Status of the LEGEND experiment

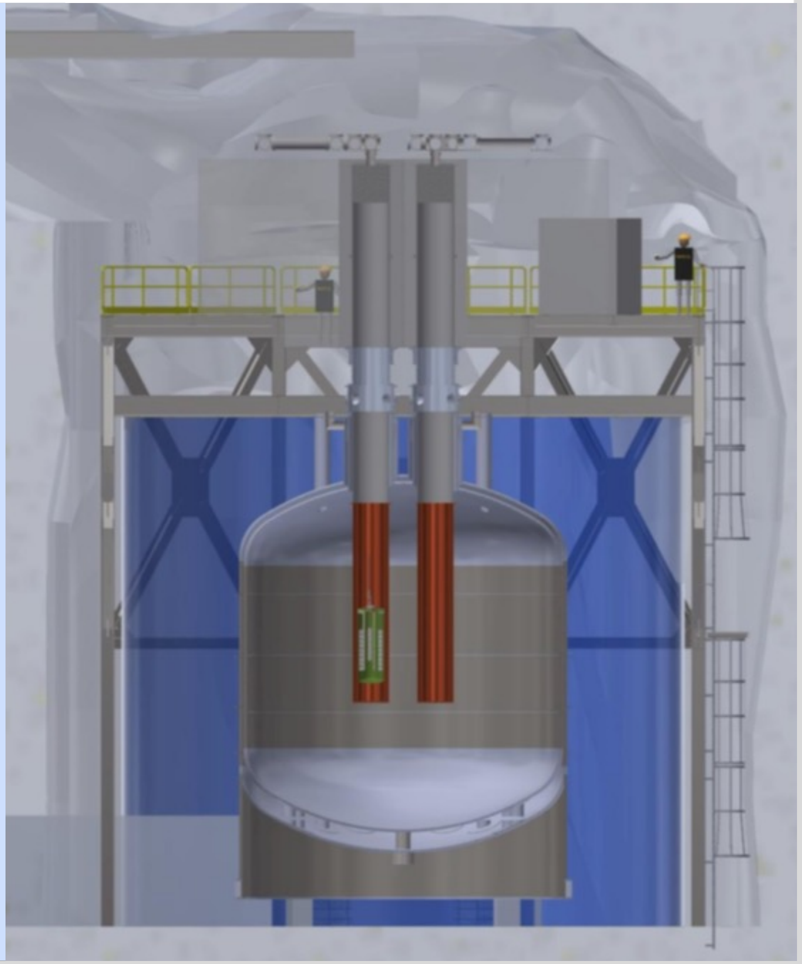
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

J.M. López-Castaño

May 12th, 2022

Conference On Science at SURF 2022



LEGEND COLLABORATION & OUTLINE

LEGEND mission: “The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results.”

INDEX:

- Neutrinoless double beta decay
- Why Germanium?
- What does it takes to measure?
- Built from past experiences
- LEGEND
- LEGEND-200
- LEGEND-1000
- Background reduction
- Background budgets
- Background model
- Conclusions

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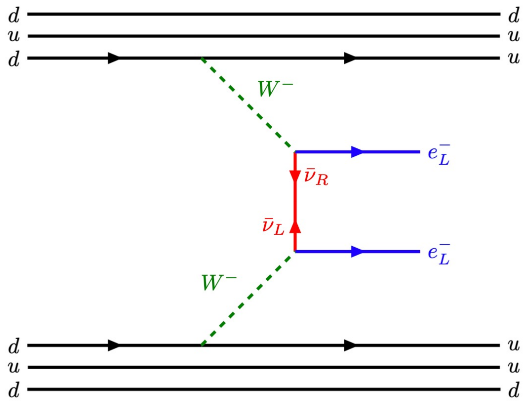
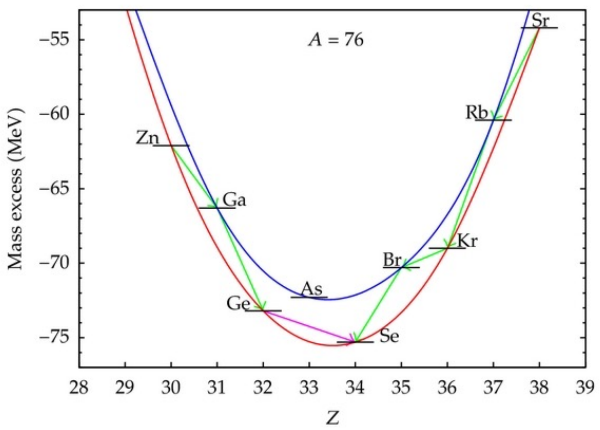
NEUTRINOLESS DOUBLE BETA DECAY

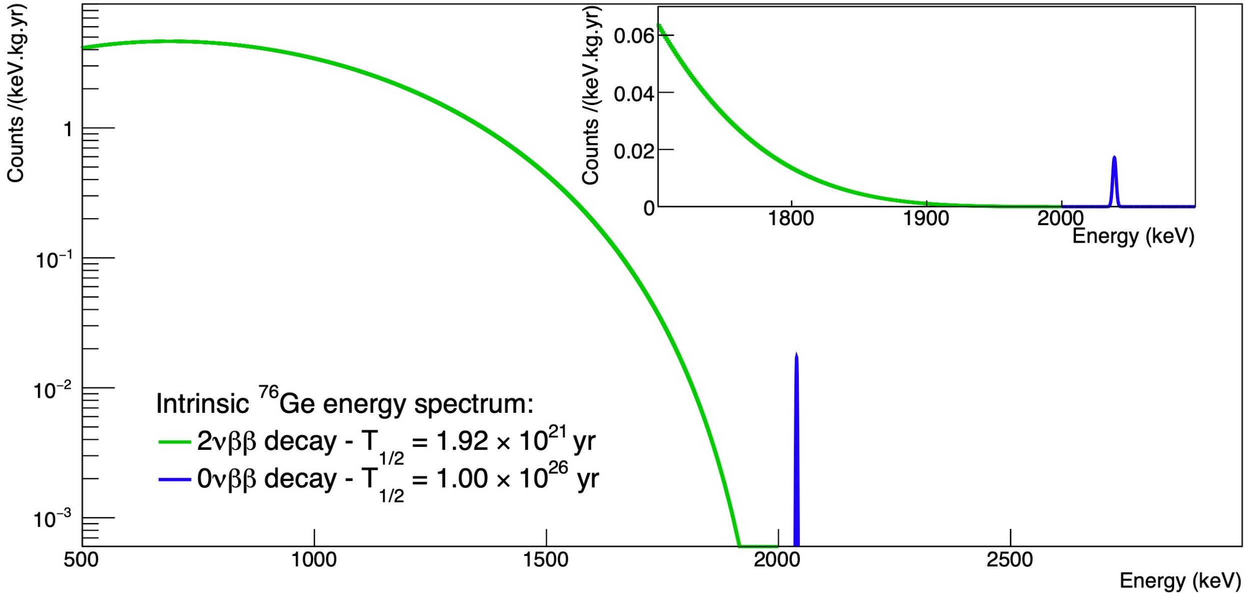
- Theoretical radiaoctive decay
  - Unknown mechanism
    - Several theoretical mechanisms have been developed
- Dramatic implications in our foundational understanding of nature
  - Neutrino mass nature
    - First Majorana elemental particle
    - Explanation for a light neutrino masses
  - Lepton number conservation
    - The lepton number is not a fundamental symmetry anymore
  - Matter–Antimatter asymmetry
    - Leptogenesis is possible



arXiv 2109.07575

Adv. High Energy Phys. 2012(1687-7357)





arXiv 2109.07575

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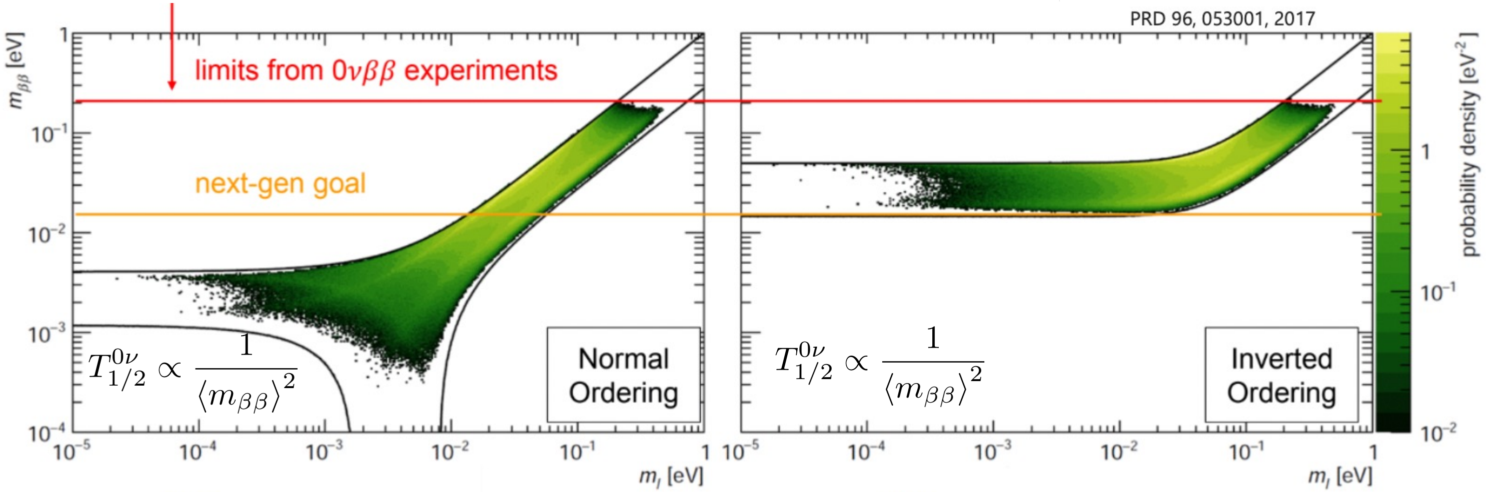
NEUTRINOLESS DOUBLE BETA DECAY

