LEGEND
(Large Enriched Germanium Experiment for Neutrinoless ββ Decay)

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on behalf of the LEGEND Collaboration

SNOLAB Future Projects Planning Workshop
August 16, 2017

UNIVERSITY OF SOUTH CAROLINA

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

SNOLAB

LEGEND

- Mission statement adopted in Oct. 2016:

> The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results.

- Collaboration-building:
  - A decade of cooperation between GERDA and MAJORANA
  - April. 2016: Meeting on the Next Generation ^{76}Ge Experiment - Munich, Germany
  - Oct. 2016: Next Generation ^{76}Ge Meeting - Atlanta, USA
  - May 2017: LEGEND Collaboration Meeting - Gran Sasso, Italy
  - Dec. 2017: LEGEND Collaboration Meeting - Berkeley, USA
- Leadership roles and collaboration structure are being formed
  - Institutional Board governs the Collaboration
  - Co-Spokespersons elected:
    - Stefan Schönert, Technische Universität München
    - Steve Elliott, Los Alamos National Laboratory
  - Steering Committee and other leadership positions being filled

LEGEND: 47 Institutions, 219 Scientists

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.

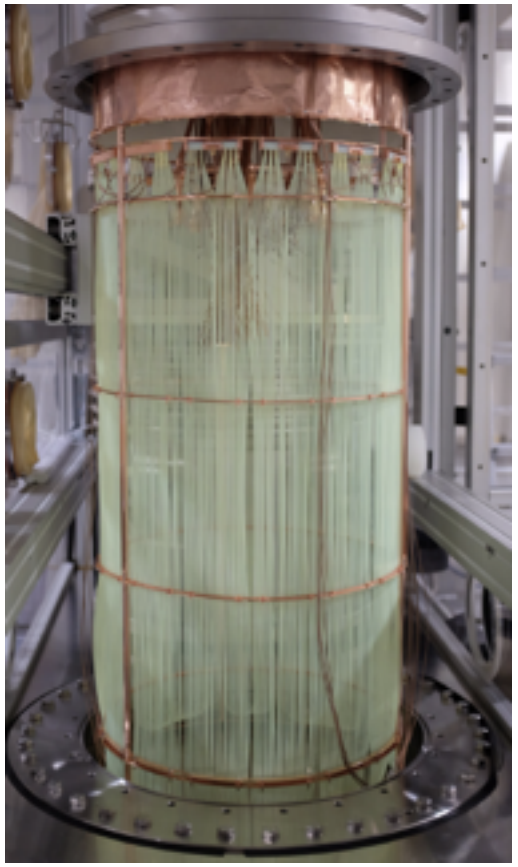
Joint Res. Centre, Geel
Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ.

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

MAJORANA and GERDA

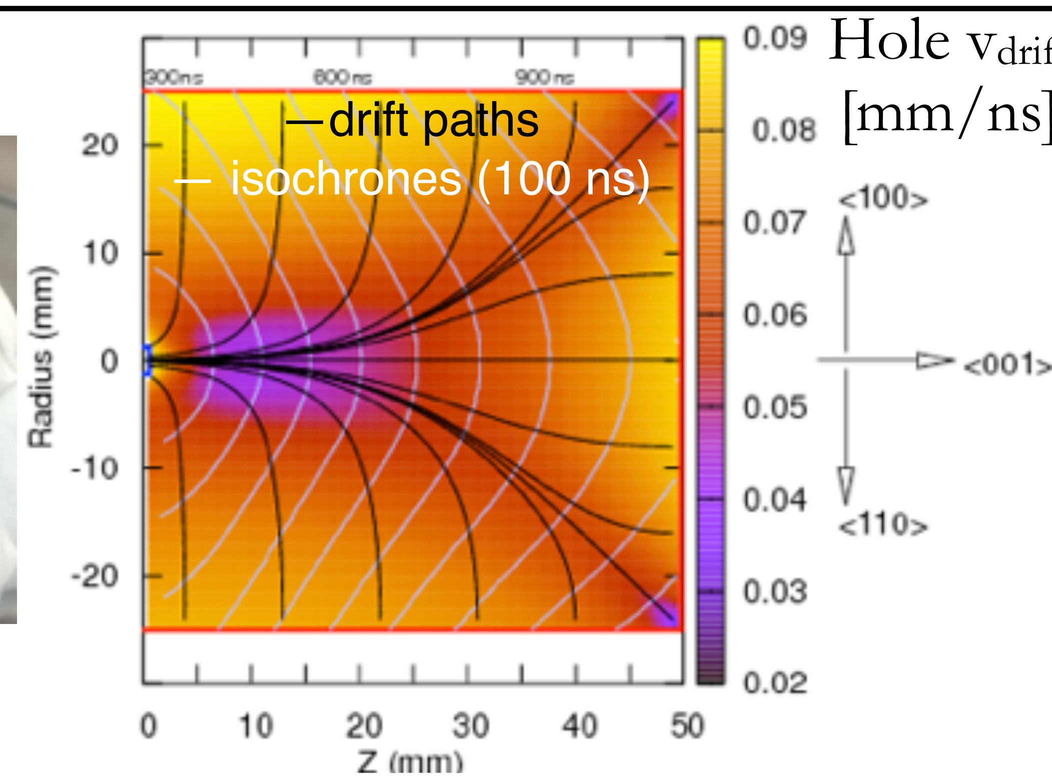
MAJORANA DEMONSTRATOR
"Traditional" configuration:
Vacuum cryostats in a
passive graded shield
with ultra-clean materials

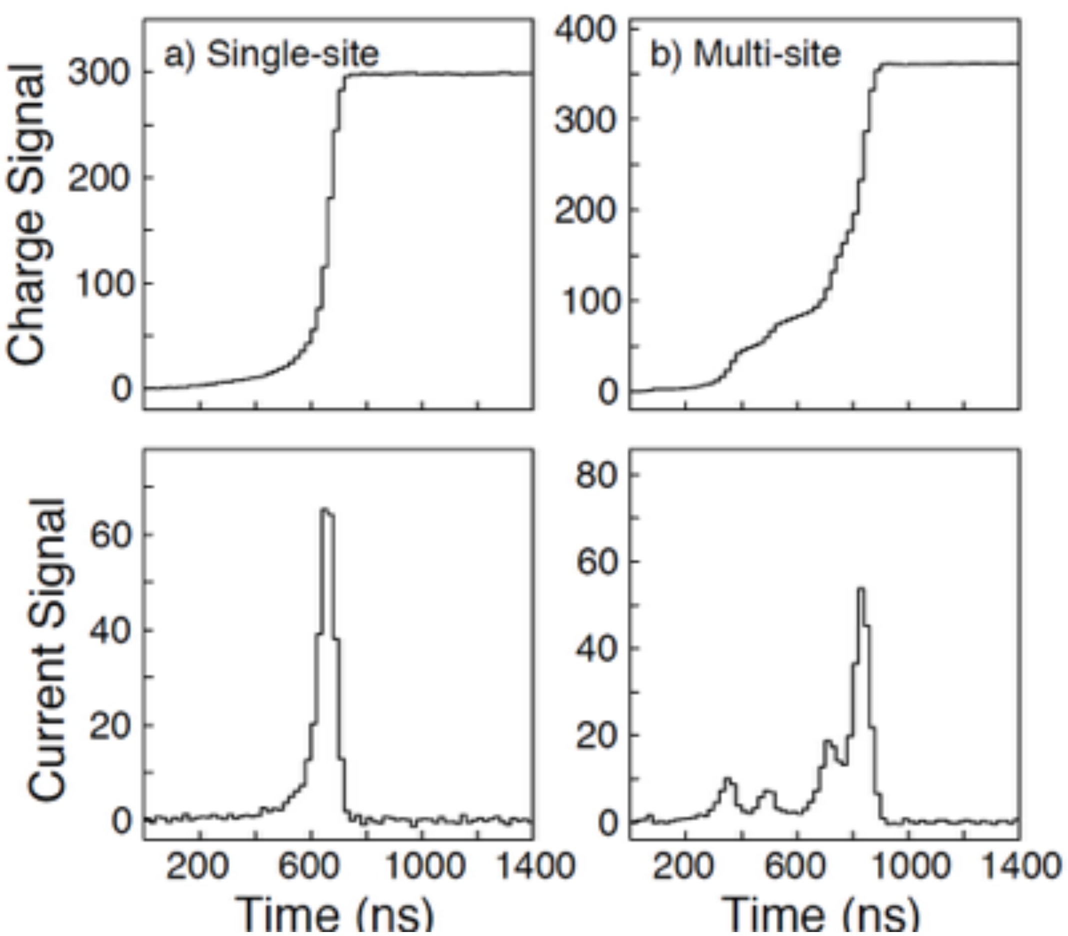


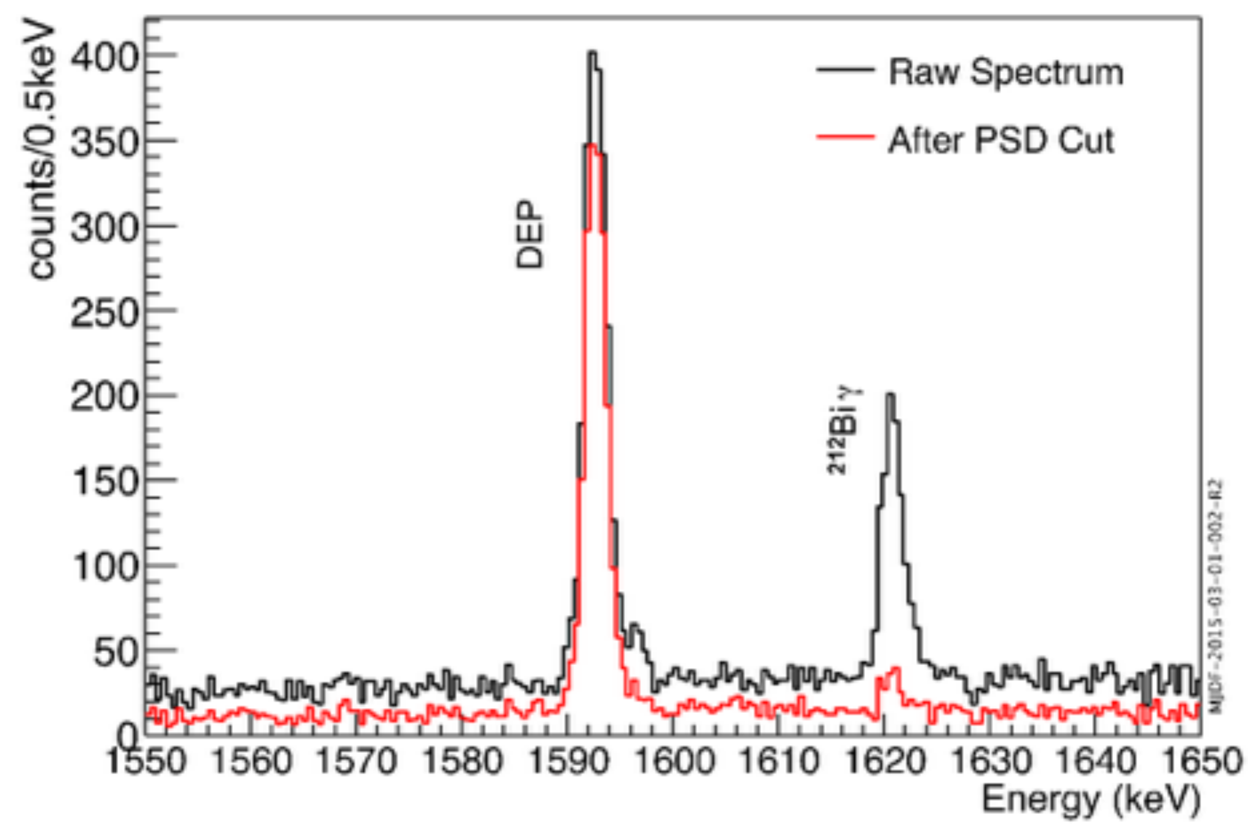
GERDA
Novel configuration:
Direct immersion
in active LAr shield

0νββ with Point Contact Detectors

- Benefit of P-type Point-Contact (PPC) style detectors for background rejection:
  - Slow drift time of the ionization charge cloud
  - Localized weighting potential gives excellent multi-site rejection
  - Surface event rejection





