Results on Neutrinoless Double Beta Decay from GERDA Phase I

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(on behalf of the GERDA collaboration)

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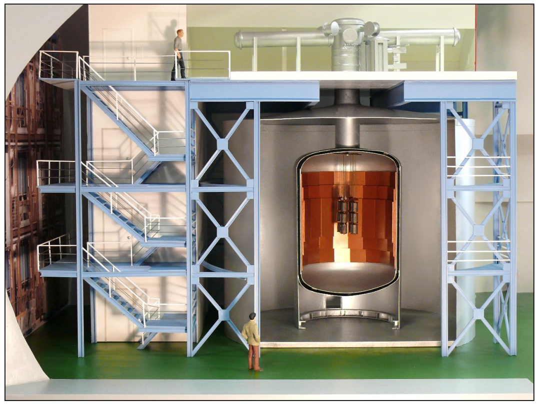
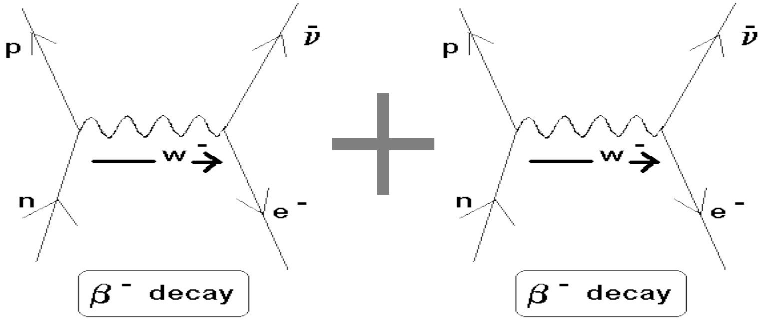


Outline

- Introduction
- Experimental requirements
- GERDA design and construction
- Phase I run parameters
- Backgrounds
- Pulse shape discrimination
- Results
- Conclusions & Implications

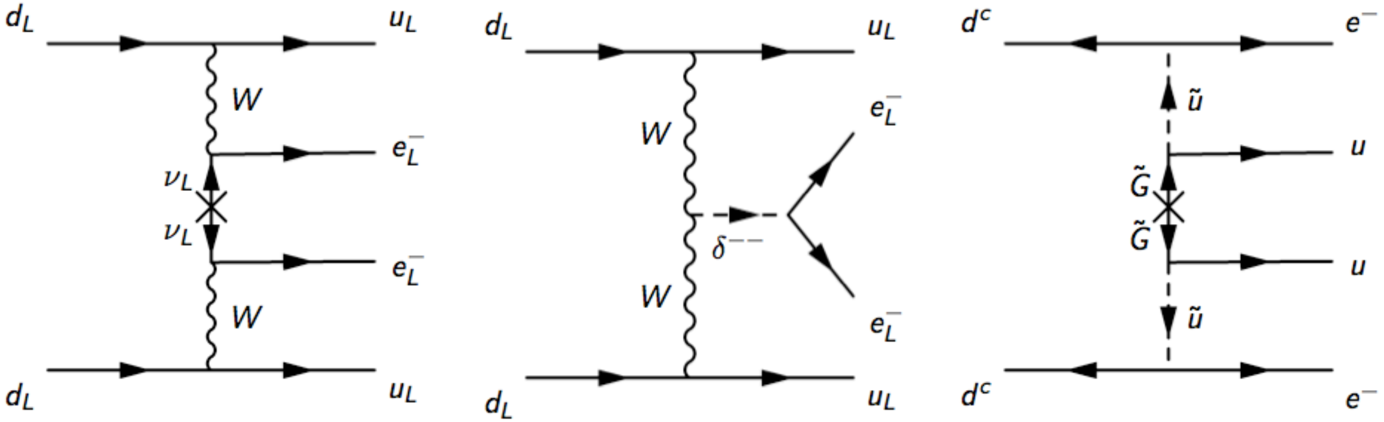
Double Beta Decay Processes

Standard Model:



➔ 2 electrons + 2 neutrinos

Majorana ν-masses or other ΔL=2 physics: ➔ 2 electrons



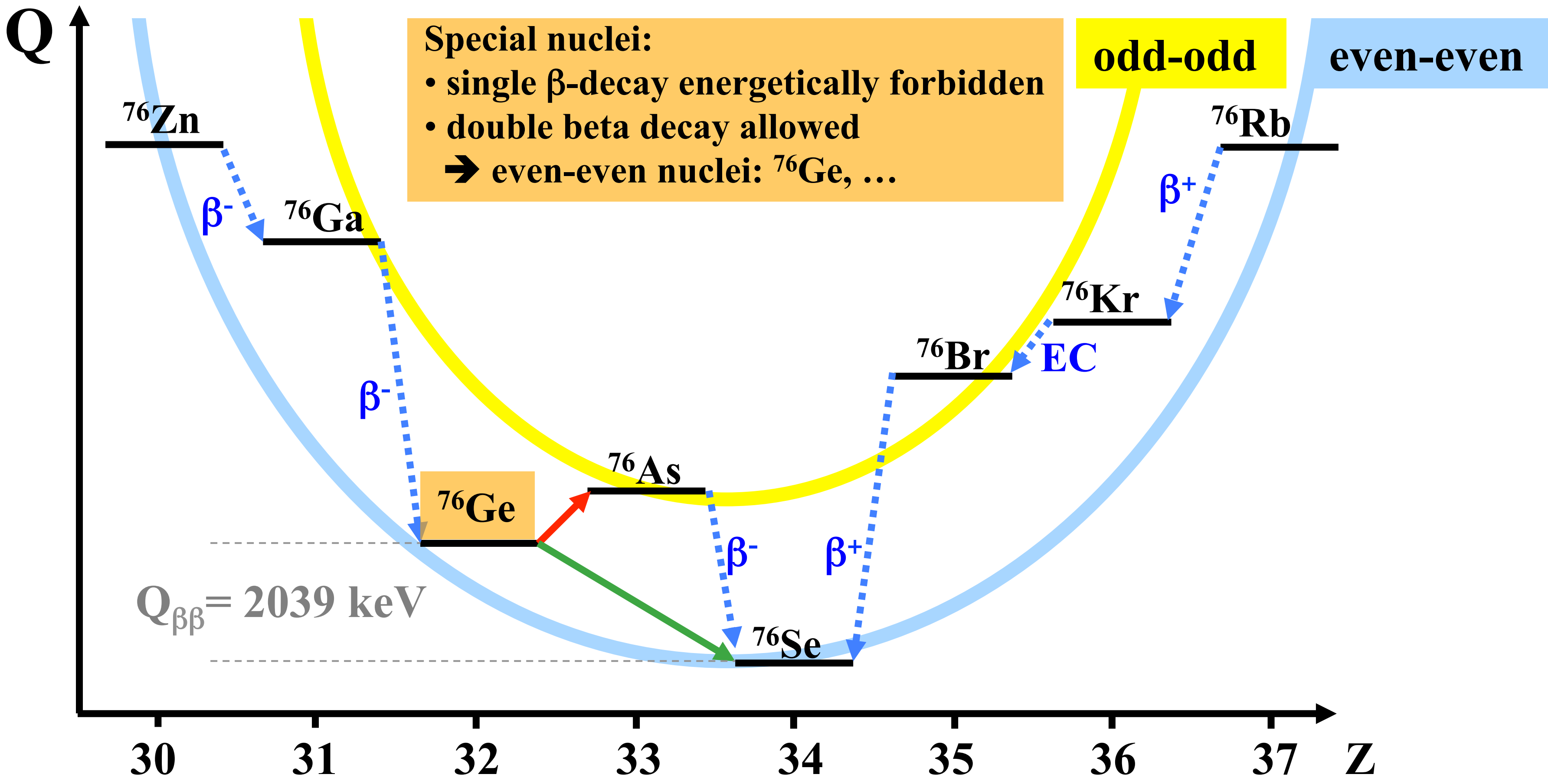
…

Majorana
neutrino masses
←→ Dirac?

SM + Higgs triplet   SUSY

important connections to LHC and LFV …
sub eV Majorana mass ←→ TeV scale physics

Double Beta Decay & Mass Parabolas



Double beta decay: 2n → 2p +X ; Q_x = -2 ; energy $Q_{\beta\beta}$ goes ≃ into X if m_X<<GeV

Standard Model: 2 weak deacys $X=2e^- +2\nu_e$ ➔ 2ν beta decay

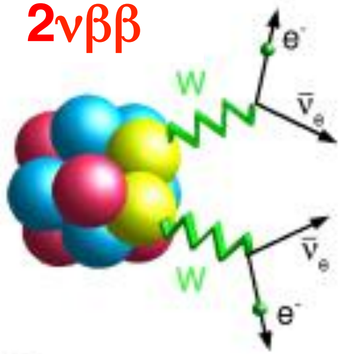
Beyond the SM: $X=2e^-$ ➔ 0ν (neutrino less) beta decay

Options: a) Majorana neutrino masses *OR* b) other ΔL=2 operators

Double Beta Decay Kinematics

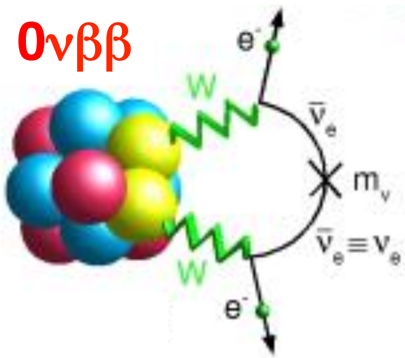
SM

$2\nu\beta\beta$

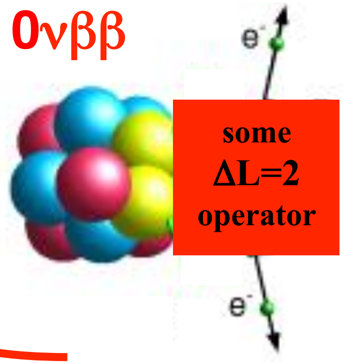


BSM

$0\nu\beta\beta$

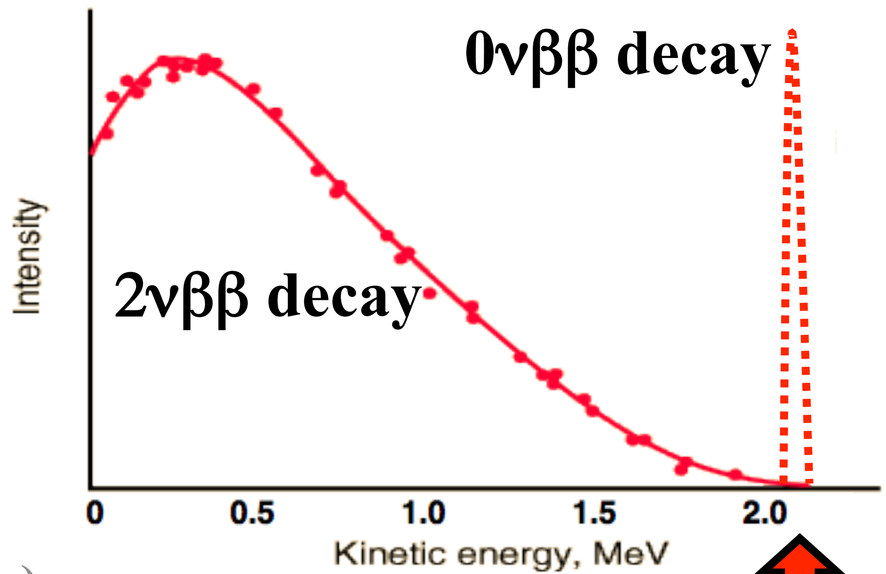


$0\nu\beta\beta$

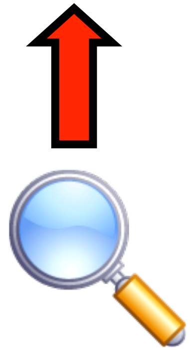


$2\nu\beta\beta$ decay seen for diff. isotopes (Kirtsen,…)

$T^{1/2} = O(10^{18}\text{-}10^{21}$ years) → up to $10^{11} \otimes T_{Universe}$

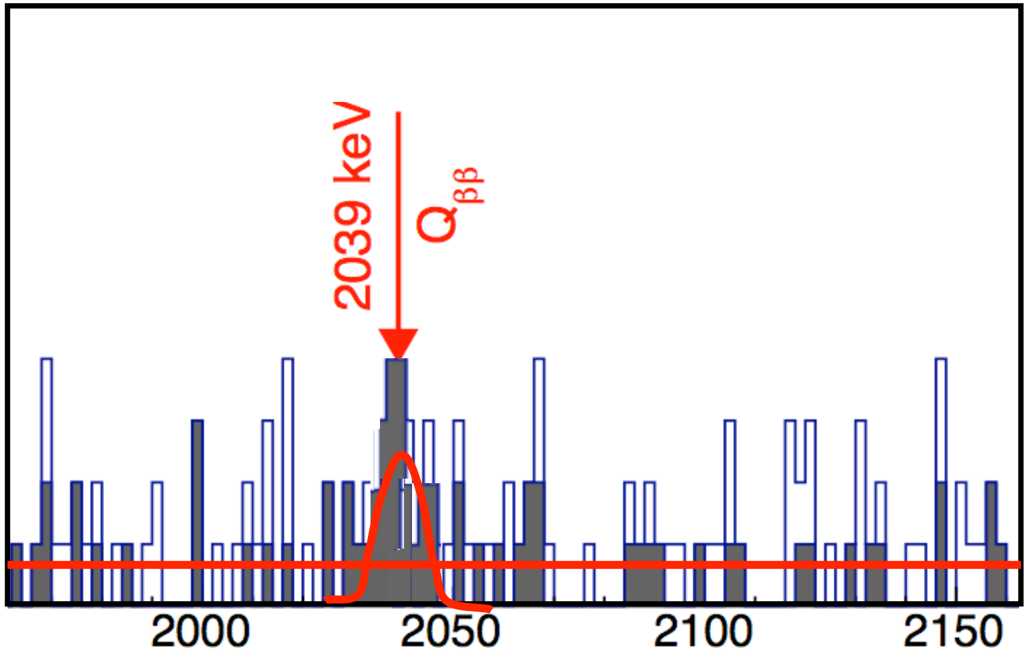


$T^{1/2} > O(10^{24}y)$



- $2\nu\beta\beta$ → improvement
- search for $0\nu\beta\beta$ signal at $Q_{\beta\beta} = 2039$ keV
- …backgrounds!

Experimental Challenges



- extremely rare process
  ➔ low statistics = few counts/bin
- known (unknown?) nuclear lines
- tail of $2\nu\beta\beta$ signal
- backgrounds
- signal at known $Q_{\beta\beta}$-value ?

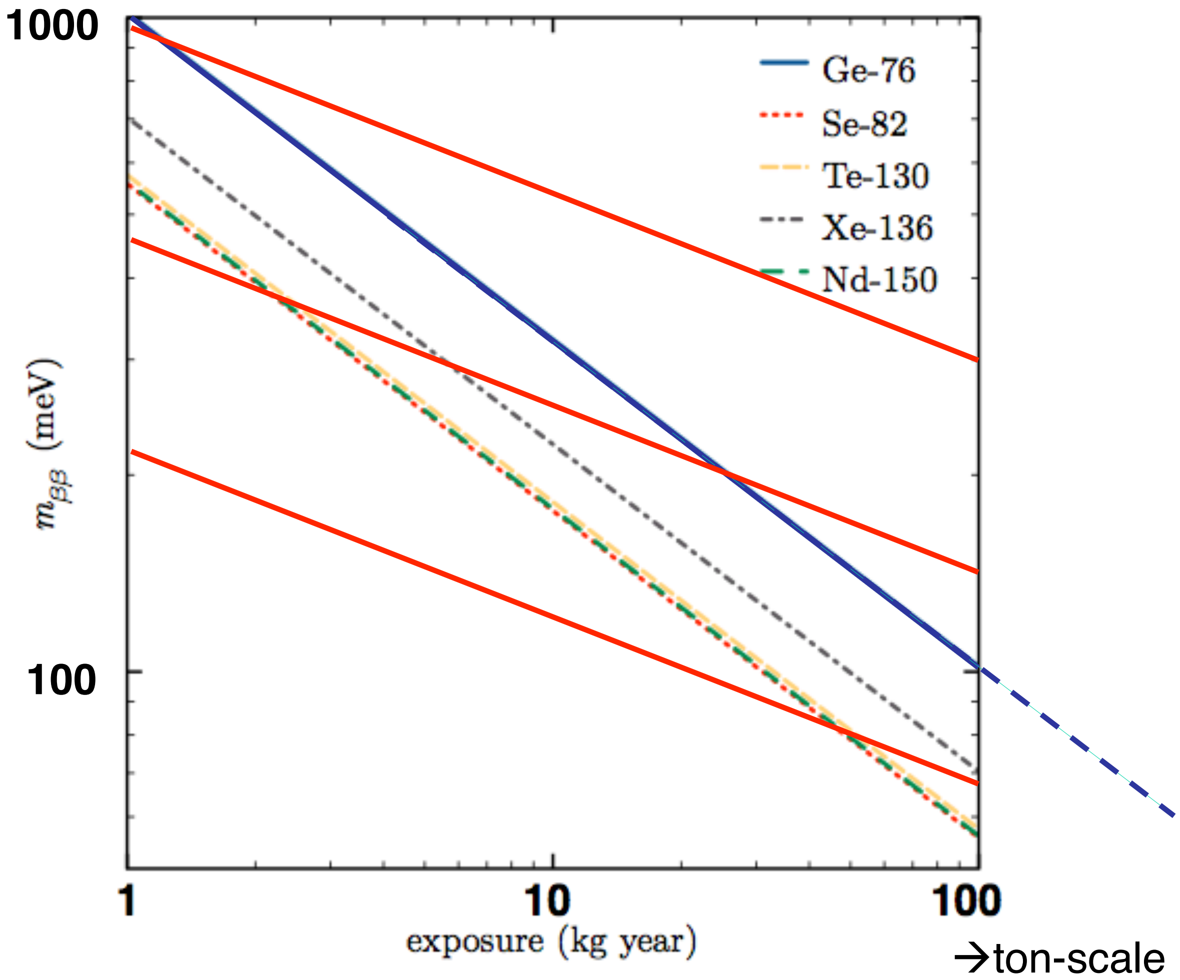
To best extract a $0\nu\beta\beta$ signal at $Q_{\beta\beta}$ and to avoid any misinterpretations:

- low background index (BI)
  ➔ careful material selection, screening, shielding, PSD (pulse shape disc.), …
- best possible energy resolution
  ➔ Germanium: source = detector (diode) ➔ few keV resolution
- if there is a signal
  ➔ different nuclei to exclude unknown nuclear physics

Sensitivity & Background (for a Majorana Mass)

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\ \left|M_{0\nu}\right|^2\ m^2_{\beta\beta}$$

$$m_{\beta\beta} = \left|\sum_i U^2_{ei}\ m_i\right|$$



Without background:

$$N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot \frac{M \cdot t}{T^{0\nu}_{1/2}}$$

N_A = Avogadro's number
W = atomic weight of isotope
ε = signal detection efficiency
M = isotope mass
t = data taking time

