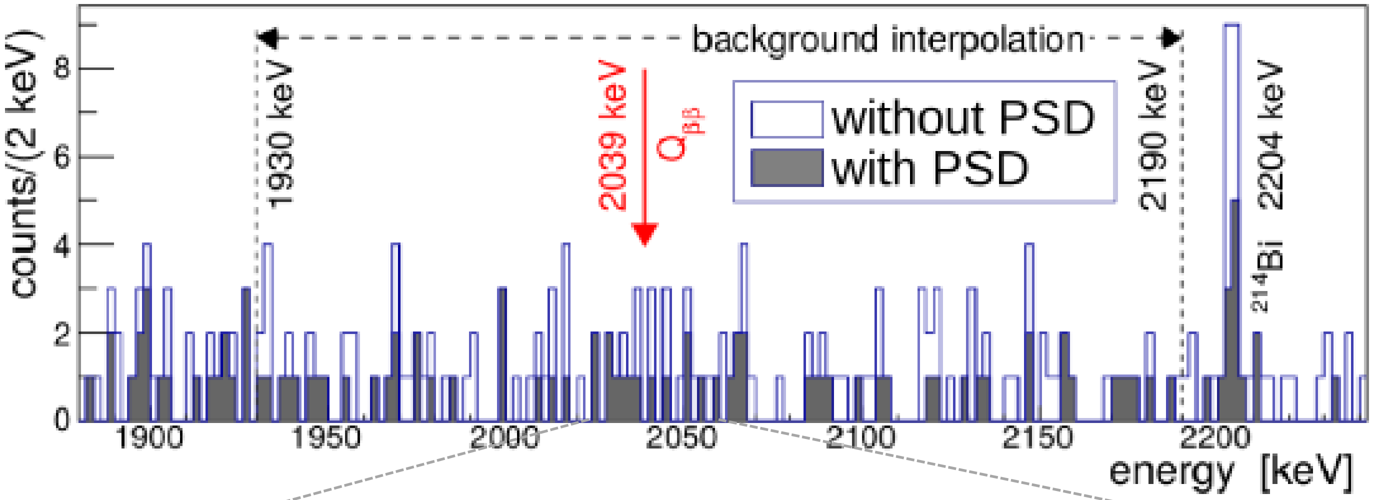
PRL 111, 12503 (2013)

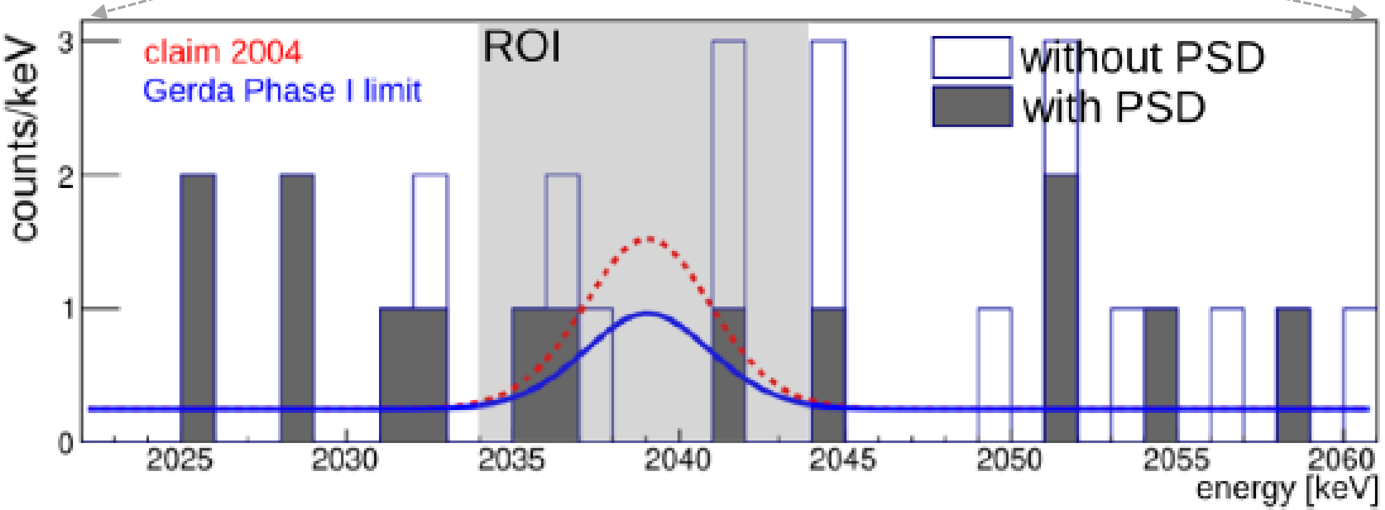
- exposure 21.6 kg yr
- full chain (after calibration + fixed data selection + fixed analysis + PSD) → unblinding
- BI = 0.01 cts/(keV kg yr) after PSD (at ROI)

expected signal (w/PSD): (5.9 ± 1.4) cts in ± 2σ
expected bckg (w/PSD): (2.0 ± 0.3) cts in ± 2σ

observed: 3.0 in ± 2 σ (0 in 1σ)

