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Title: Double Beta Decay, Neutrino Mass and the MAJORANA Project

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Intended for: Colloquium at ORNL

Los Alamos
Steve Elliott

Double Beta Decay

Science of ββ

General Experimental Issues

The MAJORANA DEMONSTRATOR Program

A Tonne-Scale Project

Toward the Normal Hierarchy Mass Scale

ββ and the neutrino

- **The ββ(0ν) decay rate is proportional to neutrino mass**
- **Decay only occurs if neutrinos are massive Majorana particles**
  - **Critical for understanding incorporation of mass into standard model**
  - **Violates Lepton number conservation**
    - **Leptogenesis?**
  - **ββ is only practical experimental technique to answer this question**
- **Fundamental nuclear/particle physics process**

What is ββ?

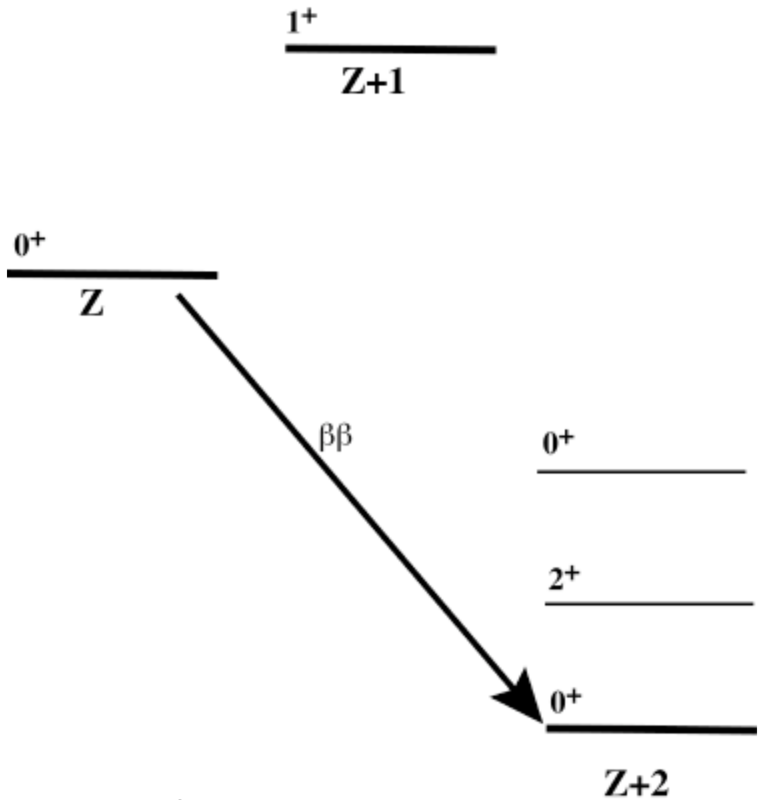


Fig. from arXiv:0708.1033

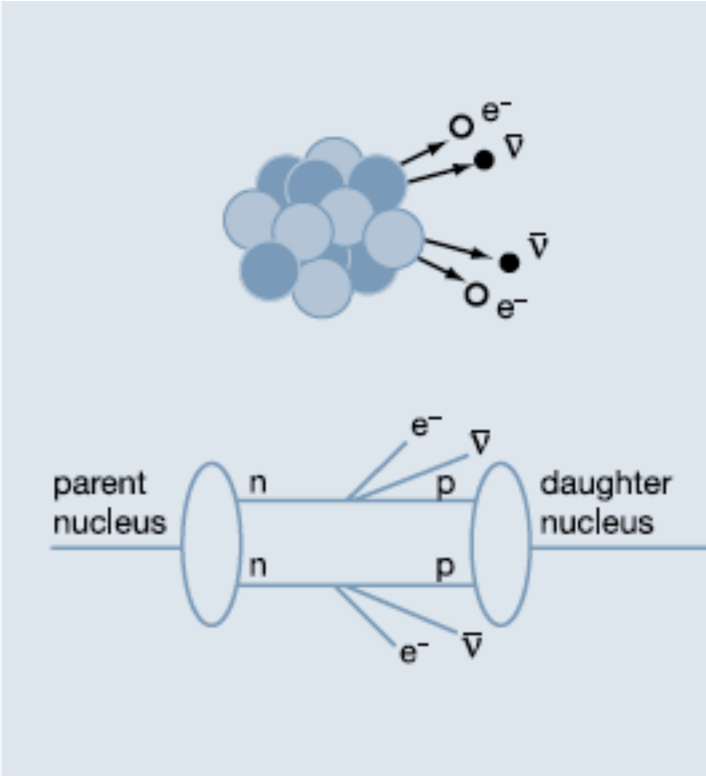


Fig. from Deep Science

What is ββ?

$n \Rightarrow p + e^- + \bar{\nu}_e$ $\nu_e + n \Rightarrow p + e^-$

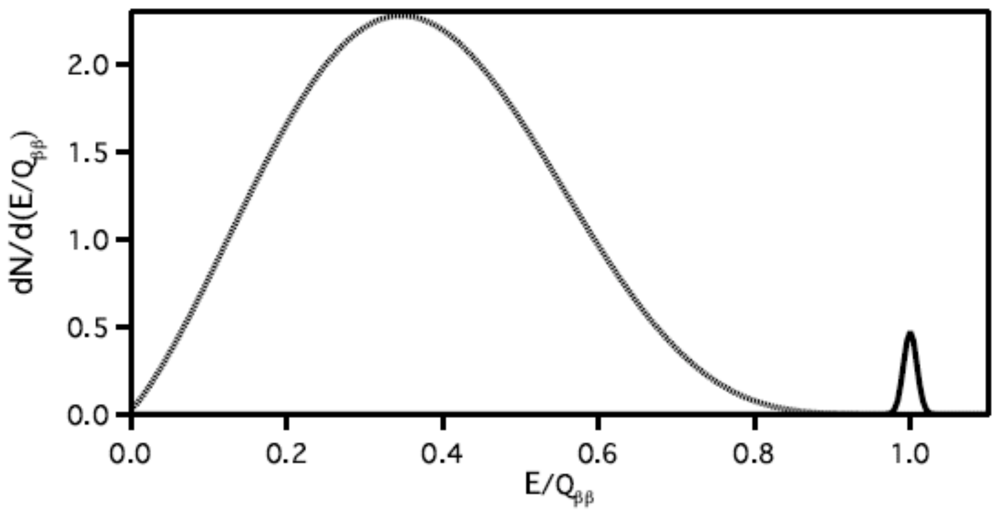


Fig. from arXiv:0708.1033

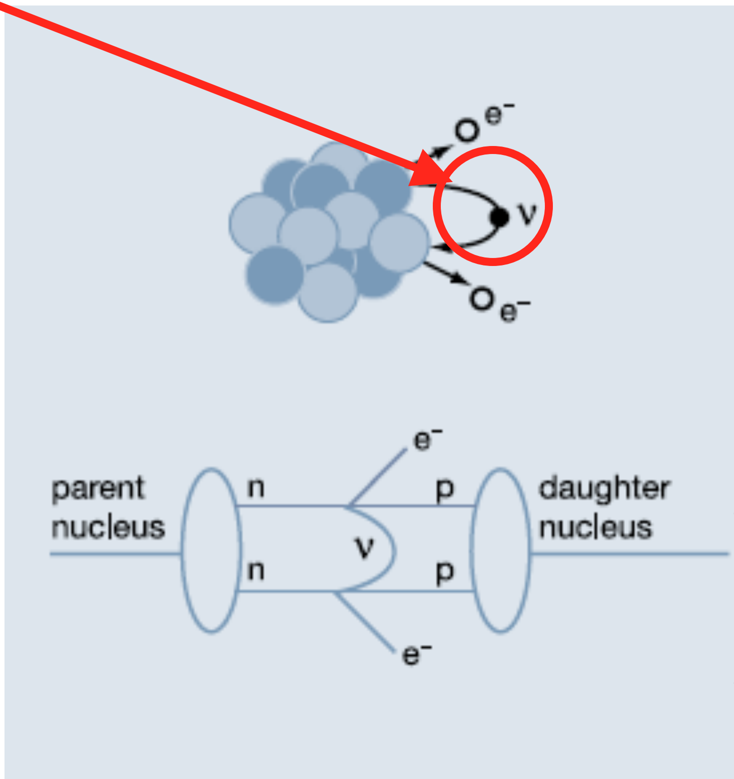


Fig. from Deep Science

ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2 \qquad \Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_{\beta\beta}^2$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

$m_{\beta\beta}$ is where the interesting physics lies.

The Effective Neutrino Mass

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i \right|$$

virtual ν exchange

Oscillation experiments indicate at least 1 of the m_i > 50 meV.
Sets target for upcoming projects.

Compare to β decay result:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

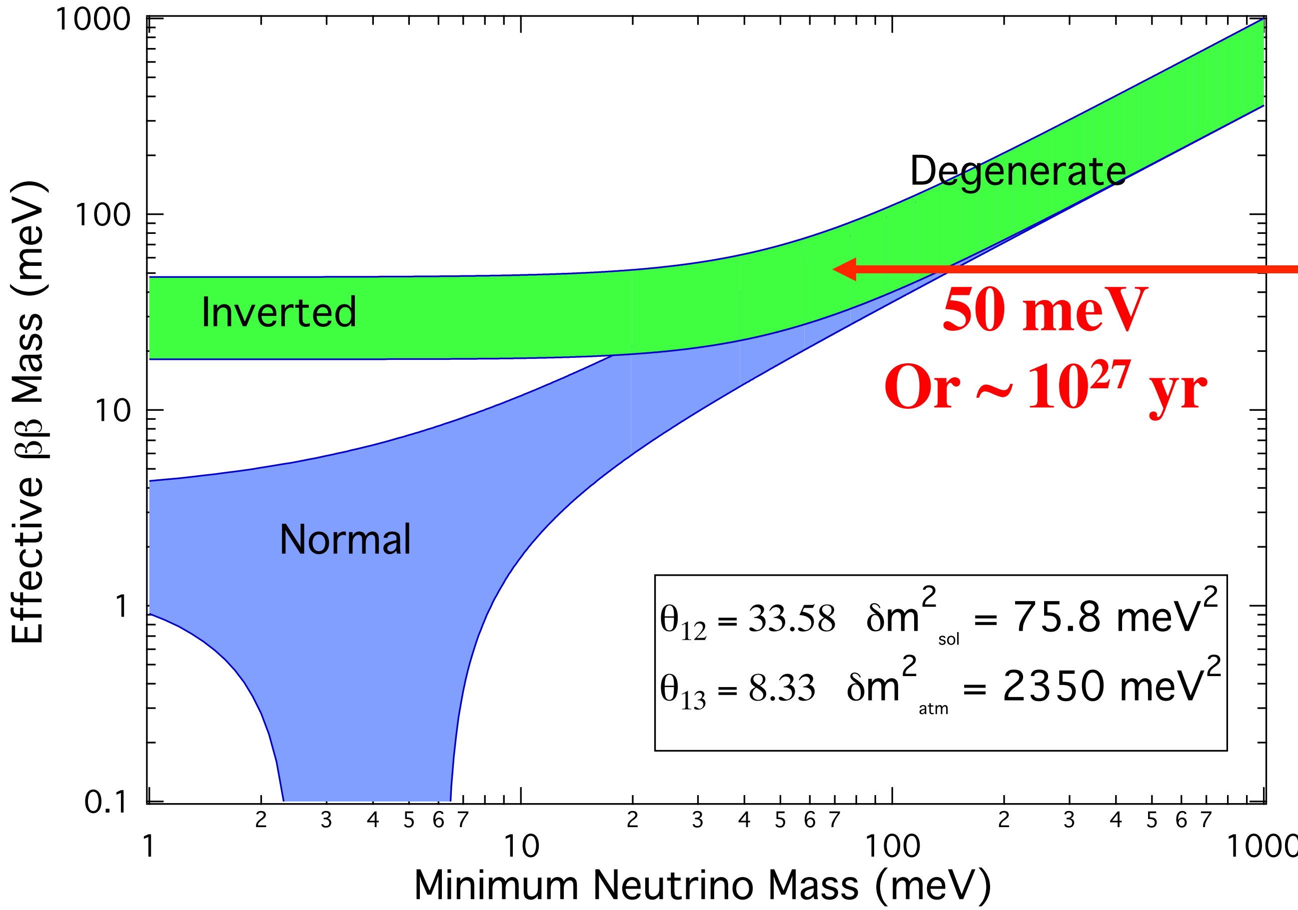
real ν emission

Compare to cosmology:

$$\Sigma = \sum m_i$$

ββ Sensitivity

(mixing parameters from arXiv:1106.6028)



