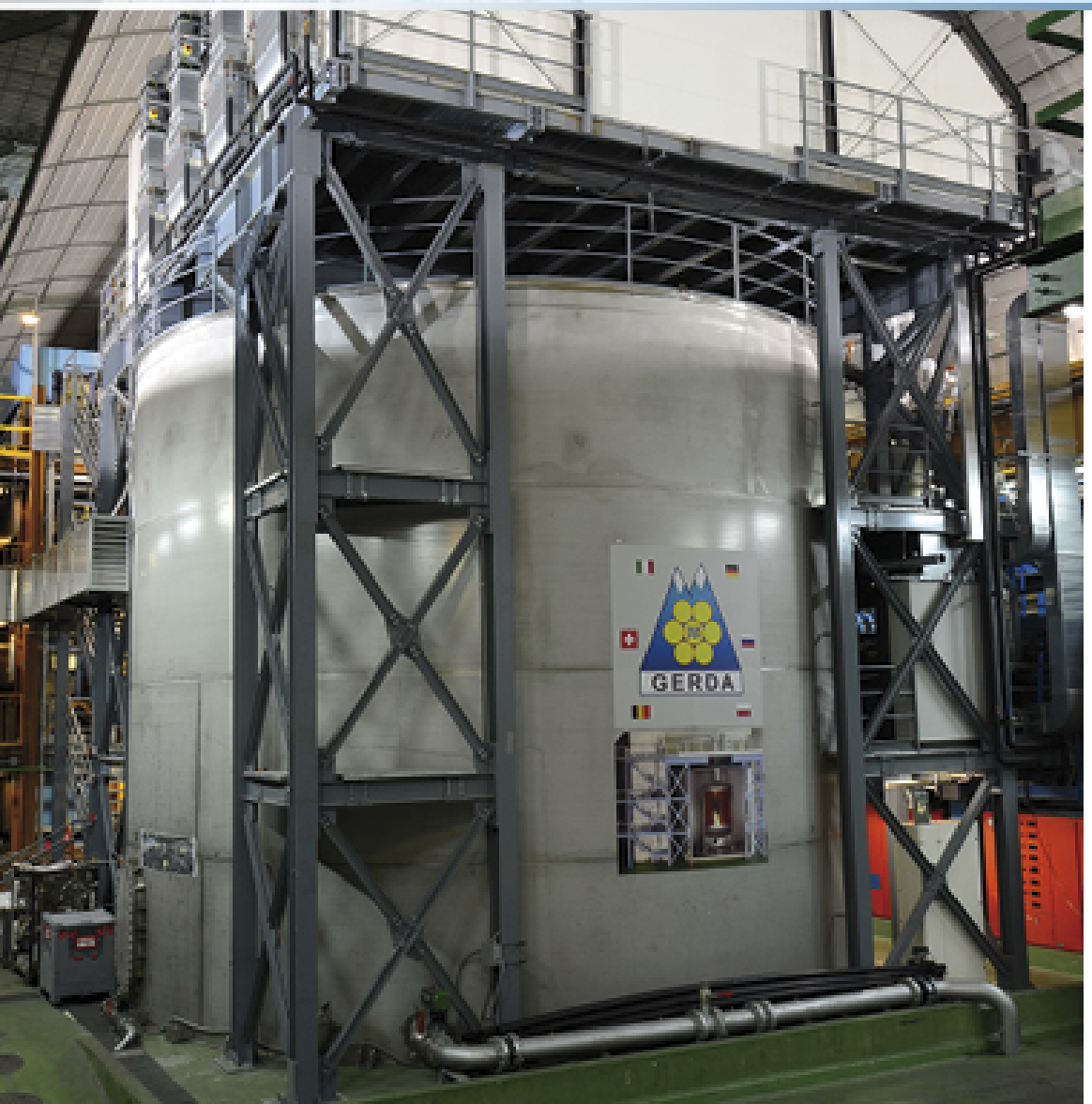
Neutrinoless Double Beta Decay in GERDA



Mark Heisel
for the collaboration

ICNFP2015
23-30 August 2015
Kolymbari, Greece

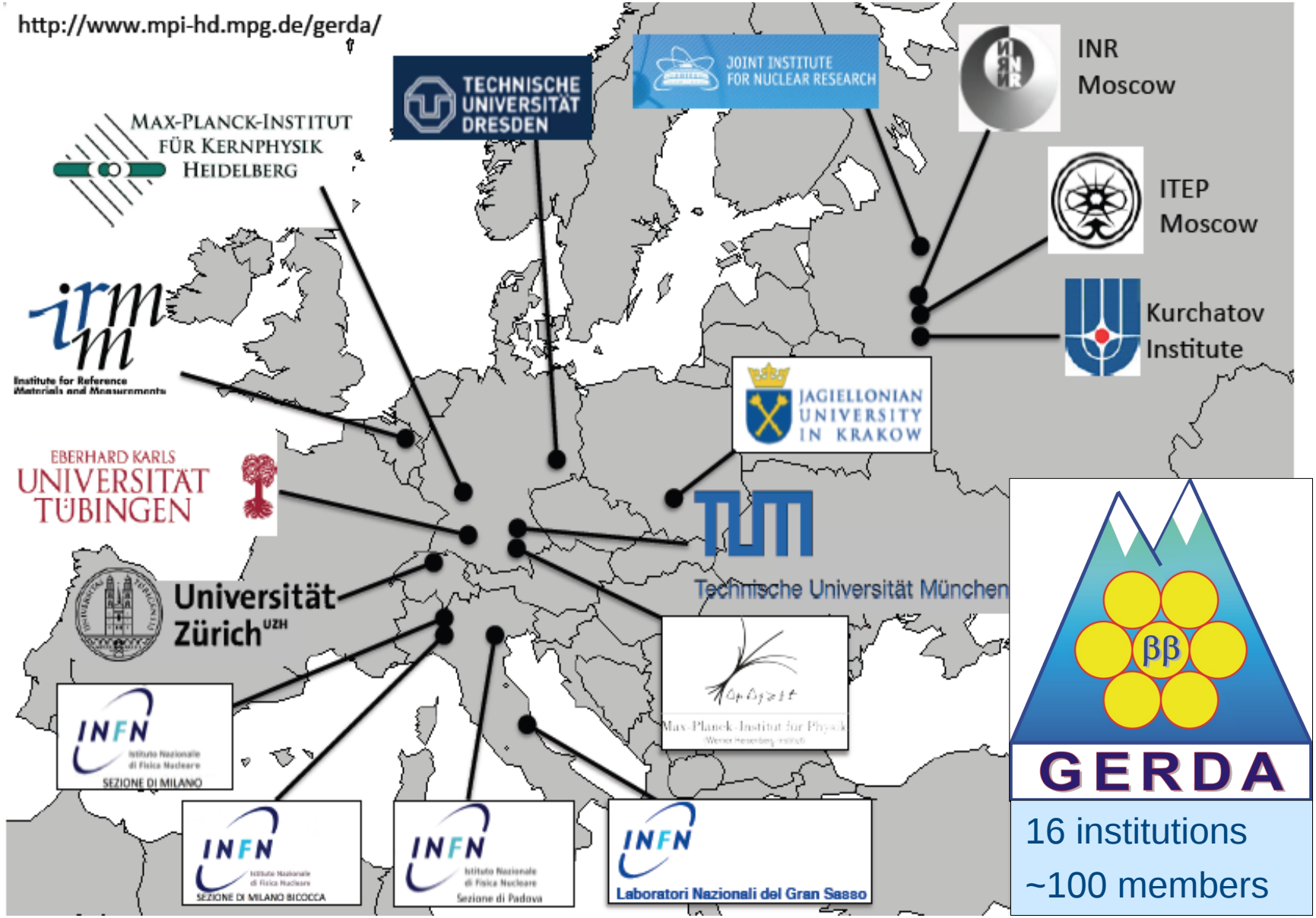
Max-Planck-Institut
für Kernphysik

The collaboration

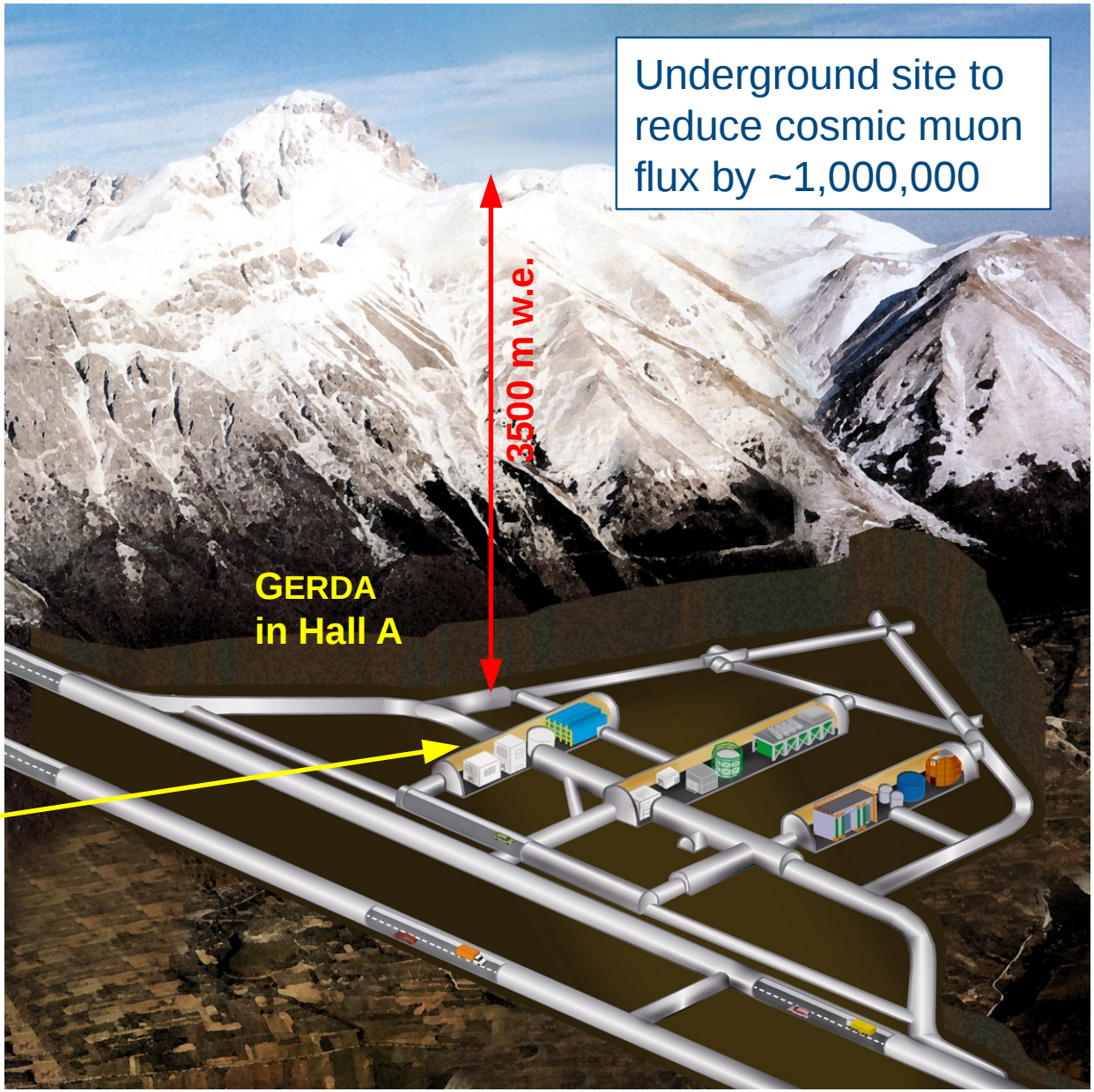
GERDA collaboration Meeting in Heidelberg, 2014

6 countries, 16 institutions, ~100 members

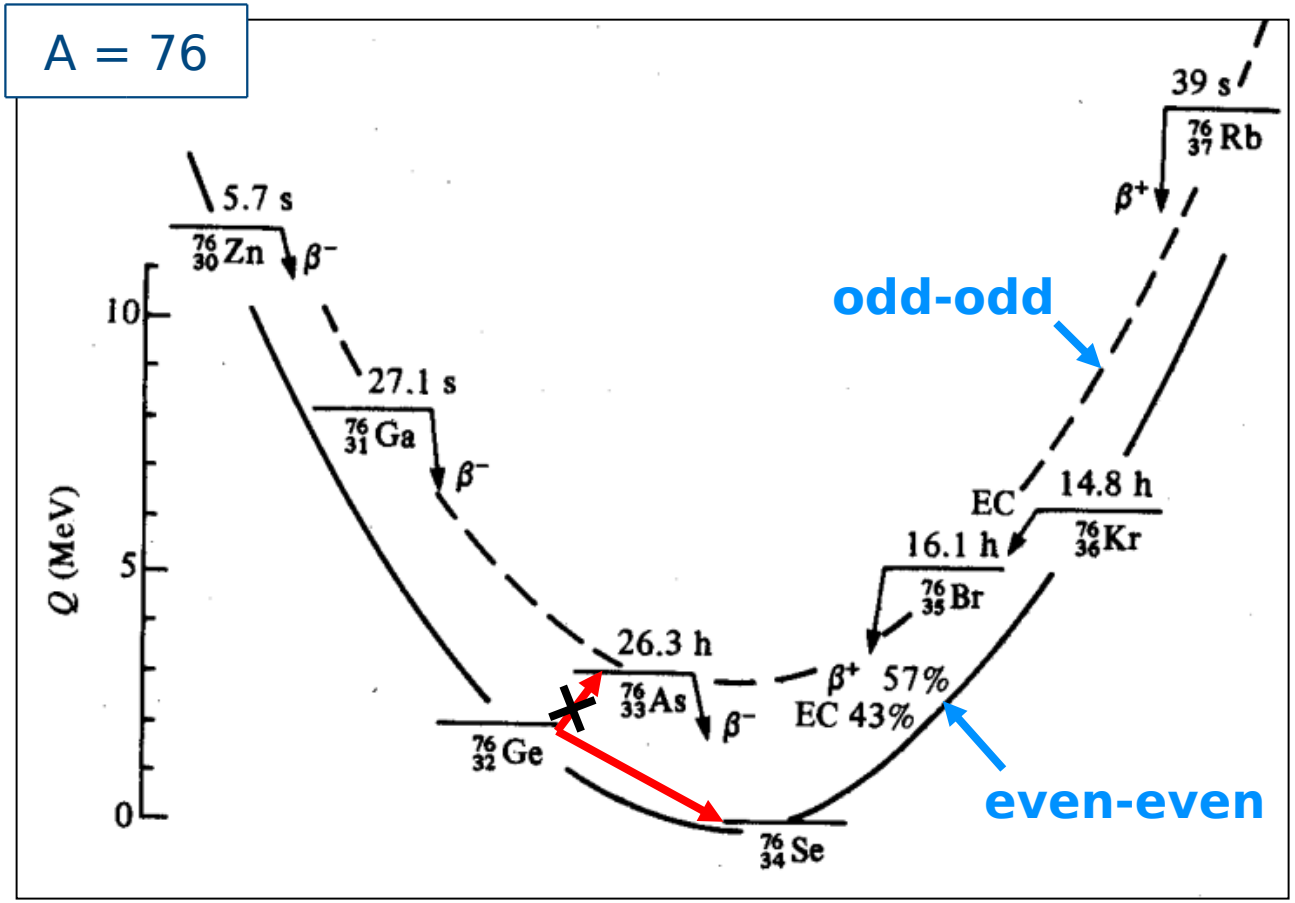
The collaboration



GERDA at Gran Sasso, Italy



Double beta decay



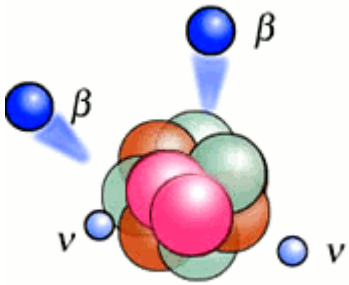
^{76}Ge: $Q_{\beta\beta}$ = (2039.061±0.007) keV

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

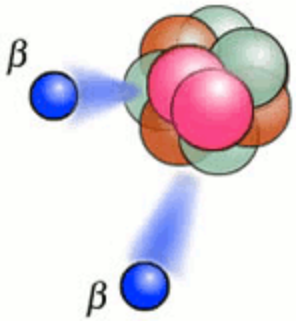
Motivation for 0νββ decay searches

2 neutrino
double beta decay

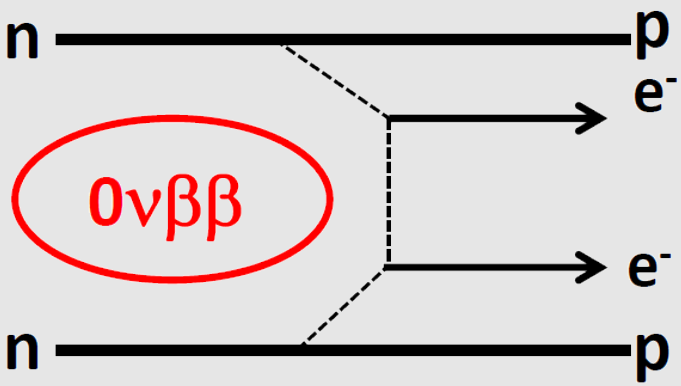


allowed by SM, ΔL = 0

0 neutrino
double beta decay



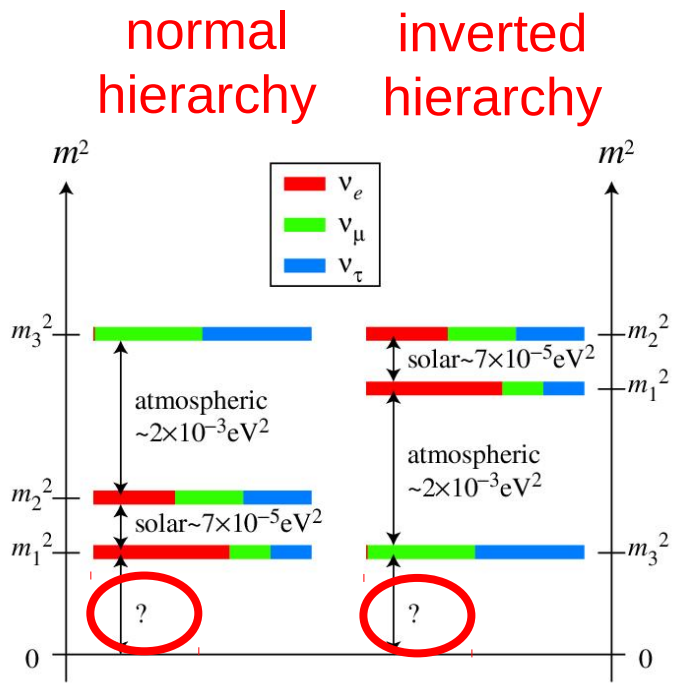
forbidden in SM, ΔL = 2

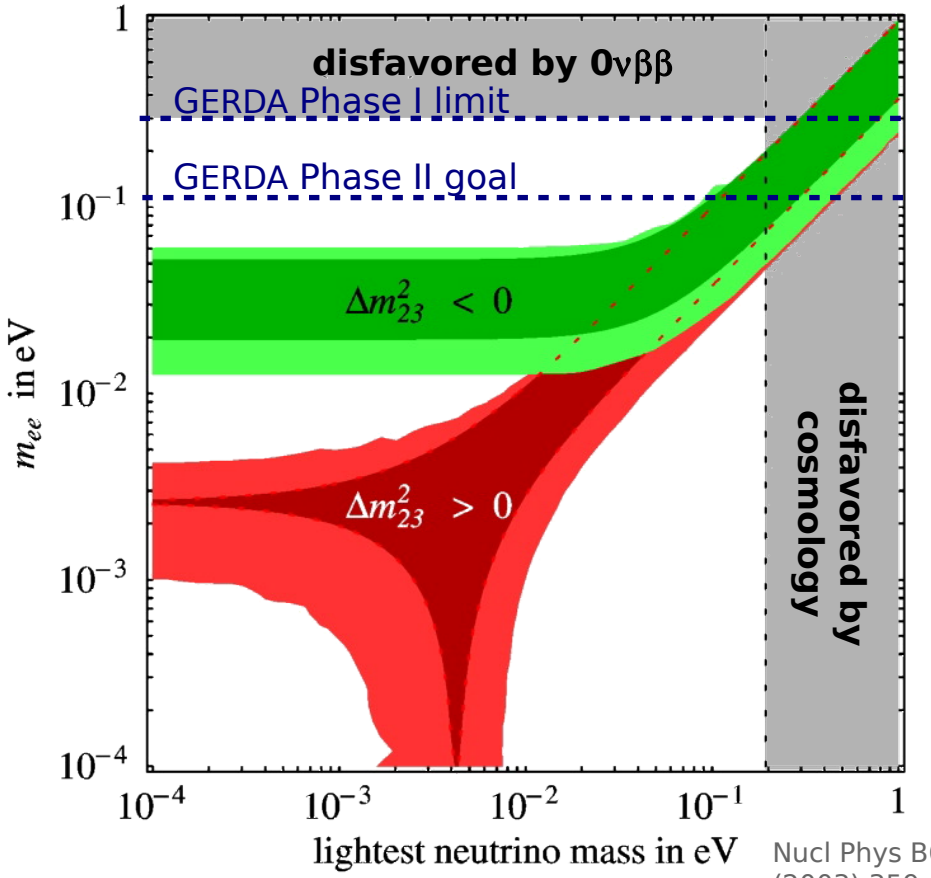


exchange of majorana neutrino

- 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?