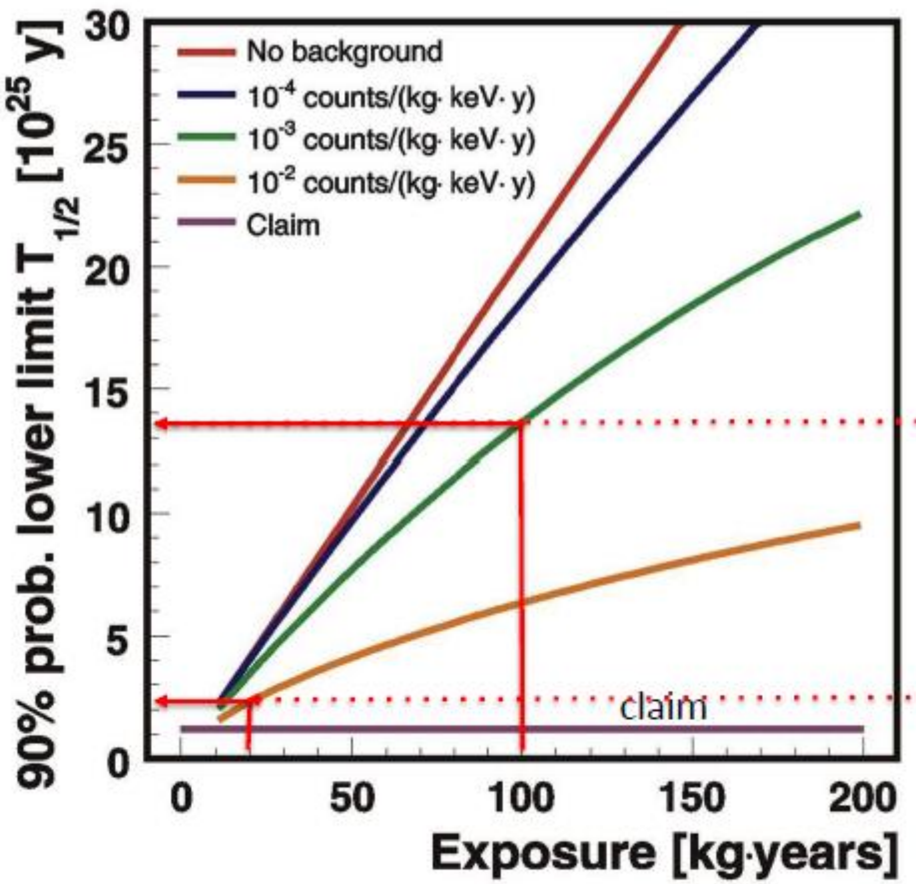
$$T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{25}\ \mathrm{yr}\ \ 90\%\ \mathrm{C.L.}$$





K.K claim (Phys.Lett. B 586 (2004)198) strongly disfavoured

GERDA on the way to Phase-II



<u>Phase-II</u>
BI ~ 0.001 cts / (keV kg yr)
..sensitivity after 100 kg yr

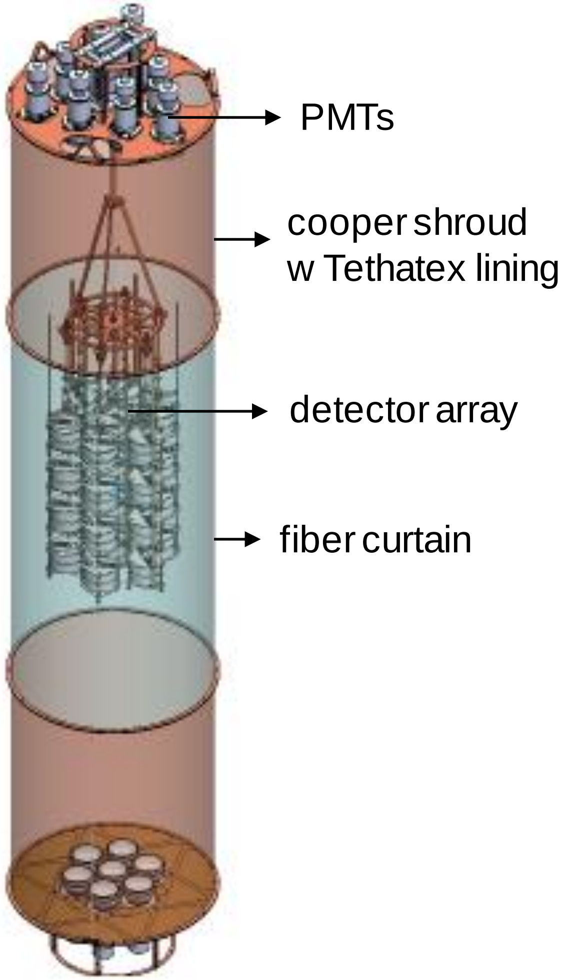
<u>Phase-I</u>
BI = 0.01 cts / (keV kg yr)
..sensitivity after 20 kg yr

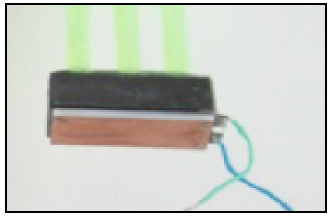
<u>Phase-II</u> main upgrades:

- 30 new BEGe detectors (20kg)
- reduce background by ~10X
  - new low mass holder
  - new front end read-out & new cabling (including HV)
  - improved PSD capabilities
  - LAr veto instrumentation
- improve the energy resolution*

