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

Overview of current and proposed searches for double-beta decay*

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Overview

- Theoretical Motivation
- US/Canadian-based efforts:
  - MAJORANA
  - EXO
  - SNO+
  - CUORE/NEMO

Flavor Mixing

Mass eigenstates different than flavor eigenstates.

$\Rightarrow$ Propagating neutrinos undergo flavor oscillations.

Mass to flavor relationship described by neutrino mixing matrix with 5 parameters.

$$\theta_{12} \approx 30^\circ \quad \delta = ?$$
$$\theta_{23} \approx 45^\circ \quad \alpha_i = ?$$
$$\theta_{13} < 10^\circ$$

CP Phase

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\,\theta_{ij} \quad s_{ij} = \sin\,\theta_{ij}$

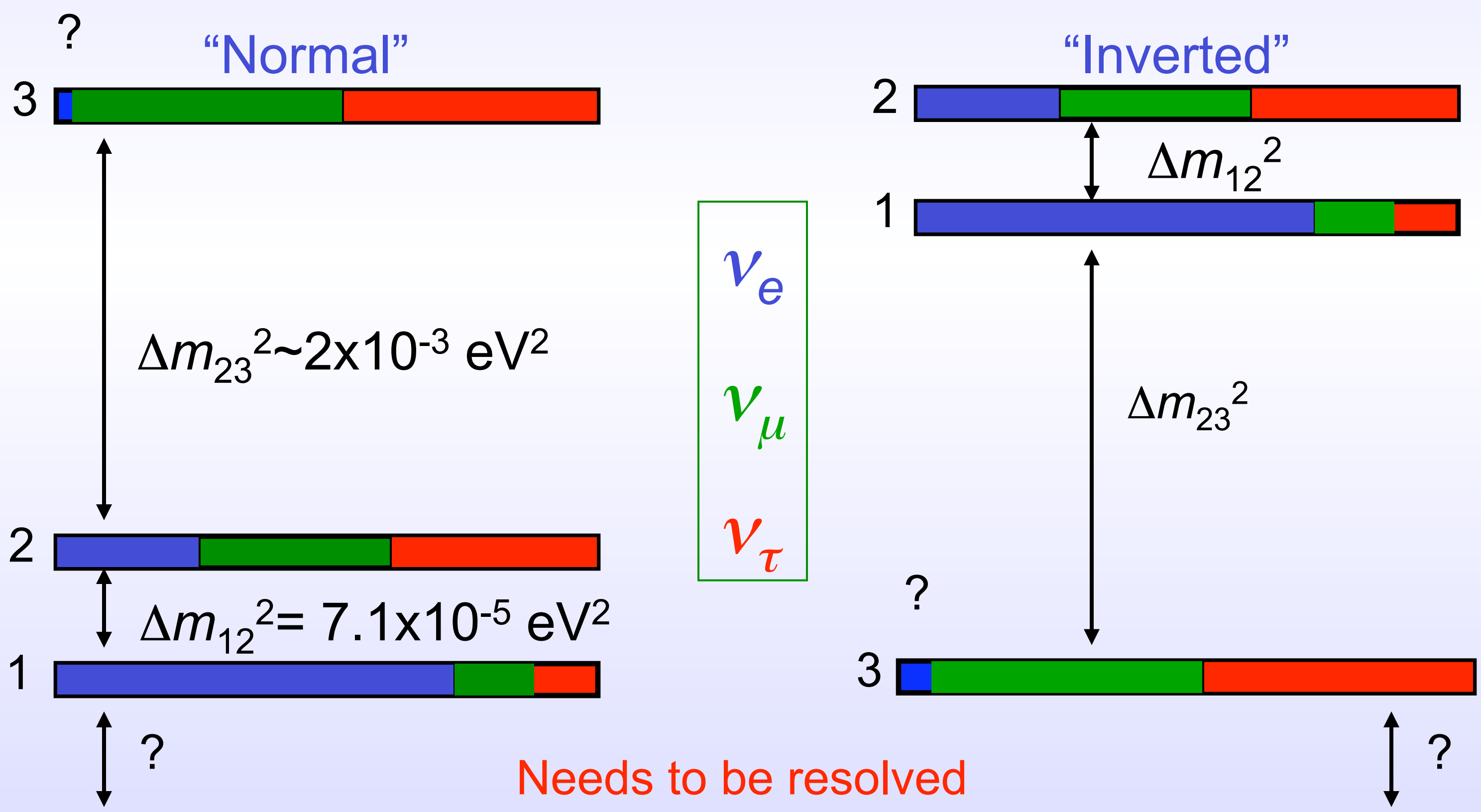
Majorana Phases

Neutrino Masses

Absolute masses weakly constrained, < 1eV.

Relative mass-squared differences known.

Three possible scenarios: Quasi-degenerate, also:



Majorana vs. Dirac

Majorana particles are their own anti-particles.

Dirac particles are not.

No fermions are known to be Majorana.

Experimental evidence consistent with both Majorana or Dirac neutrinos.

Verification difficult due to small neutrino masses and handedness of weak interaction.

Ettore Majorana

Paul Dirac

Neutrinoless double-beta decay is the only practical process that can resolve this mystery.

What is neutrinoless double-beta decay ($0\nu\beta\beta$)?

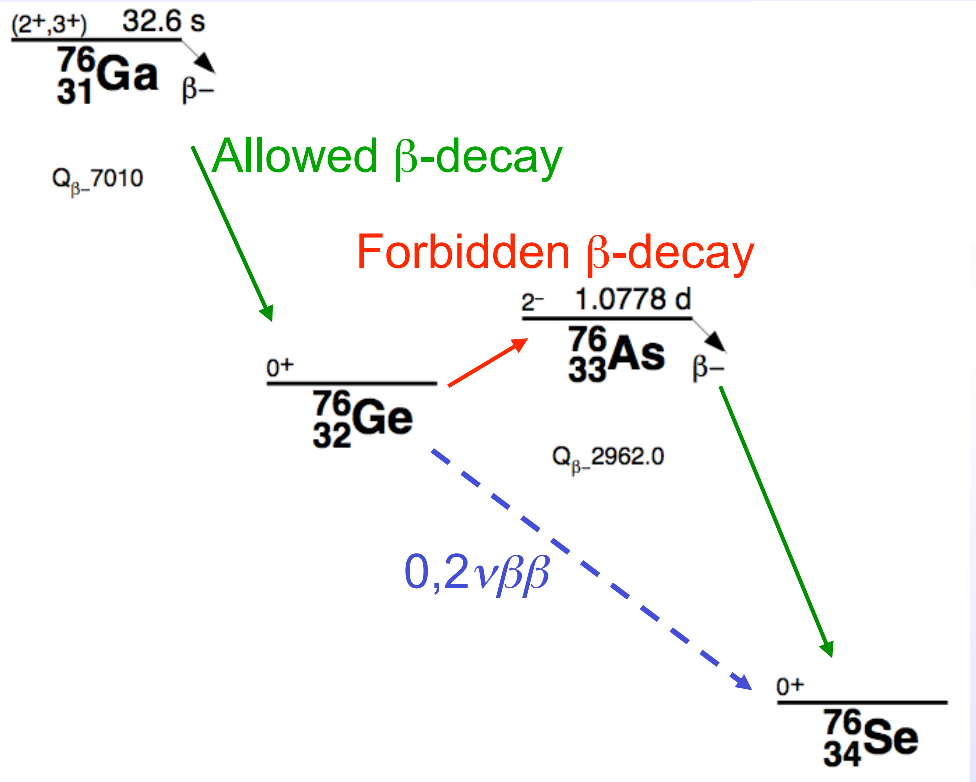
$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-}$$

Energetically allowed in many nuclei.

Prefer nuclei stable against β-decay (about 30)

$2\nu\beta\beta$: Observed 2nd order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-} + 2\bar{\nu}_e$$



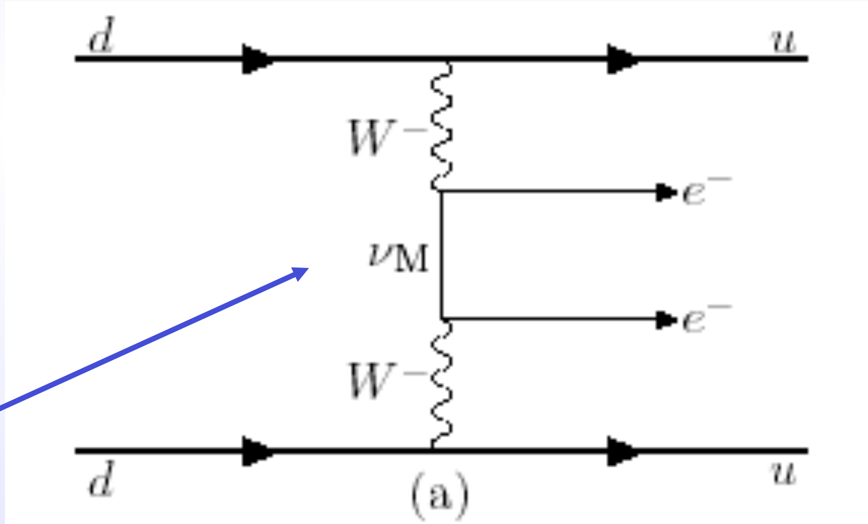
History

- **1935**: Double beta decay postulated by Maria Goeppert-Mayer (assist by Wigner) *Phys. Rev. 48 (1935) 512*
- **1937**: Ettore Majorana formulates theory with no distinction between ν and anti-ν. *Nuovo Cimento 14 (1937) 171*
- **1937**: Giulio Racah suggests zero-neutrino double-beta decay as test for Majorana's theory. *Nuovo Cimento 14 (1937) 322*

Motivation for $0\upsilon\beta\beta$ Search

Majorana

- Implications of discovery:
  - Neutrino is Majorana* (own antiparticle)
  - Total lepton number is not conserved
  - Neutrino has mass* (known)
  - Absolute neutrino mass.
- $0\upsilon\beta\beta$ nuclear decay may occur via several processes (SUSY, RH currents,…)
- Canonical example: Exchange of virtual neutrino



* Schechter et al, Phys. Rev. D**25**, 2951 (1982)

$0\nu\beta\beta$ Rate and Neutrino Mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0, Z)\left|\langle m_{\beta\beta}\rangle\right|^2\left|M^{0\nu}\right|^2$$

$T_{1/2}^{0\nu}$: Half-life

$G^{0\nu}$: Phase Space (Known)

$M^{0\nu}$: Nuclear Matrix Element (large uncertainty)

