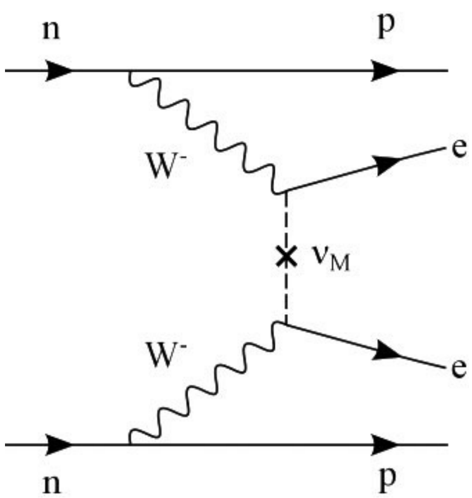
Search for neutrinoless double beta decay with GERDA

Ann-Kathrin Schütz
On behalf the GERDA collaboration

31st Rencontres de Blois Particle Physics and Cosmology
France, 4 June 2019

Neutrinoless Double Beta Decay

- process beyond SM
- lepton number violating $\Delta L = 2$
- in principle all $2\nu\beta\beta$ isotopes are candidates
- majorana mass component
- massive neutrino exchange
- constraints on lightest mass eigenstate
- neutrino mass hierarchy



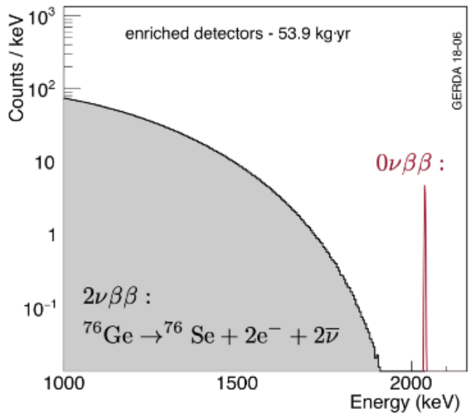
Search for $0\nu\beta\beta$ of ^{76}Ge:

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

⇒ $\Delta L = 2$

⇒ beyond Standard Model physics

⇒ Majorana mass or other L-violating physics



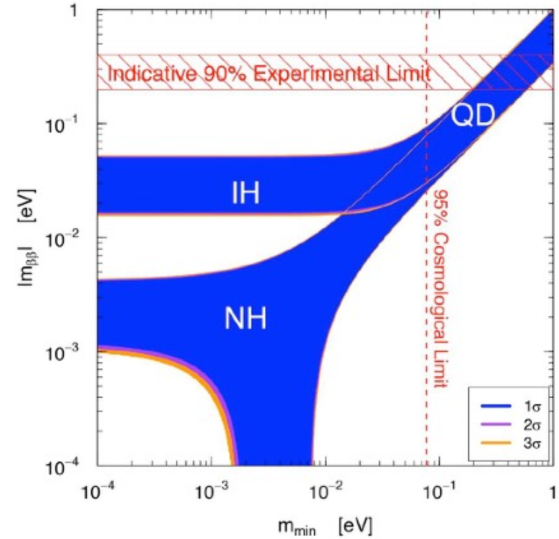
Signal and Sensitivity

$$\frac{1}{T_{1/2}} = G^{0\nu} \left(\frac{g_A^{eff}}{g_A}\right)^2 |\mathcal{M}^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

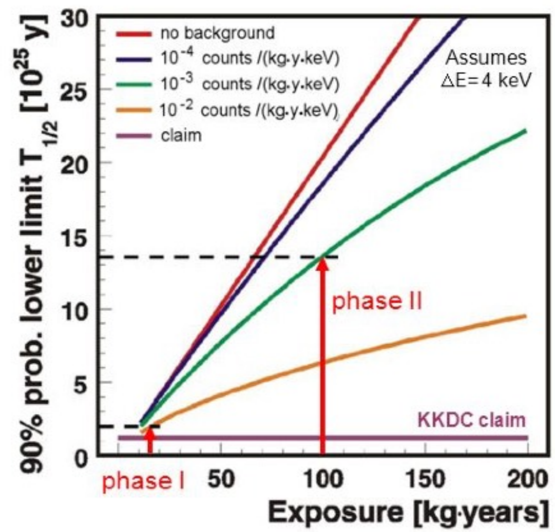
$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

with background $\quad T_{1/2} \sim \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$

background-free $\quad T_{1/2} \sim M \cdot t$

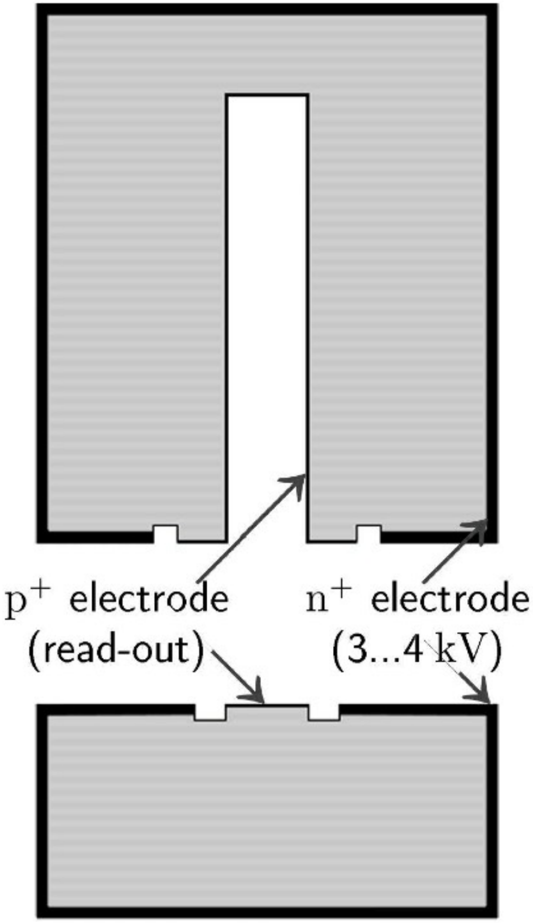


Bilenky, Giunti [Int.J.Mod.Phy. A30 (2015) 1530001]

