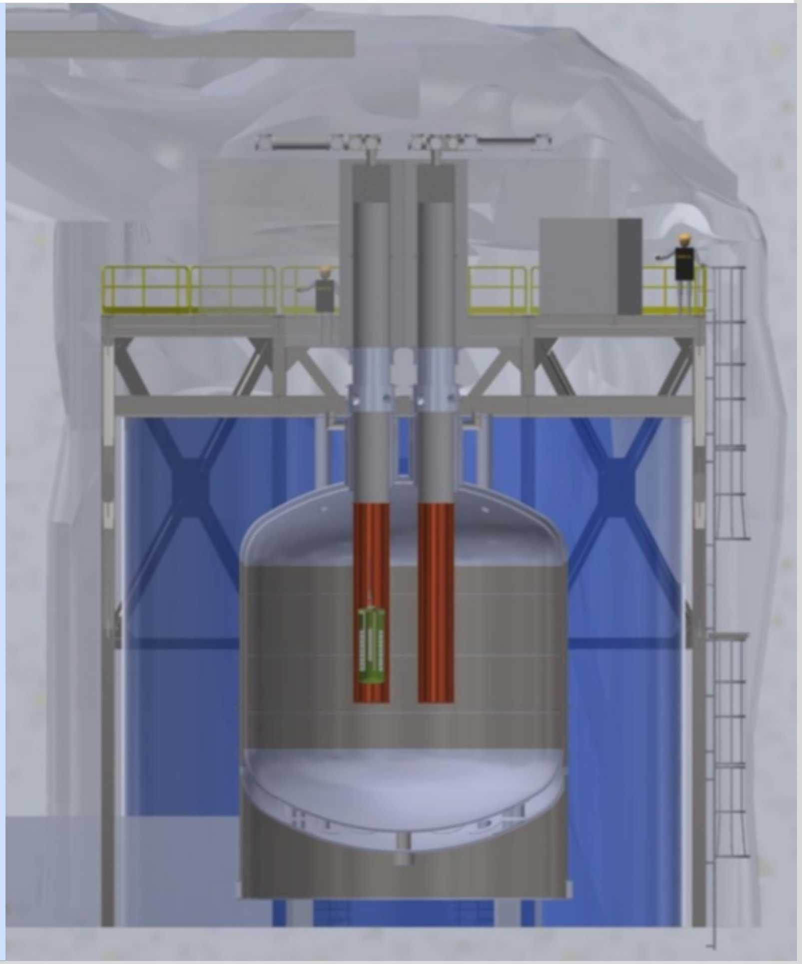
Germanium-based Search of Neutrinoless Double-Beta Decay

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



Wenqin Xu

University of South Dakota

Nov – 29 – 2022

Colloquium

Brookhaven National Laboratory

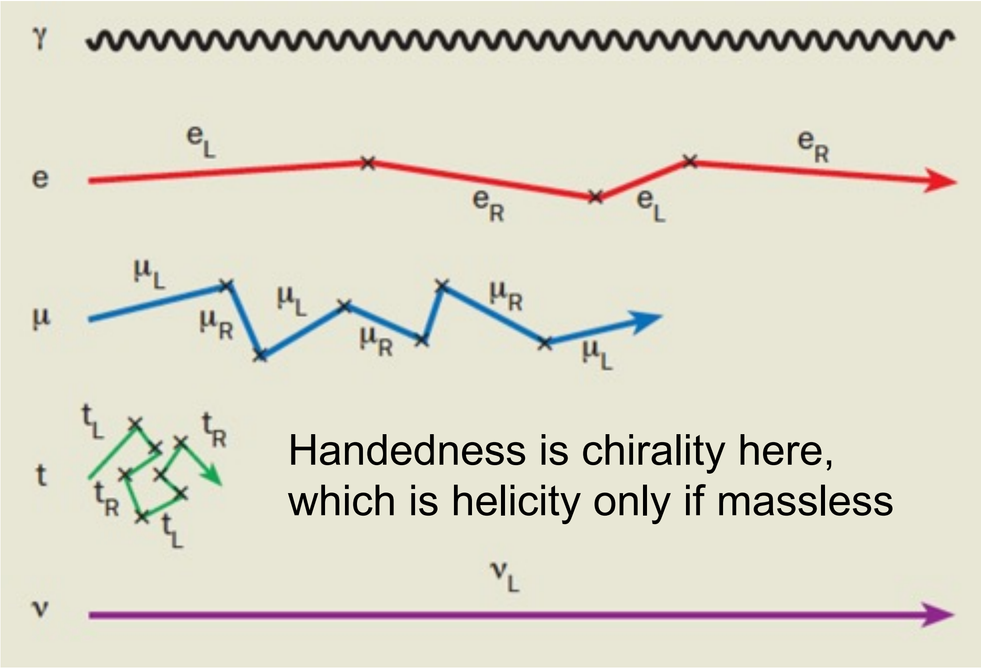
UNIVERSITY OF SOUTH DAKOTA

Brookhaven National Laboratory

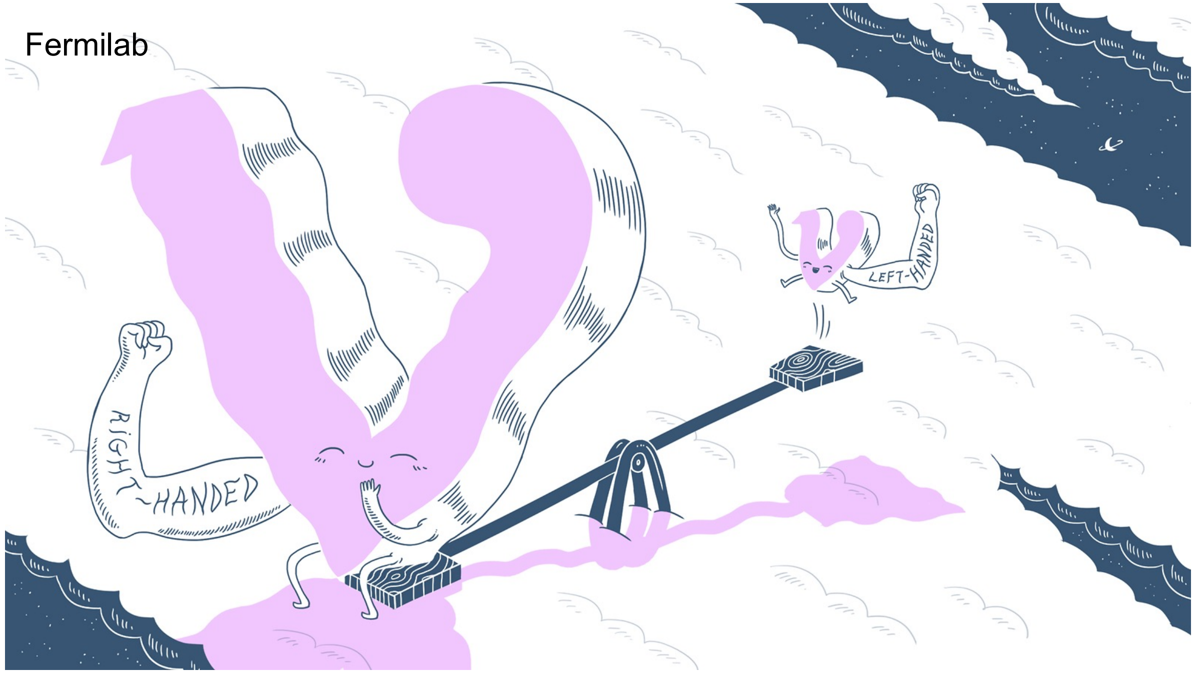
Part I
Motivation for the Discovery of Neutrinoless Double-Beta Decay

Neutrino Mass is Beyond the Standard Model

H. Murayama, Physics World, May 2002



Fermilab



Right-handed neutrinos never discovered

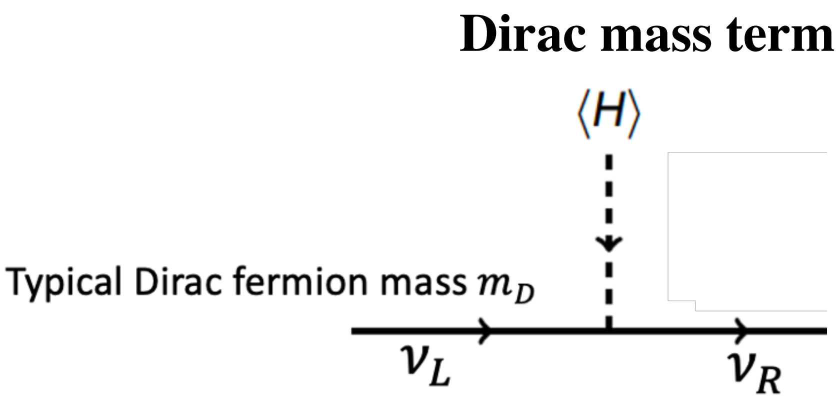
- **Neutrinos have zero mass in the Standard Model**
- Non-zero neutrino mass is **physics beyond-the-Standard Model (BSM)**
  - Need right-handed neutrinos in the mechanism for neutrino mass
  - Need to avoid light active right-handed neutrinos as they are not found in data

➡

Introduce a heavy neutrino in the seesaw model

- Heavy neutrinos are NOT sterile
- Too heavy to be created or found in experiments

Introducing Heavy Right-handed Neutrinos



Introducing Heavy Right-handed Neutrinos

If I introduce new fields, I have to write down all possible interactions allowed by the gauge symmetries given the (new) field content Adapted from Walter Winter, WIN 2017

Because neutrinos are electrically neutral, ν_R would allow a Majorana mass term $\sim m_R(\overline{\nu_L}\nu_R^c + \bar{\nu}_R^c\nu_L)$

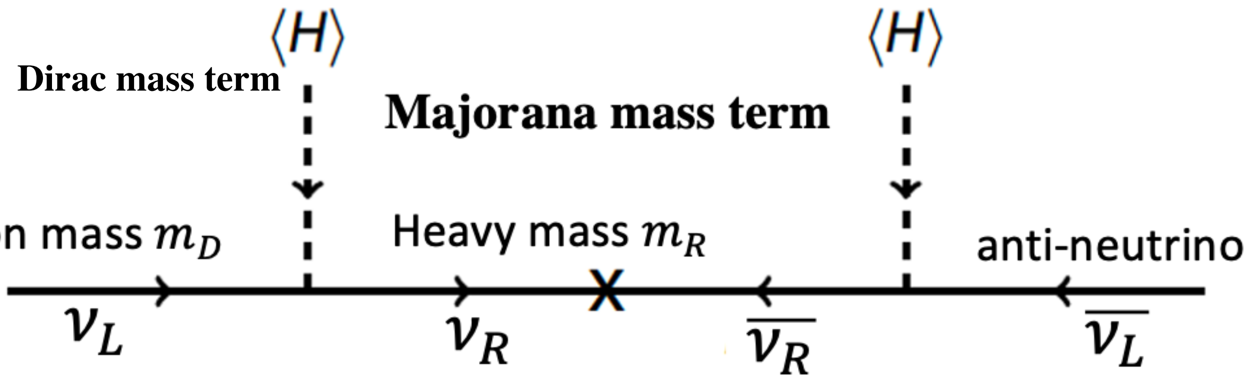


Figure adapted from Jon Engel

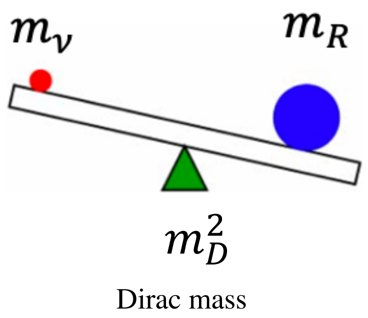
ν_R is assumed to be very heavy in the seesaw model. It can only participate as a virtual particle in the process above. It cannot be easily produced and detected.

The physical neutrino is a mixture

$$\nu = c_1\nu_R^c + c_2\nu_L$$

with a mass highly suppressed by m_R

$$m_\nu = \frac{m_D^2}{m_R}$$



The seesaw model

Introducing Heavy Right-handed Neutrinos

If I introduce new fields, I have to write down all possible interactions allowed by the gauge symmetries given the (new) field content Adapted from Walter Winter, WIN 2017

Because neutrinos are electrically neutral, ν_R would allow a Majorana mass term $\sim m_R(\overline{\nu_L}\nu_R^c + \bar{\nu}_R^c\nu_L)$

Typical Dirac fermion mass m_D

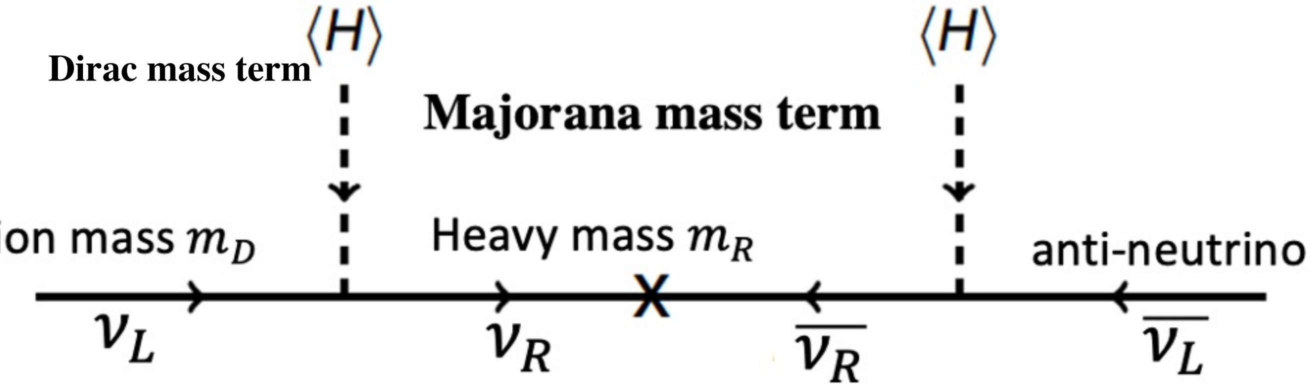
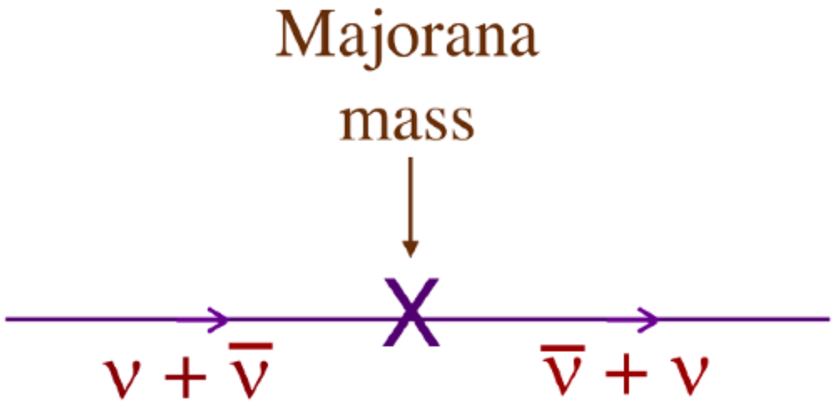


Figure adapted from Jon Engel



Lepton and Baryon Number Violation

But there is an accidental conservation law forbidding Majorana neutrinos: lepton number conservation
Neutrino: lepton number +1, Antineutrino: lepton number -1

Emmy Noether

Noether's Theorem: continuous symmetry leads to conservation laws

Baryon- and Lepton-Nonconserving Processes

Also F. Wilczek and A. Zee
Phys. Rev. Lett. 43. 1571(1979)

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, and Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

Phys. Rev. Lett.43.1566 (1979)

(Received 13 August 1979)

A number of properties of possible baryon- and lepton-nonconserving processes are shown to follow under very general assumptions. Attention is drawn to the importance of measuring μ^+ polarizations and $\overline{\nu}_e/e^+$ ratios in nucleon decay as a means of discriminating among specific models.

Of the supposedly exact conservation laws of physics, two are especially questionable: the conservation of baryon number and lepton number. As far as we know, there is no necessity for an *a priori* principle of baryon and lepton conservation. As we shall see, even without such a principle, the fact that the weak, electromagnetic, and strong interactions of ordinary quarks and leptons conserve baryon and lepton number can be understood as simply a consequence of the $SU(2) \otimes U(1)$ and $SU(3)$ gauge symmetries. Also, in contrast with the conservation of charge, conservation are likely to occur in grand unified theories that combine the gauge theory of weak and electromagnetic interactions with that of strong interactions and have leptons and quarks in the same gauge multiplets, and such violations have been found in various of these models.[3]

The purpose of this paper is to point out those features of baryon- or lepton-nonconserving processes that are to be expected on very general grounds. Other features will be indicated that may be used to discriminate among specific models.

Not fundamental

but accidental

Such as the Majorana mass term

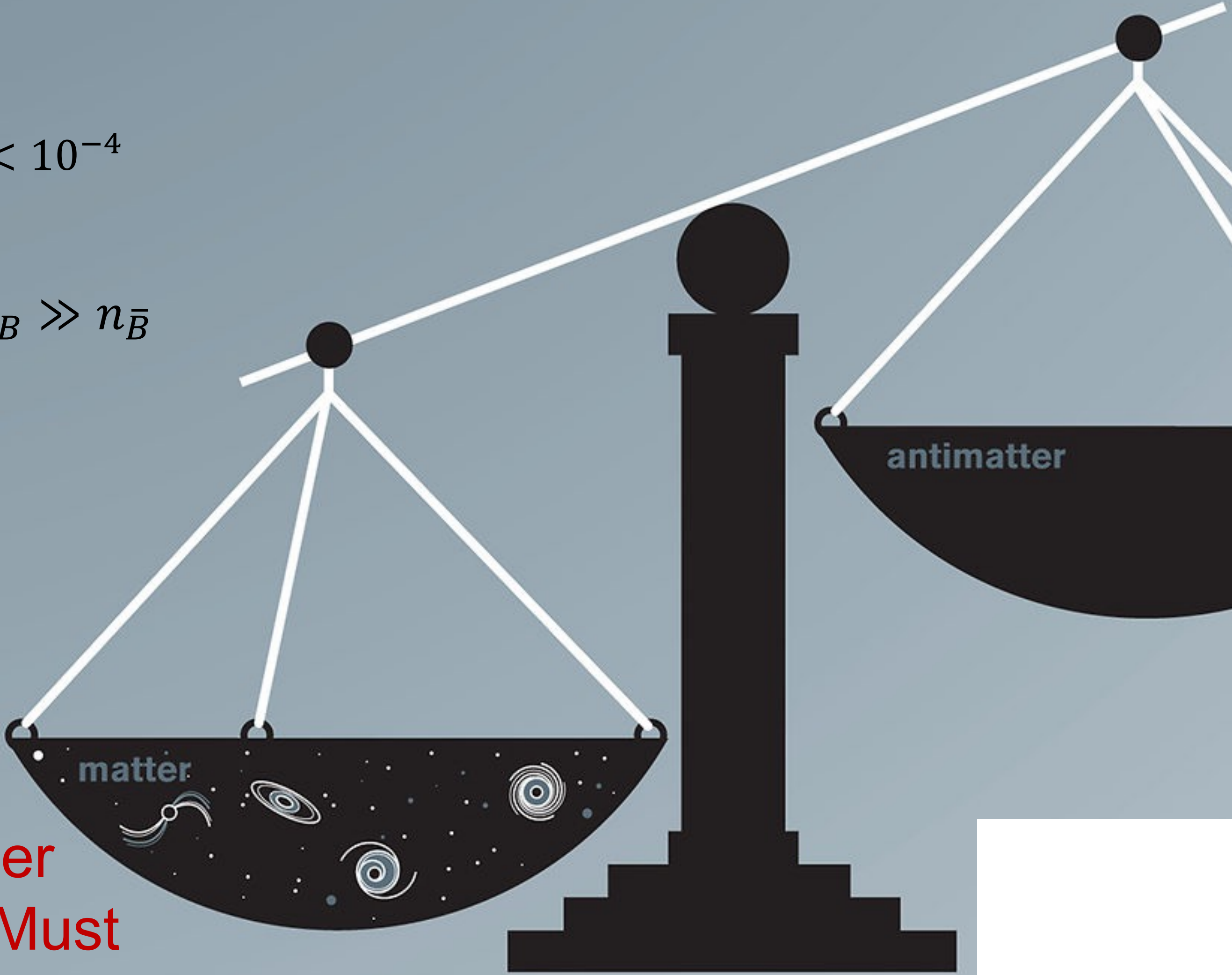
Wenqin Xu| 11/29/22

Matter Over Antimatter Excess In The Universe

symmetrymagazine.org

Cosmic Ray $\frac{\bar{p}}{p} < 10^{-4}$

Cosmic Background Radiation, etc: $n_B \gg n_{\bar{B}}$



Baryon Number Violation is a Must

Baryon number must be violated. In what process?
Is lepton number violated in the generation of neutrino mass?

