RICERCA DEL DECADIMENTO DOPPIO BETA SENZA NEUTRINI CON ^{76}GE: I RISULTATI FINALI DI GERDA E LE PROSPETTIVE FUTURE

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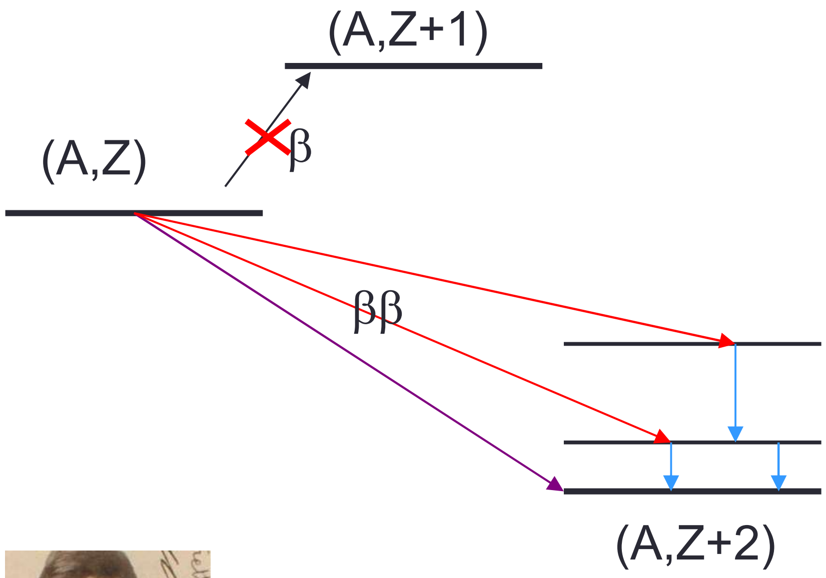
0νββ and 2νββ decay

2νββ decay

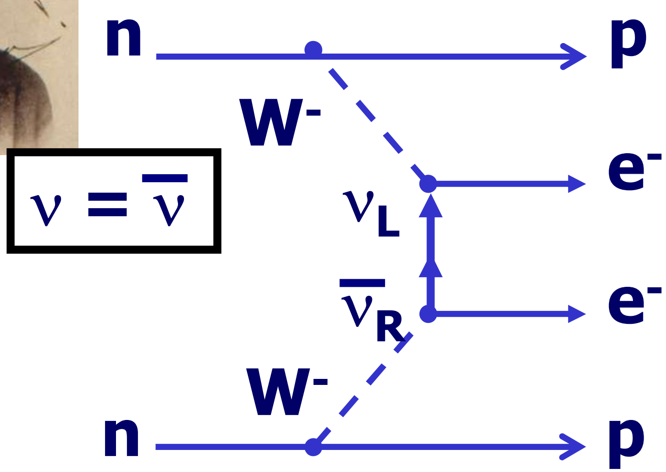
(A,Z) → (A,Z+2) +2e⁻+2$\bar{\nu}$

SM allowed and observed on several isotopes with forbidden single-β. Conserves lepton number, but long half-life because 2nd order ($10^{19} \div 10^{21}$ yr)



0νββ decay

(A,Z) → (A,Z+2) +2e⁻



Violates lepton number by two units. Forbidden in the SM. Possible **only** if νs have Majorana mass component $\langle m_{\beta\beta} \rangle > 0$ (Schechter-Valle theorem, 1982)

The search for 0νββ

Neutrino mass confirmed by flavour oscillations. There are good theoretical reasons to expect Majorana nature

Most obvious decay mechanism: exchange of massive Majorana neutrinos:

$$1/T_{1/2} = G(Q,Z)\,|M_{nucl}|^2\,\langle m_{ee}\rangle^2 \Rightarrow |\Sigma_i U_{ei}^2 m_i|$$

0νββ Decay rate

Phase space ($\sim Q^5$)

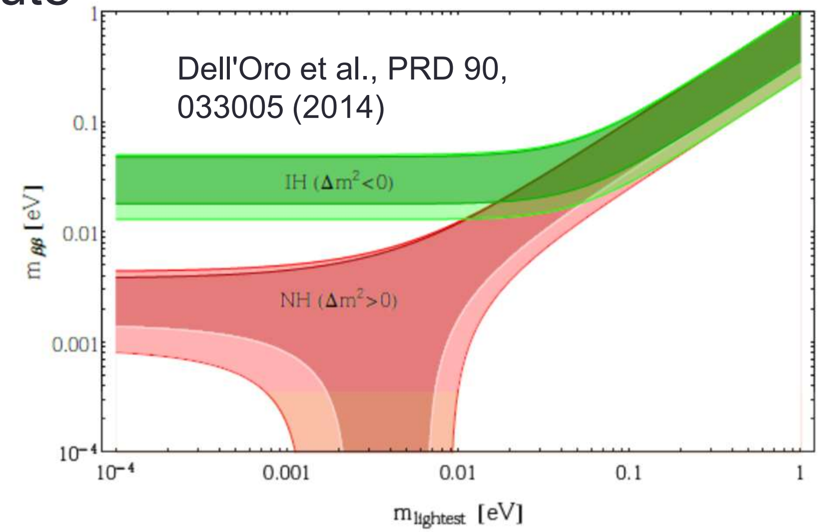
Nuclear matrix element (NME)

Majorana neutrino mass

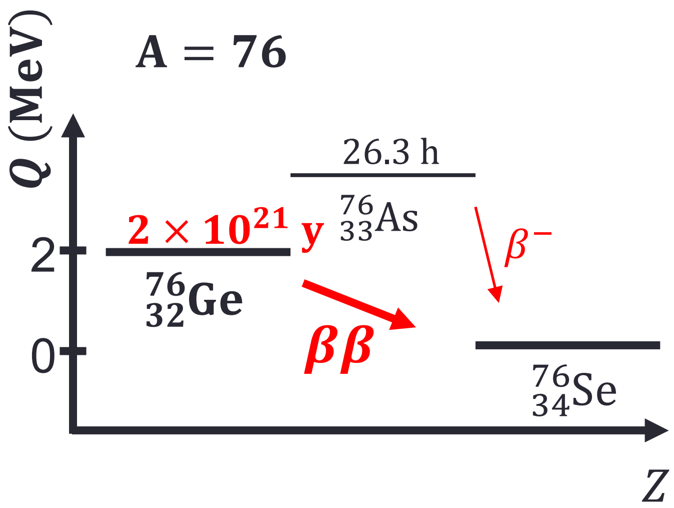
Other conceivable mechanisms can contribute

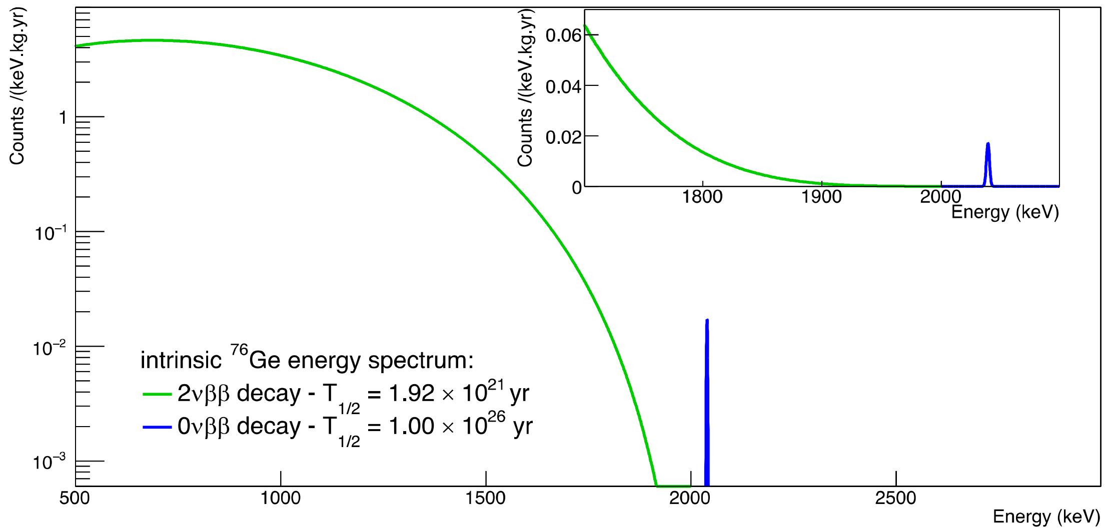
Observation of the decay would:

