THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Double beta-decay at DUSEL

Reyco Henning

U. Of North Carolina / TUNL

DuRA Meeting and PDR Roll-out, FNAL

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

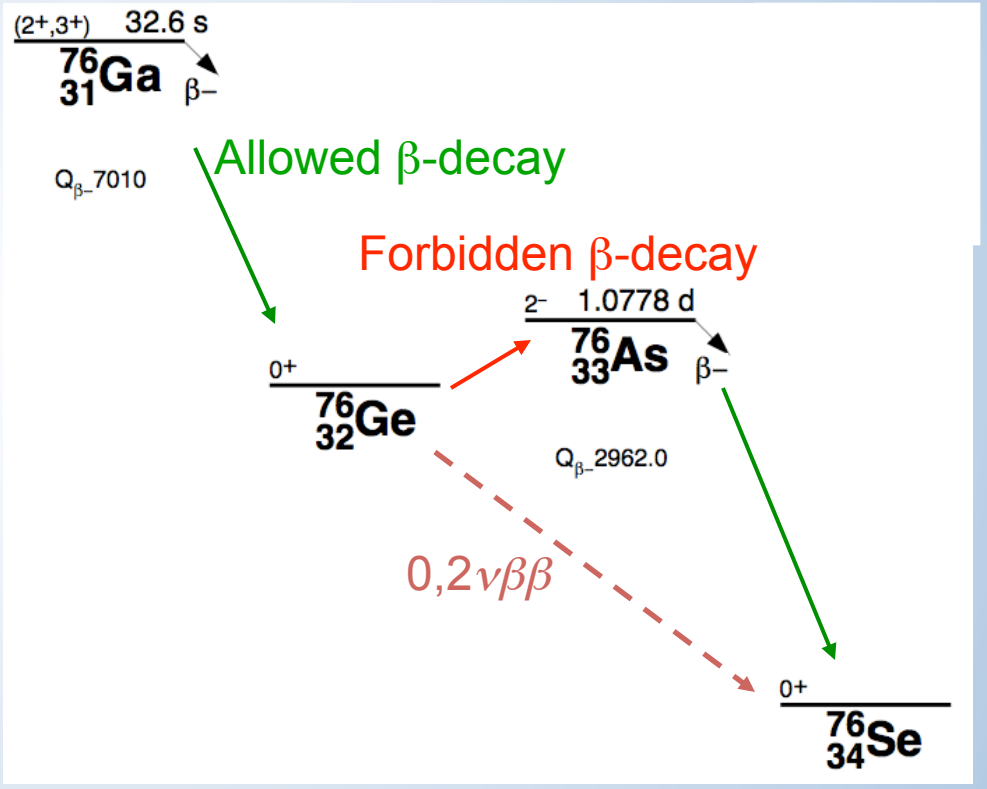
$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-}$$

Energetically allowed in many nuclei.

Prefer nuclei stable against β-decay (about 30)

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

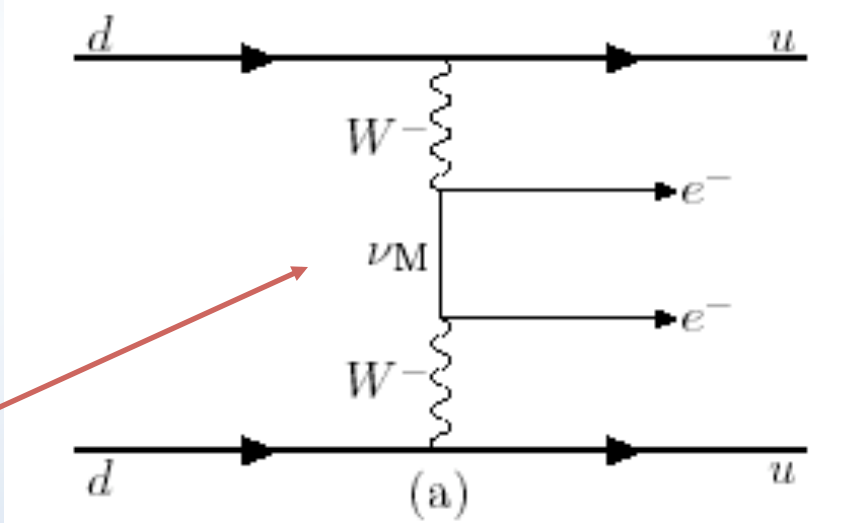
$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-} + 2\bar{\nu}_{e}$$