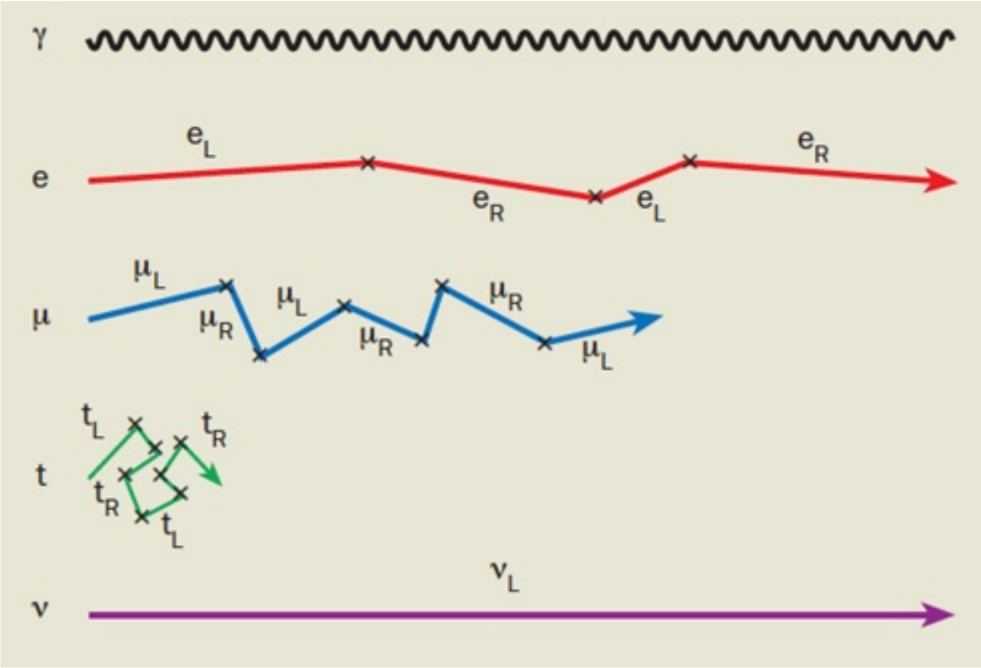
Annu. Rev. Nucl. Part. Sci. 2005. 55:311–55
doi: 10.1146/annurev.nucl.55.090704.151558

LEPTOGENESIS AS THE ORIGIN OF MATTER

W. Buchmüller,[1] R.D. Peccei,[2] and T. Yanagida,[3]

Motivation for **Neutrinoless Double Beta Decay (0𝝂ββ)**

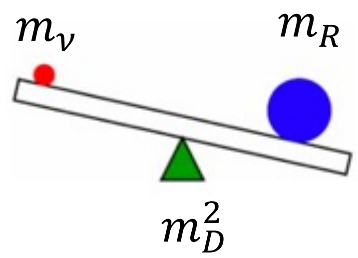
H. Murayama, Physics World, May 2002



Right-handed neutrinos never discovered

- Neutrinos have zero mass in the Standard Model
- Non-zero neutrino mass is **physics beyond-the-Standard Model (BSM)**
- **We introduce heavy neutrinos in the seesaw mechanism**

Heavy right-handed neutrino mass



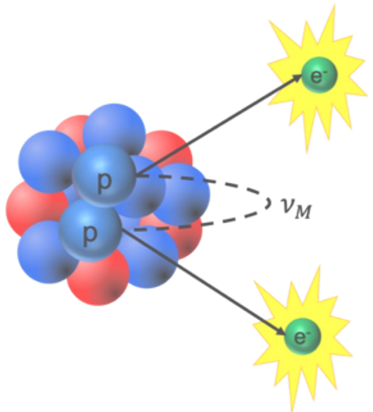
Dirac mass

The seesaw model

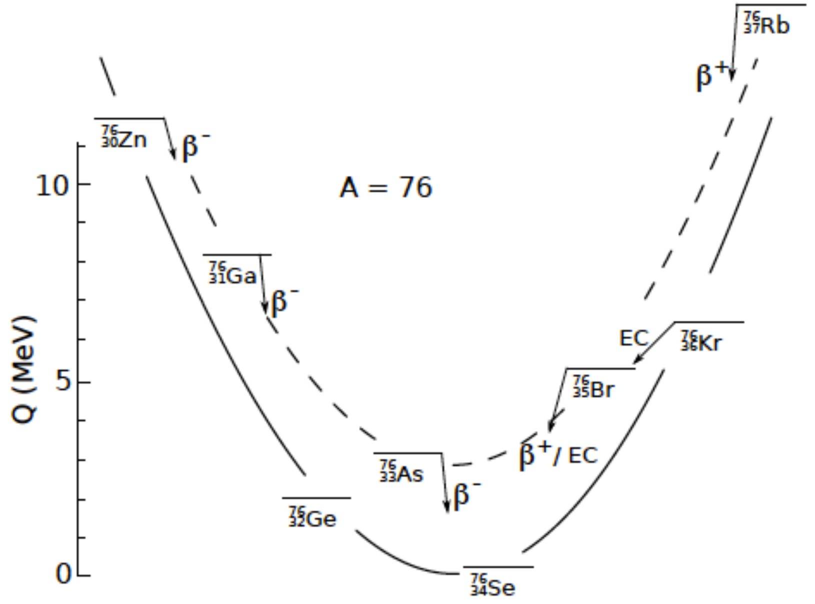
$$m_\nu = \frac{m_D^2}{m_R}$$

Dirac masses would still allow for Majorana masses neutrinos

- Seesaw mechanism explains the tininess of m_ν
- Majorana neutrinos are their own anti-particles
- Neutrinoless double beta decay (0𝝂ββ) is the only experimentally feasible way to establish neutrinos are Majorana.
- Probe the Lepton number violation

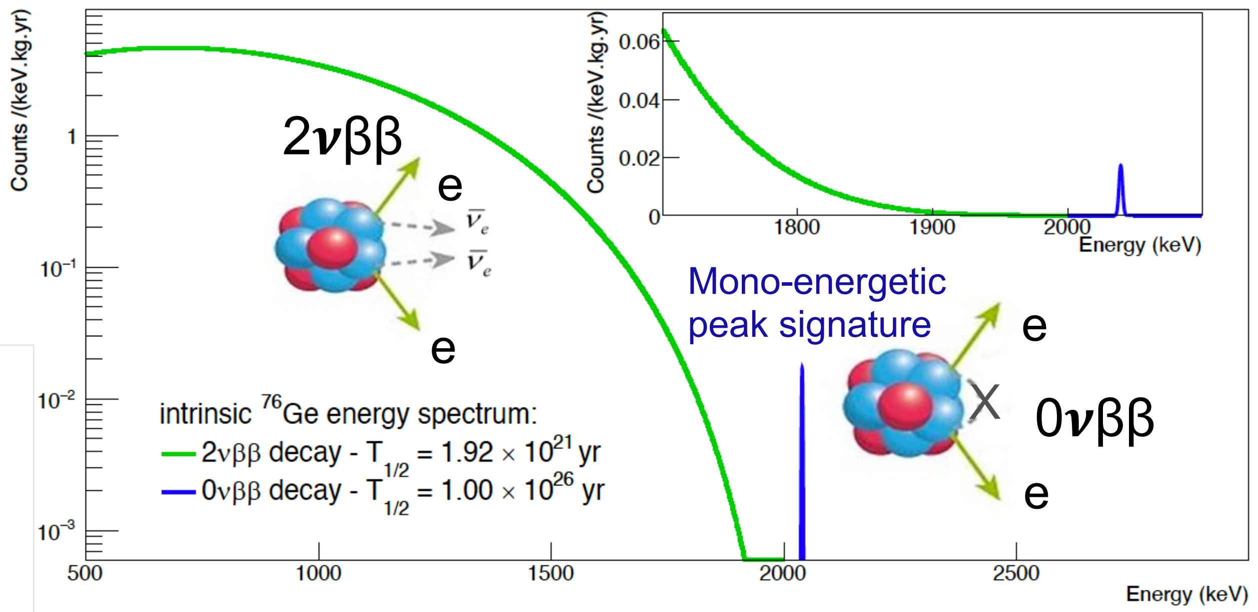


Neutrinoless Double-beta Decay ($0\boldsymbol{\nu}\beta\beta$)



Double-beta decay is possible when energetically favored

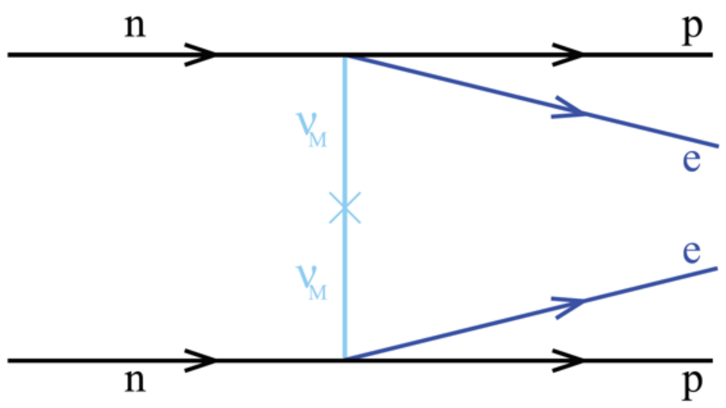
Two neutrino double-beta decay ($2\boldsymbol{\nu}\beta\beta$) is an observed Standard Model process



Observation of Neutrinoless double-beta decay (0νββ) would

- ➢ **prove the total lepton number is violated by 2 units ($\Delta L = 2$)**
- ➢ imply massive neutrinos are Majorana particles

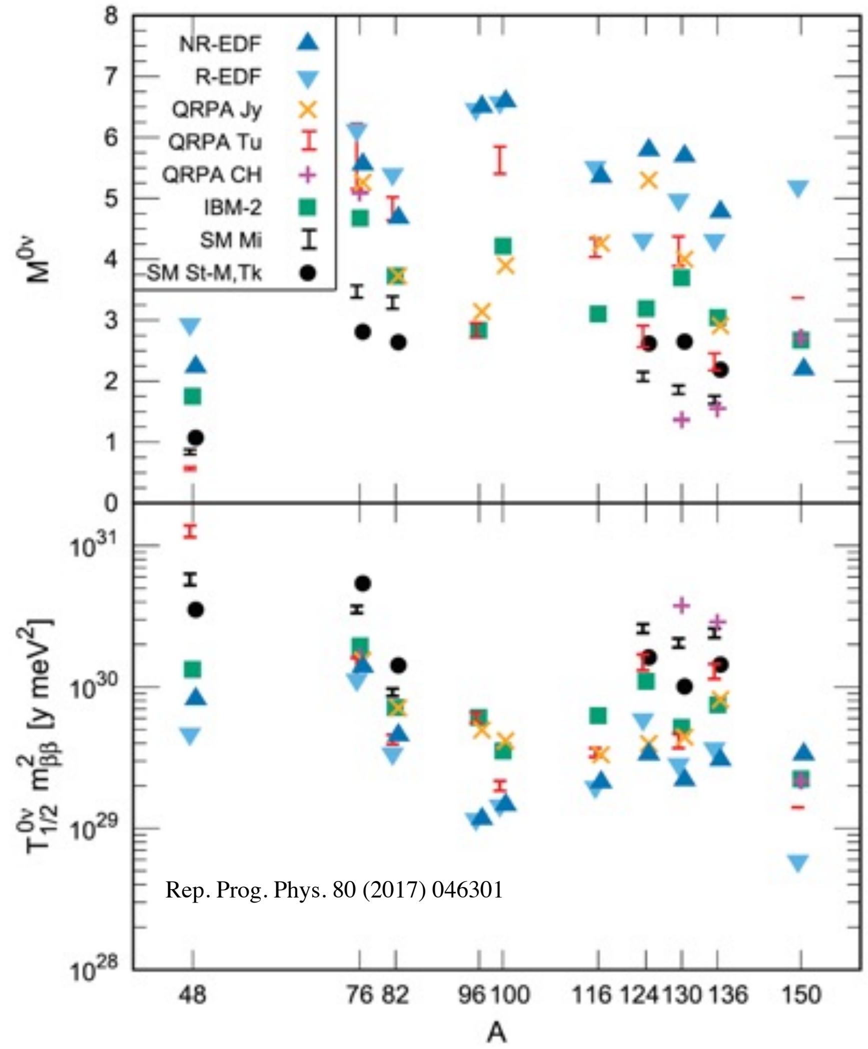
$0\nu\beta\beta$ Half Life and Effective Neutrino Mass



For light neutrino exchange model only:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Nuclear Matrix Element



$0\nu\beta\beta$

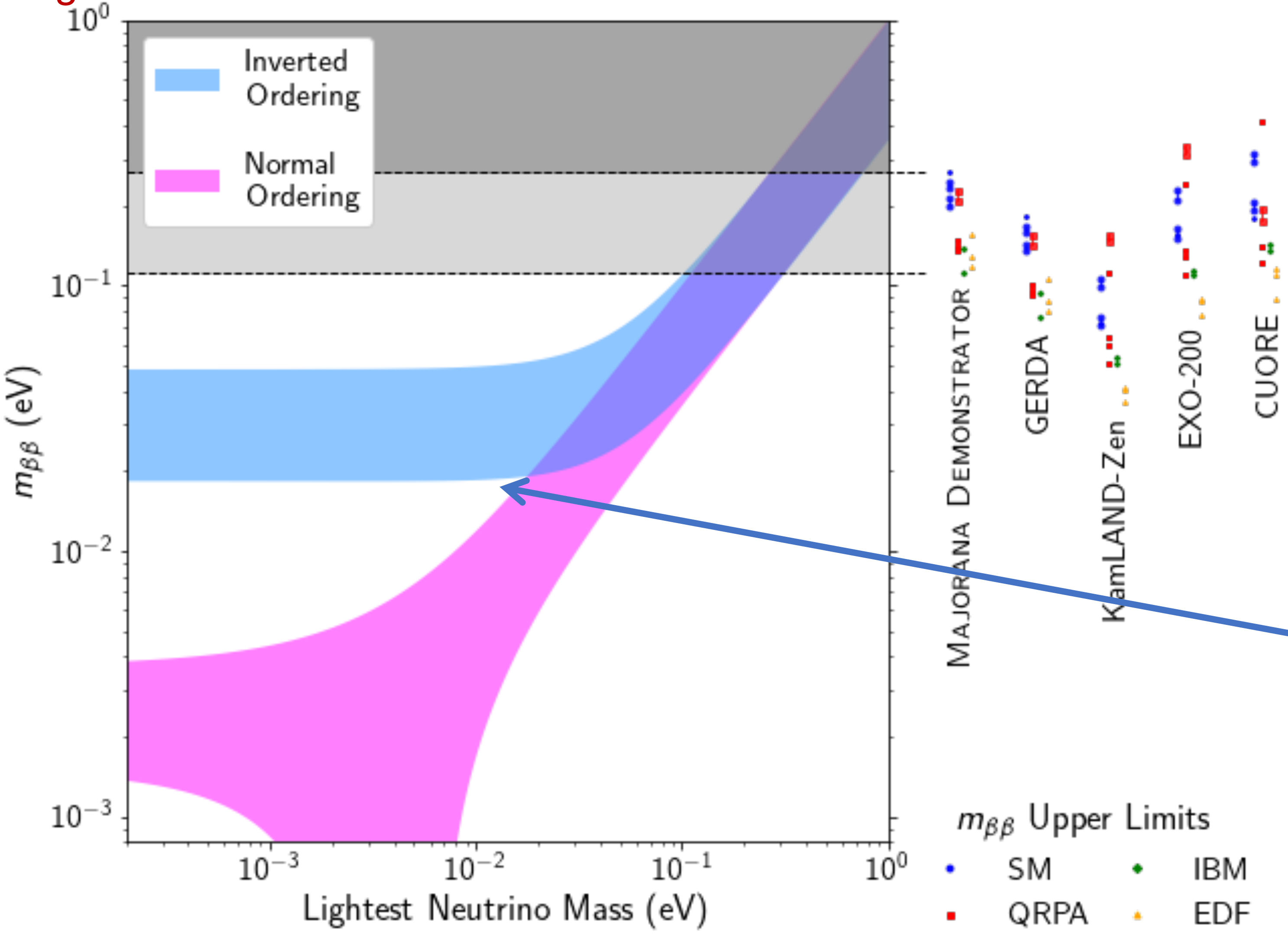
- Half life relates to the effective neutrino mass

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

- Theoretical calculations of the nuclear matrix element have significant uncertainties

Phase Space for Discovery

Log axes



A variety of isotopes and techniques in use for $0\nu\beta\beta$ searches, Ge, Xe, and more.

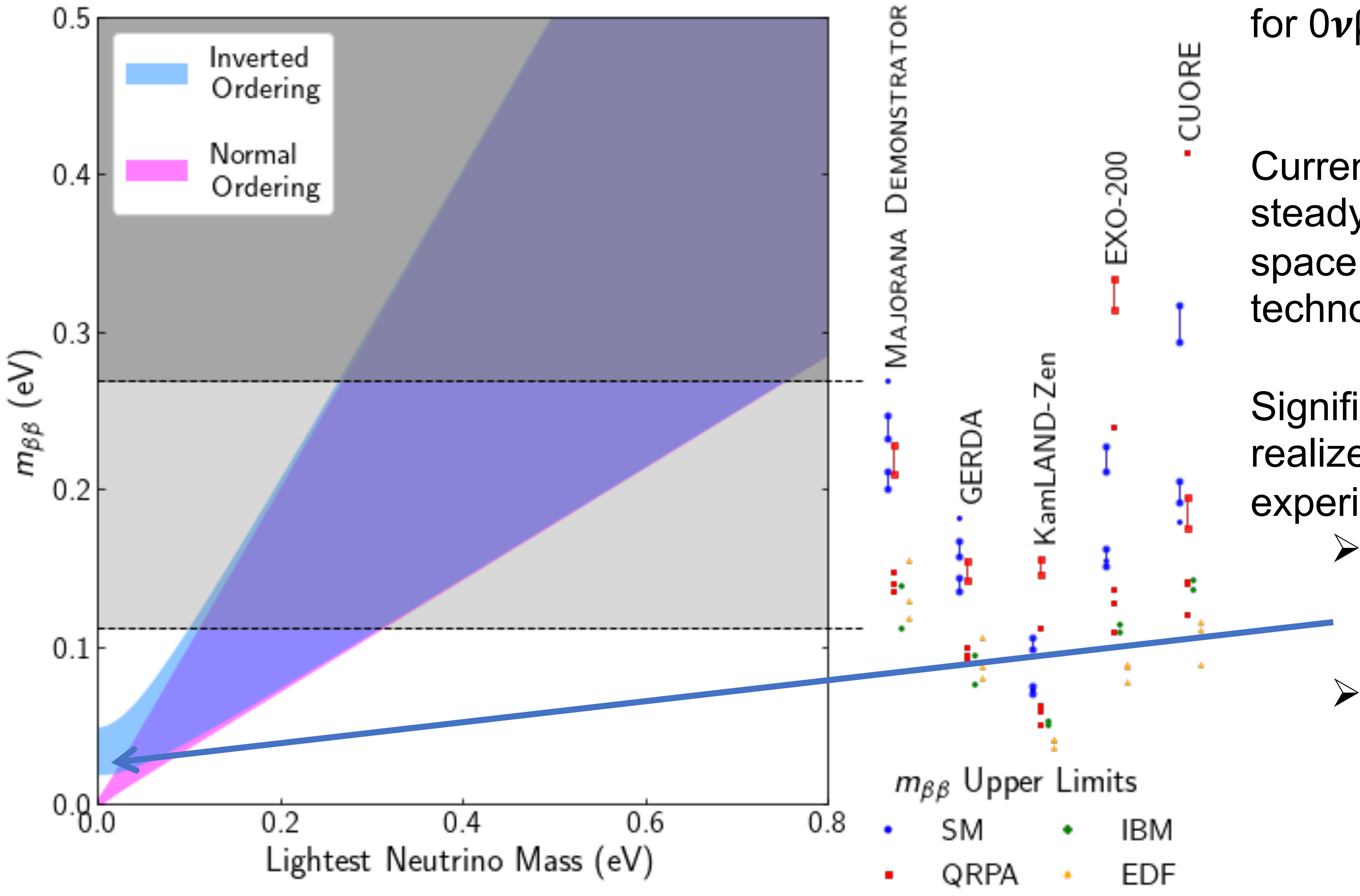
Current generation experiments make steady progresses in probing the phase space possible for $0\nu\beta\beta$ with constant technology developments

