JOINT INSTITUTE FOR NUCLEAR RESEARCH

GERDA

Results of the **GERDA** Phase II experiment

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for the GERDA collaboration

ICHEP 2020, Nowhere
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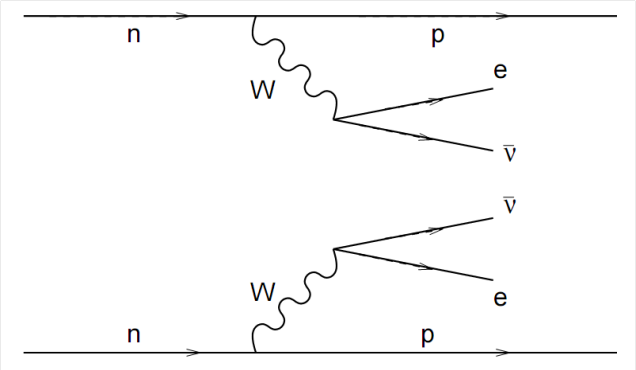
Technische Universität München

NATIONAL RESEARCH CENTER
"KURCHATOV INSTITUTE"

Search for 0νββ-decay
Why?

2νββ

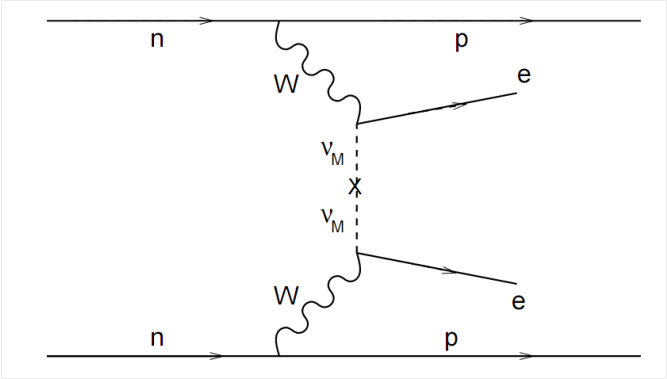


- violates lepton number? **NO**
- forbidden in SM? **NO**

- but half life is 10^{10} longer than the age of the universe, however already observed!

^{76}Ge: $T_{1/2}^{2\nu} = 1.93 \times 10^{21}$yr

0νββ



- violates lepton number? **YES!**
- forbidden in SM? **YES!**

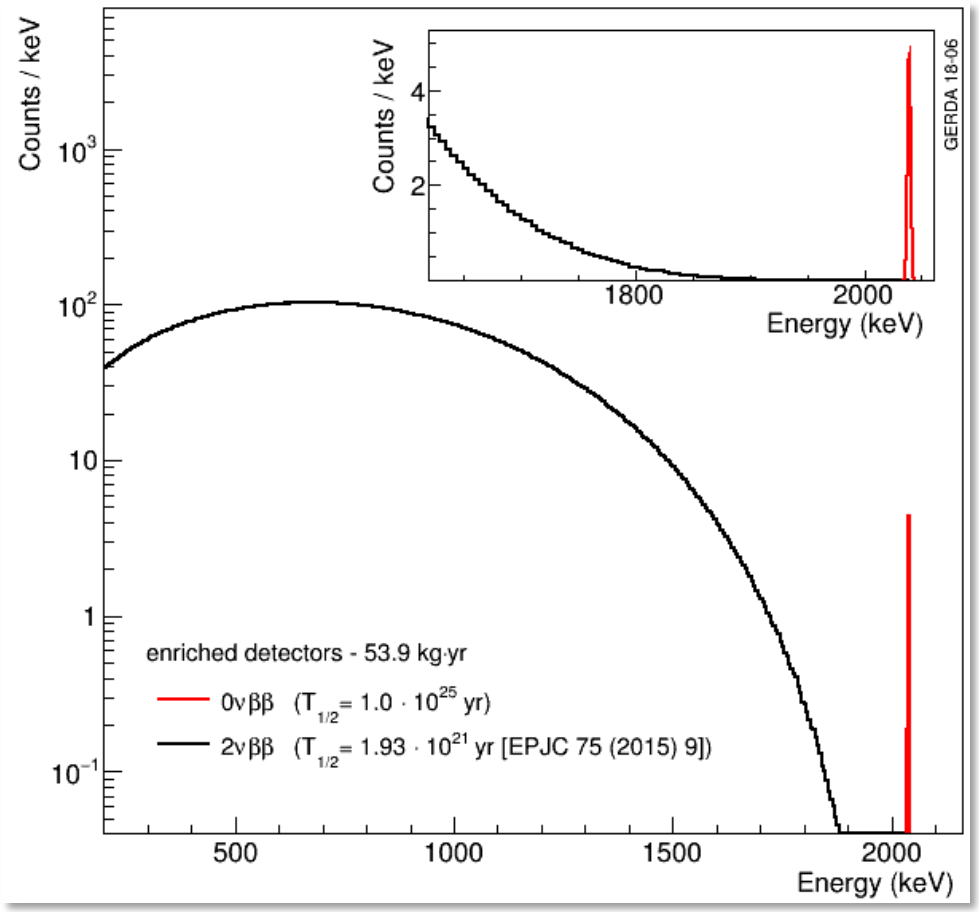
New Physics!

- **ν** has **Majorana** mass component
- **IF** light neutrino exchange

Access to ν mass scale

Search for 0νββ-decay of ^{76}Ge How?

Summed electron spectrum (^{76}Ge, GERDA Phase II):



0νββ:
Sharp peak at Q-value of the decay

$T_{1/2}^{0\nu} > 10^{25}\mathrm{yr}$

2νββ:
Continuous spectrum

$T_{1/2}^{2\nu} \sim 10^{21}\mathrm{yr}$

Background for 0νββ

Energy resolution essential

Search for 0νββ-decay of ^{76}Ge How?

Experimental sensitivity:

- **Zero** background:

$$T_{1/2}^{0\nu} \propto M\ t$$

- Non-zero background:

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M\ t}{\Delta E\ BI}}$$

$M\ t$ – exposure (kg yr)

ΔE – energy resolution (keV)

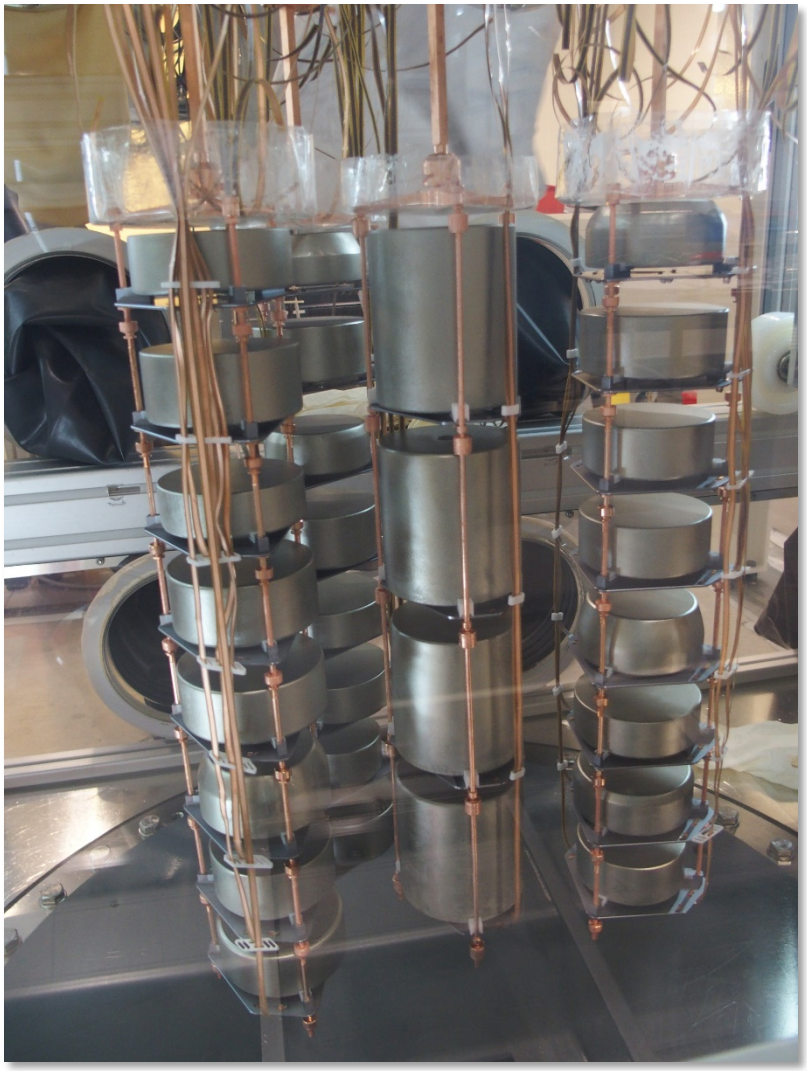
BI – background index (counts/keV kg yr)

Isotope	$G^{0\nu}$ (10^{-14}yr)	Q(keV)	Nat. ab. (%)
^{48}Ca	6.3	4273.7	0.187
^{76}Ge	0.63	2039.1	7.8
^{82}Se	2.7	2995.5	9.2
^{100}Mo	4.4	3035.0	9.6
^{130}Te	4.1	2530.3	34.5
^{136}Xe	4.3	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

✓ Target mass and detector efficiency as high as possible
✓ "**Zero-background**" to have **linear increase** of **sensitivity vs exposure**

