

## SEARCHING FOR MATTER CREATION WITH GERDA AND BEYOND

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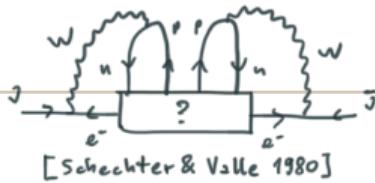
*Rencontres de Moriond* • 16 Mar 2022

TU München, INFN Padova

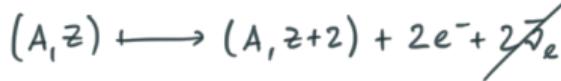


# WHY NEUTRINOLESS DOUBLE- $\beta$ DECAY?

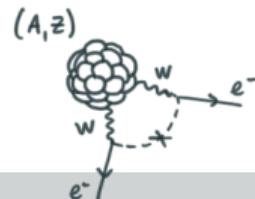
arXiv 2202.01787



"The search for  $0\nu\beta\beta$  decay is one of the most compelling and exciting challenges in all of contemporary physics"<sup>1</sup>



- $0\nu\beta\beta$  observation  $\Rightarrow$  Majorana neutrino and Lepton Number Violation
- Lepton number  $\longleftrightarrow$  Barion number  $\longleftrightarrow$  new physics, baryogenesis?



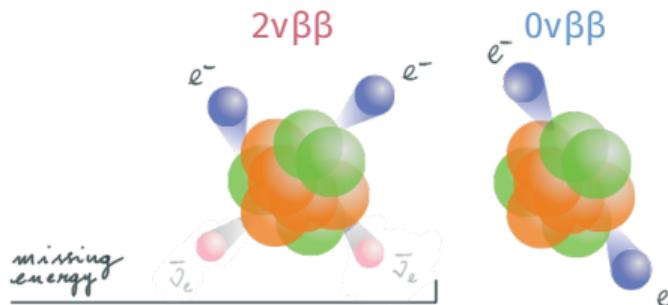
## Light neutrino mass mechanism

The (Majorana) neutrino that mediates  $0\nu\beta\beta$  is the one that oscillates and the Standard Model is an effective theory (*seesaw mechanism*)

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 \quad \text{Majorana effective mass}$$

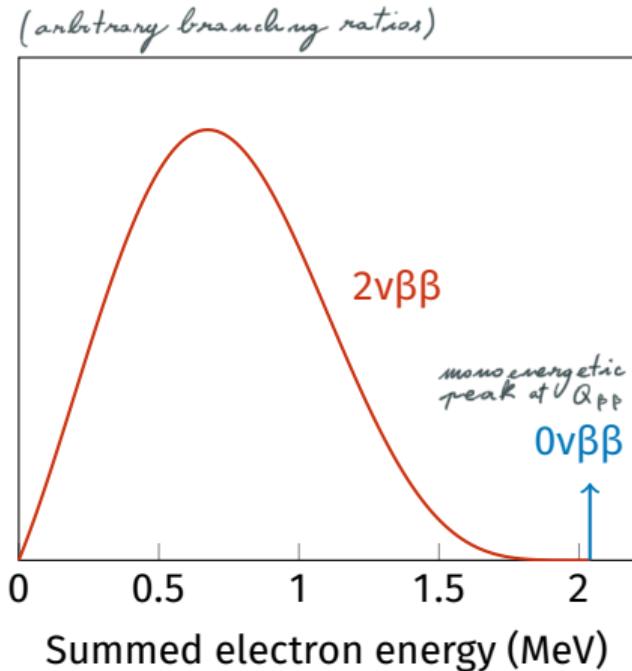
<sup>1</sup>100+ papers per year with " $0\nu\beta\beta$ " in the title [INSPIRE-HEP statistics]

## EXPERIMENTAL SIGNATURE



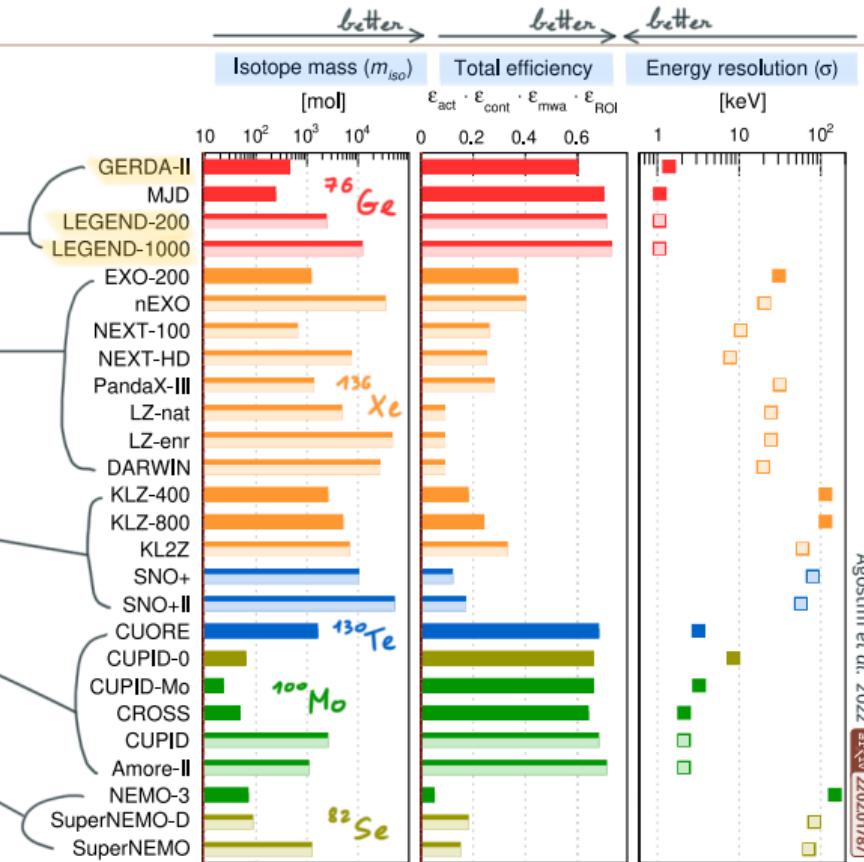
All experiments measure the **total energy of the two emitted electrons**

