MAX-PLANCK-INSTITUT
FÜR PHYSIK

GERDA

Final results from GERDA: a neutrinoless double beta decay search

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on behalf of the GERDA collaboration

ICHEP 2022 – XLI International Conference on High Energy Physics

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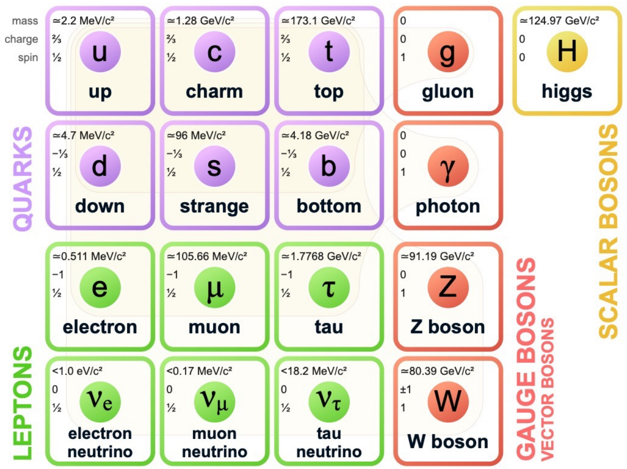
Neutrinos are special

The universe has lots of matter…but not as much antimatter?

- Baryogenesis in the early universe
- no interactions in SM can produce this asymmetry
- Sakharov conditions (1967)
  - Baryon (and lepton) number violation



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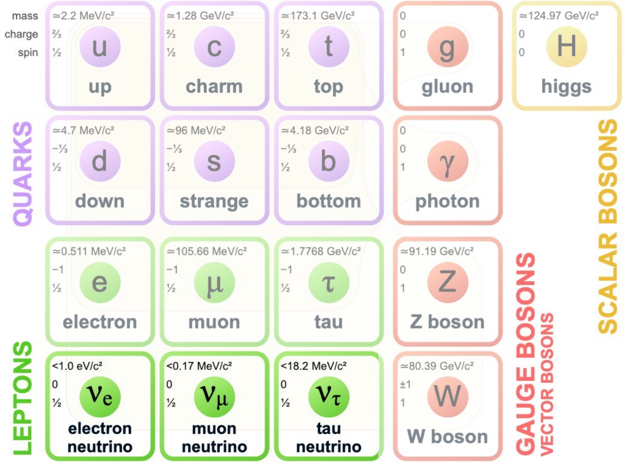

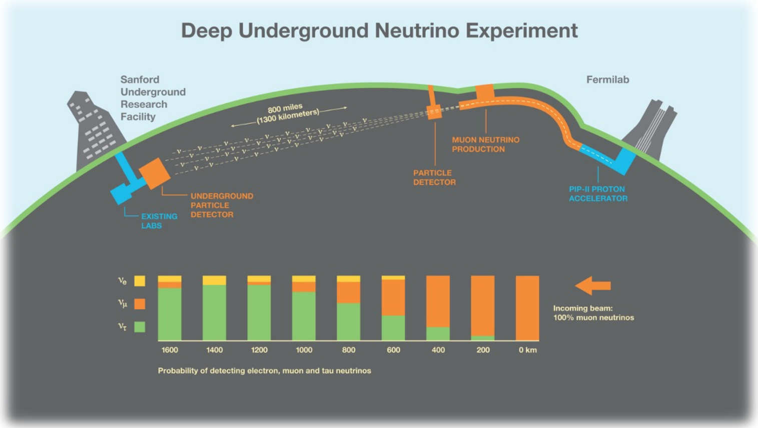

Neutrinos are special and don't quite fit in the SM…

- Only electrically neutral fermion and interacts only with weak force
- Neutrino oscillations observed → ***Neutrinos are massive particles!*** (RH neutrinos exist)
- "hierarchy" and absolute scale of mass states still unknown
- Light neutrinos: $m_\nu < 0.8\ \mathrm{eV/c^2}$
  - Without finely tuned coupling to Higgs → introduce "Majorana mass" terms

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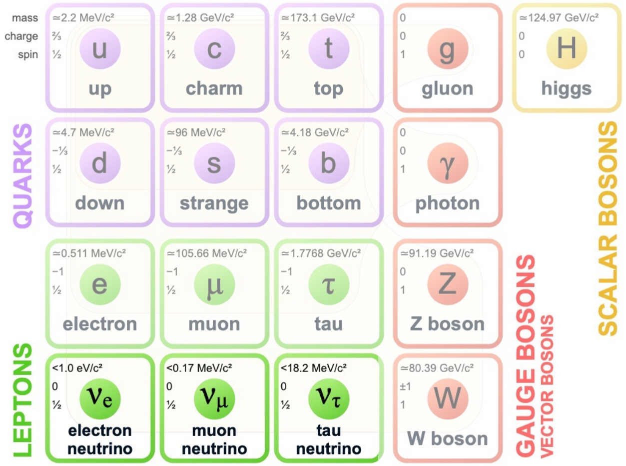

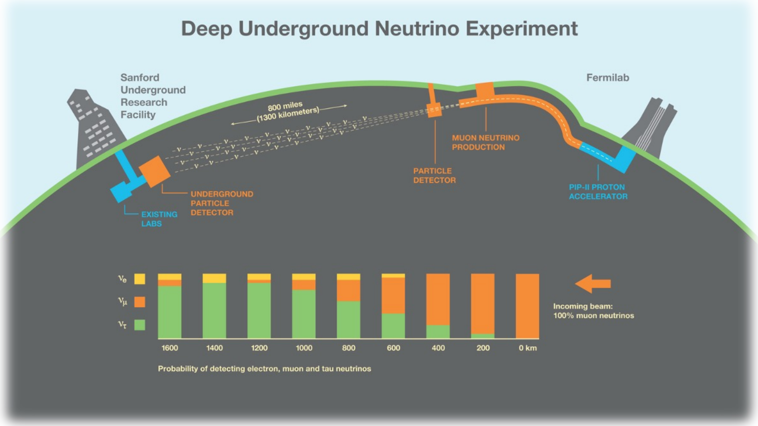

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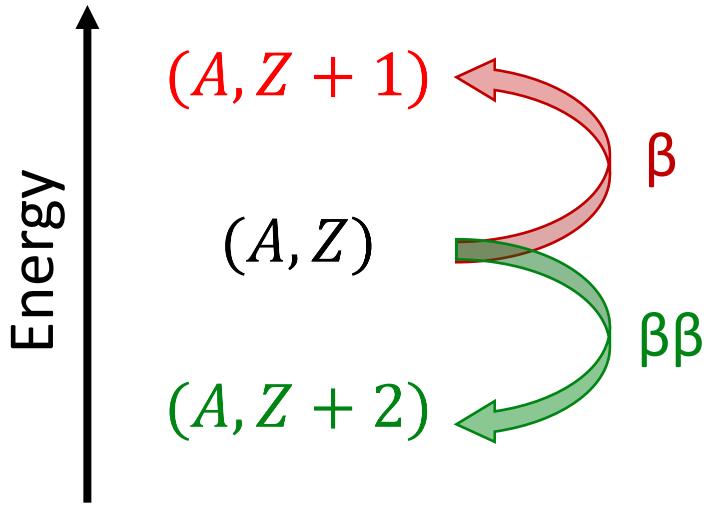
Majorana neutrinos would be a fundamentally new kind of elementary particle

- Equivalence between neutrinos and antineutrinos ($\nu = \bar{\nu}$)
- Allows CP symmetry violation and violation of lepton number

Search for $0\nu\beta\beta$-decay



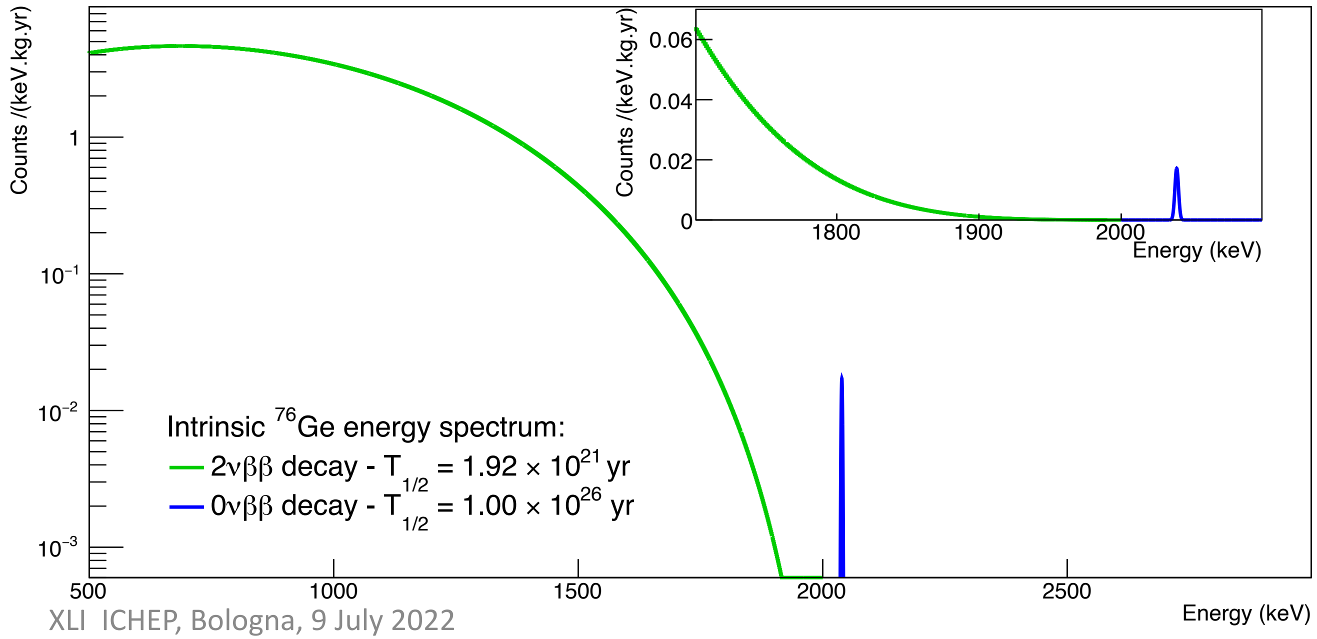
Measured in several isotopes: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe, …

<u>OBSERVED</u>

- 2νββ: $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^- + 2\bar{\nu}_e$
- broad continuous spectrum
- $T_{1/2}^{0\nu} \sim \mathcal{O}(10^{21})\ yr$
- $\Delta L = 0$

<u>NOT YET OBSERVED</u>

- 0νββ: $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$
- peak at $\mathrm{Q}_{\beta\beta} = 2039\ \mathrm{keV}$
- $T_{1/2}^{0\nu} > \mathcal{O}(10^{25})\ yr$
- $\Delta L = 2$



Experimental sensitivities

Half-life sensitivity:

