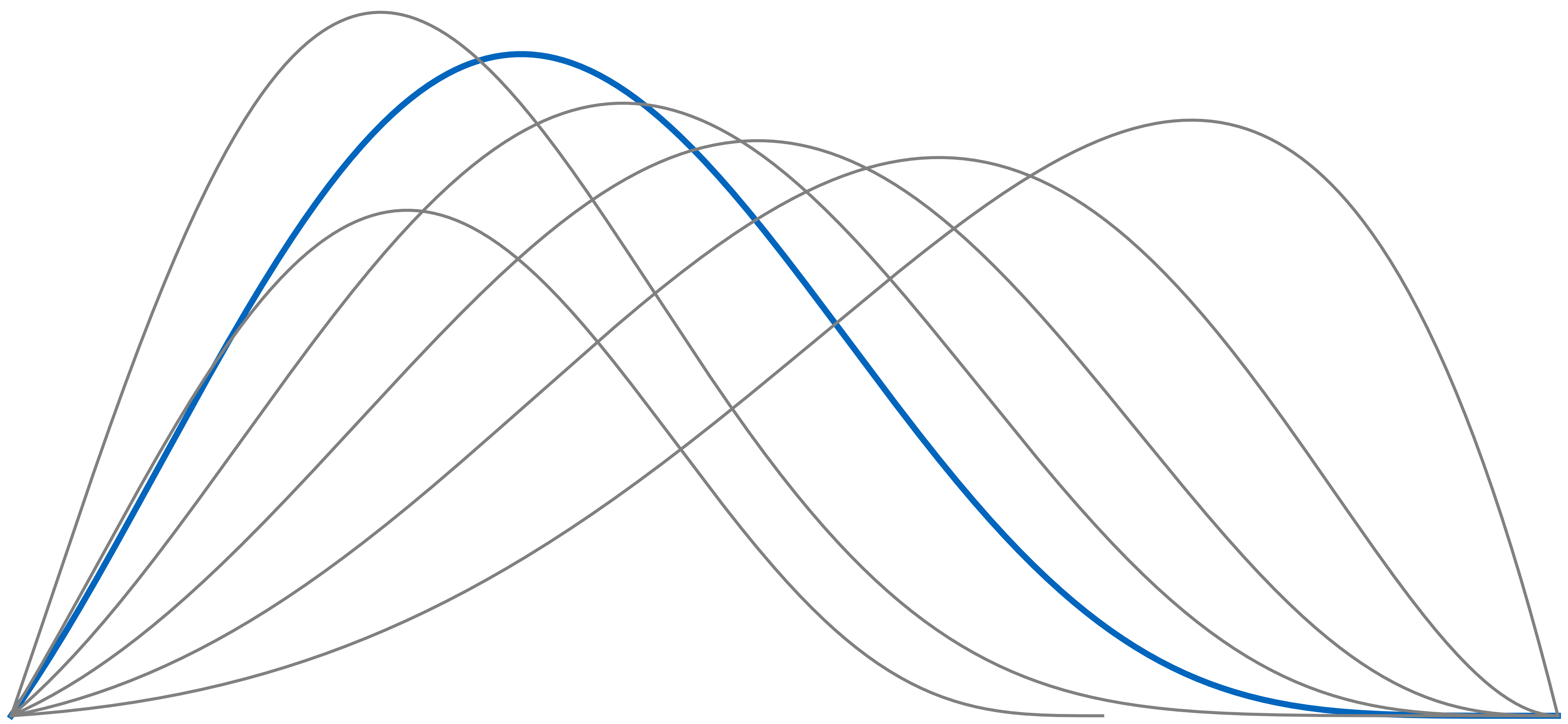
The ^{76}Ge double-β decay with neutrinos and exotic decay modes: new results from GERDA Phase II



Elisabetta Bossio (Technical University Munich)

International School of Nuclear Physics, 43rd Course: Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

Erice, Sicily, September 16-22, 2022

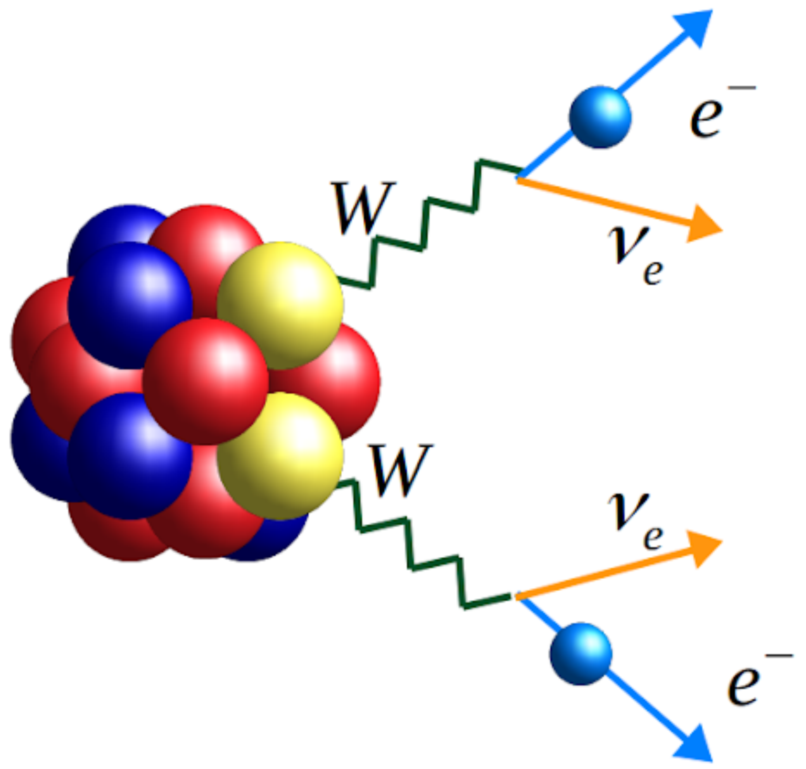
Double-β decays

In the Standard Model

- Allowed with the emission of two electrons and two anti-neutrinos ($2\nu\beta\beta$ decay)

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

- Observed in several isotopes, half-life of the order 10^{18}-10^{21}



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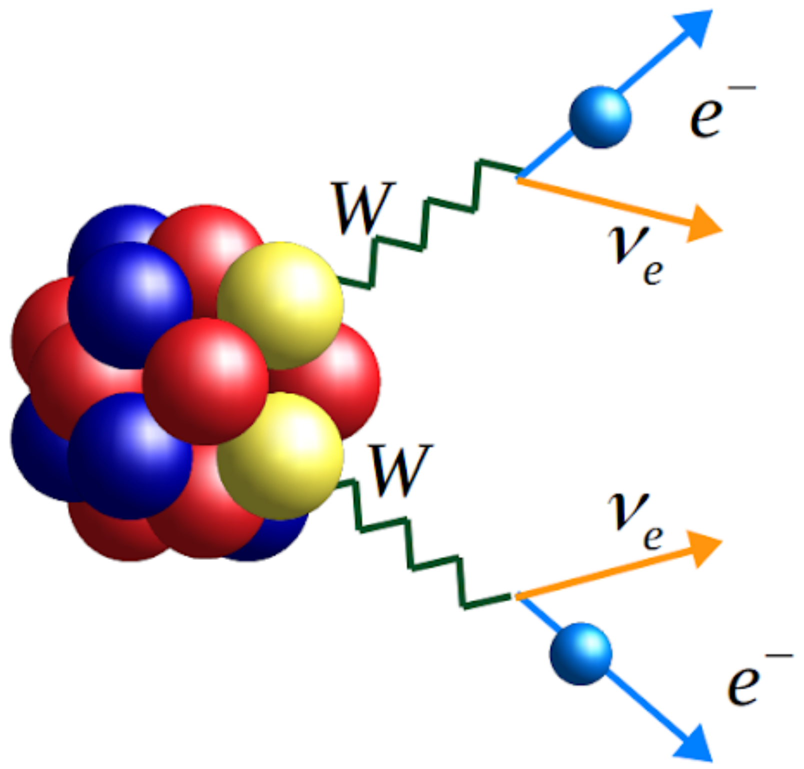
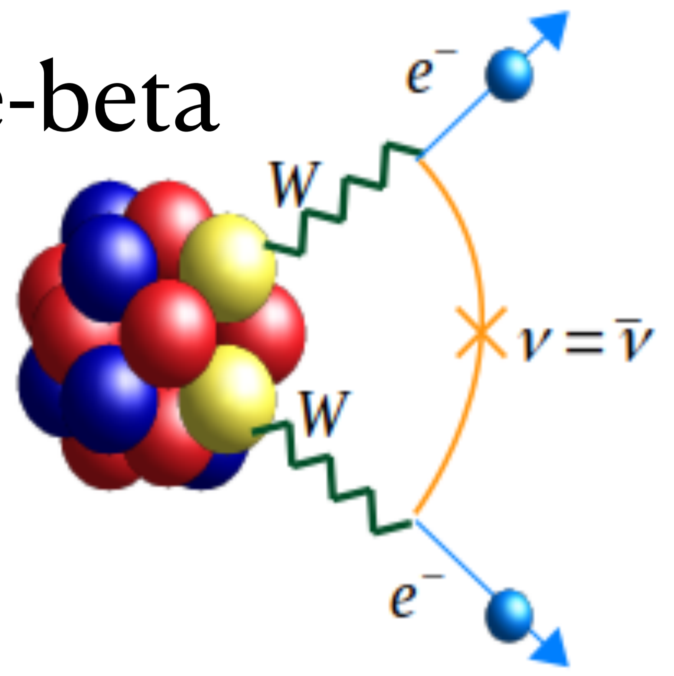


- **Majorana neutrinos & Lepton number violation**
- Neutrino-less double-beta ($0\nu\beta\beta$) decay

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



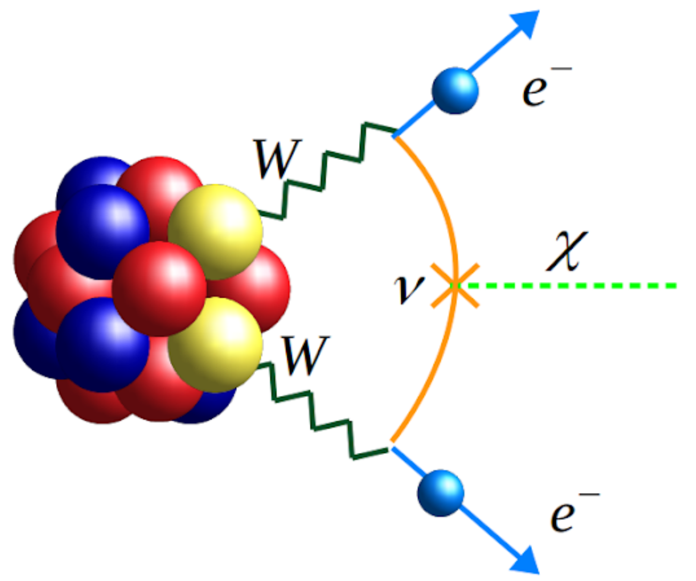
- Alternative channels, i.e. 0νECEC

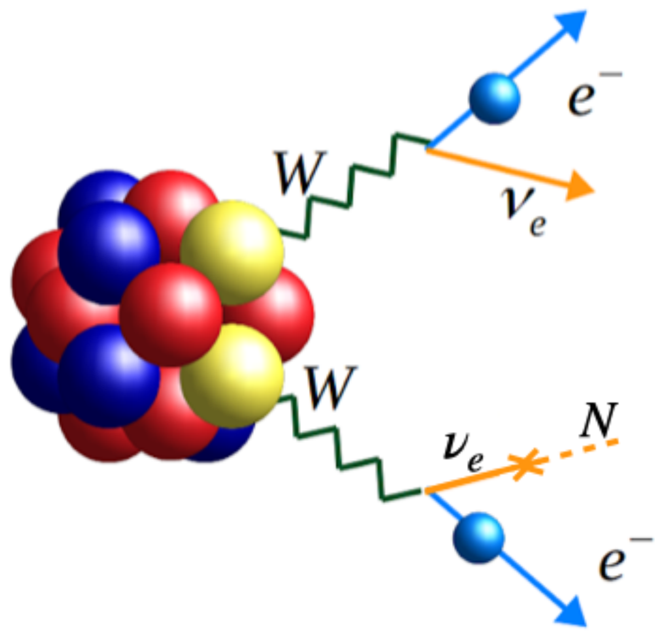
- **Violation of Lorentz and CPT symmetries** can manifest in $2\nu\beta\beta$ decay

Beyond the Standard Model

- Existence of **new particles** with a coupling to neutrinos
- Decays with Majorons, light exotic fermions (sterile neutrinos and Z2-odd fermions)

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





- And many others: bosonic neutrinos, right-handed currents, neutrino self-interactions…

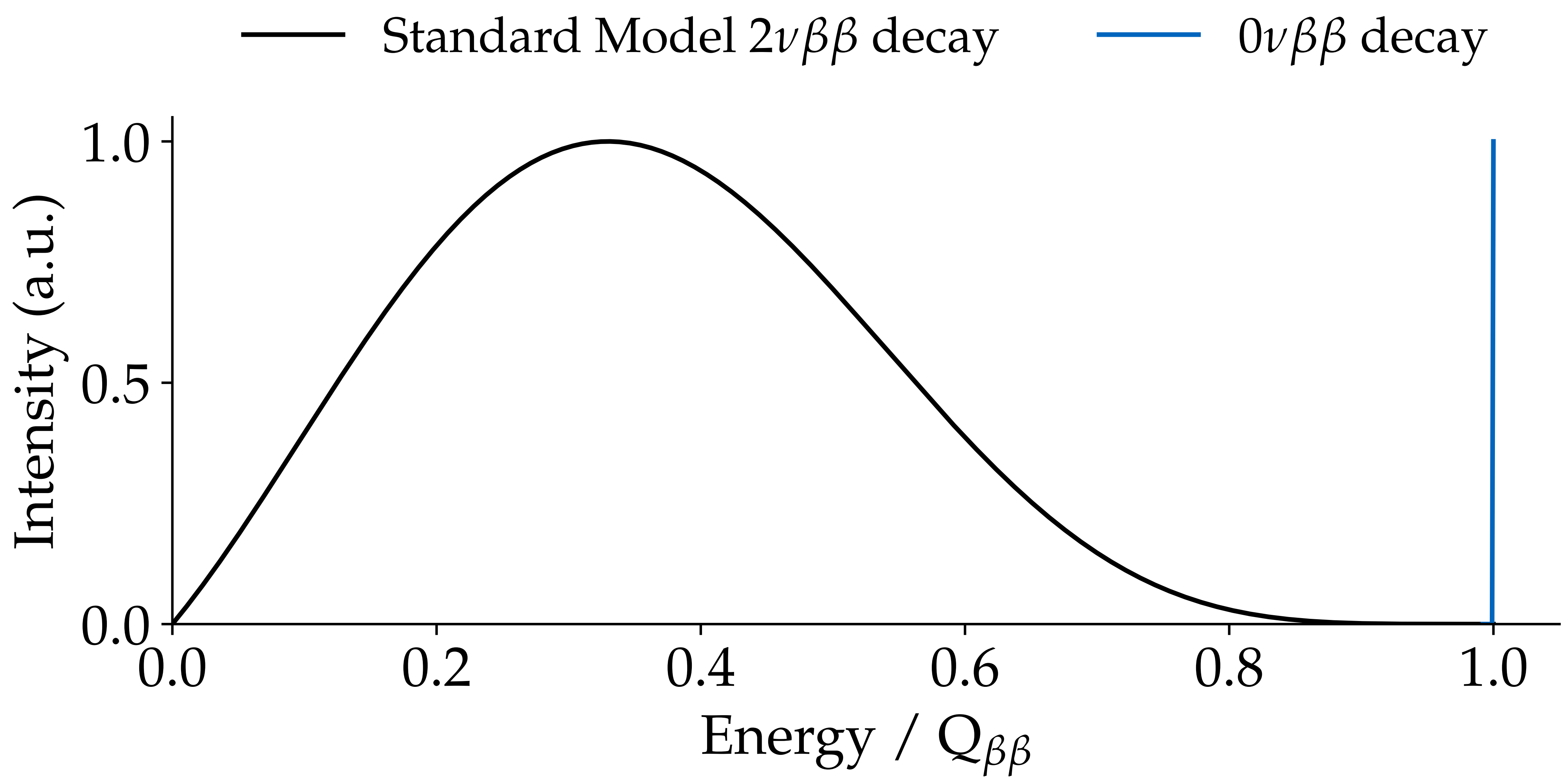
The $2\nu\beta\beta$ decay energy spectrum

Experiments measure the sum energy of the two electrons

- Rate of $2\nu\beta\beta$ decay events ∝ decay half-life

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

Provide inputs for nuclear-structure calculations



The $2\nu\beta\beta$ decay energy spectrum

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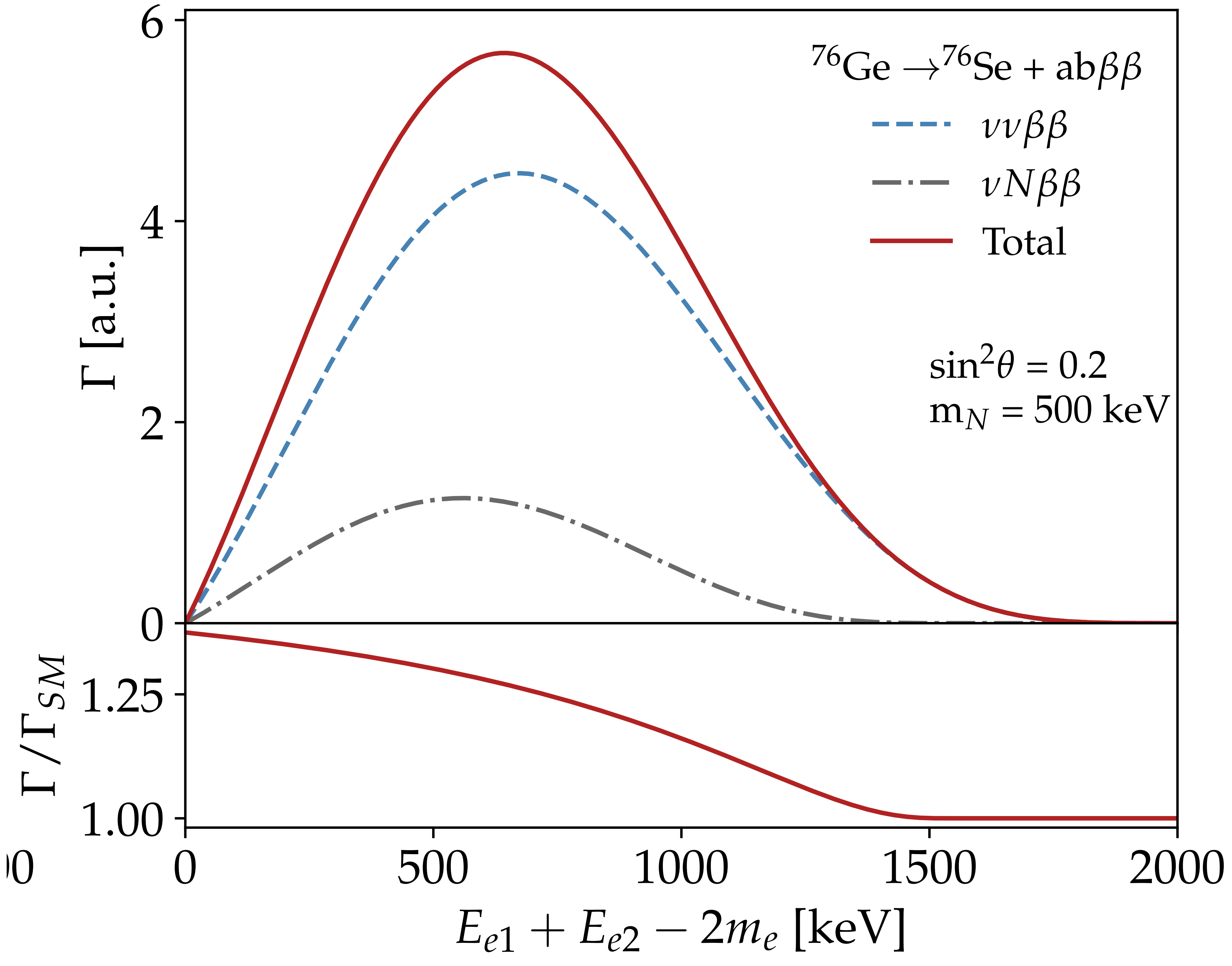
$$[T^{2\nu}_{1/2}]^{-1} = G^{2\nu} \, | \mathscr{M}^{2\nu}_{eff} |^2$$

→ Provide inputs for nuclear-structure calculations

- Shape of the $2\nu\beta\beta$ decay distribution

→ We can search for hints for new physics

[Phys. Lett. B 815 (2021)]

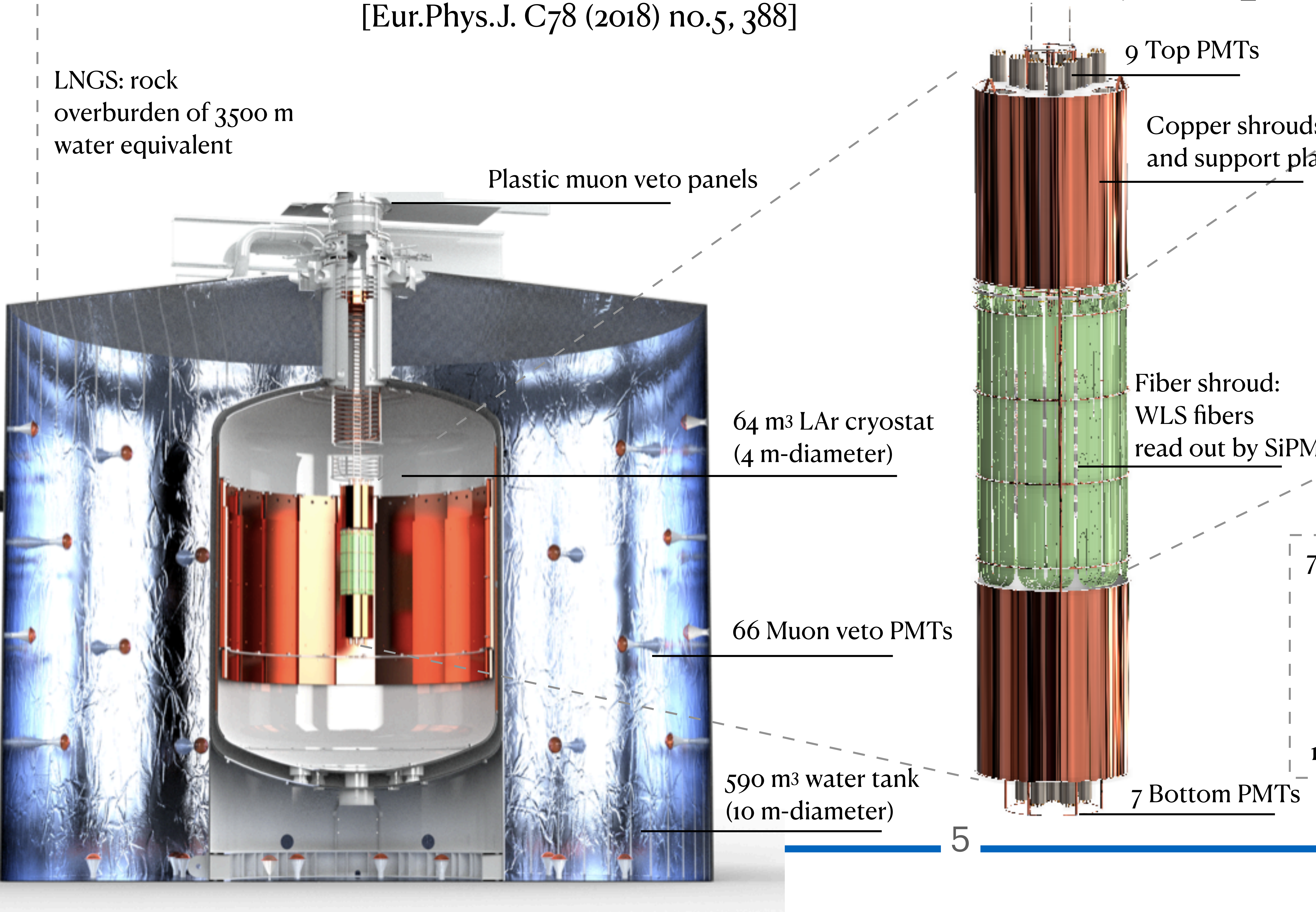


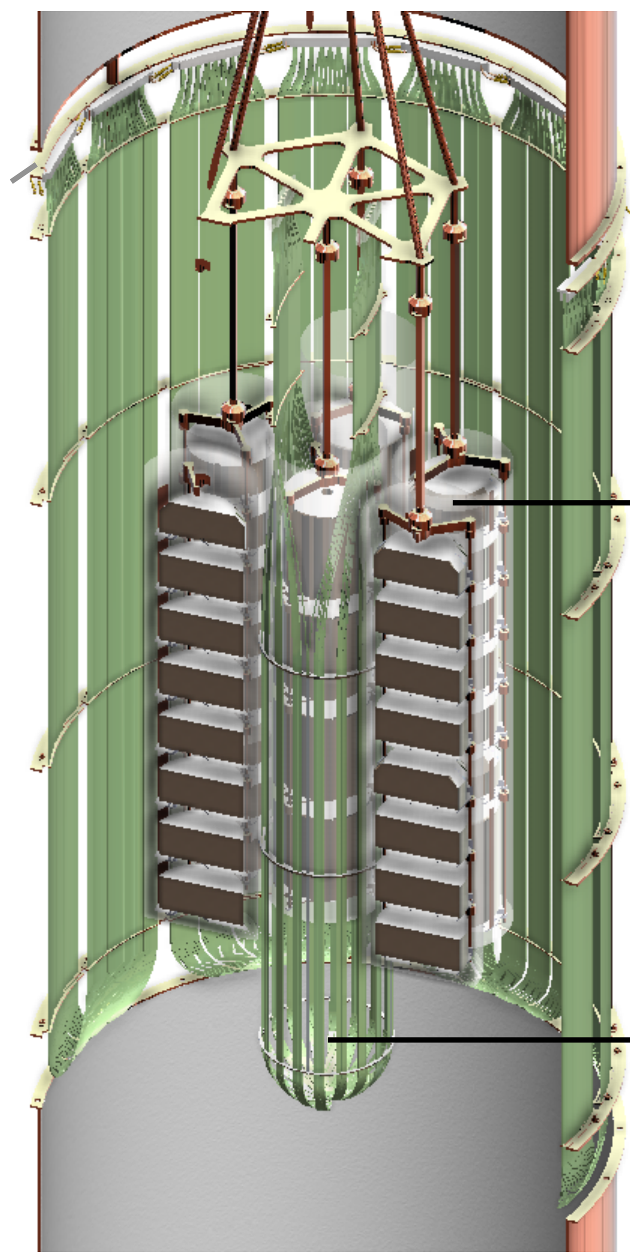
The GERDA experiment

The GERmanium Detector Array experiment at LNGS

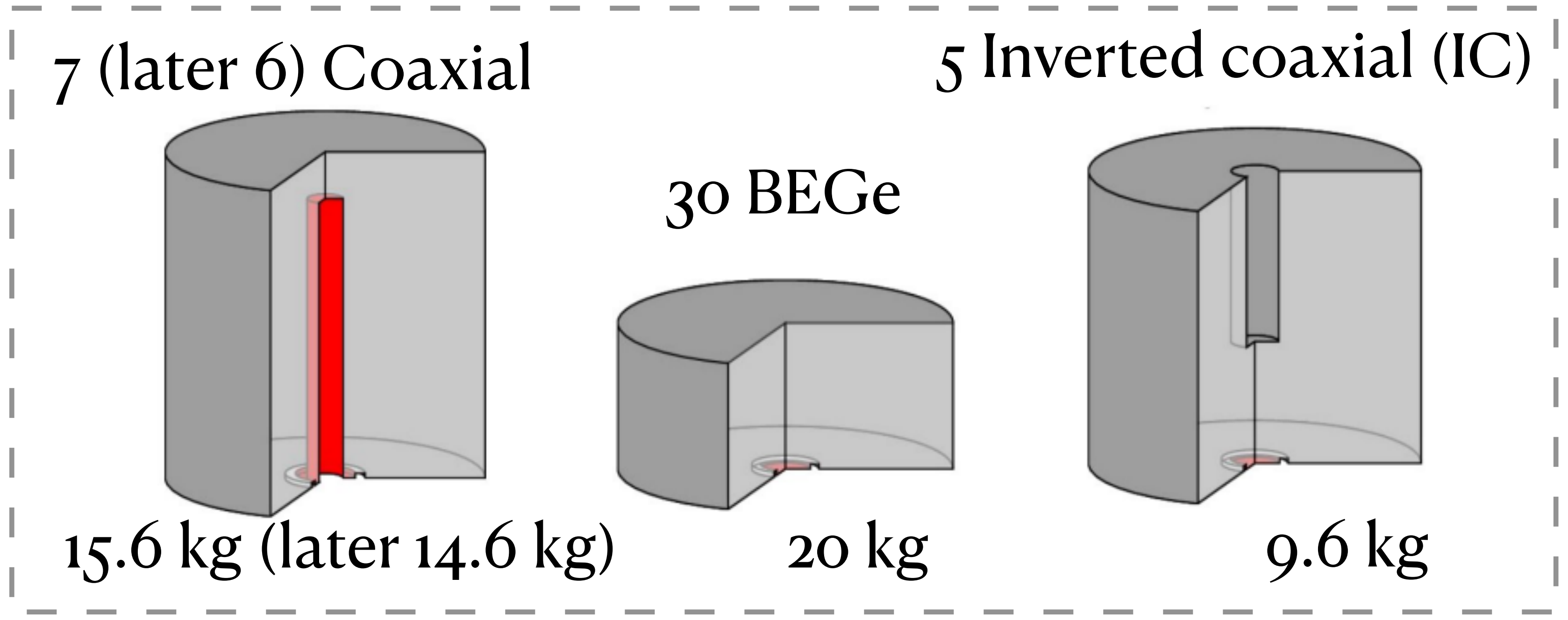
[Eur.Phys.J. C78 (2018) no.5, 388]

