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Spectral analysis for the MAJORANA DEMONSTRATOR experiment

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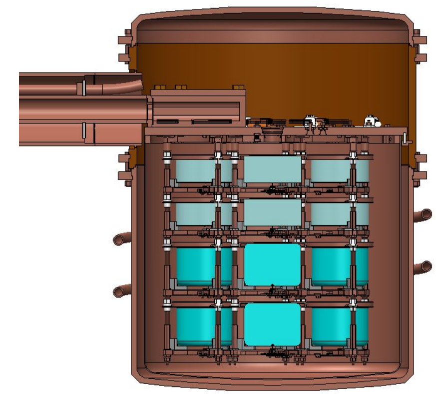
The MAJORANA DEMONSTRATOR

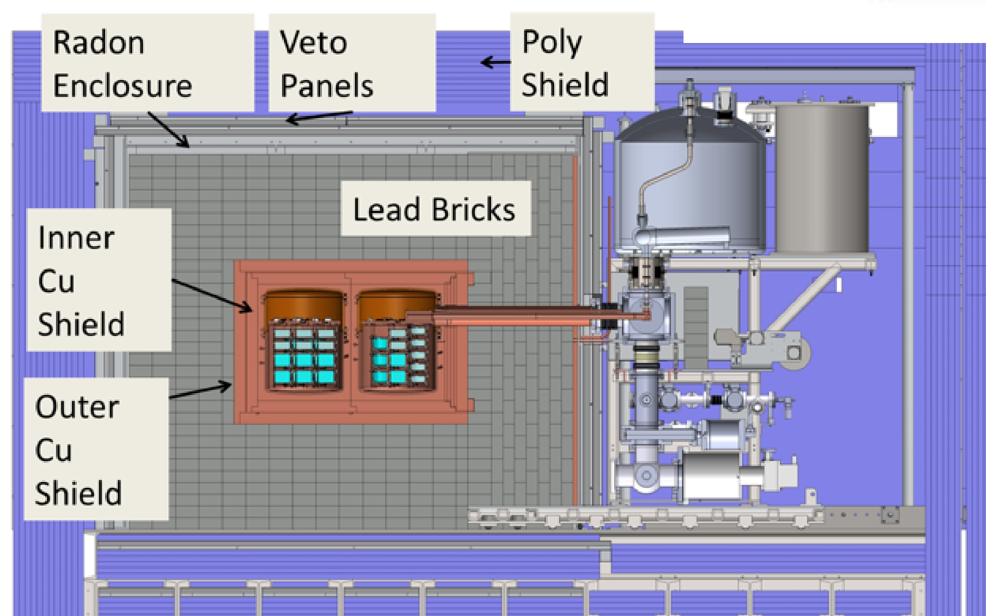
Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics
with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

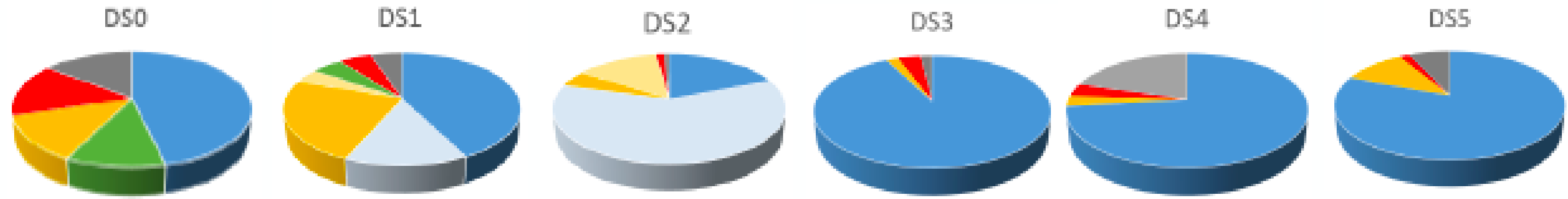


- Operating underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5

- 44.1-kg of Ge detectors
  - 29.7 kg of 87% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



MAJORANA data sets



M1 Commissioning, no inner shield	*M1 inner shield*	*M1 Multi-sampling*	*Modules 1 and 2 Together in-shield*	*Module 1 & 2 Integrated DAQ*

		DS0 (days) Module 1 June 26, – Oct. 7, 2015	DS1 (days) Module 1 Dec. 31, 2015 – May 24, 2016	DS2 (days) Module 1 May 24 – July 14, 2016	DS3 (days) Module 1 Aug. 25, – Sept. 27, 2016	DS4 (days) Module 2 Aug. 25, – Sept. 27, 2016	DS5 (days) Module 1 & 2 Oct. 13, 2016 – May 11, 2017*
Total		103.15	144.50	50.97	32.37	32.36	147.68
Total acquired		87.93	136.98	50.47	31.73	25.80	137.42
Physics	*	47.70	61.34 + 20.41*	9.82 + 30.56*	29.91	23.69	119.38
High radon		11.76	7.32	-	-	-	-
Disruptive Activities	*	13.10	34.43+ 5.92*	2.41 + 7.03*	0.63	0.93	15.68
Calibration		15.44	7.32	0.65	1.18	1.17	2.36
Down time		15.21	7.51	0.50	0.64	6.56	10.25

