Los Alamos
NATIONAL LABORATORY

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

# Dark Matter Searches with the LEGEND Experiment


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on behalf of the LEGEND Collaboration

Director’s Postdoctoral Fellow

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Managed by Triad National Security, LLC, for the U.S. Department of Energy’s NNSA.

# LEGEND Overview

**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**.”

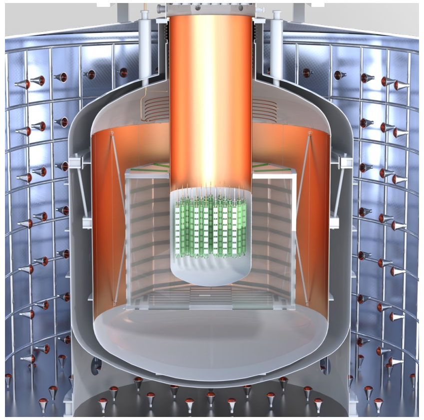
**Select best technologies**, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

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

**GERDA**
- LAr veto
- Low-A shield, no Pb

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

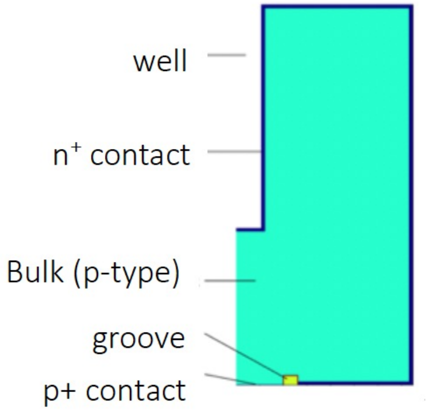
**First phase:**
- Deploy 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: $\sim 2\times10^{-4}$ cts /(kg keV year)
- Discovery sensitivity at a half-life of $10^{27}$ years
- Currently taking data

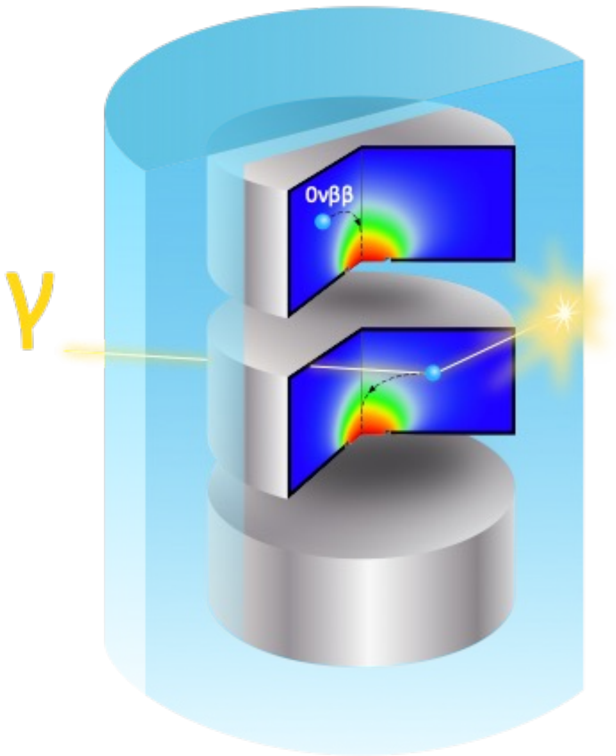


**Subsequent stages:**
- 1000 kg, staged via individual payloads
- Start construction @ LNGS in 2025
- BG goal: $< 10^{-5}$ cts /(kg keV year)
- To be located at LNGS

# High-Purity Germanium Detectors

- A well-established detector concept
  - Point-contact detection scheme
- Used in MAJORANA and GERDA
  - Ionization detectors
  - Low background
  - Excellent energy resolution, O(100) eV
  - Enriched in $^{76}$Ge for $0\nu\beta\beta$ searches