Significant discovery potential to be realized by next generation ton-scale experiments

- probing the entire inverted neutrino mass ordering assuming the light neutrino exchange model
- large discovery potential also in the normal mass ordering

Phase Space for Discovery

Linear axes



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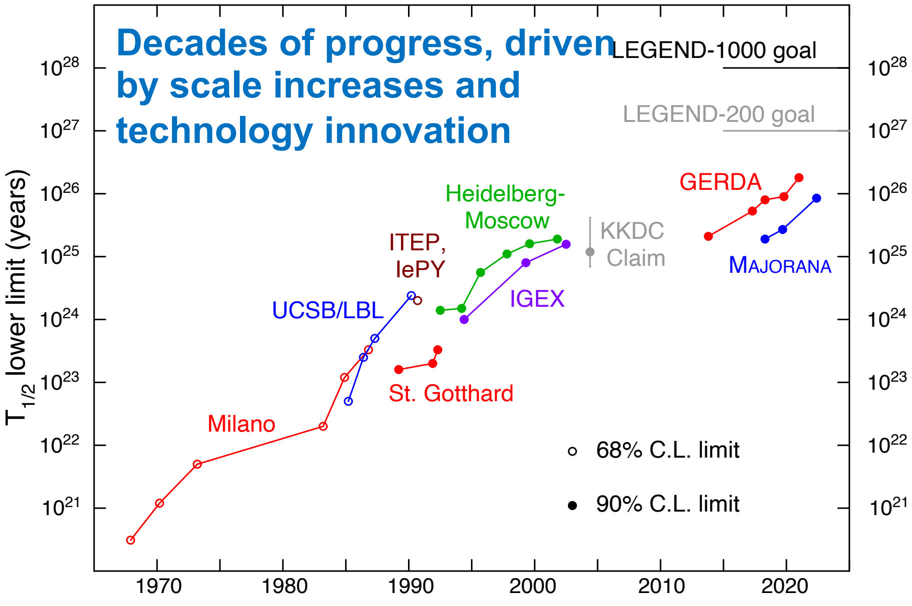
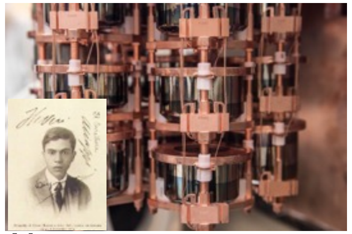
Part II
Proven Ge Technologies for the Discovery of Neutrinoless Double-Beta Decay

Generations of Ge searches of 0νββ

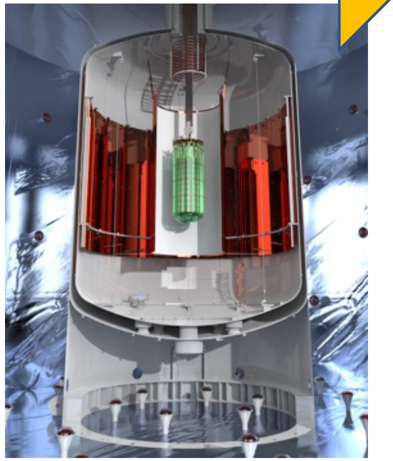


Most recent (~30-40 kg)



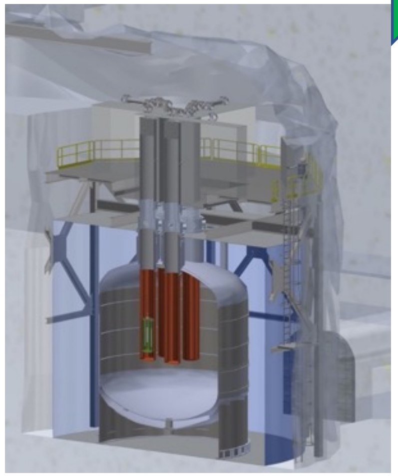
MAJORANA

Ongoing (~200 kg)



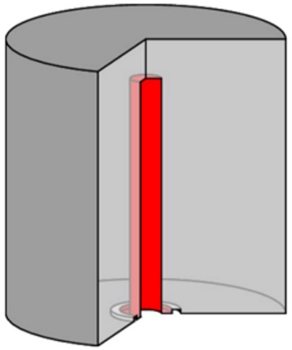
LEGEND-200

proceeding to CD-1 **(~1000kg)**



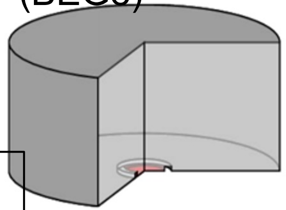
LEGEND-1000

(Semi)-Coaxial



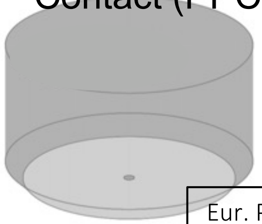
- Large mass (2-3 kg)
- Imperfect background rejection

GERDA Broad Energy Ge (BEGe)



IEEE Trans. on Nuc. Sci., 36, 1, 926-930 (1989)

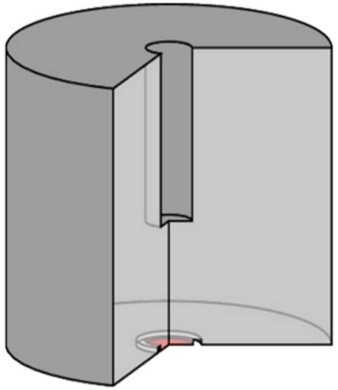
MAJORANA P-type Point Contact (PPC)



Eur. Phys. J. C 79, 978 (2019)

- Small mass (< 1 kg)
- Excellent background rejection

Inverted-Coaxial Point Contact (ICPC)



NIMA ,891, 106-110, (2018)

- Newly developed for LEGEND
- Large mass (up to 4 kg)
- Excellent background rejection

The MAJORANA DEMONSTRATOR

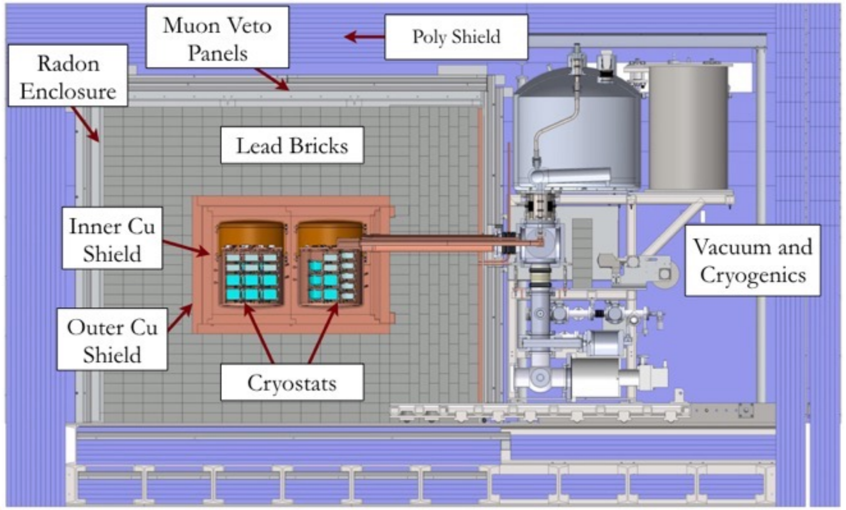
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

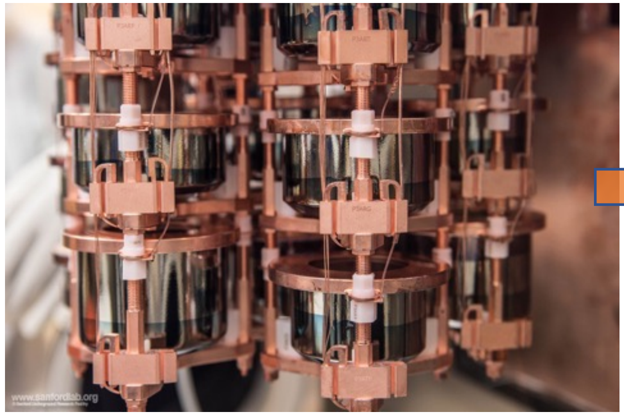
Source & Detector: Array of p-type, point contact detectors
30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run

Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV
and **Analysis Threshold:** 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS





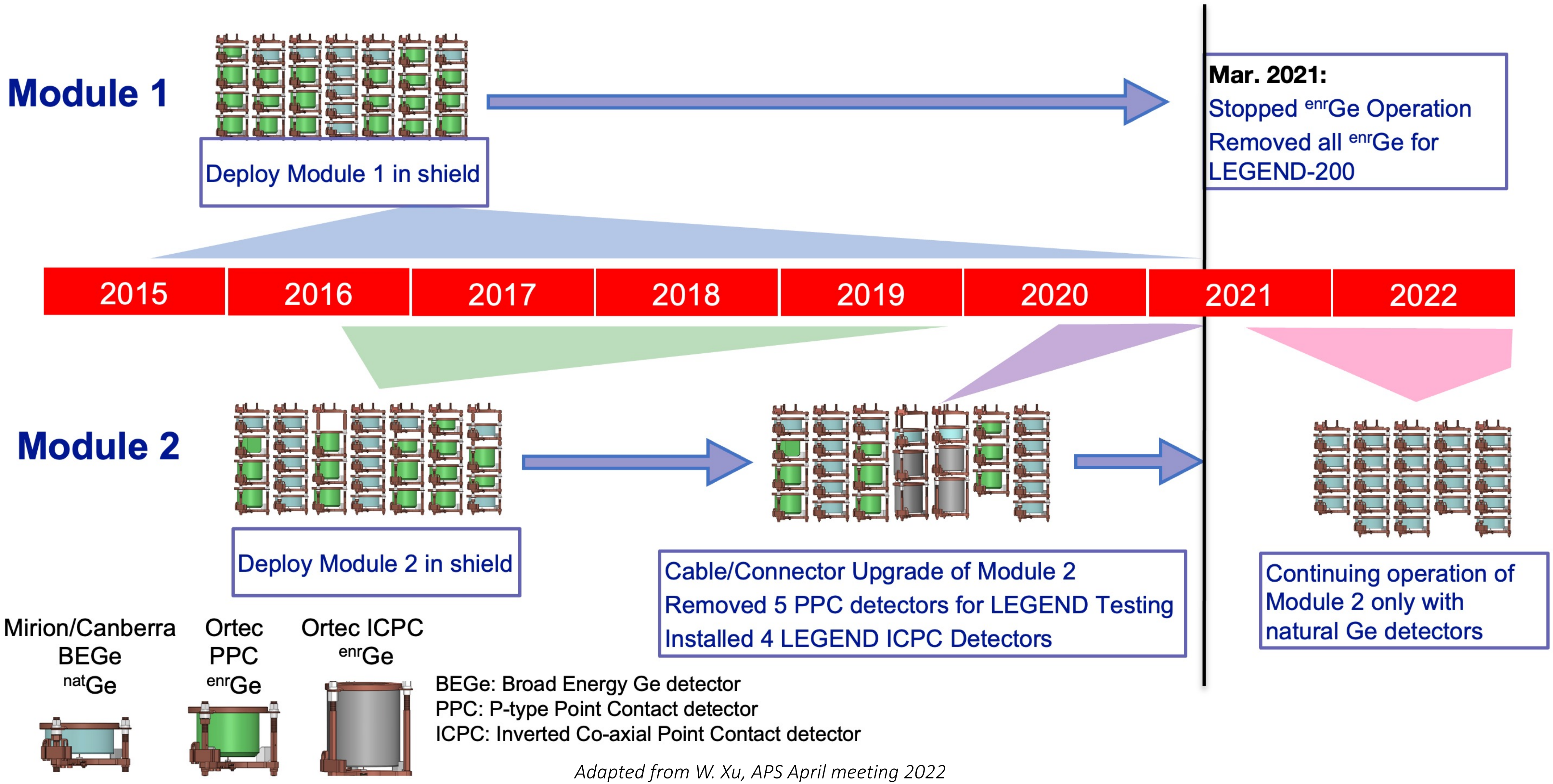
Best Energy resolution at the Q-value in 0νββ searches

Continuing to operate at the Sanford Underground Research Facility in Lead, SD with natural detectors for background studies and other physics

the MAJORANA *Collaboration*

Click here for a video of the experiment

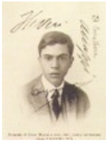
Majorana Run Configuration & Timeline



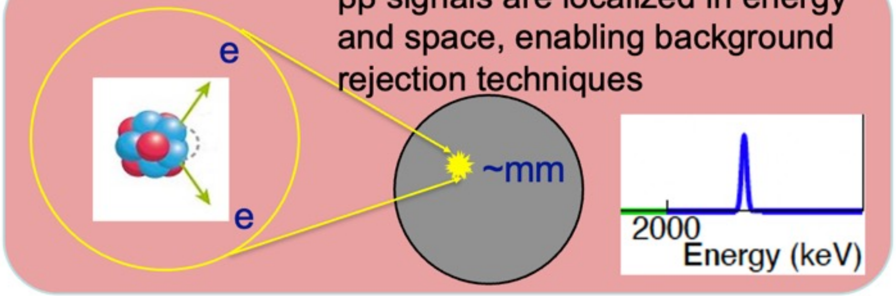
BEGe: Broad Energy Ge detector
PPC: P-type Point Contact detector
ICPC: Inverted Co-axial Point Contact detector

Adapted from W. Xu, APS April meeting 2022

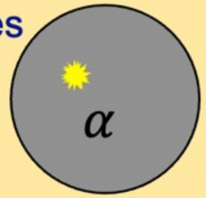
MAJORANA Background Reduction



ββ signals are localized in energy and space, enabling background rejection techniques

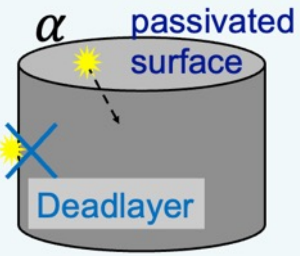


Internal alpha particle background:
- different energies
- never observed



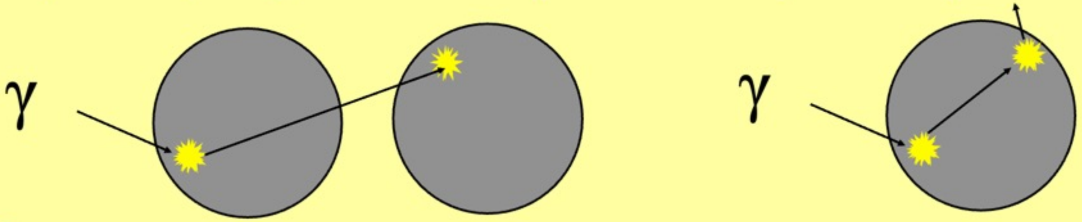
Cosmic ray backgrounds:
- reduced by being 4850’ underground
- rejected by high efficient muon veto

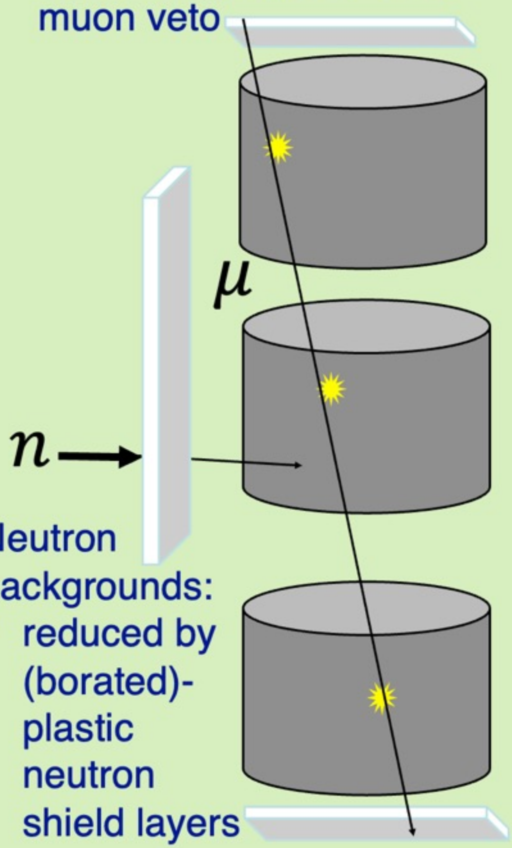
External alpha particle background:
- reduced by radio purity
- stopped by ~1mm dead layer everywhere except on the passivated surface
- rejected by pulse shape discrimination



Main backgrounds requiring analysis cuts

Photon background:
- reduced by radio purity + shielding + radon purge
- rejected by single detector requirement and pulse shape discrimination





Neutron backgrounds:
- reduced by (borated)-plastic neutron shield layers

Adapted from W. Xu, APS April meeting 2022

Pulse Shape Analysis (PSA) for HPGe detectors

Amplitude of current pulse is suppressed for a multi-site event compared to a single-site event of the same event **E**nergy

Comparing **A** against **E** effectively rejects multi-site backgrounds

Various powerful PSA event topology tools can be used to reject different backgrounds

Alternative machine learning algorithms are available

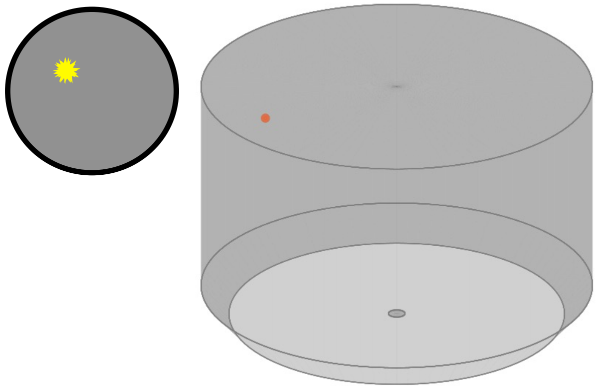
GERDA EPJC 82 (2022) 284

MAJORANA arXiv: 2207.10710

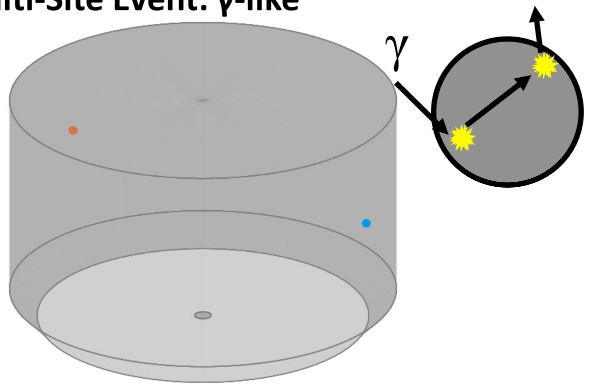
Laxman Paudel (USD PhD student)
***Pulse-Shape-Based Analysis using Machine learning in the MAJORANA DEMONSTRATOR*, CIPANP 08 2022**

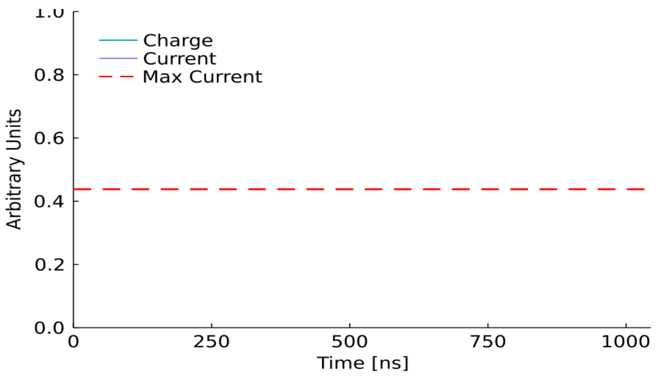
Simulations for MAJORANA PPC for illustration, courtesy of David Hervas.