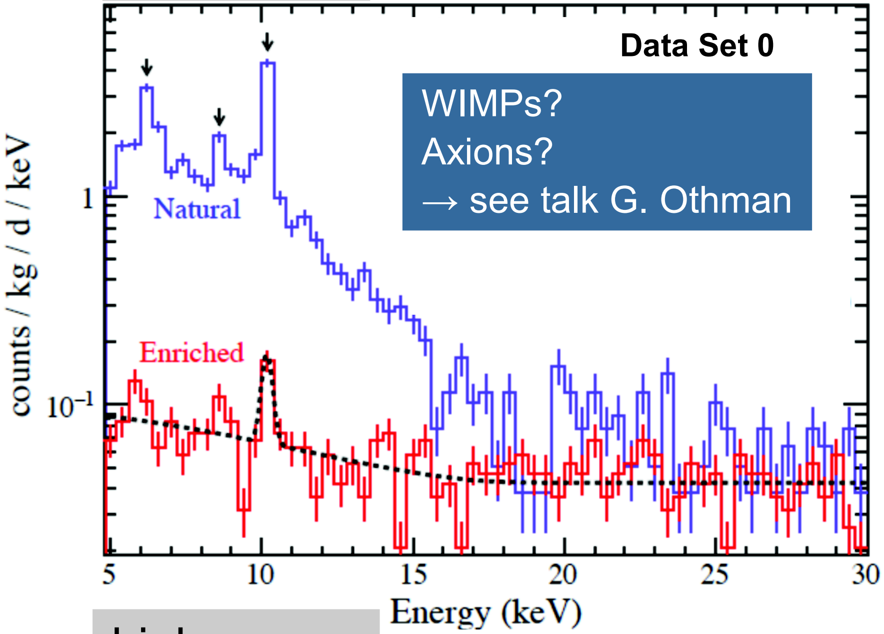
*Values thru 03/10/17

Currently taking blind data in DS6 with multi-sampling

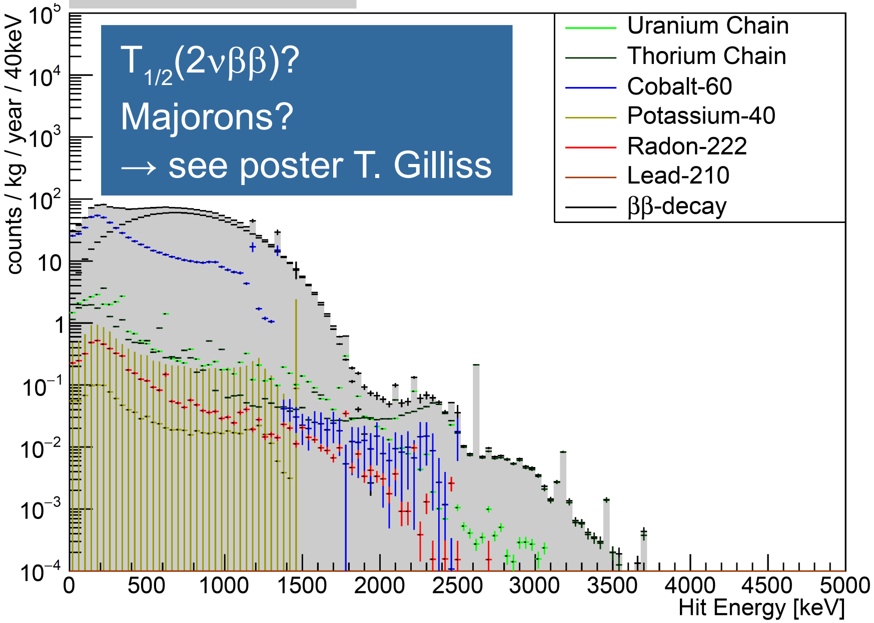
Physics searches with (enriched) Ge-detectors