Nucl Phys B659 (2003) 359

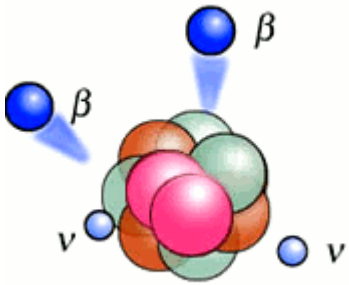
effective electron neutrino mass:

$$|m_{\beta\beta}| \equiv \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$$

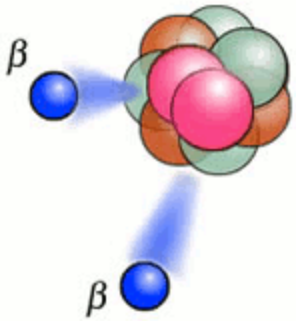
m_i=masses of n mass eigenstates, U_{ei}=elements of neutrino mixing matrix, $e^{2i\alpha,\beta}$ = Majorana CP phases

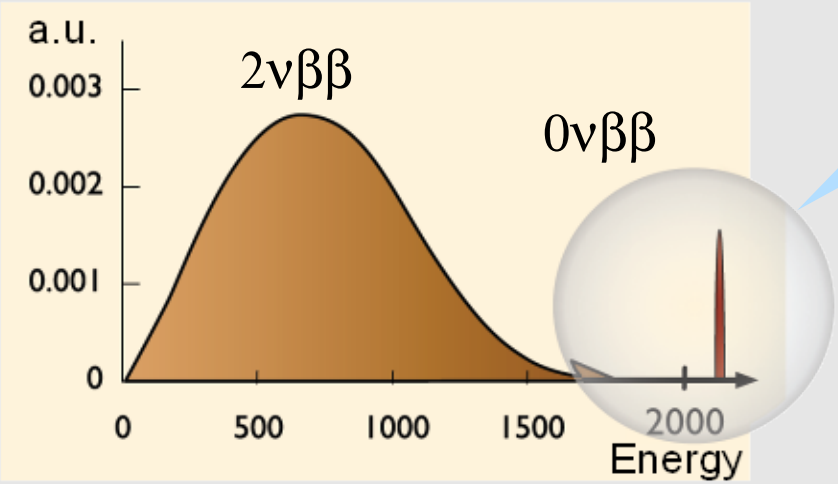
Double Beta Decay detection in ^{76}Ge

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:

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

half life — phase space integral — nuclear matrix element — effective ν mass

Double Beta Decay detection in GERDA

Sensitivity:

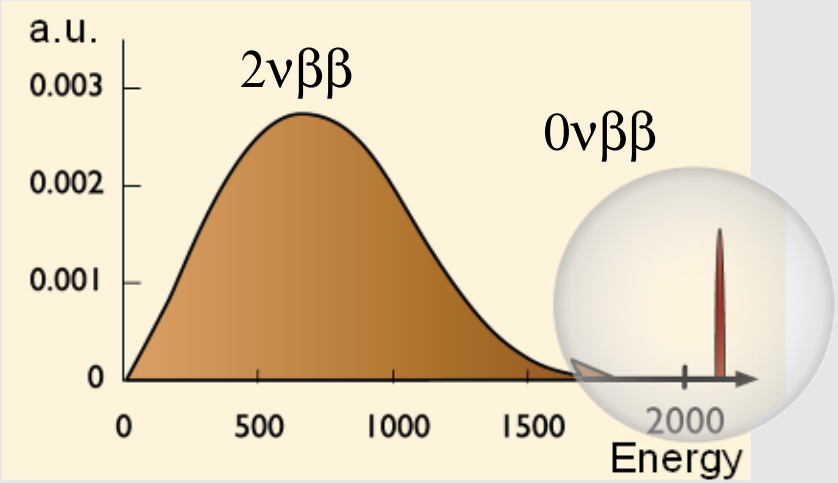
$$T_{1/2}^{0\nu} \sim \epsilon_{eff} \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

M·t = exposure

ε_{eff} = detection efficiency

ΔE = energy resolution

B = background index



electron-energy spectrum

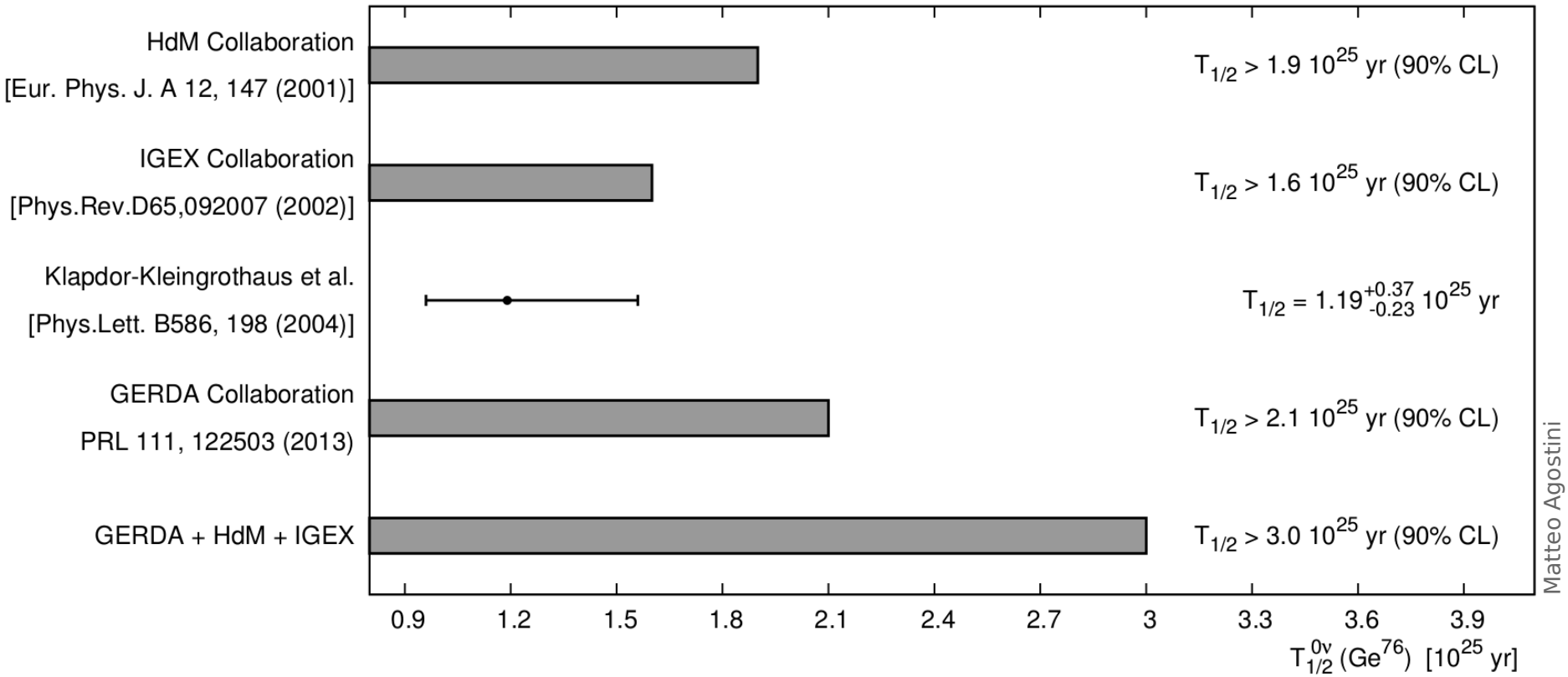
Detector = Source

detectors enriched to 86% ^{76}Ge

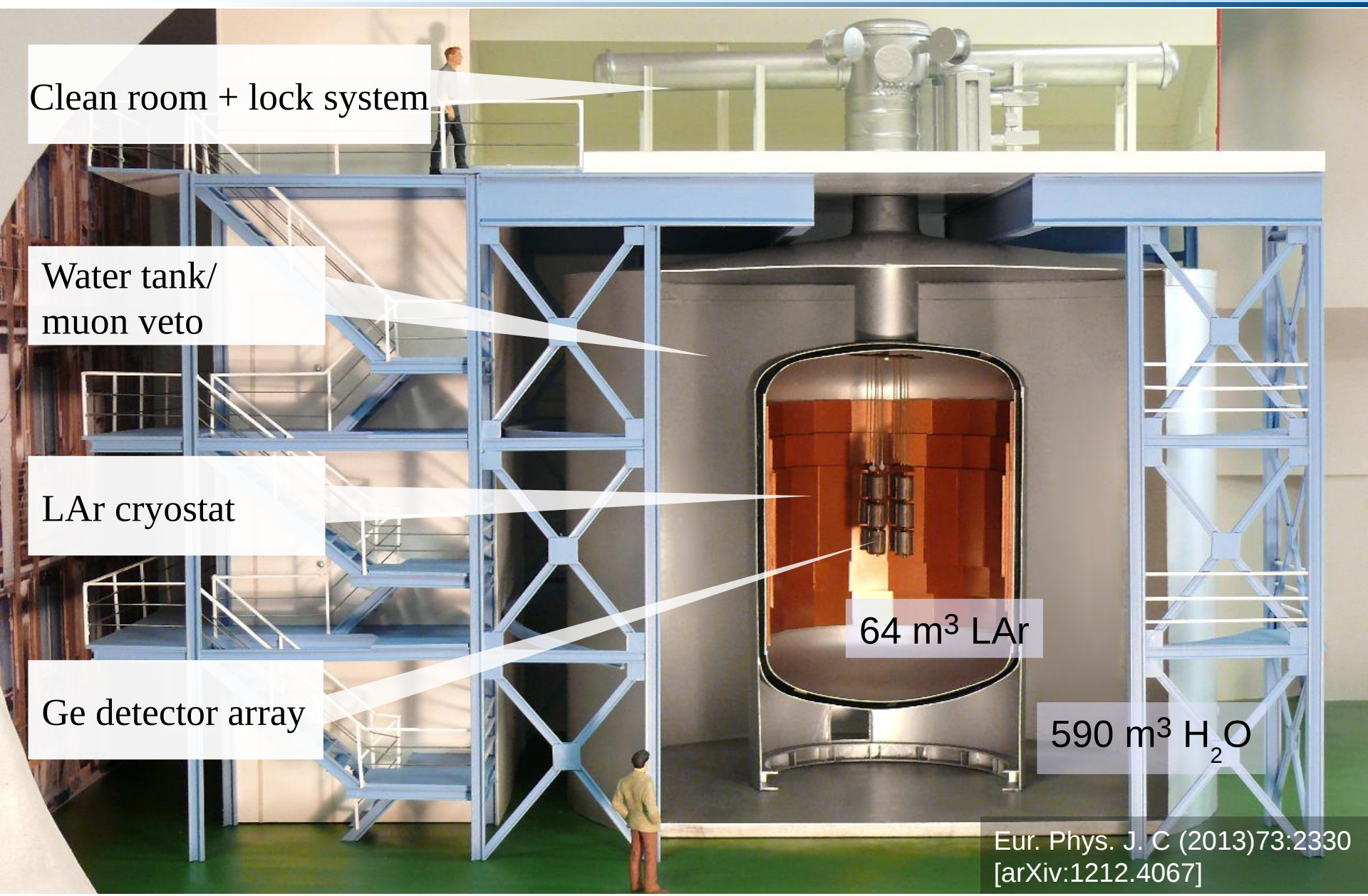
Phase	I	II
Exposure [kg ·yr]	15	100
Bg [counts/(keV·kg·yr)]	10^{-2}	10^{-3}
Upper limit $m_{\beta\beta}$ [eV]	0.23-0.39	0.09-0.15

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

State of the art of $0\nu\beta\beta$ search in ^{76}Ge



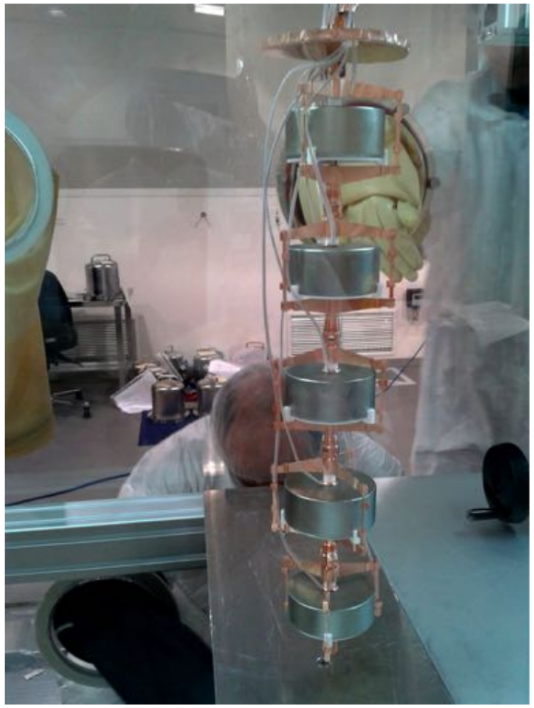
Germanium Detector Array



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

Phase I detector configuration

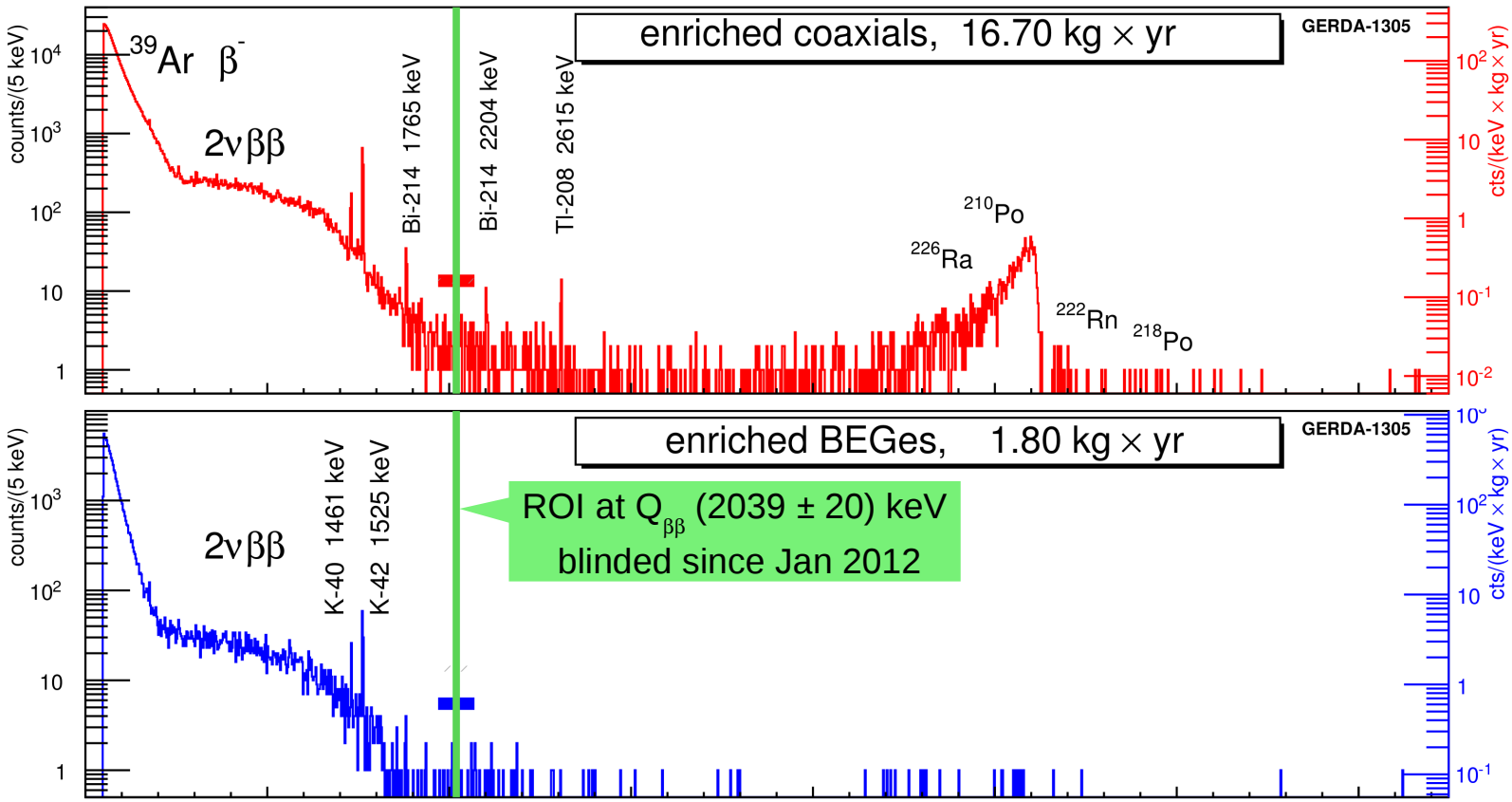




- 3 + 1 detector strings
- 8 ^{enr}Ge coaxial detectors (2 not considered in the analysis)
- 5 ^{enr}Ge BEGe detectors (1 not considered in the analysis)
- 1 ^{enr}Ge natural Ge detector