→ $$m_{\beta\beta} = K_1 \sqrt{\frac{N}{\varepsilon M t}}$$

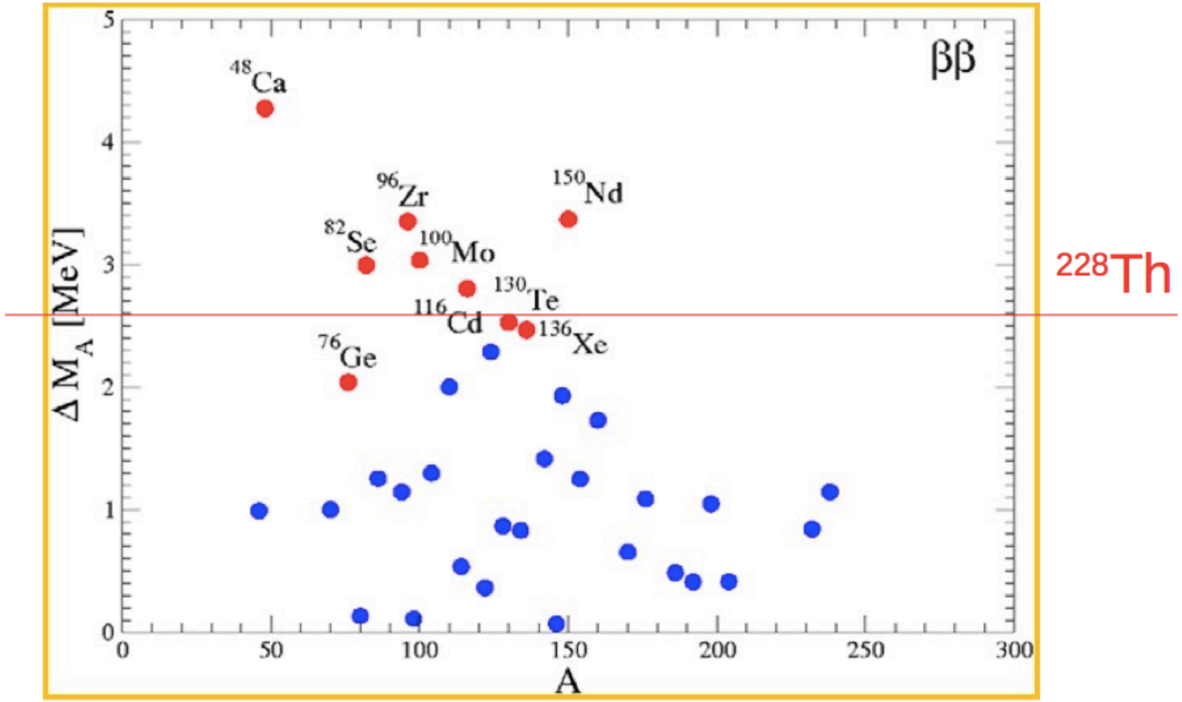
With background:

$$N' = N + N_{background}$$

→ $$m_{\beta\beta} = K_2\ \sqrt{1/\varepsilon}\ \left(\frac{c\ \Delta E}{M t}\right)^{1/4}$$

c = cts/keV kg yr ; ΔE = ROI

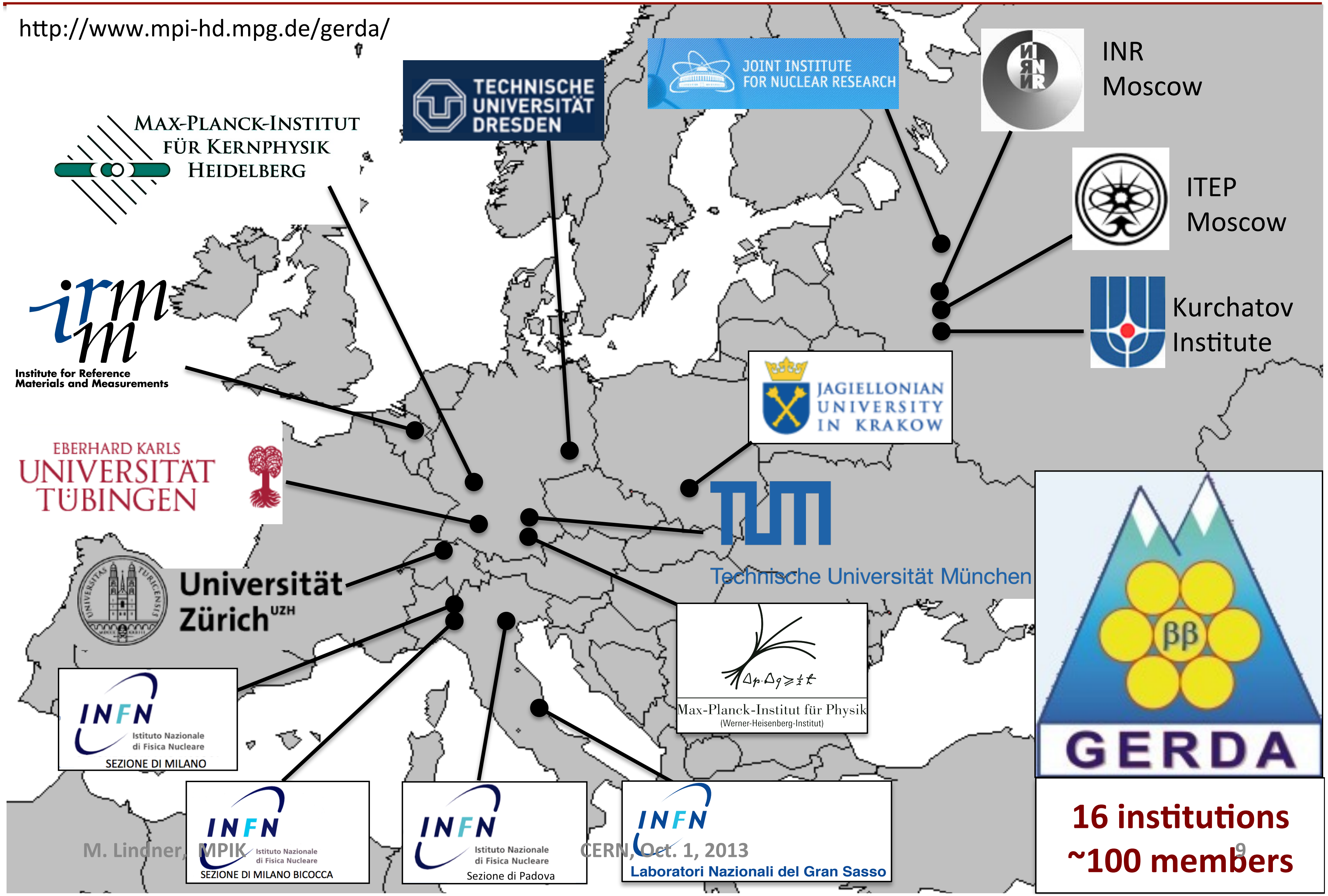
Which 0νββ Isotope?



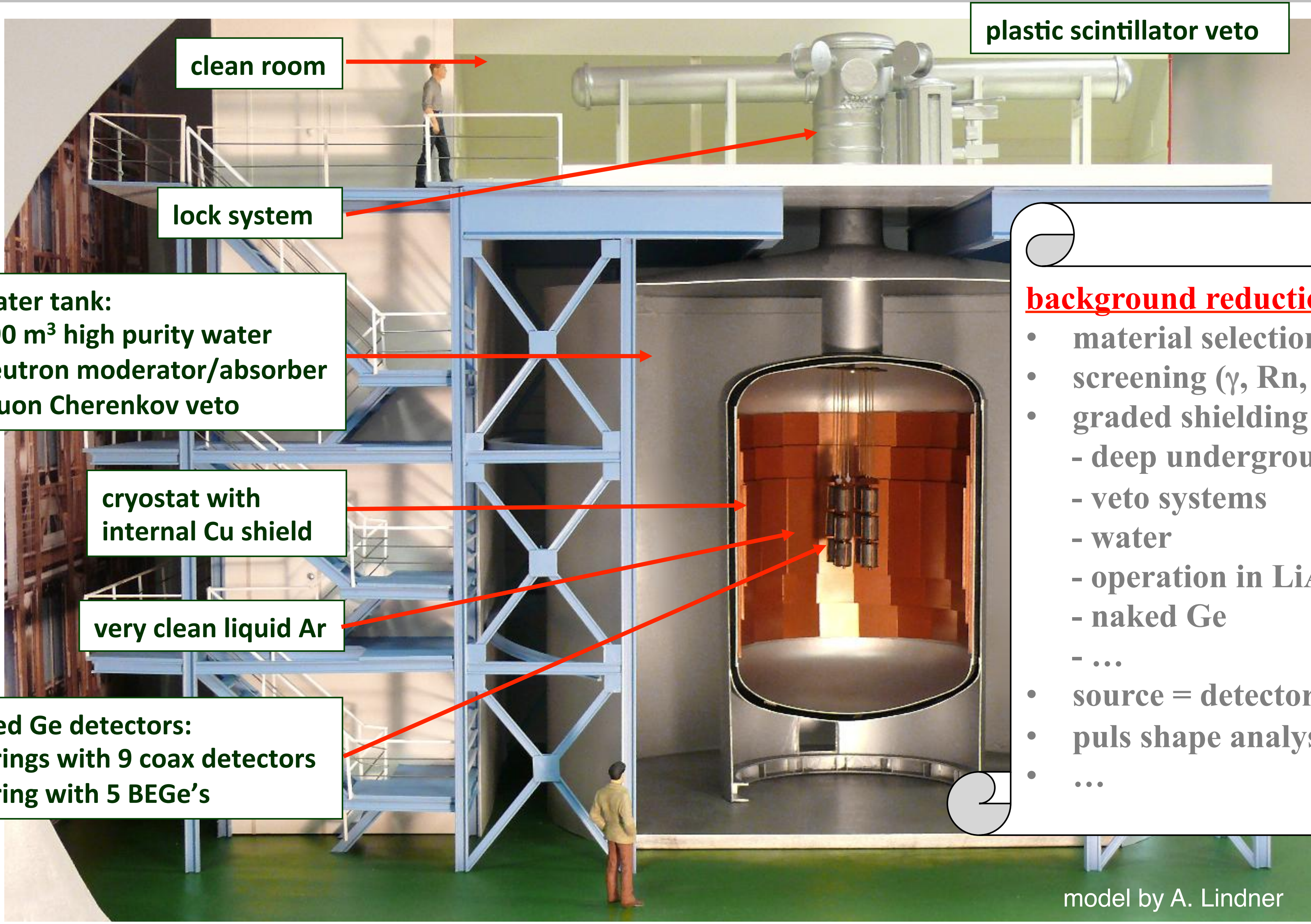
- mass ←→ isotopic abundance / enrichment ←→ cost, feasability
- cleanliness (radioputity) of 0νββ source and instrumentation
- high $Q_{\beta\beta}$ ←→ less nuclear backgrounds
- good energy resolution
- uncertainties in nuclear matrix elements (later…)
- … ➔ Germanium is a very good choice

The GERDA Collaboration

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



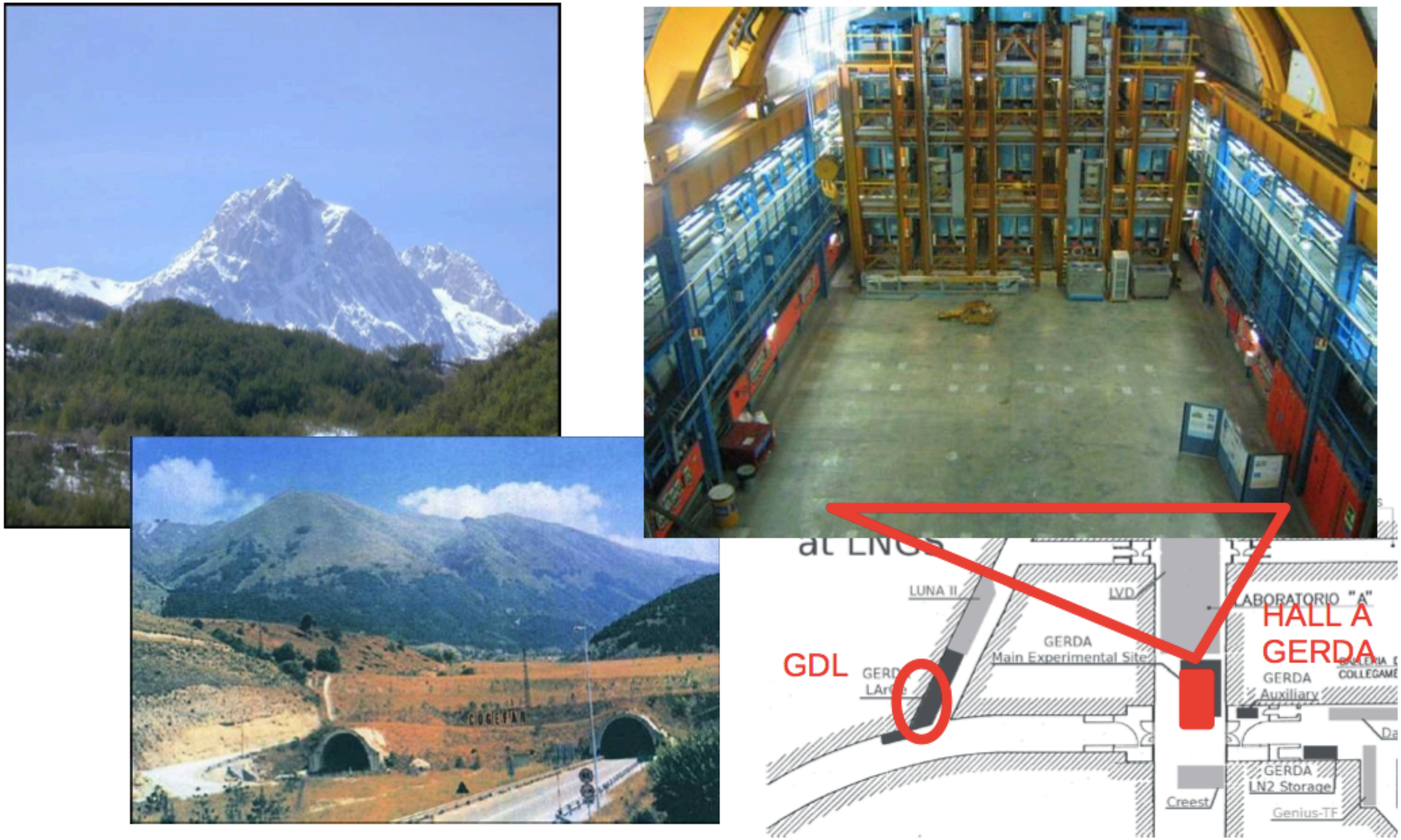
The GERDA Detector (original idea by G. Heusser, MPIK)



background reduction:

- material selection
- screening (γ, Rn, …)
- graded shielding
  - deep underground
  - veto systems
  - water
  - operation in LiAr
  - naked Ge
  - …
- source = detector
- puls shape analysis
- …

GERDA Location: LNGS Hall A



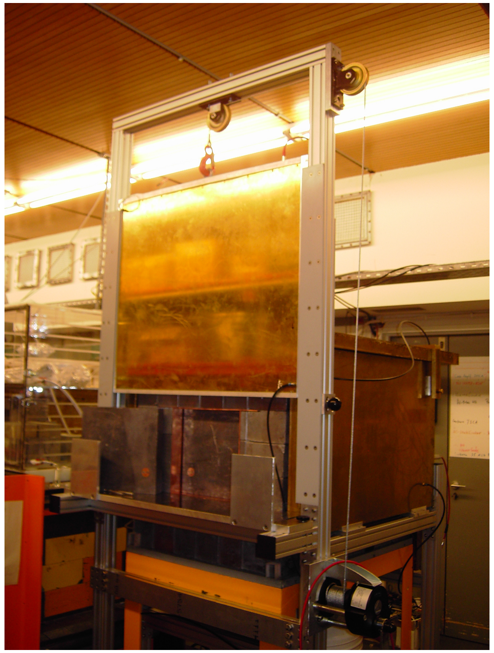
Material γ-Screening Facilities

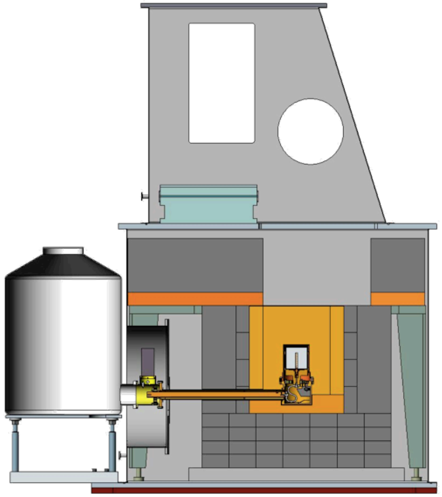
- Different screening stations@MPIK underground lab (1mBq/kg)

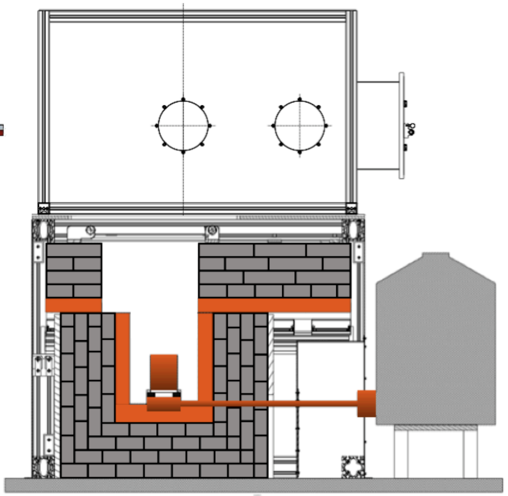
- 4 GEMPIs @LNGS (10μBq/kg)

- New: GIOVE @MPIK (50μBq/kg)

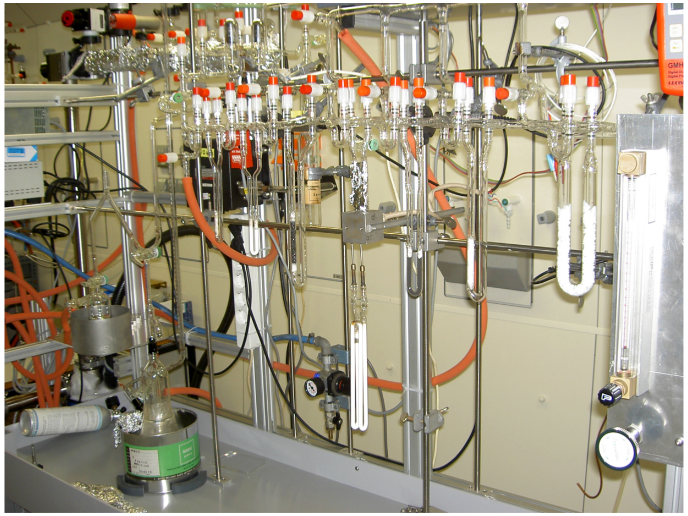
➔ extensive task for GERDA and other experiments (XENON, …)







Rn Screening Facilities



Gas counting systems
@ LNGS and @ MPIK

^{222}Rn emanation technique:

- sensitivity = few atoms/probe
- large samples ←→ absolute sens.
- non-trivial; not commonly available; routine @MPIK
- established numbers:

Nylon (Borexino) < 1μBq/m^2

Copper (Gerda): 2μBq/m^2

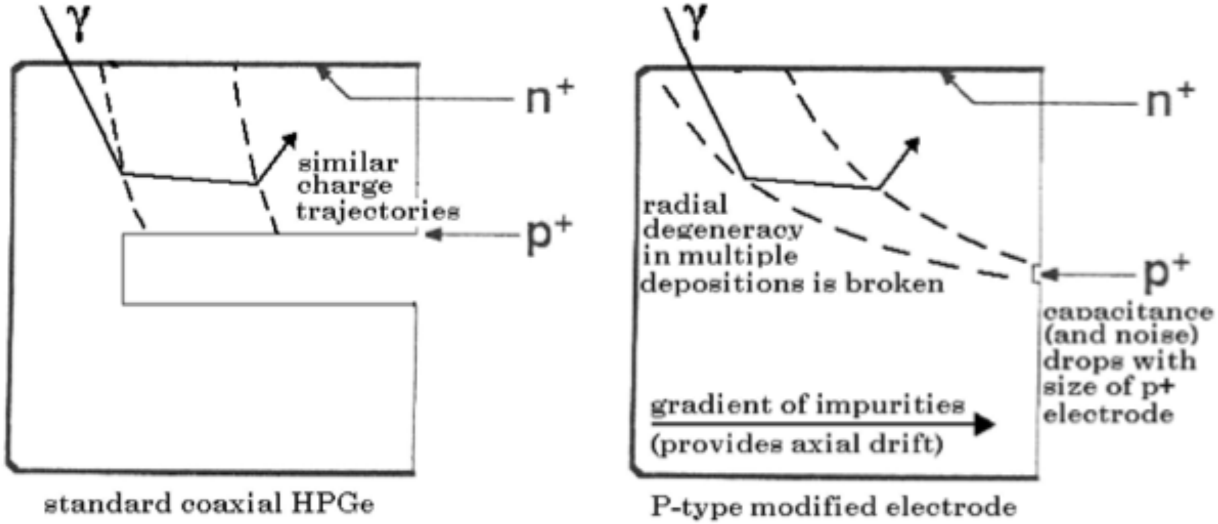
Stainless steel (Borexino): 5μBq/m^2

Titanium (preliminary): (100 ± 30) μBq/m^2

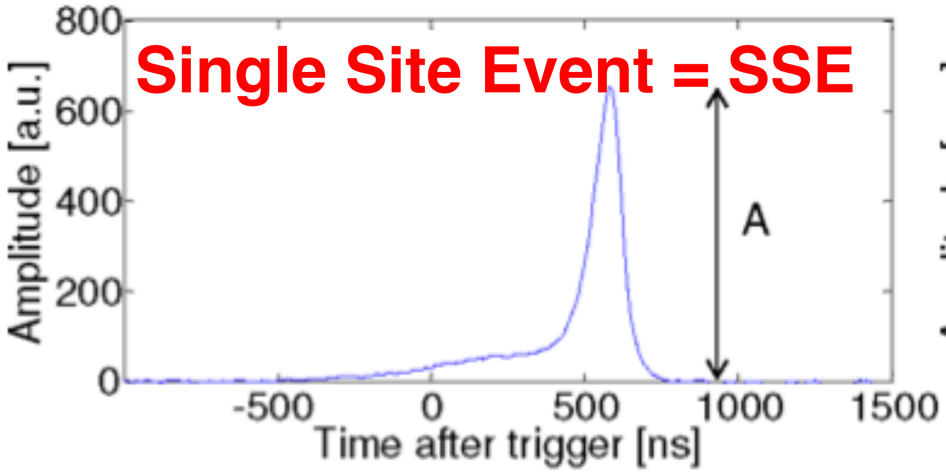
Detector Construction

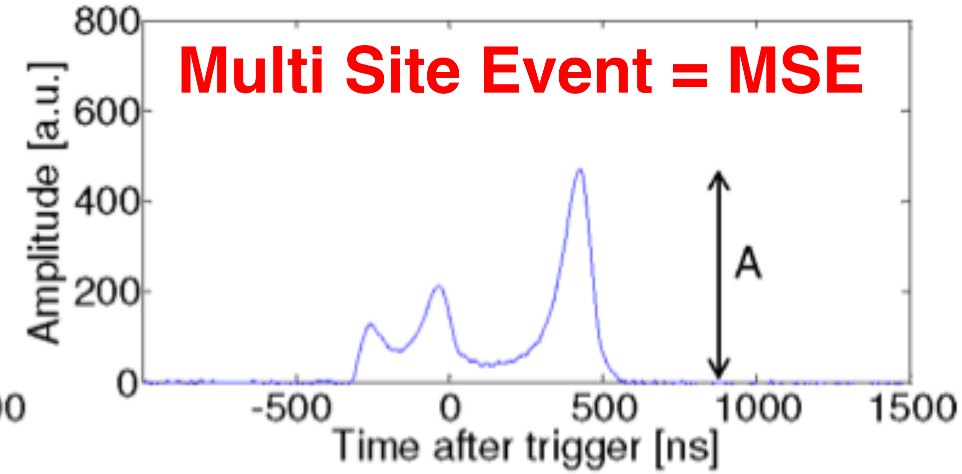
- **2004: Letter of Intent**
- **R&D:** material selection and screening, tests of bare diodes in LAr
- **2008-2010: construction at LNGS (Gran Sasso, Italy)**
  - infrastructure & cryostat
  - water tank & muon veto
  - clean room, lock 6 clean benches
- **2010-2011:** comissioning
- **Nov. 2011:** start of phase I data taking

