Searches for neutrinoless double beta decay – results from phase I of the GERDA experiment

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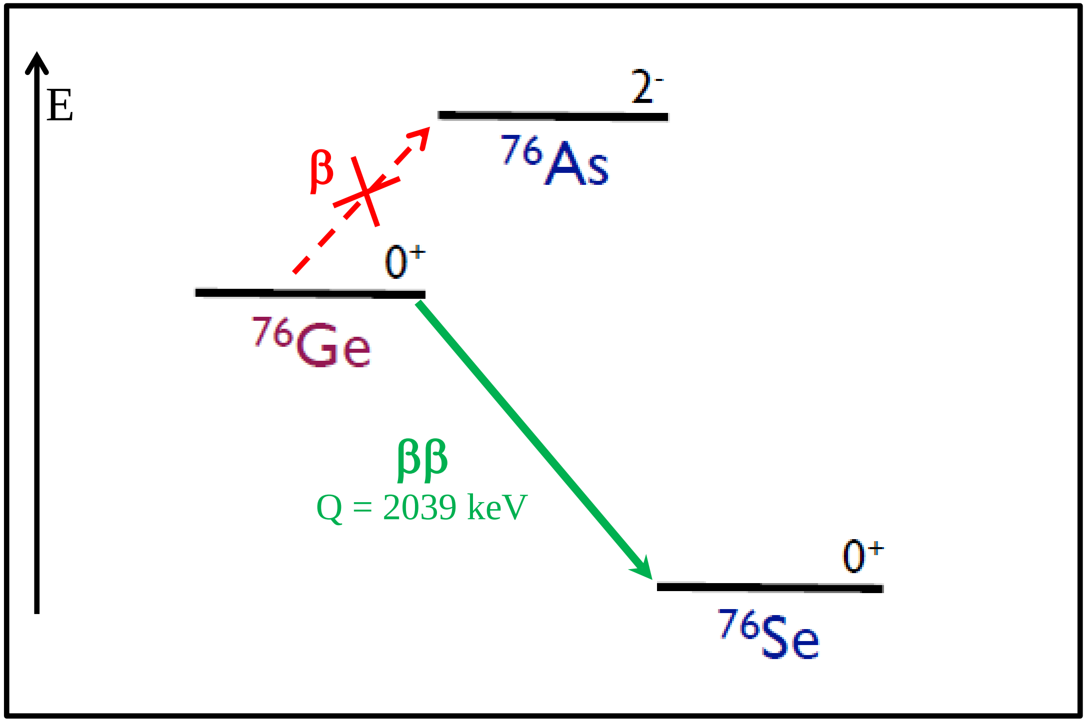
Outline

- Double beta decay
- Design and goals of GERDA
- Phase I results
- Conclusions

Double beta decay

In a number of even-even nuclei, β decay is energetically forbidden, while double beta decay from a nucleus of (A,Z) to (A, Z+2), is energetically allowed.



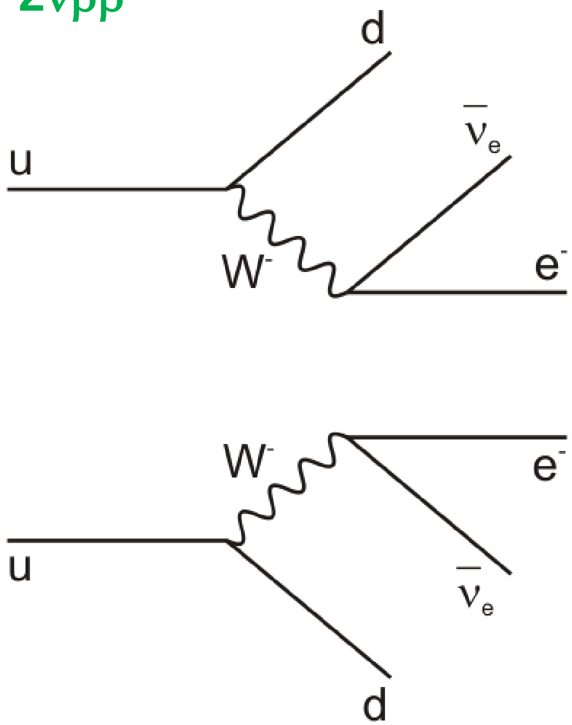
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

Double beta decay modes

GERDA

- ββ decay
- GERDA D&G
- Phase I results
- Conclusions

2νββ

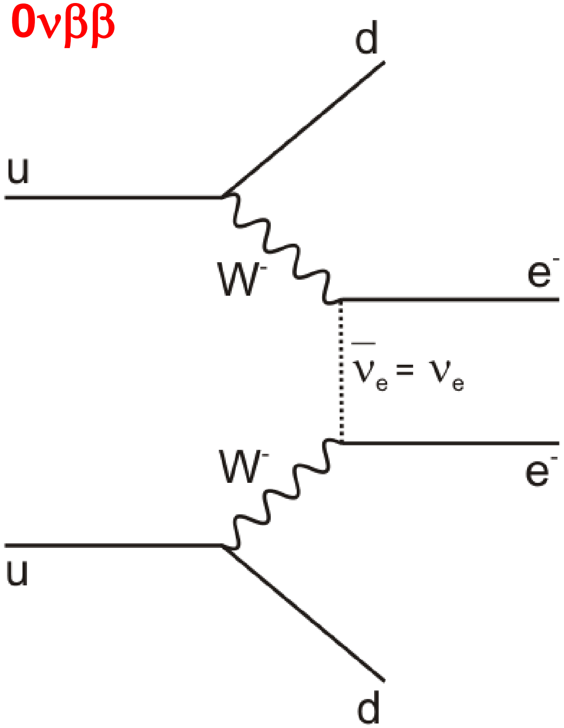


$(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$\Delta L = 0$

$T_{1/2} \sim 10^{18} – 10^{21}$ y

0νββ



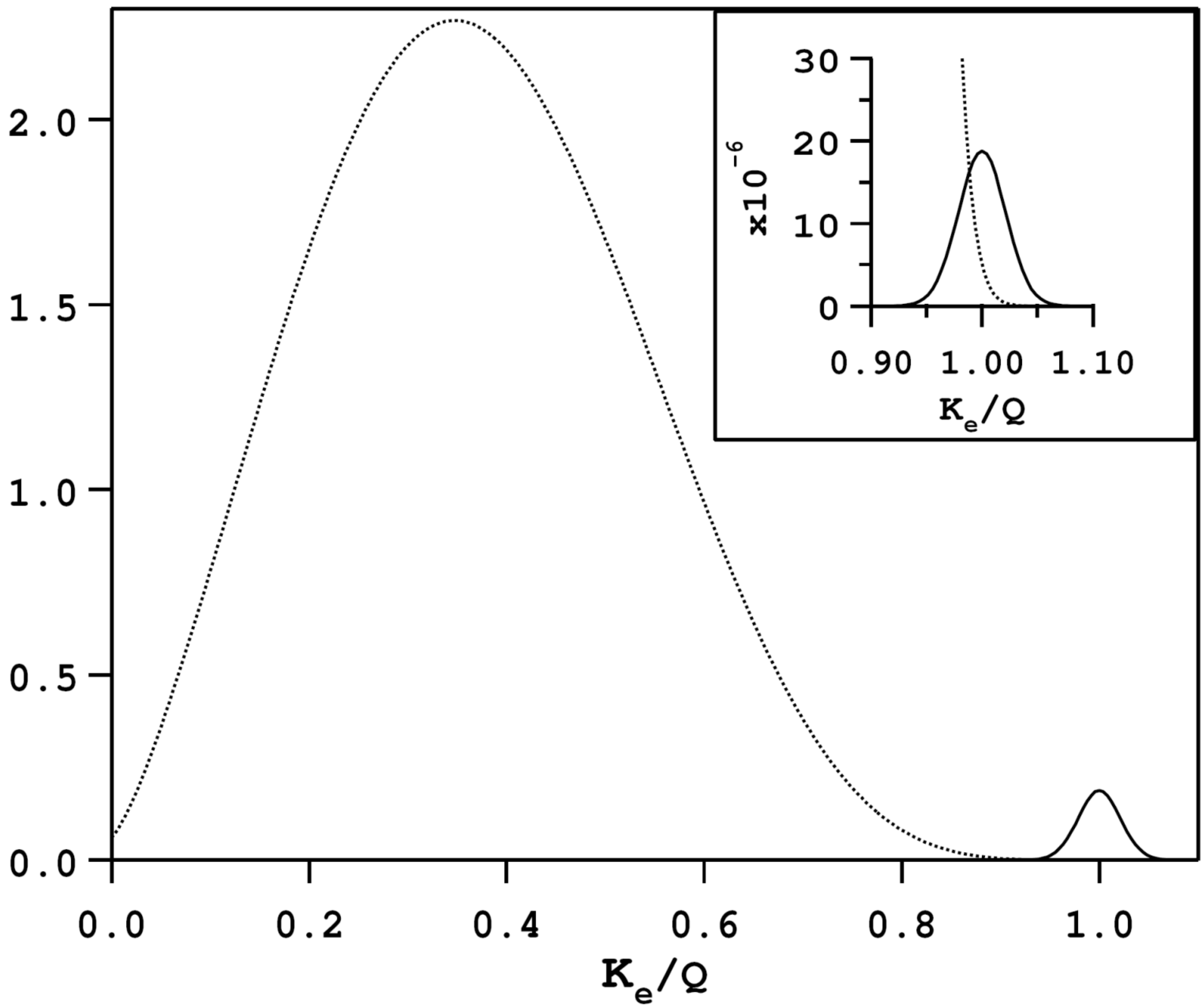
$(A,Z) \rightarrow (A, Z+2) + 2e^-$

$\Delta L = 2$

$T_{1/2} \sim 10^{26} – 10^{27}$ y

$T_{1/2}^{exp} > 2\times10^{25}$ y

Double beta decay modes



ββ decay

GERDA D&G

Phase I results

Conclusions

Neutrinoless ββ beta decay (0νββ)

- ββ decay
- GERDA D&G
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$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

ε – detection efficiency
A – isotope molar mass
a – isotope mass fraction
M – active mass
T – measurement time
B – background rate
ΔE – energy resolution
M·T – exposure

Neutrinoless ββ beta decay (0νββ)

ββ decay

GERDA D&G

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Conclusions

If 0νββ observed:

- Neutrino is a Majorana particle (its own antiparticle)
- Lepton number is not conserved
- Dealing with physics beyond the Standard Model
- Absolute neutrino mass scale
- Neutrino mass hierarchy
- CP violation in the lepton sector

