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

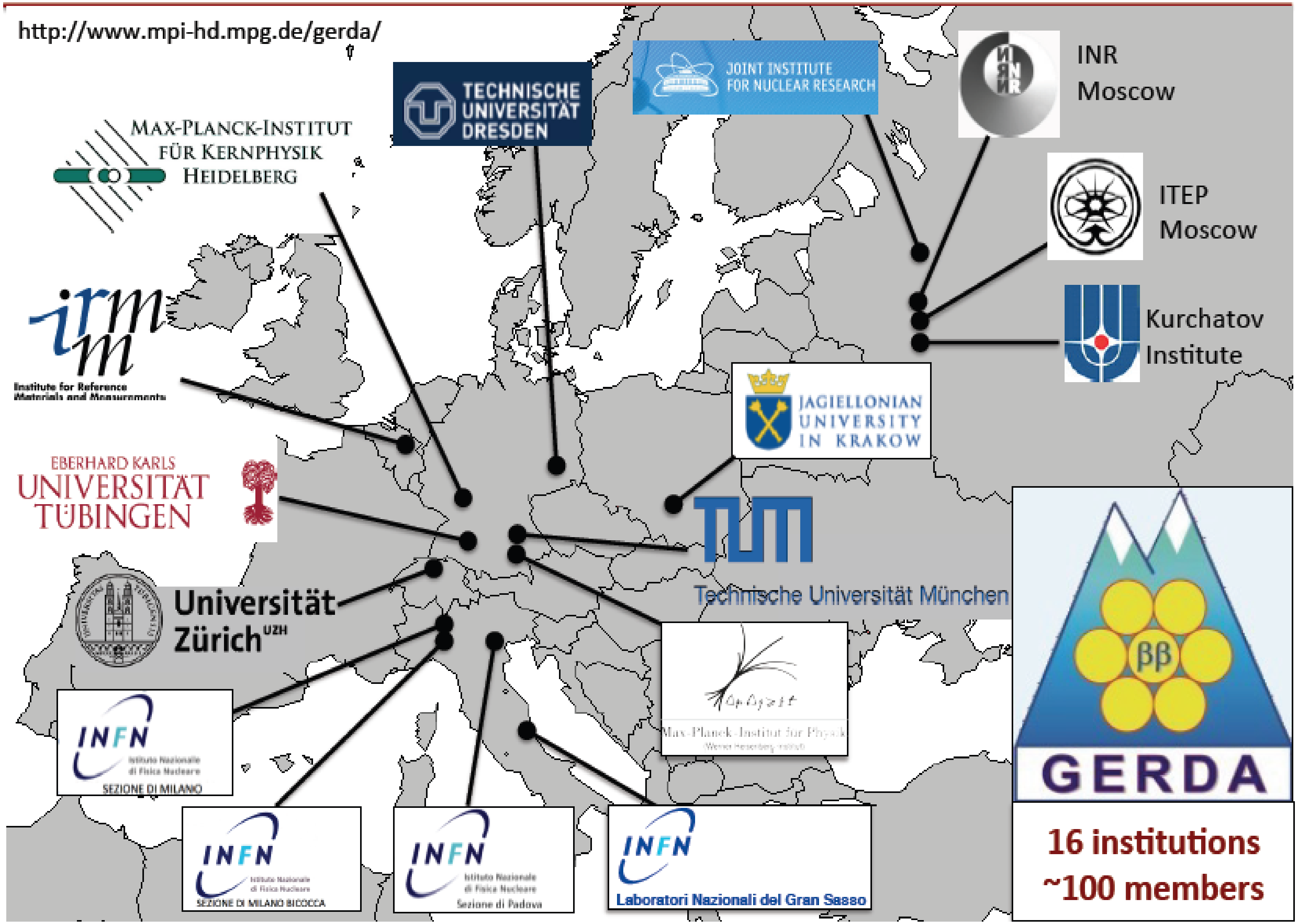
GERDA

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

Mark Heisel
for the collaboration

Seminar talk @ CEA Saclay,
February 2014

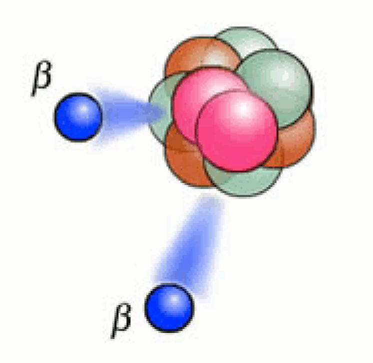
The collaboration

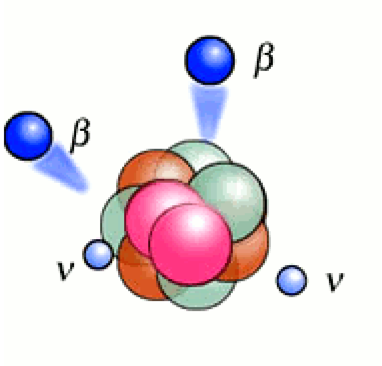


16 institutions
~100 members

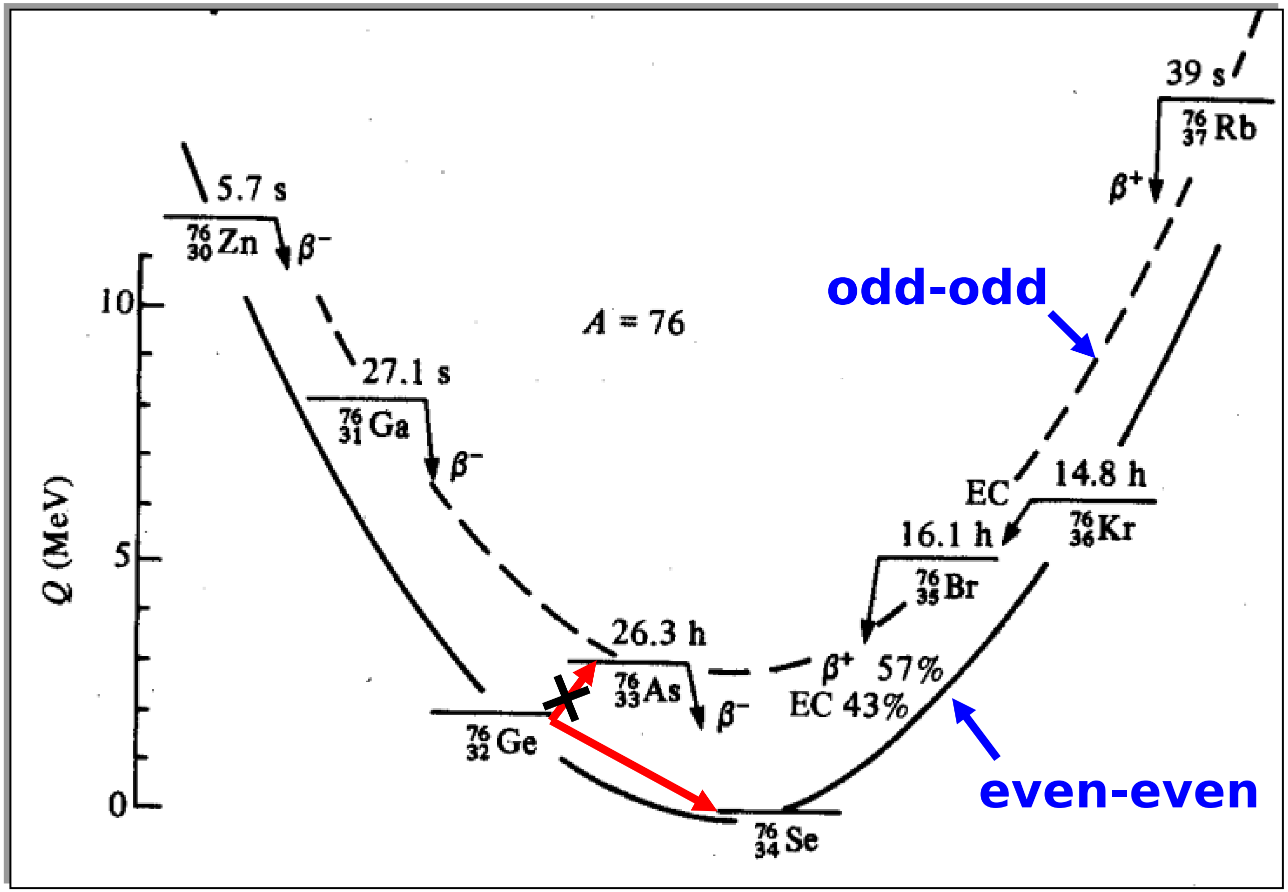
Outline

1. (1) 0νββ physics
2. (2) GERDA setup
3. (3) Background & 2νββ
4. (4) Phase I result
5. (5) Outlook on Phase II





Double beta decay



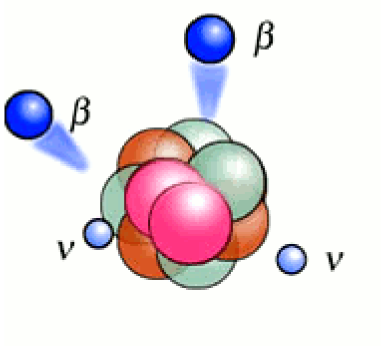
^{76}Ge: $Q_{\beta\beta}$ = (2039.061±0.007) keV

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

other ββ isotopes: ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

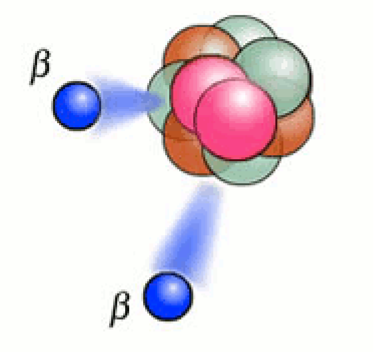
Motivation for 0νββ decay searches

2 neutrino
double beta decay



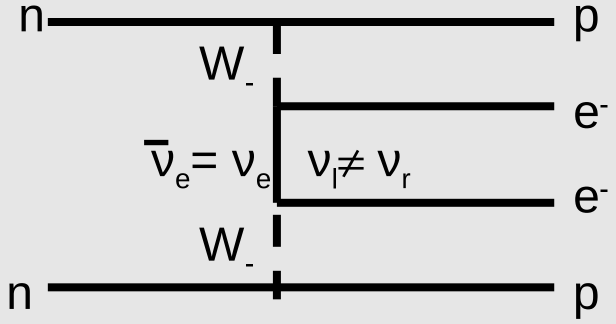
allowed by SM, ΔL = 0

0 neutrino
double beta decay



forbidden in SM, ΔL = 2

0νββ decay:

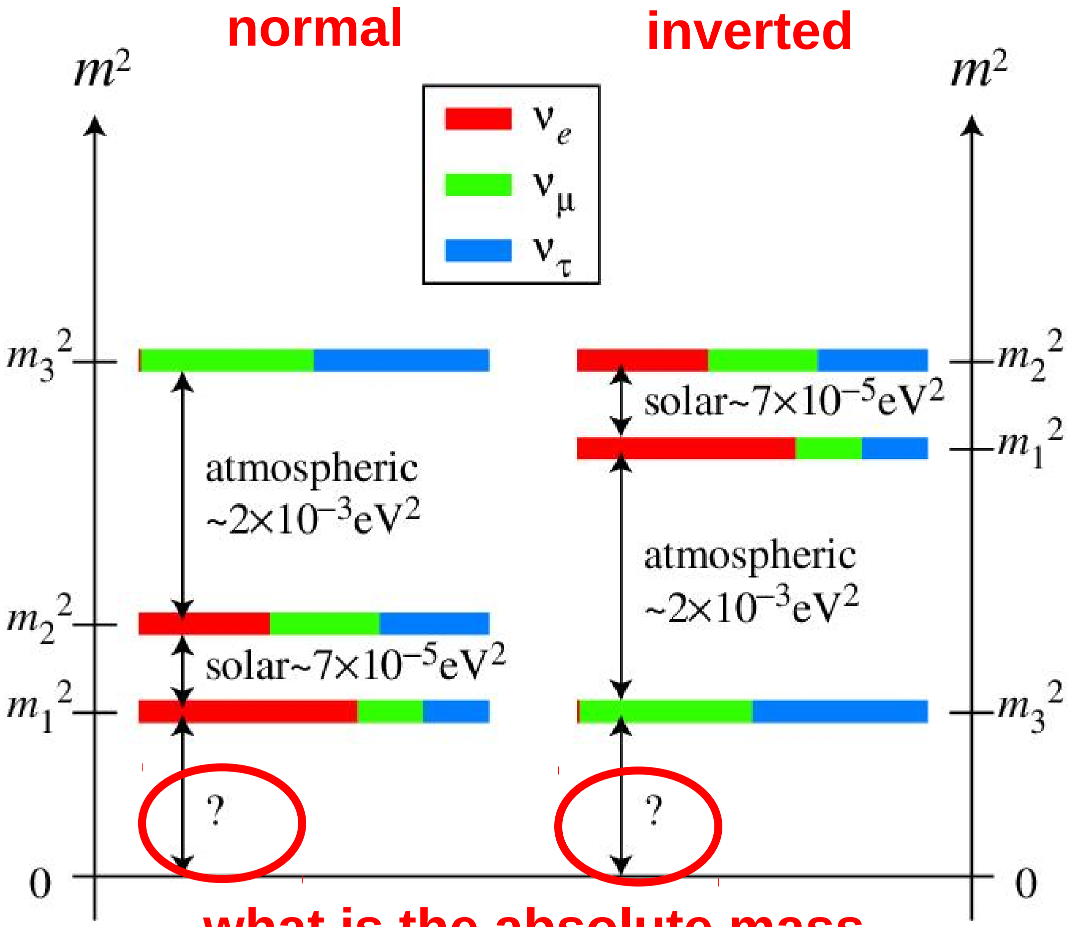


exchange of majorana neutrino

- ► Majorana nature of neutrino
- ► lepton number violation ΔL=2 !
- ► effective ν mass: $\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$
- ► access to ν mass hierachy

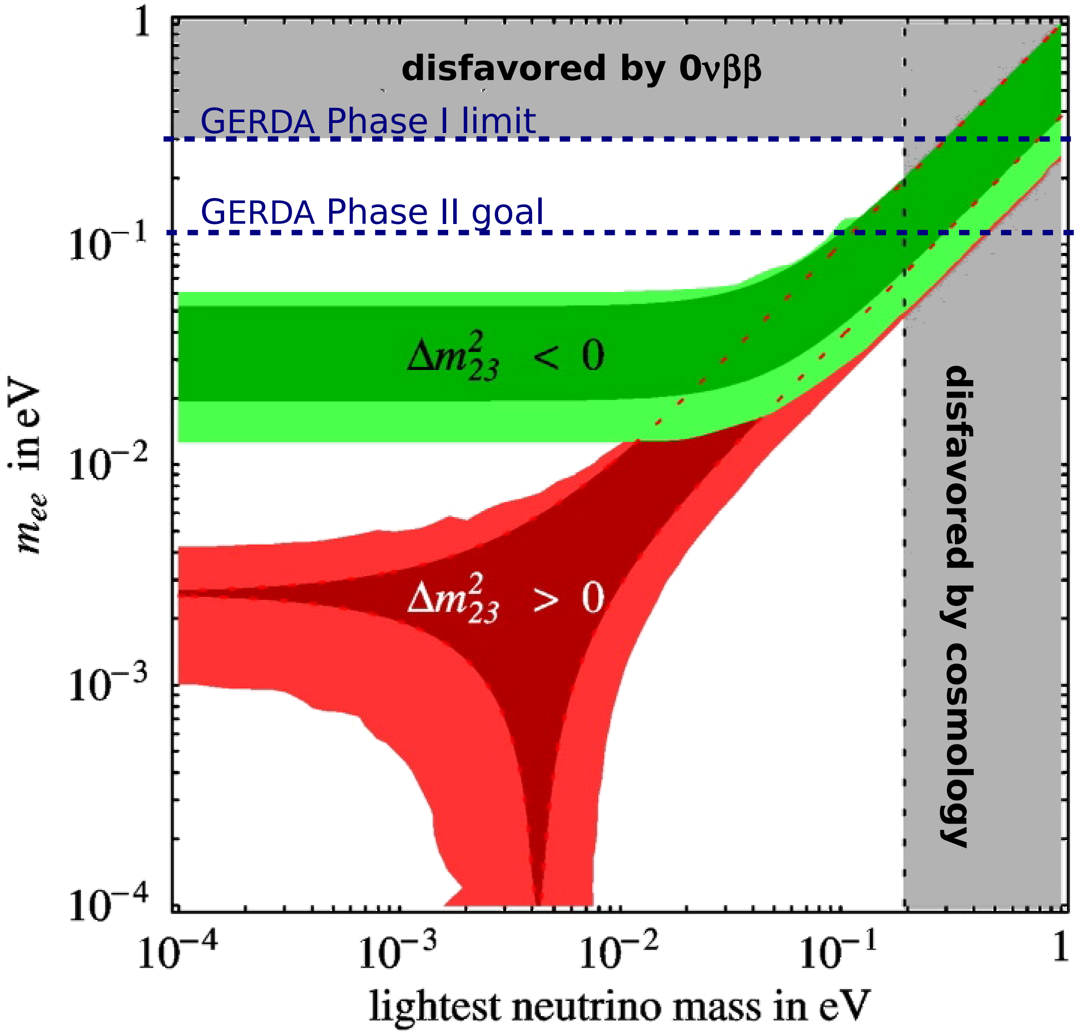
Neutrino hierarchy? Neutrino mass scale?

Neutrino oscillation tells us → Neutrinos have non vanishing rest mass!



what is the absolute mass scale?

Neutrino hierarchy? Neutrino mass scale?



Nucl Phys B659 (2003) 359

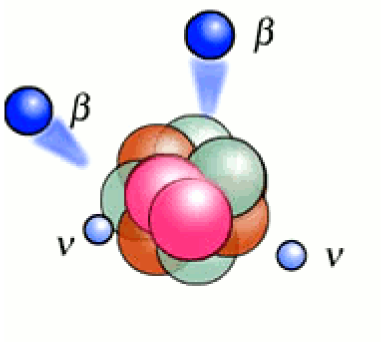
effective electron neutrino mass:

$$|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left||U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}|^2\, m_3\, e^{2i\beta}\right|$$

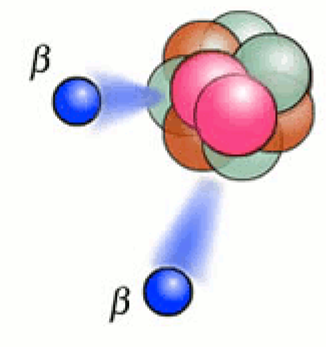
m_i=masses of ν mass eigenstates, U_{ei}=elements of neutrino mixing matrix, $e^{2i\alpha,\beta}$ = Majorana CP phases

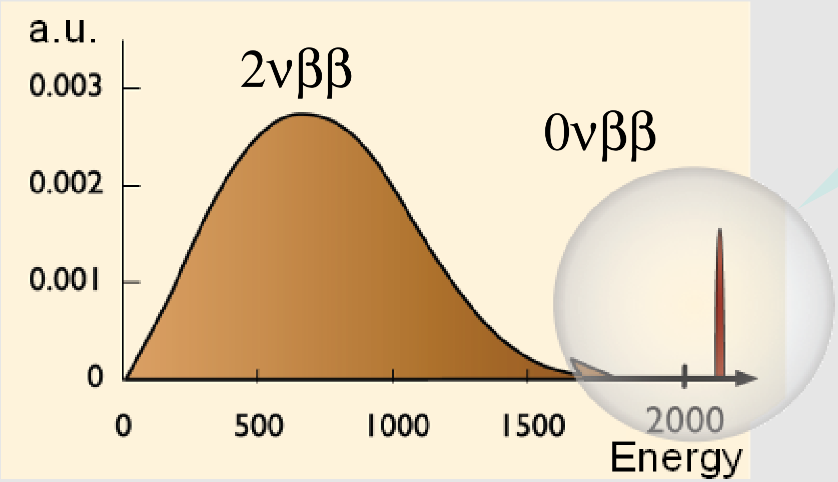
Double Beta Decay detection in ^{76}Ge

2 neutrino
double beta decay



0 neutrino
double beta decay





electron-energy spectrum

search for 0νββ peak at
$Q_{\beta\beta}$ = 2039 keV (^{76}Ge)

Expected decay rate:

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

half life

phase space integral

nuclear matrix element

effective ν mass

Double Beta Decay detection in GERDA

Sensitivity:

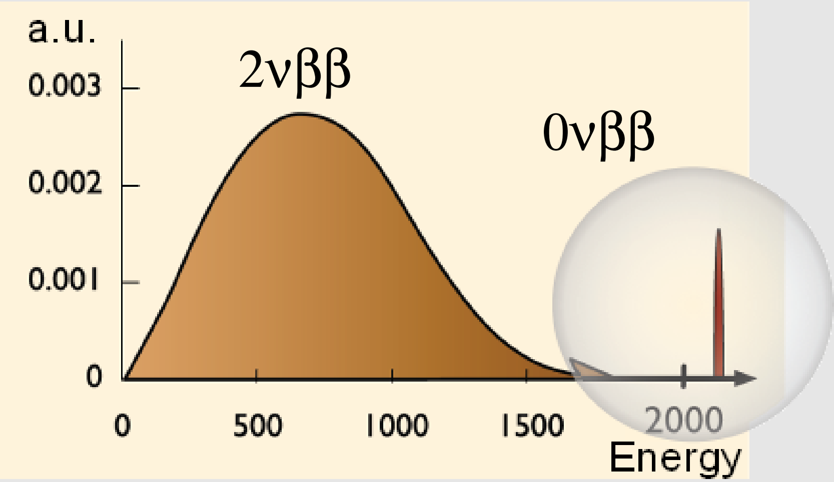
$$T^{0\nu}_{1/2} \sim \epsilon_{eff} \sqrt{\frac{M\cdot t}{\Delta E\cdot B}}$$

M·t = exposure

ε_{eff} = detection efficiency

ΔE = energy resolution

B = background index



electron-energy spectrum

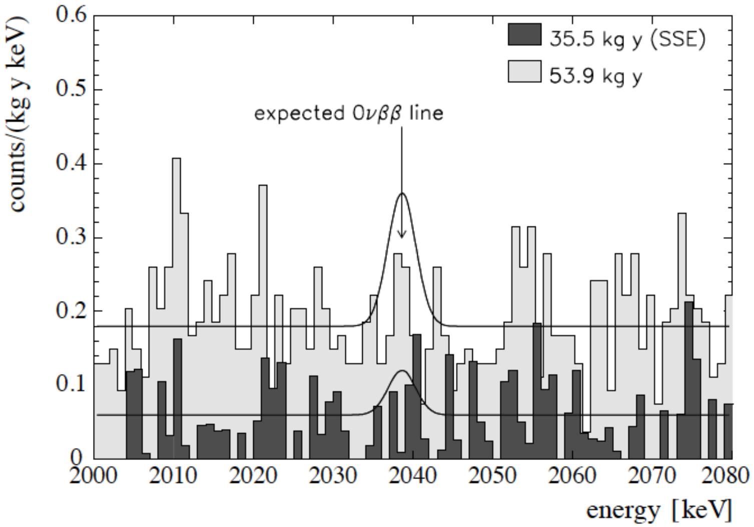
Detector = Source

detectors enriched to 86% ^{76}Ge

Phase	I	II
Exposure [kg ·yr]	15	100
Bg [counts/(keV·kg·yr)]	10^{-2}	10^{-3}
Upper limit $m_{\beta\beta}$ [eV]	0.23-0.39	0.09-0.15

A. Smolnikov, P. Grabmayr PRC 81 028502(2010)

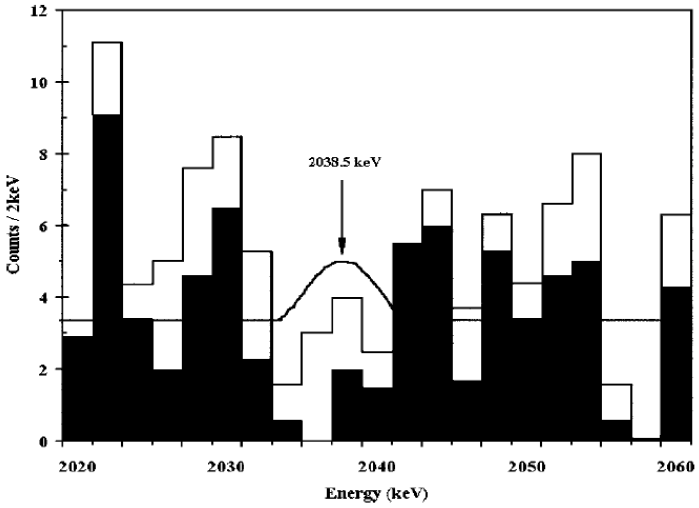
^{76}Ge 0νββ search before GERDA



Heidelberg-Moscow

[H.V. Klapdor-Kleingrothaus et al.,
(Eur. Phys. J. A 12, 147-154 (2001)]

Exposure	Result $T^{0\nu}_{1/2}$	
53.9 kg·yr	> 1.3 × 10^{25} yr	(no PSD)
35.5 kg·yr	> 1.9 × 10^{25} yr	(with PSD)
		(90% C.L.)