LNGS: rock overburden of 3500 m water equivalent



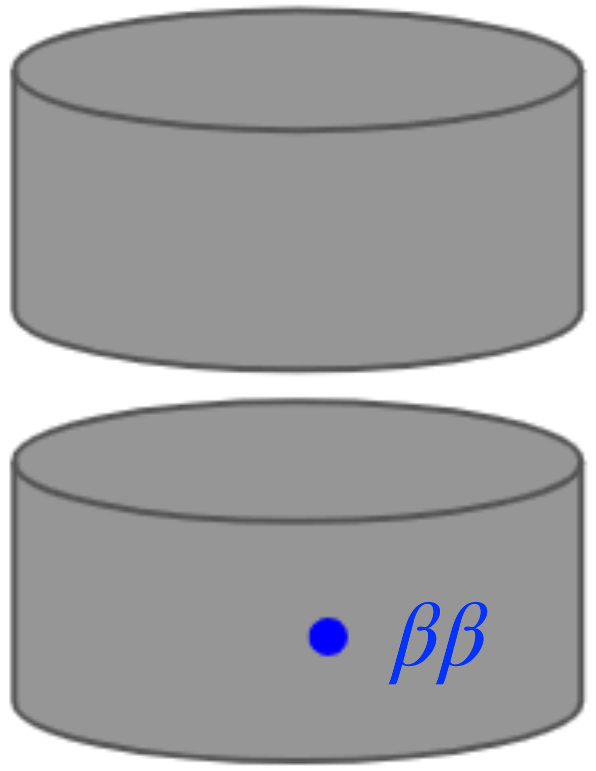


HPGe detectors enriched in ^{76}Ge



Background discrimination by event topology

Double-beta decays: Single-site & single-detector



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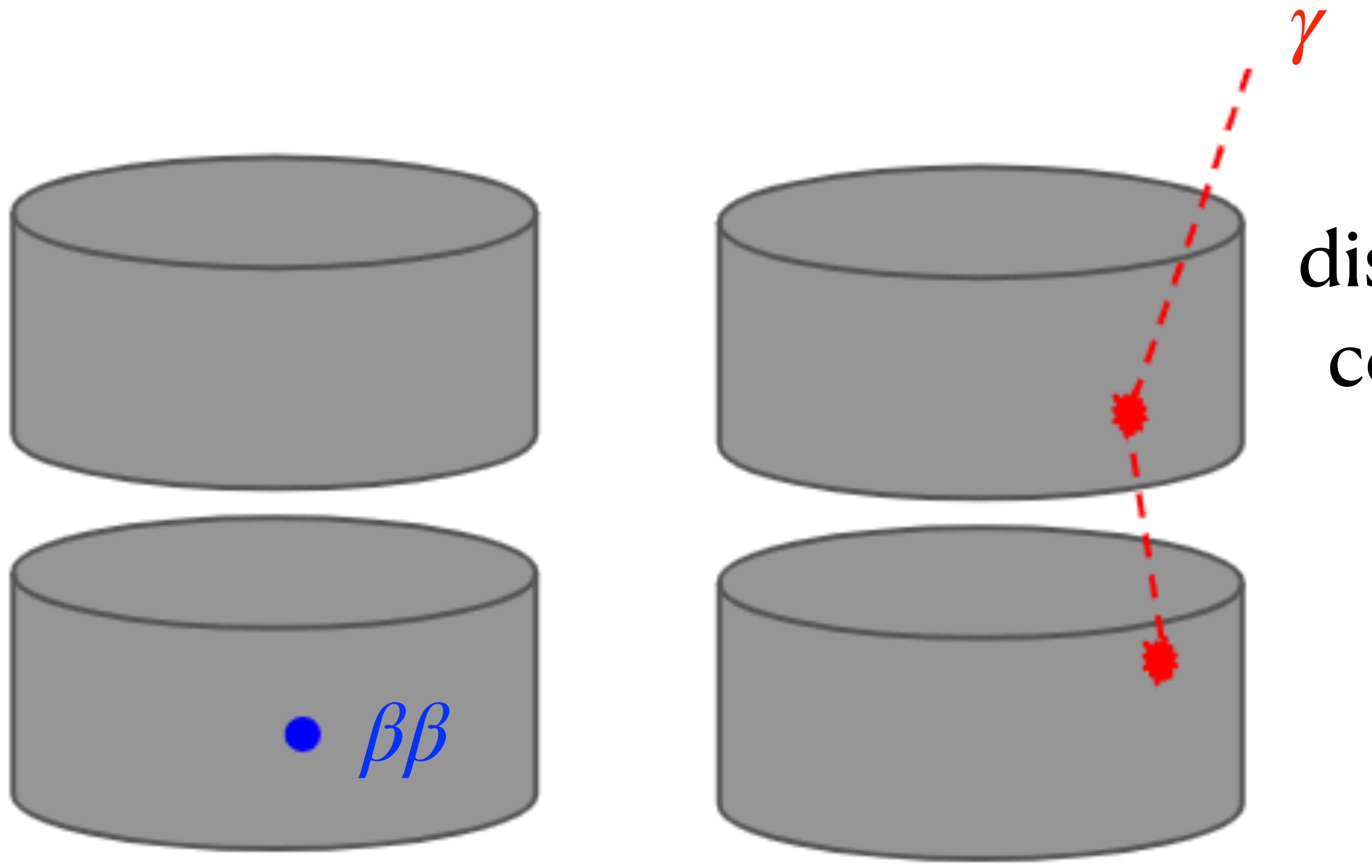

Detector-detector coincidences: discrimination by anti-coincidence (AC) cut

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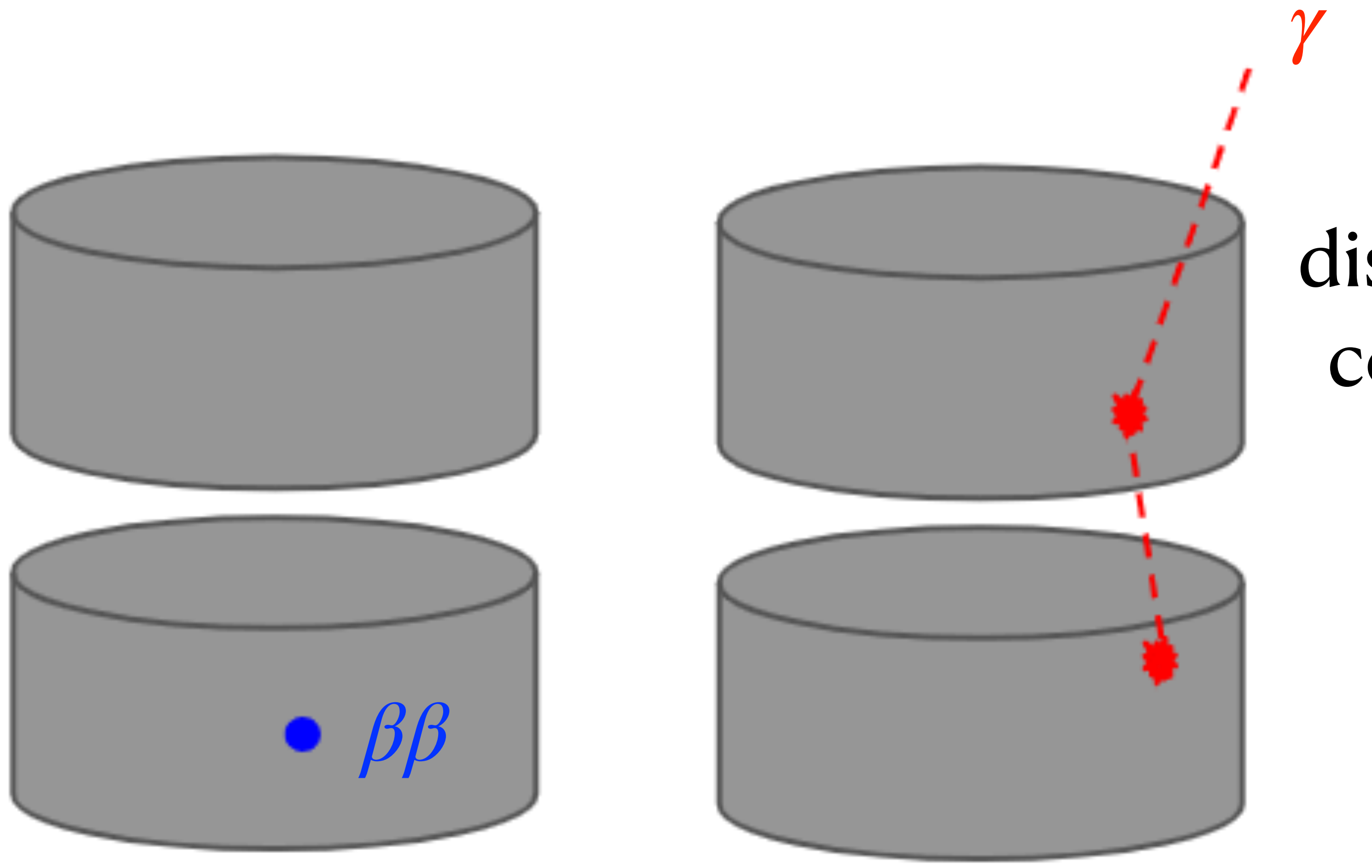
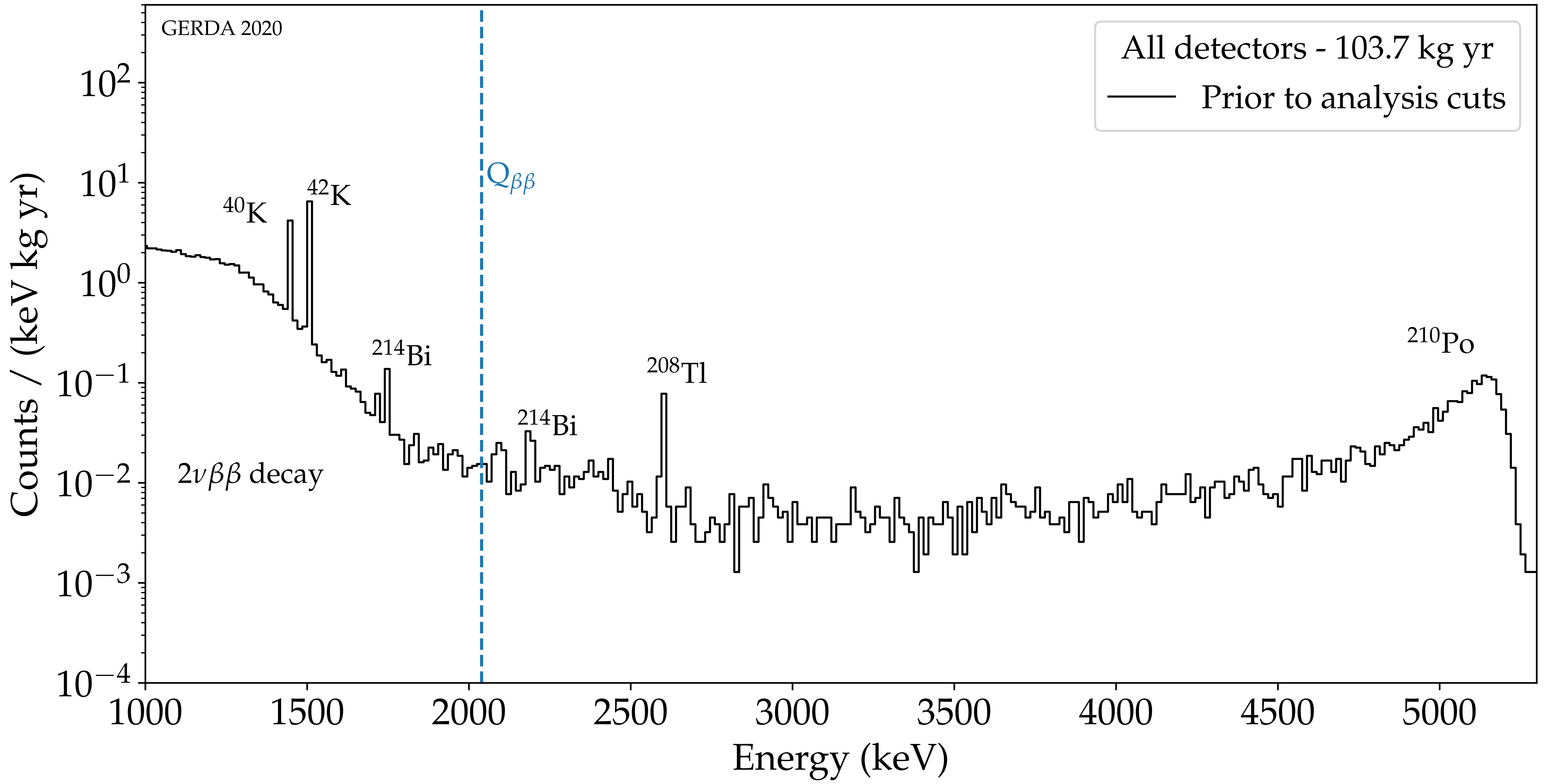


Detector-detector coincidences: discrimination by anti-coincidence (AC) cut

After AC cut only



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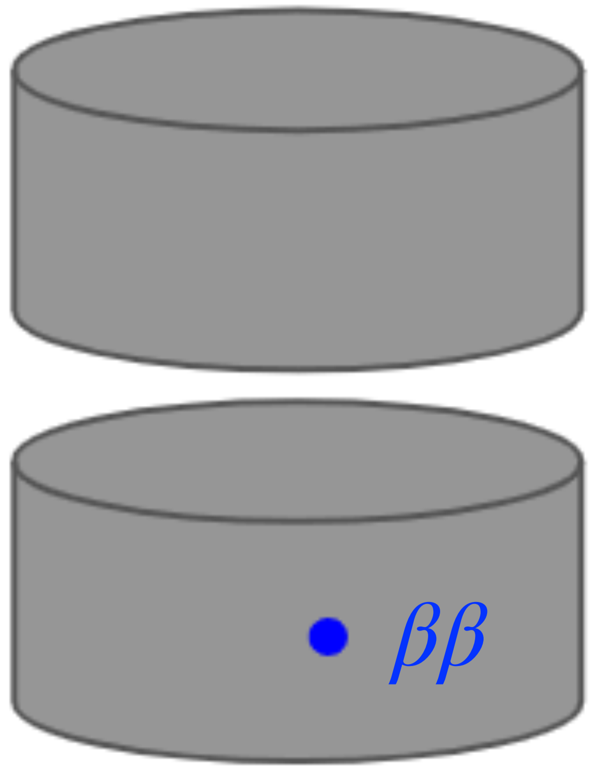

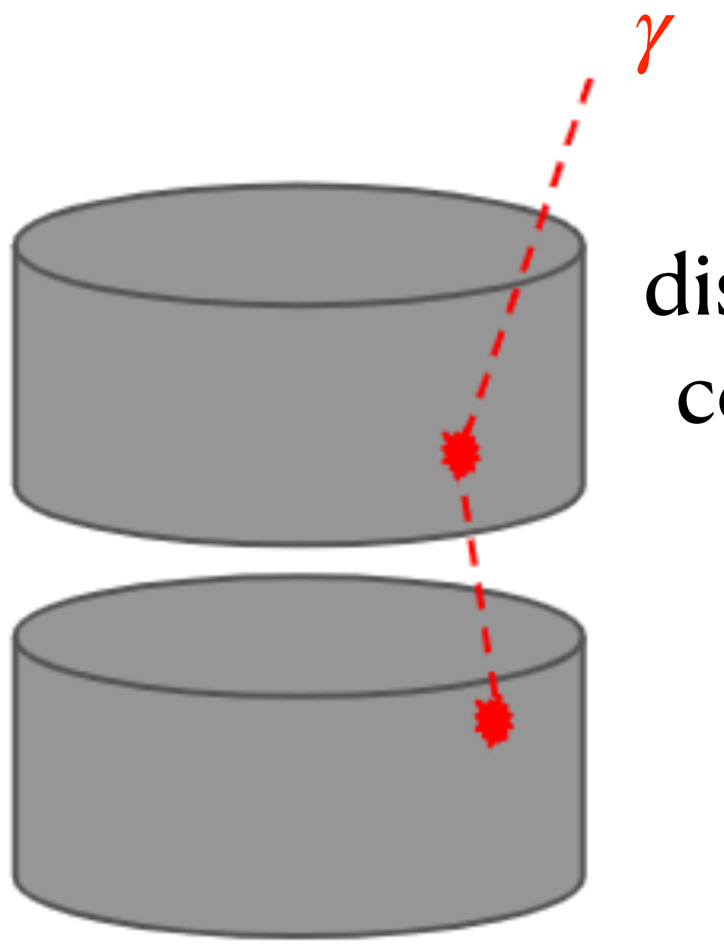

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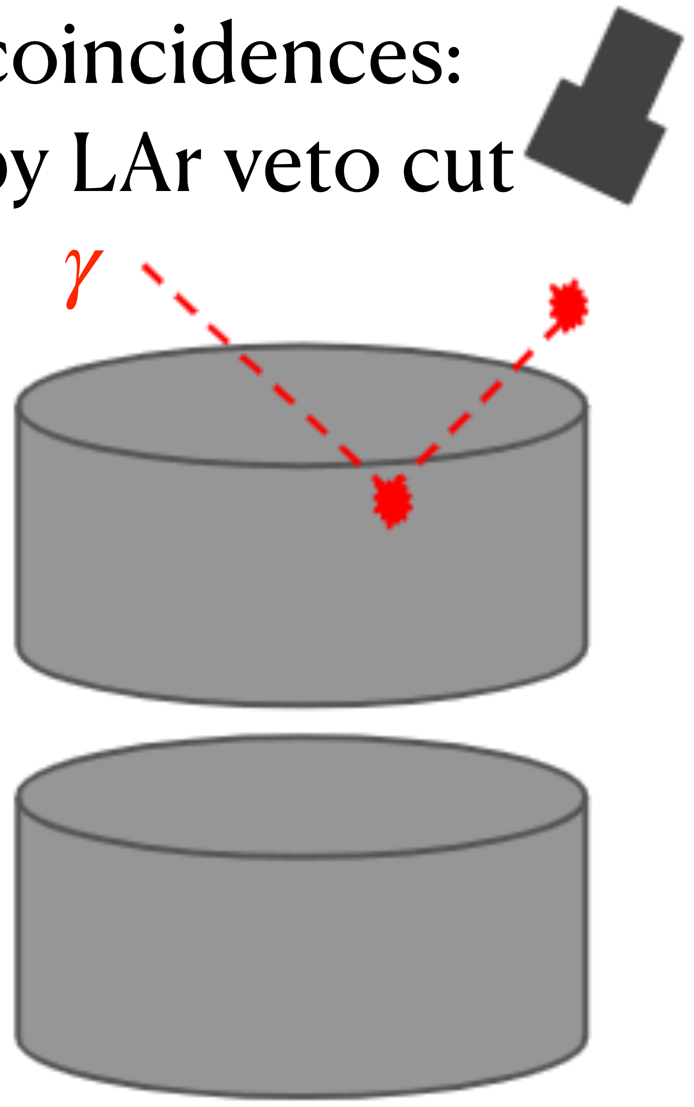
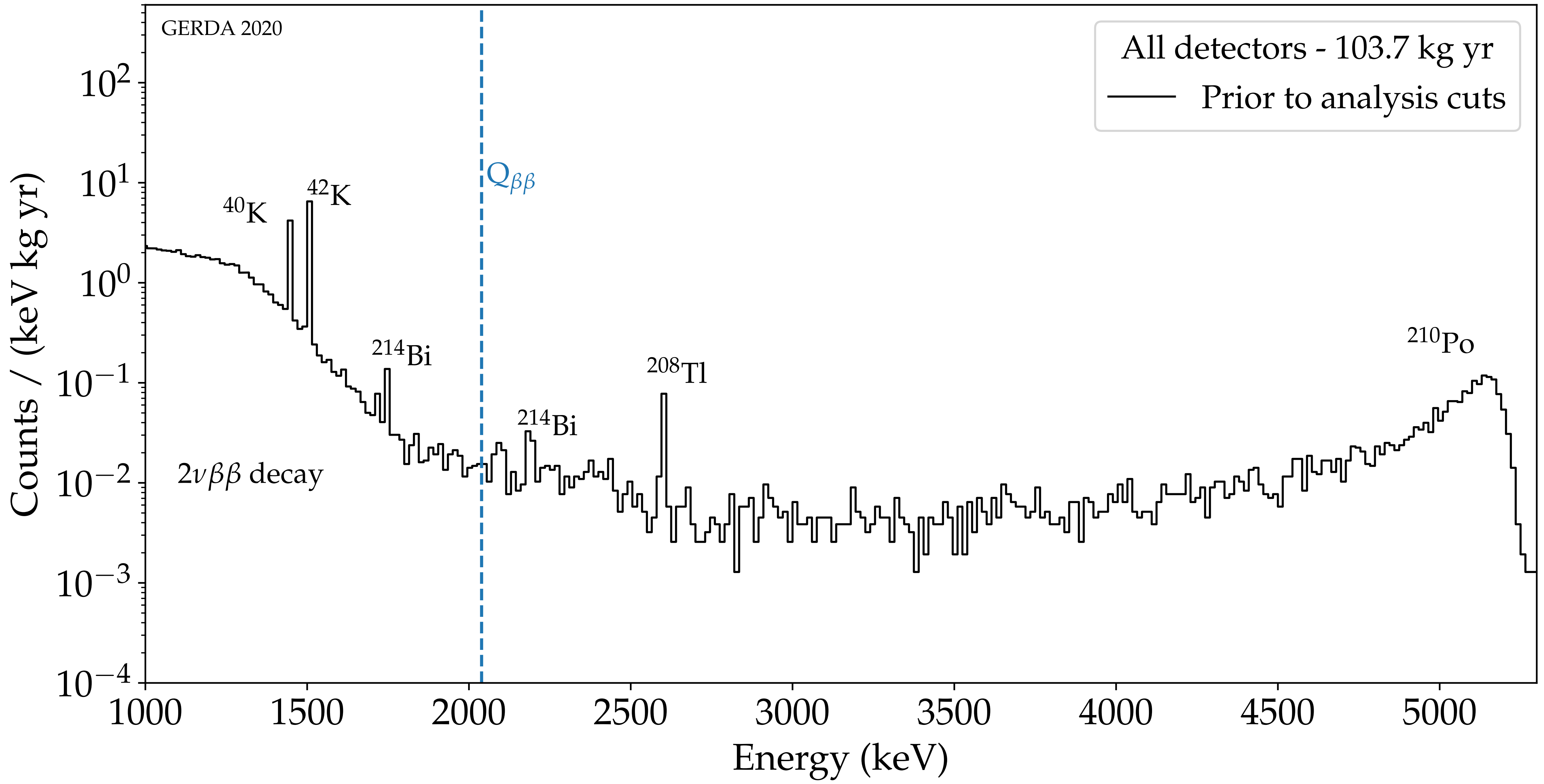
Detector-LAr coincidences: discrimination by LAr veto cut



