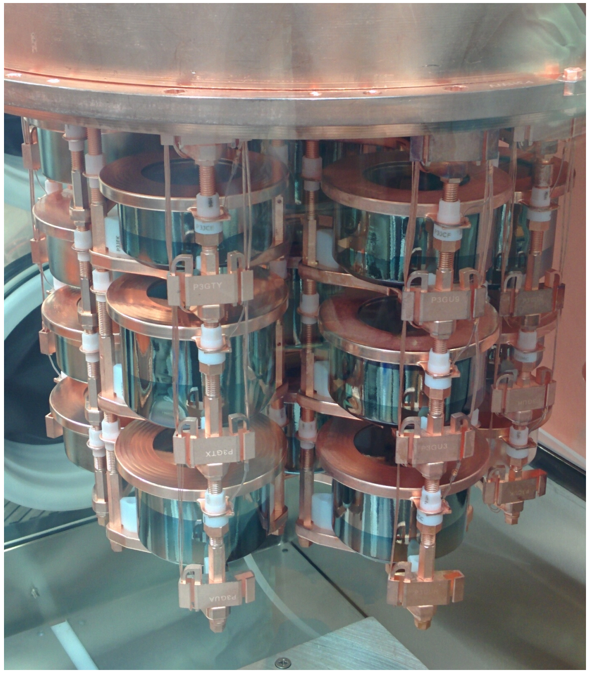
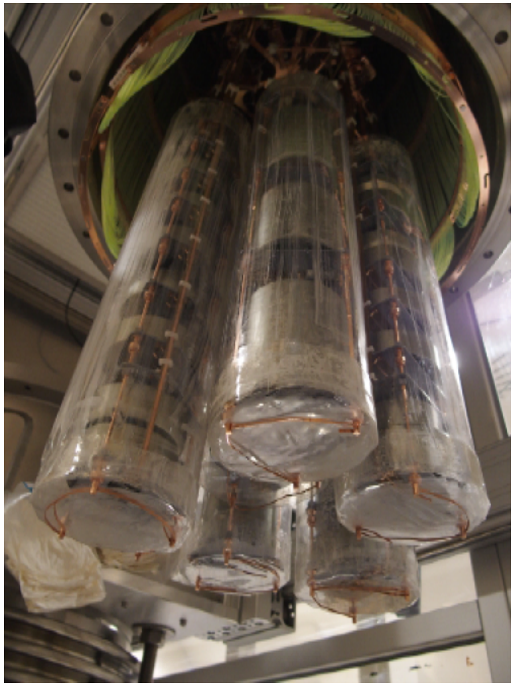
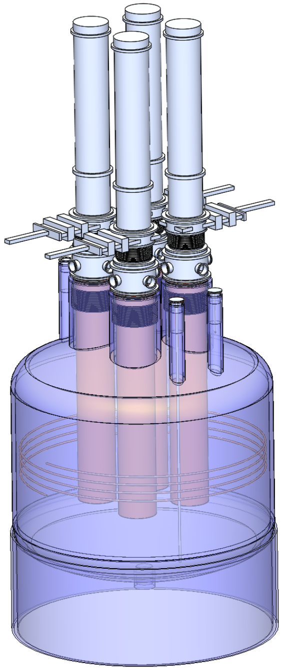
The Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND)







J.F. Wilkerson
on behalf of the LEGEND Collaboration

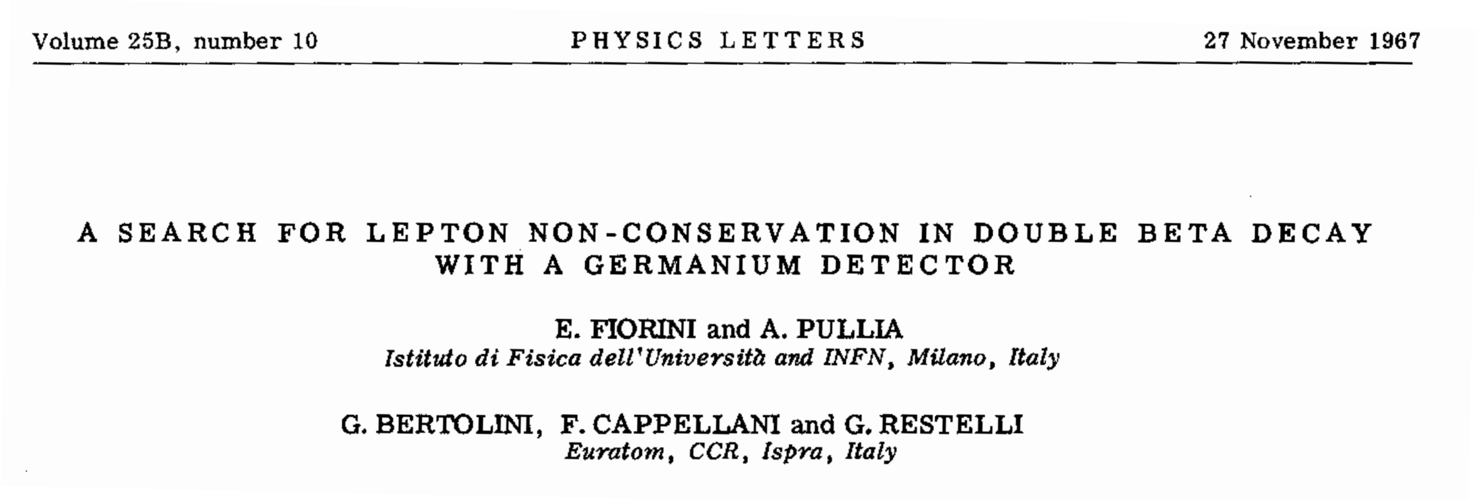
COSMS INSTITUTE

THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

TUNL

XV International Conference on
Topics in
Astroparticle and
Underground Physics
TAUP
2017

Fifty years ago - “New Expt. Method” for ββ-decay



Volume 25B, number 10 PHYSICS LETTERS 27 November 1967

A SEARCH FOR LEPTON NON-CONSERVATION IN DOUBLE BETA DECAY WITH A GERMANIUM DETECTOR

E. FIORINI and A. PULLIA
Istituto di Fisica dell'Università and INFN, Milano, Italy

G. BERTOLINI, F. CAPPELLANI and G. RESTELLI
Euratom, CCR, Ispra, Italy

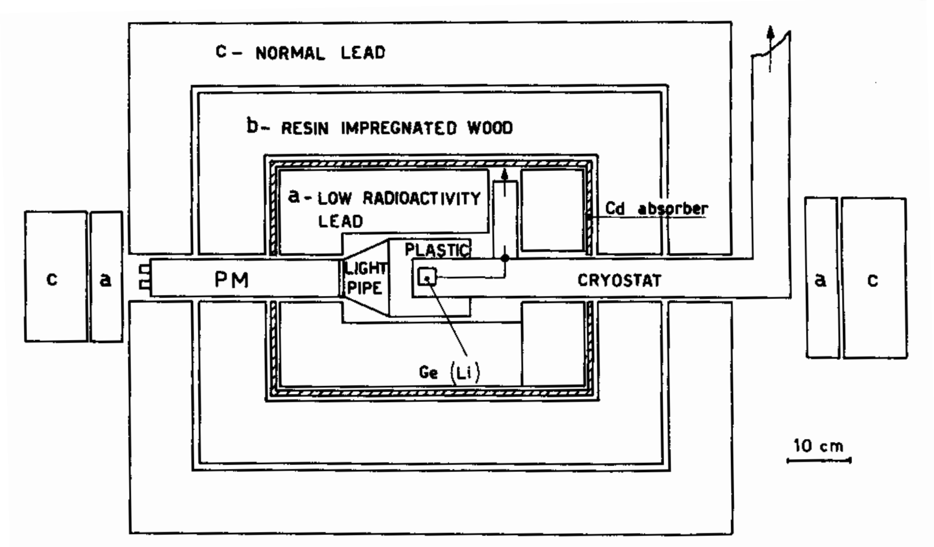
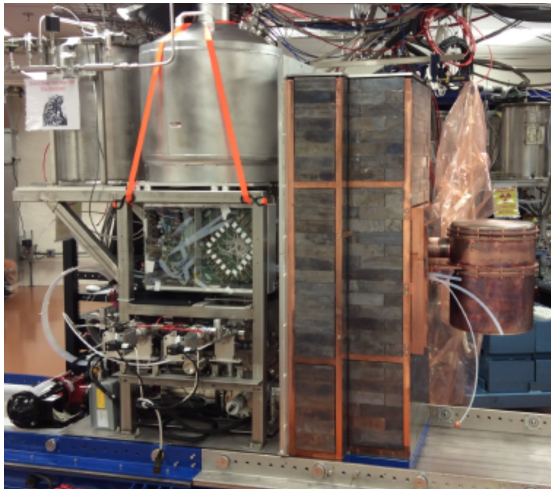


Fig. 1. Experimental setup.