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)

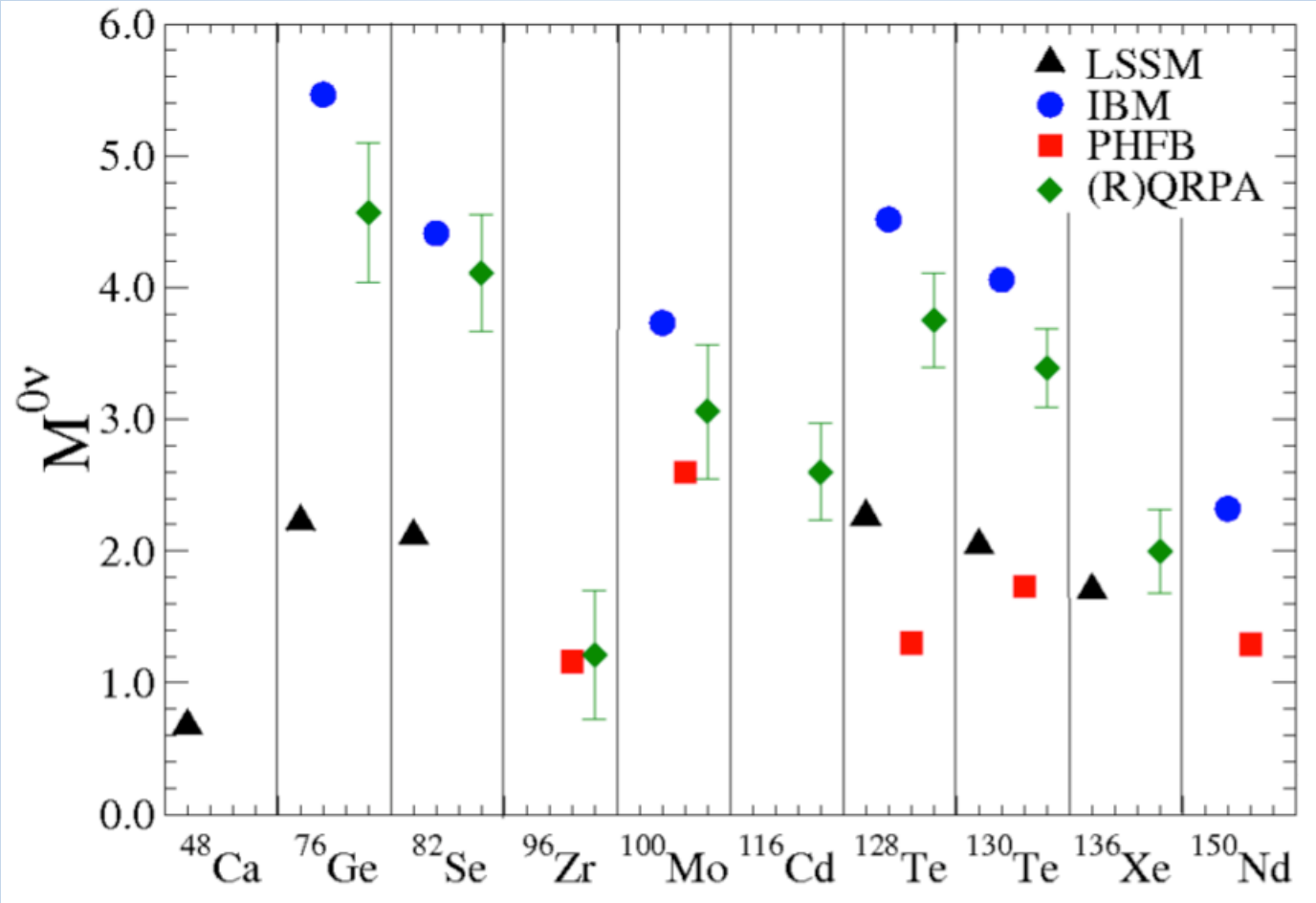
$$\left|< m_{\beta\beta} >\right| = \left|\sum_i \left|U_{ei}\right|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

