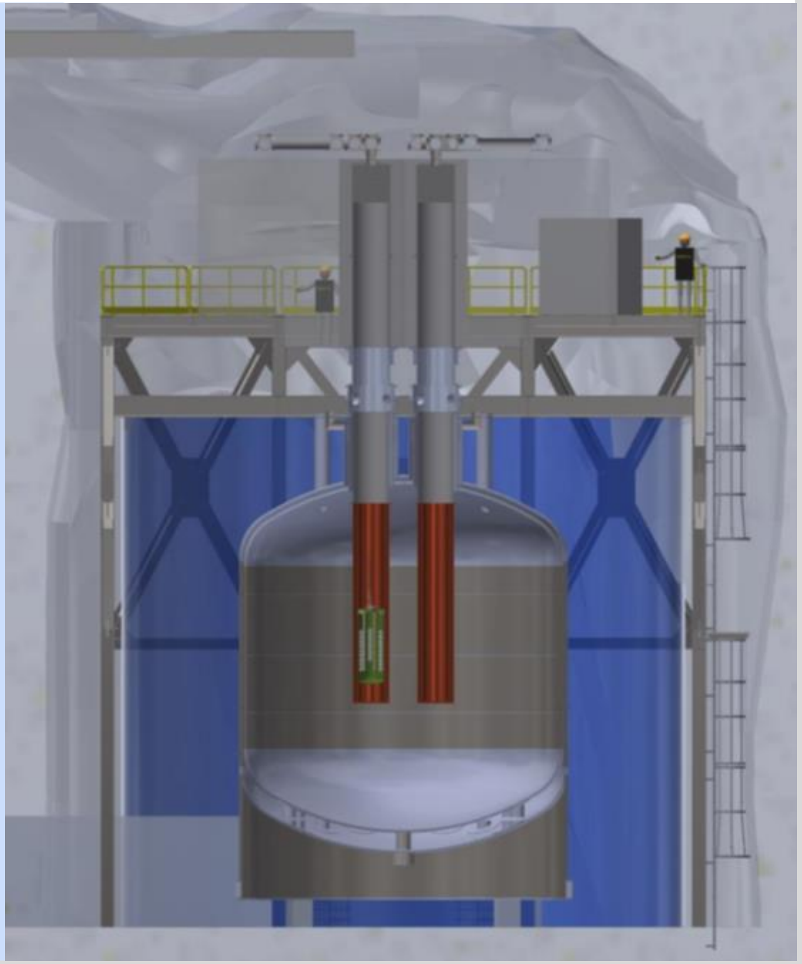
# Search for Majorana Neutrinos in the LEGEND Experiment

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



Chris Jillings for the LEGEND Collaboration

2023-06-21

Canadian Association of Physicists Congress

# Overview

- Introduction to neutrinoless double beta decay
- Why Germanium?
- The LEGEND design
  - Majorana and GERDA to LEGEND
- LEGEND-1000 discovery potential
- LEGEND-200 installation and operation

} With a Canadian-centric aside


CIEMAT
Comenius Univ.
Czech Tech. Univ. Prague and IEAP
Daresbury Lab.
Duke Univ. and TUNL
Gran Sasso Science Inst.
Indiana Univ. Bloomington
Inst. Nucl. Res. Rus. Acad. Sci.
Jagiellonian Univ.
Joint Inst. for Nucl. Res.
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Univ. of California and LBNL
Univ. College London
Univ. of L'Aquila and INFN
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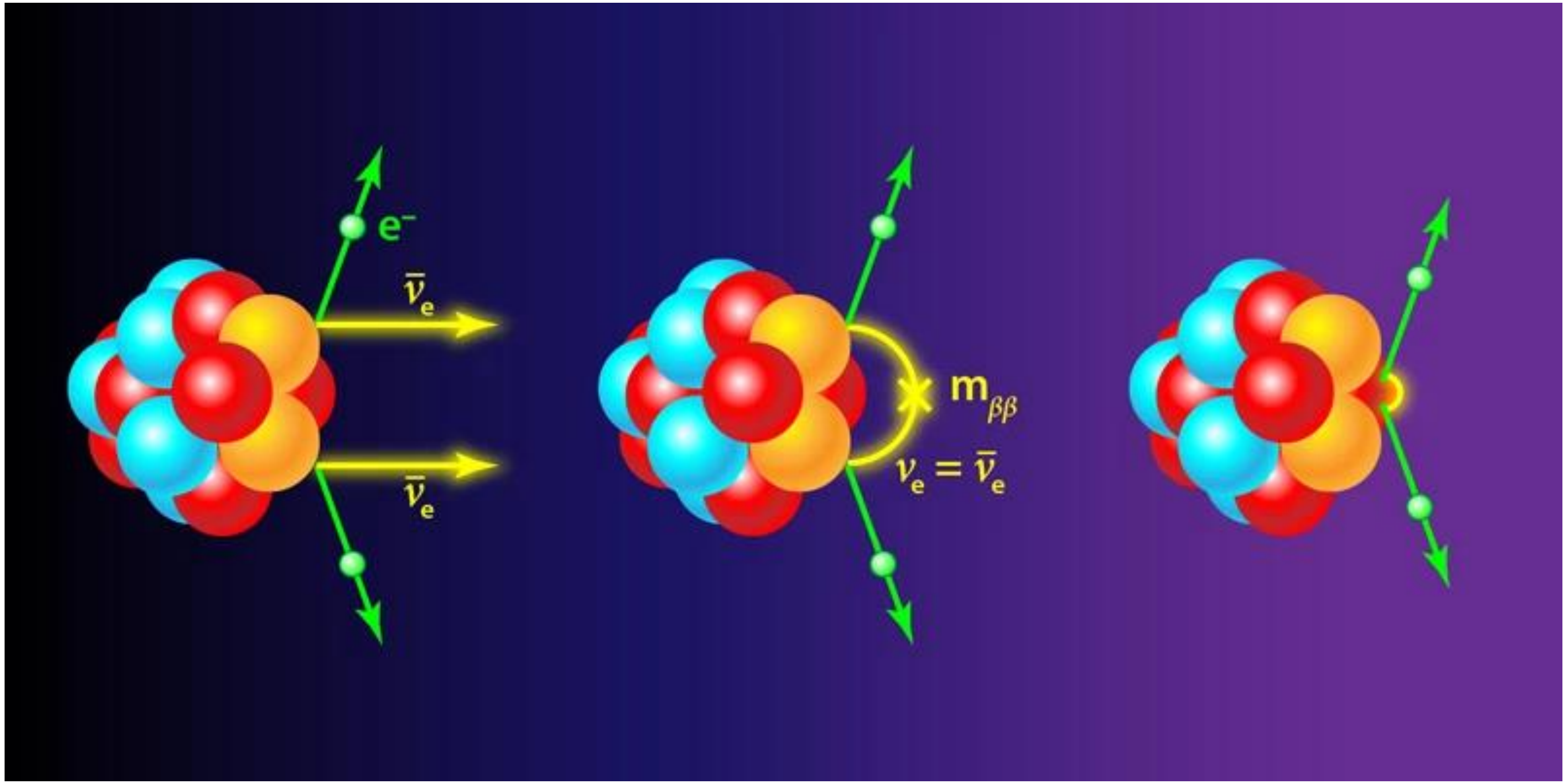
Univ. of Milan and INFN
Univ. of Milano Bicocca and INFN
Univ. of New Mexico
Univ. of North Carolina at Chapel Hill
Univ. of Padova and INFN
Univ. of Regina
Univ. of South Carolina
Univ. of South Dakota
Univ. of Tennessee
Univ. of Texas at Austin
Univ. of Tuebingen
Univ. of Warwick
Univ. of Washington and CENPA
Univ. of Zuerich
Williams College

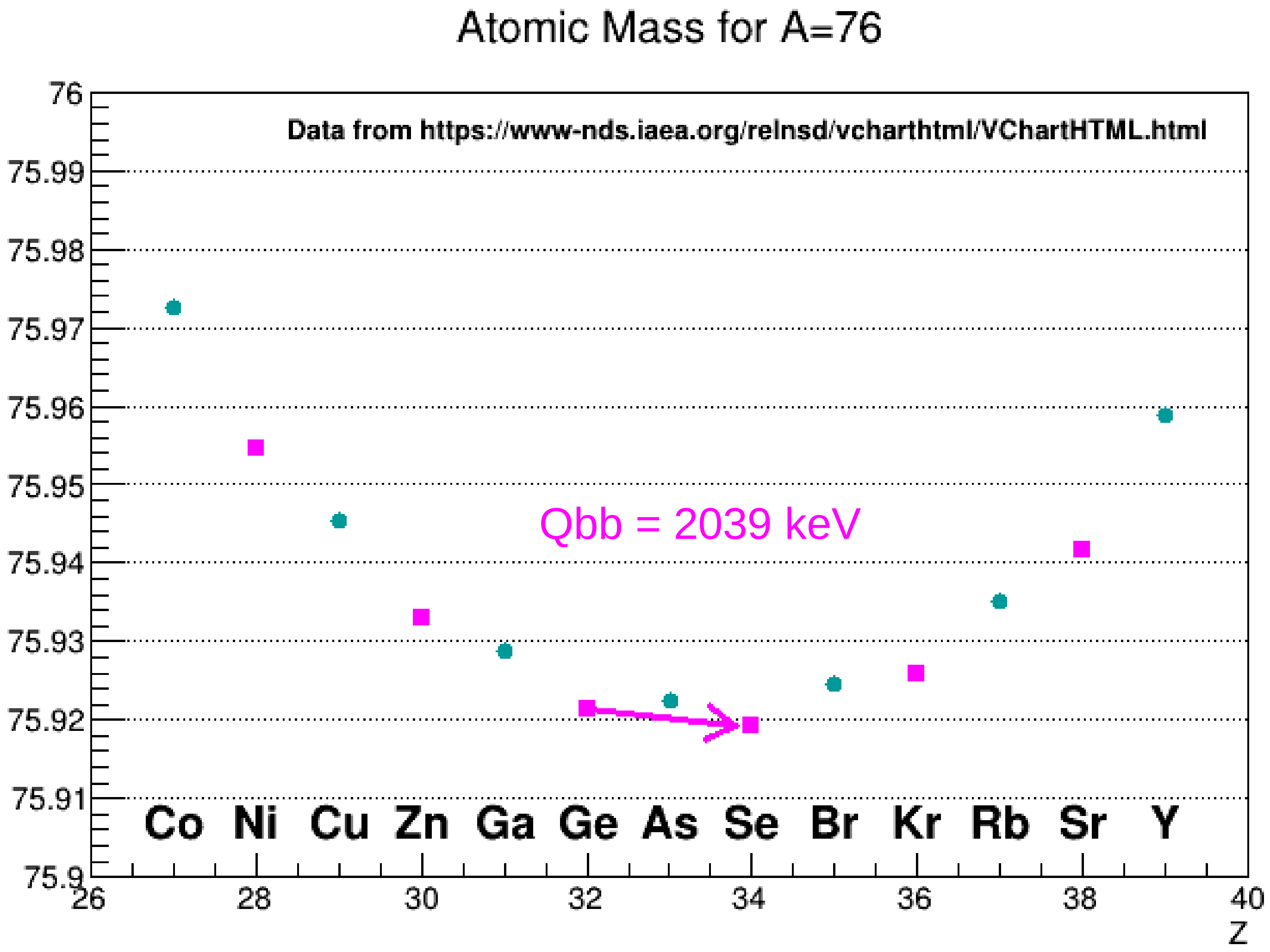
Double beta decay is a second order weak process. $2\nu\beta\beta$ is a standard model process. $0\nu\beta\beta$ requires neutrinos be their own antiparticle and violates lepton number.




See https://arxiv.org/abs/1403.4976 for an excellent introduction.