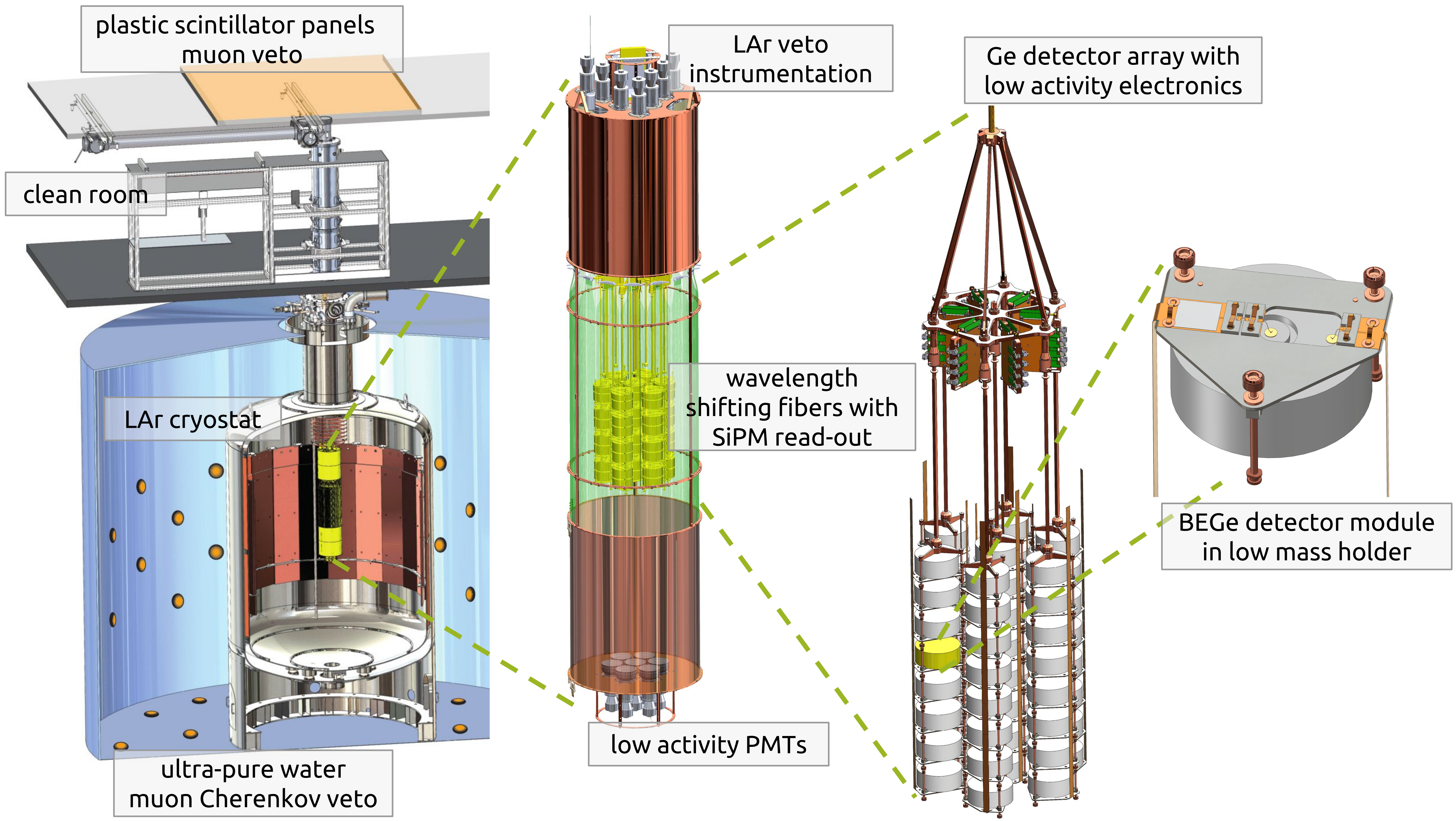


Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)

Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).

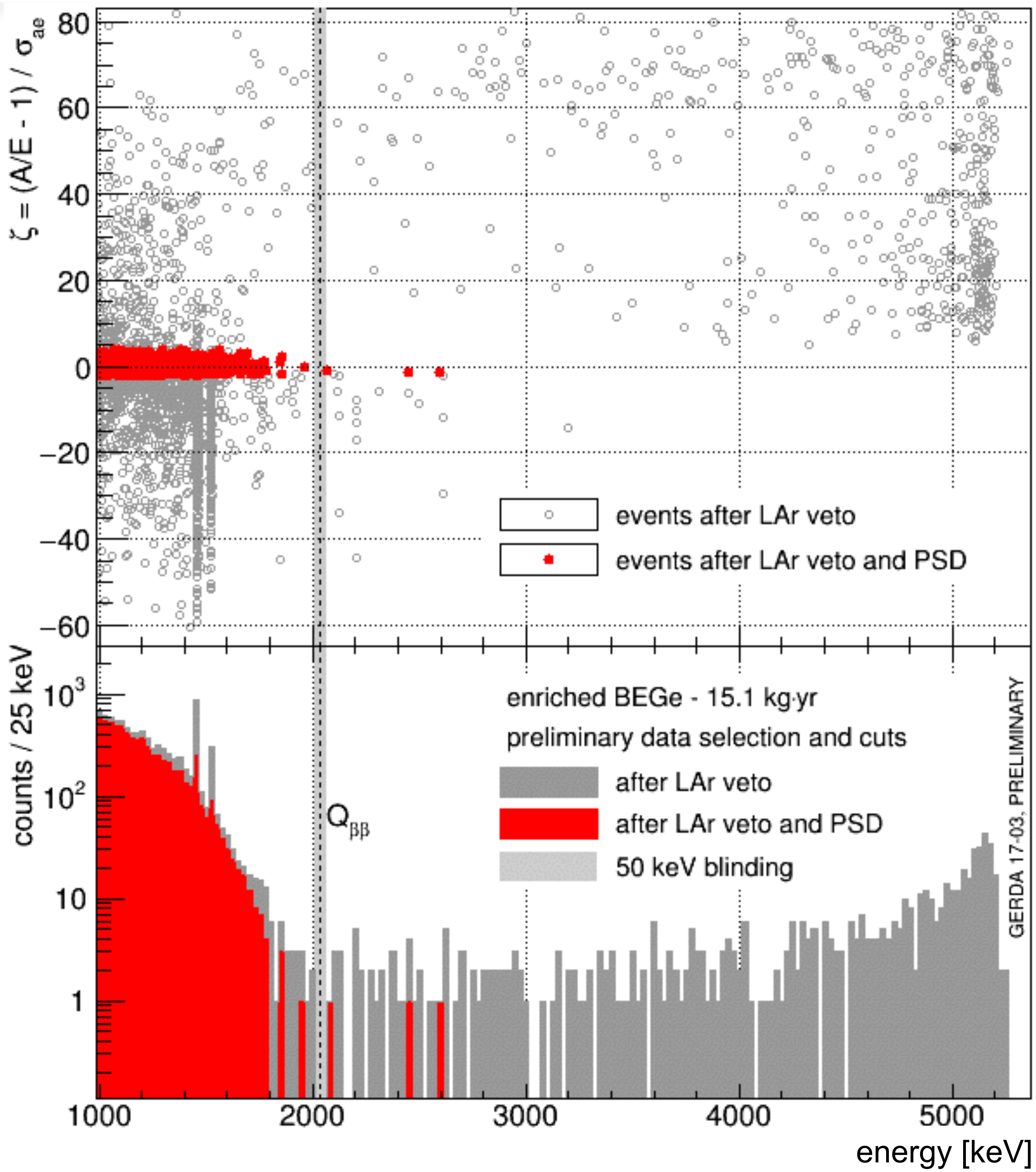
Nature 544, 47-52 (2017)

GERmanium Detector Array



AJ Zsigmond LEGEND meeting 2017 May 3

GERDA Pulse Shape Discrimination



Highe A/E cut: surface alpha

signal band

gamma band: multisite events

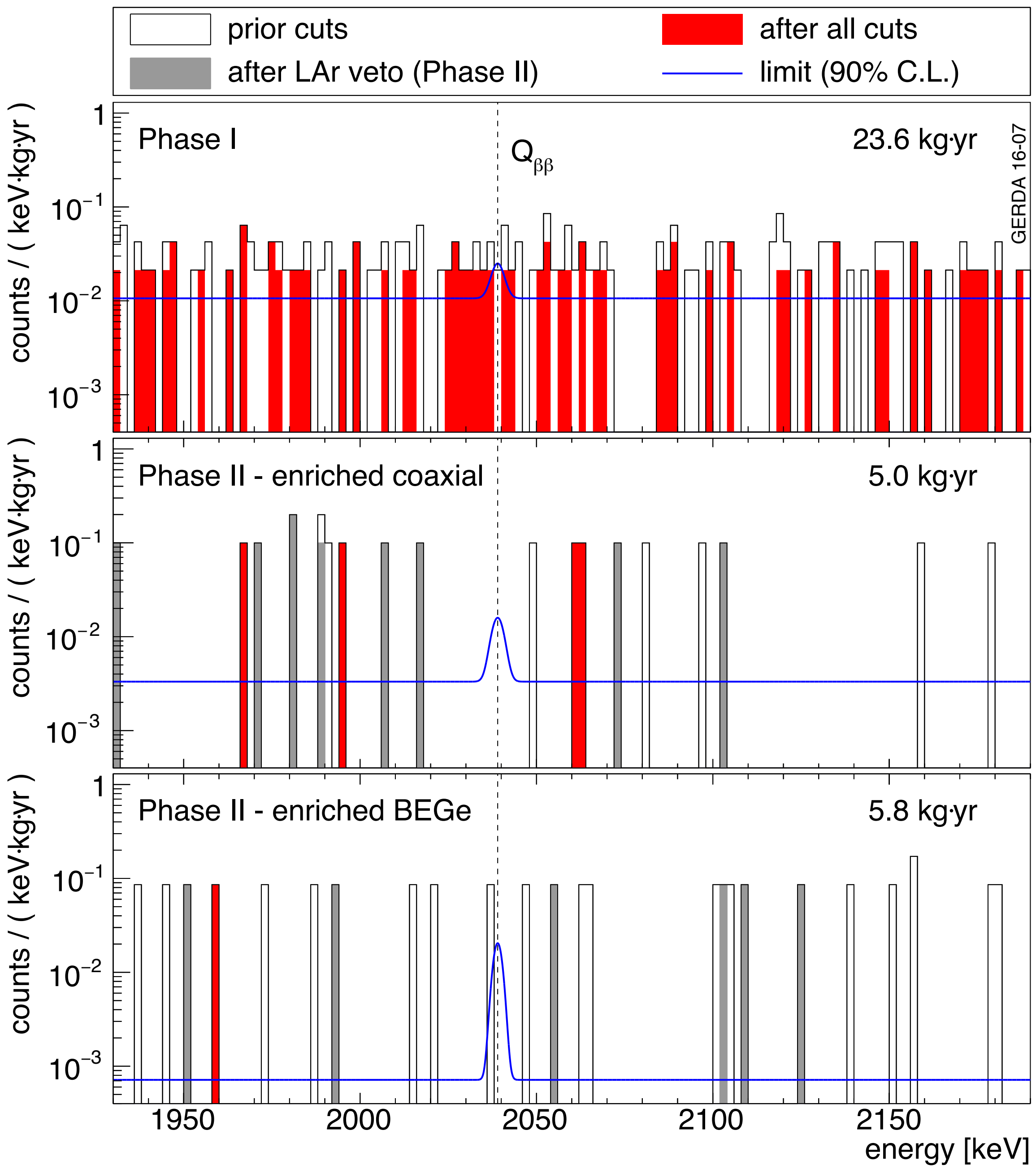
J. Janicsko MEDEX'17

Technische Universität München

Results: GERDA Phase II

- Analysis window from 1930 to 2190 keV
  - Excludes 2104 ± 5 keV and 2119 ± 5 keV.

