


Results on neutrinoless double beta decay of ^{76}Ge from GERDA Phase I

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on behalf of the GERDA collaboration

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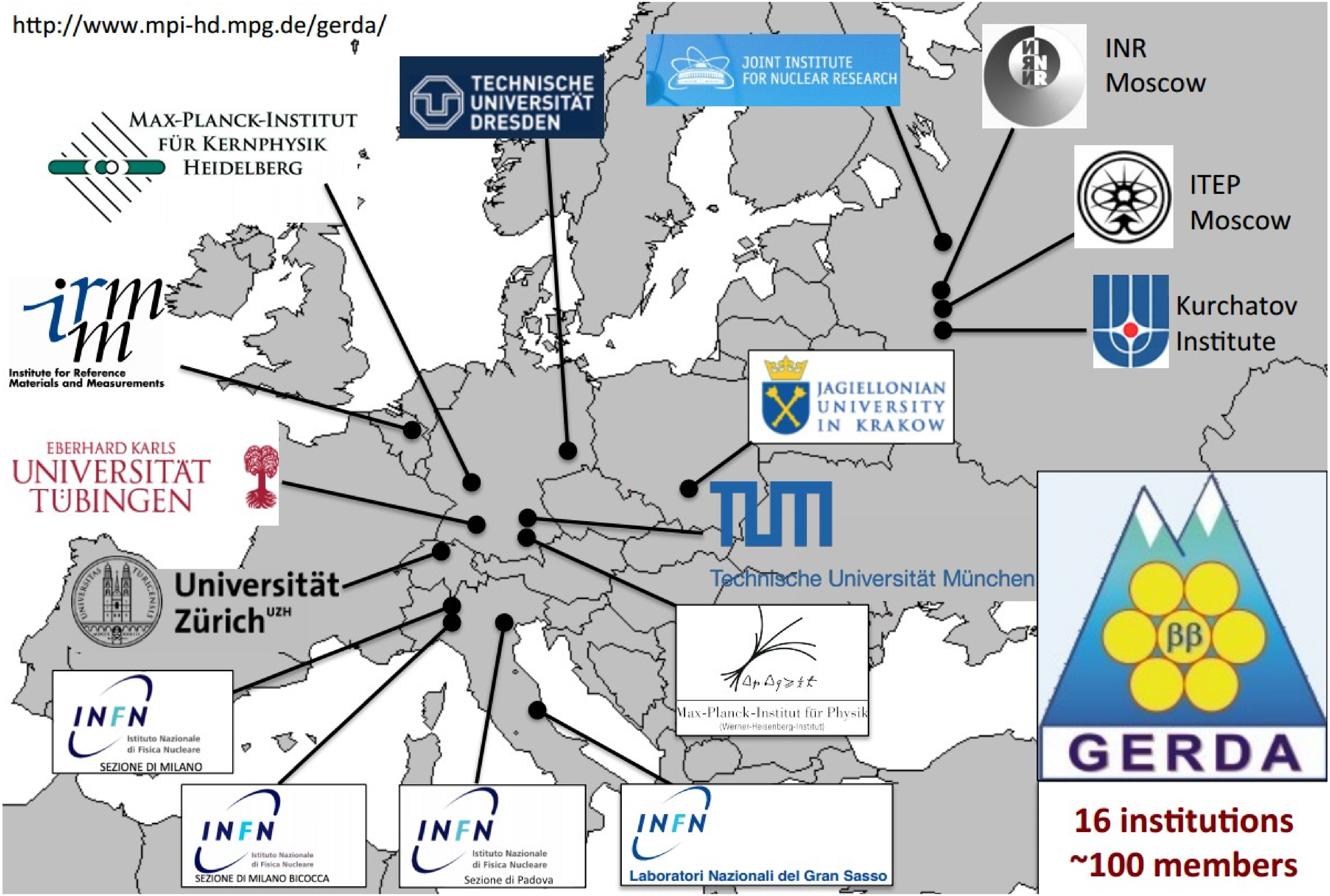
Rencontres de Blois, 18 – 23 May 2014



http://www.mpi-hd.mpg.de/gerda/
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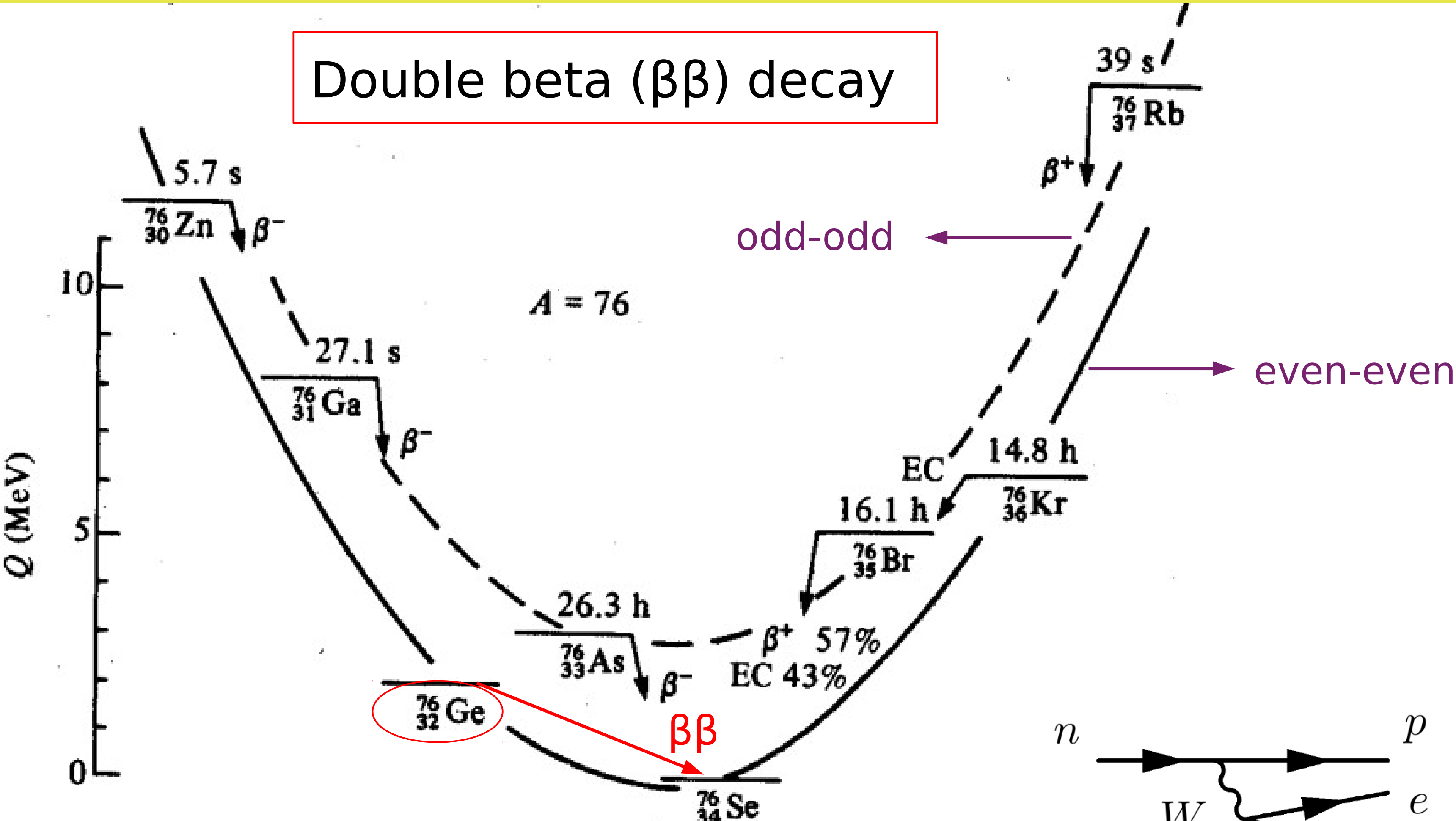
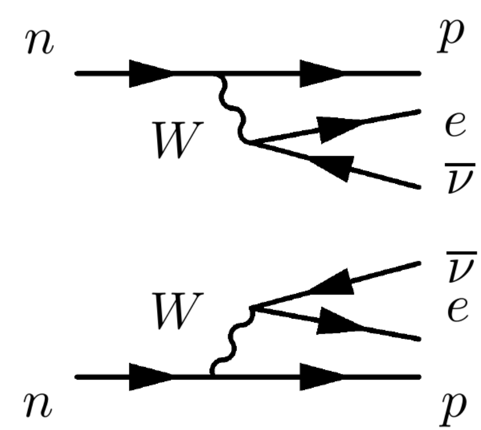
GERDA
16 institutions
~100 members

OUTLINE

- Double beta decay → neutrinoless final state 0νββ
- GERDA experimental design
- Phase I data taking: energy calibration & resolution, energy spectrum
- Background modeling (before unblinding of the signal window)
- Unblinding
- Results of 0νββ analysis
- Outlook on Phase II

Double beta (ββ) decay





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

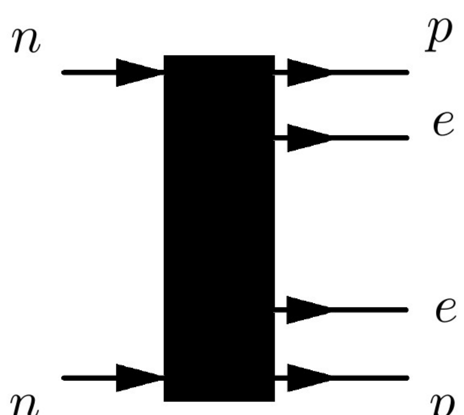
→ observed in e.g. ^{76}Ge, ^{130}Te, ^{136}Xe, …
with $T_{1/2}$ in the range of 10^{19} – 10^{24} yr

$T_{1/2}$ (^{76}Ge) = $(1.84\,^{+0.14}_{-0.10}) \cdot 10^{21}$ yr GERDA result (in backup slides)

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

Neutrinoless double beta (0νββ) decay:

(A, Z) → (A, Z+2) + 2e⁻



$\nu = \bar{\nu}$

ΔL = 2 light Majorana ν, R-handed weak currents, SUSY particles...

Assuming light Majorana ν ($m_{\beta\beta}$) exchange dominating:

$$(T_{1/2})^{-1} = G_{0\nu} \, |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Phase-space factor Nuclear matrix element

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

ν mass spectrum: inverted/normal hierarchy? absolute mass scale?