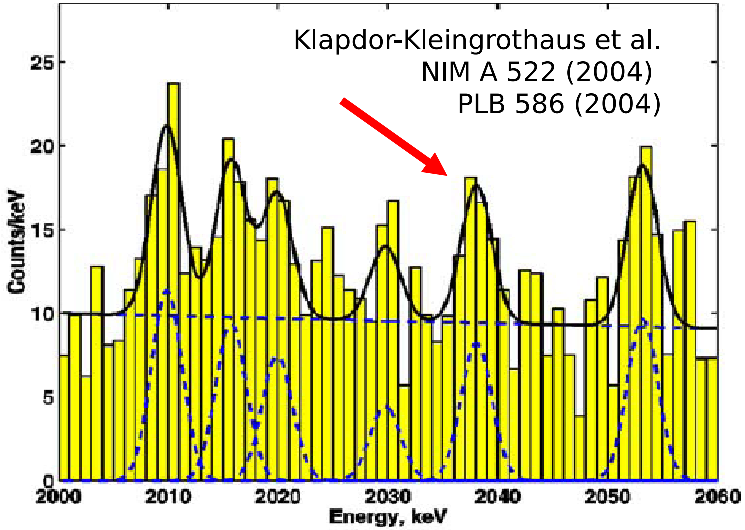
IGEX

[Aalseth et al.,
Phys. Rev. D 65 (2002) 092007]

Exposure	Result $T^{0\nu}_{1/2}$
8.8 kg·yr:	> 1.6 × 10^{25} yr

(90%C.L.)

^{76}Ge 0νββ: the claim



Klapdor-Kleingrothaus et al. (2004)

[NIM A 522 371 (2004), PLB 586 198 (2004)]

- ► Claim: 4.2σ evidence for 0νββ
  $T_{1/2} = 1.19 \times 10^{25}$ yr
- ► Exposure: 71.7 kg·yr,
  Background: 0.17 / (kg·yr·keV)
- ► Events: 28.75 ± 6.87 (bgd: ~60)

Klapdor-Kleingrothaus et al. (2006)

[Mod. Phys. Lett. A 21, 1547 (2006)]

- ► Claim: $T_{1/2} = 2.23 \times 10^{25}$ yr (~6σ)
- ► not considered by us, because:
  - (1) reported half-life can be reconstructed* only with $\varepsilon_{psd} = 1$ (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
  - (2) $\varepsilon_{fep} = 1$ (also used in result from 2004), GERDA value for same detectors is $\varepsilon_{fep} = 0.9$

* B. Schwingenheuer in Ann. Phys. 525, 269 (2013)

Outline

(1) 0νββ physics

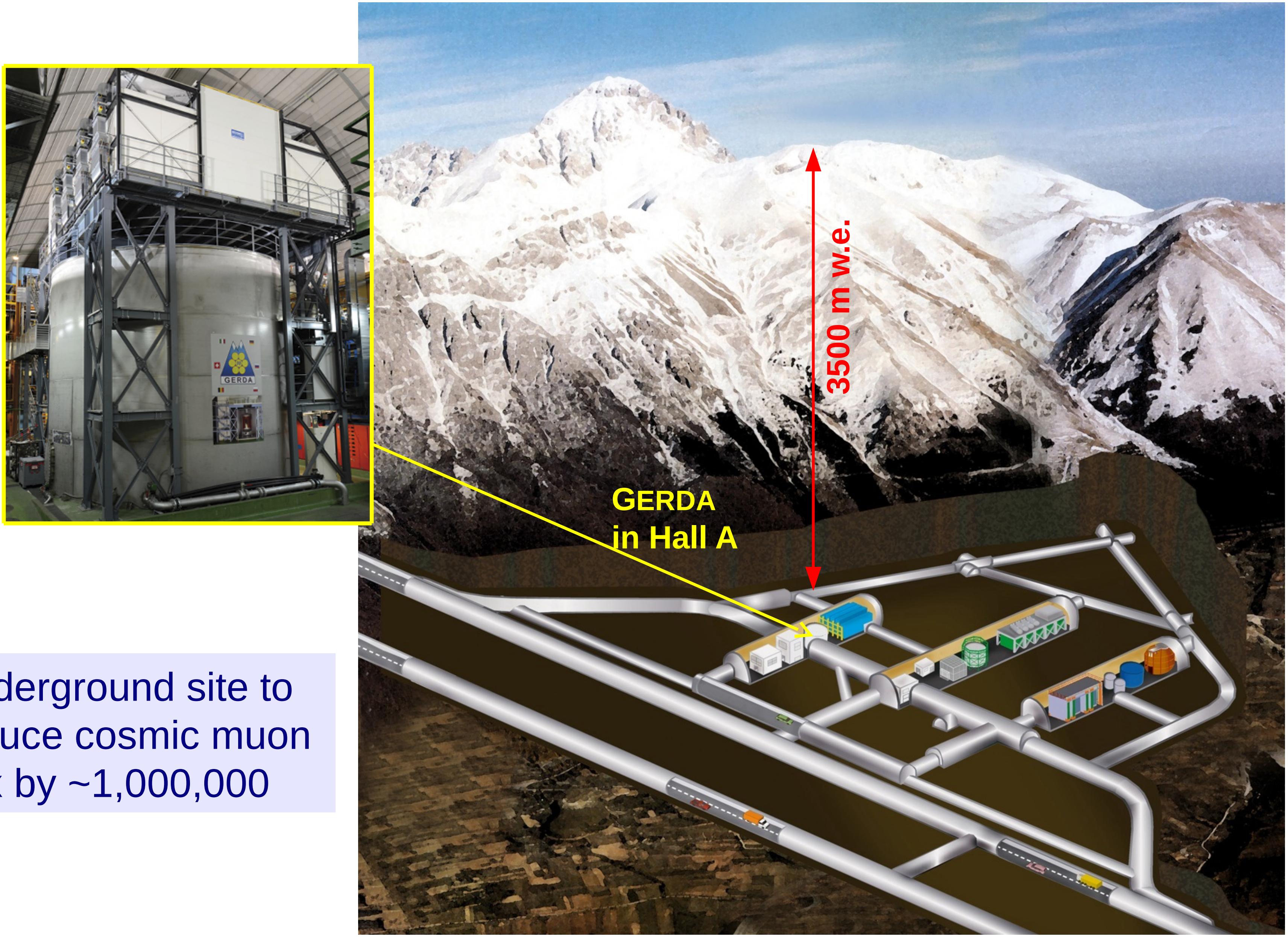
(2) GERDA setup

(3) Background & 2νββ

(4) Phase I result

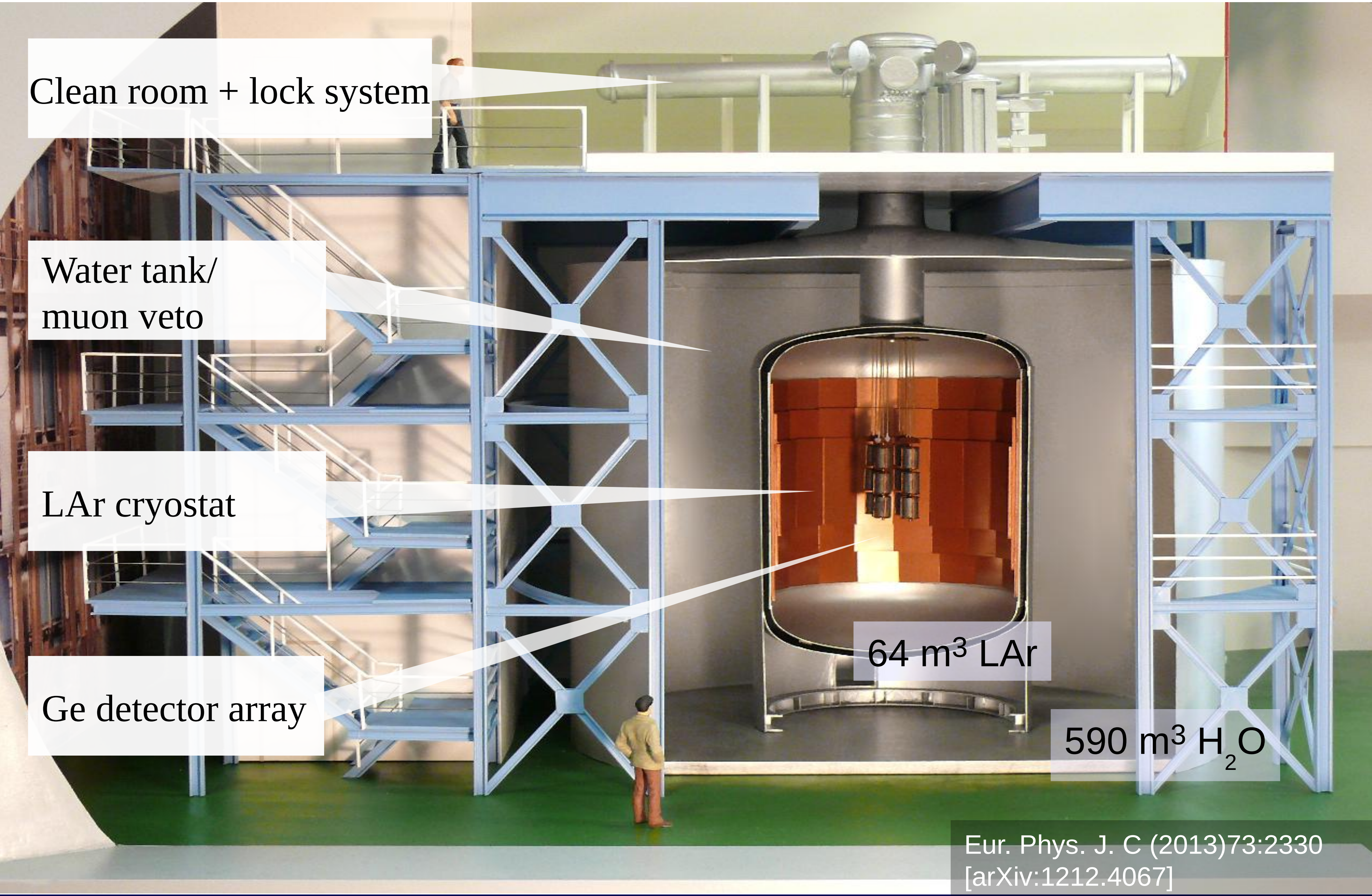
(5) Outlook on Phase II

GERDA at Gran Sasso



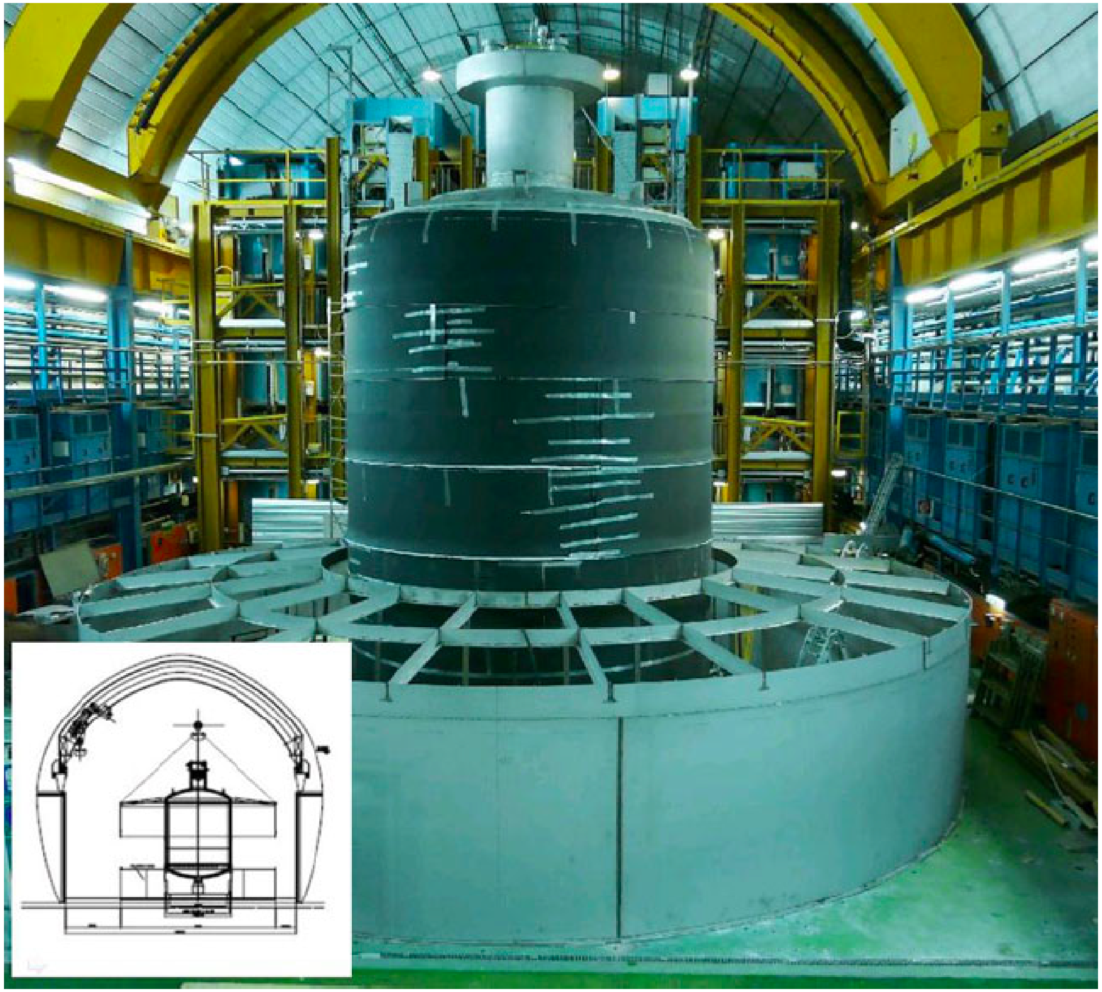
Underground site to reduce cosmic muon flux by ~1,000,000

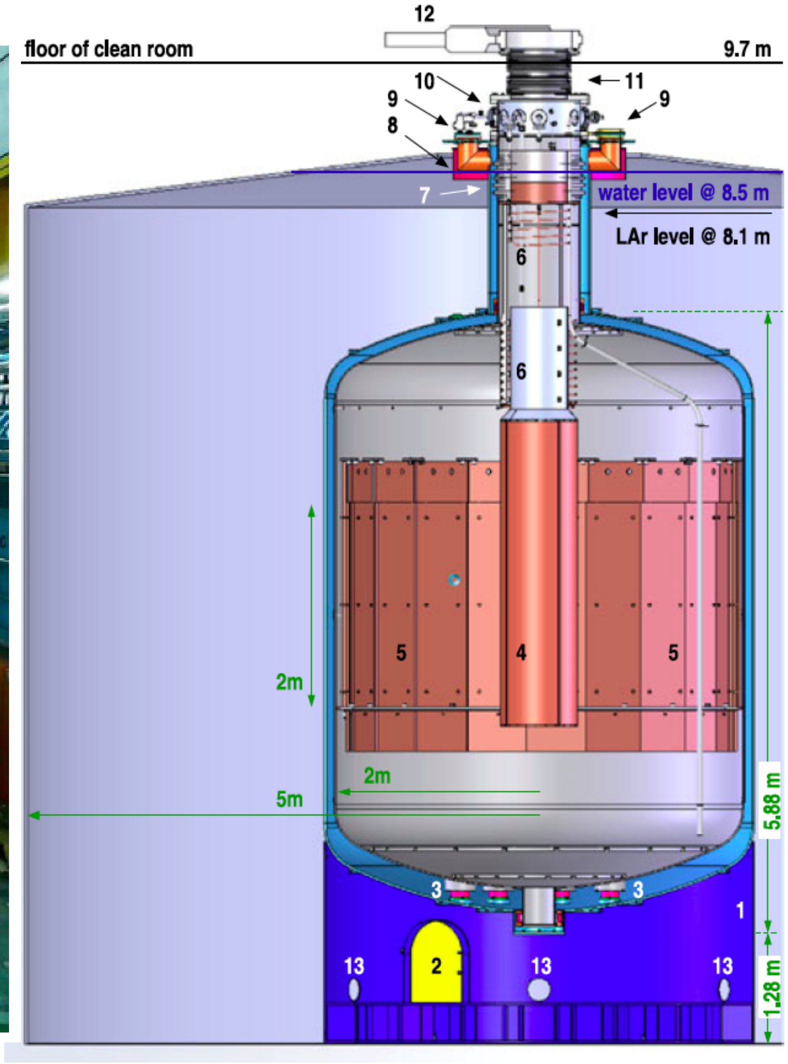
Germanium Detector Array



Eur. Phys. J. C (2013)73:2330
[arXiv:1212.4067]

Water tank and cryostat





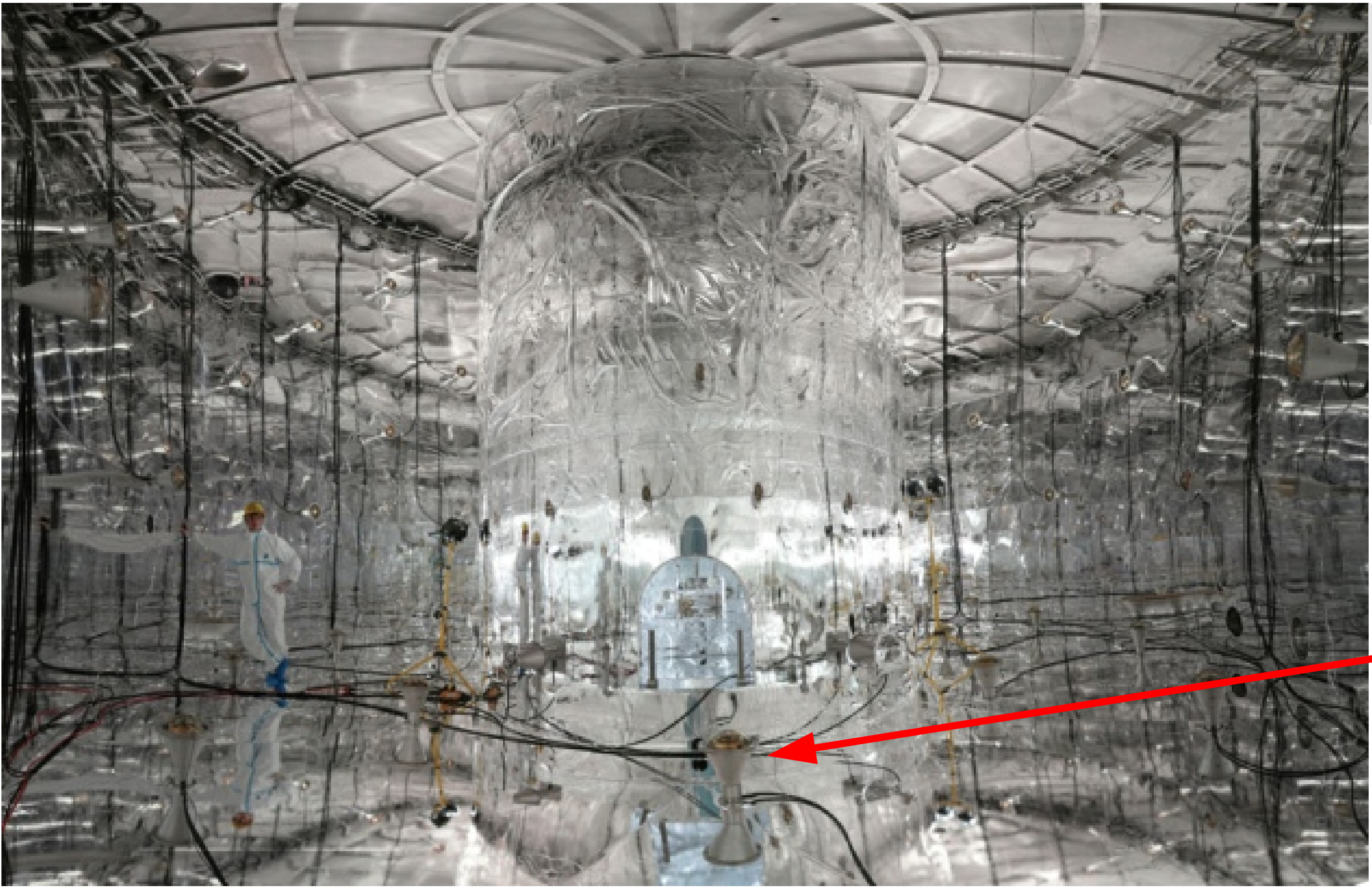
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