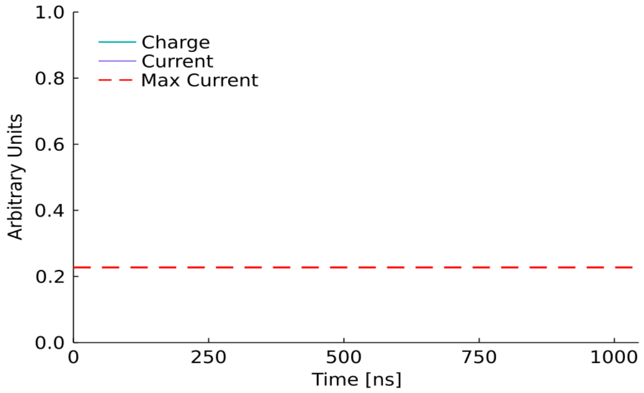
Single-Site Event (SSE):0νββ-like



Multi-Site Event: γ-like



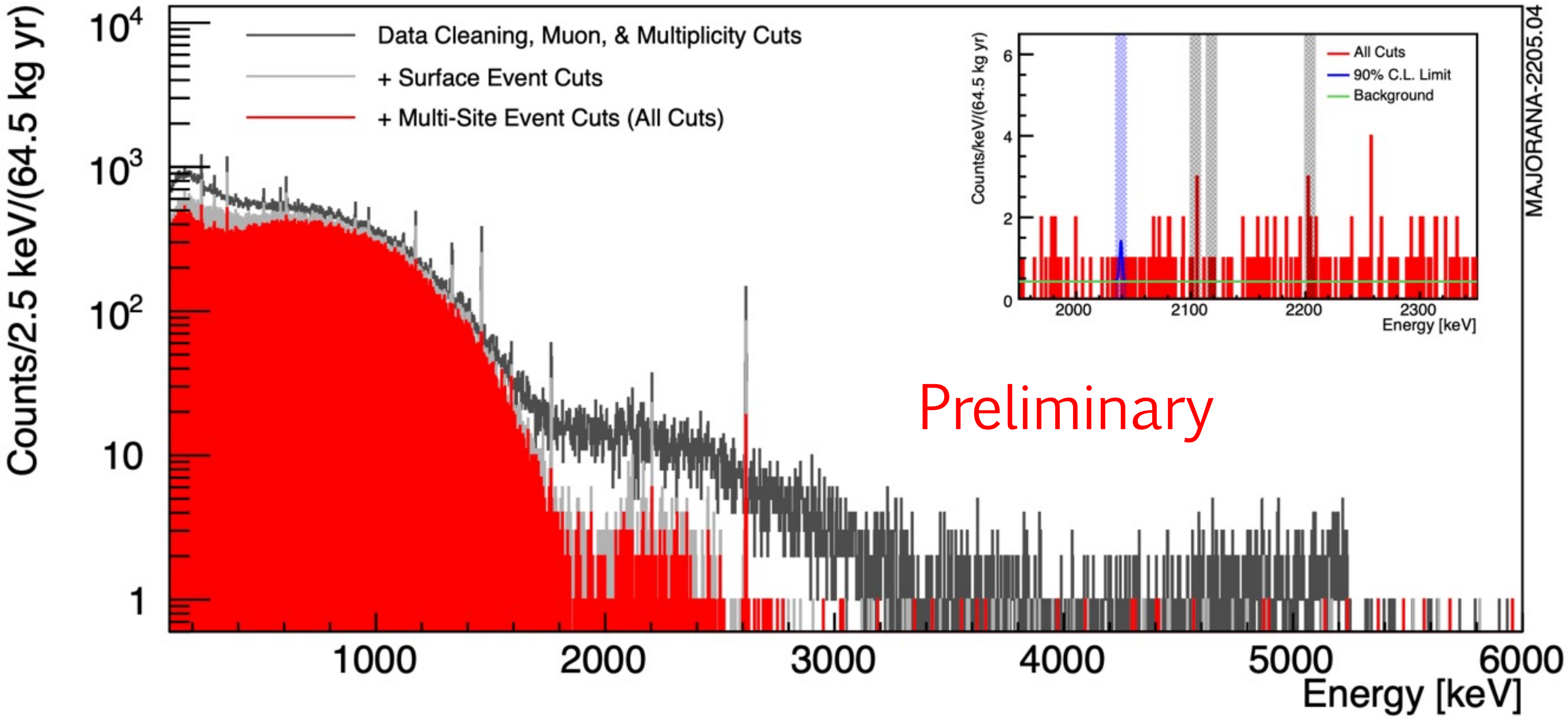




Final Results of MAJORANA DEMONSTRATOR

Operated in a low background regime, particularly with extreme radiopurity of near-detector parts, benefiting from excellent energy resolution

arXiv: 2207.07638



Full spectrum with a total of 65 kg-yr.

Final enriched detector active exposure:

64.5 ± 0.9 kg yrs

Background Index:

$(6.2 \pm 0.6) \times 10^{-3}$ cts/(keV kg yr)

Energy resolution:

2.5 keV FWHM @ $Q_{\beta\beta}$

Frequentist Limit:

Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.L.)

Bayesian Limit: (flat prior on rate)

Limit: $T_{1/2} > 7.0 \times 10^{25}$ yr (90% C.I.)

$m_{\beta\beta} < 113 - 269$ meV

Using $M_{0\nu} = 2.66 - 6.34$

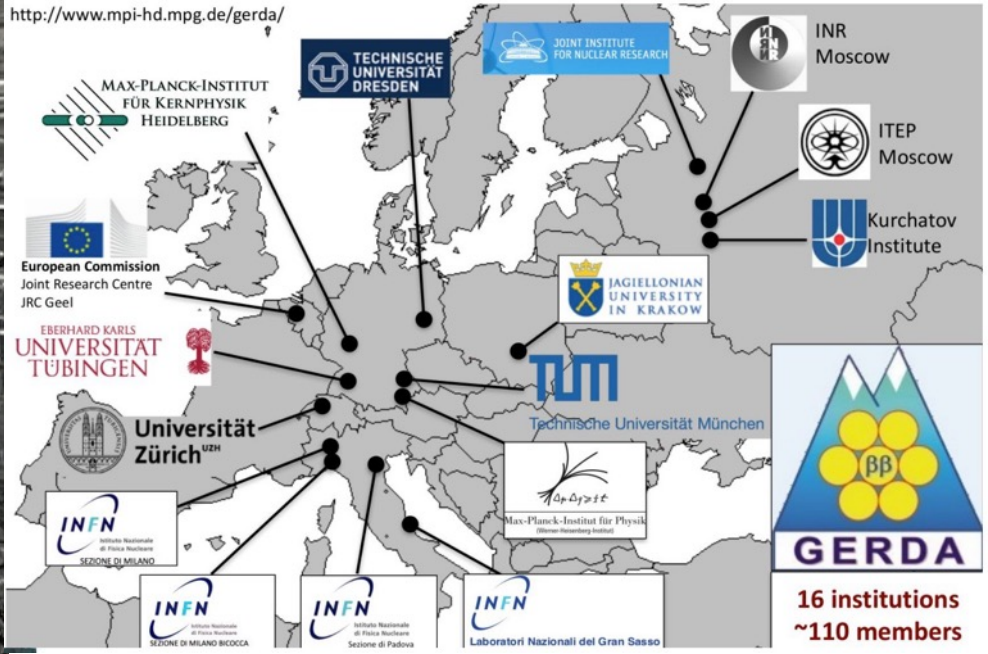
Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

GERmanium Detector Array - GERDA Collaboration

https://www.aip.org/fyi/2022/doe-nuclear-physics-program-approaches-pivot-point

the GERDA *Collaboration*

(Image credit – © Kai Freund / LNGS-INFN)

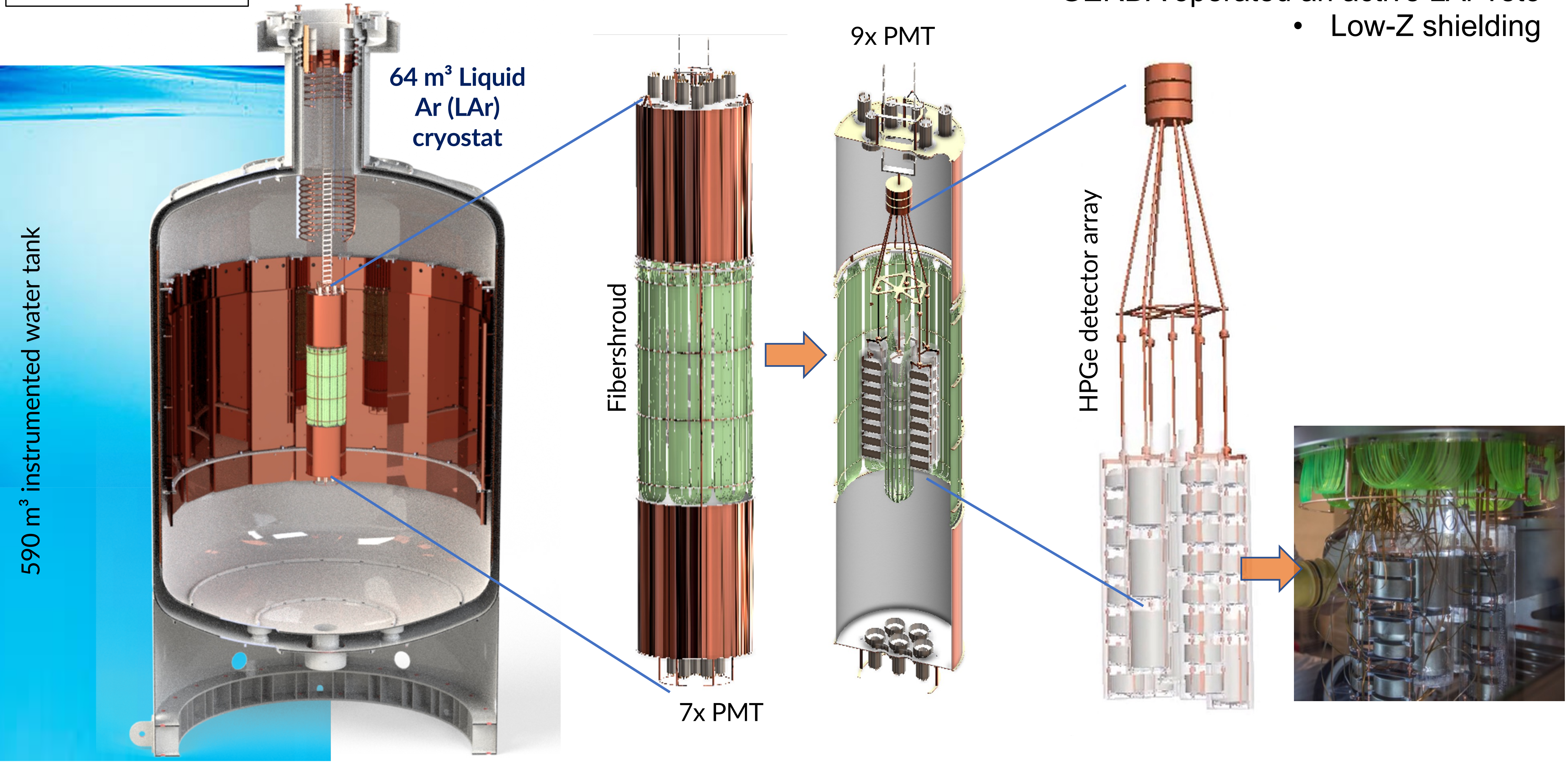


L Shtembari, ICHEP 2022

GERDA at Gran Sasso National Laboratory (LNGS) in Italy

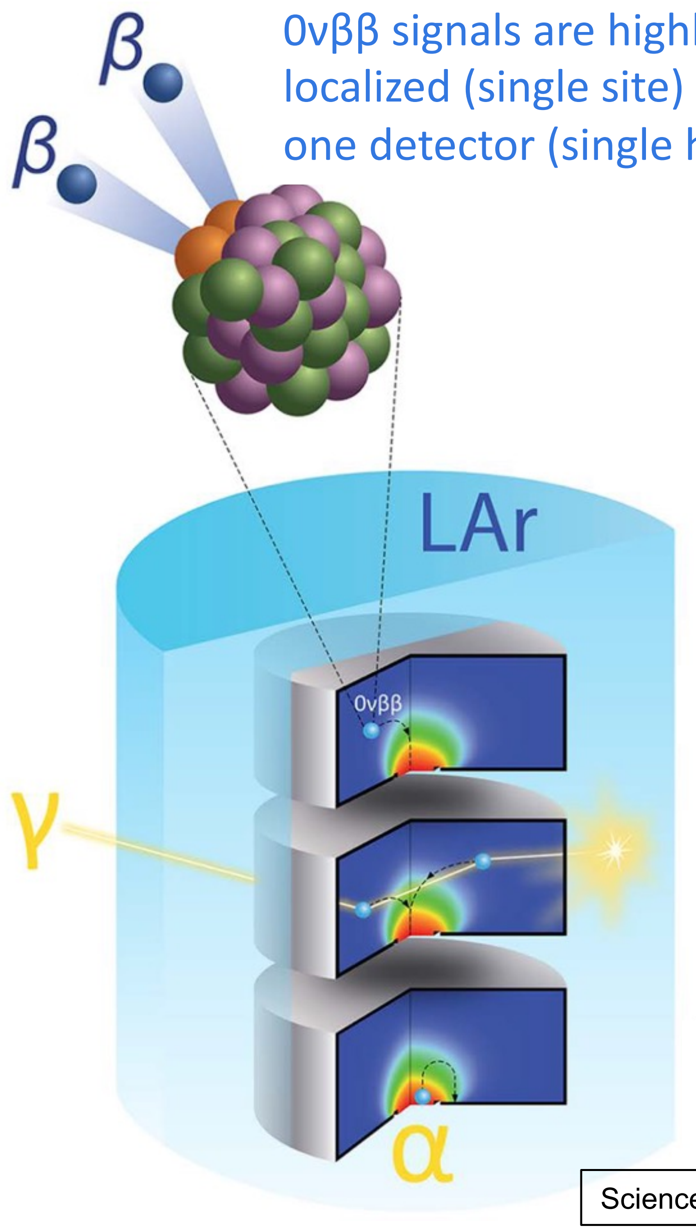
EPJC 78, 388 (2018)

- GERDA operated an active LAr veto
  - Low-Z shielding



GERDA Background Rejection Strategy

0νββ signals are highly localized (single site) in one detector (single hit)



0νββ signals

Multi-site backgrounds

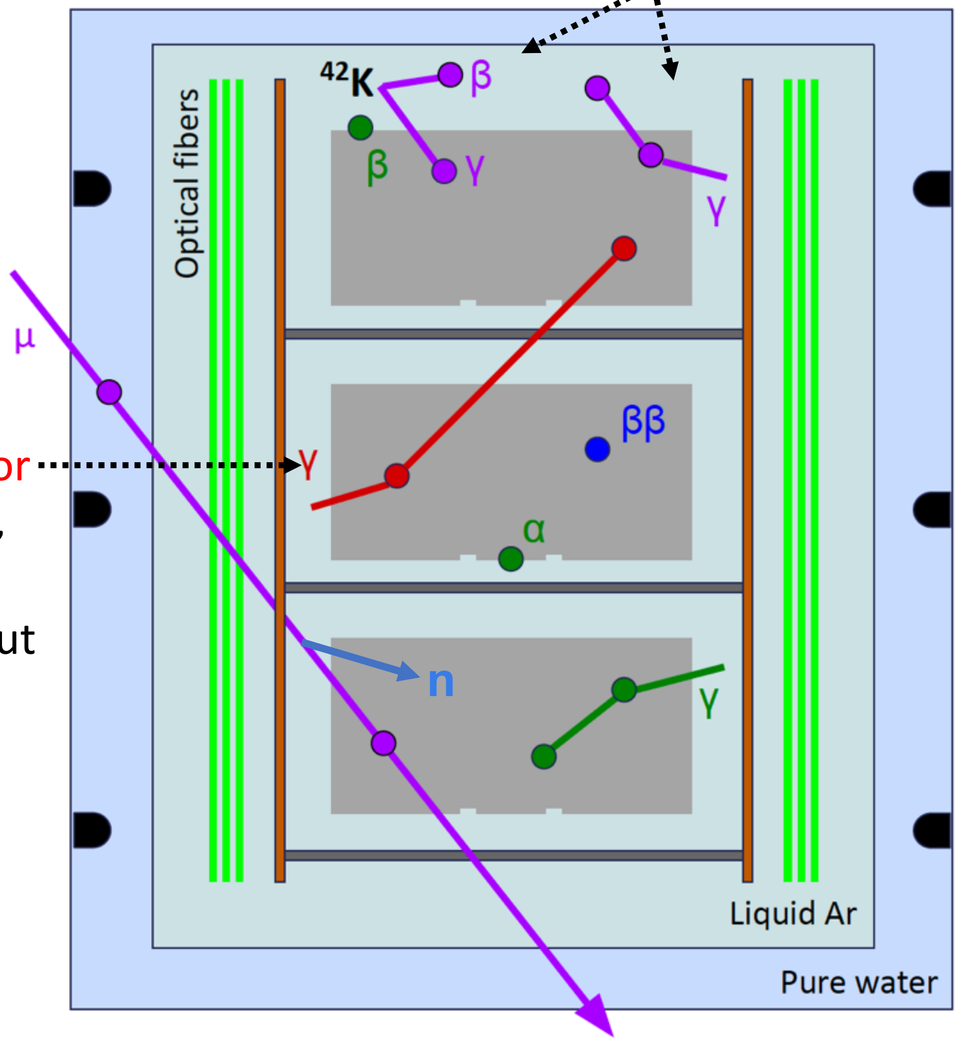
Surface backgrounds

Rejected by Pulse Shape Analysis

Science 365 (2019) 1445-1448

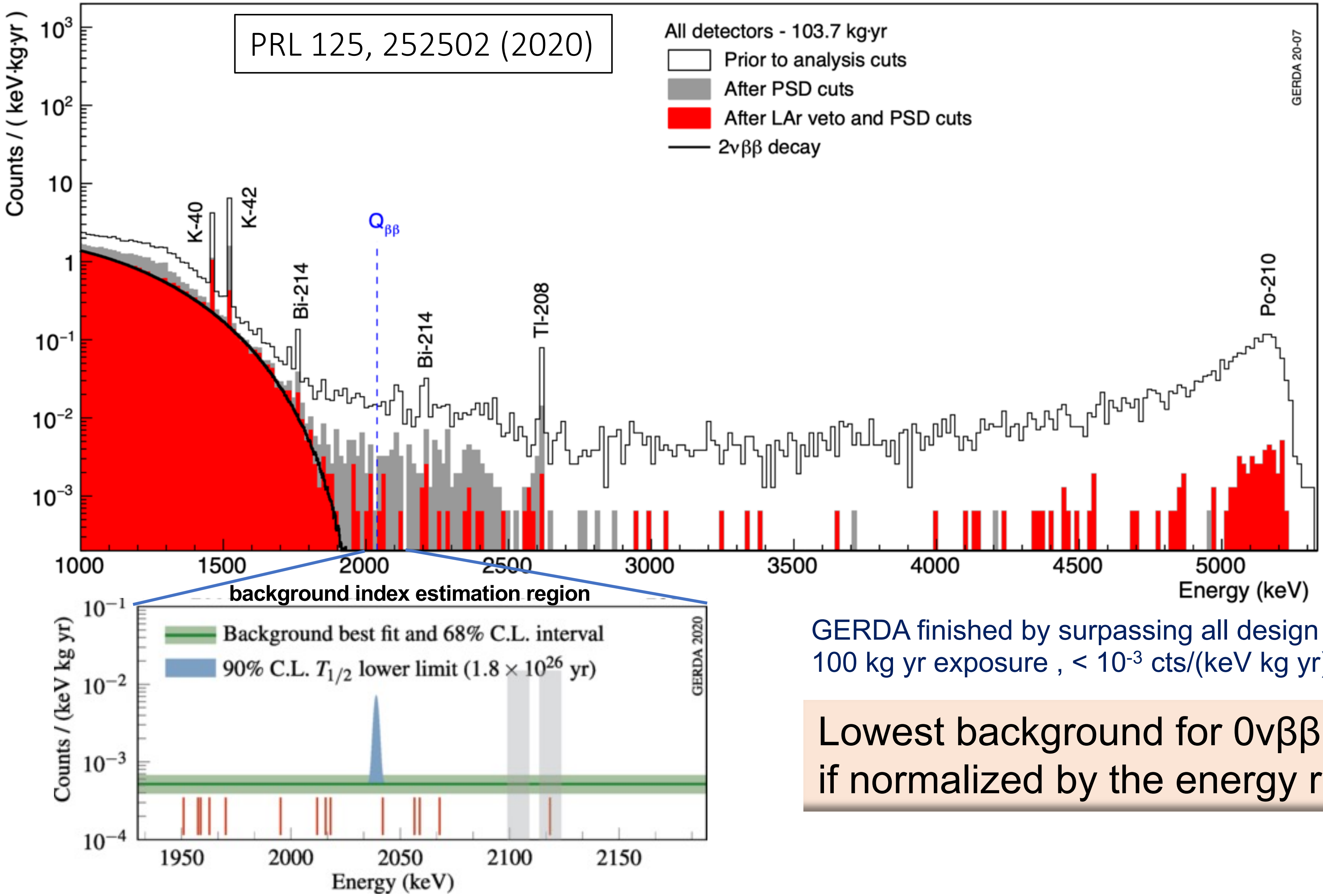
Backgrounds with energy depositions in LAr, rejected by LAr veto

Multi-detector backgrounds, rejected by multiplicity cut



muon backgrounds, rejected by muon veto, except neutron-induced delayed ones

Final Results of GERDA



Background index:

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

Energy resolution:

~2.6 keV (FWHM)

Frequentist limit:

$T_{1/2} > 1.8 \cdot 10^{26}$ yr at 90% C.L.

