Neutrinoless double beta decay searches of ^{76}Ge

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

LEGEND

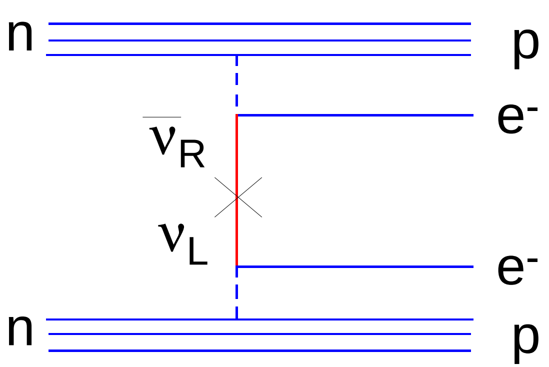
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

GERDA

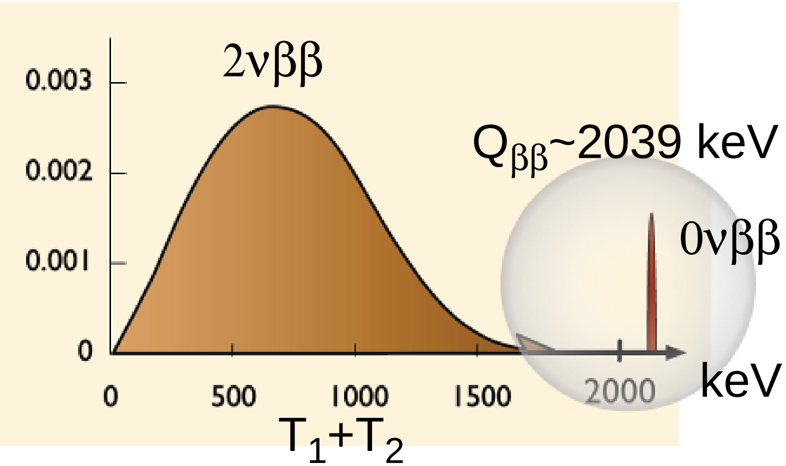
Bernhard Schwingenheuer
ICPPA, 26 Oct 2018

Signal and Sensitivity

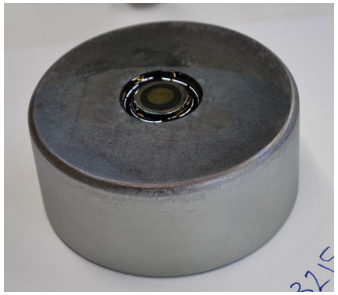
$0\nu\beta\beta$ decay, $\Delta L=2$



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



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 $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

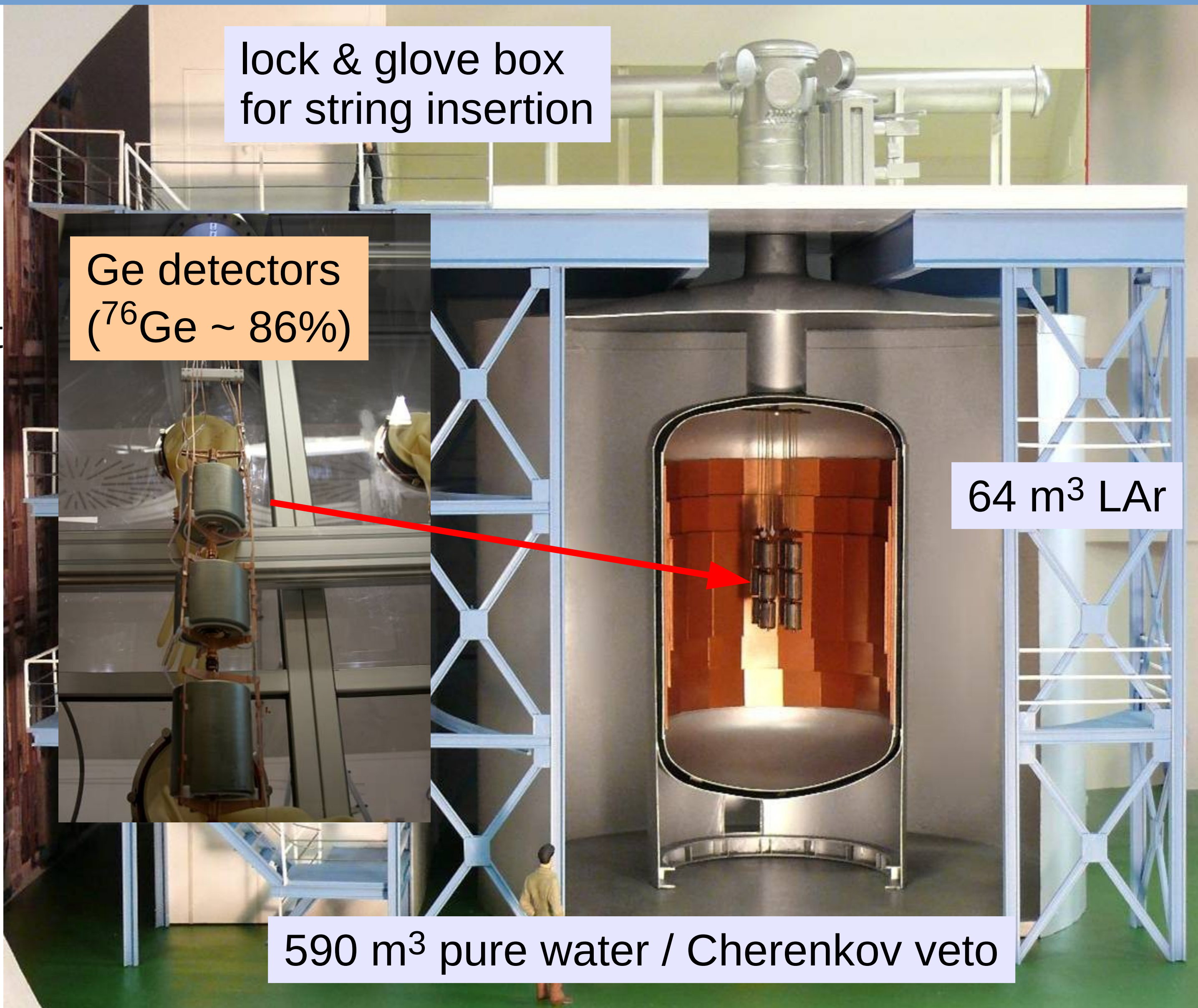
Experimental sensitivity

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

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A = Avogadro constant
a = fraction of $0\nu\beta\beta$ 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

GERDA @ LNGS

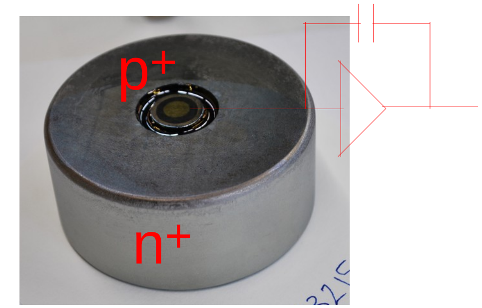


EPJ C73 (2013) 2330 and Eur. Phys. J. C78 (2018) 388

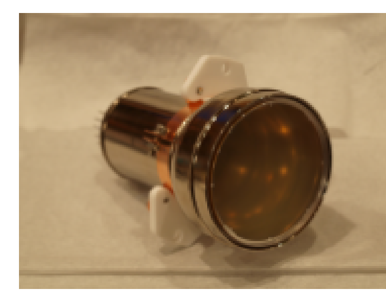
Phase I (2011-13)

Phase II:

2x Ge mass (30 BEGe det.)

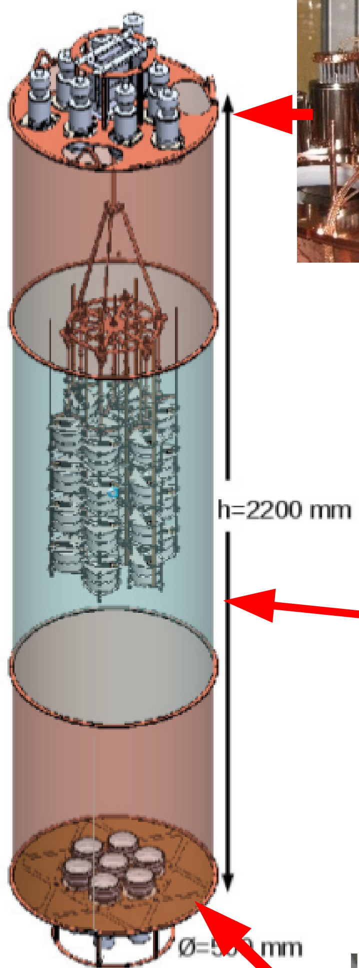


LAr scint. light readout

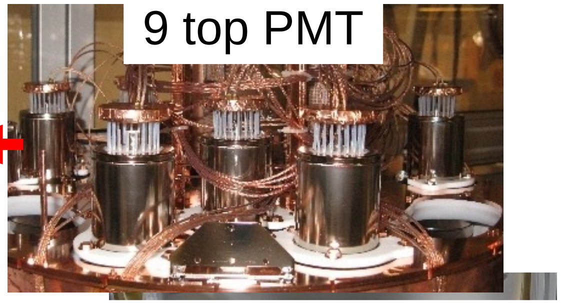


started end 2015

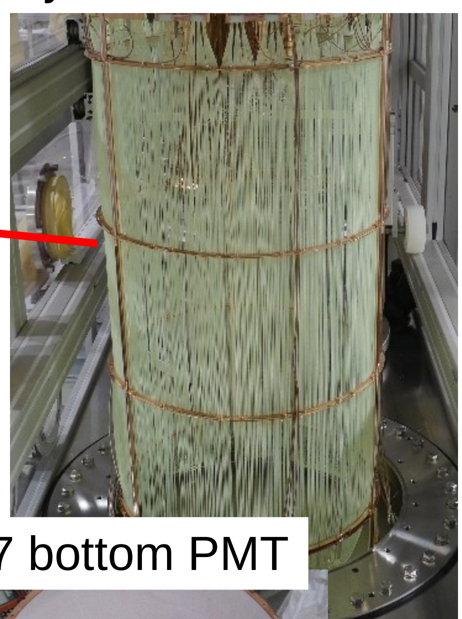
Liquid argon veto



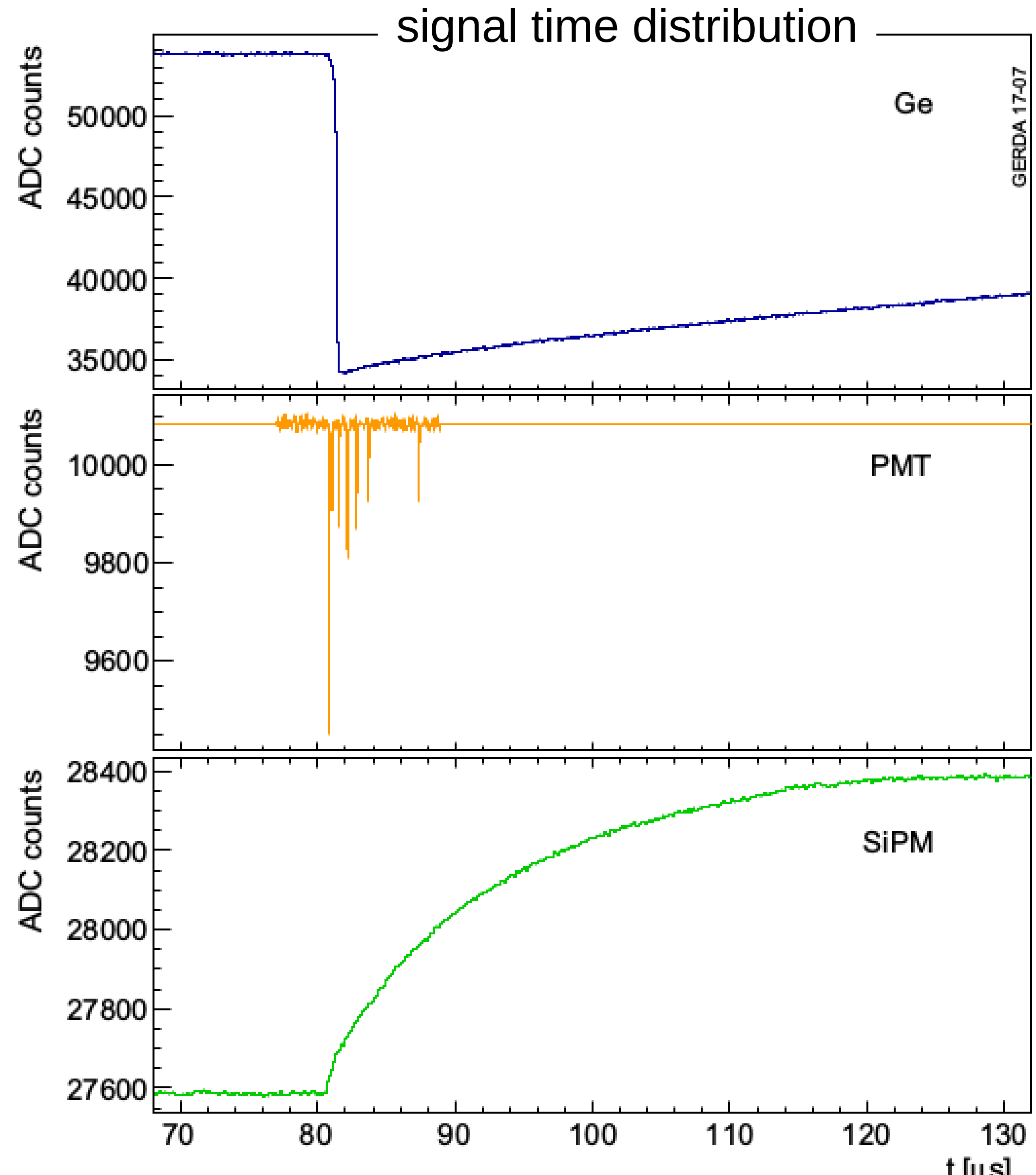
9 top PMT



810 fibers read out
by 90 SiPM → 15 ch



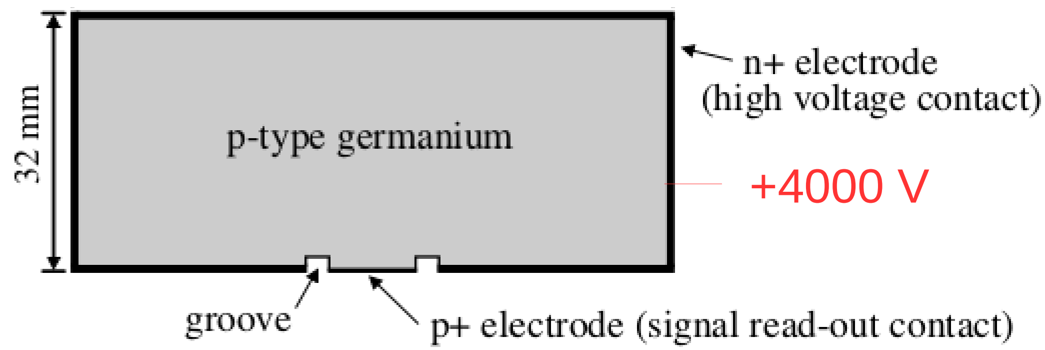
7 bottom PMT



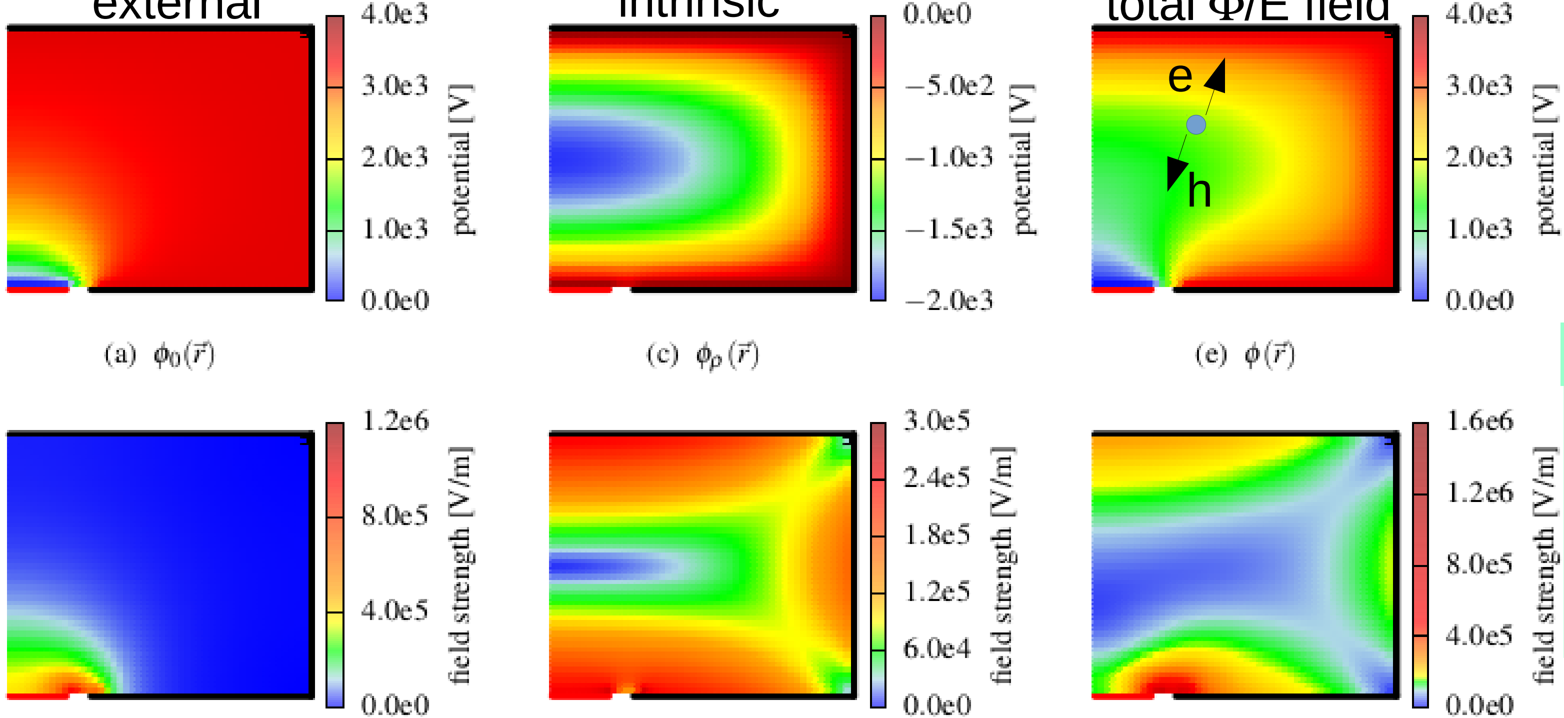
EPJ C78 (2018) 388

Time profile of Ge signal

Broad Energy Germanium det. (BEGe)



diode in reverse bias:
- no free carriers
- all 'holes' filled with e⁻
  - → space charge
  - → external field E
  - & intrinsic field E



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

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

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

→ intrinsic field does not provide "work" on moving charges

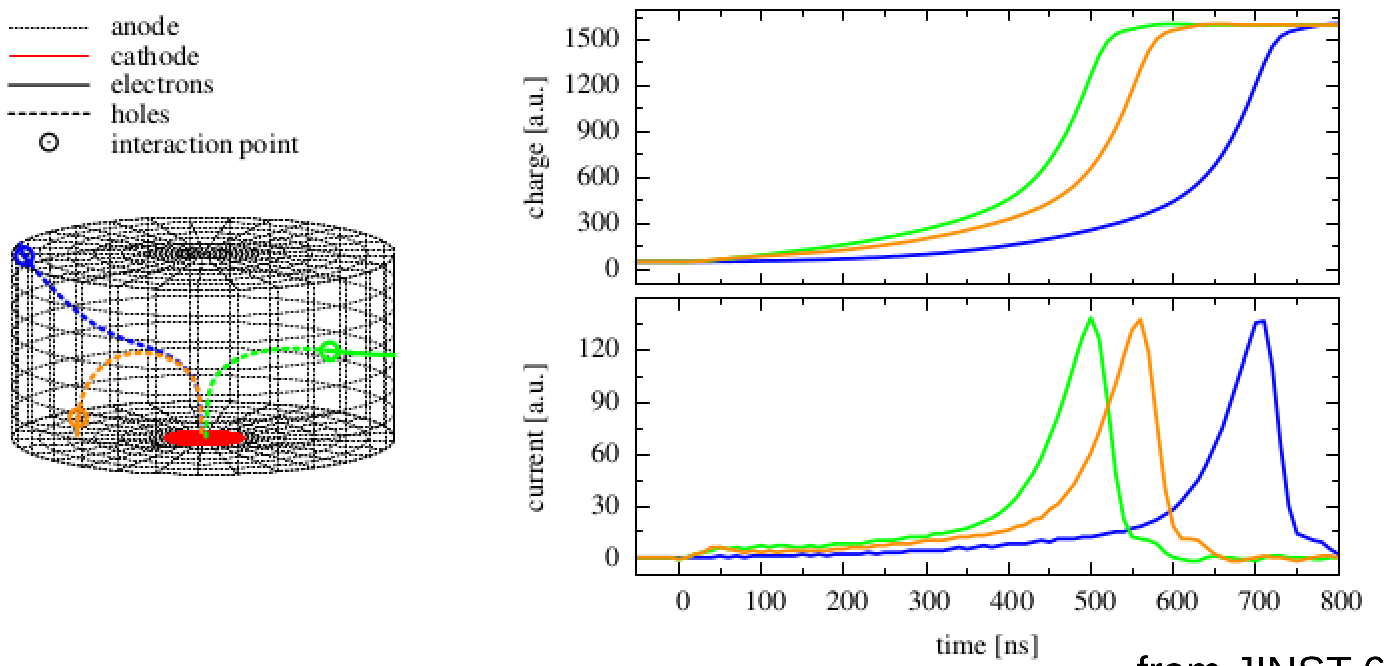
$signal\ Q(t) \propto \phi_{ext}(\vec{r}(t))$

Shockley-Ramo theorem

drift velocity ~ total E
signal ~ external Φ
➔ peaks at p+ electrode

from JINST 6 (2011) P03005

Pulse shape discrimination



(a) Trajectories

(b) Charge and current pulses

from JINST 6 (2011) P03005

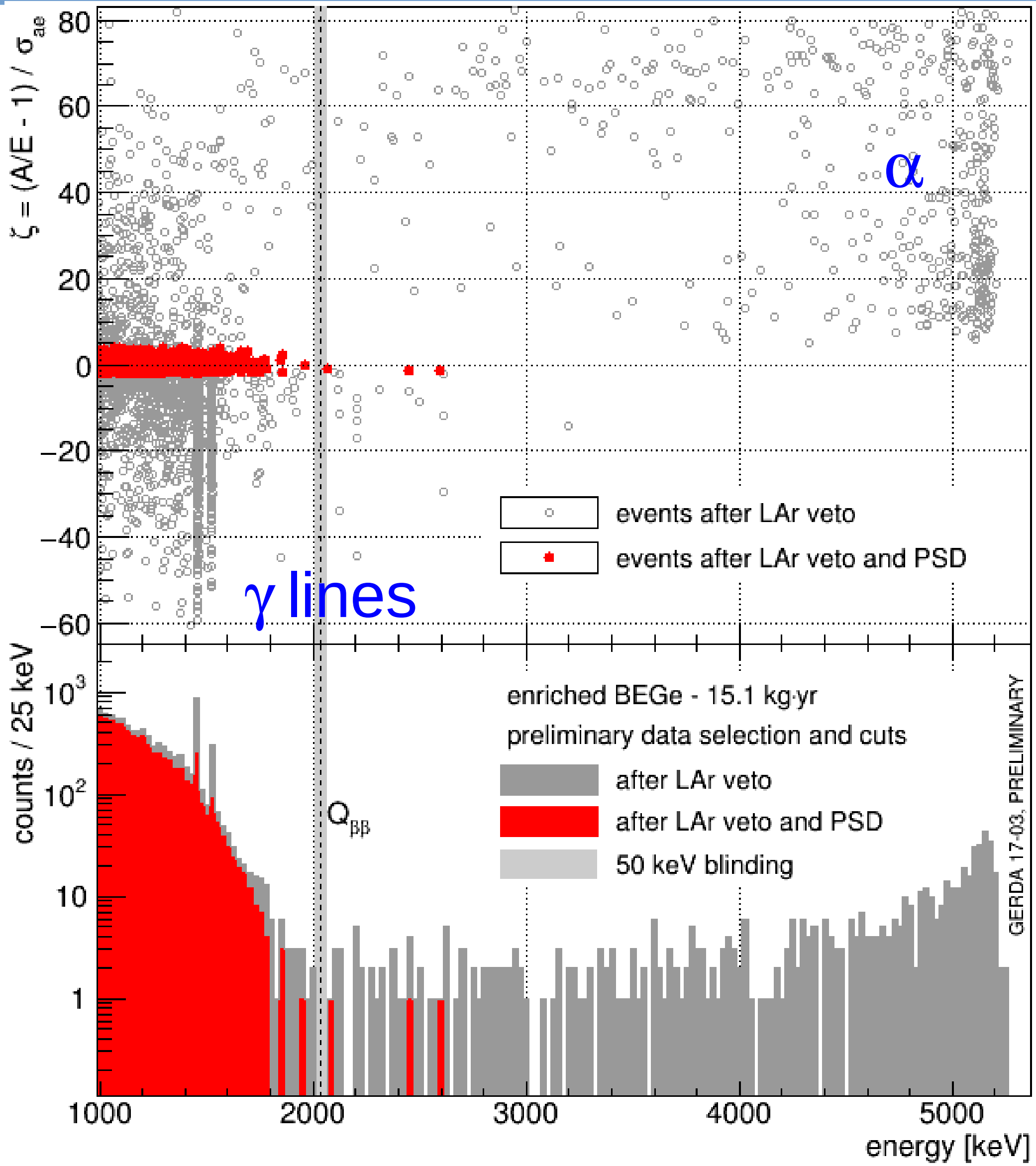
0νββ: single-site event,

γ with multiple Compton = multi-site

A = maximum of current is reduced for multi-site versus single-site

A/E powerful discrimination variable (E=energy)

GERDA: BEGe pulse shape discrimination



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

Double Escape Peak of 2615 keV γ

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

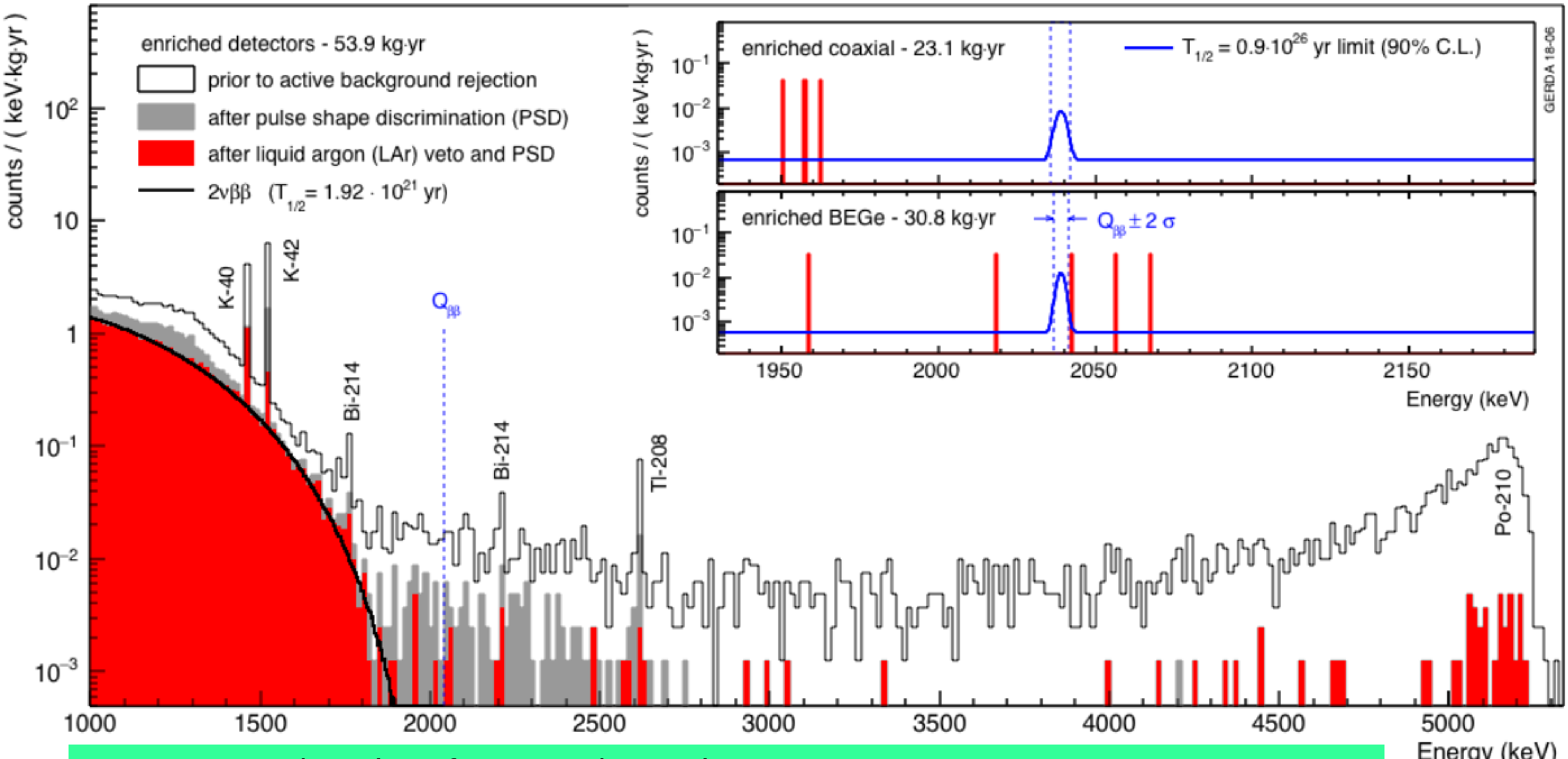
"all" α (surface) events removed,

γ lines suppressed by factor ~6

keep 87.6 ± 2.5 % of signal events

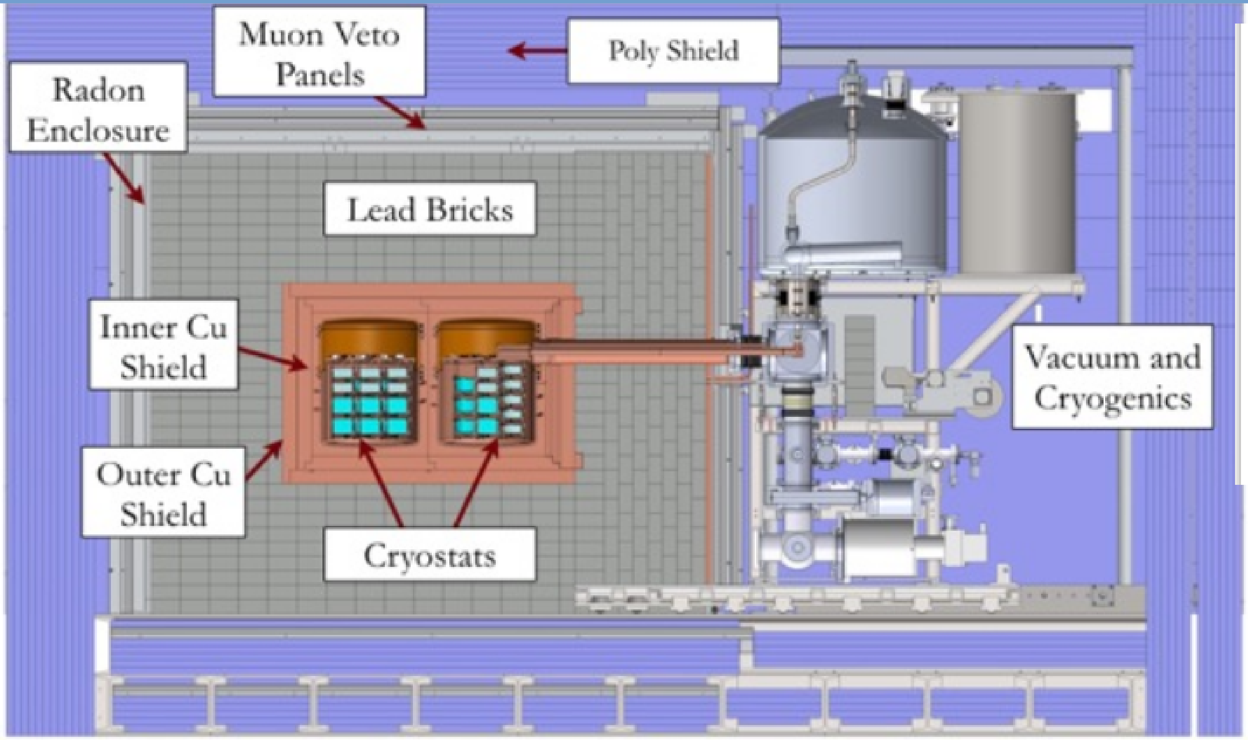
GERDA spectrum (data until April 18)

after unblinding



FWHM ~ 3.0 / 3.6 keV for BEGe/coax detectors
background 0.6 cts/(keV t yr) recent data set → “background-free” until 100 kg yr

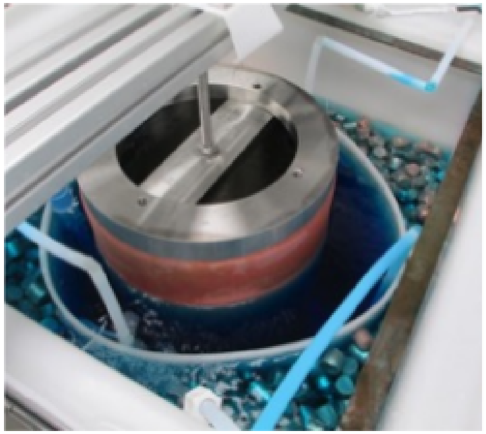
Majorana @ SURF

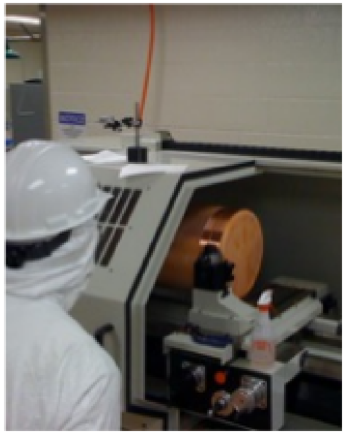


[N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)]

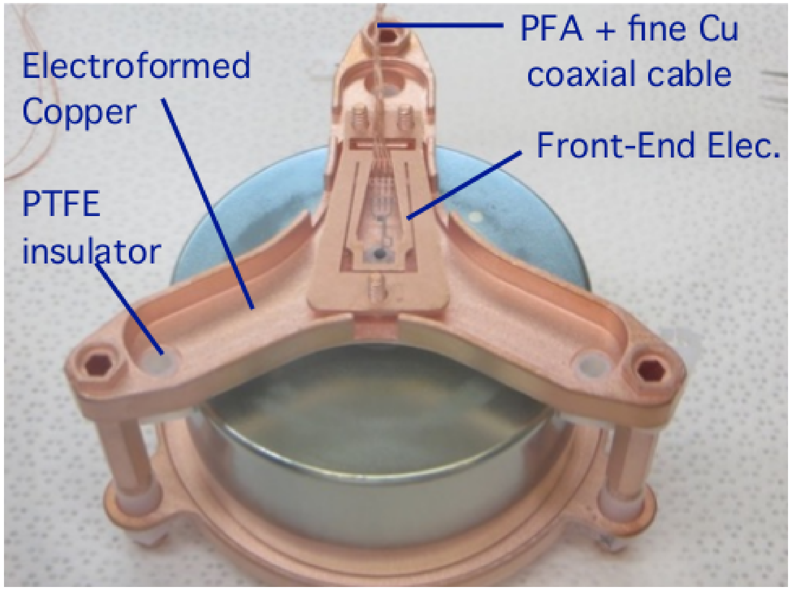
‘conventional’ shielding with Cu+Pb
low background electronics, cables, ...

35 PPC with 88% ^{76}Ge (30 kg)
23 BEGe (natural, 14 kg)

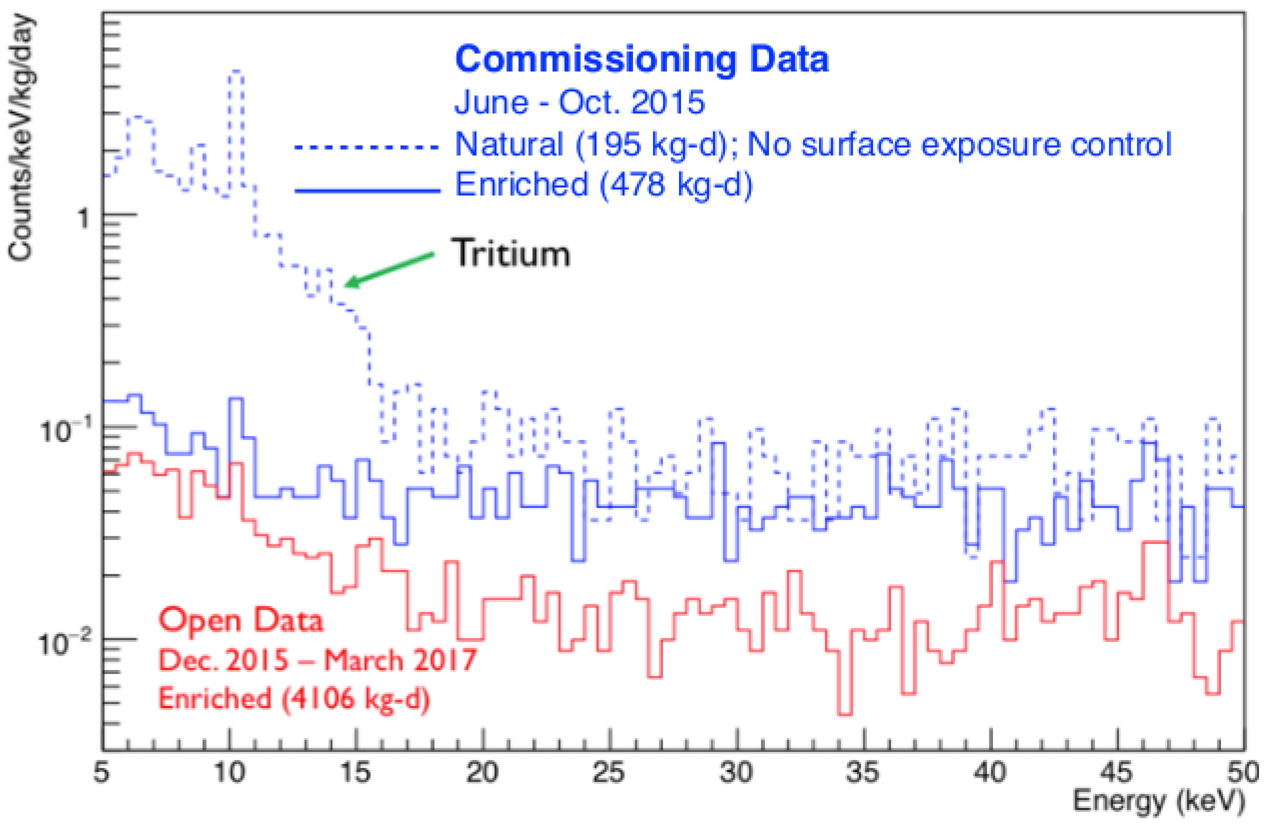




Cu with <0.1 μBq/kg in Th/U (avg)



Majorana: low energy results



very good energy resolution:
0.4 keV at 10.4 keV
→ sub keV trigger threshold!
2.5 keV at $Q_{\beta\beta}$

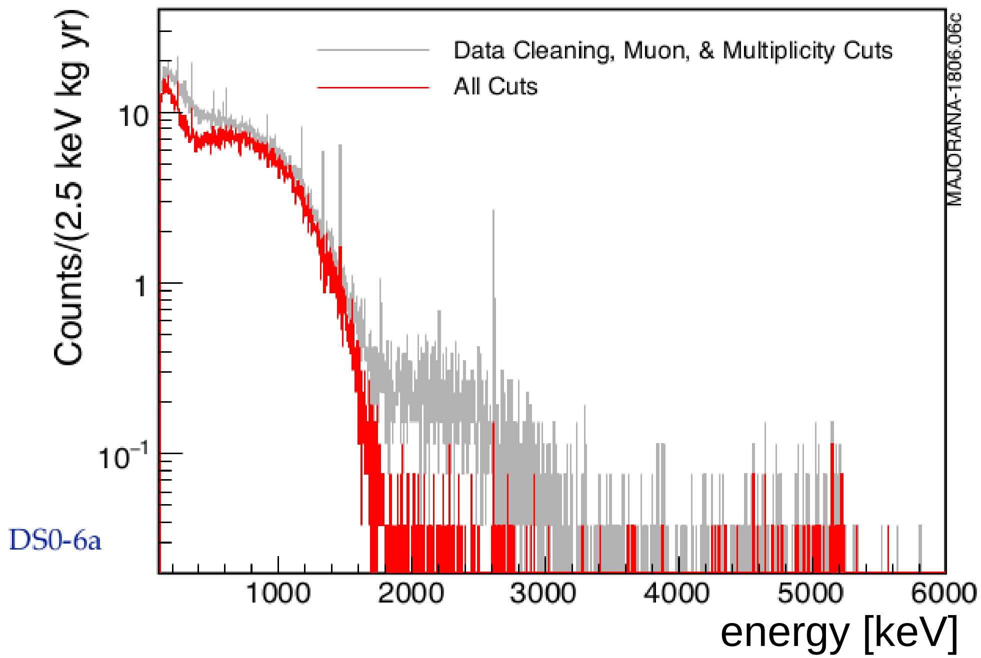
allows analysis of
- dark matter
- solar axion
- e → 3ν

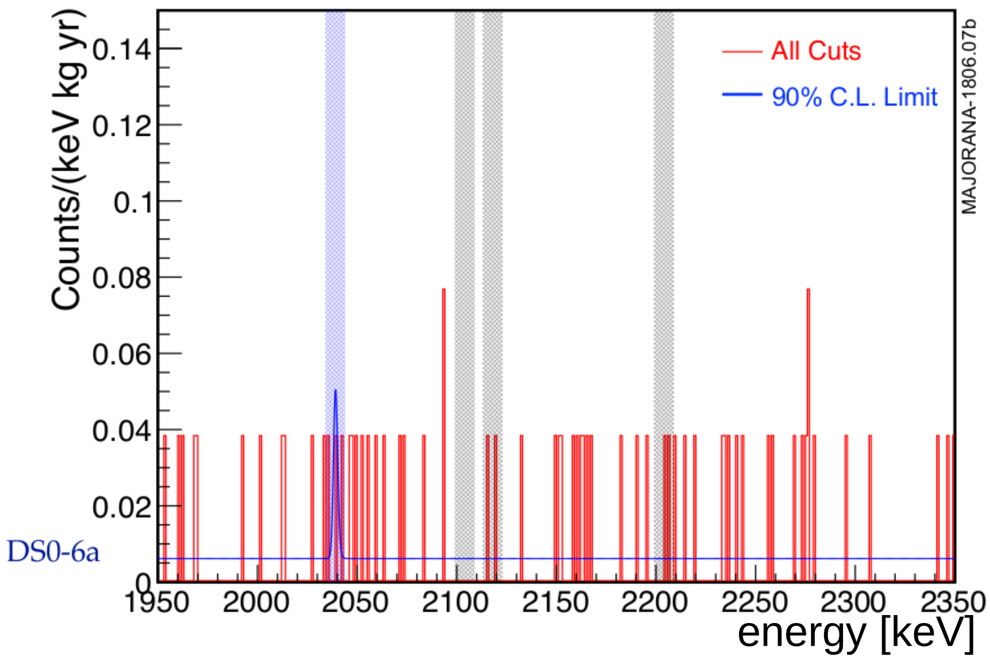
Pauli exclusion principle
PRL 118 (2017) 161801

lightly ionizing particles
PRL 120 (2018) 211804

Majorana 2018 update on 0νββ

point contact detectors → same A/E pulse shape analysis
additional background from α decays → additional 'delayed charge recovery' cut (99% eff.)
first result in PRL 120 (2018) 132502, at Neutrino 2018 update with 26.0 kg yr exposure





FWHM = 2.5 keV, background ~ 5 cts/(keV t yr)

Results on 0νββ

		exposure* [kg yr]	FWHM [keV]	background# [cts/(FWHM t yr)]	$T_{1/2}$ limit [10^{25} yr]	sensitivity [10^{25} yr]	$m_{\beta\beta}$ limit$ [meV]
GERDA	Ge	64	3	4	9	11	110-230
Majorana	Ge	21	2.5	17	2.7	4.8	160-350
Cupid-0	Se	1.8	23	200	0.24	0.23	390-810
CUORE	Te	24	7.7	400	1.3	0.7	160-760
EXO-200	Xe	180	72	130	1.8	3.8	90-290
Kaml-Zen	Xe	500	260	100	10.7	5.6	80-230

* exposure using isotope mass in active volume

background scaled by 1/efficiency

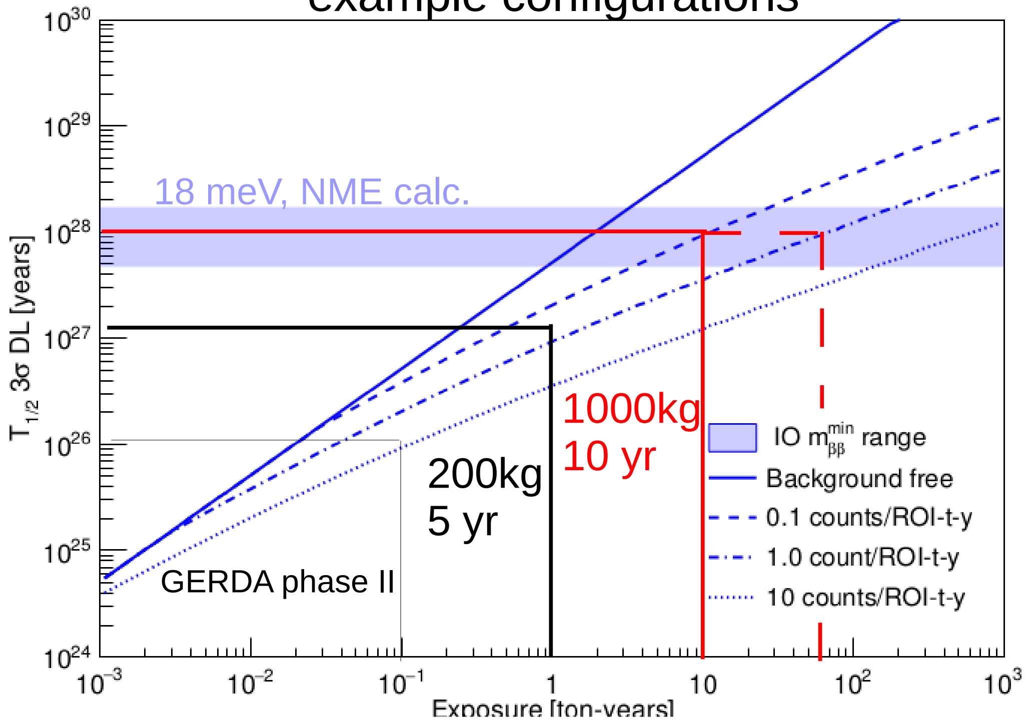
$ since the exp. limits have random values half-life sensitivity values are used, g_A=1.25, using NME listed in J. Engel, J. Menéndez, Rept. Prog. Phys. 80, 046301 (2017)

Future project for ^{76}Ge: LEGEND

Ge experiments have currently the lowest background in FWHM units
→ motivates new projects with more mass & reduced background
to remain "background-free"

"ultimate" goal is to reach a **discovery** potential below 20 meV using **worst** NME

example configurations



discovery: 50% chance for a 3σ signal

possible configuration:
1000 kg, 10 yr live, bkg <0.1 cts/(ROI t yr)

bad alternative:
1000 kg, 60 yr live, bkg ~ 1 cts/(ROI t yr)

proceed with a staged approach:
improve mass and background in steps
- faster start
- learn about backgrounds in each step
- physics – incl. topics for PhD students

LEGEND-200: reuse existing infrastructure

Idea: background in GERDA from 'close sources' like

→ 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: use the current GERDA infrastructure
+ improvements from Majorana and other experiments

LEGEND-200 history:

- 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.

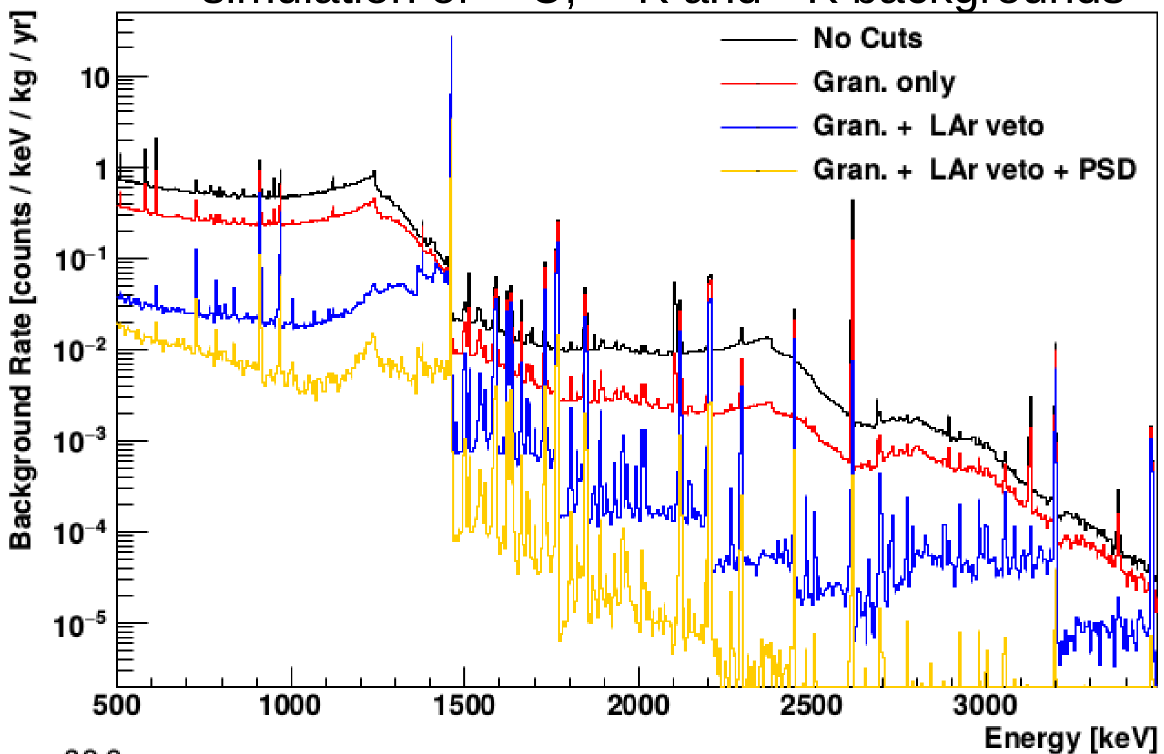
Joint Res. Centre, Geel
Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ.
Queens Univ.

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

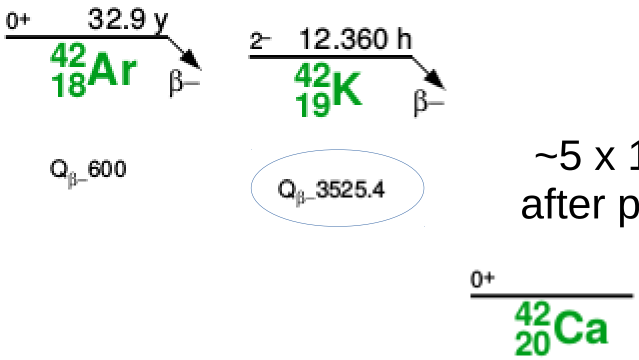
L200 background simulation

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)



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

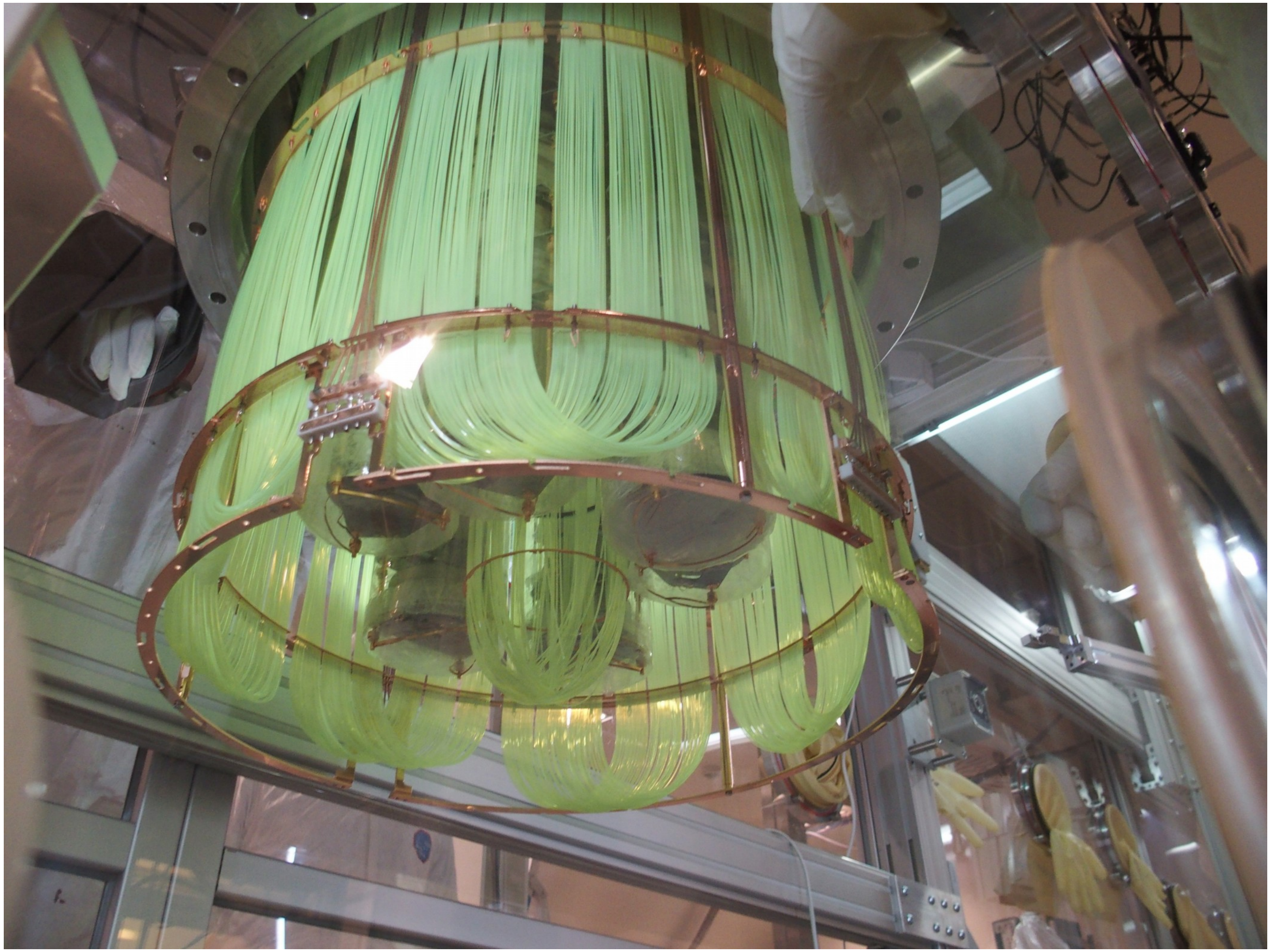
total 2 x 10^{-4} cnt/(keV kg yr)
~ 1/3 current GERDA level,
"modest" goal

Summary

- Ge experiments have the lowest background (in ROI) and best energy resolution
- $0\nu\beta\beta$ half-life sensitivity reached 10^{26} yr for ^{76}Ge
- LEGEND is next ^{76}Ge project
- LEGEND-200 is using existing infrastructure – construction has started

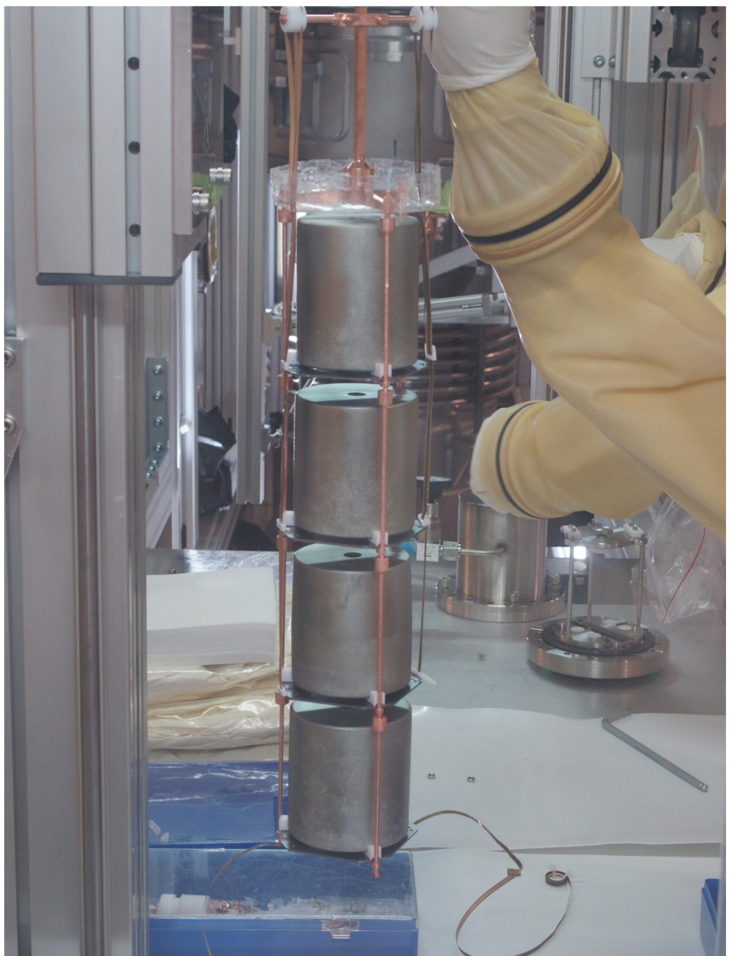
GERDA upgrade(2)

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



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