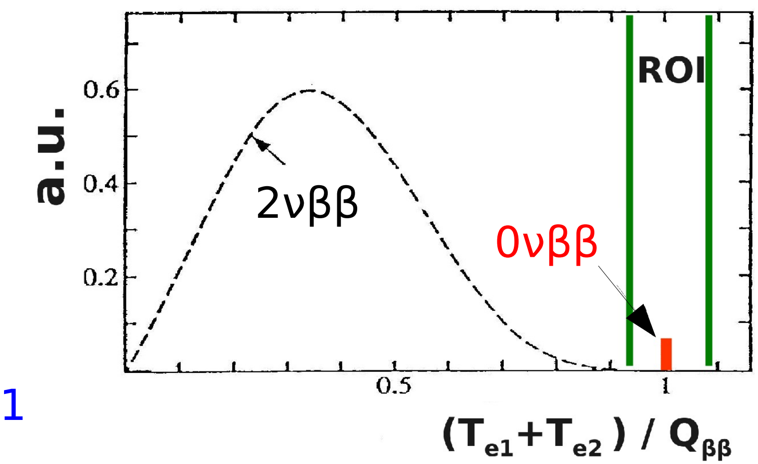
$T_{1/2}$ limits in the range of 10^{21} – 10^{26} yr

(one claim for ^{76}Ge 0νββ decay signal)

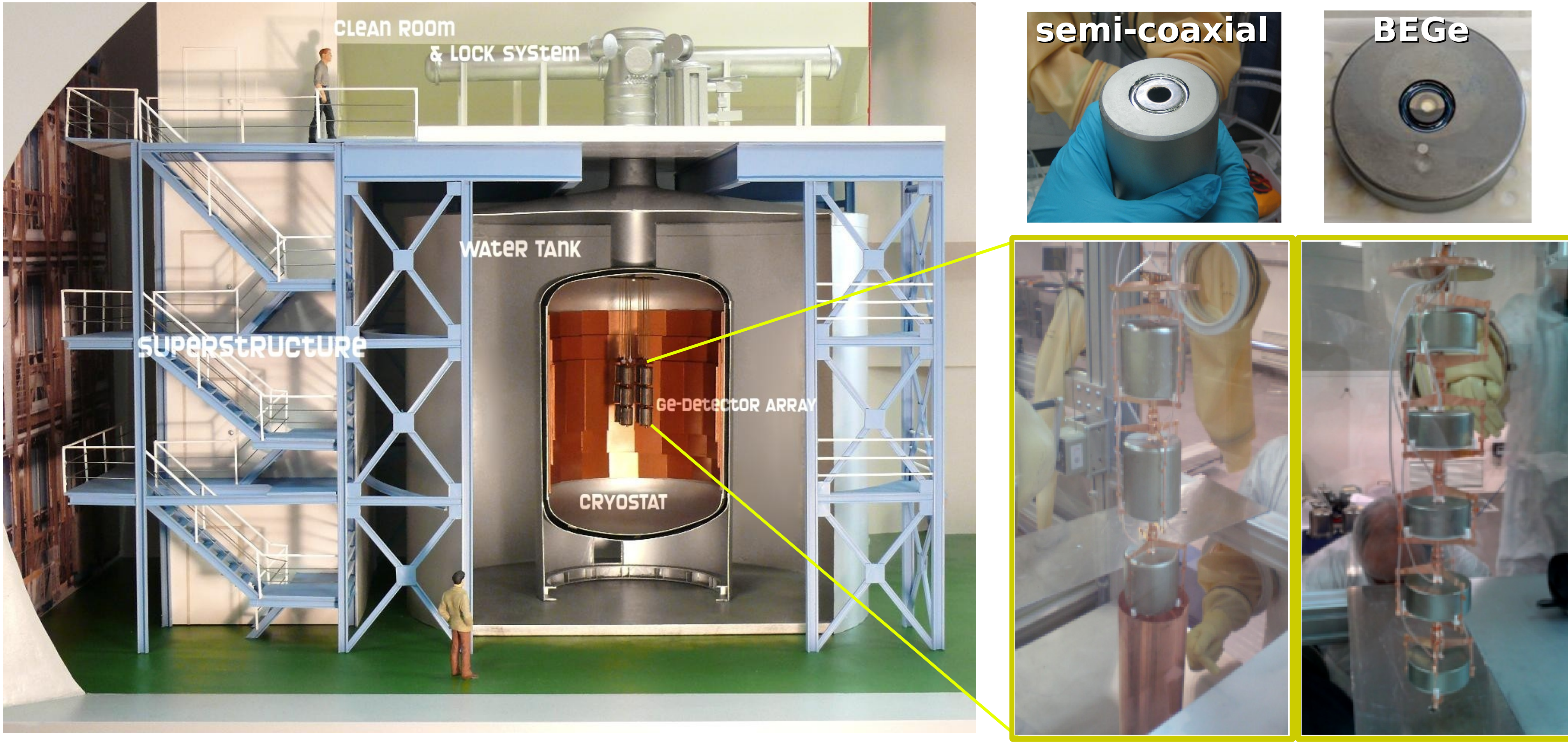
Experimental signature: peak at $Q_{\beta\beta}$

for ^{76}Ge: $Q_{\beta\beta}$ = (2039.061 ± 0.007) keV

B. J. Mount *et al.*, Phys. Rev. 401 C81 (2010) 032501



GERDA experiment @ LNGS of INFN, Italy search for 0νββ decay in ^{76}Ge



- Novel idea: operate HPGe detectors in LAr
- High-purity shields: LAr, ultra-pure water (active muon-veto)
- Minimal amount of (screened) material close to detectors

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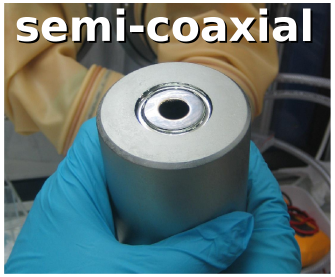
Phase-I data taking: November 2011 – May 2013



8 semi-coaxial p-type HPGe detectors
(reprocessed HdM and IGEX diodes)

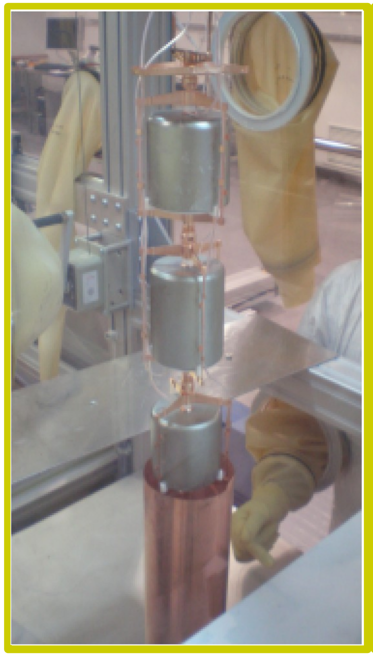
→ Total mass: 14.6 kg (2 unstable dets. omitted)

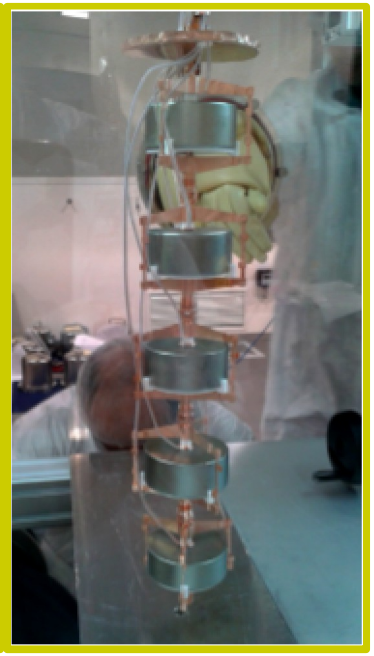
5 new custom-made p-type (Phase II) BEGe detectors

→ Total mass: 3.0 kg (1 unstable det. omitted)

Enrichment fraction (^{76}Ge abundance):

Semi-coaxials ~86%   BEGes ~88%





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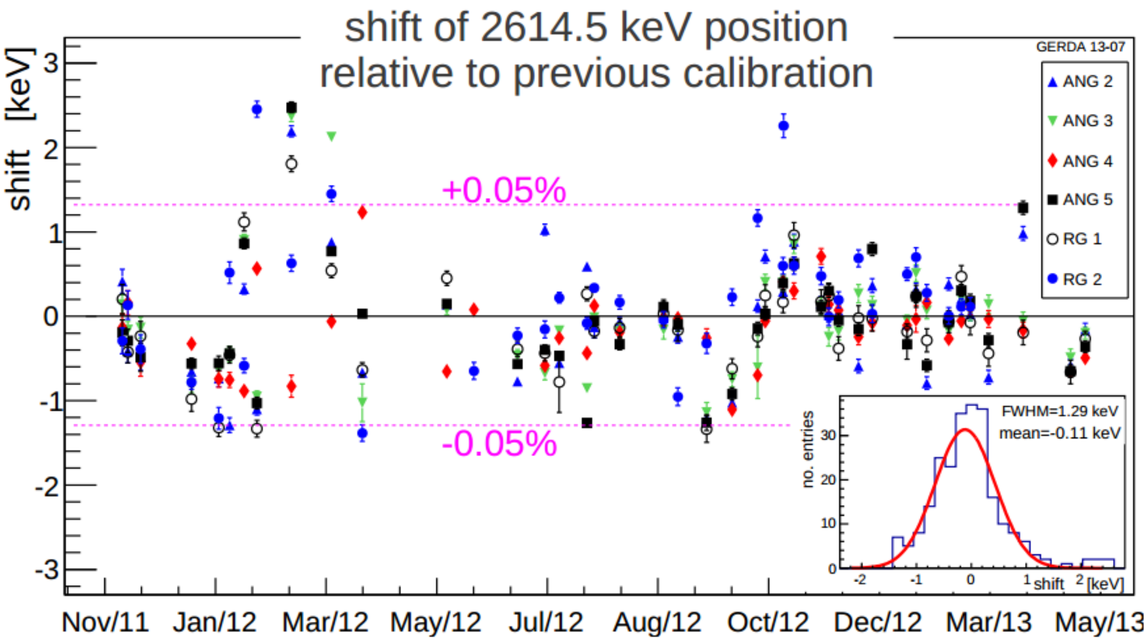
Calibration and energy resolution

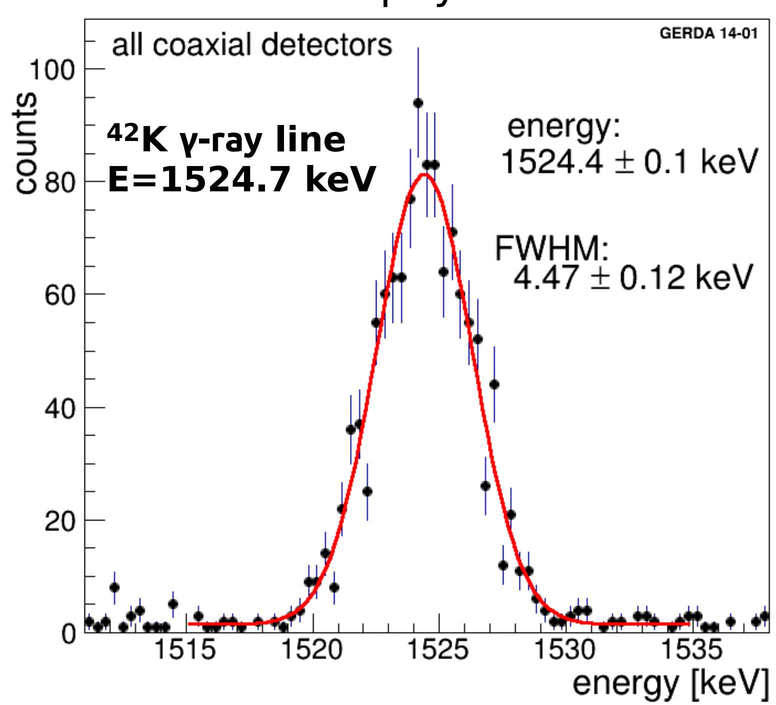
(Bi-)weekly calibration runs with ^{228}Th source