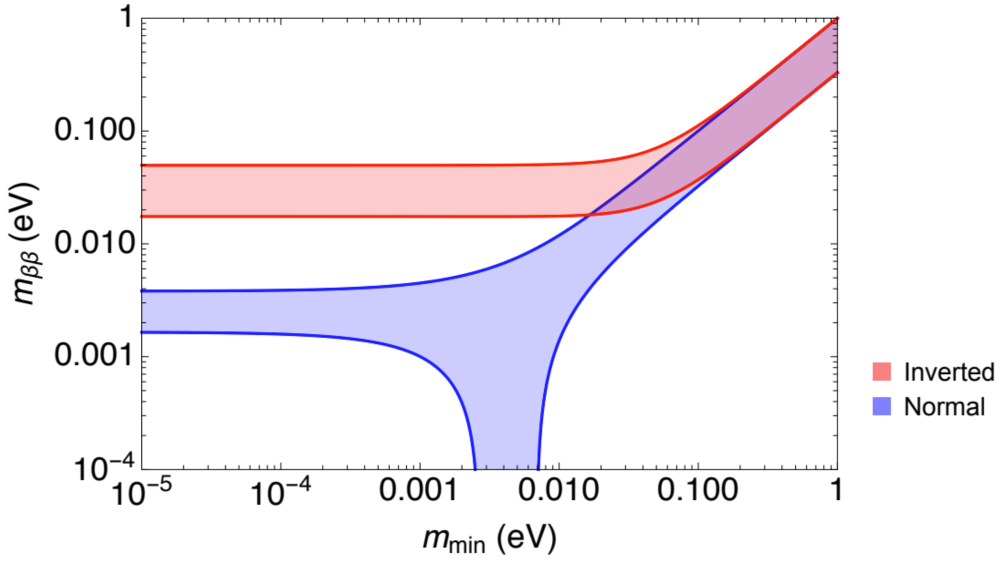
$n_b \gg 1$ $\qquad T_{1/2}^{0\nu} \propto fe\sqrt{\frac{Mt}{B\sigma_E}}$

(background free) $n_b < 1$ $\qquad T_{1/2}^{0\nu} \propto feMt$

- f: enrichment fraction
- e: efficiency
- M: mass
- t: measurement time

(M and t:) $\mathcal{E} = Mt$: exposure

- B: background index
- σ_E: energy resolution at $Q_{\beta\beta}$
- n_b : expected background events

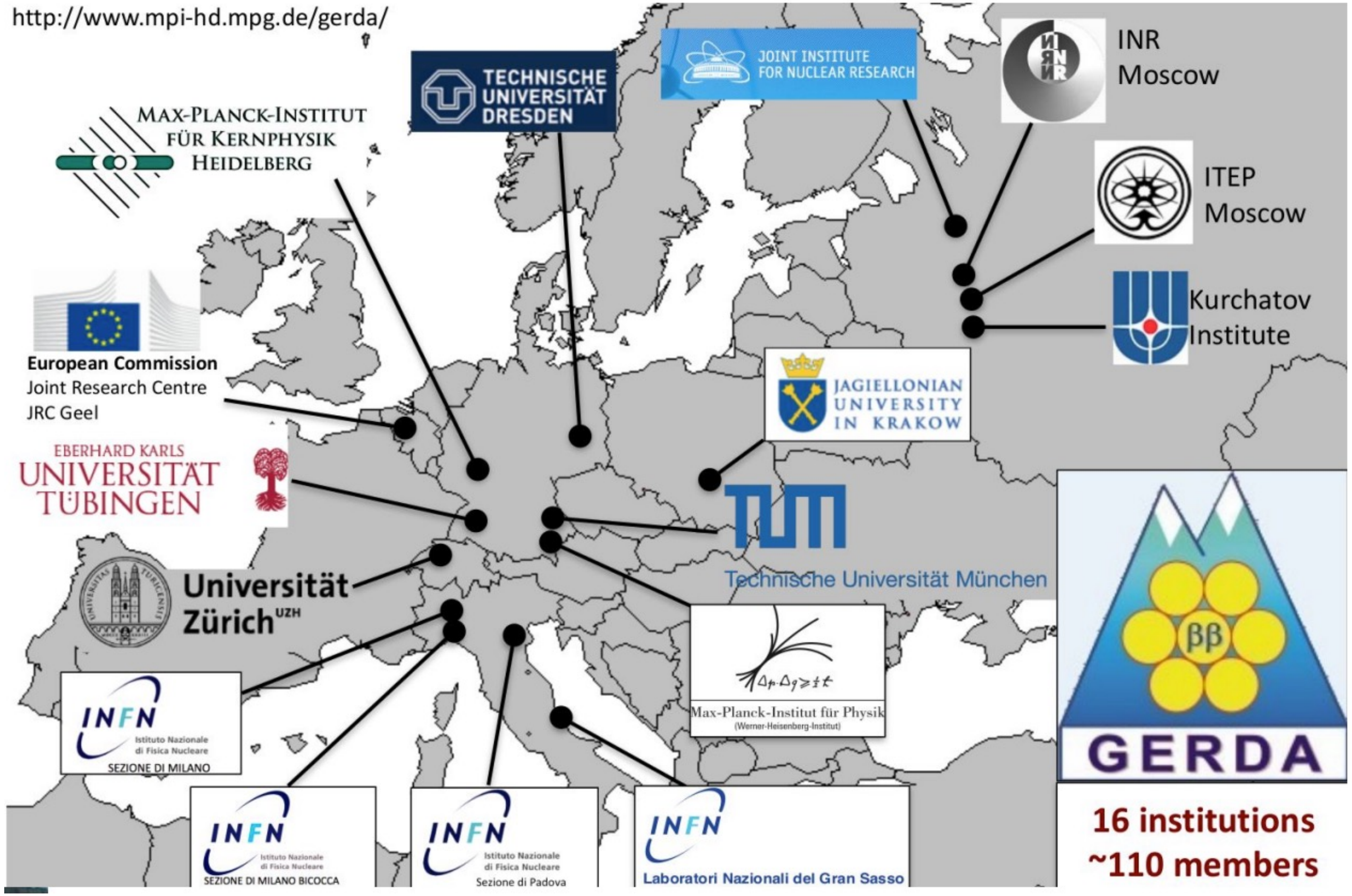


Majorana mass sensitivity:

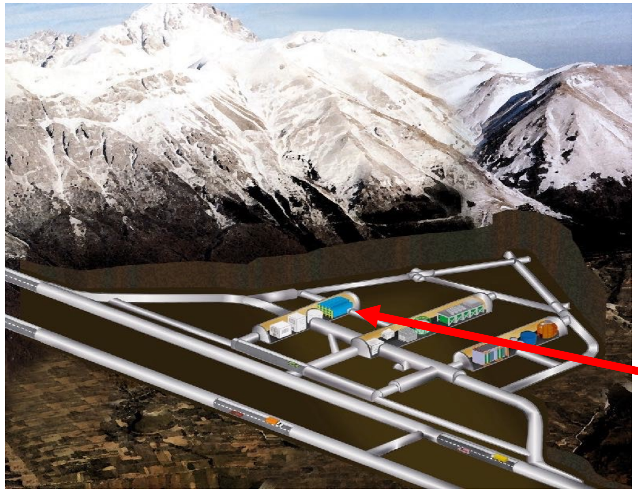
$$\frac{1}{\sqrt{T_{1/2}^{0\nu}}} \propto |M^{0\nu}| g_A^2 \sqrt{G^{0\nu}} \frac{\langle m_{\beta\beta}\rangle}{m_e}$$

- $\langle m_{\beta\beta}\rangle = m_1|U_{e1}|^2 e^{i\rho} + m_2|U_{e2}|^2 + m_3|U_{e3}|^2 e^{i\sigma}$
  effective neutrino mass (Majorana)
- $M^{0\nu}$: nuclear matrix element
- g_A: nucleon axial-vector coupling constant
- $G^{0\nu}$: phase space factor
- ρ, σ : Majorana phases

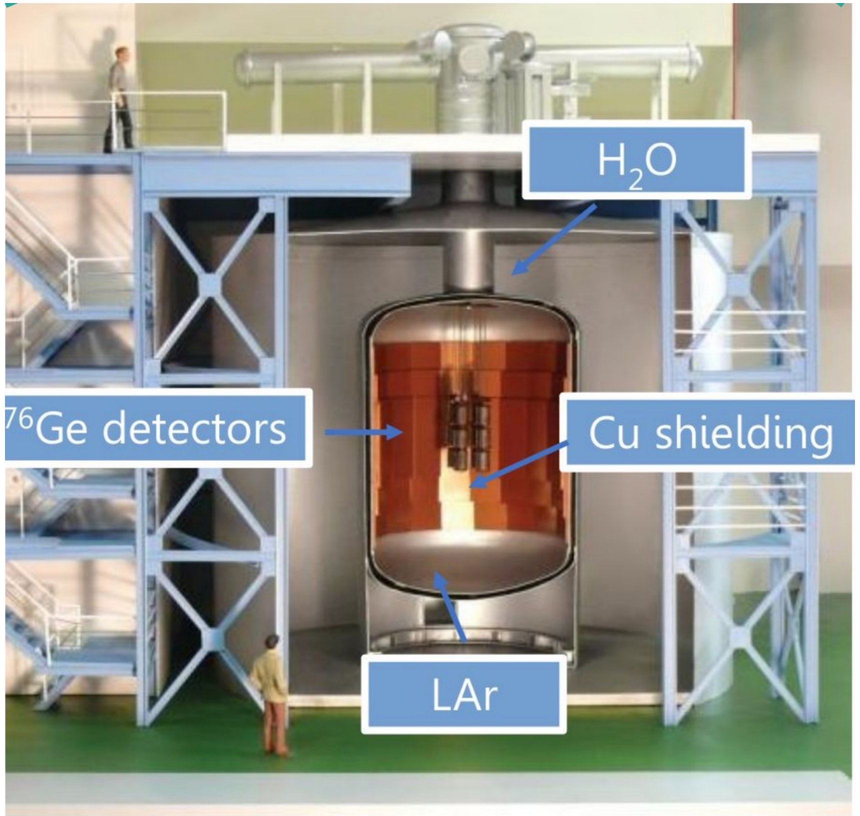
GERmanium Detector Array - GERDA Collaboration



GERDA Experiment: site and infrastructure



- Laboratori Nazionali del Gran Sasso (LNGS), Italy
- 1400 m rock overburden (3500 mwe)
- Cosmic muon reduction $\mathcal{O}(10^6)$



- 590 m^3 pure water tank equipped with PMTs:
  - Cherenkov light detection
- cryostat filled with Liquid Argon (LAr):
  - shielding
  - cooling
  - active veto
- Detector Array

Eur. Phys. J. C 78 388 (2018)