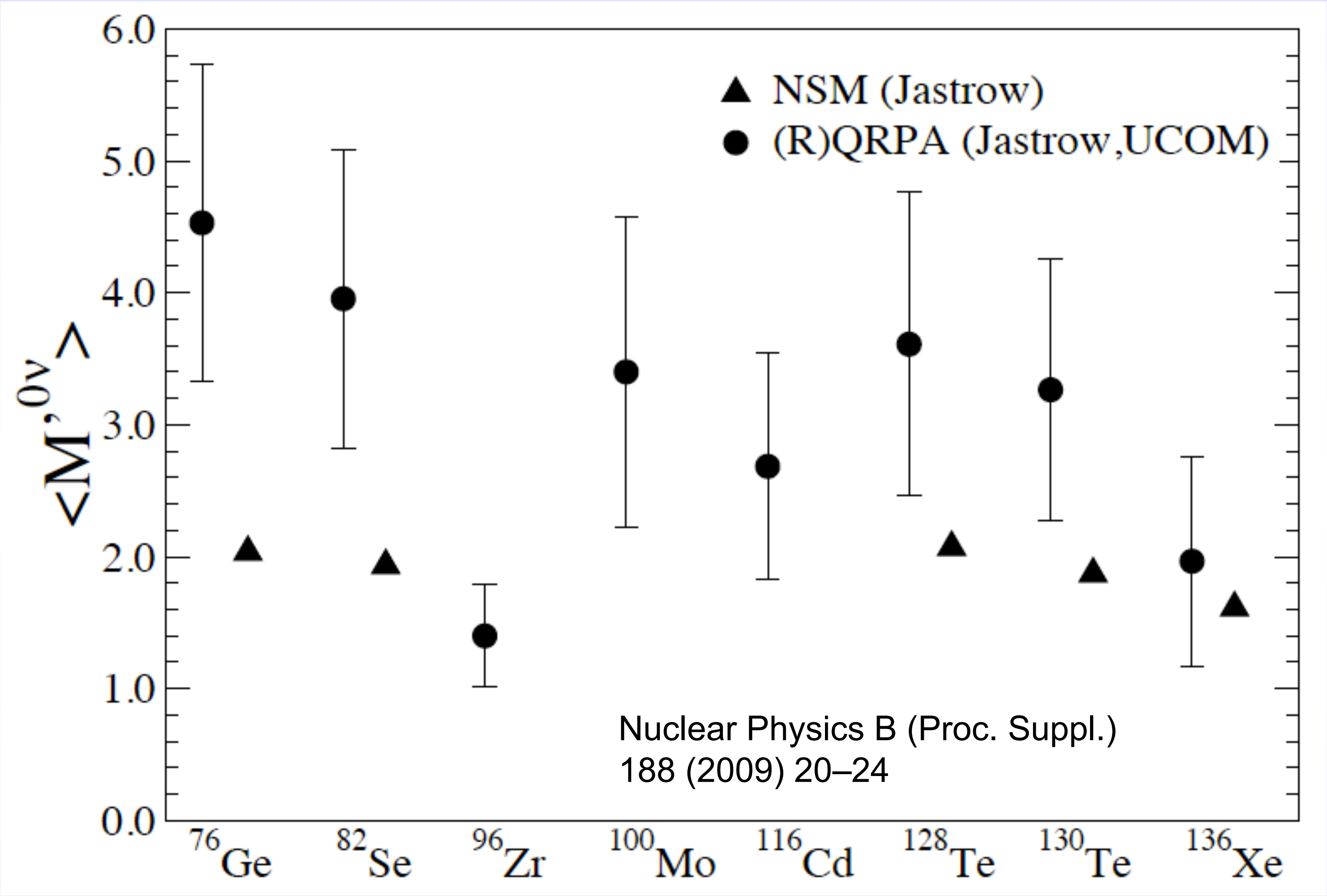
$$\left|< m_{\beta\beta} >\right| = \left|\sum_i \left|U_{ei}\right|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

Effective Majorana electron neutrino mass*

- ☞ $0\nu\beta\beta$ decay can probe **absolute** neutrino mass scale and mixing.
- ☞ Current neutrino experiments measure mass squared differences: Δm^2.

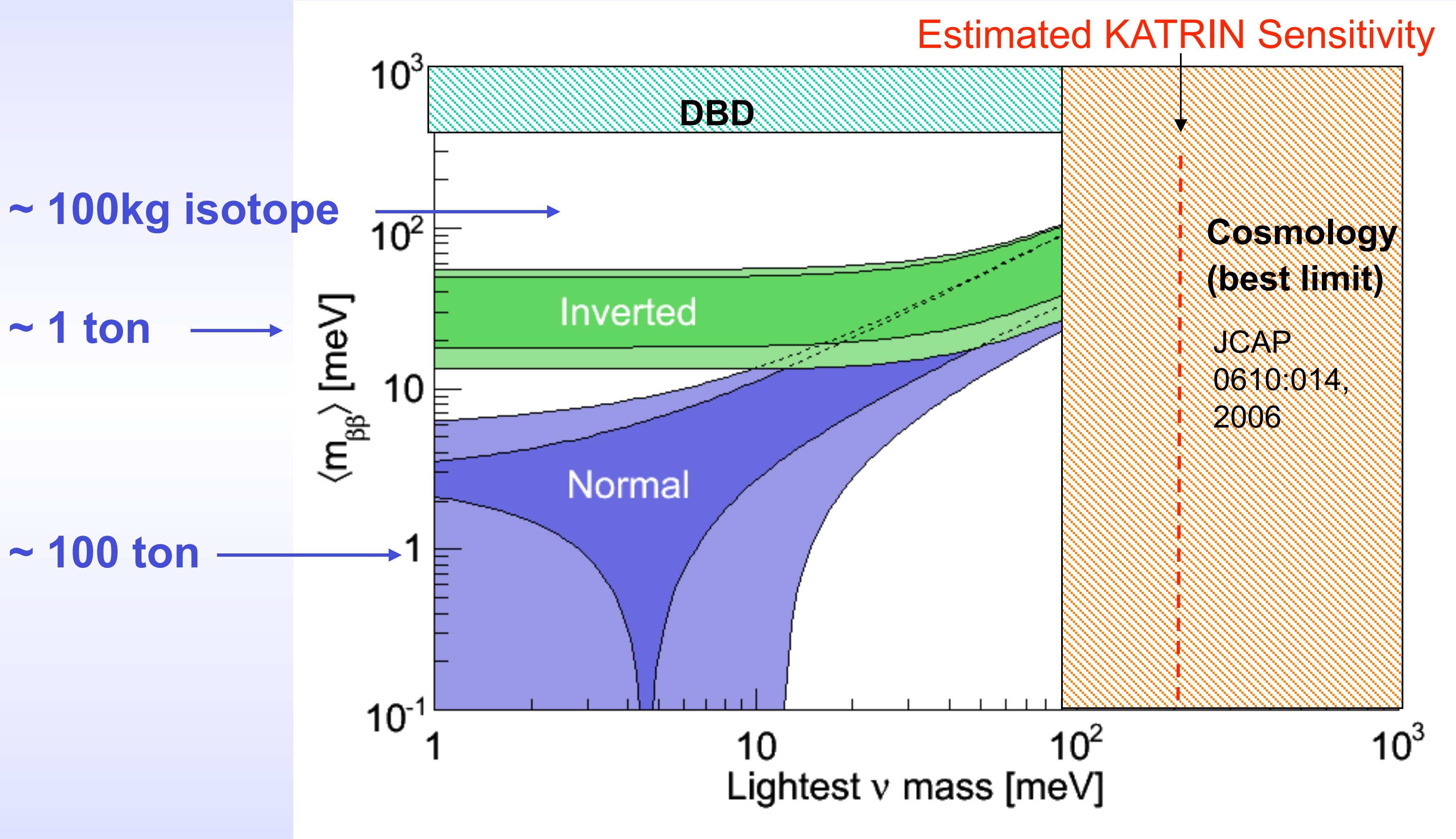
* Assumes ν_m exchange

Nuclear Matrix Elements



Nuclear Physics and Background Uncertainties Require Multiple Isotope Program

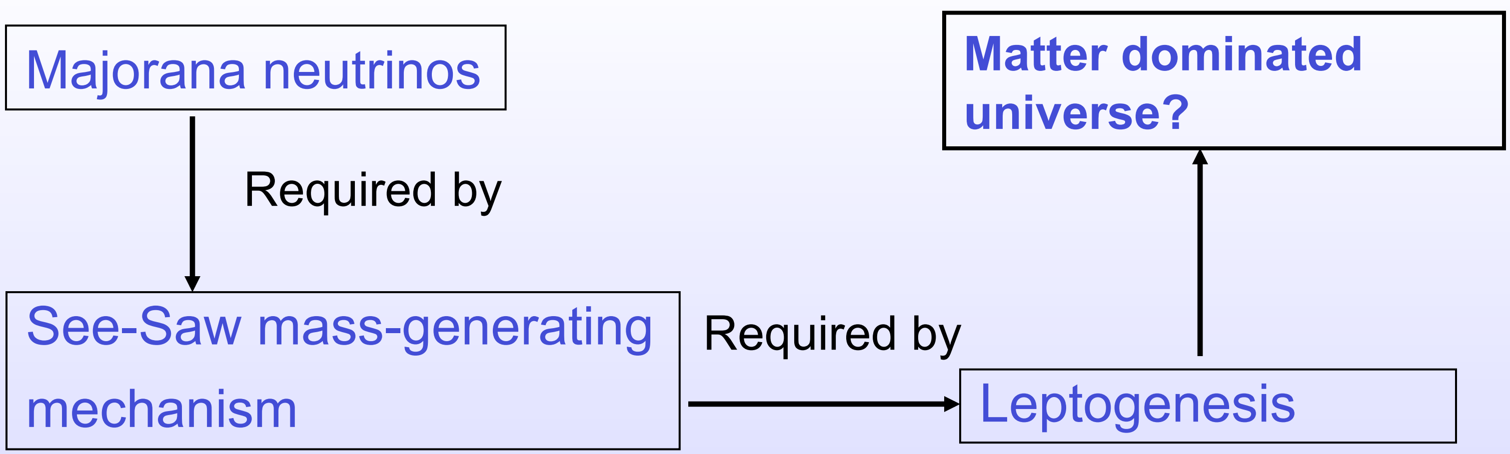
Combined Mass Limits



Two Comments

Direct search for neutrinos mass via Tritium-decay experiments (KATRIN) are complementary to neutrinoless double-beta decay searches.

Neutrinos and Cosmology:

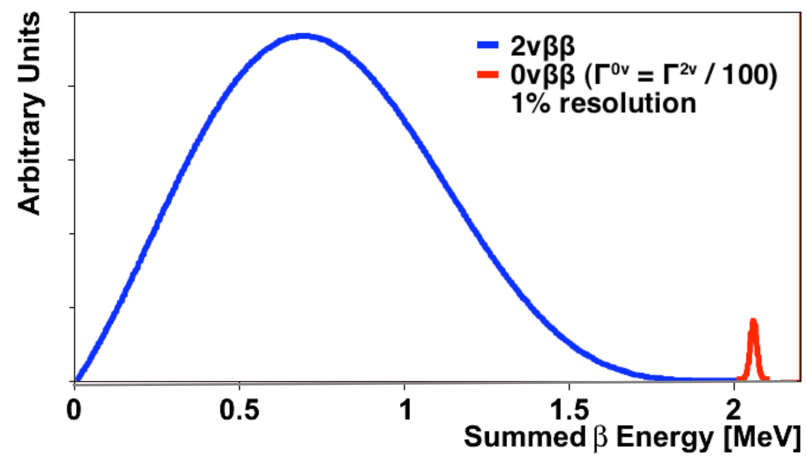


Experimental Considerations

- Measure ***extremely*** rare decay rates :

  $T_{1/2} \sim 10^{26}-10^{27}$ years
- Large, highly efficient source mass.
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region-of-interest (ROI): 1 count/t-y after analysis cuts.