- establish lepton number violation
- prove that ν has a Majorana mass component
- provide information about the (so-far unknown) absolute mass scale



0νββ experimental signature in ^{76}Ge

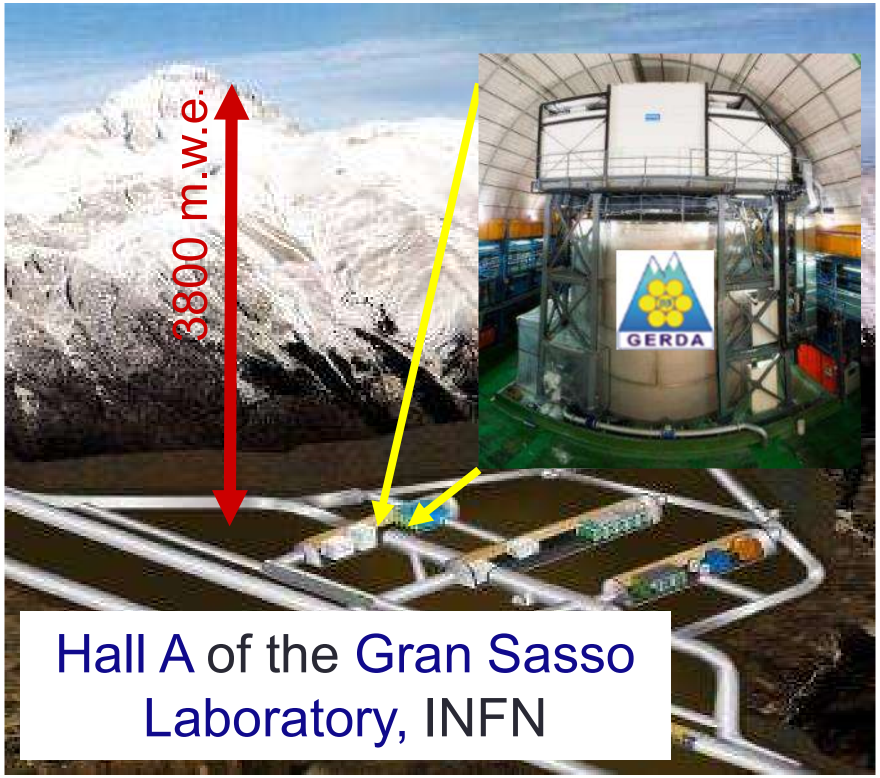


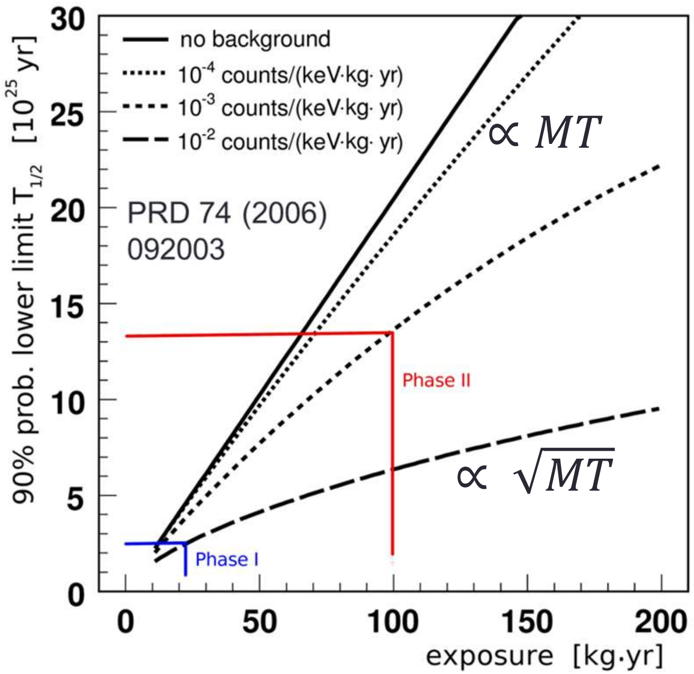


- **Signature:** Expected **line at the ^{76}Ge Q-value** (2039 keV), above measured 2νββ continuum
- ^{76}Ge → **HPGe detectors!**
  - High detection efficiency (detector = ββ source)
  - Enrichment from 7.7% up to ~87-92%
  - Best proved energy resolution at the Q-value (~0.13% FWHM) → **narrow search region**, important in the case of discovery
  - Intrinsic radiopurity (→ best background/FWHM in the field)

Looking for ^{76}Ge decay with GERDA

GERmanium Detector Array (INFN-LNGS, Italy) searched for $0\nu\beta\beta$ decay in ^{76}Ge using HPGe detectors enriched in ^{76}Ge





Design strategy: «zero background» regime in a phased approach:

PhaseI: 20 kg·yr, 10^{-2} cts/(keV·kg·yr) [2011-13]

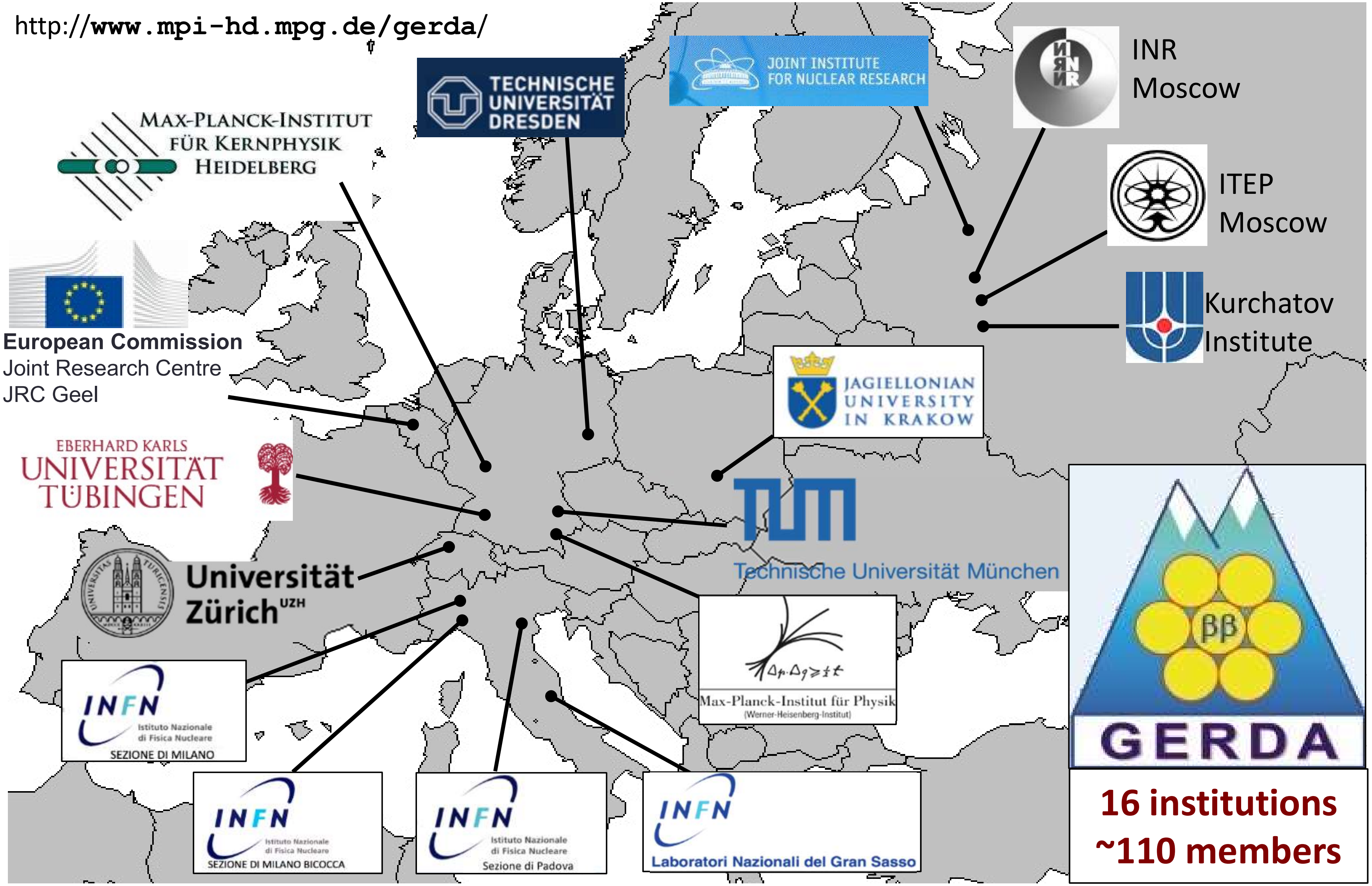
PhaseII:100 kg·yr, 10^{-3} cts/(keV·kg·yr) [2015-19]