Significant contribution to Particle Physics, Astrophysics and Cosmology

Observation claim

GERDA

- ββ decay
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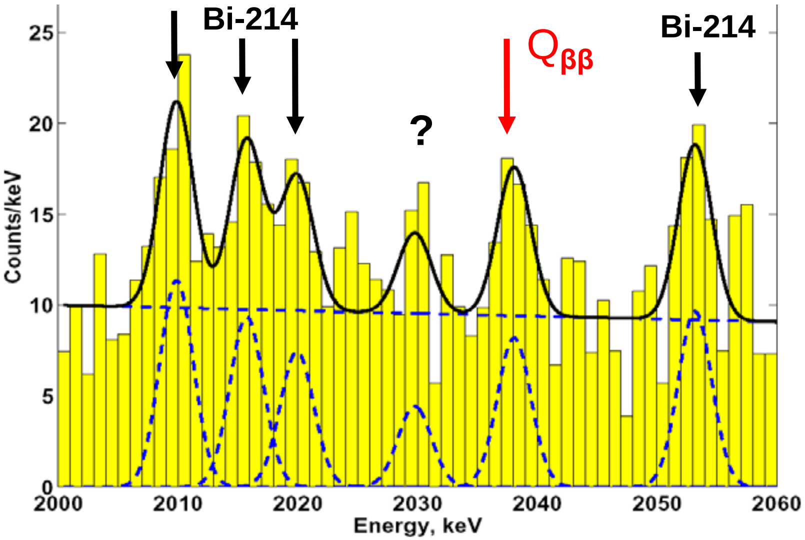


Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

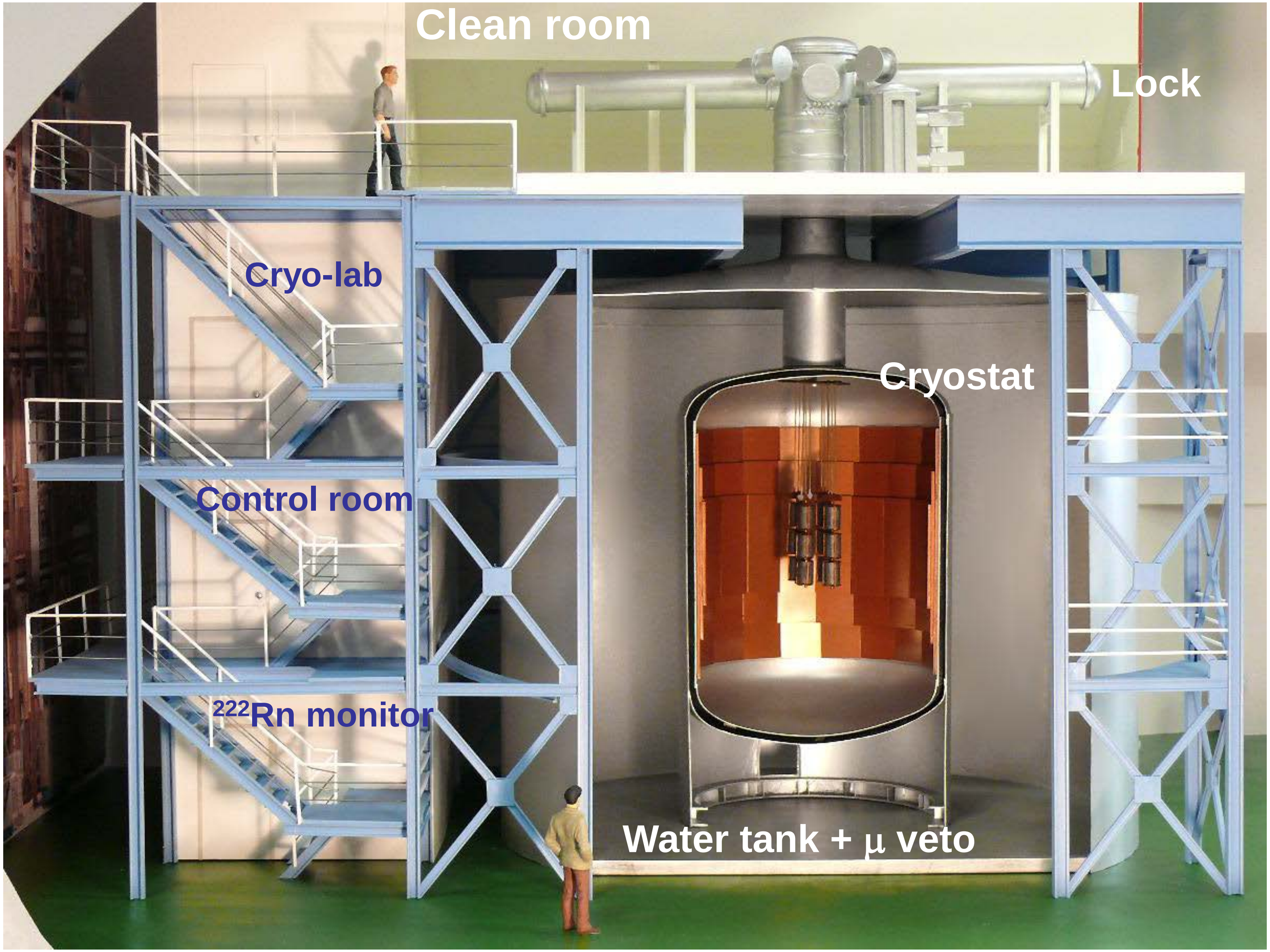
- 71.7 kg year - bgd 0.16 / (keV×kg×yr)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported **$T_{1/2}^{0\nu} = (1.19^{+0.37}_{-0.23})\times10^{25}$ yr**

N.B. Half-life $T_{1/2}^{0\nu} = 2.23\times10^{25}$ yr; $T_{1/2}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006)) is not considered because it misses efficiencies (i.e. $\varepsilon_{PSD} \sim 0.5$).

GERDA

- GERDA (GERmanium Detector Array) has been designed to investigate neutrinoless double beta decay of ^{76}Ge ($Q_{\beta\beta}$ = 2039 keV)
  - Ge mono-crystals are very pure
  - Ge detectors have excellent energy resolution
  - Detector = source ($\varepsilon \approx 1$)
  - Enrichment required (7.4 % $\rightarrow$ 86 %)
- Background (index) around $Q_{\beta\beta}$: $10^{-2} – 10^{-3}$ cts/(keV×kg×yr); 10 – 100 times lower compared to previous experiments (HdM/IGEX)

