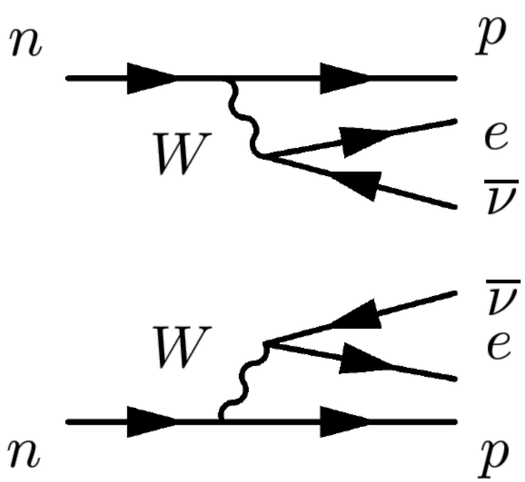
Background free search for neutrinoless double beta decay with GERDA Phase II

Christoph Wiesinger for the GERDA collaboration
Physik-Department and Excellence Cluster Universe, Technical University of Munich

PANIC 2017, September 1st, Beijing

(neutrinoless) double beta decay

$\boldsymbol{2\nu\beta\beta}$:



- allowed in standard model (SM)
- second order weak process
- $T_{1/2} \approx 10^{19} - 10^{24}$ yr

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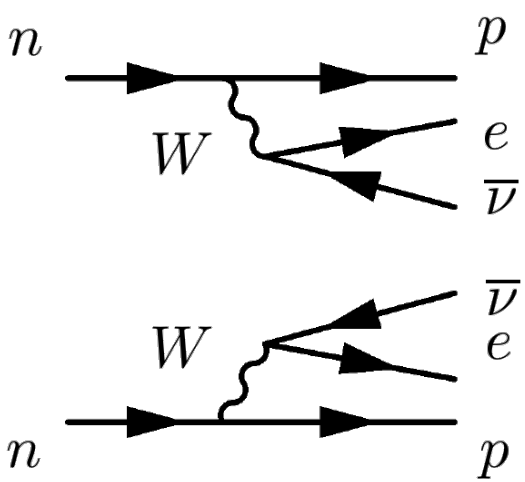

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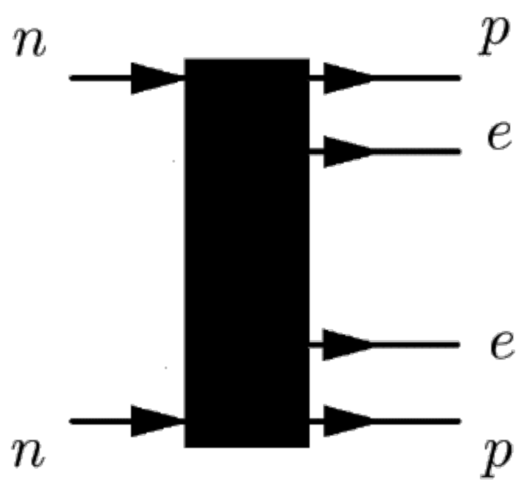
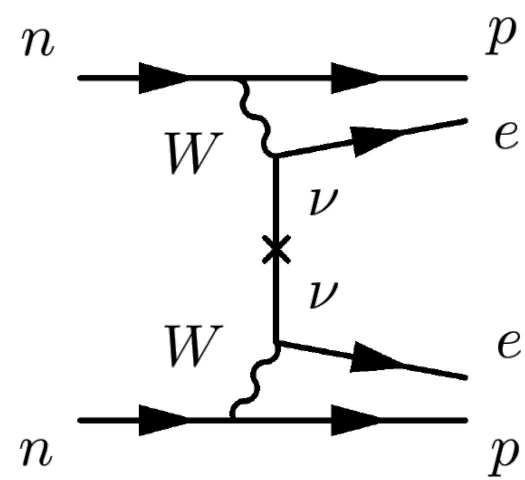
$0\nu\beta\beta$:



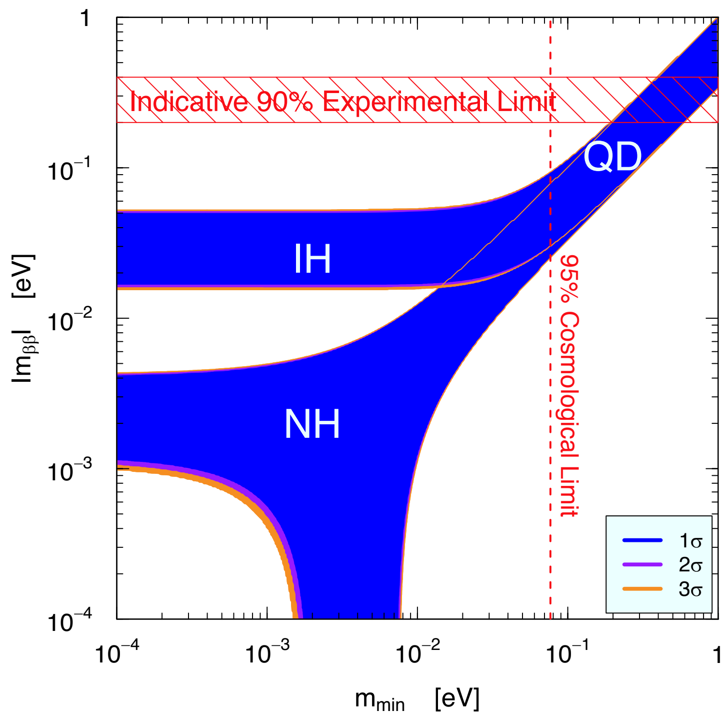


- lepton number violation → beyond SM, ΔL=2 operator
- ν has Majorana mass component
- $T_{1/2} > 10^{21} - 10^{26}$ yr

- exchange of massive Majorana neutrino
- constraints on lightest neutrino mass eigenstate
- mass hierarchy

neutrinoless double beta decay

Parameter space:



Bilenky, Giunti [Int.J.Mod.Phy. A30 (2015) 1530001]

$$\left(T_{1/2}\right)^{-1} \propto |M|^2 \cdot F \cdot \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

$$\langle m_{\beta\beta}\rangle = \left|\sum_{j=1}^{3} m_j \cdot U_{ej}^2\right| = \left|\sum_{j=1}^{3} m_j \cdot |U_{ej}|^2 \cdot e^{i\alpha_j}\right|$$

neutrinoless double beta decay

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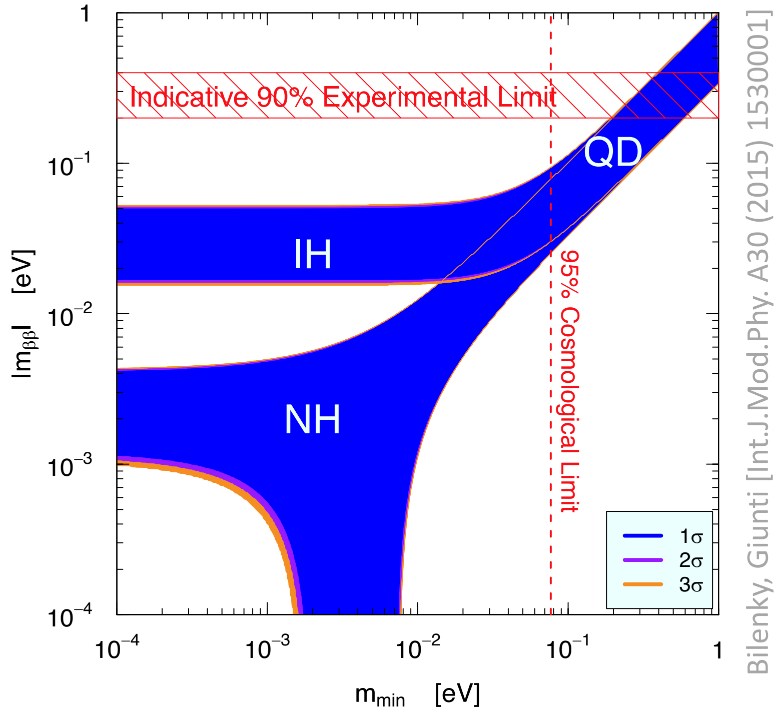

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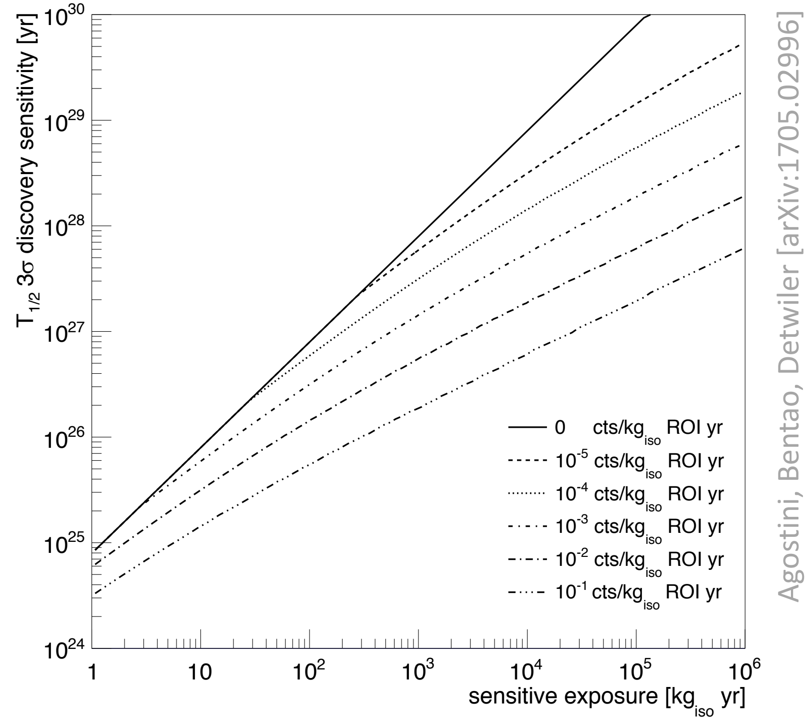
Sensitivity:

$$T_{1/2}^{0\nu} \propto \sqrt{M \cdot t / BI \cdot \Delta E}$$

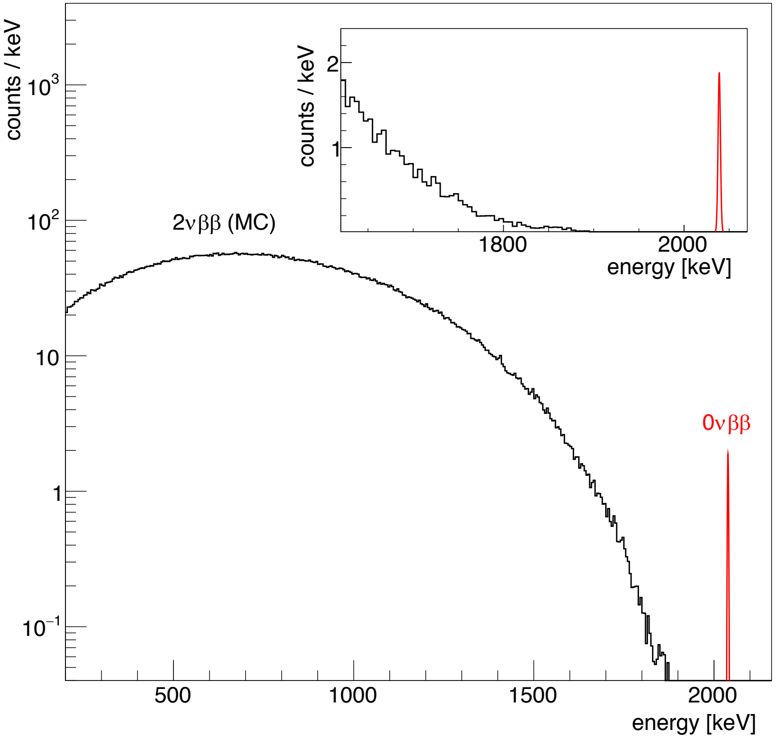
GERDA goal: **quasi background free**

$$\rightarrow T_{1/2}^{0\nu} \propto M \cdot t$$



double beta decay in ^{76}Ge

Summed electron spectrum (^{76}Ge):



- $2\nu\beta\beta$: ^{76}Ge → ^{76}Se + $2e^-$ + $2\bar{\nu}_e$
- $0\nu\beta\beta$: ^{76}Ge → ^{76}Se + $2e^-$

→ search for **peak** @ $Q_{\beta\beta} = 2039\ \mathrm{keV}$

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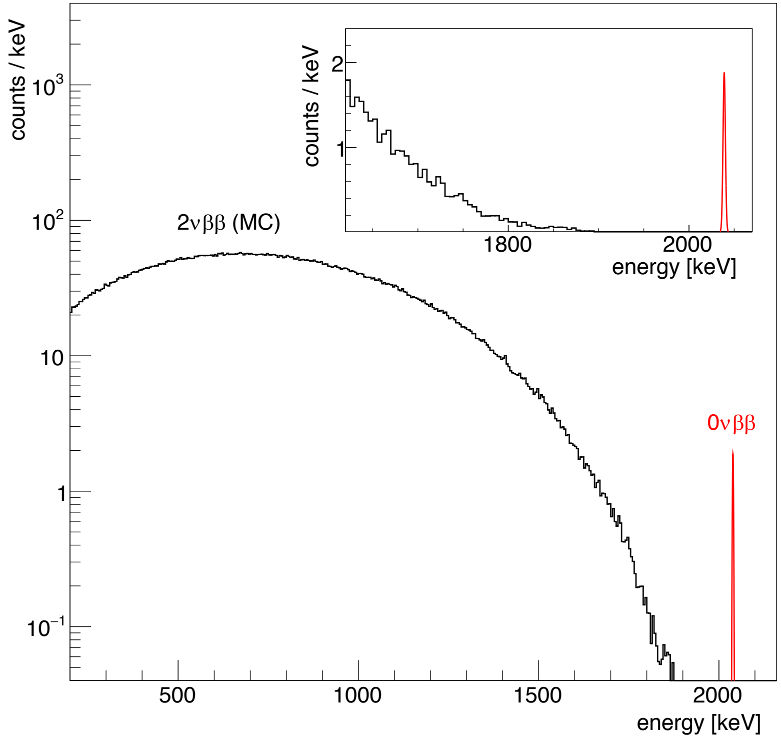

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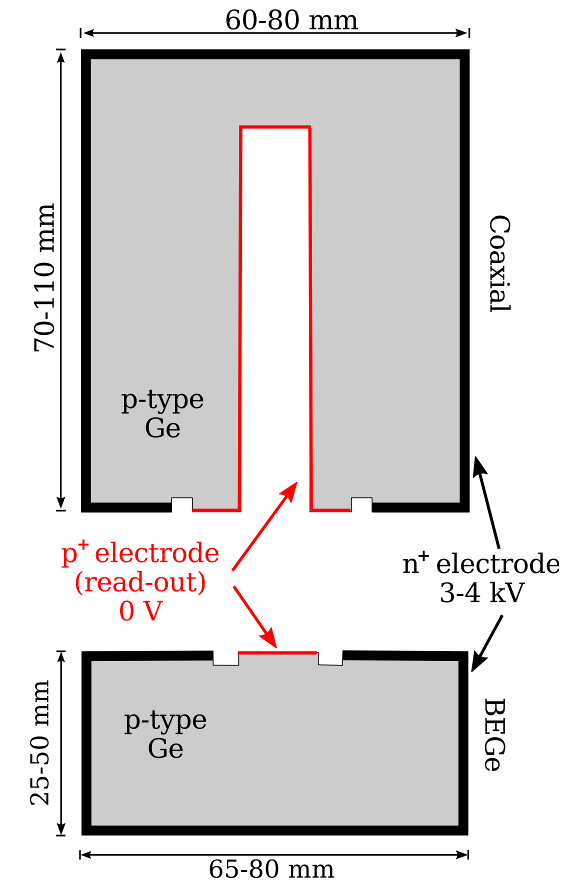
GERDA detectors:

- HPGe detectors enriched in ^{76}Ge
- (semi-)coaxial and broad energy (BE)Ge type detectors
- high purity → low background
- high density -> $\beta\beta$ **point like**
- very good energy resolution ~0.2% at $Q_{\beta\beta}$
- source = detector → high detection efficiency



[Eur.Phys.J. C74 (2014) 2764, Eur.Phys.J. C75 (2015) 39]

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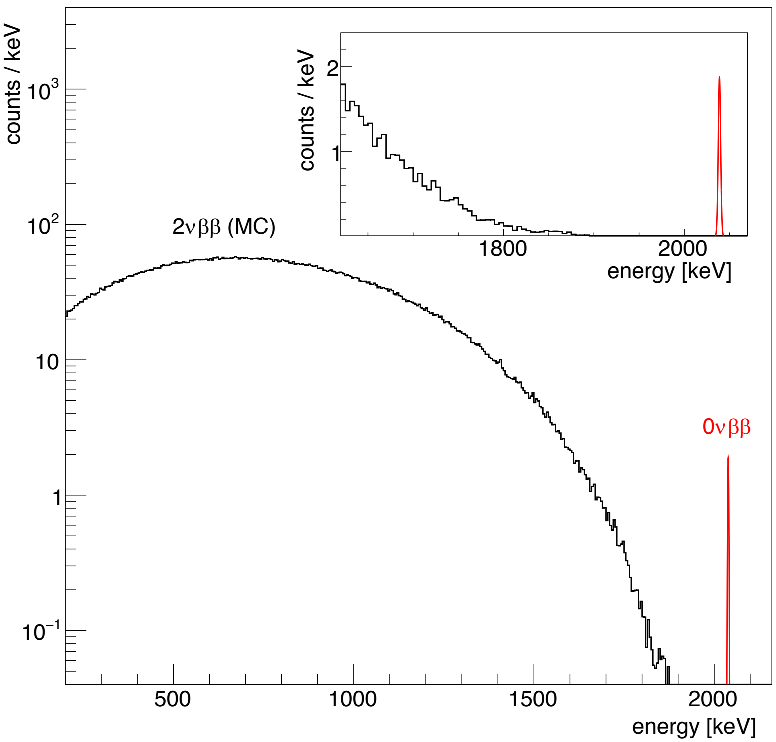

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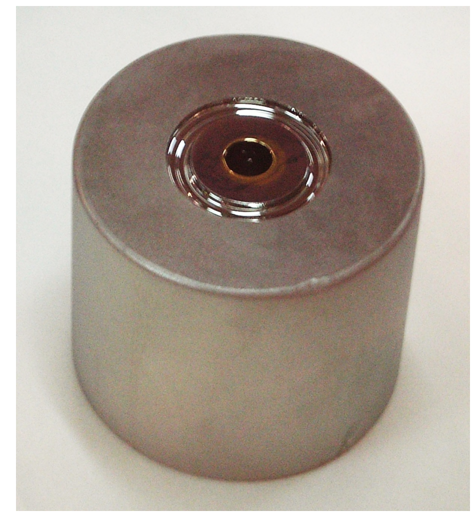