1. High Q value
2. Best possible energy resolution
   - Minimize $0\nu\beta\beta$ peak ROI to maximize S/B
   - Separate $2\nu\beta\beta/0\nu\beta\beta$



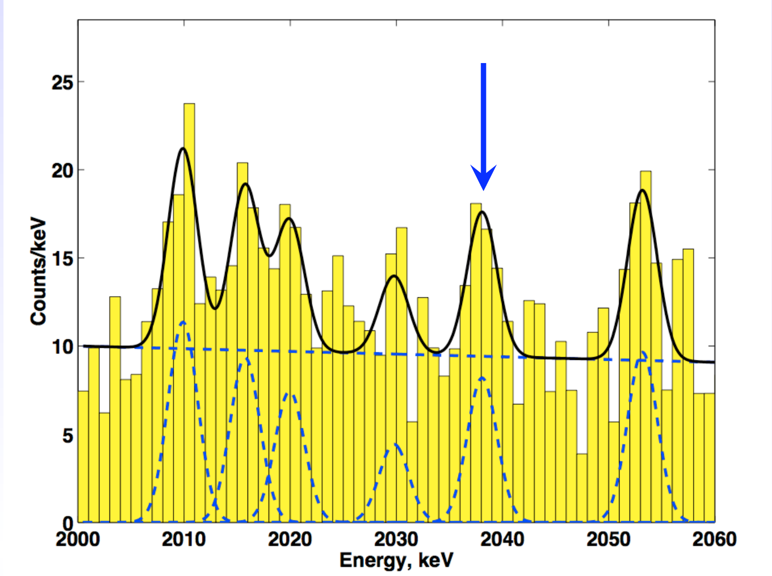
A Recent Claim

Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

KKDC used five ^{76}Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data.

$T_{1/2} = 1.2 \times 10^{25}$ y

$0.24 < m_{\nu} < 0.58$ eV (3 sigma)

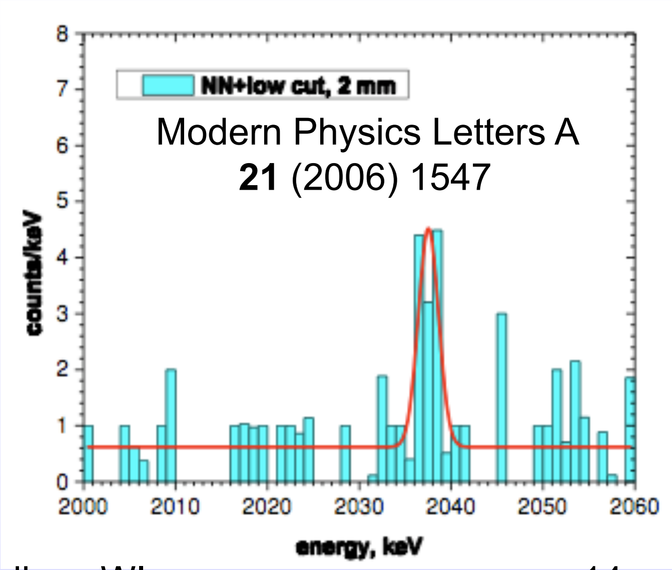


Background level depends on intensity fit to other peaks.

A More Recent Claim

6.8 sigma

Neural Net Analysis



THE MAJORANA EXPERIMENT

THE MAJORANA DEMONSTRATOR, R. JOHNSON
THE GERDA EXPERIMENT, A SEARCH FOR NEUTRINOLESS DOUBLE BETA DECAY, D. LENZ

The MAJORANA Collaboration (Feb. 2009)

Note: Red text indicates students

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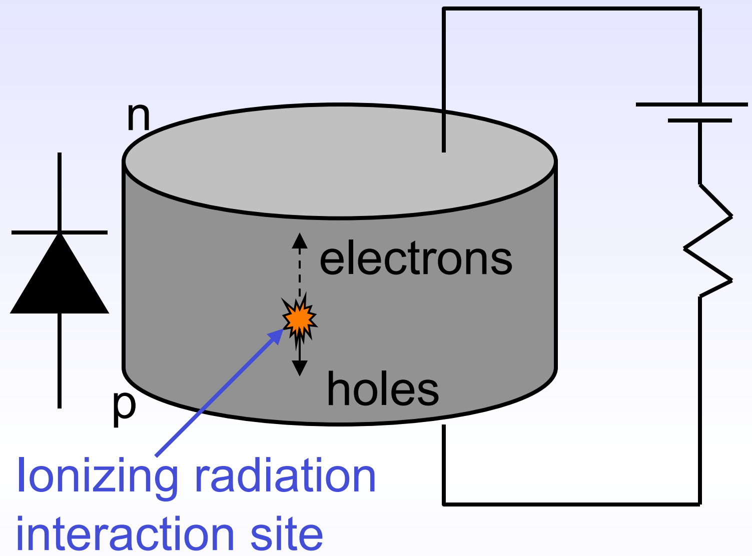
Alexis Schubert, Tim Van Wechel

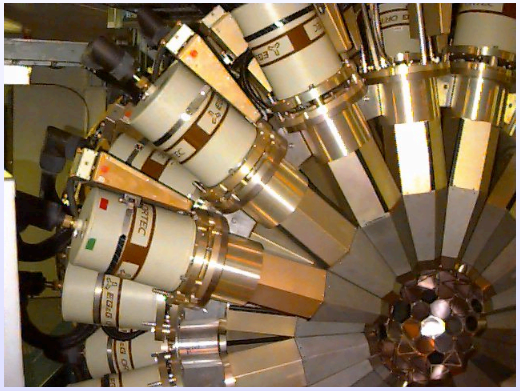
Ge Detection Principle

- Fiorini et al, Il Nuovo Cimento 13 (1974) 747
- enrGe is semiconductor -- Diode.
- Ionizing radiation creates electron-hole pairs.
- Signal generated by collecting electrons and holes.
- Gamma-ray spectroscopy

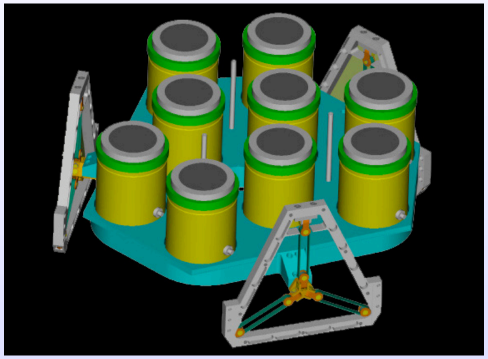
Mature Technology



Gammasphere



RHESSI

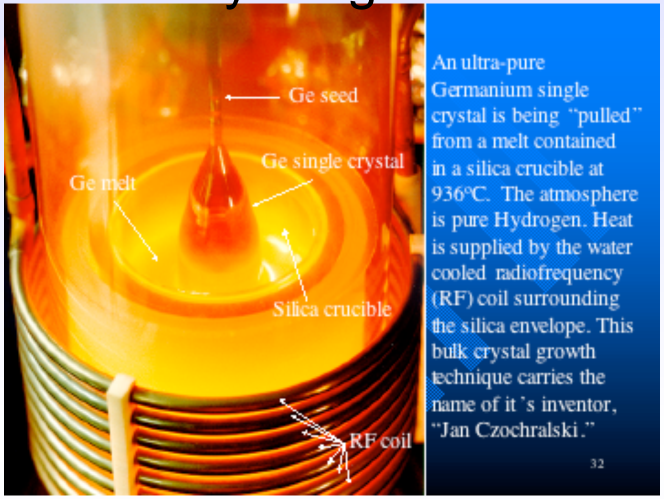


Commercial

Crystal Production

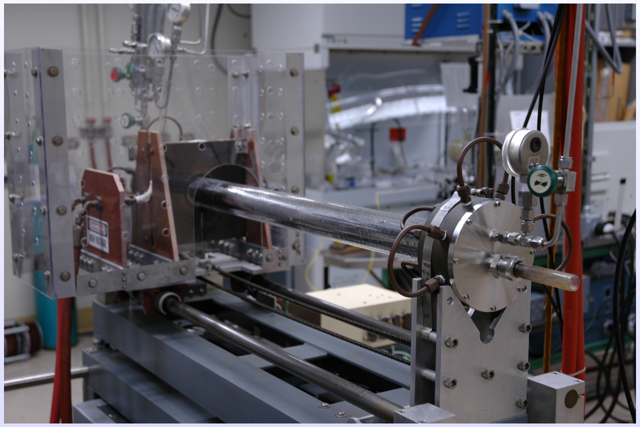
Enrichment (86% ^{76}Ge)

E.E Haller   Crystal growth



Polycrystalline bars

Zone refinement



MAJORANA Collaboration Goals

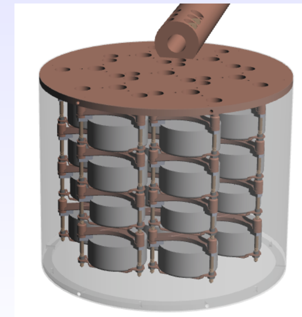
Actively pursuing the development of R&D aimed at a ~1 tonne scale ^{76}Ge $0\nu\beta\beta$-decay experiment.

- Technical goal: Demonstrate background low enough to justify building a tonne scale Ge experiment.
- Science goal: build a prototype module to test the recent claim of an observation of $0\nu\beta\beta$. This goal is a litmus test of any proposed technology.
- Work cooperatively with GERDA Collaboration to prepare for a single international tonne-scale Ge experiment that combines the best technical features of MAJORANA and GERDA.
- Pursue longer term R&D to minimize costs and optimize the schedule for a 1-tonne experiment.