Effective Majorana electron neutrino mass*

- ☞ $0\upsilon\beta\beta$ 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



F. Simkovic, Neutrino 2010

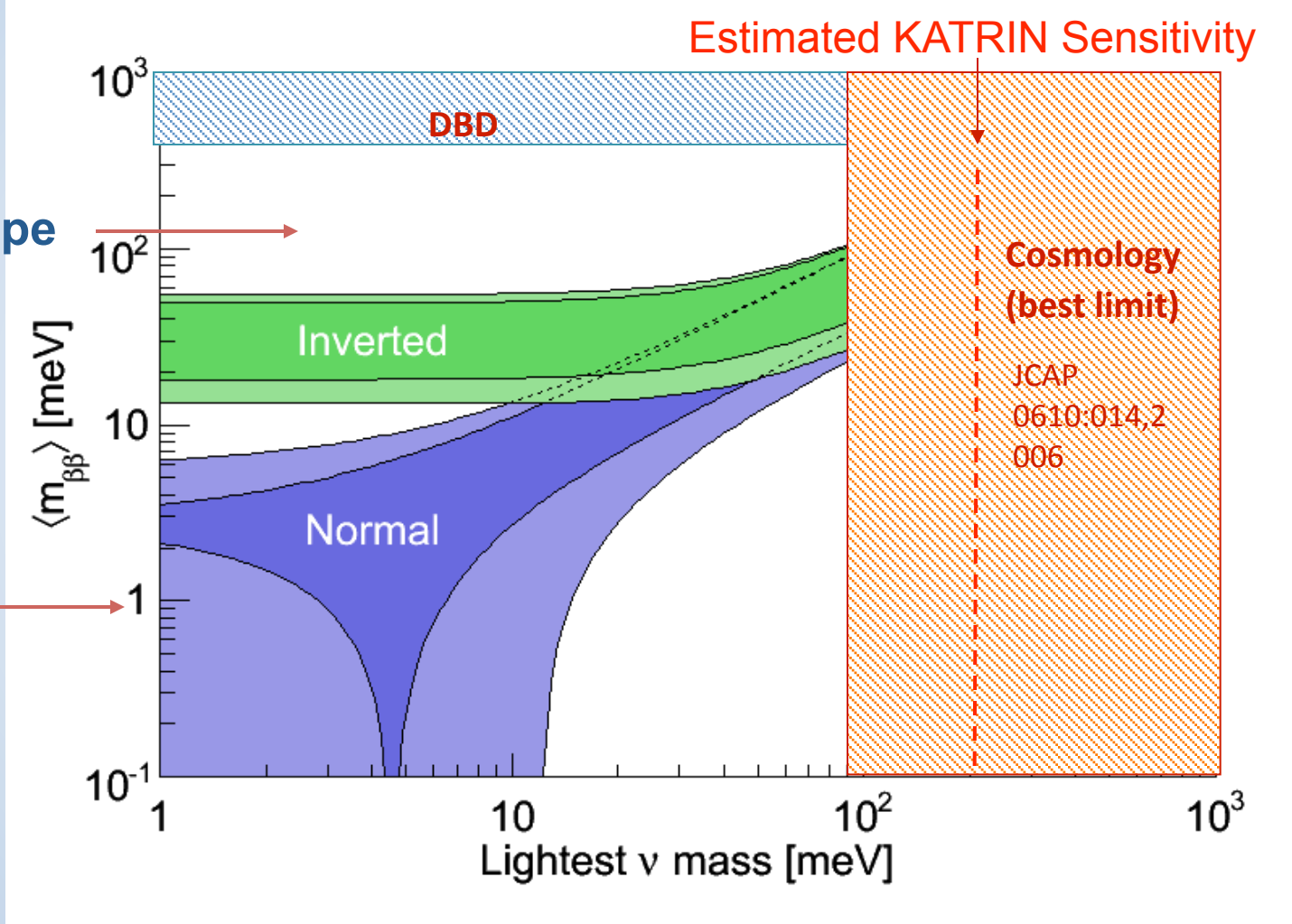
Large Matrix Elements Uncertainties Require Multiple Isotope Program