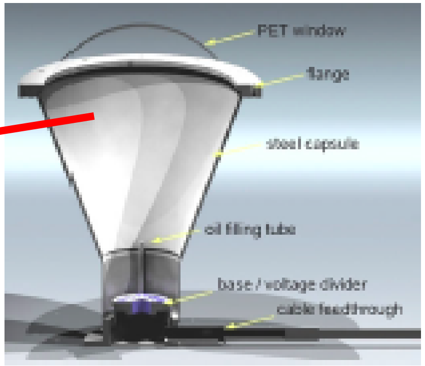
Cherenkov muon veto

plastic scintillator plates
on top of cryostat (3 layers)

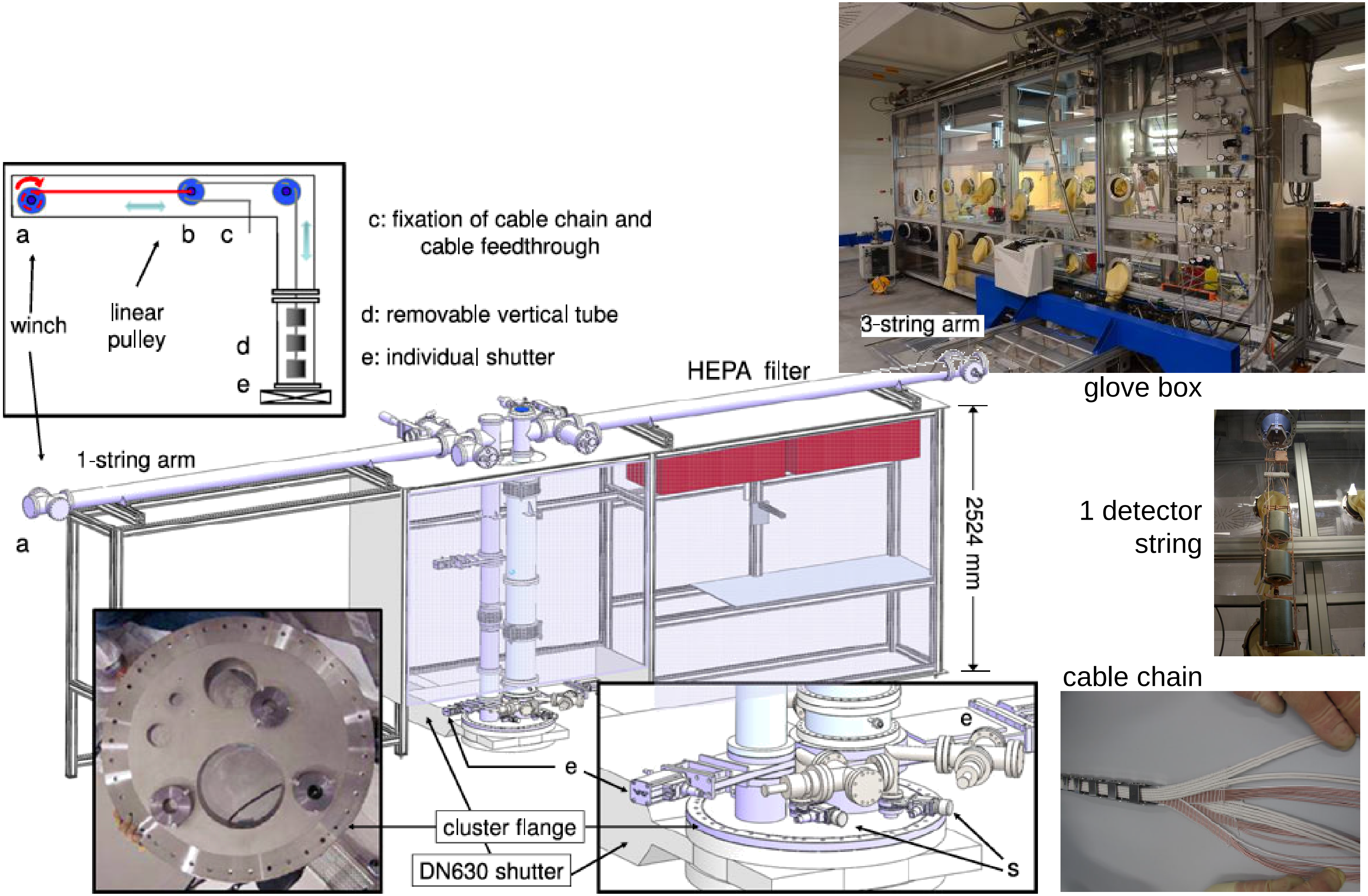
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

view into water tank
with 66 8-inch PMTs





Clean room, lock system, calibration devices



GERDA history (1)

- idea Gerd Heusser 1995
- GERDA proposal 2004


cryostat

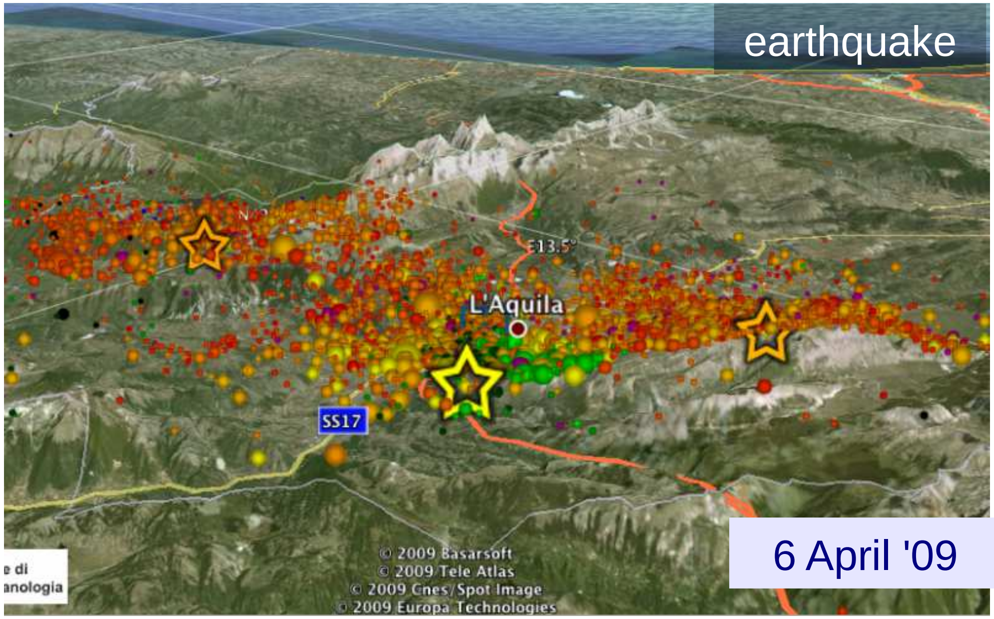
6 March '08


building watertank

5 May '08


cleanroom

29 February '09


earthquake

6 April '09

GERDA history (2)

inside water tank

August '09

active cooling system

18 July '09

glove box

18 May '10

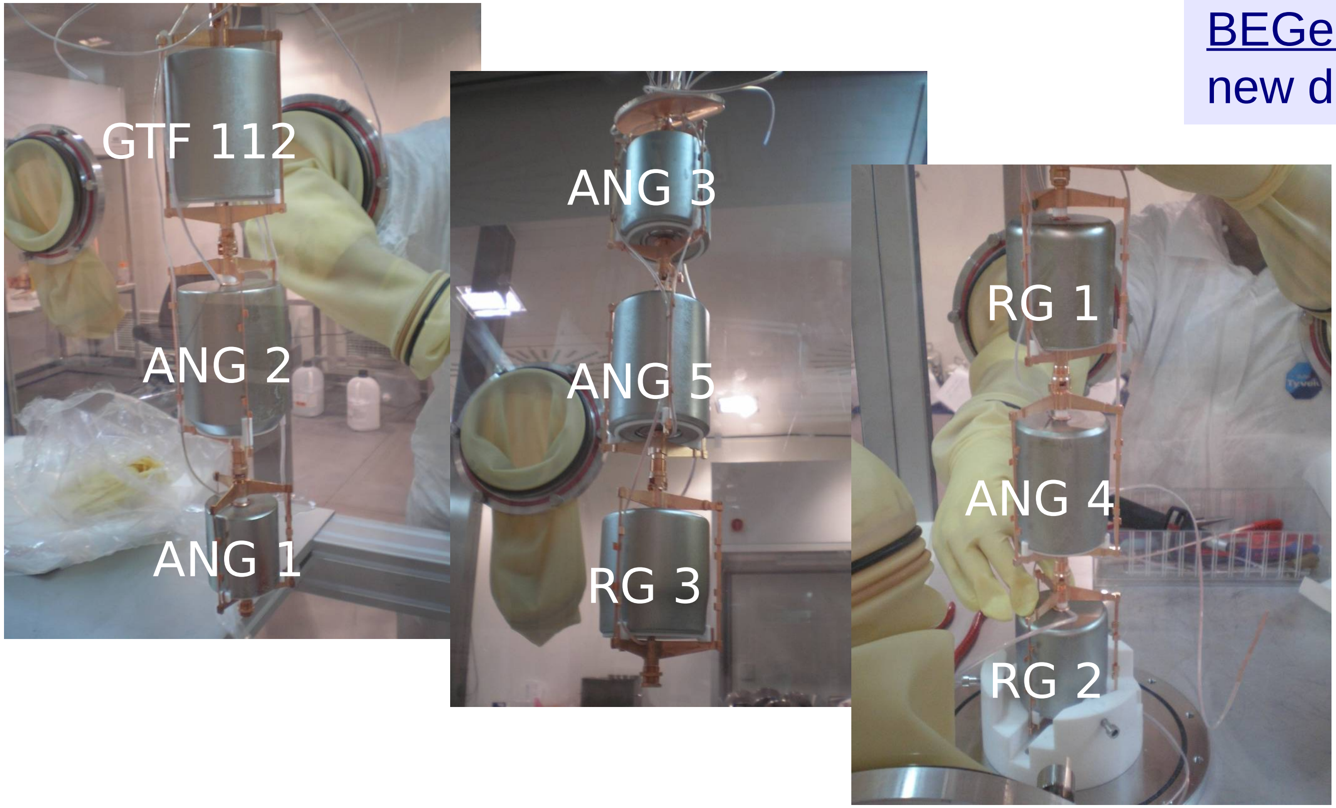
official inauguration

9 November '11

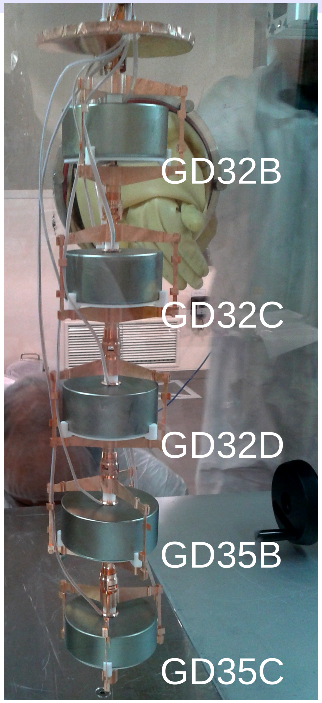
GERDA Phase I detectors

Semi coaxial detectors:

- 8 refurbished diodes from HdM & IGEX (86% enriched in ^{76}Ge)
  → mass of operational detectors **14.2 kg** (~87% active mass)
  (2 detectors shut off due to high leakage current)
- 1 natural Ge detector (GTF)



BEGe detectors: **3.6 kg**
new detectors, inserted later



GERDA Phase I detectors

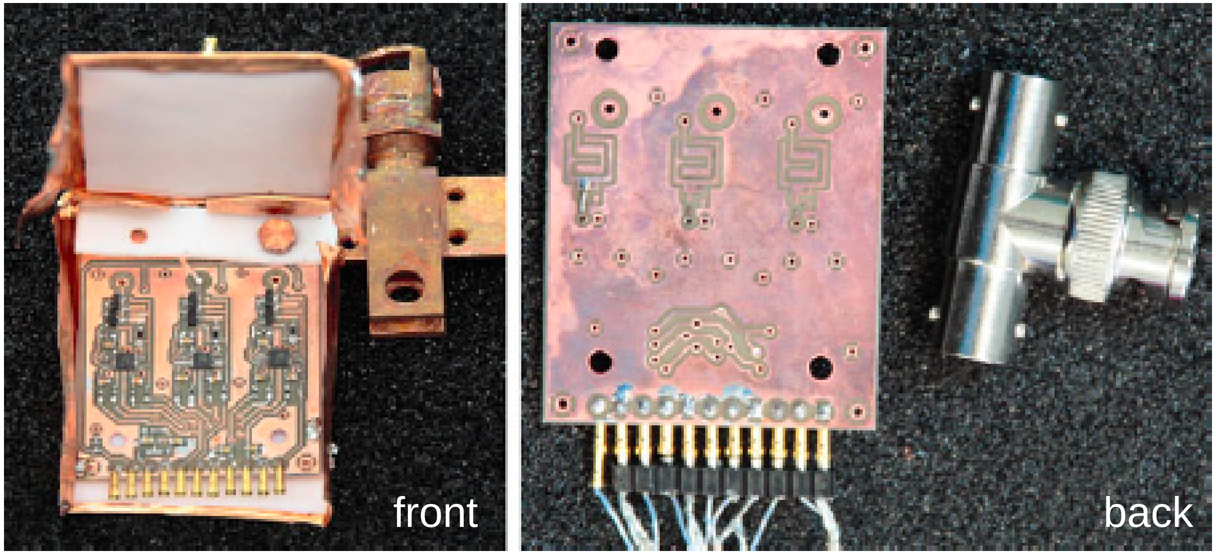
Semi coaxial detectors:

- ▶ 8 refurbished diodes from HdM & IGEX (86% enriched in ^{76}Ge)

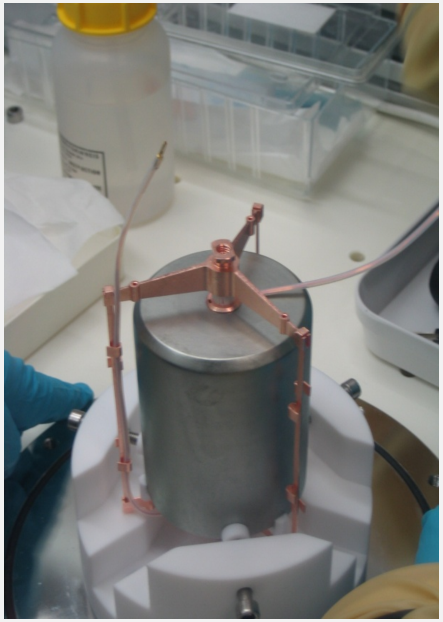
  → mass of operational detectors **14.2 kg** (~87% active mass)

  (2 detectors shut off due to high leakage current)
- ▶ 1 natural Ge detector (GTF)

CC2 charge sensitive preamplifier (3 channels)
→ low radioactivity



low mass copper holder



GD35C

Data processing & selection

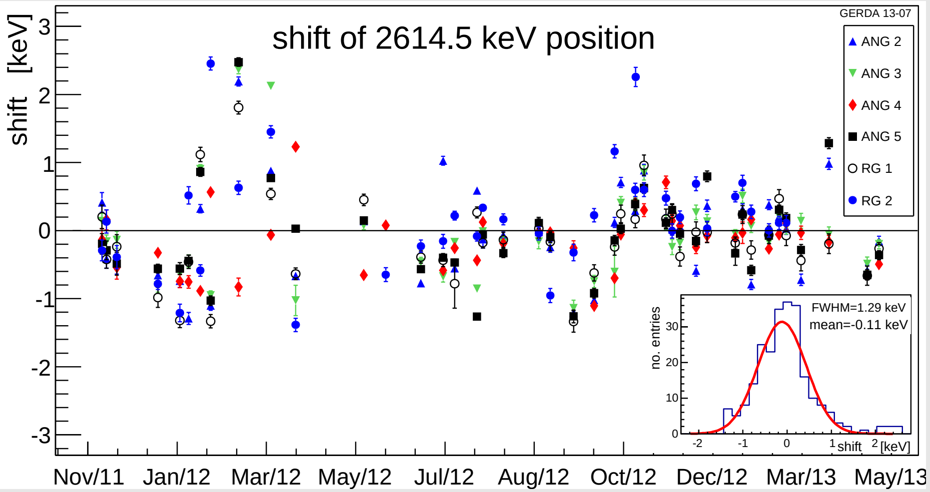
Processing:

diode → amplifier → FADC → digital filter
→ energy, rise time, pulse shape, ...

- ▶ Data processing frame work ‘Gelatio’
- ▶ 2nd independend software 'Geana' for cross check

Energy calibration:

- ▶ (bi)weekly with ^{228}Th (+ pulser)
- ▶ resolution: ~4.5 keV at $Q_{\beta\beta}$ (mass weighted average)
- ▶ stable gain within 1 keV at $Q_{\beta\beta}$

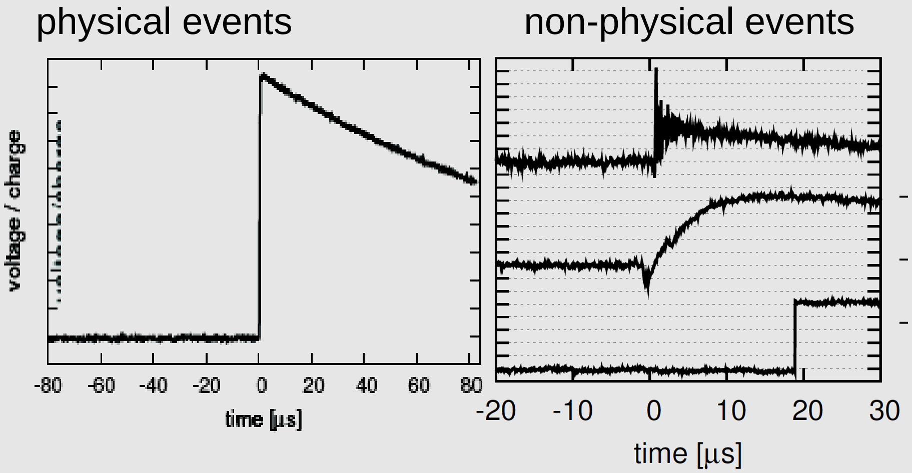


Data selection:

- ▶ muon-veto
- ▶ 2nd detector
- ▶ quality cuts

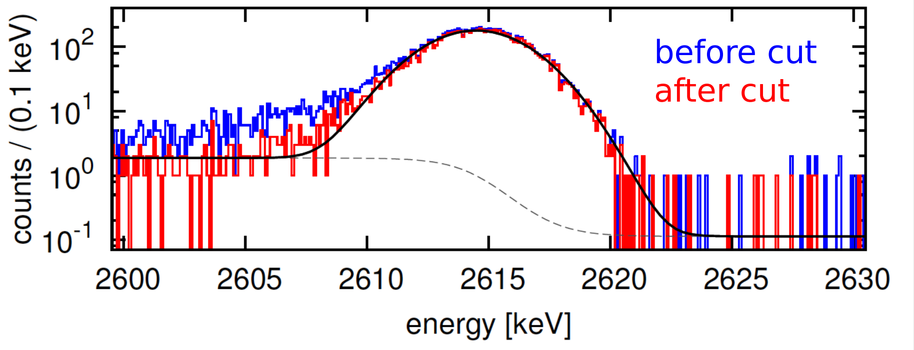
muon-veto, 2nd detector: ~20 % rejected @ $Q_{\beta\beta}$

quality cuts: ~9 % rejected


physical events

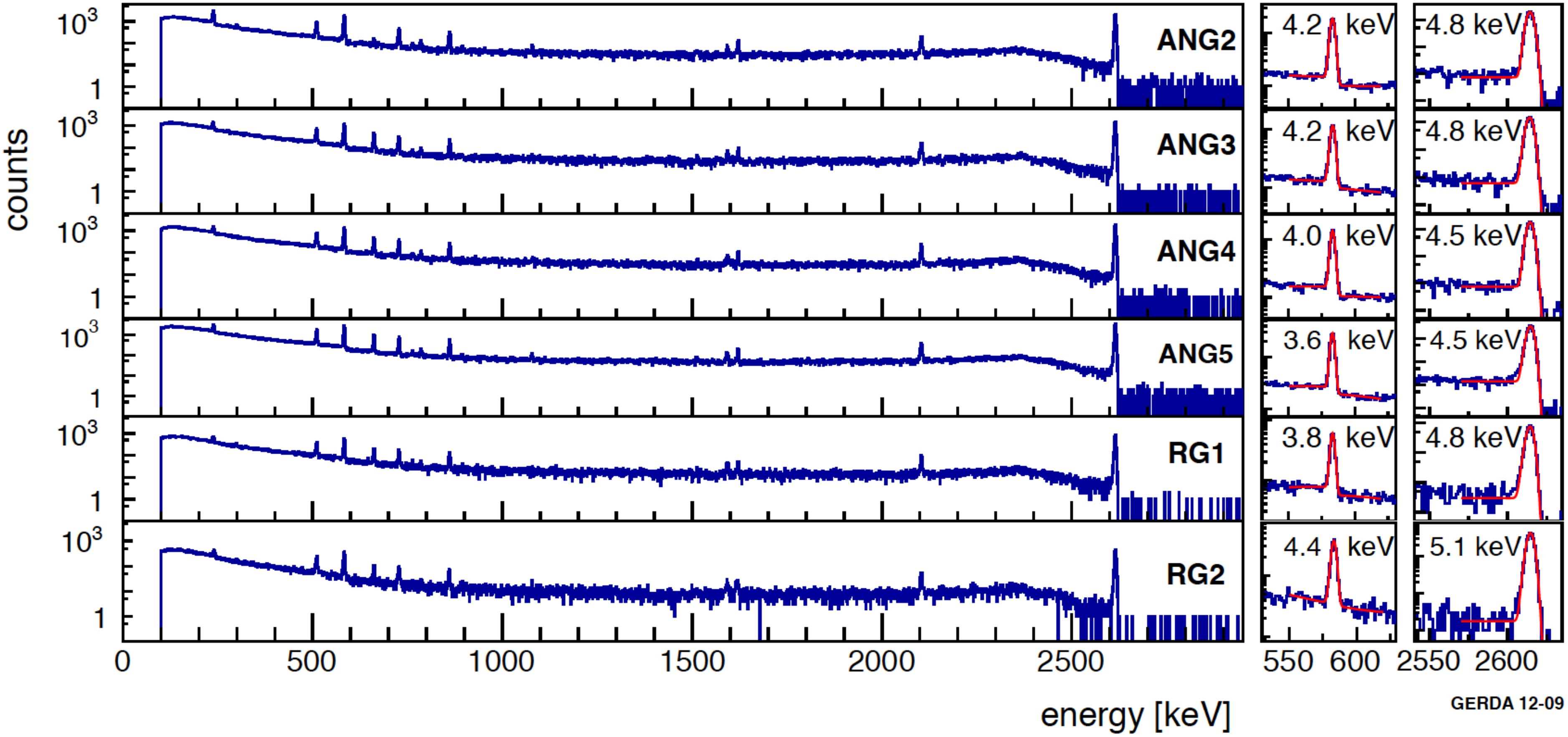
non-physical events

Quality cut @ 2615 keV line of ^{228}Th



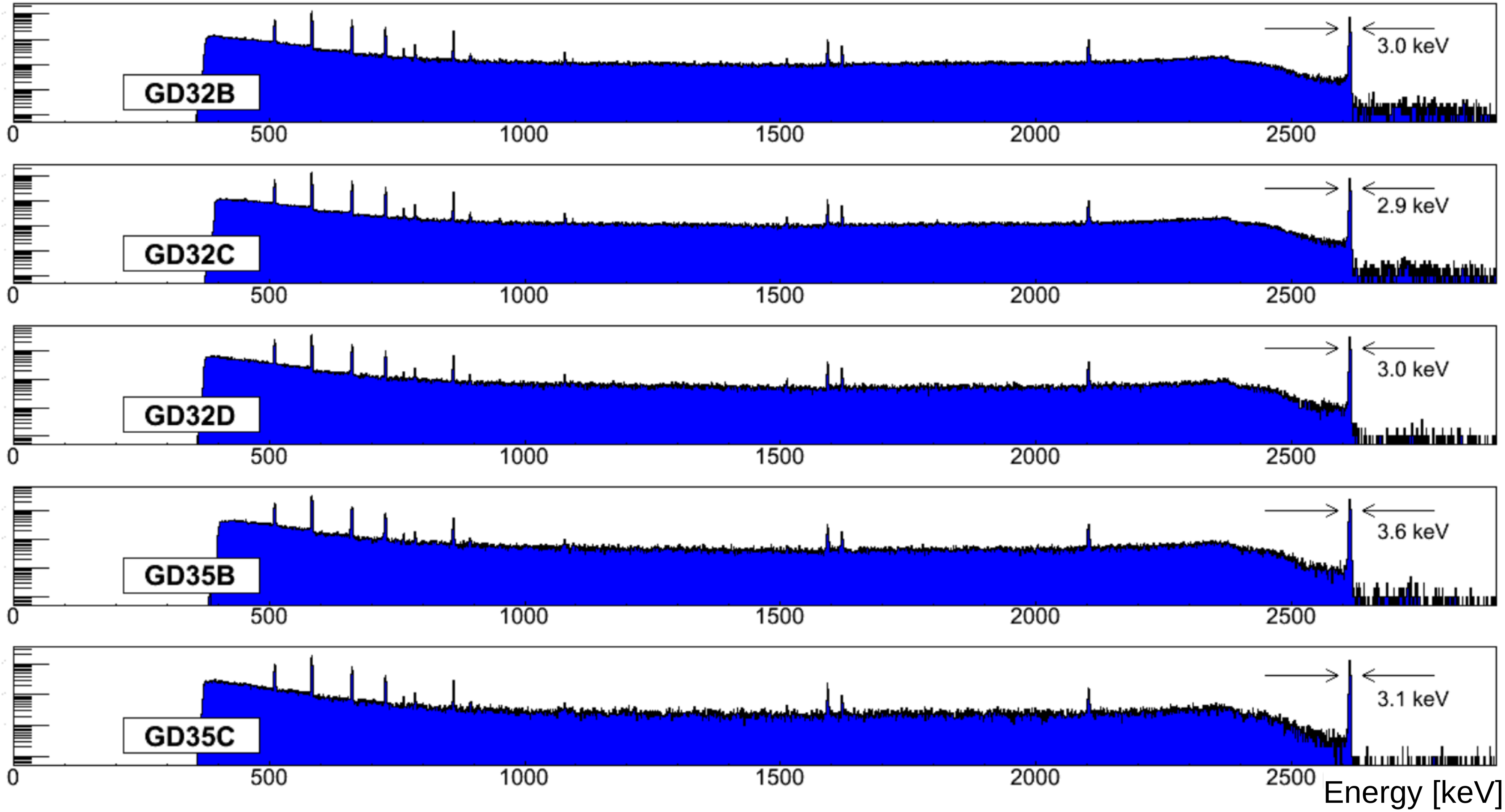
Commissioning: first calibration data

- enriched semi-coaxial detectors



GERDA 12-09

July 2012: 5 ^{enr}BEGe's deployed in GERDA

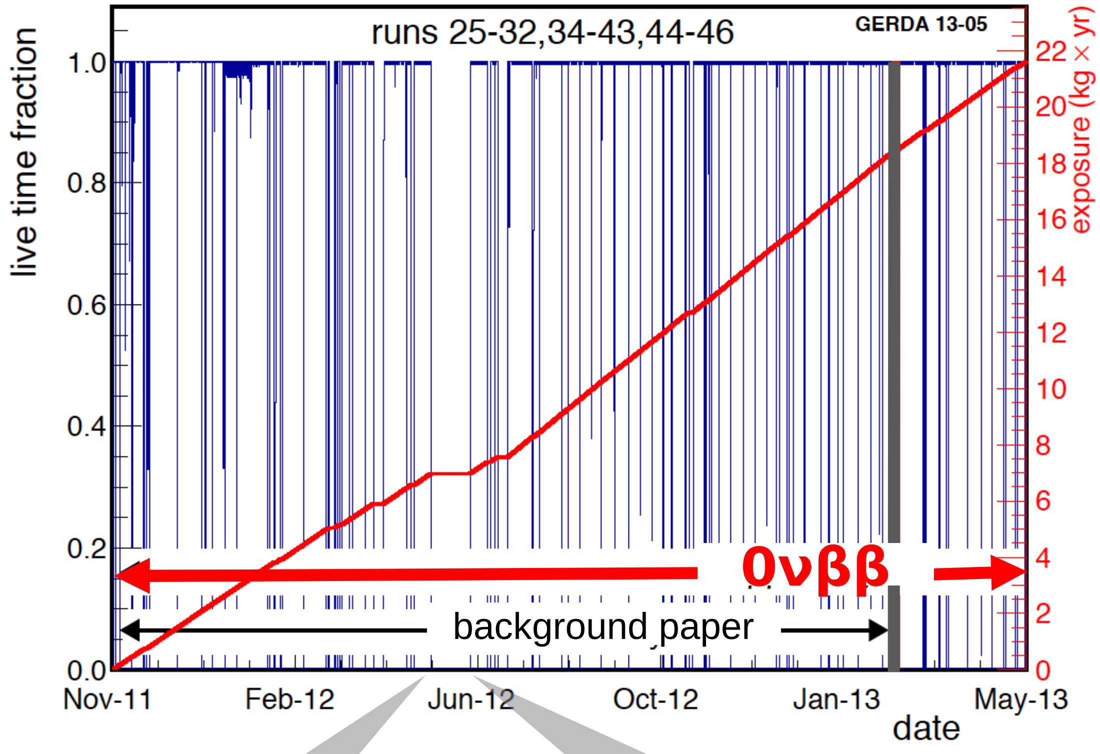


total mass: 3.6 kg

Overview on data taking

- start phase I: November 9, 2011
- total exposure for $0\nu\beta\beta$ analysis: 21.6 kg·yr
- duty factor: ~90%

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



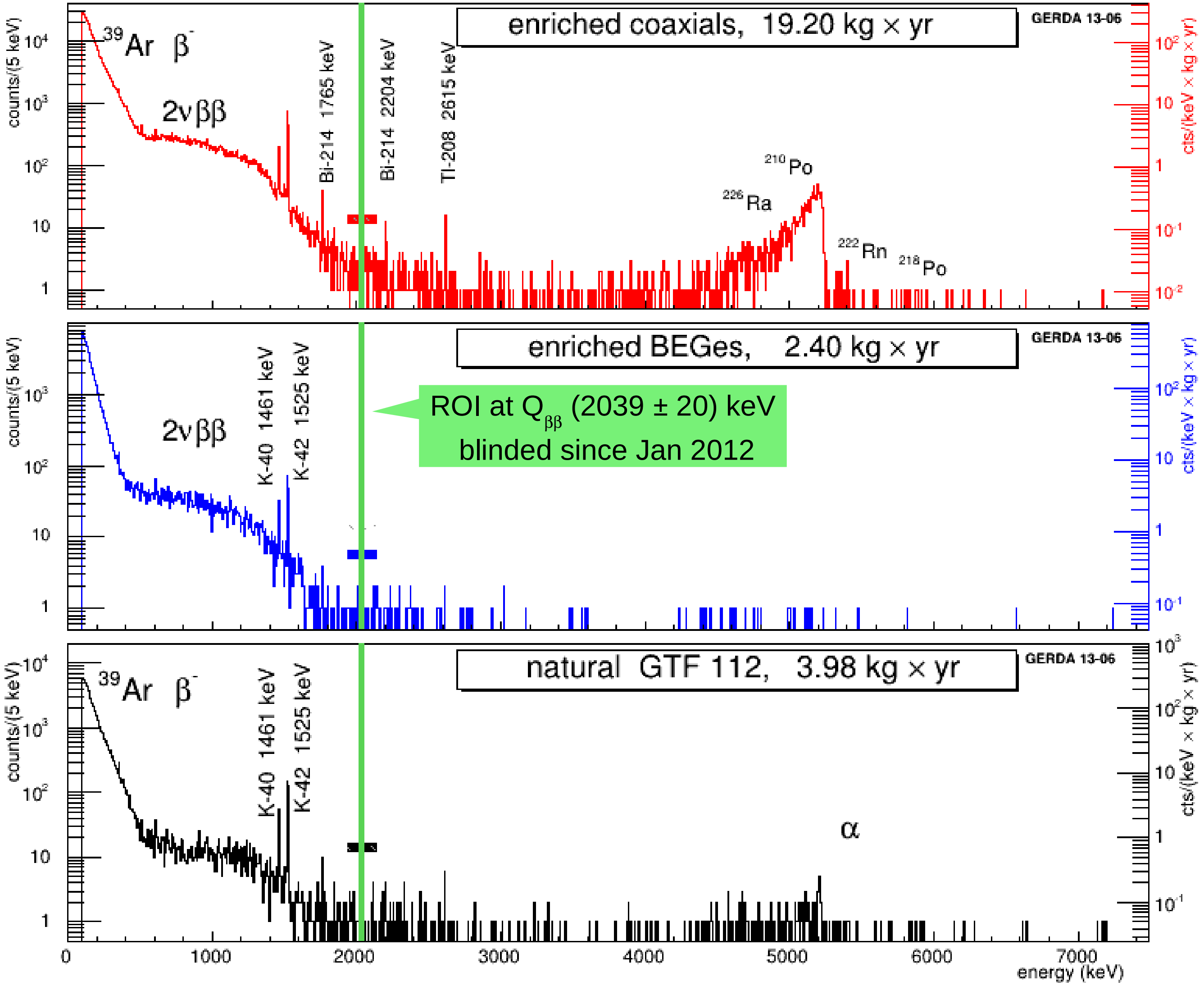
$2\nu\beta\beta$ analysis

insertion of 5 ^{enr}BEGe

Outline

1. $0\nu\beta\beta$ physics
2. GERDA setup
3. Background & $2\nu\beta\beta$
4. Phase I result
5. Outlook on Phase II

Phase I physics run, energy spectra

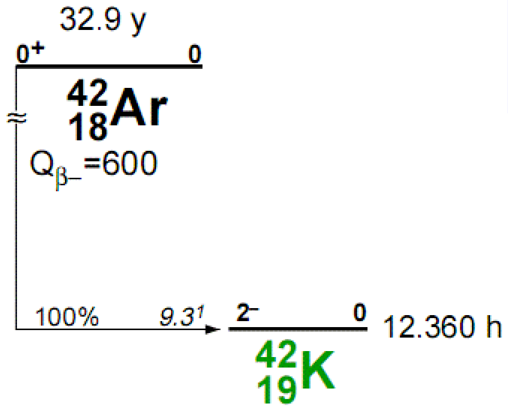


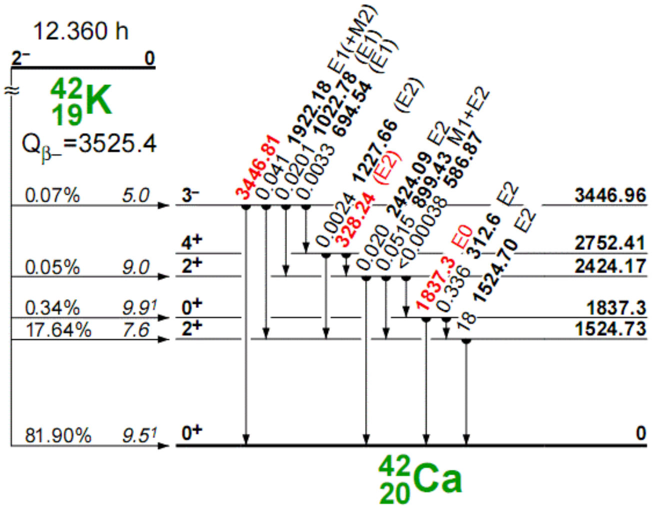
<u>Dominant background sources:</u> ^{42}Ar, ^{228}Th & ^{226}Ra in holder, α on detector surface

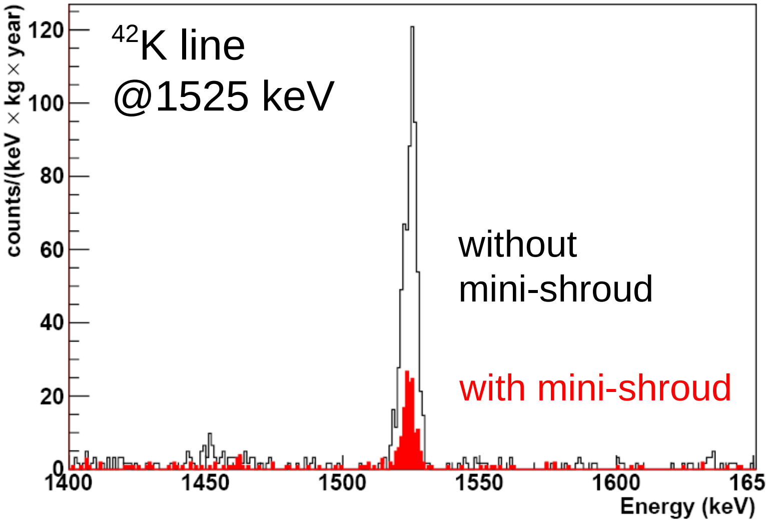
^{42}K background

^{42}Ar activity used for proposal:	<41 µBq/kg @90% CL	[Barabash et al.,2002]
measured in GERDA:	(93.0 ± 6.4) µBq/kg	(preliminary result)

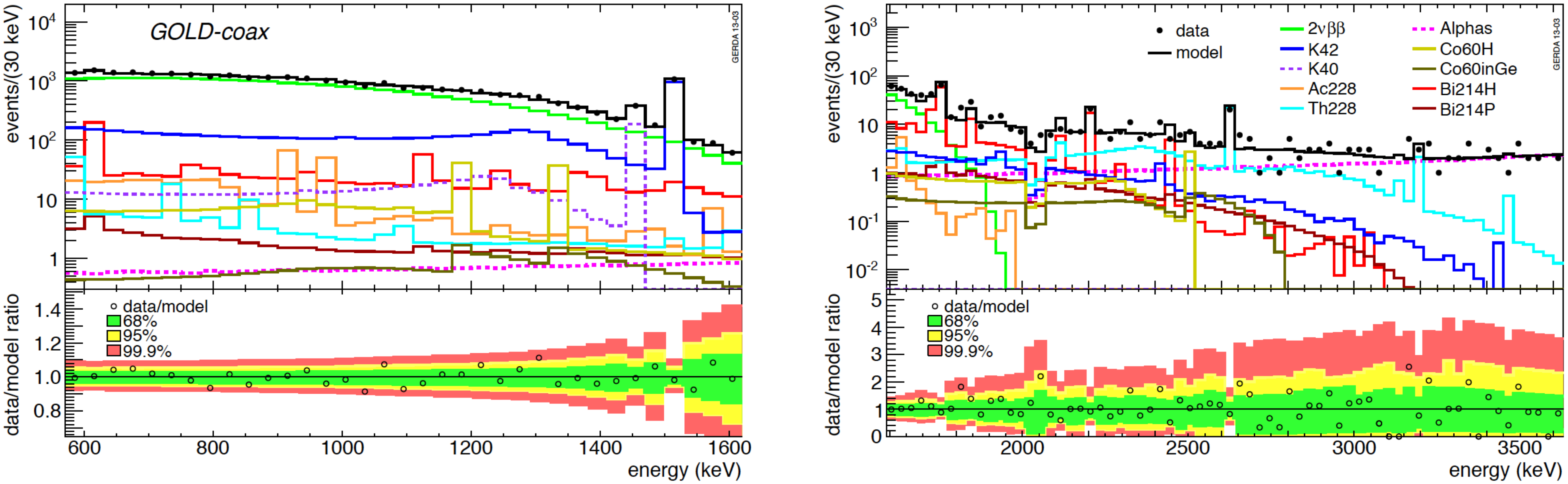
- ► background enhanced by collection of ^{42}K ions via E-field
- ► therefore: E-field & convection free configuration in 'mini-shroud'

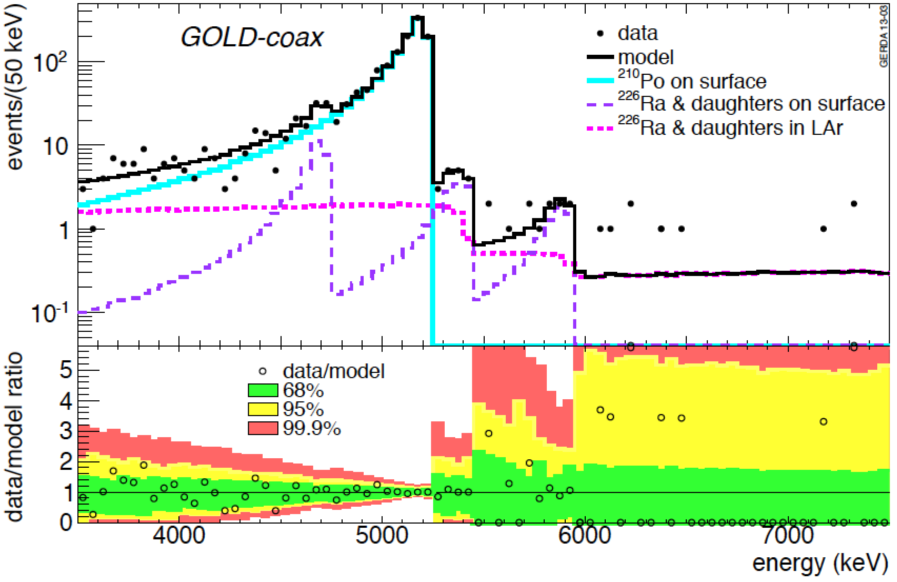






Background model





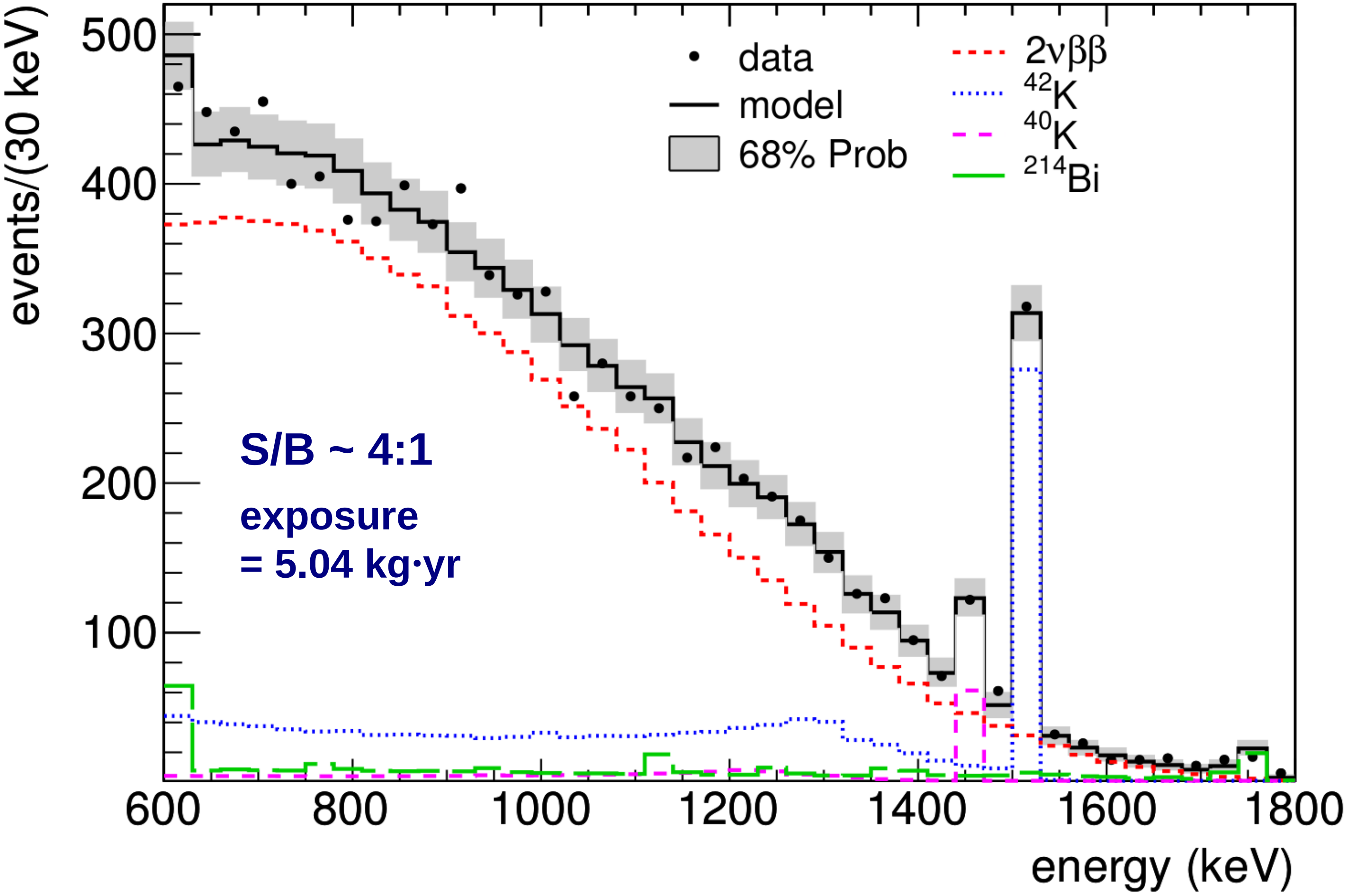
- ▶ simulated known & observed background contributions
- ▶ fit combined Monte Carlo spectra to data in interval 570 keV – 7500 keV
- ▶ different combinations of backgrounds tested (location & contribution)