GERDA approach

HPGe detectors enriched in ^{76}**Ge**



- ✓ detector-grade germanium is high-purity material

  ⇒ low background

- ✓ established detector technology

  ⇒ industrial support

- ✓ very good energy resolution

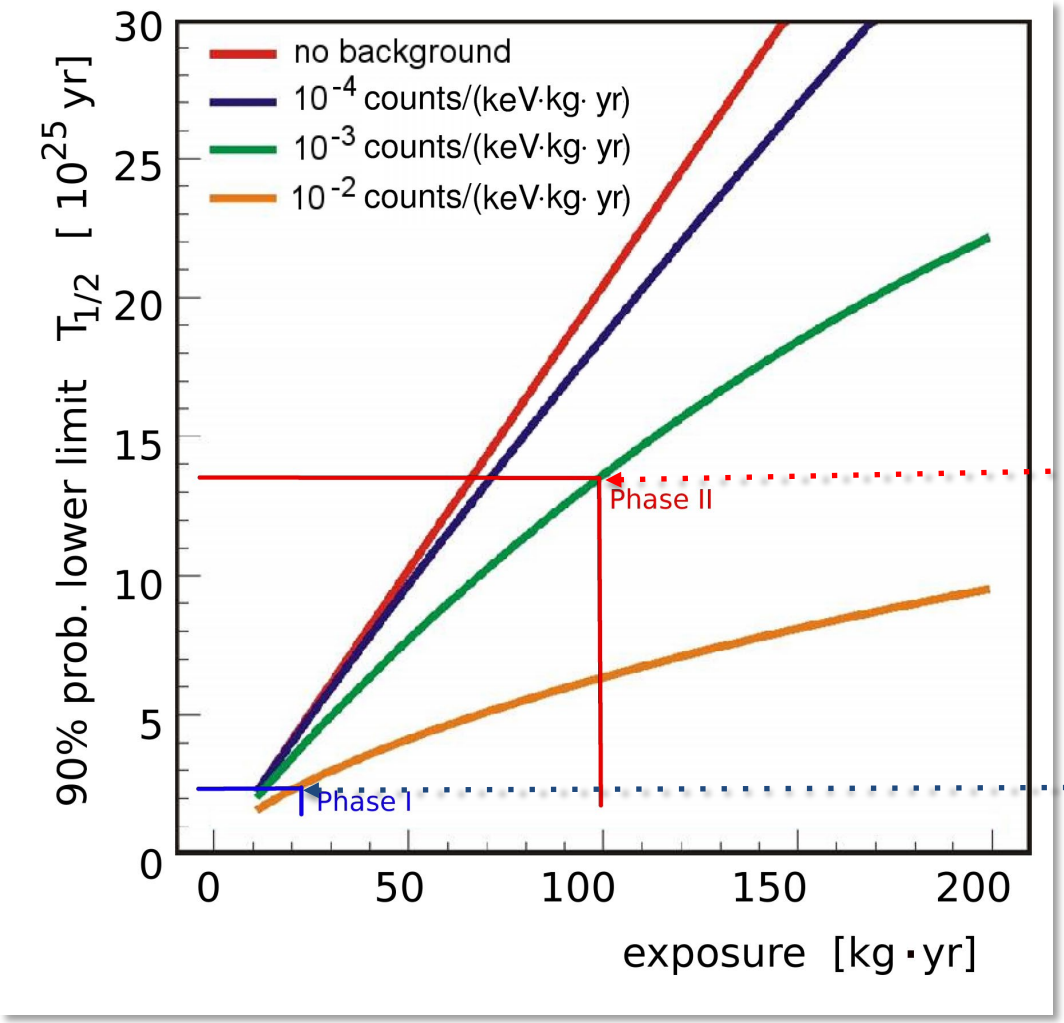
  ~0.1% at $Q_{\beta\beta}$

- ✓ high detection efficiency

  source = detector

GERDA

Phased approach



Phase II (Dec 2015 – May 2018):
Add new BEGe detectors (20 kg)
Phase II+ (July 2018 – Dec 2019):
Add new inverted coaxes (9 kg)
BI ≈ 0.001 cts / (keV kg yr)
Sensitivity after 100 kg yr

Phase I (Nov 2011 – May 2013):
Use HdM & IGEX detectors(18 kg)
BI ≈ 0.01 cts / (keV kg yr)
Sensitivity after 20 kg yr

$$T_{1/2}^{0\nu} > 2.1 \times 10^{25}\ \text{yr}\ (90\%\ \text{CL})$$

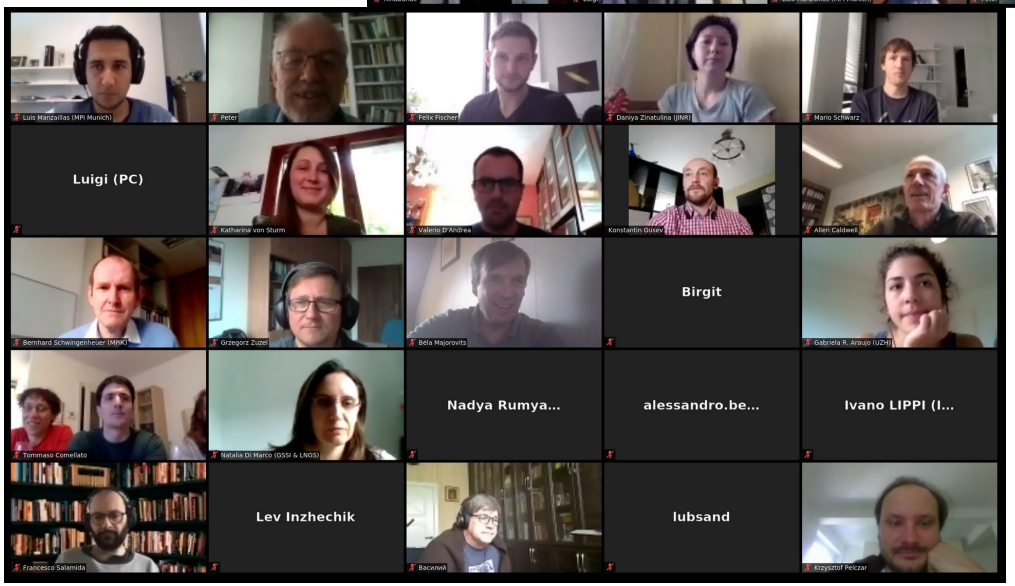
[PRL 111 (2013) 122503]