Blinding of events at **$Q_{\beta\beta}$ ± 25 keV**

Open box when all cuts finalized

GERDA: the Collaboration

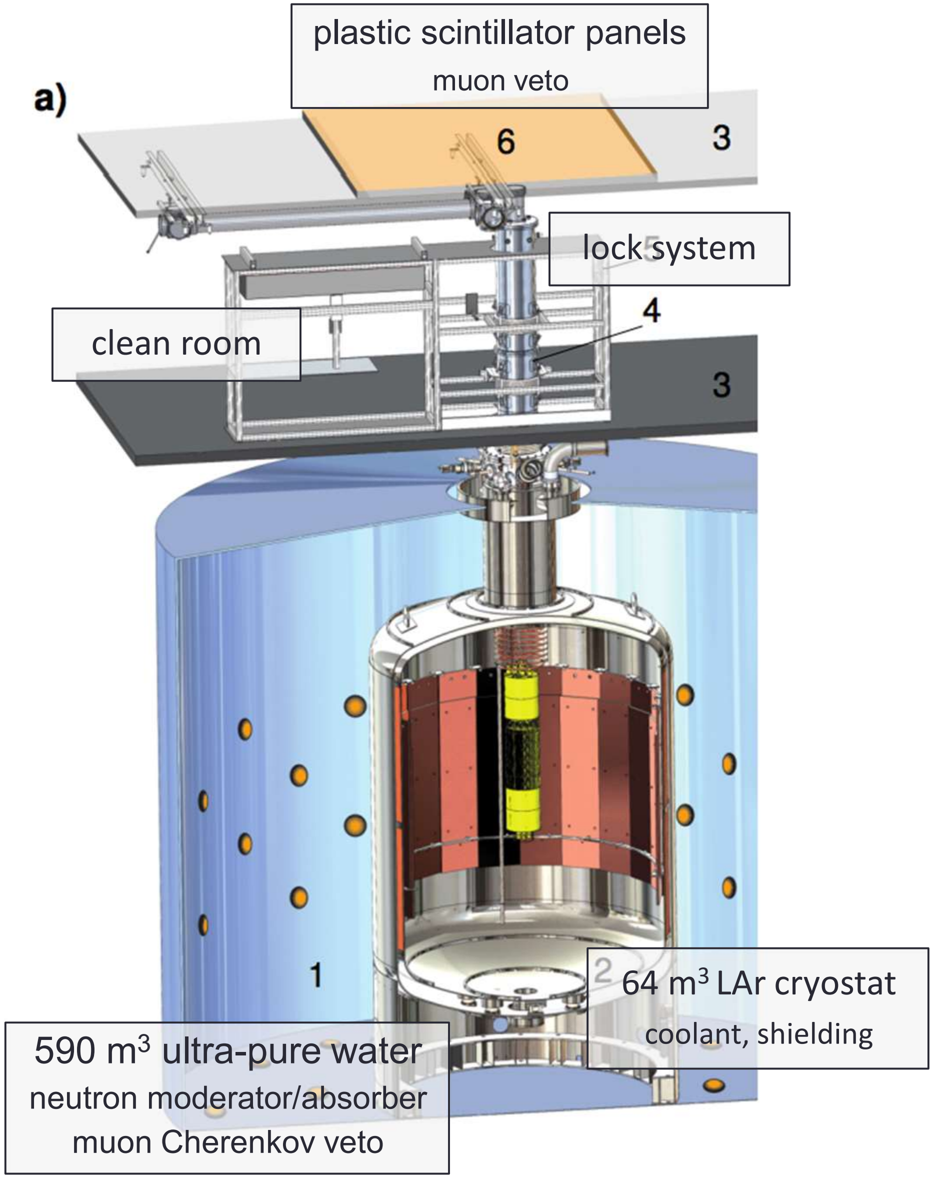
http://www.mpi-hd.mpg.de/gerda/



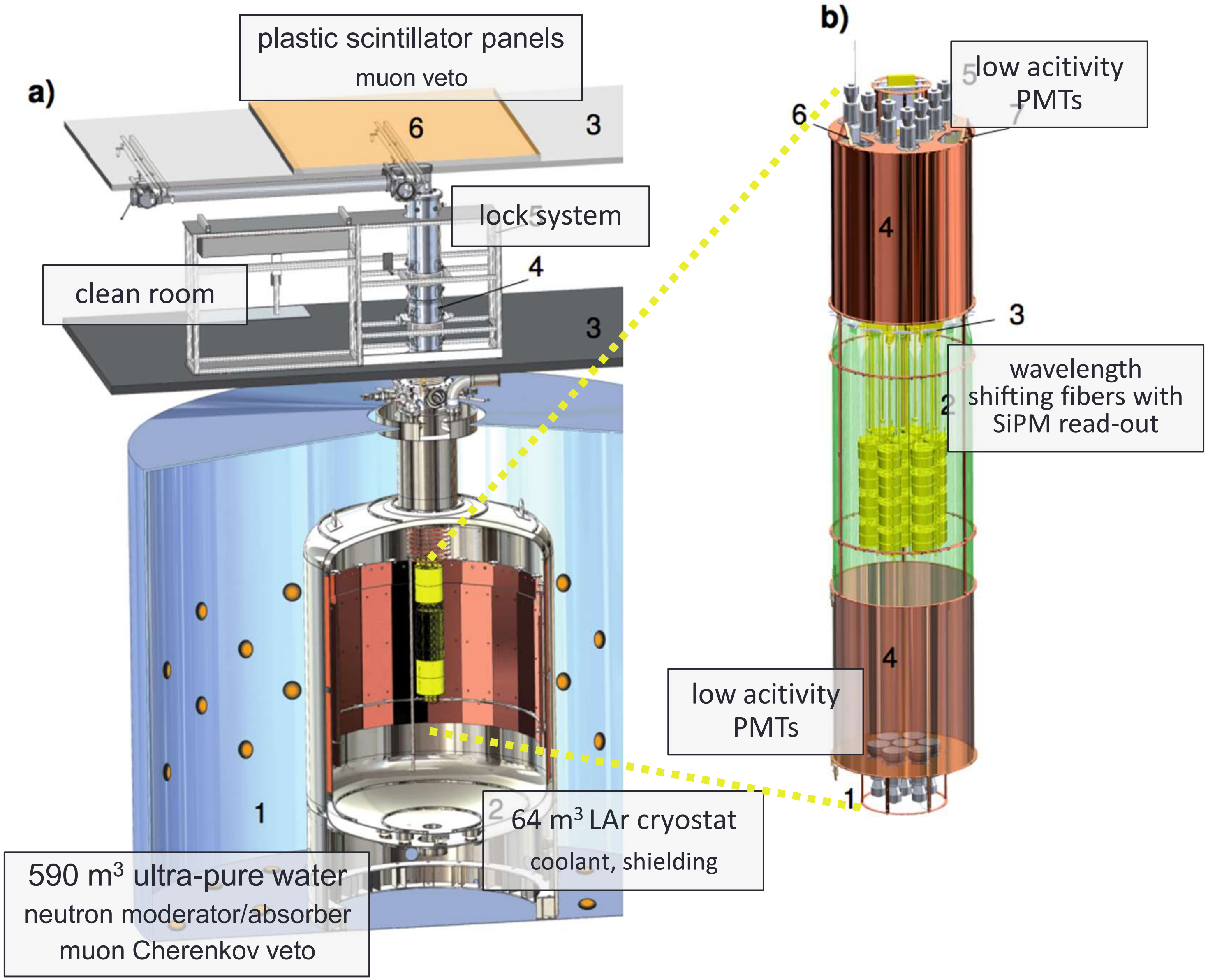