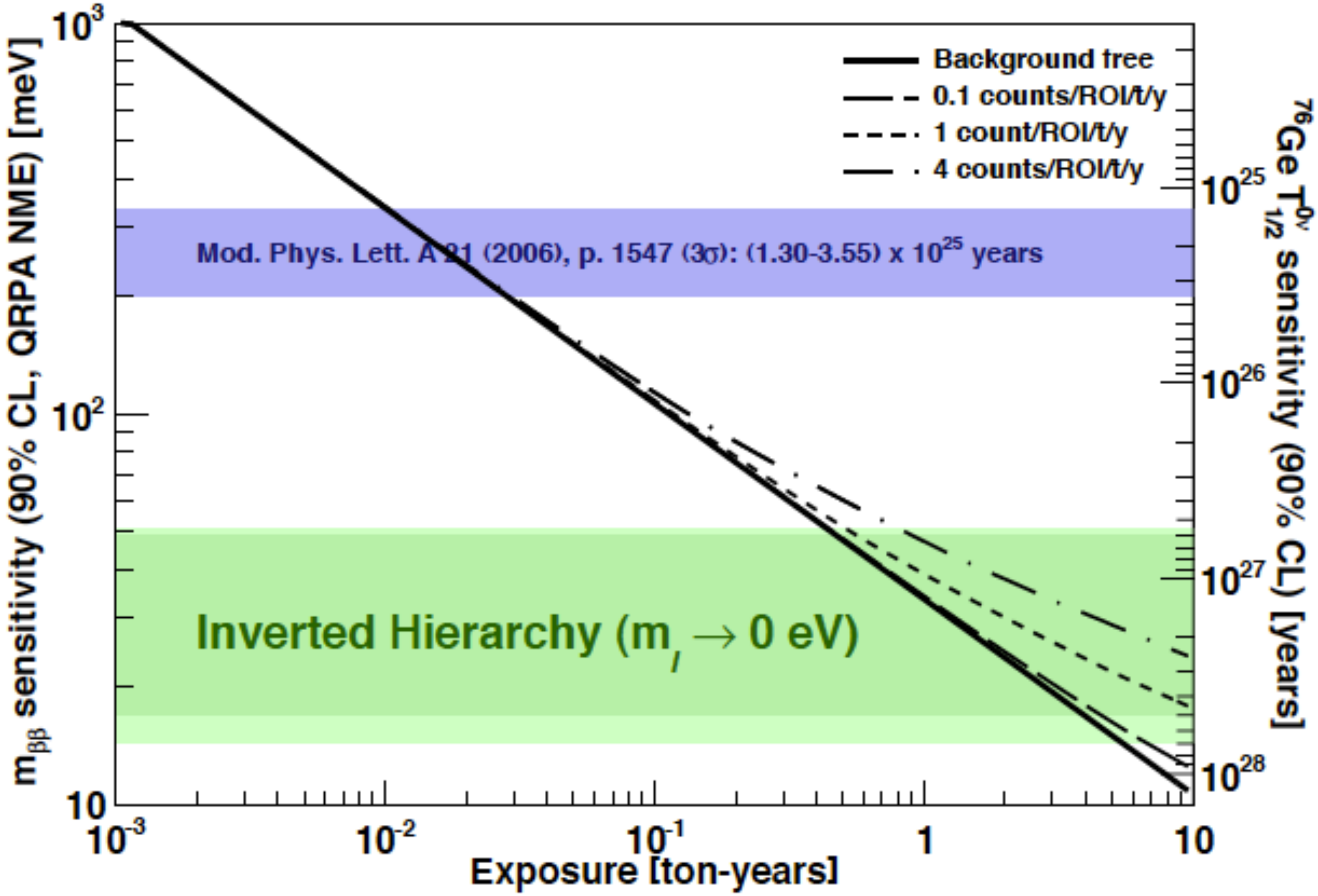
Even a null result will constrain the possible mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.

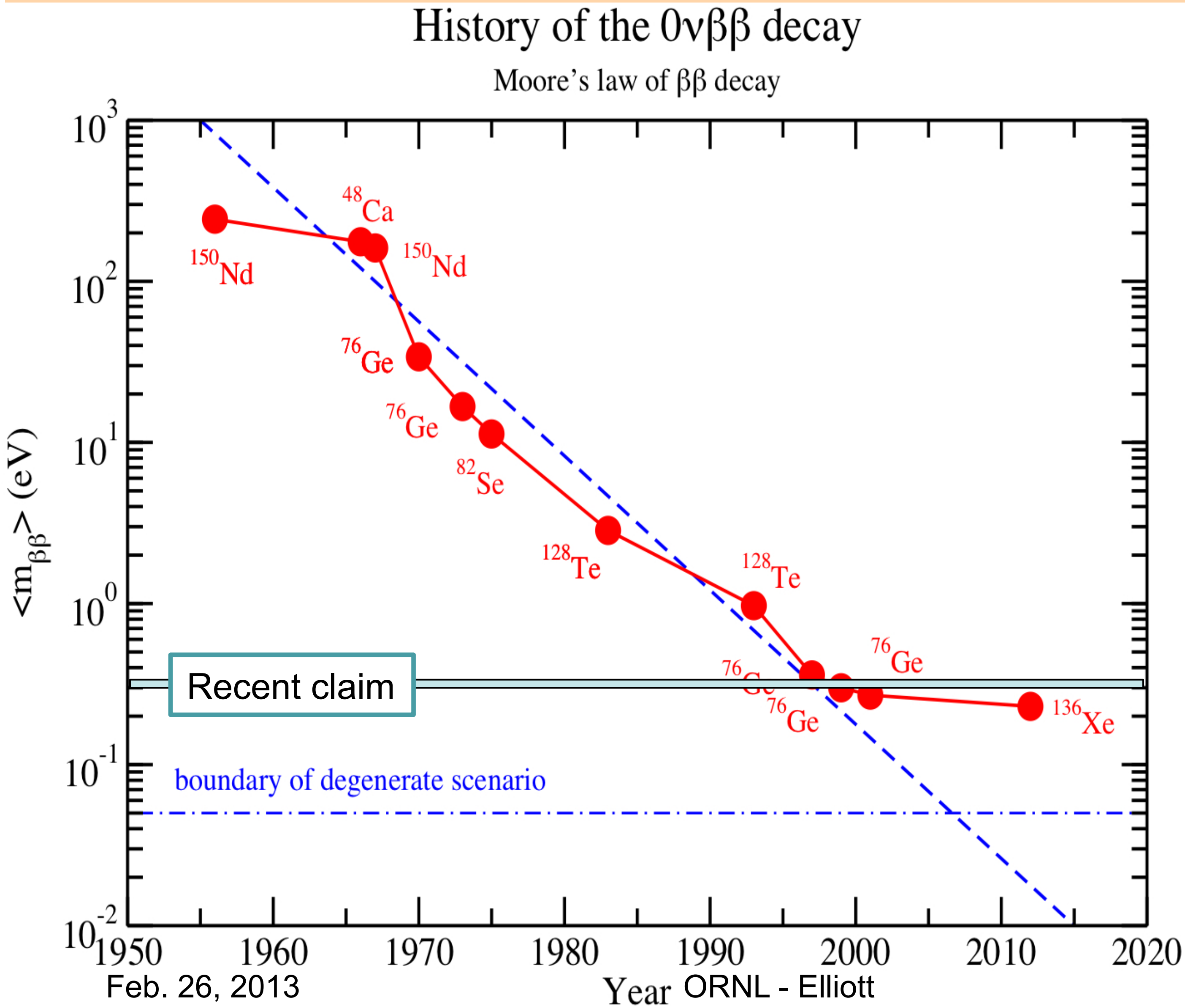
Signal:Background ~ 1:1
Its all about the background

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
$5x10^{26}$	10	100	
$5x10^{27}$	**To reach atmospheric scale need BG on order 1/t-y.**	40	Atmospheric
$>10^{29}$	<0.05	<10	Solar

Sensitivity, Background and Exposure



ββ trends (updated Elliott/Vogel plot by Vogel)



