Final results of the neutrinoless double-beta decay search with GERDA

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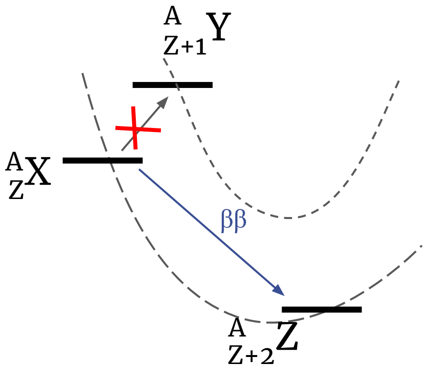
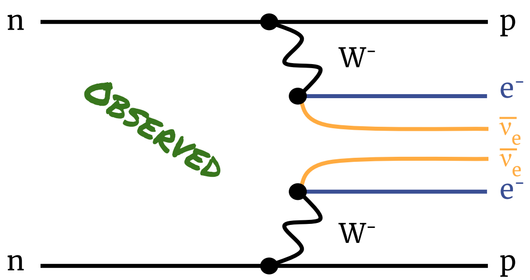
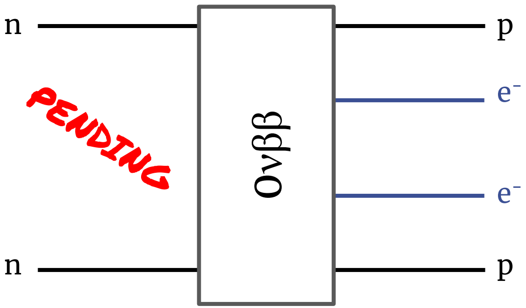
(Neutrinoless) double beta decay



Required for observation: purely double beta (**ββ**) decaying isotope
^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe, ...



2νββ allowed in SM
Among the rarest radioactive processes ever observed



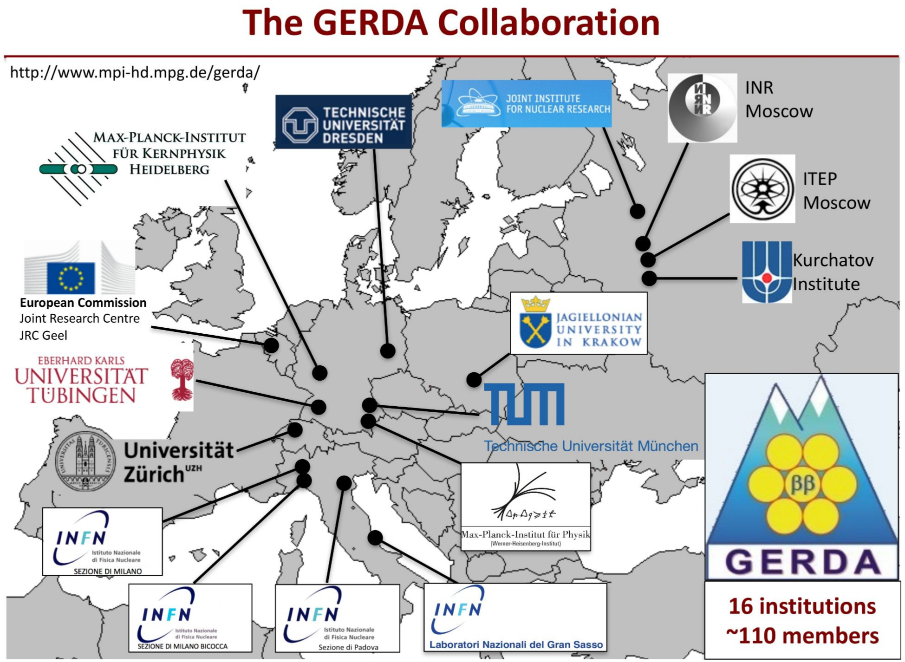
Observation of **0νββ**:
... → Lepton number non-conservation
↳matter-antimatter asymmetry
... → Majorana nature of **ν**
... → Effective Majorana mass

$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

... exciting challenge in contemporary physics!

The GERDA Collaboration

GERDA meeting LNGS June 2022



Experimental approach

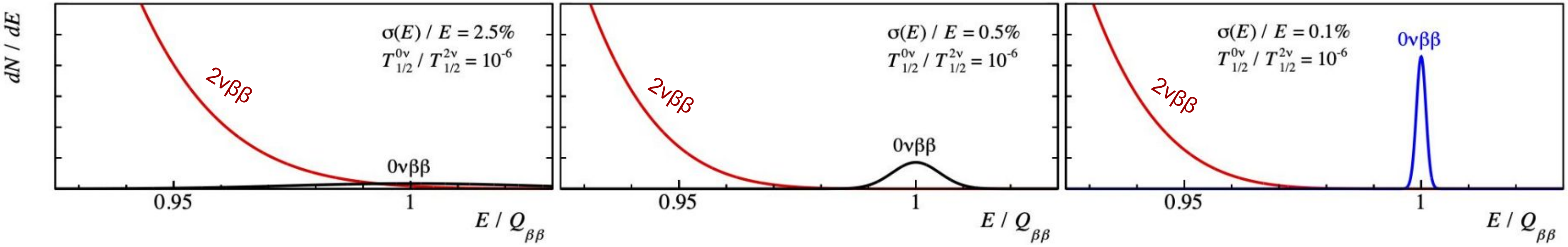
Key concept: use of **HPGe** (High-Purity Germanium) detectors enriched in **^{76}Ge** (~ 87%)

→ Source = detector → High detection efficiency

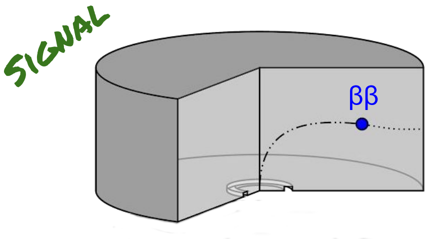
→ No intrinsic backgrounds [Astropart.Phys. 91 (2017) 15-21]

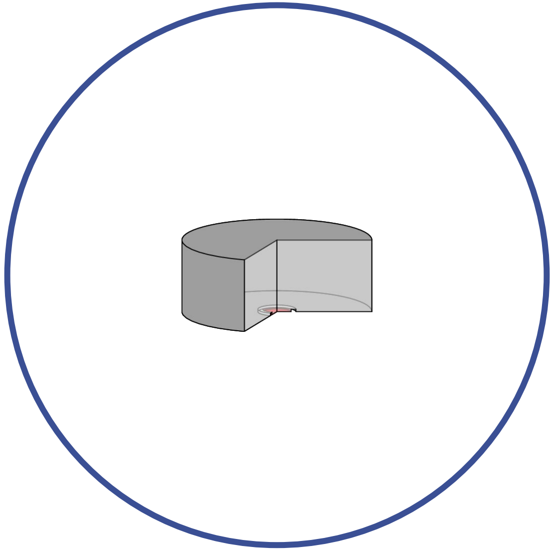
→ Application of Pulse-Shape Discrimination (PSD)