16 institutions
~110 members

GERDA: the concept

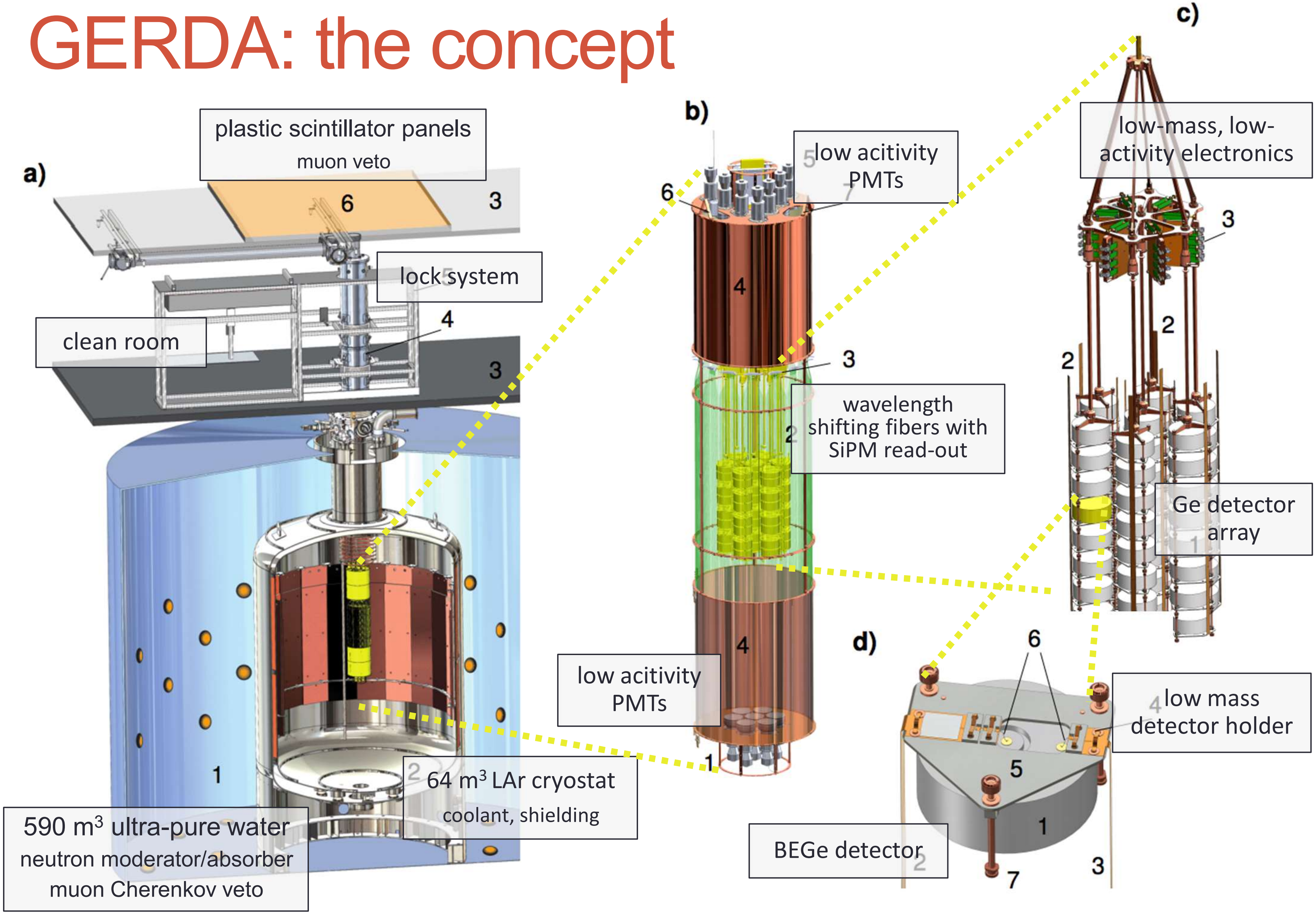
Eur. Phys. J. C 73 (2013) 2330
Nature 544 (2017) 47
Phys Rev Lett 128 (2018) 13
Science 365 (2019) 1445
arXiv 2009.06079