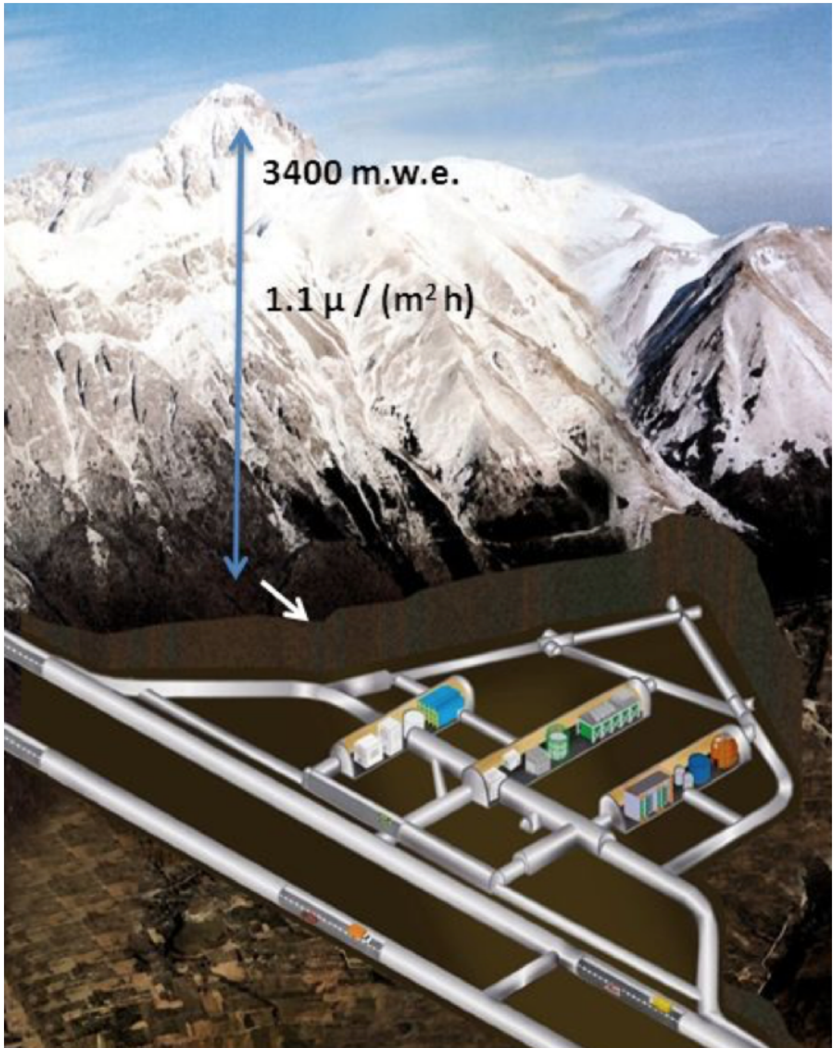


Germanium Detectors

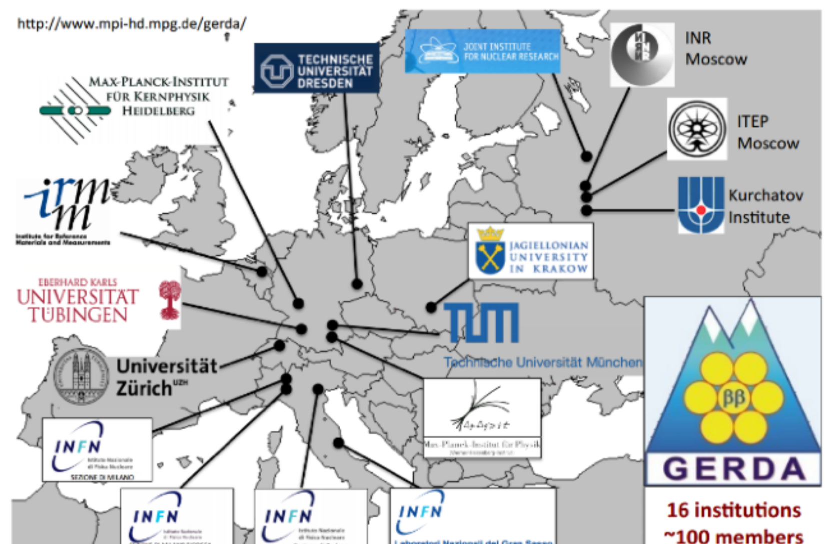
- **Q-value of ^{76}Ge: $Q_{\beta\beta}$=2039 keV**
- **High purity Ge detectors (87% ^{76}Ge):**
  - source=detector
    ⇒ high detection efficiency
  - ultra radio-pure
    ⇒ no intrinsic U/Th background
  - high density
    ⇒ 0vββ point like events
  - semiconductor ⇒ ΔE ≈ 0.2% at $Q_{\beta\beta}$
- **0vββ signature:**
  - point-like energy deposition in detector bulk volume
  - sharp energy peak at 2039 keV (FWHM = 3-4 keV)



