LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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LA-UR-18-29731

Los Alamos NATIONAL LABORATORY EST. 1943

NSAC 2015 Long Range Plan

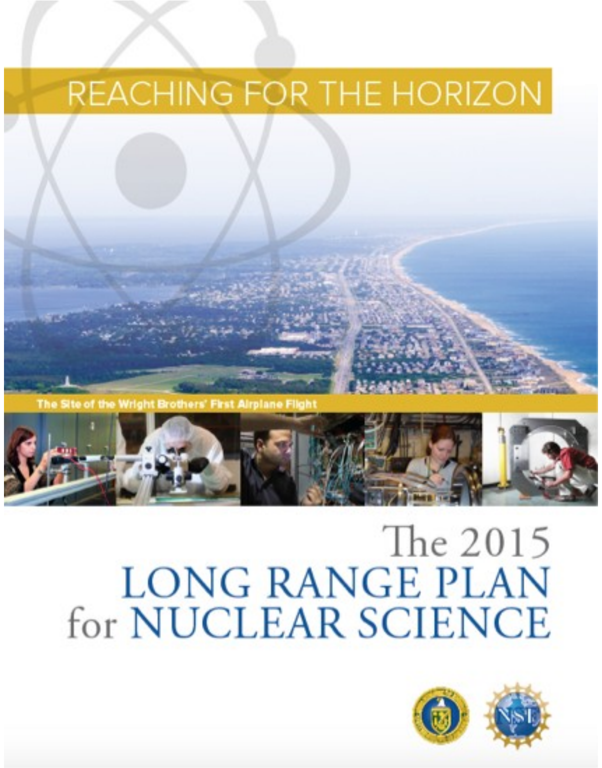
RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

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

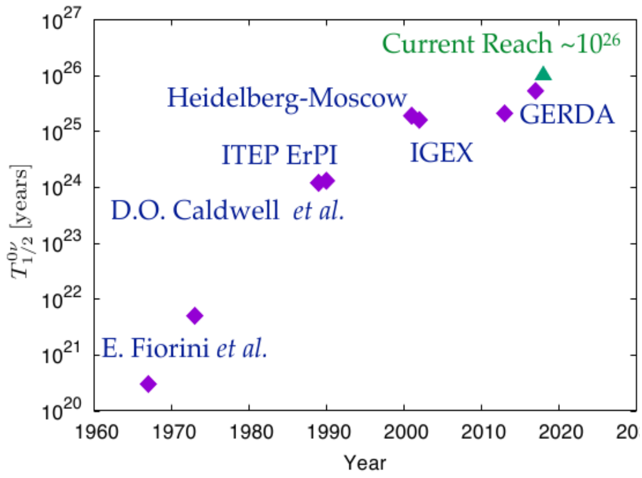
A ton scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.



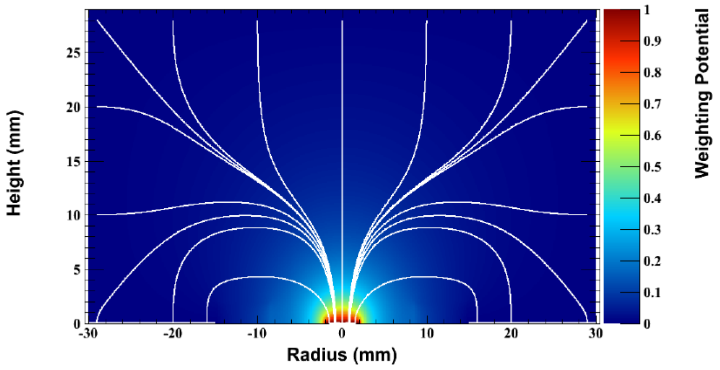
So why ^{76}Ge ?

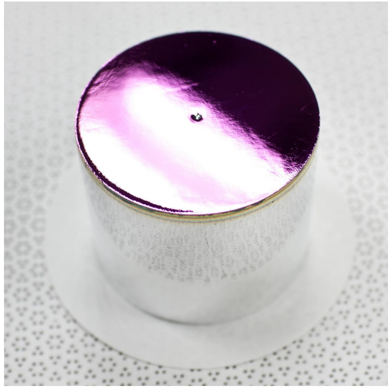
- Germanium as material has several advantages
- Well understood Ge-detector technology
  source = detector
- Excellent energy resolution (best of all 0νββ)
  2.5 keV FWHM @ 2039 keV (Q-Value) = 0.12%
- Only 7% natural abundance
  <u>BUT</u>
  Demonstrated ability to enrich to 87% (and beyond)
- Powerful background rejection
  - Multiplicity
  - Timing
  - Pulse-shape discrimination
- Ge experiments have achieved the lowest background level over the 0νββ-ROI among all other technology



Point Contact Detector Technology

- Significant contribution typically only made by holes, relatively insensitive to electron trapping
- Charge collection and signal induction characteristics can be used to separate single-site and multi-site events





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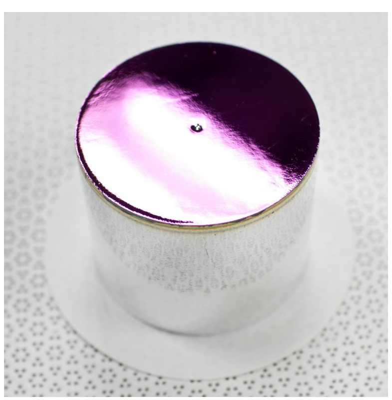
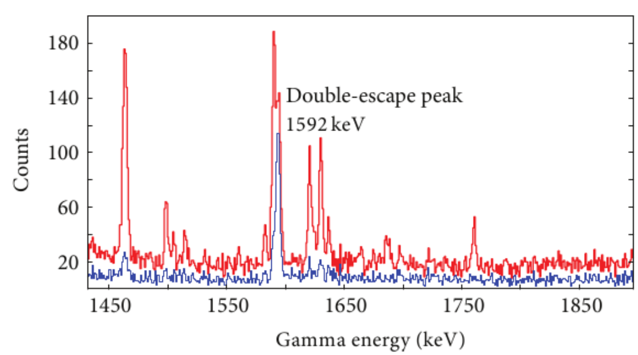
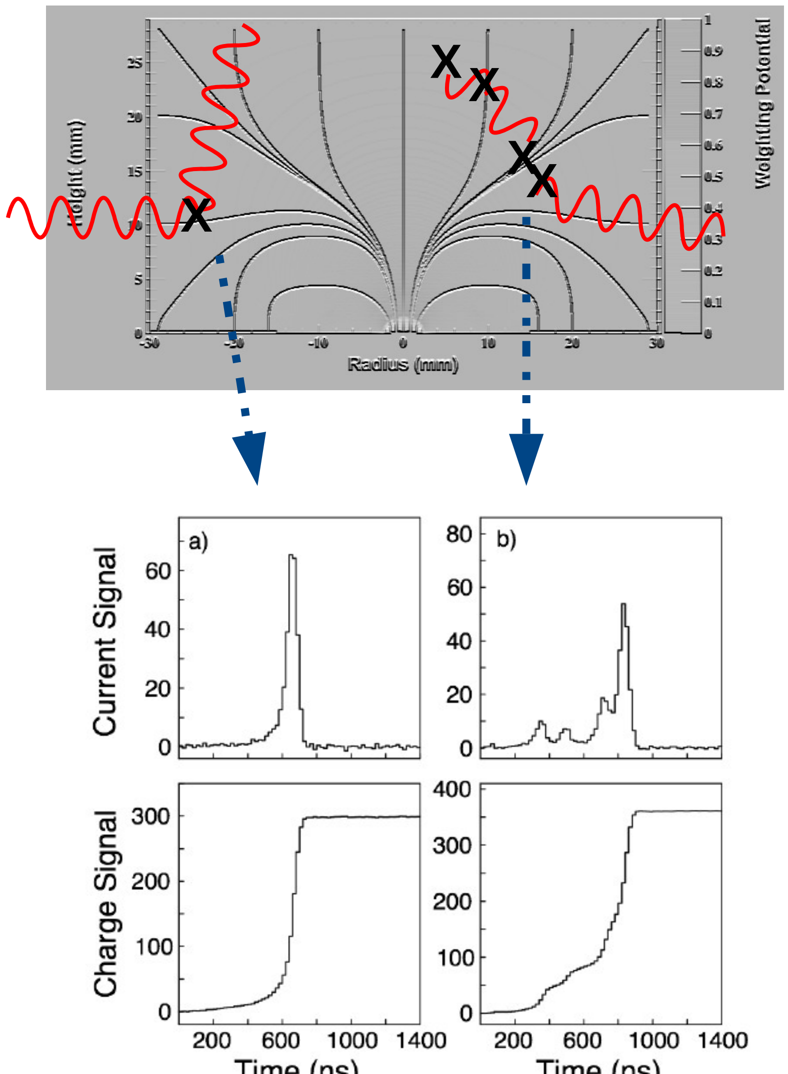






single-site *multi-site*

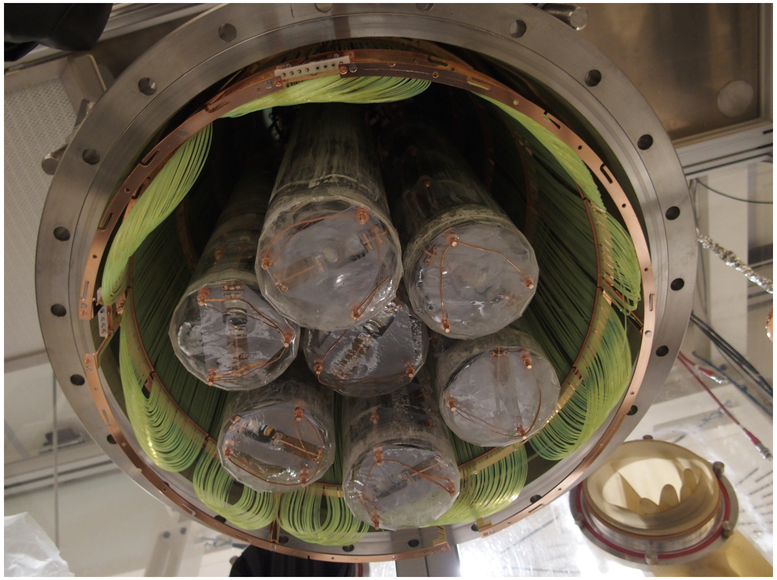
MAJORANA and GERDA

- MAJORANA DEMONSTRATOR:

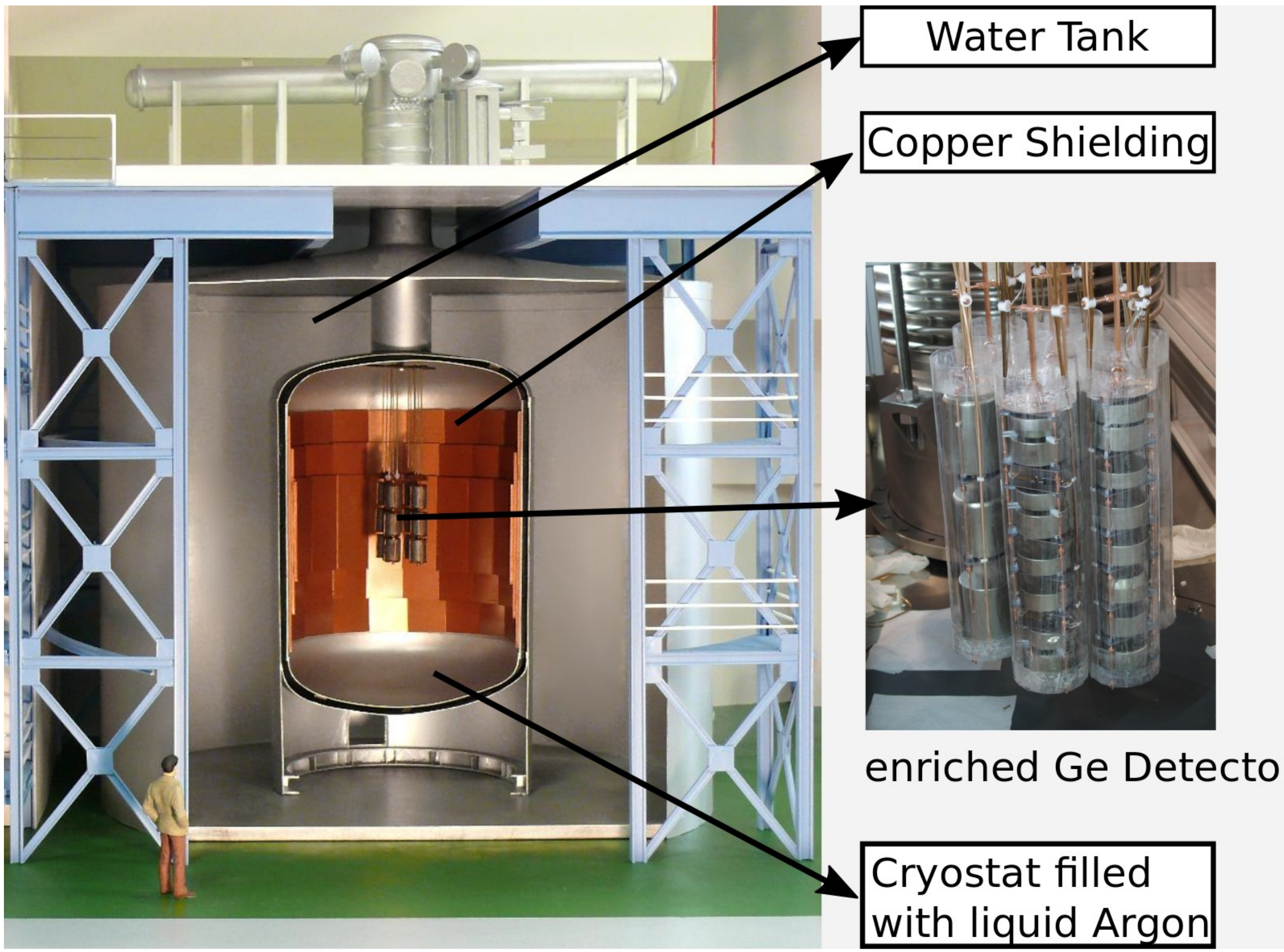
  “traditional” approach,
  high-Z shielding,
  vacuum cryostats,
  ultra-clean materials
  and construction

- GERDA

  Novel configuration
  Germanium crystals
  immersed in LAr,
  “additional veto”

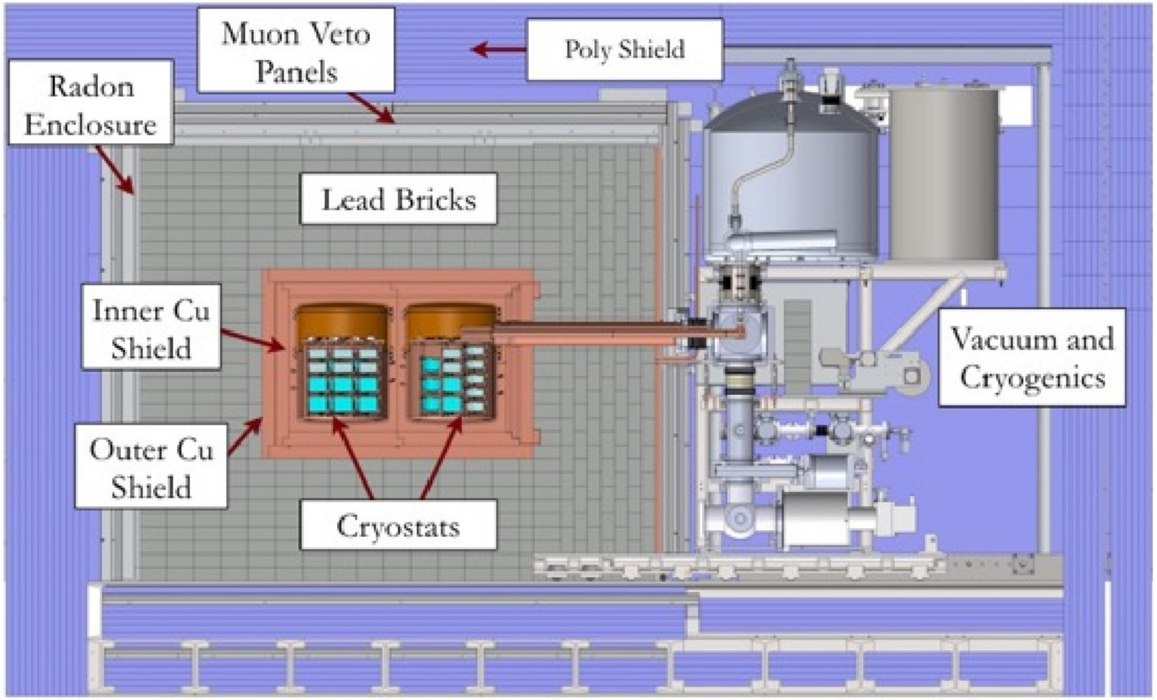


GERDA at LNGS (ITA)



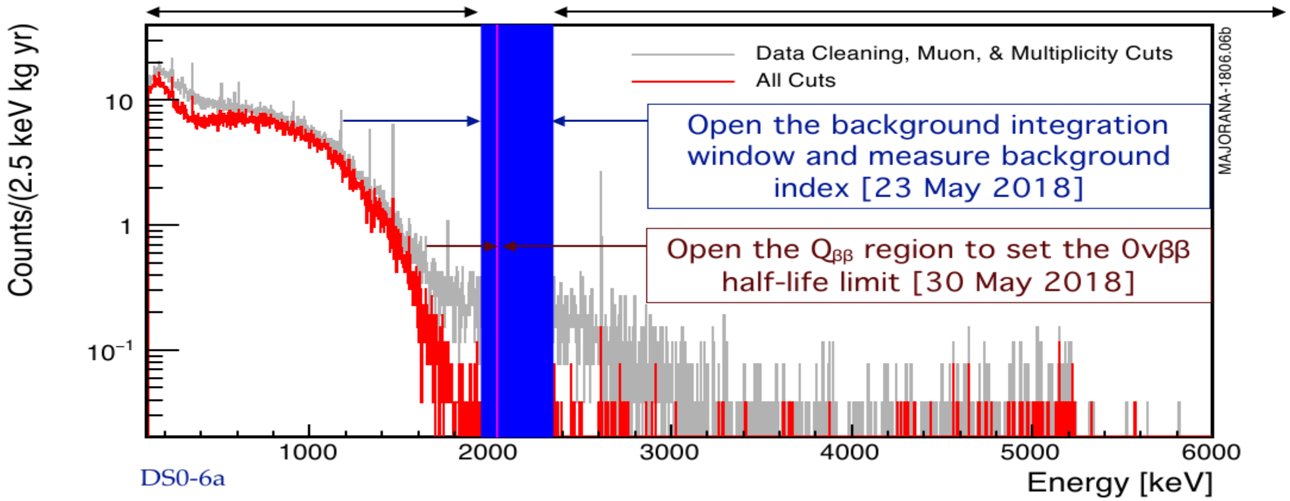
- 3000 m.w.e of rock
- 590m^3 of Water (diameter 10m)
- 64 m^3 of LAr (diameter 4m)
- Ge detector array
  - 30 BeGe (20kg)
  - 7 Coax (15.6kg)
  - 3 nat (7.6kg)
- 58.9 kg yr exposure (Neutrino 2018)

MAJORANA at SURF (USA)