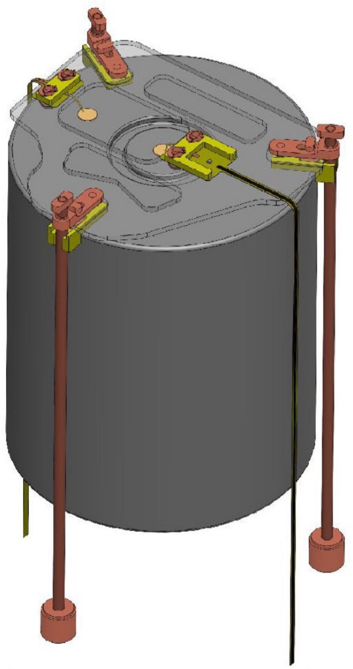


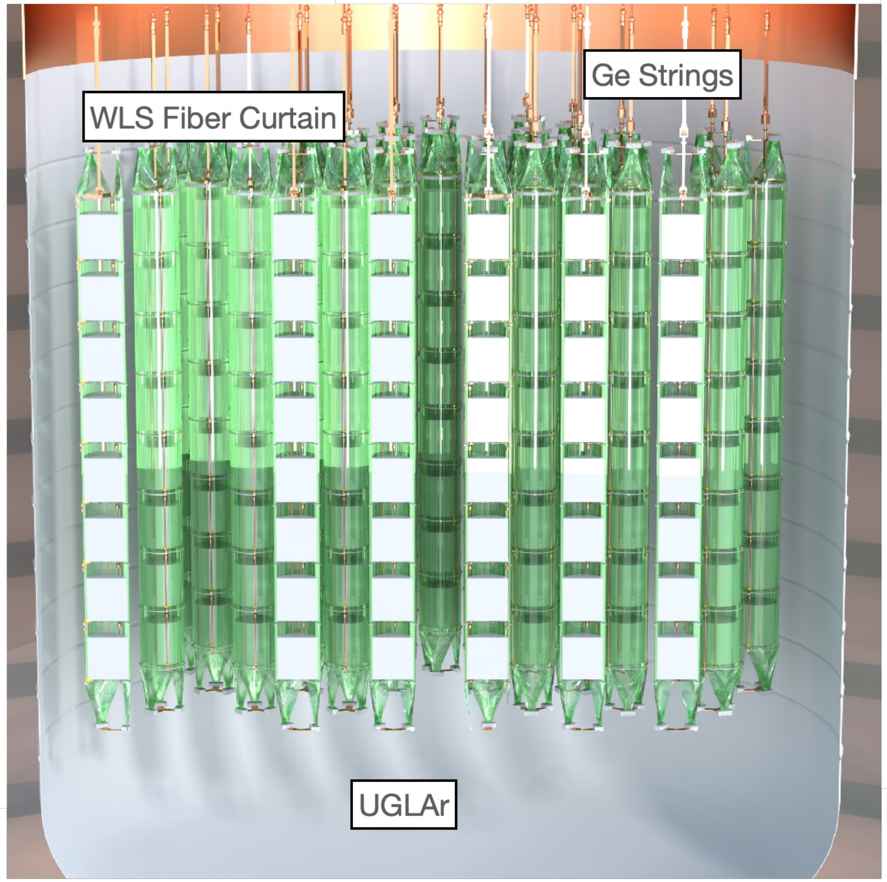
# LEGEND-1000: Experimental Design

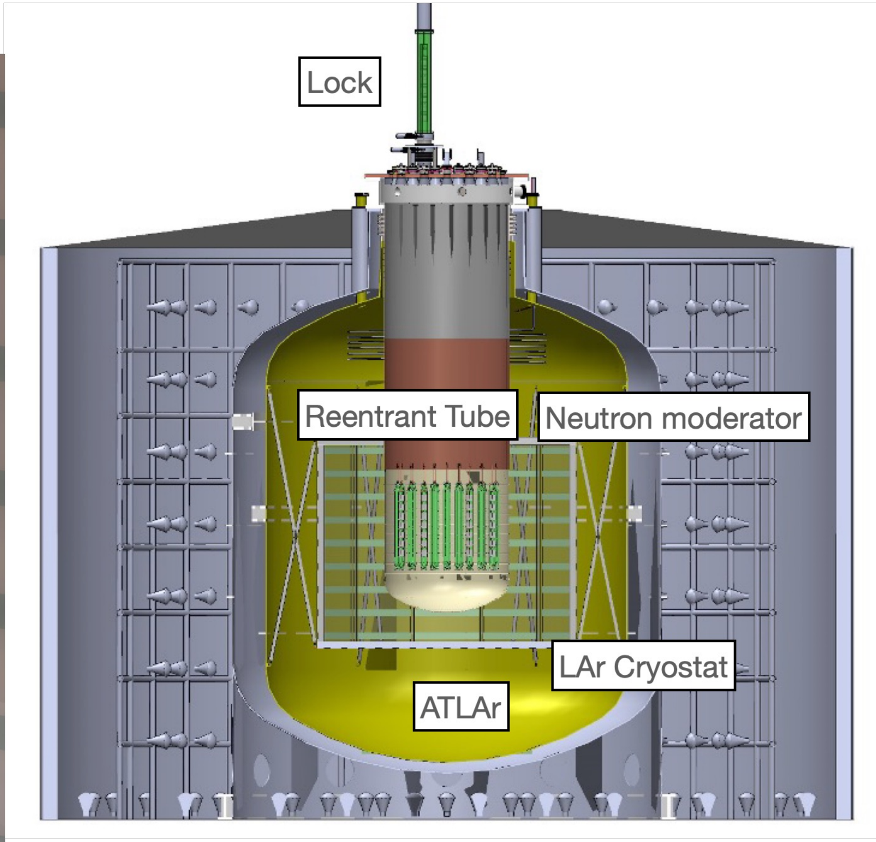
ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar
ATLAr: Atmospheric Liquid Ar

336 detectors of 3 kg avg. mass




Detector strings can be individually installed: Early data as detectors are produced




Reference design accommodates siting in LNGS Hall C

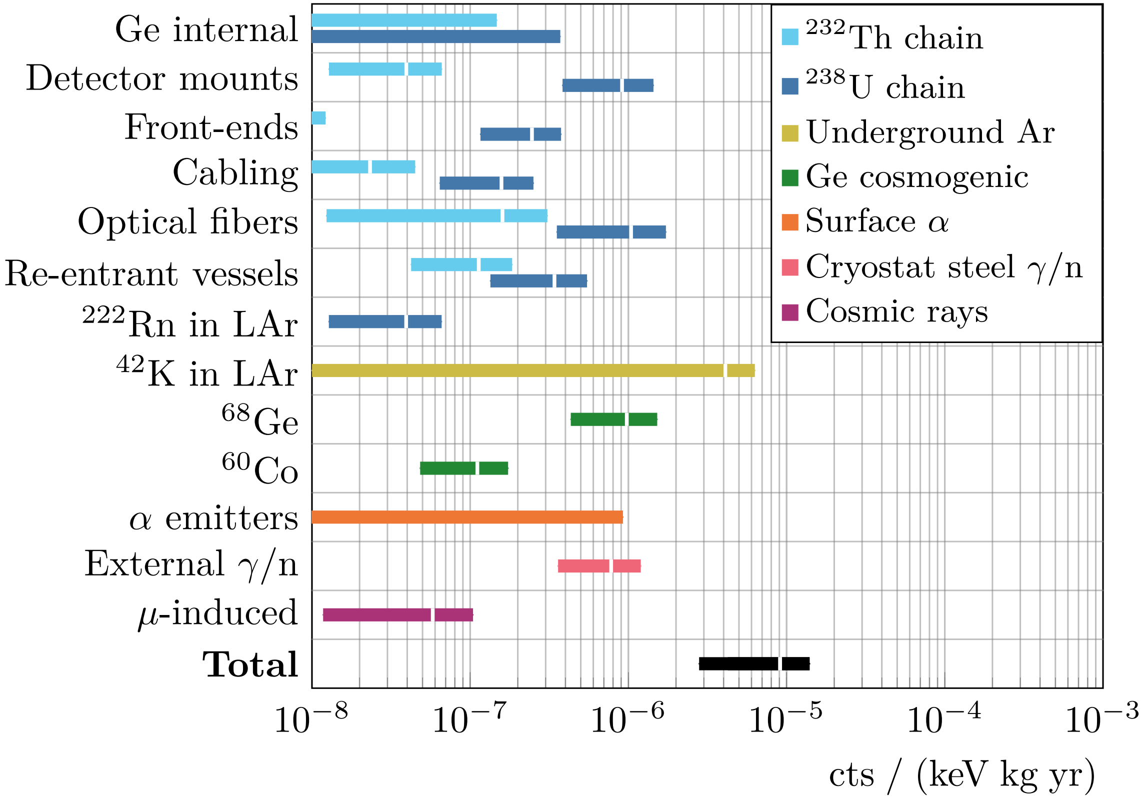
LEGEND-1000 pre-CDR: arXiv:2107.11462

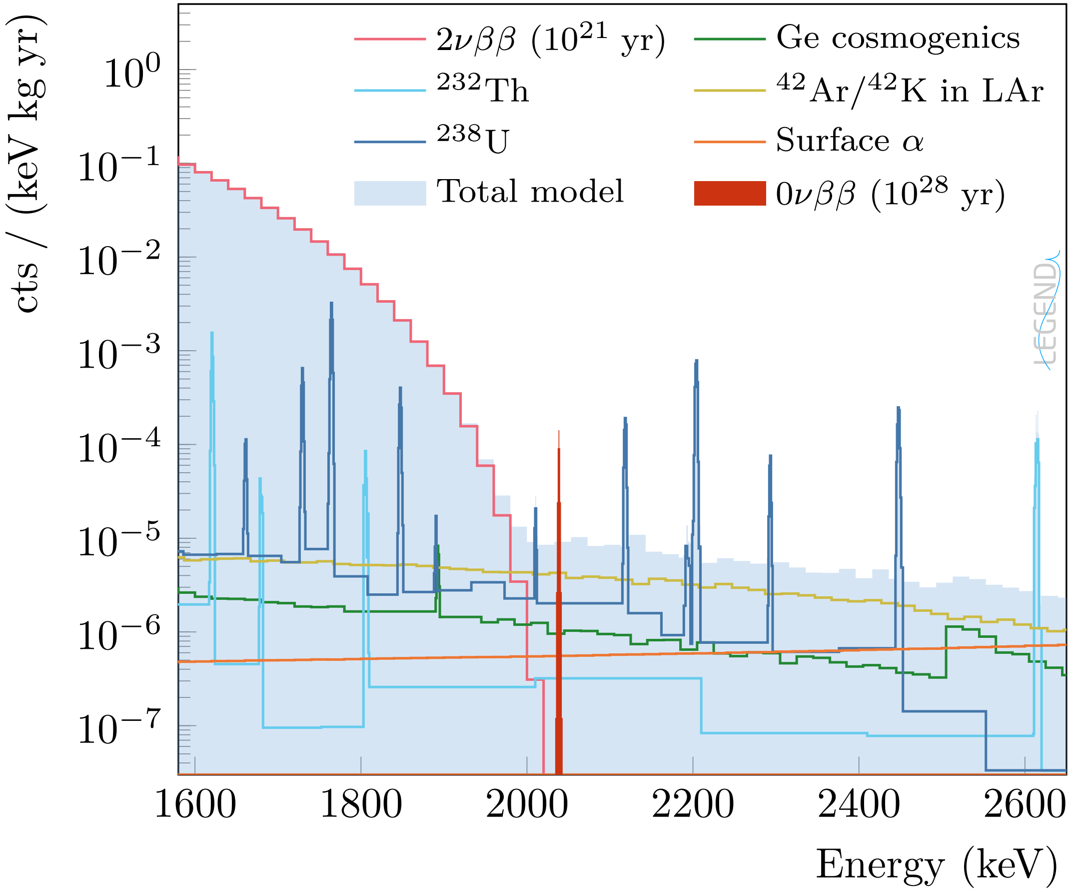
For more on UGLAr, see talk by R. Stefanizzi (Monday, Parallel 1)