GERDA
the Collaboration

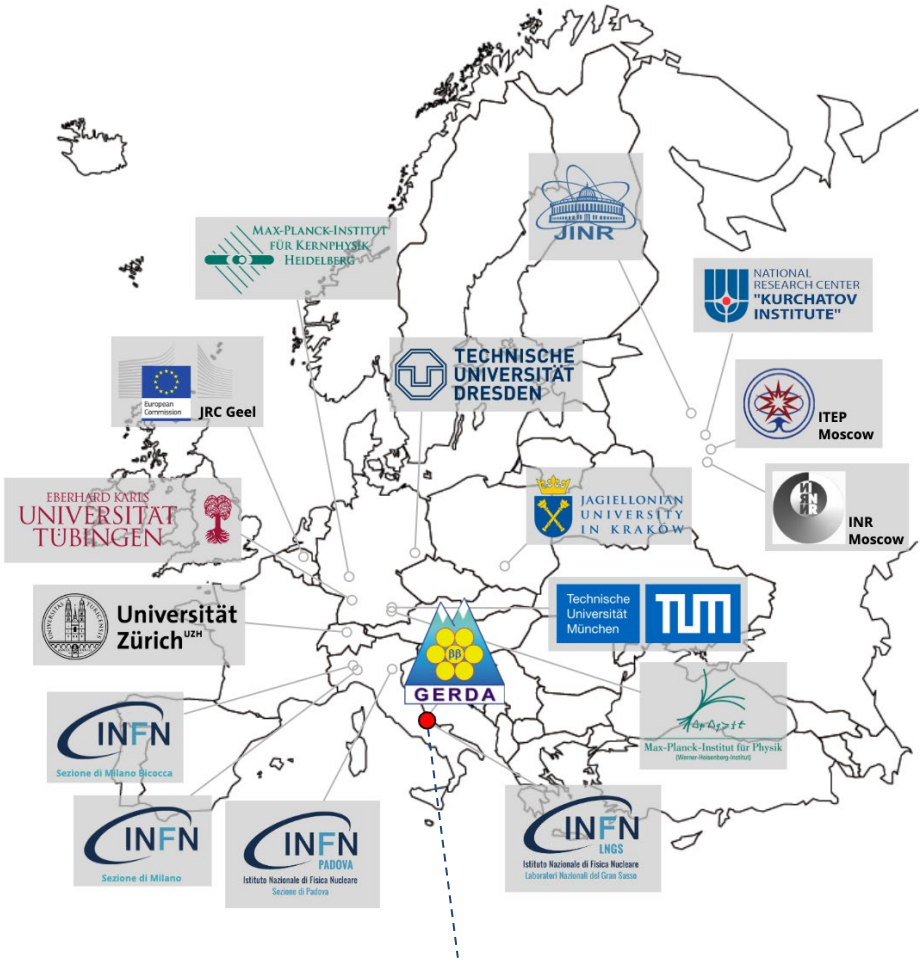
GERDA
the Collaboration

in virtuality

GERDA unblinding
@ Nowhere, 2020

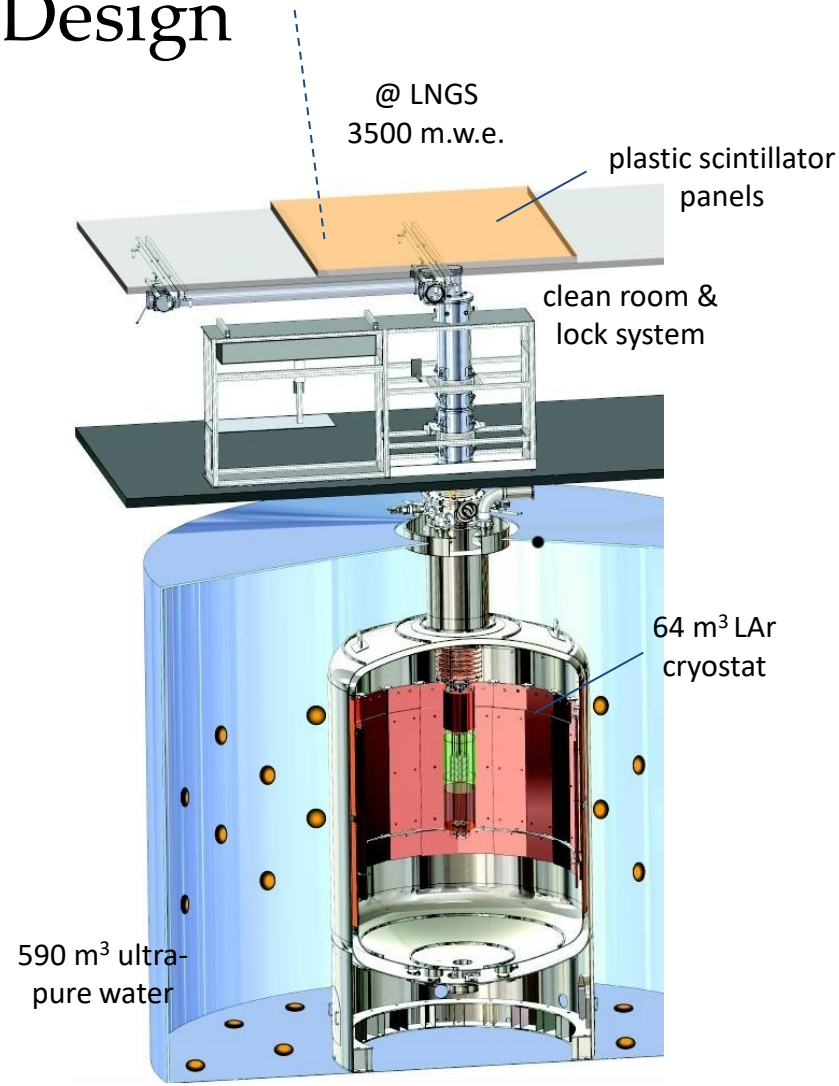


GERDA
the Collaboration

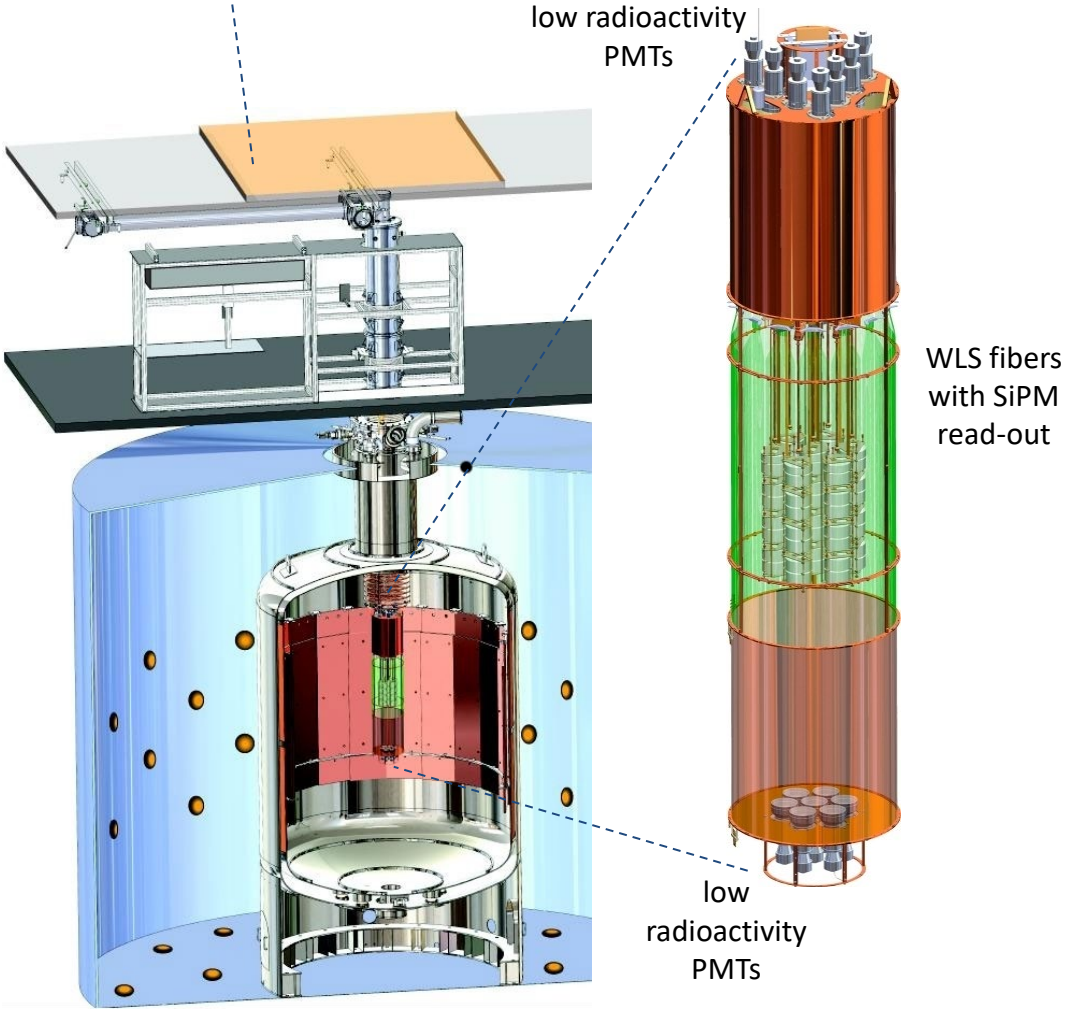


GERDA Phase II

Design

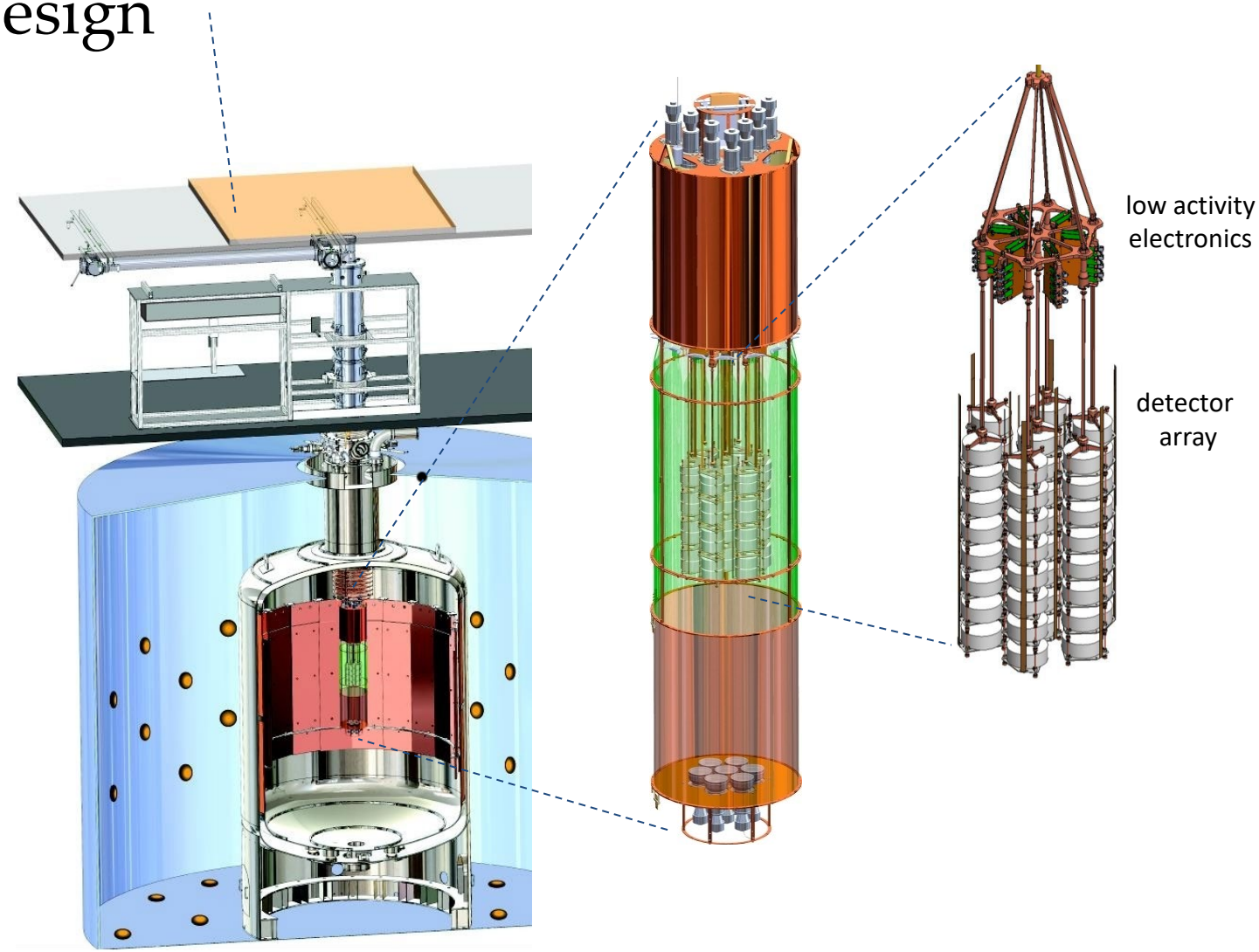


GERDA Phase II
Design



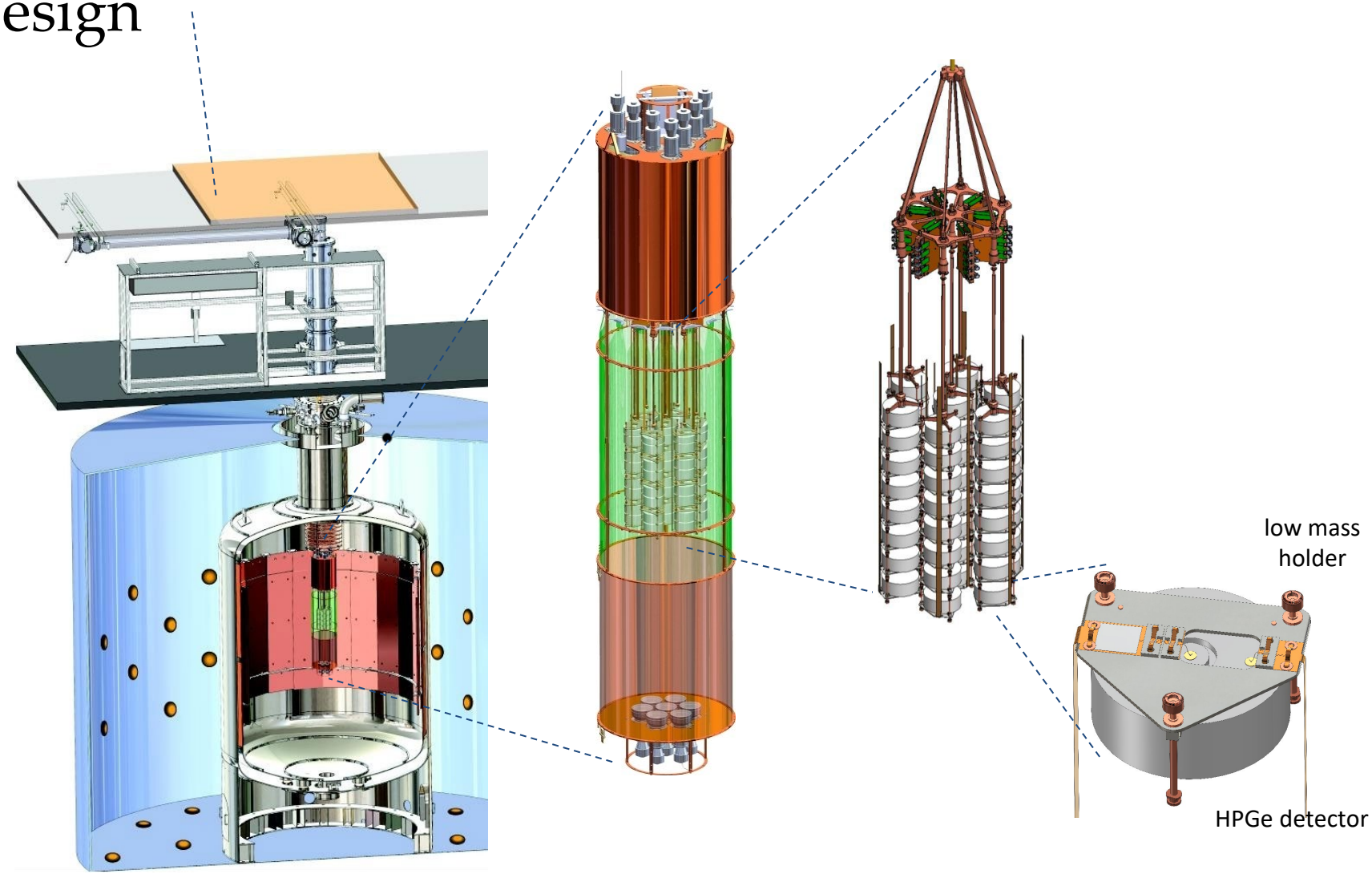
GERDA Phase II

Design

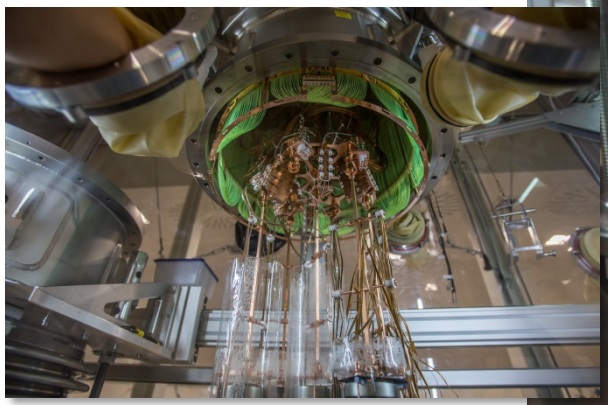


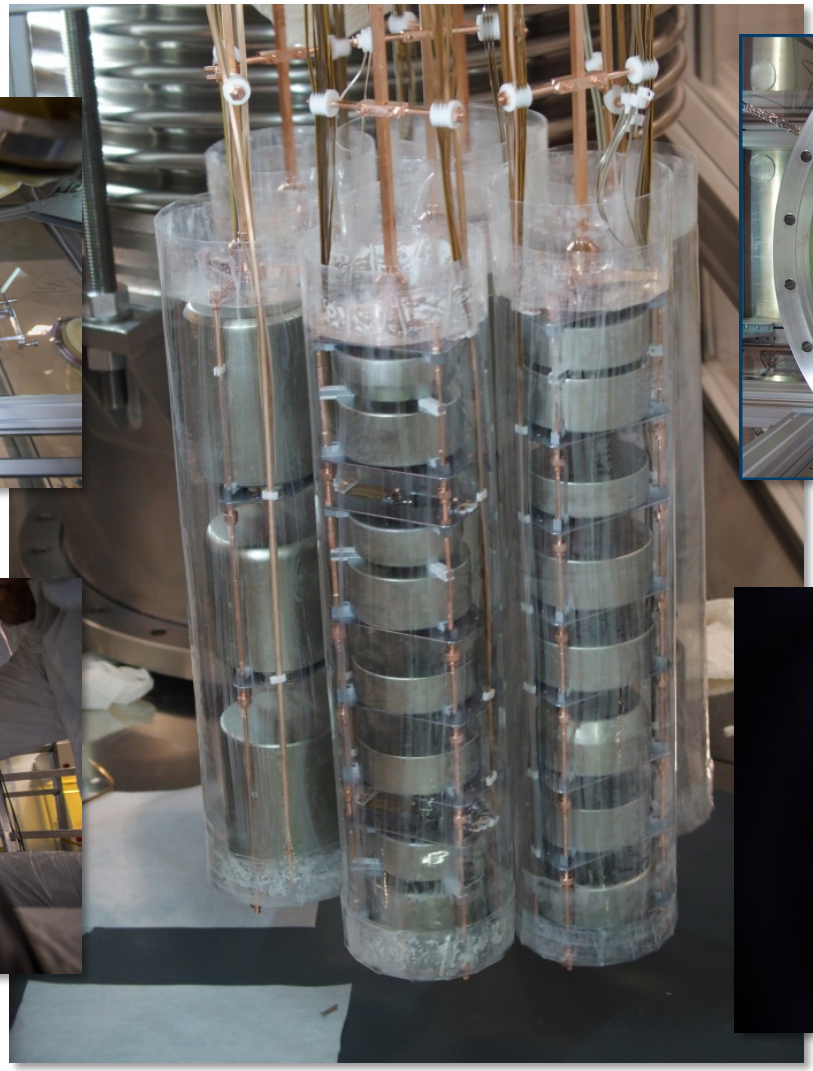
GERDA Phase II

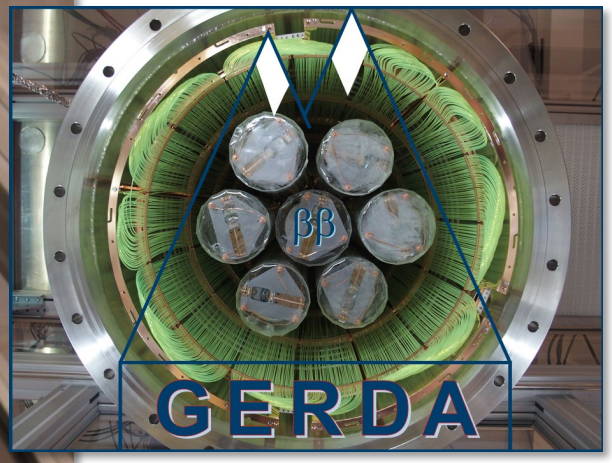
Design