# 0νββ candidates are even-even nuclei as the mass parabola for odd-odd nuclei is shifted

76 AMU




75.9 AMU

**Odd odd nuclei**

**Even even nuclei**

Single beta decay to As is energetically forbidden

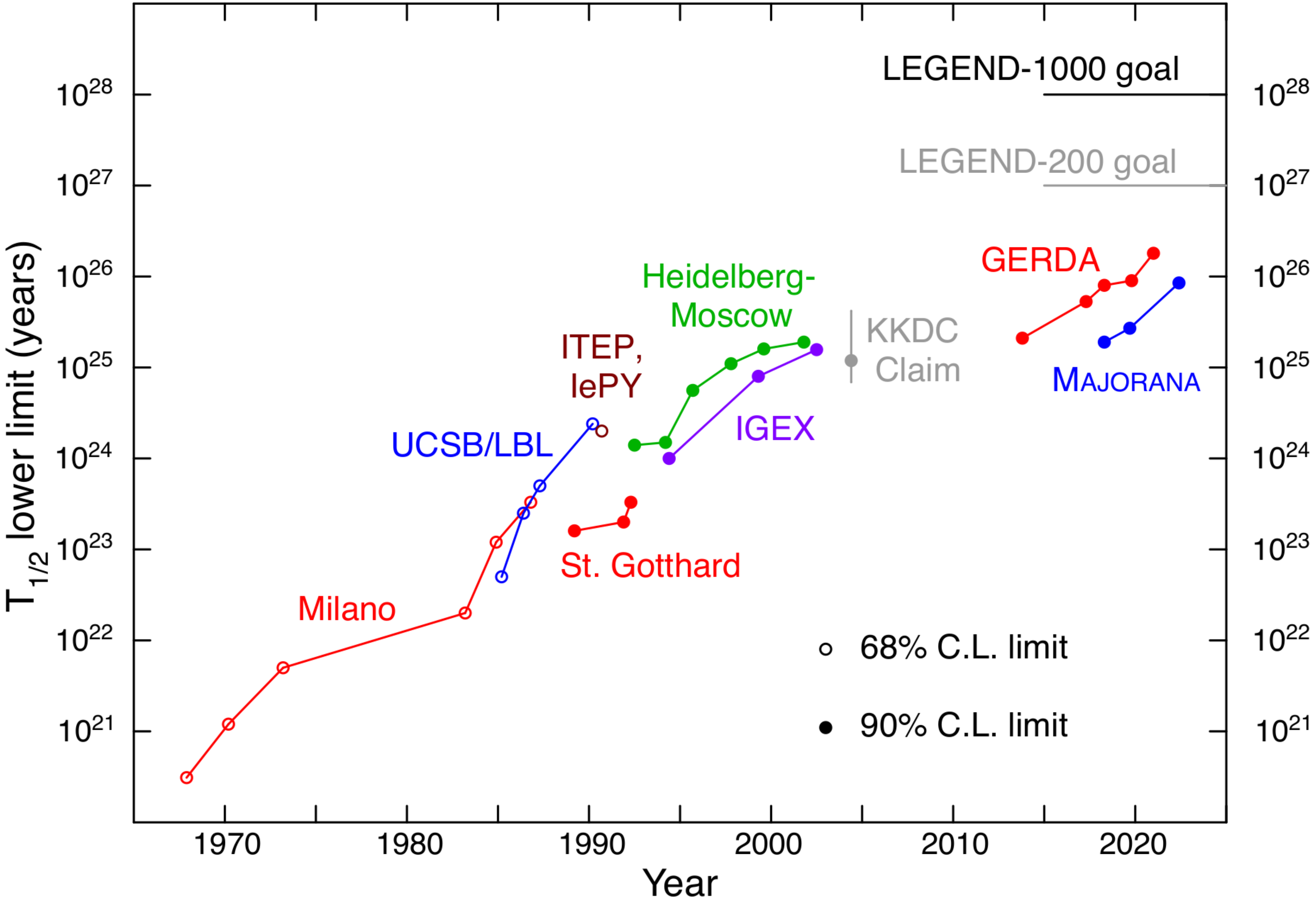
# Germanium has been used since the 1960s to search for 0νββ for many reasons

- Crystals have exquisite energy resolution –reduces background.
- Crystals from pure metallic Ge, or enriched Ge: *no "wasted" atoms in detector*
  - Except for the dead layer
- The crystal-pulling process removes impurities. (Zone refinement)
- There are companies able to make crystals of high quality

- Ge, along with Te, Xe, Mo, and other nuclei, is used in tonne-scale experiments

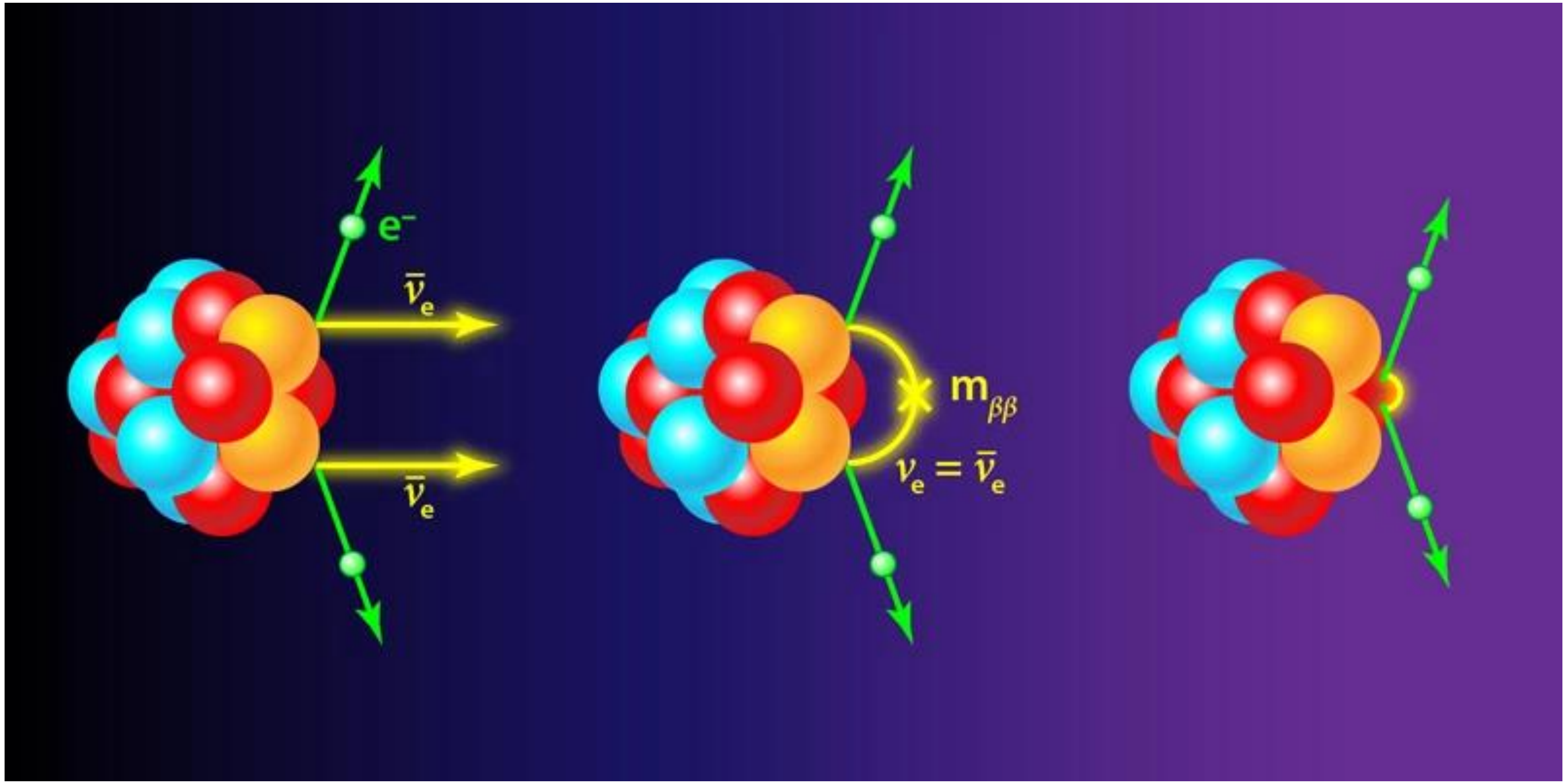
See Avignone and Elliott for an informative review of Ge 0νββ experiments: https://arxiv.org/abs/1901.02805

# Germanium has been used since the 1960s to search for $0\nu\beta\beta$




Data source for plot:
https://arxiv.org/abs/1901.02805

# The lifetime of 0νββ depends on a phase space term, a nuclear matrix element, and an effective neutrino mass.




$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

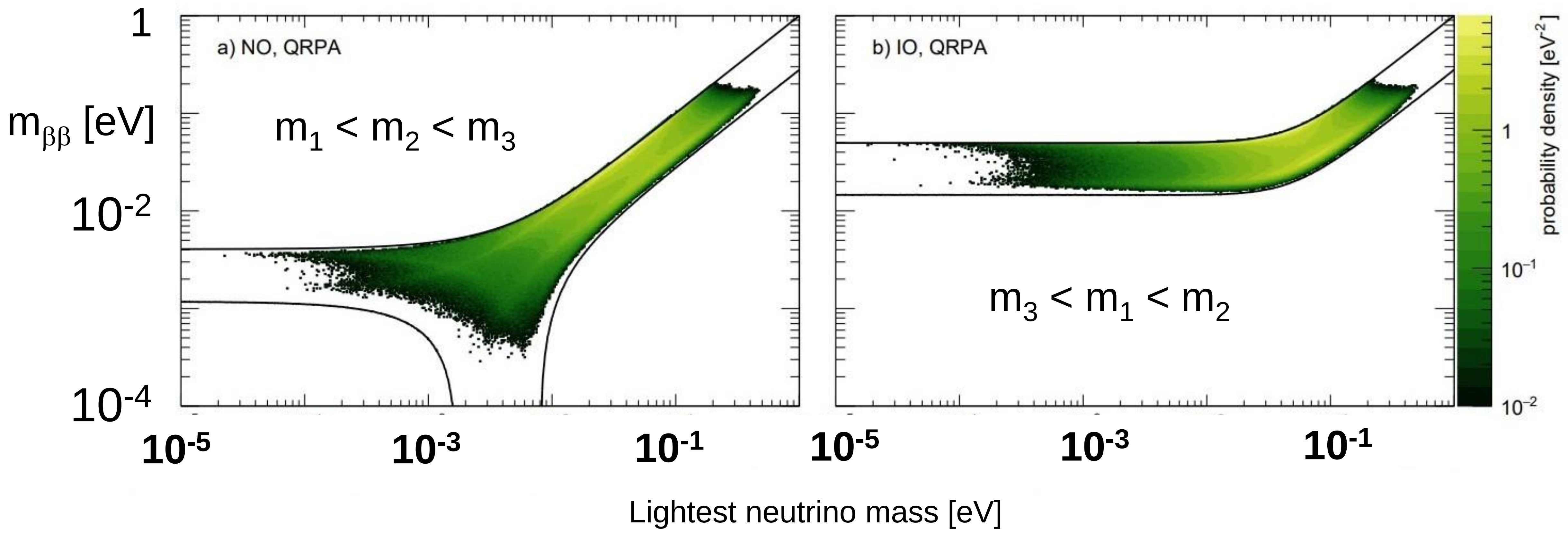
See https://arxiv.org/abs/1403.4976 for an excellent introduction.

# $m_{\beta\beta}$ is not currently well-constrained

$$\langle m_{\beta\beta} \rangle = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$
$$= |U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e2}^2 m_2|$$
$$= |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i\alpha_{31}}|.$$

The lines represent 3$\sigma$ uncertainties on oscillation parameters.

The colour scale represents a PDF for $m_{\beta\beta}$ given certain assumptions.
https://arxiv.org/abs/1705.02996



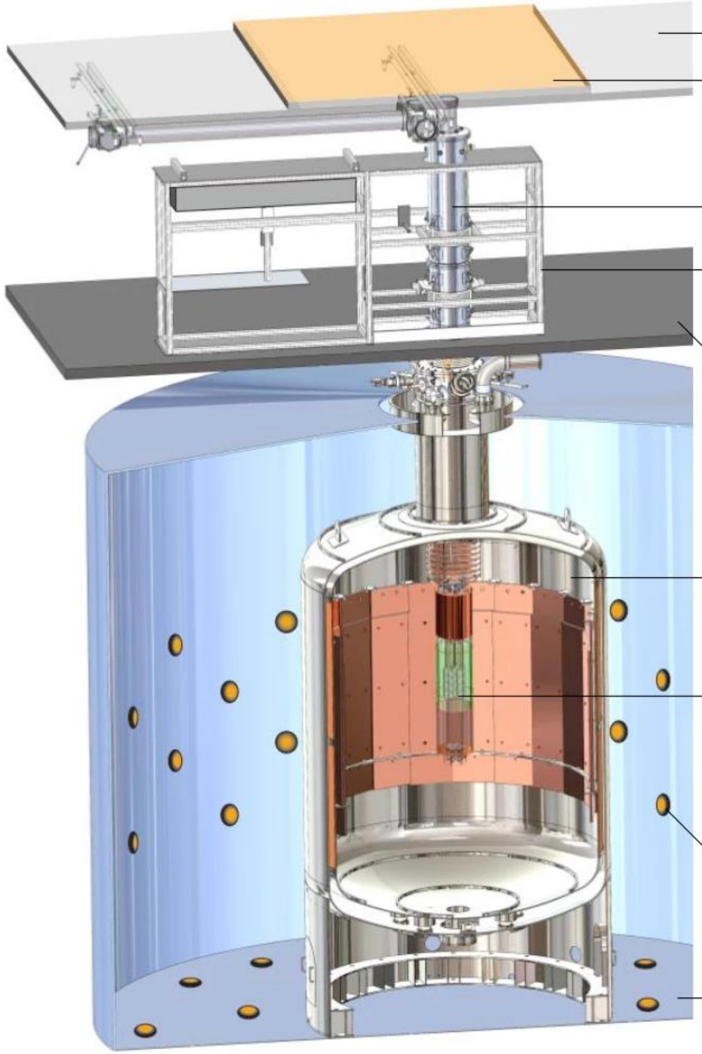
This section will show the LEGEND design from the inside out.

Concepts will be illustrated with the relevant data from the Majorana Demonstrator or GERDA.