GERDA Setup

- Germanium is a promising candidate since 1967

  E. Fiorini et al., *Phys Lett B*, 25 (1967), no. 10, 602–603

- Up to 41 detectors in 6 to 7 strings covered by nylon cylinders

- high-purity bare detectors (HPGe) with enriched ^{76}Ge fraction

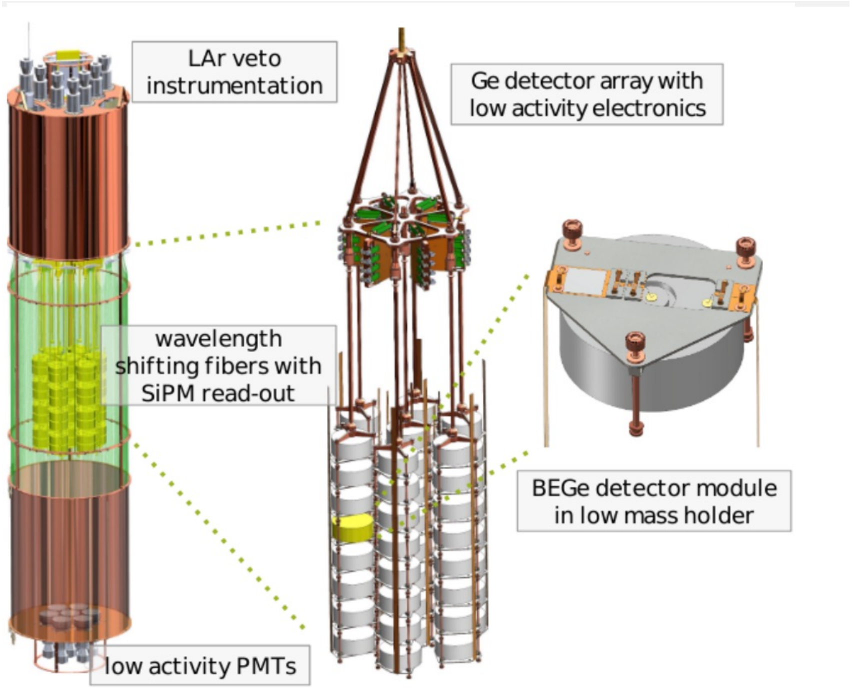
  (up to ~87%)

  GERDA, Astropart.Phys. 91 (2017) 15-21

  - maximizes detection efficiency: source = detector
  - Excellent energy resolution: ~0.1% FWHM at $Q_{\beta\beta}$

- lowest background per FWHM energy resolution in the field

- surrounded by fibers coated with the wavelength-shifter TPB (tetraphenyl butadiene)

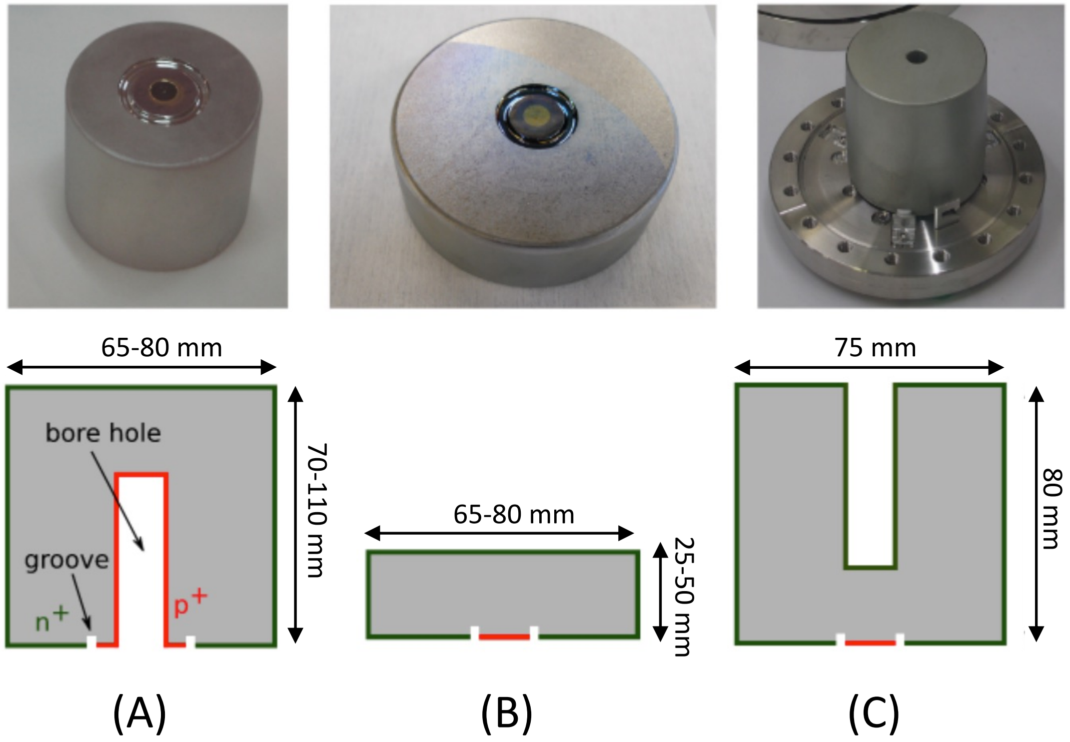


Germanium detectors

A. Semi-coaxial (Coax): 7 - 6
- typical mass 2-3 kg

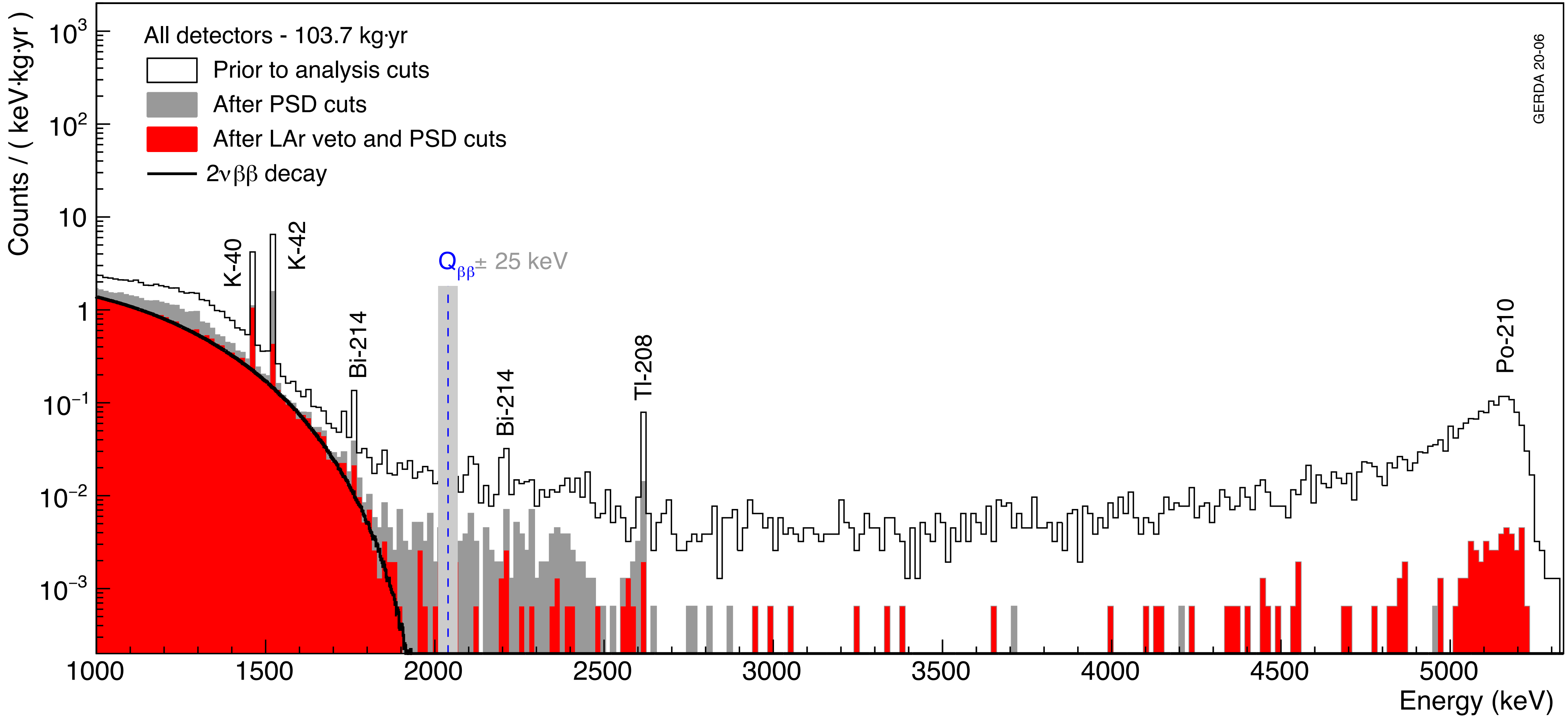
B. Broad Energy Germanium (BEGe): 30
- average mass 670 g
- small p+ contact at bottom: good for PSD (Pulse Shape Discrimination)
- excellent energy resolution

C. Inverted Coaxial (IC): 5
- Average mass 2 kg
- excellent energy resolution & PSD (like BEGe)



Eur. Phys. J. C. 79 11 978 (2019) Eur. Phys. J. C, 81 6 505 (2021)