→ no hint for additional (strong) peaks

→ model describes data well

accepted by EPJC
[arXiv:1306.5084]

GERDA result: halflife of 2νββ



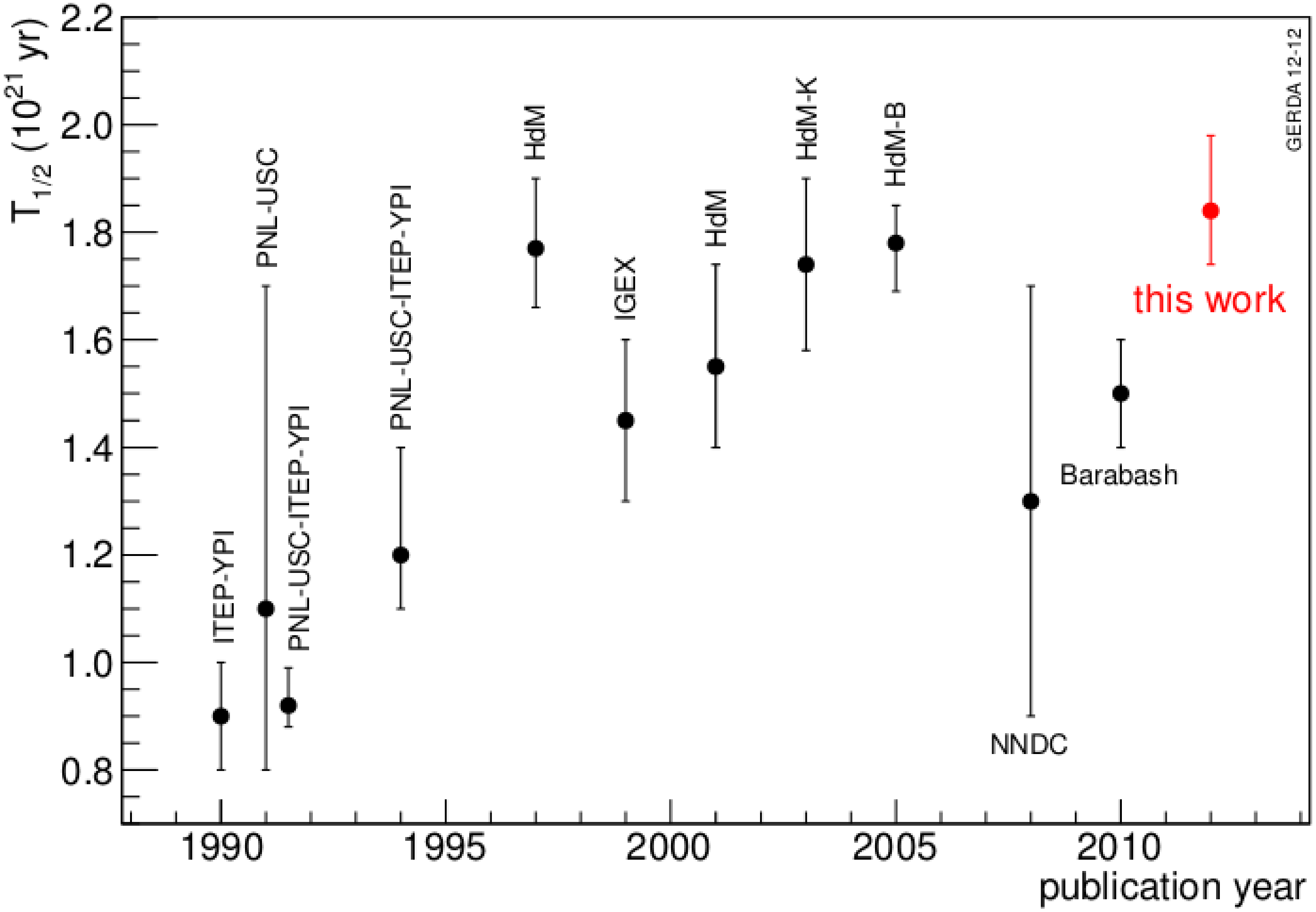
S/B ~ 4:1

exposure
= 5.04 kg·yr

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

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

Comparison of 2νββ measurements

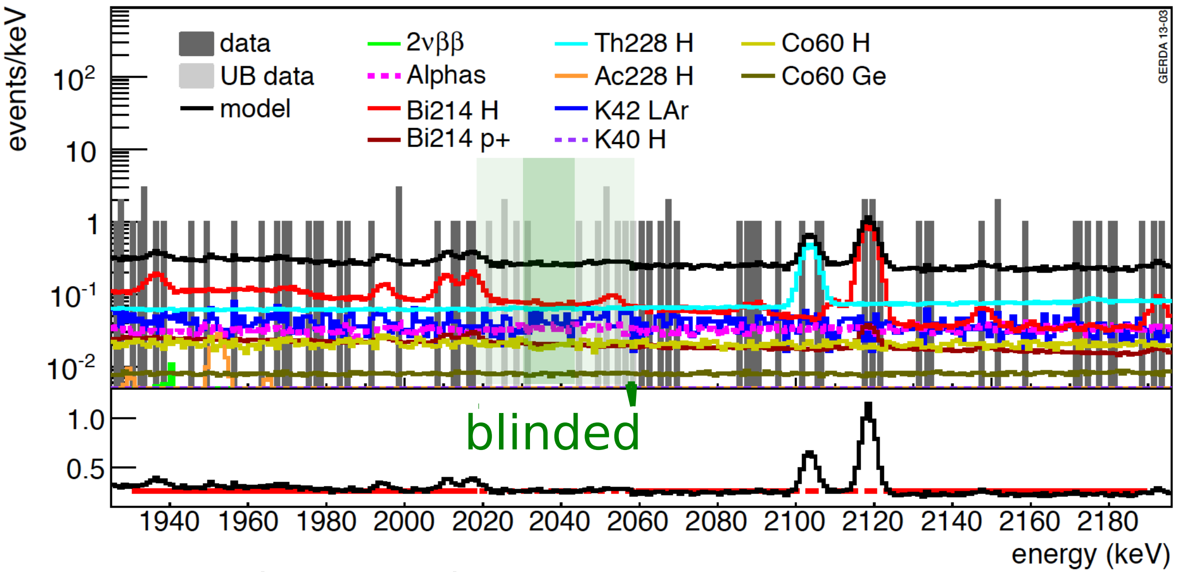


$$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08}\ {}_{\text{fit}}\ {}^{+0.11}_{-0.06}\ {}_{\text{syst}}) \cdot 10^{21}\ \text{yr} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}\ \text{yr}$$

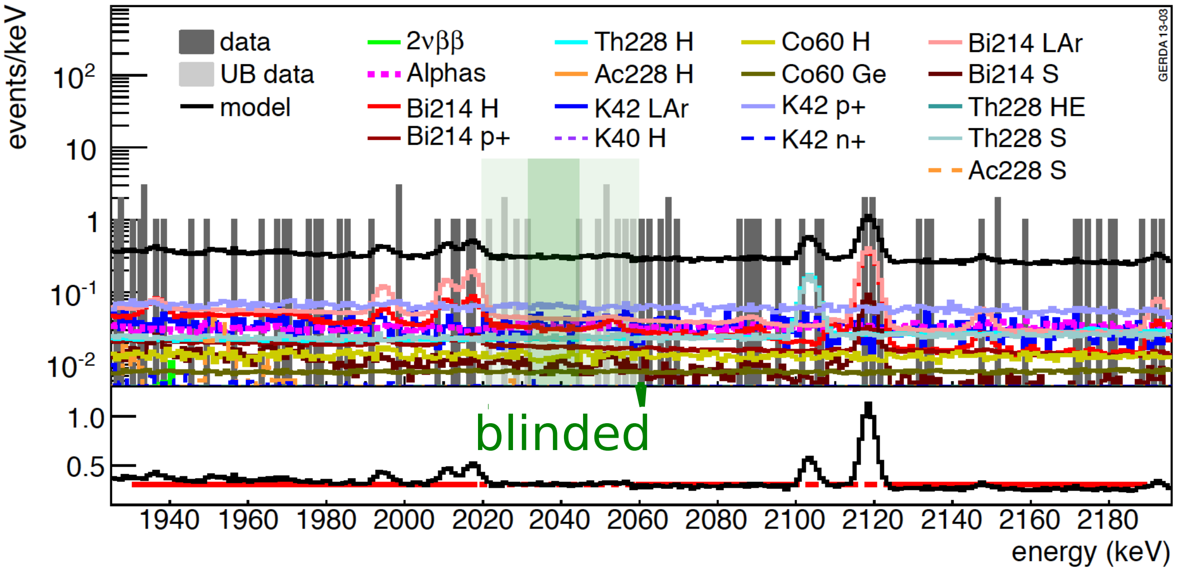
[J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110]

Background model at $Q_{\beta\beta}$

Minimal model



Maximum model



- **no background peak at $Q_{\beta\beta}$**
- **background is flat**
  in 1930-2190 keV
  - → excluding known peaks at 2104 and 2119 keV
  - → expect <<1 event in other weak ^{214}Bi lines (e.g. 2017, 2053 keV)
- **partial unblinding**
  after fixing calibration & background model

Background index:

Golden coax:

$$\mathrm{BI} = 1.75^{+0.26}_{-0.24} \cdot 10^{-2}\ \mathrm{cts/(keV\ kg\ yr)}$$

BEGe:

$$\mathrm{BI} = 3.6^{+1.3}_{-1.0} \cdot 10^{-2}\ \mathrm{cts/(keV\ kg\ yr)}$$

Outline

(1) 0νββ physics

(2) GERDA setup

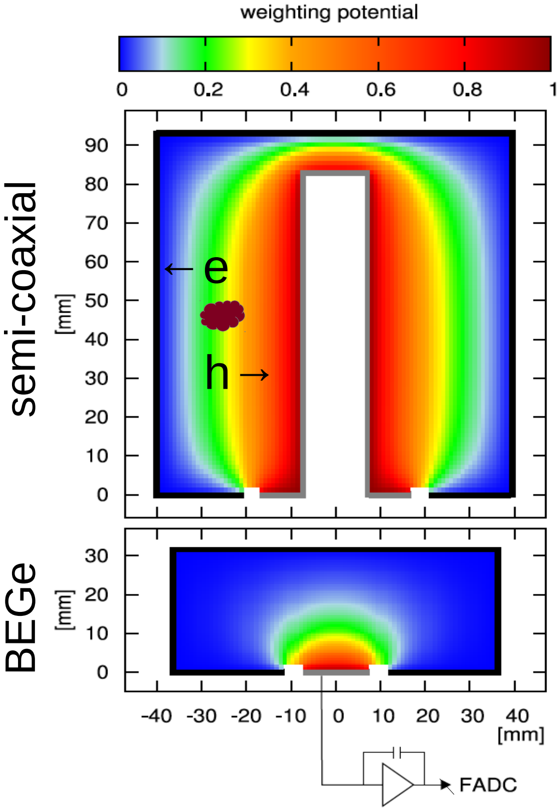
(3) Background & 2νββ

→ Pulse shape discrimination (PSD)

(4) Phase I result

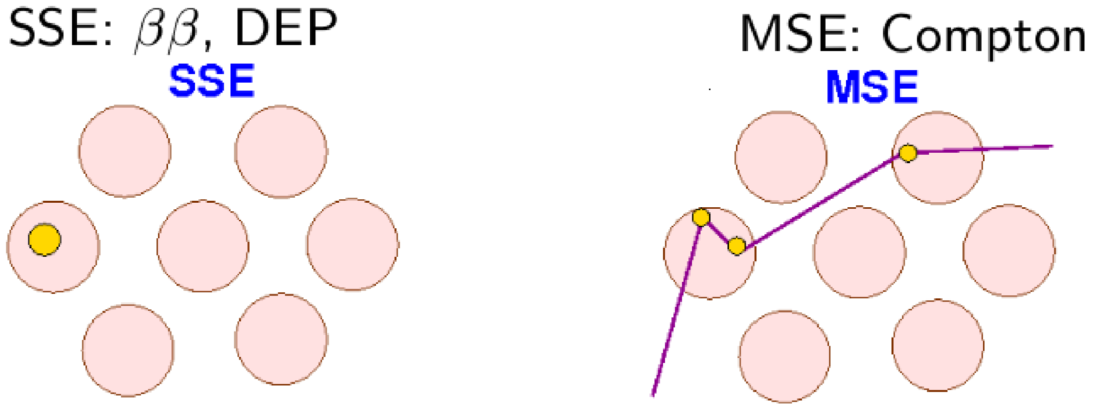
(5) Outlook on Phase II

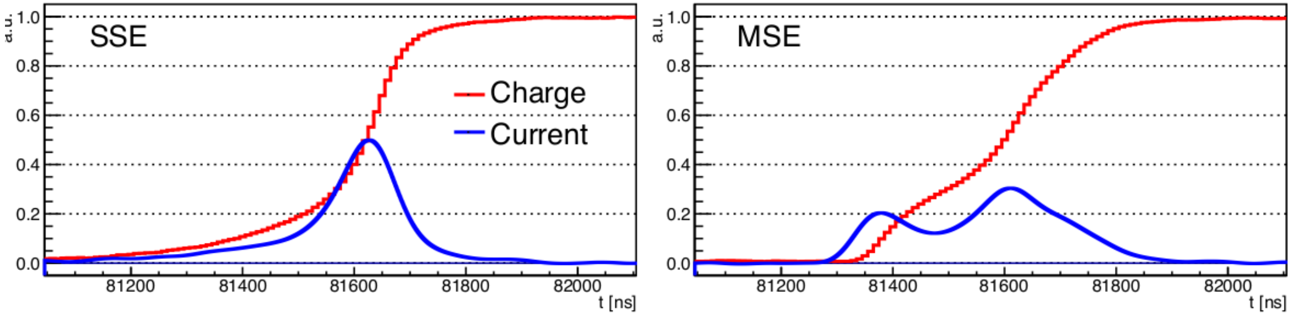
Pulse shape discrimination



$$\text{current signal} = q \cdot v \cdot \nabla \Phi$$

q= charge, v = velocity
(Shockley-Ramo theorem)





$0\nu\beta\beta$ events: 1 MeV electrons in Ge ~ 1mm range one drift of electrons and holes SINGLE SITE EVENTS (SSE)

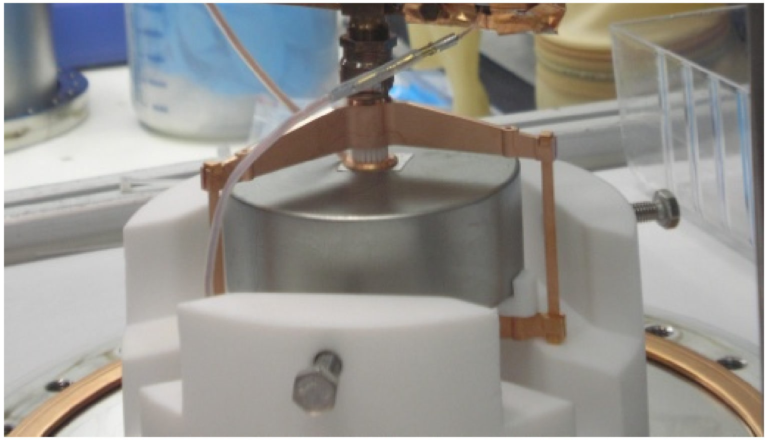
Background from γ's: MeV γ in Ge ~ cm range several electron/holes drifts MULTI SITE EVENTS (MSE)

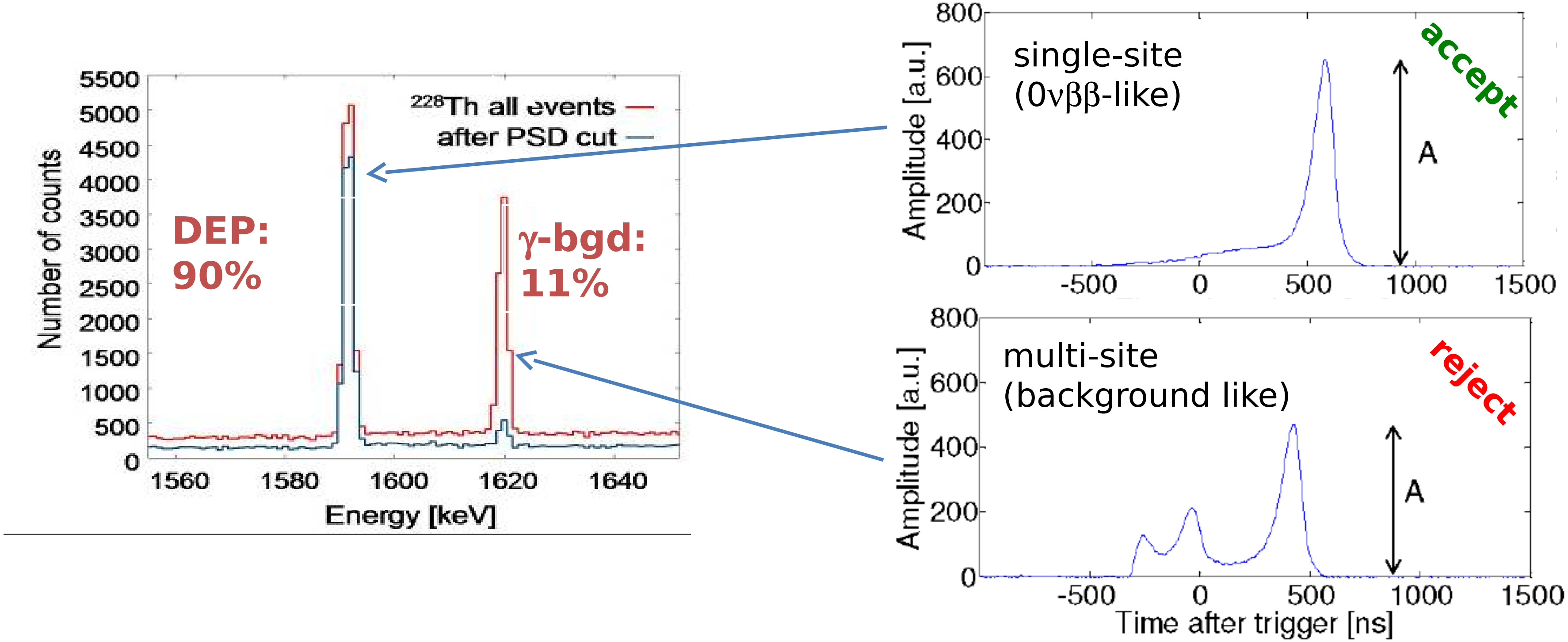
Surface events: only electron or hole drift

[Eur. Phys. J. C (2013) 73:2583]

BEGe detector pulse shape discrimination

- developed with calibration data robust & well understood method
- double escape peak (DEP) of ^{228}Th are single-site-events (SSE) and serve as proxy for $0\nu\beta\beta$
- use ratio A/E for discrimination (amplitudes of *current* and *charge* pulse) accept events 0.965 < A/E < 1.07