HP Germanium Detectors

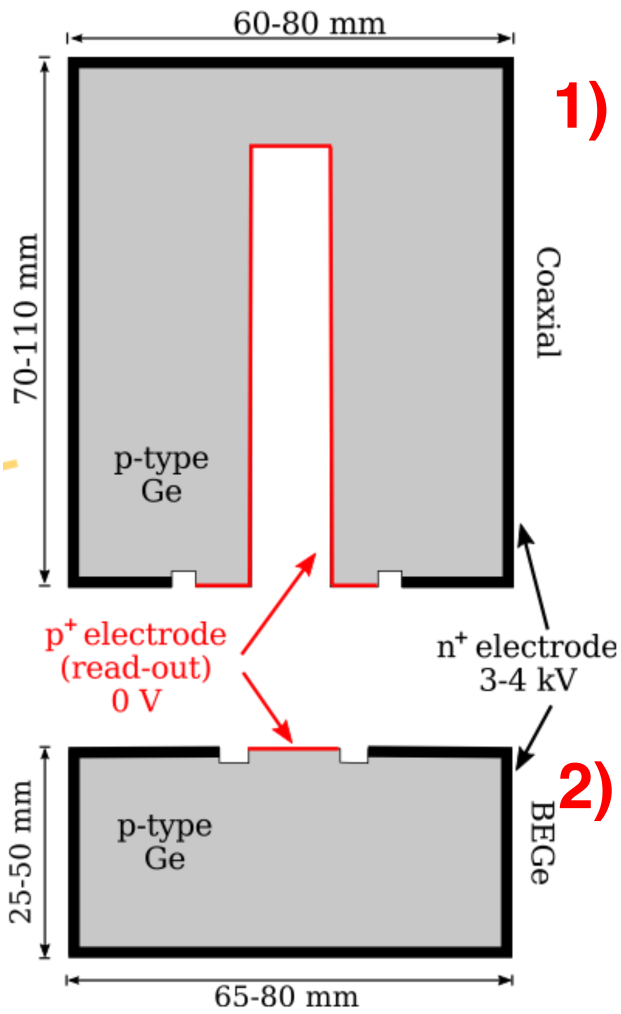


Wanted:
- energy resolution
  ←→ Ge diode
- fast det. response
  ←→ small capacity
- pulse shape discr.
  ←→ shape
- very high radiopurity
  ←→ crystals
  ←→ “naked”



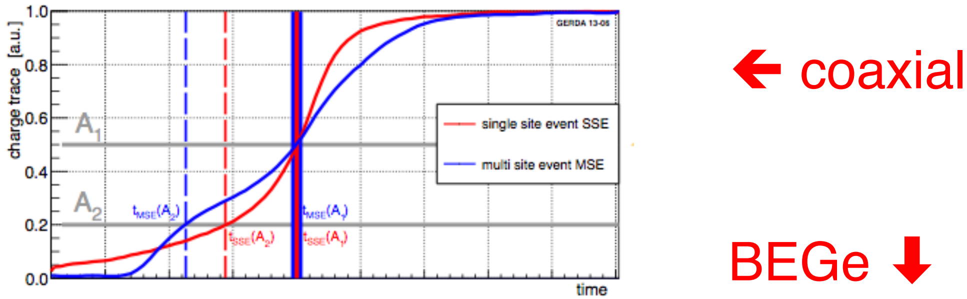


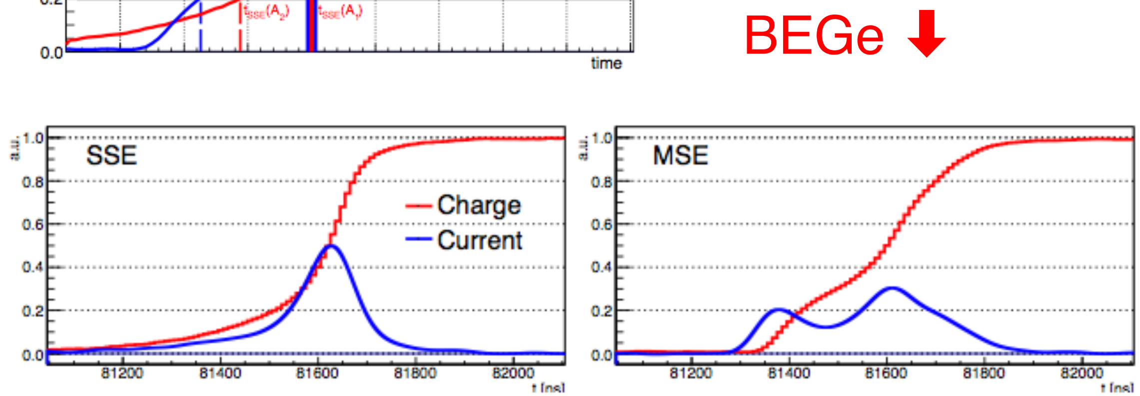
GERDA Detector Types



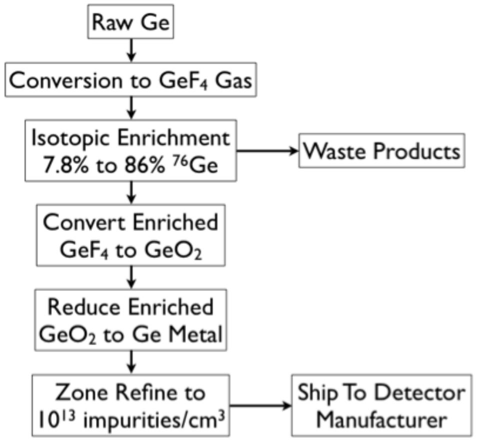
1) re-processed HdM, IGEX and GTF detectors p-type semi-coaxial
2) new p-type BEGe (Broad Energy Ge) detectors

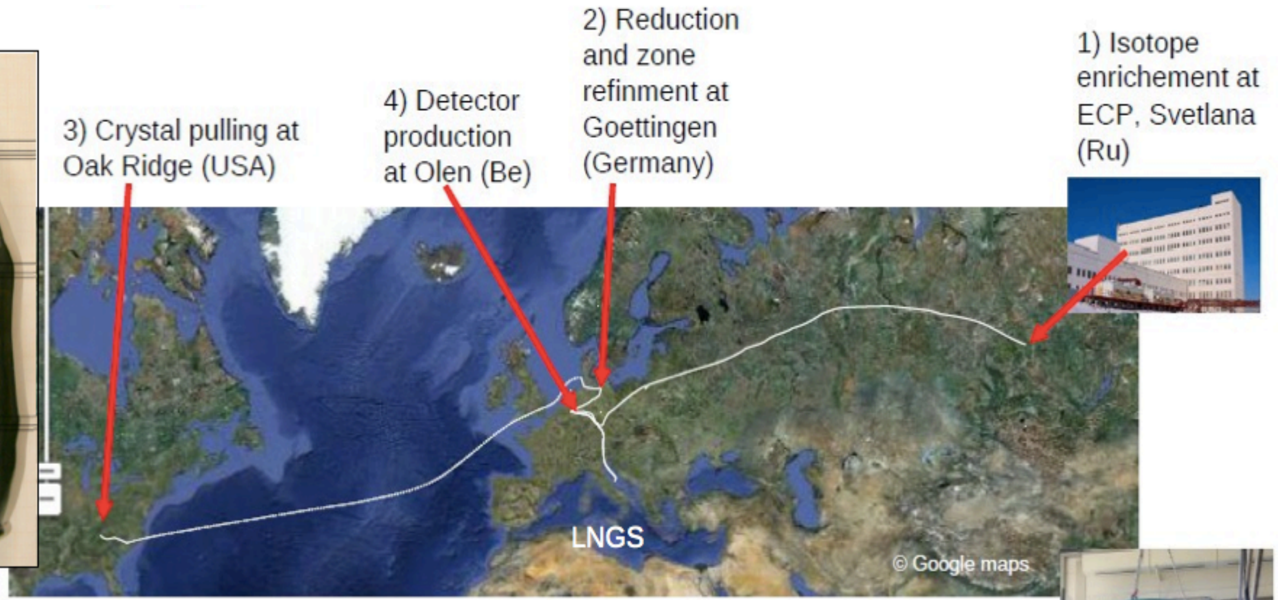
- n^+ conductive Li layer, separated by a grove from the boron implanted p^+ contact
- operated as ``diode"
- SSE/MSE (single/multi site event) discrimination





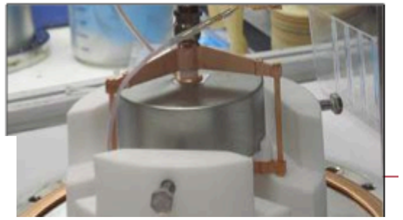
BEGe Detector production

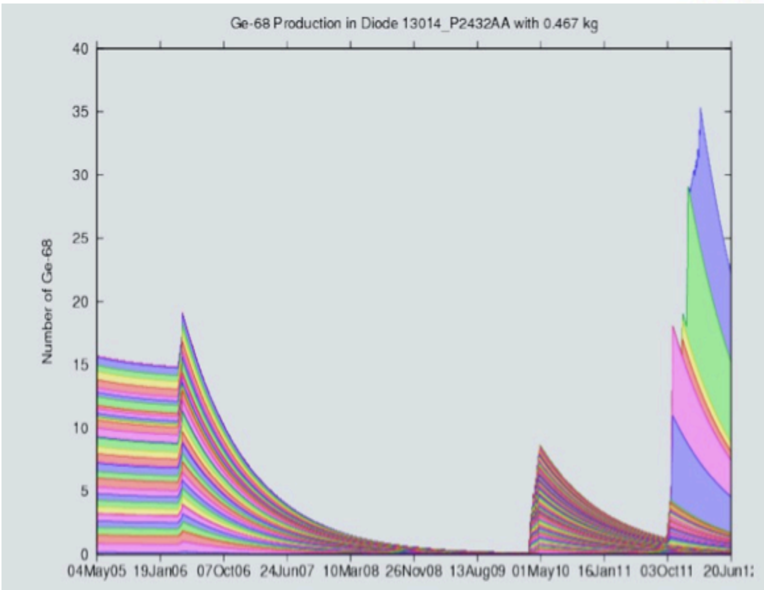




To minimize activation by cosmic ray:

- Transportation by truck or ship in shielded containers
- deep underground storage





← accumulated activity and its decay

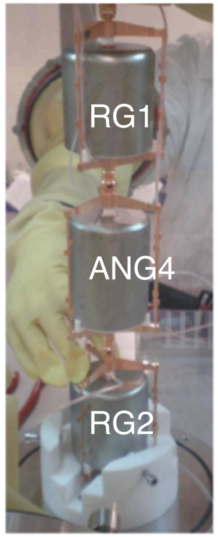
GERDA Phase I Detectors

Since Nov. 2011:
6 enriched (86% of ^{76}Ge)
ANG2, ANG3, ANG4, ANG5, RG1, RG2
→ 14.63 kg

1 natural (7,83% of ^{76}Ge)
GTF112
→ 2.96 kg

Since July 2012:
4 BEGe (87% of ^{76}Ge)
GD32B-GD32D, GD35B
→ 3.00 kg

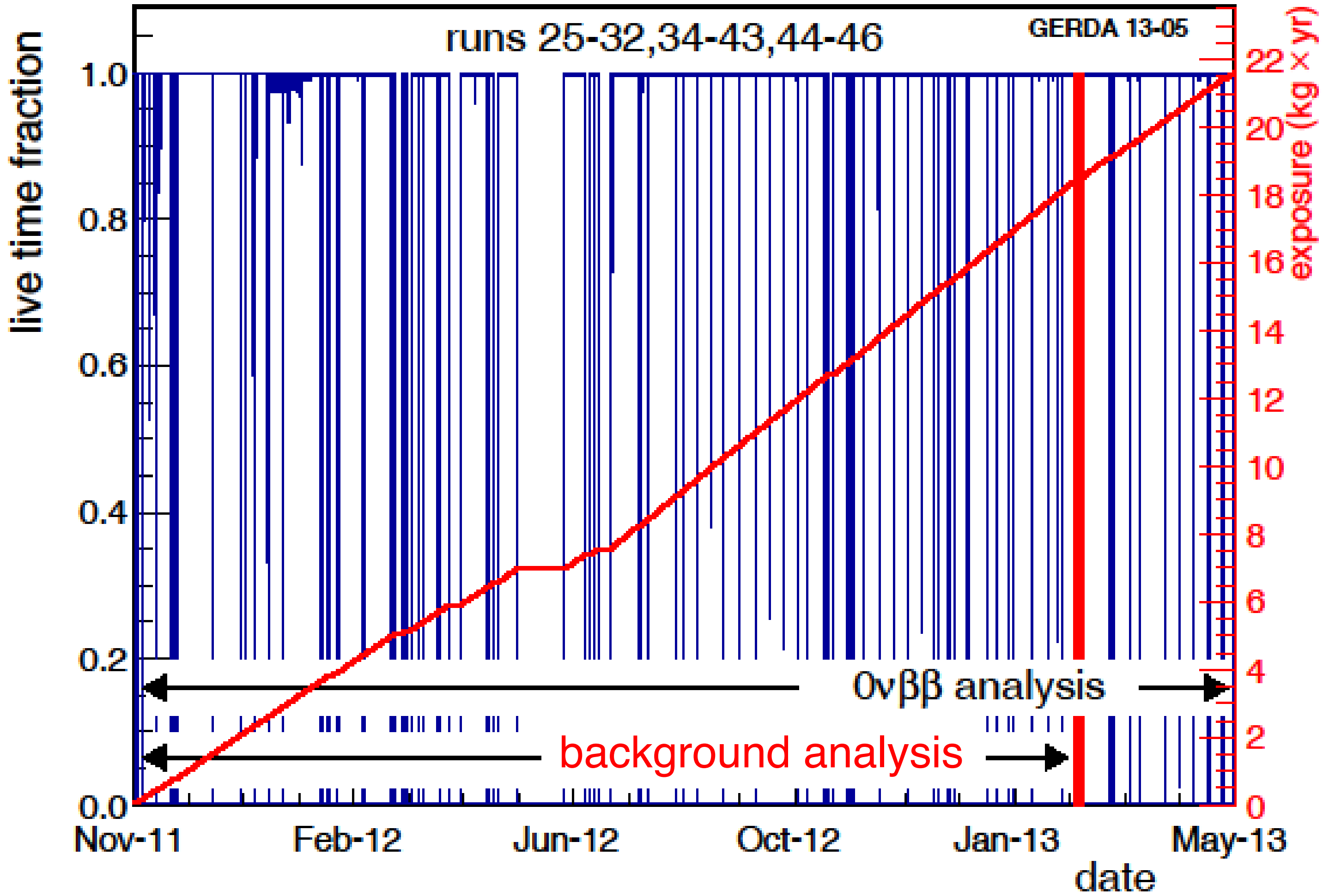
In addition: 2 coaxial and 1 BEGe unused due to high leakage currents



Detector Parameter Details

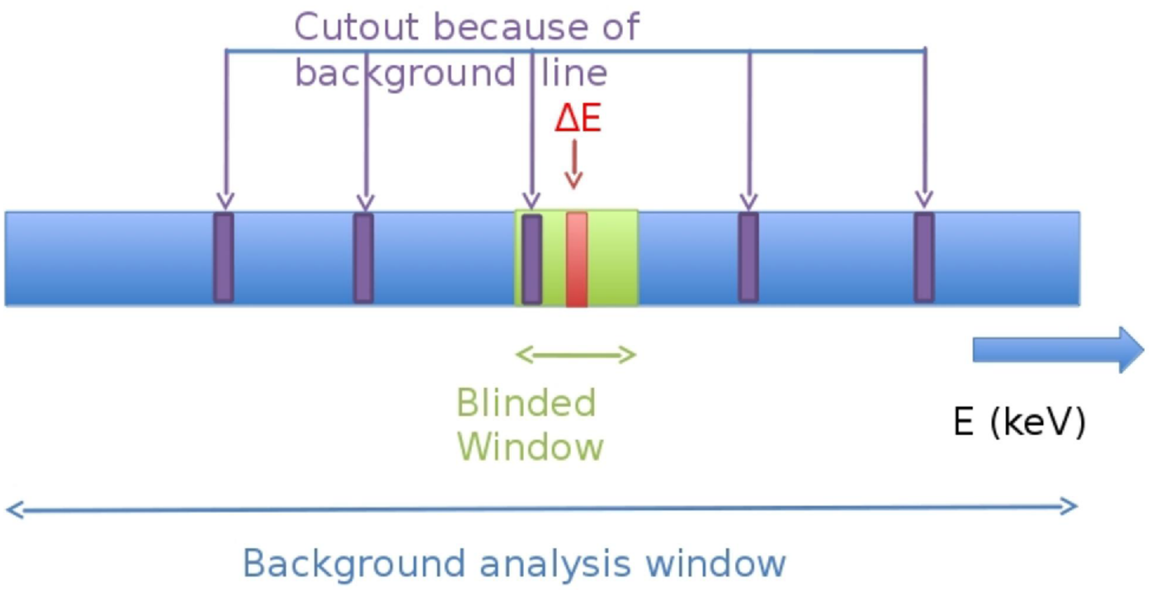
detector	enrichment factor	mass [g]	active mass [g]	active mass fraction	d_{dl} mm
enriched coaxial detectors					
~~ANG 1 †)~~	0.859(29)	958	795(50)	0.830(52)	1.8(5)
ANG 2	0.866(25)	2833	2468(145)	0.871(51)	2.3(7)
ANG 3	0.883(26)	2391	2070(136)	0.866(57)	1.9(7)
ANG 4	0.863(13)	2372	2136(135)	0.901(57)	1.4(7)
ANG 5	0.856(13)	2746	2281(132)	0.831(48)	2.6(6)
RG 1	0.855(15)	2110	1908(125)	0.904(59)	1.5(7)
RG 2	0.855(15)	2166	1800(115)	0.831(53)	2.3(7)
~~RG 3 †)~~	0.855(15)	2087	1868(113)	0.895(54)	1.4(7)
enriched BEGe detectors					
GD32B	0.877(13)	717	638(19)	0.890(27)	1.0(2)
GD32C	0.877(13)	743	677(22)	0.911(30)	0.8(3)
GD32D	0.877(13)	723	667(19)	0.923(26)	0.7(2)
GD35B	0.877(13)	812	742(24)	0.914(29)	0.8(3)
~~GD35C †)~~	0.877(13)	635	575(20)	0.906(32)	0.8(3)
natural coaxial detectors					
GTF 32 †)	0.078(1)	2321	2251(116)	0.97(5)	0.4(8)
GTF 45 †)	0.078(1)	2312			
GTF 112	0.078(1)	2965			

Data Taking



Stable data taking during most of the time (556 d, duty cycle 88%)
→ 20 kg*y in April 2013 **➔ final exposure 21.6 kg * yr**

The Blinding Procedure



After Jan. 2012:
blinding of $Q_{\beta\beta}\pm 20$keV
←→ avoid biases

Data processing details fixed before unblinding
- quality cuts
- puls shape discrimination parameters
- analysis method → three data sets

golden	**= 17.9 kg*yr**
silver	**= 1.3 kg*yr**
BEGe	**= 2.4 kg*yr**

unblinding
In June 2013

Backgrounds

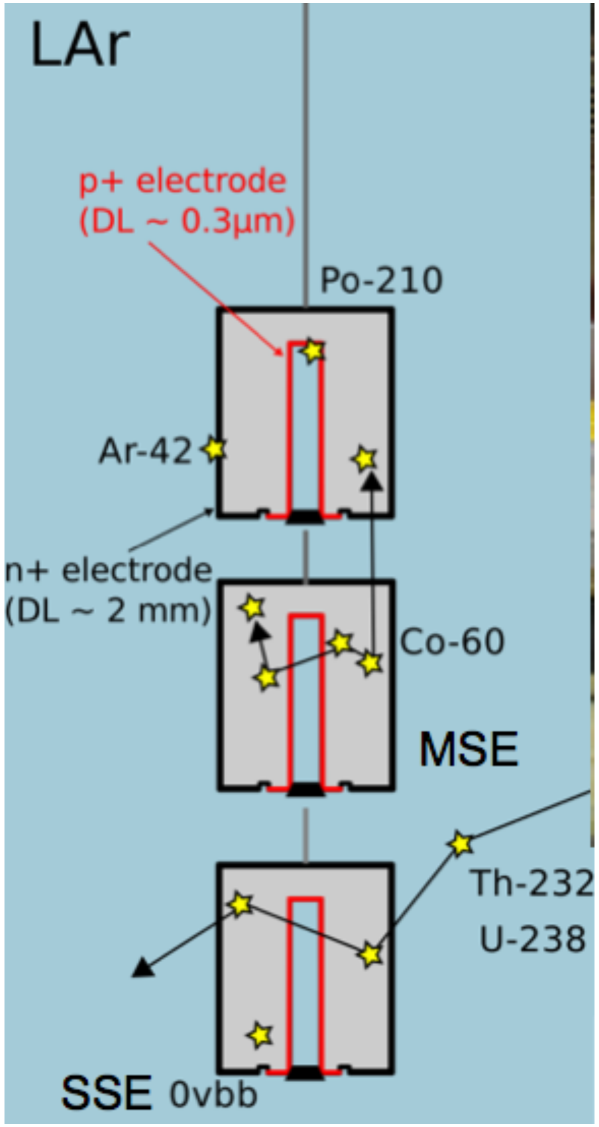
The outer dead layer of the detectors is not active

Background sources:

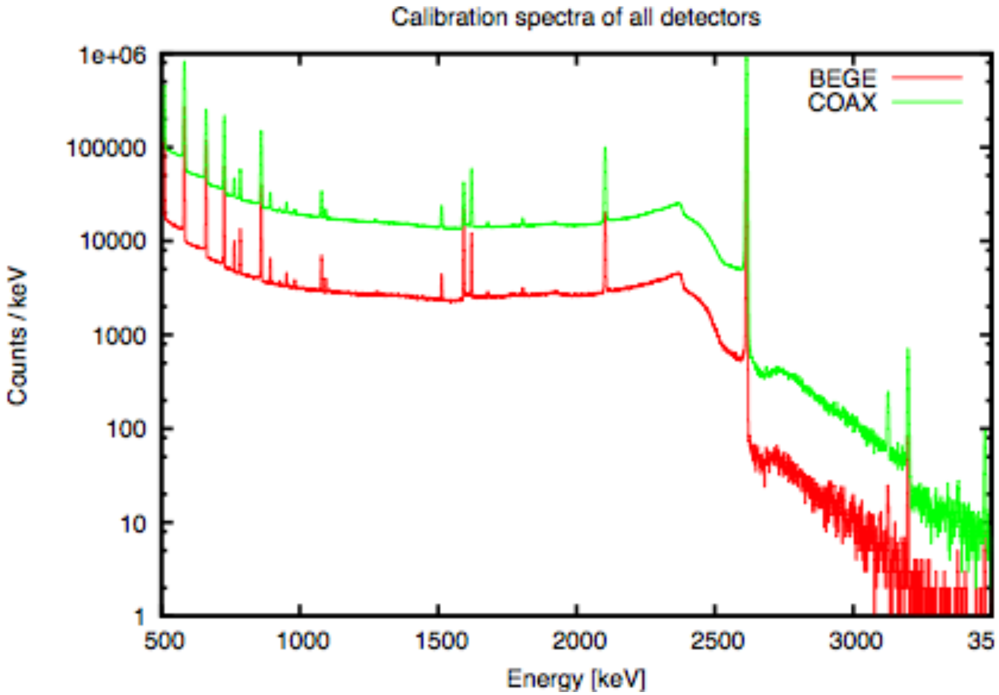
– α decays on the p^+ surface
– β decay of ^{42}K on the surface or close to the detector from ^{42}Ar (10x more than expected)
– β decay of ^{60}Co inside detectors
– γ from ^{208}Tl, ^{214}Bi and from various set-up components