Energy shift between successive calib.
≤ 1 keV @ $Q_{\beta\beta}$ (20 – 30% of FWHM)
→ can sum all data for analysis

mean FWHM @ $Q_{\beta\beta}$ = 2039 keV:
Semi-coaxials (4.8 ± 0.2) keV
BEGes (3.2 ± 0.2) keV
stable over the entire period

Sum of all physics runs



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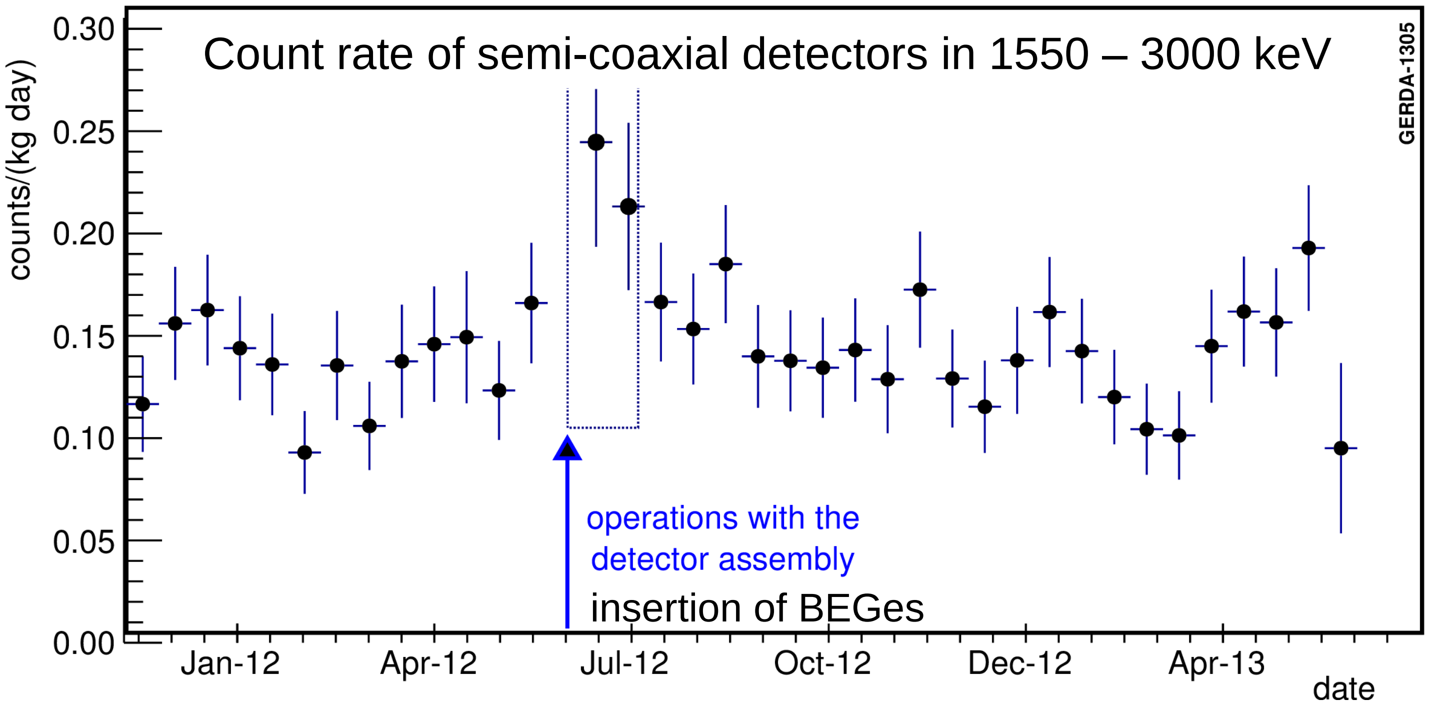
THREE DATASETS: grouping of data due to energy res. and bkg. level

Semi-coaxial detectors form two subsets:

Golden	**17.9 kg yr**
Silver	**1.3 kg yr**

BEGe detectors (starting from Jul-2012):

BEGe	**2.4 kg yr**
Total exposure	**21.6 kg yr**



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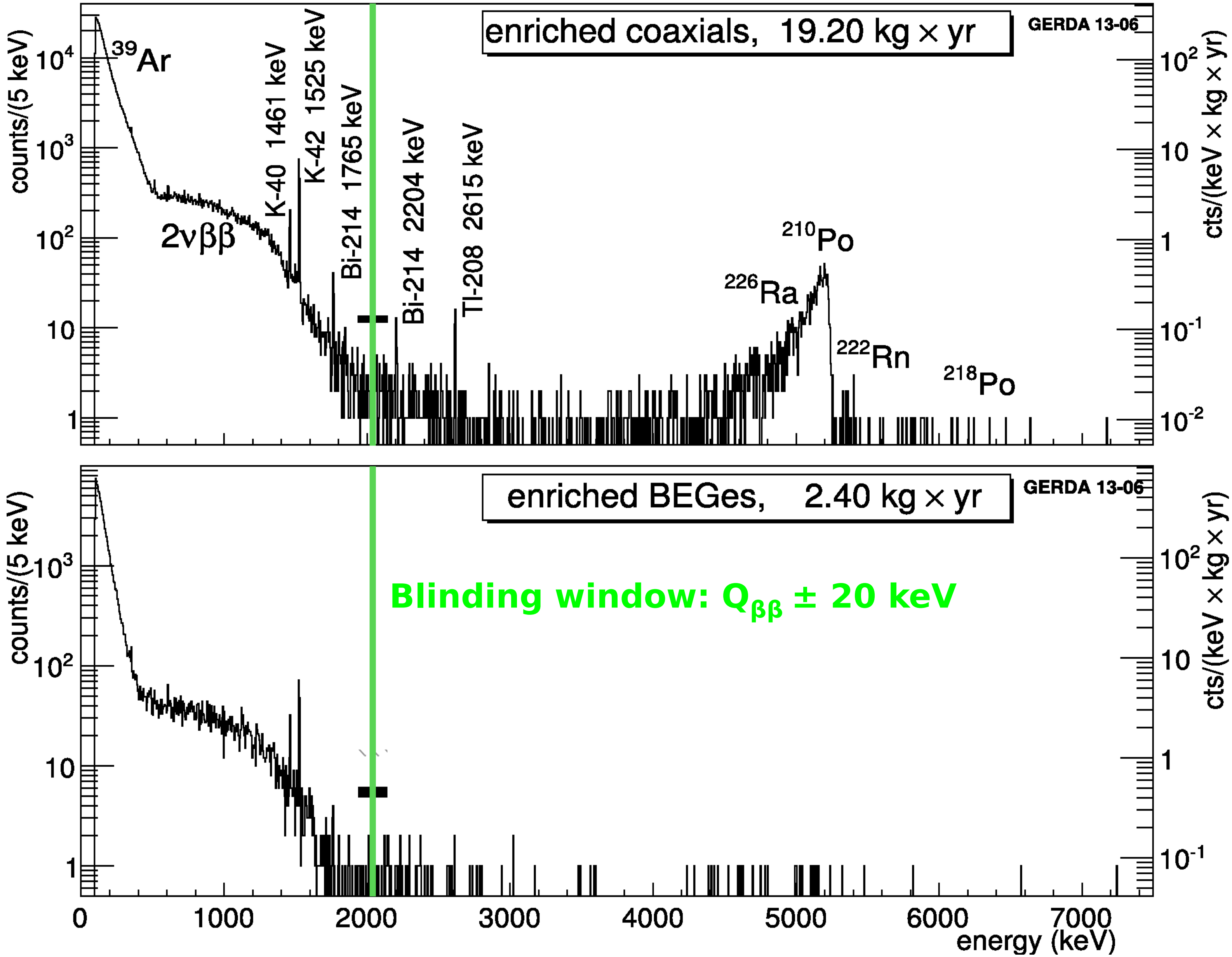

<u>Data selection & bck mitigation:</u> Quality cuts (Survival Fraction @ $Q_{\beta\beta}$ ~ 99%), detector anti-coincidence + muon veto (SF ~60%), time coincidence Bi-Po cut (SF ~ 100%)