Combined Mass Limits

~ 100kg isotope

~ 1 ton

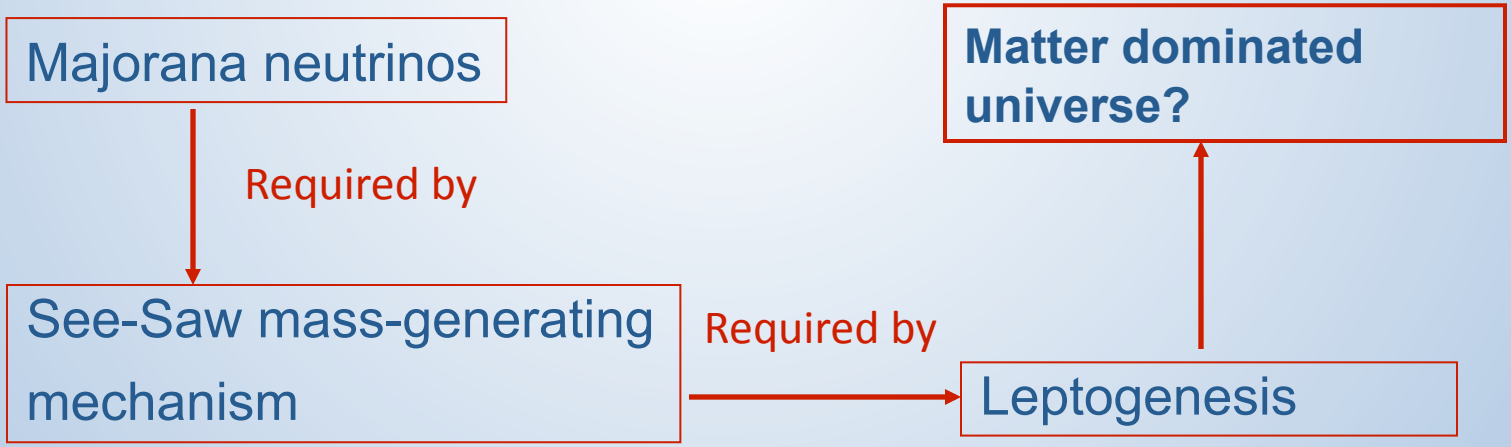
~ 100 ton



Two Comments

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

Neutrinos and Cosmology:

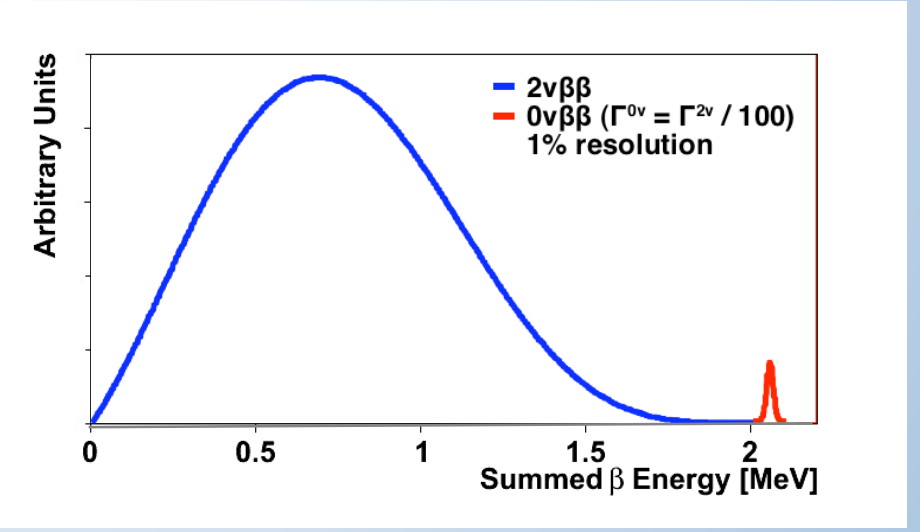


Experimental Considerations

- 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 $2\nu\beta\beta/0\nu\beta\beta$