→ Superior energy resolution @ $Q_{\beta\beta}$ (2039 keV): **σ(E) / E < 0.1 %**



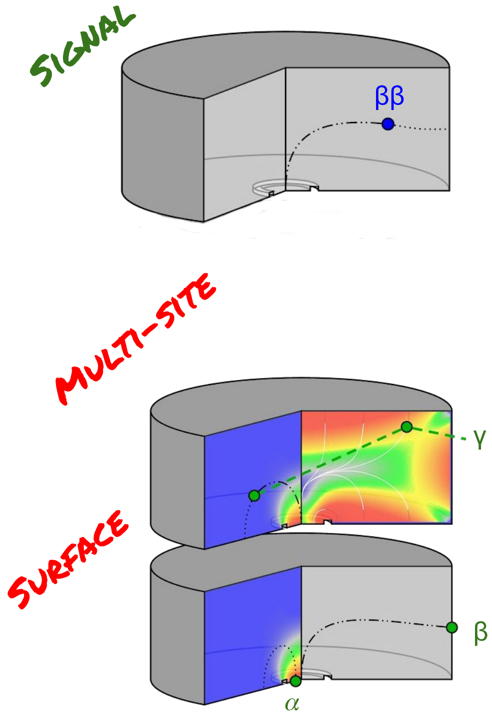
Discriminating ββ and background

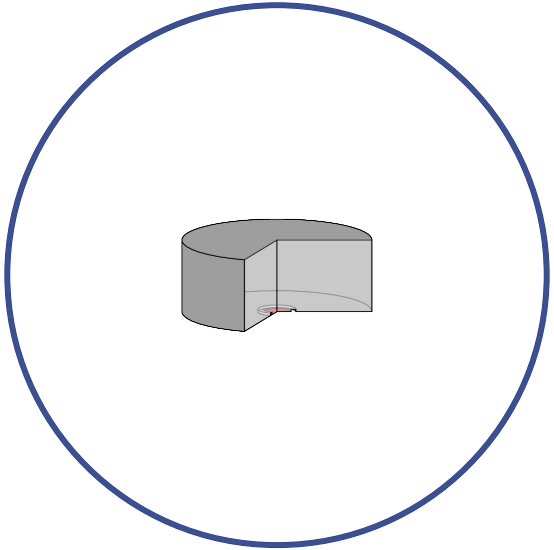




germanium detector …

Discriminating ββ and background





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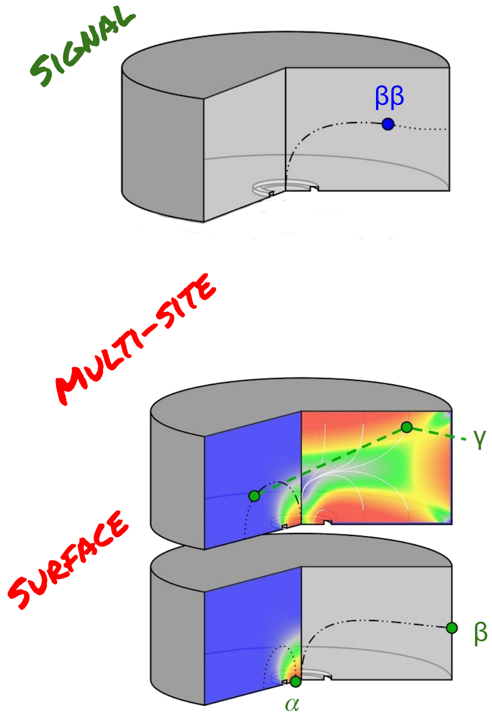
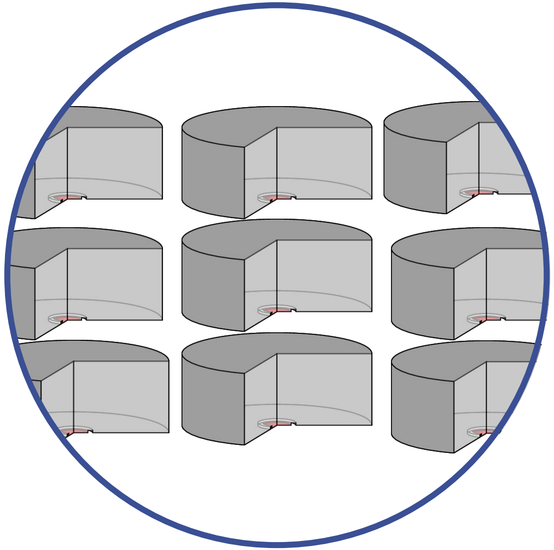
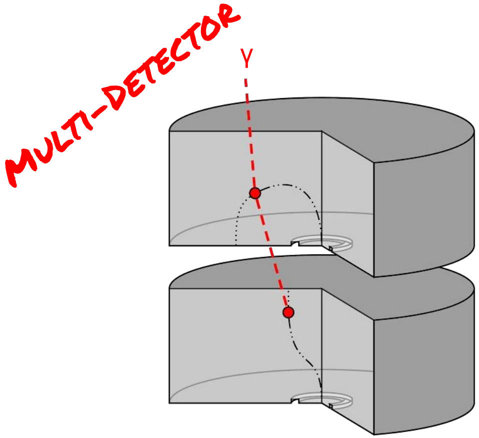
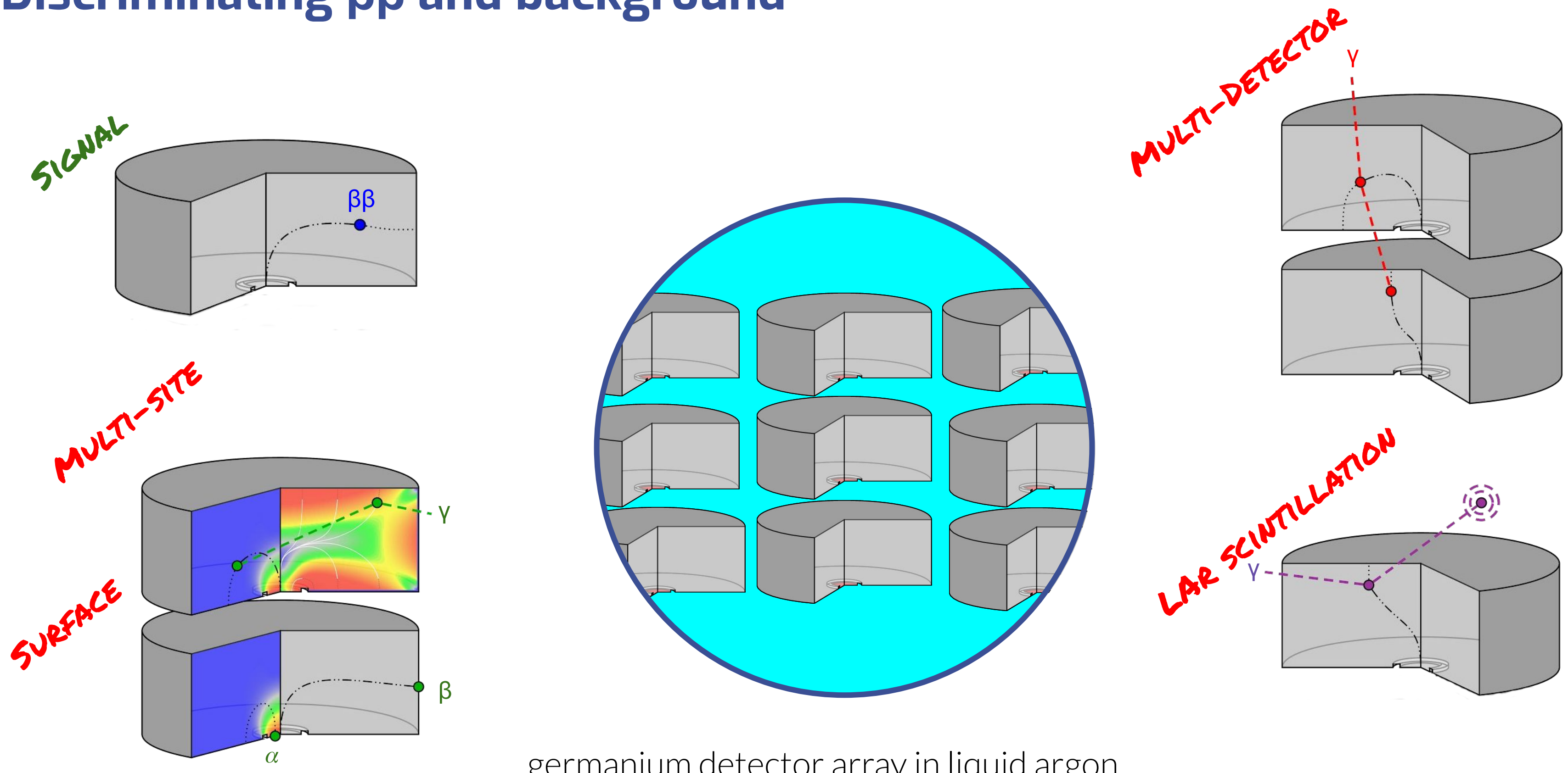




