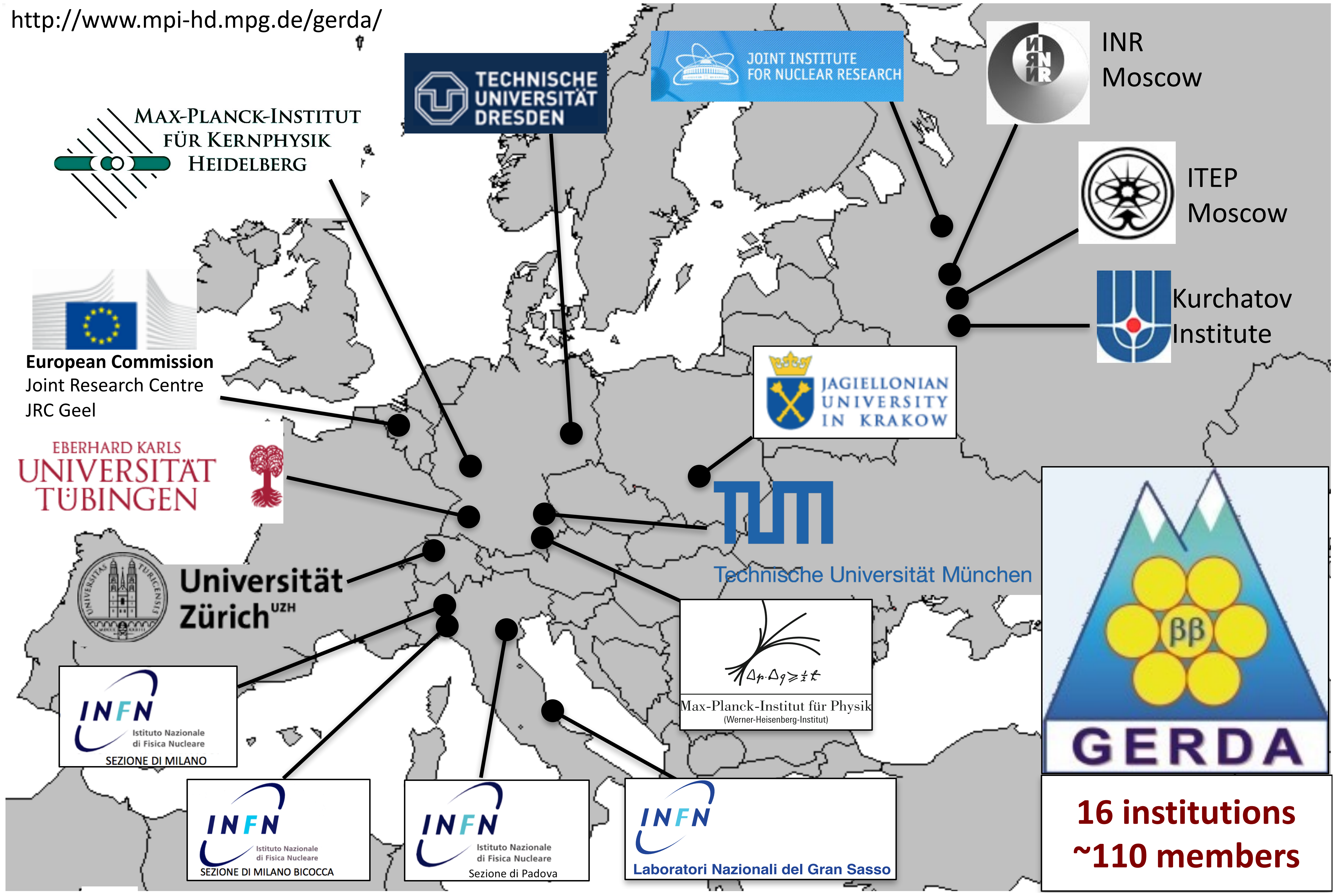
Search for ^{76}Ge $0\nu\beta\beta$ decay and beyond with the GERDA experiment

Elisabetta Bossio (TUM), on behalf of the GERDA Collaboration
IPA2022 Vienna, 8 September 2022

The GERDA Collaboration

Collaboration meeting:
LNGS June 2022

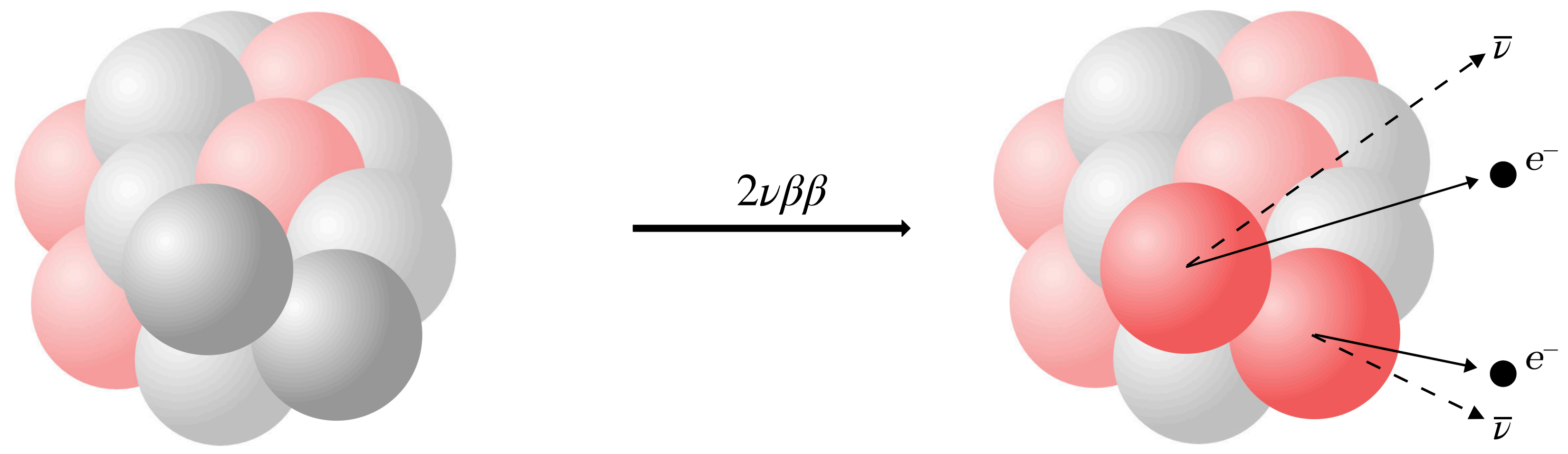


16 institutions
~110 members

The physics goal

The question of lepton number violation and the Majorana nature of neutrinos

- Double-beta decay transitions: the atomic number changes by two units while the number of nucleons stays constant
- Allowed in the Standard Model of particle physics if two electrons and two anti-neutrino are emitted to ensure lepton number conservation ($2\nu\beta\beta$ decay):
  $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\overline{\nu}$
- Observed in 11 isotopes (half-life $T_{1/2} \sim 10^{18} - 10^{24}$ yr)



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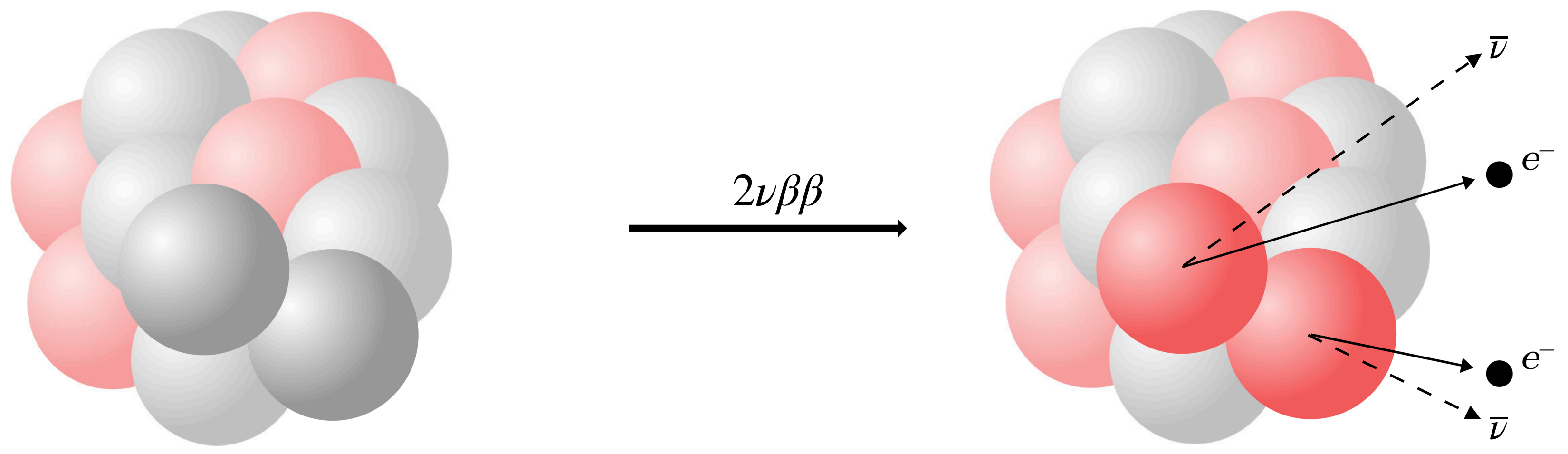
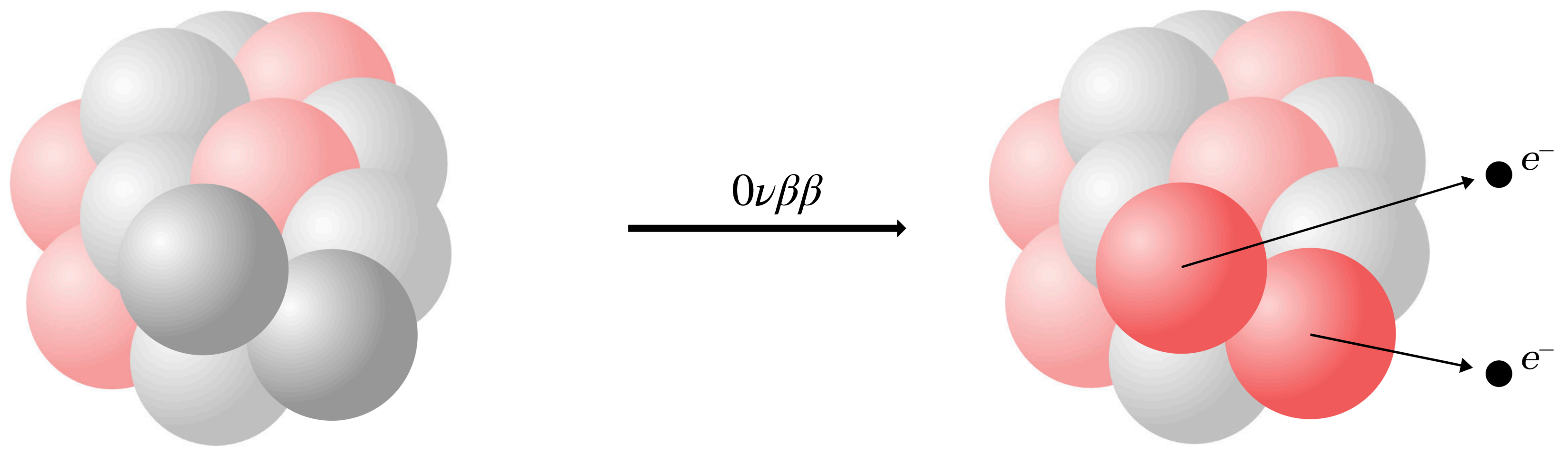
- Observed in 11 isotopes (half-life $T_{1/2} \sim 10^{18} - 10^{24}$ yr)

- Neutrino-less double-beta ($0\nu\beta\beta$) decay is predicted in BSM theories: only two electrons are emitted
- Imply Lepton number non-conservation and that neutrinos have a Majorana mass component
- Provide information about the neutrino mass through the effective Majorana mass: $m_{\beta\beta} = \sum_i U_{ei}^2 m_i$

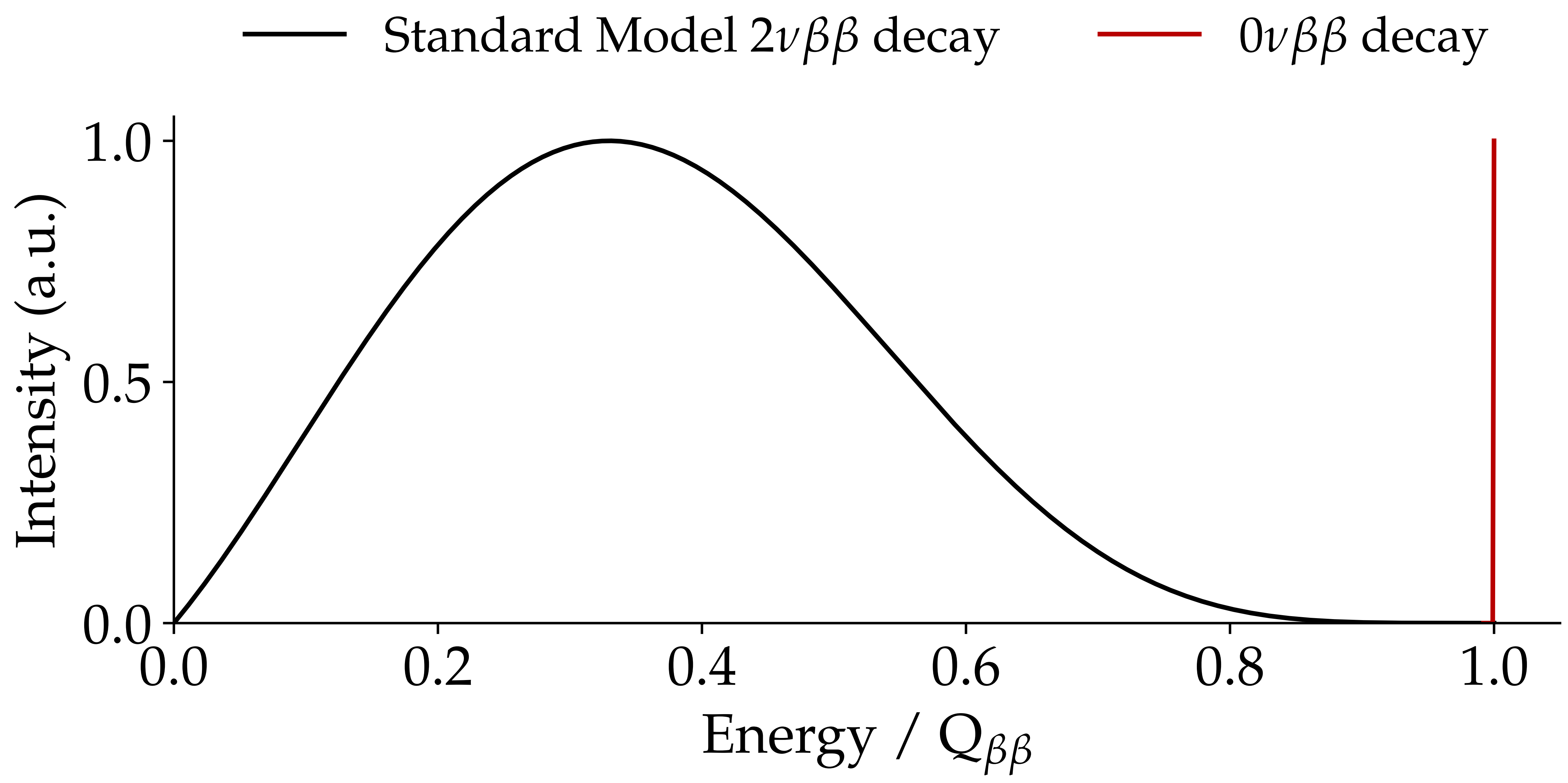




The physics goal

The question of lepton number violation and the Majorana nature of neutrinos

The experimental signature of the $0\nu\beta\beta$ decay is a peak at the $Q_{\beta\beta}$, while the SM $2\nu\beta\beta$ decay events are continuously distributed between 0 and $Q_{\beta\beta}$.



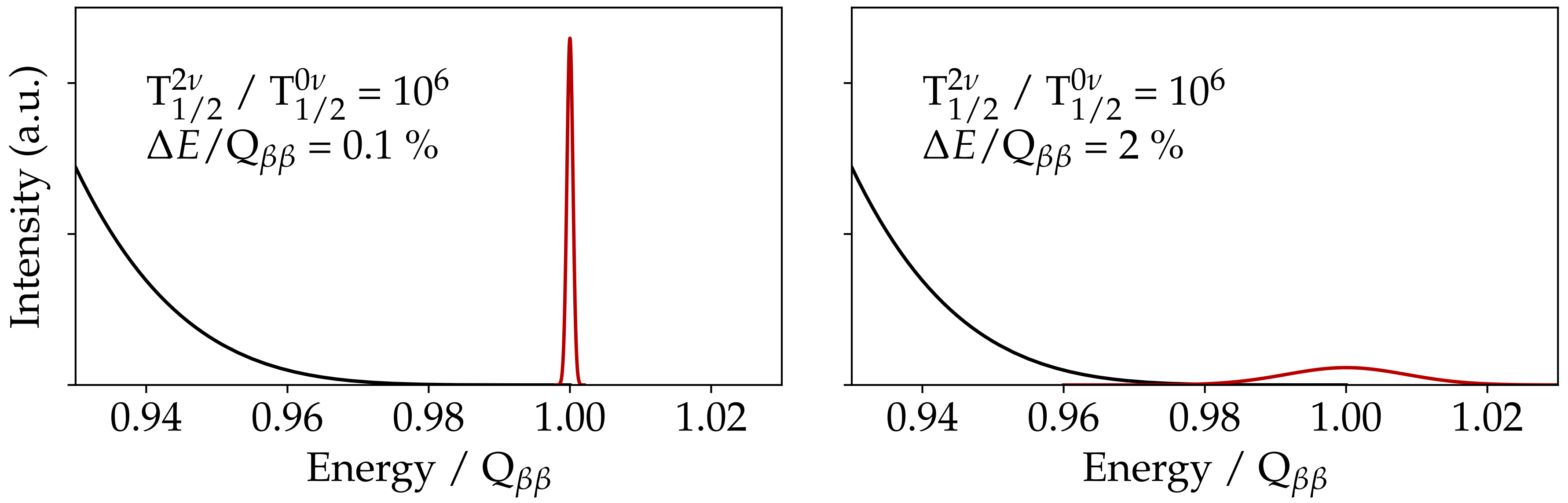
Experimental approach

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



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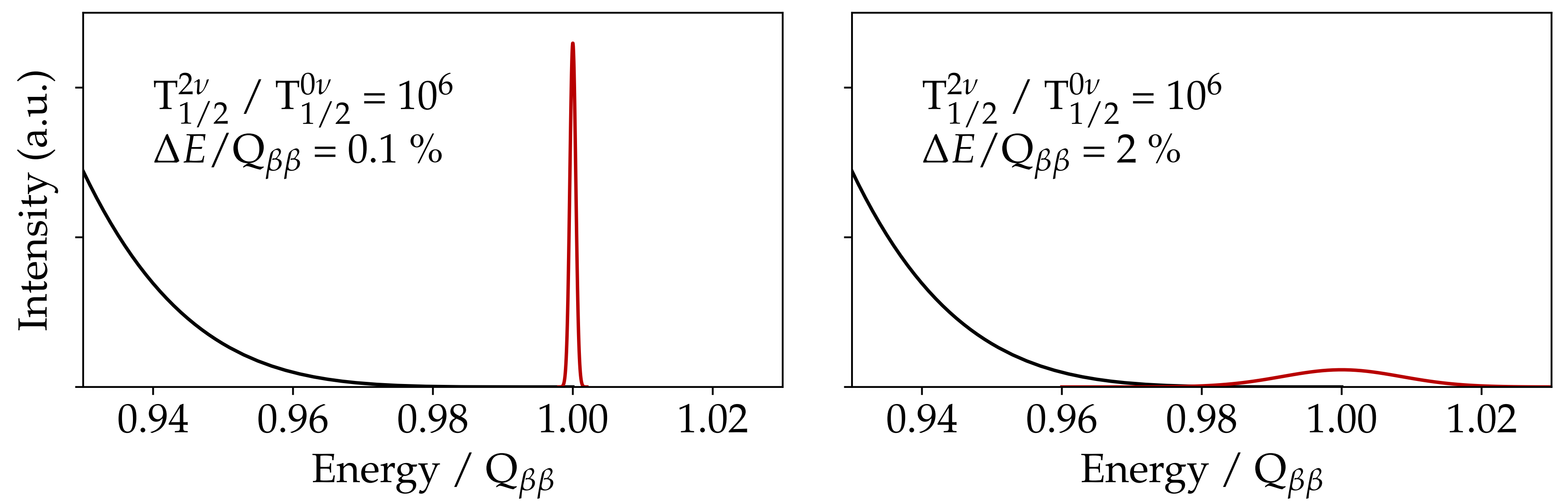
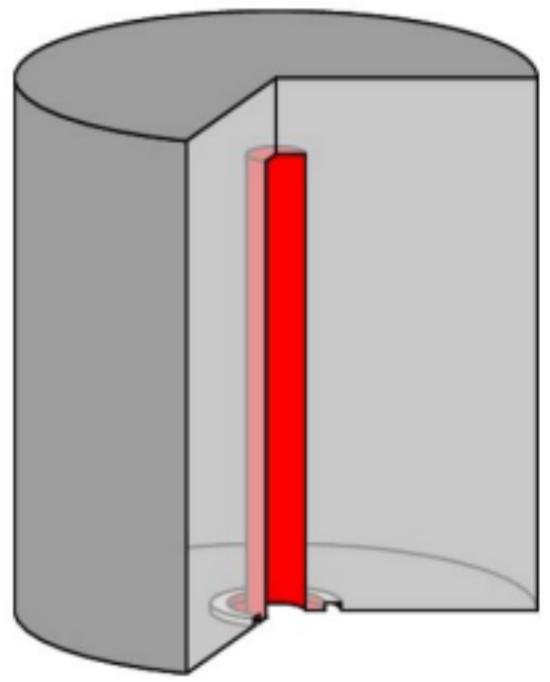
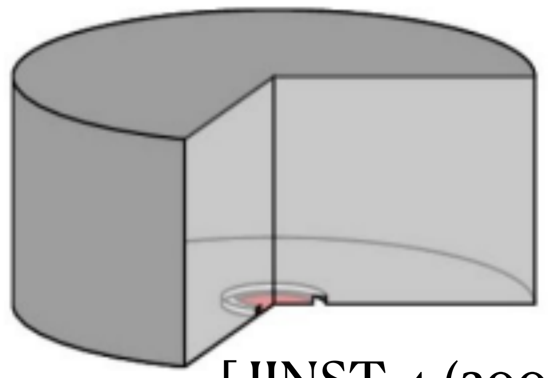


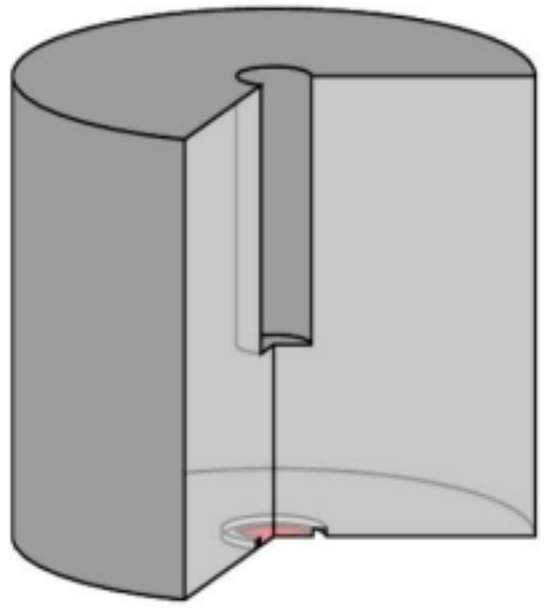


7 (later 6) Coaxial detectors (15.6 kg, later 14.6 kg):
- [x] Big
- [ ] Good PSD performance



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

[JINST 4 (2009) P10007]



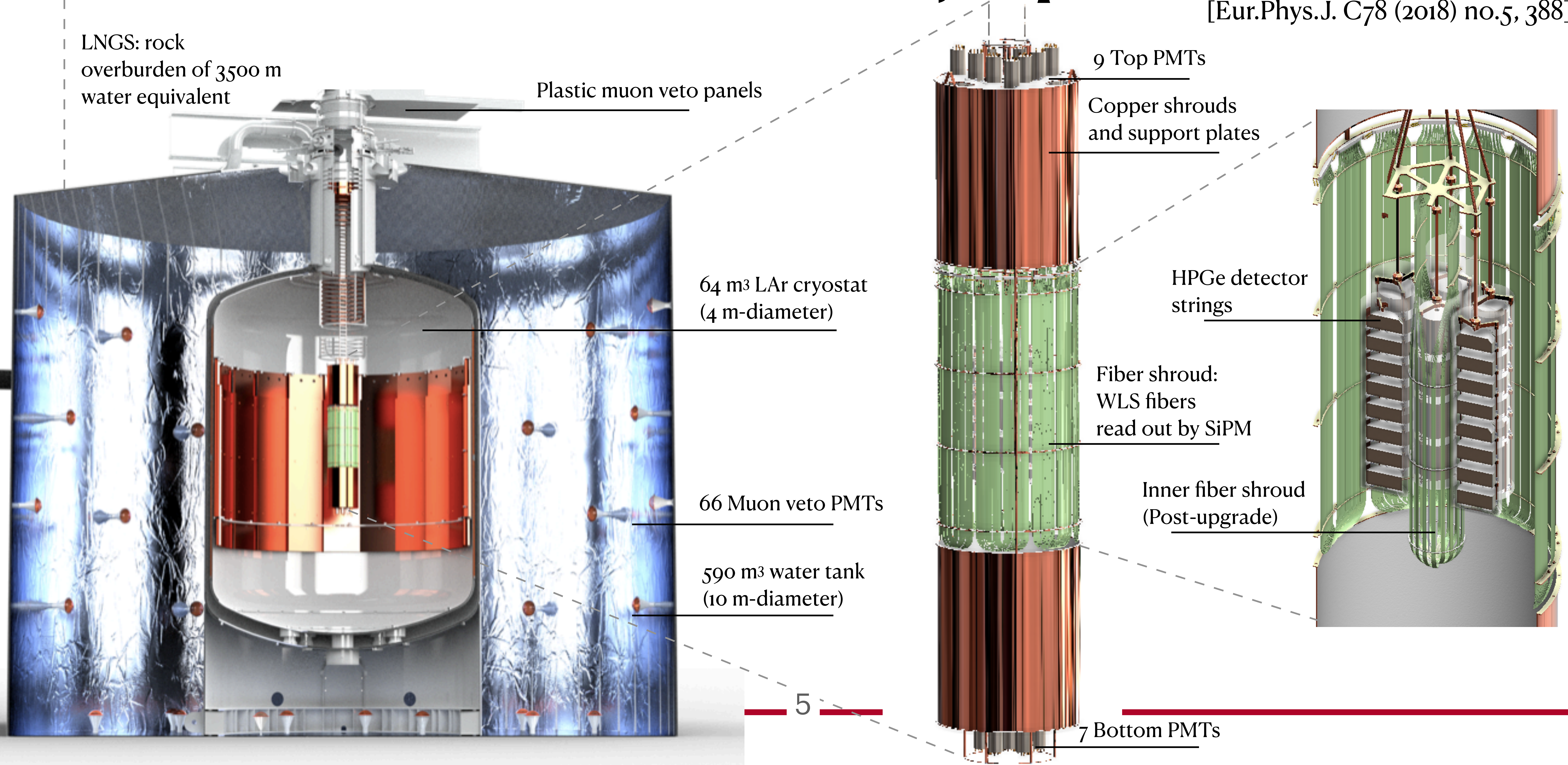
5 Inverted Coaxial detectors added after upgrade (9.6 kg):
- [x] Big
- [x] Very good PSD performance

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

The GERmanium Detector Array experiment at LNGS

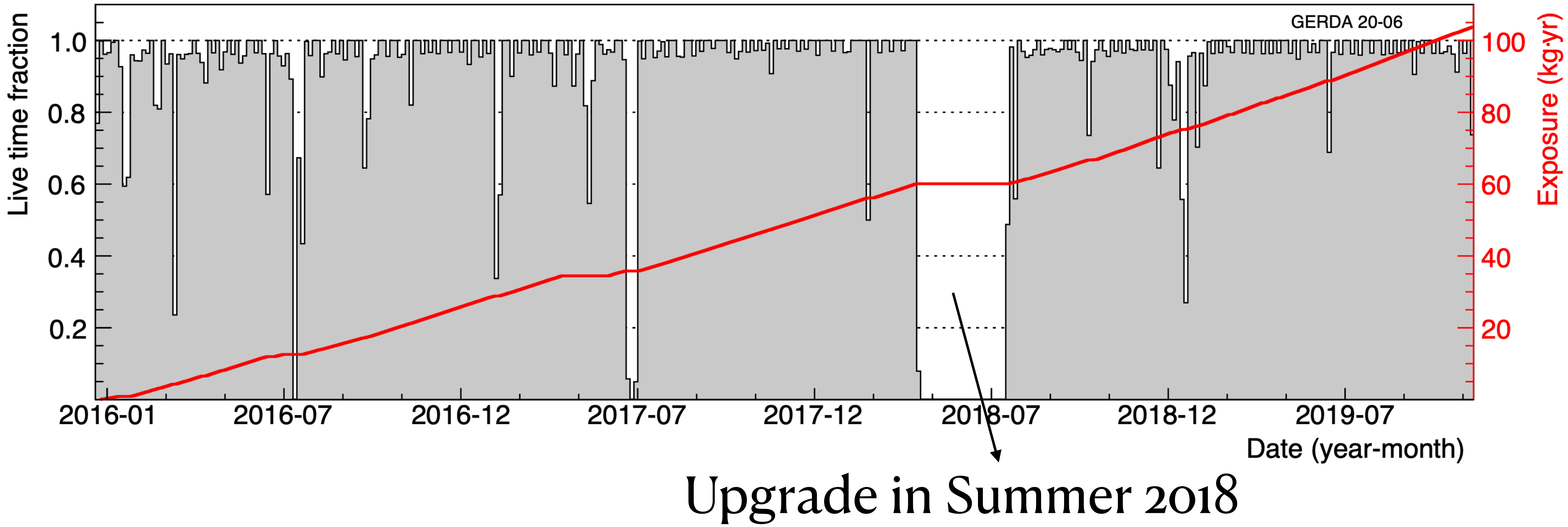
[Eur.Phys.J. C78 (2018) no.5, 388]

LNGS: rock overburden of 3500 m water equivalent



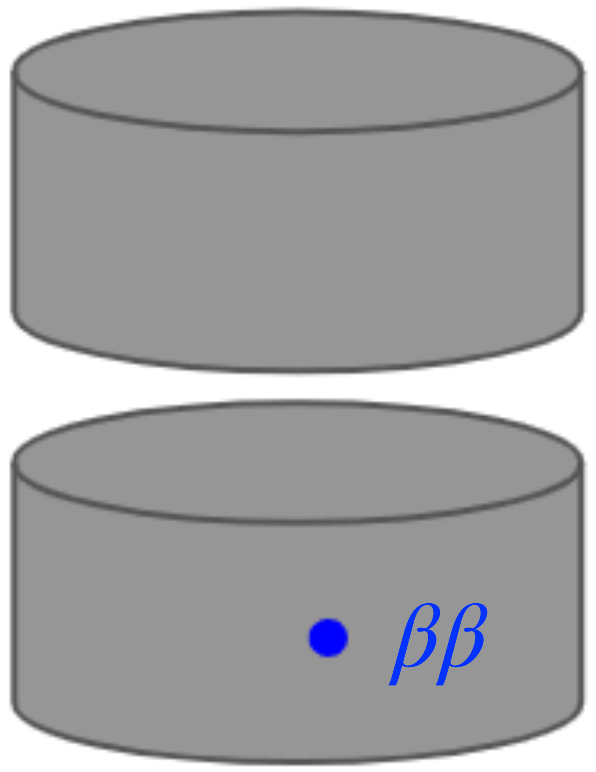
Phase II data taking & exposure

- 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)



Background discrimination by event topology

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



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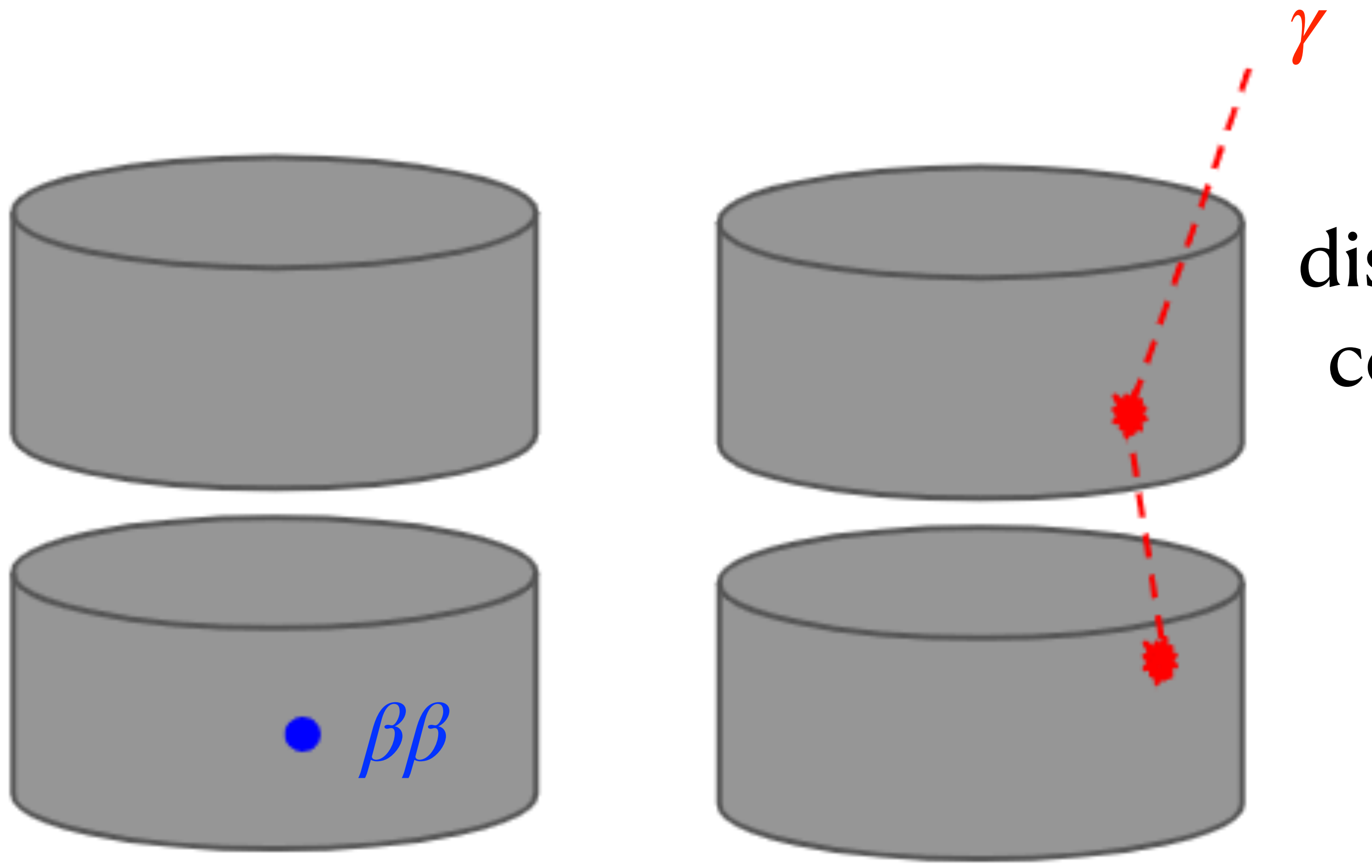

Detector-detector coincidences: discrimination by anti-coincidence (AC) cut

Background discrimination by event topology

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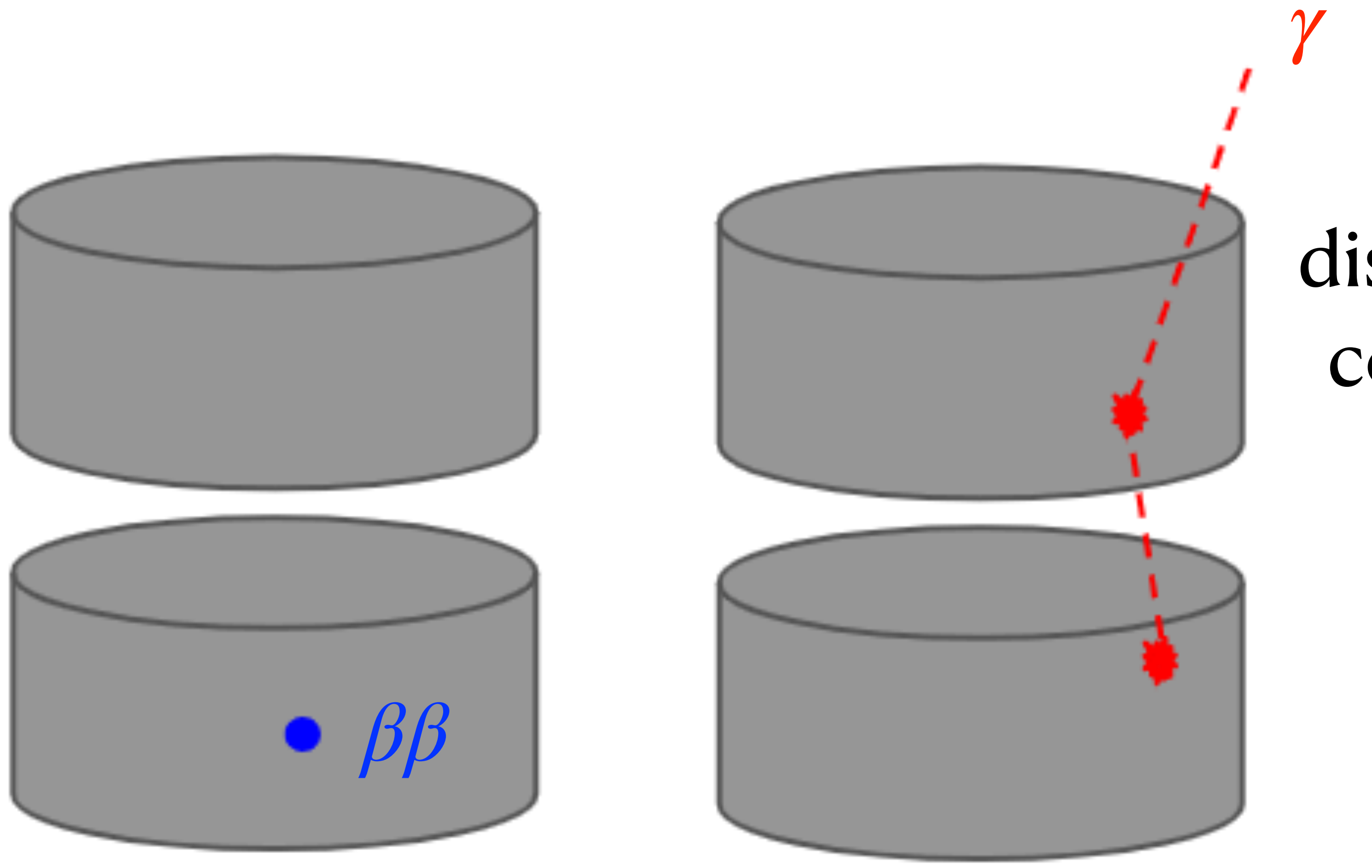

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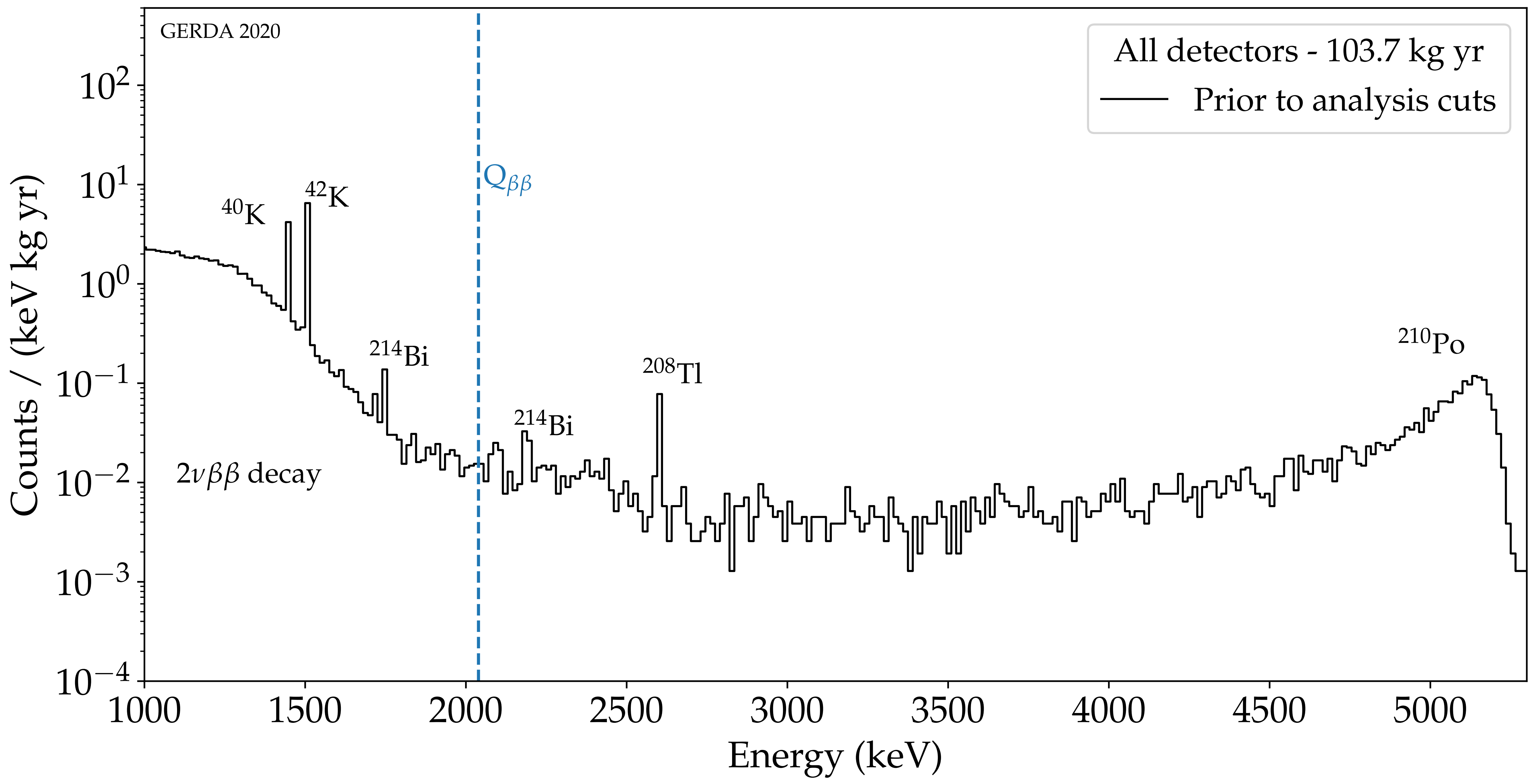
After AC cut only



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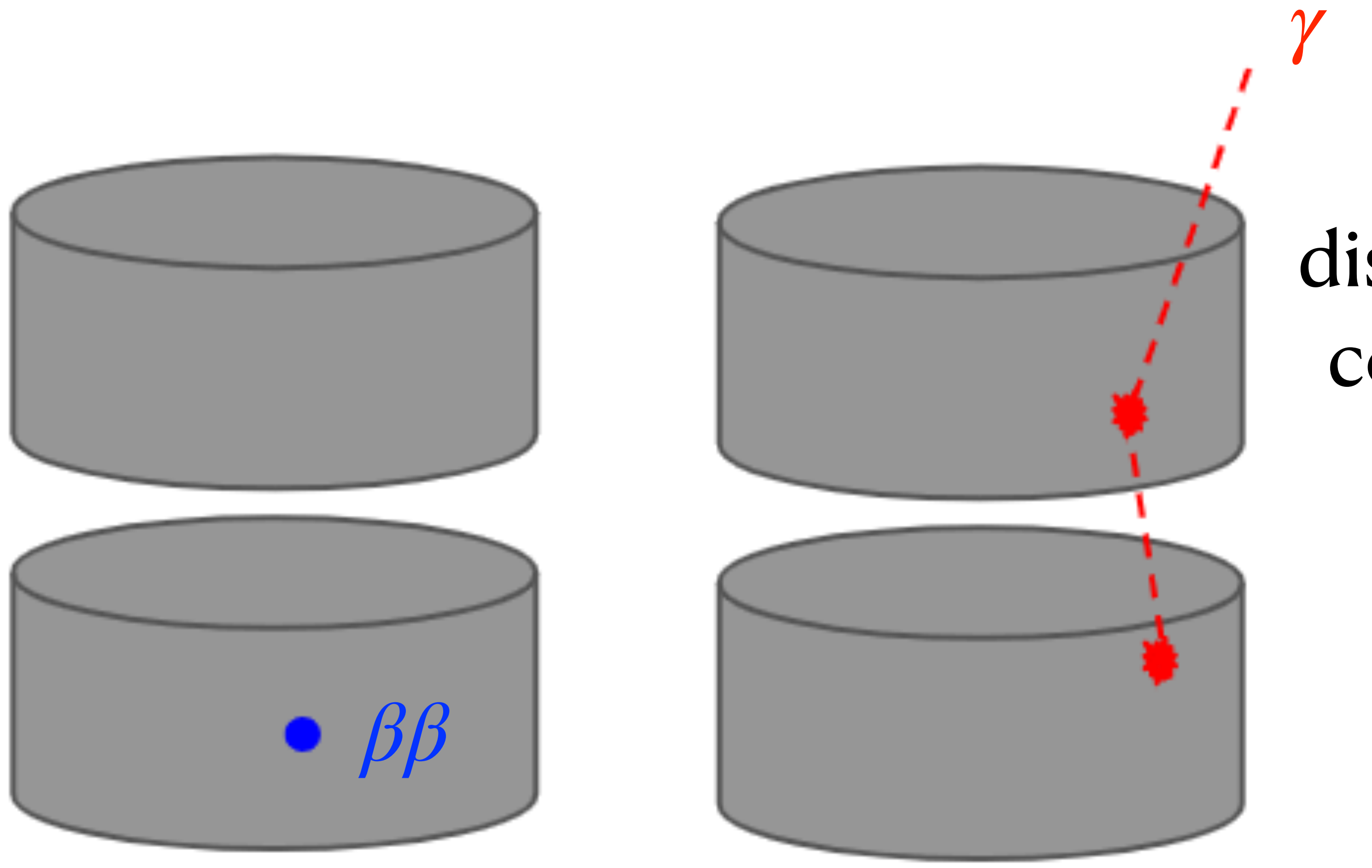

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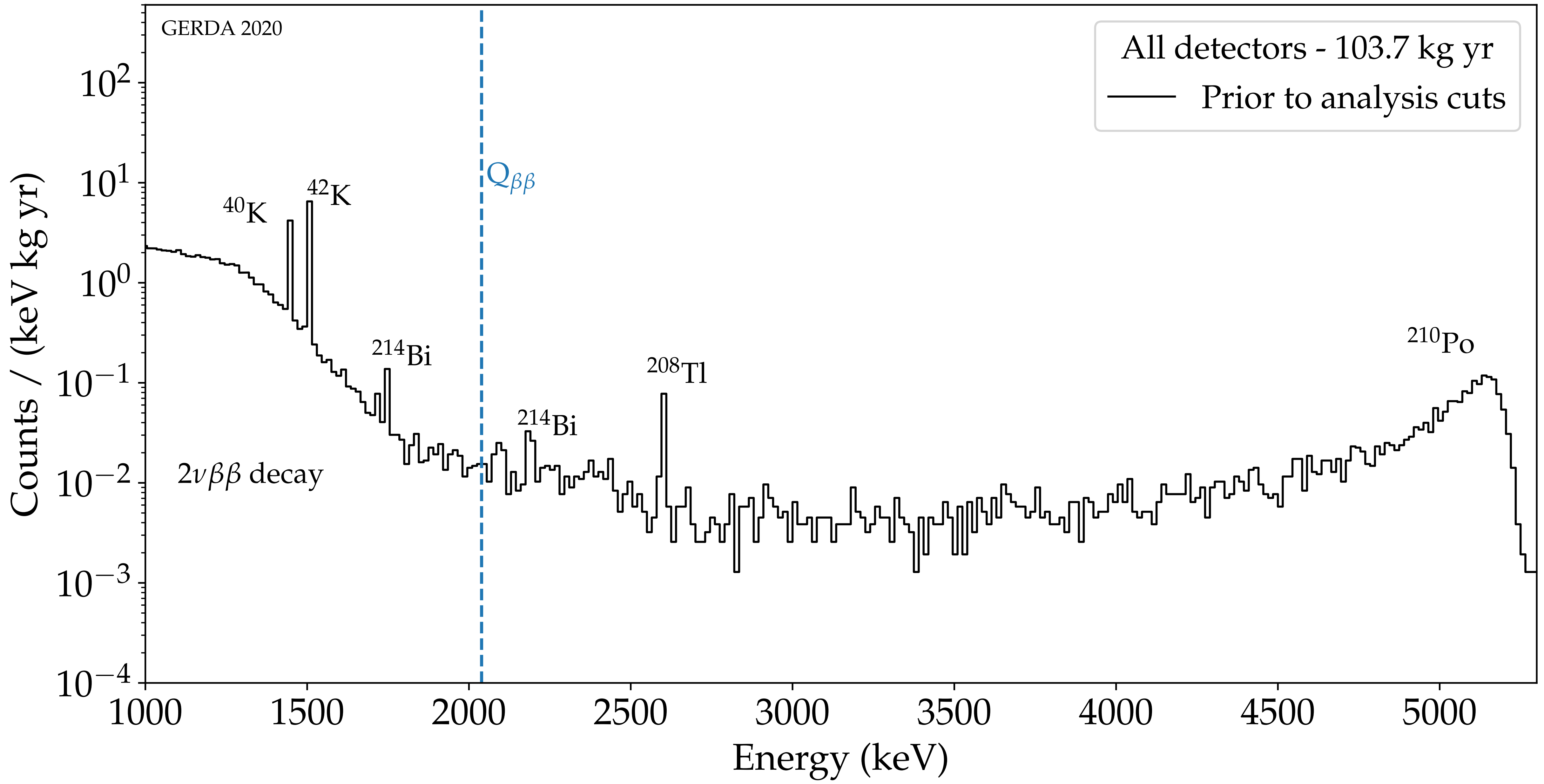
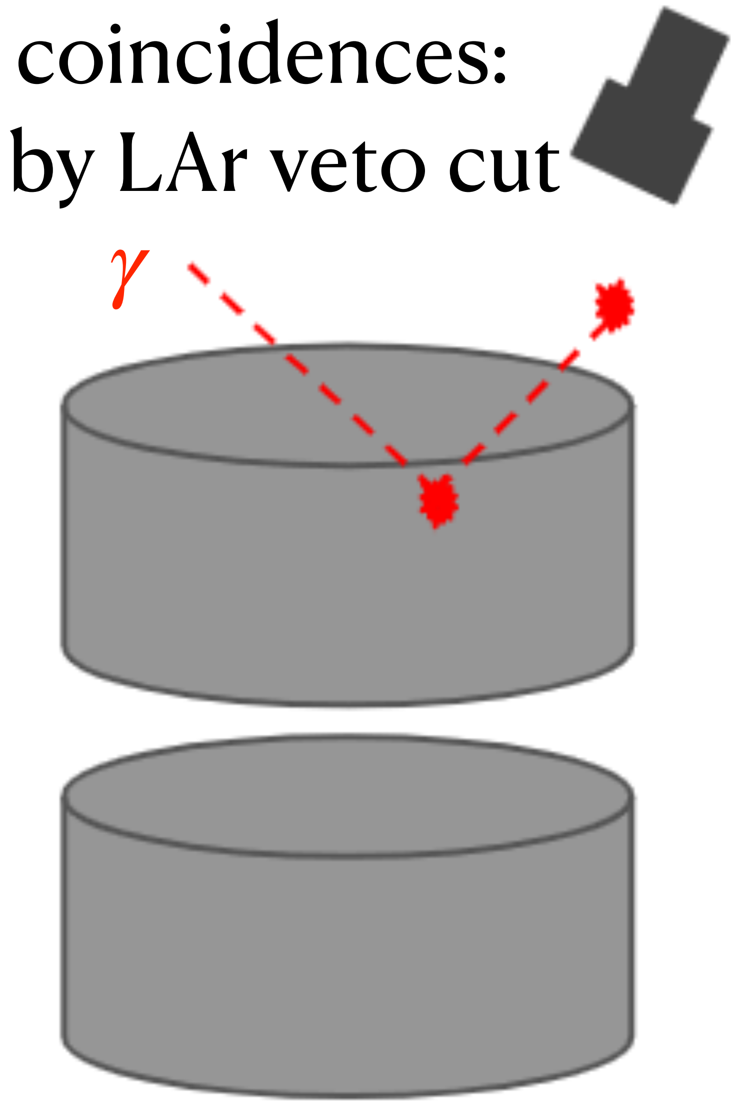


Detector-LAr coincidences: discrimination by LAr veto cut



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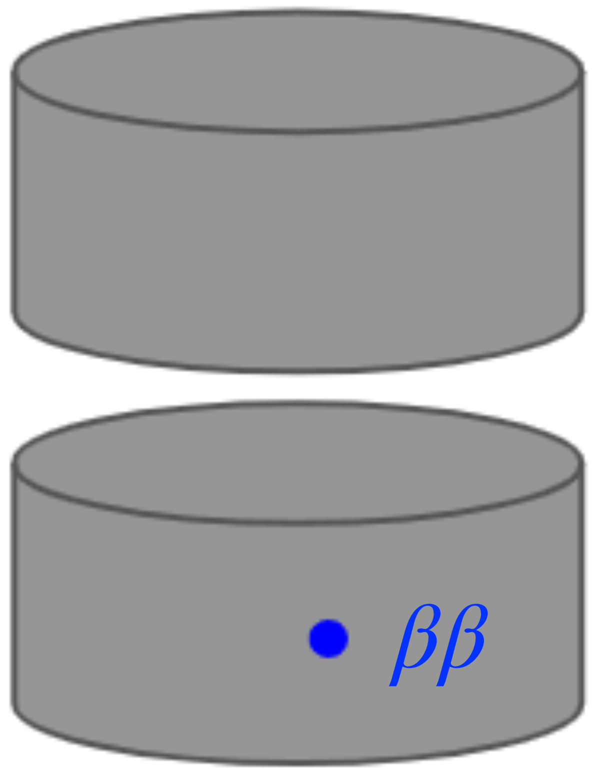
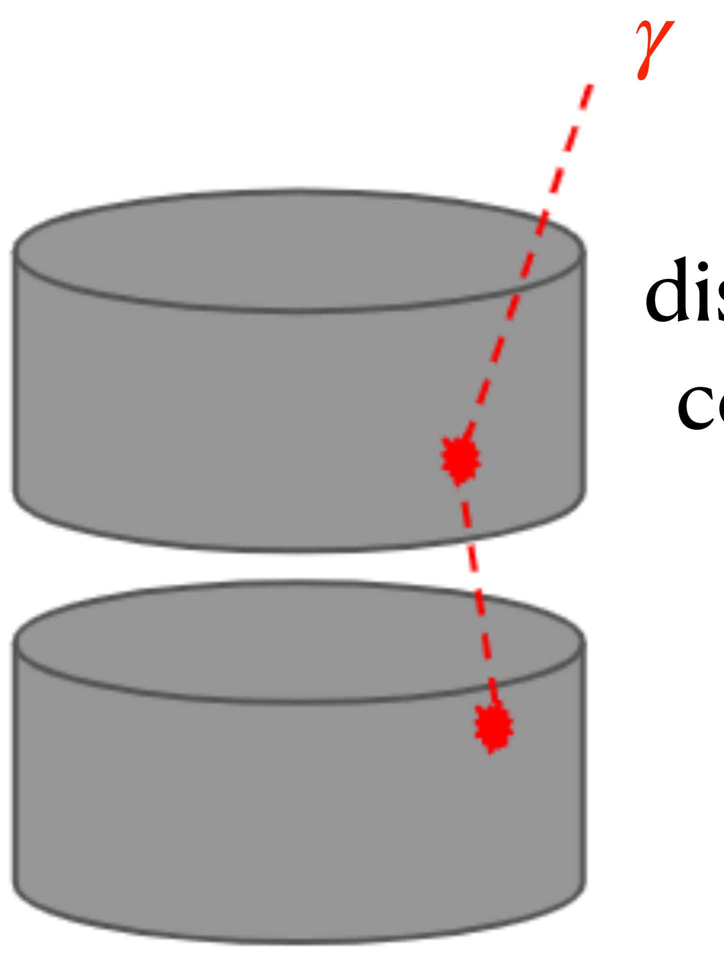
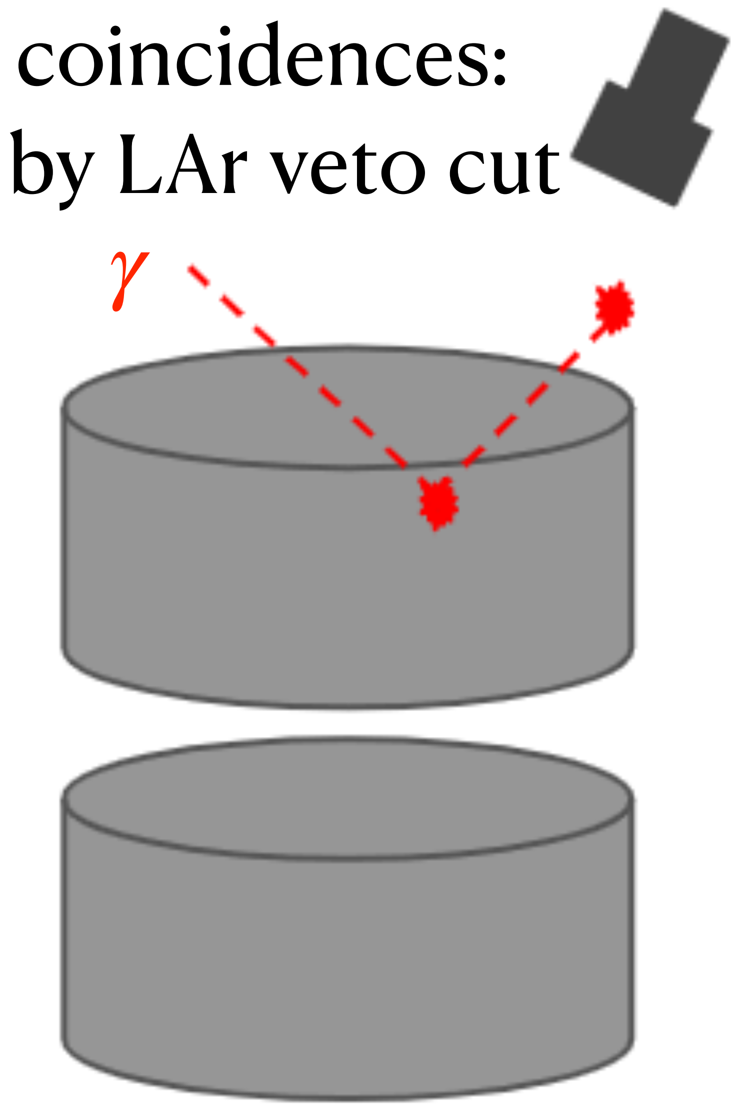


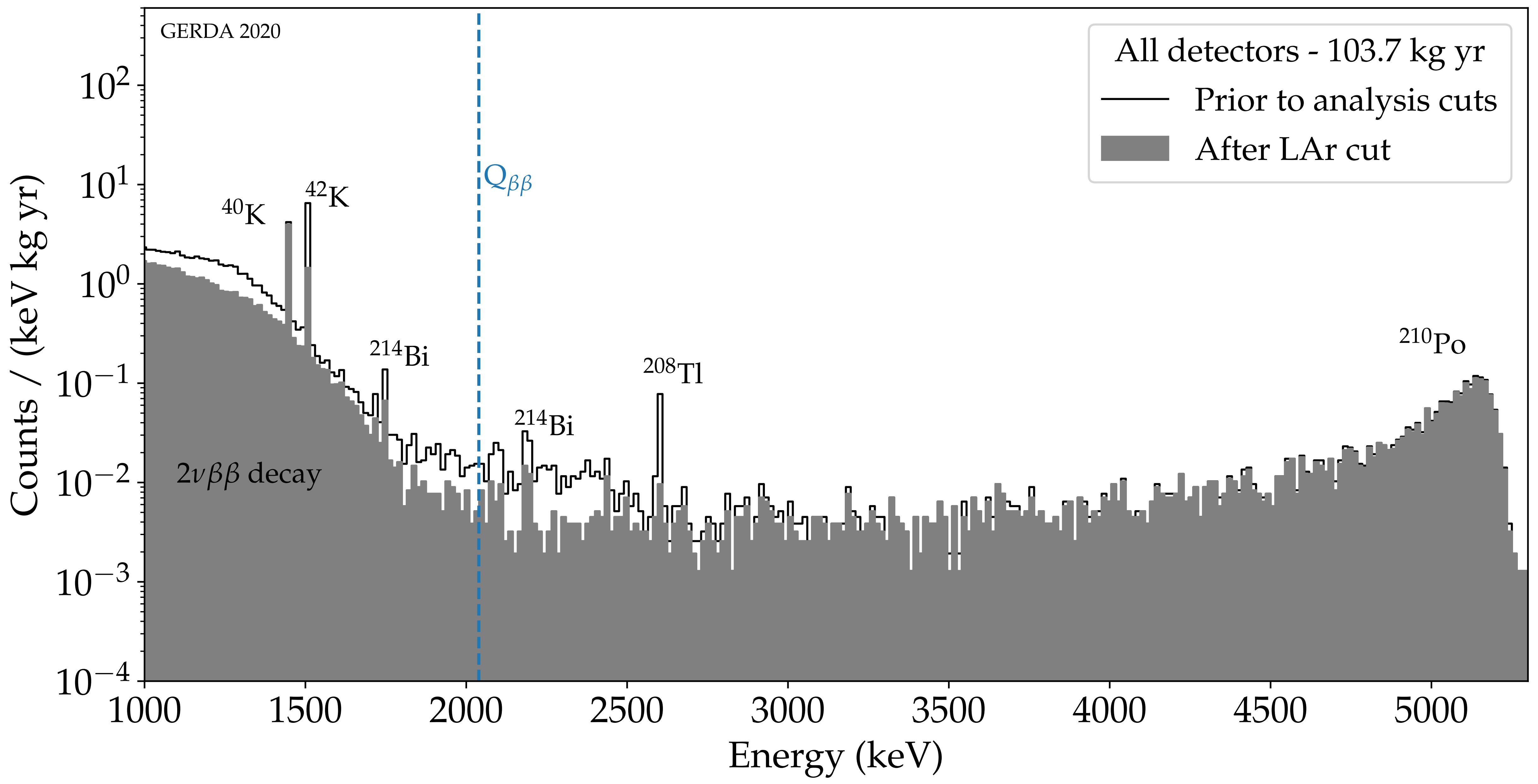
Detector-detector coincidences: discrimination by anti-coincidence (AC) cut



Detector-LAr coincidences: discrimination by LAr veto cut

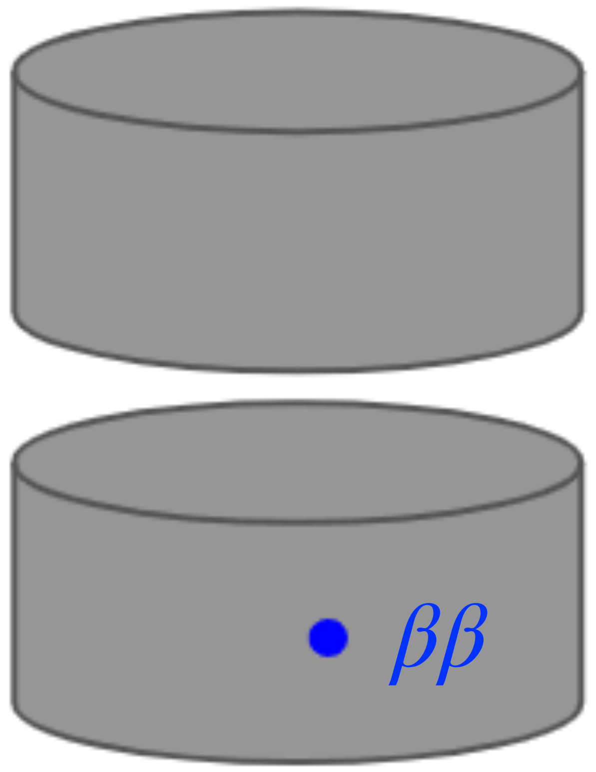


After AC and LAr veto cuts

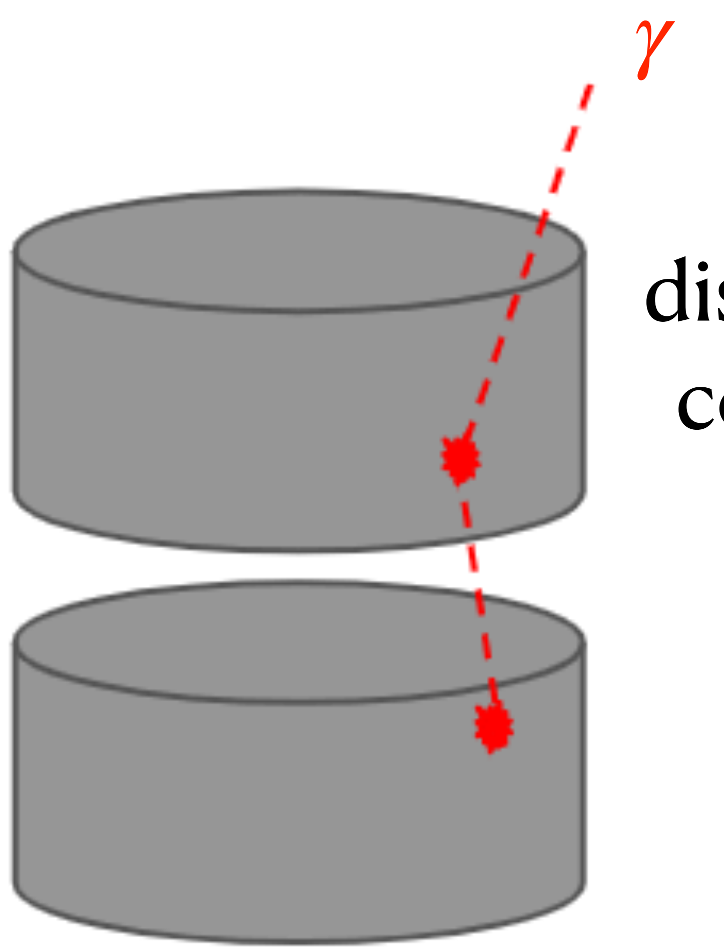


Background discrimination by event topology

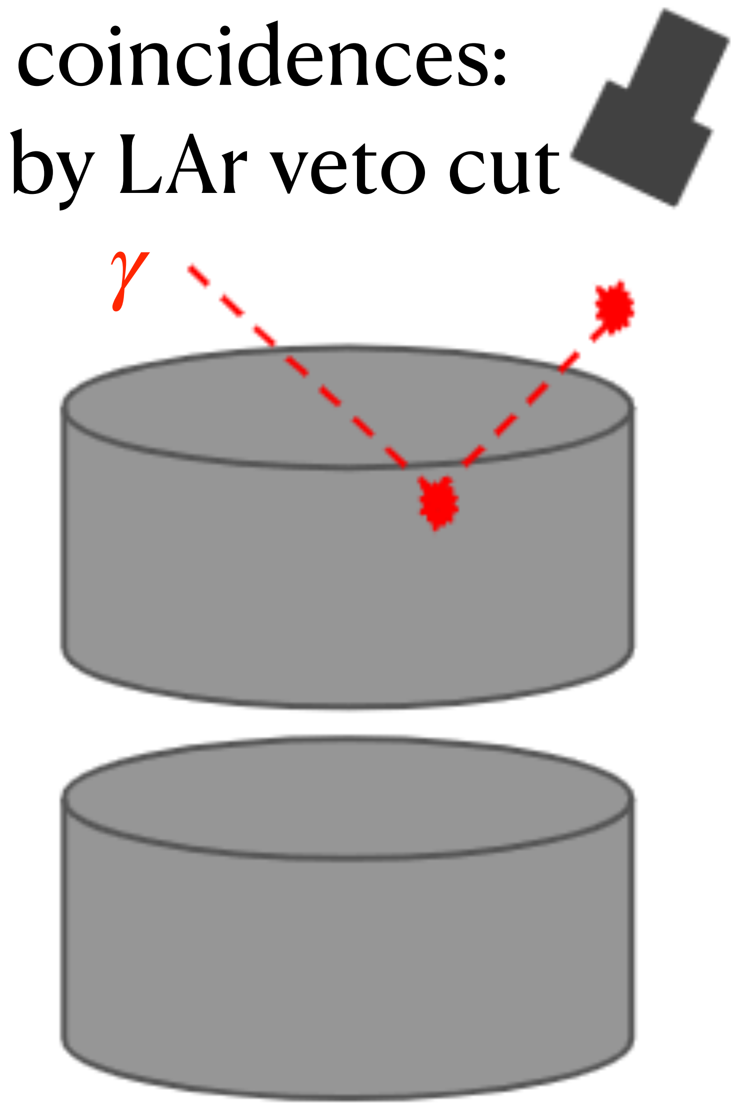
Double-beta decays: Single-site & single-detector

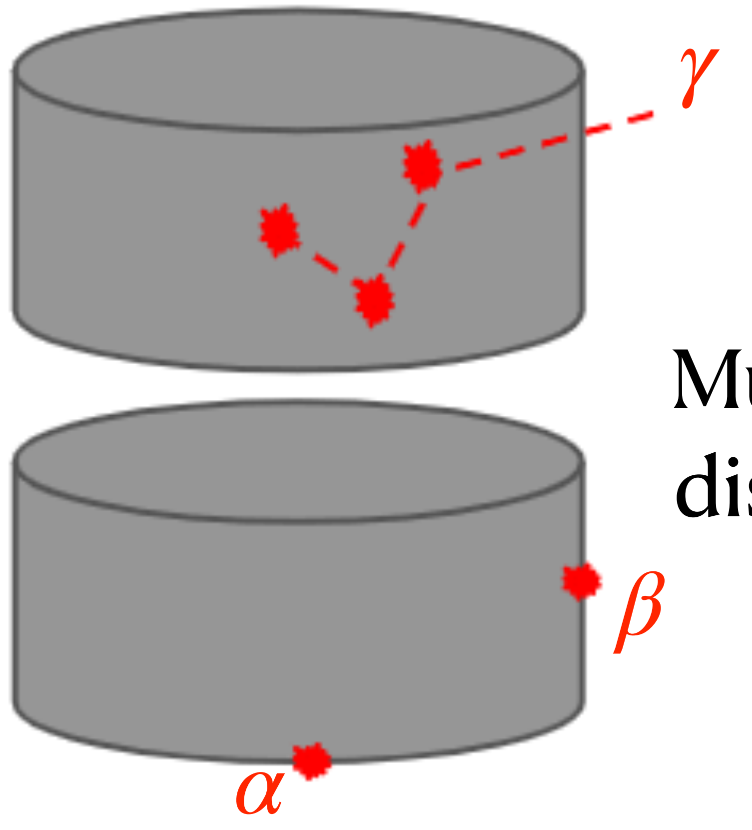


Detector-detector coincidences: discrimination by anti-coincidence (AC) cut



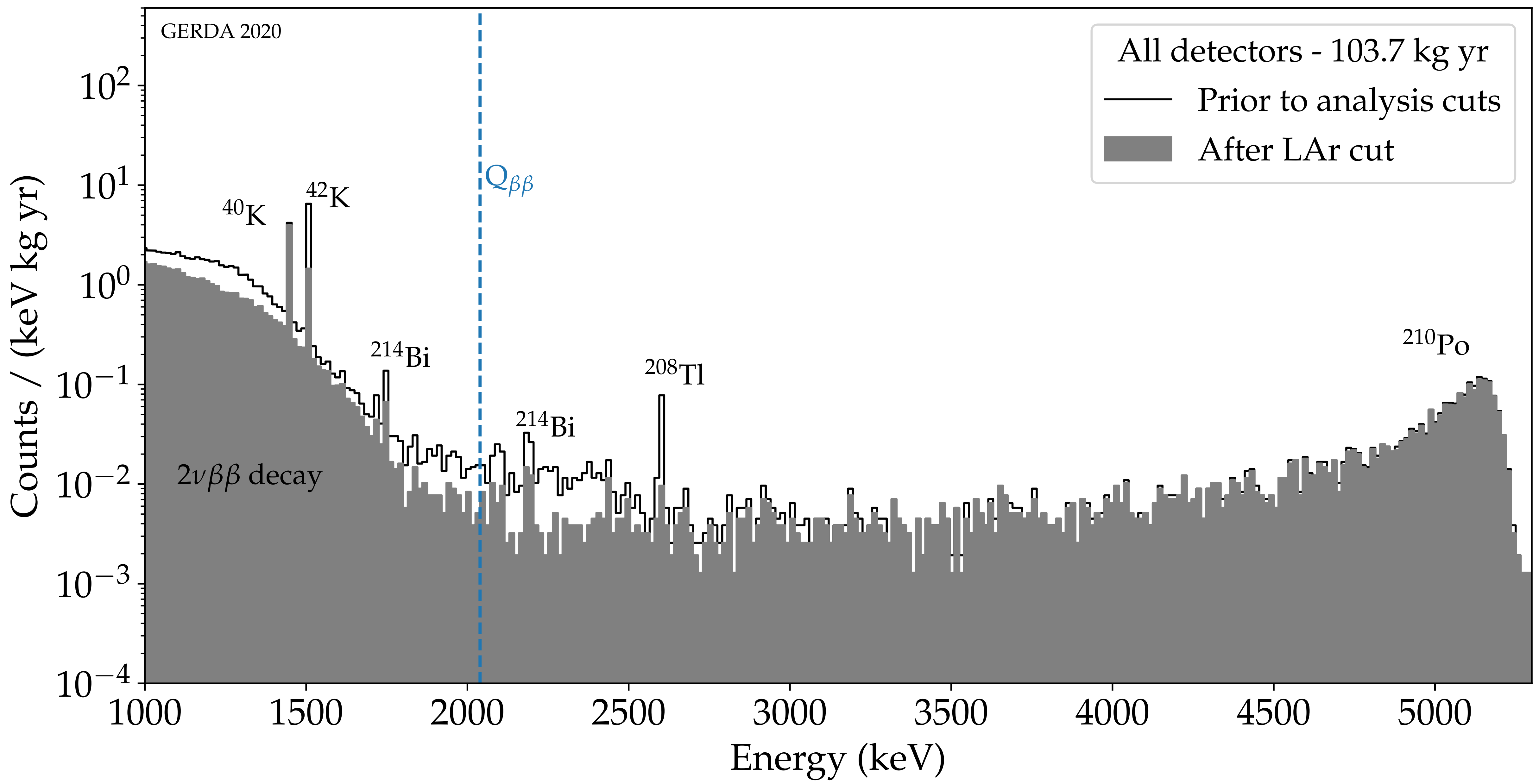
Detector-LAr coincidences: discrimination by LAr veto cut





Multi-site / surface events: discrimination by PSD cut

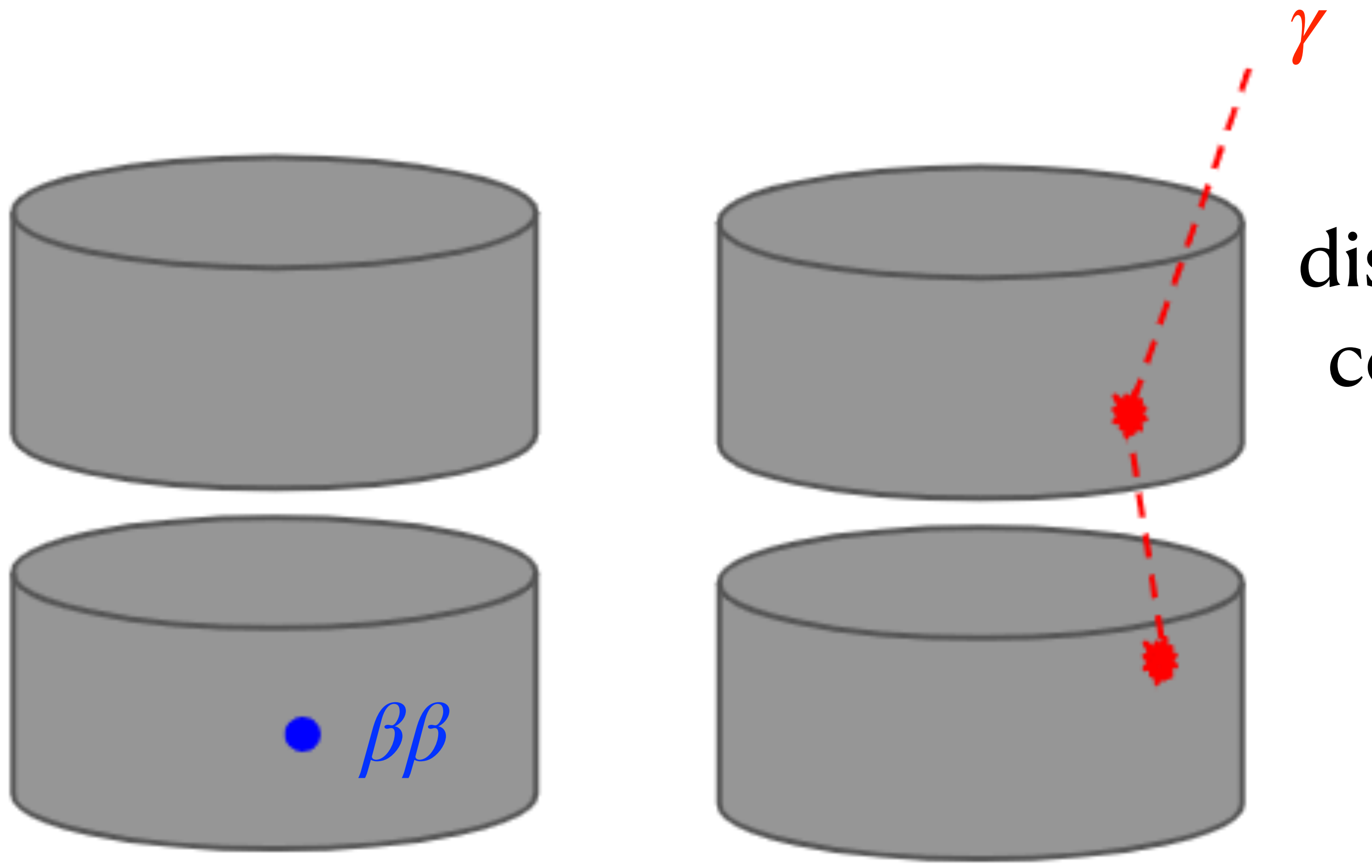
After AC and LAr veto cuts



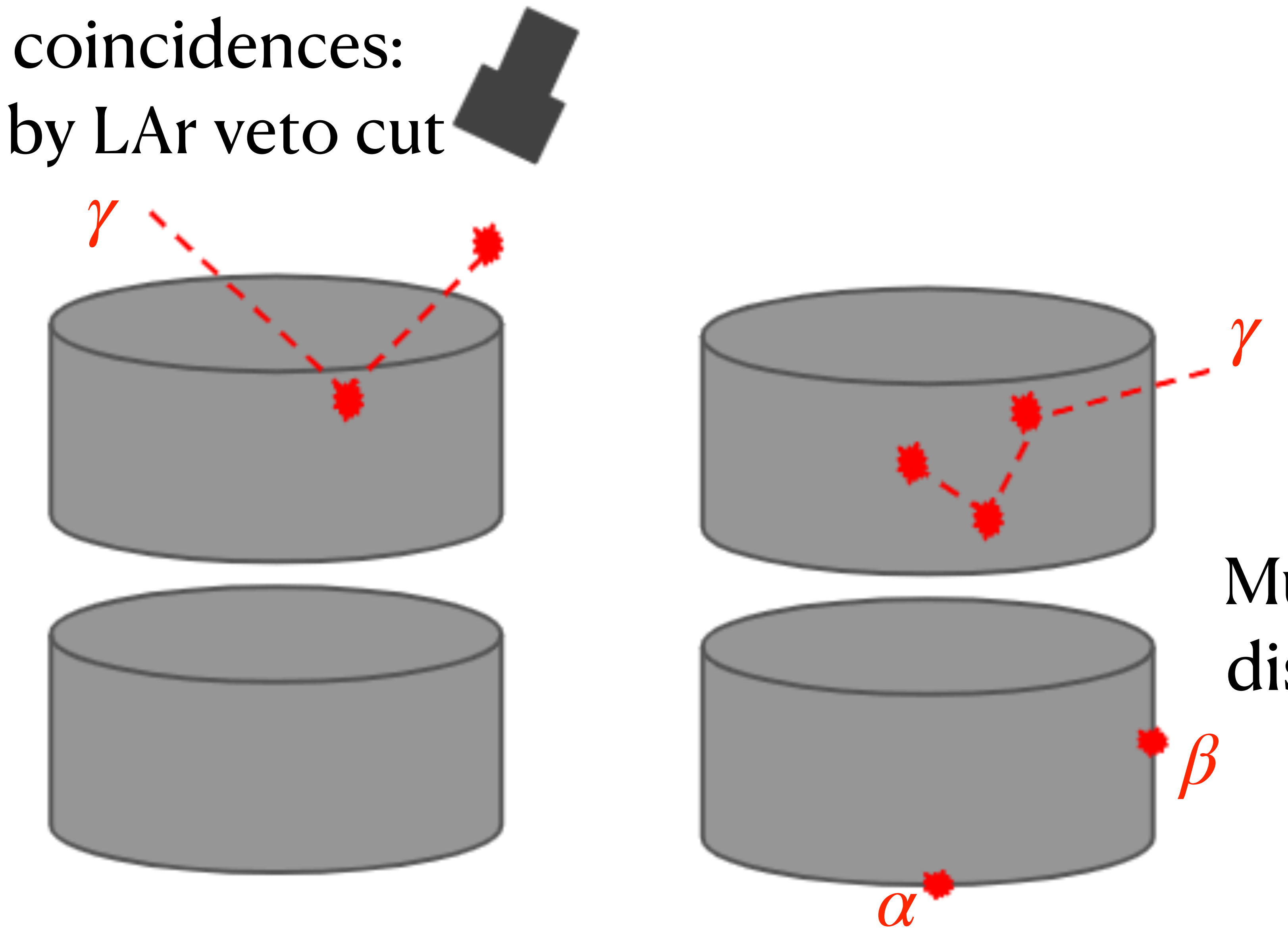
Background discrimination by event topology

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

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

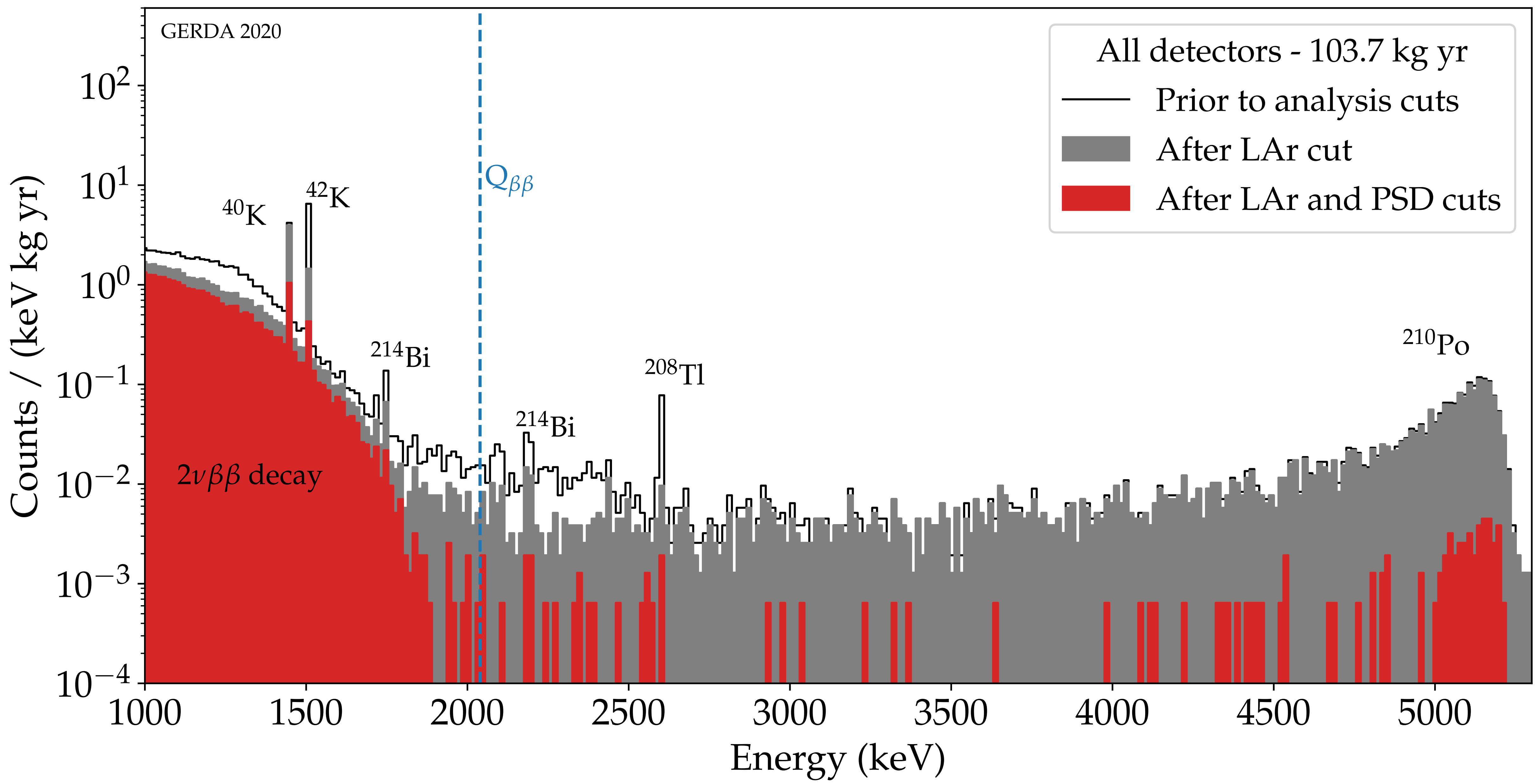


Detector-LAr coincidences: discrimination by LAr veto cut



Multi-site / surface events: discrimination by PSD cut

After AC, LAr veto and PSD cuts



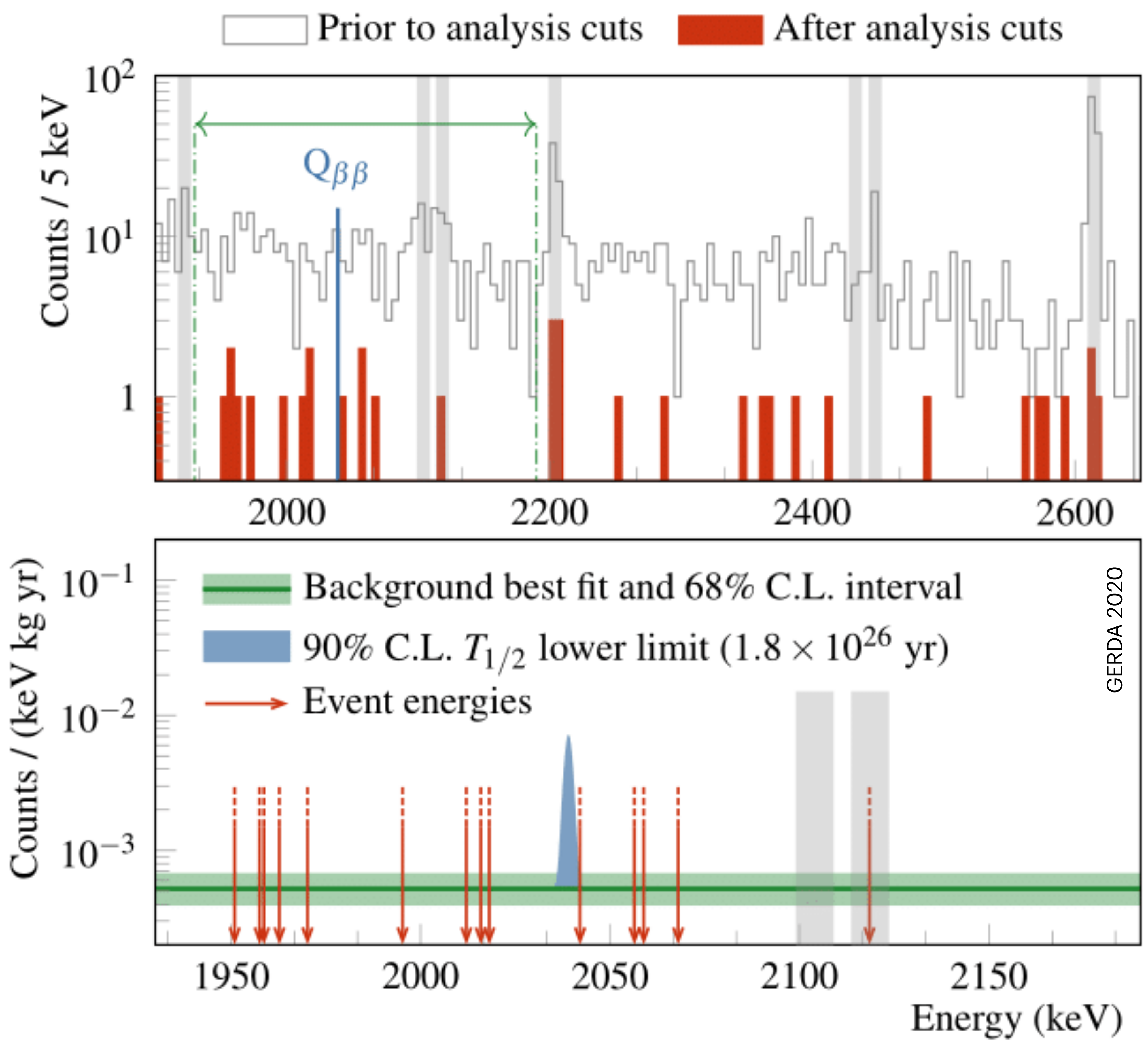
Final results on the search for $0\nu\beta\beta$ decay

[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 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



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  $5.2^{+1.6}_{-1.3}\ 10^{-4}$ cts/(keV kg yr) ☑ BI < 10^{-3} cts/(keV kg yr)

- Energy resolution at $Q_{\beta\beta}$ ~ 3keV (FWHM)

  ☑ Exposure ~ 100 kg yr

- No signal 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.)

  ☑ Sensitivity > 10^{26} yr

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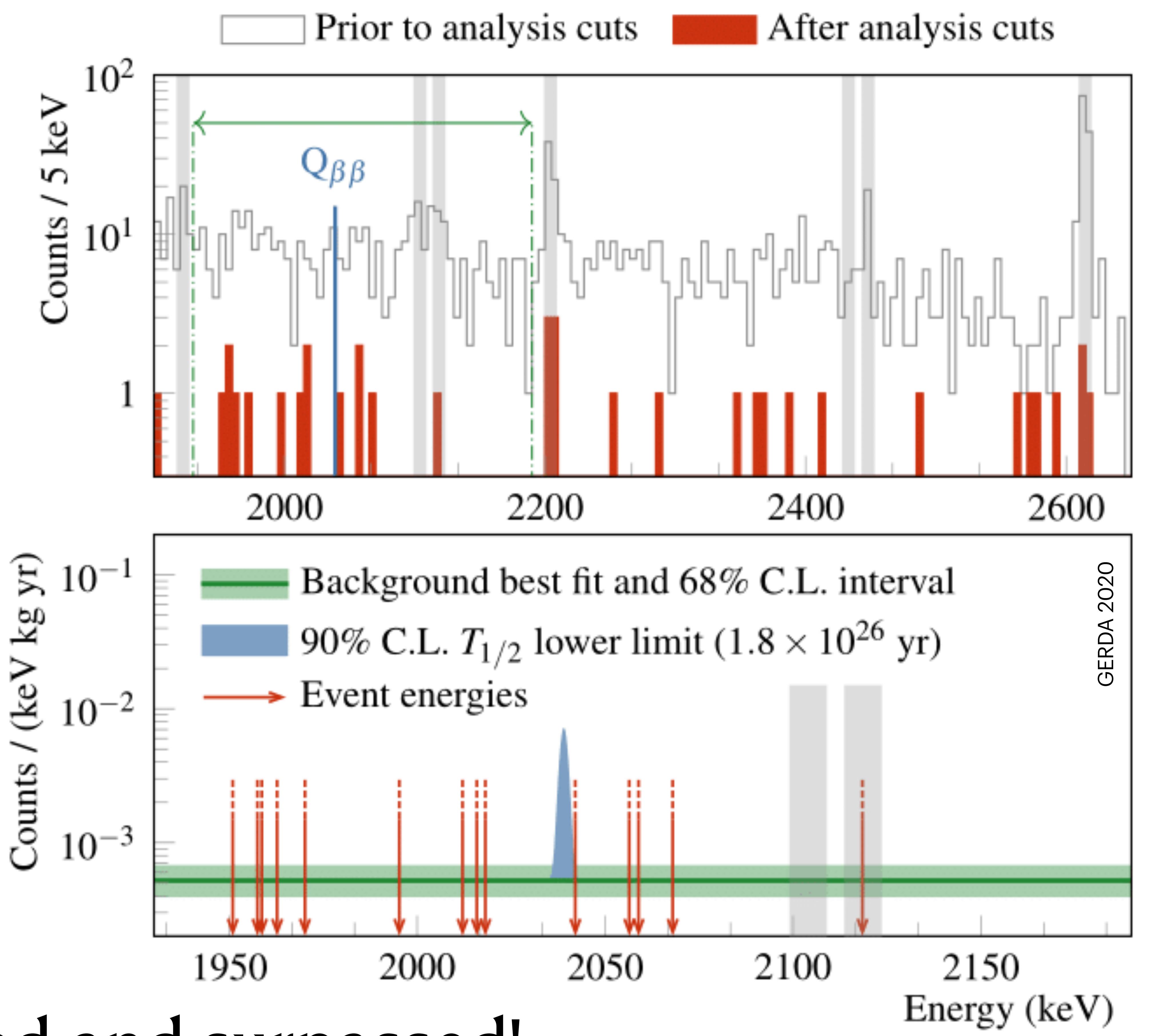
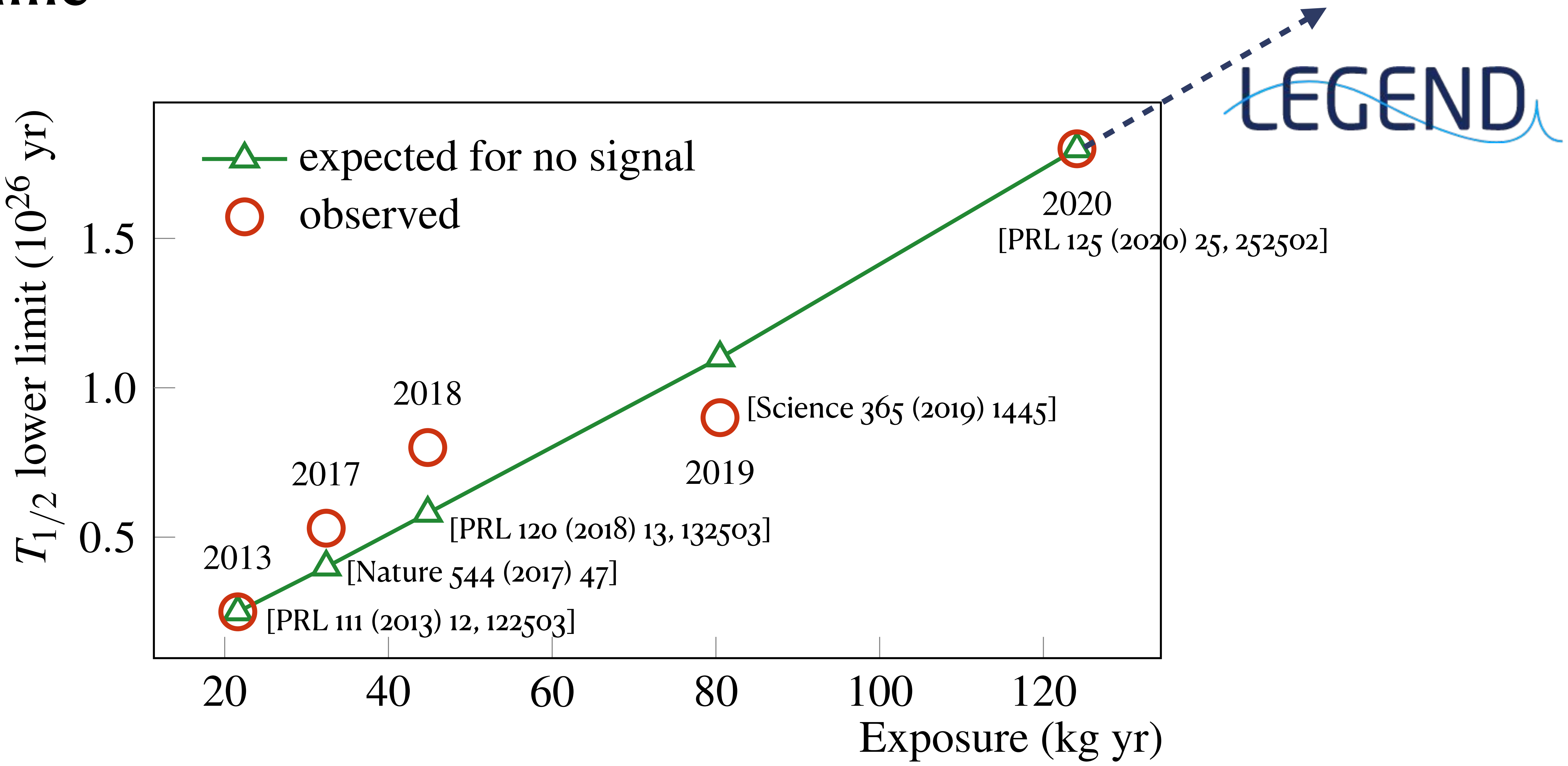


☑ All design goals were reached and surpassed!

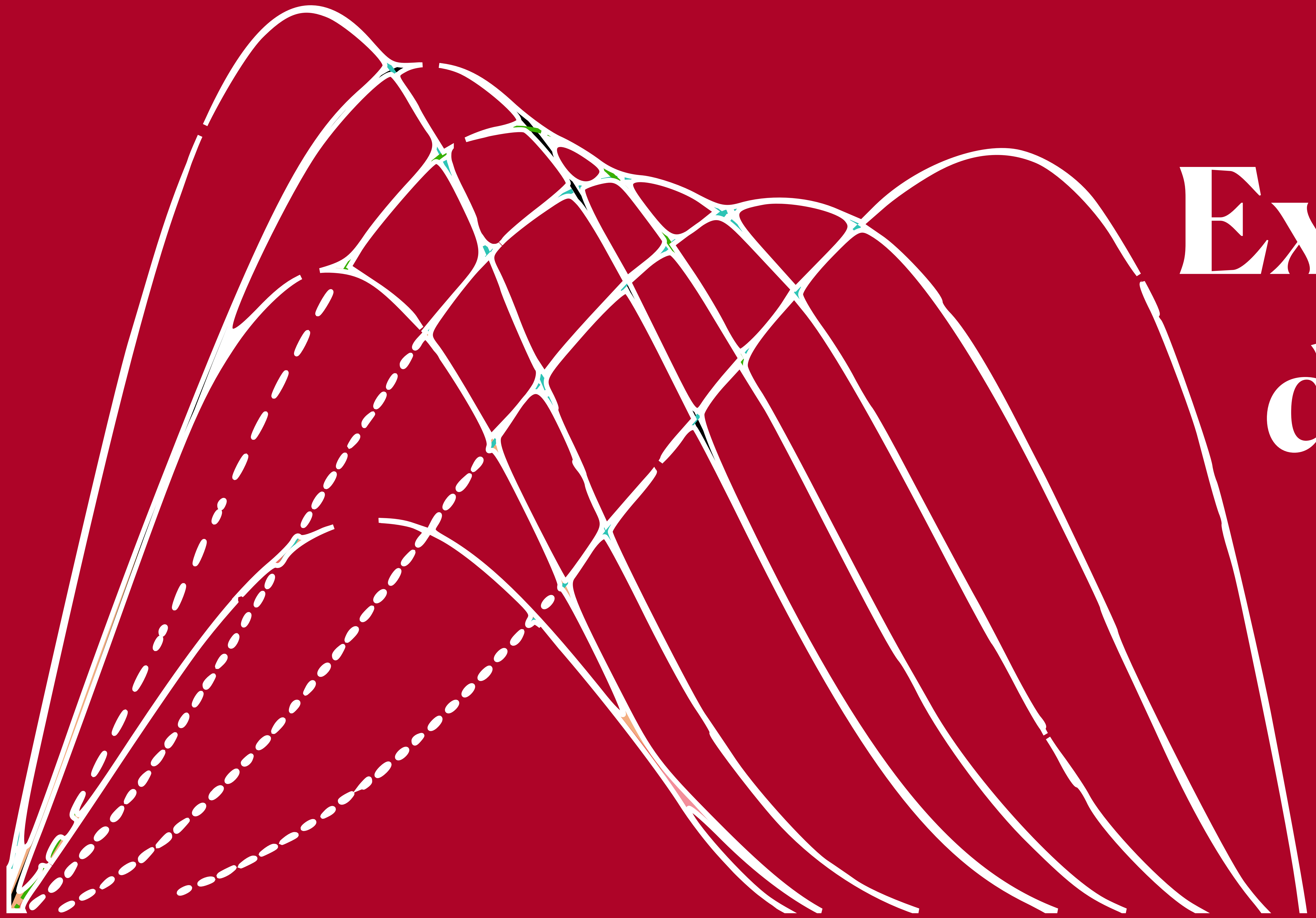
Background-free search for $0\nu\beta\beta$ decay

GERDA operated in the (quasi) background-free regime. LEGEND will continue on this track.

- The sensitivity on $T_{1/2}$ scales linearly with the exposure due to the (quasi) background-free regime*



*The number of background events expected in the ROI over the whole exposure is < 1



$2\nu\beta\beta$ decay & Exotic double-β decay modes

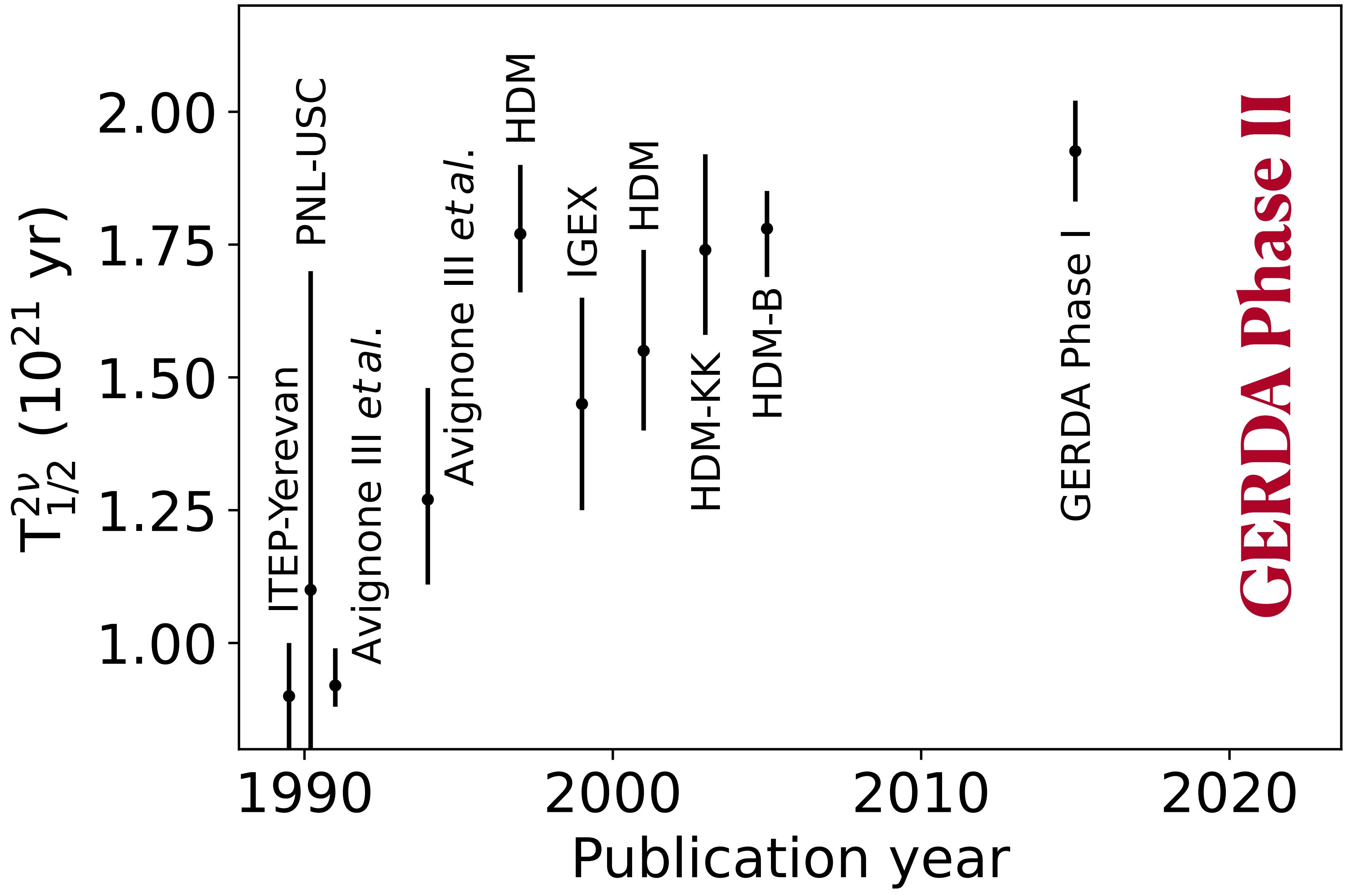
The half-life of ^{76}Ge $2\nu\beta\beta$ decay

Past measurements

- Measurement in GERDA Phase I:

  $T_{1/2}^{2\nu} = (1.926 \pm 0.094)\ 10^{21}$ 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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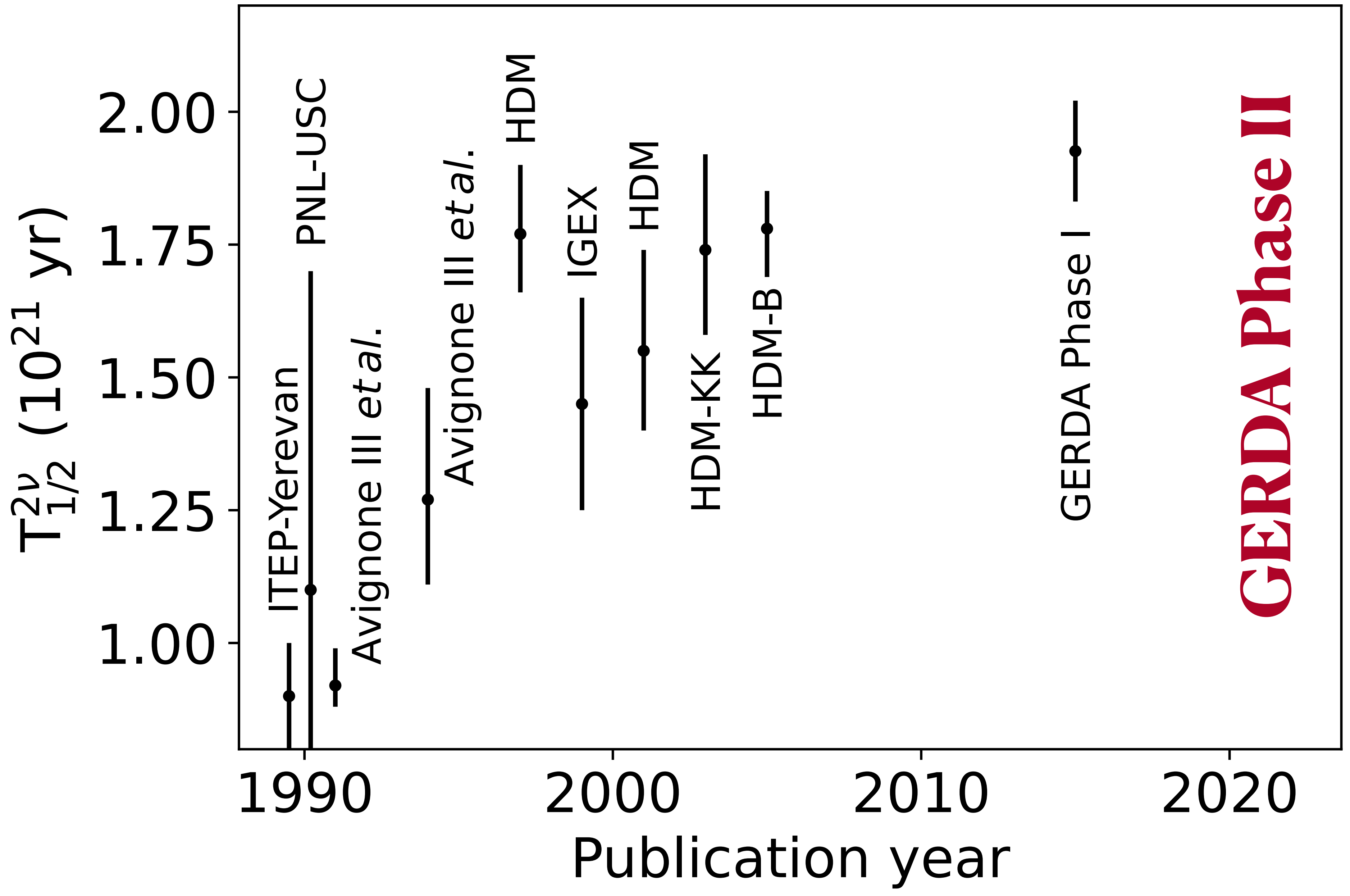
We can improve the precision of this measurement in GERDA Phase II:

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



The half-life of ^{76}Ge $2\nu\beta\beta$ decay (GERDA Phase II)

[publication coming soon...]

- 9 BEGe dataset after LAr veto cut: 11.8 kg yr exposure
- Binned maximum likelihood fit (560-2000) keV with 10 keV binning

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

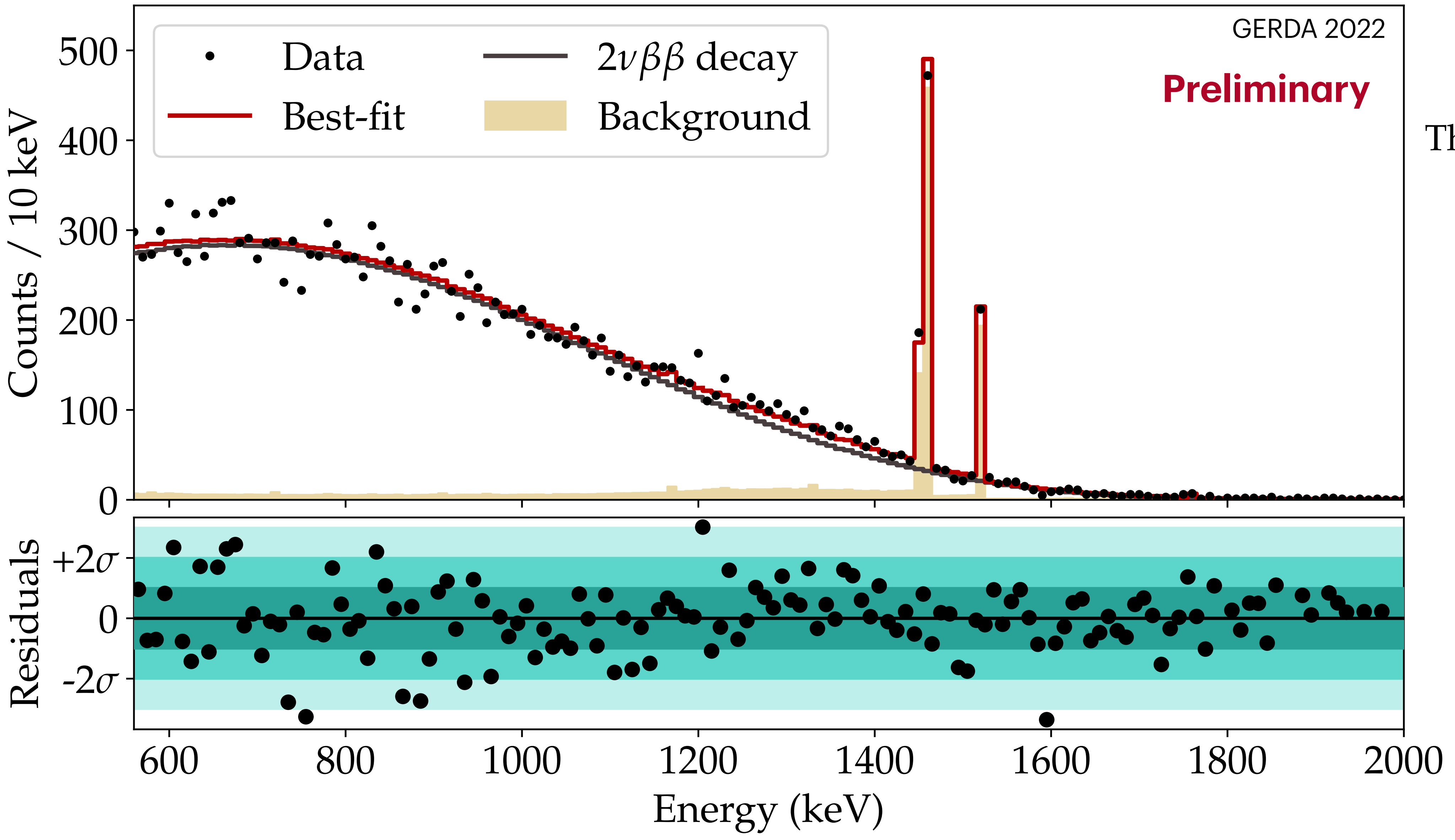
Number of observed events

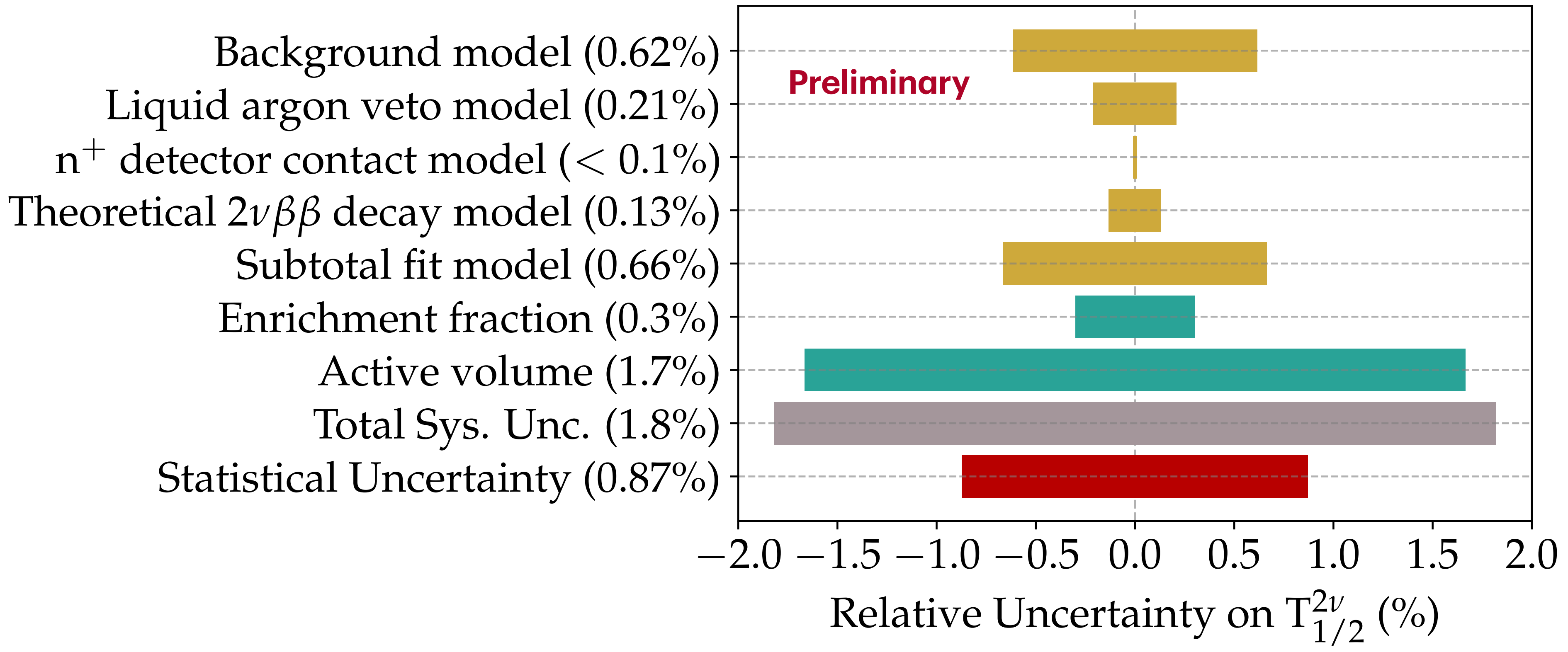
Cuts efficiency (QC, LAr)

Active volume fraction & containment efficiency

Enrichment fraction of ^{76}Ge

Detector exposure





Preliminary

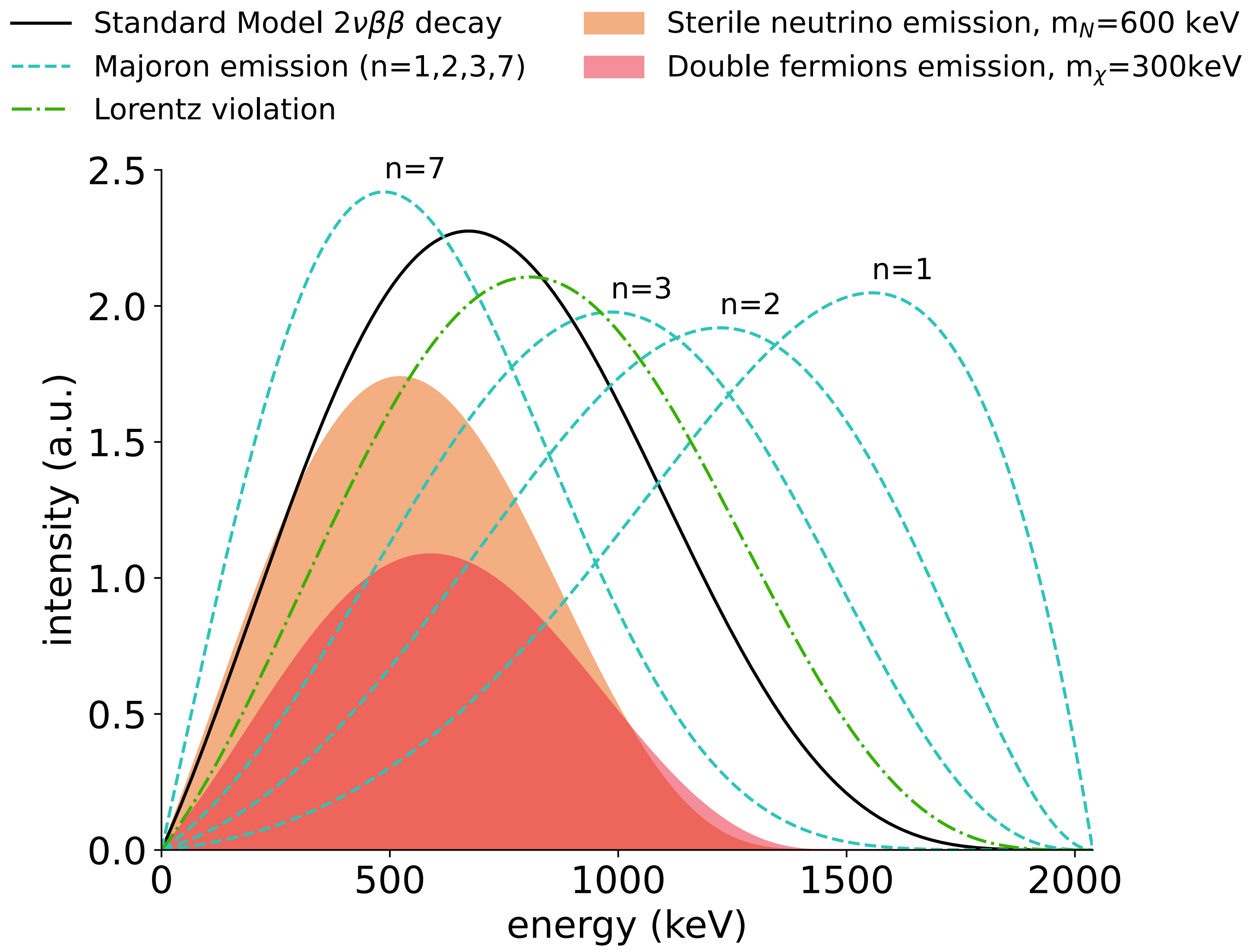
$$T_{1/2}^{2\nu} = (2.022 \pm 0.041)\, 10^{21}\ \mathrm{yr}$$

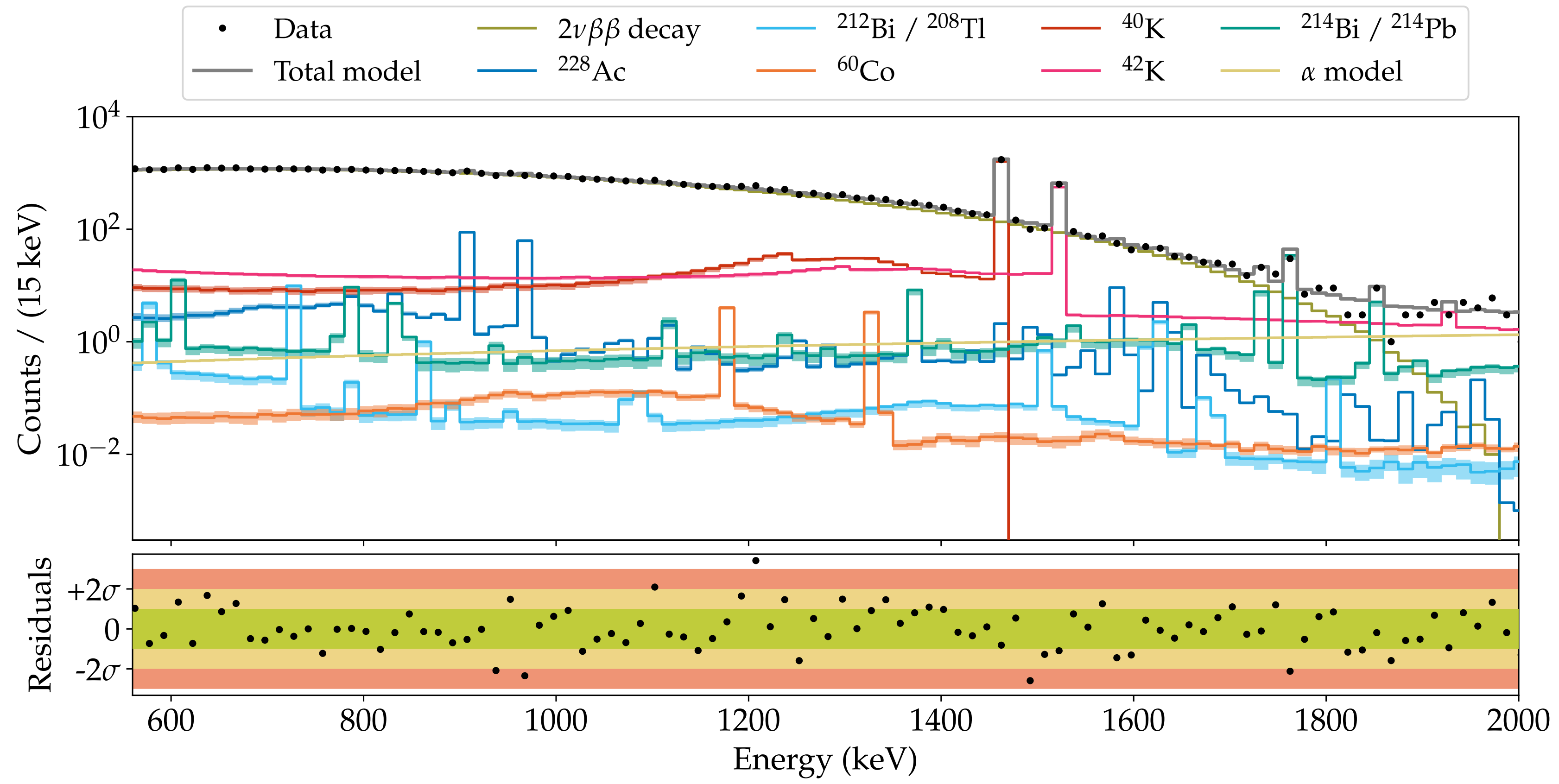
Total uncertainty 2.0%: most precise determination of ^{76}Ge half-life

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)





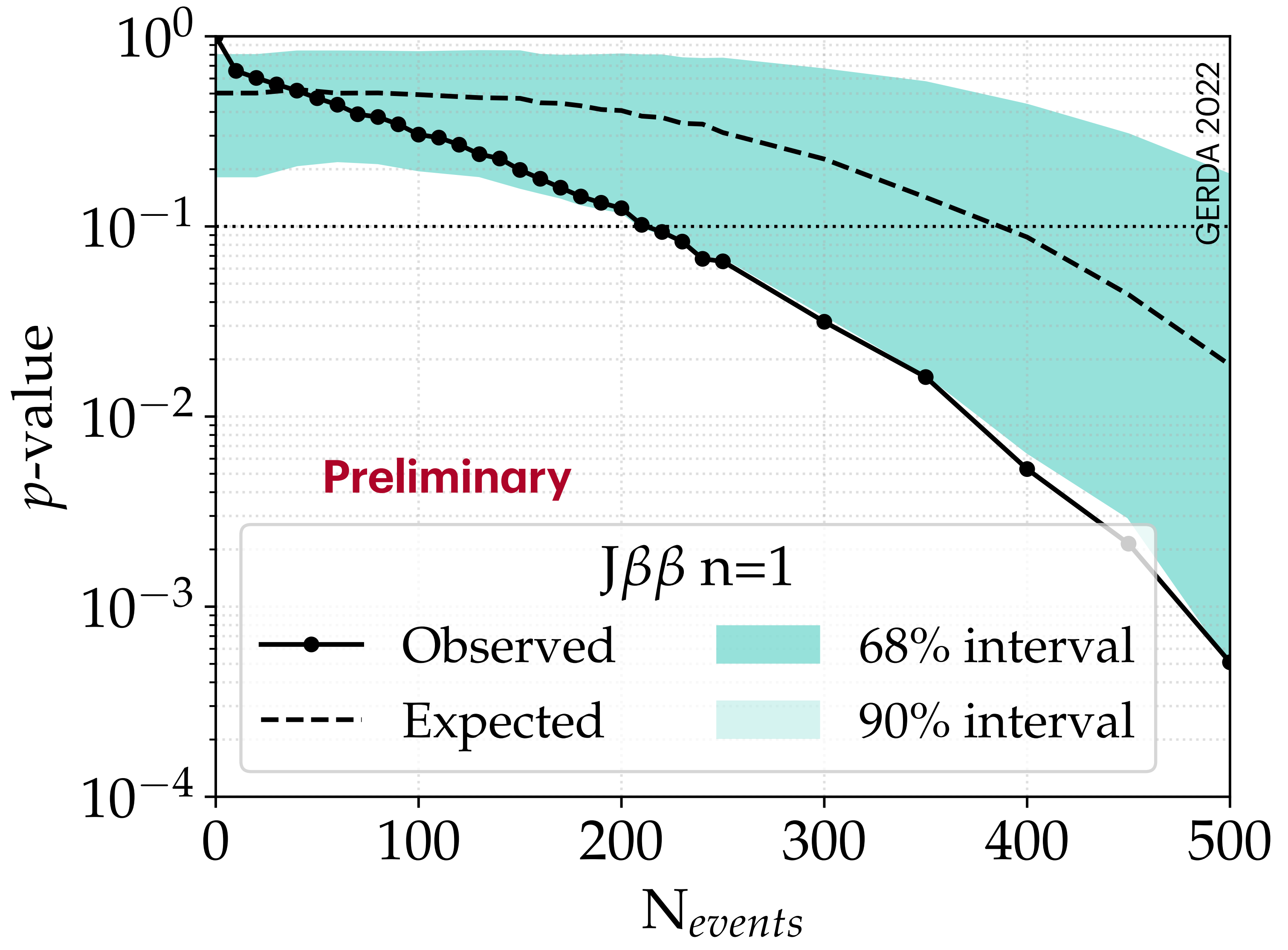
Results on the search for Majoron-involving decays

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

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



Preliminary

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

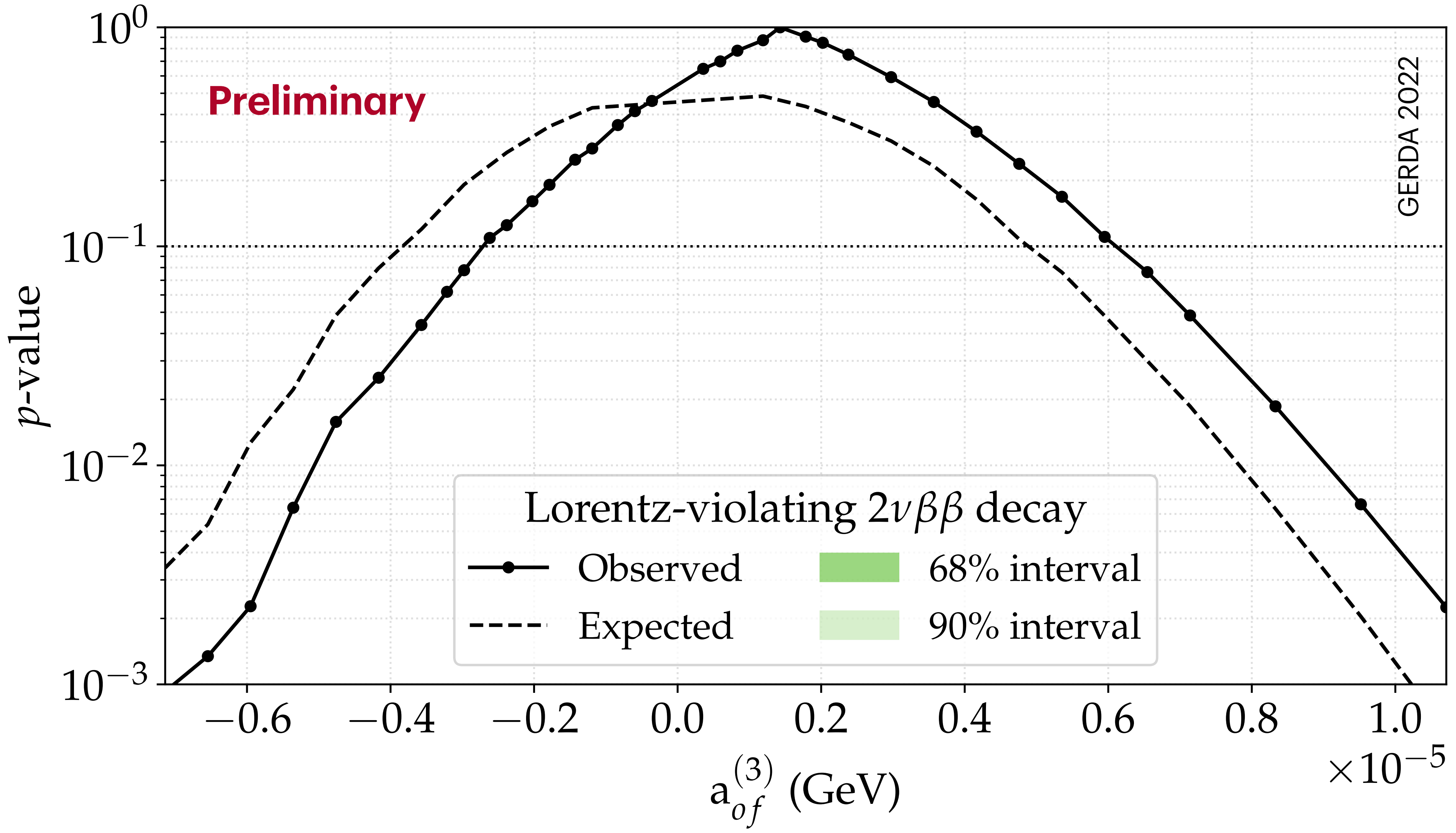
Phase space from [Phys. Rev. C 91 (2015), p. 64310], NMEs from [Phys. Rev. C 103 (2021), arXiv:2202.01787]

Results on the search for Lorentz violation

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

[arXiv:2209.01671]

- 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 $a_{of}^{(3)}$
- The decay rate can be written as the sum of the SM decay rate plus a perturbation proportional to $a_{of}^{(3)}$, which is the parameter we want to constrain
- 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]

Results on the search for light exotic fermions

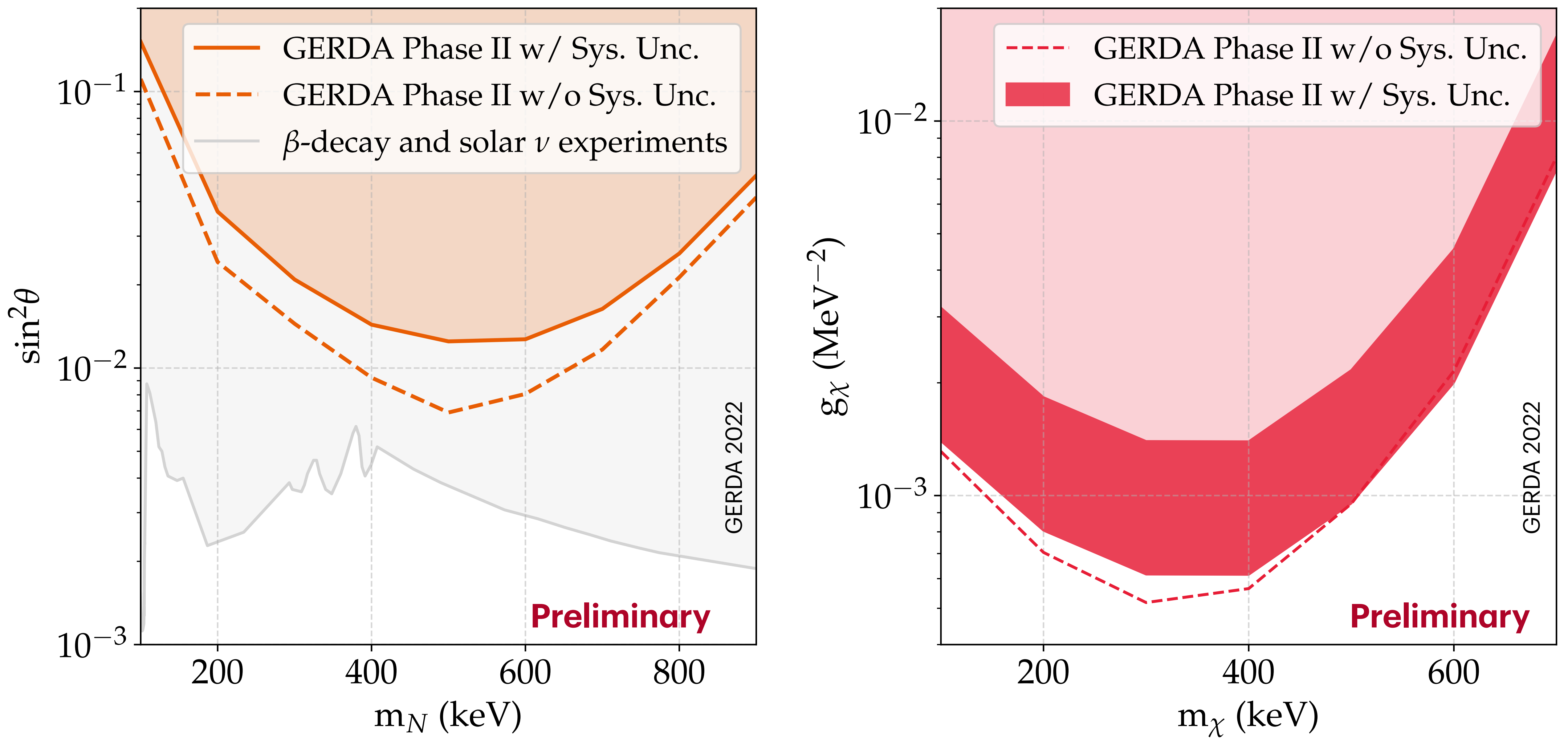
$(A,Z) \rightarrow (A,Z+2) + 2e + \bar{\nu} + N$

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

[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

- GERDA searched for the $0\nu\beta\beta$ decay of ^{76}Ge in a (quasi) **background-free regime.**
- Phase II data taking finished in November 2019, achieving and **surpassing all design goals.**
- We set the **best limit on the non-observation of $0\nu\beta\beta$ decay of ^{76}Ge**: $T^{0\nu}_{1/2}$ > **1.8 10^{26} yr at 90% C.L.** (with 127.2 kg yr of combined Phase I and Phase II exposure).
- GERDA demonstrated the **background-free operation of HPGe detectors**, paving the way for next-generation searches with LEGEND.
- We obtained a **precision determination of the half-life of ^{76}Ge** $2\nu\beta\beta$ decay: $T^{2\nu}_{1/2}$ = **(2.022 ± 0.041) 10^{21} yr** Preliminary (**total uncertainty of 2.0 %**, most precise determination of the ^{76}Ge $2\nu\beta\beta$ half-life)
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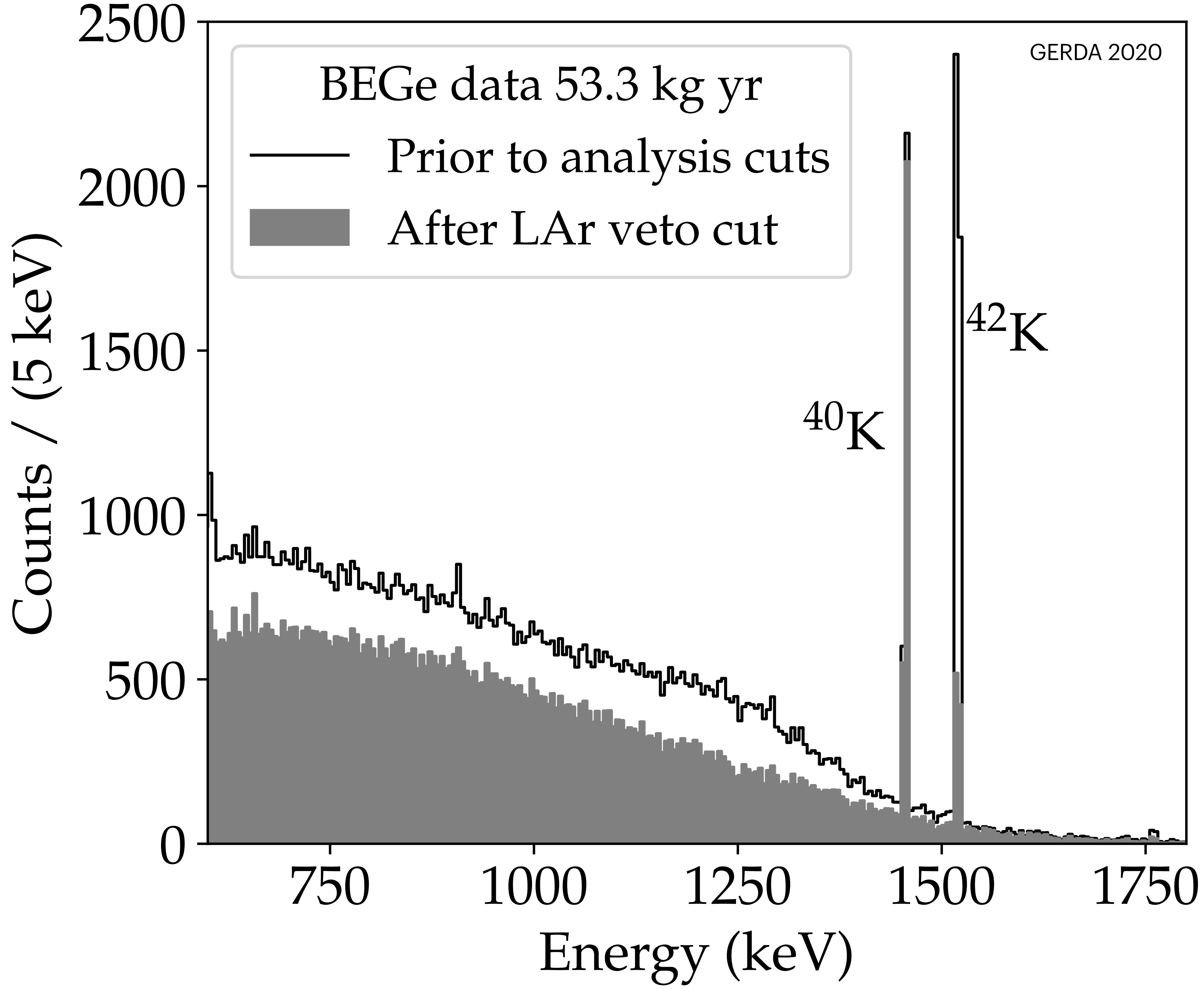
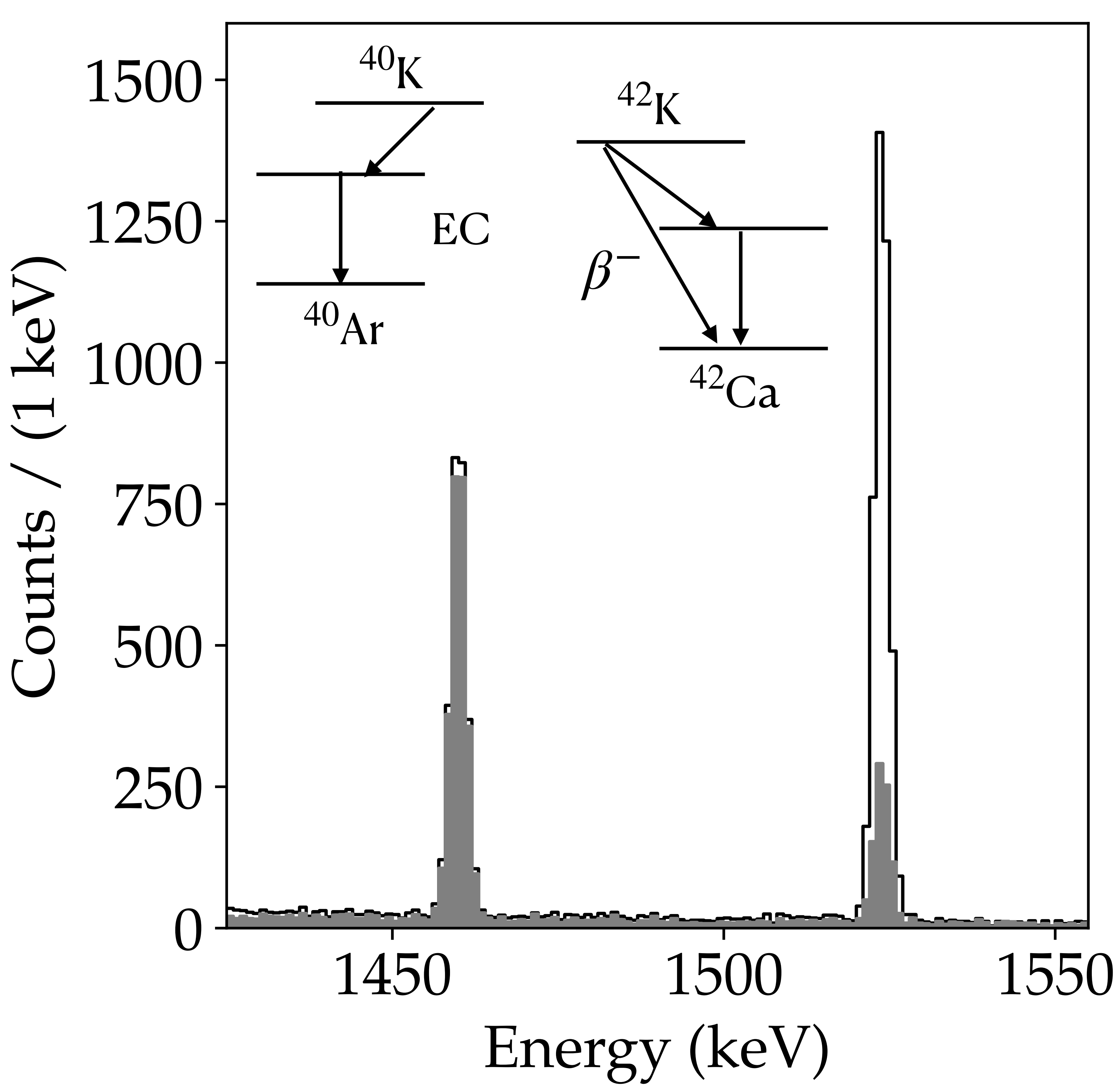
Thank you for your attention!

Back up

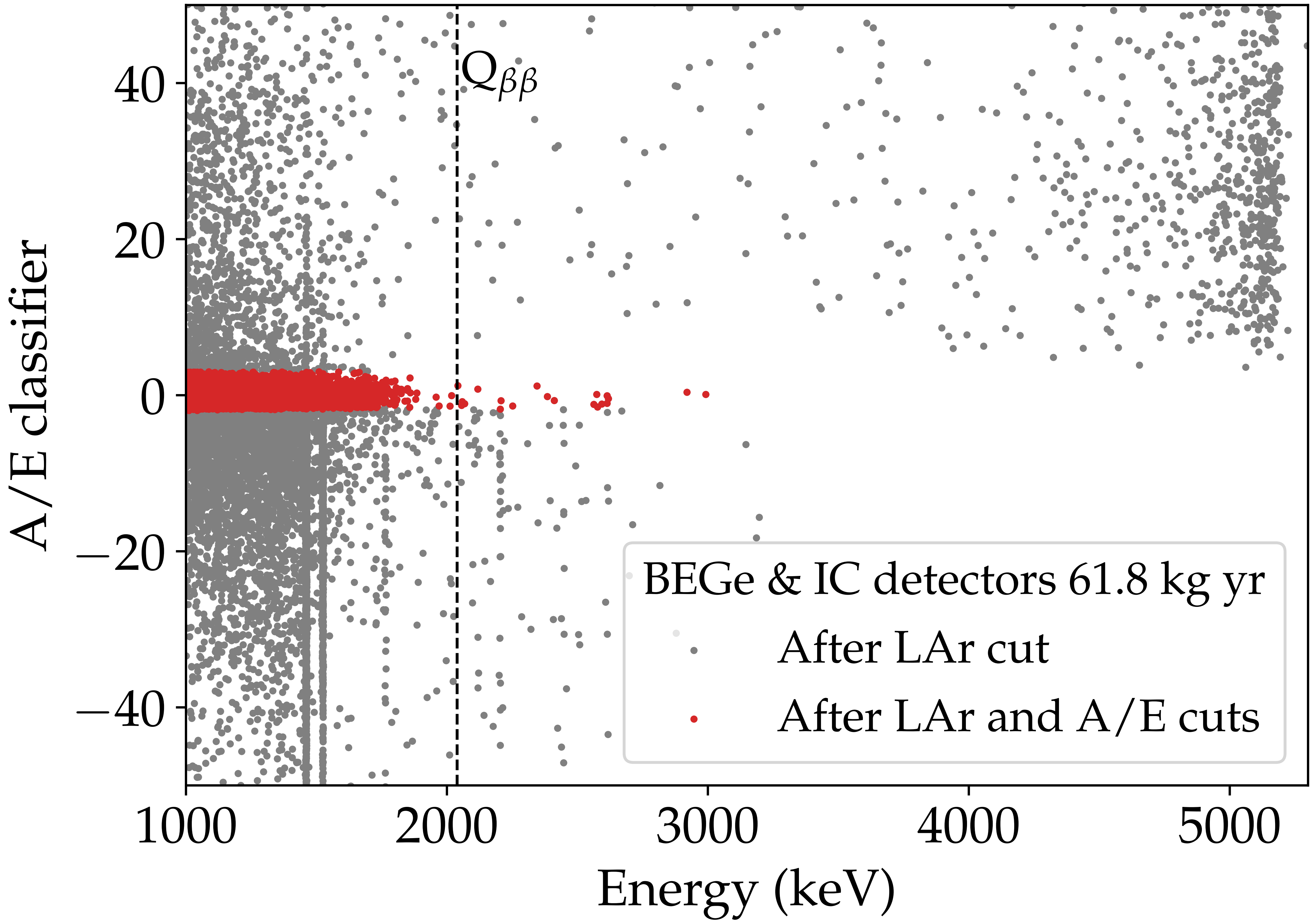
LAr veto cut performance



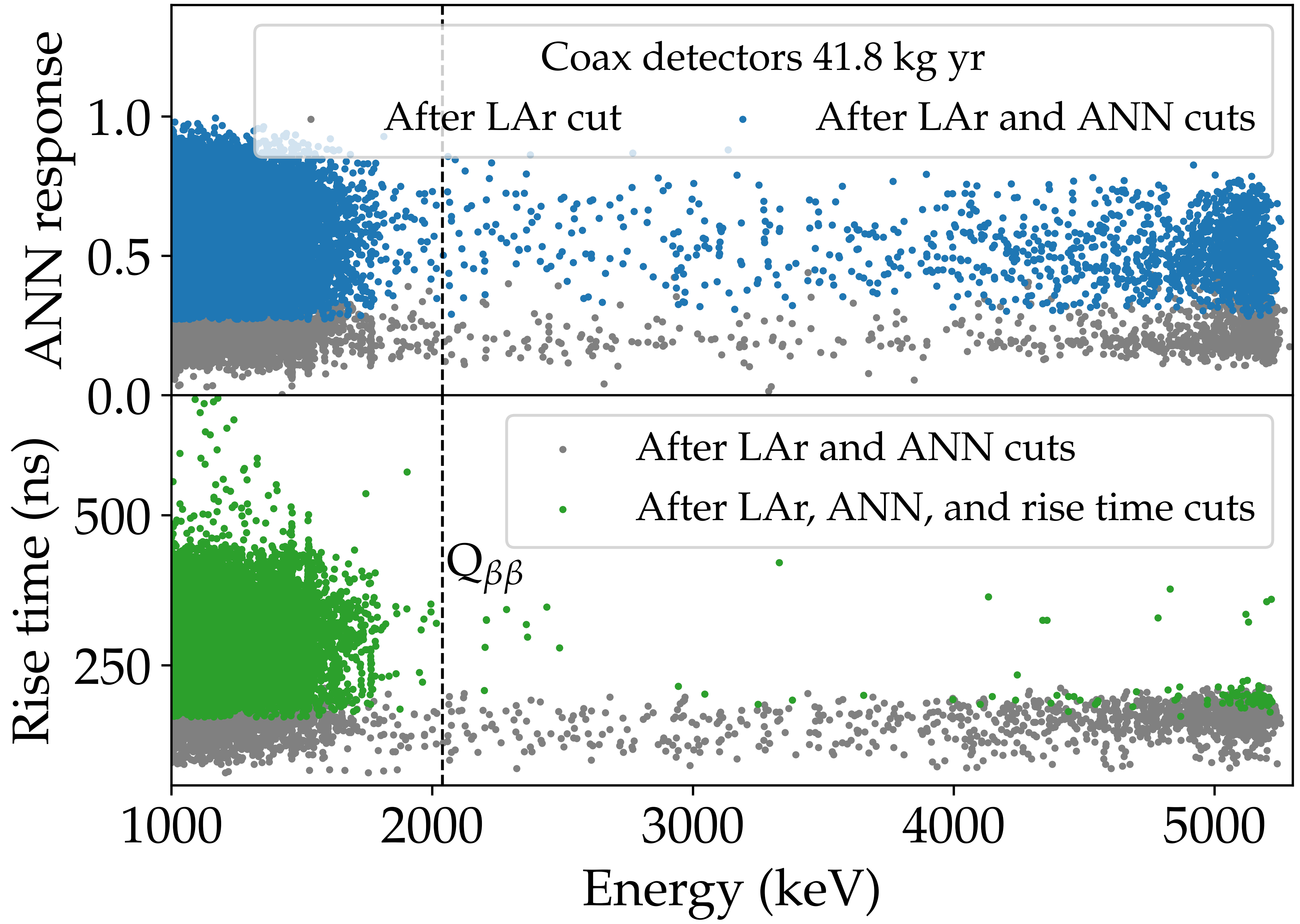


Pulse Shape Discrimination performance

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



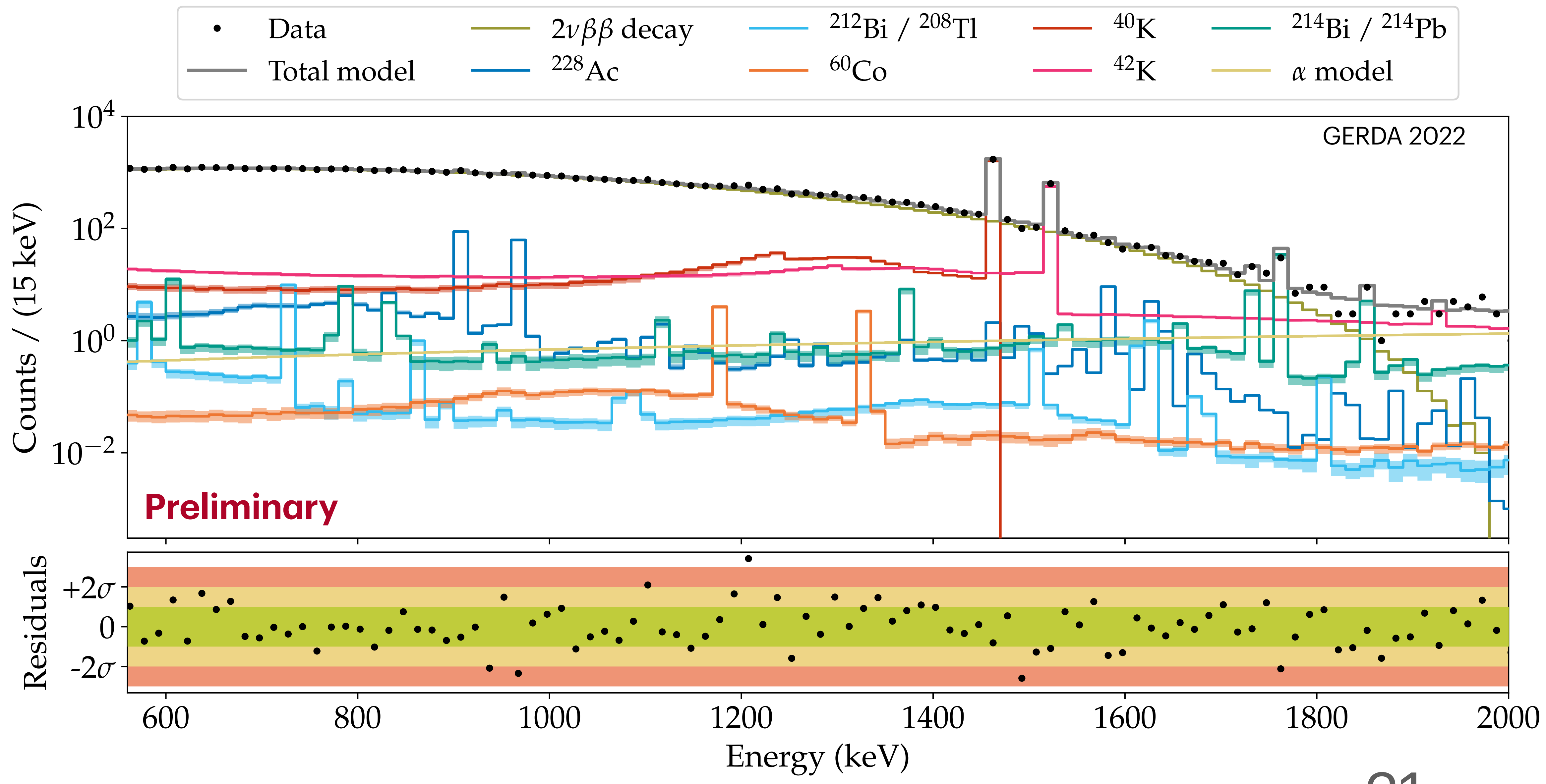
- Artificial neural network (ANN) for single-site/multi-site discrimination
- Additional rise time cut for fast p+ surface events



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

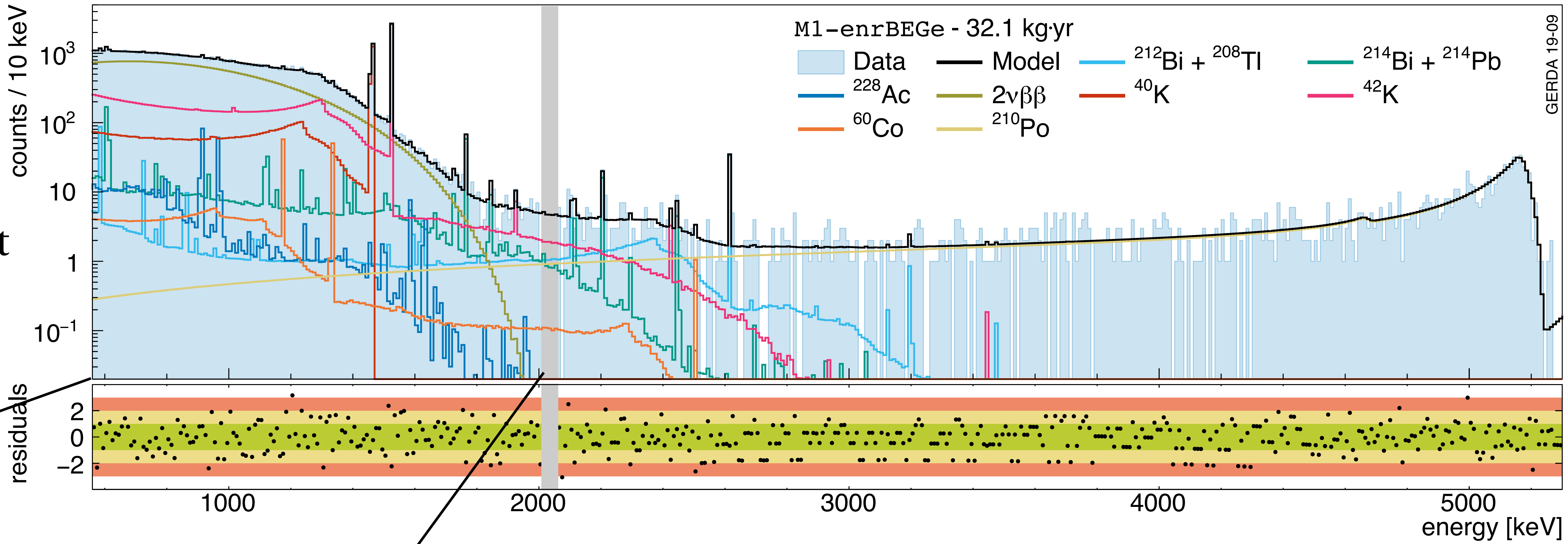
- A model of the LAr veto system has been developed [publication coming soon!]
- The expected background after LAr veto cut was obtained by applying this model to the background decomposition prior to analysis cuts [JHEP 03 (2020) 139]

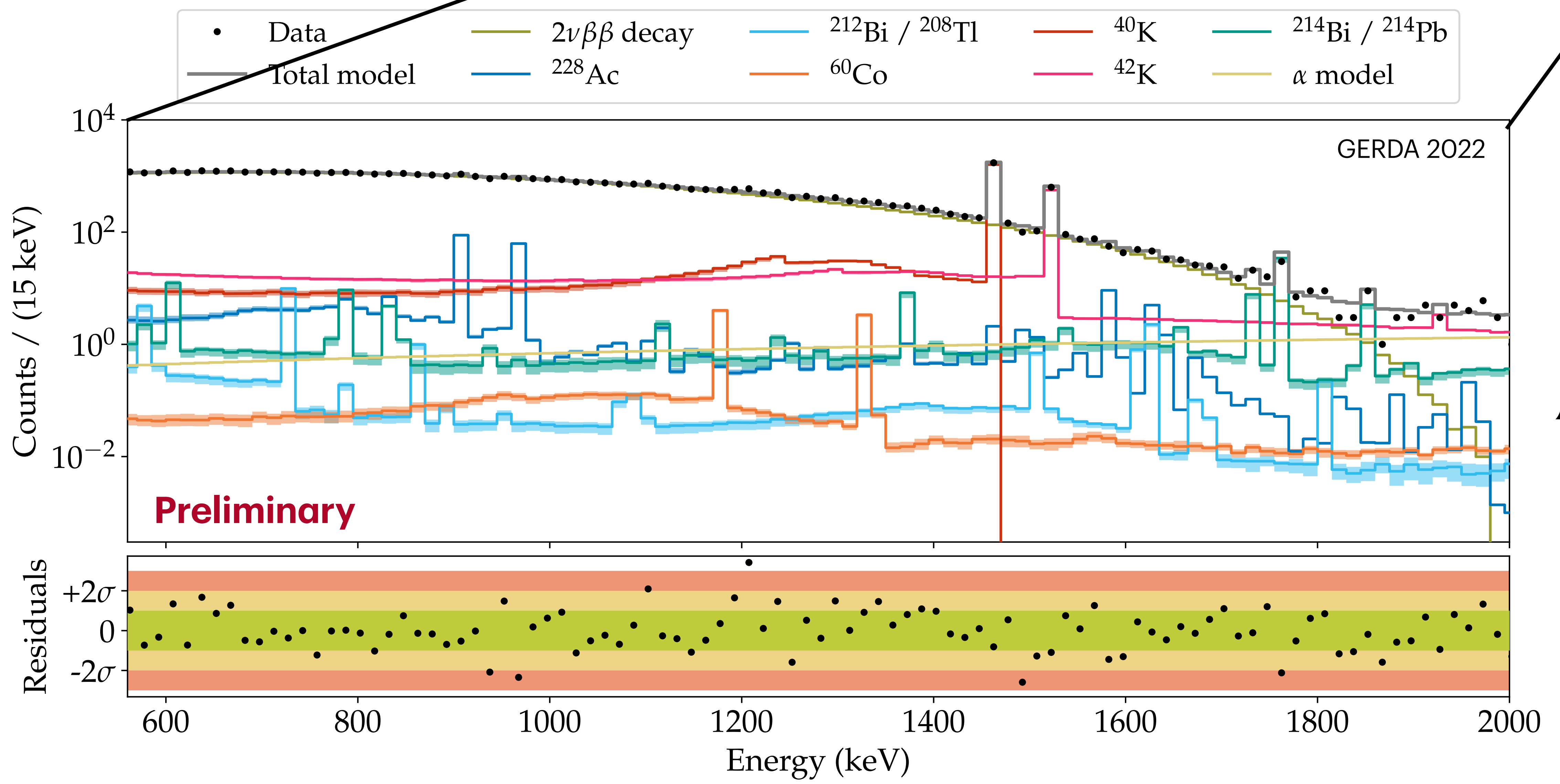


Expected background decomposition for all BEGe detectors pre-upgrade data (32.8 kg yr)

Comparison of the background model before and after LAr veto cut

Before LAr veto cut

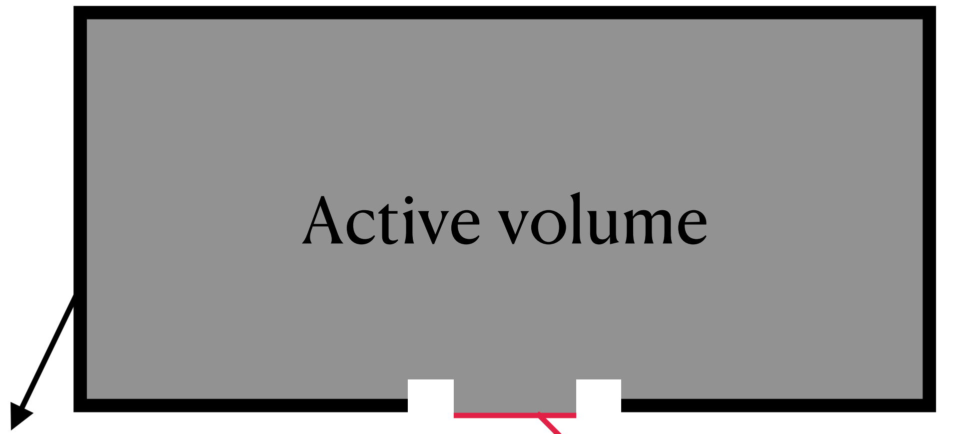




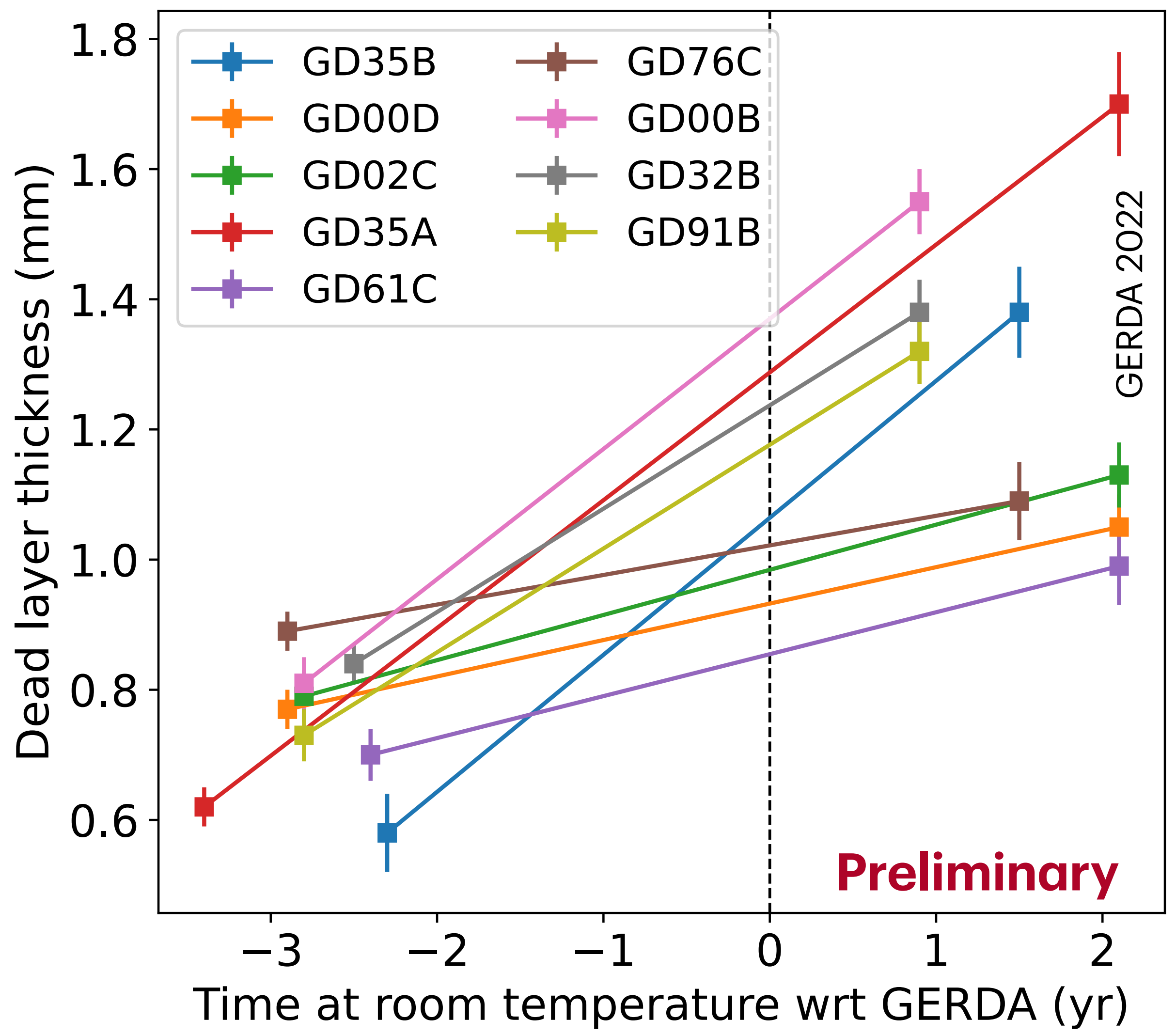
After LAr veto cut

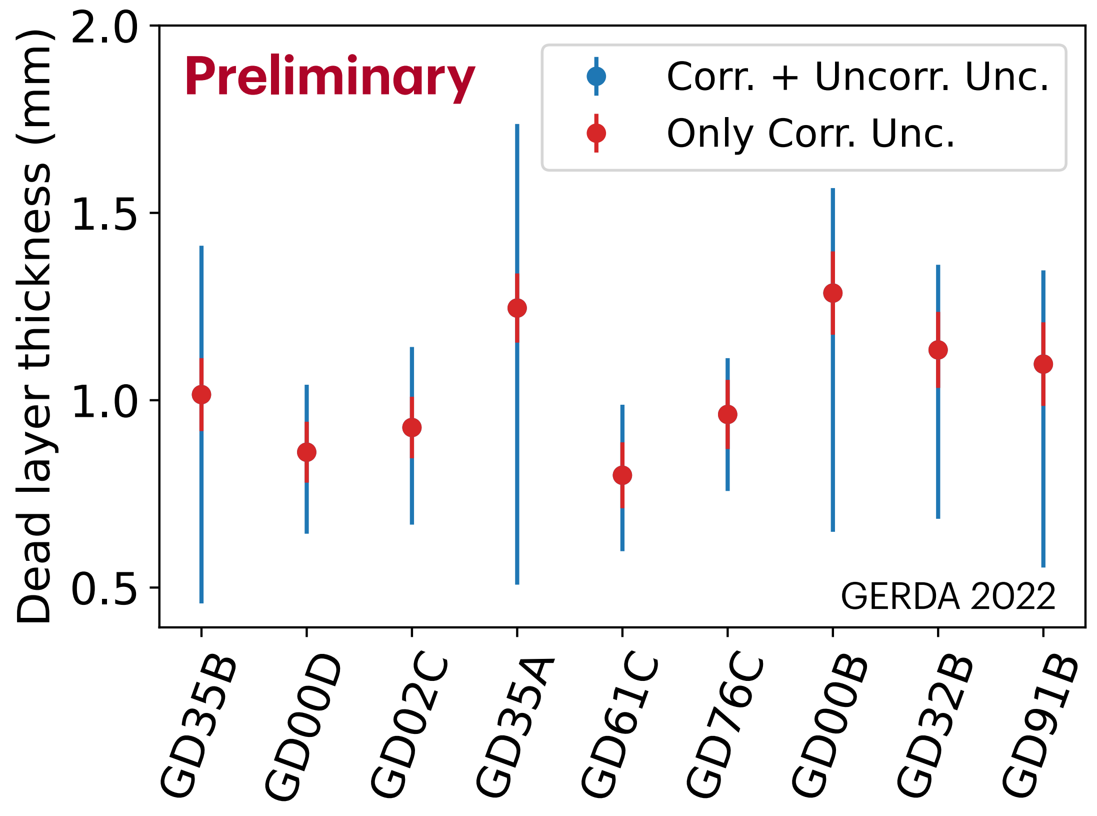
Active volume characterization

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



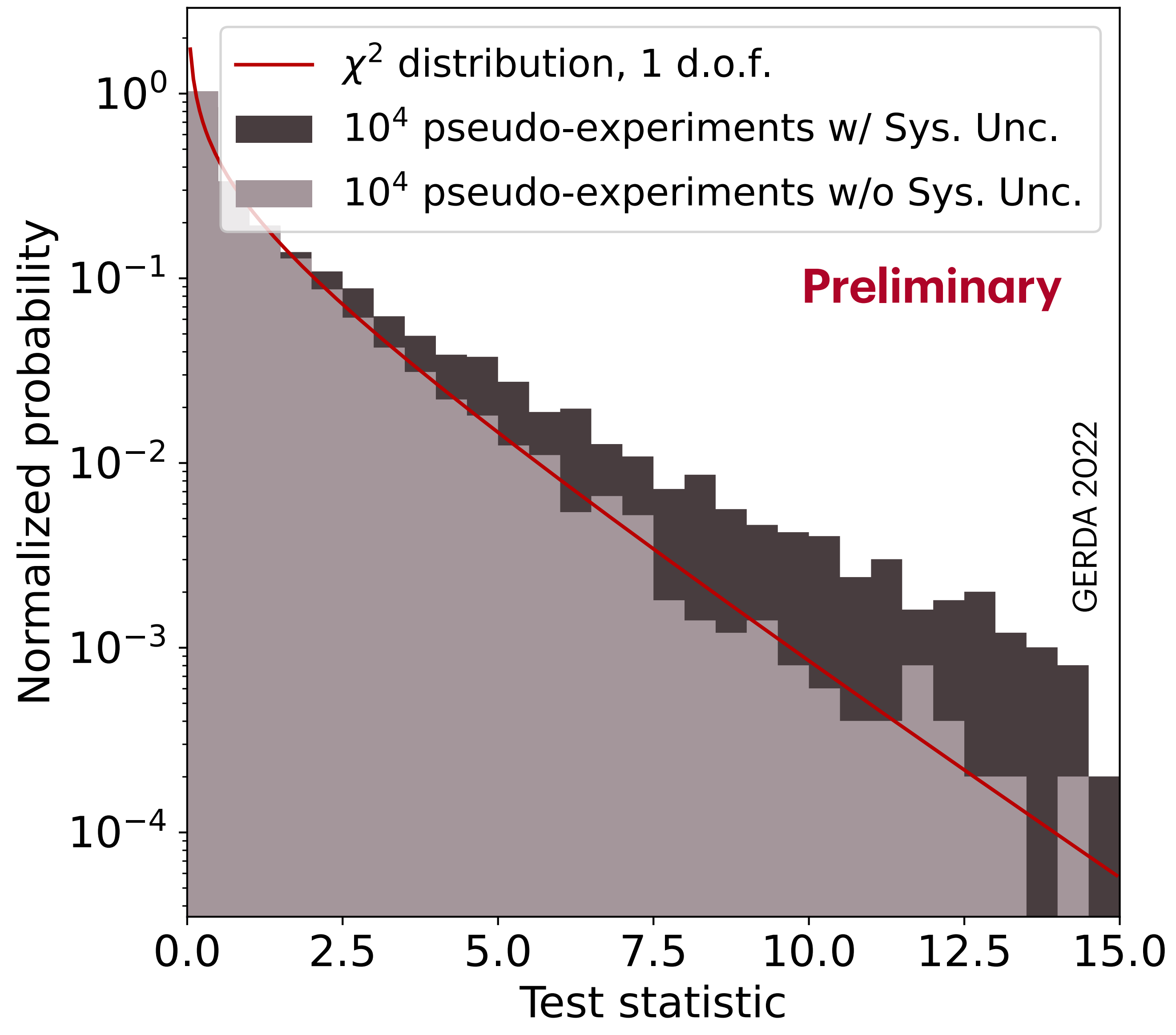


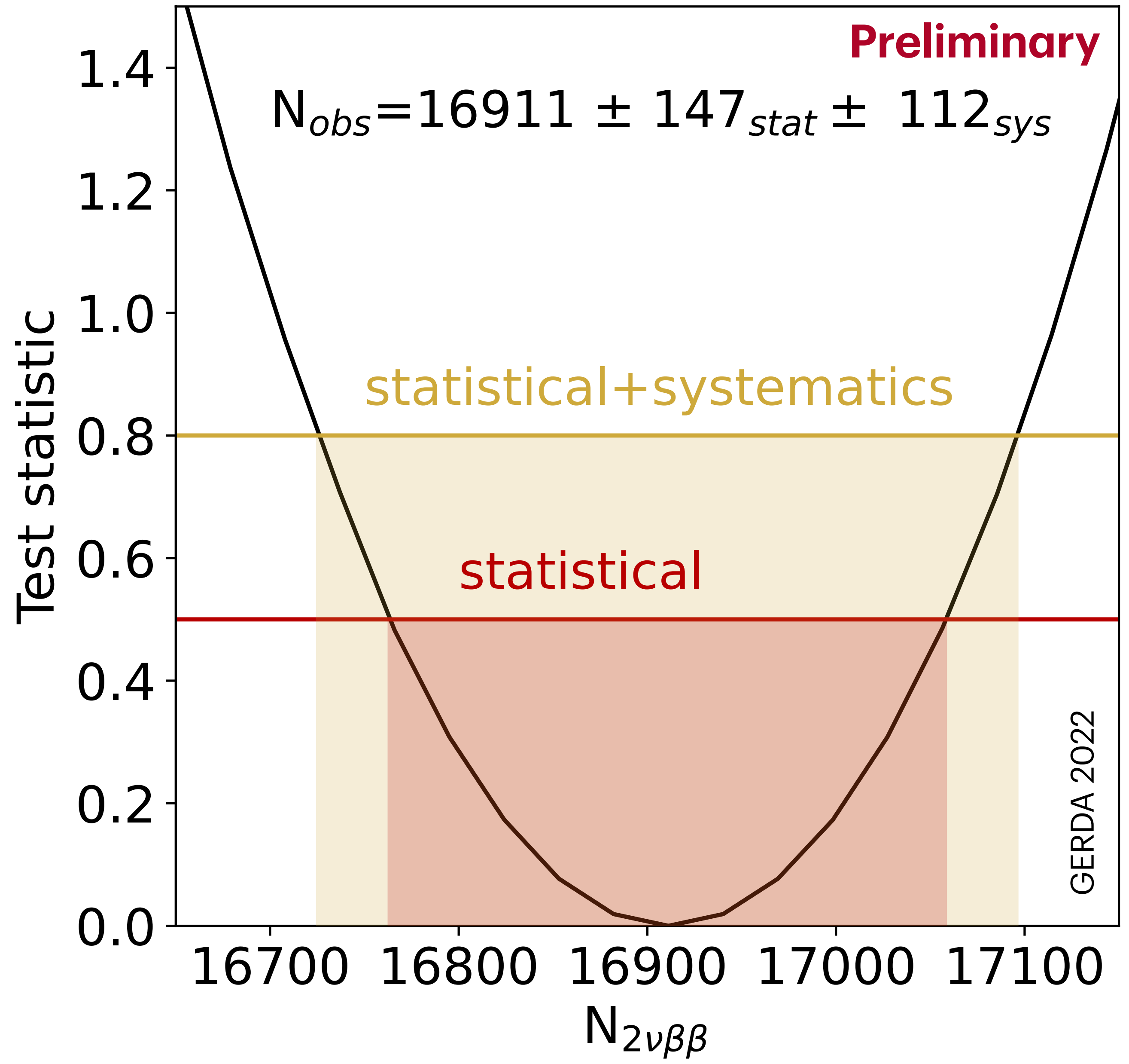
- We extracted detector specific growth and interpolate the active volume at the time of GERDA data taking

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)]





Effective nuclear matrix element

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

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

[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: $|\, \mathcal{M}^{2\nu}_{eff} | = 0.101(1)$

- This can be used to validate and improve nuclear-structure calculations and benefit the interpretation of future $0\nu\beta\beta$ decay discoveries.