This discussion will start with one fundamental concept:

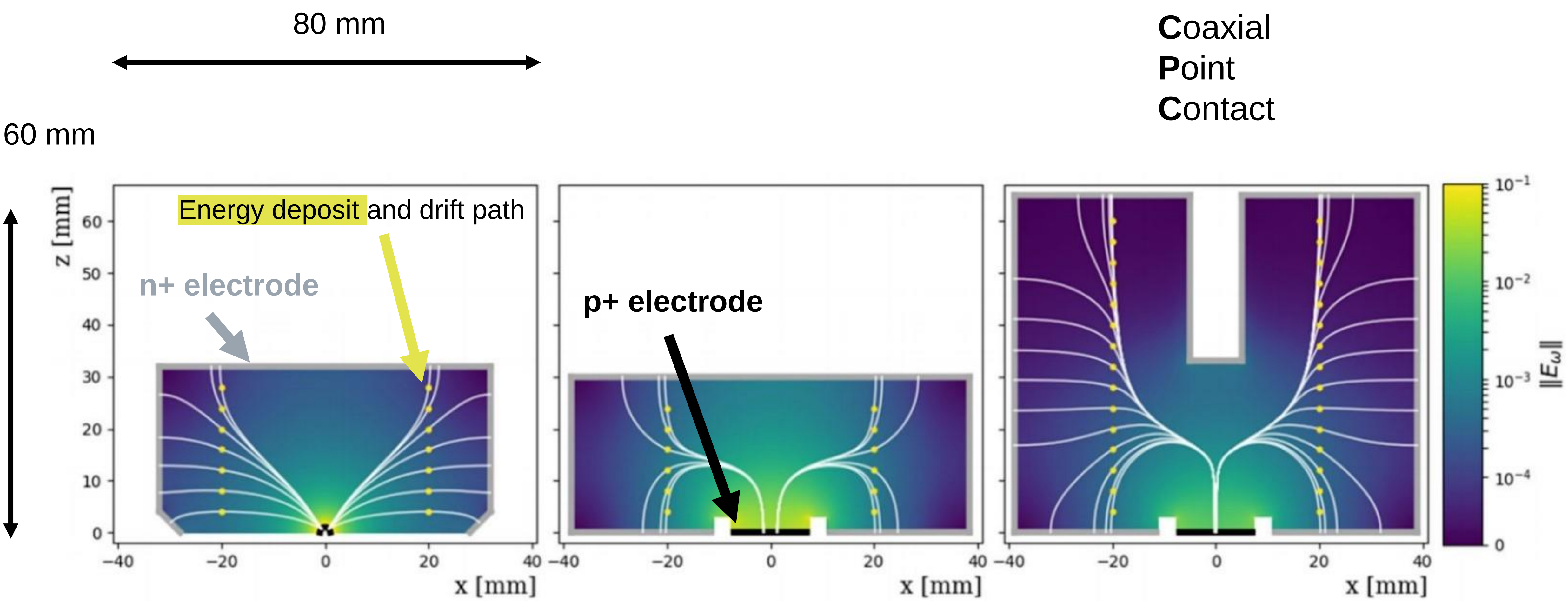
*$0\nu\beta\beta$ are isolated events at a single site in a single crystal.*

## LEGEND-200 at LNGS



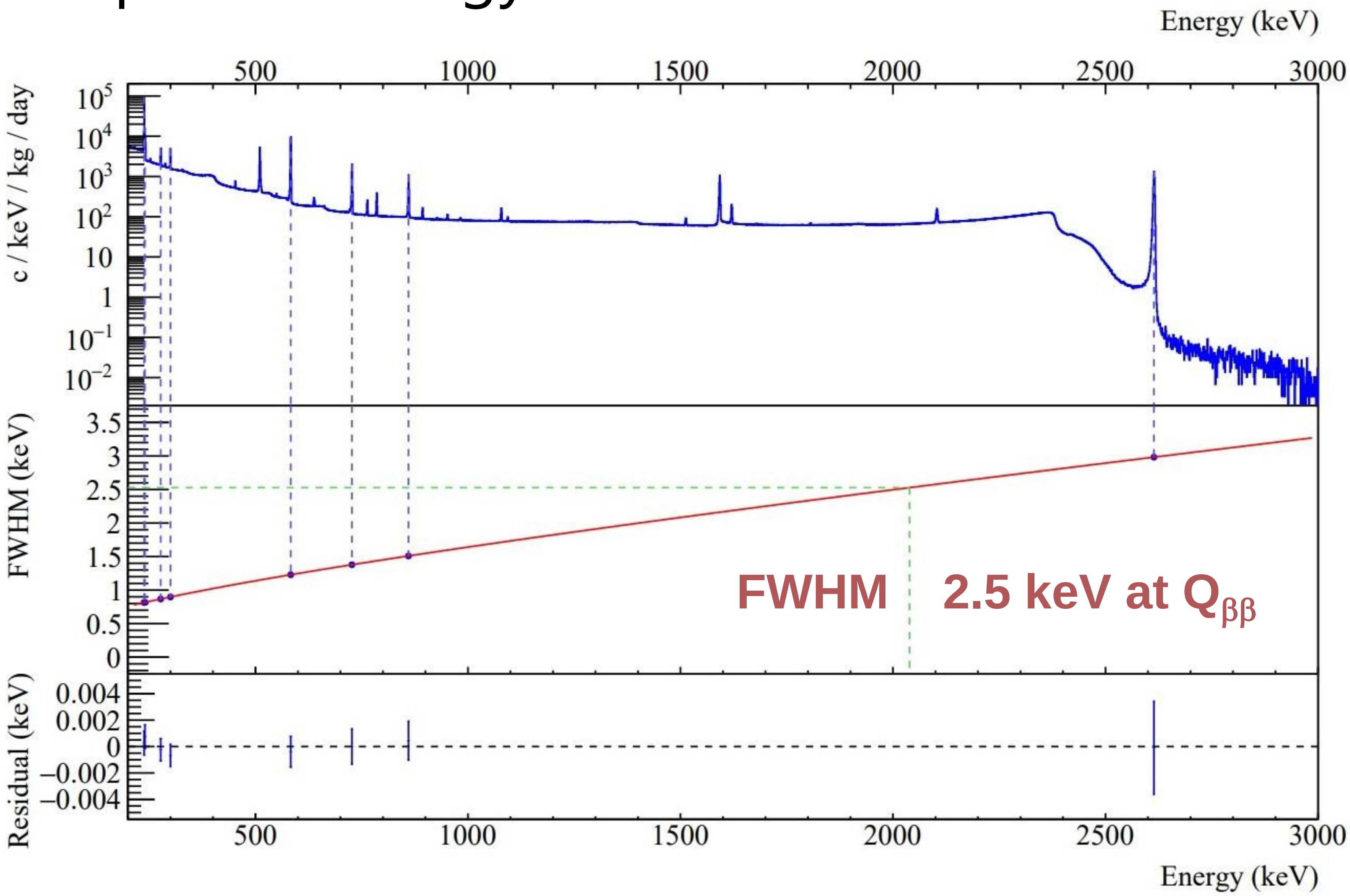
# LEGEND uses sophisticated large enriched Ge-76 detectors building on work by Majorana and GERDA.