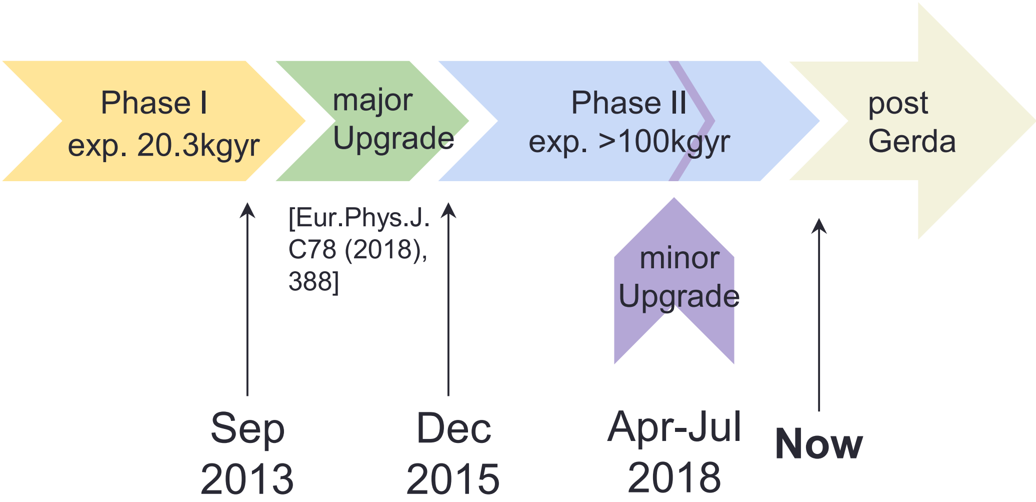
GERDA: the concept



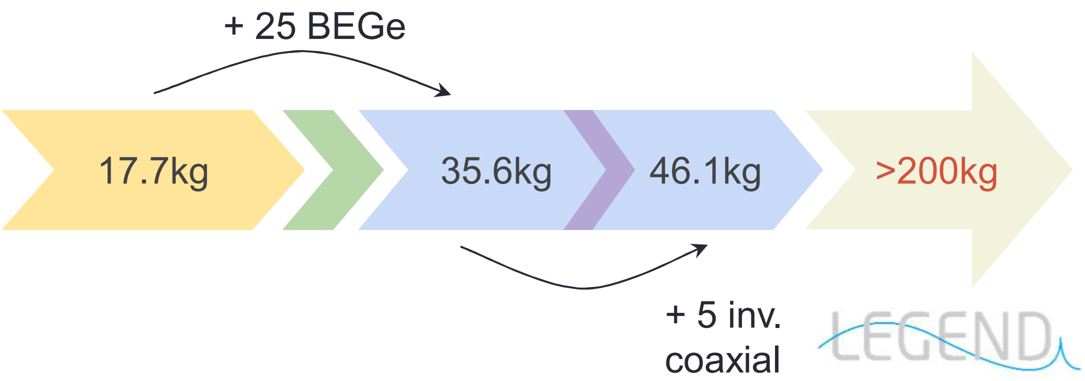
GERDA: the concept

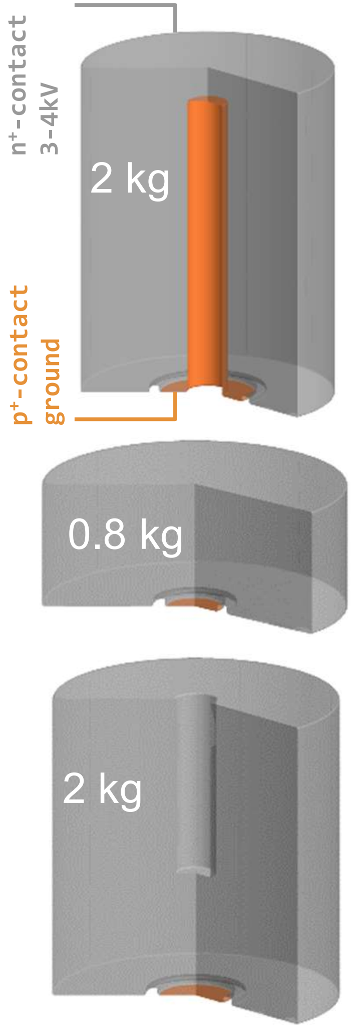


GERDA history and Ge detectors

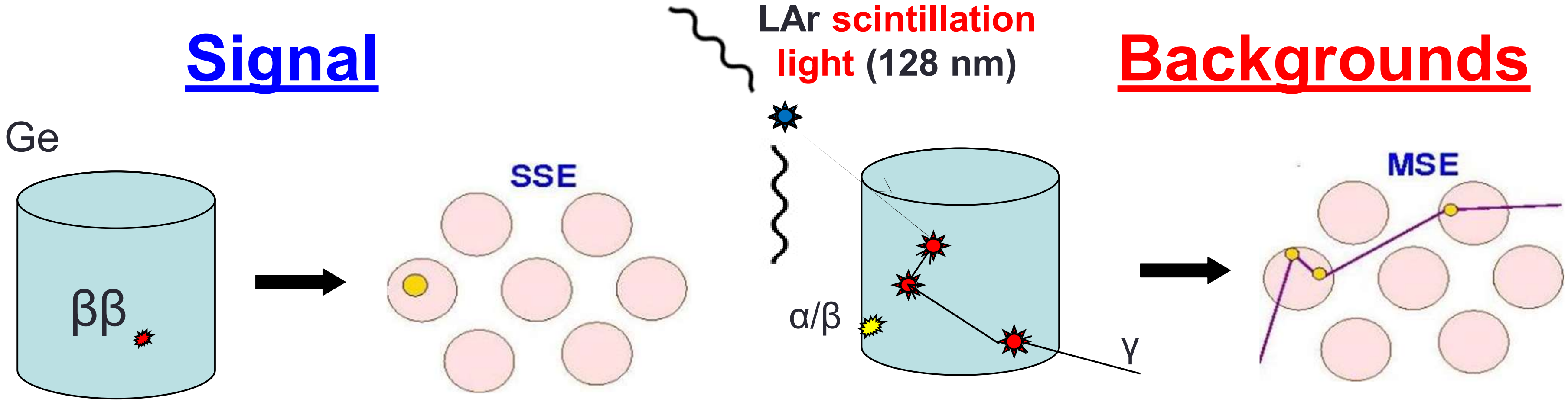


Enriched detectors deployed





Background reduction tools



Point-like (single-site) energy deposition inside one HP-Ge diode

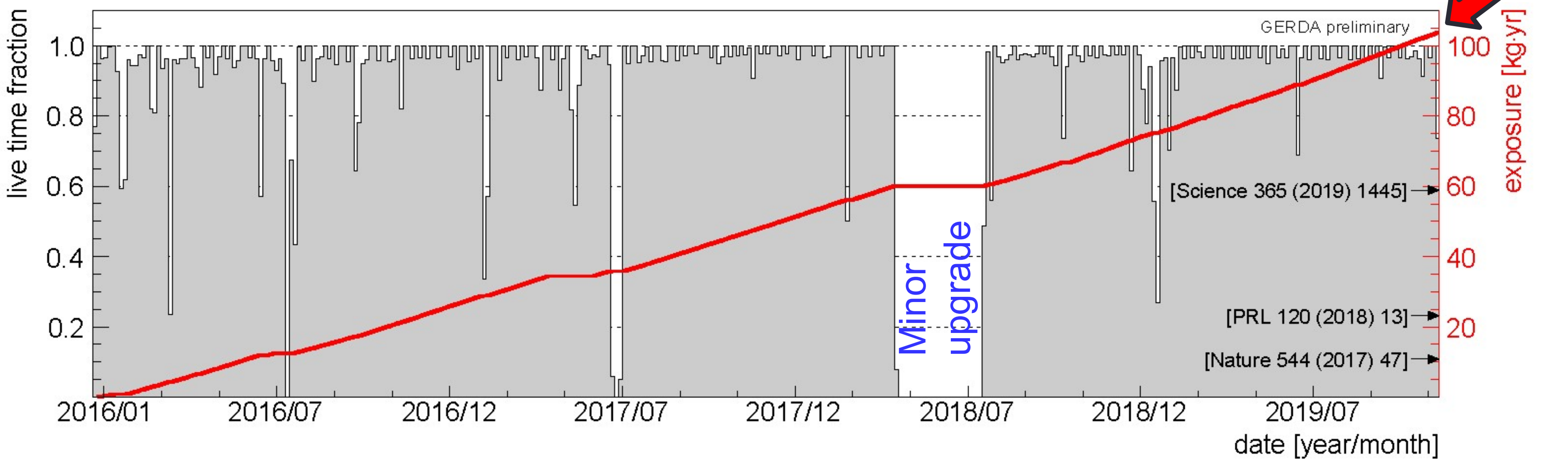
Multi-site energy deposition inside HP-Ge diode (Compton scattering), or **surface** events

- **Anti-coincidence** with the **muon veto**
- Anti-coincidence **between detectors** (cuts multi-site)
- **Active veto** using LAr scintillation
- **Pulse shape** discrimination (PSD)
  - MSE within one detector and surface events
  - Very efficient for the BEGe and inverted coaxial detectors