Bayesian: flat prior on rate:

$T_{1/2} > 1.4 \cdot 10^{26}$ yr at 90% C.I.

$m_{\beta\beta}$ < 79 - 180 meV

GERDA finished by surpassing all design goals:
100 kg yr exposure , < 10^{-3} cts/(keV kg yr) background, >10^{26} yr sensitivity

Lowest background for 0νββ searches if normalized by the energy resolution

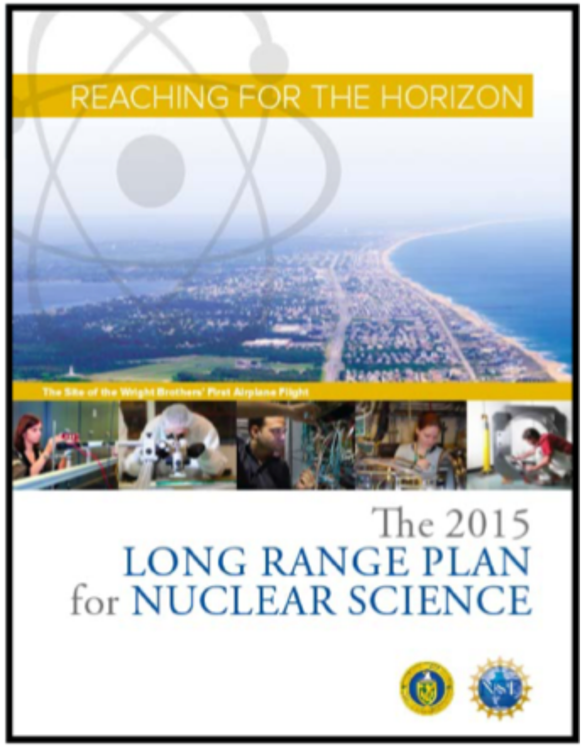
Part III
LEGEND for the Discovery of Neutrinoless Double-Beta Decay

Large Enriched Germanium Experiment for Neutrinoless ββ Decay
(LEGEND)

The European and North-American Process

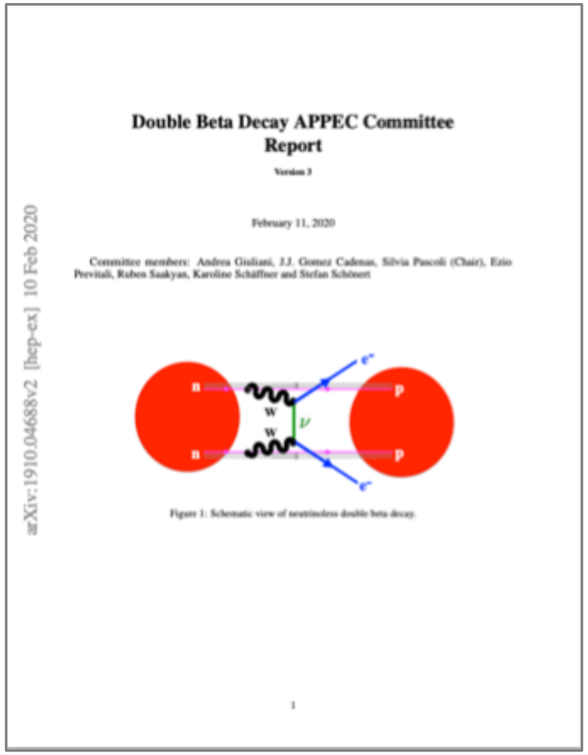
Compiled by S. Schönert @ Neutrino 2022

https://science.osti.gov/np/nsac



"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

https://arxiv.org/abs/1910.04688


Double Beta Decay APPEC Committee Report

Version 3

February 11, 2020

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

Figure 1: Schematic view of neutrinoless double beta decay.

arXiv:1910.04688v2 [hep-ex] 10 Feb 2020

- Oct 2019: Roadmap document for the APPEC SAC on the future $0\nu\beta\beta$ decay experimental programme in Europe
- $0\nu\beta\beta$ town meeting London
- Roadmap update 2022, town meeting in Berlin, June 2022

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO

- Outcome: Realize international portfolio LEGEND-1000, nEXO and CUPID with European partners
- LEGEND-1000 was evaluated extremely positively at the Portfolio review. Now being funded by DOE to move to the next step, CD-1

https://agenda.infn.it/event/27143/

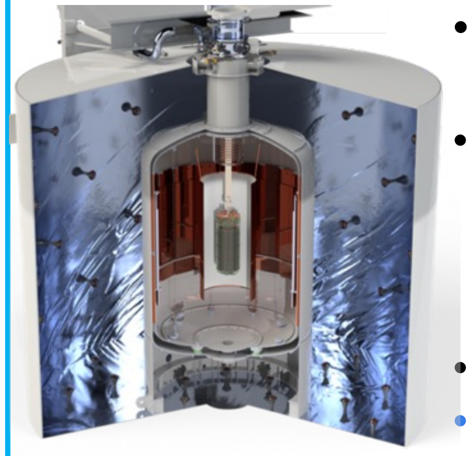
"The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade, with one ton scale experiment in Europe and the other in North America. "

Wenqin Xu| 11/29/22

LEGEND

Mission: “The collaboration aims to develop a phased, **Ge-76 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**.”

Build upon best and proven technologies from GERDA and the MAJORANA DEMONSTRATOR

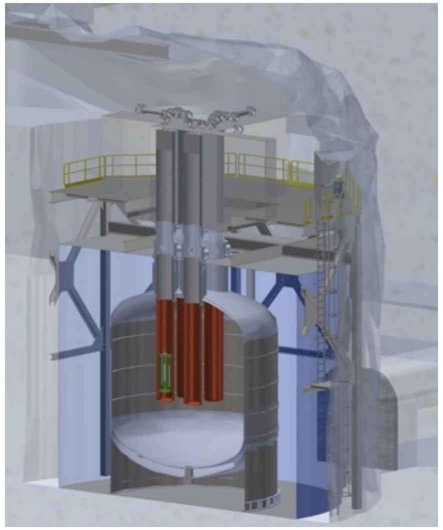


LEGEND-200

- 200 kg in upgrade of existing infrastructure at LNGS
- Background goal:

  < 0.6 cts/(FWHM t yr)

  i.e. < 2×10^{-4} cts/(keV kg yr)
- Discovery sensitivity 10^{27} years
- Currently commissioning
- Physics data starting in 2022



LEGEND-1000

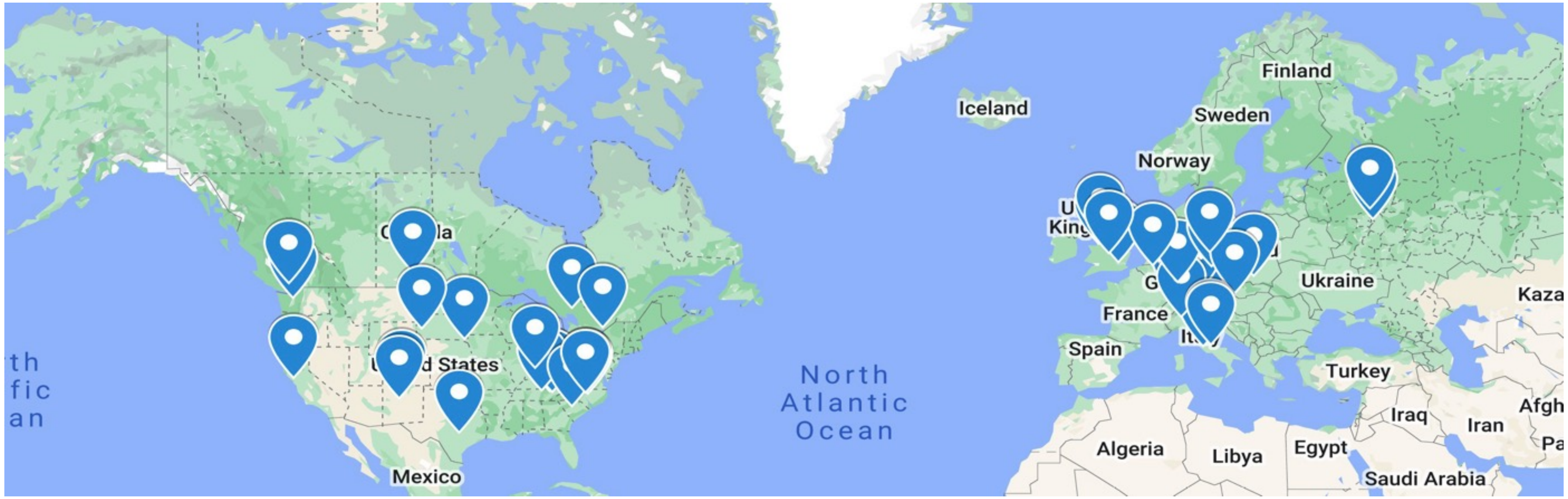
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal:

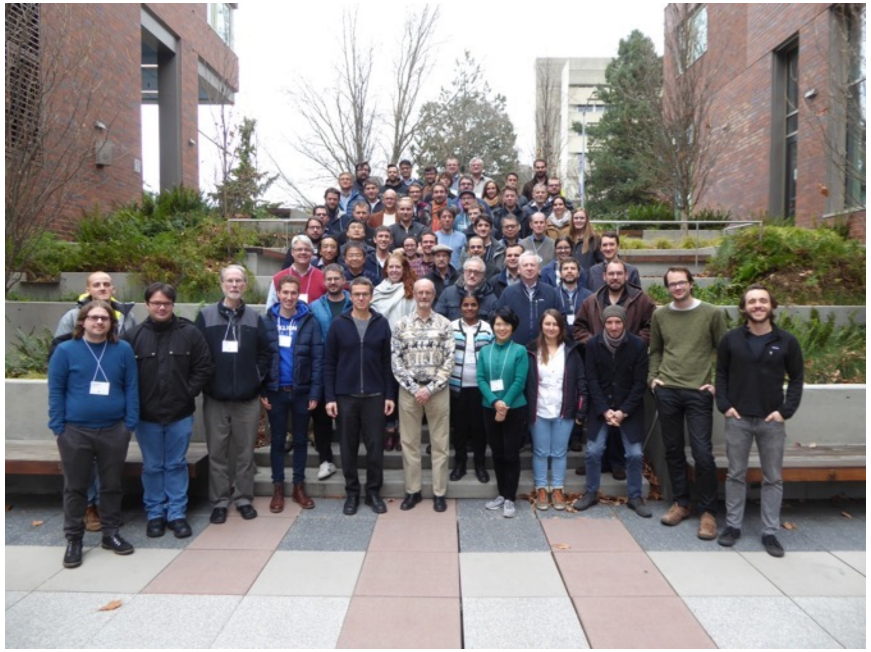
  <0.025 cts/(FWHM t yr)

  i.e. <1×10^{-5} cts/(keV kg yr)
- Discovery sensitivity beyond 10^{28} years
- Location to be selected

Preconceptual Design Report arXiv: 2107.11462

The LEGEND Collaboration



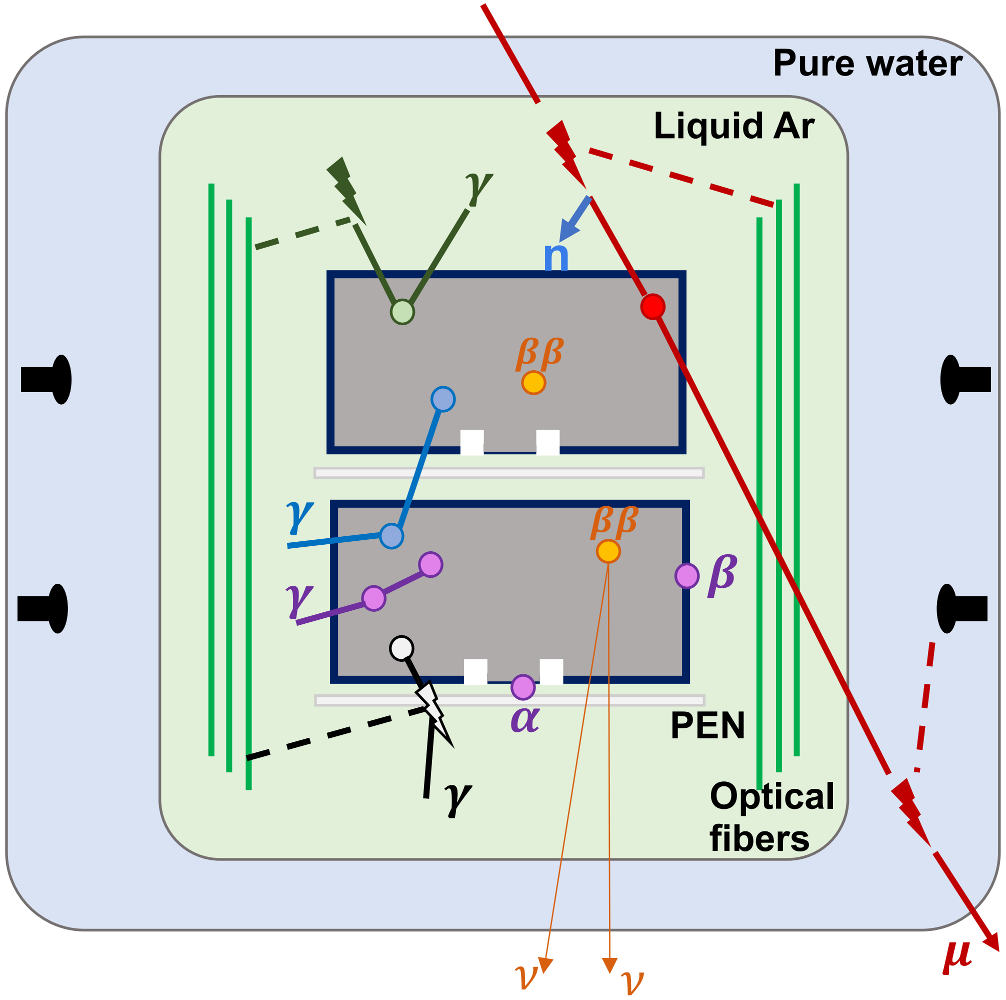


Approximately
250 members,
49 institutions,
11 countries
https://legend-exp.org/

LEGEND Background Rejection

$\beta\beta$ decay signal: single energy deposition in a 1 mm³ volume

Ge detector with PEN plate holders



Pulse shape discrimination (PSD) for multi-site and surface α events

Ge detector anti-coincidence

Scintillating PEN plate holder under test

LAr veto based on Ar scintillation light read by fibers and SiPM

Muon veto

LEGEND-200
background goal is x2.5 reduction from GERDA

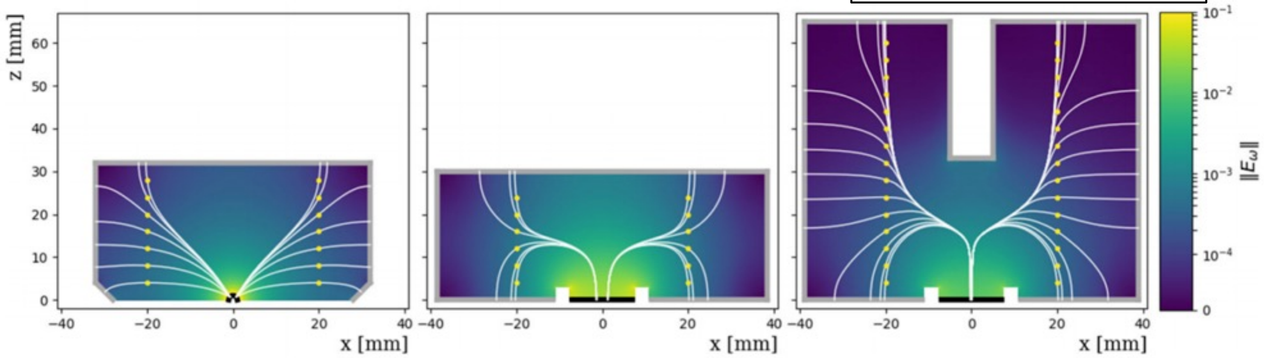
uses small and large detectors

LEGEND-1000
background goal is x20 reduction from LEGEND-200

uses only large detectors

Background Reduction: LEGEND-1000

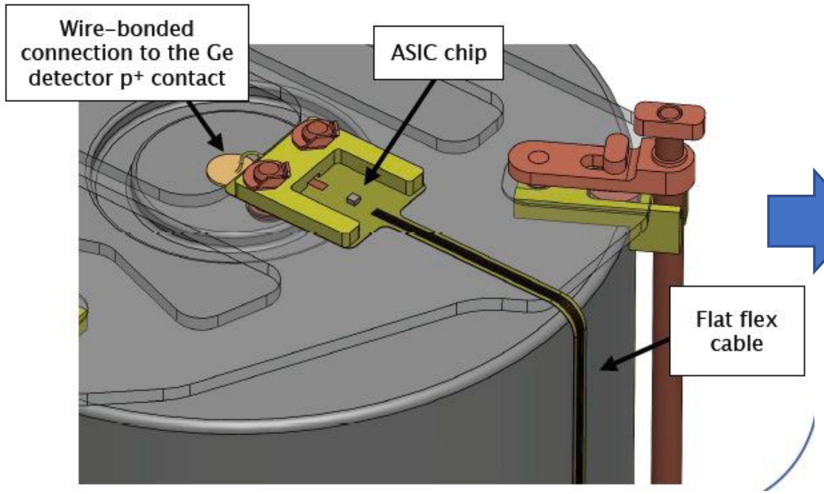
Eur. Phys. J. C 81, 76 (2021)



MAJORANA PPC — GERDA BEGe

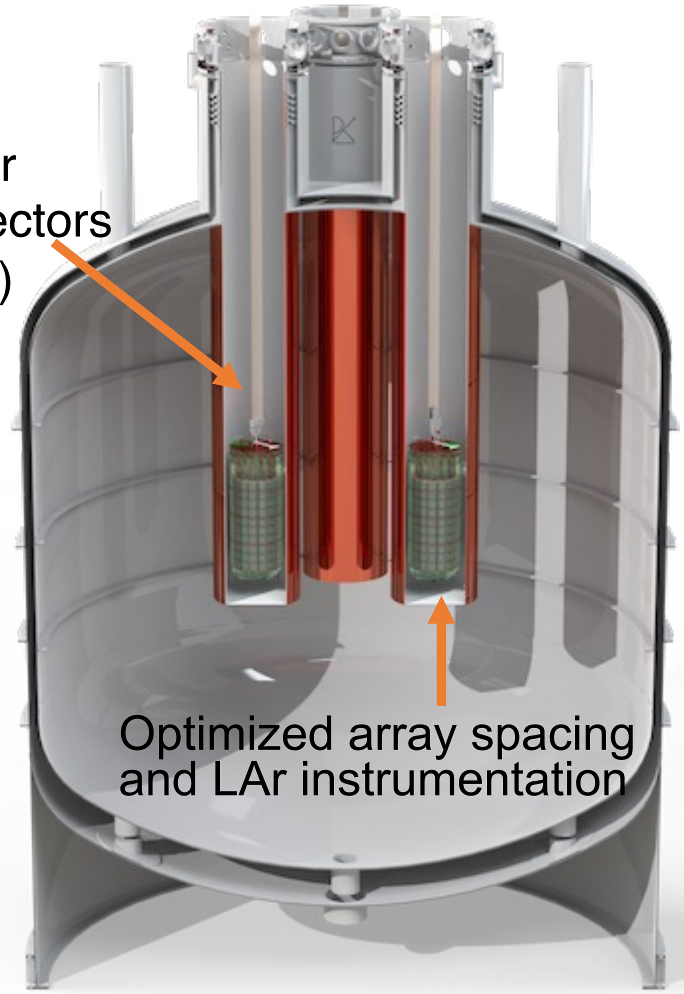
Used by LEGEND-200 as well

LEGEND-1000 uses only larger ICPC detectors, average 2.6 kg



Significant reduction of number of channels and hence total radioactivity to near-detector materials