**I**nverted
**C**oaxial
**P**oint
**C**ontact




Majorana GERDA LEGEND

# Point-contact with electronics near crystal allows for exceptional energy resolution.

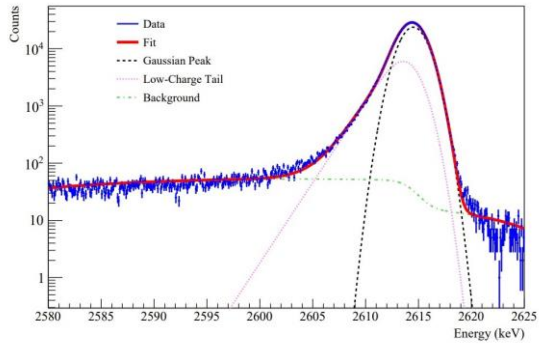



Combined energy calibration for DS0-6

**Majorana Demonstrator**

https://arxiv.org/abs/1902.02299

Zoom into Tl-208 peak



# Pulse shapes for single-site and double-site events are different

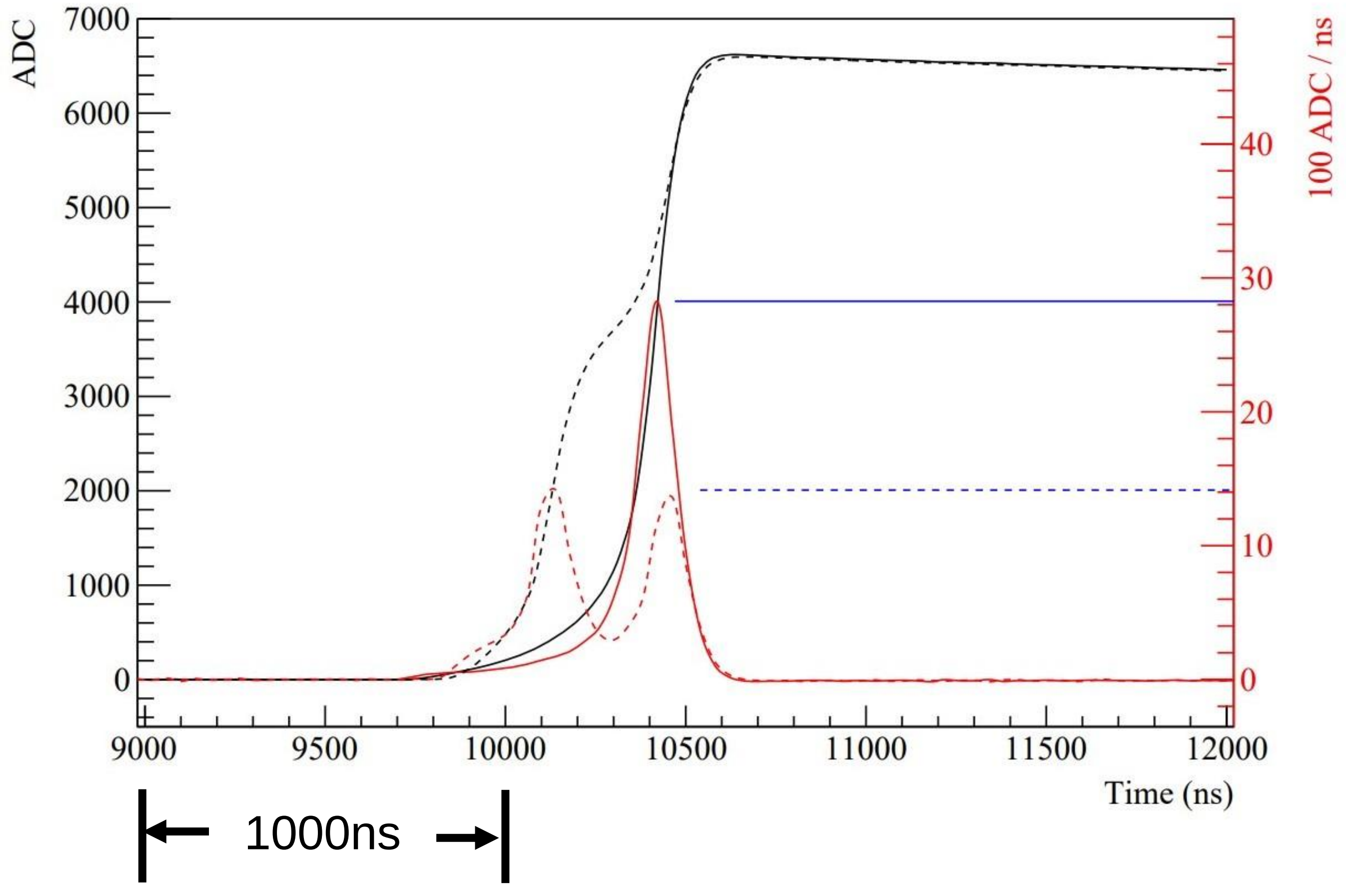



Figure from the Majorana Demonstrator
https://arxiv.org/abs/1902.02299

# Pulse shapes for single-site and double-site events are different

— Single site Q vs t

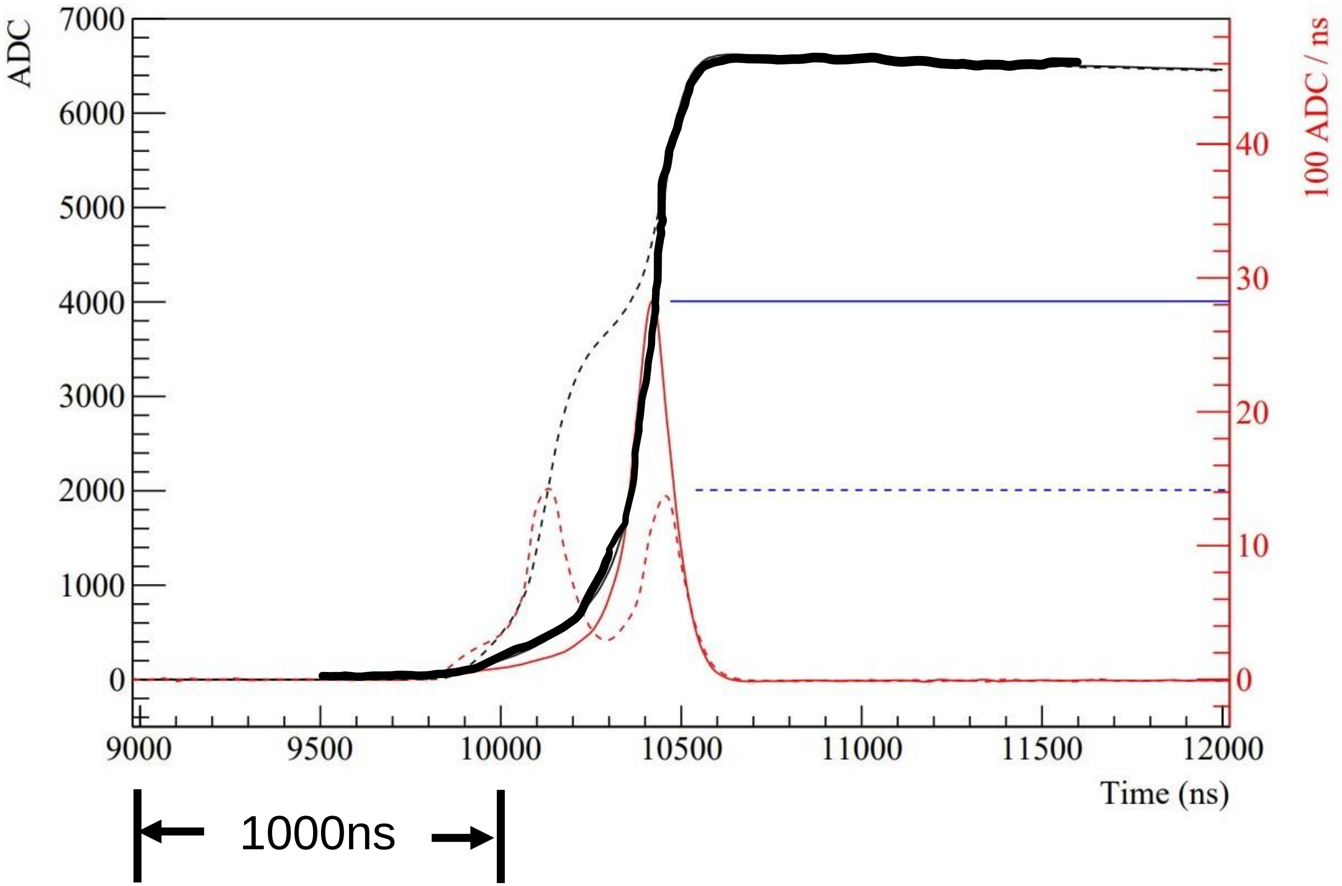



Figure from the Majorana Demonstrator
https://arxiv.org/abs/1902.02299

# Pulse shapes for single-site and double-site events are different

— Single site Q vs t

— Single site I vs t

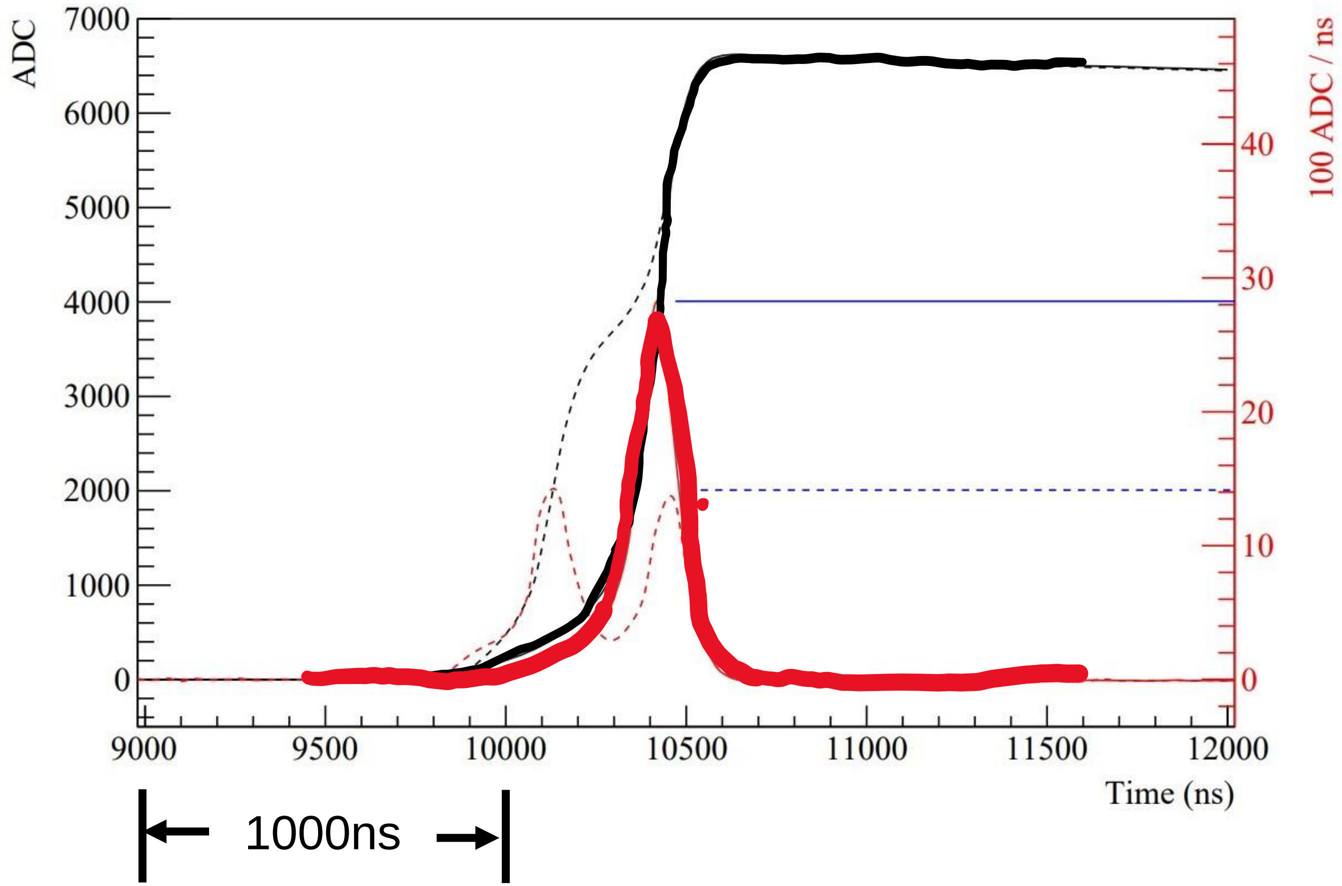



Figure from the Majorana Demonstrator
https://arxiv.org/abs/1902.02299

# Pulse shapes for single-site and double-site events are different

- - - Two site Q vs t

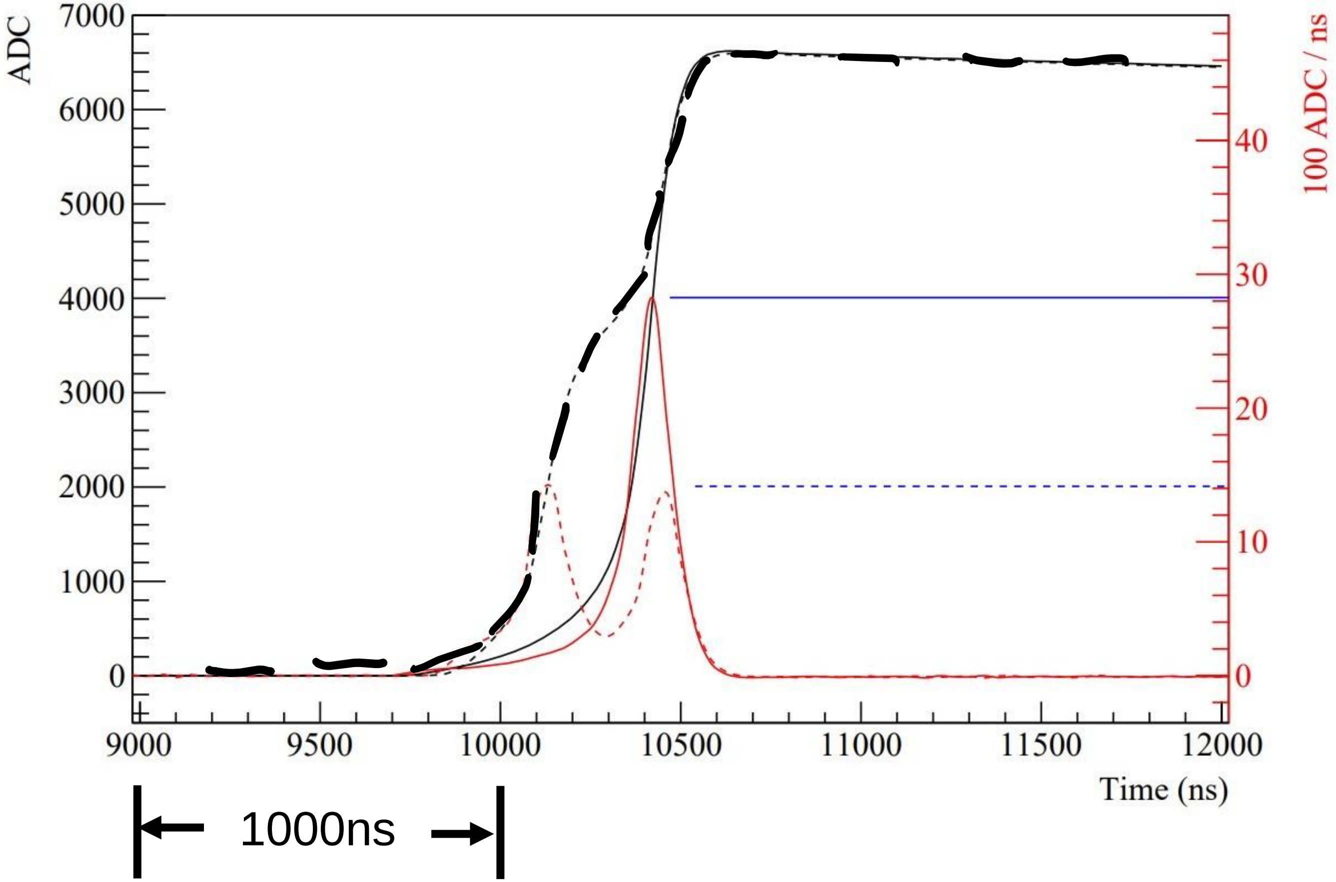
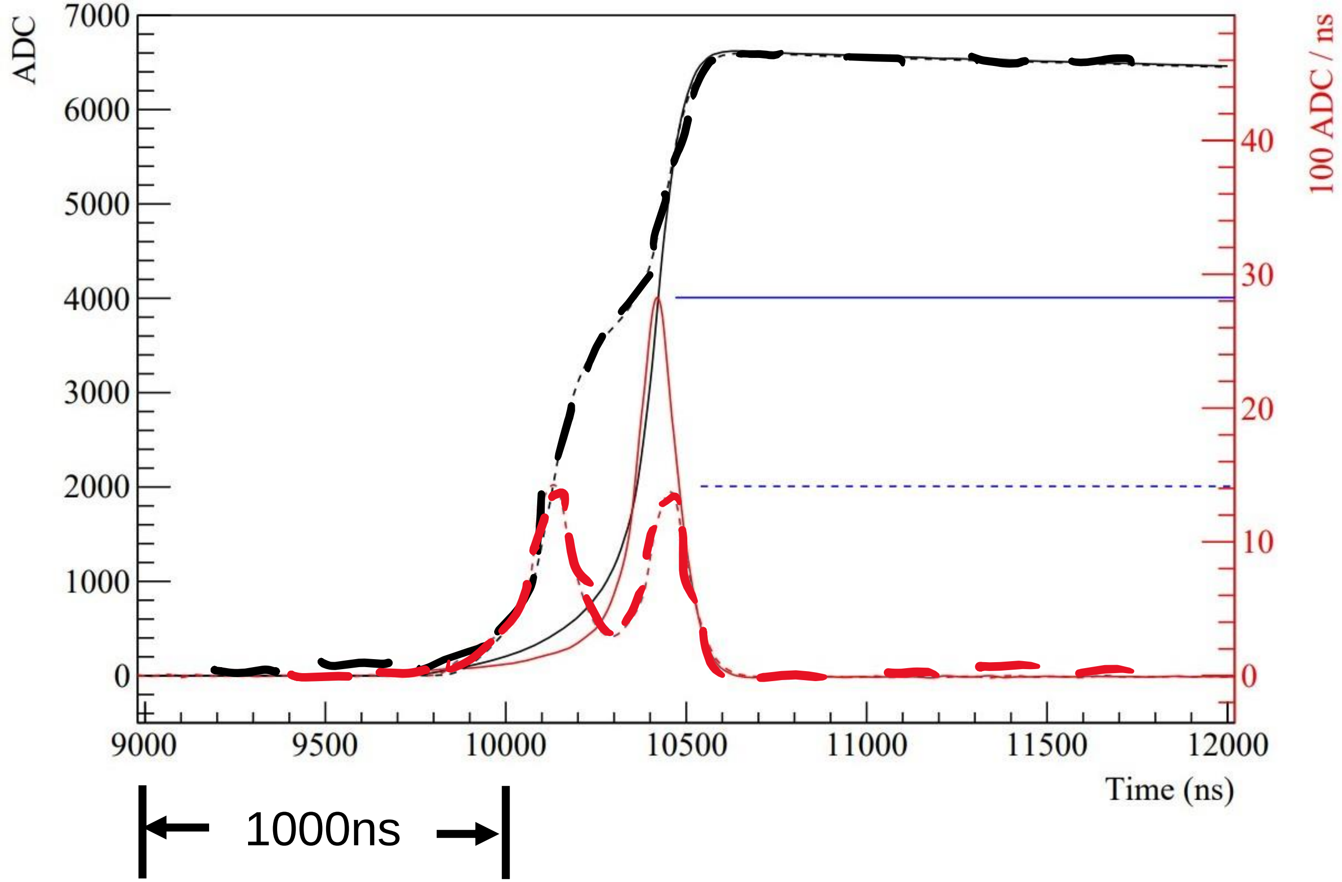