Generic phase I background reduction

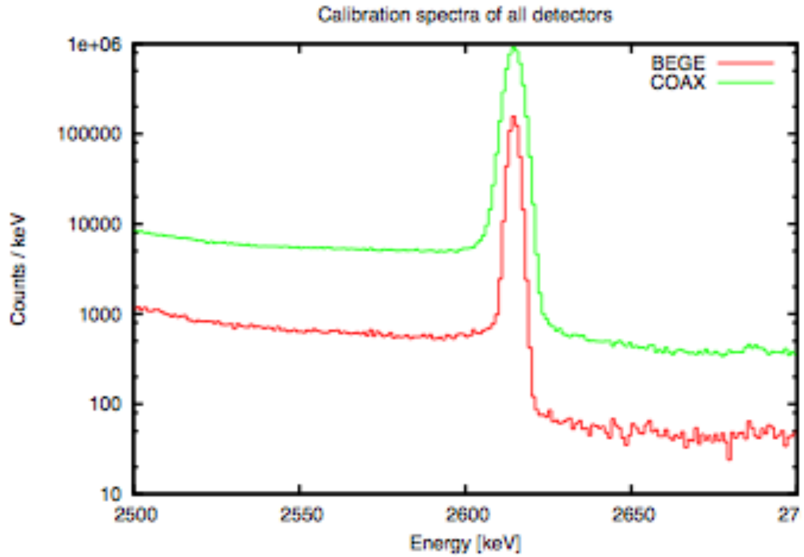
– use cleanest possible material
– cut detector coincidences
– prevent ^{42}K ions from drifting to detectors using minishrouds



Detector Performance



from ^{208}Tl

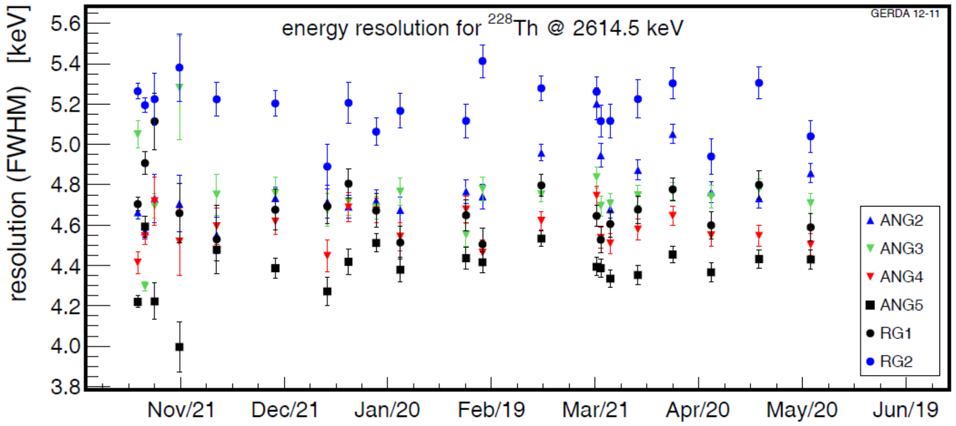


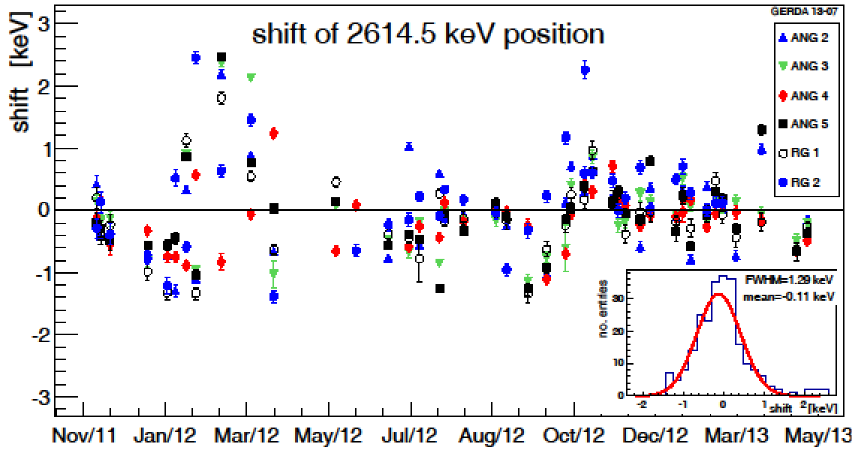
Energy resolution:

coaxial at $Q_{\beta\beta}$: (4.8 ± 0.2) keV at 2614.5 keV (4.2 - 5.8) keV
BEGe (3.2 ± 0.2) keV (2.6 - 4.0) keV

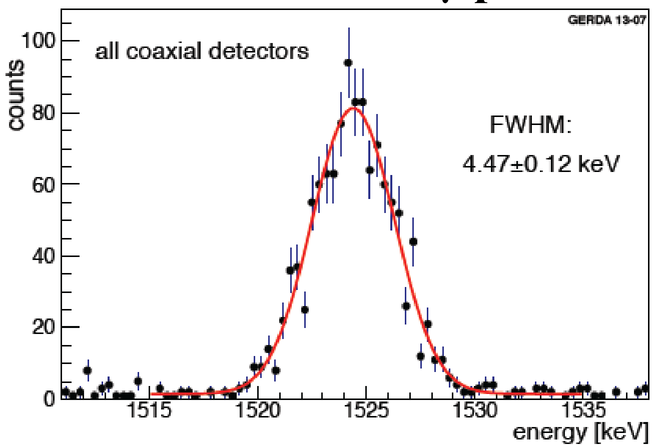
- stable energy resolution
- no energy drift between consecutive calibrations (<0.05%)
- leakage currents stable (except RG2)

Good Energy Resolution and Gain Stability





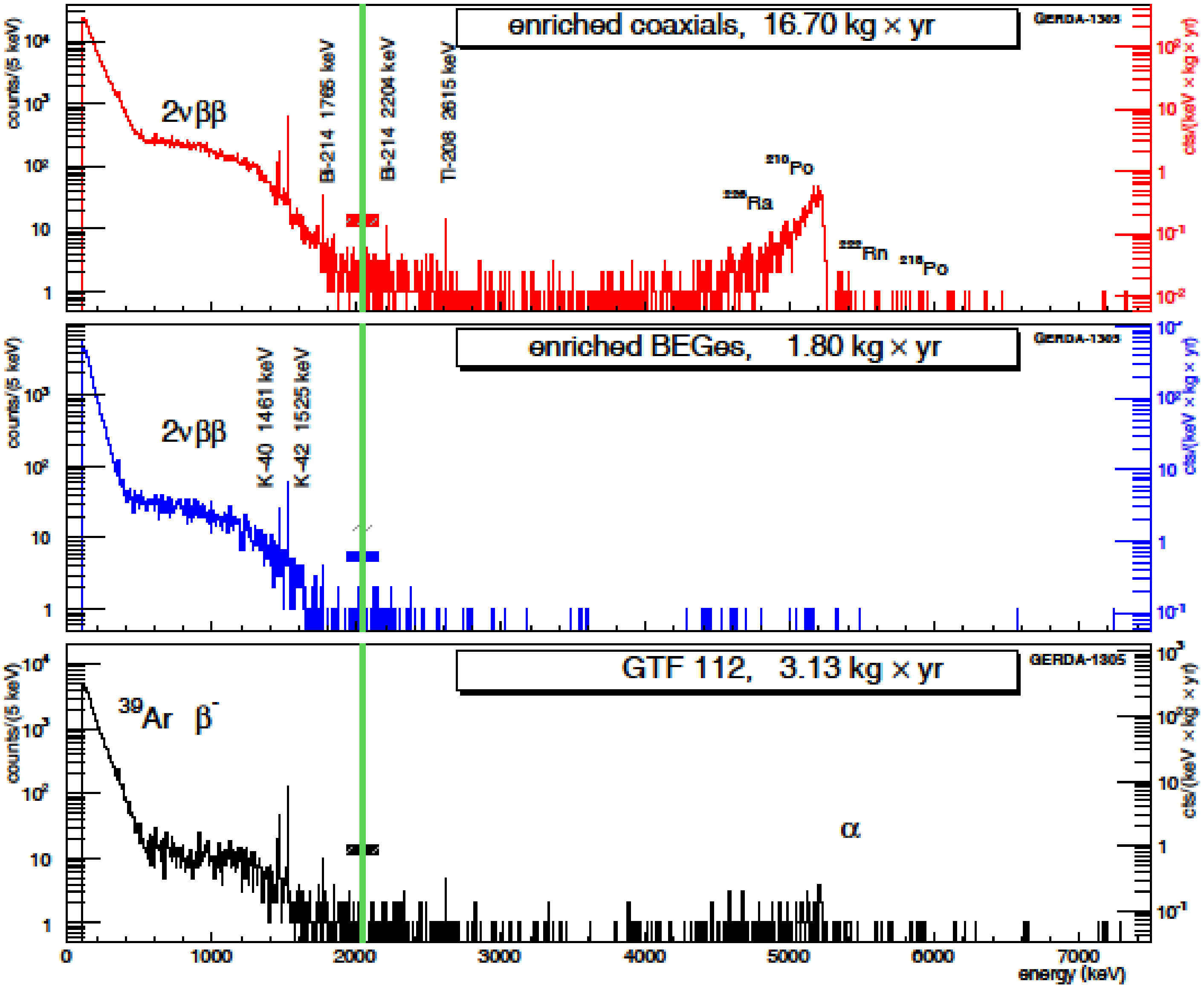
FWHM of long term data at ^{42}K 1525 keV γ-peak



FWHM (resolution) of 0νββ data at $Q_{\beta\beta}$

detector	FWHM [keV]	detector	FWHM [keV]
SUM-coax		*SUM-bege*	
ANG 2	5.8 (3)	GD32B	2.6 (1)
ANG 3	4.5 (1)	GD32C	2.6 (1)
ANG 4	4.9 (3)	GD32D	3.7 (5)
ANG 5	4.2 (1)	GD35B	4.0 (1)
RG 1	4.5 (3)		
RG 2	4.9 (3)		
mean coax	4.8 (2)	mean BEGe	3.2 (2)

The Background Spectrum



green = blinded

2νββ result
arXiv:1212.3210
J.Phys.G: Nucl. Part. Phys. 40(2013) 035110

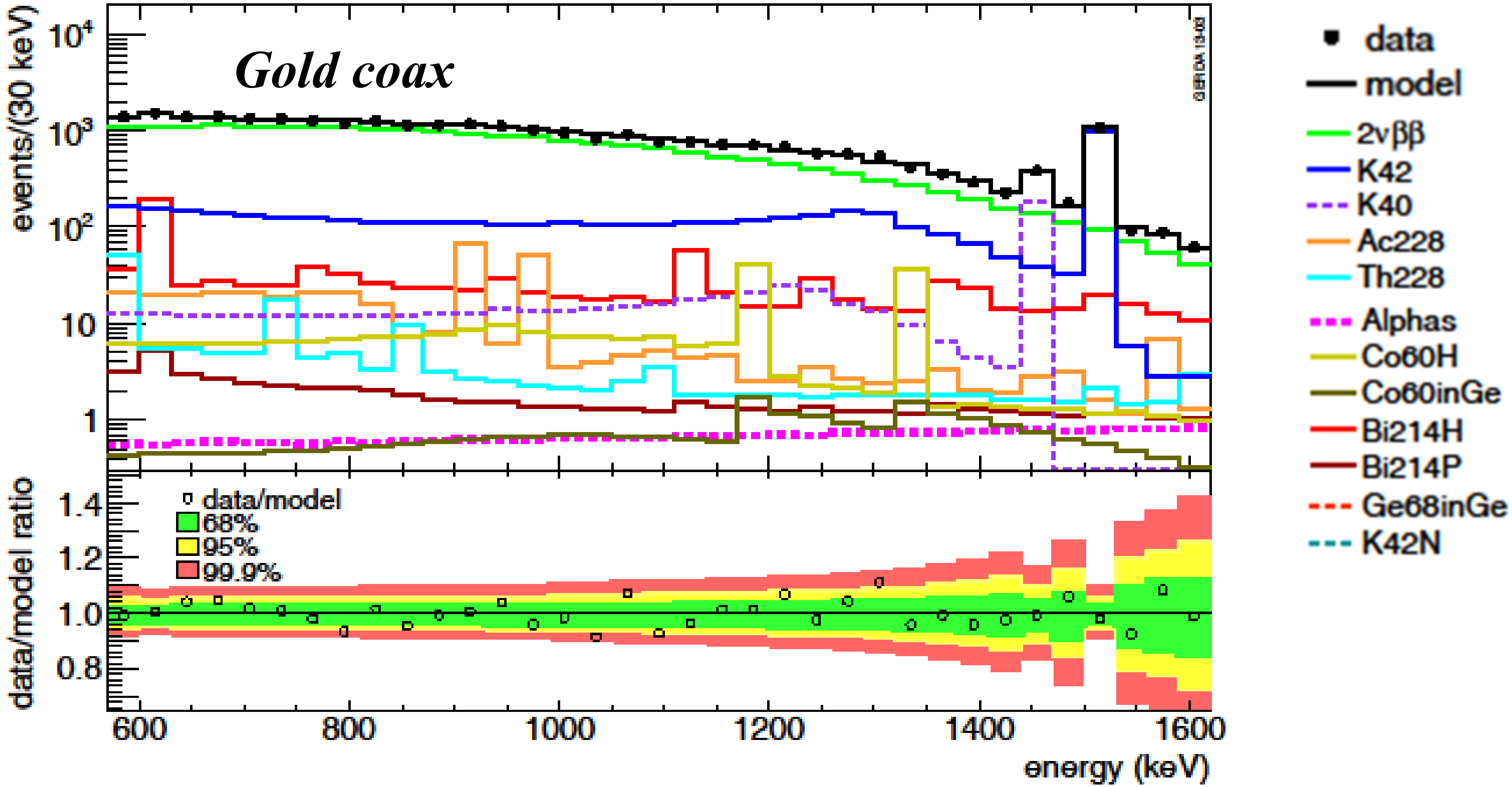
$T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.08})\, 10^{21}$ yr

backgrd. paper
arXiv:1306.5084
to appear in EPJ C

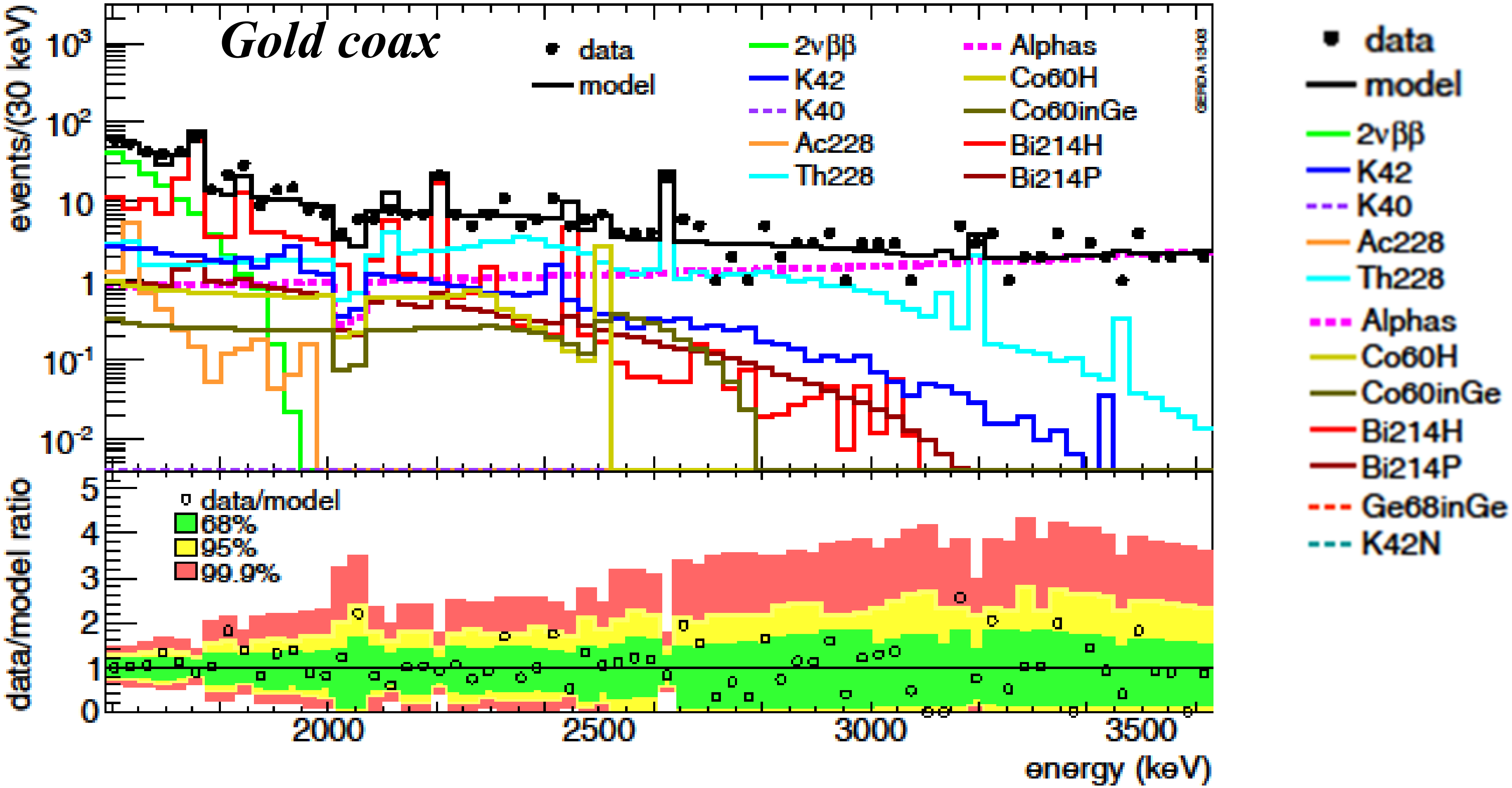
The Background Model

Background decomposition with all simulated components; fit window 570-7500 keV

Minimum model: minimum set of background components

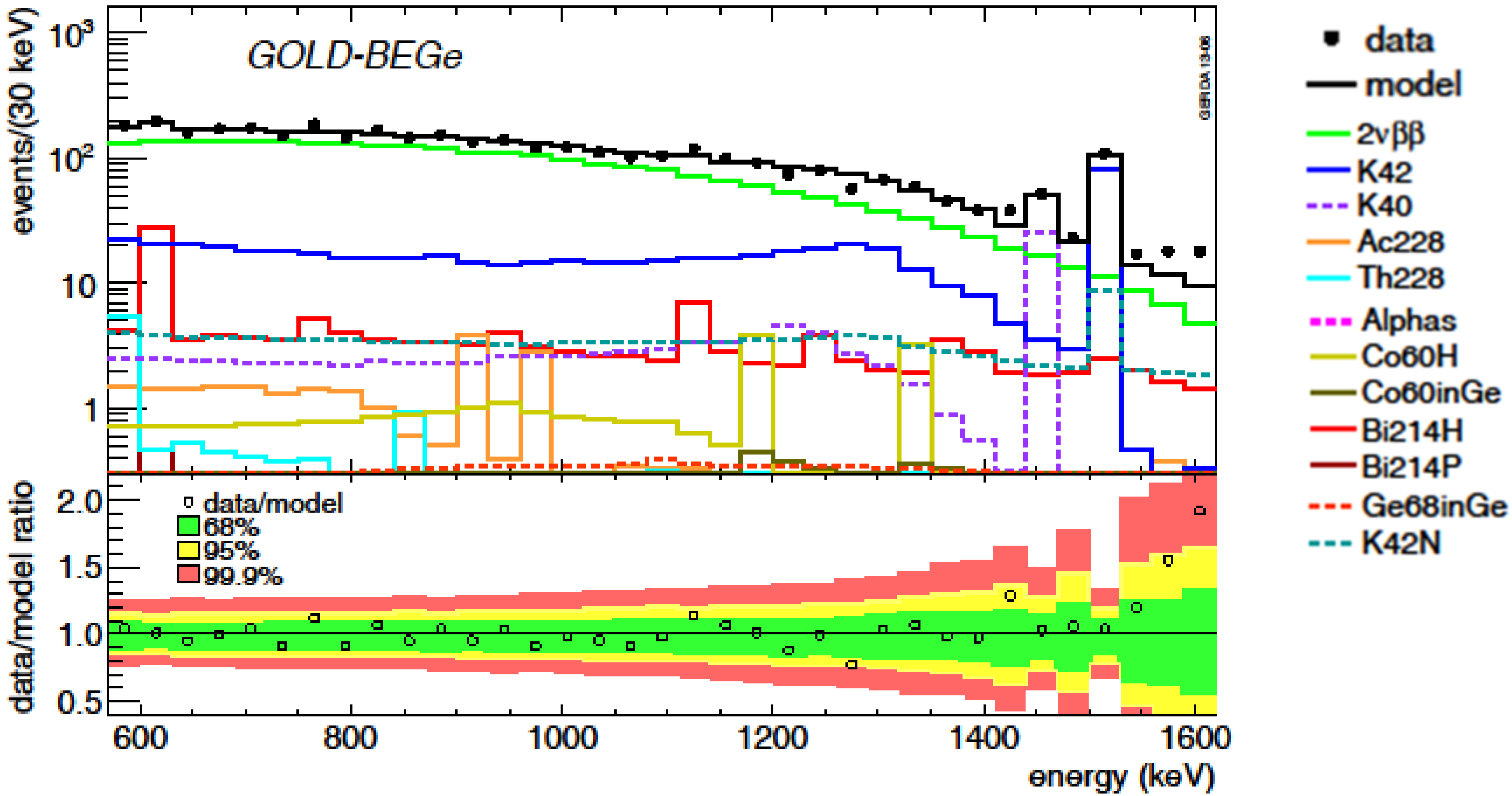


Larger energy range...