After AC cut only



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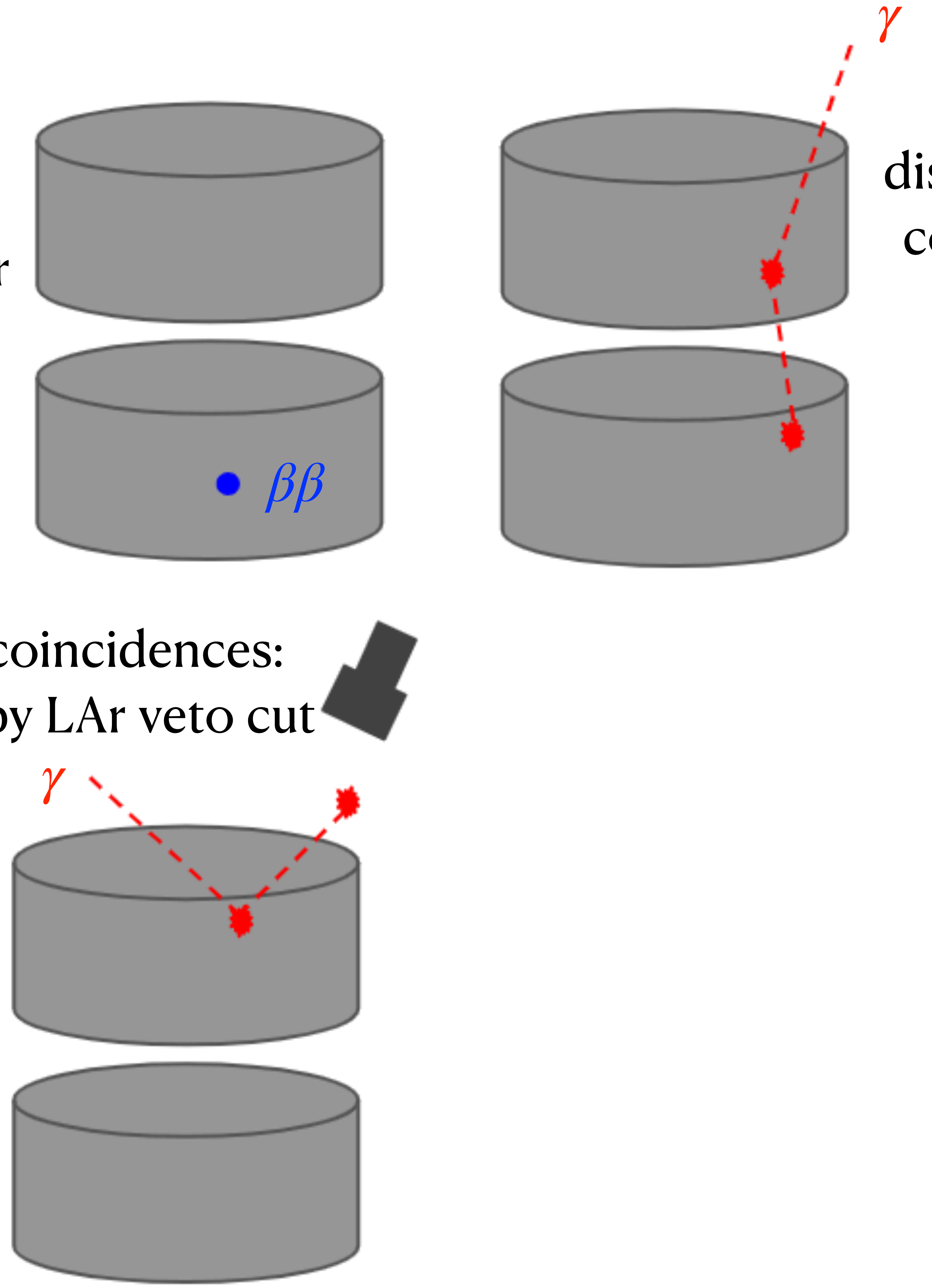
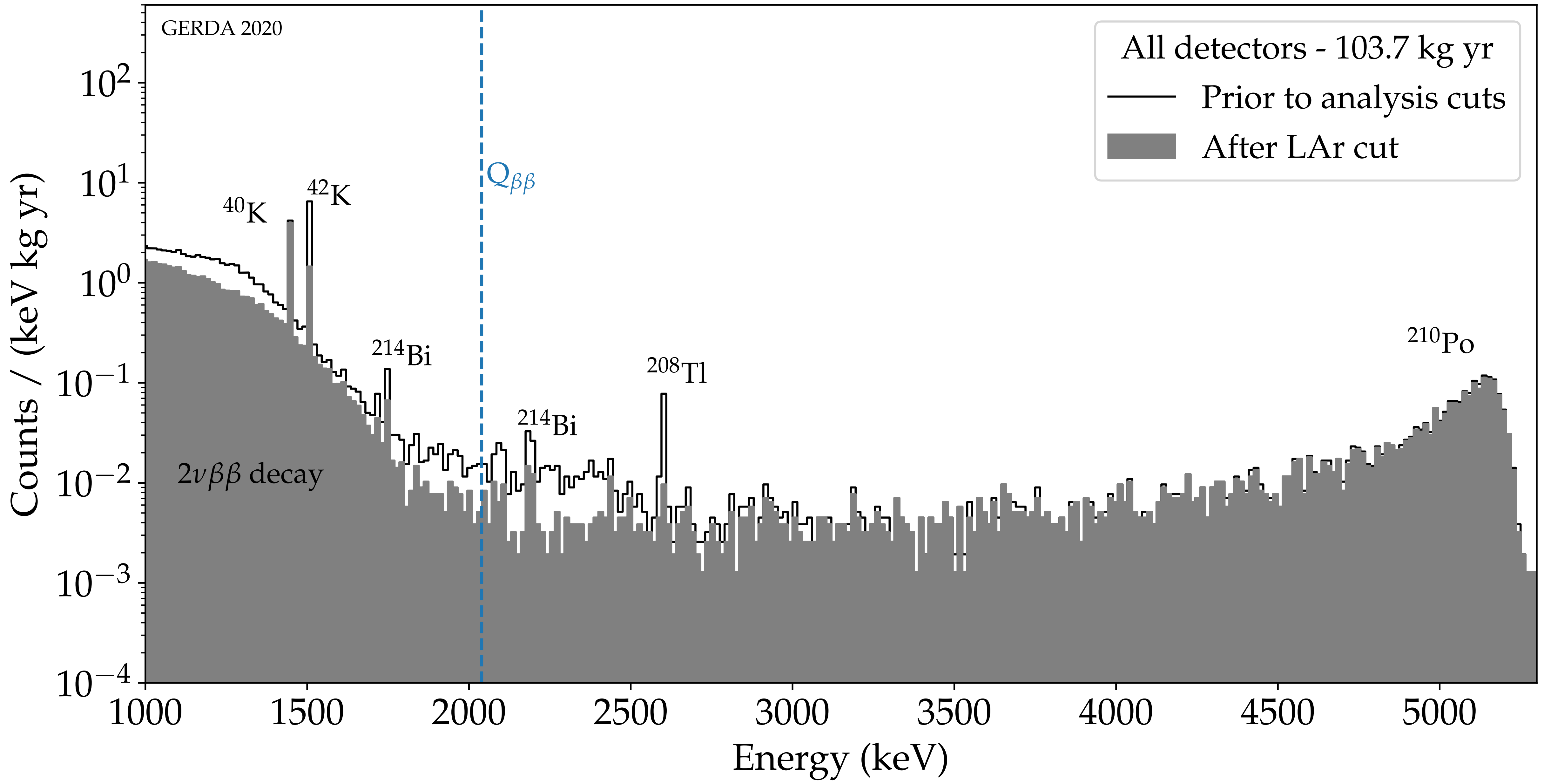


After AC and LAr veto cuts



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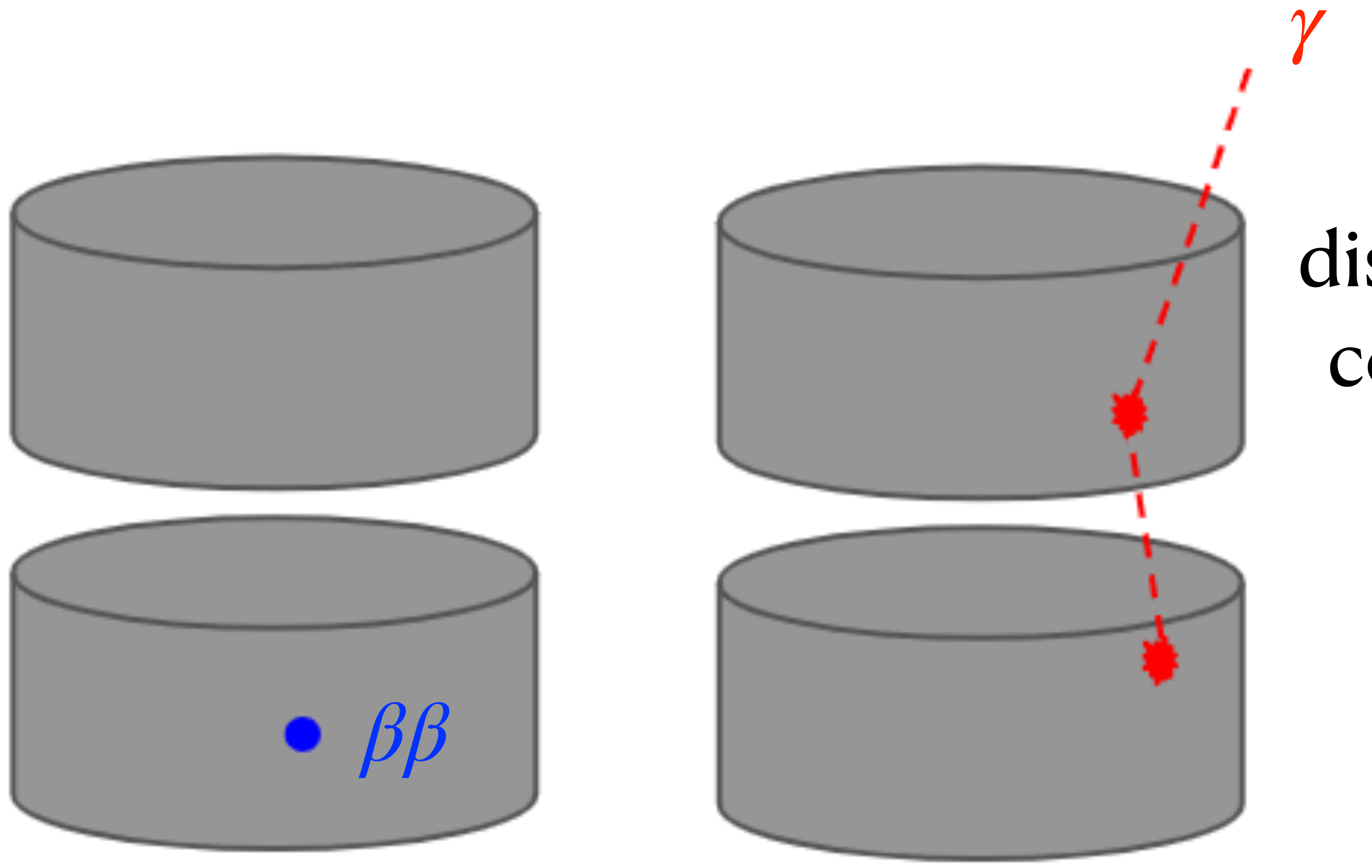

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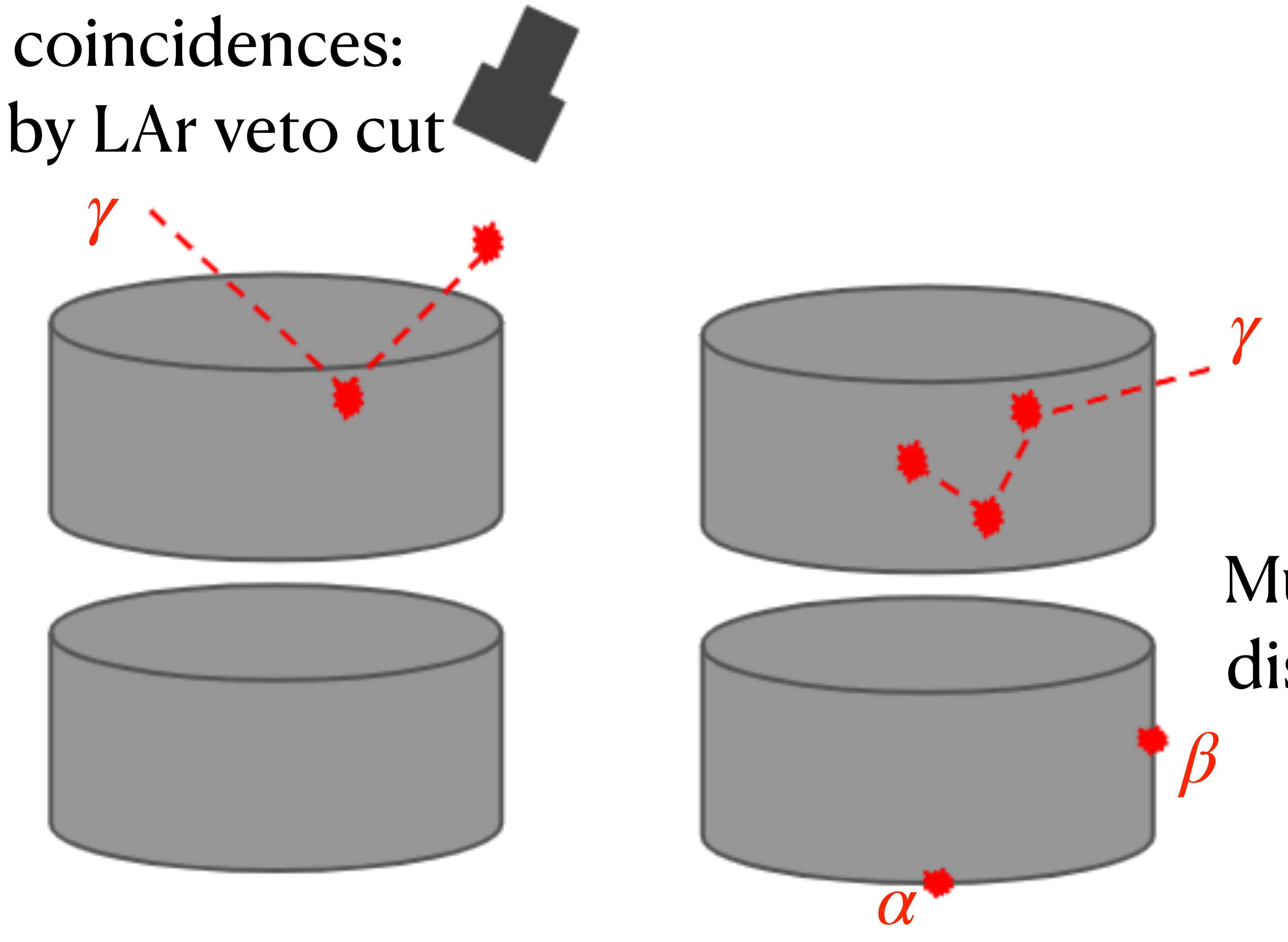
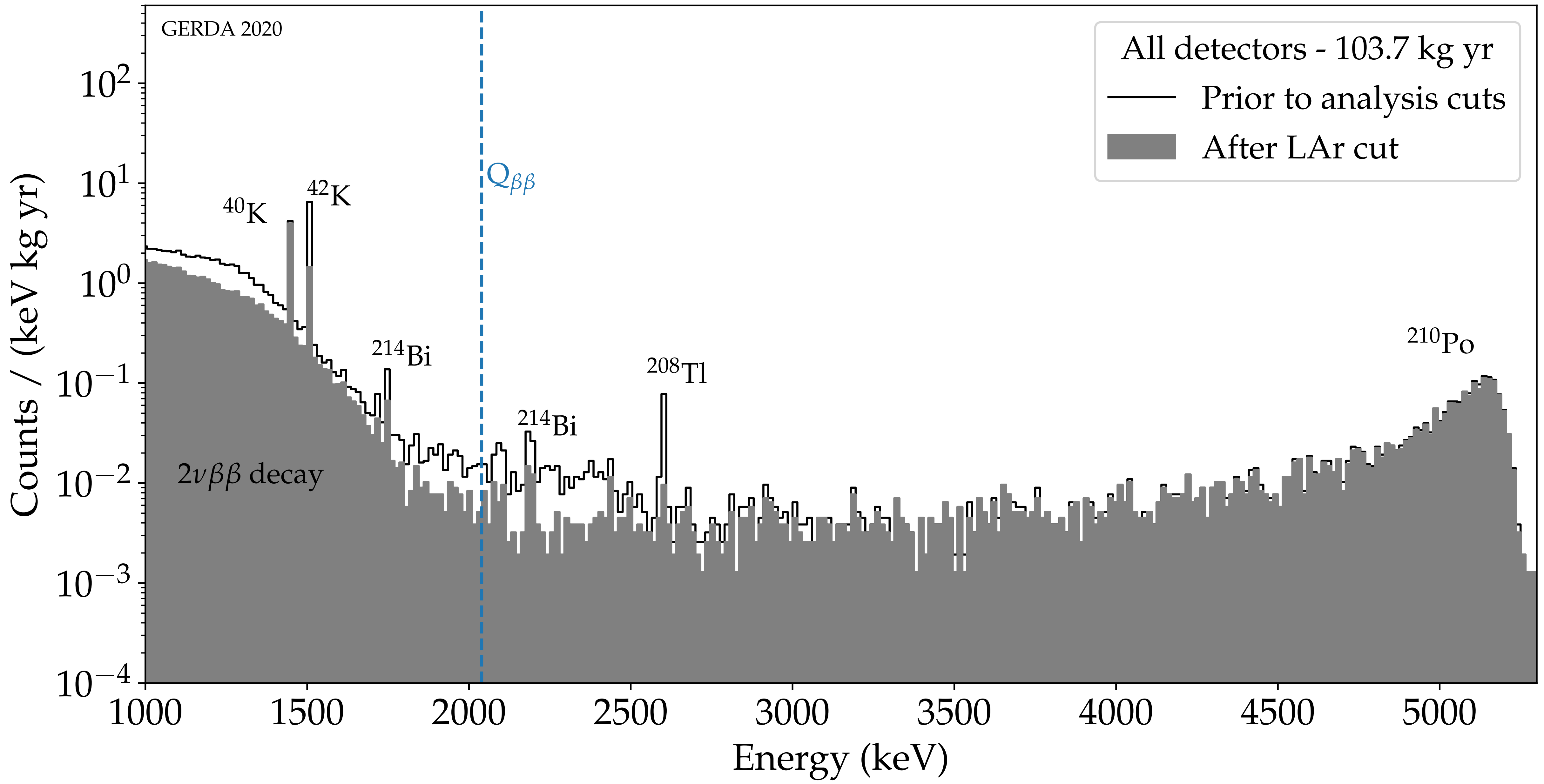


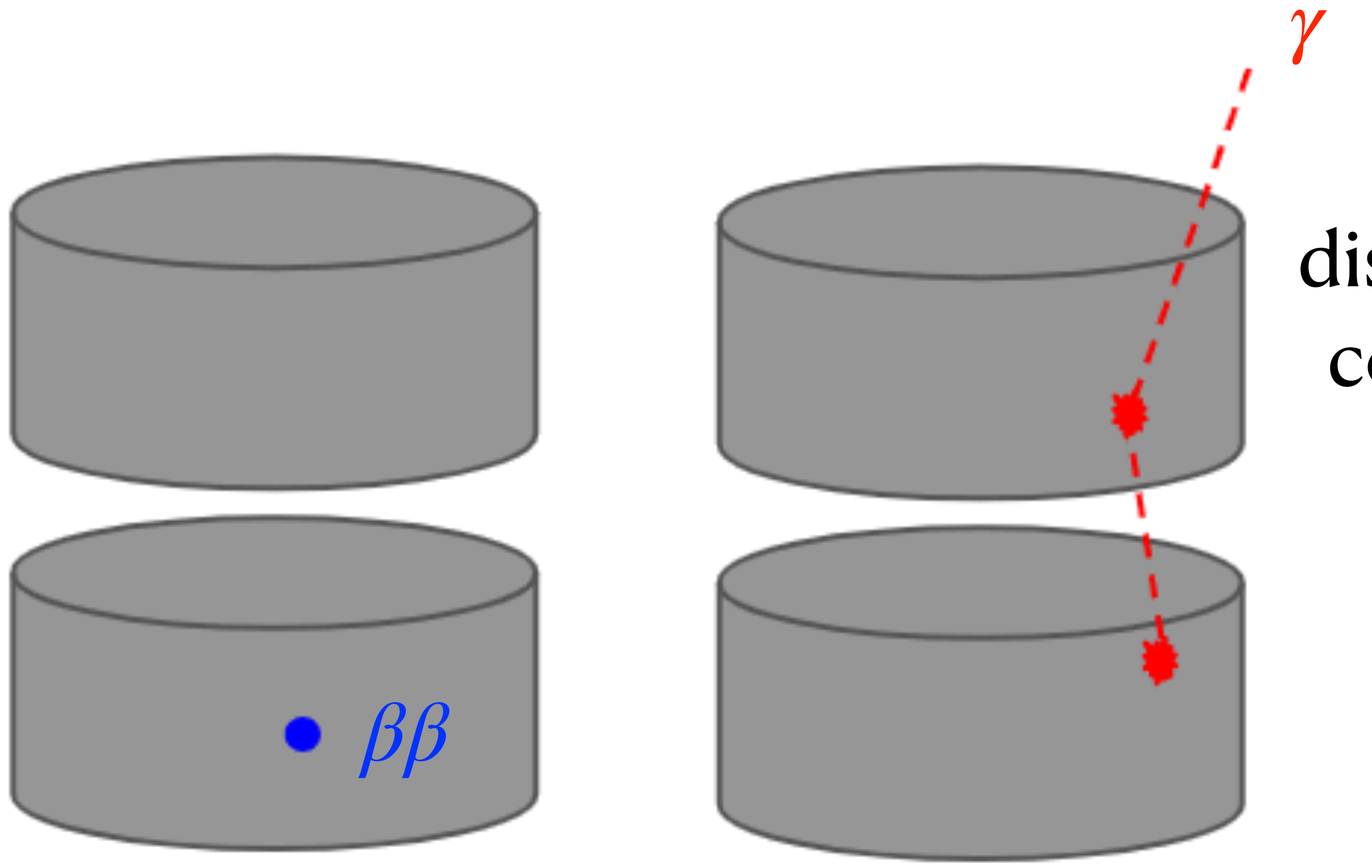
Multi-site / surface events: discrimination by PSD cut

After AC and LAr veto cuts



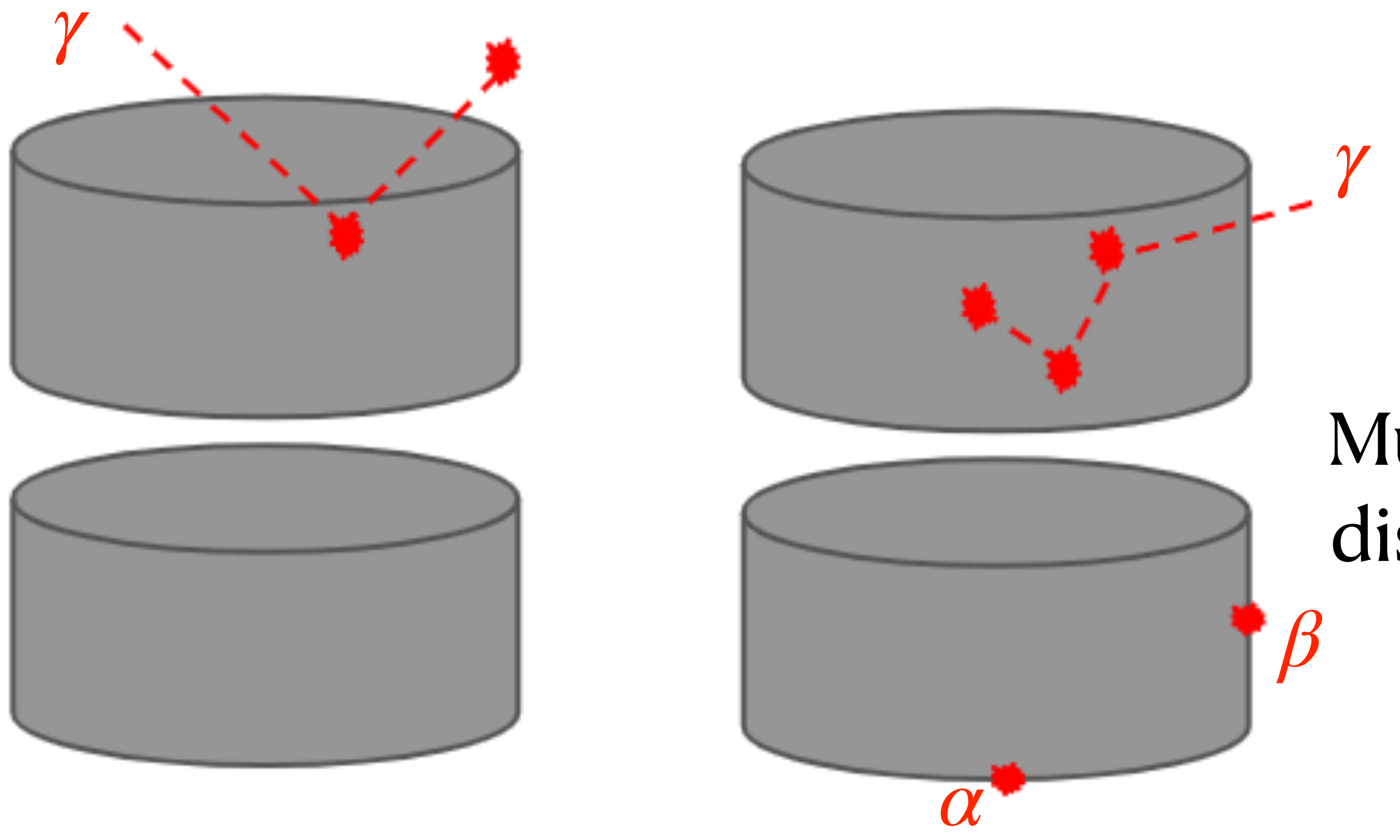
Background discrimination by event topology