BEGe detector pulse shape discrimination

- developed with calibration data
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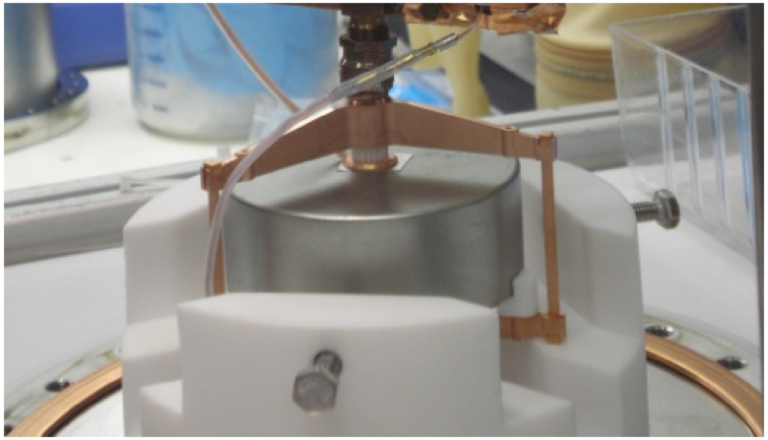
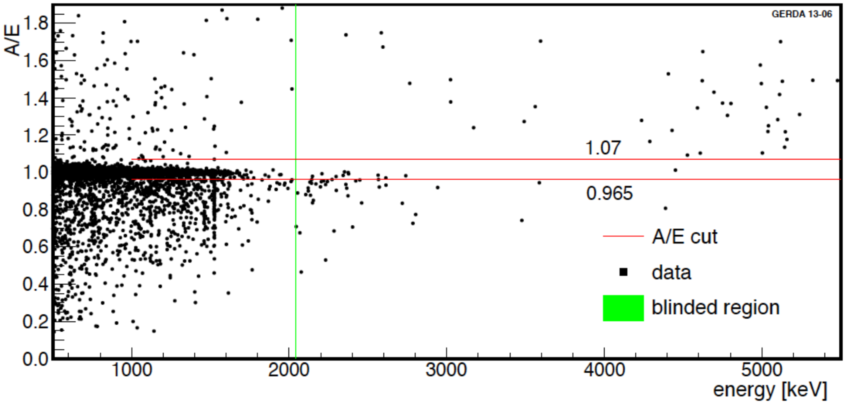
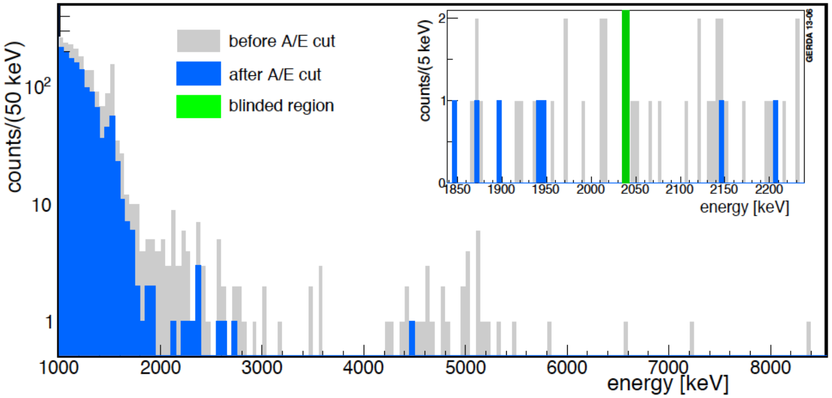


A/E versus E for physics data



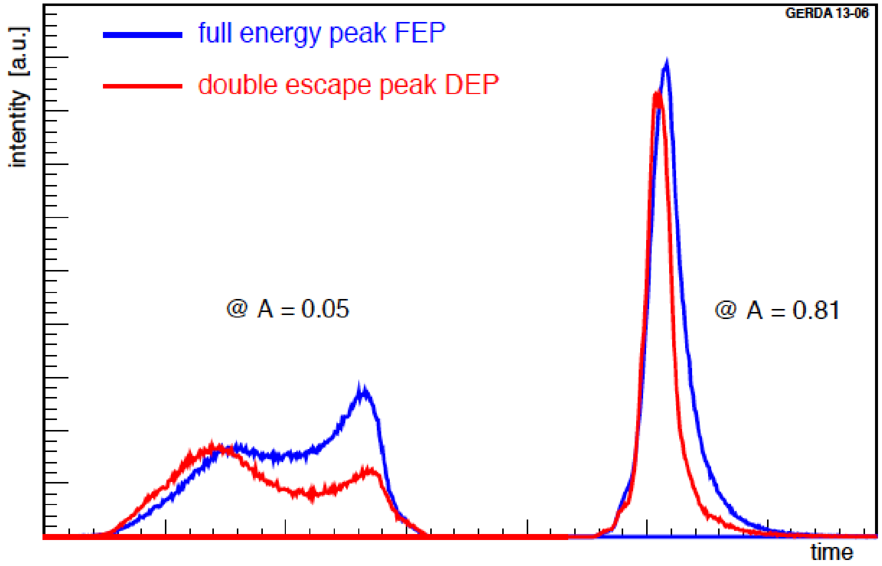
spectrum with PSD applied (blue)

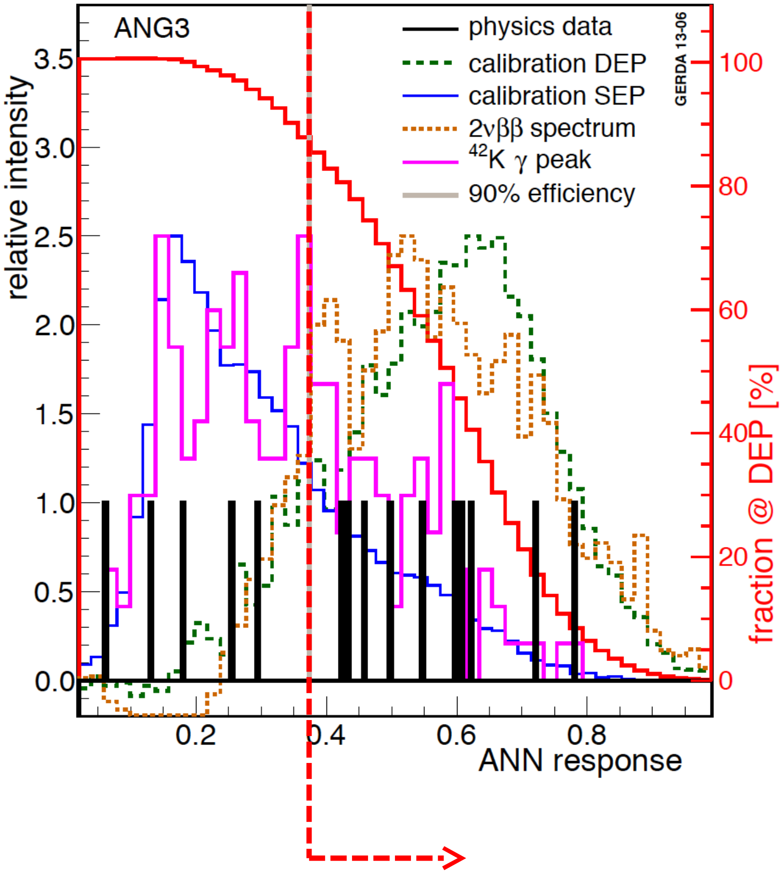


0νββ efficiency = 92±2 % determined from DEP efficiency & simulation
2νββ efficiency = 91±5 % in good agreement to DEP efficiency
reject > 80% of background events

Pulse shape discrimination for semi-coaxial

Input: time when charge signal reaches 1%, 3%, …, 99% of maximum





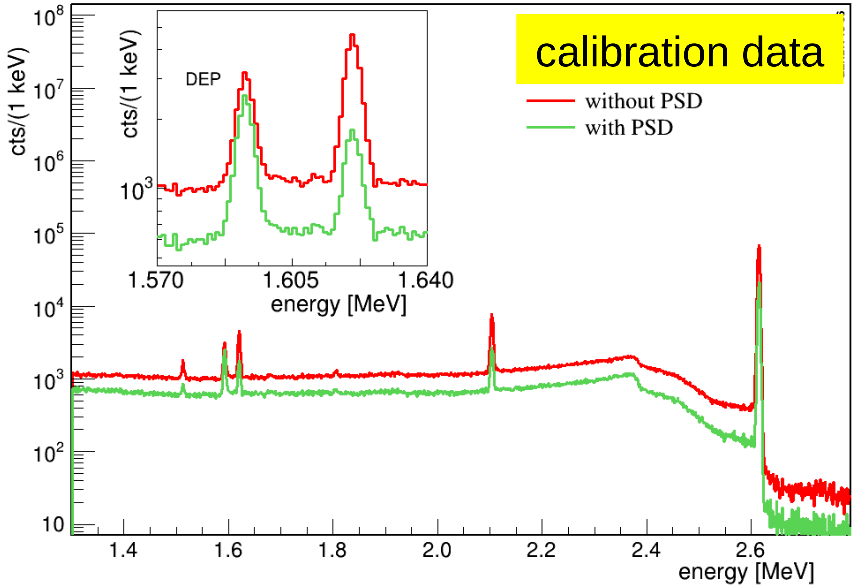
- ► tested many methods implemented in TMVA, selected artificial neural network TMlpANN
- ► select ANN cut position @ DEP survival = 90%

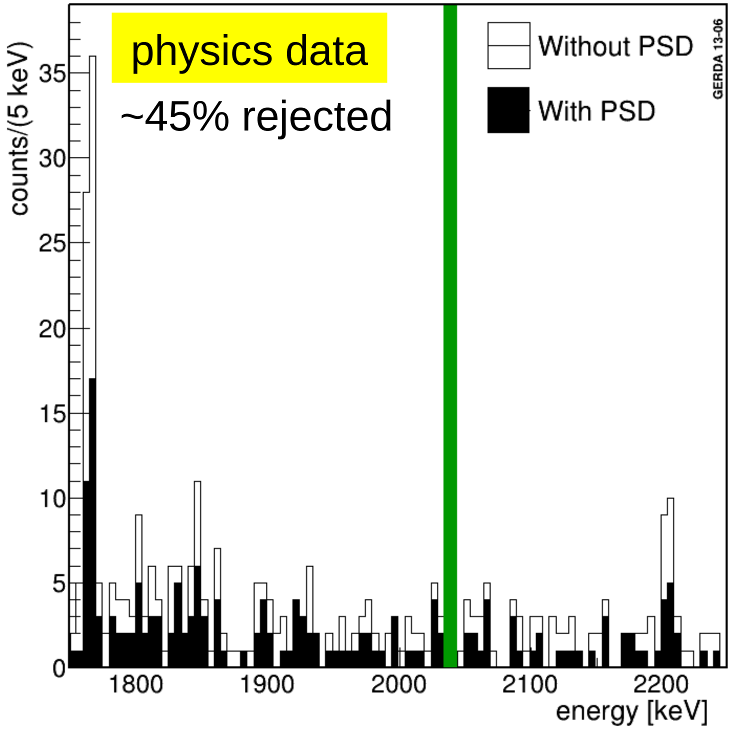
accepted as SSE-like

<u>cross checks:</u>
2νββ eff. = 85±2 %,
2.6 MeV γ Compton edge eff. = 85-94%,
^{56}Co DEP (1576 keV) eff. = 83%-95%
^{56}Co DEP (2231 keV) eff. = 83%-93%

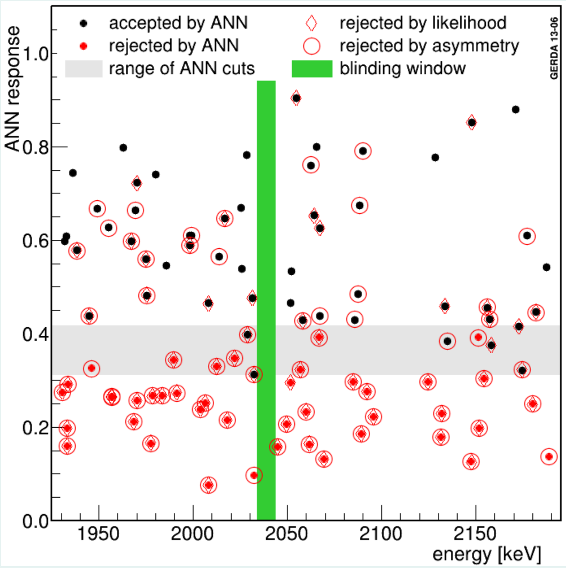
$$0\,\nu\beta\beta\,\text{efficiency} = 0.90^{+0.05}_{-0.09}$$

Pulse shape discrimination for semi-coaxial





cross check ANN with two other methods:



Method 2: projective **likelihood**
trained with Compton edge events

Method 3: “current pulse **asymmetry** * A/E”

- 90% of ANN rejected events also rejected by both,
- 3% only rejected by ANN

→classification of background like events meaningful!

Outline

(1) 0νββ physics

(2) GERDA setup

(3) Background & 2νββ

(4) Phase I result

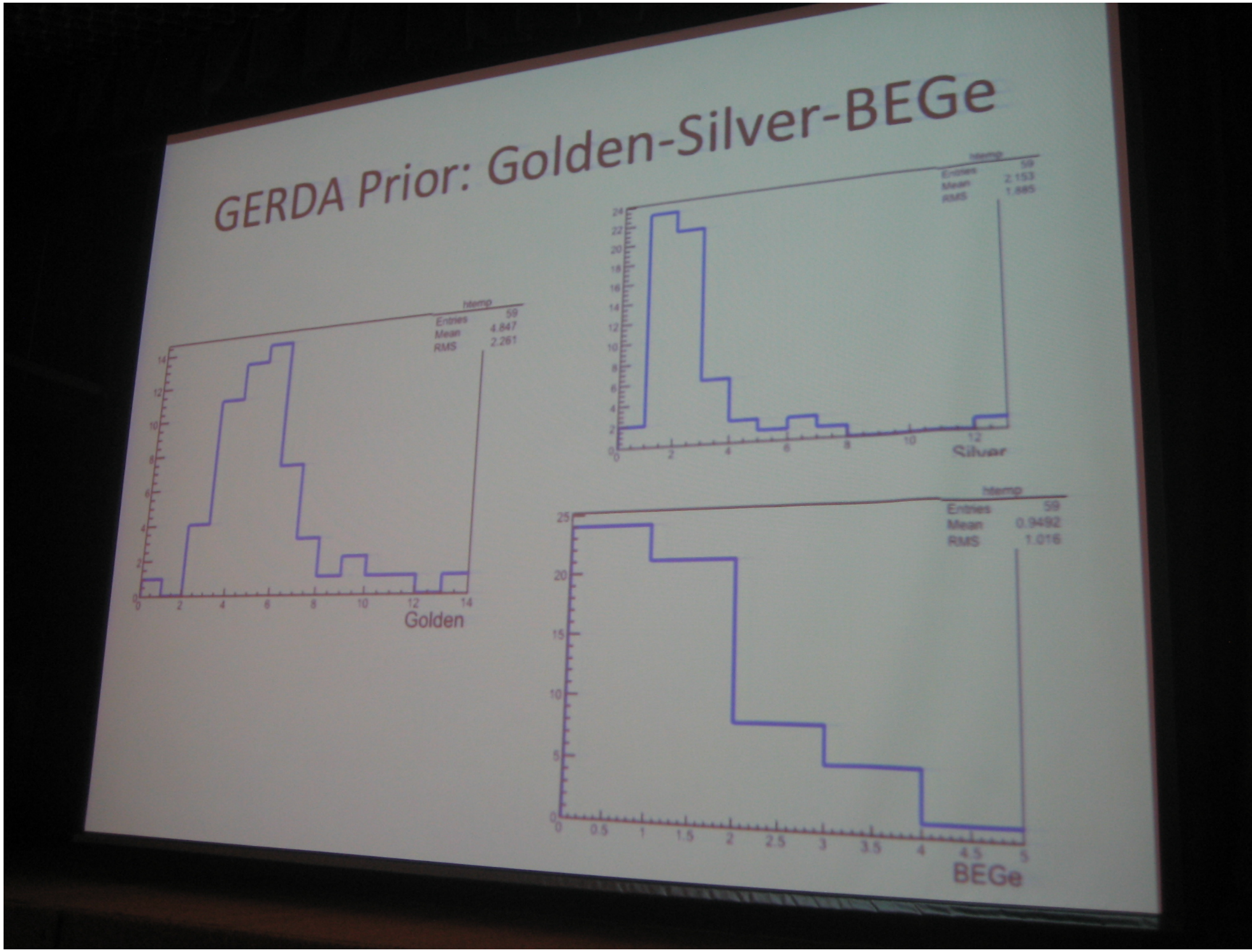
(5) Outlook on Phase II

Unblinding at GERDA collaboration meeting in Dubna/Russia, June 12-14 2013

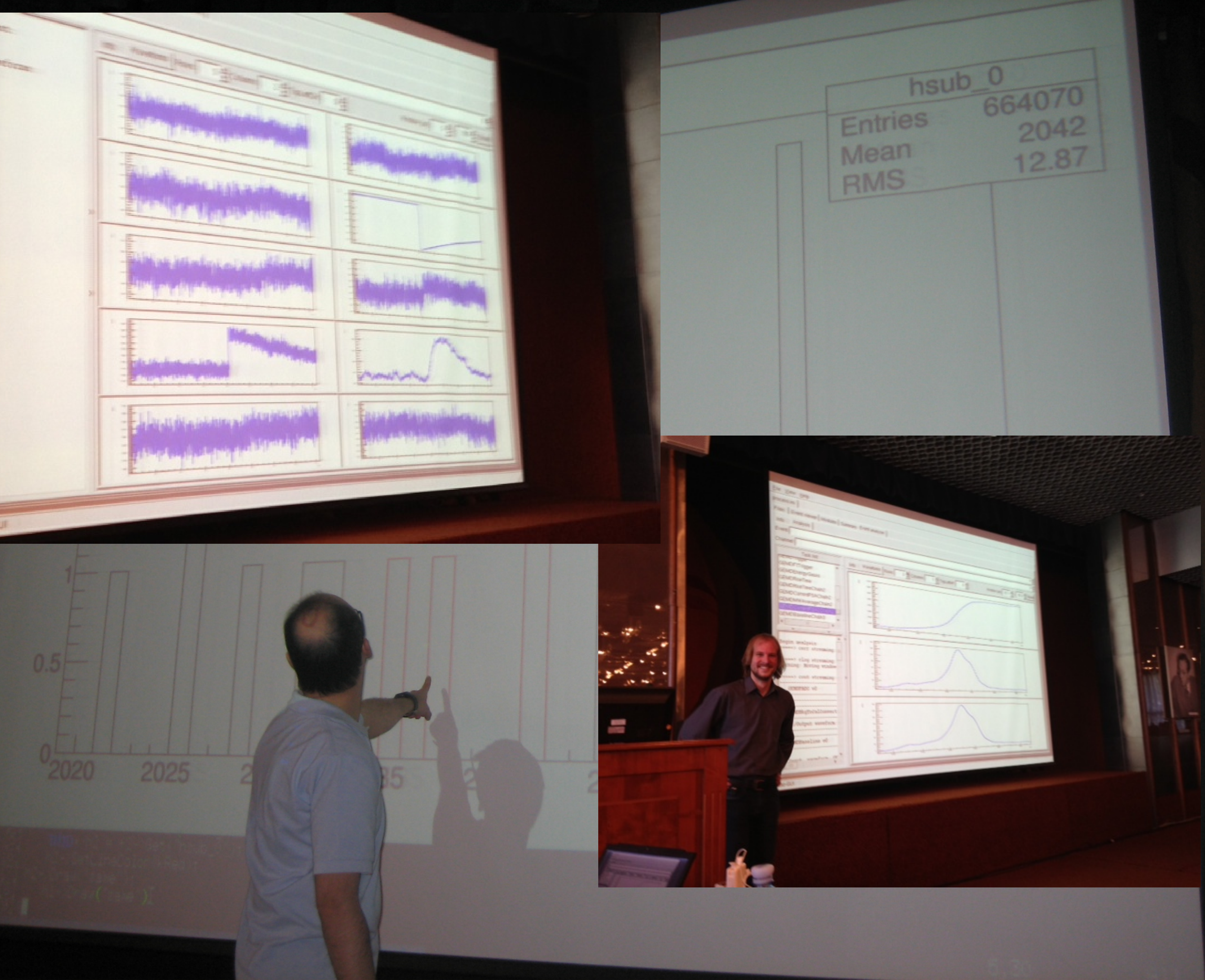
Discussions & preparation for unblinding: freezing all parameters and methods...

- 3 Data sets: golden, silver, BEGe
- Energy calibration method and parameters
- define PSD method and cuts
- define statistical methods

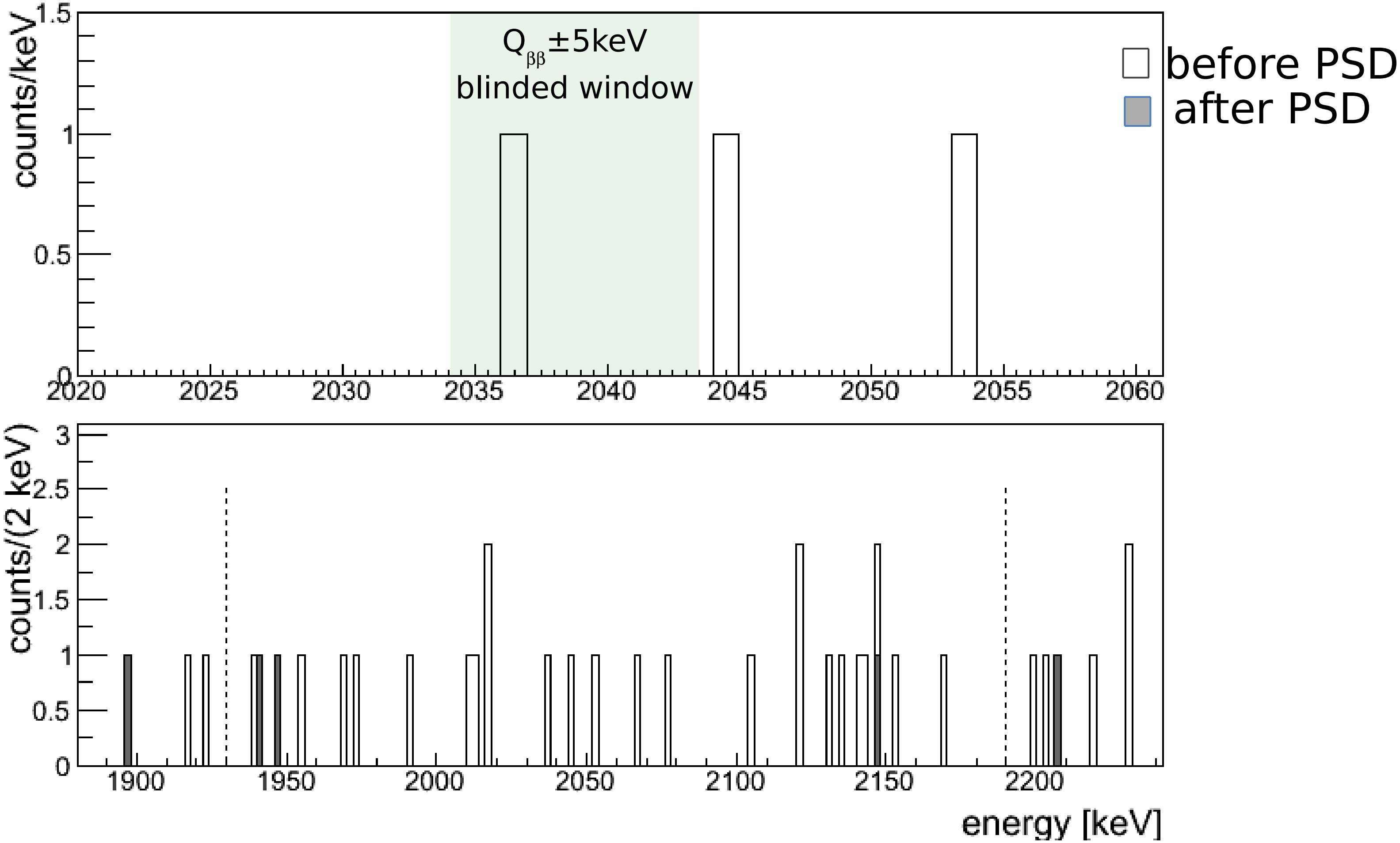
Unblinding: analysing collaboration bets



GERDA Prior: Golden-Silver-BEGe

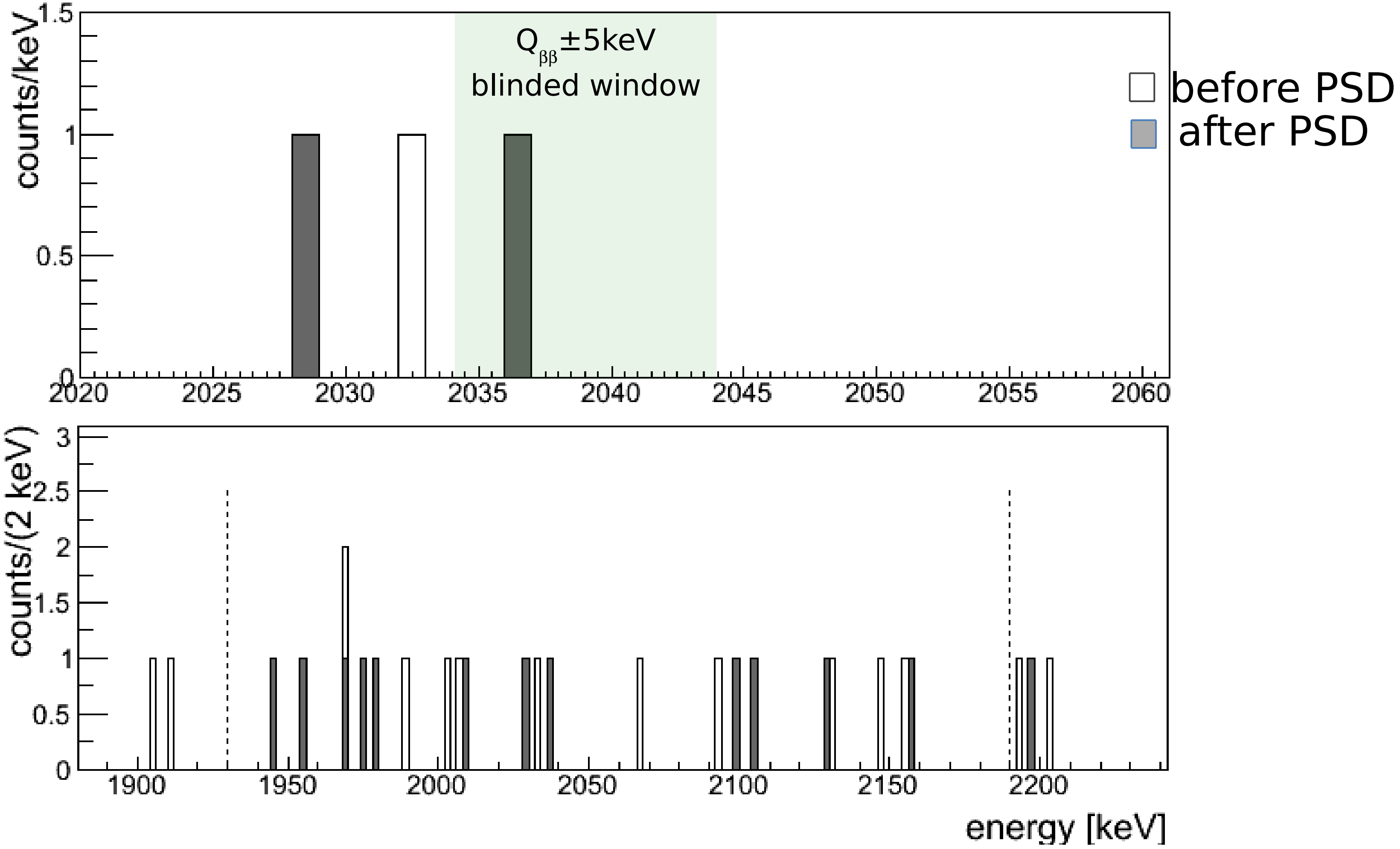

hsub_0
Entries 664070
Mean 2042
RMS 12.87
1
0.5
0
2020
2025

Unblinding BEGe data set (2.4 kg·yr)



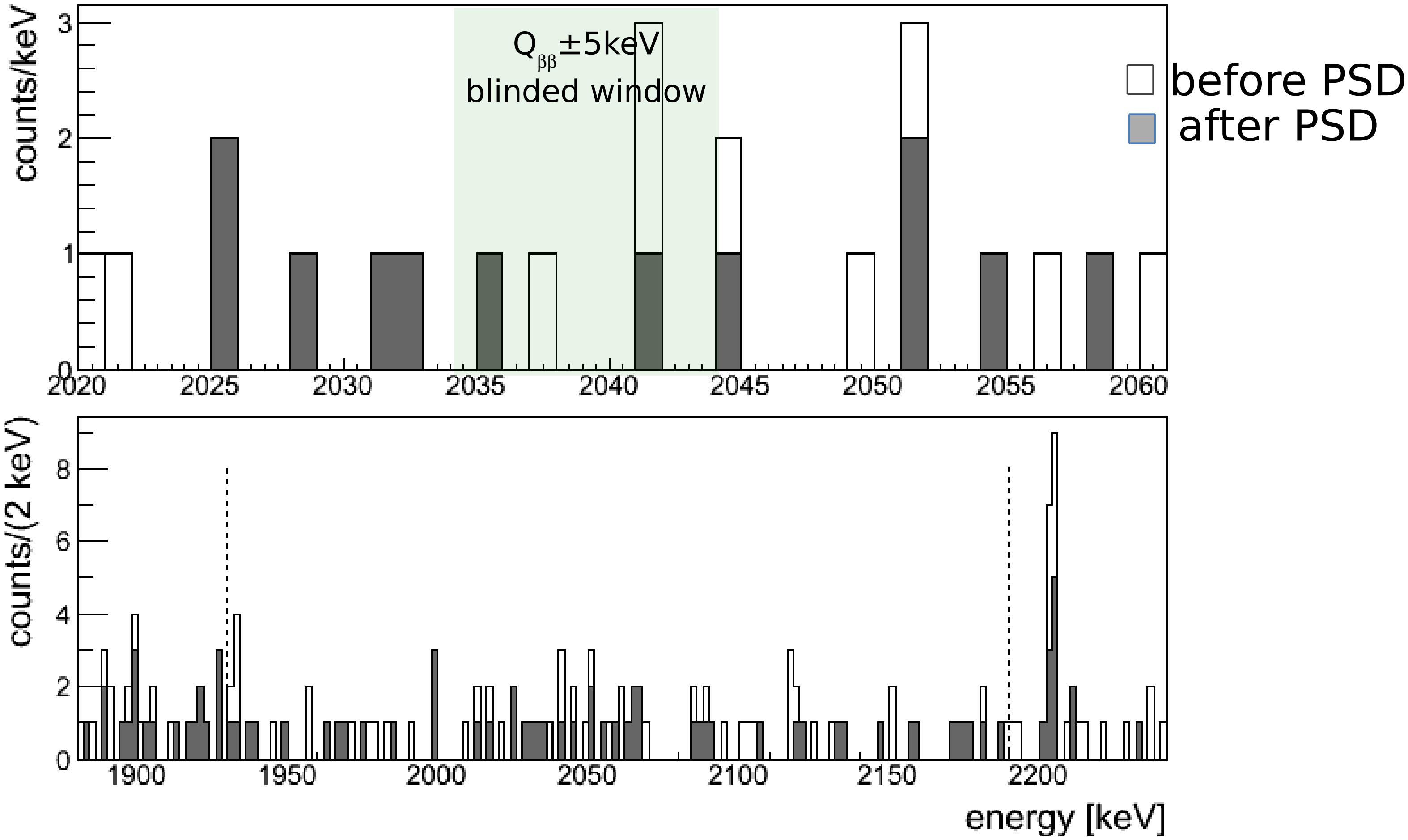
BEGe data set: 1 event in blinded window
0 events survive PSD cut

Unblinding silver coaxial data set (1.3 kg·yr)



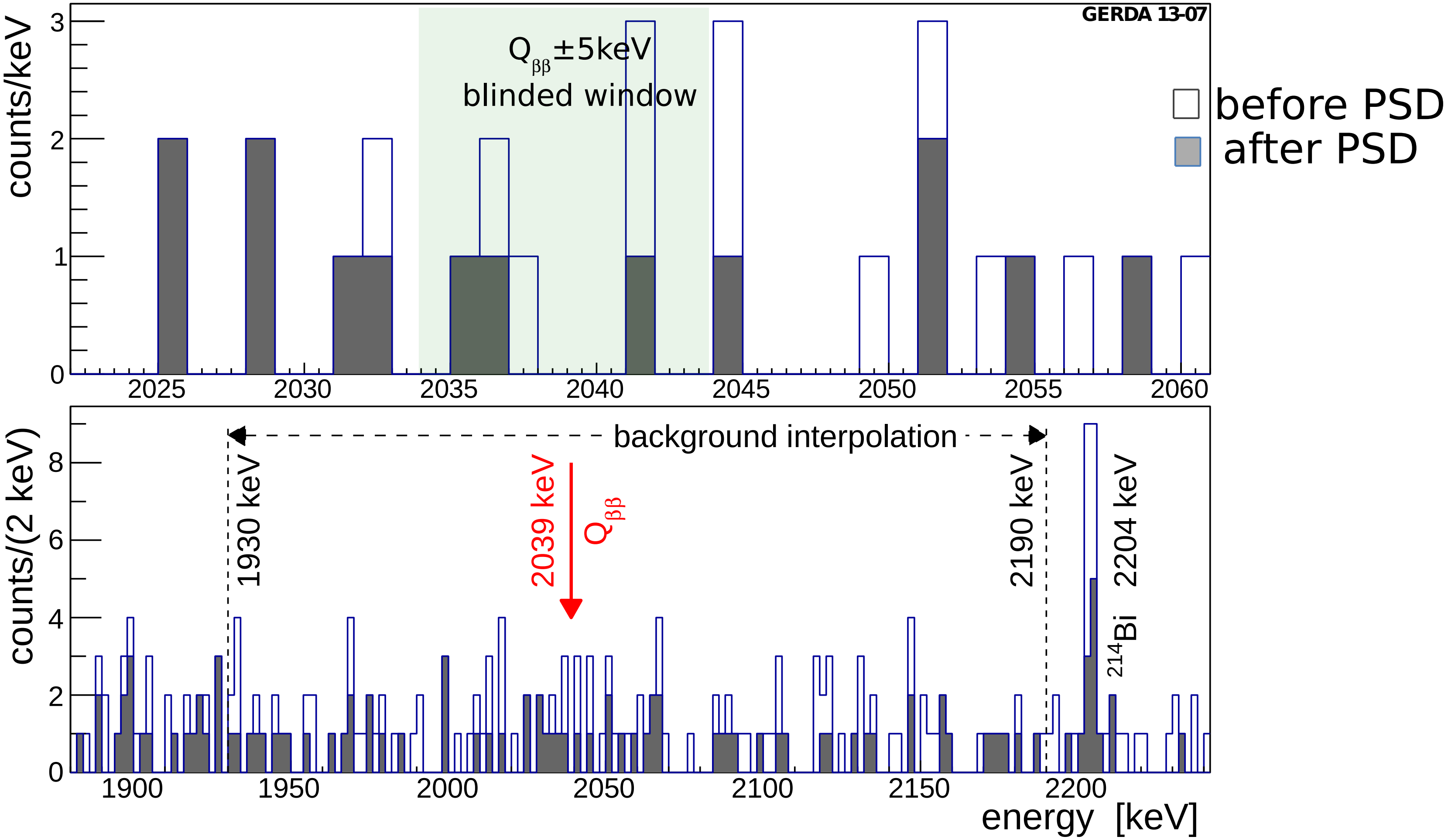
Silver data set: 1 event in blinded window
1 event survives PSD cut

Unblinding golden coaxial data set (17.9 kg·yr)



Golden data set: 5 events in blinded window
2 events survive PSD cut

Unblinding full data set (21.6 kg·yr)



Full data set: 7 events in blinded window
3 events survive PSD cut

Parameters of the three data sets

data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg (in 230 keV)	BI †)	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	18±2	5
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11±2	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

†) in units of 10^{-3} cts/(keV·kg·yr).

Counts in region of interest (ROI)

Total counts in ROI	Expected (background only)	Observed
without PSD	5.1	7
with PSD	2.5	3

From counts to half-life limit

$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} M \cdot t \cdot \eta_{76} \cdot f_{av} \cdot \epsilon_{fep} \cdot \epsilon_{psd}$$

data set	$M*t$	η_{76}	f_{av}	ε_{fep}	ε_{psd}
golden	17.9 kg yr	0.86	0.87	0.92	0.90
silver	1.3 kg yr	0.86	0.87	0.92	0.90
BEGe	2.4 kg yr	0.88	0.92	0.90	0.92

exposure averaged efficiencies

- fit 3 data sets in 1930-2190 keV with 4 free parameters:
  - 3x constant background
  - 1x gauss with $(T^{0\nu})^{-1} > 0$
- fix gaussian:
  - μ=(2039.06±0.2) keV
  - σ_{coax}=(2.0±0.1) keV
  - σ_{BEGe}=(1.4±0.1) keV

systematic uncertainties on f, ε, μ, σ:
Monte Carlo sampling & averaging

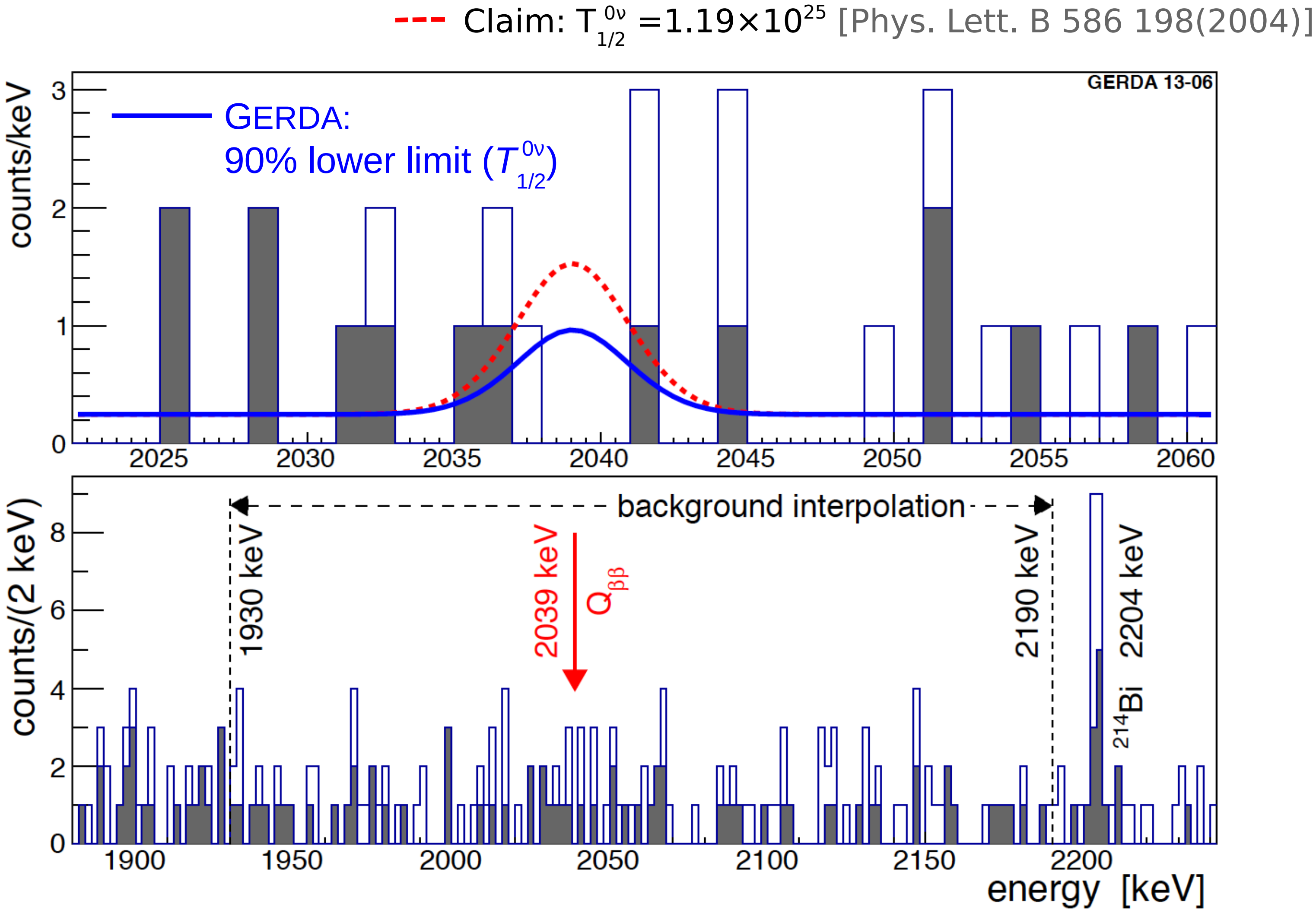
Frequentist: profile likelihood fit → best fit $N^{0\nu}$=0, $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

Bayes: flat 1/T prior 0 - 10^{-24} yr → best fit $N^{0\nu}$=0, $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr (90% C.L.)

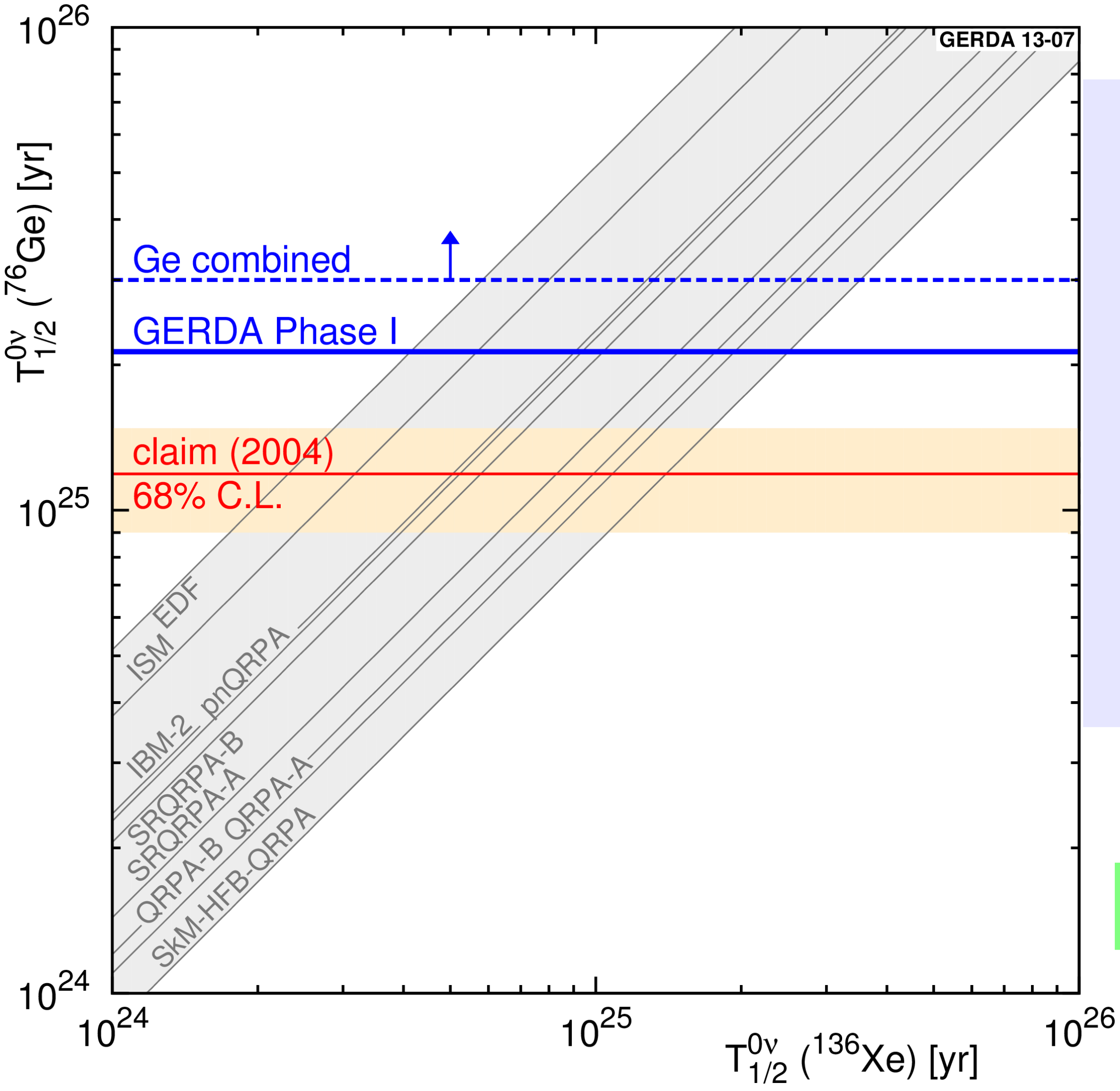
Frequentist: combined with HdM [1] & IGEX[2] → $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr (90% C.L.)