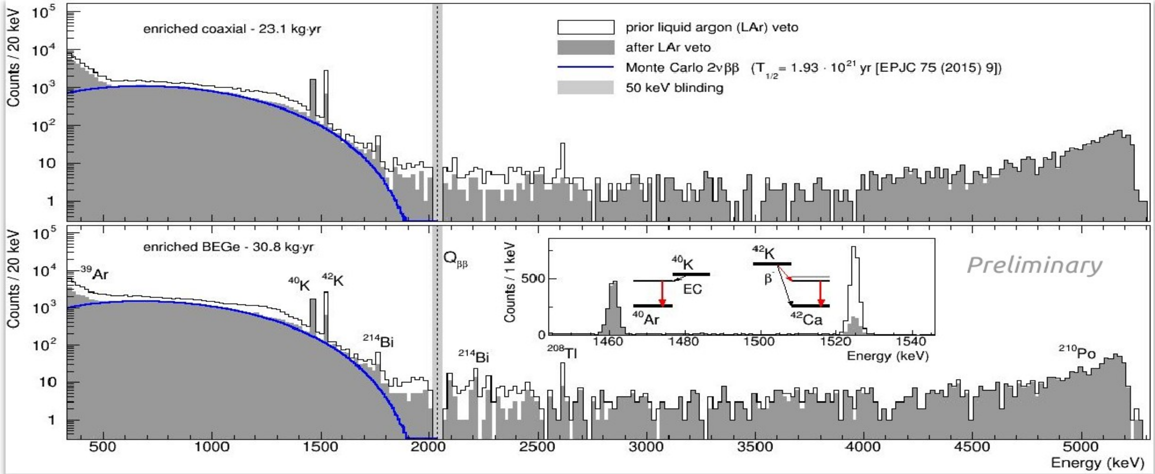


- 4300 m.w.e of rock
- 12inch of PolyShield
- Radon exclusion box
- 54 ton of Lead (90cm)
- 2.7 ton of Copper (inner 4inch electro-formed)
- 2 independent cryostats
  - 29.7kg enriched Ge
  - 14.4kg nat Ge
- 26 kg yr exposure (Neutrino 2018)

MAJORANA and GERDA



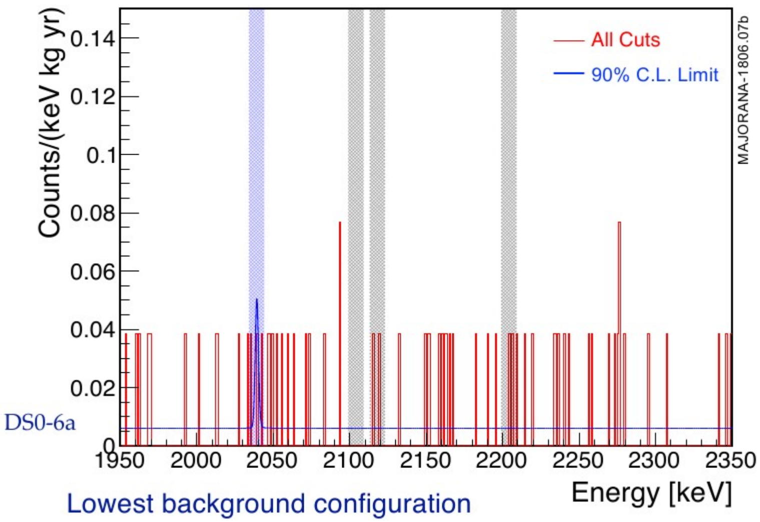
doi.org/10.5281/zenodo.1286900

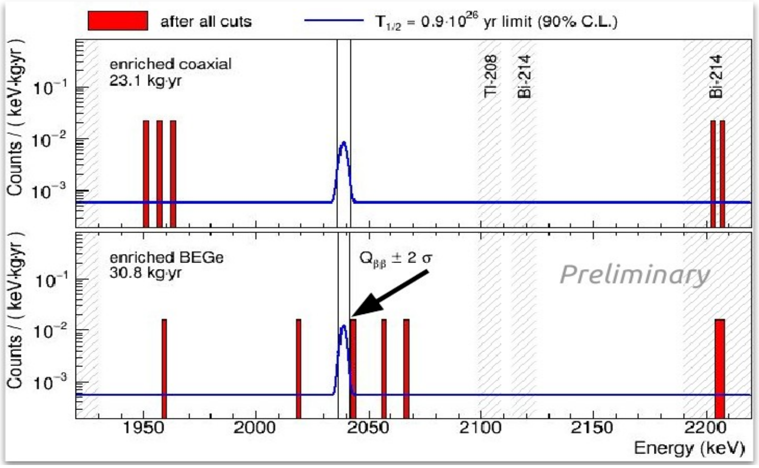


doi.org/10.5281/zenodo.1287604

MAJORANA and GERDA

LEGEND





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GERDA

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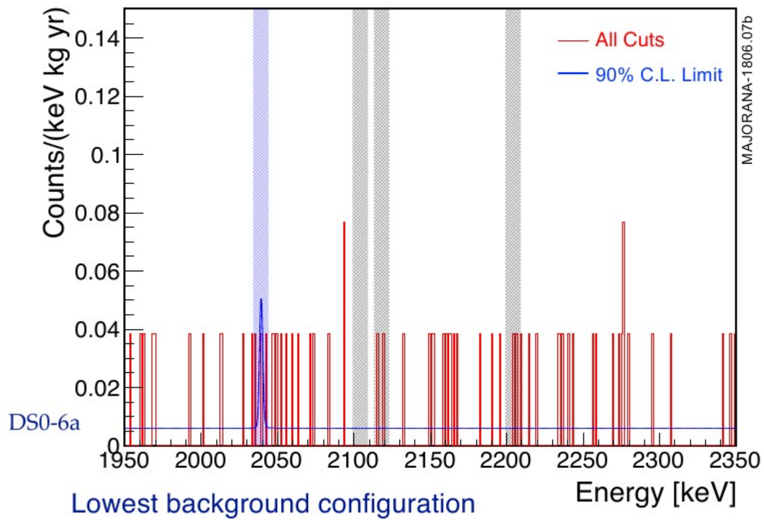
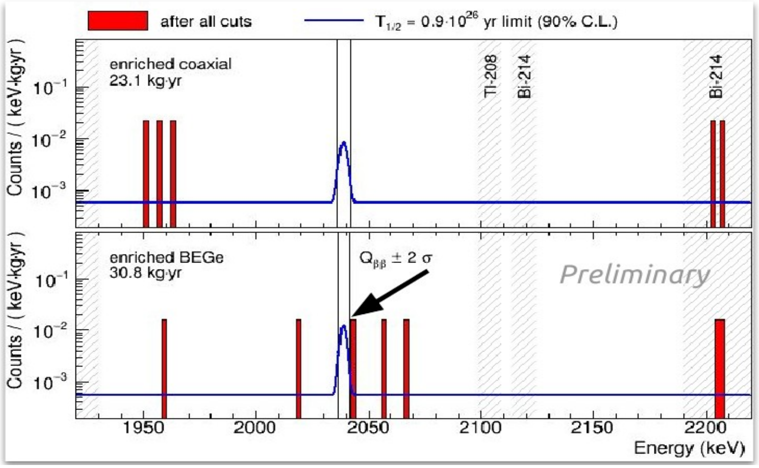


- background
  4.7±0.8 x 10^{-3} cts/(keV kg yr)
- resolution (FWHM)
  2.5 keV @ Q-Value
- Sensitivity
  4.8 x 10^{25} yr (90% CL)
- Limit
  $T_{1/2}$ > 2.7 x 10^{25} yr

world's best

doi.org/10.5281/zenodo.1286900



- background
  $0.6^{+0.4}_{-0.2}$ x 10^{-3} cts/(keV kg yr)
- resolution (FWHM)
  3.0 keV @ Q-Value
- Sensitivity
  1.1 x 10^{26} yr (90% CL)
- Limit
  $T_{1/2}$ > 0.9 x 10^{26} yr

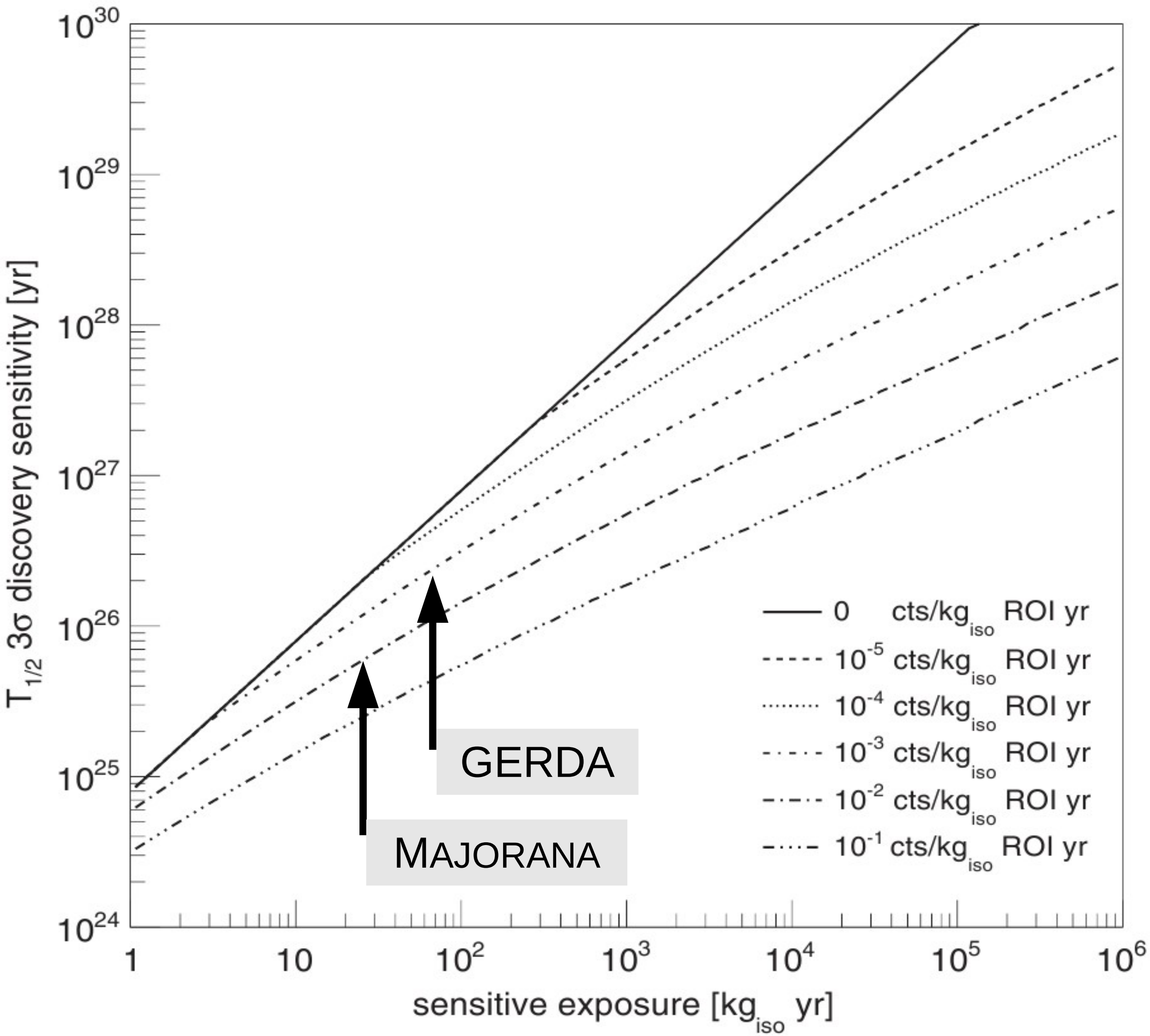
world's best

GERDA

doi.org/10.5281/zenodo.1287604

So whats next ?

Sensitivity vs Exposure for ^{76}Ge

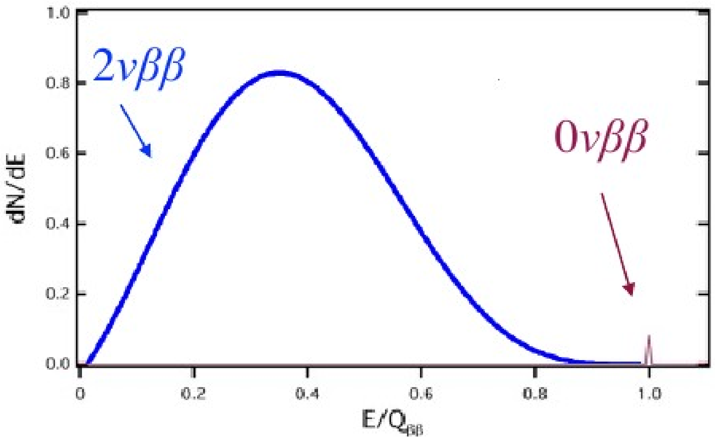


Assuming ROI = 3σ
≈ 1.3 FWHM

Figure taken from
PRD 96, 053001 (2017)

General 0νββ searches

- ^{76}Ge, ^{130}Te, and ^{136}Xe experiments have attained results $T_{1/2} > 10^{25}$ years with 30-100 kg years exposures
- To cover inverted hierarchy ($T_{1/2} \sim 10^{27}$-10^{28} years)
- Aim for backgrounds of less than 0.1 cts / t-year in the ROI



Half life (years)	~Ge Signal (cnts/ton-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1
$>10^{29}$	0.05

Background contributions

- Primordial natural radioactivity (Th, U, K)
- Cosmogenic activation while material is above ground
- Background from surroundings
- Rn plate-out
- Muon induced backgrounds
- 2-neutrino decay background !!!
  (negligible for Ge because of excellent resolution)

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- Muon induced backgrounds
- 2-neutrino decay background !!!
  (negligible for Ge because of excellent resolution)

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

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Mission statement

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.*

LEGEND

47 Institutions, 250 Scientists, worldwide

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.

Joint Res. Centre, Geel
Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ.
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London
Los Alamos Natl. Lab.

Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Tech. Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

Best of MJD and GERDA

- Radiopurity of nearby parts (FETs, Cables, Cu mounts, ...)
- Low noise electronics, better PSD
- Low energy threshold (cosmogenic and low-E background)
- LArgon active veto
- Low-A shield, no Pb
- Clean fabrication techniques
- Control of surface exposure

Staged approach

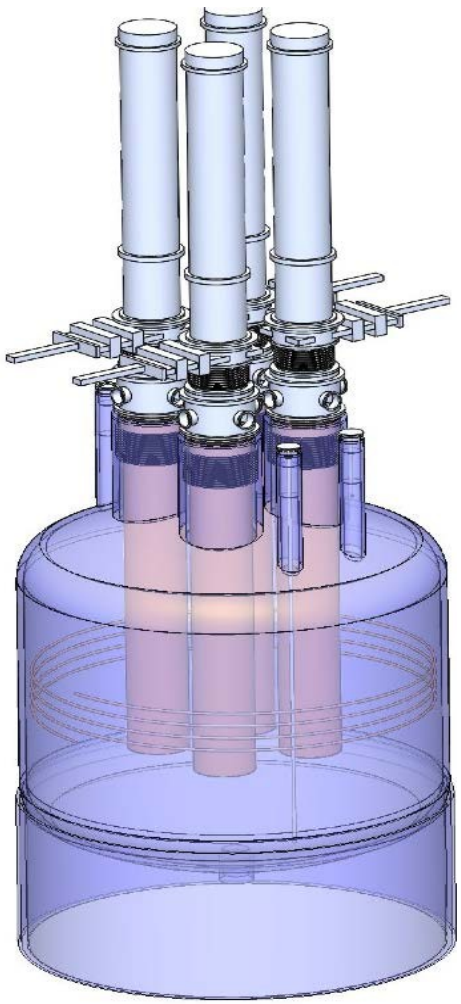
LEGEND-200:

- Up to 200kg of ^{enr}Ge
- Modification of existing GERDA infrastructure at LNGS / Italy
- BG goal:
  0.6 cts/(FWHM-t-yr)
  (x 2-3 lower than current)
- Start in 2021

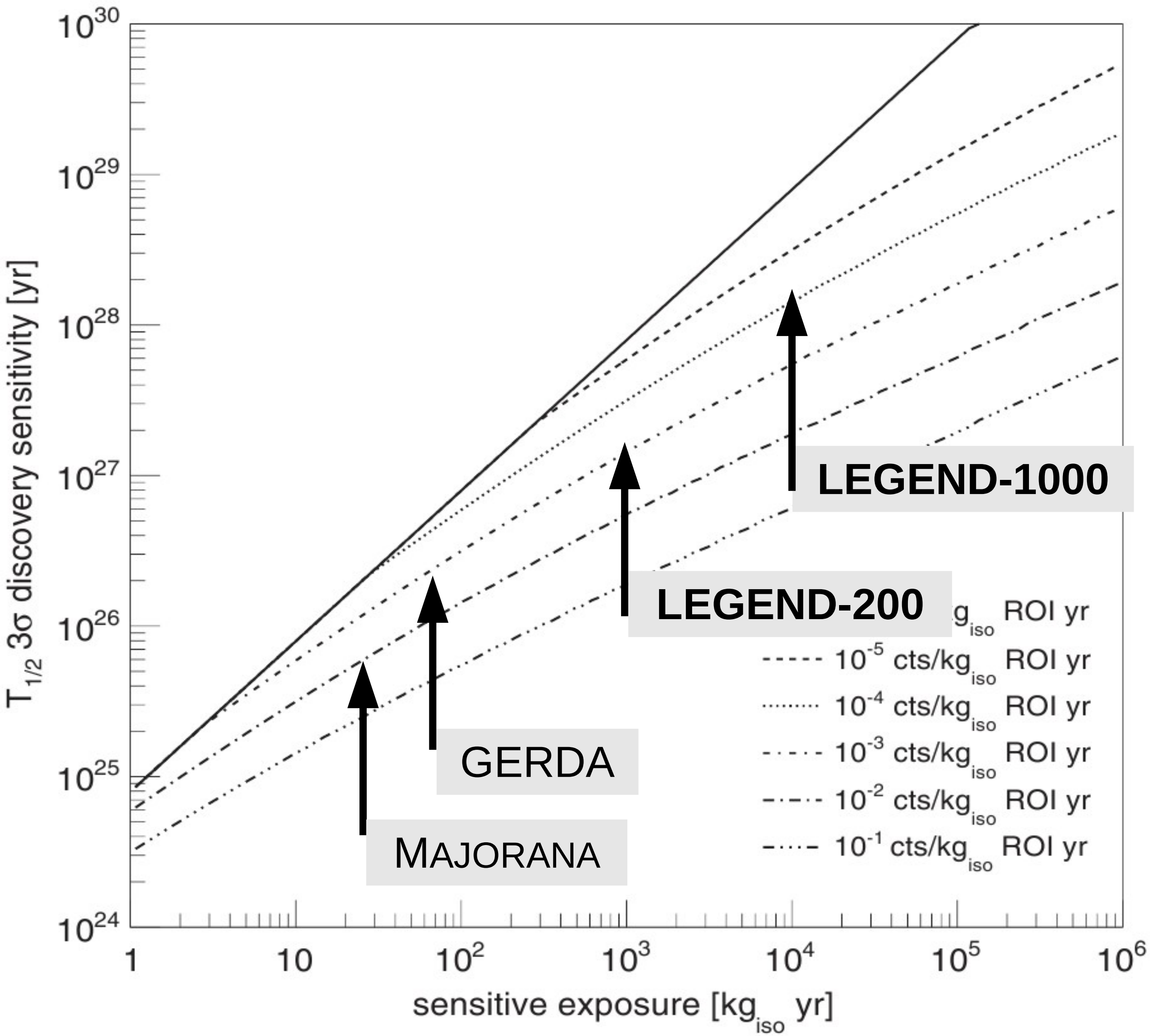
Staged approach

LEGEND-1000:

- 1000kg of ^{enr}Ge
- Staged construction
- Location: TBD
- BG goal: < 0.1 cts/(FWHM-t-yr)
- Start in mid 2020s



Sensitivity vs Exposure for ^{76}Ge



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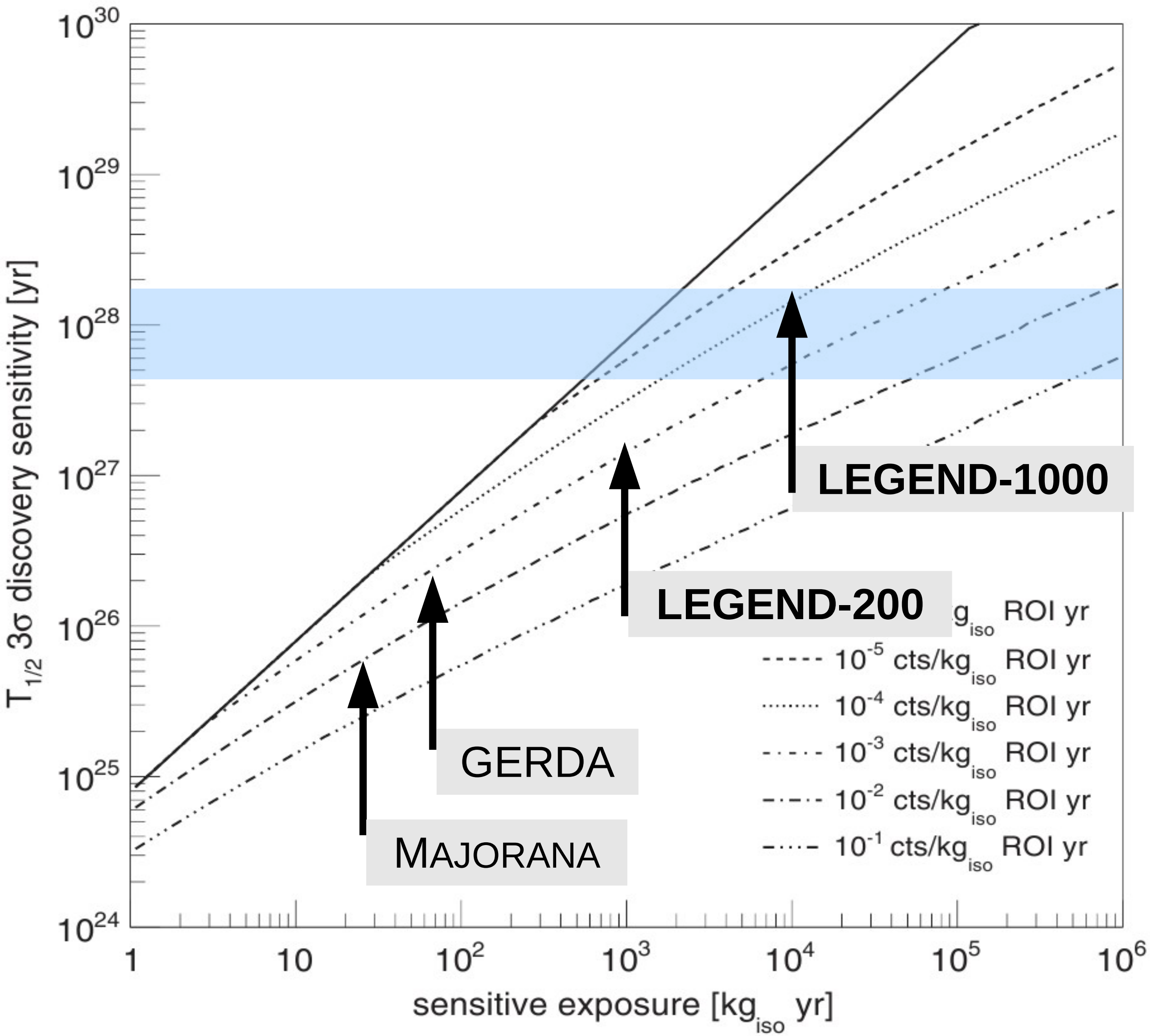


Inverted hierarchy range
(range for various theories)

Assuming ROI = 3σ
≈ 1.3 FWHM

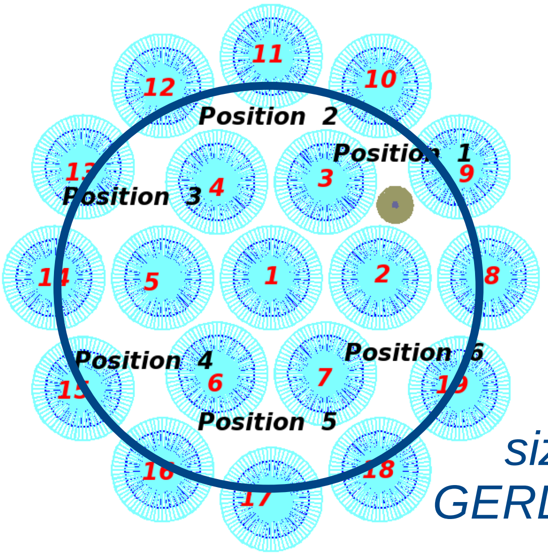
Figure taken from
PRD 96, 053001 (2017)

Design Criteria

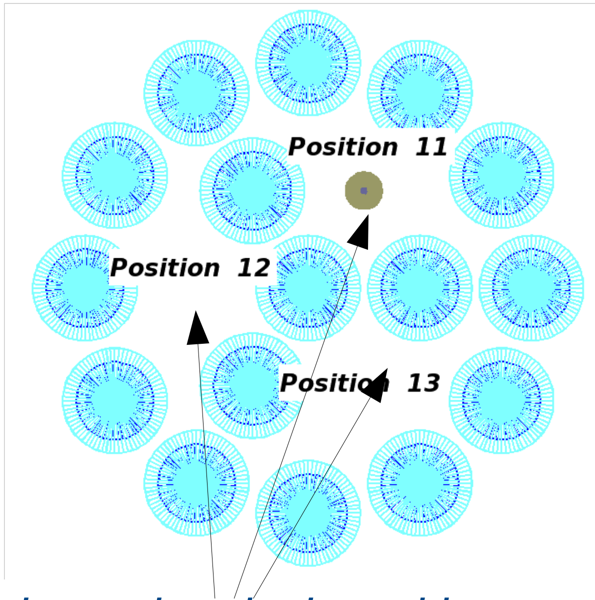
- 200 kg – Phase allows operation of previously installed detectors in existing infrastructure to obtain near term physics results
- Ton-scale phased approach allows to take physics data while array expands
- 1000 kg of enriched material :
about 300-500 detector units with an average detector mass of 2-3 kg
- Maintain energy resolution of ~2.5keV@2039keV

LEGEND 200

- Reuse existing GERDA infrastructure at LNGS
- Modify internal cabling/piping to accommodate bigger array
- Under investigation: alternative string arrangements for calibration and improved LAr readout
- Improvements:
  - LAr readout (~factor of 2 as shown on test stands)
  - cleaner cables, lower mass
  - lower noise electronics
  - use of MJD efCu structures
  - first larger Ge-detectors (1.5 – 4 kg)
- Data taking by 2021



size of the GERDA-Phase II array



alternative design with extra space for calibration sources or LAr readout

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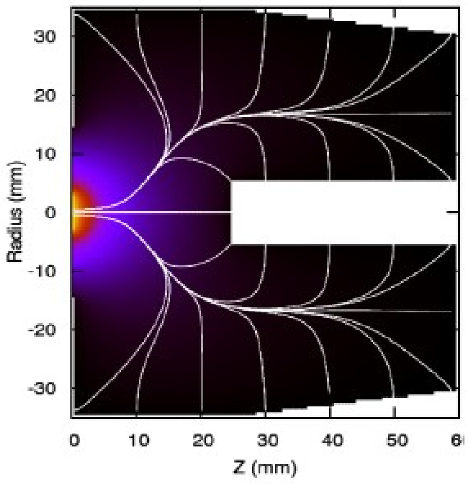
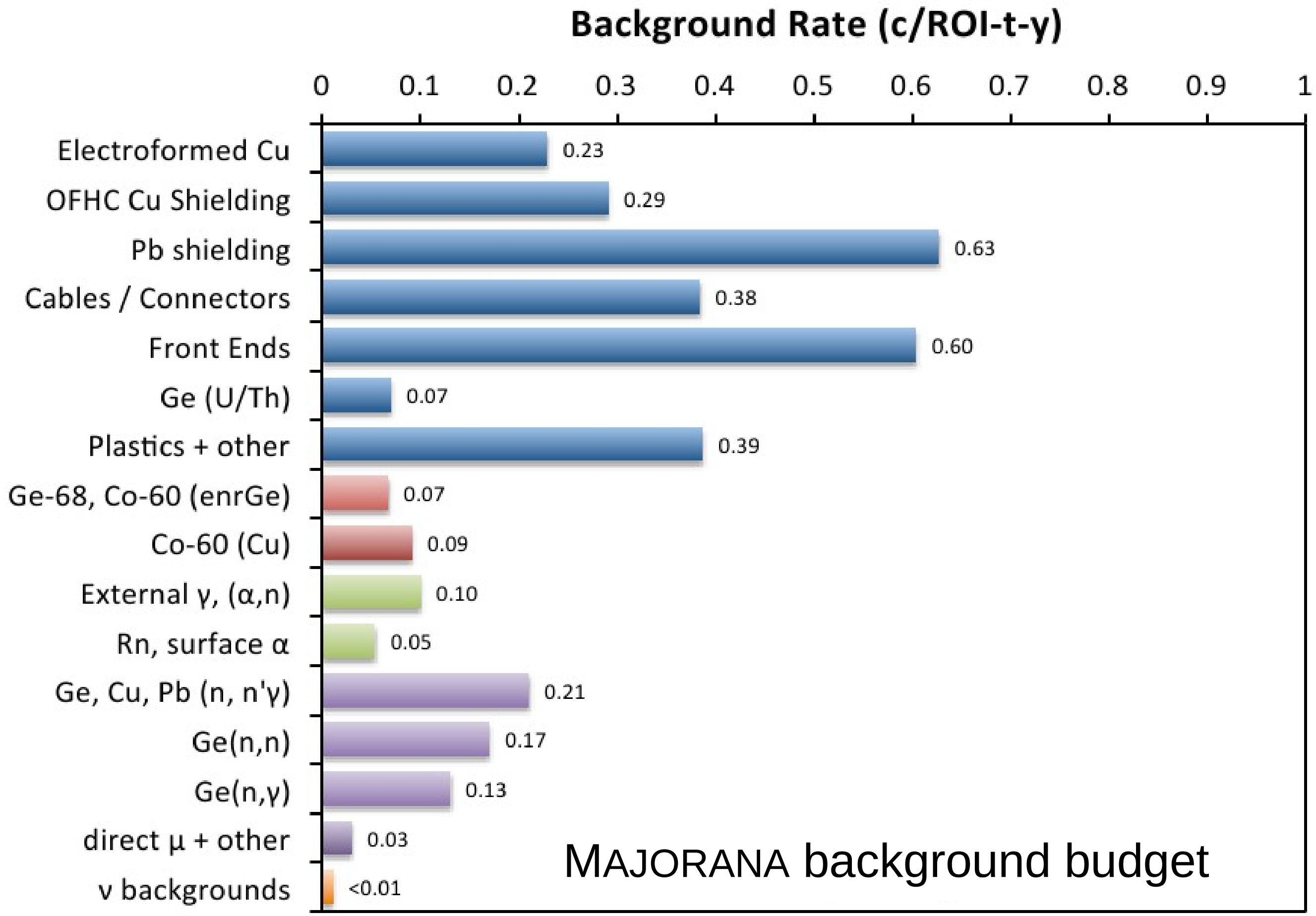
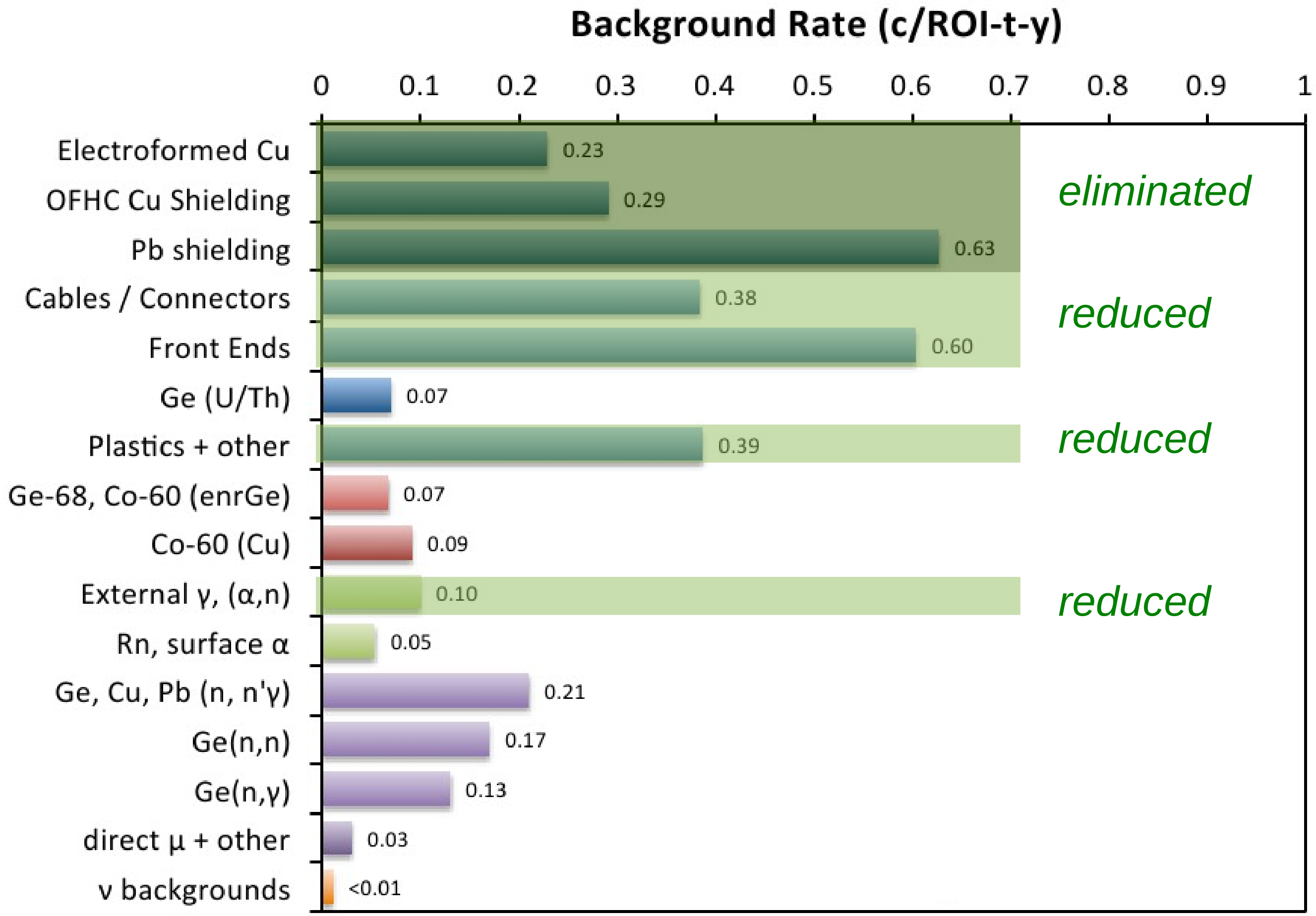


LEGEND 200 - Background



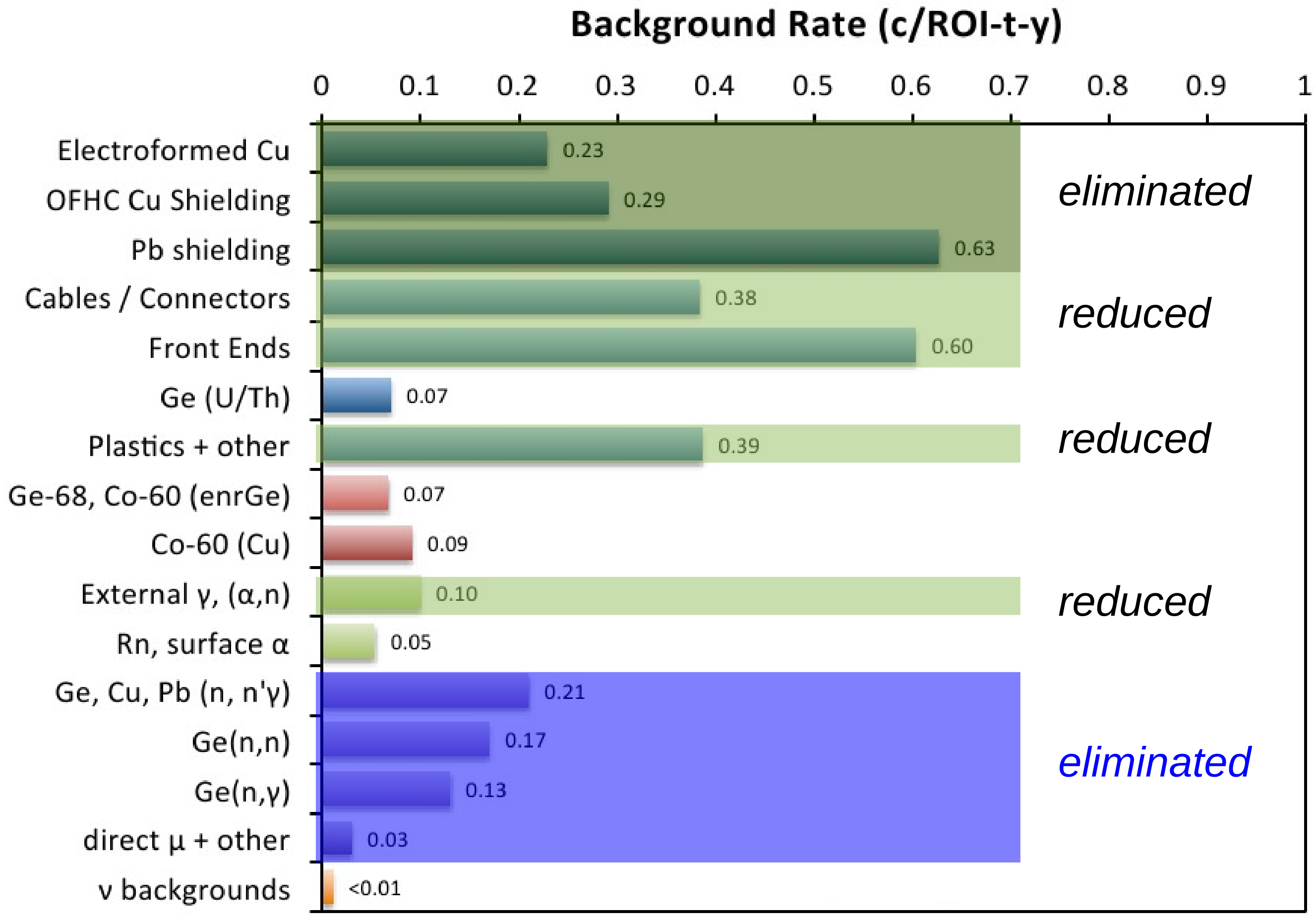
LEGEND 200 - Background

- clean active shield



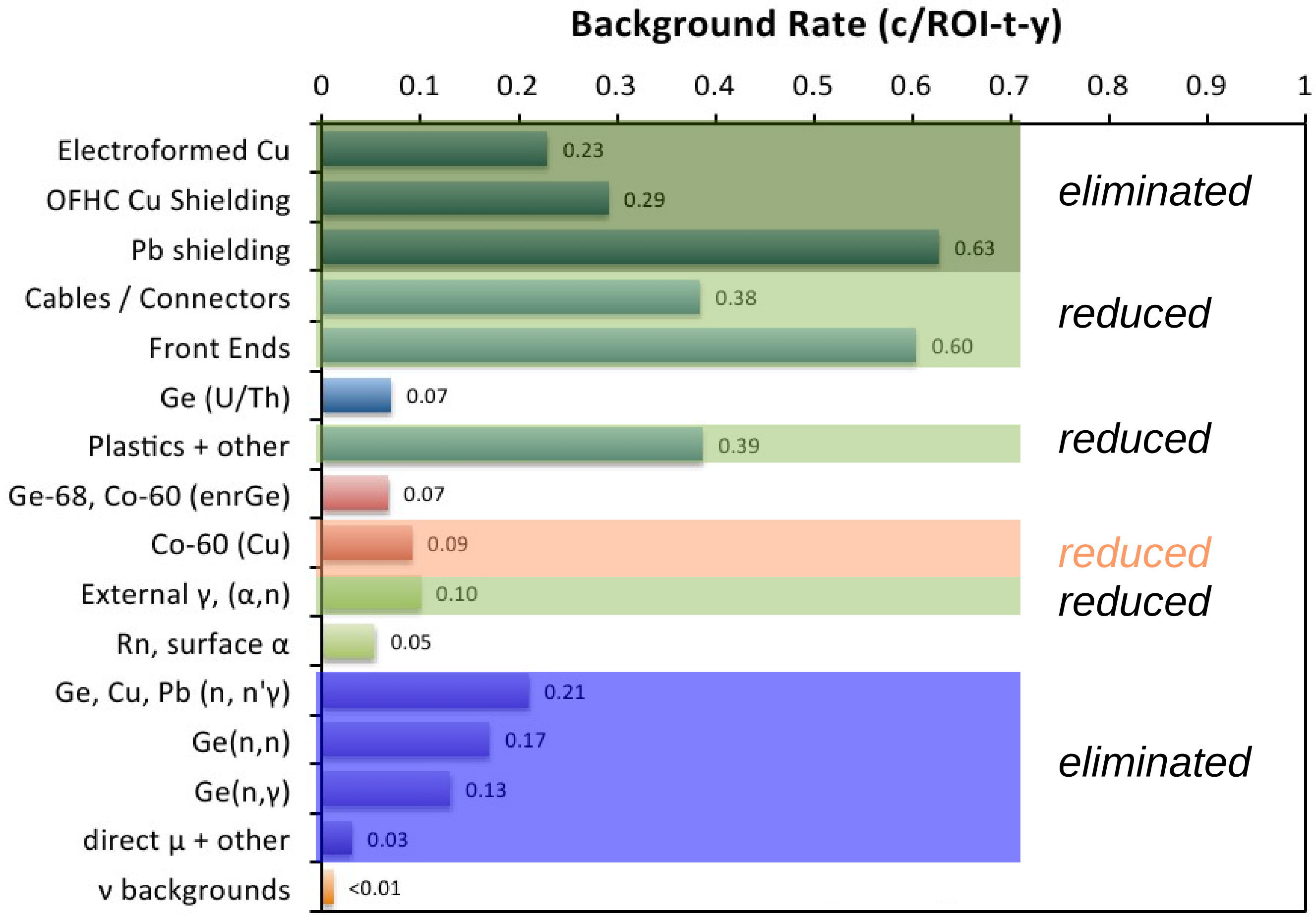
LEGEND 200 - Background

- clean active shield
- active shield (and deeper for LEGEND-1000)



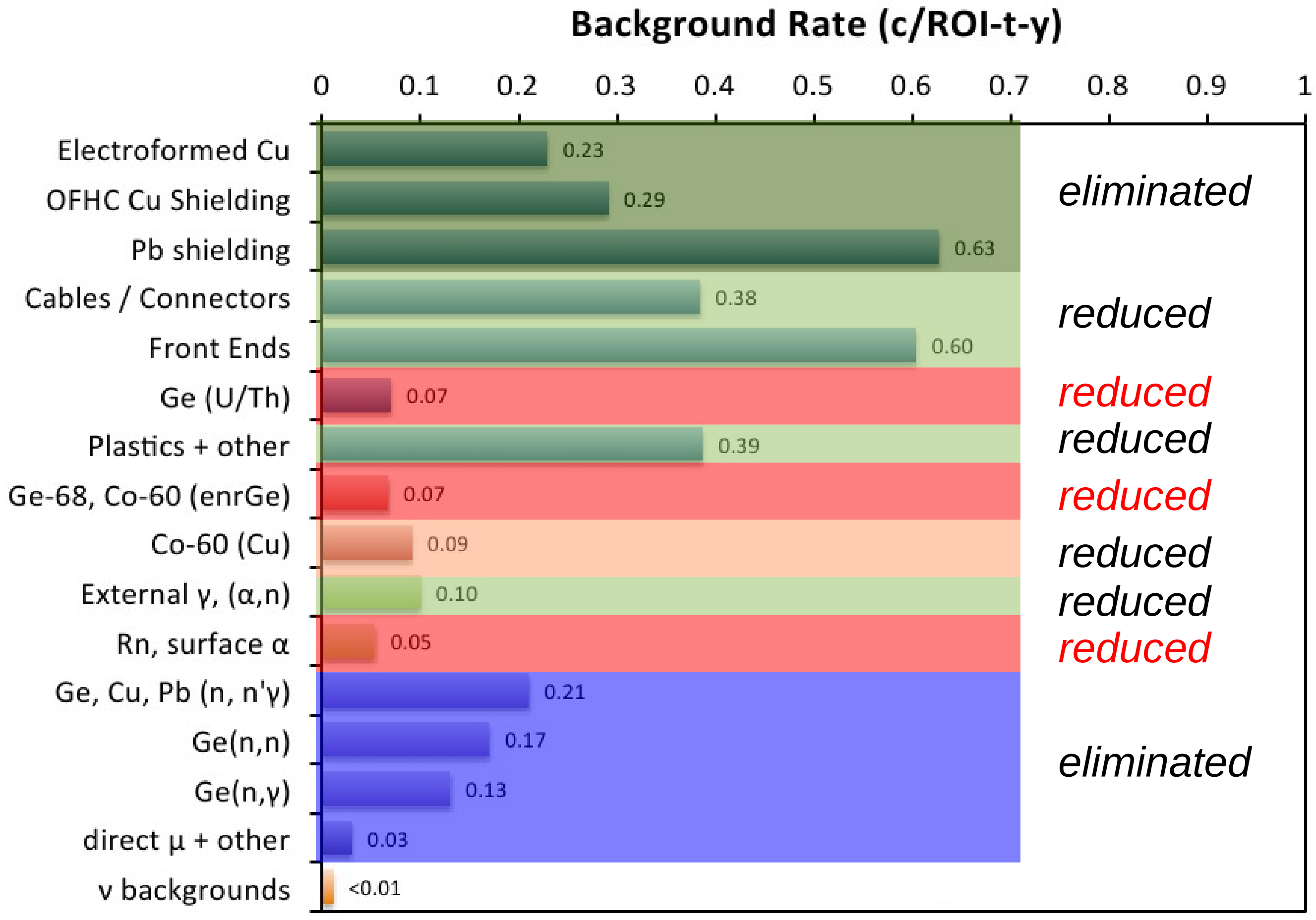
LEGEND 200 - Background

- clean active shield
- active shield (and deeper for LEGEND-1000)
- all efCu from SURF



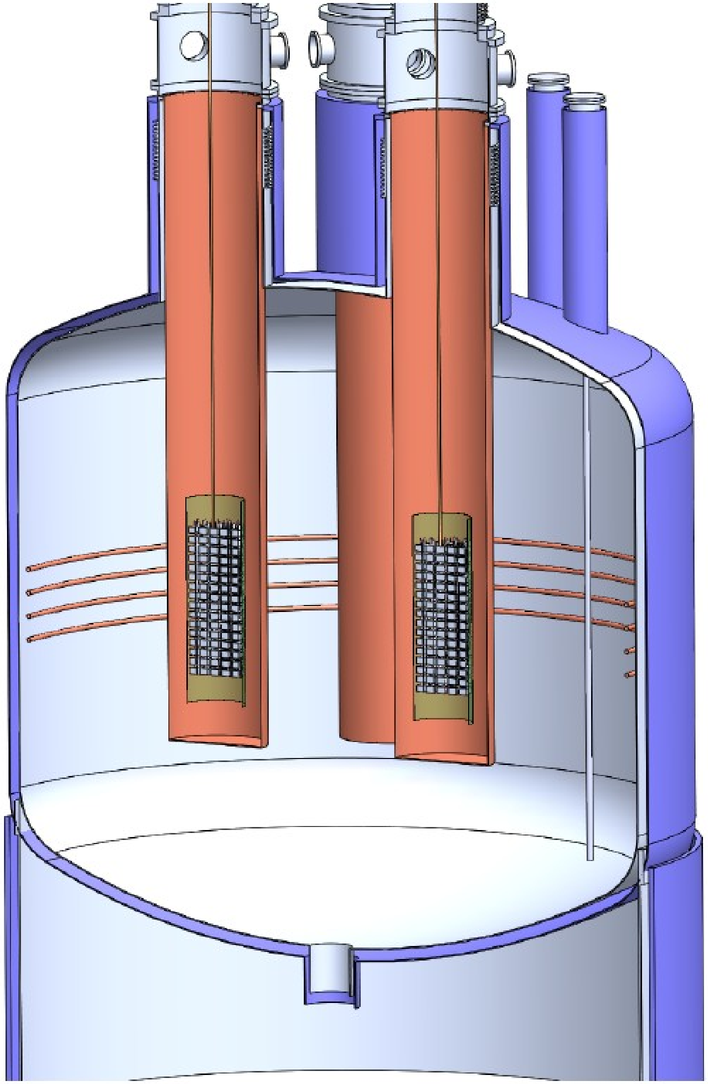
LEGEND 200 - Background

- clean active shield
- active shield (and deeper for LEGEND-1000)
- all efCu from SURF
- Current values are upper limits, use MJD and GERDA to quantify it better



LEGEND 1000

- BG: 0.1 cts / (FWHM t year)
- 4-5 independent cryostats with ~100 detectors (200-250kg) each
- Use of depleted Argon
- modest-size Argon in water tank OR larger LAr cryostat with separate neutron moderator
- **Goal**:
  10 ton-years exposure with 1 ton detector to reach 10^{28} year limit ($m_{\beta\beta}$ < 10meV)

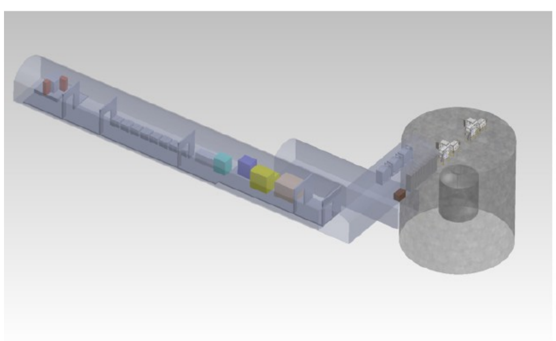


LEGEND 1000 Laboratory

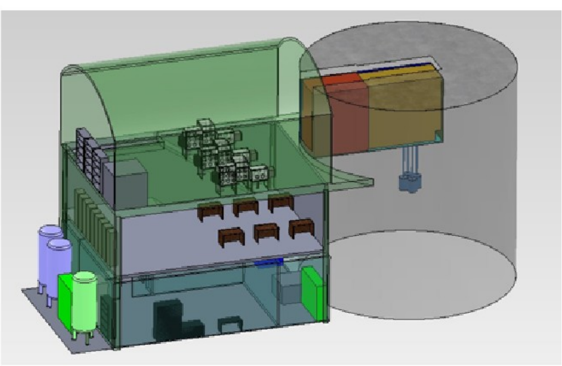
- Several host labs under investigation
- Cosmogenic background studies on-going with GERDA and MJD designs and data

Eur.Phys.J. C78 (2018) no.7, 597 in preparation

SNOLAB cryopit concept

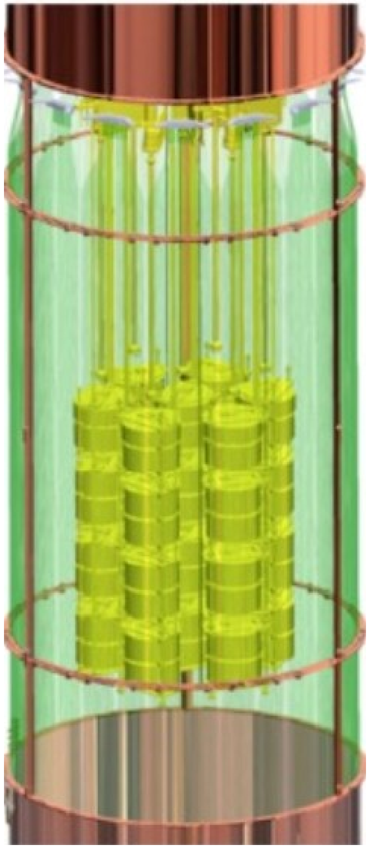


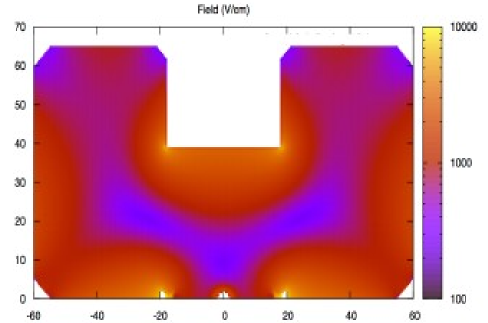
Generic Cavity design

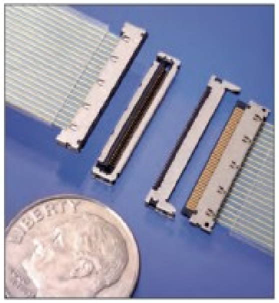


LEGEND R&D

- Larger detector units
  - fewer components per kg
  - enhanced PSD
  - alternative designs
- Improved LAr readout
- Depleted Argon in the active veto region
- Electronics, Front ends and cabling
- Advanced electroformed materials
- Alternative shielding/cooling materials (LNe, PEN, doped LAr)
- Low-mass connectors
- Alternative cryostat designs
- Cosmogenic backgrounds
- Analysis – machine learning, advanced PSD







LEGEND R&D

- Larger detector units
  - fewer components per kg
  - enhanced PSD
  - alternative designs → Reine,MH 00001 (10/27/18)
- Improved LAr readout
- Depleted Argon in the active veto region
- Electronics, Front ends and cabling → Clark,LN 00007 (10/27/18); Willers,EN 00002 (10/25/18)
- Advanced electroformed materials
- Alternative shielding/cooling materials (LNe, PEN, doped LAr) → Cheng, HA 00077 (10/26/18)
- Low-mass connectors
- Alternative cryostat designs
- Cosmogenic backgrounds → Barton, FN 00010 (10/26/18)
- Analysis – machine learning, advanced PSD → Hainsel, HA 00072 (10/26/18)

Talks / Poster @DNP

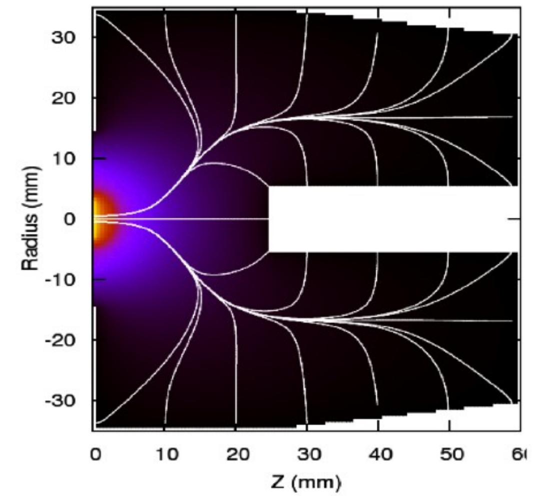
- Reine,MH 00001 (10/27/18)
- Clark,LN 00007 (10/27/18)
- Willers,EN 00002 (10/25/18)
- Cheng, HA 00077 (10/26/18)
- Barton, FN 00010 (10/26/18)
- Hainsel, HA 00072 (10/26/18)

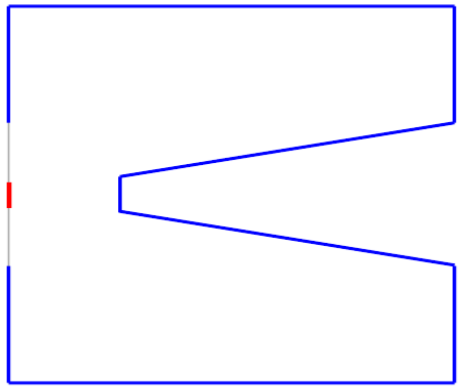
LEGEND Summary

- Ultimate Goal:
  - build a ton-scale experiment with
  - 10-t-year exposure,
  - background less than 0.1 cts/FWHM-t-year
- Selecting the best technologies from MJD and GERDA, as well as contributions from other groups
- Phased implementation 200—500—1000 kg
- Some LEGEND-200 funding secured
- LEGEND-1000 R&D ongoing
- Coupled with excellent energy resolution ^{76}Ge has a discovery potential at a half-life near 10^{28} years

LEGEND Larger Detectors

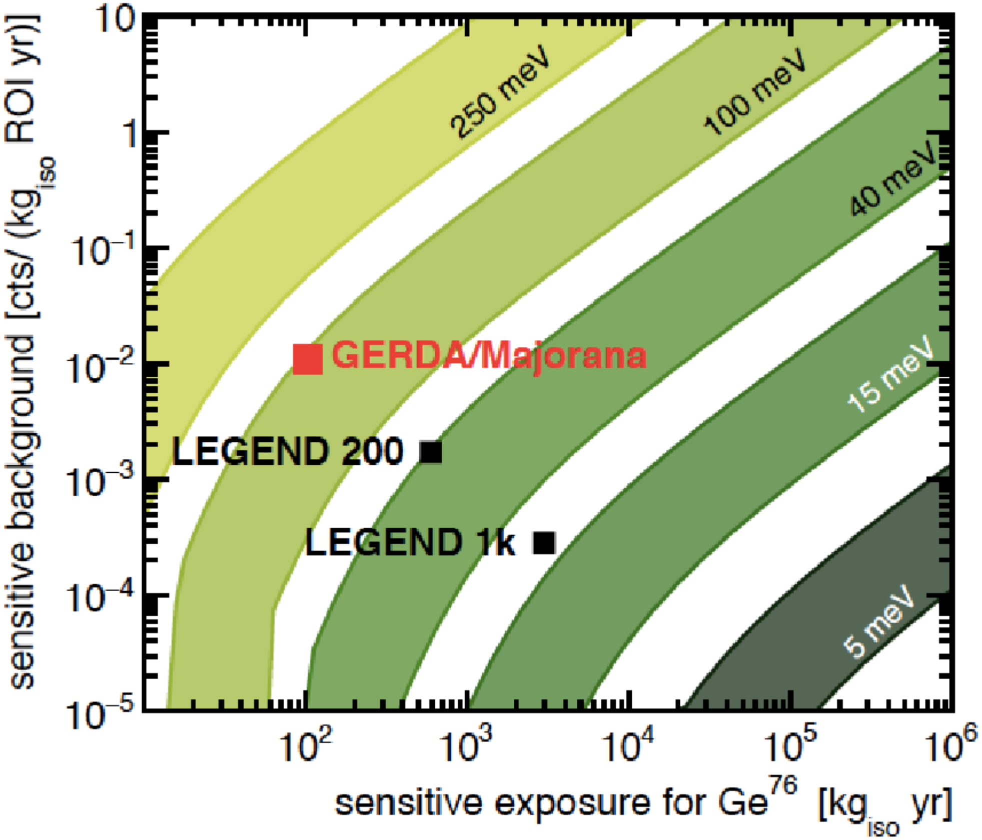
- BEGe and PPC detectors are limited in size (~1.5 kg, 8x5 cm)
- inverted coax,
  - first smaller units installed in GERDA
  - first large prototypes (~3kg) delivered (2 at ORNL, 1 at LANL)
  - tapered cylindrical hole inside
- goal up to 4kg





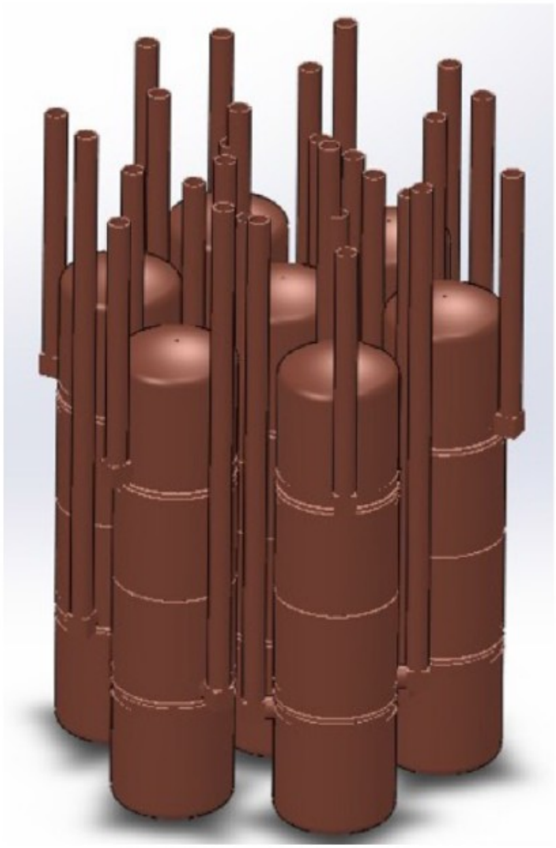
Backgrounds, Resolution, Discovery

Discovery probability of next-generation neutrinoless double-beta decay experiments
Matteo Agostini, Giovanni Benato, and Jason Detwiler arXiv:1705.02996v1



LEGEND 1000 Designs

7 strings with 5 modules each containing 30 kg provides 1050 kg. (4 mods. Shown) About 2 m tall, 1.6 m diam.



Hang from cable feedthru/pump ports for insertion into liquid. Removable flange allows variable cryostat length.

Electroformed Copper

- MJD copper electroformed underground at PNNL and SURF
  - Th decay chain < 0.1 µBq/kg
  - U decay chain < 0.1 µBq/kg
- Machined and stored underground
- LEGEND production ready to go