low energy

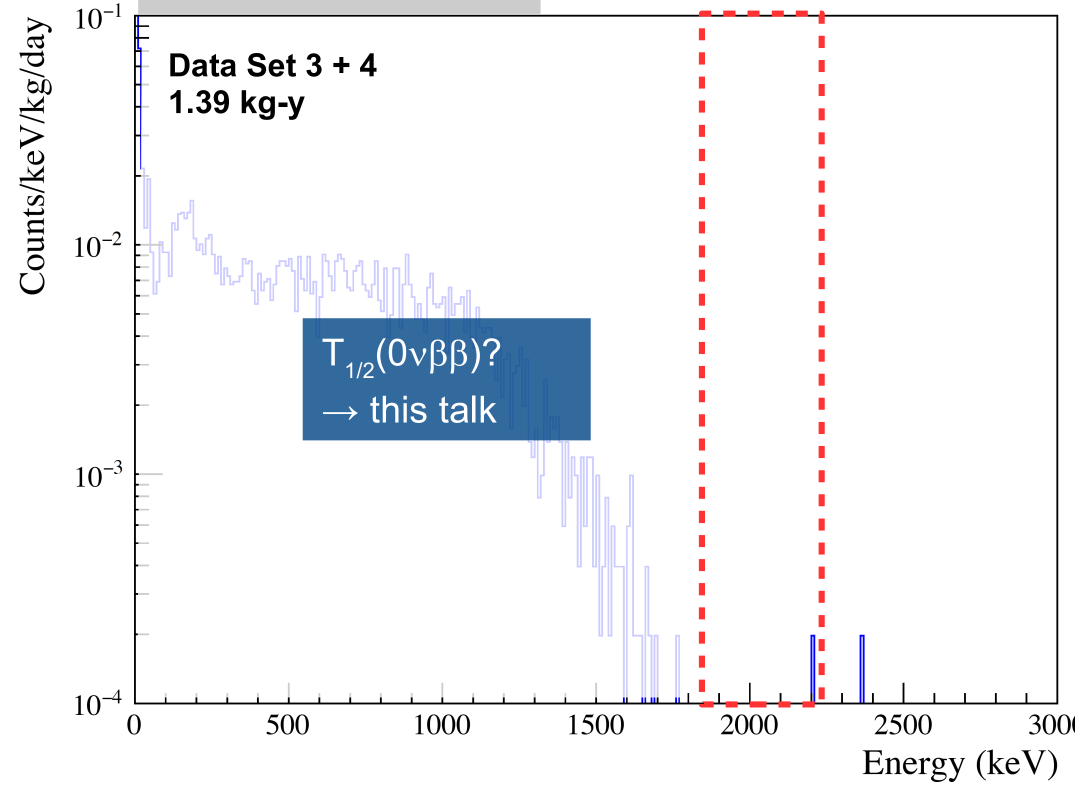
PRL 118, 2016



high energy



around 2039 keV



after *Delayed Charge Recovery* α-cut:

1 event in 400 keV window

→ BI = $1.8 \cdot 10^{-3}$ cnts / (keV·kg·y)

Statistical methods for $0\nu\beta\beta$-search

variety of statistical methods used to search for a signal:

Frequentist

- ***Feldman-Cousins*** *MJD, Neutrino 2016*

  eliminates flip-flop problem (exclusion vs. discovery)

  possible significant over-coverage

- ***profile likelihood***

  systematic uncertainties & constraints taken into account

  simultaneous treatment of multiple datasets

  large-sample case: Wilks' theorem *EXO200, Nature 2014*

  small sample case (~10 events): Monte Carlo toy data *GERDA, Nature 2017*

  also as modified ("*CLs*") method against down-fluctuations of background *NEMO-3, PRD 2016*

Bayesian

different definition of probability *CUORE0, PRL 2015*

needs prior for unknown parameters

Minimal signal + background likelihood model

- likelihood function for each dataset (based on **_GERDA, Nature 2017_**)

$$\mathcal{L}(\mathcal{D}|\mathcal{S},\mathrm{BI},\theta) = \prod_{n=1}^{N^{\mathrm{obs}}} \frac{1}{\mu^S+\mu^B} \cdot \Bigg[\underbrace{\mu^S \cdot \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-(E_n - Q_{\beta\beta} - \delta)^2}{2\sigma^2}\right)}_{\text{Gaussian signal}} + \underbrace{\mu^B \cdot \frac{1}{\Delta E}}_{\text{flat background}}\Bigg]$$

signal rate: $\mu^S = \ln 2 \cdot (N_A/m_a) \cdot \epsilon \cdot \mathcal{E} \cdot \mathcal{S}$ where $\mathcal{S} = \left(T_{1/2}\right)^{-1}$