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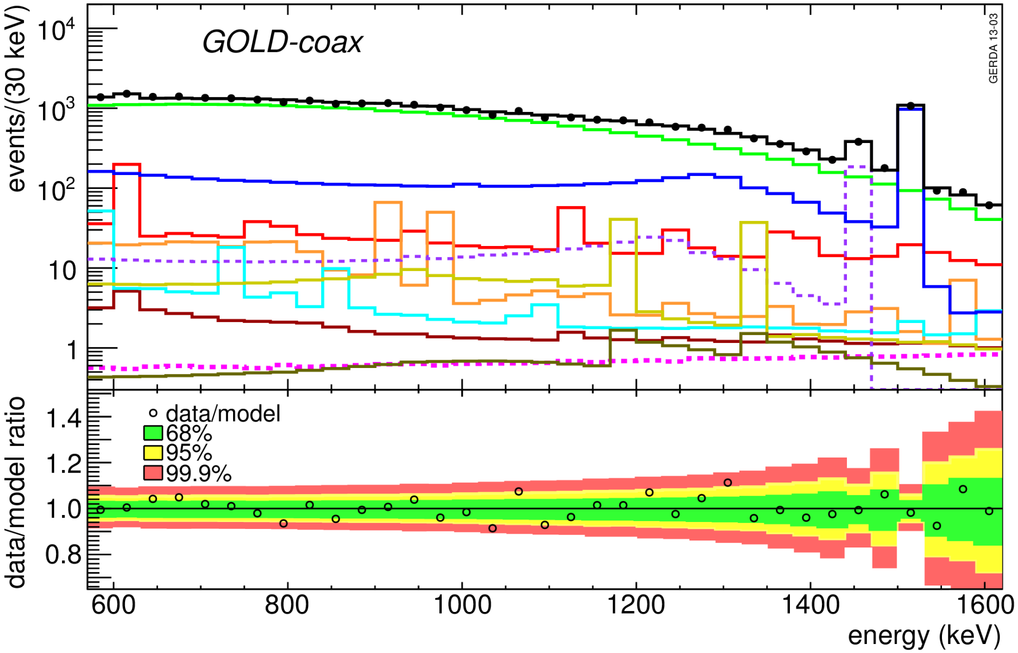
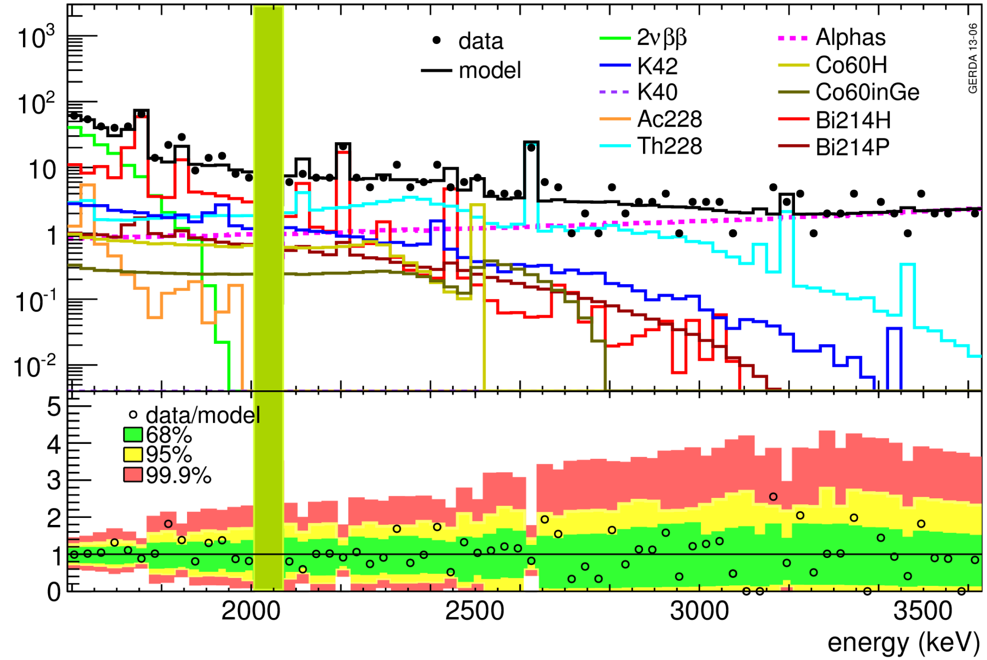
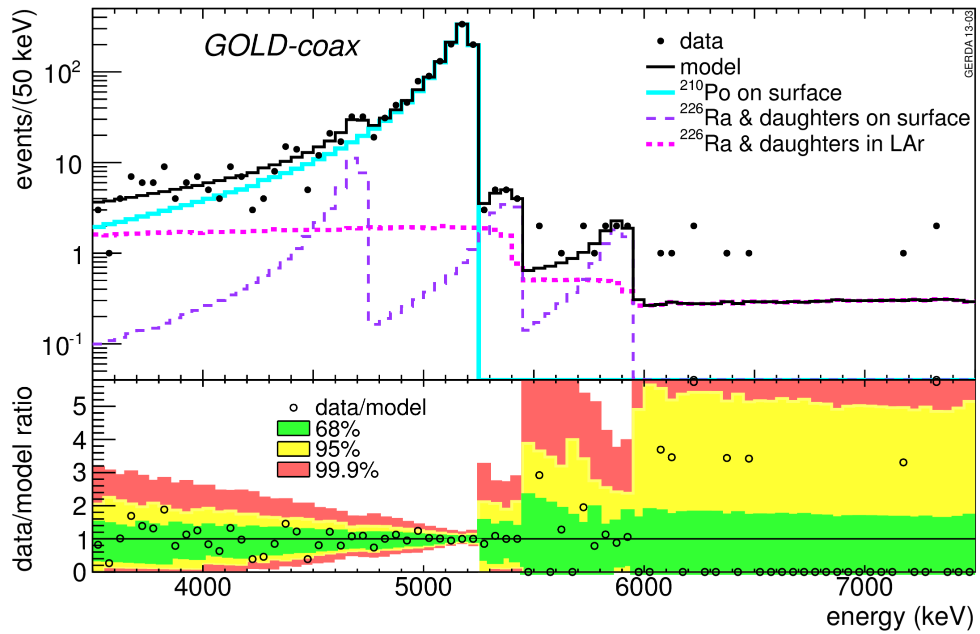




Spectral fit with simulated spectra in 570 – 7500 keV minus **$Q_{\beta\beta}$ ± 20 keV** (above ^{39}Ar Q = 565 keV)



Contributions at $Q_{\beta\beta}$:
β-/γ-induced events from
^{42}K (Q = 3.5 MeV), ^{60}Co (Q = 2.8 MeV),
^{214}Bi (^{238}U) & ^{208}Tl (^{228}Th)
α's from surf. contam. + ^{222}Rn in LAr

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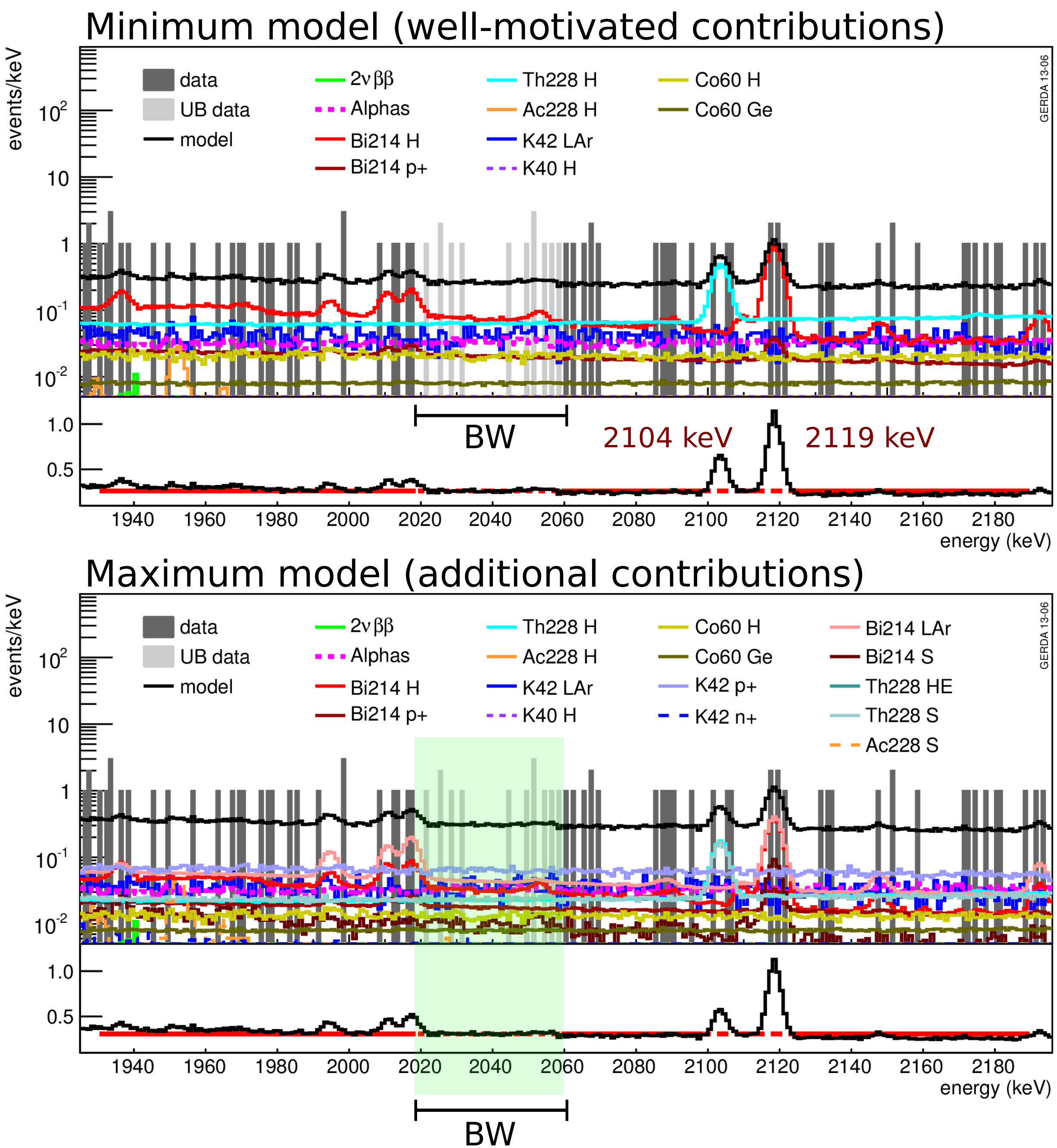
BACKGROUND MODEL AND EXPECTATIONS FIXED PRIOR TO UNBLINDING



No γ-ray line in the BW $Q_{\beta\beta}$±20 keV

Partial unblinding (light grey) after calib. & bkg model fixed

→ no γ-ray line

→ expectations and observed agree

Background evaluation:

Flat distribution in 1930 – 2190 keV excluding two γ-ray lines

2104 ± 5 keV (^{214}Bi)

2119 ± 5 keV (^{208}Tl SEP)

→ same for all datasets (Golden, Silver and BEGe)

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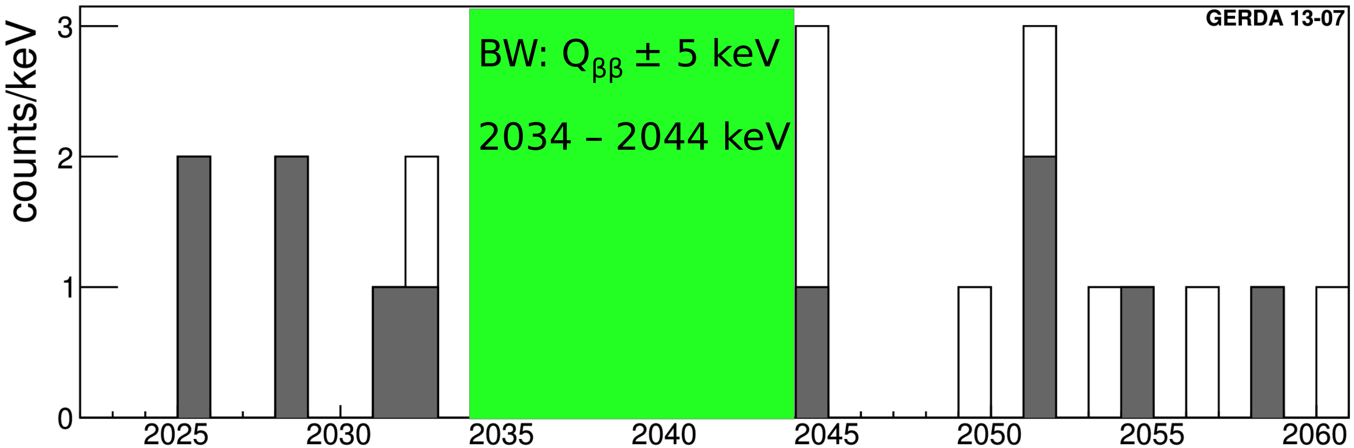
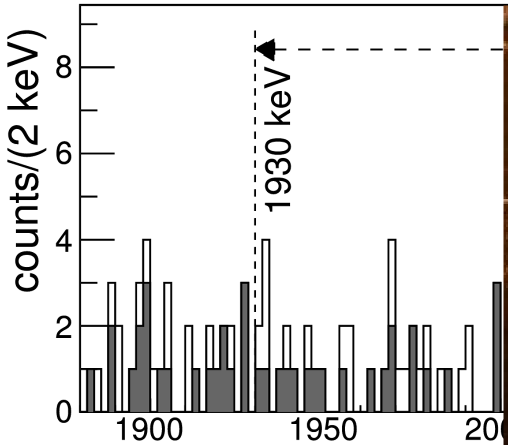
UNBLINDING AT THE COLLABORATION MEETING IN JUNE 2013 @ DUBNA