*EPJ 75(2015) 255

Phase-II: LAr veto instrumentation

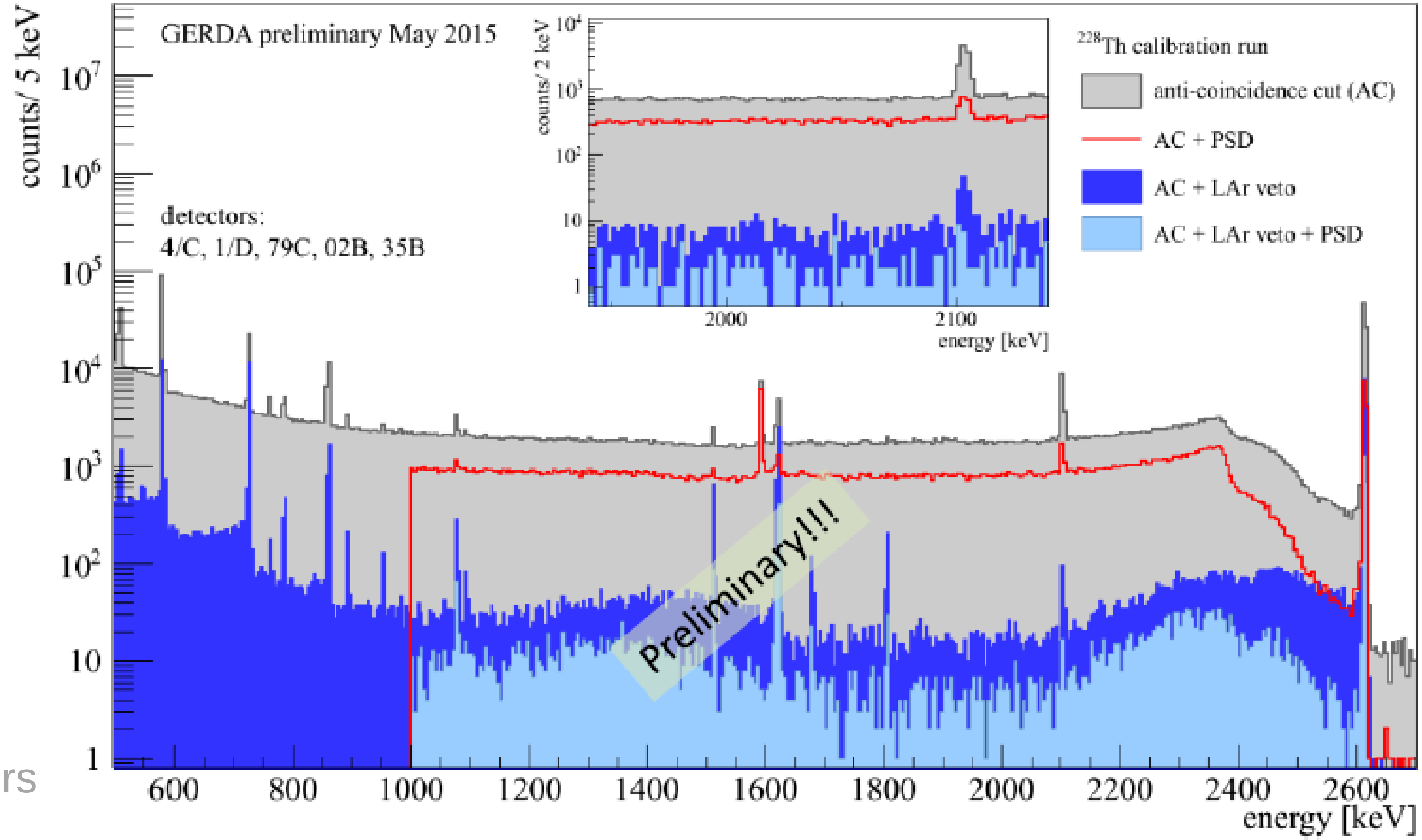




- fiber curtain (coated with WLS) coupled to SiPMs
- 3'' PMTs on top and bottom of the array

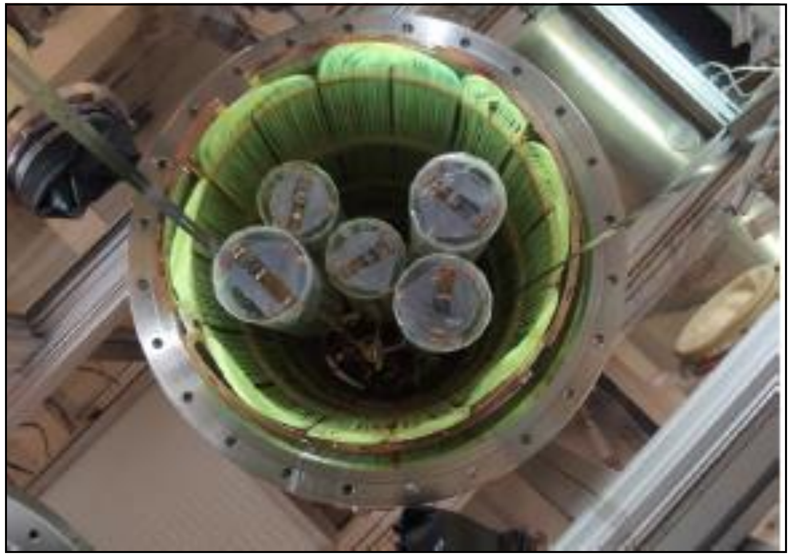
LAr veto + PSD allows a strong background reduction at $Q_{\beta\beta}$

Phase-II: commissioning (pilot string assembly)



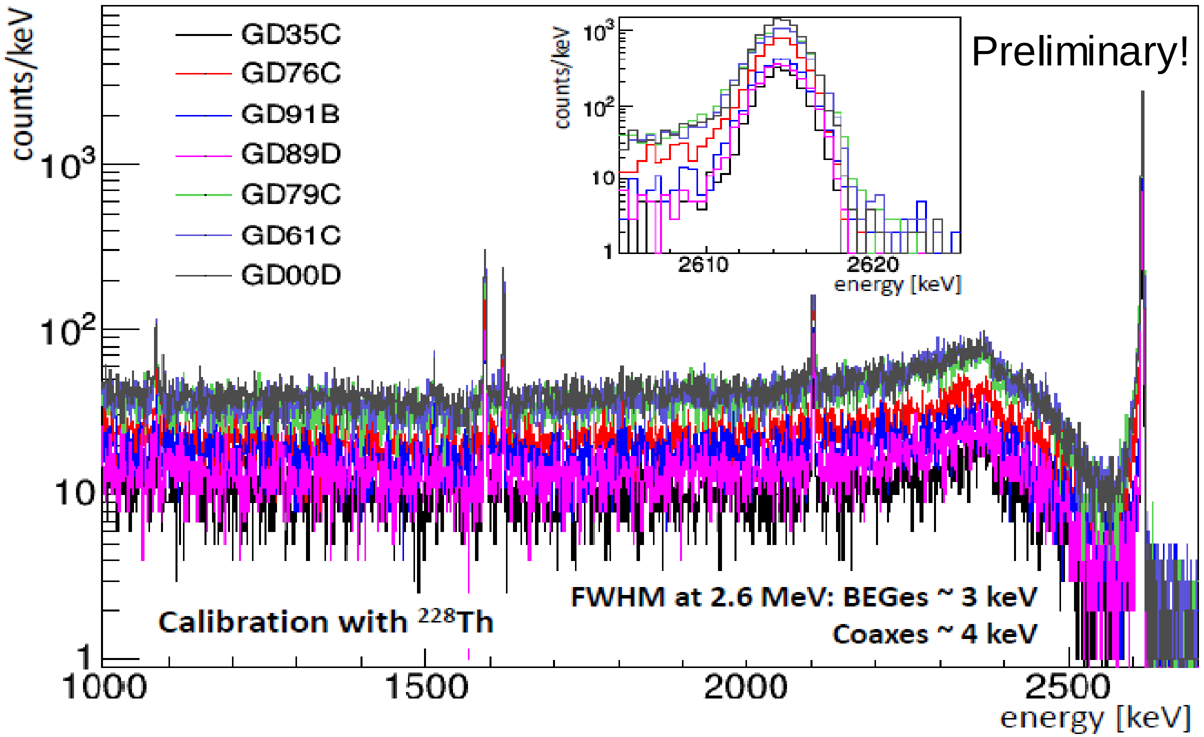
- spectrum of ^{228}Th source
- 15 hours data – 3 BEGe detectors
- 15 PMTs and 7 SiPM running
- Th background suppressed by x 100 including LAr data

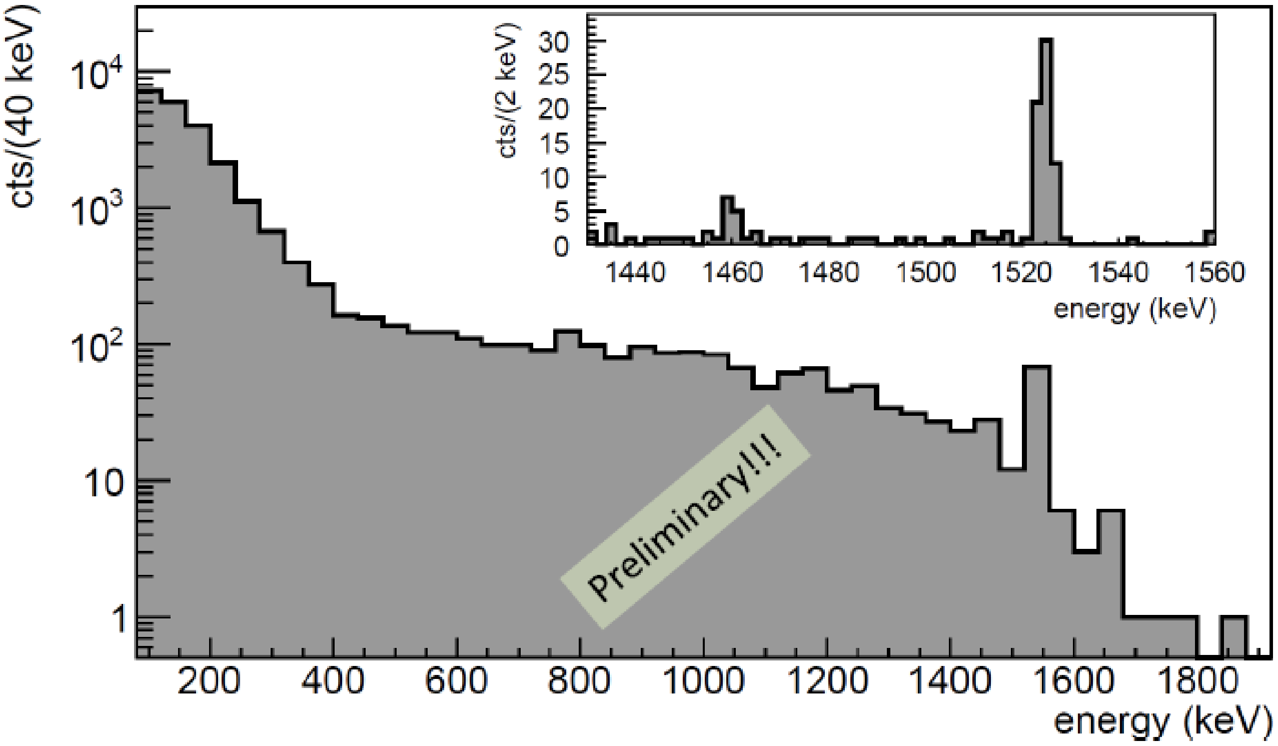
Phase-II: commissioning (5 string assembly)



GERDA

Phase-II: commissioning (5 string assembly)





energy resolution: FWHM at 2.6 MeV: BEGEs ~ 3 keV
Coaxes ~ 4 keV

$2\nu\beta\beta$ decay spectra, using ~ 1 kg yr

Summary

GERDA phase-I

- completed and still providing new results:
  - ✓ $0\nu\beta\beta$ of ^{76}Ge $T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{25}$ yr 90% C. L.
  - ✓ $2\nu\beta\beta$ of ^{76}Ge $T_{1/2}^{2\nu\beta\beta} = (1.926 \pm 0.0095) \cdot 10^{21}$ yr
  - ✓ signal from previous claim disfavoured with 99% probability
  - ✓ more results not shown here (Majoron emission Eur.Phys. J. C75(2015)416, excited states of $2\nu\beta\beta$ J. Phys. G: Nucl. Part. Phys. 42(2015)115201

GERDA phase-II

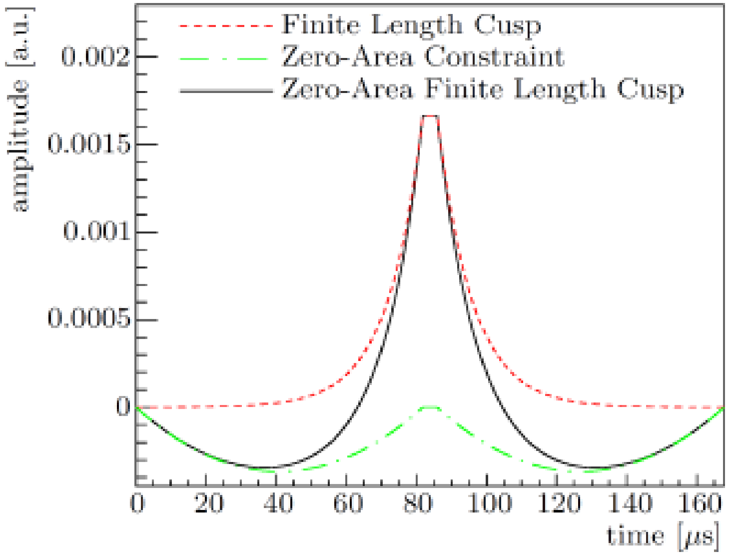
✓ commissioning finished
  - o LAr veto fully installed and operational
  - o all 40 HPGe detectors installed
  - o all diodes show stable behaviour (good energy resolution = Phase-I ~ 4 keV)
  - o during commissioning runs background reduction was improved

- phase-II started on December 2015, currently on-going (stay tuned for results …)

spares

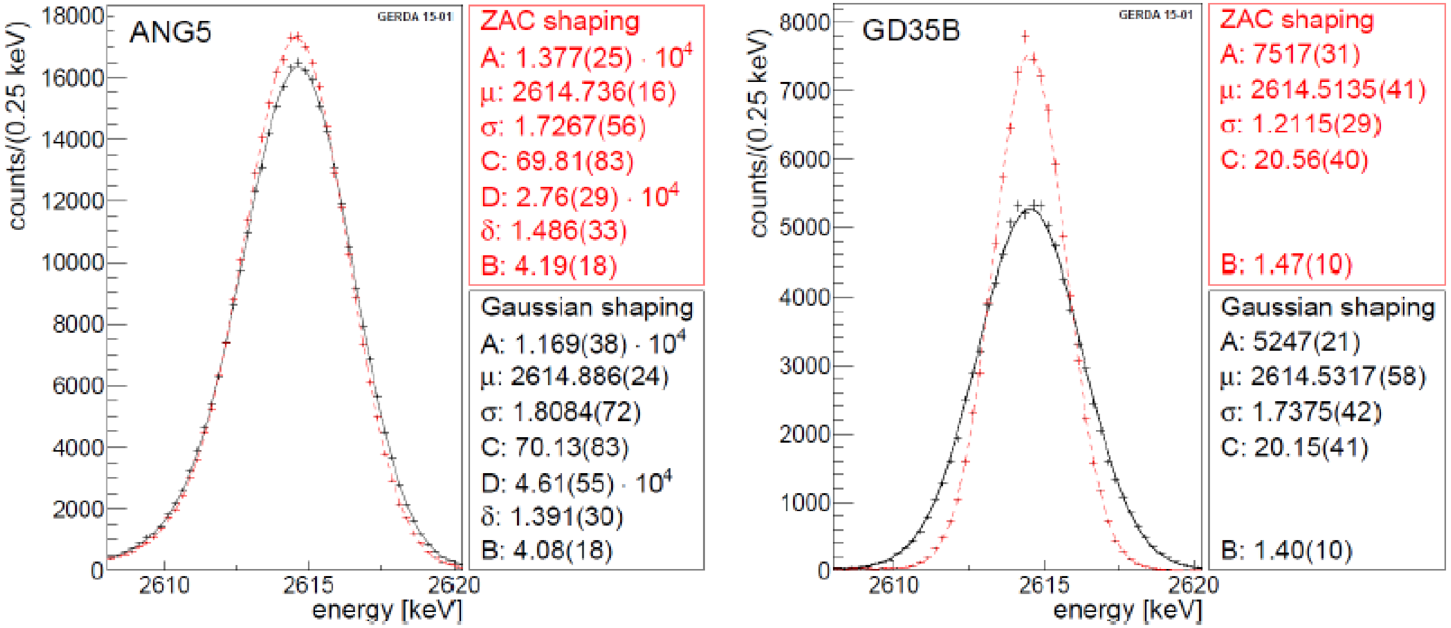
Improvement in the Energy Resolution

Zero Area Cusp filter



comparison of the 2614.5 keV peak

Coaxial BEGe



- filter optimized for each detector
- sinh-like cusp,
  central flat top (maximize charge integration)
  total zero area (filter out 1/f noise)
  baseline sustraction (with parabolic filters)

- better low frequency rejection
- low-E tail reduced thanks to a better charge integration
- enegy resolution of Phase-I/II can be improved for both detectors

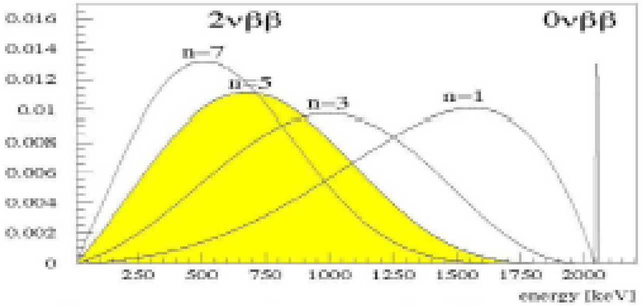
EPJ 75(2015) 255

Phase I: emission of Majoron(s)

alternative processes to 0νββ:

e.g. Majoron emission ββχ & ββχχ

- many models
- continuous spectra with shapes different to 2νββ

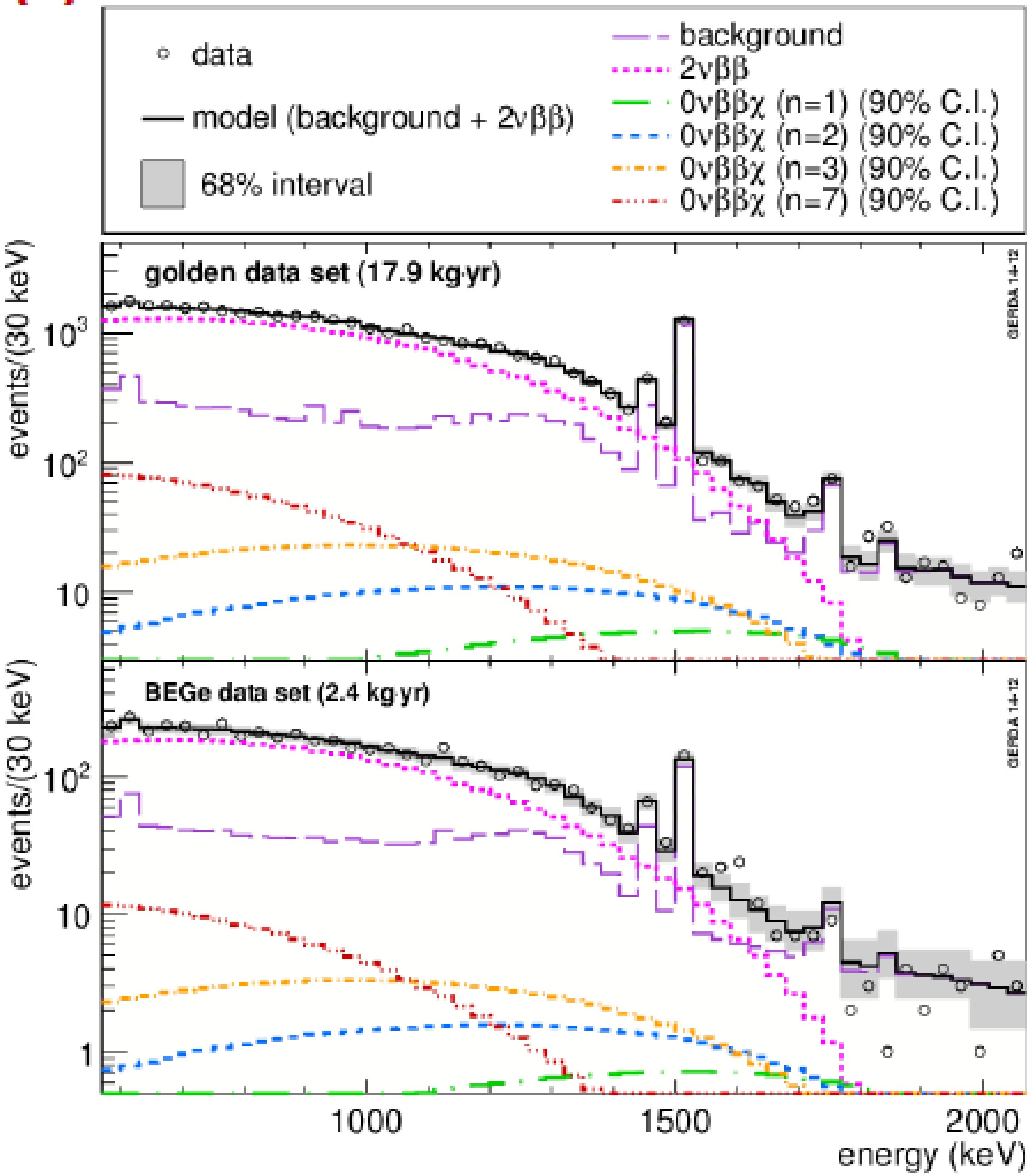


- global fit of spectrum (coax &BEGe)
- for n=1

$T_{1/2}$ (0νββχ)= 4.2 x 10^{23} yr (90% CL)

- improved by factor > 6

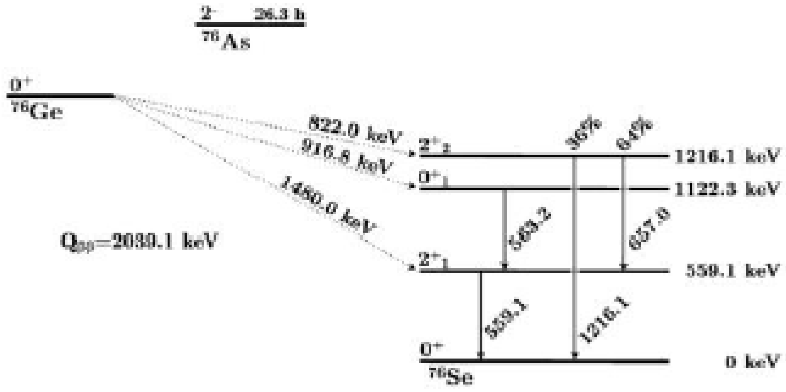
Eur. Phys. J. C 75 (2015) 416

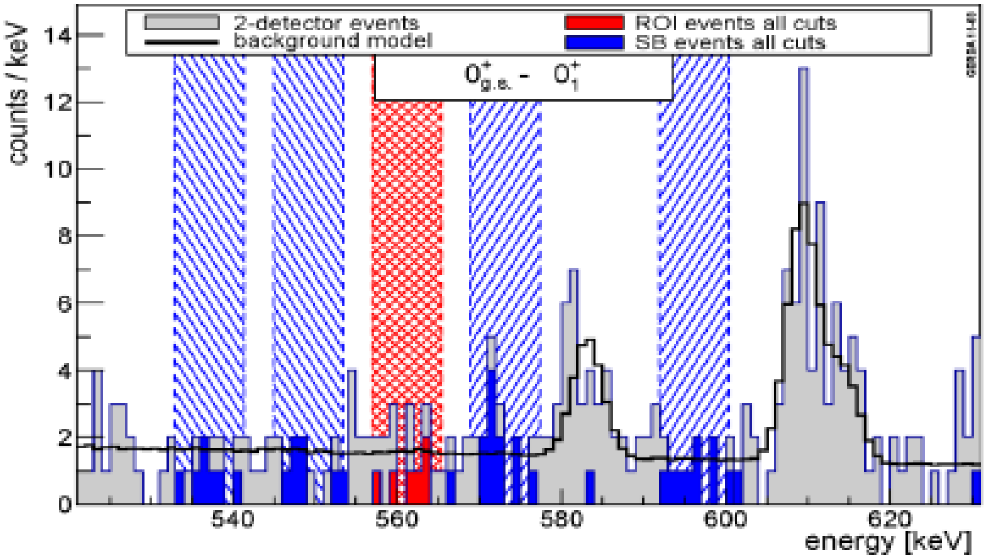


New Phase I results:

2νββ to excited states

- (2ν)ββ of ^{76}Ge can occur into excited states of ^{76}Se
  - Not observed by now.
    Previous limits for $T_{1/2}$ in the range of few 10^{21} yr.
  - Most probable: 0^+_1 level at 1122 keV.
    Predictions 10^{21}-10^{24} yr for $T_{1/2}$
  - Benchmark for NME calculations





- Search for coincidence of ββ-decay in one detector and 560 keV γ-ray in another
- NO evidence found
- Limits improved by ~100
- For 0^+_1 level:

$$T_{1/2} > 3.7 \times 10^{23}\ \text{yr}\ (90\%\ \text{CL})$$

arXiv:1506.03120 (in print at J.Phys G)

Experimental Sensitivity

Sensitivity $T_{1/2} \propto \epsilon \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$ and $T_{1/2} \propto \frac{1}{m_{\beta\beta}^2}$

ϵ	detection efficiency	$\gtrsim$ 85%
ε	enrichment fraction	high natural or enrichment
M	active target mass	increase mass
T	measuring time	increase time
b	background rate (cts/(keV kg yr))	minimize & select radio-pure material
ΔE	energy resolution	use high resolution spectroscopy

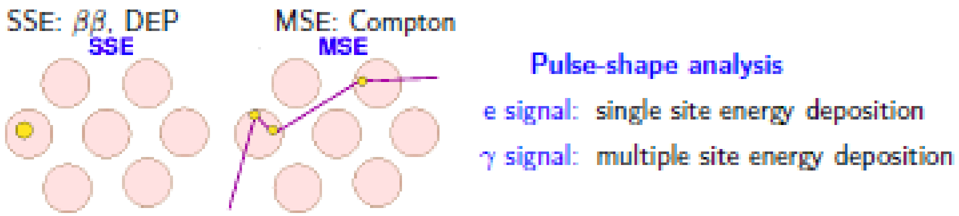
Requirements:

- high enrichment of isotope material
- M and T large
- very good energy resolution
  For GERDA $\Delta E < 0.2\%$
- very good detection efficiency because
  GERDA detector ≡ source, $\epsilon \sim 1$
- high-purity detectors → low background
  For GERDA $b < 10^{-2}$ cts/(keV kg yr)
- higher $M^{0\nu}$ w.r.t. other isotopes

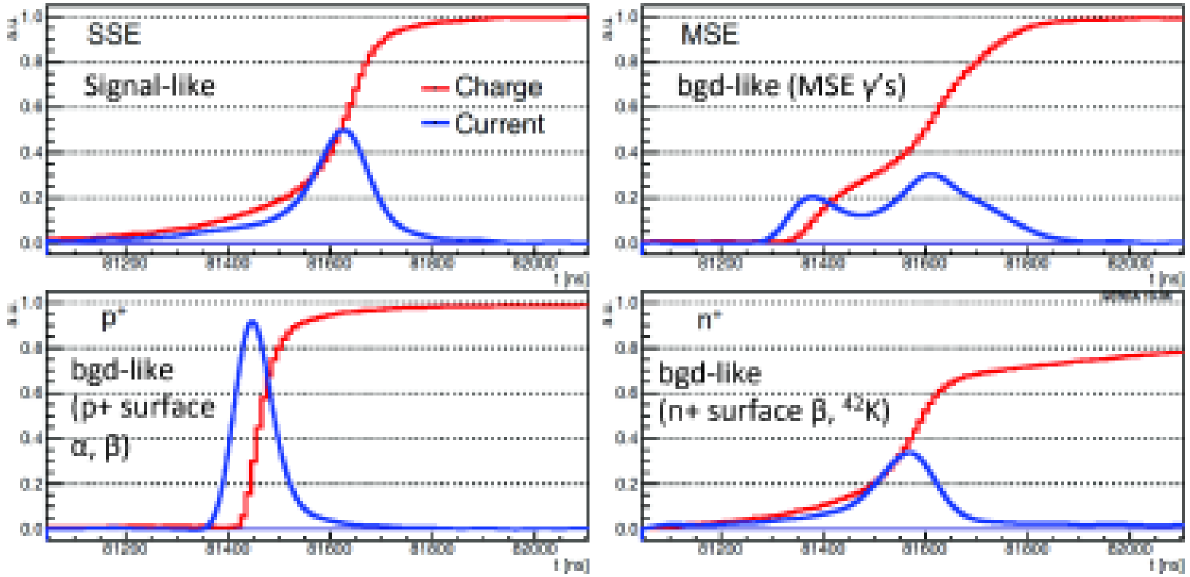
Additional tools to distinguish from background:

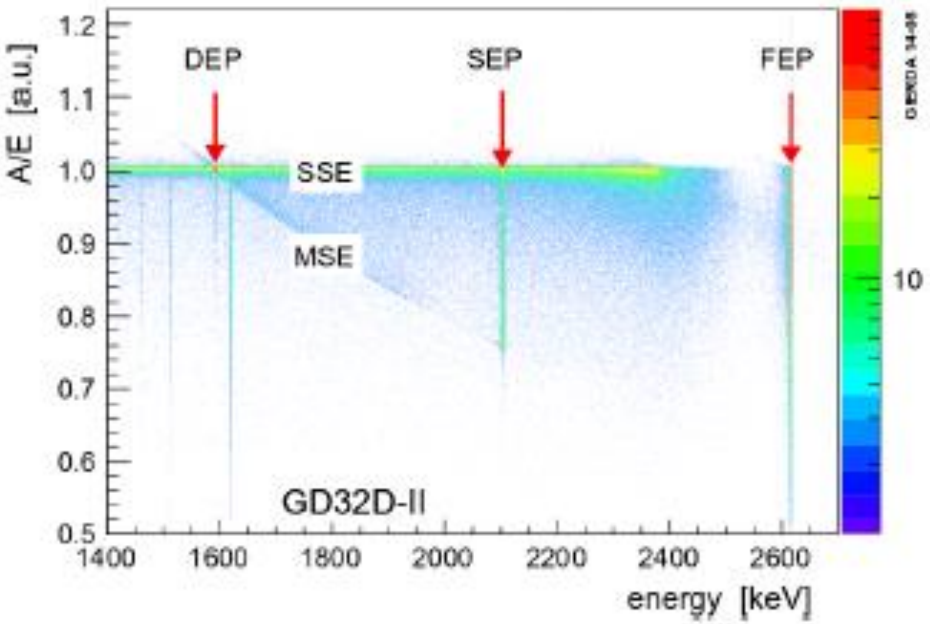
- Angular distribution
- Single electron spectrum
- Decay to excited states (gamma-rays)
- Identification of daughter nucleus

Gemanium Pluse Shape Discrimination



Different energy deposition between gamma and electron
Different recorded pulses





$0\nu\beta\beta$ decay signal perspectives