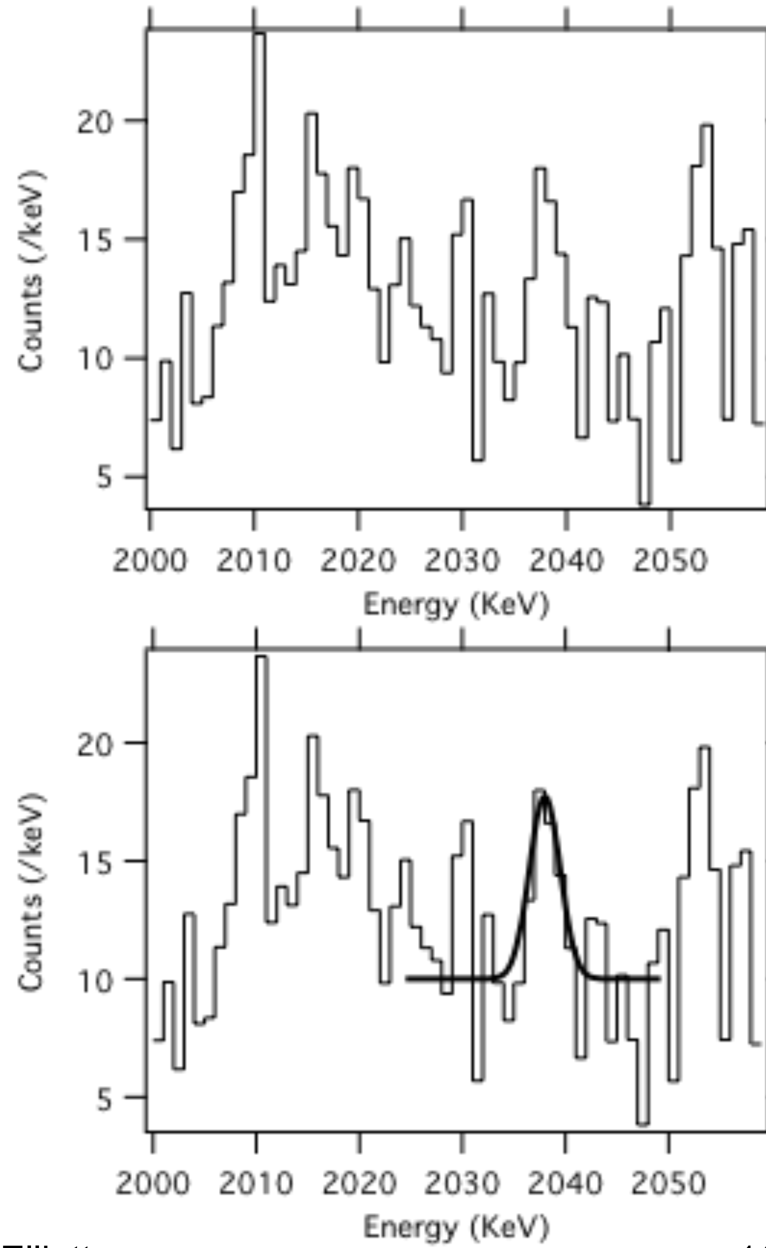
Historically, there are > 100 experimental limits on $T_{1/2}$ of the 0νββ decay.
Here are the records expressed as limits on $\langle m_{\beta\beta} \rangle$ using one set of nuclear matrix elements (RQRPA of Simkovic et al. 2009.)
Note the approximate linear slope vs time on such semilog plot.
However, during the last decade the complexity and cost of such experiments increased dramatically.
The constant slope is no longer maintained.

A Claim
has become a litmus test for future efforts

ββ is the search for a *very* rare peak on a continuum of background.

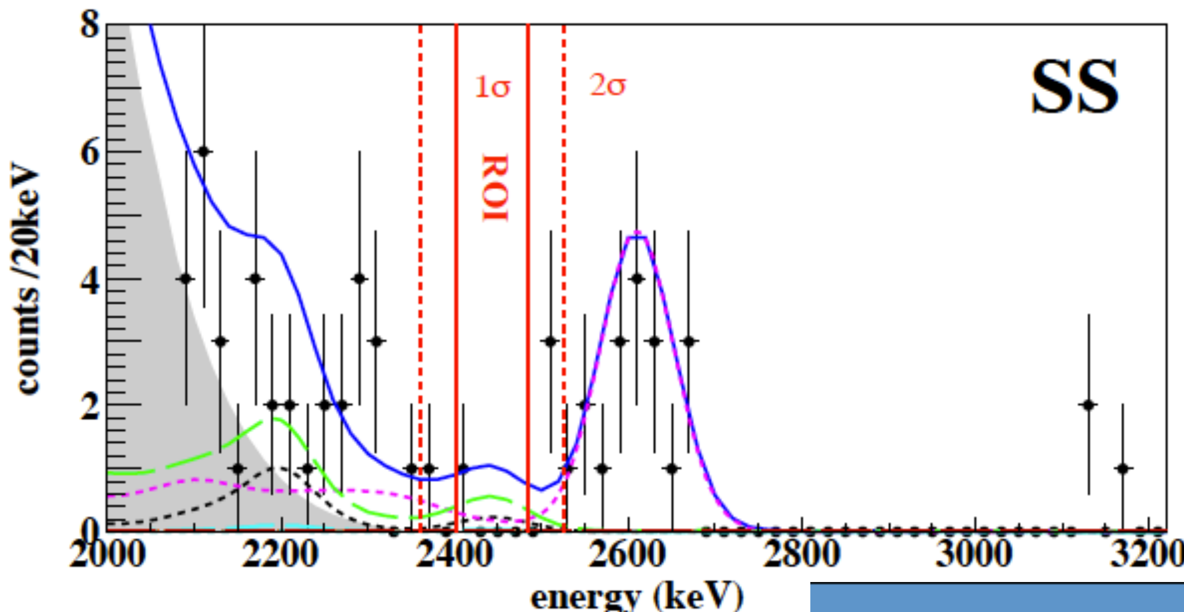
~70 kg-years of data
13 years

The "feature" at 2039 keV is arguably present.



NIM A522, 371 (2004)

EXO result



Joint analysis with KamLAND-Zen gives 3.4×10^{25} y, 120-250 meV

arXiv:1211.3863

$T_{0\nu} > 1.6 \times 10^{25}$ y
$m_{\beta\beta} < 140\text{-}380$ meV
120.7 days
79.4 kg ^{136}Xe
PRL 109, 032505

	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	

Feb. 26, 2013

Great Number of Proposed Experiments

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
LUCIFER	^{82}Se	18 kg	ZnSe scintillating bolometers	Development	Gran Sasso
DCBA	^{150}Nd	20 kg	^{150}Nd foils and tracking	Development	Kamioka
SNO+[9]	^{150}Nd	43.7 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
Quantum Dots[8]	Various		Quantum Dots with isotope in liq. Scint.	Development	

- Calorimeter
  - Semi-conductors
  - Bolometers
  - Crystals/nanoparticles immersed in scintillator
- Tracking
  - Liquid or gas TPCs
  - Thin source with wire chamber or scintillator

Experiments that will test claim in coming few years.

	Mass	Run Plan
CUORE	~200 kg	2014
EXO-200	~100 kg	2011
GERDA I/II	~34 kg	2011/2013
KamLAND-Zen	~125kg	2012
MAJORANA	~30 kg	2013
NEXT	~100 kg	2014
SNO+	~44 kg	2014
SuperNEMO Dem.	~7 kg	2013

Good guess that we'll reach about 100 meV in the 2013-2015 time frame.

Ton-scale projects might be starting by 2020.

The MAJORANA Collaboration

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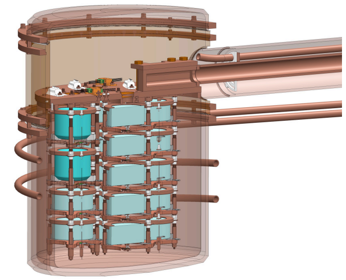
MAJORANA DEMONSTRATOR R&D Goals

- **Technical goals:**
  - –Demonstrate backgrounds low enough to justify building a tonne scale Ge experiment.
  - –Establish feasibility to construct & field modular arrays of Ge detectors.
  - –Minimize costs, optimize the schedule, and retire risks for a future 1-tonne experiment.
- **Science goals:**
  - –Although we are driven by technical goals, we also aim to extract the maximum science from the DEMONSTRATOR prototype,
    - Test the recent claim of an observation of $0\nu\beta\beta$ in ^{76}Ge.
    - Exploit the low-energy sensitivity to perform searches for dark matter, axions.
- **Work cooperatively with GERDA Collaboration toward a single international tonne-scale Ge experiment that combines the best features of MAJORANA and GERDA.**

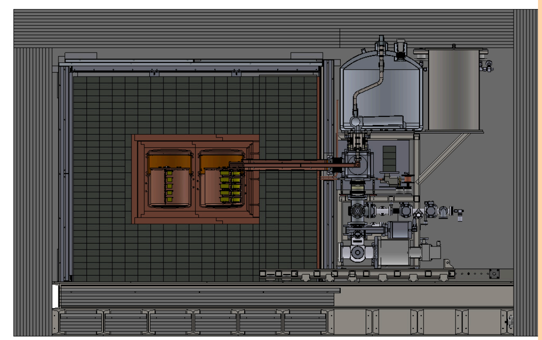
The MAJORANA DEMONSTRATOR Module

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

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- **40-kg of Ge detectors**
  - 30-kg of 86% enriched ^{76}Ge crystals required for science and background goals
  - Point-contact detectors for DEMONSTRATOR
- **Low-background Cryostats & Shield**
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto

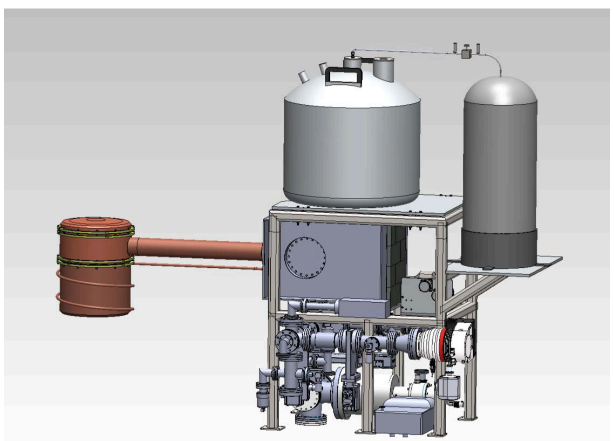


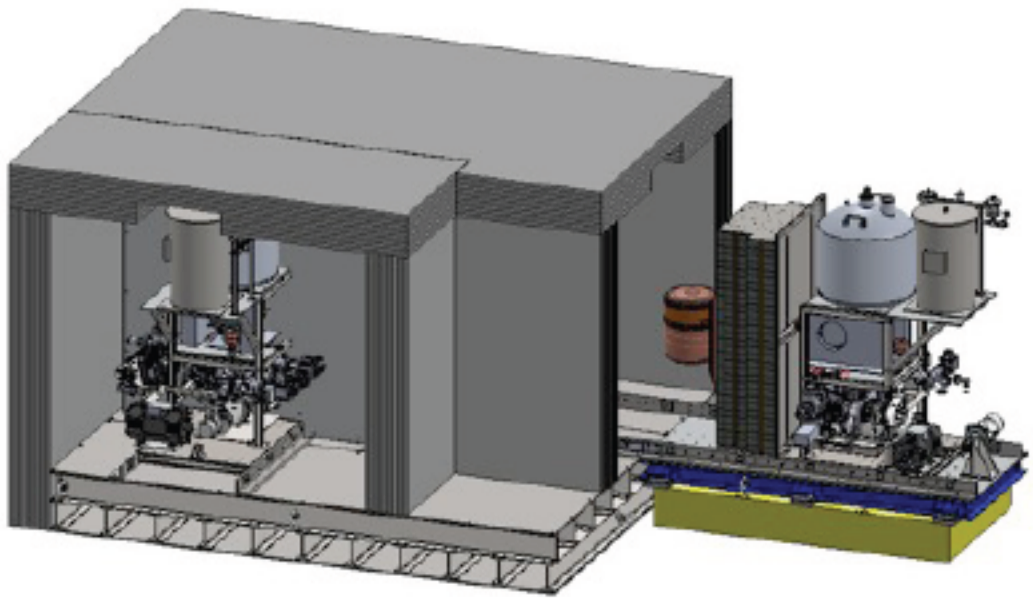
- **Located at 4850' level at Sanford Lab**
- **Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)**