→ *necessary and sufficient for discovery*



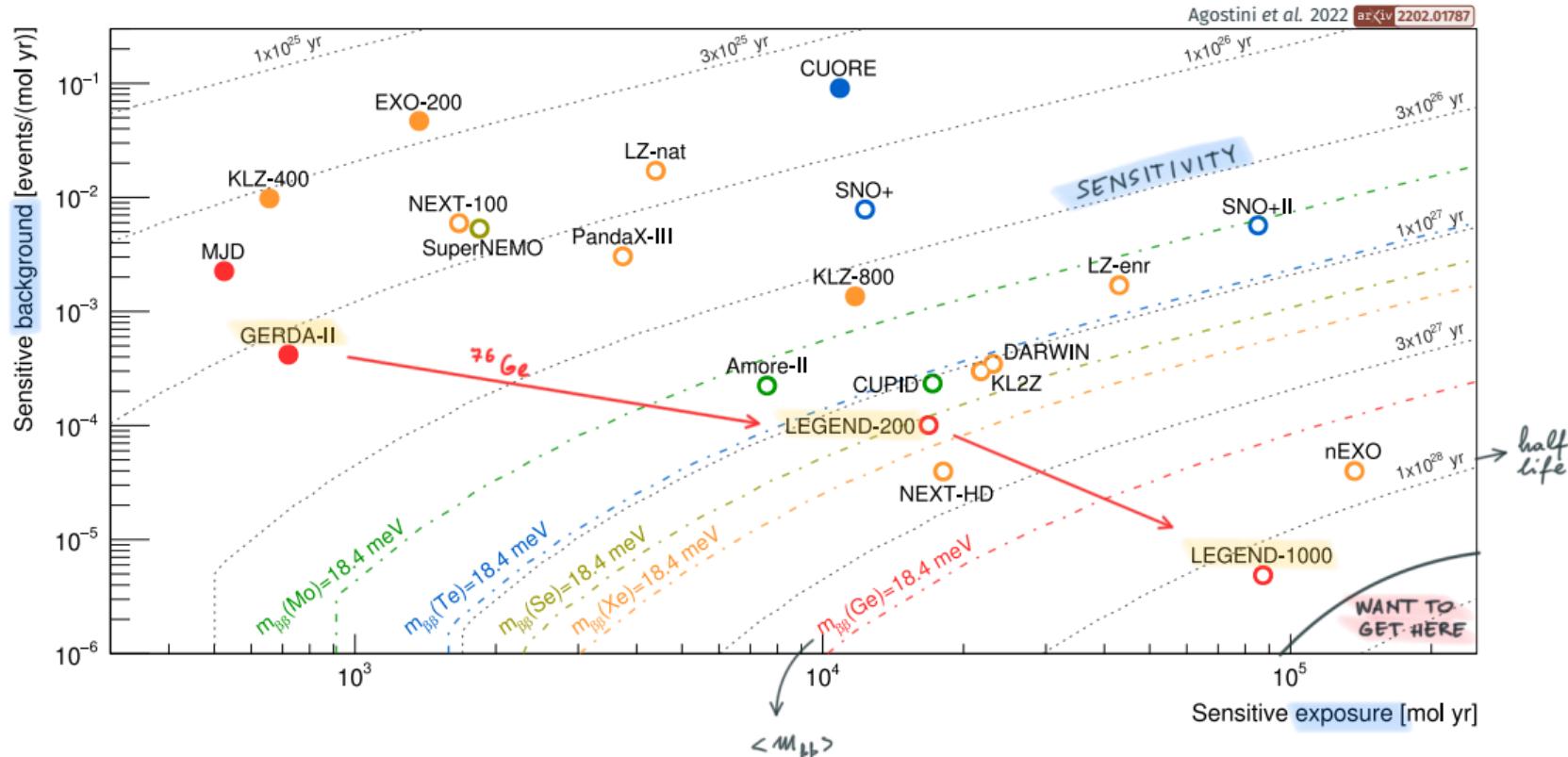
# A ZOO OF DETECTOR CONCEPTS

- **High-purity Germanium detectors** ←  
energy resolution, efficiency, background
- **Xenon Time Projection Chambers** ←  
isotope mass, particle tracking
- **Large Liquid Scintillators** ←  
isotope mass
- **Cryogenic Calorimeters** ←  
energy resolution, efficiency, granularity
- **Tracking Calorimeters** ←  
particle tracking, decay kinematics



Agostini et al. 2022 arXiv:2202.01787

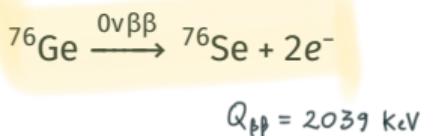
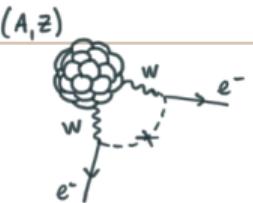
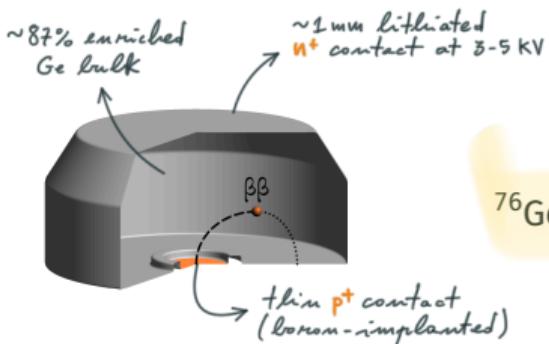
# DETECTOR CONCEPTS: SENSITIVITY



# THE GERDA EXPERIMENTAL CONCEPT

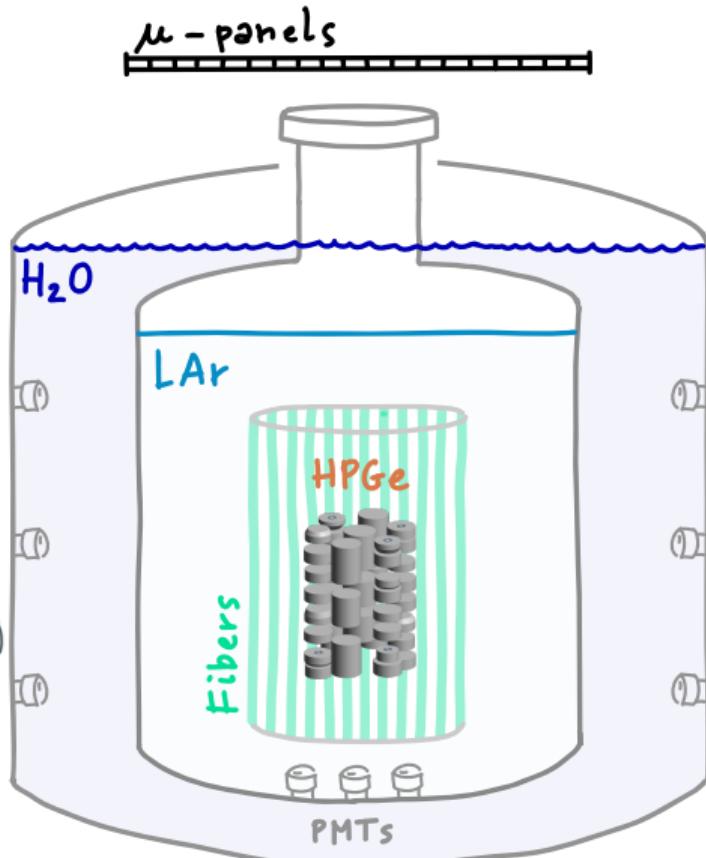


--- holes (+)  
..... electrons (-)

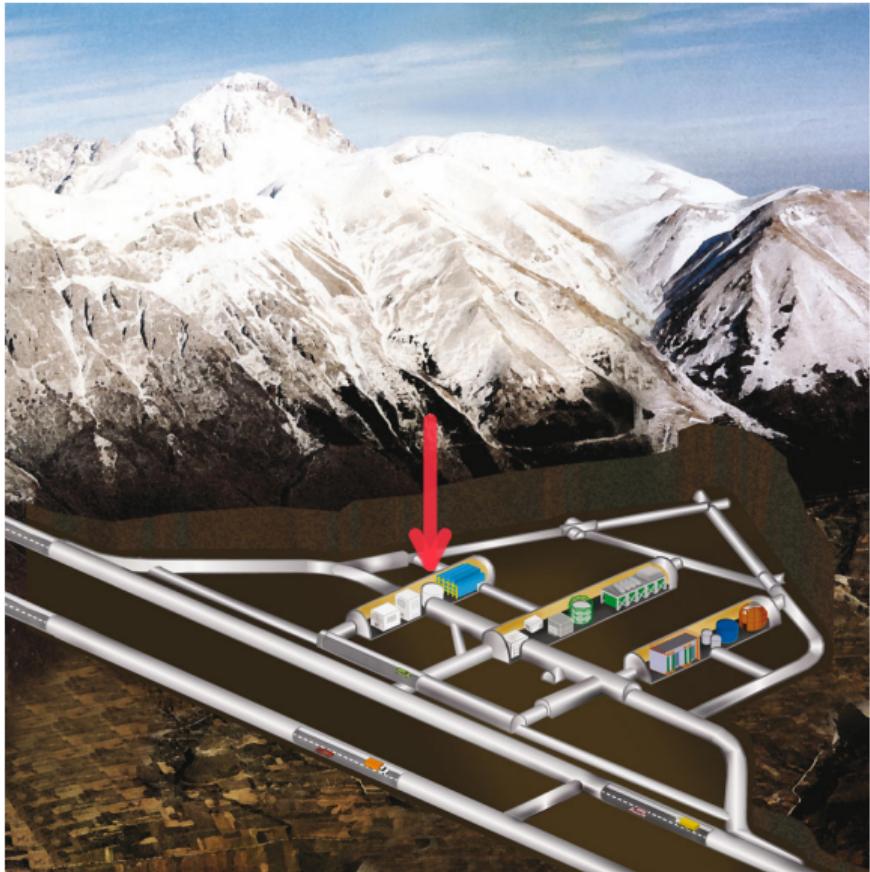


High-Purity Germanium detectors enriched in  $^{76}\text{Ge}$

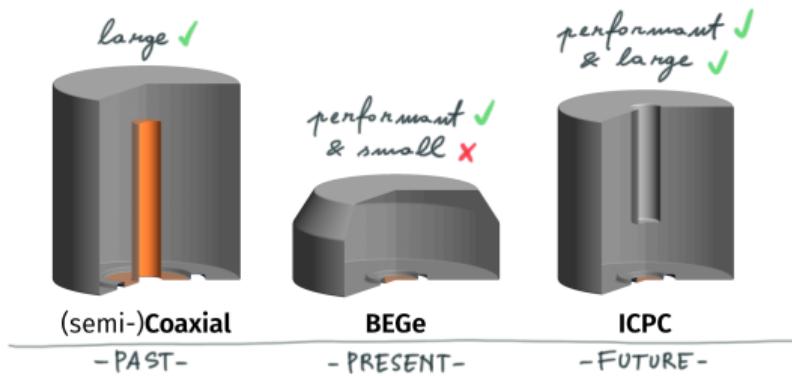
- source = detector  $\mapsto$  high efficiency
- pure  $\mapsto$  low intrinsic background 99.9999% Ge (6N)
- Ge crystal  $\mapsto$  outstanding energy resolution 0.1% @  $Q_{\beta\beta}$  (FWHM)
- solid-state TPC  $\mapsto$  topological discrimination *Pulse Shape Analysis*