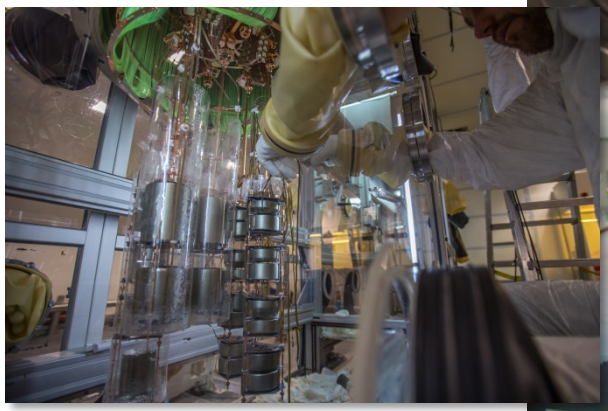


GERDA **Phase II**









GERDA **Phase II**

Detectors and goals

Phase II:

- 7 enriched coaxial **(15.6 kg)**
- 30 enriched BEGe **(20.0 kg)**
- 3 natural coaxial (7.6 kg)

Phase II+:

+ 5 enriched inverted coaxial (9.5 kg)
- 3 natural coaxial (7.6 kg)
+ **new LAr veto** instrumentation
+ cleaner materials

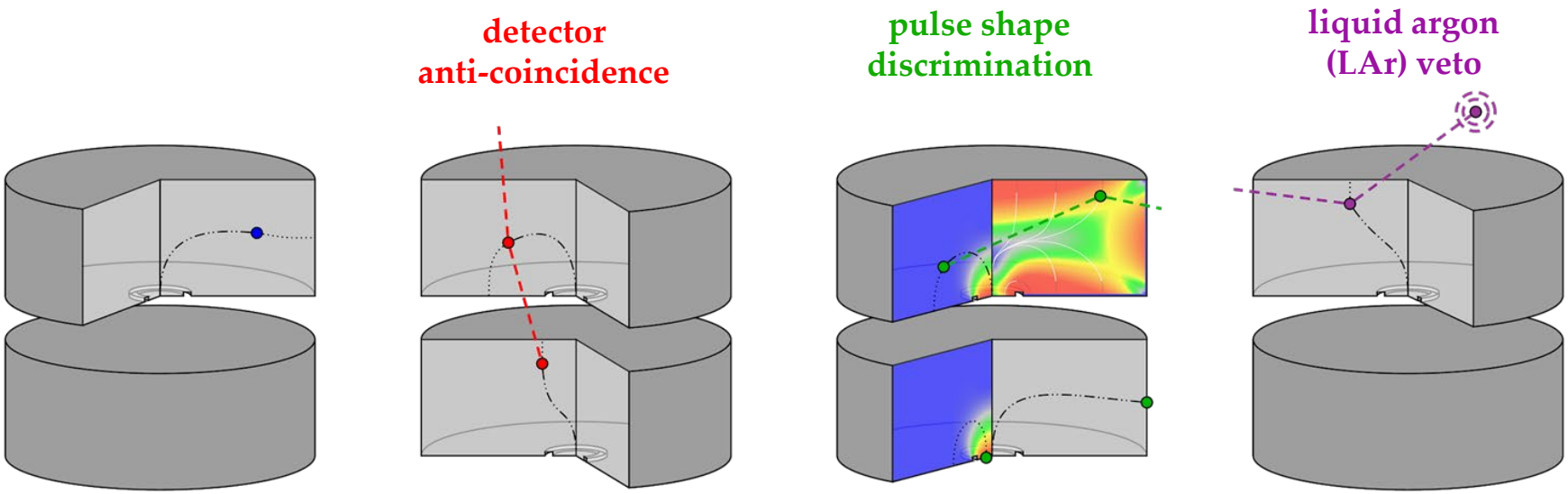
(upgrade performed in Spring-Summer 2018)

GERDA Phase II goals

background	~ 10^{-3} cts/(keV kg yr)
exposure	≥ 100 kg yr
sensitivity	$T_{1/2}^{0\nu} \geq 10^{26}$ yr