GERDA Detector Design



GERDA Phase I detectors

GERDA

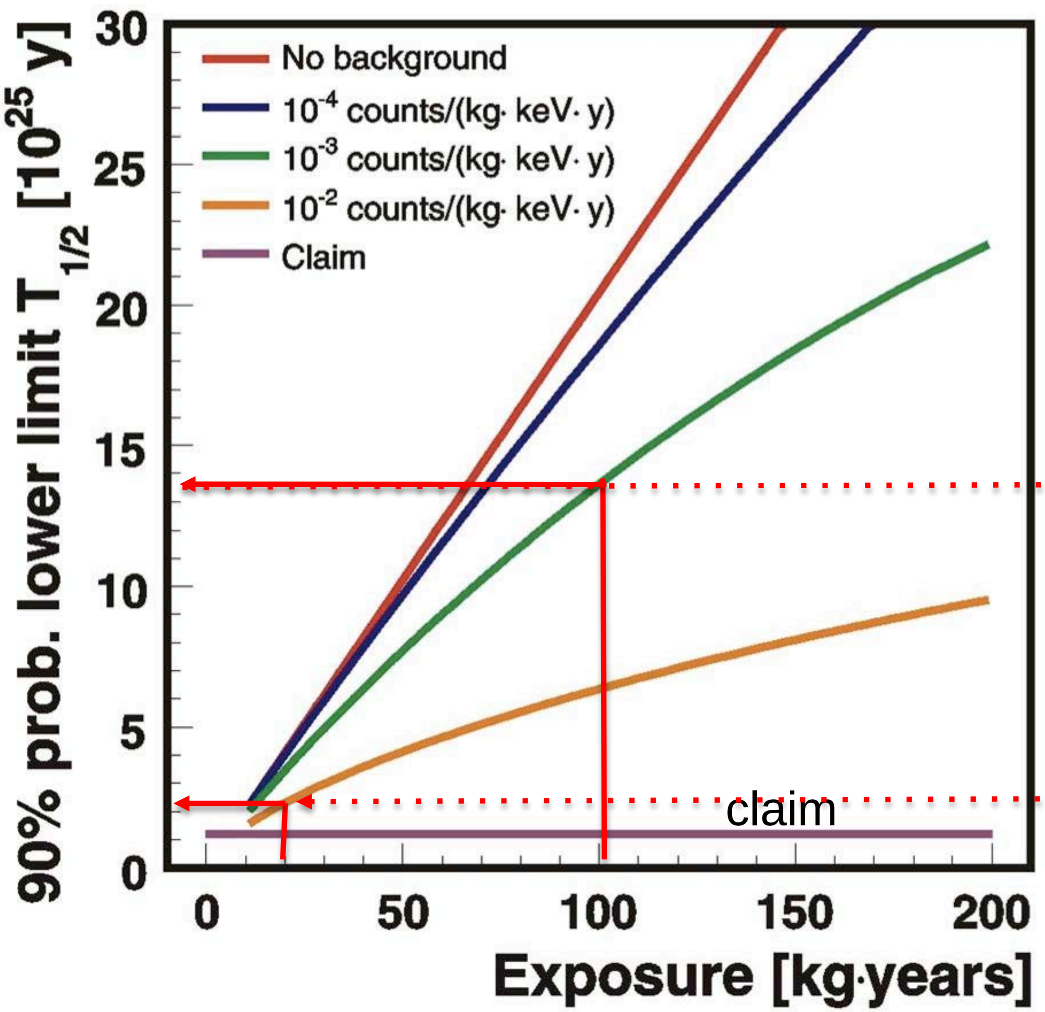
βγ decay

GERDA D&G

Phase I results

Conclusions

Realization in phases

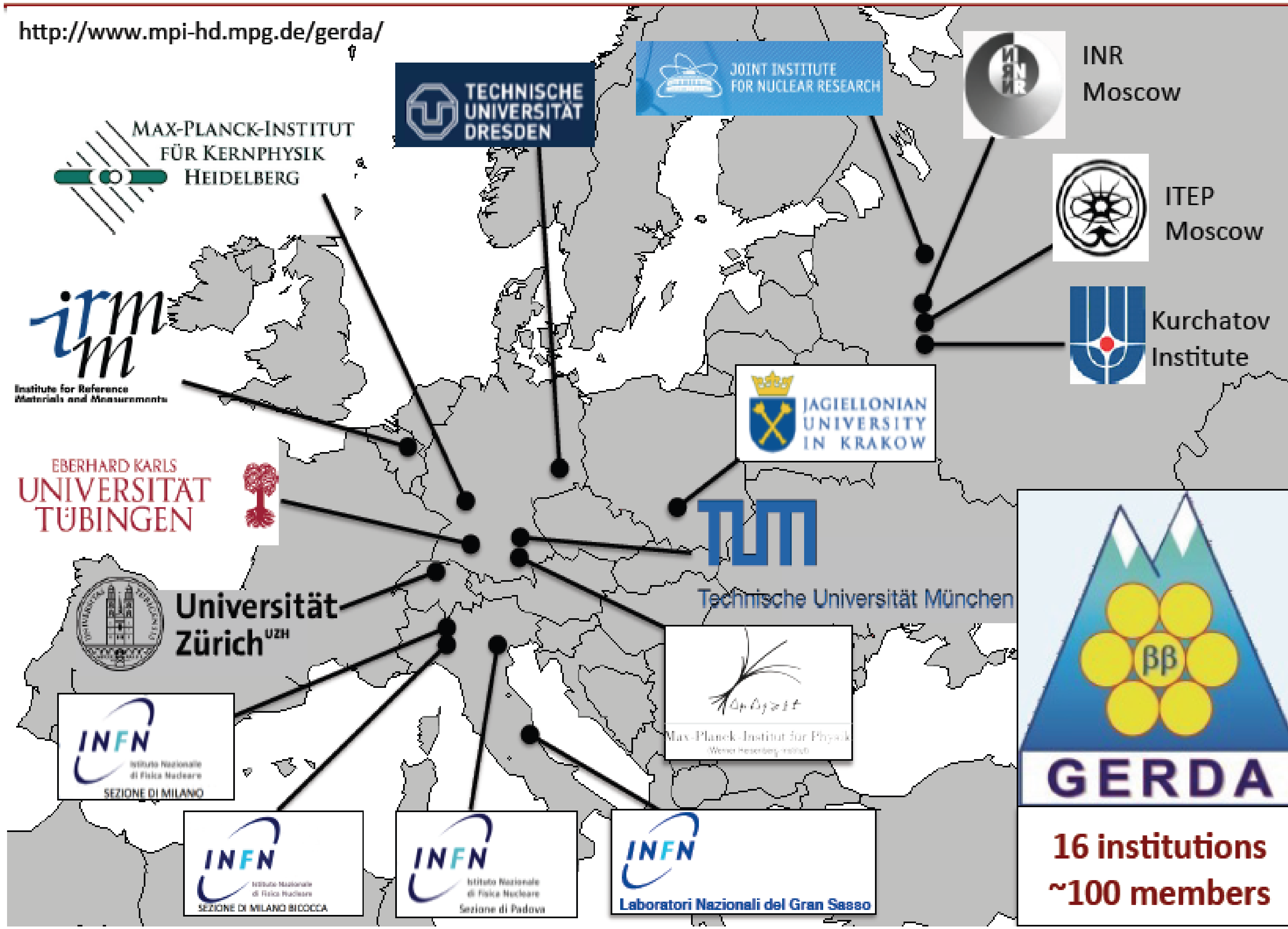


<u>Phase II:</u>
Add new enr. BEGe detectors (~20 kg)
BI ≈ 0.001 cts / (keV×kg×yr)
Sensitivity after 100 kg×yr

<u>Phase I:</u>
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV×kg×yr)
Sensitivity after 20 kg×yr

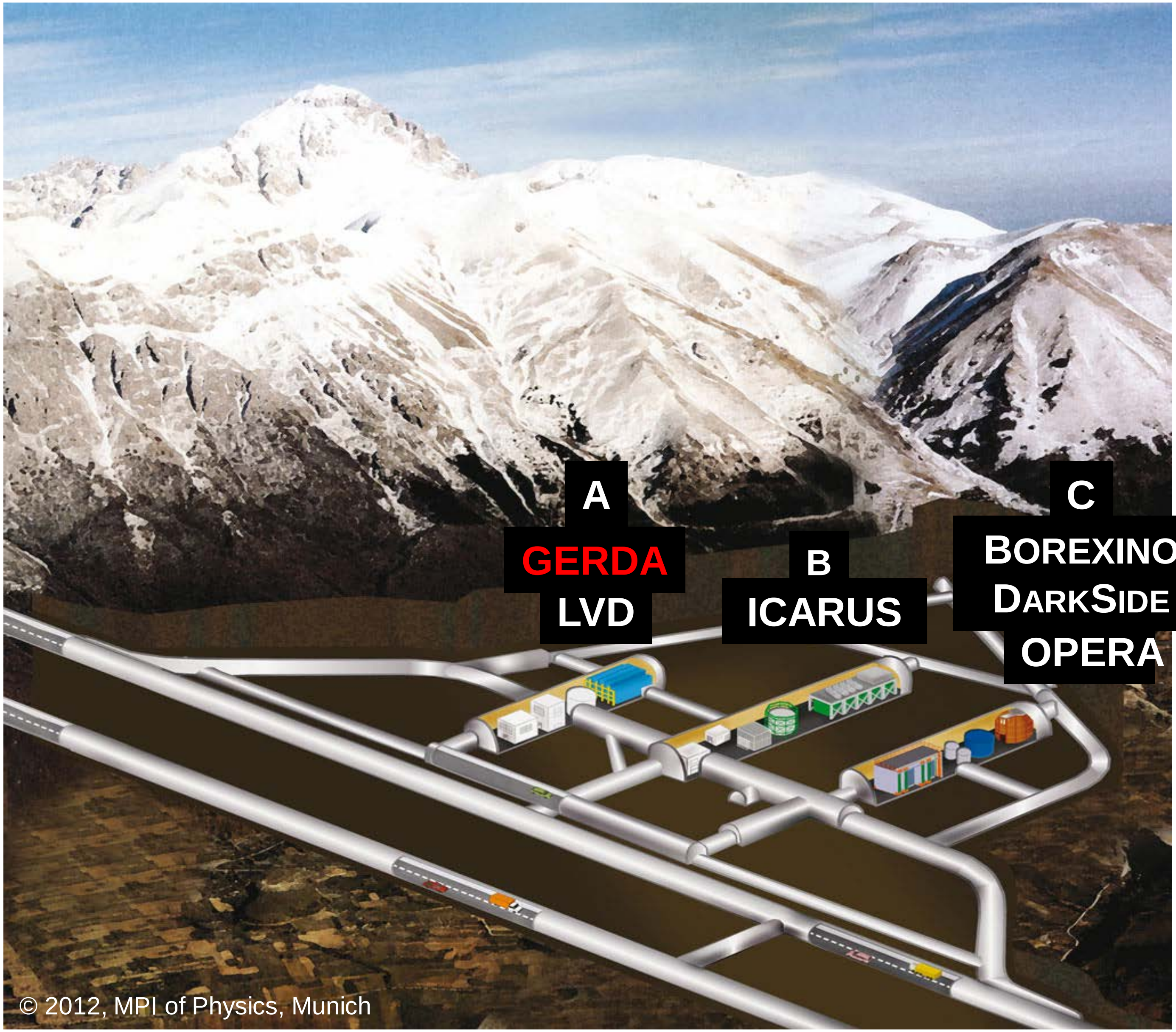
The GERDA Collaboration

- ββ decay
- GERDA D&G
- Phase I results
- Conclusions



GERDA in LNGS

ββ decay
GERDA D&G
Phase I results
Conclusions



GERDA milestones

- ββ decay
- GERDA D&G
- Phase I results
- Conclusions

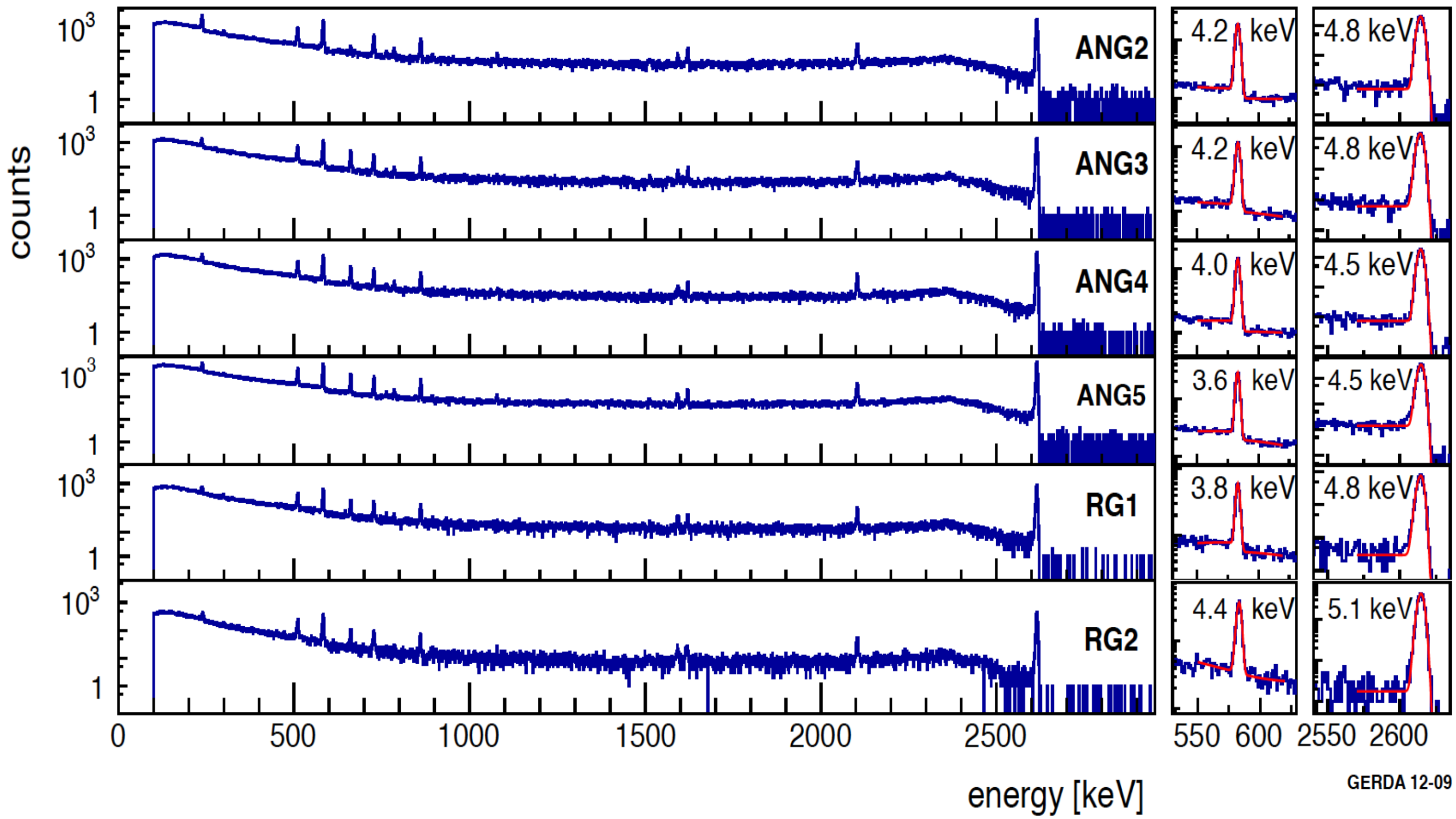
- 2004 – 2005: The collaboration was formed
- 2005 – 2010: GERDA funded, designed and constructed in LNGS Hall A
- June 2010: Commissioning started. One string (3 ^{nat}Ge detectors, 7.6 kg) deployed for the first time. Checking the detector's performance
- June 2010 – June 2011: Detailed investigation of background sources with ^{nat}Ge (^{42}Ar, ^{228}Th, cosmogenics)
- June 2011: Deployment of the first string of ^{enr}Ge (3 detectors, 6.7 kg)
- 01.11.2011: Start data taking with all 8 Phase I ^{enr}Ge crystals (17.8 kg) and 1 ^{nat}Ge crystal (from GTF)
- June 2012 5 Phase II enr. BEGe detectors inserted into the cryostat (3.6 kg)
- Phase I data: 09.11.11 – 09.05.13 (21.6 kg×yr acquired)

