Search for new physics with $2\nu\beta\beta$ decay in GERDA

L. Pertoldi • Ph.D. defense

GERDA clean room • 23 Feb 2021

Università degli Studi di Padova / INFN Padova

About me

Currently postdoc at Technische Universität München (TUM)

- gipert.github.io
- orcid.org/0000-0002-0467-2571
- inspirehep.net/authors/1667599

GERDA simulation & background studies task group leader

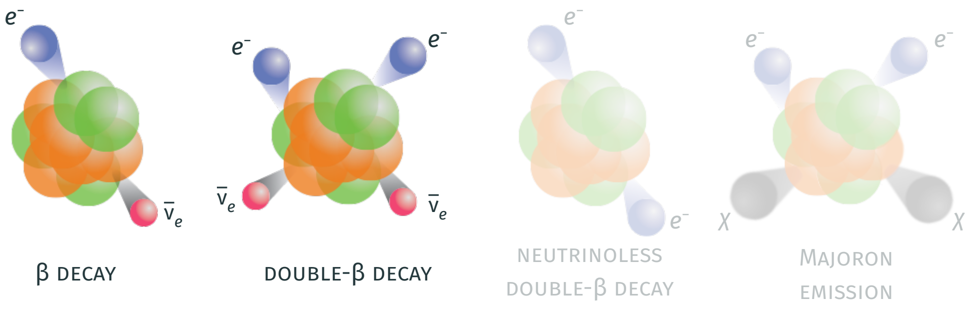
[slides] l.infn.it/pertoldi-phd-sl
[thesis] l.infn.it/pertoldi-phd-th

Outline

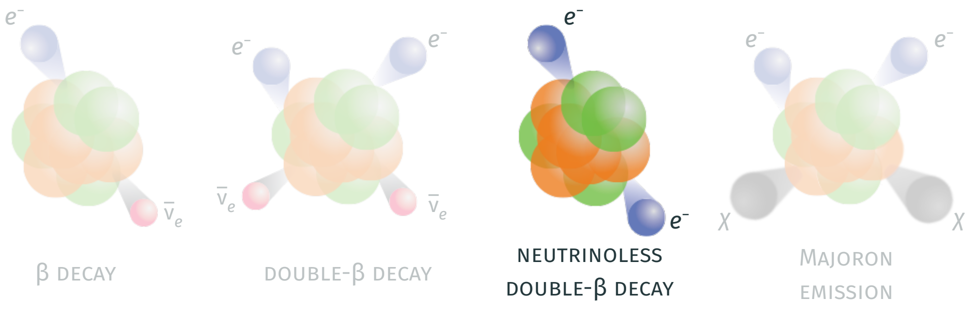
1. Why studying double-beta decay?
   - Rare physics, origins of the Universe, Majorana neutrino, Standard Model probe
2. GERDA — science goal and experimental design
   - ^{76}Ge detectors, background mitigation techniques, latest results
3. The GERDA background model before analysis cuts
   - Monte Carlo simulations, background expectations and statistical decomposition techniques
4. The GERDA background model after the LAr veto cut
   - LAr veto system, optical Monte Carlo simulations, tuning with calibration data
5. Precision analysis of the $2\nu\beta\beta$ event distribution
   - Statistical analysis, half-life measurement, new-physics constraints, systematic effects

Double-beta decay

Two-neutrino double-beta decay



Neutrinoless double-beta decay



Why searching for neutrinoless double-β decay?

Huge literature production[1]

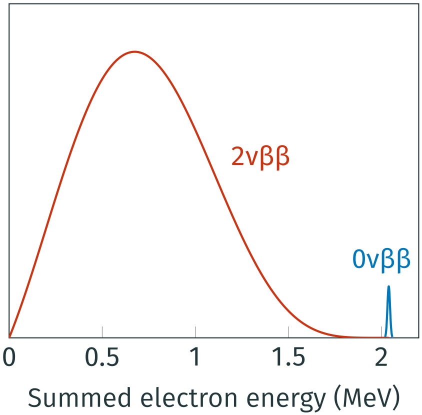
- $0\nu\beta\beta$ observation $\Rightarrow$ Majorana neutrino and Lepton symmetry violation
- Lepton number $\longleftrightarrow$ Barion number $\longmapsto$ new physics, baryogenesis?
- Access to fundamental parameters, shared or not with other physics searches
- standard interpretation: *the neutrino that mediates* $0\nu\beta\beta$ *is the one that oscillates and the Standard Model is an effective theory of some GUT* (seesaw mechanism)
  - Majorana effective mass: $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2 m^2_{\beta\beta} \longmapsto$ PMNS matrix and neutrino mass
- countless non-standard interpretations[2]

[1] 100+ papers per year with "$0\nu\beta\beta$" in the title [INSPIRE-HEP statistics]
[2] See e.g. *New J. Phys.* 17 (2015) 11, 115010

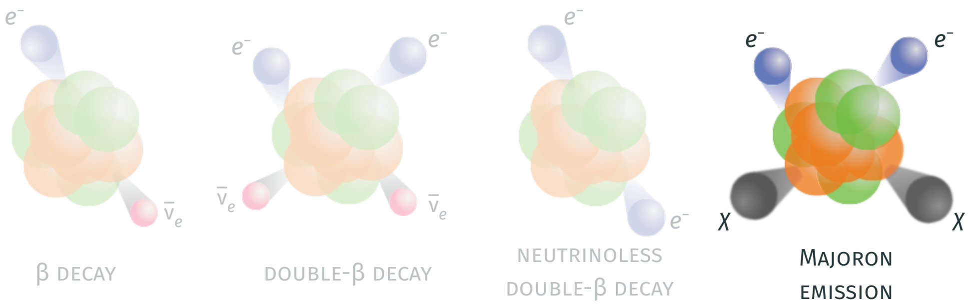
Neutrinoless double-beta decay

Most experiments measure the total energy of the two electrons emitted

$\longmapsto$ *necessary and sufficient* for discovery



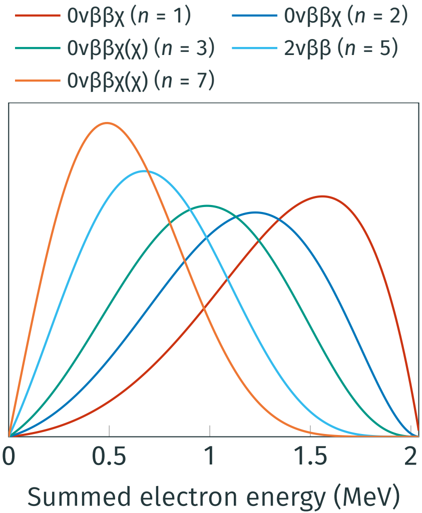
Double-beta decay and physics beyond the Standard Model



Neutrinoless double-beta decay with Majoron emission

- The Majoron (χ) is an hypothetical massless particle
- Many models for $0\nu\beta\beta$ with one or more emitted Majorons

$$G_{\alpha}^{0\nu\chi(\chi)} \sim (Q_{\beta\beta} - K)^{n}$$



The GERDA experiment

0νββ experimental searches

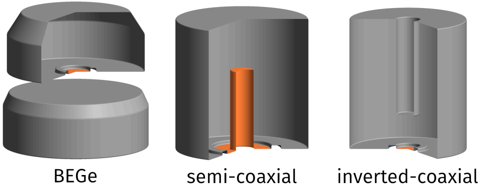
- **Bolometers** CUORE (^{130}Te), CUPID, AMoRE
- **Time projection chambers (^{136}Xe)** EXO, NEXT, PandaX
- **Scintillators** KamLAND-Zen (^{136}Xe), SNO+, CANDLES
- **Tracking calorimeters** NEMO, SuperNEMO

Semiconductors: Gerda, Majorana Demonstrator, LEGEND (^{76}Ge)

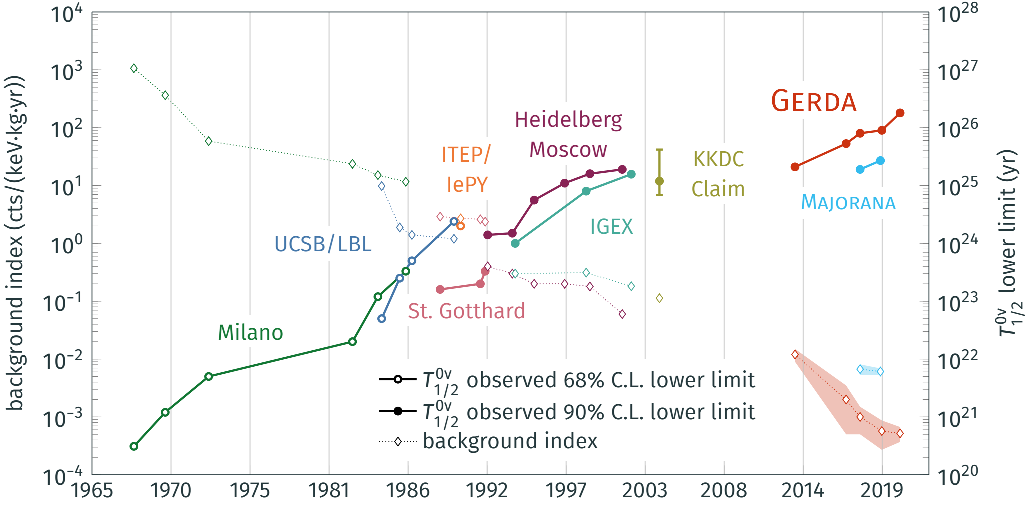
✓ ^{76}Ge-enriched detector technology maturity

✓ Excellent energy resolution

✗ Production cost, Low Q-value



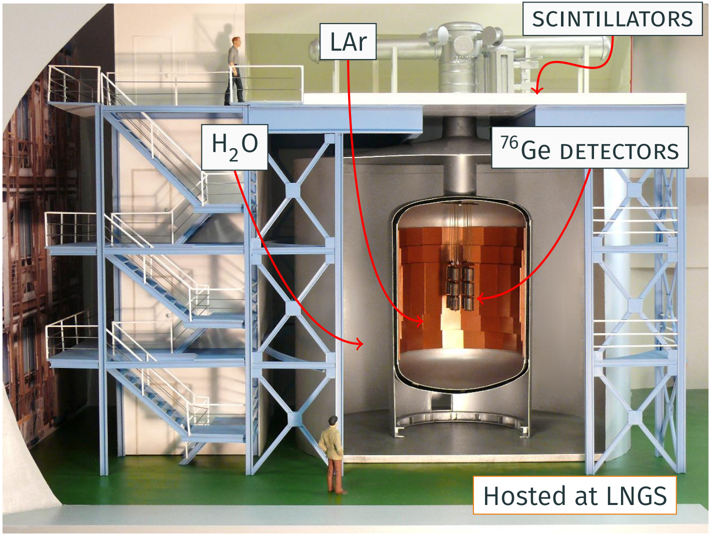
50 years of ^{76}Ge experimental $0\nu\beta\beta$ searches



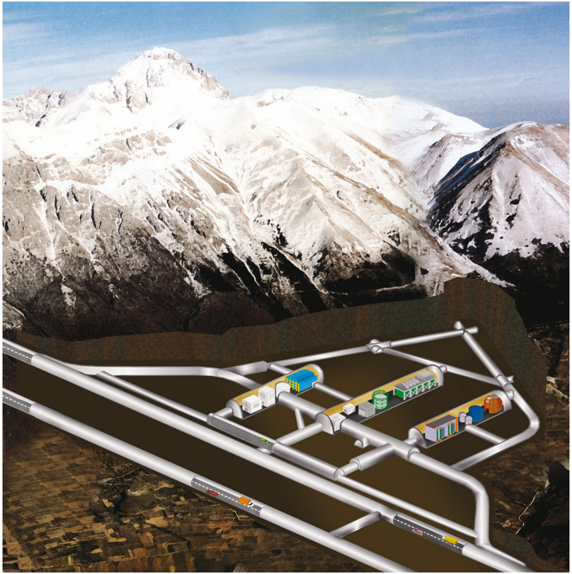
GERmanium Detector Array

Enriched, high-purity
^{76}Ge detectors
source = detector

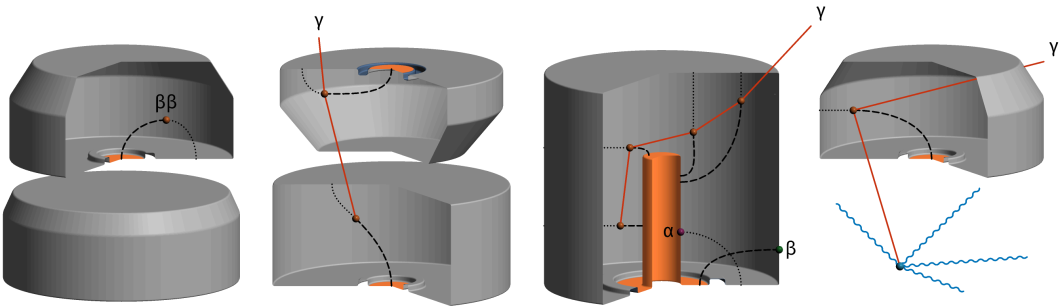
- Installed at LNGS (3500 m.w.e.), in activity since 2009 $\longmapsto$ Phase I
- Hardware upgrade 2015 $\longmapsto$ Phase II
- Decommissioned in 2020 $\longmapsto$ LEGEND-200



GERmanium Detector Array



Signal and background discrimination techniques



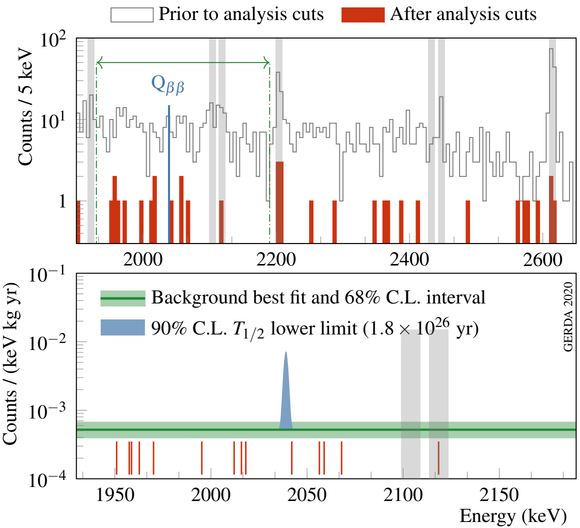
SIGNAL-LIKE | GRANULARITY CUT | PULSE-SHAPE DISCRIMINATION | LAr VETO

$0\nu\beta\beta$ detection efficiency between 45–65% depending on the detector type

Final results

Phys. Rev. Lett. 125, 252502 (2020)

- New, advanced statistical analysis
- $5.2^{+1.6}_{-1.3}\ 10^{-4}$ cts/(keV·kg·yr) at $Q_{\beta\beta}$
- No evidence for a signal with 127.2 kg·yr exposure
- $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr (90% C.L., frequentist)
- $\langle m_{\beta\beta} \rangle$ < 79–180 meV



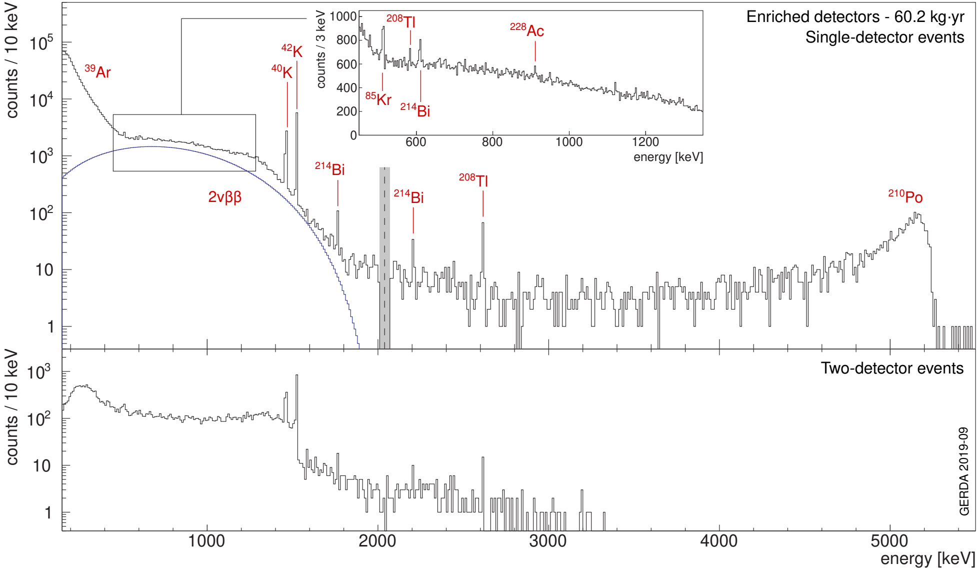
The background model before analysis cuts

Motivations

Can one claim the presence of a **signal** without having understood the **background**?

- Background composition at $Q_{\beta\beta}$
- Cross-check background intensity expectations
- Characterize location of background sources for future improvements
- Key to $2\nu\beta\beta$ characterization and beyond...

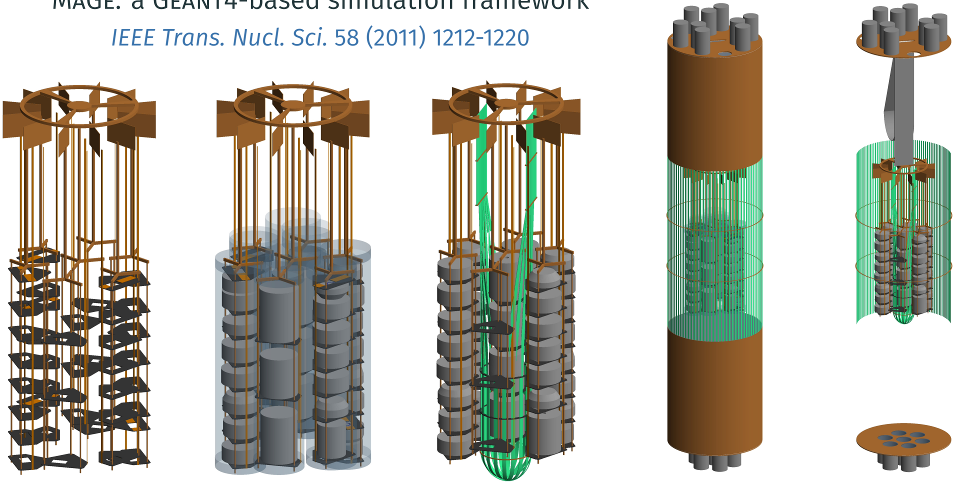
The data before cuts



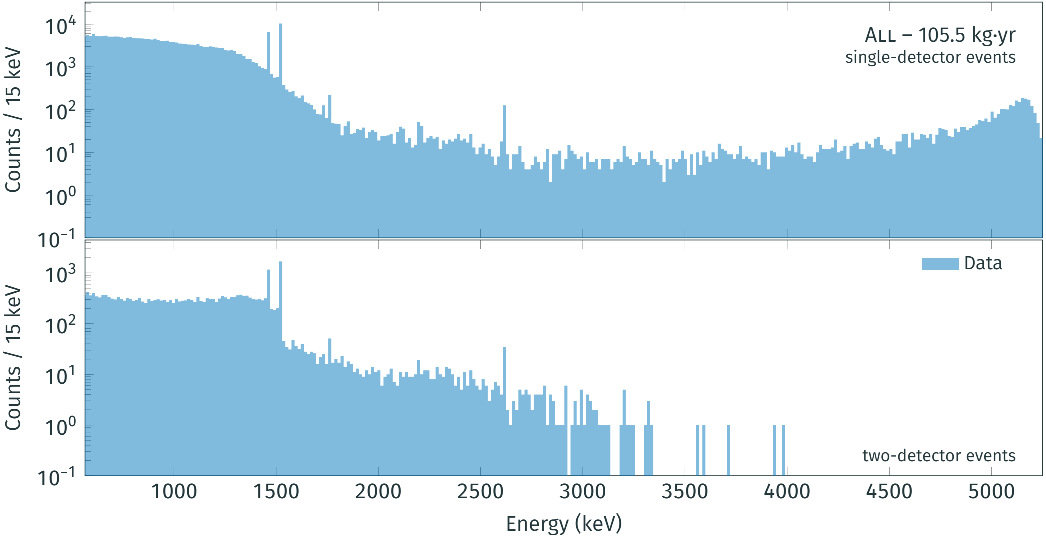
Background expectations: Monte Carlo simulation

MaGe: a Geant4-based simulation framework

IEEE Trans. Nucl. Sci. 58 (2011) 1212-1220



Analysis strategy



Analysis strategy

Bayesian analysis[3] with *binned-likelihood* and *priors* from material screening measurements

- **α-model** high-energy events (α) on the p^+ contact
- **K-model** potassium full-energy peak events divided by detector

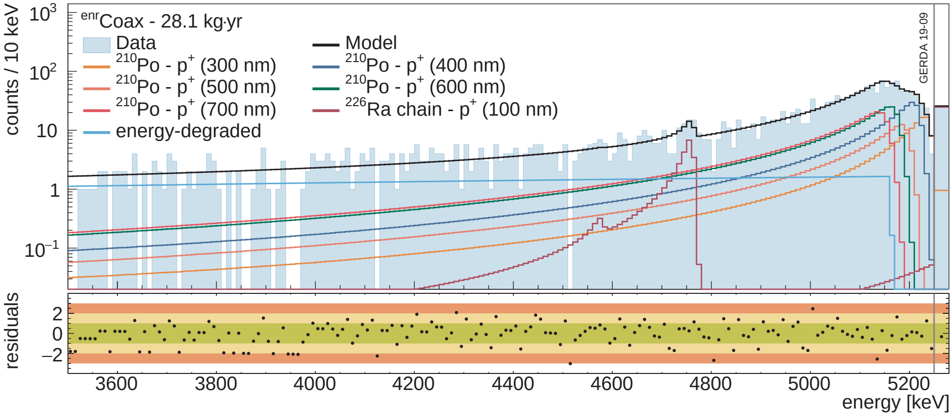
global-model final analysis on the full energy range, incorporates α-model and K-model

⟼ Open-source fitting framework: **GitHub**: gipert/gerda-fitter

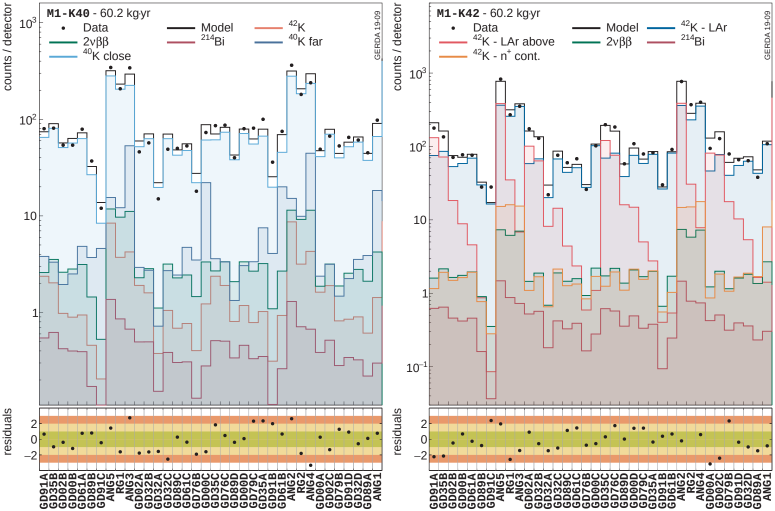
[3] With the Bayesian Analysis Toolkit (BAT): https://bat.mpp.mpg.de

α-model: coaxial detectors

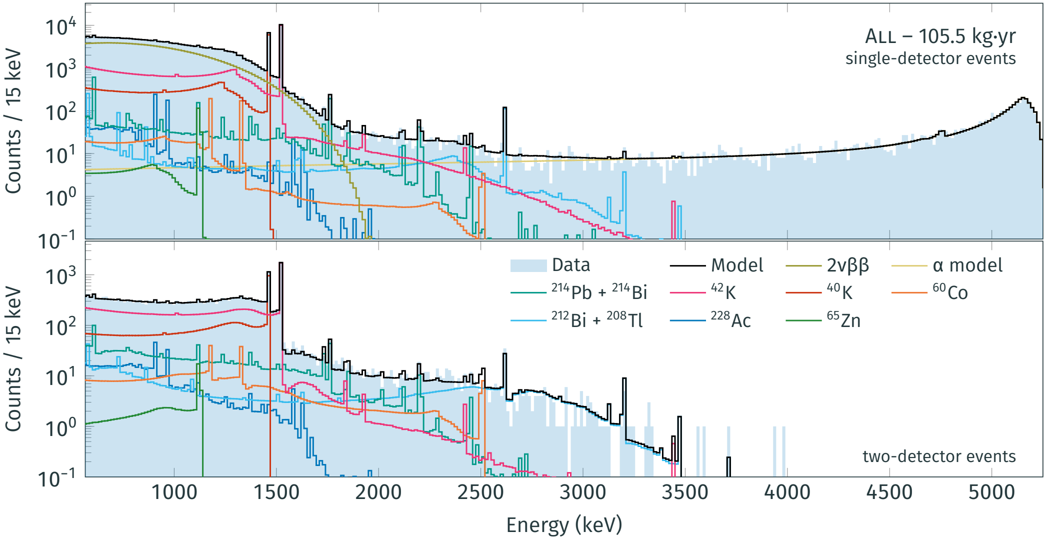
Combination of p⁺ thicknesses well describes the data



K-model: single-detector events

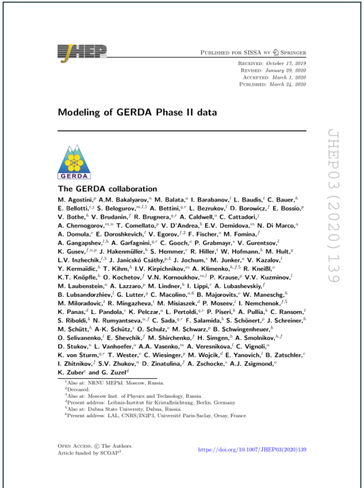


global-model: full Phase II dataset (105.5 kg·yr)



J. High Energ. Phys. 03 (2020) 139

- Excellent goodness-of-fit, we understand our background
- Screening measurements reproduced, except for ^{40}K
- Inhomogeneous ^{42}K distribution
- Indication of a biased BEGe active volume size



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Modeling of GERDA Phase II data

GERDA

The GERDA collaboration

M. Agostini,[p] A.M. Bakalyarov,[n] M. Balata,[a] I. Barabanov,[l] L. Baudis,[t] C. Bauer,[h] E. Bellotti,[i,j] S. Belogurov,[m,l,1] A. Bettini,[q,r] L. Bezrukov,[l] D. Borowicz,[f] E. Bossio,[p] V. Bothe,[h] V. Brudanin,[f] R. Brugnera,[q,r] A. Caldwell,[o] C. Cattadori,[j] A. Chernogorov,[m,n] T. Comellato,[p] V. D'Andrea,[b] E.V. Demidova,[m] N. Di Marco,[a] A. Domula,[e] E. Doroshkevich,[l] V. Egorov,[f,2] F. Fischer,[o] M. Fomina,[f] A. Gangapshev,[l,h] A. Garfagnini,[q,r] C. Gooch,[o] P. Grabmayr,[s] V. Gurentsov,[l] K. Gusev,[f,n,p] J. Hakenmüller,[h] S. Hemmer,[r] R. Hiller,[t] W. Hofmann,[h] M. Hult,[g] L.V. Inzhechik,[l,3] J. Janicskó Csáthy,[p,4] J. Jochum,[s] M. Junker,[a] V. Kazalov,[l] Y. Kermaïdic,[h] T. Kihm,[h] I.V. Kirpichnikov,[m] A. Klimenko,[h,f,5] R. Kneißl,[o] K.T. Knöpfle,[h] O. Kochetov,[f] V.N. Kornoukhov,[m,l] P. Krause,[p] V.V. Kuzminov,[l] M. Laubenstein,[a] A. Lazzaro,[p] M. Lindner,[h] I. Lippi,[r] A. Lubashevskiy,[f] B. Lubsandorzhiev,[l] G. Lutter,[g] C. Macolino,[a,6] B. Majorovits,[o] W. Maneschg,[h] M. Miloradovic,[t] R. Mingazheva,[t] M. Misiaszek,[d] P. Moseev,[l] I. Nemchenok,[f,5] K. Panas,[d] L. Pandola,[c] K. Pelczar,[a] L. Pertoldi,[q,r] P. Piseri,[k] A. Pullia,[k] C. Ransom,[t] S. Riboldi,[k] N. Rumyantseva,[n,f] C. Sada,[q,r] F. Salamida,[b] S. Schönert,[p] J. Schreiner,[h] M. Schütt,[h] A-K. Schütz,[s] O. Schulz,[o] M. Schwarz,[p] B. Schwingenheuer,[h] O. Selivanenko,[l] E. Shevchik,[f] M. Shirchenko,[f] H. Simgen,[h] A. Smolnikov,[h,f] D. Stukov,[n] L. Vanhoefer,[o] A.A. Vasenko,[m] A. Veresnikova,[l] C. Vignoli,[a] K. von Sturm,[q,r] T. Wester,[e] C. Wiesinger,[p] M. Wojcik,[d] E. Yanovich,[l] B. Zatschler,[e] I. Zhitnikov,[f] S.V. Zhukov,[n] D. Zinatulina,[f] A. Zschocke,[s] A.J. Zsigmond,[o] K. Zuber[e] and G. Zuzel[d]

[1] Also at: NRNU MEPhI, Moscow, Russia.
[2] Deceased.
[3] Also at: Moscow Inst. of Physics and Technology, Russia.
[4] Present address: Leibniz-Institut für Kristallzüchtung, Berlin, Germany.
[5] Also at: Dubna State University, Dubna, Russia.
[6] Present address: LAL, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

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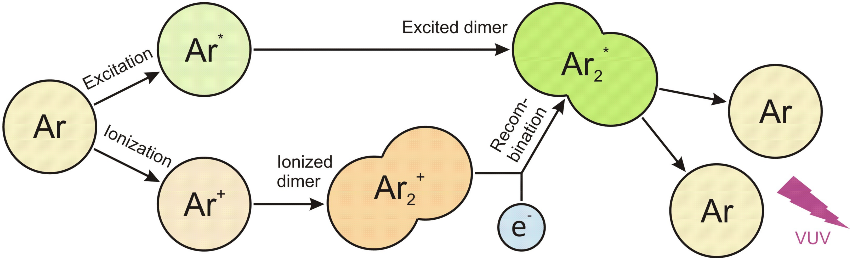
The background model after the LAr veto cut

The scintillation of liquid argon (LAr)

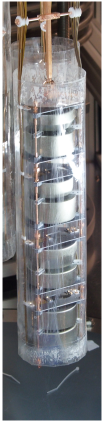
Liquid argon as a *cooling medium*, *passive shield* against backgrounds (Phase I) and active shield (Phase II).

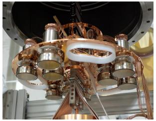


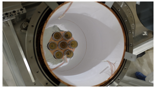
$\longmapsto$ light is produced at the passage of ionizing radiation, *detector medium*

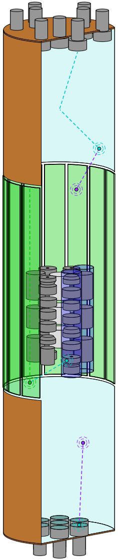
Collecting the LAr scintillation light

- 16 PMTs
- light-guiding fibers + SiPM readout
- nylon mini-shrouds for each string
  ⟼ mechanical barrier against ^{42}K ions









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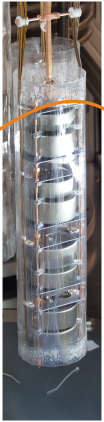

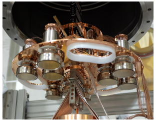

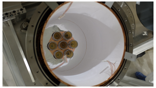

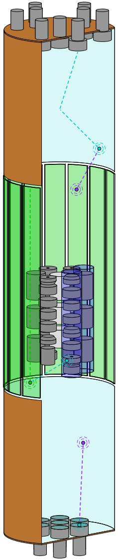

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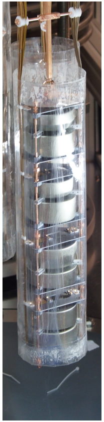
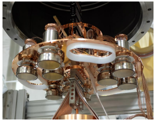
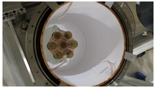
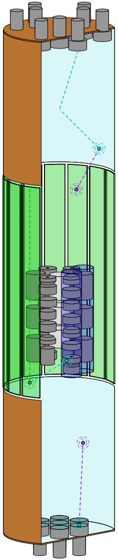






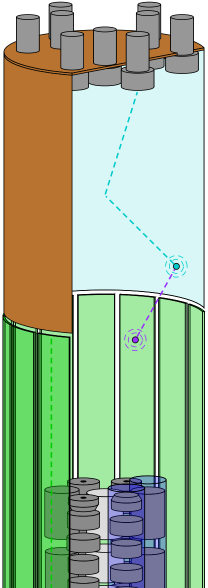


The data after the LAr veto cut

LAr veto cut definition

Ge events with coincident light detection in LAr are cut (No light is expected from ββ-decay events)

Removes a lot of background in the 2νββ energy region
⇒ higher sensitivity to (new) physics searches (exotic 2νββ decays, ββ-decays to excited states...)



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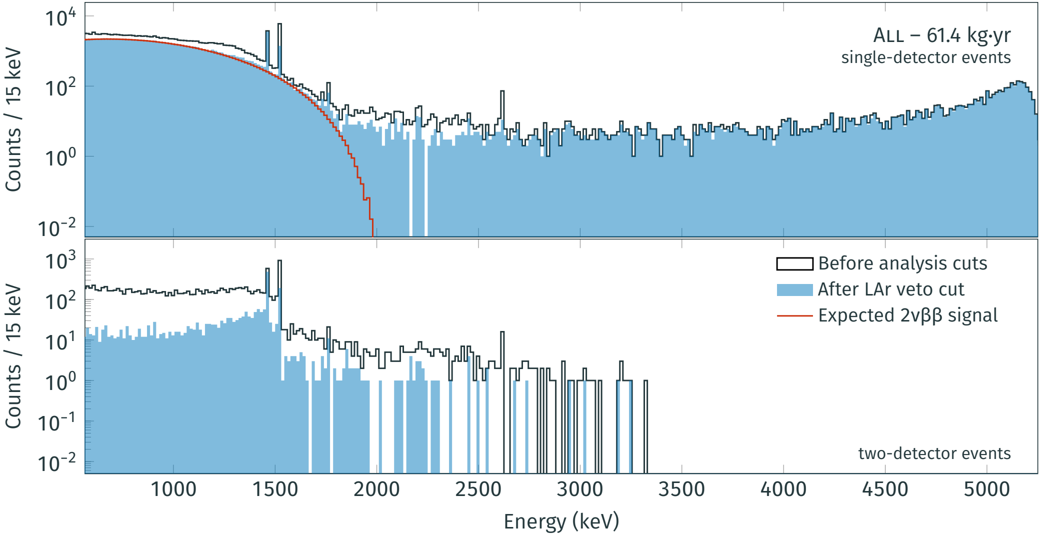

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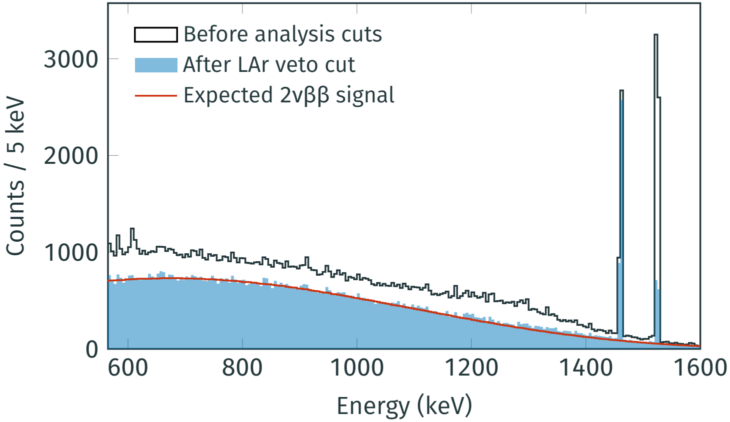
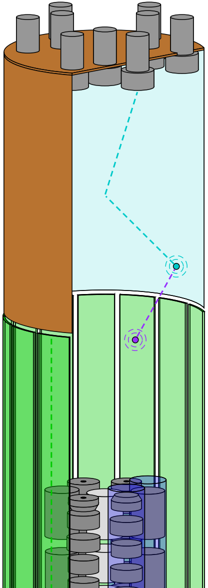




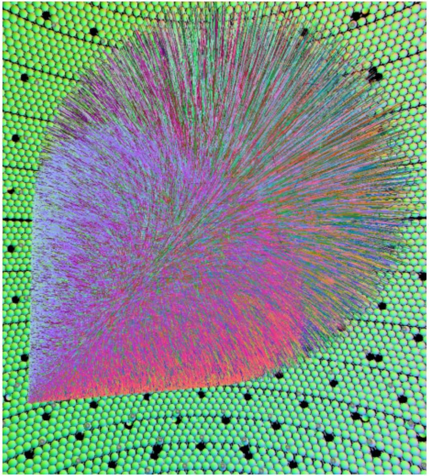
Simulating background sources

Once optical specifications are implemented, photon tracking can be enabled in GEANT4. Problem:

it's SLOW (on CPUs)

too many photons to track! Typical simulation rate of scintillation photons in the GERDA setup is 100 ph/s.

Can we be smart and pre-compute the information we really need?



Determining the LAr veto flag in MC: probability map approach

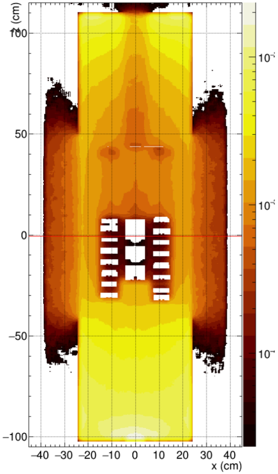
The LAr probability map: Track optical photons once and for all:

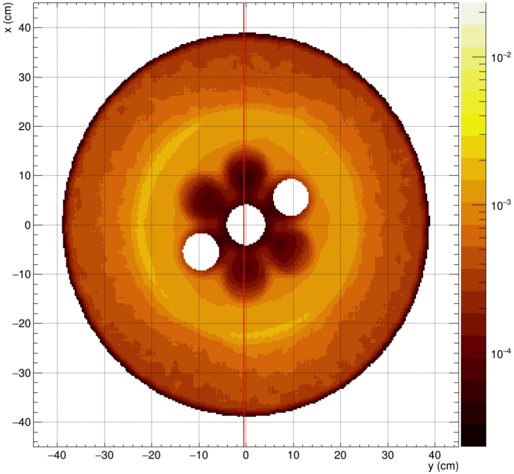
- Directly simulate 128 nm scintillation photons in LAr
- Partition the LAr volume in voxels (~ 3^3 mm^3)
- Calculate LAr veto detection probability for a photon in a voxel

Still…

- Computationally intensive, probabilities are generally very low
- Several thousands of CPU hours are needed to produce a map

Determining the LAr veto flag in MC: probability map approach

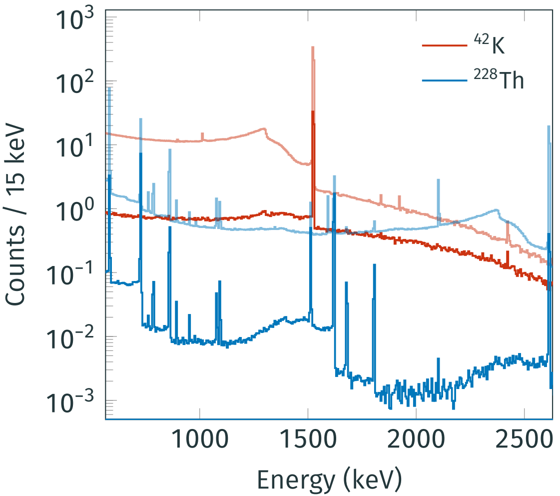




Determining the LAr veto flag in MC: probability map approach

From the probability map to the LAr veto flag:

- A Monte Carlo event deposits energy in LAr
- # of photons determined with nominal light yield (~28 ph/keV)
- Use the map to determine how many get detected (statistical)
- If detected ≥ 1 ⇒ vetoed



Pinning the unknowns with calibration data

The Monte Carlo parameters which are completely missing are the SiPMs and PMTs channel efficiencies ⟼ need to be extracted from real data[a]

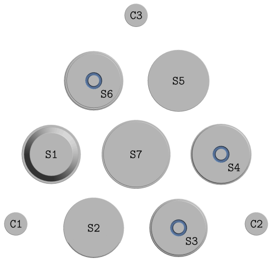
[a] Note: we are not able to say something precise about the other MC parameters (LAr attenuation length, fiber coverage etc.), and it's definitely easier to constrain them with independent measurements.

`run68` and `run76` are special calibration runs with LAr veto ON and weak $\mathcal{O}(1)$ kBq radioactive sources

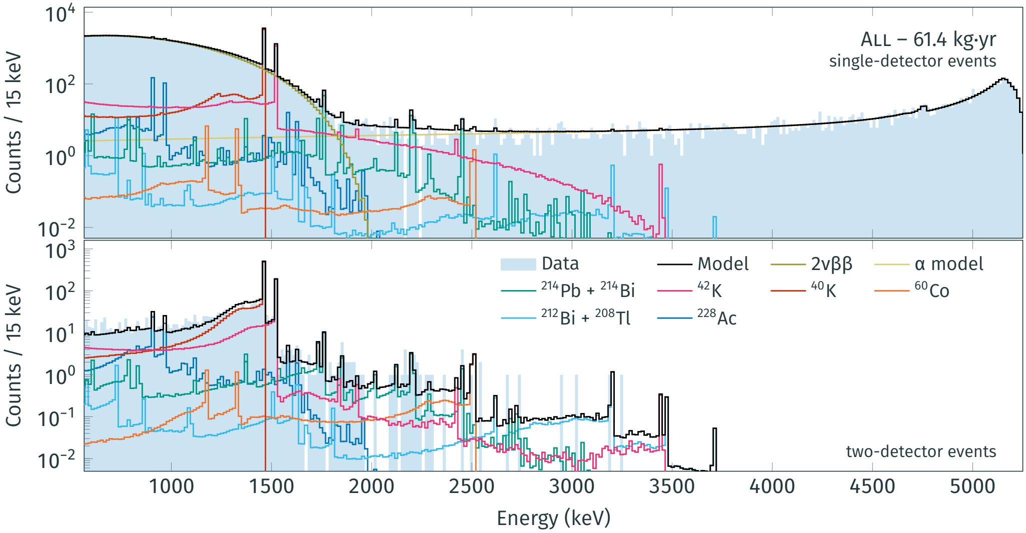
`run68` ^{228}Th source, in Jul 2016

`run76` ^{226}Ra source, in Feb 2017

⟼ Natural candidate LAr veto model tuning datasets



global-model — partial Phase II dataset (61.4 kg·yr)



Precision fit of $2\nu\beta\beta$ events: standard and new physics

Motivations

Motivations[4]

- **High-statistics** $2\nu\beta\beta$ **sample:** ~50 000 events in BEGE detectors[5]
- **Low background level:** signal-to-background ratio of ~20 (~2 before the cut)

Science goal

- Precision measurement of the Standard Model $2\nu\beta\beta$ **half-life**, check shape
- Constraints on **new-physics** models (Majorons, Lorentz violation...)

[4] Legacy of analogous analysis of GERDA Phase I data, see *Eur. Phys. J. C* 75, 416 (2015)
[5] Above the ^{39}Ar Q-value

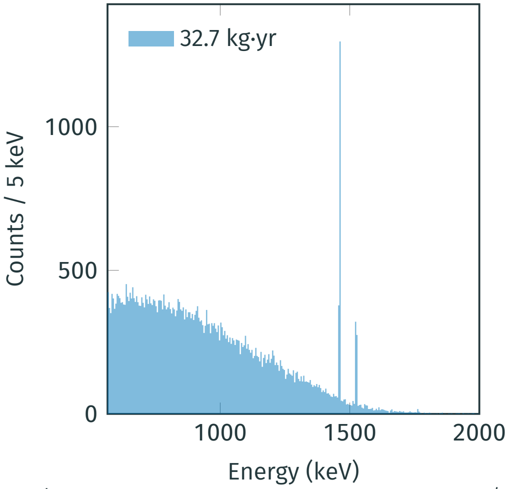
Analysis strategy

Dataset First 32.7 kg·yr from Phase II BEGe single-detector event data

Likelihood Usual binned-Poisson

$$L(S, \vec{B} | \vec{n}) = \prod_i^N \frac{\nu_i(S, \vec{B})^{n_i} e^{\nu_i(S,\vec{B})}}{n_i!}$$

Test statistic Standard $t_S = -2 \log \lambda(S)$ where $\lambda(S)$ is the profile likelihood ratio. Sampled with MC methods



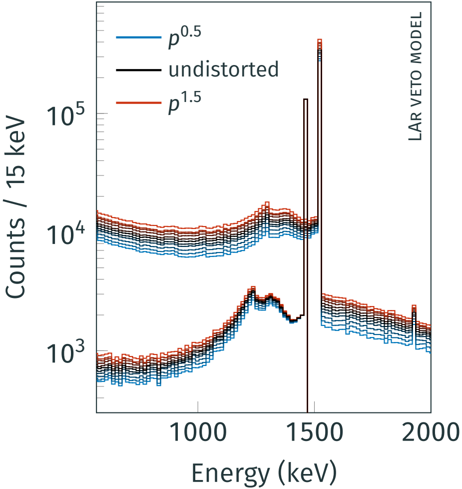
Inclusion of systematic uncertainties

Hybrid Bayesian-frequentist approach

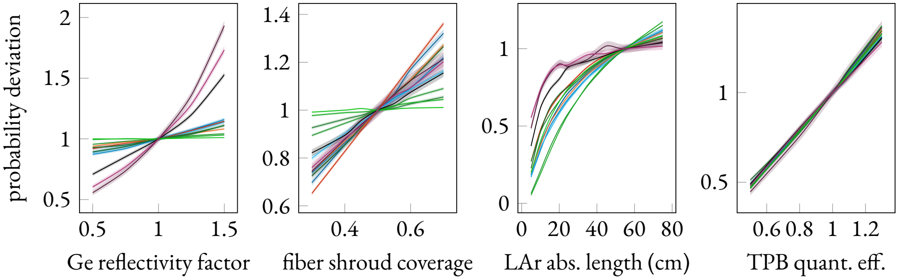
Sample toy data from systematically distorted models, according to "prior" distributions

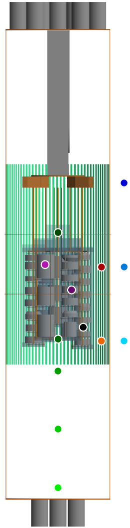
$$f(t_s) = \int f(t_s|S,\vec{B},\nu)\cdot\pi(\vec{\nu})\,d\vec{\nu}$$

- **Effect:** $f(t_S)$ smearing, weaker confidence intervals
- **GitHub:** gipert/gerda-factory



LAr veto model uncertainties

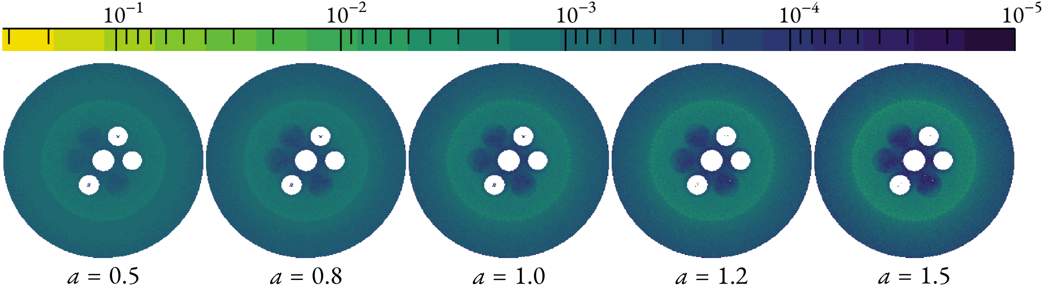




Simulations parameters have *local* and *global* effects $\longmapsto$ systematic uncertainty distorts the map

LAr veto model uncertainties

The map generation is computationally expensive ($\mathcal{O}(10^4)$ CPU hours), we can produce only one from scratch $\longmapsto$ what about *artificial*, power-law[6] distortions?



[6] $p_k \rightarrow c \cdot p_k^a$ where p is the detection probability and a is the distorting parameter

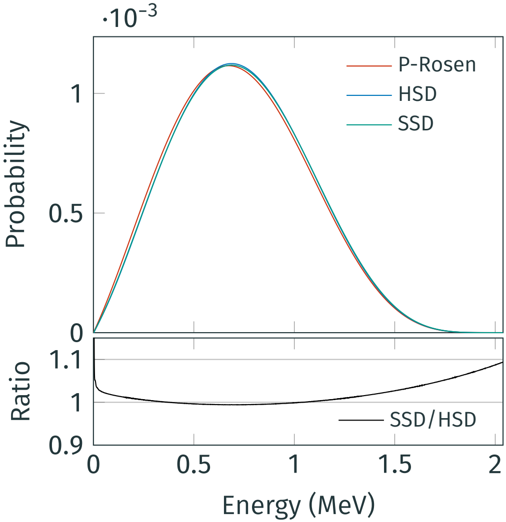
2νββ theoretical shape uncertainties

Assumption on configuration of intermediate ββ-decay nucleus

- *Higher-state* dominance (HSD)
- *Single-state* dominance (SSD)

Discrimination sensitivity is low[a]
⇒ include in sytematics budget

[a] In contrast to e.g. ^{82}Se (CUPID-0), see *Phys. Rev. Lett.* 123, 262501



Other systematic uncertainties

- **Active ^{76}Ge mass:** HPGe active volume and Ge enrichment fraction
- **Background model:** Location (far/close to the array) of sources
- **Transition layer model:** Charge collection efficiency in the dead region
- **Simulation uncertainties:** MaGe geometry and Geant4 tracking

Source	$T^{2\nu}_{1/2}$ contribution
Background model	0.42%
Transition layer model	<0.01%
LAr veto model	0.26%
2νββ model	<0.01%
Sub-total fit model	0.53%
Active volume	1.37%
Enrichment fraction	0.3%
Total	1.6%

Results: $2\nu\beta\beta$ half-life

$$S^{2\nu} = 46427 \pm 250_{\mathrm{stat}} \pm 350_{\mathrm{sys}}\ \mathrm{cts}$$

$$T^{2\nu}_{1/2} = (2.043 \pm 0.011_{\mathrm{stat}} \pm 0.033_{\mathrm{sys}}) \cdot 10^{21}\ \mathrm{yr}$$

- Remarkably reduced uncertainty[7]
- The most precise (1.6%) half-life measurement ever found in literature[8]

[7] See Eur. Phys. J. C 75, 416 (2015)

[8] Competing with CUPID-Mo (2.9%), CUPID-0 (2.2%), CUORE (2.8%), EXO-200 (2.8%) and KamLAND-Zen (3.4%)

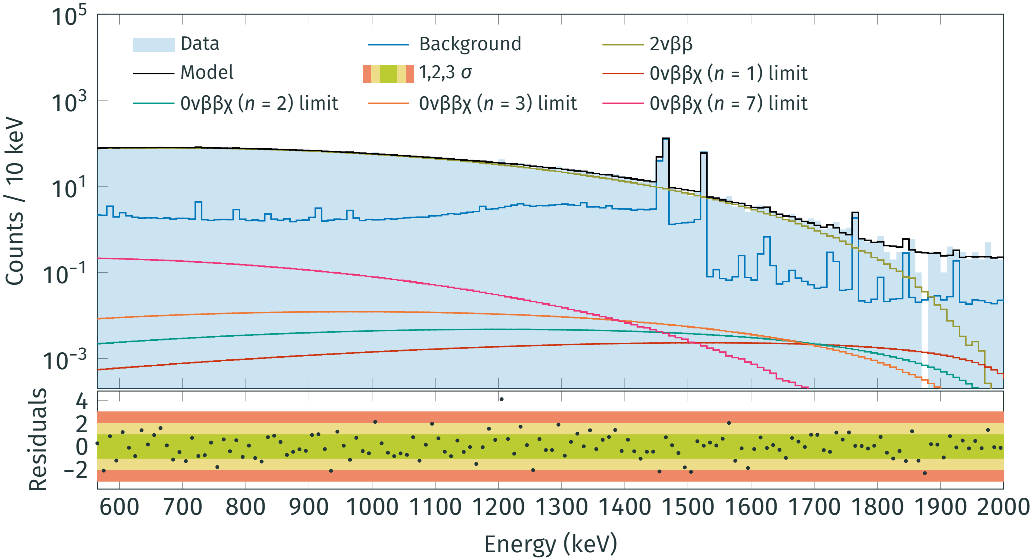
Results: Majoron-emitting $0\nu\beta\beta$

Model	Mode	n	90% C.L. limits: Counts	$T_{1/2}$ (10^{23} yr)	g_α
IB, IC, IIB	$0\nu\beta\beta\chi$	1	197	6.3	$(1.9–4.3) \cdot 10^{-5}$
IF (bulk)	$0\nu\beta\beta\chi$	2	405	2.9	–
ID, IE, IID	$0\nu\beta\beta\chi\chi$	3	917	1.3	0.95
IIC, IIF	$0\nu\beta\beta\chi$	3	917	1.2	$1.3 \cdot 10^{-2}$
IIE	$0\nu\beta\beta\chi\chi$	7	705	1.0	0.87

- Dominated by statistical uncertainty, a factor ~2 better than previous results[9]
- Comparable to ^{136}Xe constraints, a factor ~10 better for $n = 7$
- New ^{76}Ge NMEs and phase-space factors from J. Kotila and F. Iachello

[9] Compared to Phase I analysis Eur. Phys. J. C 75, 416 (2015)

Results: Majoron-emitting $0\nu\beta\beta$



Known issues and work in progress

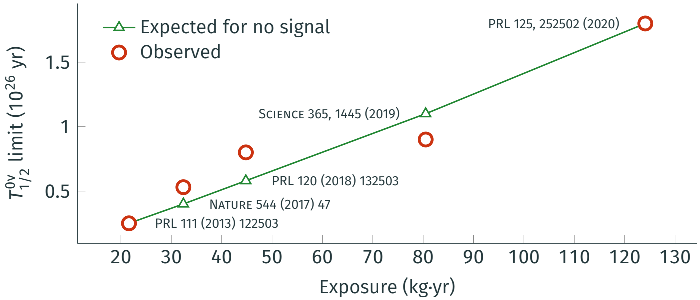
- Constrain more physics models (Lorentz violation, sterile neutrinos...)
- Evidence of systematic bias in the BEGe active volume size
  $\longmapsto$ re-estimation with ^{39}Ar data and detector re-characterization in progress
- Out soon: $2\nu\beta\beta$ analysis publication(s) + supporting LAr veto modeling publication

Closing out

The future of 0νββ with ^{76}Ge

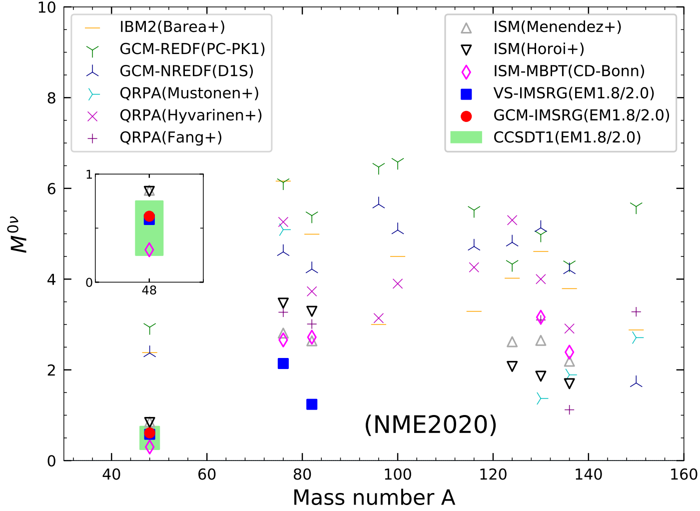
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Backup

Nuclear matrix elements for 0νββ



Best $0\nu\beta\beta$ limits

Experiment	Isotope	Exposure (kg·yr)	$T^{0\nu}_{1/2}$ (10^{25} yr)	$\langle m_{\beta\beta} \rangle$ (meV)
GERDA	^{76}Ge	127.2	18	79–182
MAJORANA		26	2.7	200–430
CUORICINO	^{130}Te	19.8	0.28	300–710
CUORE-0		9.8	0.24	270–760
CUORE		372.5	3.2	75–350
EXO-200	^{136}Xe	234.1	3.5	93–286
KAMLAND-ZEN		504	10.7	61–165

Best $2\nu\beta\beta$ half-life measurements

Experiment	Isotope	Exposure (kg·yr)	$T^{2\nu}_{1/2}$ (yr)
GERDA	^{76}Ge	17.9	$(1.926\,^{+0.025}_{-0.022}{}_{\text{stat}} \pm 0.092_{\text{sys}}) \cdot 10^{21}$
CUPID-Mo	^{100}Mo	0.12	$(7.12\,^{+0.18}_{-0.14}{}_{\text{stat}} \pm 0.10_{\text{sys}}) \cdot 10^{18}$
CUPID-0	^{82}Se	9.95	$(8.60 \pm 0.03_{\text{stat}}\,^{+0.19}_{-0.13}{}_{\text{sys}}) \cdot 10^{19}$
CUORE	^{130}Te	86.34	$(7.9 \pm 0.1_{\text{stat}} \pm 0.2_{\text{sys}}) \cdot 10^{20}$
KAMLAND-ZEN	^{136}Xe	504	$(2.23 \pm 0.03_{\text{stat}} \pm 0.07_{\text{sys}}) \cdot 10^{21}$
EXO-200		23.14	$(2.165 \pm 0.016_{\text{stat}} \pm 0.059_{\text{sys}}) \cdot 10^{21}$

Best Majoron-emitting 0νββ limits

			$T_{1/2}^{0\nu\chi(\chi)}$ (10^{21} yr)				$g_\alpha / 10^{-5}$
Experiment	Isotope	Exposure (kg·yr)	$n = 1$	$n = 2$	$n = 3$	$n = 7$	$n = 1$
GERDA	^{76}Ge	20.3	420	180	80	30	2.3–5.1
EXO-200	^{136}Xe	100	1200	250	27	6.1	0.6–1.8
KAMLAND-ZEN	^{136}Xe	36.8	2600	1000	250	11	0.4–1.2
NEMO-3	^{100}Mo	34.3	44	9.9	4.4	1.2	1.8–3.1
NEMO-3	^{82}Se	4.9	37	–	–	–	3.1–6.4
NEMO-3	^{116}Cd	2.16	8.5	–	–	–	5.3–9.1
NEMO-3	^{48}Ca	0.037	4.6	–	–	–	7.9–40
NEMO-3	^{150}Nd	0.19	30	–	–	–	1.2–2.9
NEMO-3	^{130}Te	2.31	16	–	–	–	4.2–17
NEMO-3	^{96}Zr	0.031	1.9	0.99	0.58	0.11	7.2–16

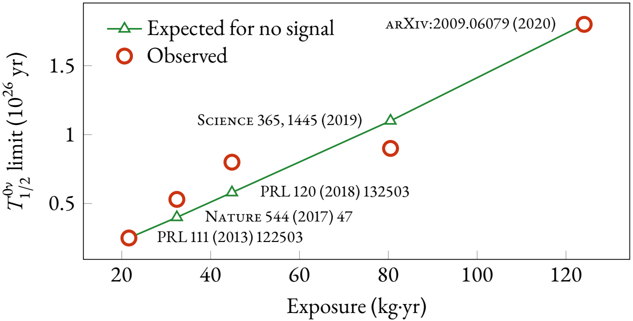
GERDA Phase II was *background-free*

Background-free

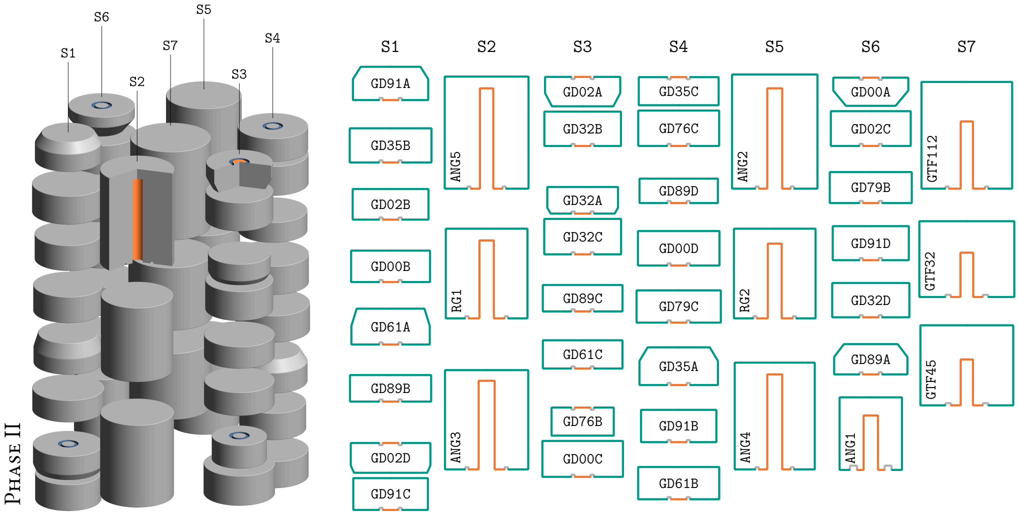
$$M \cdot T \cdot B \cdot \Delta E < 1$$

Sensitivity

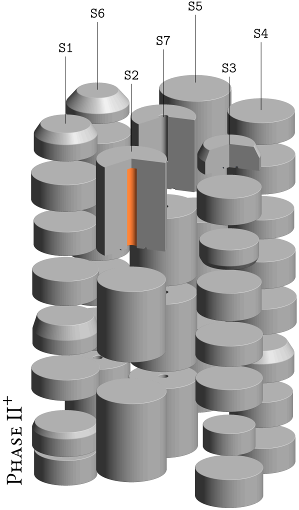
$$T^{0\nu}_{1/2} = \begin{cases} aM\epsilon t & \text{background-free} \\ a\epsilon\sqrt{\dfrac{Mt}{B\Delta E}} & \text{with background} \end{cases}$$

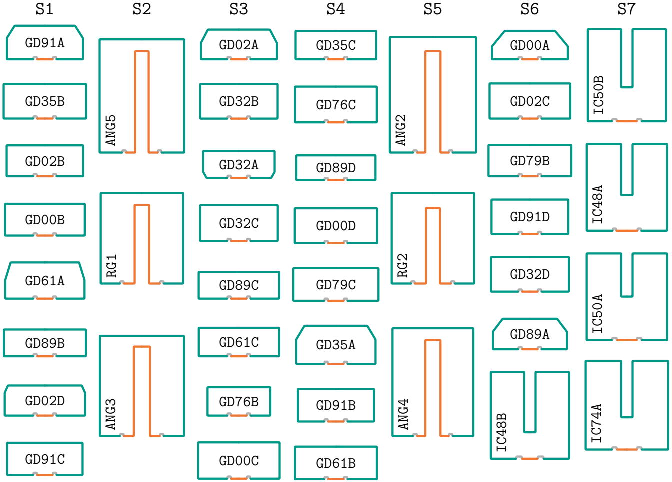


Detector array configuration (Phase II)

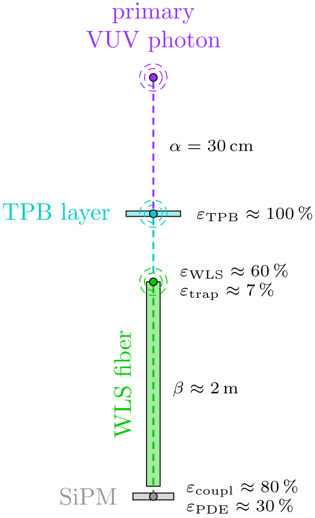


Detector array configuration (Phase II$^+$)





A day in the life of a photon in GERDA



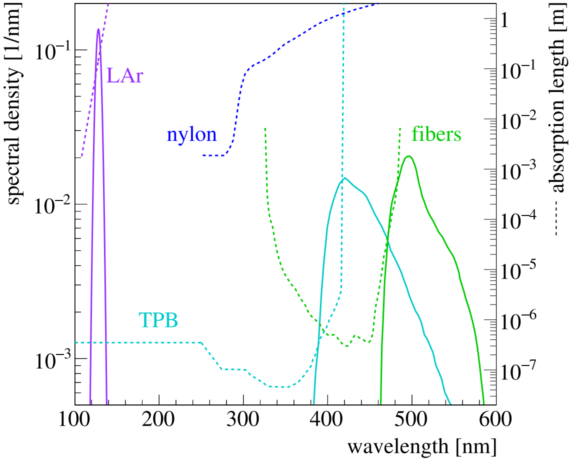
- Primary 128 nm photon emission ($\mathcal{O}(10)$ per keV)
  - Reflected
  - Shifted to blue by TPB coating
  - Absorbed
- Detected by PMTs or...
- ...trapped (and shifted to green) in fibers
- Detected by SiPMs

Implementing optical processes and specifications

To-Do list:

- LAr scintillation physics and optical properties
- TPB wavelength-shifting properties
- Fibers optical properties
- Reflectivity of structural materials (Ge, Si, Cu...)

GEANT4 libraries allow to specify all this.
But do we know all this...?



Implementing optical processes and specifications

Liquid argon

- Scintillation spectrum arXiv:1511.07718
- Scintillation yield: sample dependent
- Attenuation length: sample dependent
- Refraction index and Rayleigh length

Ge, Si, Cu, [...] Reflectivity

- Poorly known at cryogenic temperatures
- Can depend on sample

TPB absorption & emission

- Poorly known at cryogenic temperatures
- Depend on deposition method and partly on thickness

Recent effort to characterize TPB surfaces

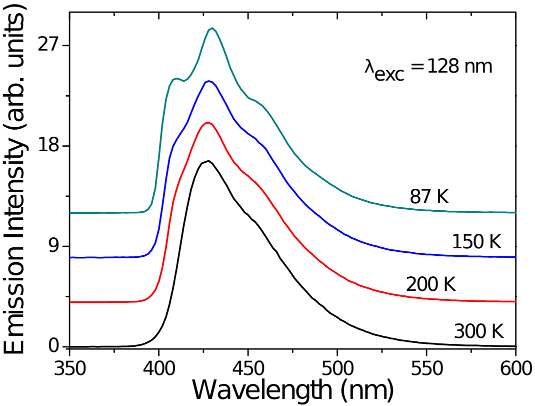
arXiv:1304.6117

Take home message

Materials must be characterized before deployment at the (cryogenic) experimental conditions

Optical specifications: TPB emission

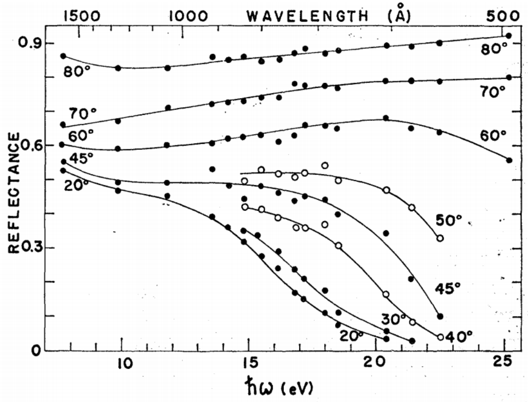
arXiv:1304.6117



Vibronic structures (TPB molecules) show up at low temperatures in the TPB emission spectrum

Optical specifications: germanium reflectivity

10.1103/PhysRev.160.602

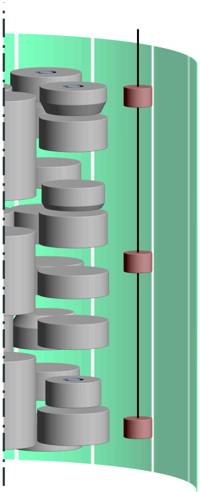


Very old measurement of (evaporated) germanium reflectivity at 128 nm

Strong dependence on incident angle (no possibility to code this in GEANT4!)

Pinning the unknowns with calibration data

isotope	source port	position (mm)	run time (h)	random coincidences (%)
^{228}Th	C2	8168	10.2	–
		8396	3.2	–
		8570	12.5	–
	C3	8220	6.4	7.5 ± 0.6
		8405	4.3	7.2 ± 1.0
		8570	3.6	10.2 ± 1.4
^{226}Ra	C2	8139	8.9	12.2 ± 0.3
		8405	4.3	11.2 ± 0.4
		8570	6.9	12.9 ± 0.3
	C3	8128	8.0	10.8 ± 0.3
		8292	3.6	8.9 ± 0.4
		8570	8.5	10.7 ± 0.3



The statistical analysis

Data

A set of veto flags (one for each of the (7 + 9) PMTs + 9 SiPM mod. = 25 LAr veto channels) for each germanium trigger. Each event defined a detection pattern

Expectations

The calibration setup is simulated with full optical photon tracking. Monte Carlo parameters fixed to best values (attenuation length = 55 cm, fiber coverage = 0.5...). Channel efficiencies set to 1

Expectations are matched to data in a likelihood function that includes 'effective' single-channel efficiencies $\vec{\epsilon}$

The statistical analysis: background

Random coincidences

False-positive, LAr-vetoed events in which the physical process generating the coincident light is distinct from the one that triggers the germanium detectors.

e.g.

- Two nuclei decaying at the same time: one of them triggers the germanium and the other one produces coincident light.

Note: The probability that a LAr veto channel is triggered in data is the logic OR between the signal and background (*random coincidences* not available in MC) probability.

$$\lambda[n] = \lambda_s[n] * \lambda_b[n] = \lambda_s \vee \lambda_b \ .$$

The statistical analysis

The likelihood

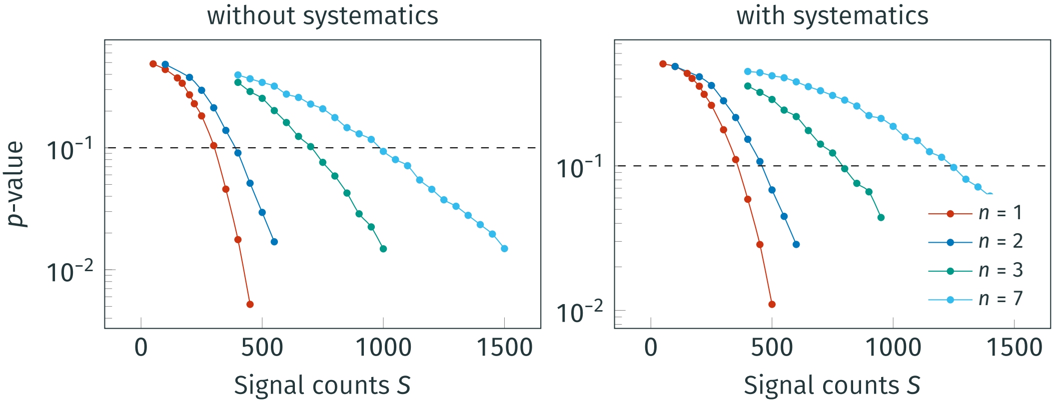
$$L(\vec{\epsilon}, \ldots) = \prod_P B^{N}_{N_{\text{tot}}}\left(\sum_G \left[\lambda_s(\vec{\epsilon}) + \sigma \cdot \Delta\lambda_s(\vec{\epsilon})\right] \cdot \lambda_b\right) \cdot \prod_G B^{M}_{M_{\text{tot}}}(\lambda_b) \cdot G(\sigma)$$

- each single pattern considered $\dim[P] = 2^{N_{\text{ch}}} = 2^{25}$
- pattern generator pairs $G = \{\{A, B\}, \{B, C\}, \ldots\}$
- N = # of events in which light was seen over the total N_{tot}
- additional $\sigma\Delta\lambda_s(\vec{\epsilon})$ accounts for the low statistics in the MC sample. Regulated by the σ with Gauss pull term $G(\sigma)$
- maximize w.r.t. channel efficiencies $\vec{\epsilon}$

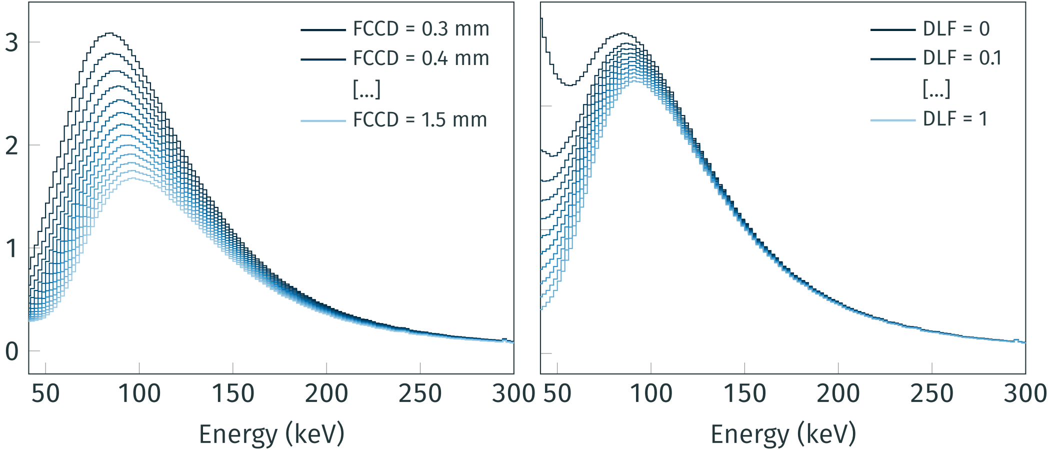
Sensitivity to Majoron-emitting $0\nu\beta\beta$ decays

Decay Mode	Spectral index n	Sensitivity: Statistical Counts	Statistical $T_{1/2}$ (10^{23} yr)	With systematics Counts	With systematics $T_{1/2}$ (10^{23} yr)
$0\nu\beta\beta\chi$	1	302	4.5	358	3.5
$0\nu\beta\beta\chi$	2	386	3.3	456	2.5
$0\nu\beta\beta\chi(\chi)$	3	698	1.7	792	1.3
$0\nu\beta\beta\chi\chi$	7	984	0.71	1200	0.58

Median p-values for the null-hypothesis (Majoron models)



^{39}Ar energy spectrum and HPGe active volume model



^{39}Ar example optimization