GERDA **Phase II**

Background rejection



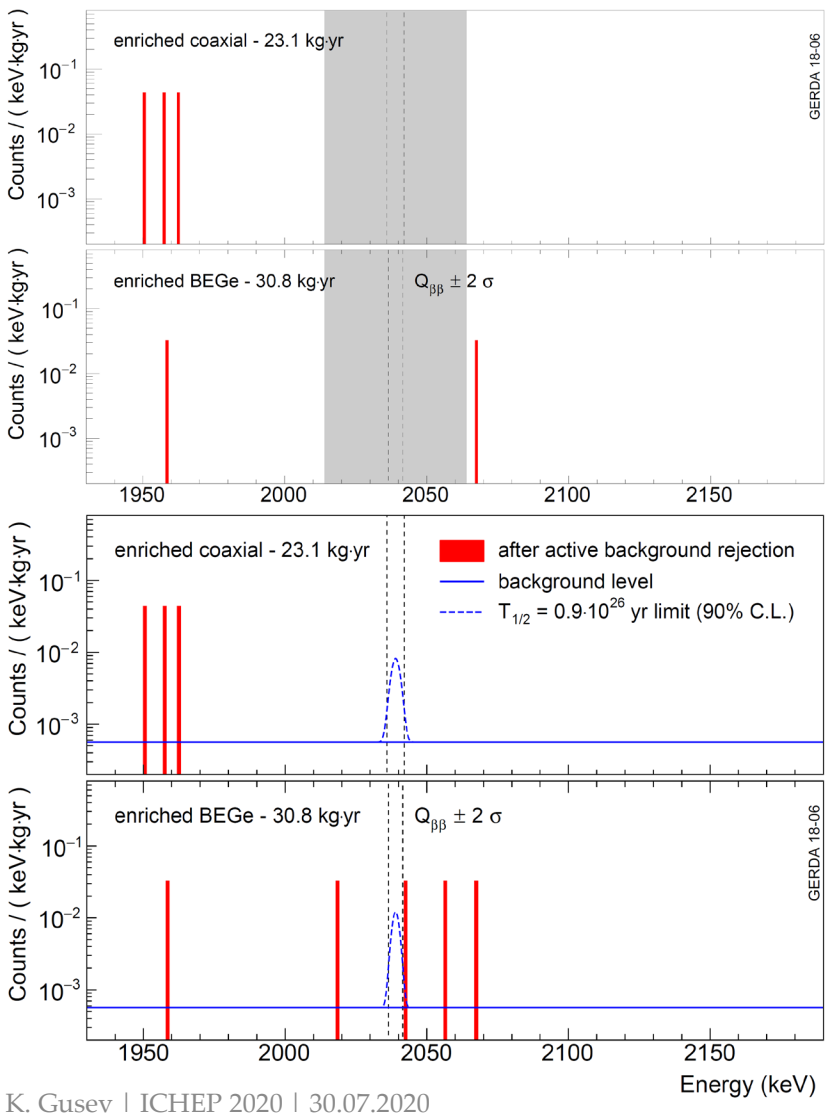
(Picture of C. Wiesinger)

Point like (single site) **ββ** topology versus:

- **multi-detector** interactions
- **multi-site/surface** interactions
- **coincidence with energy deposition** in liquid argon

GERDA **Phase II**

Previous achievements



Unique background indices achieved:

- ✓ Coax: $\mathbf{5.7^{+4.1}_{-2.6} \times 10^{-4}}$ cts/(keV·kg·yr)
- ✓ BEGe: $\mathbf{5.6^{+3.4}_{-2.4} \times 10^{-4}}$ cts/(keV·kg·yr)

***best** in the field when normalized to FWHM!*

GERDA Phase II limits* @ 2019:

- ✓ Median sensitivity for limit setting:
  $\mathbf{1.1 \times 10^{26}}$ **yr** (world best!)
- ✓ Best fit → no signal
  $\boldsymbol{T^{0\nu}_{1/2} > 0.9 \times 10^{26}}$ **yr** (90% CL)

* – frequentist analysis

GERDA Phase II goals

background	~ 10^{-3} cts/(keV kg yr)	✓
exposure	≥ 100 kg yr	
sensitivity	$T^{0\nu}_{1/2} \geq 10^{26}$ yr	✓

GERDA **Phase II**

Successful upgrade 2018

Upgrade of the GERDA experiment aims to:

- ✓ Test the novel detectors + increase the mass of ^{76}Ge
- ✓ Prove the robustness and reproducibility of the GERDA approach

Upgrade included:

- New LAr veto:
  - ✓ new fiber curtain (improved light collection) + central module to read out hidden Ar volume
- Installation of 5 novel **inverted coaxial detectors** made from **^{76}Ge**
- Exchange of all signal and HV cables by new ones with better radiopurity
- New signal cable routing to reduce the cross-talk and improve resolution
- Repairing of broken electronic channels and installation of protective diodes

old curtain

810 fiber ends, 90 SiPMs

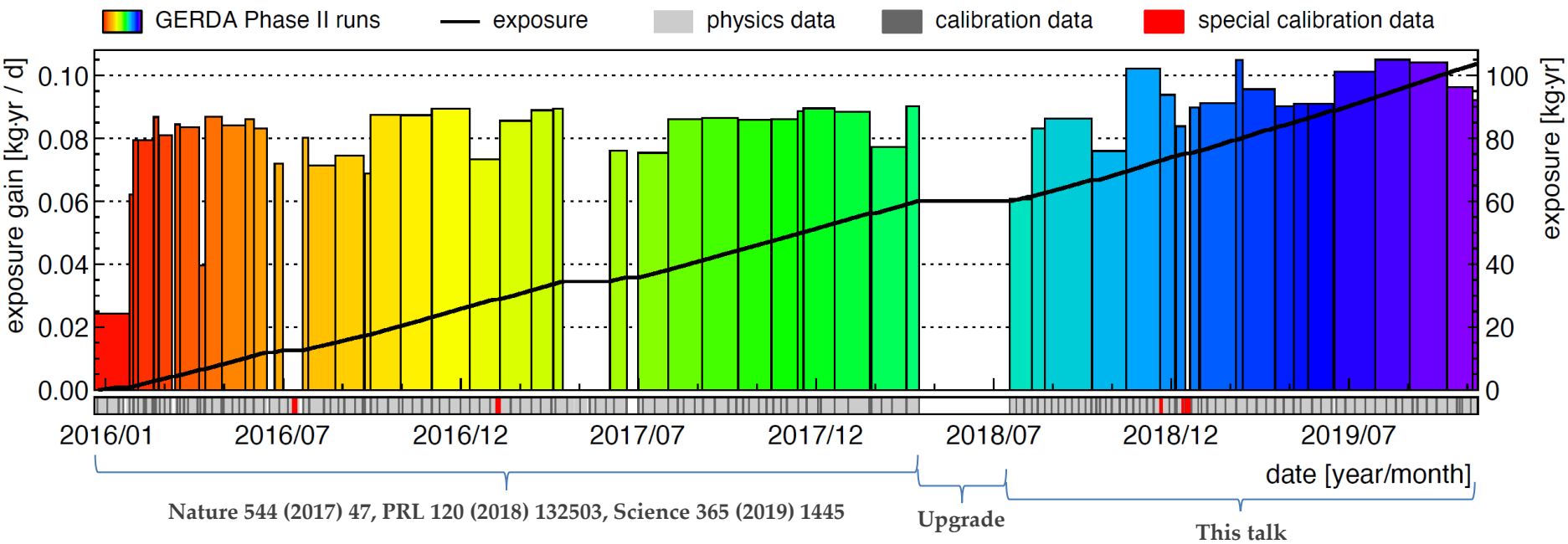
new curtain

1215 fiber ends, 135 SiPMs

Central module

GERDA **Phase II**

Data taking



- Phase II duty cycle (including upgrade period): **87.7%**

✓ **103.7 kg yr** (**127.2** kg yr with Phase I)

✓ Full data set analyzed

GERDA **Phase II**

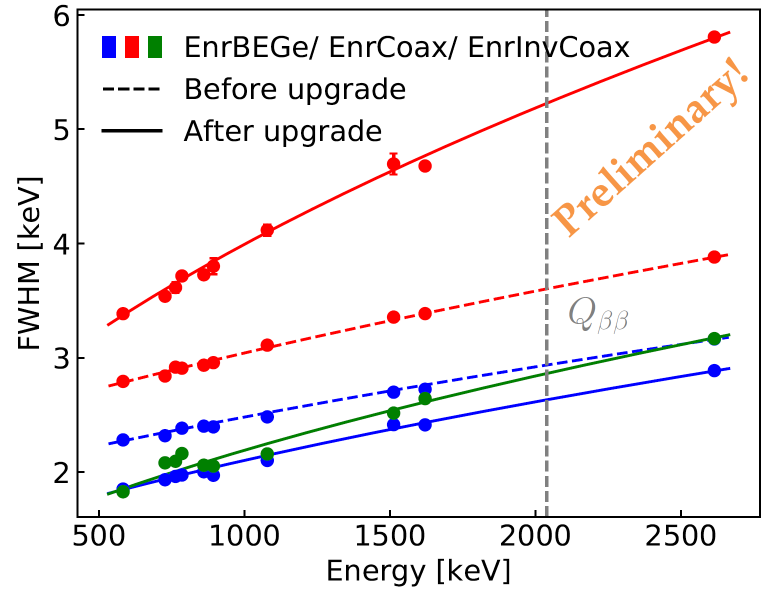
Performance

- ✓ Weekly calibrations with ^{228}Th source
- ✓ IC detectors perform similar to BEGe (mass ~ 3x)