Background Identification

- Future Experiments Reduce Backgrounds factor ~100
- Backgrounds:
  - Compton scattered gammas, surface alphas.
  - Natural isotope chains: ^{232}Th, ^{235}U, ^{238}U, Rn
  - $2\nu\beta\beta$-decays.
  - Cosmic Rays:
    - Activation at surface creates ^{68}Ge, ^{60}Co.
    - Hard neutrons from cosmic rays in rock and shield.
  - **Tonne-scale 1tGe experiments (S4) need depth of > 5000mwe.**
- Pushing limits in ICP-MS, materials science, radio-assay.

Selected Current and Future Experiments

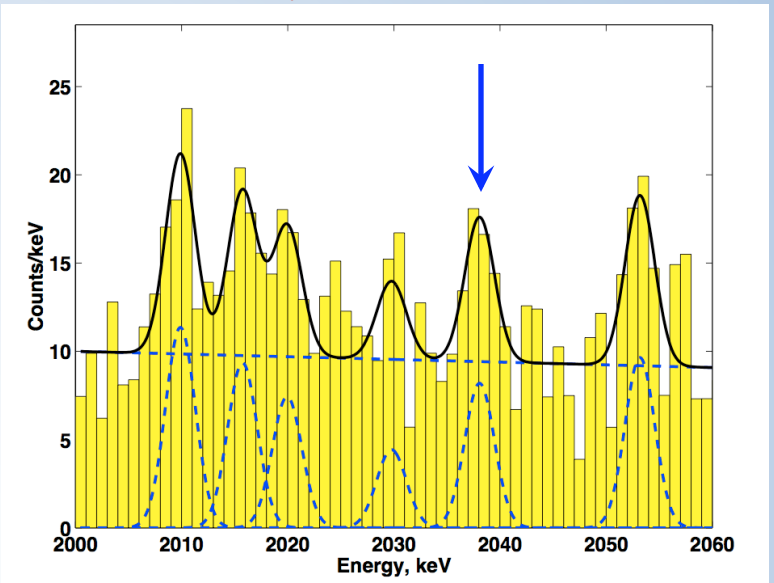
Many different technologies…

Cryogenic Bolometry	CUORE/Cuoricino-^{130}Te
Scintillation	CANDLES-^{48}Ca, SNO++-^{150}Nd **EXO-^{136}Xe**
Ionization	COBRA-CdTe , GERDA-^{76}Ge (LAr), **MAJORANA-^{76}Ge**
Time Projection and Tracking	MOON-^{100}Mo, Nemo/Super-Nemo (many)

Possible Discovery Requires Confirmation with Different Isotope(s)

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.

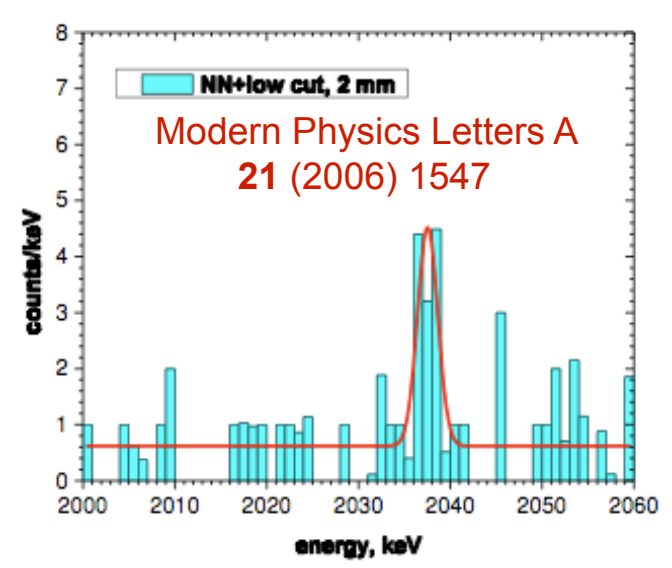
$T_{1/2} = 1.2 \times 10^{25}$ y

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

Background level depends on intensity fit to other peaks.