Nature 544, 47-52 (2017)

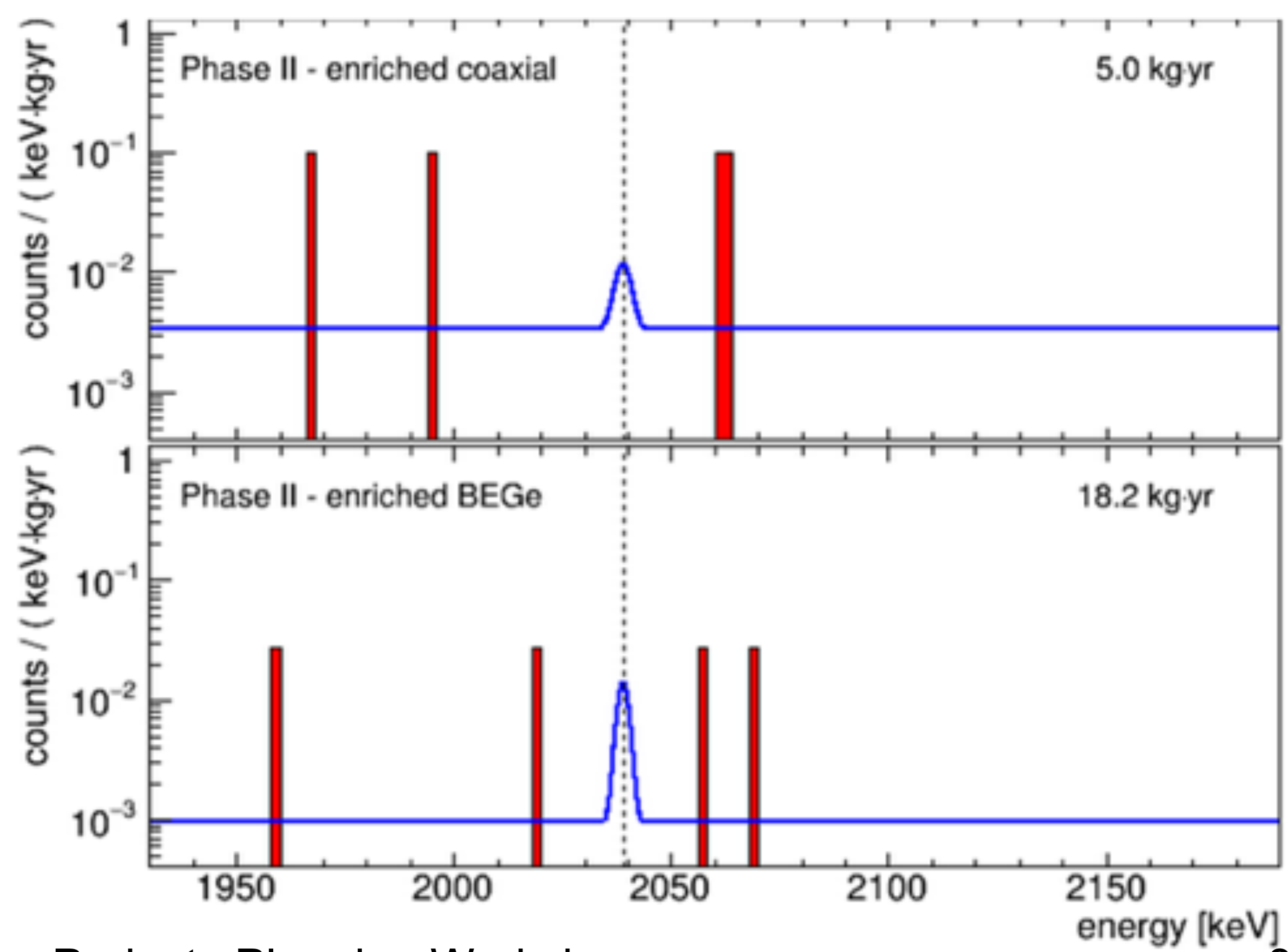


- Phase II BEGes have achieved "background free" measurement with a background index of:

$$1.0^{+0.6}_{-0.4} \times 10^{-3}\,\mathrm{cts/(keV\,kg\,yr)}$$

$$T^{0\nu}_{1/2} > 8.0 \times 10^{25}\,\mathrm{yr}\ (90\%\ \mathrm{CL})$$

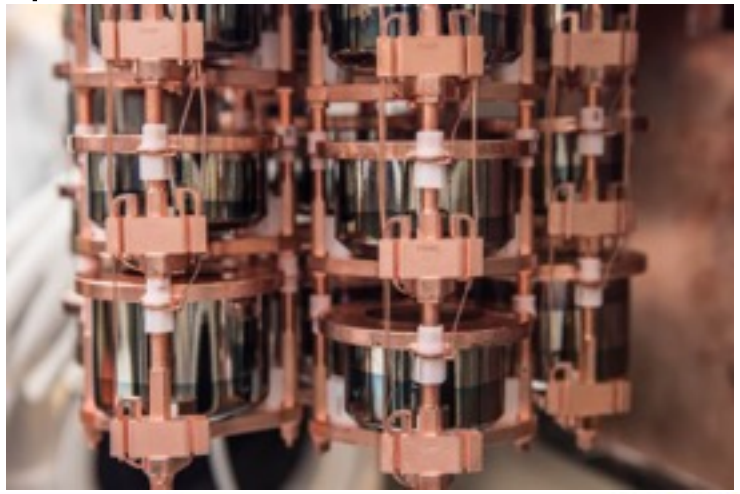
L. Pandola, TAUP 2017



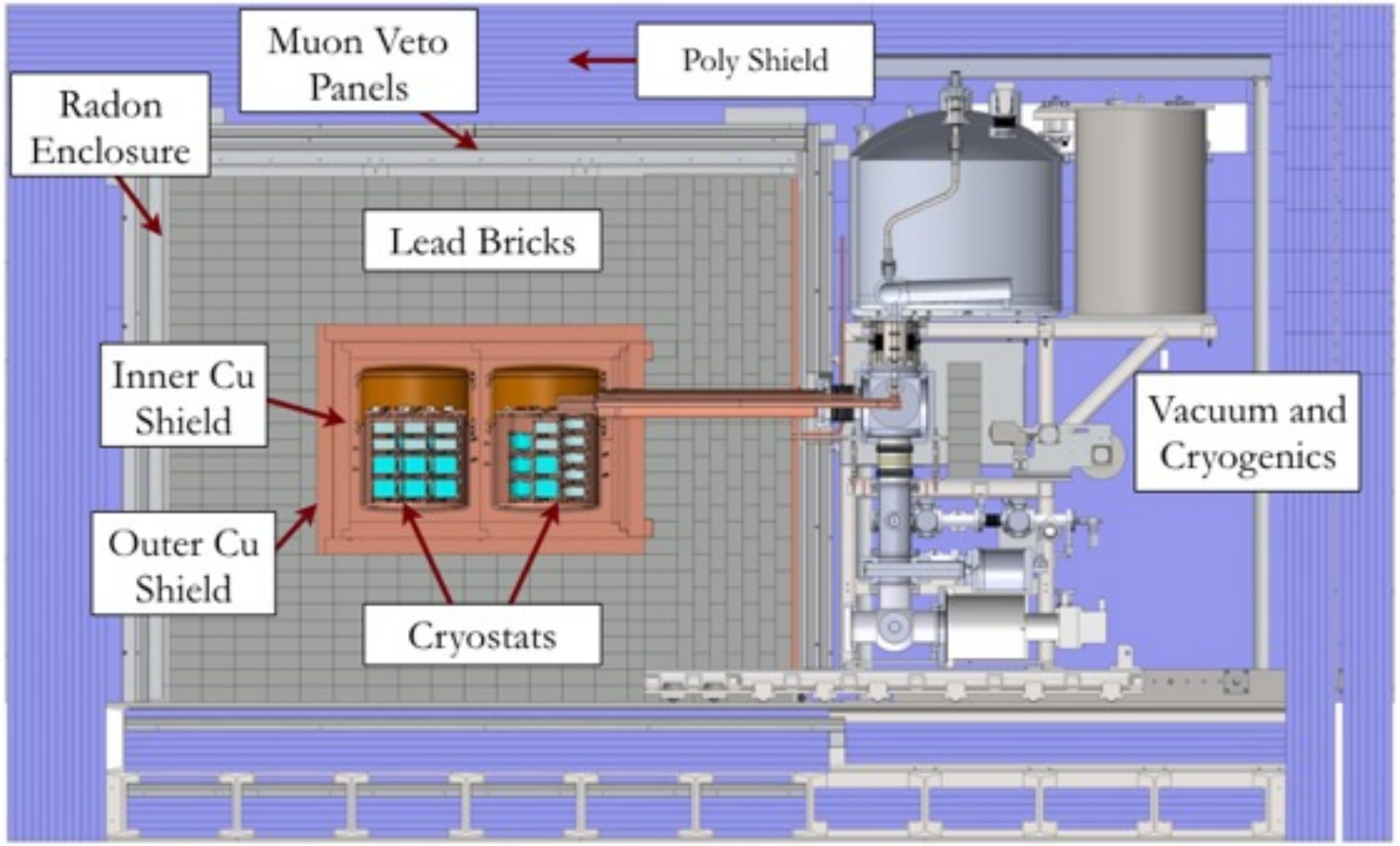
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



- Operating underground at 4850′ Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
  44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
    - resolution: 2.4 keV FWHM at 2039 keV
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto

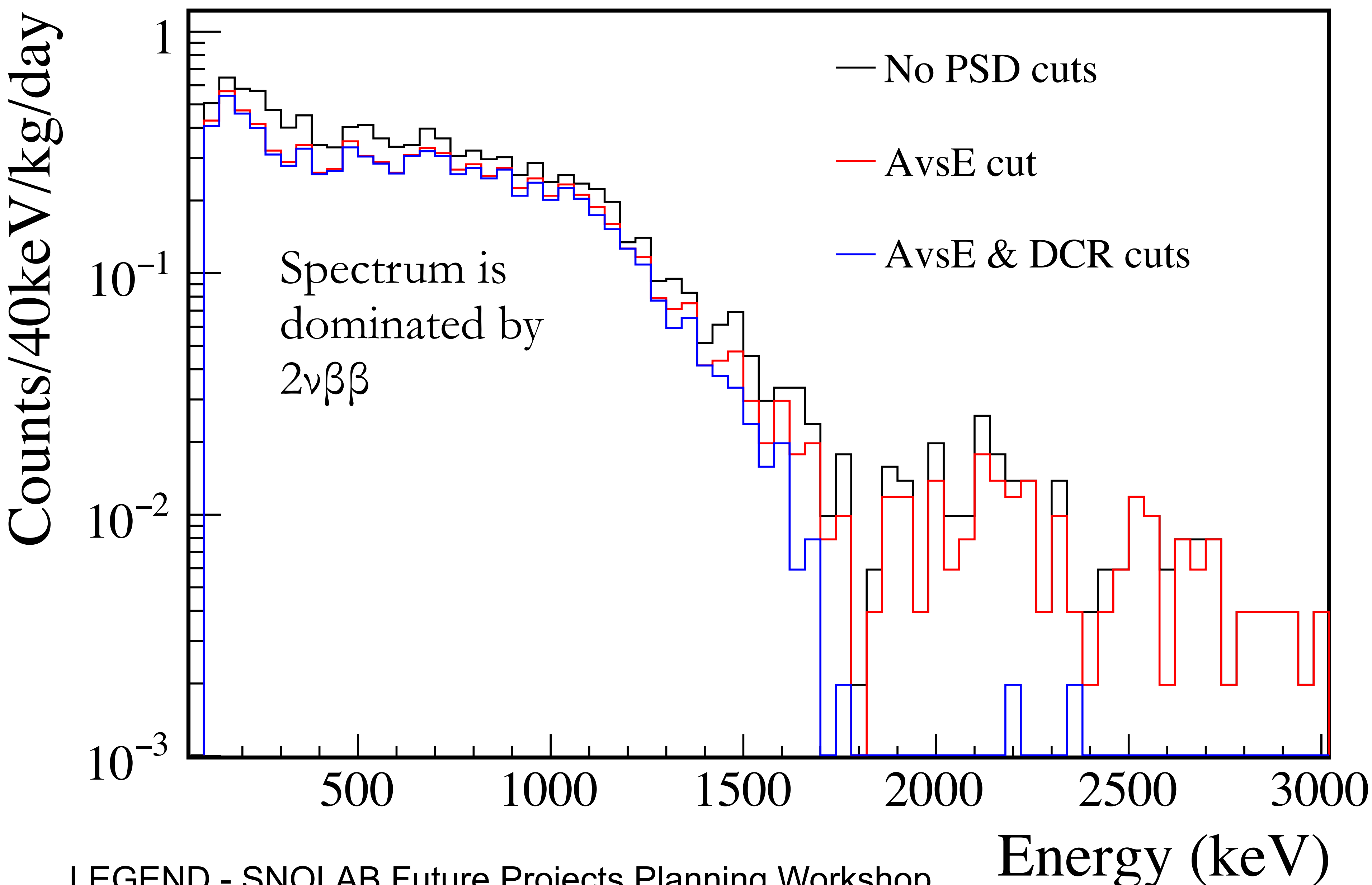


N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)