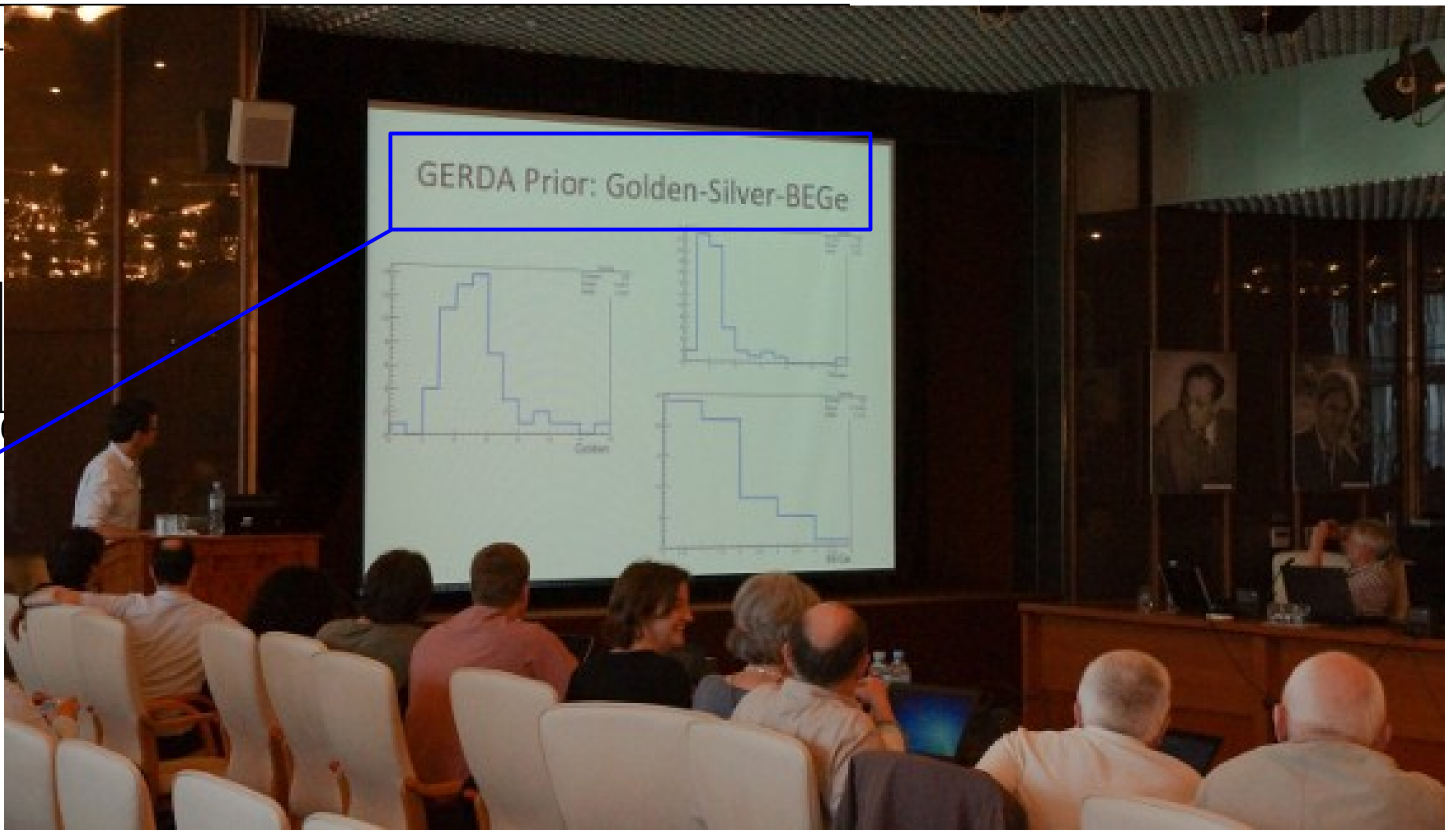


w/o PSD

with PSD

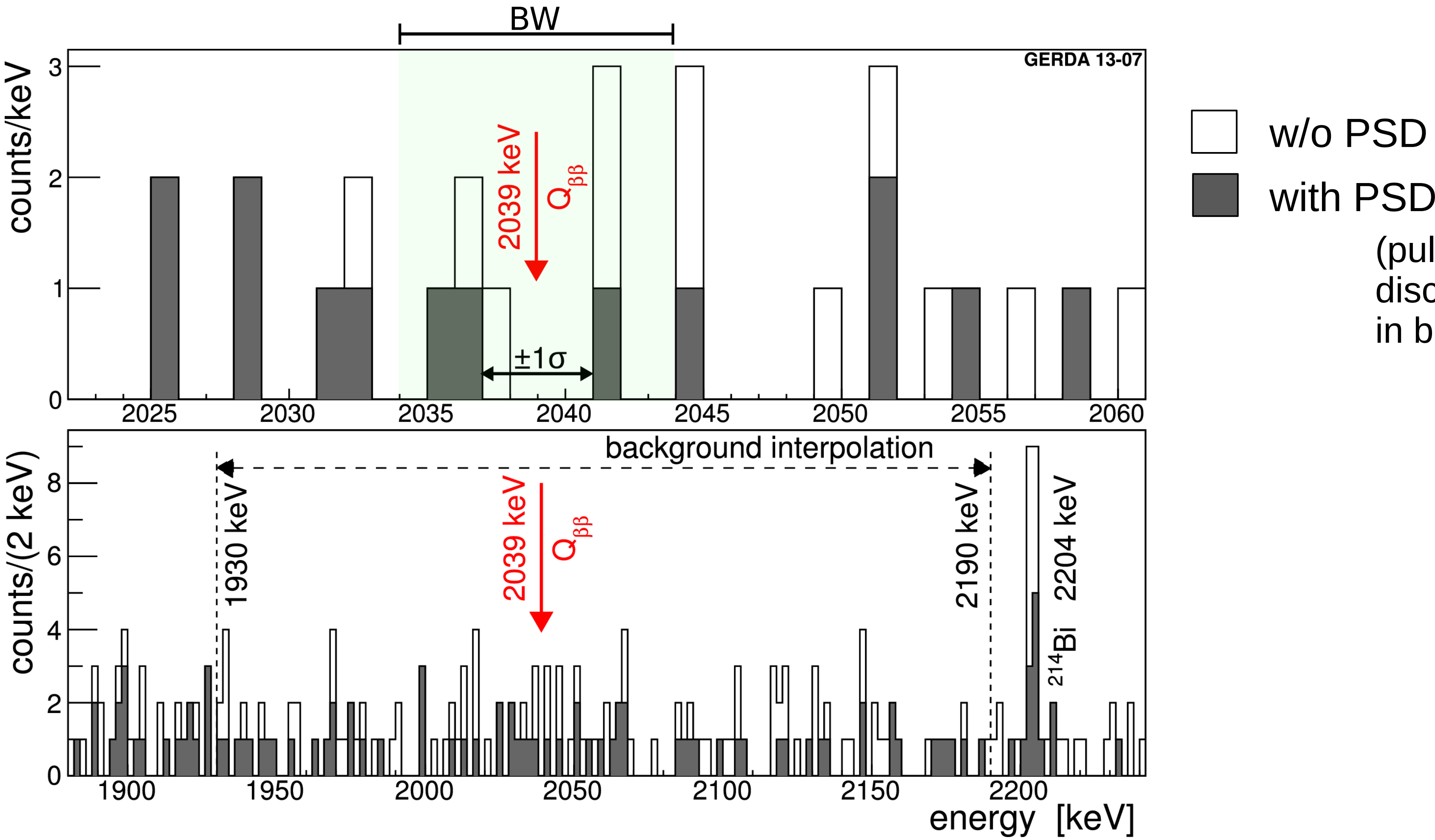
(pulse shape discrimination in backup slides)





Not used in the analysis

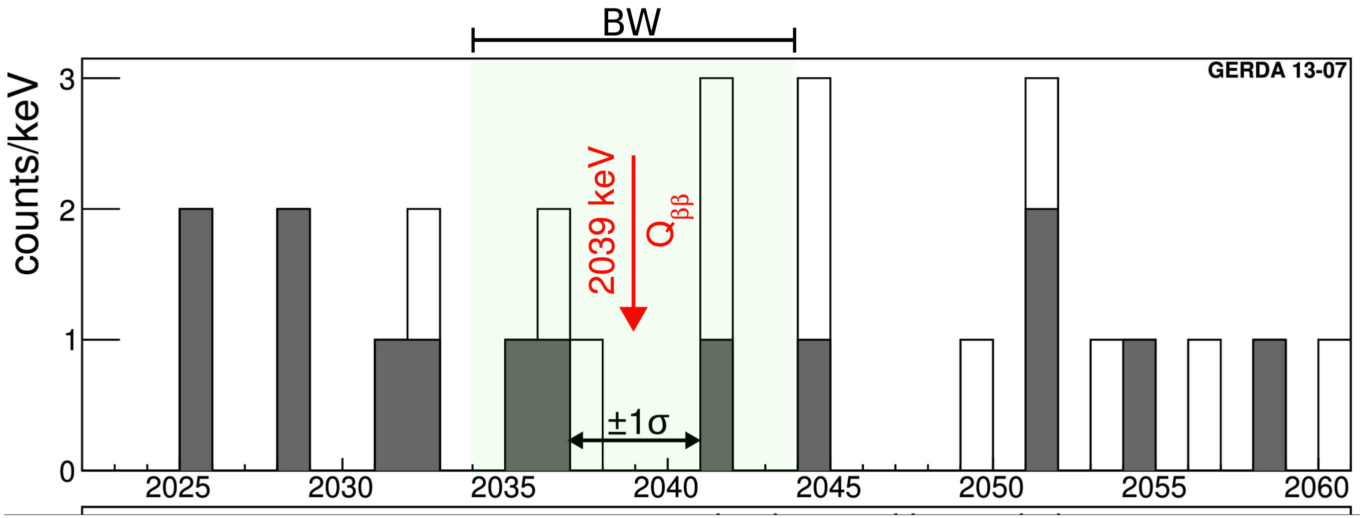
UNBLINDING AT THE COLLABORATION MEETING IN JUNE 2013 @ DUBNA



(pulse shape discrimination in backup slides)