Double-beta decays: Single-site & single-detector



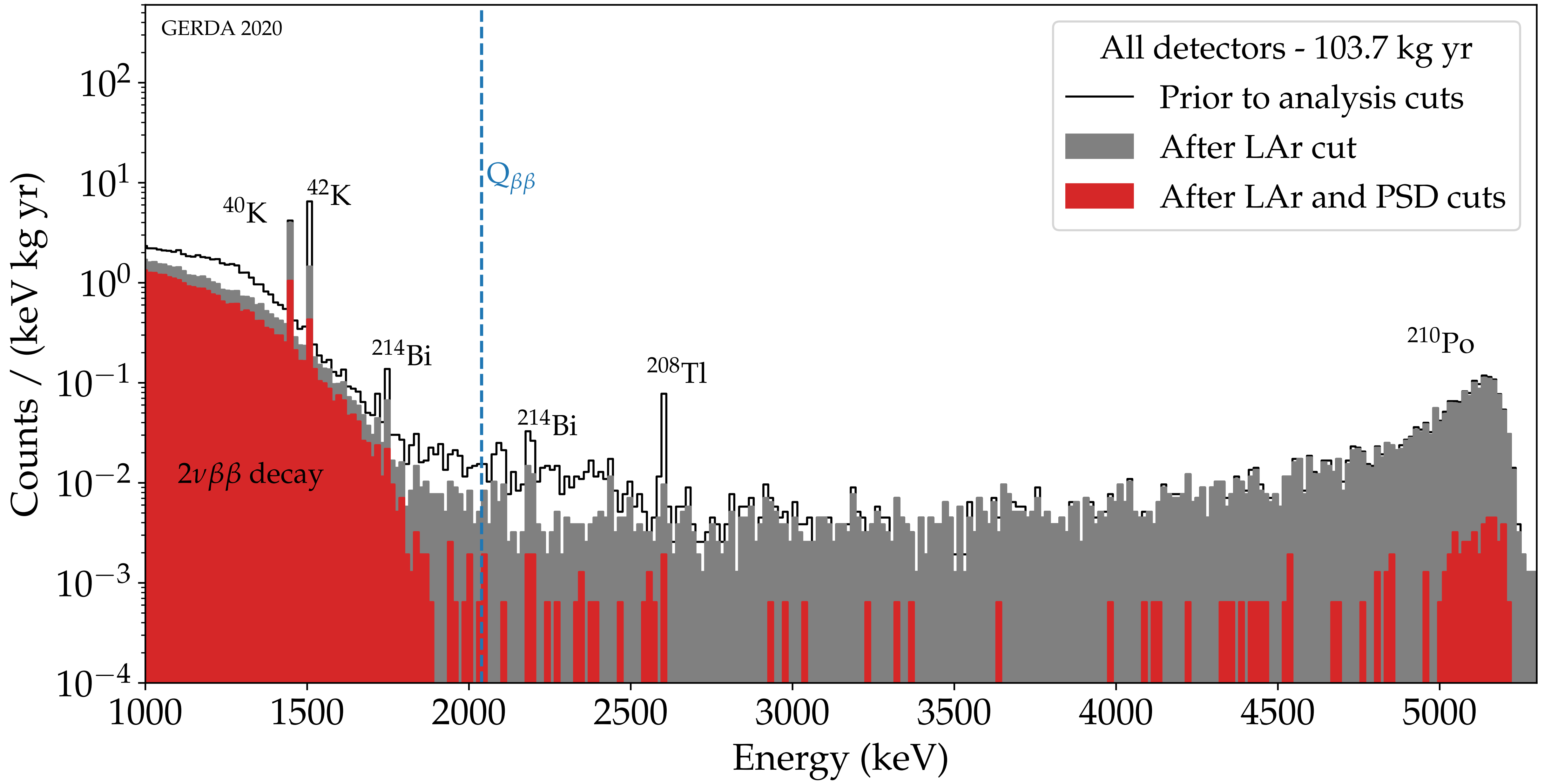
Detector-detector coincidences: discrimination by anti-coincidence (AC) cut

Detector-LAr coincidences: discrimination by LAr veto cut



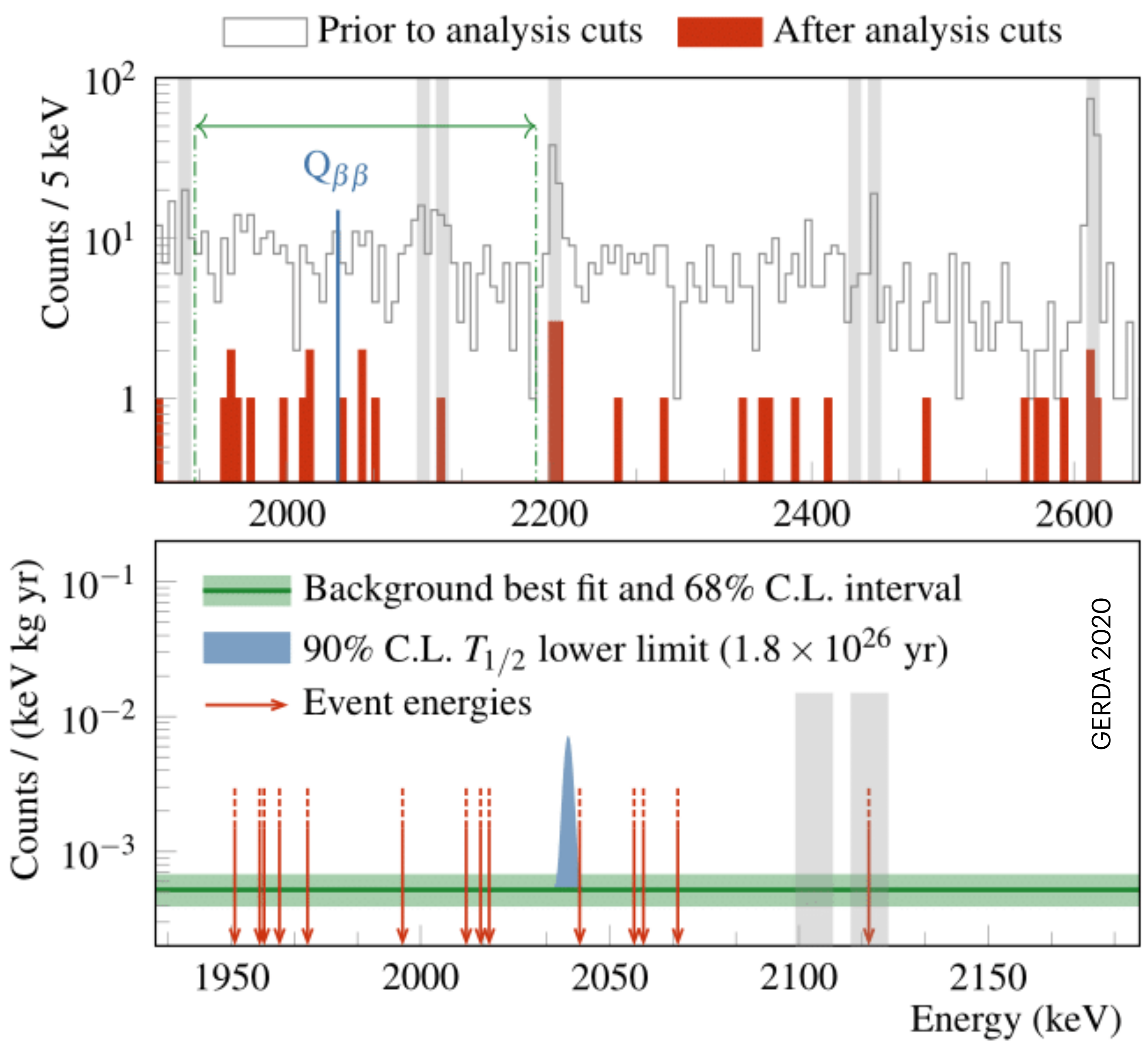
Multi-site / surface events: discrimination by PSD cut

After AC, LAr veto and PSD cuts



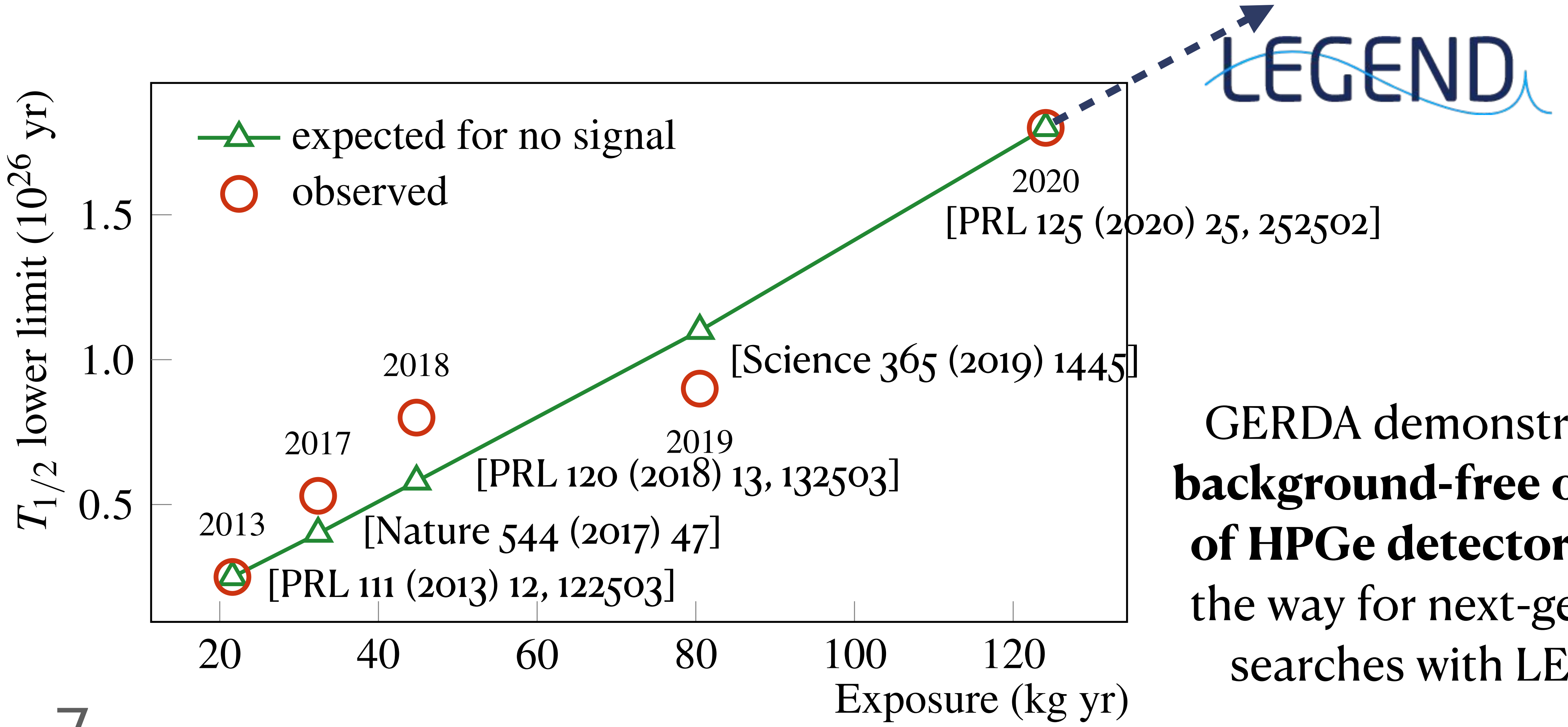
Final results on the search for $0\nu\beta\beta$ decay

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



- Lowest background index: $5.2^{+1.6}_{-1.3}$ 10^{-4} cts/(keV kg yr)
- Energy resolution at $Q_{\beta\beta}$ ~ 3keV (FWHM)
- No signal was observed in 103.7 kg yr of exposure

- Combined frequentist Phase I/ PhaseII analysis [Nature 544 (2017), 47–52]
- Best-fit N=0, $T^{0\nu}_{1/2}$ > 1.8 10^{26} yr at 90% C.L. (Sensitivity 1.8 10^{26} yr at 90% C.L.)
- $m_{\beta\beta}$ < 79-180 meV



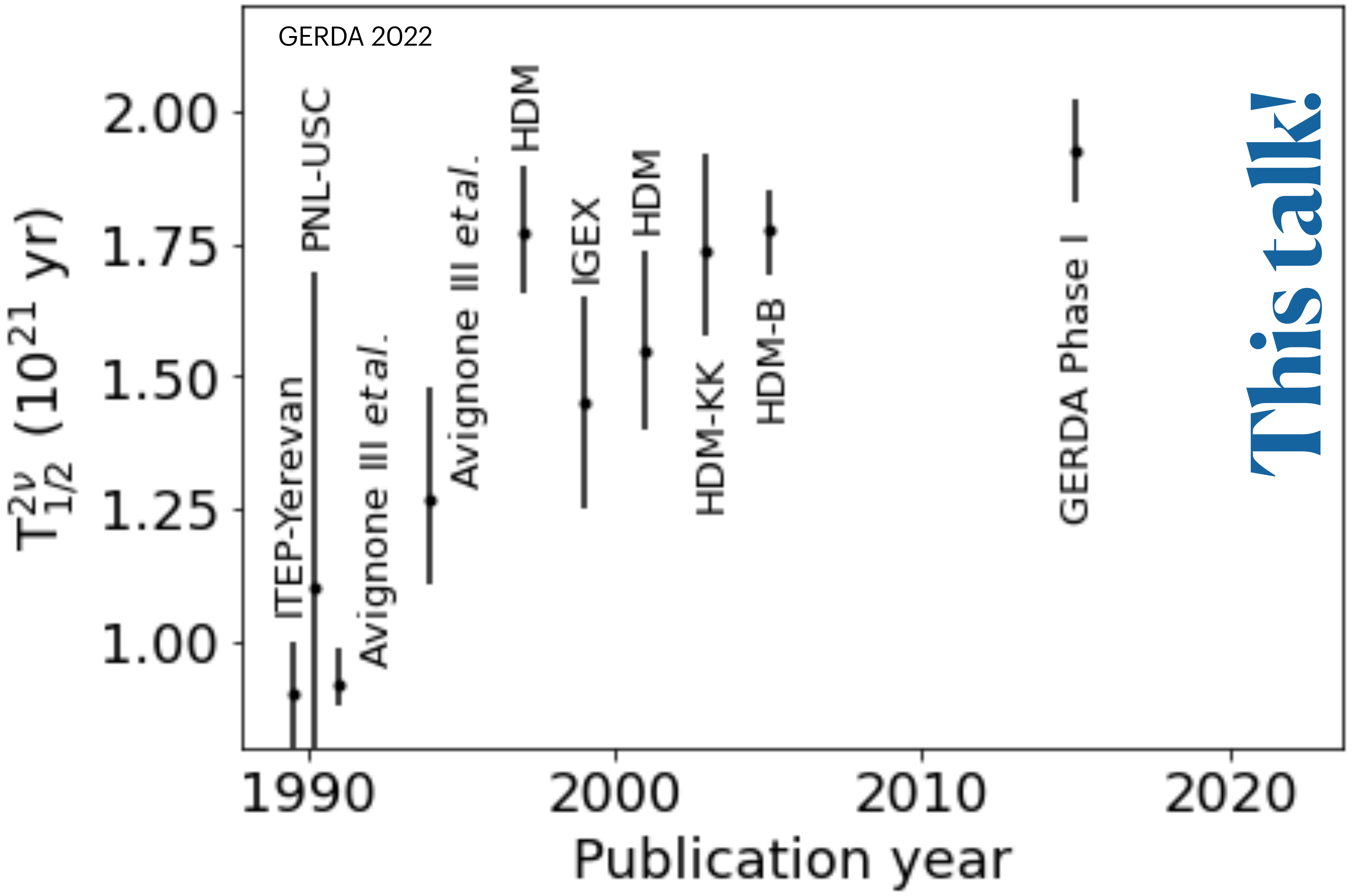
GERDA demonstrated the **background-free operation of HPGe detectors**, paving the way for next-generation searches with LEGEND.

The half-life of the 76Ge $2\nu\beta\beta$ decay

The half-life of ^{76}Ge $2\nu\beta\beta$ decay

Previous measurements

- Measurement in GERDA Phase I:
  [Eur. Phys. J. C (2015) 75:416]
  $T^{2\nu}_{1/2} = (1.926 \pm 0.094)\ 10^{21}$ yr
- Uncertainty dominated by systematic uncertainty on the active volume of Coax detector (4%) and background model and MC simulation (1.4% + 2.2%)



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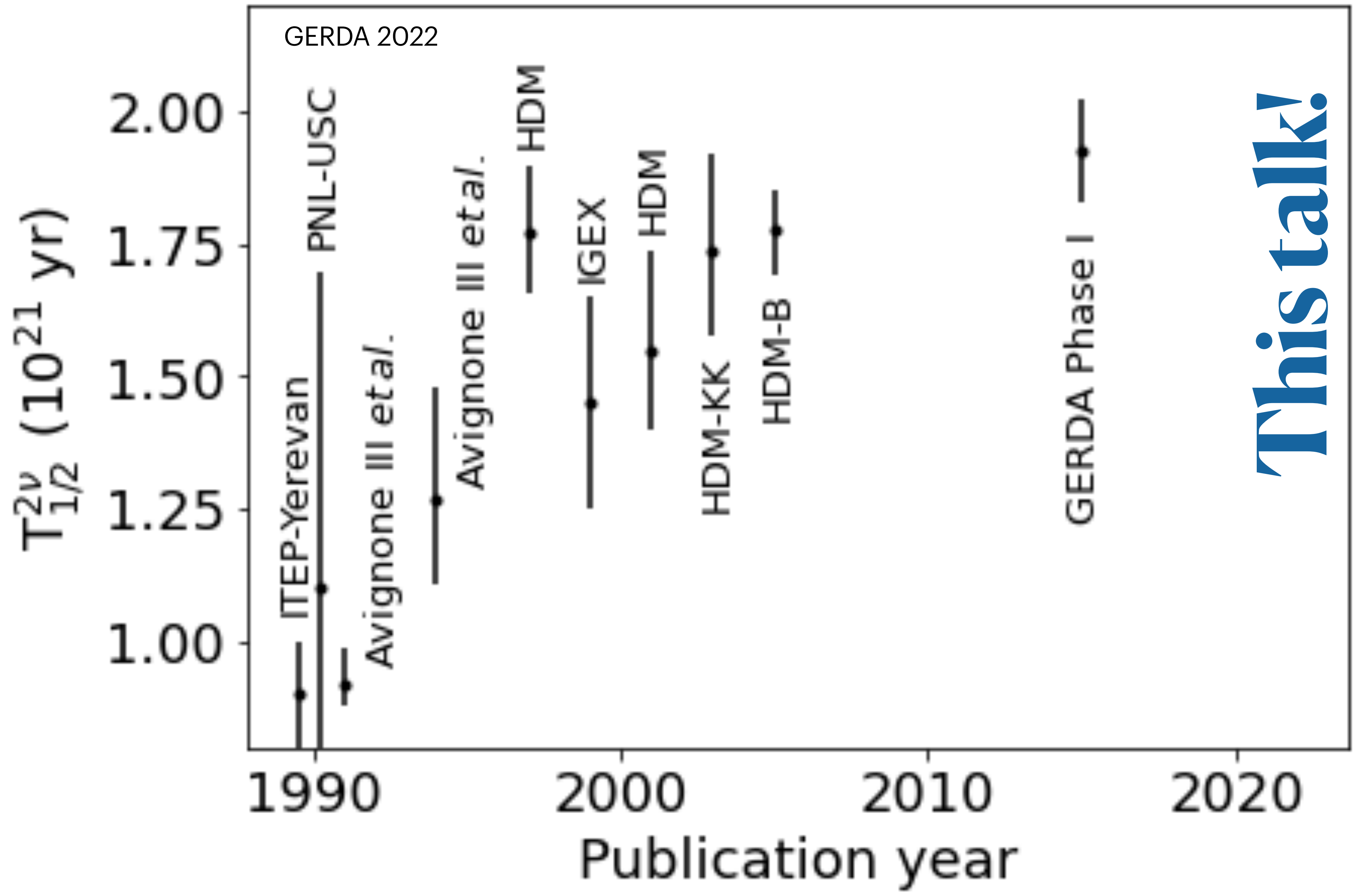
- Uncertainty dominated by systematic uncertainty on the active volume of Coax detector (4%) and background model and MC simulation (1.4% + 2.2%)

We can improve the precision of this measurement in GERDA Phase II:

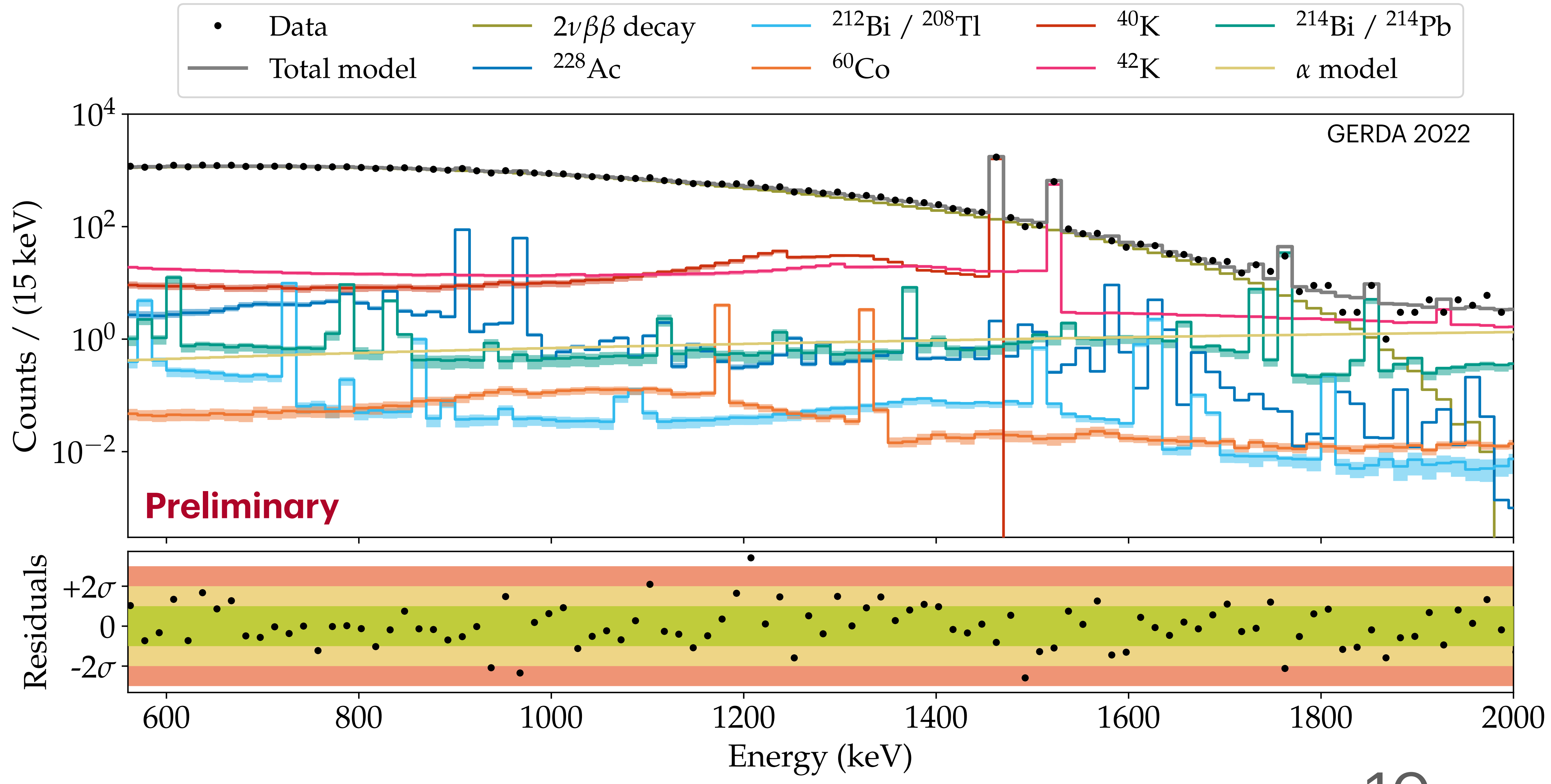
- Very low background after LAr veto cut
- Better determination of the active volume of BEGe detectors



Background Model after LAr veto cut

The LAr veto cut reduces the background by a factor of ~10 in the $2\nu\beta\beta$ decay-dominated region [560-2000] keV compared to before cuts

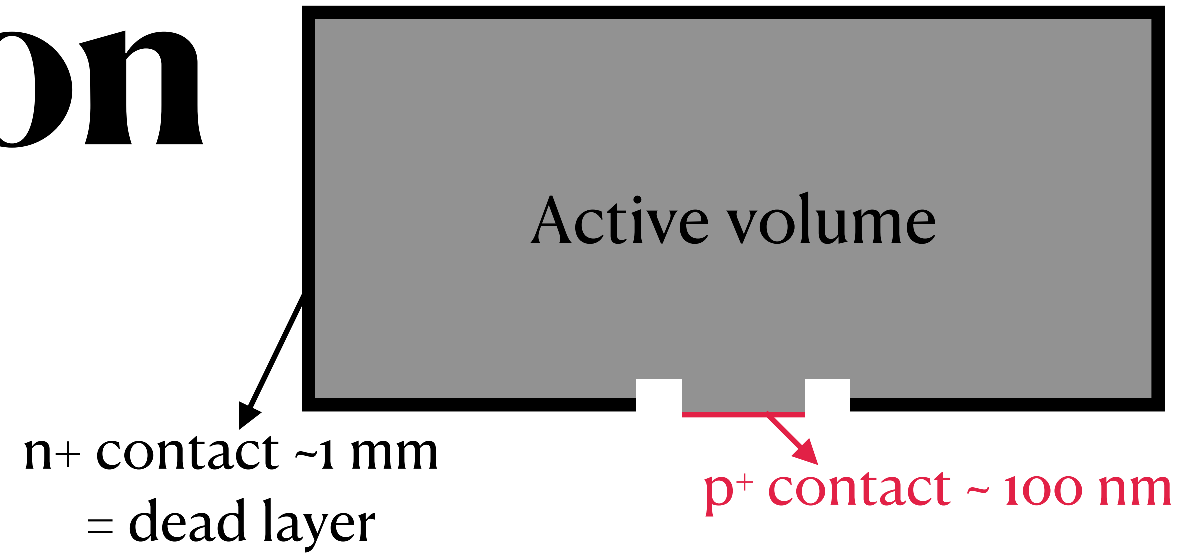
- A model of the LAr veto system has been developed [publication coming soon!]
- The expected background after LAr veto cut was obtained by applying this model to the background decomposition prior to analysis cuts [JHEP 03 (2020) 139]