germanium detector array …



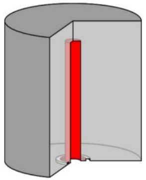
Discriminating ββ and background



germanium detector array in liquid argon

GERDA Phase II setup

[Eur.Phys.J. C78 (2018) no.5, 388]

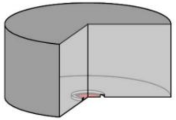


Past
Semi-coaxial
BIG
POOR PSD

7 (6)
Σ 15.6 kg (14.6 kg)

After upgrade

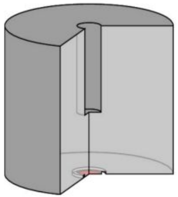
[Budjas et al., JINST 4 (2009) P10007]



Present
BEGe
SMALL
GOOD PSD

30
Σ 20 kg

[Cooper et al., NIM A665, 25 (2011) 25-32]

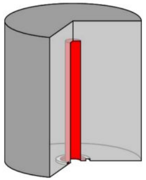


Future
Inverted Coaxial
BIG
GOOD PSD

5
Σ 9.6 kg

GERDA Phase II setup

[Eur.Phys.J. C78 (2018) no.5, 388]



Past

Semi-coaxial

BIG

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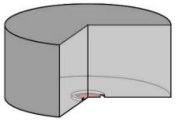

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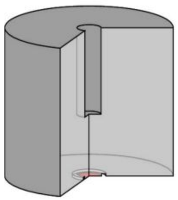

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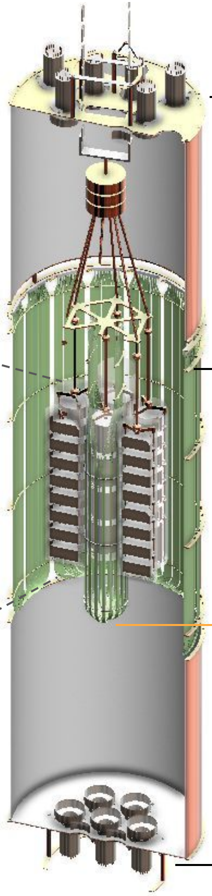


9 PMTs

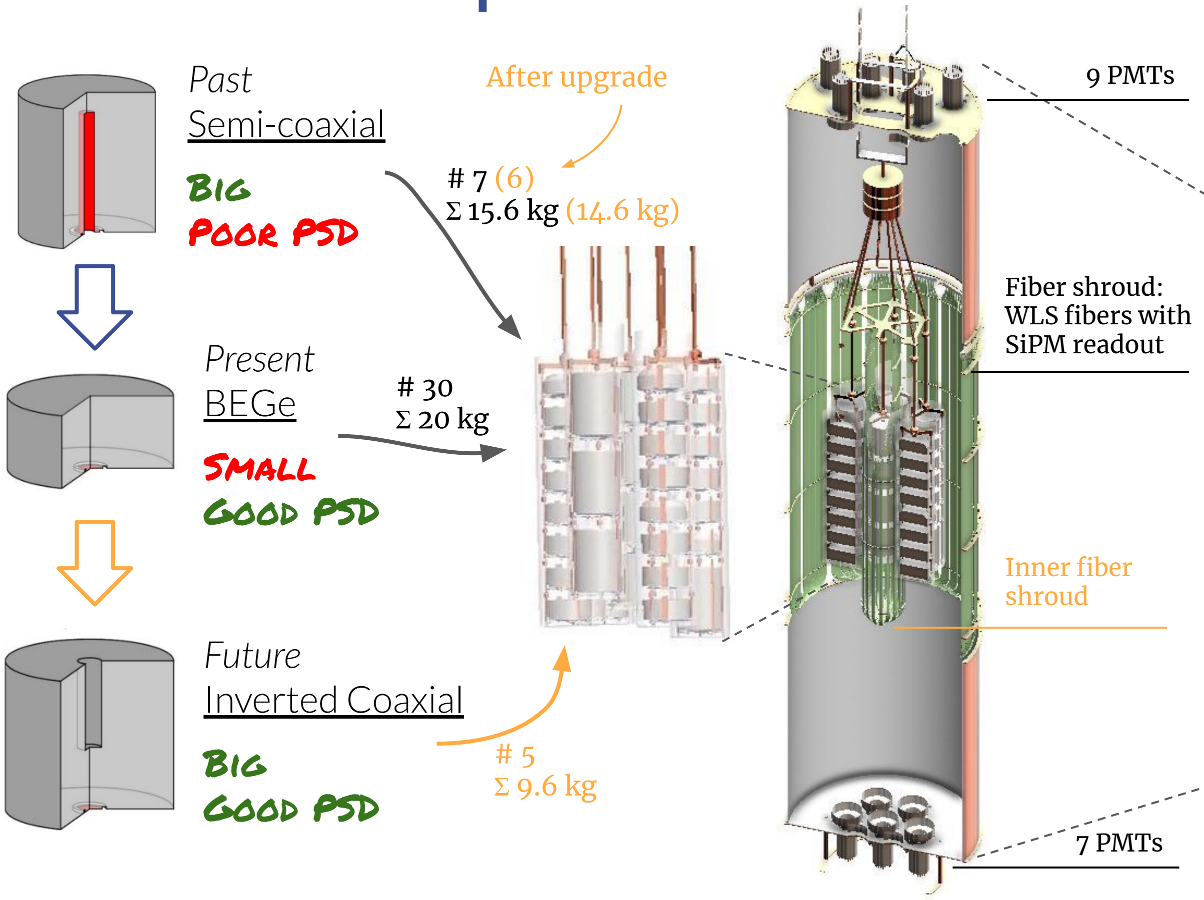
Fiber shroud: WLS fibers with SiPM readout