Background reduction

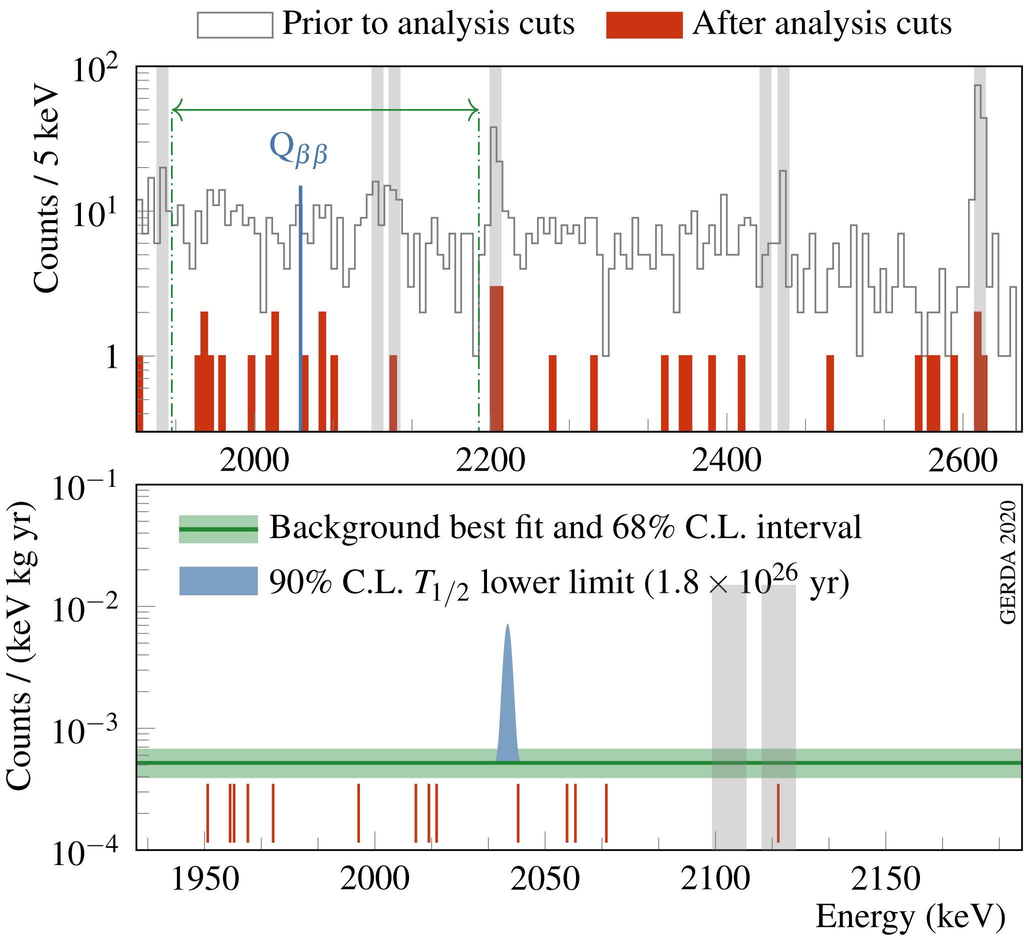


- < 0,5 MeV: ^{39}Ar
- [0,5 - 2] MeV: 2νββ
- > 4 MeV: α

Analysis workflow

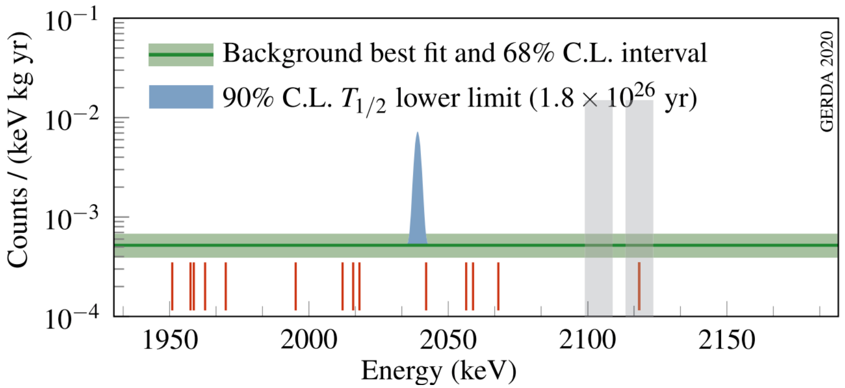
The analysis proceeds as follows:

- events in the interval $Q_{\beta\beta} \pm 25$ keV are not analysed but only stored on disk
- continuous monitoring of detectors
- freezing of analysis procedure and parameters
- blinded events are processed
- data analysis of events detected in the analysis window (1930−2190 keV) excluding the 2 gamma line regions:
  - 2104 ± 5 keV : ^{208}Tl (from ^{232}Th decay chain)
  - 2119 ± 5 keV : ^{214}Bi (from ^{238}U decay chain)



Data and Results

PRL 125, 252502 (2020)



In the analysis window we detect 13 events but we cannot claim a signal

- **Bayesian half-life limit (*and sensitivity*):** SN COMPUT. SCI. **2,** 210 (2021)
  - Uniform signal strength ($\left[T_{1/2}^{0\nu}\right]^{-1}$) prior:

    $T_{1/2}^{0\nu} > 1.4 \cdot 10^{26}\ yr$ (90% C.I.)
  - Uniform Majorana neutrino masses ($m_{\beta\beta}$) prior:

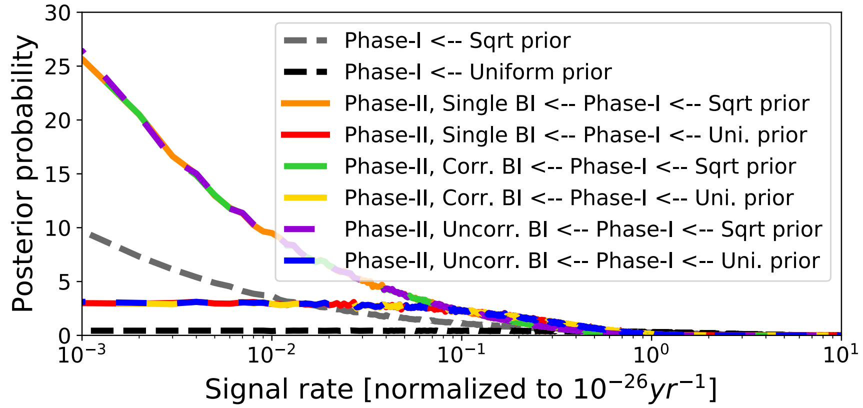
    $T_{1/2}^{0\nu} > 2.3 \cdot 10^{26}\ yr$ (90% C.I.)
- **Frequentist limit (*and sensitivity*):**

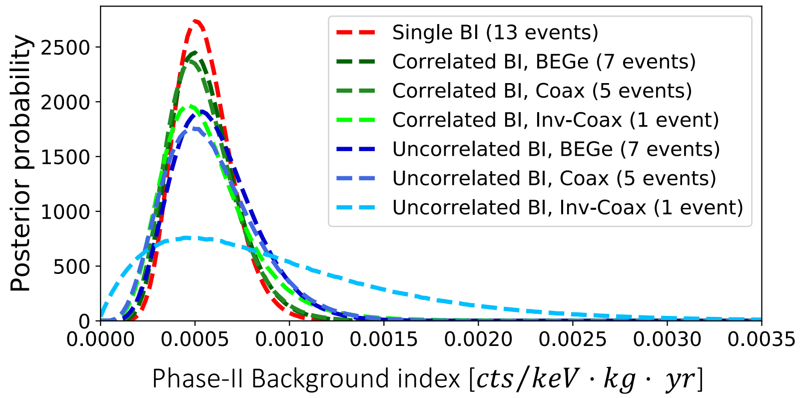
  $T_{1/2}^{0\nu} > 1.8 \cdot 10^{26}\ yr$ (90% C.L.)
- **Limits on effective neutrino mass:**

  $\left|m_{\beta\beta}\right| < [79\ - 180]\ meV$

  depending on the NME values at $g_A = 1.27$
- Background index for Phase-II analysis of Single B model is:

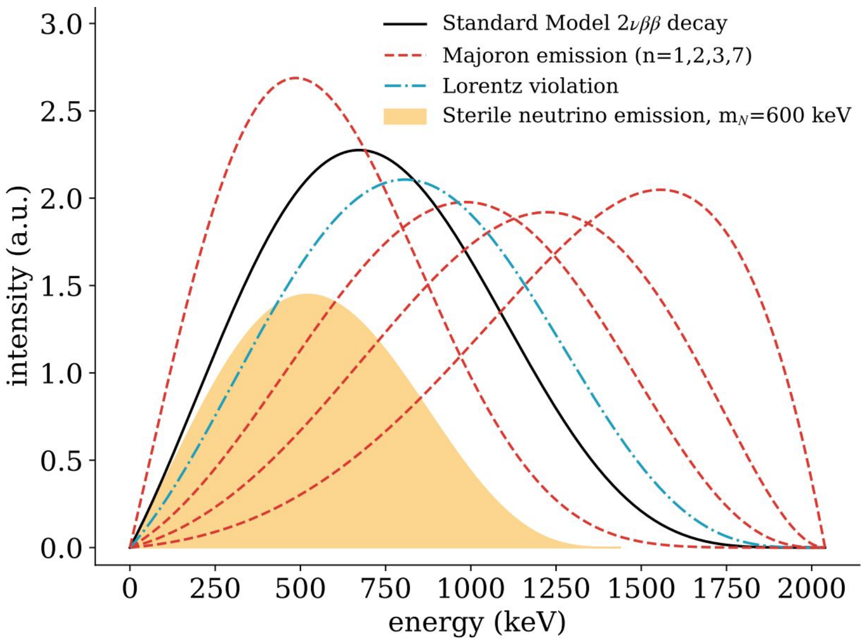
(Phase−II) $\mathrm{B} = 5.2^{+1.6}_{-1.3} \cdot 10^{-4} \left[\frac{\mathrm{cts}}{\mathrm{keV \cdot kg \cdot yr}}\right]$ (68% SI)



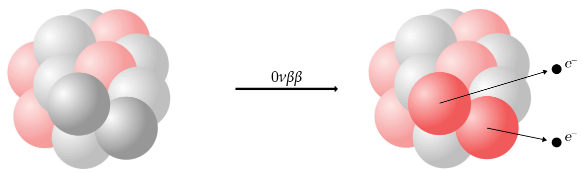


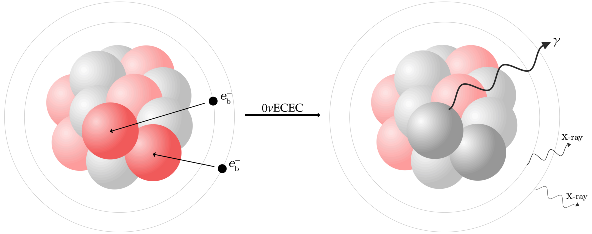
Other physics and current studies

- **Searching for other physics in the 2νββ decay:**
  - Precise fit of the 2νββ spectrum
  - Estimate half-lives on potential other physics:
    - ➢ Majoron emission
    - ➢ Lorentz violation
    - ➢ Sterile neutrino emission



- **Limit on the radioactive 0νECEC of ^{36}Ar**
- **Searches for Trinucleon Decays of ^{76}Ge**





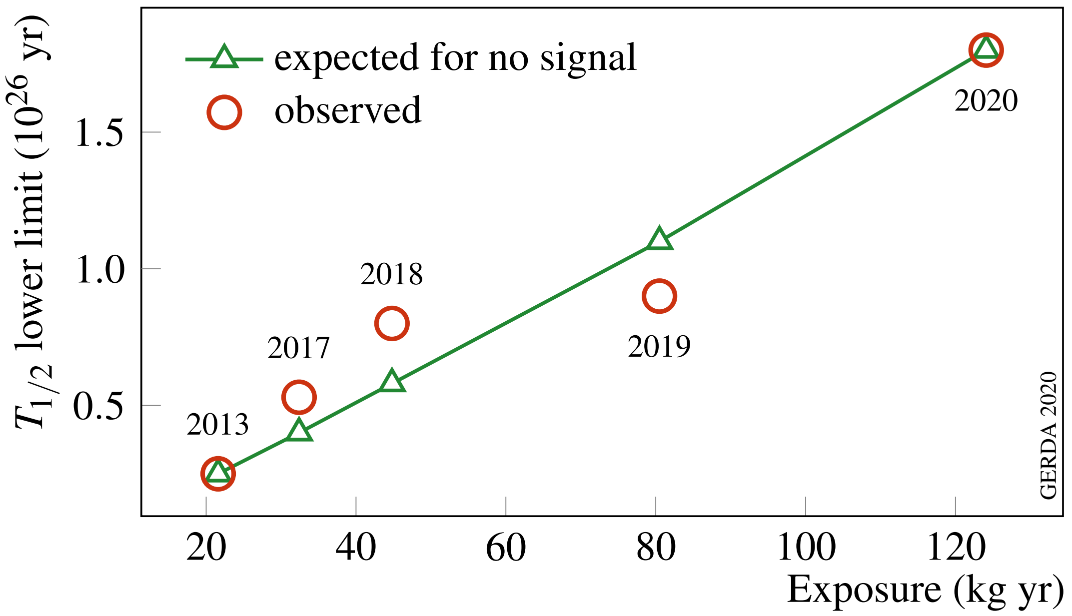
- **Searching for Super-WIMPs**
  - search for axion-like particles (ALPs), and vector (aka dark photons) super-WIMPs via their absorption in detector materials (similar to photoelectric effect)