Initial Results: MAJORANA DEMONSTRATOR

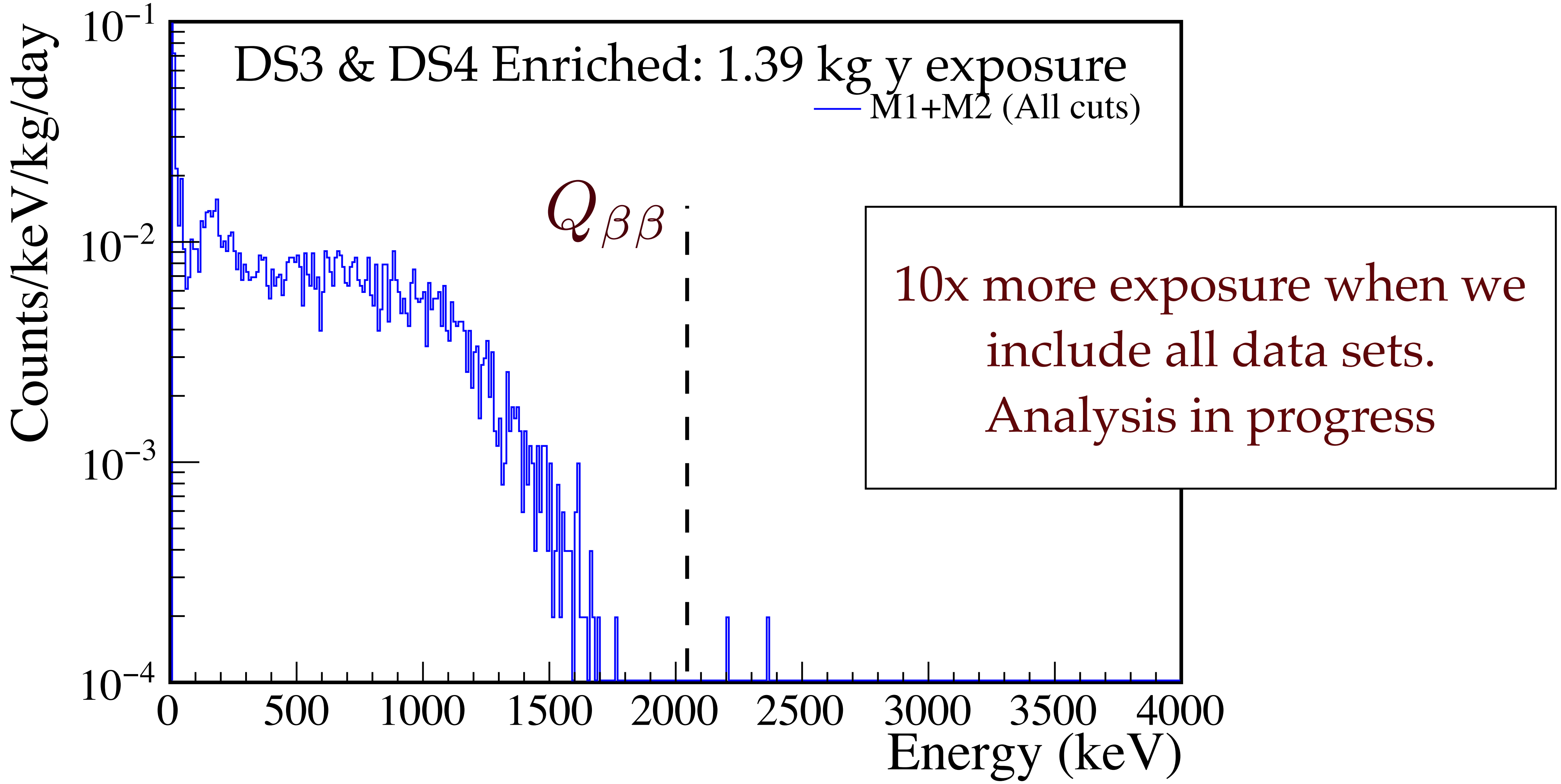
- Lowest background configuration with both modules in shield
- Pulse Shape Discrimination:
  - 'AvsE' rejects multi-site events
  - 'DCR' rejects surface events

Enriched detectors in Modules 1 & 2 , before and after PSD cuts



Initial Results: MAJORANA DEMONSTRATOR

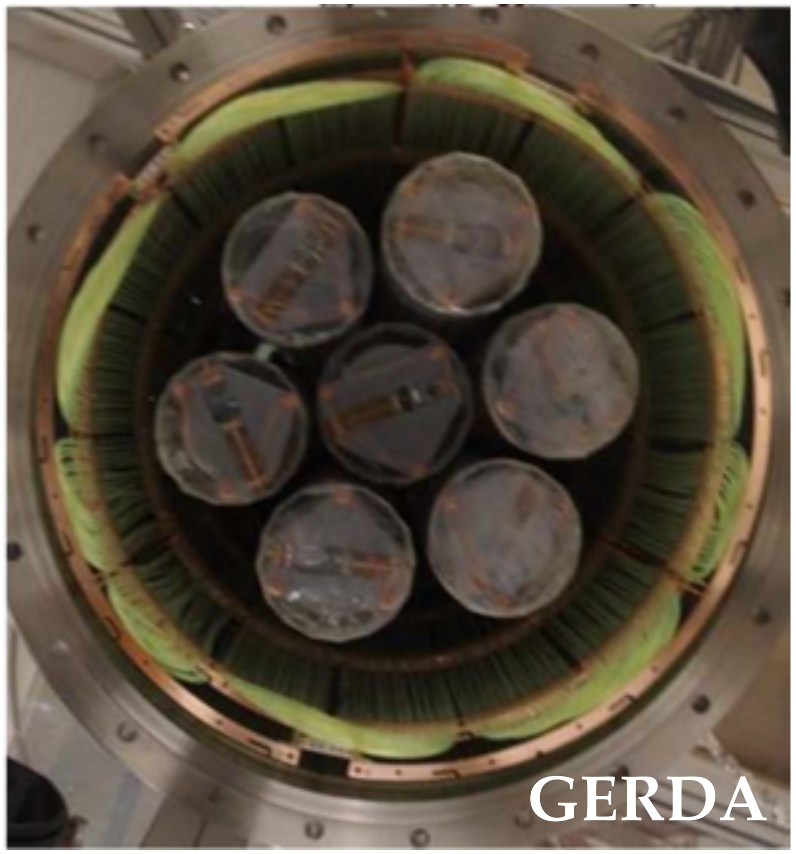
- First results from Modules 1 and 2 in shield
- After cuts, 1 count in 400 keV window centered at 2039 keV (0νββ peak)
  - Projected background rate is $5.1^{+8.9}_{-3.2}$ c /(ROI t y)
    - using a 2.9 (M1- DS3) & 2.6 (M2 - DS4) keV ROI (68% CL).
  - Background index of 1.8 x 10^{-3} c/(keV kg y)
- Analysis cuts are still being optimized.



The Best of GERDA and MAJORANA

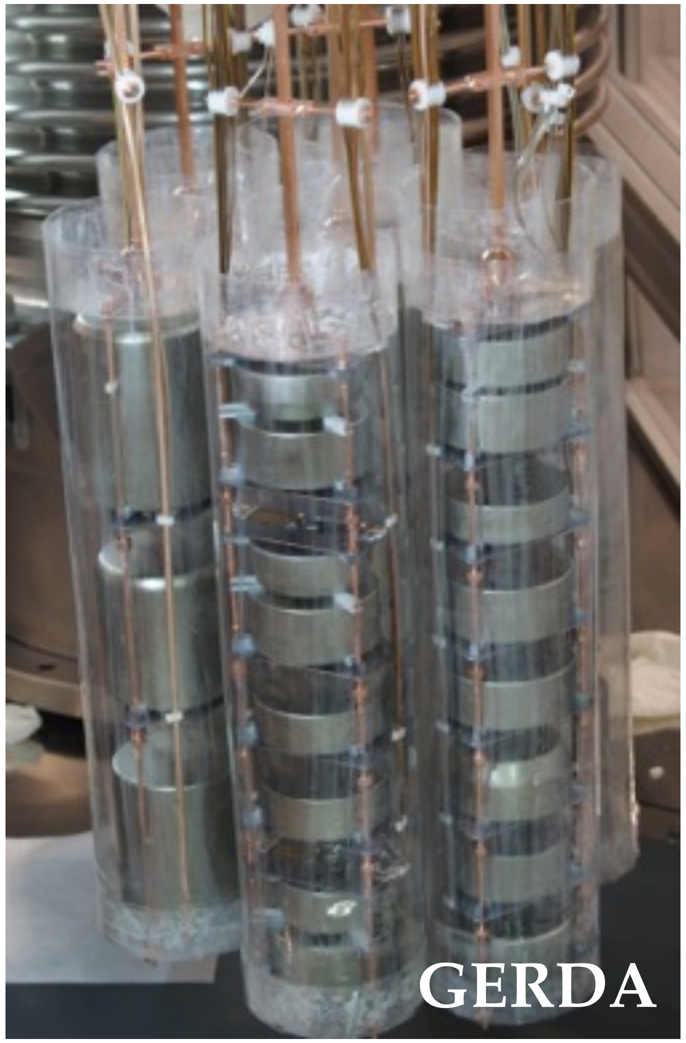
- Moving forward with a phased program selecting the best technologies based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

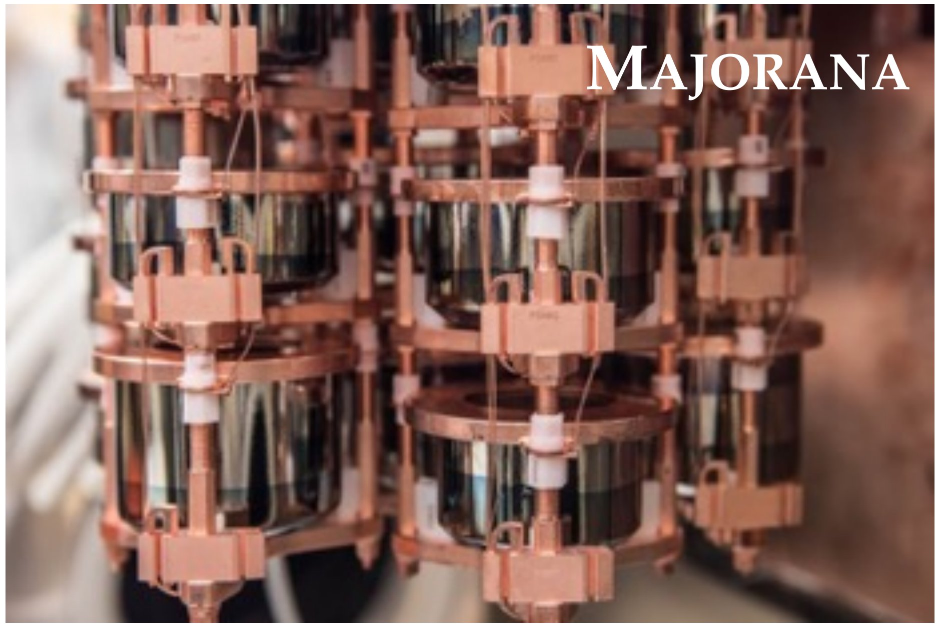
- MAJORANA
  - Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
  - Low noise electronics yields better PSD
  - Low energy threshold (cosmogenic and low-E background)
- GERDA
  - LAr active veto
  - Low-A shield, no Pb
- Both
  - Clean fabrication techniques
  - Control of surface exposure
  - Development of large point-contact detectors



LEGEND Design Criteria

- Phased Approach
  - 200; 500-1000 kg
  - Allow operation of previous installed detectors
  - Use existing infrastructure for early phase to obtain near-term physics results
- Background goals
  - 200 kg: 0.6 c/(FWHM t y)
  - 1000 kg: 0.1 c/(FWHM t y)
- Total of 1200 kg of enriched ^{76}Ge material
- 1000 kg of p-type, point-contact ^{76}Ge detectors
  - (2-3 kg/300-500 detectors)
- Resolution ~2.5 keV FWHM @ 2039 keV





LEGEND Plan

First Phase:

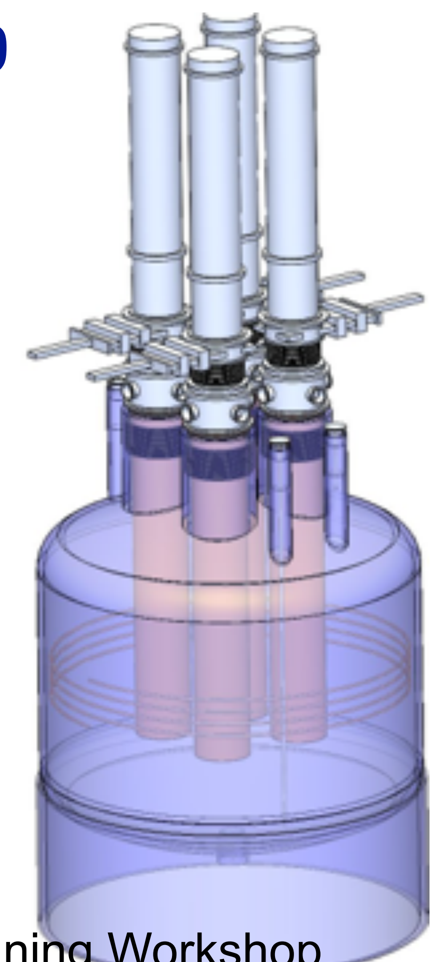
- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal 0.6 c / (FWMH t y)
  - (x5 lower than current best)
- start by 2021 (favorable funding scenarios)

LEGEND-200

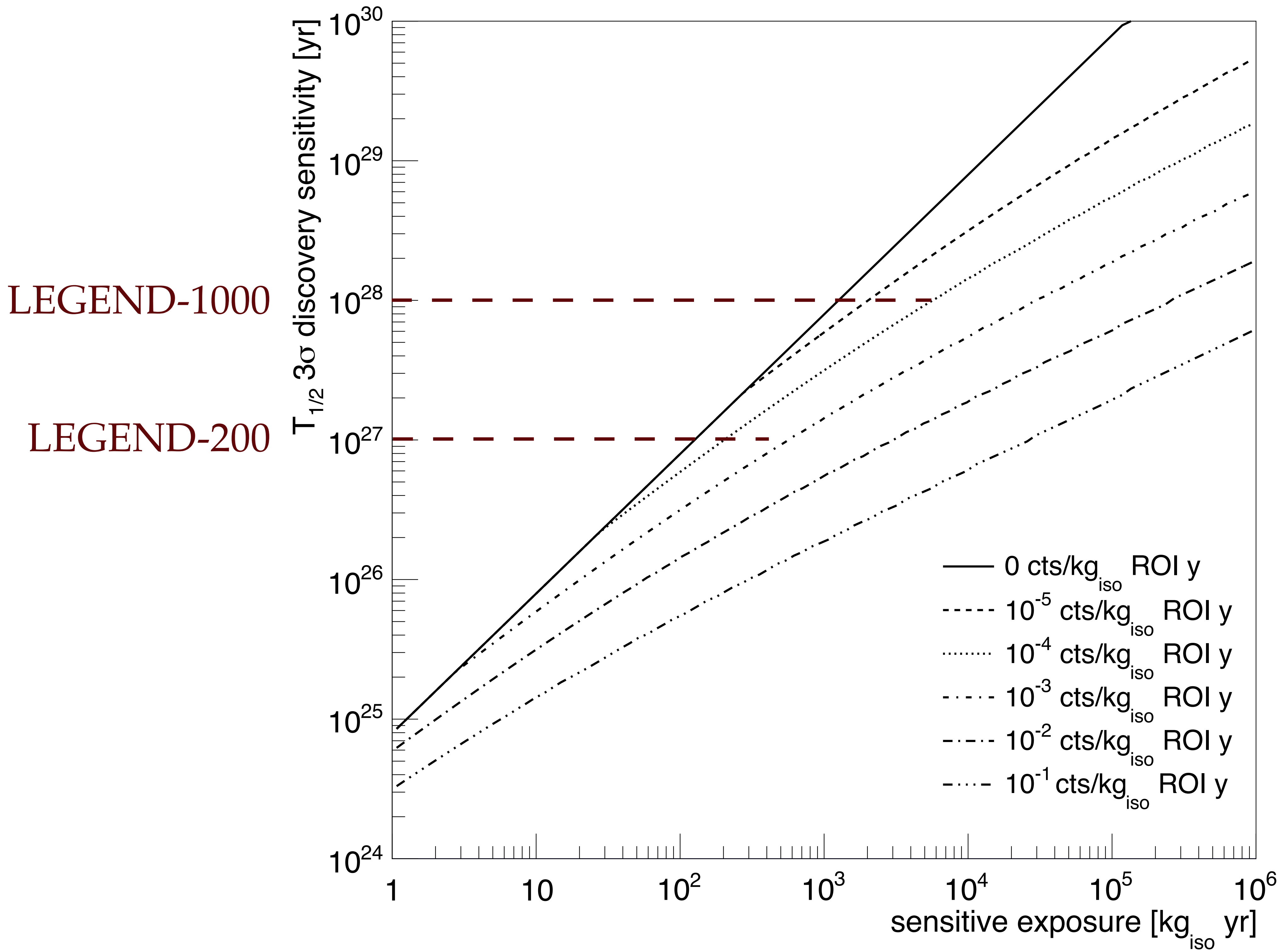
Subsequent stages:

- 1000 kg (staged)
- timeline connected to U.S. DOE down select process
- BG goal: 0.1 c / (FWHM t y)
  - (x30 lower than current best)
- Location: TBD
- Required depth under investigation

LEGEND-1000



3σ Discovery: Background vs. Exposure

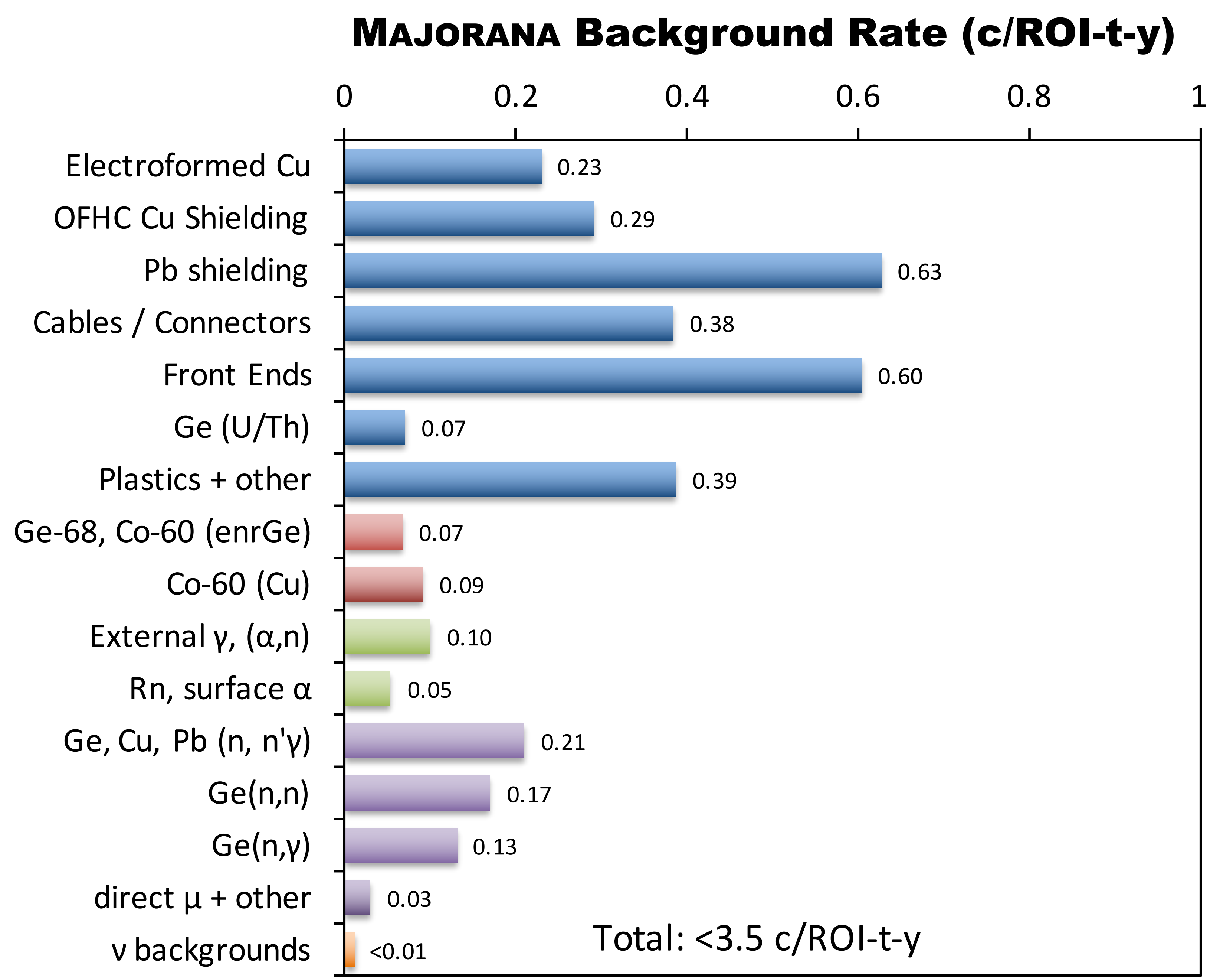


Agostini, Benato, Detweiler (2017) arXiv:1705.02996v3

LEGEND Background Budget Estimate

Based on both discovery level and sensitivity considerations, would like to aim for a total background budget of ≤ 0.1 c/ROI-t-y.

Building on GERDA and MAJORANA DEMONSTRATOR how does one get the factor of ~ x30?



LEGEND Background Budget Estimate

Based on both discovery level and sensitivity considerations, would like to aim for a total background budget of ≤ 0.1 c/ROI-t-y.

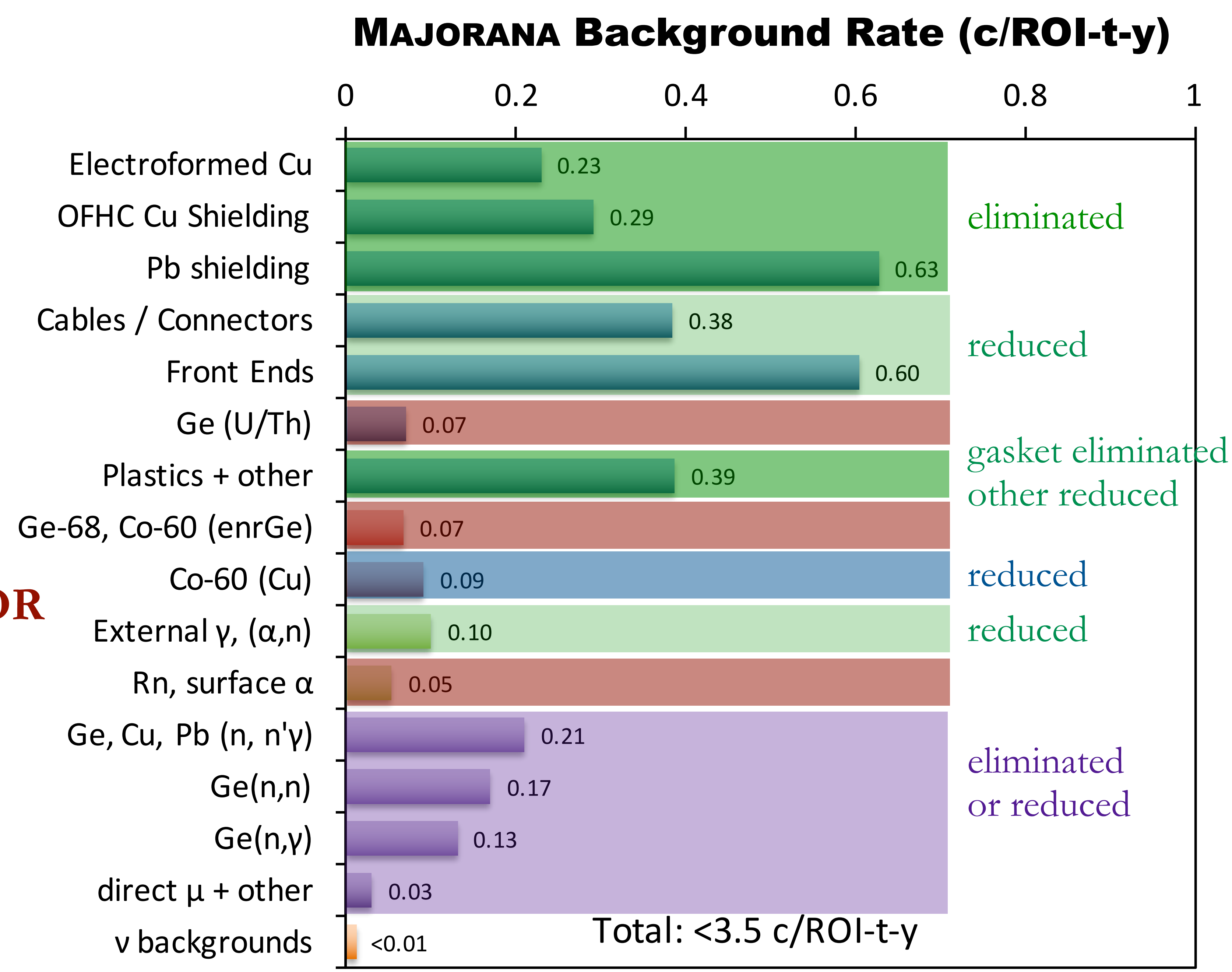
Building on GERDA and MAJORANA DEMONSTRATOR how does one get the factor of ~ x30?

clean, active shield

deeper and/or active shield

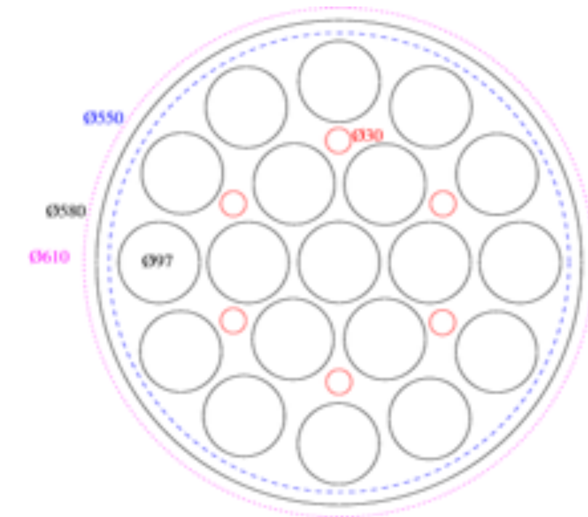
EF all Cu underground

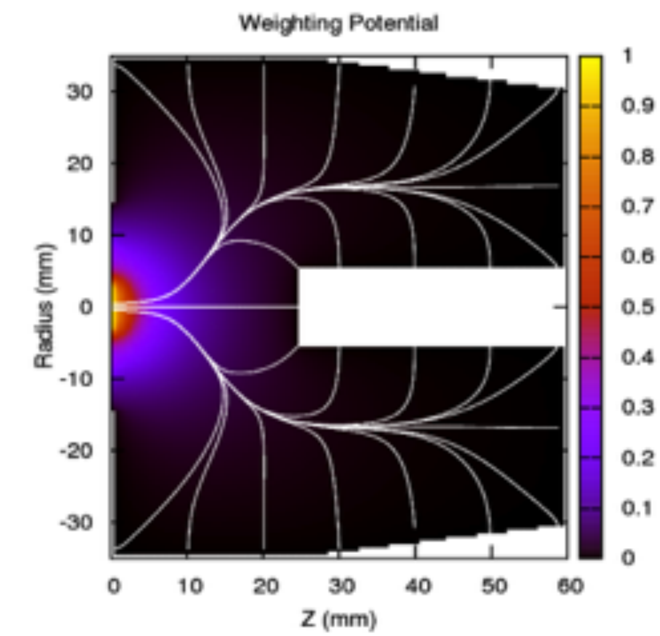
Learn from DEMONSTRATOR & GERDA II (values are currently largely upper limits)

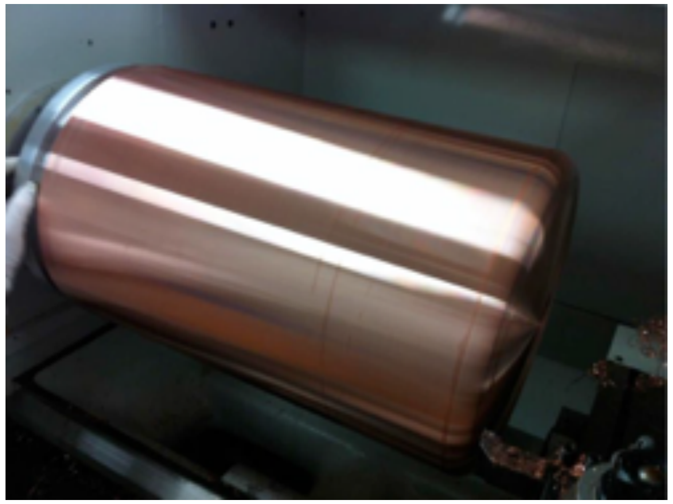


LEGEND 200 - 1st step of phased approach

- Reuse existing GERDA infrastructure at LNGS.
- Modifications of internal cryostat piping so can accommodate up to 200 kg of detectors.
- Improvements
  - use some larger Ge detectors (1.5 - 2.0 kg)
  - cleaner LAr
  - improve LAr scintillator light collection (2x in test stand)
  - lower mass, cleaner cables
  - lower noise electronics
- Estimate background improvement by ~ x5 over GERDA/ MAJORANA; Goal: 0.6 c /(FWMH t y)
  - intrinsic : including ^{68}Ge/^{60}Co all OK
  - external Th/U: cleaner materials based on those used in DEMONSTRATOR
  - surface events : alpha & β rejection via PSD
  - ^{42}Ar : better suppression & mitigation (demonstrated in the LArGe test stand)
  - muon induced : OK
- Contingent upon funding, data taking by 2021





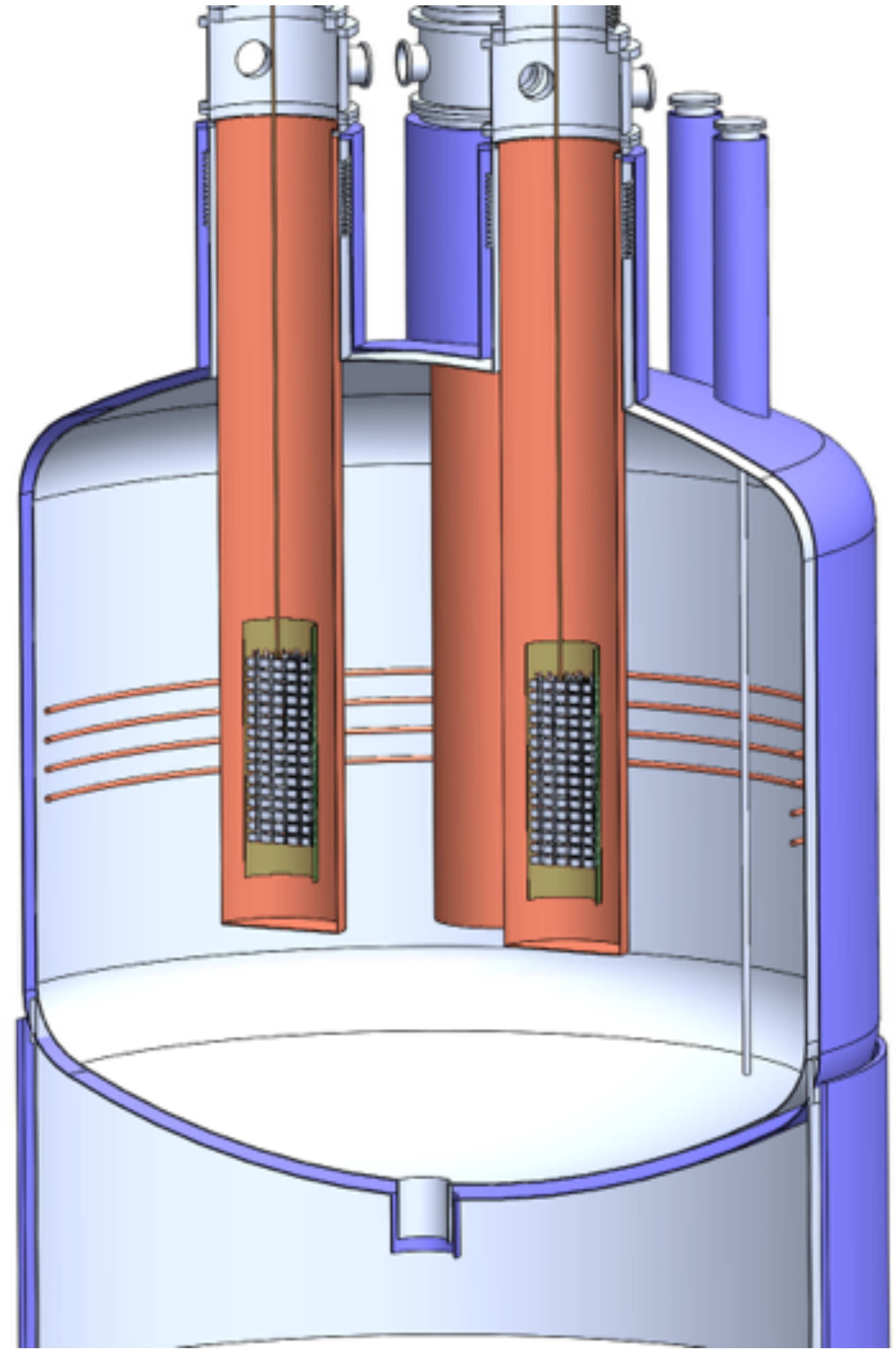


LEGEND 1000 - "Baseline" Design

- 1000 kg
- BG goal (x30 lower) : 0.1 c / (FWHM t y)
- 4-5 payloads in LAr cryostat in separate 3 m^3 volumes
  - payload 200/250 kg, with ~100+ detectors.
- Every payload "independent" with individual lock
- LAr detector volume separated by thin(electro-formed) Cu from main cryostat volume.
- Use depleted LAr in inner detector volumes
- Modest sized LAr cryostat in "water tank"
  - (6 m Ø LAr, 2-2.5 m layer of water)

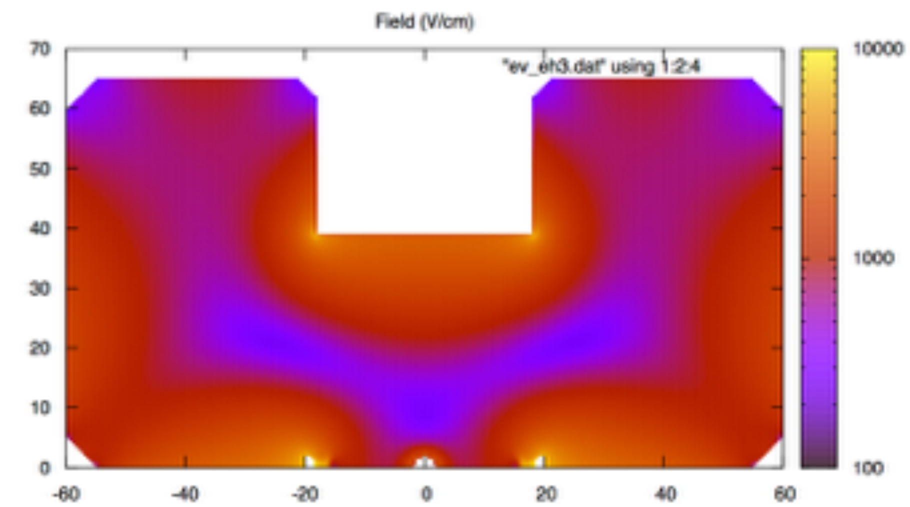
  or

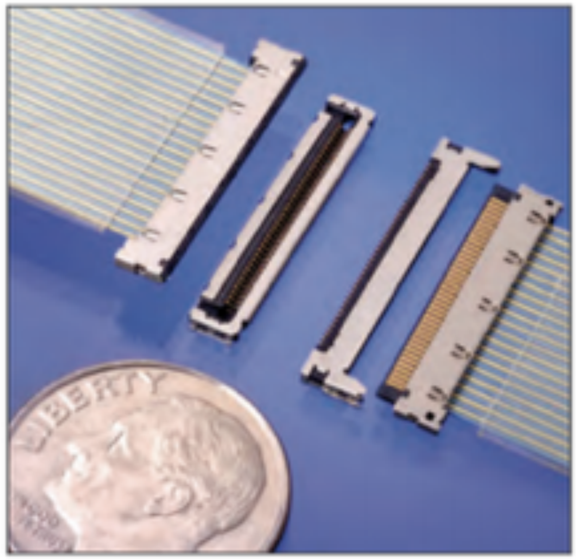
  Large LAr cryostat w/o water (9 m Ø) with separate neutron moderator

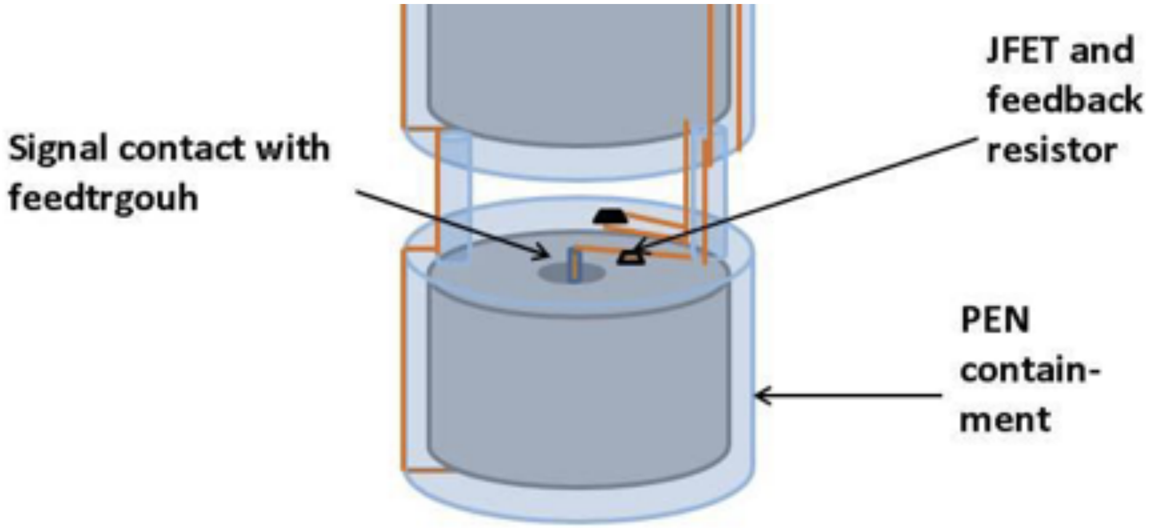


LEGEND 1000 - Optimization Activities

- Larger detectors (dia: 12 cm, ~ 3-4 kg)
  - reduced components, better volume to surface
  - enhanced PSD properties
- Improved LAr Veto readout and light collection
- Depleted Ar in the active veto region
  - improved low-energy sensitivity (^{68}Ge)
- Electronics and related cabling
  - Challenge of long cable readout distances
  - low noise, low activity
- Advance electroformed materials and alloys
- Alternate active shielding (LNe, doped LAr,) and construction (PEN, …) materials.
- Engineering
  - Low mass, low activity connectors
  - advance fabrication
  - mechanical design, alternate cryostat designs
- Analysis - machine learning, advanced PSD, …





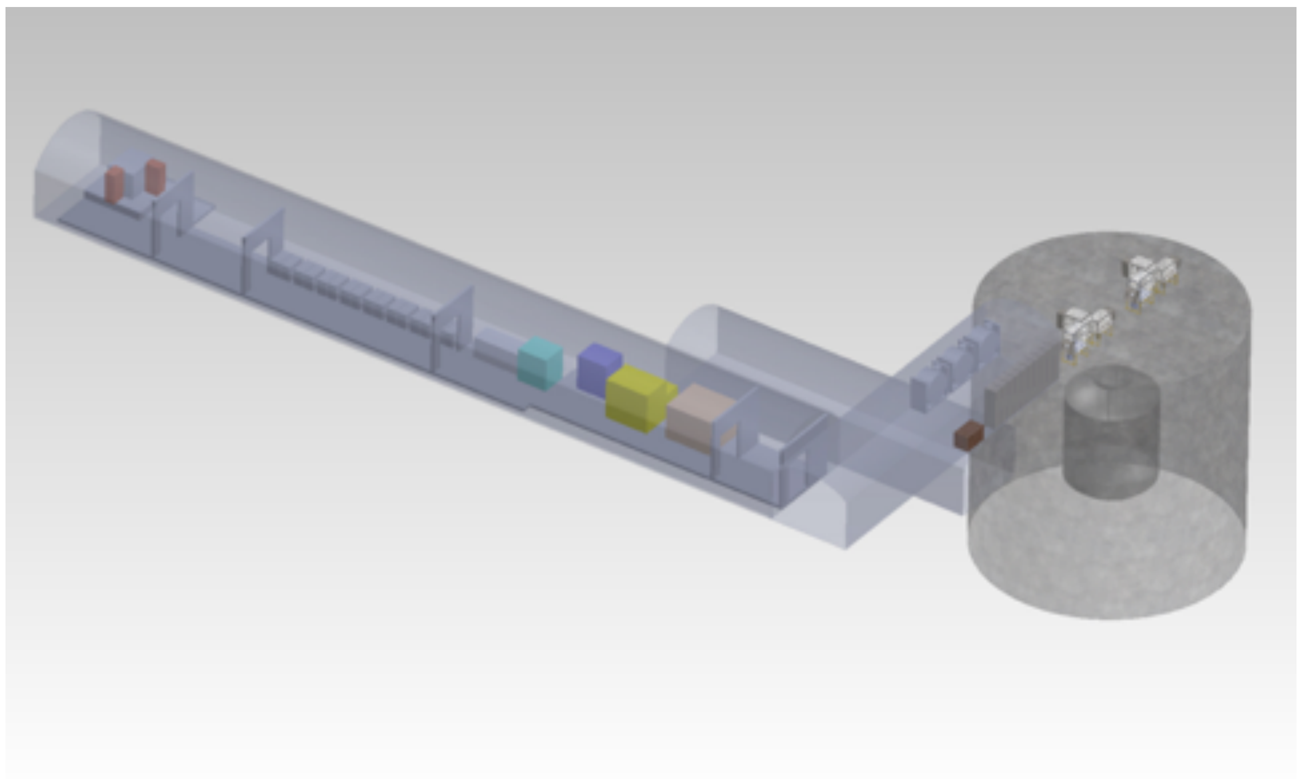


LEGEND 1000 Laboratory Configuration

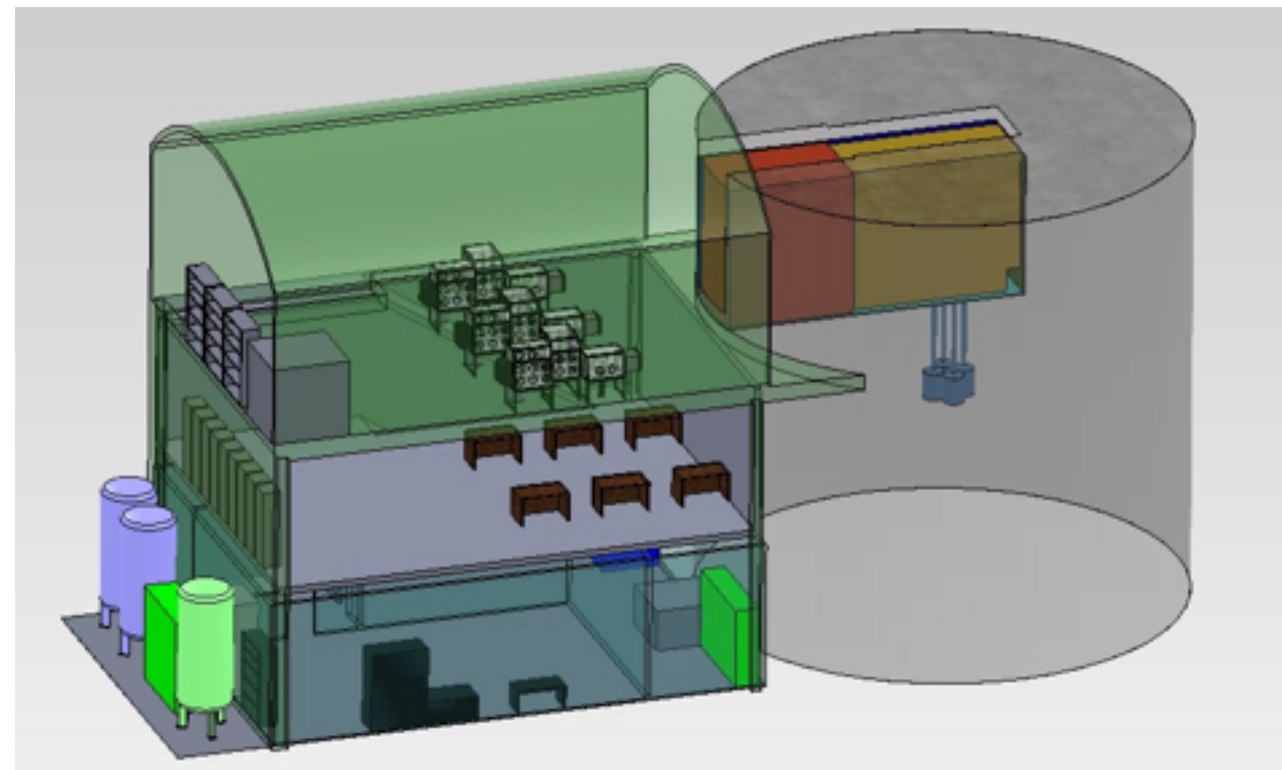
Possible laboratory layouts

Depth is a necessary consideration for the 1000-kg phase

SNOLAB cryopit concept



Generic Cavity design (CJPL,SURF)

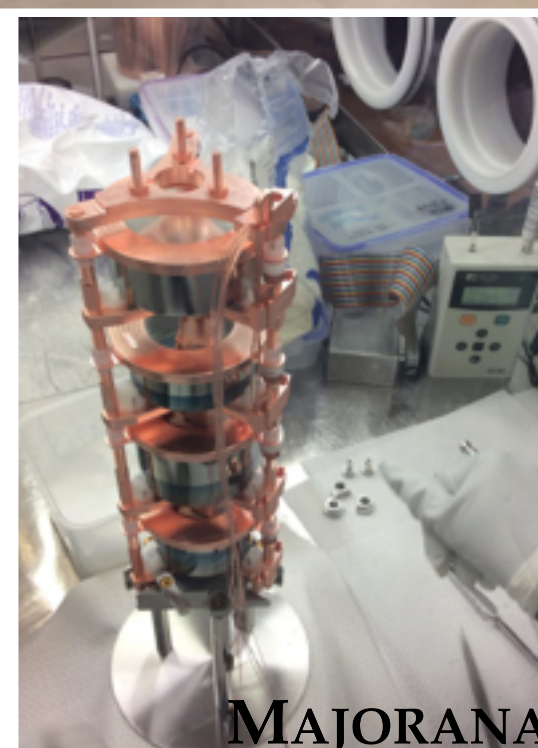


Laboratory Infrastructure Needs

- Default setup (a large LAr cryostat in a water tank) requires a cylindrical cavity 15 m high and 15 m in diameter
- Auxiliary space for a control room and for detector testing and mounting.
- Safety considerations:
  - Sufficient gas ventilation
  - Possibility of fast water drainage
- Areas used for detector manipulation and mounting will require Rn control.
- Secondary concerns:
  - cavity access and the maximum size of apparatus that can be delivered
  - local infrastructure and technical resources
  - network capability for large data handling
  - laboratory technical support

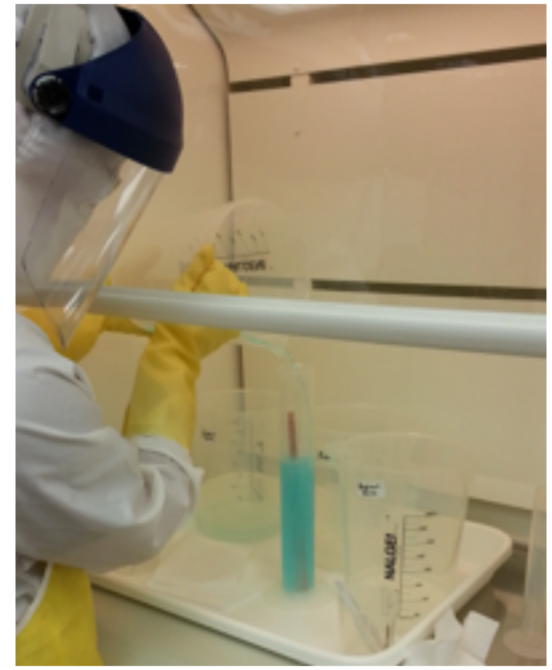
Example Laboratory Infrastructure Needs

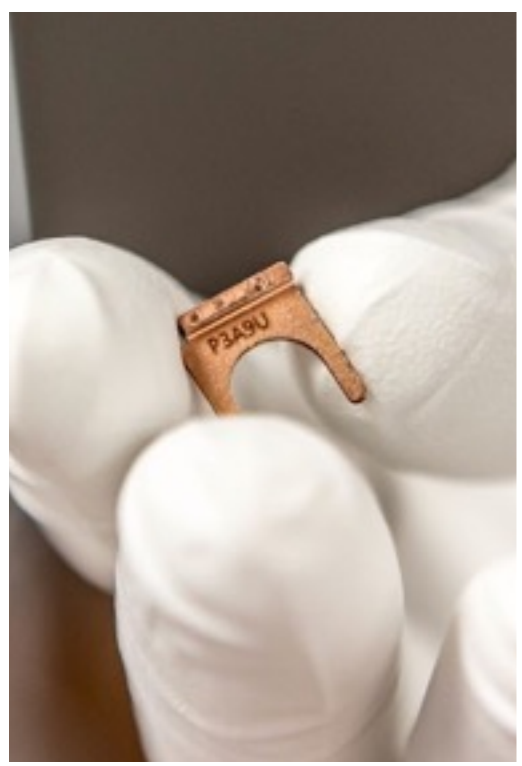
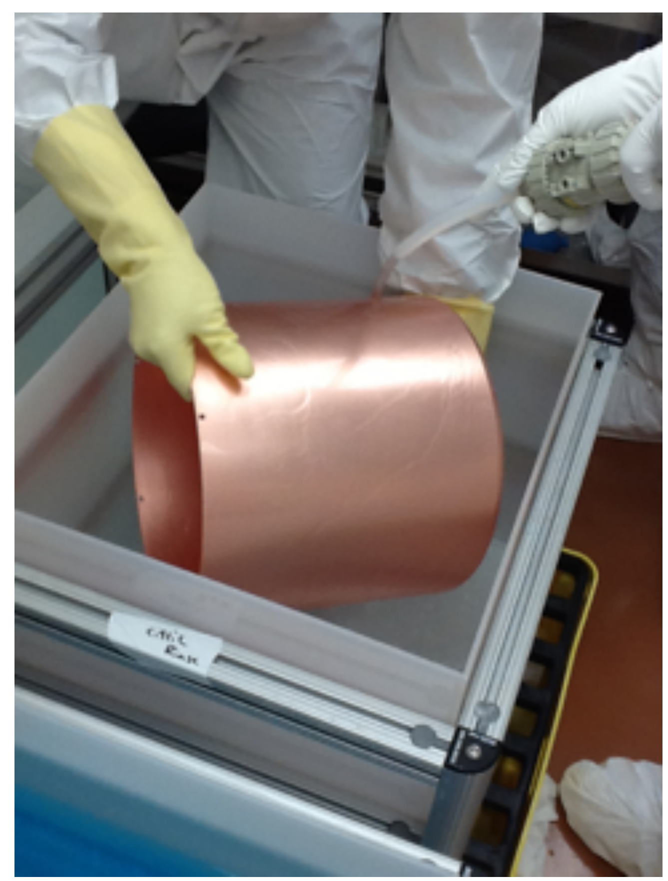
- Cleanroom(s) for Ge detector testing and assembly
  - Lock system for detector array deployment



Example Laboratory Infrastructure Needs

- Cleanroom(s) for support facilities
  - Cu electroforming
  - Cu/plastic part fabrication
  - Component cleaning
  - Component QC/inventory storage