~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

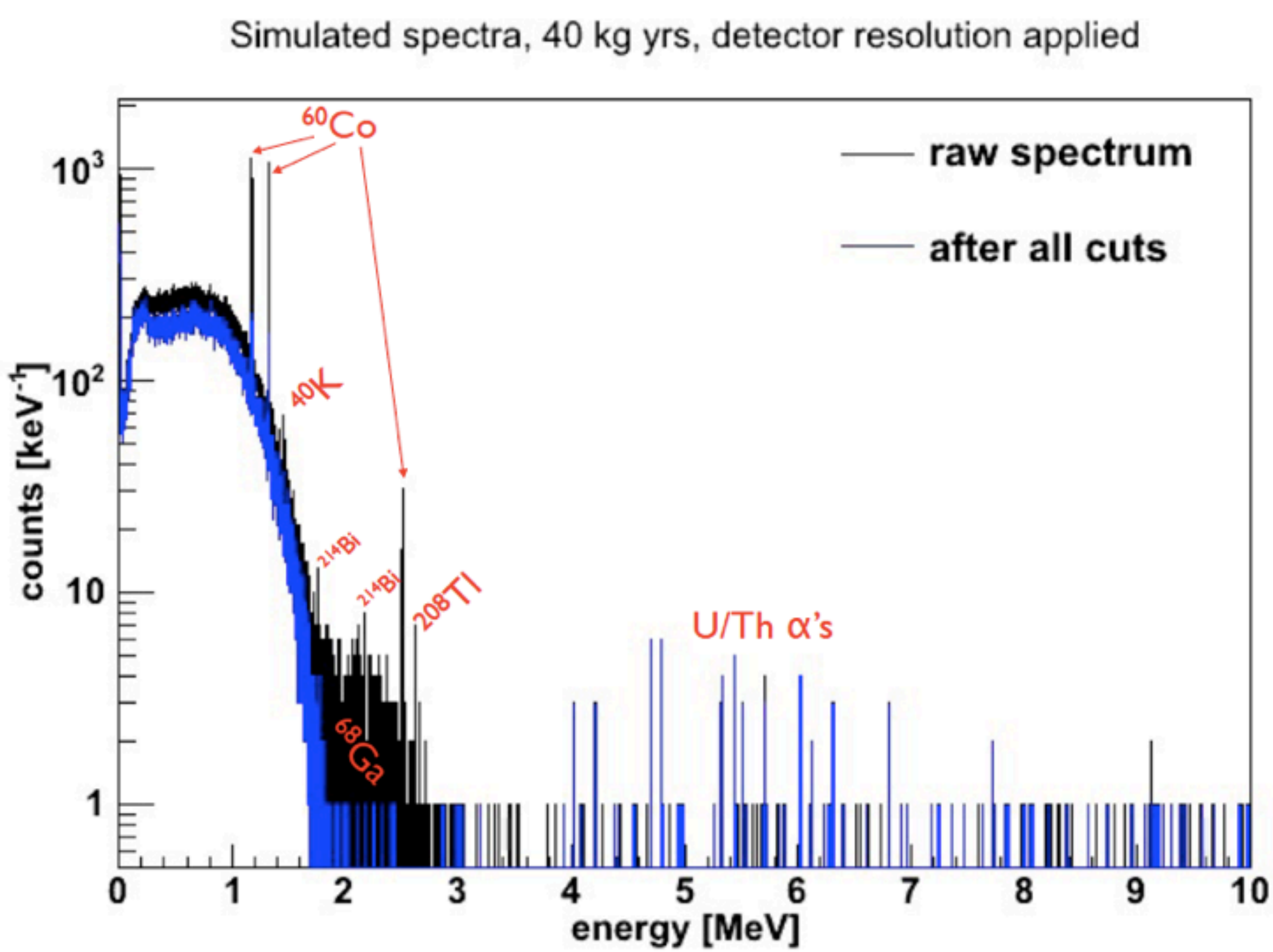
MJD Implementation

- **Three Phases**
  - **–Prototype cryostat (2 strings, ^{nat}Ge)** **(Spring 2013)**
  - **–Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge)** **(Late 2013)**
  - **–Cryostat 2 (up to 7 strings ^{enr}Ge)** **(Fall 2014)**