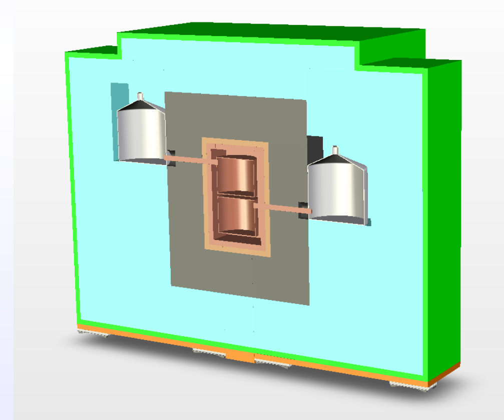
Intermediate Step: The MAJORANA Demonstrator Module

^{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)

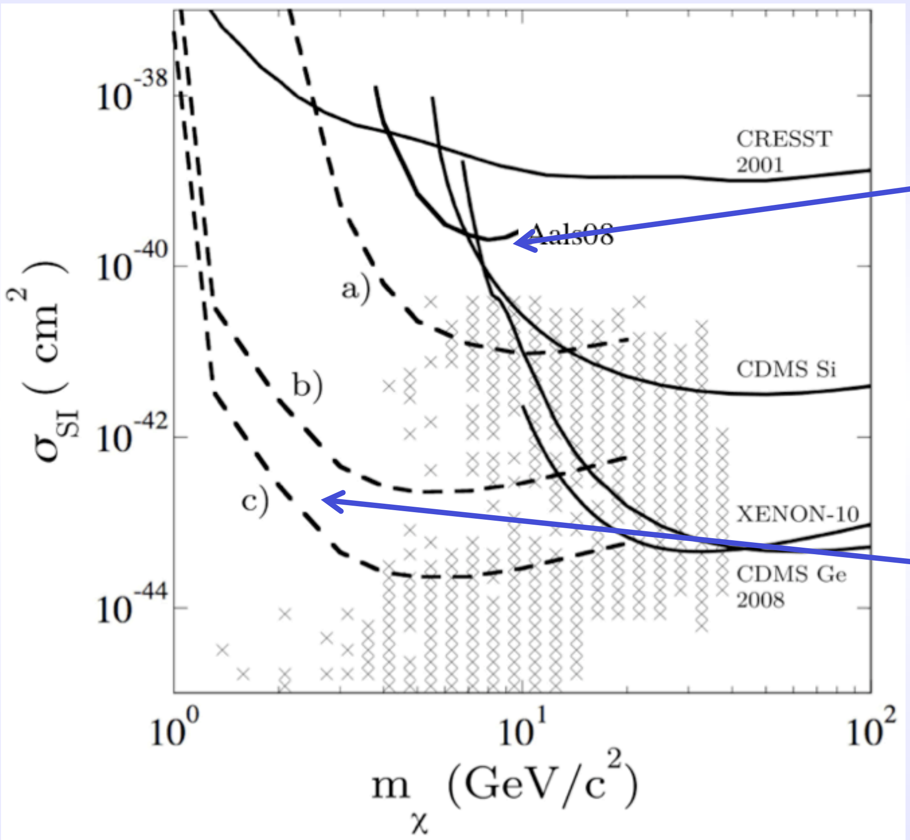


- 60-kg of Ge detectors
  - 30-kg of 86% enriched ^{76}Ge crystals required for science goal; 30-kg ^{nat}Ge for background sensitivity
  - Examine detector technology options p- and n-type, segmentation, point-contact.
- Low-background Cryostats & Shield
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto



- 'CD-1 like' review in 10/2009.
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV) ~ 1 count/ROI/t-y (after analysis cuts)

Direct Search for Light WIMPs



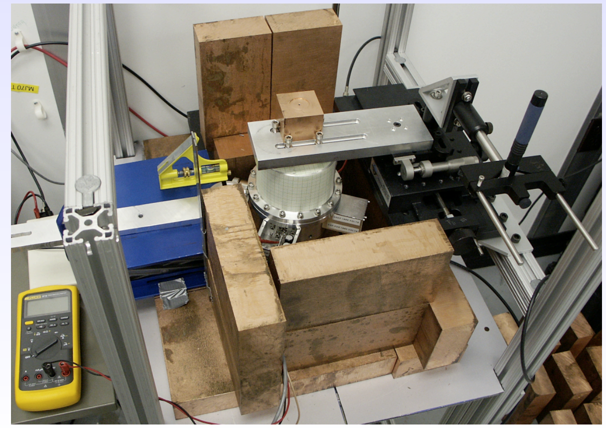
- CoGeNT Collaboration Demonstrated Very low Threshold HPGe Detectors
- Sensitivity to light WIMPS
- MAJORANA can probe this region further