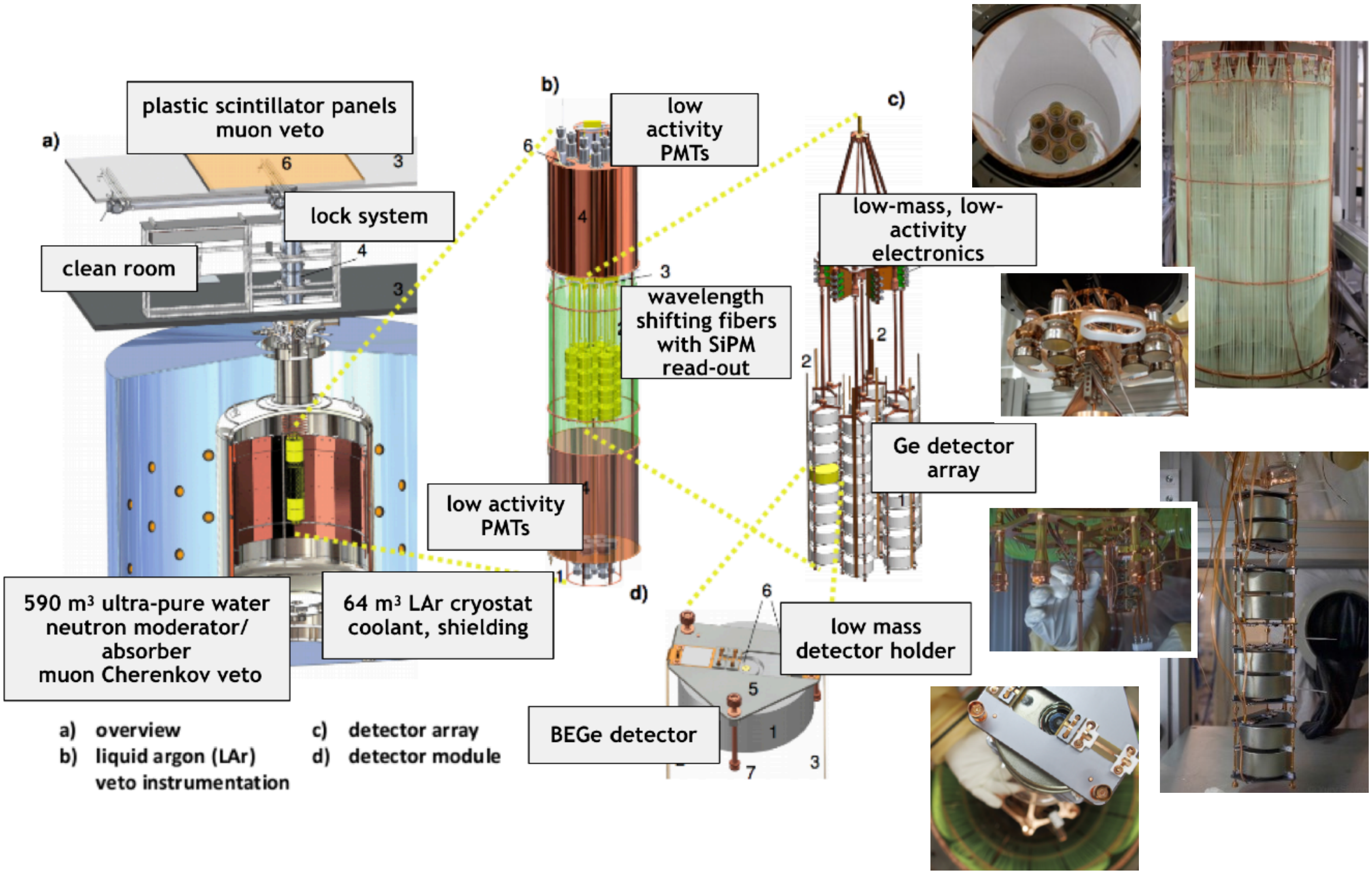
GERDA @ LNGS


3400 m.w.e.
1.1 μ / (m² h)


LNGS


http://www.mpi-hd.mpg.de/gerda/
Max-Planck-Institut für Kernphysik Heidelberg
Technische Universität Dresden
Joint Institute for Nuclear Research
INR Moscow
ITEP Moscow
Kurchatov Institute
irmm
Eberhard Karls Universität Tübingen
Jagiellonian University in Krakow
Technische Universität München
Universität Zürich
INFN
INFN
INFN
INFN Laboratori Nazionali del Gran Sasso
GERDA
16 institutions
~100 members

The GERDA Experimental Setup



Phase II: Final Integration & Upgrade

Final Integration in Dec 2015

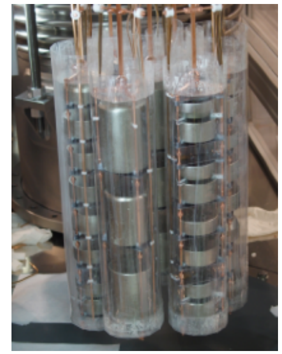
40 detectors in 7 strings:

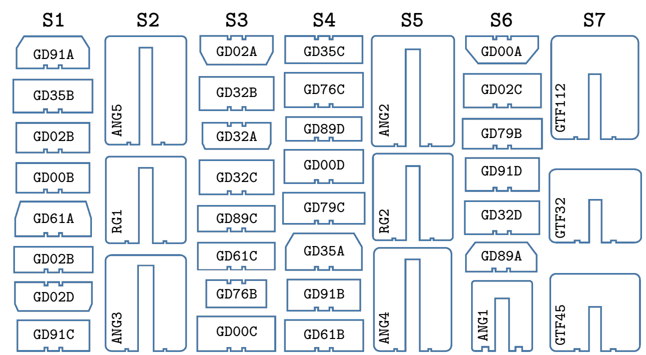
30 enr BEGe (20.0 kg)

7 enr semi-coaxial (15.6 kg)

3 nat semi-coaxial (7.6 kg)

→ 35.6 kg of enr detector mass



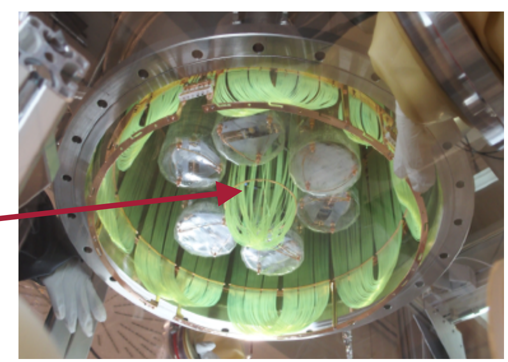


Upgrade in Jul 2018

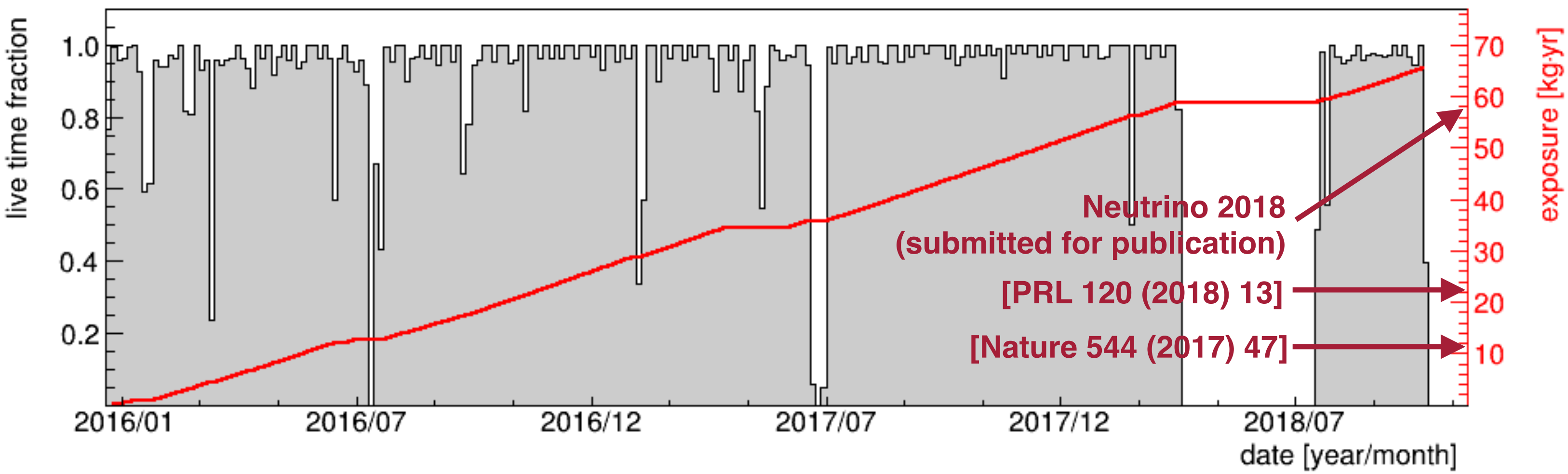
- 3 nat & 1 enr semi-coaxial (replaced)

+ 5 enr inverted coaxial (9.5 kg)

