Neutrinoless double beta decay searches of ^{76}Ge at LNGS

Max-Planck-Institut für Kernphysik

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

GERDA

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JINR Dubna, 22 Oct 2018

Topics in ν physics

- mixing parameters: matrix U, Δm^2, neutrino mass hierarchy, CP violating phase
  → DUNE/SURF, JUNO, NOVA, Hyper-K, T2K, ORCA, …

- absolute neutrino mass scale
  → Katrin, Echo, Holmes, Project 8, …

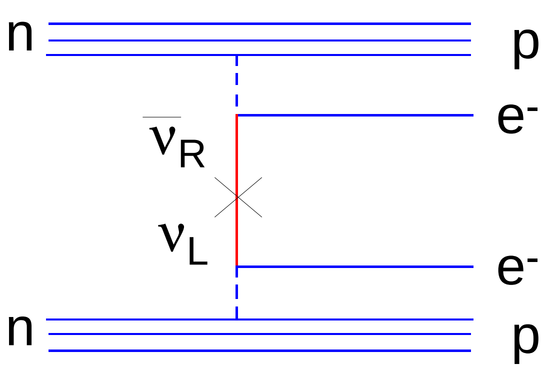
- sterile neutrinos: heavy right-handed ν without coupling to W/Z bosons, only mixing
  → DANSS, NEOS, Stereo, SoLid, MiniBoone, ...

- $\nu = \bar{\nu}$: Lepton number violation, neutrinoless double beta decay (A,Z) → (A,Z+2) + $2e^-$
  → Kamland-Zen ^{136}Xe, EXO-200 ^{136}Xe, Cuore ^{130}Te, SNO+ ^{130}Te, SuperNEMO ^{82}Se, ...
  GERDA & Majorana & LEGEND (& CDEX) ^{76}Ge

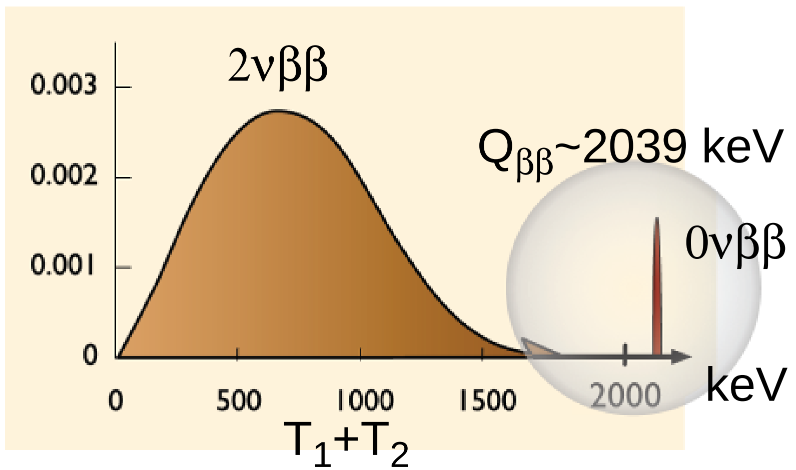
half-life $0\nu\beta\beta > 10^{26}$ yr →
for a discovery need many moles of isotope and low background

Signal and Sensitivity

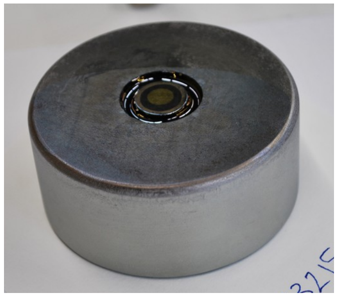
0νββ decay, ΔL=2



$^{76}Ge \rightarrow {}^{76}Se + 2\,e^-$



Ge detector



^{76}Ge: 7% → 87%

Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

Experimental sensitivity

$$T_{1/2}(90\% CL) > \begin{cases} \frac{\ln 2}{2.3} \frac{N_A}{A} a \cdot \epsilon \cdot M \cdot t & \text{for } N^{bkg} = 0 \\ \frac{\ln 2}{1.64} \frac{N_A}{A} a \cdot \epsilon \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A = Avogadro constant
a = fraction of 0νββ isotope
ε = detection efficiency
B = background index in units cnt/(keV kg y)
ΔE = energy resolution = energy window size

"background-free": N^{bkg} <1 within 1xFWHM @ $Q_{\beta\beta}$ at design exposure M t

Background reduction for 0νββ

background sources: α, β decays with/without γ, muons, neutrons, 2νββ, ...
intrinsic to detector or external

1) good energy resolution

2) underground laboratory like Baksan or Gran Sasso

3) shielding with “clean” material: best are liquids like liq. scintillator, liquid argon, water

4) measure all energy depositions of background events

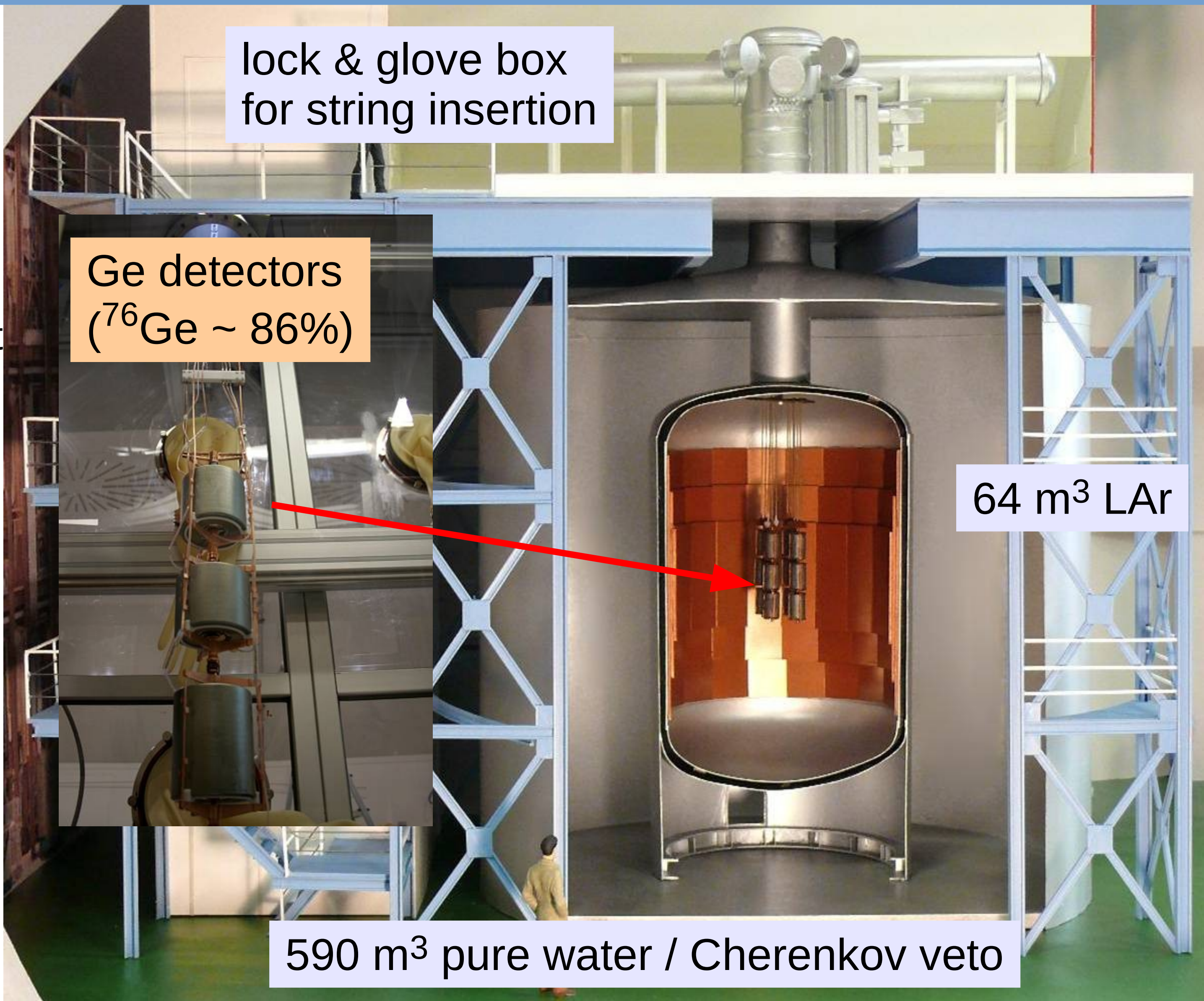
5) location and number of interactions/energy depositions

6) identify chemically the daughter nucleus (e.g. Ba tagging for Xe decay daughter)

GERDA & LEGEND apply all (but one) measures:

1) Ge detectors have currently best energy resolution of all experiments
& “no” intrinsic U/Th contamination (Astroparticle Phys 91 (2017) 15-21)
3) shielding by argon and water
4) read out scintillation light of argon & small mass of ‘inactive’ material
5) time profile of Ge detector signal → number & location of interactions

GERDA @ LNGS

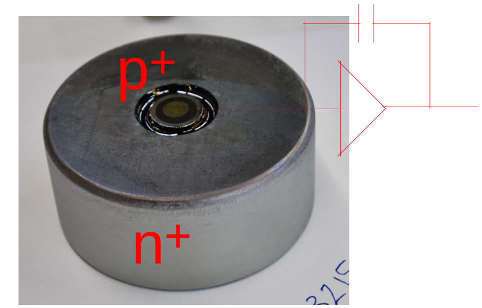


EPJ C73 (2013) 2330 and Eur. Phys. J. C78 (2018) 388

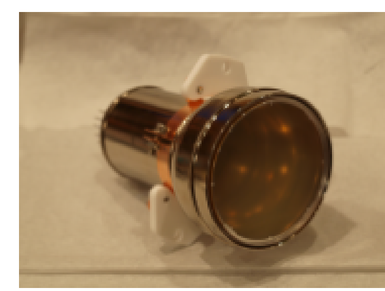
Phase I (2011-13):

Phase II:

2x Ge mass (30 BEGe det.)

