Status of the MAJORANA DEMONSTRATOR and Prospects for a Tonne-Scale ^{76}Ge 0νββ Search

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TRIUMF Double-Beta Decay Workshop

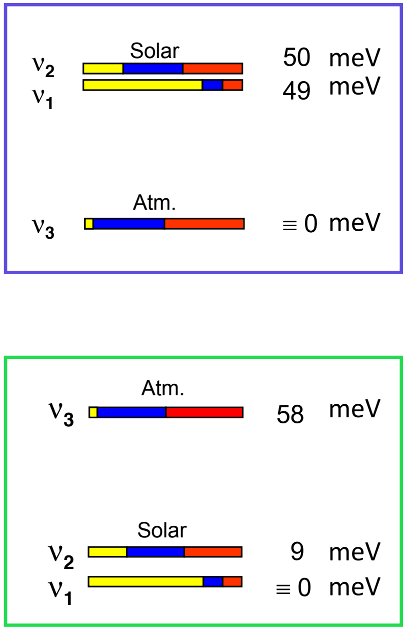
Outline

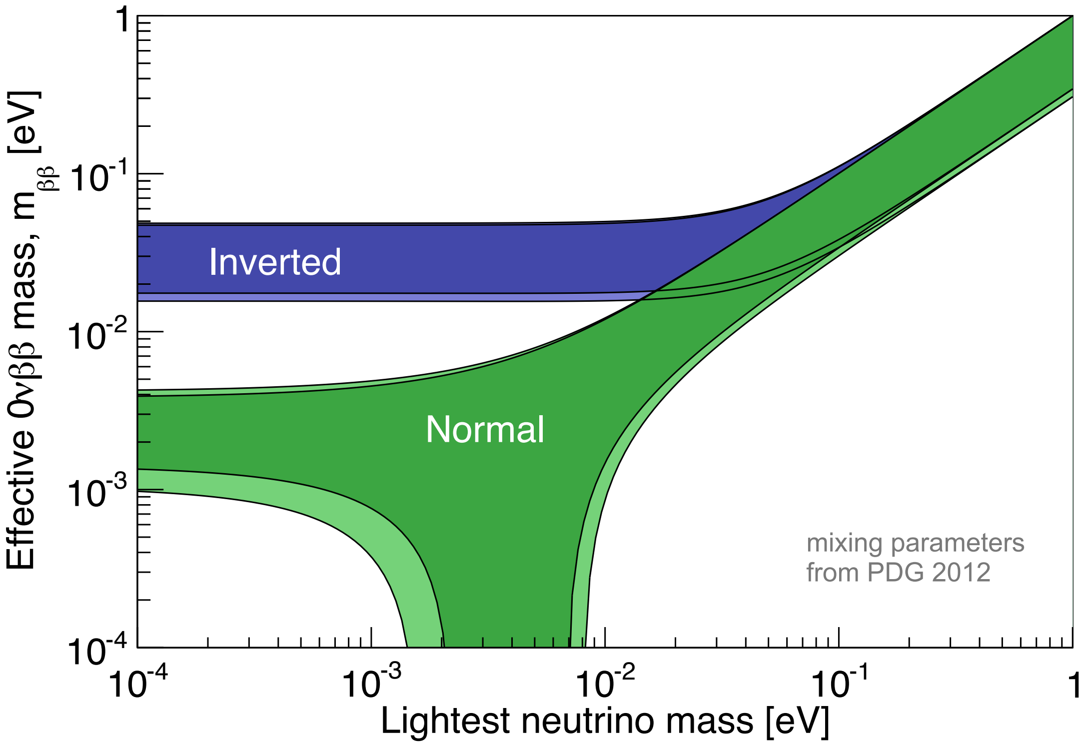
- $0\nu\beta\beta$ at the tonne scale
  - Sensitivity requirements and implications
  - Challenges
- The MAJORANA DEMONSTRATOR
  - Goals
  - Overview
  - Status
  - Schedule
- GERDA
- Path to a next-generation experiment
  - NSAC long range plan and the funding process
  - Possible concepts
  - Collaboration

Sensitivity for Inverted Mass Ordering

The rationale for a tonne-scale experiment has generally been given as:

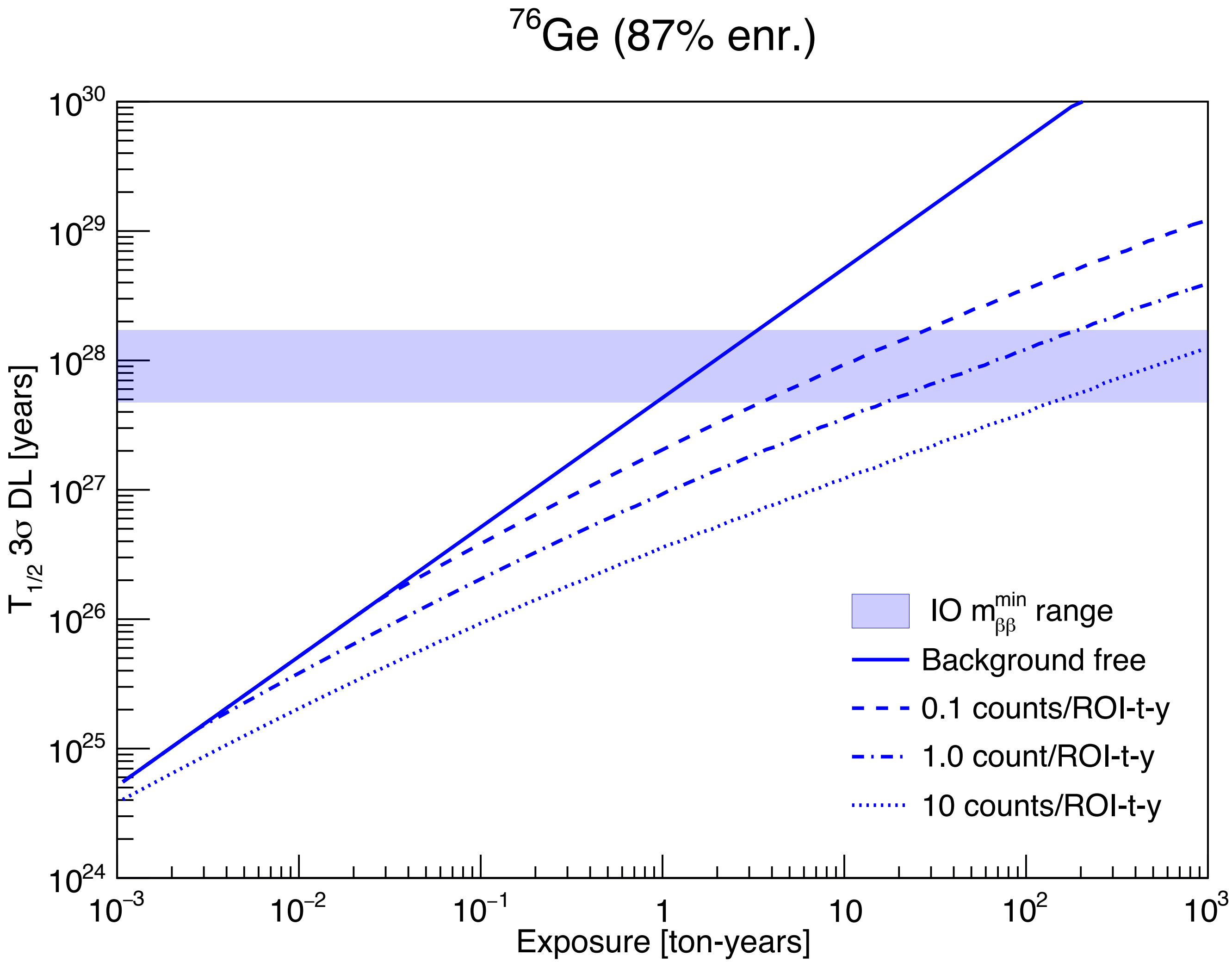
- To have good *discovery potential* for 0νββ over *the whole $m_{\beta\beta}$ mass range* of the Inverted Mass Ordering
- Assuming that 0νββ is mediated by the exchange of a light Majorana neutrino





Discovery Level, Inverted Mass Ordering

J. Detwiler

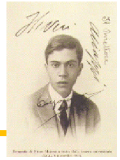


Inverted Ordering (IO)

Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

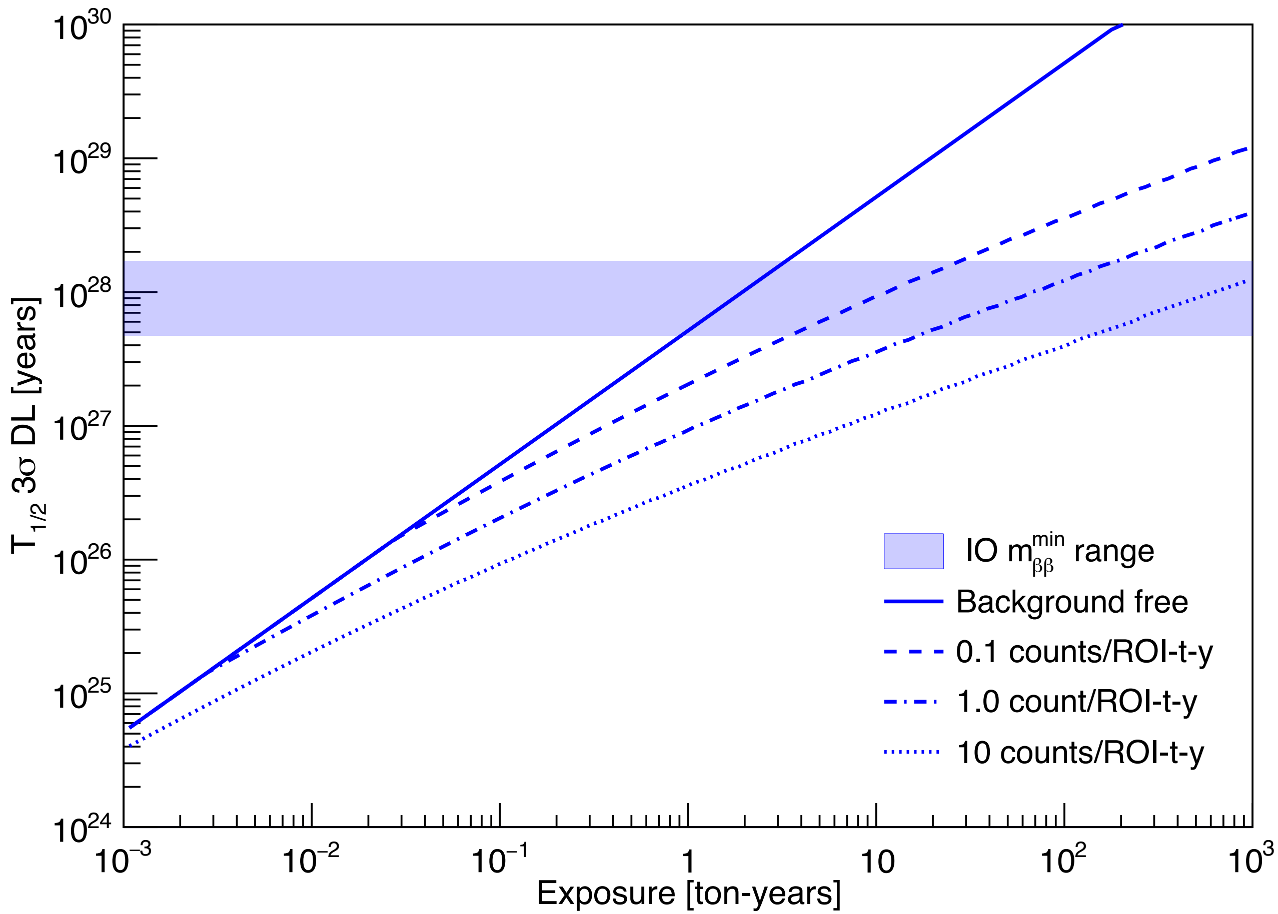
Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

Discovery Level, Inverted Mass Ordering



To probe entire region of inverted mass ordering requires

- About 10 tonne-years of exposure
- Background rates of ~ 0.1 counts per tonne-year in the energy ROI



Inverted Ordering (IO)

Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Sensitivity Requirements

- Ten tonne-years of exposure
  - Large, efficient, easily scalable detector
  - Source as detector
  - Isotopic enrichment
- Background rates of ~ 0.1 c/t-y in the $0\nu\beta\beta$ peak region
  - Best background rates to date are ~ 40 c/t-y
  - Ultra-clean materials and shielding
- Best possible energy resolution

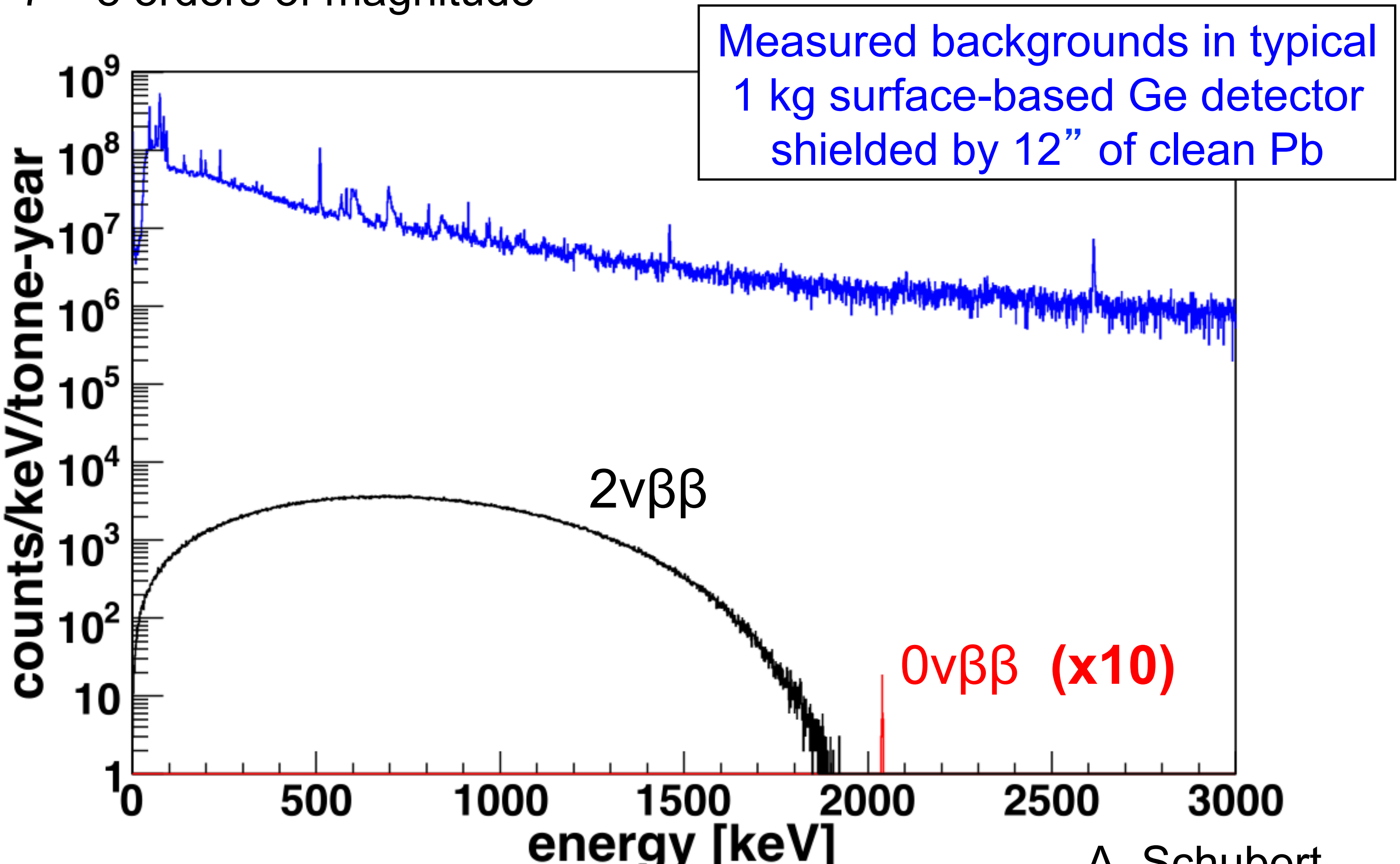
One way to think of this:

- Build seven GammaSpheres out of enriched ^{76}Ge
- Use only ultra-clean materials for cryostats, readout, cables, …
- Bury in an active shield 2 km underground
- Run for 10 years
- Look for a peak with ≤10 counts at 2039 keV

Sensitivity Requirements

An illustration of how hard this really is…

- 7 – 8 orders of magnitude



A. Schubert

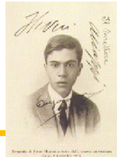
What are the Backgrounds?

- Primordial: U, Th, K in or close to the detectors
- Cosmogenic activation of detector or shield materials above ground (^{60}Co, ^{3}H...)
- External γ, (α,n)
- μ-induced backgrounds generated at depth:
  Cu,Pb(n,n' γ), (n,γ), direct μ
- 2νββ decay (irreducible; energy-resolution dependent)

Background Reduction

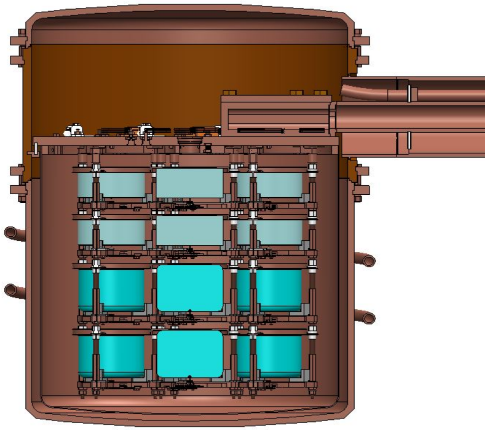
- Primordial: U, Th, K in or close to the detectors
  - Ultra-pure materials; minimize non-source material; PSA; active shielding
- Cosmogenic activation of detector or shield materials above ground (^{60}Co, ^{3}H...)
  - Minimize time above ground; ultra-clean/active shielding
- External γ, (α,n)
  - Ultra-clean/active shielding; data cuts such as PSA
- μ-induced backgrounds underground:
  Cu,Pb(n,n' γ), (n,γ), direct μ
  - Go deep
- 2νββ decay (irreducible; energy-resolution dependent)
  - Energy resolution (also important for believability of discovery)

The MAJORANA DEMONSTRATOR (MJD)



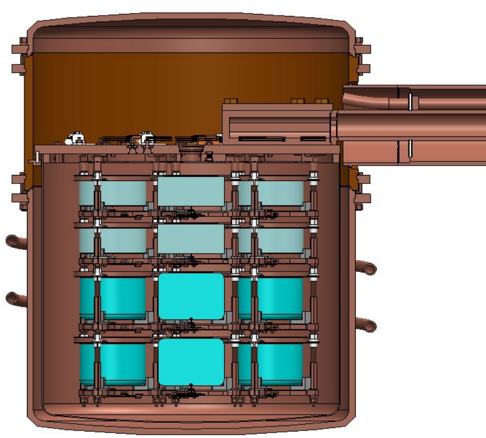
- At 4850-foot level of Sanford Underground Research Facility, Lead, SD
- Funded by
  - U.S. DOE Office of Nuclear Physics
  - NSF Nuclear Physics
  - Additional contributions from international collaborators
- Project completion (CD-4) scheduled for Sept 2016

> - ^{76}Ge enriched from 7.8% to 87%
> - 29 kg ^{enr}Ge detectors,
> - 15 kg ^{nat}Ge detectors,
> - In two independent cryostats
> - Ultra-pure materials
> - Passive and active compact shield

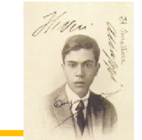


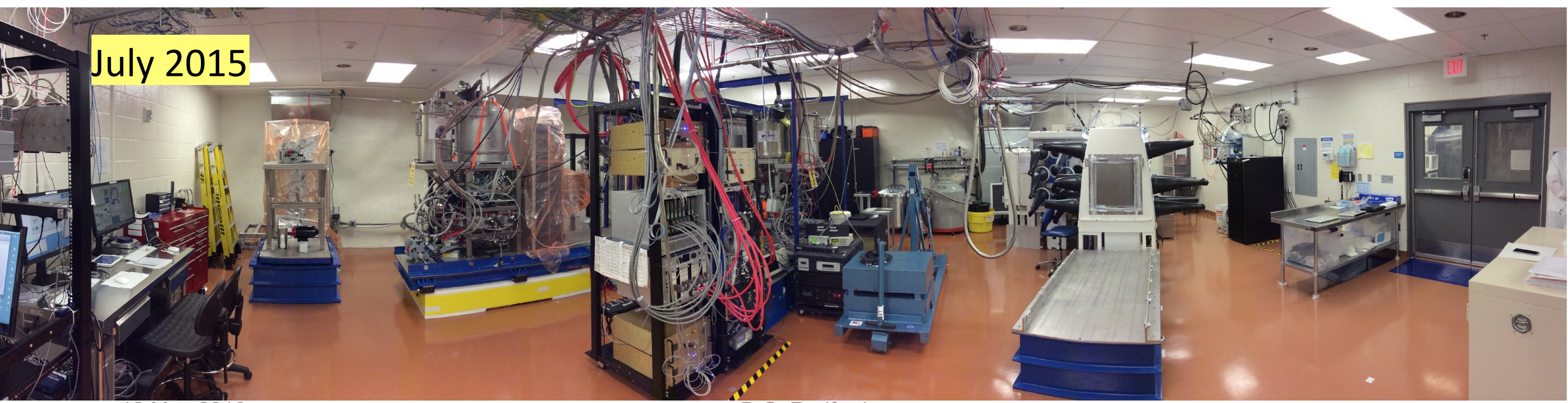
Goals

- The MAJORANA collaboration plans to built a tonne-scale experiment
- The primary goal is to show that we can reach the ultra-low backgrounds required to justify a tonne-scale ^{76}Ge experiment
  - Background goal: 3 c/t-y in 4-keV-wide ROI
  - Expected to scale to 1 c/t-y for a tonne-scale experiment
- Also search for low-energy dark matter
  - Light WIMPs, axions, …

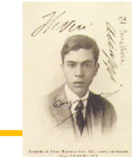


The Majorana Demonstrator



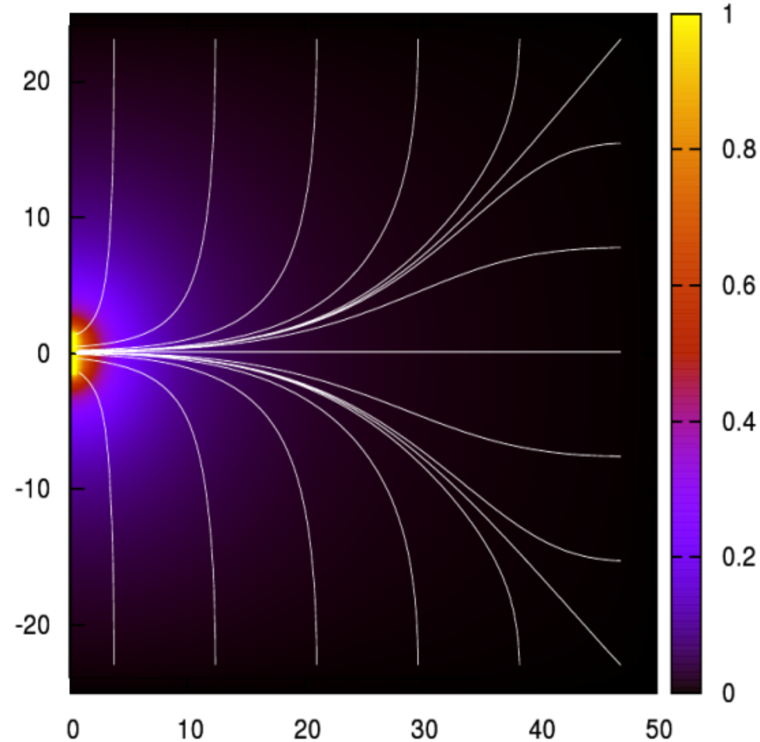


HPGe Detector Geometry

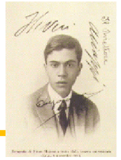


P-type Point Contact (PPC) HPGe detectors

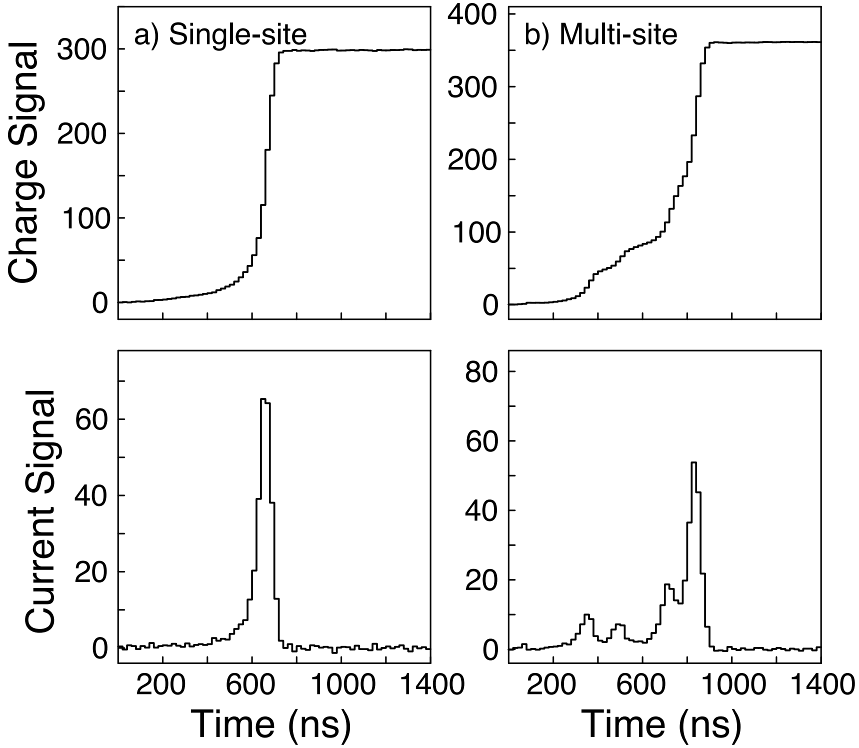
- Developed quite recently
- Significantly longer drift paths than in a coaxial detector
- Superb pulse-shape sensitivity allows discrimination between single-site and multi-site events
- Superb energy resolution, especially at low energies; allows very low energy threshold
- Also being used in Dark Matter searches
- MJD enriched detectors average ~ 900 g



Signal Shapes and Pulse-Shape Analysis

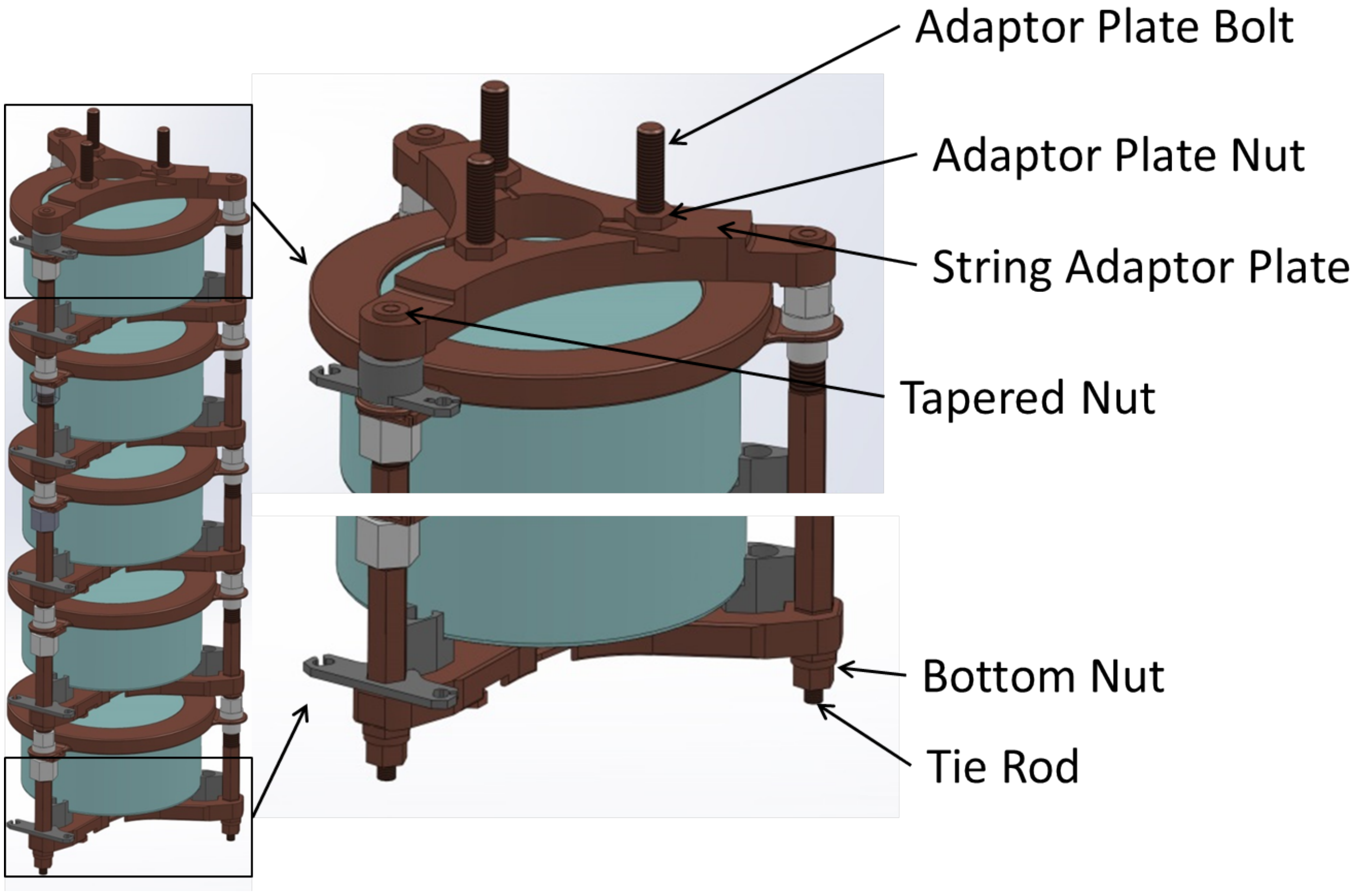


- $0\nu\beta\beta$ events are inherently single-site
- But gamma rays usually interact multiple times in detectors
  - Several Compton scatters, followed by photoelectric effect
- PPC detectors have unique sensitivity to multiple interactions
  - Long charge drift times and localized “weighting potential” give separate current pulse for each charge cloud
- This allows for discrimination between $0\nu\beta\beta$ events and gamma backgrounds



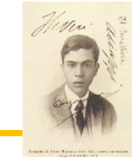
MJD Detectors

- Mounted in “strings” of 4 or 5 detectors each
- Seven strings per module

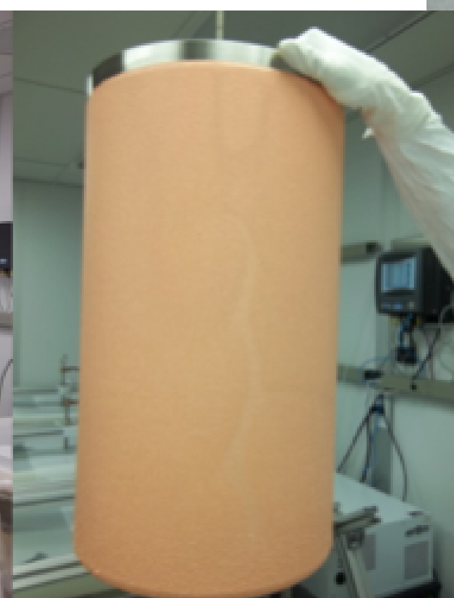


Detector Strings

Ultra-Pure Copper

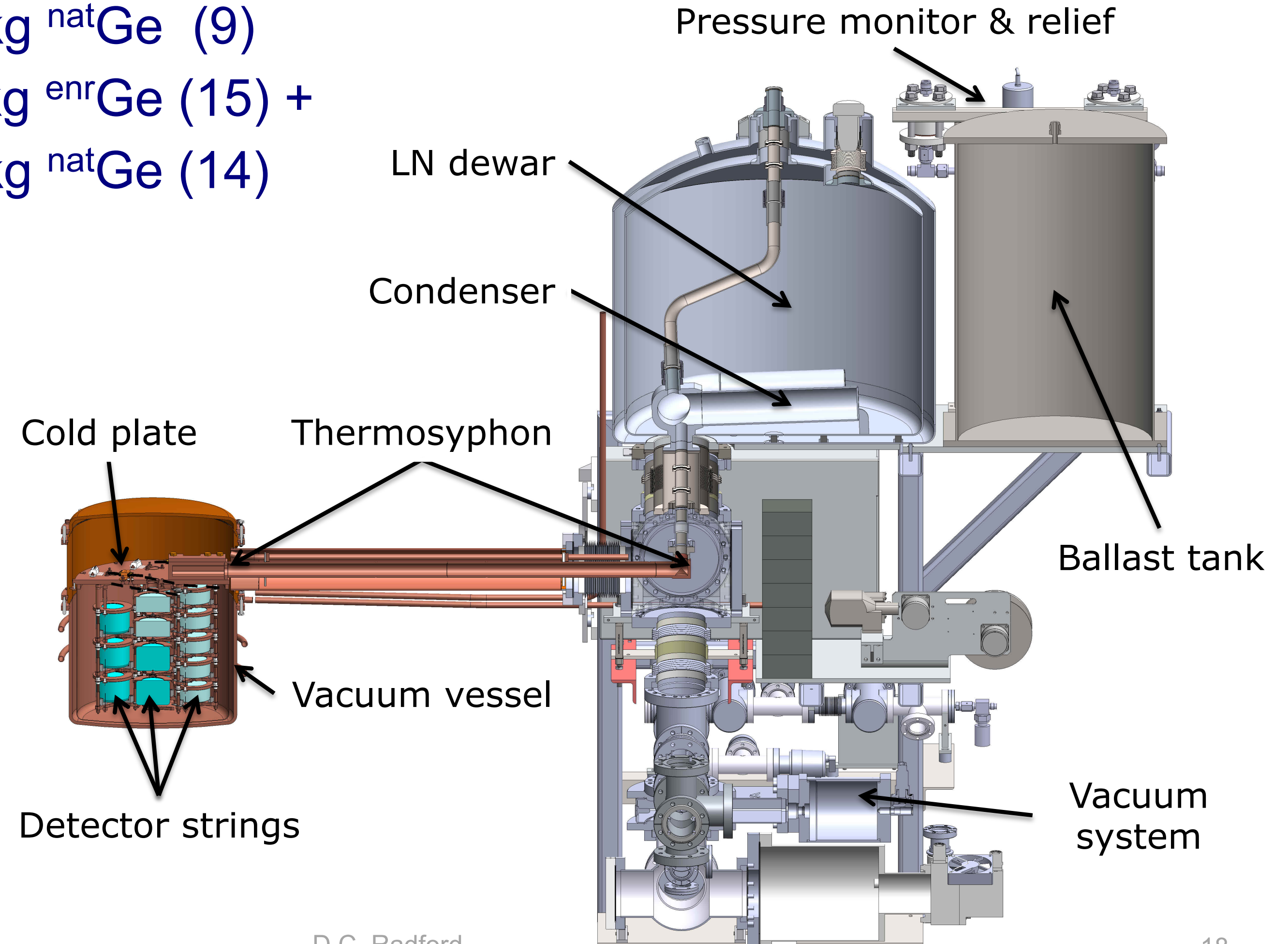


- Slow electroforming in 16 large baths to produce ultra-pure copper
- Electroforming and machining both done underground to avoid cosmogenic activation (~ atoms / kg / day)
  - 10 baths at SURF, 6 in shallow lab at PNNL
  - 2654 kg of electroformed Cu produced
  - 1196 kg installed in the Demonstrator.

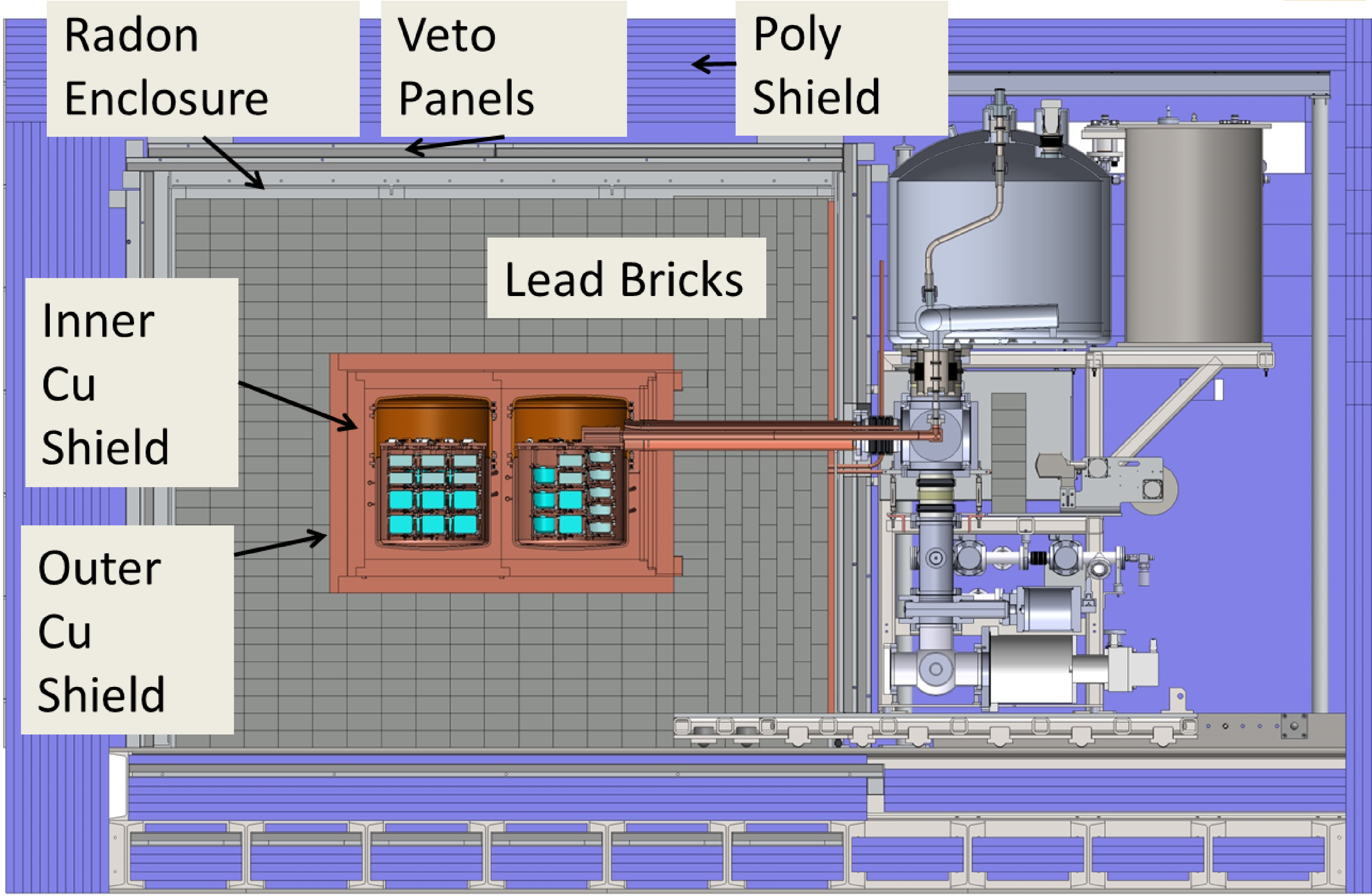


MJD Modules

- Three Steps
  - Prototype Cryostat: 7 kg ^{nat}Ge (10 detectors, commercial copper)
  - Module 1: 16.8 kg ^{enr}Ge (20) +
    5.7 kg ^{nat}Ge (9)
  - Module 2: 12.8 kg ^{enr}Ge (15) +
    9.4 kg ^{nat}Ge (14)



MJD Shield

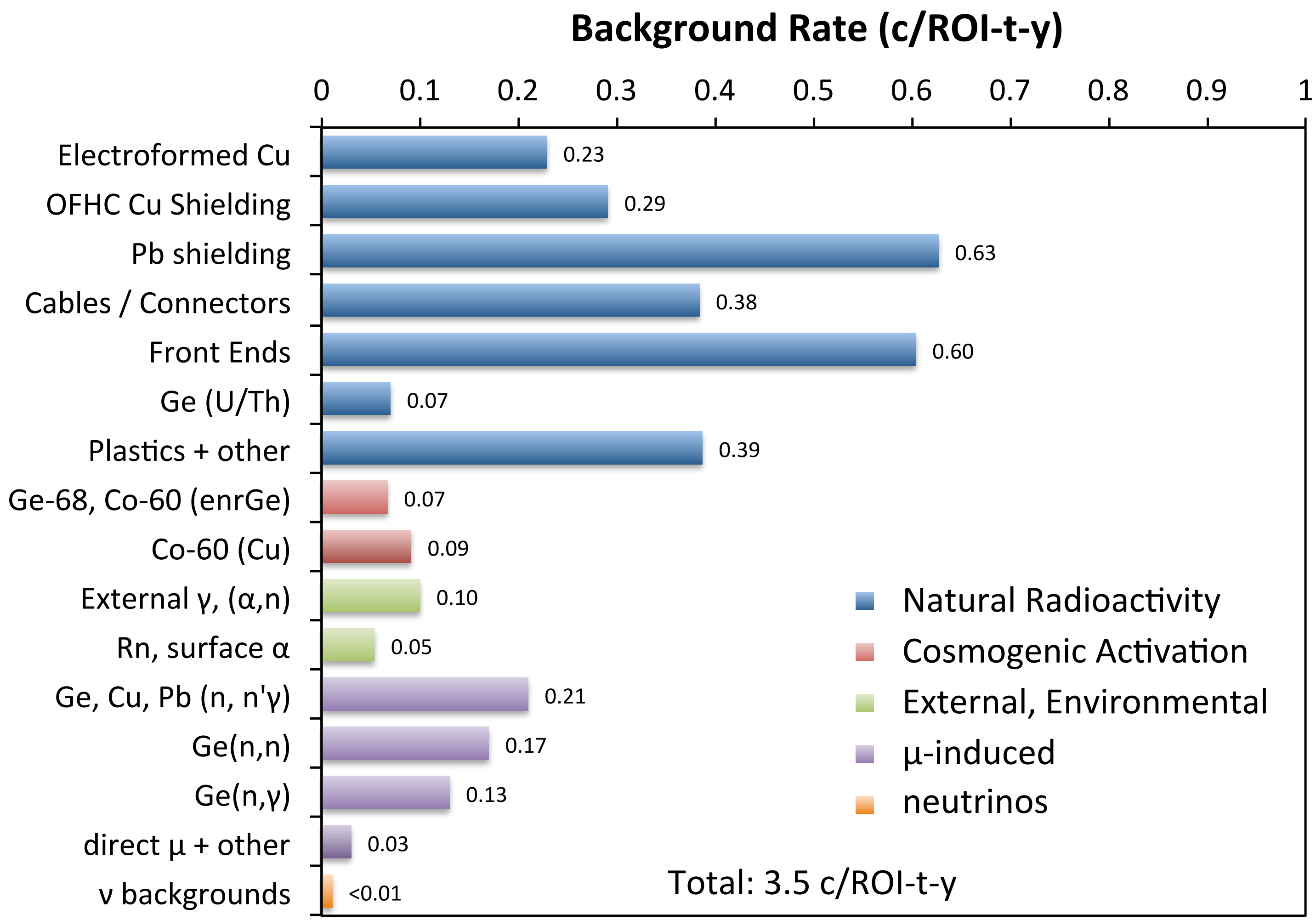

Radon Enclosure
Veto Panels
Poly Shield
Lead Bricks
Inner Cu Shield
Outer Cu Shield

Demonstrator Background Budget

Total: ≤ 3.5 cts / 4 keV / t-y

Goal: 3.0 cts / 4 keV / t-y

- Based on achieved assay of materials
- Upper limits for some materials



MJD Status

- Detector production complete
  - 29.5 kg of enriched detectors underground
  - Produced by AMETEK/ORTEC from 42.5 kg of 87%-enriched ^{76}Ge
- Modules
  - Prototype module decommissioned;
  - Module 1 running in shield, taking background data
  - Module 2 complete, commissioning to begin this month
- Shield
  - Lead, copper, and veto installation complete
  - Radon exclusion box complete
  - Polyethylene installation in process
- Electroformed copper production and machining complete
- Project completion (CD-4) scheduled for Sept.

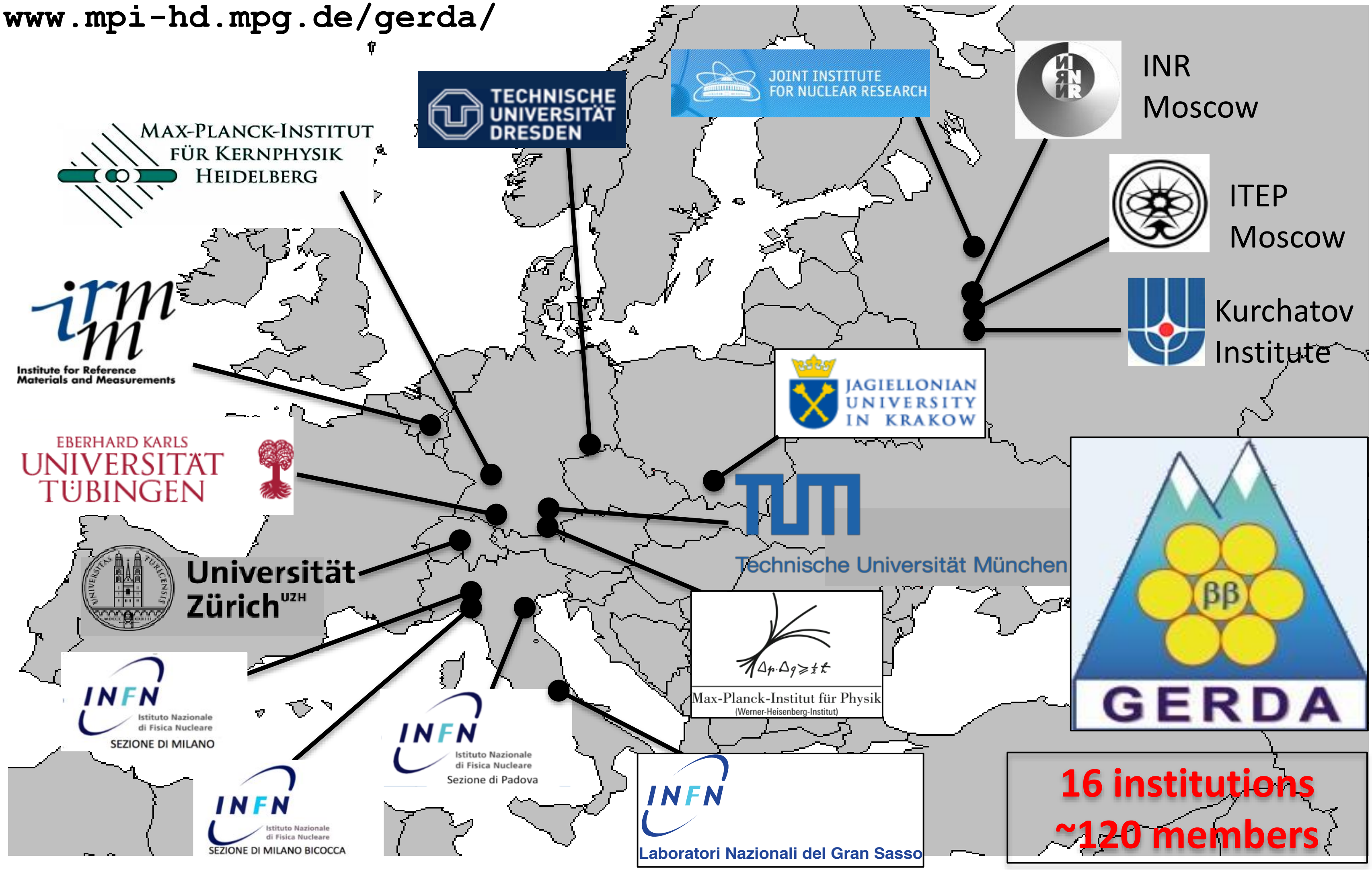
GERDA

- GERmanium Detector Array
- "Friendly competition" with MAJORANA; planning joint next experiment
- Primarily European collaboration, plus Russia
- Located at LNGS (Gran Sasso)
- General concept: Bare Ge detectors in liquid argon
  - Both coaxial and point-contact detectors (BEGes, by Canberra Olen)
  - LAr acts as both coolant and active shield
  - Scintillation light read out by PMTs plus wavelength-shifter-coated fibers coupled to SiPMs

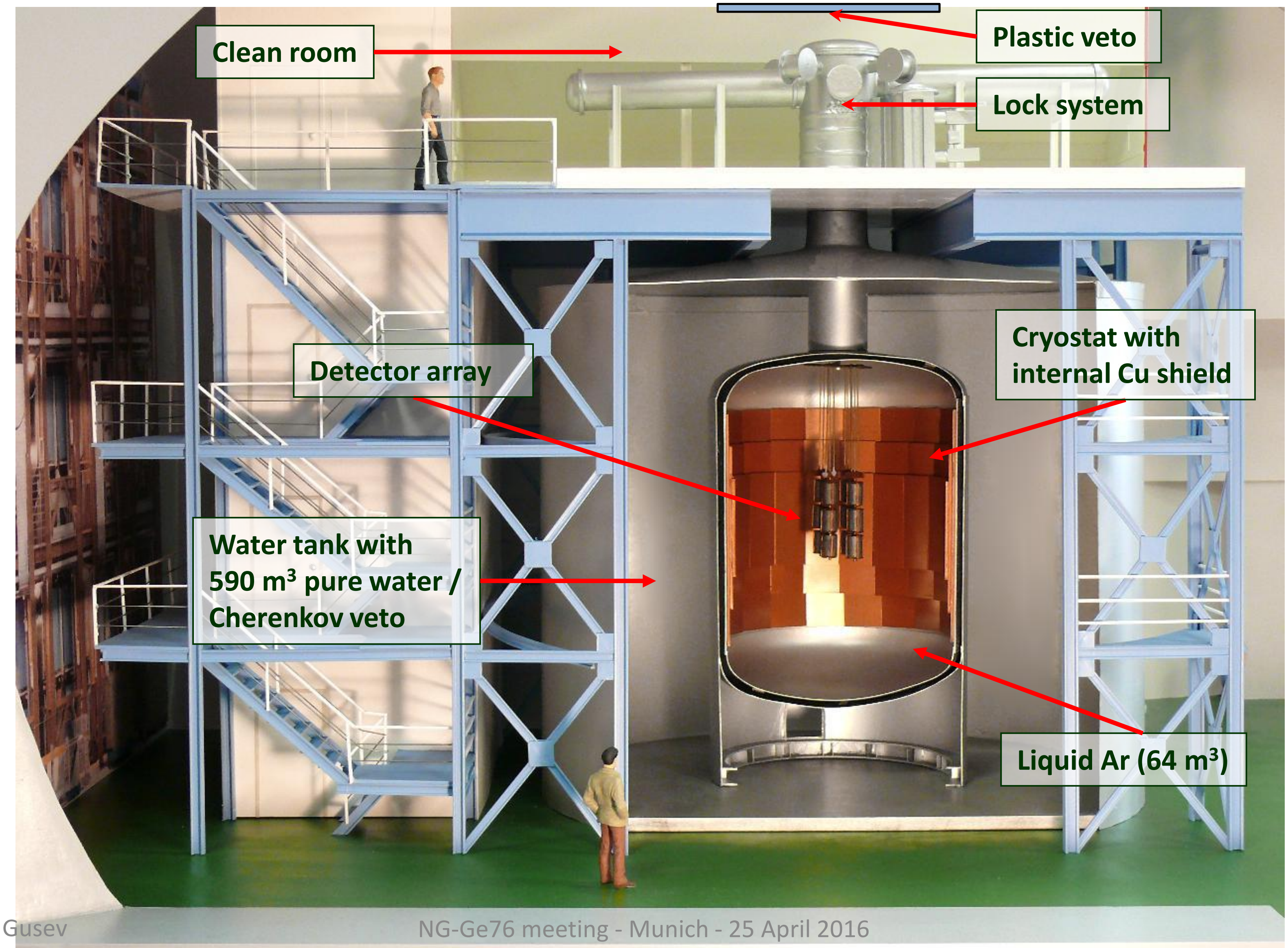
- Phase I complete, published
  - Observed background rate of 40 c/t-y in 4 keV ROI
  - Results strongly disfavor previous claim (Phys. Lett. B586 198 (2004))
- Phase II data-taking started Dec 2015
  - Goal is 4 c/t-y in 4 keV ROI, same as MJD
  - Additional enriched BEGe detectors

Collaboration

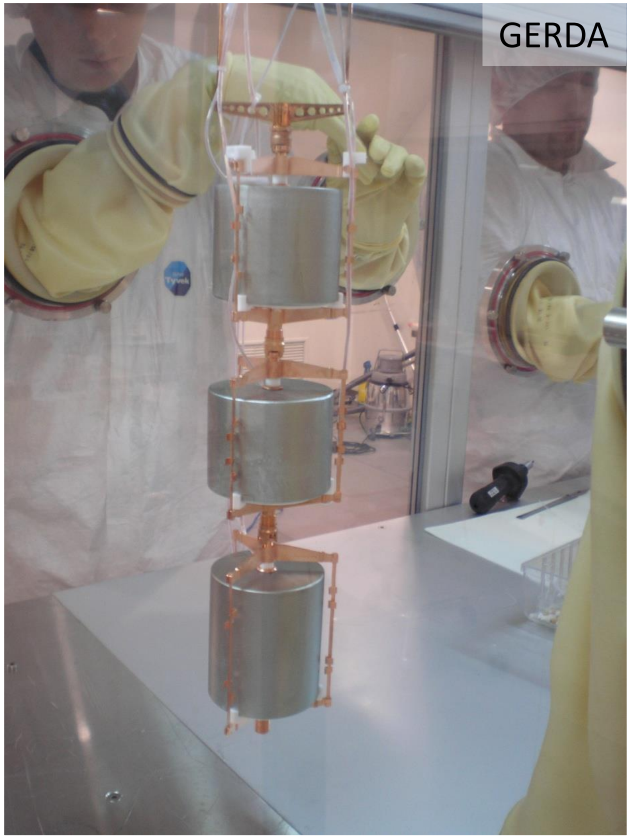
www.mpi-hd.mpg.de/gerda/

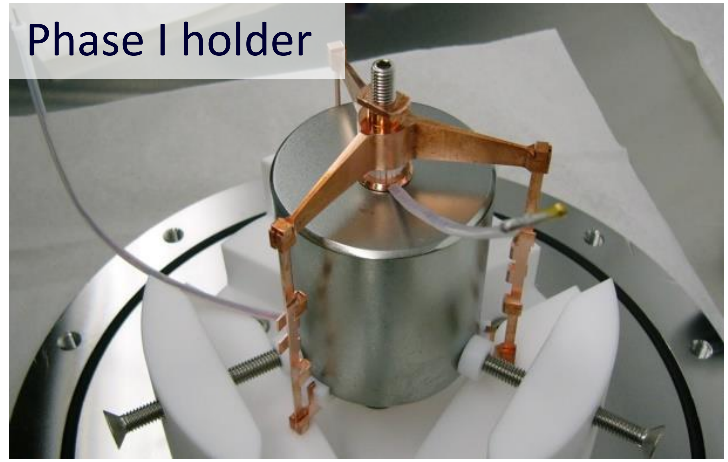


GERDA design



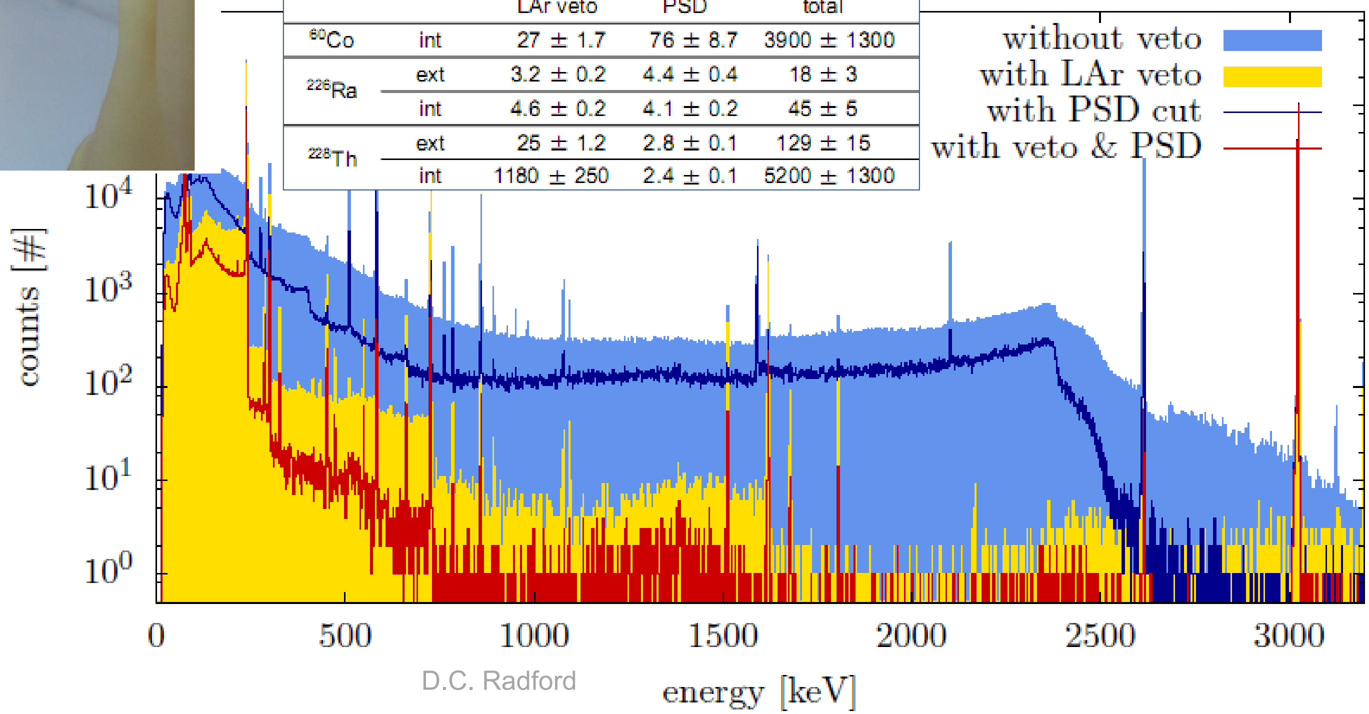
Idea: G. Heusser, nnu.Rev. Nucl. Part. Sci. 45(1995) 543



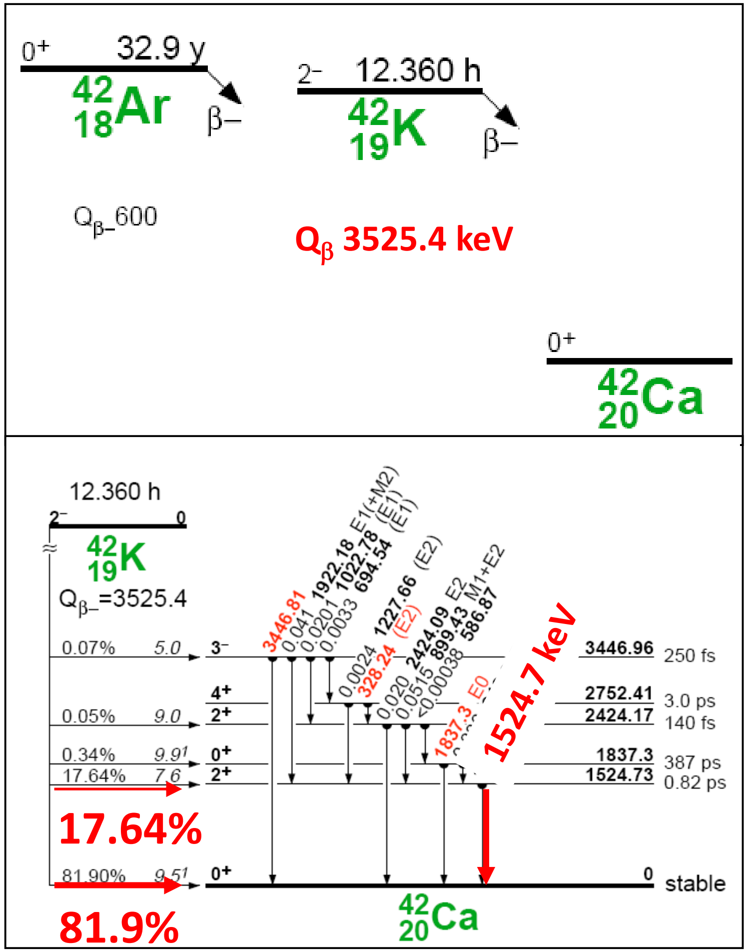


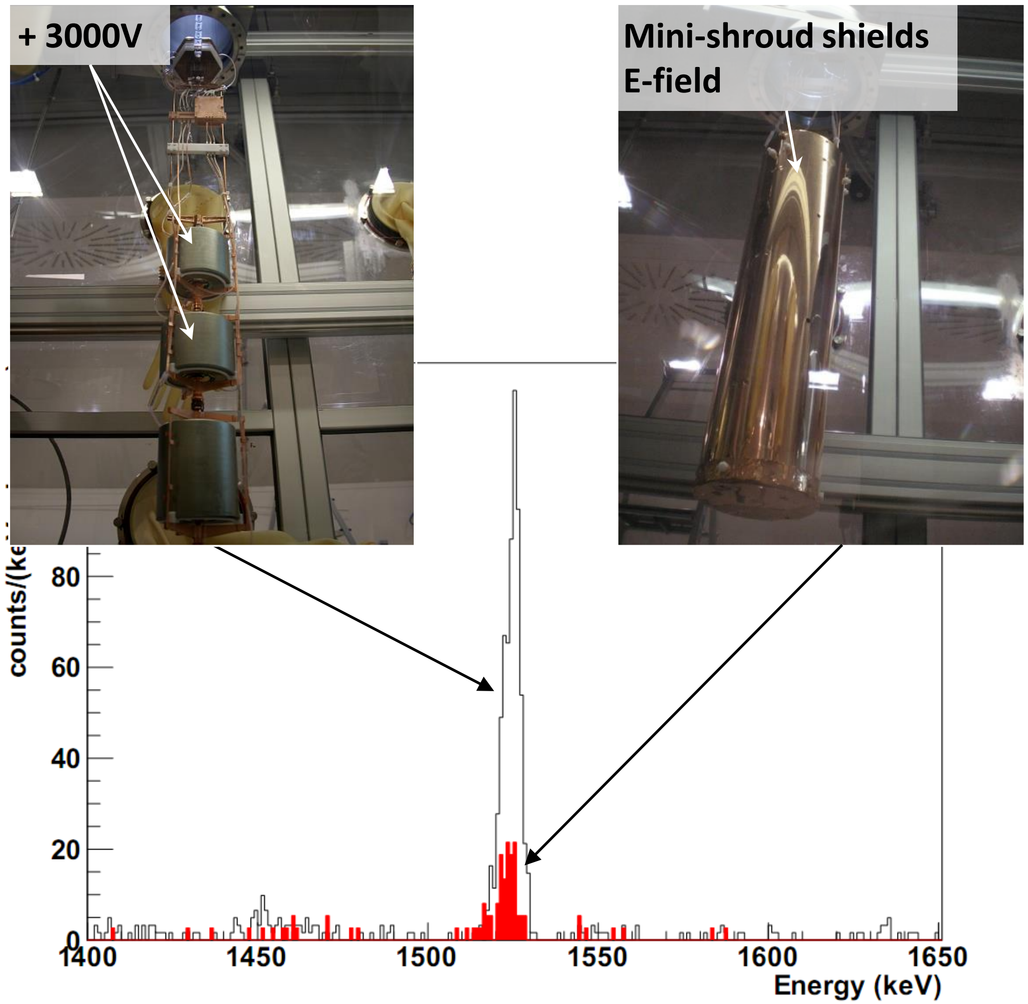
Low mass holder made of ultrapure materials:
low-activity Cu (80 g), PTFE, Si

source	position	suppression factor		
		LAr veto	PSD	total
^{60}Co	int	27 ± 1.7	76 ± 8.7	3900 ± 1300
^{226}Ra	ext	3.2 ± 0.2	4.4 ± 0.4	18 ± 3
	int	4.6 ± 0.2	4.1 ± 0.2	45 ± 5
^{228}Th	ext	25 ± 1.2	2.8 ± 0.1	129 ± 15
	int	1180 ± 250	2.4 ± 0.1	5200 ± 1300



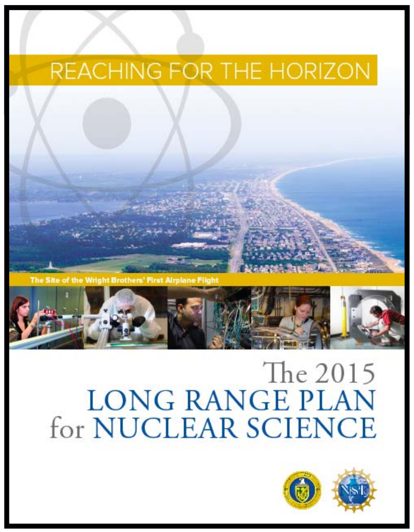
Phase I commissioning (from June 2010)
^{42}Ar (^{42}K) problem and solution (mini-shroud)





The Next Step

- Leading a tonne-scale 0νββ experiment is the stated highest priority new activity for the US Nuclear Physics community
  - The Nuclear Science Advisory Committee (NSAC) just released the latest Long Range Plan for nuclear science in the US



RECOMMENDATION II

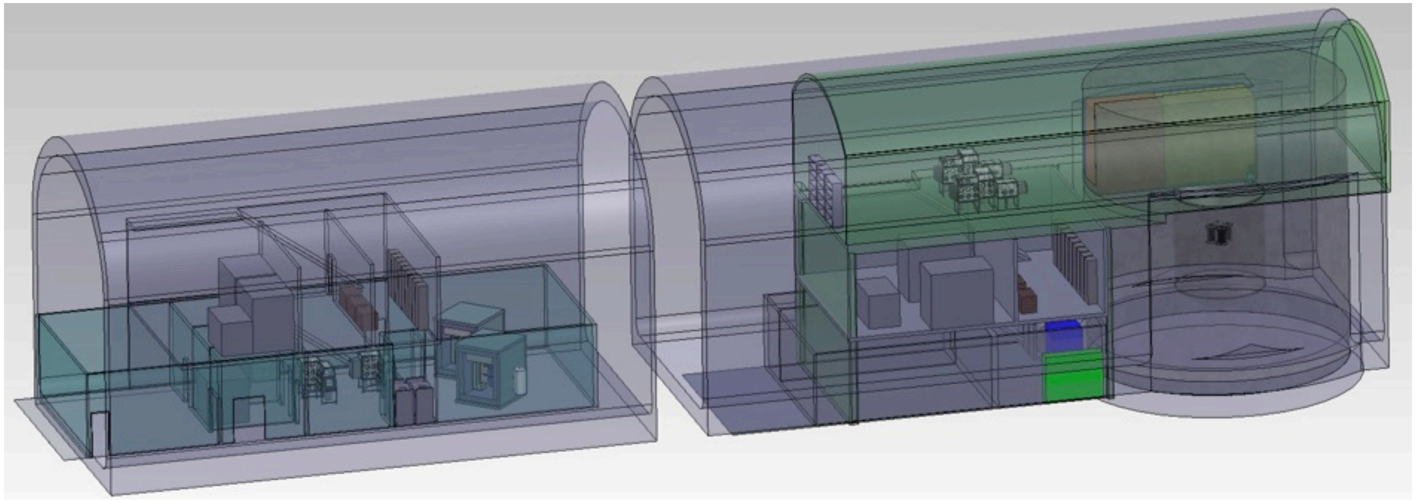
The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding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

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

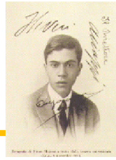
- The US funding agencies (DOE and NSF) are keen and supportive
  - They expect to spend ~ $250M for the US contribution
  - Down-select between proposed experiments in 2-3 years?

Next-Generation 0νββ Experiment

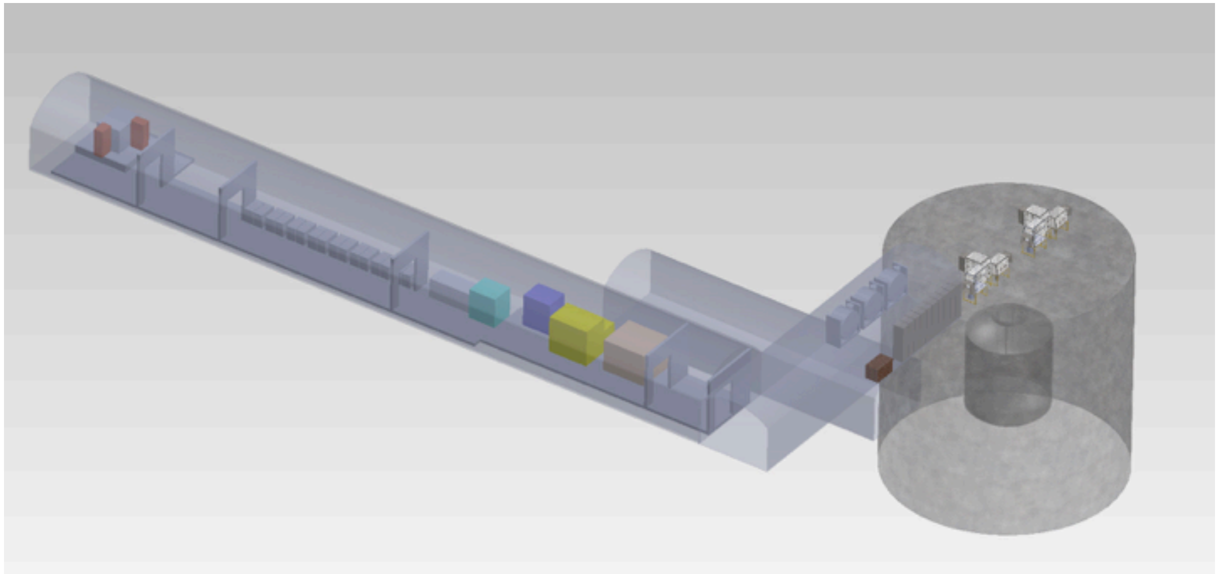
- The MAJORANA collaboration is working together with the GERDA group in Germany to establish a single international ^{76}Ge 0νββ collaboration
  - Held a joint meeting in Munich two weeks ago
- Anticipate down-select of best technologies, based on results of the two experiments
- Moving forward is predicated on demonstration of projected backgrounds



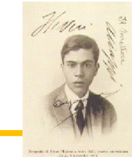
Next-Generation 0νββ Experiment



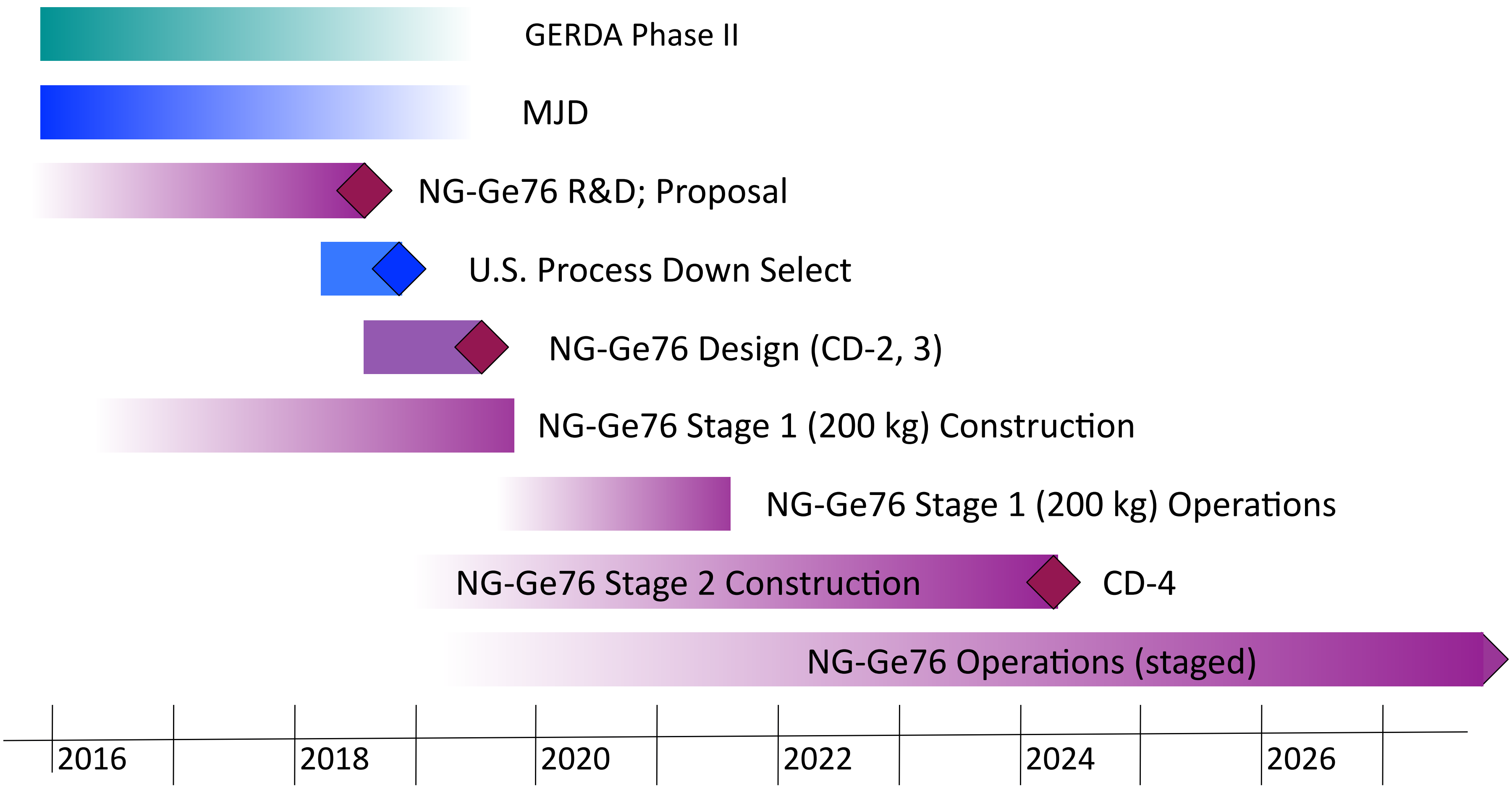
- MJD and GERDA Phase II are optimistic they will make their background goals of ~ 4 c/t-y
  - Should be releasing initial results this summer
- Background goal for next-generation experiment is ~ 0.1 c/t-y
  - Original goal was 1 c/t-y, but guidance from NSAC on importance of Discovery Level suggested that large scale goal should be reduced
- By combining the best of MJD (materials and cleanliness) with GERDA (active shield), it appears a NG - Ge76 experiment could realistically achieve 0.1



Conceptual Timeline



- Operation of GERDA and the Demonstrator: 2016-18
- Technical down-select and conceptual design in 2018-19
- Possible intermediate stage (200 kg) using existing GERDA shield



Summary

- The field is almost ready to proceed with tonne-scale 0νββ experiments.
  - Aim for sensitivity and discovery levels at $T_{1/2} \sim 10^{28}$ years
  - Top priority for new activity in 2015 NSAC Long Range Plan
  - Background is major challenge; require 2 orders of magnitude further reduction
- The ultimate goal of the MAJORANA collaboration is to field a tonne-scale ^{76}Ge 0νββ decay search.
  - ^{76}Ge combines the best detector resolution with the best backgrounds to date
  - MJD construction and commissioning almost complete, one module operating
  - GERDA and the MAJORANA DEMONSTRATOR are establishing the feasibility of proceeding with a next-generation ^{76}Ge experiment
  - Working towards an international collaboration; held meeting two weeks ago
  - Will cherry-pick the best technology from both MJD and GERDA
  - Construction could begin as early as 2019
- Much work needs to be done to go from a conceptual design to a viable, competitive proposal.

The MAJORANA Collaboration

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