GERDA data analysis

- Data around $Q_{\beta\beta}$ (±20/5 keV) were blinded
- Background analyzed in a wider window of $Q_{\beta\beta} \pm 200$ keV
- PSD procedures (for coax and BEGe detectors) developed and documented (internally) in advance
- Discussion and freezing of all parameters and methods prior to unblinding
- Unblinding at Dubna Collaboration meeting (22-24 June 2013)

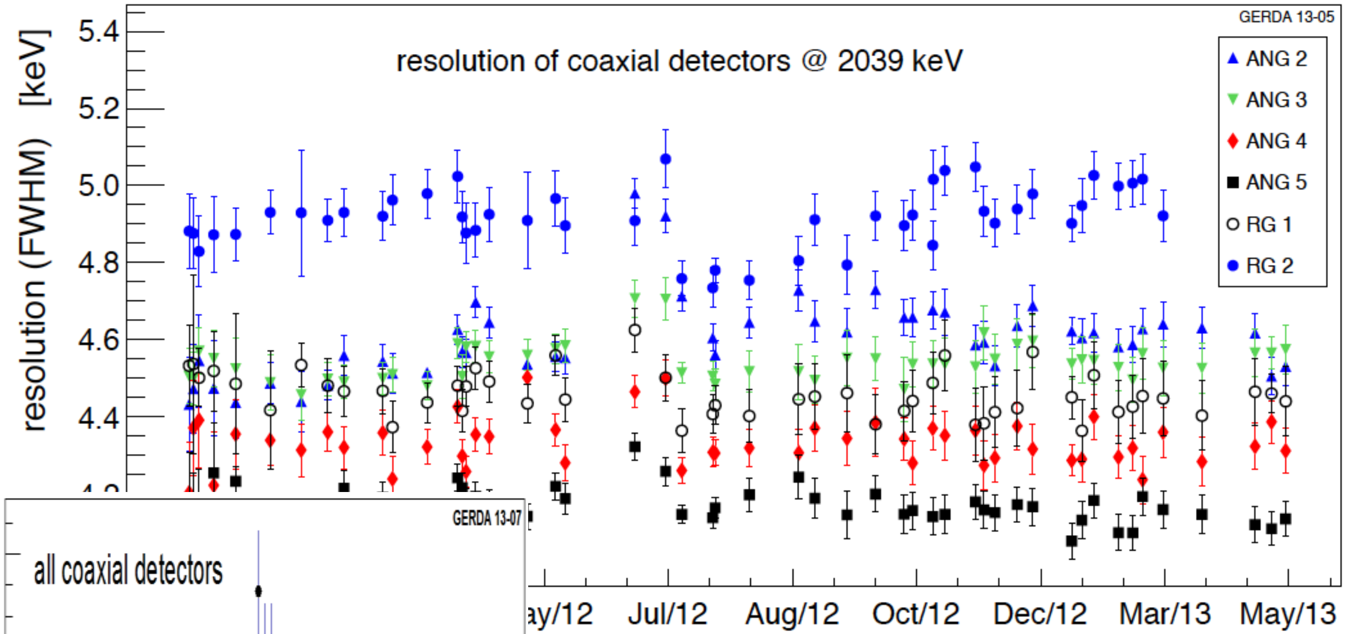
Calibration

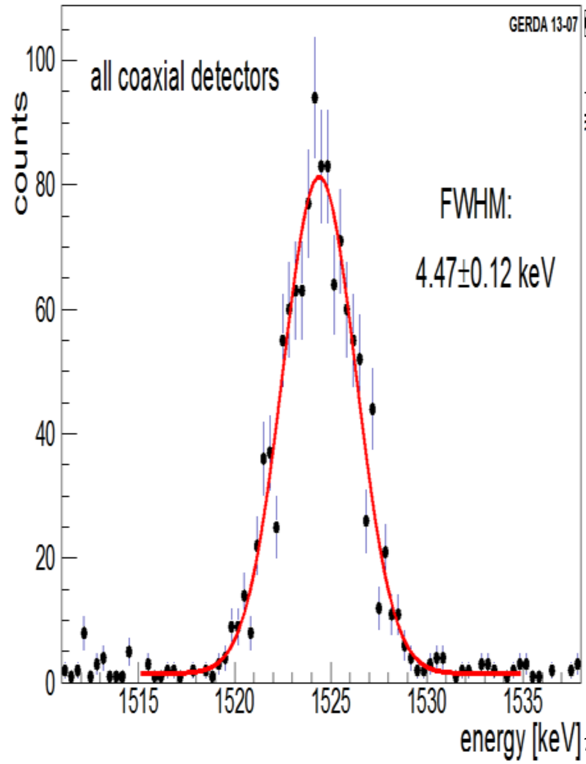
^{228}Th calibration once every one to two weeks; stability continuously monitored with pulser



Stability of detectors

- ββ decay
- GERDA D&G
- Phase I results
- Conclusions





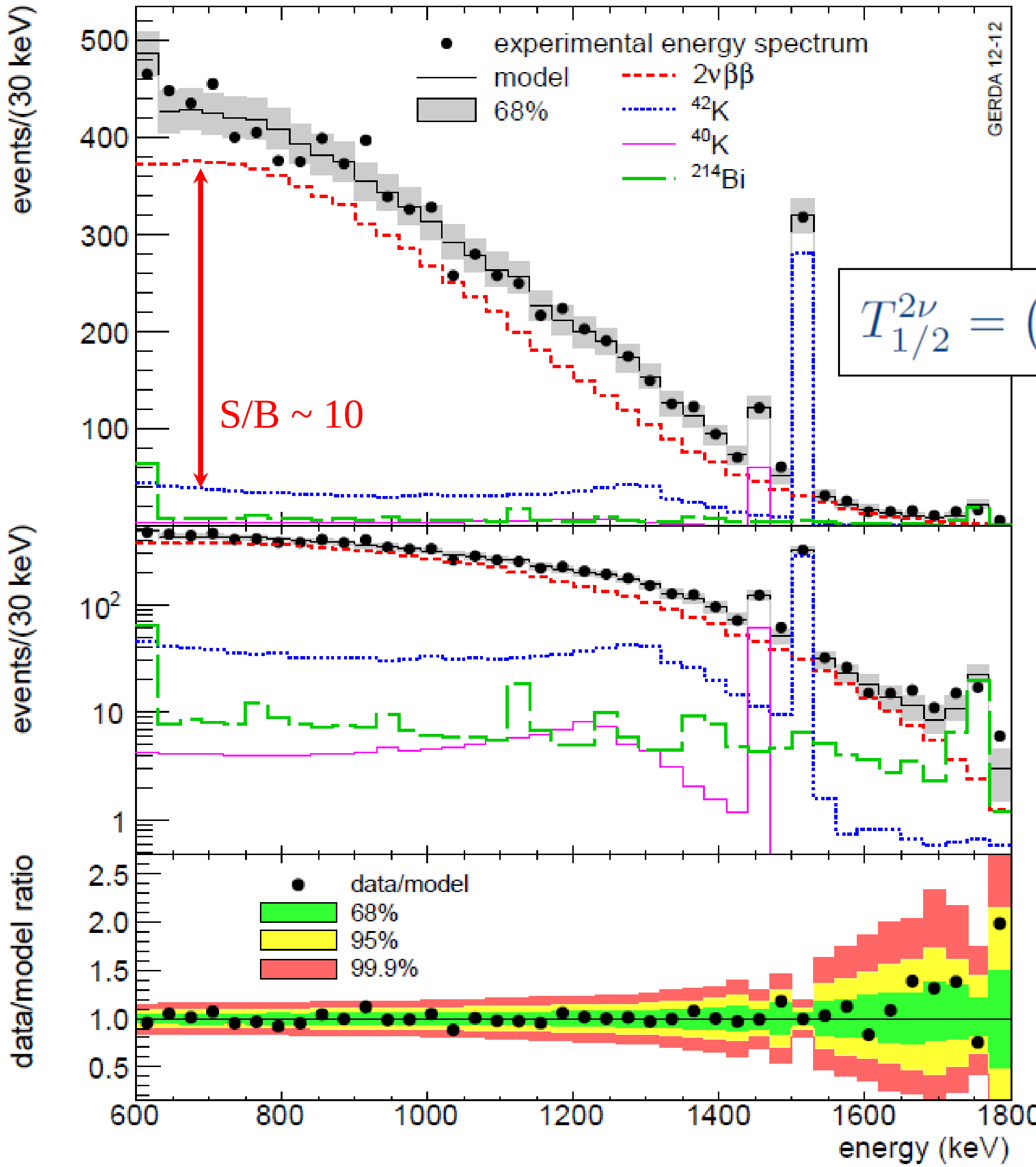
Peak position stability of 2614.5 keV calibration line: coax: 1.5 keV / BEGe: 1.0 keV (FWHM)