+ new fibres + new central module with increased LAr light collection



Data Taking & Duty Cycle



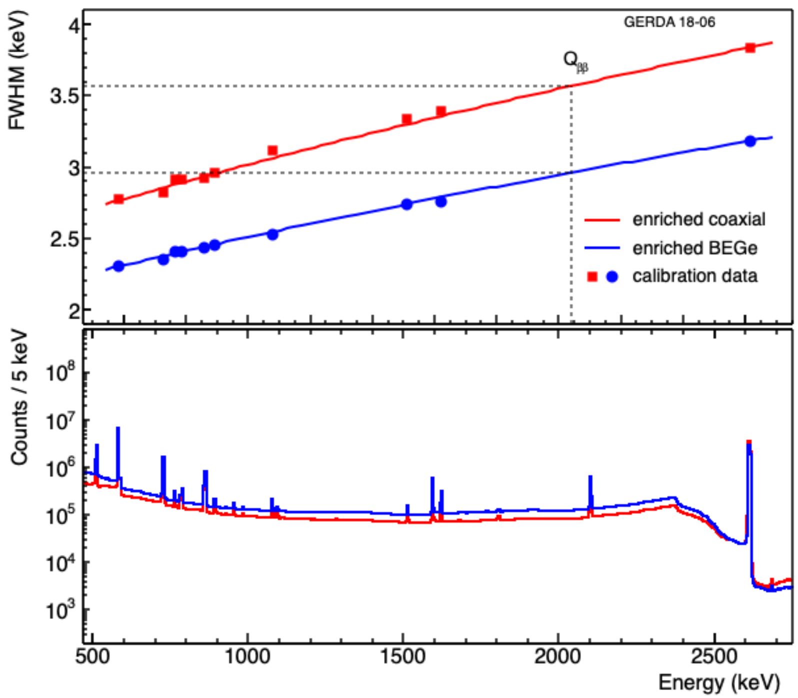
Phase II: Dec 2015 → April 2018

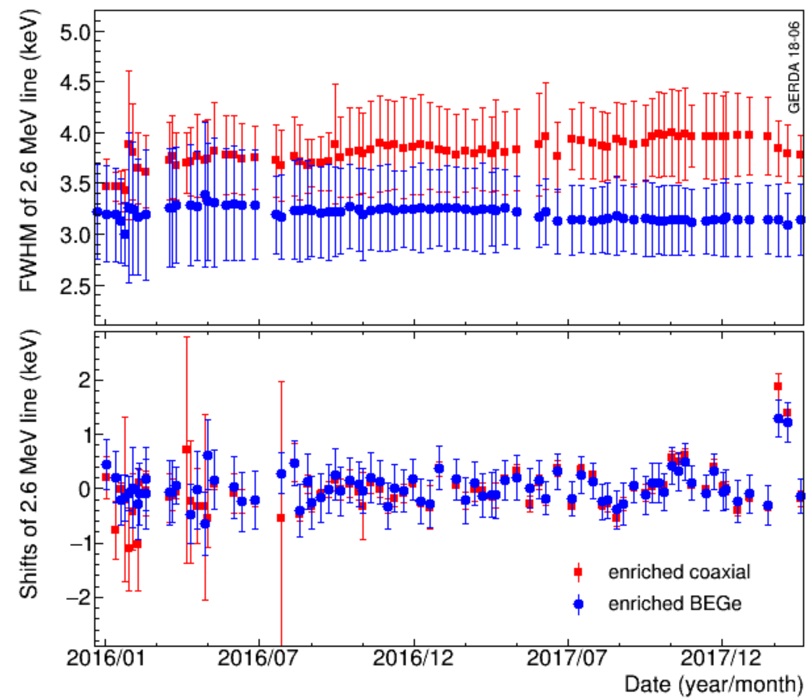
- Live time 834.8 d
- Duty cycle 92.9%
- Exposure 53.9 kg·yr

Phase II + July 2018 → ongoing

GOAL: exposure of 100 kg·yr

Stability and Energy Resolution





Weekly calibrations with ^{228}Th

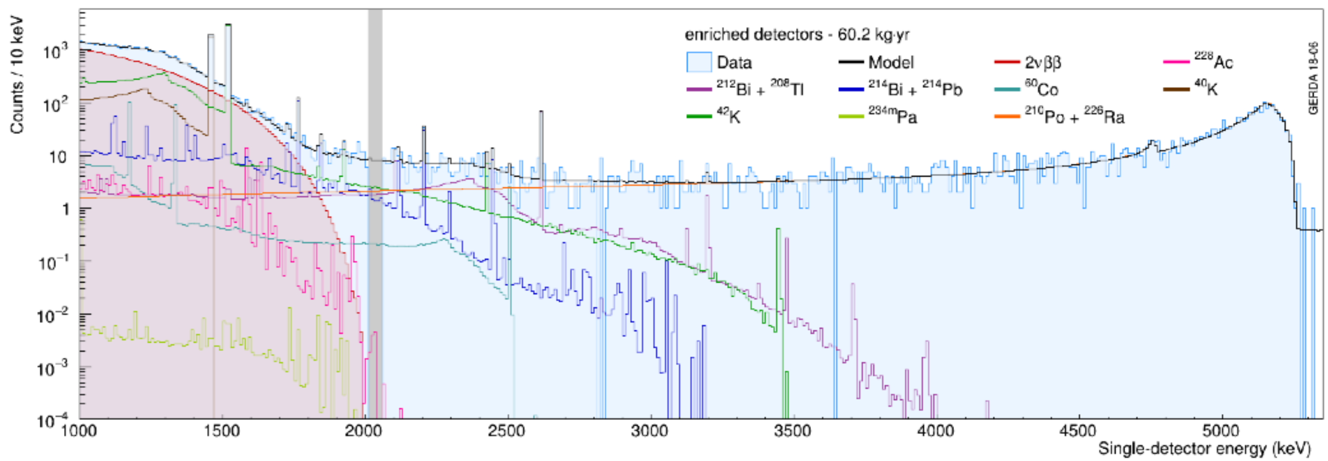
FWHM @ $Q_{\beta\beta}$ = 2039 keV

- BEGe 3.0(1) keV
- Coax 3.6(1) keV

- adopted filter for energy
- Stability monitored online with test pulses, injected every 20 s
- Fluctuations between calibrations < 1 keV

Background Modeling

Bayesian fit of multiple datasets (BEGe, coaxial, multiplicity=2, $^{40}K/^{42}K$ tracking) with Monte Carlo PDFs, screening measurements as priors, before analysis cuts

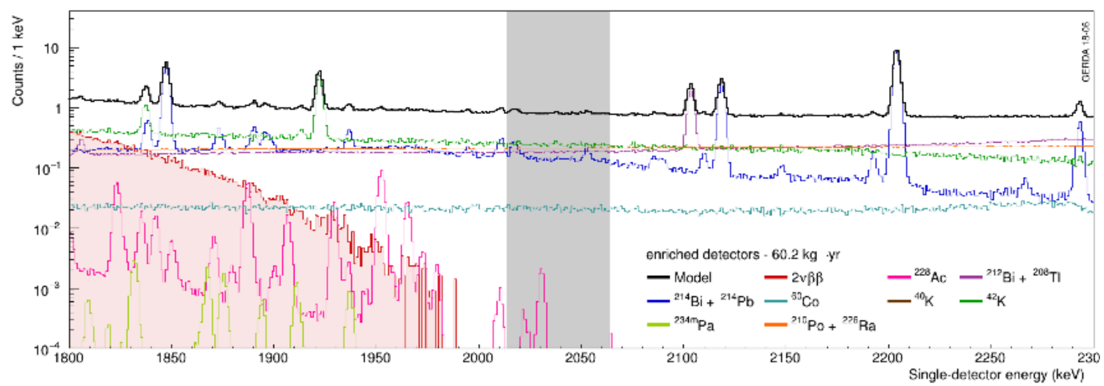


Background @ $Q_{\beta\beta}$:

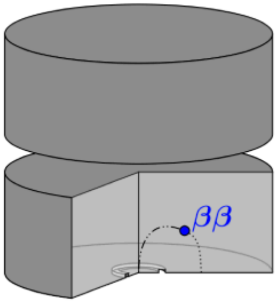
α from ^{210}Po, ^{226}Ra

β from ^{42}K

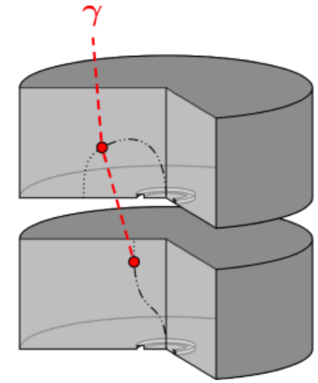
γ from ^{214}Bi, ^{208}Tl



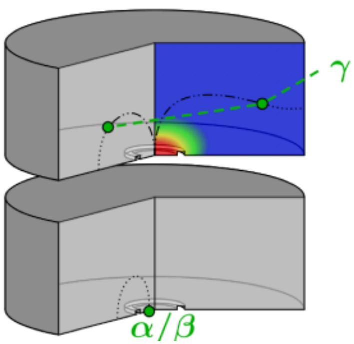
Background Suppression



Signal-like events (0νββ/ 2νββ events)
local energy deposit in single detector

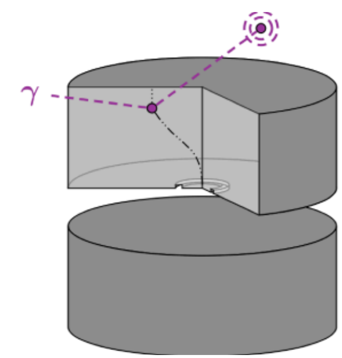


Background events (γ events)
coincident energy deposition in more than one detector
→ detector anti-coincindence



Background events (γ events)
deposition in multiple locations (MSE) **→ PSD** ***(analysis of time profile of current signal)***

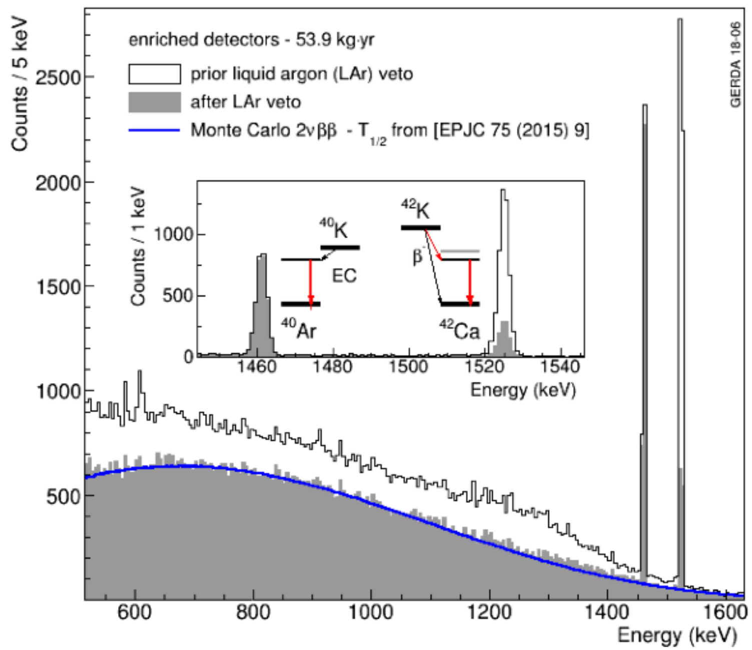
Surface events (α/β events)
energy deposited on or close by the detector contacts **→ PSD *(short (p+) or long (n+) current pulse)***



Background events (γ events)
additional energy deposition in LAr
→ LAr veto

Liquid Argon Veto Cut

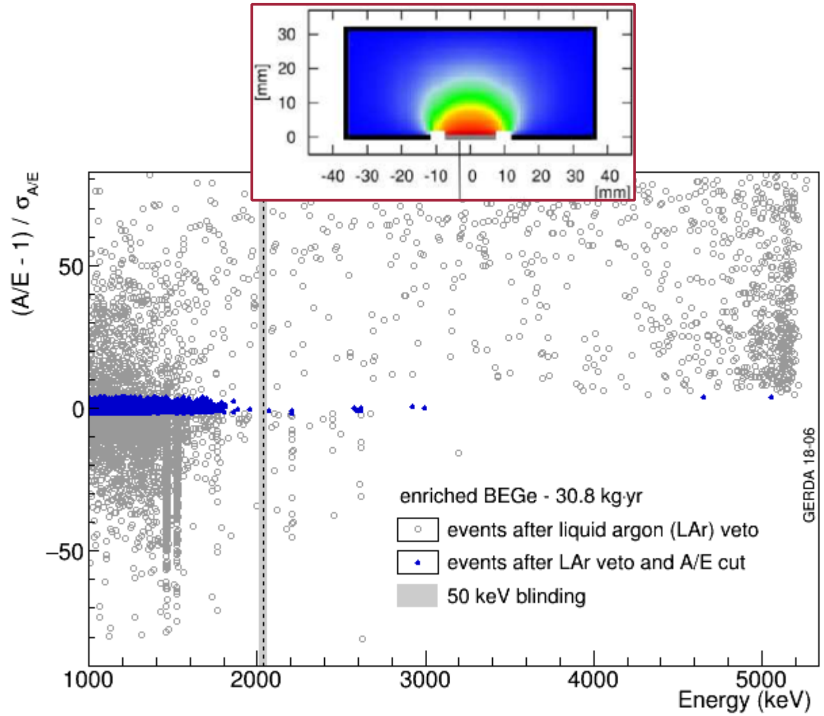
- Channel-wise (PMT/SiPM) anti-coincidence condition
- Thresholds at ~0.2-0.9 P.E.
- Background at $Q_{\beta\beta}$ reduced by factor 2
- No reduction of α
- Compton continuum strongly suppressed
- Almost pure 2νββ after LAr cut (97%, 600-1300 keV)
- LAr cut signal acceptance: 97.7(1)%