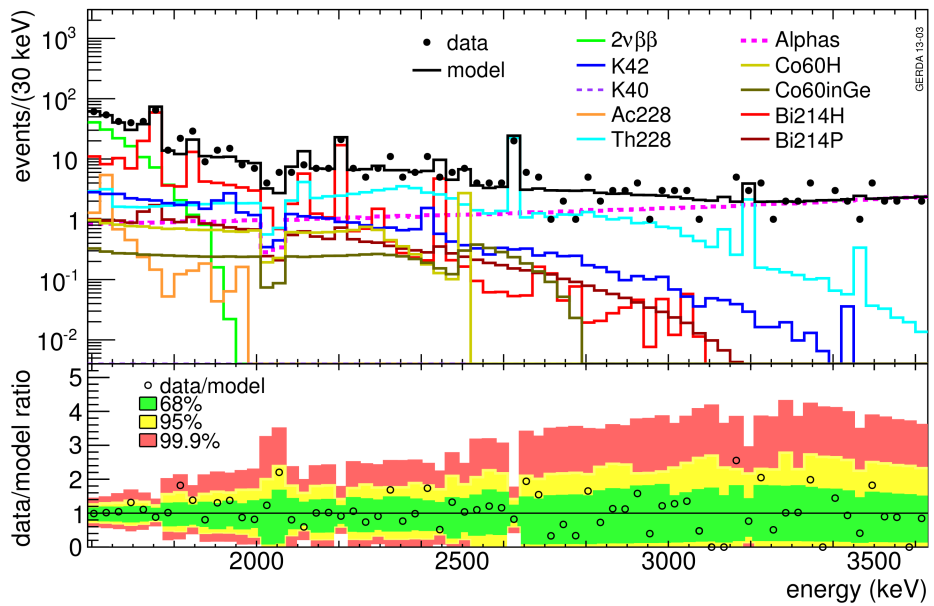
- ^{enr}Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)
- total exposure: 21.6 kg·yr

Phase I background



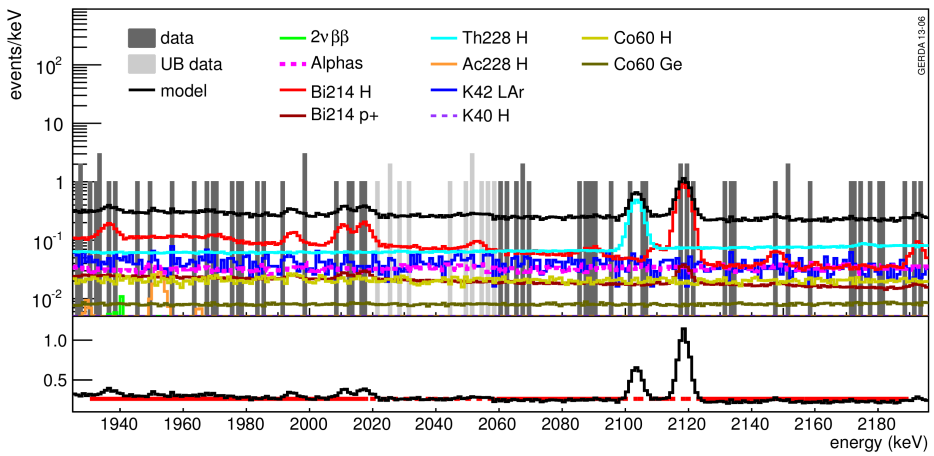
- Dominant background sources: ^{42}Ar, ^{228}Th and ^{226}Ra in detector holder, α on detector surface

Background model & blinding



Background in full energy range:

- fit combined Monte Carlo spectra to data in interval 570 keV – 7500 keV
- simulated known & observed background contributions
- different combinations of position & contribution tested (min/max model)

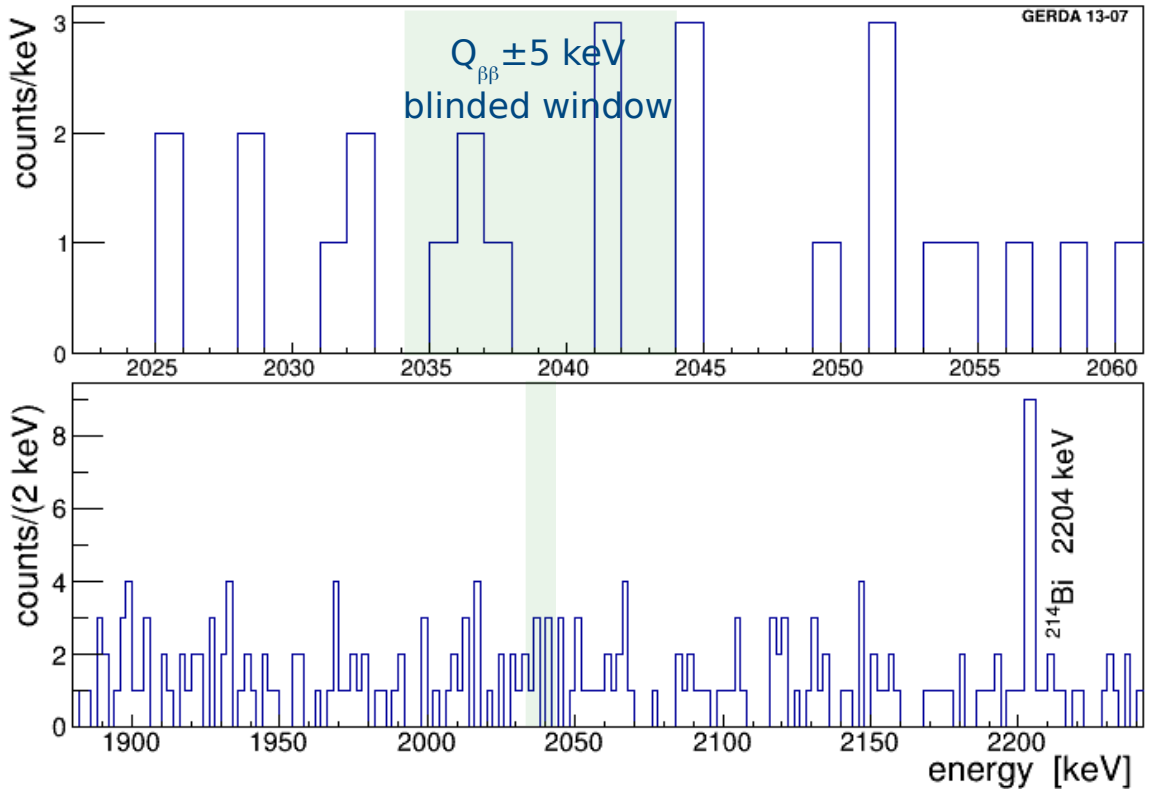


Background in ROI (2039 keV):

- background is flat in 1930-2190 keV (excluding known peaks at 2104 and 2119 keV)
- partial unblinding ($Q_{\beta\beta}$ ± 20 keV) after fixing calibration & background model
- $Q_{\beta\beta}$ ± 5 keV remains blinded for 0νββ analysis

EPJC [arXiv:1306.5084]

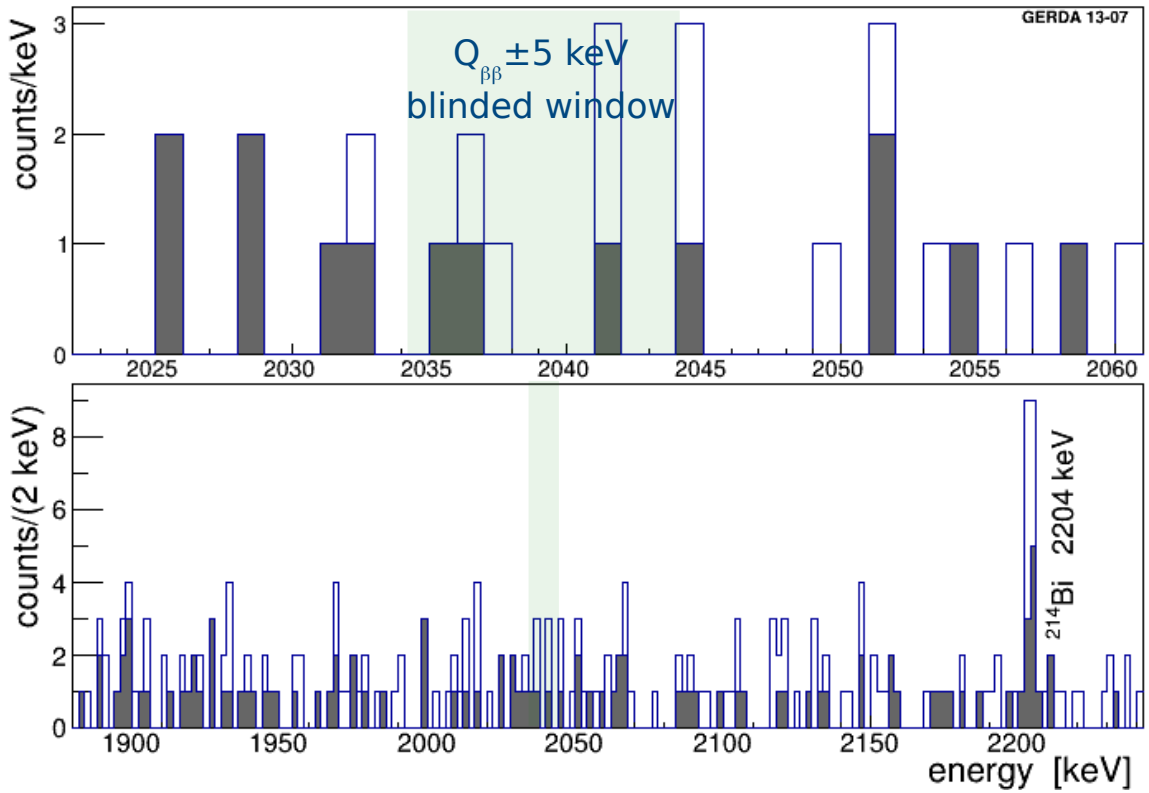
GERDA Phase I result (0νββ)



7	events observed in blinded window
5.1	events expected from background

spectrum around $Q_{\beta\beta}$ (2039 keV) of full data set (21.6 kg·yr)

GERDA Phase I result (0νββ)



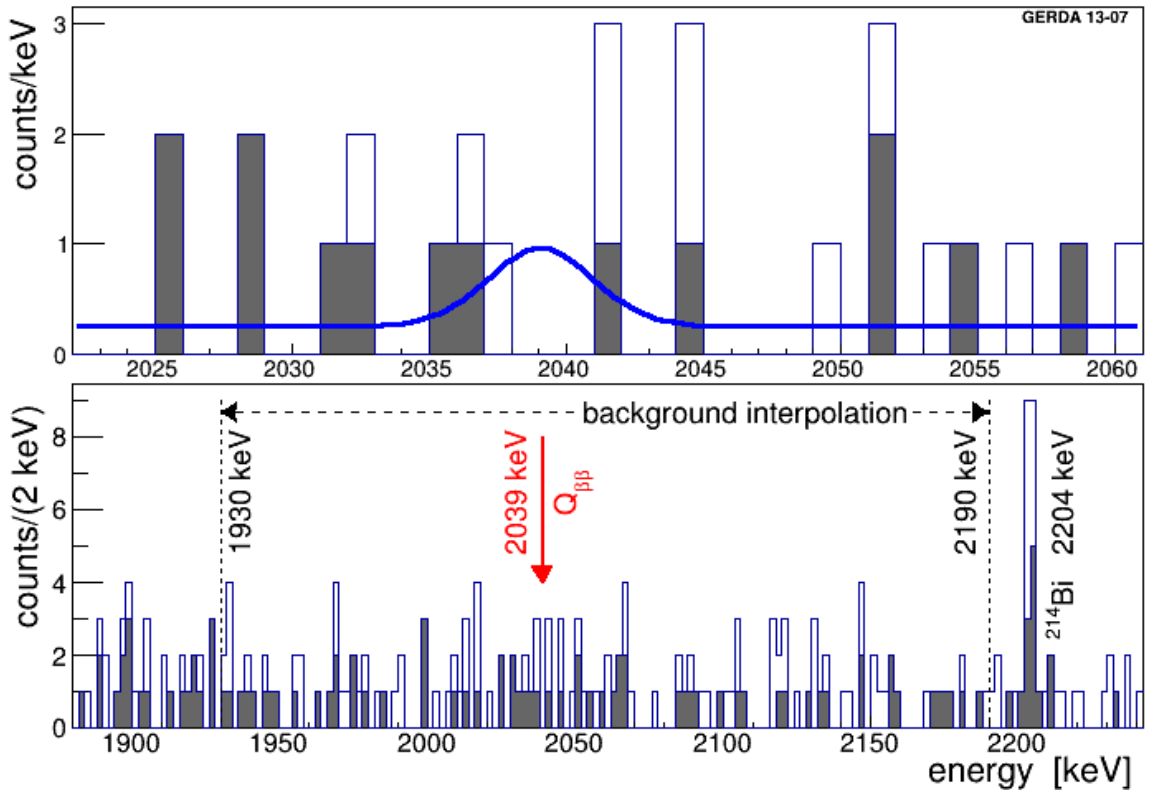
before PSD
after PSD

0ν

3	events observed w/ pulse shape discrimination (PSD)
2.5	events expected from background → BI: ~1 x 10^{-2} cts/(keV·kg·yr)

spectrum around $Q_{\beta\beta}$ (2039 keV) of full data set (21.6 kg·yr)

GERDA Phase I result (0νββ)



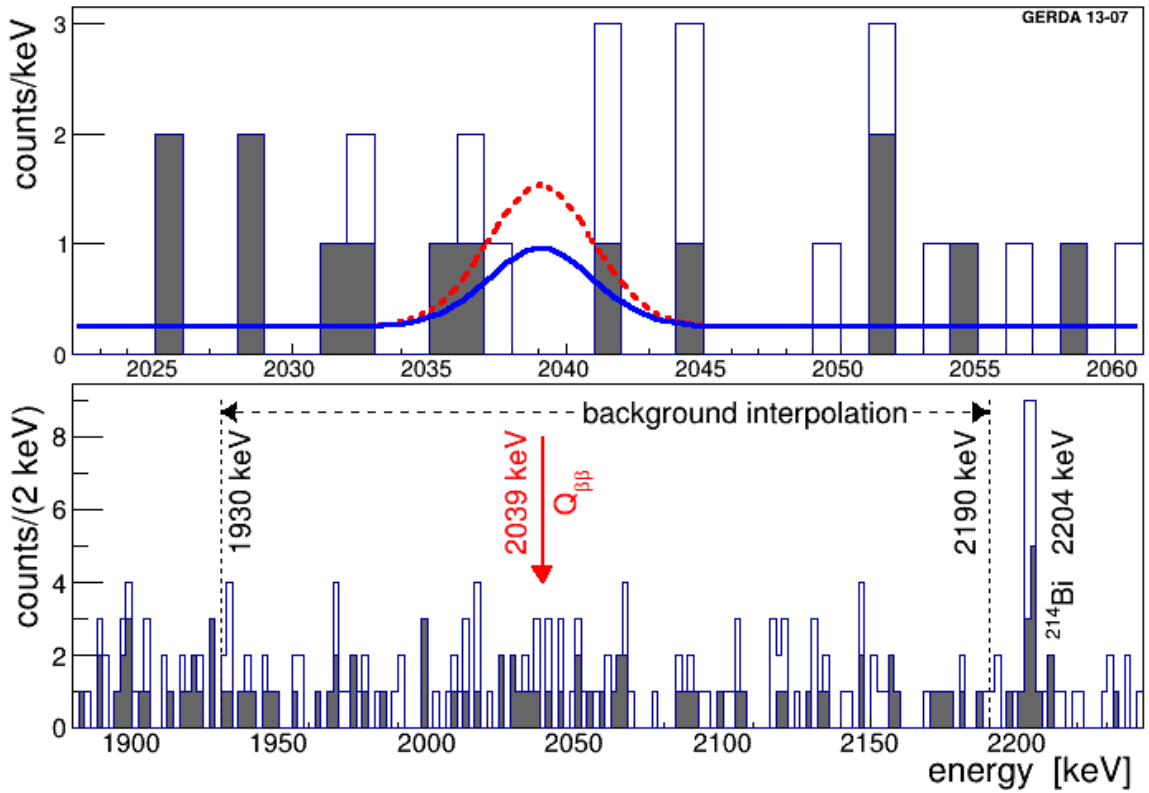
before PSD
after PSD

GERDA: 90% lower limit ($T^{0\nu}_{1/2}$)

[Phys. Rev. Lett. 111 (2013) 122503]

3	events observed w/ PSD	
2.5	events expected from background	→ BI: ~1 x 10^{-2} cts/(keV·kg·yr)
<3	events expected from 0νββ limit (best fit for $N^{0\nu}$=0)	→ profile likelihood fit for 0νββ: $T^{0\nu}_{1/2}$ > 2.1 x 10^{25} yr

GERDA Phase I result (0νββ)



before PSD
after PSD

GERDA: 90% lower limit ($T^{0\nu}_{1/2}$)

[Phys. Rev. Lett. 111 (2013) 122503]

Claim: $T_{1/2} = 1.19\times10^{25}$ yr

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

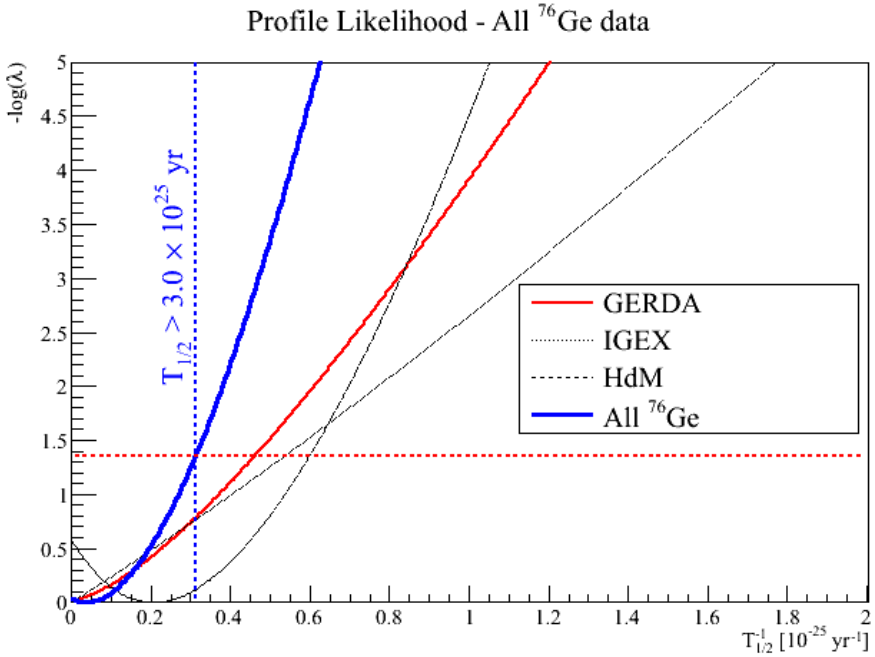
3	events observed w/ PSD	
2.5	events expected from background	→ BI: ~1 x 10^{-2} cts/(keV·kg·yr)
<3	events expected from 0νββ limit (best fit for $N^{0\nu}$=0)	→ profile likelihood fit for 0νββ: $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr
5.9 ± 1.4	events expected from claim (2004)	→ claim is rejected with 99% prob.