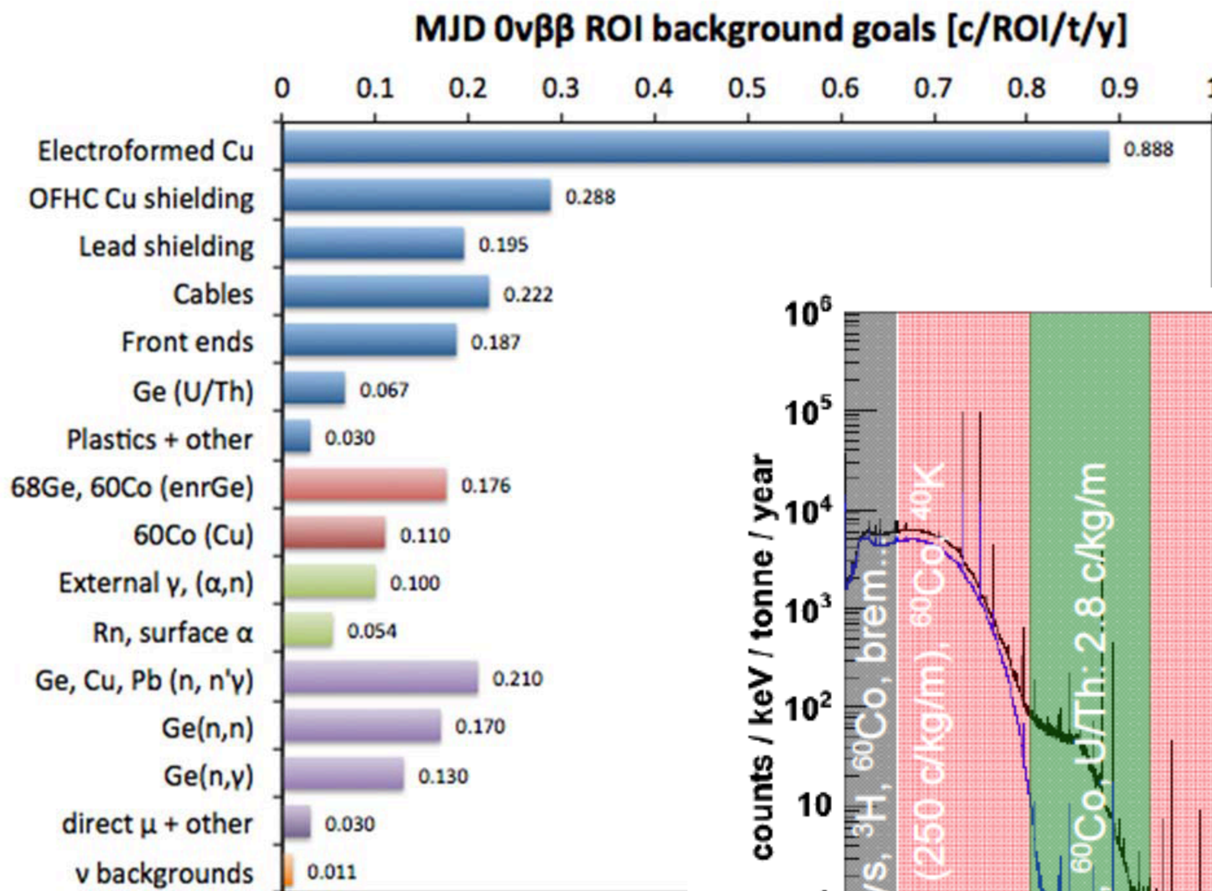


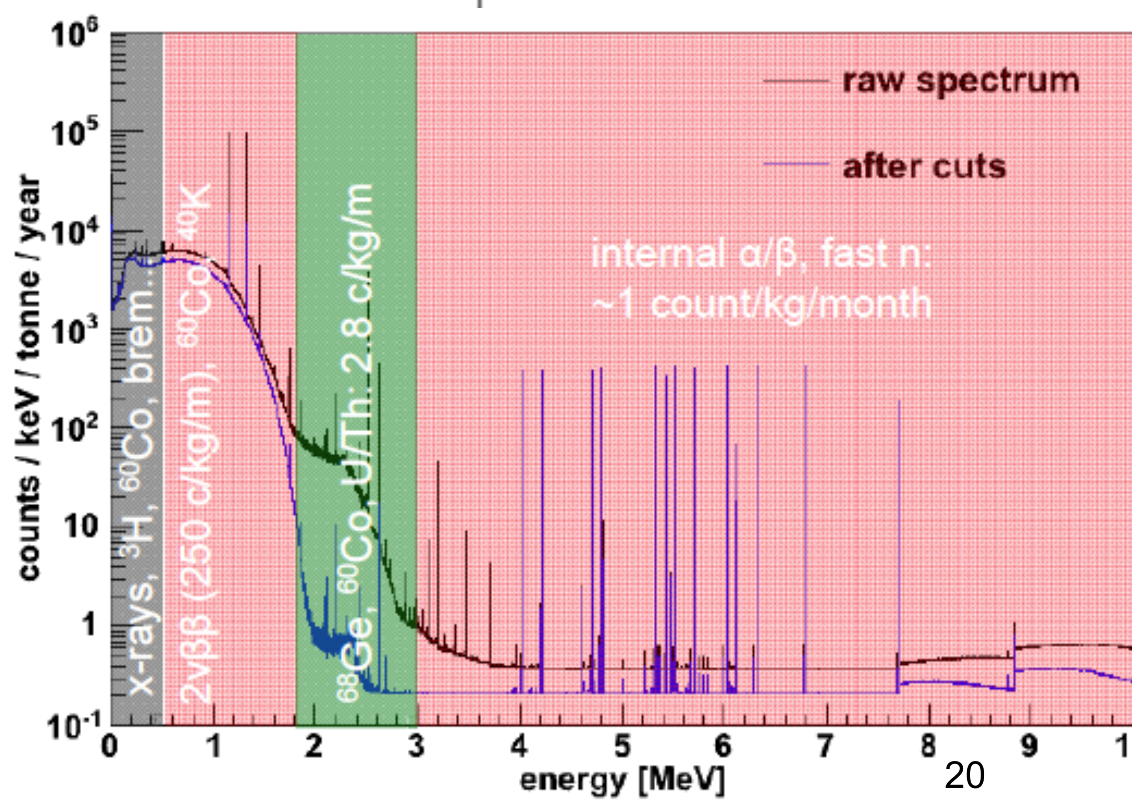


Simulation: MJD 0-10 MeV

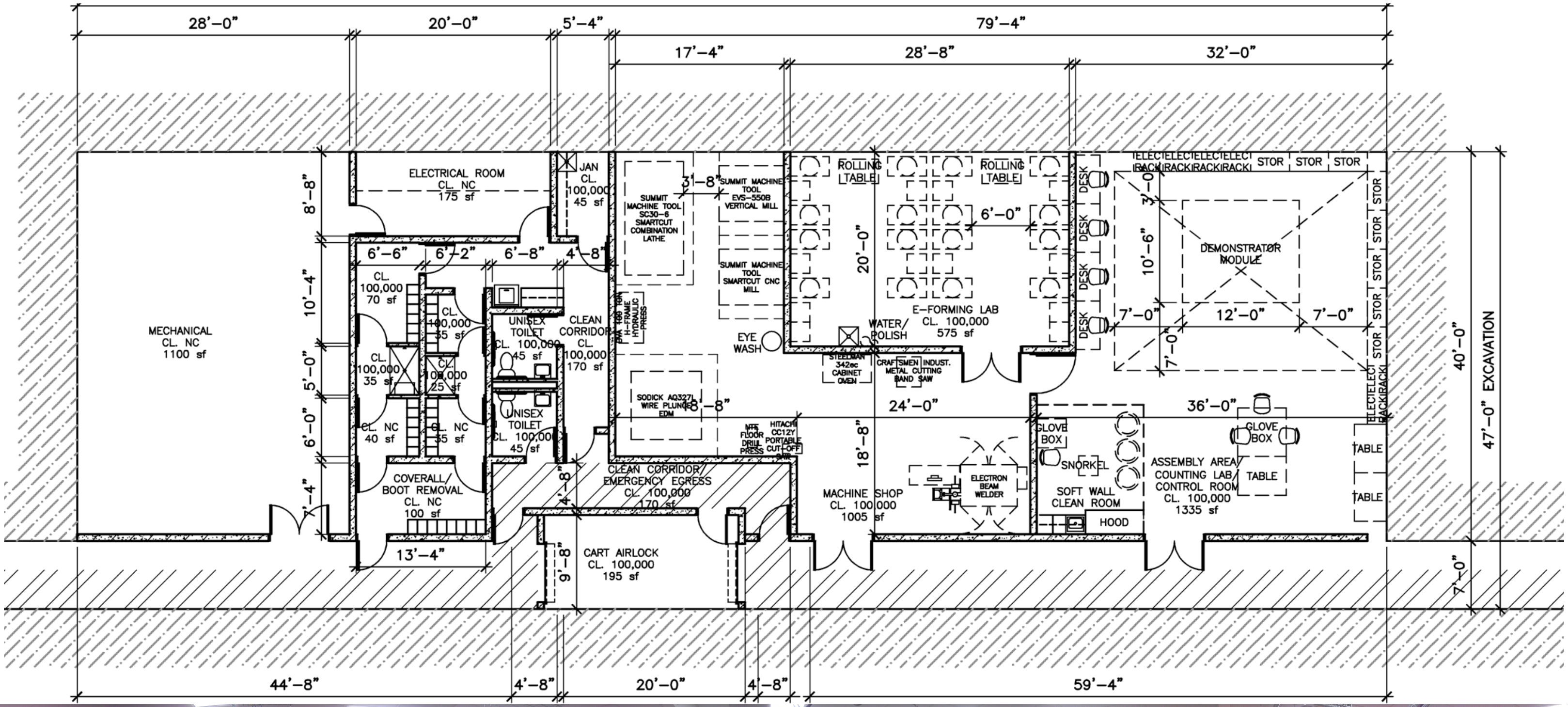


DEMONSTRATOR Background Model

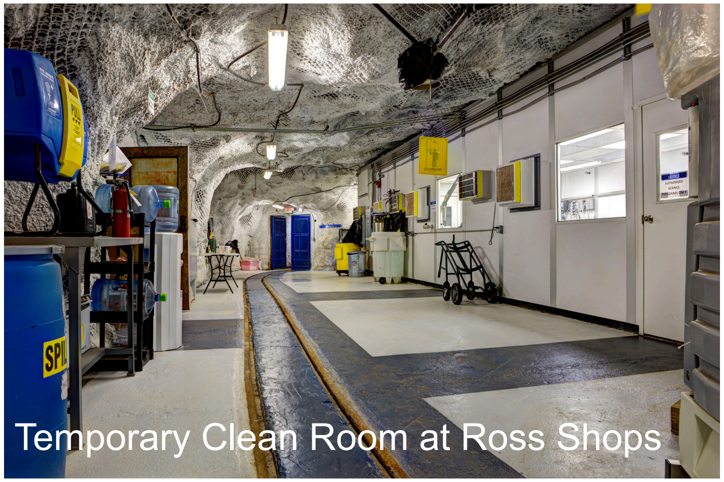




Underground Laboratory

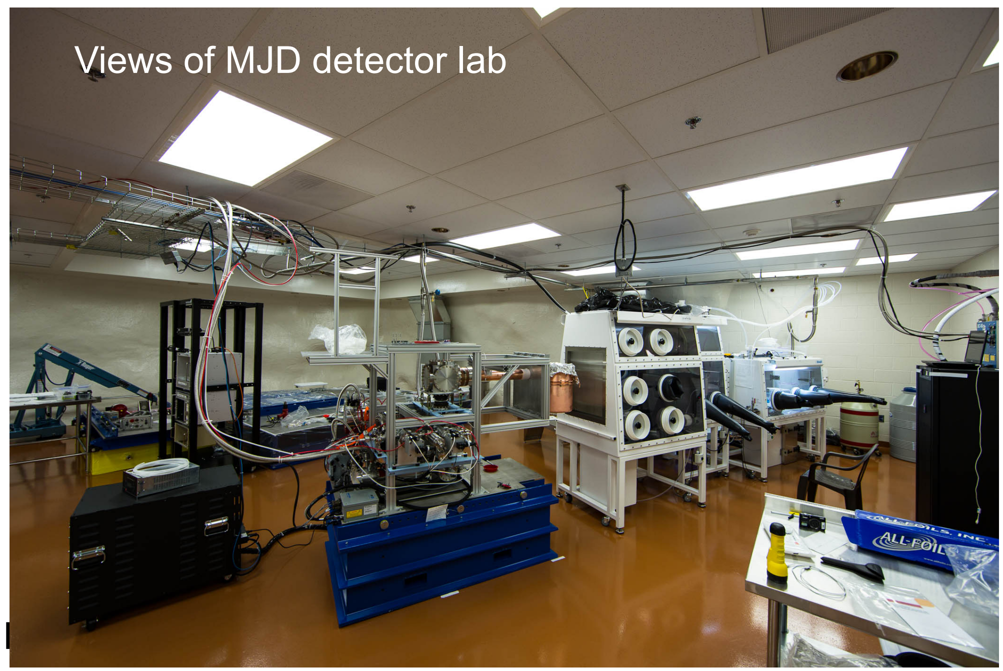


Underground Lab - Status



Temporary Clean Room at Ross Shops

- Eforming lab operational since summer 2011
- Davis Campus lab outfitting finished
- Shield floor, LN system, assembly table, air bearing system, glove boxes, localized clean space all installed

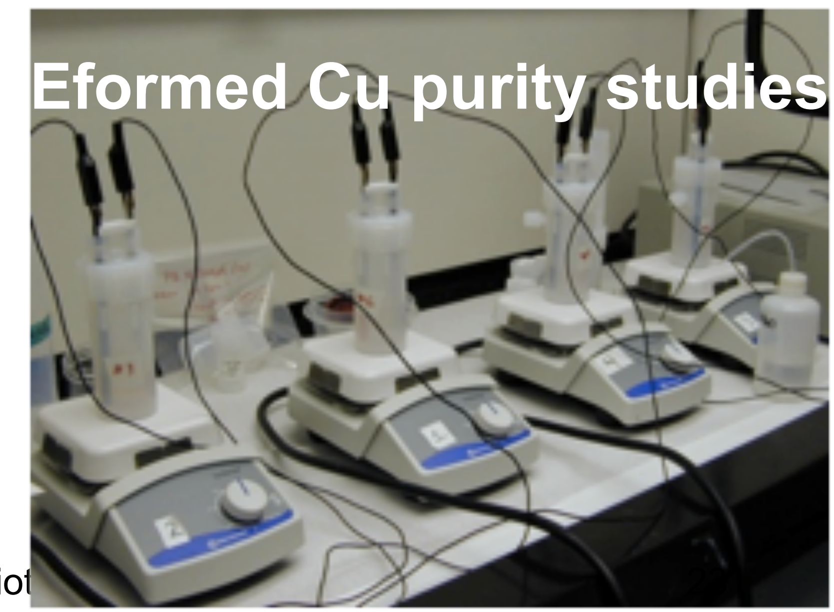


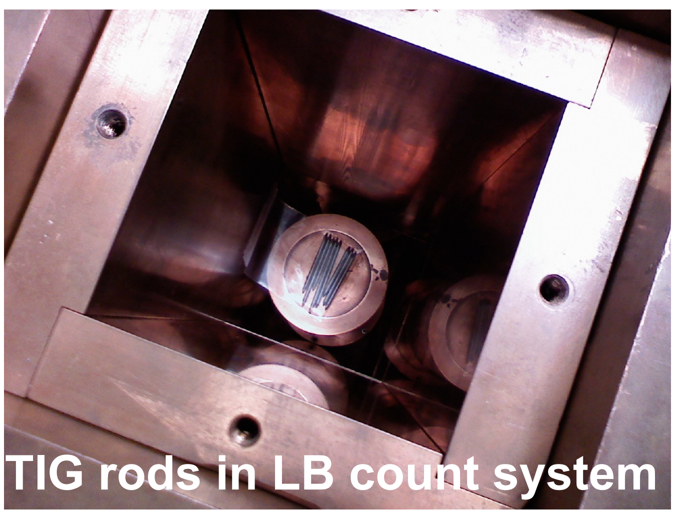
Views of MJD detector lab

Materials and Assay

- Significant R&D and advances made in improvement of ICP-MS sensitivity for U and Th in copper approaching sub μBq/kg level.
- Monitoring U and Th in copper baths electolyte.
- All plastic materials selected after high sensitivity NAA analysis. Assay complete.
- Significant progress made in development of low background front-end electronics.