Phys.Rev.Lett.101: 251301, 2008

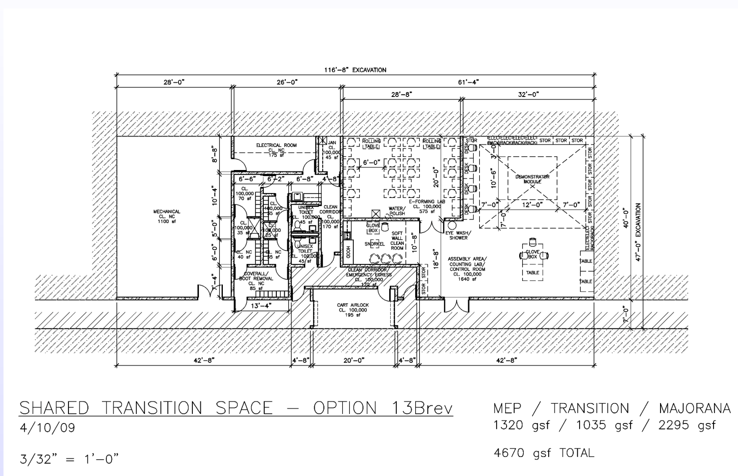
MAJORANA R&D for 1-t ββ

Materials and Assay

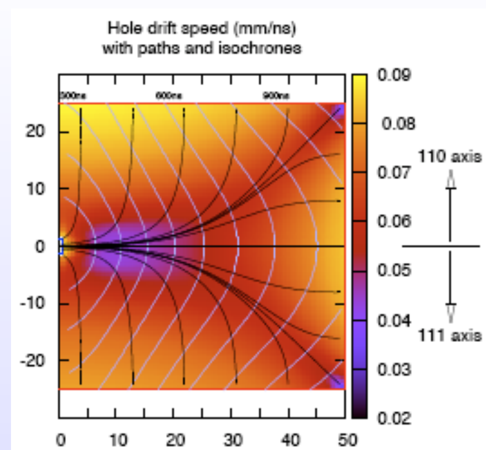
Prototypes



Infrastructure



Simulation and Analysis

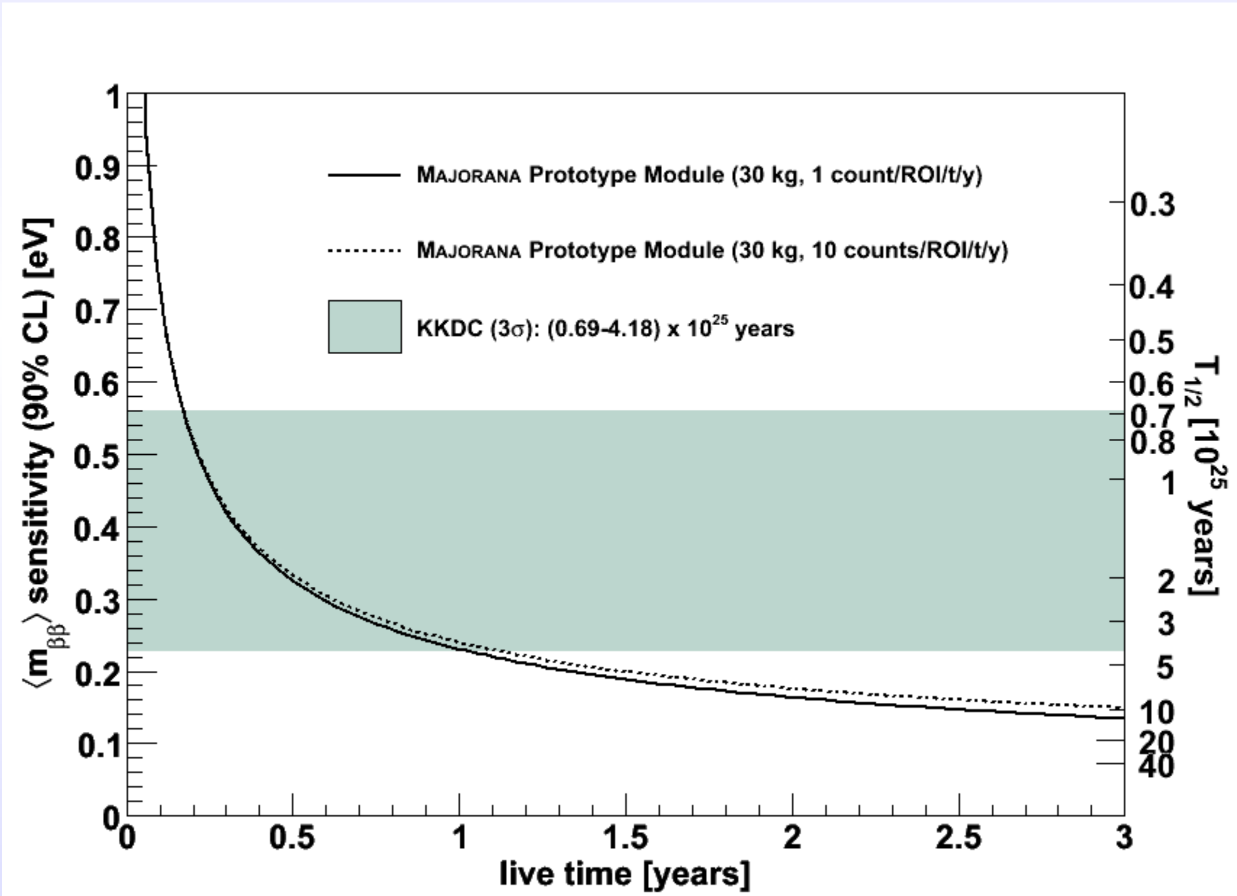


Enrichment

MAJORANA DEMONSTRATOR Module Sensitivity

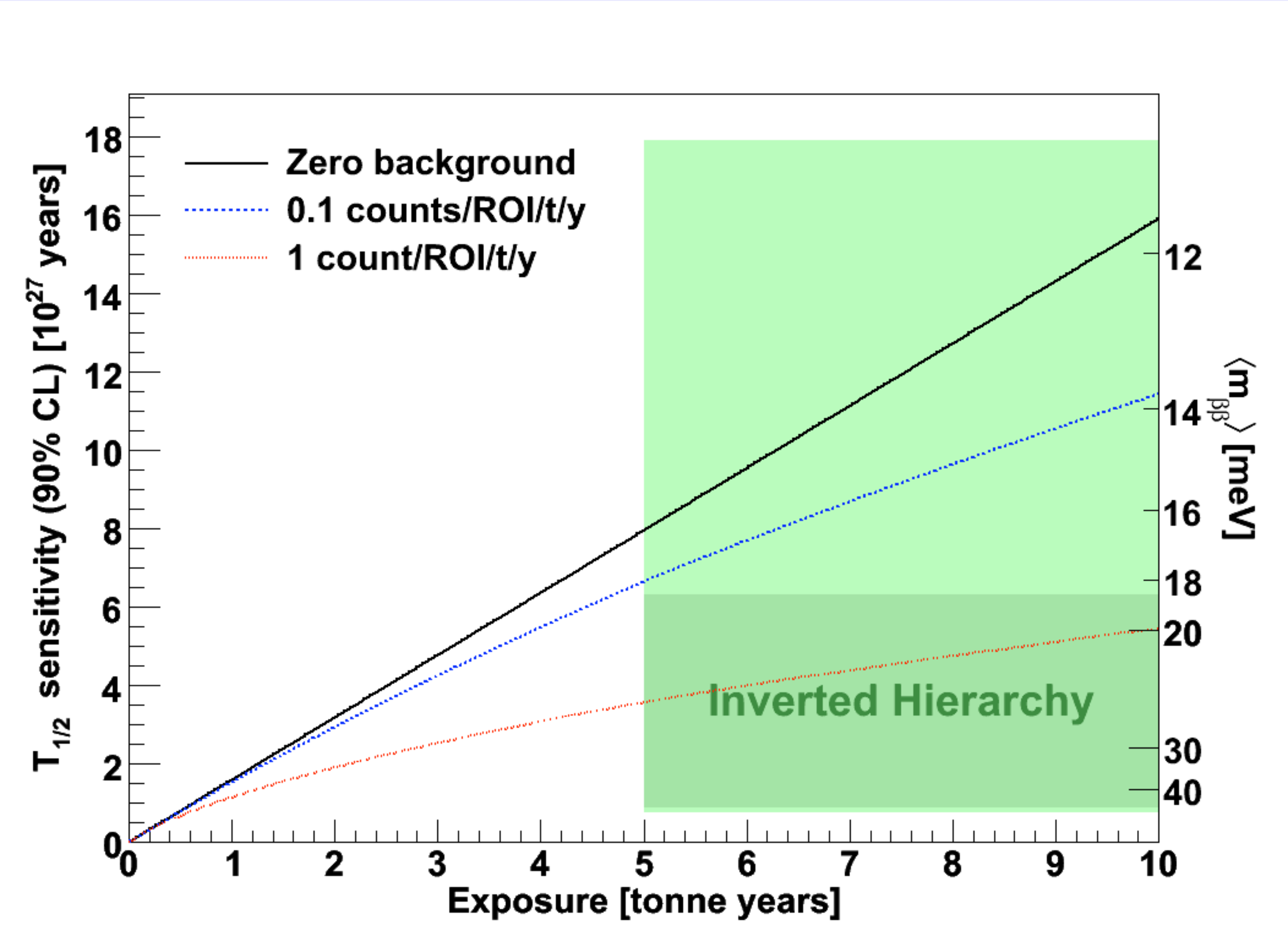
Expected Sensitivity to 0νββ
(30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

$T_{1/2} \geq 10^{26}$ y (90% CL).Sensitivity to $<m_{\nu}>$ < 140 meV (90% CL) [Rod05,err.]



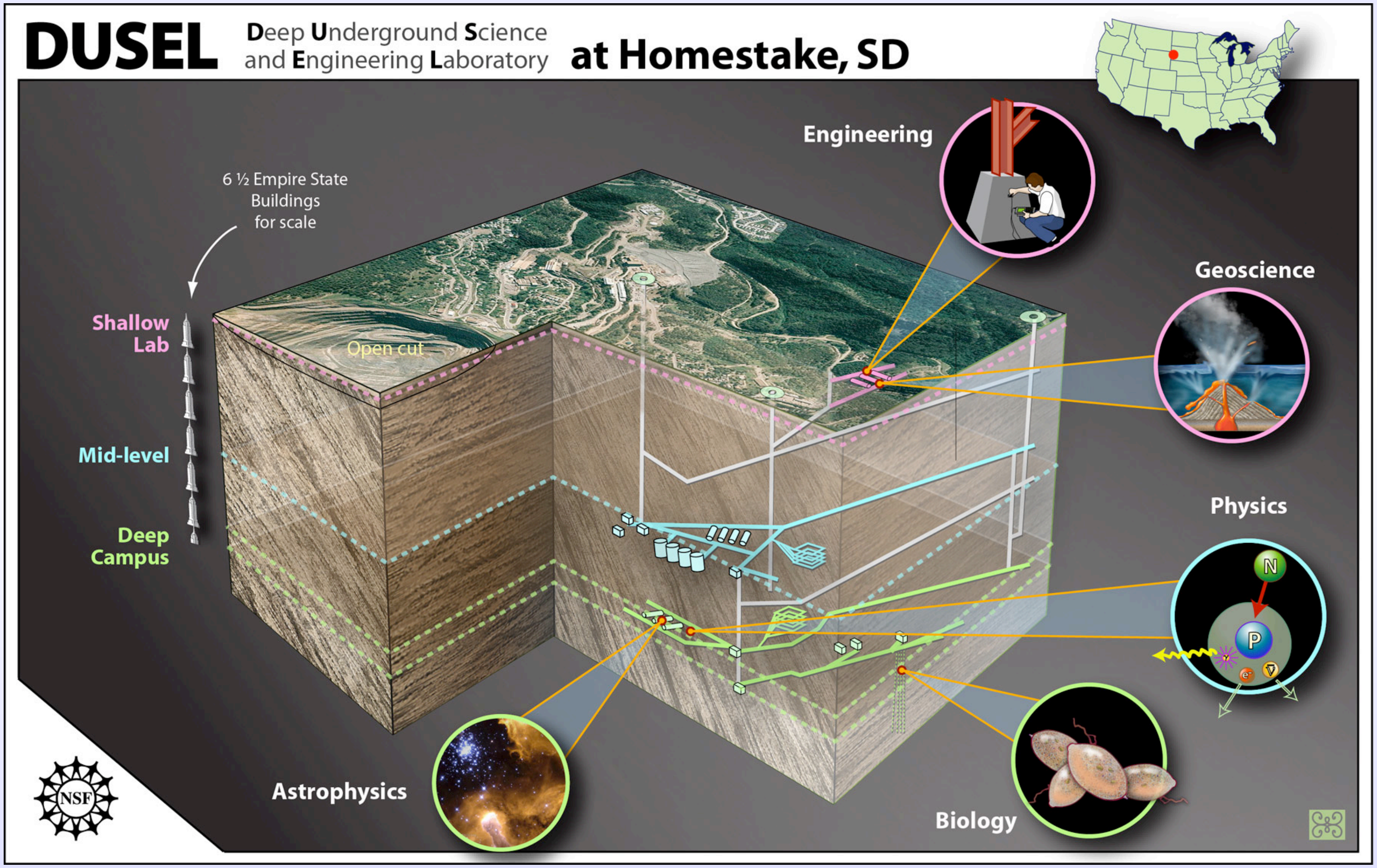
1-tonne Ge - Projected Sensitivity vs. Background

Goal is to achieve ultra-low backgrounds <1 count per ton of material per year in the Region of Interest (ROI)



Sanford Lab

Intermediate phase of DUSEL



EXO: ENRICHED XENON OBSERVATORY

EXO Collaboration

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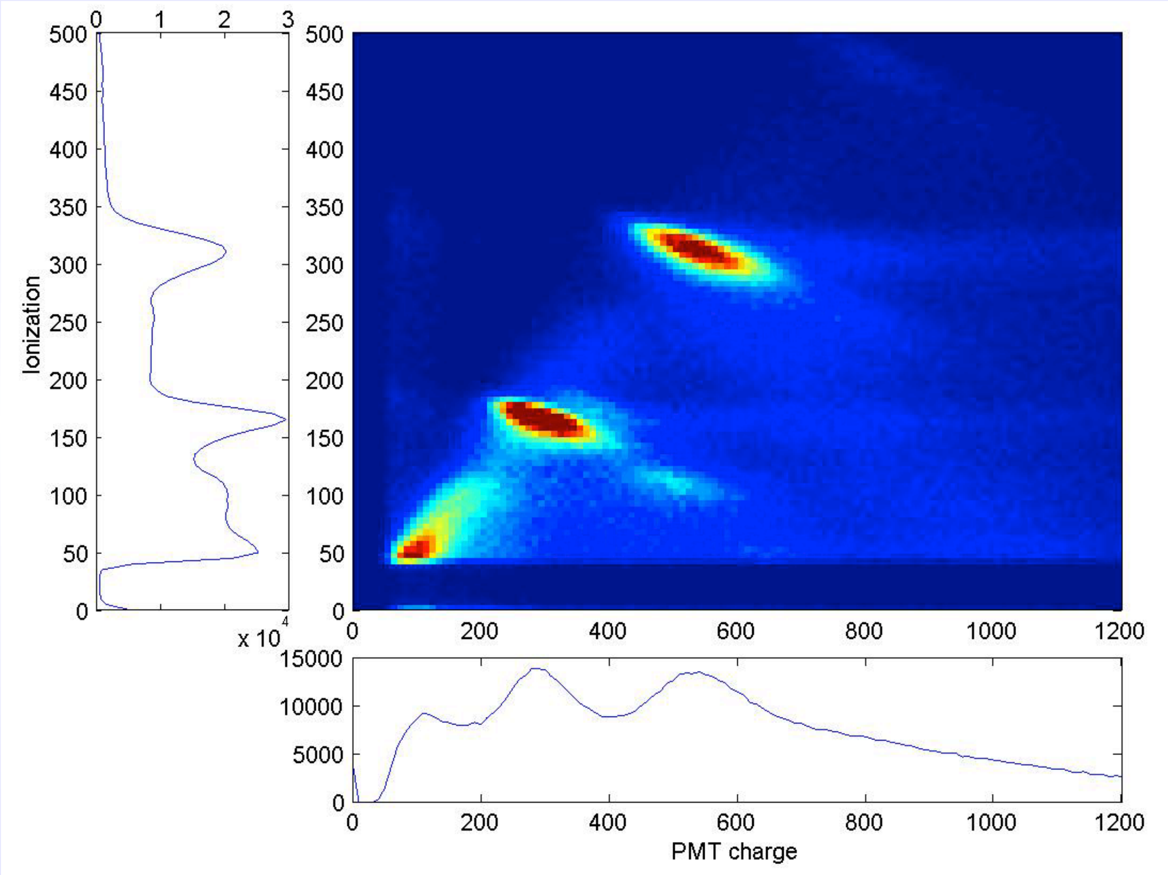
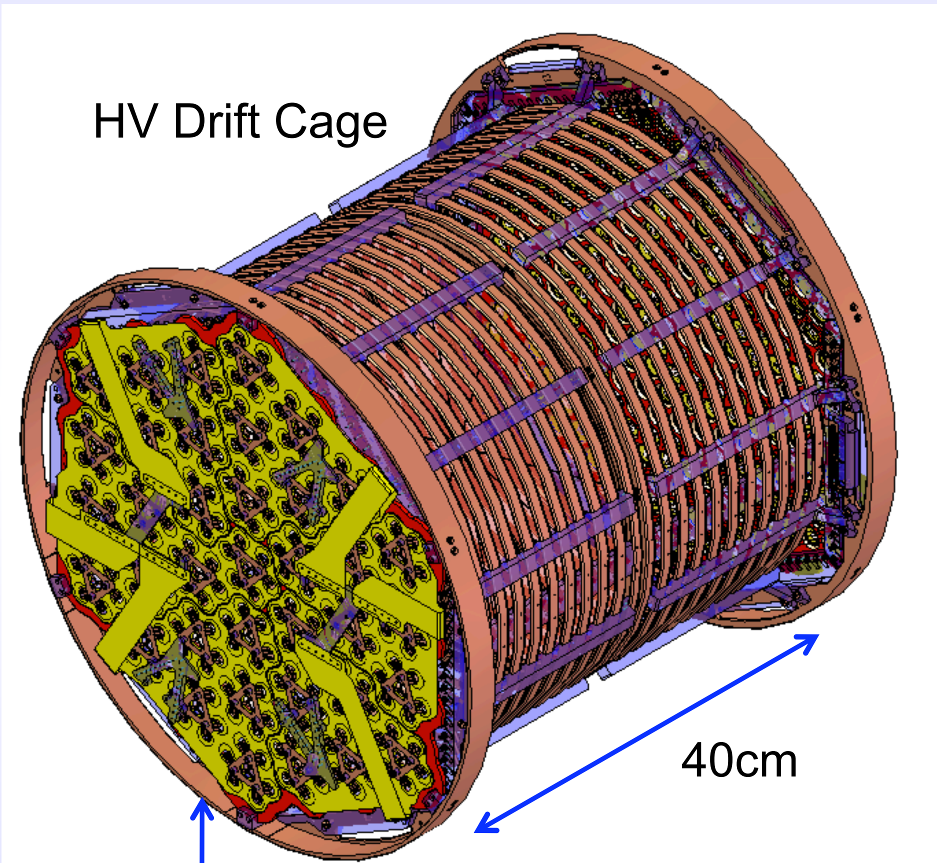
EXO Overview