Combined ^{76}Ge Results

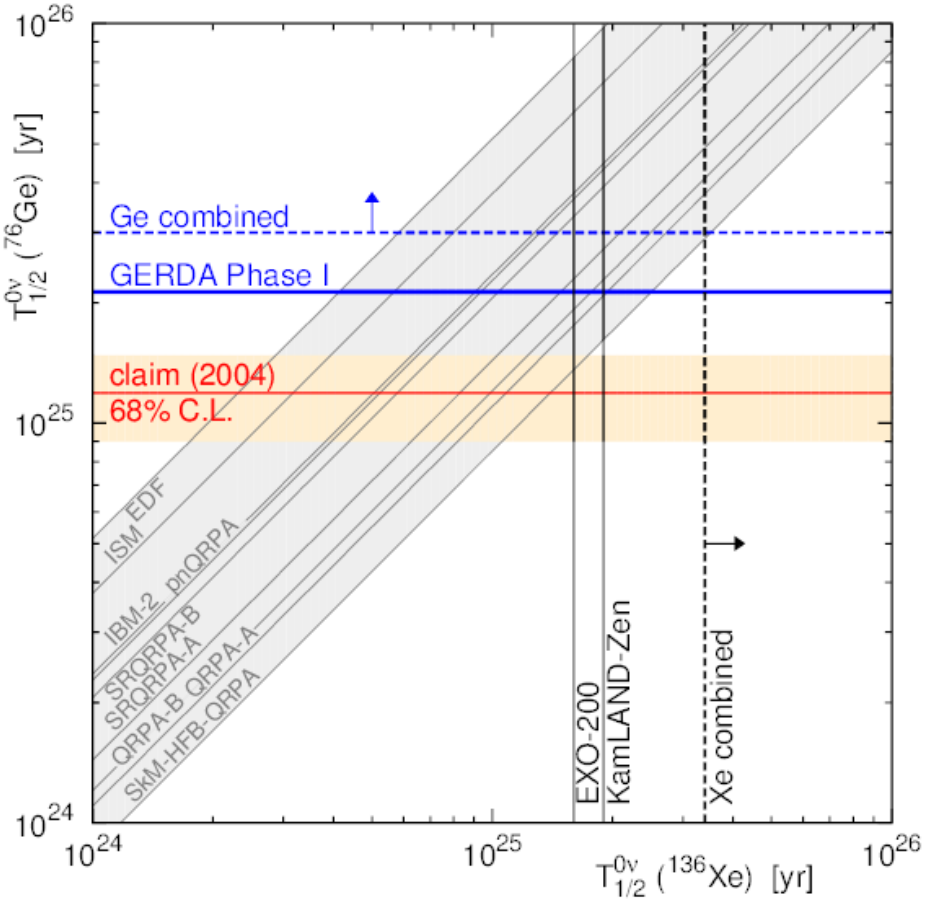
GERDA + HDM[1] + IGEX[2]:

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

more detail in PRL 111, 122503 (2013)

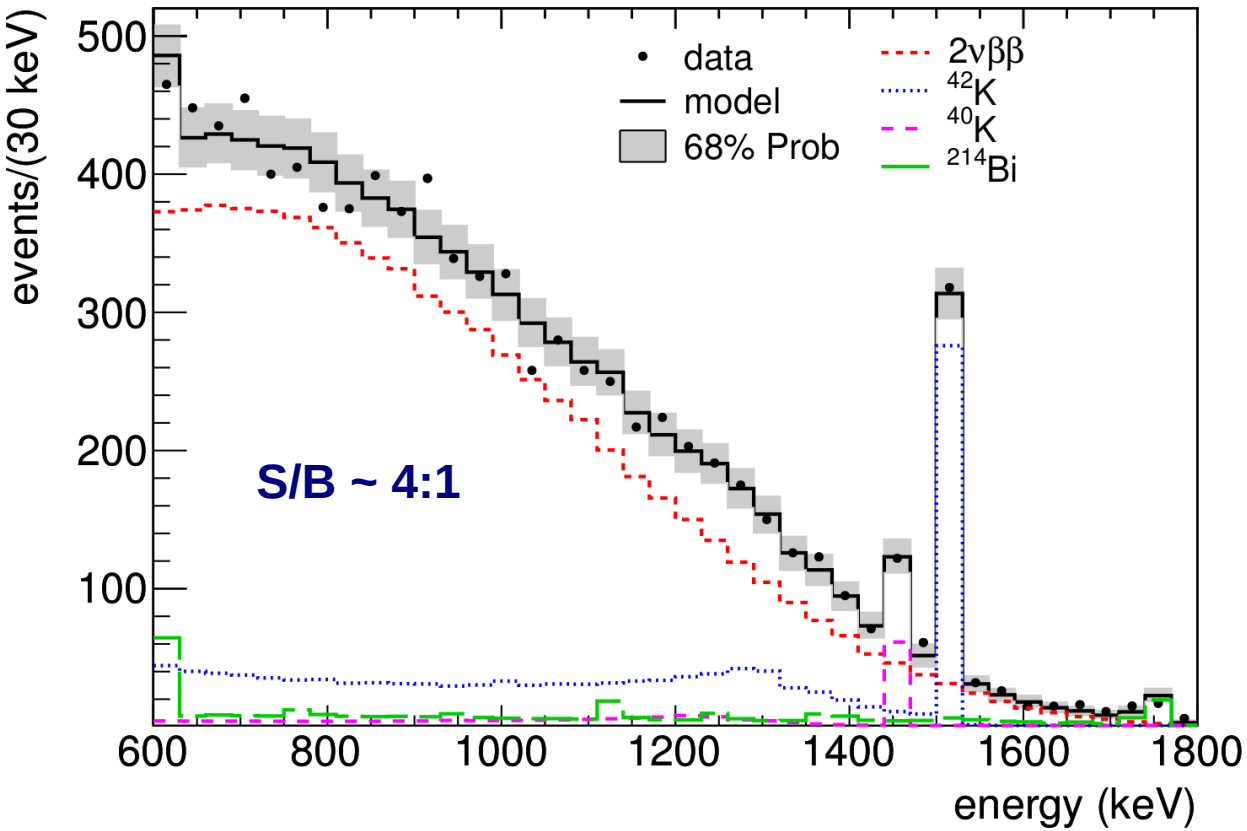


Comparison to results from ^{136}Xe experiments:



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

GERDA Phase I result (2νββ)



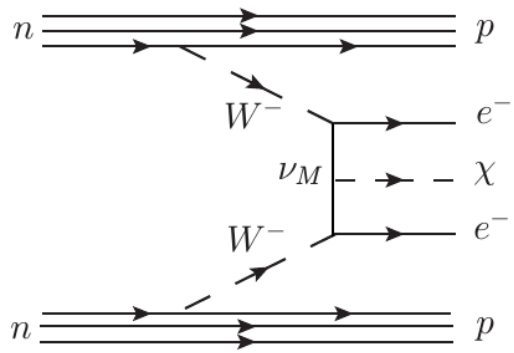
- updated analysis using 20.3 kg·yr coaxial/BEGe detectors

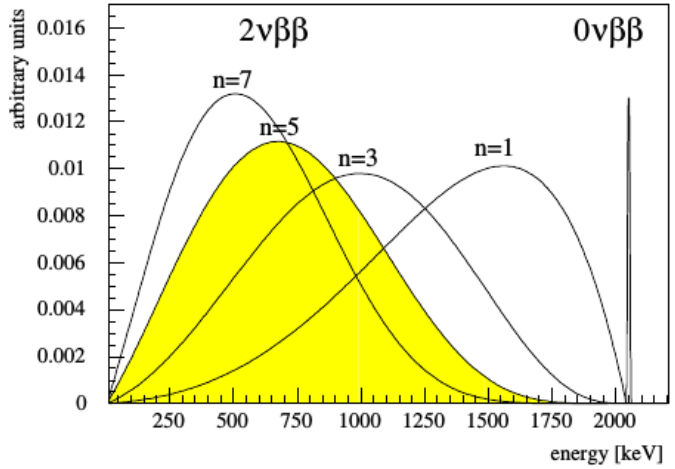
- measured 2νββ half life: $T^{2\nu}_{1/2} = (1.926 \pm 0.095) \cdot 10^{21}$ yr

[Eur. Phys. J. Plus (2015) 130: 139]

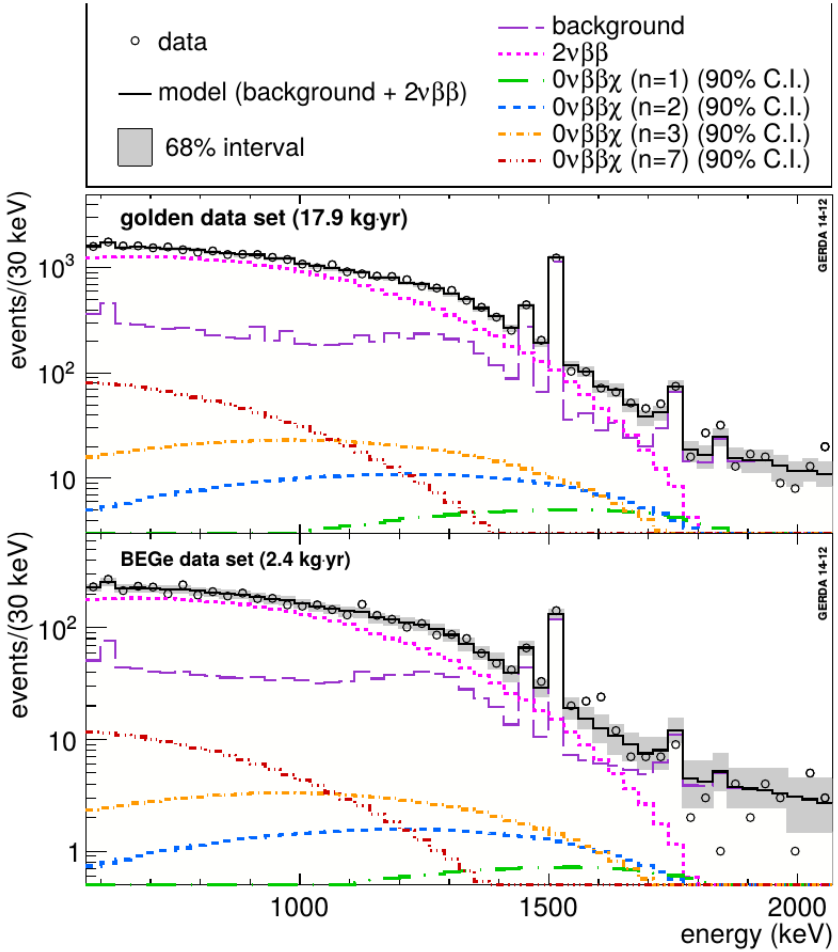
Results on Majoron emission

- search for 0νββ decay with Majoron(s) emission performed for spectral index n = 1, 2, 3, 7
- No signal found, limits of O(10^{23}) yr on half-lives





[Acta Phys. Polon. B **37** (2006) 1905]

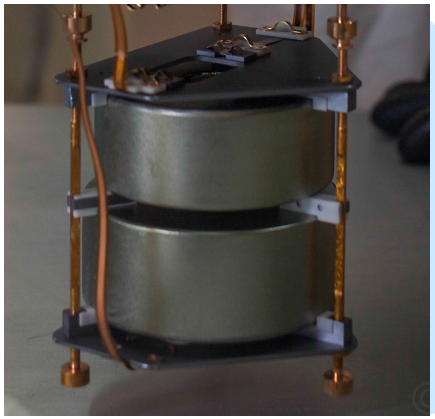


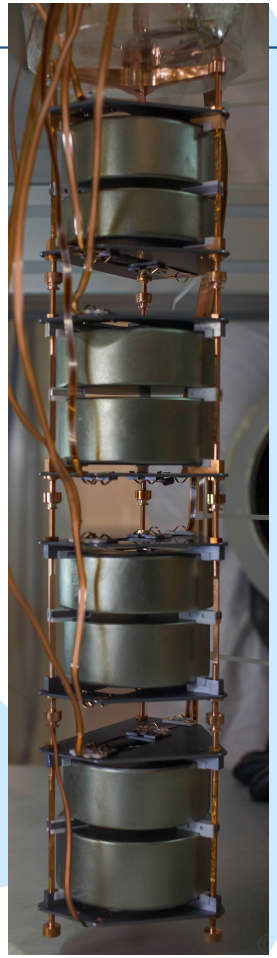
[Eur. Phys. J. Plus (2015) 130: 139]

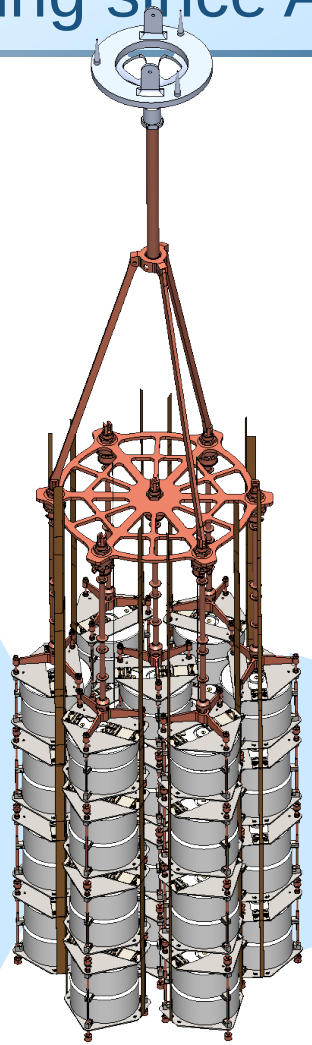
Phase II upgrade – commissioning since April '15

Additional 25 new BEGe detectors
~ 35 kg total mass
► enhanced energy resolution
► enhanced pulse shape discrimination

► new low-mass holders with reduced mass
► new front-end electronics
→ less radioactivity



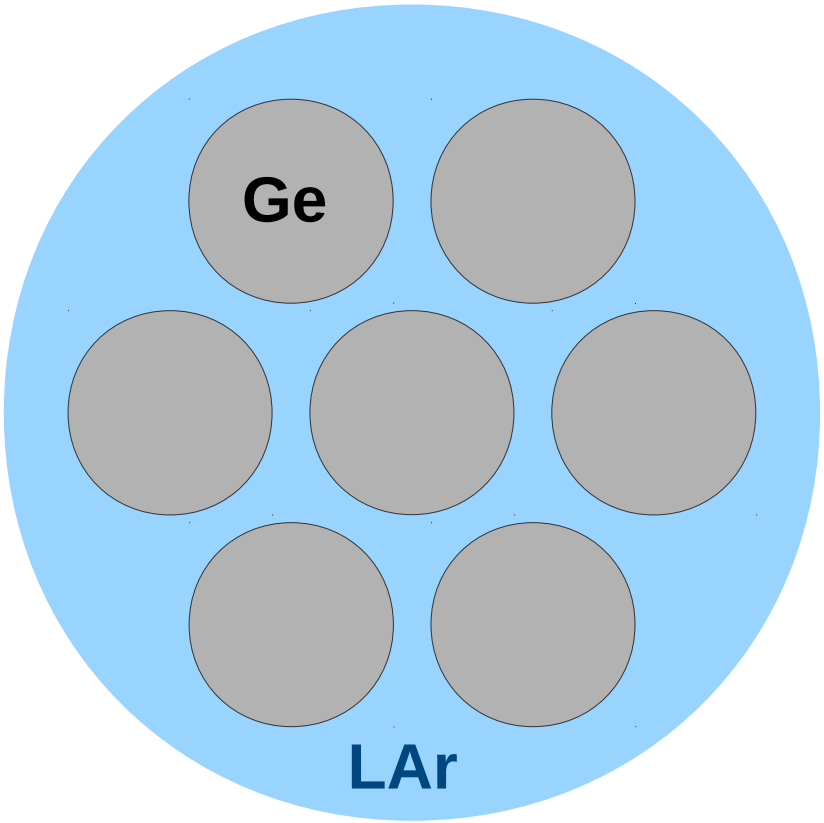




7 detector string array

► LAr veto light instrumentation w/ PMTs and SiPMs

Background types & mitigation techniques



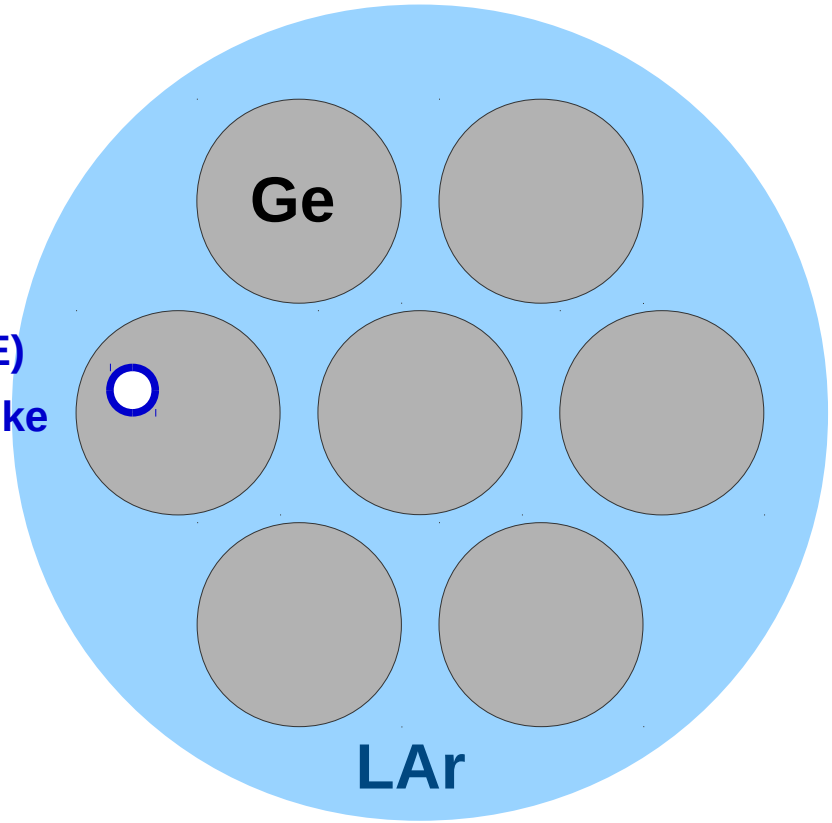
Background types:

- ►single & multi site events from γ background, e.g. ^{228}Th, ^{226}Ra, ^{60}Co
- ►surface events from α and β background, e.g. ^{42}K, ^{210}Po
- ►muons

Mitigation techniques:

- ► detector anti-coincidence (AC)
- ► pulse shape discrimination (PSD)
- ► argon scintillation veto (LAr veto)
- ► nylon 'mini shroud' (NMS)
- ► water cerenkov muon veto