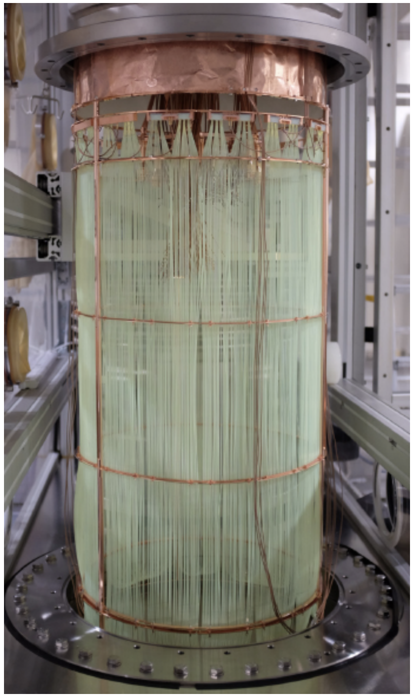
^{76}Ge

- Ge(Li) detector (HPGe crystal)
- Source == Detector
- $T_{1/2}$ $(0\nu\beta\beta) \geq 3 \times 10^{20}$ years

MAJORANA and GERDA

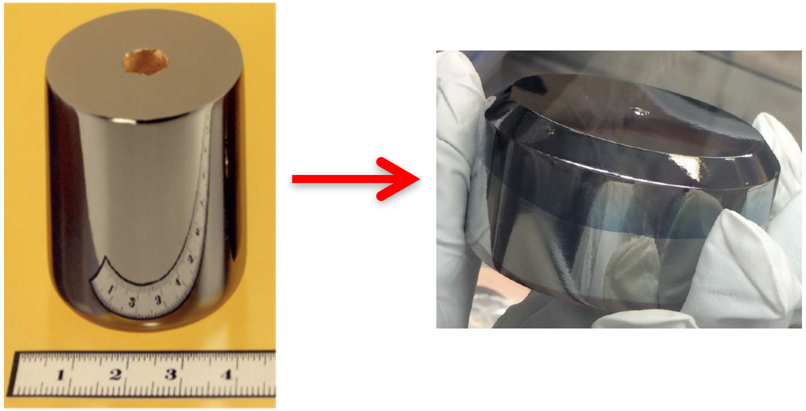


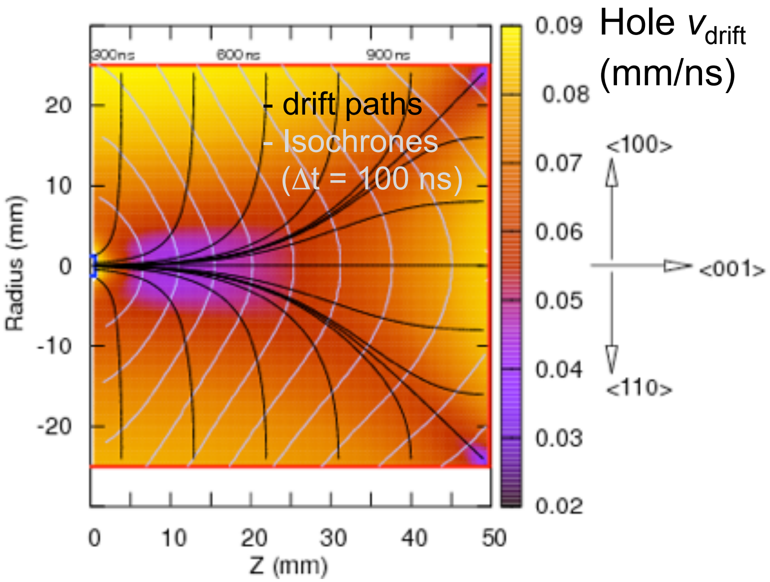
MAJORANA DEMONSTRATOR
“Traditional” configuration:
Vacuum cryostats in a
passive graded shield
with ultra-clean materials

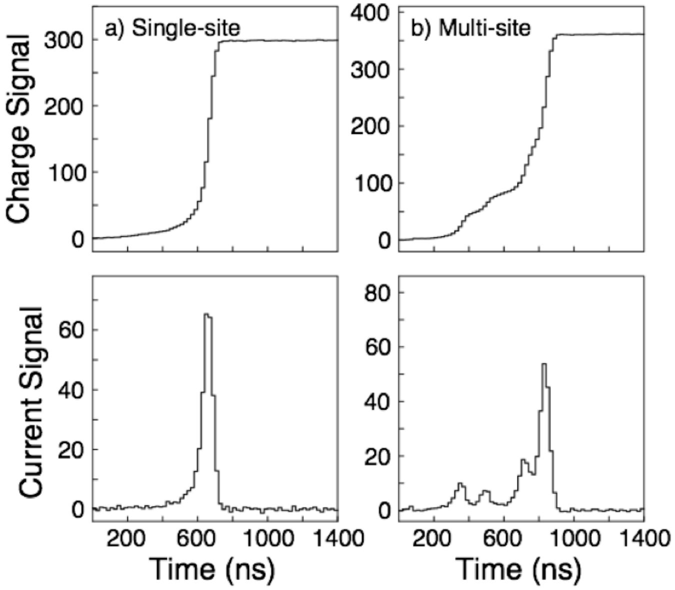


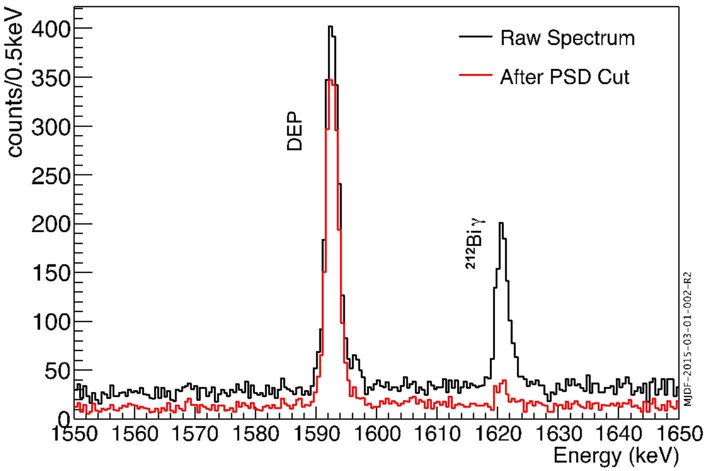
GERDA
Novel configuration:
Direct immersion
in active LAr shield