Figure from the Majorana Demonstrator
https://arxiv.org/abs/1902.02299

# Pulse shapes for single-site and double-site events are different

- - - Two site Q vs t

- - - Two site I vs t

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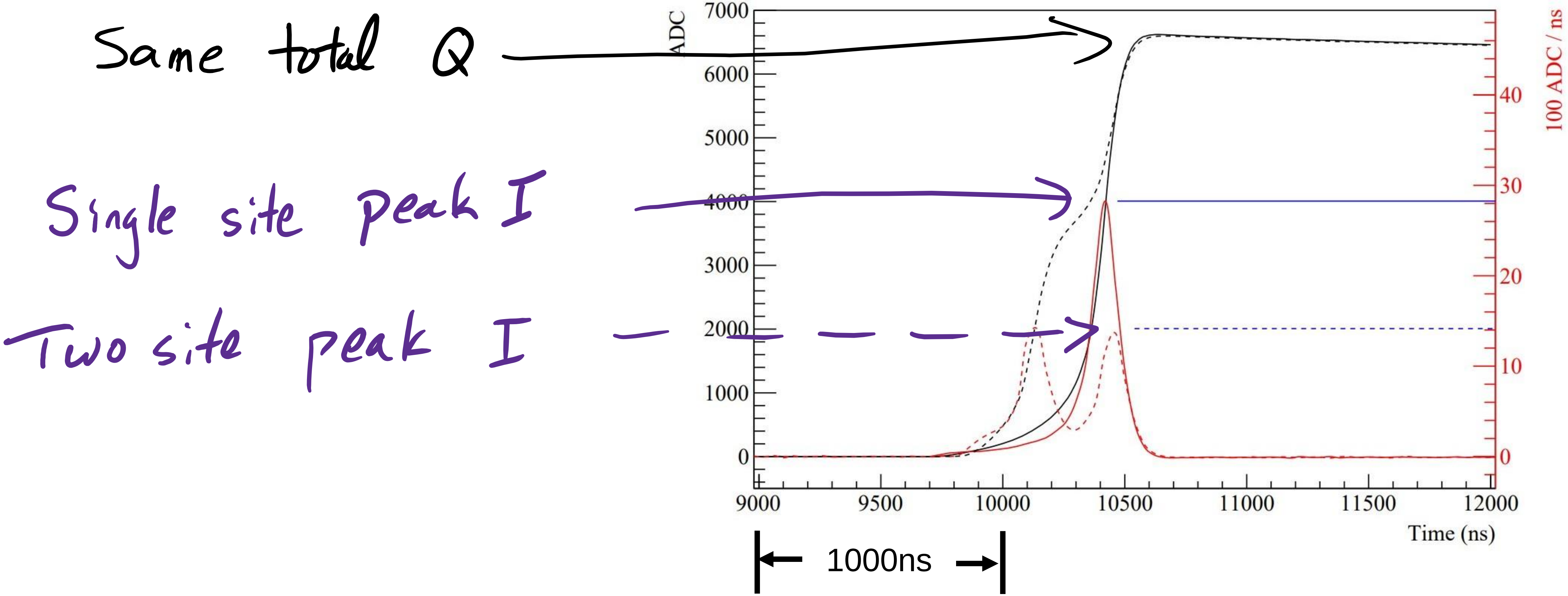



Figure from the Majorana Demonstrator
https://arxiv.org/abs/1902.02299

# The crystals are surrounded by an active LAr veto.

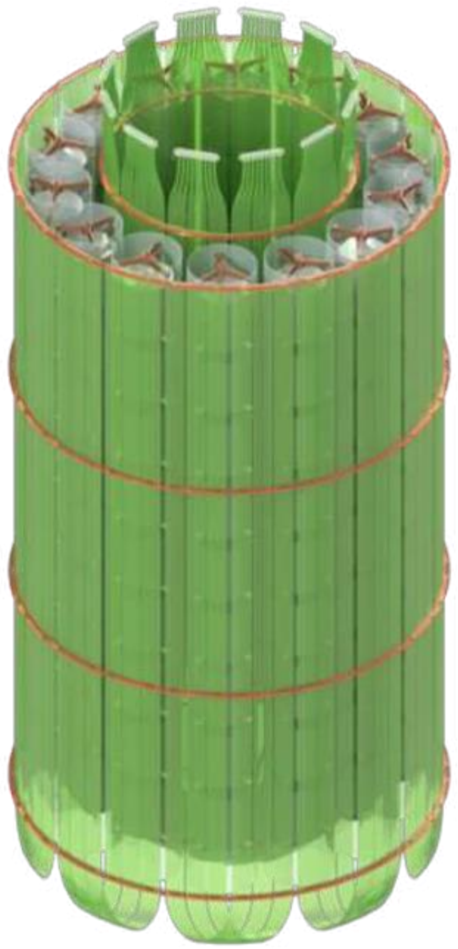
- Liquid argon easily purified from any impurity (except other nobles!)

  *Low background*

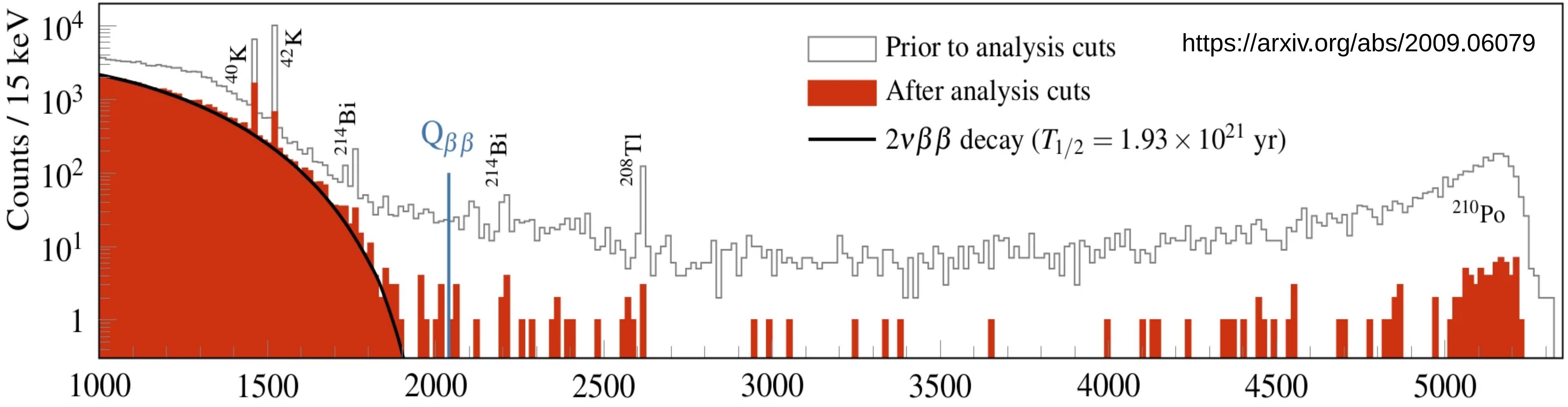
- Supplies an active veto / multi-site suppression

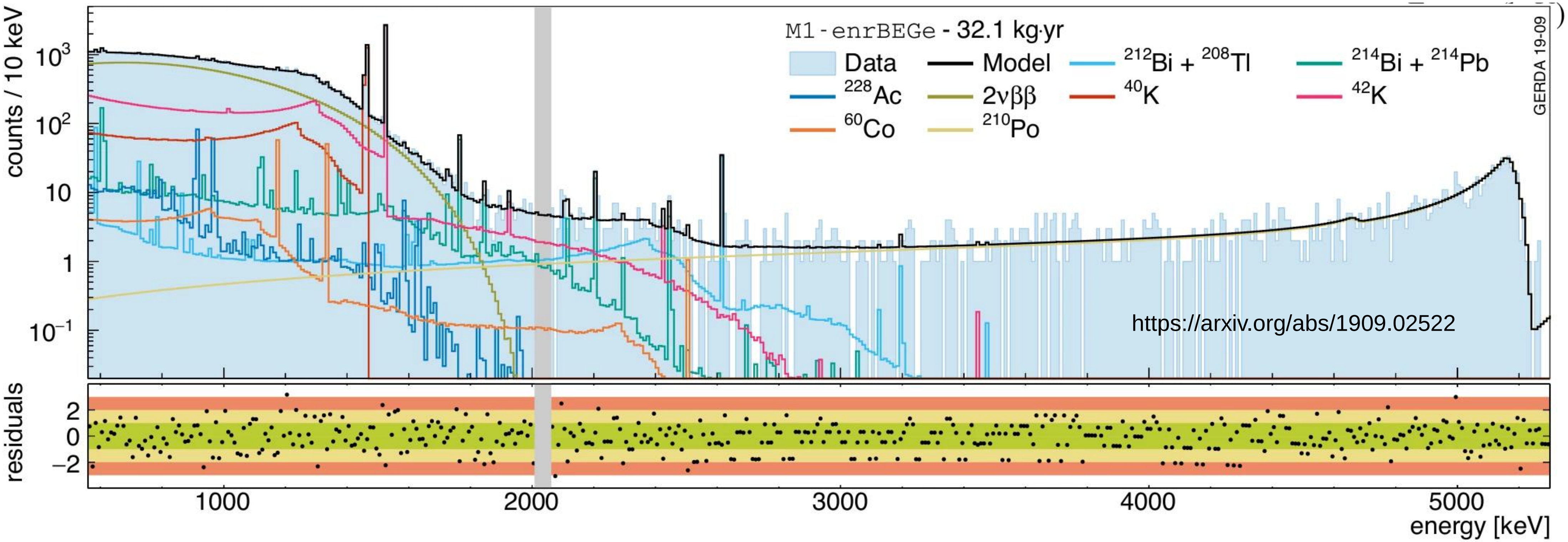
- Cools crystals

LEGEND-200 atmospheric argon veto system
Fibre curtain for Ar scint readout



# GERDA final analysis shows utility of multisite, veto, surface cuts




**GERDA**
127.2 kg-yr total exposure

No signal seen:

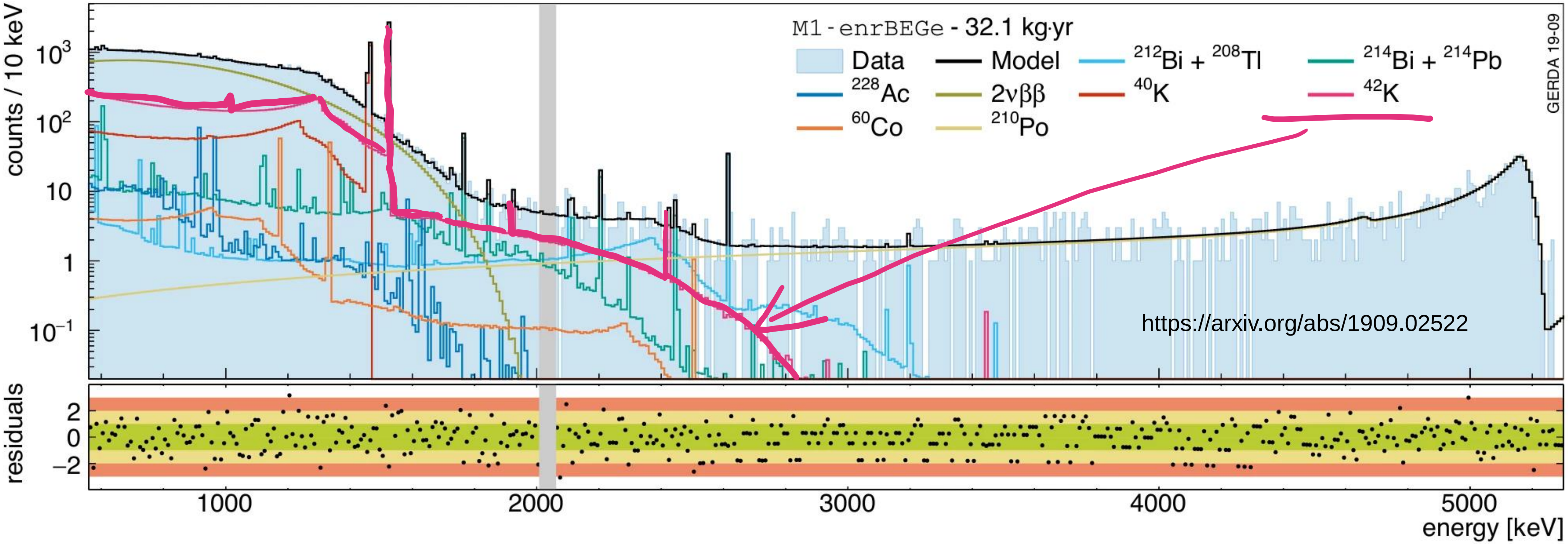
**$T_{1/2}$ > 1.8 x $10^{26}$ years**

# In GERDA, K-42 (from Ar-42) is an important background.

DarkSide-50 has demonstrated that the specific activity of Ar-39 is (at least) a factor of 1400 less in underground argon than surface argon. https://arxiv.org/abs/1802.07198

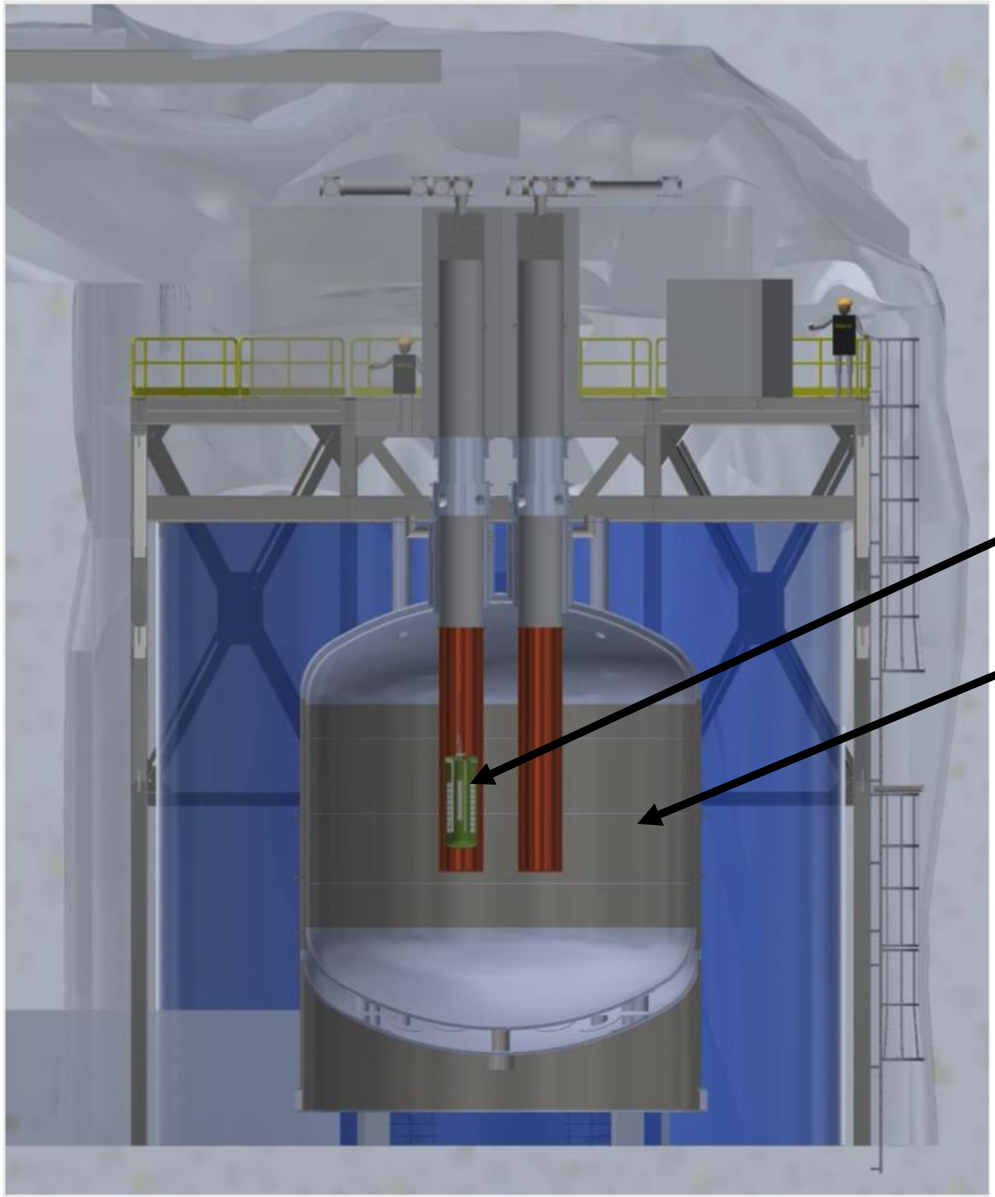
**If the same or better ratio holds for Ar-42, then this background is acceptable in LEGEND-1000.**

DEAP-3600 is considering a run with underground argon to measure [A(Ar-42)]. Session T4-3, this meeting




Data before analysis cuts

# LEGEND-1000 will use <u>underground argon</u> in re-entrant copper tubes to reduce Ar42/K-42 background



Electroformed copper stored underground to avoid cosmogenic production of Co-60

Crystals and underground liquid argon

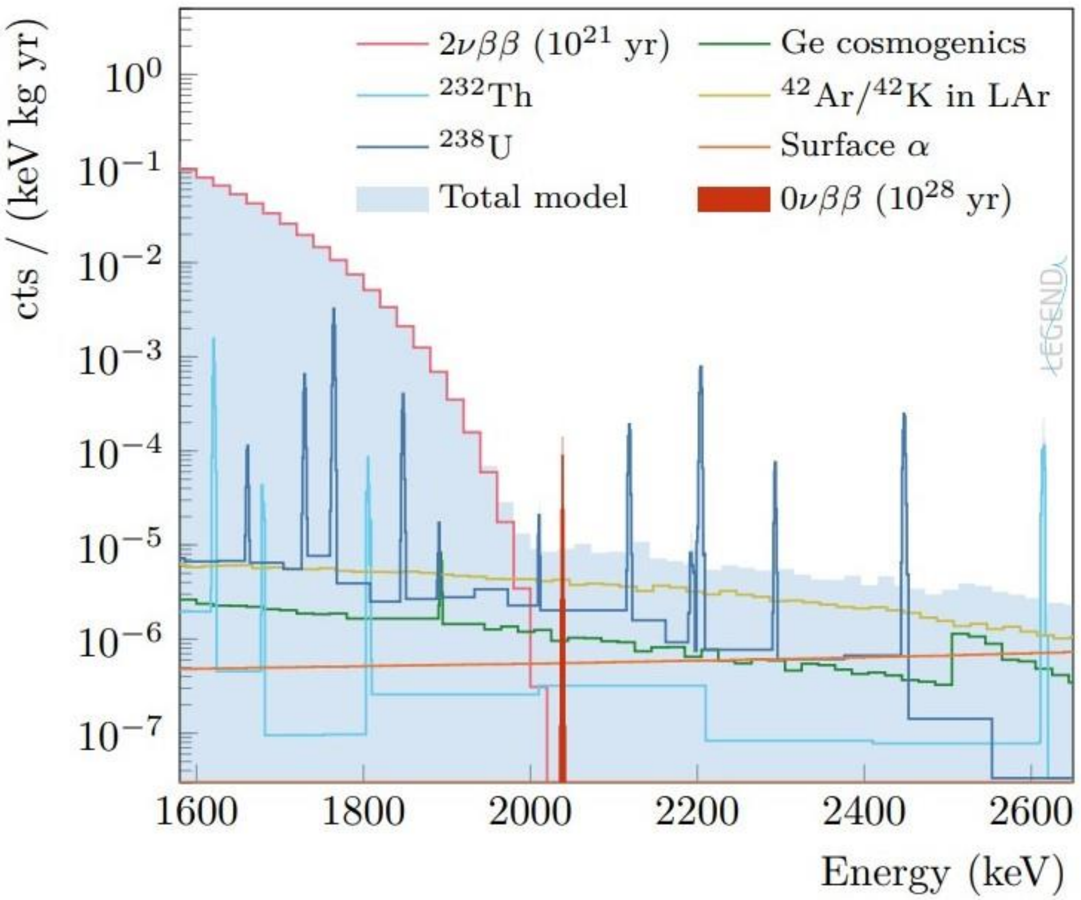
Atmospheric liquid argon

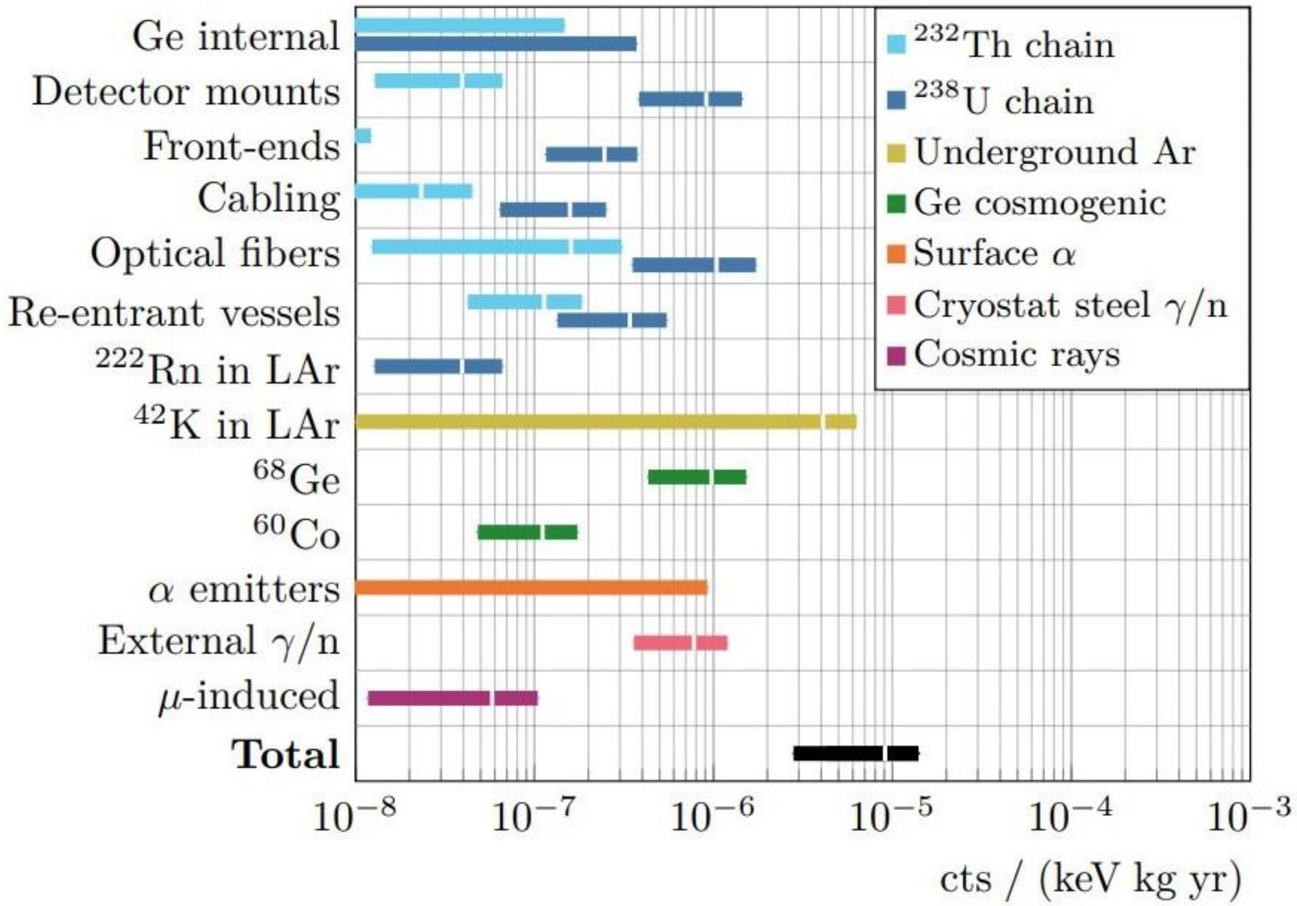
<u>Two designs under consideration:</u>

One large re-entrant tube (baseline)