Mean energy resolution at $Q_{\beta\beta}$ =2039 keV:

- Coax: 4.8 keV (FHWM)
- BEGe: 3.2 keV (FWHM)

Half life for 2νββ

- ββ decay
- GERDA D&G
- Phase I results
- Conclusions



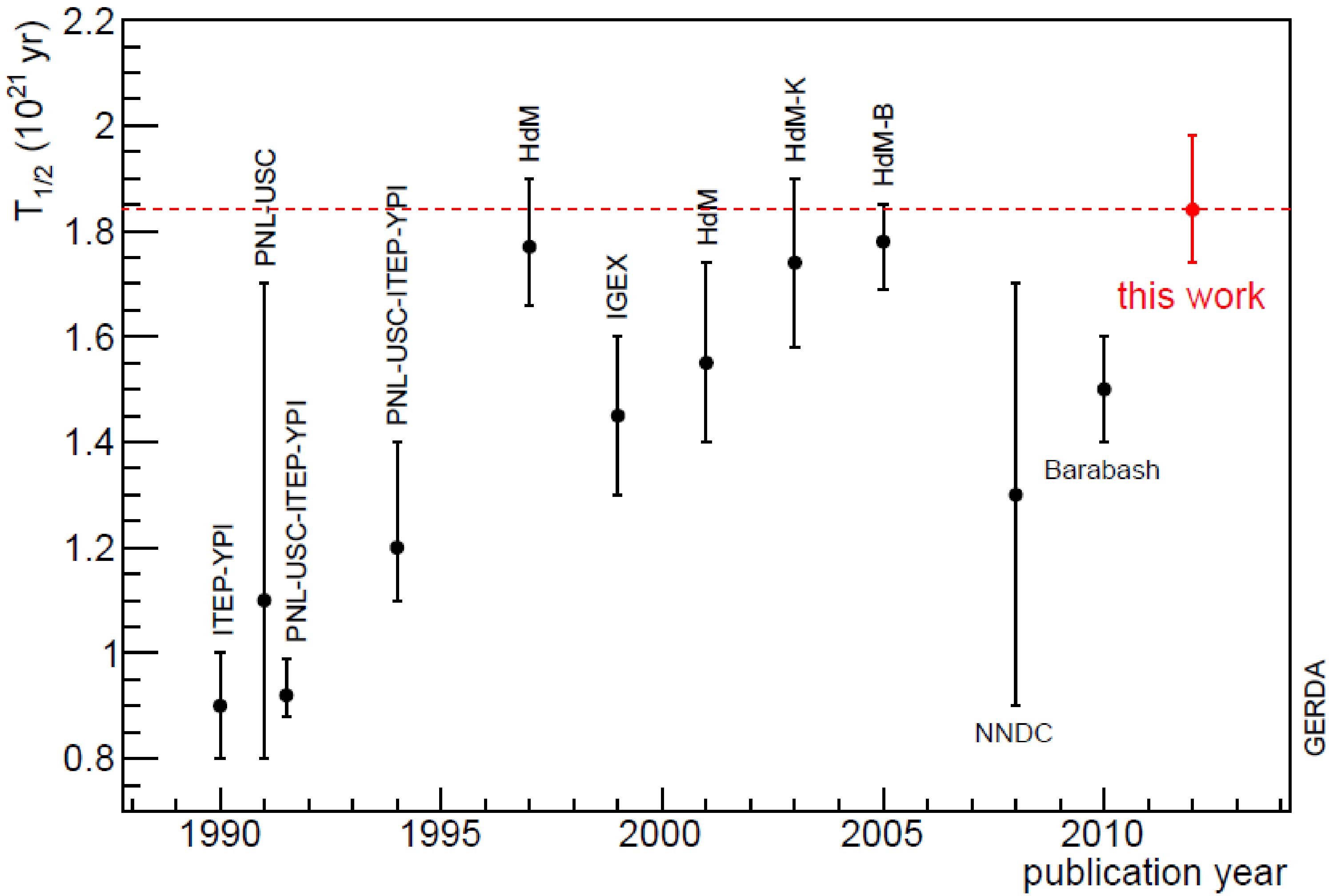
$$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08}) \times 10^{21}\ \text{yr}$$

J. Phys. G: Nucl. Part. P hys. 40 (2013) 035110

Background model: arXiv:1306.5084 submitted to EPJC

Half life for 2νββ

$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08}) \times 10^{21}\ \mathrm{yr}$$



ββ decay

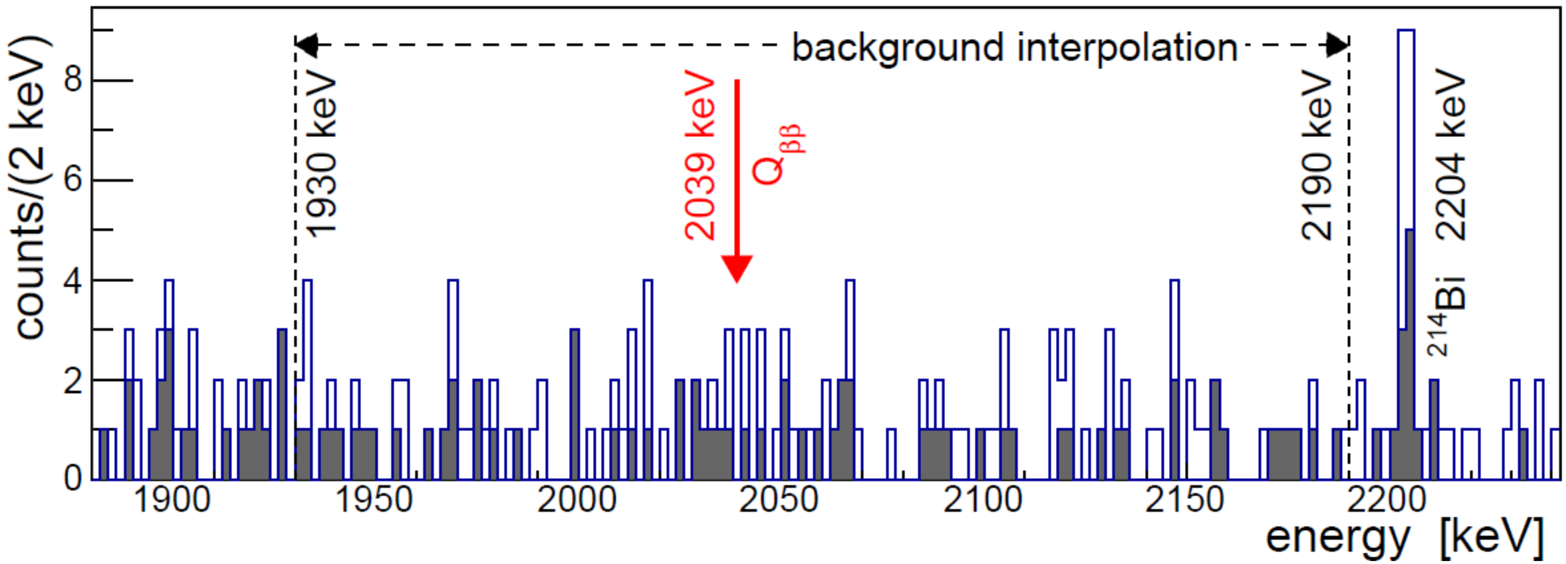
GERDA D&G

Phase I results

Conclusions

After data unblinding

Analysis details in paper accepter by Phys. Rev. Lett.; arXiv:1307.4720



before PSD

after PSD

Total counts in BW (10 keV)	Expected (bgd only)	Observed
without PSD	5.1	7
with PSD	2.5	3

PSD methods for coaxial and BEGe's: arXiv:1307.2610
(submitted to EPJC)

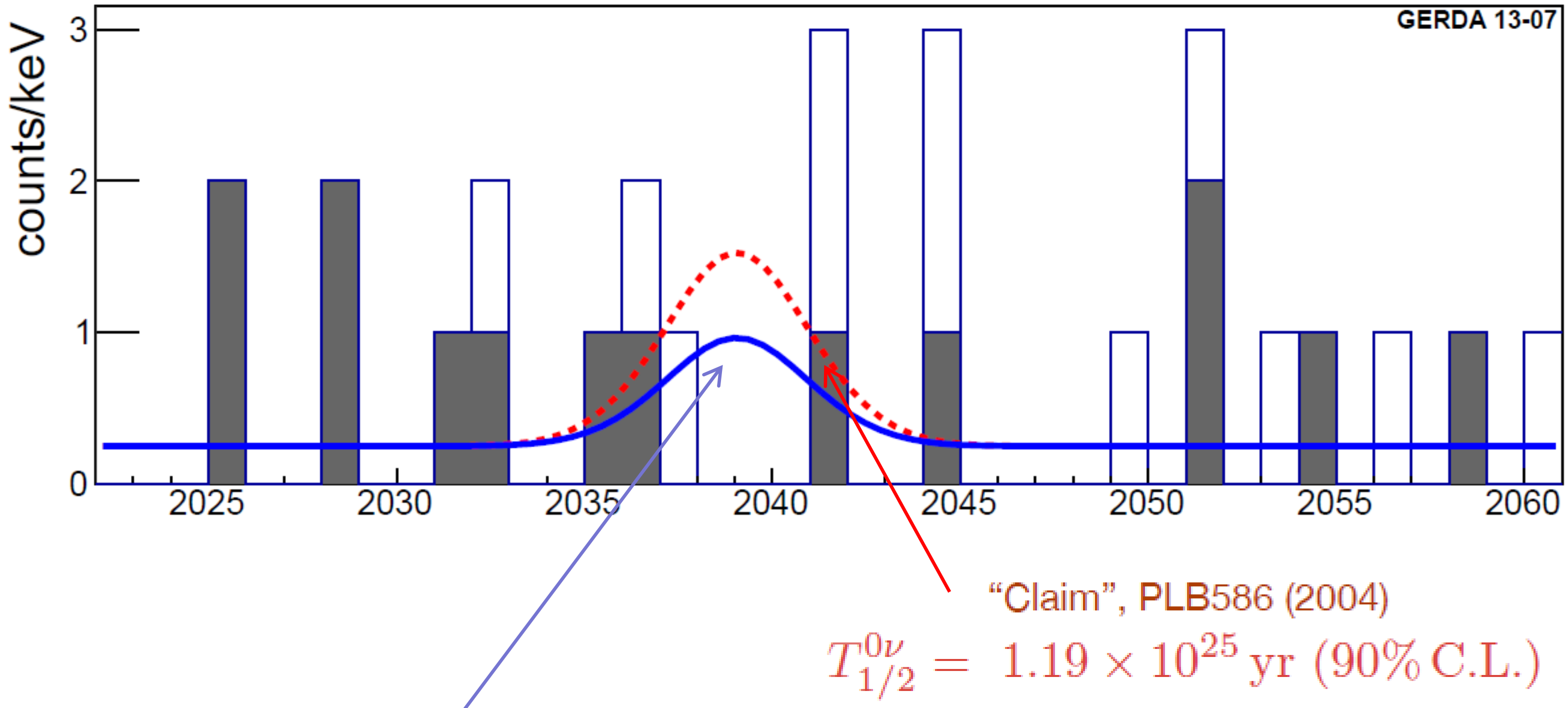
After data unblinding

ββ decay

GERDA D&G

Phase I results

Conclusions



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

- 90% lower limit derived from profile likelihood (Frequentist limit, flat bgd)
- BW = 10 keV
- Best fit: **$N^{0\nu} = 0$**
- **No excess** of signal counts above the background
- Limit on half-life corresponds to $N^{0\nu} < 3.5$ cts