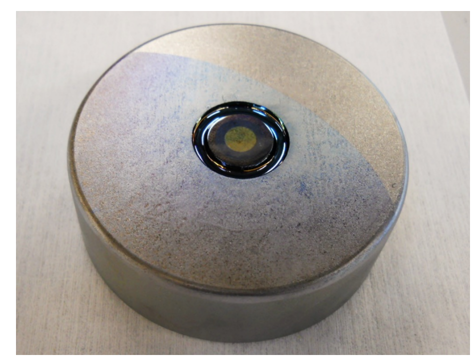

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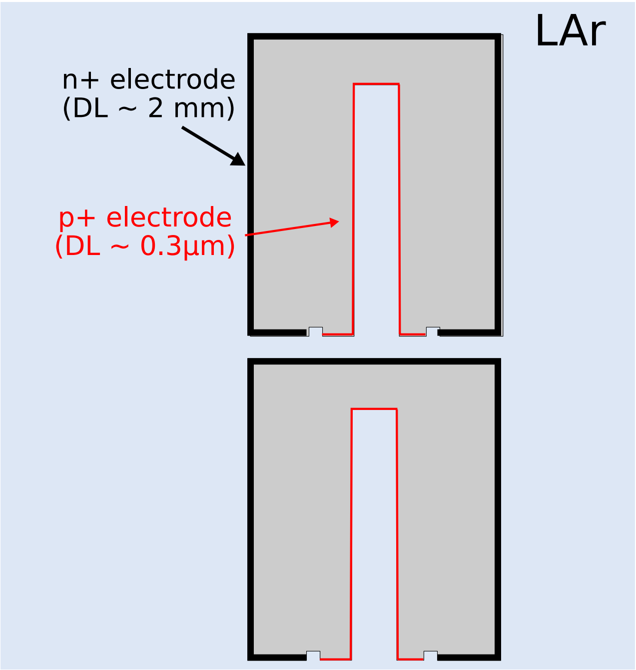
the GERDA approach

- staged high resolution background free $0\nu\beta\beta$ search
- background reduction by
  - material selection / passive shielding
  - **active background suppression**

-> bare detectors in liquid argon (LAr)



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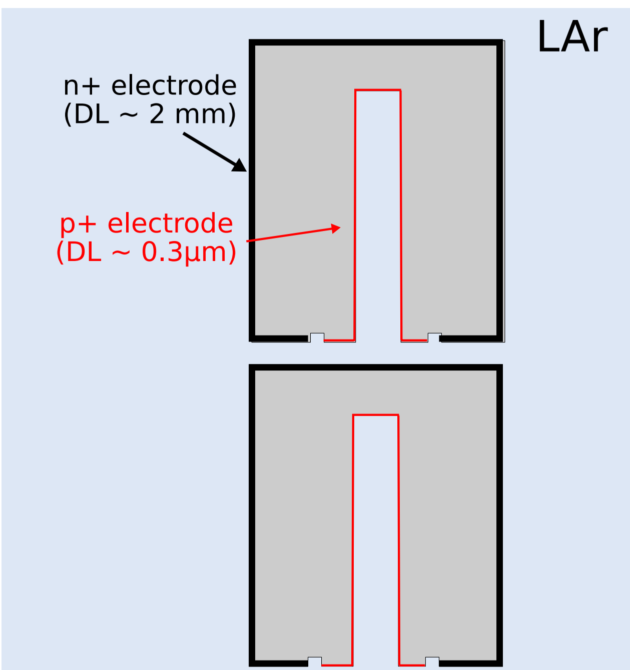
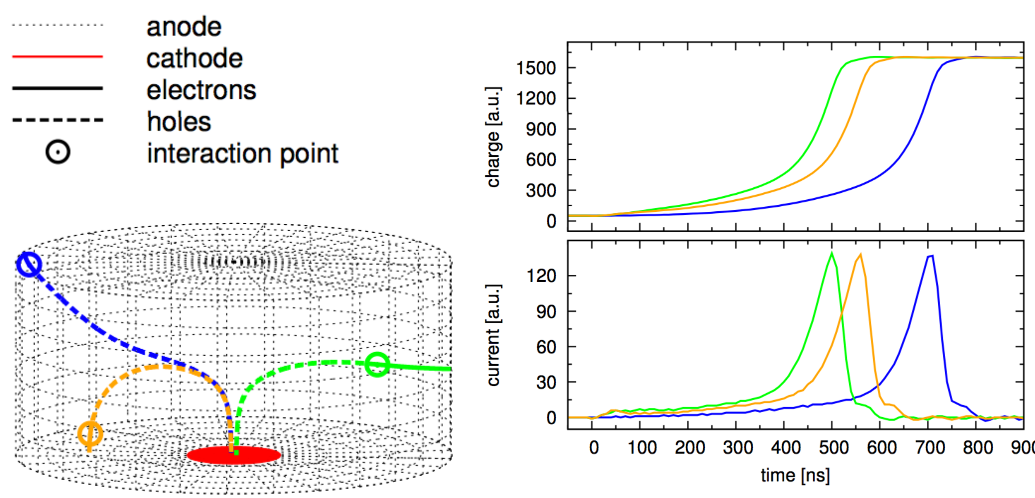


active background suppression

discriminate point-like (single site) $\beta\beta$ interaction in bulk from background processes by event topology

- **AC:** detector anti-coincidence
- **LAr veto:** scintillation light read-out (Phase II)
- **PSD:** pulse shape discrimination



[Eur.Phys.J. C75 (2015) 38, Eur.Phys.J. C73 (2013) 2583]

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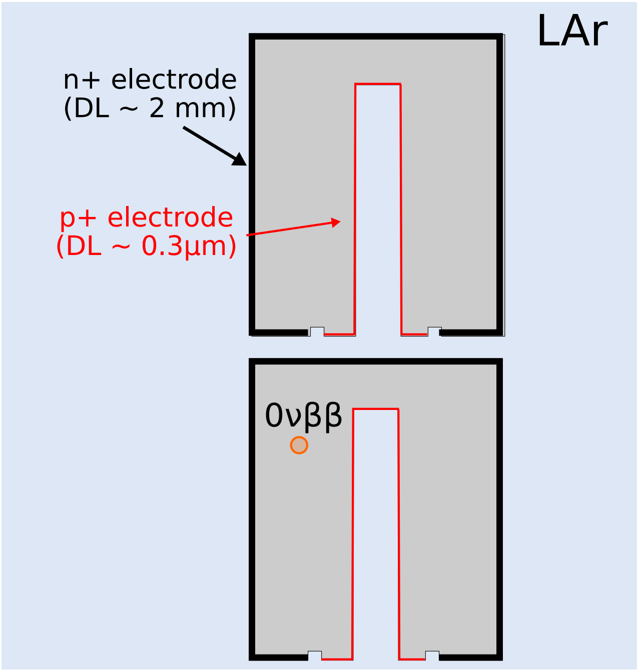

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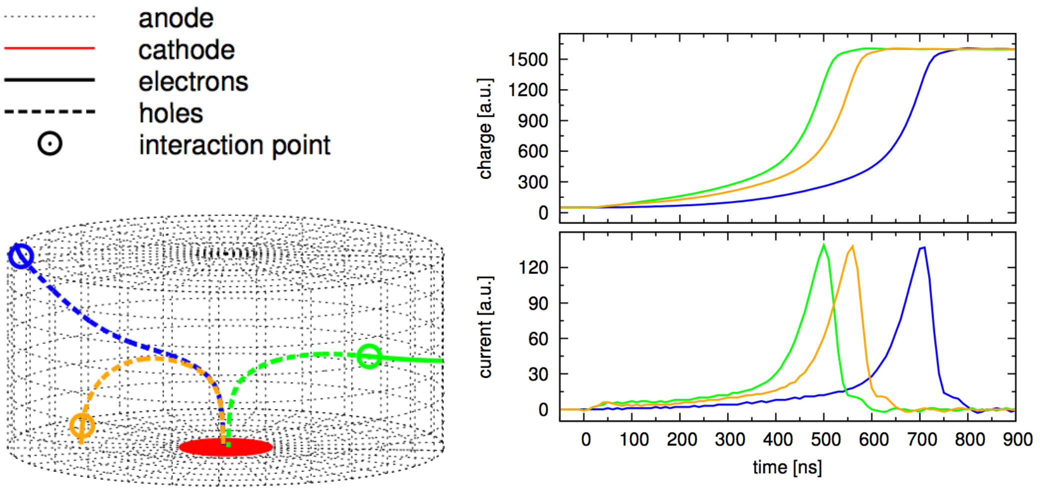

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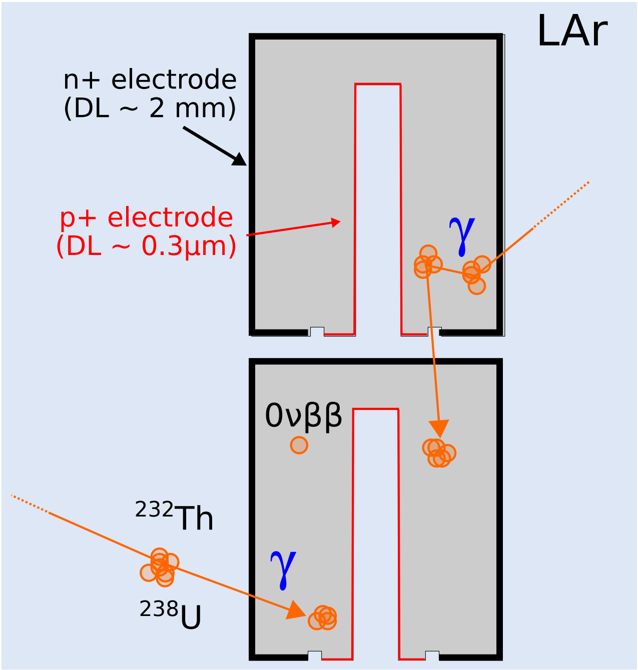

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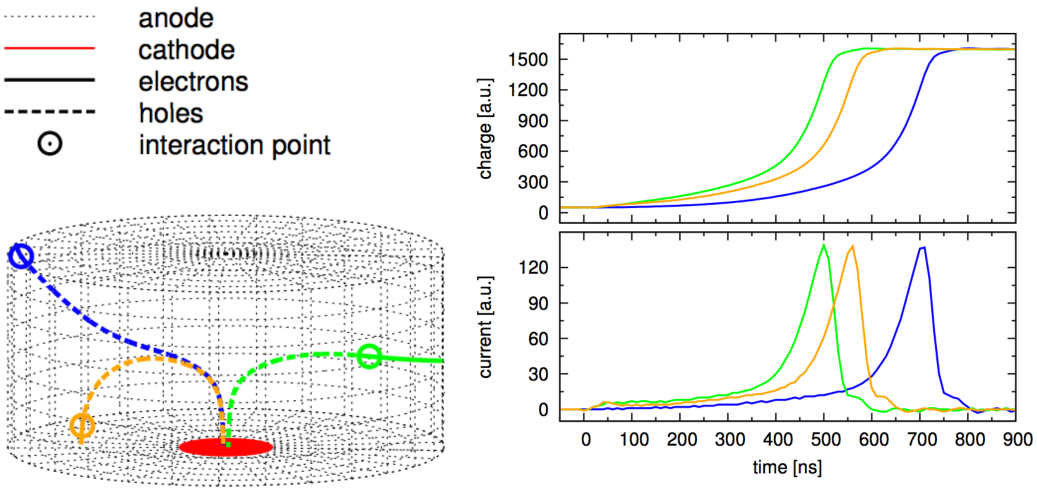

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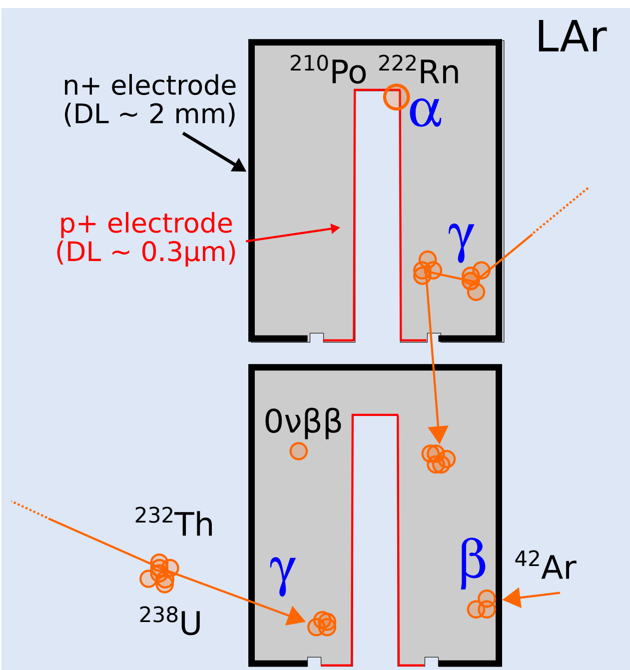

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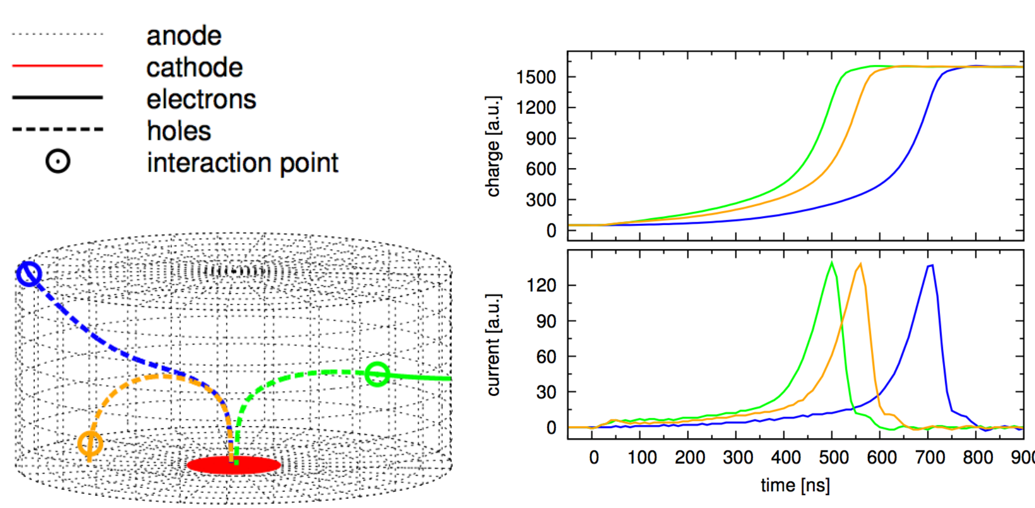
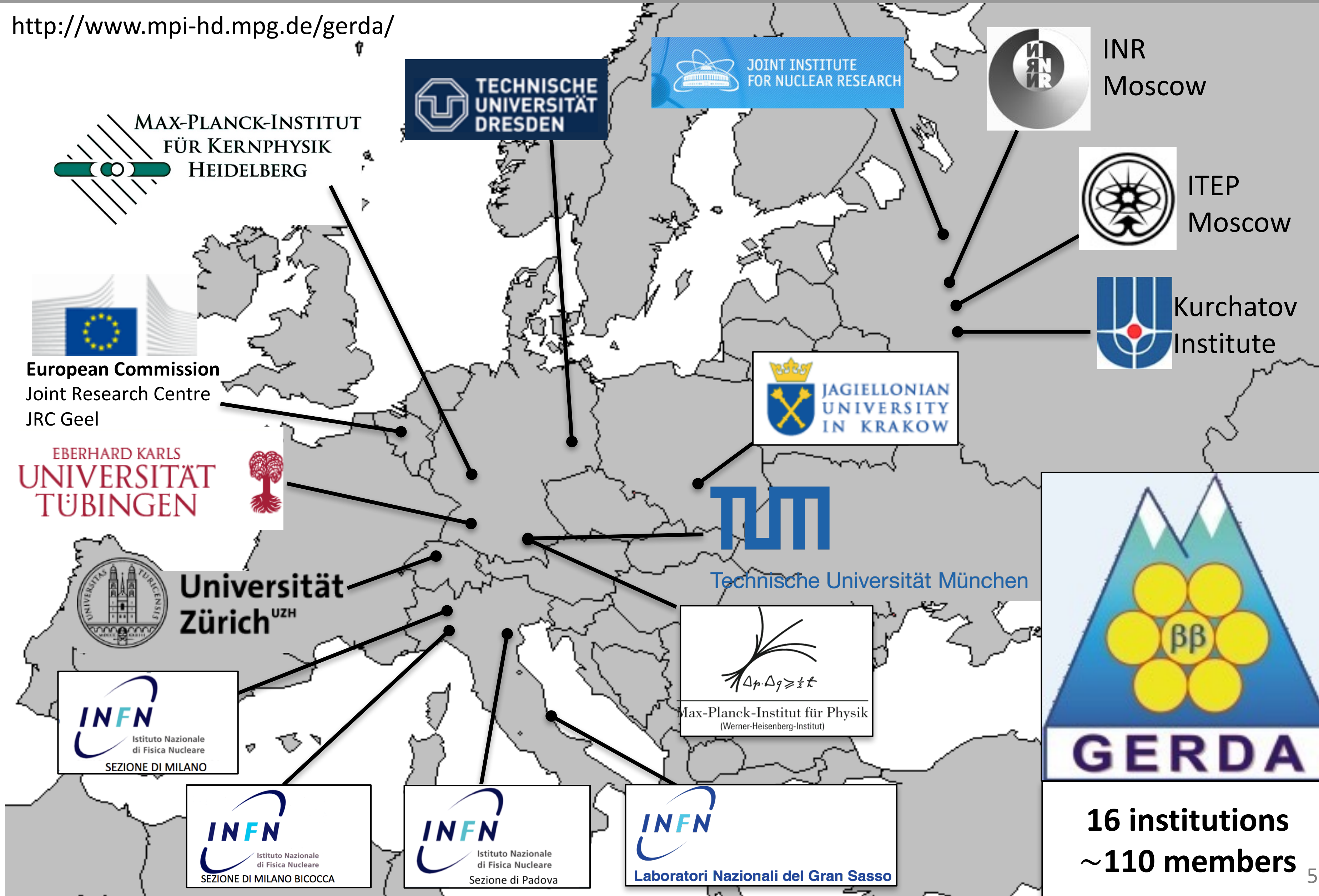