Four smaller ones

# LEGEND-1000 has a detailed background budget



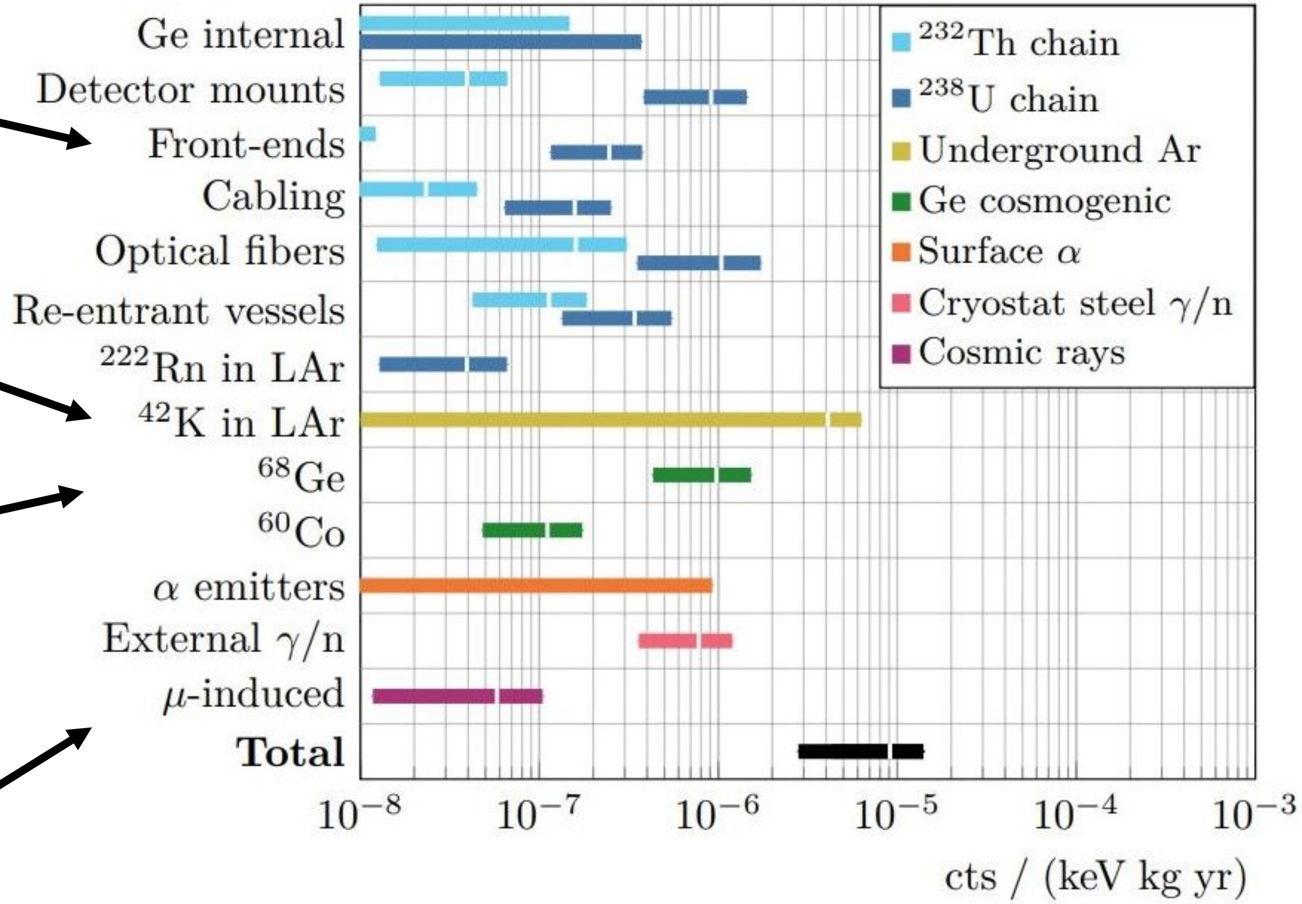
# LEGEND-1000 has a detailed background budget

Low mass and low radioactivity electronics from Majorana program being improved for LEGEND-1000

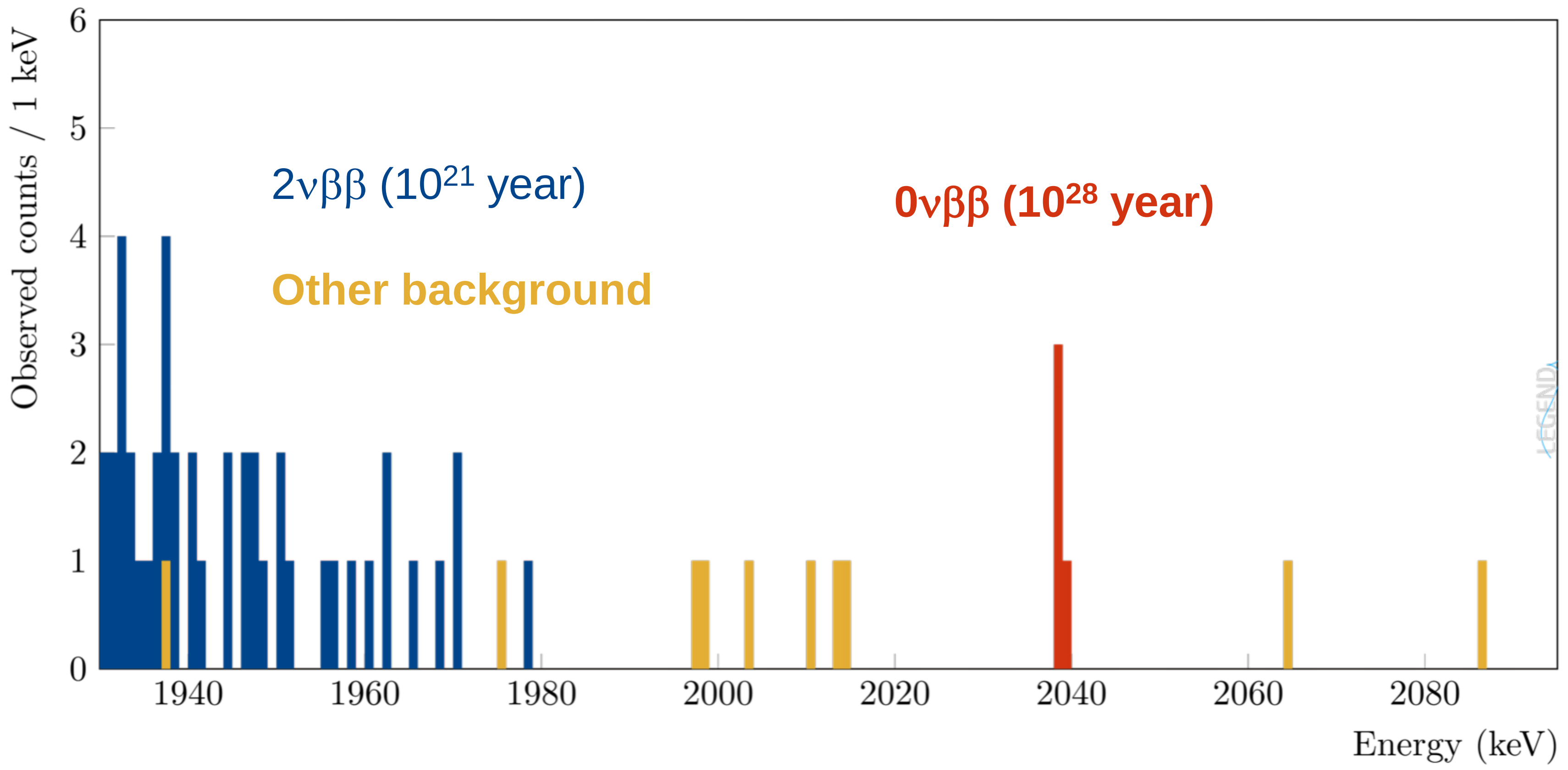
Based on 1400x reduction based on DarkSide-50k. (Note 1400 is a limit on the reduction factor.)

Ge crystal production is underground with carefully controlled budget for time at surface. Shipping in shielded sea cans.

At SNOLAB the fast-n rate is small enough this is not expected to be an issue. For LNGS deployment, use an acrylic moderator in the atmospheric argon and veto/tag with only small loss in livetime

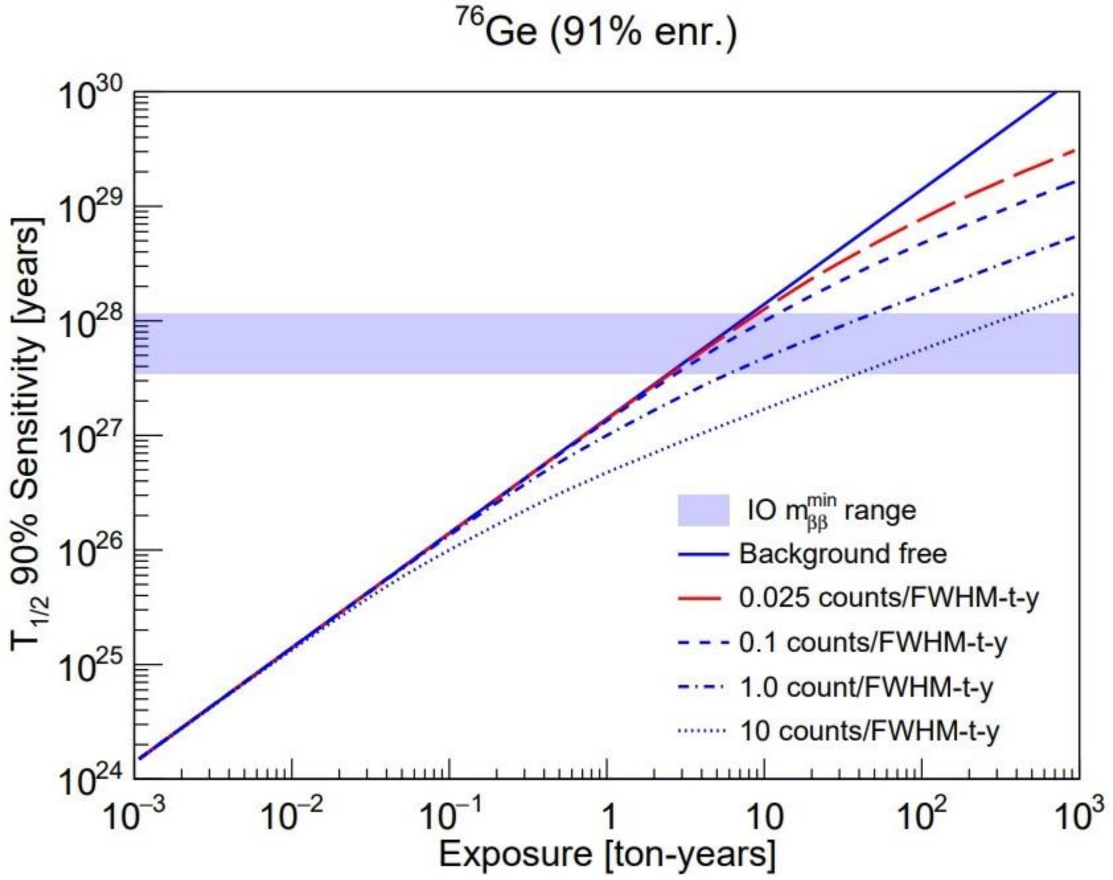


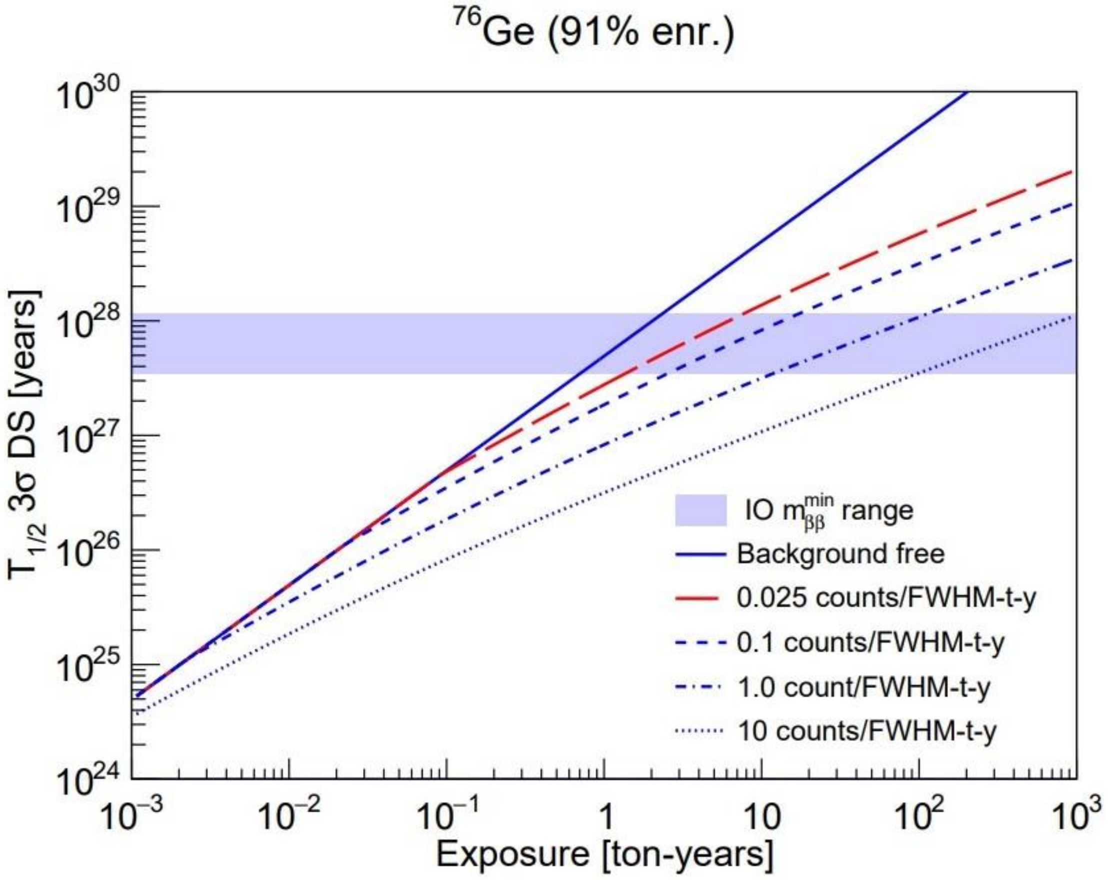
# LEGEND-1000 has discovery potential for a 0νββ half life of $10^{28}$ years



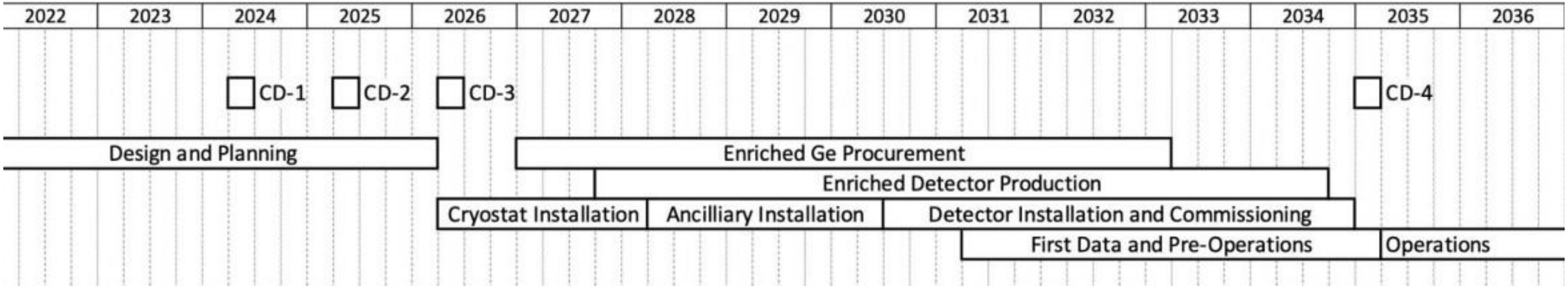

<u>Definition of discovery potential:</u>
a 50% chance or greater that a 10 tonne-year exposure results in a signal 3σ above null hypothesis

# LEGEND-1000 has discovery potential for a 0νββ half life of $10^{28}$ years



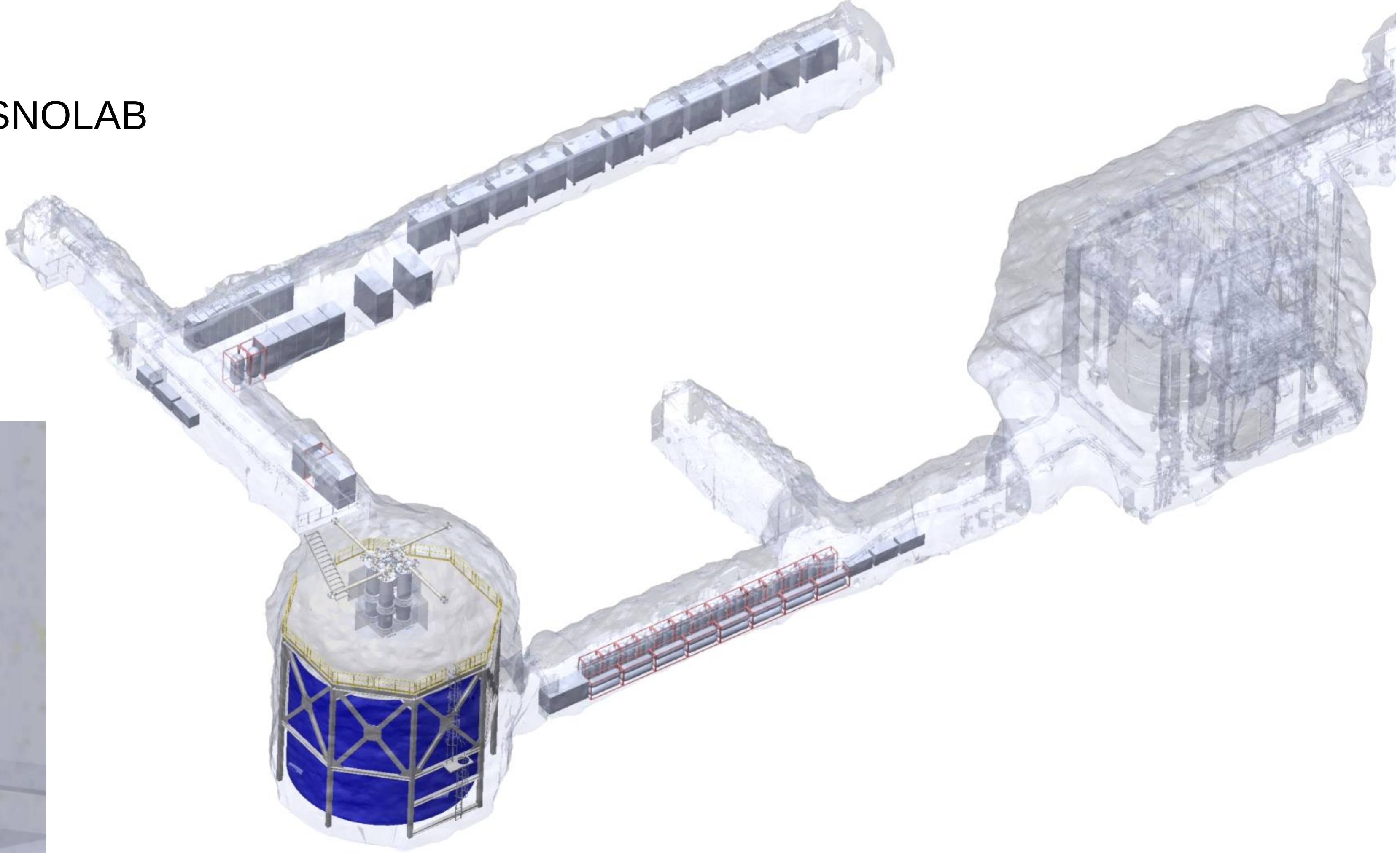
# The LEGEND-1000 CDR is under advanced preparation.

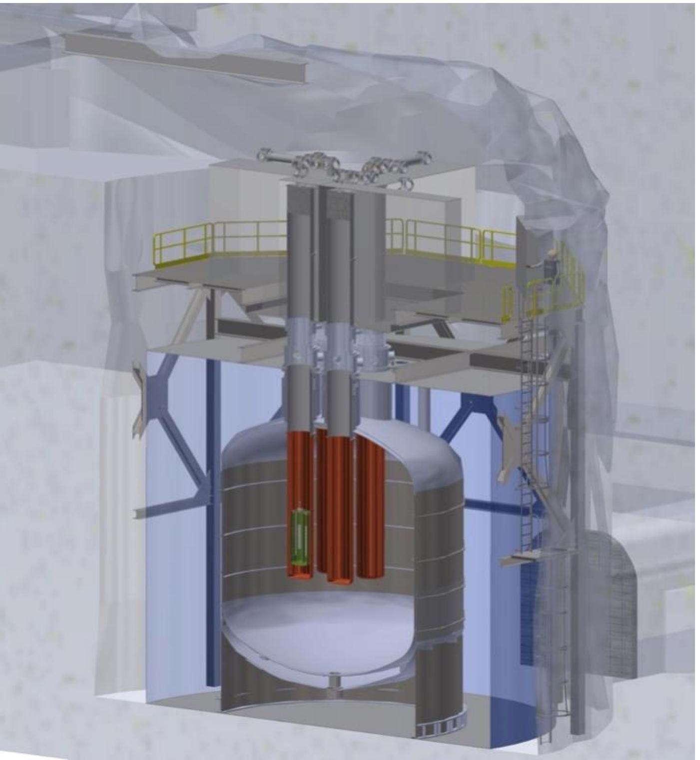



The CDR contains an LNGS and a SNOLAB design.
Final siting decision is not yet made.

# Canadian effort is growing!

Preparation for hosting at SNOLAB





# Canadian effort is growing!

Mark Anderson's talk Monday

Analysis/optimization of signal processing from germanium crystals.

Eur. Phys. J. C (2022) 82:1084
https://doi.org/10.1140/epjc/s10052-022-11000-w

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

## Performance of a convolutional autoencoder designed to remove electronic noise from p-type point contact germanium detector signals

**Mark R. Anderson**[1,a], **Vasundhara Basu**[1], **Ryan D. Martin**[1], **Charlotte Z. Reed**[1], **Noah J. Rowe**[1], **Mehdi Shafiee**[1,2,3], **Tianai Ye**[1]

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Received: 14 April 2022 / Accepted: 4 November 2022 / Published online: 1 December 2022


https://doi.org/10.1140/epjc/s10052-022-11000-w

# Canadian effort is growing!

LEGEND

Radiopurity of materials.

Assay

Development of new assay techniques

For a discussion of these techniques, see talk at this meeting by Ian Lawson: https://indi.to/4tfqZ

ICPMS

Surface screening for materials

Radon emanation
(emanation of thin materials at increased temperature to measure Ra-226 in ribbon cables etc)

Gamma counting

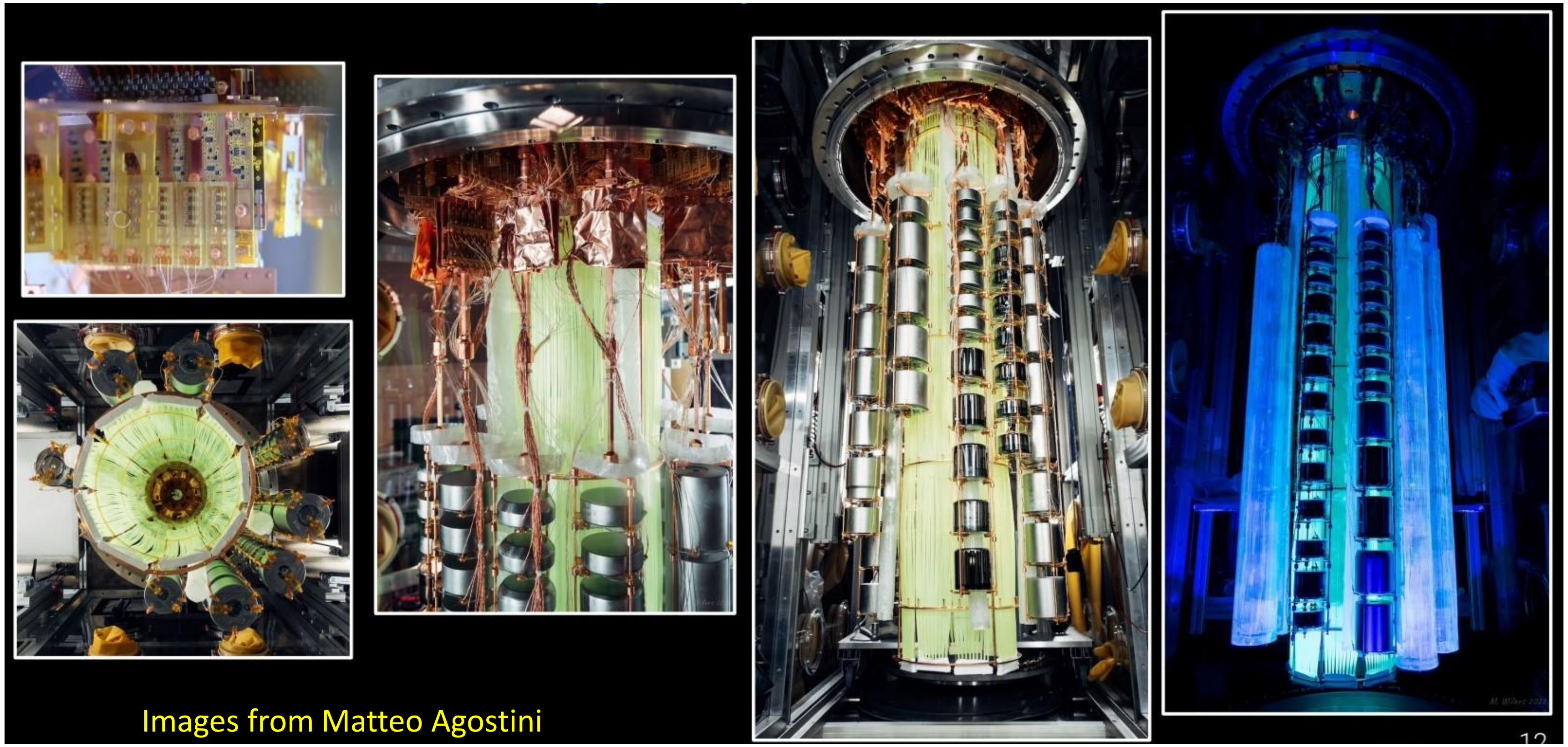
# LEGEND-200 deployment complete and physics data taking started March 12, 2023

140 kg of detectors deployed

122 kg usable for analysis

<u>Exposure:</u> 2 kg year / week

100 kg year by end of this year




We hope to release early data in autumn 2023.

# Thank you for your attention

The LEGEND program seeks to measure $0\nu\beta\beta$ with a discovery potential for a $10^{28}$ year half life, thus probing all the inverted hierarchy space and much of the normal hierarchy space.

LEGEND builds on the work for GERDA and the Majorana Demonstrator.

Designed for exquisite energy resolution and ultra-low backgrounds.

Deployment planning for LEGEND-1000 @ LNGS and SNOLAB.

Canadian involvement strong and growing.

LEGEND-200 is taking data at LNGS.