Phys. Rev. Lett 111 (2013) 122503

UNBLINDING AT THE COLLABORATION MEETING IN JUNE 2013 @ DUBNA



0 events in $Q_{\beta\beta}\pm1\sigma$ after PSD

Data set	Exposure [kg yr]	FWHM [keV]	Efficiency	Background index [10^{-3} cts/(keV kg yr)]	Exp. bck in BW [cts]	Obs. in BW [cts]
w/o PSD						
Golden	17.3	4.8±0.2	0.688 ± 0.031	18 ± 2	3.3	5
Silver	1.3	4.8±0.2	0.688 ± 0.031	63^{+16}_{-14}	0.8	1
BEGe	2.4	3.2±0.2	0.720 ± 0.018	42^{+10}_{-8}	1.0	1
with PSD						
Golden	17.3	4.8±0.2	$0.619^{+0.044}_{-0.070}$	11 ± 2	2.0	2
Silver	1.3	4.8±0.2	$0.619^{+0.044}_{-0.070}$	30^{+11}_{-9}	0.4	1
BEGe	2.4	3.2±0.2	0.663 ± 0.022	5^{+4}_{-3}	0.1	0

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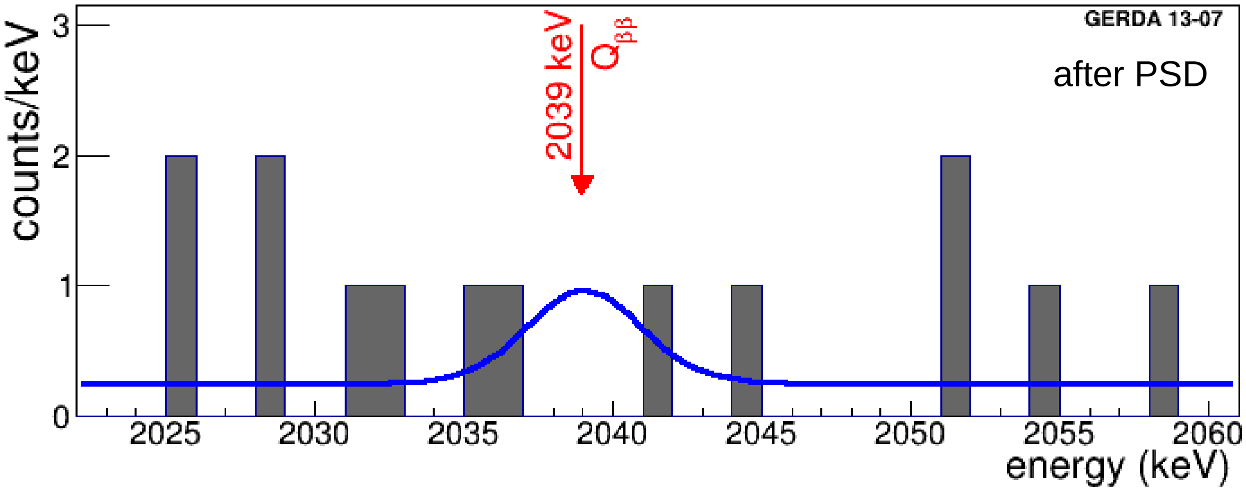
Both Bayesian and Frequentist analyses performed for deriving $T_{1/2}$ limit



Maximum likelihood spectral fit

Fit window: 1930 – 2190 keV
(minus 20 keV γ-ray line regions)

4 free parameters:
3 constant bkg terms
(for Golden, Silver, BEGe datasets)
+ 1 common $1/T_{1/2}$

Systematic uncertainties on the analysis parameters accounted for

Bayesian results:
Flat prior on $1/T_{1/2}$ in $(0, 10^{-24})$ yr^{-1} range

Best fit $N_{0\nu} = 0$ cts

$N_{0\nu} < 4.0$ cts (90% C.I.)

$T_{1/2} > 1.9 \times 10^{25}$ yr (90% C.I.)

Median sensitivity for no signal (MC)
$T_{1/2} > 2.0 \times 10^{25}$ yr (90% credible interval)

Frequentist profile likelihood results:

Best fit $N_{0\nu} = 0$ cts

$N_{0\nu} < 3.5$ cts (90% C.L.)

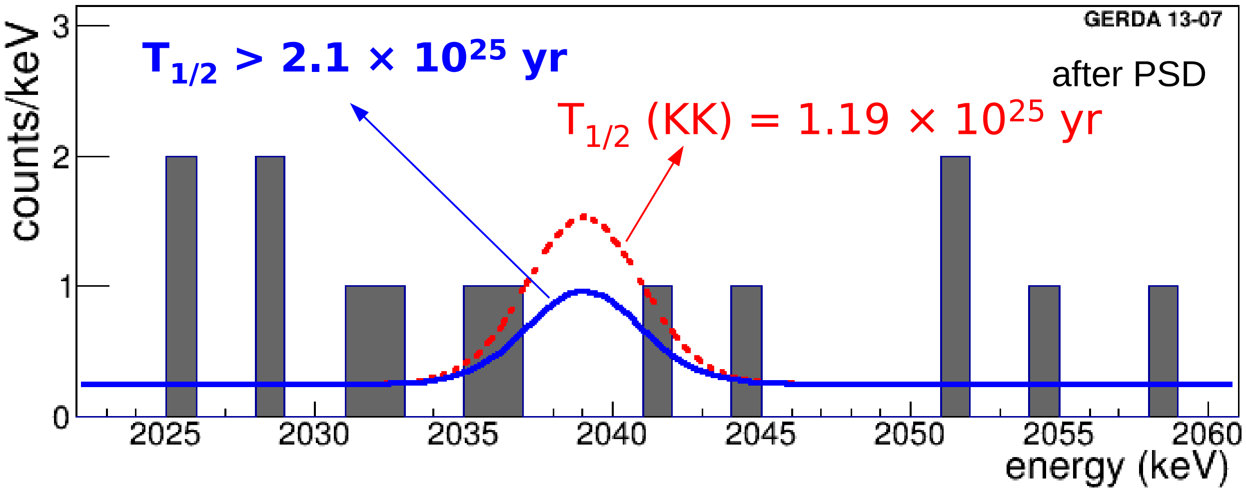
$T_{1/2} > 2.1 \times 10^{25}$ yr (90% C.L.)

Median sensitivity for no signal (MC)
$T_{1/2} > 2.4 \times 10^{25}$ yr (90% C.L.)

Phys. Rev. Lett 111 (2013) 122503

Hypothesis test for the claimed 0νββ signal by Klapdor-Kleingrothaus *et al*.

[Phys. Lett. B 586 (2004)198]



H0 = background only
H1 = background + signal (KK-claim) hypothesis

KK-claim for ^{76}Ge 0νββ signal:

$T_{1/2} = 1.19^{+0.37}_{-0.23} \times 10^{25}$ yr

exp. signal = 5.9 ± 1.4

exp. bkg = 2.0 ± 0.3 , observed = 3

Bayesian result:

Prior on $1/T_{1/2}$ modeling KK-claim
Gaussian with mean = 0.84 · 10^{-25} yr $^{-1}$
and standard deviation = 0.20 · 10^{-25} yr $^{-1}$

Bayes Factor: P(D|H1)/P(D|H0) = 0.02

Frequentist profile likelihood result:

p-value: P($N_{0\nu}$ = 0|H1) = 0.01

→ Long standing claim disfavored!

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Combined ^{76}Ge experiments

GERDA + IGEX + HdM

HdM: Eur. Phys. J. A 12 (2001) 147

IGEX: Phys. Rev. D 65 (2002) 092007, Phys. Rev. D 70 (2004) 078302

Frequentist profile likelihood result:

Best fit $N_{0\nu}$ = 0 cts

$T_{1/2} > 3.0 \times 10^{25}$ yr (90% C.L.)

Hypothesis test:

H0 = bkg only
H1 = bkg + signal (KK-claim)

Bayes Factor: **$P(D|H1)/P(D|H0) = 2 \cdot 10^{-4}$**

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SUMMARY OF PHASE-I

- Blind analysis & Comprehensive background model
- Blinding window $Q_{\beta\beta} \pm 5$ keV ($\sigma_E \sim 0.1\%$ @$Q_{\beta\beta} = 2039$ keV)
  Expected background (2.5 ± 0.3) cts ↔ Observed 3 cts (0 cts in $Q_{\beta\beta} \pm 1\sigma_E$)
  → No evidence for signal!

GERDA Phase-I:

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

^{76}Ge combined (GERDA+HdM+IGEX):

$T_{1/2} > 3.0 \cdot 10^{25}$ yr at 90% C.L.

Long standing claim for ^{76}Ge $0\nu\beta\beta$ decay signal ($T_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr) excluded with high probability in a model-independent way.

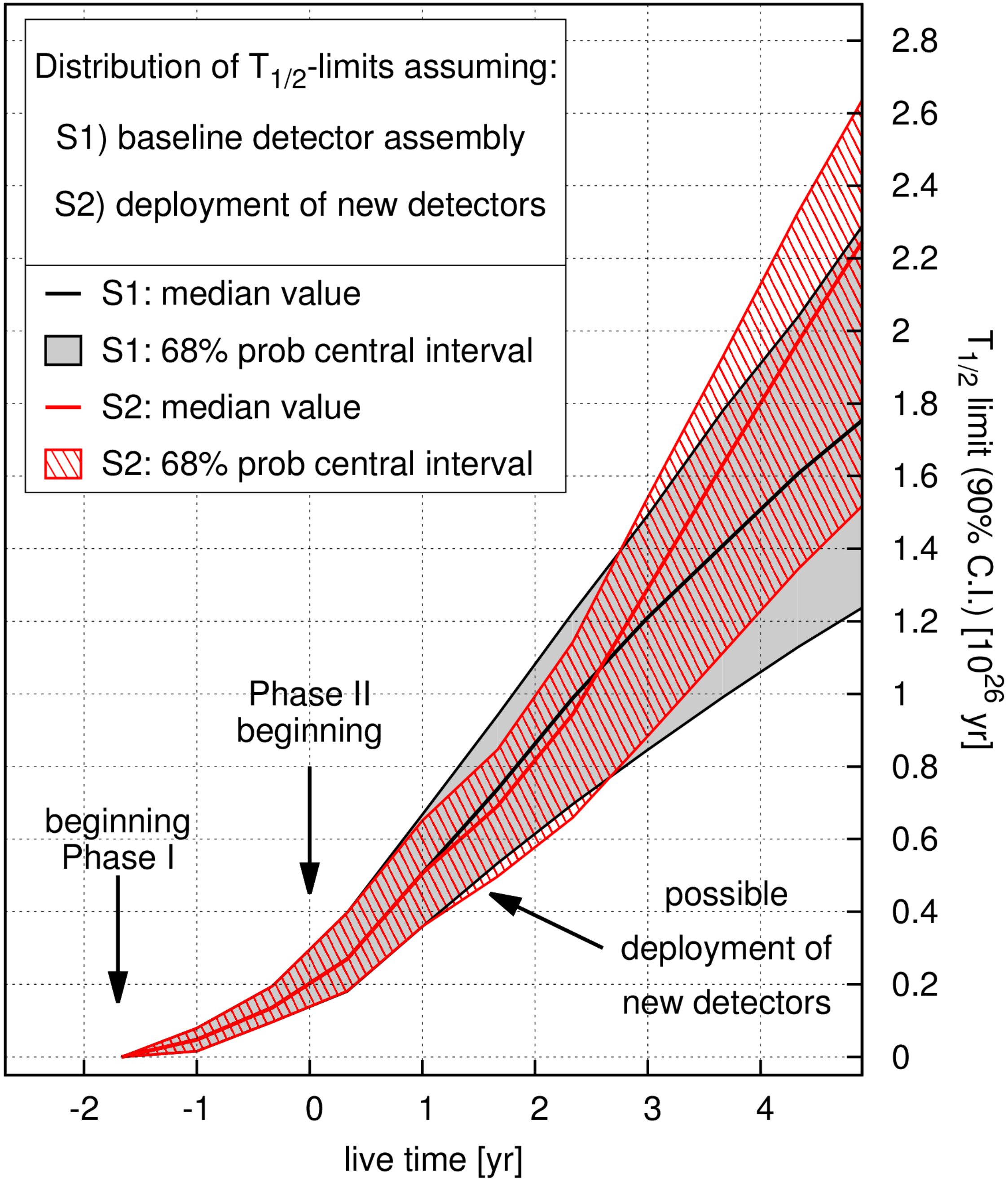
OUTLOOK ON PHASE-II

Transition to Phase-II ongoing

- New BEGe detectors (20 kg):
  - Increased target mass (total ∼35 kg)
  - Enhanced energy resolution and background suppression (due to PSD performance of BEGes)
- LAr instrumentation:
  - Background rejection through detection of coincident LAr scintillation light