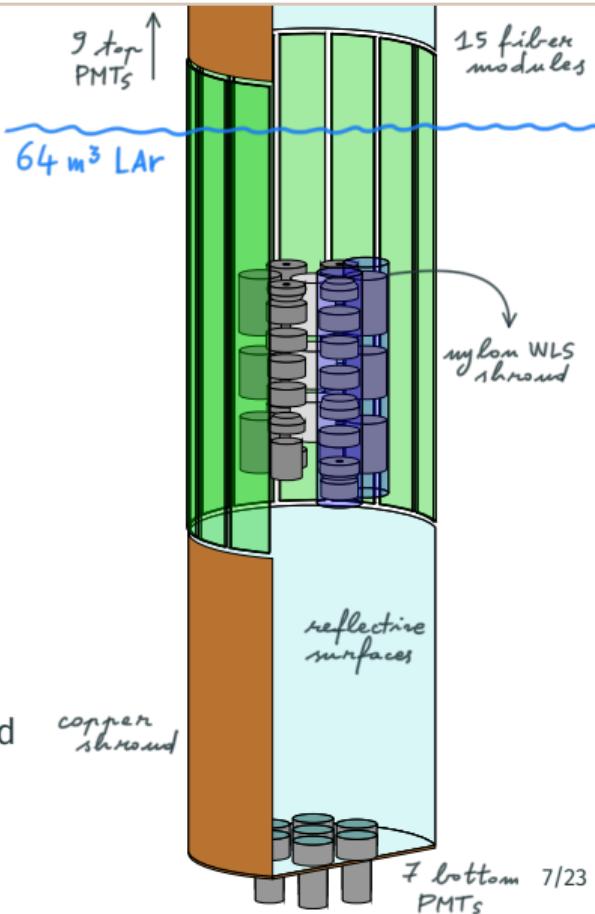
# GERMANIUM DETECTOR ARRAY AT LNGS — 3500 m.w.e. —



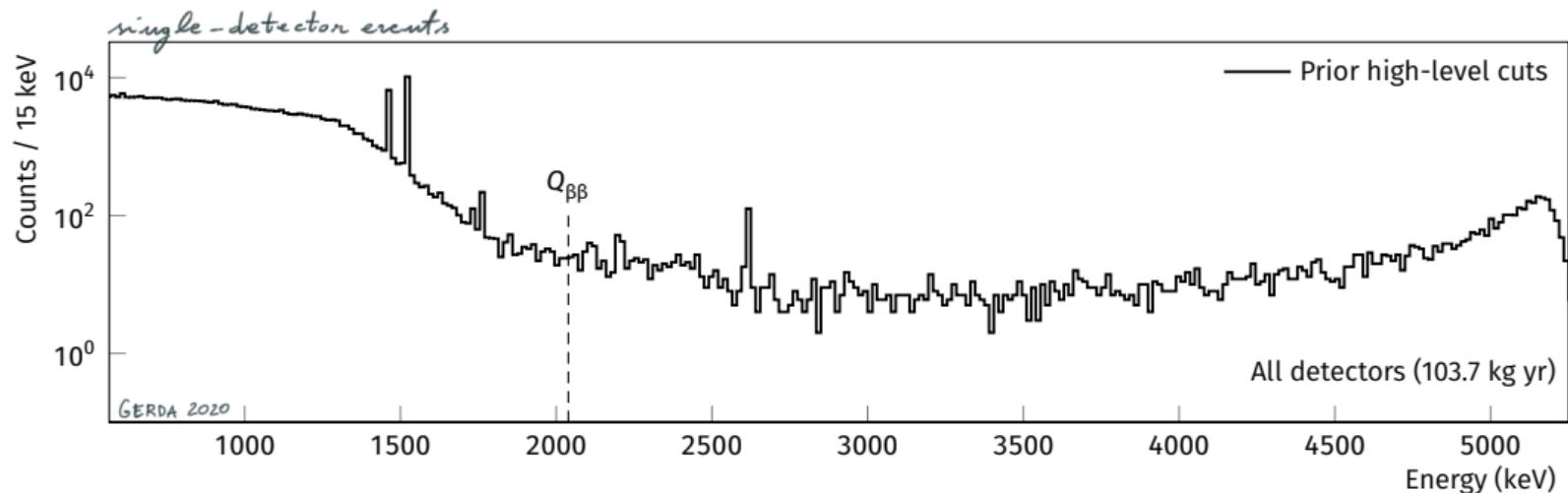
- 35.6 kg (later 44.2 kg) of HPGe REF EPJC 79 (2019) 11, 978 REF EPJC 81 (2021) 505



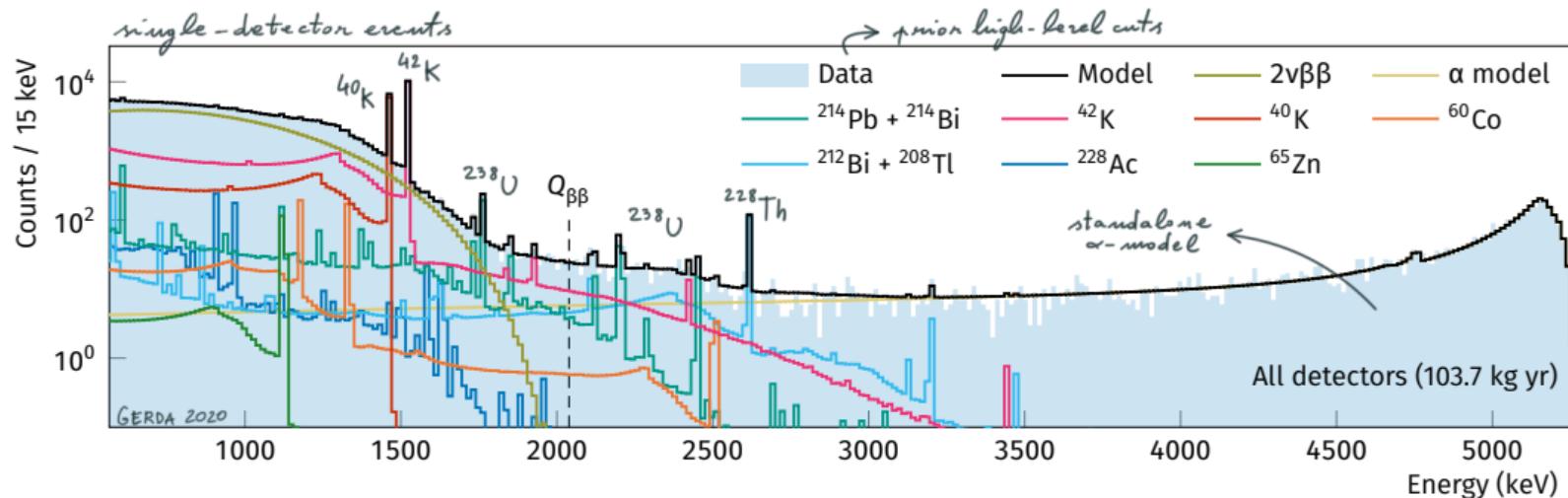
- Hybrid LAr light collection system: WLS fibers / SiPMs / PMTs
- $\mu$ -veto: water Cherenkov, scintillating panels REF EPJC 76 (2016) 298
- Ultra radio-pure materials, small passive mass, deep underground



## PHASE II DATA ENERGY SPECTRUM BEFORE HIGH-LEVEL CUTS



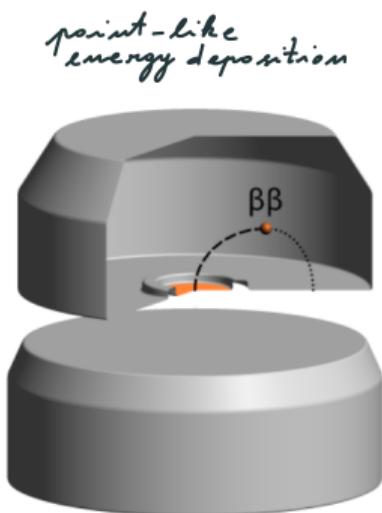
- Data taken from Dec 2015 to Nov 2019 (**~90% duty cycle**, including upgrade works)
- Energy resolution: **~ 0.1% FWHM** at  $Q_{\beta\beta}$  REF [Eur. Phys. J. C 81 \(2021\) 8, 682](https://doi.org/10.1140/epjc/s10050-021-09280-0)
- **103.7 kg yr** of exposure selected for analysis, largest ever collected with  $^{76}\text{Ge}$



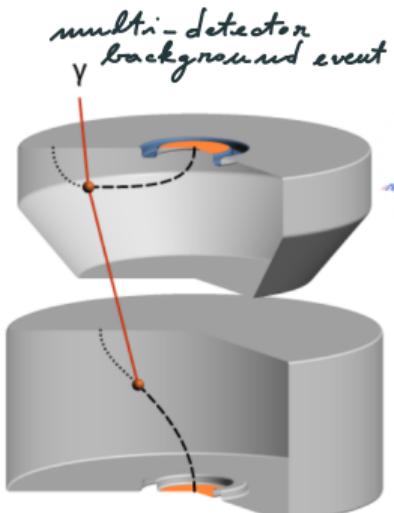
- Bayesian multivariate fit of Monte Carlo predictions (with screening measurements as priors)
- $Q_{\beta\beta}$  dominated by  $\beta$  from  $^{42}\text{K}$  (from  $^{42}\text{Ar}$  in LAr),  $\alpha$  from  $^{210}\text{Po}$ ,  $\gamma$  from  $^{228}\text{Th}$  and  $^{238}\text{U}$  chains
- Results are input to several physics analyses and inform future experiments (LEGEND.)