[Eur.Phys.J. C75 (2015) 38, Eur.Phys.J. C73 (2013) 2583]

the GERDA collaboration

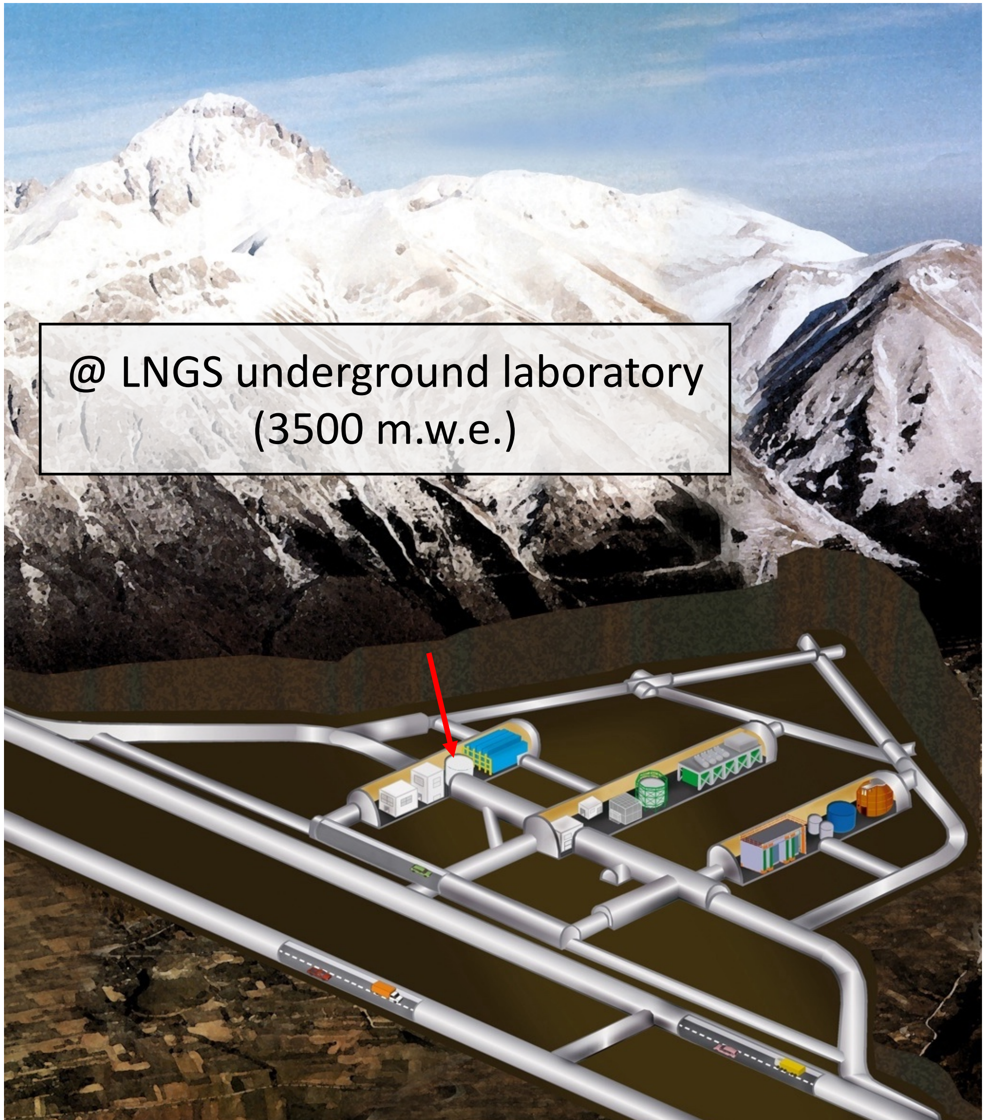
http://www.mpi-hd.mpg.de/gerda/

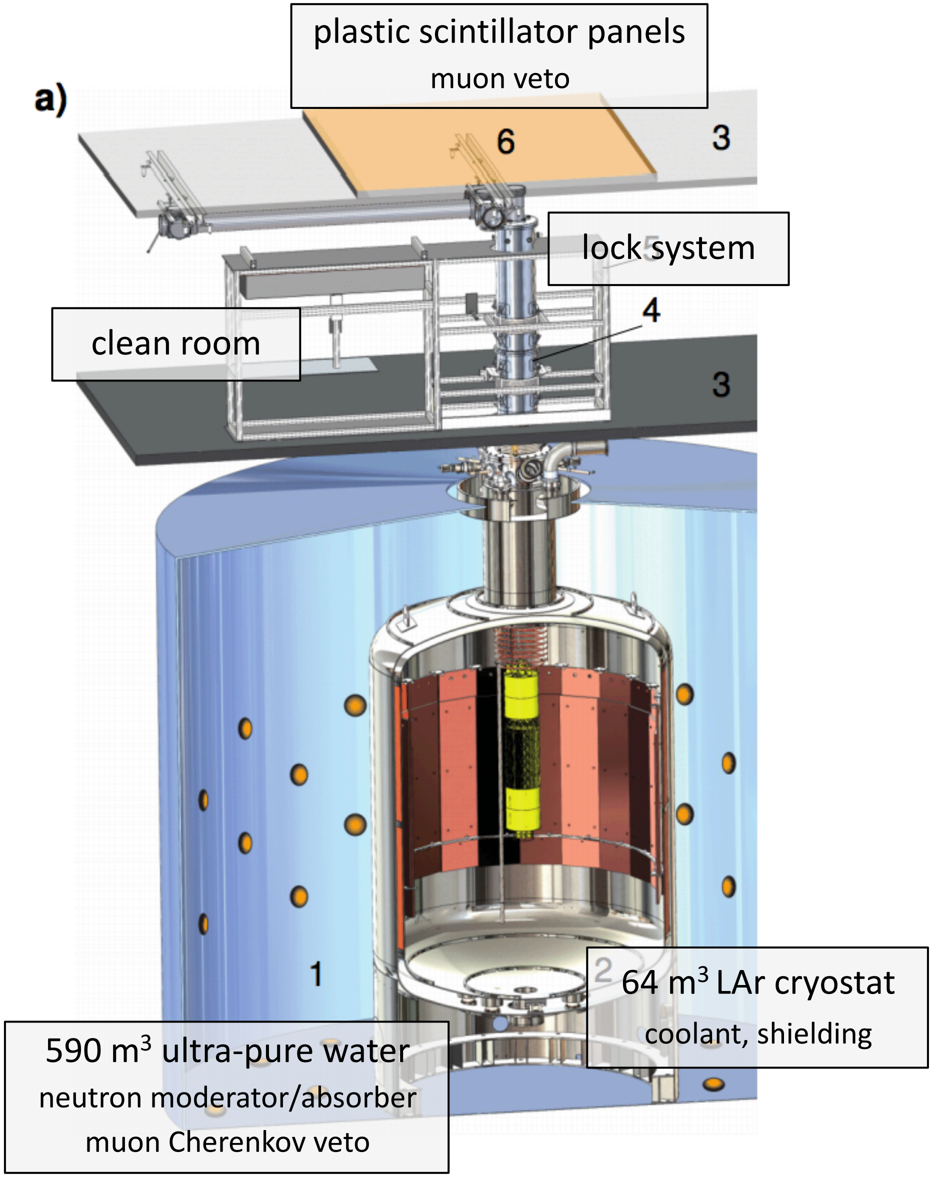


16 institutions

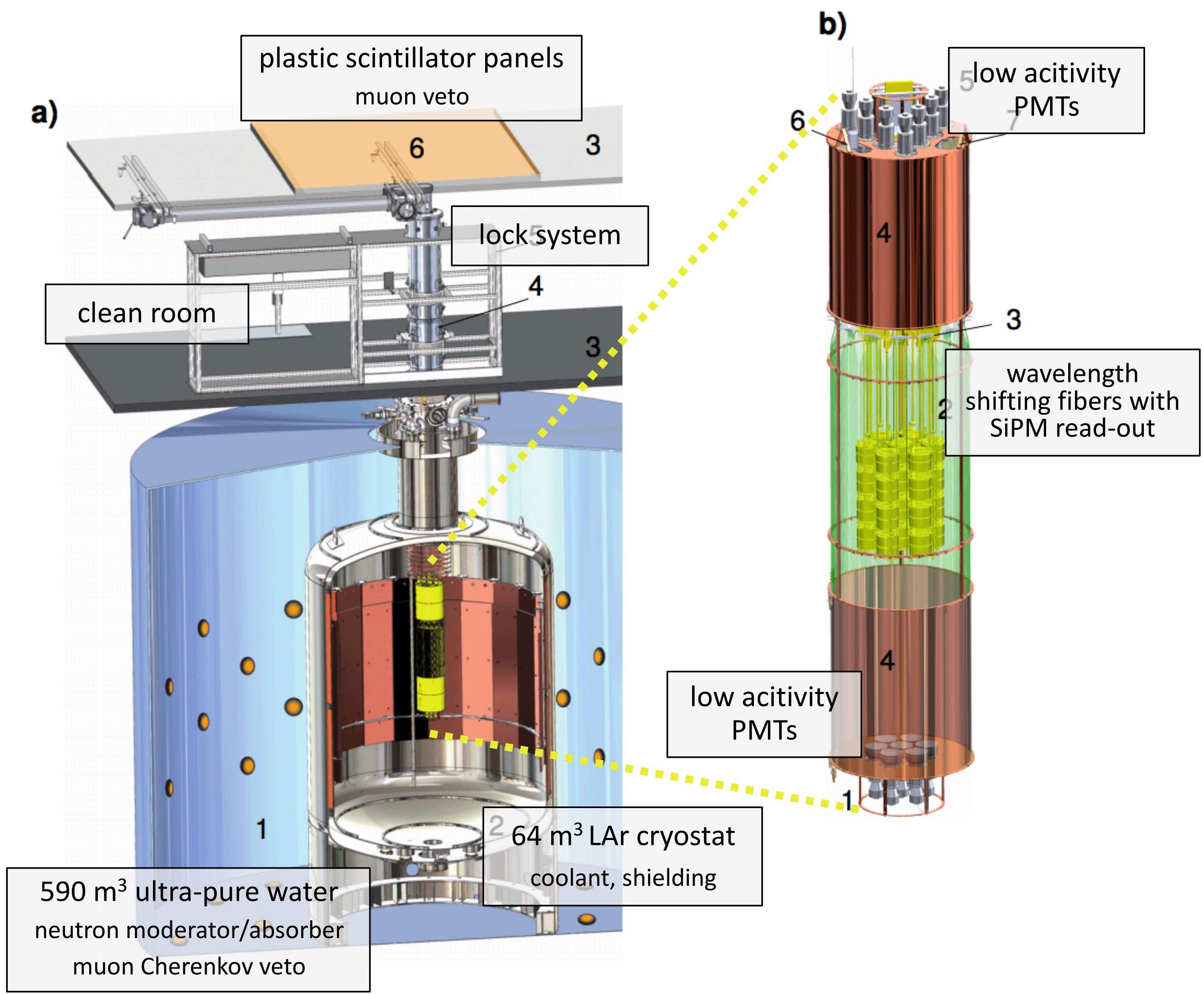
~110 members

GERmanium Detector Array - GERDA

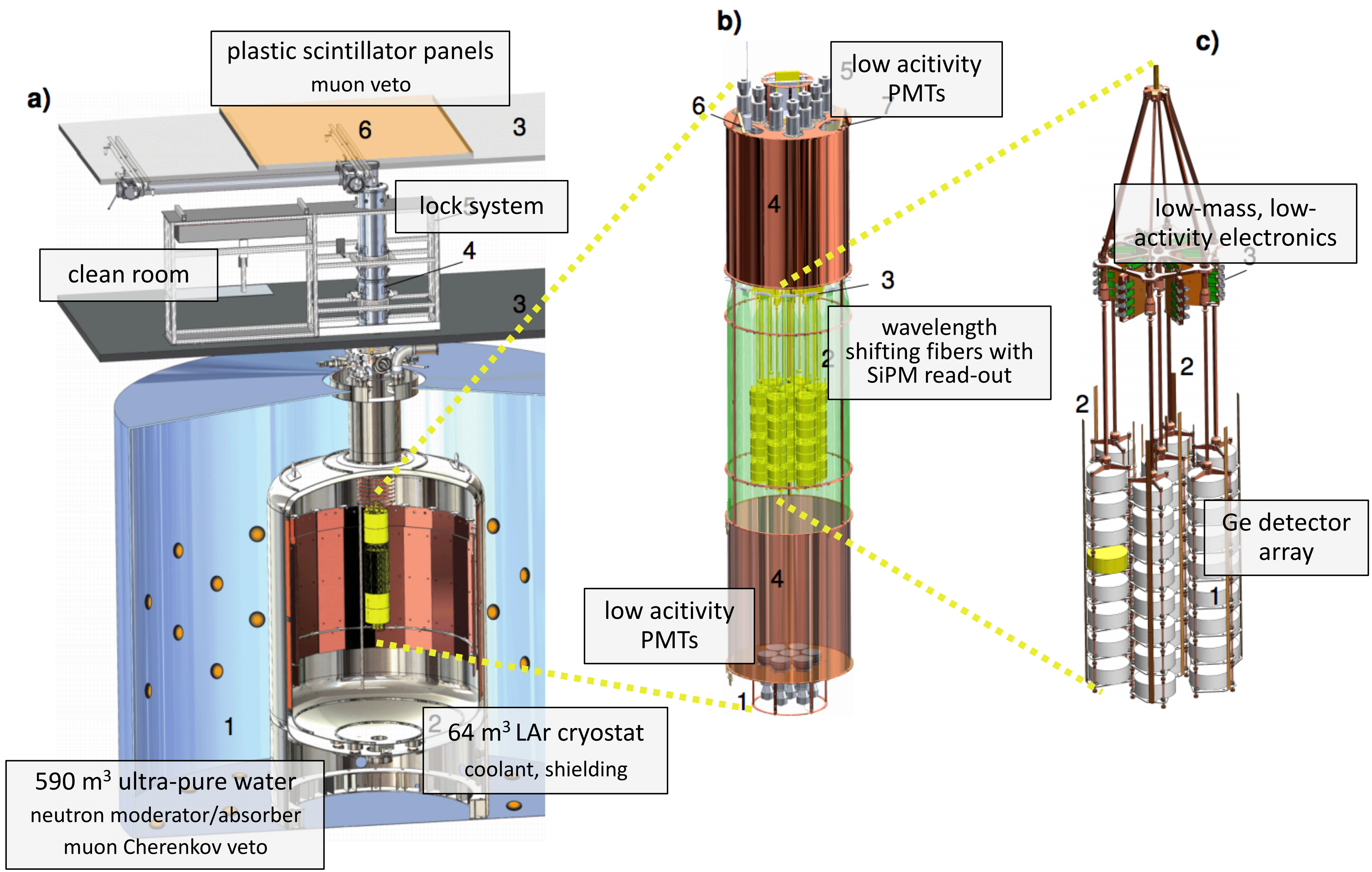



plastic scintillator panels
muon veto
a)
6
3
lock system
4
clean room
3
1
2
64 m³ LAr cryostat
coolant, shielding
590 m³ ultra-pure water
neutron moderator/absorber
muon Cherenkov veto

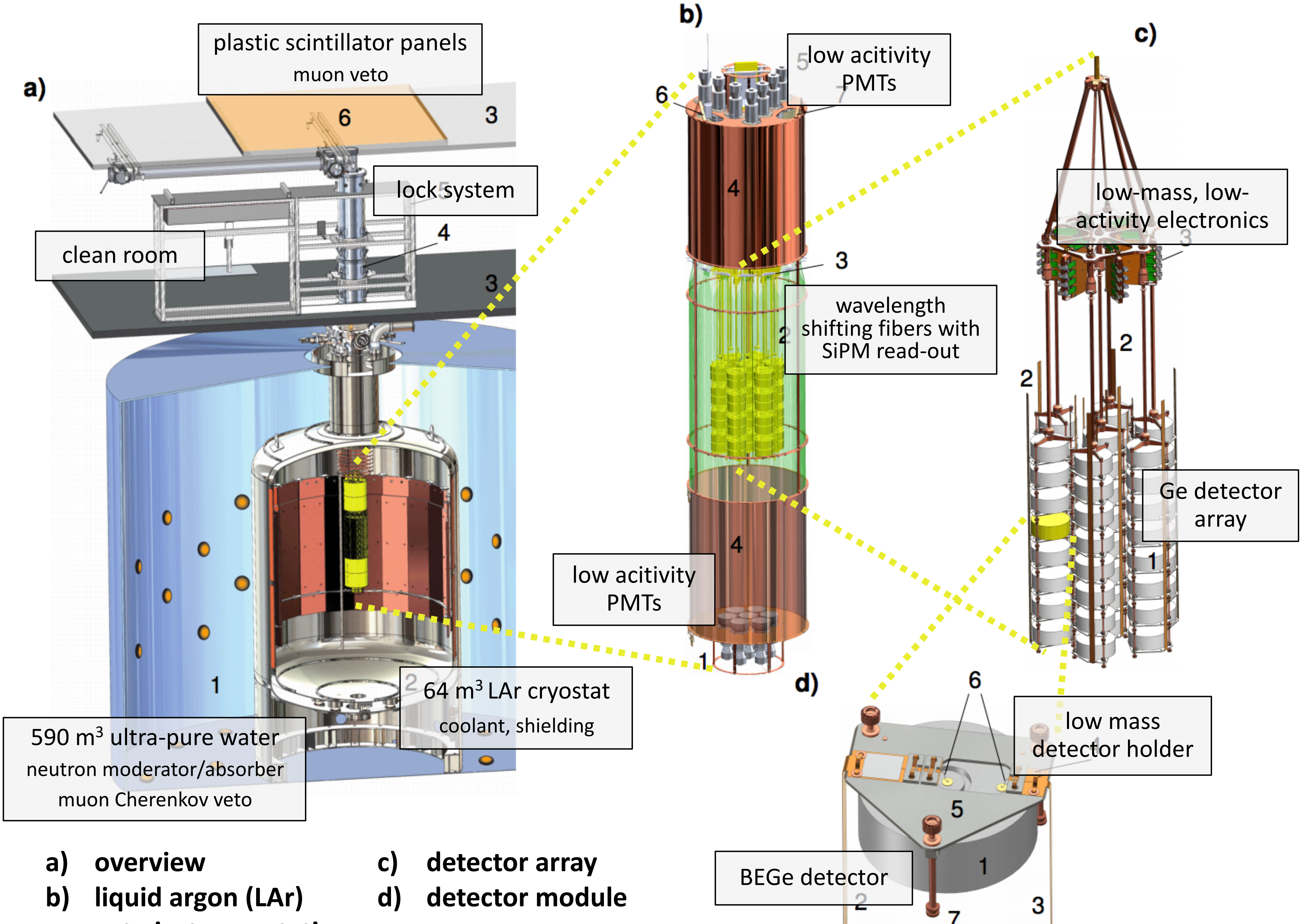
a) overview



- a) **overview**
- b) **liquid argon (LAr) veto instrumentation**

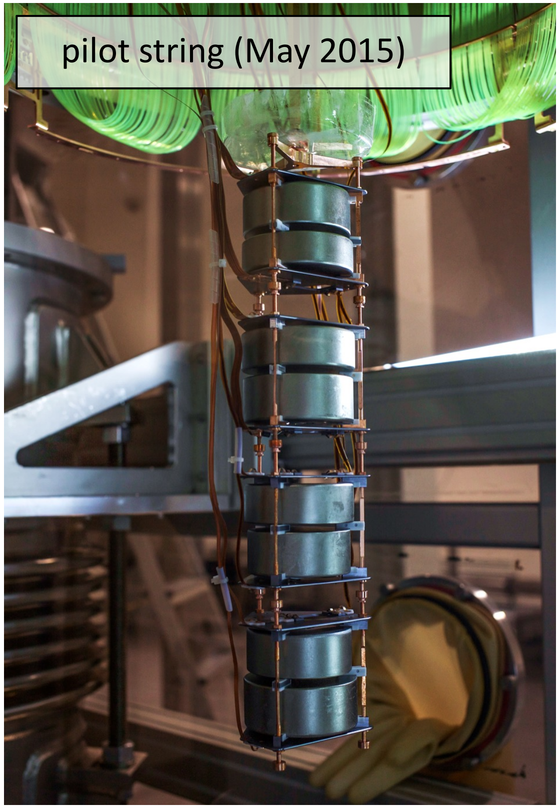


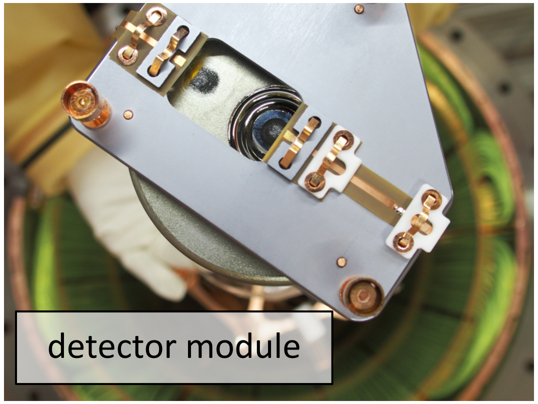
a) **overview**
b) **liquid argon (LAr) veto instrumentation**
c) **detector array**