New and less-radioactive cables and new application-specific integrated circuit (ASIC) read-out for LEGEND-1000



Underground LAr surrounding detectors (low in Ar-42, 39)

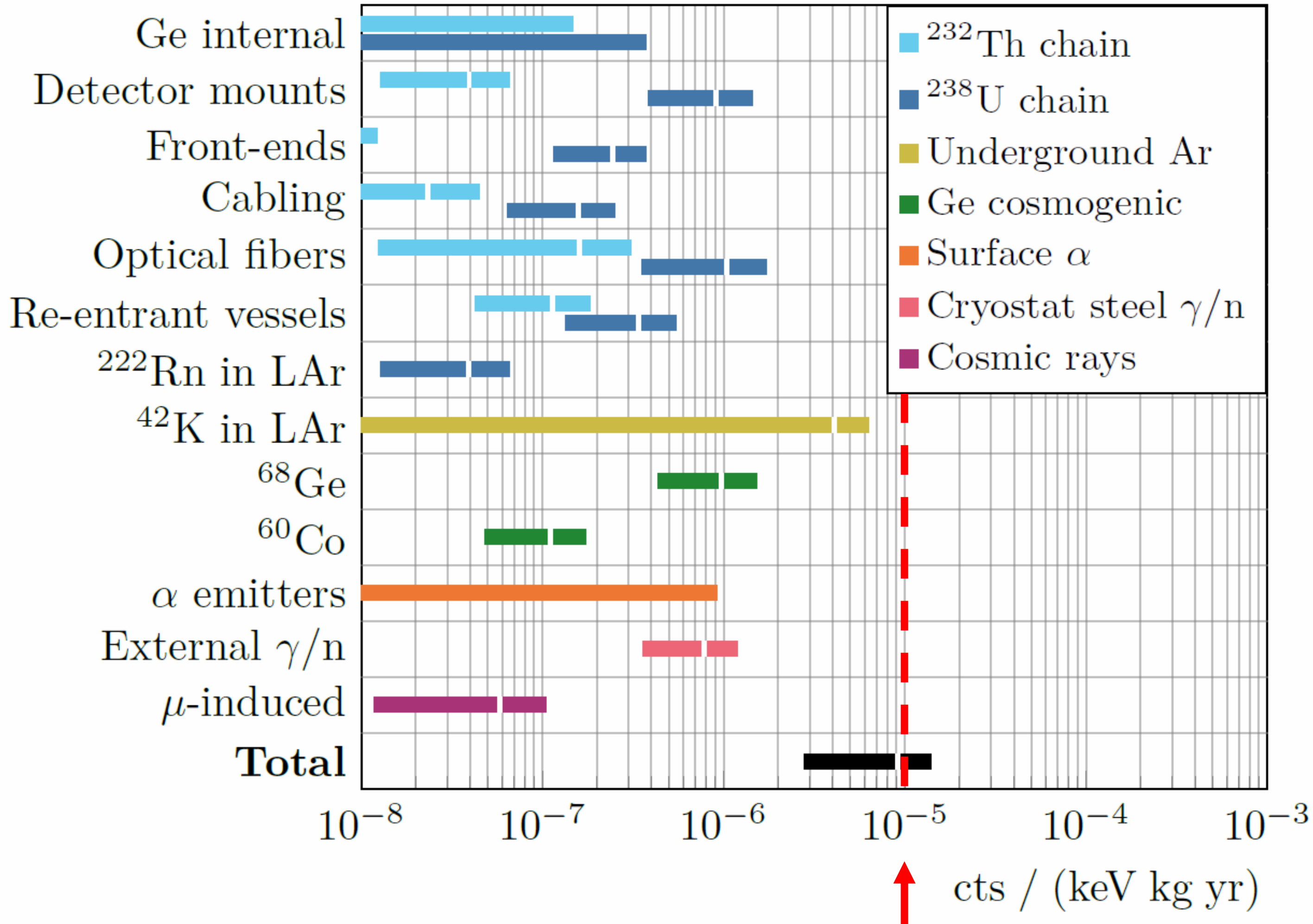
Optimized array spacing and LAr instrumentation

Deeper underground site or additional neutron shielding & tagging: SNOLAB and LNGS options

LEGEND-1000 Background Projections

LEGEND

Background index at $Q_{\beta\beta}$ after all cuts



LEGEND-1000 background goal

Projected background index after all cuts:

$$9.1^{+4.9}_{-6.3} \times 10^{-6} \text{ counts/(keV kg yr)}$$

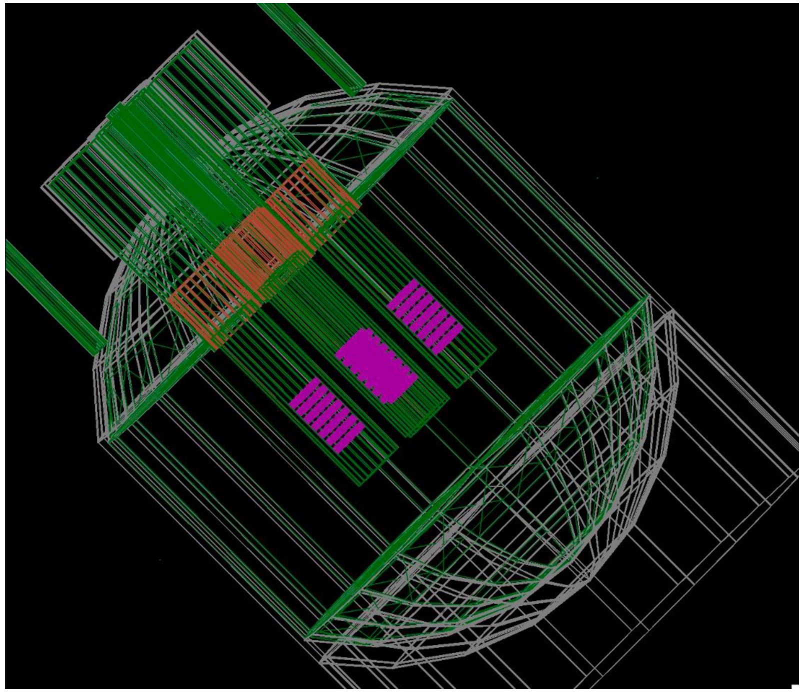
SNOLAB was used as the reference lab here

LNGS has ~x100 higher muon flux

pCDR: arXiv: 2107.11462

Wenqin Xu| 11/29/22

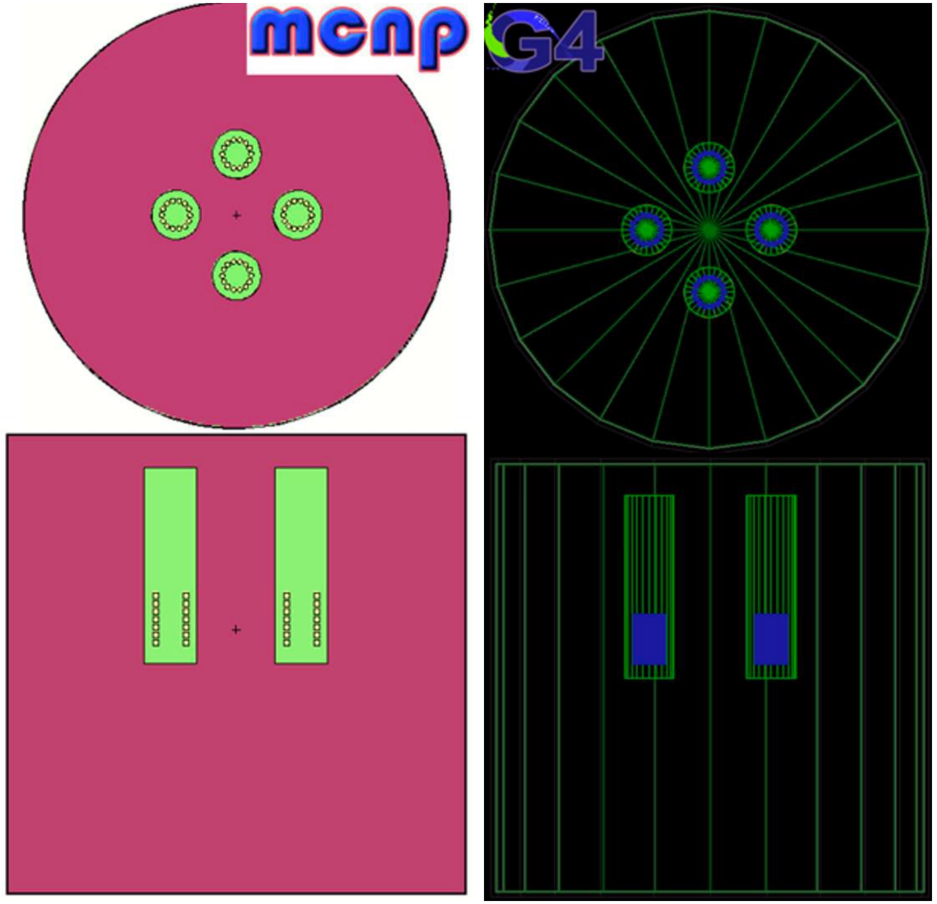
Extensive Muon Studies for Shallower LNGS



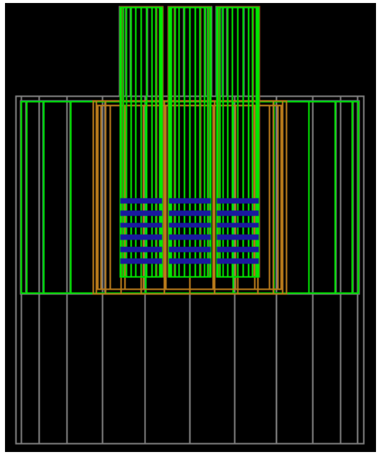
Standalone Geant4 simulation completely written from scratch for main estimation

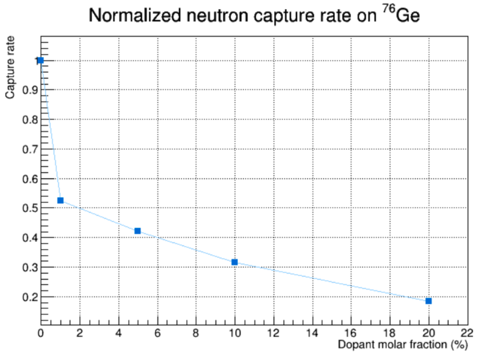
CJ Barton (USD PhD student)
An update on muon-induced backgrounds in LEGEND-1000
CIPANP 08 2022

Extensive study on muon-induced bkgs and additional neutron shielding for LNGS option.



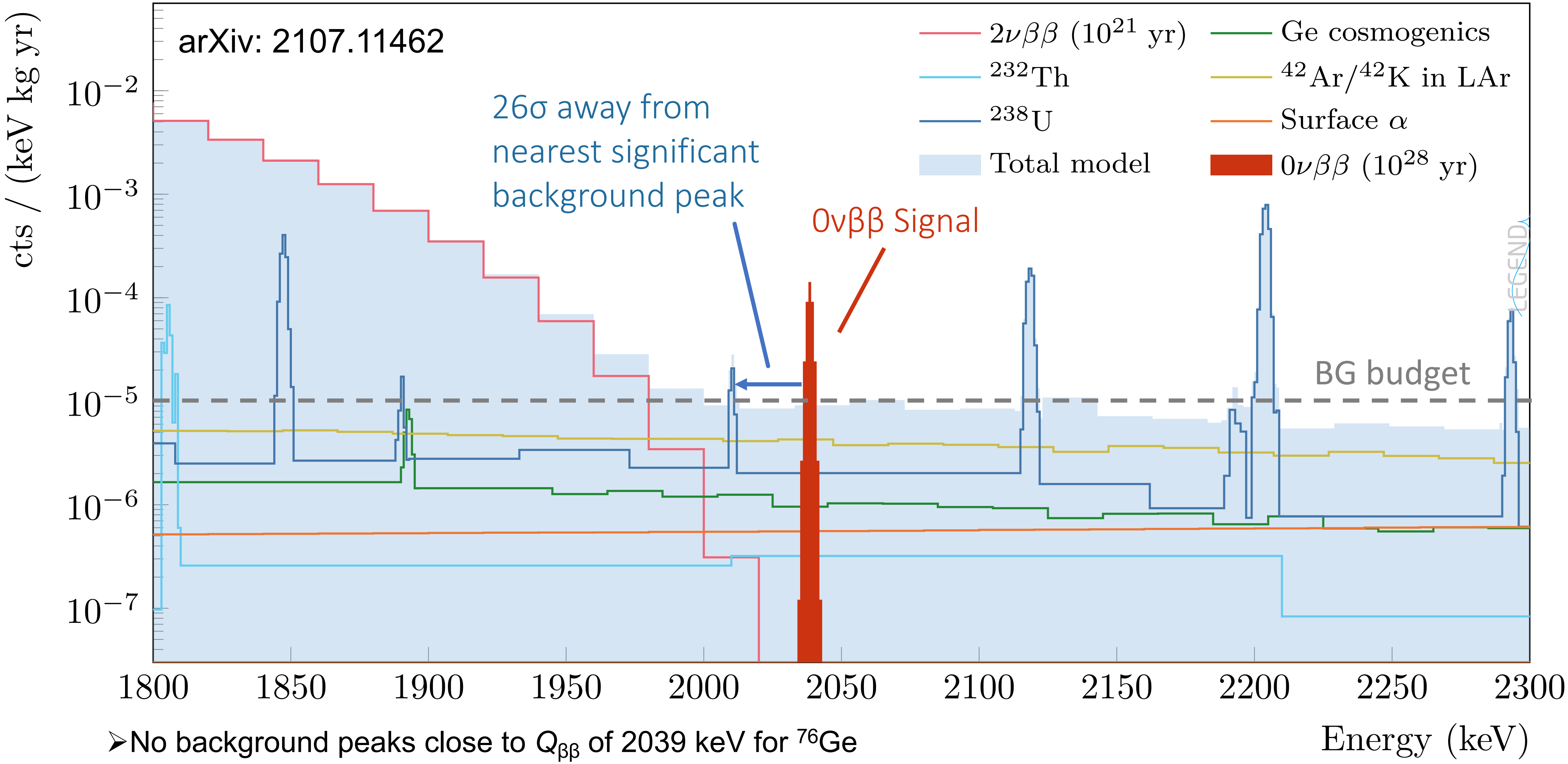
MCNP-Geant4 simulation comparisons across different software for uncertainty assessment





Additional neutron moderation using solid plastic shield and liquid methane-doping in LAr

The LEGEND-1000 Background Model



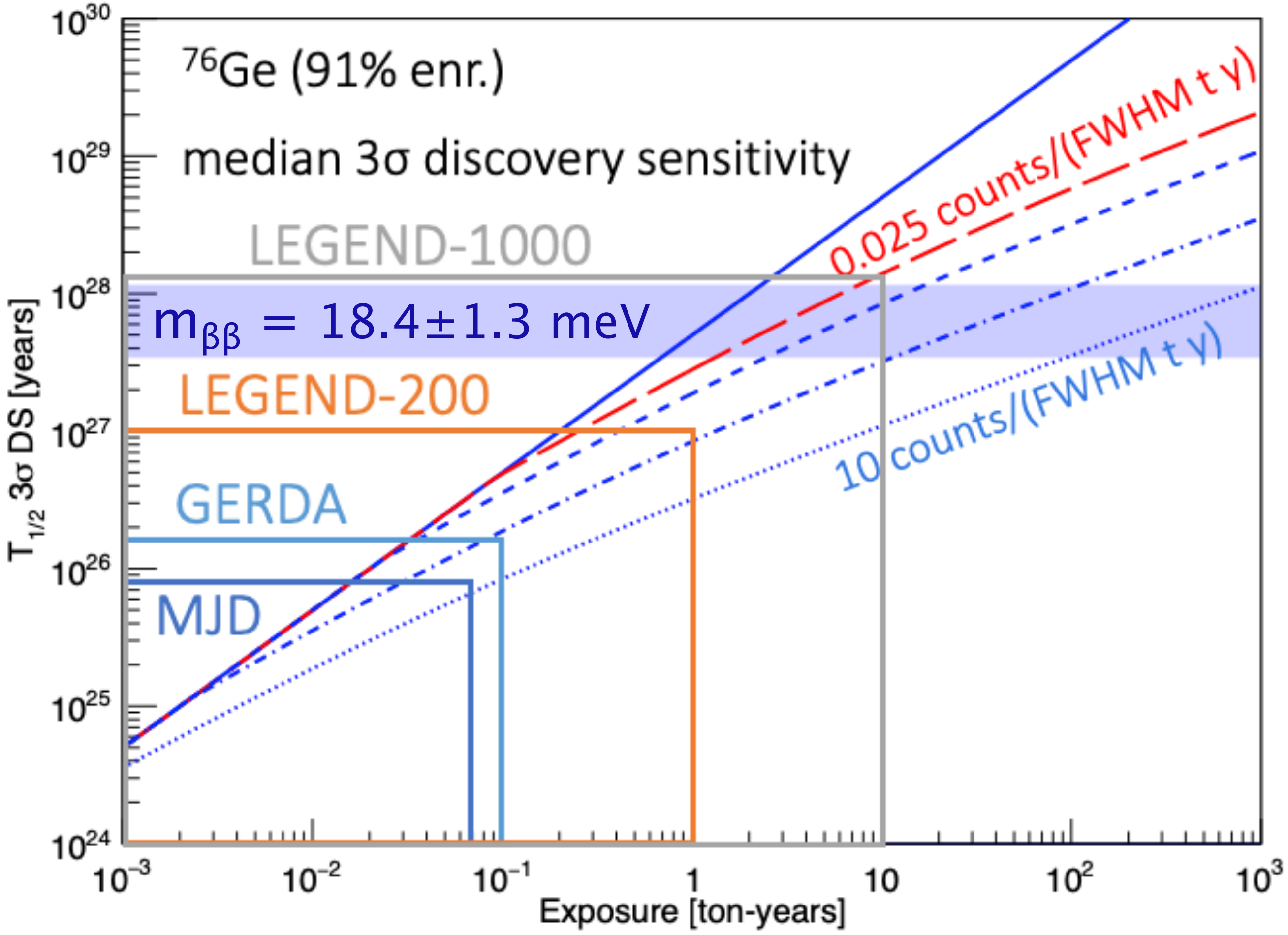
- ➢No background peaks close to $Q_{\beta\beta}$ of 2039 keV for ^{76}Ge
- ➢Background is flat and well understood. No reliance on background modeling
- ➢No 2νββ background

Wenqin Xu| 11/29/22

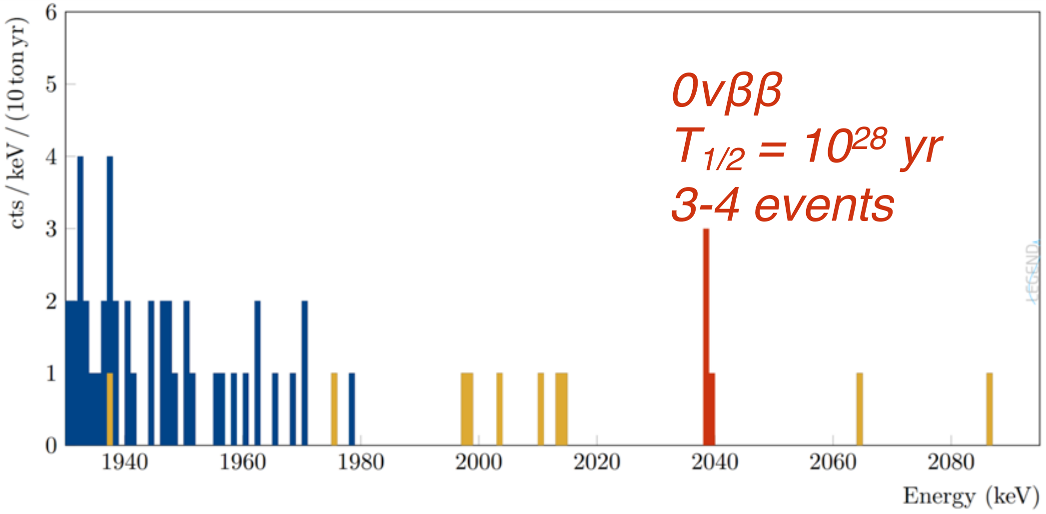
Discovering Sensitivity Enabled

The LEGEND program builds on successes of current generation experiments to probe half-lives beyond 10^{28} yrs

– Unambiguous discovery enabled by best energy resolution and lowest background



Simulated LEGEND-1000 example spectrum for $T_{1/2} = 10^{28}$ yrs, BI < 10^{-5} cts/keV kg yr, after cuts, from 10 years of data



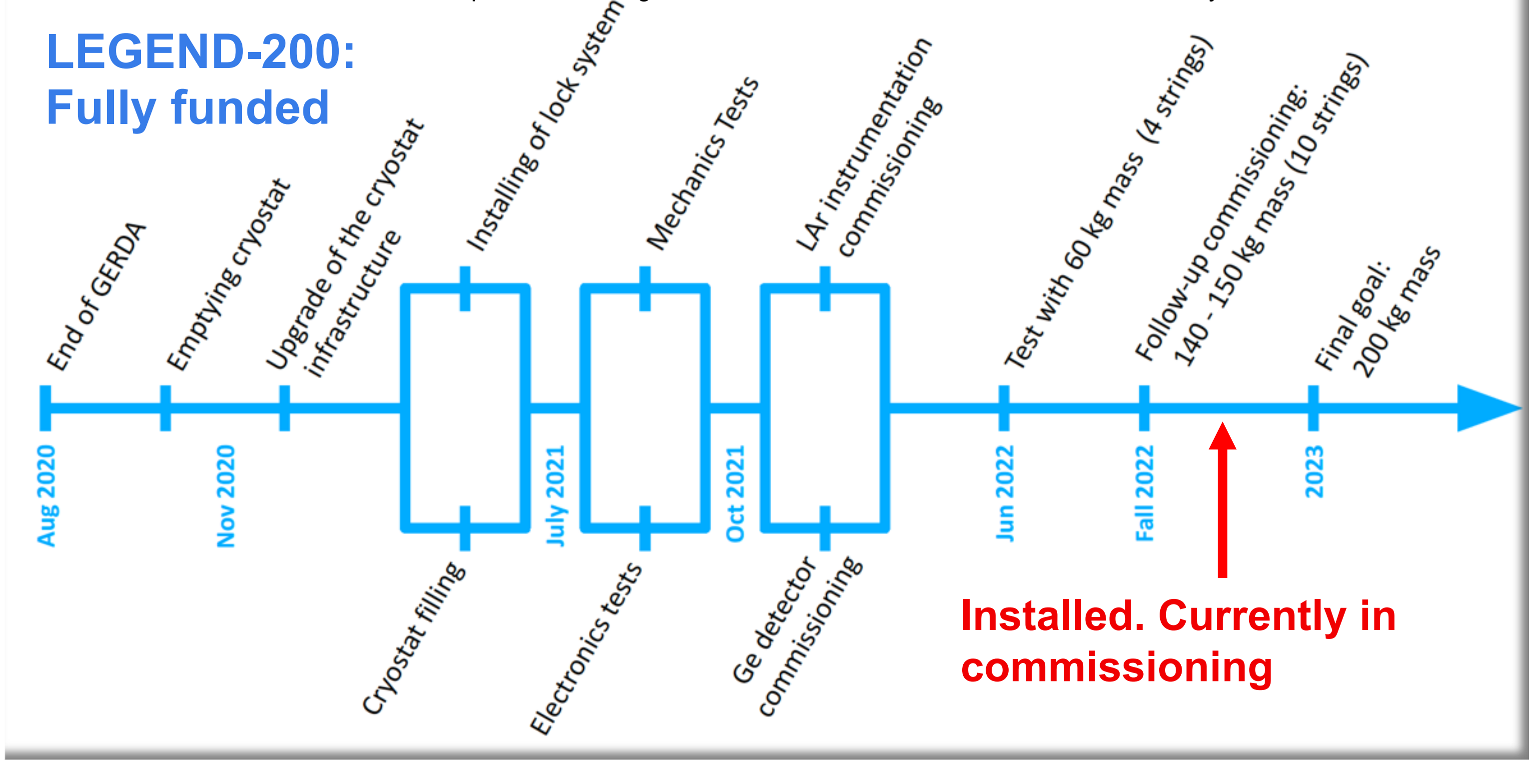
Quasi-background free operation up to 10 ton-year exposure, for unambiguous convincing discovery beyond 10^{28} years

Wenqin Xu| 11/29/22

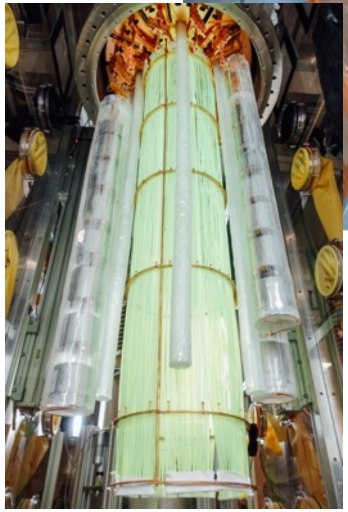
LEGEND Timelines

Adapted from F. Hagemann, 18th Rencontres du Vietnam on Neutrino Physics 2022

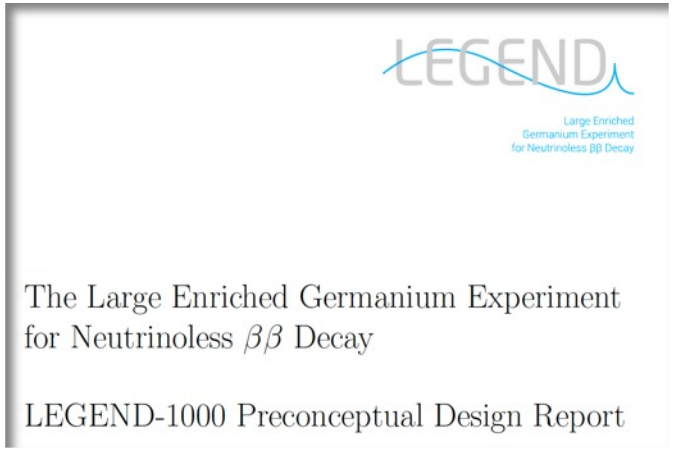
LEGEND-200: Fully funded



WaveLength-Shifting Reflector (WSLR) installed



4 string installed with optical fibers



LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

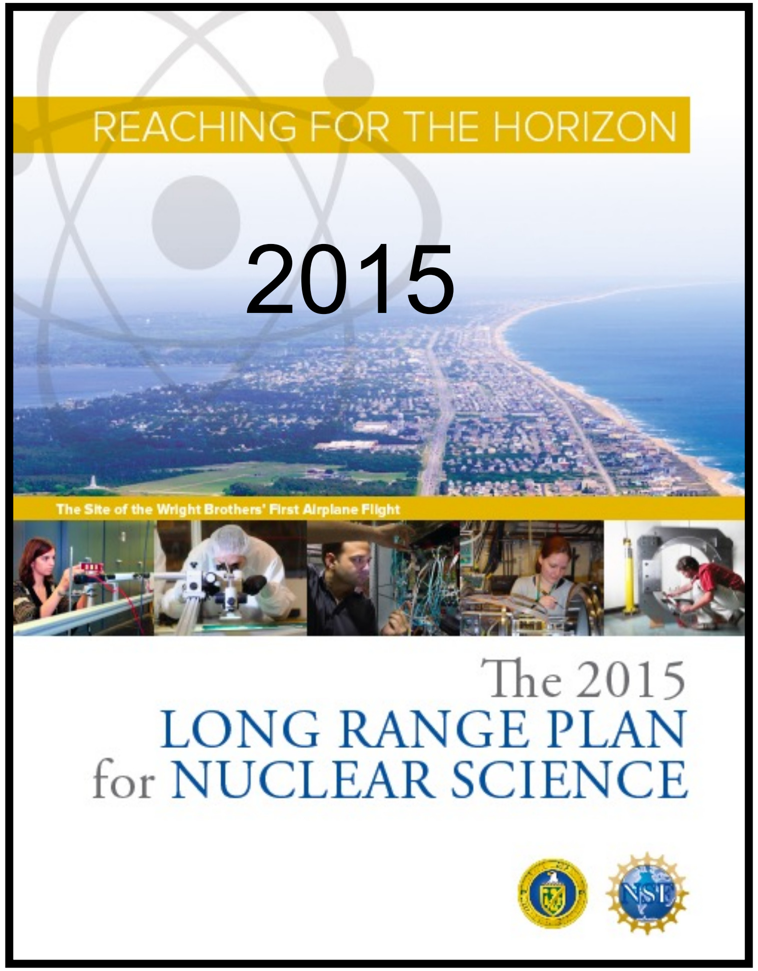
The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

LEGEND-1000 Preconceptual Design Report

LEGEND-1000 (positively reviewed for funding):

- Pre-Conceptual Design Report released:
  arXiv: 2107.11462
- Developing a conceptual design with a refined technical design and background model, proceeding to CD-1
- Many R&D activities are ongoing

US Next Long-Range Plan



Charge to NSAC for the Next Long Range Plan for Nuclear Science

U.S. Department of Energy
and the
National Science Foundation

2022

Professor Gail Dodge
Chair, DOE/NSF Nuclear Science Advisory Committee
College of Sciences
Old Dominion University
4600 Elkhorn Avenue
Norfolk, Virginia 23529

Dear Professor Dodge:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for United States nuclear physics research and recommend a long-range plan (LRP) that will provide a framework for coordinated advancement of the Nation's nuclear science research programs over the next decade.

U.S. DEPARTMENT OF ENERGY | Office of Science   NSAC Meeting   July 13, 2022

Fundamental Symmetries, Neutrons, and Neutrinos Town Meeting

13-15 December 2022
UNC - Chapel Hill
America/New_York timezone

- Overview
- Code of Conduct
- Accessibility

The 2022 Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) Town Meeting will be held at the Friday Center for Continuing Education in Chapel Hill, NC. This meeting is organized to engage our community in preparation for the next NSAC Long Range Plan.

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

Part IV

Rich and Broad Physics Programs with HPGe detectors

Rich and Broad Physics Programs for Ge experiments

Fundamental Symmetries
- L violation in 0νββ decays
- B violation in Baryon decays
- Pauli Exclusion Principle violation
- Lorentz violation and Majorons in 2νββ
- BSM Physics in Ar
- Charge violation

^{39}Ar reduction due to the use of underground-sourced argon enables a suite of BSM physics searches at LEGEND

Standard Model Nuclear Physics
- 2νββ decays
- In-situ cosmogenics
- neutron physics

Superb Energy Resolution
High Granularity
Low Backgrounds

Dark Matter Signatures
- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Solar Axions

Exotic Physics
- Lightly ionizing particles
- Quantum Wavefunction collapse

+ Prompt Supernova Neutrinos, SuperWIMPS, Solar Neutrinos, …

BSM Physics

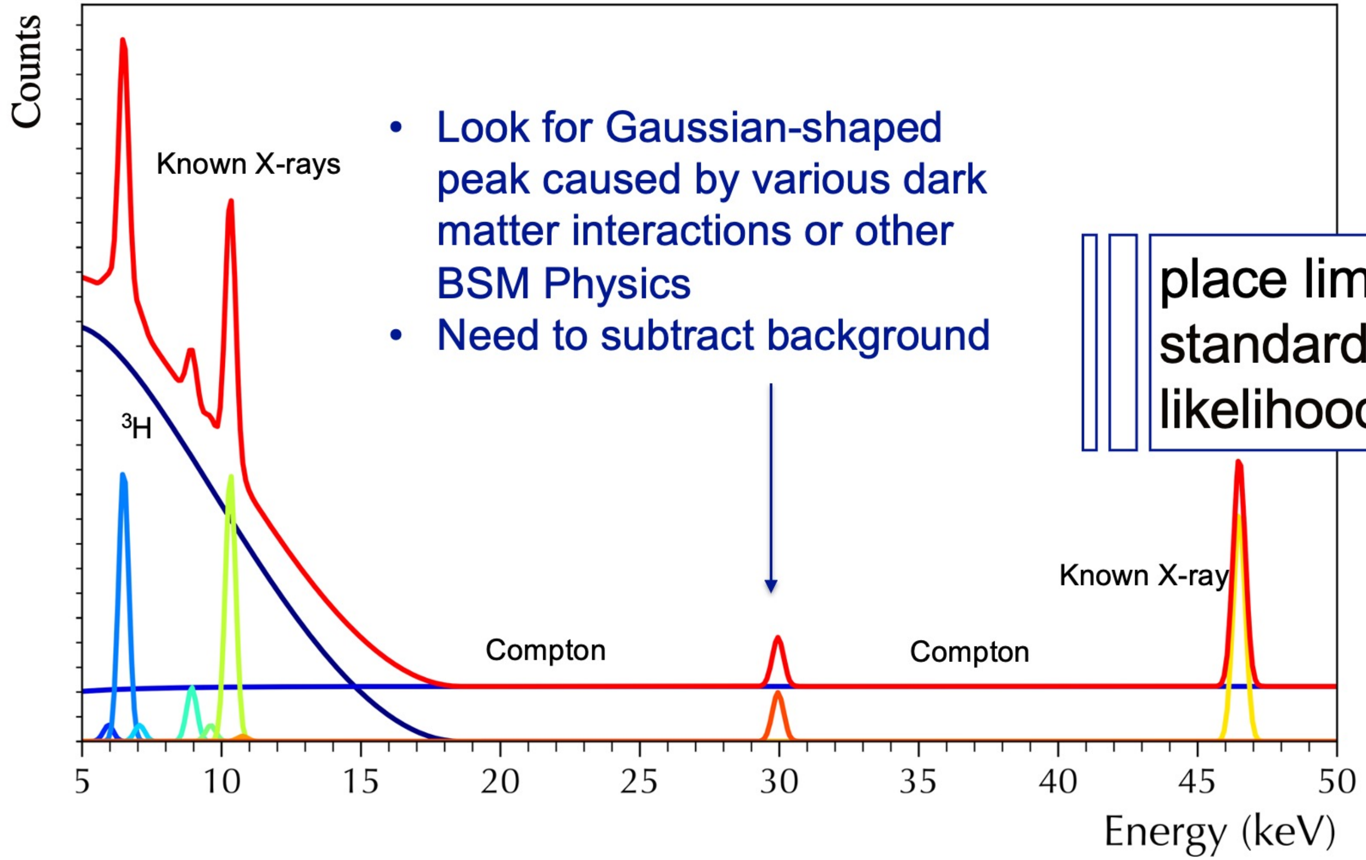
Superb Energy Resolution, High Granularity, and Low Backgrounds make HPGe detectors excellent in a range of BSM physics searches using analyses looking at peaks, spectral distortion, time correlation, and more

Non-inclusive list of examples

Mechanism	Signature	Energy range
Bosonic Dark Matter	Peak at m_b	5 — 100keV
Baryon Decay	Time Correlation, High Energy	0-10 MeV
Fractionally Charged Cosmic rays	High Multiplicity-coincidence events	Few keV
WIMP searches	Exponential Excess + Annual Modulation. Migdal Effect	< 10 keV
Solar axions	Peaked Spectra + daily modulation	< 10 keV
Majoron Emission	2νββ spectral distortion	$Q_{\beta\beta}$
Lorentz Violation	2νββ spectral distortion	$Q_{\beta\beta}$
Electron Decay	Peak at 11.8 keV	~10 keV
Pauli Exclusion Principle Violation	Peak at 10.6 keV	~ 10 keV

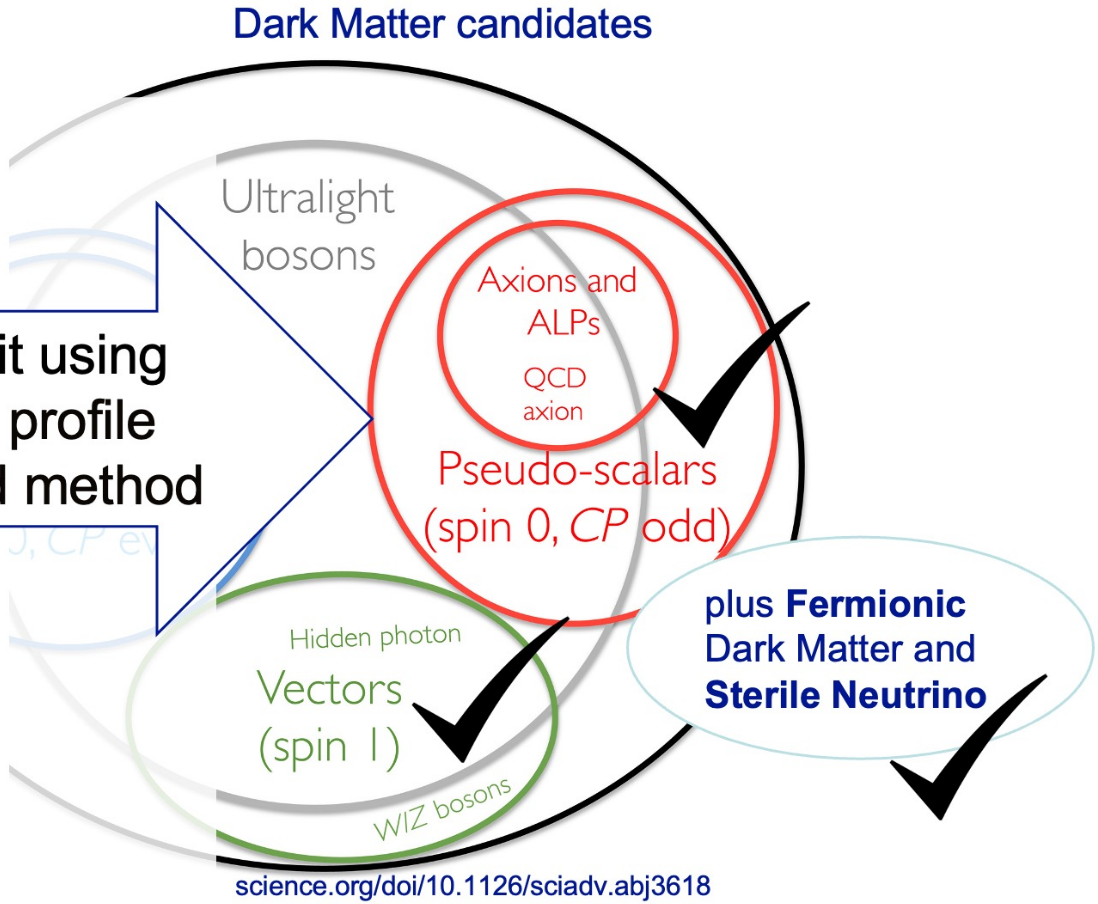
These BSM Physics are parts of the rich and broad physics programs of LEGEND-1000

BSM Peak Searches in Energy Spectrum



- Look for Gaussian-shaped peak caused by various dark matter interactions or other BSM Physics
- Need to subtract background