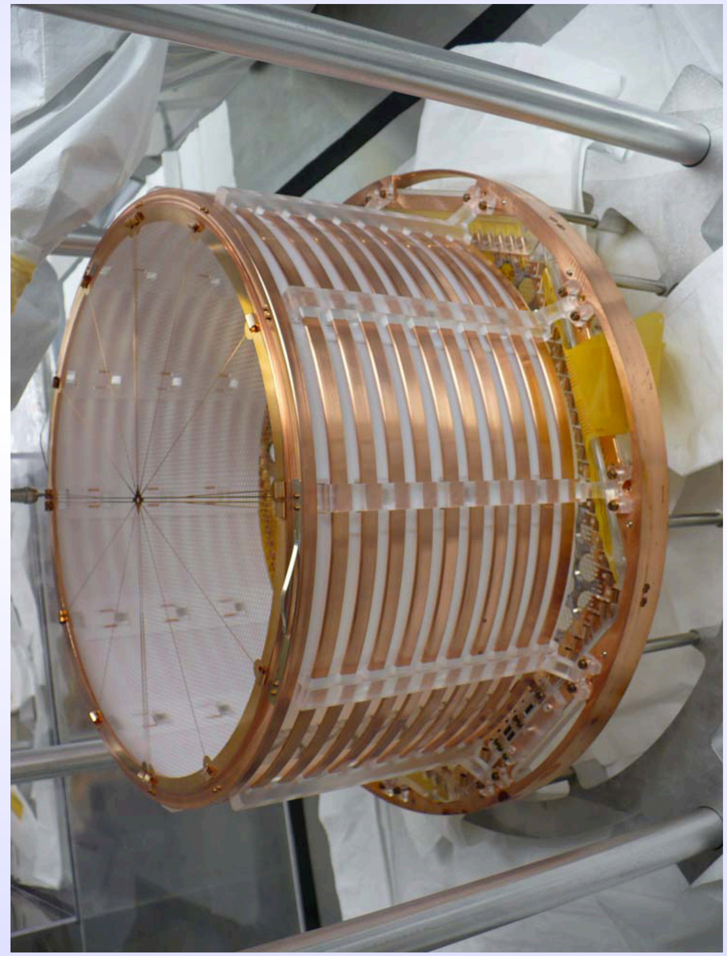
- Detect ionization and scintillation from liquid Xe
- Have 200kg Xe enriched to 80% ^{136}Xe
- Building 200kg prototype
- Install at WIPP
- Start with natural Xe in 2010
- Achieve $6x10^{25}$ yr.
- Scale to ~10 ton



EXO-200 LXe TPC



APD Plane and Grid

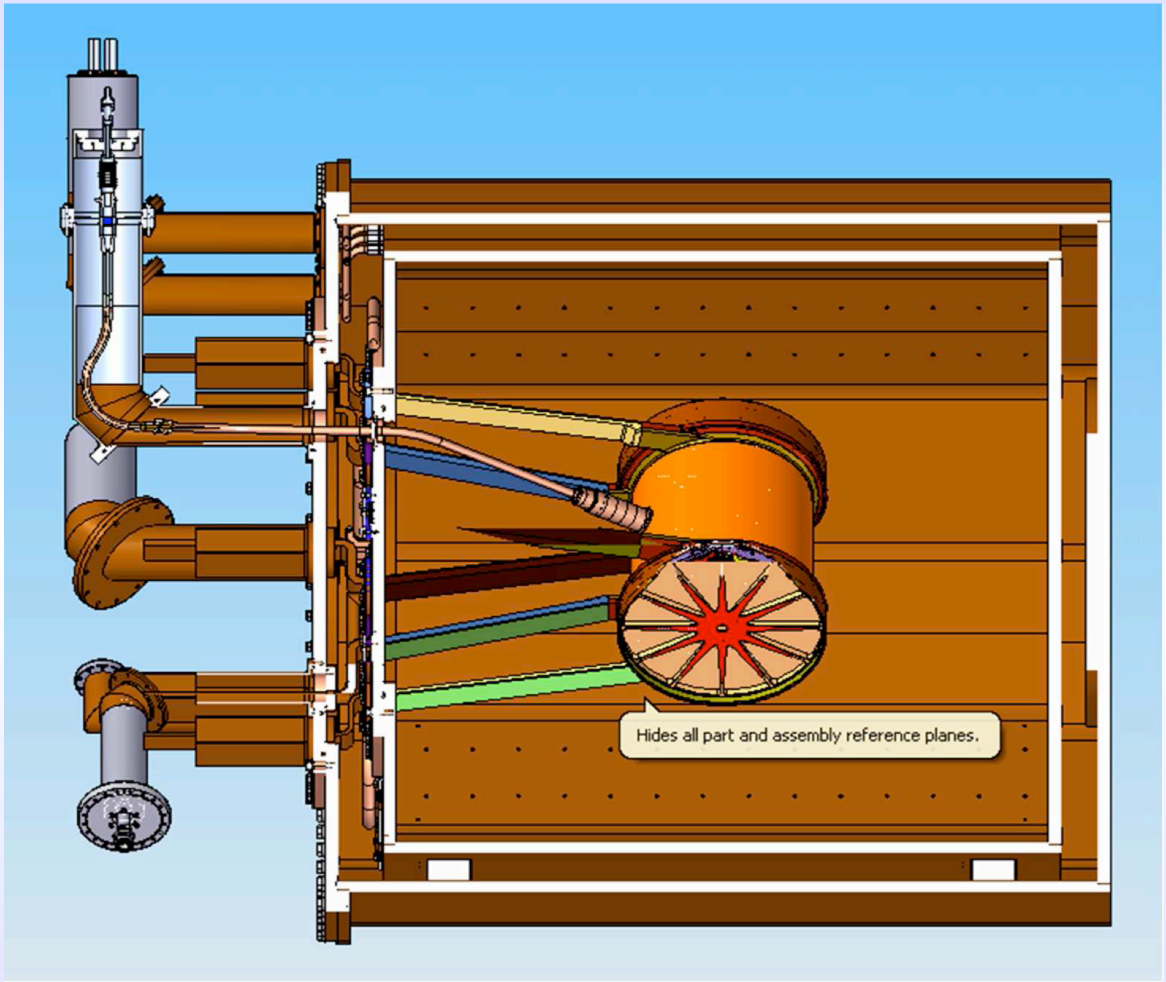


Ultra-low activity Cu vessel

EXO APD Plane

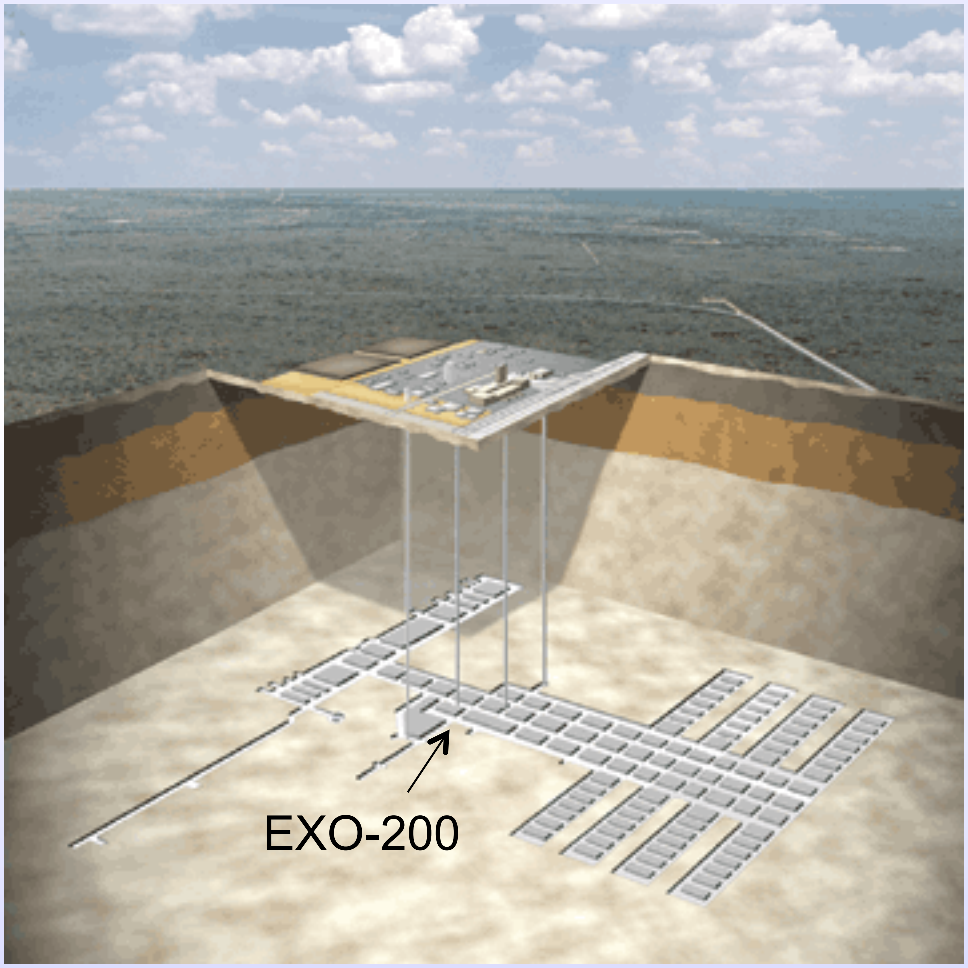
- Extensive R&D to reduce component backgrounds
- APD clean & lightweight
- Sensitive to VUV