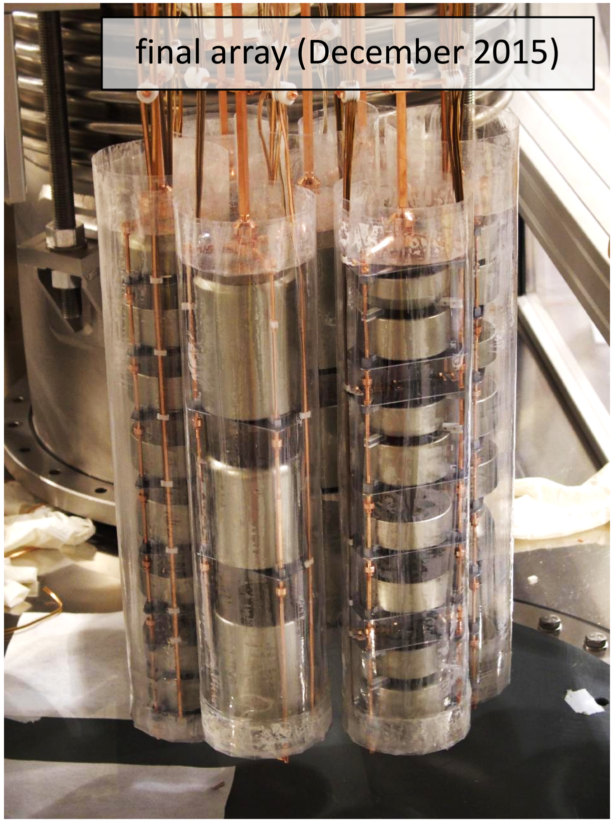


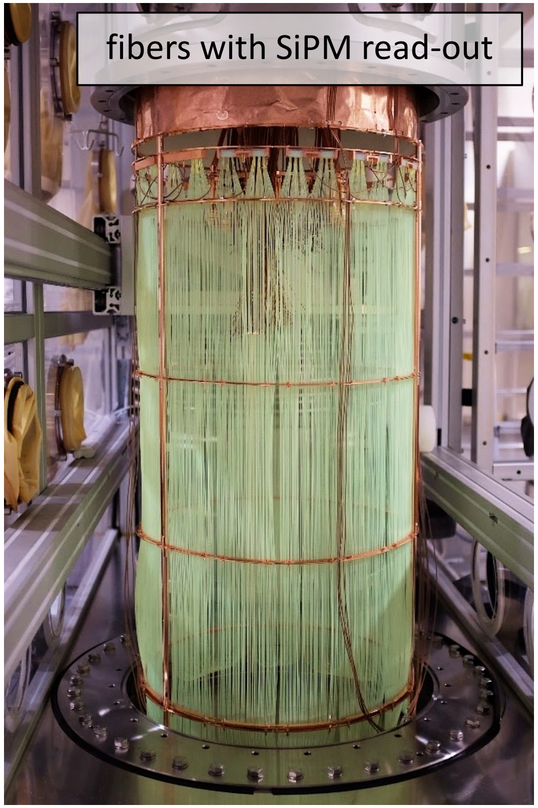
a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array
d) detector module

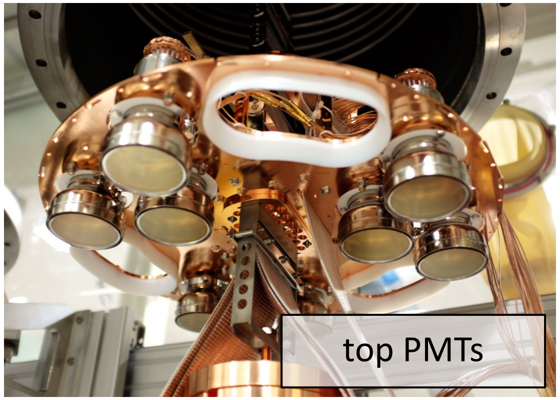
… in pictures

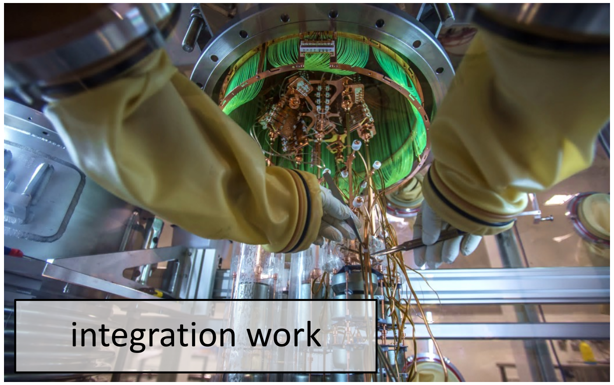

pilot string (May 2015)


detector module

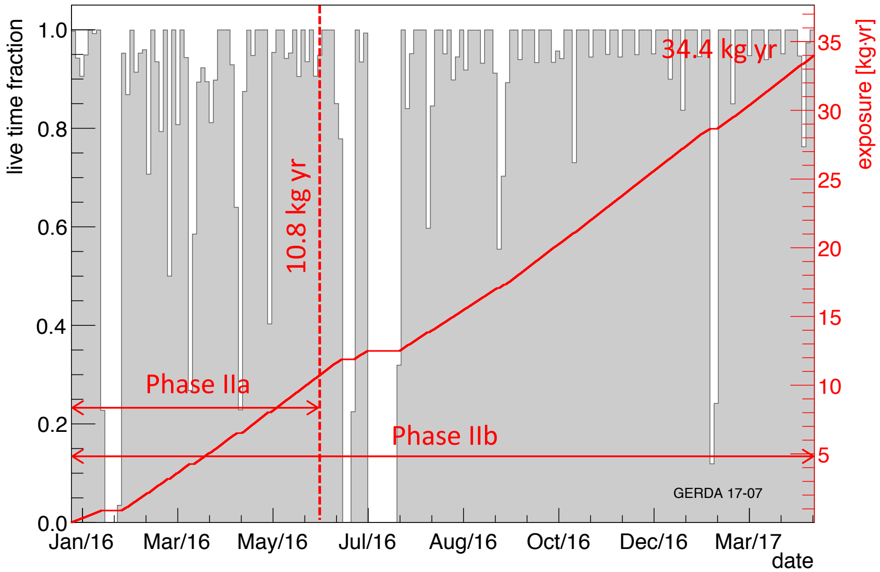

final array (December 2015)


fibers with SiPM read-out


top PMTs


integration work

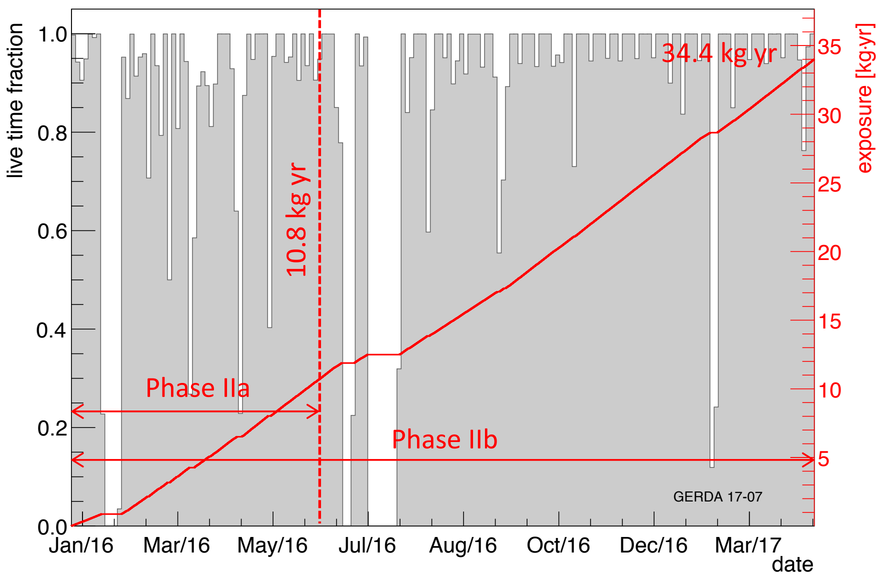
data taking



- 30 **enriched BEGe** detectors (20.0 kg)
- 7 **enriched coaxial** detectors (15.6 kg)
- Dec 2015 to April 2017, 93% duty cycle

	exposure
coaxials	$\mathbf{5.0\ kg \cdot yr}$ -> $16.2\ \mathrm{kg \cdot yr}$ -> …
BEGe	$\mathbf{5.8\ kg \cdot yr}$ -> $18.2\ \mathrm{kg \cdot yr}$ -> …

data taking, previous Phase II result



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[Nature 544 (2017) 47]

ARTICLE

doi:10.1038/nature21717

Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA

The GERDA Collaboration*

background index @ $Q_{\beta\beta}$ $[\mathrm{cts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})]$	
coaxials	$3.5^{+2.1}_{-1.5} \cdot 10^{-3}$
BEGe	$0.7^{+1.1}_{-0.5} \cdot 10^{-3}$

-> background < 1 cts for full **design exposure** ($\gtrsim 100\ \mathrm{kg \cdot yr}$)

limit on $0\nu\beta\beta$ decay in ^{76}Ge
$\mathbf{4.0 \cdot 10^{25}\ yr}$ median sensitivity
$\mathbf{T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}\ yr\ (90\%\ CL)}$

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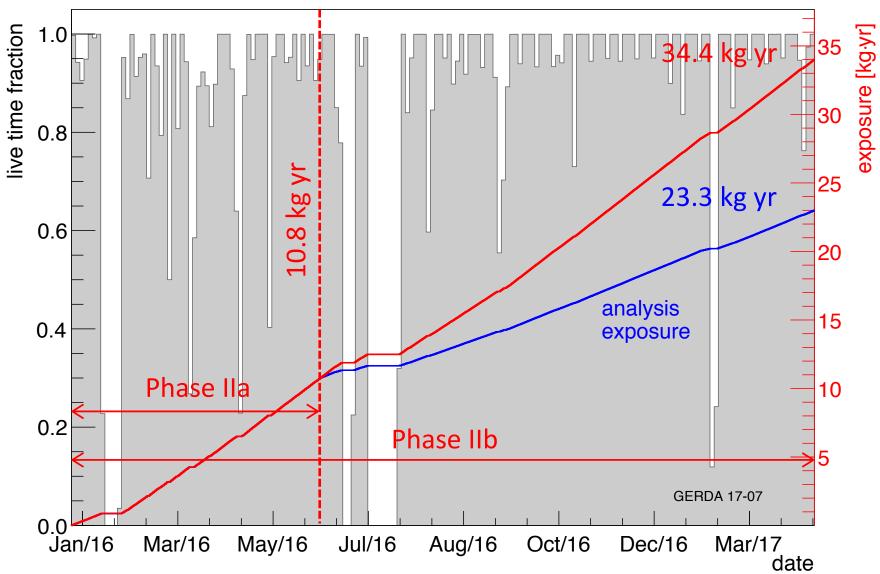

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...only BEGe data unblinded for this release

[Nature 544 (2017) 47]

ARTICLE

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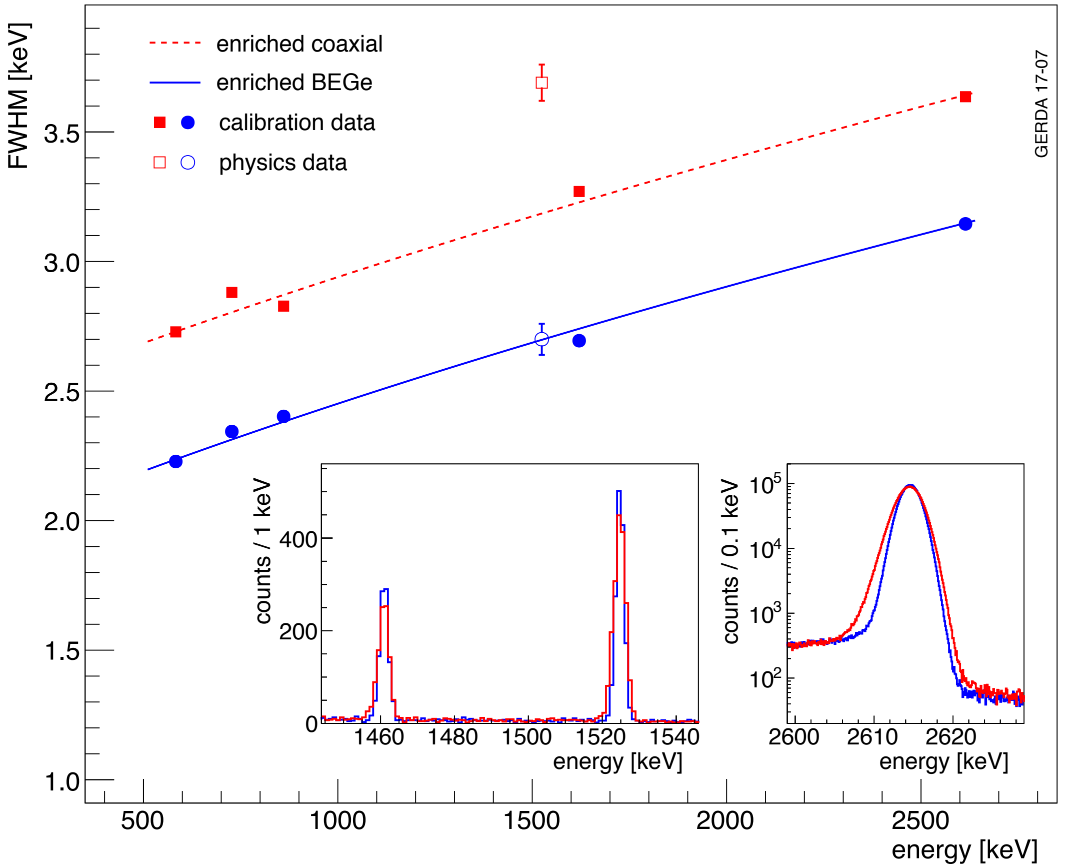
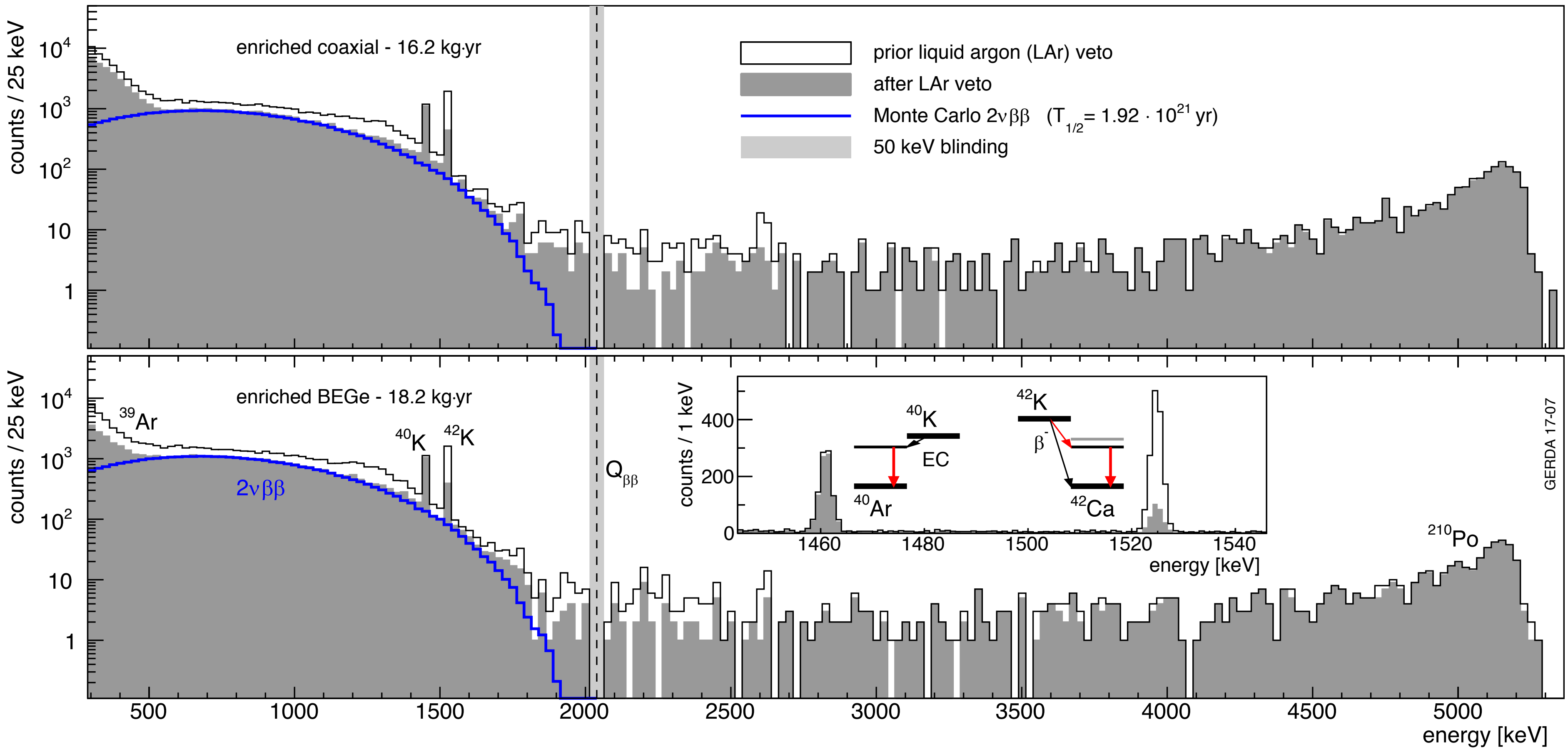
energy reconstruction / resolution