0νββ with Point Contact Detectors



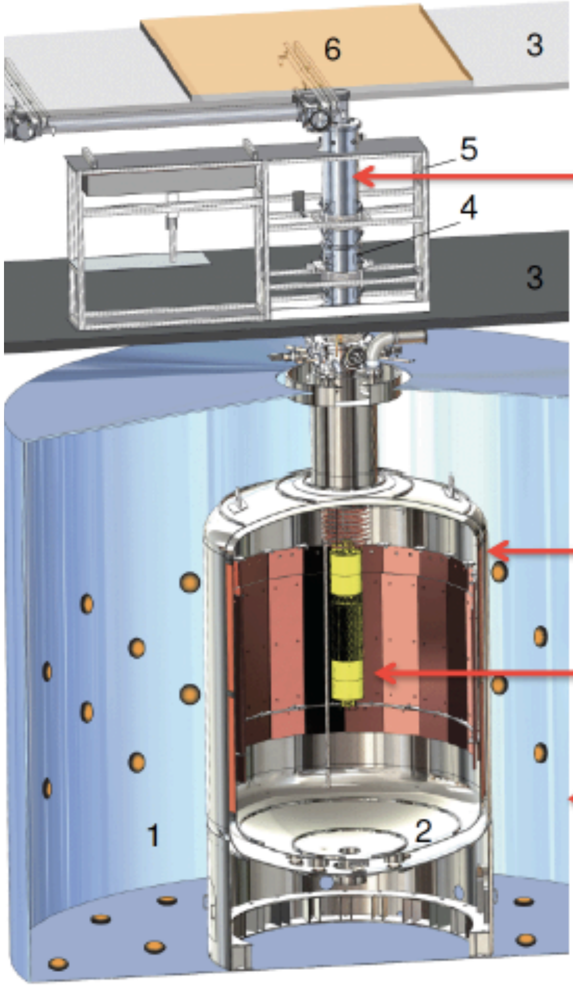






Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)
Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).

GERDA Phase II (Luciano Pandola, Wed. Plenary)



Plastic muon veto system

Glove box

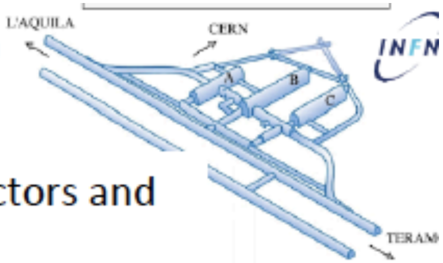
Lock to insert HPGe detectors and LAr instrumentation

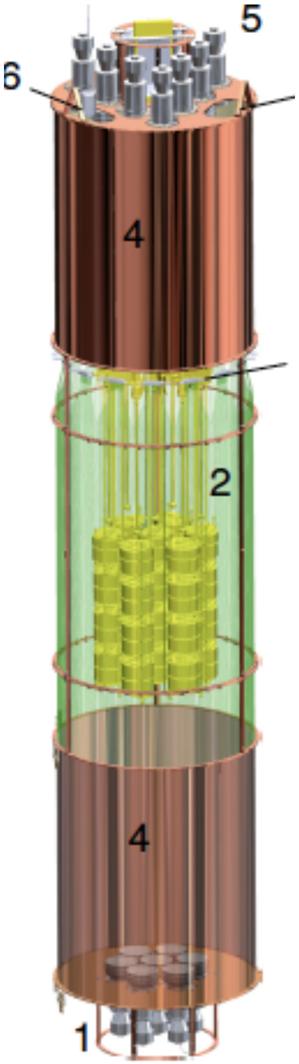
Clean room floor

Liquid Ar cryostat (64 m^3, diameter 4 m)

Ge detector array and LAr instrumentation
30 BEGe (20 kg) and 7 Coax (15.6 kg)

Water tank with muon veto system PMTs (590m^3, 10 m diameter)

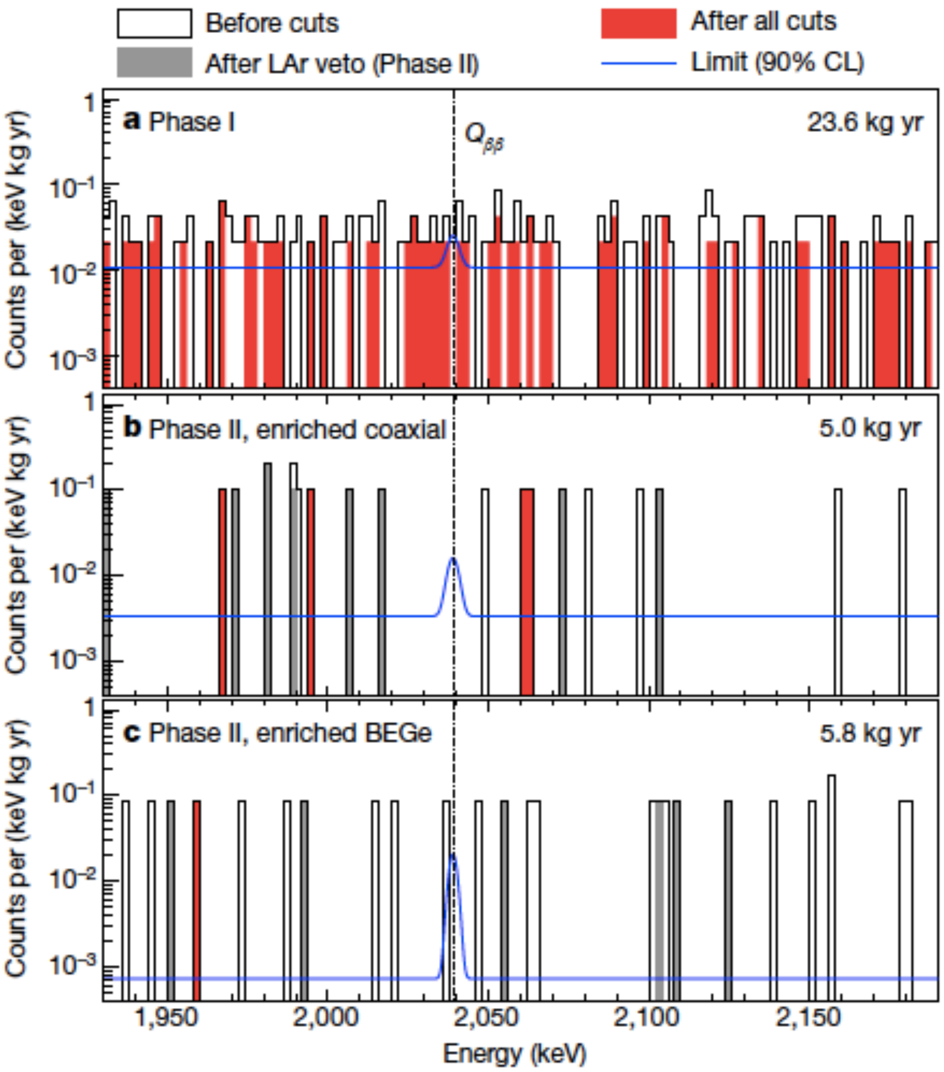




GERDA Phase II

Nature 544, 47–52 (2017)

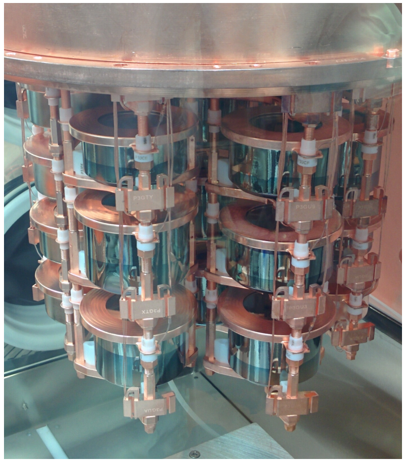
- Phase I and II Exposure:
  34.4 kg y
- Projected background from 1930 to 2190 keV window excludes 2104 ± 5 keV and 2119 ± 5 keV. Window of ± 20 keV around 0νββ Q blinded.
- For Phase II BEGes, have achieved "background free" measurement with background index of 1.8 c/(FWHM-t-y) or
  $(0.6^{+0.6}_{-0.4}) \times 10^{-3}$ c/(keV kg y)
- **$T_{1/2}$ (0νββ) ≥ 5.3 x 10^{25} years (90%CL)**