# Expected Backgrounds in $0\nu\beta\beta$ ROI

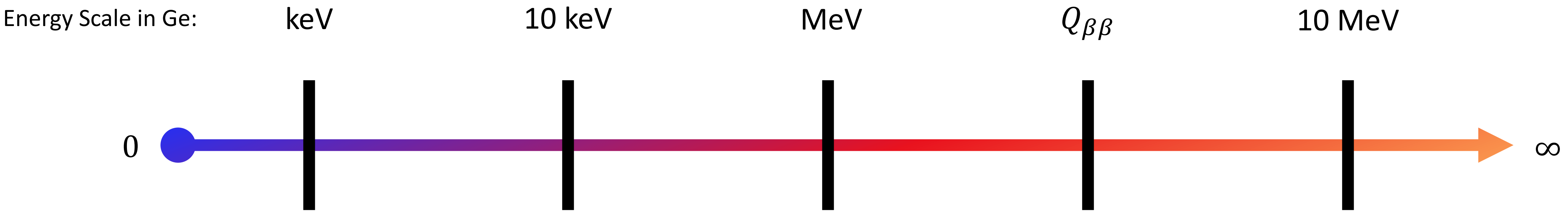
LEGEND pCDR, arXiv:2107.11462

- Expect $\sim 1\times 10^{-5}$ cts/keV/kg/yr at $Q_{\beta\beta}$
  - Quasi-background free!



# BSM Physics Opportunities beyond $0\nu\beta\beta$




Bosonic DM

Majoron Emission

Thermal WIMPs

Baryon Decay

Light Fermionic DM

Lorentz Violation

Solar Axions

Solar Neutrinos

Electron Decay

Inelastic Boosted DM

Fractionally Charged Particles

PEP Violation

Exotic Fermions

Exotic Currents

Supernova Neutrinos

Composite DM

Time-Dependent $2\nu\beta\beta$

Magnetic Monopoles

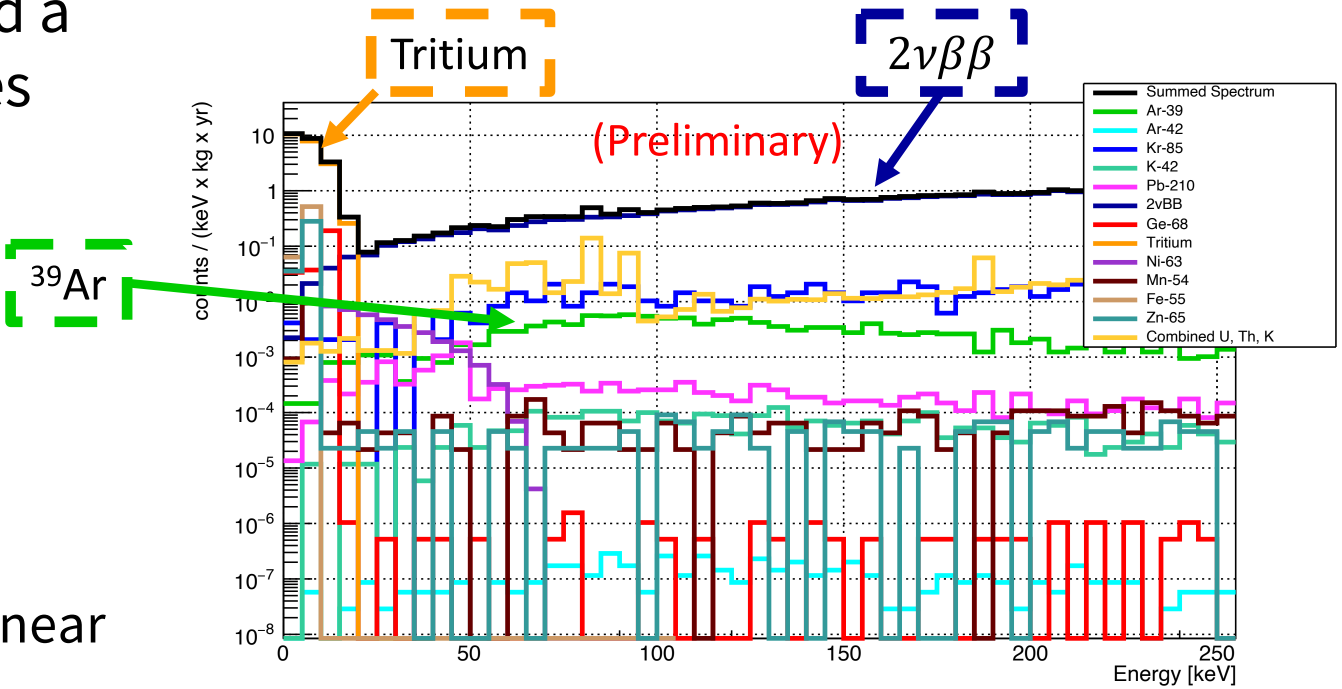
Wave Function Collapse

Presupernova Neutrinos

Legend:
- Dark Matter Candidates
- $2\nu\beta\beta$ Spectral Effects
- Tracklike Signatures
- Tests of Fundamental Physics
- Astrophysical Neutrinos

# Low-Energy Backgrounds

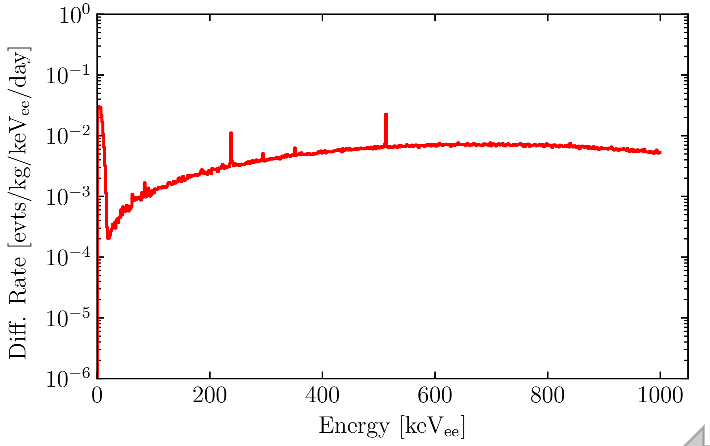
- For BSM physics sensitivities, we need a model that extends to lowest energies
  - Geant4-based simulations with the LEGEND-1000 geometry
  - Realistic detectors
- Analysis cuts:
  - Multi-detector events
  - LAr scintillation veto
  - Remove energy-degraded events from near detector surface