Inner fiber shroud

7 PMTs

GERDA Phase II setup

[Eur.Phys.J. C78 (2018) no.5, 388]



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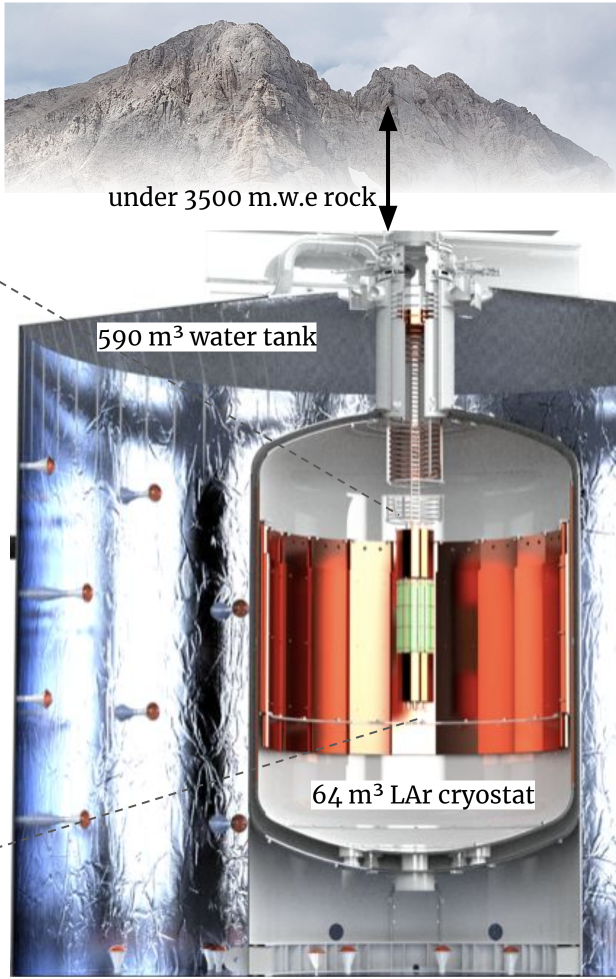
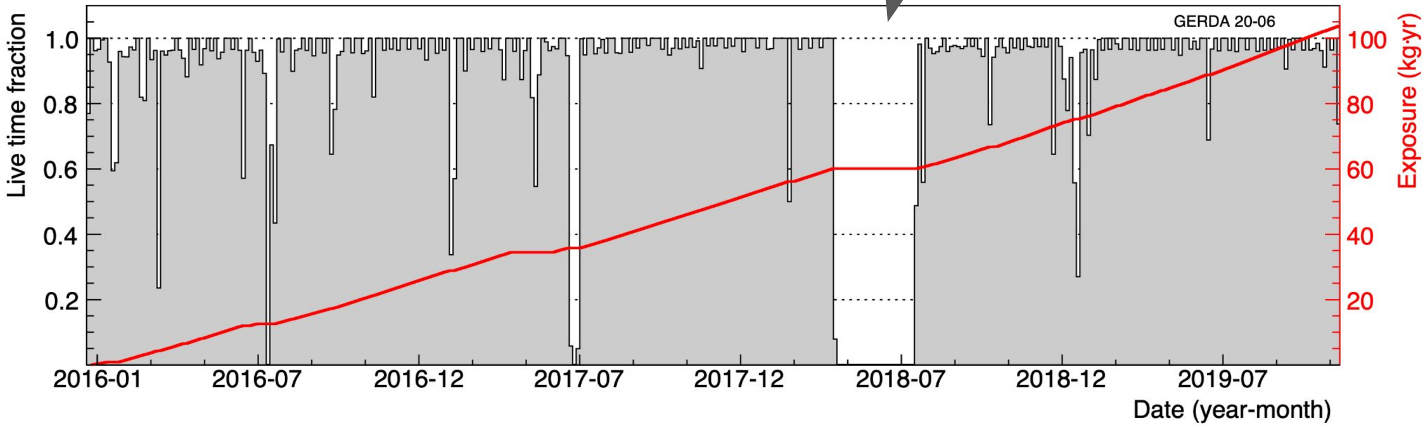
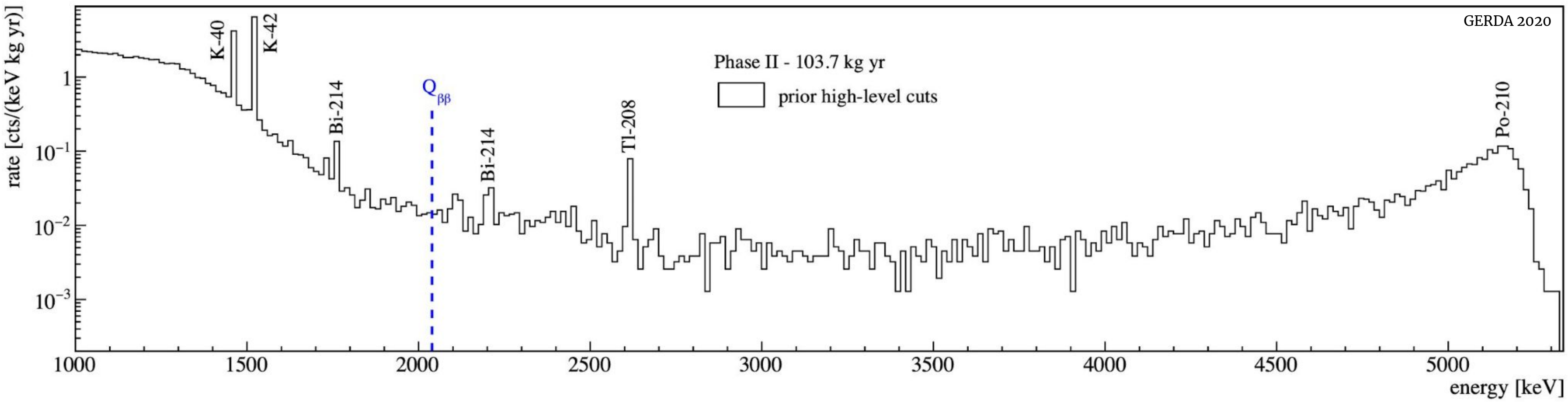


Data taking in Phase II

- Phase II data taking from December 2015 to November 2019
- High duty cycle, only short interruption for upgrade in Summer 2018
- In total, collected 103.7 kg yr of exposure
  (127.2 kg yr when combined with Phase I)