The MAJORANA DEMONSTRATOR

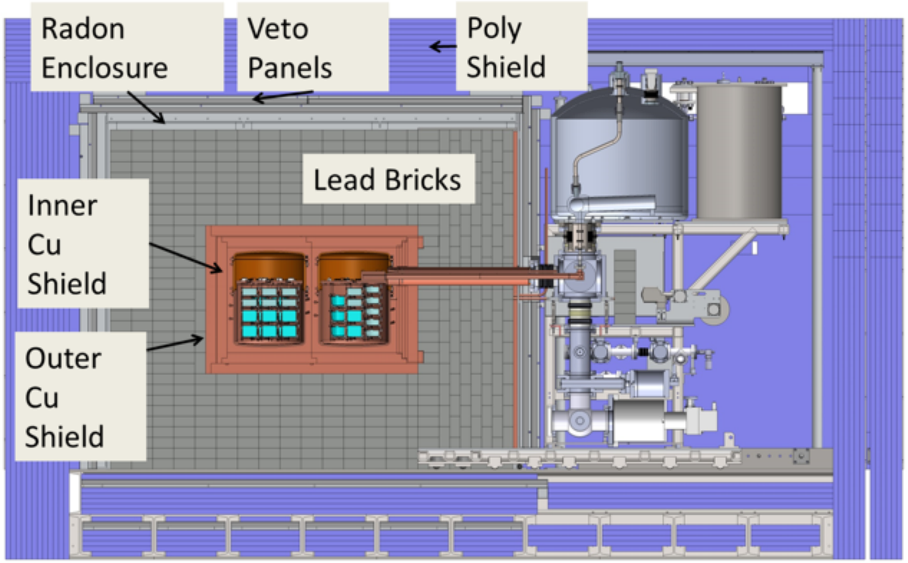
(Tom Caldwell,
Mon. Neutrino 2)

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



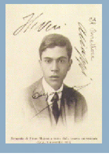
Goals: - Demonstrate backgrounds low enough to justify building a tonne scale expt.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

- 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
  scales to 1 count/(ROI t y) for a tonne experiment
- 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.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Ultra low-activity components and construction
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto

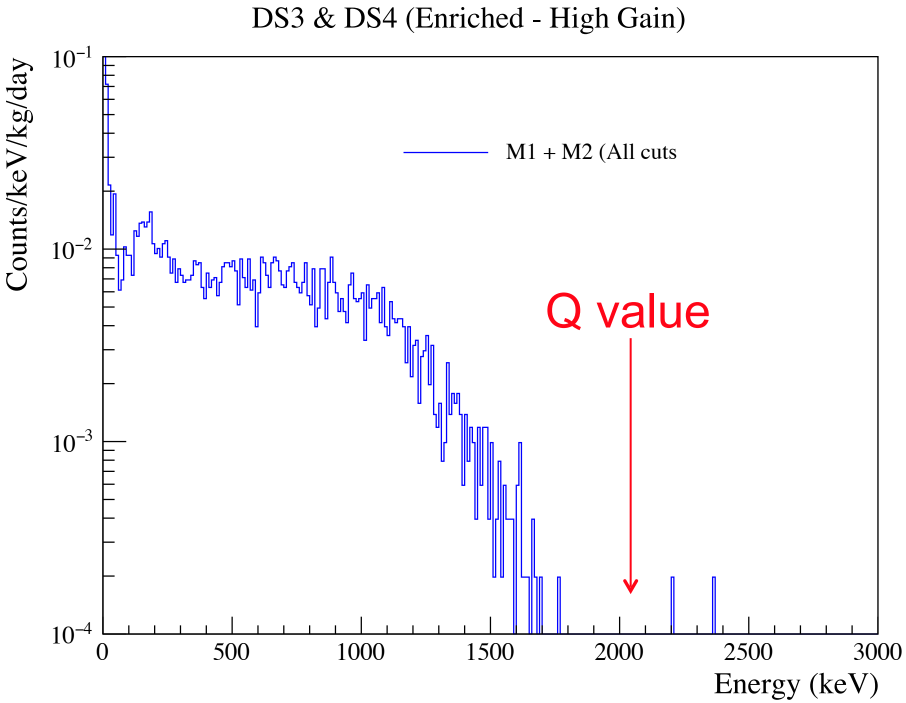


N. Abgrall *et al.*, Adv. High Ener. Phys. **2014**, 365432 (2013); arXiv:1308.1633

Initial Results from the Majorana Demonstrator



- The ^{76}Ge enriched point contact detectors developed by Majorana
  - have attained the best energy resolution (2.4 keV FWHM at 2039 keV) of any ββ-decay experiment.
  - provide excellent pulse shape discrimination reduction of backgrounds.
  - at low energies have sub-keV energy thresholds and excellent resolution allowing the Demonstrator to perform sensitive tests in this region for physics beyond the standard model (PRL **118**, 161801 (2017) & Othman later in this session).
- The Demonstrator's initial backgrounds and the GERDA Phase II backgrounds are the lowest backgrounds in the region of interest (ROI) achieved to date of all current or previous 0νββ experiments.



First results from Modules 1 and 2 in-shield

Exposure: 1.39 kg y

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) or 4.1 c/(FWHM t y) for a 2.9 (Modue 1- DS3) & 2.6 keV (Module 2 - DS4) keV ROI, (68% CL).

Background index of 1.8 x 10^{-3} c/(keV kg y)

Analysis cuts are still being optimized.

Through mid-May, have 10x more exposure in hand. Analysis is in progress.

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Mission: "The collaboration aims to develop a phased, Ge-76 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."

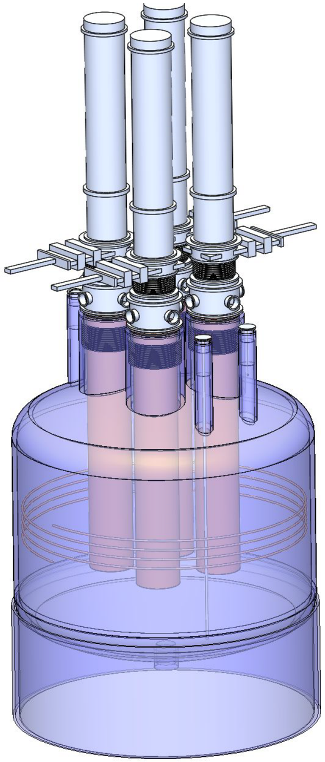
Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First phase:

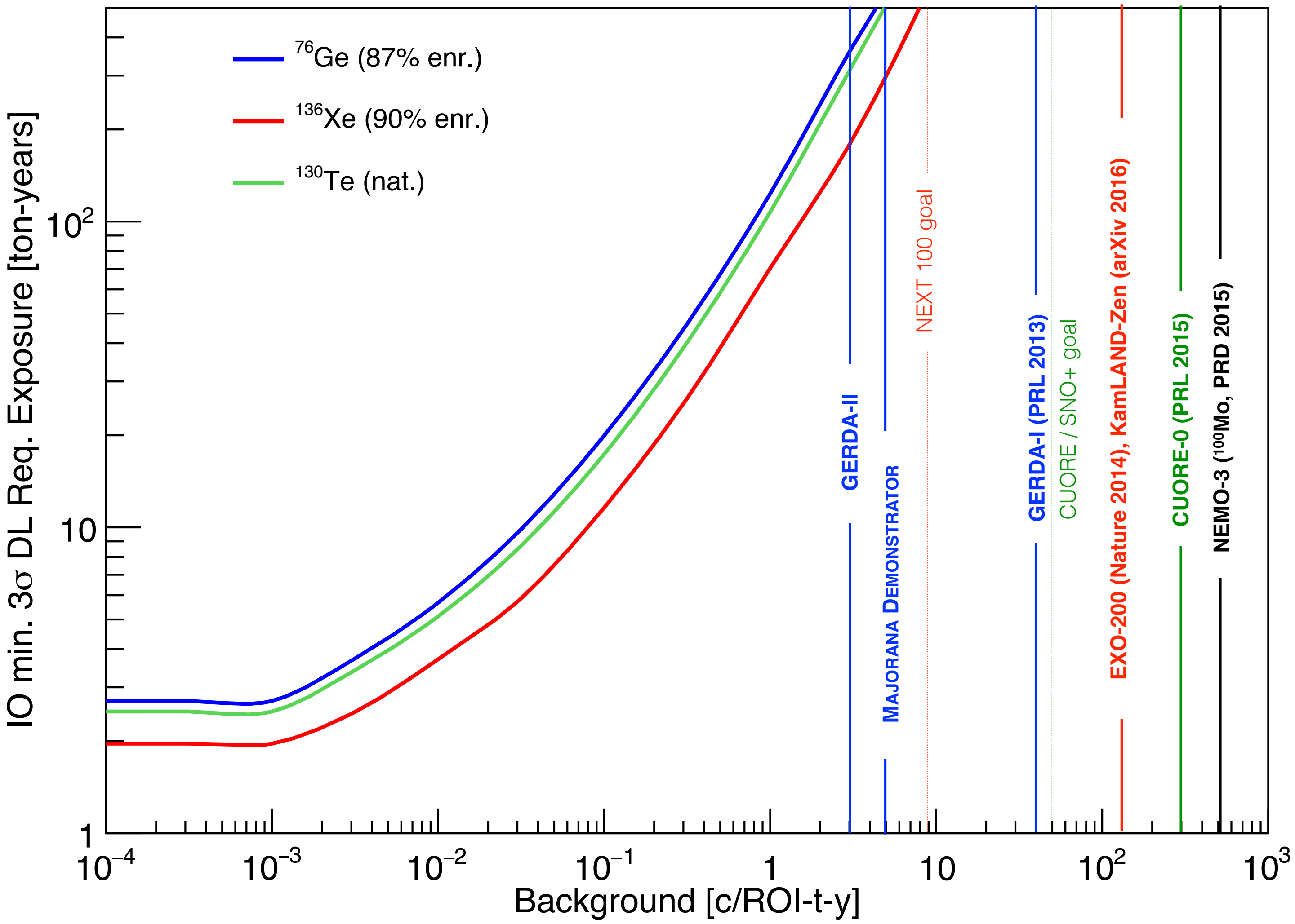
- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c /(FWMH t y)
- start by 2021

Subsequent stages:

- 1000 kg (staged)
- timeline connected to U.S. DOE down select process
- BG: goal (x30 lower) 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (Ge-77m) under investigation



3σ Discovery : Exposure vs. Background



J. Detwiler

The Best of MAJORANA & GERDA

- 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

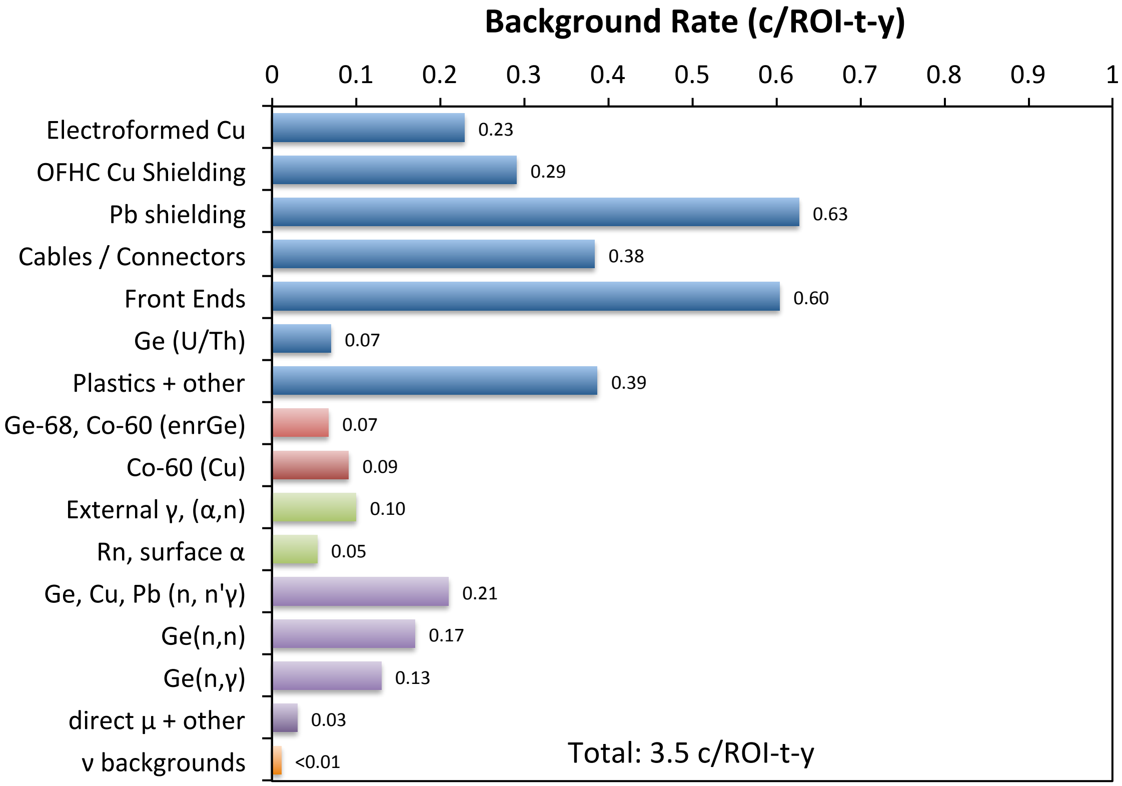
LEGEND Design Criteria

- 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@2039 keV

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?

