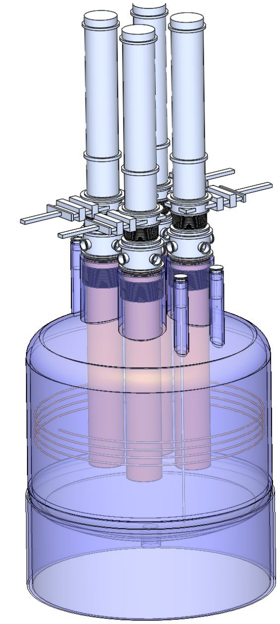


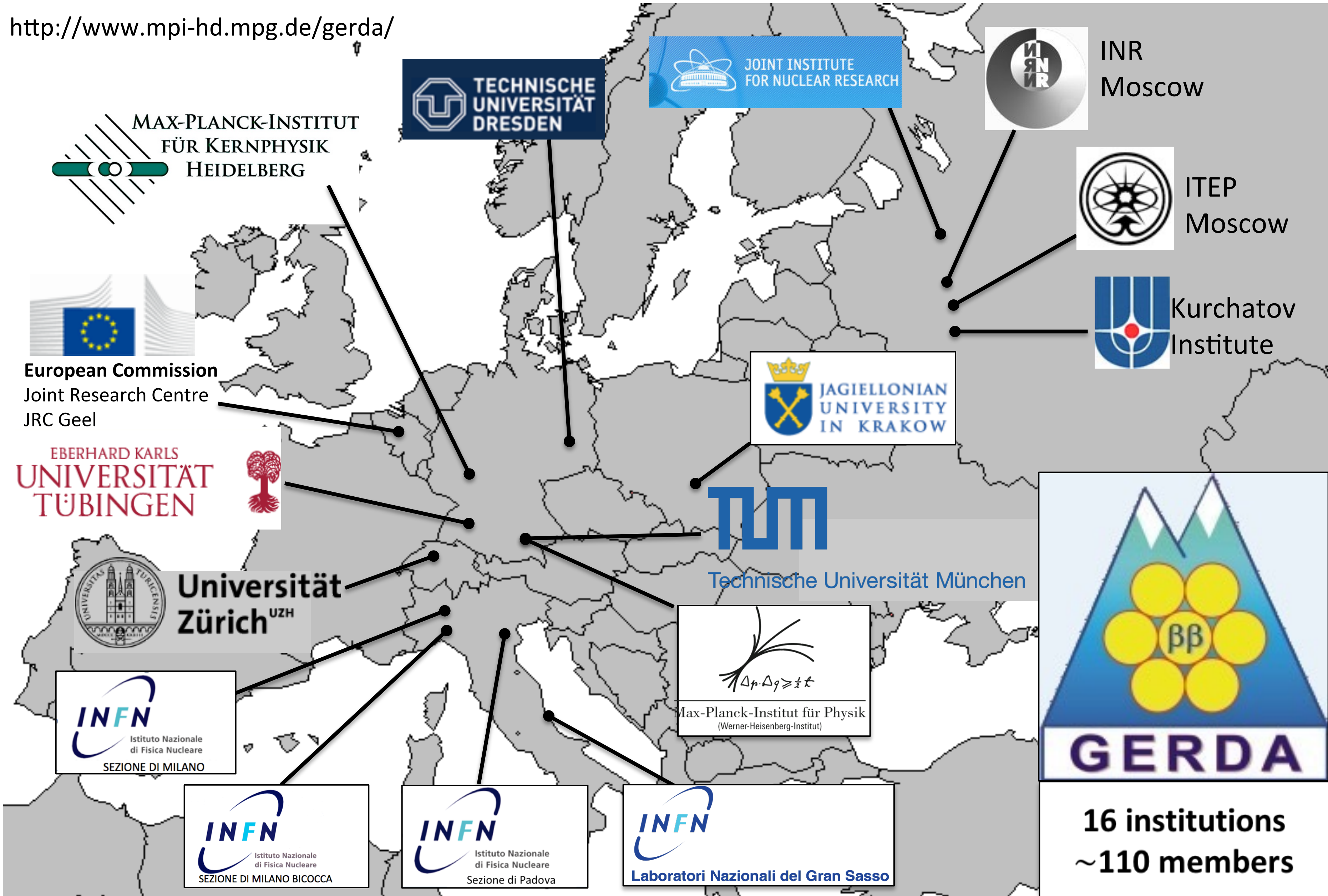
Results from GERDA and prospects for LEGEND: background-free search for neutrinoless double beta decay of ^{76}Ge

Stefan Schönert, TU München
on behalf of the GERDA and LEGEND collaborations

XVII International workshop on neutrino telescopes,
13-17 March 2017, Venice, Palazzo Franchetti - Istituto Veneto di Scienze, Lettere ed Arti

the GERDA collaboration

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



16 institutions
~110 members

GERDA detection strategy

- Search for neutrinoless double beta decay of ^{76}Ge:

$$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + 2e^-$$

$\Rightarrow$ $\boxed{\Delta L = 2}$ $\Rightarrow$ $\boxed{\text{beyond Standard Model physics}}$

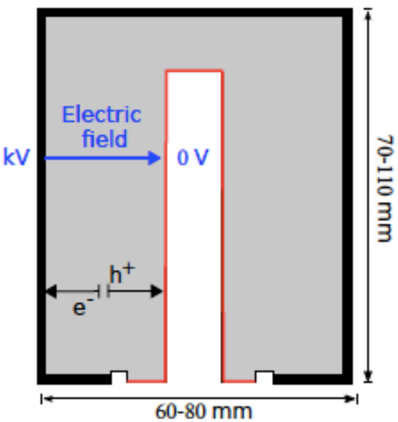
$\Rightarrow$ $\boxed{\text{Majorana mass or other L-violating physics}}$

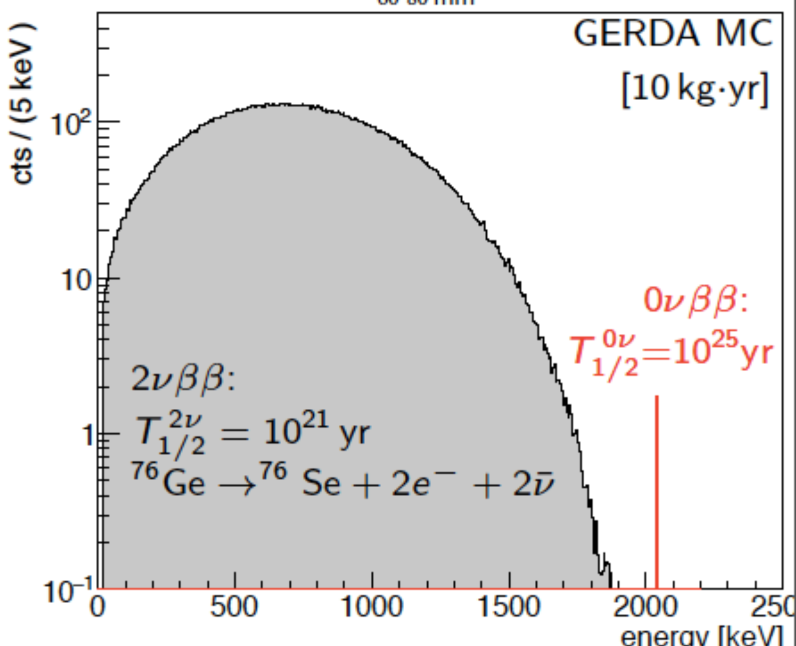
- Q-value of ^{76}Ge: $Q_{\beta\beta}$=2039 keV

- High purity Ge detectors (87% ^{76}Ge):
  - source=detector $\Rightarrow$ high detection efficiency
  - ultra radio-pure $\Rightarrow$ no intrinsic background
  - high density $\Rightarrow$ $0\nu\beta\beta$ point like events
  - semiconductor $\Rightarrow$ $\Delta E \approx 0.2\%$ at $Q_{\beta\beta}$

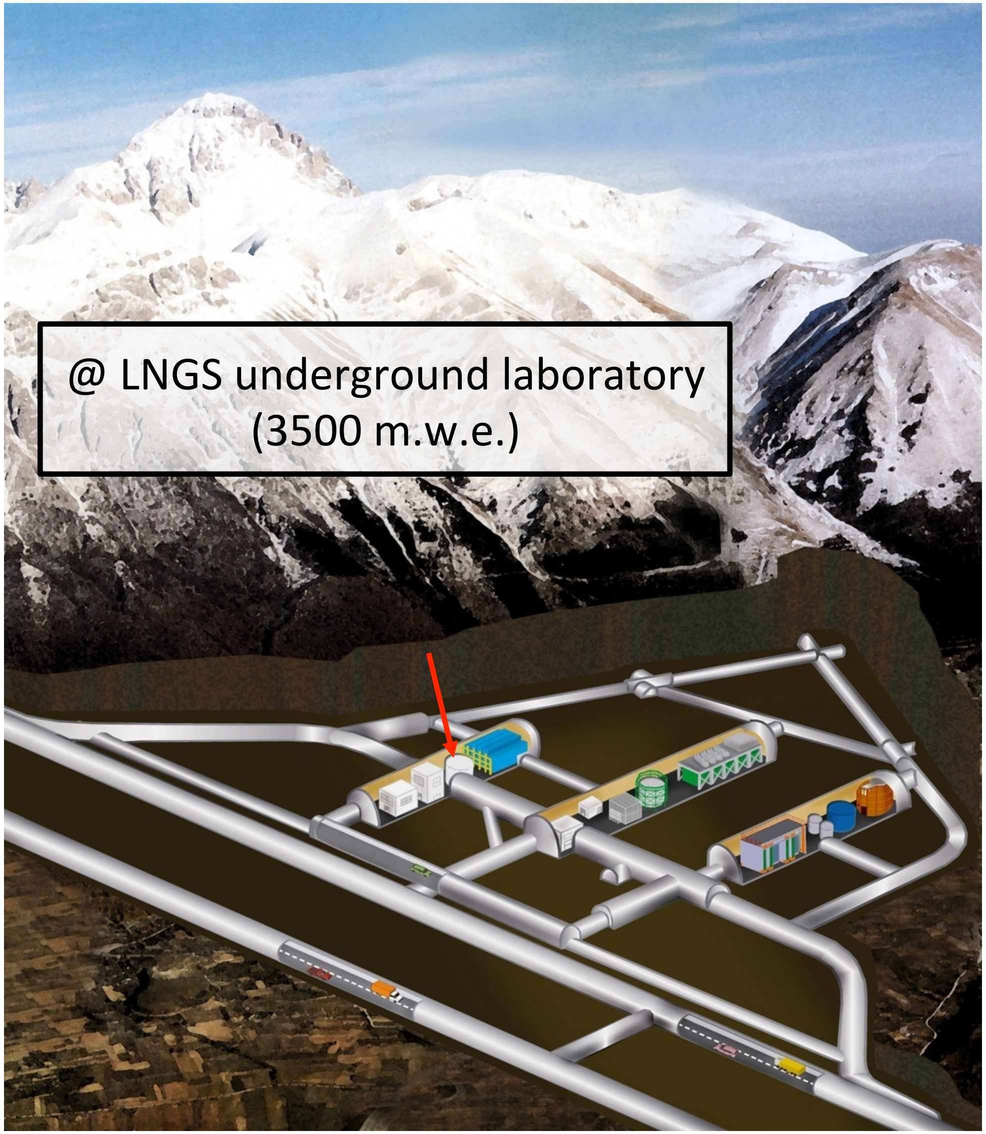
- $0\nu\beta\beta$ signature:
  - point-like energy deposition in detector bulk volume
  - sharp energy peak at 2039 keV (FWHM = 3-4 keV)