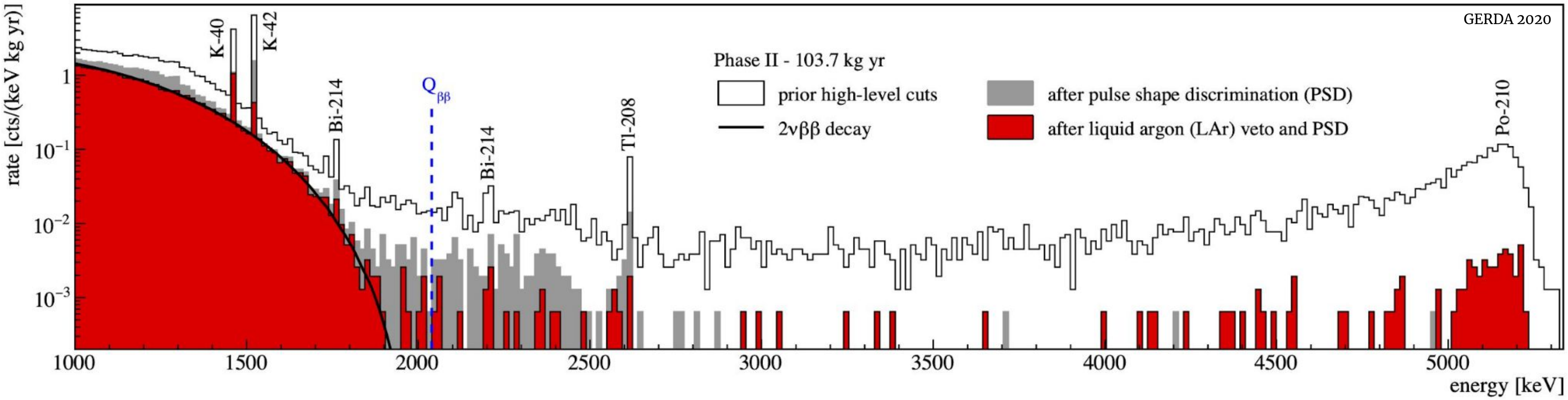


Final energy spectrum of Phase II



- Before high-level cuts → quality cuts, muon anti-coincidence and detector anti-coincidence applied

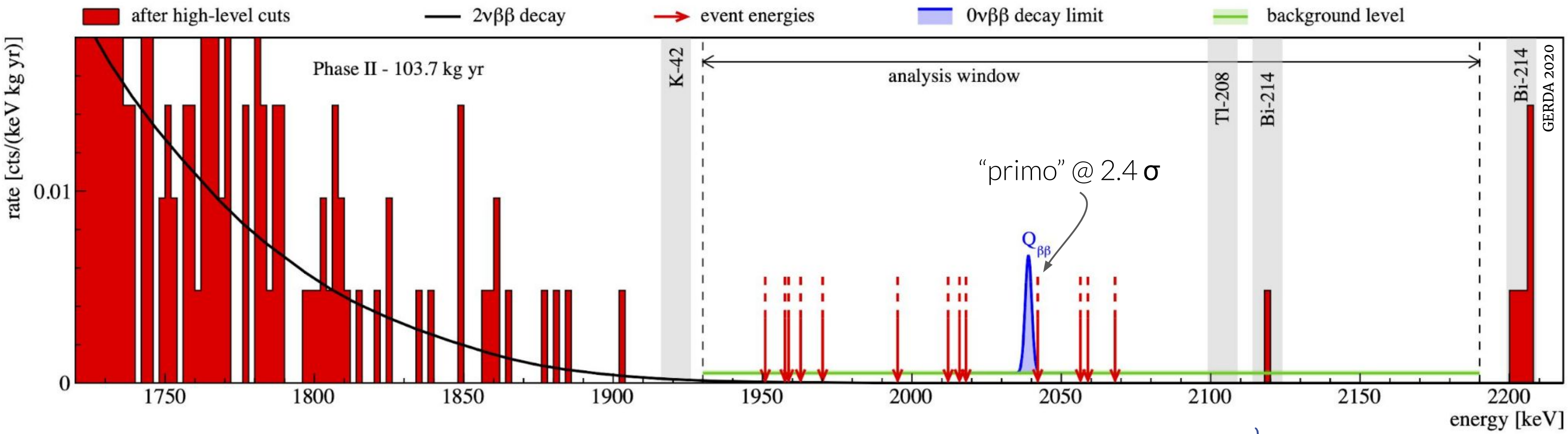
Final energy spectrum of Phase II



- Synergy between PSD and LAr veto around region of interest
  → background gets reduced to single counts in ROI

Final GERDA result on 0νββ

[Phys.Rev.Lett. 125 (2020) 25, 252502]

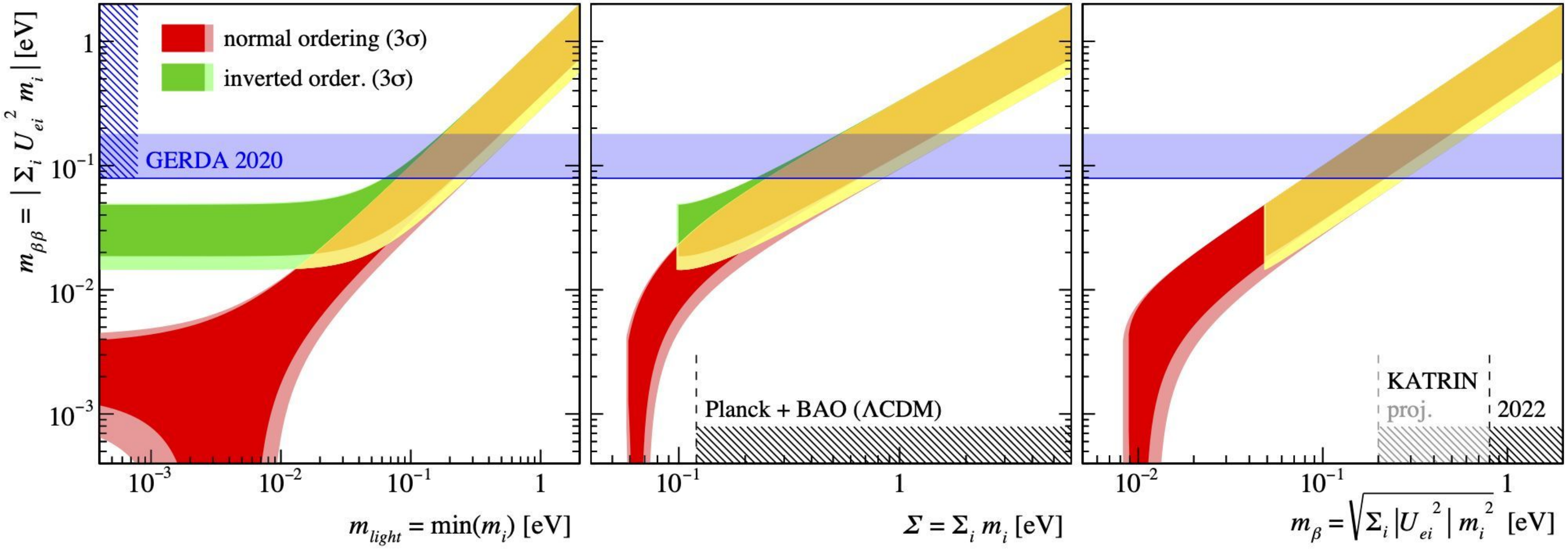


- Lowest background index in the field: **$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)** $< 10^{-3}$ cts/(keV kg yr)
- No signal observed in total exposure of **103.7 kg yr** > 100 kg yr
- Frequentist: **$T_{1/2}$ > 1.8 · 10^{26} yr** at 90% C.L. (same median sensitivity) $> 10^{26}$ yr
- $m_{\beta\beta}$ < 79 .. 180 meV

All design goals surpassed!