Comparison with the claim

Expectation for claimed $T_{1/2}^{0\nu}$ =1.19×10^{25} yr: 5.9 ±1.4 signal over 2.0 ± 0.3 bgd in ±2σ energy window to be compared with 3 cts (0 in ±1σ)

H1: claimed signal: 5.9 ± 1.4 cts
H0: background only

Bayes factor: P(H1)/P(H0) = 0. 024

p-value from profile likelihood
$P(N^{0\nu} = 0|H1) = 0.01$

➔Claim refuted with high probability

Combining available Ge data:

HdM: Eur. Phys. J. A 12, 147 (2001)
IGEX: Phys. Rev. D 65, 092007 (2002)
Phys. Rev. D 70 078302 (2004)

$$T_{1/2}^{0\nu} > 3.0 \cdot 10^{25} \text{ yr} \quad (90\,\% \quad \text{C.L.})$$

P(H1)/P(H0) = 2×10^{-4} strongly disfavors the claim: Comparison is independent of NME and of physical mechanism which generates 0νββ

ββ decay
GERDA D&G
Phase I results
Conclusions

Conclusions

- **GERDA Phase I design goals reached:**
  - Background index after PSD: 0.01 cts / (keV×kg×yr)
  - Exposure 21.6 kg×yr

- **No $0\nu\beta\beta$-signal observed at $Q_{\beta\beta}$ = 2039 keV; best fit: $N^{0\nu} = 0$**
  - Background-only hypothesis H_0 strongly favored
  - Claim strongly disfavored (independent of NME and of leading term)

- **Limit on half-life:**

  GERDA: $T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)

  GERDA+IGEX+HdM: $T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.)

  $\langle m_{ee} \rangle < 0.2 - 0.4$ eV

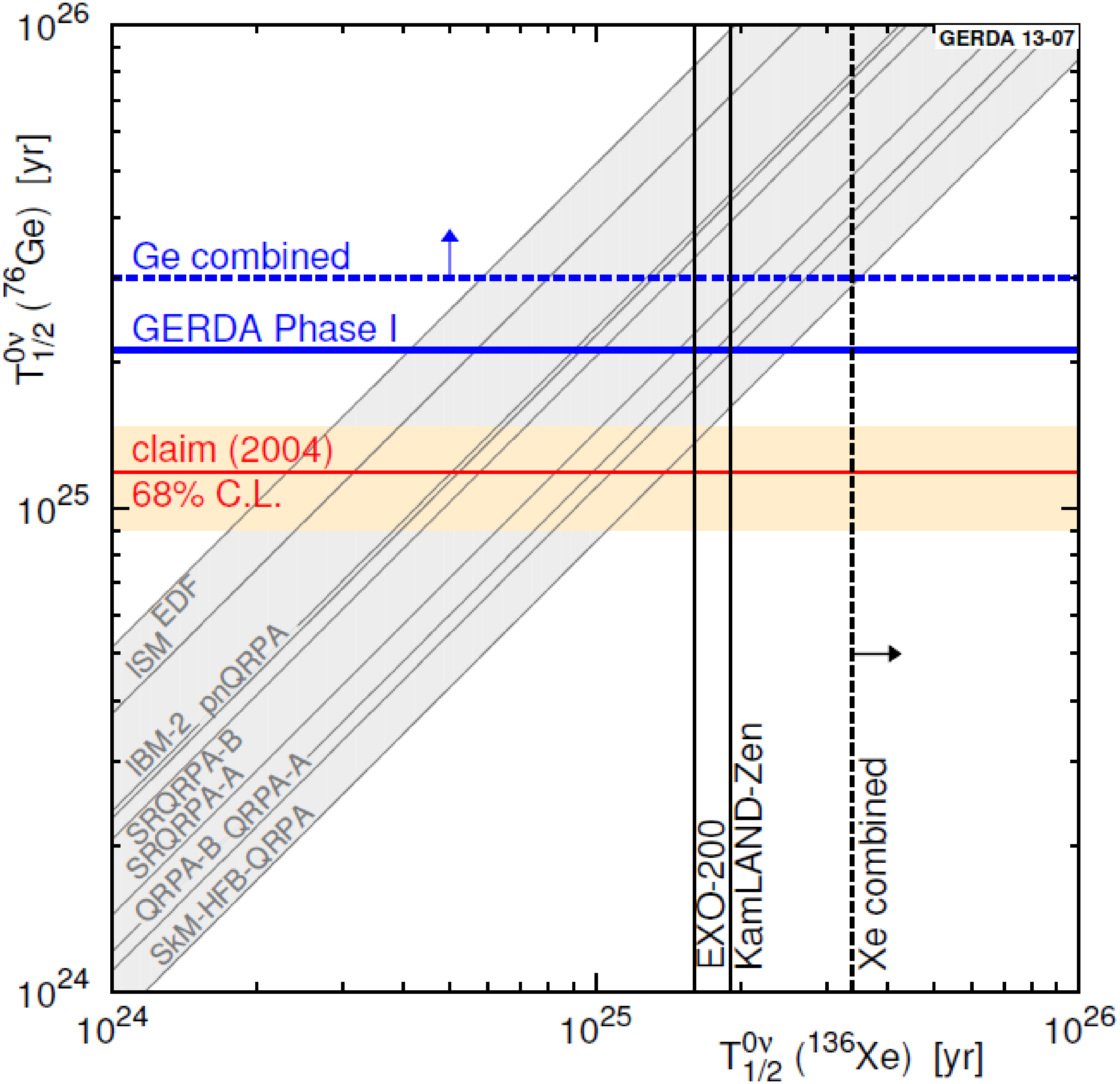
- Results reached after only 21.6 kg×yr exposure because of **unprecedented low background:** bgd counts in ±2σ after analysis cuts:

  0.01 cts /(mol×yr) (EXO: 0.07, KL: 0.67)

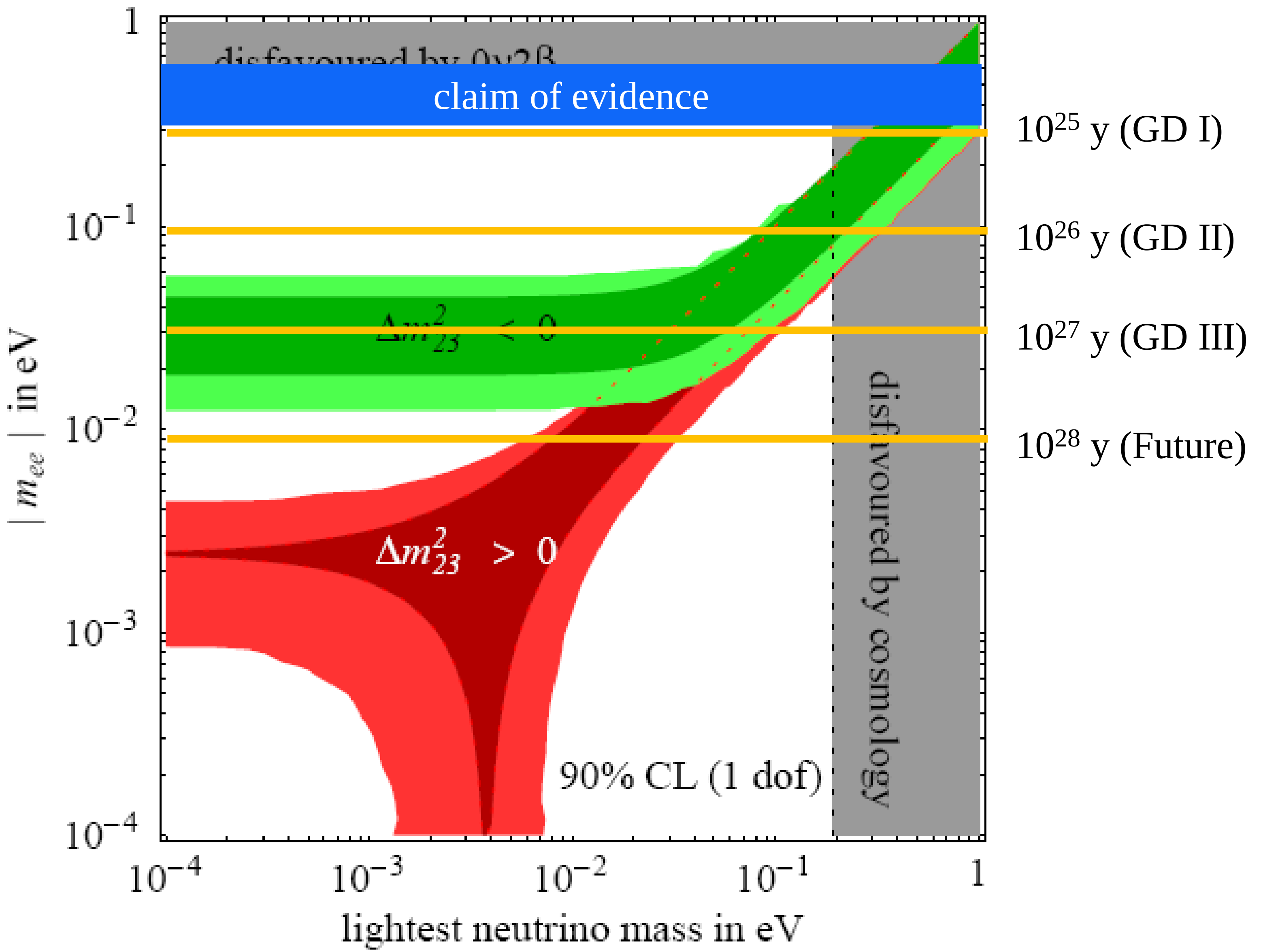
- **GERDA Phase II will start in late 2013**

Backup slides

Ge / Xe combined results



Effective neutrino mass



From counts to half life

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}$$

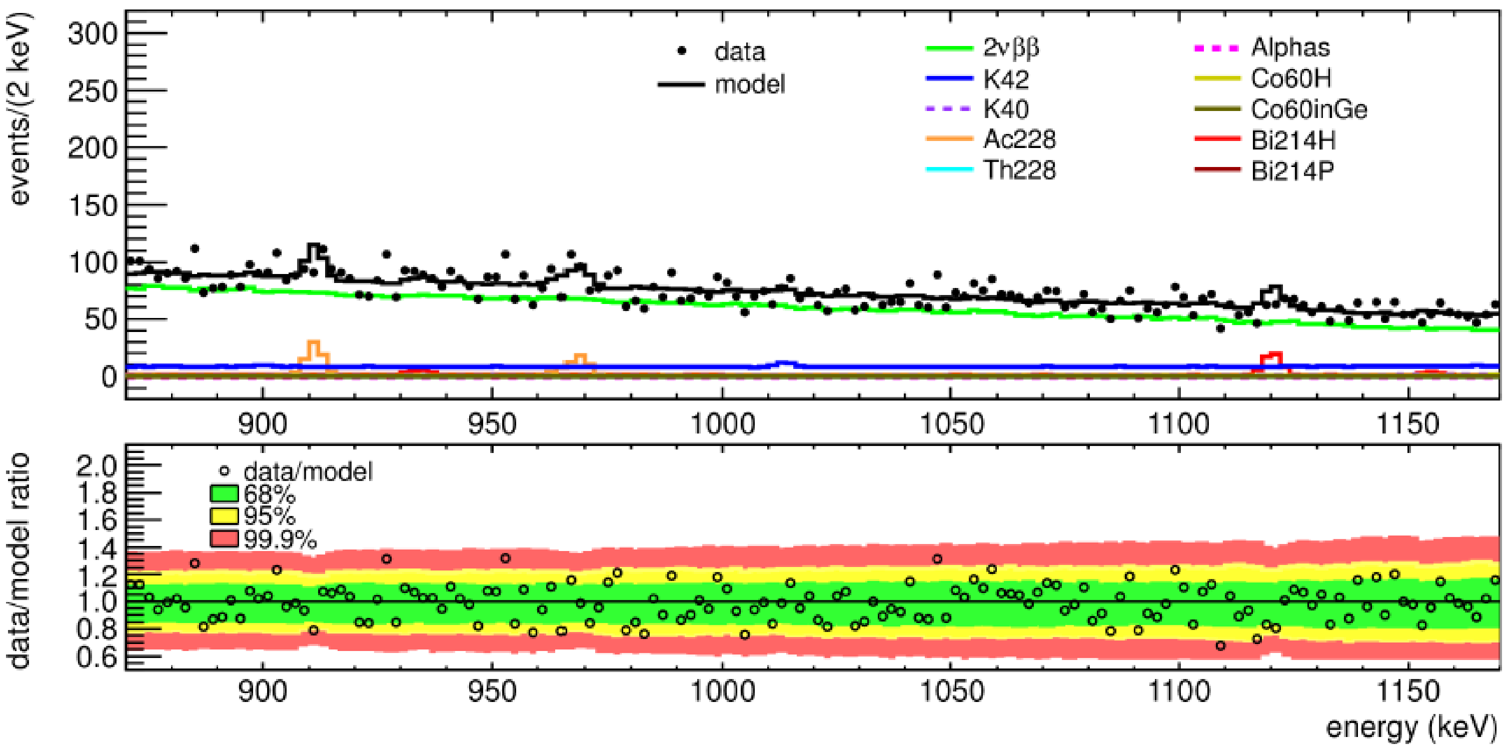
Data set	Exposure (kg yr)
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

f_{76}: enrichment fraction
f_{av}: fraction of active detector volume
ε_{fep}: full energy peak efficiency for 0νββ
ε_{psd}: signal acceptance

	$\langle f_{76} \rangle$	$\langle f_{av} \rangle$	$\langle \varepsilon_{fep} \rangle$	$\langle \varepsilon_{psd} \rangle$	$\langle \varepsilon \rangle$
Coax	0.86	0.87	0.92	0.90 +0.05/ -0.09	0.619 +0.044/-0.070
BEGe	0.88	0.92	0.90	0.92 ± 0.02	0.663 ± 0.022

Min. model Gold-coax data (17.9 kg·yr)



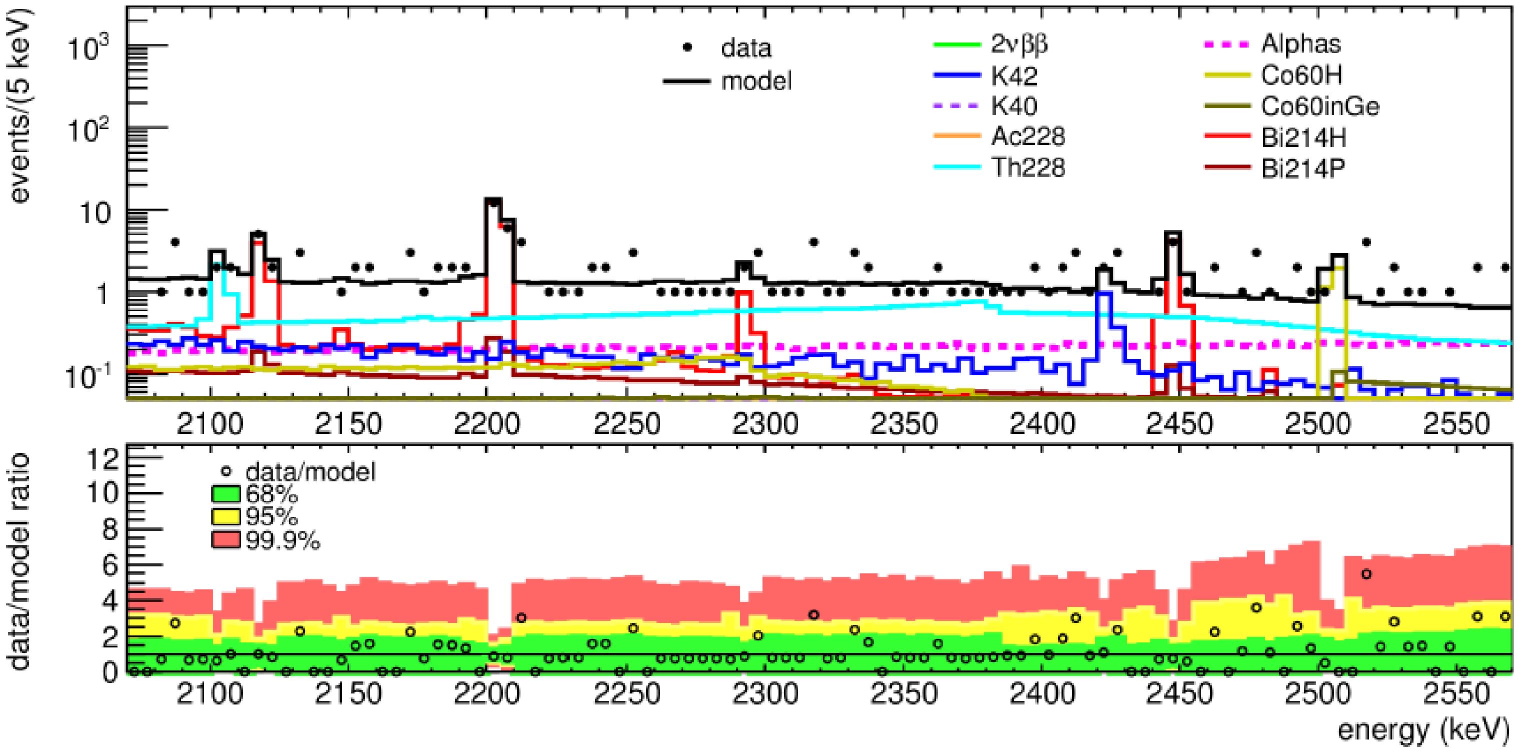
(870 – 1170) keV in 2 keV bins → (1170-870)/2 = 150 data points

116 out of 150 points (77%) are inside the green band (expected 68%)

143 out of 150 points (95%) are inside the yellow band (expected 95%)

150 out of 150 points (100%) are inside the red band (expected 99.9%)

Min. model Gold-coax data (17.9 kg·yr)



(2070 – 2570) keV in 5 keV bins → (2570-2070)/5 = 100 data points

81 out of 100 points (81%) are inside the green band (expected 68%)

97 out of 100 points (97%) are inside the yellow band (expected 95%)

100 out of 100 points (100%) are inside the red band (expected 99.9%)

Neutrinoless ββ beta decay

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot \gamma \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