Plastics for NAA analysis


Eformed Cu purity studies


TIG rods in LB count system

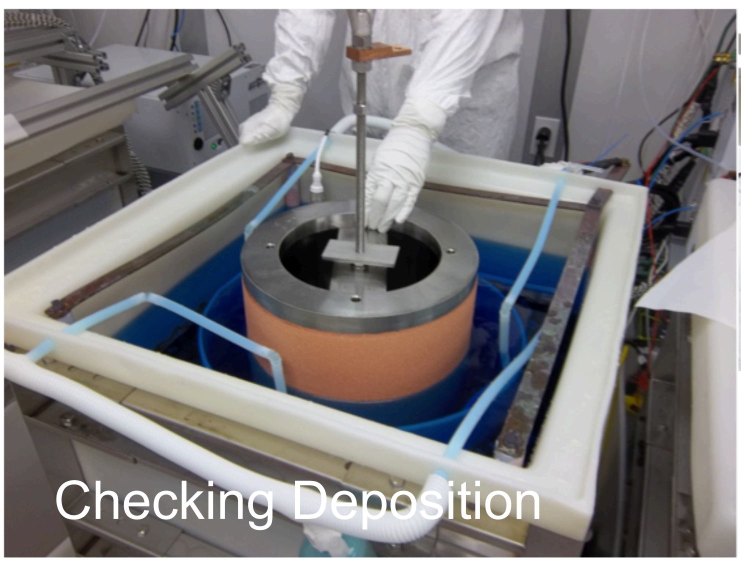
Electroforming


Installation of mandrel in bath

- Eforming at PNNL and at 4850’ at SURF
- Machine shop operational


Copper ready to cut


EDM installed UG


Checking Deposition


Bake/Quench


Lathe installed UG

ORNL - Elliott

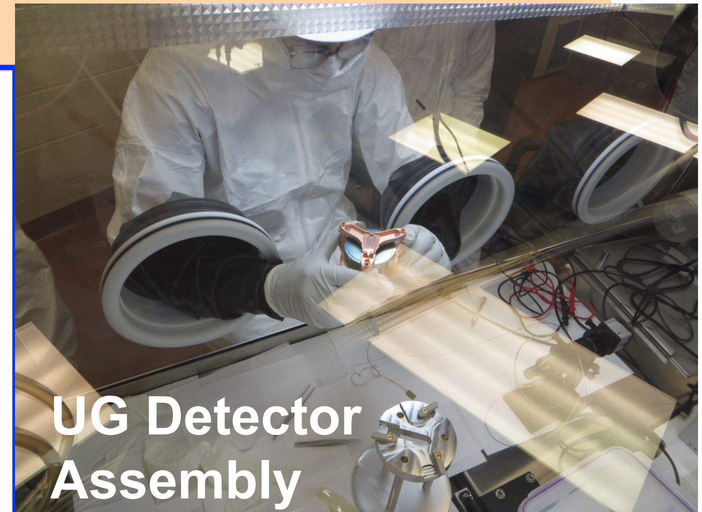
Enriched Ge

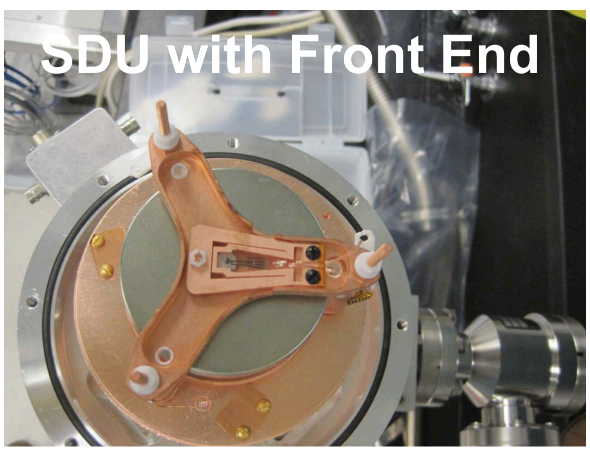
- 42.5 kg ^{enr}Ge received as oxide and stored UG in Oak Ridge
- 4-5 kg Russian contribution

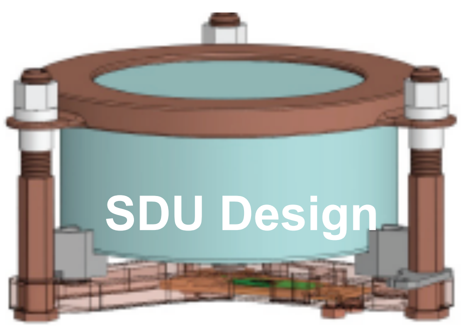
	Specs	ECP	ORNL Physics (Sample 1)	ORNL CSD (sample 2)	PNNL (Sample 3)
^{76}Ge	≥86.0	87.67	86.9 (2)	87.9 (9)	88.2 (3)
^{74}Ge		12.16	12.5 (1)	12.0 (1)	11.8 (3)
^{73}Ge		0.07	< 0.2	0.052 (1)	0.04 (2)
^{72}Ge		0.05	<0.2	0.0058 (3)	0.02 (1)
^{70}Ge	≤0.07	0.05	<0.2	0.0157 (3)	0.005 (4)

Detectors

- 20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 dets. UG).
- ORTEC selected to produce enriched detectors. Excellent projected yield.
- First enriched detectors (5) delivered UG in February 2013.



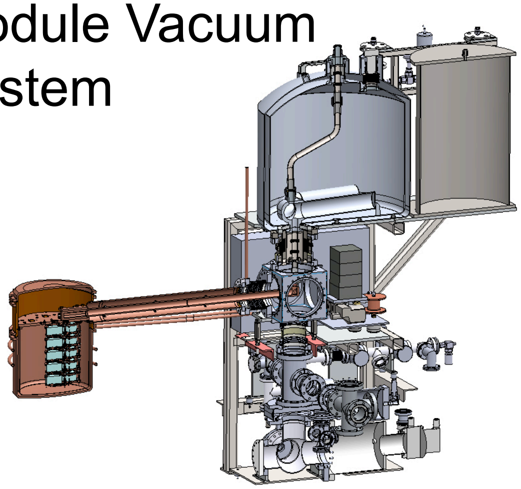




Modules

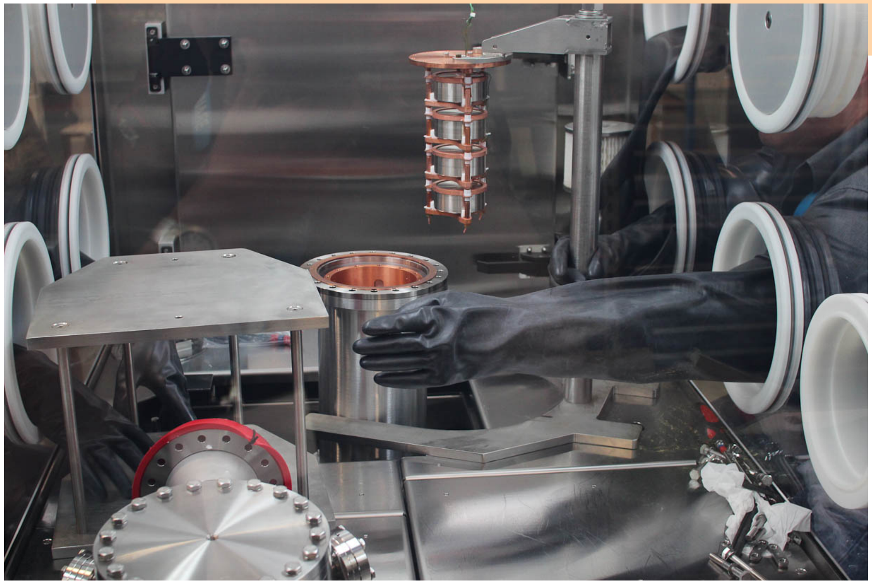
- Prototype cryostat being fabricated and assembled. E-beam welds completed
- Thermosyphon design validated. Fabricated and tested.
- Prototype vacuum system designed, reviewed, assembled, and being operated.
- String test cryostats built.
- Parts and material tracking in place.
- Clean machining implemented underground.

Module Vacuum System

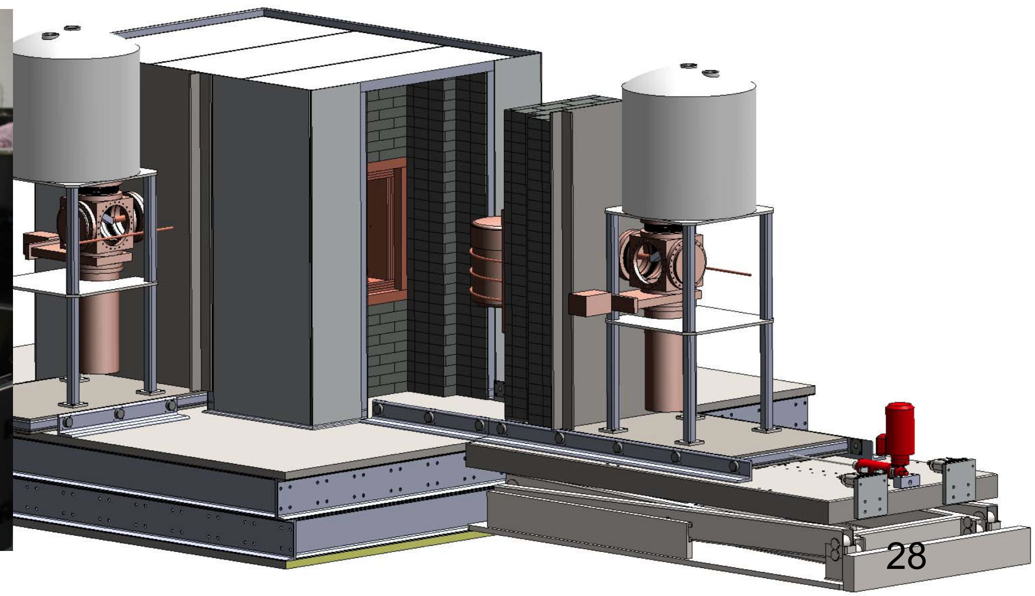


Prototype Module Vacuum System

Mechanical Systems

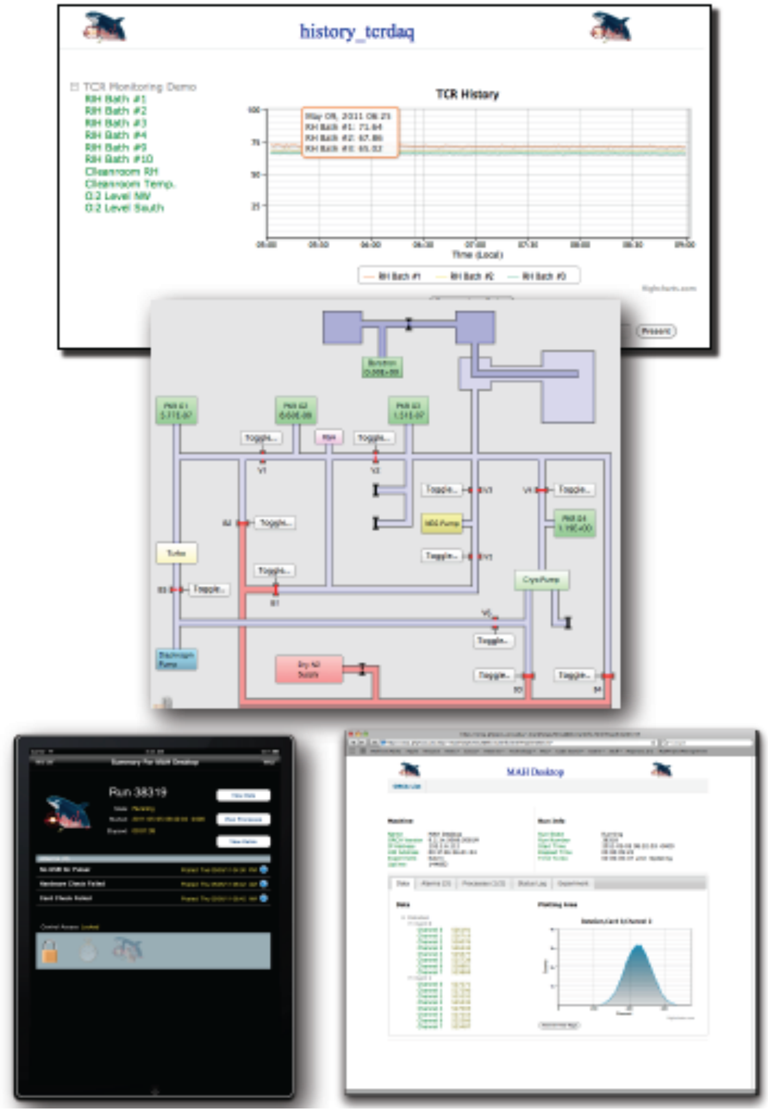


- Glove box (Mbraun) underground.
- Hovair delivered and tested.
- Overfloor installed UG.
- Majority of shielding material in hand, some is underground.
- Prototype calibration system demonstrated.