bkg-rate: $\mu^B = \mathcal{E} \cdot \mathrm{BI} \cdot \Delta E$

constrained nuisance parameter: $\theta = \{\epsilon, \sigma, \delta\}$

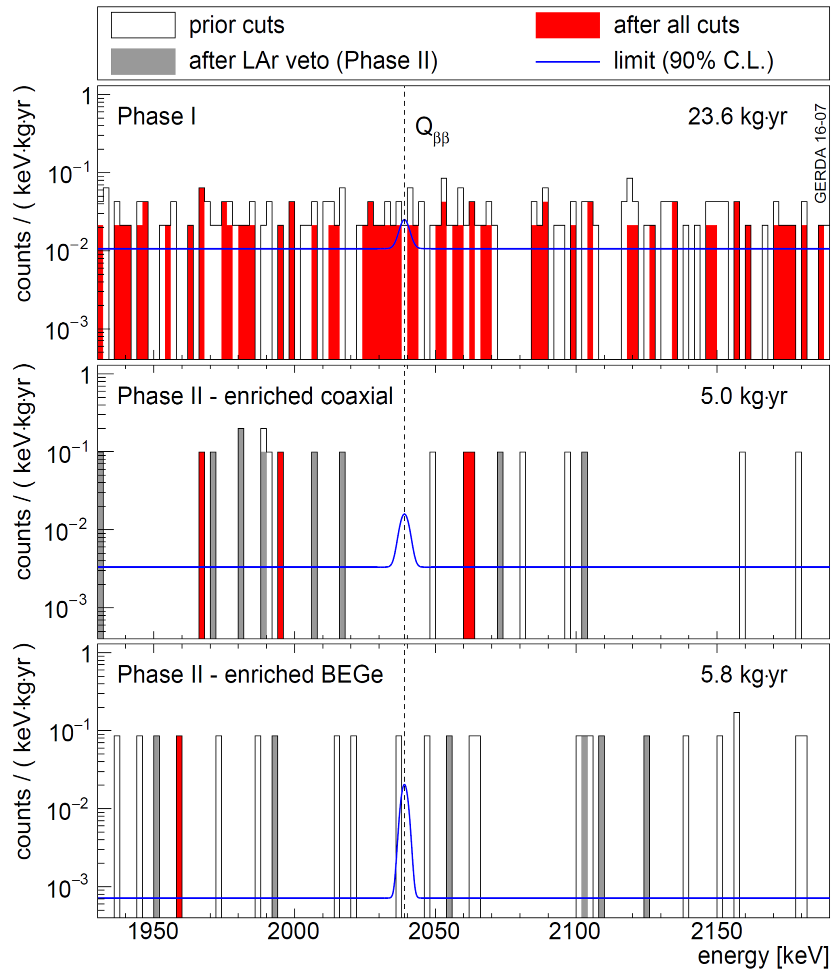
- simultaneous fit of multiple datasets ***i***

$$\mathcal{L}(\boldsymbol{\mathcal{D}}|\mathcal{S},\mathbf{BI},\boldsymbol{\theta}) = \prod_i \left[\frac{e^{-(\mu_i^S+\mu_i^B)} \cdot (\mu_i^S + \mu_i^B)^{N_i^{\mathrm{obs}}}}{N_i^{\mathrm{obs}}!} \cdot \mathcal{L}_i(\mathcal{D}_i|\mathcal{S},\mathrm{BI}_i,\theta_i)\right]$$

Validation of analysis code with GERDA data

Goal: testing of statistical analysis code (based on **RooStats** *arXiv:1009.1003*)
with well studied data from ***GERDA, Nature 2017***

published data



→ reconstruction of 6 unbinned datasets

published model parameters

TABLE I. List of data sets, exposures (for total mass), energy resolutions in FWHM, efficiencies (including enrichment, active mass, reconstruction efficiencies and dead times) and background indices (BI) in the analysis window.

data set	exposure [kg·yr]	FWHM [keV]	efficiency	BI 10^{-3}cts/(keV · kg · yr)
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIa BEGe	5.8	3.0(2)	0.60(2)	$0.7^{+1.1}_{-0.5}$

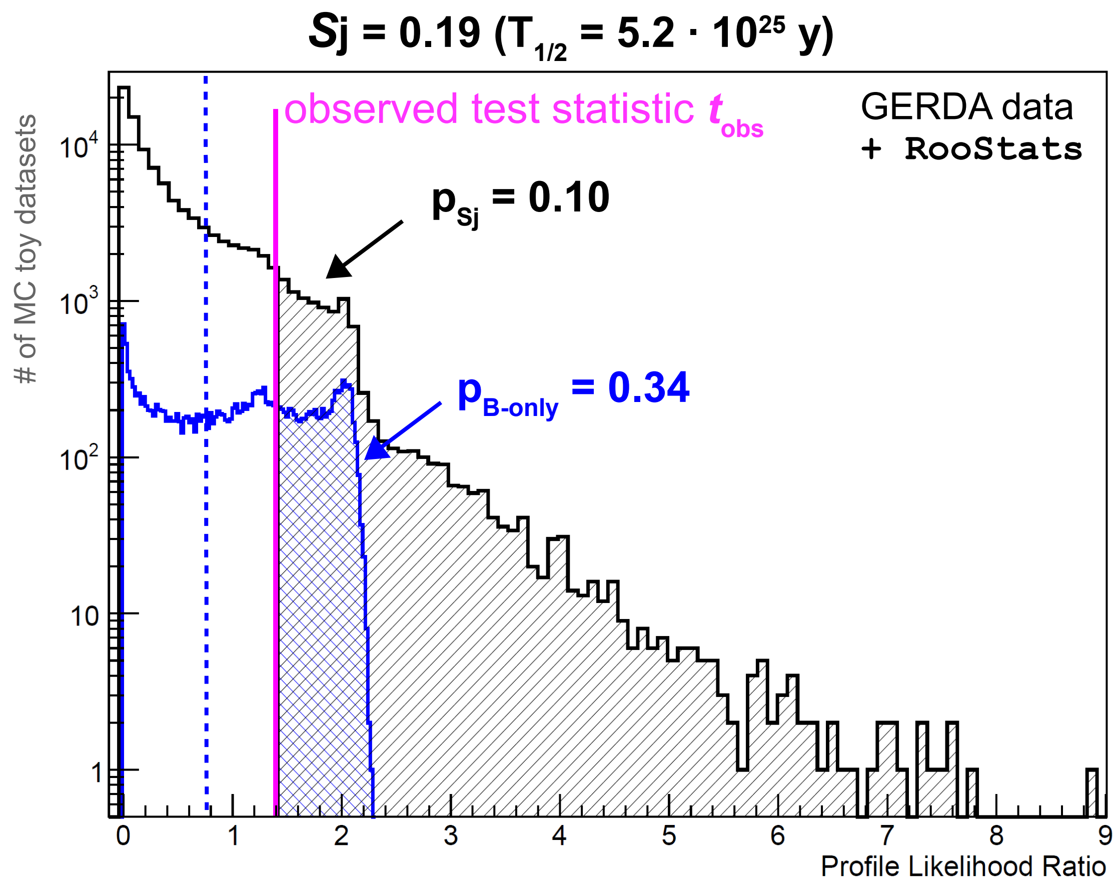
nearly full reconstruction of likelihood model