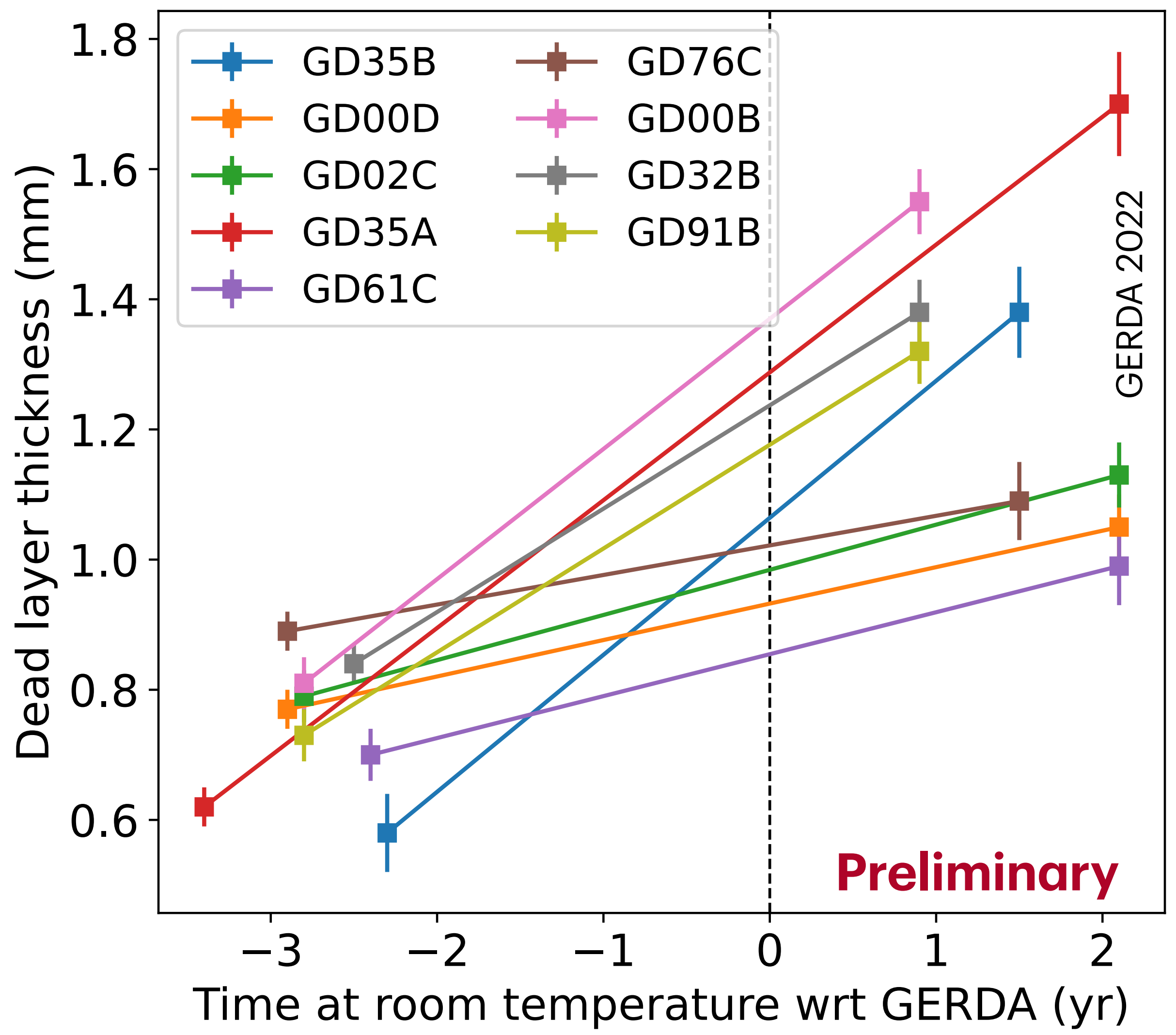
Expected background decomposition for all BEGe detectors pre-upgrade data (32.8 kg yr)

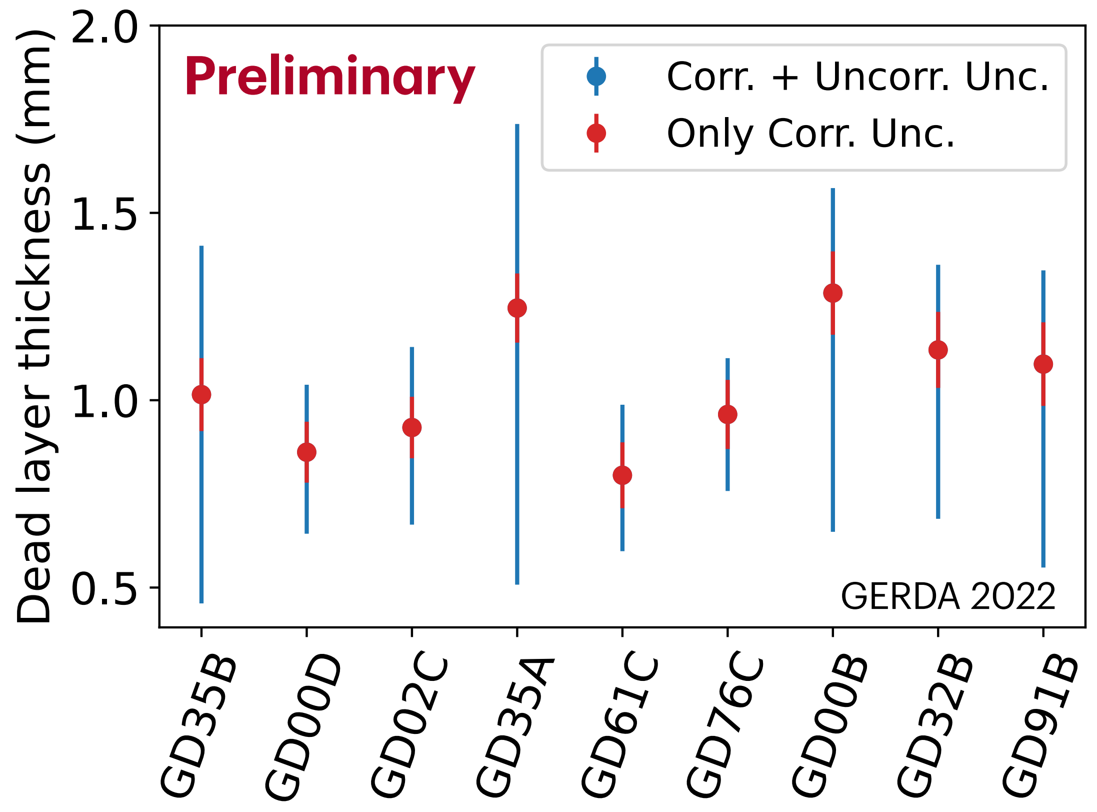
Active volume characterization

The 9 BEGe dataset



- The AV of the BEGe detectors was determined during a detector characterization campaign ~3 yr before GERDA Phase II
- We expect the dead layer to grow over time when the detectors are at room temperature, but little (and old) literature on the topic
- We selected and re-measured 9 BEGe detectors (11.8 kg yr for analysis) at the end of GERDA: different growths observed



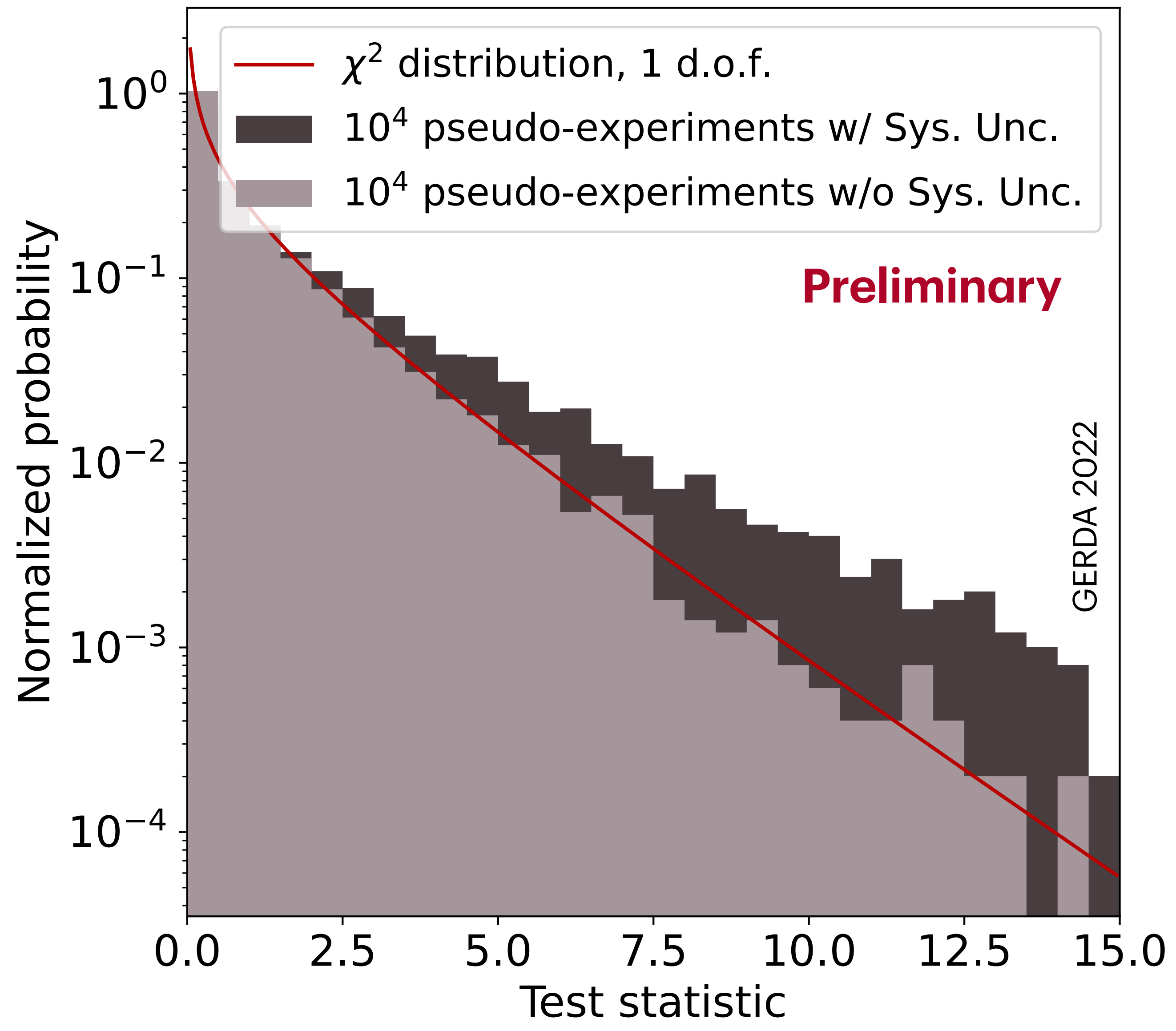


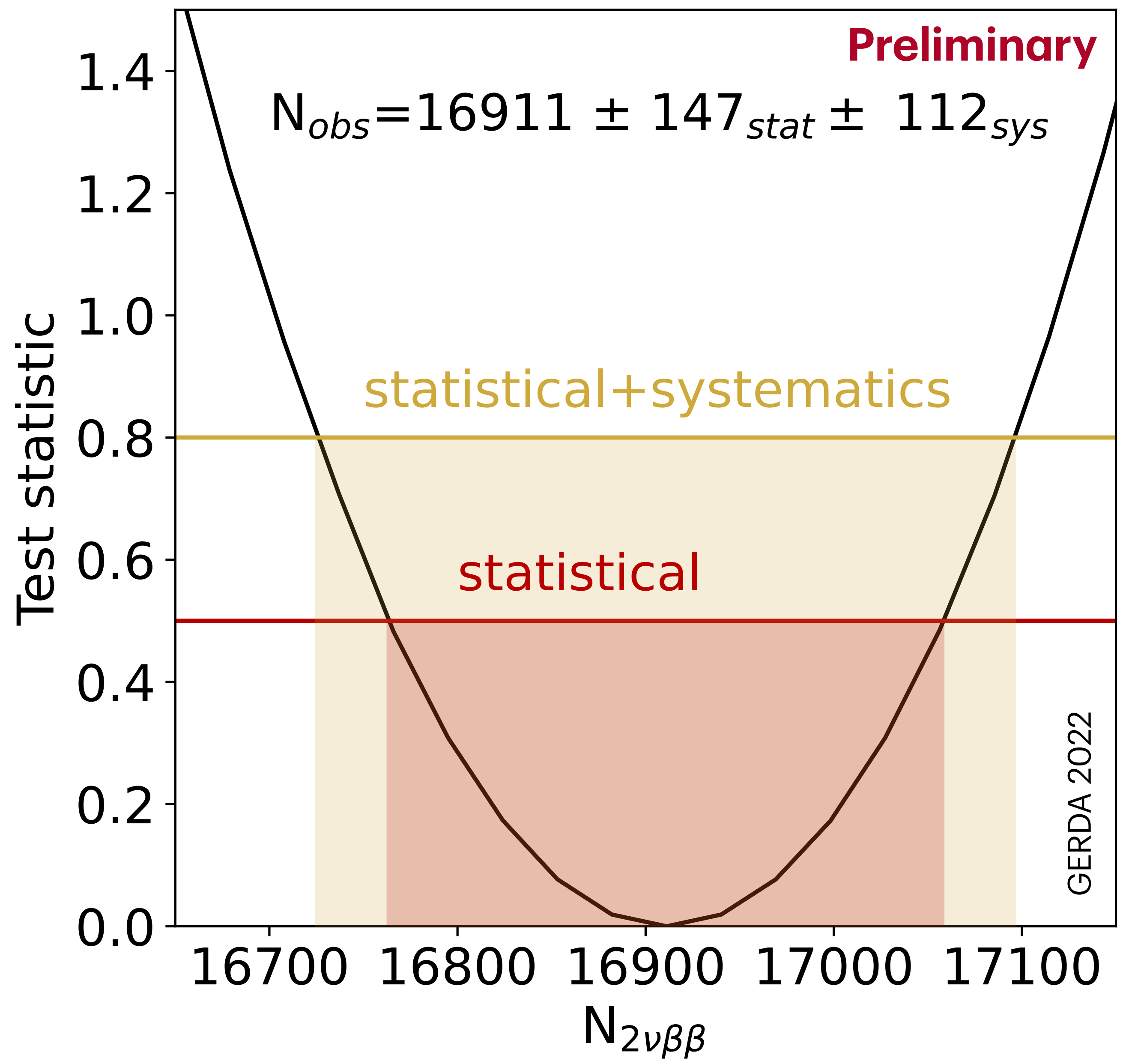
- We extracted detector specific growth and interpolate the active volume at the time of GERDA data taking

Statistical analysis

- Binned maximum likelihood fit in the energy window (560-2000) keV with 10 keV binning
- Statistical inference based on the profile likelihood ratio [Eur. Phys. J. C 71:1554, 2011]
- Distribution of the test statistic evaluated with Monte Carlo methods
- Systematic uncertainties on the fit model (background model, detector model, LAr veto model, and theoretical $2\nu\beta\beta$ decay model) are folded in the distribution of the test statistic

[Prog. Theor. Exp. Phys., 083C01 (2020)]





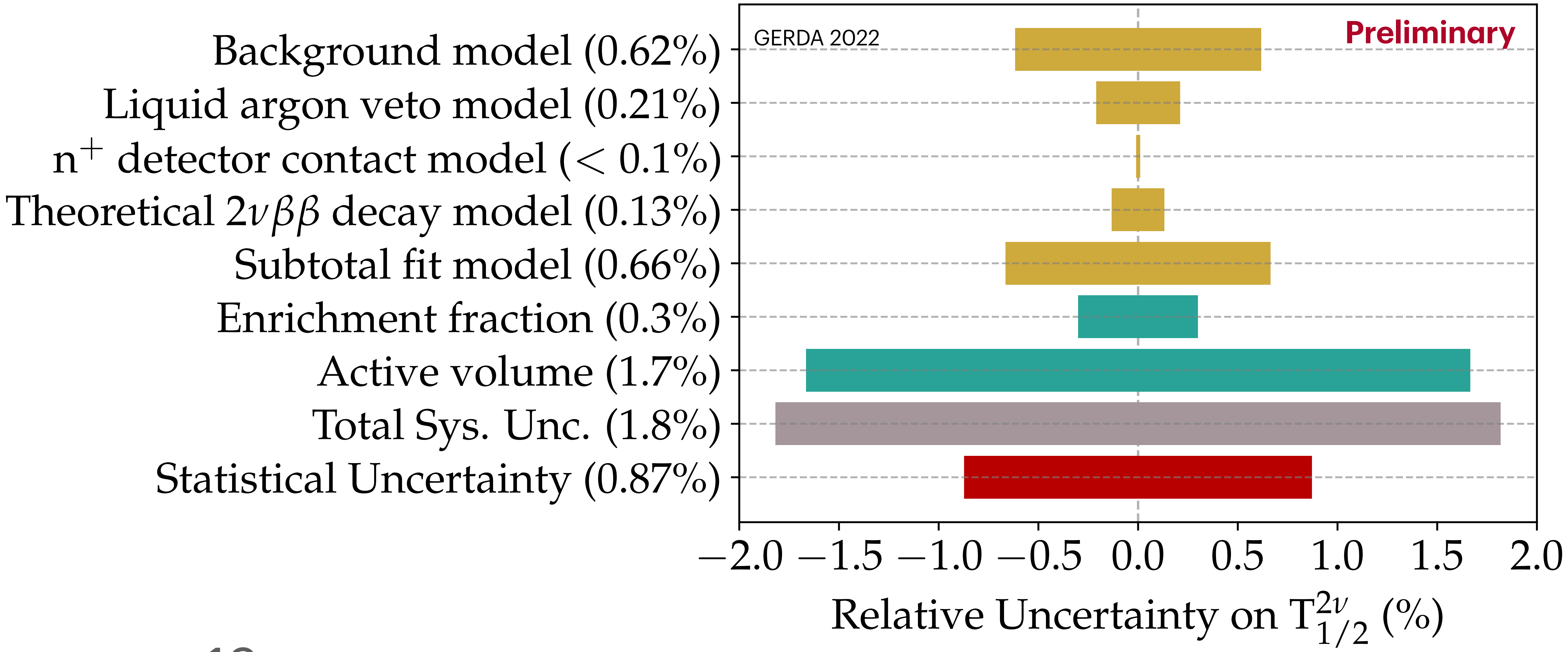
Half-life uncertainty

Breakdown of different contributions

- The fit uncertainty contributes to the half-life with 1.1% (stat+sys) uncertainty (dominant contribution from background model)
- Active volume and enrichment fraction add a 1.7% and 0.3% systematic uncertainty
- Total uncertainty 2.0%

$$T^{2\nu}_{1/2} = \frac{1}{N_{2\nu}} \cdot \frac{N_A log2}{M_{76}} f_{76} \epsilon_{cuts} \sum_i m_i t_i f_{AV,i} \epsilon_{c,i}$$

- $N_{2\nu}$: Number of observed events
- f_{76}: Enrichment fraction of ^{76}Ge
- ϵ_{cuts}: Cuts efficiency (QC, LAr)
- $m_i t_i$: Detector exposure
- $f_{AV,i} \epsilon_{c,i}$: Active volume fraction & containment efficiency

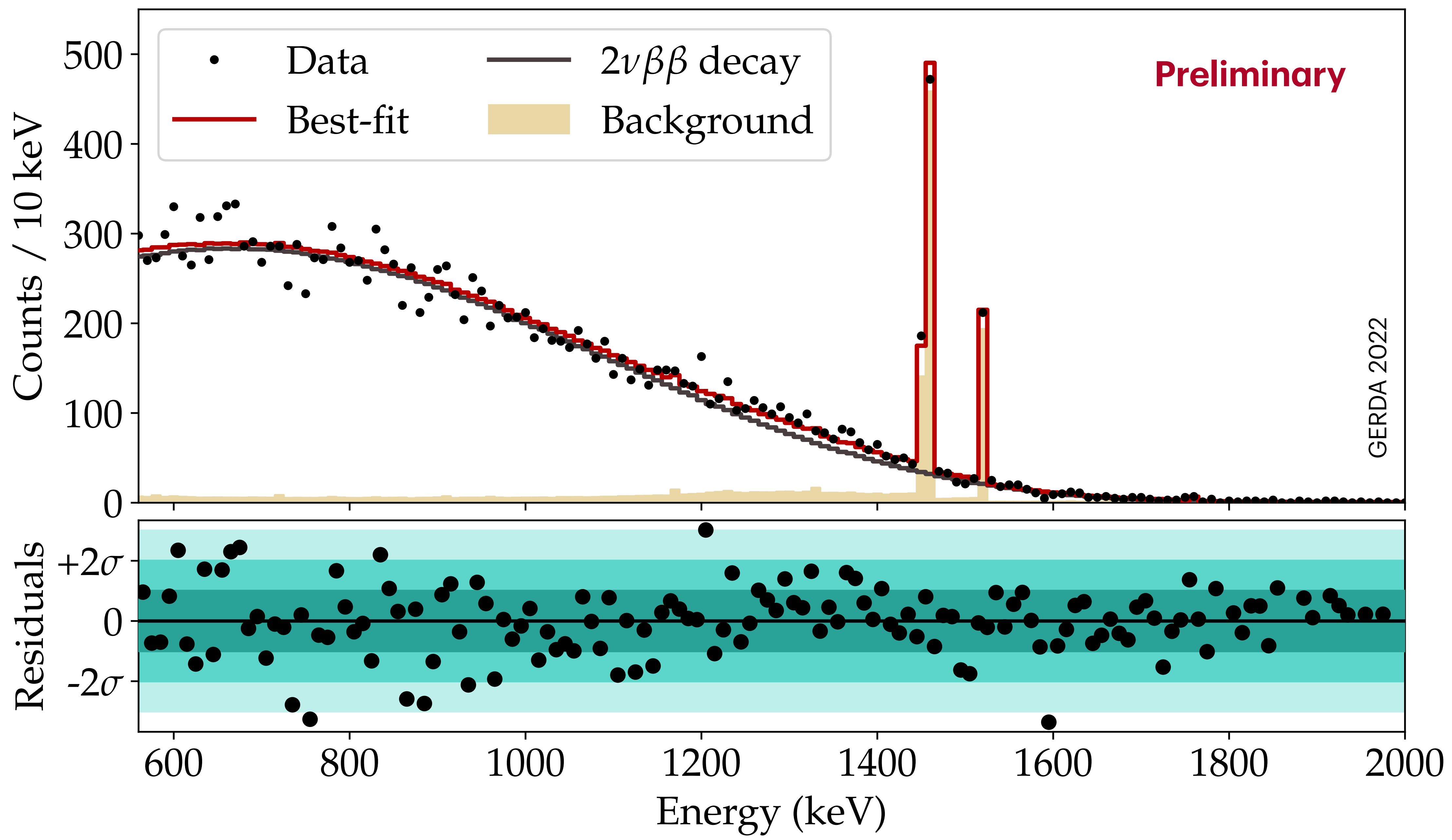


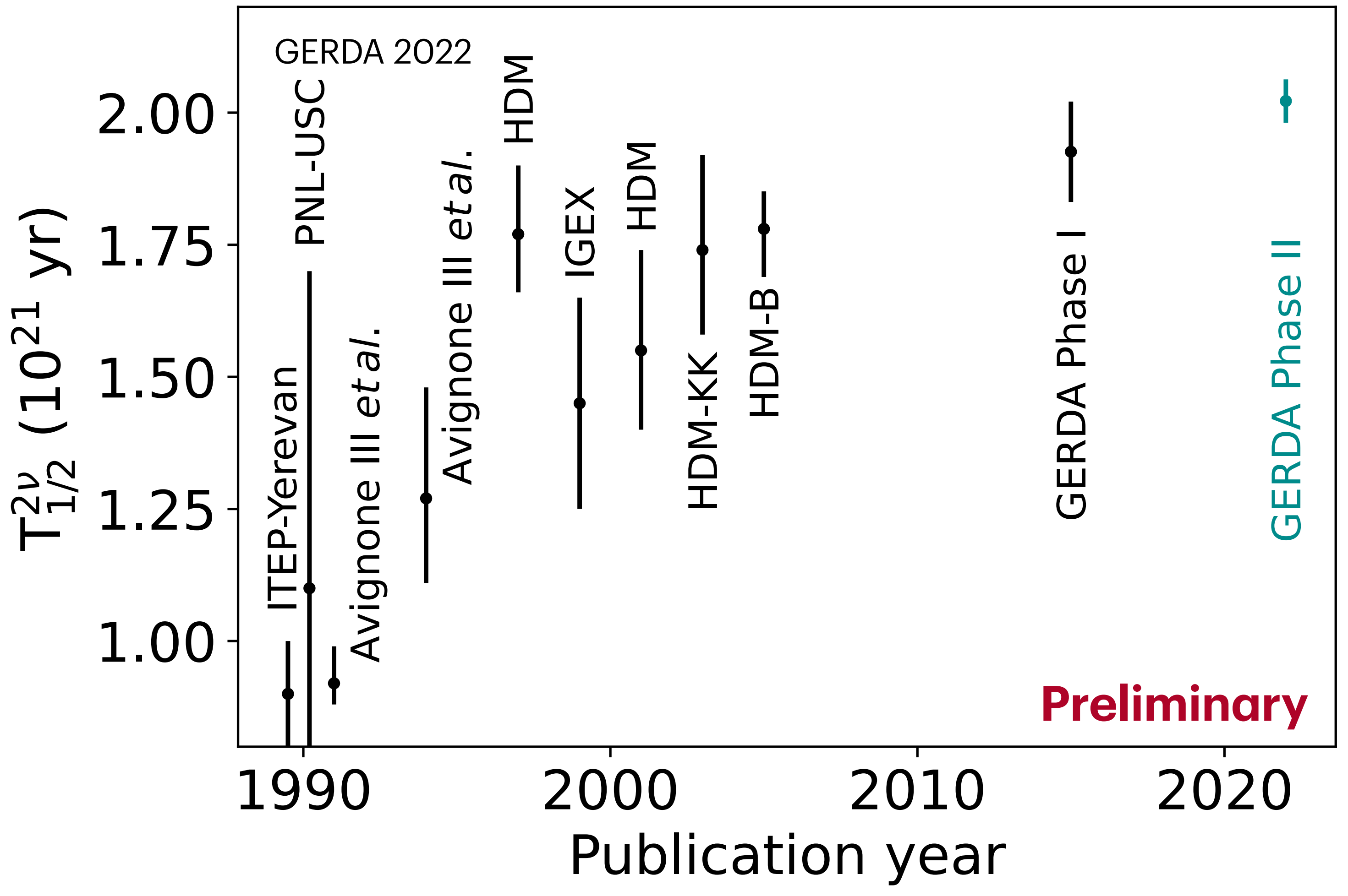
Results

We obtained the half-life of ^{76}Ge $2\nu\beta\beta$ decay: $T^{2\nu}_{1/2}$ = (2.022 ± 0.041) 10^{21} yr

[publication coming soon...]