Mass observables

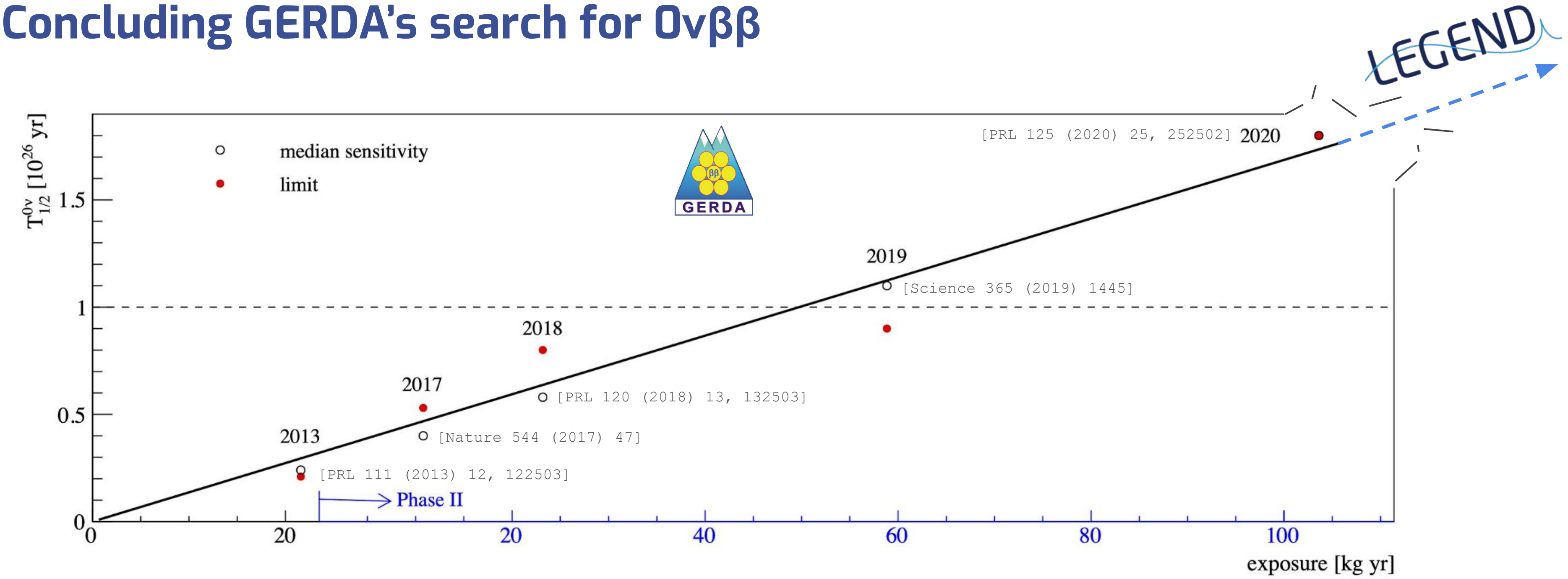
three flavour scenario [Esteban et al., JHEP 09 (2020) 178]



[Aghanin et al, Astron.Astrophys. 641 (2020) A6]
[Aker et al., Nature Phys. 18 (2022) 2]

- Given standard assumptions, 0νββ constrains neutrino mass
- Complementarity to cosmology and direct mass measurements

Concluding GERDA's search for 0νββ



- $T_{1/2}$ sensitivity scales linear to exposure due to quasi background-free regime
- GERDA is the first experiment to reach sensitivity beyond 10^{26} yr
- LEGEND will continue the search for 0**νββ** staying on the quasi background-free track

$2\nu\beta\beta$ decay study with GERDA Phase II

2vββ decay half life

- Half-life of 2**vββ** → input for nuclear structure calculations

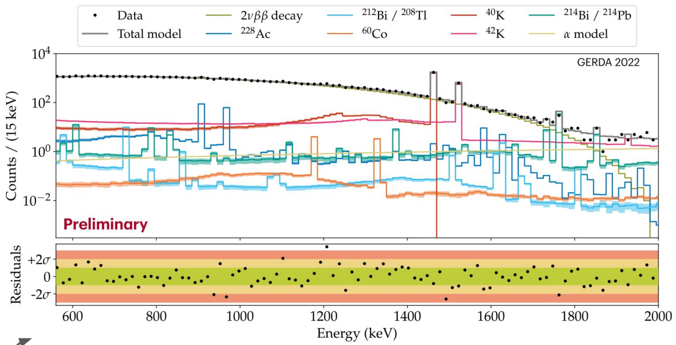
$$[T_{1/2}^{2\nu}]^{-1} = G^{2\nu}\,|\,\mathcal{M}_{eff}^{2\nu}|^2$$

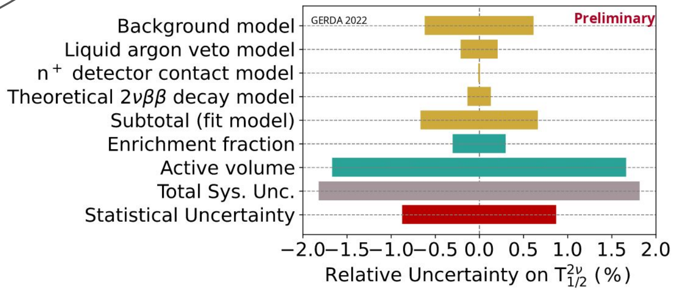
- GERDA Phase I: $T_{1/2}^{2\nu}$ =(1.926 ± 0.094) 10^{21} yr [Eur. Phys. J. C (2015)]
  Uncertainty dominated by active volume, background model and MC simulation
- Improve in Phase II: low background after LAr veto & enhanced active volume determination of BEGes
- Total uncertainty is now 2.0 %
  → most precise determination of ^{76}Ge half-life
- Final result for Phase II: **$T_{1/2}^{2\nu}$ =(2.022 ± 0.041) 10^{21} yr**
- Convert to nuclear matrix element: $|\mathcal{M}_{eff}^{2\nu}| = 0.101(1)$

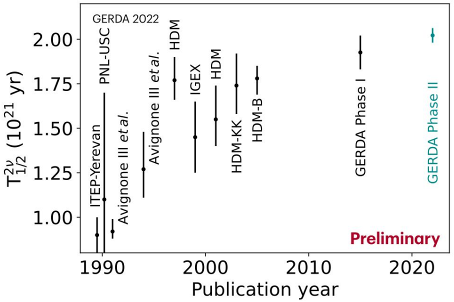
[Phase space from Phys. Rev. C 85, 034316 (2012)]

- Publication coming soon!