Data Acquisition

- Slow controls fielded and in operation in TCR and Davis campus Prototype cryostat vacuum system in operation.
- Low sub-keV threshold digital system operating for MALBEK.
- The DAQ software and hardware is up and running and in continuous use in test stands at UNC, PNNL, LBNL, LANL, and UW.
- Detector acceptance and characterization systems operating at SURF.
- Tablet and smart phone support.



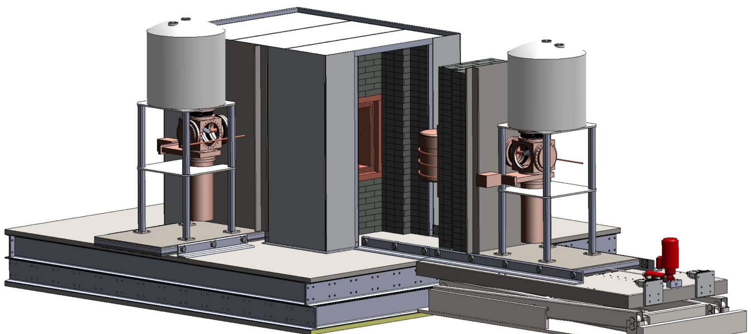
MJD Overview

- Assembly and construction proceeding at Sanford Davis Campus laboratory.
- Based on assays, material backgrounds projected to meet cleanliness goals.
- EF copper being produced underground at SURF and PNNL
- Successful reduction and refinement of first 20 kg of ^{enr}Ge with 97.3% yield. Second batch purification underway.
- Detector vendor AMTEK (ORTEC) has produced detectors from the reduced/refined ^{enr}Ge. 5 underground at SURF.

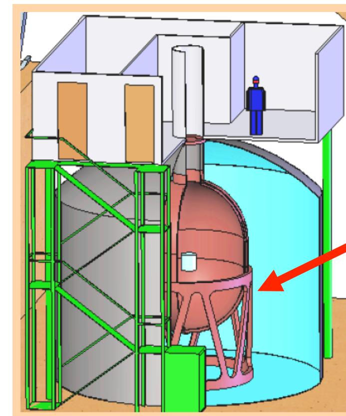
Schedule
– Prototype Cryostat – Spring 2013
– Cryostat 1 – Late 2013
– Cryostat 2 - Fall 2014

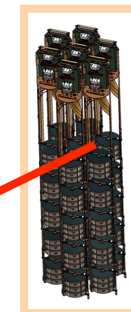
Towards 1TGe

MAJORANA



GERDA





- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~40 kg (up to 30 kg enr.)

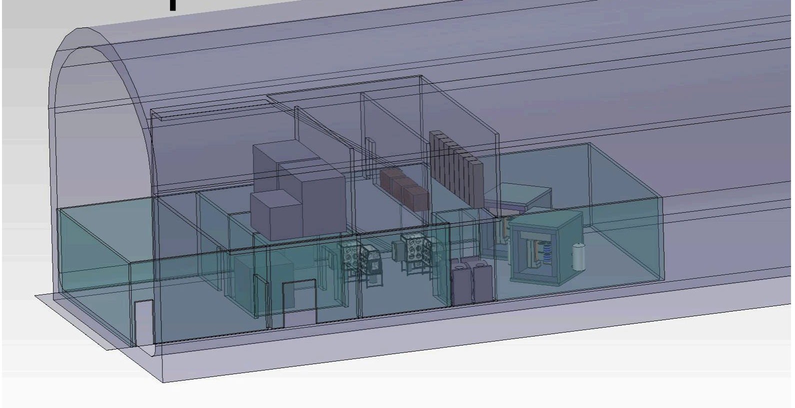
- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I (2012): ~18 kg (HdM/IGEX diodes)
- Phase II (2013): add ~20 kg new detectors - Total ~40 kg

Joint Cooperative Agreement:

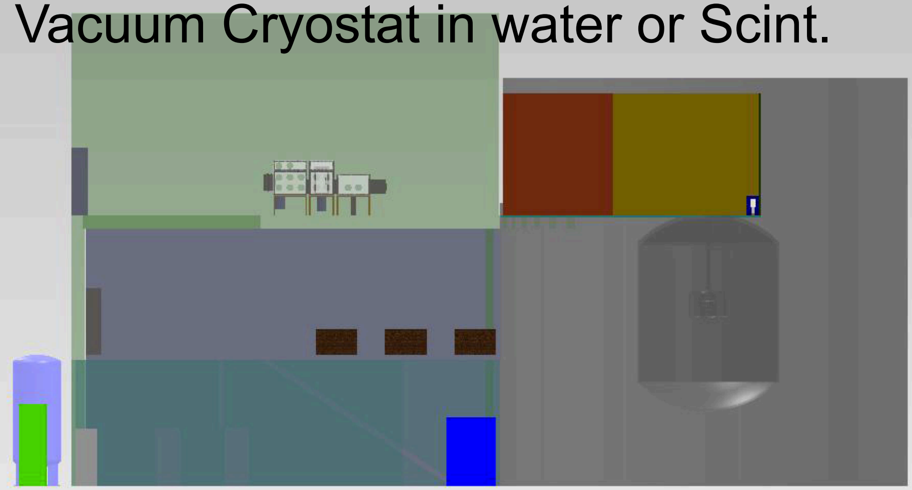
- **Open exchange of knowledge & technologies (e.g. MaGe, R&D)**
- **Intention is to merge for tonne-scale experiment. Select best techniques developed and tested in GERDA and MAJORANA**

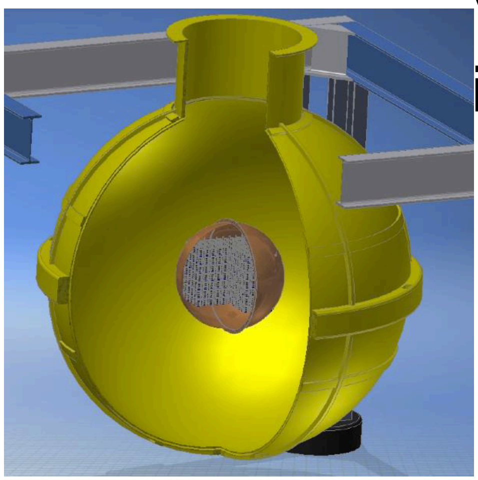
Alternative Shield Concepts

Compact Shield

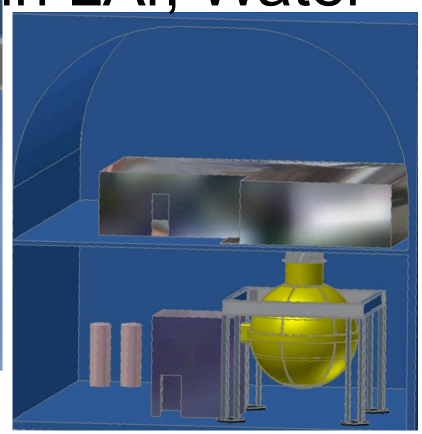


Vacuum Cryostat in water or Scint.

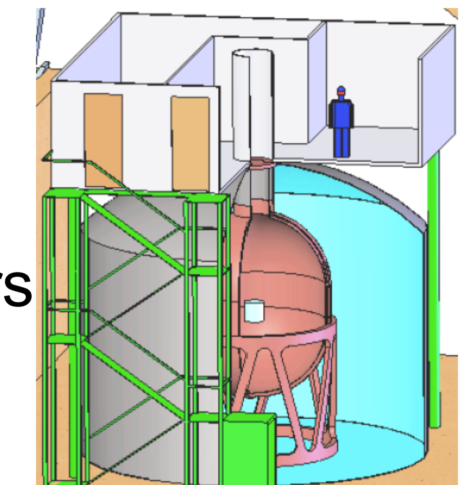




Vacuum Cryostat
in LAr, Water

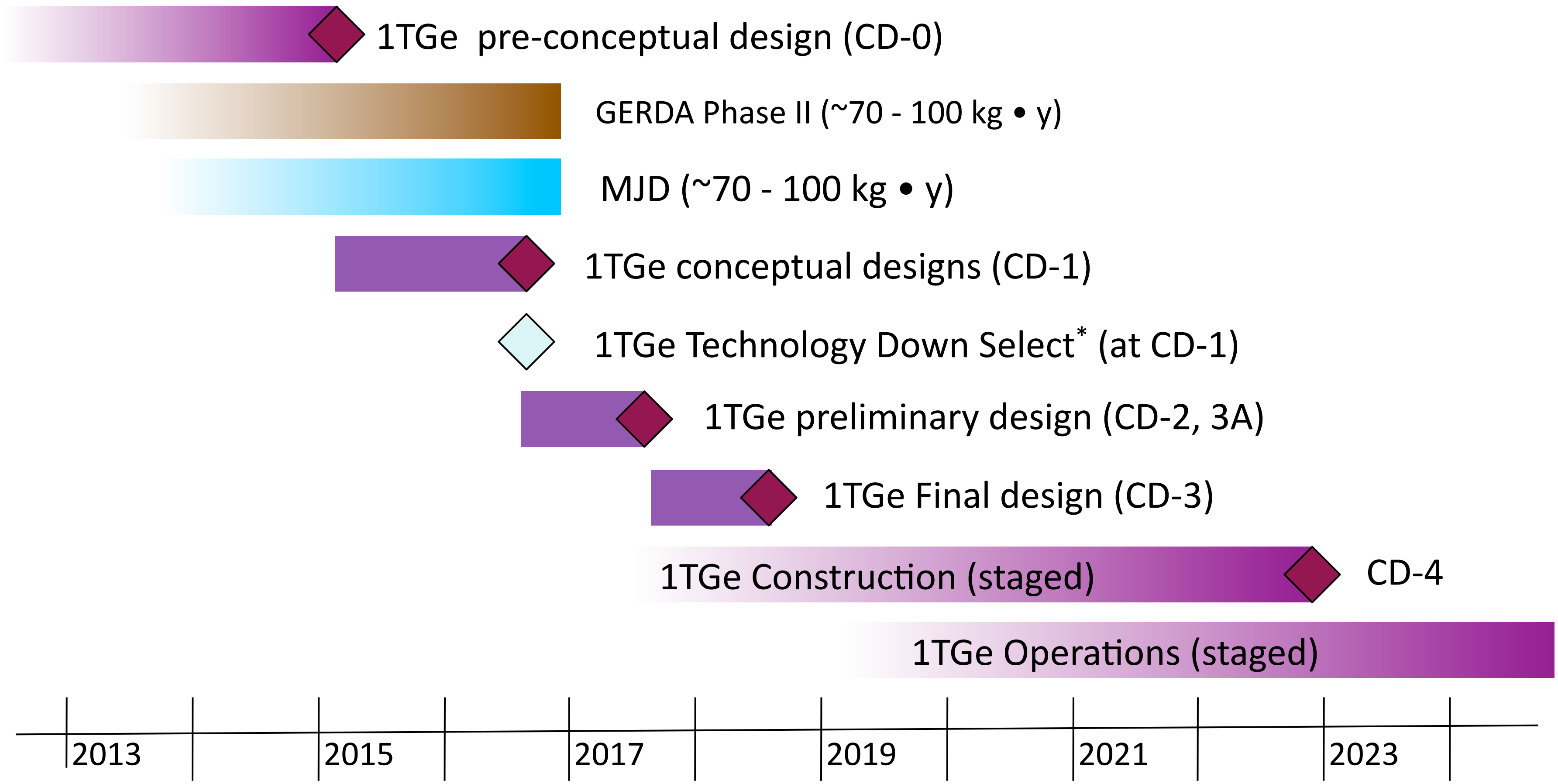


Bare Detectors
in LAr, Water



1TGe Projected Timeline

Technically Driven



✳ Technology down select will be based on 1TGe R&D, GERDA Phases I and II, and MJD.