EXO 200 Detector



1.5 m

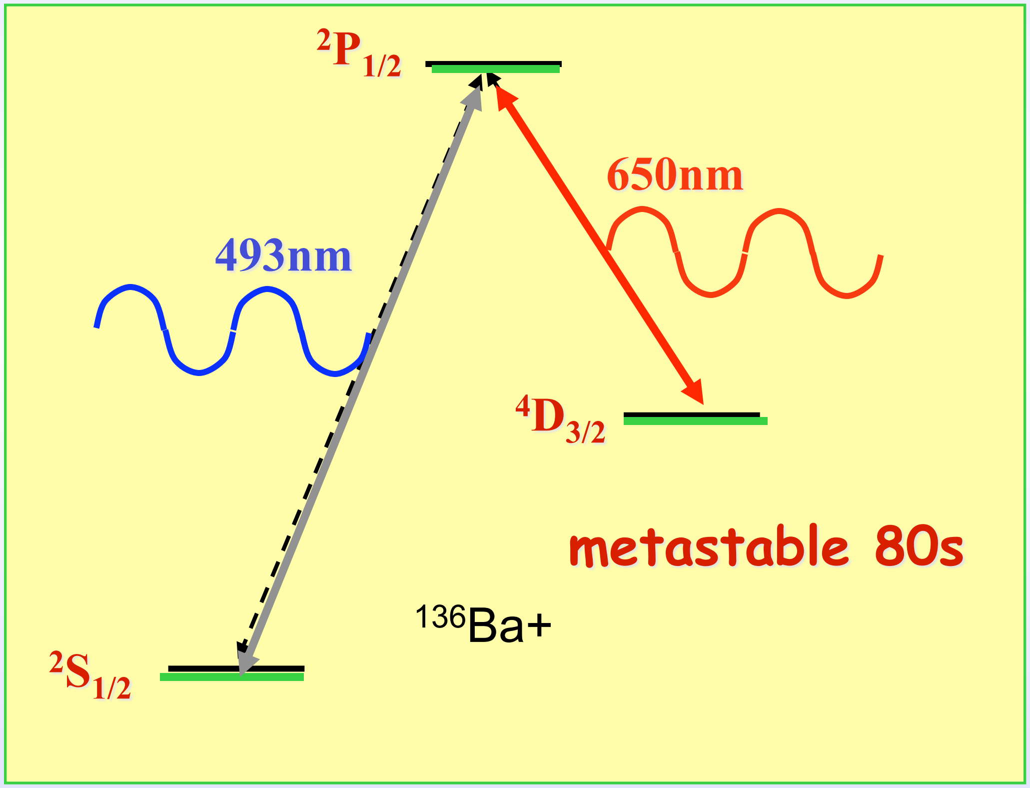
Waste Isolation Pilot Plant



- Carlsbad, NM
- 1500 mwe
- Salt, low radio-activity

Ba tagging R&D

- M. Moe PRC44 (1991) 931
- $^{136}Ba^{+}$ final state can be identified using optical spectroscopy.
- Provides almost background free confirmation.



SNO+

SNO+ Collaboration

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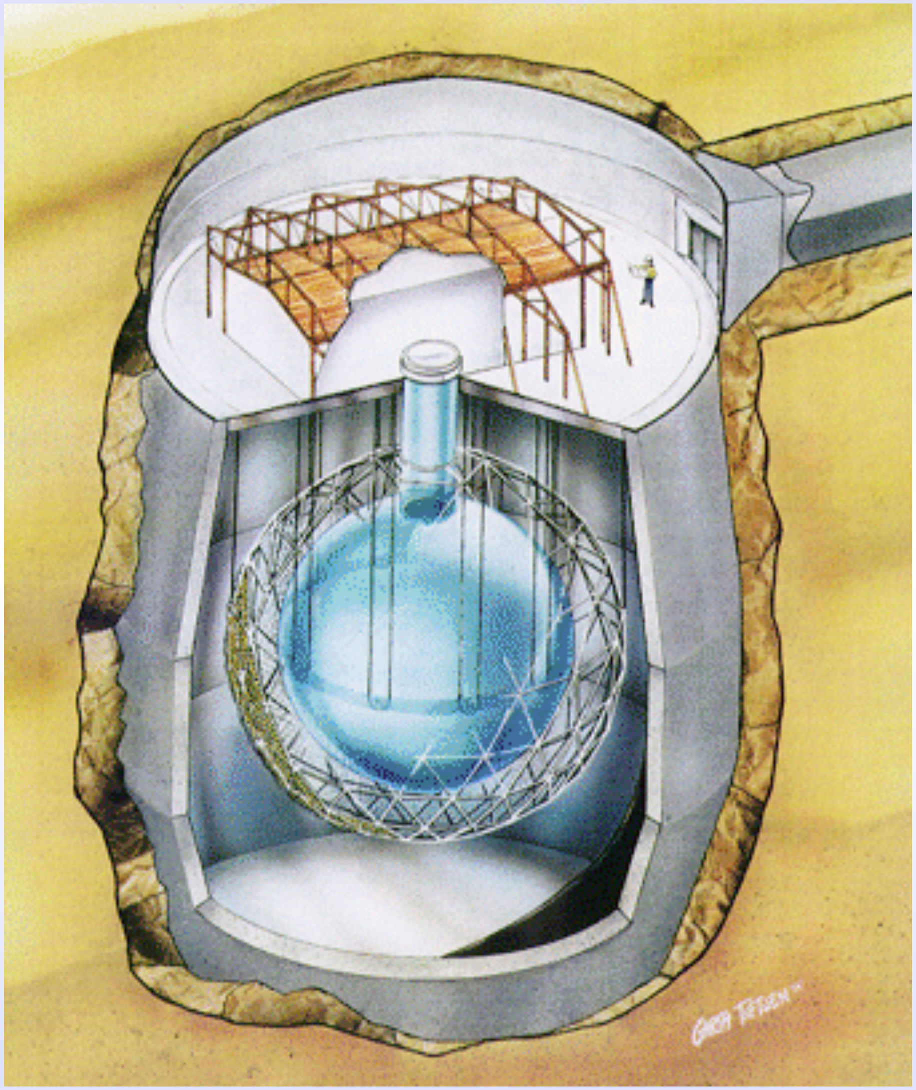
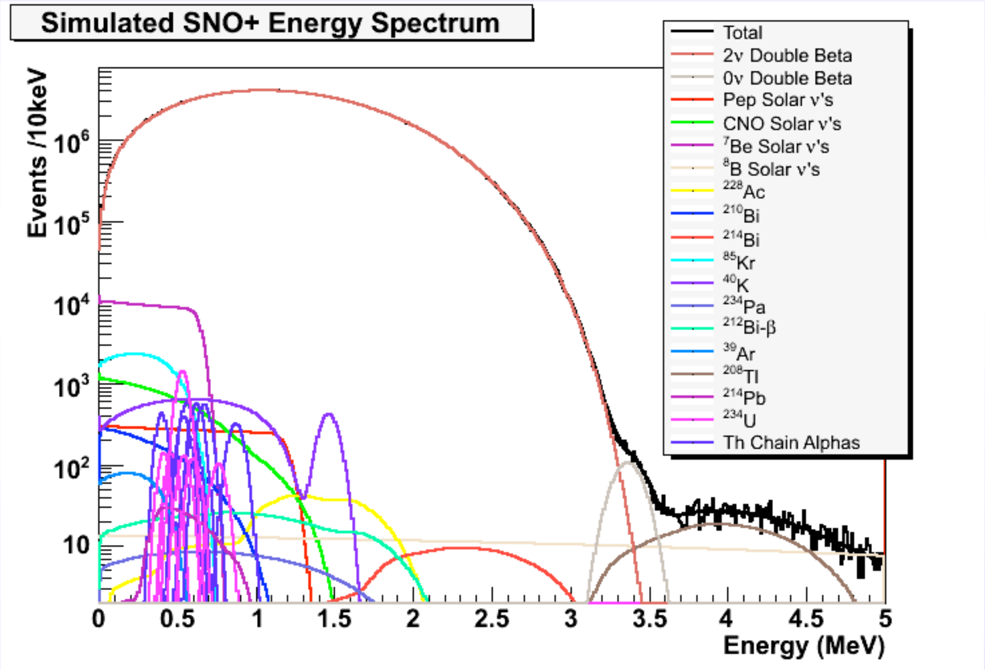
SNO+



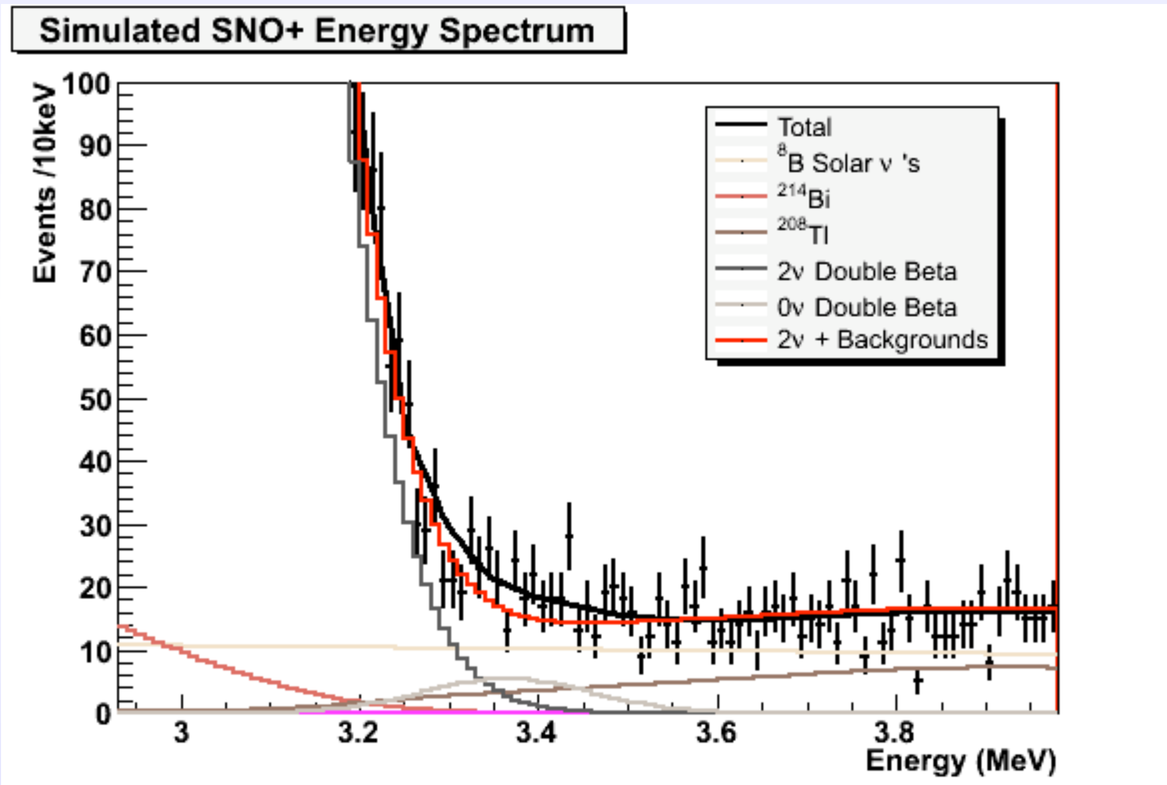
- Use existing SNO PMTs and Acrylic Vessel
- 6000 mwe
- Physics Goals
  - Neutrinoless Double Beta Decay
  - Solar Neutrinos
  - Reactor Anti-neutrinos
  - Geo Neutrinos
  - Supernova Neutrinos

