Probing Beyond the Standard Model physics with the GERDA experiment

Elisabetta Bossio (TUM), on behalf of the GERDA Collaboration
"34th Rencontres de Blois" May 14-19 2023

The physics goal

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- ν is a special particle in the SM:
  - Only ***neutral fermion***
  - Only ***left-handed*** ν's
  - ***Massless*** ν

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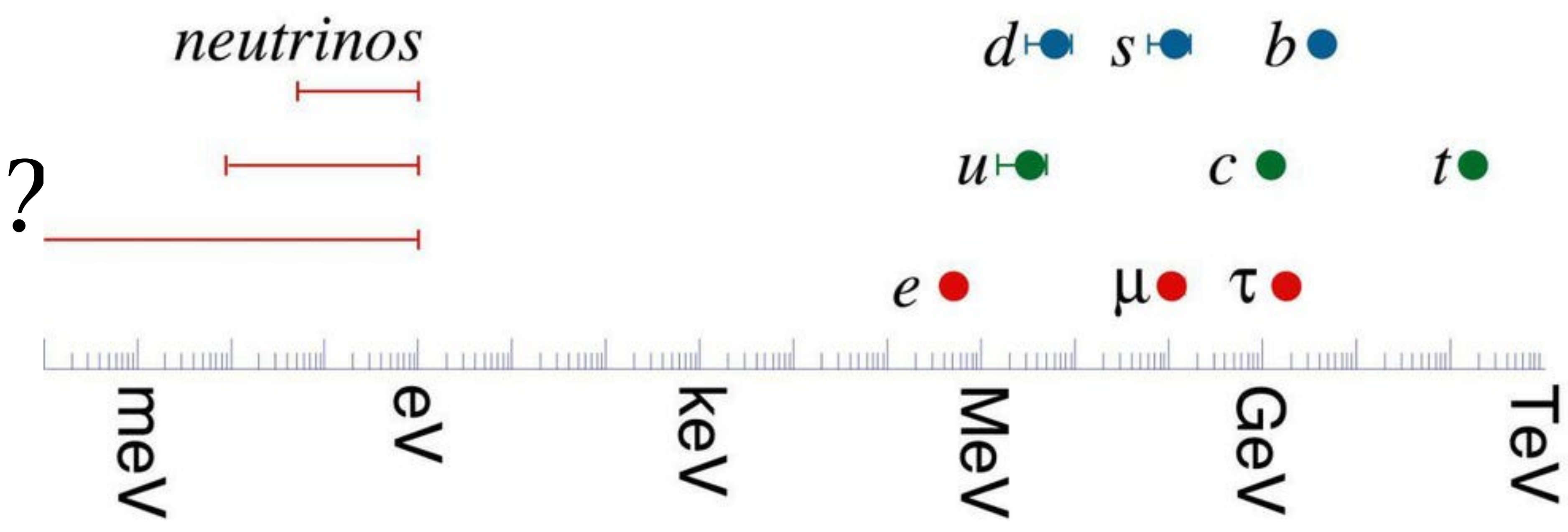
  - BSM physics needed
  - Tiny masses ($m_\beta < 0.8$ eV KATRIN, Nature Phys. 18, 2 (2022))?



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  - ***Massless*** ν

E. Majorana, Nuovo Cim. 14 (1937) 171-184,
G. Racah, Nuovo Cim. 14 (1937) 322-328

ν could be a ***Majorana particle***:

$$\nu = \bar{\nu}$$

▶ Lepton number non-conserved

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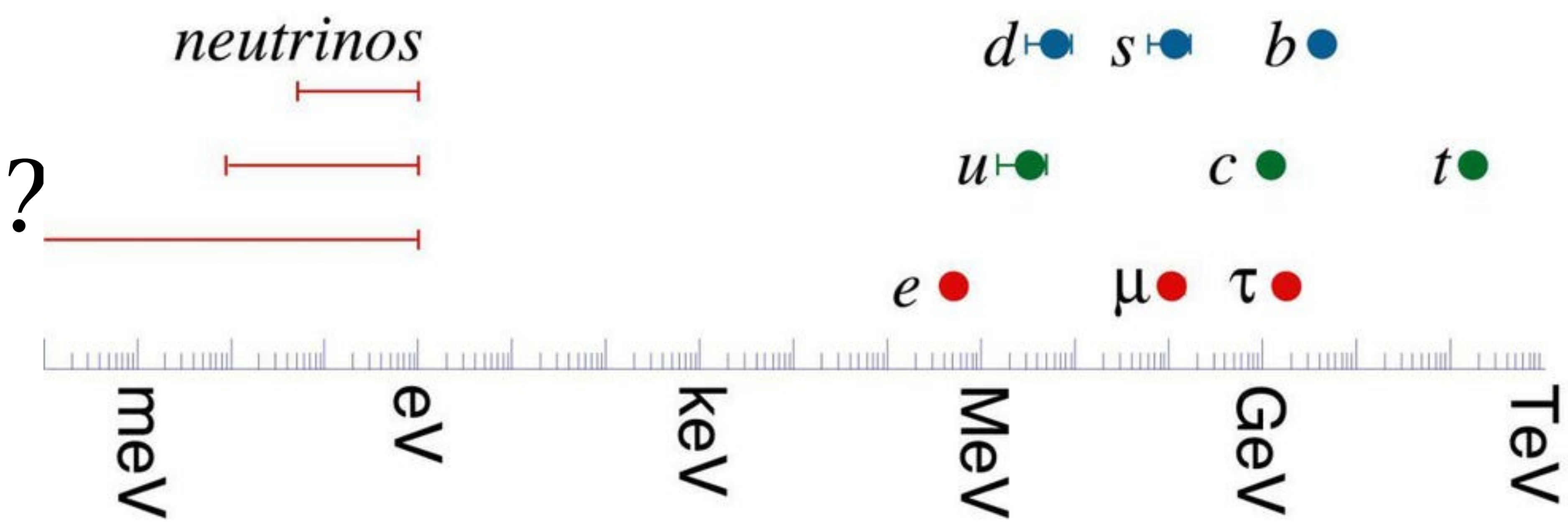

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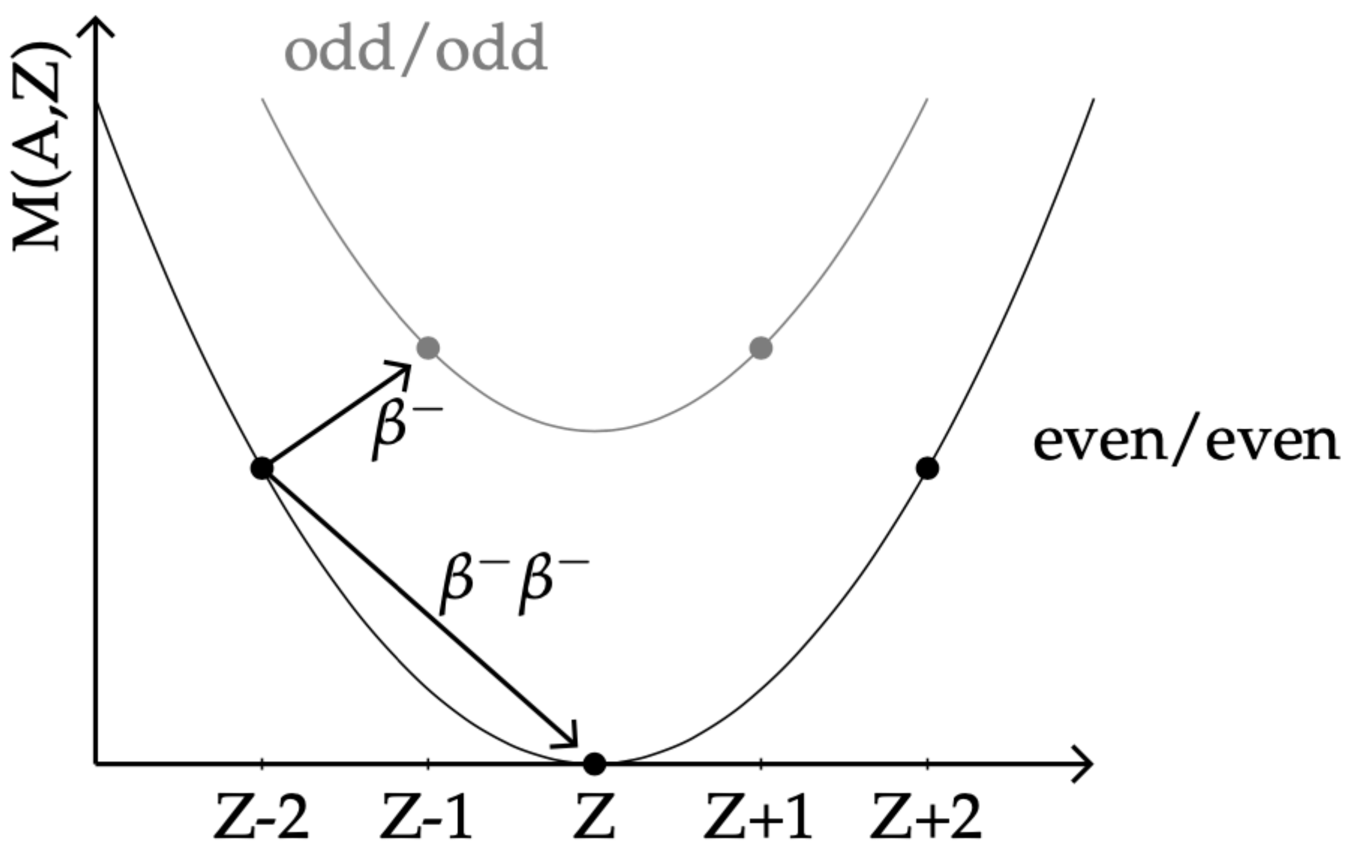

M. Goeppert Mayer, Phys. Rev. 48 (1935) 512

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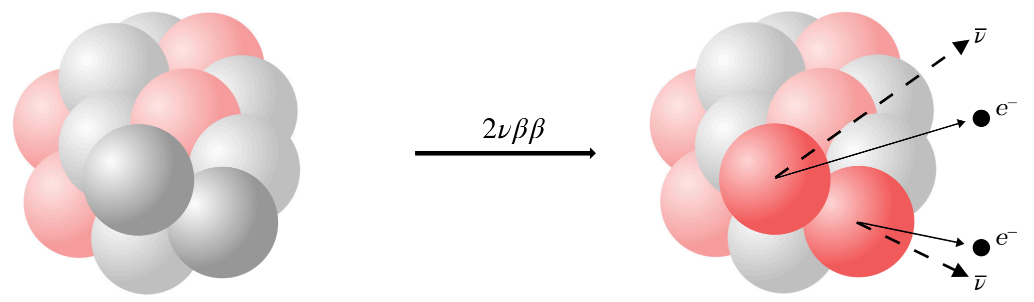
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}$$



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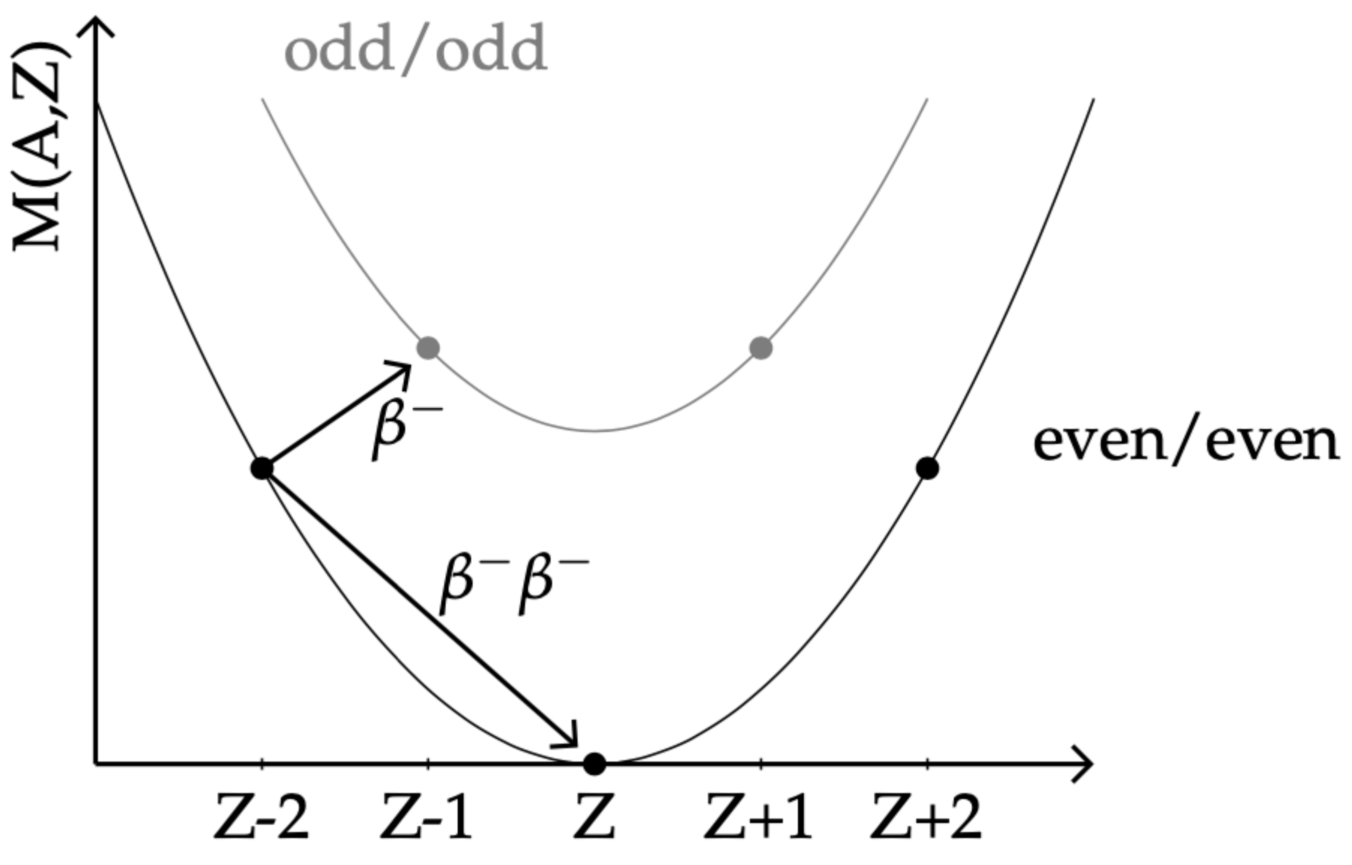

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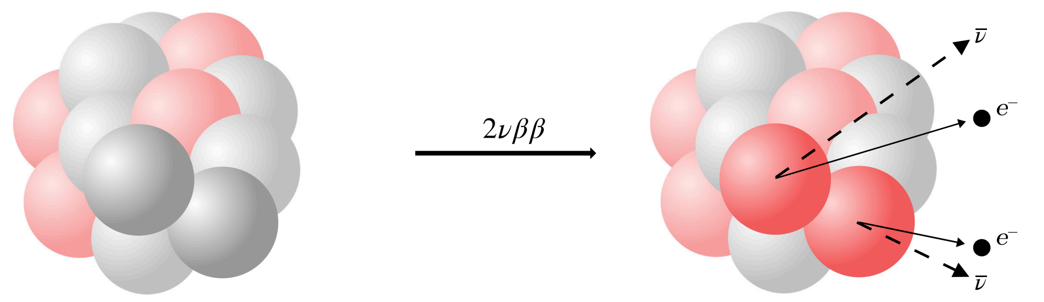

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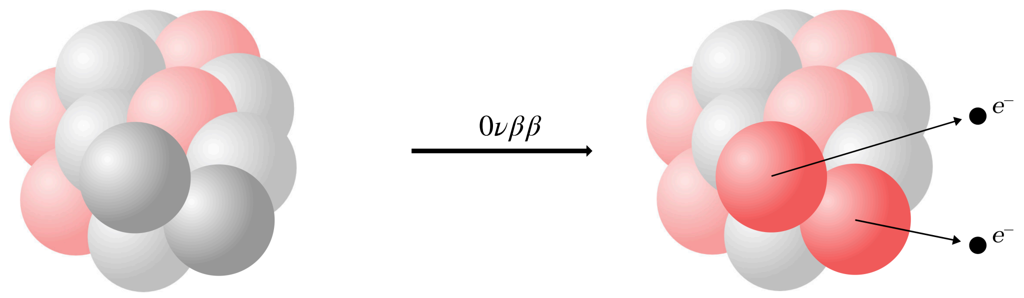

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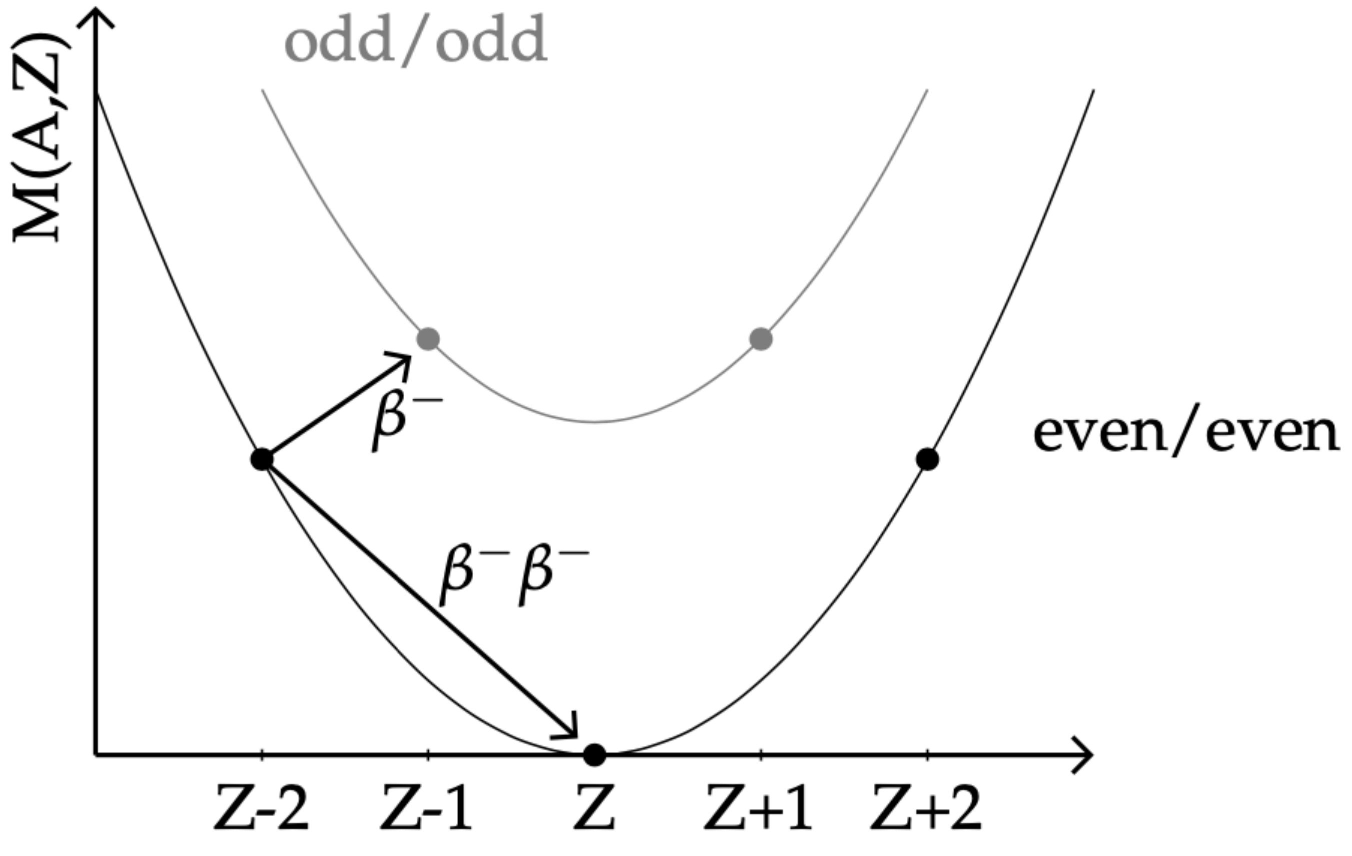

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  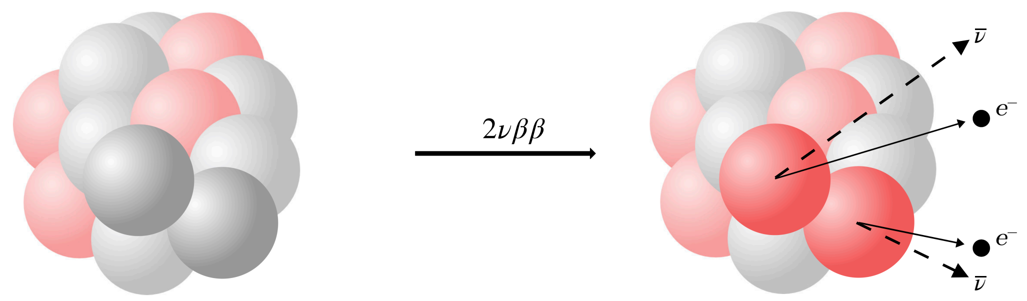

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  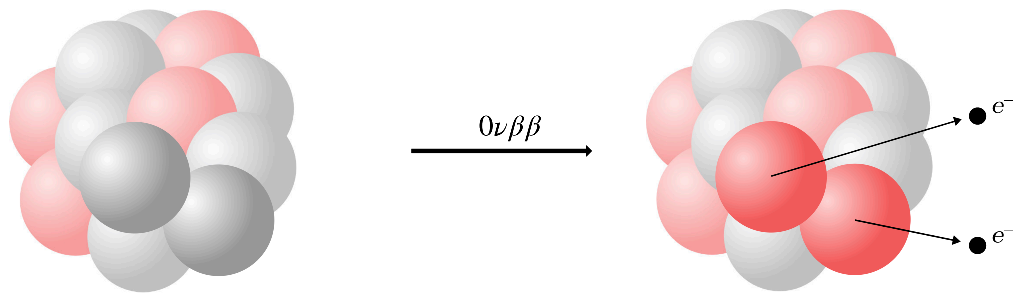

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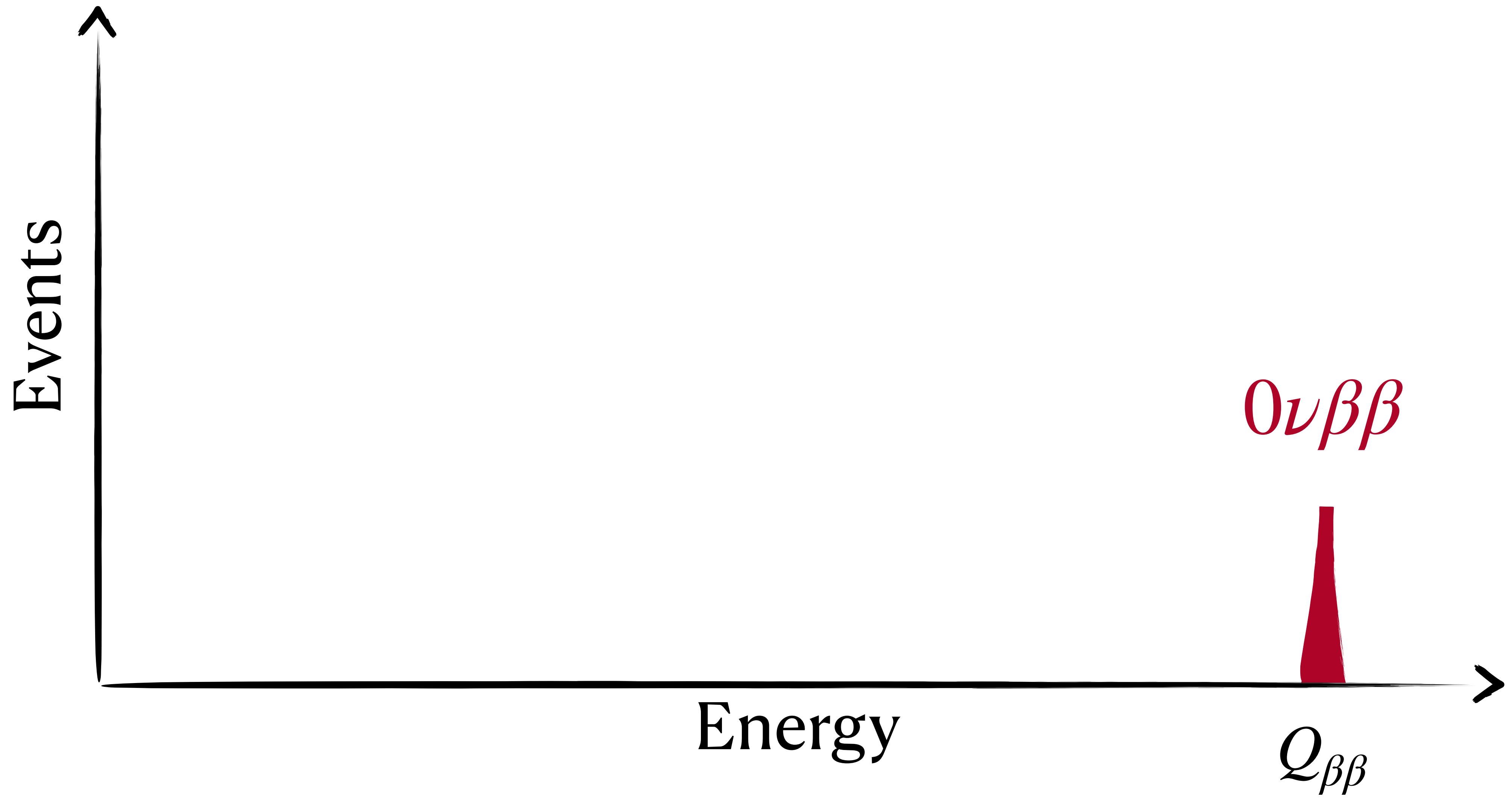

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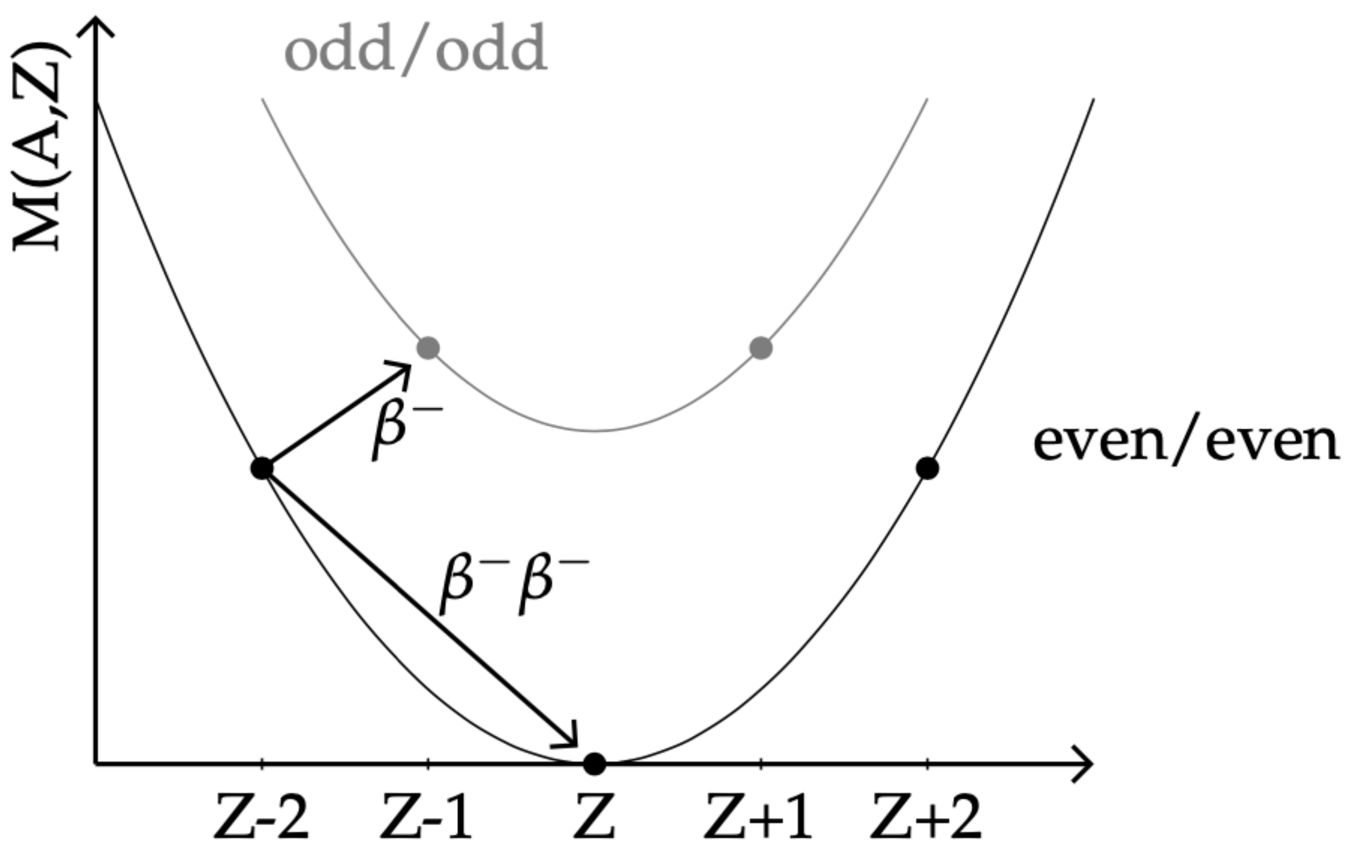