- Very good agreement between data and best-fit model
- signal-to-background ratio 22:1 (excluding ^{40}K and ^{42}K γ-lines)





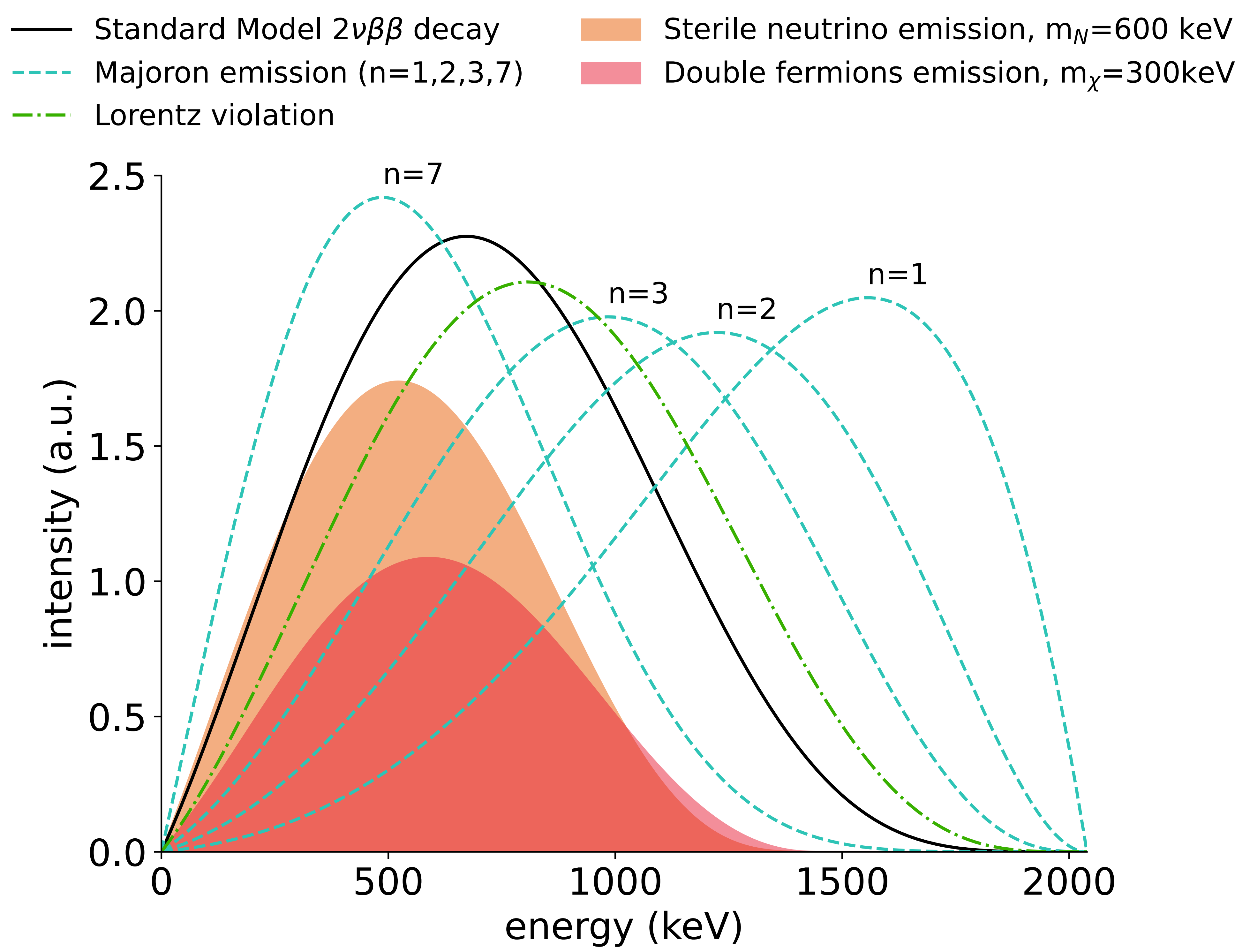
- Total uncertainty 2.0%: most precise determination of ^{76}Ge $2\nu\beta\beta$ decay half-life.

Search for exotic physics

Search for exotic double-β decays

[arXiv:2209.01671]

- In all the considered decay modes two neutrinos or exotic particles are emitted along with the two electrons
- Different distributions are predicted depending on the BSM physics involved (also continuous distributions between 0 and $Q_{\beta\beta}$): would manifest as a distortion of the $2\nu\beta\beta$ decay distribution compared to the SM prediction
- We used data collected with all the BEGe detectors before the upgrade: total exposure 32.8 kg yr (after LAr veto cut)



Results on the search for Majoron-involving decays

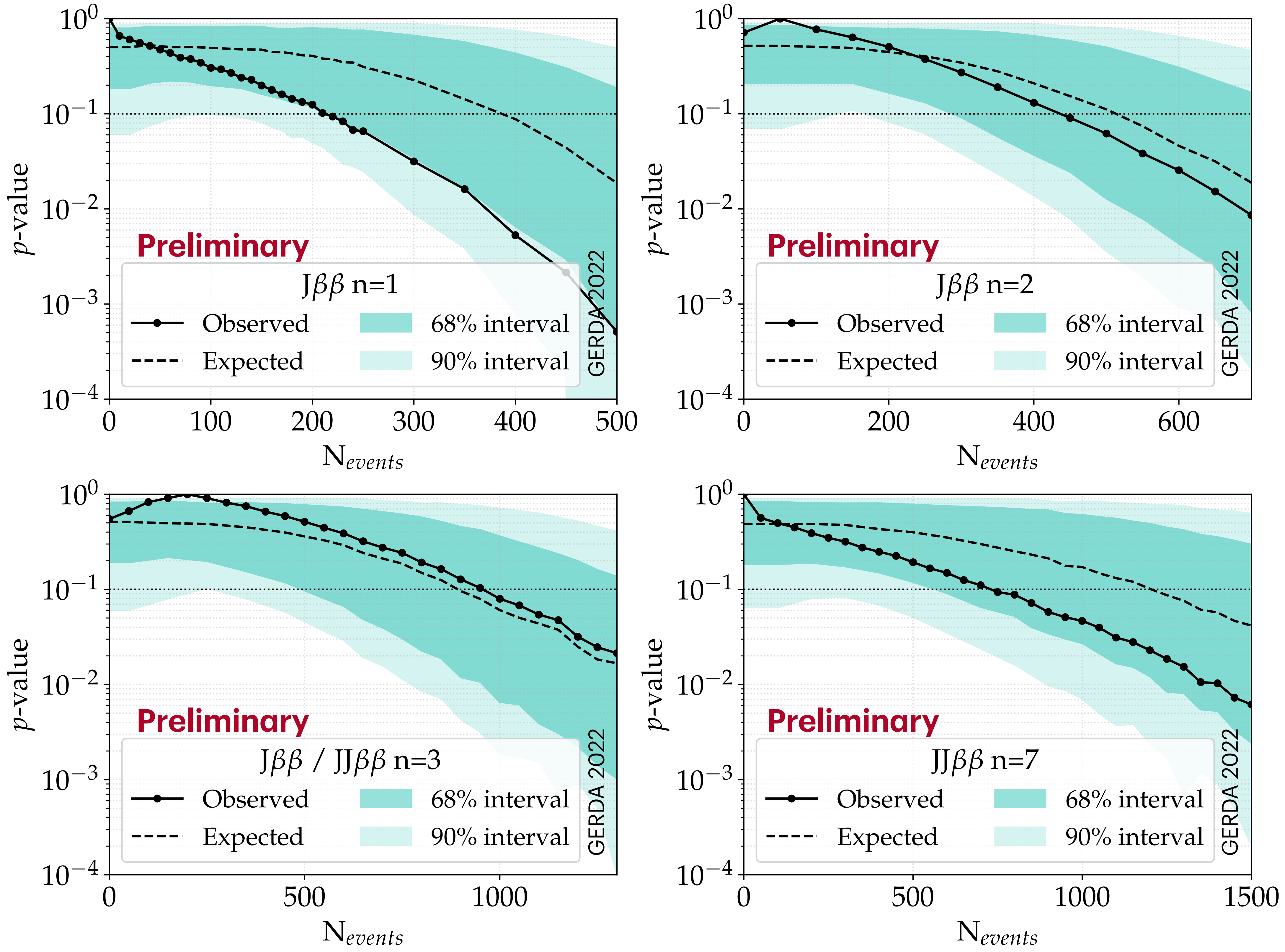
(A,Z) → (A,Z+2) + 2e + J(2J)

arXiv:2209.01671

- We searched for double-beta decays with the emission of one or two Majorons according to 4 different models (spectral index n=1,2,3, and 7)

$$\frac{dN}{dE} \sim G \sim (E - Q_{\beta\beta})^n$$

- No evidence of positive signal: 90% C.L. limits set
- We evaluate the observed p-value for a discrete set of values of N_{events} together with the expected p-value distribution



Results on the search for Majoron-involving decays

- Limits on the number of events converted to lower limits on the half-life, which can be related to the neutrino-Majoron coupling constant g_J:

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

arXiv:2209.01671

Decay mode	$T_{1/2}$ (yr) Sensitivity	$T_{1/2}$ (yr) Observed limit	Observed g_J
$J\beta\beta$ ($n=1$)	$3.5 \cdot 10^{23}$	$> 6.4 \cdot 10^{23}$	$< (1.9 - 4.4) \cdot 10^{-5}$
$J\beta\beta$ ($n=2$)	$2.5 \cdot 10^{23}$	$> 2.9 \cdot 10^{23}$	–
$J\beta\beta$ ($n=3$)	$1.3 \cdot 10^{23}$	$> 1.2 \cdot 10^{23}$	< 0.017
$JJ\beta\beta$ ($n=3$)	$1.3 \cdot 10^{23}$	$> 1.2 \cdot 10^{23}$	< 1.2
$JJ\beta\beta$ ($n=7$)	$5.8 \cdot 10^{22}$	$> 1.0 \cdot 10^{23}$	< 1.1

Preliminary

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

- Improvement of a factor ~2 compared to previous GERDA Phase I result
- Results comparable with limits obtained with other double-beta decay isotopes
- Impact of systematic uncertainties on these limits 12-25%

Results on the search for Lorentz violation

$(A,Z) \rightarrow (A,Z+2) + 2e + 2\bar{\nu}_{LV}$

- Lorentz violation in the neutrino sector would affect the energy distribution of $2\nu\beta\beta$ decay through the isotropic component of the counter-shaded coefficient $a_{of}^{(3)}$

$$\frac{d\Gamma}{dE} \sim \frac{d\Gamma_{SM}}{dE} + a_{of}^{(3)} \frac{d\Gamma_{LV}}{dE}$$

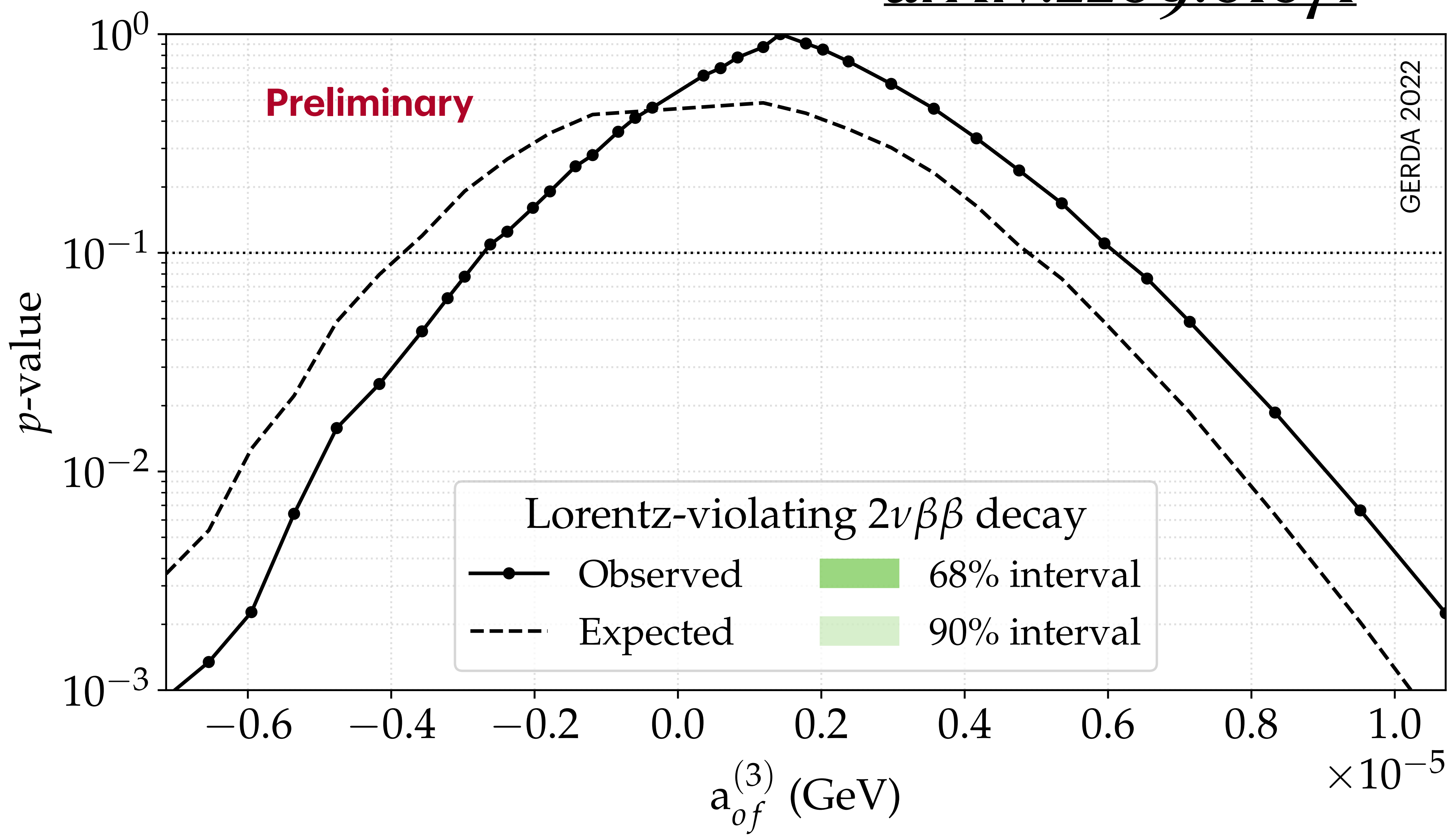
- No evidence of deviation from SM distribution: set limit on $a_{of}^{(3)}$ (both positive and negative values)

Preliminary

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

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

arXiv:2209.01671



- First constraints with ^{76}Ge
- Results comparable to limits obtained with other double-beta isotopes
- Impact of systematic uncertainties on the limit estimated at 30%

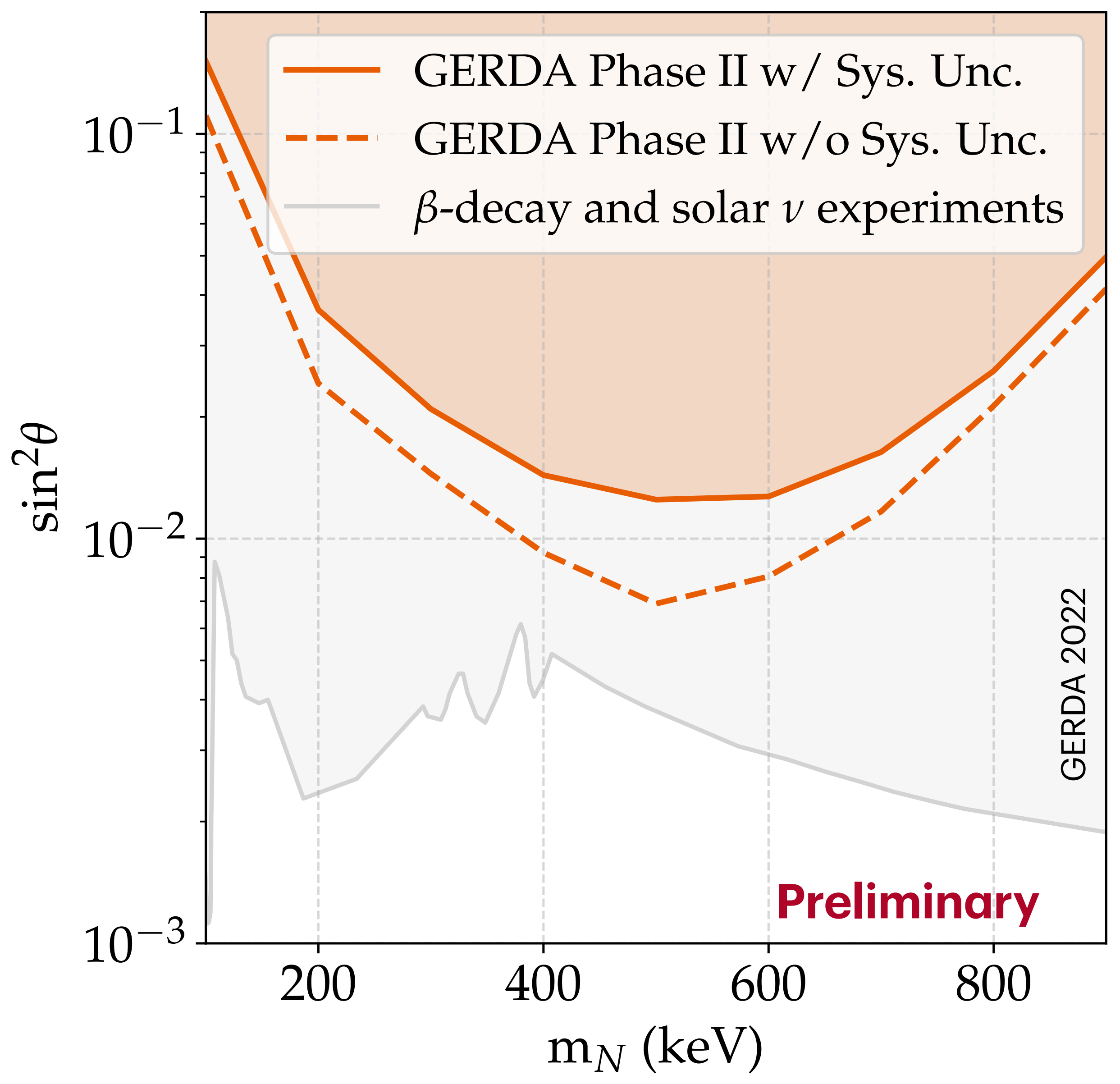
Results on the search for light exotic fermions

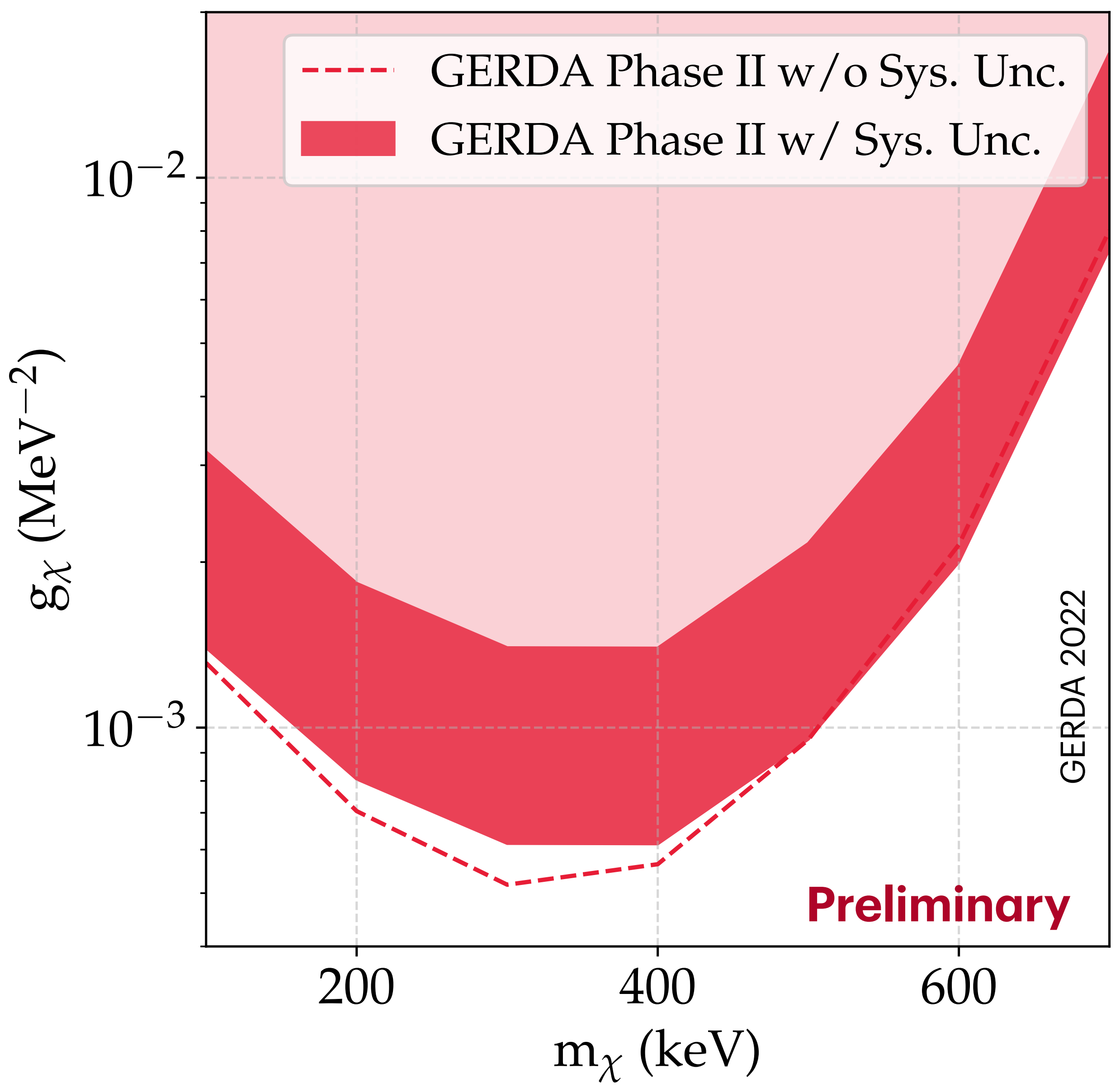
(A,Z) → (A,Z+2) + 2e + $\bar{\nu}$ + N
(A,Z) → (A,Z+2) + 2e + 2χ

arXiv:2209.01671

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

- Exotic fermions with masses < $Q_{\beta\beta}$ can be emitted in double-beta decay: the endpoint of the distribution is shifted by the particle mass
- We searched for sterile neutrinos (N) and their Z_2-odd variant (χ) with masses between 100 and 900 keV
- No evidence of positive signals: set limits at 90% C.L. on the couplings





- First experimental constraints on light exotic fermions
- Constraints from single-beta decay on sterile neutrinos are still more stringent
- Pair production of exotic fermion can only be tested in double-beta decay

Conclusions

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- The GERDA experiment had the main goal of searching for the $0\nu\beta\beta$ decay of ^{76}Ge using enriched HPGe detectors operated in LAr.

▶ *In this work*, we studied the ^{76}Ge $2\nu\beta\beta$ decay energy spectrum using data from GERDA Phase II.

- We obtained a ***precision determination of the half-life***

$$T^{2\nu}_{1/2} = (\,2.022 \pm 0.041)\ 10^{21}\ \text{yr},$$

[publication coming soon...]

benefiting from the very low background after the LAr veto cut and a re-characterization of nine BEGe detectors (11.8 kg yr) to determine their active volume.

⭐ This is the most precise determination of the ^{76}Ge $2\nu\beta\beta$ decay half-life and one of the most precise of a double-beta decay process.

- We searched for exotic decays through the search for distortion of the energy spectrum compared to the SM prediction. We set limits on the ***emission of Majorons, Lorentz violation, and the emission of light exotic fermions***.