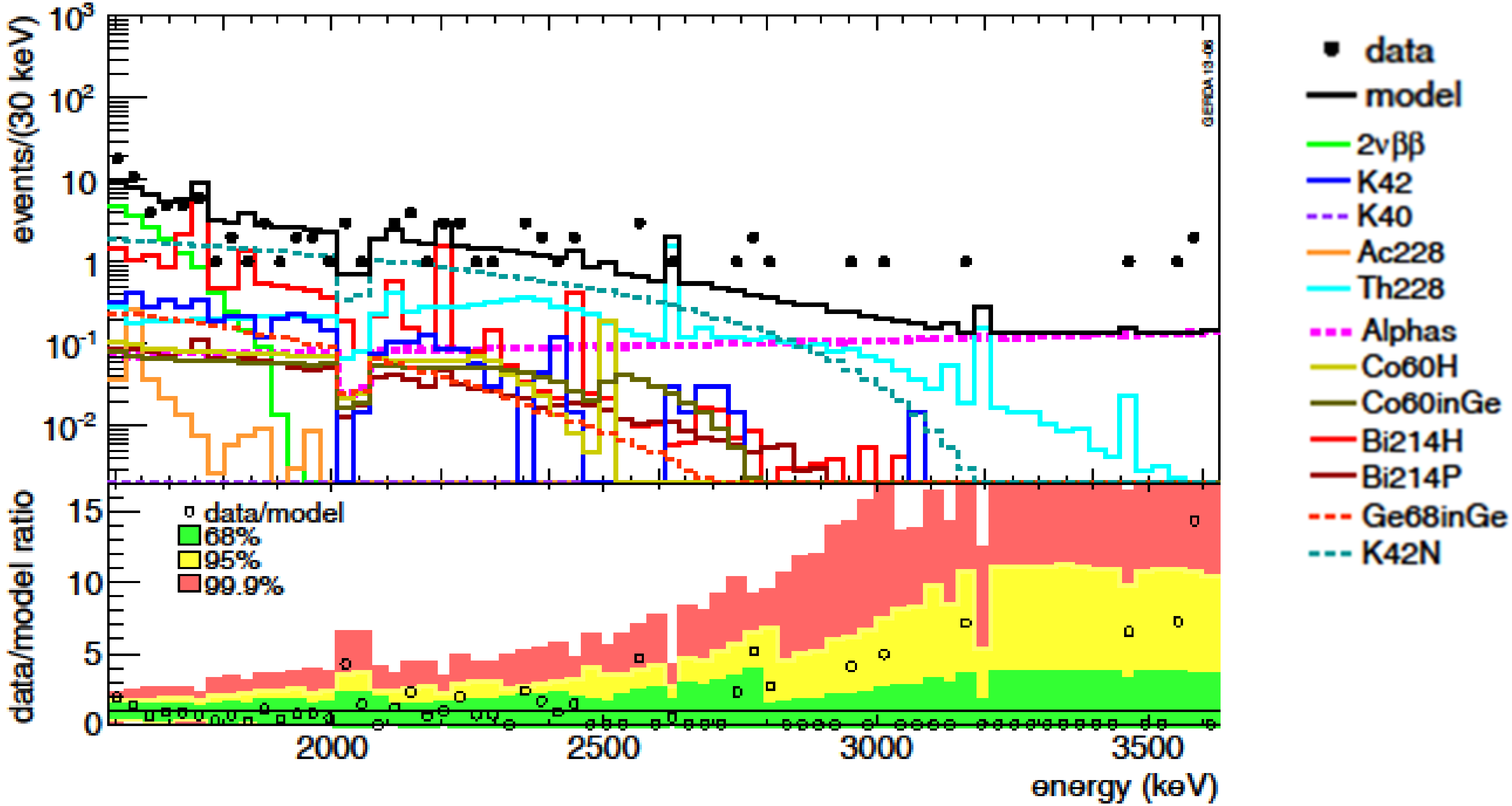
➔ fits data very well ➔ background is FLAT in ROI

For BEGEs...



GOLD-BEGe
events/(30 keV)
10^3
10^2
10
1
data/model ratio
2.0
1.5
1.0
0.5
data/model
68%
95%
99.9%
600
800
1000
1200
1400
1600
energy (keV)
data
model
2νββ
K42
K40
Ac228
Th228
Alphas
Co60H
Co60inGe
Bi214H
Bi214P
Ge68inGe
K42N

Larger energy range for BEGE's



Derived Background Composition

source	location	units	*GOLD-coax* minimum	*GOLD-coax* maximum	*GOLD-nat* minimum
^{40}K ^{c})	det. assembly	µBq/det.	152[136,174]	151[136,174]	218[188,259]
^{42}K ^{c})	LAr	µBq/kg	106[103,111]	91[72,99]	98.3[92,108]
^{42}K ^{c})	p^+ surface	µBq		11.6[3.1,18,3]	
^{42}K ^{c})	n^+ surface	µBq		4.1[1,2,8.5]	
^{60}Co ^{c})	det. assembly	µBq/det.	4.9[3.1,7.3]	3.2[1.6,5.6]	2.6[0,6.0]
^{60}Co ^{c})	germanium	µBq	>0.4 †)	>0.2 †)	6[3.0,8.4]
^{214}Bi ^{c})	det. assembly	µBq/det.	35[31,39]	15[3.7,21.1]	34.1[27.3,42.1]
^{214}Bi ^{c})	LAr close to p^+	µBq/kg		<299.5	
^{214}Bi ^{m})	radon shroud	mBq		<49.9	
^{214}Bi ^{c})	p^+ surface	µBq	2.9[2.3,3.9] †)	3.0[2.1,4.0] †)	1.6[1.2,2.1] †)
^{228}Th ^{c})	det. assembly	µBq/det.	15.1[12.7,18.3]	5.5[1.8,8.8]	15.7[10.0,25.0]
^{228}Ac ^{c})	det. assembly	µBq/det.	17.8[10.0,26.8]	<15.7	25.9[16.7,36.7]
^{228}Th ^{m})	radon shroud	mBq		<10.1	
^{228}Ac ^{m})	radon shroud	mBq		91.5[27,97]	
^{228}Th ^{f})	heat exchanger	Bq		<4.1	

good agreement between model and activities of ^{40}K, ^{42}K, ^{60}Co

the position of some components can not be resolved (^{214}Bi, ^{228}Th, ...)

More on Backgrounds…

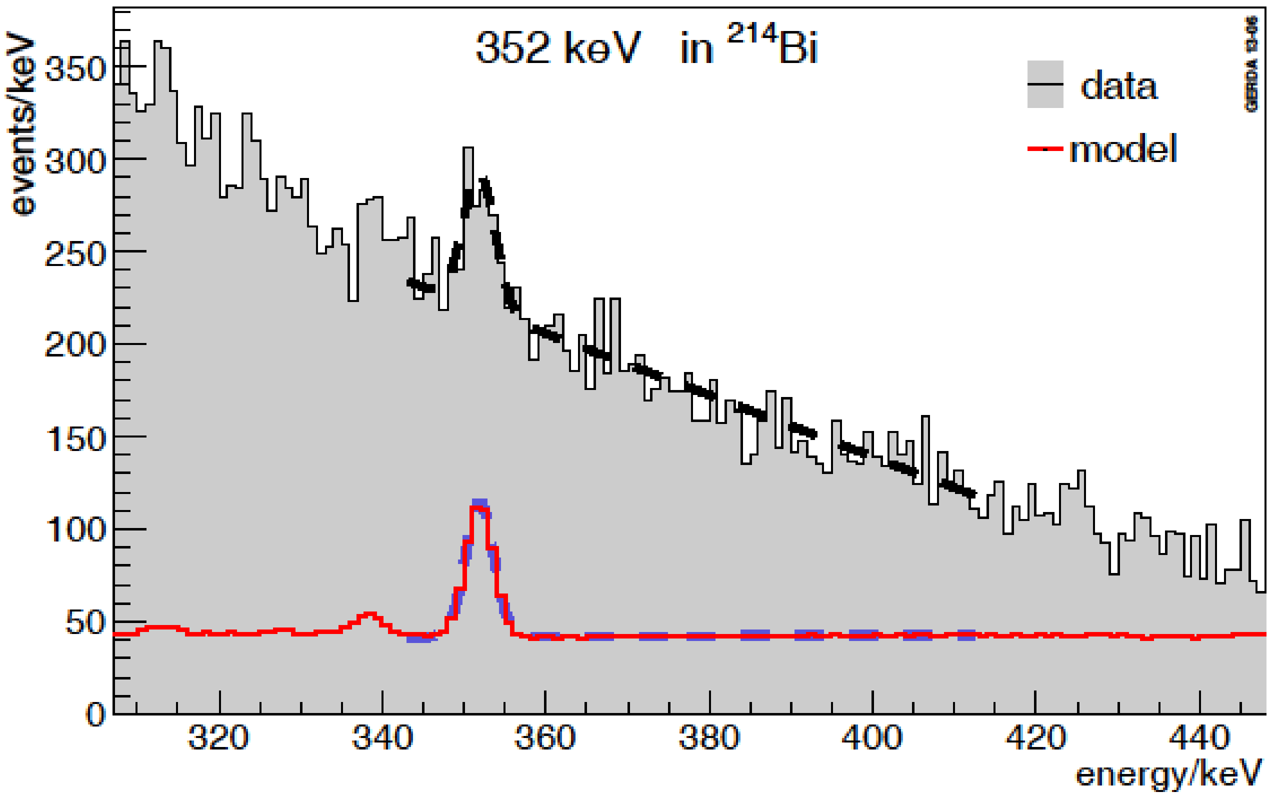
Intensity of gamma peak outside background analysis energy window

Gold Coax:

Min model	294±27
Max model	258±27
Data	262±48

GTF112:

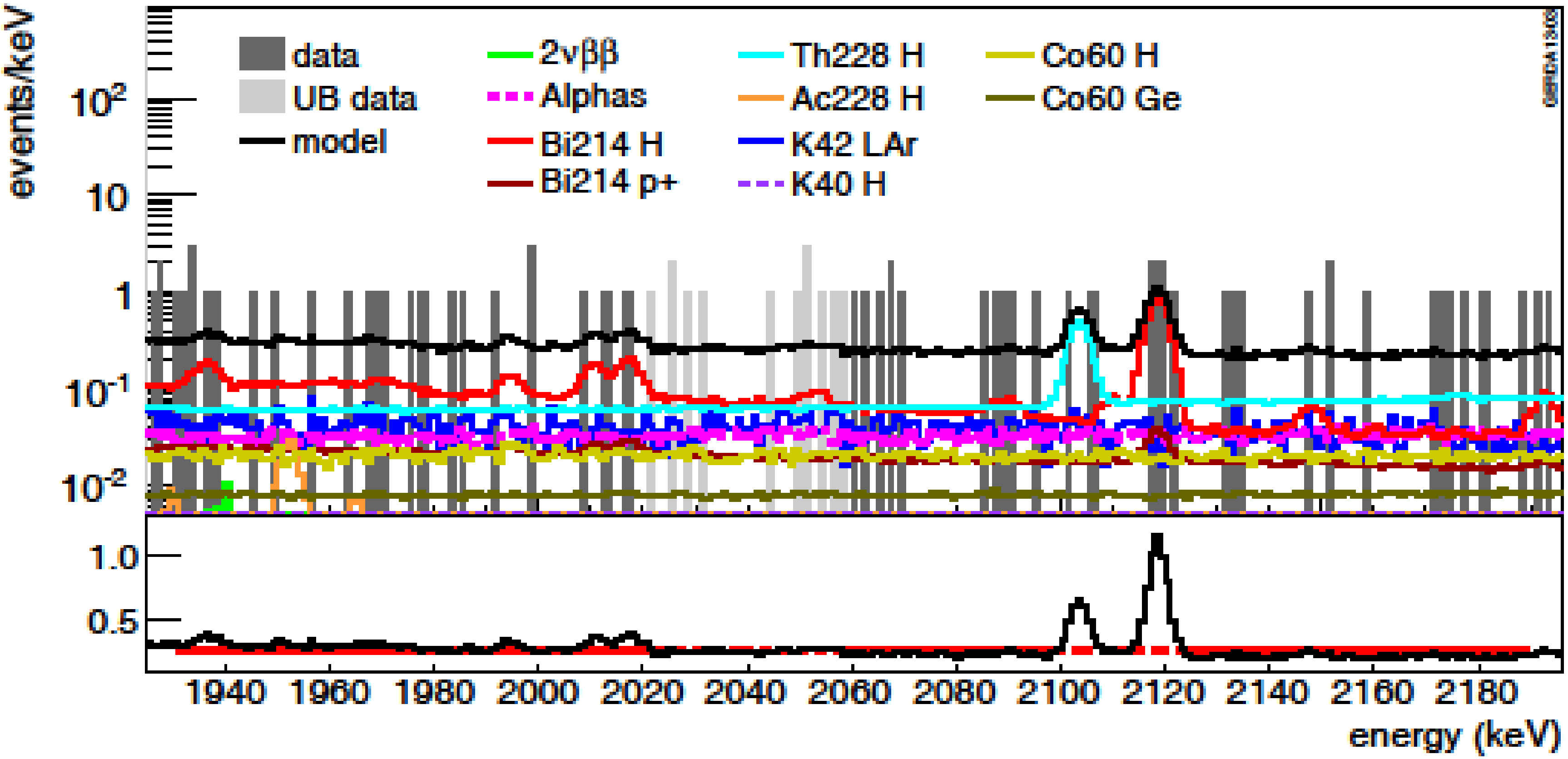
Min model	70±11
Data	77±19



➔ Very good agreement between peak intensities vs. background model
➔ further cross checks... (BiPo coincidences, PSA)

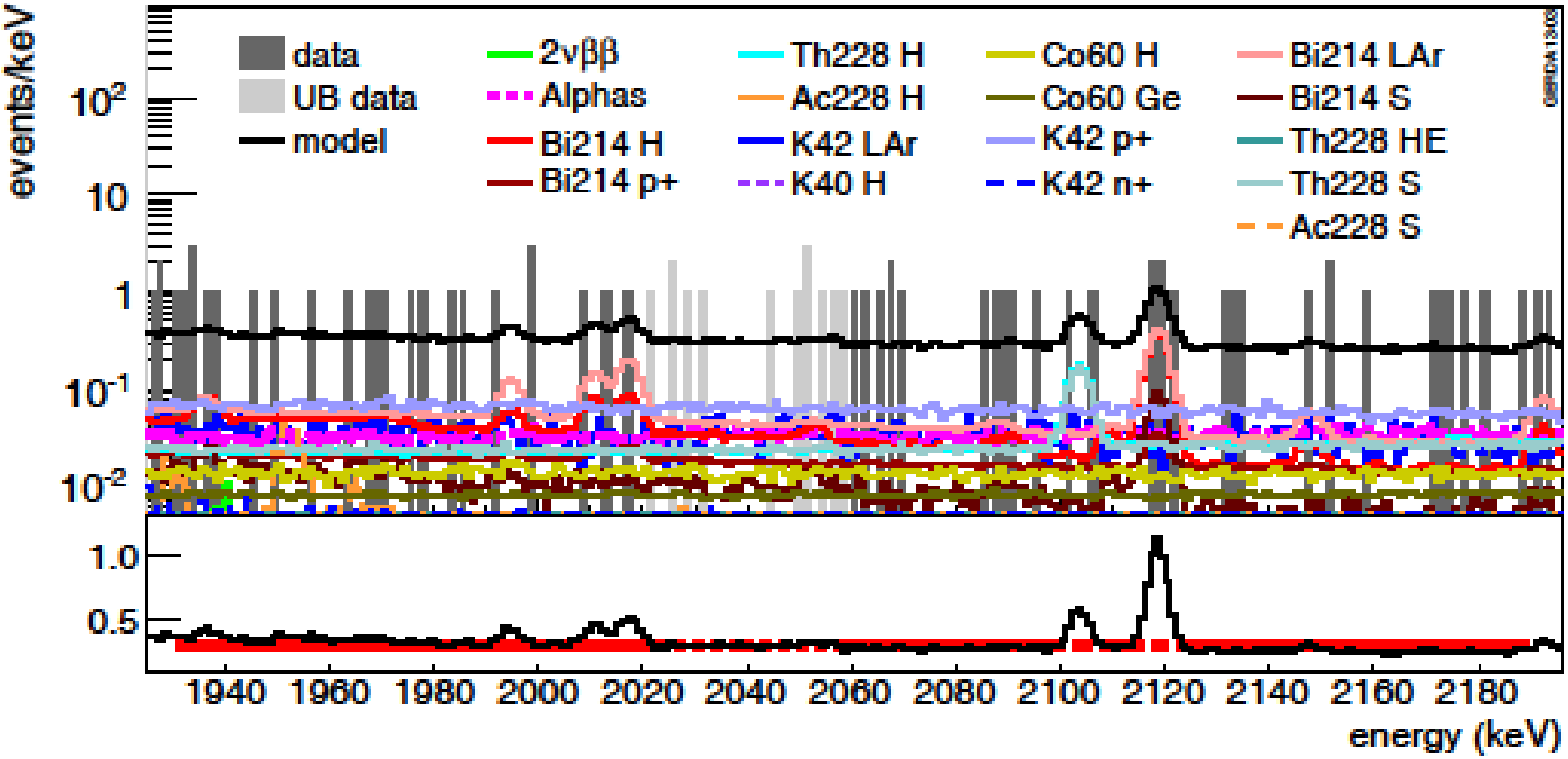
Background Composition: Minimum Model

minimum set of background components ➔

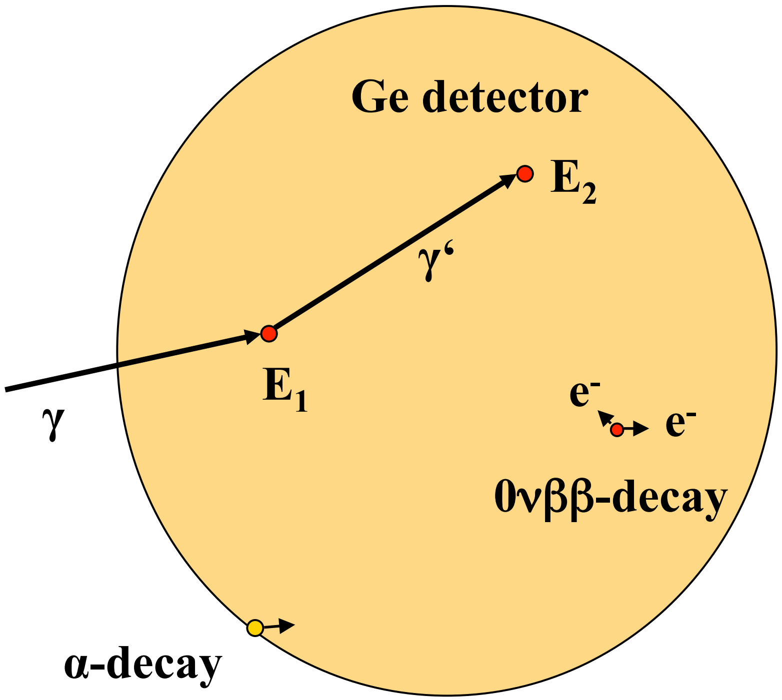


Background Composition: Maximum Model

total set of known background components leading to distinguishable spectra ➔

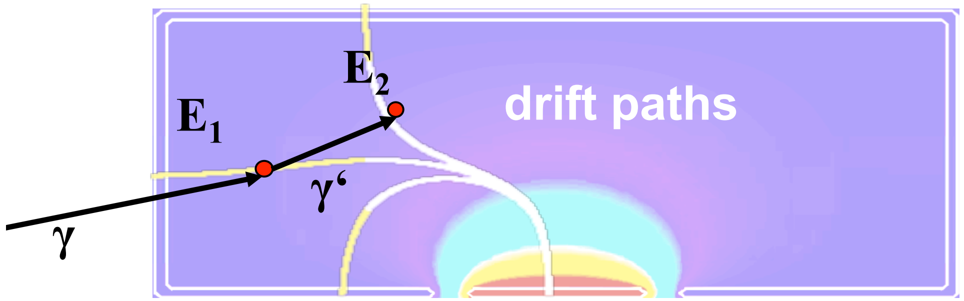


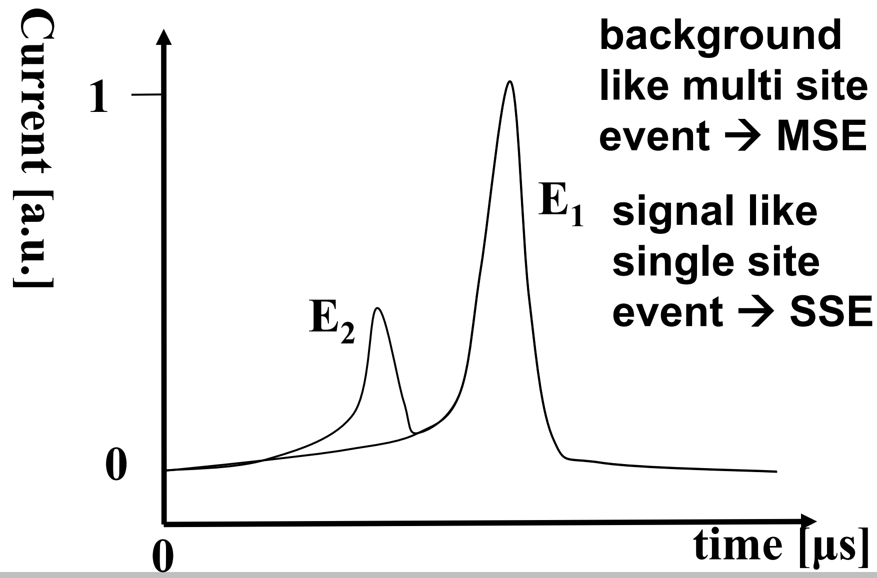
Pulse Shape Discrimination



- Single Site Events (SSE)
- Multi Site Events (MSE)