^{150}Nd SNO+ Summary

- Stable Nd-loaded liquid scintillator
- Developed acceptable purification techniques to remove Th and Ra from Nd
- Physics sensitivity
  - below 100 meV (using natural Nd)
  - below to 30 meV (using enriched Nd)
- SNO+ plans to deploy 0.1% natural Nd-loaded liquid scintillator for the first phase

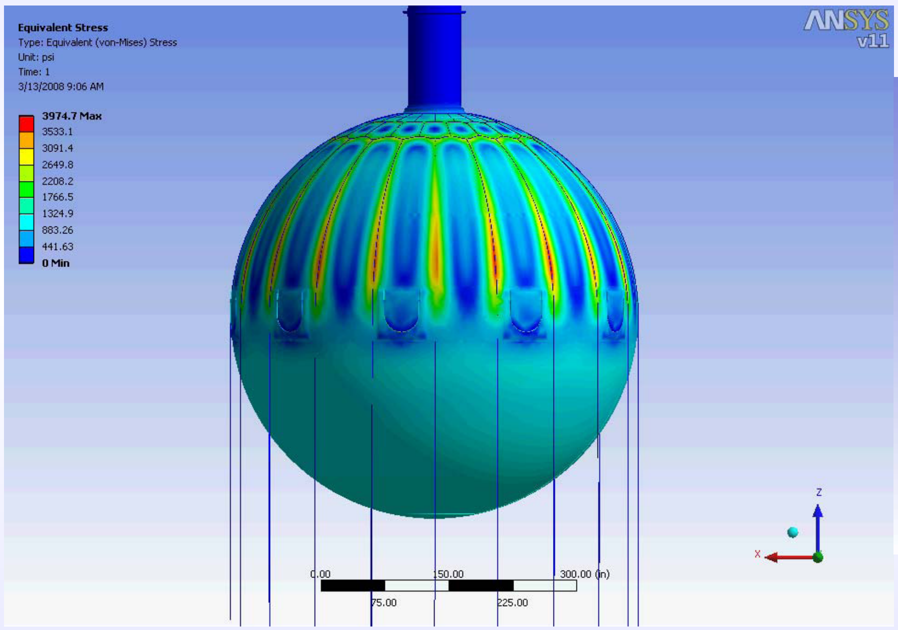


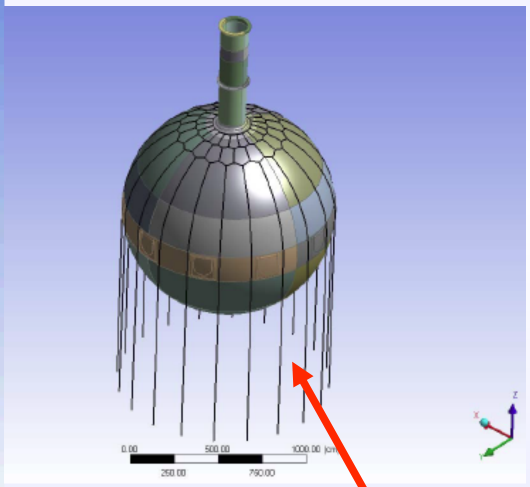
56 kg of ^{150}Nd and $\langle m_\nu \rangle$ = 100 meV



- 6.4% FWHM at Q-value
- 3 years livetime
- 5σ sensitivity
- Dominant background is ^{8}B solar neutrinos!

SNO+ Rope Hold Down Net





SNO+ rope will be Tensylon: low U, Th, K ultra-high molecular weight polyethylene

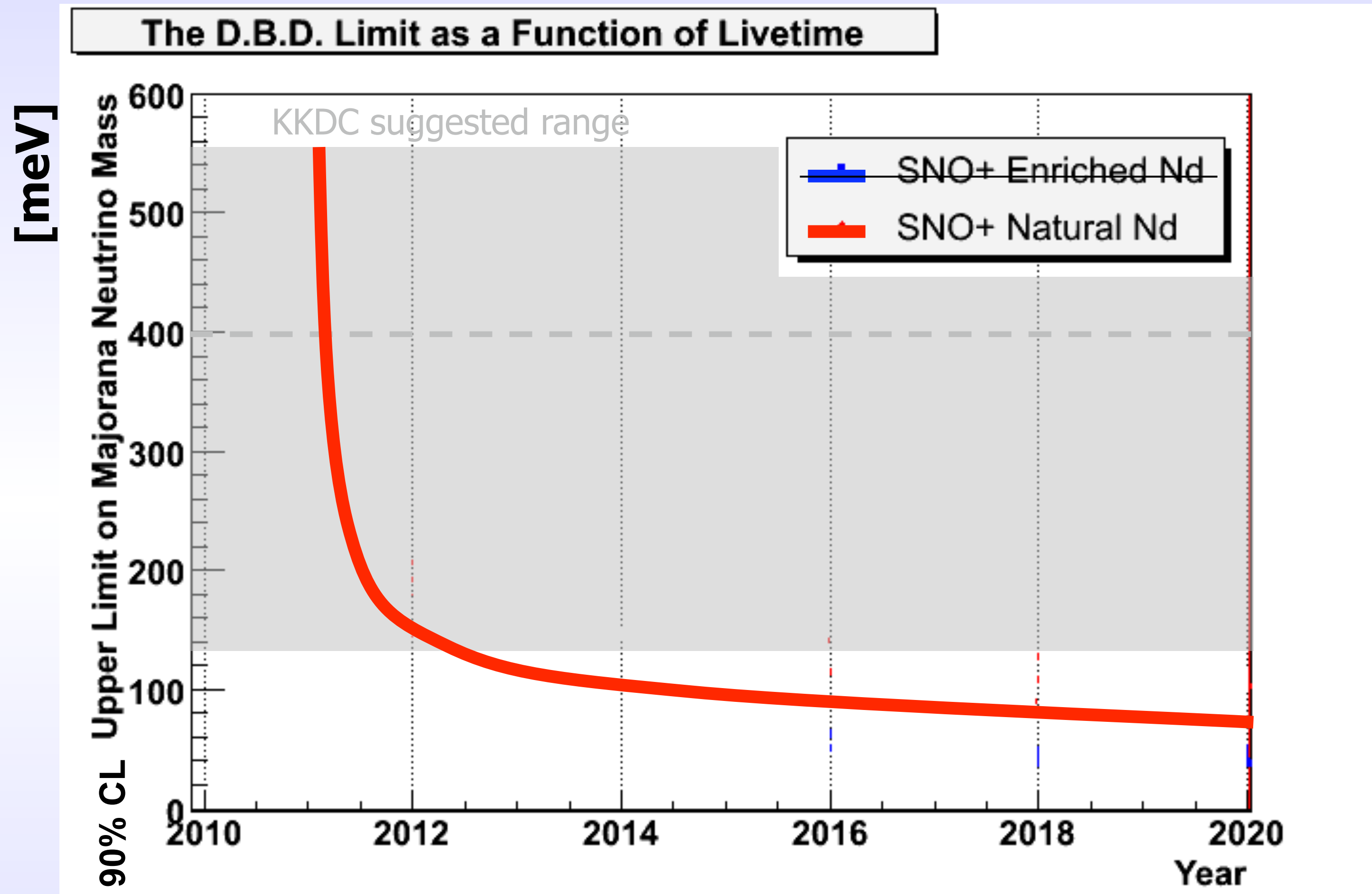
AV Hold Down Ropes

Inspecting the SNO Cavity

SNO to SNO+ Transition Activities

- >$10M proposal submitted to CFI LEF/NIF competition: October 2008
- Approved in June 2009.
- Commissioning and data taking in 2011
- Inspections *inside* the acrylic vessel

SNO+ ββ Sensitivity



SNO+ Operating Plan:

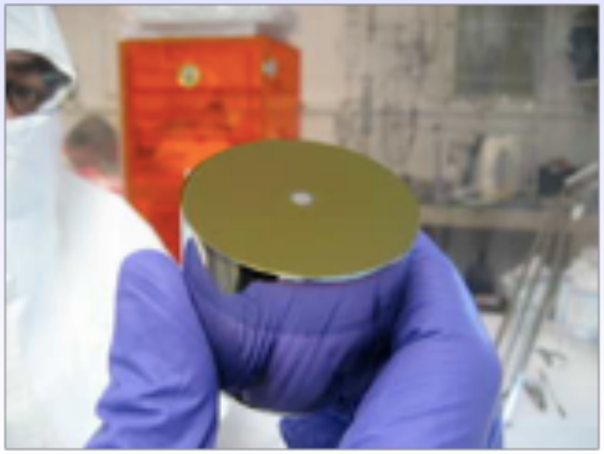
- Natural Nd in 2011
- ~~Enriched Nd in 2014~~
- 50% fiducial volume
- 75% livetime

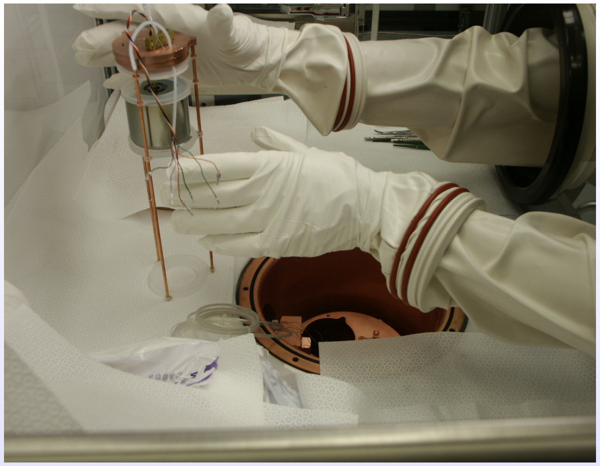
Conclusion

North America has three competitive DBD experiments utilizing a rich variety of experimental approaches.

Extras

Refinements to the MAJORANA DEMONSTRATOR





- Concentrate on P-PC Detectors.
  - Advantages of cost and simplicity, with no loss of physics reach.
  - Will continue N-SC R&D.
- Additional physics opportunities with low-energy P-PC detectors.
  - Exploits low-energy thresholds (~100 eV threshold) of P-PC detectors
- Several Prototypes in hand. 18 Additional ^{nat}Ge detectors ordered (LANL).
  - First module of DEMONSTRATOR