- Clear milestone for the next-generation experiments
  - To cover the inverted-ordering neutrino hierarchy



NO: $m_1 < m_2 < m_3$ **IO:** $m_3 < m_2 < m_1$

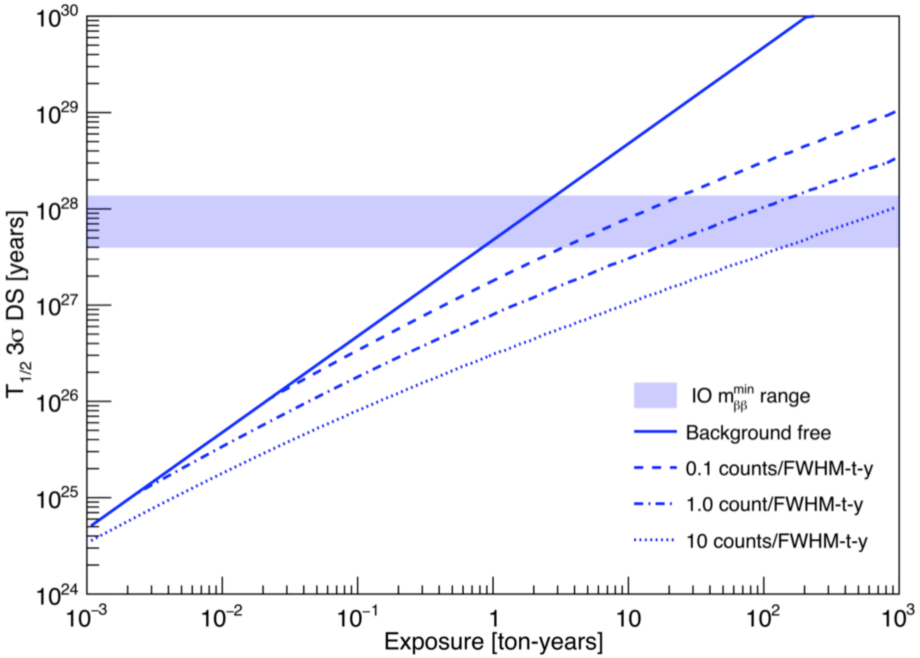
- Experimental challenges of a rare-event search:

Background free

$$(T^{0\nu}_{1/2}) \propto a M \varepsilon t$$

With background

$$(T^{0\nu}_{1/2}) \propto a\varepsilon \sqrt{\frac{Mt}{B\,\Delta E}}$$



  - Low rate of occurrences
    - Use a large amount of mass
    - Run for a long duration time
  - Background
    - Background free: ideal case
    - With background, the sensitivity increases slower

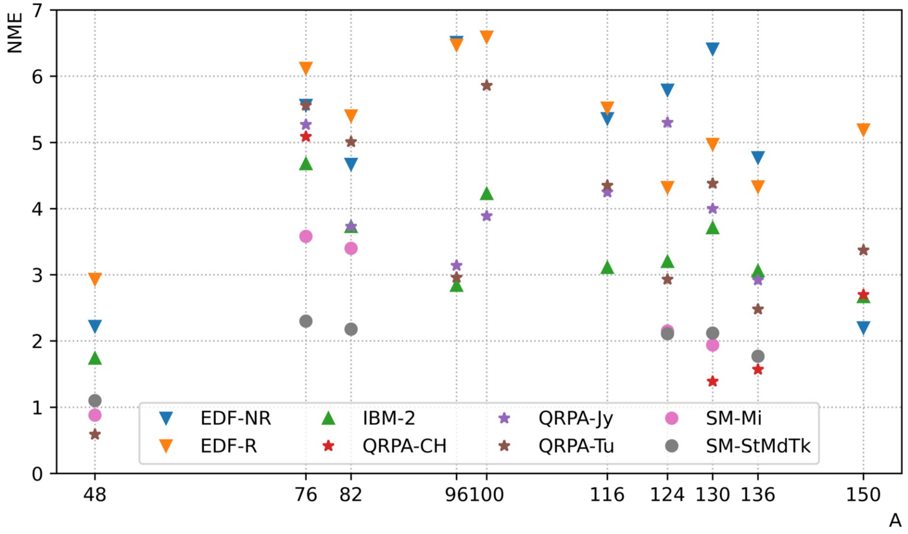
WHY GERMANIUM?

- The half-life is calculated by:

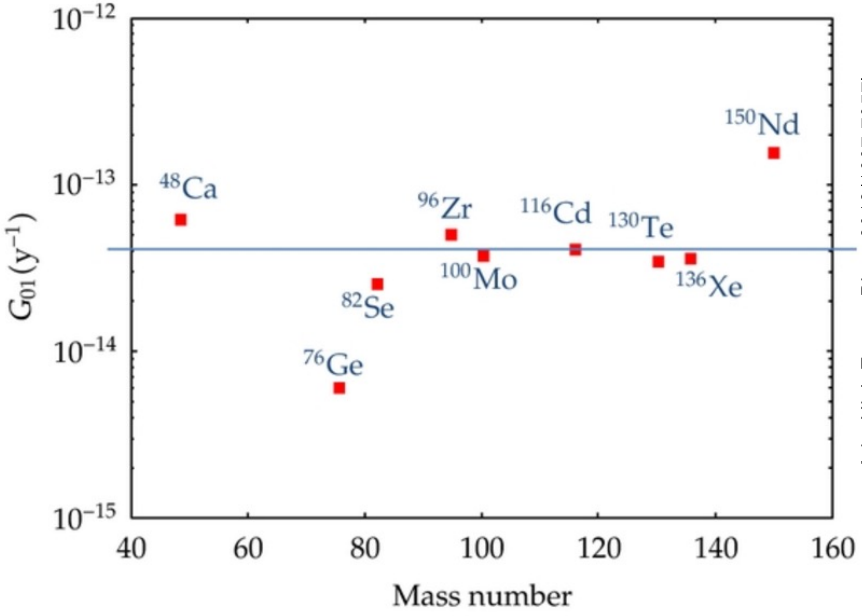
$$T_{1/2}^{0\nu} = \left(G\,|M|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1}$$

Phase-space factor — Nuclear matrix element

  - Majorana effective neutrino mass: $\langle m_{\beta\beta}\rangle = \sum_i U_{ei}^2 m_i$
  - The Phase-space factor can be calculated accurately
  - The NME is a source of uncertainty, it can change a factor 2-3 depending on the model
    - The uncertainty on the $<m_{\beta\beta}>$ limits is introduced by the term



ArXiv:2109.07575v1



Adv. High Energy Phys. 2012(1687-7357)

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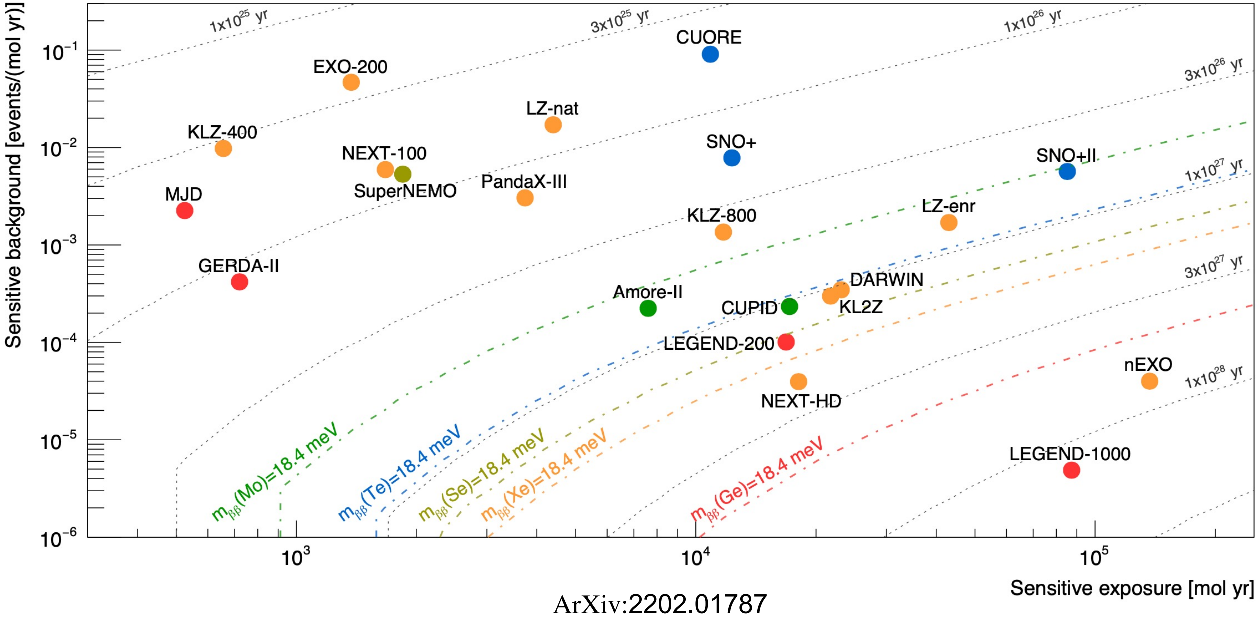
WHY GERMANIUM?

