GERDA e LEGEND: sonde ad alta sensibilità su natura e massa del neutrino

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Carla Cattadori, Valerio D’Andrea, Francesco Salamida

INFN & Università Milano Bicocca
Università dell’Aquila & LNGS

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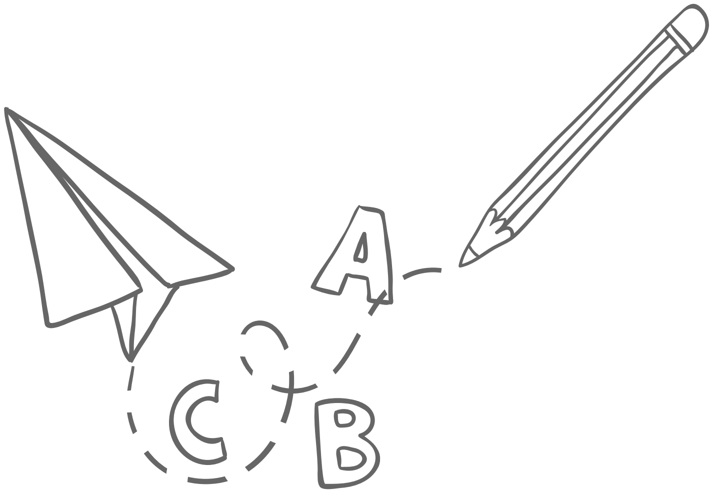
Outline

A. Intro al Decadimento Doppio Beta (F. Salamida)
B. GERDA (F. Salamida & C.M. Cattadori)
C. LEGEND (V. D’Andrea)



The birth of 0νββ decay

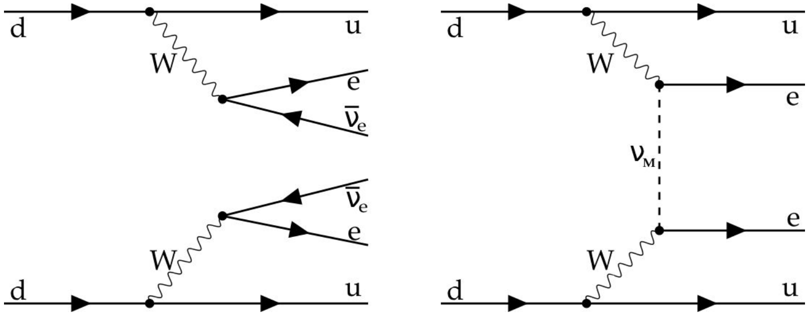
- in 1897 J.J. Thomson discovers the electron, later (1911-1919) E. Rutherford discovers the atom and the proton.
- this model goes into crisis (among mass inconsistencies) with the observation of the continuous spectrum of beta decay;
- in 1930 Pauli to overcome this problem proposes the a new particle the **neutron**, but it is E. Fermi that in 1932 after the discovery of neutron by J. Chadwick calls the Pauli particle neutrino;
- in 1937 E. Majorana propose a description of neutral ½ spin particles (e.g neutrinos) where particle and anti-particle are identical.
- as a consequence in 1939 H. Furry suggests that 0νββ decay can be observed

Search for 0νββ decay

Powerful method to study the unknown neutrino properties

Observation of 0νββ decay will imply:

1. neutrino has Majorana nature
2. lepton number violation (ΔL = 2)
3. determination of ν absolute mass (nuclear model dependent)



The half life of 0νββ in case of light Majorana neutrino exchange:

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu} \times \left|M_{0\nu}\right|^2 \times \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- **Phase Space Integral:** well known quantity
- **Nuclear Matrix Element:** most critical ingredient, produces uncertainty in the determination of $m_{\beta\beta}$ (quenching problem)
- **Neutrino Effective Mass:** estimated by measuring $T^{2\nu}_{1/2}$

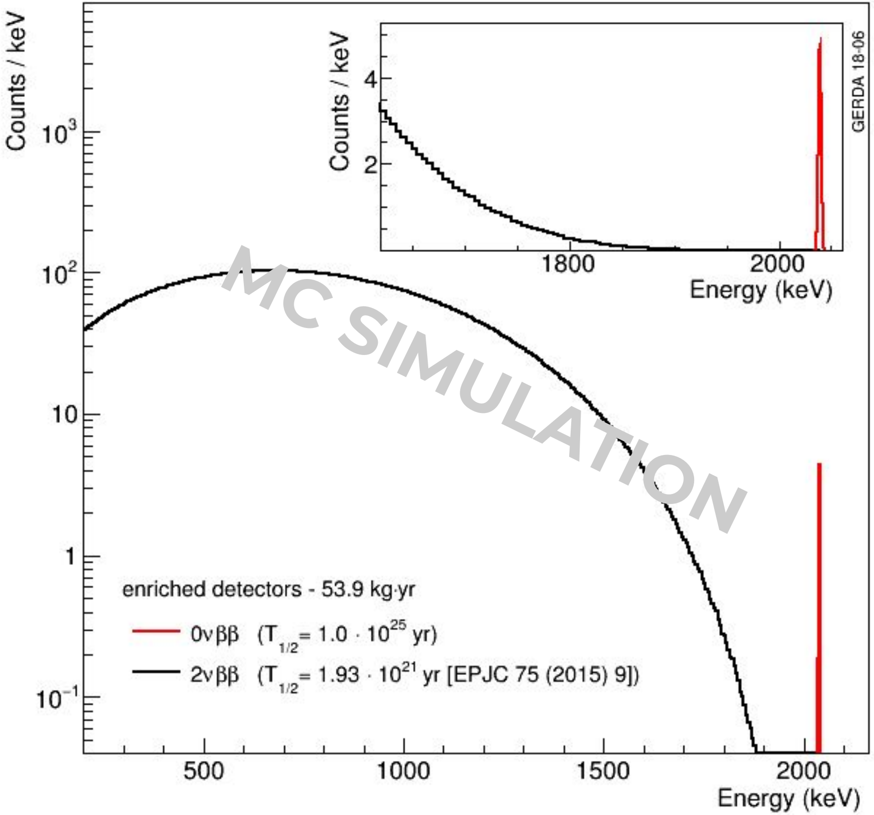
Experimental signature of 0νββ

Experimental sensitivity

$$S \propto \underset{\substack{\uparrow \\ \text{abundance}}}{a}\overset{\substack{\text{efficiency} \\ \downarrow}}{\varepsilon}\sqrt{\frac{\overset{\substack{\text{exposure} \\ \swarrow}}{M\cdot t}}{\underset{\substack{\uparrow \\ \text{energy} \\ \text{resolution}}}{\Delta E}\cdot \underset{\nwarrow\ \text{background index}}{BI}}}$$

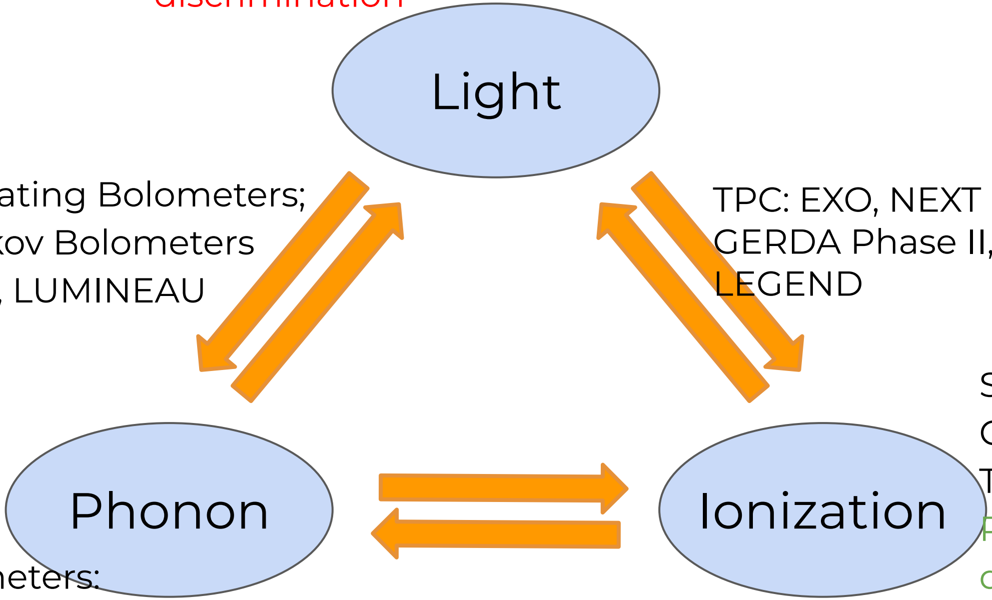
Sensitivity in case of “background-free” experiment , i.e $N_{bkg} < 1$ at full exposure, is reduced to:

$$S \propto a\varepsilon \cdot M \cdot t$$



0νββ: choosing the technique

Liquid Scintillators: Kamland-Zen, SNO+
Scintillating Crystals: Candles
PRO: High Masses possible
CONS: Limited En. Res. Limited Bkg discrimination



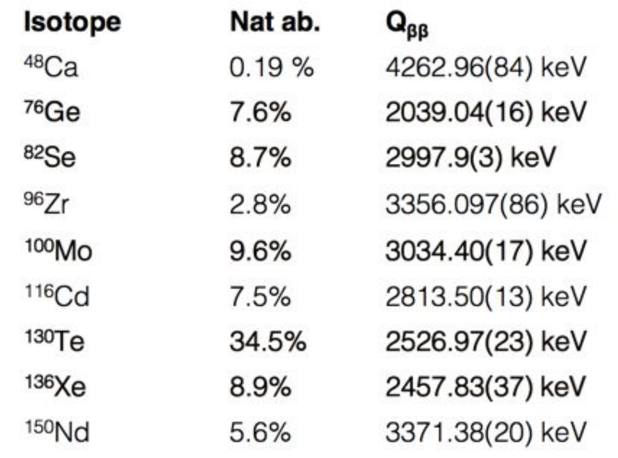
Scintillating Bolometers;
Cerenkov Bolometers
CUPID, LUMINEAU

TPC: EXO, NEXT
GERDA Phase II, LEGEND

Bolometers:
CUORE

Semiconductor Calorimeters:
GERDA; MAJORANA, LEGEND
Tracking Calorimeters: SuperNEMO; DCBA
PRO: Good En. Res. Good Bkg discrimination
CONS: Difficult/Costly to scale up Masses

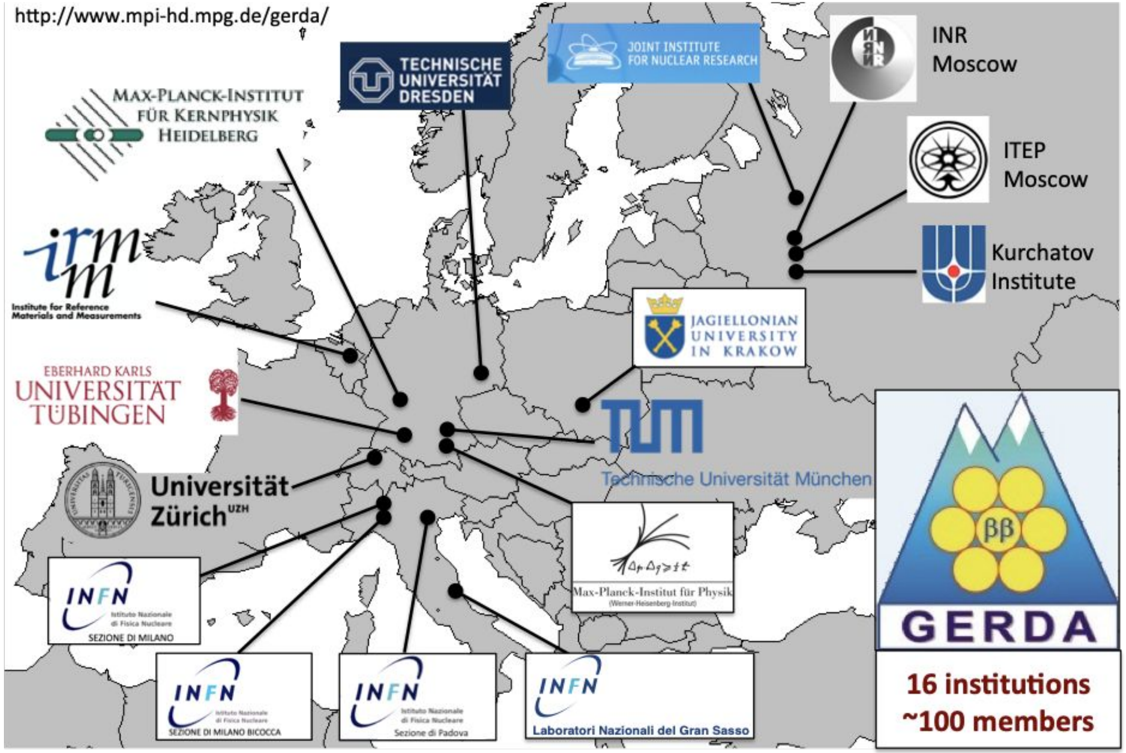
Energy of 0νββ for different isotopes



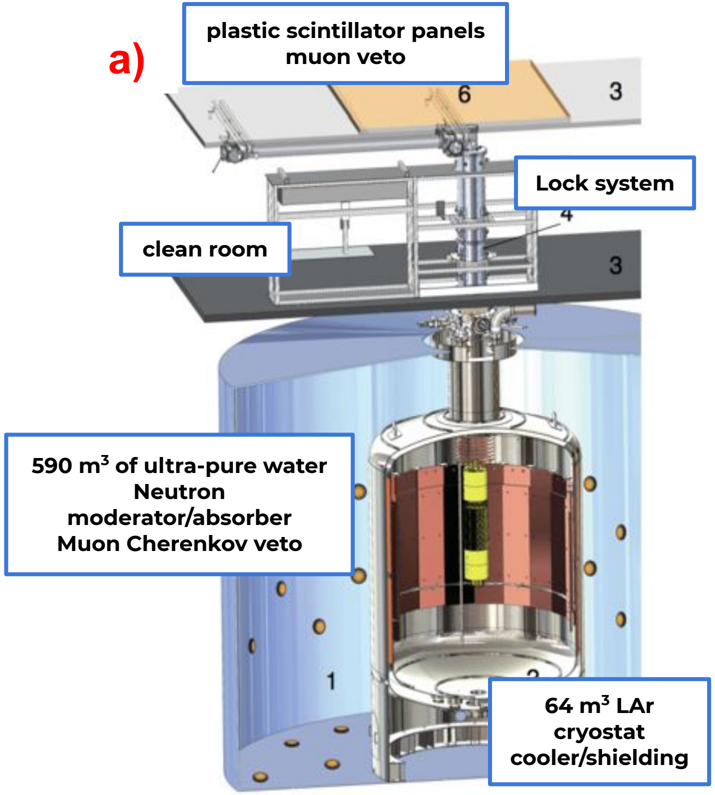
Isotope	Nat ab.	$Q_{\beta\beta}$
^{48}Ca	0.19 %	4262.96(84) keV
^{76}Ge	7.6%	2039.04(16) keV
^{82}Se	8.7%	2997.9(3) keV
^{96}Zr	2.8%	3356.097(86) keV
^{100}Mo	9.6%	3034.40(17) keV
^{116}Cd	7.5%	2813.50(13) keV
^{130}Te	34.5%	2526.97(23) keV
^{136}Xe	8.9%	2457.83(37) keV
^{150}Nd	5.6%	3371.38(20) keV

GERDA Experiment

- In 2004 Heidelberg-Moscow experiment sub-group claims the observation of $0\nu\beta\beta$ observation ($T^{0\nu}_{1/2}$=1.19 10^{25} y) [Phys. Lett. B 586, 3–4, 2004]
- In 2006 GERDA Collaborations borns with the aim to confirm/disprove the claim
- 16 institutions from Italy, Germany, Russia, Switzerland, Poland
- GERDA starts data taking 2010 and stopped in 2020



GERDA Setup



plastic scintillator panels muon veto

Lock system

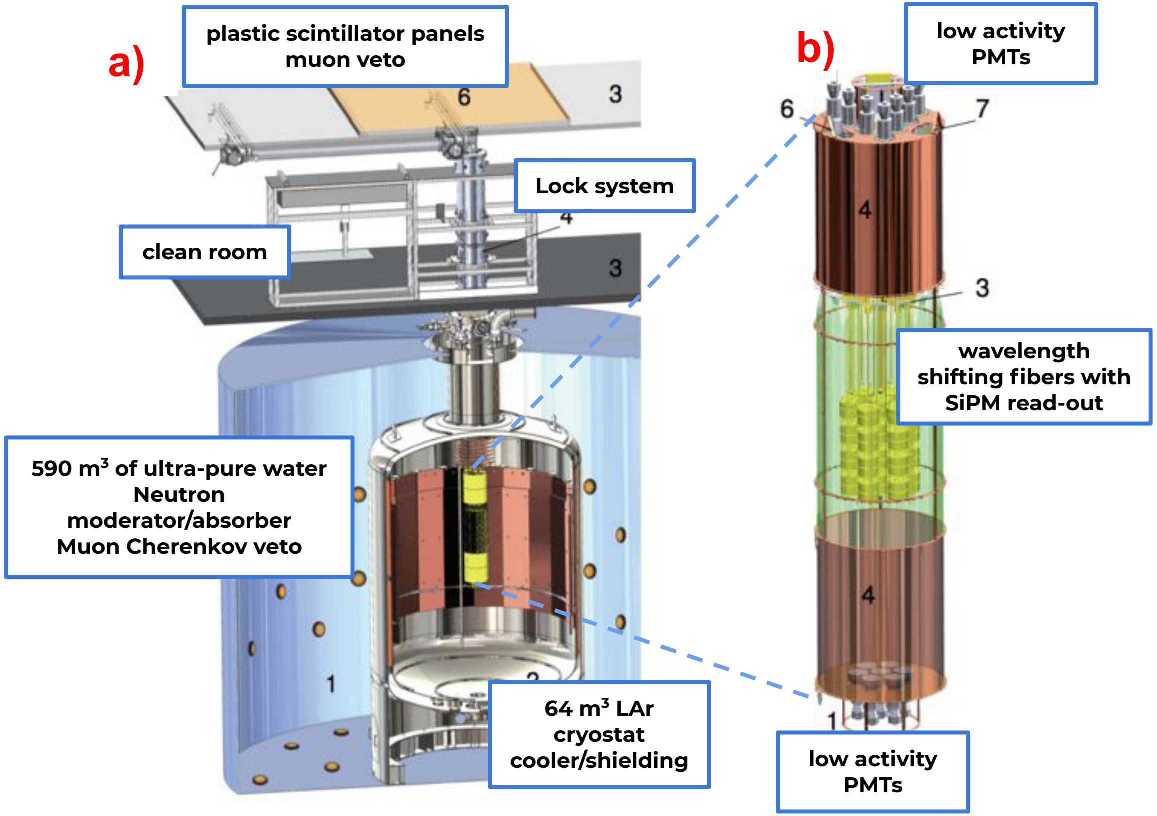
clean room

590 m^3 of ultra-pure water
Neutron moderator/absorber
Muon Cherenkov veto

64 m^3 LAr cryostat cooler/shielding

a) overview

GERDA Setup



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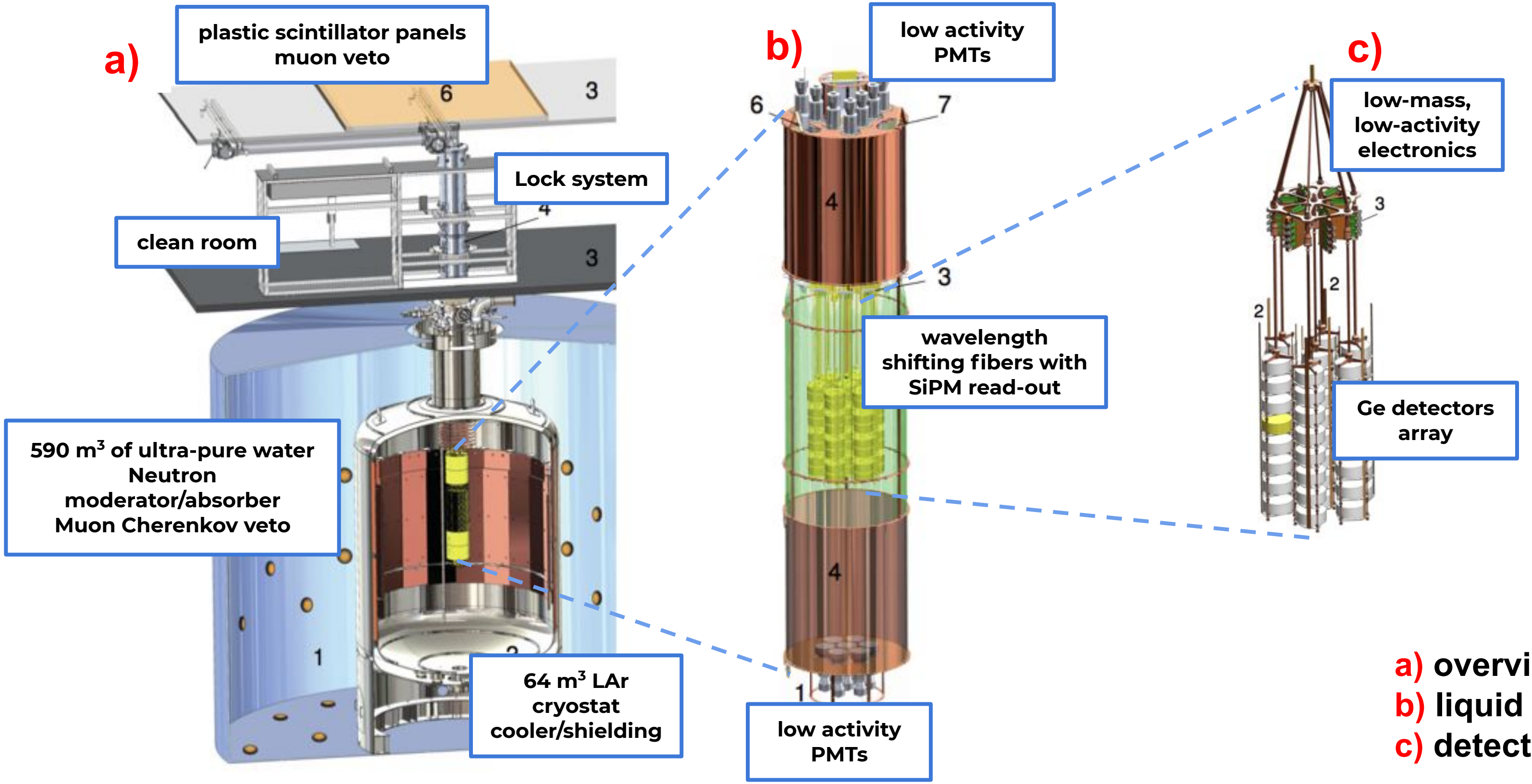
low activity PMTs

wavelength shifting fibers with SiPM read-out

low activity PMTs

a) overview
b) liquid argon veto (LAr)

GERDA Setup



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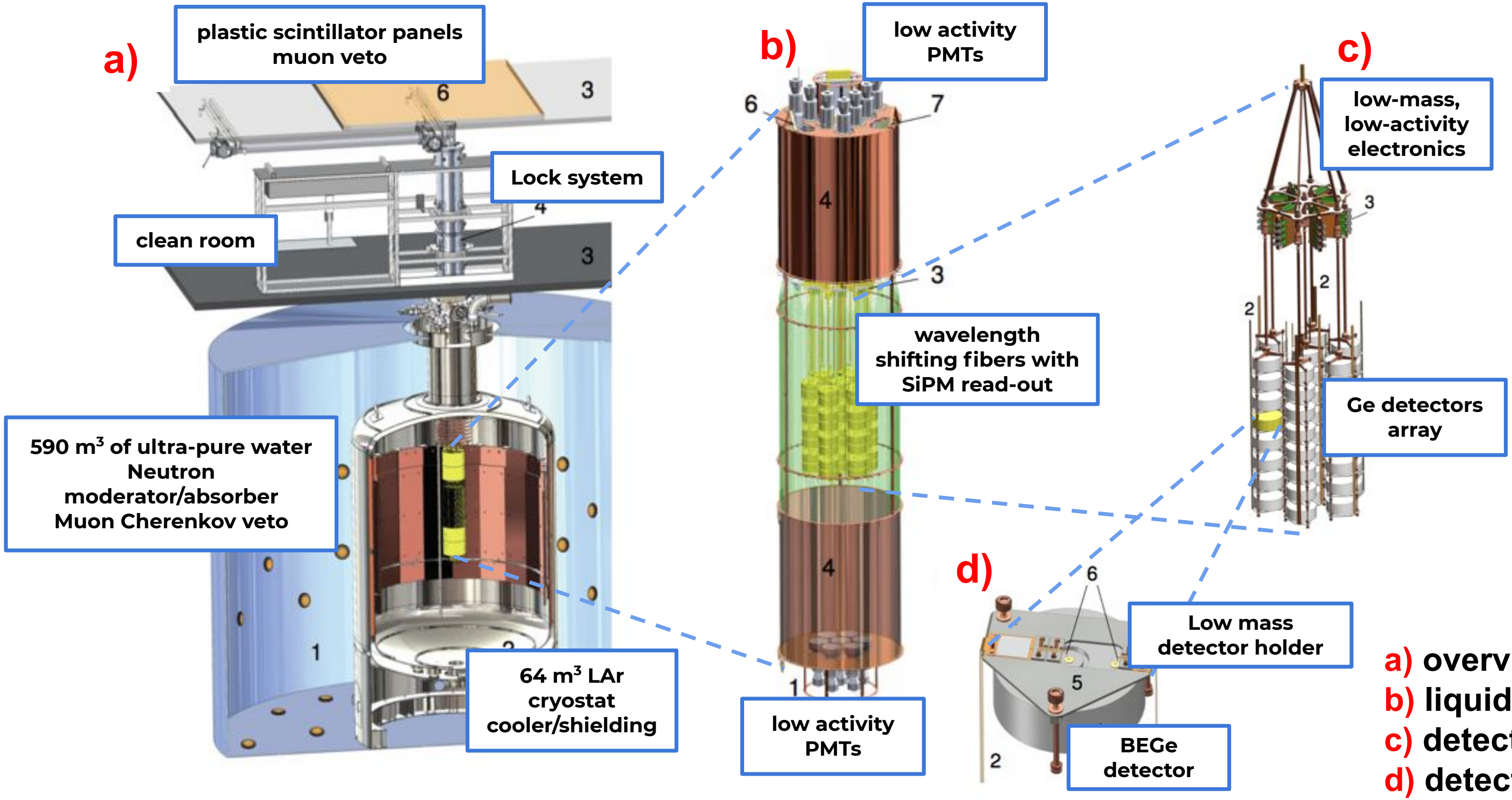
low-mass, low-activity electronics

Ge detectors array

a) overview
b) liquid argon veto (LAr)
c) detector array

GERDA Setup



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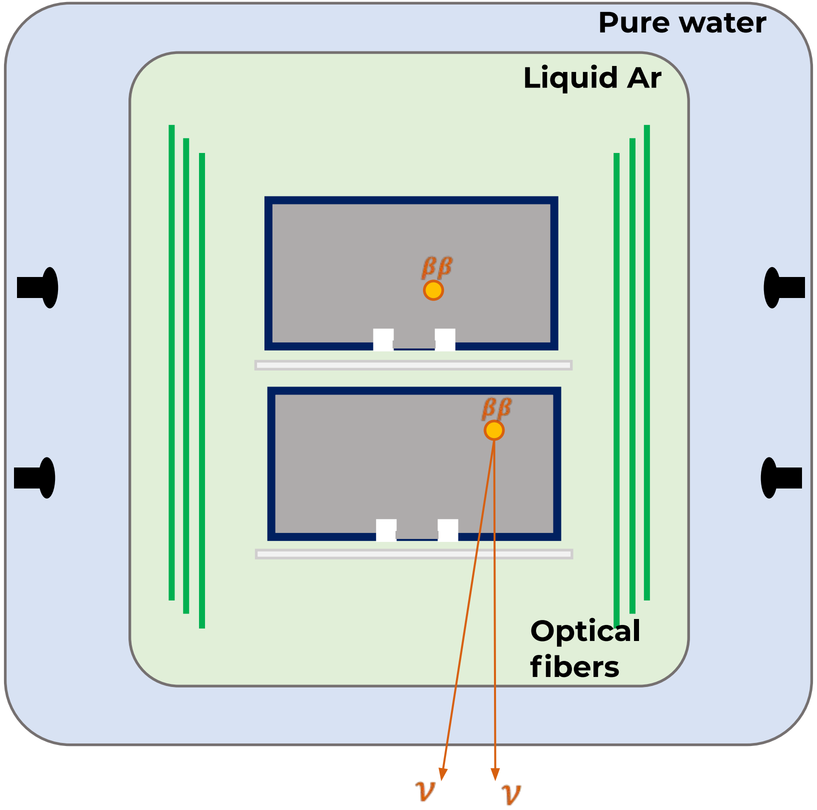
Ge detectors array

Low mass detector holder

BEGe detector

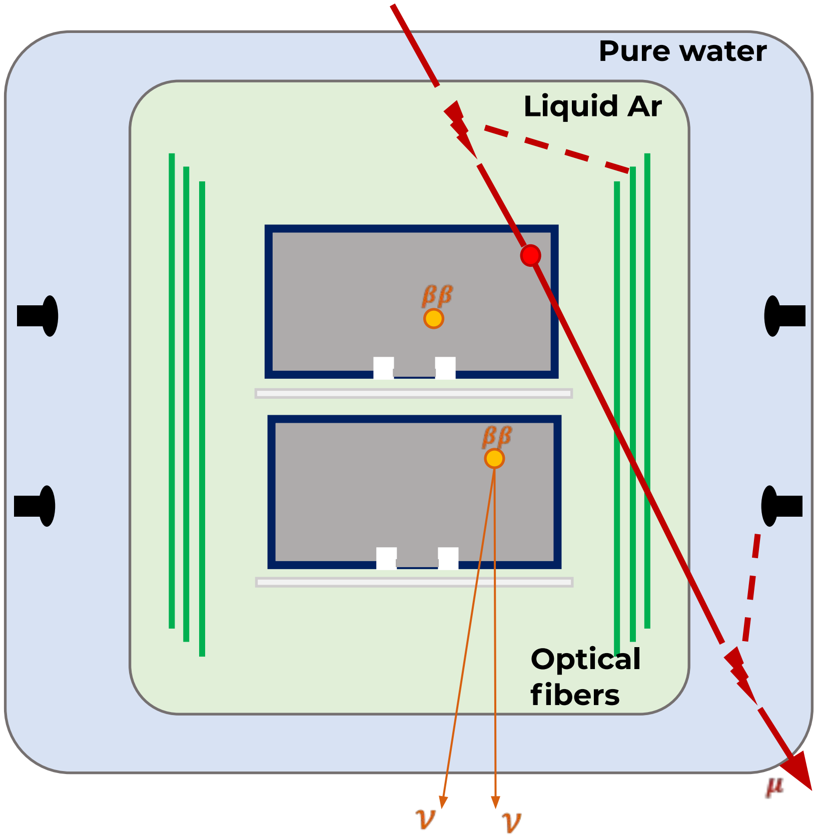
a) overview
b) liquid argon veto (LAr)
c) detector array
d) detector module

Active Background Reduction Strategy



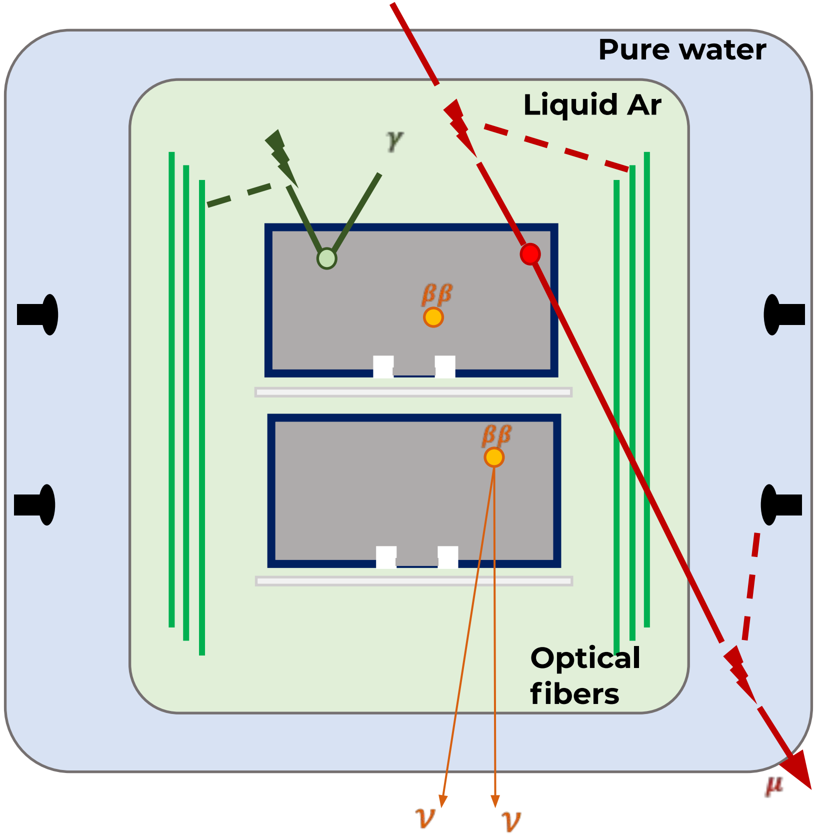
- ββ decay signal: single energy deposition in a 1 mm^3 volume

Active Background Reduction Strategy



- $\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume
- Muon veto based onCherenkov light and plastic scintillator

Active Background Reduction Strategy



- $\beta\beta$ **decay signal: single energy deposition in a 1 mm^3 volume**
- **Muon veto based onCherenkov light and plastic scintillator**
- **LAr veto based on Ar scintillation light read by fibers and PMT**

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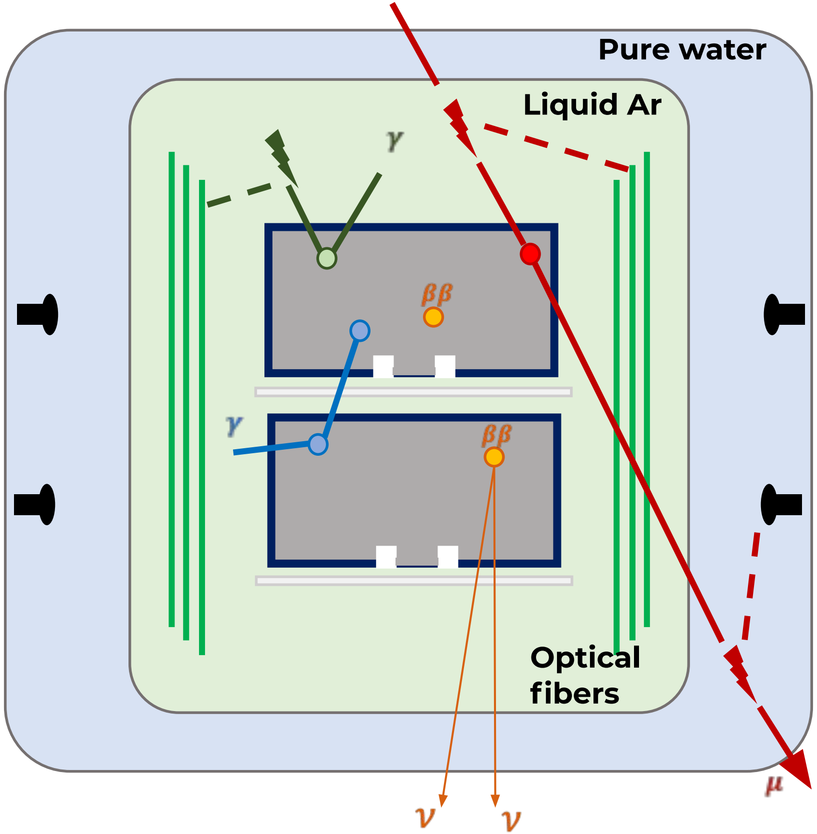

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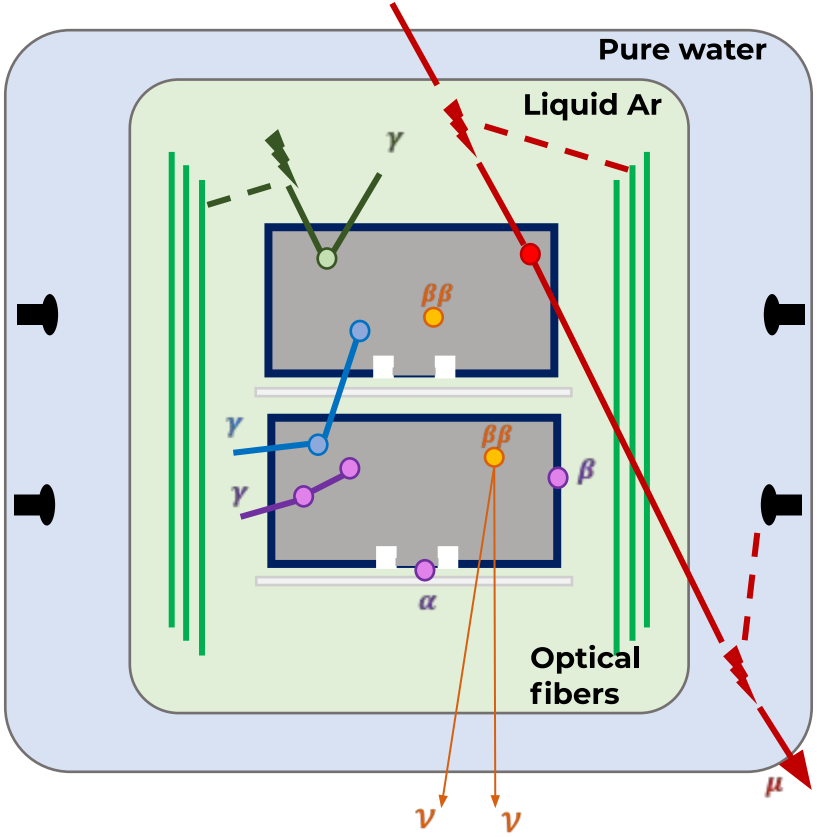

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- **LAr veto based on Ar scintillation light read by fibers and PMT**
- **Ge detector anti-coincidence**
- **Pulse shape discrimination (PSD) for multi-site and surface** α **events**

GERDA final setup

Semi-Coaxial detectors: 15.6 kg

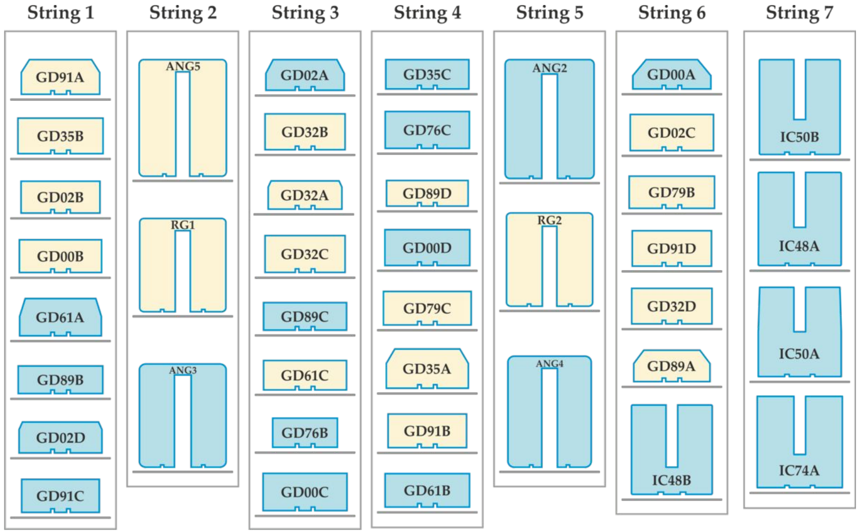
- from previous experiments (HdM, IGEX)
- energy resolution: 3.6 keV (FWHM) Qββ

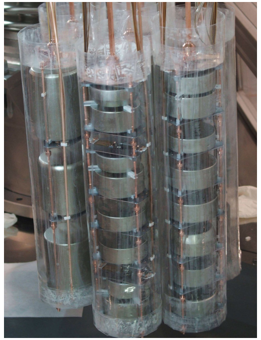
BEGe detectors: 20 kg

- produced for Phase II
- energy resolution: 3.0 keV (FWHM) Qββ
- improved Pulse Shape Discrimination with A/E (current-amplitude/energy)

Inverted-Coaxial detectors: 9.5 kg

- In production for LEGEND-200
- Excellent resolution and pulse shape discrimination performance
  [A. Domula et al., NIM A891, 106 (2018)]
- Lower surface to volume ratio





Outcome of a ββ-decay experiment

- Sensitivity (S): it is a computed value
- Half-life ($T^{0v}_{1/2}$) of the 0νββ → $m_{\beta\beta}$ is derived
- Half-life ($T^{2v}_{1/2}$) of the 2νββ
- Beyond SM/exotic physics

$$(T^{0\nu}_{1/2})^{-1} = \underset{\text{phase space integral}}{G_{0\nu}}\,|\underset{\text{nuclear matrix element}}{M_{0\nu}}|^2 \left(\frac{\overset{\text{effective neutrino mass}}{m_{\beta\beta}}}{m_e}\right)^2$$

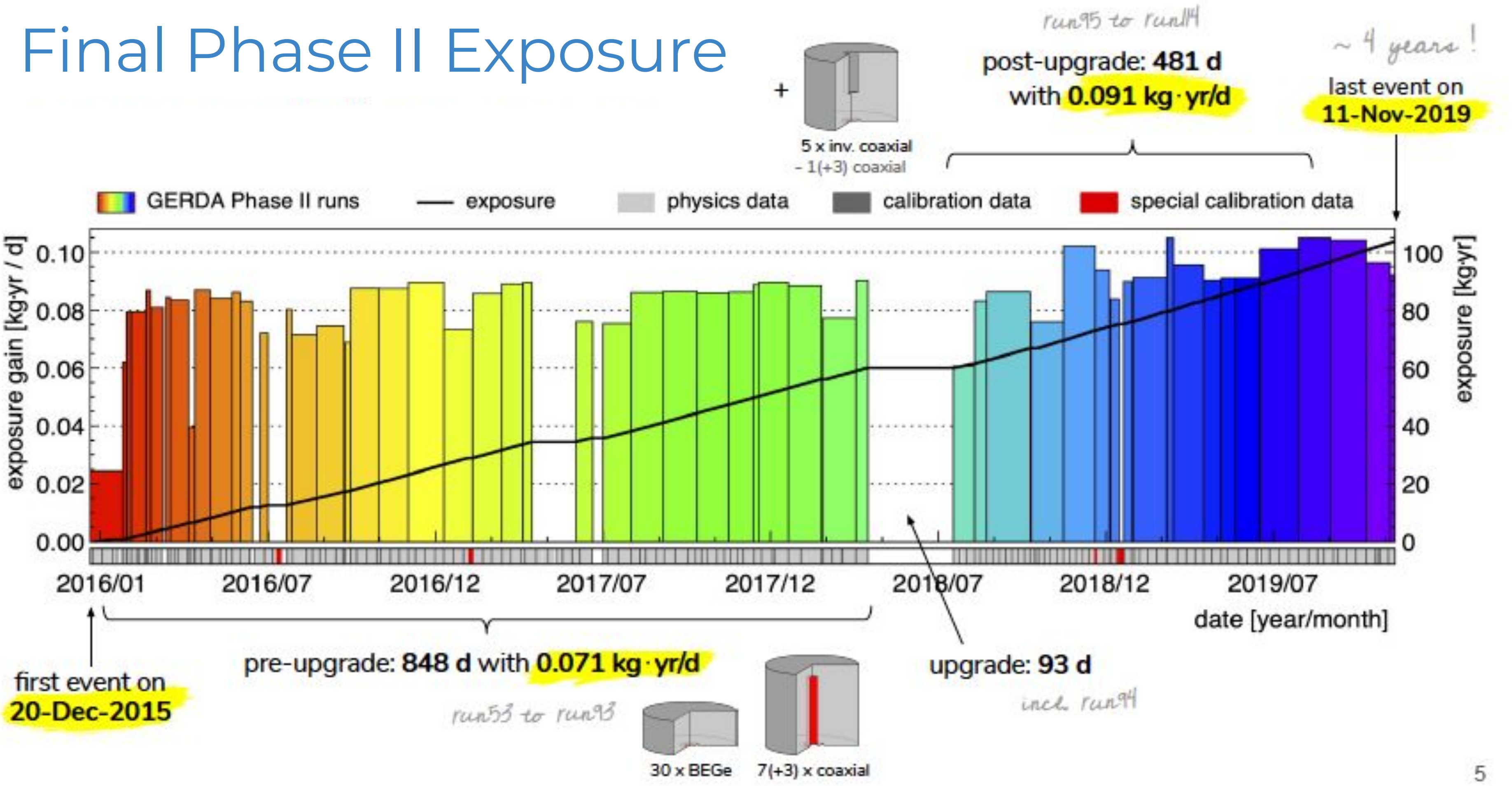
Results depend on achieved performances:

- **Exposure (M·T)** units [kg·yr]: it expresses the amount of isotope you “observed” · the “observation time”
- **Background Index (B or BI)** in units of [cts/(keV·kg·y)] i.e. how much is the residual background in the ROI
- **Energy resolution (ΔE)** [keV]: how well your system is able to resolve peaks in the energy spectra over the exposure time

$$S \propto a\varepsilon \cdot M \cdot t$$

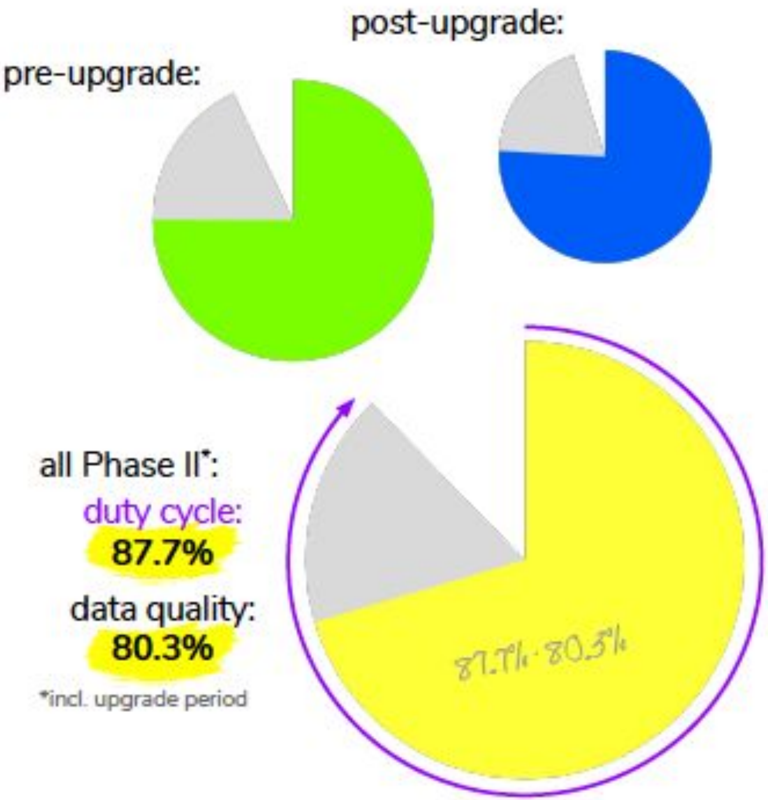
$$S \propto \underset{\text{abundance}}{a}\overset{\text{efficiency}}{\varepsilon}\sqrt{\frac{\overset{\text{exposure}}{M\cdot t}}{\underset{\text{energy resolution}}{\Delta E}\cdot\underset{\text{background index}}{BI}}}$$

Final Phase II Exposure



Exposure of Phase II

+49.8 kg yr exposure since last release

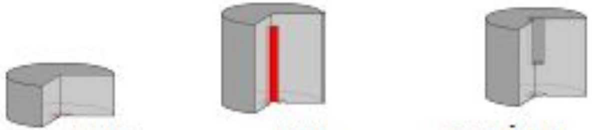


all Phase II*:

duty cycle:
87.7%

data quality:
80.3%

*incl. upgrade period



	enr. BEGe	enr. coaxial	enr. inv. coaxial	[kg·yr]
pre-upgrade:	31.5	28.6		60.1*
post-upgrade:	21.9	13.2	8.5	43.6
	53.3	41.8	8.5	103.7

*incl. 58.9 kg·yr unblinded in 2018

... + Phase I = 127.2 kg·yr

Data treatment & Analysis

1) Data are blinded in the region ± 25 keV (ROI) around Qbb (thanks to a coarse calibration).
2) Apply Quality cuts (to discard trigger on noise, microdischarges, etc.)
3) Calibrate energy of raw spectra (thanks to calibration runs)
4) Select events with multiplicity 1 (only 1 Ge has a signal)--> discard γ scattering in detectors
5) Apply Muon veto anticoincidence.
6) Apply LAr anticoincidence
7) Apply Pulse Shape Discrimination Cuts tailored to select single site events (SSE) i.e. discard multisites (MSE).
    a) Cuts are tailored for each detector (category and individual) on the basis of calibrations
    b) Cuts efficiencies for MSE are evaluated by γ lines Suppression Factors (SF)
    c) Cuts efficiencies for acceptance of 0νββ events are evaluated on 0νββ proxies structures (2νββ, Compton Edges)
8) Apply cut to reject α events
9) Measure the Background, in a ±120 keV range around Q_{bb} (excluded the blinded 50 keV)
10) Unblind the data in the ROI and apply the (freezed) cuts (1. to 8.)
11) Perform Statistical analysis: from the fit of the unblinded ROI extract the free parameter: 0νββ Signal Intensity→ $T^{0\nu}_{1/2}$-> $m_{\beta\beta}$

Energy Scale and Resolution

To achieve high R in spectra integrated over years of the 40 detectors it is required

- High ΔE (order of 0.1%) of the individual detectors
- Stable system and/or capability to track/compensate instability -> calibrations

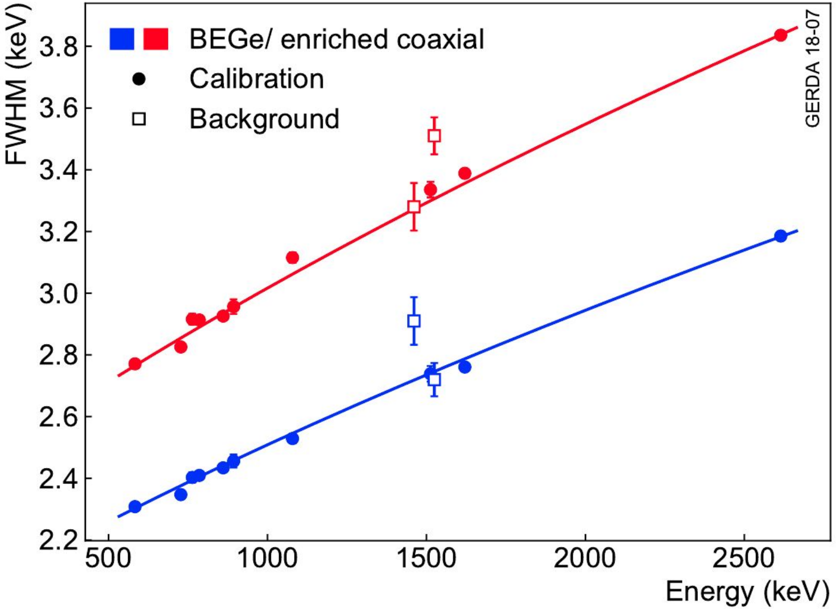
Energy Calibration Strategy in GERDA

- ~ bi-weekly ^{228}Th calibrations
- pulser injected into FE every 20 s to monitor stability
- Digital Filter applied: Customized Cusp Filter [EPJC 75 (2015) 255]

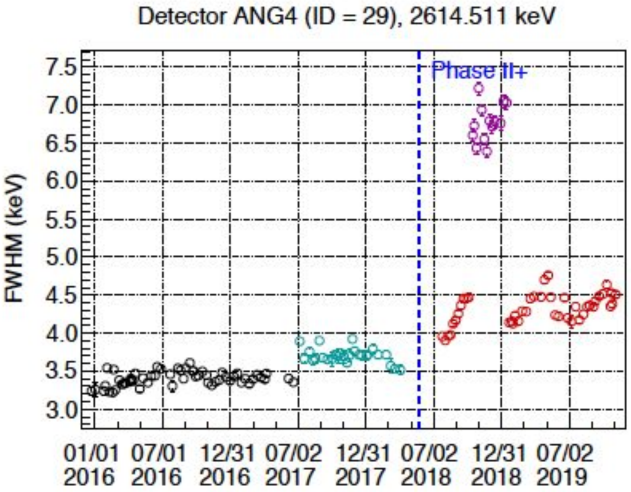
To Check quality of calibration:

- calibrate and sum-up physics data: $\delta(E_{true}-E_{cal})$ and FWHM of known lines in integrated phy-data reflects the quality of the calibration procedure

Energy Scale and Resolution



- In forthcoming data release, calibration strategy has been revised:
- Data are partitioned: FWHM and Energy scale, and uncertainties are evaluated on individual detectors, and for validity period, to reflect variations

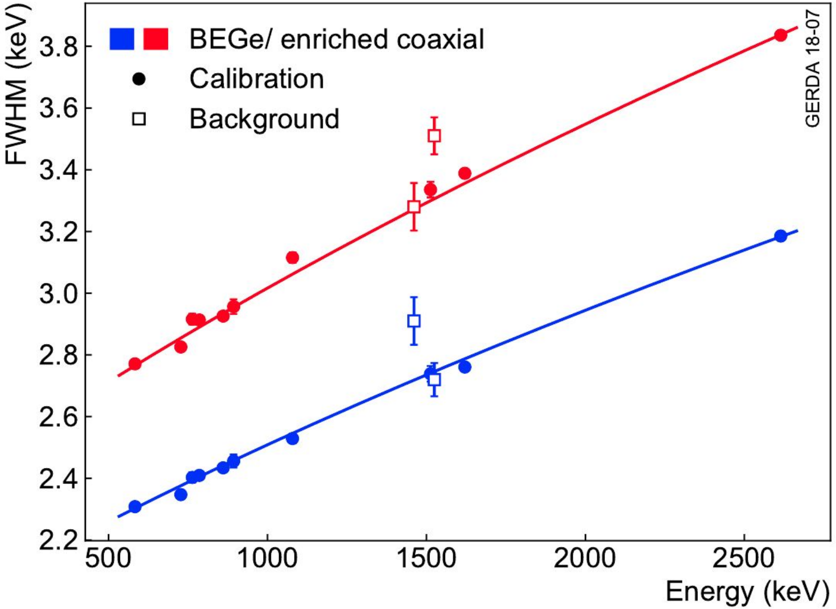


Average FWHM values (until 2018)

^{enr}BEGE: FWHM @ $Q_{\beta\beta}$= 3.0 keV

^{enr}Coax: FWHM @ $Q_{\beta\beta}$ = 3.6 keV

Energy Scale and Resolution



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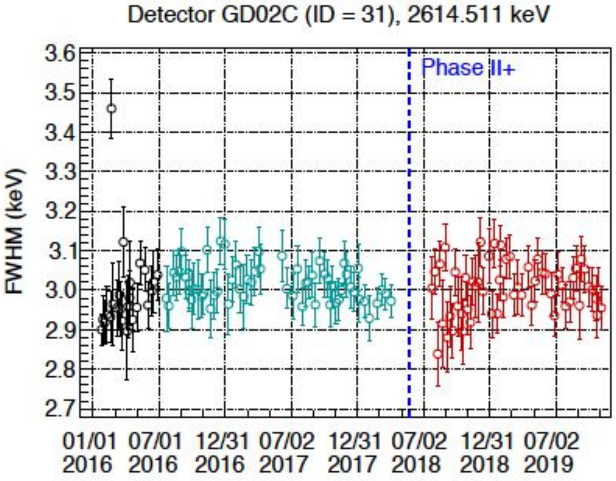

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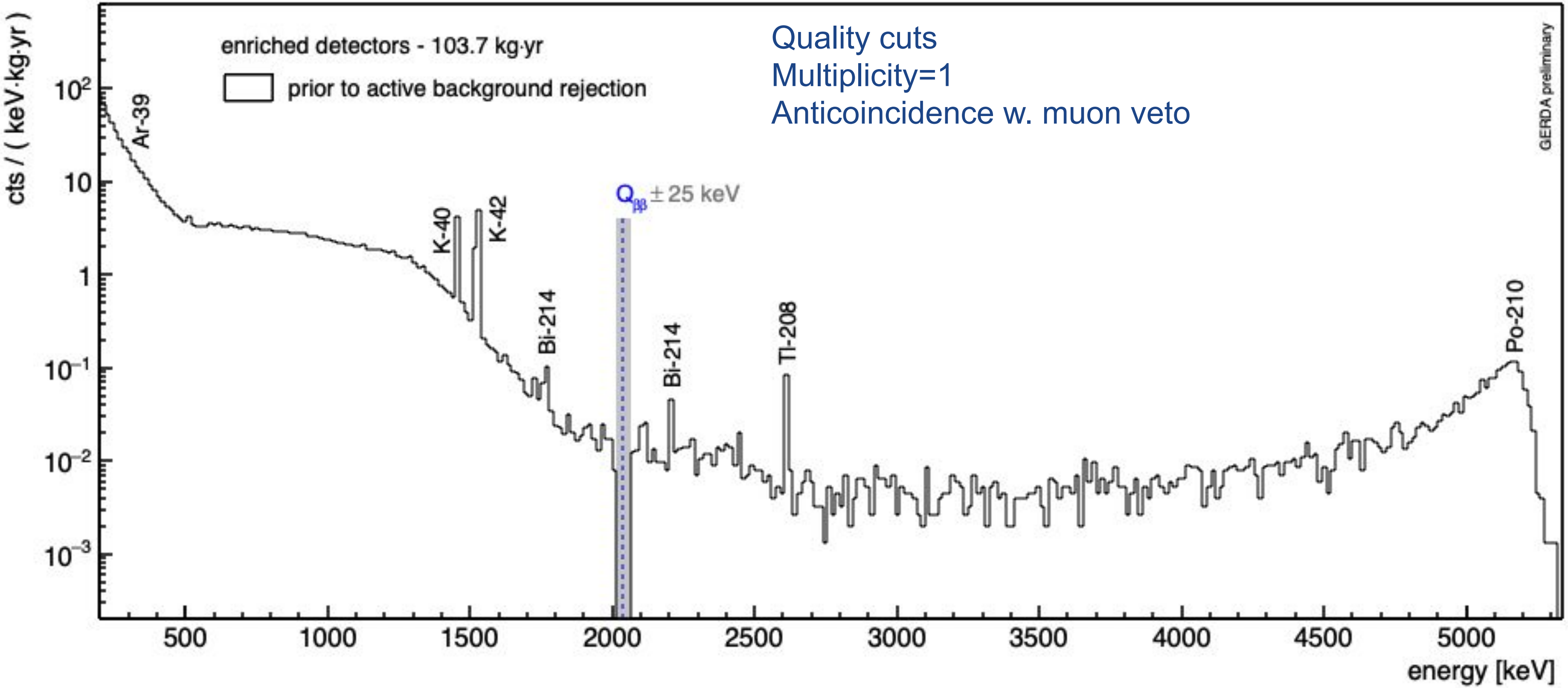
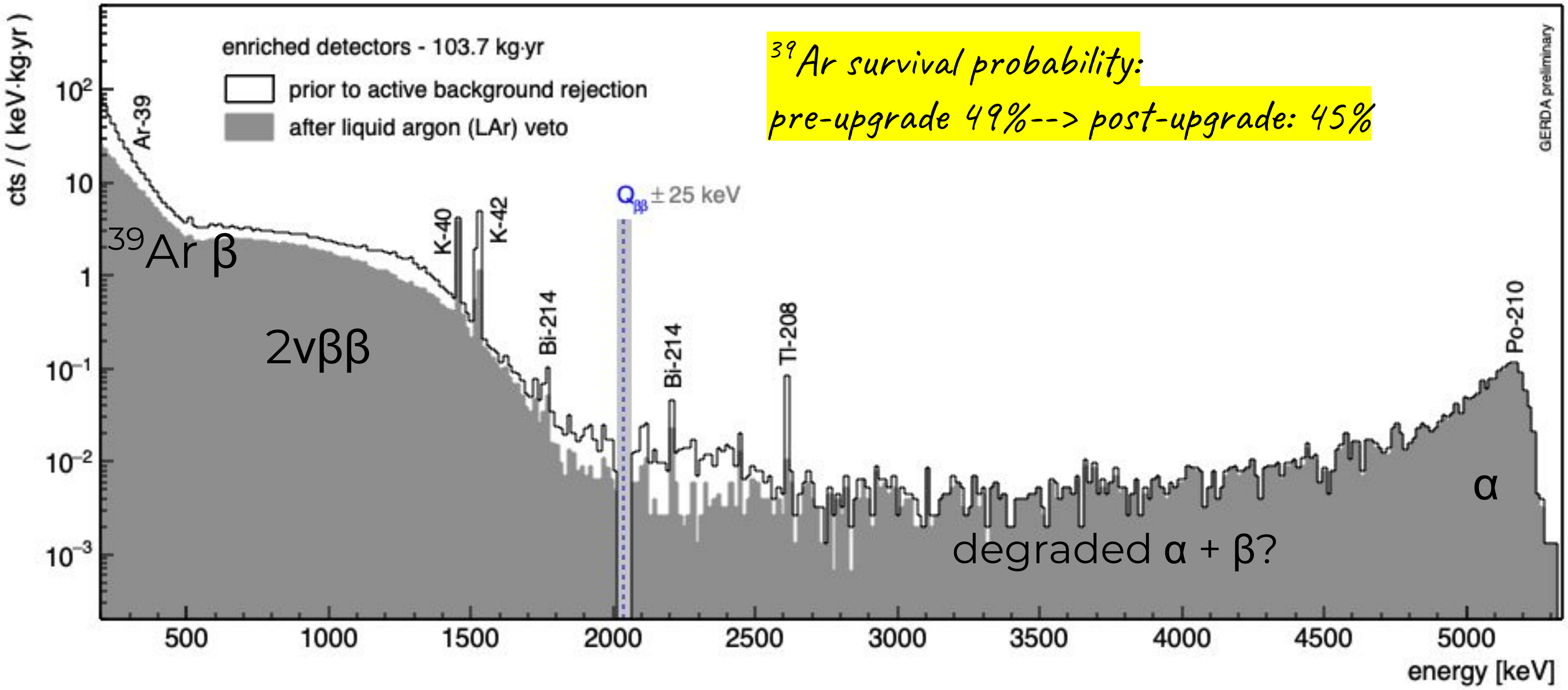
GERDA Global Blinded Spectra



Quality cuts
Multiplicity=1
Anticoincidence w. muon veto

Effect of LAr veto on data collected



^{39}Ar survival probability:

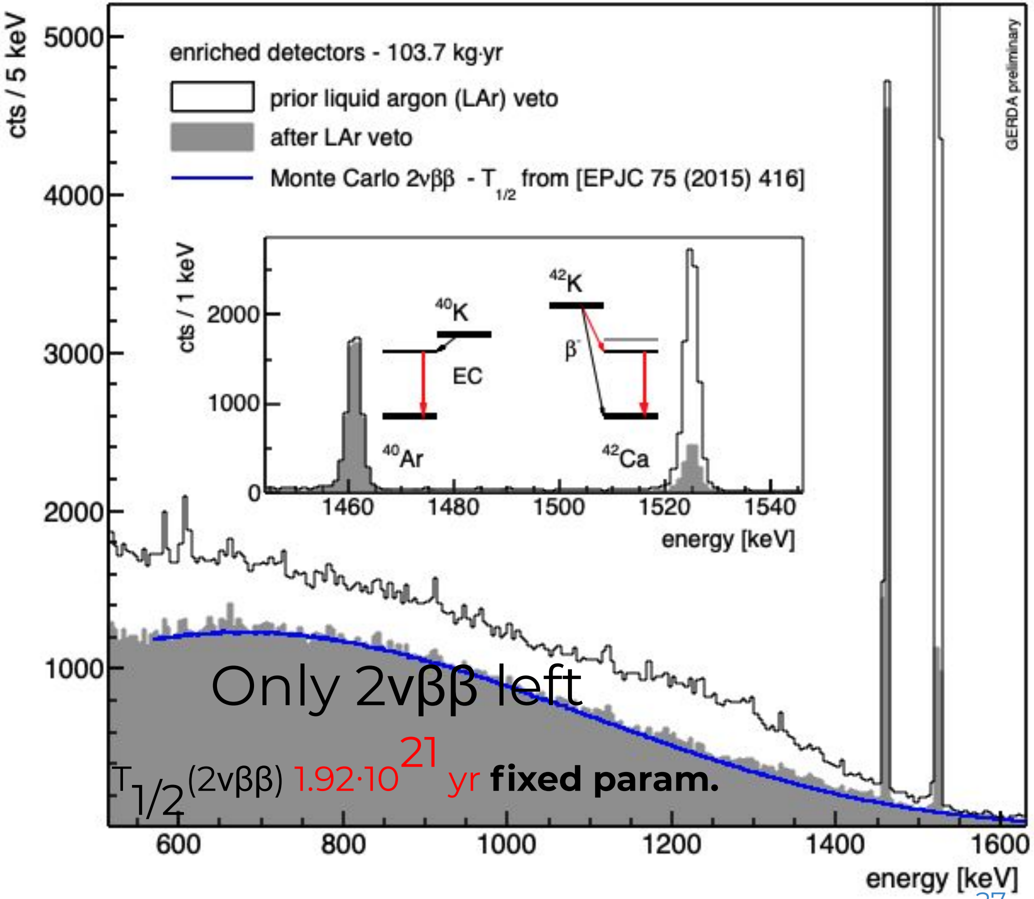
pre-upgrade 49%--> post-upgrade: 45%

Effect of LAr veto on gamma lines

γ-rays Survival Fractions (SF):

- ^{40}K (EC: pure γ) : ~97.7 ± 0.4%
- ^{42}K (β^- + γ): ~20%

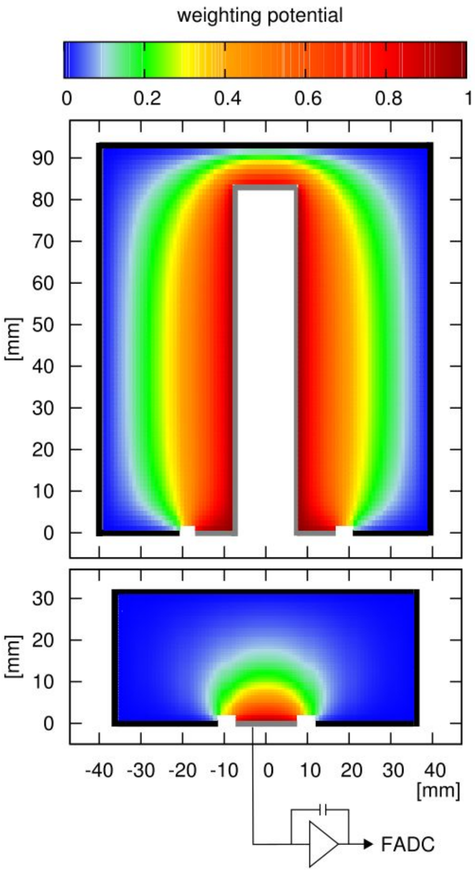
^{42}K from the β^- decay (33 yr) of cosmogenic ^{42}Ar which is ~6 $\cdot 10^{-21}$ [^{40}Ar]



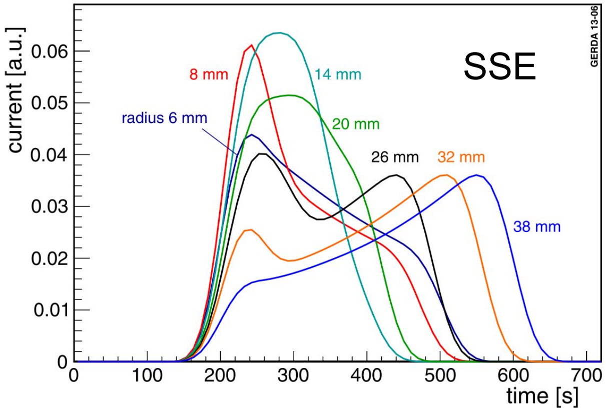
Only 2νββ left

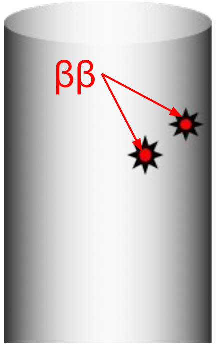
$T_{1/2}$(2νββ) 1.92·10^{21} yr **fixed param.**

Pulse Shape Discrimination (PSD)

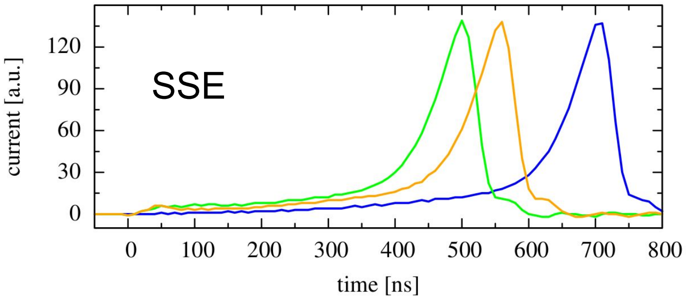


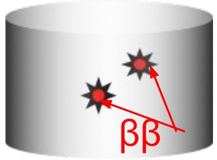
COAX: Artificial Neural Network (ANN) estimator used as PSD parameter





Pulses have different shapes based on location and number of interactions in the detector





BEGe: Amplitude of Current/Amplitude of Charge Pulse (A/E) is the PSD parameter

Events selection based on pulse shape (PSD)

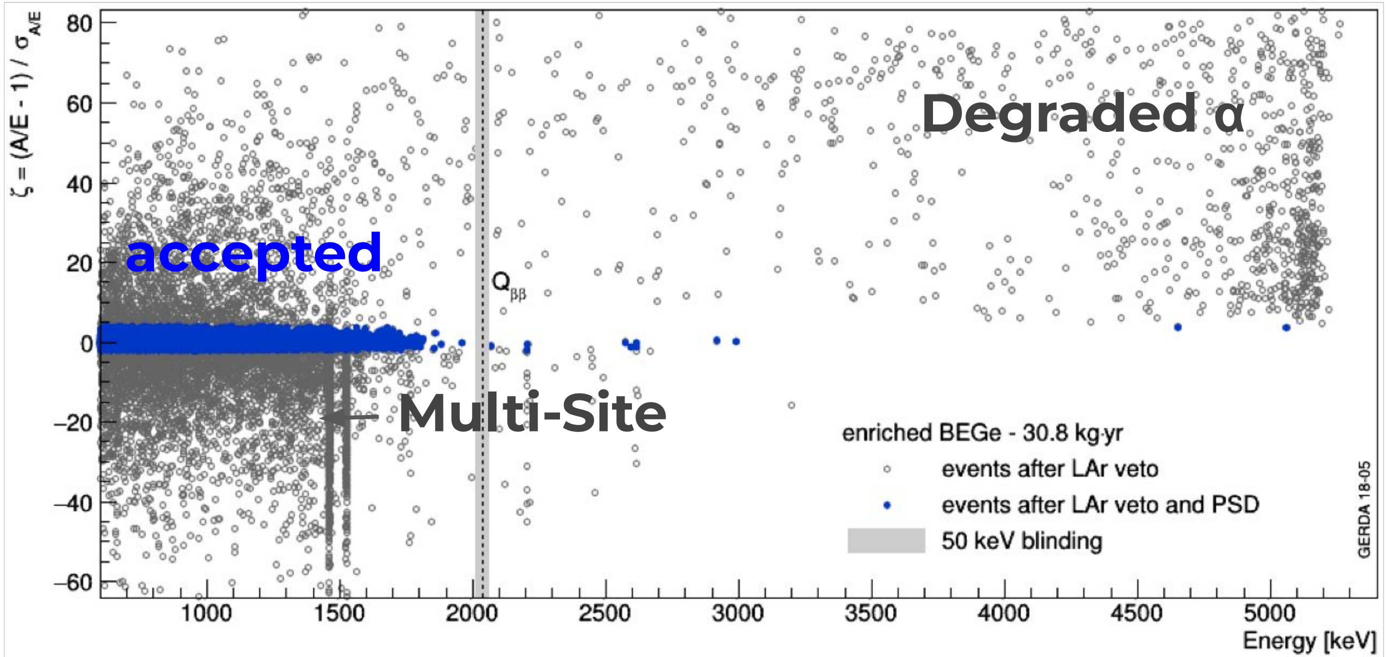
- *Event-per-event* selection
  - **Above band**: events on p+ electrode (e.g. α's from ^{210}Po)
  - **Below band**: events on n+ electrode, multiple scattering

Acceptance for 0ν2β events:

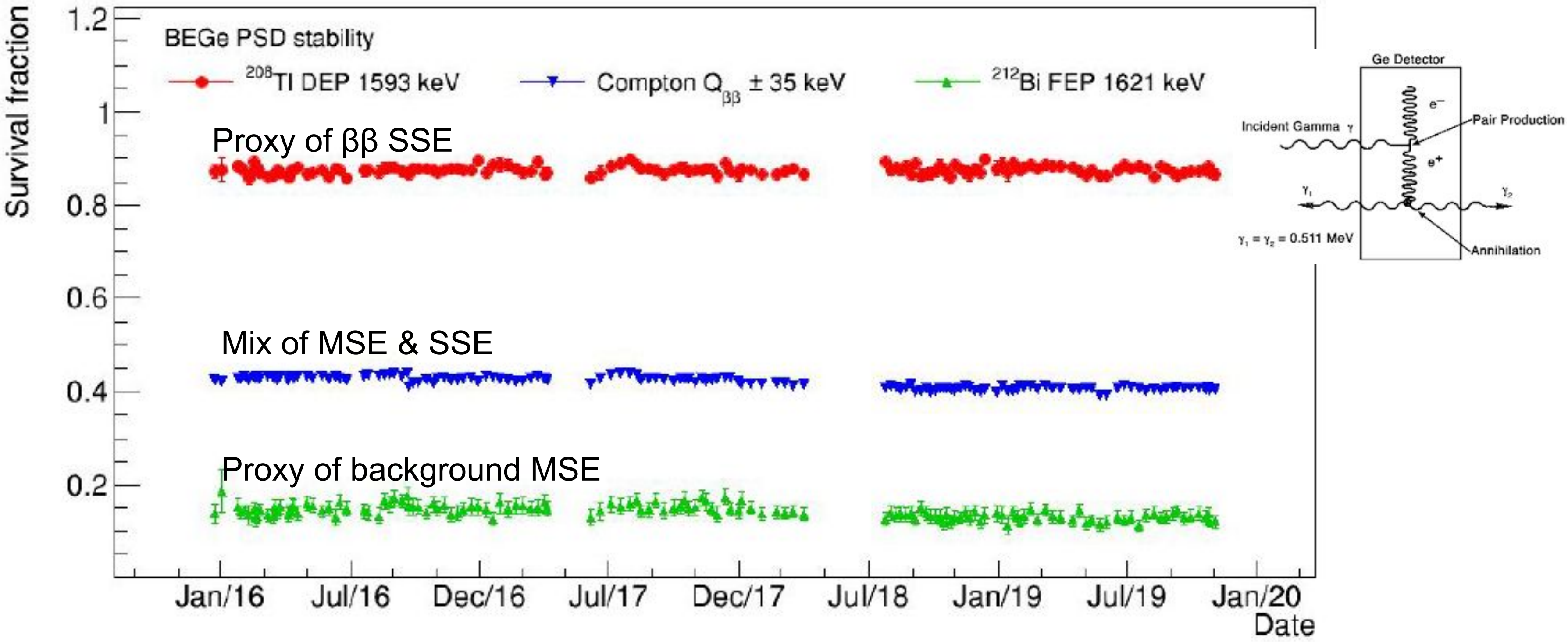
(87.6 ± 2.5)%

- Estimated from ^{208}Tl DEP

Double-check at low energy with 2νββ events (LAr cut) **(85.4 ± 1.9)%**



Pulse shape cuts BEGE: Survival Fractions



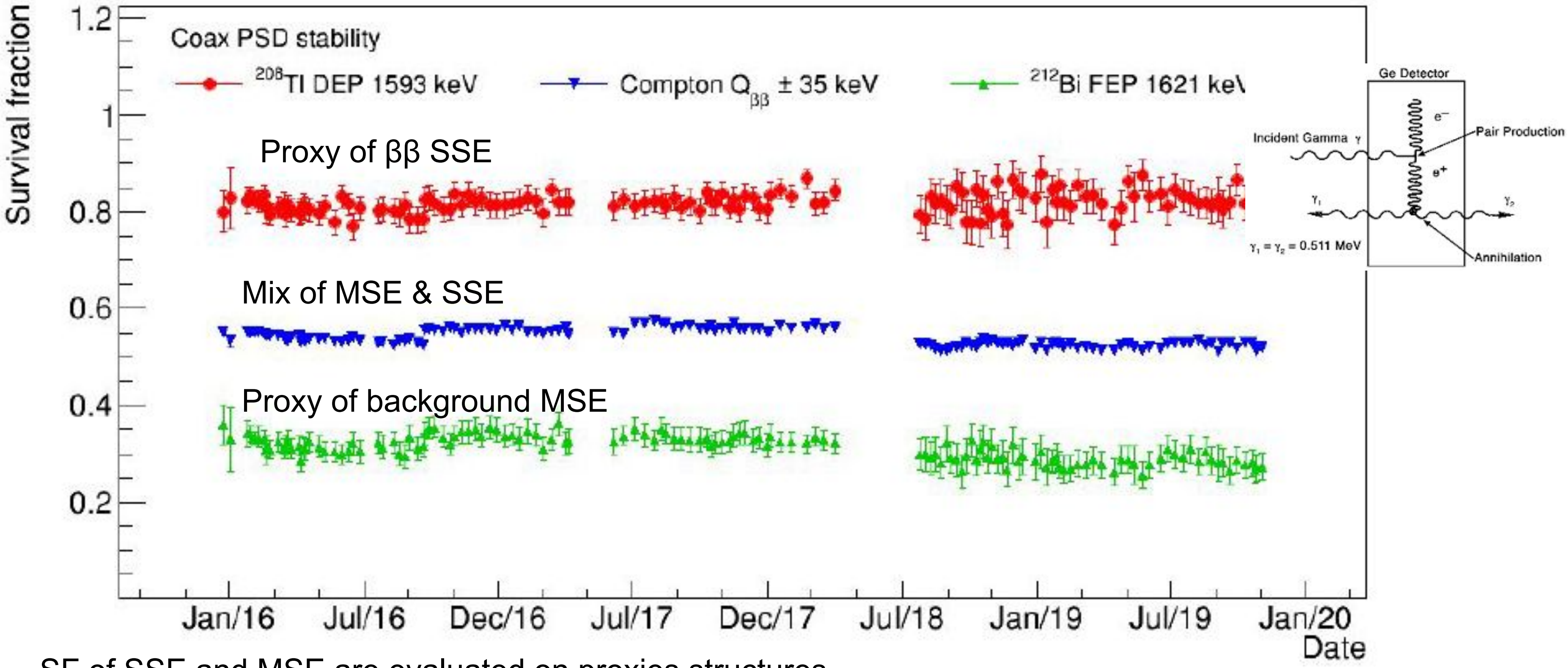
Proxy of ββ SSE

Mix of MSE & SSE

Proxy of background MSE

SF of SSE and MSE are evaluated on proxies structures

Pulse shape cuts COAX: Survival Fractions



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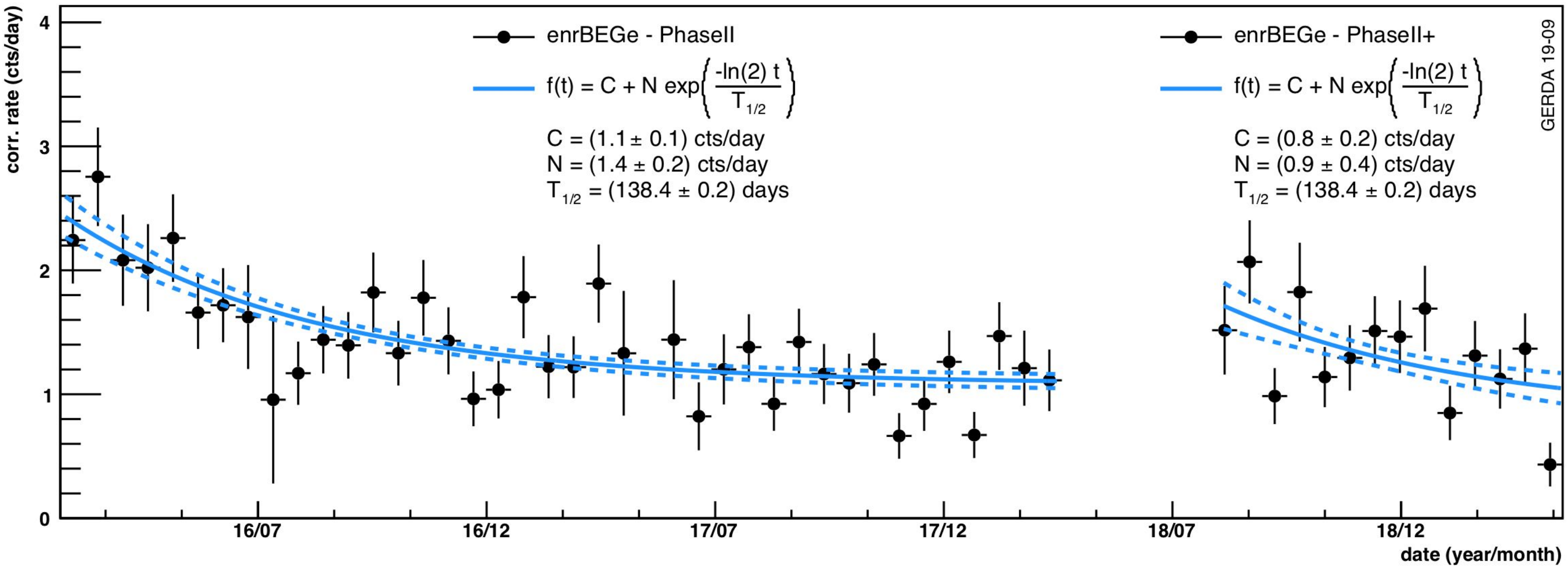
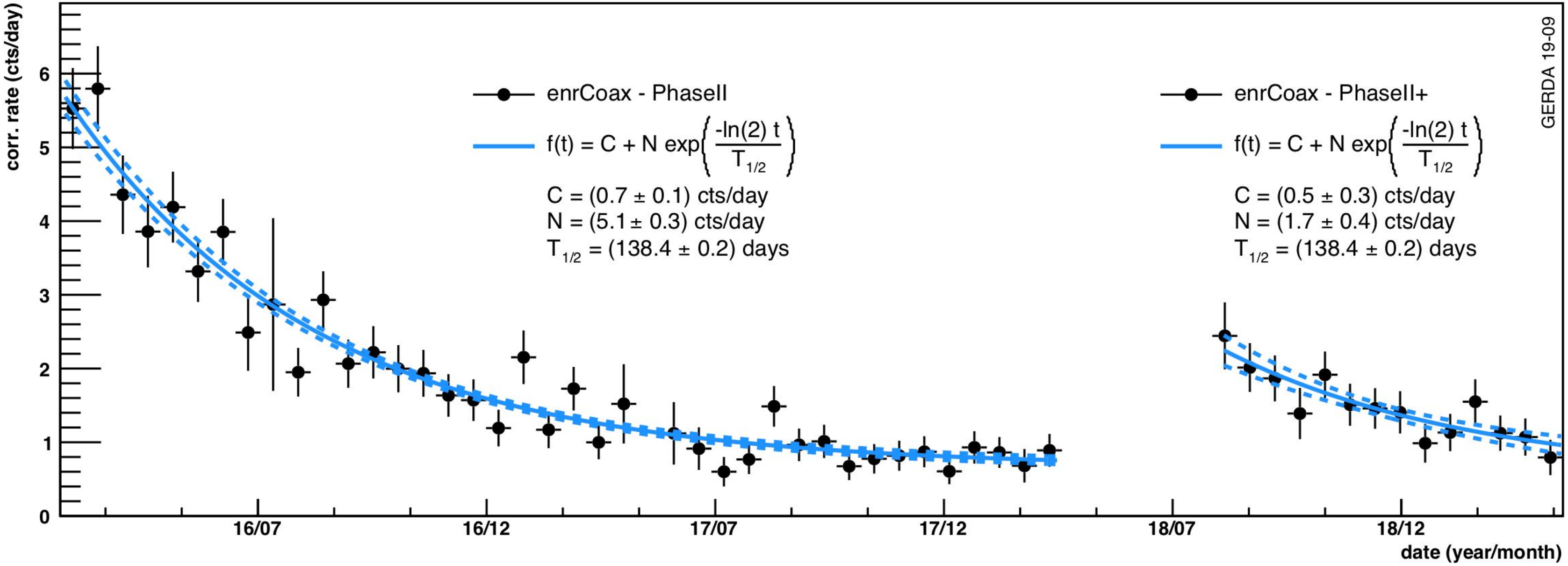
Background from α in ^{enr}BEGe

α from ^{210}Po decayed: we are left with a residual rate of ~1 cts/day



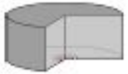
Background from α in ^{enr}Coax

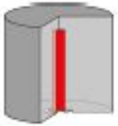
α from ^{210}Po decayed: we are left with a residual rate of <1 cts/day



Background Indexes of the whole GERDA data-set

8.5 kg yr

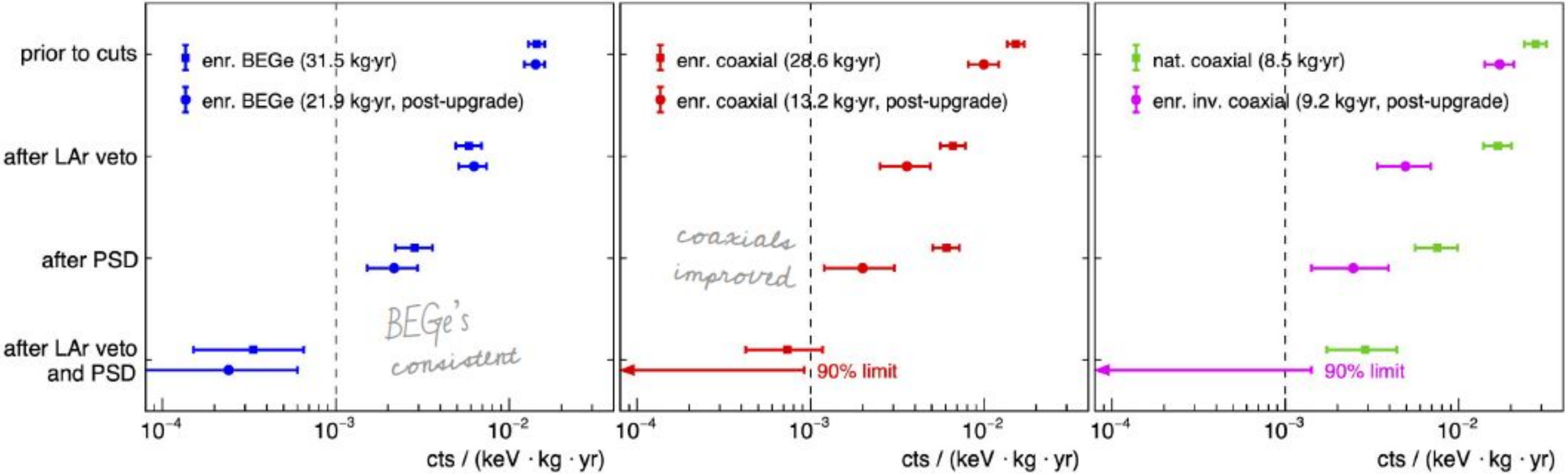




	enr. BEGe	enr. coaxial	enr. inv. coaxial	[10^{-4} cts/(keV·kg·yr)]
pre-upgrade	$3.3^{+3.2}_{-1.8}$	$7.4^{+4.4}_{-3.1}$		$5.3^{+2.5}_{-1.9}$
post-upgrade	$2.4^{+3.6}_{-1.7}$	< 9.2	< 14.2	$1.2^{+1.8}_{-0.8}$
	$3.0^{+2.2}_{-1.4}$	$5.0^{+3.0}_{-2.1}$	< 14.2 -> 90% limit	$3.6^{+1.6}_{-1.2}$

*differs from [Science 365, 1445 (2019)] due to larger exposure, different dataset definition and blinding

Background Indexes of the whole GERDA data-set

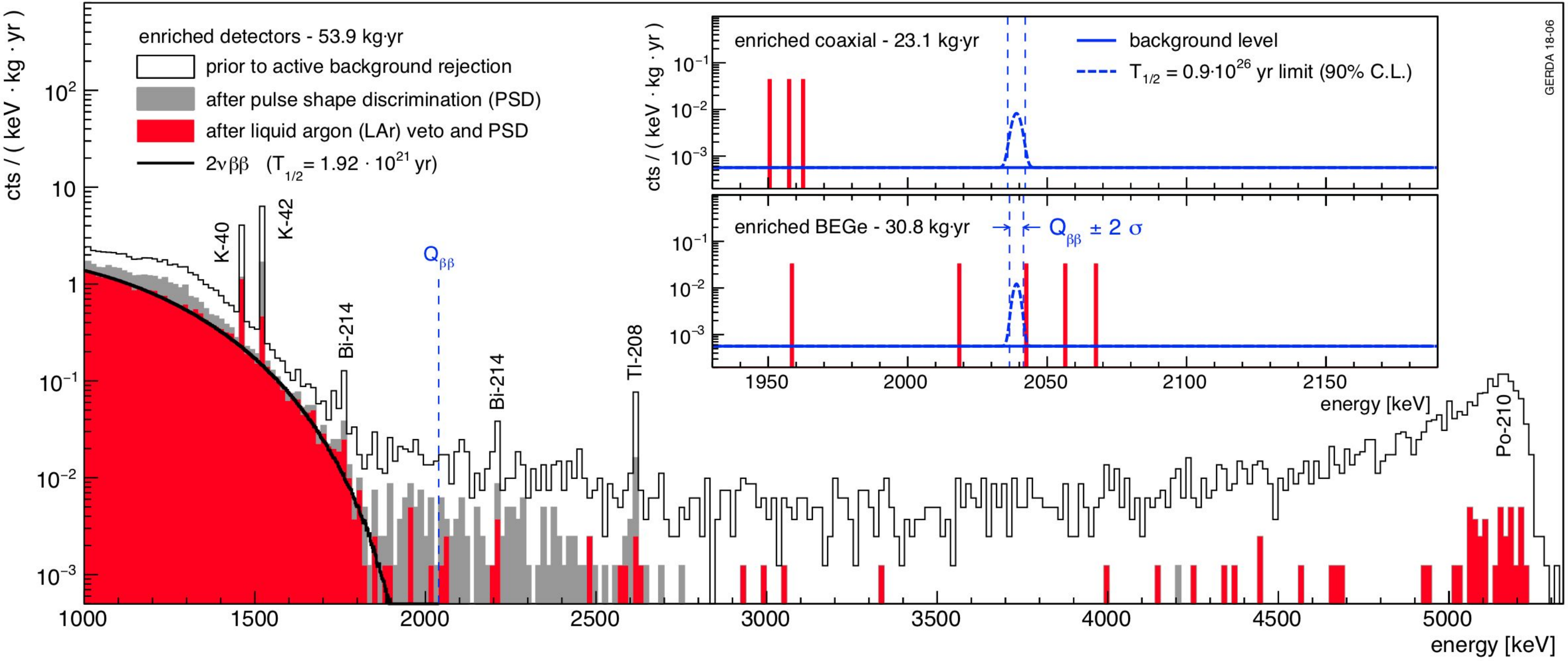


Last Published Statistics and results

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

GERDA

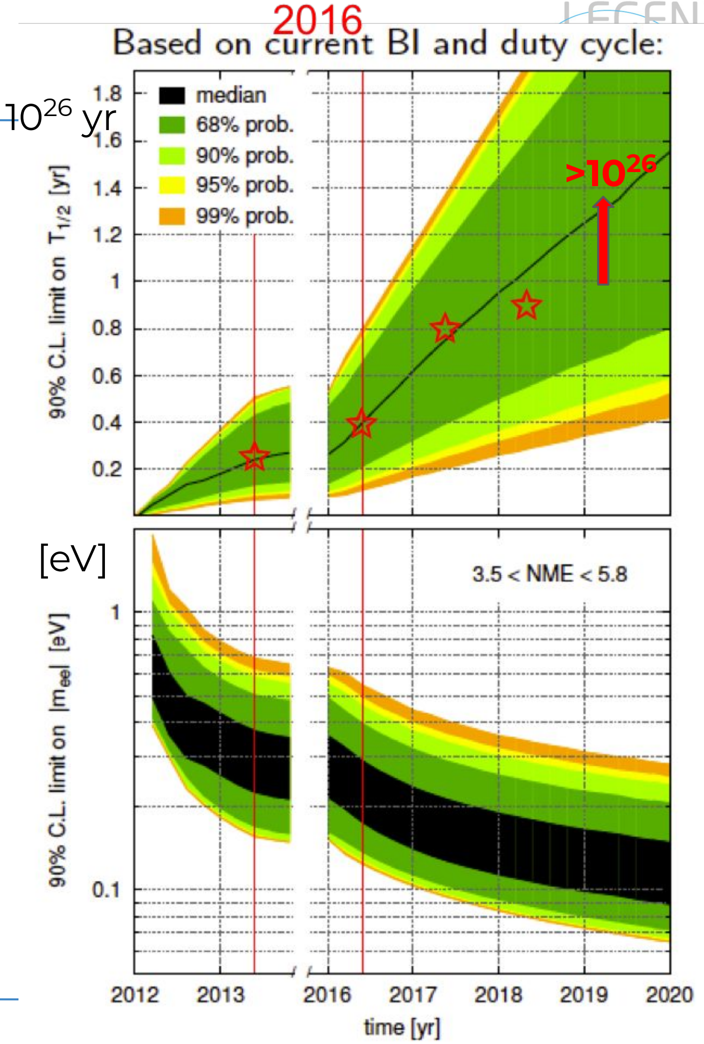


Measured vs expected

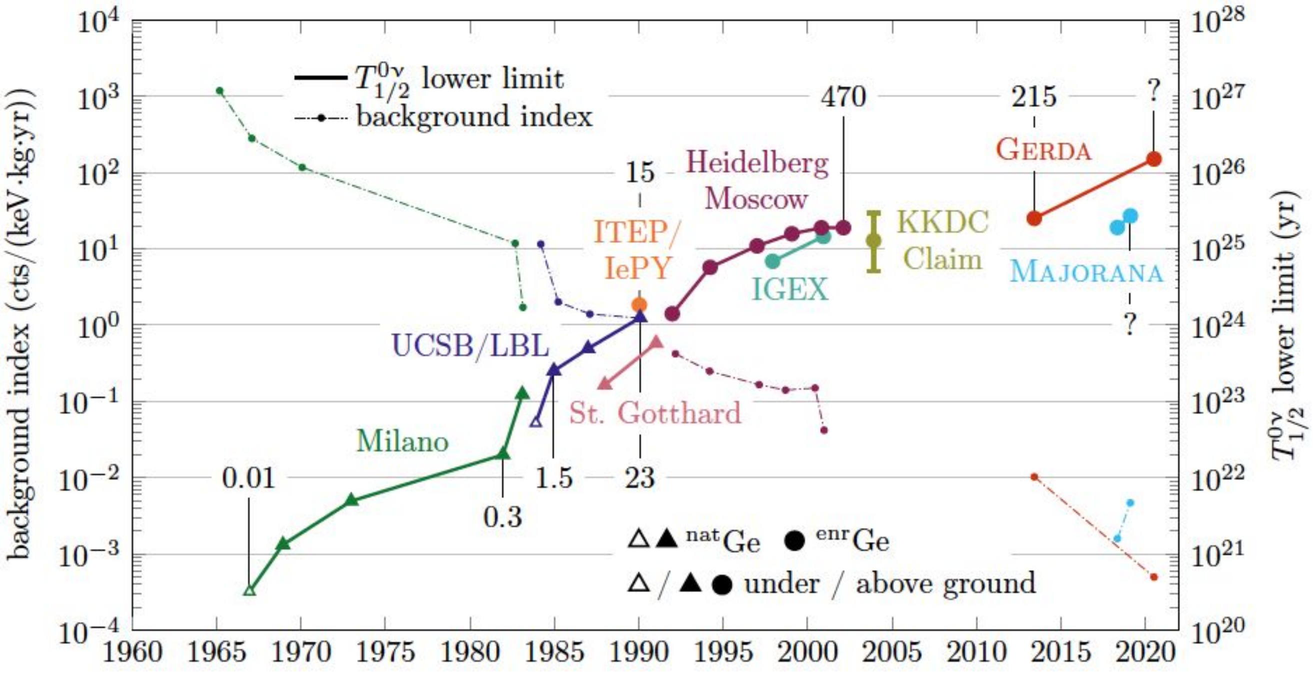
GERDA published results overlapped to expected evolution of sensitivity based on 2016 BI and expectation of duty cycle

Gerda Data Releases

1. PRL 111 (2013) 122503	
2. Nature 544, 47 (2017)	10.8 kg · yr
3. PRL 120, 132503 (2018)	23.2 kg · yr
4. Science 365, 1445 (2019)	82.4 kg · yr
5. **New Release at Neutrino 2020**	**103.7 kg · yr**



History of ^{76}Ge experiments: lessons learned



Lessons learned

- Increase the mass
- Increase radiopurity
- Decrease Z of shielding materials surrounding the Ge detectors (GERDA technology)
- Improve PSD
- ....

Comparison of Experimental Results

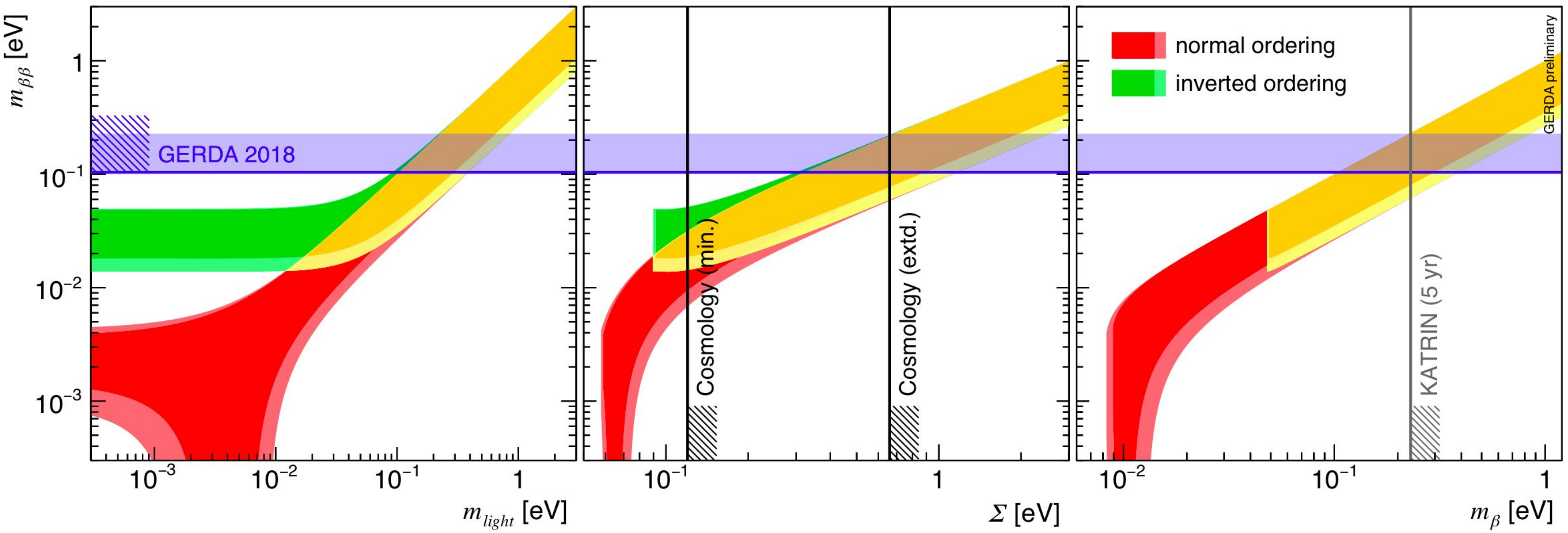
		Tot. M Isot. [kg]	Design Achi.vd BI [cts/kevkgy]	Design Achi.vd FWHM [keV]	Exposure [kg·y]	$T_{1/2}$ Sensitivity (90%CL) [y]	$T_{1/2}$ Achieved Limit (90%CL) [y]	m_{ee} Limit (90%CL) [meV]
Gerda II -	^{76}Ge	31.0	10^{-3}	< 4	~100	> 10^{26} †	Preliminar	90-150
Gerda II		31.0	$0.36 \cdot 10^{-3}$	3.0-3.7	103.7	$1.1 \cdot 10^{26}$	> 10^{26}	120-250#
Majorana	^{76}Ge		<10^{-3}	< 4		>10^{26}		
Demonstrator		27.1	$4.7 \cdot 10^{-3}$	2.5	26	$4.8 \cdot 10^{25}$	$2.7 \cdot 10^{25}$	200-433
n-EXO	^{136}Xe	5000						10
EXO 200 ult.				73				50
EXO 200		200	$1.7 \cdot 10^{-3}$	112	100	$1.9 \cdot 10^{25}$	$1.1 \cdot 10^{25}$	170-490
KZ comb.	^{136}Xe			265	138	$5.6 \cdot 10^{25}$	$1.07 \cdot 10^{26}$	50 -160
Kam-Zen II		348	$3.0 \cdot 10^{-4}$	265	126		$9.6 \cdot 10^{25}$	
Kam-Zen II		348	$6.0 \cdot 10^{-4}$	285	29.6		$1.3 \cdot 10^{25}$	
Cuore	^{130}Te	206	10^{-2}	5	1000	$9.5 \cdot 10^{25}$ † †		50-190
Cuore			$1.38 \cdot 10^{-2}$	7.0	372.5	$1.7 \cdot 10^{25}$	$3.2 \cdot 10^{25}$	75-350
CUPID	^{100}Mo							
CUPID-0	^{76}Se		$3.5 \cdot 10^{-3}$	20	5.29	$5.0 \cdot 10^{24}$	$3.5 \cdot 10^{24}$	311-638

This mass range corresponds to 0.9 $\cdot 10^{26}$ yr

If 2004 claim of 0νββ evidence (1.19 10^{25} y) were true GERDA would observe ~30 events

RED: ~10^{26}/100 meV range; Blue: Achieved ; #(2018 Release) ; †Design Sensitivity; ††5 yr projected sensitivity

Neutrino Mass Observable



^{76}Ge based 0νββ decay experiments

GERDA Phase I
M ~ 10 kg
T ~ 10^{25} yr
2011 - 2013

MAJORANA
M ~ 40 kg
T ~ 10^{26} yr
2016 - running

LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

GERDA Phase II
M ~ 40 kg
T ~ 10^{26} yr
2015 - 2019

LEGEND 200
M ~ 200 kg
T ≥ 10^{27} yr
2021 - 2026 ?

LEGEND 1000
M ~ 1000 kg
T ≥ 10^{28}yr
2027 ??

PAST **FUTURE**

The LEGEND Experiment

LEGEND

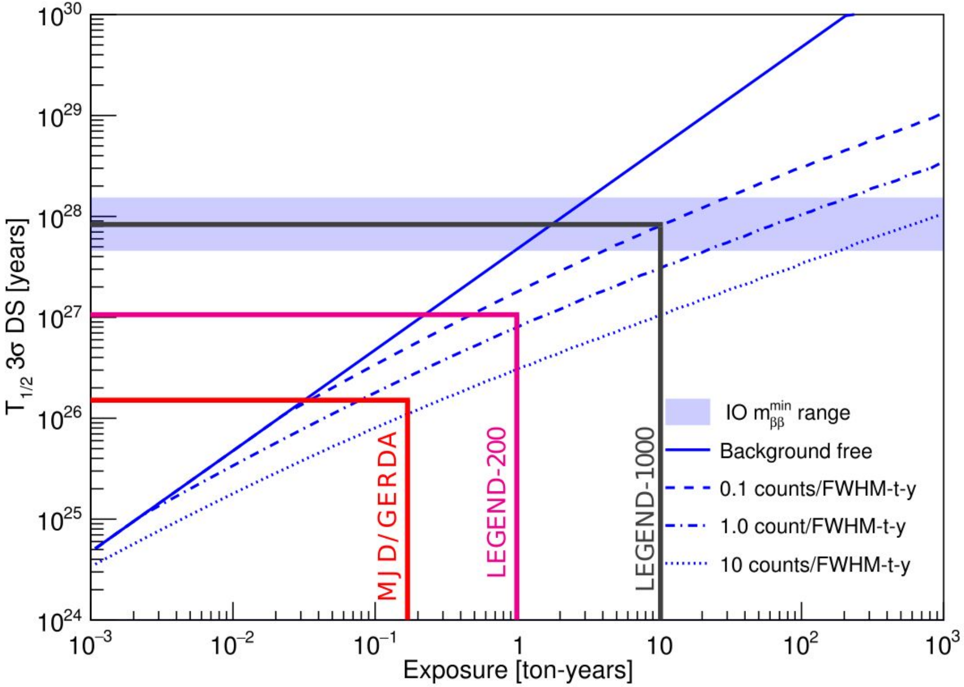
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

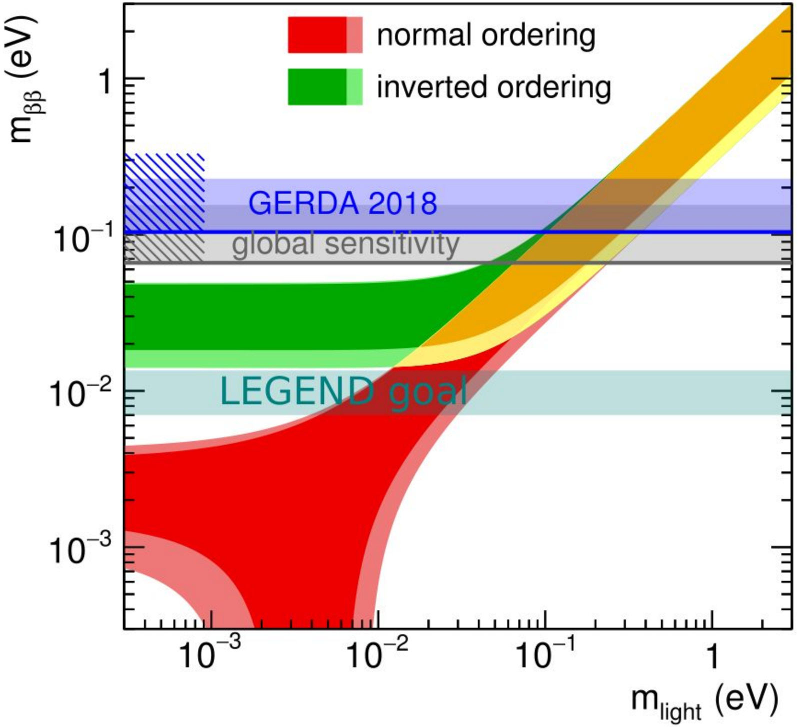
0νββ decay experimental program with discovery potential at half-life of 10^{28} years,

- more than 50 institutions, ~250 members
- based on GERDA & MAJORANA techniques

LNGS, May 27-30, 2019

The LEGEND goal





LEGEND aims to cover the inverted ordering region

First Stage: LEGEND-200

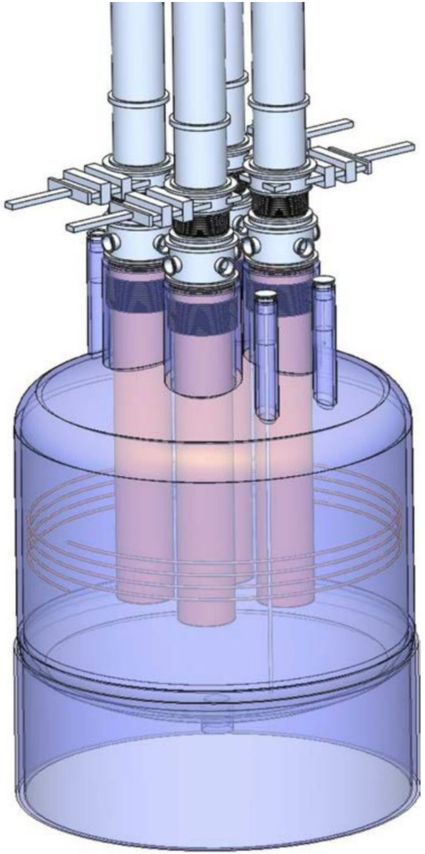
arXiv:1905.06572

- 200 kg of ^{76}Ge detectors
- modification of existing GERDA infrastructure at Gran Sasso Laboratory
- reduced background
- discovery sensitivity at 10^{27} yr
- **preparation started in 2019
data taking planned in 2021**

Subsequent Stage: LEGEND-1000

arXiv:1905.06572

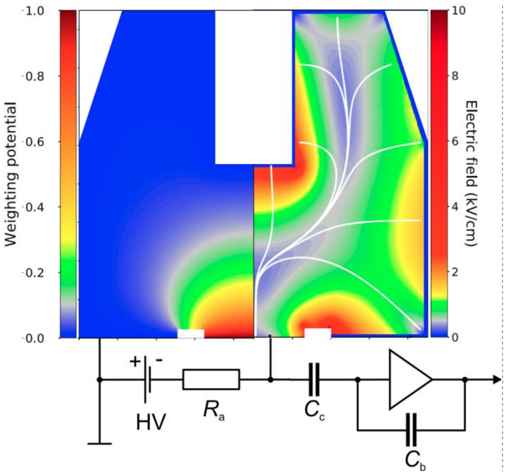
- 1000 kg of ^{76}Ge
- location to be selected, required depth under investigation
- timeline connected to review process

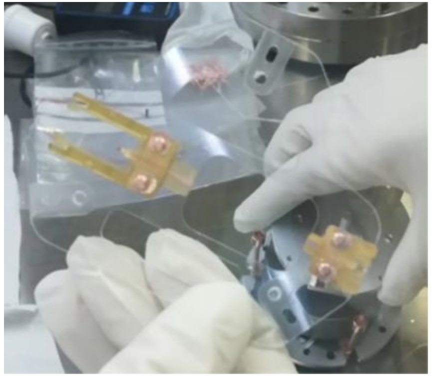


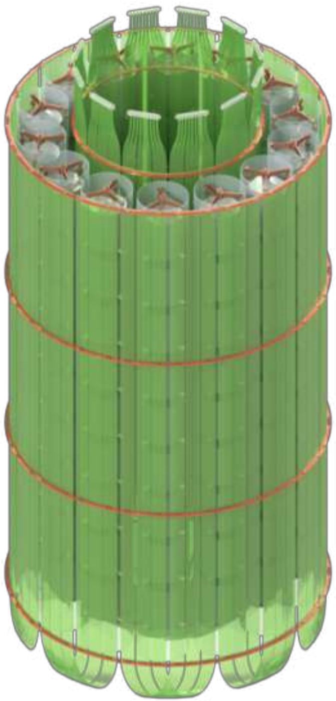
Improvements of LEGEND-200

arXiv:1905.06572

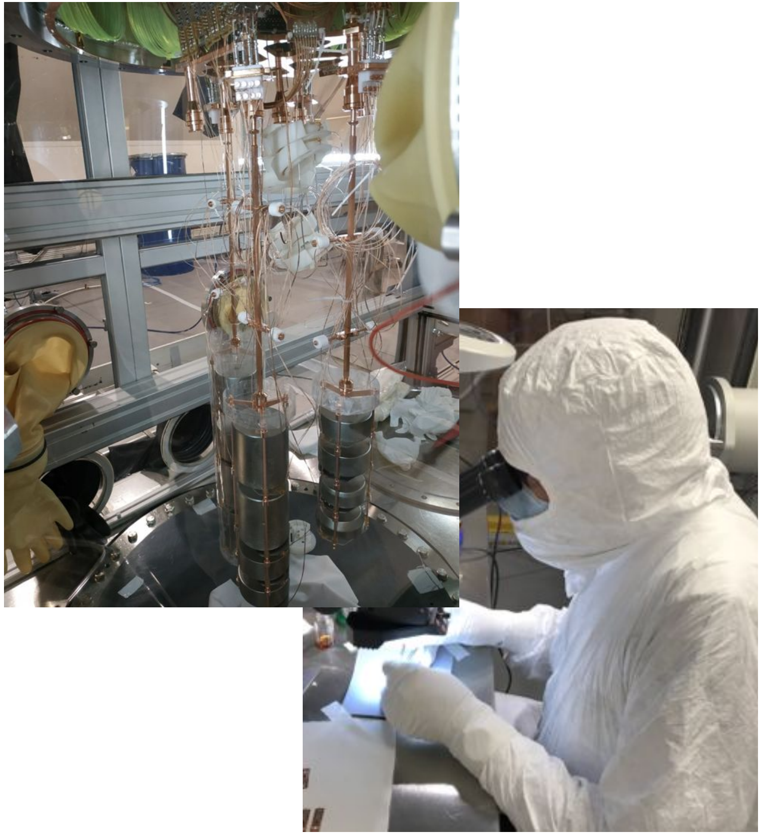
- **New Inverted Coaxial Point-Contact Ge detectors**, large active mass up to 3 kg
- **Improved LAr veto system**, optimization of light collection
- **PEN based** detector unit parts
- **Low Mass electronics** with underground electroformed Cu







Status of LEGEND-200

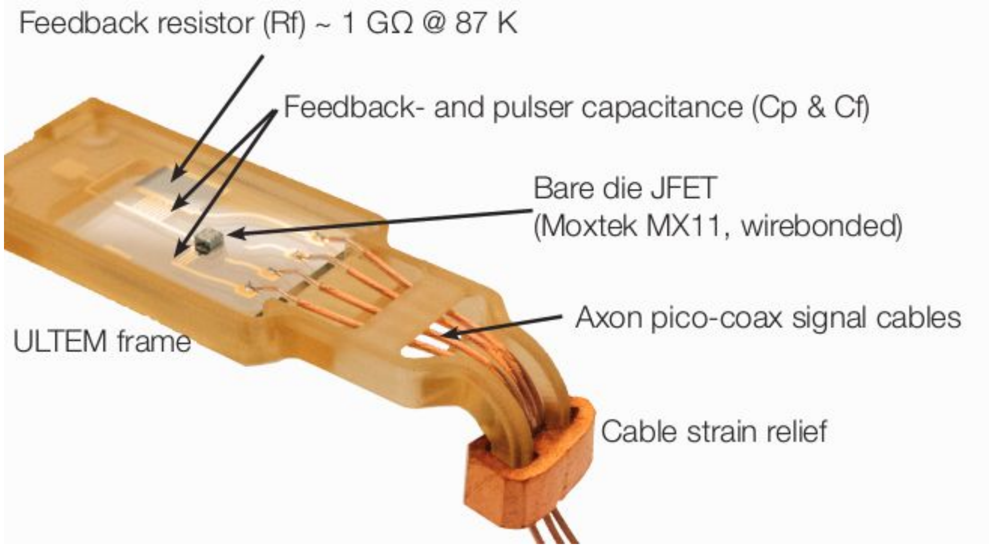


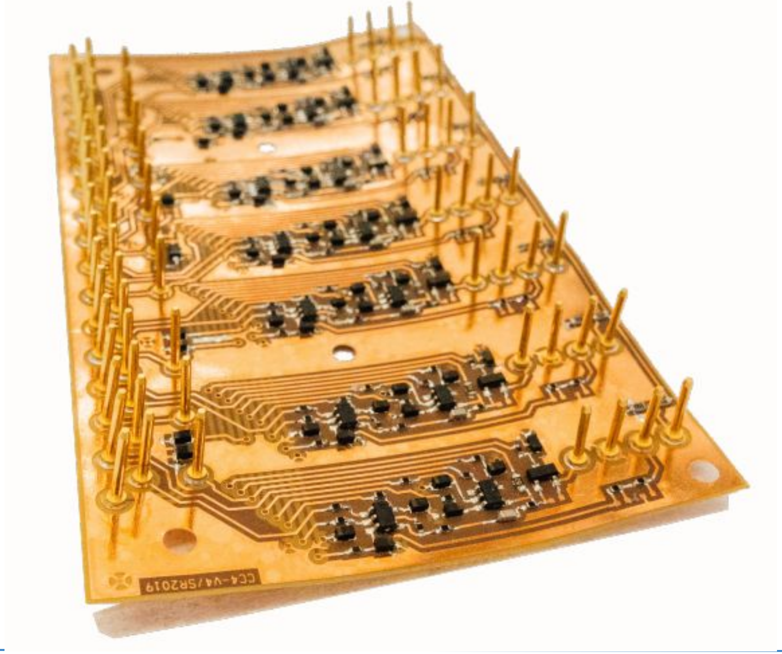
- GERDA infrastructure now operated by LEGEND from **February 2020 with installation of the first setup**
- **Electronics chain:** demonstrated with 20 channels in the first setup
- **New Detectors:** production of 155 kg of Inverted Coaxial HPGe in progress
- **New Active LAr veto**: production of fiber shroud and SiPMs in progress
- **Monte Carlo Simulations and Analysis Software** in preparation

Our activity in LEGEND: read-out electronics

1st stage: Low-Mass Front End
in close proximity of detectors,
stringent radiopurity constraints

2nd stage: Preamplifier
based on the GERDA electronics,
about 30 cm above the detectors



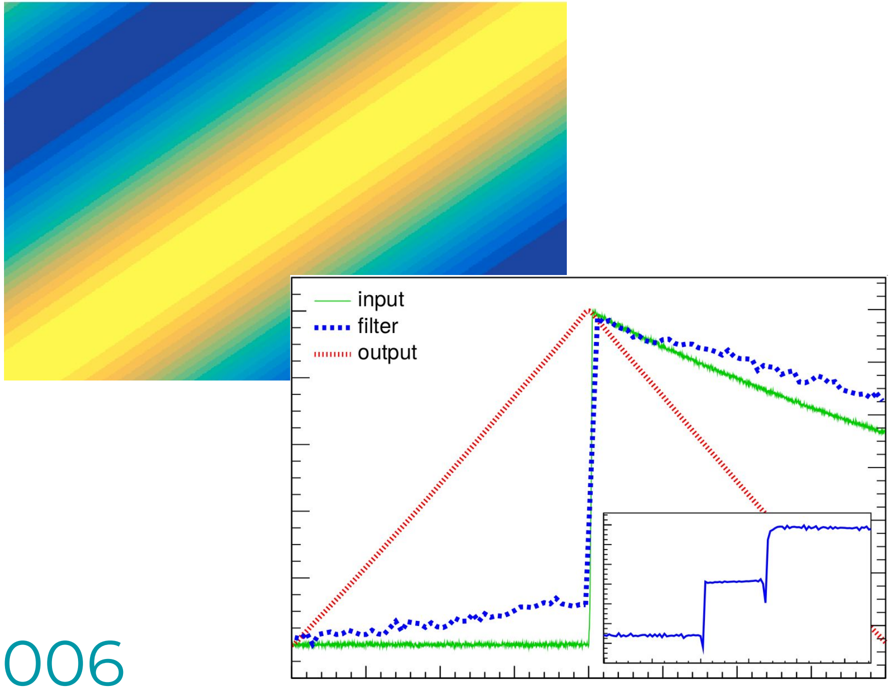


EPJ Web Conf 225 (2020) 01006

Our activity in LEGEND: digital signal processing

We are working on the implementation of a digital filter that maximize the signal-to-noise ratio

- based on the DPLMS method, taking into account the real environmental noise
- minimization of the deviations between the experimental samples and a reference curve
- **first application on GERDA & LEGEND data shows an improved energy resolution**



EPJ Web Conf 225 (2020) 01006

Summary

GERDA reached important milestones in the 0νββ decay search:

- energy resolution ~ 0.15% at $Q_{\beta\beta}$ i.e. ≤ 3 keV BEGe (~4 keV COAX)
- lowest background ever achieved: **$0.36 \cdot 10^{-3}$ cts/(keV·kg·yr)**
- probe of the 0νββ decay **beyond 10^{26} yr**

the search for 0νββ decay in ^{76}Ge will be continued by LEGEND-200 to reach a sensitivity of 10^{27} yr

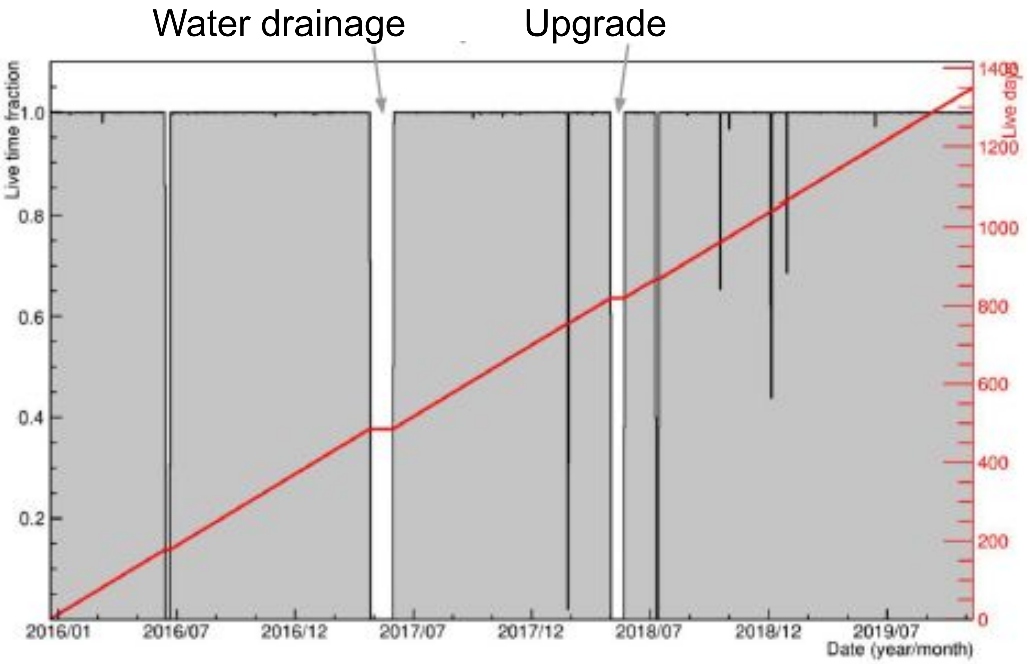
LEGEND-200 is in preparation, ongoing efforts to start in 2021

Thesis Opportunities

- Test and integration of the new electronics for LEGEND-200
- Digital Signal Processing on GERDA/LEGEND data
- Data analysis of new LEGEND-200 data from 2021

Muon Veto

- Fully operational along the whole analysis data taking
- ± 10μs anti-coincidence window around HPGe signal
- Muon rate crossing GERDA: (3182 ± 2) muons/d
- **Random Coincidence Probability with a Ge event < 10^{-6}**
- Muon contribution in the background window **O(10-3) cts/(kev·kg·yr)**
- Detection efficiency (99.935 ± 0.015) % [EPJC 76(2016)298]


Water drainage

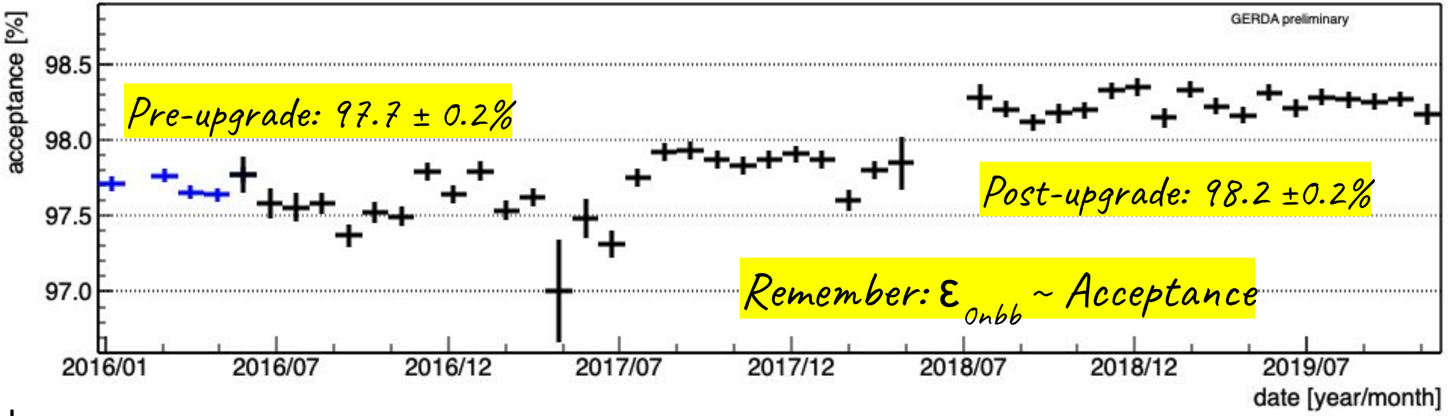
Upgrade

Liquid Argon Veto: Ge event acceptance Veto & LAr Triplet half-life

LAr Veto:
16 PMTs + 15 (+2) SiPMs

Acceptance determined on randomly triggered events (pulser/BL)

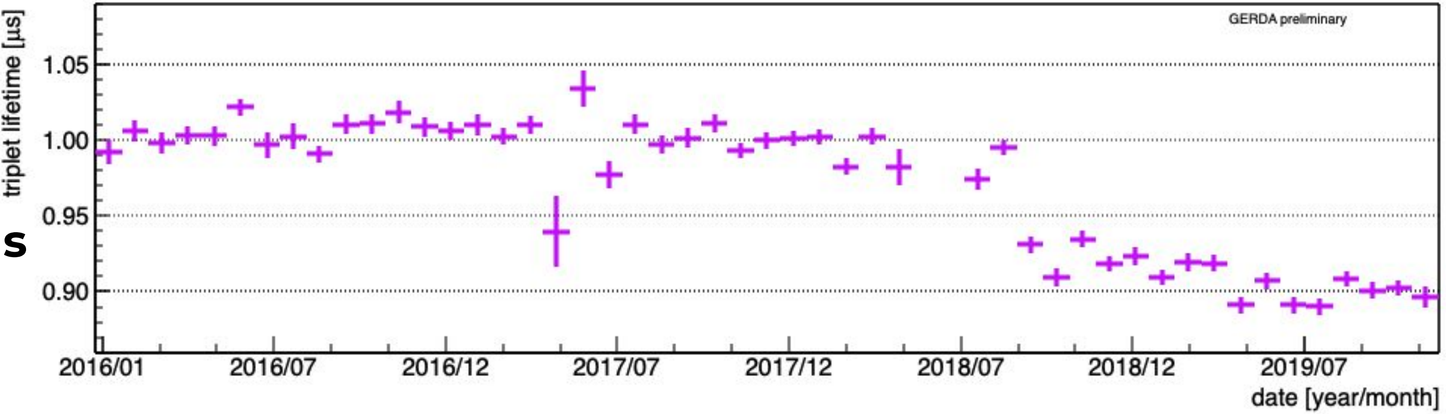
Anticoincidence condition:
≥ 0.5 PE in [-1,+5] μs around HPGe trigger



Pre-upgrade: 97.7 ± 0.2%

Post-upgrade: 98.2 ±0.2%

Remember: ε_{0nbb} ~ Acceptance



Background interpretation