Summary

- GERDA employed an array of HPGe detectors enriched in ^{76}Ge to search for 0νββ

- GERDA ended up surpassing all design goals and provides stringent constraints on the half-life of 0νββ decay
  - $T_{1/2}^{0\nu} > 1.8 \cdot 10^{26}\ yr$ (90% C.L.)
  - $|m_{\beta\beta}| < [79\ - 180]\ meV$

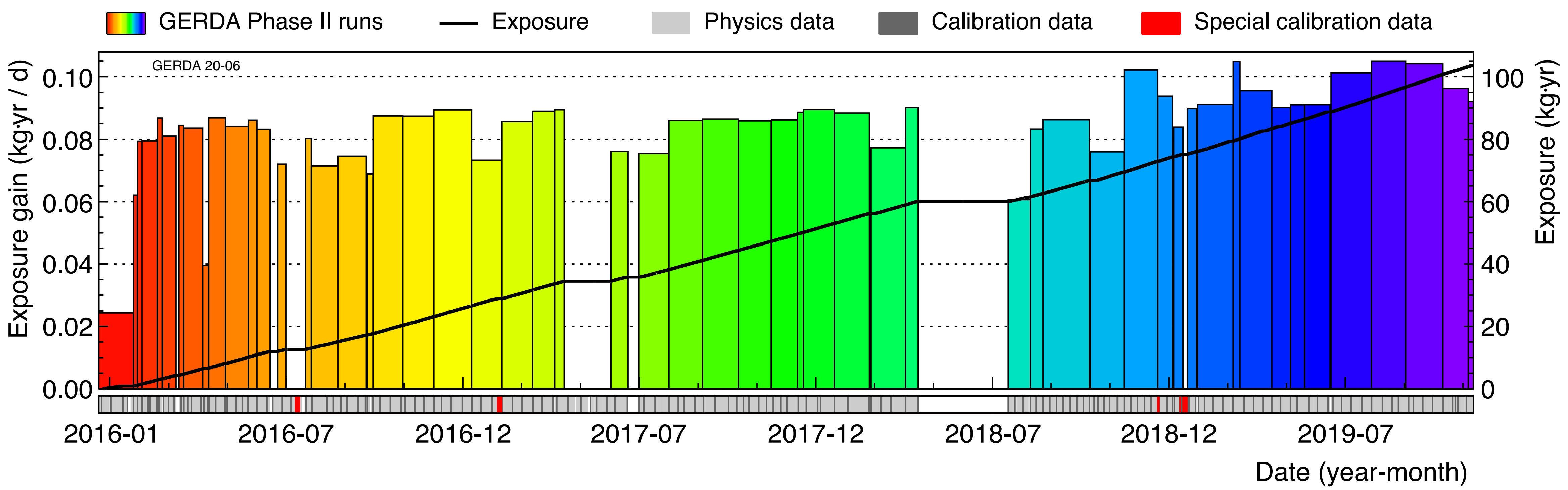
    depending on the NME values at $g_A = 1.27$
  - $B = 5.2^{+1.6}_{-1.3} \cdot 10^{-4} \left[\frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}\right]$ (68% SI)



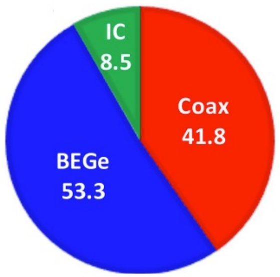
- GERDA is the only experiment to run in **background-free regime** for the entire duration of its data taking
  - most convincing for discovery
  - paved the way for LEGEND

BACKUP

Data taking



- 2011 – 2013: Phase I, 23.5 kg yr exposure
- 2015 – 2019: Phase II, 103.7 kg yr exposure
  - Installation of LAr veto
  - 2018: upgrade with 5 IC detectors
  - Operation in bkg-free regime



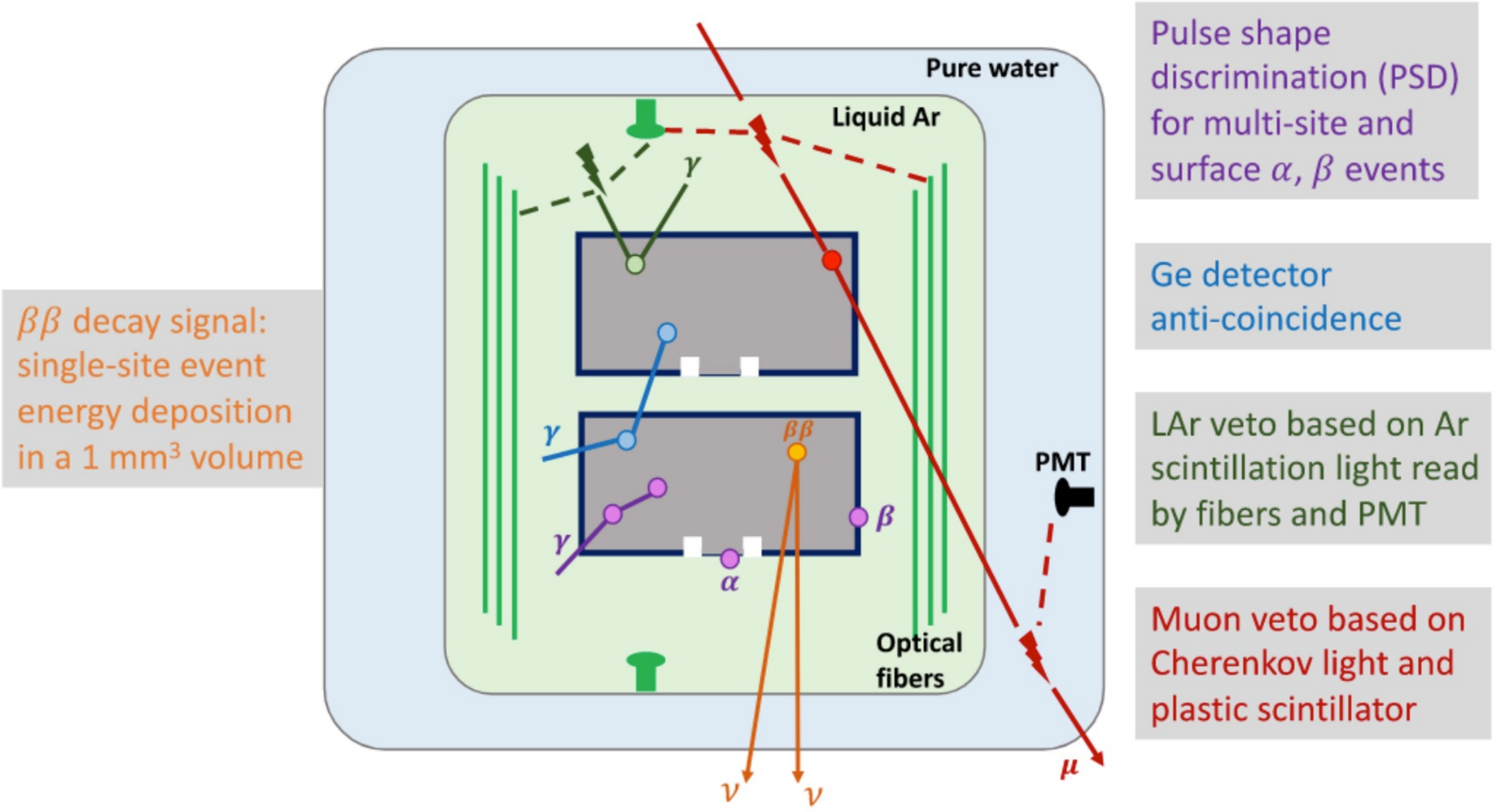
Background reduction

Analysis cuts:

- PSD
- multiplicity/coincidence
- Lar veto
- muon veto

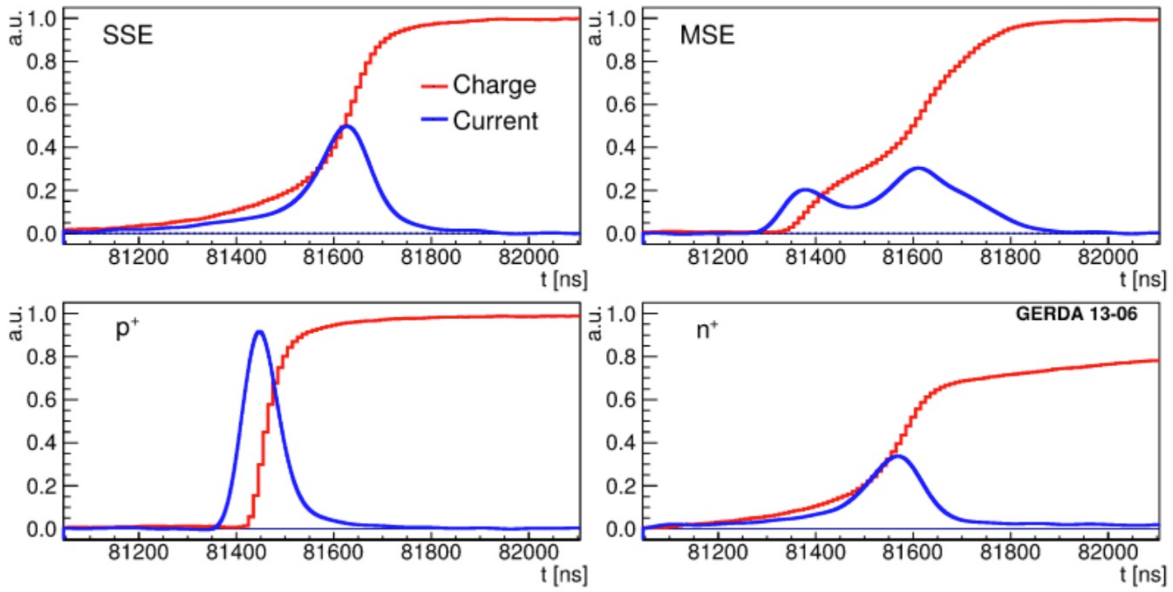
Signal efficiencies after cuts:

- Coax 46%
- BEGe 61%
- IC 66%



Pulse Shape Discrimination

- single-site events: signal-like
- multi-site events: induce double-peak structure
- surface α events: fast risetime, high current
- surface β events: incomplete charge collection
- rejection based on current amplitude over energy (A/E) for BEGe, IC & on artificial neural network comparing pulse shape for Coax



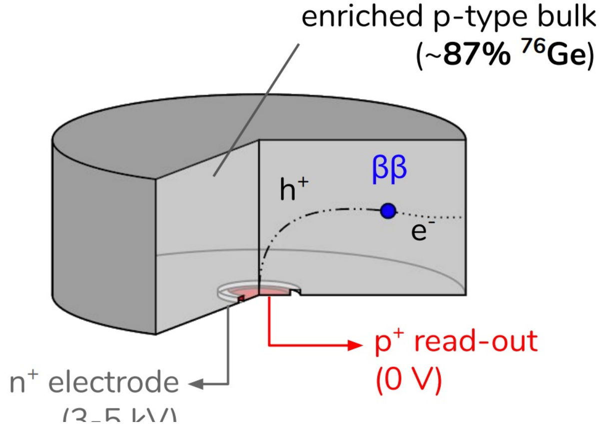
Eur. Phys. J. C 73 2583 (2013)