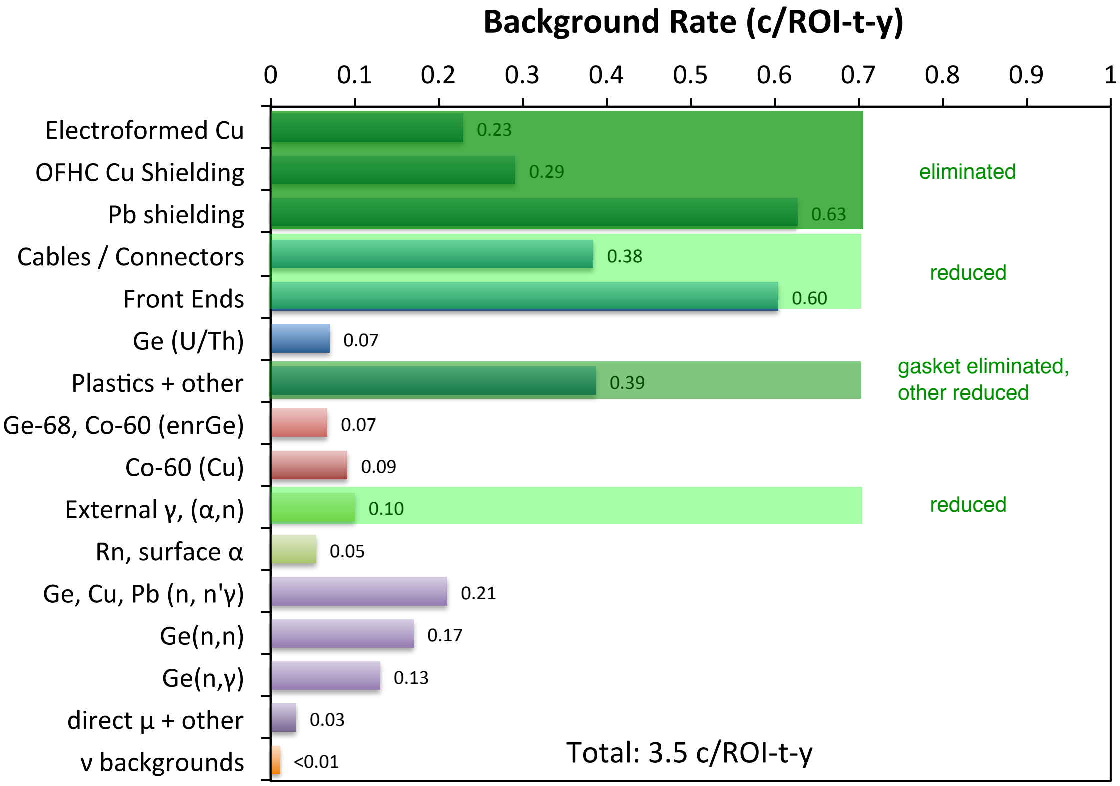


LEGEND Background Budget Estimate

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

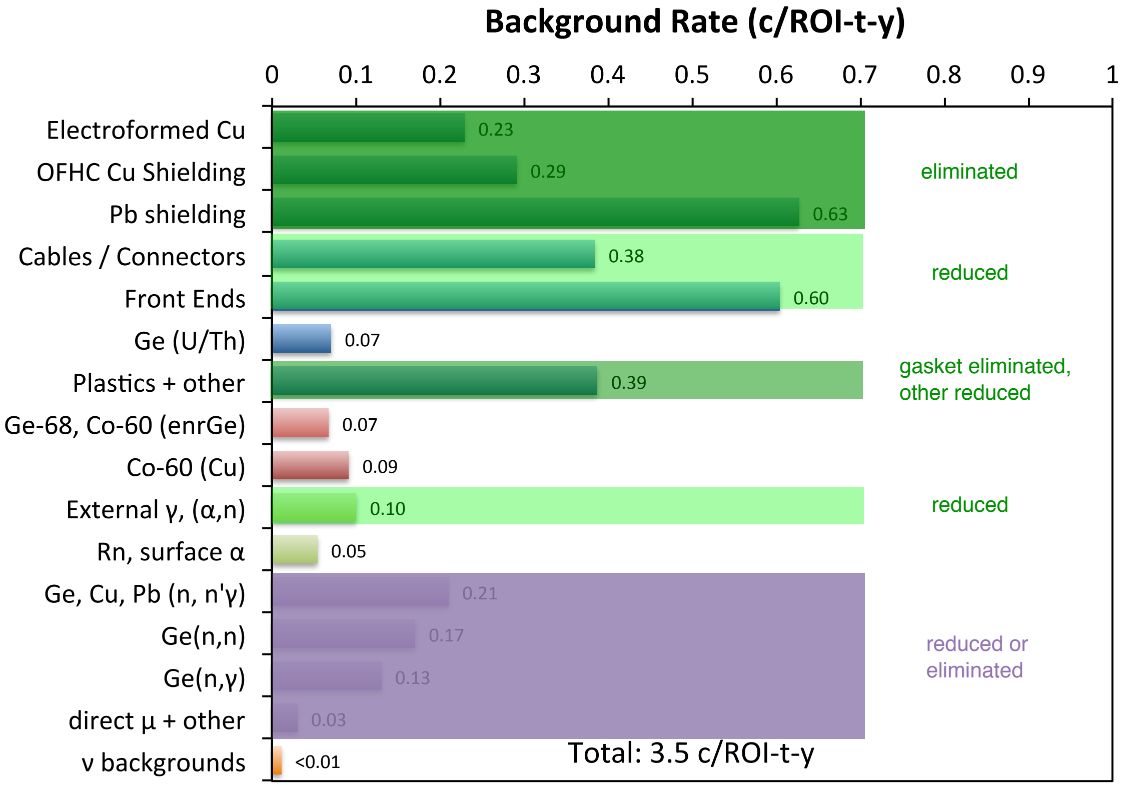


LEGEND Background Budget Estimate

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

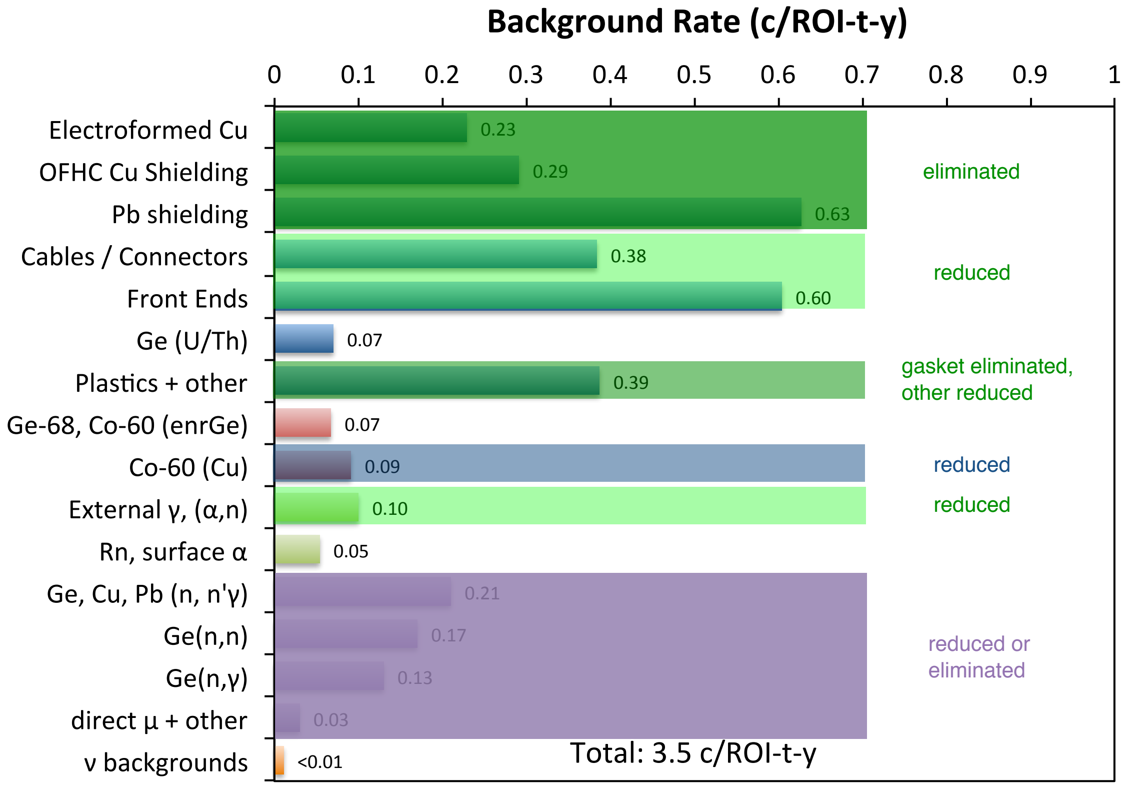


LEGEND Background Budget Estimate

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

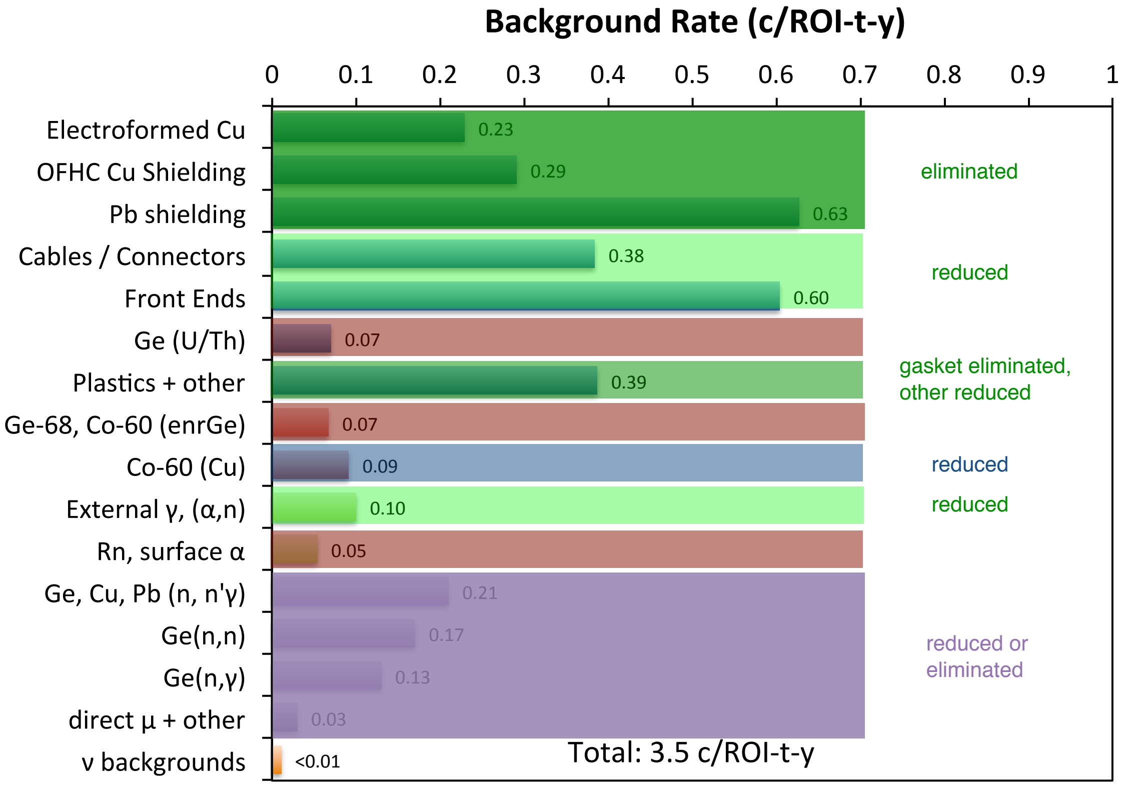


LEGEND Background Budget Estimate

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

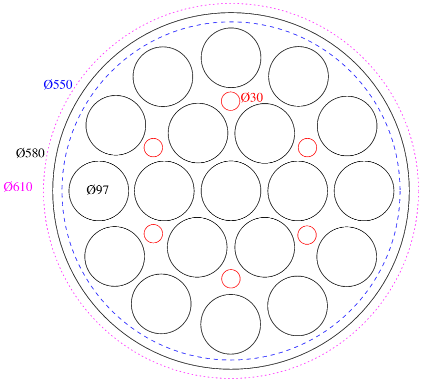
Building on GERDA and MAJORANA DEMONSTRATOR how does one get the factor of ~ x30?

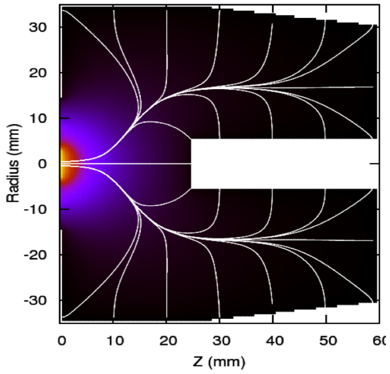