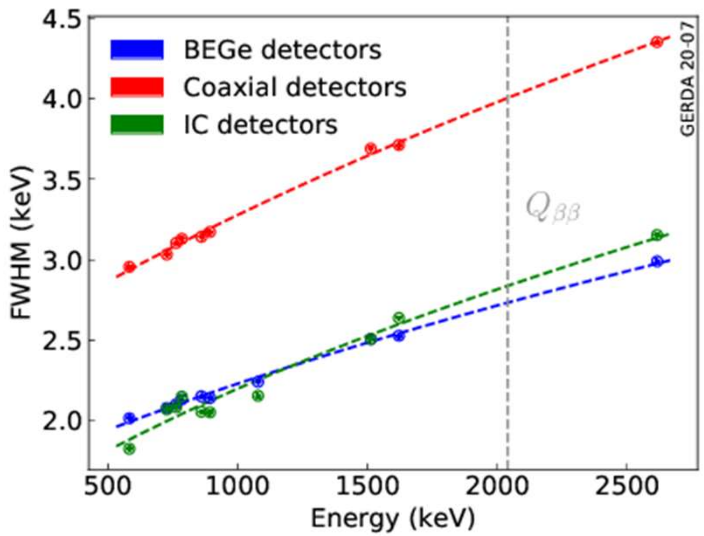
See communication #960 by N. Burlac

Data taking

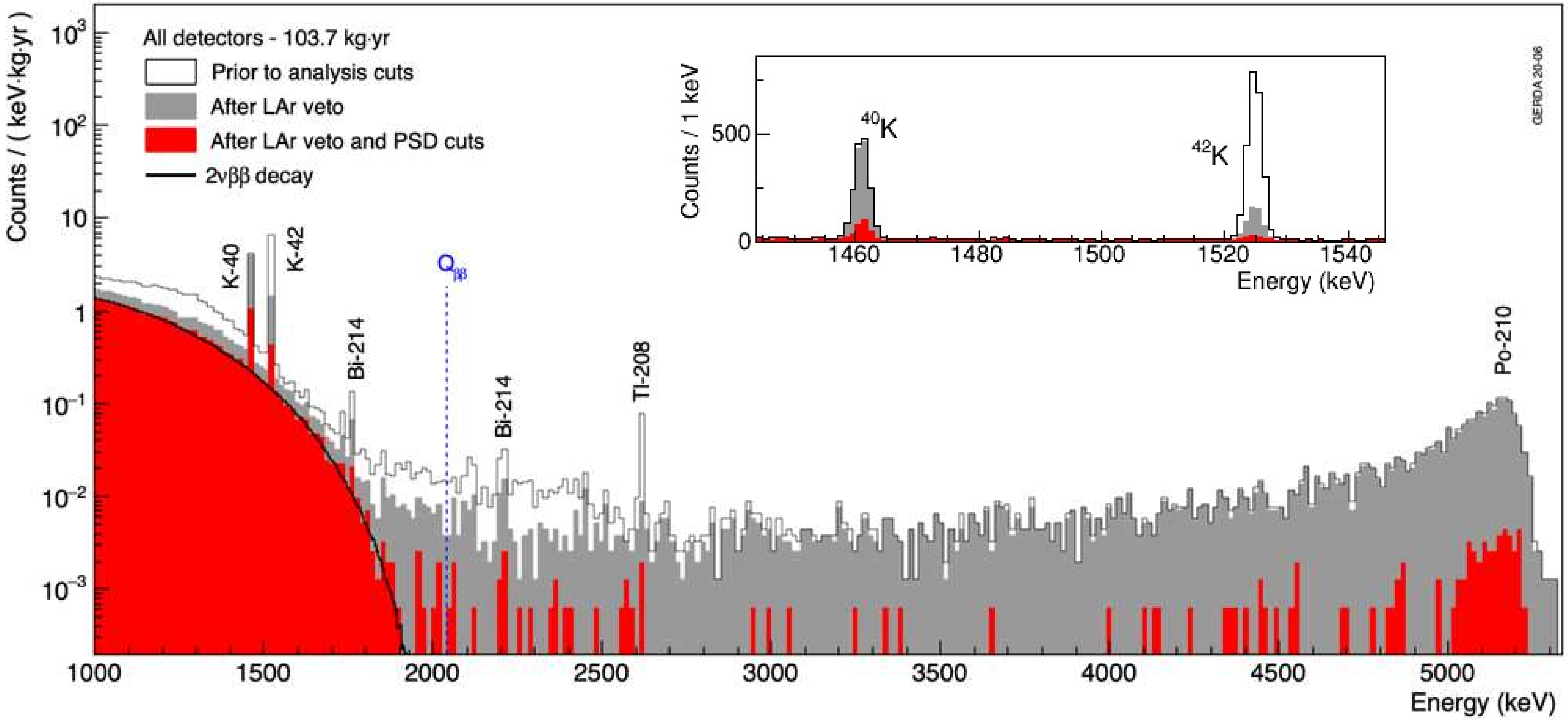
- **Completed** in Dec 2019
  - Target exposure of 100 kg yr achieved: **103.7 kg yr**



- Energy scale & resolution
  - Offline, using optimized ZAC filter on traces (digitized at 25 MHz) [EPJ C 75, 255]
  - Stability monitored online with test pulses, 0.05 Hz
  - Energy scale and resolution profile derived from weekly ^{228}Th calibrations



GERDA spectra: active veto and PSD



- Most prominent features > 500 keV: 2νββ, ^{42}K and ^{40}K γ-rays, α
- PSD clears completely the α region
- LAr and PSD **complementary**

See communication #955 by L. Pertoldi

0νββ analysis

Nature 544 (2017) 47

	Exposure (kg·yr)
Phase I	**23.5**
Phase II	**103.7**
	127.2 kg· yr

- Unbinned **maximum likelihood fit**
  - **Frequentist** and Bayesian
  - Systematic uncertainties folded as pull terms or by Monte Carlo

- Frequentist:

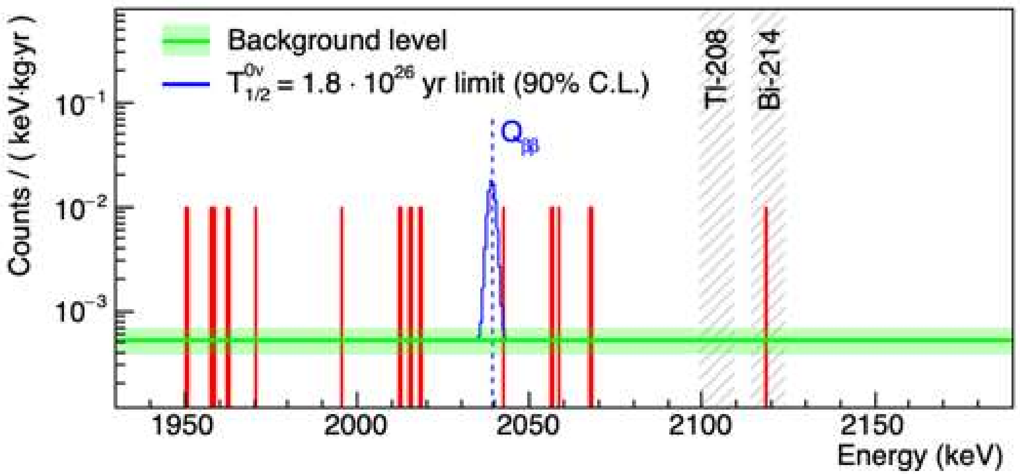
Best fit: $N^{0\nu} = 0$

$\mathbf{T_{1/2} > 1.8 \cdot 10^{26}}$ **yr @** 90% CL

$\mathbf{m_{\beta\beta} <}$ **79 – 180 meV**

MC **Median sensitivity** (no signal) $\mathbf{1.8 \cdot 10^{26}}$ **yr**

arXiv: 2009.06079



Background:

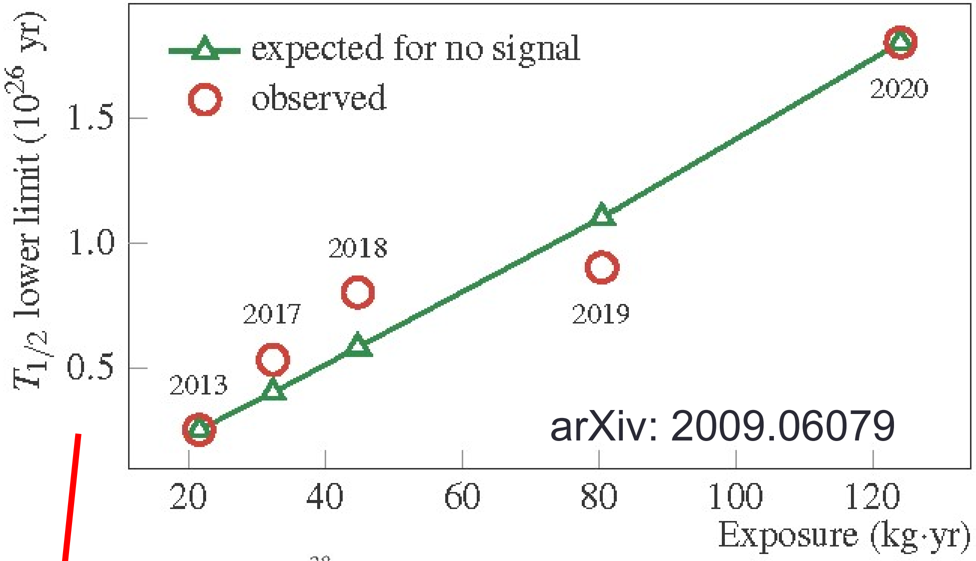
$\mathbf{5.2^{+1.6}_{-1.3} \cdot 10^{-4}}$ **cts/(keV kg yr)**

Expected events in $(Q_{\beta\beta} \pm 2\sigma)$:

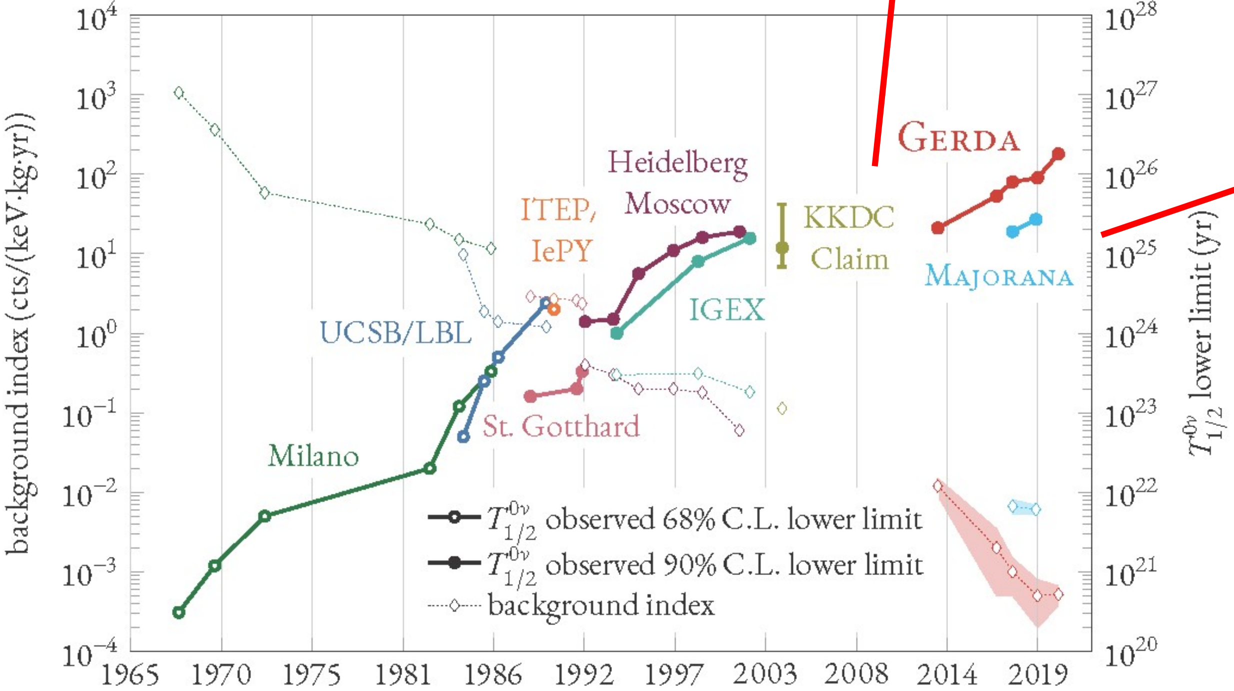
0.3 counts →"background free"

(most probable value = 0)

History of ^{76}Ge experiments

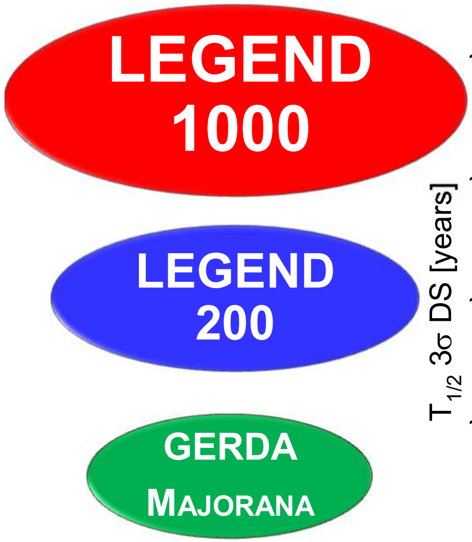


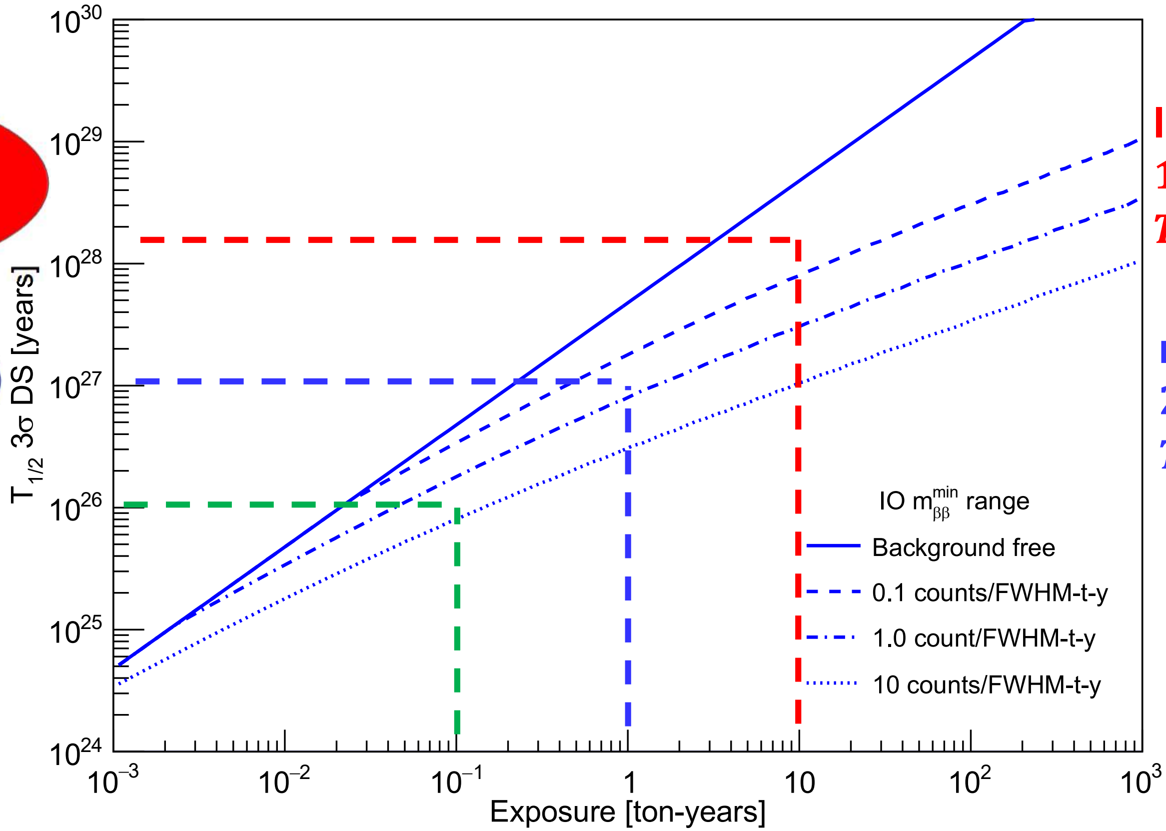
Courtesy of L. Pertoldi



…and future

AIP Conf. Proc. 1894 (2017) 020027
J. Phys. Conf. Ser. 1468 (2020) 012111





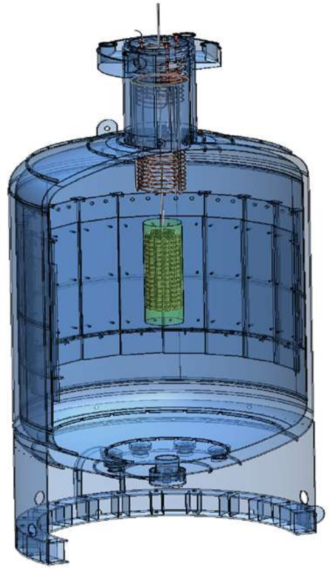
long-term
1 ton
$T^{0\nu}_{1/2} > 10^{28}$ **yr**

mid-term
200 kg
$T^{0\nu}_{1/2} > 10^{27}$ **yr**

running/ended
30 kg
$T^{0\nu}_{1/2} > 10^{26}$ **yr**

Pursue «background-free» approach to higher exposures, to achieve the linear increase of sensitivity with exposure
→ requires lower and lower background

Taking the best from MJD and GERDA


MAJORANA

- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold (helps reject background)

MAJORANA achieved best energy resolution: 2.5 keV FWHM at $Q_{\beta\beta}$

Both

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution $0\nu\beta\beta$ experiments

GERDA

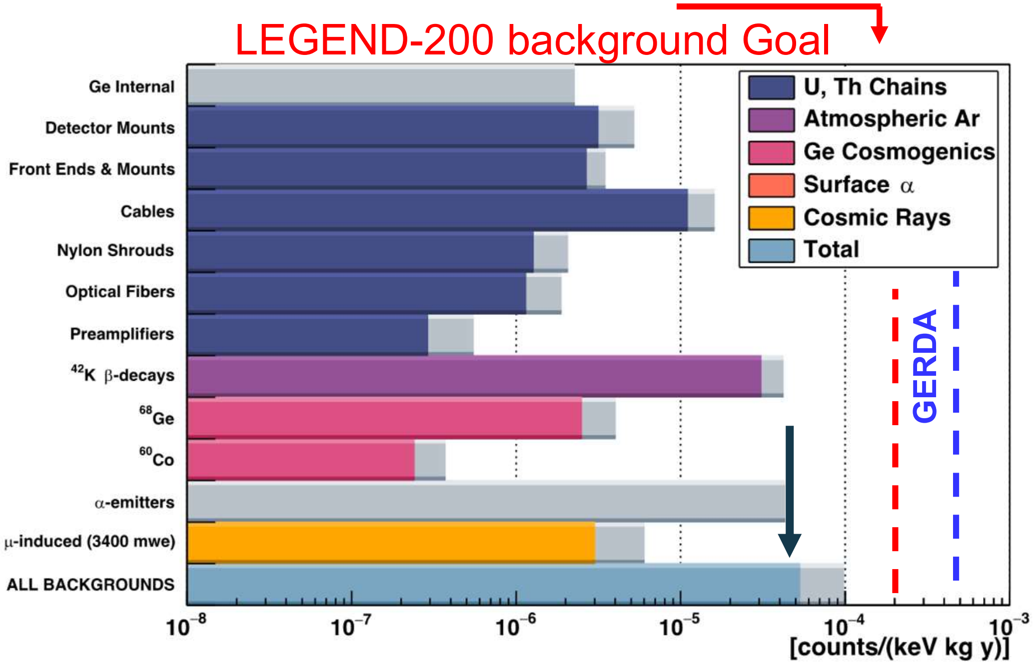
- LAr veto
- Low-A shield, no Pb

GERDA achieved the lowest background index: $5 \cdot 10^{-4}$ cts/(keV kg yr)

LEGEND-200 needs only x3-5 better.

LEGEND-200 at LNGS

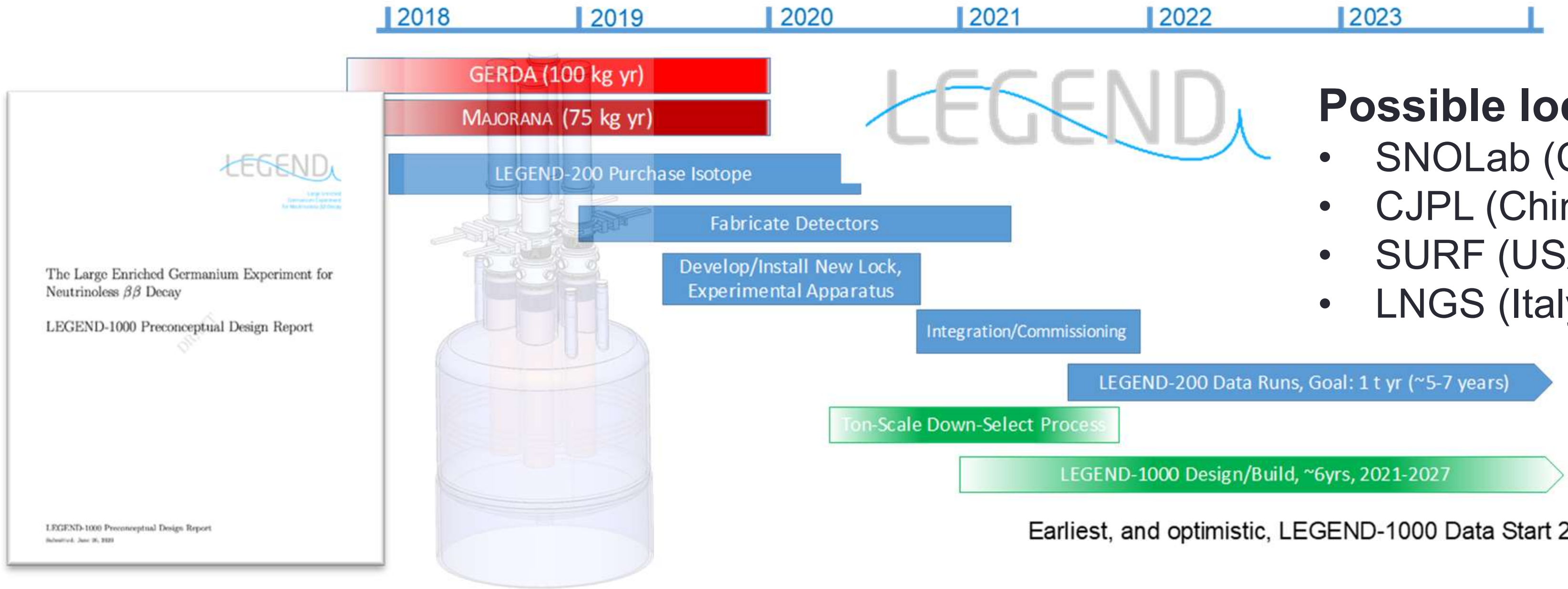
- Ongoing since **Feb 2020** at **LNGS**
- GERDA detectors + 4 L200 ICPC + 5 MJD PPC detectors operating LAr
- First tests of new DAQ, calibration system under real conditions. **First spectrum in March 2020**
- **Enriched** material ordered (170 kg)



LEGEND

- **Background budget**
- Monte Carlo + data-driven projections of Ge U/Th, ^{42}K, α based on GERDA, MJD data
- All others: Monte Carlo + assay-based projections

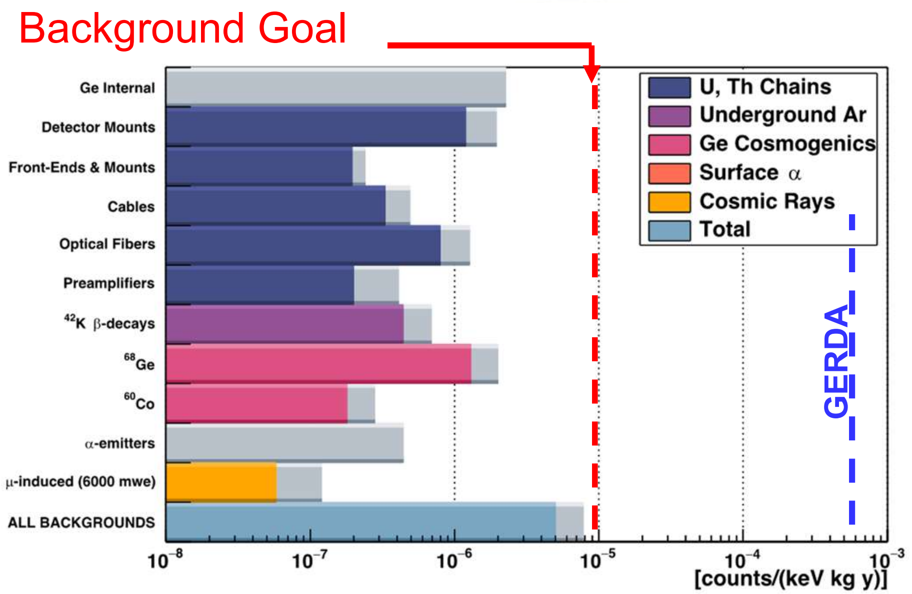
LEGEND-1000: towards a ton-scale exp



Possible locations:

- SNOLab (Canada)
- CJPL (China)
- SURF (USA)
- LNGS (Italy)

Earliest, and optimistic, LEGEND-1000 Data Start 2025/6



Background **reduction strategy** for LEGEND-1000:

- **U/Th**: optimized array spacing, minimize opaque materials, larger detectors, better light collection, cleaner materials
- **^{42}Ar**: strong suppression by using UAr
- **μ-induced**: improved shielding, SNOLab depth assumed
- **Surface α's**: assumes achieved upper limits for BEGes and ICs in GERDA

Conclusions

- **GERDA completed** the data taking
  - Met Phase II design goals in exposure (> 100 kg yr) and in background
  - «Background-free» regime achieved: **0.3** counts expected in ($Q_{\beta\beta} \pm 2\sigma$), background index $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)
  - Linear increase of sensitivity vs. exposure
    - Sensitivity for null signal: $1.8 \cdot 10^{26}$ yr (first experiment to pass 10^{26} yr)
  - Tested inverted coaxial detectors
- **0νββ** data analysis **released** (Phase I+II, 127.2 kg yr)
  - **$T_{1/2} > 1.8 \cdot 10^{26}$ yr** @ 90% CL (world record on $T_{1/2}$)
  - **$m_{\beta\beta} <$ 79 – 180 meV**

arXiv: 2009.06079

- **LEGEND** has taken over infrastructure
  - first stage ~200kg, aiming at 10^{27} yr sensitivity
  - start taking data with LEGEND-200 in 2021
  - LEGEND-1000 targets 10^{28} yr
  - Always pursue the "background-free" regime