- ~weekly calibration with ^{228}Th calibration sources
- only data with energy scale stability better than resolution is used for analysis
- energy reconstruction with "zero area cusp" (ZAC) filter [Eur.Phys.J. C75 (2015) 255]
- final resolution @ $Q_{\beta\beta}$ corrected for $^{40/42}$K lines in physics data

	FWHM at $Q_{\beta\beta}$
coaxials	3.90(7) keV
BEGe	2.93(6) keV



background spectrum / LAr veto suppression



- compton continuum suppression by LAr veto
  -> left with “pure” $2\nu\beta\beta$ continuum

$0\nu\beta\beta$ acceptance (random coincidences)	
LAr veto	(97.7 ± 0.1) %

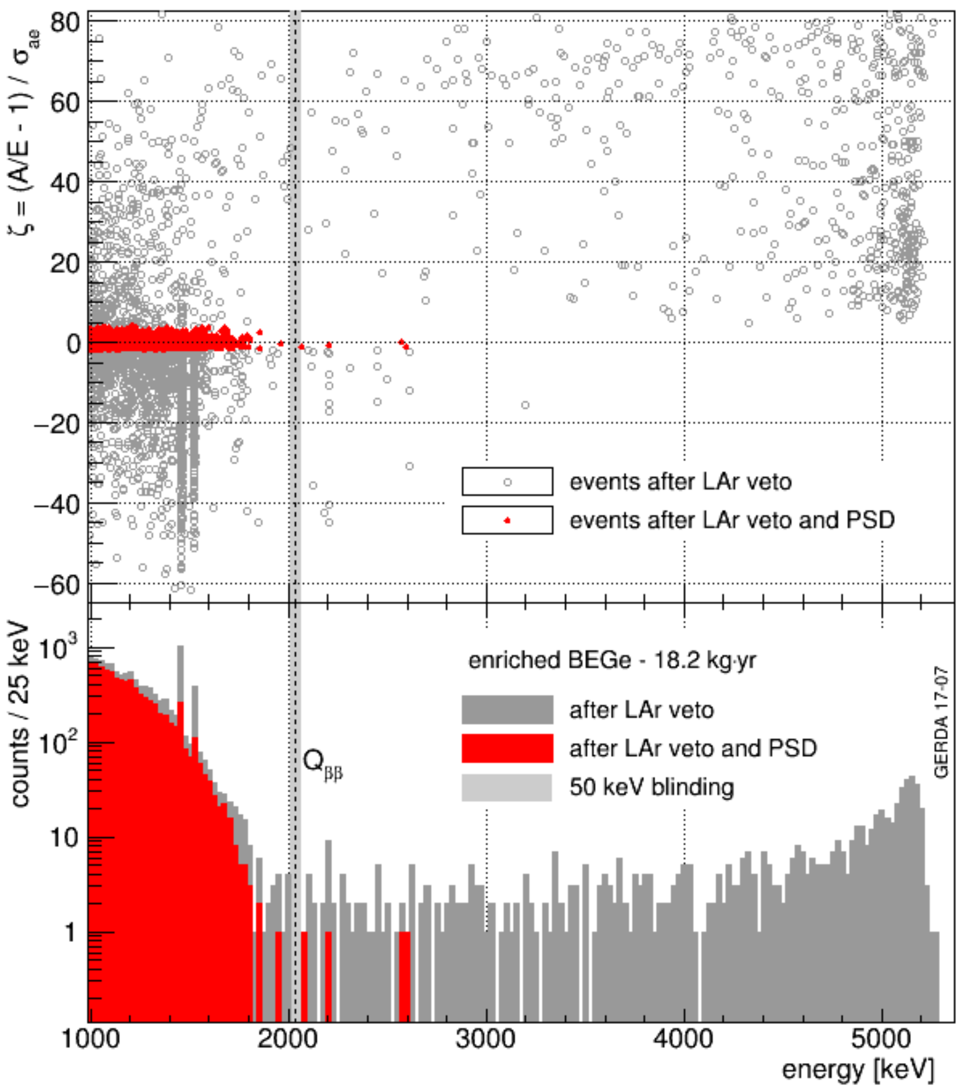
PSD performance

- coaxial detectors:
  - artifical neutral network analysis
  - multi site event recognition, as in Phase I, tuned with calibration data
  - new α event suppression under development

$0\nu\beta\beta$ acceptance (Phase IIa)	
coaxials	(79 ± 5) %

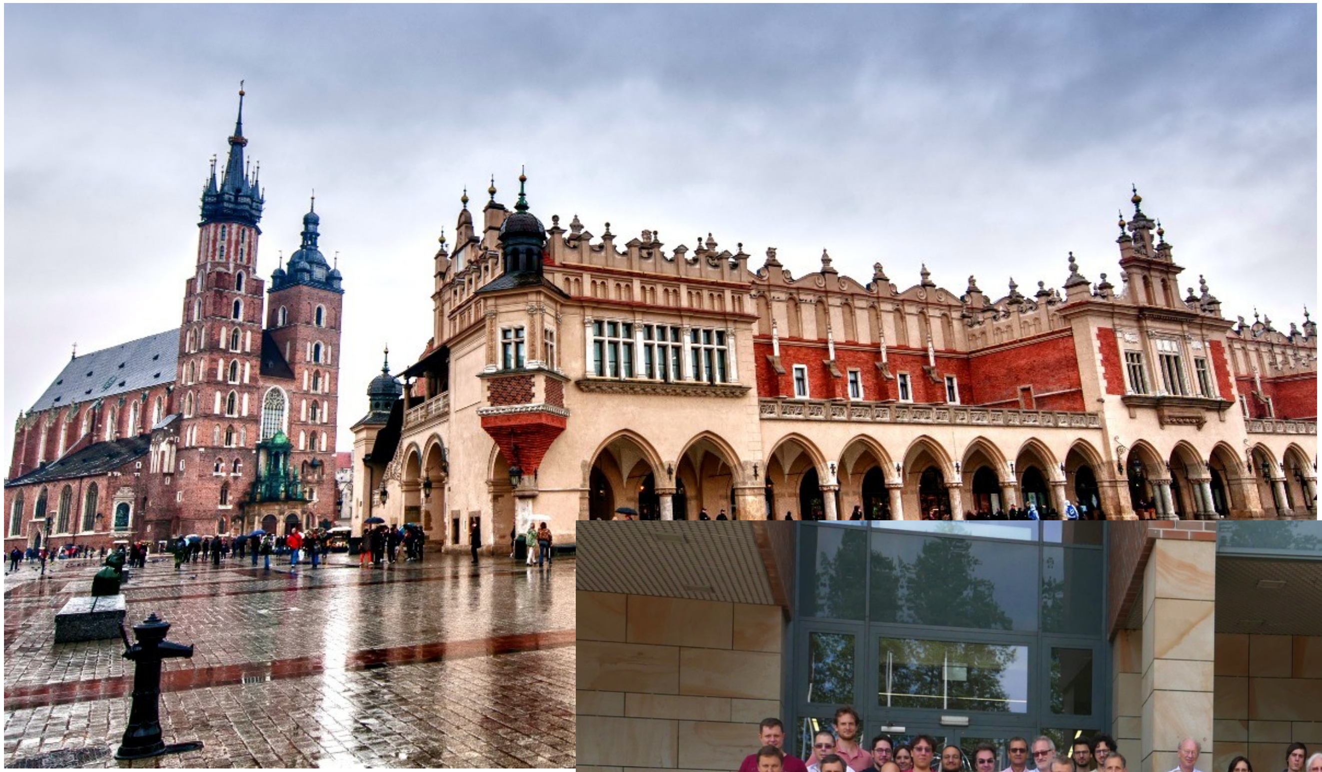
- BEGe detectors:
  - mono-parametric cut based on current pulse amplitude A and total energy E
  - tuned by calibration data

$0\nu\beta\beta$ acceptance	
BEGe	(87 ± 3) %



[Eur.Phys.J. C73 (2013) 2583]

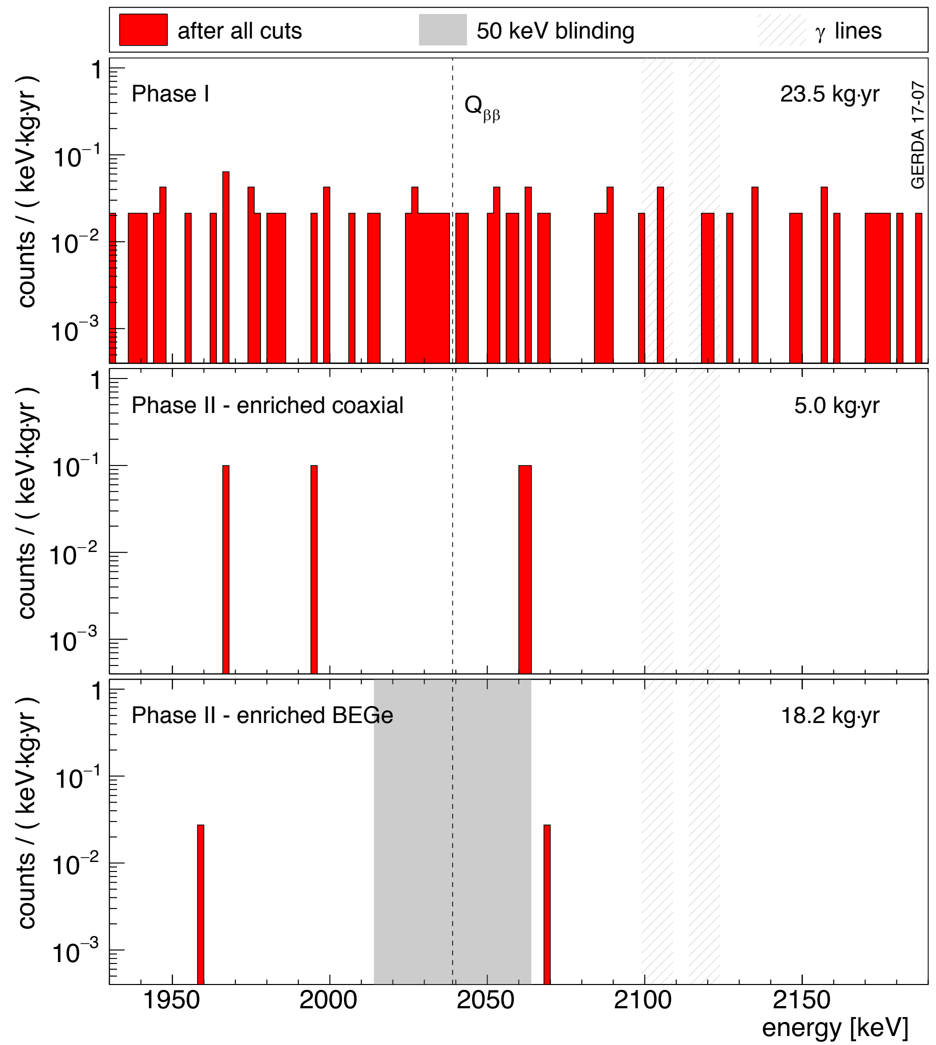
unblinding @ Cracow (30th of June 2016)



new result, statistical analysis

- unblinding of $18.2 \text{ kg} \cdot \text{yr}$ BEGe data

background index at $Q_{\beta\beta}$
2 cts -> $0.5^{+0.5}_{-0.3} \cdot 10^{-3} \cdot \text{cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$



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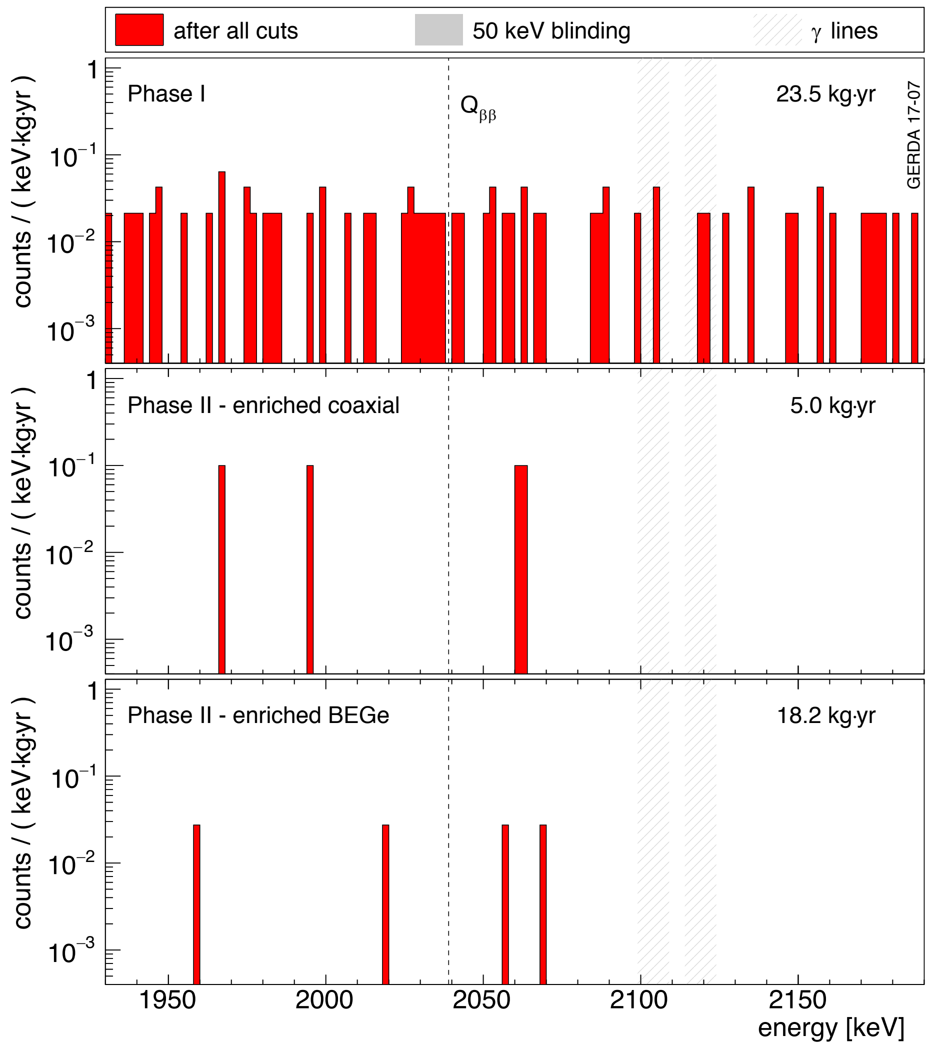
background index at $Q_{\beta\beta}$
4 cts -> $1.0^{+0.6}_{-0.4} \cdot 10^{-3} \cdot \mathrm{cts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})$

-> 2 new events $> 10\ \sigma$ from $Q_{\beta\beta}$



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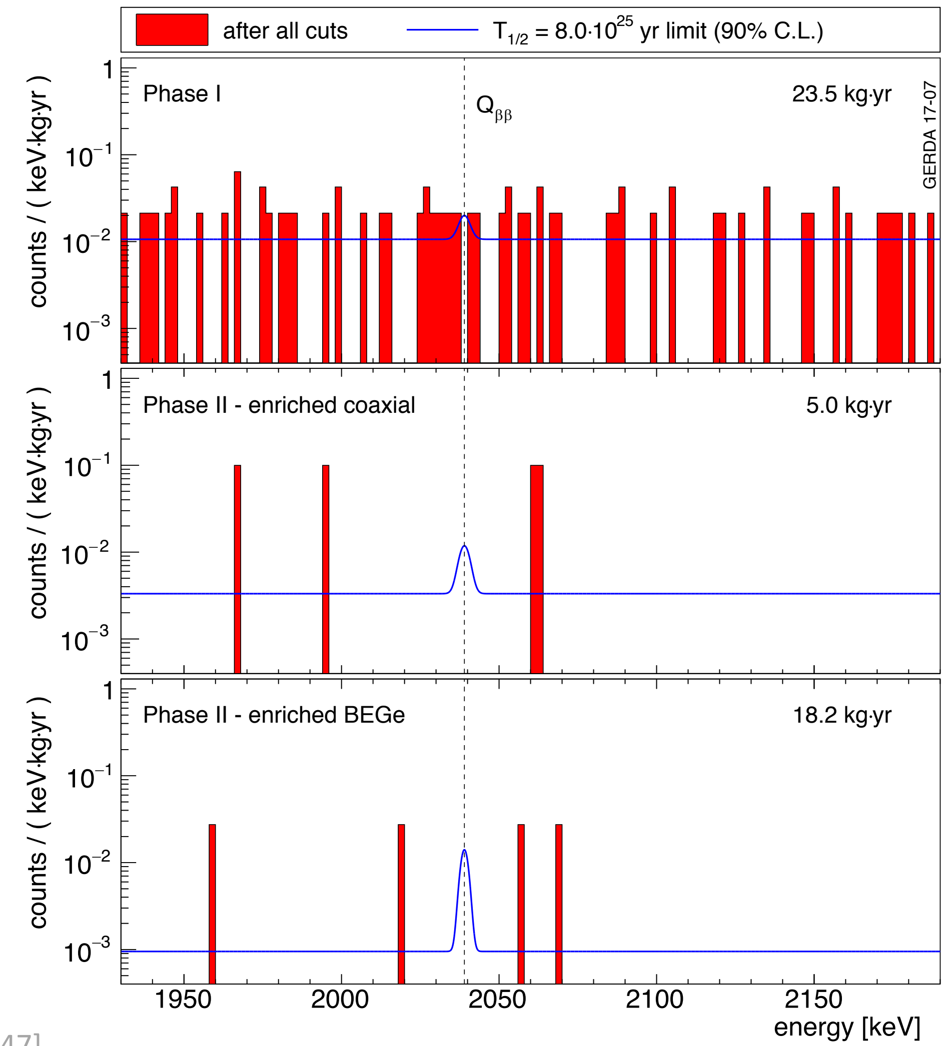
background index at $Q_{\beta\beta}$
4 cts -> $1.0^{+0.6}_{-0.4} \cdot 10^{-3} \cdot \mathrm{cts/(keV \cdot kg \cdot yr)}$