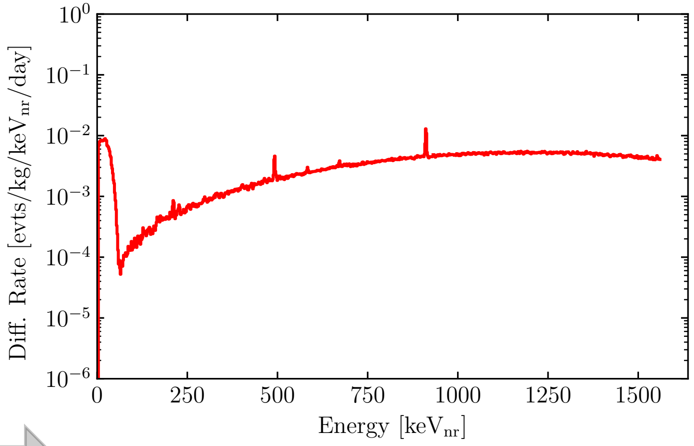


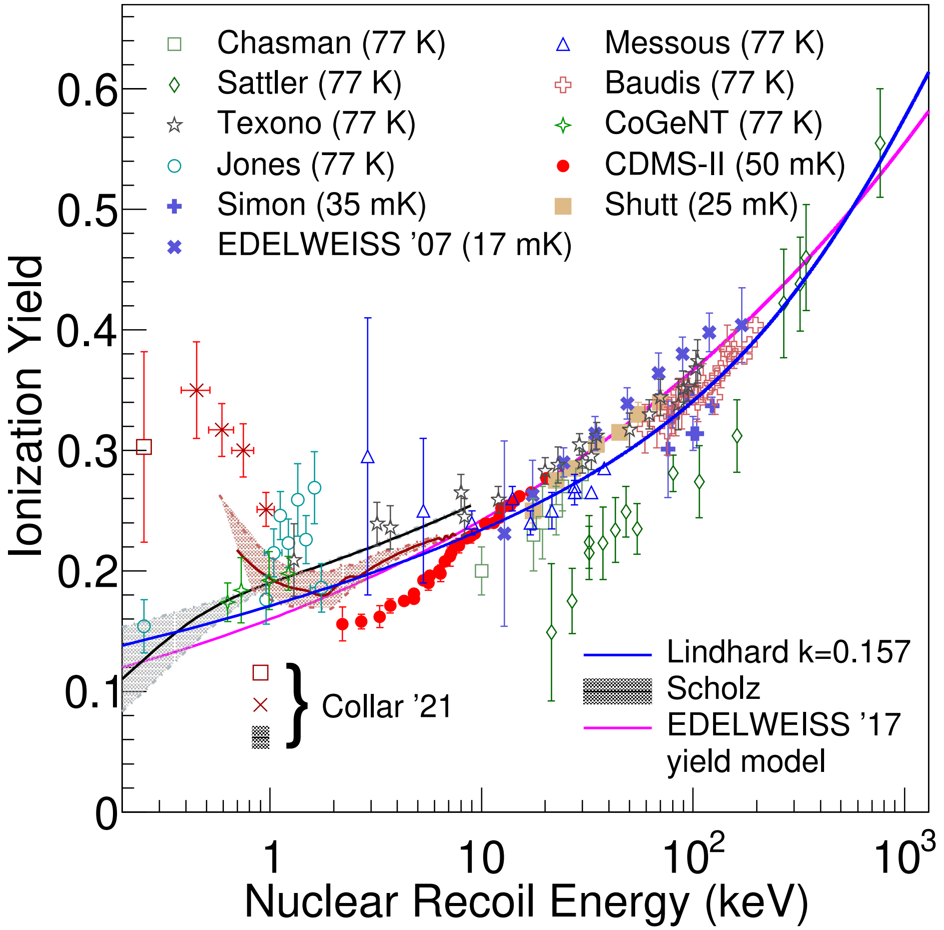

J. Waters Master's Thesis (UNC)

# Electron Recoil vs. Nuclear Recoil DM

- HPGe detectors in LEGEND are ionization detectors
  - No ER/NR discrimination
- To convert between NR and EE energy scales, use Lindhard Model with $k = 0.157$
  - $1\ \mathrm{keV_{ee}} \equiv 4.7\ \mathrm{keV_{nr}}$ in Germanium



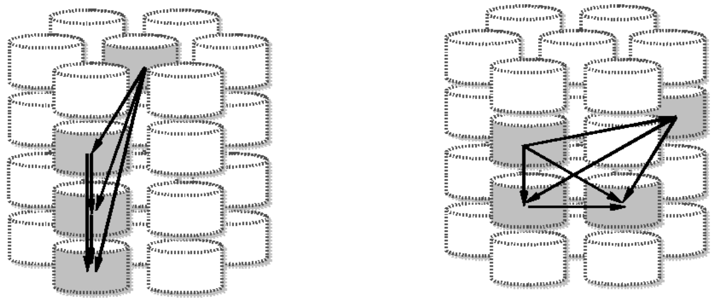




arXiv:2202.07043

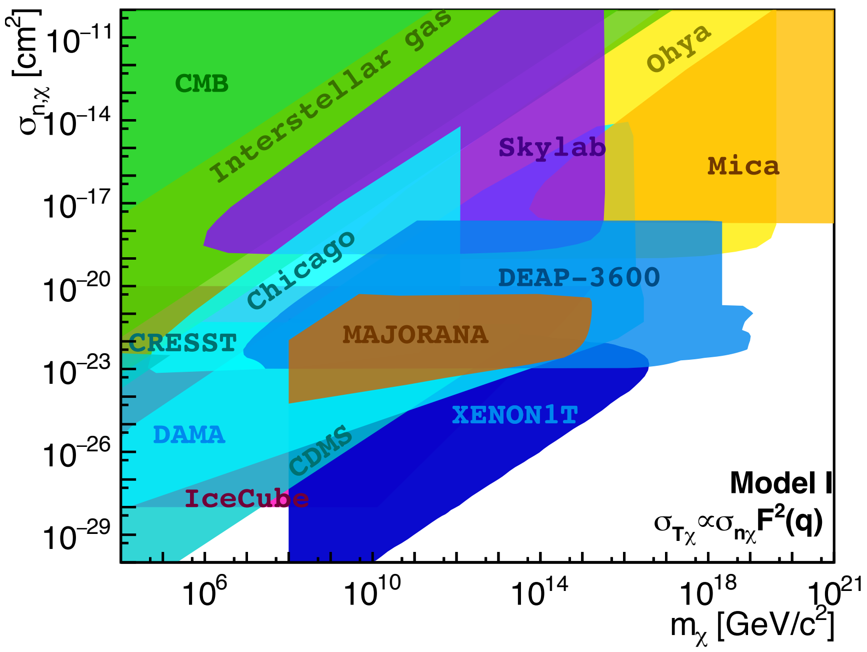
# Ultraheavy DM

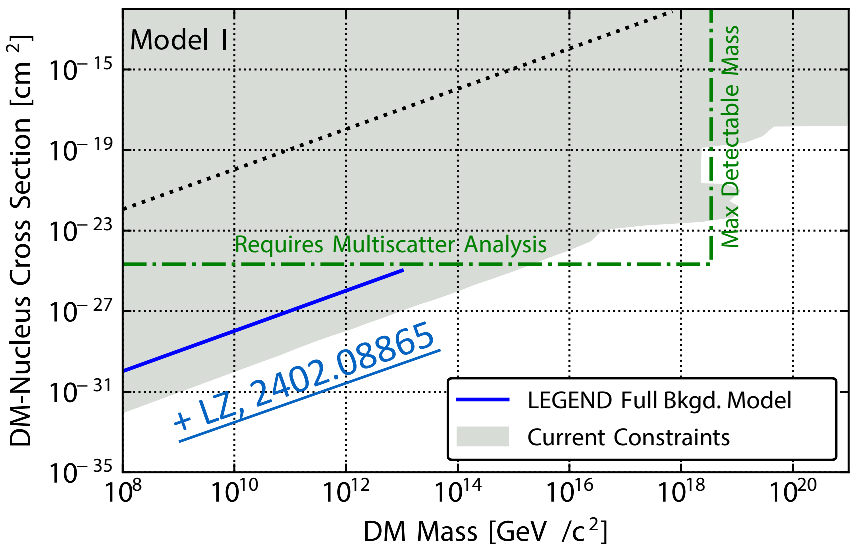
- Ultraheavy DM with large cross sections
  - Would interact multiple times
  - Would interact in a line (track)
  - Potentially can be background free via requirement of multiple scatters **in a line**
- Thanks to large exposure, potential to probe very high masses