Background types & mitigation techniques



single-site event (SSE)
→ signal like

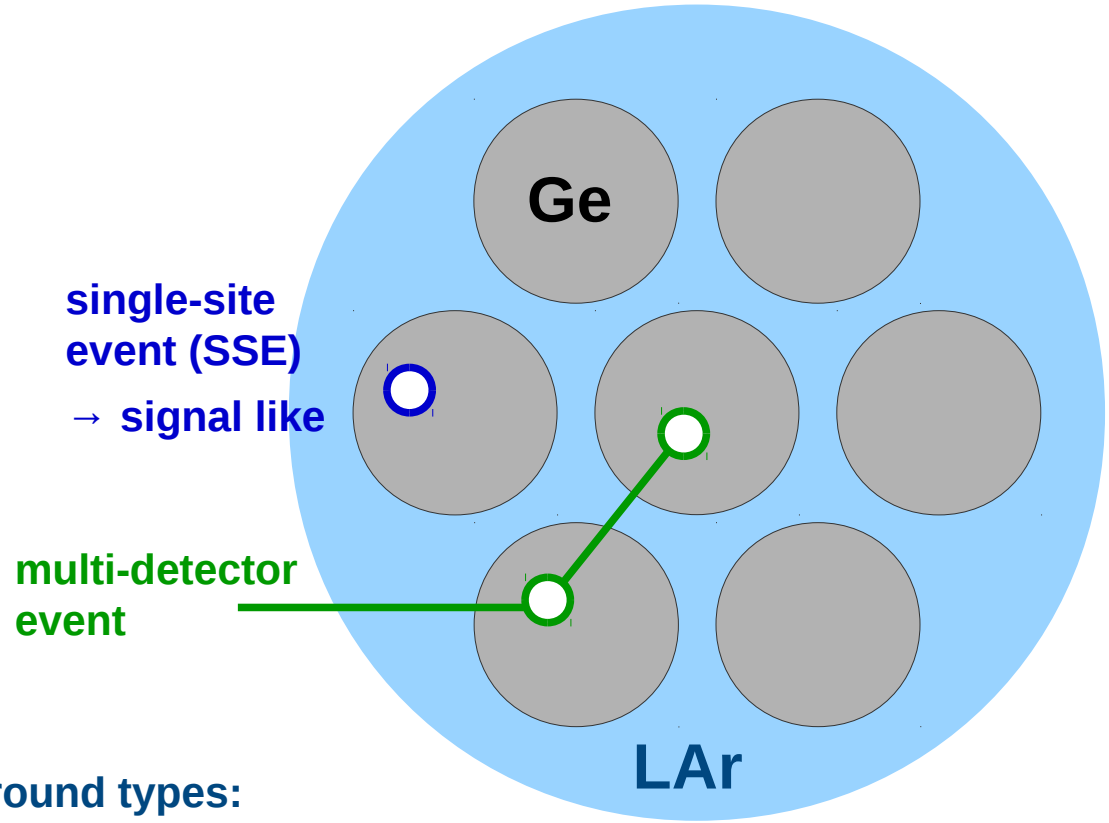
Background types:

- ►single & multi site events from γ background, e.g. ^{228}Th, ^{226}Ra, ^{60}Co
- ►surface events from α and β background, e.g. ^{42}K, ^{210}Po
- ►muons

Mitigation techniques:

- ► detector anti-coincidence (AC)
- ► pulse shape discrimination (PSD)
- ► argon scintillation veto (LAr veto)
- ► nylon 'mini shroud' (NMS)
- ► water cerenkov muon veto

Background types & mitigation techniques



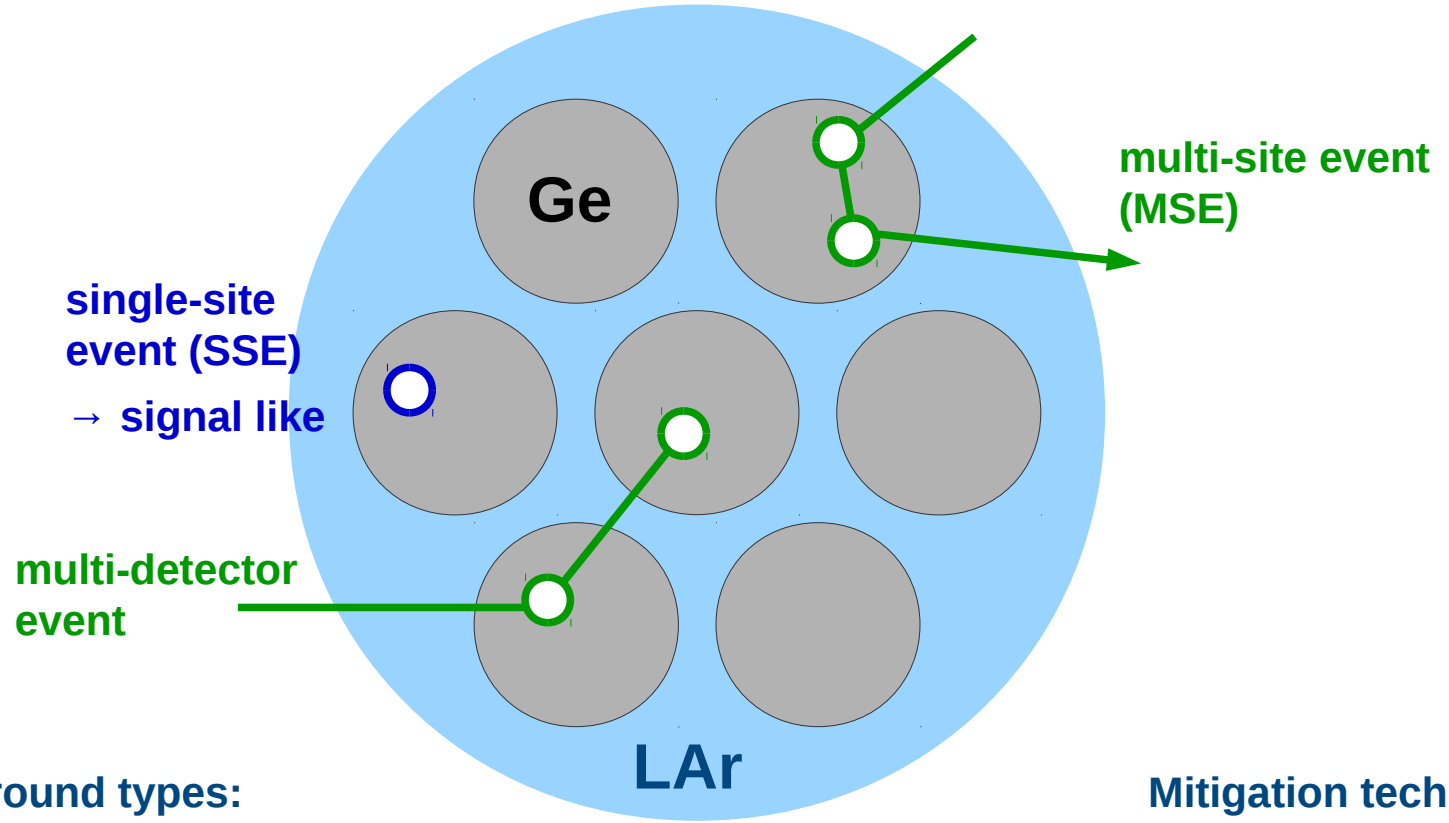
Background types:

- ► single & multi site events from γ background, e.g. ^{228}Th, ^{226}Ra, ^{60}Co
- ► surface events from α and β background, e.g. ^{42}K, ^{210}Po
- ► muons

Mitigation techniques:

- ► detector anti-coincidence (AC)
- ► pulse shape discrimination (PSD)
- ► argon scintillation veto (LAr veto)
- ► nylon 'mini shroud' (NMS)
- ► water cerenkov muon veto

Background types & mitigation techniques



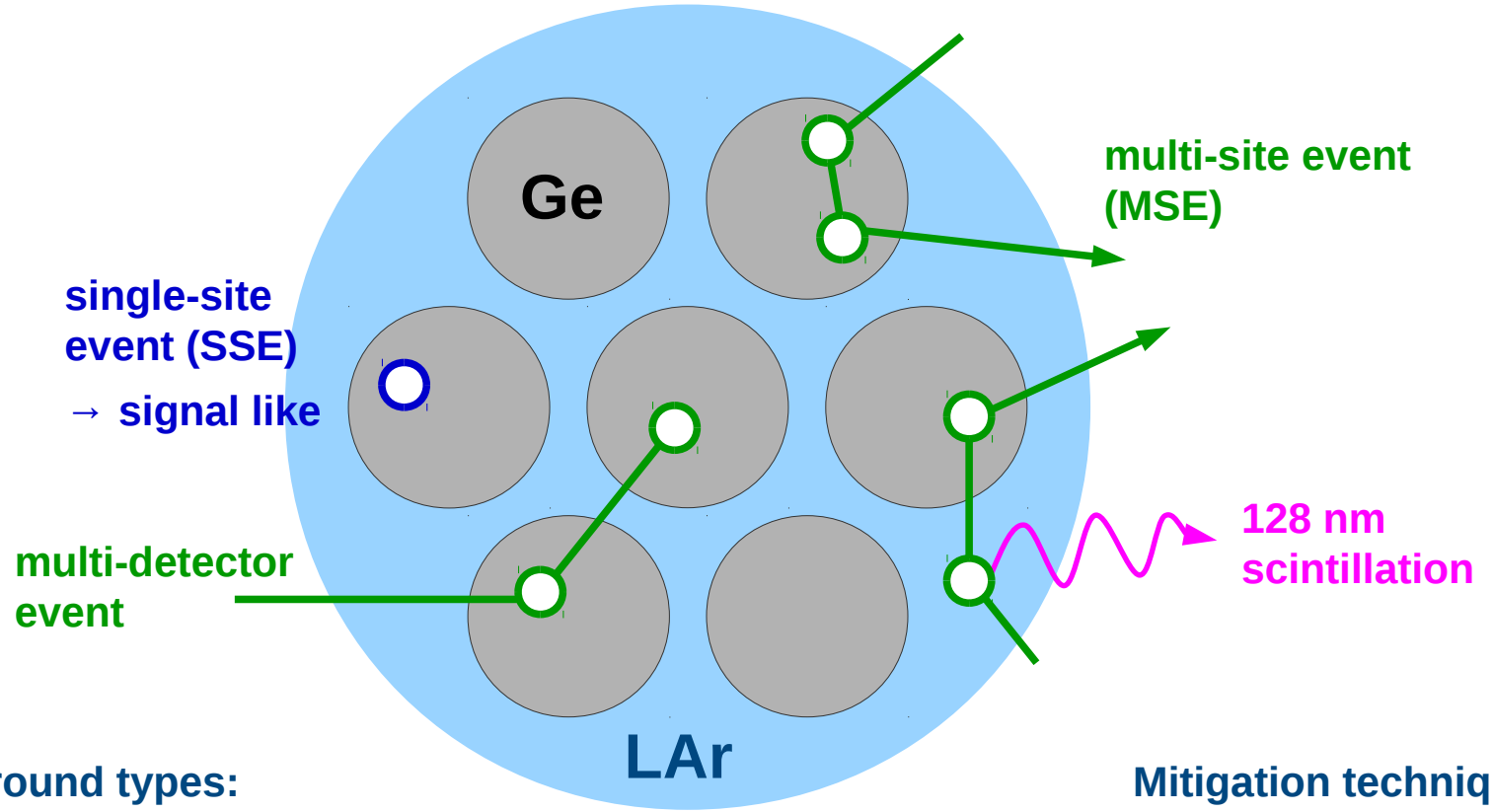
Background types:

- ► single & multi site events from γ background, e.g. ^{228}Th, ^{226}Ra, ^{60}Co
- ► surface events from α and β background, e.g. ^{42}K, ^{210}Po
- ► muons

Mitigation techniques:

- ► detector anti-coincidence (AC)
- ► pulse shape discrimination (PSD)
- ► argon scintillation veto (LAr veto)
- ► nylon 'mini shroud' (NMS)
- ► water cerenkov muon veto

Background types & mitigation techniques



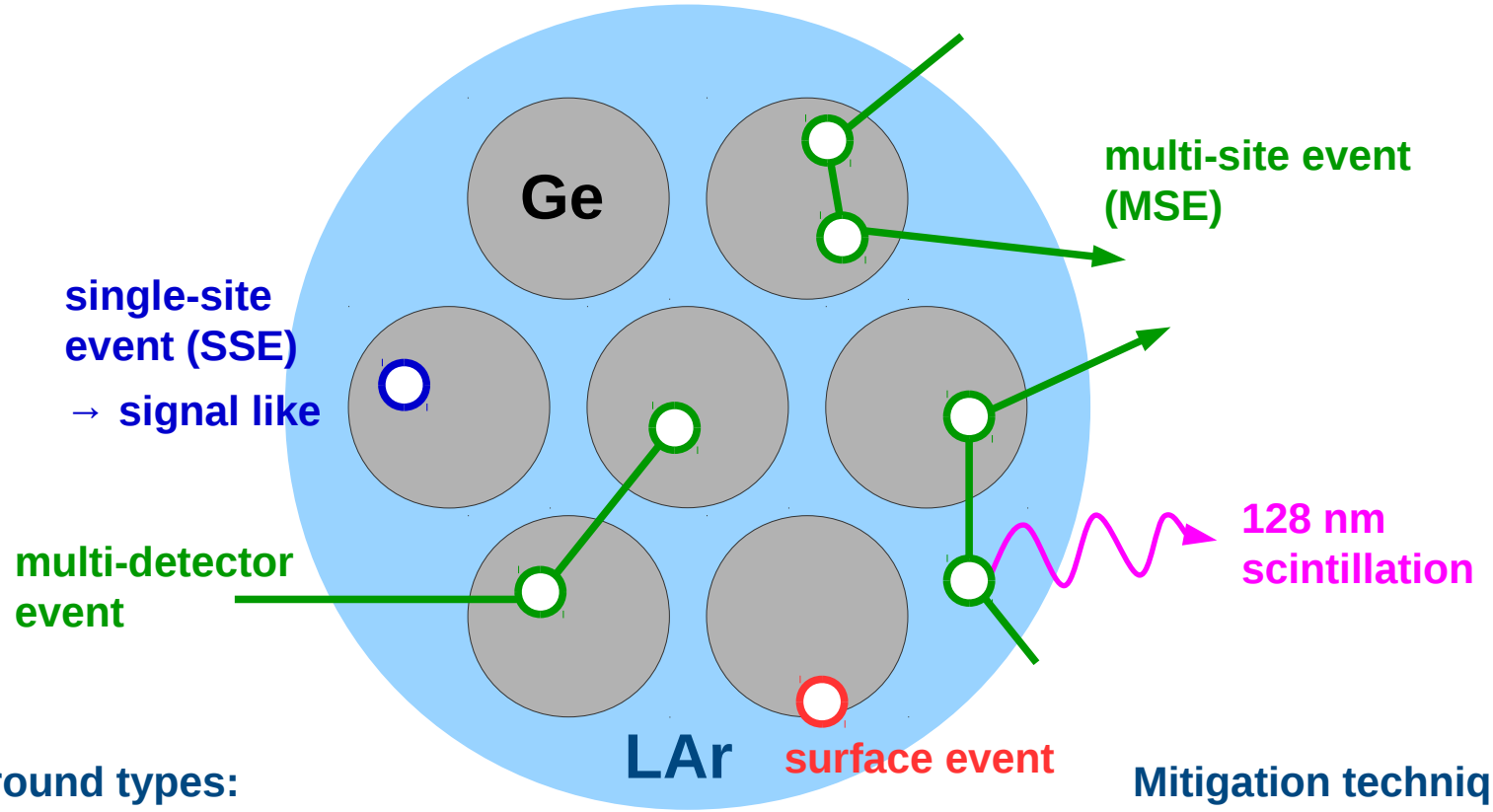
Background types:

- ► single & multi site events from γ background, e.g. ^{228}Th, ^{226}Ra, ^{60}Co
- ► surface events from α and β background, e.g. ^{42}K, ^{210}Po
- ► muons

Mitigation techniques:

- ► detector anti-coincidence (AC)
- ► pulse shape discrimination (PSD)
- ► argon scintillation veto (LAr veto)
  - ► nylon 'mini shroud' (NMS)
  - ► water cerenkov muon veto

Background types & mitigation techniques



Background types:

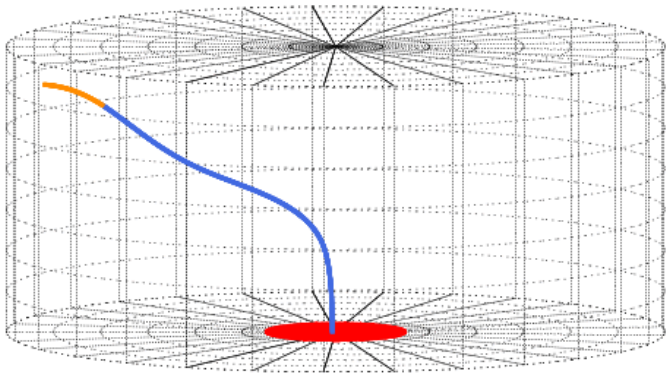
- ► single & multi site events from γ background, e.g. ^{228}Th, ^{226}Ra, ^{60}Co
- ► surface events from α and β background, e.g. ^{42}K, ^{210}Po
- ► muons

Mitigation techniques:

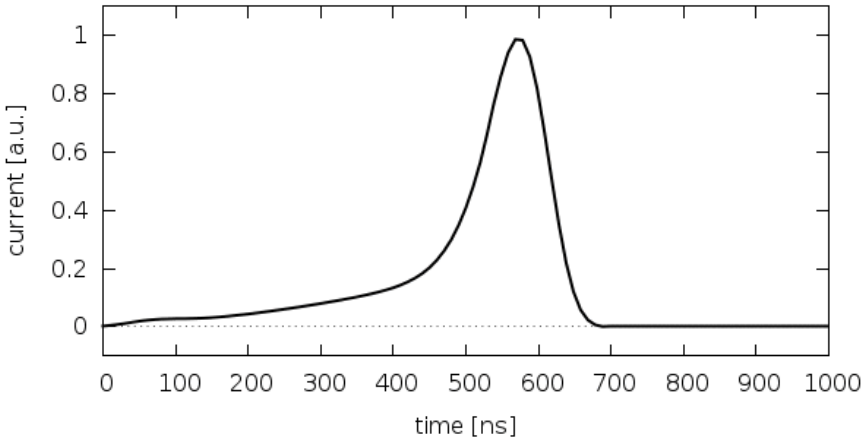
- ► detector anti-coincidence (AC)
- ► pulse shape discrimination (PSD)
- ► argon scintillation veto (LAr veto)
- ► nylon 'mini shroud' (NMS)
- ► water cerenkov muon veto

BEGe pulse shape discrimination

Single-site event (signal like):