-> 2 new events > 10 σ from $Q_{\beta\beta}$

- combined unbinned maximum likelihood fit of
  - Phase I (4 datasets), $\mathbf{23.5\ kg \cdot yr}$
  - Phase IIa coaxials, $\mathbf{5.0\ kg \cdot yr}$
  - Phase IIb BEGe, $5.8 + 12.4 = \mathbf{18.2\ kg \cdot yr}$

	Profile likelihood 2-side-test-stat*	Bayesian flat prior
$0\nu\beta\beta$ best fit value [cts]	0	0
$T^{0\nu}_{1/2}$ lower limit [10^{25} yr]	> **8.0 (90% CL)**	> 5.1 (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity [10^{25} yr]	> **5.8 (90% CL)**	> 4.5 (90% CI)



**frequentist test-statisitics and methods à la [Nature 544 (2017) 47]

conclusions

- GERDA Phase II is taking data since > 1.5 yr
  - valid exposure of 34.4 kg $\cdot$ yr
  - this data release with 23.3 kg $\cdot$ yr

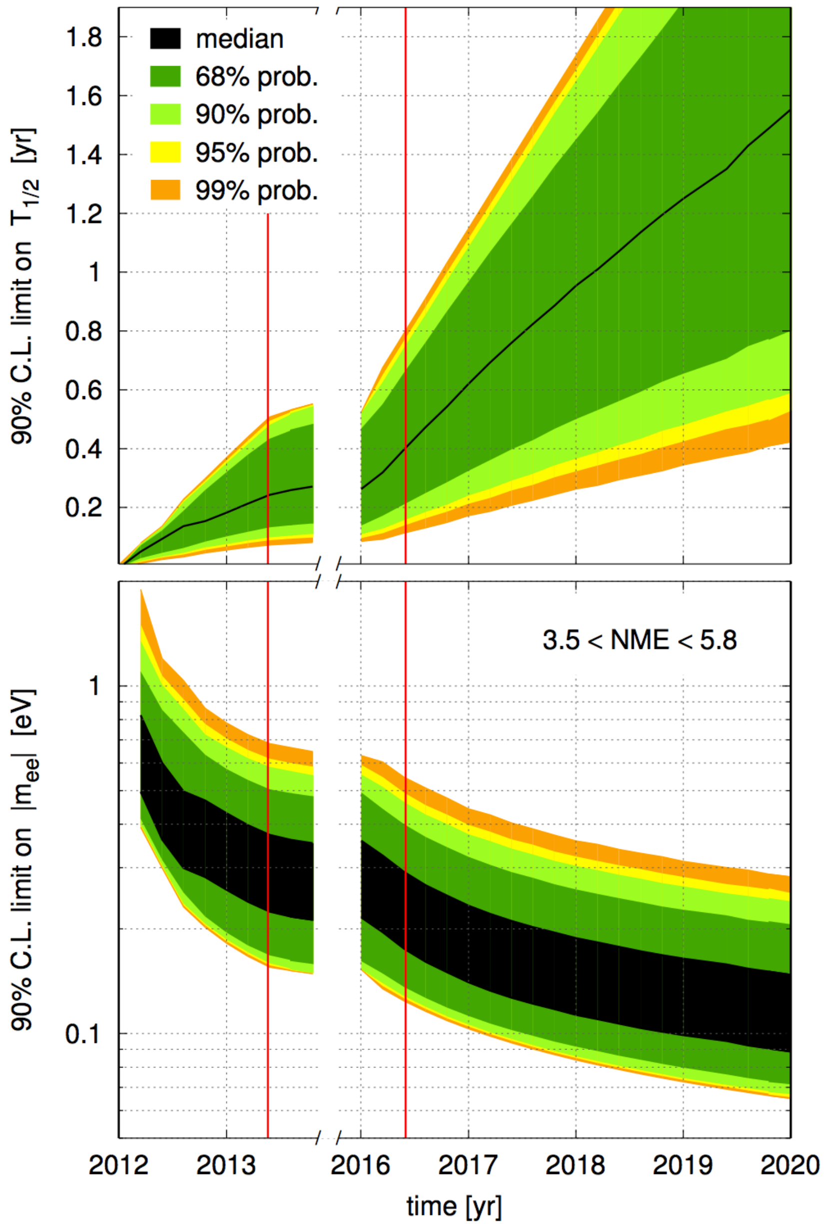
new limit on $0\nu\beta\beta$ decay in ^{76}Ge
$\mathbf{T_{1/2}^{0\nu} > 8.0 \cdot 10^{25}}$ **yr (90% CL)**
$\boldsymbol{m_{\beta\beta} < 0.12 - 0.27}$ **eV (90% CL)**

background index at $Q_{\beta\beta}$	
coaxials	$2.7^{+1.0}_{-0.8} \cdot 10^{-3} \cdot \mathrm{cts/(keV \cdot kg \cdot yr)}$
BEGe	$1.0^{+0.6}_{-0.4} \cdot 10^{-3} \cdot \mathrm{cts/(keV \cdot kg \cdot yr)}$

> high resolution background free $0\nu\beta\beta$ search

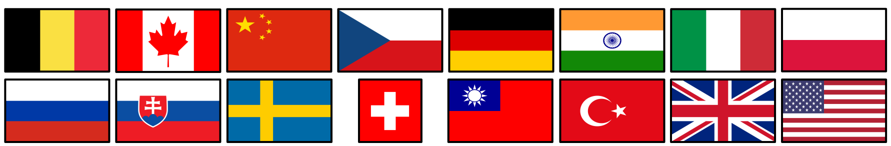
> GERDA will stay background free

Phase II goals		
background	$\sim 10^{-3}$ cts/(keV $\cdot$ kg $\cdot$ yr)	✓
exposure	$\gtrsim 100$ kg $\cdot$ yr	
sensitivity	$\mathbf{T_{1/2}^{0\nu} \gtrsim 10^{26}}$ **yr**	



…and beyond

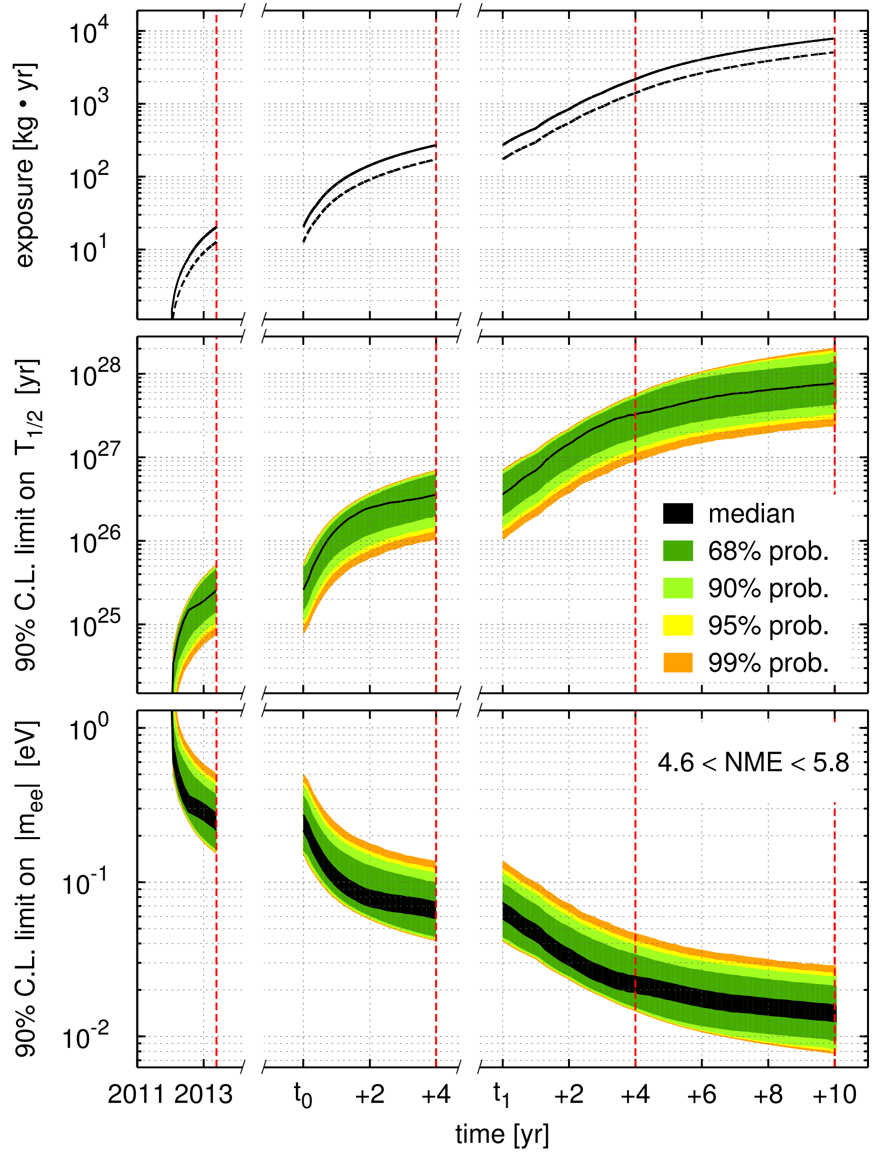
- **LEGEND** (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay) collaboration has been formed in October 2016
  - 219 members, 48 institutions, 16 countries
  - www.legend-exp.org



- first stage: 200 kg upgrade of existing infrastructure at LNGS

LEGEND-200 goals	
background	$\sim 2 \cdot 10^{-4}$ cts/(keV · kg · yr)
discovery potential	$\mathbf{T^{0\nu}_{1/2} > 10^{27}}$ **yr**

LEGEND-1K goals	
background	$< 3 \cdot 10^{-5}$ cts/(keV · kg · yr)
discovery potential	$\mathbf{T^{0\nu}_{1/2} > 10^{28}}$ **yr**

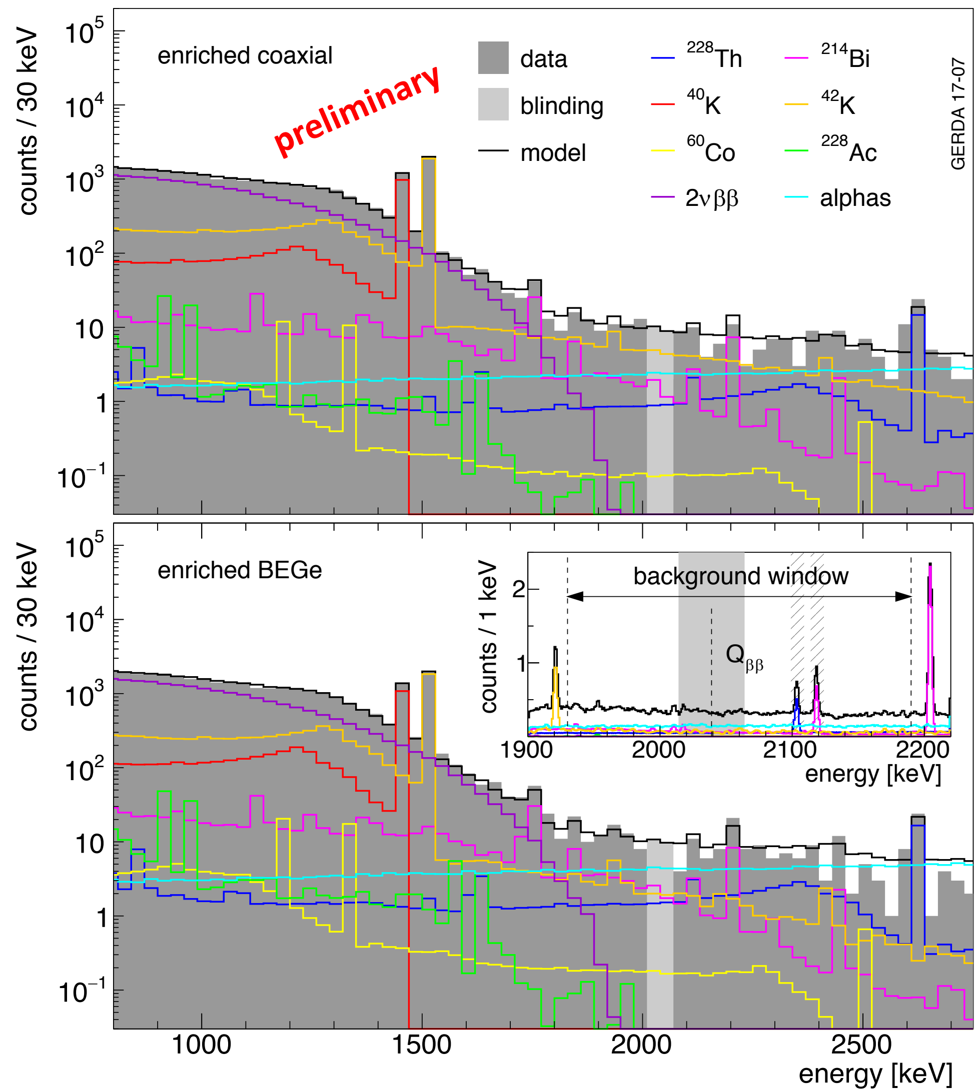


[Eur.Phys.J. C76 (2016) 176]

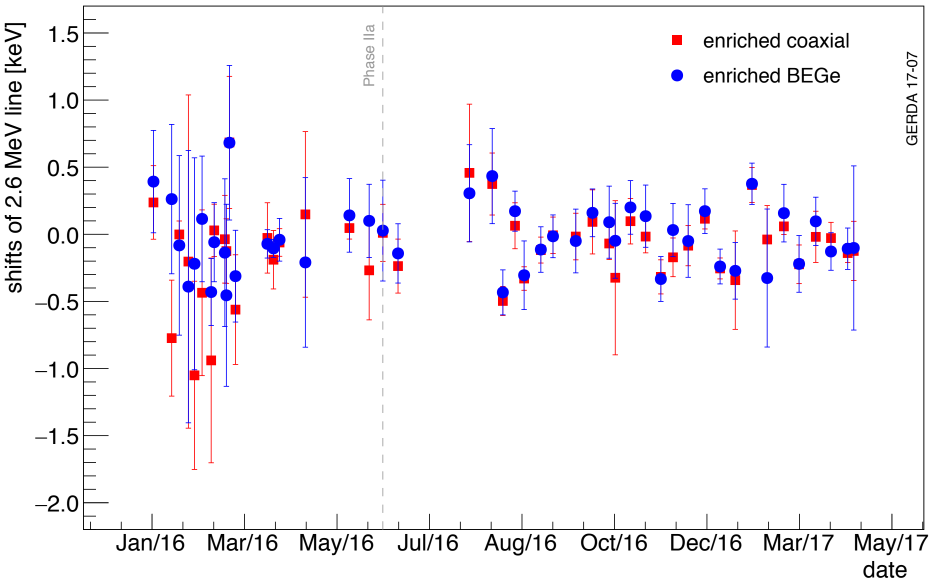
backup

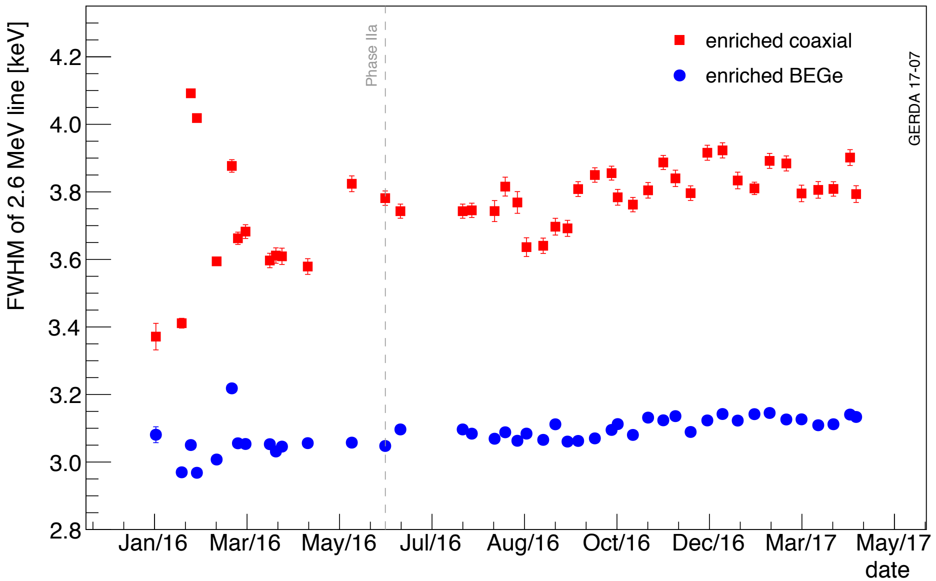
background model

- same approach as in Phase I
  [Eur.Phys.J. C74 (2014) 2763]
- low statistics, constrainty by e.g. screening measurements
- before LAr veto & PSD
- full combined fit including LAr veto and PSD under development
- analysis window $1930 - 2190\ \mathrm{keV}$ excl. $\pm 5\ \mathrm{keV}$ around known γ lines
- flat background in ROI