arXiv:1801.10145



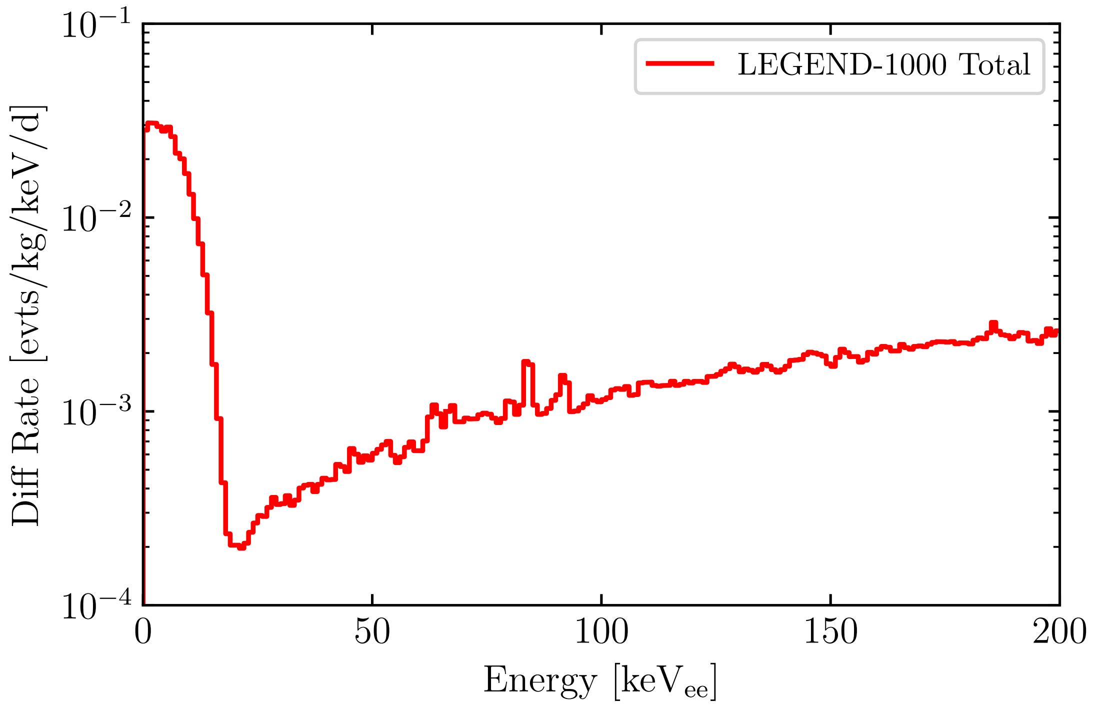

arXiv:2203.06508



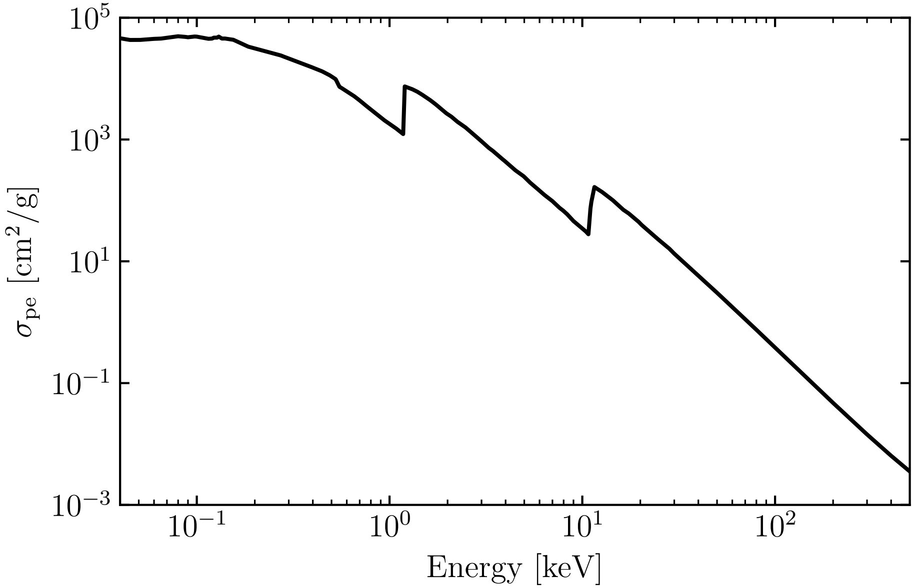
# Peak Search Signatures from DM

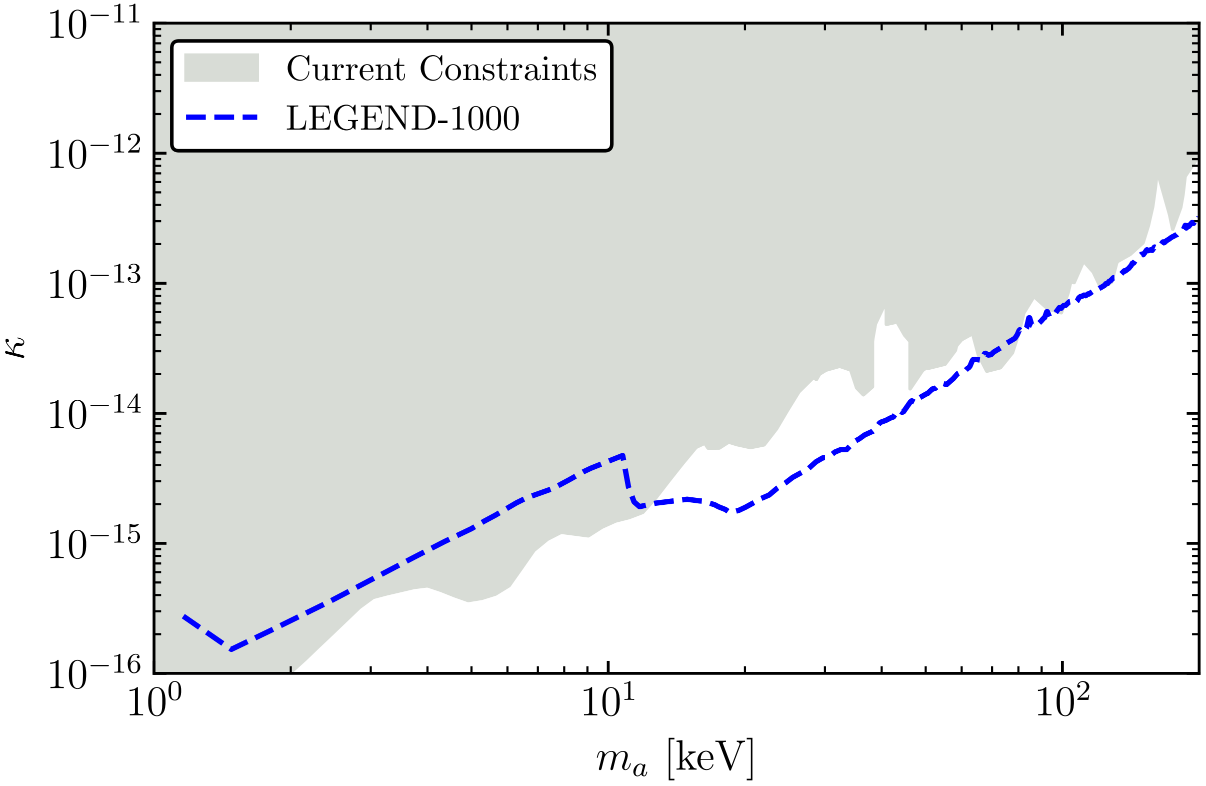
- keV-scale bosonic dark matter
  - Axion-like particles
  - Hidden photons
- Absorption of Fermionic Dark Matter
- Sub-GeV DM-nucleus 3 → 2 scattering
- Sterile neutrino transition magnetic moment
- Sensitivity method:
  - Calculated 90% C.L. fluctuation above background model within $E \pm 2\sigma$



# keV-Scale Dark Photons

- $R_V = \frac{\rho_\chi}{m_V}\kappa^2 c\sigma_{pe}(m_V)$
  - where we use the measured photoelectric cross section, as compiled in [arXiv:1911.11905]

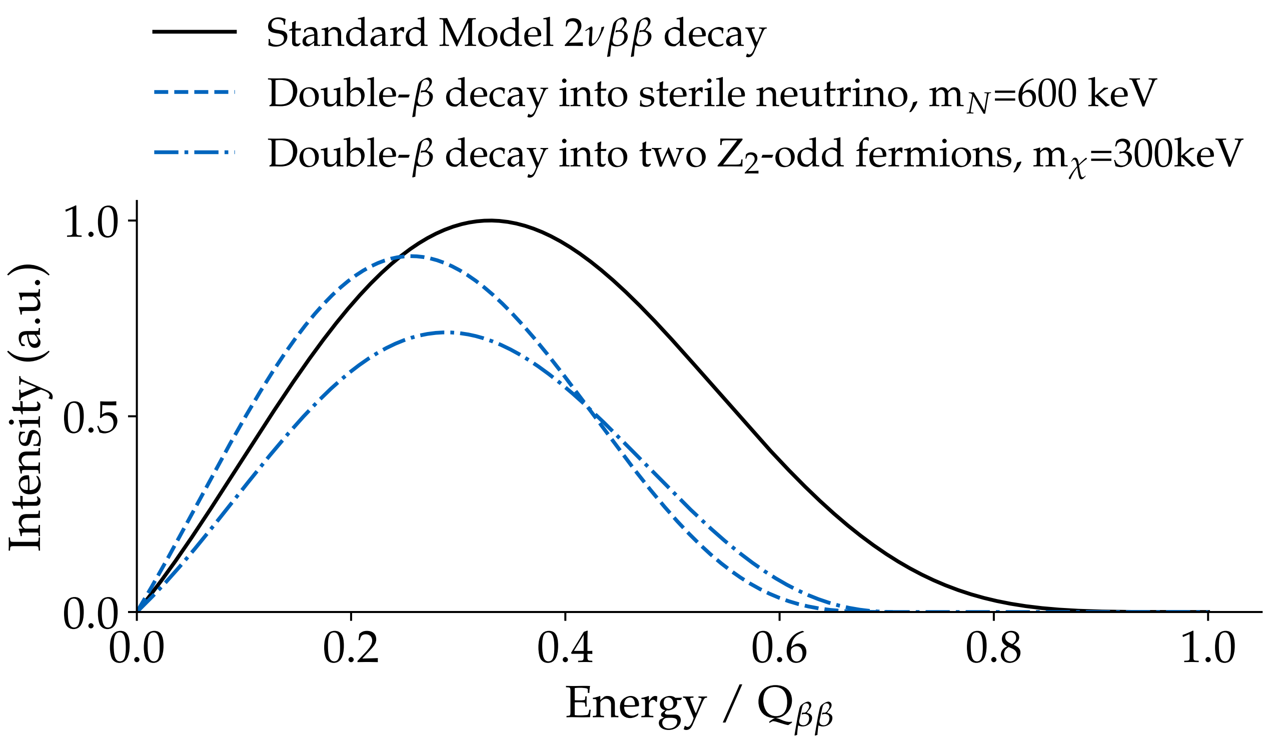



Current constraints dominated by XENONnT below $m_\chi = 200$ keV [arXiv:2207.11330]

# Distortions of the $2\nu\beta\beta$ Spectrum

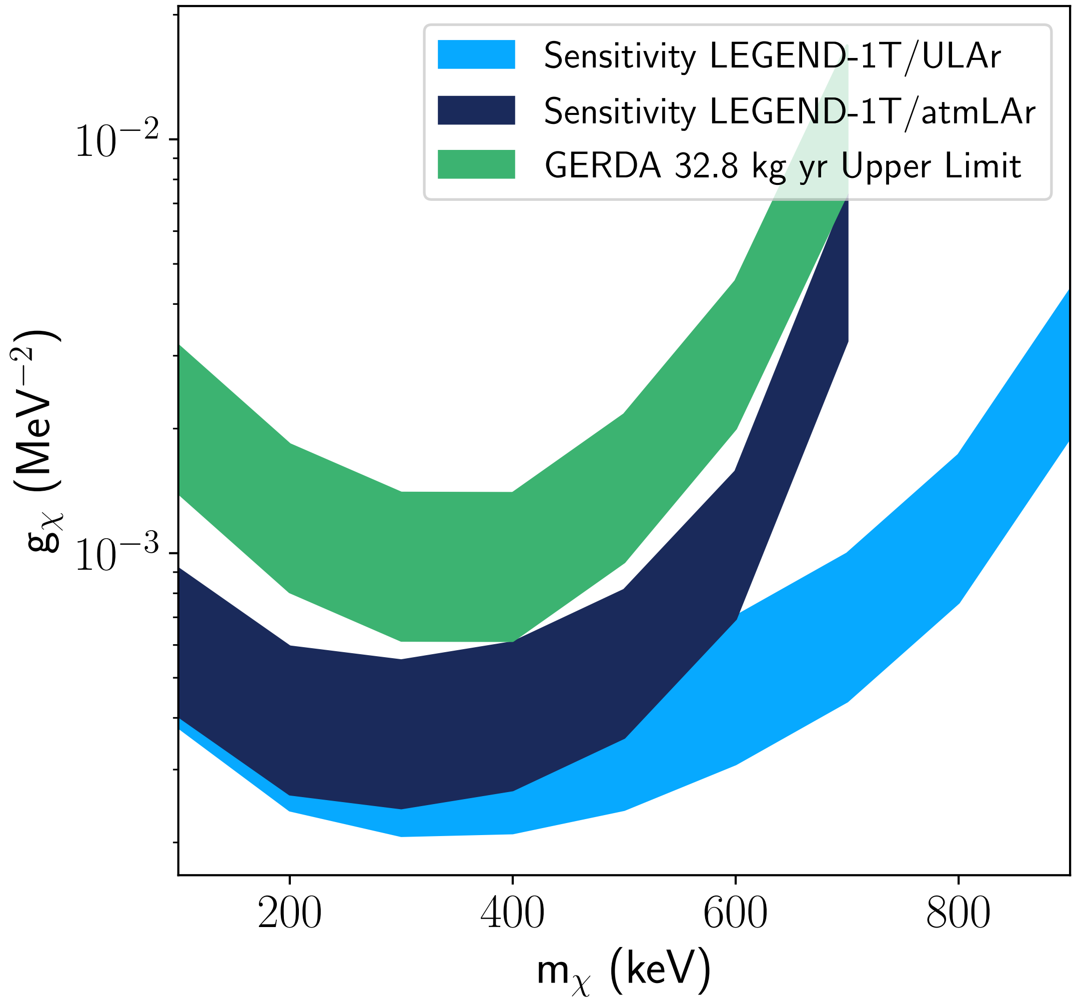
- Emission of two exotic fermions
  - $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\chi$
- Neutral singlet fermion charged under a discrete $Z_2$ symmetry for stability
  - Interacts through an effective four-fermion scalar interactions
  - Cannot be produced in single-$\beta$ decays, but possible in double-$\beta$ decays




arXiv:2304.07198

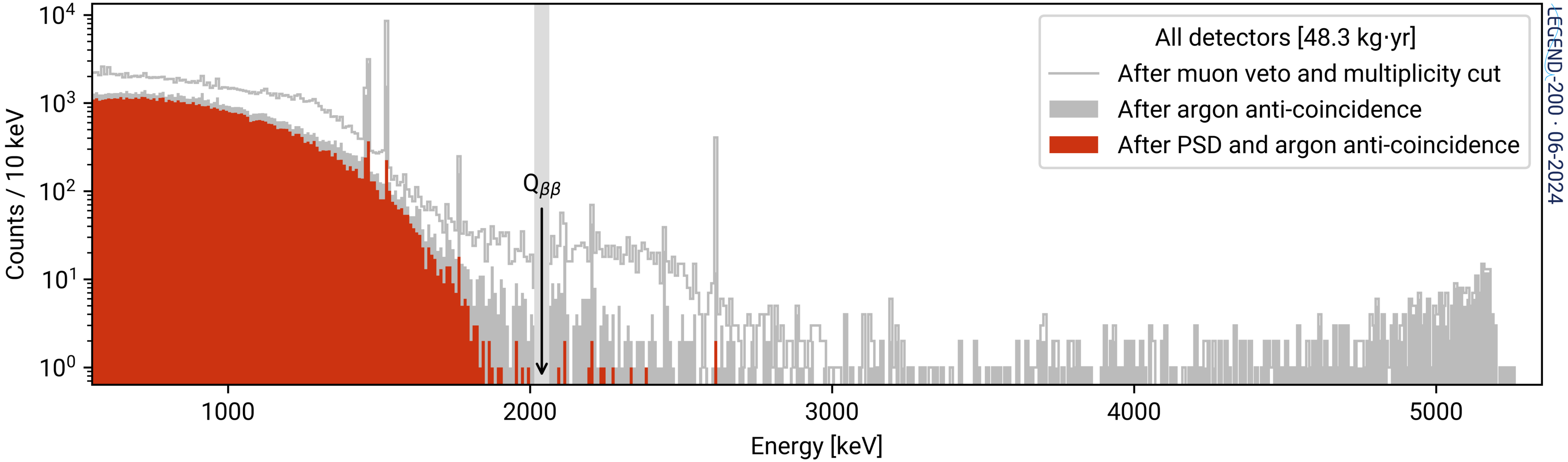
# Sensitivity to Exotic Fermions

- Parameter space probed so far by GERDA ([arXiv:2209.01671](arXiv:2209.01671))
- Half life defined by
  - $\Gamma_{\chi\chi} = \frac{g_\chi^2 m_e^2}{8\pi^2 R^2} |M^{0\nu}|^2 \mathcal{G}^{\chi\chi}$
- Limits on half-life are converted to limits on $g_\chi$
  - Use range of nuclear matrix element calculations to create bands



# Status of LEGEND-200: First Physics Result!

- Apply: muon veto, multiplicity cut, argon anti-coincidence, pulse shape discrimination
- Have: a nearly pure $2\nu\beta\beta$ spectrum, with some events around 2 MeV
  - See Neutrino 2024 results for more, including a new limit on $0\nu\beta\beta$!

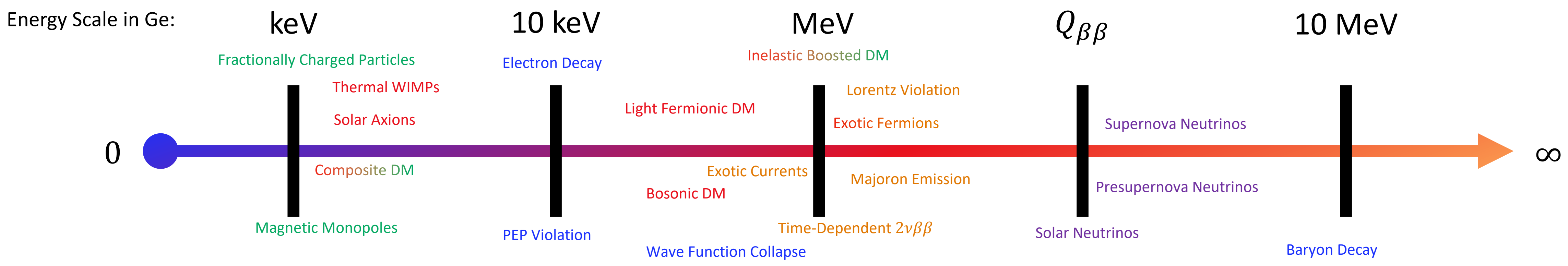


# BSM Physics with L-200

- With atmospheric argon, we are dominated by $^{39}$Ar below $Q_\beta$~565 keV
- Interesting physics to search for, e.g.
  - Ultraheavy dark matter
  - $2\nu\beta\beta$ spectral distortions
  - keV-scale bosonic DM absorption
- Thresholds are at ~50 keV, more BSM physics accessible with lower thresholds
- DM (and more) analyses ongoing!

# Summary and Outlook

- LEGEND has a rich BSM physics program, encompassing DM and more!
- Data incoming now with LEGEND-200 phase
- Many searches are complementary to DM experiments
- Sensitivities for LEGEND-1000 are being compiled in an upcoming white paper



# Thank you!



CIEMAT
Comenius Univ.
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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 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 Zurich
Williams College

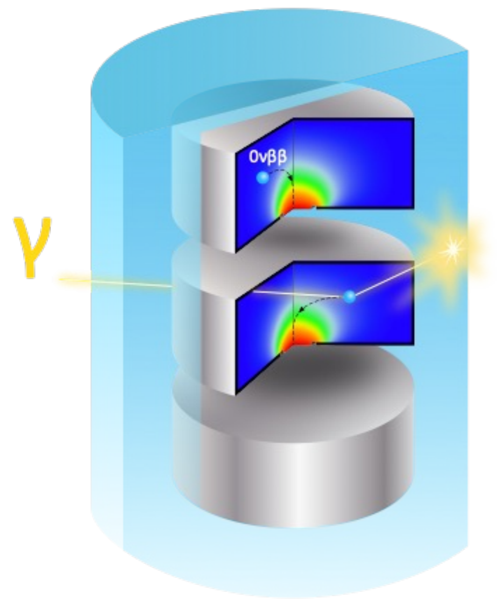
# Backup

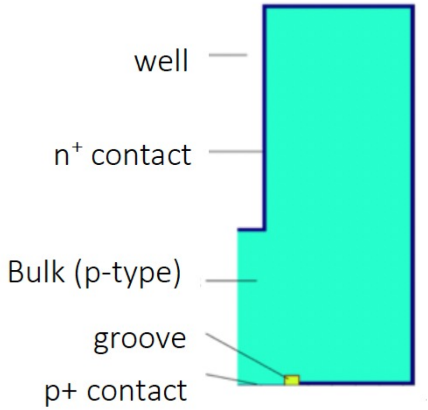
# Effect of Underground LAr

- $\times 1400$ reduction of $^{39}Ar$ background seen by DarkSide (arXiv:1802.07198)
- Expect same reduction of $^{42}Ar$
  - Also cosmogenically produced
  - Its beta-decaying progeny $^{42}K$ is a major background in the $0\nu\beta\beta$ ROI
  - This is a key part of obtaining the low backgrounds needed!
- Use of UGLAr means we are dominated by $2\nu\beta\beta$ at low energies, not $^{39}Ar$!
  - Allows lots of interesting physics searches through spectral distortions