- 0νββ-decays → localized energy deposition → SSE
- Compton scattering evt. → background like MSE
- surface events → SSE @ surface
- SSE by γ's look like events (cannot be rejected)
- β particles enter via n^+ surface → slow pulses
- α's @ p^+ contact → comparatively high signal





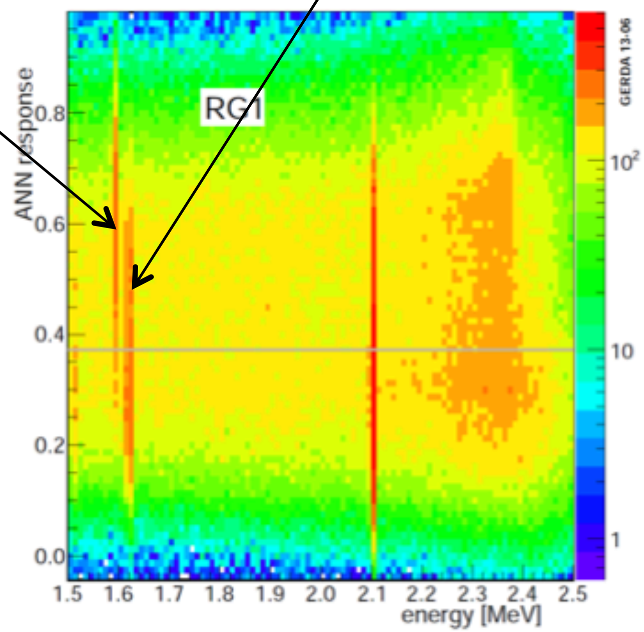
Pulse Shape Discrimination: Coaxial

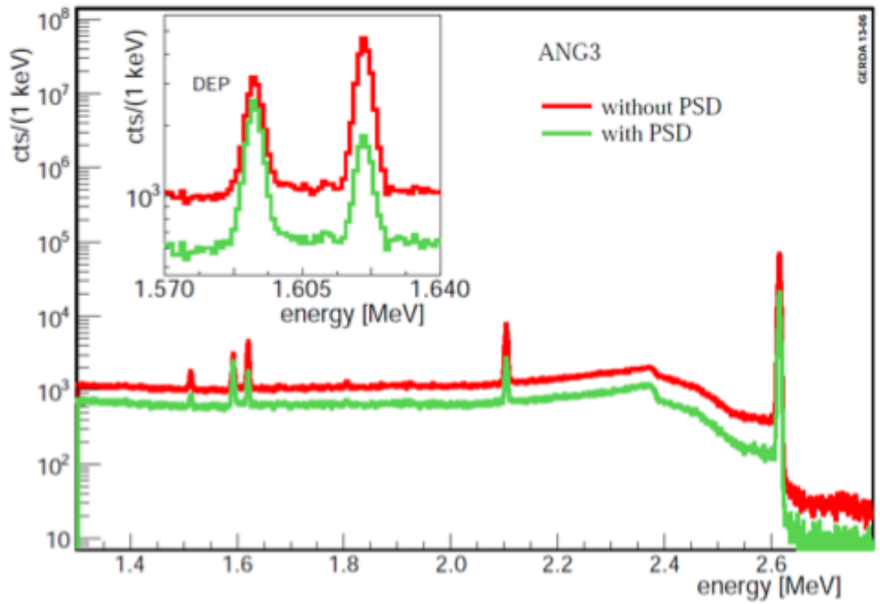
3 independent PSD methods:

- likelihood classification
- PSD selection based on pulse asymmetry
- **neural network analysis (ANN)**
  ➔ **training with calibration data**

SSE library: DEP peak of ^{208}Tl → gamma at 1592 ± 1 keV

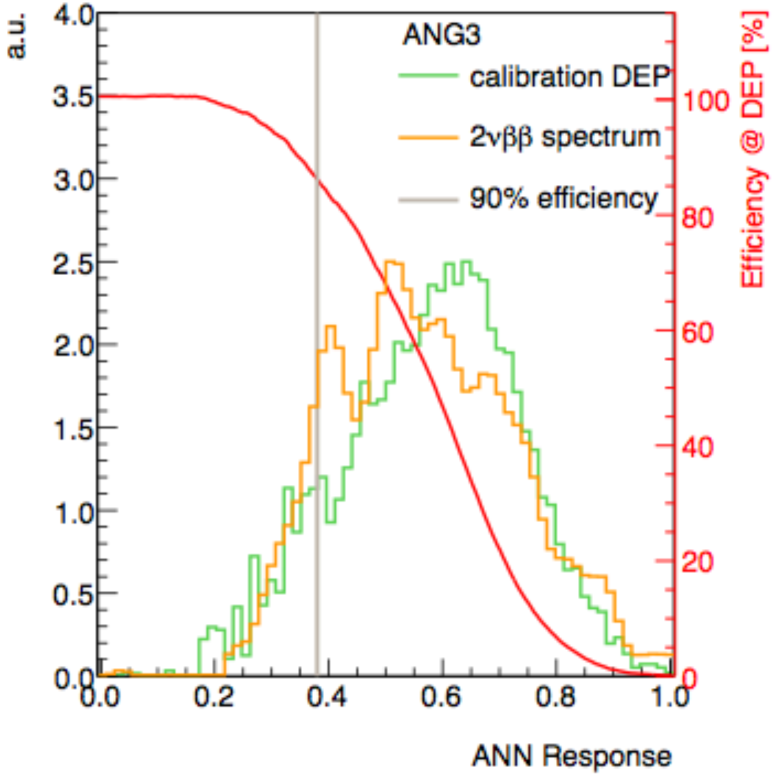
MSE library: FAP (Full Absorption Peak) of ^{212}Bi at 1620 keV

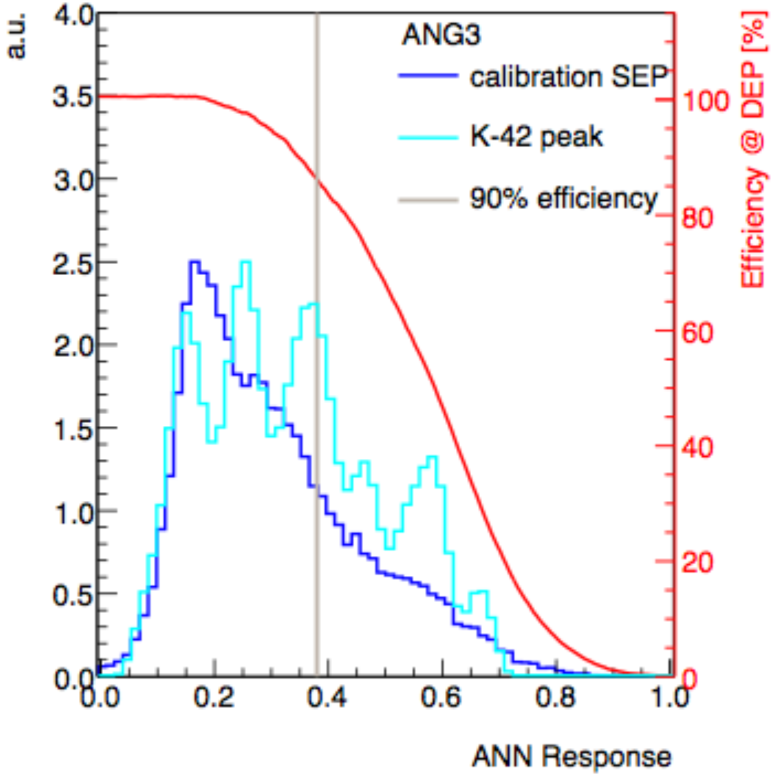




Neural Network Training with Calibration Data

- DEP events in the interval 1592 keV $\pm 1 FWHM$ serve as proxy for SSE
- Full energy line of ^{212}Bi in the equivalent interval around 1620 keV are dominantly MSE, taken as background events

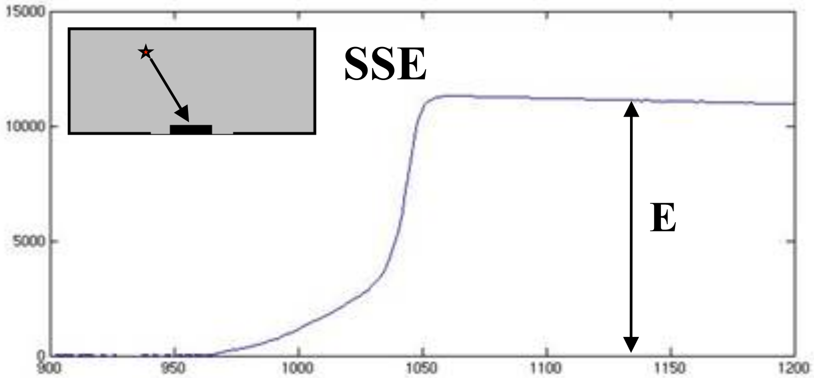




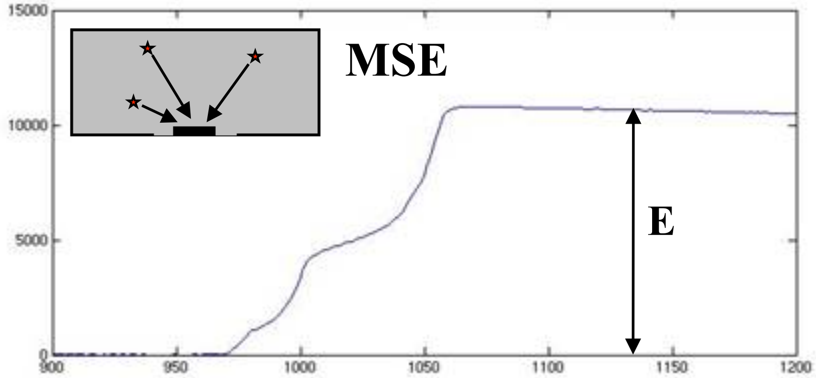
Pulse Shape Discrimination: BEGe A/E Cuts

Typical SSE (electron) — **raw preamplifier output:** — **Typical MSE (gamma)**

charge pulse



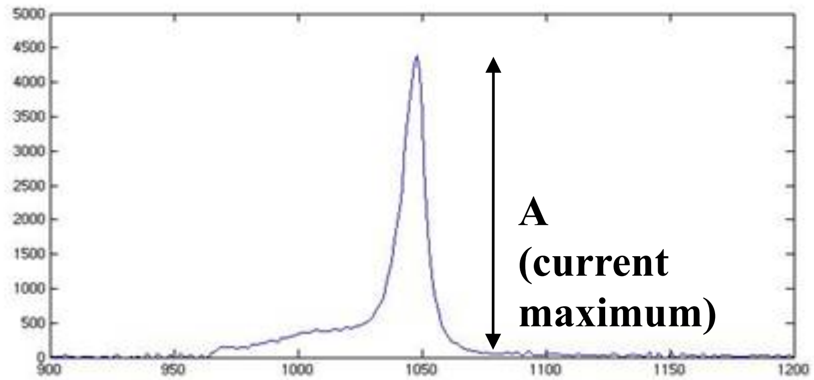
Time [10 ns]



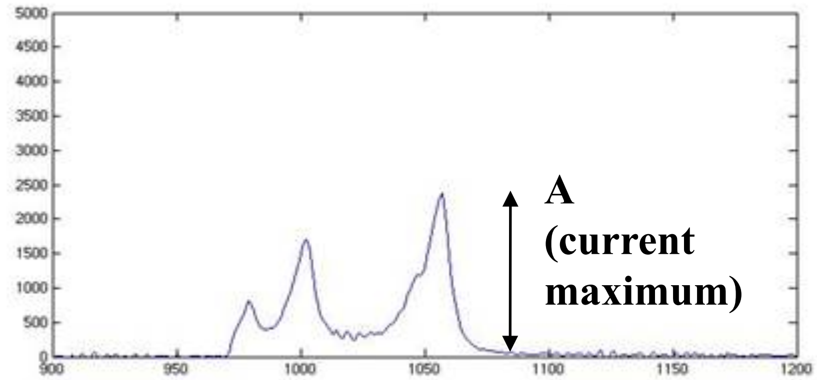
Time [10 ns]

after differentiation:

current pulse



Time [10 ns]

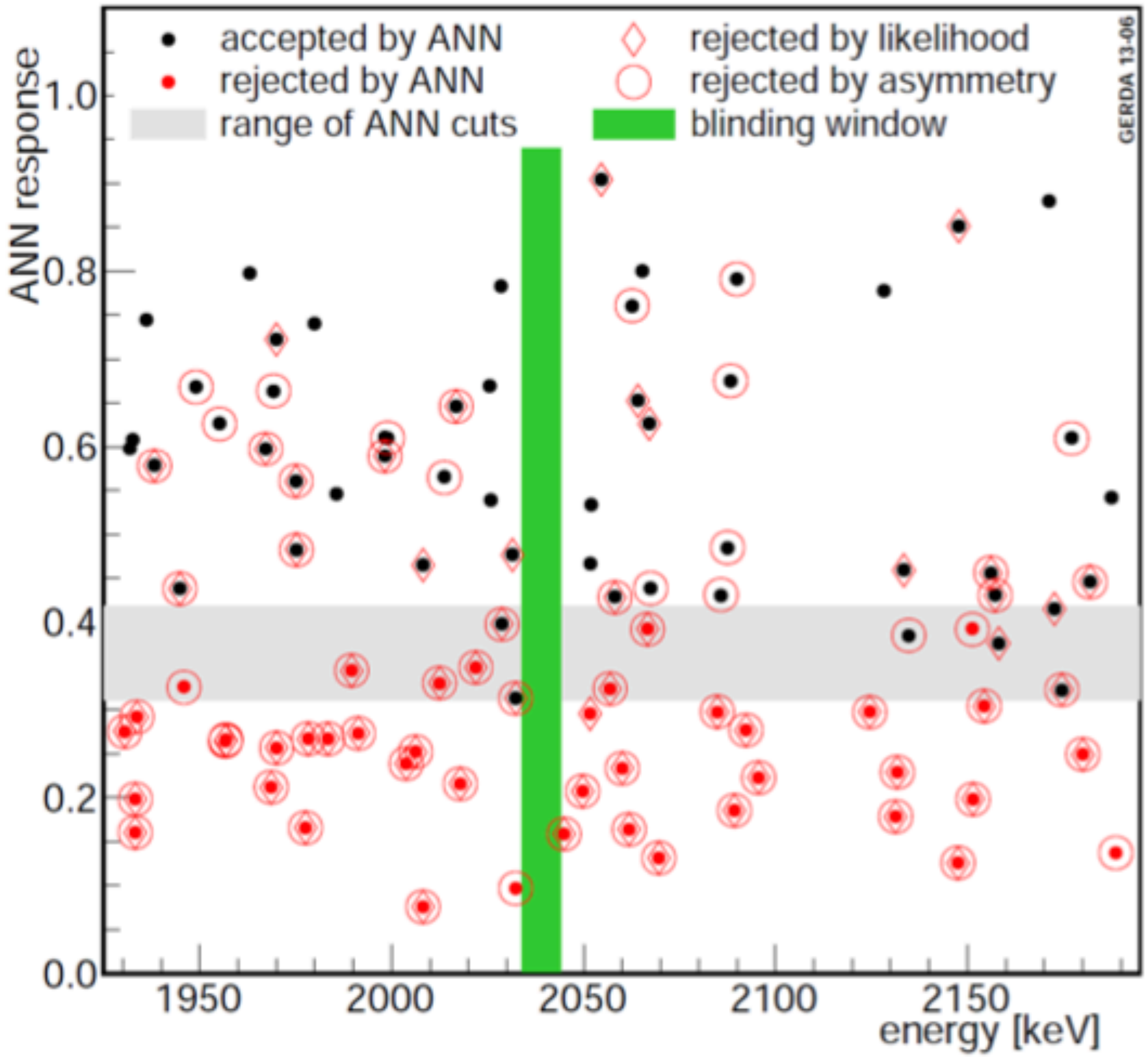


Time [10 ns]

➔ Cutting in A/E ➔ rejects background like MSEs

➔ $\varepsilon_{PSD} = 0.92 \pm 0.02$ ➔ ca. 85% of background events at $Q_{\beta\beta}$ rejected

Application of PSD to Phase I Data

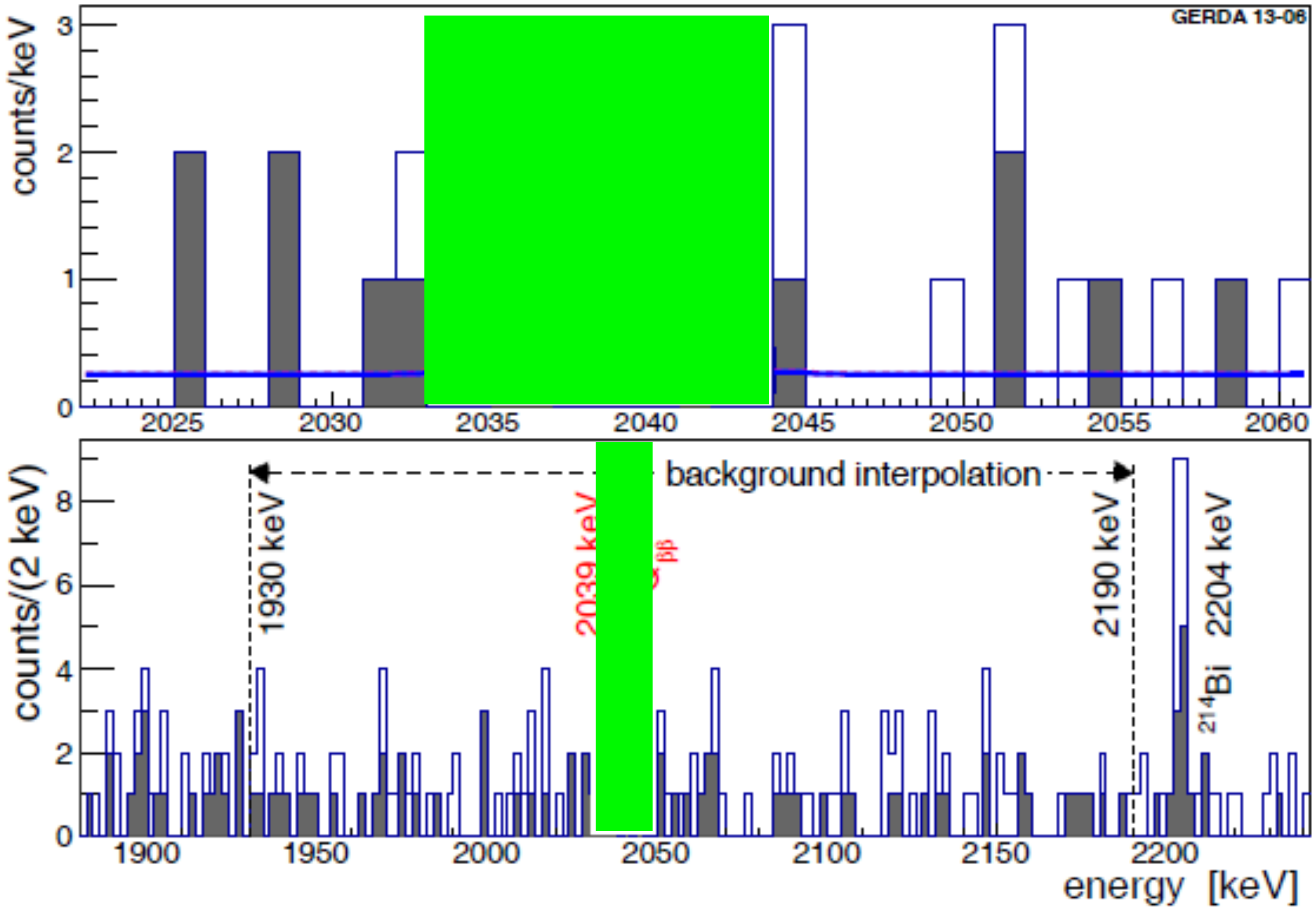


- all events removed by ANN are removed by at least one other method
- events discarded by ANN are in 90% of the cases discarded by all 3 methods
- in a larger energy window about 3% are only rejected by ANN

⇒ About 45% of events are rejected

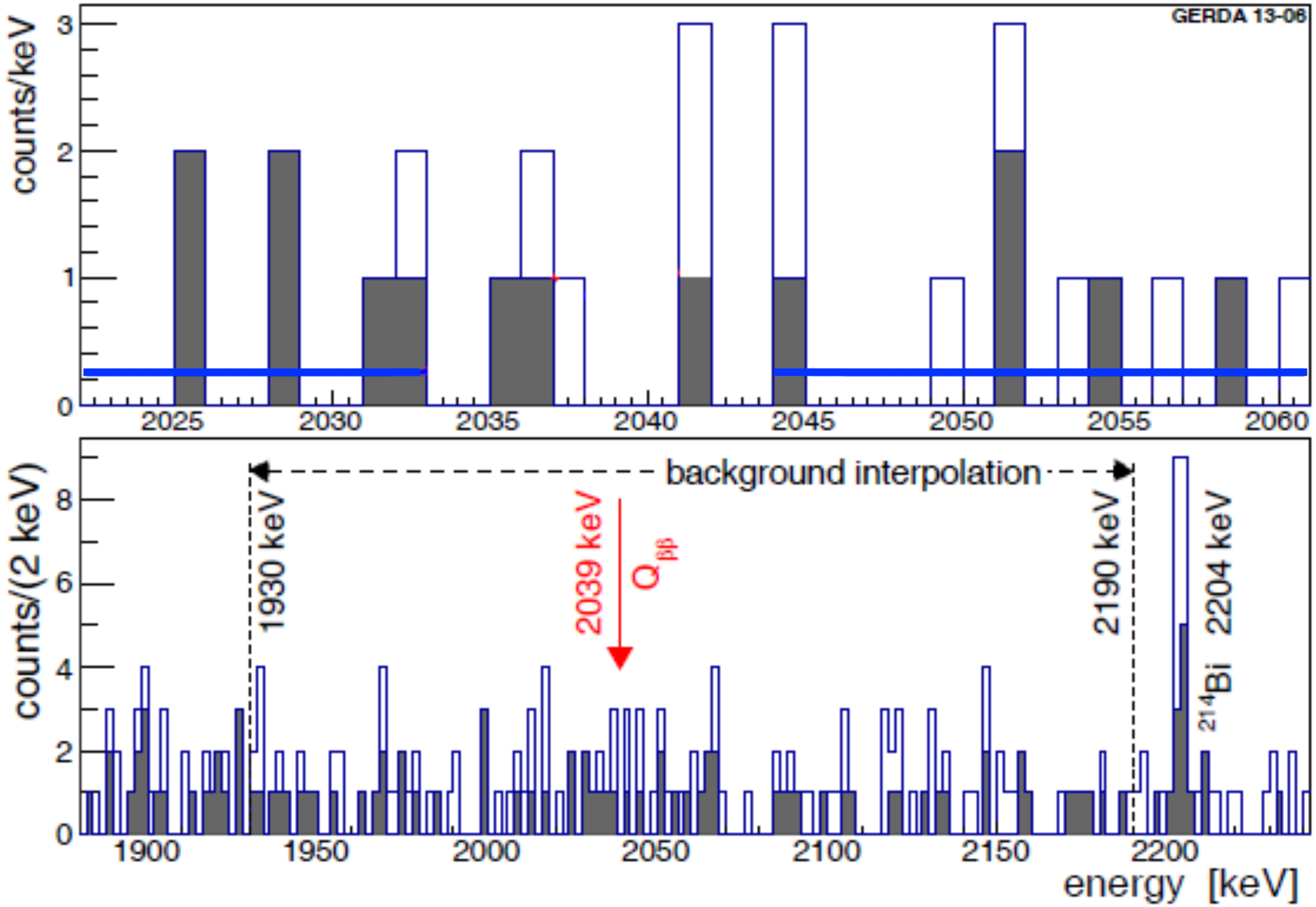
Efficiency: $\epsilon_{0\nu\beta\beta} = 0.90^{+0.05}_{-0.09}$