A More Recent Claim

6.8 sigma



Neural Net Analysis

Why >1 isotope?

- Unknown, technique-specific backgrounds
- Unknown isotope-specific backgrounds
- Ratio between half-lives can help determine decay mechanism.
- Nuclear matrix element uncertainties

Other Physics with DBD experiments

- Light WIMP Dark Matter
- Solar Axions
- Neutrino physics with radionuclide sources
- Pauli Exclusion Principle

The MAJORANA Collaboration (August 2010)

Note: Red text indicates students

Black Hills State University, Spearfish, SD
Kara Keeter

Duke University, Durham, North Carolina , and TUNL
Matthew Busch, James Esterline, Gary Swift, Werner Tornow

Institute for Theoretical and Experimental Physics, Moscow, Russia
Alexander Barabash, Sergey Konovalov,
Igor Vanushin, Vladimir Yumatov

Joint Institute for Nuclear Research, Dubna, Russia
Viktor Brudanin, Slava Egorov, K. Gusey,
Oleg Kochetov, M. Shirchenko, V. Timkin, E. Yakushev

Lawrence Berkeley National Laboratory, Berkeley, California and the University of California - Berkeley
Mark Amman, Marc Bergevin, Yuen-Dat Chan,
Jason Detwiler, Brian Fujikawa, James Loach,
Paul Luke, Ryan Martin, Alan Poon, Gersende Prior, Jing Qian,
Kai Vetter, Harold Yaver, Sergio Zimmerman

Los Alamos National Laboratory, Los Alamos, New Mexico
Melissa Boswell, Steven Elliott, Victor M. Gehman,
Andrew Hime, Mary Kidd, Kieth Rielage, Larry Rodriguez,
Michael Ronquest, Harry Salazar, David Steele

North Carolina State University, Raleigh, North Carolina and TUNL
Henning Back, Lance Leviner, Albert Young

Oak Ridge National Laboratory, Oak Ridge, Tennessee
Fred Bertrand, Greg Capps, Ren Cooper, Kim Jeskie,
David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan
Hiroyasu Ejiri, Ryuta Hazama, Masaharu Nomachi, Shima Tatsuji

Pacific Northwest National Laboratory, Richland, Washington
Craig Aalseth, James Ely, Jim Fast, Eric Hoppe, Todd Hossbach, Marty Keillor,
Richard T. Kouzes, Harry Miley, John Orrell, Doug Reid

Queen's University, Kingston, Ontario
Art McDonald

South Dakota School of Mines and Technology
Xinhua Bai, Haiping Hong, Stanley Howard, Dana Medlin, Vladimir Sobolev

University of Alberta, Edmonton, Alberta
Aksel Hallin

University of Chicago, Chicago, Illinois
Juan Collar, Nicole Fields

University of North Carolina, Chapel Hill, North Carolina and TUNL
Padraic Finnerty, Graham Giovanetti, Matthew Green, Florian Hauler, Reyco
Henning, Mark Howe, Sean MacMullin, David Phillips II, Jacquie Strain, Kris Vorren
John F. Wilkerson

University of South Carolina, Columbia, South Carolina
Frank Avignone, Richard Creswick, Horatio A. Farach, Leila Mizouni

University of South Dakolta, Vermillion, South Dakota
Vince Guiseppe, Tina Keller, Thomas Keenan, Dongming Mei, Wenchang Xiang,
Chao Zhang

University of Tennessee, Knoxville, Tennessee
William Bugg, Yuri Efremenko

University of Washington, Seattle, Washington
Tom Burritt, Jonathon Diaz, Peter J. Doe, Greg Harper, Robert Johnson,
Andreas Knecht, Michael Marino, Mike Miller, David Peterson
R. G. Hamish Robertson, Alexis Schubert, Tim Van Wechel, Bret Wolfe