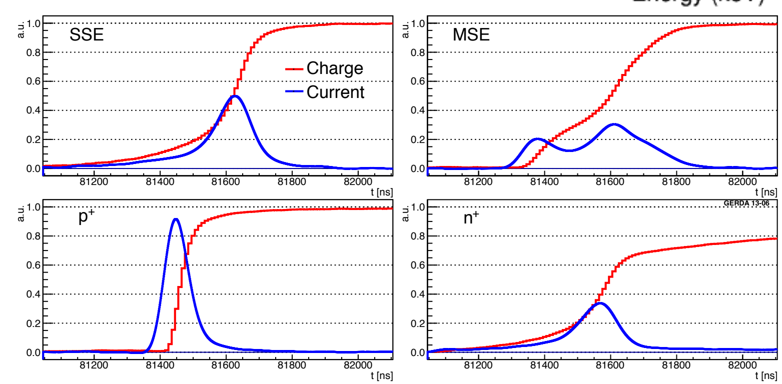


Pulse Shape Discrimination for BEGe’s

“A/E cut “
single parameter based on current amplitude A and event energy E

- low A/E: slow events on n+ electrode, multiple scattering
- high A/E: fast events on p+ electrode (e.g. α’s from ^{210}Po)
- tuned by 90% DEP acceptance of 2615 keV (signal-like) from calibration data
- 82% of background events rejected at $Q_{\beta\beta}$
- γ-lines suppressed by factor of 6
- **0νββ acceptance (87.6 ± 2.5)%**

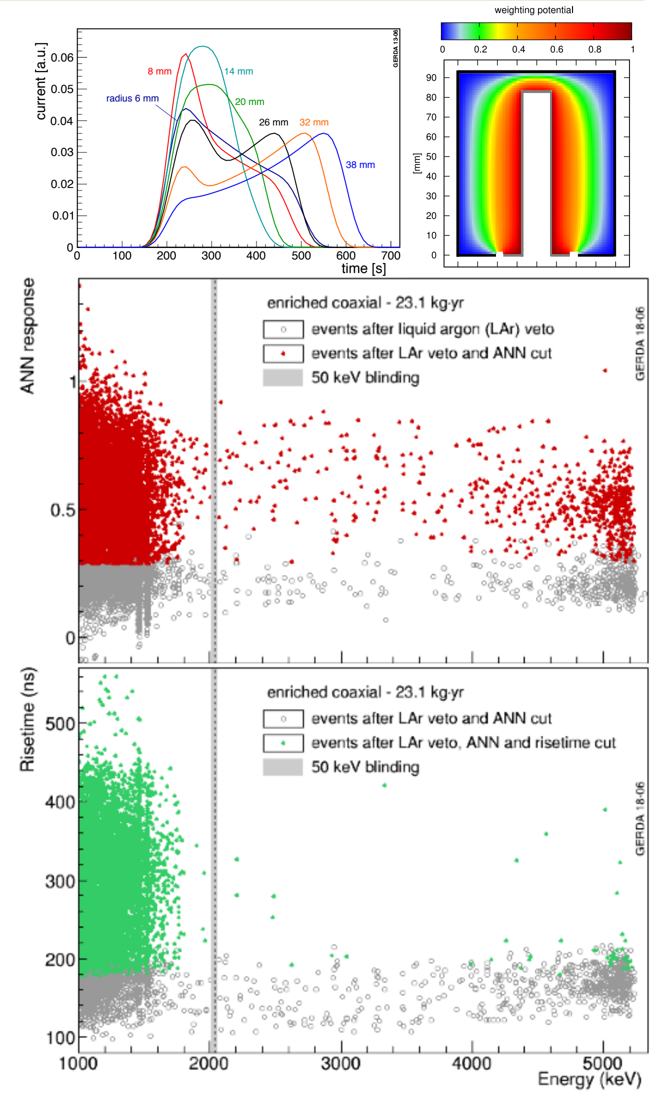




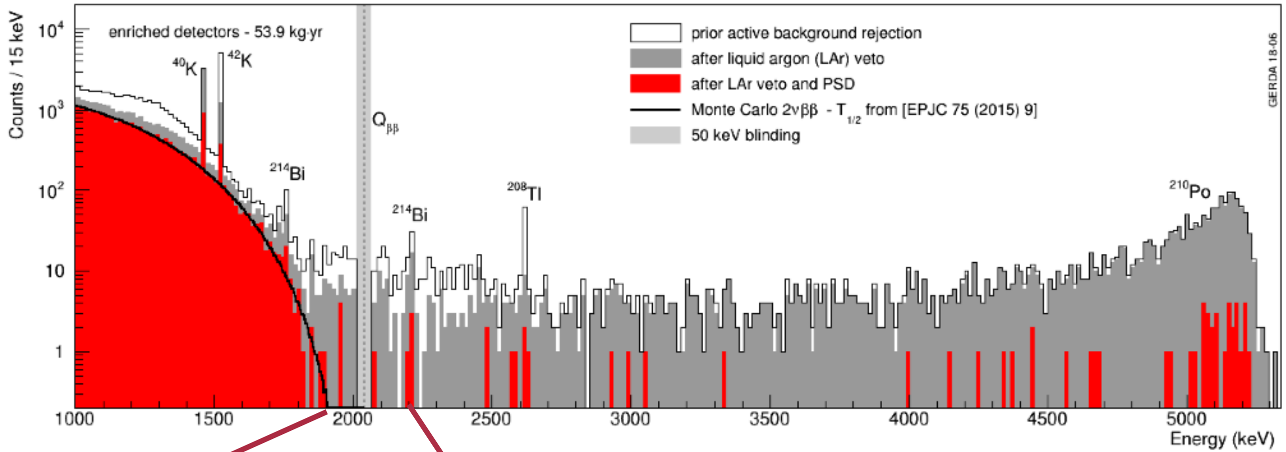
Pulse Shape Discrimination for Coaxials

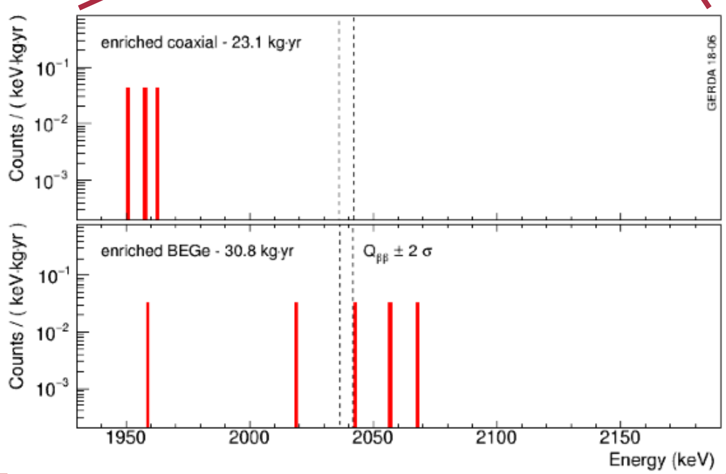
“ANN cut “
artificial neural network

- trained on ^{208}Tl DEP (signal) and ^{212}Bi FEP (bkg)
- acceptance from pulse shape simulations, cross-checked with 2νββ events
- additional α rejection based on (fast) signal rise time, tuned after ANN MSE rejection
- **0νββ acceptance (84 ± 5)% x (85 ± 1)%**



Background Index



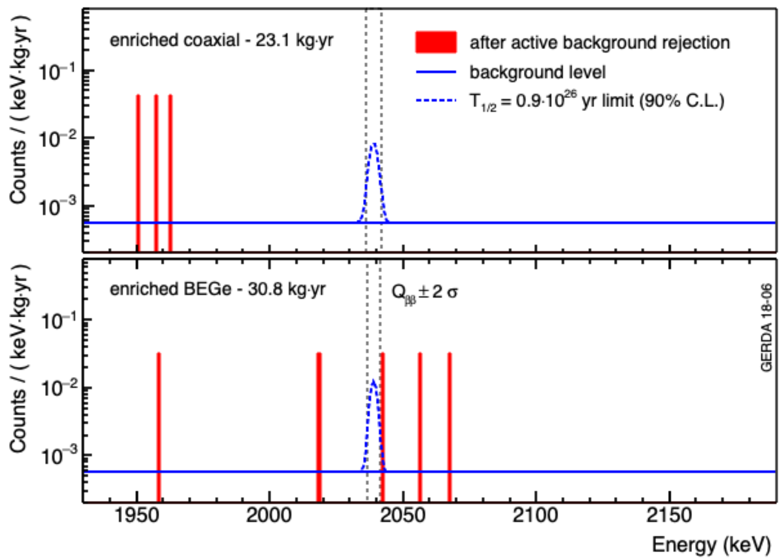


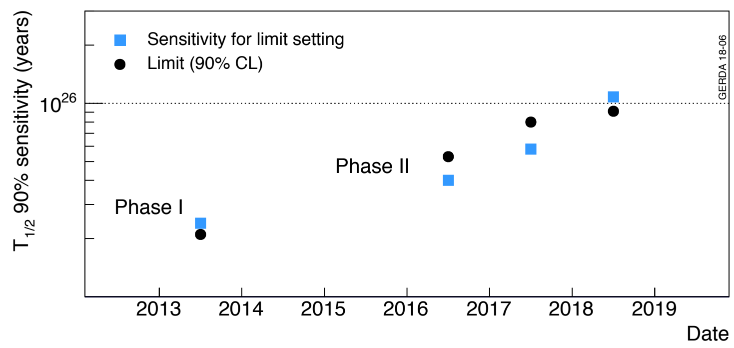
Calculated in [1930,2190] keV, excluding ± 5 keV around ^{208}Tl, ^{214}Bi and $Q_{\beta\beta}$

BEGe $5.7^{+4.1}_{-2.6} \cdot 10^{-4} \frac{\text{cts}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}$

Coax $5.6^{+3.4}_{-2.4} \cdot 10^{-4} \frac{\text{cts}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}$

Phase I+II - Results (82.4 kg yr)

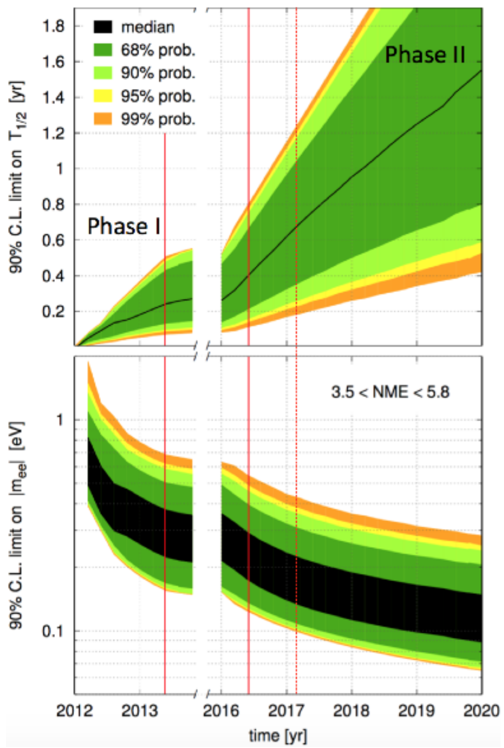




	Frequentist	Bayesian
median sensitivity	$1.1 \cdot 10^{26}$ yr (90%CL)	$0.8 \cdot 10^{26}$ yr (90%CL)
best-fit $N^{0\nu}$	0	0
$T_{1/2}^{0\nu}$	> $0.9 \cdot 10^{26}$ yr (90%CL)	> $0.8 \cdot 10^{26}$ yr (90%CL)
$\langle m_{\beta\beta} \rangle$	< 0.11-0.25 eV	
probability of a stronger limit	63 %	59 %

Summary and Outlook

- GERDA Phase II is running stable
- 3-4 keV energy resolution @$Q_{\beta\beta}$
- new inverted coaxial detectors → more ^{76}Ge mass
- new LAr veto system → improved light yield



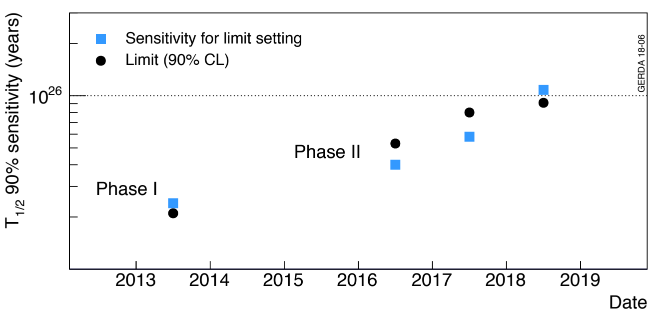
Phase IIa achievements

background	~ 10^{-4} cts/(keV·kg·yr)
exposure	82.4 kg·yr
limit	$T^{0\nu}_{1/2}$ > 0.9·10^{26} yr (90%CL) $m_{\beta\beta}$ < (0.11-0.25) eV (90%CL)

GERDA Phase II is the high-resolution and background-free 0νββ experiment

Phase II goals

background	~10^{-3} cts/(keV·kg·yr) ✓
exposure	≳ 100 kg·yr
sensitivity	> 10^{26} yr ✓



Beyond GERDA

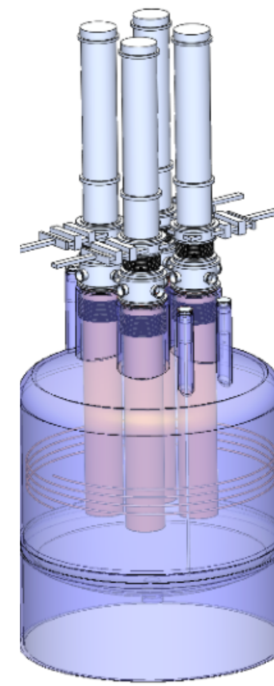
LEGEND

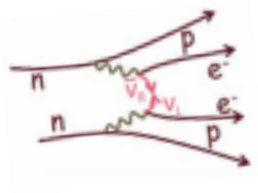
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

new collaboration formed in Oct 2016
(=GERDA + Majorana + new groups)