- clean, active shield
- deeper and/or active shield
- EF all Cu underground
- Learn from DEMONSTRATOR & GERDA II (values are currently largely upper limits)

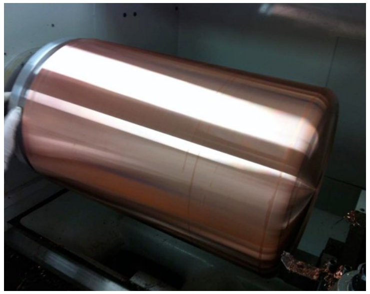


LEGEND 200 - 1st step of phased approach

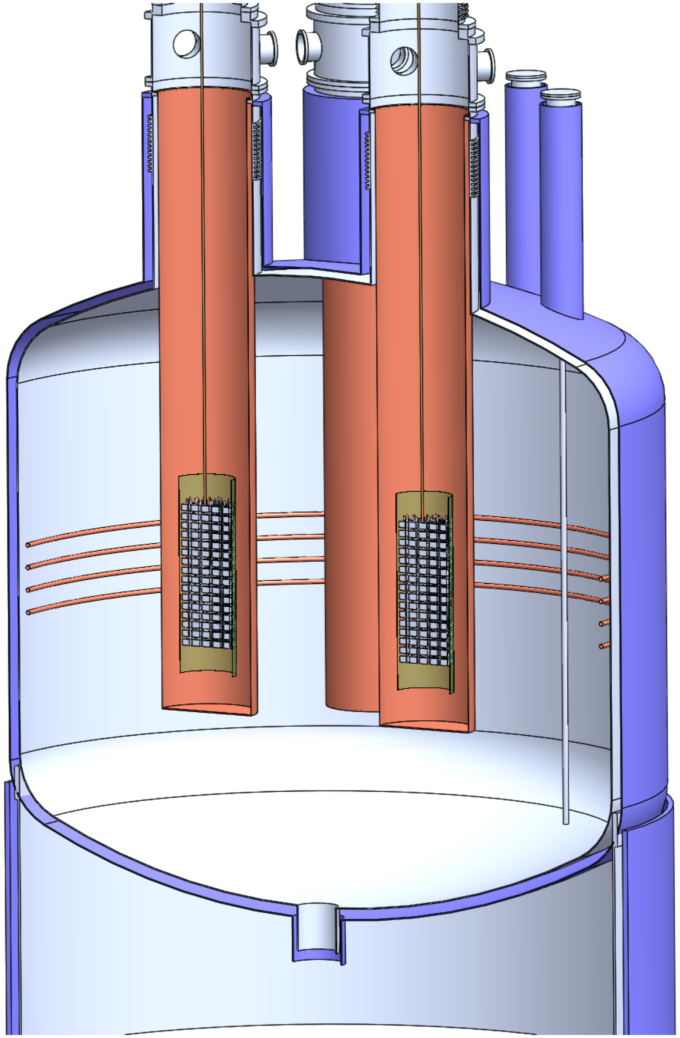
- Reuse existing GERDA infrastructure at LNGS.
- Modifications of internal cryostat piping so can accommodate up to 200 kg of detectors.
- Improvements
  - use some larger Ge detectors (1.5 - 2.0 kg)
  - improve LAr scintillator light collection (2x in test stand)
  - lower mass, cleaner cables
  - lower 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
  - 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)