# SIGNAL AND BACKGROUND DISCRIMINATION TECHNIQUES

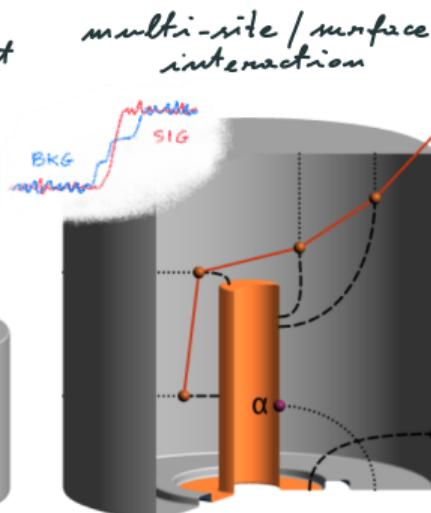
--- holes (+)  
..... electrons (-)



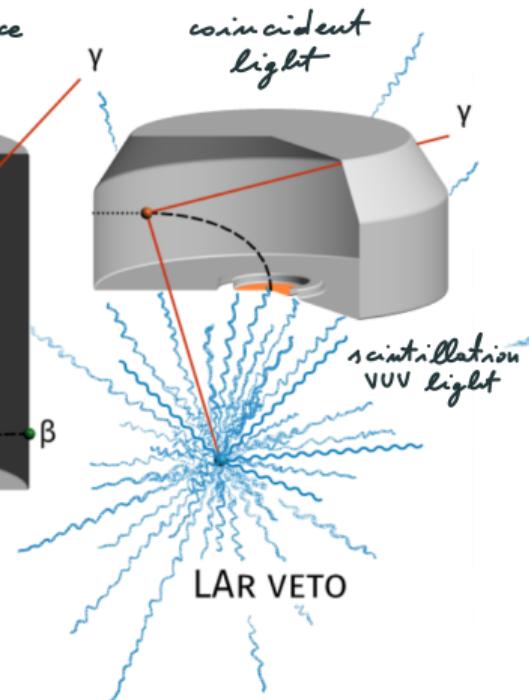
SIGNAL-LIKE



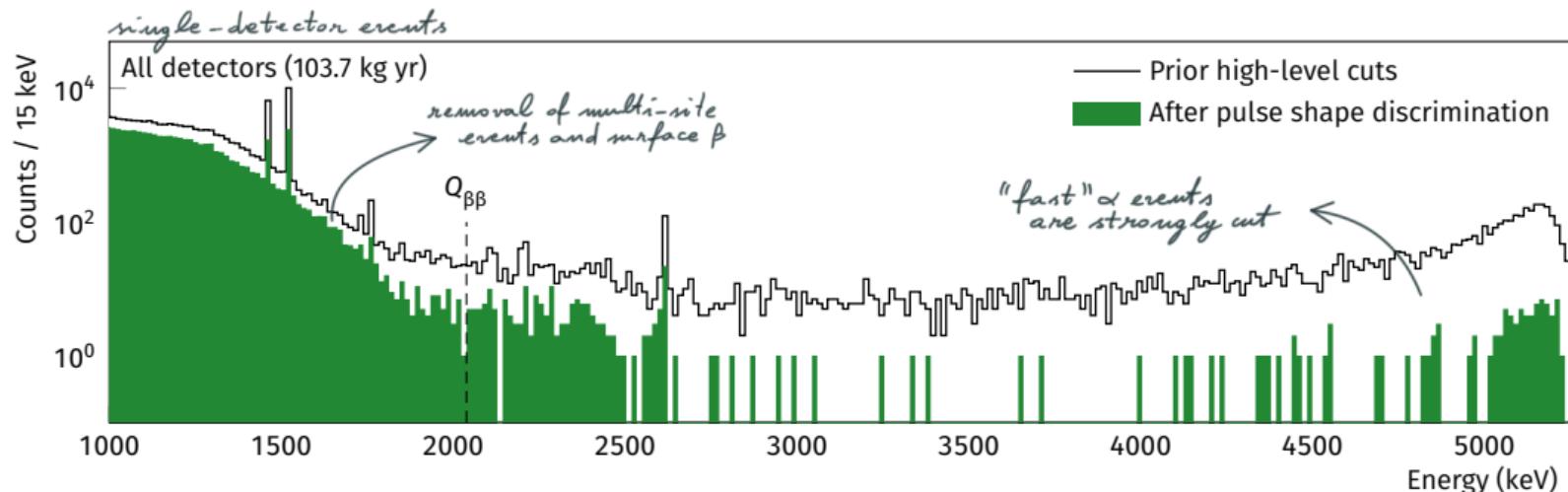
GRANULARITY CUT



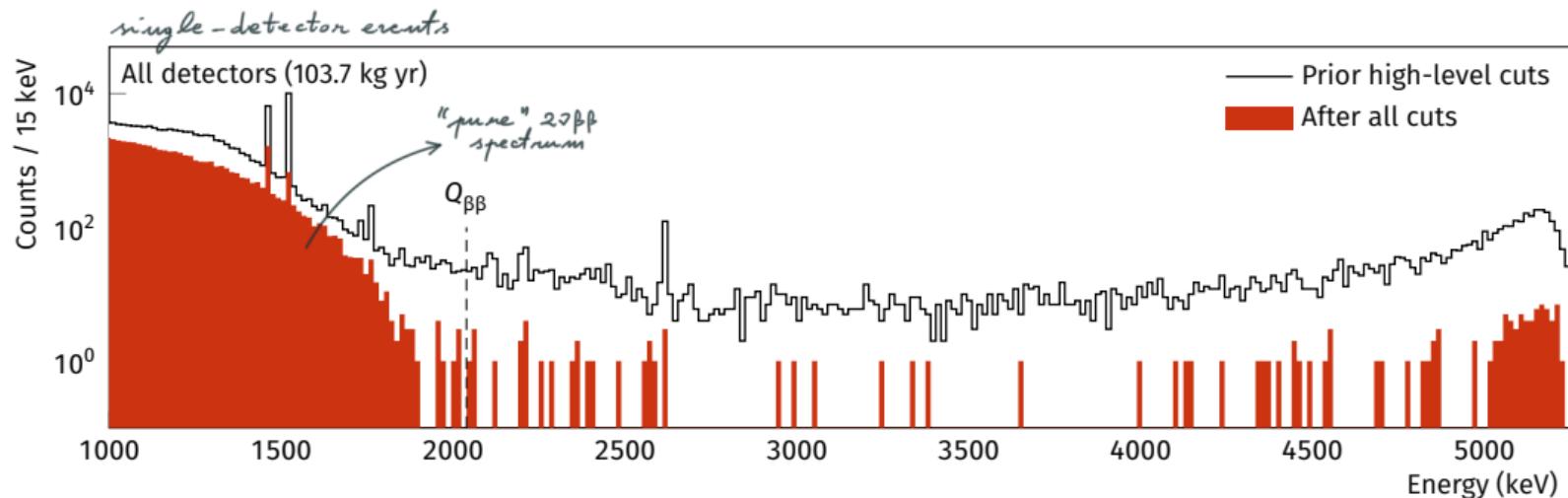
PULSE-SHAPE  
DISCRIMINATION



# PULSE SHAPE DISCRIMINATION...



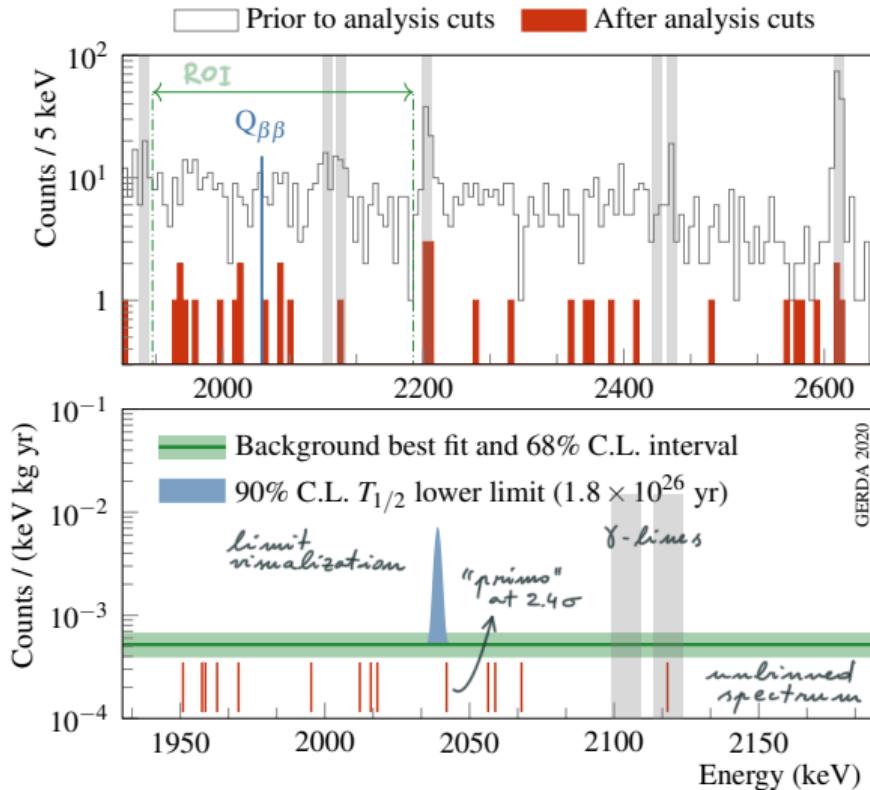
- Point-contact detectors: two-sided univariate  $A/E$  cut REF JINST 4 (2009) P10007
- Coaxial detectors: artificial neural network and risetime cut REF EPJC 73 (2013) 10, 2583  *$^{228}\text{Th}$  calibration data as tuning sample*
- $0\nu\beta\beta$  signal efficiency: 90% (70% for coaxials) arXiv 2202.13355 (to appear soon on EPJC)