Deriving upper limits using hypothesis tests

- hypothesis tests performed for a assumed signal strength *Sj*
- two-sided test statistic t_{Sj} is based or *Profile Likelihood Ratio*
- generated MC toy datasets:

  100,000 *Sj* + Background

  20,000 B-only
- p-value of test statistic observed dat
  → determine ***upper limit***
- p-value of B-only distribution median
  → determine ***sensitivity***



$$p_{\mathcal{S}_\mathrm{j}} = \int_{t_{obs}}^{\infty} f(t_{\mathcal{S}}|\mathcal{S}_\mathrm{j})\, d(t_{\mathcal{S}_\mathrm{j}})$$

Test: Reproduction of GERDA $0\nu\beta\beta$ exclusion limit

- hypothesis test performed for increasing values of S_j
- observed limit at 90% C.L. when:

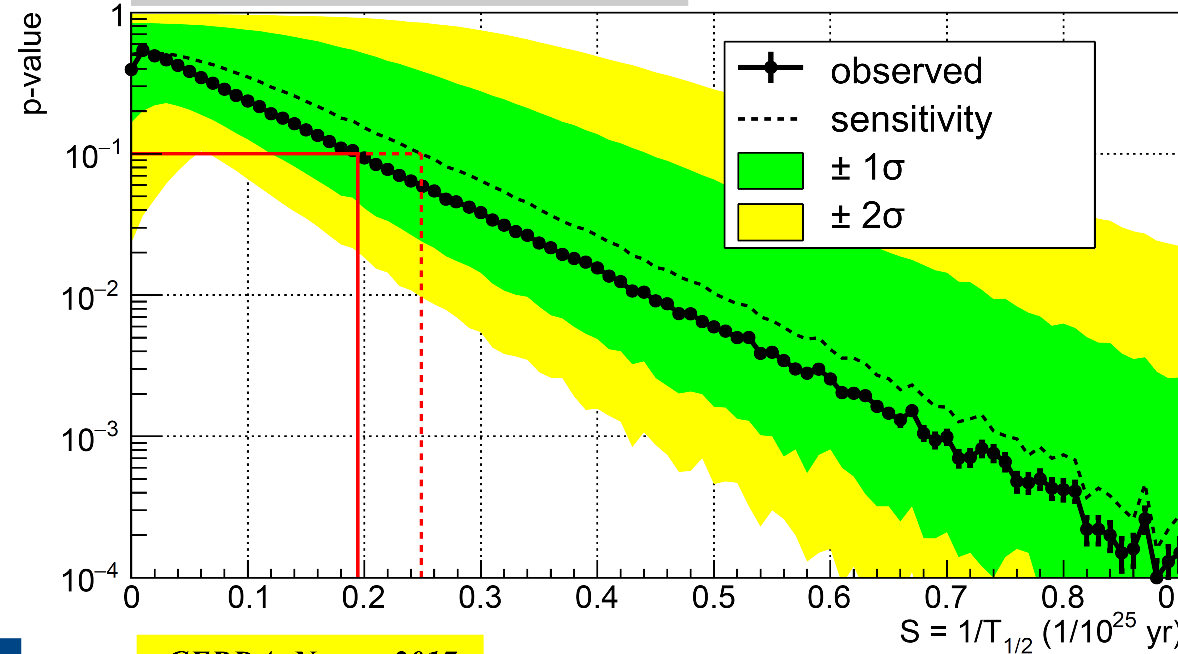
$$p'_{S_j} \leq 0.1$$

- w/ actual GERDA data but w/o all correlation terms: `RooStats` code reproduces official limits to ~ 2% accuracy ✓