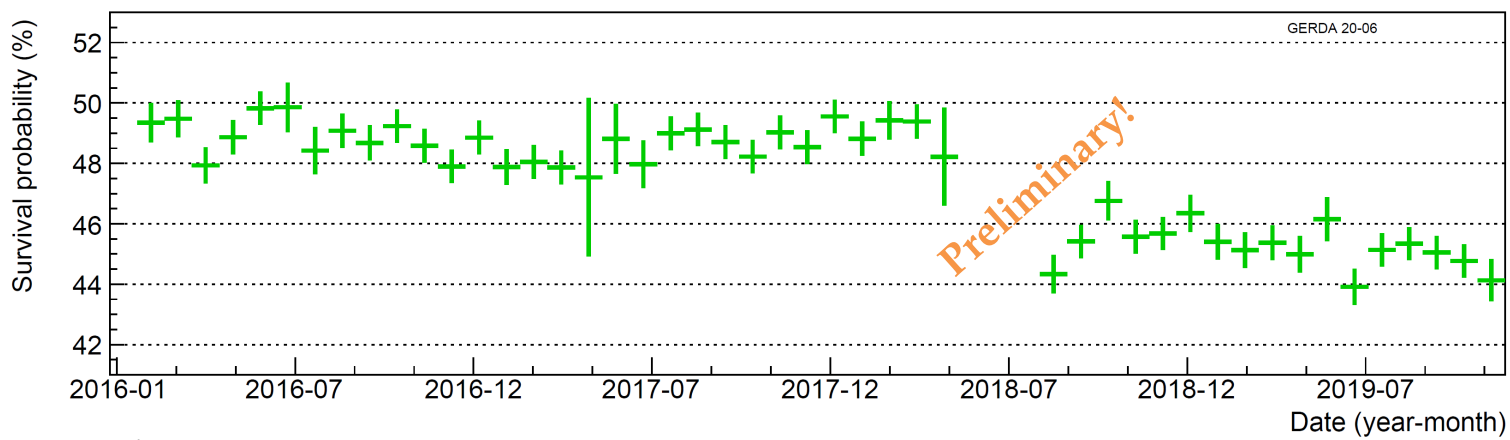
FWHM @ $Q_{\beta\beta}$ (keV):

	BEGe	Coax	IC
Before upgrade	**2.9 ± 0.3**	**3.6 ± 0.3**	
After upgrade	**2.6 ± 0.2***	**5.2 ± 1.9****	**2.9 ± 0.1**

* – improved due to new cable routing
** – dominated by one detector with the leakage current

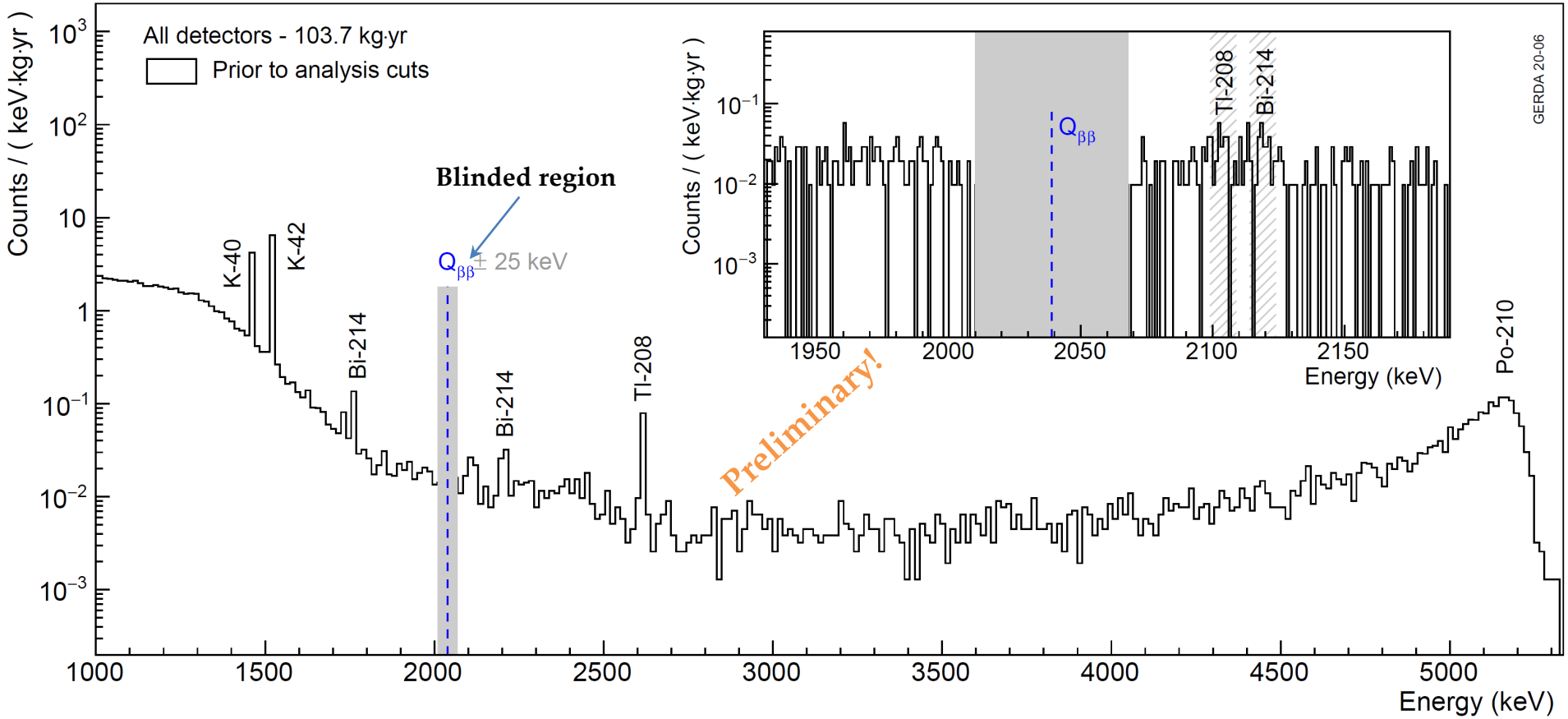


- ✓ Improved performance of the LAr veto after upgrade



GERDA **Phase II**

Physics spectrum – full data set!

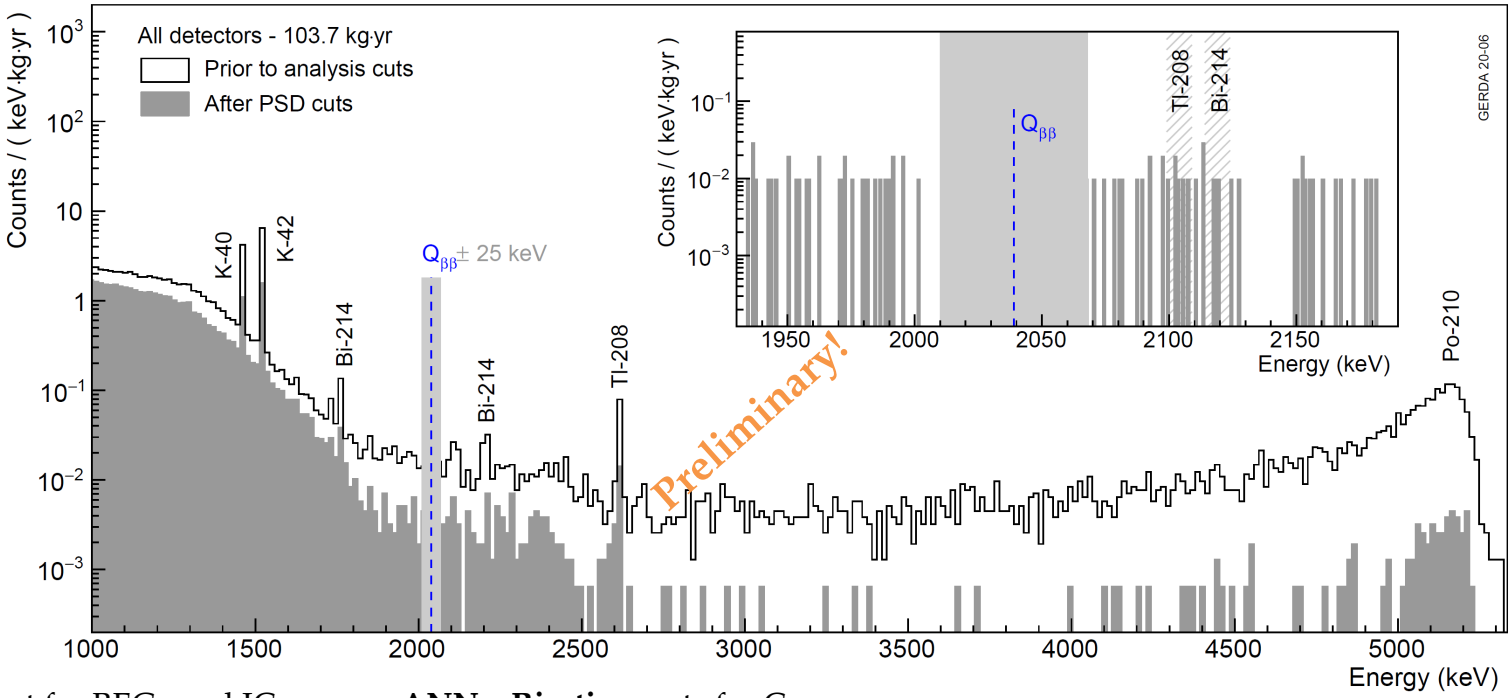


- ✓ Data quality, muon veto and anticoincidence cuts applied
- ✓ BI in the analysis window [1930-2190] keV **before** active cuts:

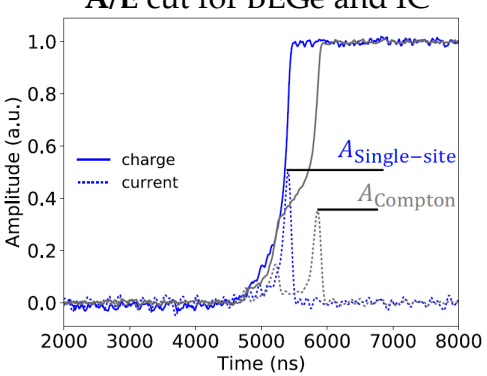
$$\mathrm{BI} = 143^{+9}_{-8} \times 10^{-4} \mathrm{cts}/(\mathrm{keV} \times \mathrm{kg} \times \mathrm{yr})$$