M. Agostini et al.
JINST 6 (2011) P03005



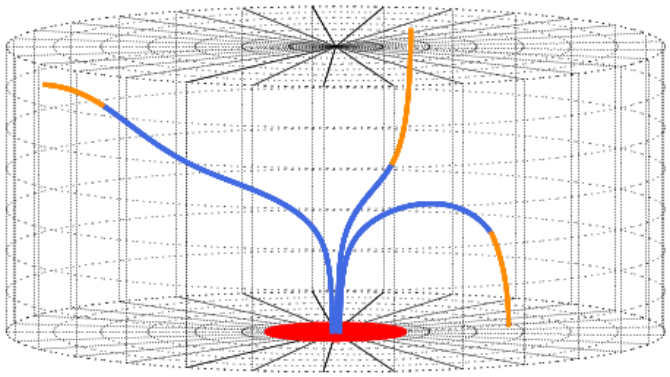
- well established cut parameter
  A/E = current pulse / charge pulse

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

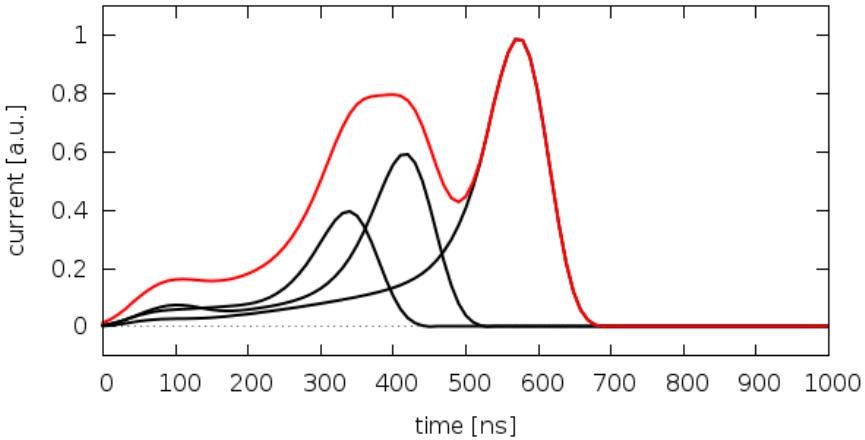
[EPJ C73 (2013) 2583]

BEGe pulse shape discrimination

Multi-site event (background like):



M. Agostini et al.
JINST 6 (2011) P03005

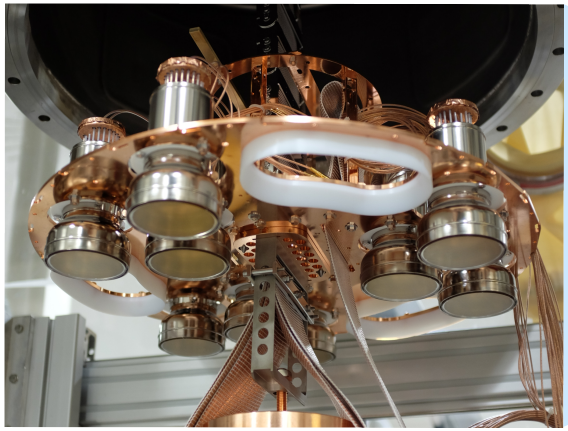


- well established cut parameter
  A/E = current pulse / charge pulse

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

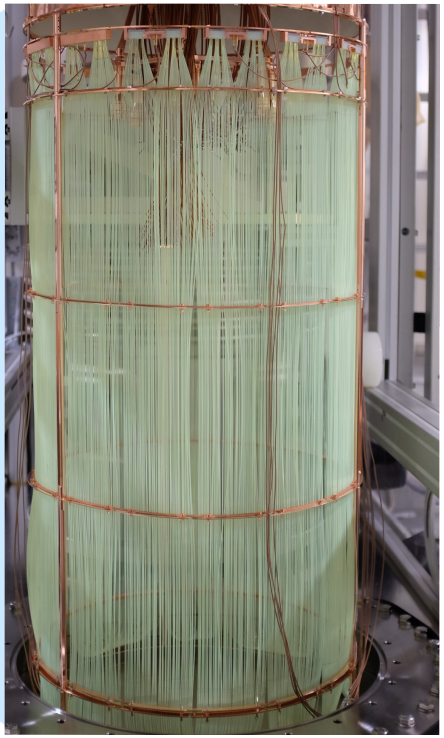
[EPJ C73 (2013) 2583]

LAr veto – light instrumentation



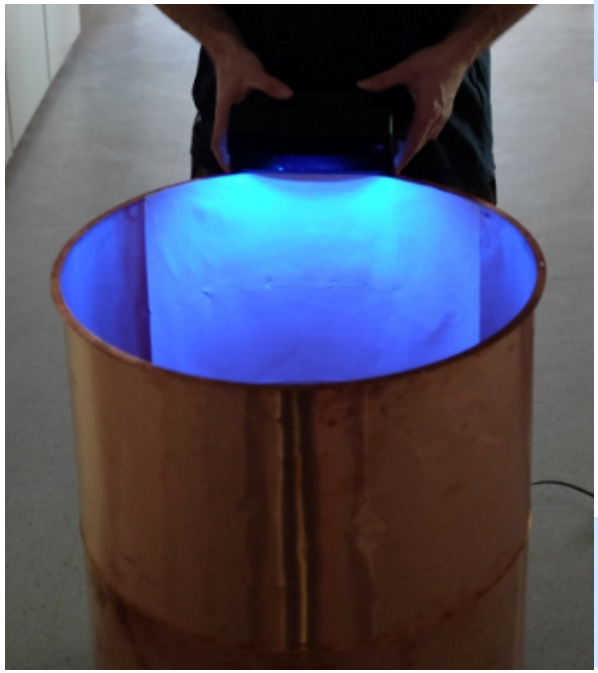
16 low background 3“ PMTs
Ham RG11065-10/20 MOD

810 scintillating fibres
coupled to 90 KETEK SiPMs

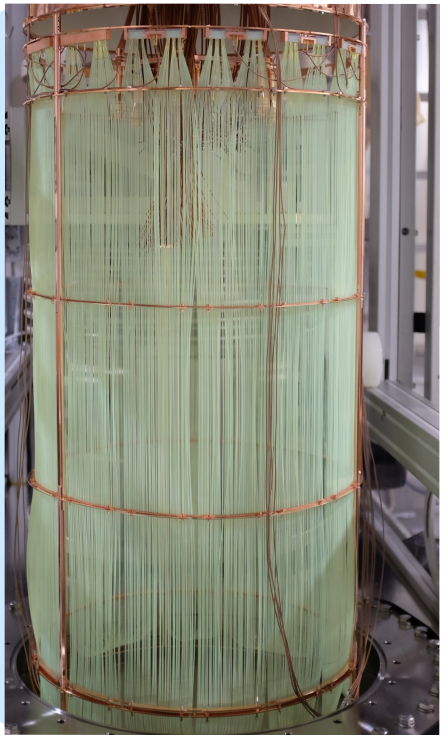


LAr veto – light instrumentation

100 µm Cu shrouds
w/ wavelength shifting
TETRATEX foil

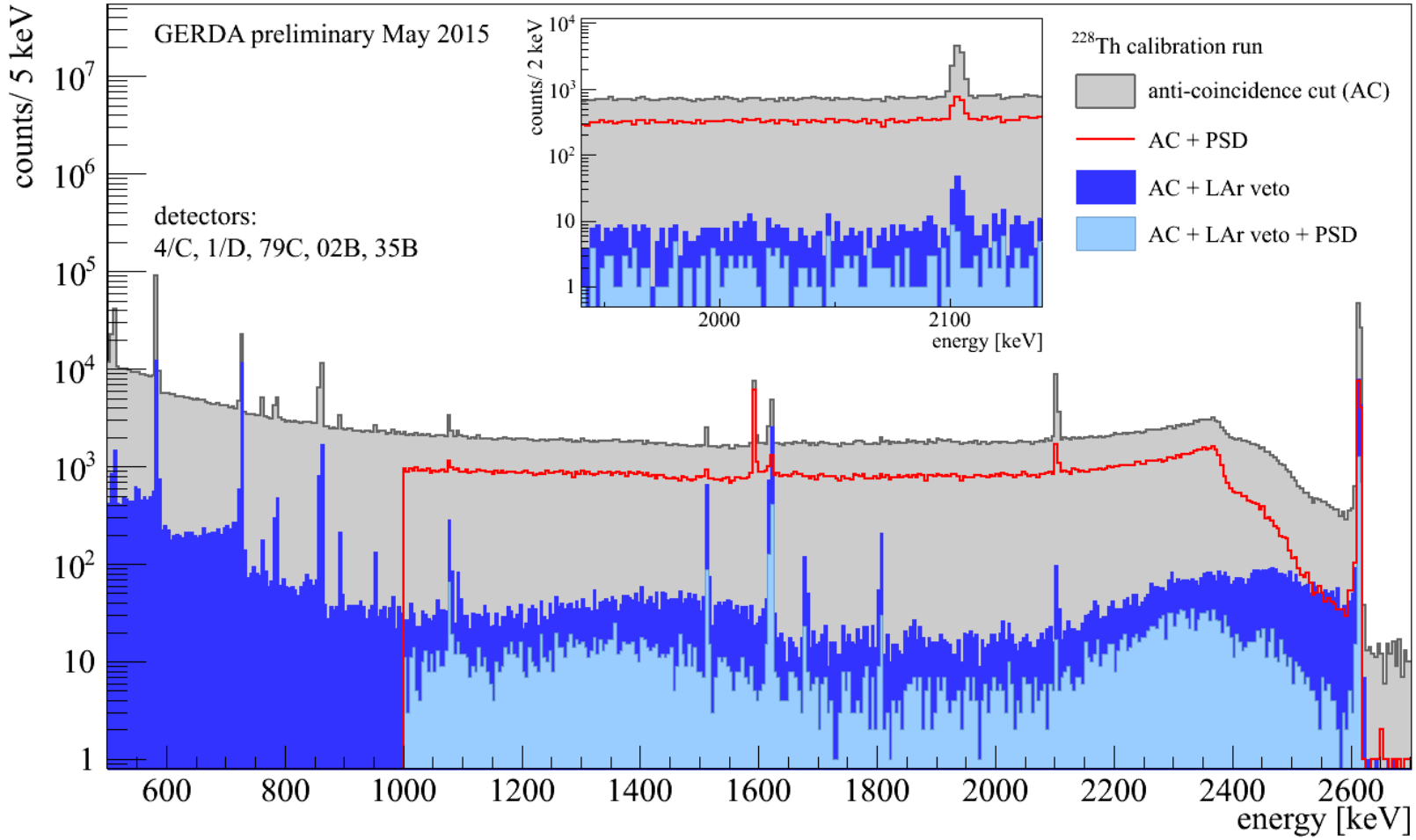


810 scintillating fibres
coupled to 90 KETEK SiPMs



Phase II commissioning – ^{228}Th source

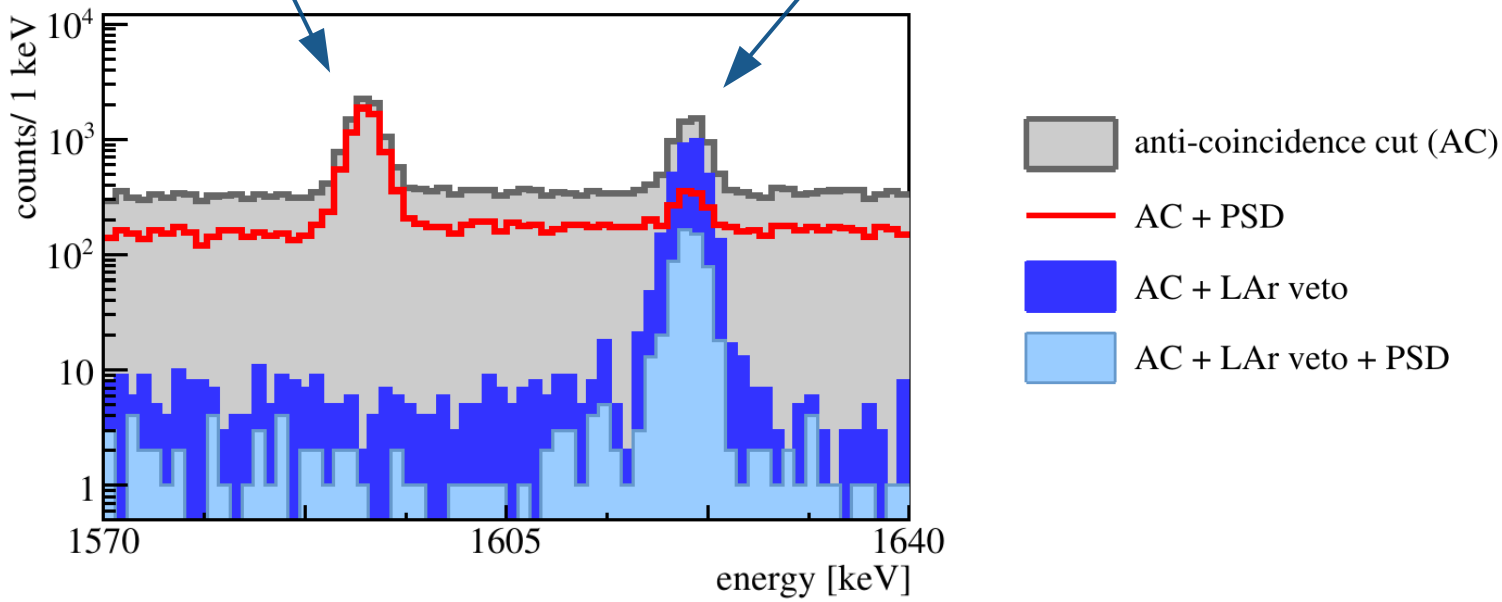
preliminary



Phase II commissioning – ^{228}Th source

double escape peak
of the ^{208}Tl 2.6 MeV line
→ signal-like events

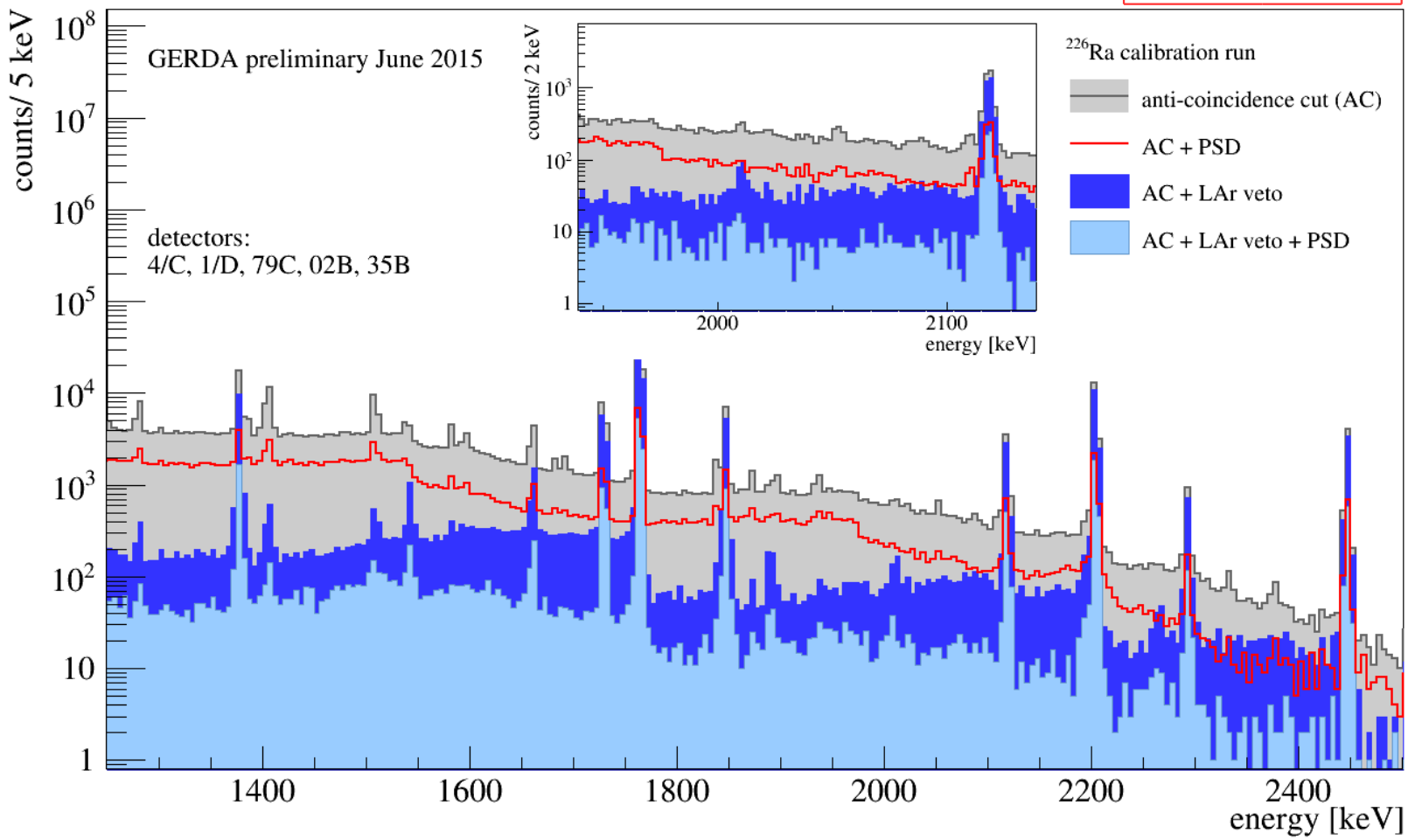
full energy peaks
of the ^{212}Bi 1.6 MeV line
→ background events



→ in case of discovery PSD + LAr veto will show if γ or 0νββ line

Phase II commissioning – ^{226}Ra source

preliminary



Phase II sensitivity projection

► MC realization of data sets w/ profile likelihood analysis of each set

→ global analysis including Phase I & Phase II

► Phase II input/goal:

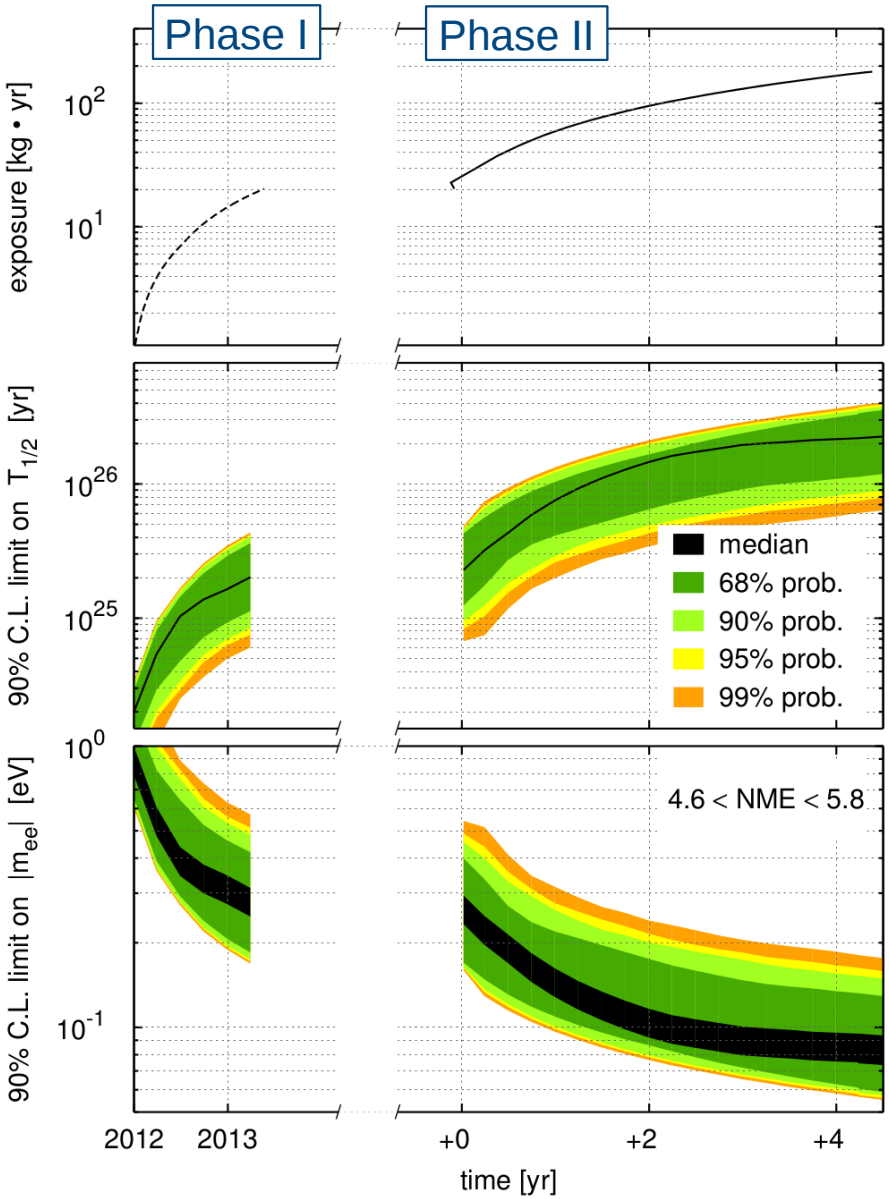
mass: 37 kg ^{76}Ge

backgr.: 1 x 10^{-3} cts/(keV·kg·yr)

► median sensitivity after two years of data taking:

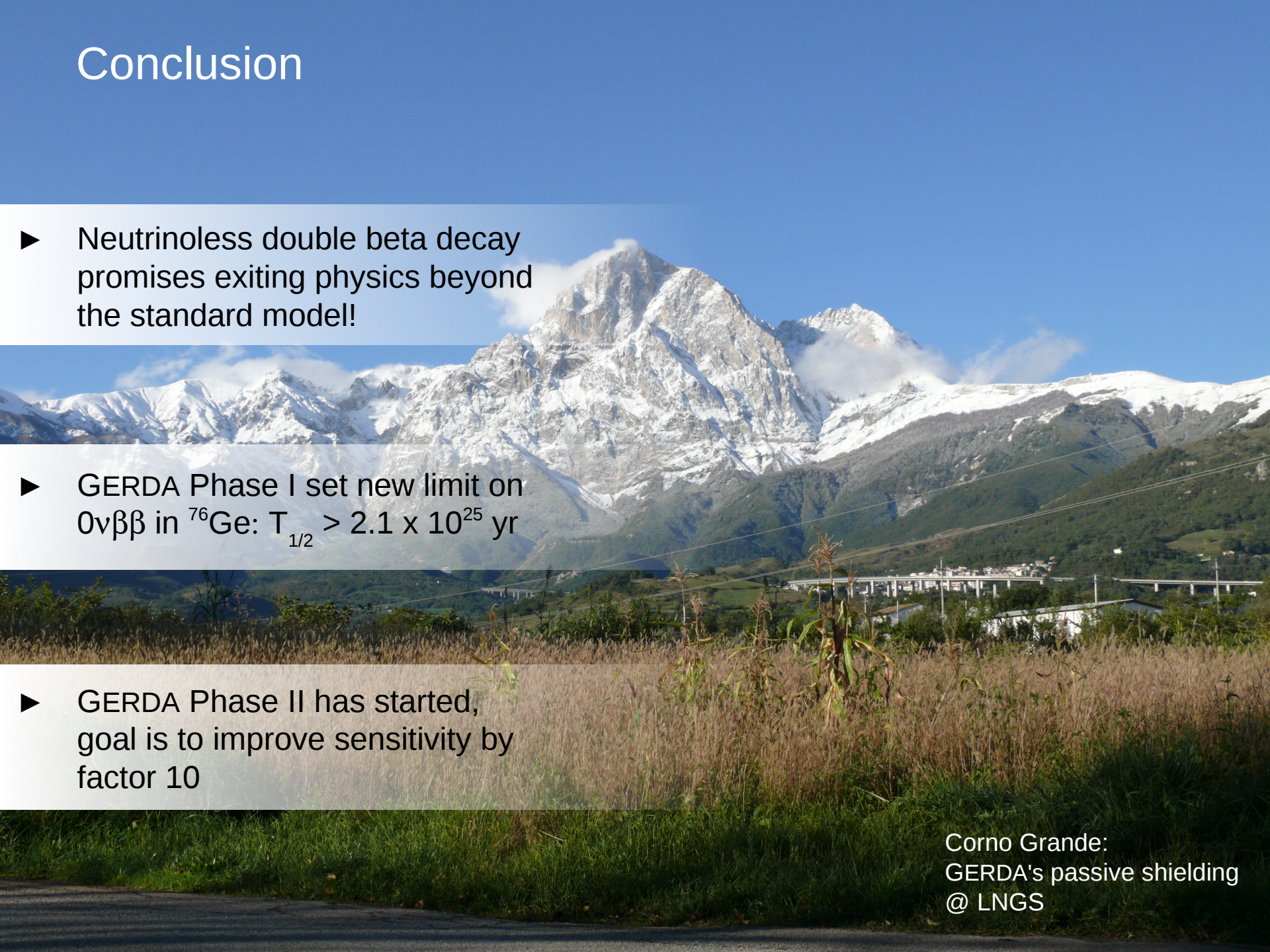
$T^{0\nu}_{1/2} > 1 \times 10^{26}$ yr

$|m_{ee}| < 100$ meV



Conclusion

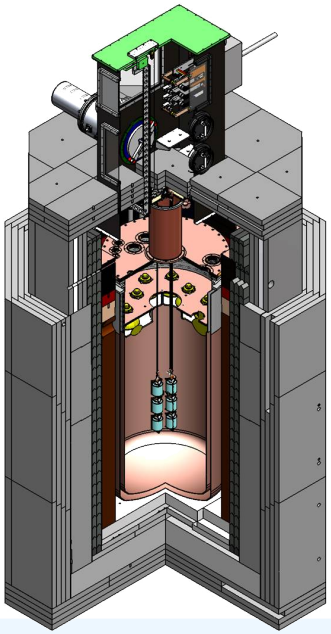
- Neutrinoless double beta decay promises exiting physics beyond the standard model!
- GERDA Phase I set new limit on $0\nu\beta\beta$ in ^{76}Ge: $T_{1/2} > 2.1 \times 10^{25}$ yr
- GERDA Phase II has started, goal is to improve sensitivity by factor 10



Corno Grande:
GERDA's passive shielding
@ LNGS

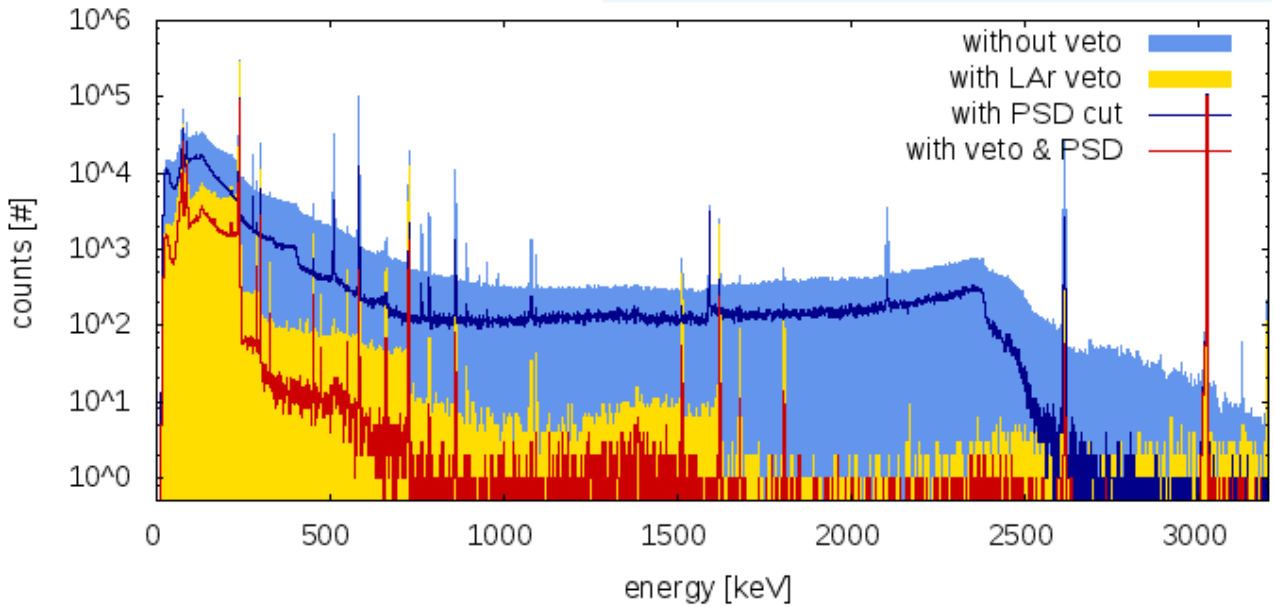
backup slides

LArGe test bench



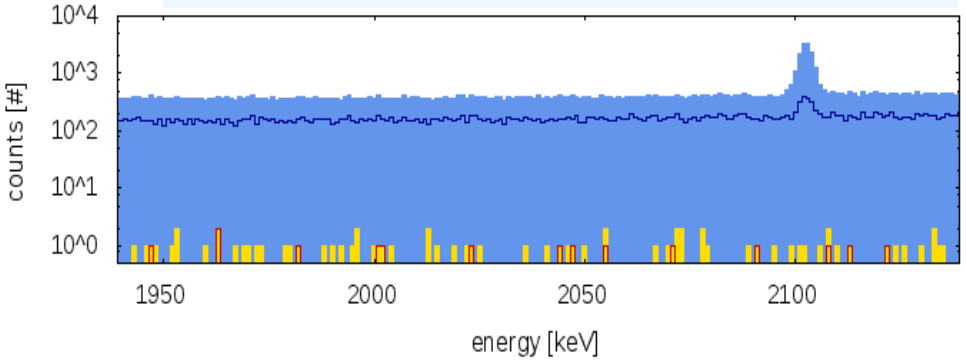
LArGe test bench at Gran Sasso

e.g. close-by Th-228 source

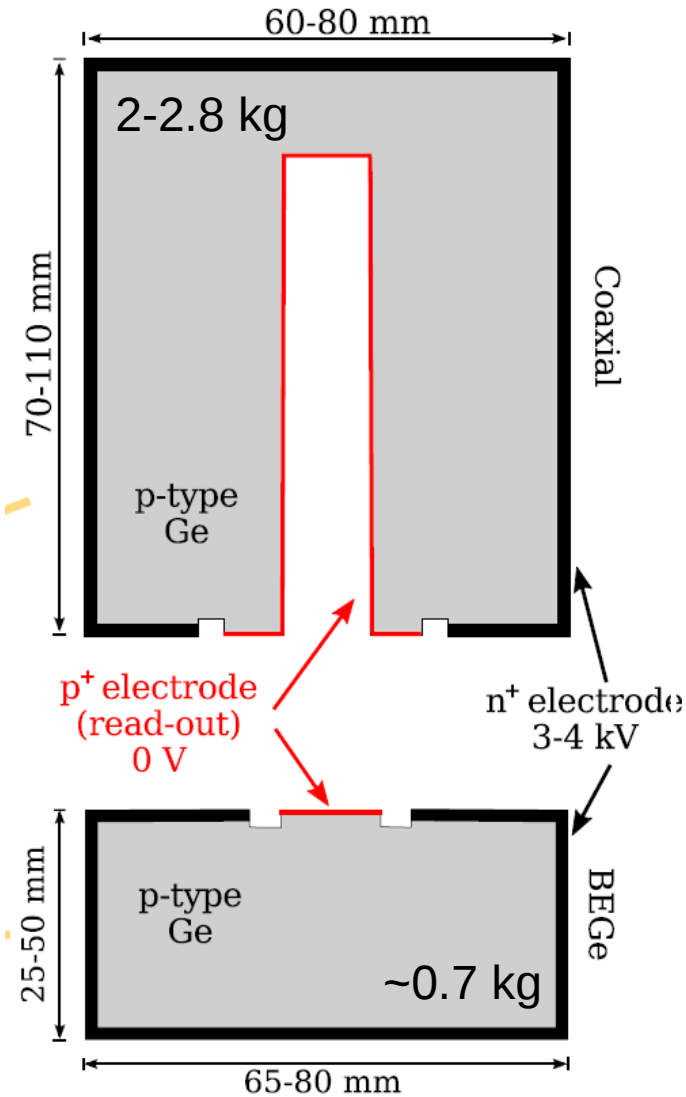


source	position	suppression factor		
		LAr veto	PSD	total
^{60}Co	int	27 ± 1.7	76 ± 8.7	3900 ± 1300
^{226}Ra	ext	3.2 ± 0.2	4.4 ± 0.4	18 ± 3
	int	4.6 ± 0.2	4.1 ± 0.2	45 ± 5
^{228}Th	ext	25 ± 1.2	2.8 ± 0.1	129 ± 15
	int	1180 ± 250	2.4 ± 0.1	5200 ± 1300

... suppression at region of interest



Detectors in Phase I & II



Phase I:

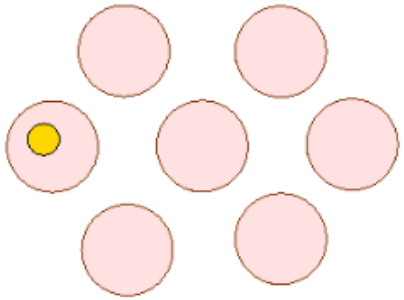
- use 8 refurbished semi-coaxial diodes from HdM & IGEX (total mass 17.67 kg)
- use pulse shape discrimination (PSD) based on artificial neural network
- also use 5 ^{enr}BEGe detectors (3.63 kg)

Phase II:

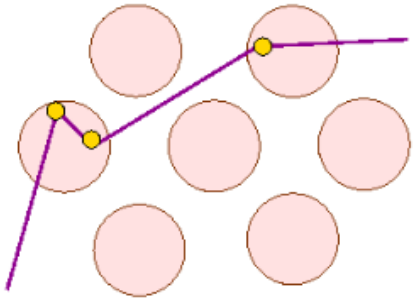
- use 30 ^{enr}BEGe detectors (20.5 kg) (in addition to semi-coaxial ones)
- small 'point-like' contact allows for superiour PSD & ΔE
- already tested in Phase I

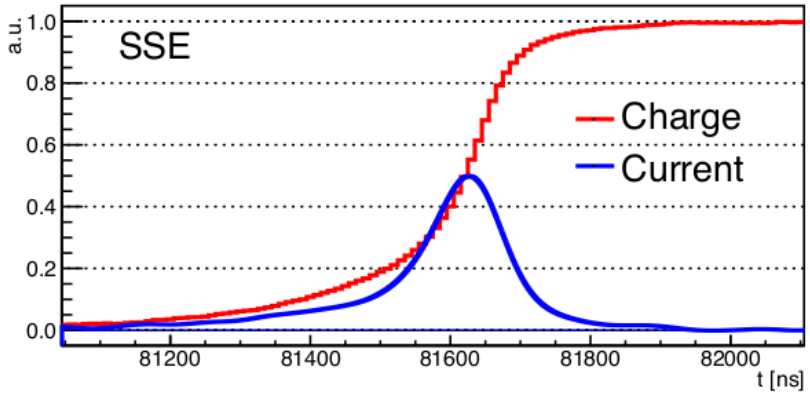
BEGe pulse shape discrimination

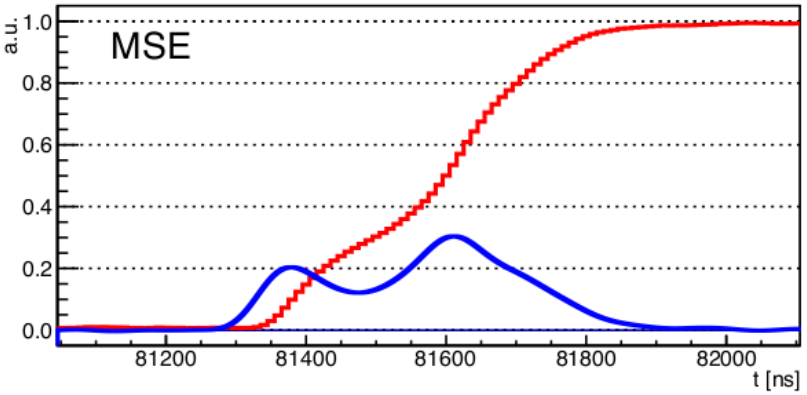
single site events: ββ, DEP
(signal like)



multi site events: Compton
(background like)







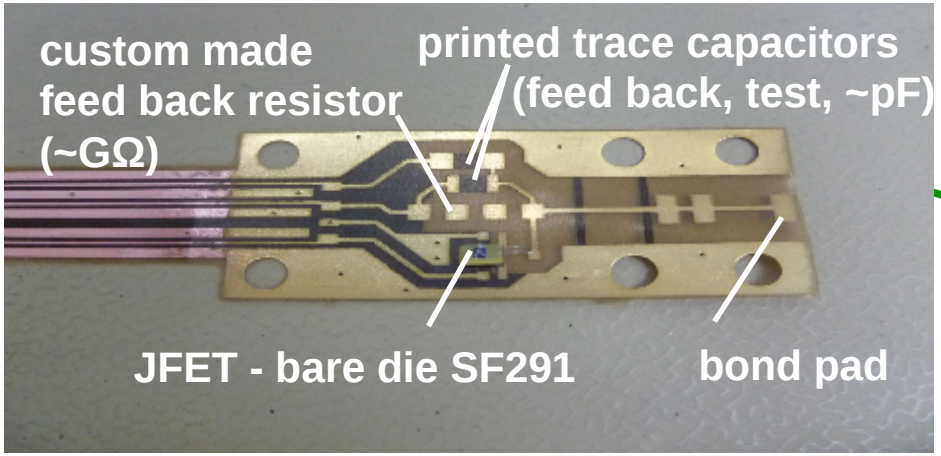
- well established cut parameter A/E = current pulse / charge pulse

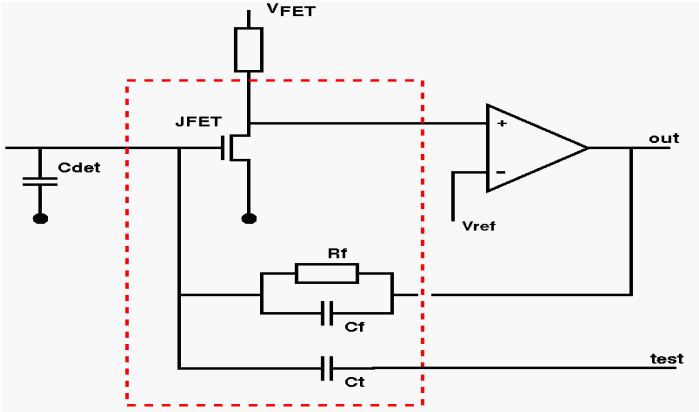
- 0νββ efficiency = 92±2 % determined from DEP efficiency & simulation
- 2νββ efficiency = 91±5 % in good agreement to DEP efficiency
- reject > 80% of background events

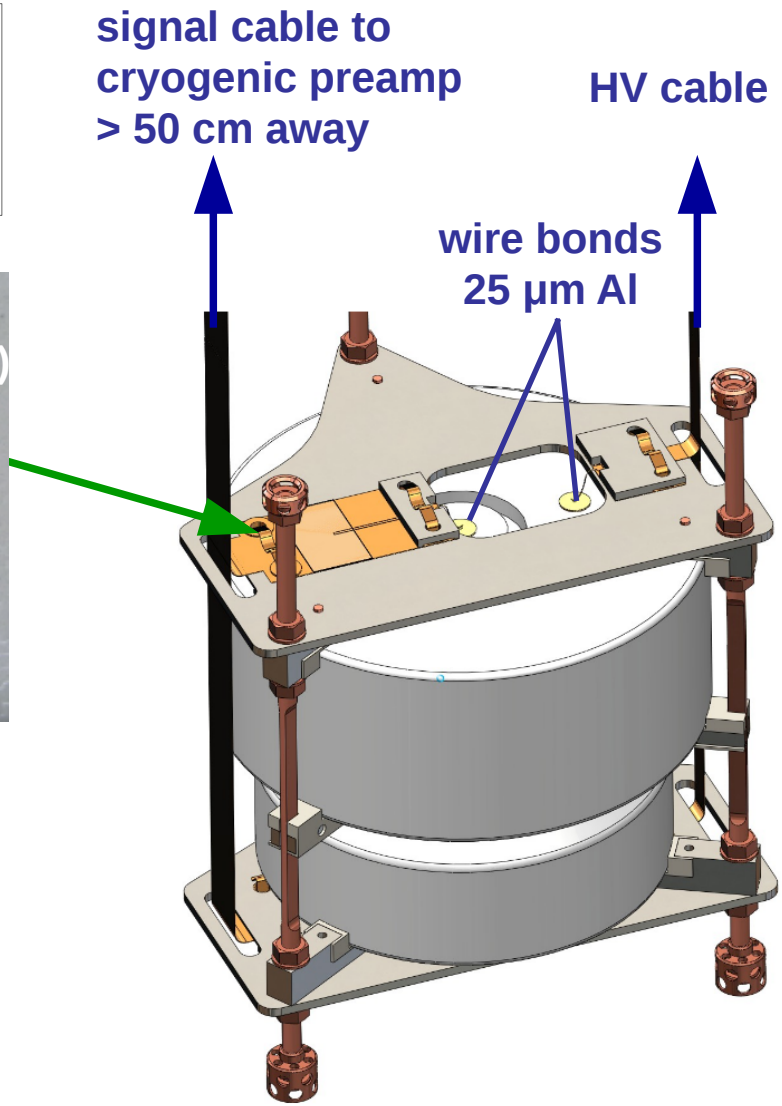
[EPJ C73 (2013) 2583]

Front end electronics

Phase II:	very front end electronics are very close to detector!
Phase I:	distance was > 30 cm





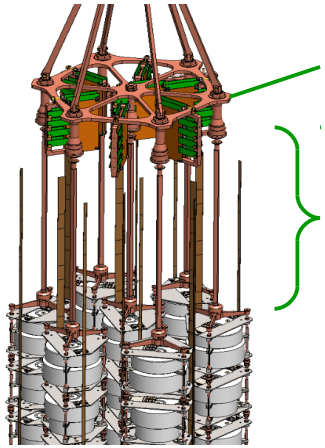


Front end electronics

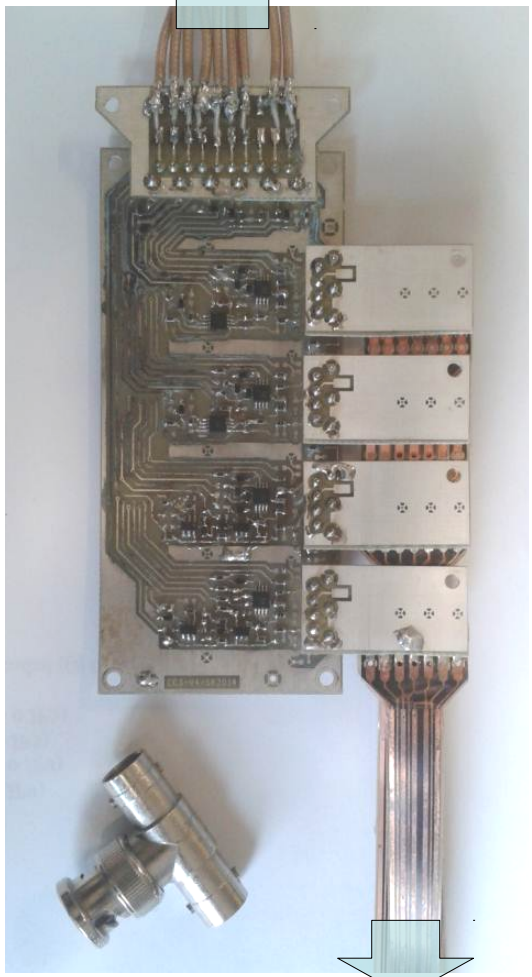
CC3: 4 Channel Charge Sensitive Preamplifier

→ upgrade of CC2 preamplifier of GERDA Phase I, based on commercially available op-amps

- **low-noise:**
  - → 0.7 keV FWHM pulser resolution
  - → 2.6 keV FWHM at 2.6 MeV with BEGe detector
  - → 20 MHz bandwidth allows PSD (A/E)
- **cryogenic:**
  - → suitable for operation in liquid Argon (50 mW/channel)
- **radio-pure electronics:**
  - → ≈ 50 µBq/channel (including pins) expected



10 m long coaxial cables to feedthrough flange

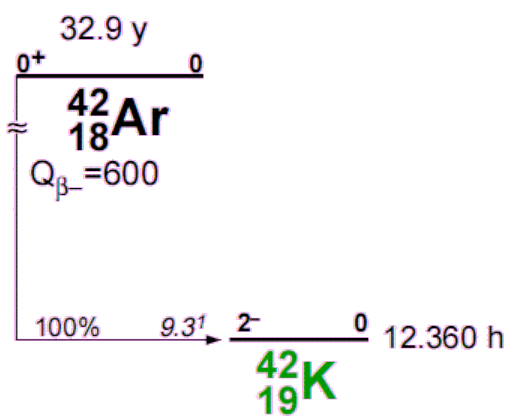


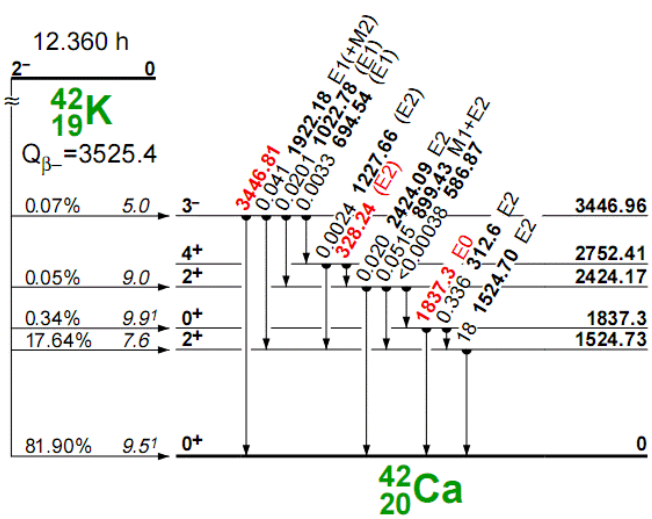
prototype version (FR4 laminate)

4x 0.5-1 m flex cables to VFE and detectors

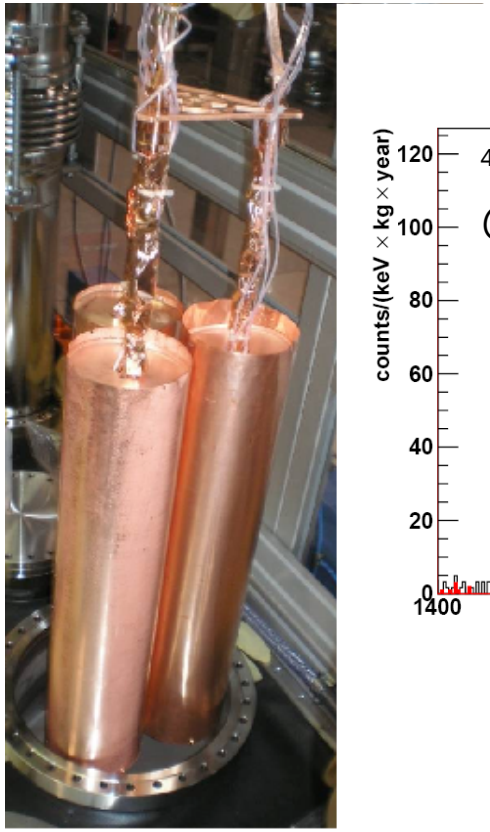
^{42}K background

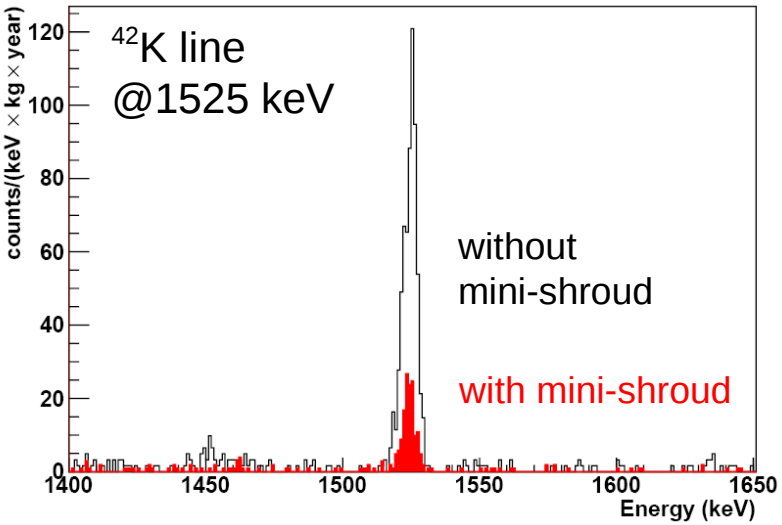
^{42}Ar activity used for proposal:	<41 µBq/kg @90% CL	[Barabash et al.,2002]
measured in GERDA:	(93.0 ± 6.4) µBq/kg	(preliminary result)





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

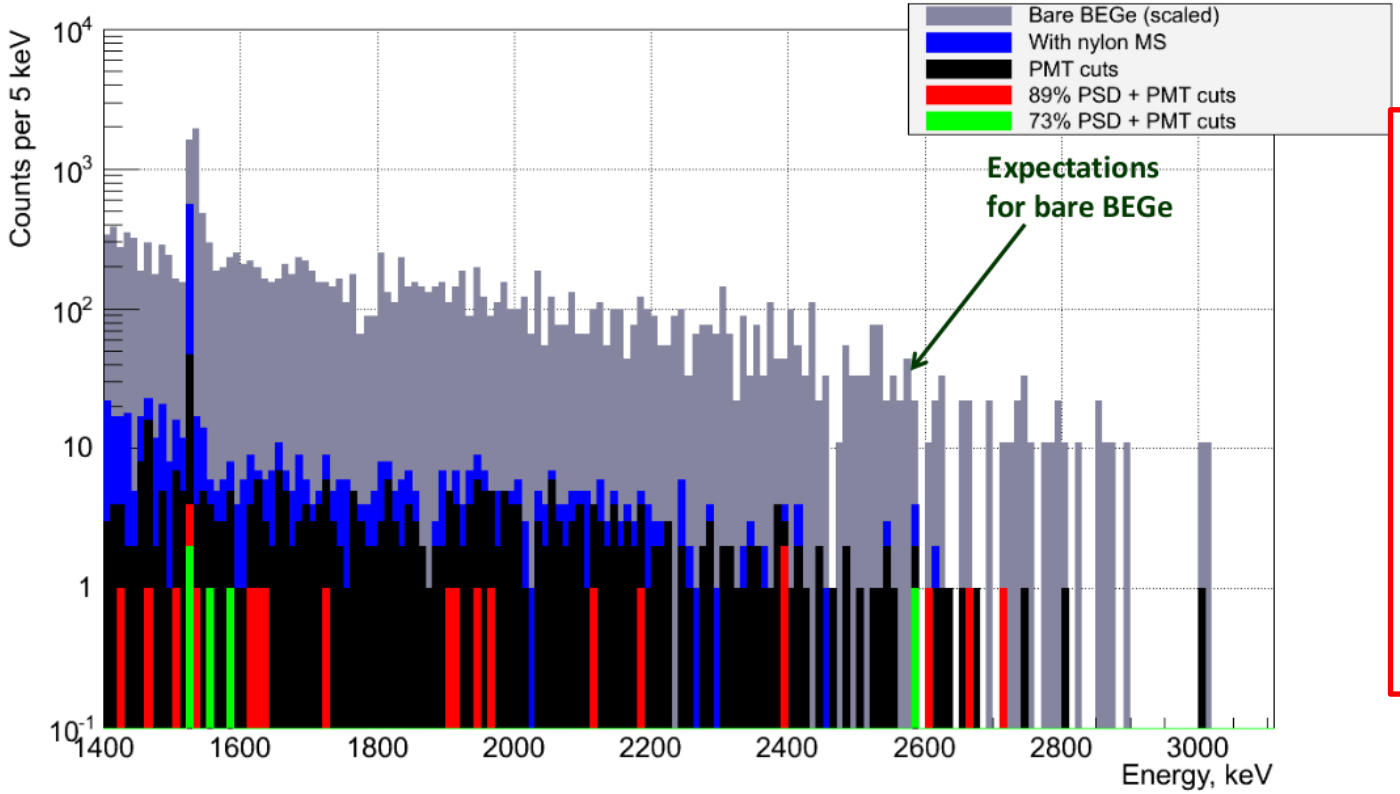




'Mini-shroud' against ^{42}K β-background

Phase II:

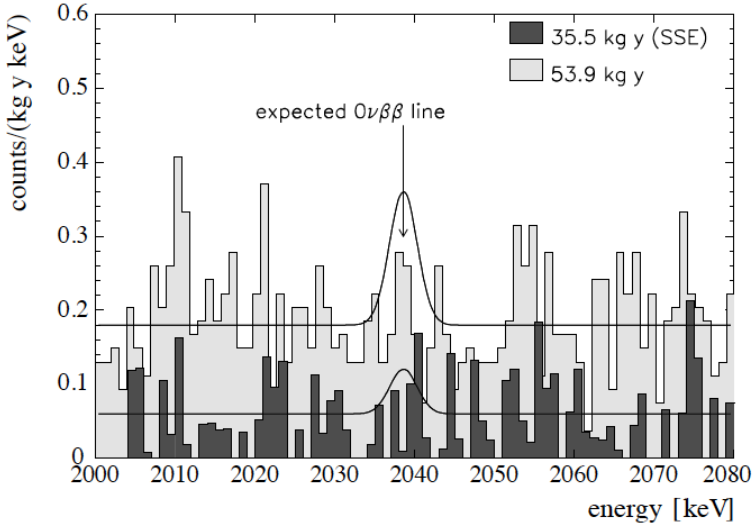
suppression of ^{42}K background by three orders of magnitude at $Q_{\beta\beta}$ using LAr veto /w nylon mini-shroud and PSD:



nylon mini-shroud coated with TPB/PS

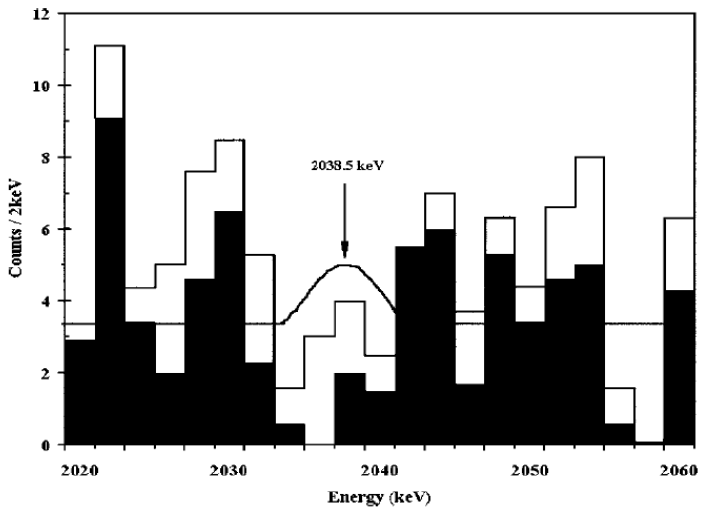
measurement in LArGe test bench spiked with ^{42}Ar statistics corresponding to ~17 kg×yr in natural argon.

^{76}Ge 0νββ search before GERDA



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

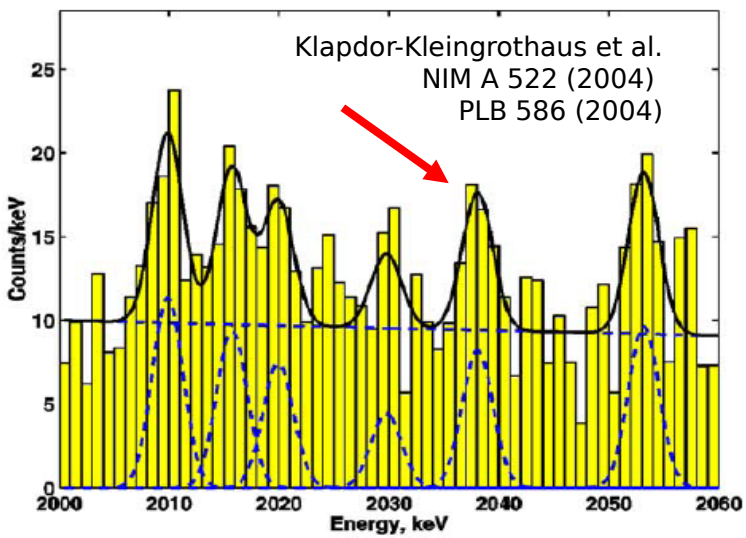
Exposure	Result $T^{0\nu}_{1/2}$	
53.9 kg·yr	> 1.3 × 10^{25} yr	(no PSD)
35.5 kg·yr	> 1.9 × 10^{25} yr	(with PSD)
		(90% C.L.)



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 x 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 x 10^{25} yr (~6σ)
- not considered by us, because:
  (1) reported half-life can be reconstructed* only with ε_{psd} = 1 (previous similar analysis ε_{psd} ≈ 0.6)
  (2) ε_{fep} = 1 (also used in result from 2004), GERDA value for same detectors is ε_{fep} = 0.9

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

New detectors: from raw material to diode production

[3] Canbe

[1]
[2]
[3]
[4]
[5]