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  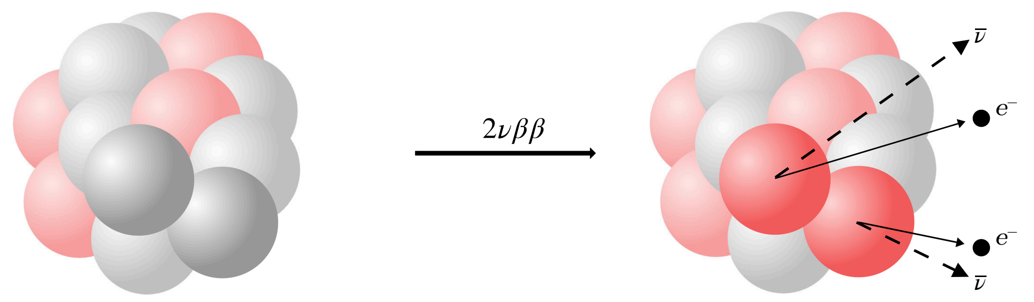

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  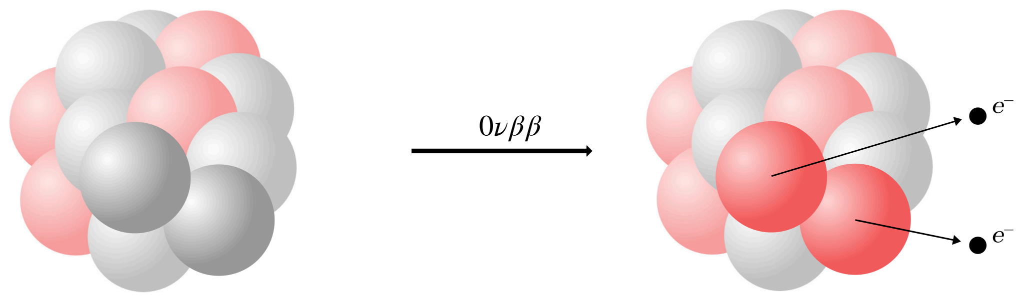

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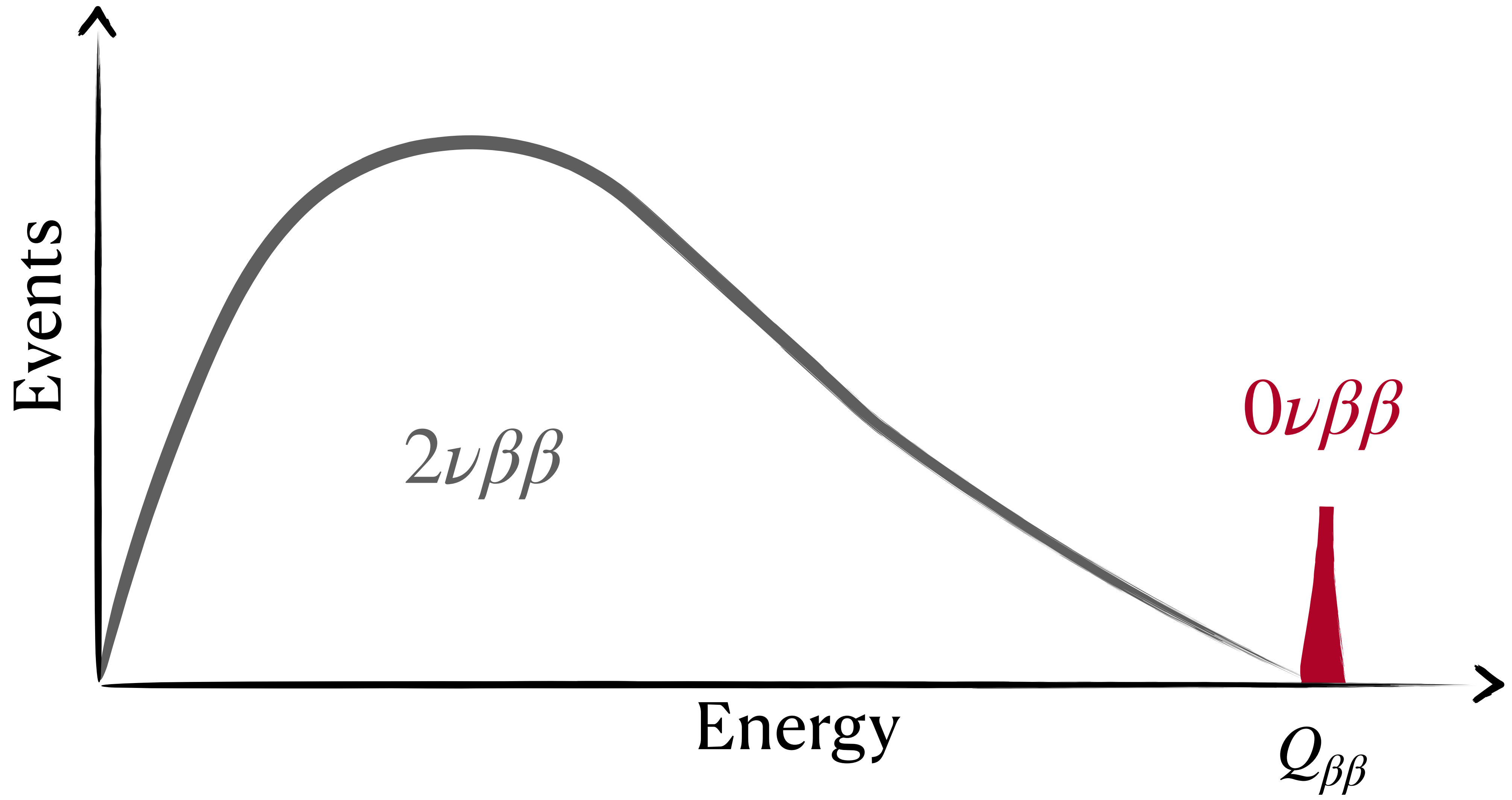

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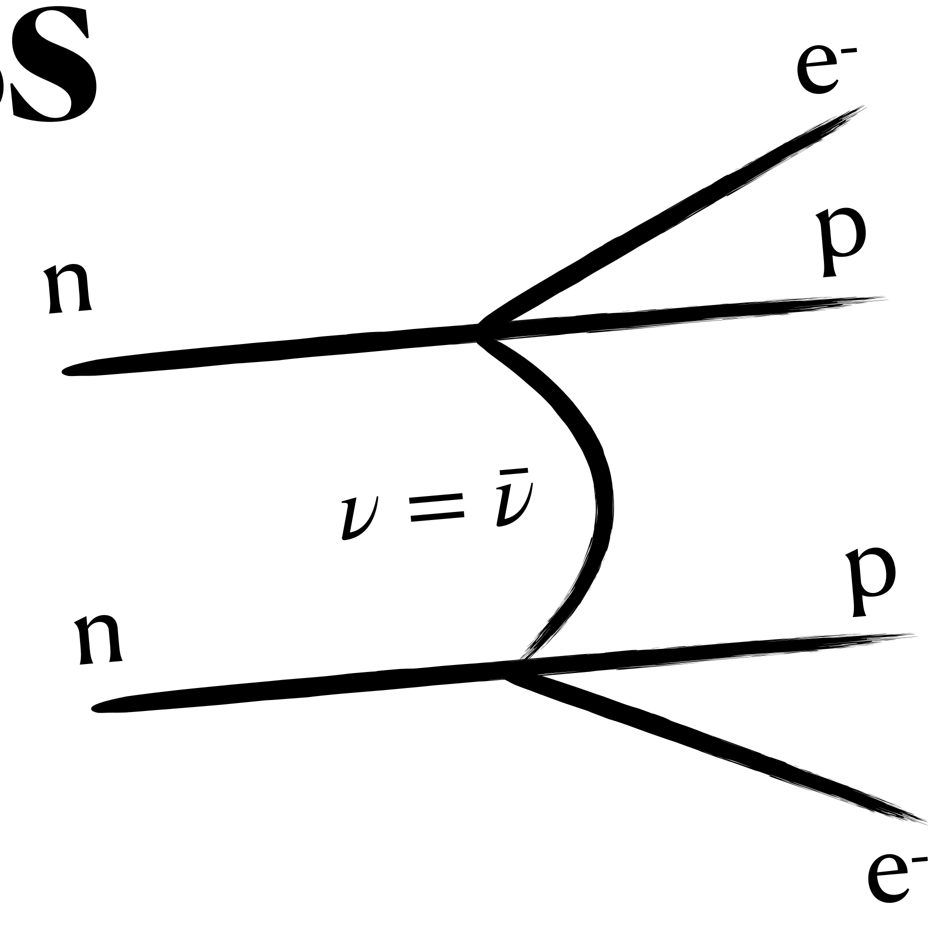

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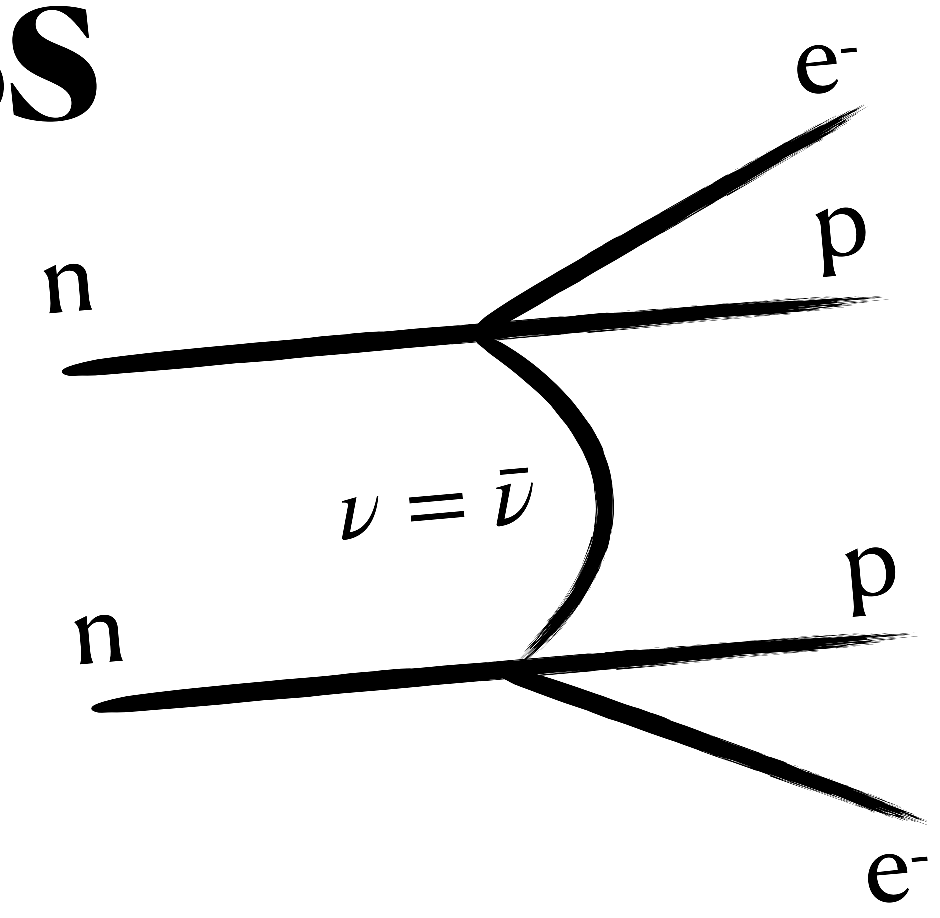
Majorana neutrino mass



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$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_A^4 \, |\mathscr{M}^{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

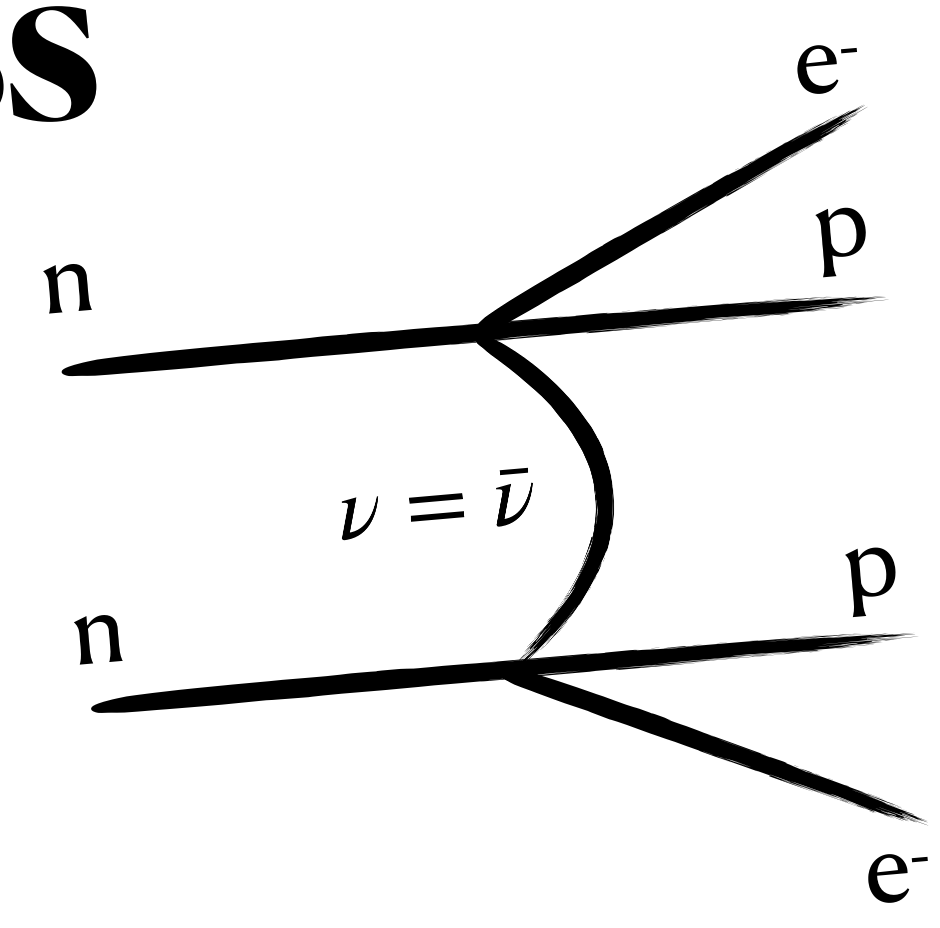
Phase-space factor: well understood

Nuclear matrix element (NME) & axial vector coupling constant: must be calculated from nuclear theory, large uncertainties

Effective Majorana neutrino mass: related to neutrino parameters

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

Majorana neutrino mass



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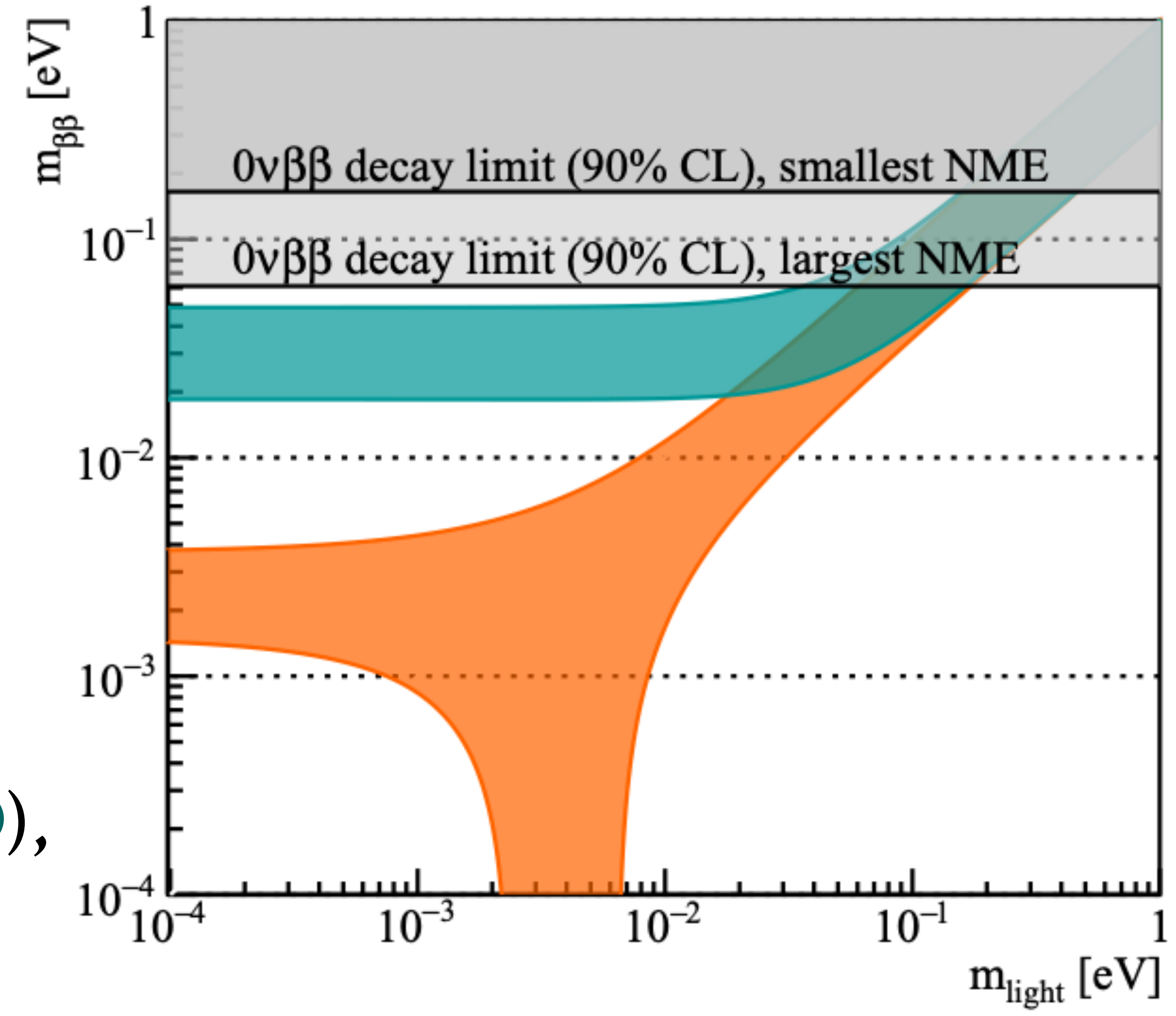
arXiv:2202.01787

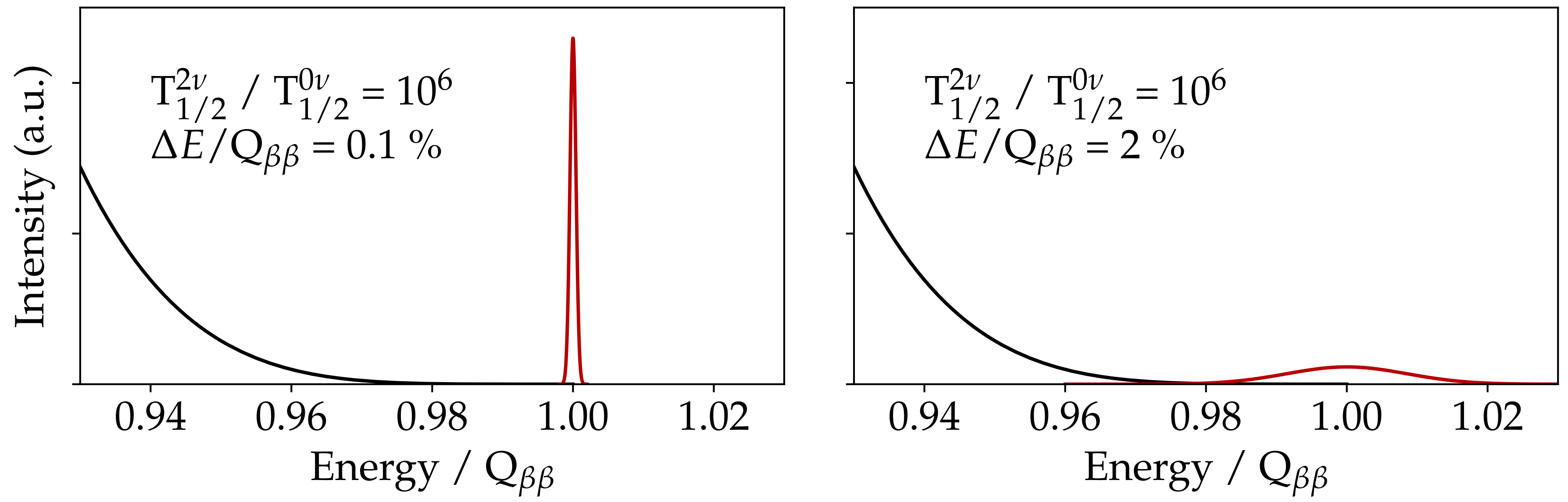


▶ Unknown parameters: absolute mass scale (m_{light}), mass hierarchy (**NO** vs **IO**), Majorana phases

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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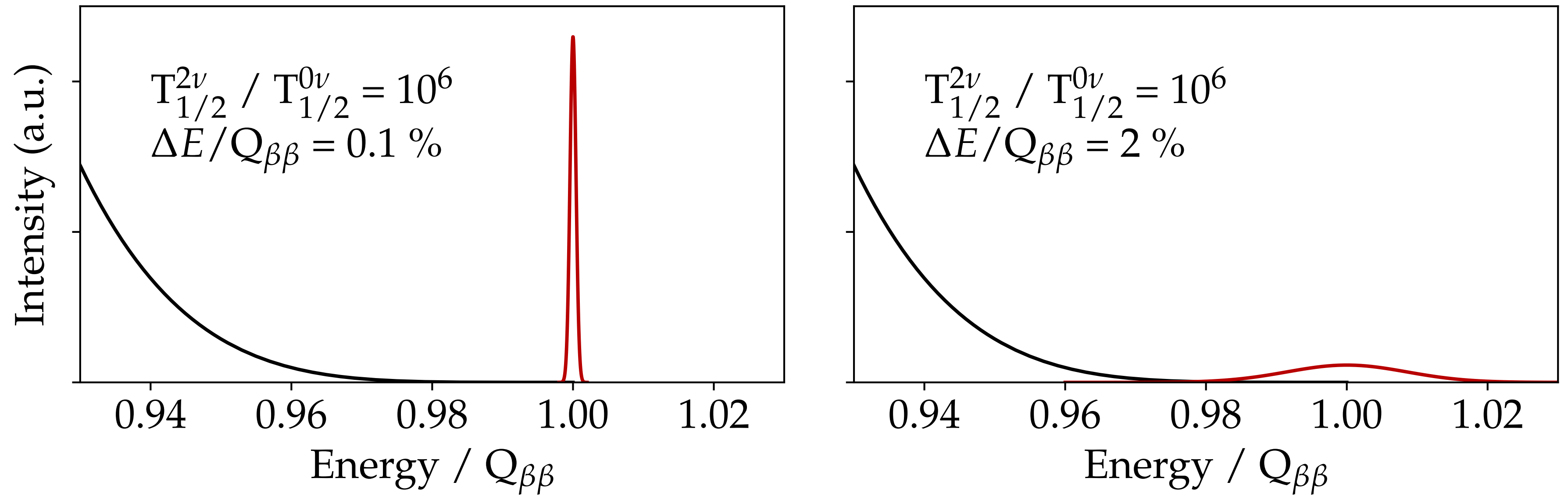
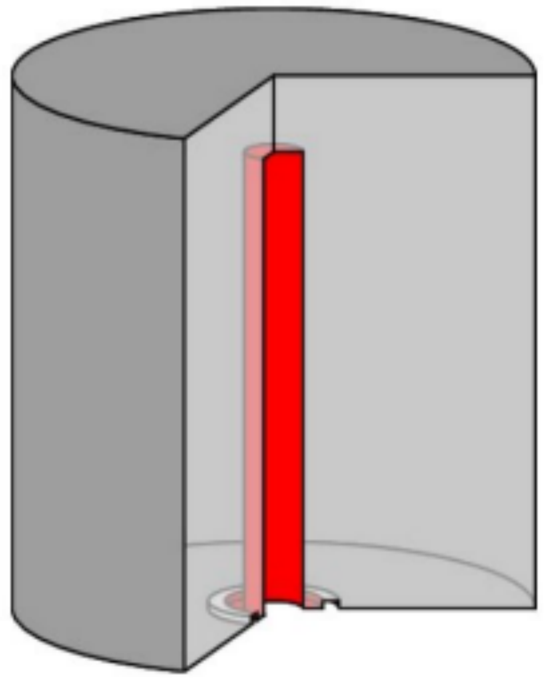
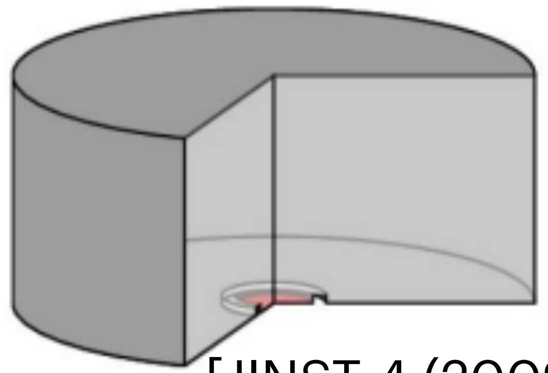


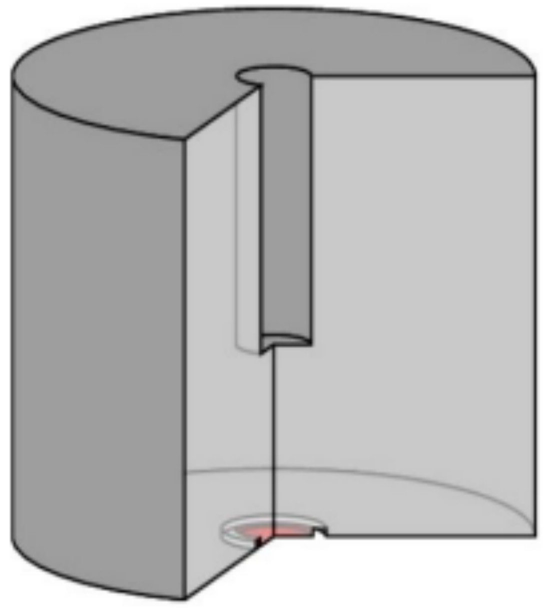


7 (later 6) Coaxial detectors (15.6 kg, later 14.6 kg):
- ☑ Big
- ☐ Good PSD performance



30 BEGe detectors (20 kg):
- ☑ Very good PSD performance
- ☐ Small

[JINST 4 (2009) P10007]

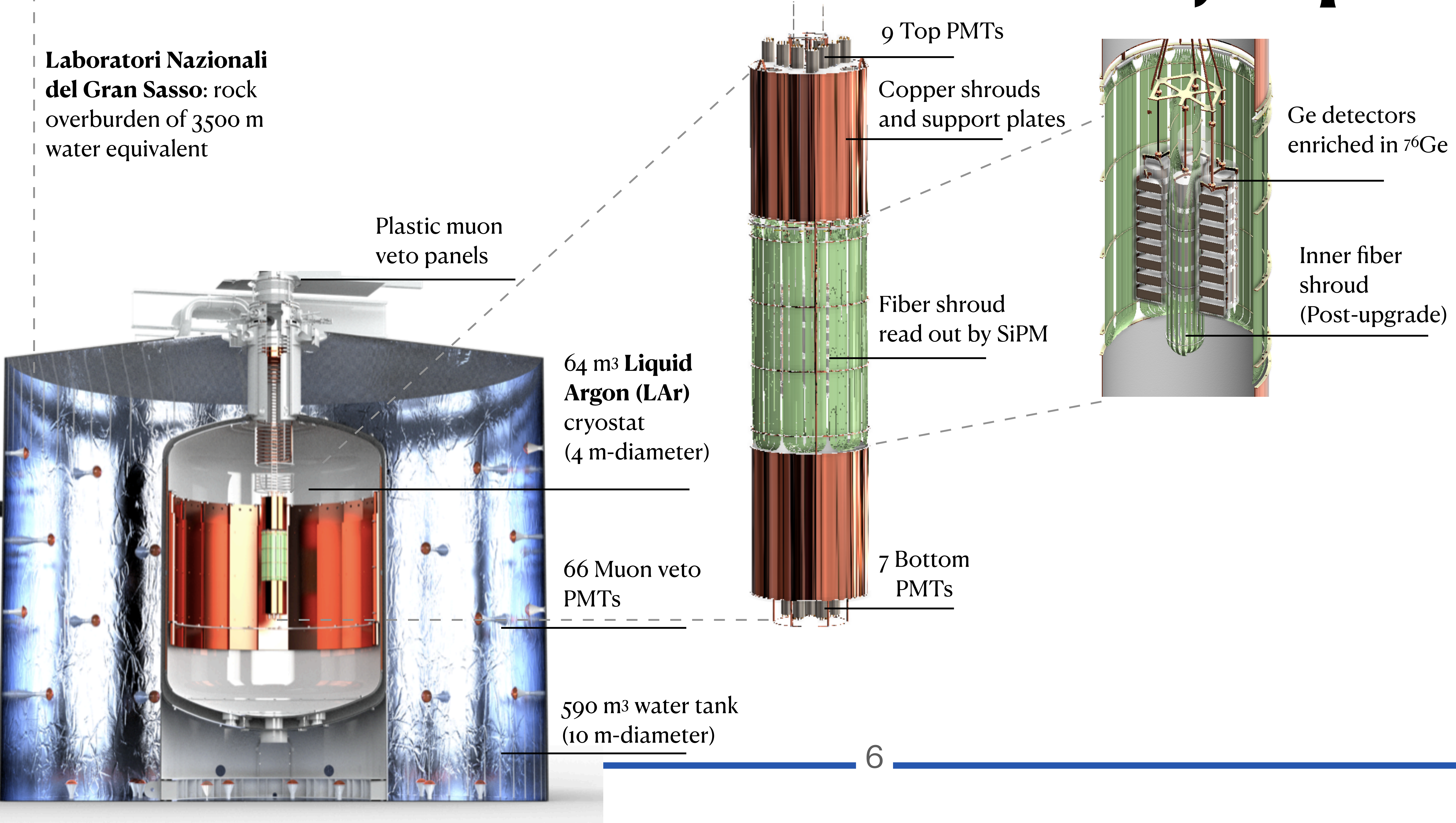


5 Inverted Coaxial detectors added after upgrade (9.6 kg):
- ☑ Big
- ☑ Very good PSD performance

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

The GERmanium Detector Array experiment

Laboratori Nazionali del Gran Sasso: rock overburden of 3500 m water equivalent



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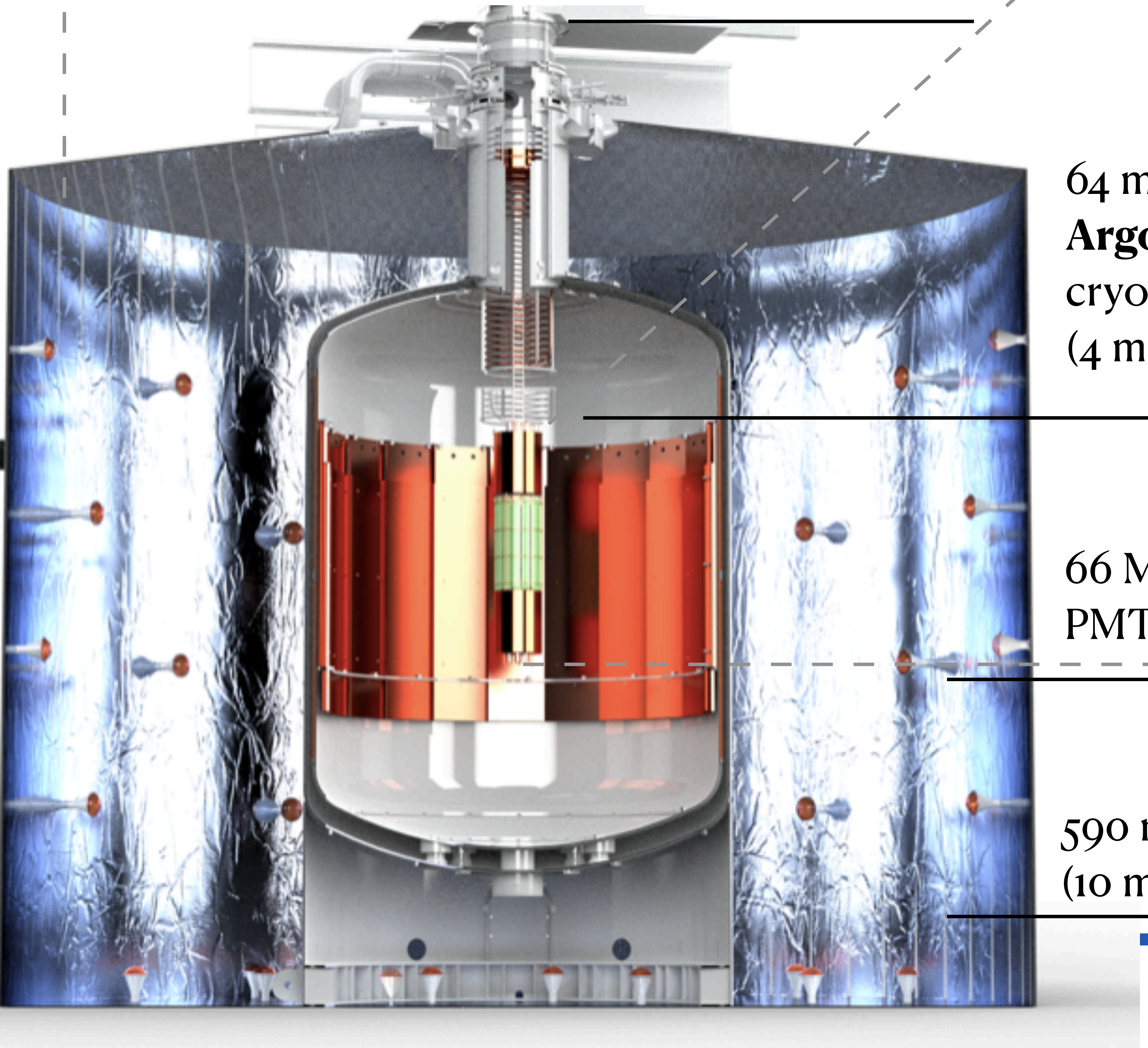
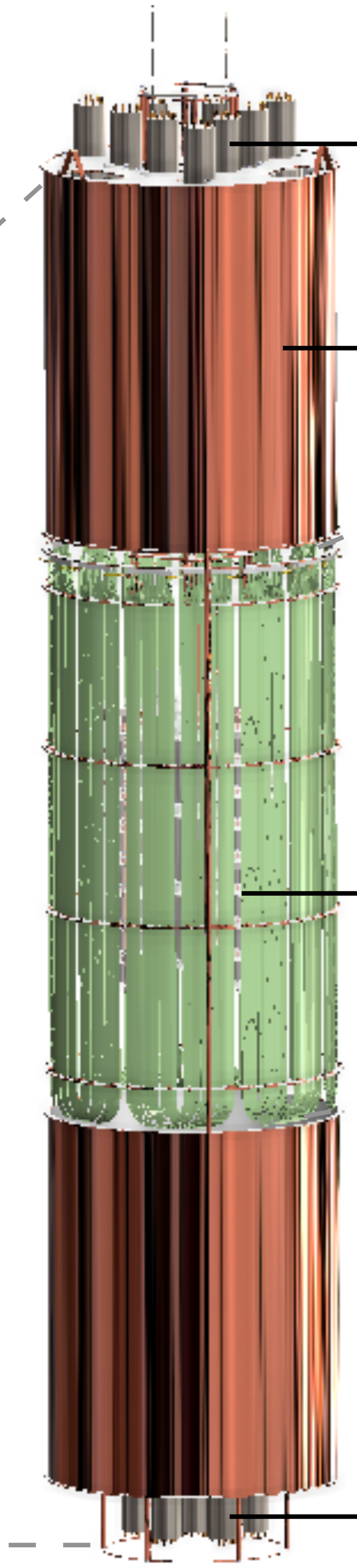


Plastic muon veto panels

64 m^3 **Liquid Argon (LAr)** cryostat (4 m-diameter)

66 Muon veto PMTs

590 m^3 water tank (10 m-diameter)

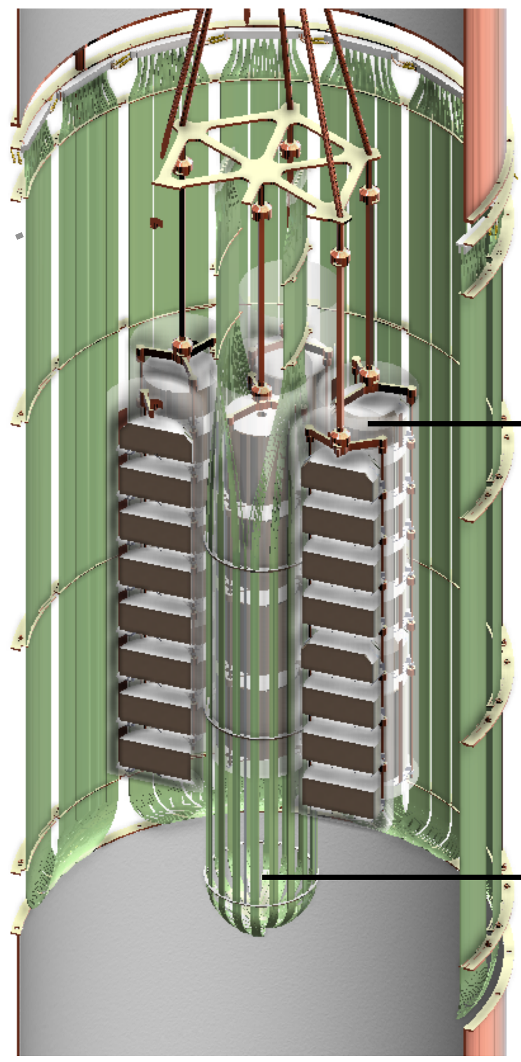


9 Top PMTs

Copper shrouds and support plates

Fiber shroud read out by SiPM

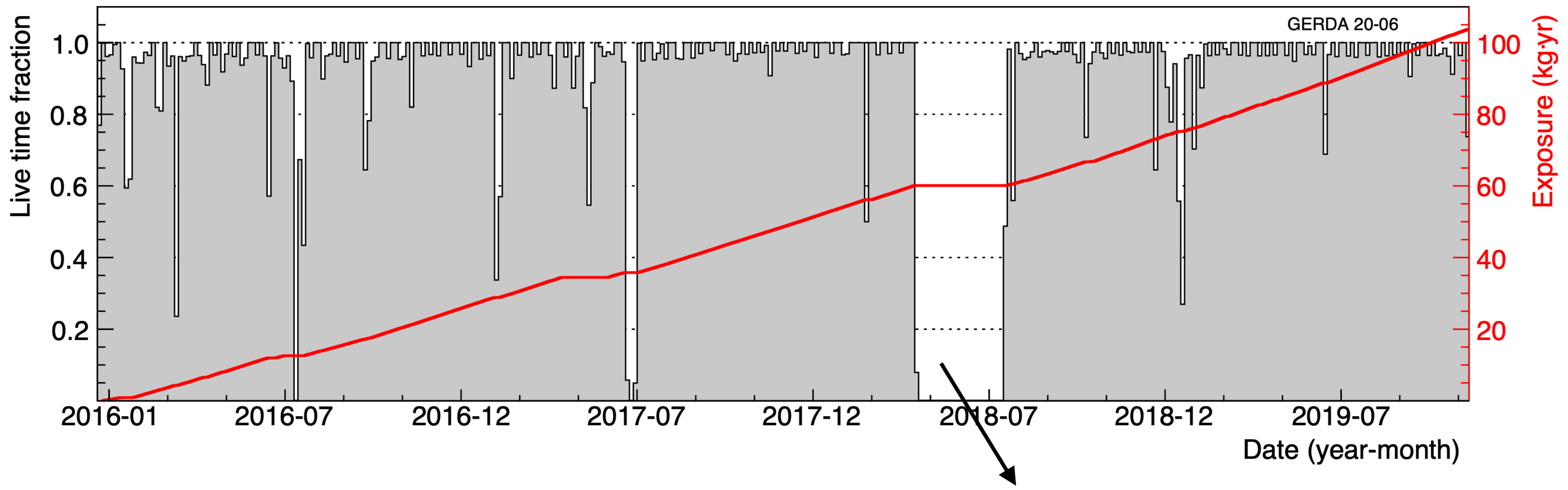
7 Bottom PMTs



Ge detectors enriched in ^{76}Ge

Inner fiber shroud (Post-upgrade)

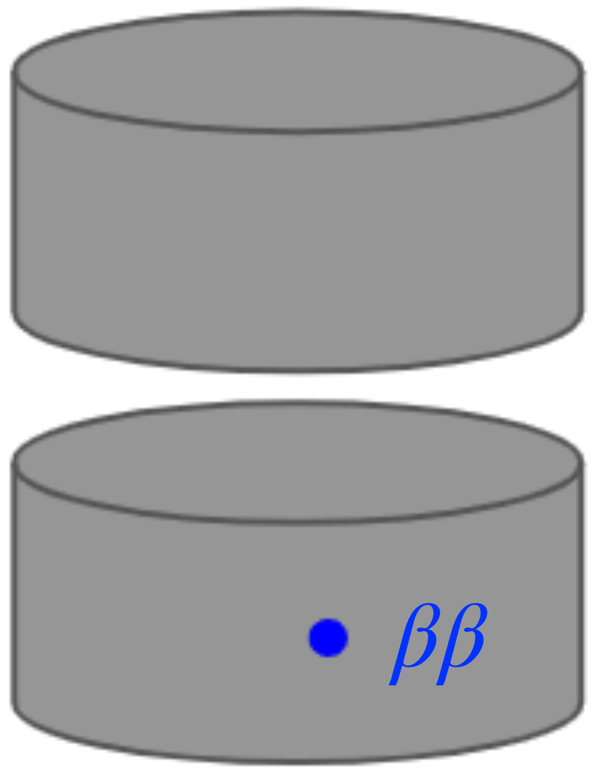
- Data taking from December 2015 to November 2019
- Phase II exposure 103.7 kg yr



Upgrade in Summer 2018

Background discrimination by event topology

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



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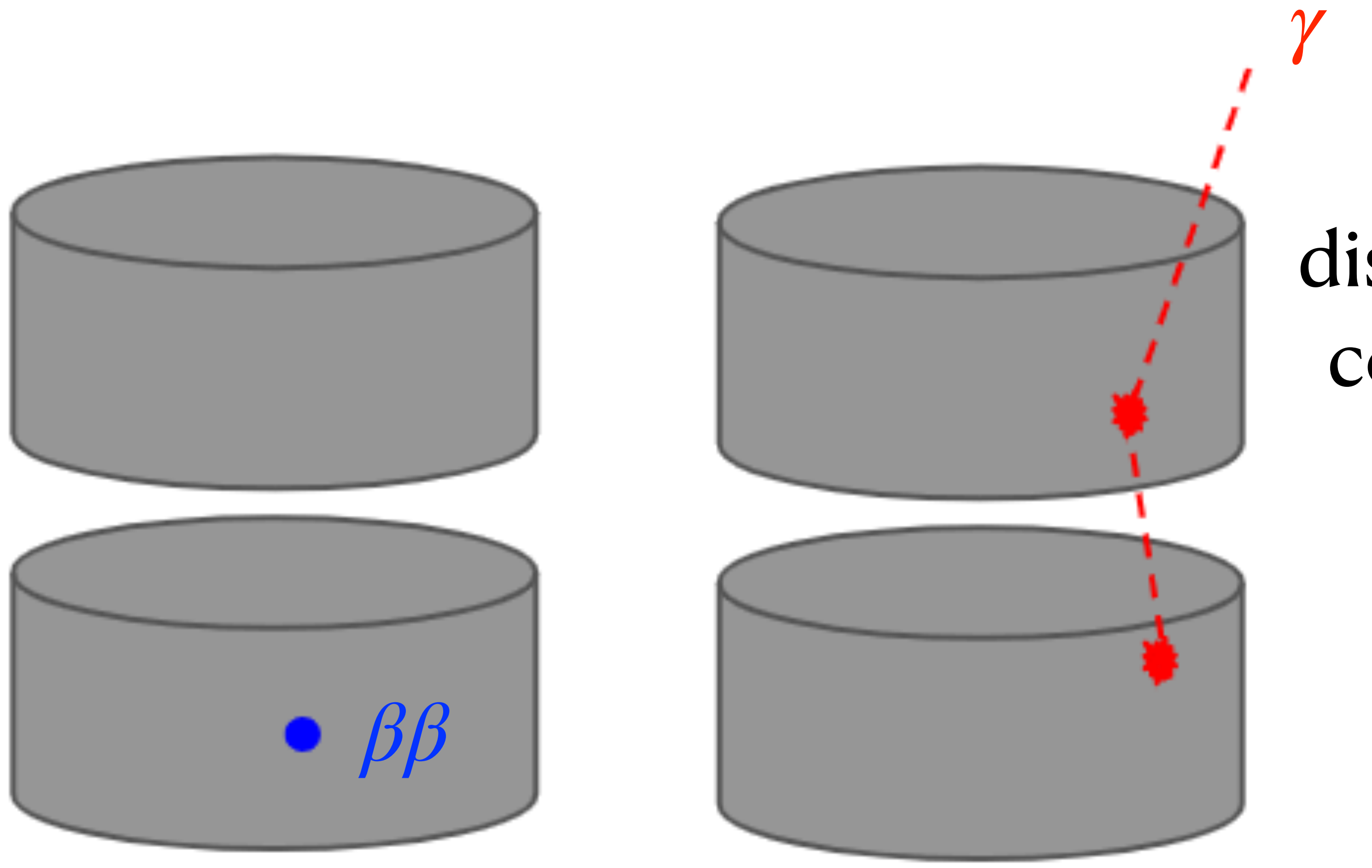

Detector-detector coincidences: discrimination by anti-coincidence (AC) cut

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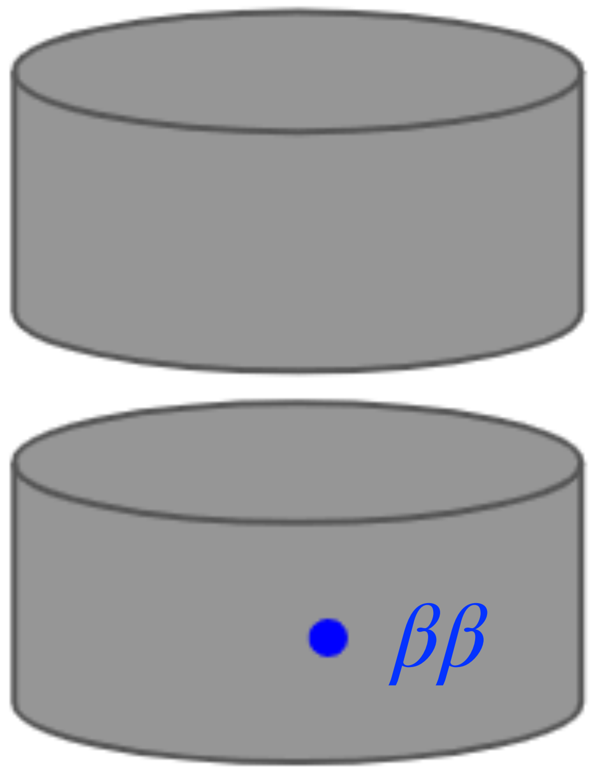

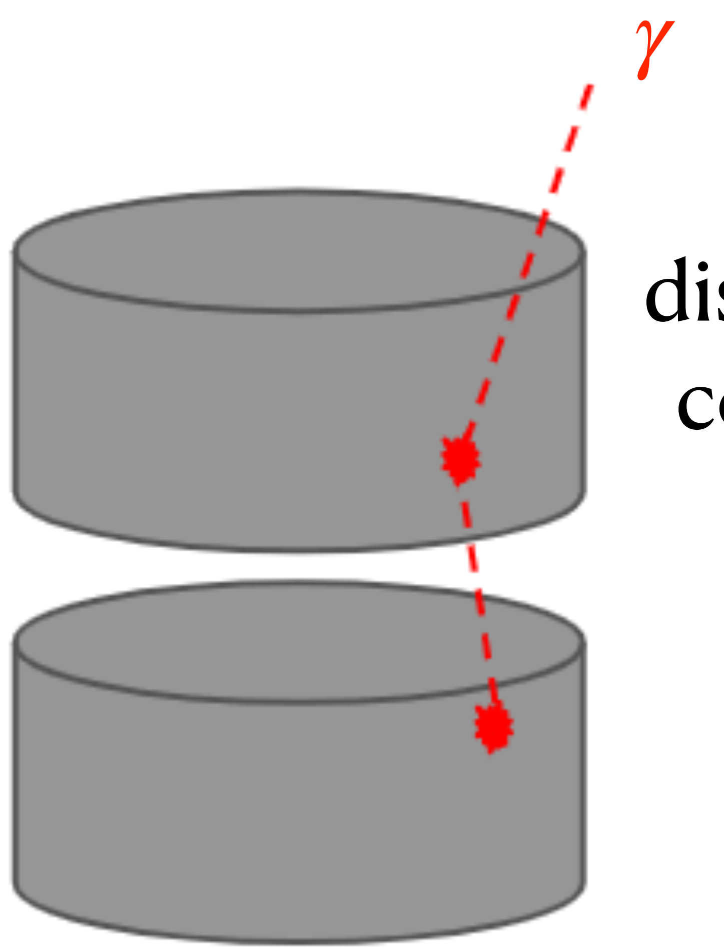

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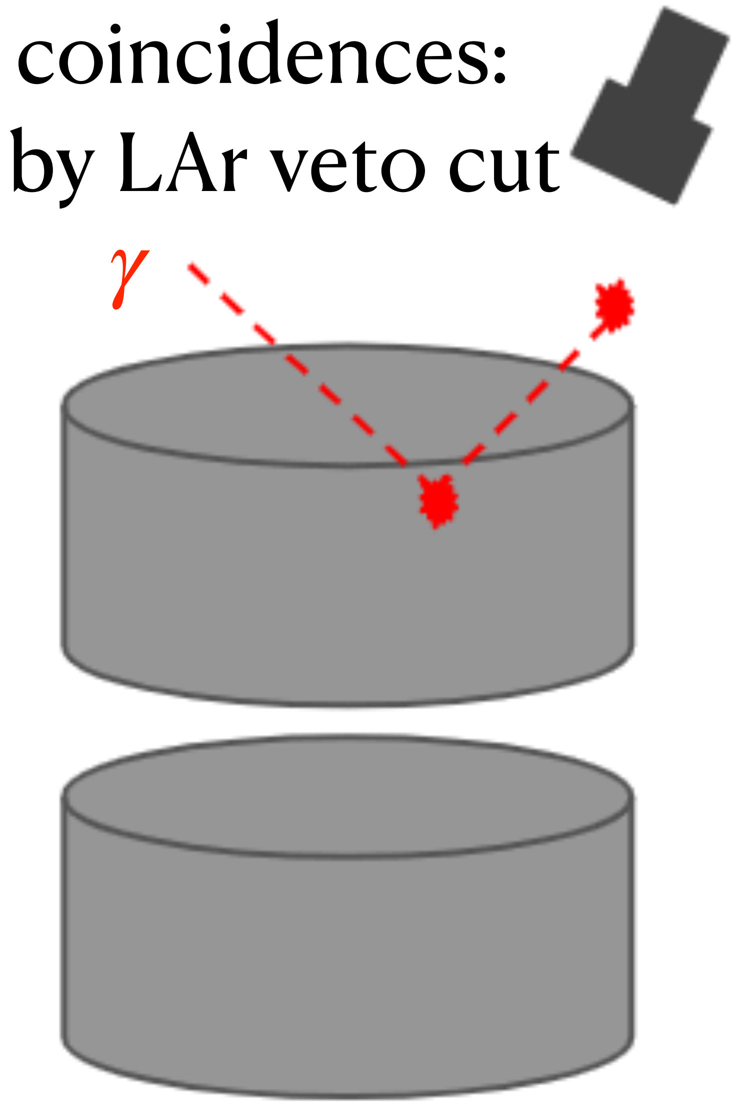
Detector-LAr coincidences: discrimination by LAr veto cut



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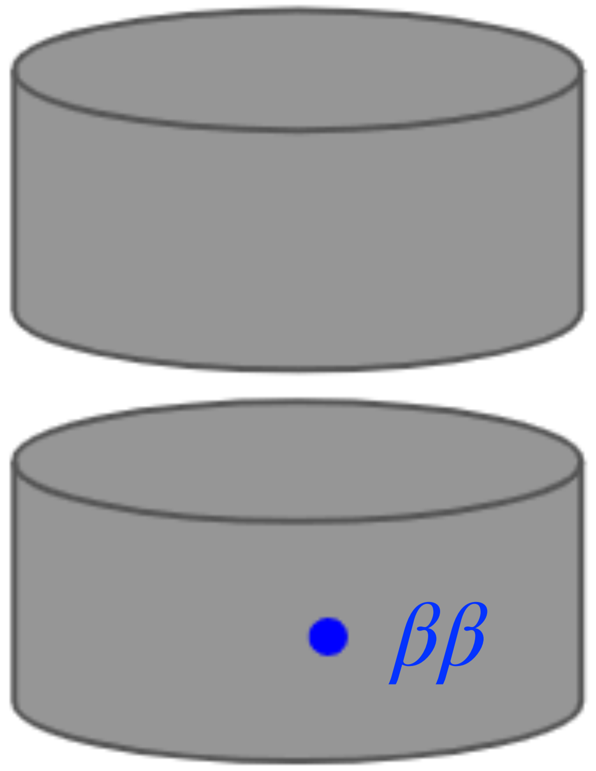

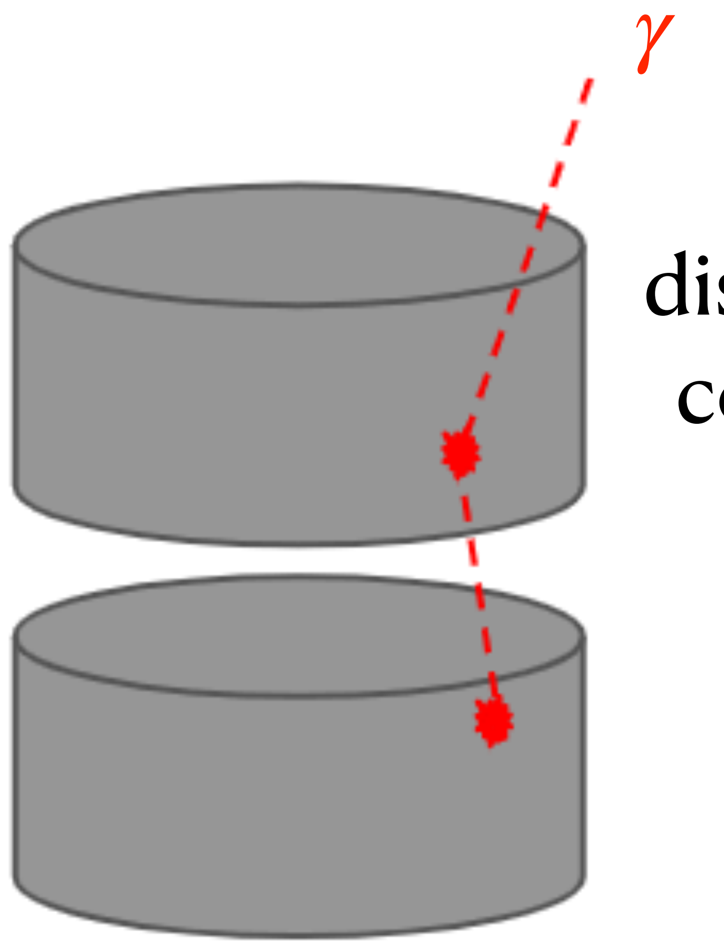

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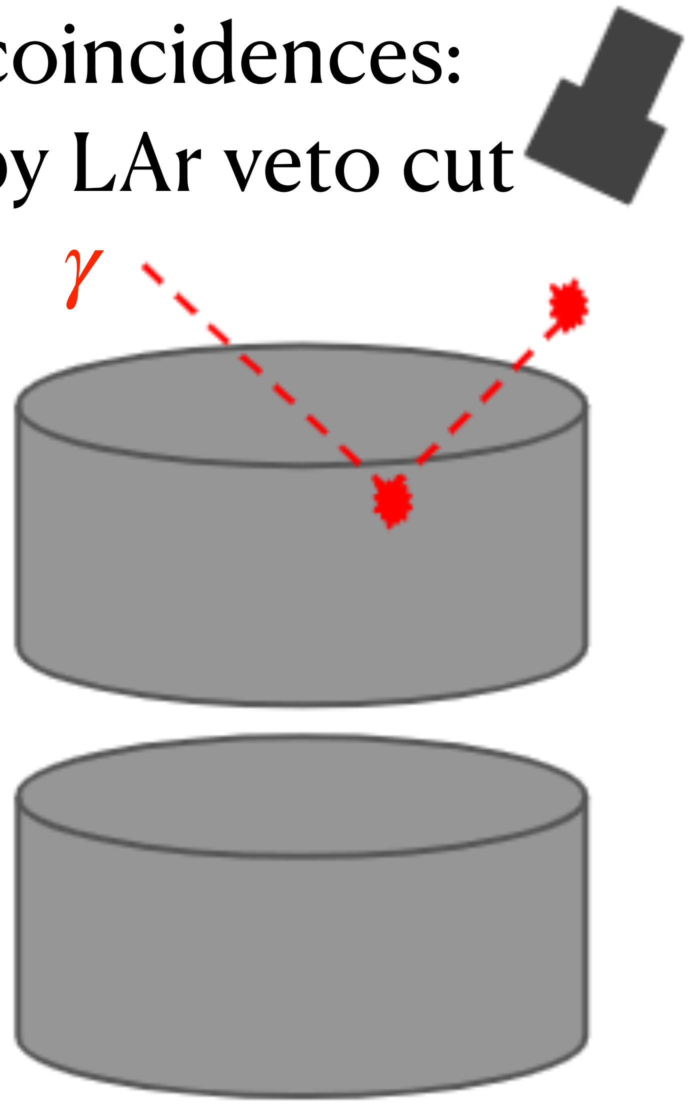

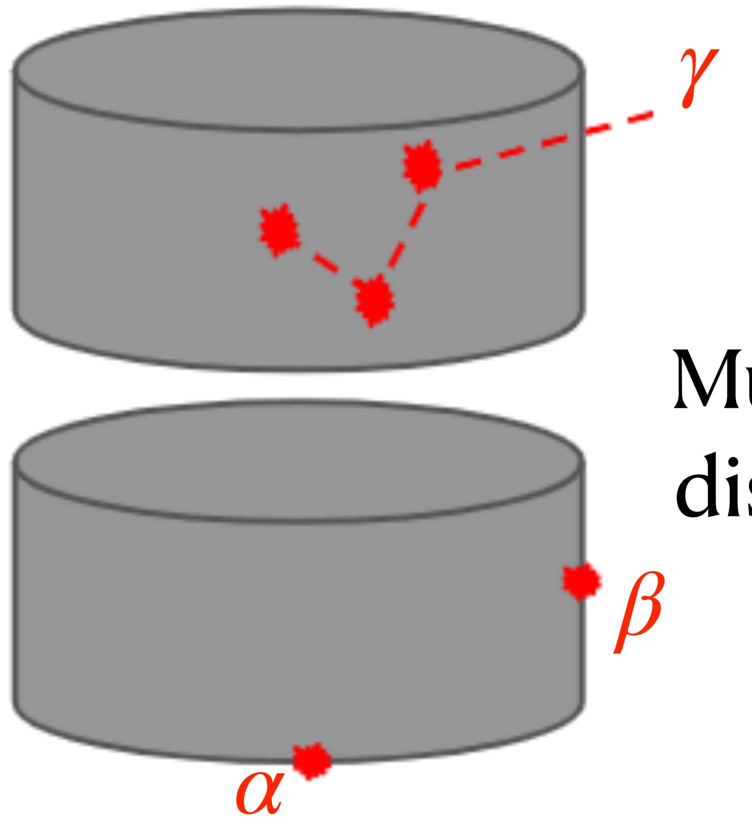

Multi-site / surface events: discrimination by PSD cut

Background discrimination by event topology

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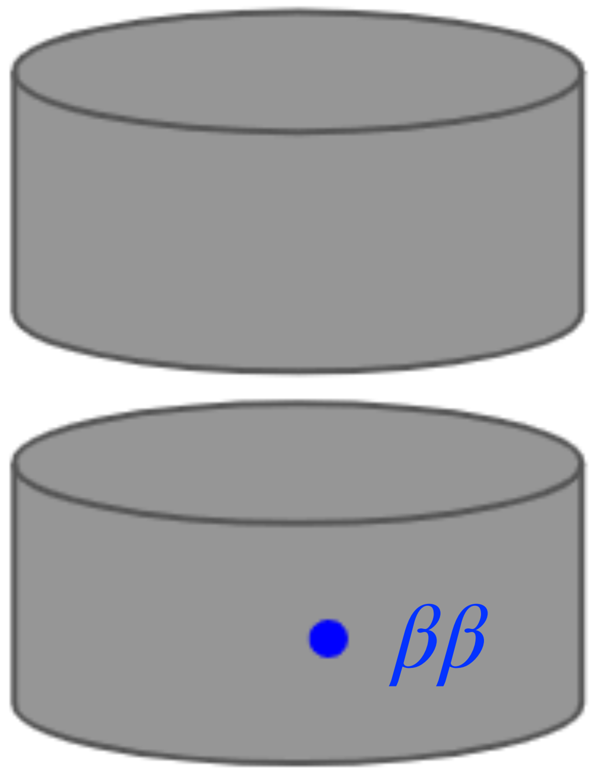

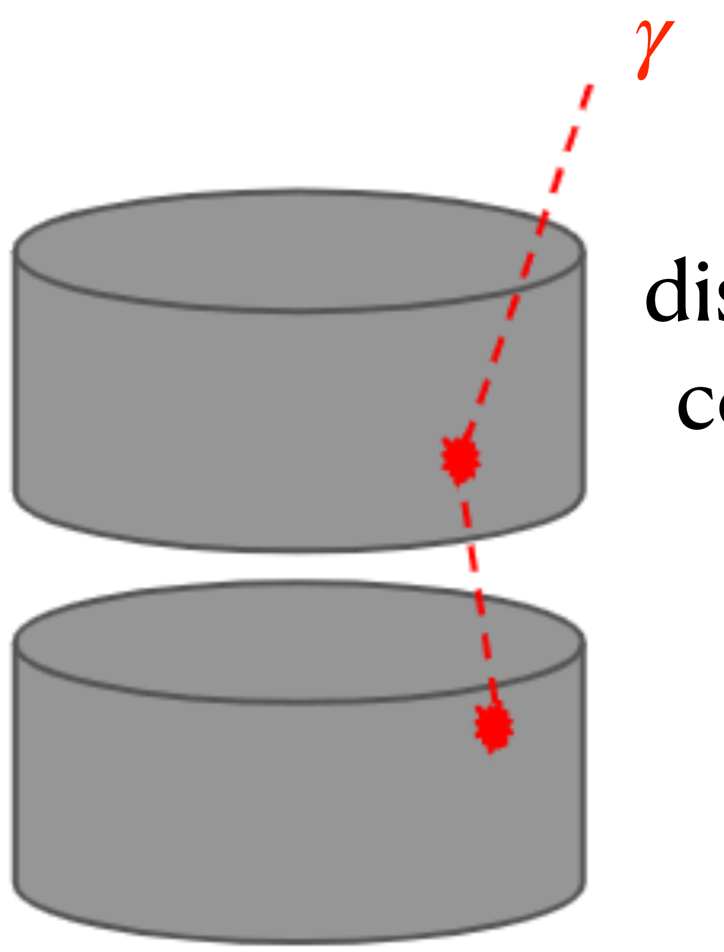

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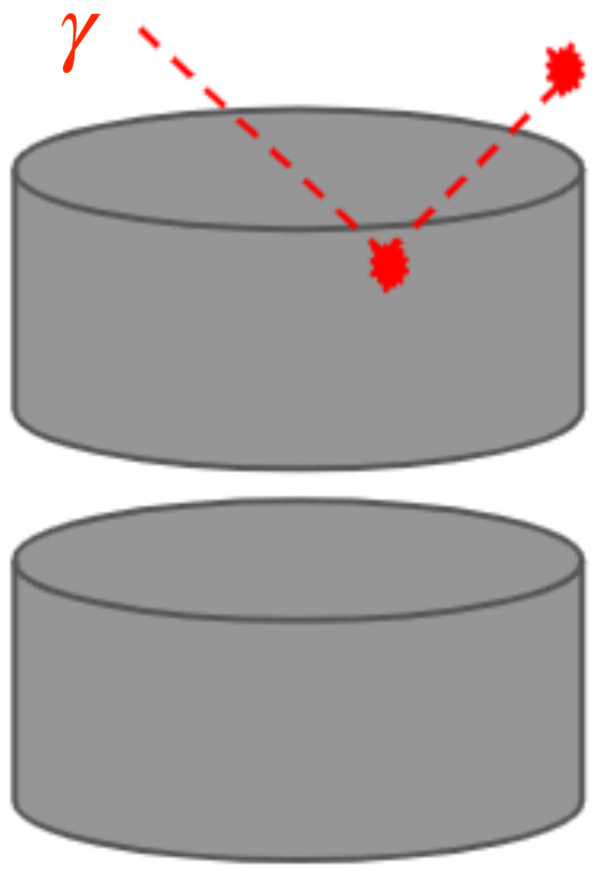

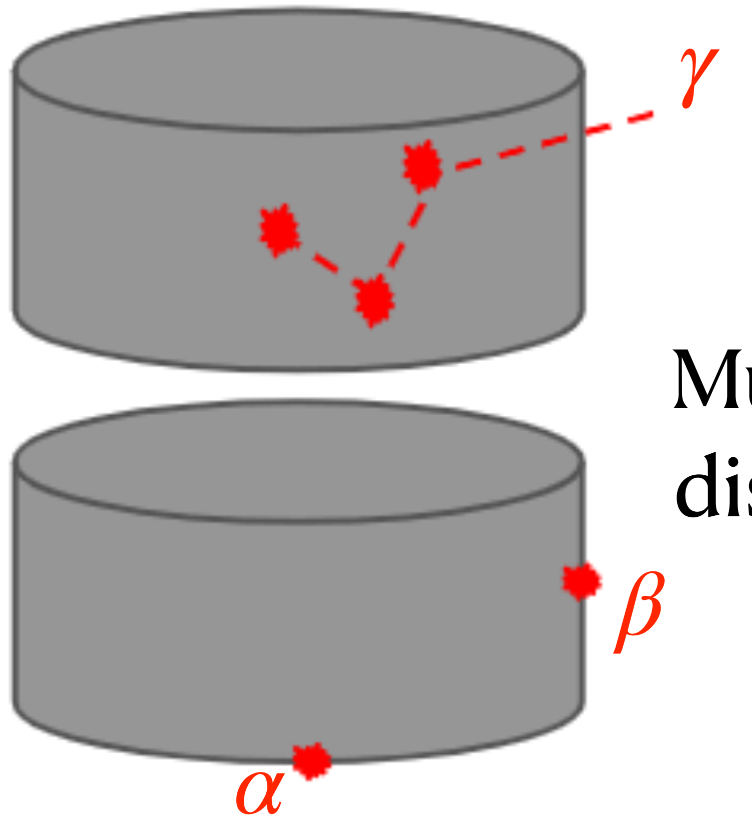

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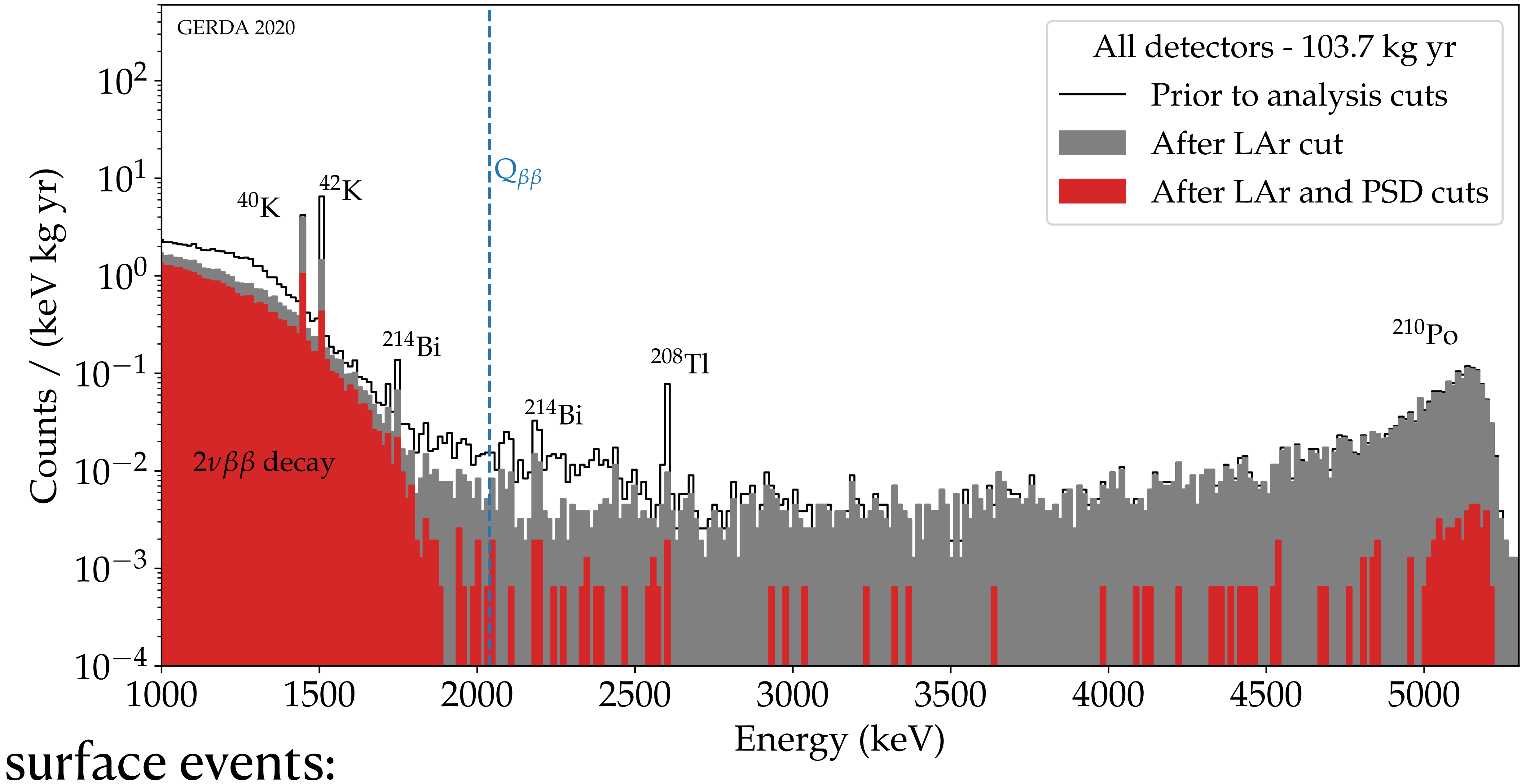


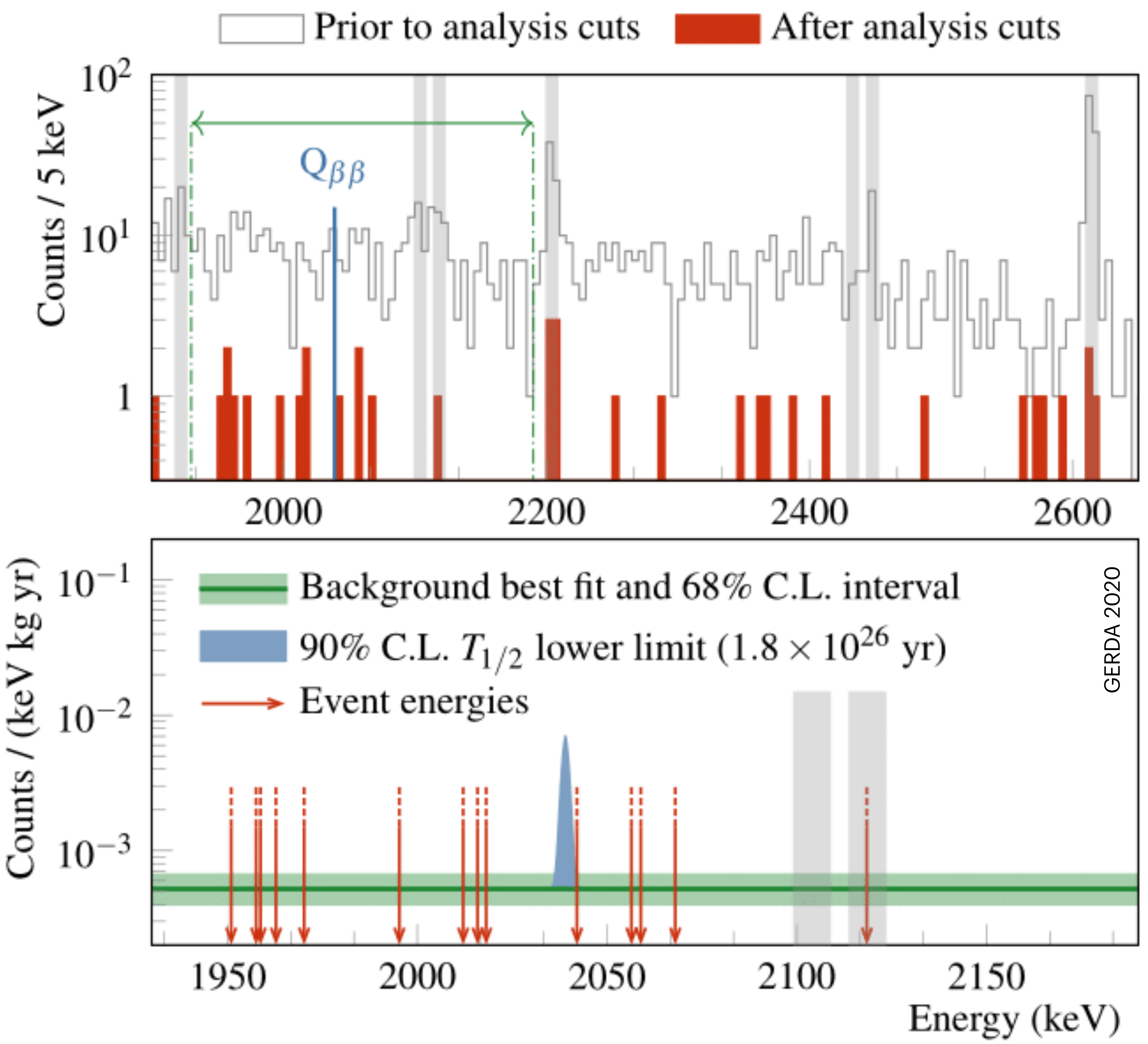
Final results on the search for $0\nu\beta\beta$ decay

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

- Lowest background index:

  $5.2^{+1.6}_{-1.3}$ 10^{-4} cts/(keV kg yr)

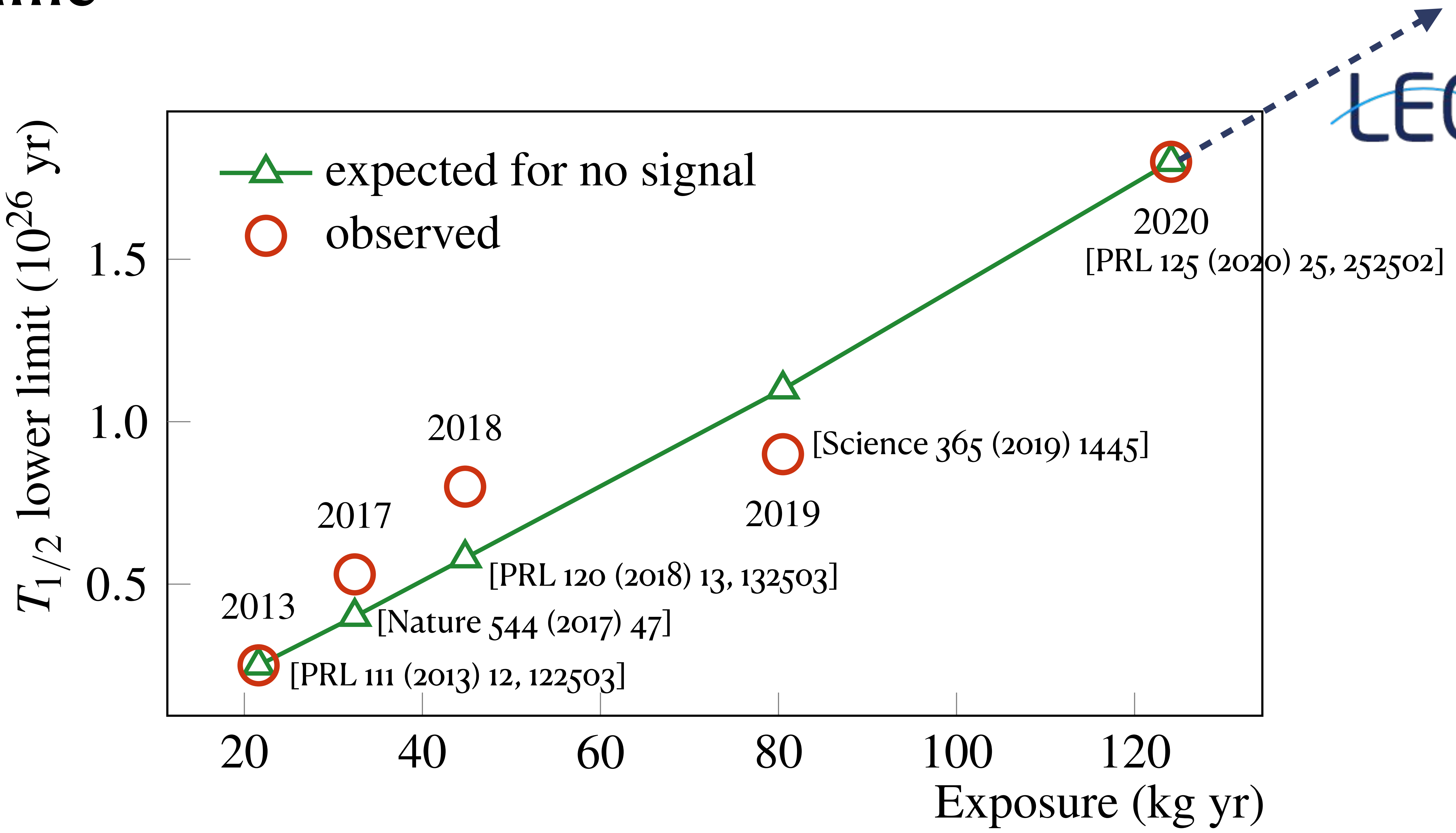
- Energy resolution at $Q_{\beta\beta}$ ~ 3keV (FWHM)
- No signal observed in 103.7 kg yr of exposure
- Combined frequentist Phase I/PhaseII analysis
- Best-fit N=0, $T^{0\nu}_{1/2}$ > 1.8 10^{26} yr at 90% C.L. (Sensitivity 1.8 10^{26} yr at 90% C.L.)
- $m_{\beta\beta}$ < 79-180 meV



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*



LEGEND

See M. Morella's talk on Thursday!

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

More Beyond the Standard Model physics

- While hunting for $0\nu\beta\beta$ decay, we collected a large statistics of $2\nu\beta\beta$ decay events:
  - We performed a precision measurement of the $2\nu\beta\beta$ decay ***half-life*** [publication coming soon!]
  - We searched for more ***BSM physics*** [JCAP12(2022)012, arXiv:2209.01671]

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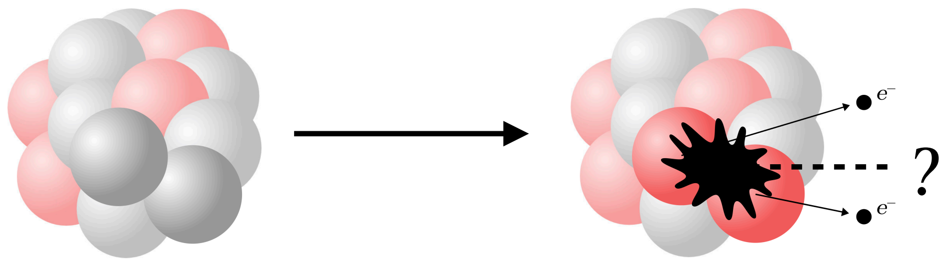

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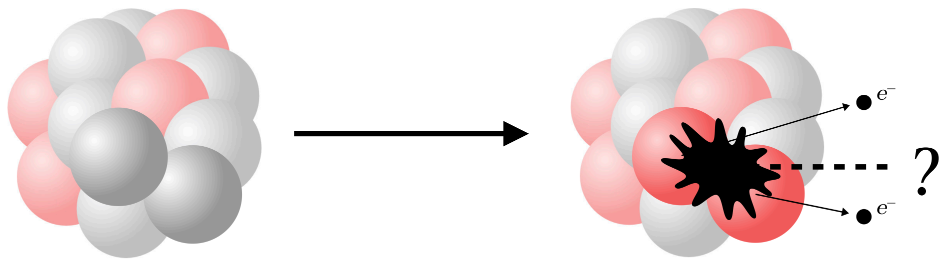
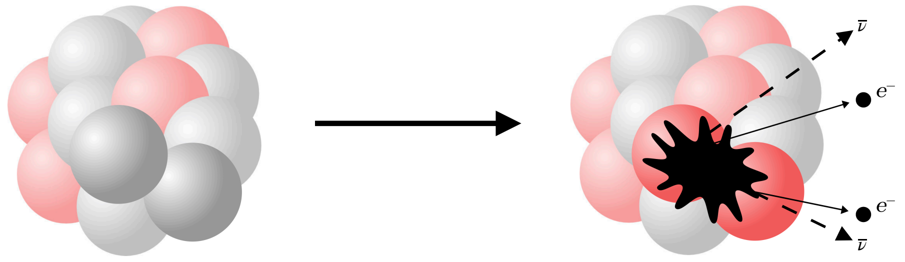


- ***Non-standard neutrino properties/interactions (i.e. Lorentz violation, RH currents, …):***

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



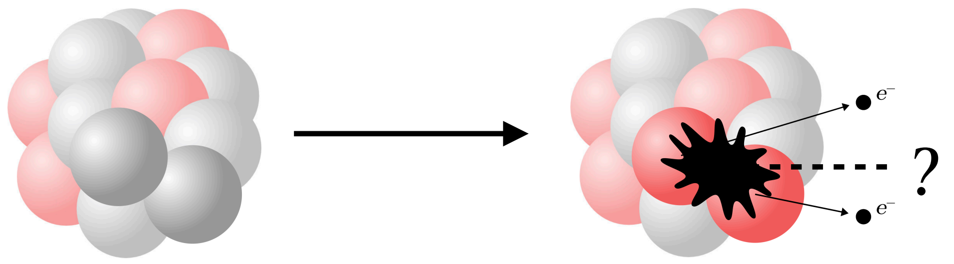
Check out the review: E.Bossio and M.Agostini, arXiv:2304.07198

More Beyond the Standard Model physics

- While hunting for $0\nu\beta\beta$ decay, we collected a large statistics of $2\nu\beta\beta$ decay events:
  - We performed a precision measurement of the $2\nu\beta\beta$ decay ***half-life*** [publication coming soon!]
  - We searched for more ***BSM physics*** [JCAP12(2022)012, arXiv:2209.01671]

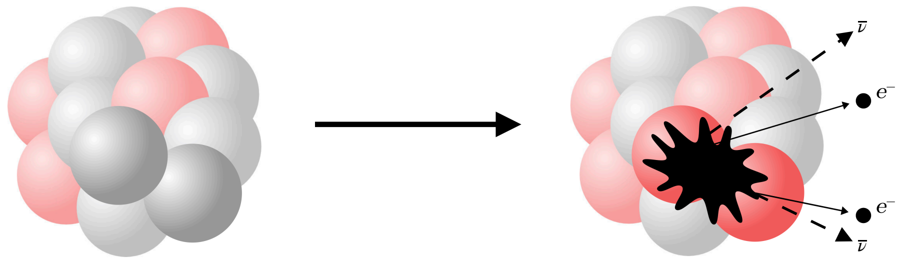
- ***New particles coupling to neutrinos (i.e. Majorons, light exotic fermions, …):***

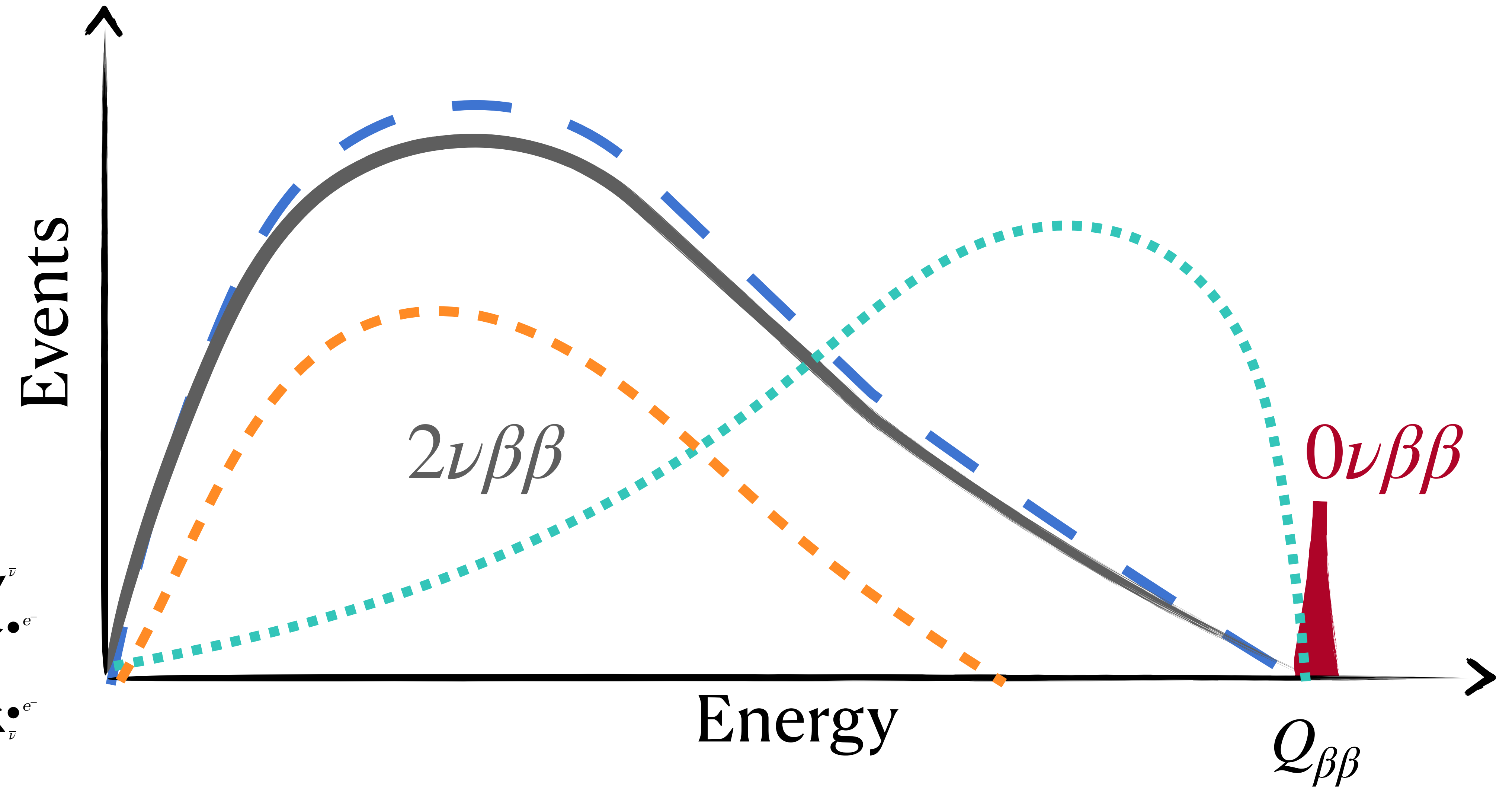
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + X(2X)$$



- ***Non-standard neutrino properties/interactions (i.e. Lorentz violation, RH currents, …):***

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





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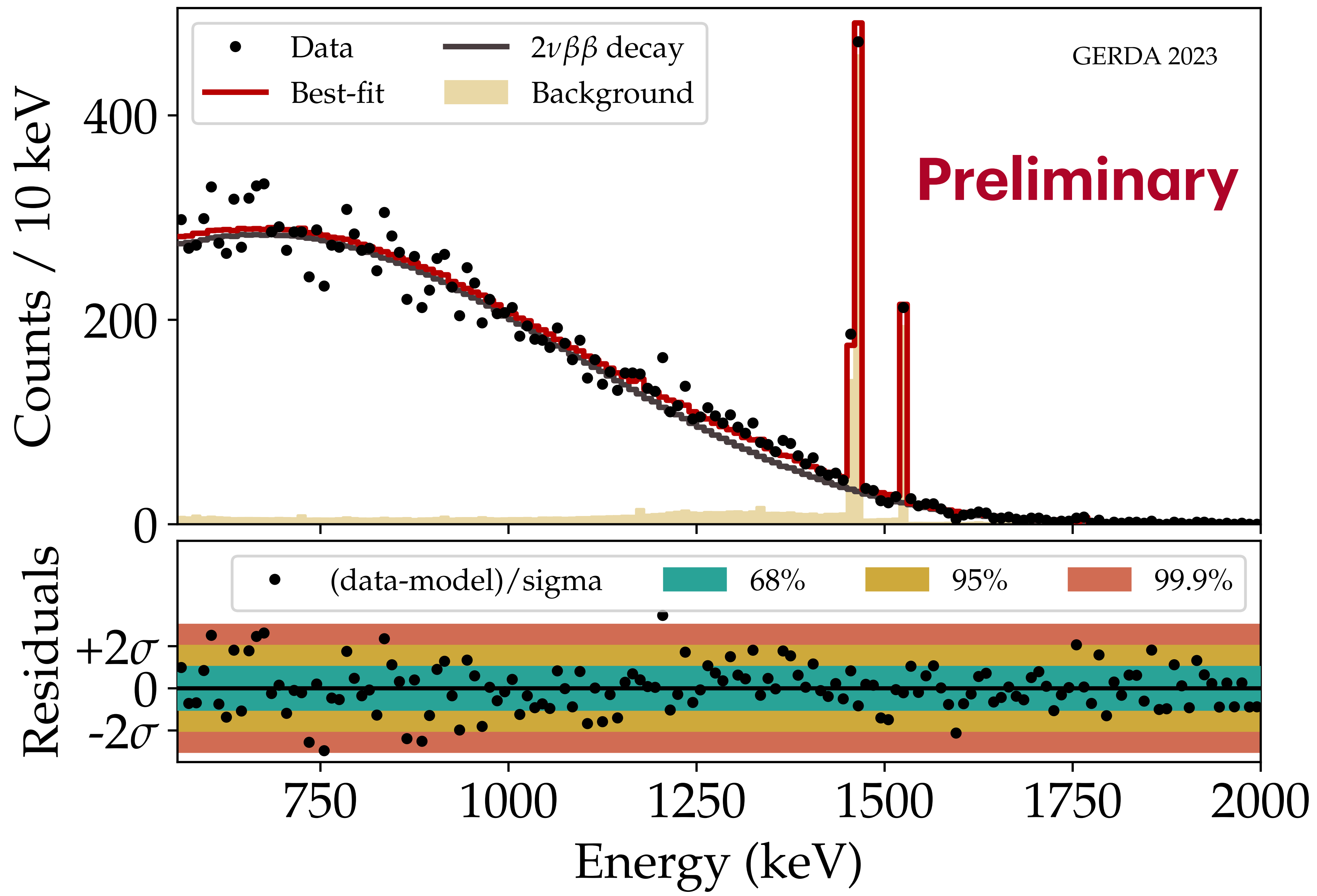
The half-life of ^{76}Ge $2\nu\beta\beta$ decay

[publication coming soon!]

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



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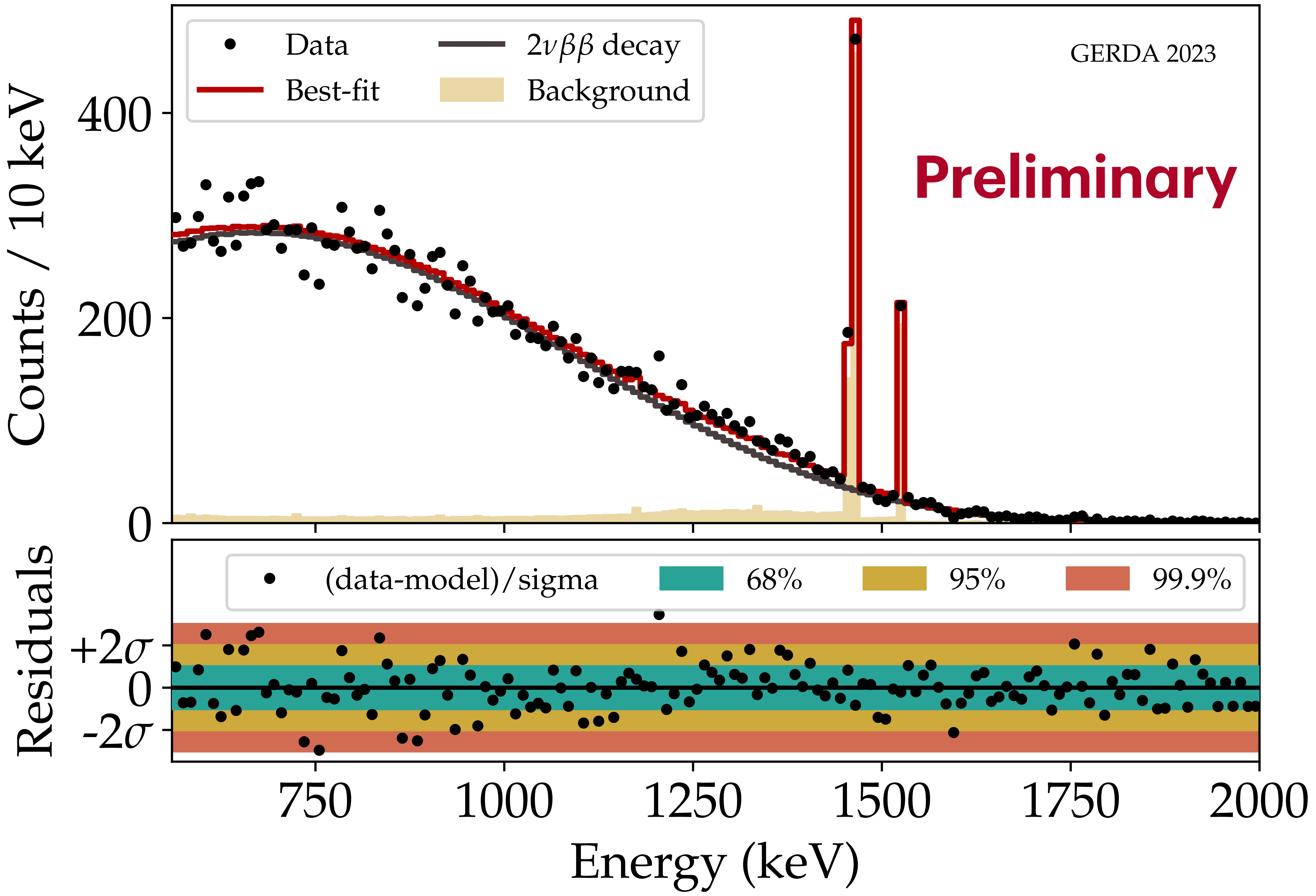

$$T_{1/2}^{2\nu} = \frac{1}{N_{2\nu}} \cdot \frac{N_A \ln(2)}{M_{76}} f_{76}\epsilon_{cuts} \sum_i m_i t_i f_{AV,i} \epsilon_{c,i}$$

- Number of observed events
- Cuts efficiency (QC, LAr)
- Active volume fraction & containment efficiency
- Enrichment fraction of ^{76}Ge
- Detector exposure

Preliminary

$$T_{1/2}^{2\nu} = (2.022 \pm 0.042)10^{21}\ yr$$

Total uncertainty 2.1%: most precise determination of ^{76}Ge half-life

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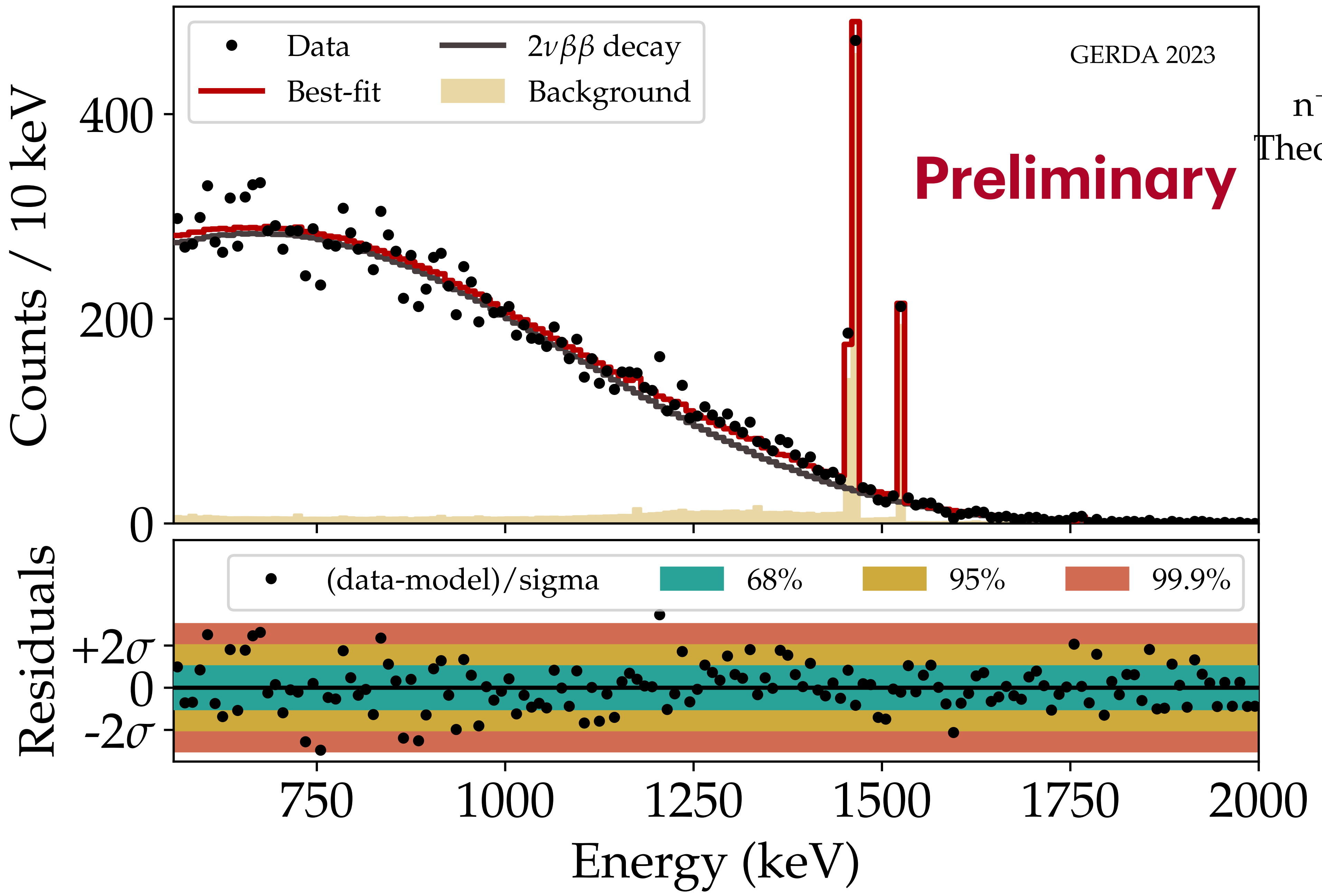
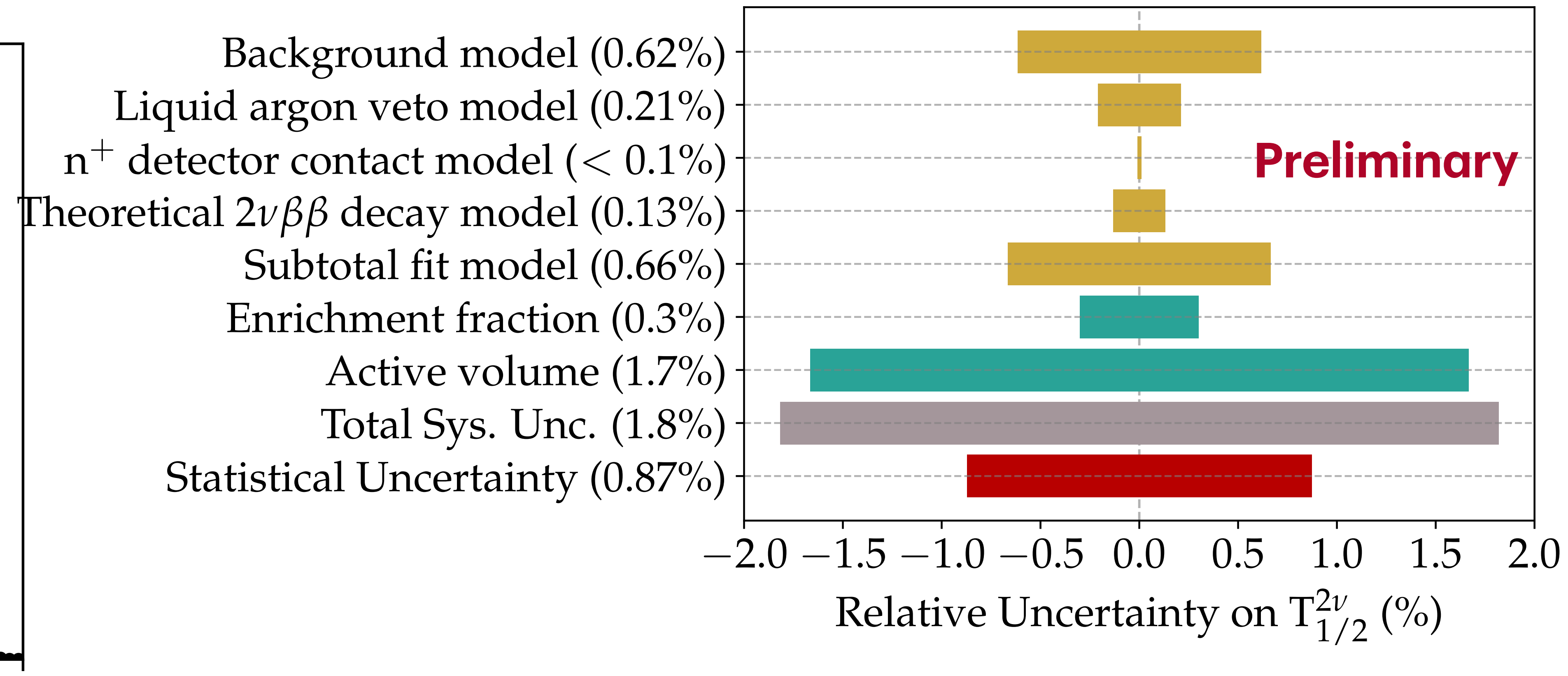
Enrichment fraction of ^{76}Ge · Detector exposure





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Search for exotic double-β decays

[JCAP12(2022)012, arXiv:2209.01671]

- Data from all the BEGe detectors after LAr veto cut: total exposure 32.8 kg yr
- We searched for decays with emission of Majorons, light exotic fermions (including sterile neutrinos), and Lorentz violation

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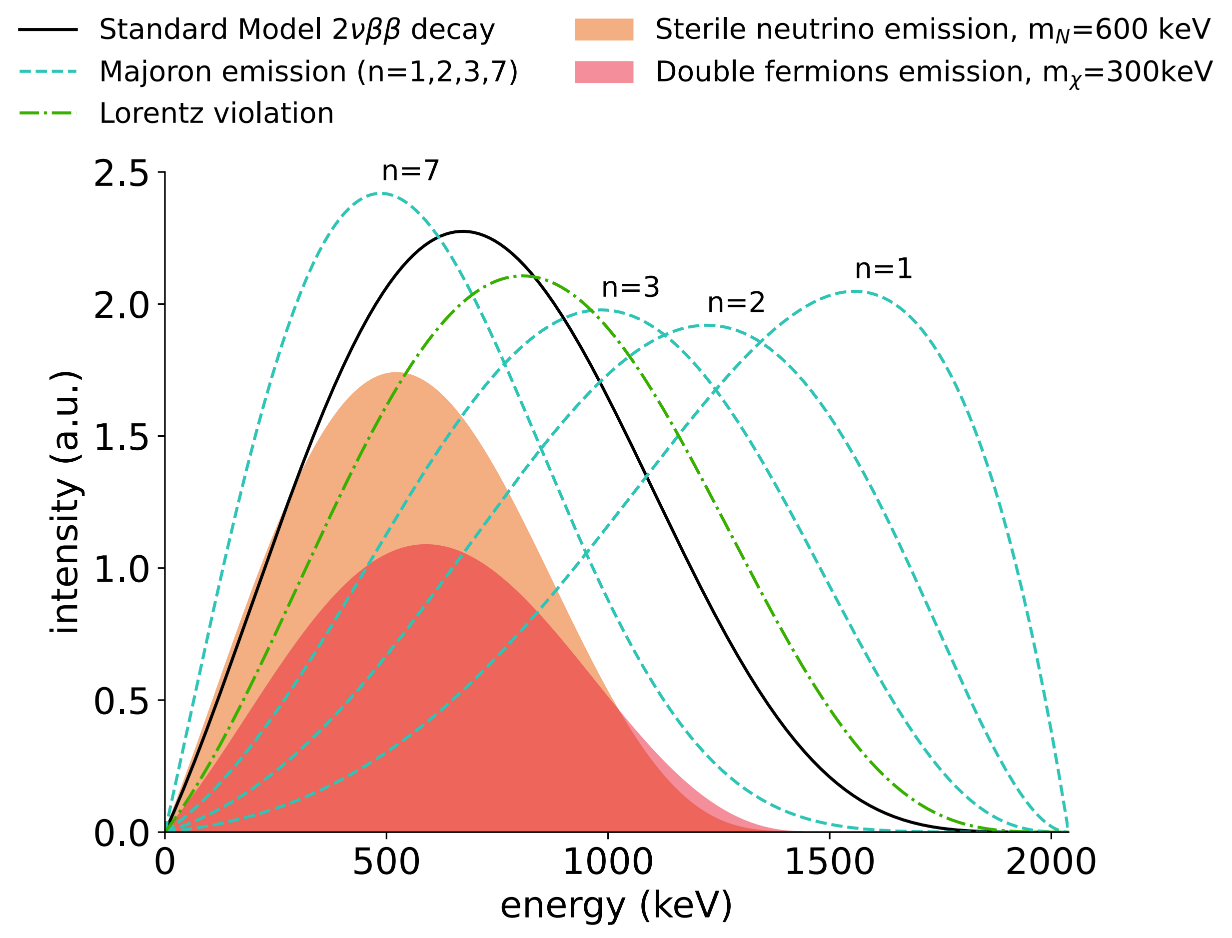

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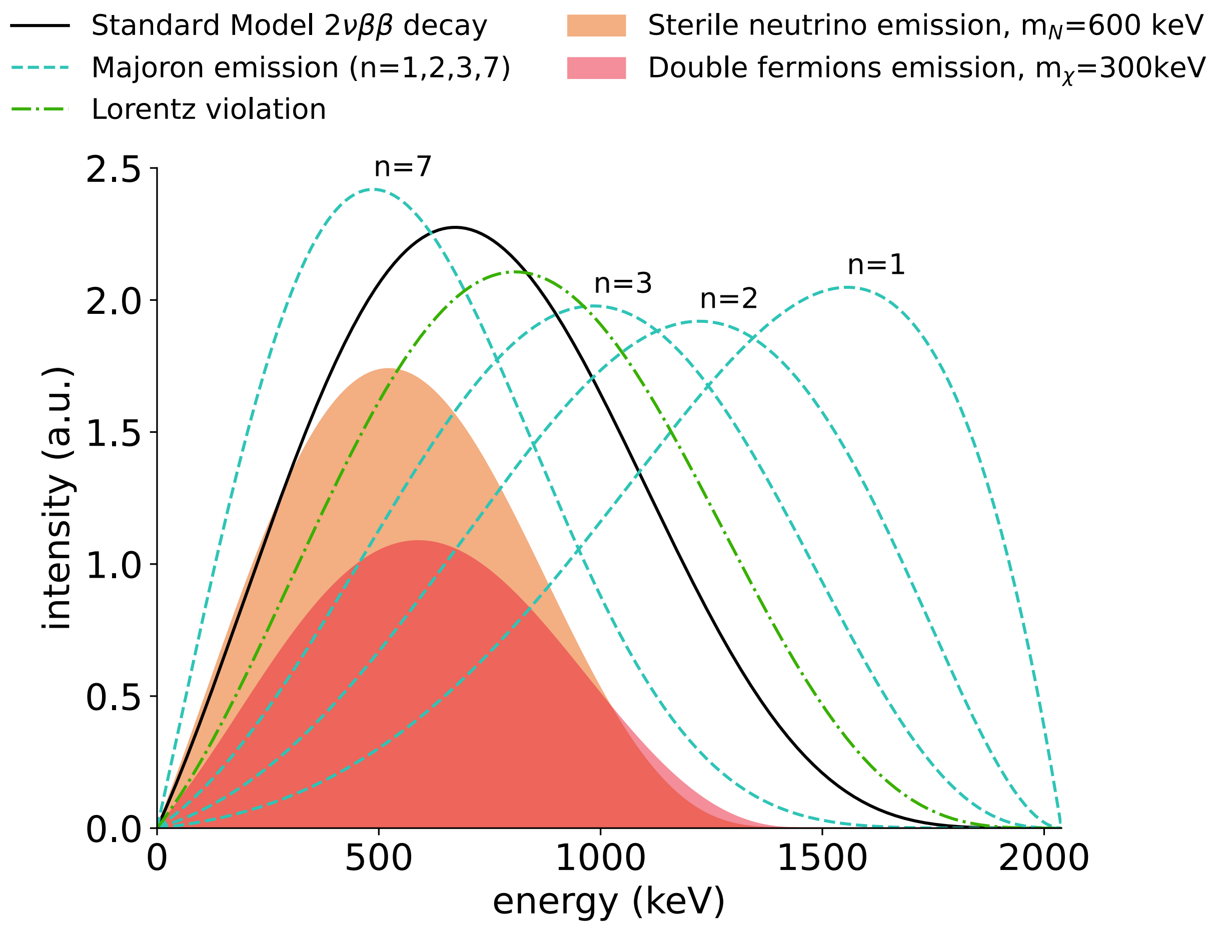
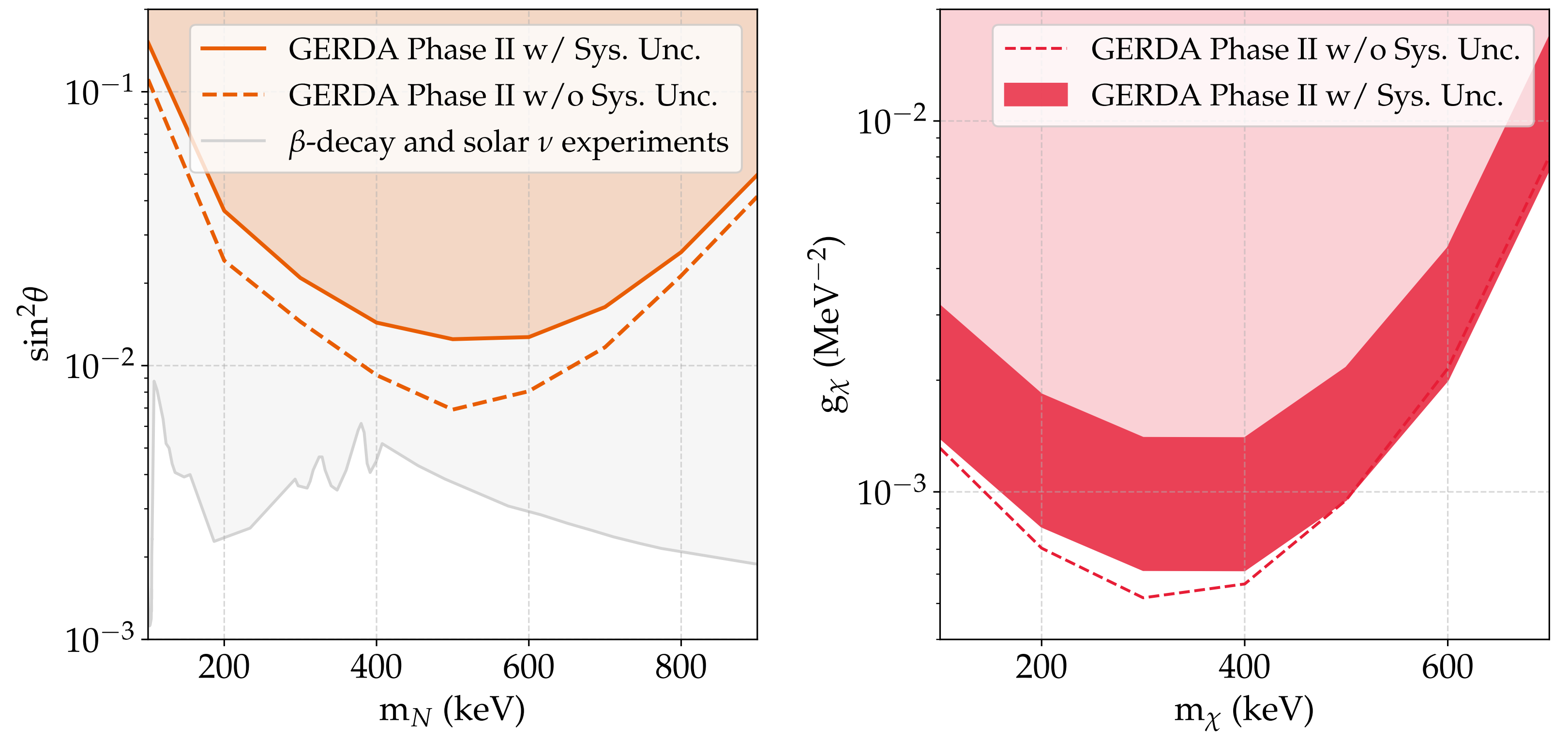


[JCAP12(2022)012, arXiv:2209.01671]

^{76}Ge Exotic decay mode	Observed Limit
Decays with Majorons (n=1)	$T_{1/2}$ > 6.4 10^{23} yr - g_J < (1.9-4.4) 10^{-5}
(n=2)	$T_{1/2}$ > 2.9 10^{23} yr
(n=3)	$T_{1/2}$ > 1.2 10^{23} yr - g_J < 0.017 / 1.2
(n=7)	$T_{1/2}$ > 1.0 10^{23} yr - gJ < 1.1
Lorentz violation	(-2.7 < $a_{of}^{(3)}$ < 6.2) 10^{-6} GeV



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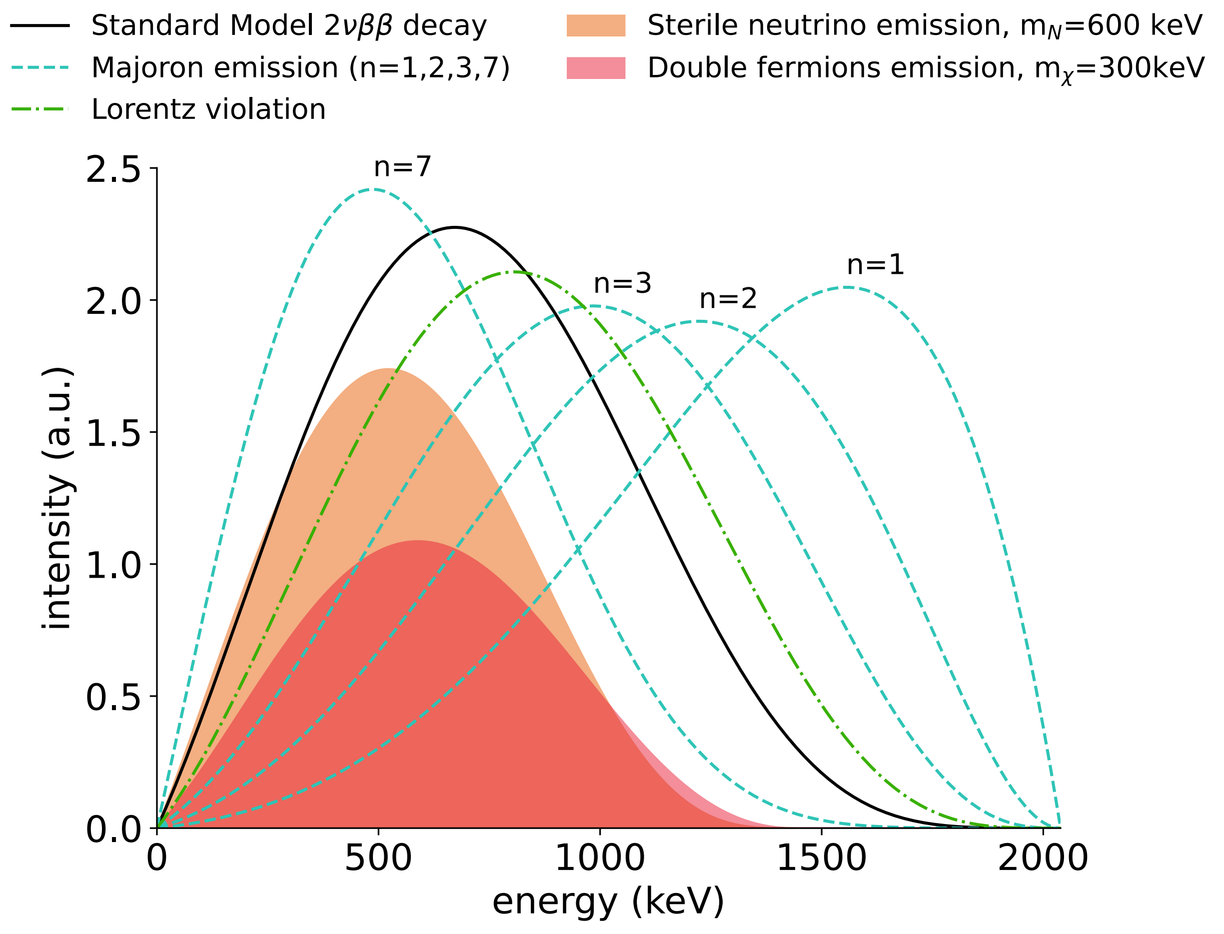
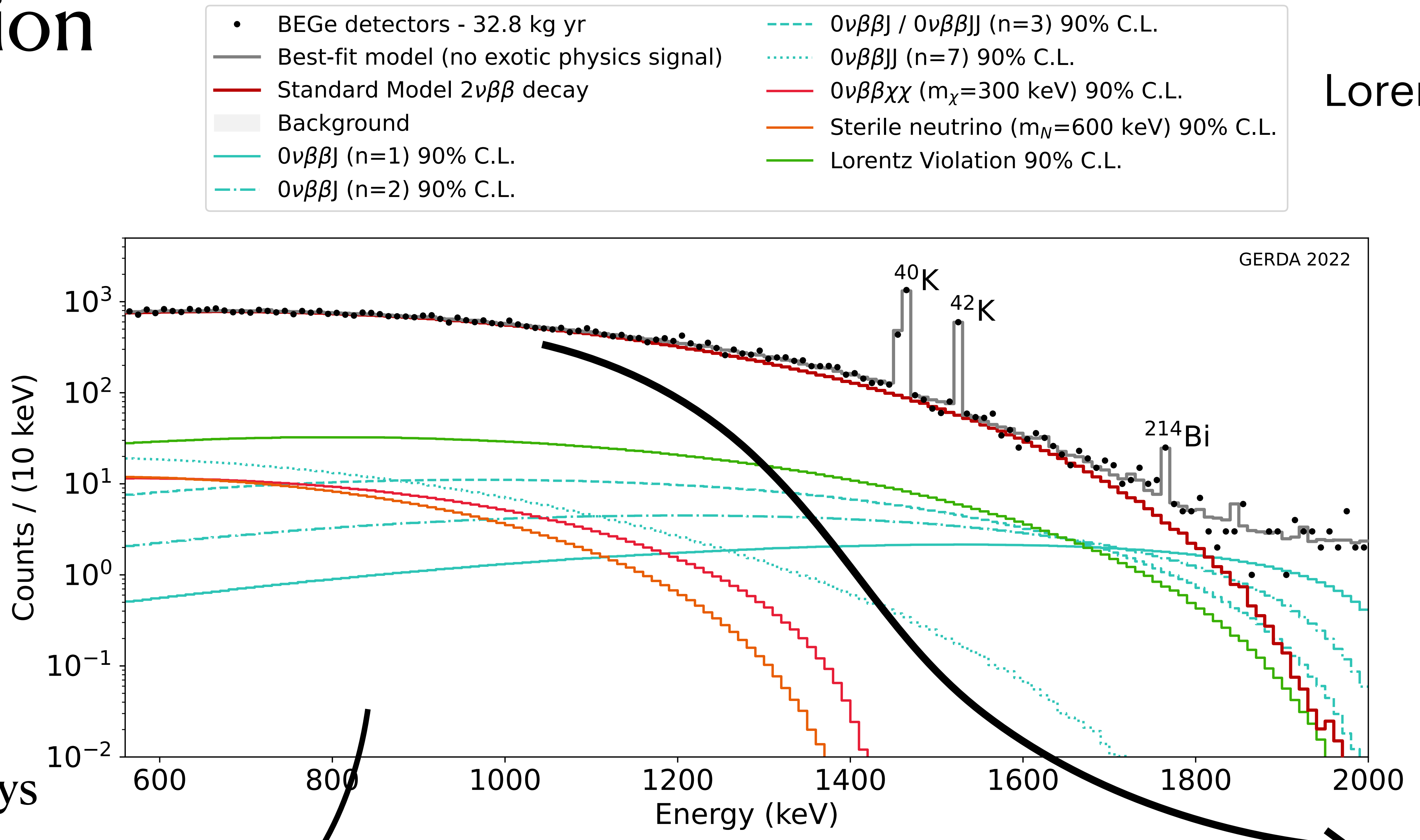
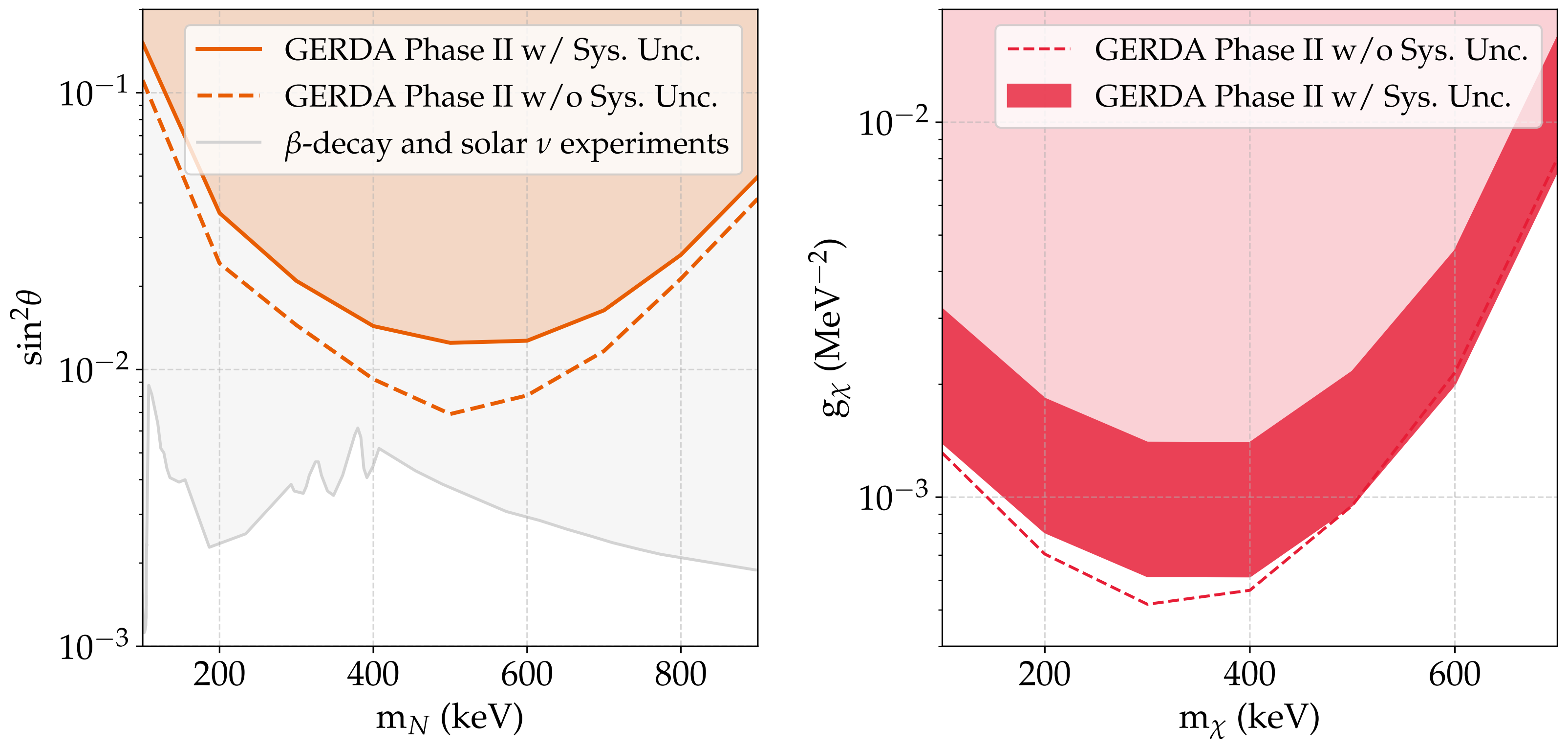


Energy distributions of the exotic decays normalized to the 90% C.L. limits





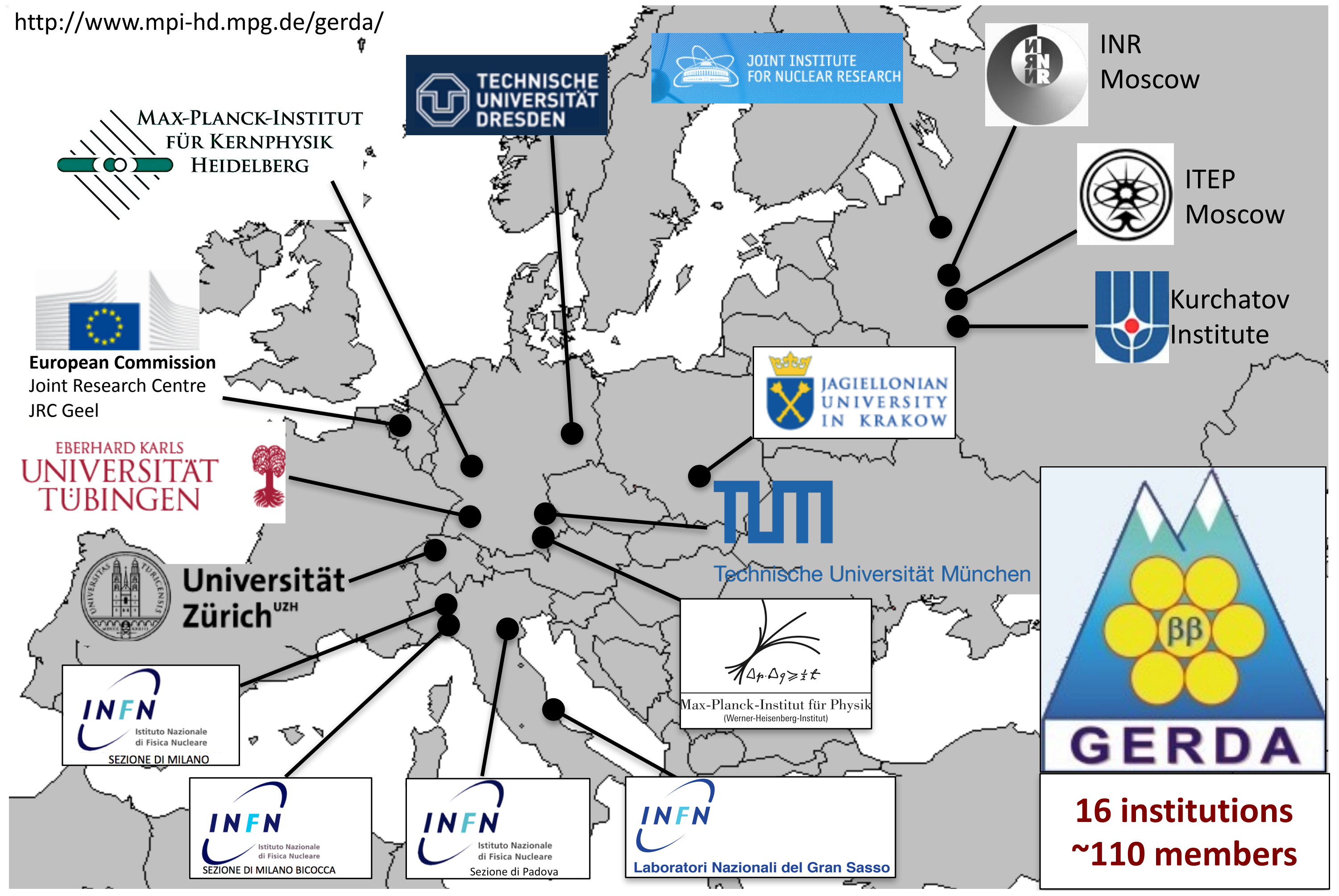
Best fit model for no exotic physics signal, almost pure $2\nu\beta\beta$ decay continuum

Conclusions

- The main goal of the GERDA experiment was the **search for the $0\nu\beta\beta$ decay of ^{76}Ge**
  - One of the world's best-performing $0\nu\beta\beta$ decay experiments: lowest background index and leading sensitivity
  - **Best limit on the half-life of $0\nu\beta\beta$ decay of ^{76}Ge: $T^{0\nu}_{1/2} > 1.8\ 10^{26}$ yr at 90% C.L.** [Phys.Rev.Lett. 125 (2020) 25, 252502]
  - Demonstrated the **background-free operation of HPGe detectors**, paving the way for next-generation searches with LEGEND
- More physics results…
  - **Most precise determination of the half-life of ^{76}Ge** $2\nu\beta\beta$ decay: $T^{2\nu}_{1/2} = (2.022 \pm 0.042)10^{21}\ yr$ [publication out soon…]
  - Limits on **Majoron-involving decays, Lorentz violation, and light exotic fermions** [JCAP12(2022)012, arXiv:2209.01671]

Thank you!

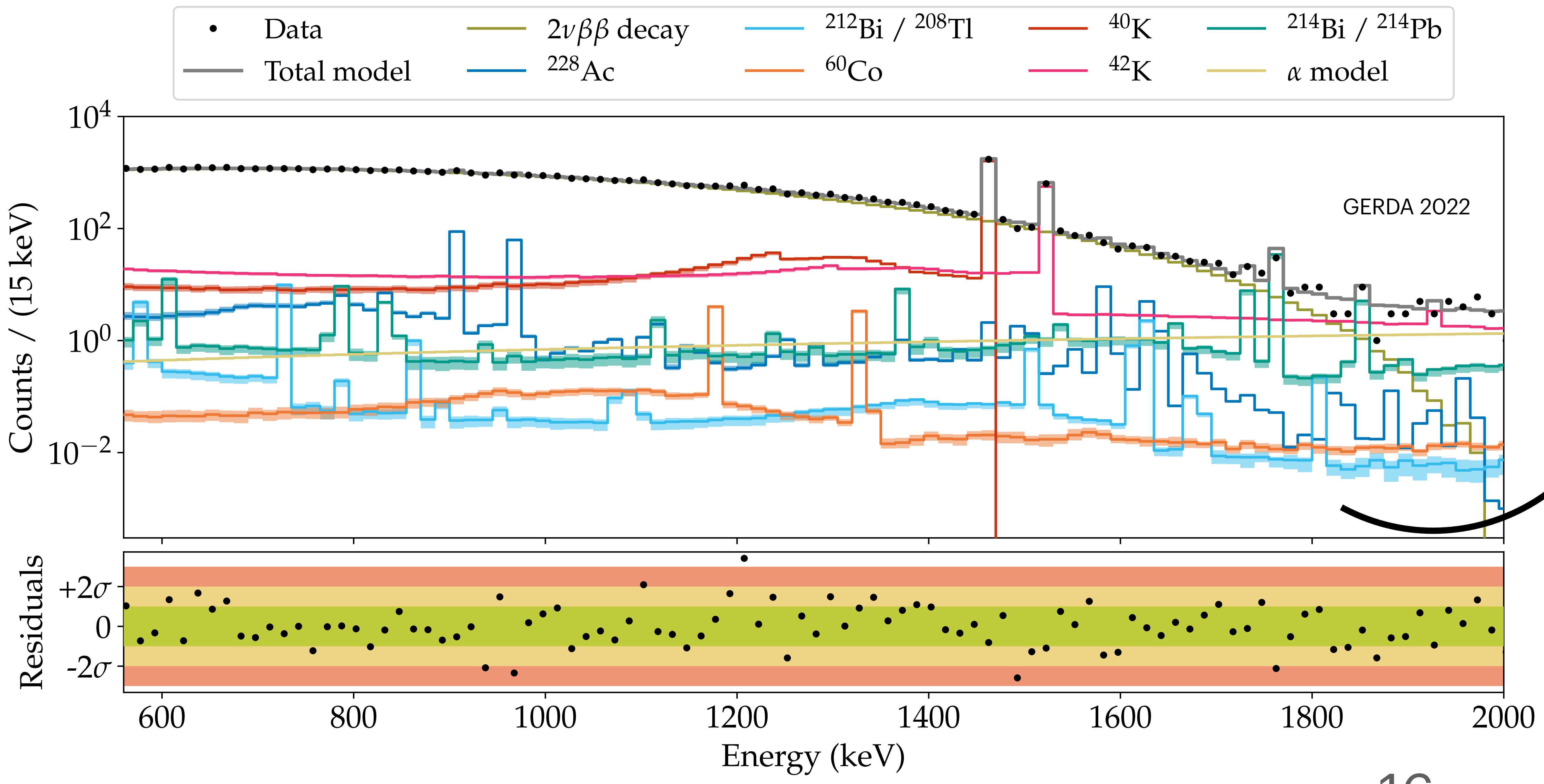
The GERDA Collaboration



Back up

Background Model after LAr veto cut

- A model of the LAr veto system has been developed [Eur.Phys.J.C 83 (2023) 4, 319]
- 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]

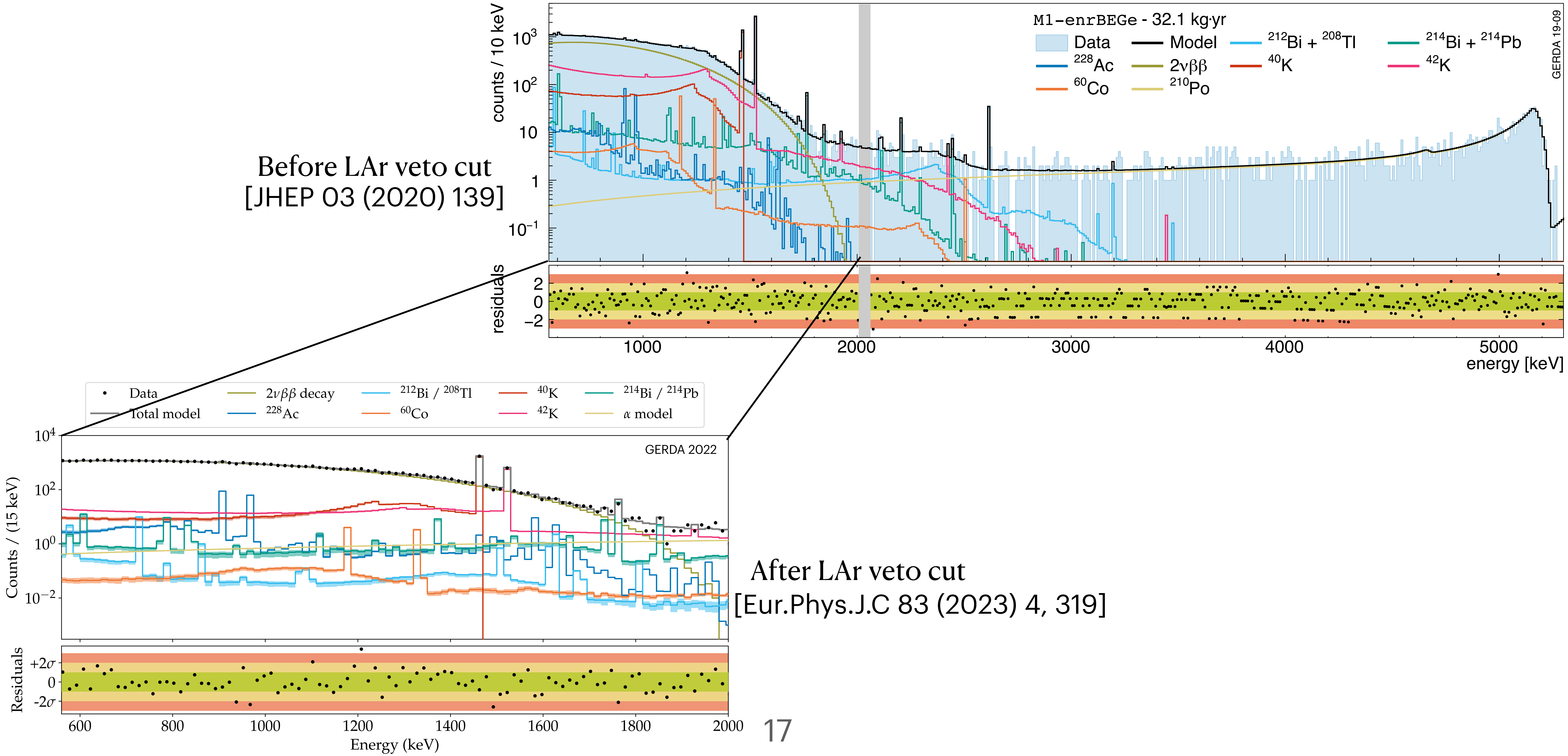


Expected background decomposition for all BEGe detectors pre-upgrade data (32.8 kg yr)

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

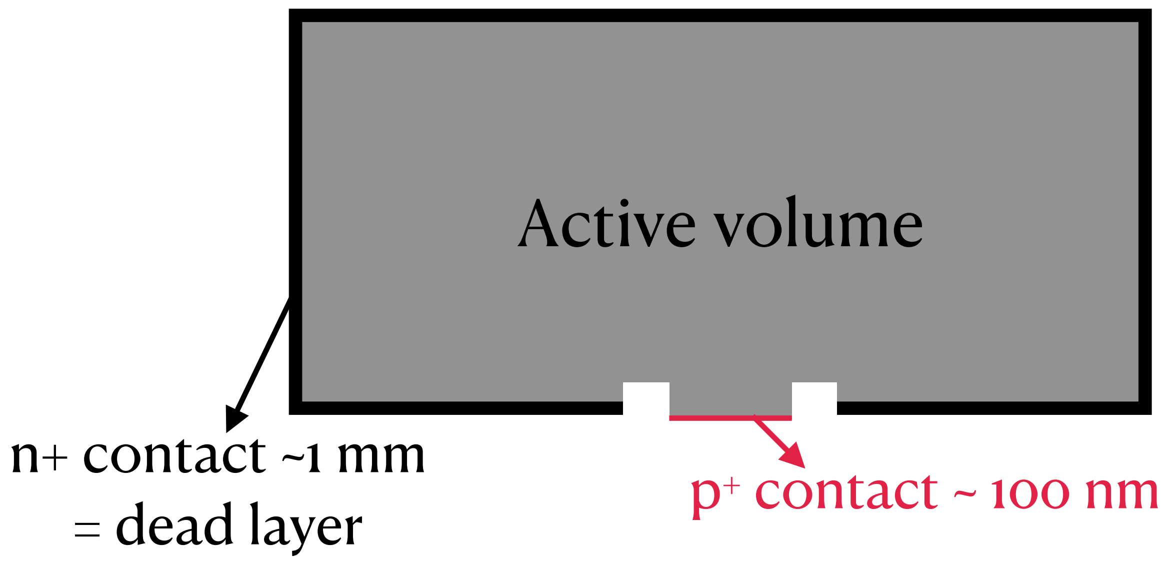
Comparison of the background model before and after LAr veto cut

Before LAr veto cut
[JHEP 03 (2020) 139]

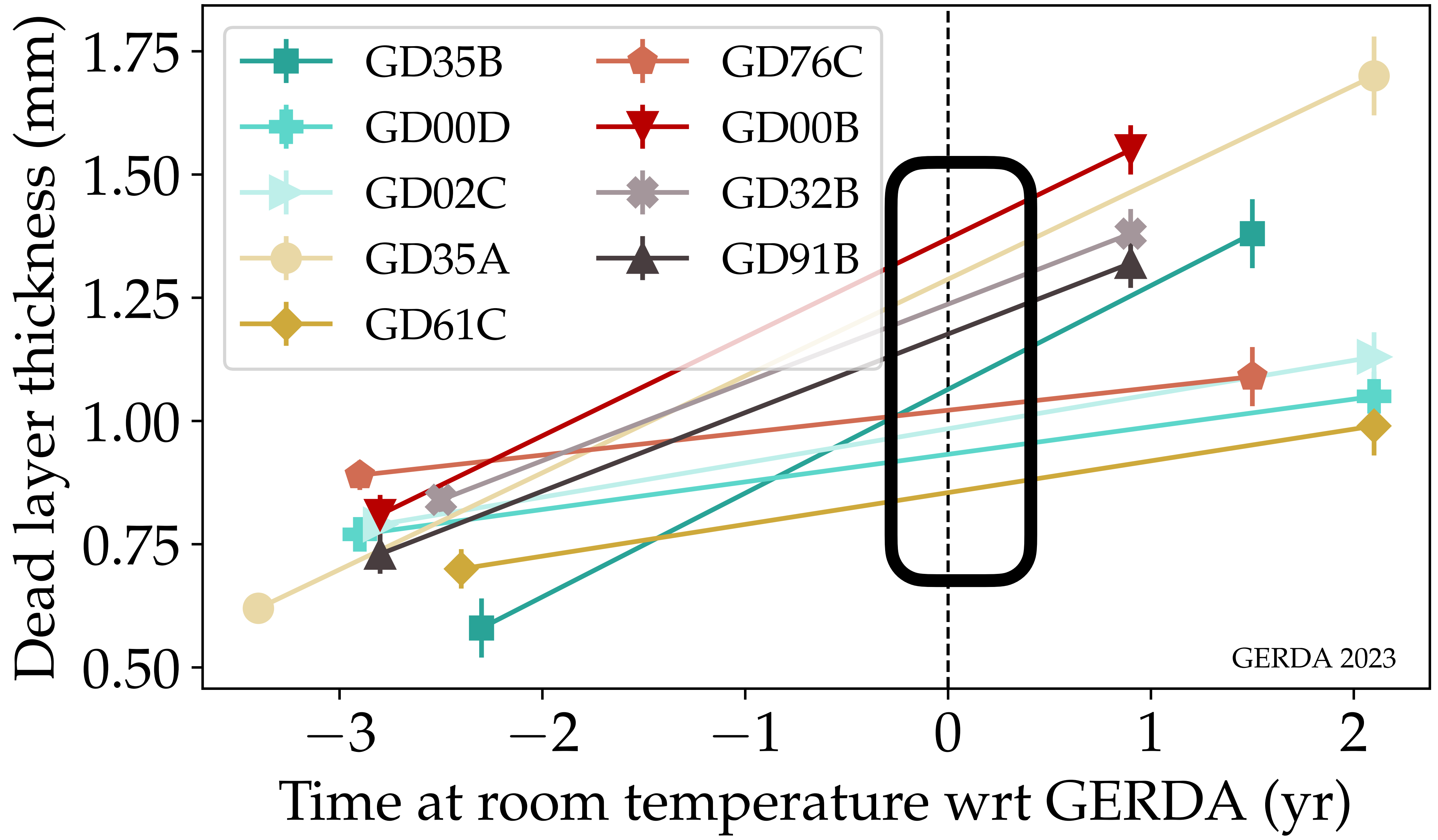


After LAr veto cut
[Eur.Phys.J.C 83 (2023) 4, 319]

Active volume of BEGe detectors



- The AV of the BEGe detectors was determined ~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
  - attempt to model the growth not yet conclusive
- We selected and re-measured 9 BEGe detectors at the end of GERDA: different growths observed



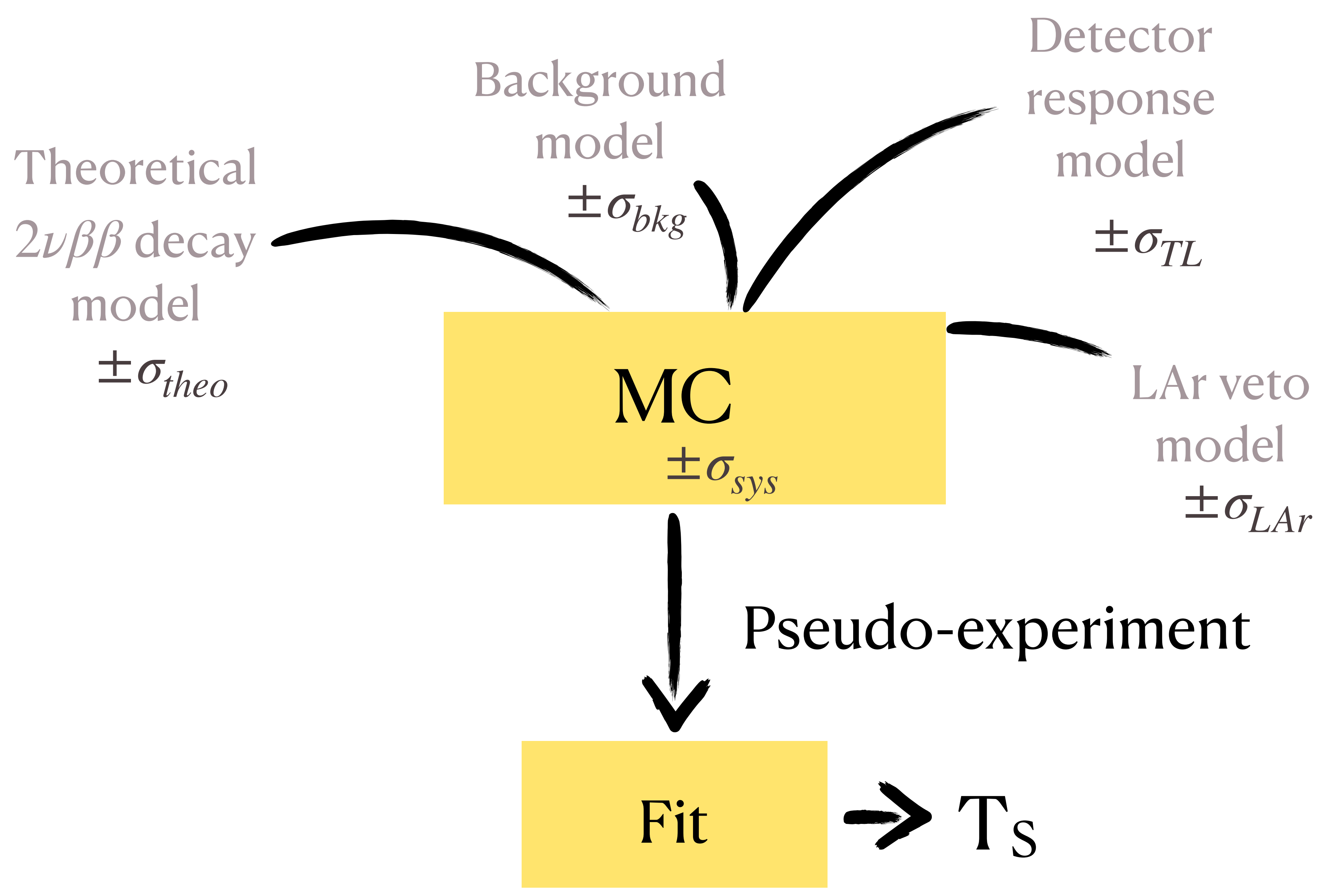
▷ ***We extracted detector specific growth and interpolate the active volume at the time of GERDA data taking***

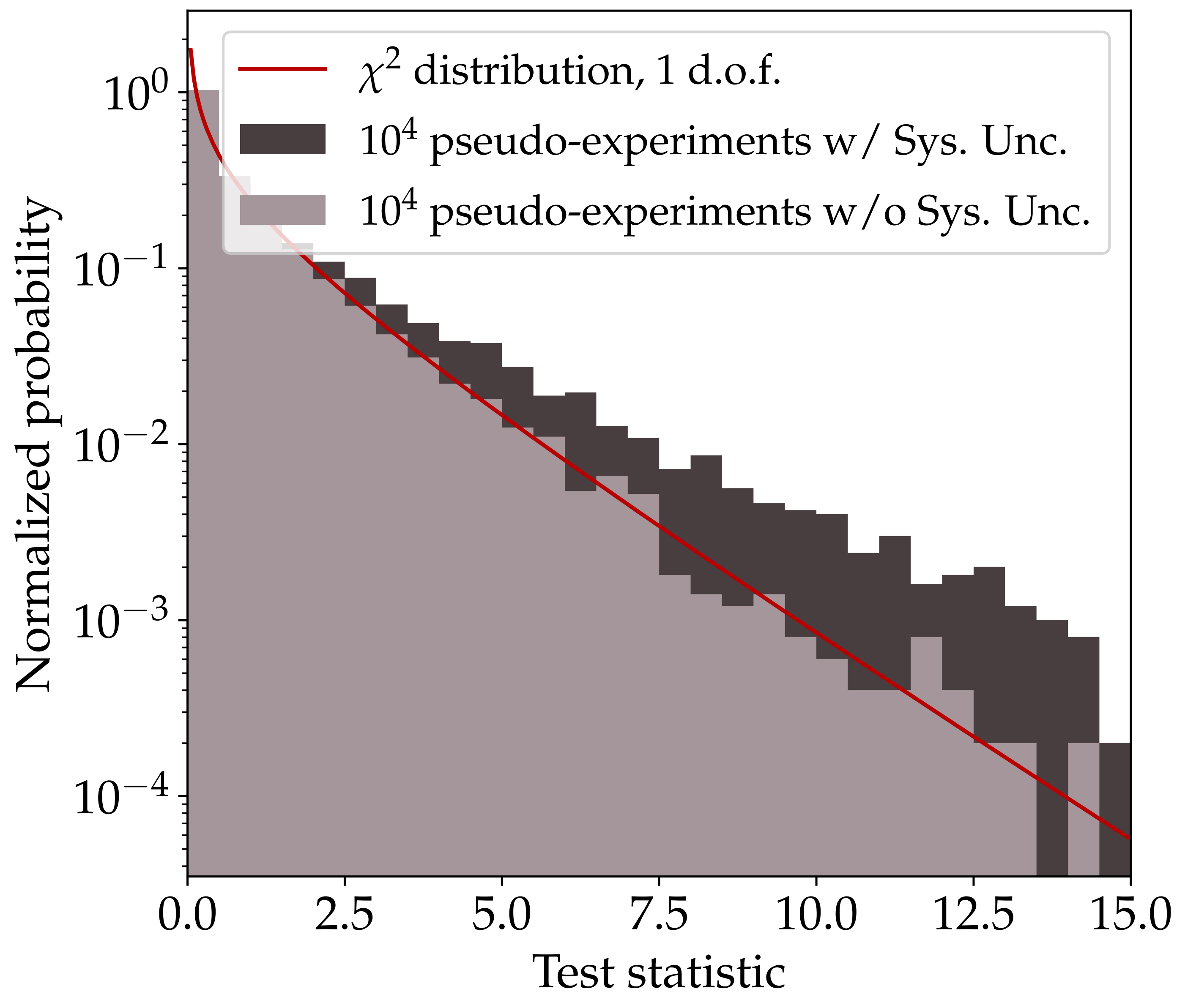
Statistical analysis

- 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)

$$T_S = -2 \ln \frac{\mathscr{L}(S|\hat{\hat{\theta}})}{\mathscr{L}(\hat{S}|\hat{\theta})}$$

- Distribution of the test statistic evaluated on pseudo-data generated with Monte Carlo methods
- **Systematic uncertainties** on the fit 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:

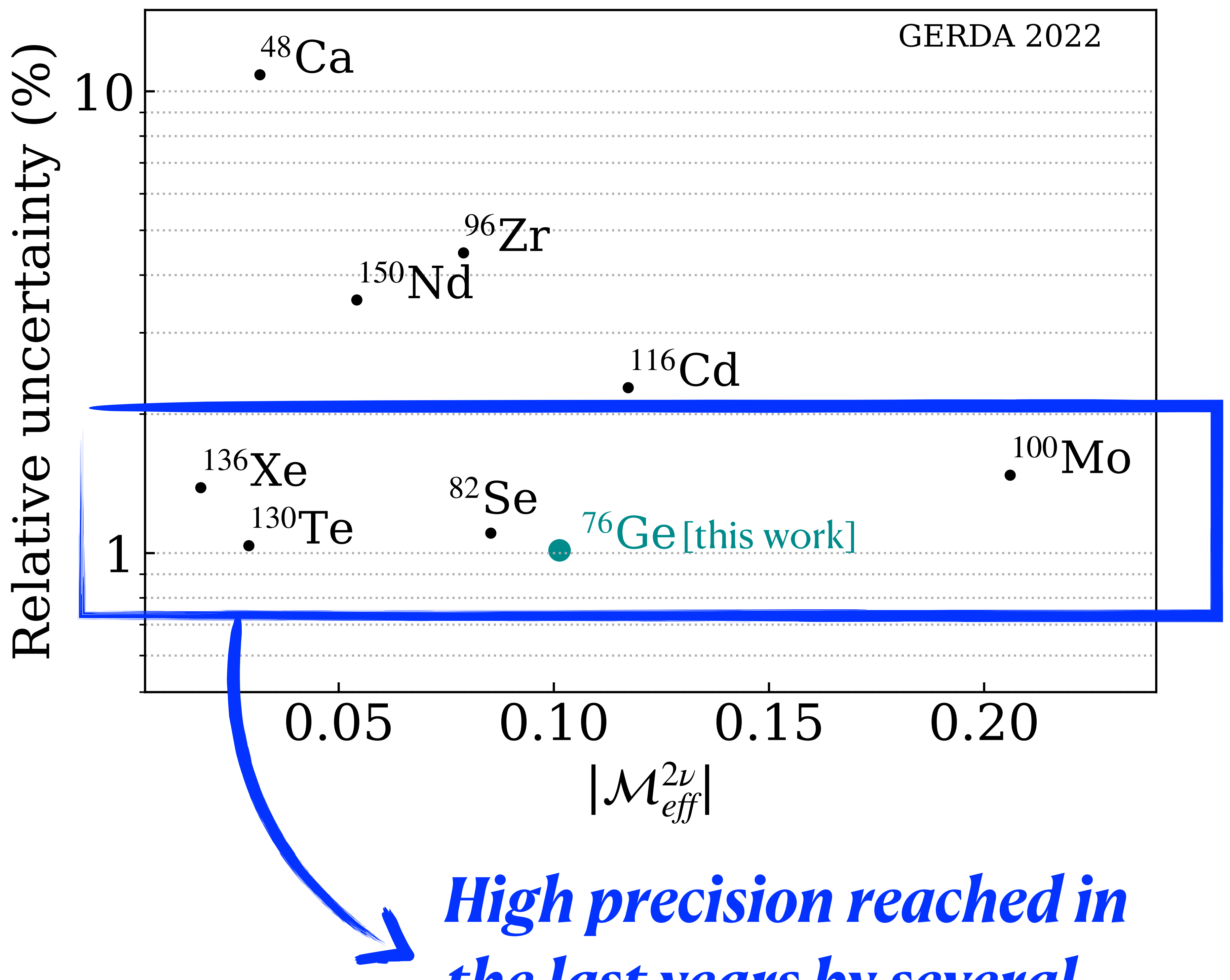
$$[T_{1/2}^{2\nu}]^{-1} = G^{2\nu} \, | \mathscr{M}_{eff}^{2\nu} |^2$$

Phys. Rev. C 85, 034316 (2012)

- With the phase space $G^{2\nu}$= 48.17 10^{21} yr^{-1}, our measurement gives: $| \mathscr{M}_{eff}^{2\nu} | = (0.101 \pm 0.001)$

➢ Benefit the interpretation of future $0\nu\beta\beta$ decay discoveries (e.g. exploit correlation between $2\nu\beta\beta$ decay NMEs and $0\nu\beta\beta$ decay NMEs)

[Phys. Rev. C 107, 044305]



High precision reached in the last years by several experiments

Double-β decays with emission of Majorons

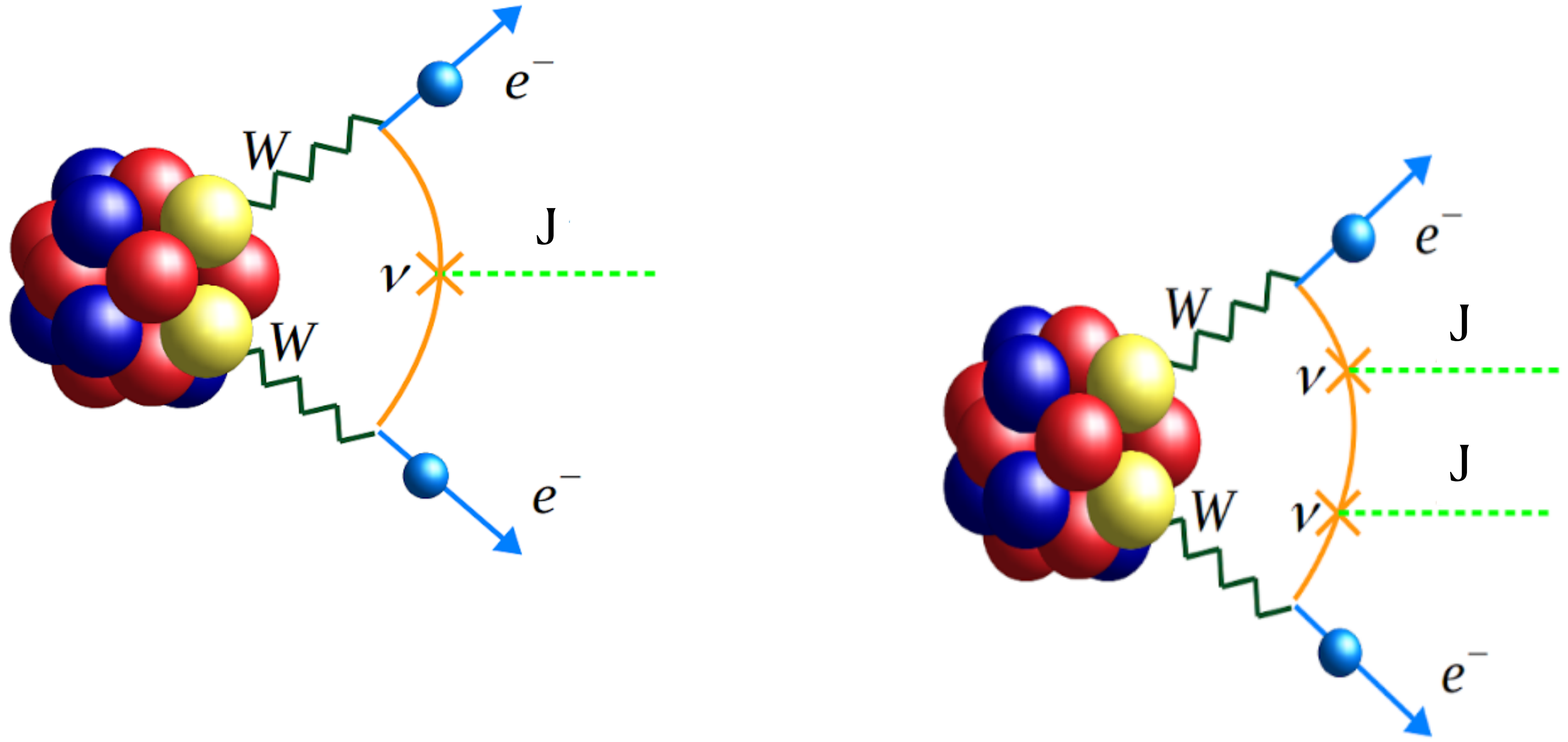
(A,Z) → (A,Z+2) + 2e + J(2J)

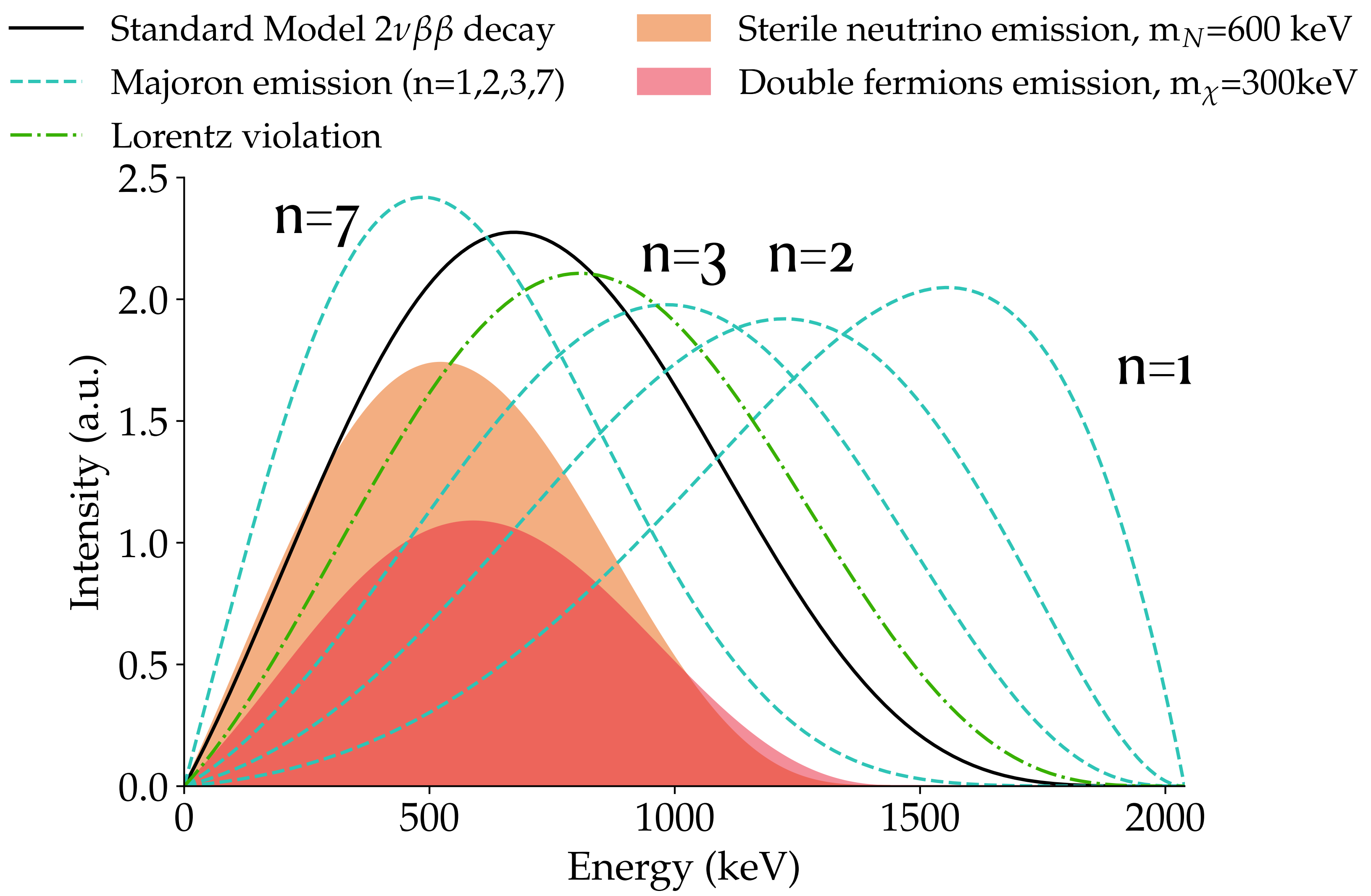
Phys.Lett.B 291 (1992) 99-105, and many more

- Lepton number could be spontaneously broken: the **Majoron** is the resulting Goldstone-boson
- *Many models* today also different from the original formulation
- The decay rate is determined by the phase space:

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

n=spectral index





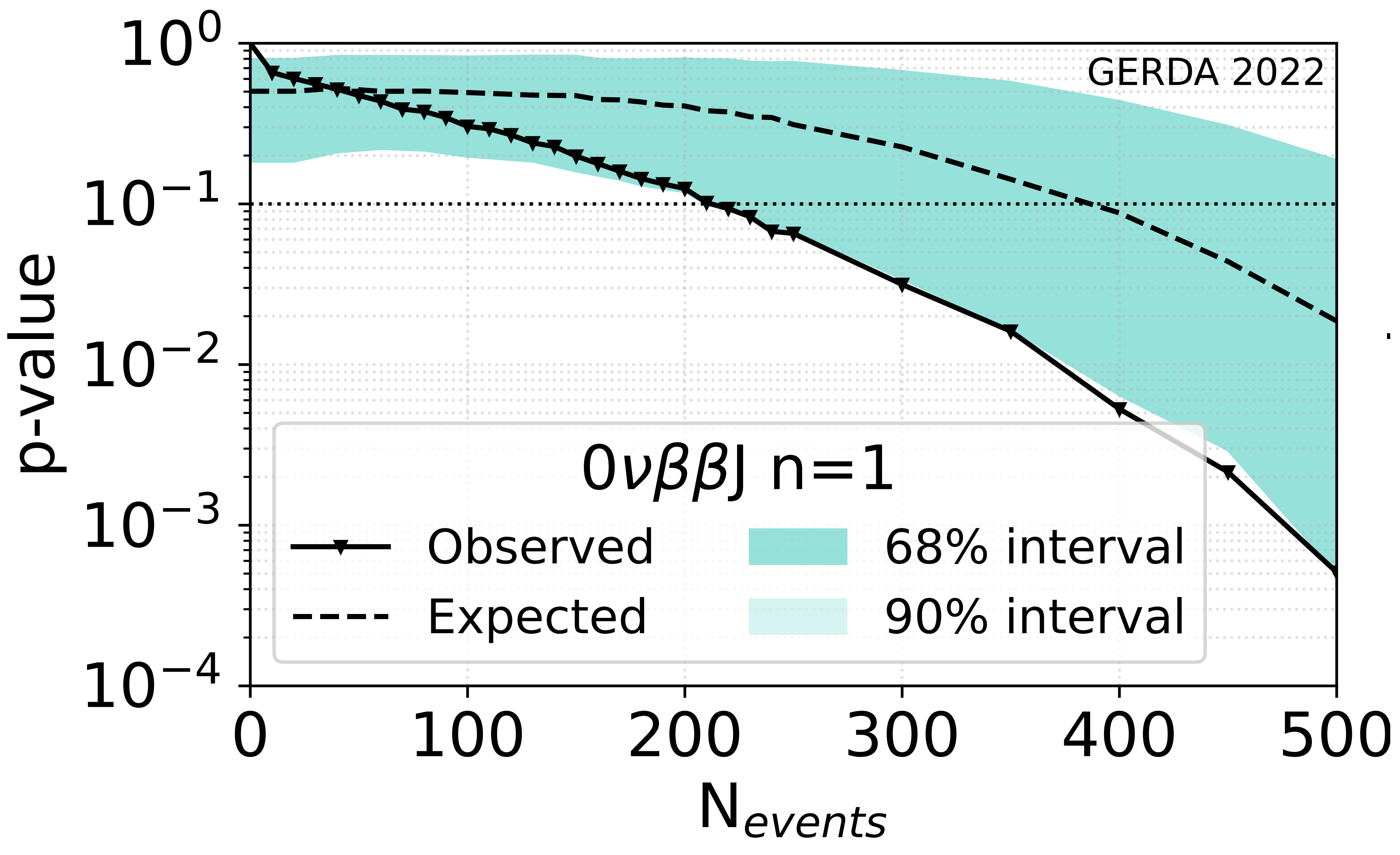
Results: search for Majoron-involving decays

- No evidence of positive signal: set 90% C.L. limits
- Limits translated into constraints of the neutrino-Majoron coupling constant g_J:

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

Decay mode	$T_{1/2}$ (yr) Sensitivity	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 comparable with limits obtained with other double-beta decay isotopes (most stringent half-life limit for n=7)

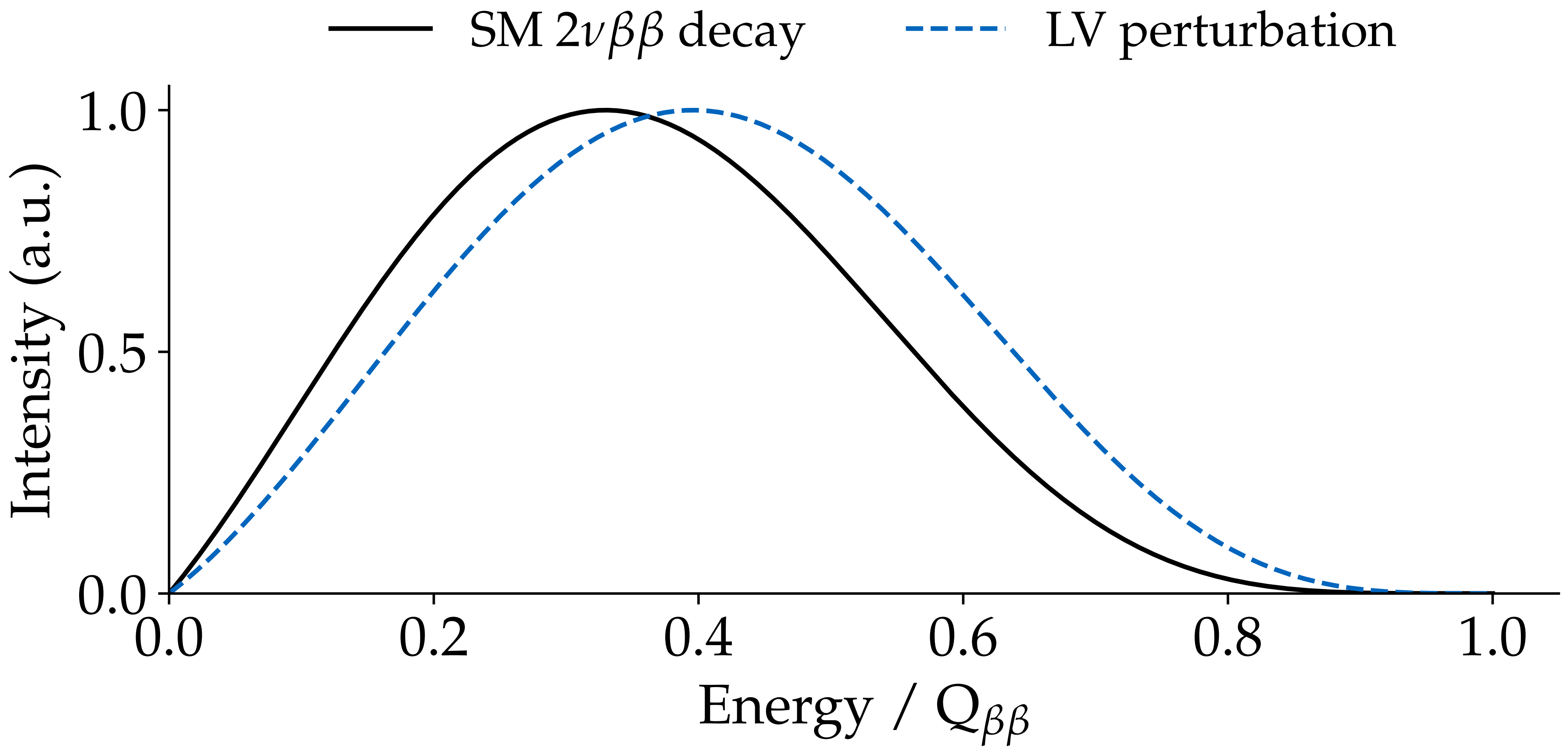
Double-β decay with Lorentz violation

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

Phys.Rev.D 89 (2014) 036002,
Phys.Rev.D 105 (2022) 5, 055032

- Lorentz violation at the Plank scale: suppressed effects at lower energies
- Oscillation-free coefficients $a_{of}^{(3)}$: only affect the neutrino phase space, accessible through weak decays (β and double-β decays)
- The modified neutrino phase space affects the $2\nu\beta\beta$ decay rate:

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

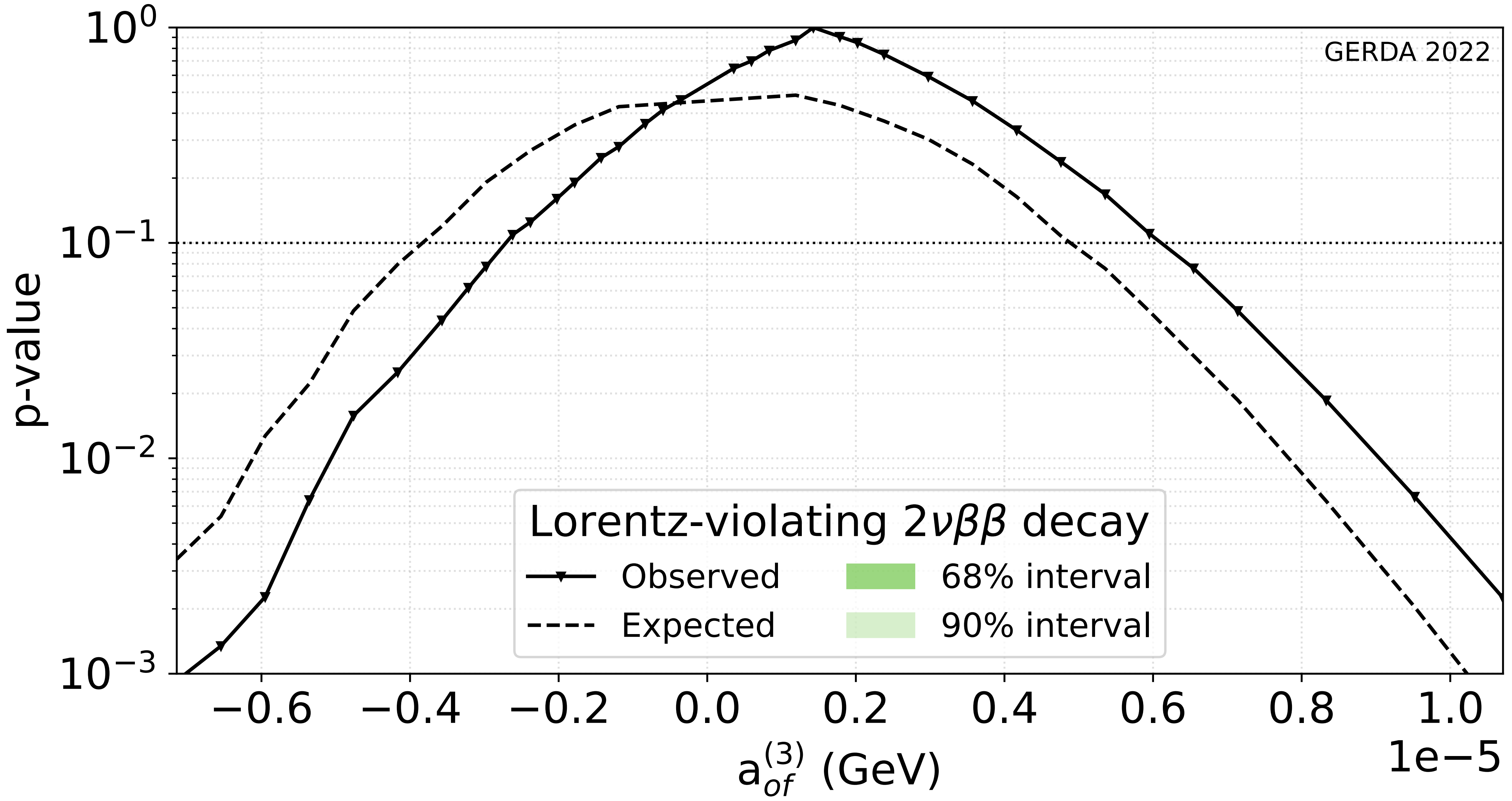


Results: search for Lorentz Violation

- No evidence of deviation from SM distribution: set 90% C.L. limit on $a_{of}^{(3)}$ (both positive and negative values)

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]



- First constraints with ^{76}Ge
- Results comparable to limits obtained with other double-beta isotopes

M.Agostini, EB, A. Ibarra, X. Marcano, Phys. Lett. B 815 (2021) 136127

Double-β decay into exotic fermions

- ***Sterile neutrino N***, coupling to ν via Dirac mass term: $m_D \bar{\nu} N$

β decay $\quad (A,Z) \to (A,Z+1) + e^- + N$

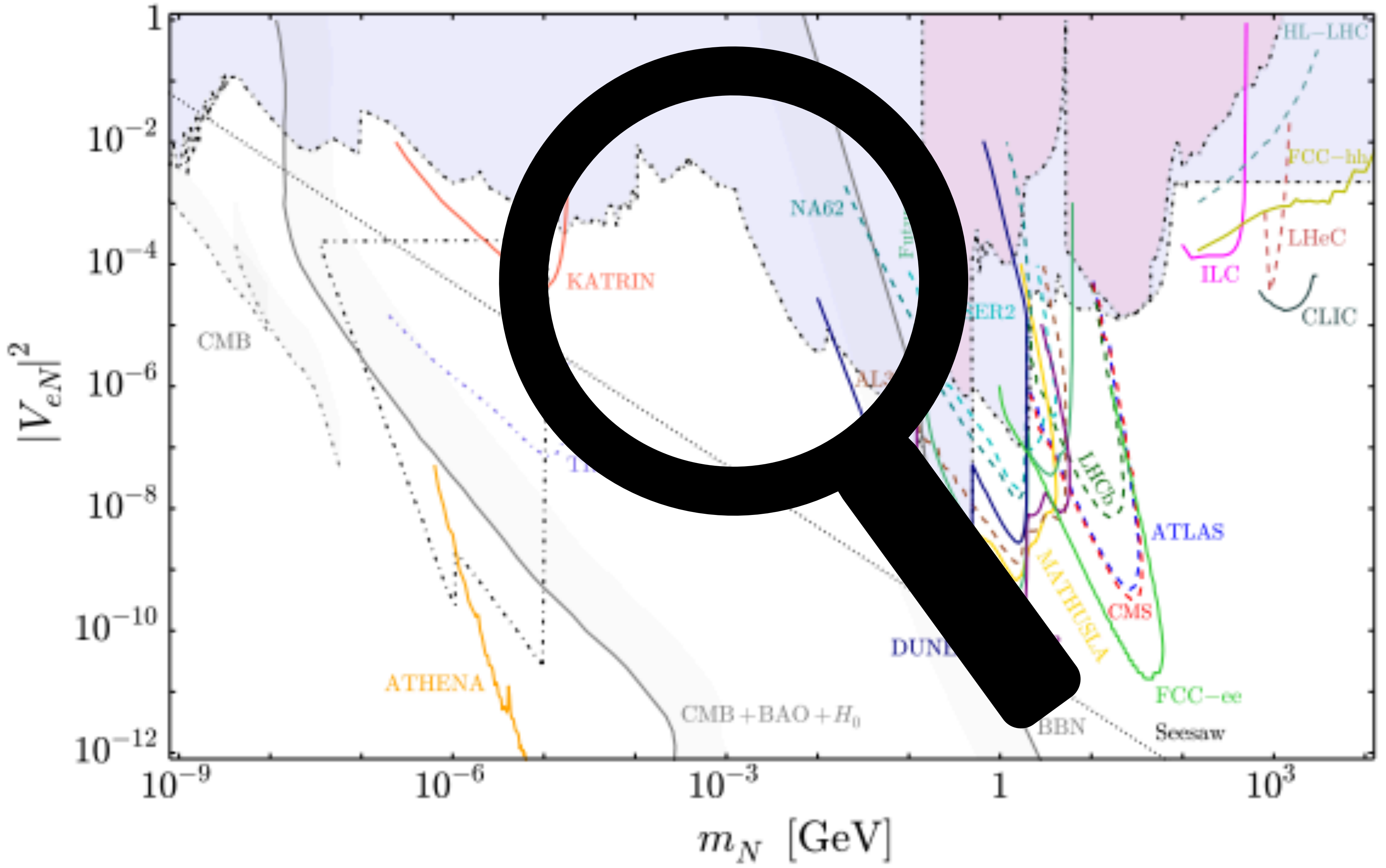
$\beta\beta$ decay $\quad (A,Z) \to (A,Z+2) + 2e^- + \bar{\nu} + N$

$\quad (A,Z) \to (A,Z+2) + 2e^- + 2N$

$$\frac{d\Gamma}{dT} = \cos^4\theta \, \frac{d\Gamma_{\nu\nu}}{dT} \, \theta(T_0 - T) + 2\cos^2\theta \sin^2\theta \, \frac{d\Gamma_{\nu N}}{dT} \, \theta(T_0 - T - x_N)$$

$$\cancel{+\sin^4\theta \, \frac{d\Gamma_{NN}}{dT} \, \theta(T_0 - T - 2x_N)}$$

[arXiv:1912.03058]



- Extend the symmetry group by a Z2 discrete symmetry (e.g. DM sector), ***exotic fermion*** χ coupling to ν via effective interaction: $g_\chi \nu\nu\chi\chi$

β decay $\quad$ ~~$(A,Z) \to (A,Z+1) + e^- + \chi$~~

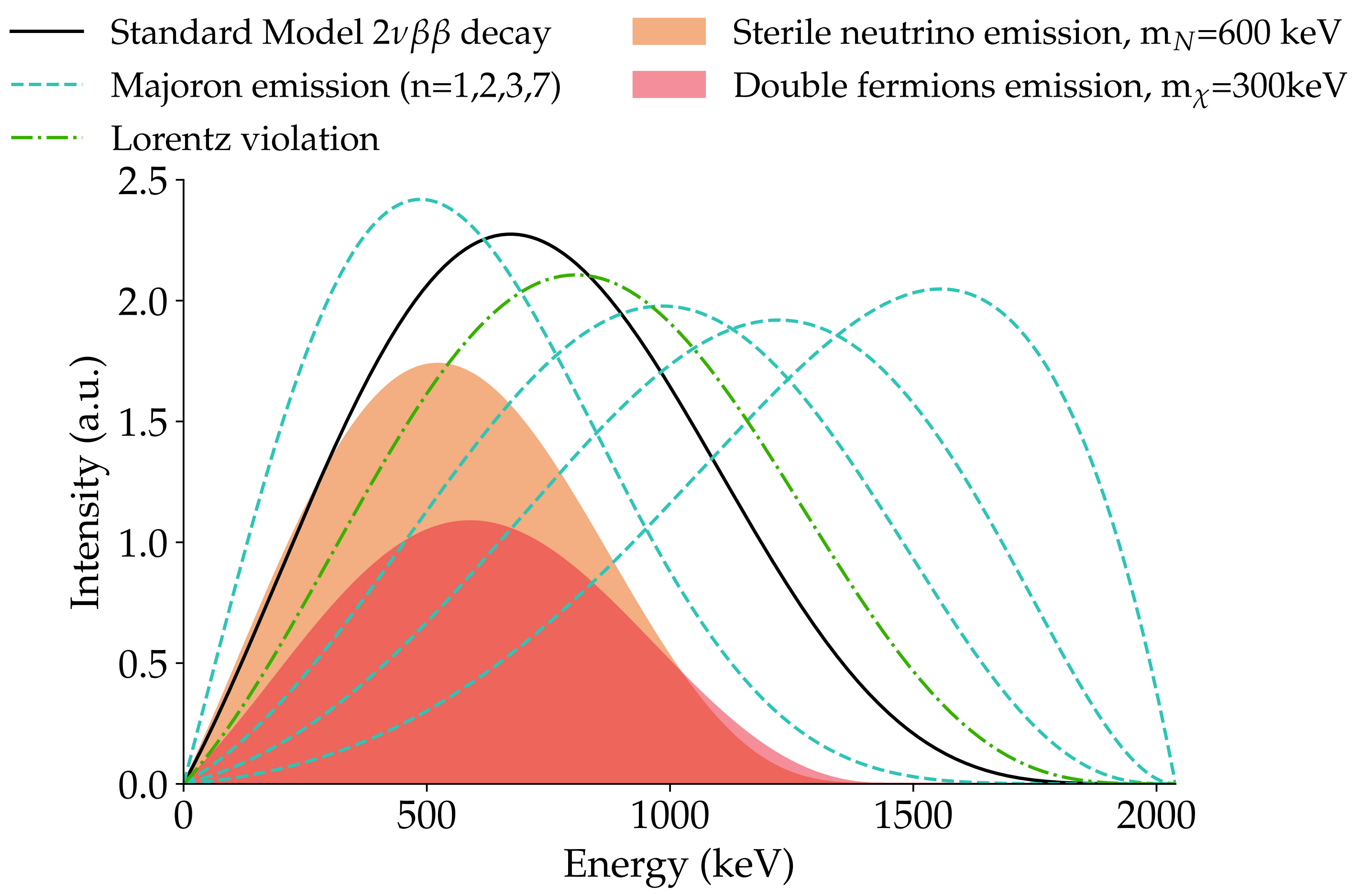
$\beta\beta$ decay $\quad$ ~~$(A,Z) \to (A,Z+2) + 2e^- + \bar{\nu} + \chi$~~

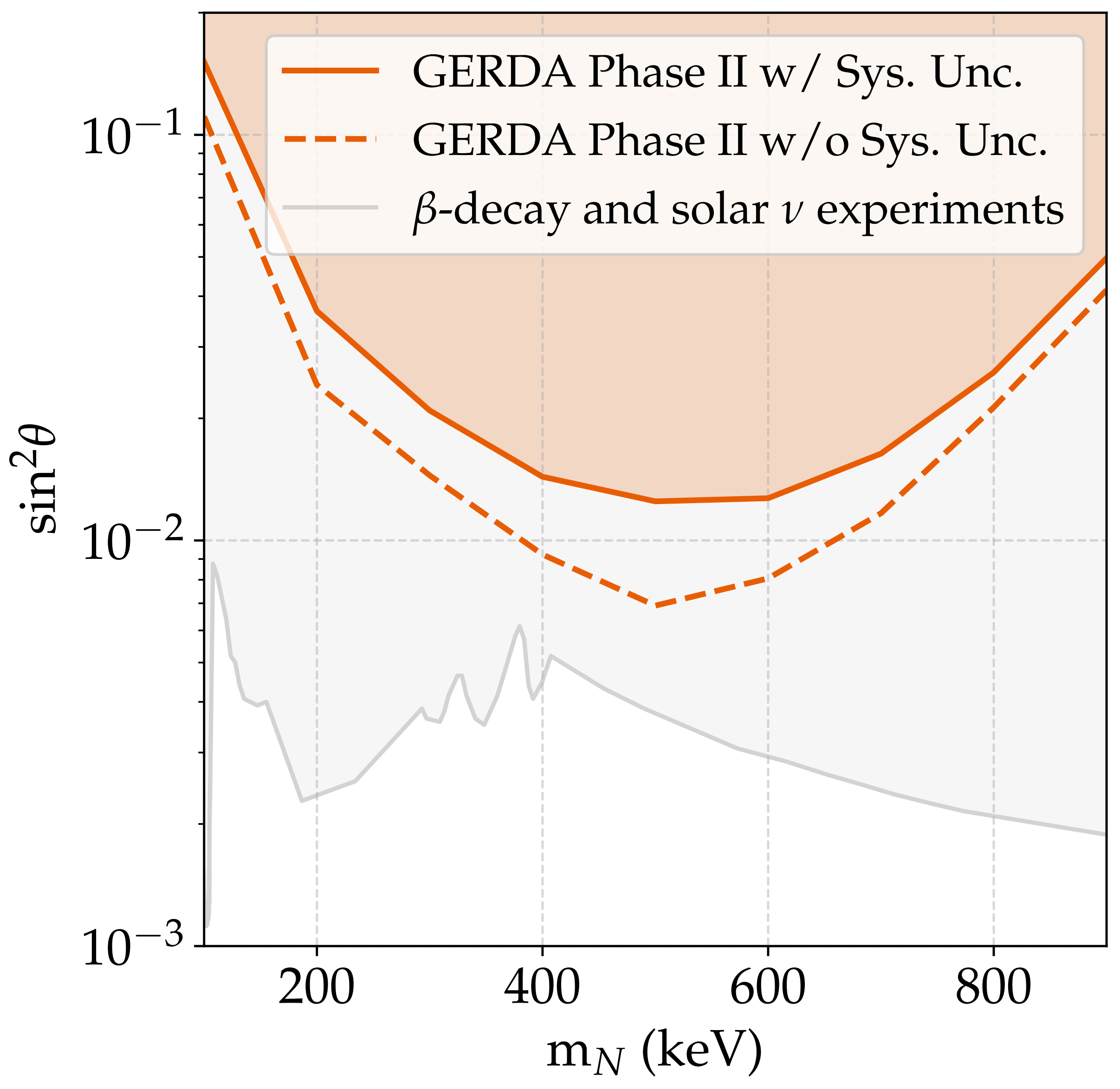
$\quad (A,Z) \to (A,Z+2) + 2e^- + 2\chi$

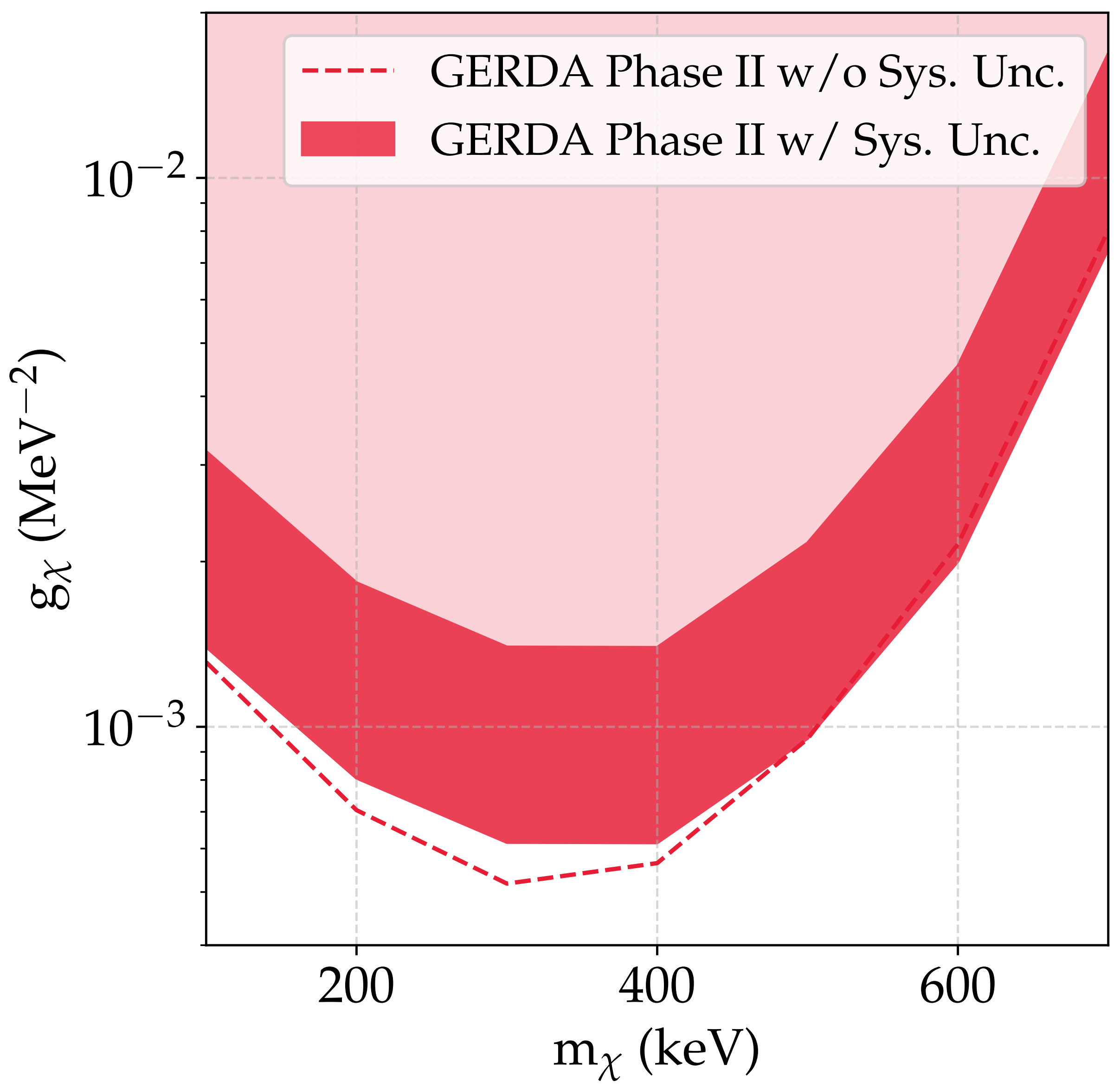
$$\frac{d\Gamma}{dT} = \frac{d\Gamma_{\nu\nu}}{dT} \, \theta(T_0 - T) + \frac{d\Gamma_{\chi\chi}}{dT} \, \theta(T_0 - T - 2x_\chi)$$

Results: search for light exotic fermions

- We searched for sterile neutrinos (N) and their Z_2-odd variant (χ) with masses between 100 and 900 keV
- No evidence of positive signal: set 90% C.L. limit on the couplings



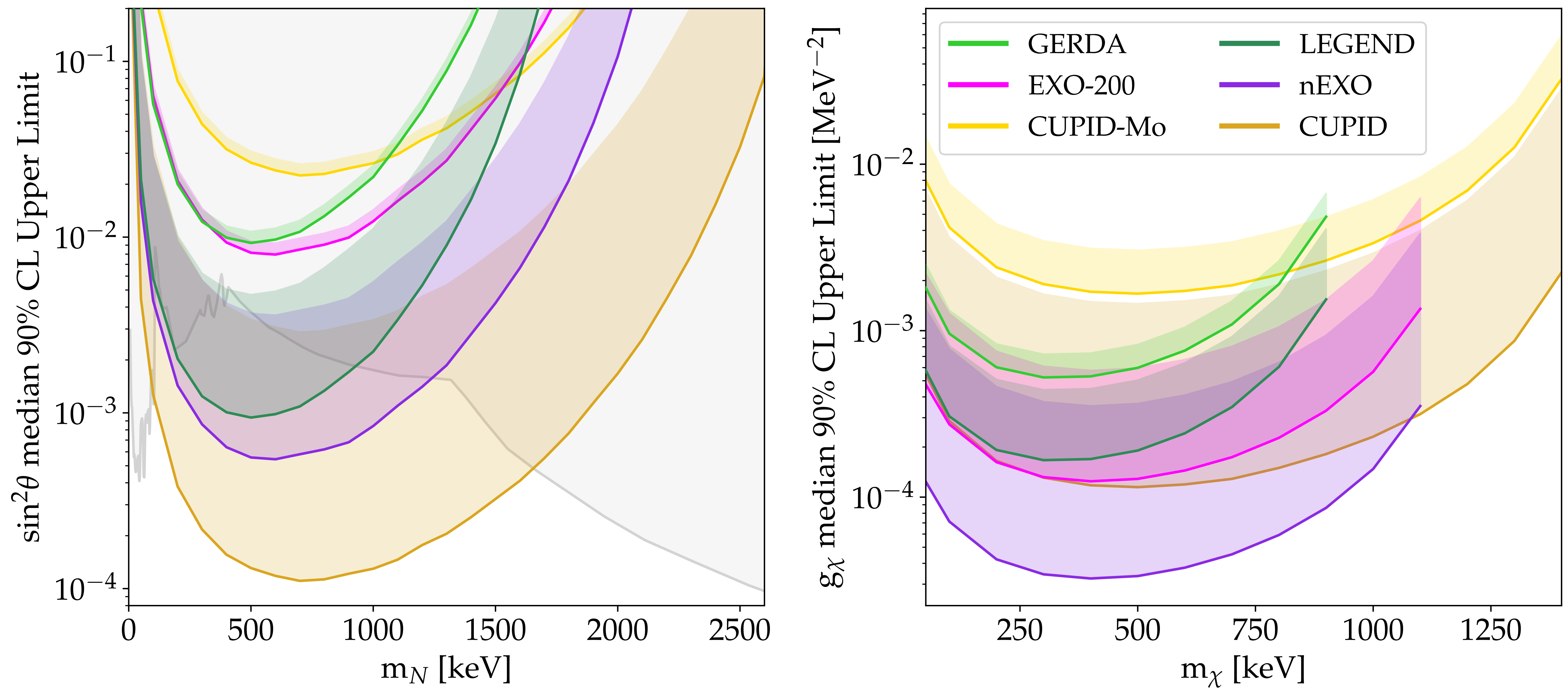




- First experimental constraints on light exotic fermions with double-beta decays:
  - First direct constraints on pair production of exotic fermion
  - Constraints from single-beta decay on sterile neutrinos are still more stringent, but demonstrate the potential of future double-beta decay experiments

M.Agostini, EB, A. Ibarra, X. Marcano, Phys. Lett. B 815 (2021) 136127

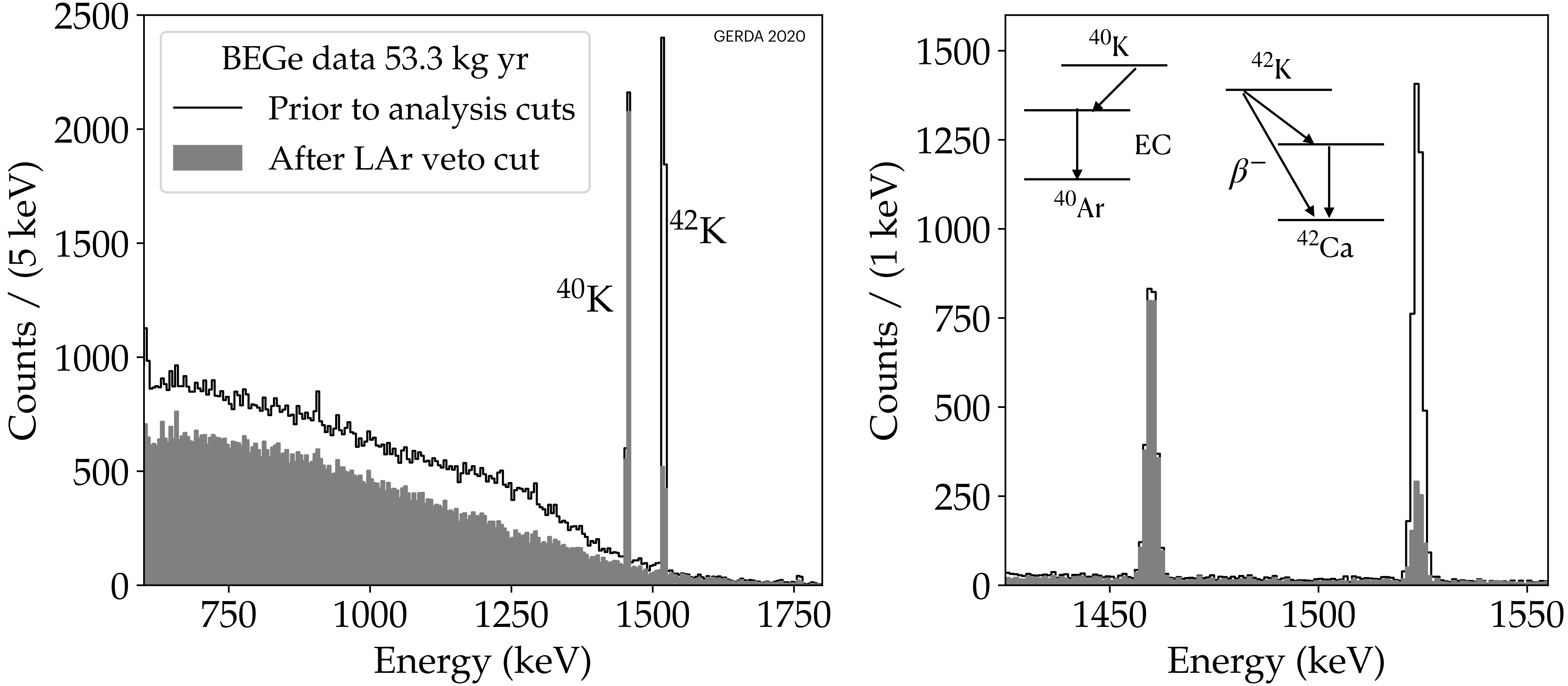
Sensitivity projections for future experiments



- Larger exposure of future experiments encourages dedicated searches: limits can be improved down to $\sin^2\theta \sim 10^{-3} - 10^{-4}$

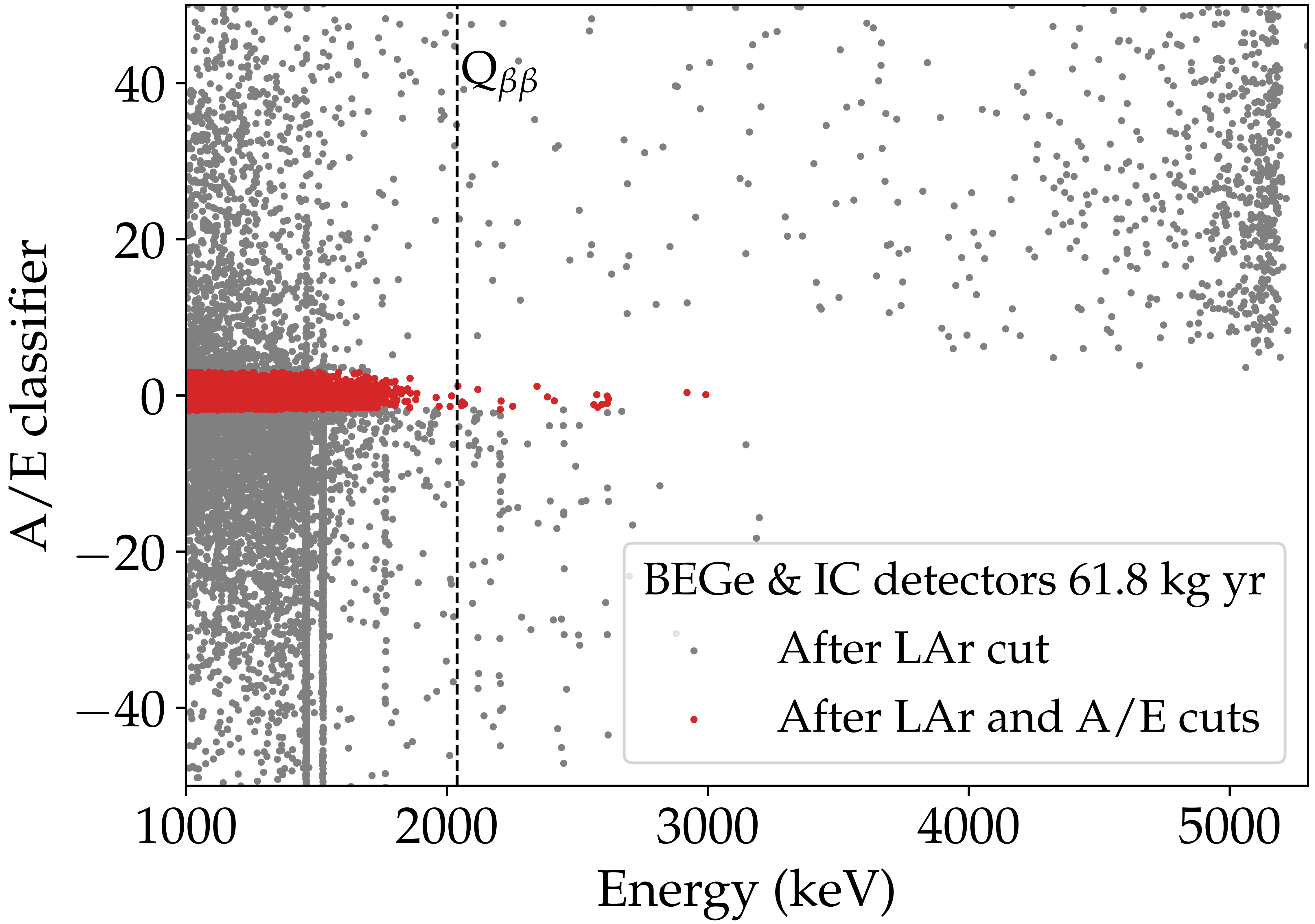
- Double-β decay experiments offer the unique opportunity to test models in which only the double production of exotic fermions is allowed

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