- Established technology
  - High purity crystal with negligible internal contamination
  - Efficient isotopic enrichment
    - 90% on ^{76}Ge
  - Well-understood detector production
- Powerful background rejection techniques
  - Pulse shape discrimination
    - GERDA has the best background index among $0\nu\beta\beta$ experiment
- Excellent energy resolution
  - 0.1% FWHM at Qbb
    - MAJORANA has the best energy resolution among $0\nu\beta\beta$ experiment

Isotope	Natural abundance (%)[a]	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

Annu. Rev. Nucl. Part. Sci. 69, 219-251 (2019)



ArXiv:2202.01787

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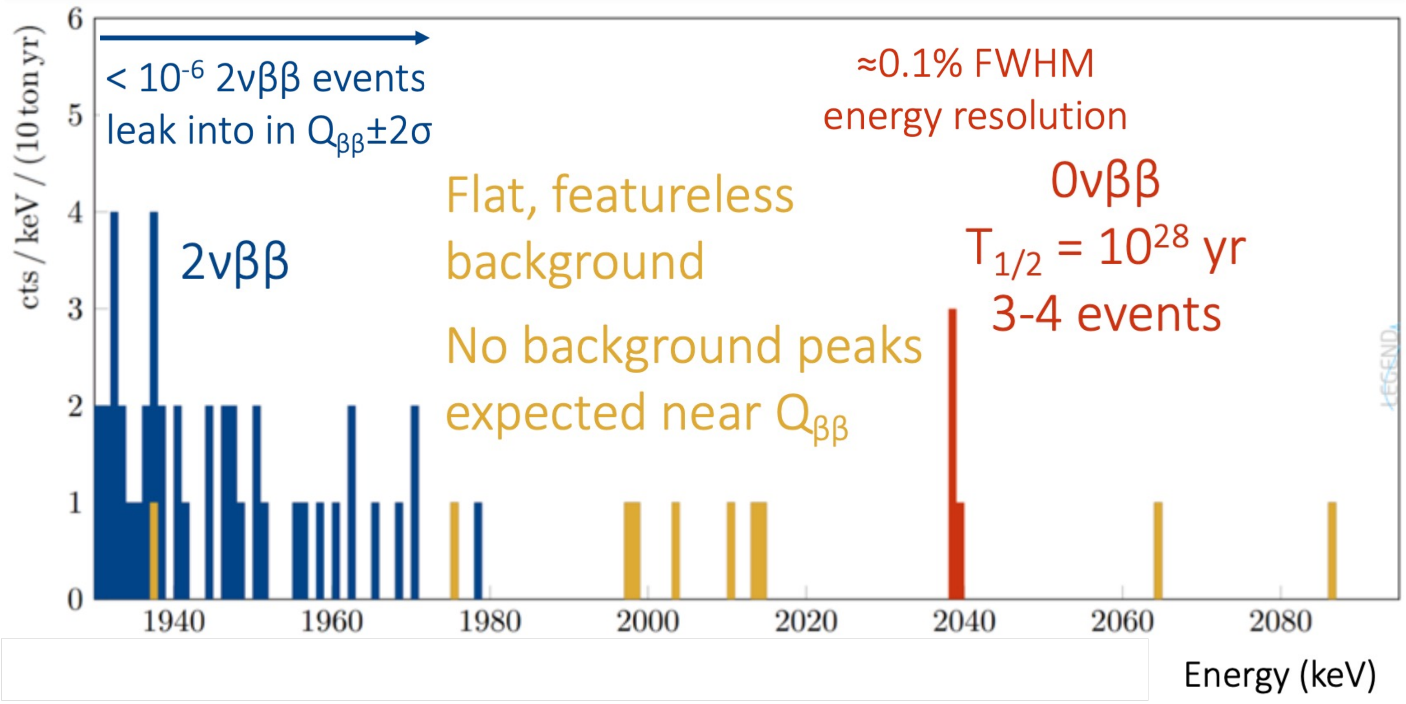
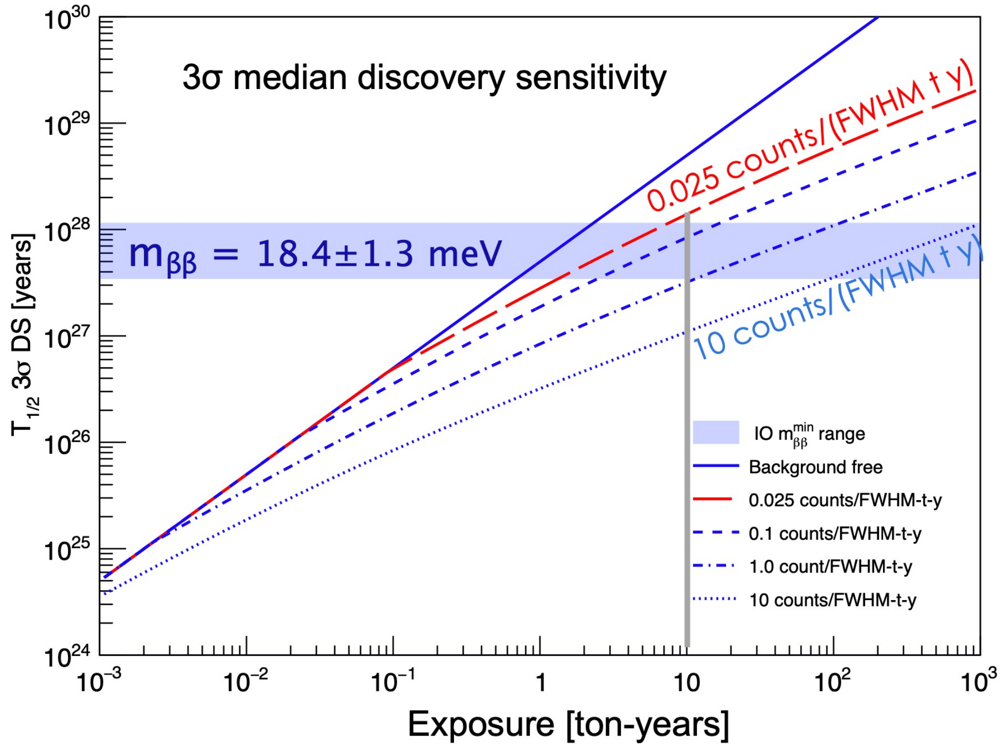
WHAT DOES IT TAKES TO MEASURE $0\nu\beta\beta$ IN ^{76}Ge?