GERDA **Phase II**

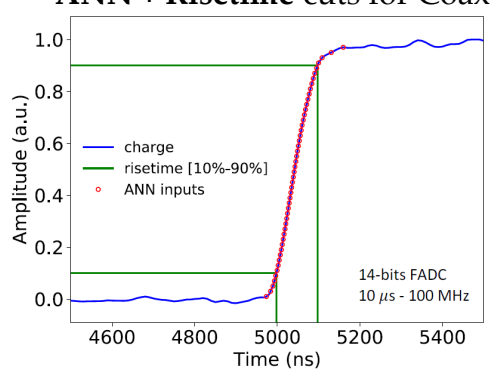
Physics spectrum after PSD



A/E cut for BEGe and IC



ANN + Risetime cuts for Coax

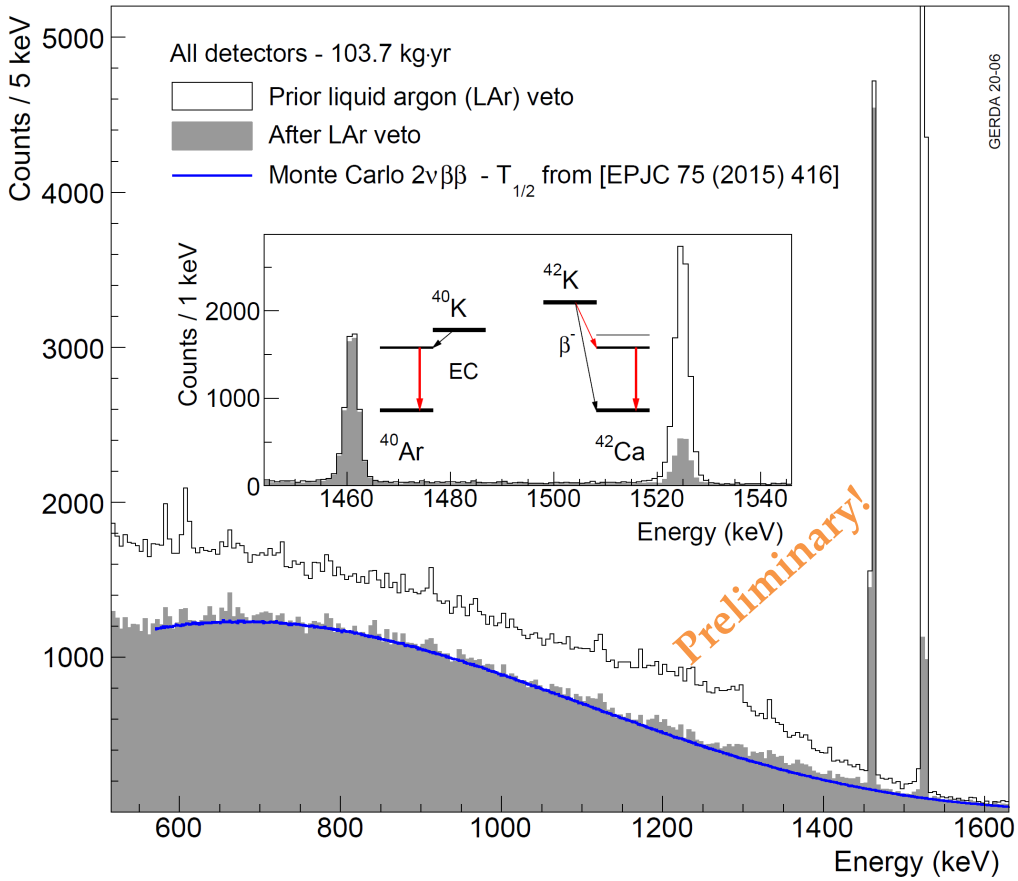


$0\nu\beta\beta$ decay signal efficiency:

- $\epsilon_{\text{PSD}}^{\text{BEGe}} = (88.7 \pm 3.2)\%$
- $\epsilon_{\text{PSD}}^{\text{IC}} = (90.0 \pm 1.7)\%$
- $\epsilon_{\text{PSD}}^{\text{Coax}} = (68.9 \pm 3.1)\%$

GERDA **Phase II**

LAr veto



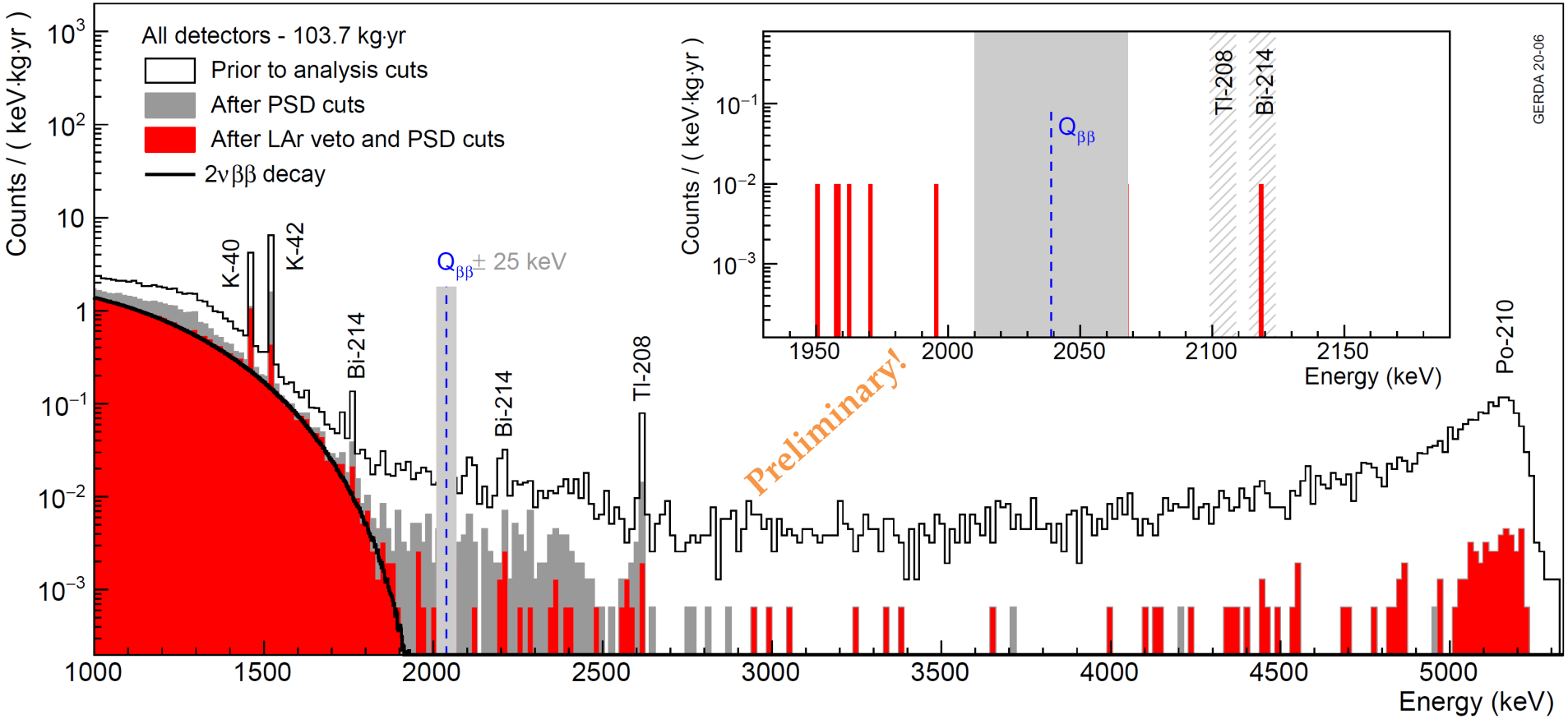
- ✓ Practically pure 2νββ spectrum after LAr veto cut < 1400 keV
- ✓ Strong suppression of ^{42}K line

$0\nu\beta\beta$ decay signal efficiency:

$$\epsilon_{\mathrm{LAr}} = (97.9 \pm 0.1)\%$$

GERDA **Phase II**

Final spectrum



- ✓ Great complementarity between LAr and PSD cuts!
- ✓ BI in the analysis window [1930-2190] keV **after** active cuts:

$$\mathrm{BI} = \mathbf{5.2}^{+1.6}_{-1.3} \times \mathbf{10}^{-4}\mathrm{cts}/(\mathrm{keV} \times \mathrm{kg} \times \mathrm{yr})$$

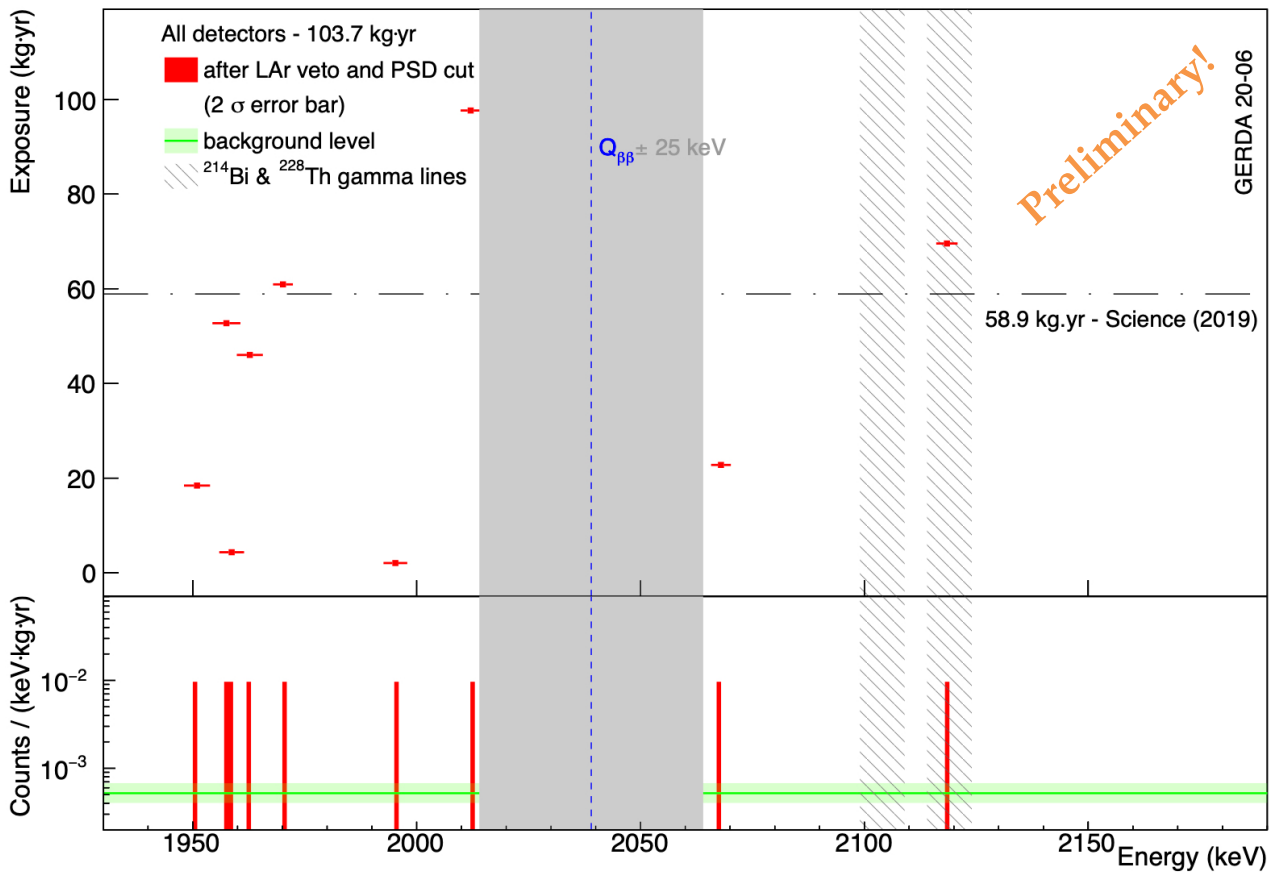
GERDA **Phase II**

Final spectrum in the analysis window

Still blinded…

Dec 2019

Dec 2015



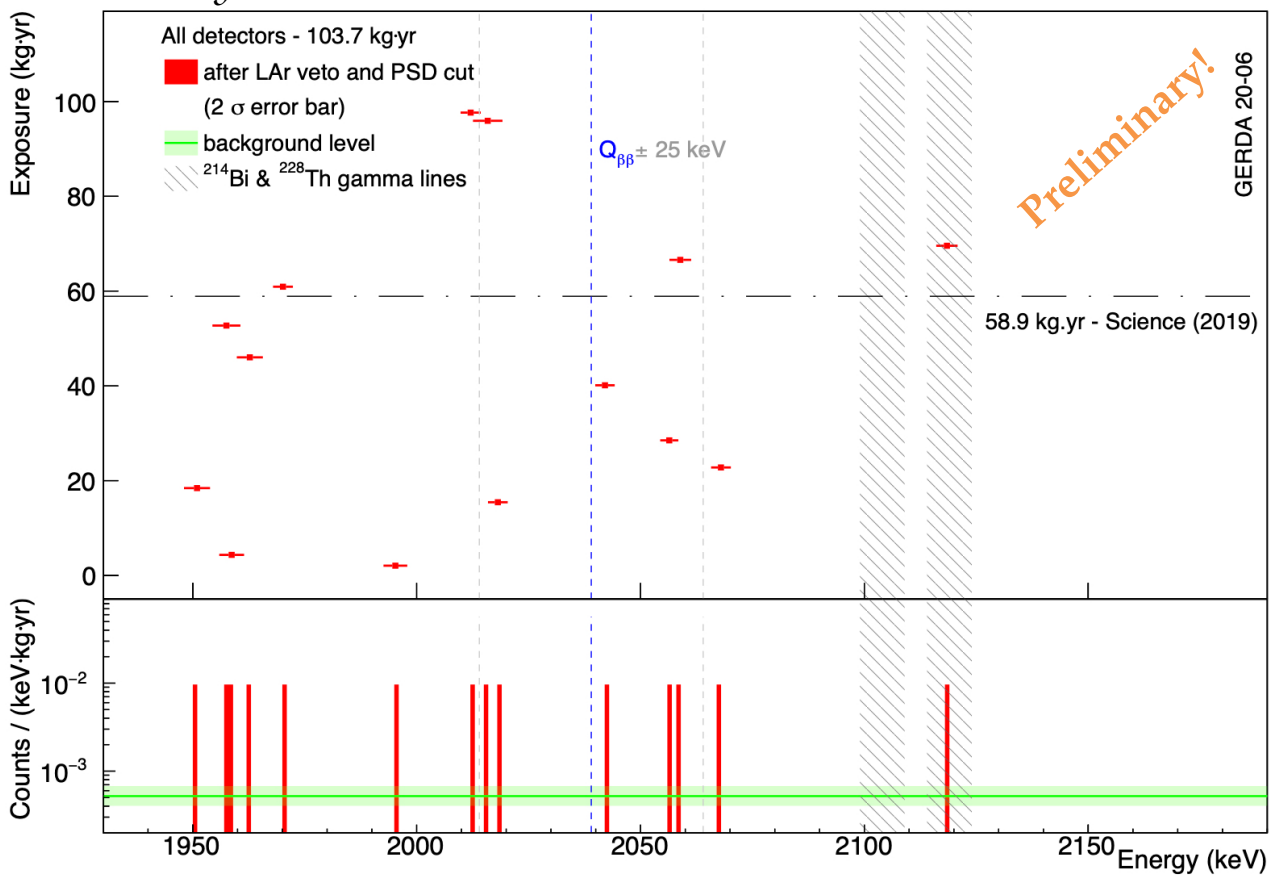
GERDA **Phase II**

Final spectrum in the analysis window

Finally unblinded!

Dec 2019

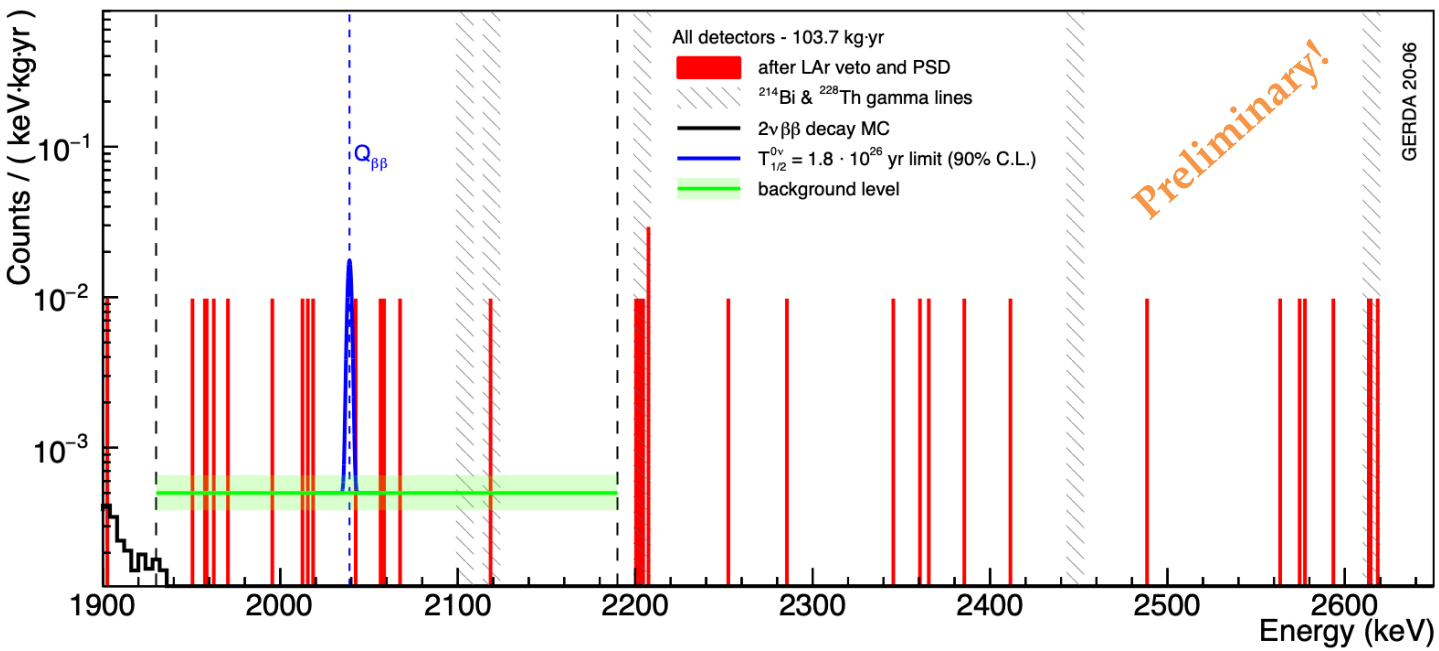
Dec 2015



- ✓ 2 new counts since the last data release
- ✓ **No** counts @ $Q_{\beta\beta}$ ± FWHM

GERDA

Statistical analysis and results



Frequentist analysis*:

- ✓ Median sensitivity for limit setting:
  $\mathbf{1.8 \times 10^{26}}$ **yr** (90% CL)
- ✓ Best fit → no signal

$\boldsymbol{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr** (90% CL)

Bayesian analysis*:

- ✓ Median sensitivity for limit setting:
  1.4×10^{26} yr (90% CI)

$T^{0\nu}_{1/2} > 1.4 \times 10^{26}$ yr (90% CI)

* – statistical treatment details in **Nature 544 (2017) 47**

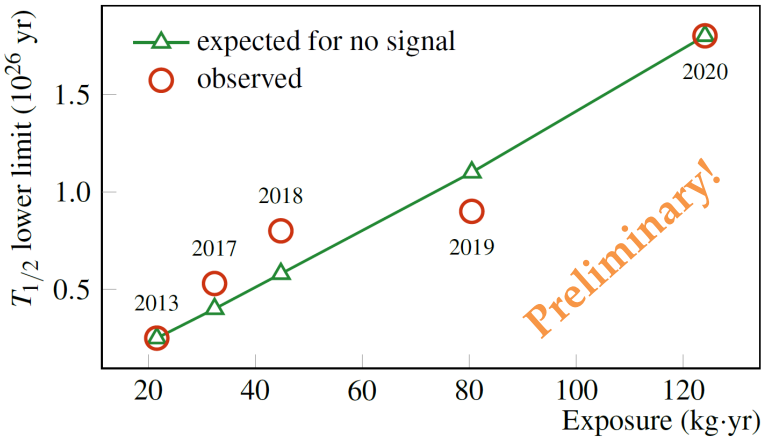
GERDA **Phase II**

First background free 0νββ search

- ✓ GERDA successfully finished data taking in December 2019
- ✓ All design goals are **surpassed**!

GERDA Phase II	goals	achievements
background	~ 10^{-3} cts/(keV kg yr)	$\mathbf{5.2^{+1.6}_{-1.3} \times 10^{-4}}$cts/(keV kg yr)
exposure	≥ 100 kg yr	**103.7** kg yr
sensitivity	$T^{0\nu}_{1/2} \geq 10^{26}$ yr	$\boldsymbol{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr**

- ✓ World best median sensitivity and limit!
- ✓ Linear increase of sensitivity vs exposure is proven!



- ✓ Bright future for the next step: LEGEND