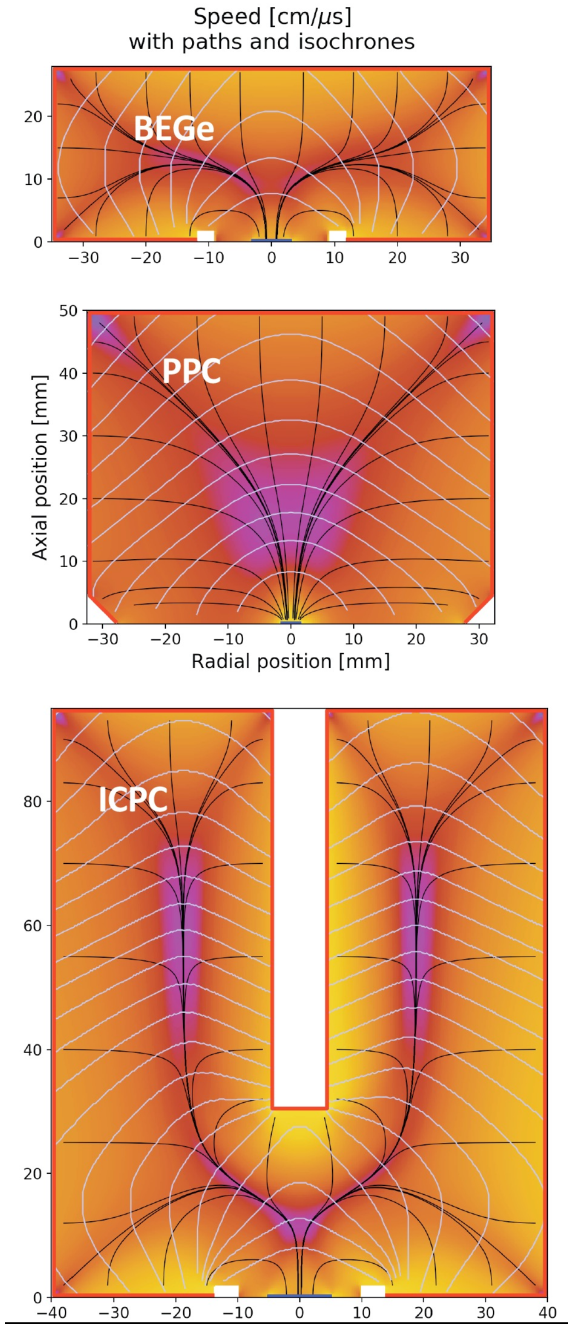
# High-Purity Germanium Detectors

- Most detectors will be of ICPC type
  - Large mass, good drift time, high surface area to volume ratio




R. J. Cooper et al., NIMA 629 (2011), 303-310

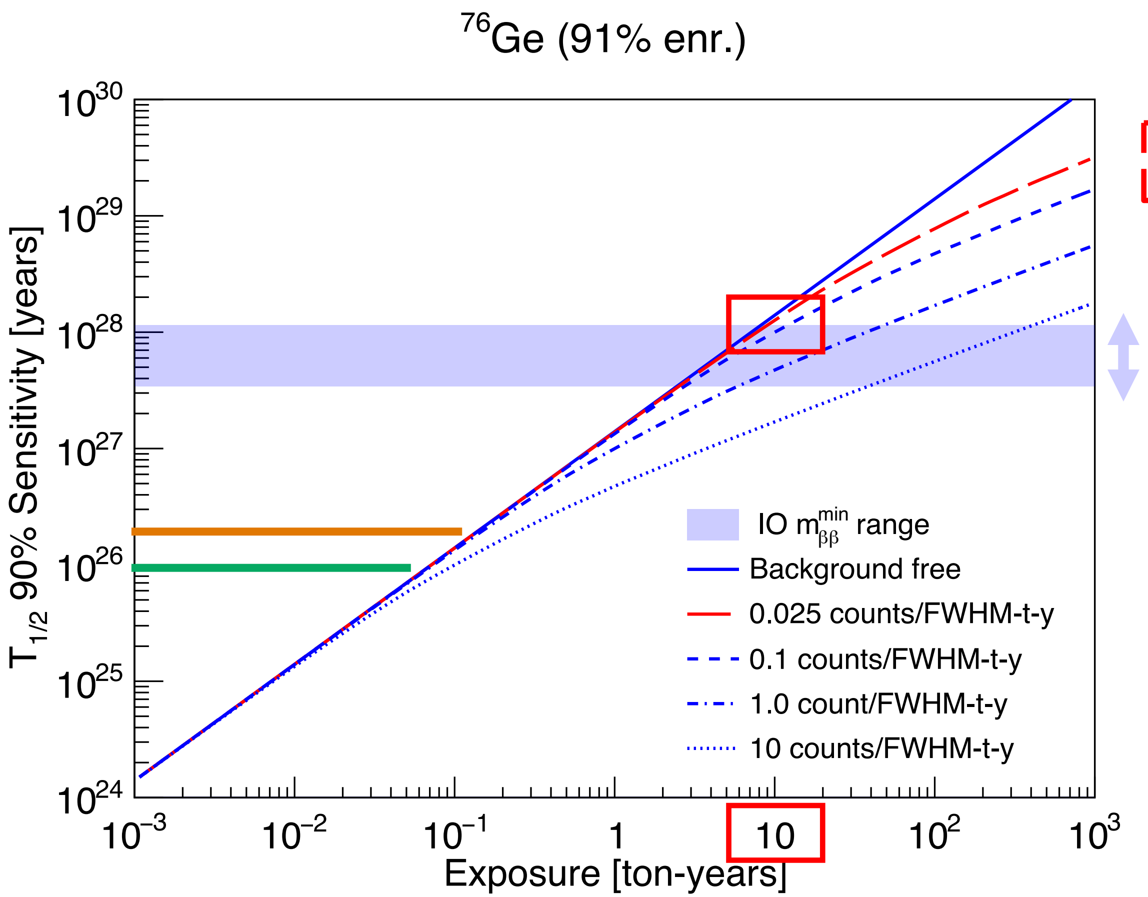


# Expected Sensitivity in ROI

- After 10 years, should probe the inverted hierarchy expectation
  - $T_{1/2}^{0\nu\beta\beta} \sim 10^{28}$ yr

GERDA final result:
- $T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{26}$ yr

MAJORANA final result:
- $T_{1/2}^{0\nu\beta\beta} > 8.3 \times 10^{25}$ yr




LEGEND-1000 expectation

Theoretical Uncertainty



arXiv:2107.11462