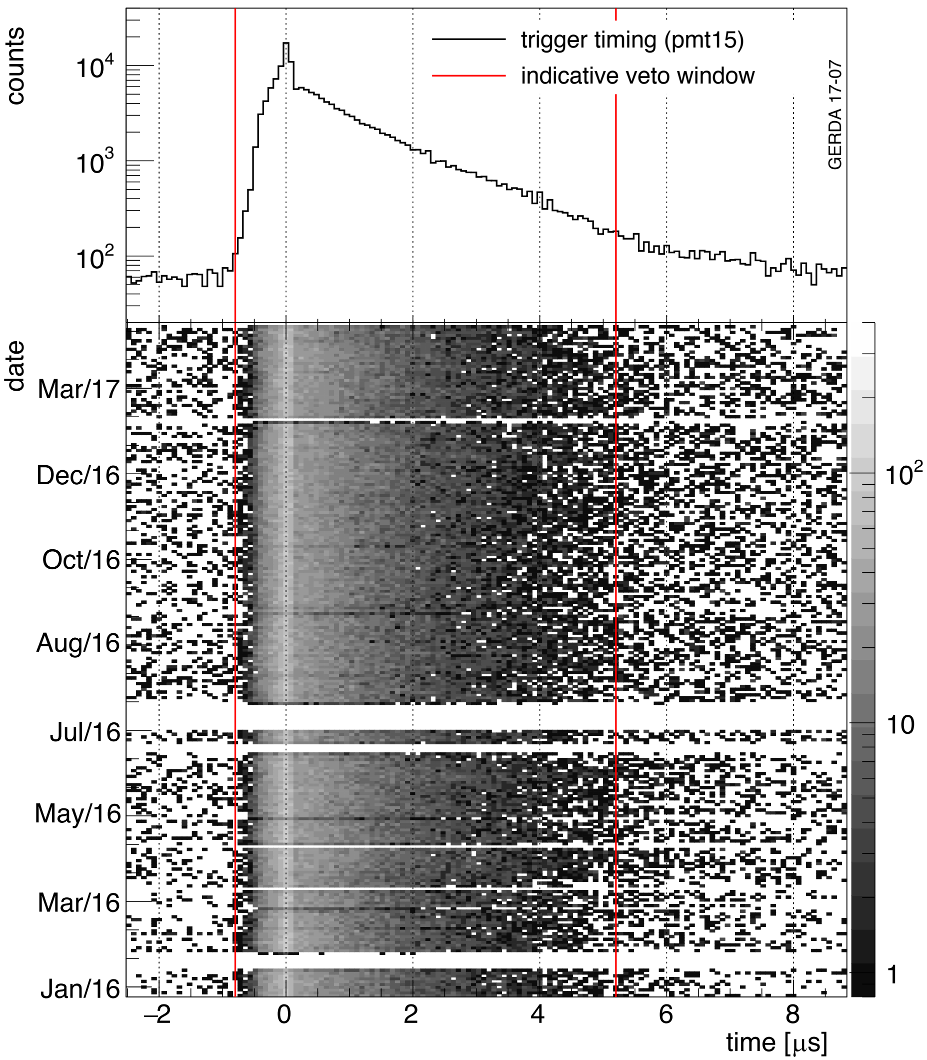
energy scale stability / calibrations

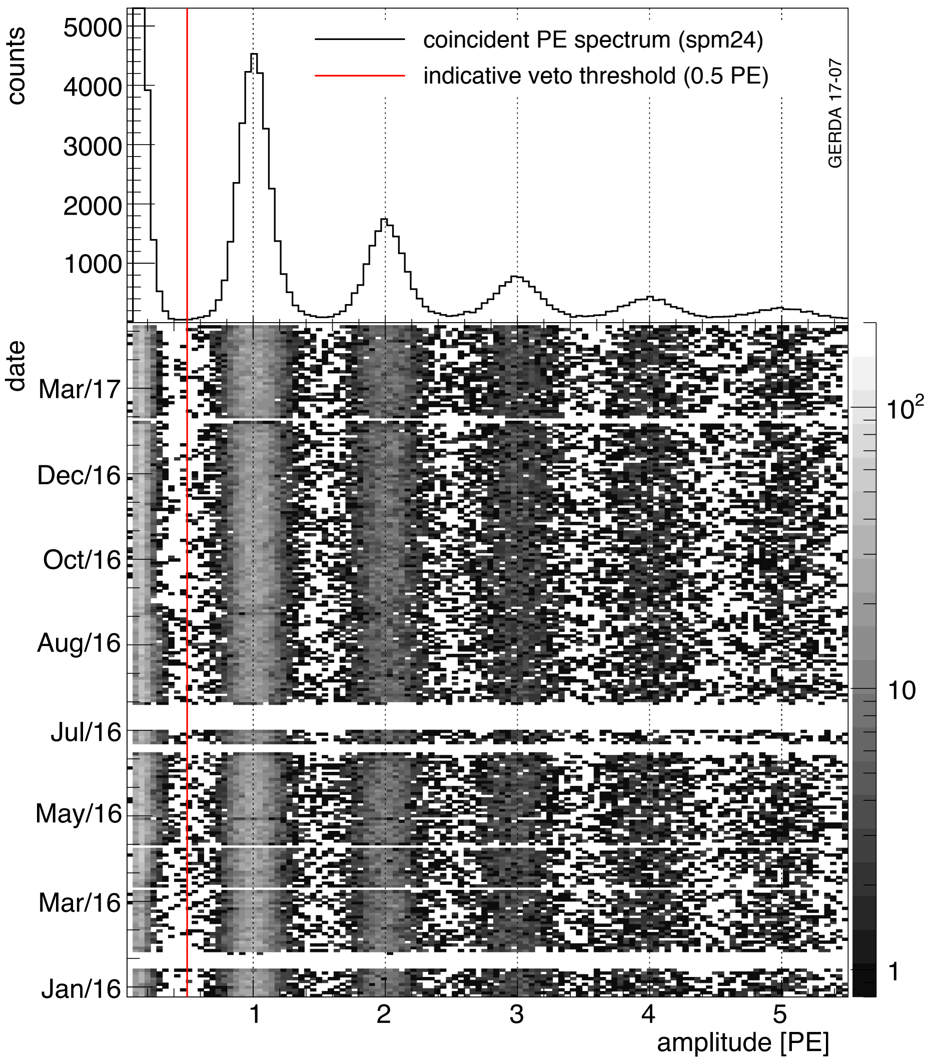




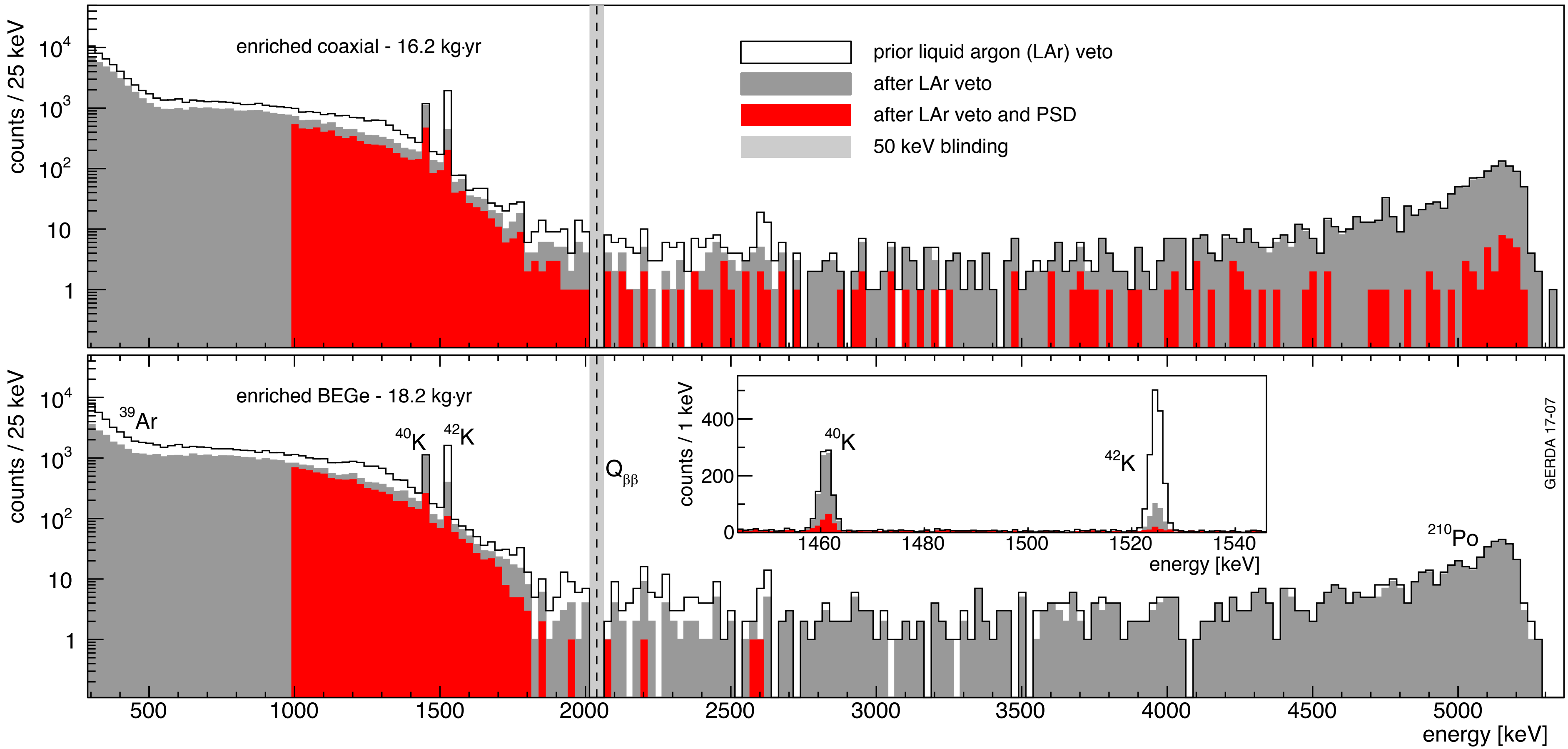
- ~weekly calibration with ^{228}Th calibration sources
- online stability monitoring by injection of test pulses
- only data with energy scale stability better than resolution is used for analysis

liquid argon veto





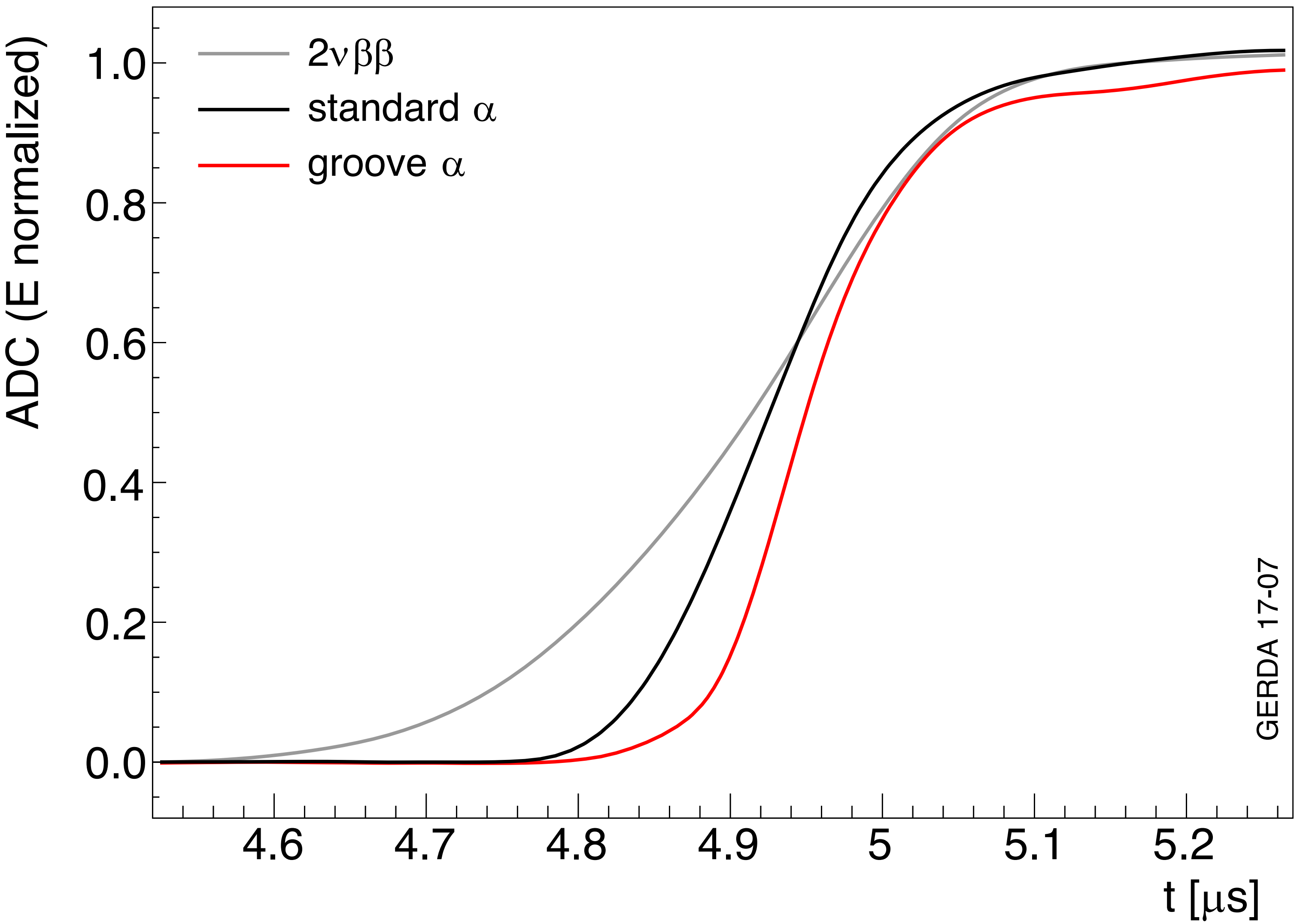
background spectrum



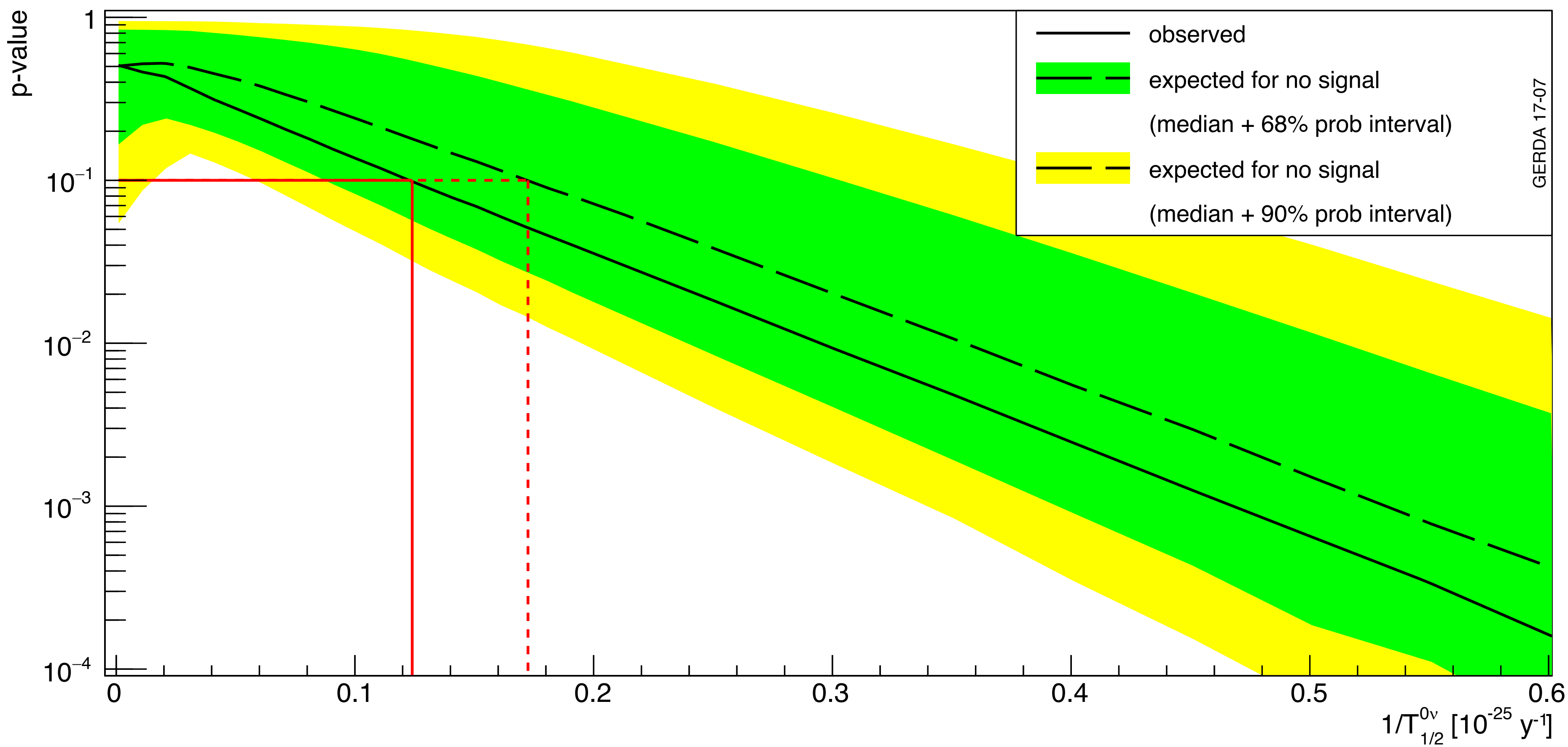
- compton continuum suppression by LAr veto
- multisite/surface event suppression by PSD
  - artifical neutral network analysis for coaxials
  - mono-parametric (A/E) cut for BEGe