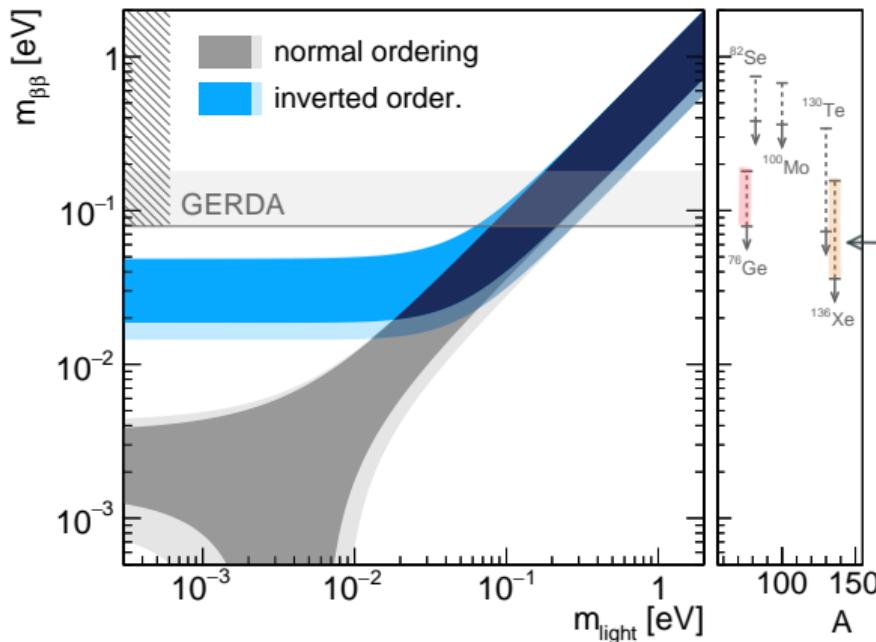
- Anti-coincidence between HPGe trigger and SiPM/PMT data ( $\geq 0.3$  p.e. in a  $5 \mu\text{s}$  window)
- Extremely low event rate at  $Q_{\beta\beta}$  of  $\sim 5 \cdot 10^{-4}$  cts / (keV kg yr)  $\mapsto$  quasi-background-free
- Few events at  $Q_{\beta\beta}$   $\mapsto$  “simple” background-model-free analysis  
 $\sim 0.3$  counts per FWHM in full exposure!

*"One of the world's best-performing  $0\nu\beta\beta$  experiments"*

- $5.2_{-1.3}^{+1.6} \cdot 10^{-4}$  cts / (keV kg yr) at  $Q_{\beta\beta}$
- No signal in 127.2 kg yr of exposure *blind analysis*
- $T_{1/2}^{0\nu} > 1.8 \cdot 10^{26}$  yr (90% C.L. frequentist)
- $\langle m_{\beta\beta} \rangle < 79\text{--}180$  meV (*NME uncertainty*)

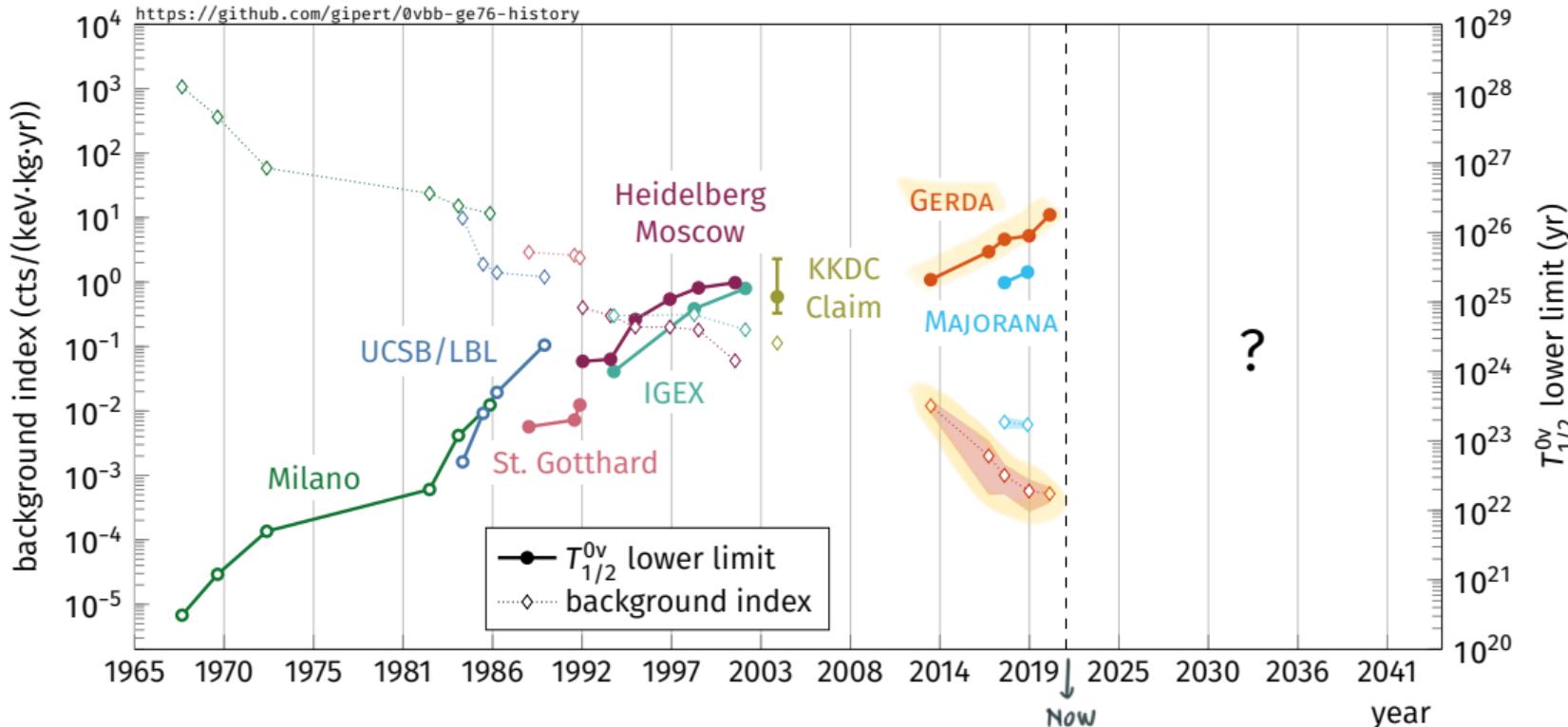


## RESULTS FROM OTHER EXPERIMENTS



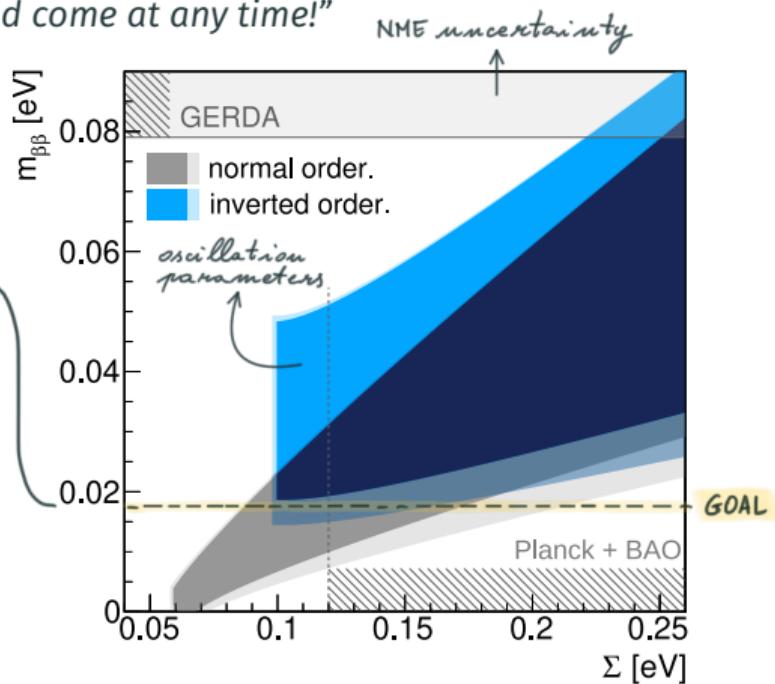
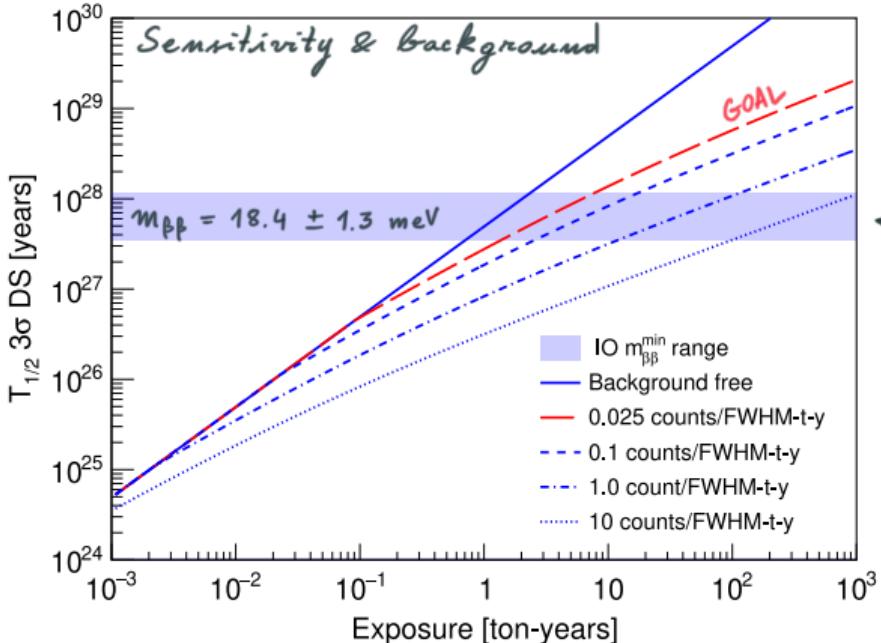
- $^{136}\text{Xe}$ ,  $^{76}\text{Ge}$  (and  $^{130}\text{Te}$ ) place the most stringent limits
  - Note:  $^{76}\text{Ge}$  limits on  $\langle m_{\beta\beta} \rangle$  are weakened by a less favorable phase space factor
- New: KAMLAND-ZEN800 results presented last week at La Thuile  
arXiv 2203.02139 :
  - $T_{1/2}^{0\nu} > 2.3 \cdot 10^{26}$  yr (90% C.L.)
  - $\langle m_{\beta\beta} \rangle < 36\text{--}156$  meV

# 50 YEARS OF DOUBLE BETA DECAY WITH $^{76}\text{Ge}$



## WHAT NEXT?

*“...an era in which a discovery could come at any time!”*



*"The collaboration aims to develop a **phased,  $^{76}\text{Ge}$ -based** double-beta decay experimental program with discovery potential at a **half-life beyond  $10^{28}$  yr**, using existing resources as appropriate to expedite physics results."*

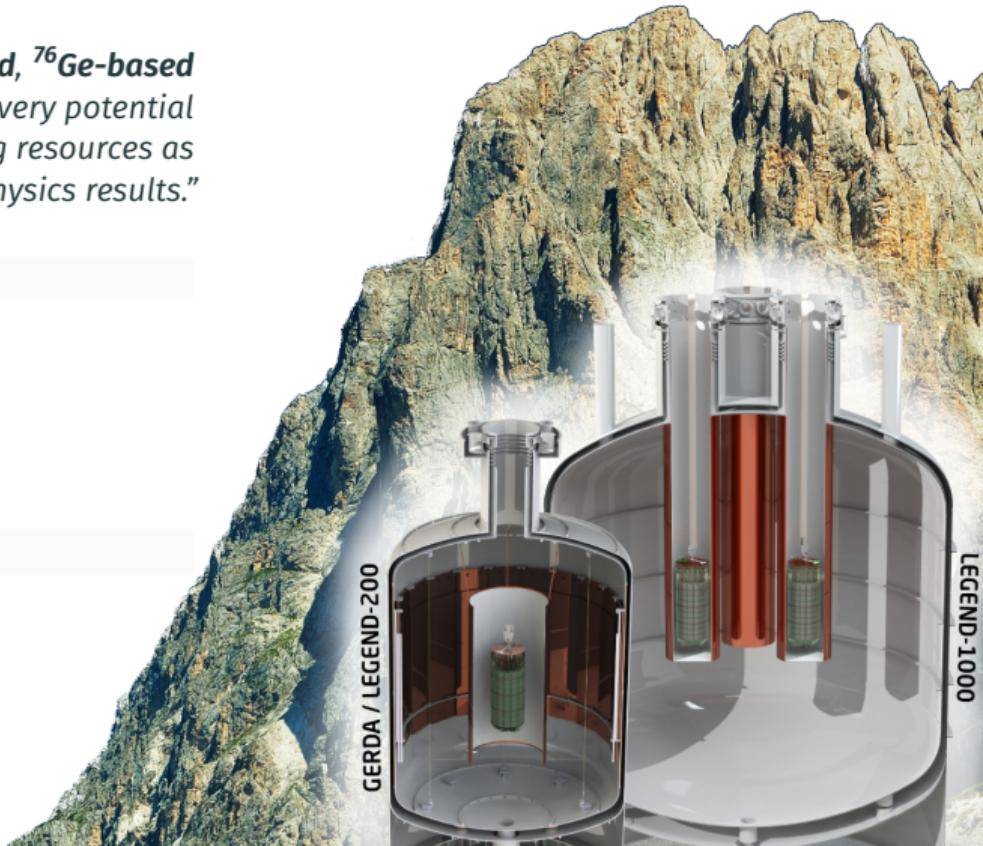
## LEGEND-200

- **200 kg** of  $^{\text{enr}}\text{Ge}$  ( $\times 5$  yr), in GERDA cryostat
- Funded, under commissioning
- $B \sim 2 \cdot 10^{-4} \text{ cts / (keV kg yr)} \mapsto T_{1/2}^{0\nu} > 10^{27} \text{ yr}$

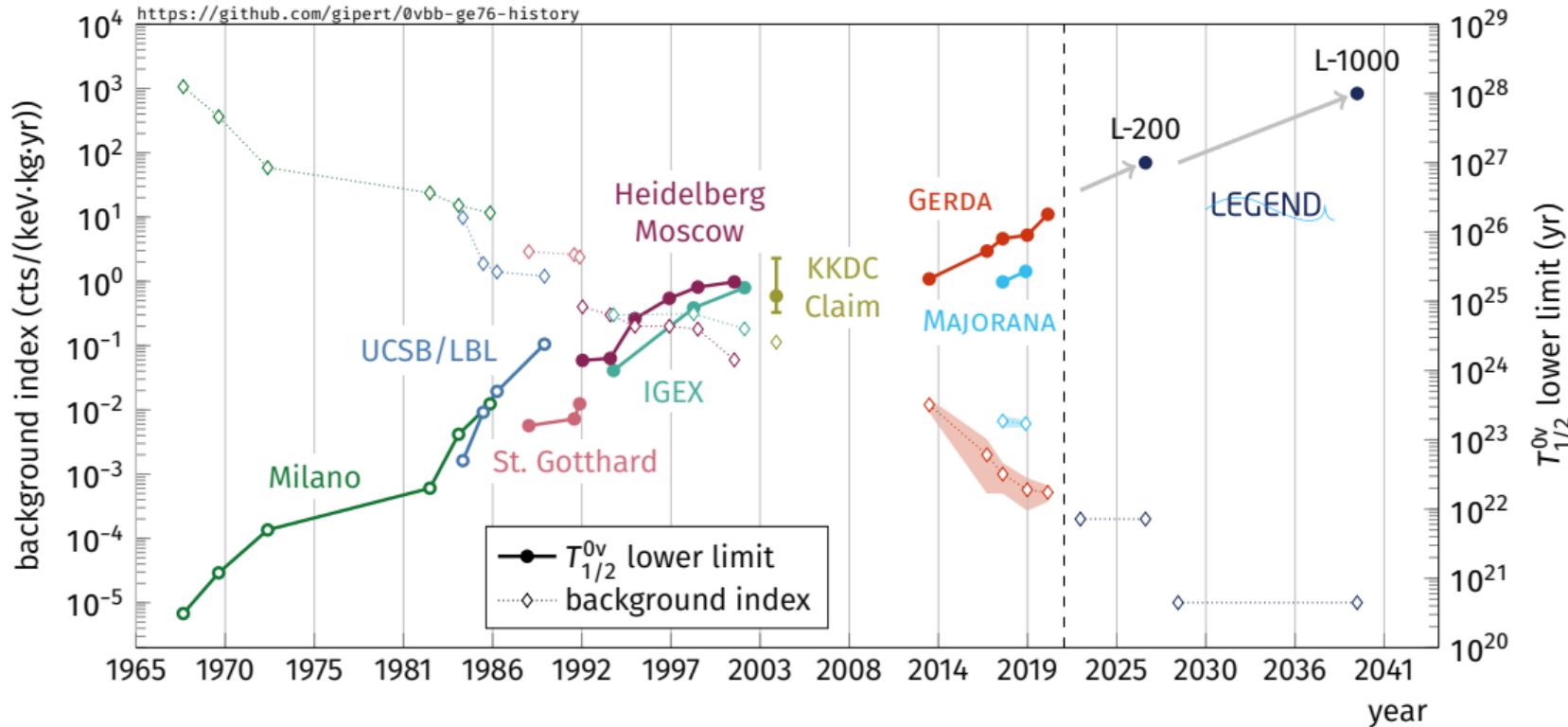
## LEGEND-1000

arXiv [2107.11462](https://arxiv.org/abs/2107.11462) "pre-conceptual design report"

- **1 ton** of  $^{\text{enr}}\text{Ge}$  ( $\times 10$  yr), awaiting funding
- $B < 10^{-5} \text{ cts / (keV kg yr)} \mapsto T_{1/2}^{0\nu} > 10^{28} \text{ yr}$
- Cover full  $\langle m_{\beta\beta} \rangle$  inverted ordering region

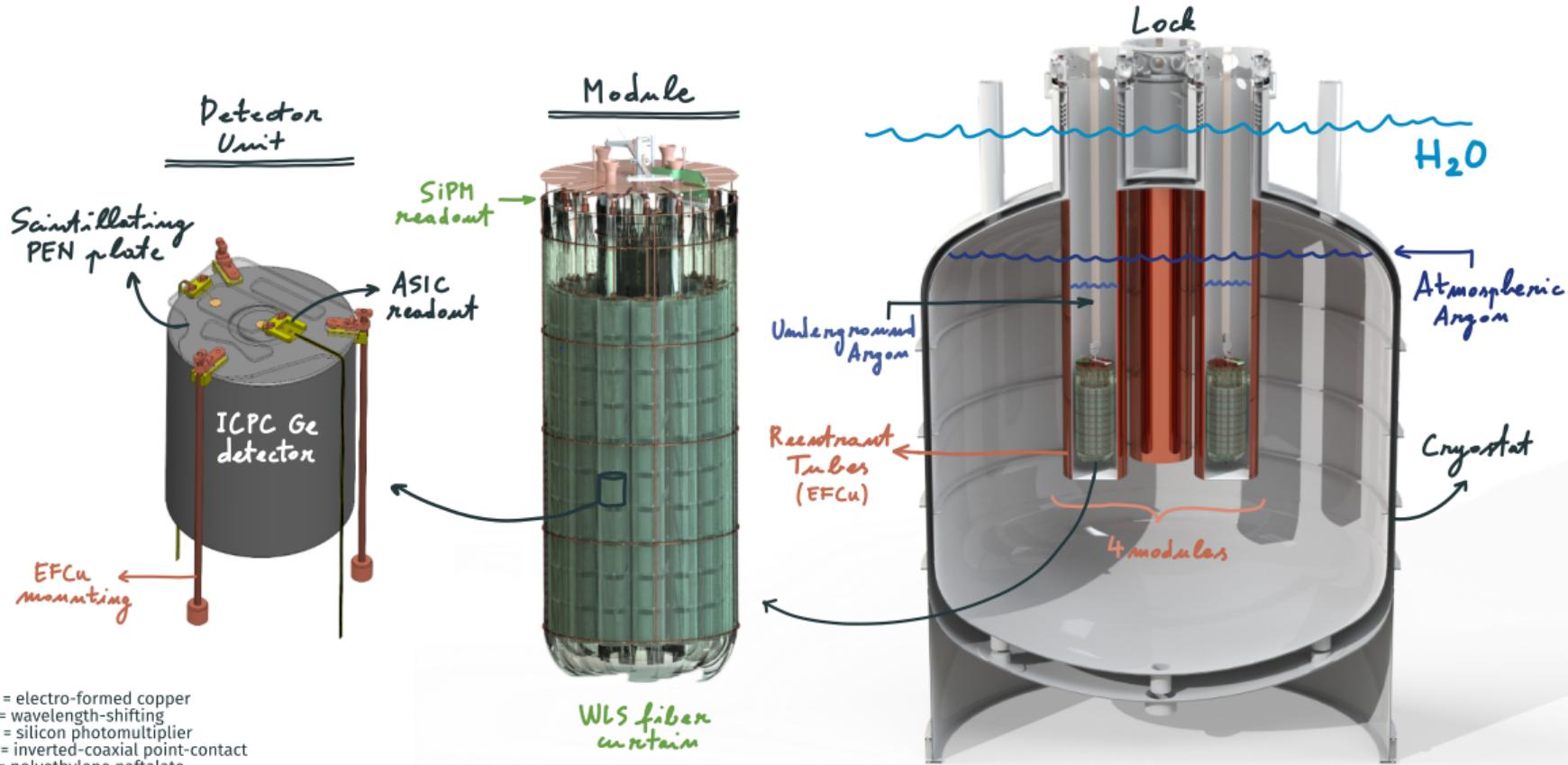


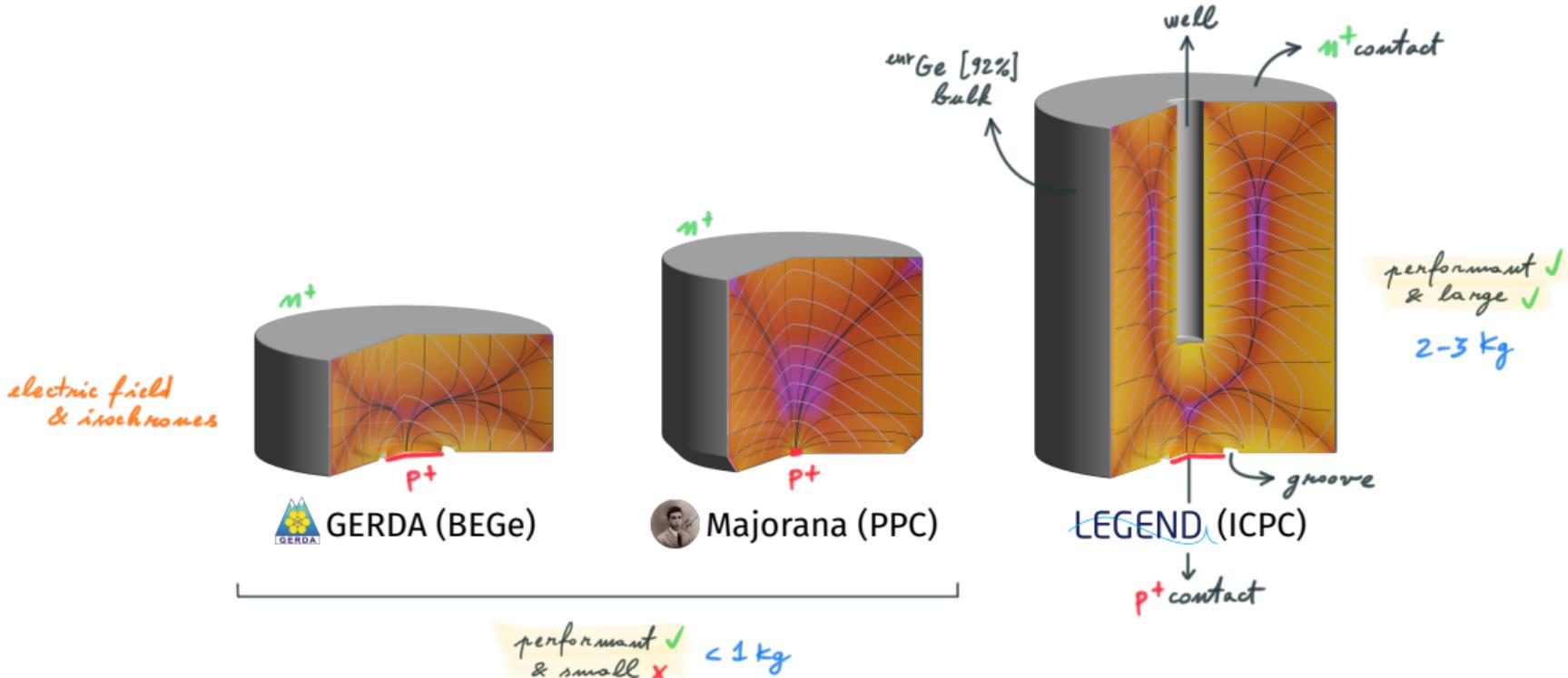
# 50 YEARS OF DOUBLE BETA DECAY WITH $^{76}\text{Ge}$



# THE LEGEND -1000 BASELINE DESIGN

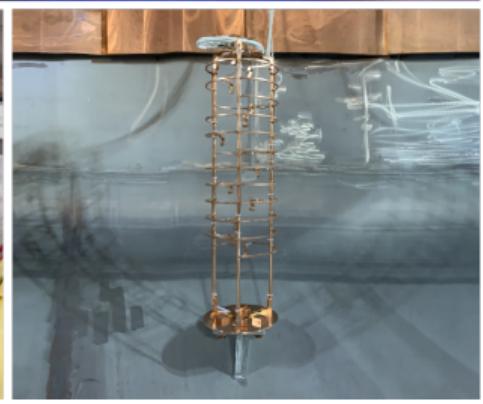
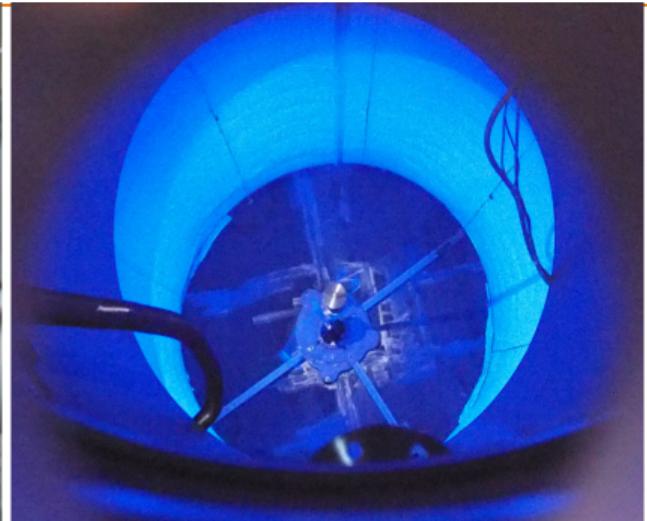
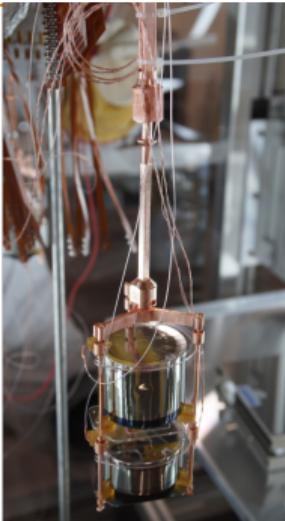
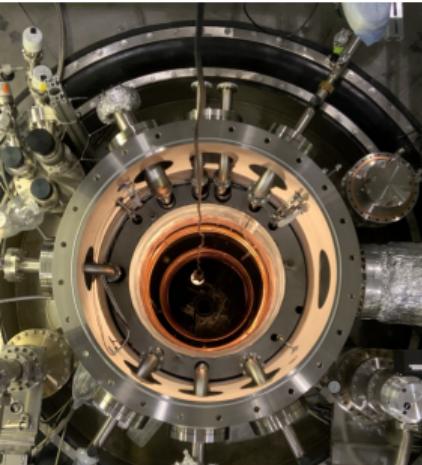
LEGEND

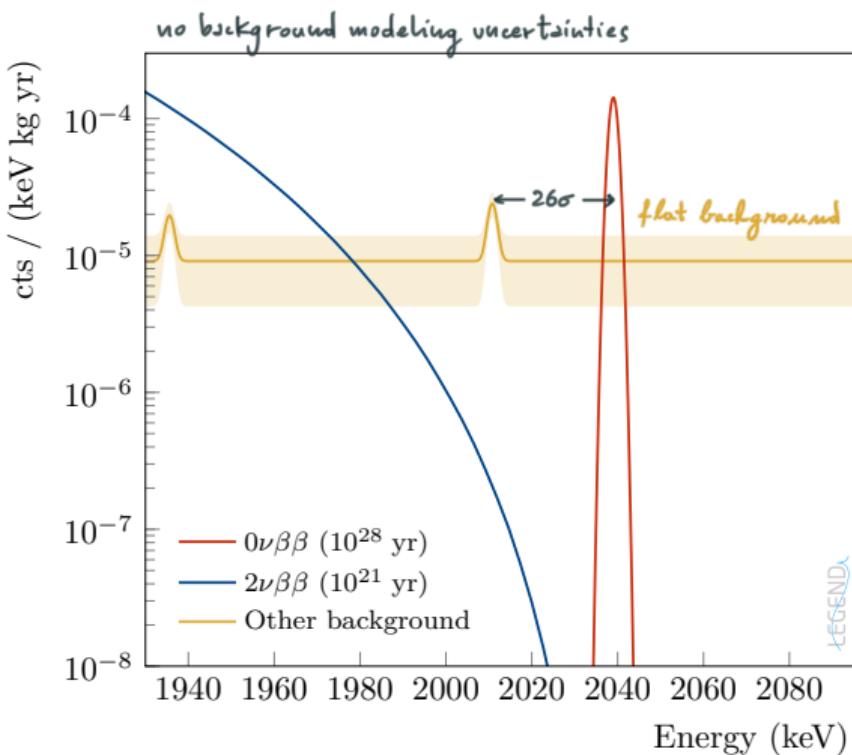
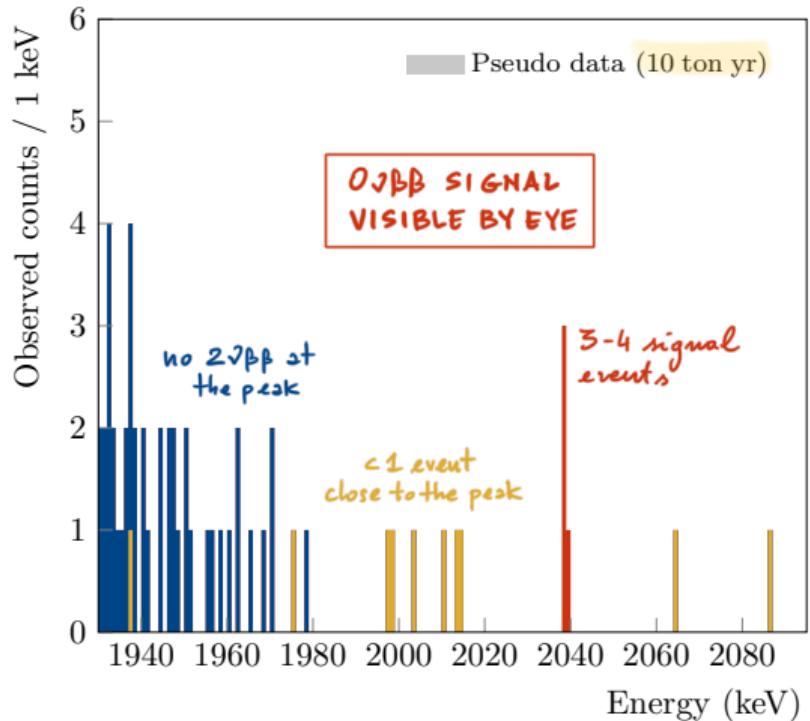




# LEGEND-200 COMMISSIONING AT LNGS

LEGEND







### GERDA:

- has searched for  $0\nu\beta\beta$  in a *quasi-background-free* regime
- has led the worldwide effort by providing **strong half-life limits**
- has demonstrated the **maturity of germanium technology** for a ton-scale project

### The scientific community:

- has acknowledged the search for  $0\nu\beta\beta$  as *one of the most compelling challenges in contemporary physics*
- strives for international funding for **ton-scale  $0\nu\beta\beta$  experiments**

### LEGEND:

- has a low-risk path to meeting its background goal and is **optimized for discovering  $0\nu\beta\beta$**
- will pioneer the exploration of *new energy frontiers beyond the inverted ordering scenario*