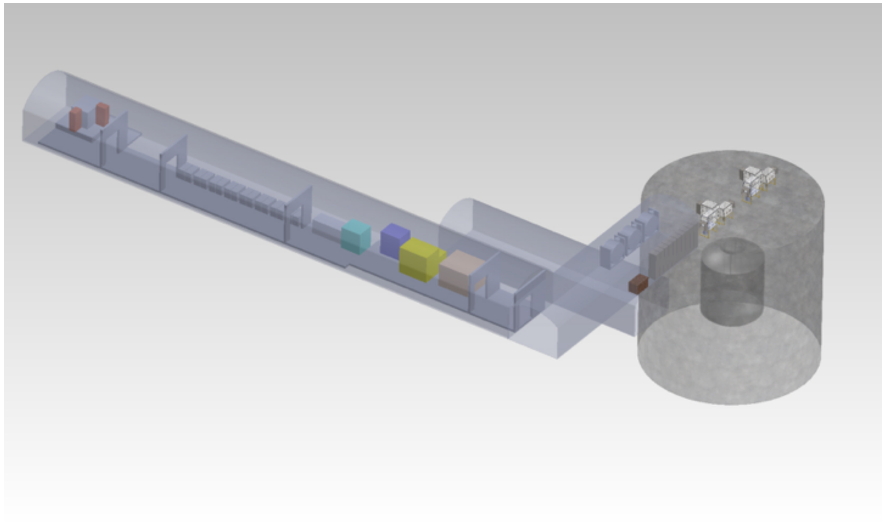
  or

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

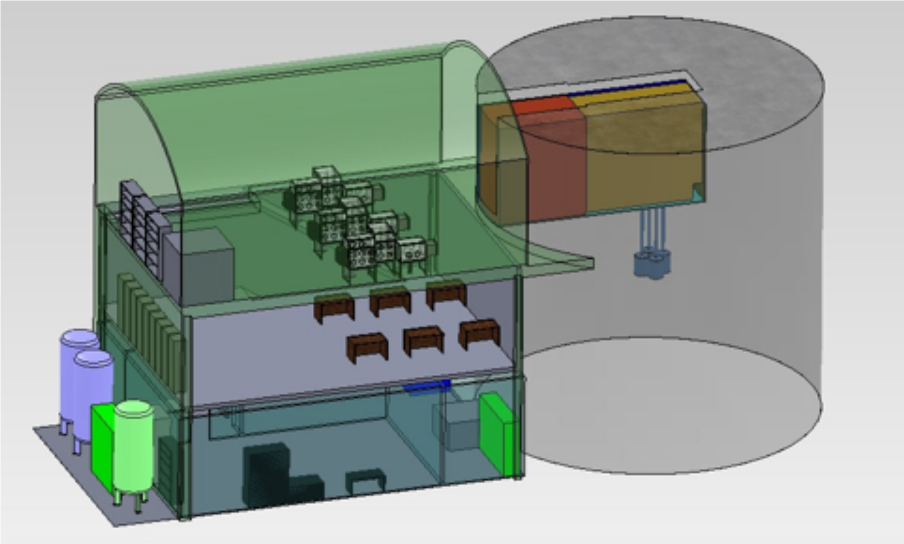
LEGEND 1000 Laboratory Configuration

Possible laboratory layouts
Depth is a necessary consideration for the 1000-kg phase

SNOLAB cryopit concept

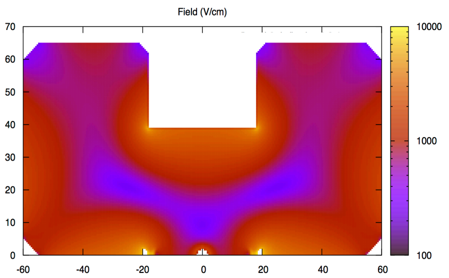


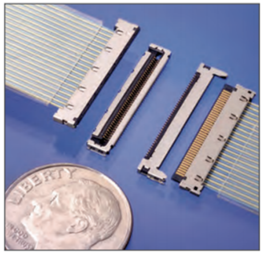
Generic Cavity design (CJPL,SURF)

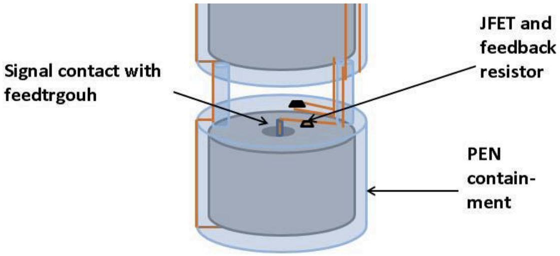


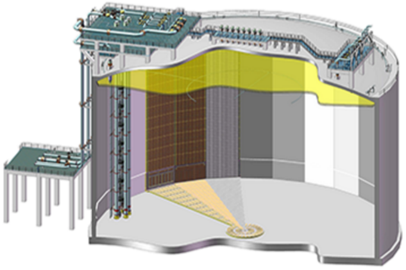
LEGEND 1000 - Optimization Activities

- 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 materials (LNe, PEN, doped LAr, …)
- Engineering
    - Low mass, low activity connectors
    - advance fabrication
    - mechanical design, alternate cryostat designs
- Analysis - machine learning, advanced PSD, …









LEGEND Summary

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

- Ultimate Goal: exposure of 10 t-y; background of 0.1 c / ROI-t-y;
- 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).
- Coupled with excellent energy resolution ^{76}Ge has a discovery potential at a half-life significantly longer than 10^{27} years.

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.

Collaboration formed:

- 1st Munich April 2016
- 2nd Atlanta October 2016
- 3rd LNGS May 2017

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


LEGEND collaboration meeting @ LNGS, 15-17.5.2017

MAJORANA Electroformed Copper

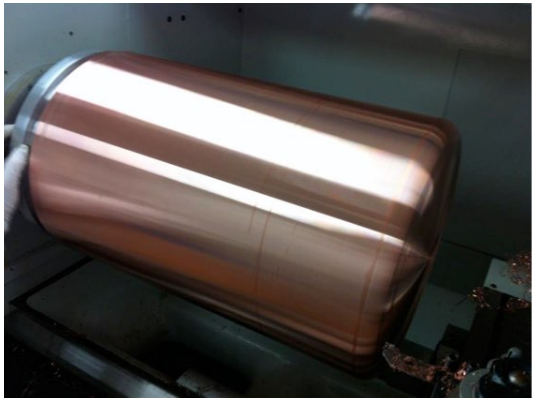
- MAJORANA operated 10 baths at the 4850′ level of Sanford Underground Research Facility (SURF) and 6 baths at a shallow UG site at PNNL. All copper was machined at the SURF Davis campus.
- The electroforming of copper completed in May 2015.
  - 2474 kg of electroformed copper on the mandrels,
  - 2104 kg after initial machining,
  - 1196 kg that will be installed in the DEMONSTRATOR.

Electroforming Baths in TCR

Inspection of EF copper on mandrels

- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

EF copper after turning on lathe



DEMONSTRATOR Cables and Connectors

	Total			Biased			Analysis		
DS3+DS4	Det(kg)	Active (kg)	#	Det (kg)	Active (kg)	#	Det (kg)	Active (kg)	#
Total	44.1	40.3 ± 0.7	58	33.8	30.9 ± 0.5	44	29.0	24.8 ± 0.4	35
Enriched	29.7	27.4 ± 0.4	35	23.2	21.4 ± 0.3	27	19.6	18.1 ± 0.3	23
Natural	14.4	12.9 ± 0.3	23	10.7	9.5 ± 0.2	17	9.4	6.7 ± 0.2	12

- 44 of the 58 installed detectors are operating
- Problems with non-operating detectors
  - 7 associated with the signal connectors that are located on the cryostat cold plate or with damaged low mass front end boards.
  - 7 detectors cannot be biased either because of problems with the HV cables, connections, or in one instance a likely detector problem.
- Upgrade underway
  - "Fuzz buttons" for signal connectors.
  - HV cable study in progress

NSAC 2015 Long Range Plan

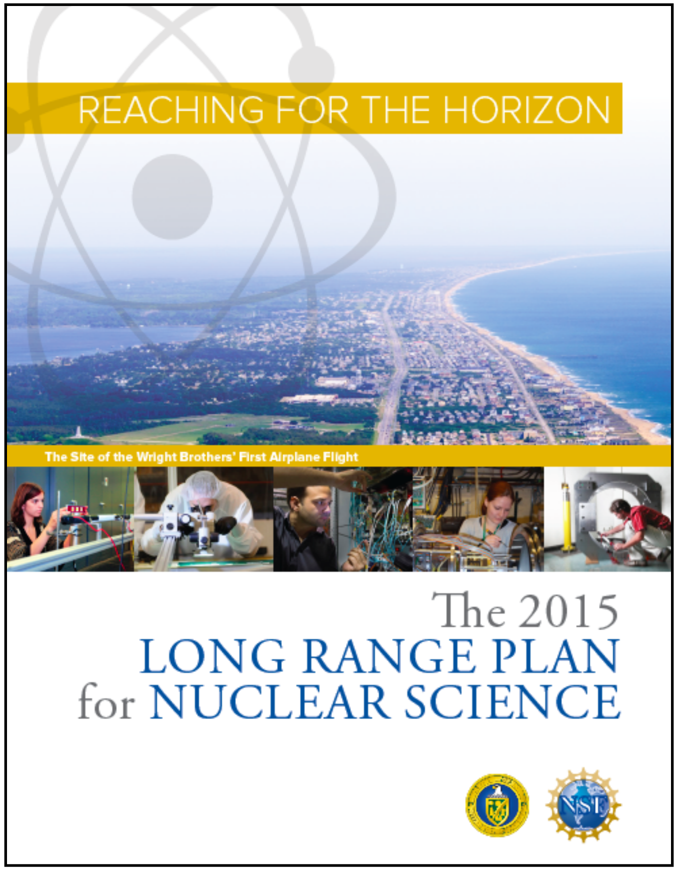
RECOMMENDATION II

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.



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE