Office of Science
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NSF

# 1TGE

# A Tonne-Scale $^{76}$Ge Neutrinoless Double-Beta Decay Experiment

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SNOLAB Future Projects Workshop

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

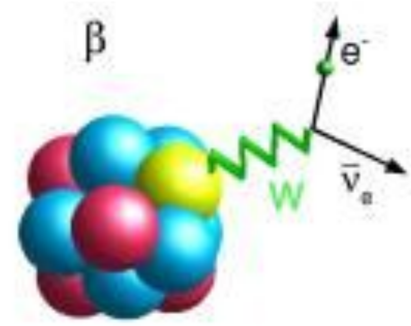
# Outline

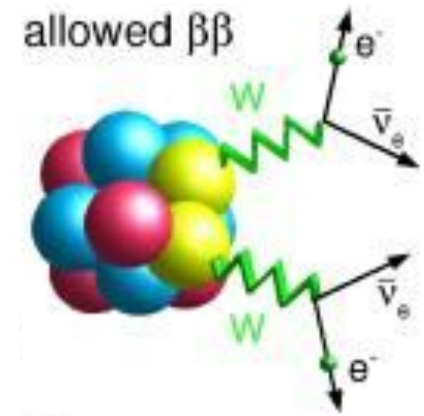
- Motivation:
  - Neutrinoless double-beta decay
  - Exposure and background requirements
- The MAJORANA DEMONSTRATOR
  - Design
  - Status
  - Expected background rates
- Path to the tonne-scale
  - Advantages of $^{76}$Ge
  - GERDA and design alternatives
  - Cost and schedule

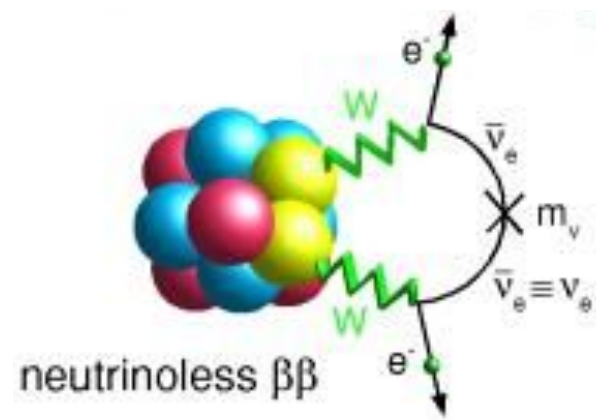
# Neutrinoless Double-Beta Decay

0νββ decay requires:

- Neutrinos have non-zero mass
  - "Wrong-handed" helicity admixture ~ $m_i/E_{\nu i}$
- Lepton number violation
  - No experimental evidence that Lepton number must be conserved (*i.e.* allowed based on general SM principles, such as electroweak-isospin conservation and renormalizability)



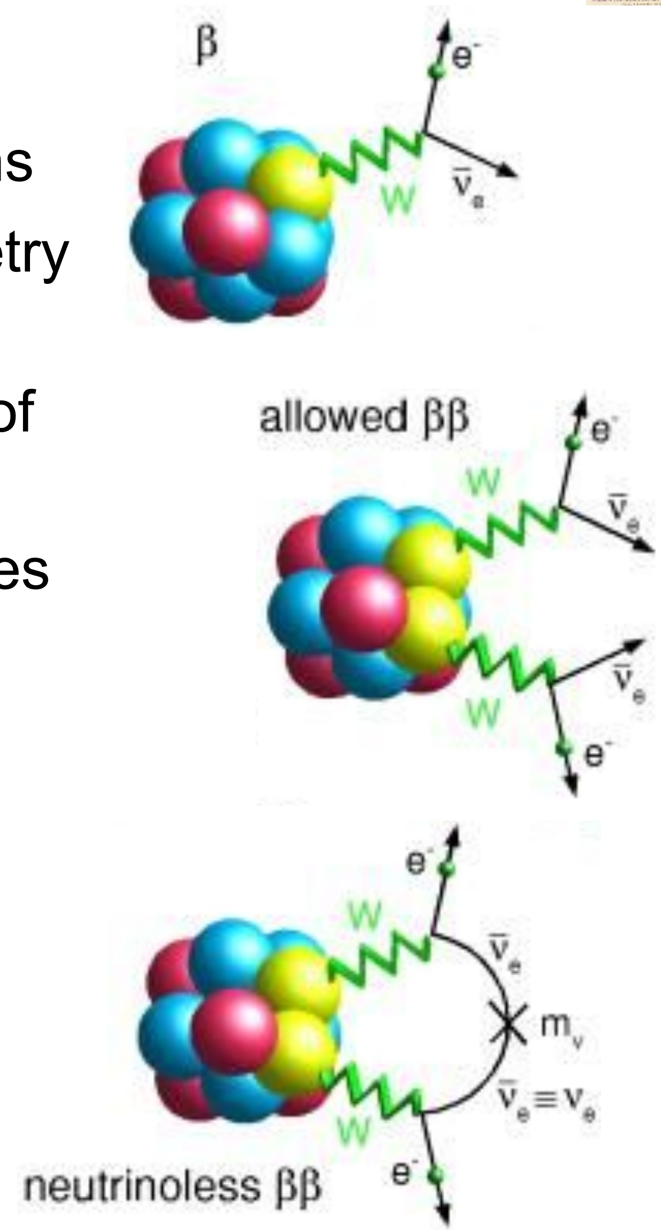



# Neutrinoless Double-Beta Decay

If observed, 0νββ decay would:

- Show that neutrinos are Majorana fermions
- Demonstrate that the fundamental symmetry of lepton number is violated
- Provide plausible scenarios for the origin of the baryon asymmetry of the universe
- Offer a potential reason for the light masses of ν's compared to that of the charged fermions
- Allow a model-dependent method of measuring neutrino mass



# 0νββ Decay Rate and $<m_{\beta\beta}>$

- Decay rate depends on nuclear processes and on effective neutrino mass $<m_{\beta\beta}>$

$$\left[ \mathrm{T}_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^2 \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2$$

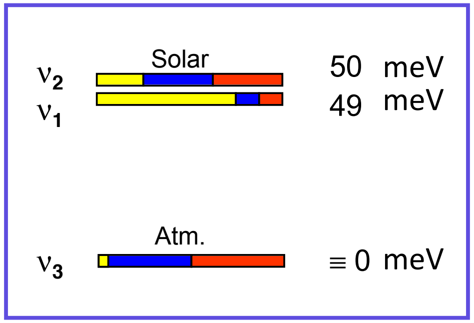
- $<m_{\beta\beta}>$ depends directly on the assumed form of LNV interactions

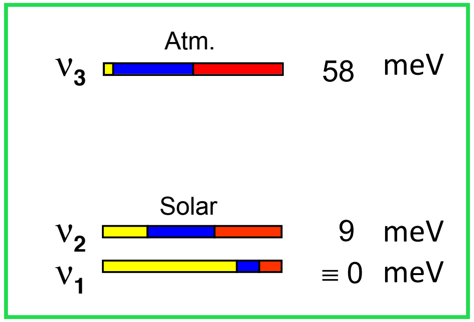
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

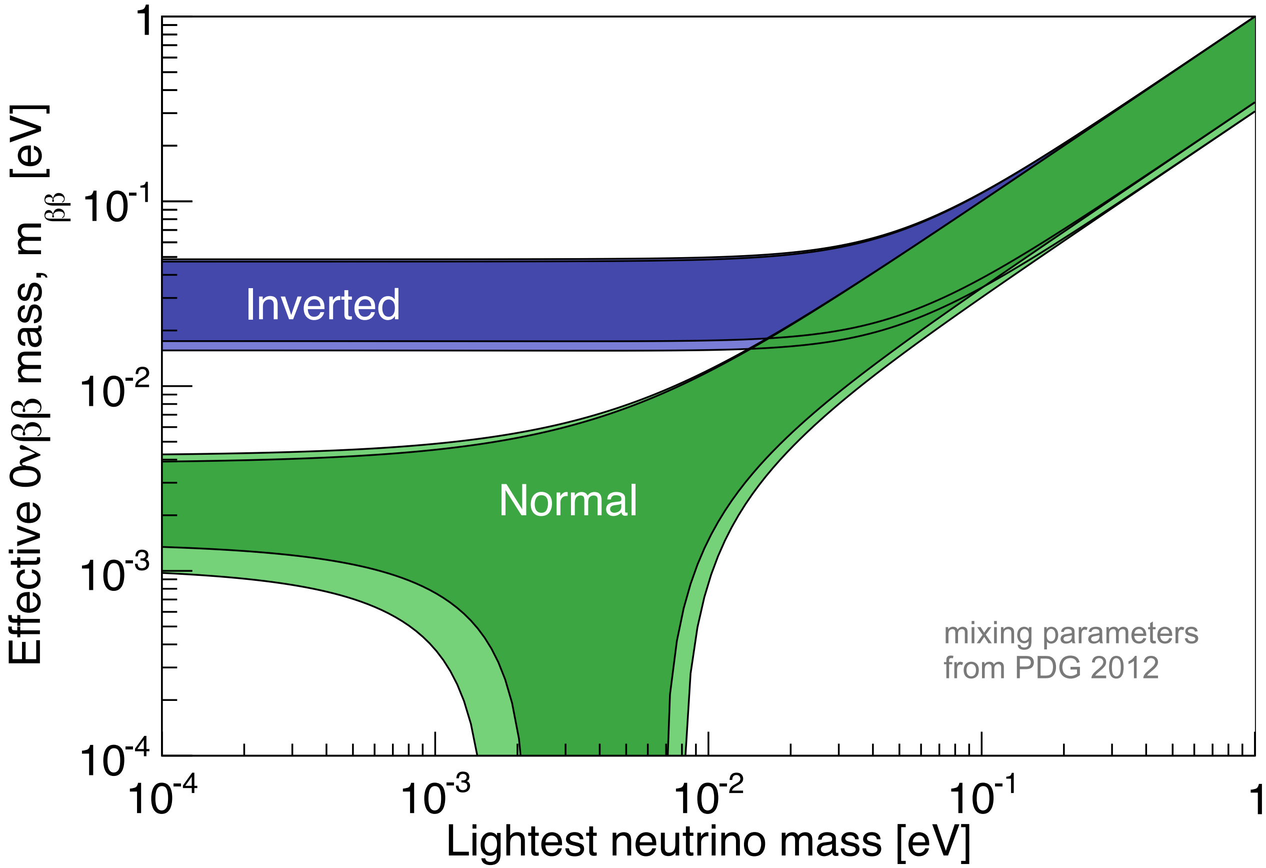
# 0νββ Decay Rate and $<m_{\beta\beta}>$

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

Plot assumes LNV mechanism is light Majorana neutrino exchange and SM interactions (W)



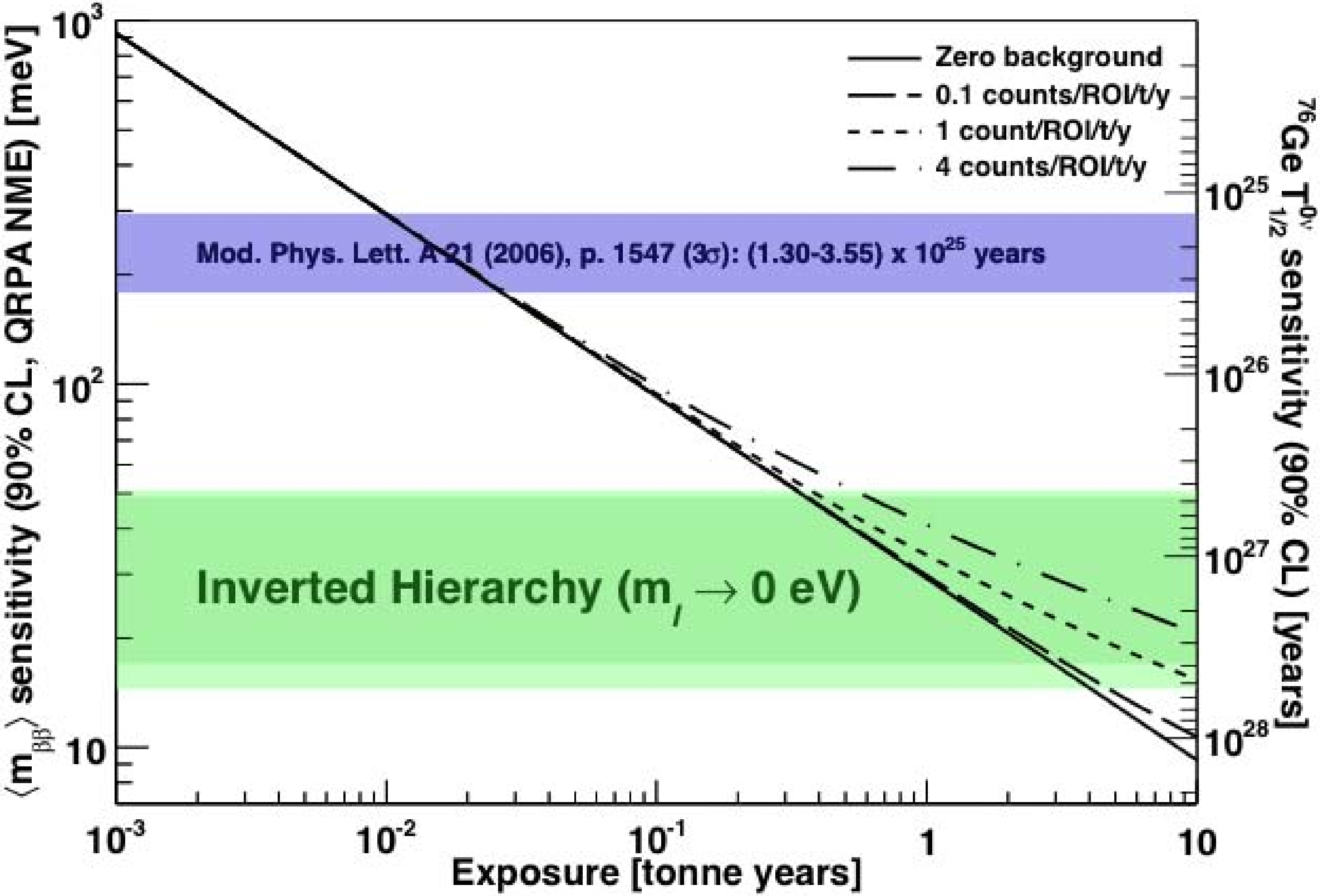



# Sensitivity for Inverted Hierarchy?

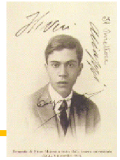
- What is needed to reach sensitivities of $T_{1/2} \sim 10^{26}$ - $10^{27}$ y?
  - Expect signals of 1 count / tonne / year for half-lives of ~$10^{27}$ years ($\langle m\beta\beta \rangle \sim 15$ meV)
- What would convince one that $0\nu\beta\beta$ has been discovered?
- Need signal-to-background ratio of 1:1 or better
  - Best background rates to date is ~40 to 140 c/t/y/ROI
  - Next generation (tonne-scale) experiments must have goals of ~ 1 c/t/y/ROI

# Tonne-Scale Sensitivity

- About ten tonne-years of exposure and background rates of ~ 1 c/t/y needed to probe entire region of inverted mass hierarchy



# Tonne-Scale Sensitivity



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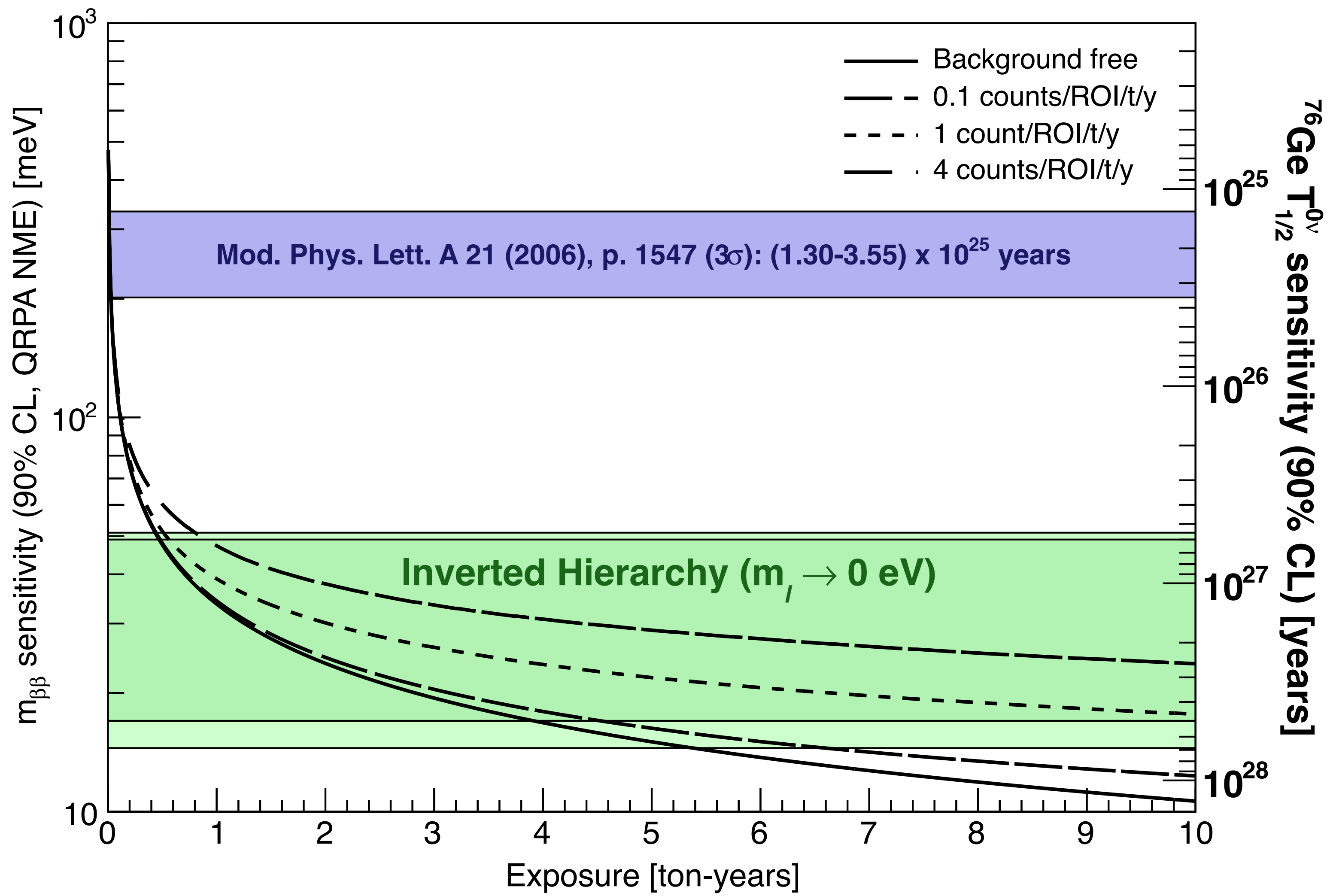


# Advantages for $^{76}Ge$

$^{76}Ge$ offers an excellent combination of capabilities and sensitivities.

- Ge as both source and detector
- Intrinsic high-purity Ge diodes
- Favorable nuclear matrix element $\langle M^{0\nu} \rangle = 2.4$ [Rod06]
- Reasonably slow $2\nu\beta\beta$ rate ($T_{1/2} \sim 1.4 \times 10^{21}$ y)
- Demonstrated ability to enrich from natural 7.8% to 86%

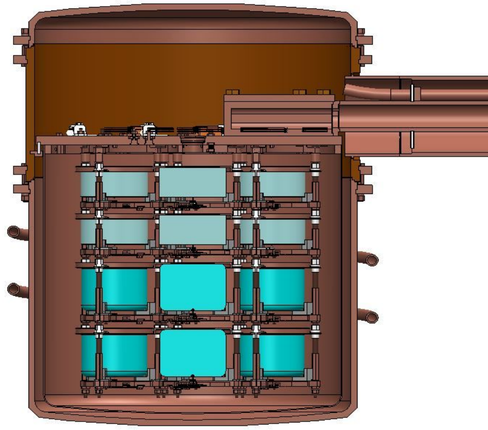
- Excellent energy resolution — 0.16% at 2.039 MeV
- Powerful background rejection

  Segmentation, granularity, timing, pulse shape discrimination
- Well-understood technologies
  - Commercial Ge diodes
  - Large Ge arrays (GRETINA, Gammasphere)
  - Point contact detectors

# The Majorana Demonstrator (MJD)

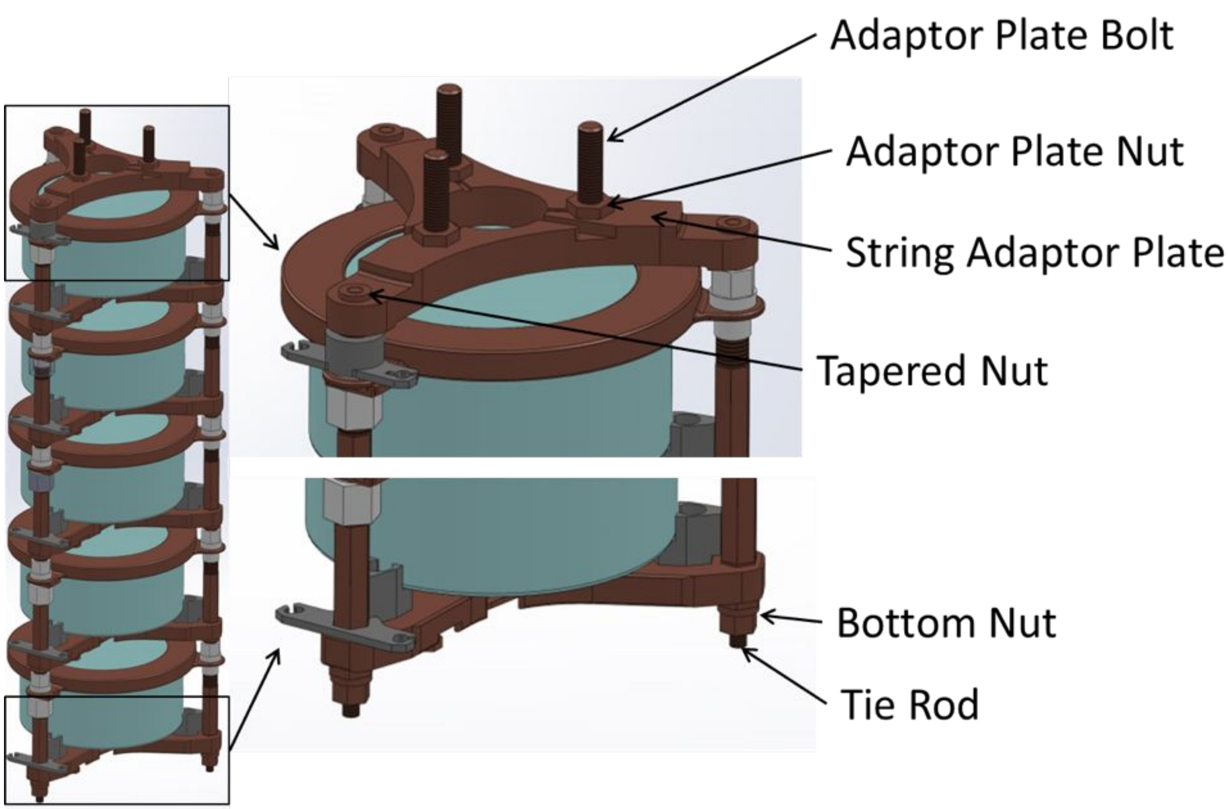
- Primary goal is to show that we can reach the ultra-low backgrounds required to justify a tonne-scale $^{enr}Ge$ 0vββ experiment
- Secondary goals:
  - Demonstrate scalable modular construction and reliable operation of multi-detector cryostats
  - Test Klapdor-Kleingrothaus claim
  - Search for low-energy dark matter (light WIMPs, axions, ...)

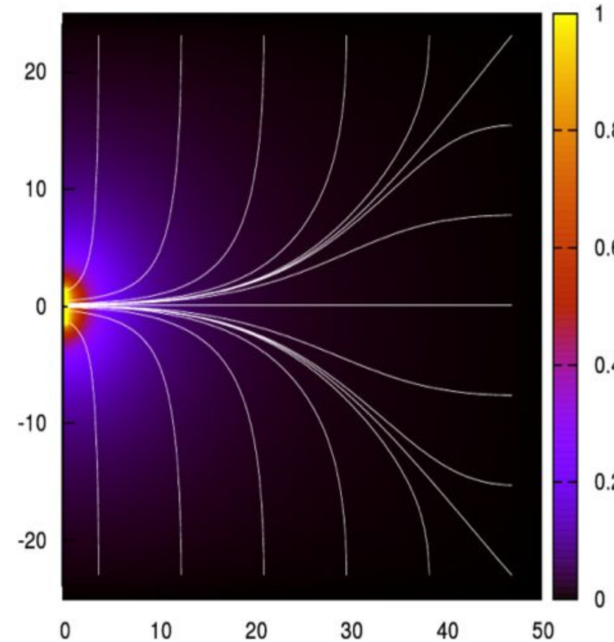
- Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics, with additional contributions from international collaborators.
- ~ 30 kg $^{enr}Ge$ + ~ 10 kg $^{nat}Ge$ detectors, in two cryostats
- Ultrapure materials; copper that has been electroformed and machined underground
- Compact passive and active shields
- At the 4850-foot level of SURF, Lead, SD
- Construction scheduled for completion in 2015



# MJD Detectors

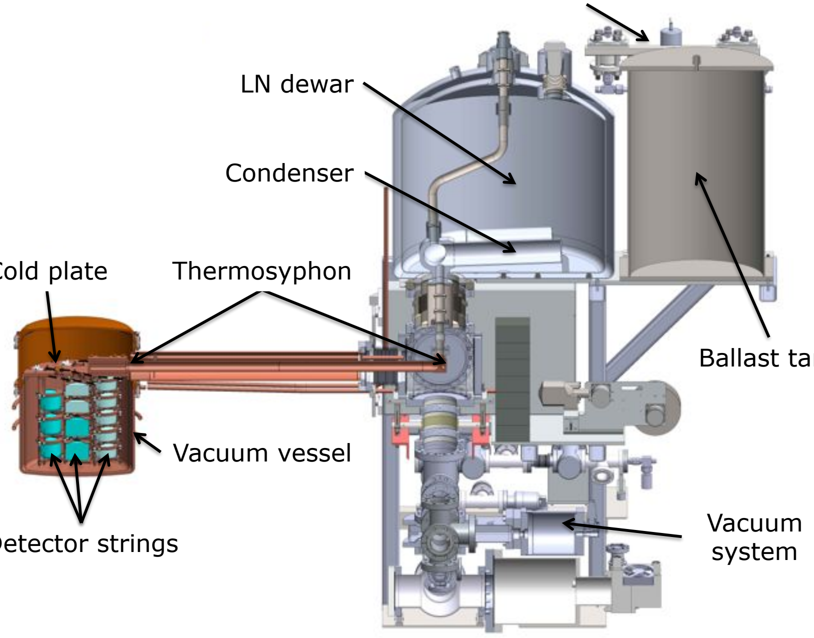
- P-type Point Contact (PPC) HPGe detectors
- Mounted in “strings” of 4 or 5 detectors each
- Enriched detectors are ~ 1 kg each
- Superb pulse-shape discrimination against multi-site events

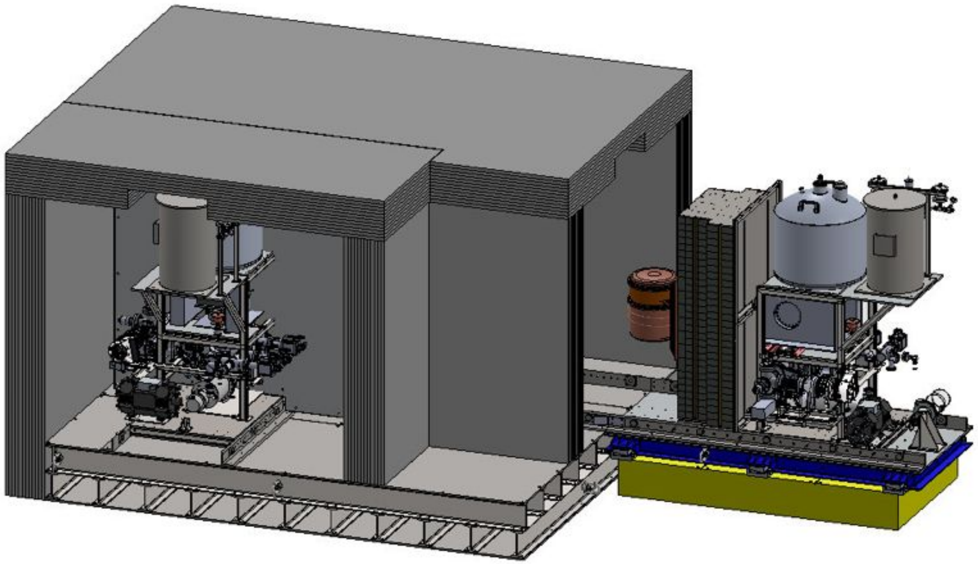


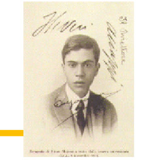
# MJD Cryostats and Shield

- Three Steps
  - Prototype Cryostat* (2 strings, $^{nat}$Ge)
  - Cryostat 1 (3 strings $^{enr}$Ge & 4 strings $^{nat}$Ge)
  - Cryostat 2 (7 strings $^{enr}$Ge)



* Same design as Cryos 1 & 2, but fabricated using OFHC Cu (non-electroformed) components.



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  - Prototype Cryostat* (2 strings, $^{nat}$Ge)
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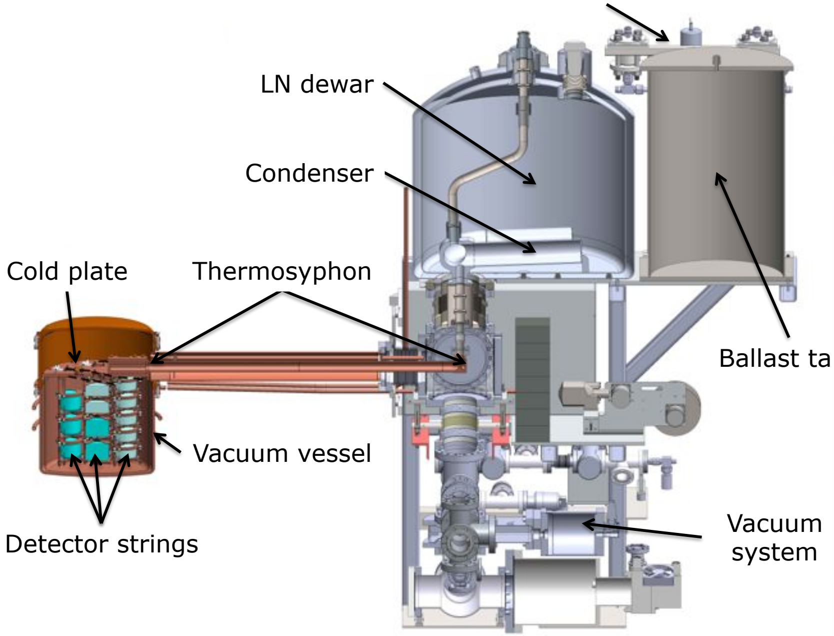
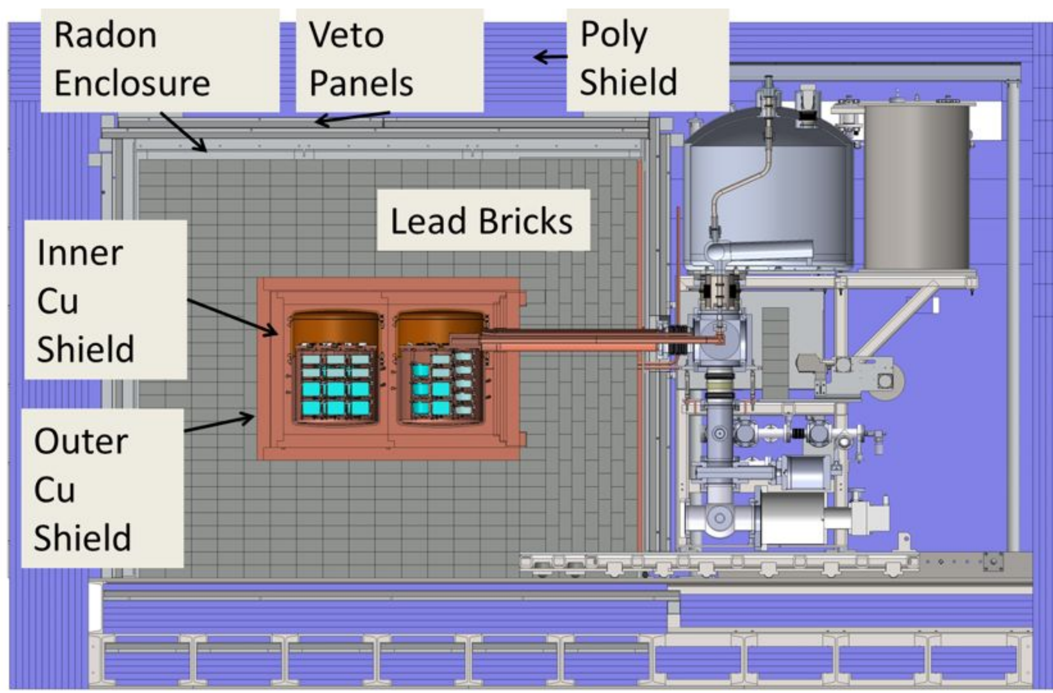
  - Cryostat 2 (7 strings $^{enr}$Ge)

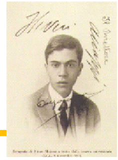
Commissioning dates (Estimated )
- (Summer 2013)
- (Winter 2013)
- (Fall 2014)



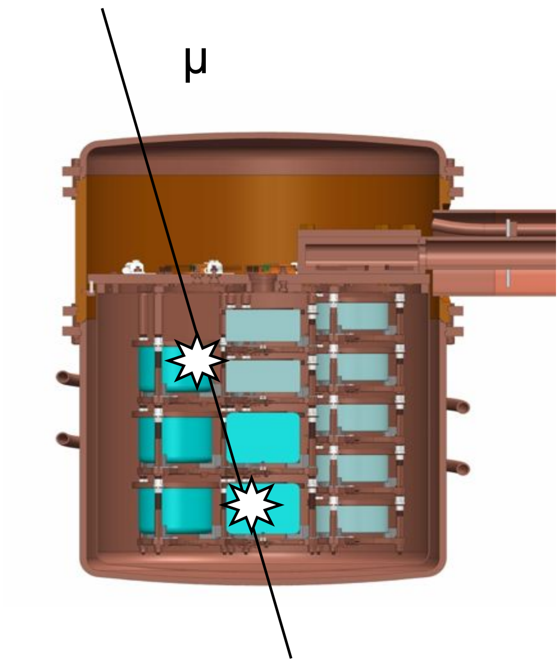

✳ Same design as Cryos 1 & 2, but fabricated using OFHC Cu (non-electroformed) components.

# Background Rejection

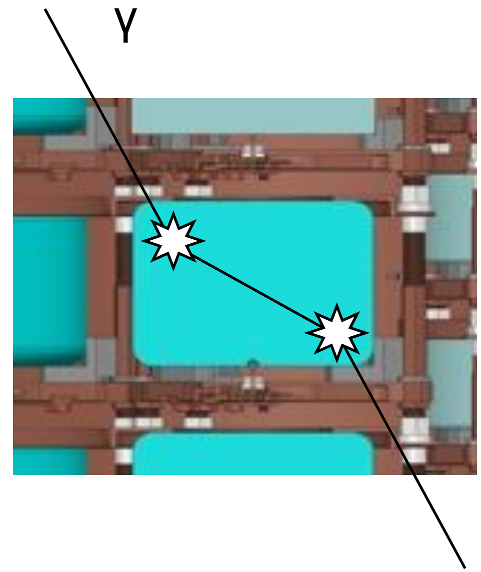


- In addition to an active muon veto, an array of Ge detectors allows other means of discriminating against background events

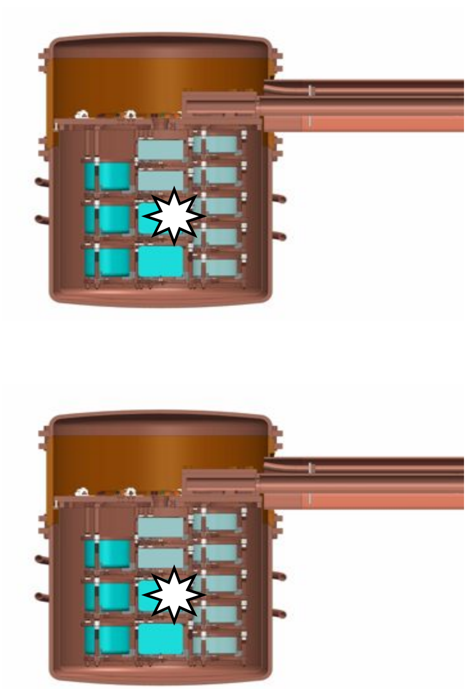
Granularity




Pulse-shape analysis




Time correlation

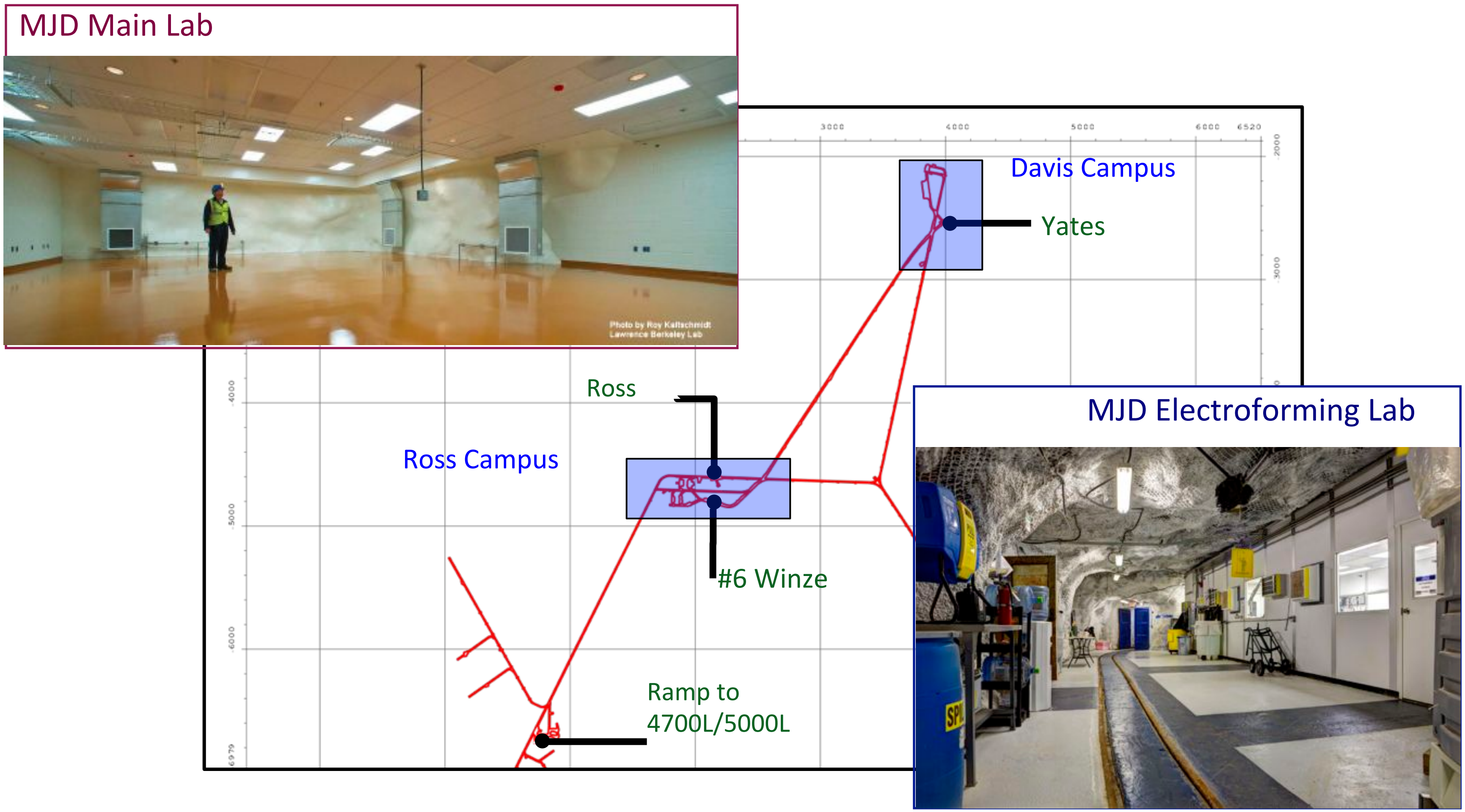


# Ultra-Pure Copper

- Slow electroforming in ~ 12 large baths to produce ultra-pure copper
- Electroforming and machining both done underground to avoid cosmogenics
- A sizable expense for feedstock, acids, etc.
- E-beam welding currently done on surface; would be UG for 1TGe

# MJD Underground Facilities

- MJD UG site is Sanford Underground Research Laboratory
  - Main MJD lab at 4850L Davis Campus, beneficial occupancy in May 2012
  - Operating Temporary Cleanroom Facility (TCR) at 4850L Ross Campus since Spring 2011



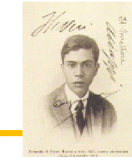
# The Majorana Demonstrator

May 2012

July 2012

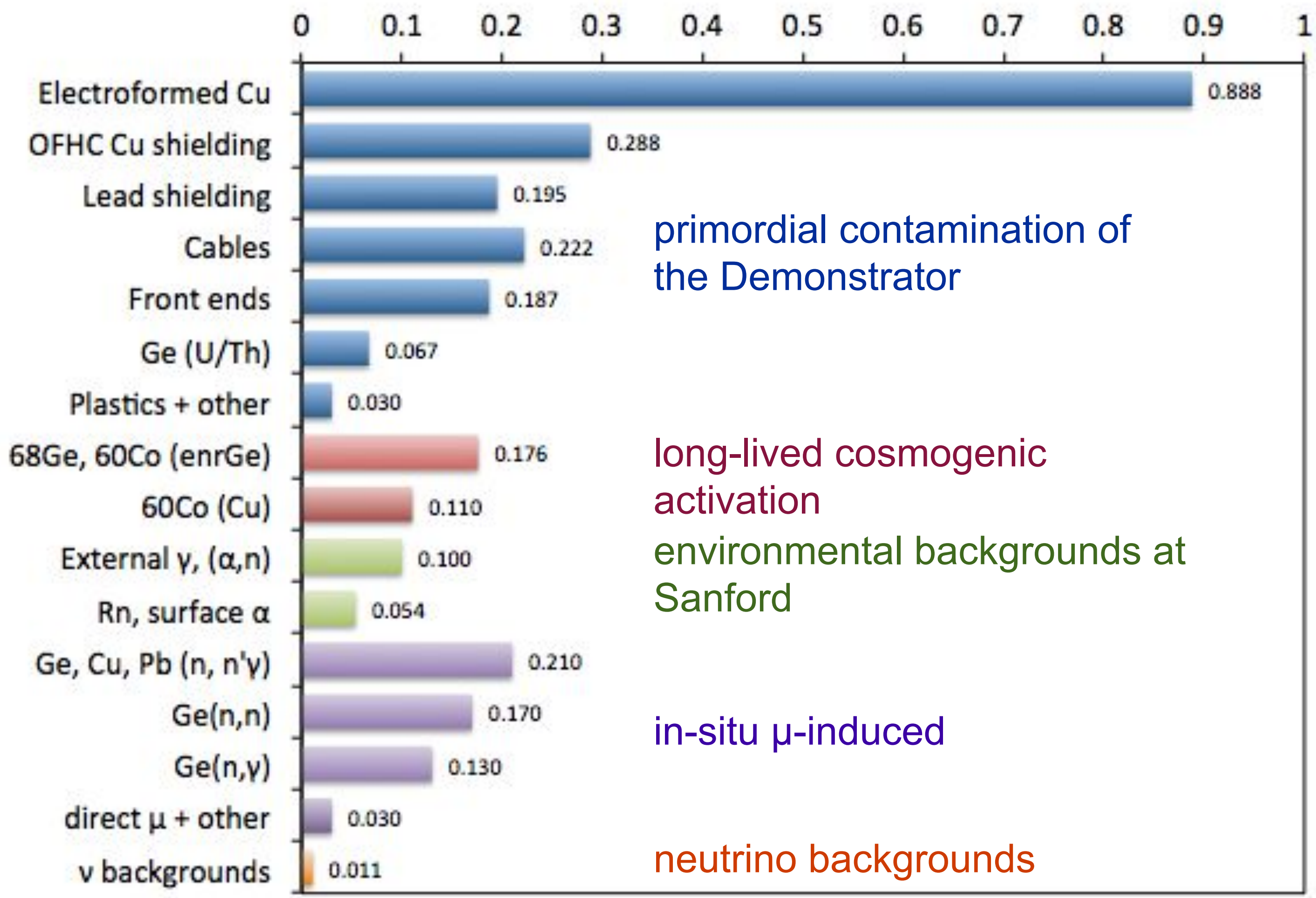
July 2013

# MJD Status



- Simulations - analyzing data from detector acceptance systems and also string data from string test cryostat (STC) system
- Infrastructure - smooth daily operations at SURF
- Assay - significant improvements in assay sensitivity, meet requirements
- Electroformed Cu - 75% of the electroformed Cu is in hand, cryostat 1 material complete and fabrication nearly complete, cleaning/etching going smoothly
- Enriched Ge - 42.5 kg delivered, high yield of reduction from oxide and purification, currently recycling material from ORTEC
- Detectors - 11 kg of enriched detectors UG, improved string assembly and cables, prototype string testing underway
- Cryostats - String Test cryostats (STC) and pumping system operational, prototype cryostat operating and loaded with first test string
- Shield - Authorized to proceed with shield, all lead bricks cleaned, veto components on site
- DAQ - Detector and STC DAQ systems in place and operational

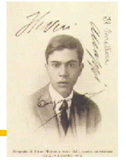
# Demonstrator Background Budget



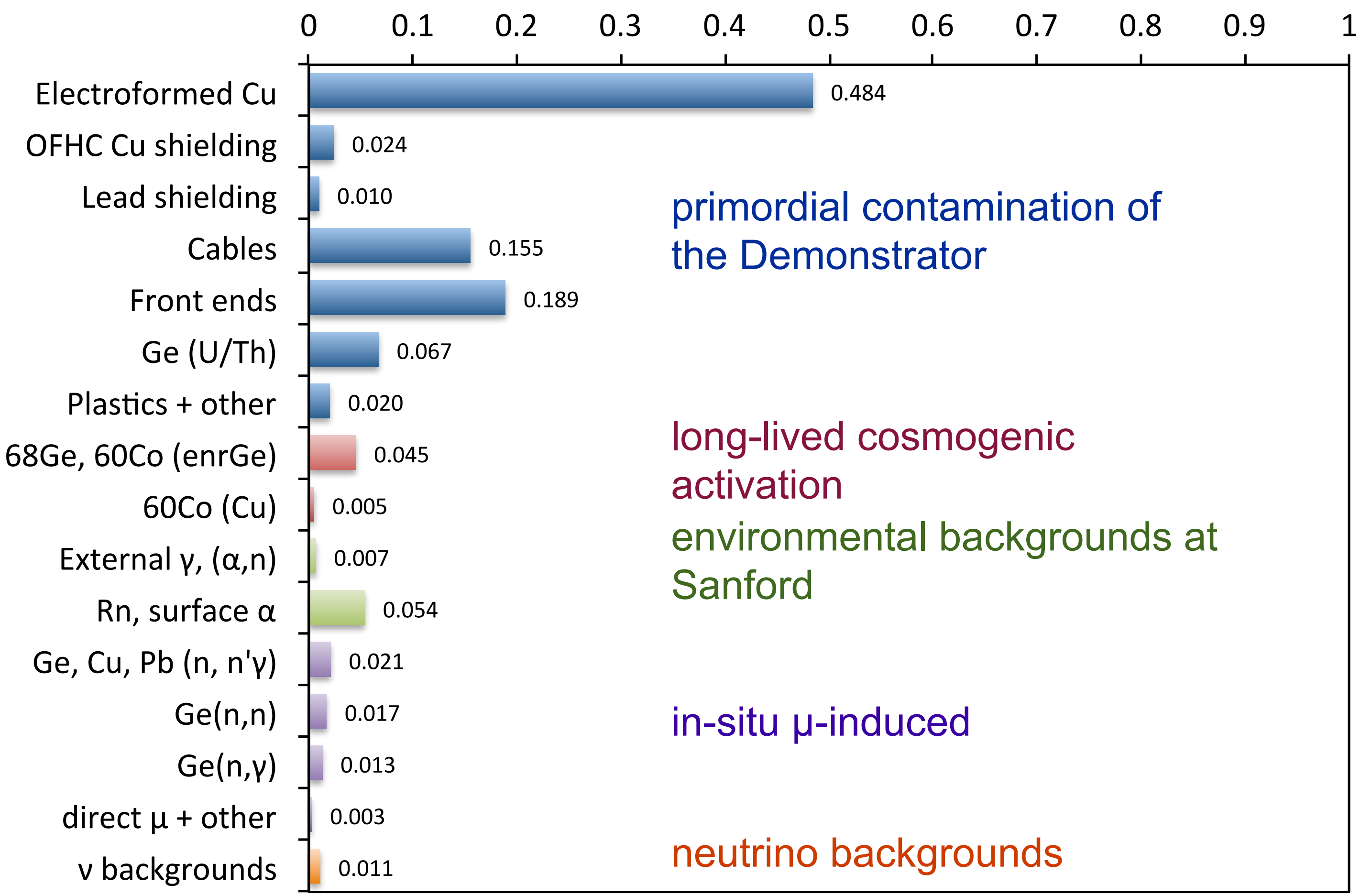

Total:
2.9 cts / 4 keV / t-y

J. Detwiler, MJ CD4 Background Criteria Report

# Scaled/Projected 1TGe Background



**Tonne-sclae 76Ge 0νββ background goals [cnts/ROI-t-y]**



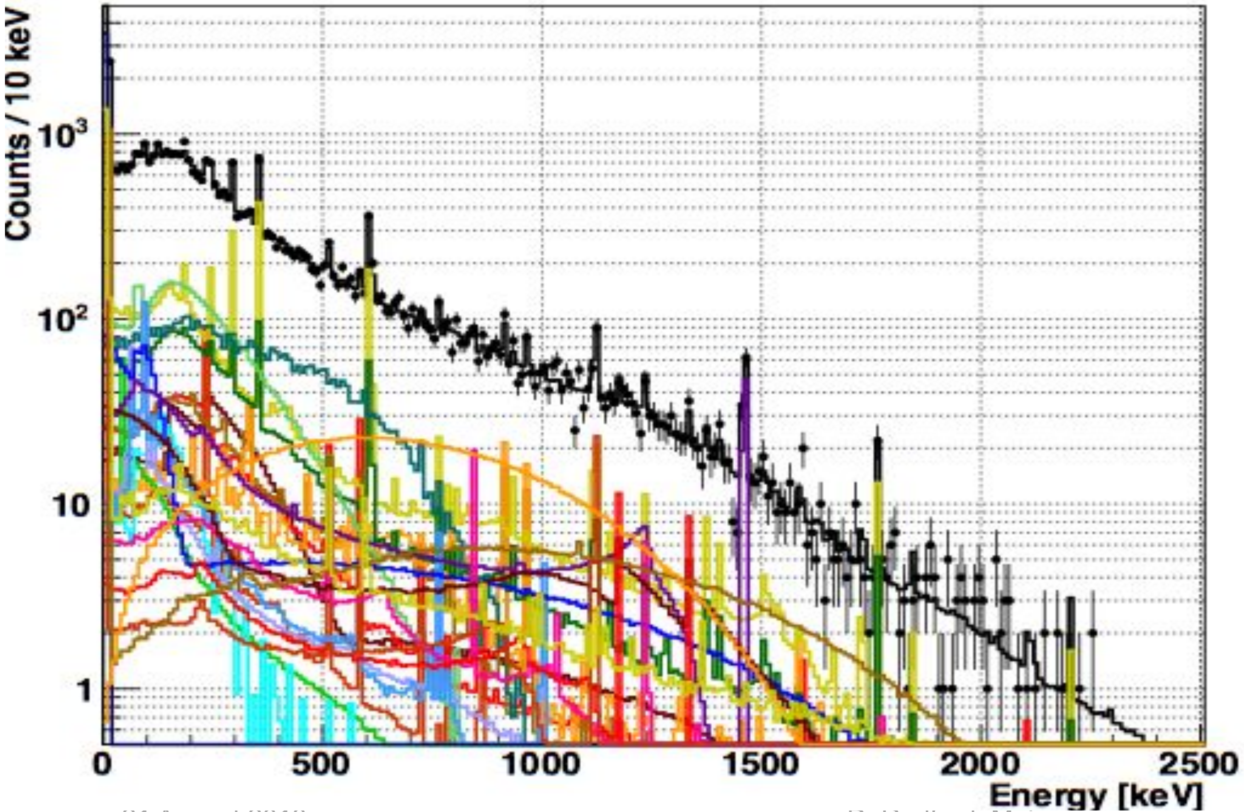

Total:
1.0 cts / 4 keV / t-y

# Background Model Fit of R&D Detector

Geant4 simulations to determine efficiencies for contamination to deposit energy in our detectors

50k CPU hours

8k+ runs, 40+ contaminants, 56 components, 21 materials

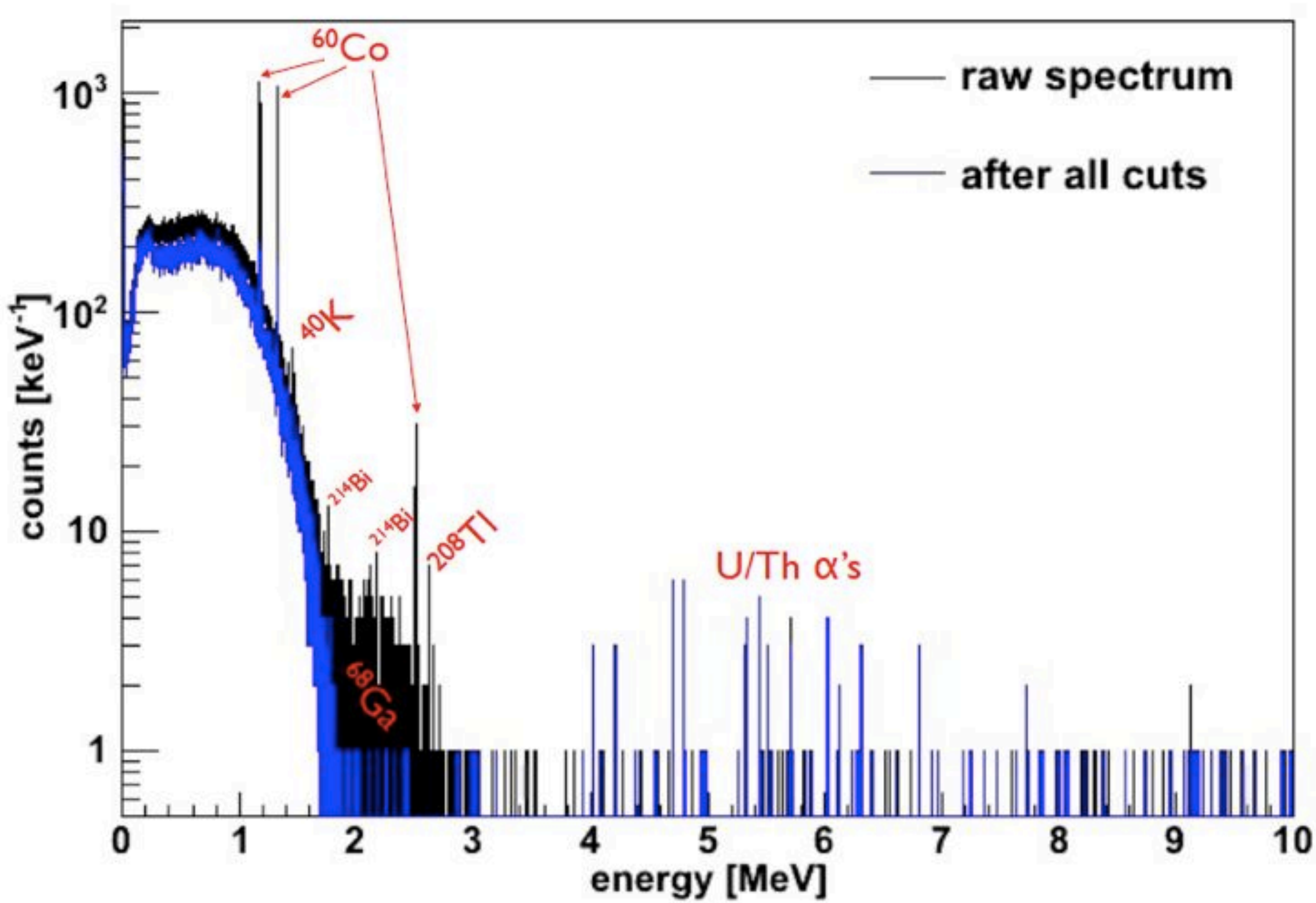



$\chi^2$ / DOF = 97.2 / 114
P-value = 0.87

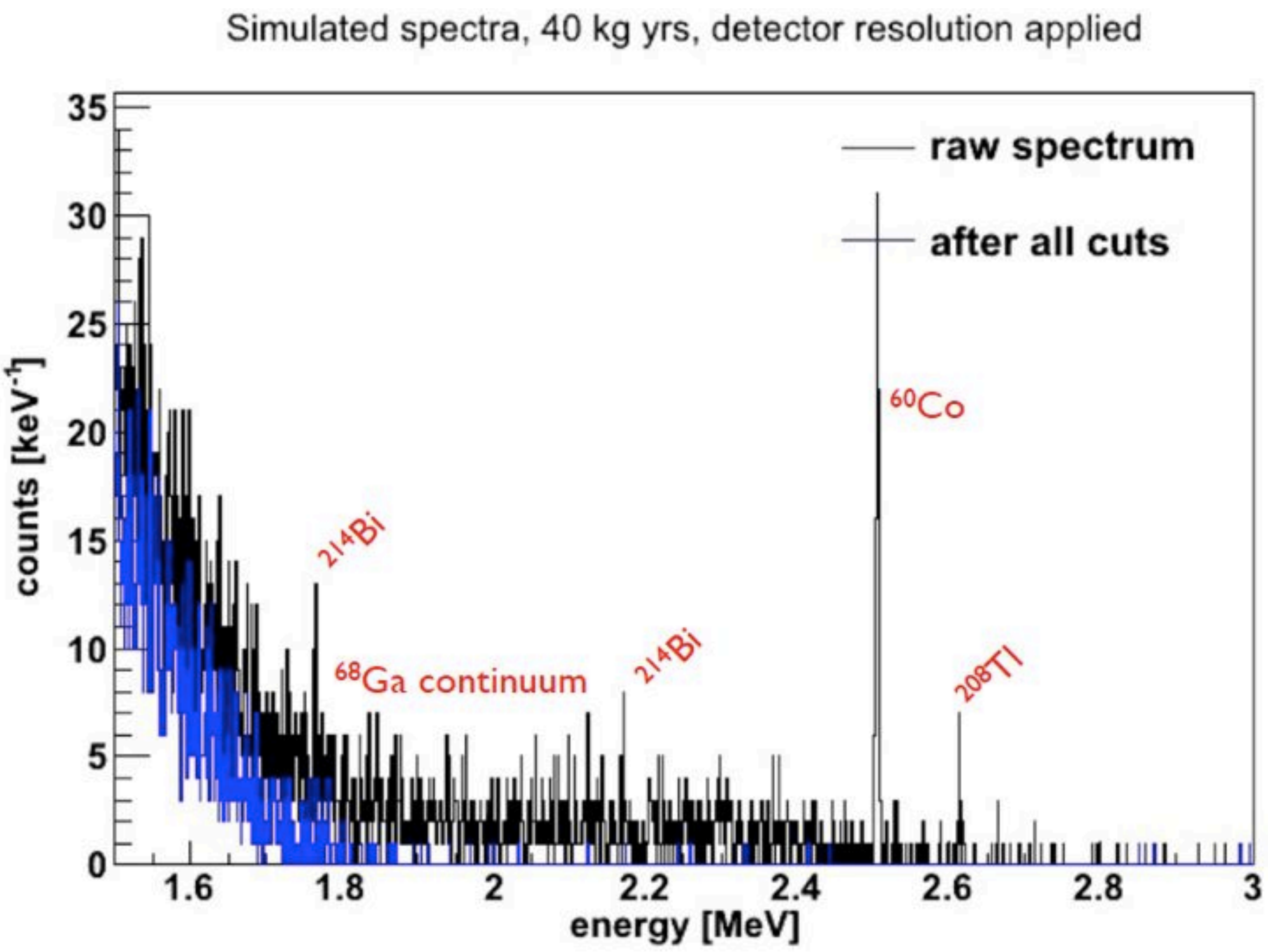
A. Schubert, Univ. Washington, PhD Dec. 2012

# MJD Spectrum - 2 years of running

Simulated spectra, 40 kg yrs, detector resolution applied

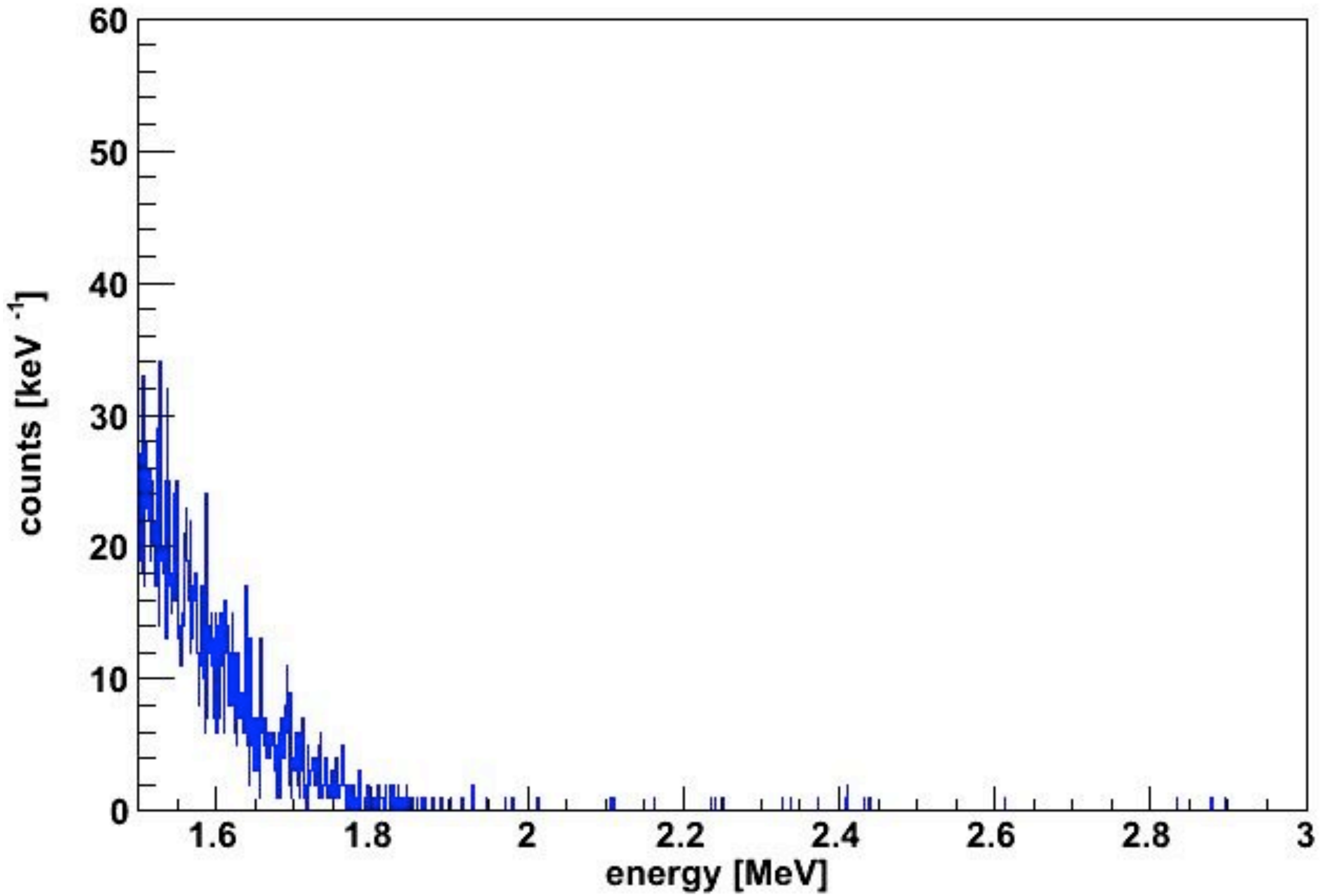


# MJD Spectrum - 2 years of running

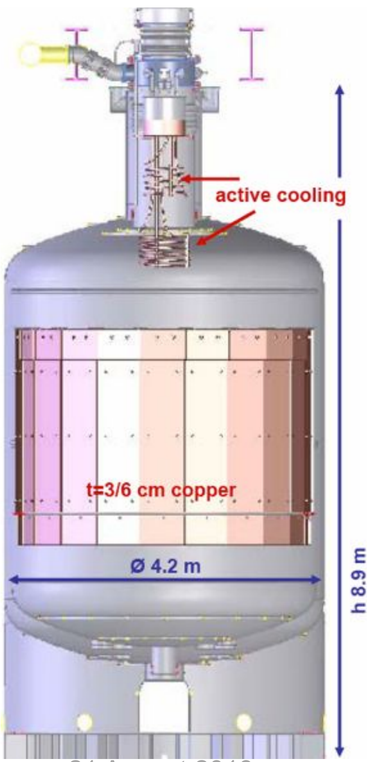


# MJD Spectrum - 2 years of running

Simulated spectra, 60 kg yrs, detector resolution + all cuts applied



# GERDA Phases I & II




Located at Gran Sasso, Italy
Individual detectors submersed in LAr

- Phase I

  18 kg of 86% $^{76}$Ge enriched P-type semi-coax detectors

  Data-taking recently completed
  KKDC result excluded at 99%
  Background achieved: 40 counts/ROI/t/y

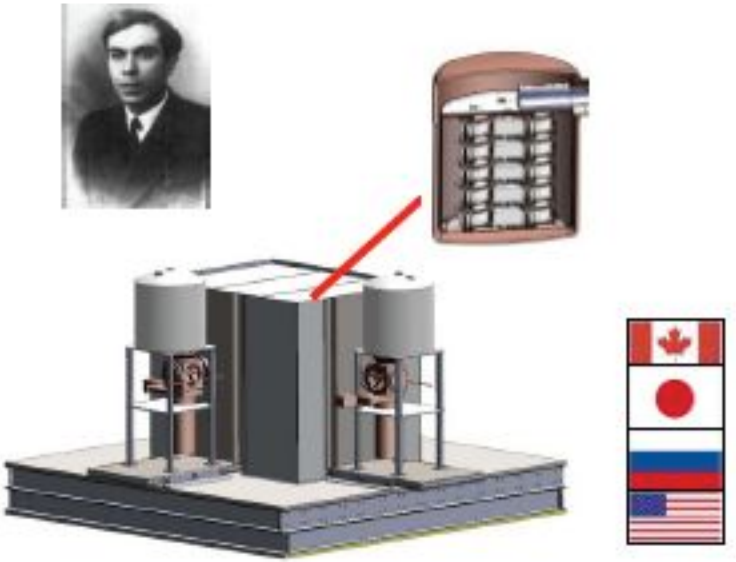
- Phase II

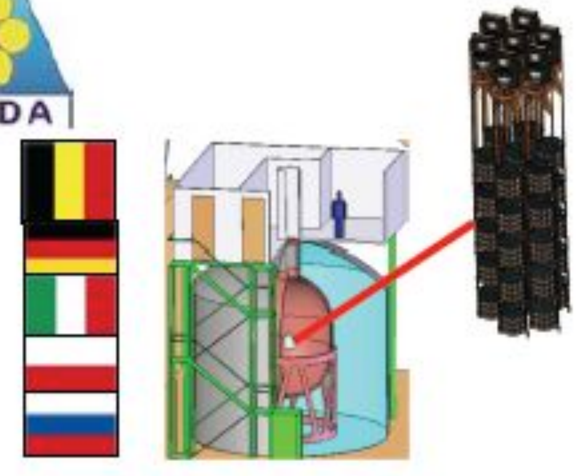
  additional ~20 kg of $^{76}$Ge N-type segmented detectors

  Goal: show feasibility for tonne scale experiment
  Background goal: 4 counts/ROI/t/y

  – Physics data taking of phase II should start in 2013-14

# MAJORANA DEMONSTRATOR and GERDA





- $^{76}$Ge modules in electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto
- DEMONSTRATOR: 30 kg $^{76}$Ge and 10 kg $^{nat}$Ge PPC xtals

- $^{76}$Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals)
- Phase II: +20 kg segmented xtals

**Joint Cooperative Agreement:**

Open exchange of knowledge & technologies (e.g. MaGe, R&D)
Intention to merge for larger scale 1-tonne exp.
Select best techniques developed and tested in GERDA and MAJORANA

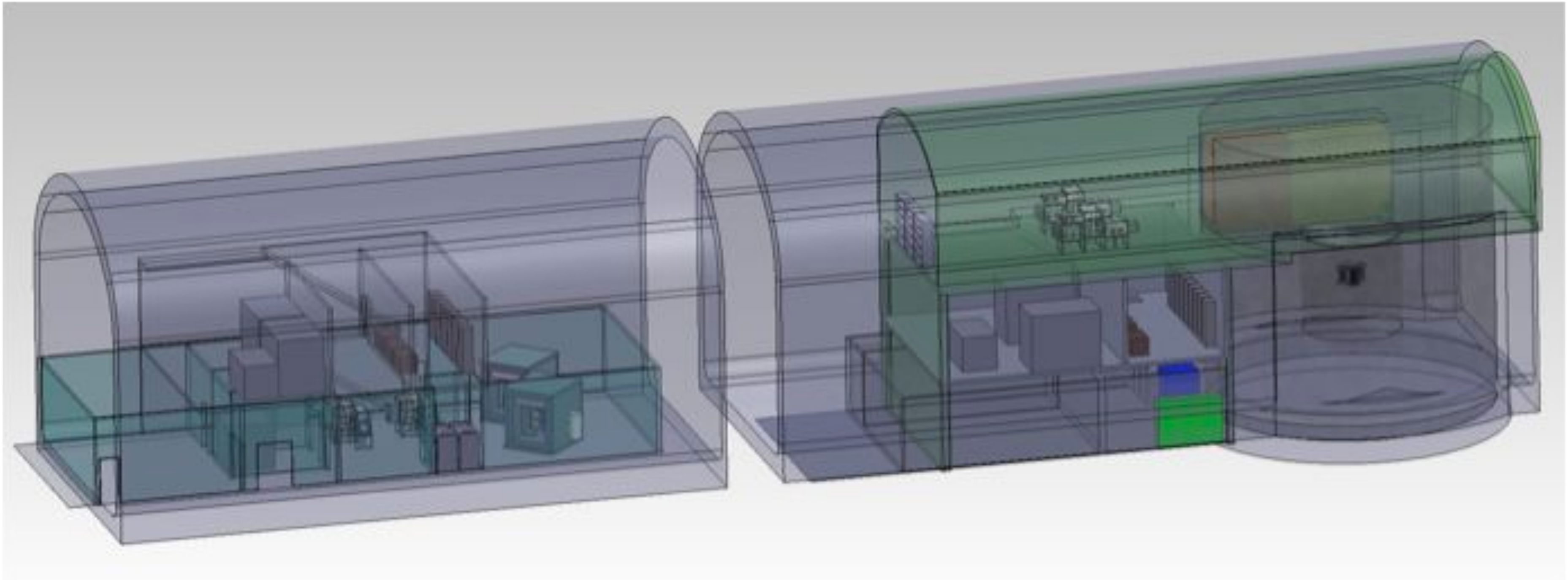
# Tonne-Scale 0νββ Experiment

- Working together with GERDA towards the establishment of a single international $^{76}Ge$ 0νββ collaboration
- Envision a phased, stepwise implementation;
  *e.g.* 250 → 500 → 1000 kg
- Moving forward predicated on *demonstration* of projected backgrounds by MJD and/or GERDA
- Anticipate down-select of best technologies, based on results of the two experiments
- During 2014 both GERDA Phase II and MJD Cryo 1 should be collecting data

# Beyond MJD: 1TGe R&D

- MAJORANA collaboration awarded a “Solicitation 4” grant from NSF (FY10-12) to contribute to preliminary design of DUSEL/SURF
- Defined two baseline experimental configurations (based on MJD and GERDA), and also a hybrid approach. Developed facility requirements, determined amount of space needed for the experiment, produced scientific justification explaining depth requirements, developed preliminary cost, workforce & timeline estimates
- R&D aimed at retiring technical risks associated with scaling up: Ge recycling, thermal analysis of larger detector arrays in vacuum cryostats, simulations of alternative shields

# Baseline Experimental Configurations



## Compact

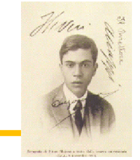
Two shields, each with 8 EFCu vacuum cryostats

## Cryogenic Vessel

Diameter of water tank:

- ~11 m for LAr,
- ~15 m for LN (shown)

# 1TGe Preliminary Design Concepts

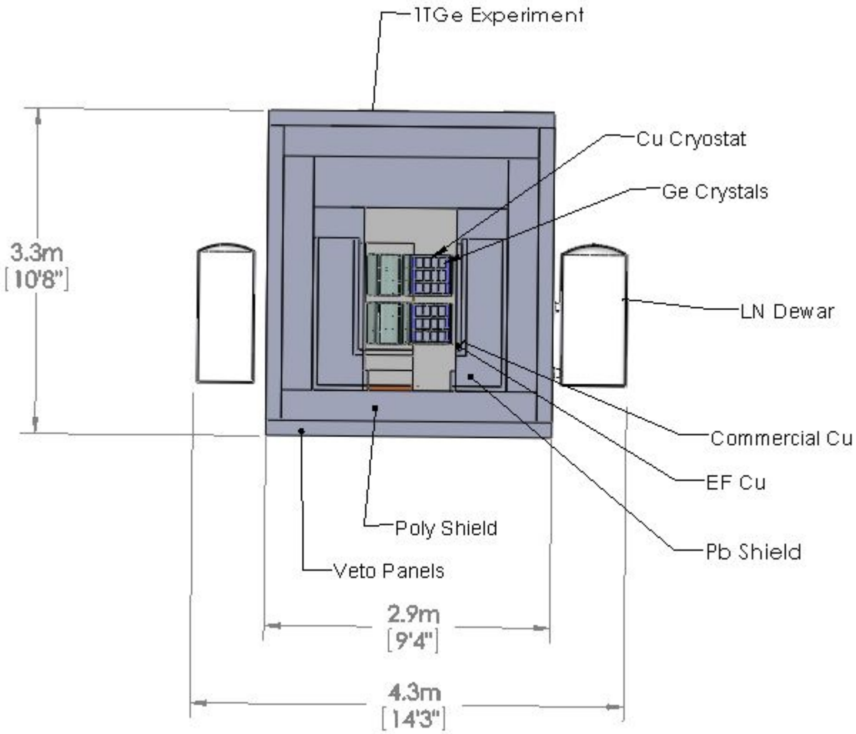


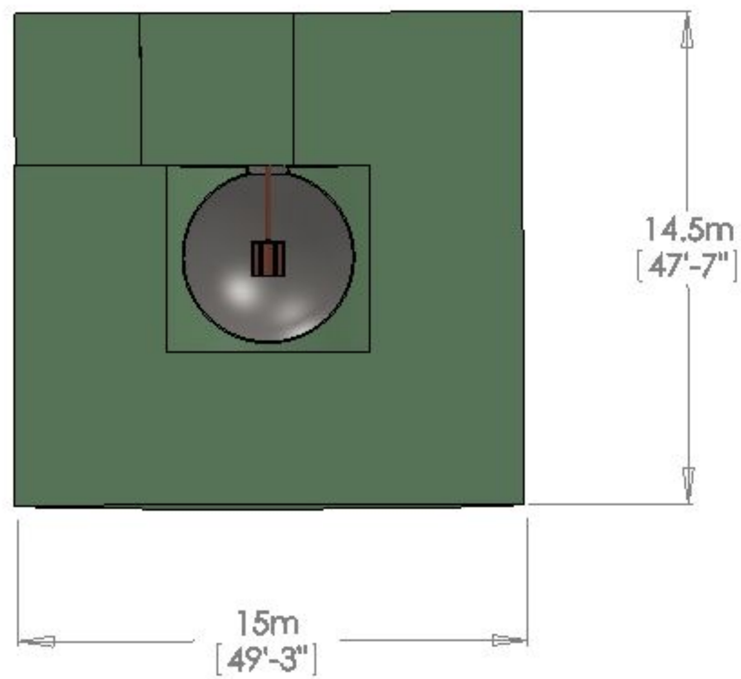
MAJORANA DEMONSTRATOR type Compact Shield

- $^{76}$Ge modules in compact electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto

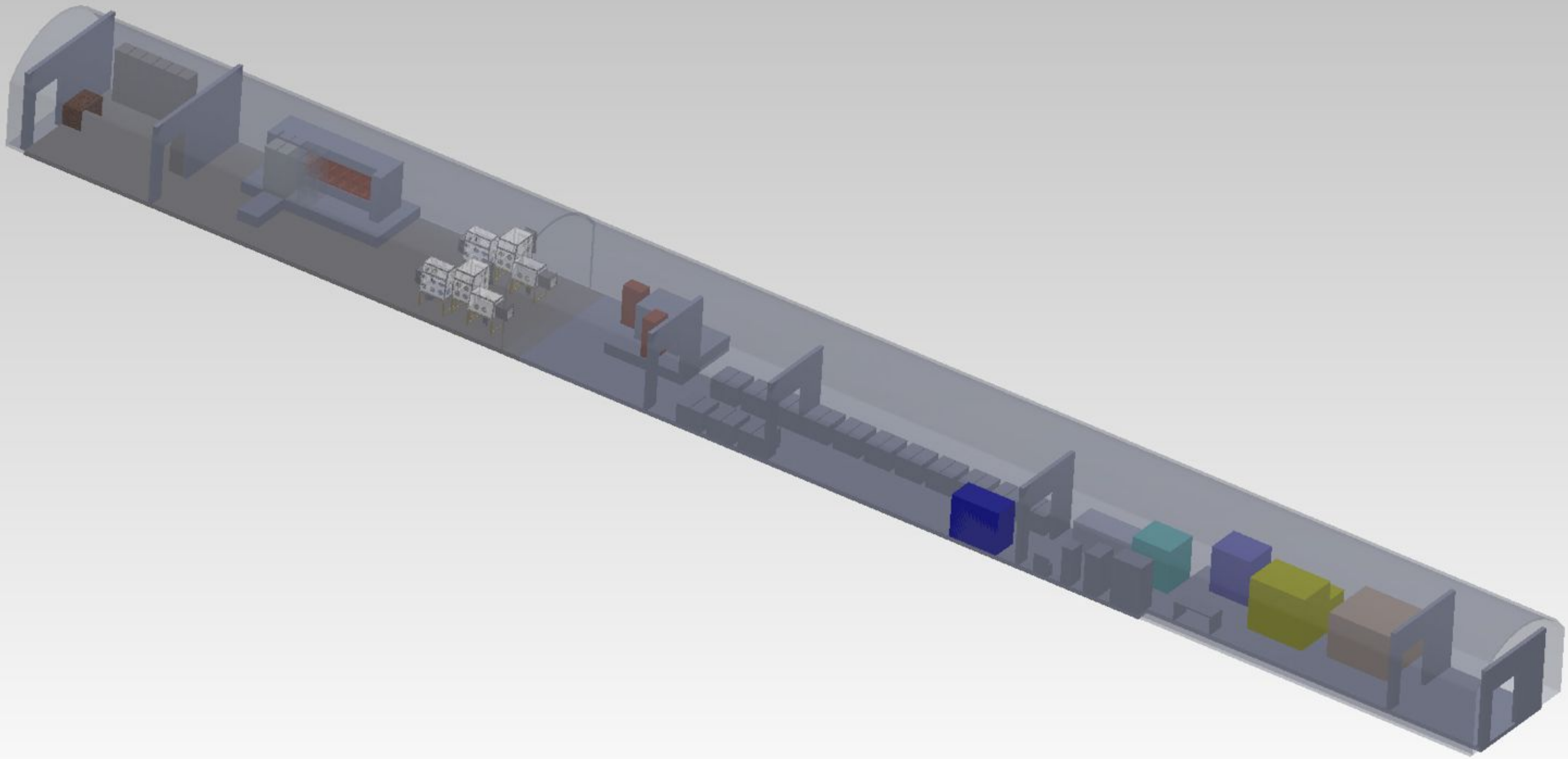
GERDA type LAr Shield

- $^{76}$Ge array submersed in LAr
- Use LAr as Compton suppression and veto
- Water Cherenkov μ veto

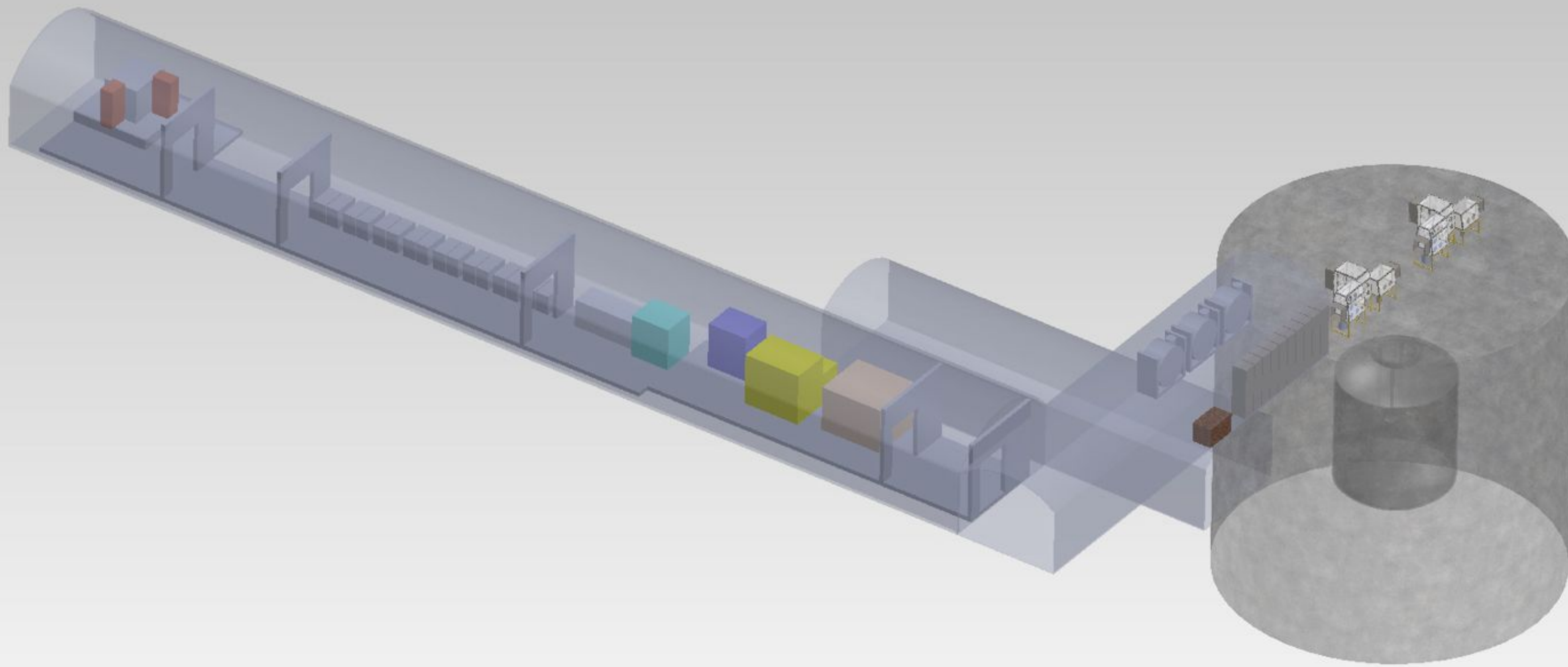


# Possible SNOLAB Compact Layout



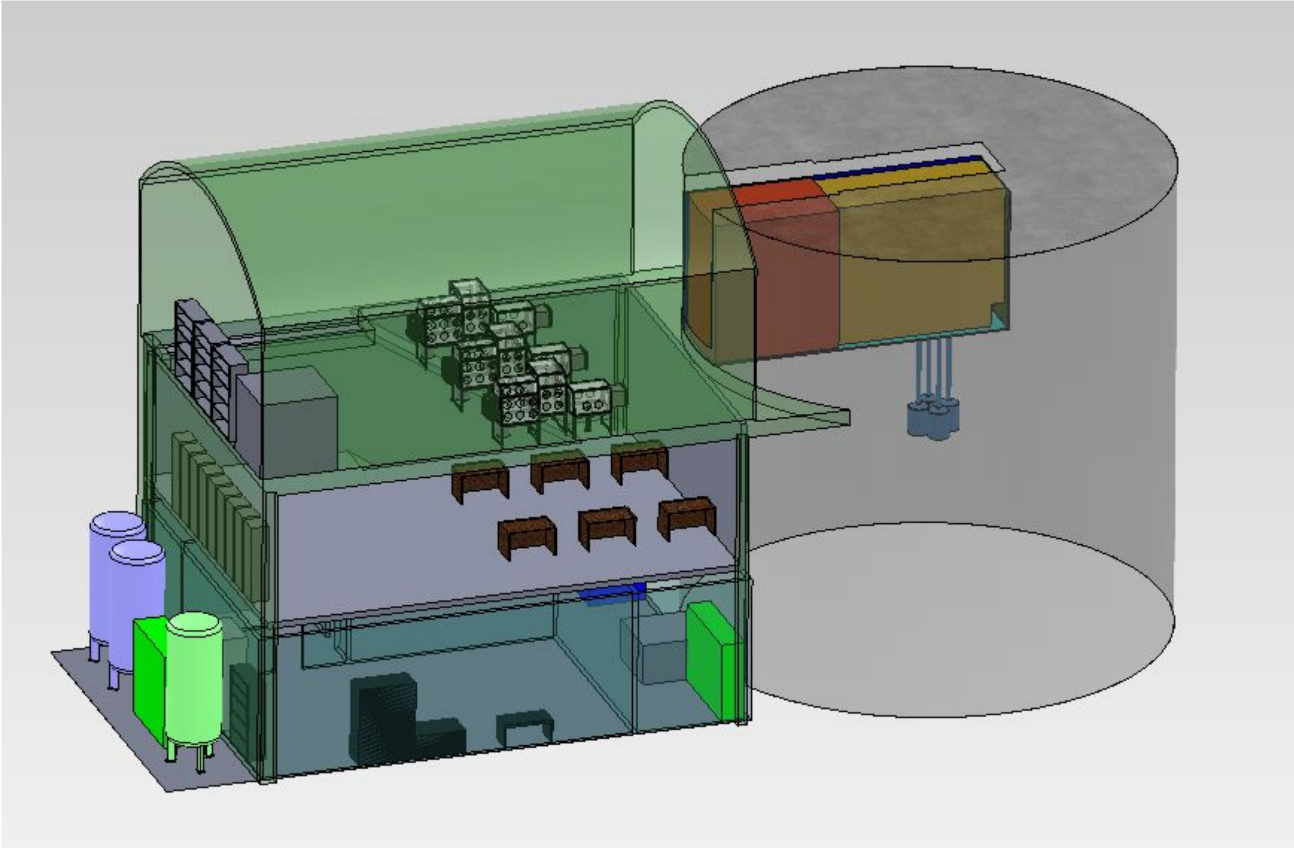
# Possible SNOLAB Liquid Shield Layout



Diameter of water tank: ~ 11 – 15 m

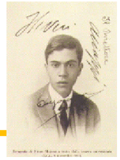
# Alternative Shield Concepts

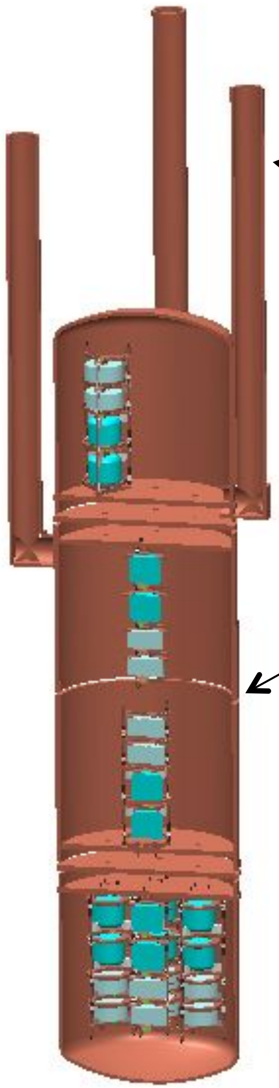
Hybrid: Vacuum cryostats in liquid scintillator or water



- Required purity of scintillator or water is within the bounds of what has previously been achieved
- Could fit inside the Cryopit

# Alternative Shield Concepts

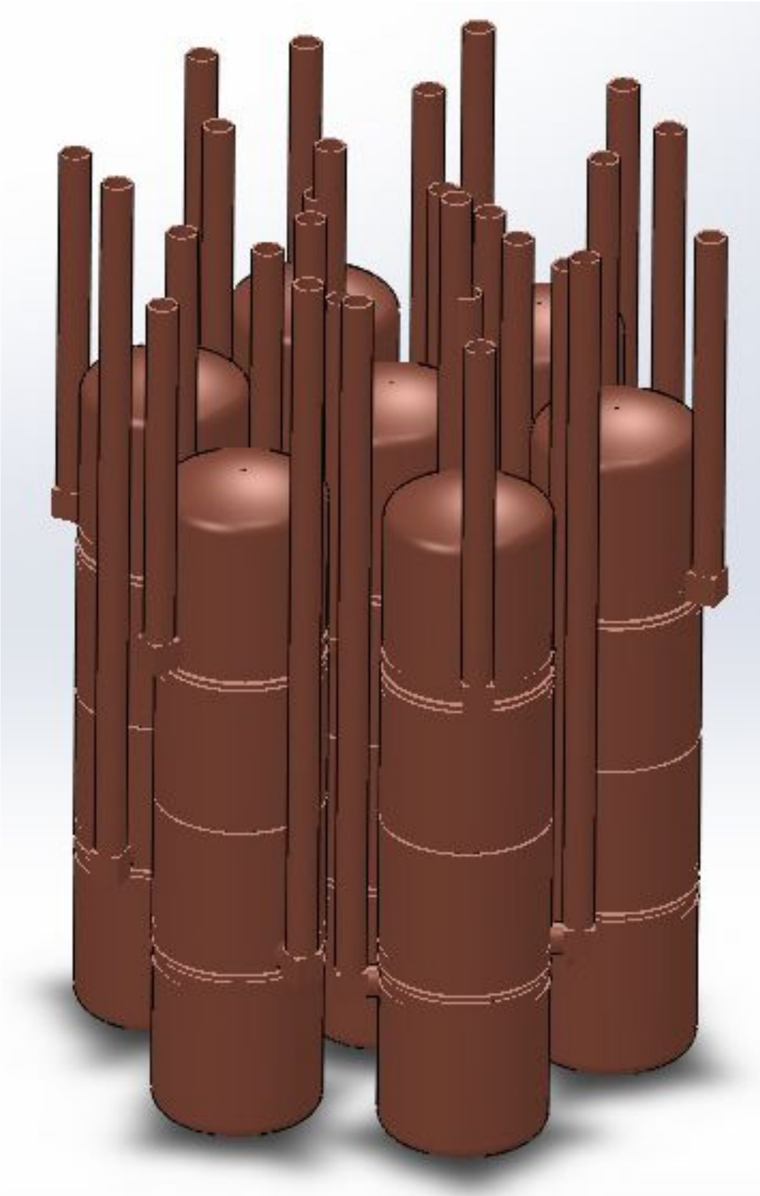




Hang from cable feed thru / pump ports for insertion into water or cryo shield

Demountable flange allows variable cryostat length for smaller module units if necessary (30-60-90-120 kg)

# Alternative Shield Concepts

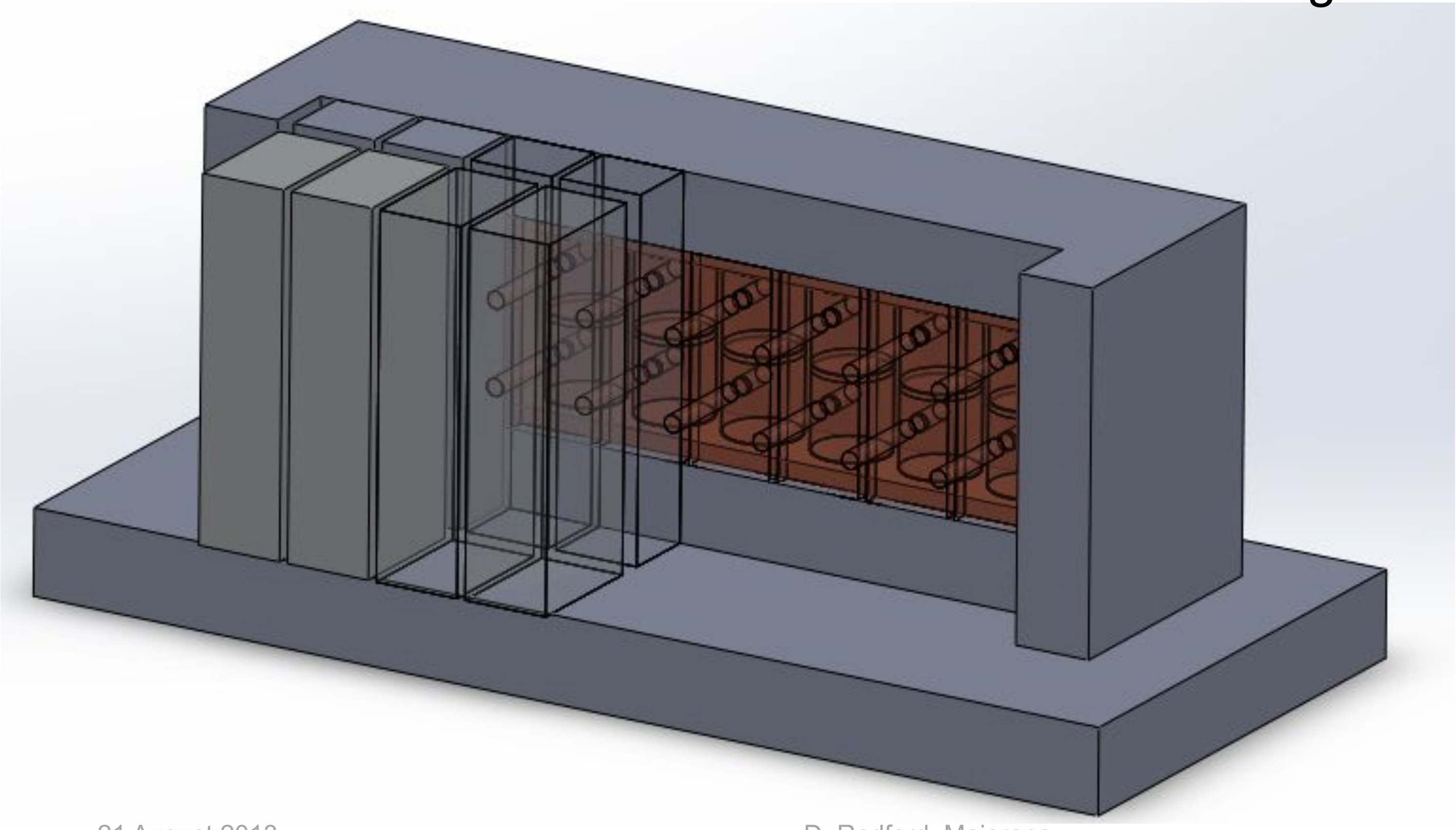


- 30kg x 4 x 7 = 840 kg nominal (longer strings for 1T)
- Overall size is ~1.6m tall x 1.6m diameter

# Alternative Shield Concepts

## Compact Linear Shield

- 30kg x 2 x 8 = 480 kg nominal as shown.
- Stretch to 4x8, 2x16, or double-sided unit for 1T, depending on facility layout
- Overall enclosure is ~ 10m long for 2x8 system

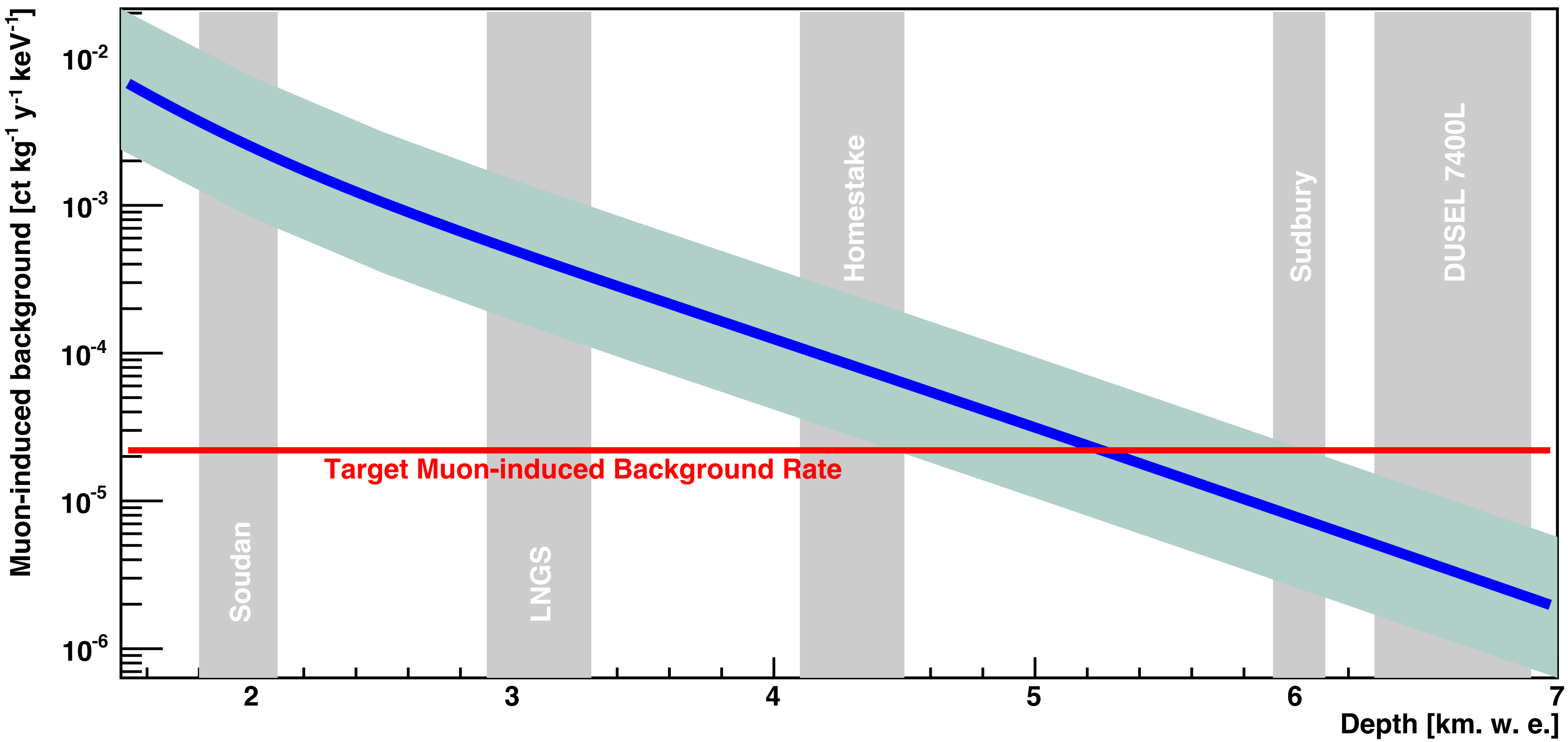


# Baseline Shield Comparisons

- Both configurations can adequately suppress external radiation, and have similar estimates of background rates from internal sources (crystals, mounts, etc.)
- Cryogenic Vessel requires more space
- Compact Shield may need to be sited deeper to achieve desired CR background rate.
- Cryogenic Vessel approach is more technically complex

Ton-scale technology down-select will be driven in large part by the background suppression performance achieved the Majorana Demonstrator and GERDA Phase II.

# Depth Requirement *for Compact Shield*




*Scaled from Mei & Hime (2006) Phys. Rev. D73, 053004*

- Depth requirement for cryogenic vessel configuration is less stringent, especially if LN is chosen for the cryogen
- Some remaining uncertainty; efficiency of EM veto of μ-induced neutrons may be better than assumed here

# 1TGe Spaces and Requirements

| Space | Power | Water | Ventilation | Temp | Rn air | Clean room | IT needs | Other |
|---|---|---|---|---|---|---|---|---|
| **Assembly room** | Ave: 28 kW | High purity DI water | | | 3 Bq/m$^3$ | class 1000 or better | 100 Mbs LAN | Compressed air, LN transport |
| **Control Room** | Ave: 42kW UPS: 4.2 kW | | | 19-23 deg C | 3 Bq/m$^3$ | | full IT + storage | |
| **Cu/Pb Detector** | included in assembly room | High purity water | LN exhaust | 19-23 deg C | 3 Bq/m$^3$ | class 2000 | 100 Mbs LAN | need strong floor , compresed air |
| **LAr Detector** | included in assembly room | High purity water purification system | LN exhaust | 19-23 deg C | 3 Bq/m$^3$ | class 2000 | 100 Mbs LAN | |

# 1TGe Spaces and Requirements

| Space | Power | Water | Ventilation | Temp | | Clean room | IT needs | Other |
|---|---|---|---|---|---|---|---|---|
| **Electroform Lab** | 136 kW<br>UPS 5kW | Industrial tap water + HP DI water | exhaust Hydrogen from EF baths | 19-23 (15%-60% humid) | 3 Bq/$m^3$ | class 2000, airlock entry | remote control and internet | spill containment lining - compressed air - Hazmat transport |
| **Cu Cleaning lab** | 28 kW | HP water | | 19-23 (15%-60% humid) | 1 Bq/$m^3$ | class 100 | remote control and internet | Hazmat transport |
| **Machine Shop** | 107 kW peak<br>45 kW ave | HP water | 30,000 cfm | Under investigation | 3 Bq/$m^3$ | class <10000 | remote control and internet | compressed air |
| **Storage Area** | | | | max 50% humid | | | | |
| **Ge Detector Fabrication Lab** | 125 kW | DI: 5 gal/min<br>tap: 75k gal/yr<br>cooling :125 gal/min | exhaust LN + HN03+HF from hoods | normal lab env. | 1 Bq/$m^3$ | <10,000, might need an area 100 | remote control and internet | compressed air - Hazmat transport- need LN |
| **Ge Purification Lab** | 250kW | DI: 5 gal/min<br>tap: 250k gal/yr<br>cooling: 125 gal/min | same | same | 1 Bq/$m^3$ | lab 10,000 + 100 room | remote control and internet | compressed air |

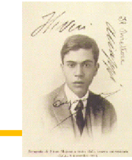
# Material Transport and LN Consumption

- LN Needs
  - Cover gas for E-forming baths, gloveboxes
  - Test cryostats
  - Detector Modules
  - Total: 200 L/day during construction, 430 L/day during operation

- Cage Trips *(based on SURF cage)*

| Shield Configuration | Cage trips | Notes |
|---|---|---|
| Compact | 180 | 130 for Pb bricks |
| Cryogenic Vessel (LAr) | 280 | ~150 for cryogen loading |
| Water only | 100 | |
| Liquid Scintillator | 1000 | ~900 trips for LS |

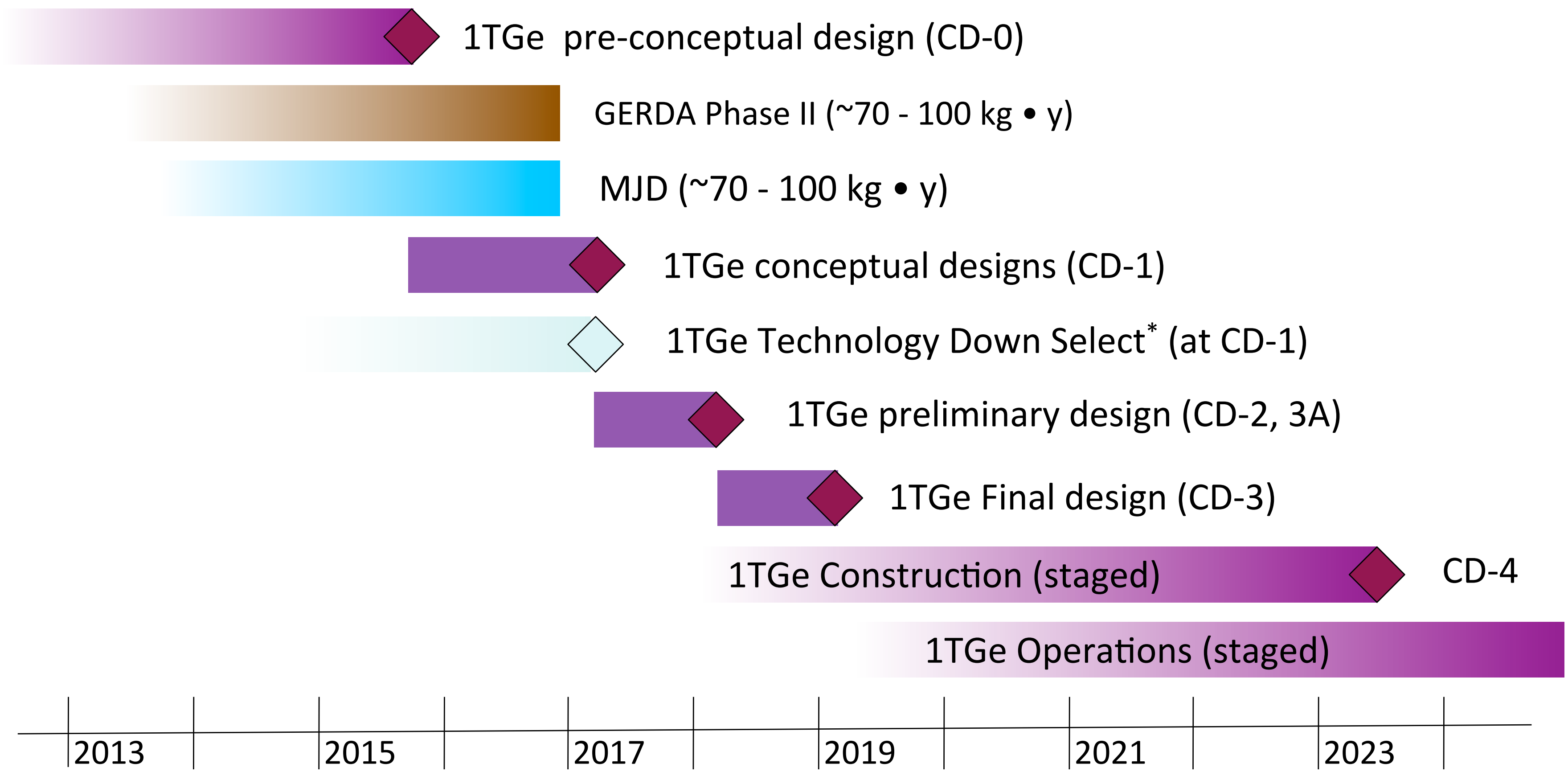
# Major Hazards and Safety Issues



- Cryogens
  - LAr/water shield configuration requires up to 50 kiloliter cryostat immersed in water tank
  - Flooding hazard if water tank fails
  - Oxygen deficiency / asphyxiation hazard if cryogen handling system fails
  - Explosive hazard: need to be able to drain water tank quickly if cryostat fails
- Chemical Hazards
  - Electroforming and Ge labs use hydrofluoric, sulfuric and nitric acids

# 1TGe Projected Timeline

- Technology down-select will be based on 1TGe R&D, GERDA Phase II, and MJD. Currently working with GERDA to define the process.
- 1TGe management will be defined based on participating institutions



# Conclusion and Summary

- The ultimate goal of the MJ collaboration is to field a tonne-scale $^{76}$Ge $0\nu\beta\beta$ decay search
- The Demonstrator aims to show that we can reach the ultra-low backgrounds required to justify the large experiment
  - Construction scheduled for completion in FY15
- Working towards an international collaboration and funding agencies to field the 1TGe expt.
  - US DOE contribution ~ $250M? Work in progress…
  - Funding decision process is likely to be lengthy
- SNOLAB offers an ideal location for such an experiment
- Two classes of possible shield designs; down-select expected within 5 years
- Construction could in principle begin as early as 2018

# The MAJORANA Collaboration

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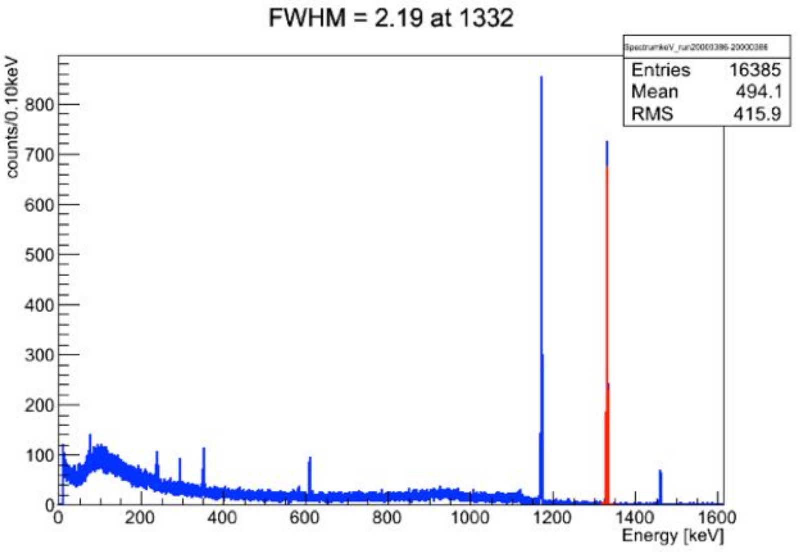
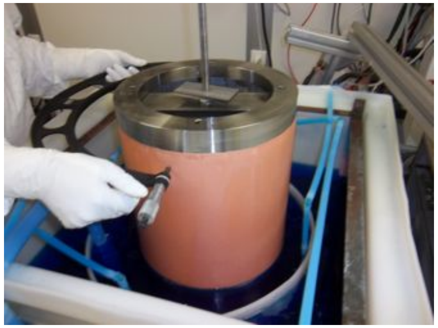
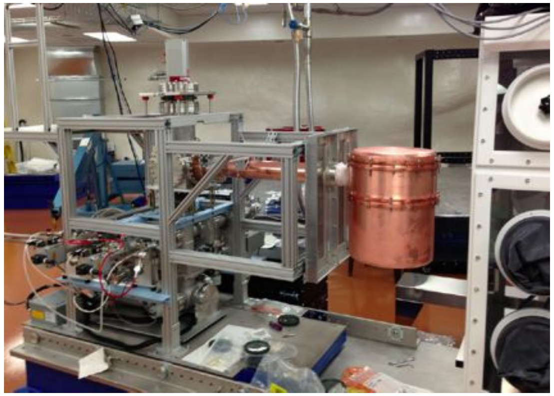
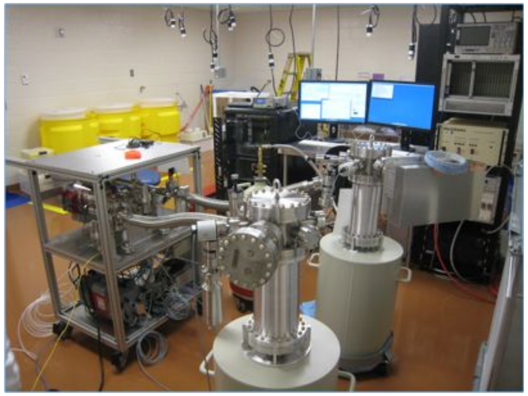
# Spare Slides

# Enriched Detectors Underground

# Recent Progress

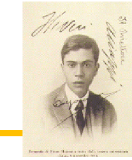




# Why search for 0νββ?

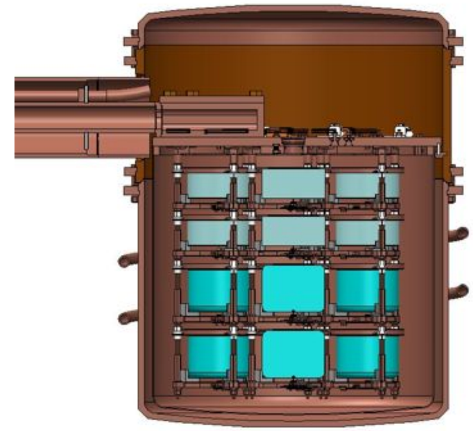
- 0νββ decay probes fundamental questions
  - Neutrino properties: The only practical technique to determine if neutrinos are their own anti-particles (Majorana particles)
  - Lepton number violation (LNV): Might Leptogenesis be the explanation for the observed matter - antimatter asymmetry?
  - *The observation of 0νββ would demonstrate LNV and the Majorana nature of the ν*
- If 0νββ is observed
  - Provides a promising laboratory method for determining the absolute neutrino mass scale that is complementary to other neutrino mass measurement techniques
  - Measurements in a series of different isotopes can potentially help reveal the nature of the LNVprocess(es)
  - *Extraction of ν mass and understanding the LNV process(es) will require significant reliance on both nuclear and particle physics*

# The Majorana Demonstrator

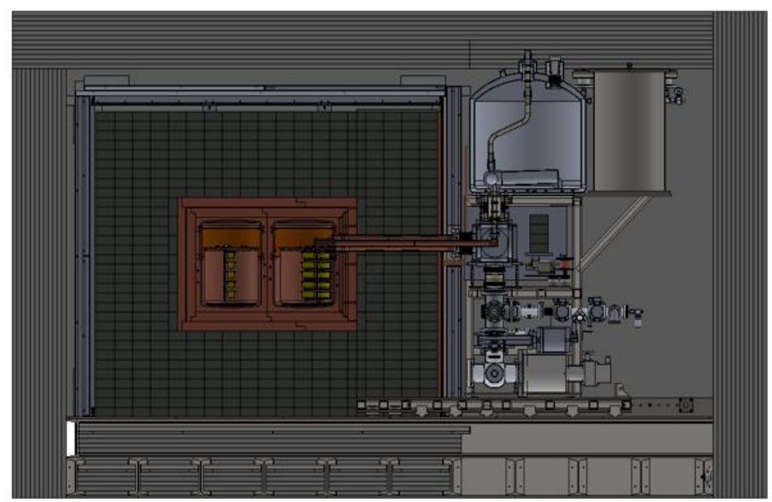


Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics, with additional contributions from international collaborators.

Goals:
- Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Test Klapdor-Kleingrothaus claim.
- Low-energy dark matter (light WIMPs, axions, ...) searches.



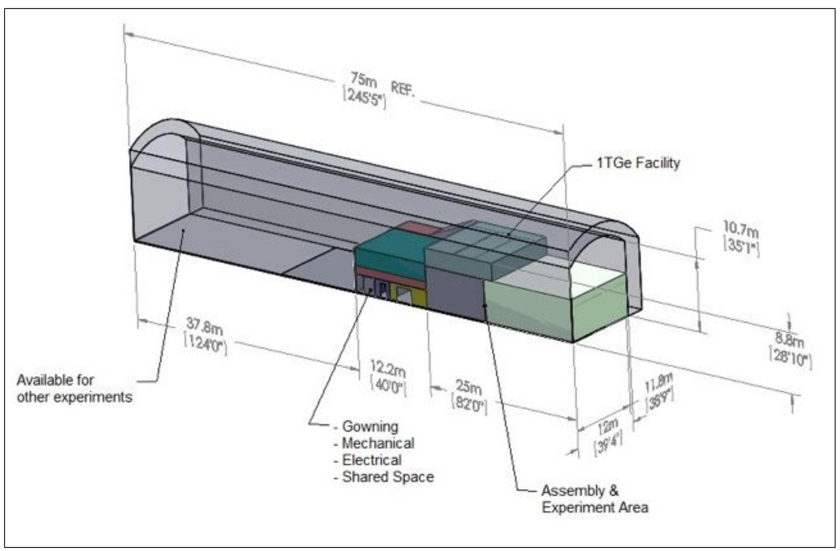
- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts)
  scales to 1 count/ROI/t/y for a tonne experiment
- 40-kg of Ge detectors (KPP of at at least 30-kg)
  - At least 15-kg of 86% enriched $^{76}$Ge crystals & up to 15-kg of $^{nat}$Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



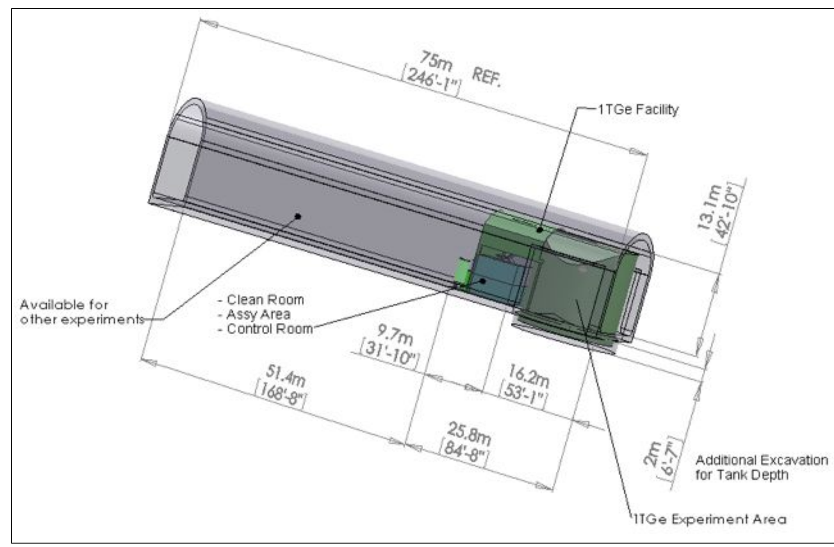
# 1TGe Facilities

- Cu electroforming and shop facilities at 4850 (already developed for MJD).
- Ideal lab location, with reduced risk from background will be at the 7400' level. (*Estimate of ~22 x better reduction in $\mu$-induced n backgrounds over 4850L. If located at 4850, then will need to study larger shield*.)

## Compact Shield

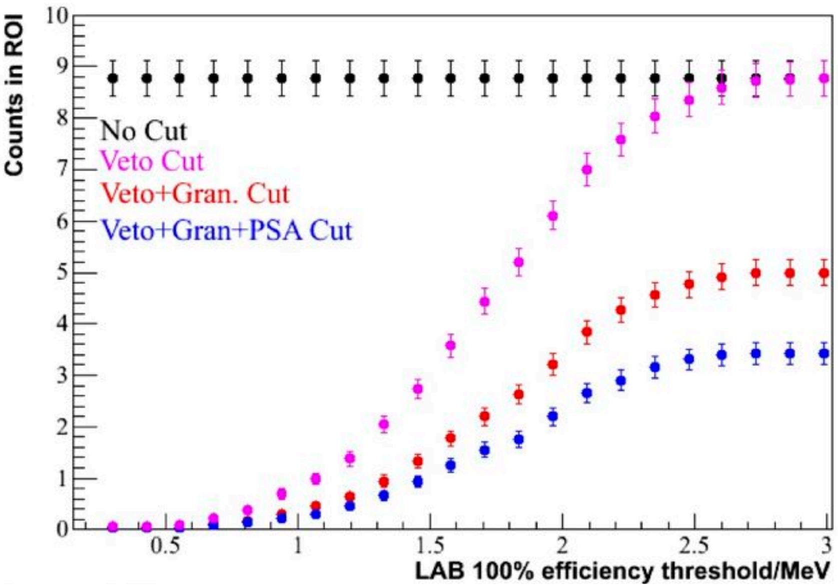


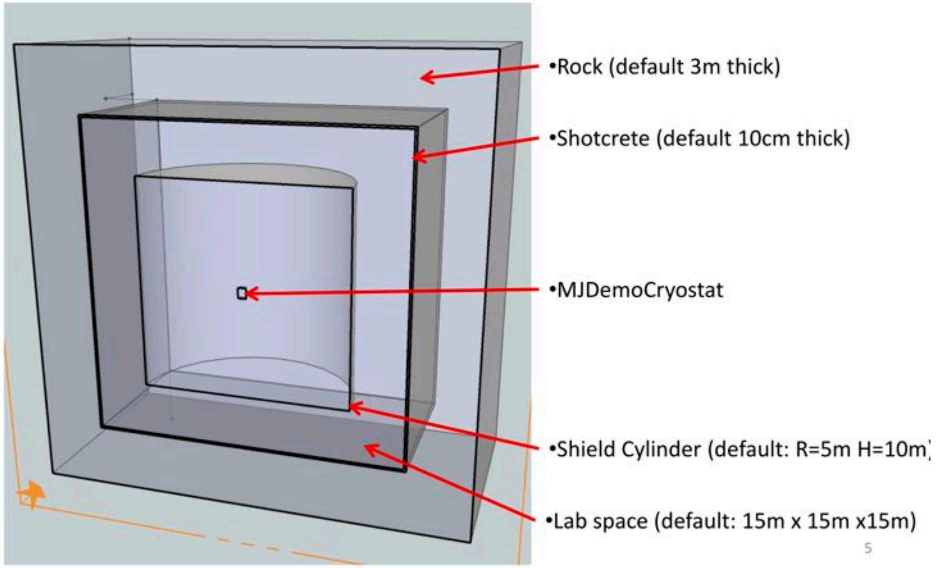

## Liquid Ar / Water Shield



# Alternative Shield Simulations

- Required purity of scintillator or water is within the bounds of what has been achieved by Borexino/SNO, and is independent of the size of the tank
- An active veto can relax the purity requirements by a factor of 2 to 3.



# 1TGe Preliminary Project Schedule

- Parametric estimate based on schedules developed for MJD and GERDA experiments, with MJD the primary source

| Description | Start | Finish | Duration (months) | DOE CD |
|---|---|---|---|---|
| Pre-conceptual R&D | 10/2009 | 9/2013 | 48 | CD-0 Q1 FY14 |
| Conceptual Design | 10/2013 | 9/2014 | 12 | CD-1 Q1 FY15 |
| *Results from GERDA Phase II & the MAJORANA DEMONSTRATOR* | | *2016* | | |
| Preliminary Design | 10/2014 | 9/2016 | 24 | CD-2, 3A Q1 FY17 |
| Final Design | 10/2016 | 9/2017 | 12 | CD-3 Q1 FY18 |
| Procurement, Fabrication, Assembly | 10/2016 | 9/2020 | 48 | |
| Actual Installation (Staged) | 10/2017 | 3/2021 | 42 | |
| Commissioning (Staged) | 10/2018 | 9/2021 | 36 | |
| Ready for Operations (1st module) | 4/2019 | | | CD-4 Q3 FY19 |
| Operations (all modules) | 10/2021 | 9/2025 | 60 | CD-4 Q1 FY21 |

# 1TGe Preliminary Cost Estimate

- Parametric estimate based on actual costs for MJD and GERDA experiments, with MJD the primary source
- Procurement costs generally scaled in linear fashion, except where cost reductions can be expected
- 30% contingency on MJD-based estimates, 50% on all others

| Option | Min TPC ($M) | Max TPC ($M) |
|---|---|---|
| Homestake 4850L | 214 | 231 |
| Homestake 7400L | 206 | 231 |
| SNOLAB 6800L | 210 | 235 |

| TPC Walk-up | Cost ($ks) |
|---|---|
| UG Crystal Fabrication | 15,000 |
| LAr Tank and shield | 10,000 |
| Rn mitigation | 1,500 |

| Major Procurements/Activities | Cost ($ks) |
|---|---|
| Host Lab Infrastructure | 2,000 |
| Materials & Assay | 2,100 |
| Ge Procurement/Enrichment | 105,000 |
| Detector Fabrication | 21,400 |
| Detector Modules | 4,000 |
| Electroforming | 1,500 |
| Mechanical Systems | 8400 |
| DAQ | 5400 |
| Project Labor | 18,500 |