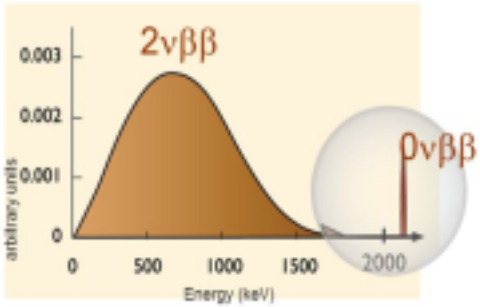
Goals:
- 1 t enriched Ge
- first phase: 200 kg in existing infrastructure @ LNGS
- reduce background with respect to GERDA
- up to 10^{27} yr sensitivity in 5 years

→ remain background-free
→ best discovery potential





Double Beta Decay and Lepton Number Violation $\Delta L \neq 0$



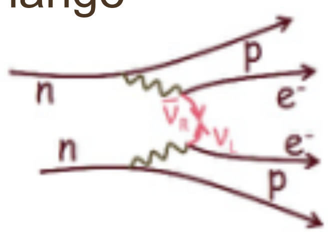
easiest but not easy way to see

if ν are Majorana-type

sensitivity on $T^{0\nu}_{1/2}$

mid term: a few 10^{26} yrs ($m_{\beta\beta}$ ~ 40-100 meV)
long term: a few 10^{27} yrs ($m_{\beta\beta}$ ~ 10- 20 meV)

via ν exchange

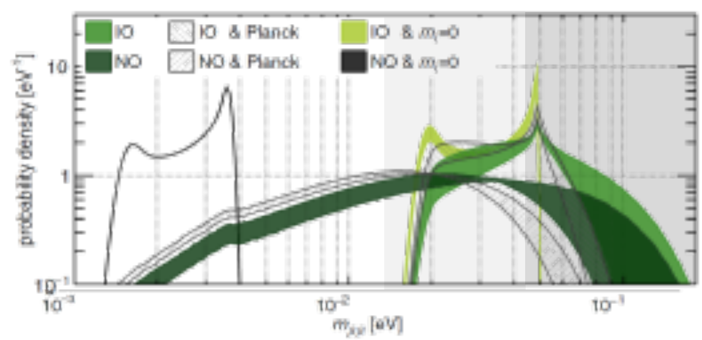


effective neutrino mass

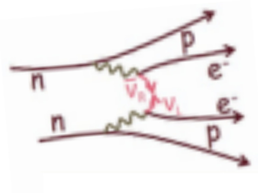
$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space nuclear matrix element

(Agostini, Benato, Detwiler, PRD 96 (2017) 053001
also A. Caldwell et al., PRD 96 (2017) 073001)



high discovery potential for IH and NH
- not hierarchy, but m_ν is important -



Search for Neutrino-less Double Beta Decay

$\Delta L \neq 0$

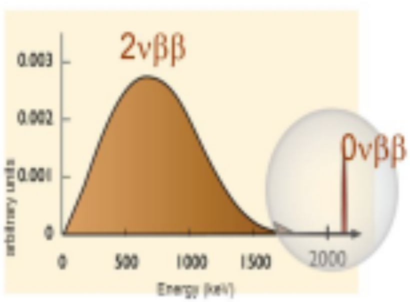
effective neutrino mass

$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space nuclear matrix element

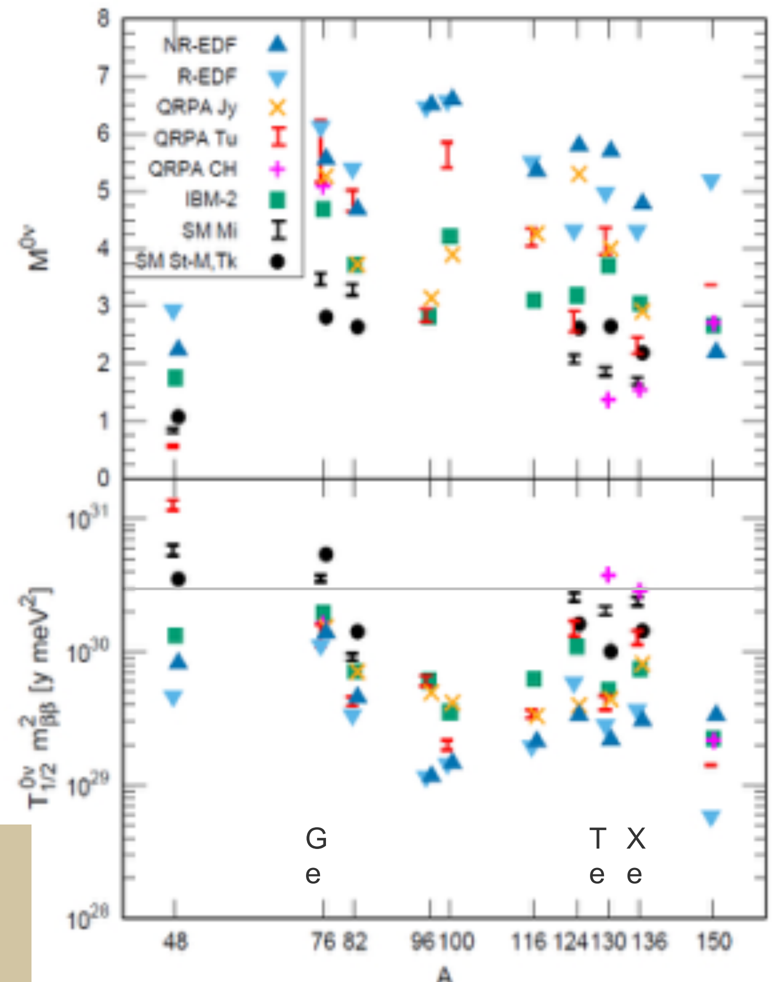
~ Q^5

no favored isotope
considering spread of nuclear matrix elements and Q-values

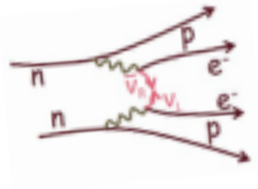


large mass
[$kg_{isotope}$]

low background in ROI
[cts / FWHM $t_{isotope}$yr]



arXiv: 1610.06548v1



Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$

			isotope mass [kg] in FV	FWHM [keV]	background [(FWHM $t_{isotope}$ yr $)^{-1}$]	3σ discovery sensitivity (taken from PRD 96(2017) 053001) $T_{1/2}$ [10^{26} yr]	$m_{\beta\beta}$ [meV]
Ge detectors	GERDA	Ge	37	3	2		
	Majorana	Ge	26	3	15		
	LEGEND 200 kg	Ge	155	3	0,6	8.4	40-73
	LEGEND 1000 kg	Ge	780	3	0.1	45	17-31
liquid noble gas	EXO	Xe	80	88	150		
	nEXO	Xe	4300	58	0.6	41	9-22
loaded liquid scintillator	KamLAND 400 kg	Xe	110	250	100		
	KamLAND 800/1000 kg	Xe	~180	250	40 / 2	1.6 /8	47-108 /21-49
	SNO+	Te	260	190	60	4.8	22-54
cryo bolometers	CUORE	Te	206	5	180/360	0.5	66-164

low background essential for discovery potential