[arXiv:2209.01671, submitted to JCAP]

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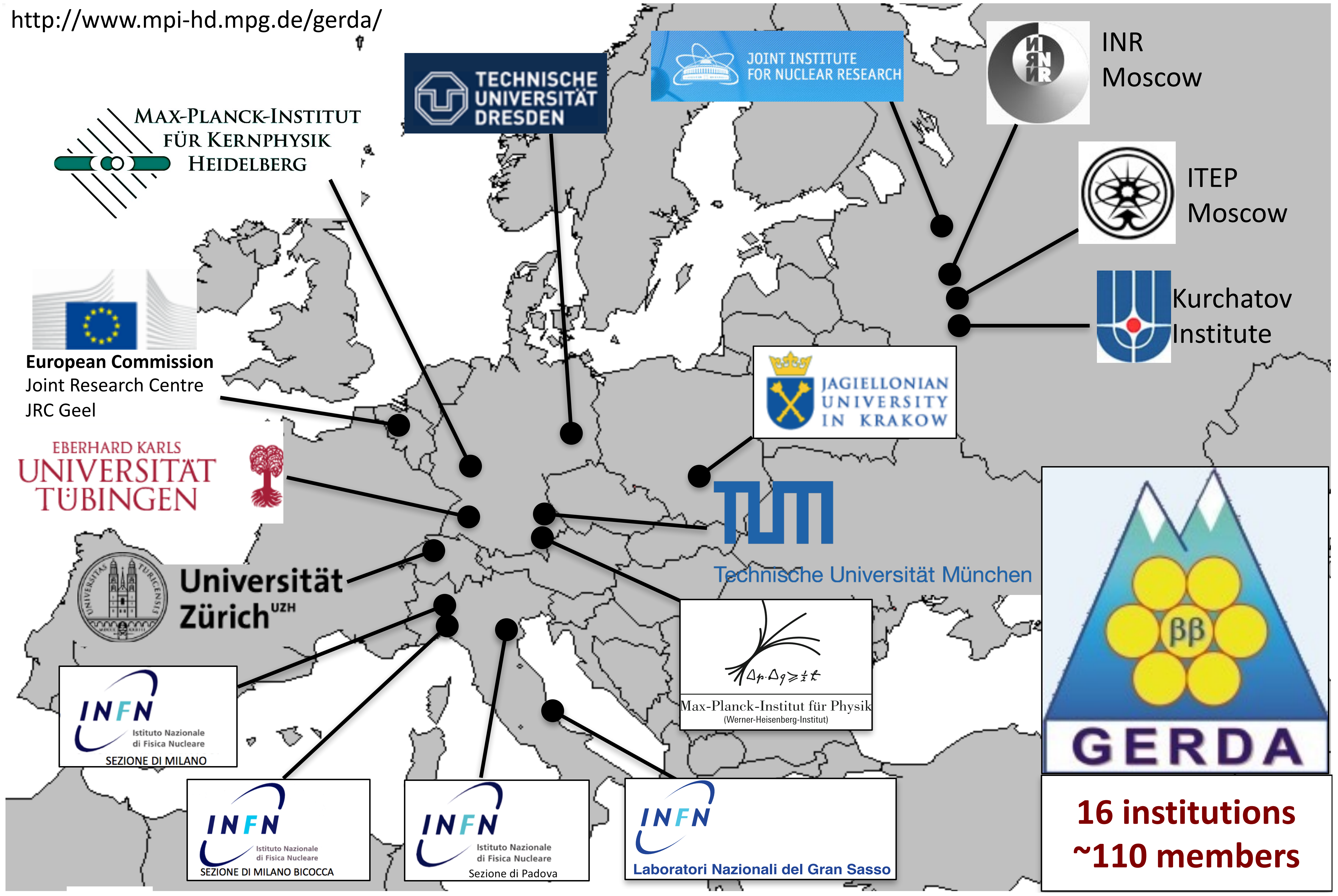
Thank you for your attention...

Backup

The GERDA Collaboration

Collaboration meeting:
LNGS June 2022



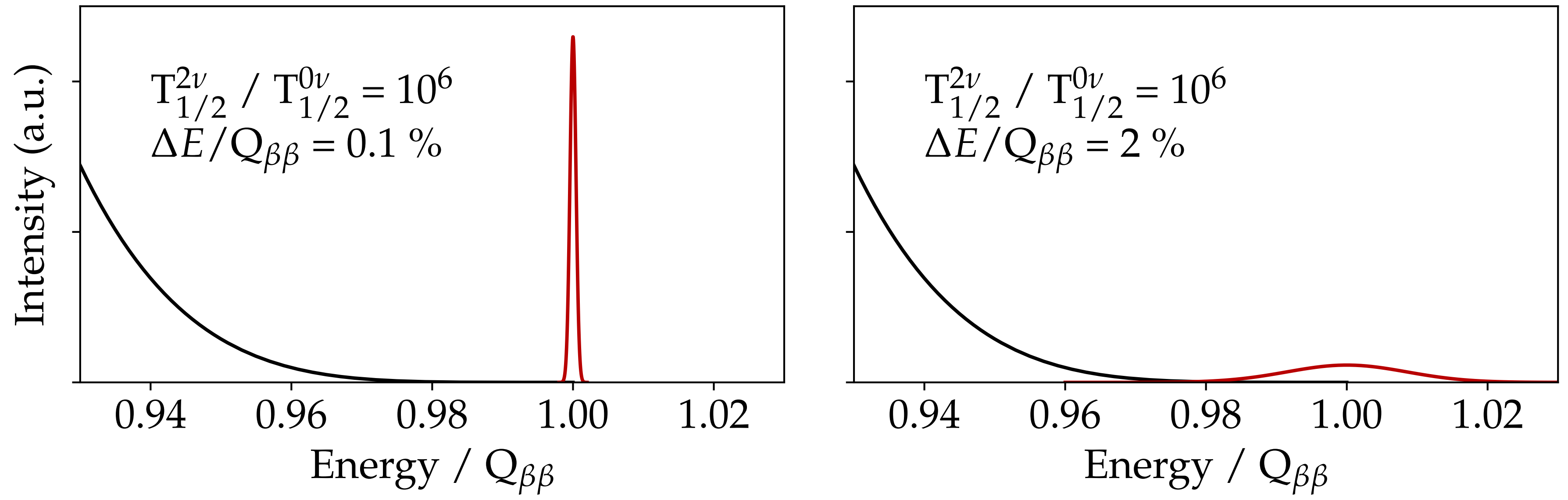
Experimental approach

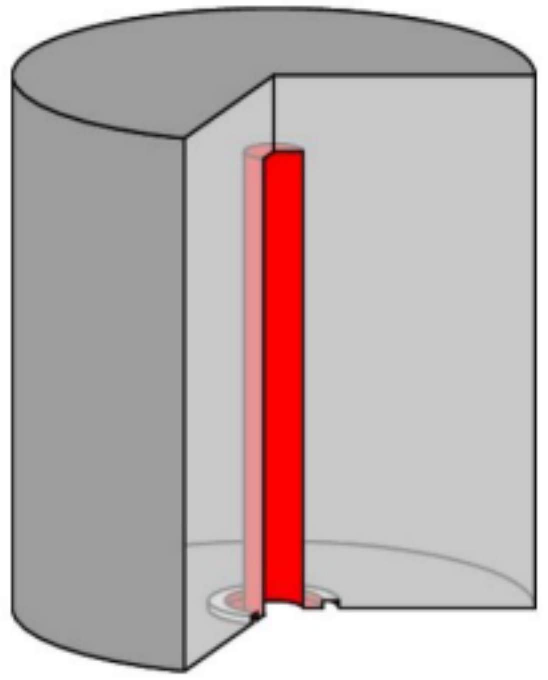
The GERDA experiment employed HPGe detectors enriched in ^{76}Ge

- High detection efficiency: source = detector
- High-purity material: no intrinsic background

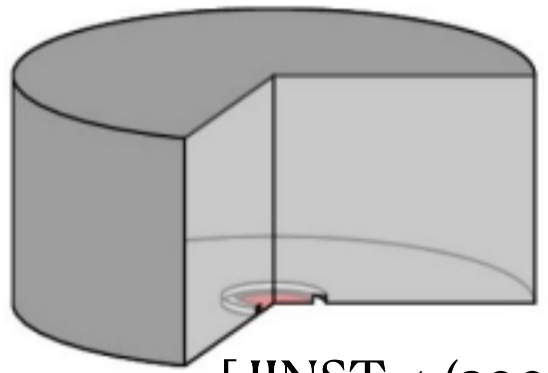
[Astropart.Phys. 91 (2017) 15-21]

- Energy resolution at $Q_{\beta\beta}$: $\sigma(E)/E < 0.1$ %
- Background discrimination by event topology



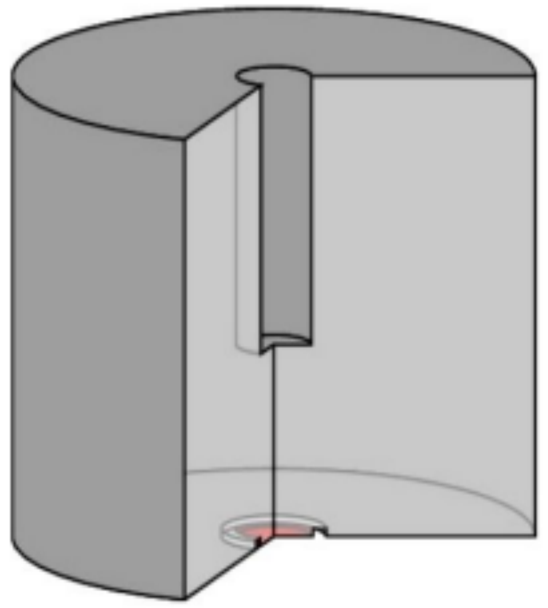


7 (later 6) Coaxial detectors (15.6 kg, later 14.6 kg):
- [x] Big
- [ ] Good PSD performance



30 BEGe detectors (20 kg):
- [x] Very good PSD performance
- [ ] Small

[JINST 4 (2009) P10007]

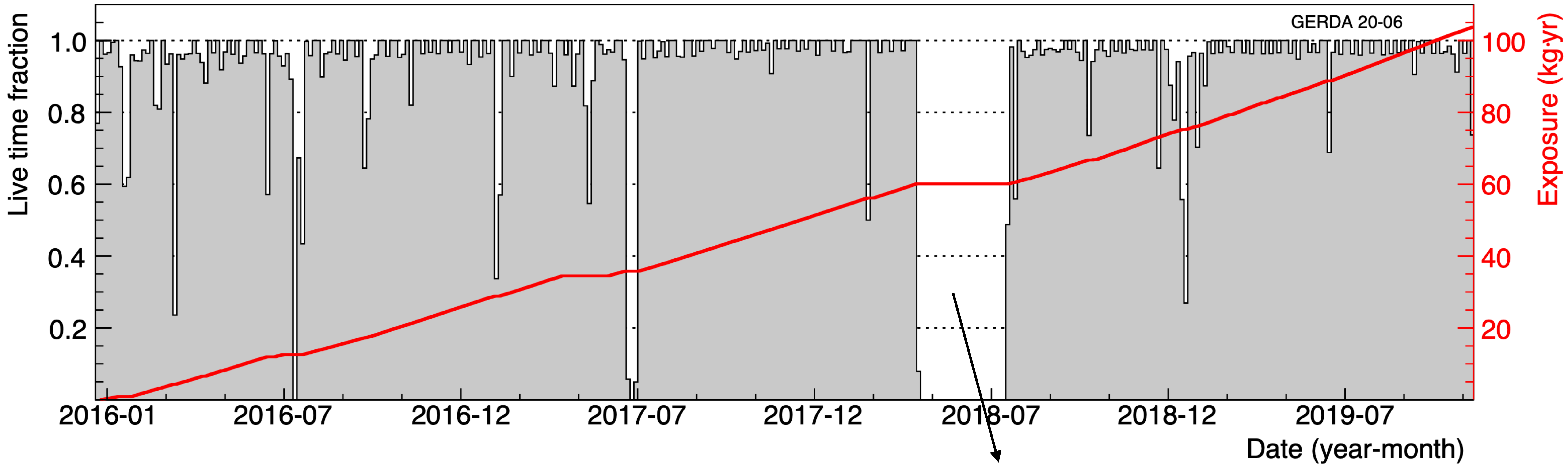


5 Inverted Coaxial detectors added after upgrade (9.6 kg):
- [x] Big
- [x] Very good PSD performance

[Nucl. Instrum. Meth. A665, 25 (2011) 25-32]

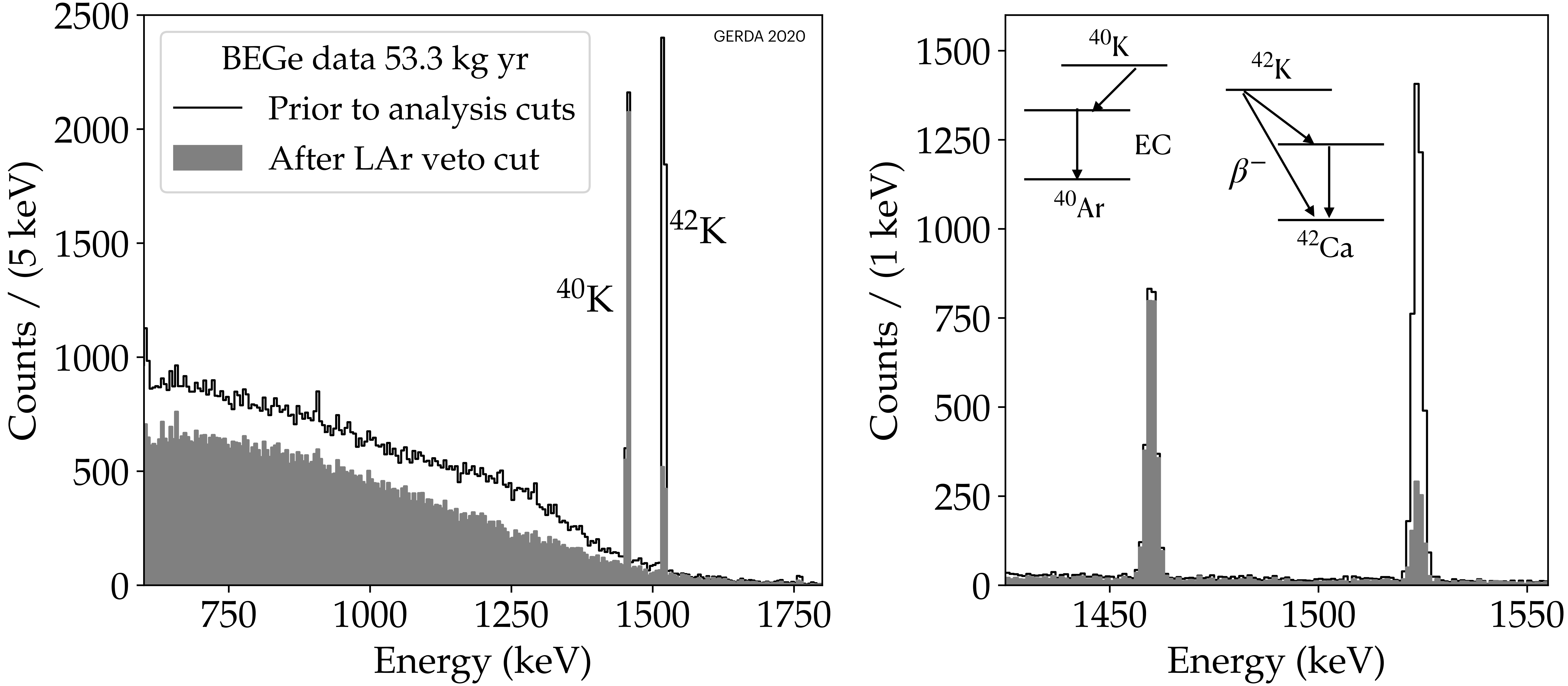
Phase II data taking & exposure

- We took data from December 2015 to November 2019 with a high duty cycle and only a short interruption for upgrade
- At the end of Phase II, we collected 103.7 kg yr of exposure (combined with Phase I 127.2 kg yr)



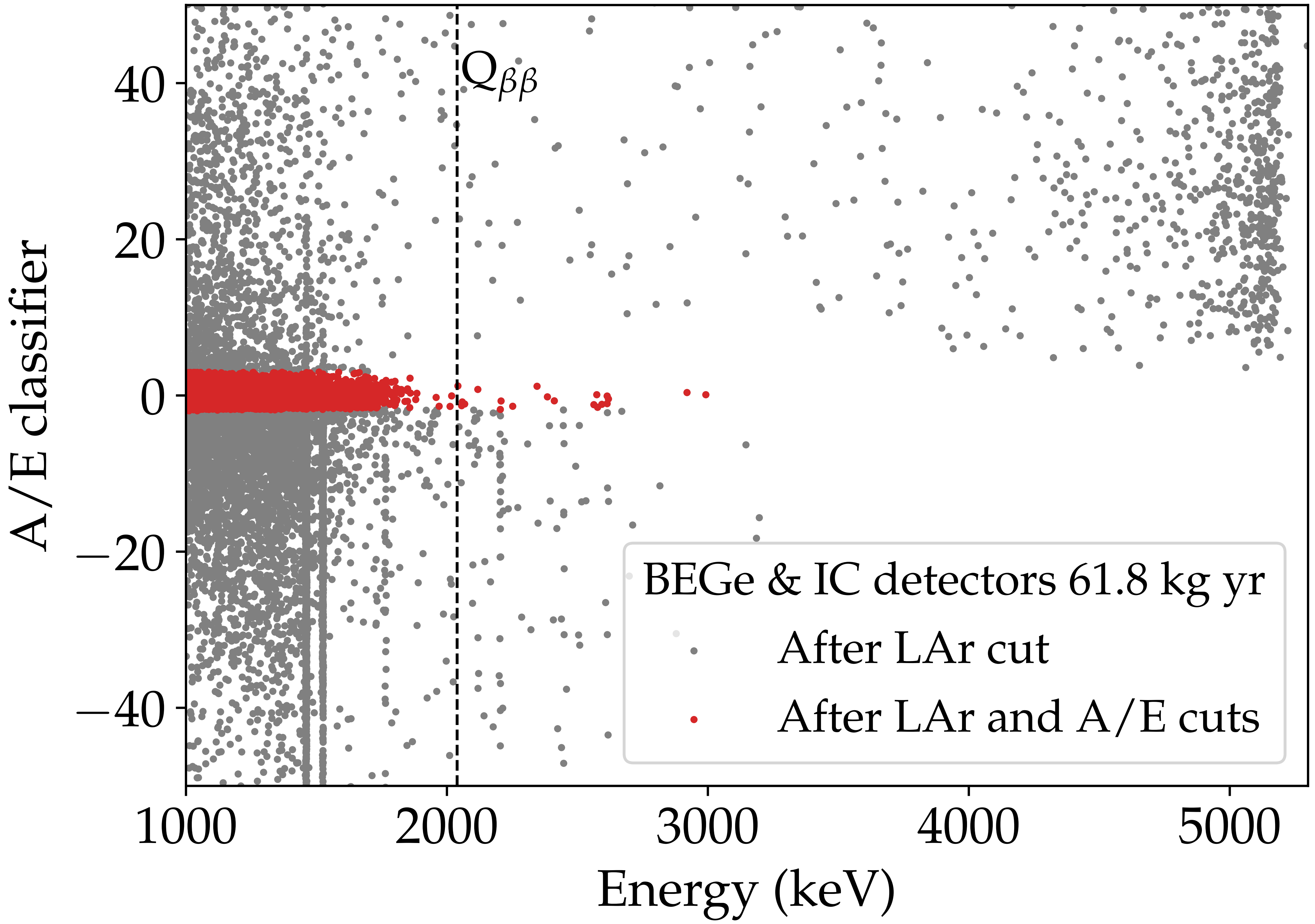
Upgrade in Summer 2018

LAr veto cut performance

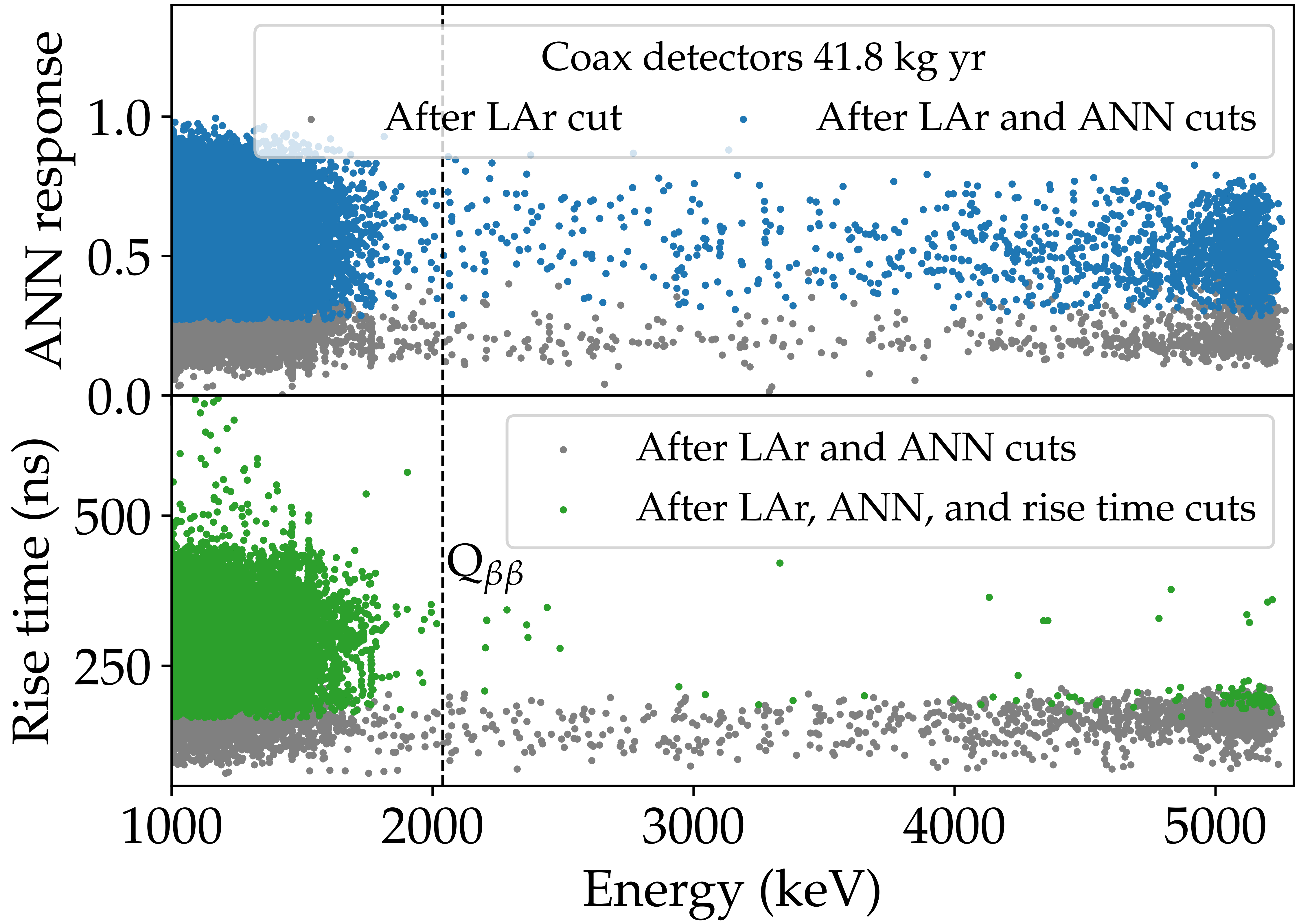


Pulse Shape Discrimination performance

- One parameter for BEGe and IC detectors
- All α events above 3525 keV discarded

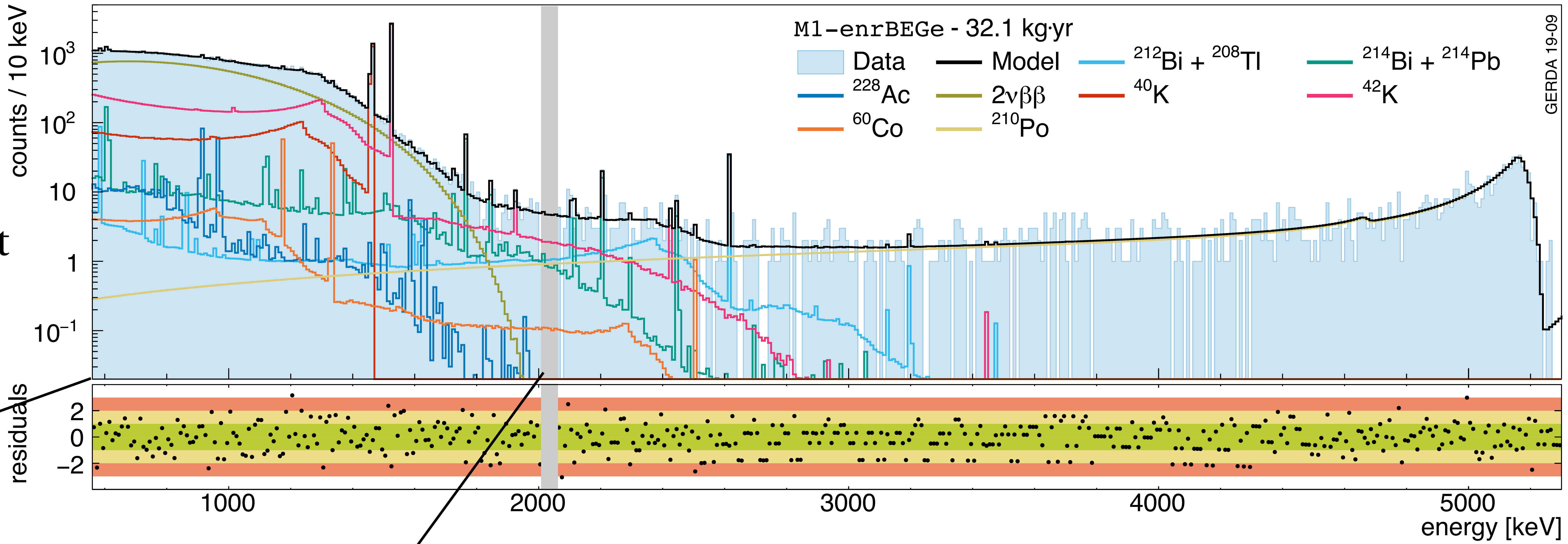


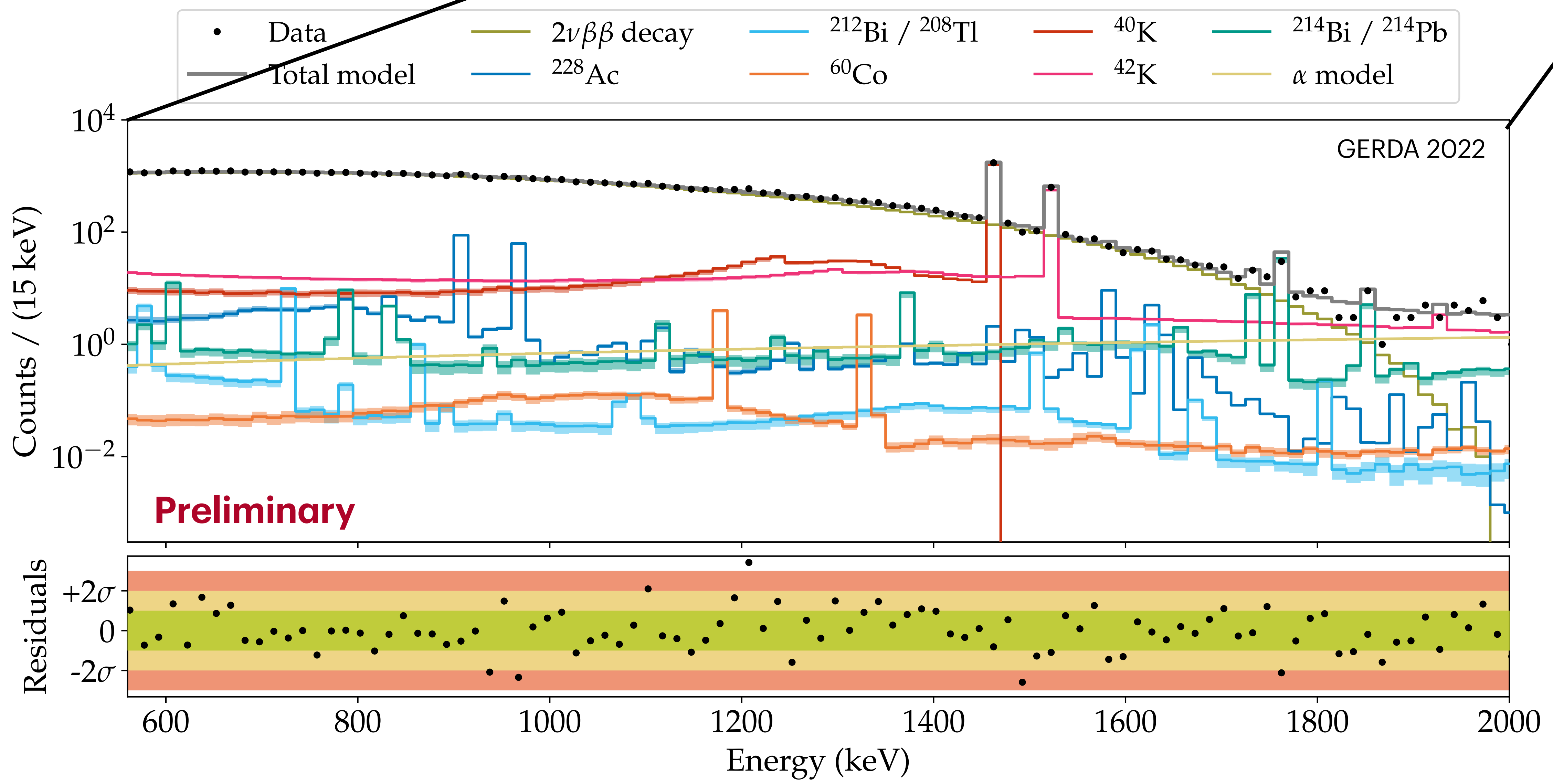
- Artificial neural network (ANN) for single-site/multi-site discrimination
- Additional rise time cut for fast p+ surface events