The Region of Interest



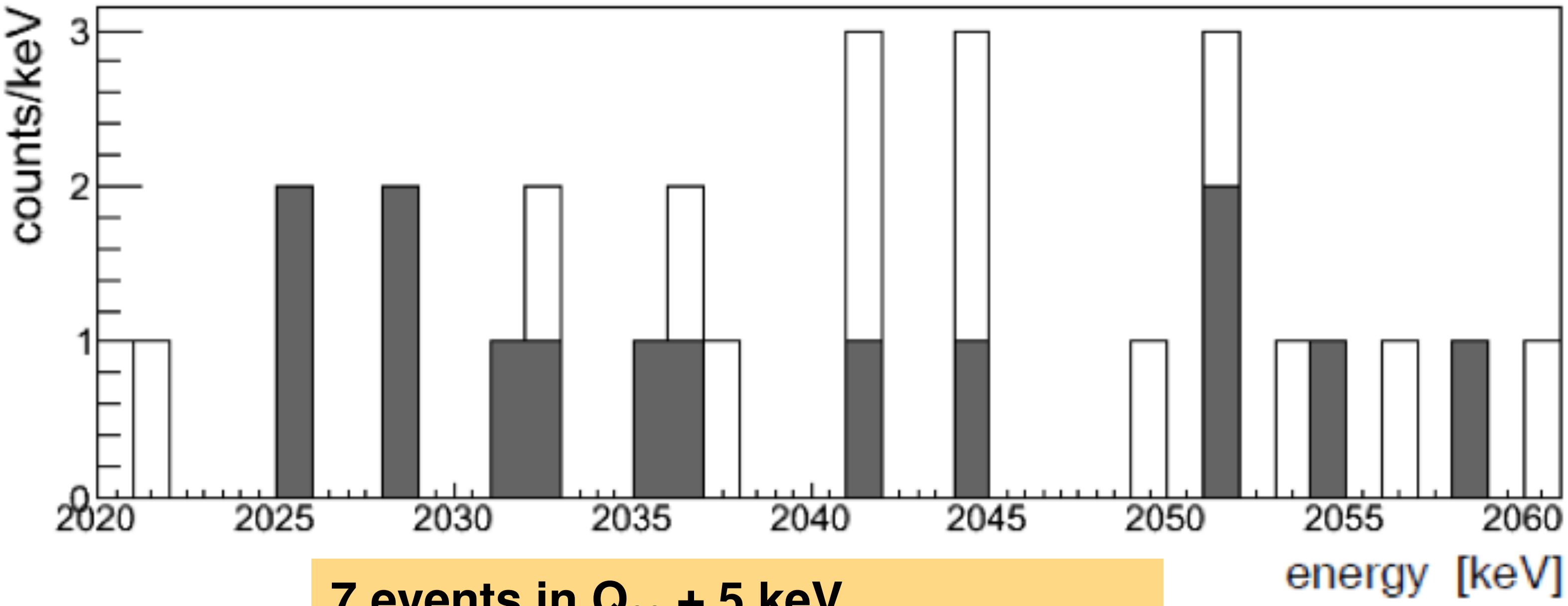
expected bg from interpolation: 5.1 events w/o PSD
2.5 events with PSD

The Region of Interest



expected bg from interpolation:	5.1 events w/o PSD 2.5 events with PSD	observed	➔ 7 events w/o PSD ➔ 3 events with PSD

Details of the unblinded Spectrum



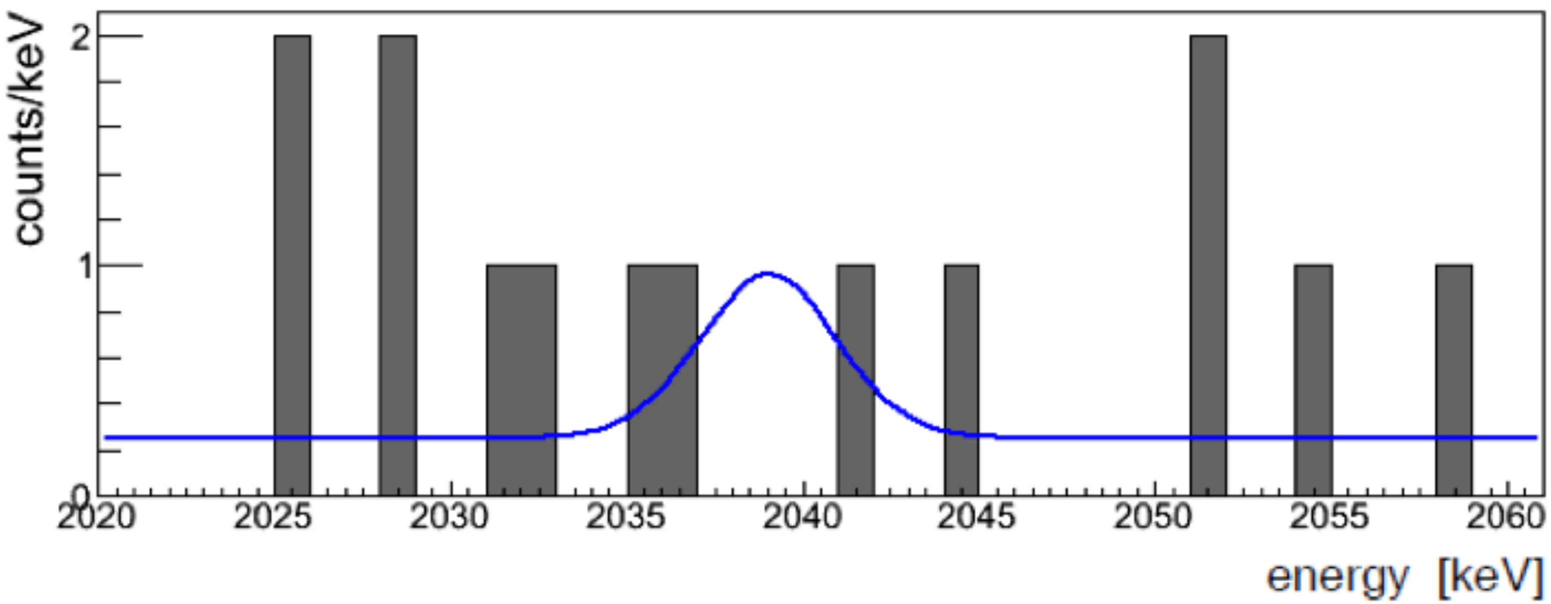
7 events in $Q_{\beta\beta}$ ± 5 keV
4 events rejected by PSD
➔ 3 events in $Q_{\beta\beta}$ ± 5 keV after PSD
➔ 0 events in $Q_{\beta\beta}$ ± 1 σ

data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG 1	2041.7	27-Apr-2013 22:21	no

data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI †)	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	$18.4^{+2.2}_{-2.1}$	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	$10.9^{+1.7}_{-1.6}$	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	$0.5^{+0.4}_{-0.3}$	0

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

Profile Likelihood Fit to PSD Spectrum



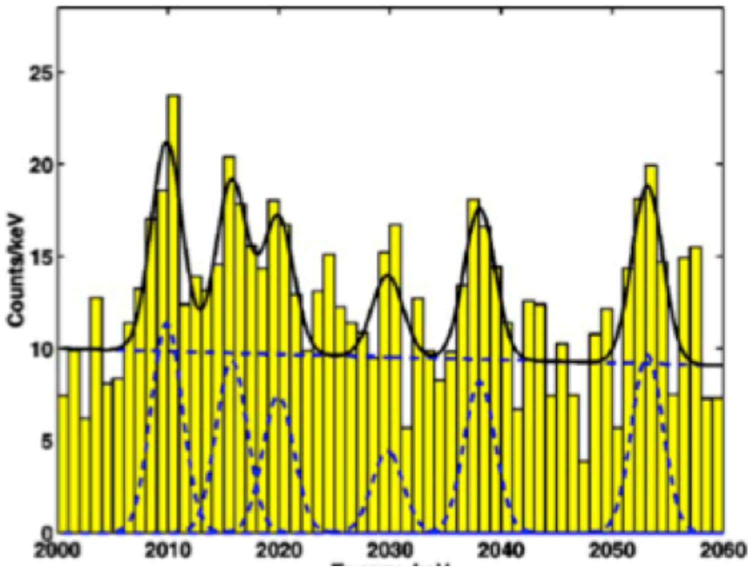
profile likelihood (PL) fit:

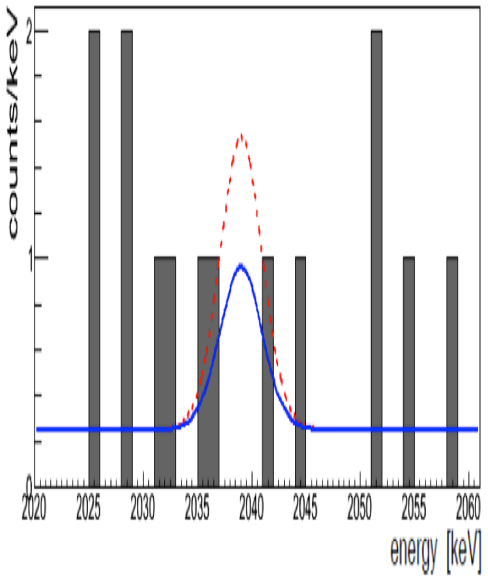
signal = a*flat background + b*line

➔ best fit: $N^{0\nu} = 0$; upper limit: $N^{0\nu} < 3.5$ (90%CL)

➔ half life limit $T_{1/2}(0\nu\beta\beta) > 2.1 * 10^{25}$ yr (90% C.L.)

Comparison with the KK Claim (2004)





claim:
$T_{1/2}(0\nu\beta\beta) = 1.19 * 10^{25}$ yr
Phys. Lett. B 586 (2004) 198

Stronger 2006 claim: 100% PSD efficiency assumed
➔ incorrect ➔ realistic efficiency = no improvement

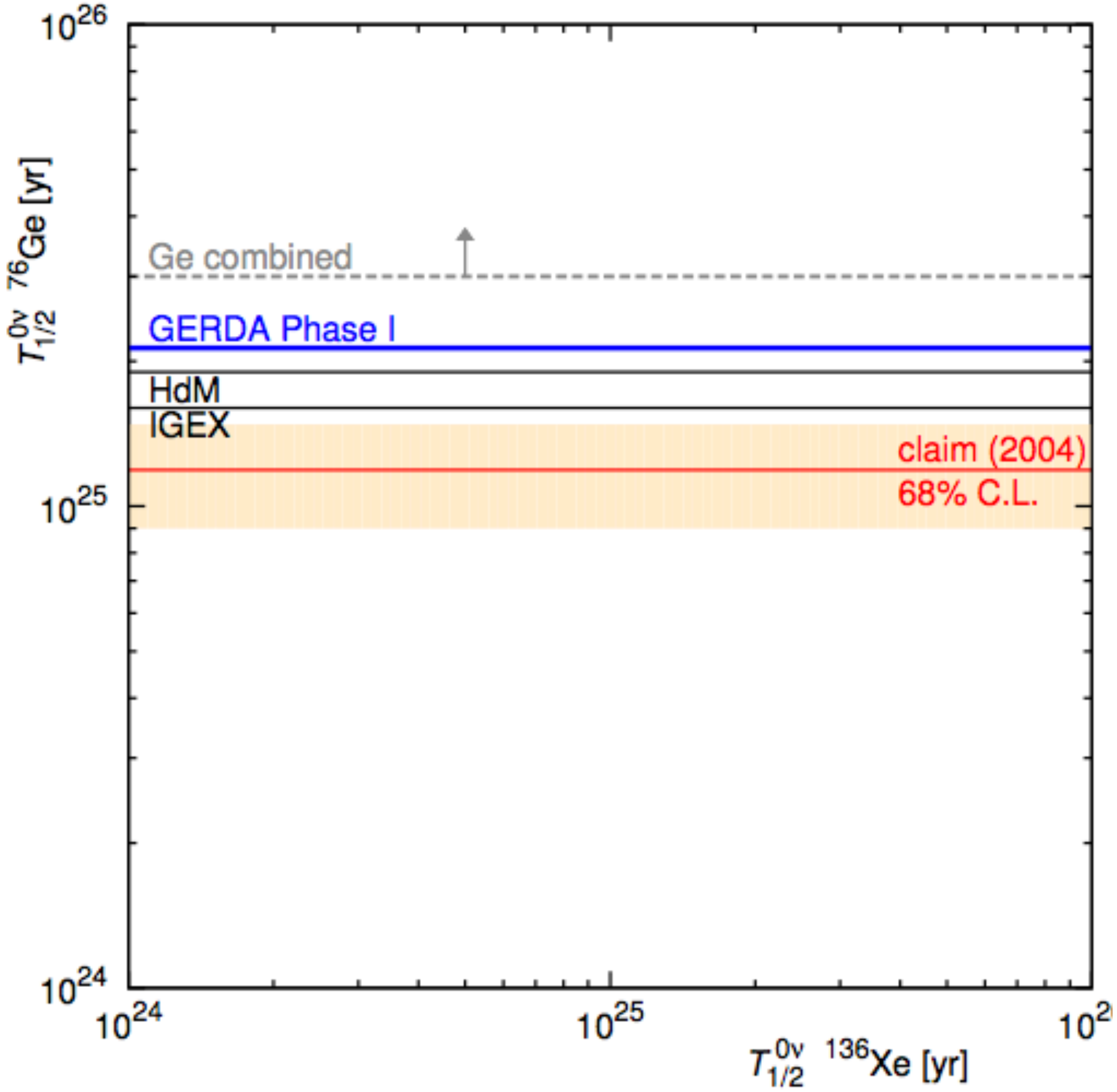
GERDA:
- much lower BI
- no unknown nuclear lines
- remaining flat background in ROI

GERDA upper limit from PL fit:
< 3.5 events (90%CL)

for the KK claim GERDA is expected to see (2σ):
5.9 $\pm$ 1.4 signal counts
2.0 $\pm$ 0.3 background counts

→ probability for a fluctuation 1%

Combination of Ge Results



Combination of

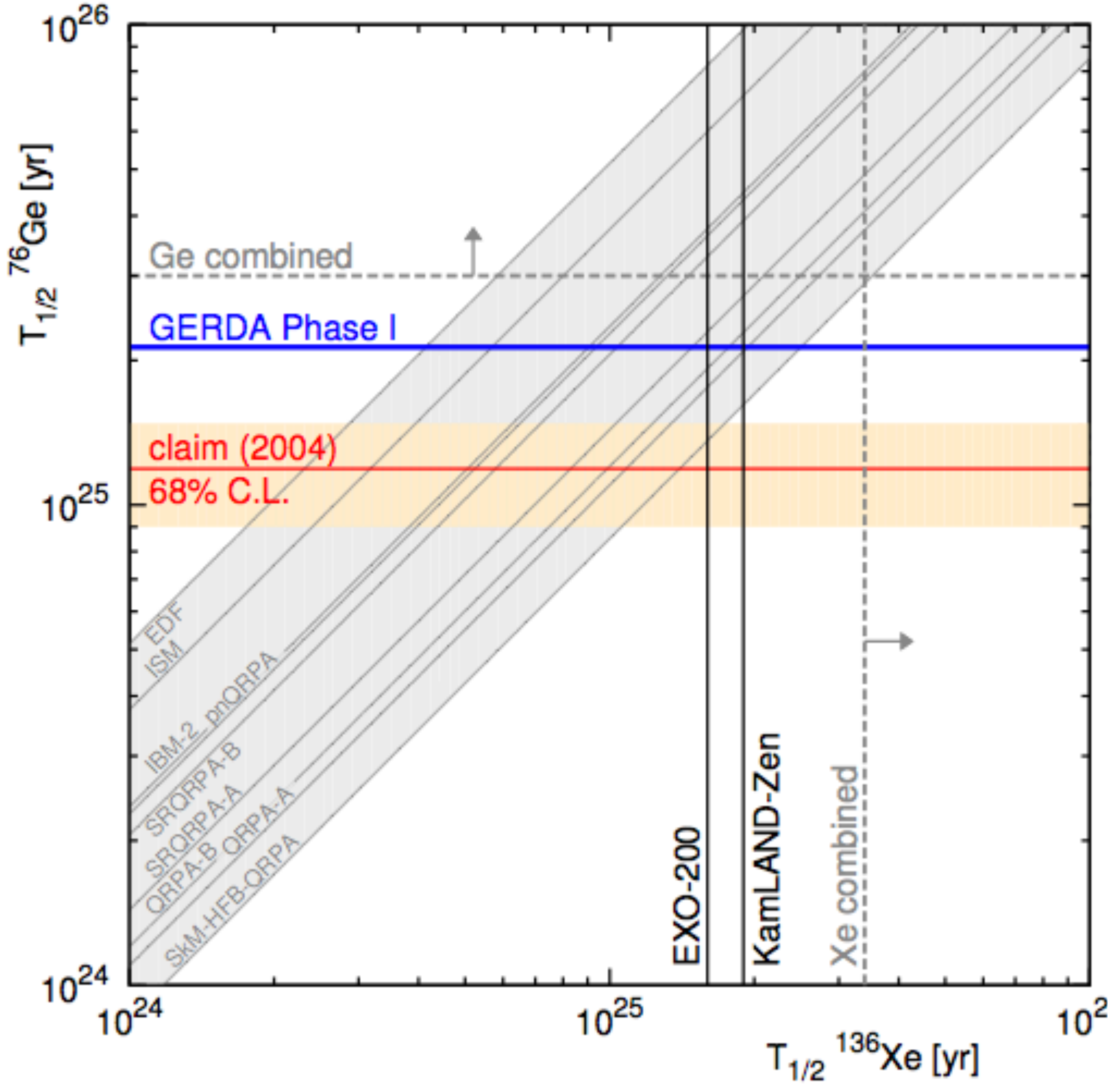
- GERDA phase I
- HdM
- IGEX

➔ PL fit to combined data
➔ backgrounds =free paramaters
➔ Best fit for $N^{0\nu} = 0$

➔ Limit:
$T_{1/2}(0\nu\beta\beta) > 3.0 \cdot 10^{25}$ yr(90% CL)

➔ claim strongly disfavoured
Bayes factor $2 \cdot 10^{-4}$

Comparison with Xenon Results



Assumptions:
- exchange of Majorana neutrinos
- NME ratios better known

→ NME ratio has spread !
→ at best one is right
→ model dependence

Bayes factors:
EXO: 0.23
KamLAND-Zen: 0.40

All with GERDA: 0.0022

➔ **claim even more disfavoured**

NME's: Relating Lifetimes & Neutrino Masses

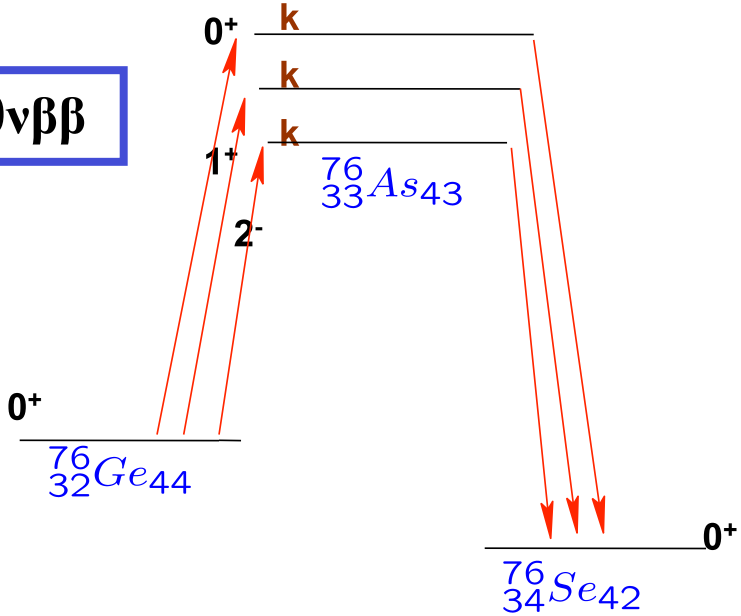
phase space — nuclear matrix elements — effectiveMajorana neutrino mass