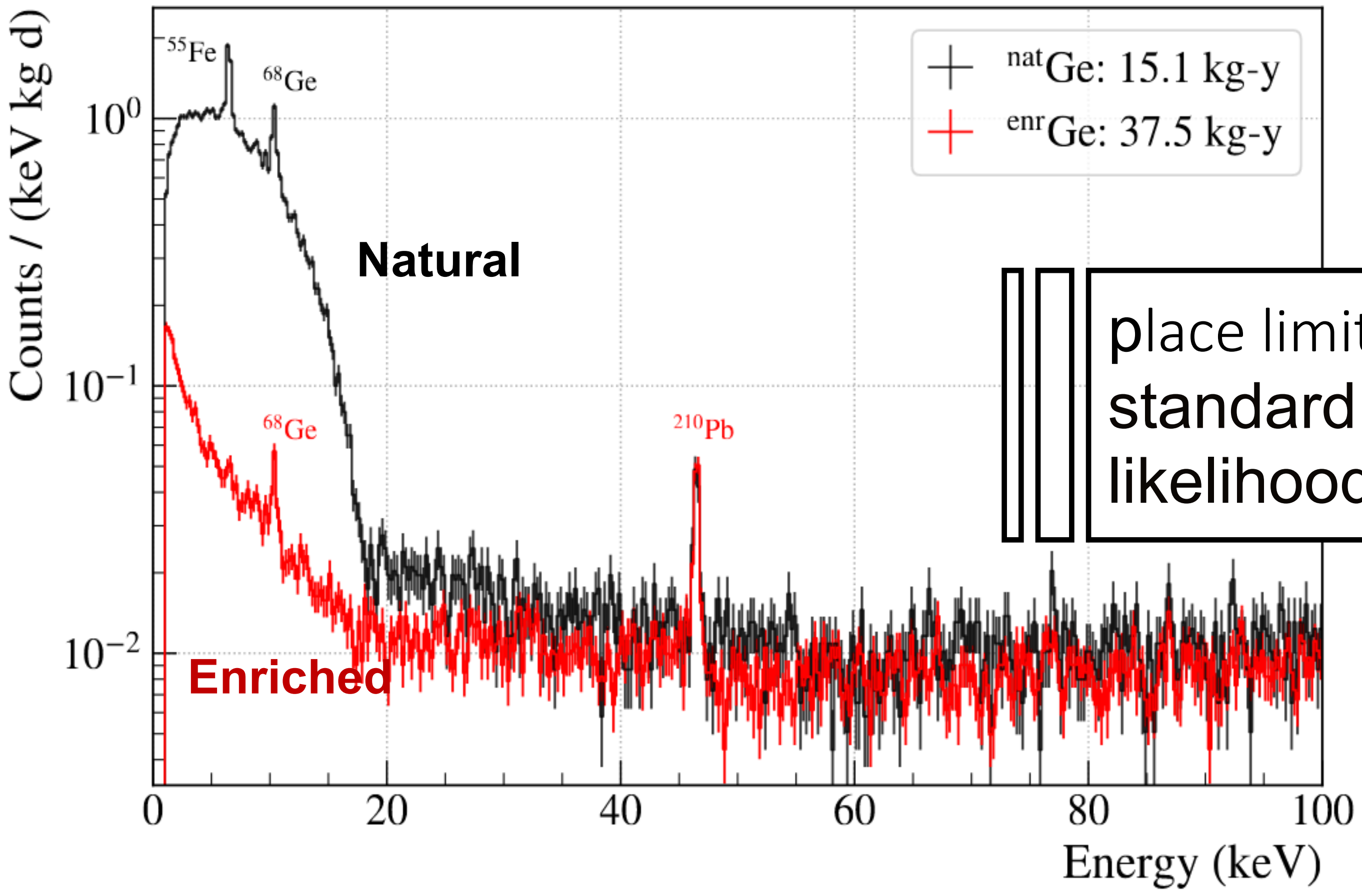
place limit using standard profile likelihood method



Wenqin Xu| 11/29/22

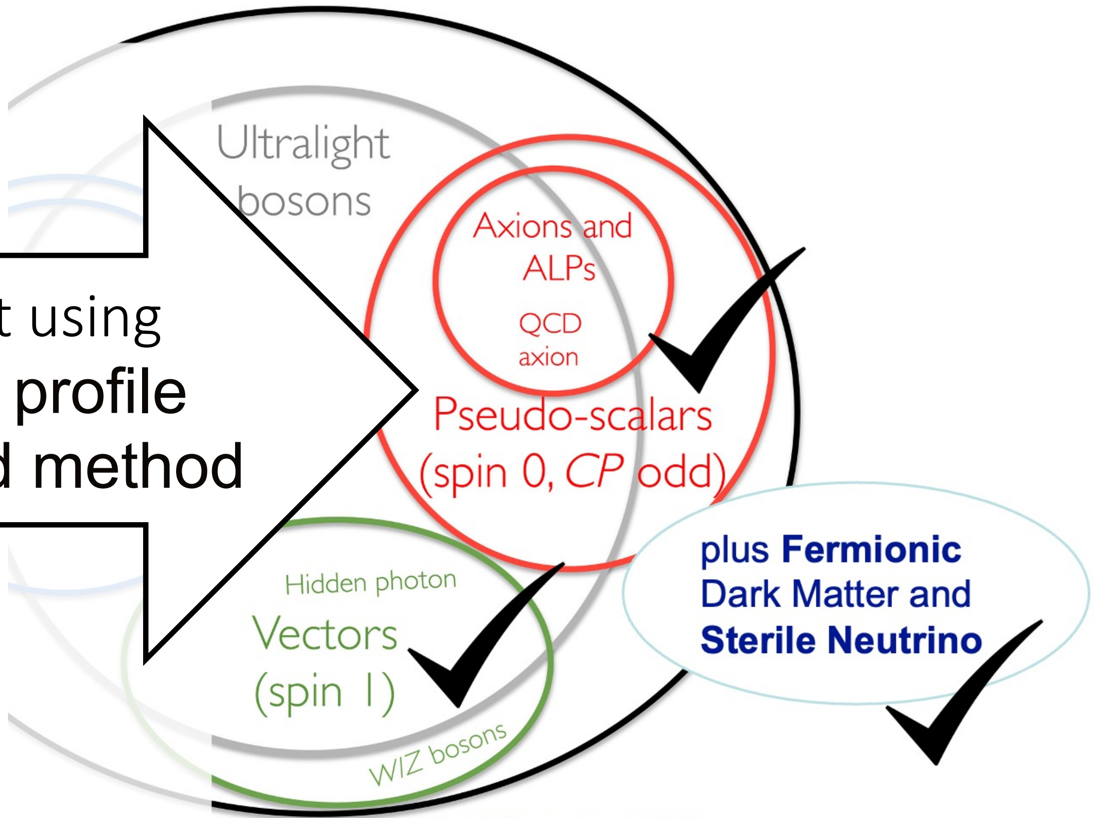
BSM Peak Searches in Energy Spectrum

arXiv:2206.10638



place limit using **standard profile likelihood method**

Dark Matter candidates



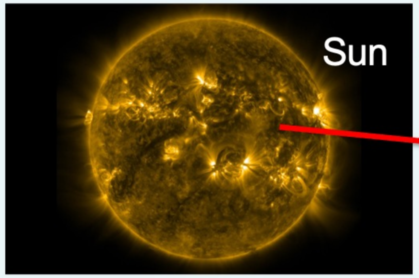
science.org/doi/10.1126/sciadv.abj3618

Solar Axion Searches via Photon Coupling

BSM Physics

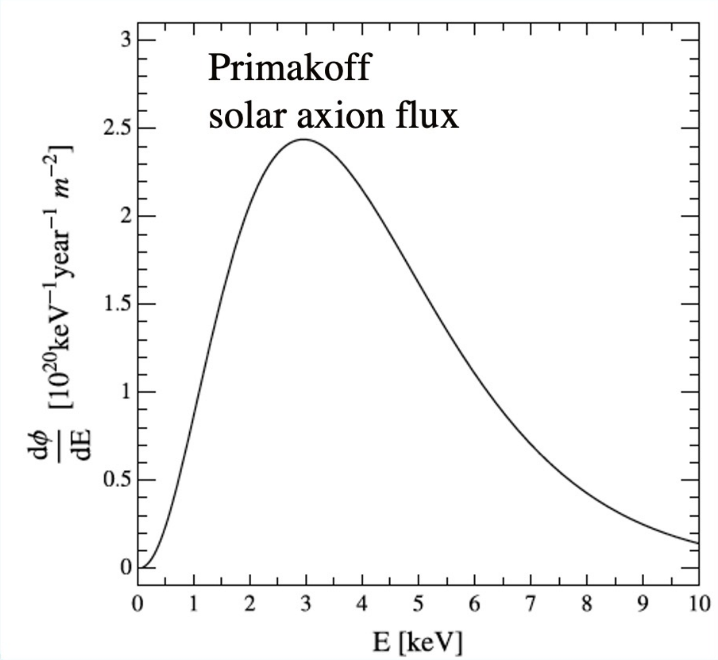
Energy-Time 2-D analysis

Production



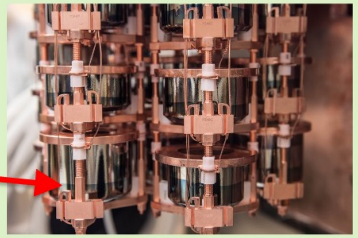
$\gamma + \gamma \rightarrow Axion$ Primakoff axions

axion-photon coupling (reverse Primakoff effect)



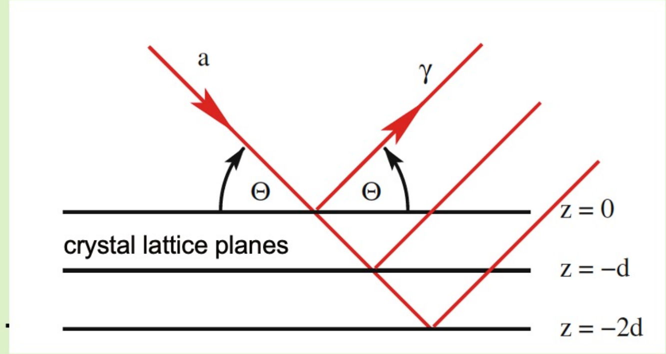
Progress in Particle and Nuclear Physics 102 (2018) 89–159

Detection



$Axion + \gamma_{virtual} \rightarrow \gamma$

- axion-photon coupling (Primakoff effect)
- enhanced by coherent Bragg diffraction



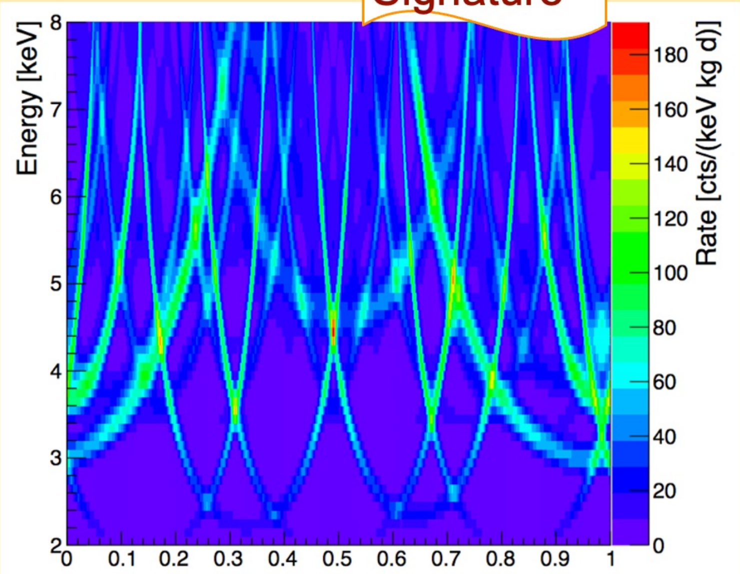
Axion signals:

- enhanced at certain incident angles for certain energy --- the Bragg condition
- follow Sun's movement over time

R. Battesti et al. Lect. Notes Phys. 741, 199–237 (2008)

pioneered by R. J. Creswick, et al., PLB 427 (1998) 235-240

Signature



W. Xu, S. Elliott, Astroparticle Physics 89 (2017) 39

plot for $g_{A\gamma} = 10^{-8} GeV^{-1}$, $g_{Ae} = 0$

- ➢ Distinct time dependence is a key strength for discovery
- ➢ Reduced sharpness if crystal orientations on the horizontal plane are unknown, but still good for analysis

Rich and Broad Physics with HPGe detectors: USD work

BSM Physics

Temporal-Energy solar axion analysis at low energy region ~ keV

On the Cover

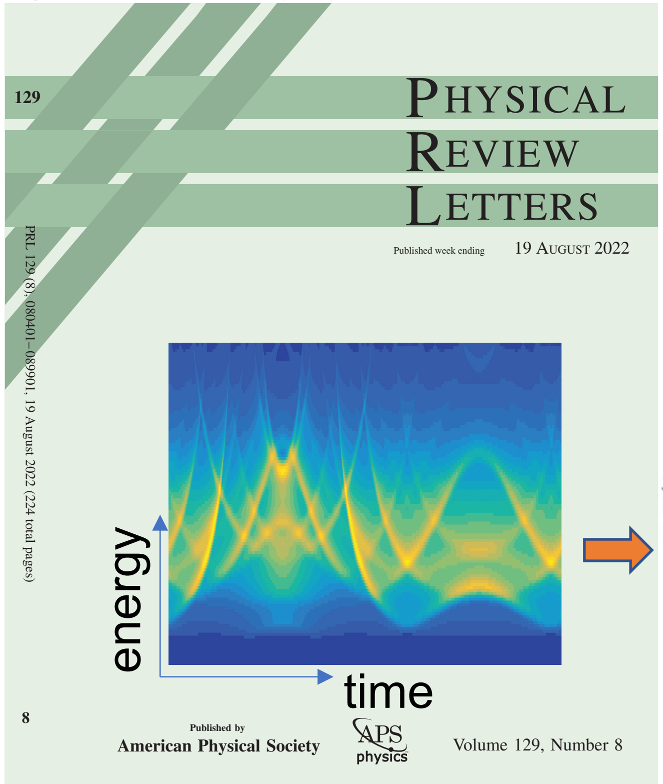
Axion signatures from coherent Primakoff-Bragg scattering over a 24-hour period.

From the article:

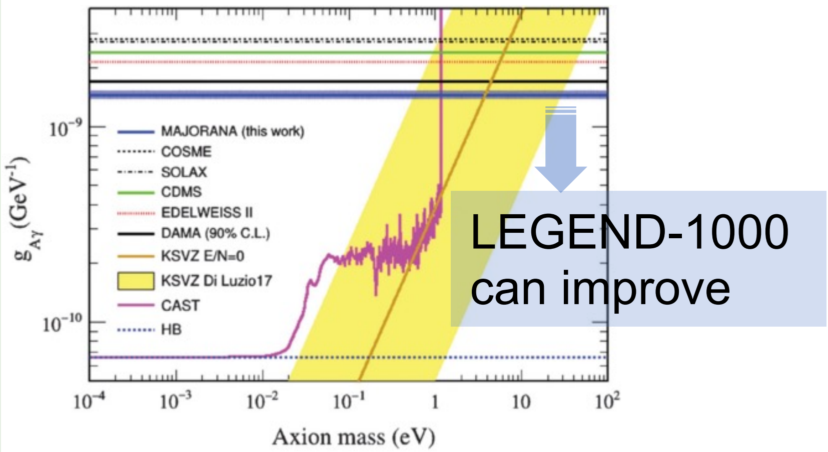
Search for Solar Axions via Axion-Photon Coupling with the MAJORANA DEMONSTRATOR

I.J. Arnquist *et al.* (MAJORANA Collaboration)

Phys. Rev. Lett. **129**, 081803 (2022)



https://journals.aps.org/prl/issues/129/8



Superb Energy Resolution
Low Backgrounds

Standard Model Nuclear Physics

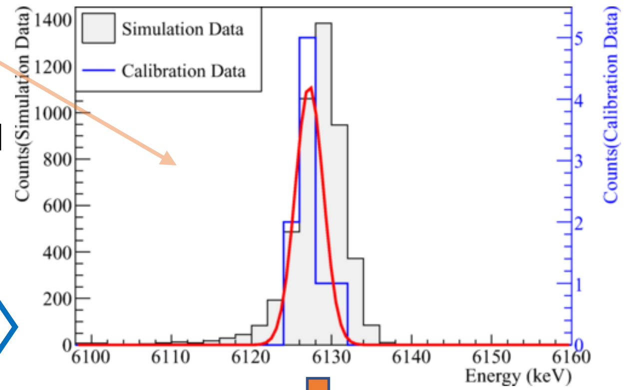
Peak analysis at high energy region ~ MeV. Calibration data

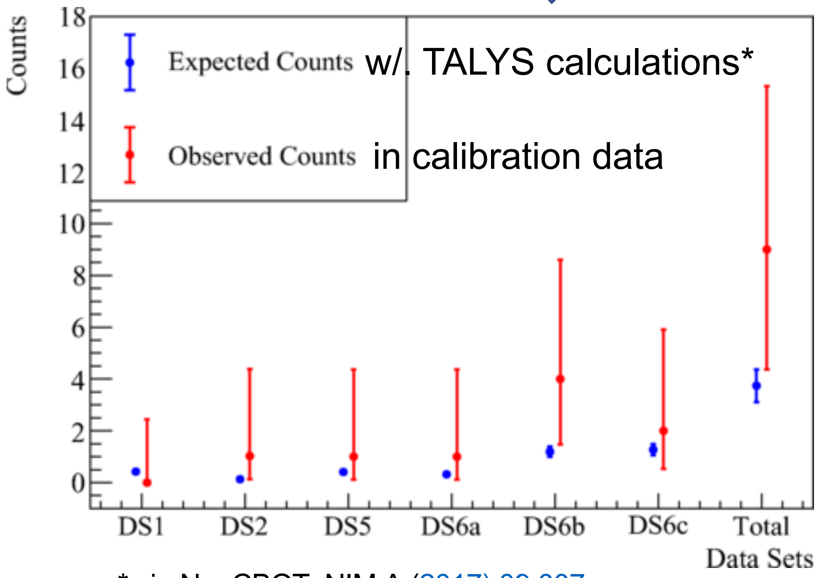
Experimental study of $^{13}C(\alpha, n)^{16}O$ reactions in the MAJORANA DEMONSTRATOR calibration data

I. J. Arnquist *et al.* (MAJORANA Collaboration)

Phys. Rev. C **105**, 064610 – Published 21 June 2022

6.13MeV isomeric photons observed





w/. TALYS calculations*

in calibration data

* via NeuCBOT, NIM A (2017) 09 007

Rich and Broad Physics with HPGe detectors: Delivered

References from MAJORANA DEMONSTRATOR and GERDA

Fundamental Symmetries

- **L violation in 0νββ decays**
- **B violation in Baryon decays**
- **Pauli Exclusion Principle violation**
- **Lorentz violation and Majorons in 2νββ**
- **BSM Physics in Ar**
- **Charge violation**

PRC **100** 025501 (2019)
Several 0νββ papers

PRD **99** 072004 (2019)

arXiv:2203.02033

Eur. Phys.J. C75 (2015) 416

Superb Energy Resolution
High Granularity
Low Backgrounds

Standard Model Nuclear Physics

- **2νββ decays**
- **In-situ cosmogenics**
- **neutron physics**

PRC **105** 014617 (2022)

PRC **105** 064610 (2022)

Astroparticle Physics 84 (2016) 29

Dark Matter Signatures

- **Pseudoscalar dark matter**
- **Vector dark matter**
- **Fermionic dark matter**
- **Sterile neutrino**
- **Solar Axions**

PRL **118** 161801 (2017)

PRL **125** 011801 (2020)

PRL **129** 081803 (2022)

arXiv:2206.10638

Exotic Physics

- **Lightly ionizing particles**
- **Quantum Wavefunction collapse**

PRL **120** 211804 (2018)

PRL **129** 080411 (2022)

Summary

Non-zero neutrino mass is physics beyond the Standard Model and a compelling mystery

$0\nu\beta\beta$ searches determine the status of total lepton number conservation and probe the Majorana or Dirac nature of massive neutrinos

Ge-based technology captures significant $0\nu\beta\beta$ discovery potential

Current-generation ^{76}Ge experiments have achieved great successes

- MAJORANA DEMONSTRATOR achieved $T_{1/2} > 8.3 \times 10^{25}$ yr and the best energy resolution
- GERDA achieved $T_{1/2} > 1.8 \times 10^{26}$ yr and the lowest background if normalized to energy resolution

Combing the best technologies, the phased LEGEND project is designed for an unambiguous discovery of $0\nu\beta\beta$

- LEGEND-200 is in commissioning at LNGS with data-taking beginning later this year
- ➢ Goal : Discovery sensitivity of 10^{27} years with modest background reduction relative to GERDA
- LEGEND-1000 is proceeding to CD-1 with, R&D and conceptual design development ongoing
- ➢ Goal : Discovery potential at a half-life beyond 10^{28} years

Ge-based experiments including LEGEND have rich and broad physics other than $0\nu\beta\beta$

- Physics results can be extracted in wide energy range with various analysis techniques