Final results of GERDA on the search for 0νββ

Natalia Di Marco – Gran Sasso Science Institute & INFN
on behalf of the GERDA Collaboration

La Thuile 2021
Les Rencontres de Physique de la Vallée d'Aoste

Searching for 0νββ

2νββ

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

Maria Goeppert-Mayer (1935)

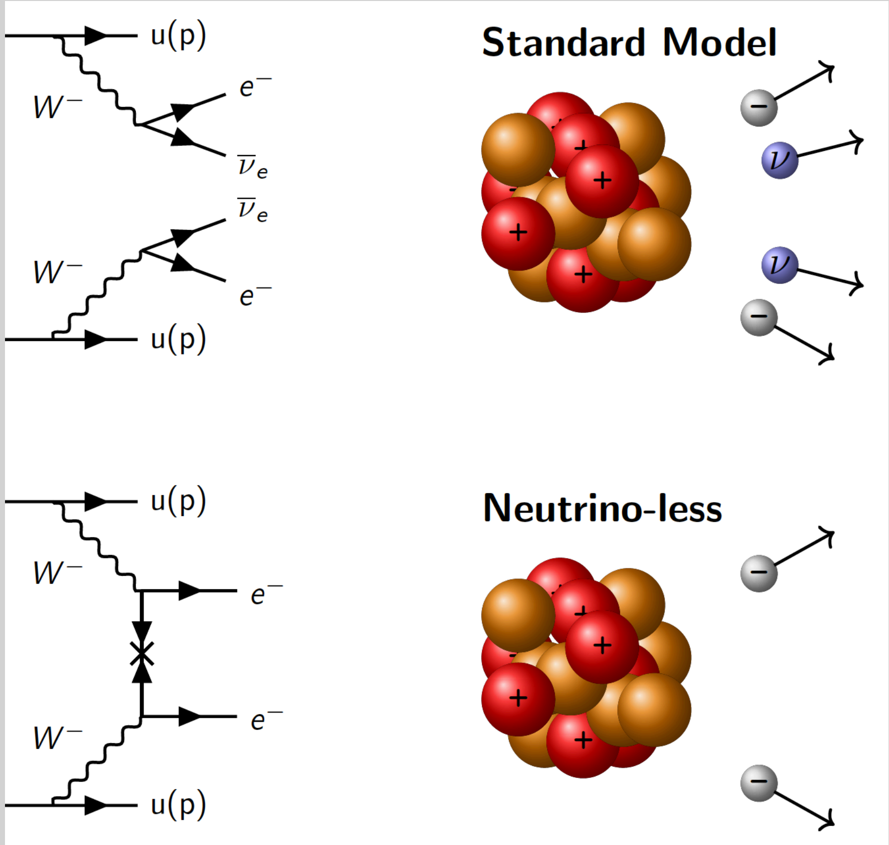
$T_{1/2}$ **~ 10^{21} yr (observed)**

0νββ

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

Wendell H. Furry (1939)

$T_{1/2}$ **> 10^{26} yr**



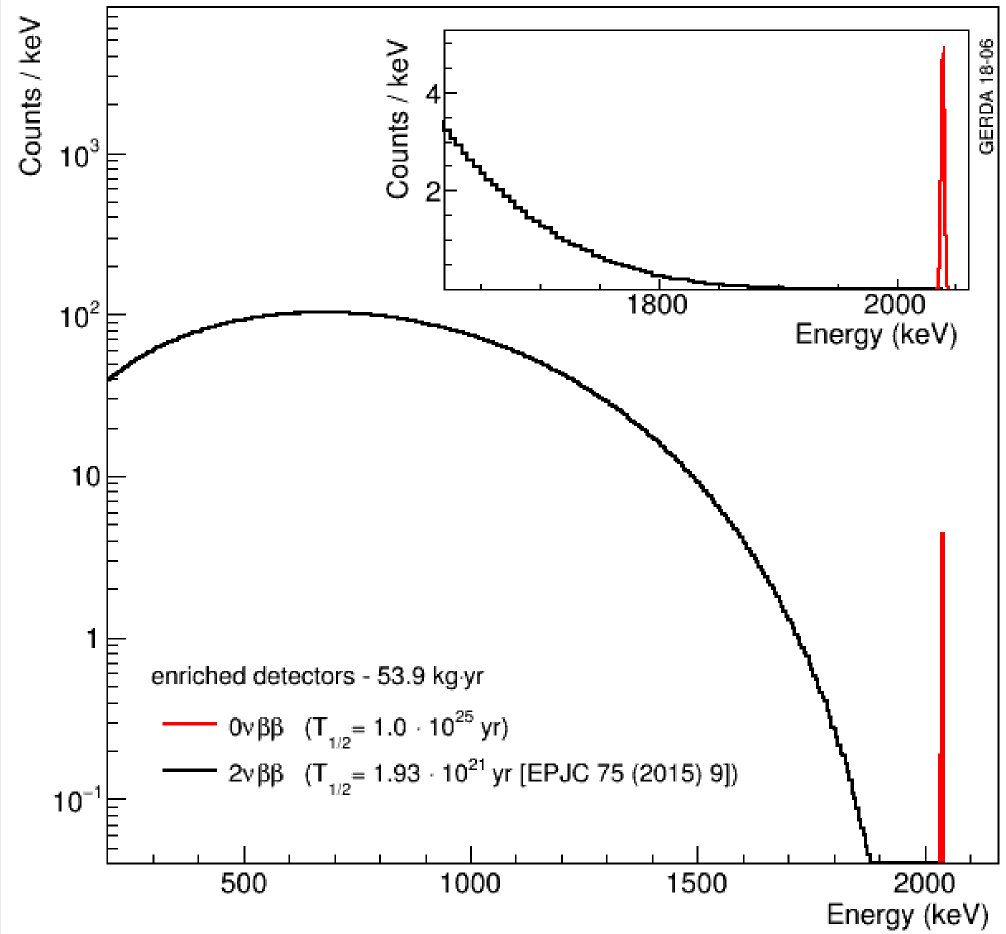
Searching for 0νββ

0νββ process:

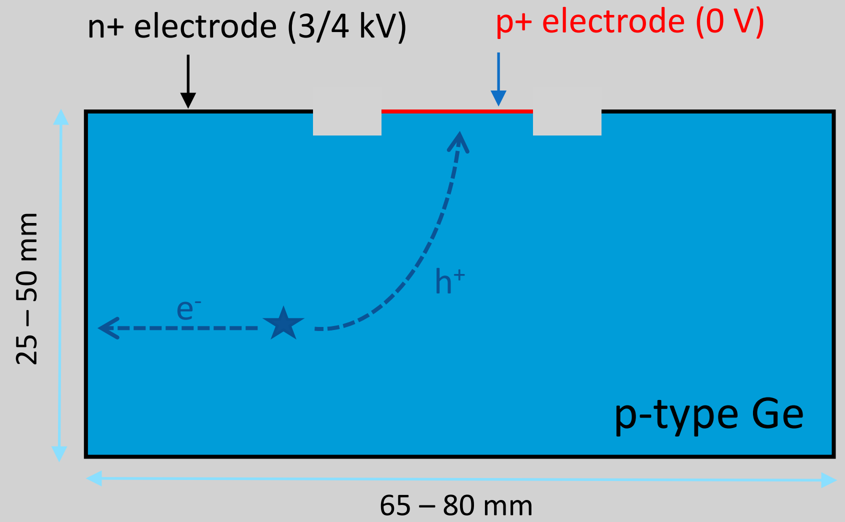
- ΔL = 2 → beyond Standard Model physics
- determines the nature of neutrinos:
  Majorana particle $\nu = \bar{\nu}$;
- gives information on the ν mass via $m_{\beta\beta}$
  (light neutrino exchange scenario)

0νββ signature:

- point-like energy deposition in detector bulk volume
- sharp energy peak at $Q_{\beta\beta}$

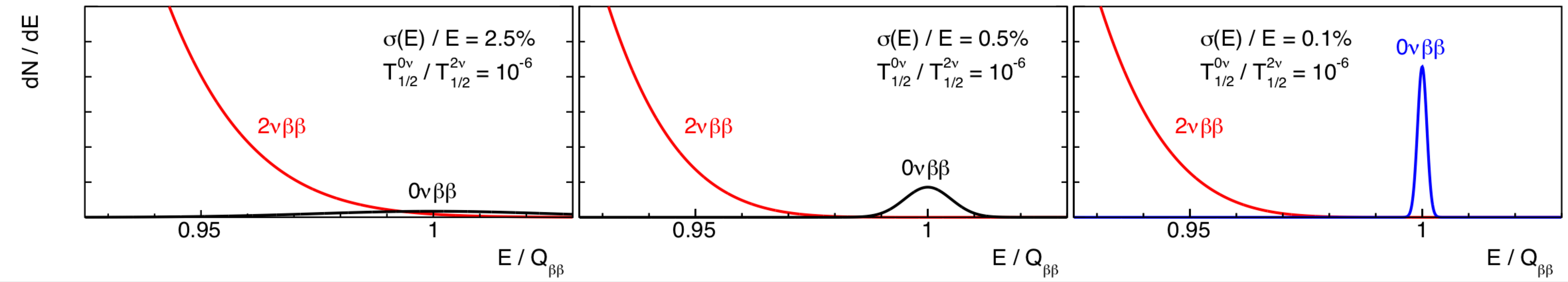


Searching for $0\nu\beta\beta$ of ^{76}Ge

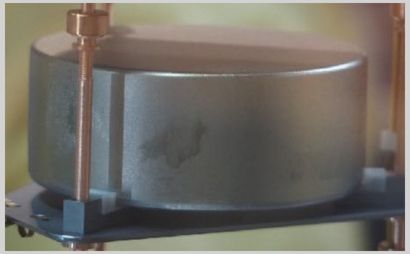


Why high purity Ge detectors?

- source = detector → high efficiency
- radio-pure → no intrinsic background
  [Astropart.Phys. 91 (2017) 15-21]
- high density → e^- range of 1-2 mm
- semiconductor → $\sigma(E)/E < 0.1\%$ at $Q_{\beta\beta}$
- enrichment up to 88% in ^{76}Ge
  [Eur. Phys. J. C 79, 978 (2019)]



The GERDA experiment



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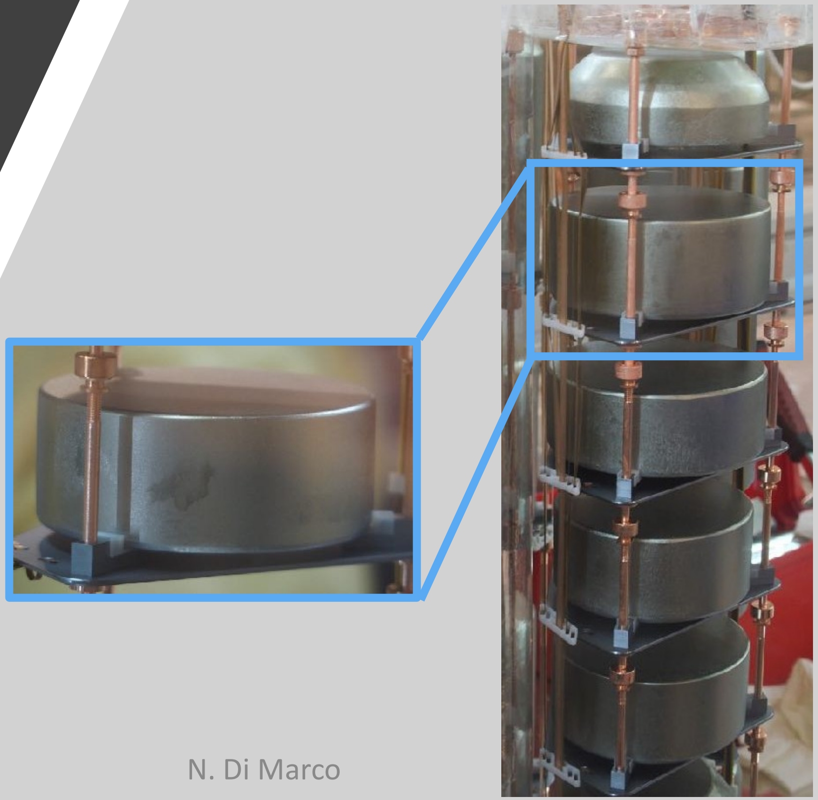

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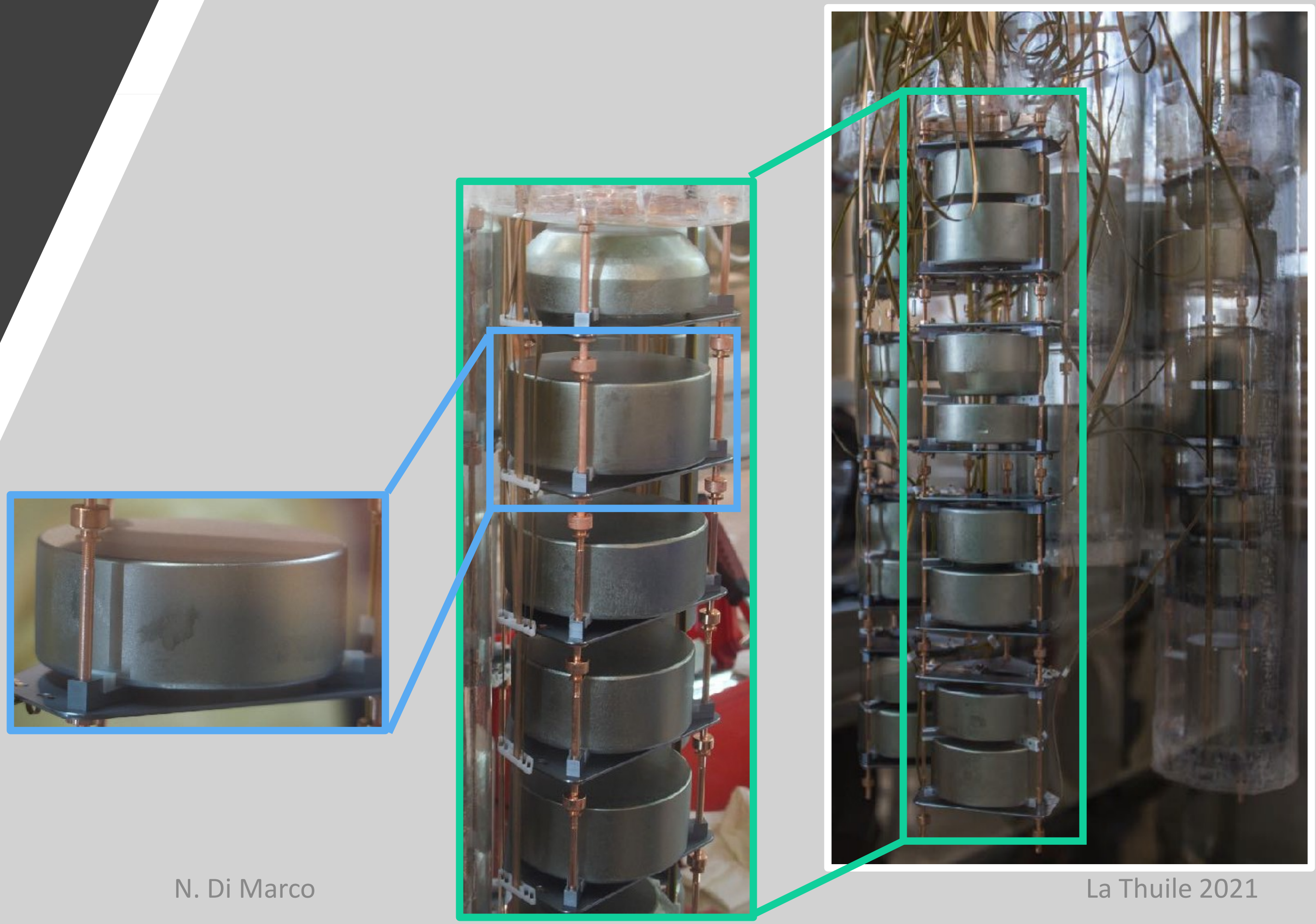

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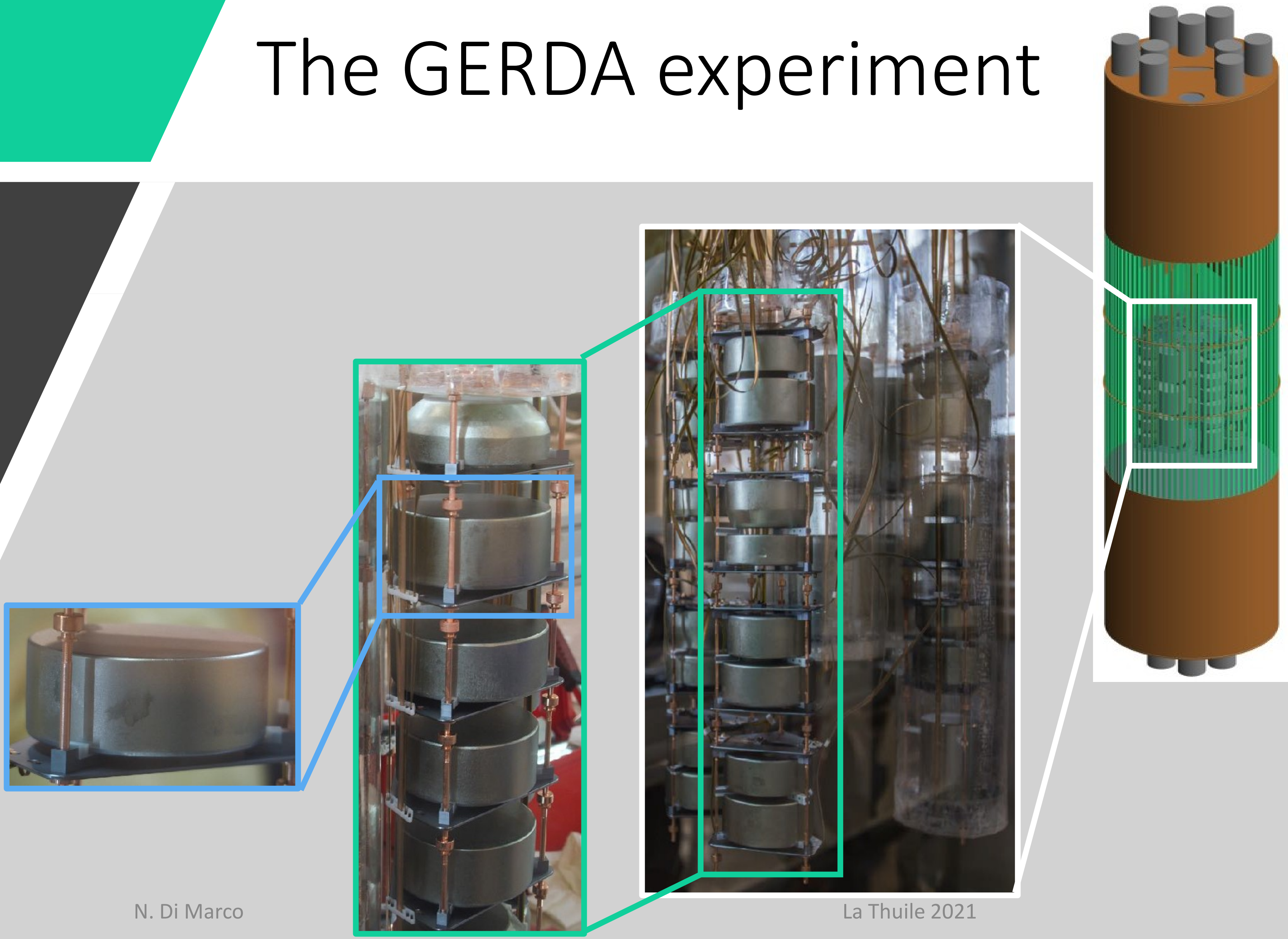
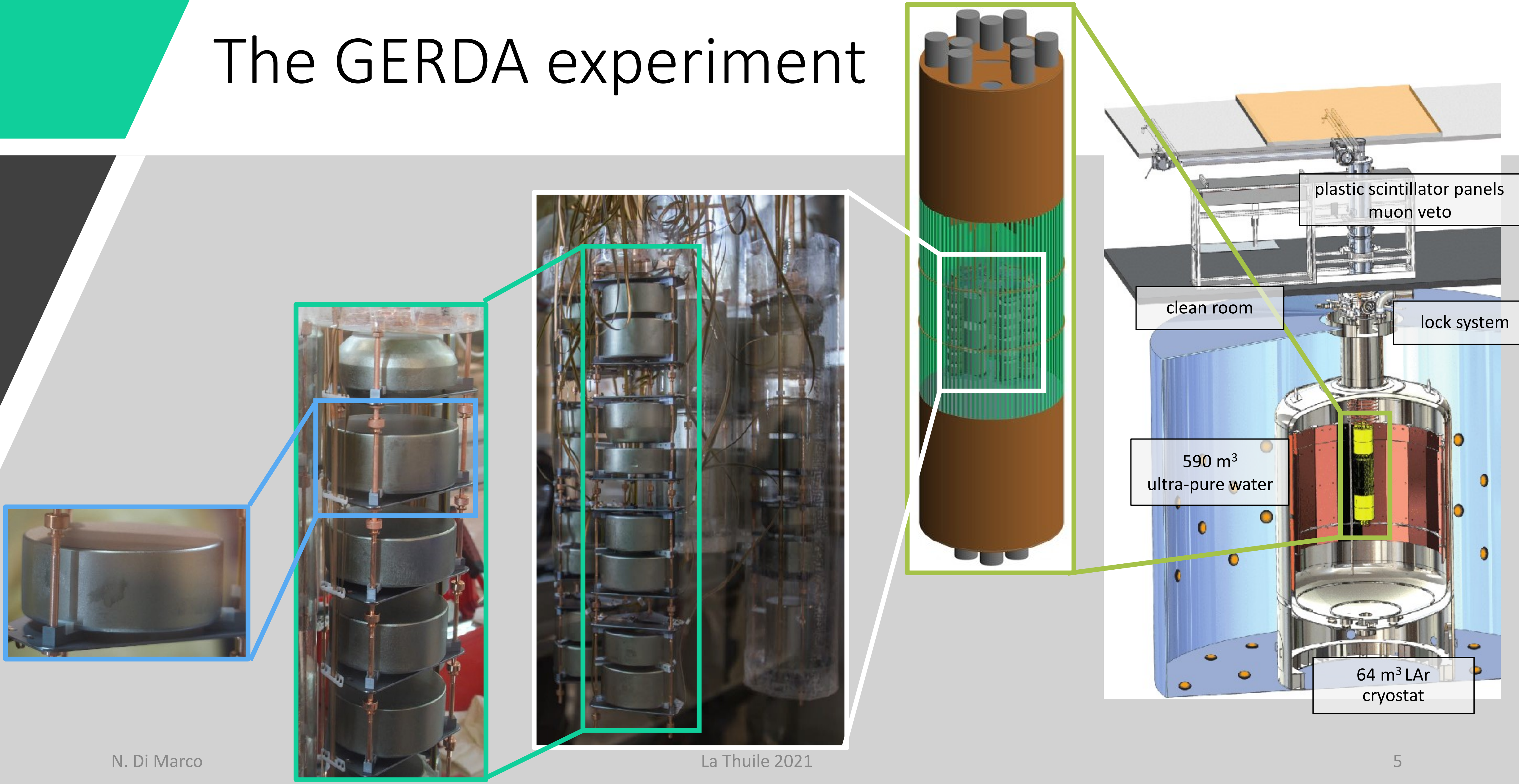
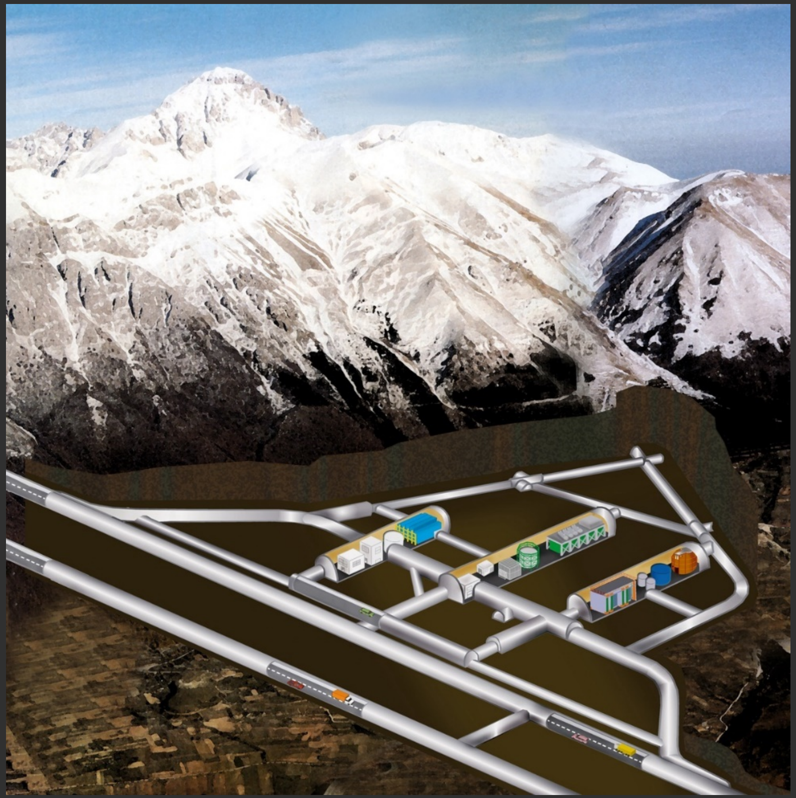


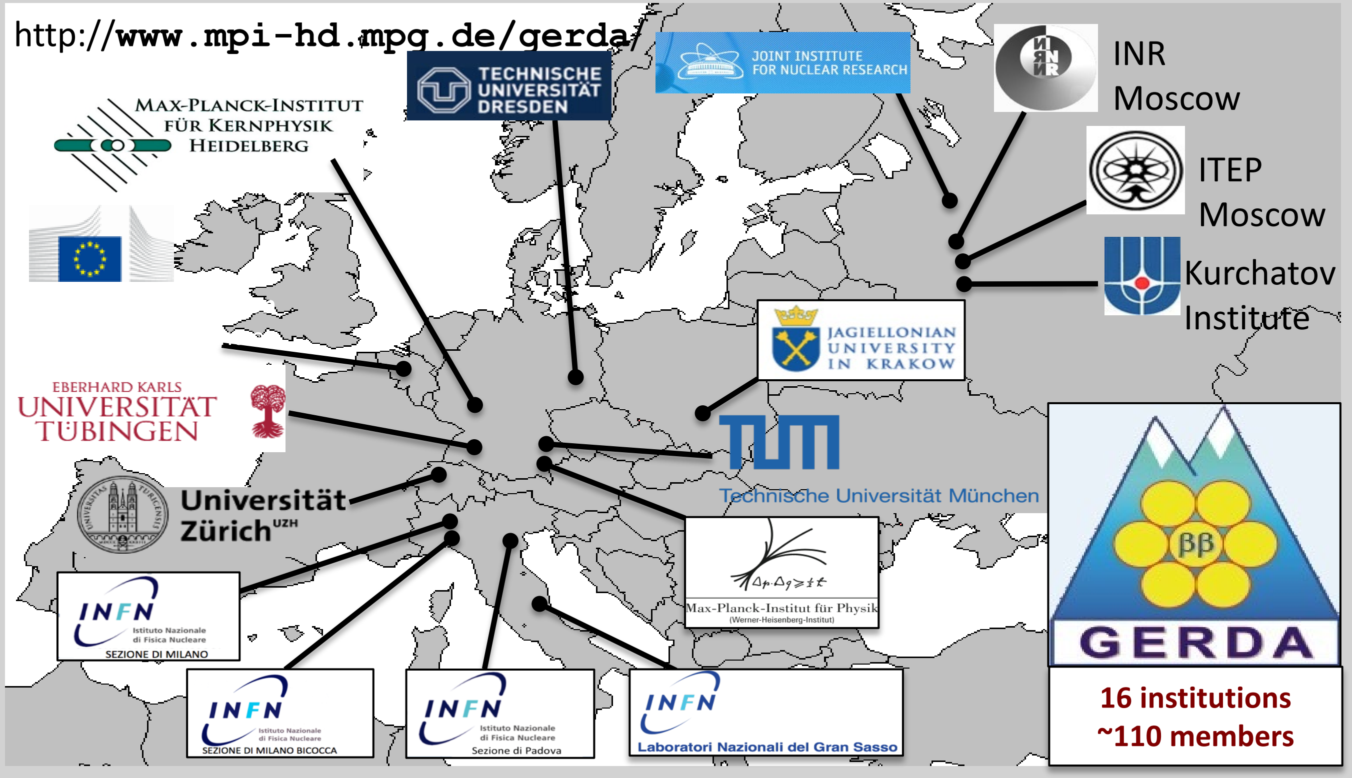
The GERDA experiment



The GERDA experiment



LNGS site: 3500 w.m.e



16 institutions
~110 members

The GERDA experiment

Phase I
- Nov 2011 – Sept 2013: exposure 23.5 kg yr, BI 11 x 10^{-3} cts/(keV kg yr) @ Q_{bb} [PRL 111, 122503 (2013)]

major upgrade
- Sep 2013 – Dec 2015 [Eur.Phys.J. C78 (2018), EPJC 75, 506 (2015)]: + 20 kg BEGe, + Lar instrumentation

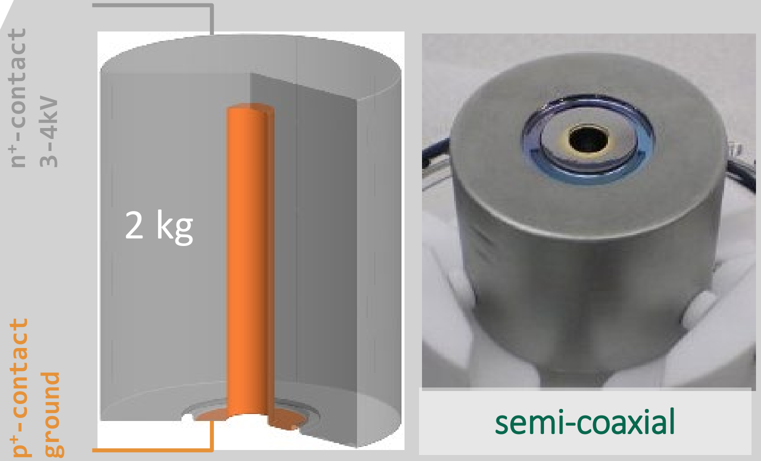
Phase II
- Nature 544 (2017) 47, PRL 120 (2018) 13, Science 365 (2019) 1445
- Exposure = 58.9 kg yr - BI = 5.6 x 10^{-3} cts/(keV kg yr) – $T^{0\nu}_{1/2}$ > $0.9 \cdot 10^{26}$ yr @ 90% C.L.

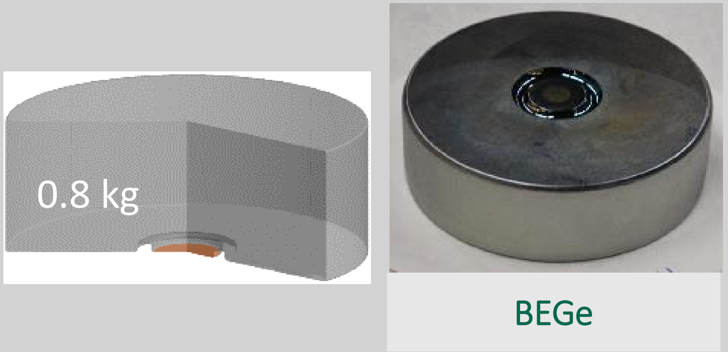
minor upgrade
- Apr-Jul 2018: +9.6 kg Inverted Coaxial (IC)

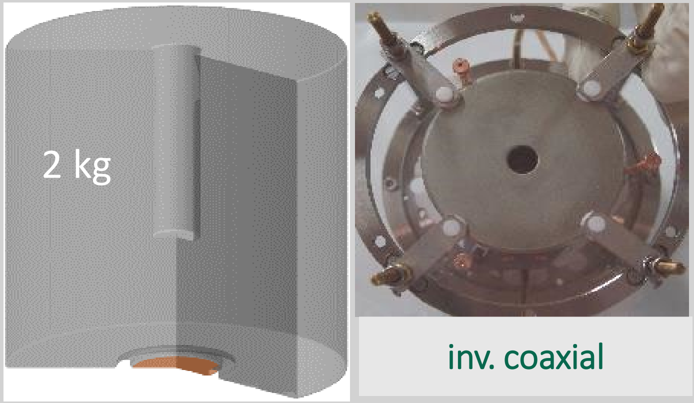
Phase II
- PRL 125 (2020) 252502
- Phase II final exposure= 103.7 kg yr

PGT
- 2020 - 2021: post GERDA test → LEGEND 200

The GERDA experiment







7 (*6) ^{enr}**Coax** (15.6 kg, *14.6 kg)

Phase I

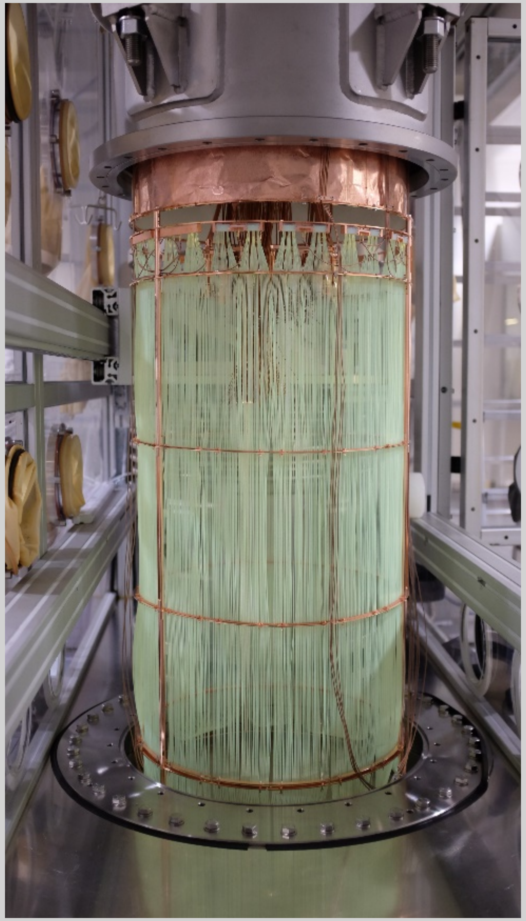
+30 ^{enr}**BEGe** (20 kg)
+Lar instrumentation

Phase II [Eur. Phys. J. C 78 (2018) 388, EPJC 75, 506 (2015)]

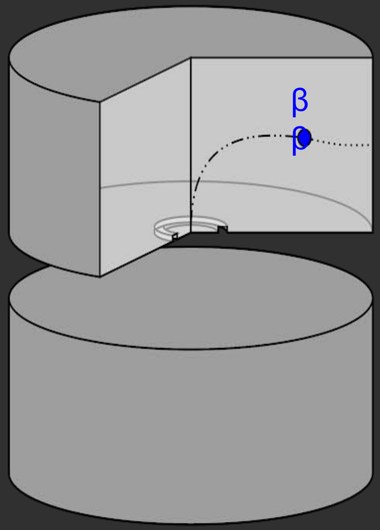
+ 5 ^{enr}**Inverted coax** (9.6 kg)
+ improved fiber geometrical coverage

Phase II post 2018 upgrade (*)

The GERDA experiment

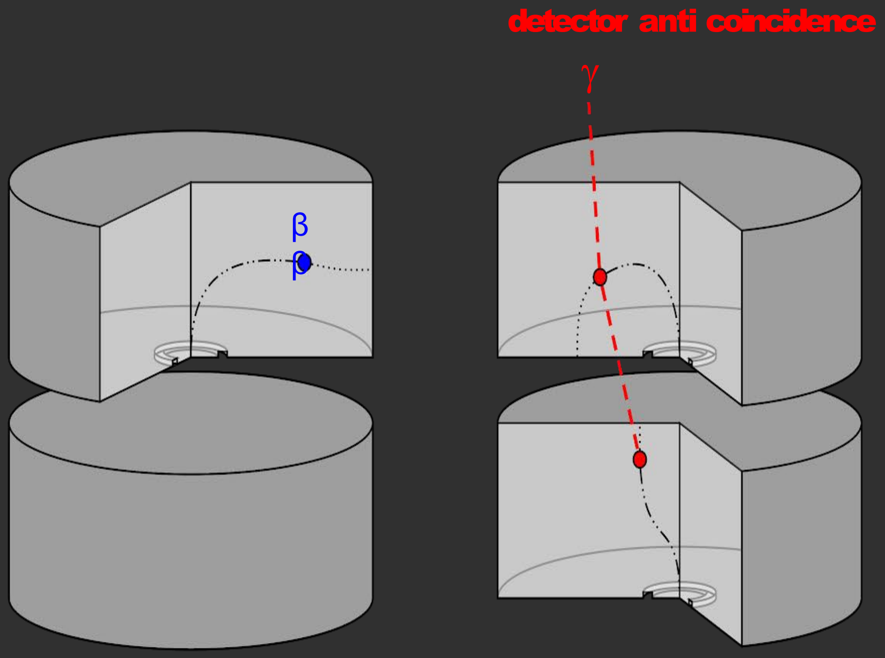


Active background suppression



Discriminate **point like** (single site) **ββ** topology from:

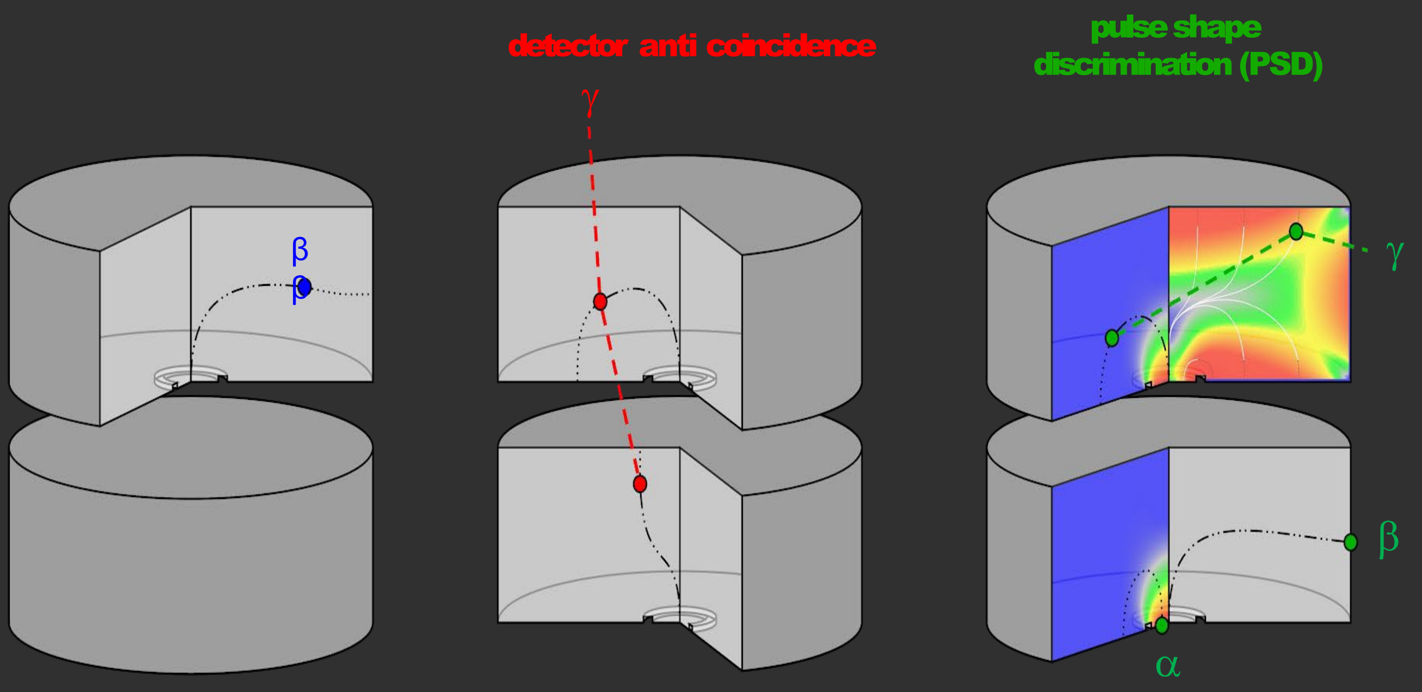
Active background suppression



Discriminate **point like** (single site) **ββ** topology from:

- **multi-detector** interactions

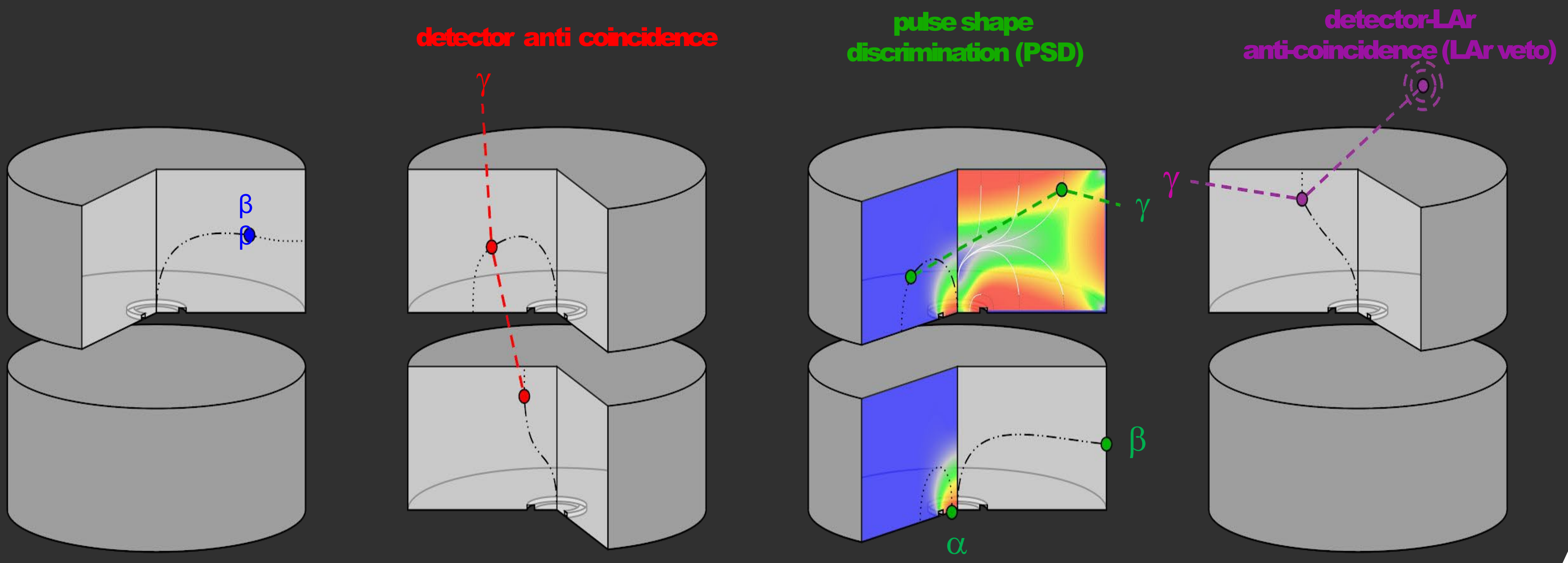
Active background suppression



Discriminate **point like** (single site) **ββ** topology from:

- **multi-detector** interactions
- **multi-site/surface** interactions

Active background suppression



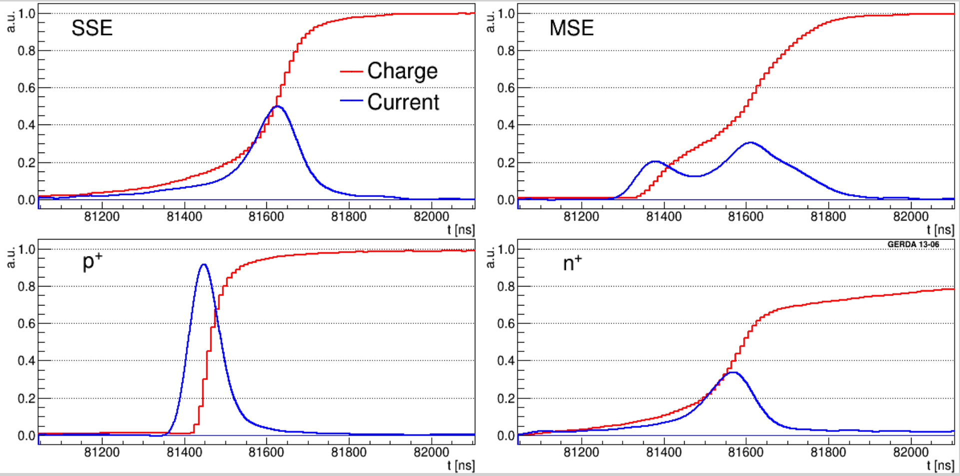
Discriminate **point like** (single site) **ββ** topology from:

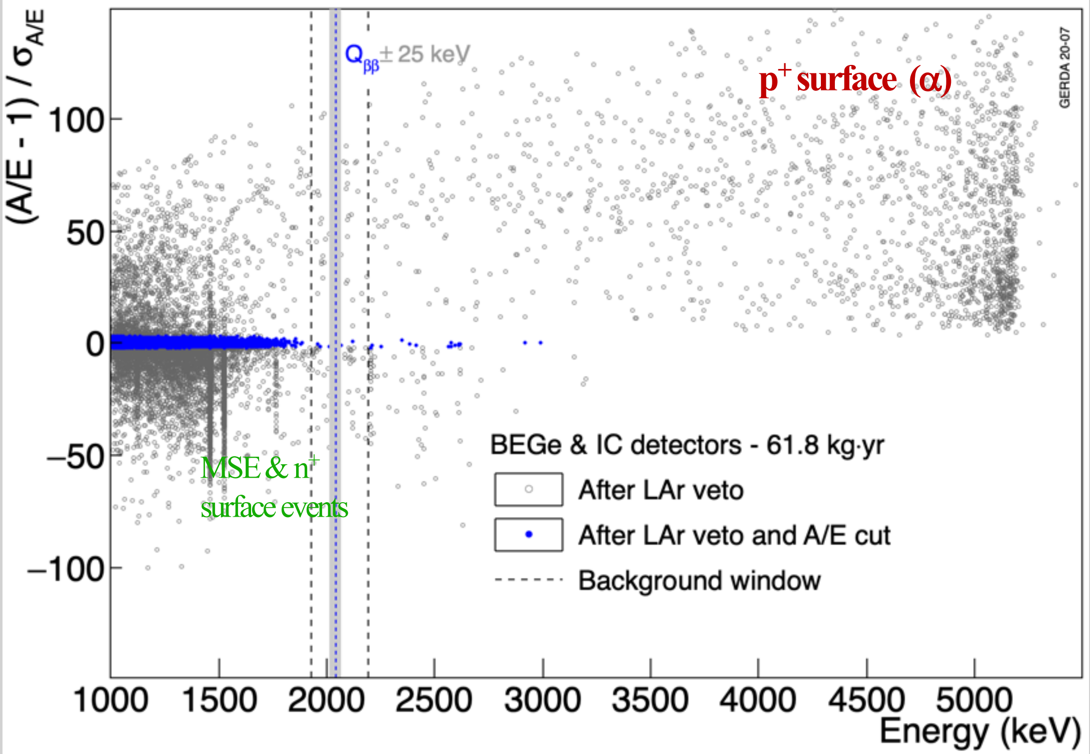
- **multi-detector** interactions
- **multi-site/surface** interactions
- interactions with **coincident energy deposition** in surroundings

Pulse Shape Discrimination

BEGe and IC detectors:

- Mono-parametric cut based on current pulse amplitude A and total energy E **(A/E)** [J. Instrum. 4, P10007 (2009)]
- normalized to single-site events
- cut value determined from **calibration data**





$0\nu\beta\beta$ acceptance: (89.0±4.1)% BEGe
(90.0±1.8)% IC

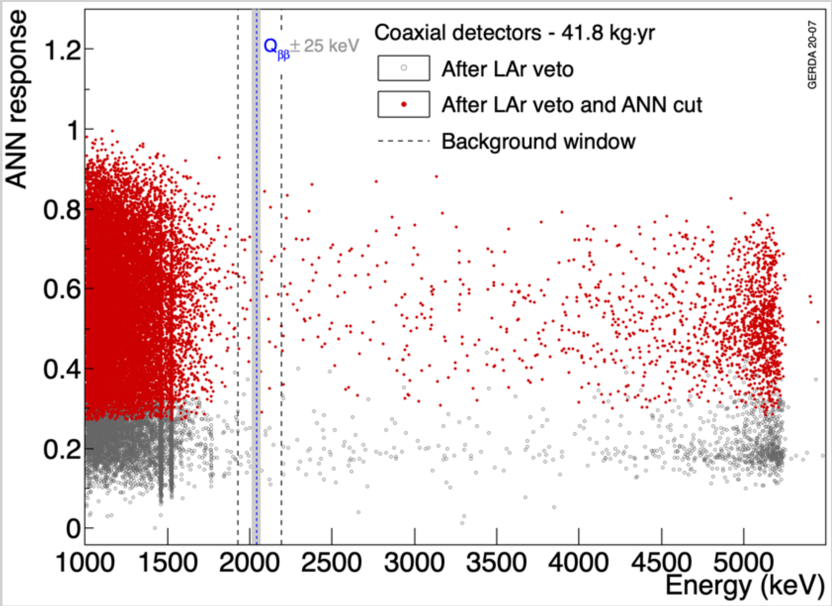
[PRL 125 252502 (2020)]

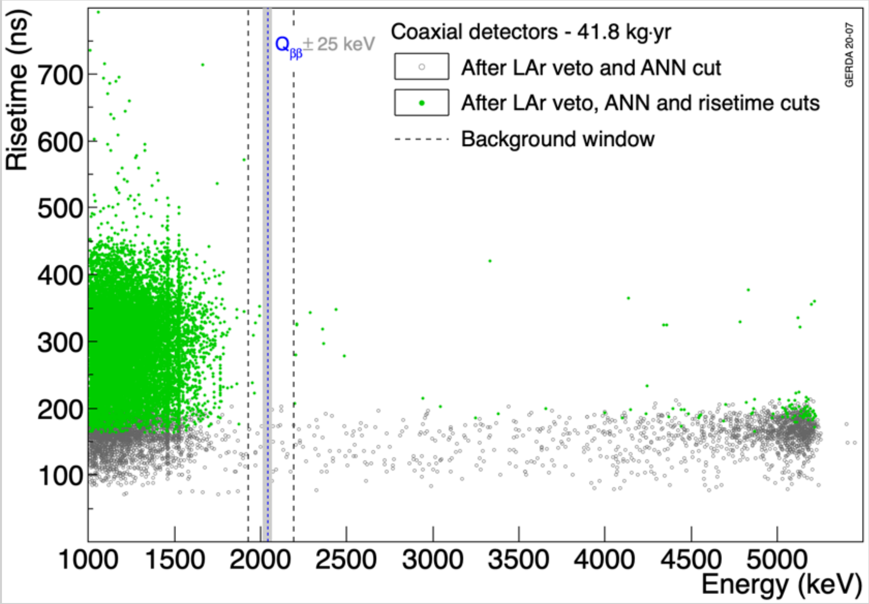
Pulse Shape Discrimination

Coaxial detectors

- Artificial neural network (ANN) trained on ^{208}Tl DEP (signal) and ^{212}Bi SEP (background) to discriminate SSE/MSE
- additional cut on signal rise time to reject events on the p+ electrode

[Science 365, 1445 (2019), Phys. J. C 73, 2583 (2013)]





0νββ acceptance Coaxial
(68.8±4.1)%

[PRL 125 252502 (2020)]

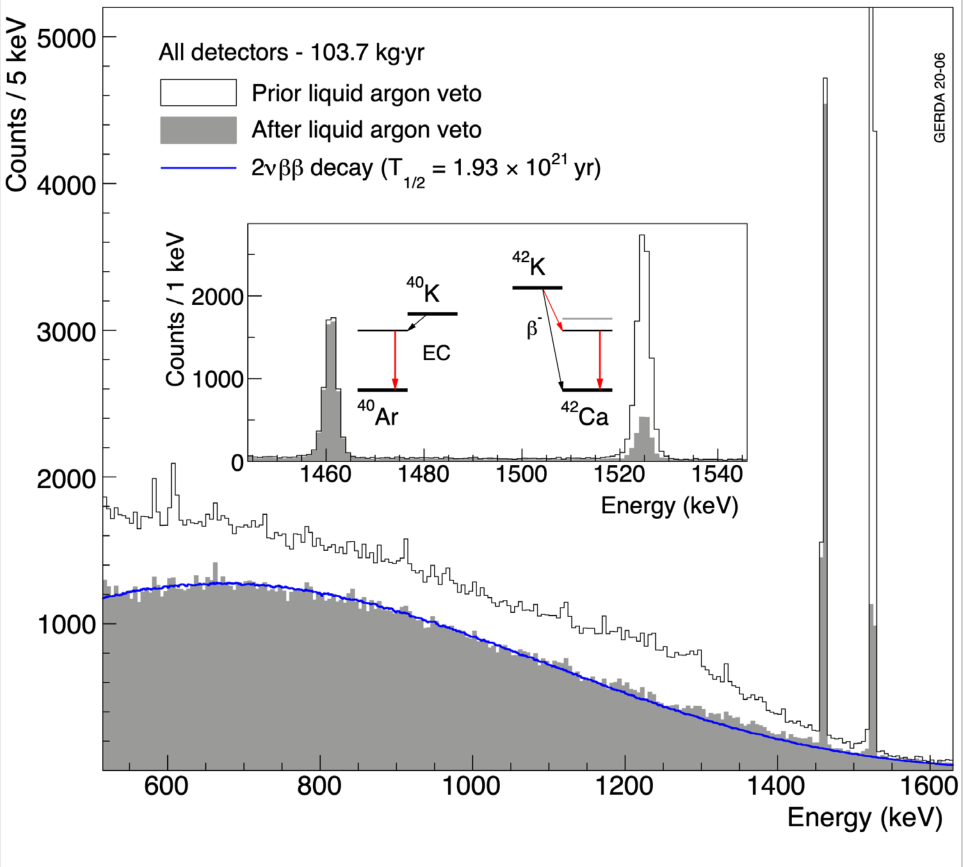
Liquid Argon VETO

[GERDA, *European Phys J C* **78** (2018), 388]

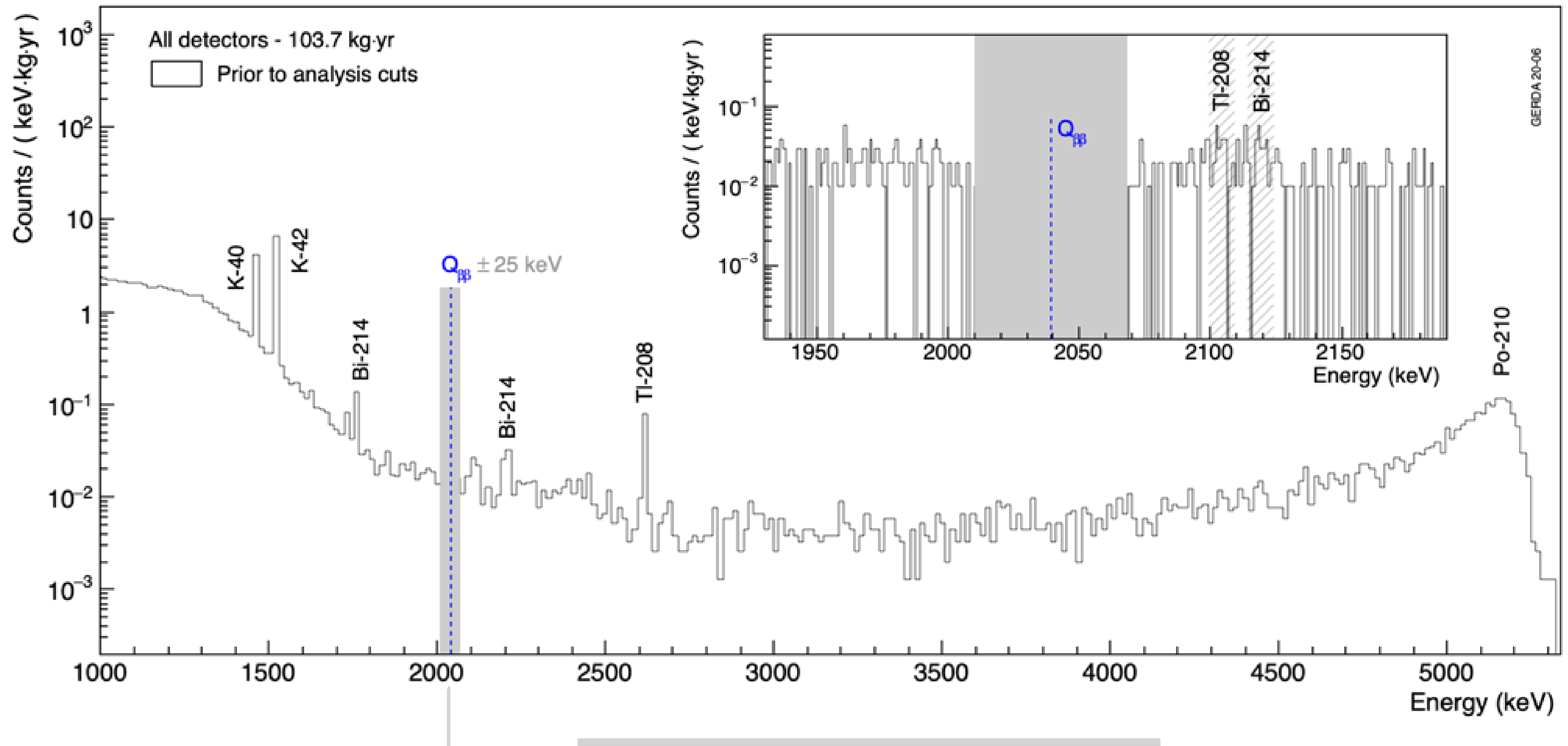
- 16 PMTs
- ~ 1.5 km light guiding fibers + SiPM readout
- At least 1 p.e. within 6 μs of Ge detector trigger

$0\nu\beta\beta$ acceptance BEGe **(98.2±0.1)%**
Dead Time 1.8%

[PRL 125 252502 (2020)]

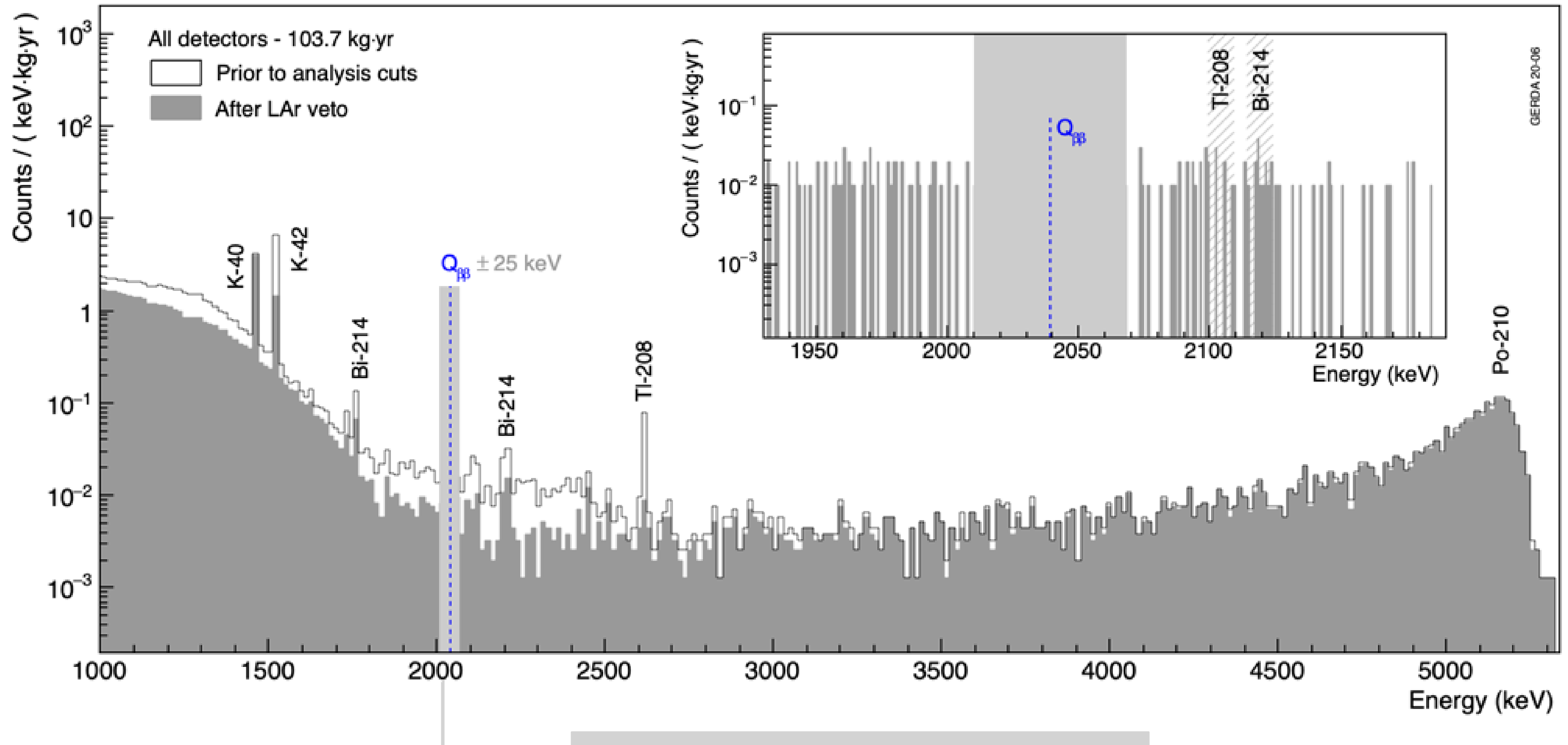


Active background suppression



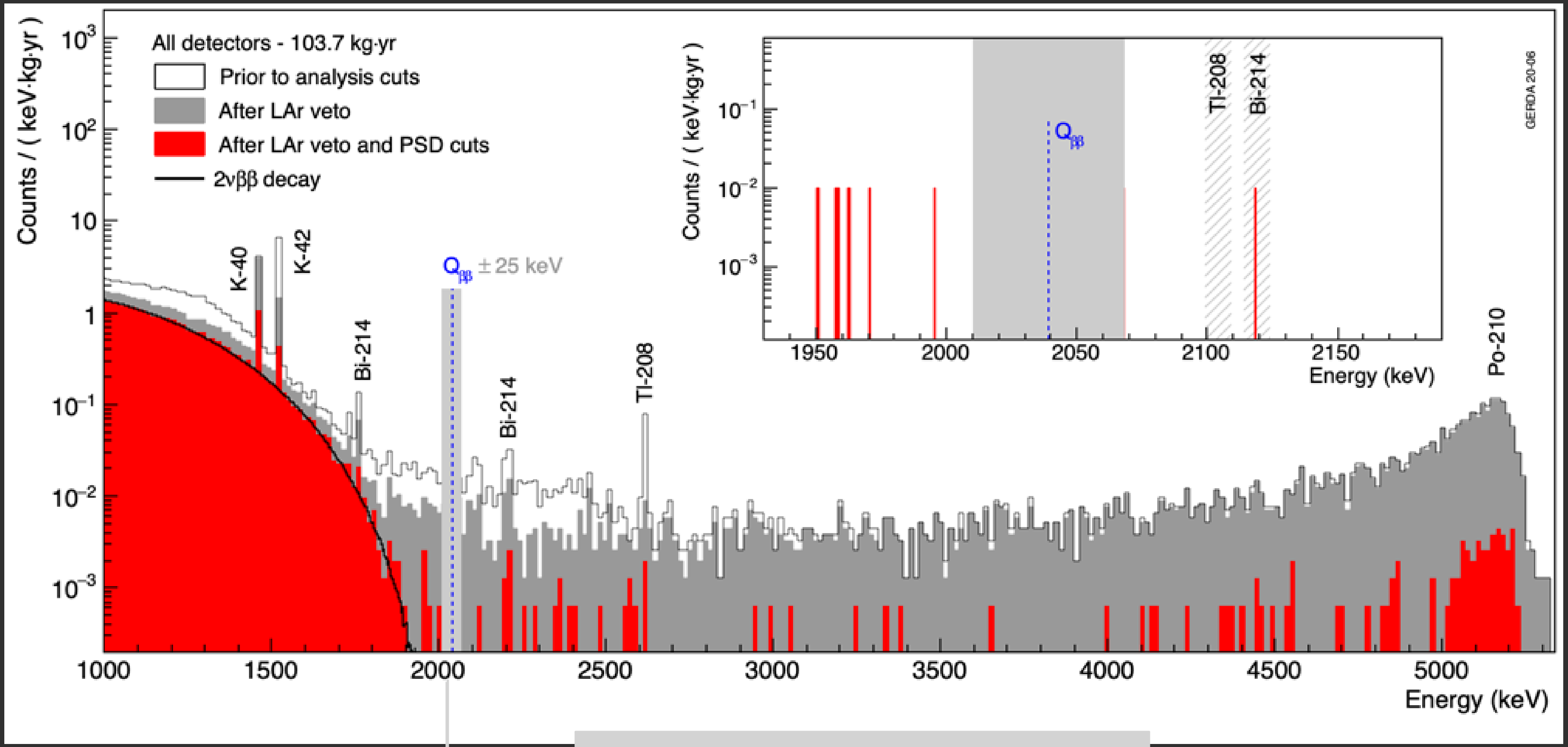
Blinded region ±25 keV @ $Q_{\beta\beta}$

Active background suppression - LAr



Blinded region ±25 keV @ $Q_{\beta\beta}$

Active background suppression – LAr&PSD

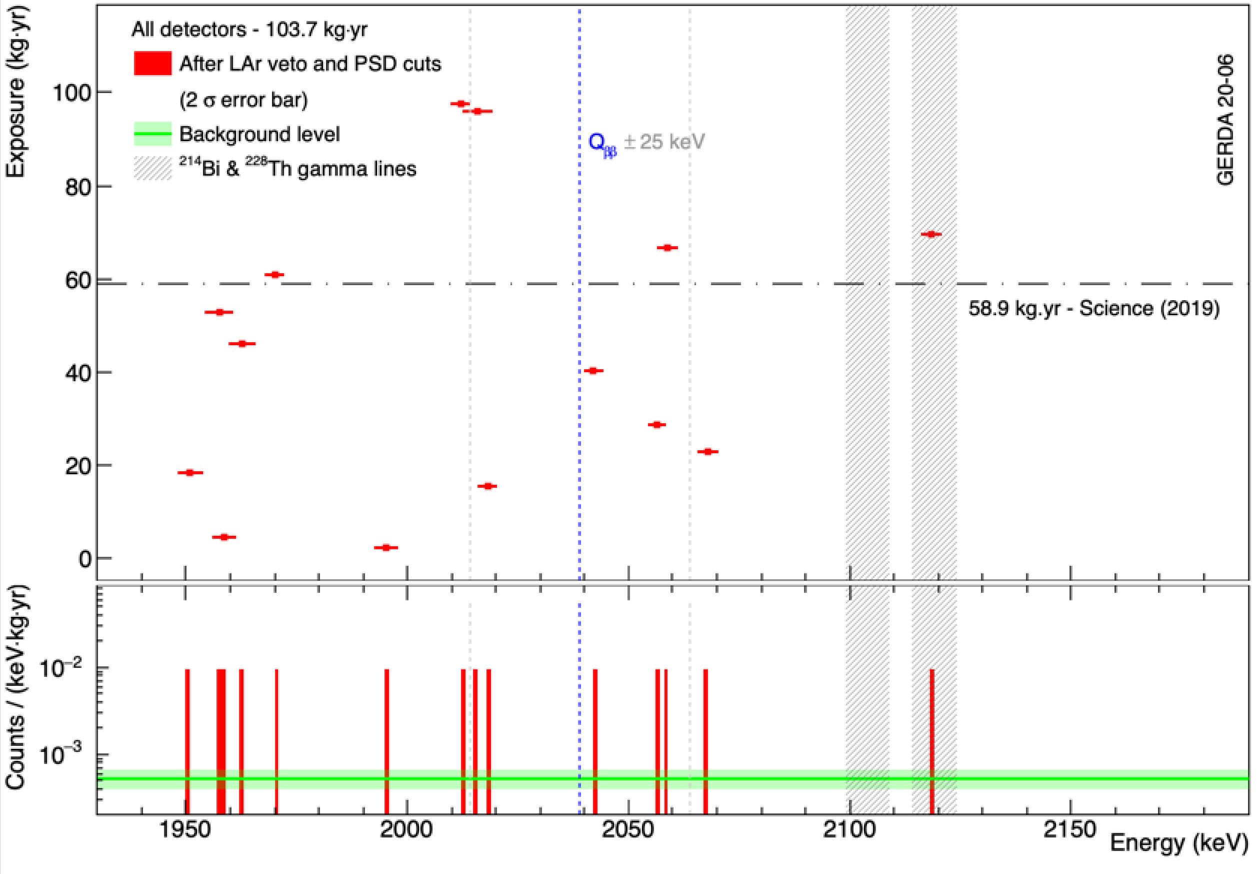


Blinded region ±25 keV @ $Q_{\beta\beta}$

Statistical analysis

[GERDA, *Phys Rev Lett* **125** (2020), 252502]

ROI:
[1930,2190] keV, excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP)



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ROI:
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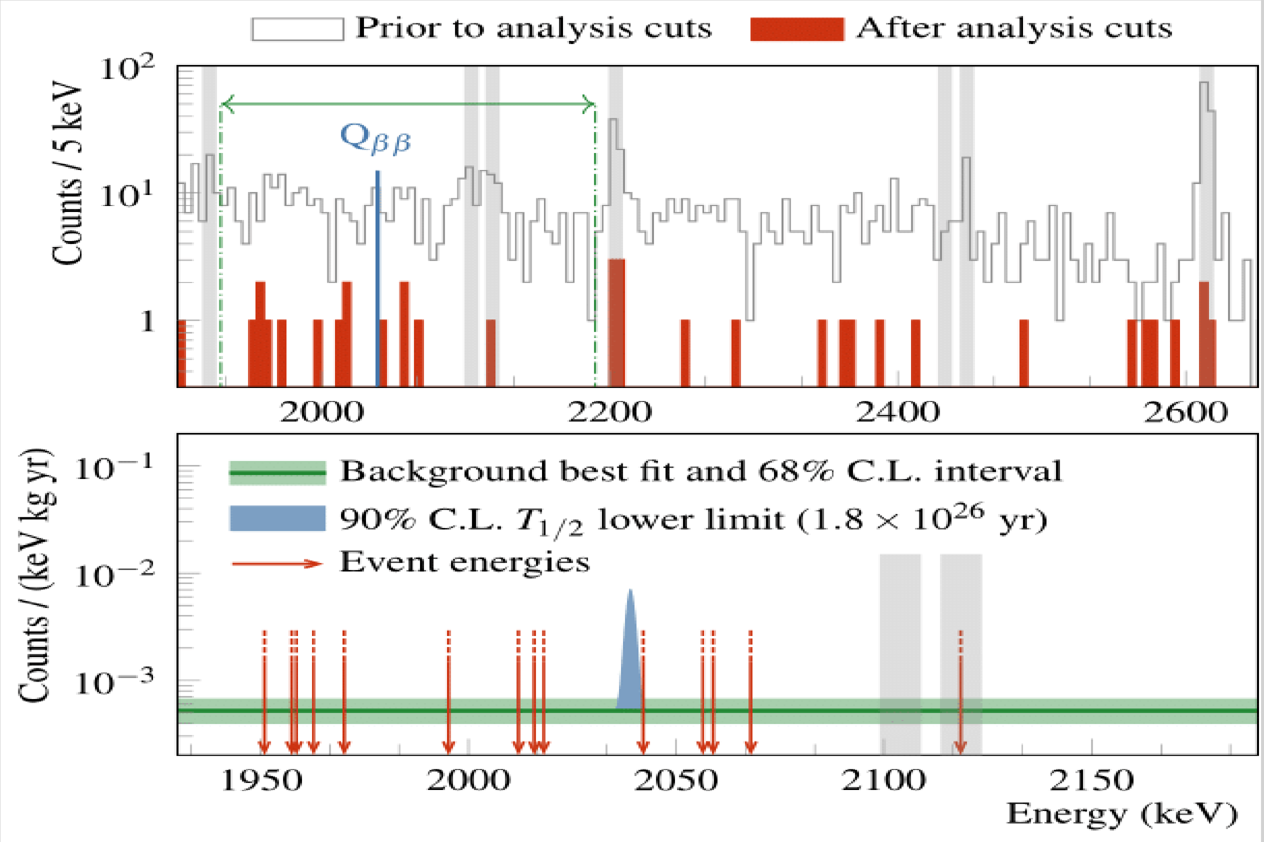
BI: $5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts/(keV·kg·yr)

Phase II (103.7 kg yr):

$T^{0\nu}_{1/2}$ > 1.5·10^{26} yr @ 90% C.L. (Frequentist)



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Phase II (103.7 kg yr):

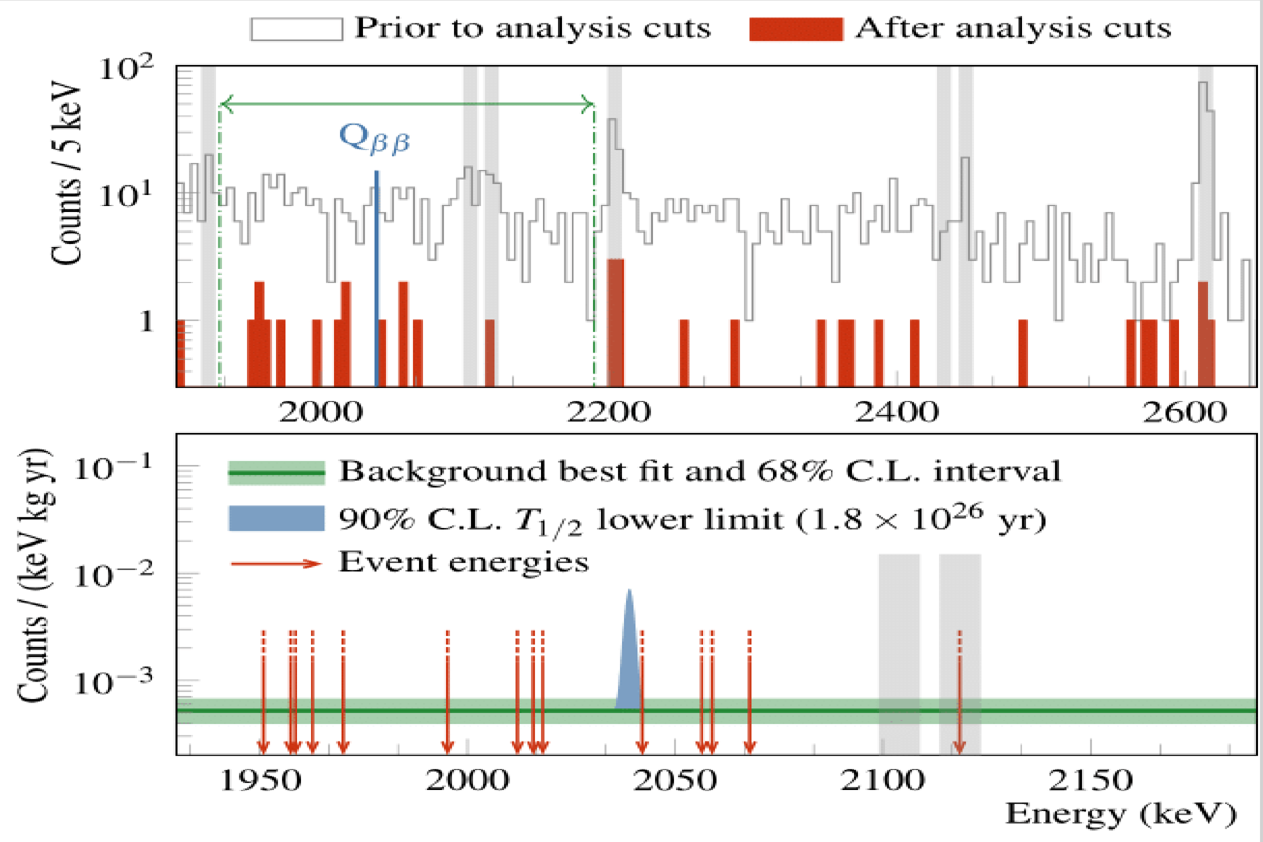
$T^{0\nu}_{1/2}$ > 1.5·10^{26} yr @ 90% C.L. (Frequentist)

Phase I + Phase II (127.2 kg yr):

$T^{0\nu}_{1/2}$ > 1.8·10^{26} yr @ 90% C.L. (Frequentist)

The limit coincides with the sensitivity, defined as the median expectation under the no signal hypothesis

$T^{0\nu}_{1/2}$ > 1.4·10^{26} yr @ 90% C.L. (Bayesian)



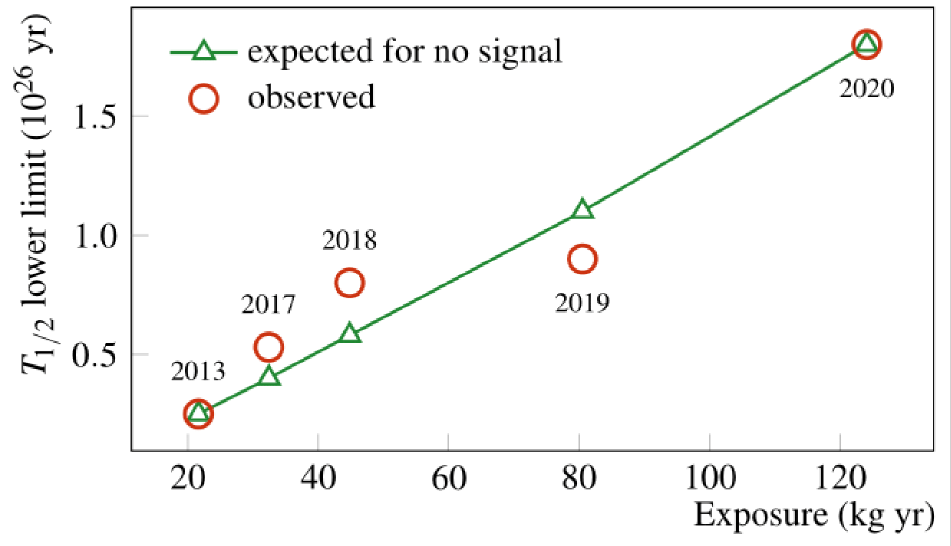
Conclusions

PhaseII	Goal	Achievements
Exposure	> 100 kg yr	103.7 kg yr
BI	10^{-3} cts/(keV·kg·yr)	$5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts/(keV·kg·yr)
$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2} > 10^{26}$ yr	$T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr @ 90% C.L.

✓ All design goals surpassed!

✓ GERDA ran in background-free regime for the entire duration of its data taking

✓ GERDA provides the most stringent constraints on the half-life of $0\nu\beta\beta$ decay



*Phase I + Phase II

EXPERIMENT	Isotope	Exposure [kg yr]	$T^{0n}_{1/2}$ [10^{25} yr]	<mbb> [MeV]
GERDA	^{76}Ge	127.2*	18	79-180
MAJORANA	^{76}Ge	26	2.7	200-433
KamLAND-zen	^{136}Xe	594	10.7	61-165
EXO	^{136}Xe	234.1	3.5	93-286
CUORE	^{130}Te	115.9	1.5	110-520

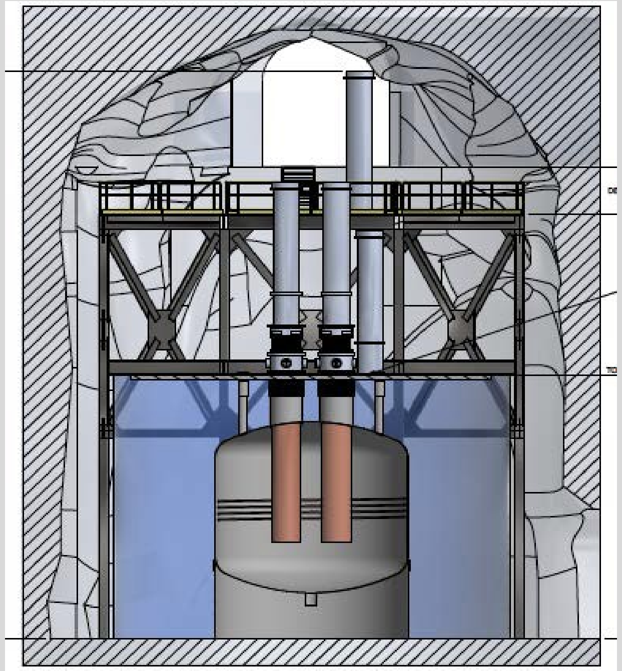
From 10^{26} yr and beyond …

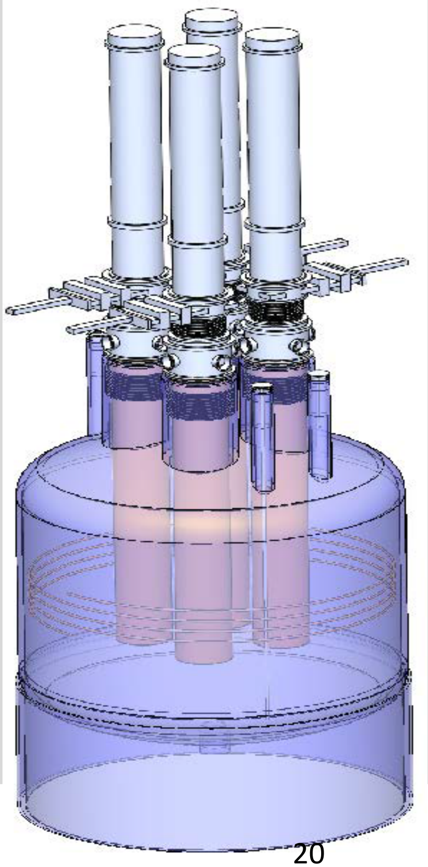
First phase:

- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: <0.6 c /(FWMH t y)
- Discovery sensitivity at a half-life of 10^{27} years
- Data start end of 2021

Subsequent stages:

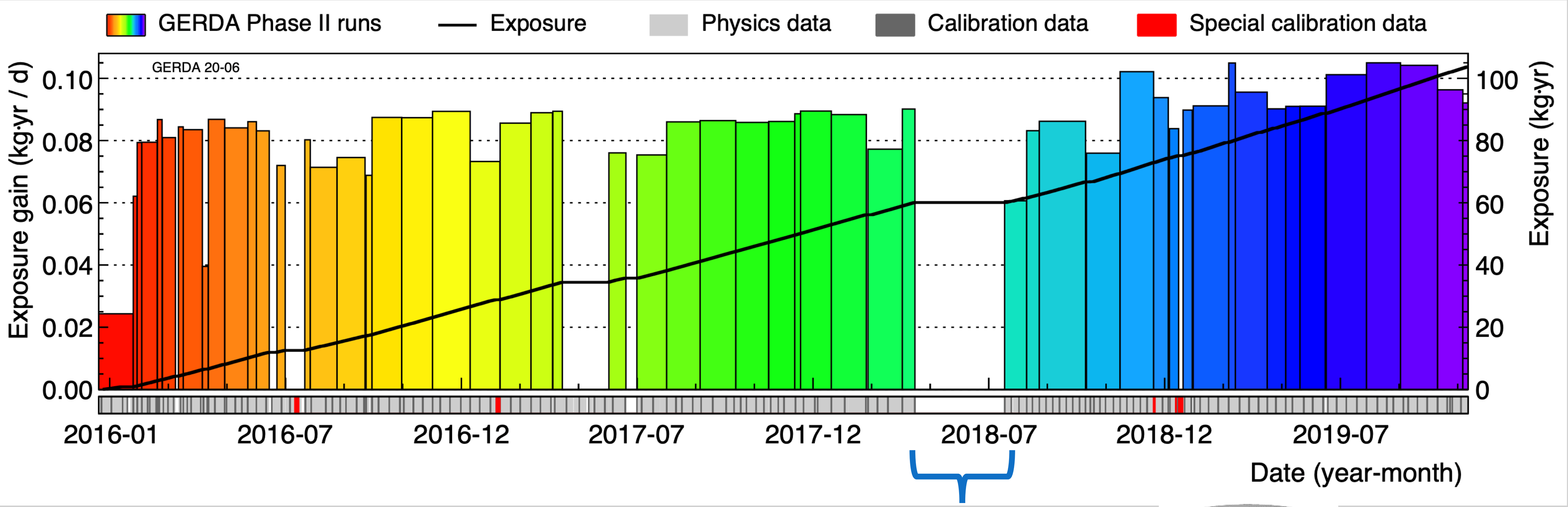
- 1000 kg, staged via individual payloads
- Background goal <0.03 cts/(FWHM t yr)
- Discovery sensitivity at a half-life of 10^{28} years
- Location to be selected





BACKUP

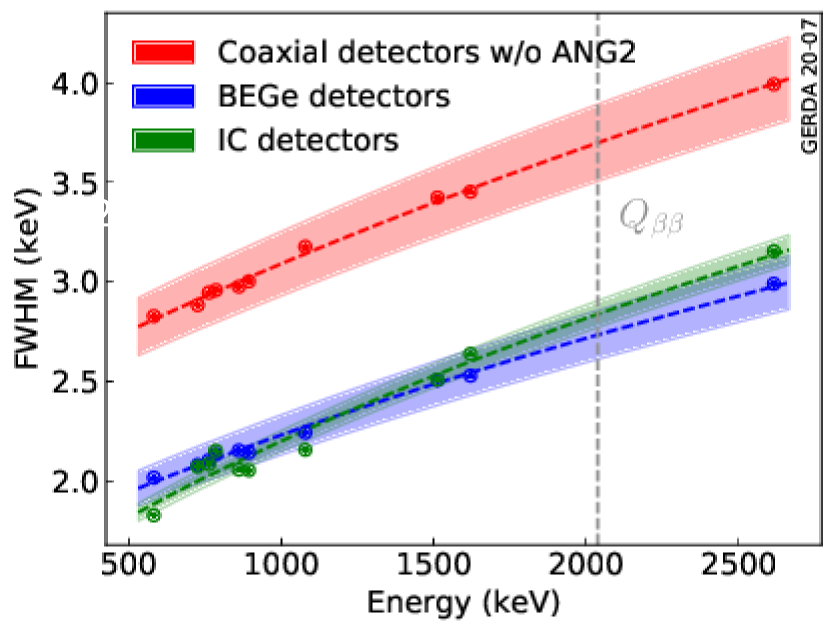
Data taking

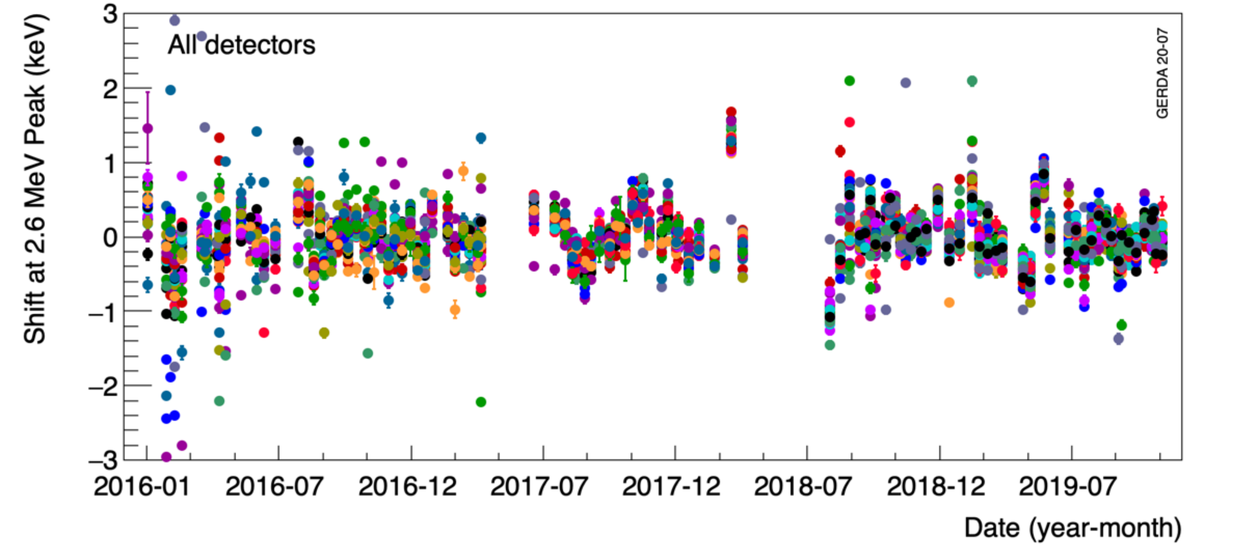


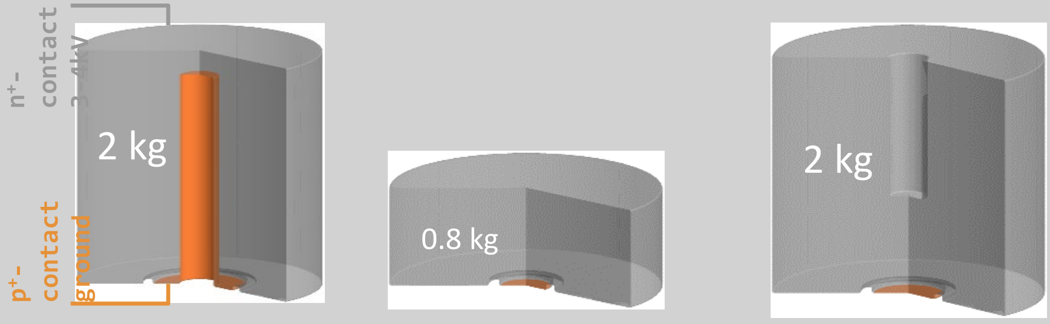
Phase II duty cycle: 87.7%
Exposure: **103.7 kg yr**

2018 upgrade
+ 5 ^{enr}**Inverted coax** (9.6 kg)
+ improved fiber geometrical coverage

Energy resolution





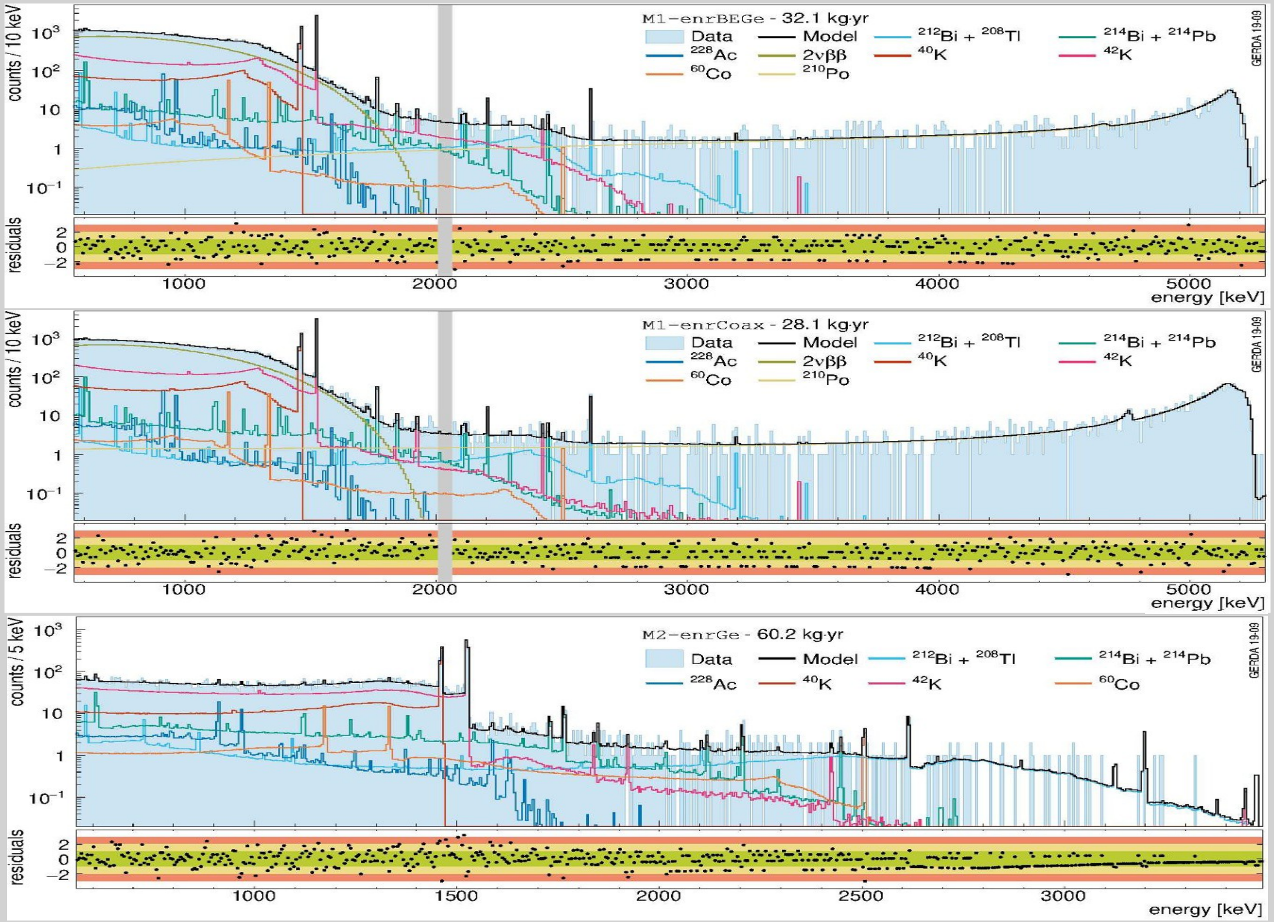


	Coaxial	BEGe	Inverted Coaxial
FWHM@Q_{bb} [keV]	4.9 ± 1.4	2.6 ± 0.2	2.9 ± 1.4

- Weekly calibrations with ^{228}Th sources
- Optimized ZAC filter (Eur. Phys. J. C 75 (2015) 255)
- Stability monitored online with Test Pulses, injected every 20 s
- Energy resolution stable within <0.1 keV
- Resolution at Q_{bb} ~0.1%

Background model

[GERDA, *J High Energy Phys*, **2020** (2020), no. 3, 139]



Full GERDA setup is reproduced in GEANT4

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

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

α from **^{210}Po/(^{222}Ra)**

β from **^{42}K**

γ from **^{208}Tl/^{214}Bi**

GERDA

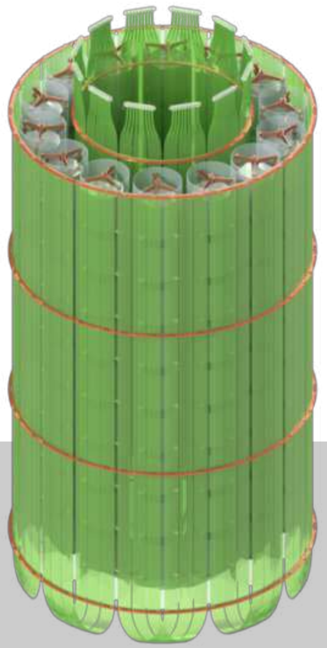
- LAr veto
- Low-A shield, no Pb

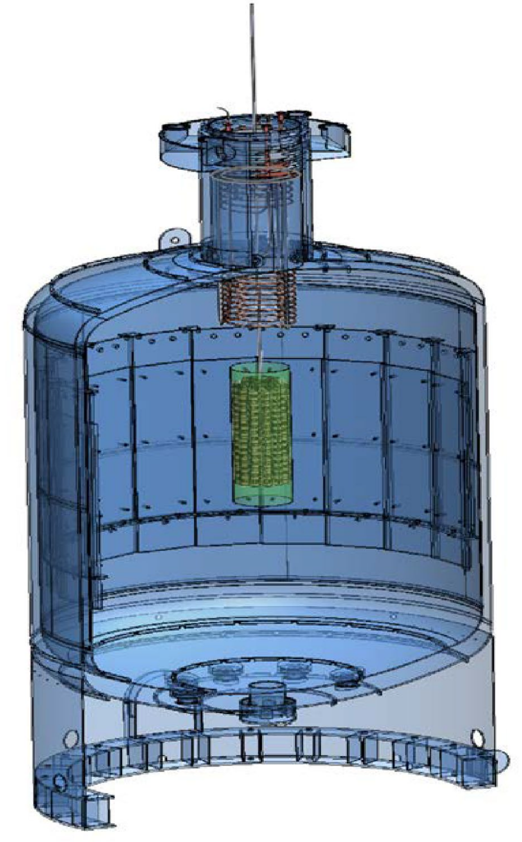
Both

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution $0\nu\beta\beta$experiments

MAJORANA

- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold (helps reject cosmogenic background)

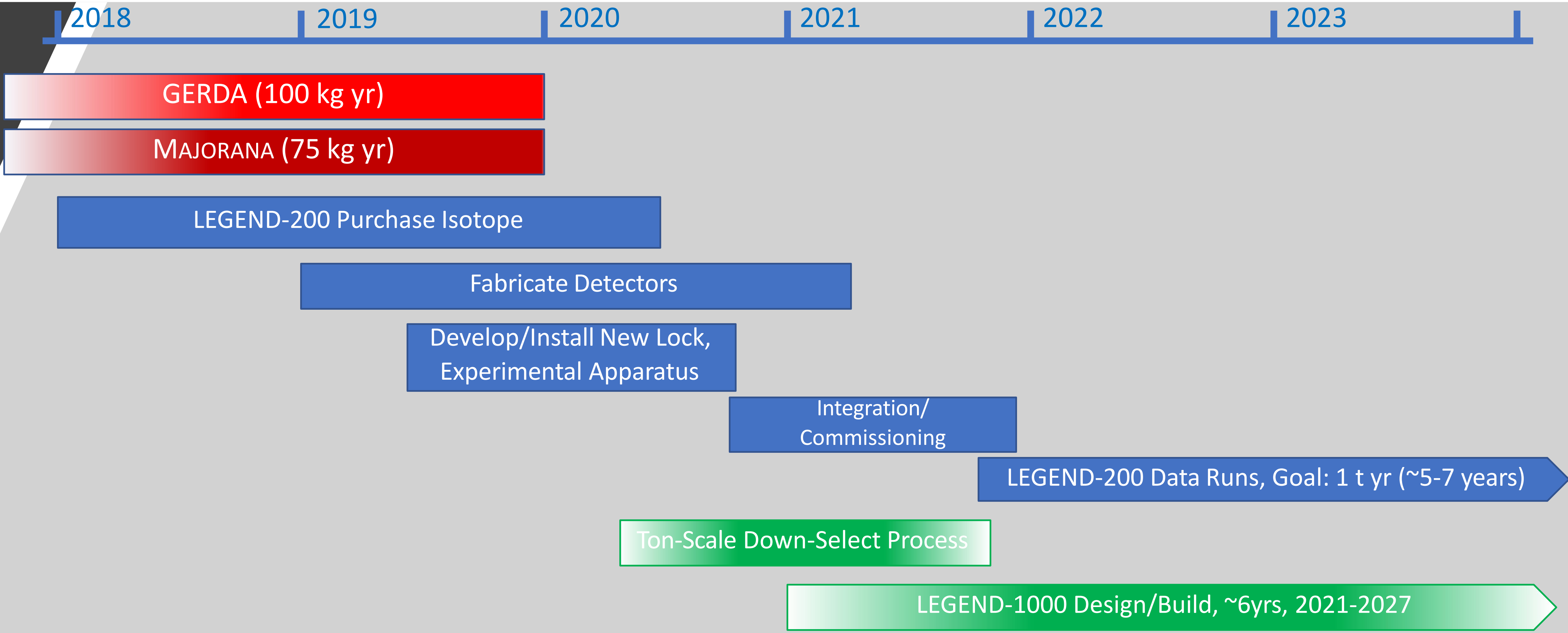




- 70 inverted coax detectors (1.5-2 kg), about 140 kg
- 28 BEGe's (0.7 kg) about 20 kg
- 5 ICPC's (2.0 kg) about 10 kg
- 33 PPC's (0.8 kg) about 28 kg
- Semi-Coax detectors (either use as is, or recycle) about 15 kg

Total ~200 kg

LEGEND


2018
2019
2020
2021
2022
2023
GERDA (100 kg yr)
MAJORANA (75 kg yr)
LEGEND-200 Purchase Isotope
Fabricate Detectors
Develop/Install New Lock, Experimental Apparatus
Integration/ Commissioning
LEGEND-200 Data Runs, Goal: 1 t yr (~5-7 years)
Ton-Scale Down-Select Process
LEGEND-1000 Design/Build, ~6yrs, 2021-2027