LEGEND aims to cover the inverse-ordering neutrino hierarchy with 10 ton-yrs of data

- 10 yrs of data taking
- 1 ton of ^{76}Ge
- Quasi-background free experiment
  - 0.025 counts/(FWHM t yr) or less
- Energy resolution: 2.5 keV FWHM at Qbb





Simulated example spectrum, after cuts, from 10 years of data

LEGEND: BUILT FROM PAST EXPERIENCE

<u>MAJORANA</u>

- Radioactivity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics
- Low energy threshold

<u>GERDA</u>

- Liquid Argon Veto
- Light nucleus shield

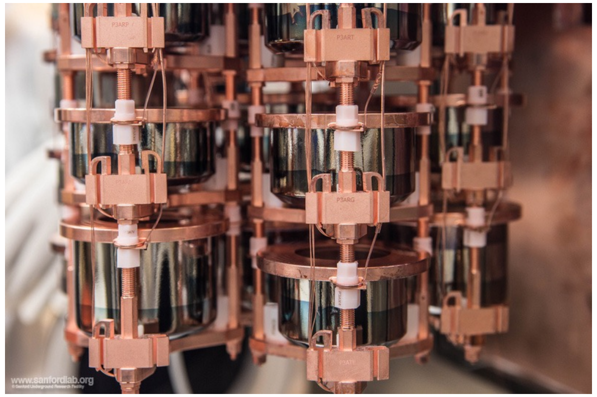
<u>Both</u>

- Clean fabrication techniques
- Control of surface exposure
- Development of large Point-Contact Detectors
- Lower background and best resolution $0\nu\beta\beta$ experiments

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

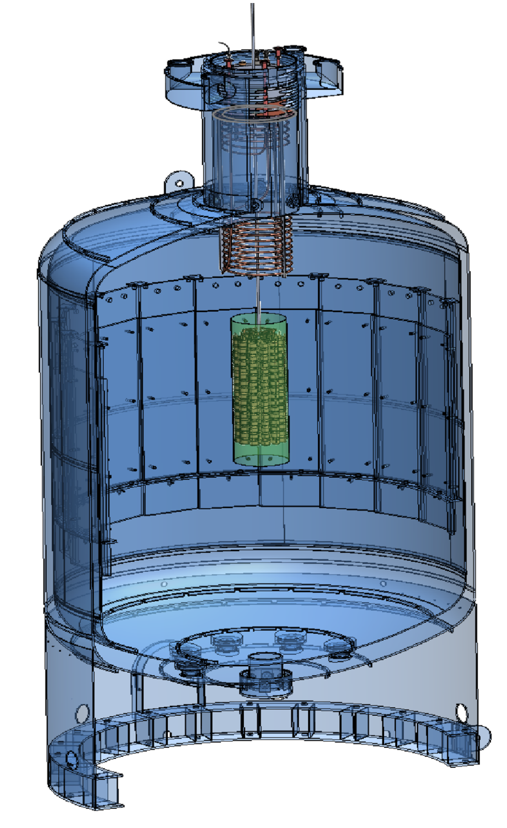
GERDA achieved the lowest background index: 6×10^{-4} cts/(keV kg yr)

MAJORANA



GERDA

LEGEND-200

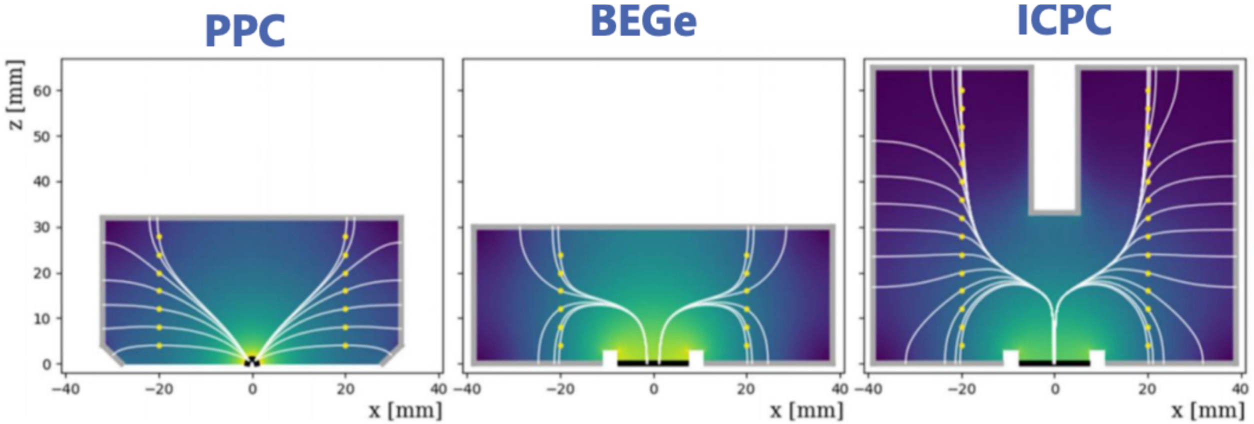


LEGEND: BUILT FROM PAST EXPERIENCE

- Developments based on previous successes
  - Same modular-array philosophy as MAJORANA and GERDA
  - New Inverted-Coaxial Point-Contact detector tested by MAJORANA and GERDA
  - Expected backgrounds known from previous experiences

DETECTOR SIZES

Eur. Phy. J. C 81,76, 2021



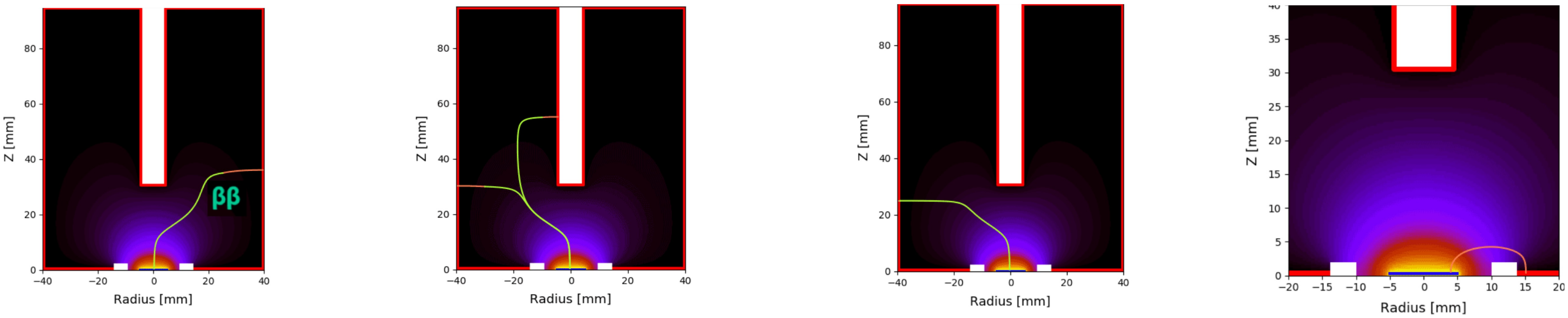
EVENT SIGNATURE IN ICPC DETECTORS

Signal: Bulk single-site event

Background: Bulk multi-site event

Background: Surface β background (e.g.^{42}K)

Background: α background on Point-Contact



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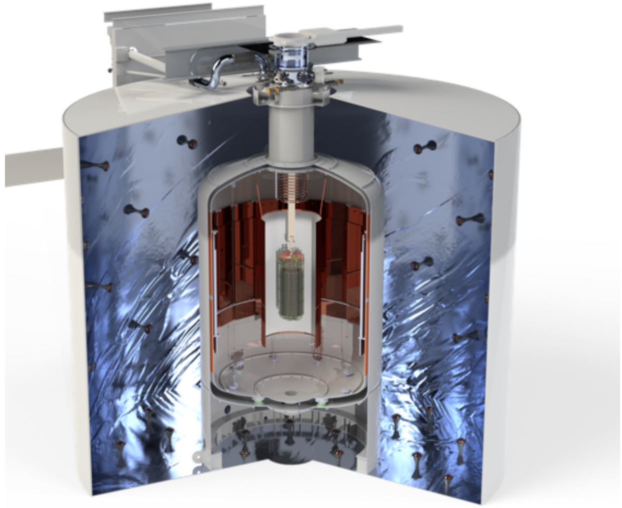
LEGEND

LEGEND: Large Enriched Germanium Experiment for Neutrinoless ββ Decay

- Phased experiment
  - Current phase: LEGEND-200
  - Next phase: LEGEND-1000
- LEGEND-200
  - Located at LNGS
  - Target half-life: 10^{27} yr
  - 2.5 times background reduction compared to GERDA
- LEGEND-1000
  - Location to be selected
    - Reference design based on SNOLAB cryopit
    - LNGS considered for alternative design
  - Target half-life 10^{28} yr
  - 20 times reduction in background compared to LEGEND-200


LEGEND-200

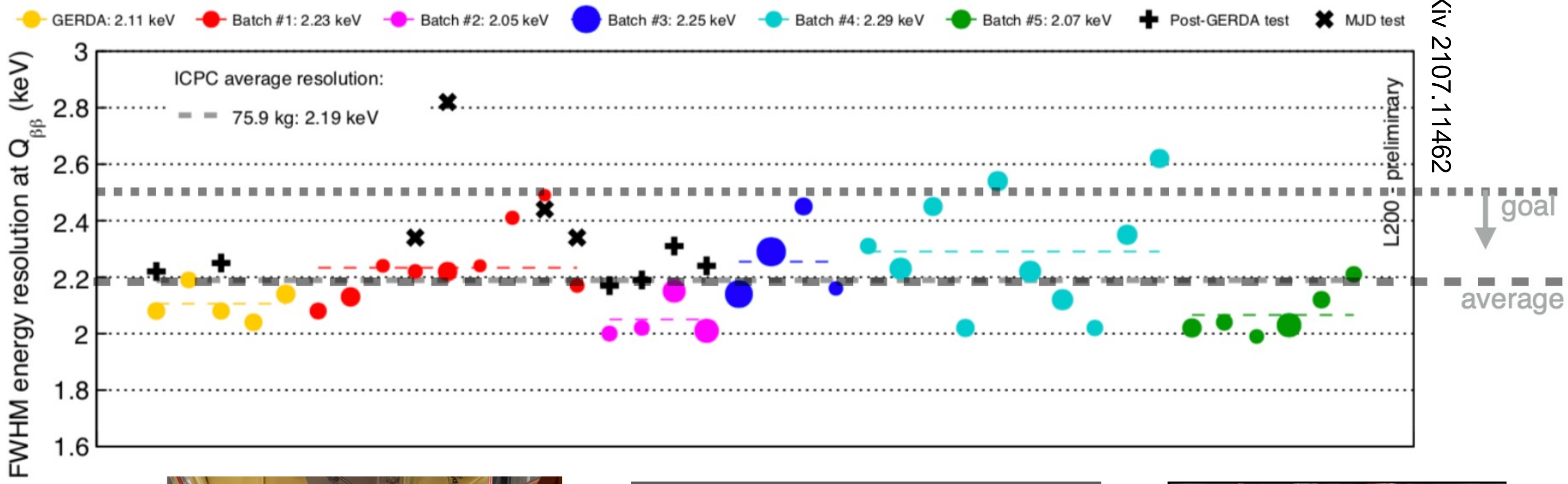

LEGEND-1000

LEGEND-200

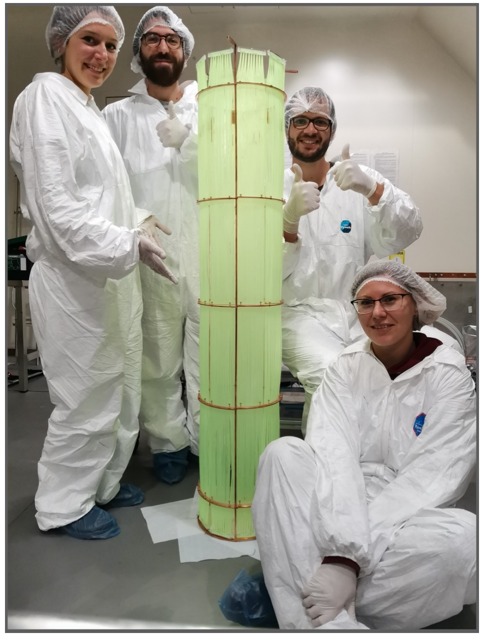
- Located within the GERDA infrastructure in LNGS
- Production and delivery of Ge electronics chain to LNGS nearing completion
- Commissioning of LAr & analyzing first data underway
- Glovebox and lock commissioning complete
- Ge detector commissioning in progress

Detector Type	#	mass
MAJORANA DEMONSTRATOR PPCs	33	28.5
GERDA BEGes	28	19
GERDA Semi-coax	6	14.6
GERDA ICPC	5	9.6
LEGEND ICPC	34	69.7
Total	106	141.4

Delivered detectors have an average 2.2 keV energy resolution.



arXiv 2107.11462



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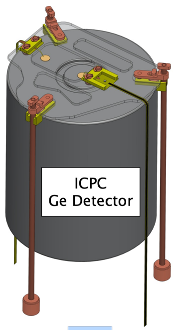
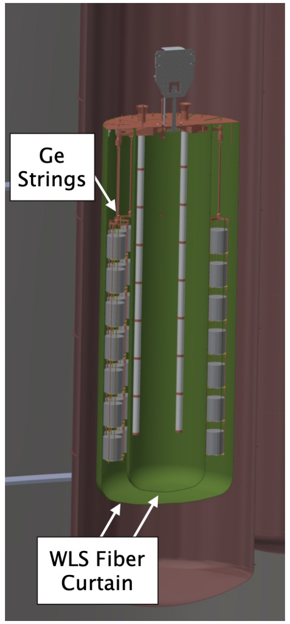
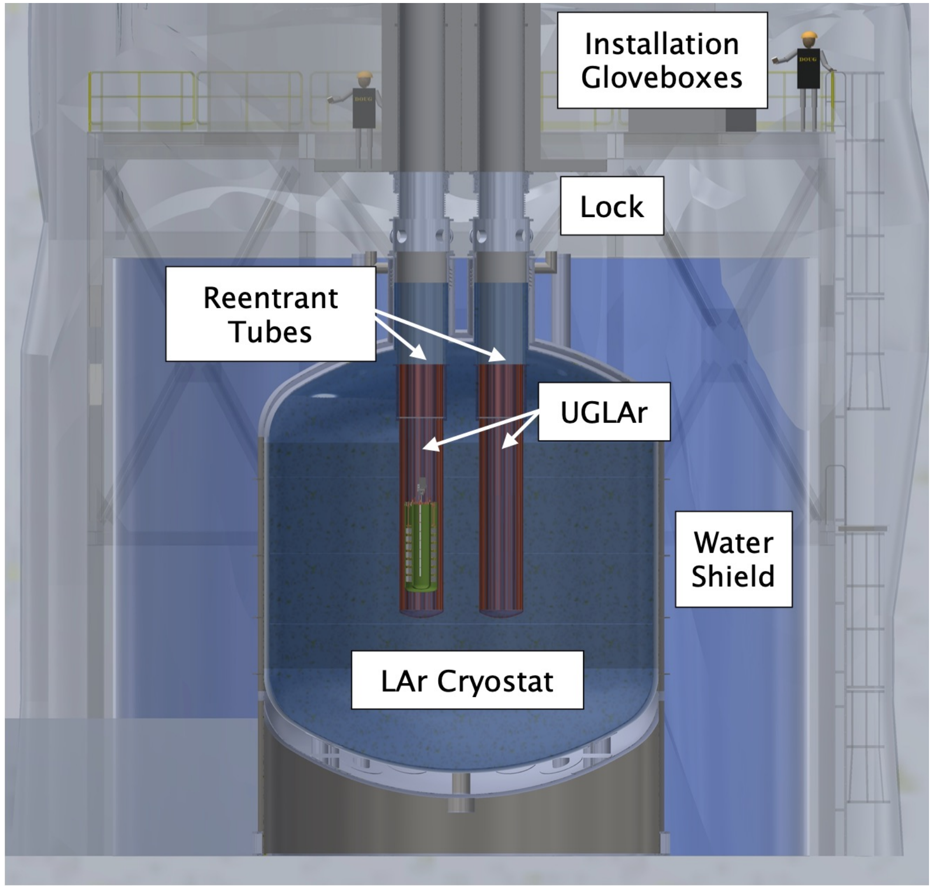
LEGEND–1000

- About 400 ICPC detectors with an average mass of 2.6 kg
  - Electroformed copper for physical support
  - 14 vertical string
- Divided in 4 arrays of 100 ICPC detectors
  - Immersed in UGLAr
  - Wavelength-shifting fiber curtain to read the scintillation light
- Pre-conceptual Design Report available at arXiv 2107.11462







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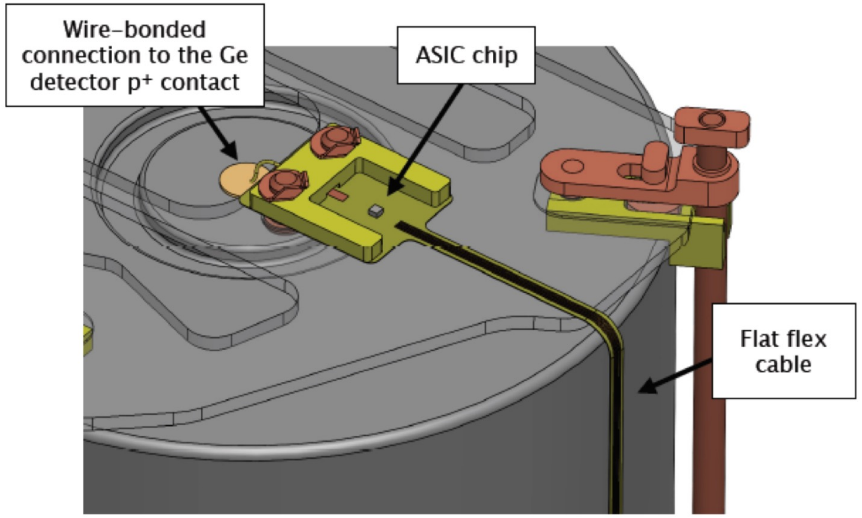
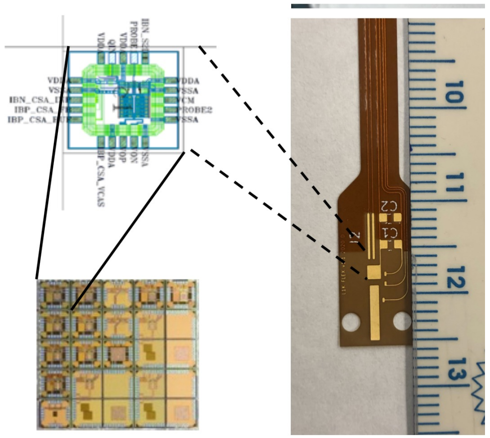
BACKGROUND REDUCTION (LEGEND-1000)

- New cables and ASIC read-out
- Underground argon (UGAr) surrounding detectors
  - Significantly reduces the ^{42}K contamination
  - It will allow a wide range of beyond the Standard Model searches below 20 keV region
    - MAJORANA has a similar low-energy program
- Deeper underground site or additional neutron shielding & tagging: SNOLAB/LNGS
- Increase detector spacing



Isotope	Abundance	Half-life ($t_{1/2}$)	Decay mode	Product
^{36}Ar	0.334%	stable		
^{37}Ar	syn	35 d	ε	^{37}Cl
^{38}Ar	0.063%	stable		
~~^{39}Ar~~	~~trace~~	~~269 y~~	~~β⁻~~	~~^{39}K~~
^{40}Ar	99.604%	stable		
^{41}Ar	syn	109.34 min	β⁻	^{41}K
~~^{42}Ar~~	~~syn~~	~~32.9 y~~	~~β⁻~~	~~^{42}K~~

ASIC front-end on a flat flex cable

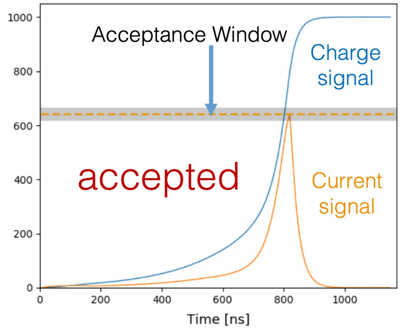


- UGAr is depleted in ^{42}Ar and ^{39}Ar
- Builds on pioneering work of DarkSide collaboration

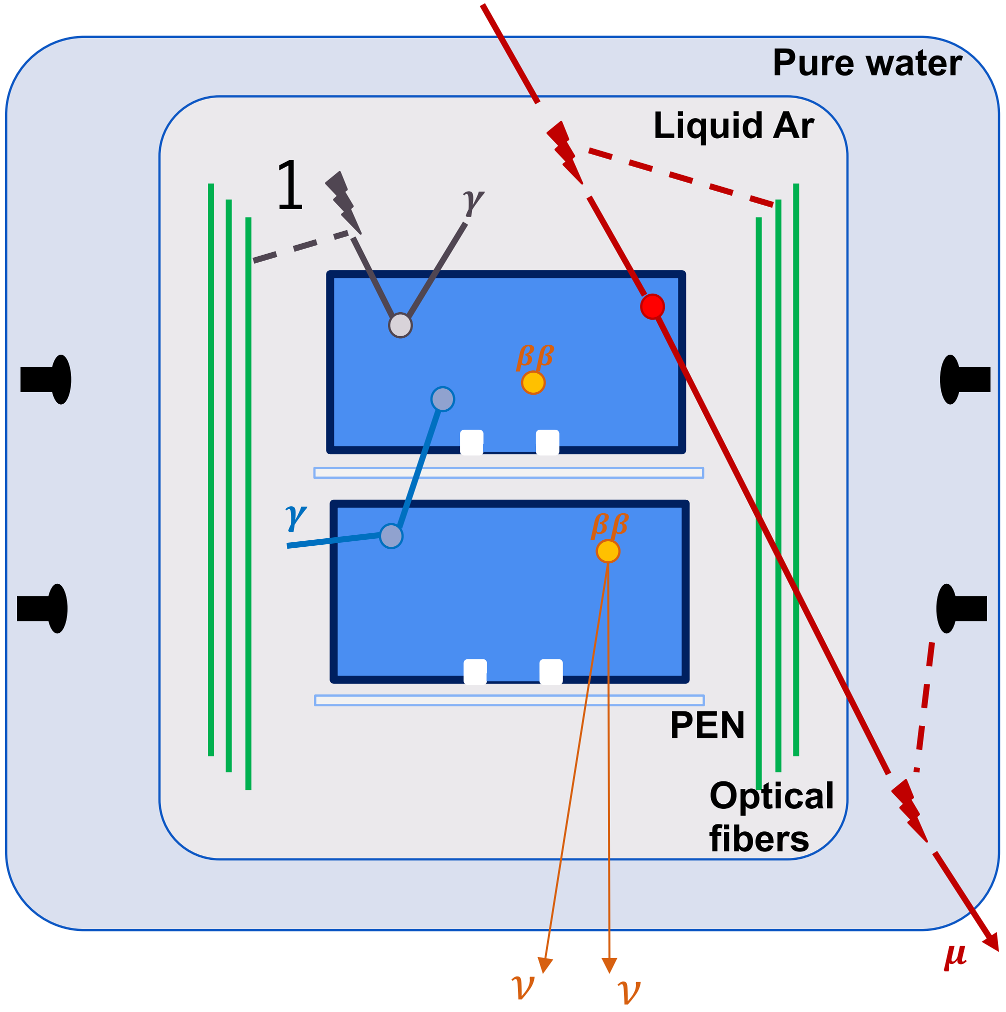
BACKGROUND REDUCTION

Remaining backgrounds after mitigation can be rejected

- Signal



- Muons and their daughters
  - Muon veto based on Cherenkov light (PMT) and plastic scintillator (Optical fiber)
- External gammas
  - Ge detectors anti-coincidence
  - LAr veto
  - Scintillator PEN plate veto



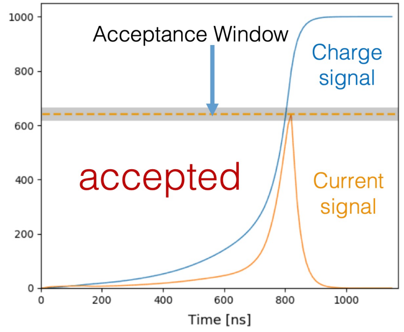
$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume

Muon passing through the array

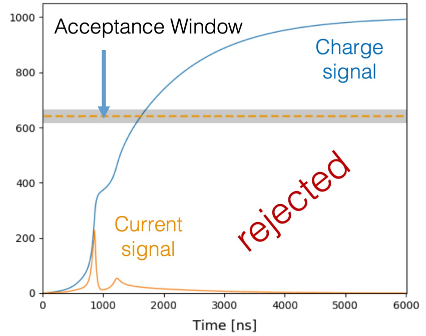
External γ: captured by a detector:
1) After or before interacting with LAr or PEN
2) Compton scattering from one detector to another

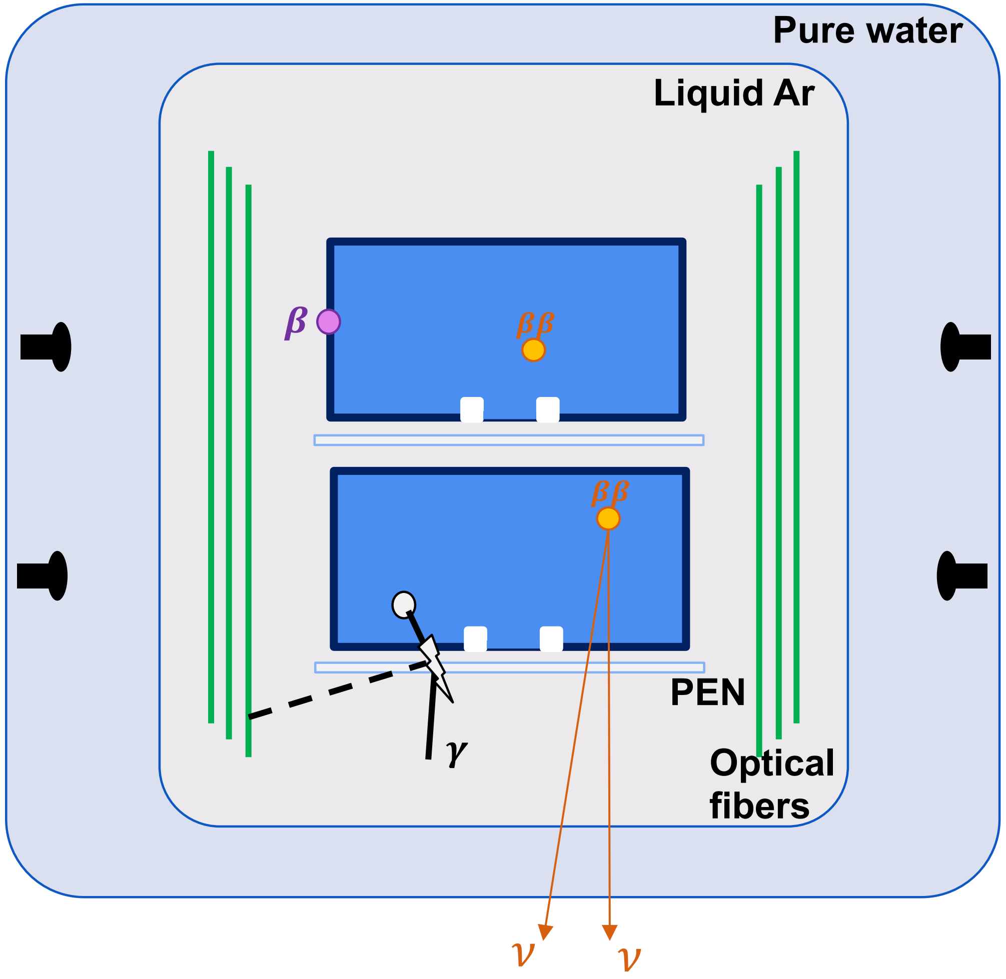
BACKGROUND REDUCTION

- Signal



- Internal γ escaping the detector
  - Ge detectors anti-coincidence
  - Scintillating PEN plate veto
  - LAr veto
- Surface β background ^{42}K (^{42}Ar) on n^+ contact





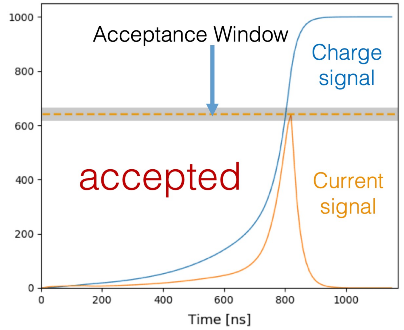
ββ decay signal: single energy deposition in a 1 mm³ volume

Escaping internal γ:
1) Interacting with LAr/PEN
2) Interacting with another detector

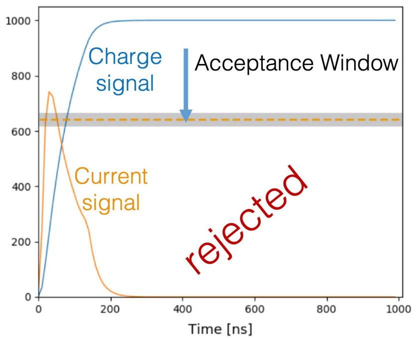
Surface β background

BACKGROUND REDUCTION

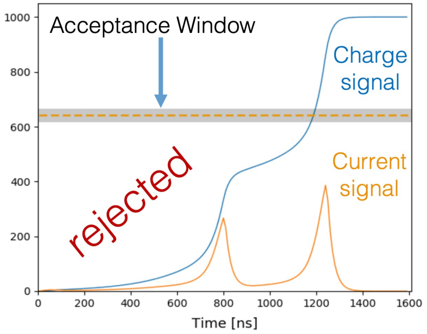
- Signal

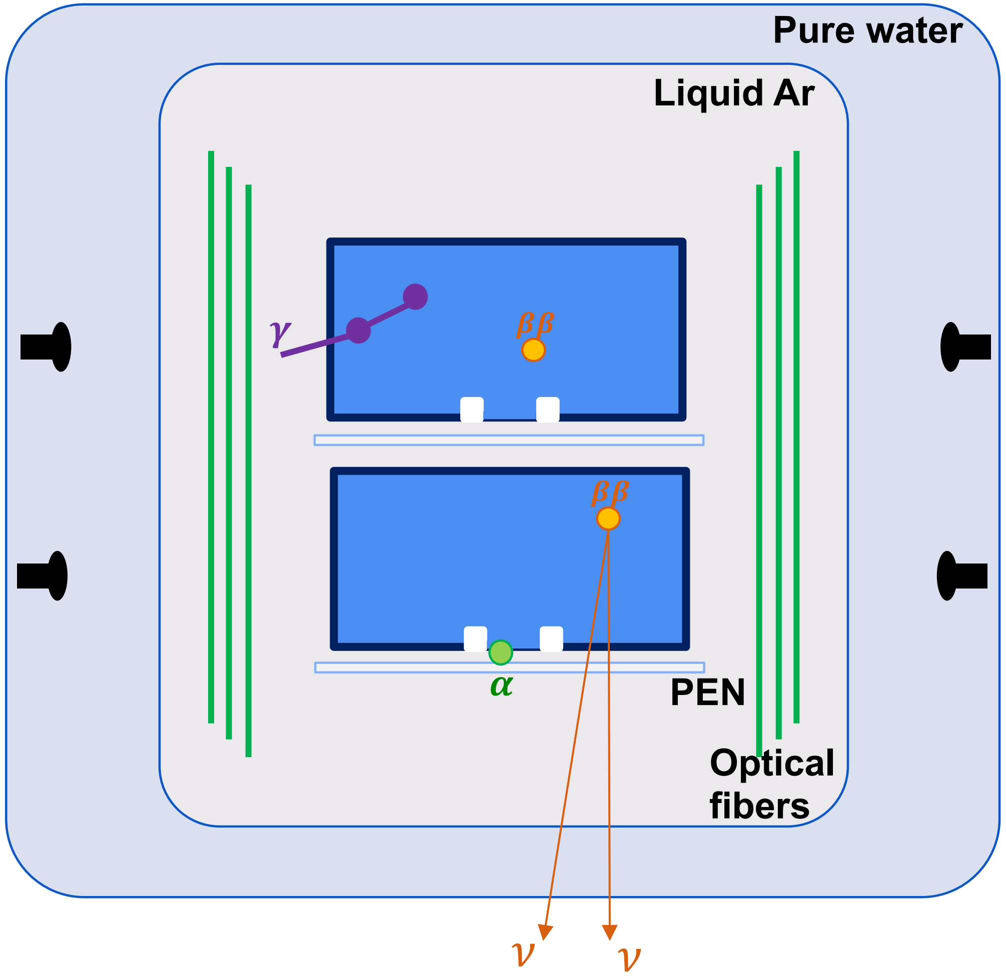


- α background on p+ contact



- Multi-site events





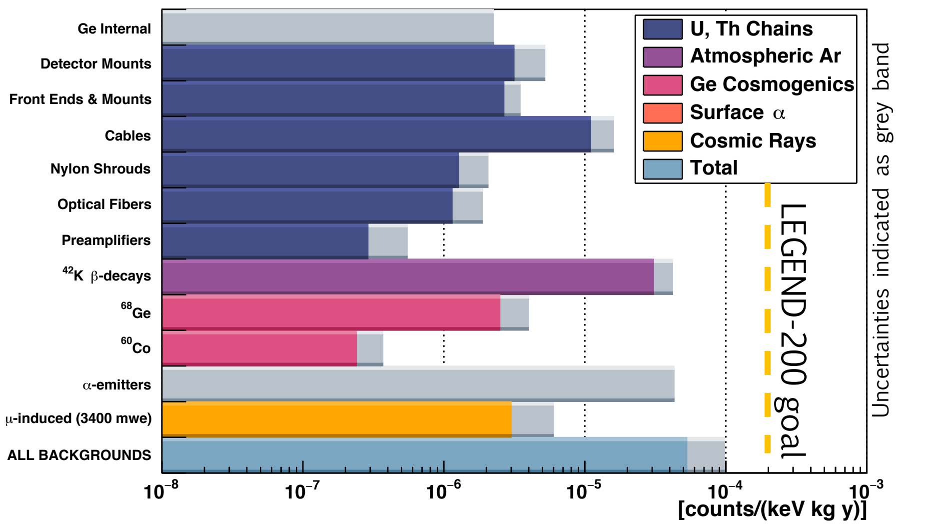
$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume

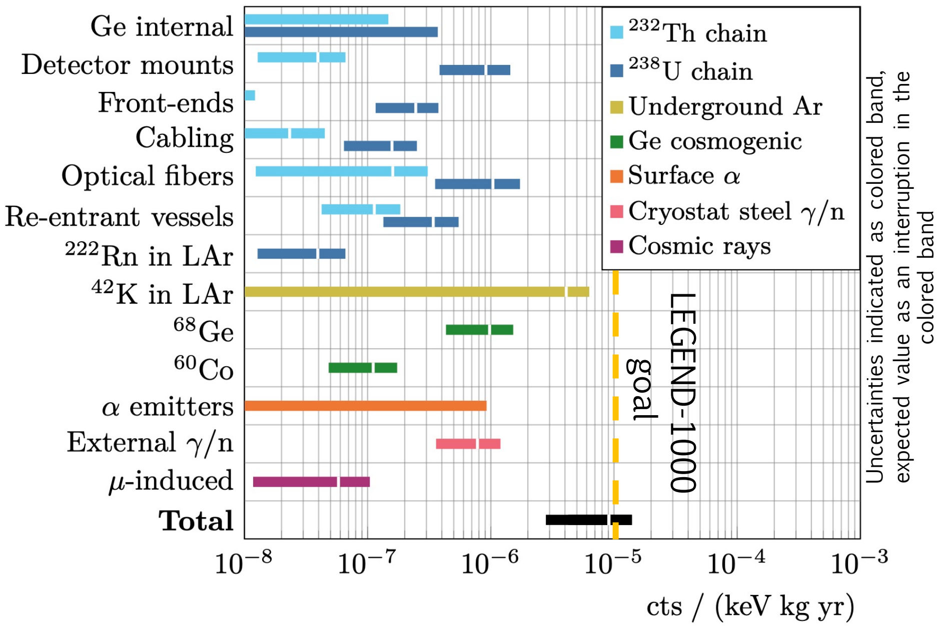
α Background on p+ contact

Multi-site events (two interactions in the same detector: Compton + ionization)

BACKGROUNDS BUDGETS

- **Background contributions near $Q_{\beta\beta}$ after all cuts**
  - Monte Carlo + data driven projections
- **LEGEND-200**
  - Projections of Ge U/Th, ^{42}K, α based on MAJORANA and GERDA data
  - Rest of contributions based on Monte Carlo + assay-based projections
- **LEGEND-1000**
  - **U/Th**: optimized array spacing, minimize opaque materials, larger detectors, better light collection, cleaner materials
  - **^{42}Ar**: eliminate by using underground sourced Ar
  - **μ-induced**: Improved shielding, SNOLab depth assumed
  - **Surface α's**: assumes achieved UL for BEGes and ICPCs in GERDA





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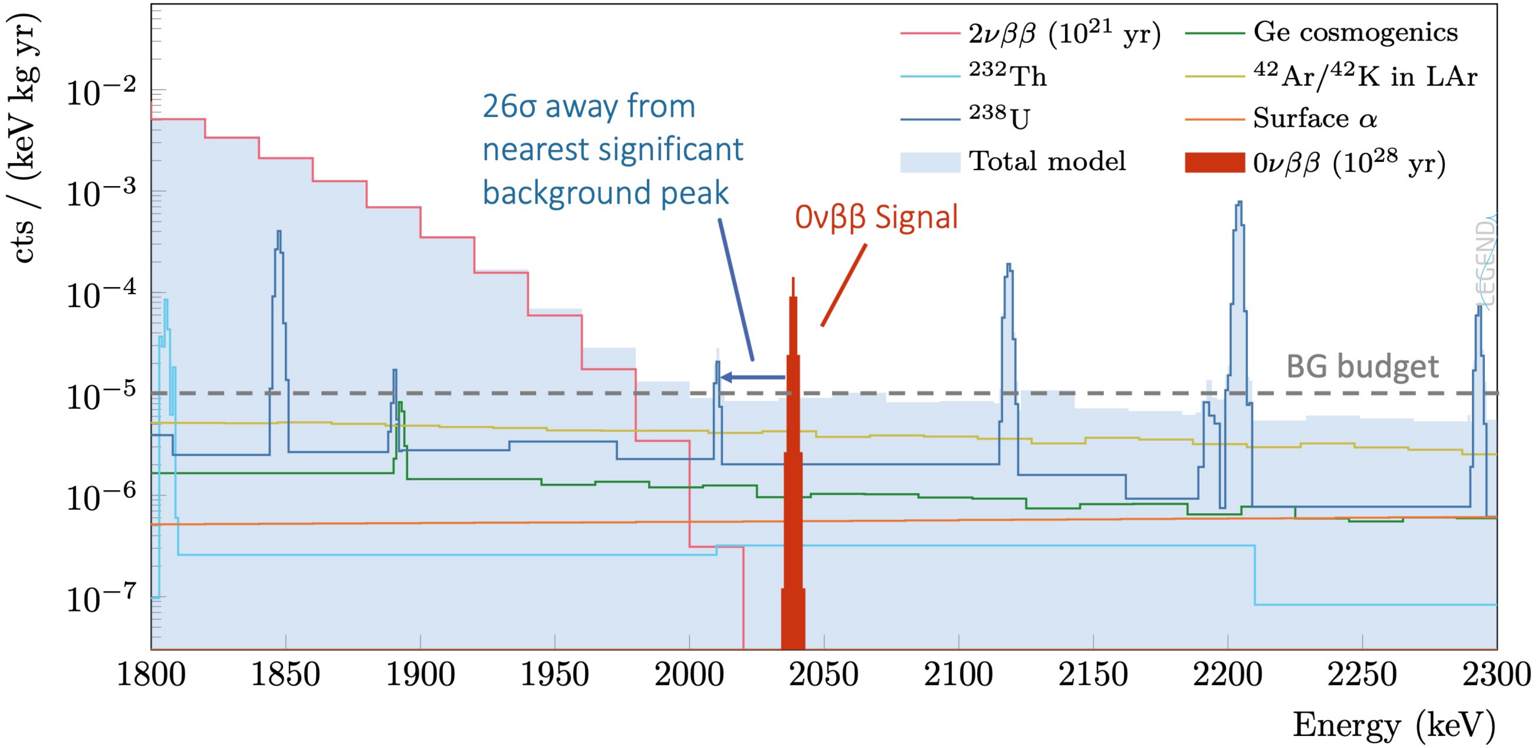
BACKGROUND MODEL

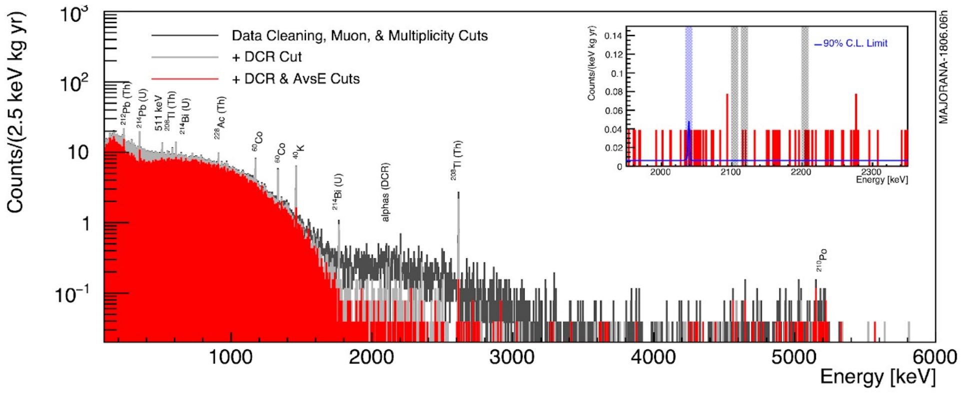
- Well known from GERDA & MAJORANA
- The peak is clearly observed with the current background budget
- 26σ away from the nearest background peak

Simulated spectra assuming $T^{0\nu}_{1/2} = 10^{28}$ yr



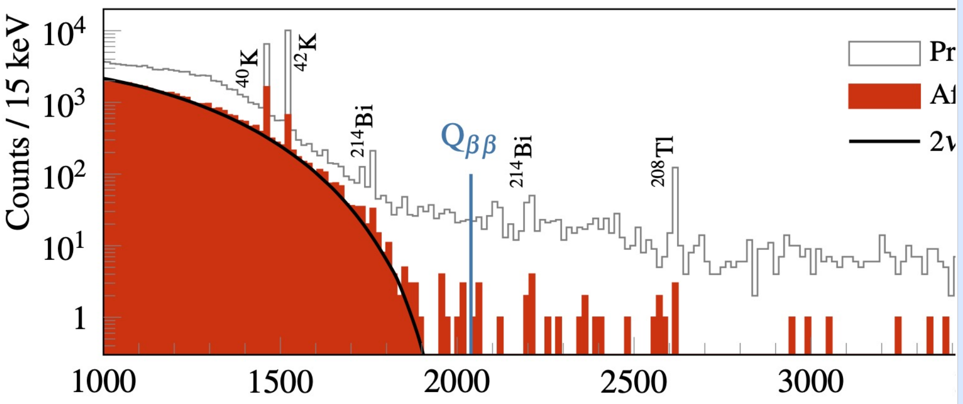
MAJORANA

Phys. Rev. C 100, 025501 (2019)



GERDA

Phys. Rev. Lett. **125**, 252502 (2020)



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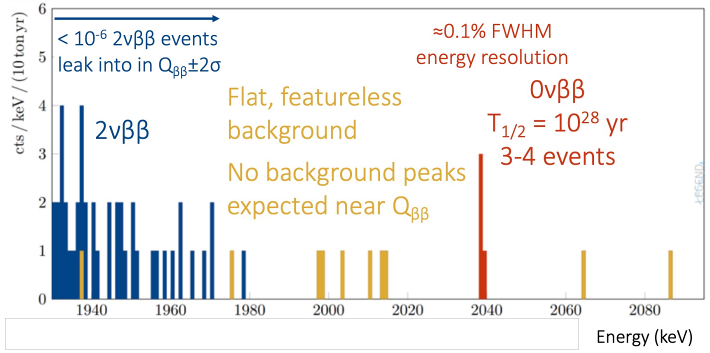
CONCLUSIONS

- LEGEND has been formed from previous experience: MAJORANA and GERDA
  - LEGEND-200 is based on the breakthrough developments of MAJORANA and GERDA
  - LEGEND-1000 includes additional improvements in its design
- LEGEND-200 is on track
  - Ge detector and LAr commissioning in progress
  - Delivery of Ge electronics chain to LNGS nearing completion
- LEGEND-1000 is designed to be a quasi-background-free experiment
  - The background model, based on the demonstrated success of MAJORANA and GERDA, detailed simulations, and well-understood improvements, shows the $0\nu\beta\beta$ peak as an isolated peak.



- Low-background and excellent energy resolution allow for a low risk of unambiguous discovery of $0\nu\beta\beta$ decay at $T_{1/2} = 10^{28}$ yr.

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