- Blind analysis

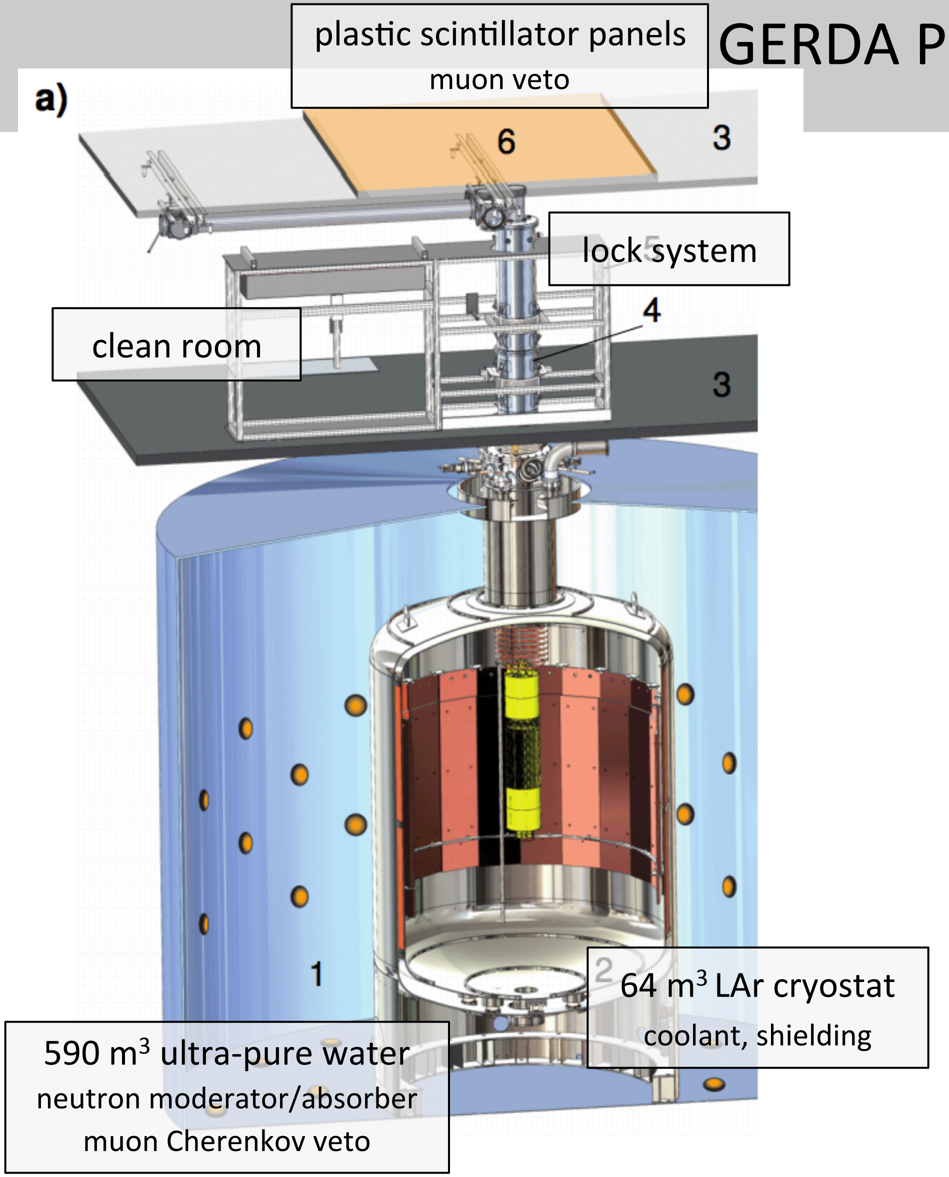




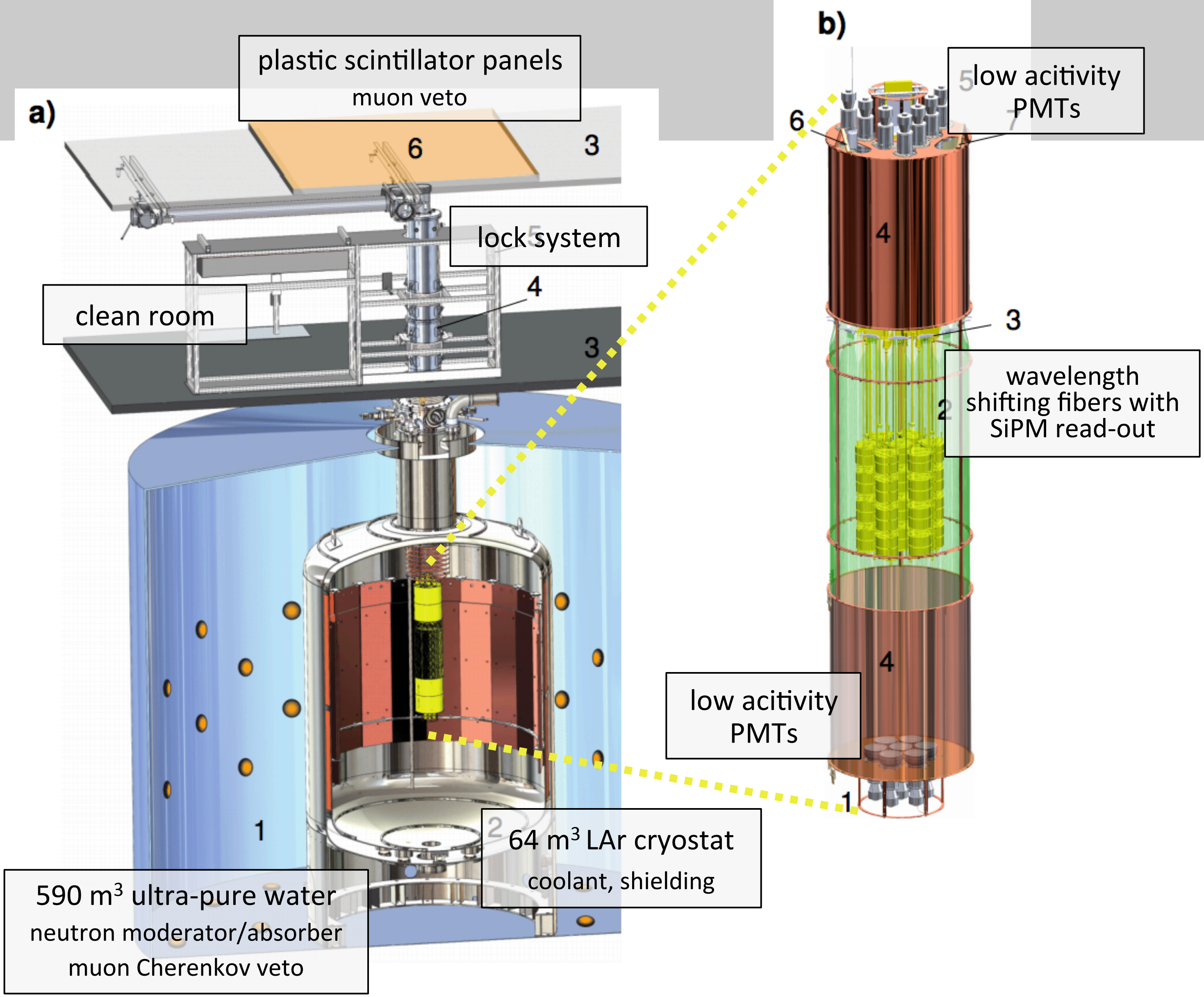
GERDA Phase II experimental setup at LNGS



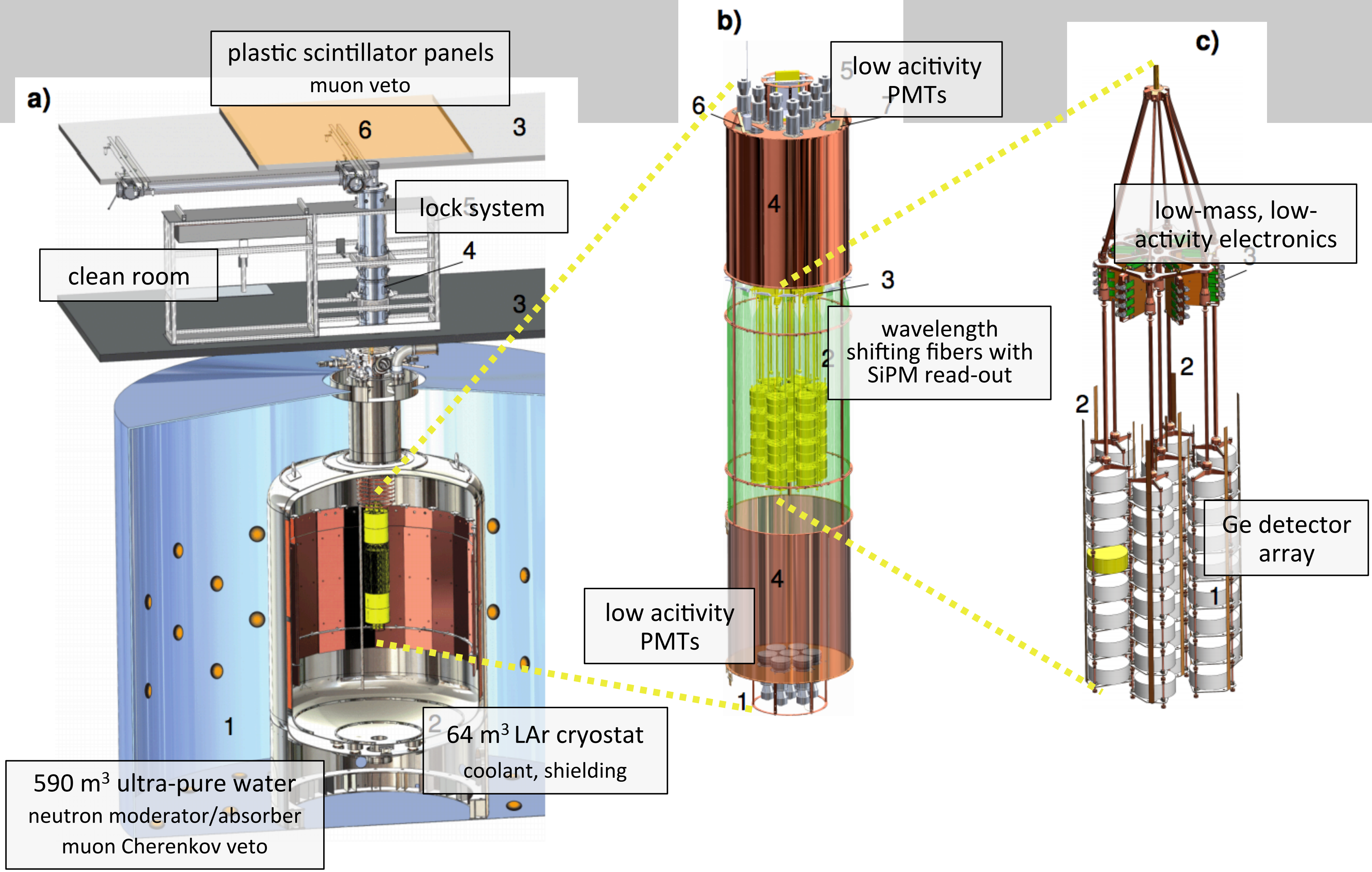
GERDA Phase II experimental setup at LNGS



a) overview



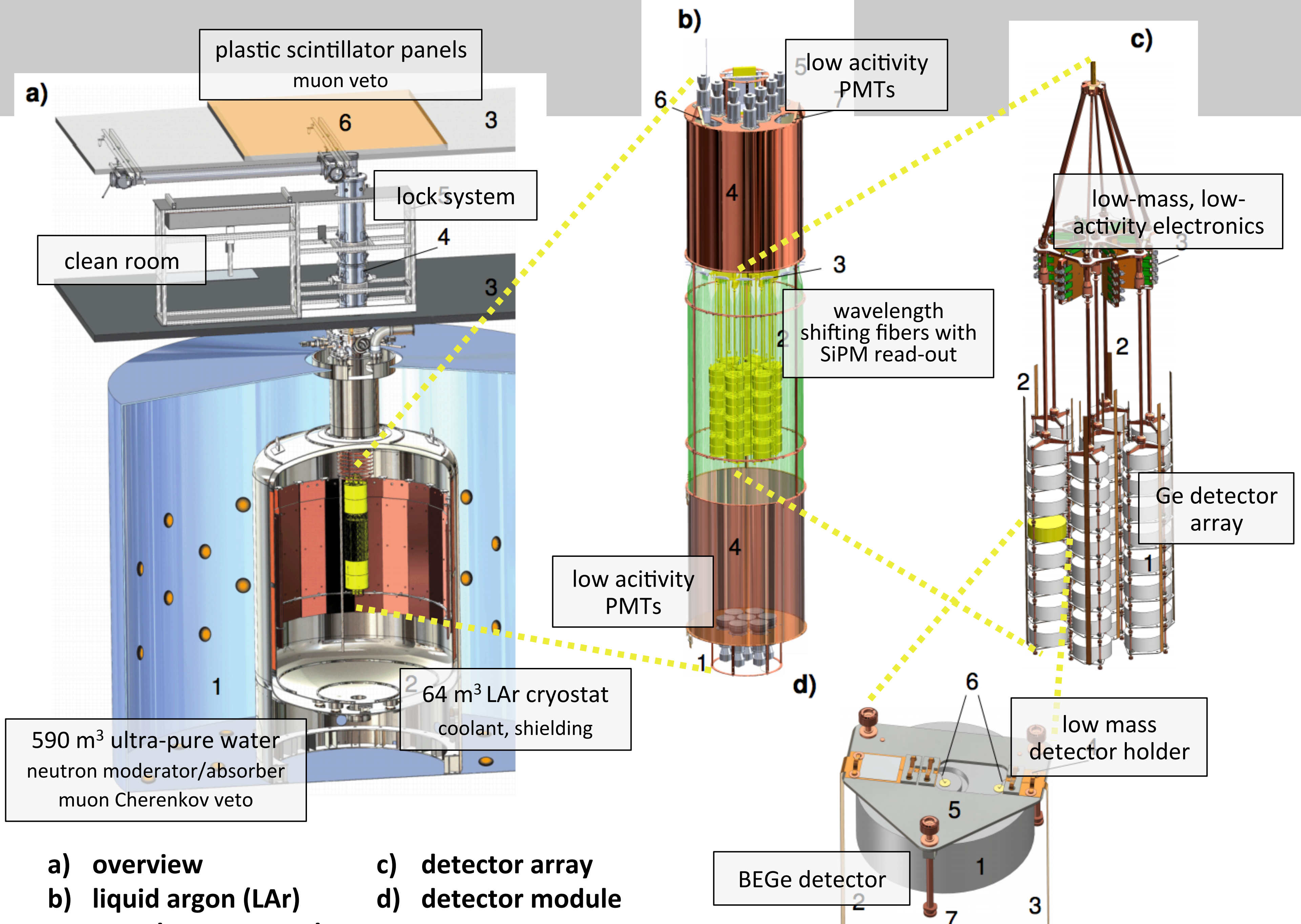
- **a) overview**
- **b) liquid argon (LAr) veto instrumentation**



a) overview

b) liquid argon (LAr) veto instrumentation

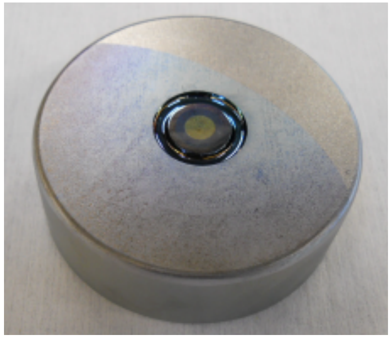
c) detector array



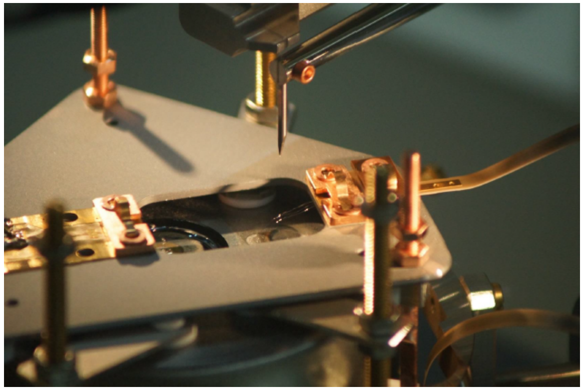
a) **overview**
b) **liquid argon (LAr) veto instrumentation**
c) **detector array**
d) **detector module**

GERDA Phase II experimental setup at LNGS

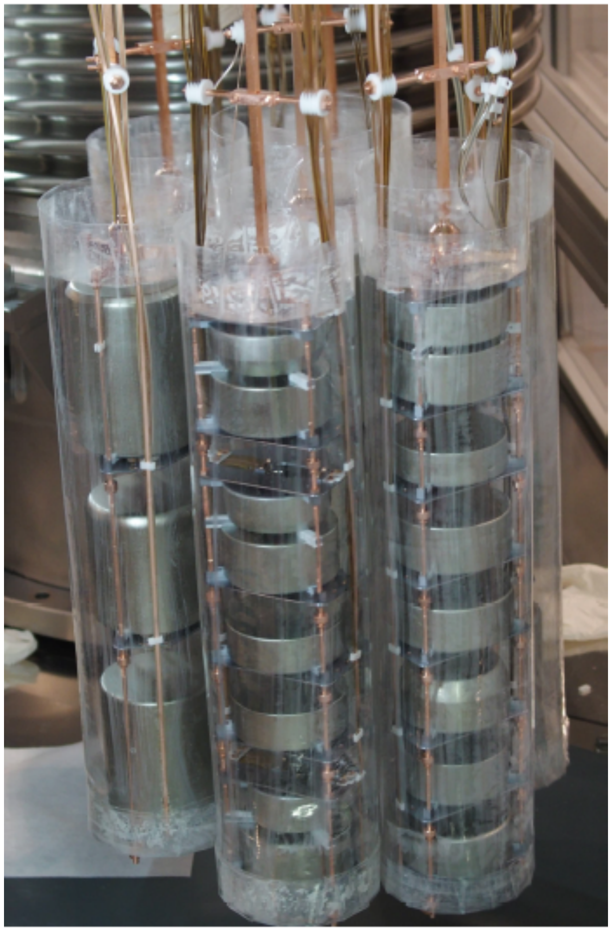
New low-mass detector holder (silicon, copper, PTFE)



New thick-window BEGe detectors

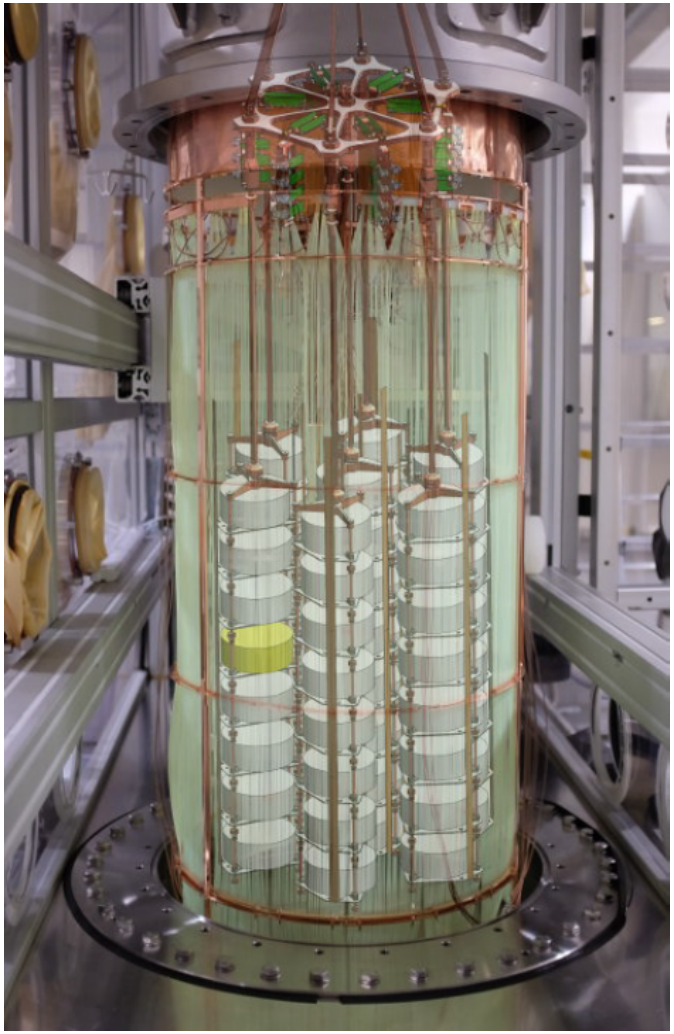


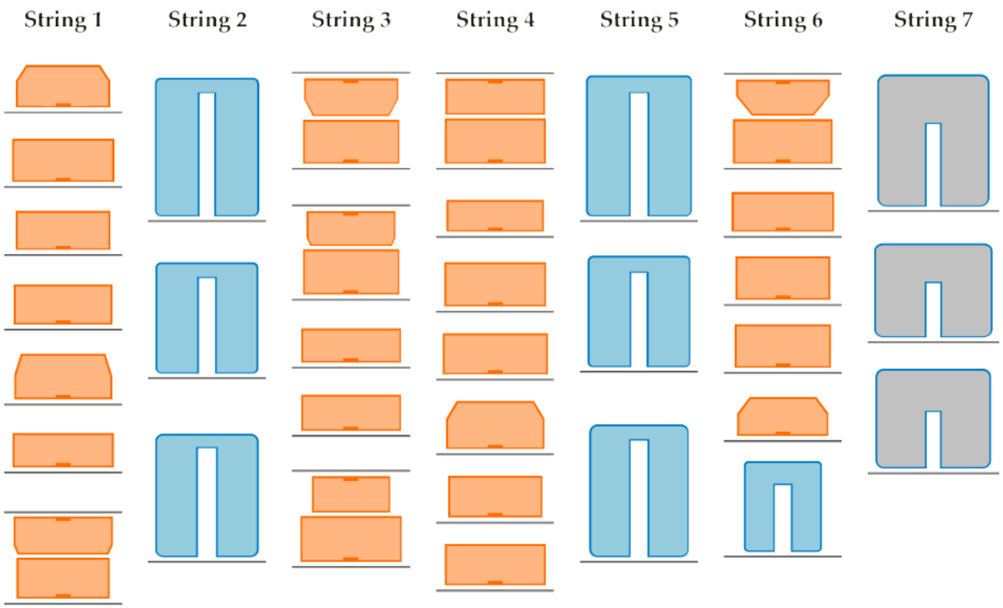
New signal and HV contacting by wire bonding flat ribbon cables



New TBP coated nylon mini-shrouds to reduce attraction K42 ions to n+ surface

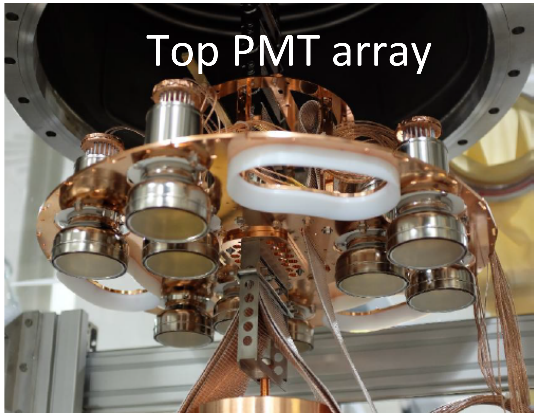
Germanium Phase II detector array

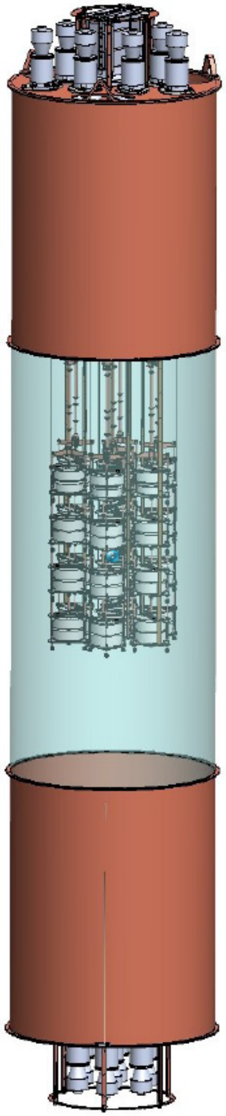


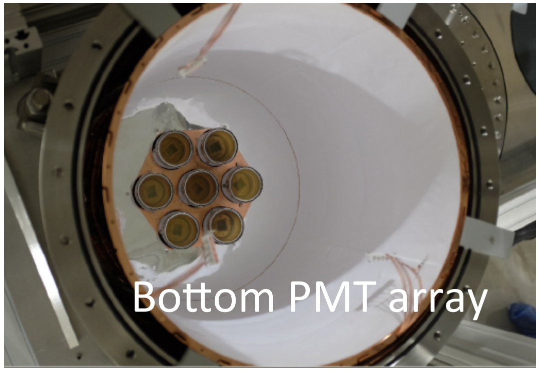


- 7 strings, 40 detectors in total
  - 7 enriched semi-coax (15.8 kg)
  - 30 enriched thick-window BEGe (20 kg)
  - 3 natural semi-coax (7.6 kg)
- HPGe array enclosed by liquid argon veto
- Phase II data started Dec. 2015

Liquid argon instrumentation to identify backgrounds

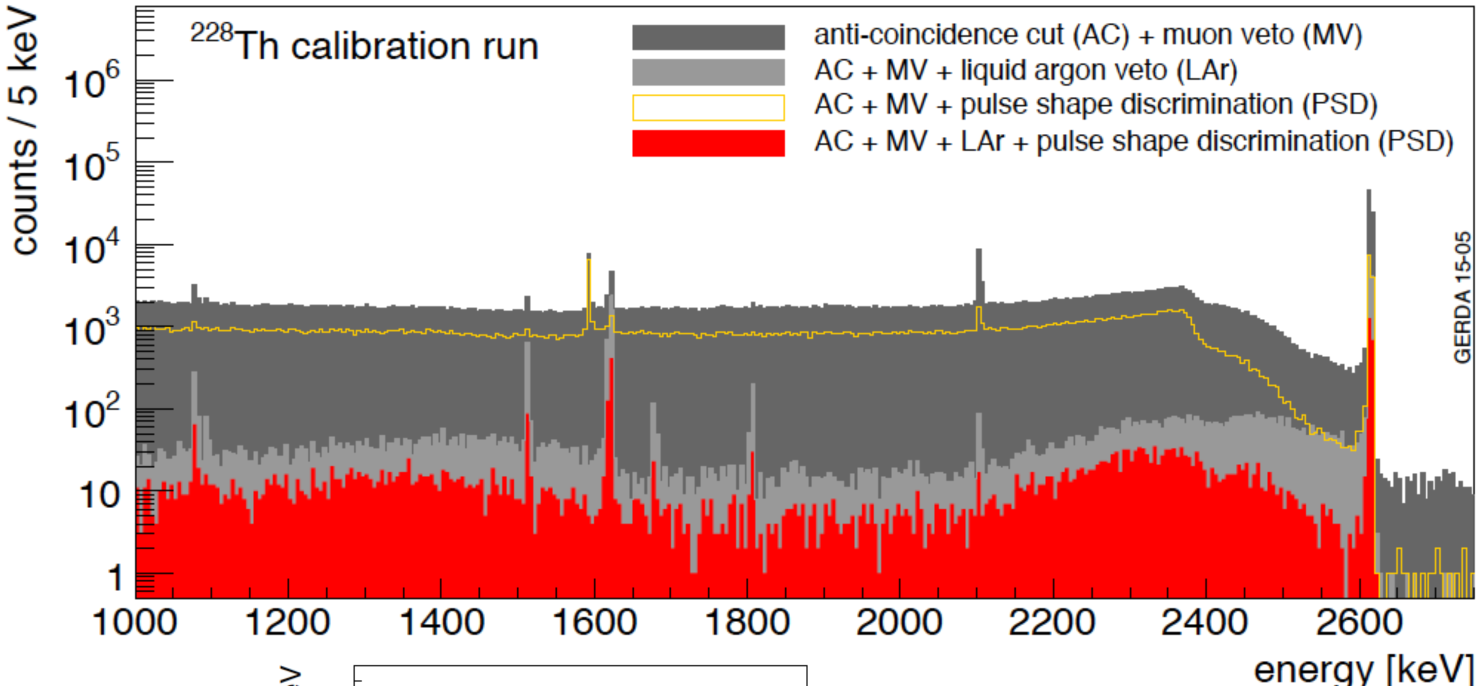


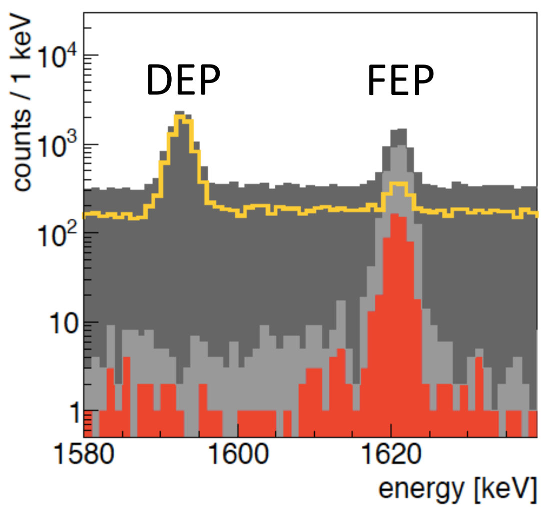




- Event rejection: >0.5 p.e. in any of SiPM or PMT channel (within 5μs of Ge trigger)
- Accidentals (dead time): 2.3±0.1% (Ar-39)

Background suppression (calibration data)

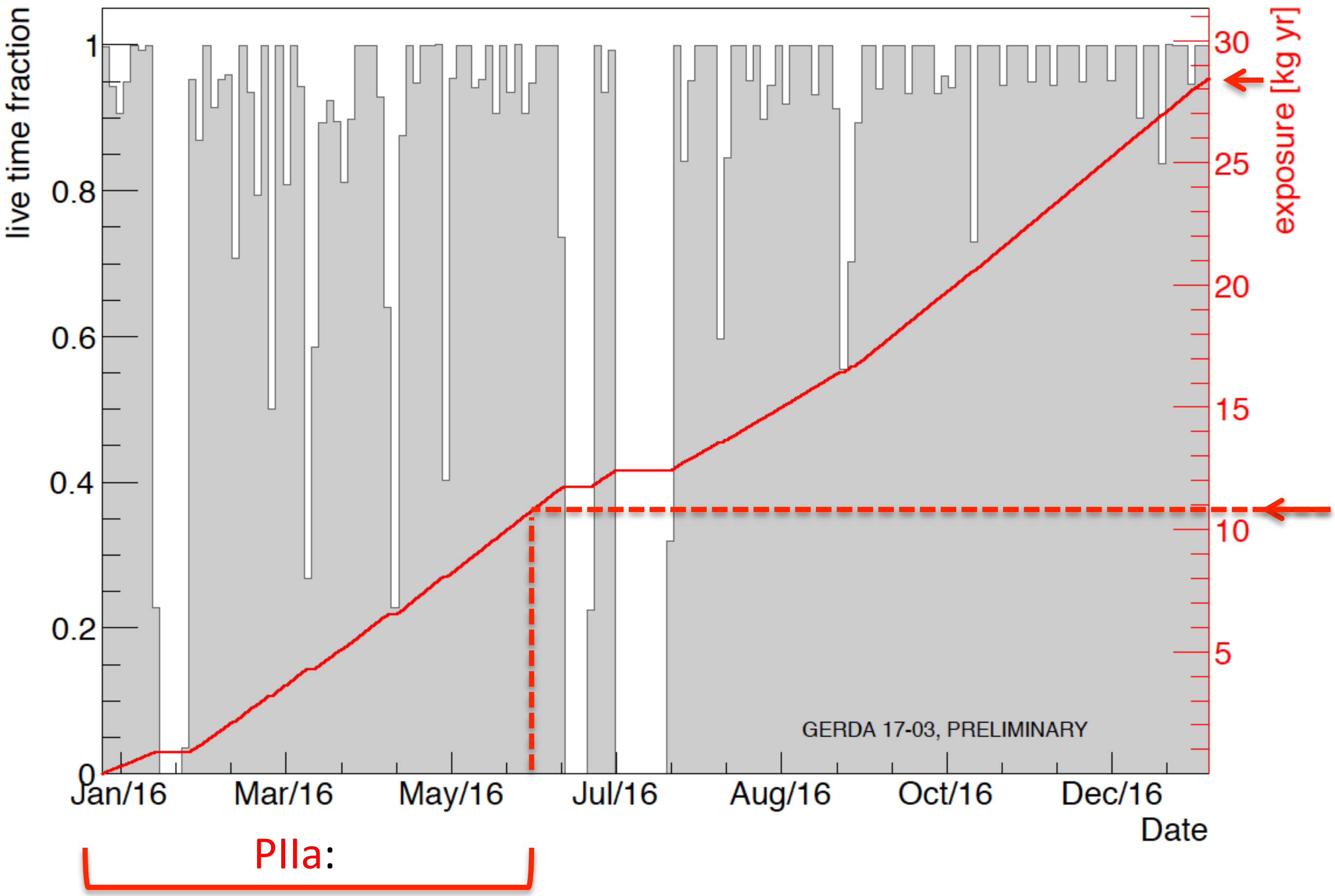




<u>Background suppression by</u>

- Muon veto (MV)
- Anti-coincidence detector array (AC)
- Luquid argon veto (LAr)
- Pulse shape discrimination (PSD)

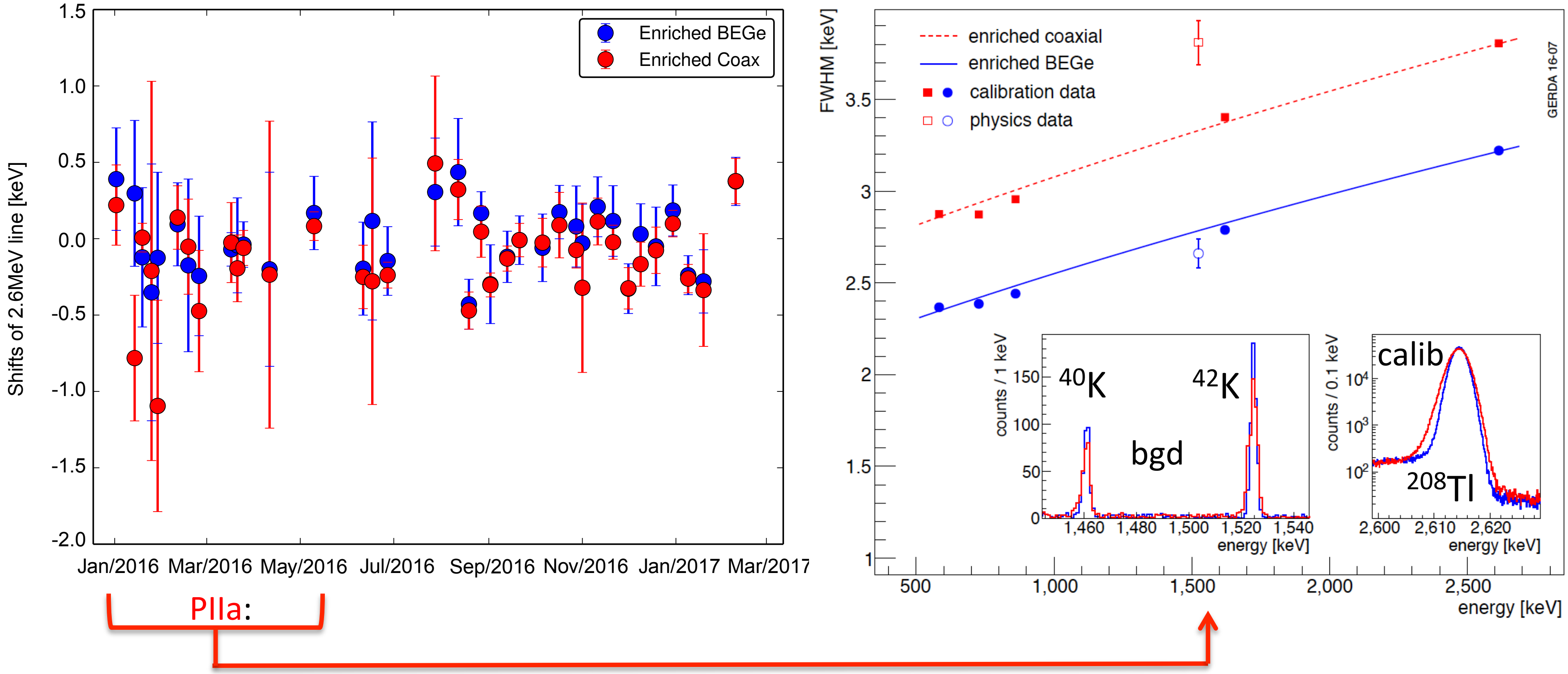
Phase II data taking and exposure



XVII NuTel Venice
28.5 kg yr
($Q_{\beta\beta}$±25 keV blind)

Neutrino 2016
10.8 kg yr
1st unblinding
arXiv:1703.00570
Accepted for publ. in Nature

Calibration: stability and energy resolution

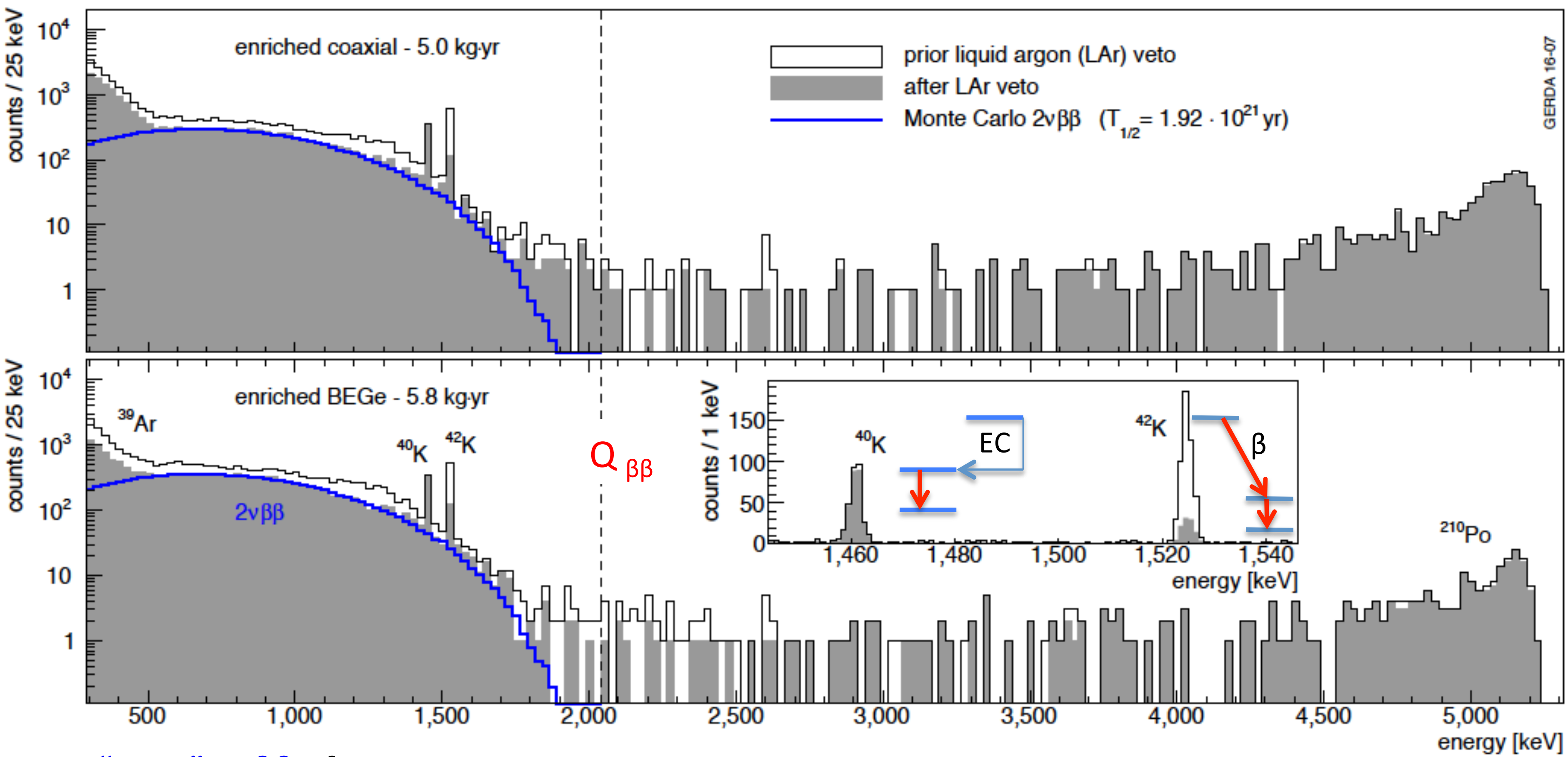


Energy resolution FWHM at at $Q_{\beta\beta}$ = 2039 keV:

- Coaxial: 4.0±0.2 keV
- BEGe: 3.0±0.2 keV

Energy spectra 10.8 kg yr (PIIa): before and after LAr veto

arXiv:1703.00570



"pure" 2νββ after LAr cut (97%, 600-1300 keV)

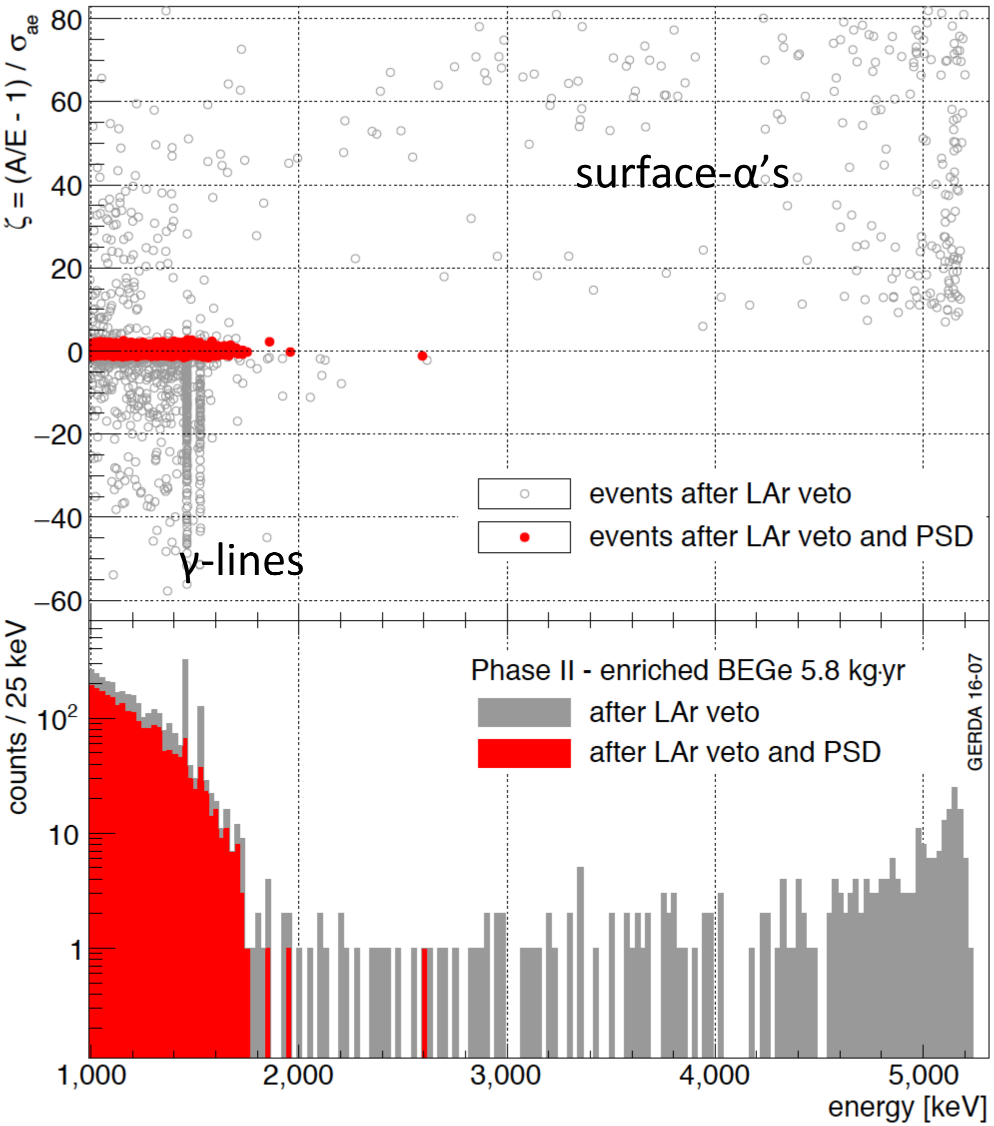
around $Q_{\beta\beta}$: background reduced by factor 2

LAr cut signal acceptance: (97.7±0.1)%

High energies: (quasi) no reduction of α's

BEGe pulse shape spectra 10.8 kg yr (PIIa)

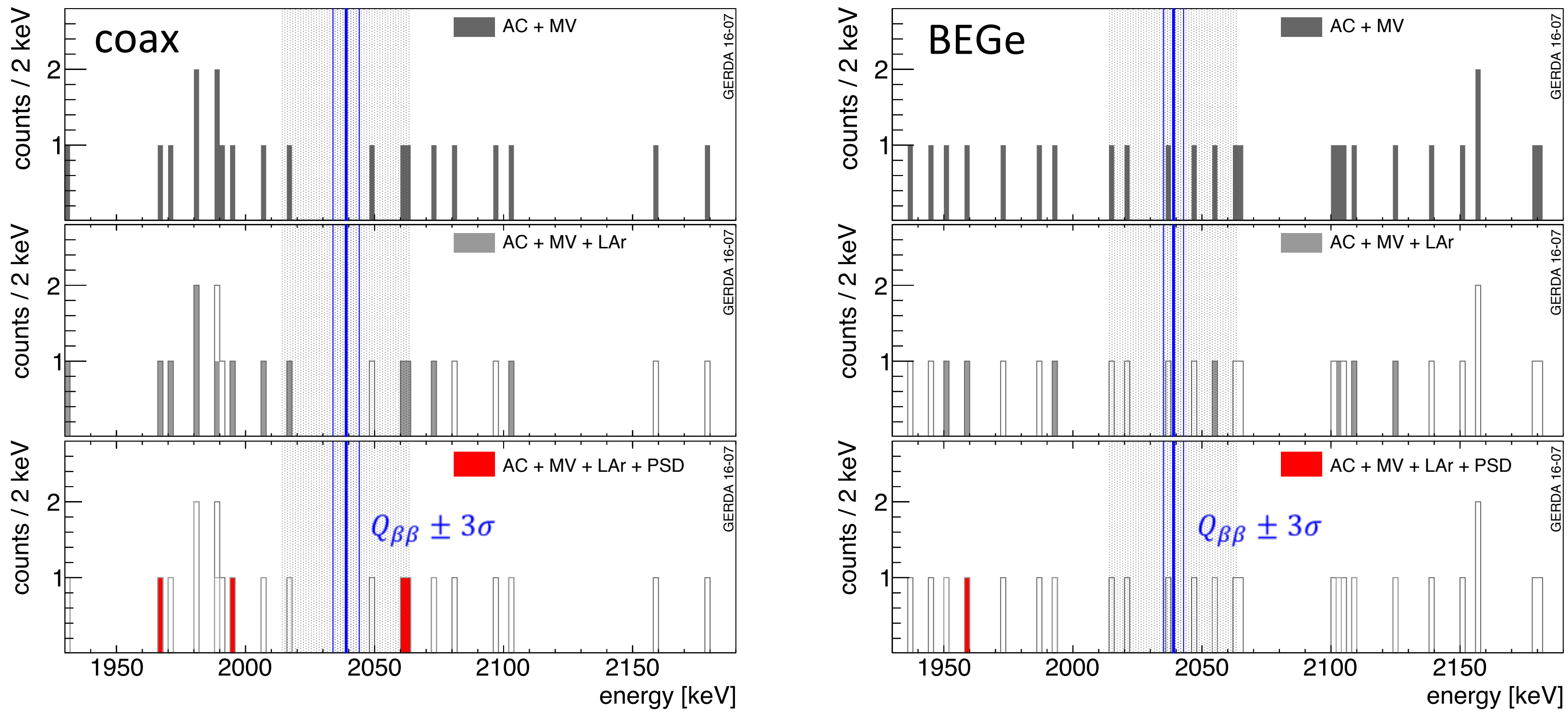
arXiv:1703.00570



- Mono-parametric cut based on current pulse amplitude *A* and total energy *E*
- Tuned by calibration data DEP of 2615 keV
- Efficiencies:
  - DEP: (87.3±0.2±0.8)%
  - 2νββ: (85.4±0.8±1.7)%
- All surface α's removed
- γ-lines factor 6 suppressed

Unblinding 10.8 kg yr (PIIa)

arXiv:1703.00570



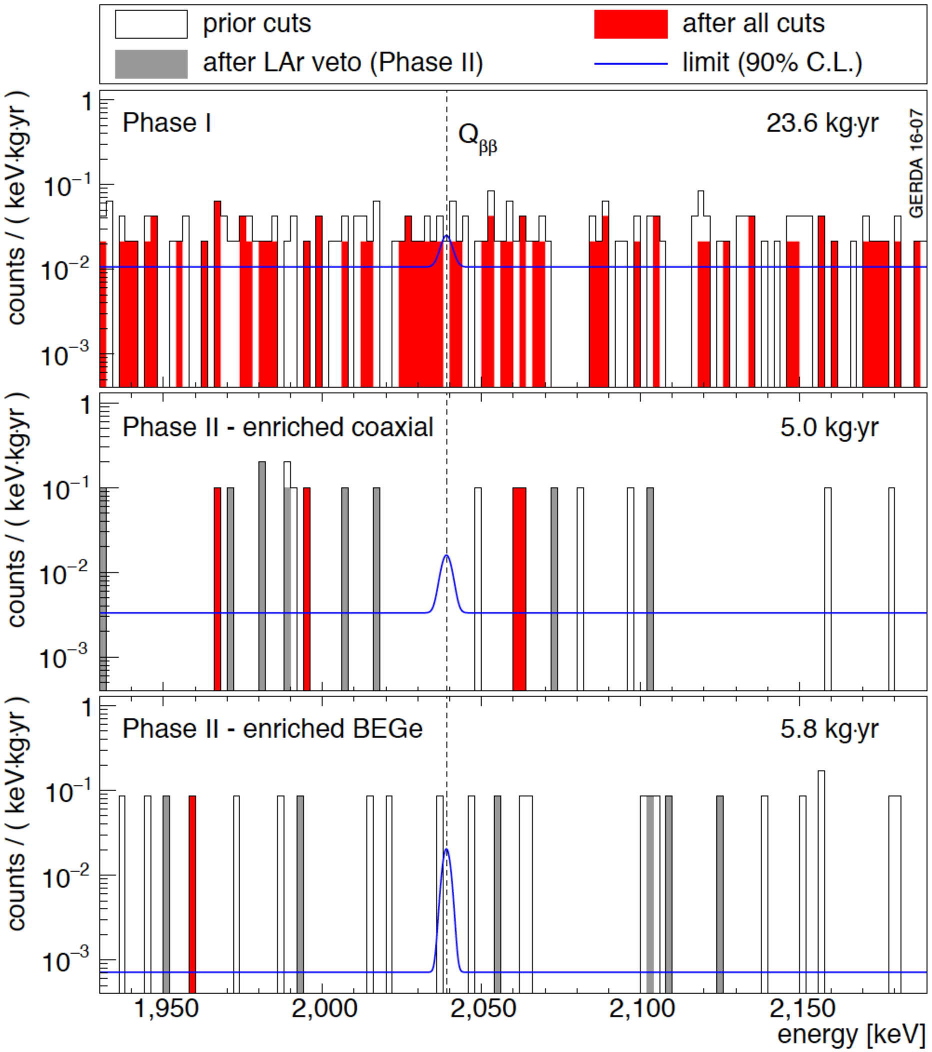
	exposure [kg · yr]	BI* $\left[10^{-3} \cdot \frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}\right]$	…after LAr veto	…after PSD	…after LAr veto + PSD
coaxial	5.0	$16.5^{+4.2}_{-3.5}$	$10.4^{+3.5}_{-2.7}$	$6.9^{+2.8}_{-2.2}$	$\mathbf{3.5^{+2.1}_{-1.5}}$
BEGe	5.8	$15.7^{+3.8}_{-3.1}$	$4.5^{+2.2}_{-1.6}$	$3.7^{+1.9}_{-1.5}$	$\mathbf{0.7^{+1.1}_{-0.5}}$

Background goal reached

*background index calculated in [1930,2019] ∨ [2044,2099] ∨ [2109,2114] ∨ [2124,2190] ⇒ 230 keV

Unblinding 10.8 kg yr (PIIa)

arXiv:1703.00570



dataset	exposure [kg · yr]	FWHM [keV]	efficiency*	BI $\left[10^{-3} \frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}\right]$
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI solver	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)	$0.7^{+1.1}_{-0.5}$

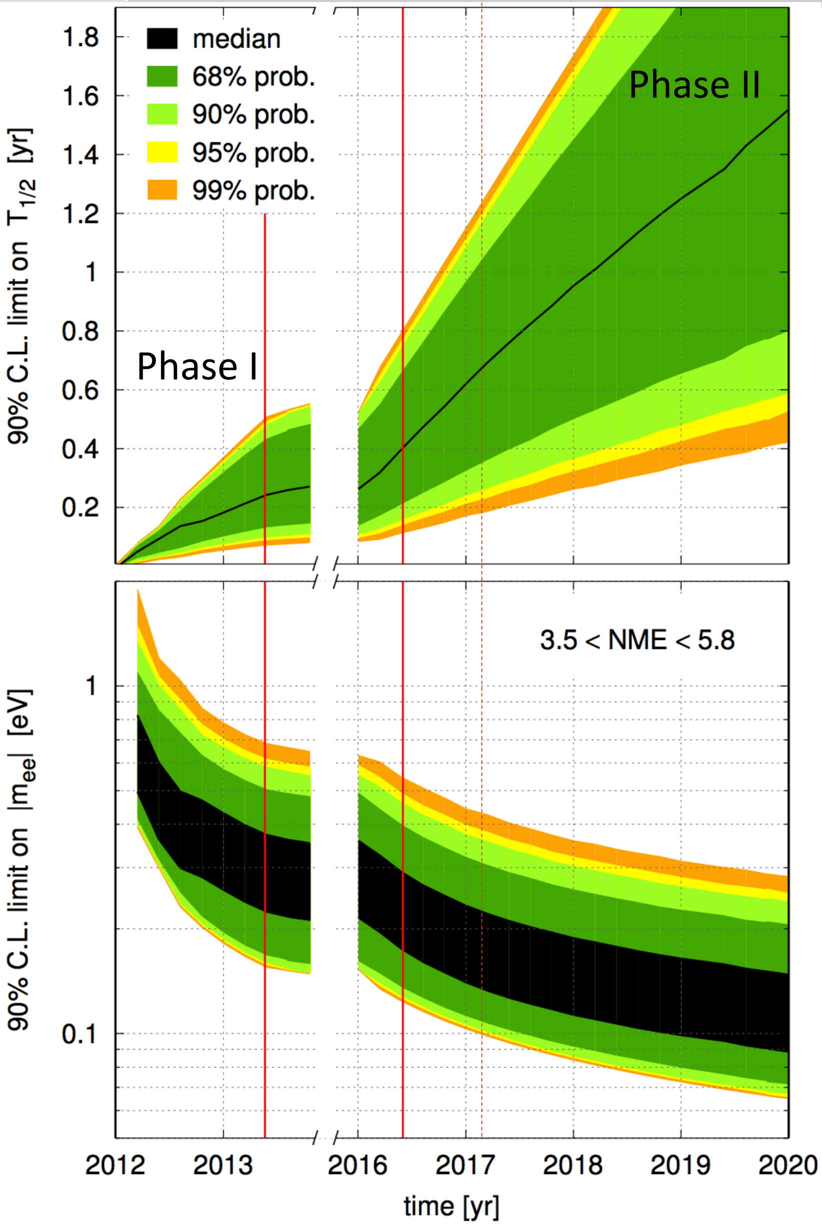
- Phase I: improved energy reconstruction, extra data
- unbinned profile likelihood: flat background, Gaussian signal

	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]	**> 5.3 (90% CL)**	> 3.5 (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity [10^{25} yr]	**> 4.0 (90% CL)**	> 3.1 (90% CI)

*including enrichment, active mass, reconstruction efficiencies, dead times

**frequentist test-statistics and methods [EPJC 71 (2011) 1554]

GERDA Phase II: first **background-free** 0νββ experiment



Phase I achievements	
background	$\sim 10^{-2}$ cts/(keV · kg · yr)
exposure	21.6 kg · yr
limit	$\mathbf{T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}}$ **yr (90% CL)**
	[Phys.Rev.Lett. 111 (2013) 122503]

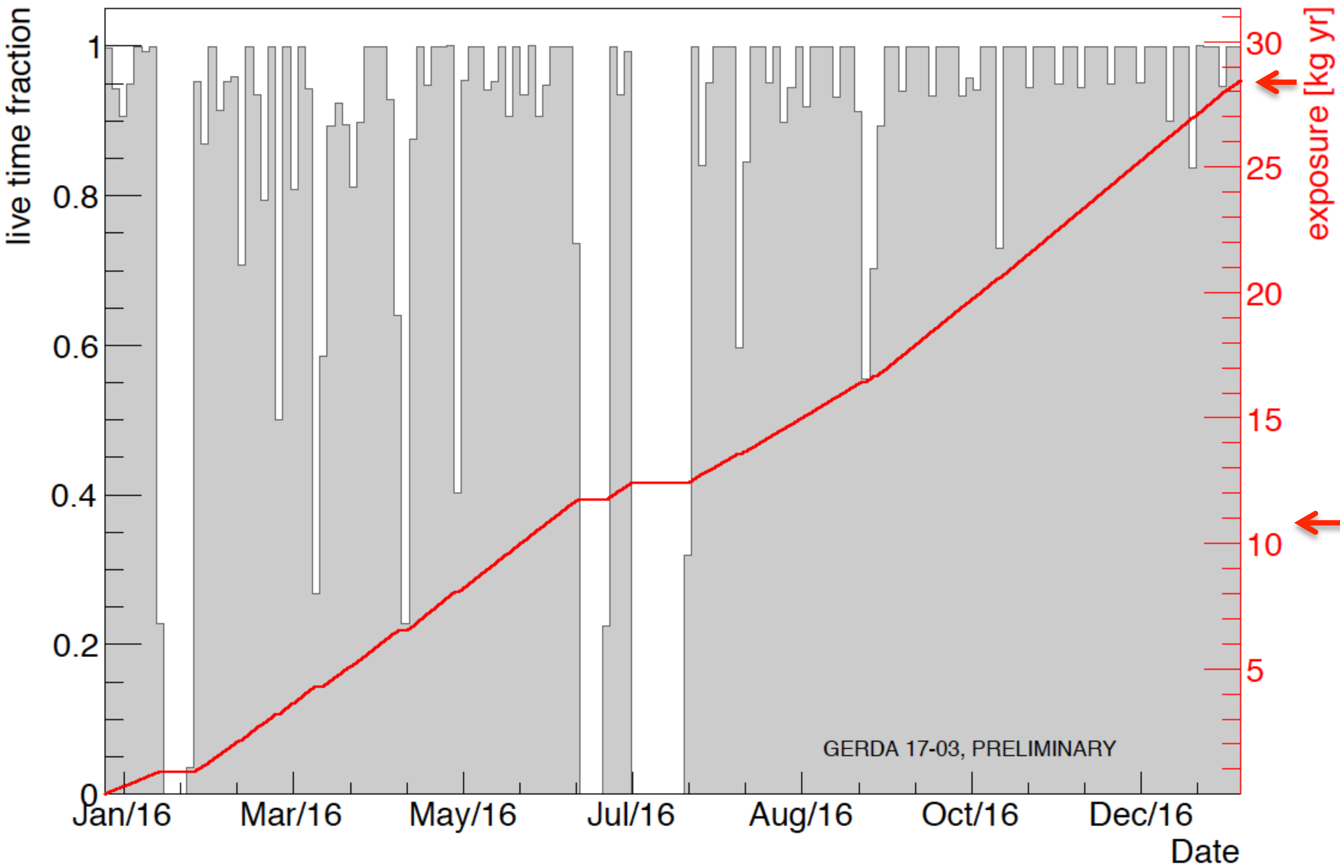
first Phase II achievements	
background	$\sim 10^{-3}$ cts/(keV · kg · yr)
exposure	10.8 kg · yr (34,4 kg · yr)*
limit	$\mathbf{T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}}$ **yr (90% CL)**
	$\boldsymbol{m_{\beta\beta} < 0.15 - 0.33}$ **eV (90% CL)**
	[arXiv:1703.00570; acc. Nature]

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

*combining Phase I and Phase II data

Phase II data taking and exposure

preliminary

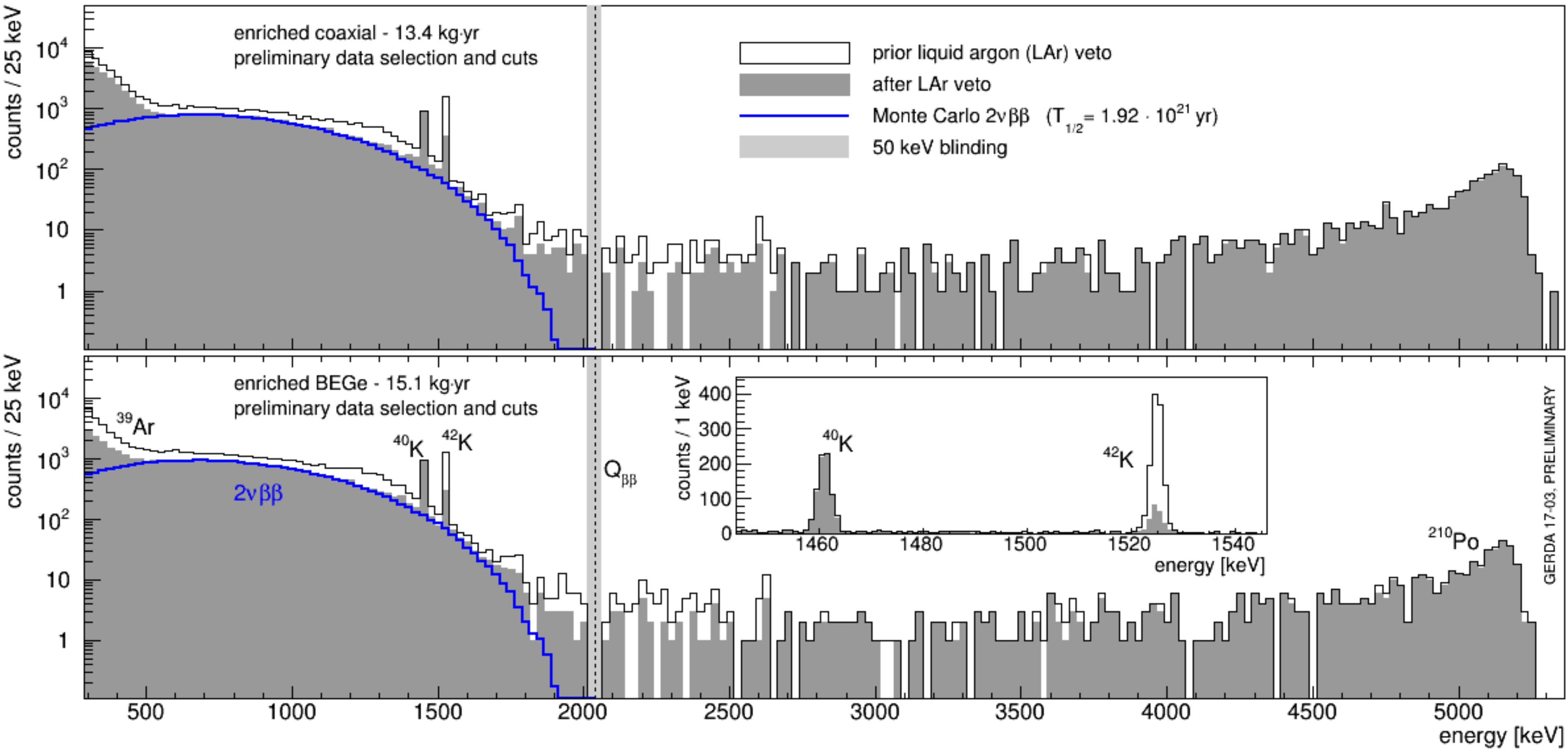


XVII NuTel Venice
28.5 kg yr
($Q_{\beta\beta}$±25 keV blind)

Neutrino 2016
10.8 kg yr
1st unblinding
arXiv:1703.00570
Accepted for publ. in Nature

Energy spectra 28.5 kg yr: before and after LAr veto

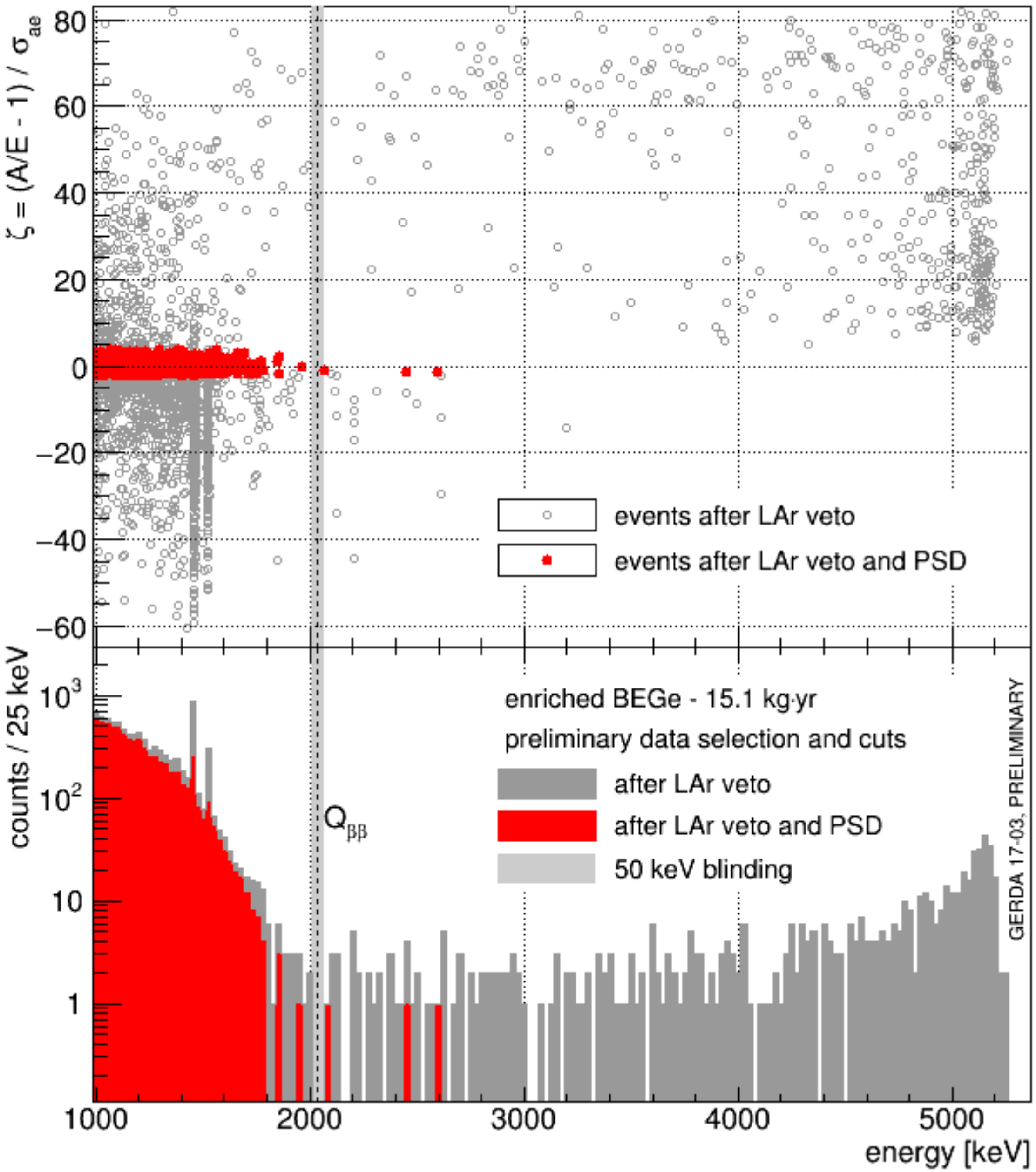
preliminary



- Same background contributions as in 10.8 kg yr data set
- Comprehensive background model under preparation
- Main contributions around $Q_{\beta\beta}$ from nearby sources: U/Th progenies, ^{42}K, surface α's

BEGe pulse shape spectra 28.5 kg yr

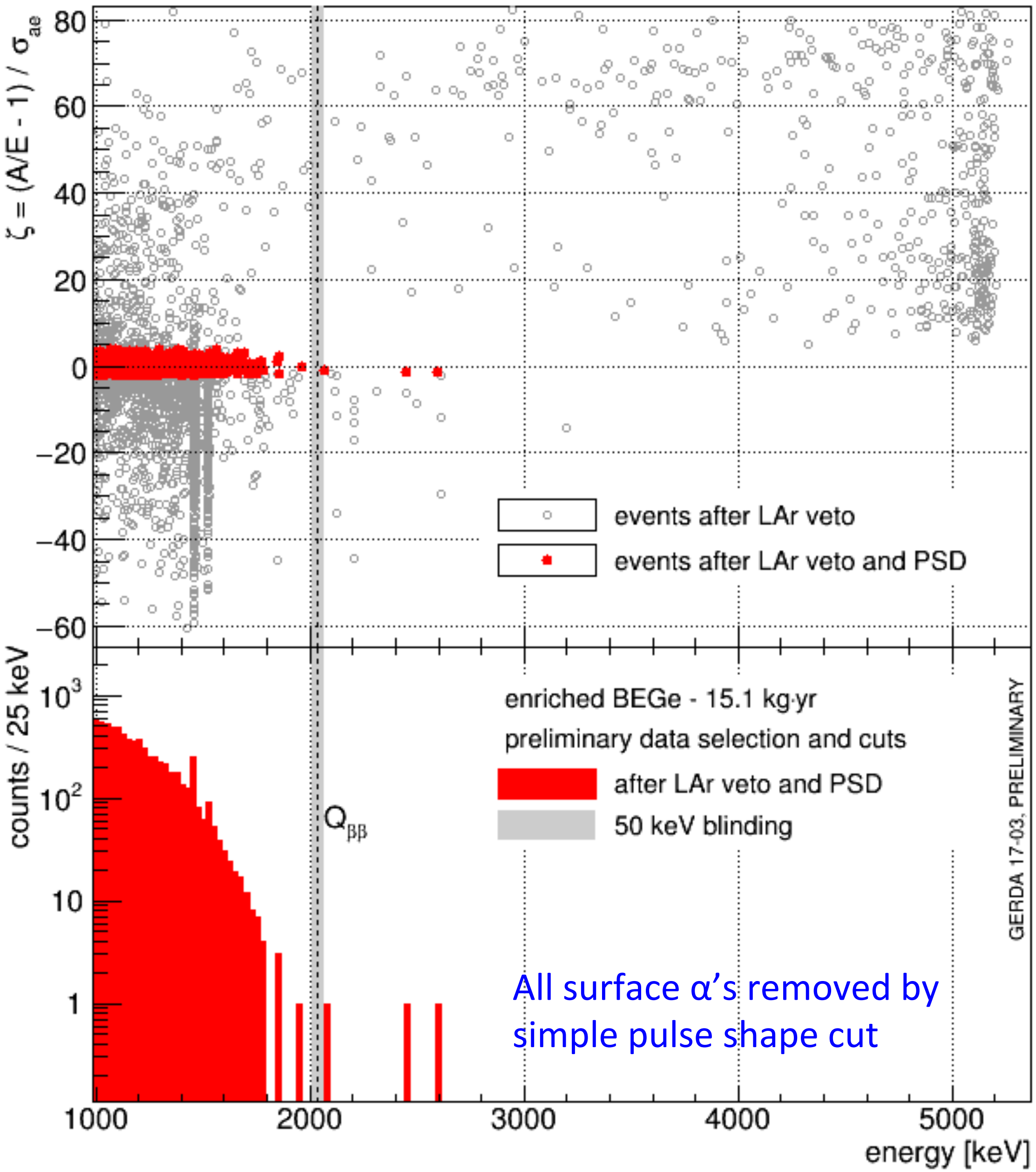
preliminary



Energy reconstruction & PSD cuts preliminary! $Q_{\beta\beta}$±25 keV blind!

BEGe pulse shape spectra 28.5 kg yr

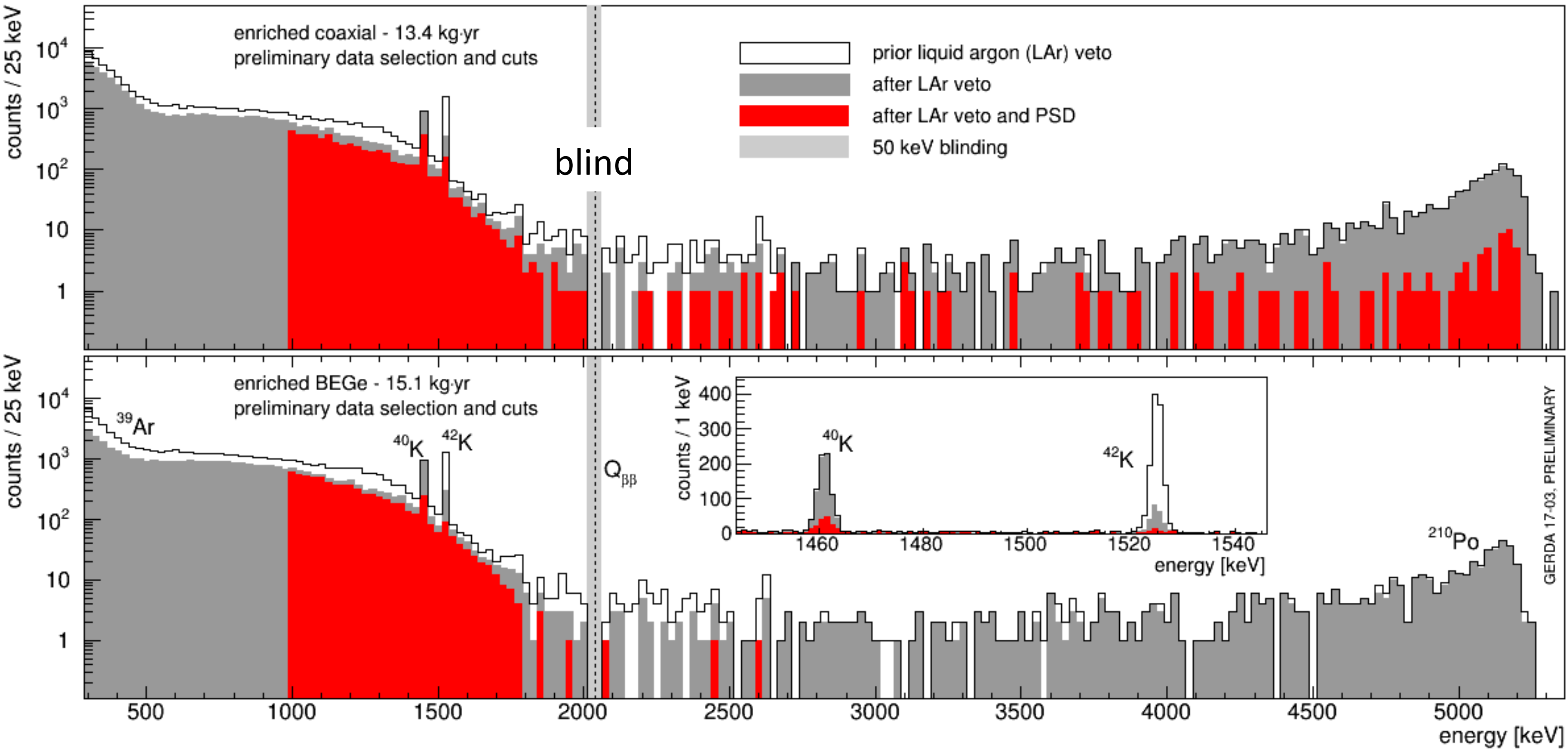
preliminary



Energy reconstruction & PSD cuts preliminary! $Q_{\beta\beta}$±25 keV blind!