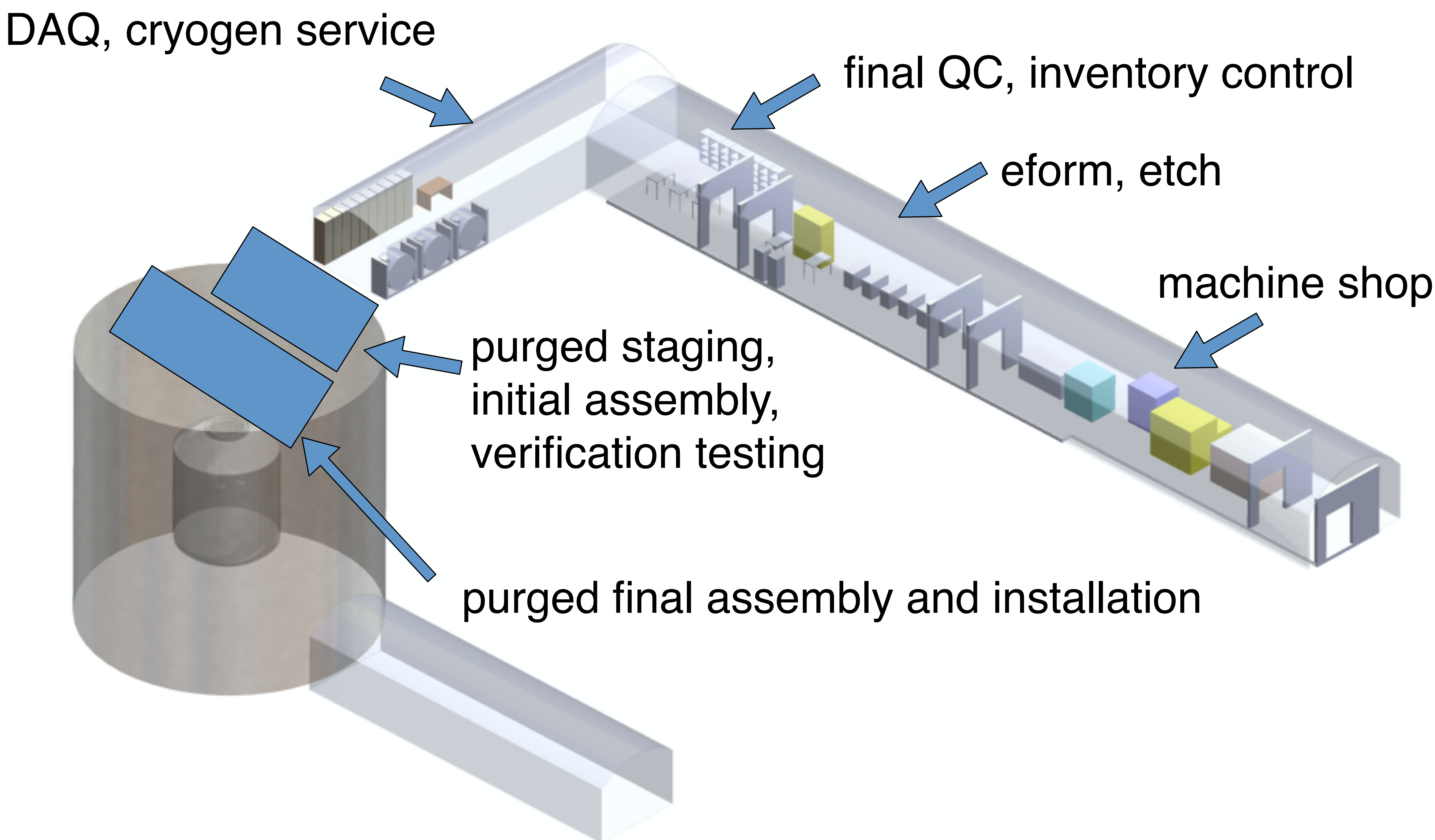





LEGEND Summary

- GERDA & the MAJORANA DEMONSTRATOR, are taking data in the “background free” regime having by an order of magnitude the lowest demonstrated backgrounds in the field.
- LEGEND is selecting the best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.
- Taking a **phased, stepwise implementation**; e.g. 200 → 500 → 1000 kg
- Preparations for LEGEND 200 are underway, working to secure funding.
- Have established a baseline design and pursuing R&D for LEGEND 1000
- Based on current backgrounds, LEGEND 1000 goal requires only a factor of x30 improvement from demonstrated backgrounds
  - (x5 for LEGEND 200 and another x6 for LEGEND 1000).
- Ultimate Goal: exposure of 10 t-y; background of 0.1 c / ROI-t-y
  - Coupled with excellent energy resolution ^{76}Ge has a discovery potential at a half-life significantly longer than 10^{27} years.

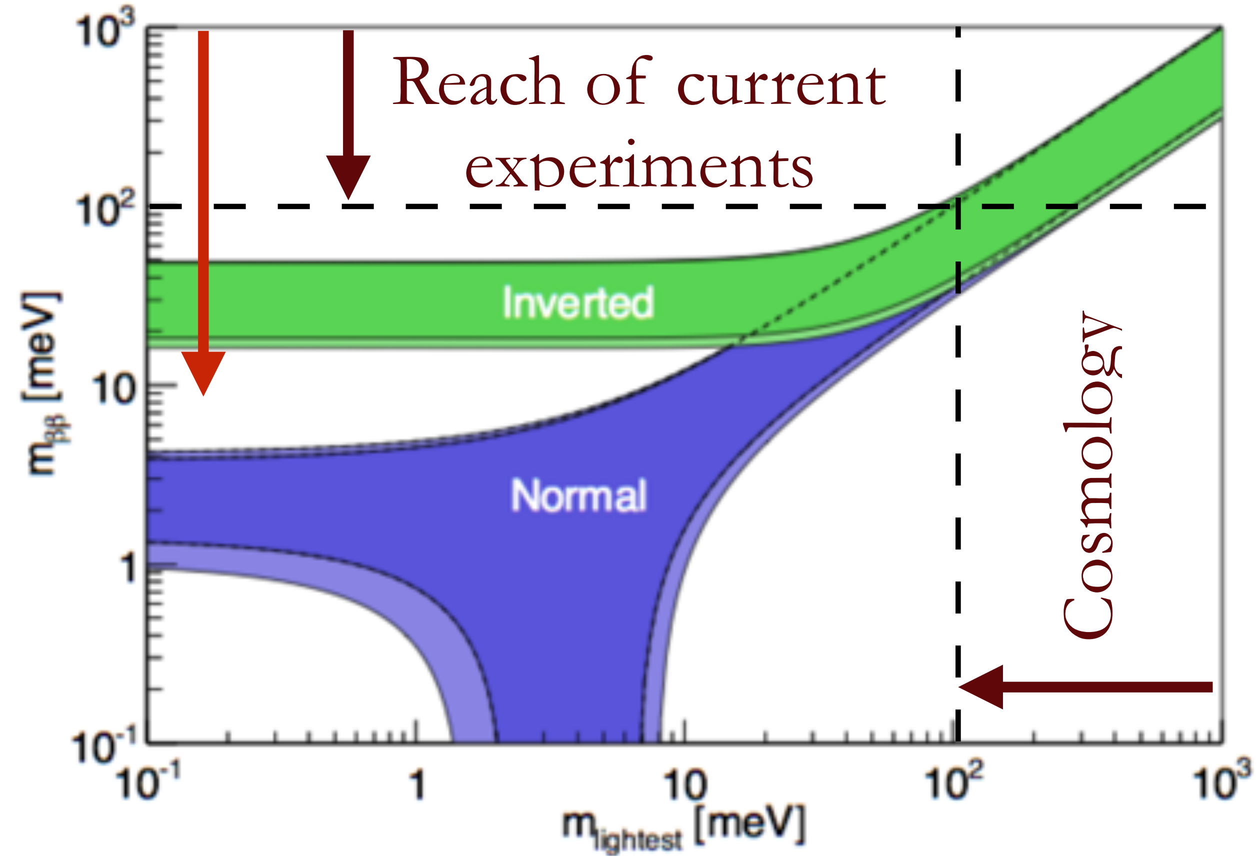
Back-up

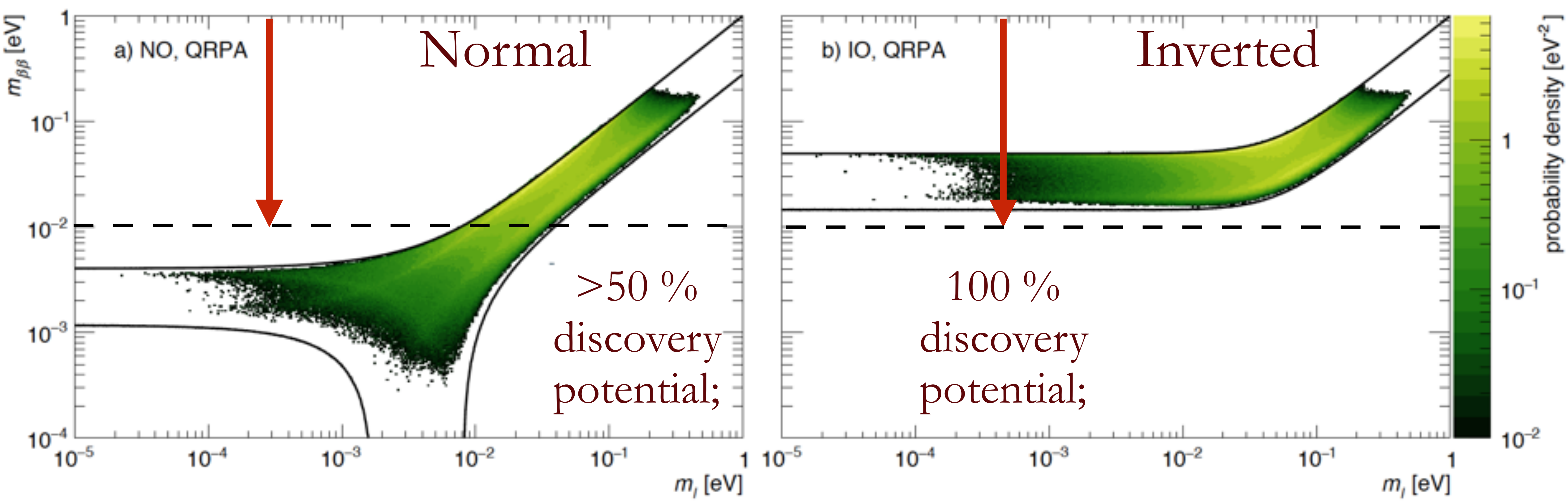
Proposed Conceptual Layout



Reach of Next Generation Experiments

- Next generation experiments aim to push through through the inverted mass ordering.
- But then what?
  - Bayesian posterior distributions reveal the promising discovery potential of the next generation experiments

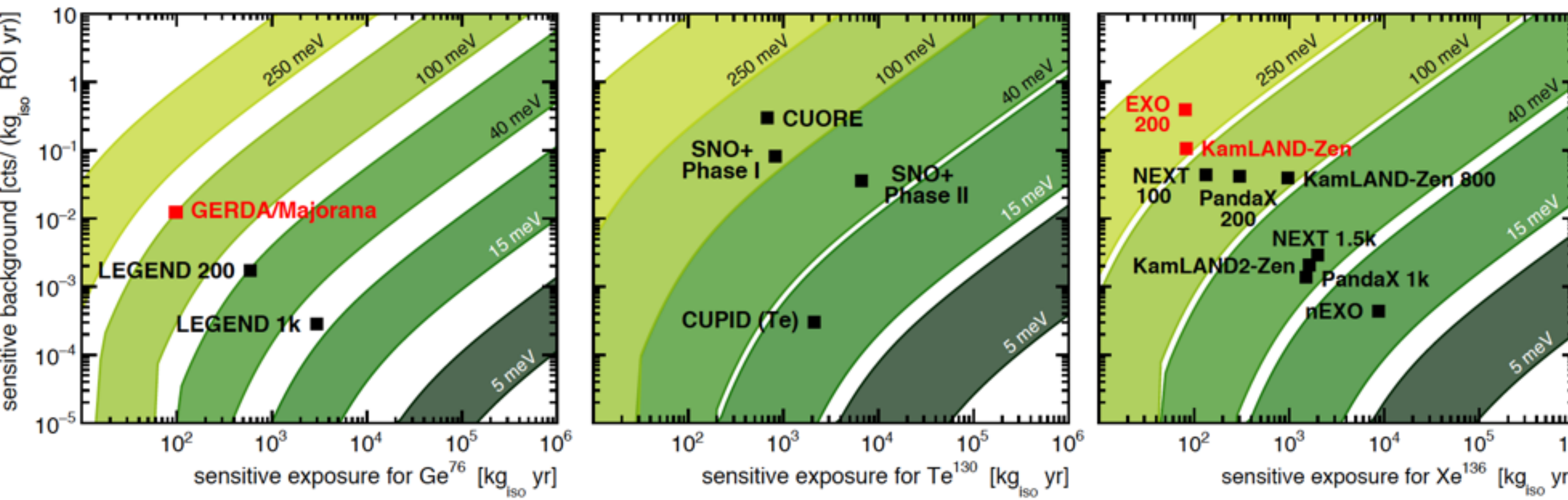




[Agostini, Benato, Detweiler (2017) arXiv:1705.02996v3

Reach of Next Generation Experiments

- 3σ discovery potential for current (red dots) and future (black dots) experiments
  - bands are due to uncertainties in nuclear matrix elements



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