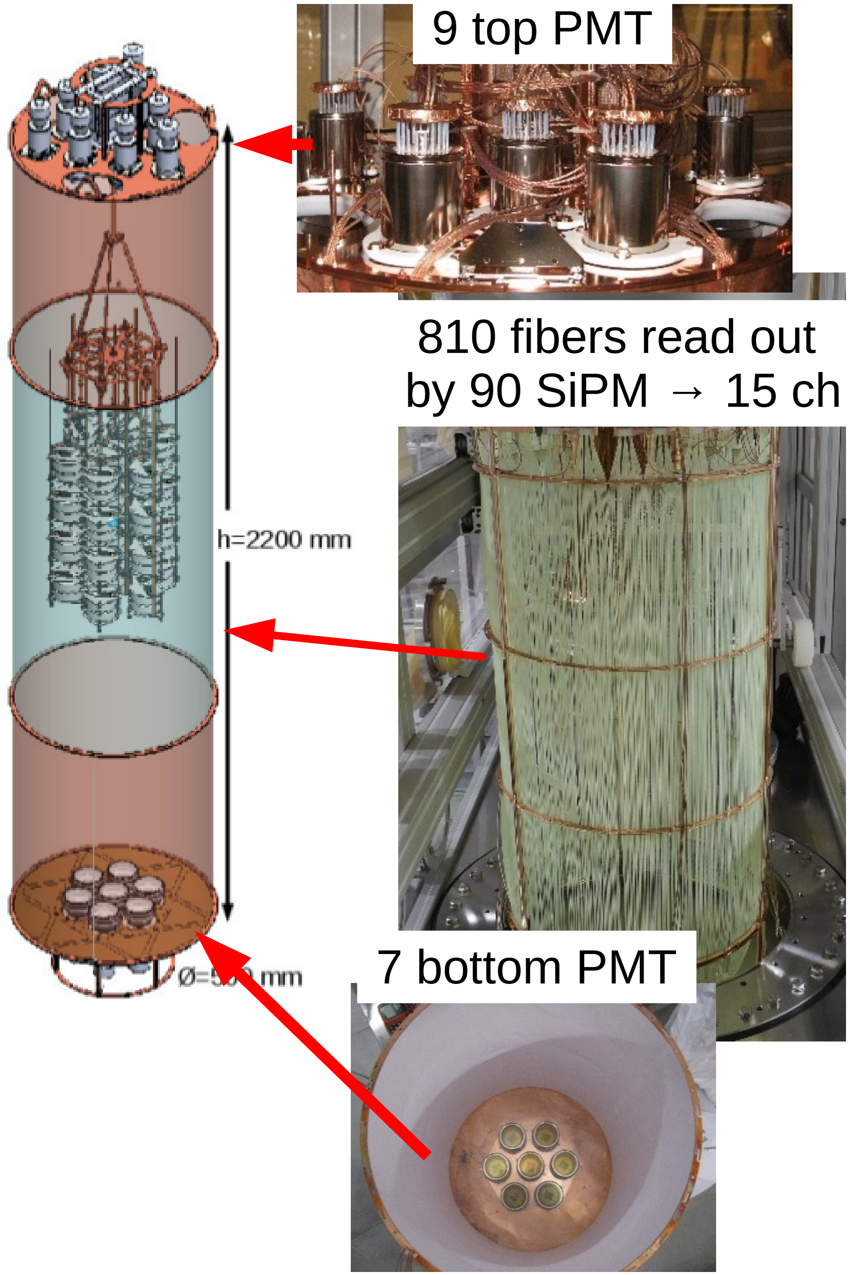


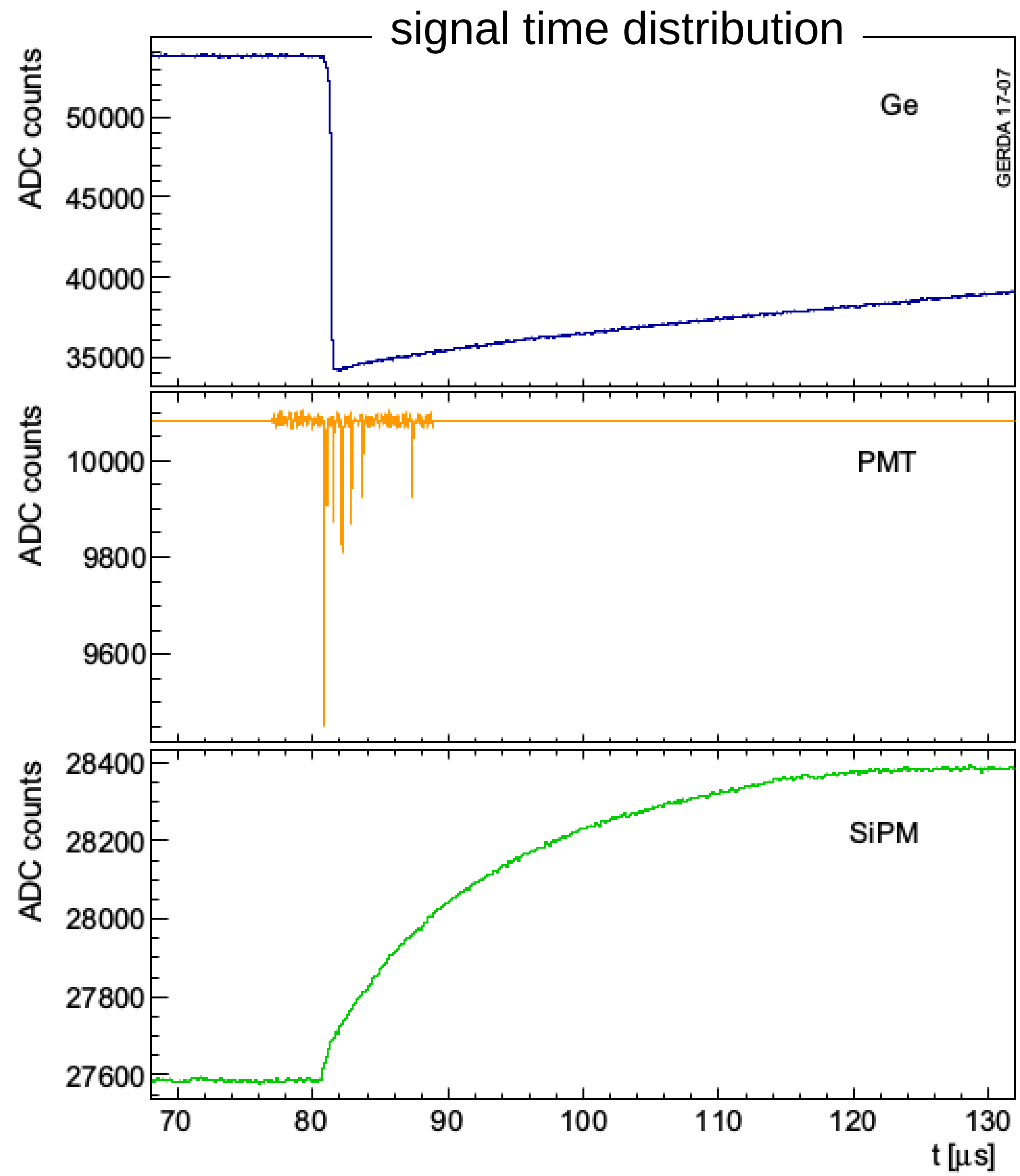
LAr scint. light readout



started end 2015

Liquid argon veto

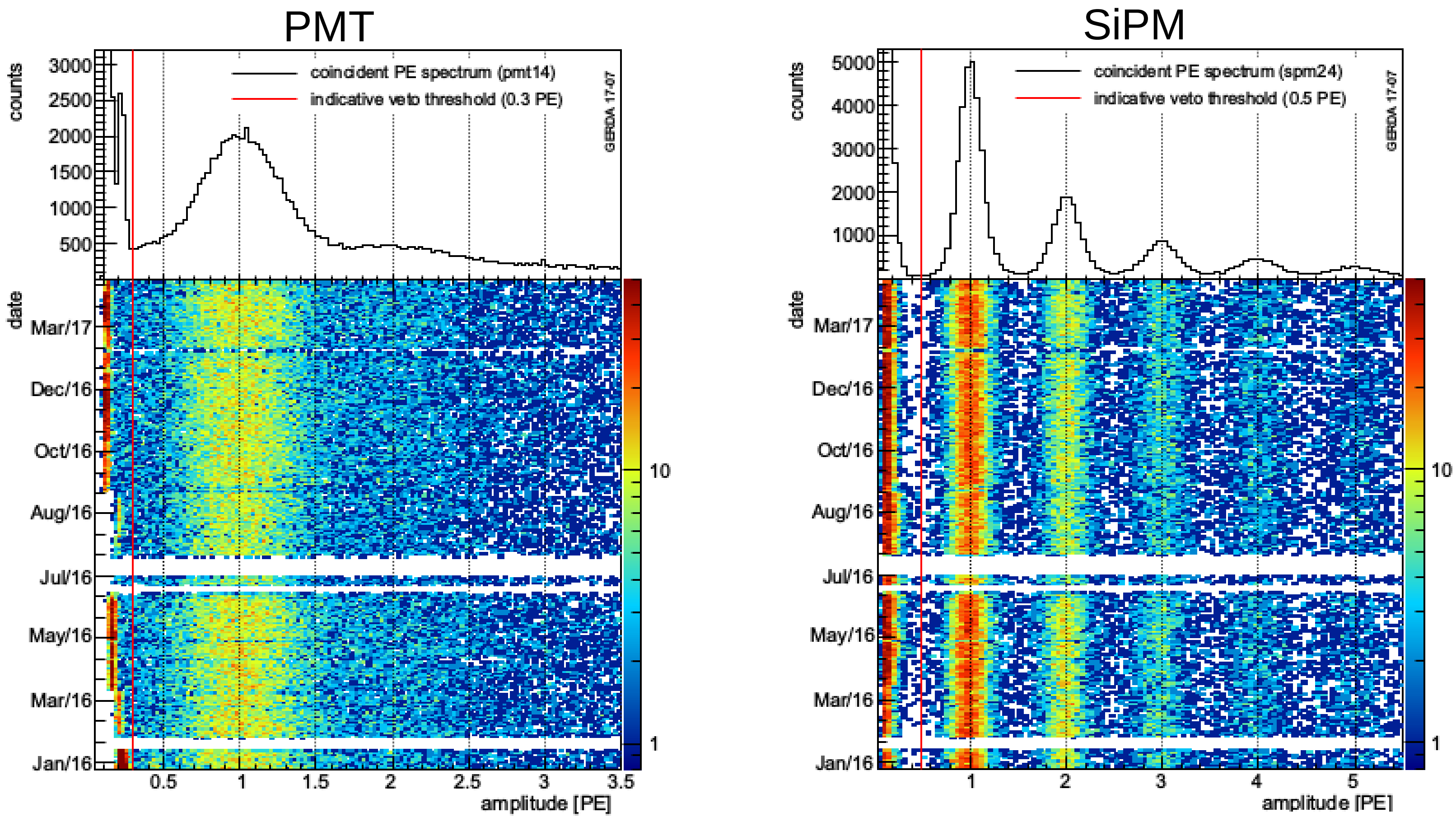




EPJ C78 (2018) 388

Liquid argon veto (2)

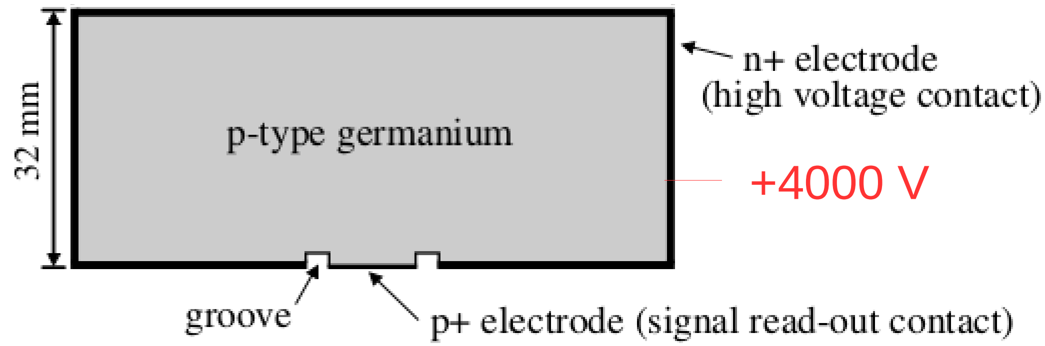
pulse height spectra for PMT and SiPM versus time (and projection)



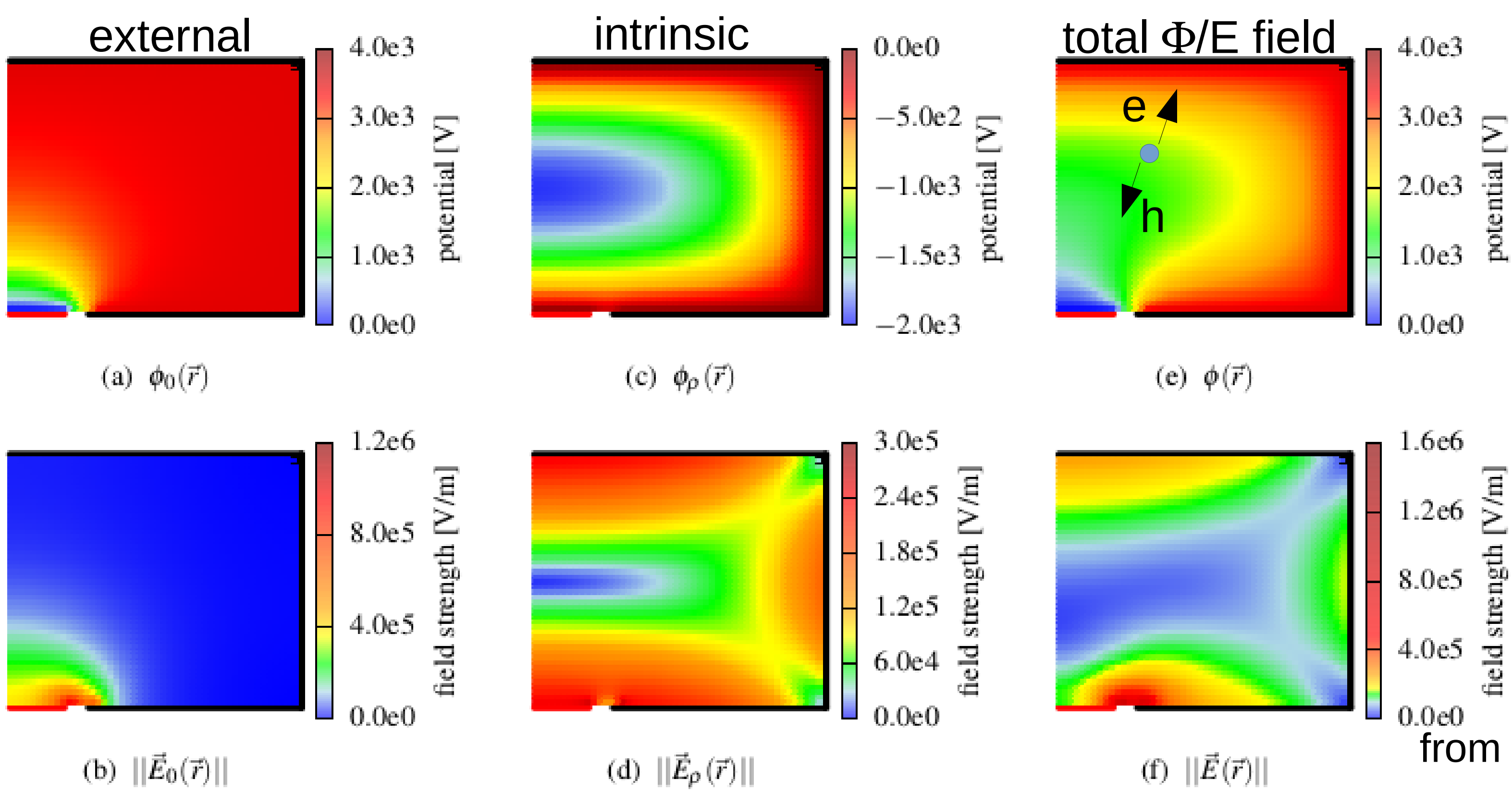
cut threshold at ~0.4 p.e. and withing 6 μs around Ge trigger
random coincidence with Ge → ~2.3% of events rejected

Time profile Ge signal

Broad Energy Germanium det. (BEGe)



diode in reverse bias:
- no free carriers
- all ‘holes’ filled with e^-
  → external field E & intrinsic field E



(a) $\phi_0(\vec{r})$ (c) $\phi_p(\vec{r})$ (e) $\phi(\vec{r})$

(b) $||\vec{E}_0(\vec{r})||$ (d) $||\vec{E}_p(\vec{r})||$ (f) $||\vec{E}(\vec{r})||$

$$\int \vec{E}_{intrinsic} \cdot \vec{ds} = 0$$

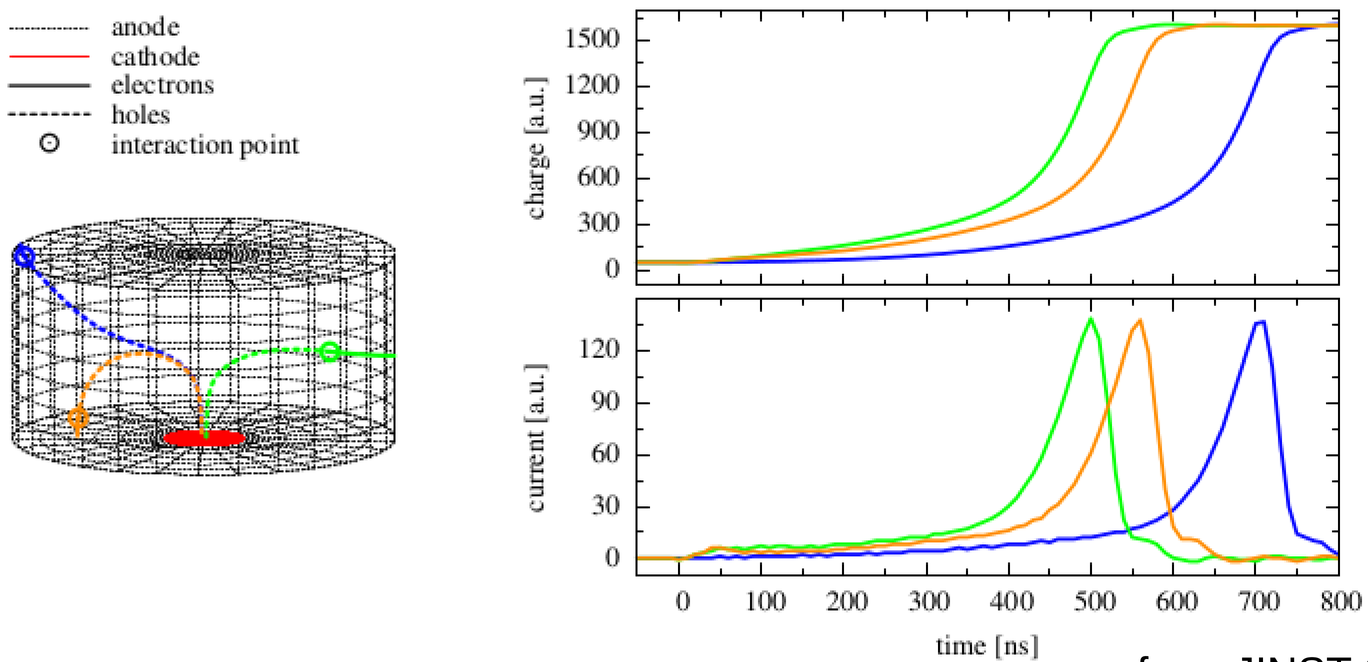
→ energy only from external field

$$signal\ Q(t) \propto \phi(\vec{r}(t))$$

drift velocity ~ total E
signal ~ external Φ

from JINST 6 (2011) P03005

Pulse shape discrimination

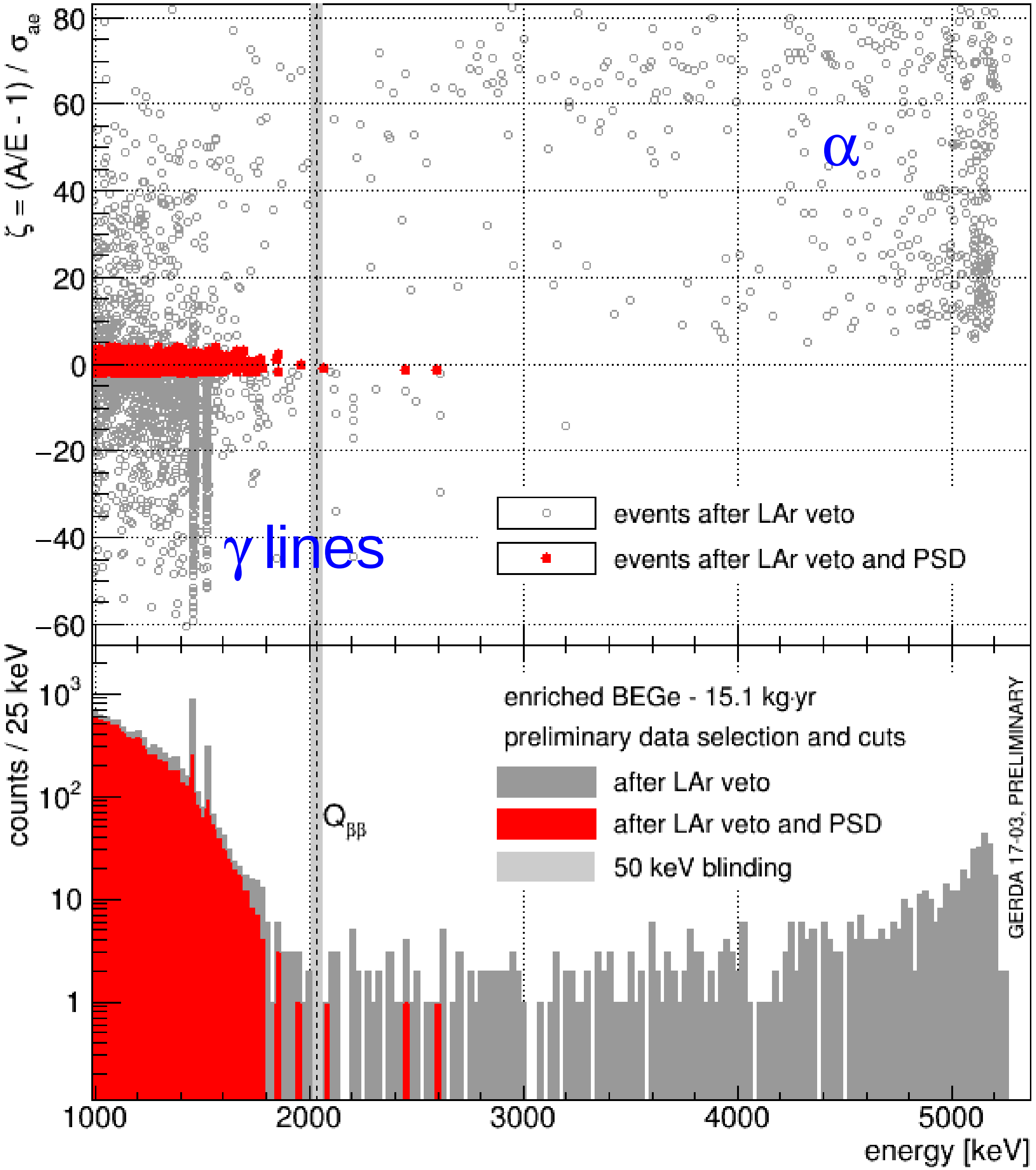


(a) Trajectories (b) Charge and current pulses

from JINST 6 (2011) P03005

BEGe = Ge drift detector: signal = sum of individual drifts
→ max current A / energy E for multi site events reduced compared to single site
A/E powerful discrimination variable

BEGe physics data



$0\nu\beta\beta$ proxies = $2\nu\beta\beta$ &

Double Escape Peak of 2615 keV γ

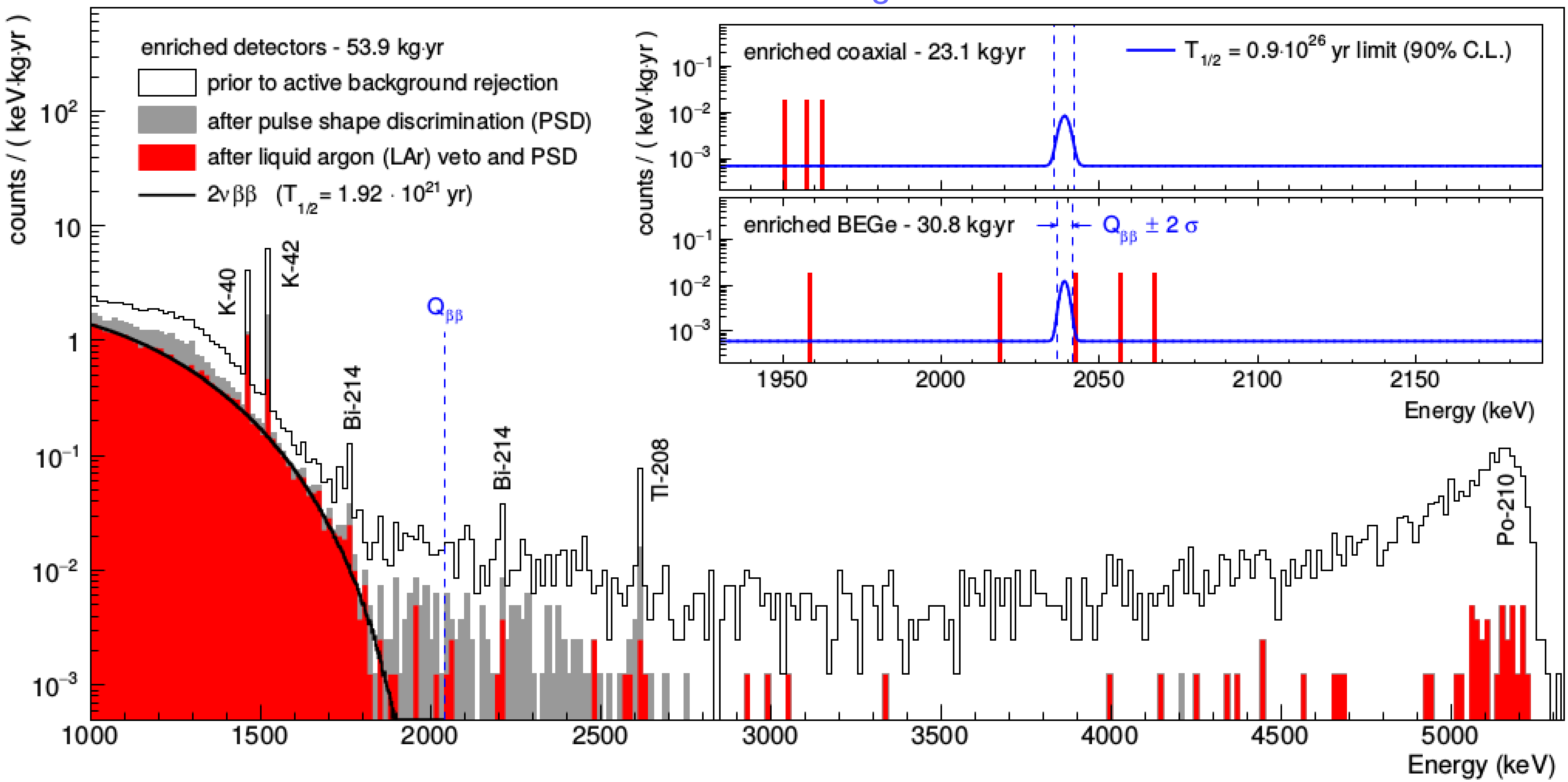
(γ + A → $e^+ e^-$ with 2x511 keV escape)

all α (surface) events removed,

γ lines suppressed by factor ~6

Final energy spectrum (until April 18)

after unblinding

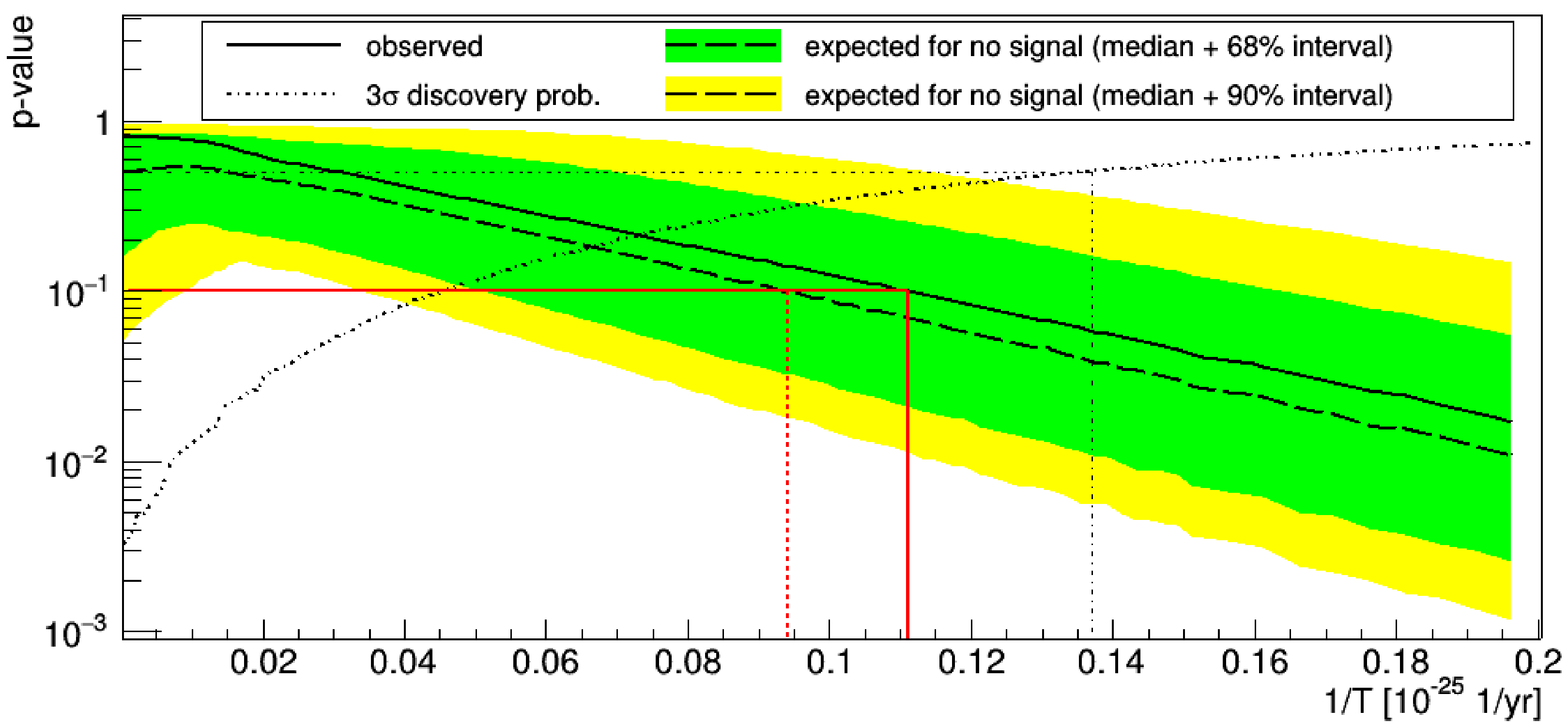


no signal, background ~0.6 cts/(keV t yr), FWHM ~ 3.0 / 3.6 keV for BEGe/coax detectors

Results (data until April 2018)

Dataset	Exposure (kg·yr)	Energy resolution FWHM (keV)	Efficiency	BI 10^{-3} cts/(keV·kg·yr)	N
PhaseI-Golden	17.9	4.3(1)	0.57(3)	11 ± 2	46
PhaseI-Silver	1.3	4.3(1)	0.57(3)	30 ± 10	10
PhaseI-BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}	3
PhaseI-Extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}	2
PhaseII-Coax1	5.0	3.6(1)	0.52(4)	$3.5^{+2.1}_{-1.5}$	4
PhaseII-Coax2	23.1	3.6(1)	0.48(4)	$0.6^{+0.4}_{-0.3}$	3
PhaseII-BEGe	30.8	3.0(1)	0.60(2)	$0.6^{+0.4}_{-0.3}$	5

BI * 100 kg yr * FWHM < 1
→ ‘background -free’



Frequentist:
90% C.L. limit
0.9×10^{26} yr
sensitivity
1.1×10^{26} yr

Bayesian:
90% C.I. limit
0.8×10^{26} yr
sensitivity
0.8×10^{26} yr

Comparison to other experiments

Experiment	Ref	Isotope	$\mathcal{E}$ kg·yr	limit $\mathcal{L}(T_{1/2})$ 10^{25} yr	sensitivity $\mathcal{S}(T_{1/2})$ 10^{25} yr	$m_{\beta\beta}$ meV using sensitivity
GERDA		^{76}Ge	82.4	9	11	112 - 228
Majorana	*(22)*	^{76}Ge	26.0	2.7	4.8	169 - 346
CUPID	*(23)*	^{82}Se	1.83	0.24	0.23	1165-2398
CUORE	*(24)*	^{130}Te	24.0	1.5	0.7	162 - 757
KamLAND-Zen	*(25)*	^{136}Xe	593.5	10.7	5.6	76 - 234
EXO-200	*(26)*	^{136}Xe	177.6	1.8	3.7	93 - 287
Combined						65 - 158

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

$G^{0\nu}$ = phase space factor

$M^{0\nu}$ = nuclear matrix element

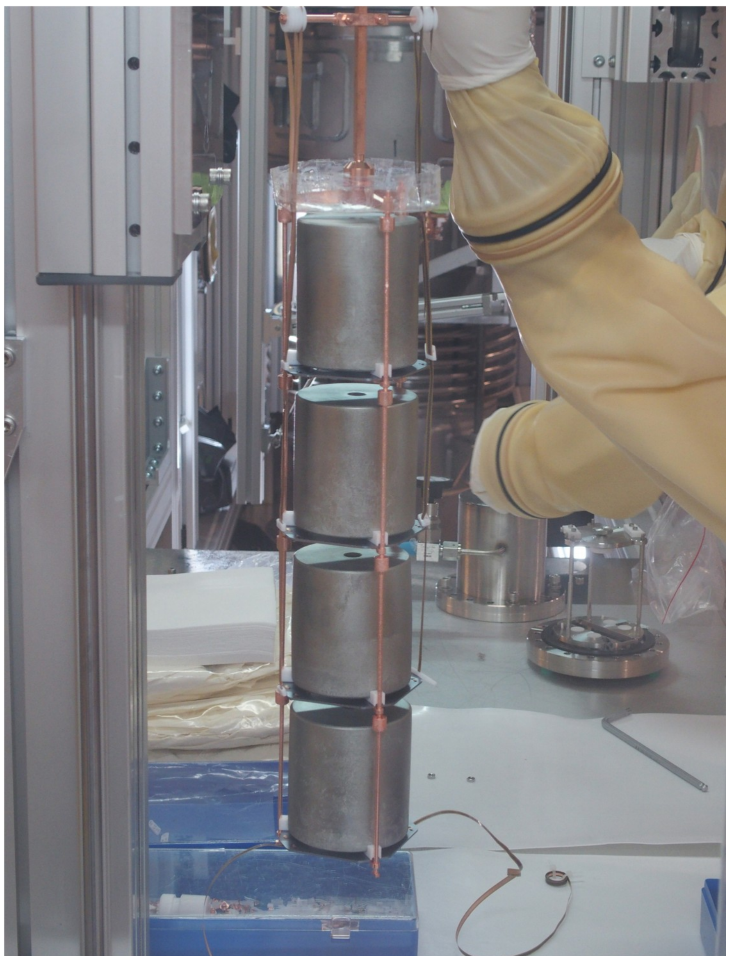
m_e = electron mass

numbers without g_A quenching

variation in $m_{\beta\beta}$ from spread $M^{0\nu}$ calc.

GERDA 2018 upgrade

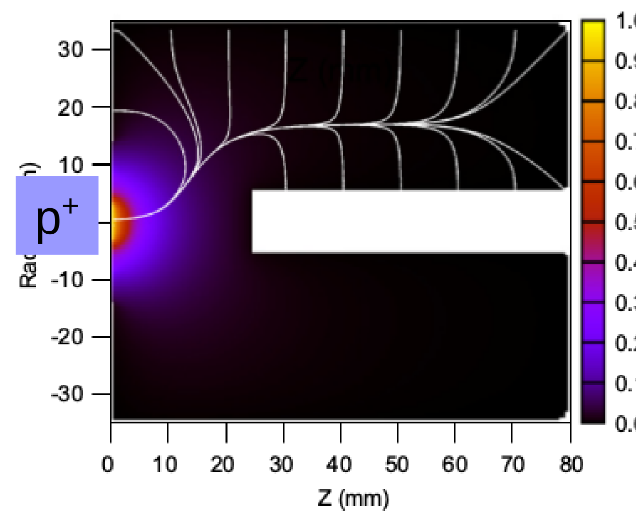
Goals: 1) more enriched Ge detectors – new type Inverted Coax



5x ~2 kg detectors (average BEGe ~700 g)
with point contact like BEGe
→ similar pulse shape performance
NIM A 891 (2018) 106

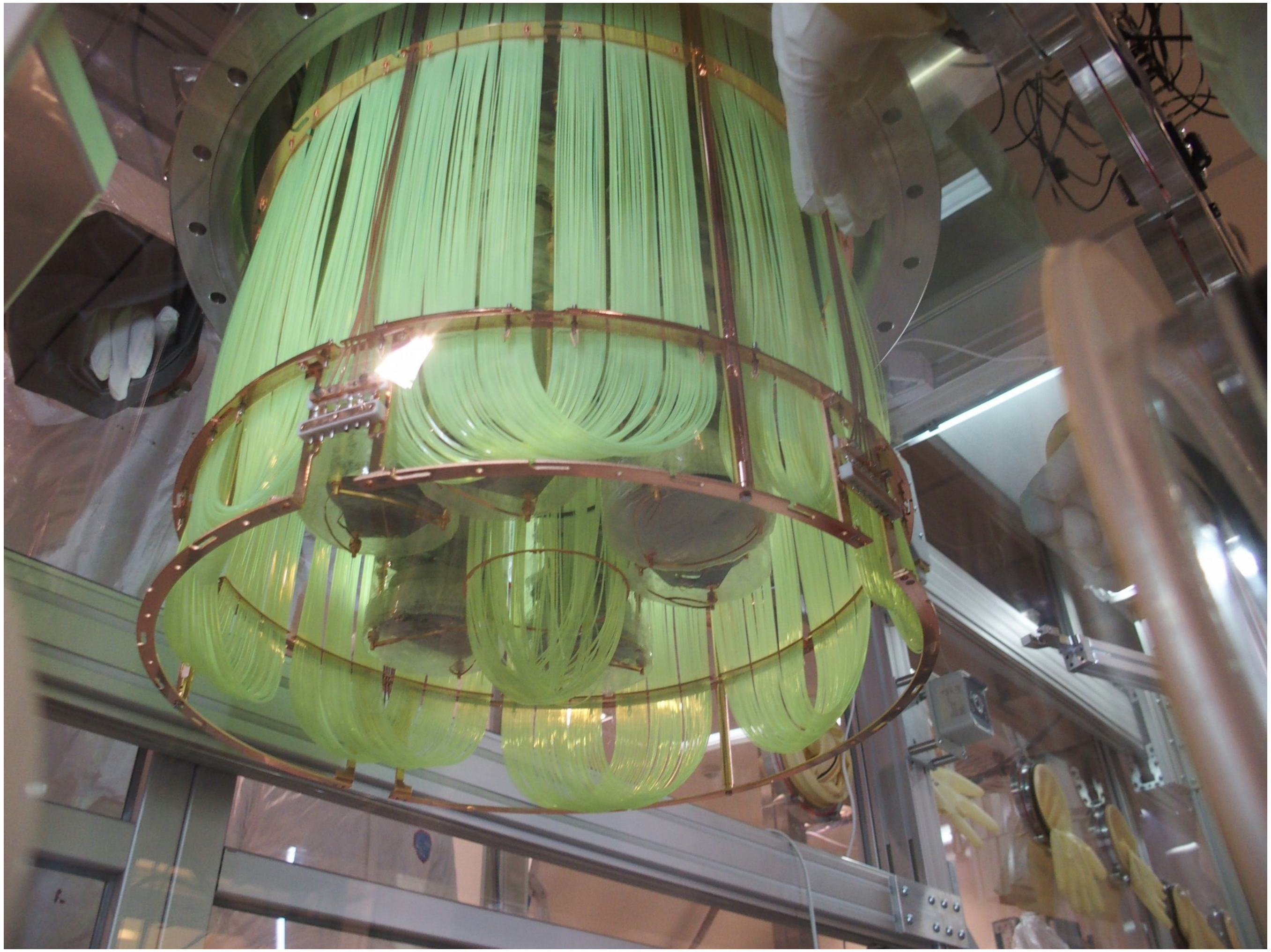
NIMA 665 (2011) 25

inverted
coax



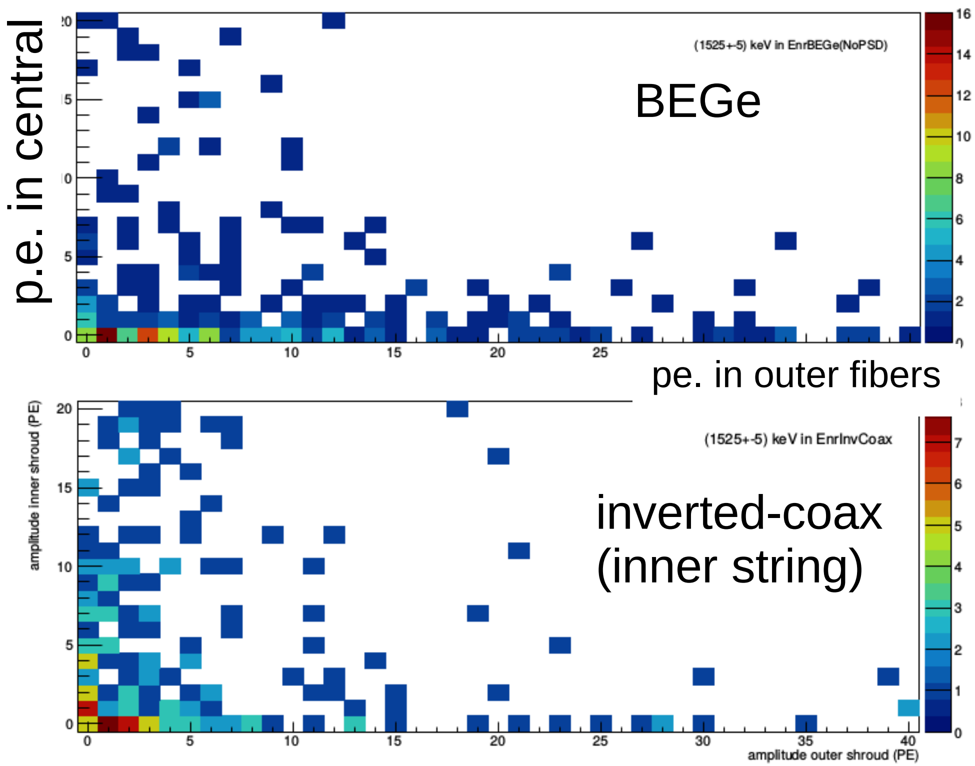
GERDA upgrade(2)

Goal: 2) replace detector readout cables with radiopurer ones
3) replace fiber shroud – more fibers and around center string (→ more light detected)



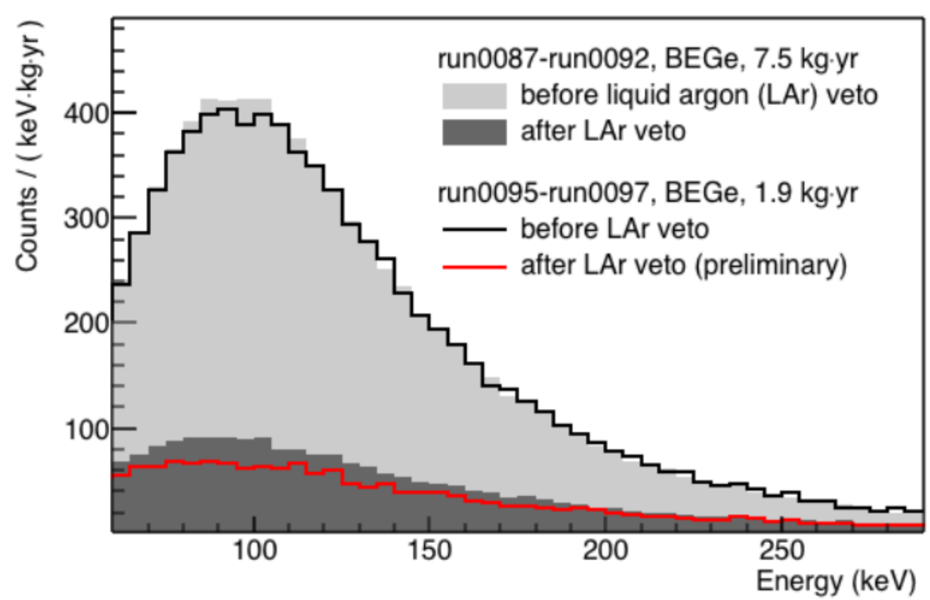
New LAr light readout

correlation of hits in outer and central fibers for ^{42}K line



additional rejection of events when outer fibers see no light

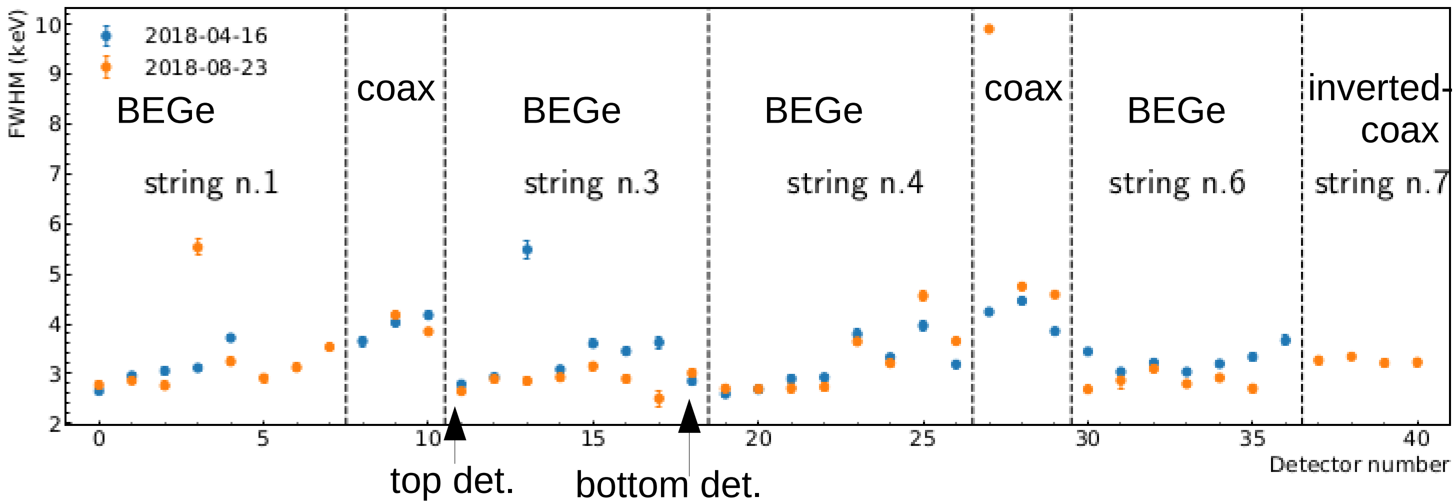
^{39}Ar suppression by LAr veto old/new

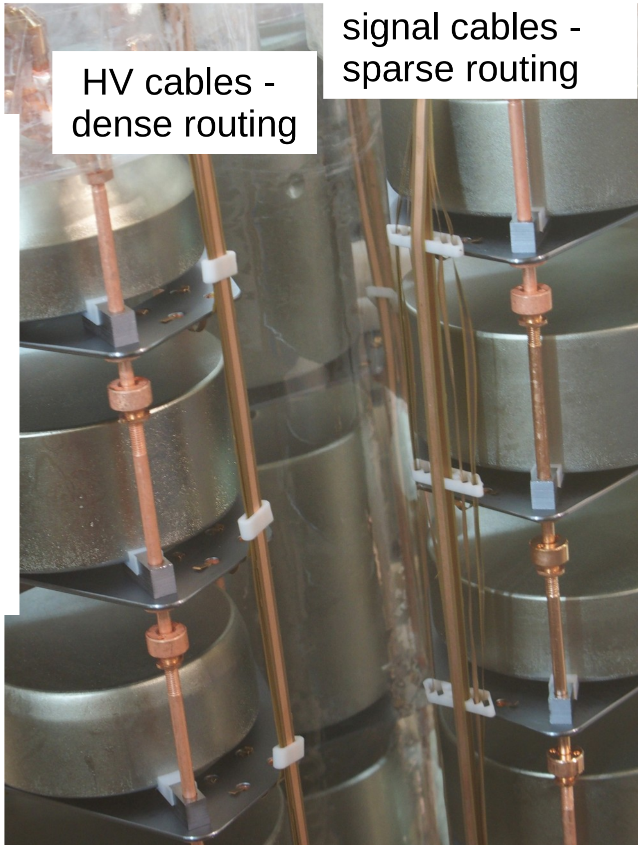


GERDA upgrade(3)

Goal: 4) improve electronics – larger drain current & lower parasitic capacitance & repair

energy FWHM of 2.6 MeV line vs channel number





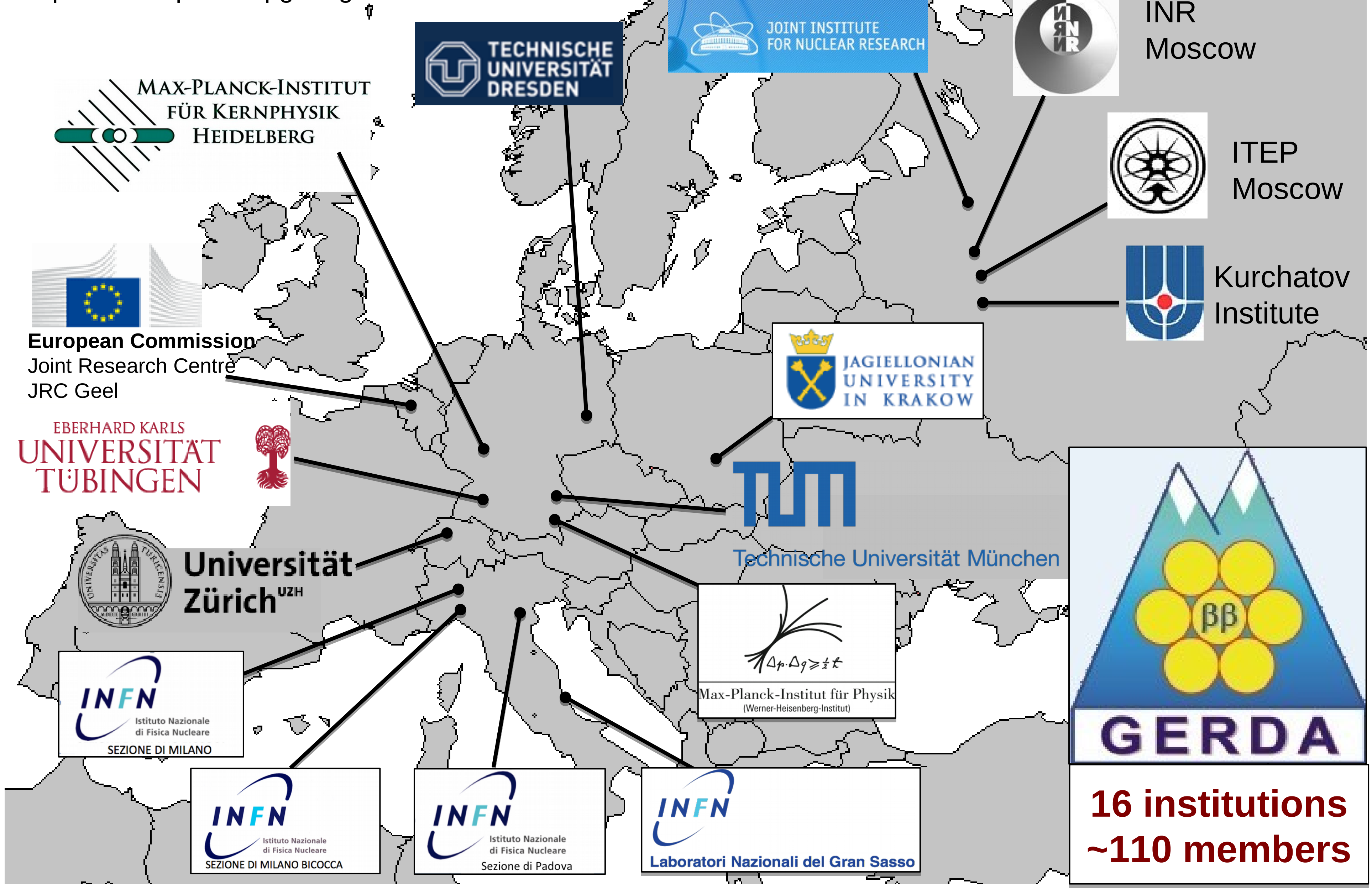
in general (BEGe) FWHM for E and A/E improved & dependence on string position much reduced

entire operation lasted ~5 weeks in April/May + 1 week in July

alpha background similar to before upgrade work → we did not contaminate detectors

GERDA collaboration

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



LEGEND-200

Idea: background in GERDA from 'close sources' like

$^{228}Th/^{226}Ra$ in cables ..., ^{42}K = daughter of ^{42}Ar, α on detector surface

→ can be reduced by purer materials & better LAr veto & better electronics

→ reduce background and increase mass

→ remain "background-free" & reach 10^{27} yr half-life sensitivity

= concept of LEGEND-200 using the current GERDA infrastructure

LEGEND-200 history:

- first presented in April 2015 at LNGS scientific committee meeting (GERDA-200)
- LEGEND collaboration formed in October 2016, first stage = 200 kg at LNGS
- proposal March 2018 at LNGS – accepted in June
- now: ~90% funded
- construction started, ~60 kg enriched Ge delivered, ~65 kg ordered, more next year
- goal: start data taking middle 2021

LEGEND collaboration

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.

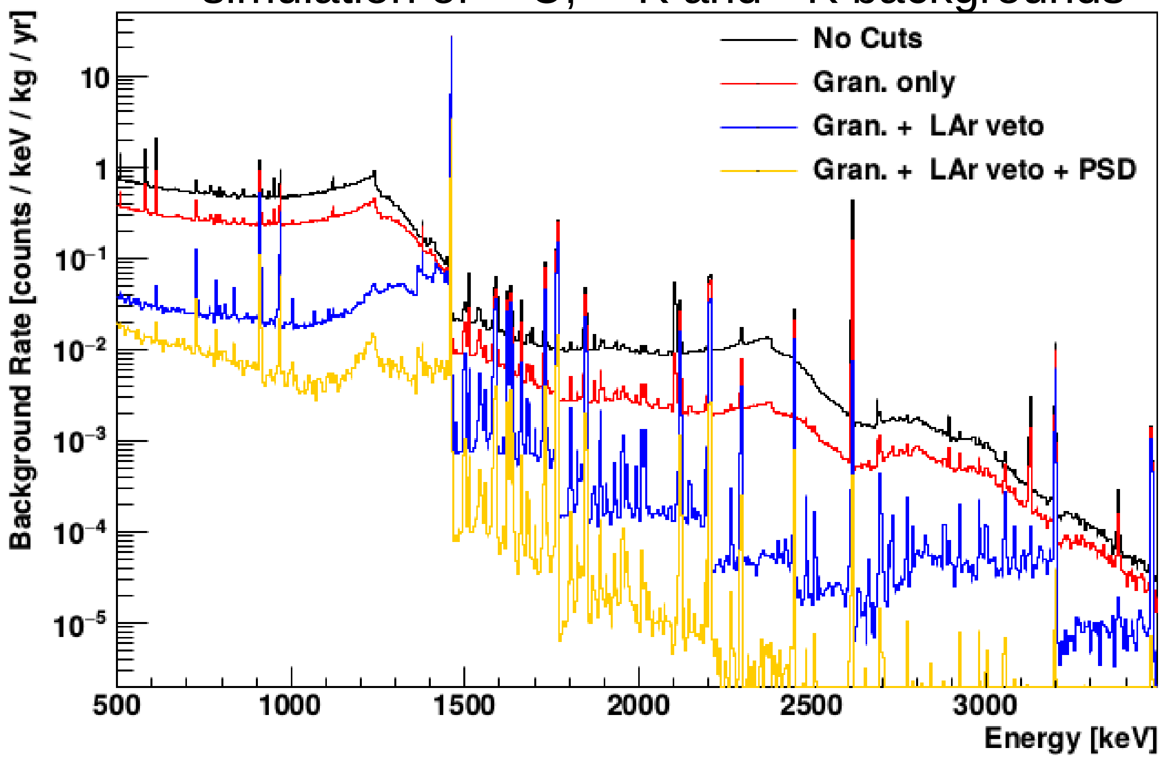
Joint Res. Centre, Geel
Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ.
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London
Los Alamos Natl. Lab.

Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Tech. Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

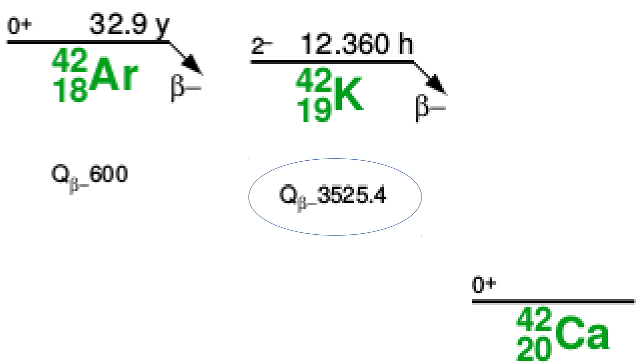
L200 background simulation

simulation of ^{238}U, ^{232}K and ^{40}K backgrounds



use known radiopurities, simulate pulse shape disc. & assumed LAr veto perf. (extrapolated from GERDA)

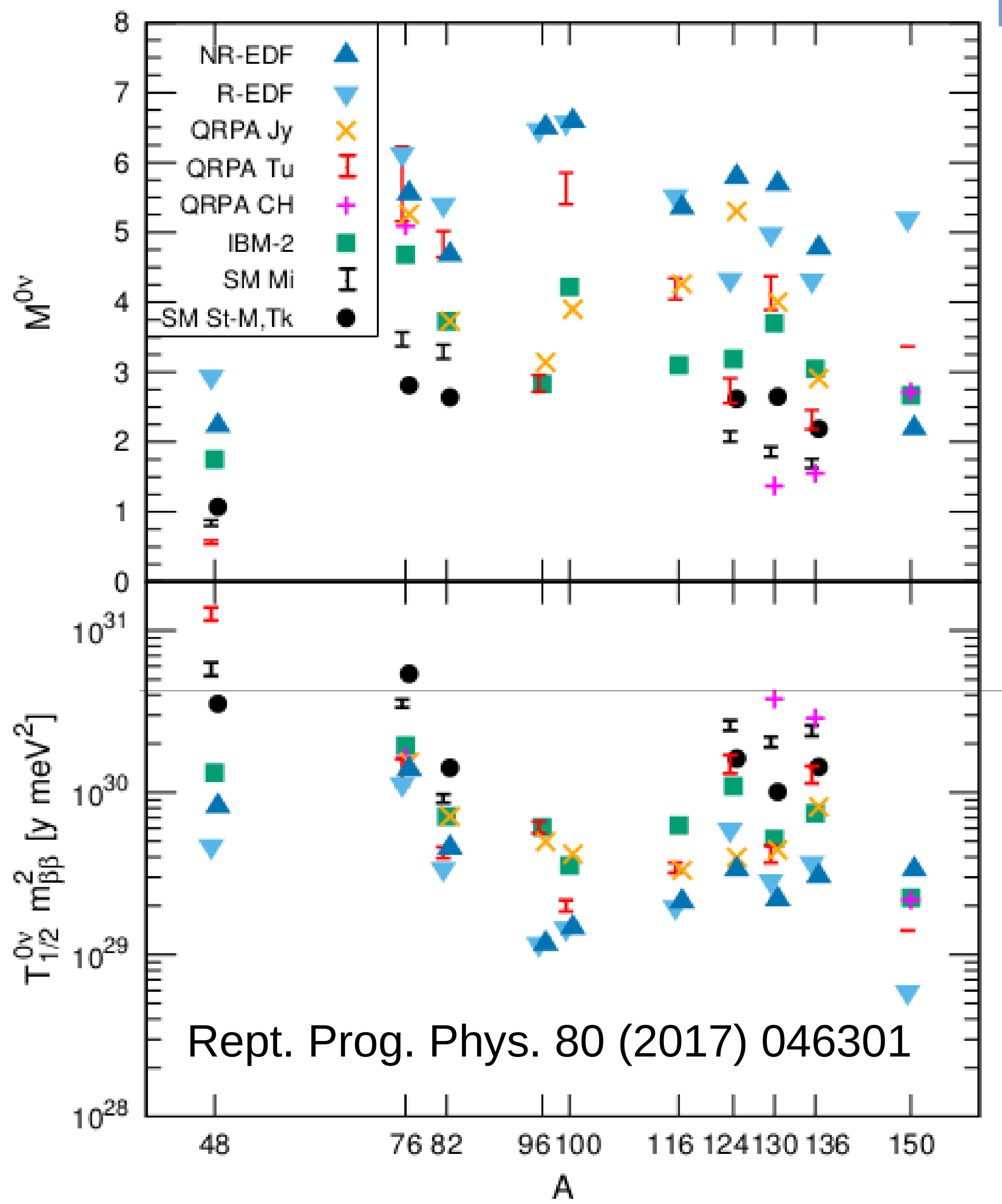
background from U/Th ~5 x 10^{-5} cnt/(keV kg yr)



total 2 x 10^{-4} cnt/(keV kg yr)
~ 1/3 current GERDA level

~5 x 10^{-5} cnt/(keV kg yr) after pulse shape

LEGEND-1000 goal



for inverted neutrino mass hierarchy
need to reach ~17 meV for mbb

→ half-life sensitivity beyond 10^{28} yr for ^{76}Ge

need background <3 x 10^{-5} cnt/(keV kg yr)

& 1000 kg enriched Ge detectors

= LEGEND-1000 goal

10^{28} yr for 20 meV effective mass
0.6 ^{76}Ge decays per t*yr exposure
0.3 ^{136}Xe decays per t*yr exposure
(before enrichment fraction & cuts)
→ background free conditions required

Summary

- GERDA is performing well, background ~ 0.6 cnt/(keV t yr) with FWHM ~3 keV
  → lowest background if normalized to resolution
- $T_{1/2}$ sensitivity reached 1.1 x 10^{26} yr last spring
- upgrade work finished, back to data taking, background further reduced ?
- future = LEGEND-200 @ LNGS, construction ongoing
- more distant program = LEGEND-1000