PRELIMINARY

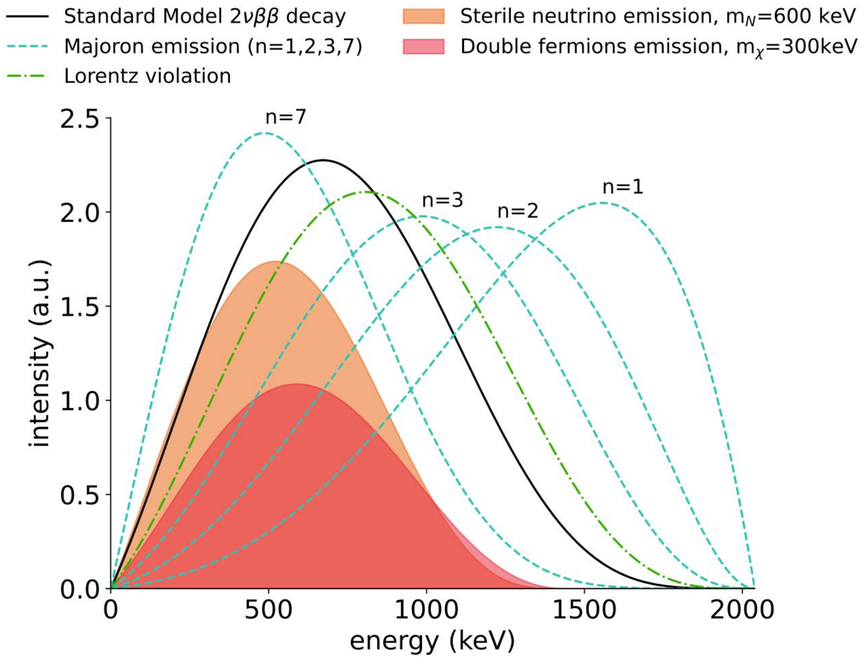


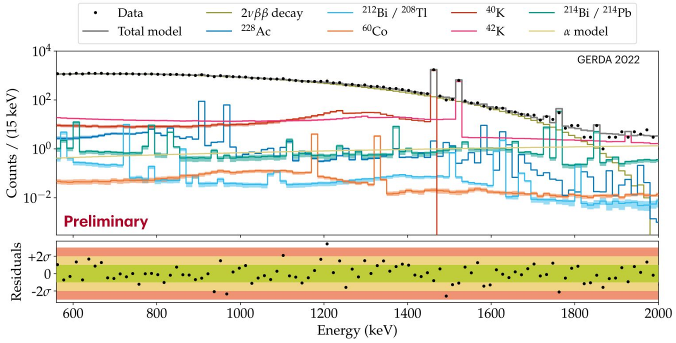




Exotic double beta decay modes

- Two ν or exotic particles emitted along both e^-
- Energy distribution of e^- continuous between 0 .. $Q_{\beta\beta}$
- Some Beyond Standard Model (BSM) physics manifest as distortions of 2νββ distribution
- Signal for new physics O(≲ 100) events
- Use 32.8 kg yr BEGe data from before upgrade
→ minimize statistical & shape systematic uncertainty
- LAr veto → "pure" 2νββ spectrum remains
- Publication in preparation





Search for Majoron-involving decays

- **(A, Z) → (A, Z+2) + 2e⁻ + J(2J)**
- Searched for ββ with emission of 1 or 2 Majorons
  → 4 models with spectral indices n = 1, 2, 3, 7
- No evidence for signal → set 90% C.L. limits
- Compute limits on half-life from limits on number of events
- Relate to neutrino-Majoron coupling constant g_J:

$$[T_{1/2}]^{-1} = g_J^{2m} \, | g_A^2 \mathcal{M}_\alpha | \, G^\alpha$$

- Improvement by factor ~2 compared to GERDA Phase I result
- Results comparable with limits from other ββ decay isotopes

Preliminary

Decay mode	$T_{1/2}$ (yr) Sensitivity	$T_{1/2}$ (yr) Observed limit	Observed g_J
$J\beta\beta$ ($n=1$)	$3.5\cdot10^{23}$	$> 6.4\cdot10^{23}$	$< (1.9-4.4)\cdot10^{-5}$
$J\beta\beta$ ($n=2$)	$2.5\cdot10^{23}$	$> 2.9\cdot10^{23}$	–
$J\beta\beta$ ($n=3$)	$1.3\cdot10^{23}$	$> 1.2\cdot10^{23}$	< 0.017
$JJ\beta\beta$ ($n=3$)	$1.3\cdot10^{23}$	$> 1.2\cdot10^{23}$	< 1.2
$JJ\beta\beta$ ($n=7$)	$5.8\cdot10^{22}$	$> 1.0\cdot10^{23}$	< 1.1

Phase space from [Phys. Rev. C 91 (2015), p. 64310],
NMEs from [Phys. Rev. C 103 (2021), arXiv:2202.01787]

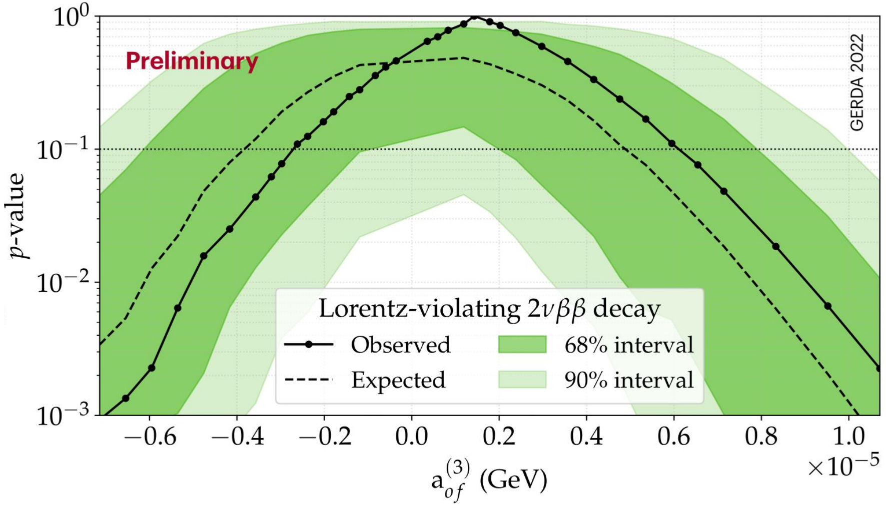
Results on the search for Lorentz violation

- **(A, Z) → (A, Z+2) + 2e⁻ + 2$\bar{\nu}_{LV}$**
- Counter-shaded operators of Lorentz- and CPT-violating Standard Model Extensions $a_{of}^{(3)}$ undetectable via **ν** oscillation or time-of-flight
- Energy distribution of 2**νββ** affected by isotropic component $\mathring{a}_{of}^{(3)}$
→ introducing additional decay rate ∝ $\mathring{a}_{of}^{(3)}$
- No evidence of deviation from SM distribution
→ set positive and negative limits on $\mathring{a}_{of}^{(3)}$