$$\frac{1}{\tau} = G(Q,Z) \cdot |M_{nuc}|^2 \cdot < mee >^2$$

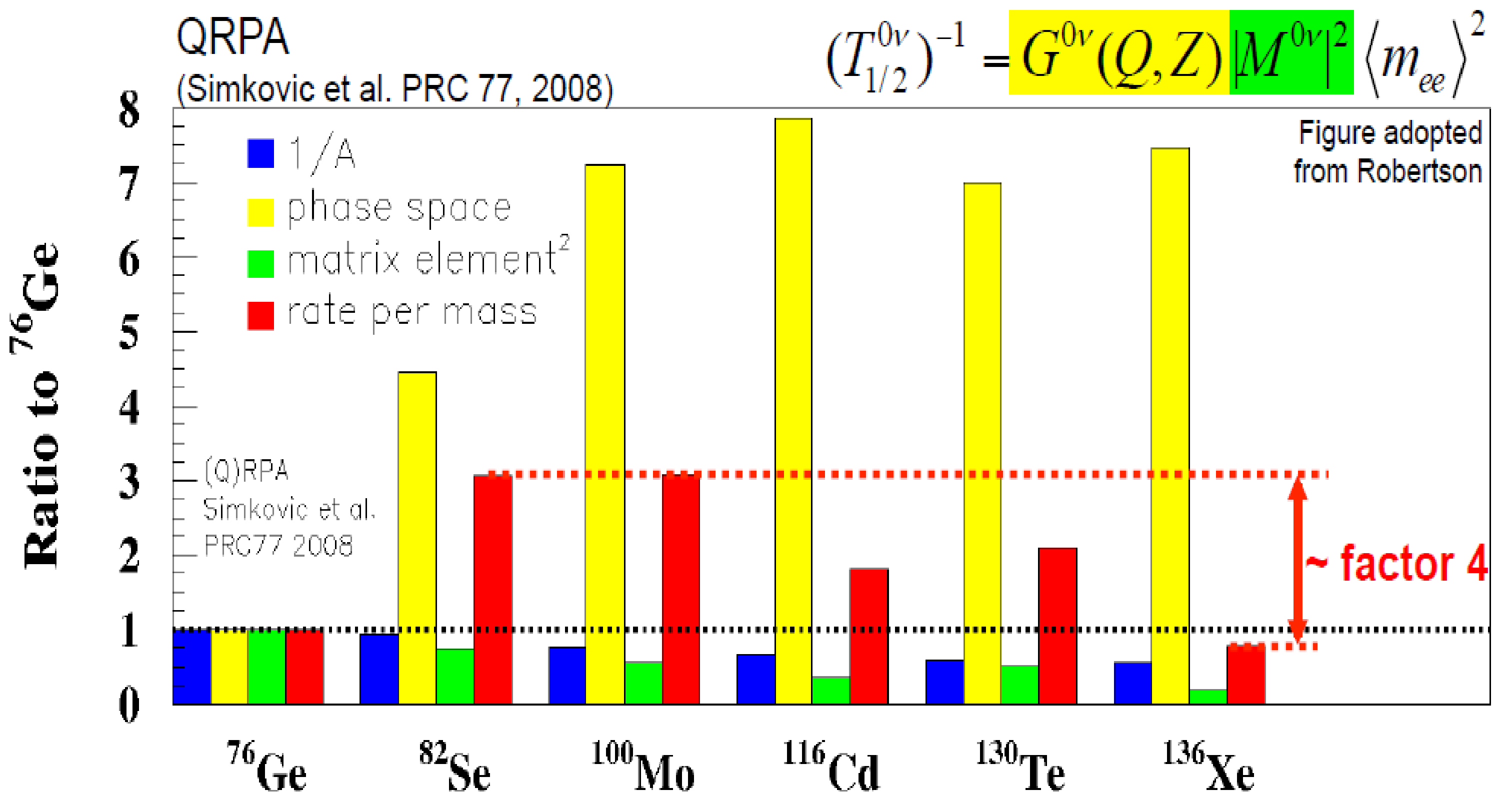
Space factor

Nuclear matrix element

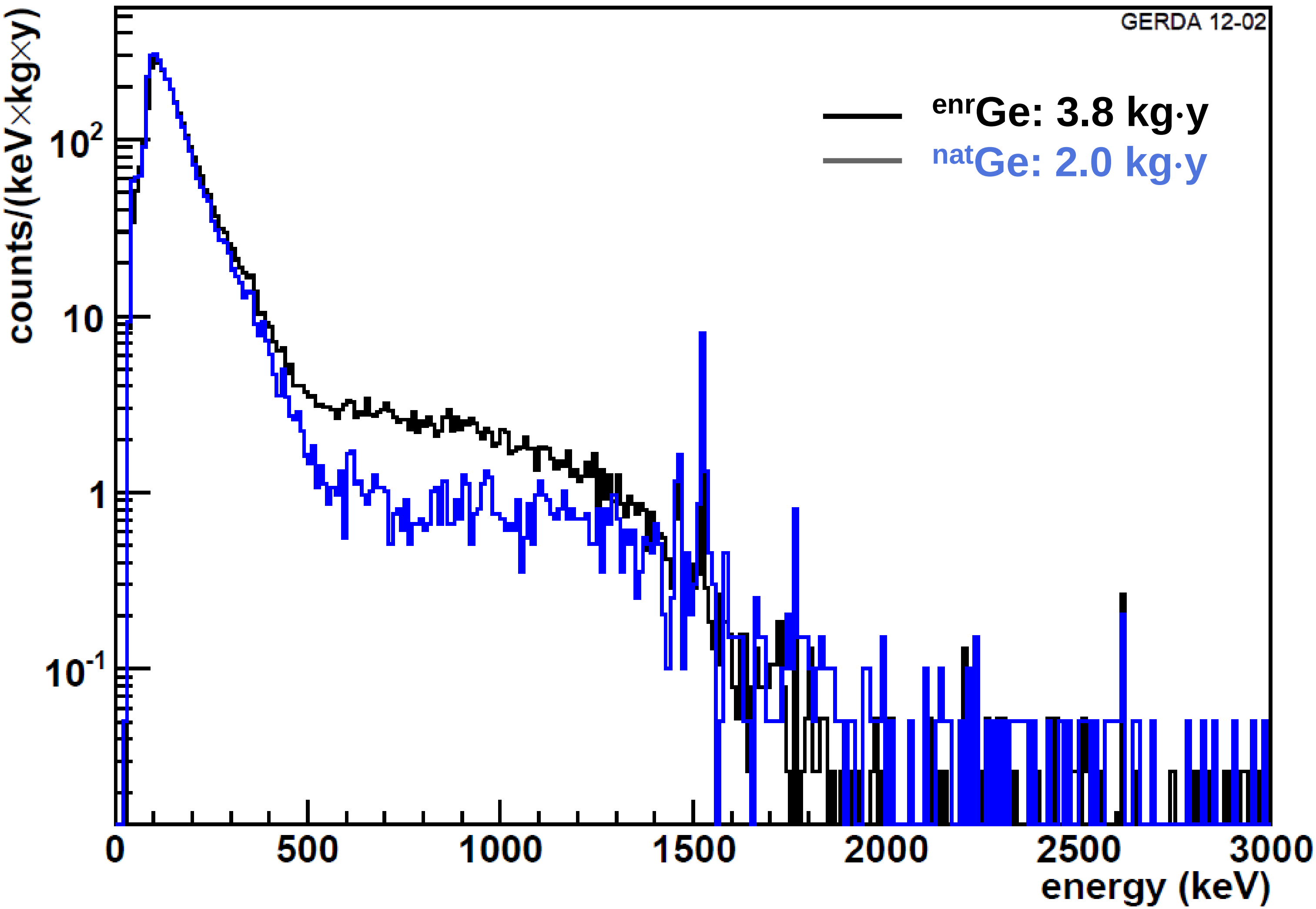
Effective neutrino mass

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

„Super" isotope for 0νββ

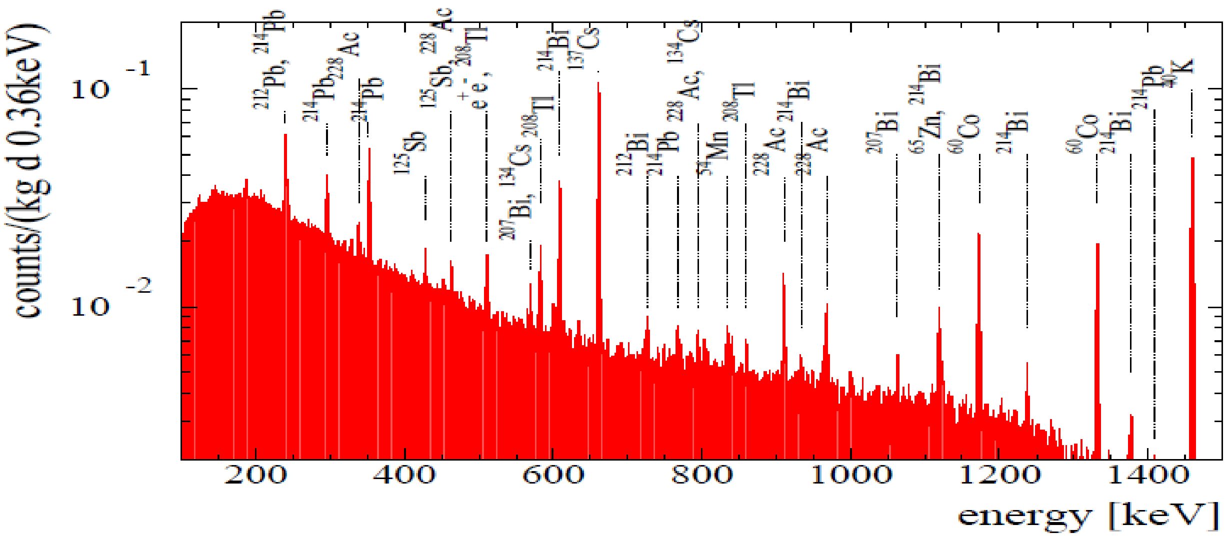


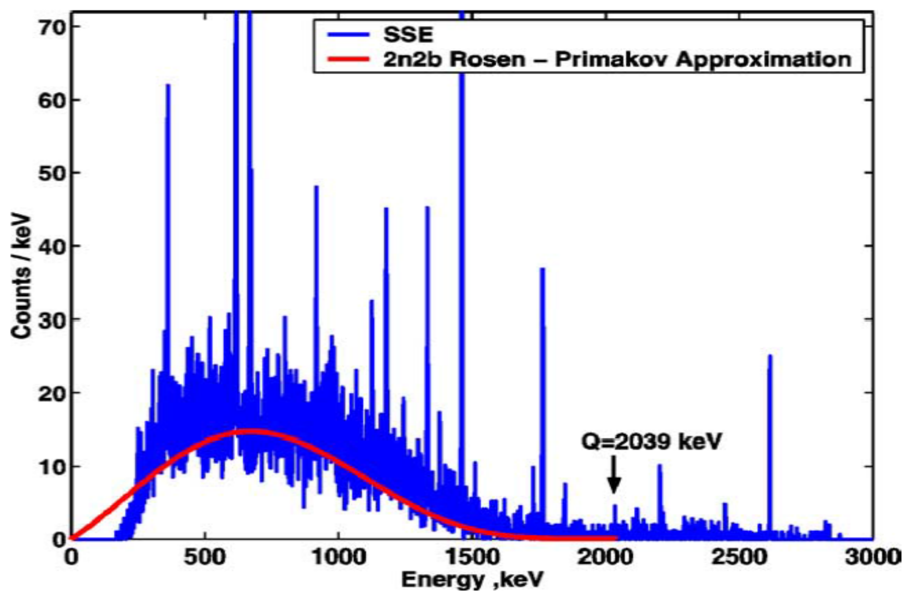
Spectra ^{nat}Ge vs ^{enr}Ge



HdM spectrum

hep-ph/0302248





$T_{1/2}^{2\nu\beta\beta} = 1.74 \cdot 10^{21}$ y

Neutrino masses

0νββ decay: $< m_{ee} > = |\sum_j m_j U_{ej}^2|$

β decay: $\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$

Cosmology: $\Sigma = \sum m_i$