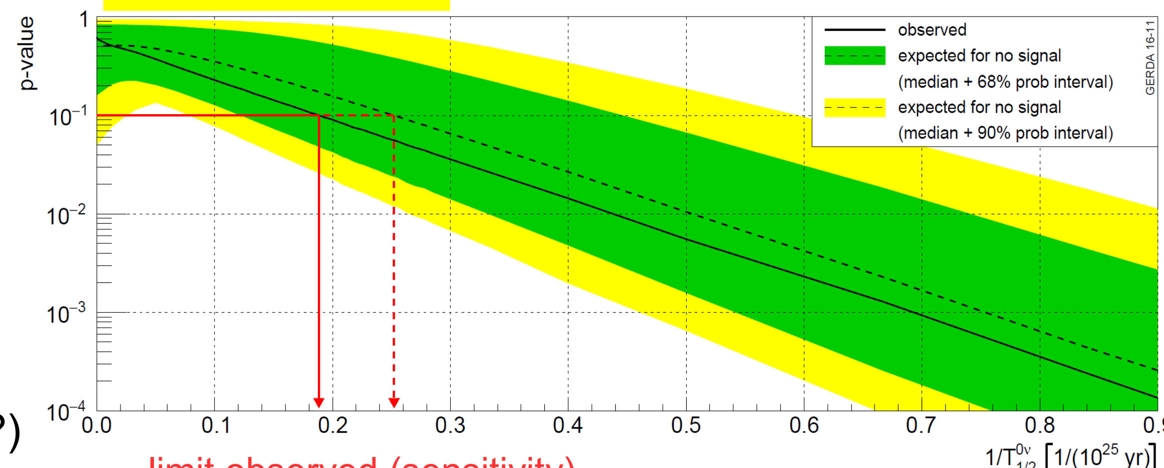
	90% C.L. limit observed (sensitivity)	
analysis	μ_s (counts)	$T_{1/2}$ (10^{25} yr)
official	2.0	5.3 (**4.0**)
reproduced	2.10±0.01 (2.77)	5.19±0.03 (**3.94**)

- test statistics in limit cases (e.g. test statistic of empty toy data sets?)

reproduced with **RooStats**



GERDA, Nature 2017



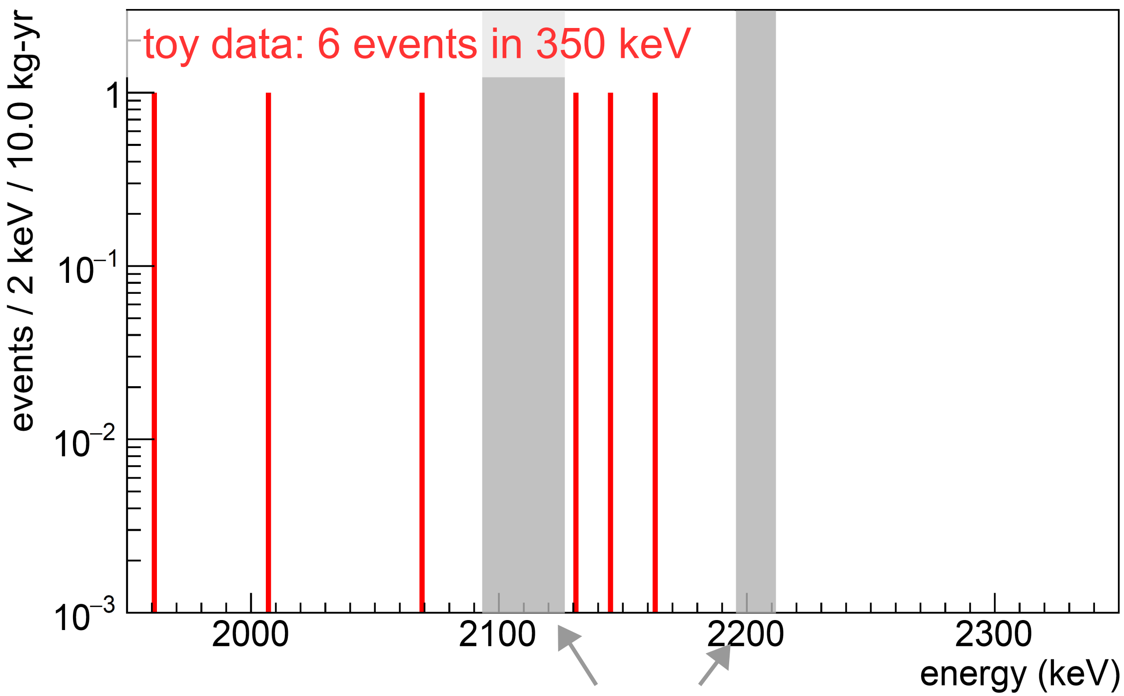
limit observed (sensitivity)

Application to MAJORANA *toy* data set

- efforts have been undertaken to optimize selection of physics data from DS0 to DS5 (improved cuts & data quality selection → poster J. Myslik)
- results based on this data: ongoing process of internal collaboration review

to demonstrate method:

single B-only toy data set with based on DS3+4 background index & typical parameter values

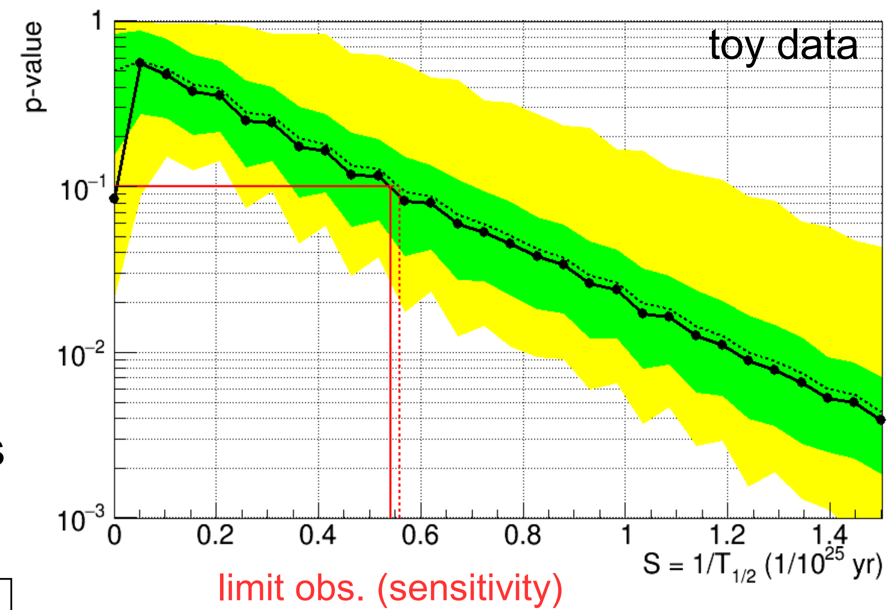


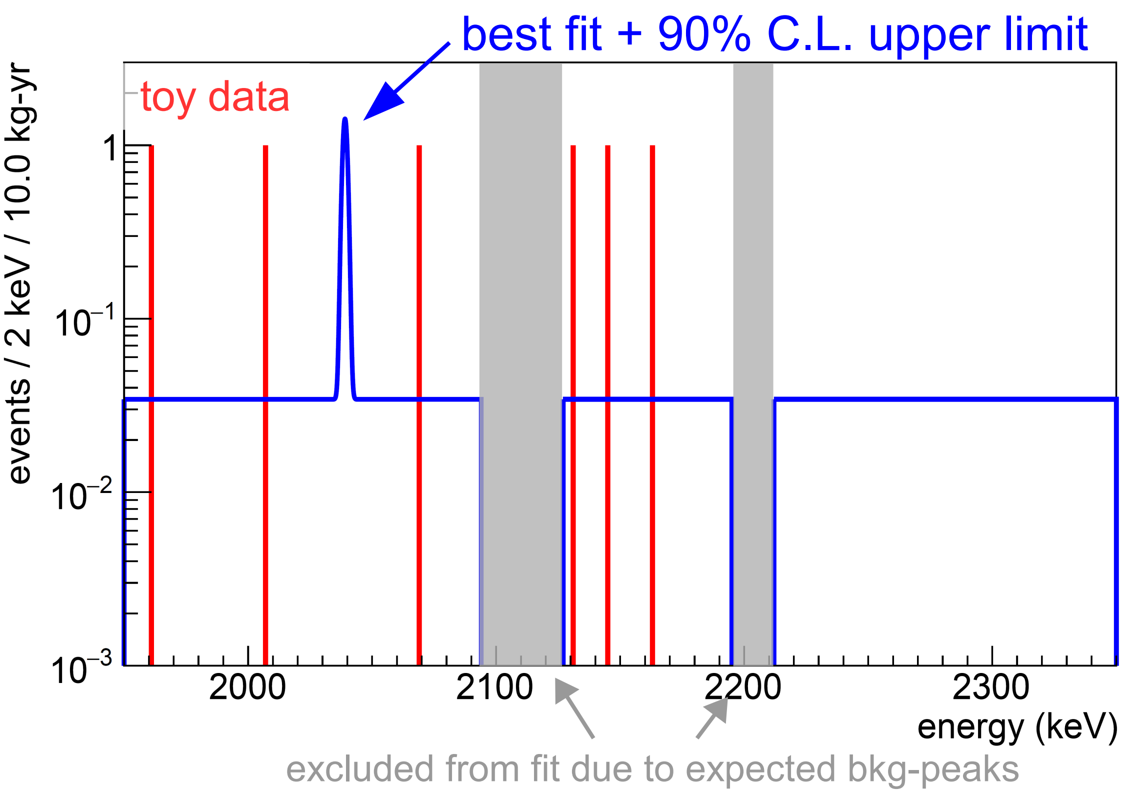
excluded from fit due to expected bkg-peaks

model parameter	model value
background index *BI* (cnts/(kg·y·keV)	$1.8 \cdot 10^{-3}$
exposure (kg·y)	10 ± 2%
FWHM (→ σ)	2.35 ± 1%
efficiency ε	0.59 ± 10%
E-shift δ (keV)	0 ± 0.2

Exclusion limit and sensitivity from *toy* data set

- B-only toy dataset
  → no fitted signal
  → all nuisance parameters at expected values
- median sensitivity: $\mathbf{T_{1/2} > 1.8 \cdot 10^{25}\ y}$
- (standard) profile likelihood method:
  significantly stricter limits than Feldman-Cousins

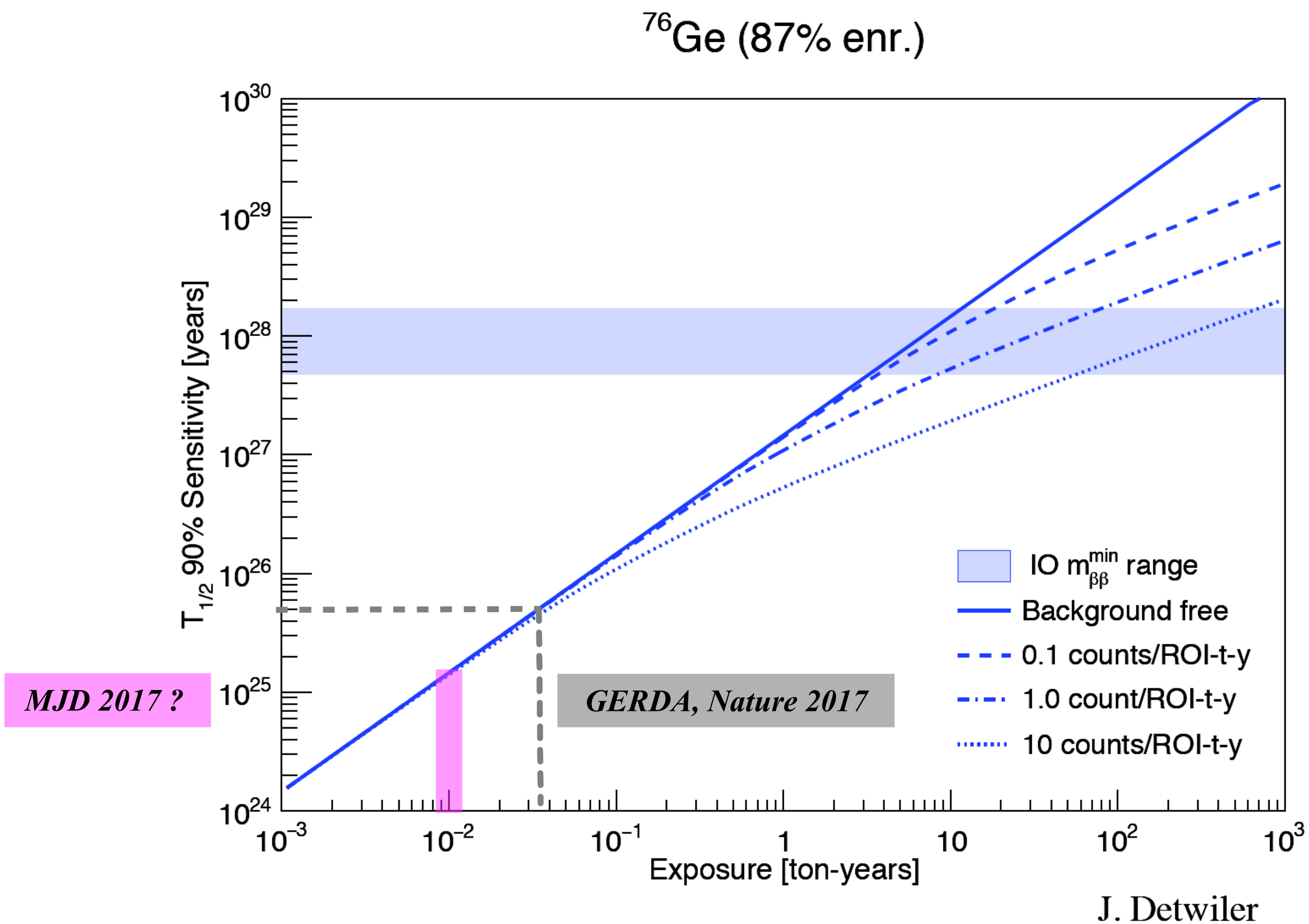




	90% C.L. limit “observed” **(sensitivity)**	
method	μ_s (counts)	$T_{1/2}$ (10^{25} yr)
standard	1.79 **(1.8)**	1.81 **(1.8)**
CLs	2.54 **(2.5)**	1.28 **(1.3)**

Conclusion & Outlook

- analysis of $0\nu\beta\beta$-search with non-blinded data from DS0–5 is nearing completion
- data taking with full shielding and both cryostat modules ongoing
- additional blinded data available and blinding scheme in effect for all new data



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