Preliminary

Sensitivity	Observed Limit
(-3.8 < $\mathring{a}_{of}^{(3)}$ < 4.9) 10^{-6} GeV	(-2.7 < $\mathring{a}_{of}^{(3)}$ < 6.2) 10^{-6} GeV

Phase space ratio to combine SM distribution and LV perturbation from [Phys. Rev. D 103, L031701]



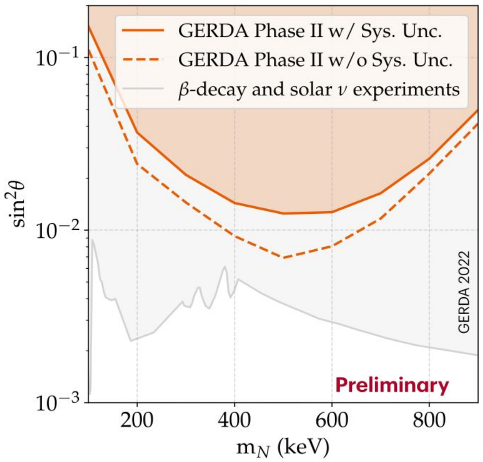
- First constraints with ^{76}Ge
- Comparable with limits from other **ββ** isotopes
- 30% impact on limit due to systematics estimated

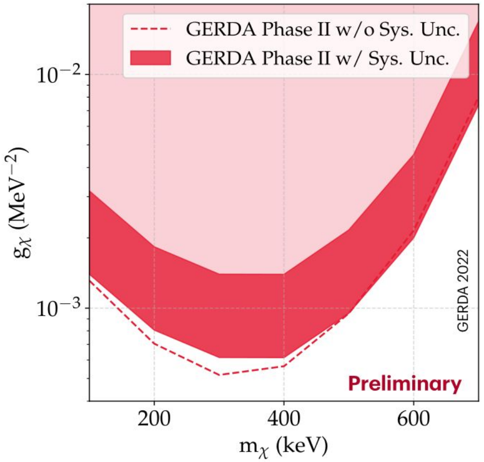
Search for light exotic fermions

- Sterile Neutrinos (N): **(A, Z) → (A, Z+2) + 2e⁻ + $\bar{\nu}$ + N**
- Z_2-odd fermions (χ): **(A, Z) → (A, Z+2) + 2e⁻ + 2χ**

[Phys.Rev.D 103 (2021) 5, 055019, Phys. Lett. B 815 (2021)]

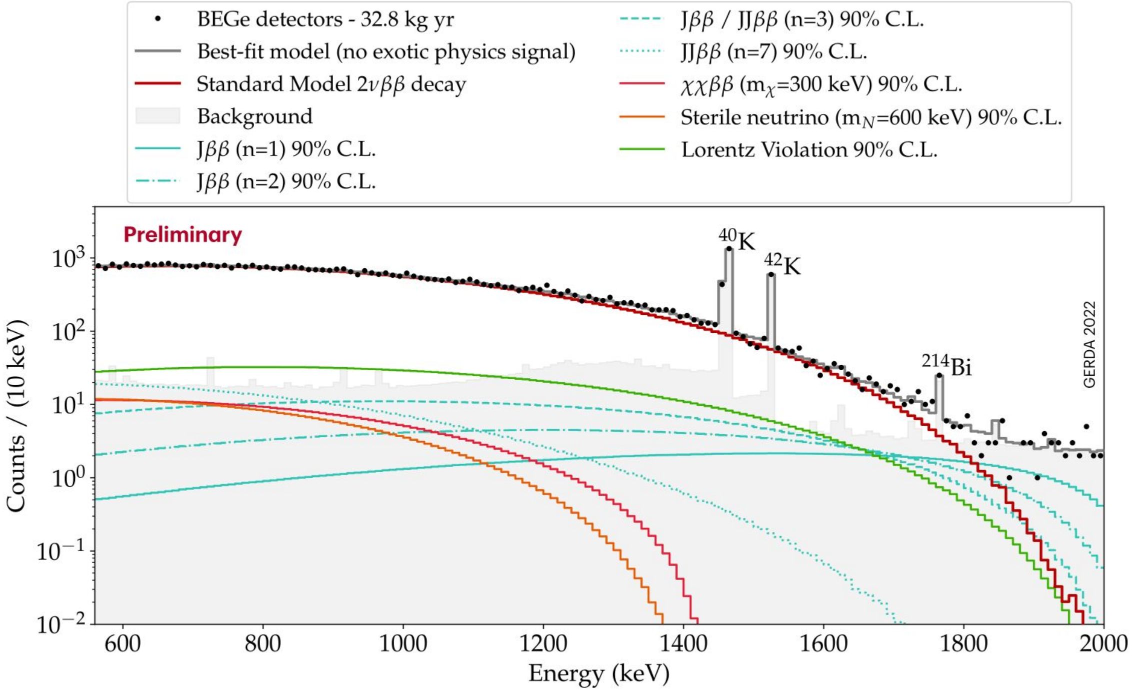
- Emission of exotic fermions in **ββ** decay with masses < $Q_{\beta\beta}$
  → Endpoint of distribution shifted by particle mass
- Searched for masses between 100 and 900 keV
  → No evidence for signal; set limits at 90% C.L.
- First experimental constraints on light exotic fermions in 2**νββ** decay
- Though single-**β** constraints more stringent, pair production of exotic fermions only testable in **ββ** decay



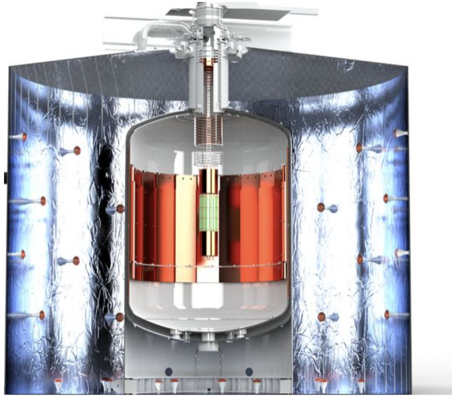


Wrapping up the search for exotic physics in GERDA

- No indication for deviation from SM 2νββ decay found
- Limits at 90% C.L.:



Conclusions



- GERDA searched for 0**νββ** in quasi background-free regime
- Data taking finished in November 2019, all design goals surpassed
- No 0**νββ** found → Limit at $T_{1/2} > 1.8 \cdot 10^{26}$ yr at 90% C.L. set
- Demonstrated quasi background-free operation with HPGe technology in LAr
  → paved the way for next generation 0**νββ** search in LEGEND
- Result on ^{76}Ge 2**νββ** half-live with unprecedented precision: $T_{1/2}^{2\nu} = (2.022 \pm 0.041)\ 10^{21}$ yr PRELIMINARY
  PUBLICATION COMING SOON!
- No indication for exotic physics
  → set limits on Majoron-involving decays, Lorentz violation and light exotic fermions
  PUBLICATION COMING SOON!