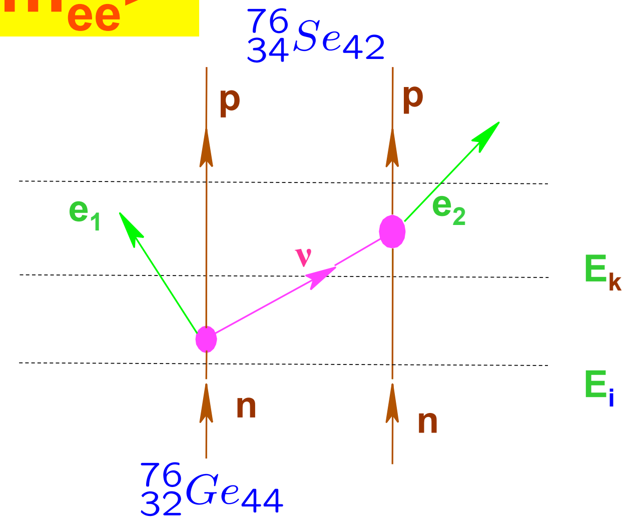
rate of $0\nu\beta\beta$ $$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \langle m_{ee}\rangle^2$$

nuclear matrix elements:

➔ virtual excitations of intermediate states

0νββ





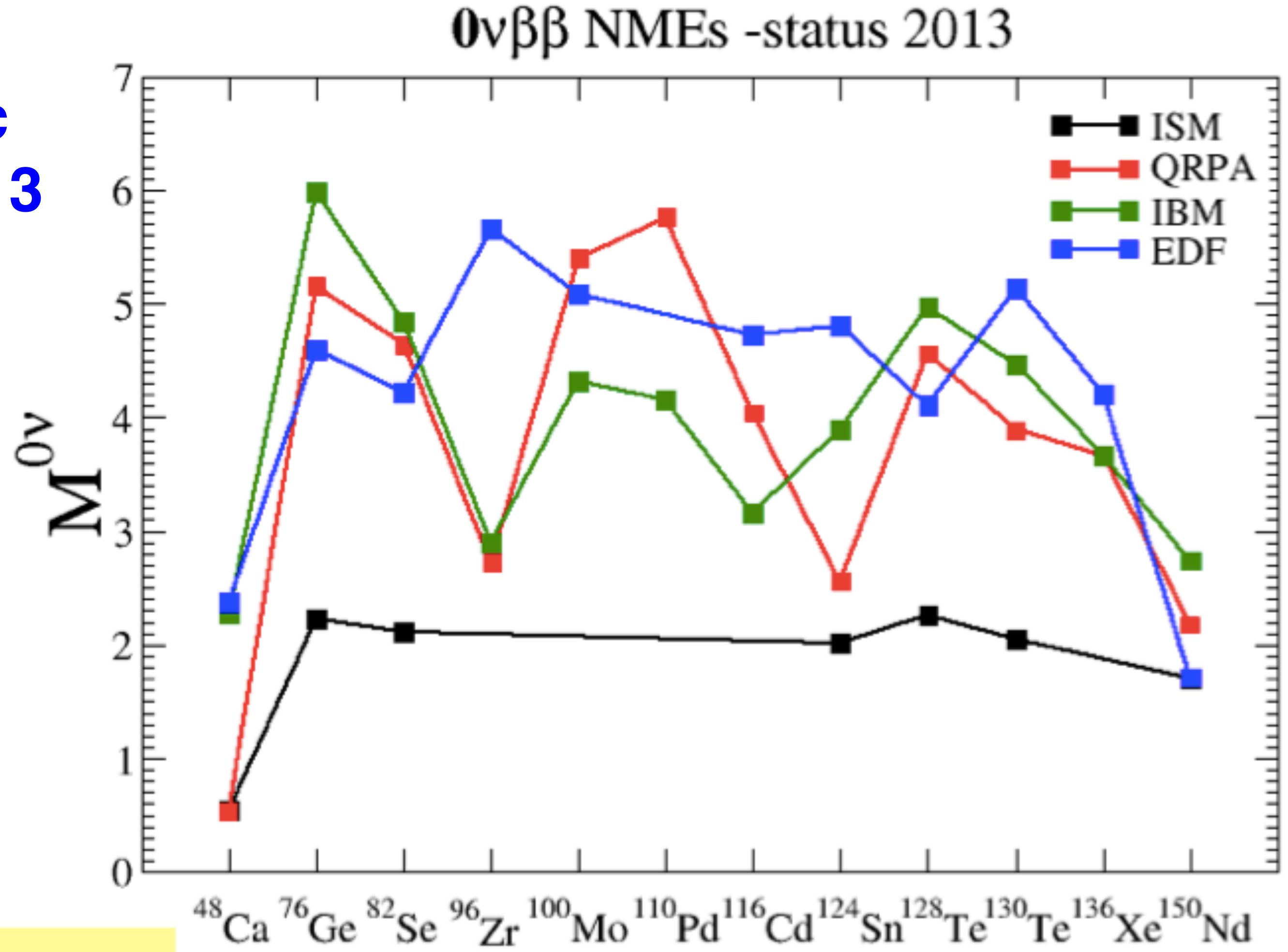
in recent years:
good progress in TH errors

➔ reduced uncertainties
➔ which NME is correct?
➔ what is a 1σ theory error?

The 0νββ-decay NMEs (Status:2013)

Nobody is perfect:

Simkovic
Erice 2013

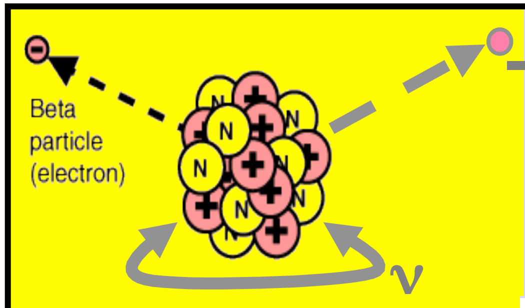


g_A=1.25(7), CCm or UCOM s.r.c., r_0=1.20 fm

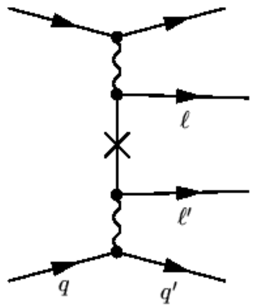
Differences:
i) mean field;
ii) residual int.;
iii) size of the m.s.
iv) many-body appr.

LSSM (small m.s., negative parity states)
PHFB (GT force neglected)
IBM (Hamiltonian truncated)
(R)QRPA (g.s. correlations not accurate enough)

m_{ee}: The Effective Neutrino Mass



Majorana ν ➔ 0ν2β decay

$\propto$ 

$\propto |\langle m_{ee} \rangle| = |\sum m_i U_{ei}^2|$ $\leq$ **0.35 eV ?**

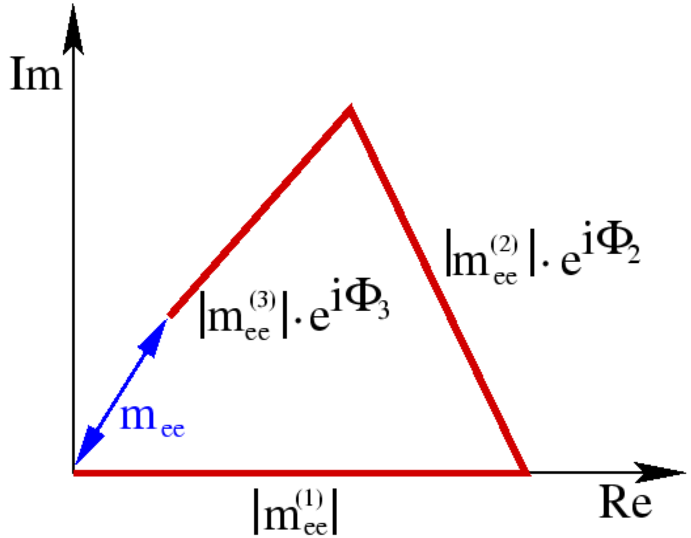
Heidelberg-Moscow experiment

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$

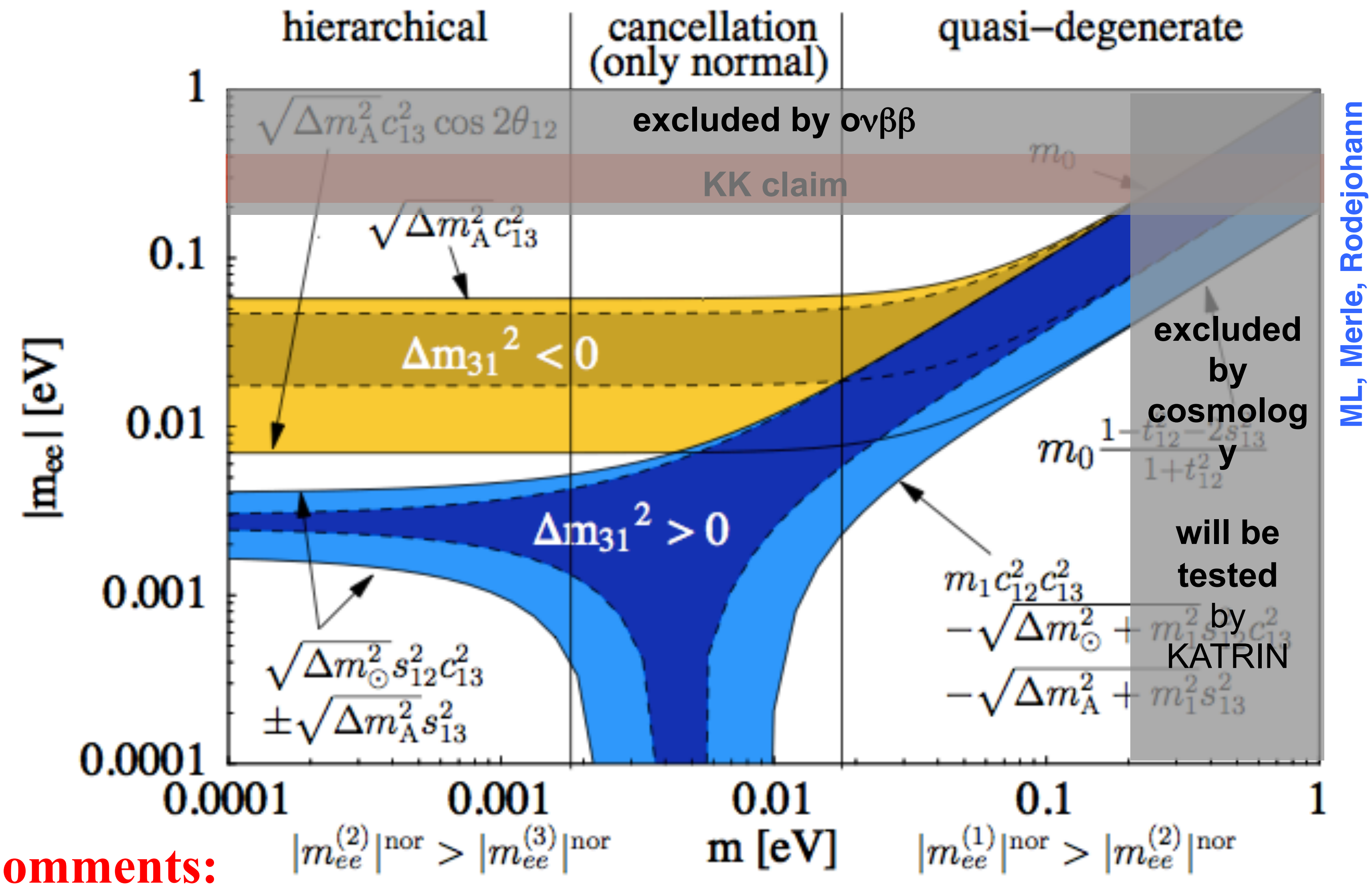
$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

➔ **free parameters: m_1, sign(Δm_{31}^2), CP-phases Φ_2, Φ_3**



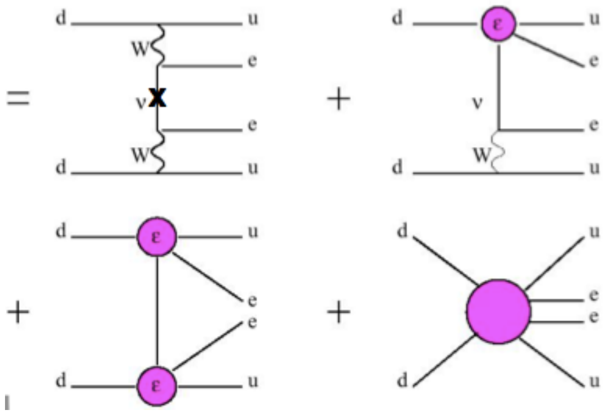
Comments:

- cosmology: further improvements ←→ systematical errors
- NMEs➔ unavoidable theory error in m_{ee}
- assumptions: no *other* $\Delta L=2$ physics, no sterile neutrinos, ...

Interferences in 0νββ Decays

Usually
$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left(\frac{|m_{0\nu\beta\beta}|}{m_e}\right)^2 |\mathcal{M}^{0\nu}|^2 G^{0\nu}.$$

with interferences



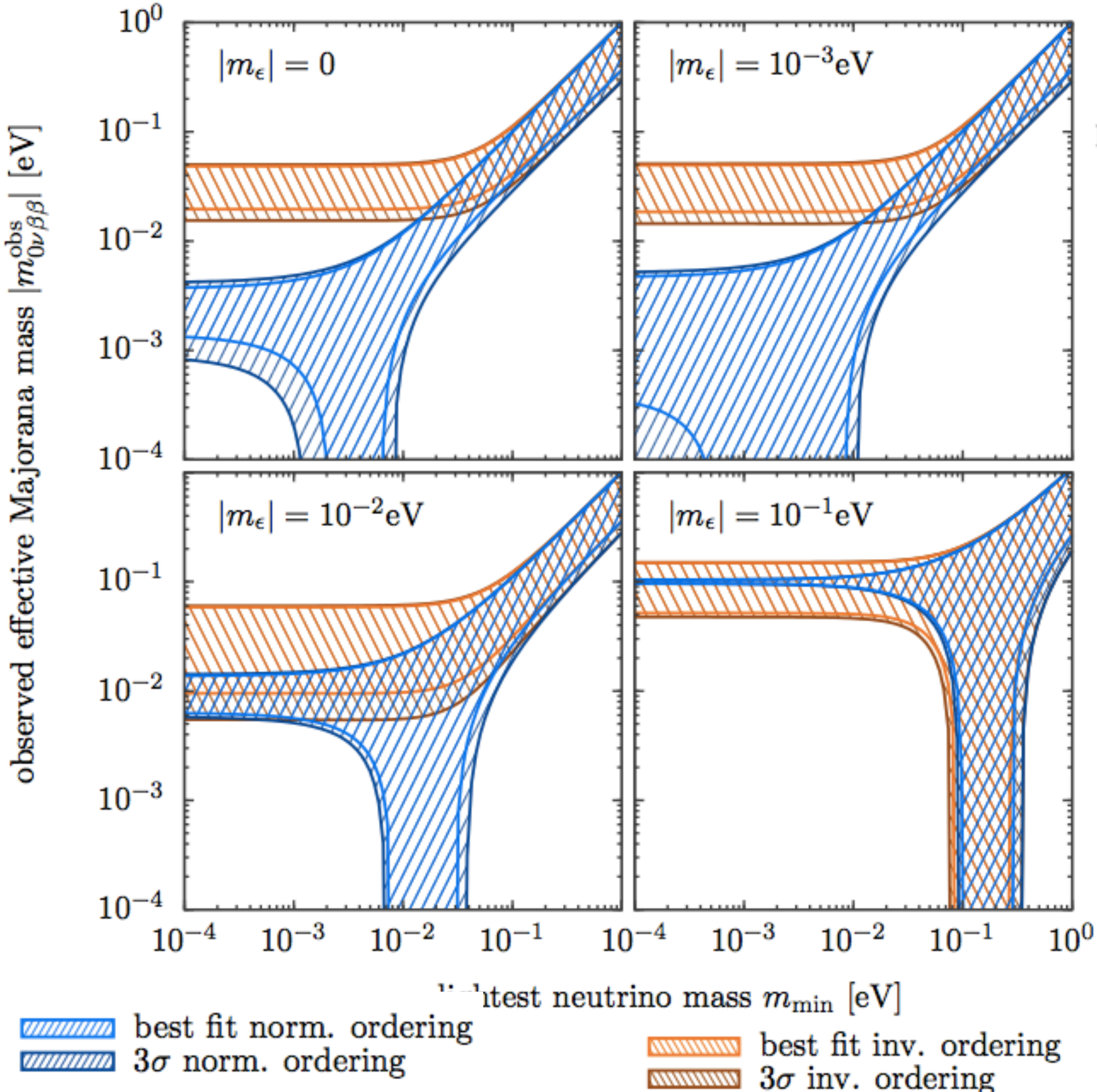
$$\begin{aligned}\left(T_{1/2}^{0\nu}\right)^{-1} &= |m_{0\nu\beta\beta}\mathcal{M}^{0\nu} + \epsilon m_e \mathcal{M}^{\epsilon}|^2 \frac{G^{\rm int}}{m_e^2} \\ &= |(m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1})\mathcal{M}^{0\nu}|^2 \frac{G^{\rm int}}{m_e^2} \\ &= |m_{0\nu\beta\beta}^{\rm int}|^2 |\mathcal{M}^{0\nu}|^2 \frac{G^{\rm int}}{m_e^2},\end{aligned}$$

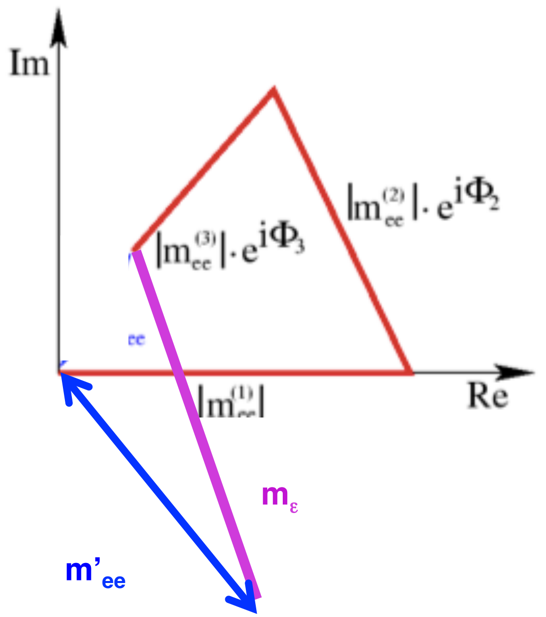
$G^{\rm int}$ = overall phase space factor

$\epsilon m_e \mathcal{M}^{\epsilon}$ ←→ determined by parameters of new physics

$$m_{0\nu\beta\beta}^{\rm int} \equiv m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1} \equiv m_{0\nu\beta\beta} + m_{\epsilon}.$$

Dürr, ML, Neuenfeld





growing m_ε
fixed $0\nu\beta\beta$→ shifts
- **masses**
- **mixings**
- **CP phases**
- **intereferences**

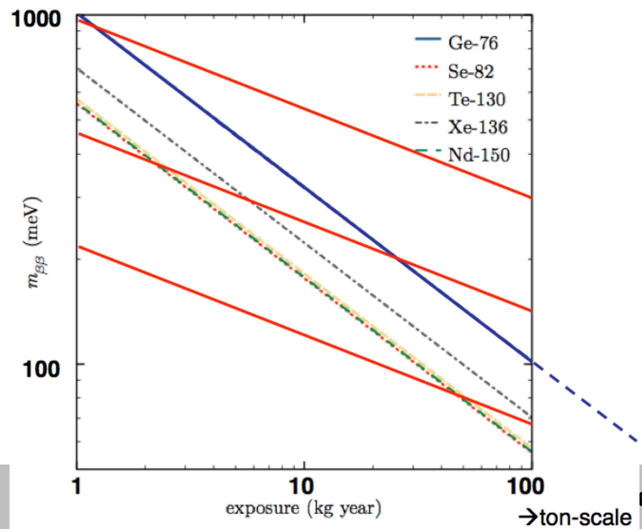
GERDA Outlook

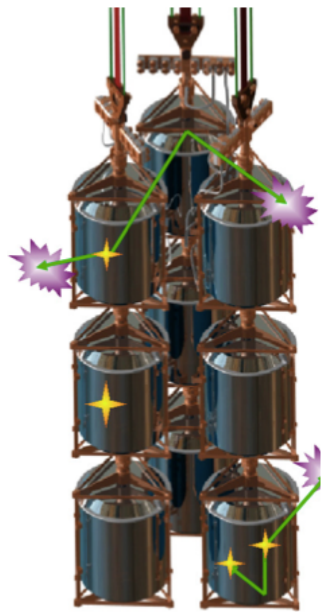
Transition to phase II:

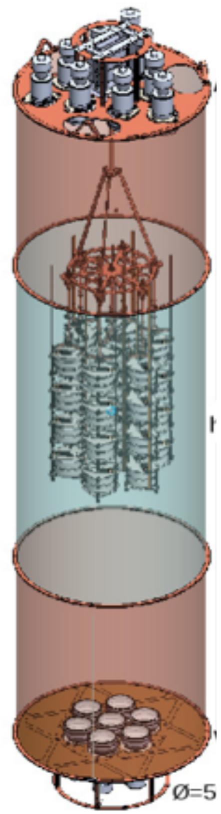
✓ drainage, inspection & refilling of WT

- Installation of more new BEGe detectors
  → ~factor 2 in ^{76}Ge mass
- Installation of light instrumentation
  → fibers and PMTs = anti-Compton veto
  → further reduction of background index
- **Continue data taking with more mass, less BI, longer time, …**

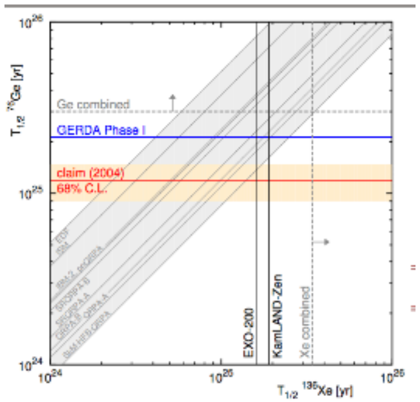
→ ?







Summary



- GERDA has finished phase I data taking with unprecedented BI in ROI
- The background in the GERDA experiment can be explained well & and is flat arounf ROI!
- 3 independent pulse shape discrimination techniques efficiently reduces background
- Half life limit for 0νββ-decay of ^{76}Ge:
  $2.1 \cdot 10^{25}$ yr (90% C.L.)
- Combined with HdM and IGEX:
  $3.0 \cdot 10^{25}$ yr (90% C.L.)
  ➔ HdM claim strongly disfavored!
- Transition to phase II is on-going