[1] Euro Phys J A12 (2001) 147. [2] Phys Rev D65 (2002) 092007.

Comparison with claim (2004)



Global picture of 0νββ results



model independend comparison:

$> 3.0\cdot10^{25}$ (90% C.L.)

$> 2.1\cdot10^{25}$ (90% C.L.)

$$\left(1.19^{+0.37}_{-0.23}\right)\cdot10^{25}$$

$p(N^{0\nu}=0|H_1) = 0.01$

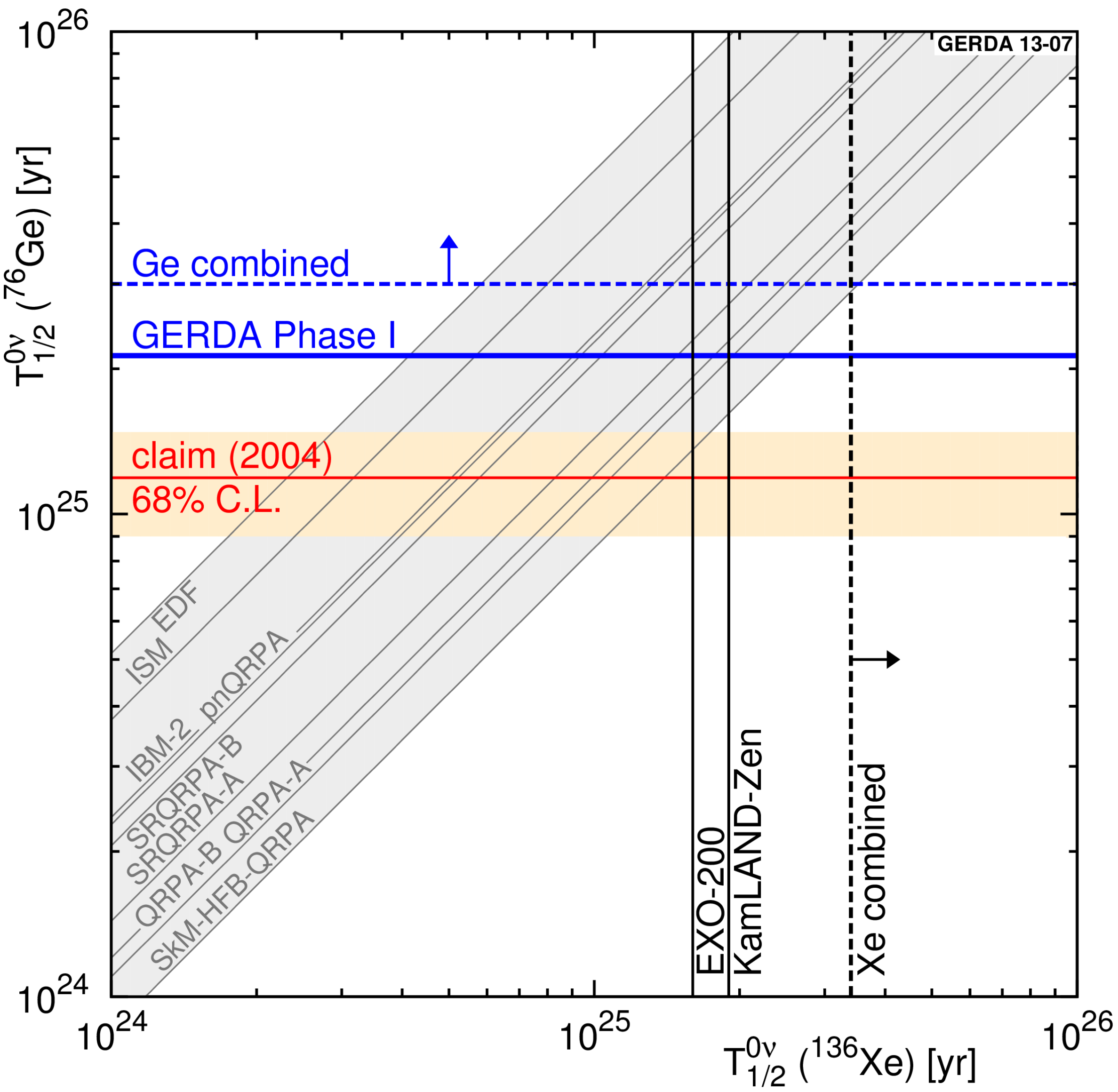
(probability for 0 events in „Ge combined“ if claim is correct)

Ge combined:

m_{ee} = 0.2 - 0.4 eV

NME from: P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

Global picture of $0\nu\beta\beta$ results



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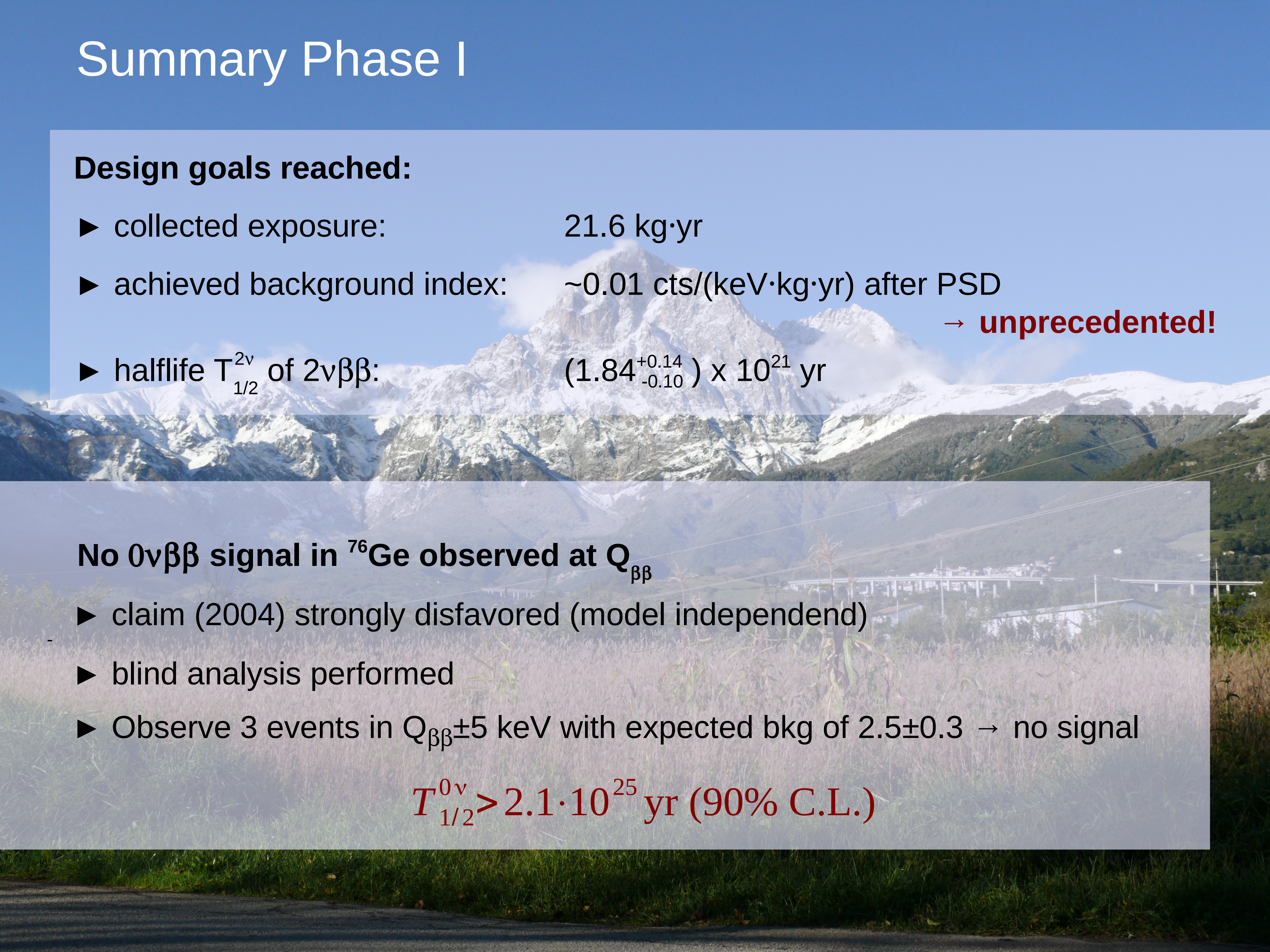
$> 2.1 \cdot 10^{25}$ (90% C.L.)

$\left(1.19^{+0.37}_{-0.23}\right) \cdot 10^{25}$

NME from: P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

Summary Phase I



Design goals reached:

- ► collected exposure: 21.6 kg·yr
- ► achieved background index: ~0.01 cts/(keV·kg·yr) after PSD → **unprecedented!**
- ► halflife $T^{2\nu}_{1/2}$ of 2νββ: $(1.84^{+0.14}_{-0.10}) \times 10^{21}$ yr

No 0νββ signal in ^{76}Ge observed at $Q_{\beta\beta}$

- ► claim (2004) strongly disfavored (model independend)
- ► blind analysis performed
- ► Observe 3 events in $Q_{\beta\beta}$±5 keV with expected bkg of 2.5±0.3 → no signal

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

Outline

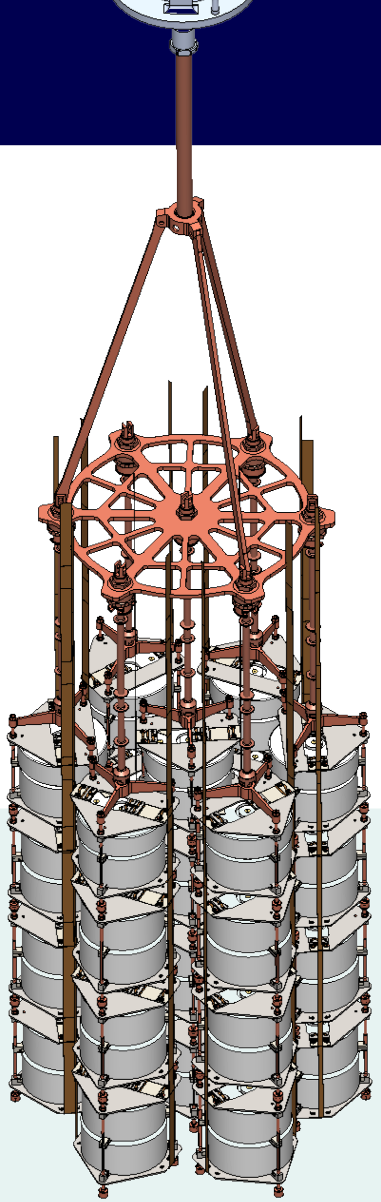
(1) $0\nu\beta\beta$ physics

(2) GERDA setup

(3) Background & $2\nu\beta\beta$

(4) Phase I result

(5) Outlook on Phase II



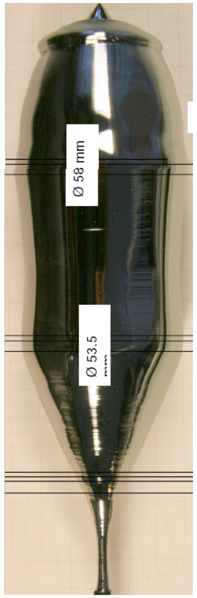
- collect total exposure: **100 kg·yr**
  - → produce ~20 kg more detectors
- aspired background index: **10^{-3} cts/(keV·kg·yr)**
  - → use improved detector support & electronics
  - → use active background suppression

Phase II diode production completed

- ▸ 30 enriched BEGe detectors (~20.5 kg) were produced & successfully tested in the HEROICA test facility

2010: reduction & zone refinement, PPM Metals GmbH, Langelsheim, Germany

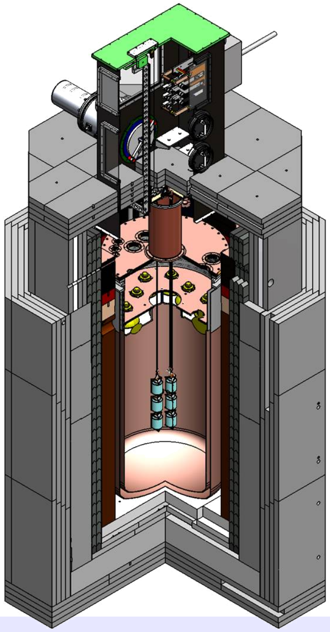
2005: isotope enrichment at ECP in Zelenogorsk, Russia (37.5 kg GeO_2)



2011/12: Crystal pulling & cutting at Canberra, Oak Ridge, USA

2012: diode production at Canberra Olen, Belgium & acceptance tests in HEROICA test facility

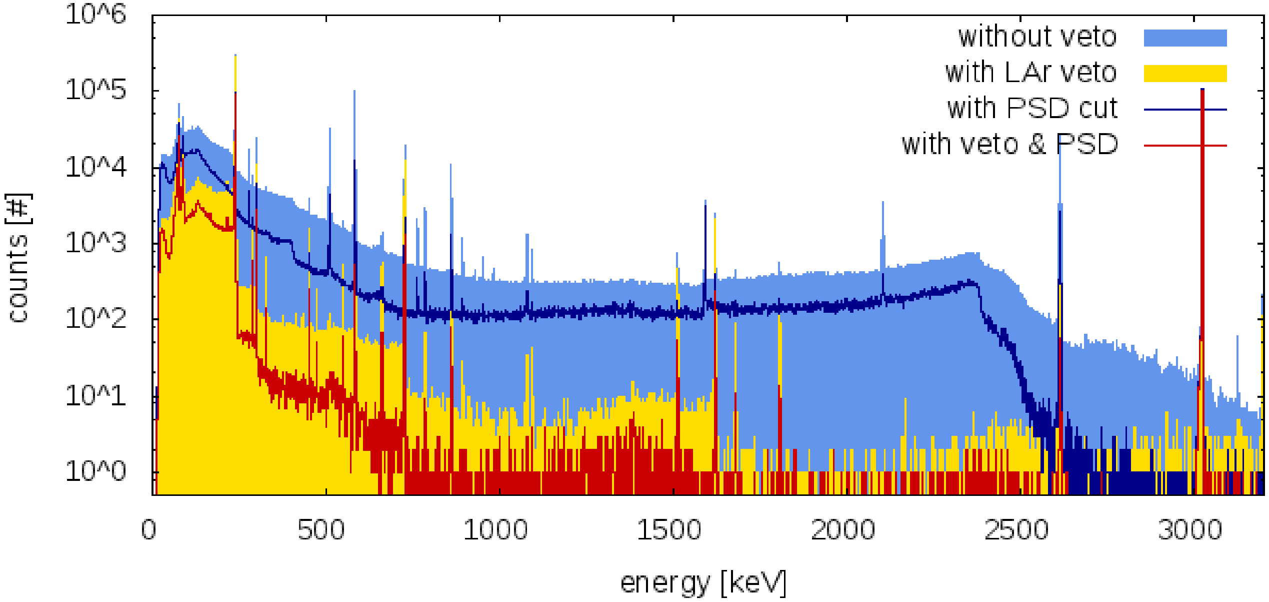
Liquid argon scintillation veto R&D



LArGe testbench

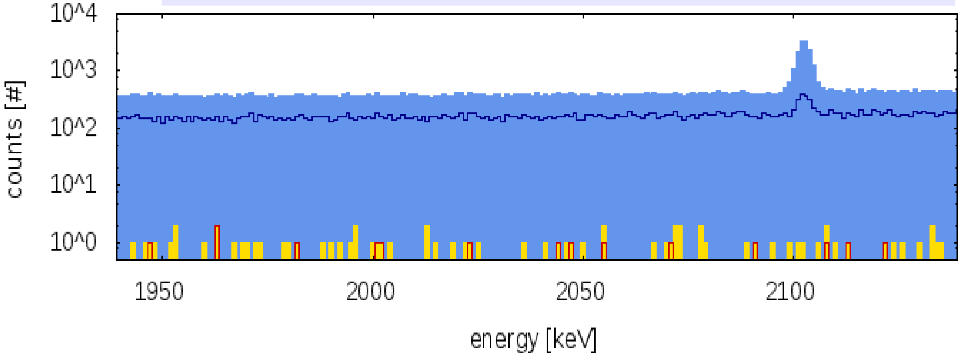
at Gran Sasso

e.g. internal Th-228 source



source	position	suppression factor		
		LAr veto	PSD	total
^{60}Co	int	27 ± 1.7	76 ± 8.7	3900 ± 1300
^{226}Ra	ext	3.2 ± 0.2	4.4 ± 0.4	18 ± 3
	int	4.6 ± 0.2	4.1 ± 0.2	45 ± 5
^{228}Th	ext	25 ± 1.2	2.8 ± 0.1	129 ± 15
	int	1180 ± 250	2.4 ± 0.1	5200 ± 1300

... suppression at region of interest



Liquid argon light instrumentation for GERDA

9x 3“ PMT

Cu shroud & wavelength-shifter

Ge detectors

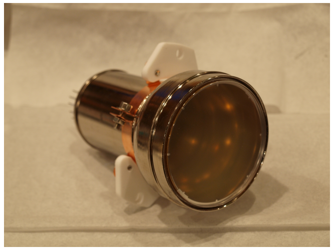
scintillating fibres & SiPM read-out

Cu shroud & wavelength-shifter

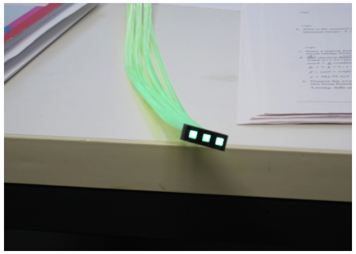
7x 3“ PMT

- MC optimization campaign completed
- hardware is beeing tested & prepared

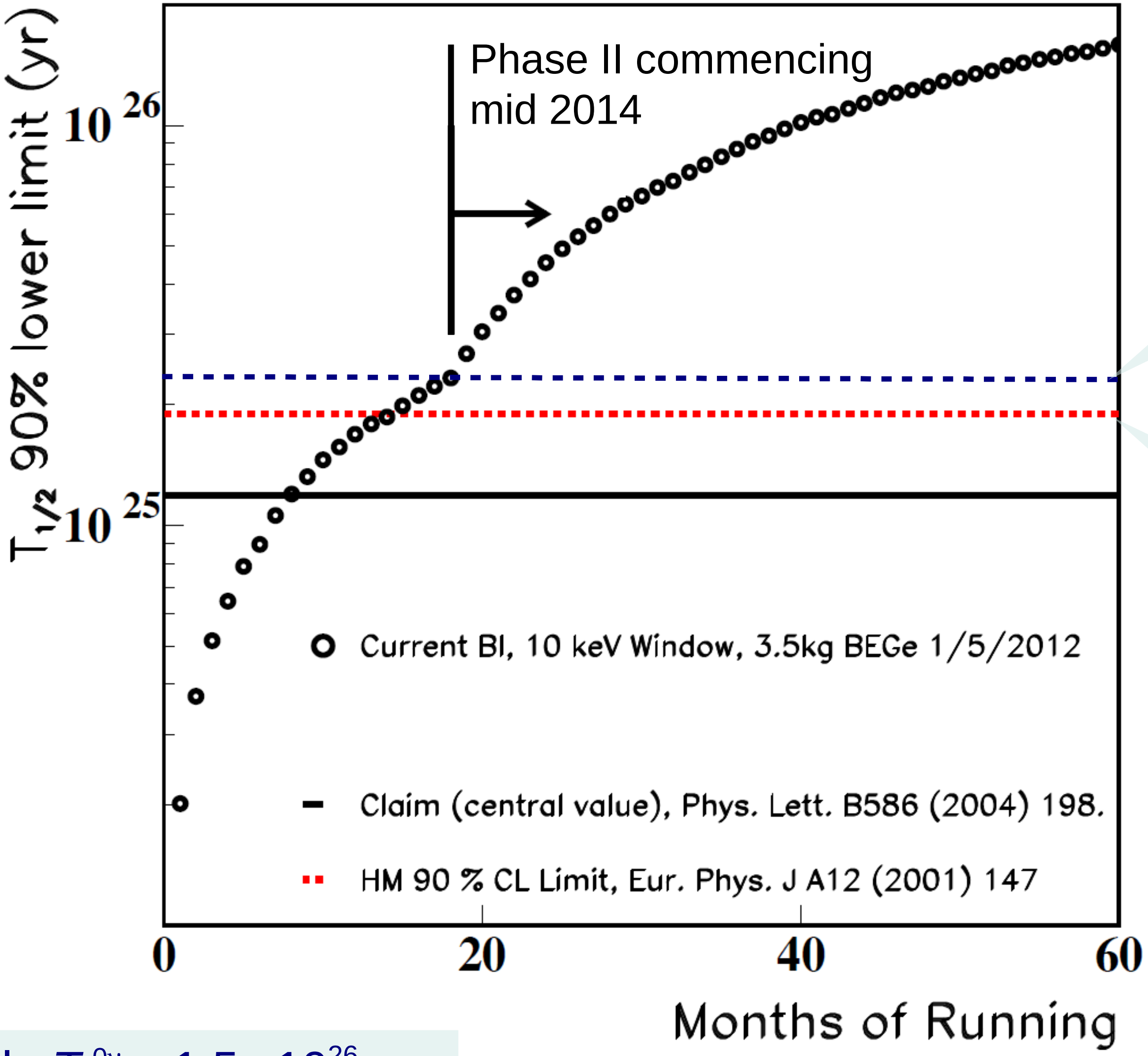
PMTs



'fibres'



GERDA 0νββ sensitivity projection



GERDA Phase I limit (90% C.L.)

Heidelberg-Moscow claim (2004)

Phase II goal: $T^{0\nu}_{1/2} > 1.5\ \mathrm{x}10^{26}$ yr