Energy spectra 28.5 kg yr: before and after LAr veto & PSD

preliminary



	exposure $[\mathrm{kg \cdot yr}]$	BI* $\left[10^{-3} \cdot \frac{\mathrm{cts}}{\mathrm{keV \cdot kg \cdot yr}}\right]$	(cts)	...after LAr veto		...after PSD		...after LAr veto + PSD	
EnrCoax	13.4	$16.7^{+2.7}_{-2.3}$	(46)	$8.0^{+1.9}_{-1.6}$	(22)	$8.0^{+1.9}_{-1.6}$	(22)	$\mathbf{2.2^{+1.1}_{-0.8}}$	(6)
EnrBEGe	15.1	$12.3^{+2.3}_{-1.8}$	(38)	$3.9^{+1.3}_{-1.0}$	(12)	$3.2^{+1.2}_{-0.9}$	(10)	$\mathbf{0.6^{+0.6}_{-0.4}}$	(2)

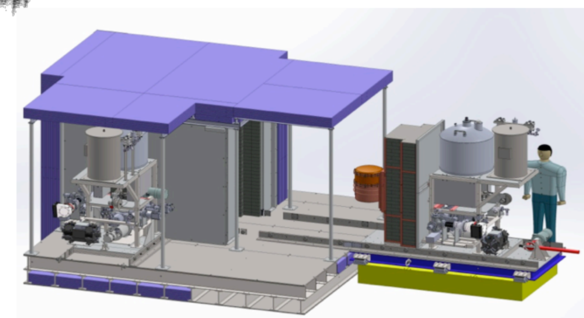
*background windows weighted by exposure (≈ 205 keV)

The ^{76}Ge-experiments: GERDA & Majorana-Demonstrator

GERDA

- Bare ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 17 kg (HdM/IGEX) - completed
- Phase II: 38 kg enriched in ^{76}Ge

Majorana-Demonstrator (MJD)



- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- 30 kg enriched in ^{76}Ge

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI

- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for future large scale ^{76}Ge experiment selecting the best technologies tested in GERDA and Majorana

Large Enriched Germaium Experiment for Neutrinoless ββ Decay – LEGEND

Laboratori Nazionali del Gran Sasso, Assergi, L'Aquila University and INFN, Gran Sasso Science Institute, Argonne National Laboratory, Univ. Texas, Tsinghua University, Lawrence Berkeley National Laboratory, Leibniz Institute for Crystal Growth (IKZ Berlin), Comenius University, North Carolina State University, University of North Carolina, University of South Carolina, Laboratori Nazionali del Sud (LNS), Jagiellonian University, Krakow, Banaras Hindu University, University of Dortmund, TU Dresden, Joint Institute for Nuclear Research (Dubna), Joint Research Centre, Geel, MPIK Heidelberg, Dokuz Eylul University (DEU), Queens University, University of South Dakota, South Dakota School of Mines and Technology, University of Liverpool, University College London, University of New Mexico, Los Alamos National Laboratory, Lund University,Milano Bicocca and INFN, Milano University and INFN, National Research Center Kurchatov Institute (NRC KI), Institute of Nuclear Research (Russian Academy of Sciences), Laboratory for Experimental Nuclear Physics of MEPhI, MPI Munich, TU Munich, Oak Ridge National Laboratory, Padova University and Padova INFN, IEAP Czech Technical University in Prague, Princeton University, University of Washington, Sichuan University, Chalmers Univ. of Technology, Academia Sinica, Taiwan, University of Tennessee, University of Tuebingen, University of Zurich

219 members, 48 institutions, 16 countries

Collaboration forming and consolidation ongoing

Interested groups contact Interim Steering Committee:
Steve Elliott, David Radford, Stefan Schönert, Bernhard Schwingenheuer, David Waters

Large **E**nriched **G**ermaium **E**xperiment for **N**eutrinoless ββ **D**ecay - LEGEND

Munich meeting, April 2016

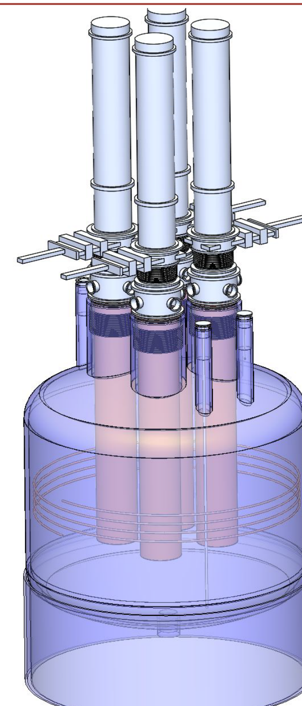
Collaboration forming:

- 1^{st} Munich April 2016
- **2^{nd}** Atlanta October 2016
- Next meeting at LNGS May 15-17

LEGEND mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with **discovery potential** at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results."

First stage:

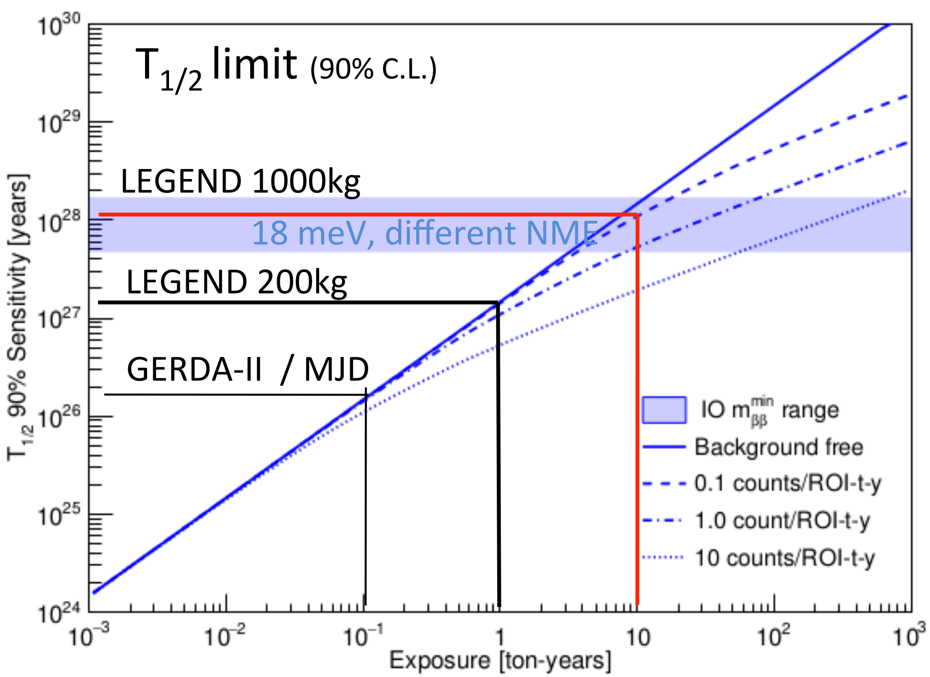
- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- bgd reduction by factor 3-5 w.r.t GERDA

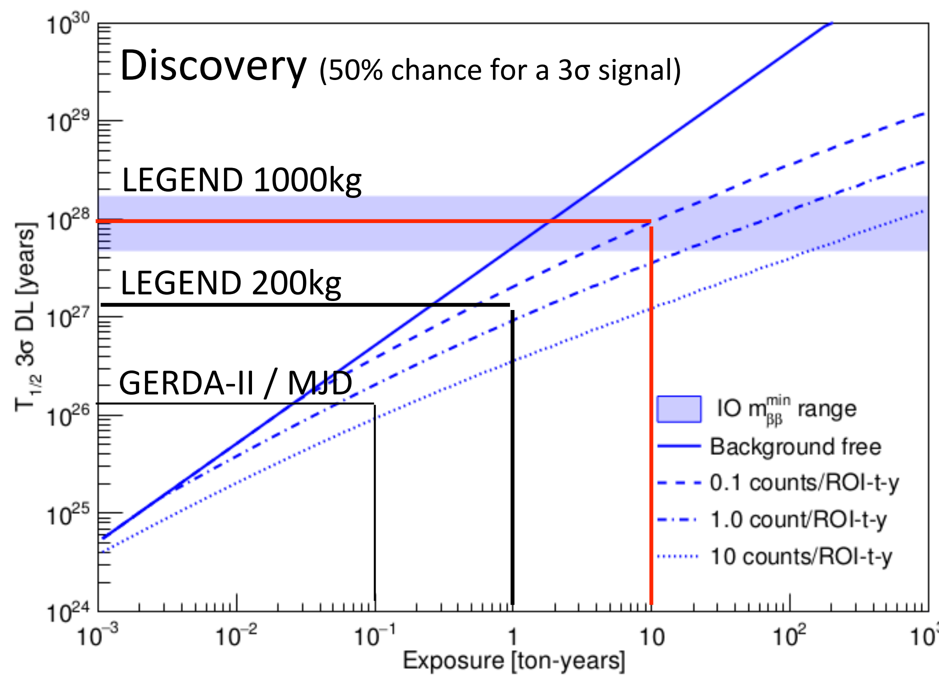


Subsequent stages:

- 1000 kg (staged)
- timeline connected to DOE down select process
- Bgd factor 30 w.r.t GERDA
- Location tbd
- Required depth (Ge-77m) under investigation

LEGEND: sensitivities for limit setting and discovery





<u>Plot details:</u>

- 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

Next stage: LEGEND-200 @ LNGS

- Cryostat neck inner-Ø enlarge to 610 mm
- Larger Ge detectors with BEGe/PPC-like PSD performance
- Improve **LAr optical purity** (light yield, attenuation)
- Improve **LAr light detection** (readout also between strings)
- Background **reduction by 3-5** wrt GERDA-II:
    - Nearby Th/U: cleaner materials (like MJD)
    - Surface α on p+ (n+) no issue
    - Surface β (^{42}K, ^{42}Ar progeny) n+: reduce LAr volume & improve electronics (PSD)
    - **Muon induced isotopes**: muon veto (water & LAr scintillation; prompt and delayed coincidence); 1t yr **ok** ; bgd for larger exposures under study
- GERDA Phase II continues data taking **until 2019**
- **LEGEND-200 start 1.5** years later
- Funding requests subm. & under preparation

comparison experiments

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/t yr FWHM]	$T_{1/2}$ limit sensitivity [10^{25} yr] after 4 yr	worst m_{ee} limit [meV] (lowest NME, g_A unquenched)	
Gerda II	Ge	35/27	3	5	15	190	running
MajoranaD	Ge	30/24	3	5	15	190	
EXO-200	Xe	170/80	88	220	6	240	
Kamland-Z	Xe	383/88 750/??	250	90 ?	6 50	240 85	design
Cuore	Te	600/206	5	230	9	210	
NEXT-100	Xe	100/80	17	30	6	240	
SNO+	Te	2340/260	190	60	17	160	
nEXO	Xe	5000/4300	58	5	600	24	future
Ge-200	Ge	200/155	3	1	100	75	
Ge-1000	Ge	1000/780	3	0.2	1000	24	

* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

[&] kg of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

Note: values are design numbers except for GERDA, EXO-200 and Kamland-Zen

Conclusions & outlook

- Established technology for ^{76}Ge isotope enrichment & Ge detector production
- Best energy resolution
- Lowest background in ROI

→ GERDA Phase II operates background-free within design exposure

- Flat background around $Q_{\beta\beta}$
- Contributing isotopes identified

→ All essential for **discovery**

- GERDA Phase II & Majorana Demonstrator are taking data
- GERDA & MJD reached background goals

→ LEGEND formed October 2016

- Collaboration forming and funding requests ongoing
- First stage: LEGEND-200 @ LNGS