Comparison of the background model before and after LAr veto cut

Before LAr veto cut





After LAr veto cut

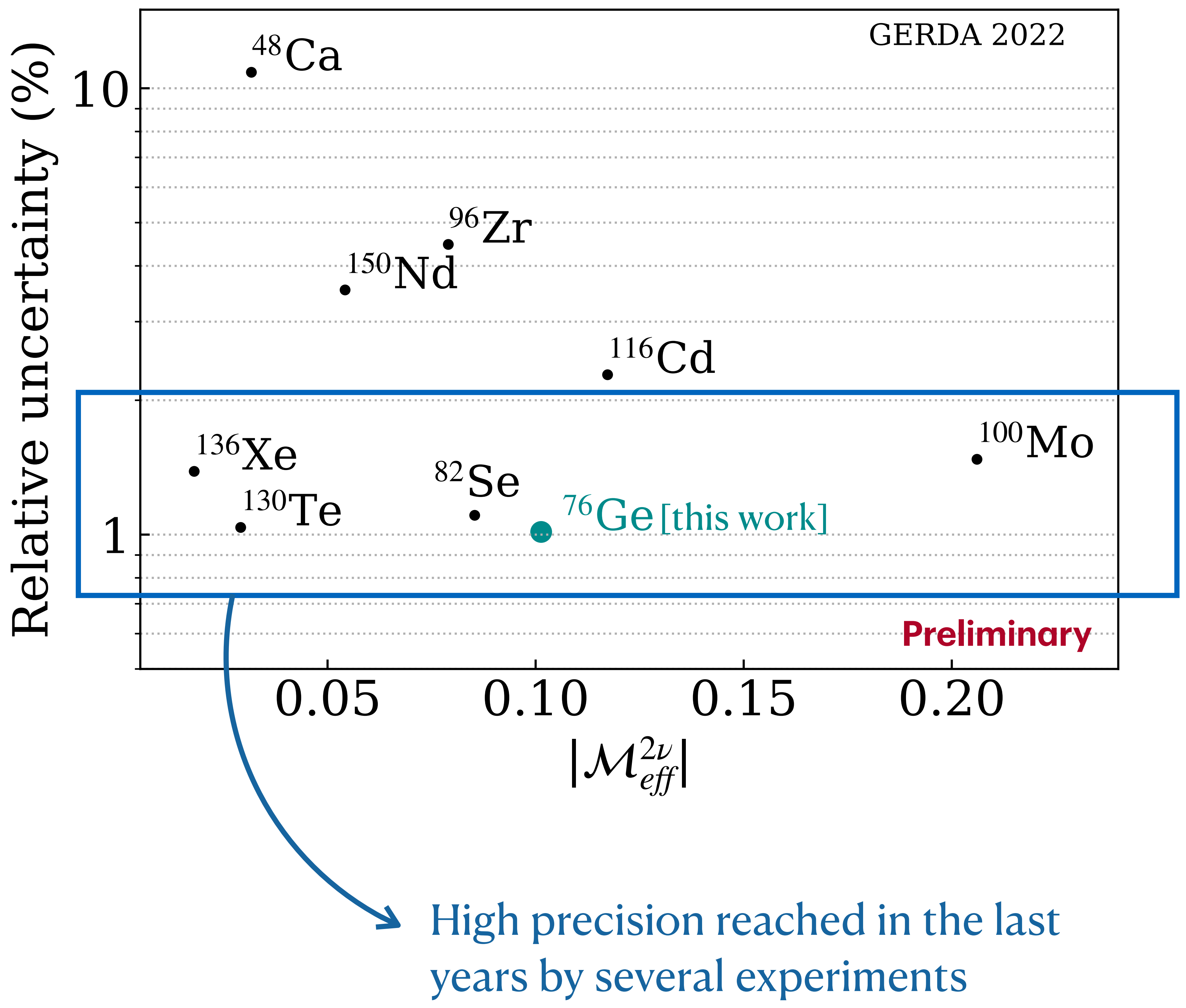
Effective nuclear matrix element

- The precision determination of the $2\nu\beta\beta$ decay half-life can be converted into the effective NME:

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

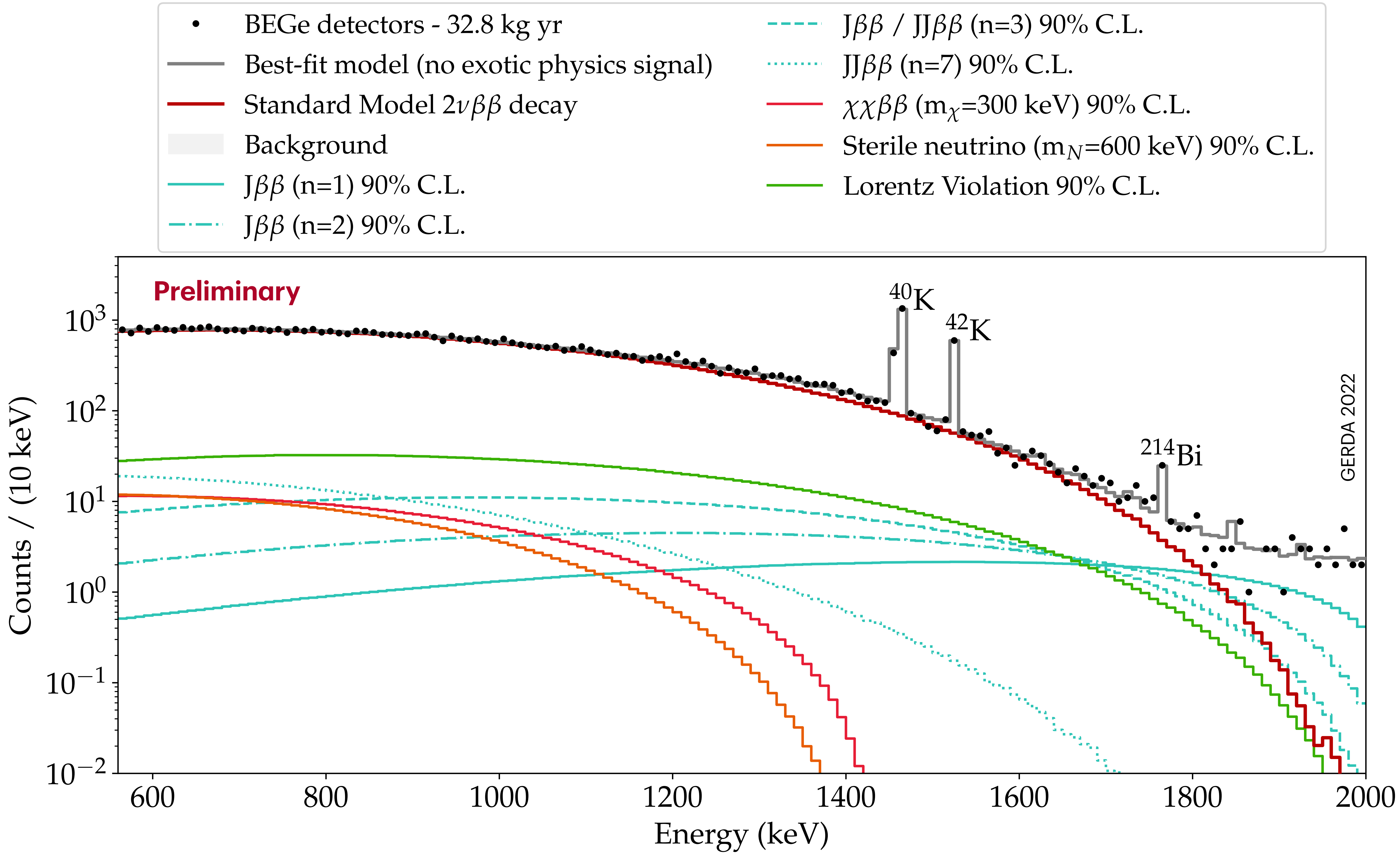
[Phase space from Phys. Rev. C 85, 034316 (2012)]

- With the phase space $G^{2\nu}$= 48.17 10^{21} yr^{-1}, our measurement gives: $| \mathcal{M}_{eff}^{2\nu} |$ = 0.101(1)
- This can be used to validate and improve nuclear-structure calculations and benefit the interpretation of future $0\nu\beta\beta$ decay discoveries.



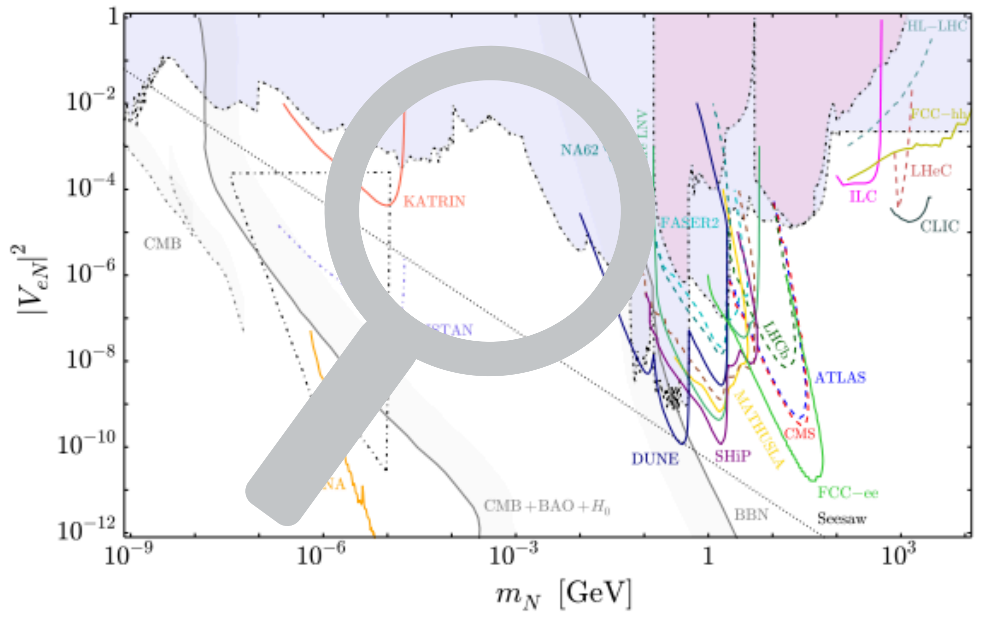
Summary of exotic physics searches

Energy distributions of exotic decays normalized to the 90% C.L. limits

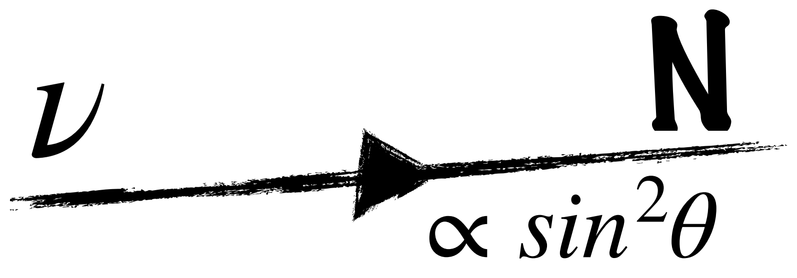


Sterile neutrino & Z_2-odd fermions

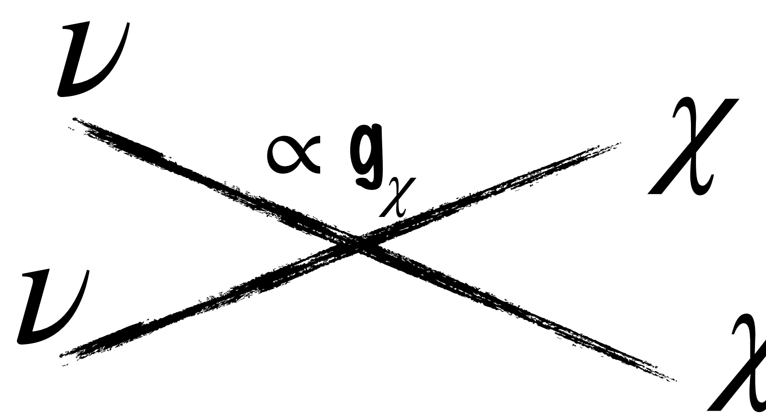
Sensitivity of current and future double-beta decay experiments



arXiv:1912.03058



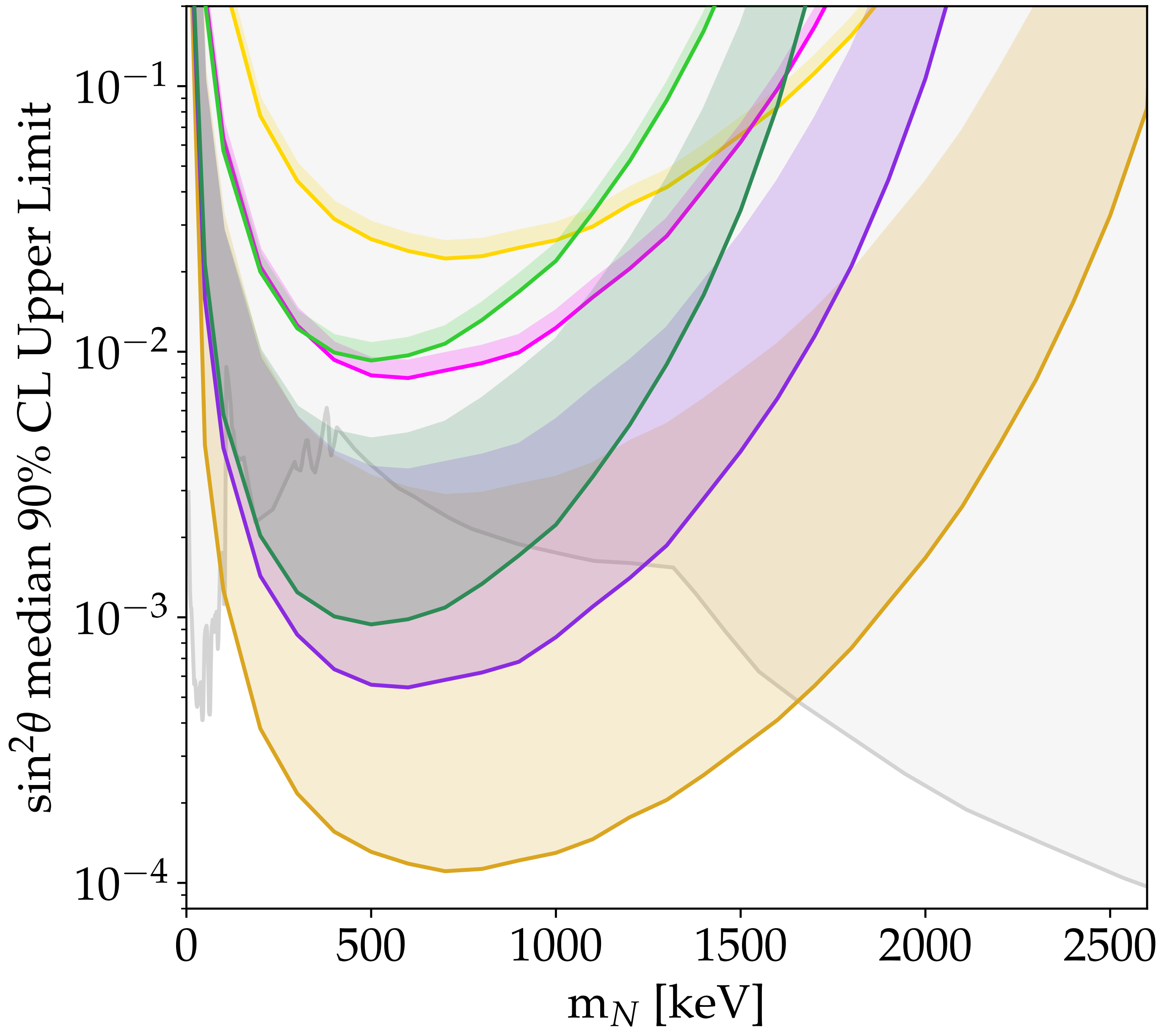
$(A,Z) \rightarrow (A,Z+2) + 2e + \bar{\nu} + N$

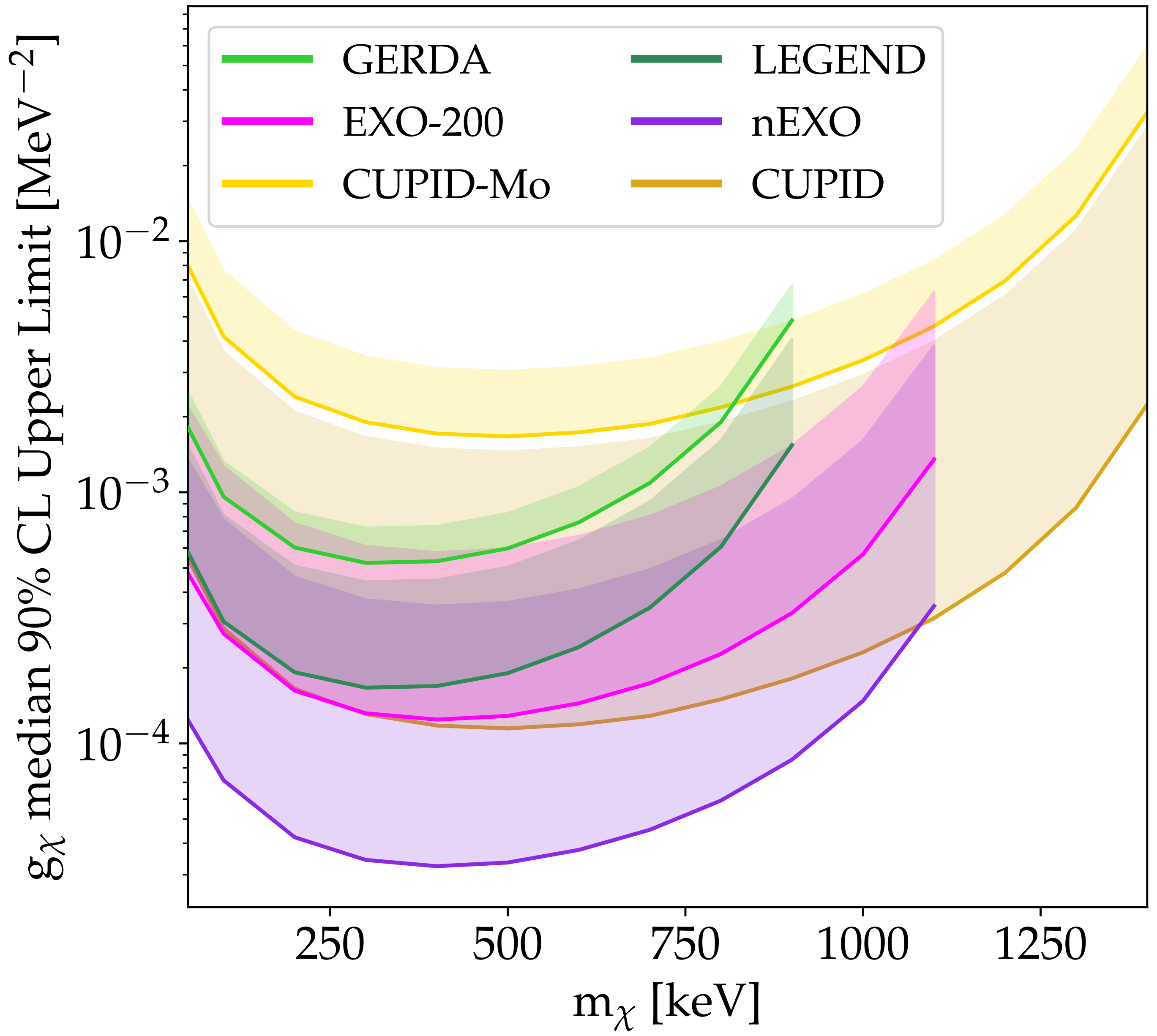


$(A,Z) \rightarrow (A,Z+2) + 2e + 2\chi$

[Phys. Let. B 815 (2021)]

- Only weak constraints on sterile neutrinos in the mass range between 100 keV and 10 MeV
- **Future double-beta decay experiments can improve these bounds**





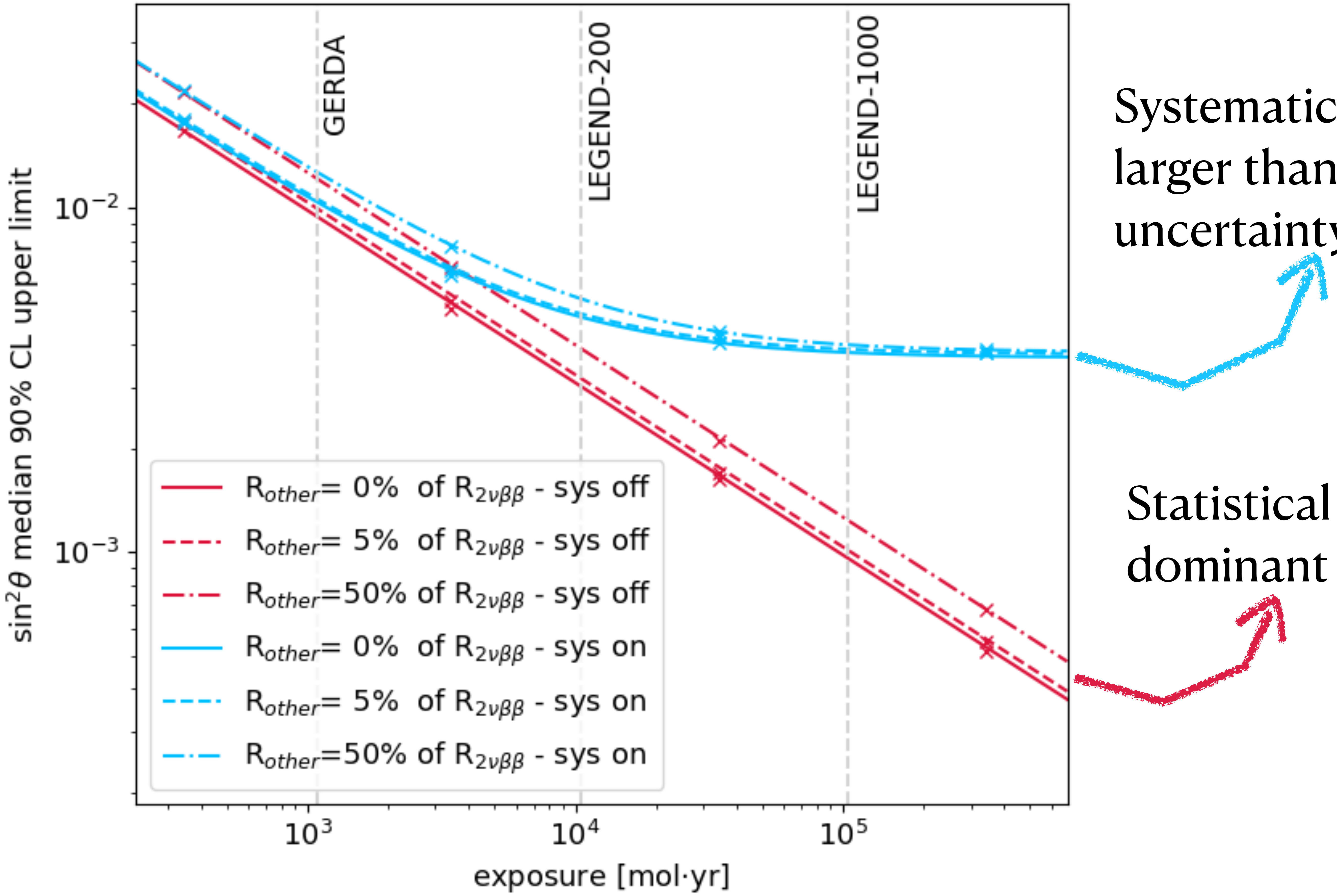
- **No laboratory constraints exist on Z2-odd fermions**

Impact of the systematic uncertainties on future searches

Background rate: dominant $R_{2\nu\beta\beta}$ + other contributions

Systematic uncertainty: parametrized by energy-dependent function $s(E)=1+aE+bE^2+c/E$, with a,b, and c normal distributed around 0 with $\sigma_a,\sigma_b,\sigma_c$.

[Phys. Let. B 815 (2021)]



Systematic uncertainty larger than statistical uncertainty

Statistical uncertainty dominant