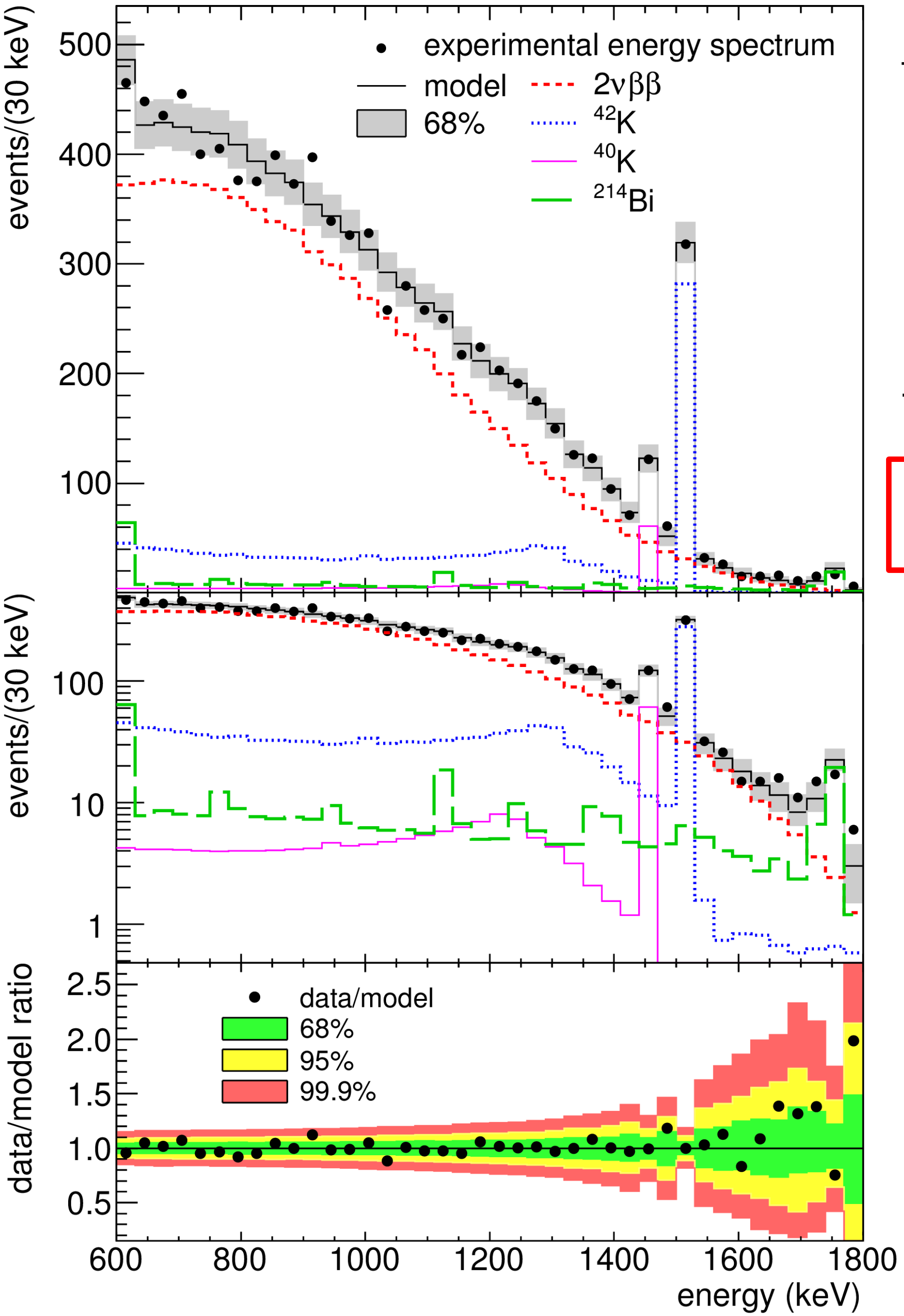
→ BI at $Q_{\beta\beta} \leq 10^{-3}$ cts/(kg keV yr)

→ An order of magnitude improvement on $T_{1/2}$ sensitivity in ∼5 years



BACKUP SLIDES

^{enr}Ge semi-coaxial detectors, total exposure: 5 kg yr



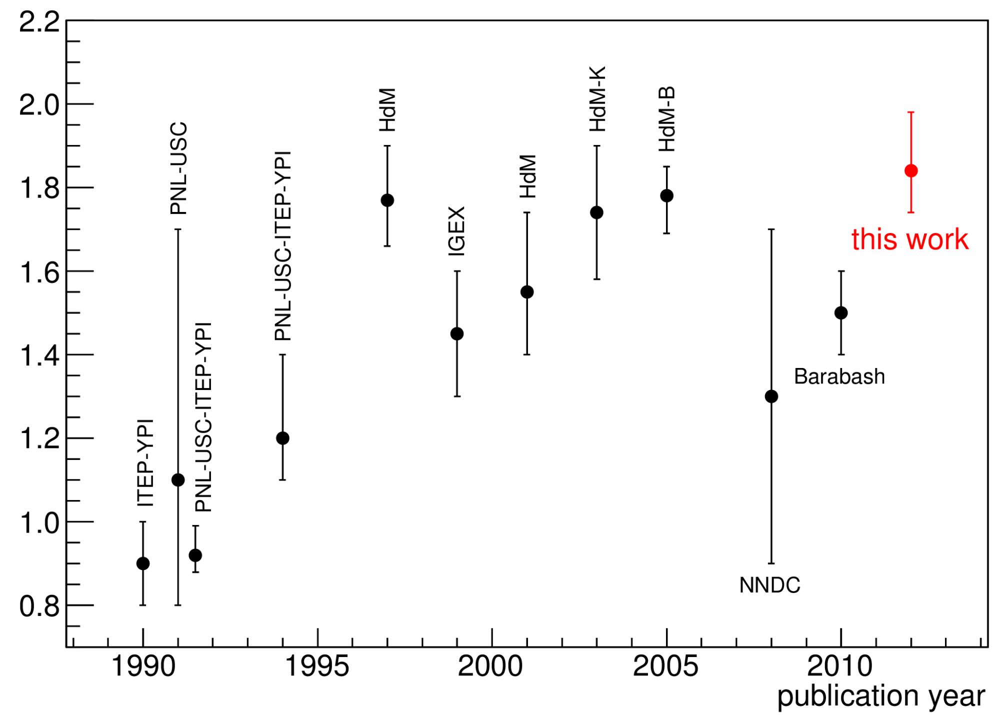
Binned maximum likelihood fit

Fit window: 600 – 1800 keV (above ^{39}Ar Q_β = 565 keV, 2νββ prob. E >1800 keV 0.02%)

Background components: ^{40}K and ^{214}Bi close source and ^{42}K uniformly dist. in LAr

Fit Parameters: Active det. masses, enrichment fractions, background contributions, common $T_{1/2}$

$$T^{2\nu}_{1/2} = \left(1.84^{+0.09}_{-0.08\ \text{fit}}\ {}^{+0.11}_{-0.06\ \text{syst}}\right) \times 10^{21}\,\text{yr} = \left(1.84^{+0.14}_{-0.10}\right) \times 10^{21}\,\text{yr}$$



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Background sources:

No contribution at $Q_{\beta\beta}$

^{39}Ar (Q_β = 565 keV), $2\nu\beta\beta$, ^{40}K, ^{228}Ac

Contribution at $Q_{\beta\beta}$

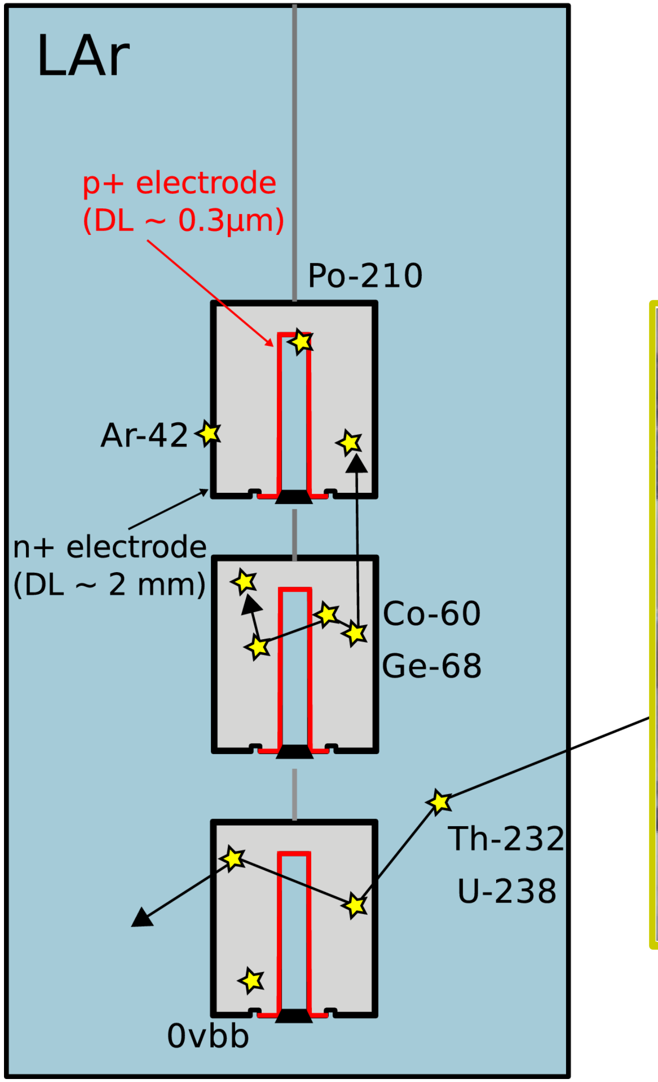
^{42}K (^{42}Ar)
Q_β = 3.5 MeV
E_γ = 2.4 MeV