Plan for Tonne Scale

- Its time to start thinking about the design concepts for a large $\beta\beta$ expt.
- Proceeding to a large scale experiment will build on MJD and GERDA experience.
- The choice of the technology will be based on science reach, ease of implementation, available lab space and cost.
  - The 1TGe R&D effort is beginning the groundwork in preparation for the technical down-select.
- There is still R&D to be done.

Observation of $\beta\beta(0\nu)$ implies massive Majorana neutrinos, but:

- **Relative rates between isotopes might discern light neutrino exchange and heavy particle exchange as the $\beta\beta$ mechanism.**
- **Relative rates between the ground and excited states might discern light neutrino exchange and right handed current mechanisms.**

Effective comparisons require at least experimental measurements with uncertainties small wrt theoretical uncertainties.

Discovery vs. Measurement

a future decision point

Expt. Size: up to 10 kg
Sensitivity: ~1 eV
~10 $\beta\beta(2\nu)$ measurements

Expt. Size: 30-200 kg
Sensitivity: ~100 meV
Quasi-degenerate
~8-10 expts. worldwide

If $\beta\beta$ obs.

Expt. Size: 100-200 kg
Several experiments
Program to measure
rate in several isotopes

Expt. Size: ~1T
~3 expts.
Sensitivity: 50 meV
Atmos. scale

If $\beta\beta$ obs.

Expt. Size: few T
>3 experiments
Program to measure
rate in several isotopes
Kinematic meas.

Expt. Size: > 10T
~3 expts.
Sens.: 5 meV
Solar scale

1985- Present | 2007-2015 | 2015- 2025 | Future

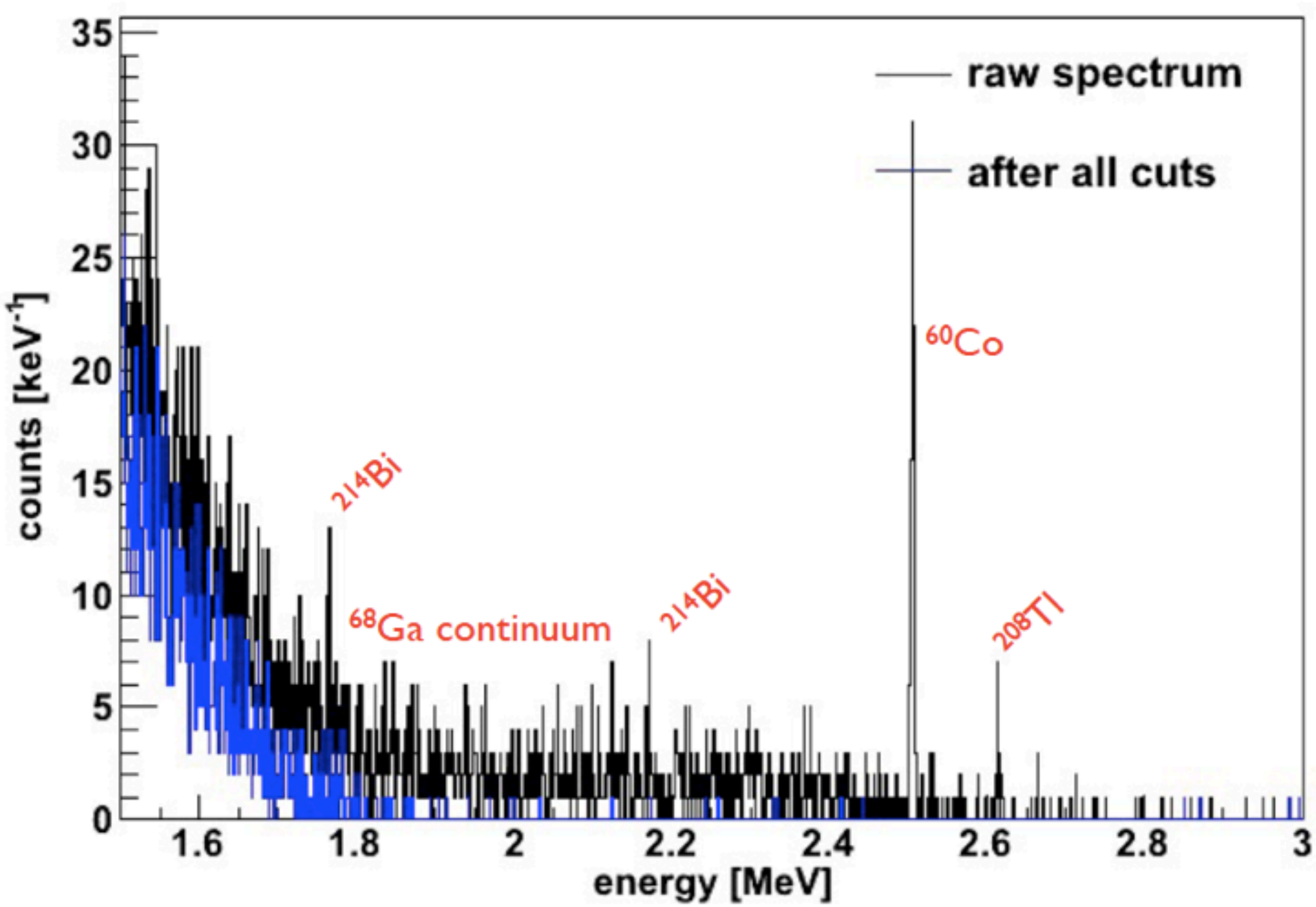
Take-Home Message

- **Due to the minimum neutrino mass scale implied by the neutrino oscillation experiments:**
  - **–The next generation ββ experiments have a good possibility of reaching an exciting $<m_{\beta\beta}>$ region.**
- **The MAJORANA DEMONSTRATOR is making strong progress**
  - **–Enriched material order**
  - **–Detector contract in place**
  - **–Lab ready to go**
- **A large scale experiment will be proposed and R&D is beginning.**

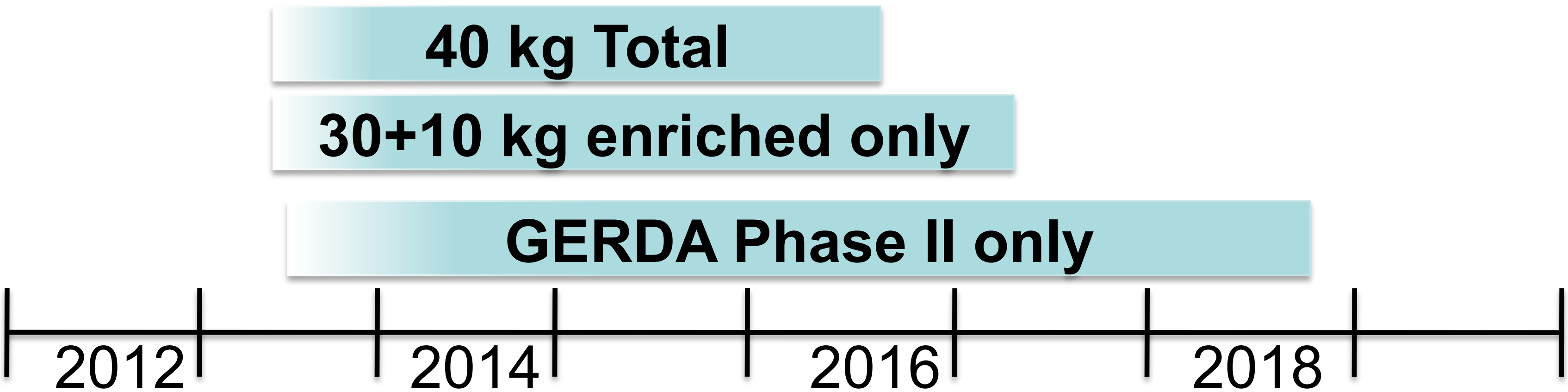
EXTRAS

Simulation: MJD 1.5 – 3.0 MeV

Simulated spectra, 40 kg yrs, detector resolution applied



Time to 100 kg-y



With 30 kg enriched and 10 kg natural, we are competitive with GERDA Phase II in total exposure.

GERDA Phase II anticipates a background level near the 1 count/t-y that we hope to demonstrate with MJD. This is necessary for the tonne-scale and both schedules are comparable.

Large-Scale Experiment R&D
Generically referred to as 1TGe

- **Materials & Assay R&D**
  - –Alternative Clean Materials
  - –Improved Assay of Cu
  - –Recycling Ge
- **Detector Studies**
  - –Advanced Detector Designs
  - –Spatial Resolution
  - –Detector Contacts
- **Small Parts Near Detectors**
  - –Paired Detectors
  - –Long String Designs
  - –Cables
- **Shielding Schemes**
  - –Cryostat in Liquid Arrangement
  - –Required Experimental Depth
- **Operating Schemes**
  - –Modular Phasing
  - –Cooling
- **Fabrication Techniques**
  - –Automated assembly
  - –Glove Boxes

Solar Scale: Showstoppers?

- Need 100 tons of isotope
  - –Enrichment costs and production rates are not sufficient yet
  - –Requires R&D to improve capability
- Need excellent energy resolution
  - –Better than 1% FWHM
  - –An experiment with 10^6 solid state detectors is possible
    - Cost/detector will need to be greatly reduced
    - Large multi-element detector electronics are improving
  - –Metal loaded liquid scintillator or Xe techniques
    - Scales more easily and cost effectively
    - Resolution requires R&D

Large-Scale Ge ββ Experiment

- Performing longer-term R&D, engineering studies, facilities planning, and costs & schedule estimates.
- Support from NSF S-4 grant, NSF PA & DOE NP program grants, Max Planck Society.
- Utilizes and builds on major R&D activities related to GERDA and MAJORANA Collaborations.
- Investigating a range of shield designs between the compact and the GERDA like. Ultimate design will be based on results from GERDA Phases I & II and the MAJORANA DEMONSTRATOR.
- Assumes that GERDA and MJD demonstrate feasibility.