$0\nu\beta\beta$ acceptance	
LAr veto	(97.7 ± 0.1) %
PSD coaxials	(79 ± 5) %
PSD BEGe	(87 ± 3) %

groove alpha events

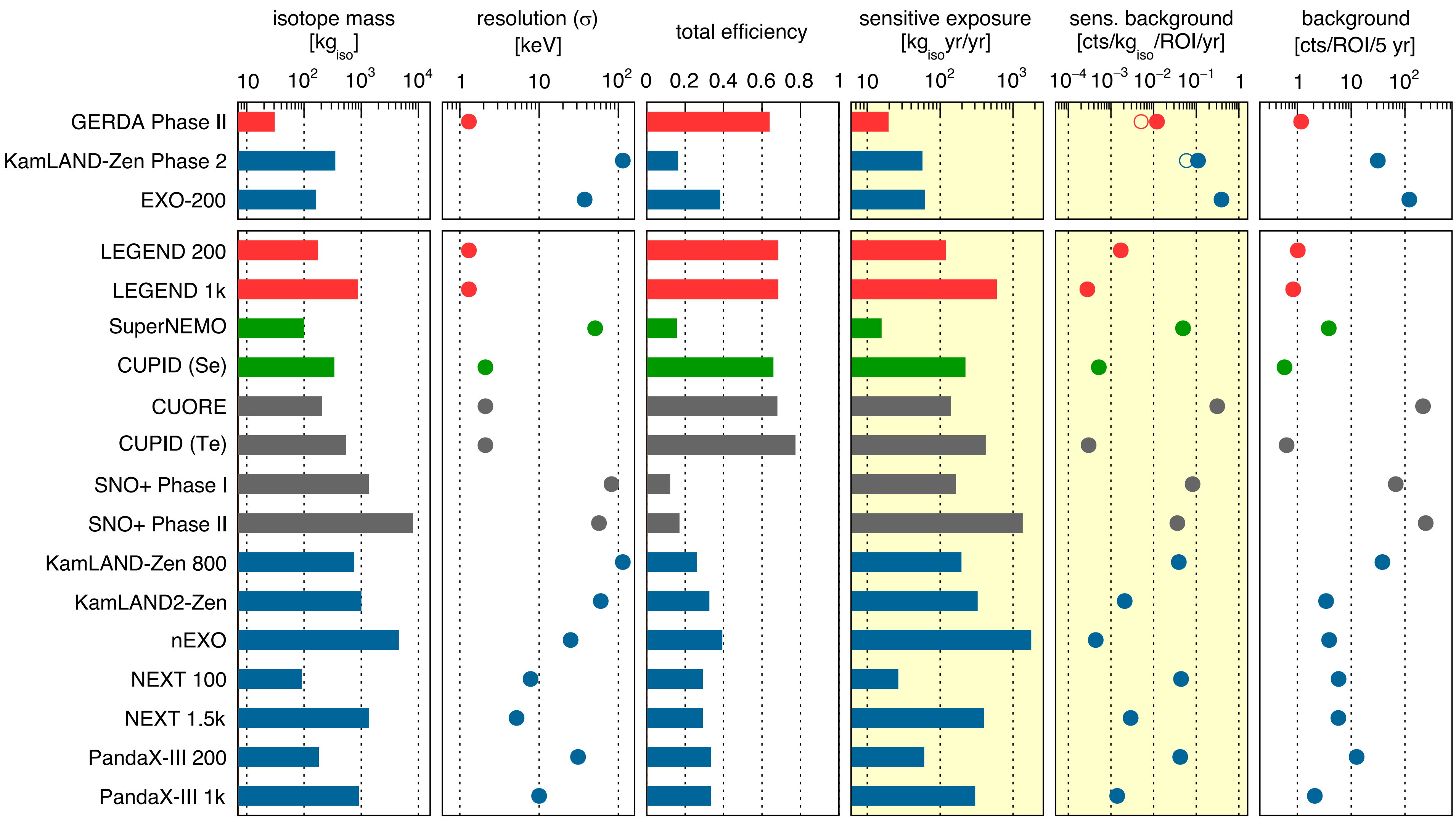


statistical analysis



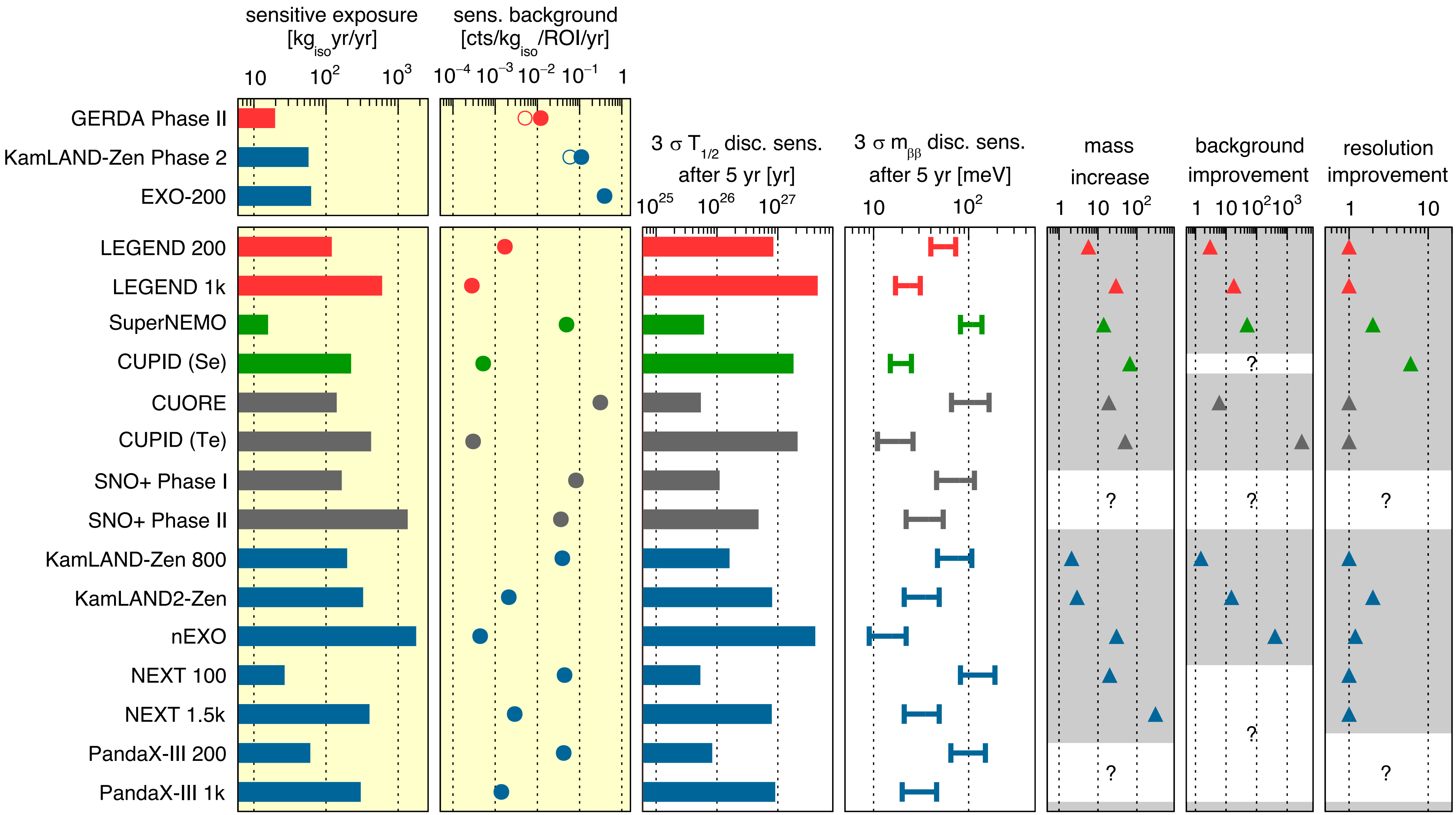
- p-value for the hypothesis test as function of the inverse $T_{1/2}$

comparison of experiments / designs



adapted from Agostini, Bentao, Detwiler [arXiv:1705.02996]

comparison of experiments / designs



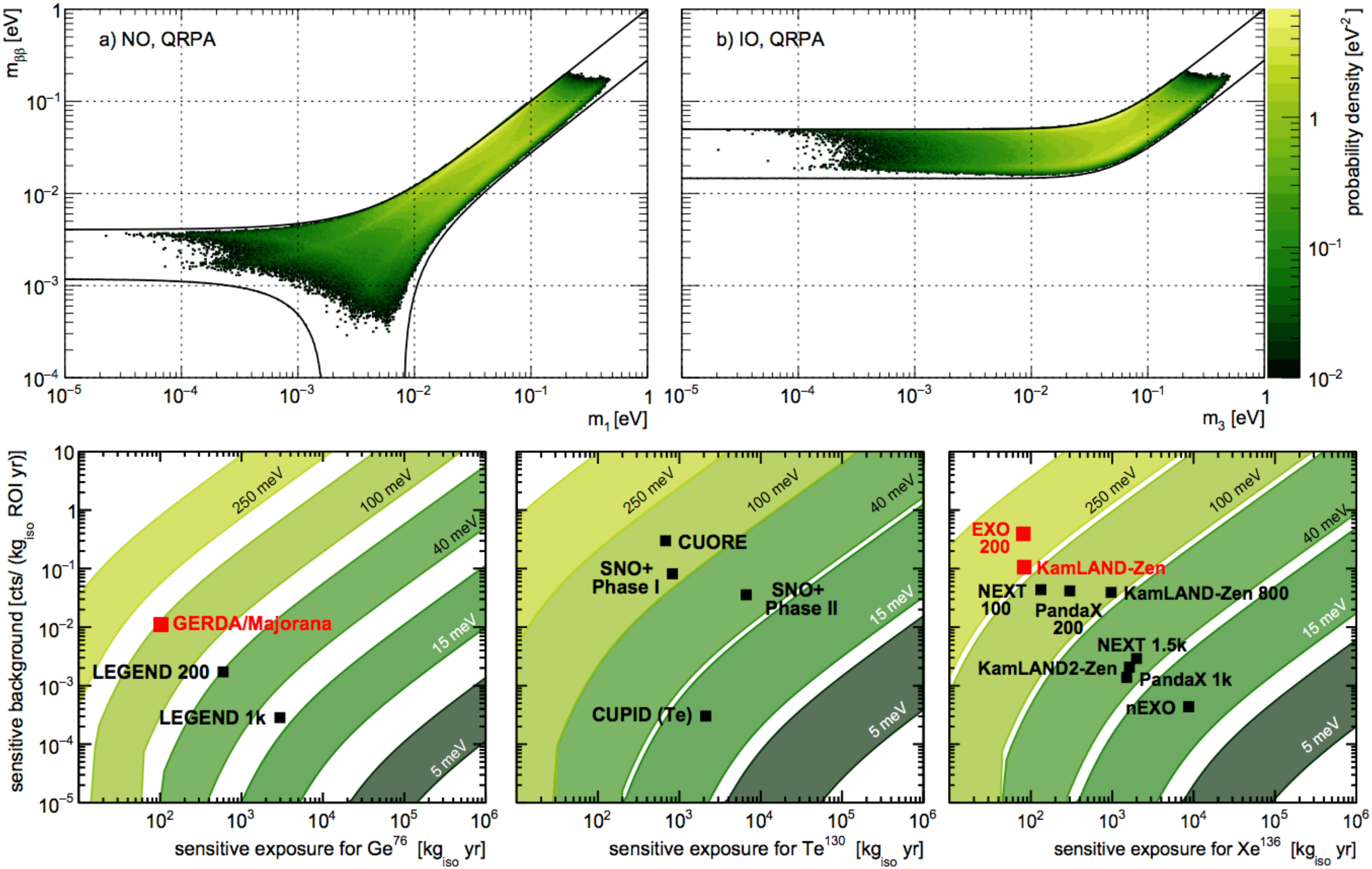
adapted from Agostini, Bentao, Detwiler [arXiv:1705.02996]

comparison of experiments / designs

Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement Bkg	Required Improvement σ	Required Improvement Iso. Mass
LEGEND 200 [61, 62]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [61, 62]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [68, 69]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [58, 59, 70]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [52, 53]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [58, 59, 70]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [66, 71]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [67]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [60]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [60]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [72]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [64, 73]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [74]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200 [65]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [65]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

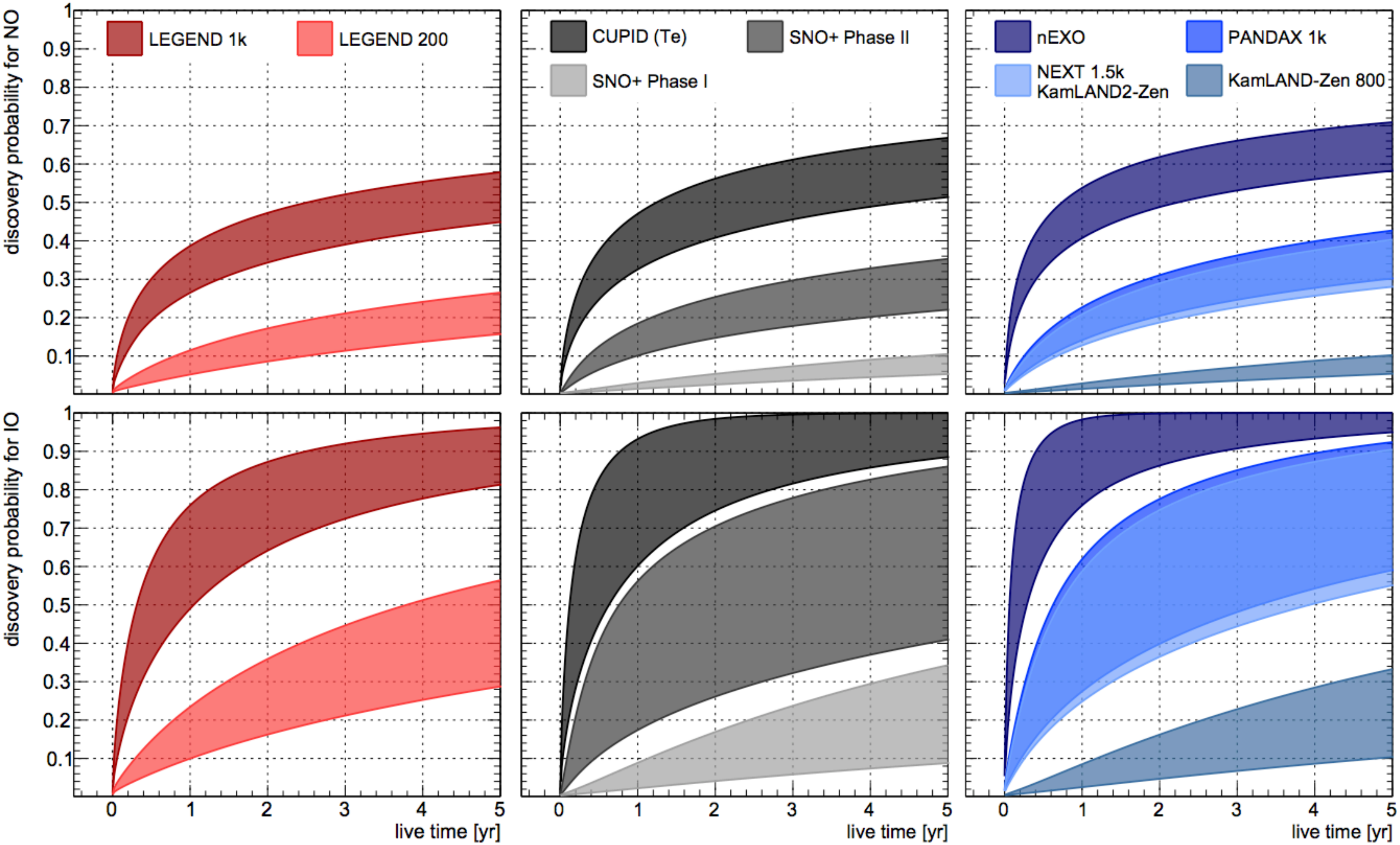
Agostini, Bentao, Detwiler [arXiv:1705.02996]

discovery sensitivity



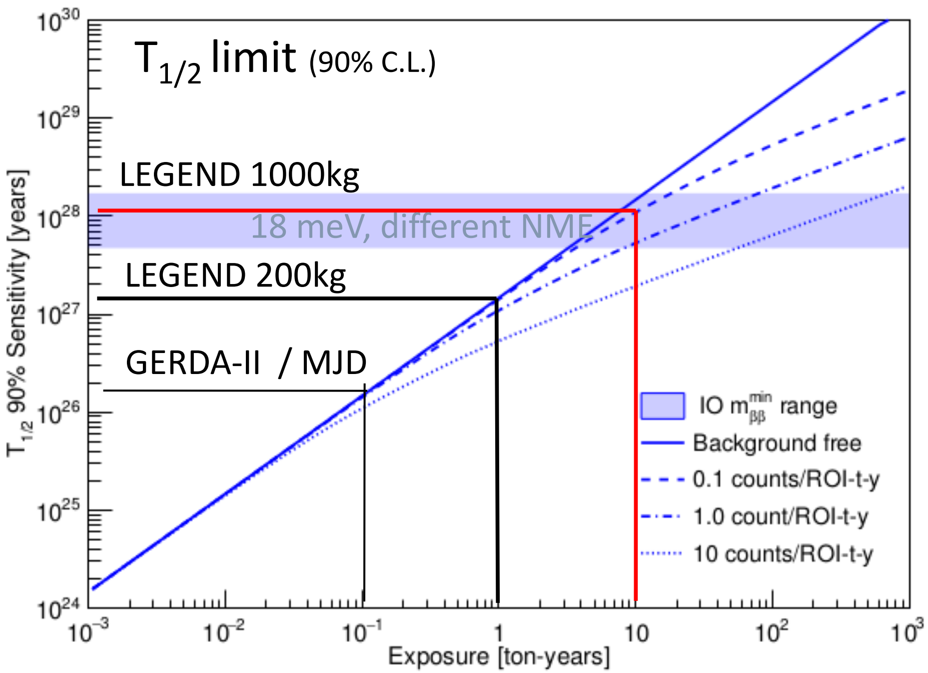
Agostini, Bentao, Detwiler [arXiv:1705.02996]

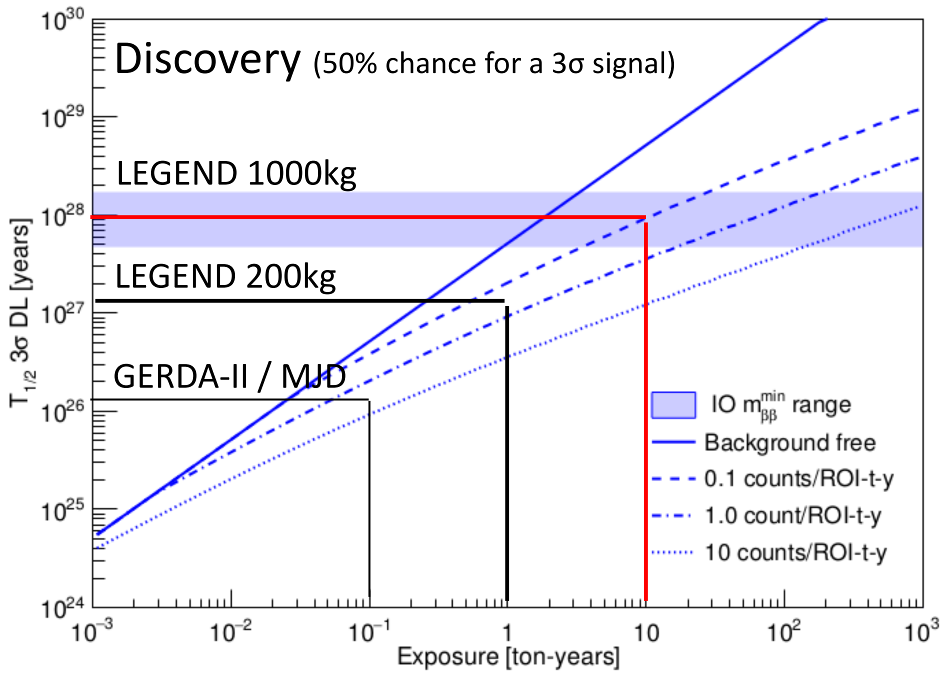
discovery probability



Agostini, Bentao, Detwiler [arXiv:1705.02996]

LEGEND: sensitivity for limit setting / discovery





Plot details:

- 60% "efficiency" including isotope fraction, active volume fraction, analysis cuts
- GERDA-II / MJD: 3 counts/(ROI t yr)
- LEGEND-200: 0.6 counts/(ROI t yr)
- LEGEND-1000: 0.1 counts/(ROI t yr)

N.B.: background-free operation is a prerequisite for a discovery