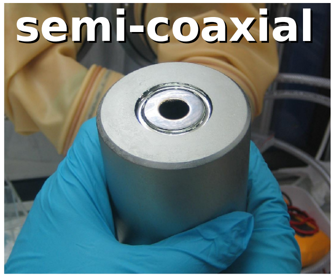
^{214}Bi (^{238}U chain)
Q_β = 3.3 MeV,
E_γ = 2.1, 2.2, 2.4 MeV

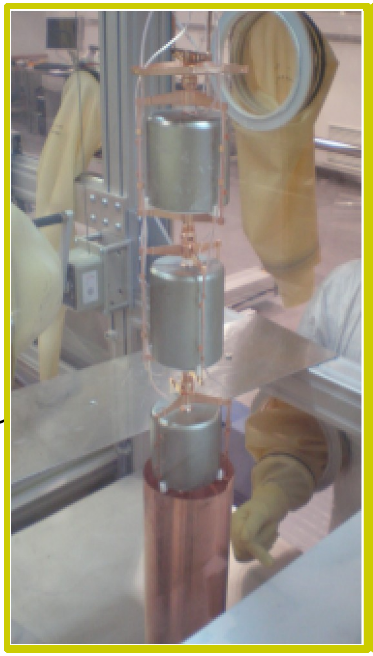
^{208}Tl (^{232}Th chain)
E_γ = 2.6 MeV

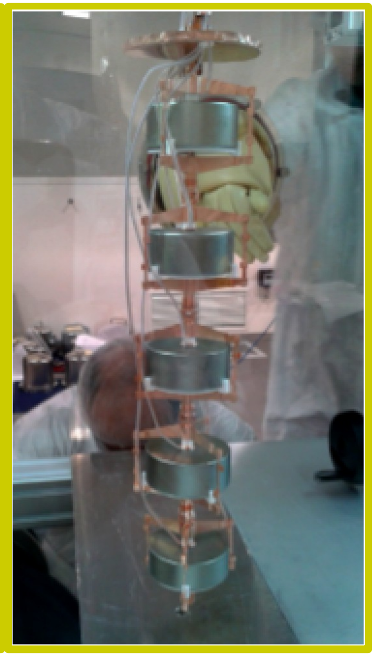
α-induced surface events (isotopes in ^{238}U chain)

^{60}Co (int. and ext.)
Q_β = 2.8 MeV









PULSE SHAPE DISCRIMINATION METHODS AND CUTS FIXED PRIOR TO UNBLINDING

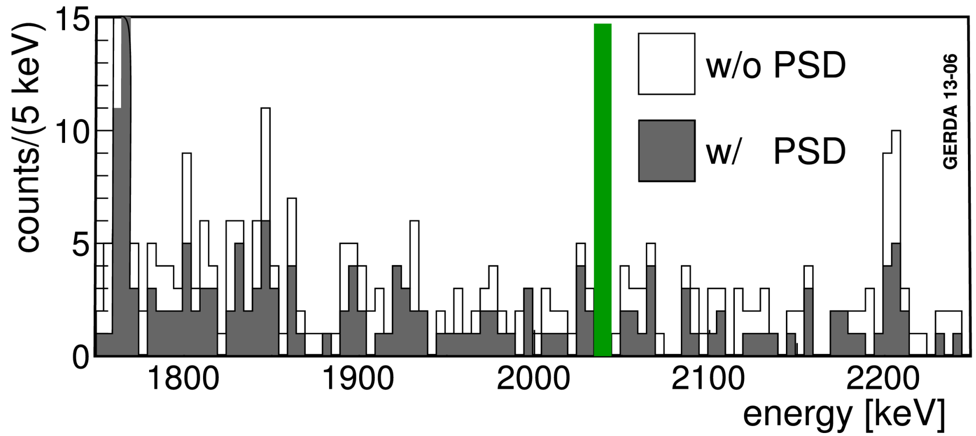
<u>Semi-coaxial detectors</u>

Artificial neural network

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

bck @ $Q_{\beta\beta}$ acc. ~ 65%

$2\nu\beta\beta$ acc. = (85±2)%



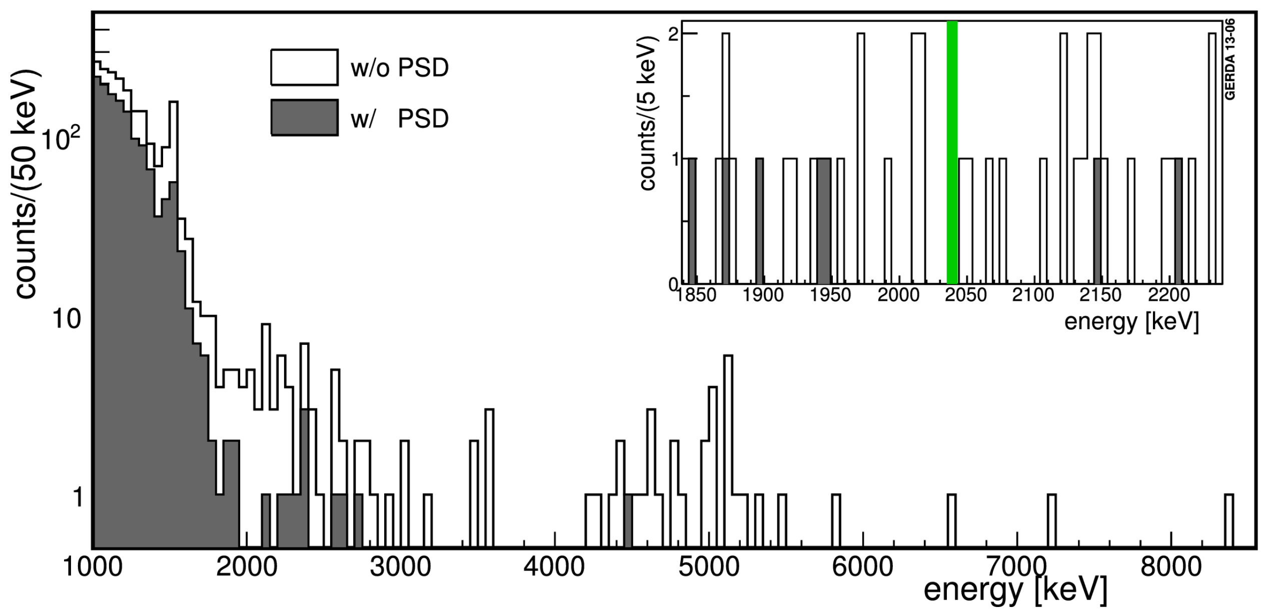
<u>BEGe detectors</u>

Mono-parametric: A/E method

$0\nu\beta\beta$ acceptance = (92±2)%

bck @ $Q_{\beta\beta}$ acc. ≤ 20%

$2\nu\beta\beta$ acc. = (91±5)%



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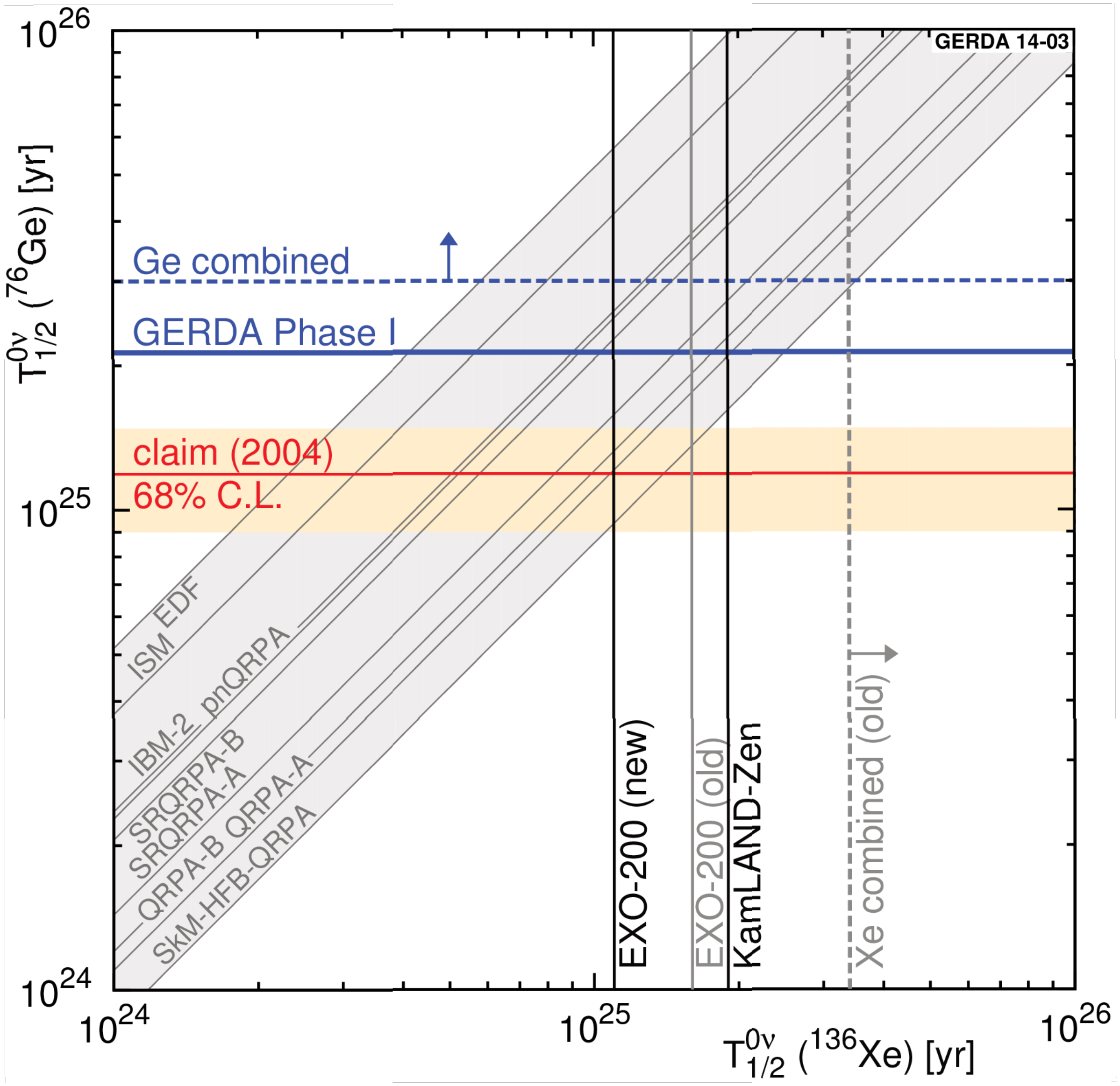
Only ^{76}Ge experiments can test the claim in a model-independent way.



Comparison with ^{136}Xe experiments

Assumption: the exchange of light Majorana neutrinos is the leading mechanism.

NME calculations:
arXiv:1305.0056

EXO-200 (new):
arXiv:1402.6956

KamLAND-Zen:
arXiv:1211.3863

^{136}Xe combined using the latest results (not shown on the plot):
$T_{1/2} > 2.2 \cdot 10^{25}$ yr at 90% C.L.
arXiv:1404.2616

Updated figure from Phys. Rev. Lett 111 (2013) 122503