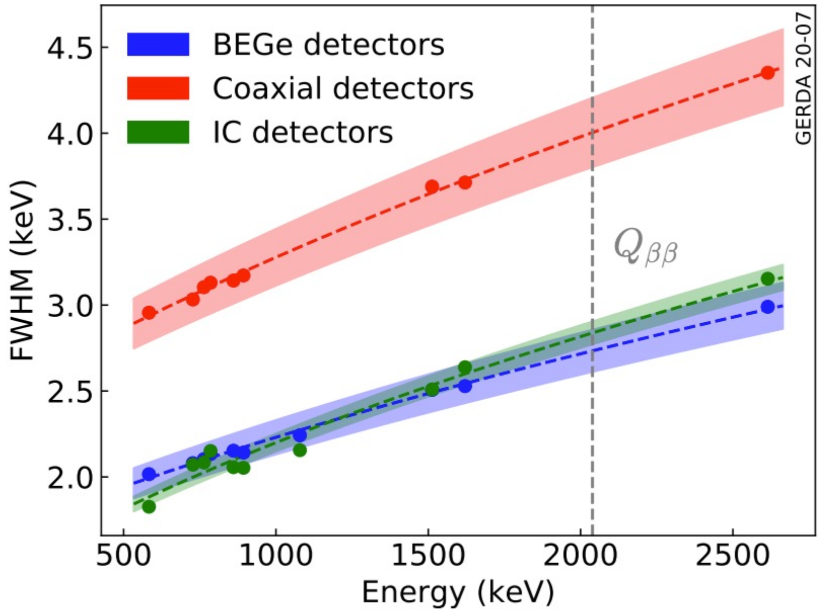
Calibration

- Detectors calibrated weekly with 3 ^{228}Th sources
- Energy shifts between calibration < 1 keV
- peak fitting algorithm to determine each detector's resolution
- Gaussian mixture models to determine resolutions per detector type
- digital shaping with "zero area cusp" (ZAC) filter

Eur. Phys. J. C 75 255 (2015)

Eur. Phys. J. C 81 682 (2021)





Detector specifications

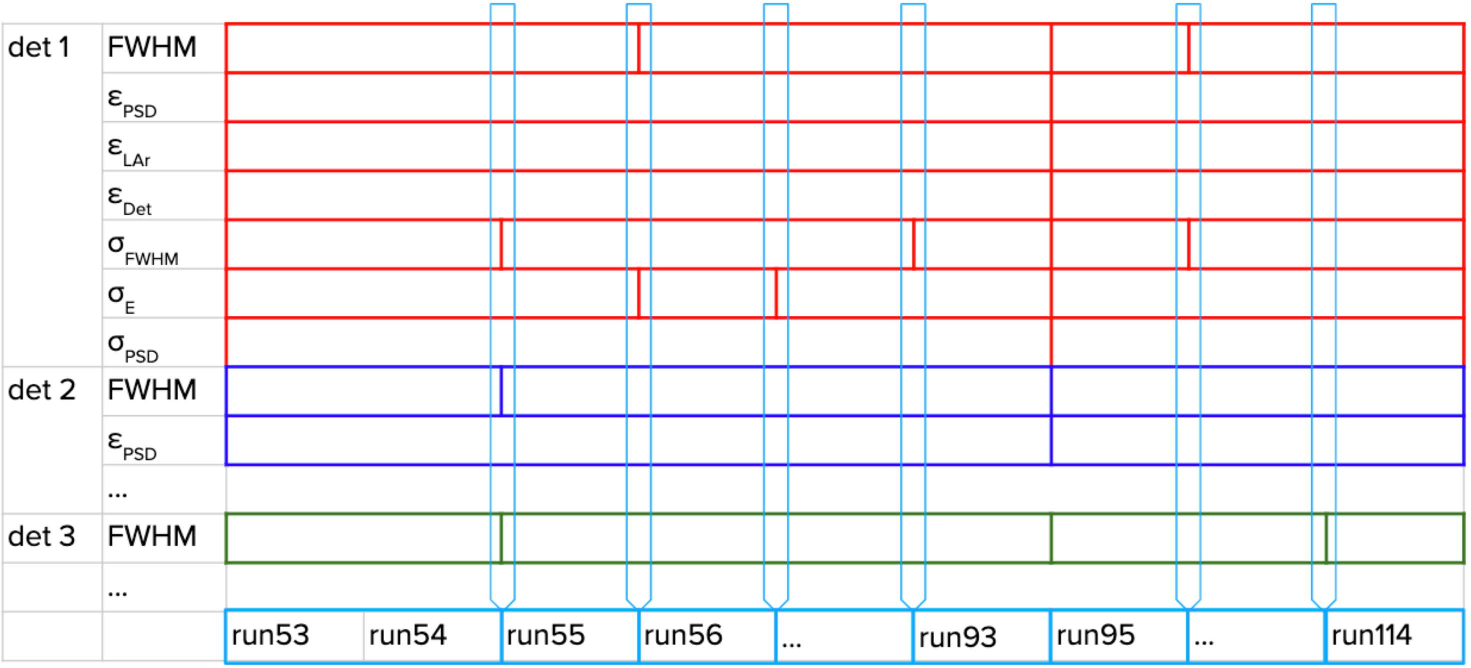
TABLE I. Summary of the GERDA Phase II parameters for different detector types and before and after the upgrade. The components of the total efficiency ε for $0\nu\beta\beta$ decays are reported individually. The efficiencies of muon veto and quality cuts are above 99.9% and are not shown. Energy resolutions and all $0\nu\beta\beta$ decay detection efficiencies are reported as exposure-weighted averages for each detector type and their uncertainties are given as standard deviations.

	Dec 2015–May 2018		July 2018–Nov 2019		
	Coaxial	BEGe	Coaxial	BEGe	Inverted coaxial
Number of detectors	7	30	6	30	5
Total mass	15.6 kg	20 kg	14.6 kg	20 kg	9.6 kg
Exposure $\mathcal{E}$	28.6 kg yr	31.5 kg yr	13.2 kg yr	21.9 kg yr	8.5 kg yr
Energy resolution at $Q_{\beta\beta}$ (FWHM)	(3.6 ± 0.2) keV	(2.9 ± 0.3) keV	(4.9 ± 1.4) keV	(2.6 ± 0.2) keV	(2.9 ± 0.1) keV
$0\nu\beta\beta$ decay detection efficiency ε:	$(46.2 \pm 5.2)\%$	$(60.5 \pm 3.3)\%$	$(47.2 \pm 5.1)\%$	$(61.1 \pm 3.9)\%$	$(66.0 \pm 1.8)\%$
Electron containment	$(91.4 \pm 1.9)\%$	$(89.7 \pm 0.5)\%$	$(92.0 \pm 0.3)\%$	$(89.3 \pm 0.6)\%$	$(91.8 \pm 0.5)\%$
^{76}Ge enrichment	$(86.6 \pm 2.1)\%$	$(88.0 \pm 1.3)\%$	$(86.8 \pm 2.1)\%$	$(88.0 \pm 1.3)\%$	$(87.8 \pm 0.4)\%$
Active volume	$(86.1 \pm 5.8)\%$	$(88.7 \pm 2.2)\%$	$(87.1 \pm 5.8)\%$	$(88.7 \pm 2.1)\%$	$(92.7 \pm 1.2)\%$
Liquid argon veto	$(97.7 \pm 0.1)\%$		$(98.2 \pm 0.1)\%$		
Pulse shape discrimination	$(69.1 \pm 5.6)\%$	$(88.2 \pm 3.4)\%$	$(68.8 \pm 4.1)\%$	$(89.0 \pm 4.1)\%$	$(90.0 \pm 1.8)\%$

- closest event at 2.4 σ   PRL 125, 252502 (2020)

Data partitioning

- **Partition**: period of time in which all parameters are constant
- cut data with respect to different detectors
- cut data with respect to time windows that share the same constant parameters
- background indices can be common parameters among partitions
- Each partition has its own efficiency (ϵ_k), exposure ($\mathcal{E}_k$), energy resolution ($\sigma_k = \mathrm{FWHM}/2.35$) and background index ($B_k$)
- the result is 383 partitions



Likelihood

- Signal rate $S = 1 \, / \, T_{1/2}^{0\nu}$
- Expected number of signal events in partition k ($\mathcal{E}_{\boldsymbol{k}}$ exposure, ϵ_k efficiency, m_{76} molar mass):

$$\mu_{s,k} = \frac{\ln 2 \, \mathcal{N}_A}{m_{76}} \, \epsilon_k \, \mathcal{E}_k \, S$$

- Expected number of background events in partition k (B_k bkg index, ΔE analysis window width):

$$\mu_{s,b} = B_k \, \Delta E \, \mathcal{E}_{\boldsymbol{k}}$$

- Gaussian distribution for the signal, centered at $Q_{\beta\beta}$ with a width corresponding to the energy resolution (σ_k), and a flat distribution for the background
  - the hypothesis of a flat background is supported by means of a test-statistic derived from Order-Statistic, which models the distribution of spacings between statistical samples

Sensitivity vs. Exposure

- Number of signal and background counts are Poisson distributed
- Expected number of signal counts (f enrichment fraction, e efficiency, $\epsilon = f \cdot e$):

$$n_s = \frac{ln(2)\ \mathcal{N}_A}{m_{76}}\ fe\ \mathcal{E}\ \frac{1}{T_{1/2}^{0\nu}}$$

- Expected number of background counts (around $Q_{\beta\beta}$, thus $\Delta E = \sigma_E$):

$$n_b = \mathcal{E}\ B\ \Delta E$$

- If $n_b = 0$ (background free), then $T_{1/2}^{0\nu}$ is the time needed to observe 1 signal event:

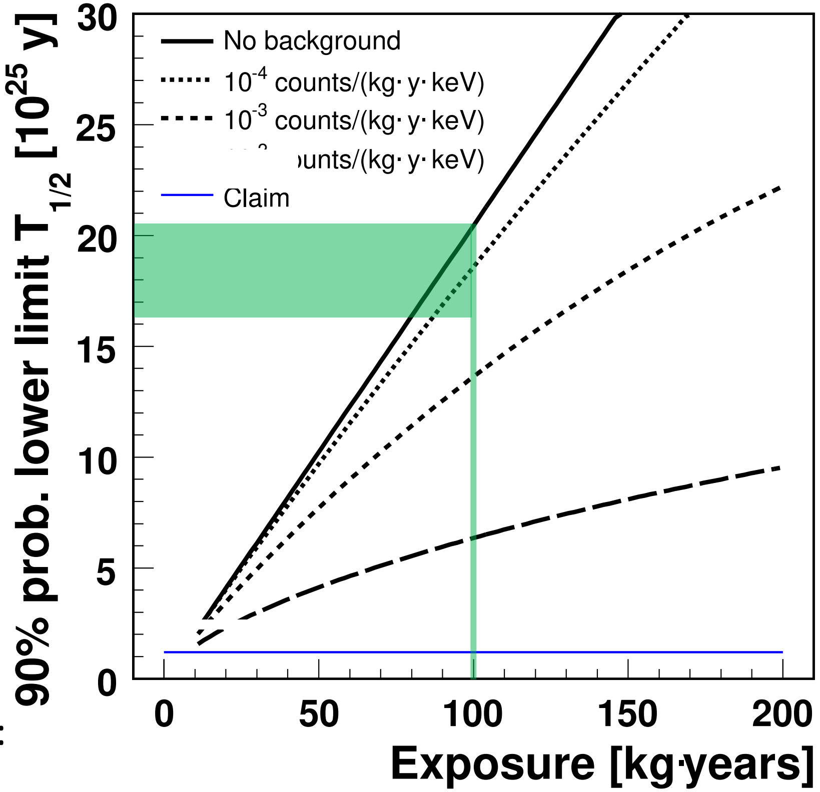
$$T_{1/2}^{0\nu} \propto fe\ \mathcal{E}$$

- If $n_b \gg 1$, then we can approximate the Poisson statistics with a Gaussian distribution:

$$n_b \sim \mathcal{N}\ (\mathcal{E}\ B\ \Delta E, \sqrt{\mathcal{E}\ B\ \Delta E})$$

- the minimal number of signal counts that can be distinguished from the background is approximately $\sqrt{n_b}$, thus:

$$T_{1/2}^{0\nu} \propto fe \sqrt{\frac{\mathcal{E}}{B \Delta E}}$$



Frequentist analysis (I)

- Two sided test statistic based on the profile likelihood $\lambda(S)$:

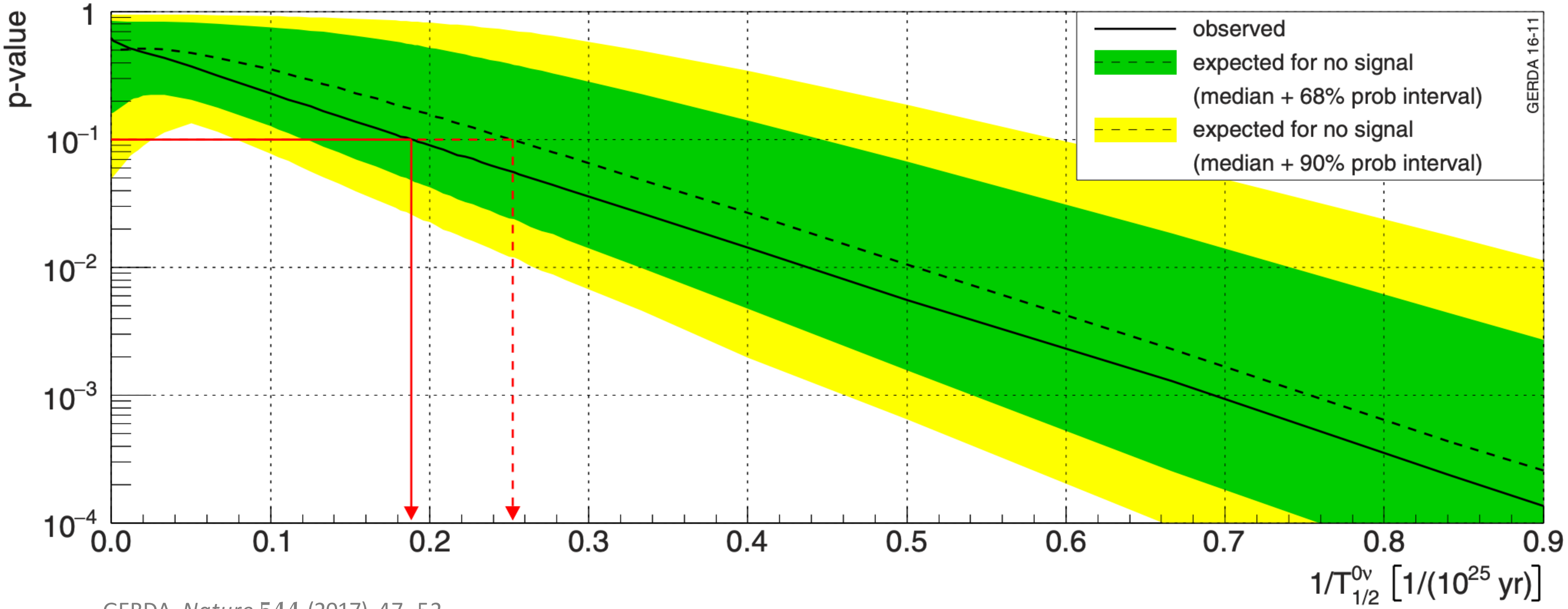
$$t_S = -2\ \ln[\lambda(S)] = -2\ln\left[\frac{\mathcal{L}(S,\hat{\hat{B}},\hat{\hat{\theta}})}{\mathcal{L}(\hat{S},\hat{B},\hat{\theta})}\right]$$

- $\hat{\hat{B}}$ and $\hat{\hat{\theta}}$ denote the value of the parameters that maximize $\mathcal{L}$ for a fixed S
- $\hat{S}$, $\hat{B}$ and $\hat{\theta}$ denote the values corresponding to the absolute maximum likelihood
- Estimate the distribution $f(t_S\ |S)$ using MCMC
- The p-value for data at a specific value of S is:

$$p_S = \int_{t_{obs}}^{\infty} f(t_S|S)d(t_s)$$

- The 90% CL is given by all S values with $p_S > 0.1$

Frequentist analysis (II)

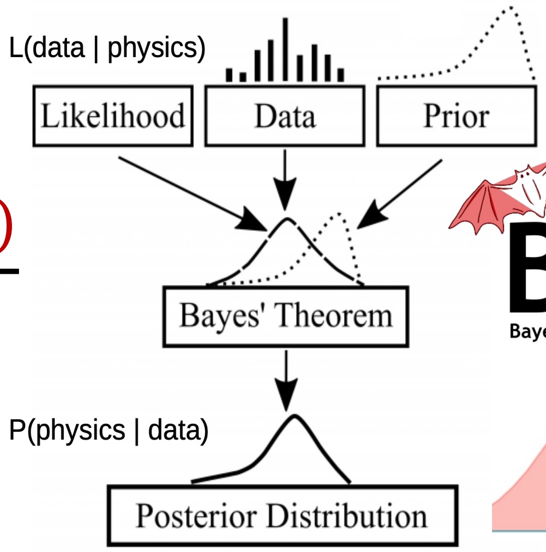


GERDA, *Nature* **544** (2017), 47–52

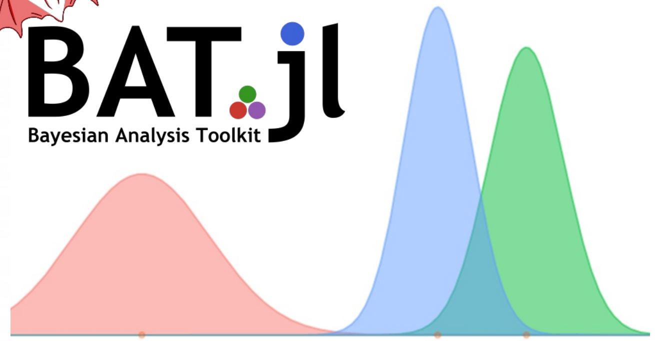
Bayesian analysis in a nutshell

https://github.com/bat/BAT.jl

Bayes' theorem: $P(\theta|D) = \dfrac{P(D|\theta) \cdot P(\theta)}{P(D)}$



BAT.jl
Bayesian Analysis Toolkit



- D: data
- θ: parameters
- allows to incorporate prior knowledge into computing statistical probabilities
- $p(D) = \int d\theta \; p(D|\theta) \cdot p(\theta)$: evidence

Bayes factor

- For a given model M_1: $P(\theta|D, M_1) = \dfrac{P(D|\theta, M_1) \cdot P(\theta|M_1)}{P(D|M_1)}$

$$BF_{12} = \frac{P(D|M_1)}{P(D|M_2)}$$

Unbinned Extended Likelihood

$$\mathcal{L} = \prod_k \left[\frac{(\mu_{s,k} + \mu_{b,k})^{N_k} e^{-(\mu_{s,k}+\mu_{b,k})}}{N_k!} \times \prod_{i=1}^{N_k} \frac{1}{\mu_{s,k} + \mu_{b,k}} \times \left(\frac{\mu_{b,k}}{\Delta E} + \frac{\mu_{s,k}}{\sqrt{2\pi}\sigma_k} e^{-\frac{(E_i - Q_{\beta\beta})^2}{2\sigma_k^2}} \right) \right]$$

Poisson weight

Flat background

Gaussian signal

Expected counts

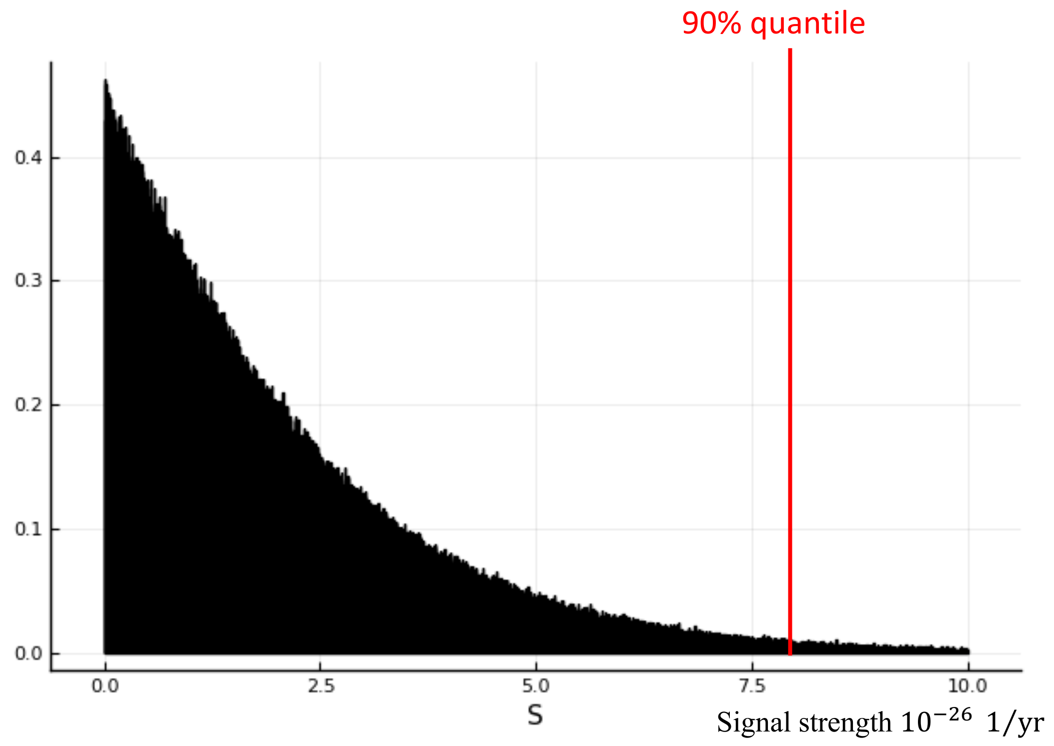
GERDA, *Nature* **544** (2017), 47–52

- E_i is the energy
- $\mu_{s,k}$ and $\mu_{b,k}$ are the expected signal and background counts respectively
- N_k is the number of events in the k-th partition
- Systematic uncertainties on E_i, ϵ_k and σ_k are included in the analysis and modelled as normal distributions
- the hypothesis of a flat background is supported by means of a test-statistic derived from Order-Statistic, which models the distribution of spacings between statistical samples arXiv:2008.02048

Models for the Signal strength

There are 2 different priors on the signal strength $S = \frac{1}{T^{0\nu}_{1/2}}$ (which ranges from 0 to 10^{-24} 1/yr):

- $p(S) \sim Uniform$
  - equiprobable signal strengths
- $p(S) \sim \frac{1}{\sqrt{S}}$
  - equiprobable Majorana neutrino masses $m_{\beta\beta}$
  - $S \propto m^2_{\beta\beta}$



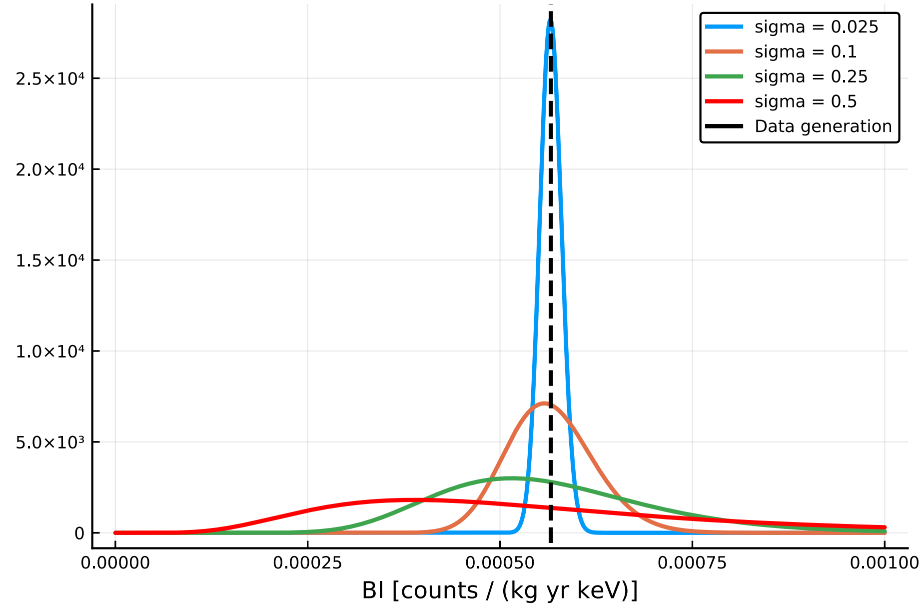
1) Perform fit to Phase I data
   - 61 events, 23.5 kg · yr exposure
2) Feed posterior from Phase-I to Phase-II analysis
   - 13 events, 103.7 kg · yr exposure
3) Get limit at 90% C. I. from posterior distribution of S

Models for the Background Indices

There are 3 types of detectors: BEGe (Broad Energy Germanium), Coax (Coaxial), Inv-Coax (Inverted Coaxial)

The background index (B) can be treated in 3 different ways, which gives rise to 3 different models:

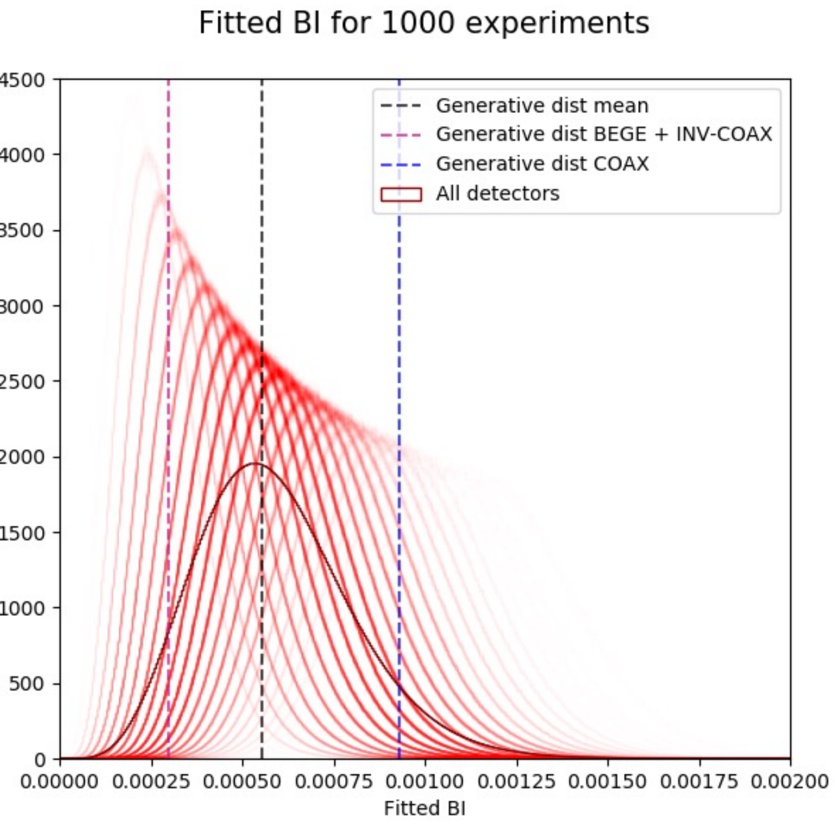
- Single background index: there is only one background index for all detector types: $B \sim Uniform$
- Uncorrelated background indices: each detector type has its own independent B_i: $B_i \sim Uniform$
- Correlated background indices: each detector type has a different B_i but they are all correlated. This implies a hierarchical model
  - $\sigma_B \sim Uniform$
  - $m_B \sim Uniform$
  - $B_i \sim LogNormal\left(\ln(m_B) - \frac{\sigma_B^2}{2},\ \ \sigma_B\right)$



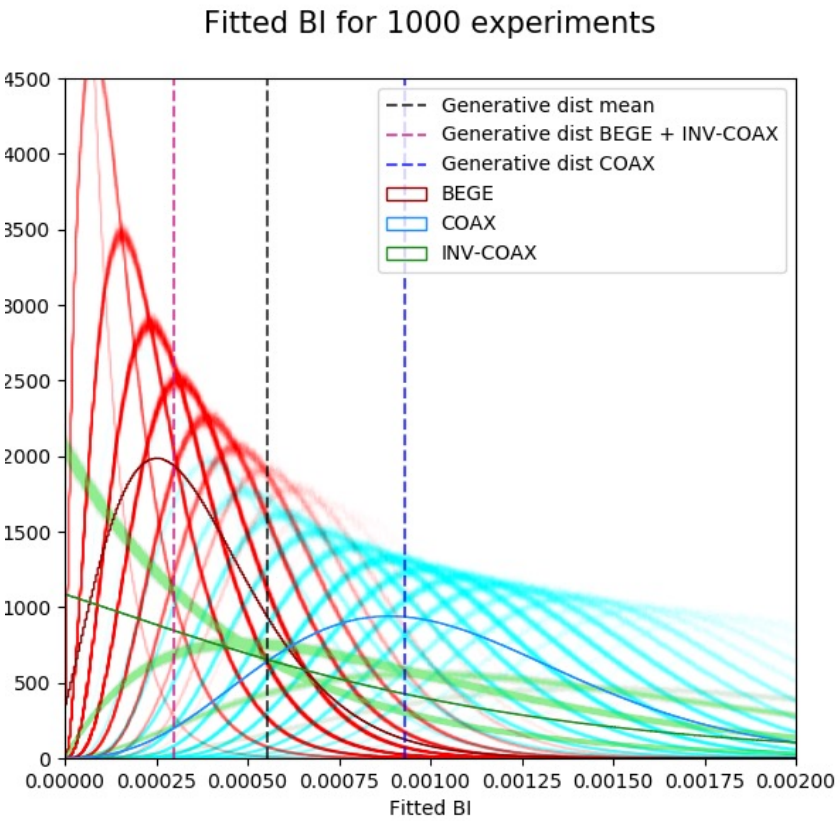
- Changing the range of σ_B allows the correlated model to replicate the previous two models: smooth change
  - Small sigma ---> Single BI
  - Large sigma ---> Uncorrelated BI

Comparison with toy experiment

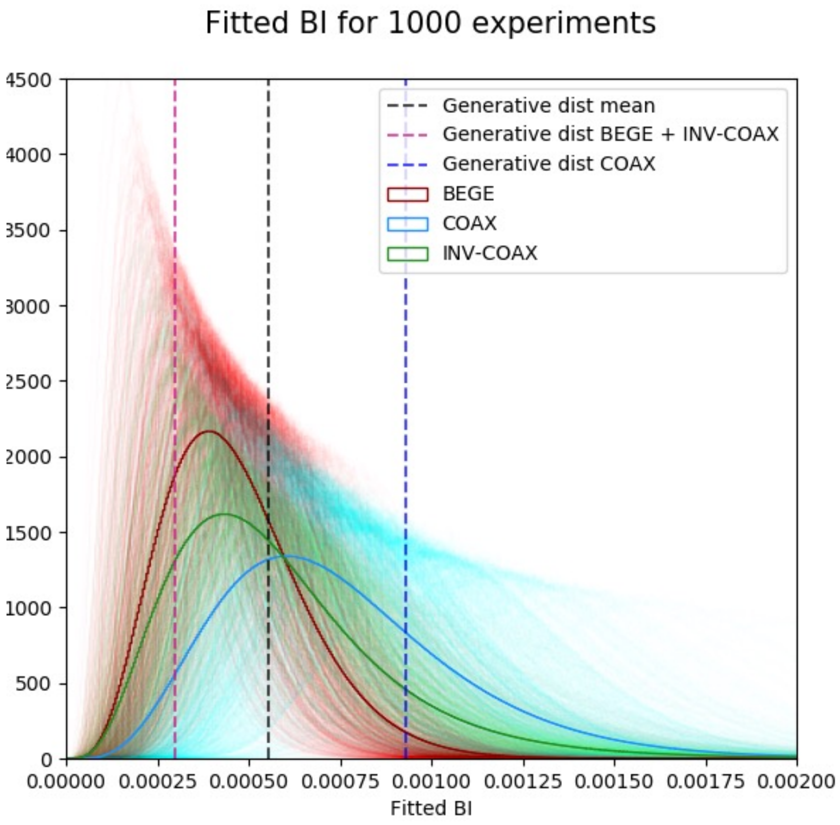
Single BI



Uncorrelated BI



Correlated BI



Model comparison

- Single B model reconstructs a larger fraction of signal events on average: stronger discovery power

- Uncorrelated B model gives on average a better half-life limit in experiments with only background events: stronger limit setting capabilities

- Correlated B model's performance is halfway between the extreme models both in discovery power and limit setting

- The (median) sensitivity of all models assuming no signal and using a uniform prior for S is

$$T_{1/2}^{0\nu} > 1.4 \cdot 10^{26} \text{ yr (90\% C.I.)}$$