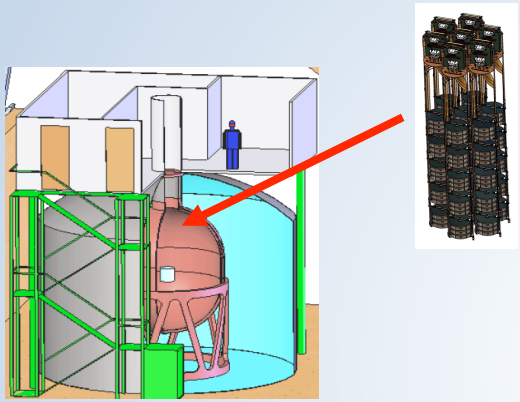
MAJORANA Collaboration Goals

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.
- MAJORANA DEMONSTRATOR Part of Early Science program
- 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.
- Sensitive to $m_{\beta\beta}$ ~ 10-20meV

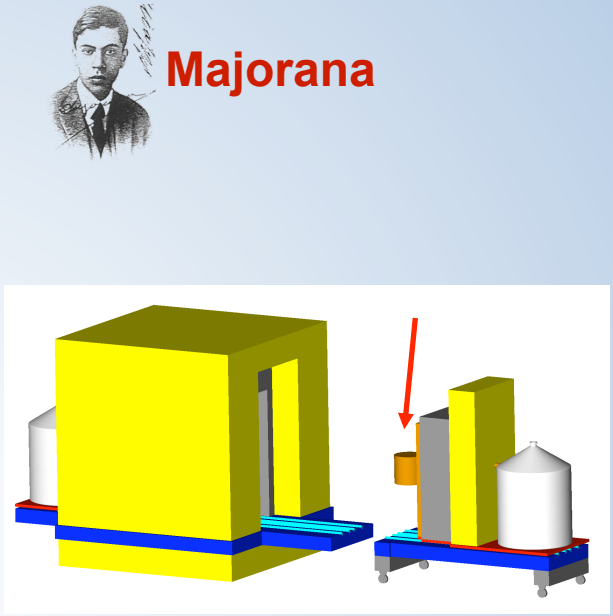
GERDA - Majorana

GERDA



- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I (mid 2008): ~18 kg (HdM/IGEX diodes)
- Phase II (mid 2009): add ~20 kg new detectors
  Total ~40 kg

Majorana



- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D prototype module
  Total 60 kg

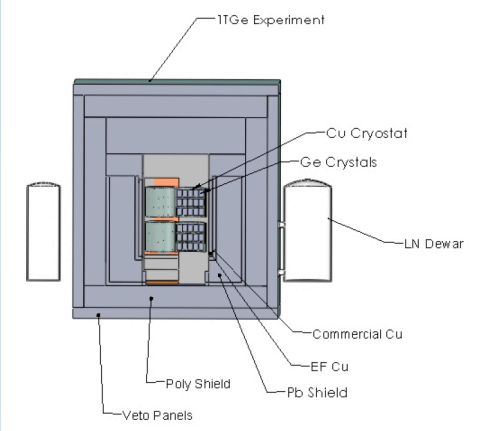
Joint Cooperative Agreement:

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

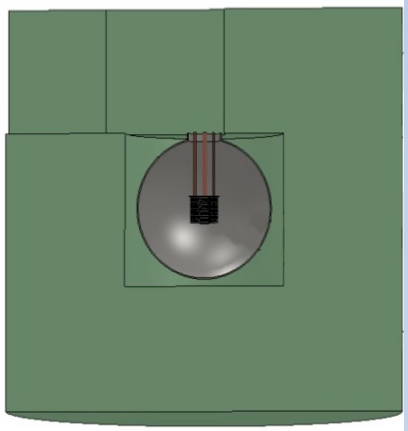
1tGe Concepts for DUSEL

(part of S4)

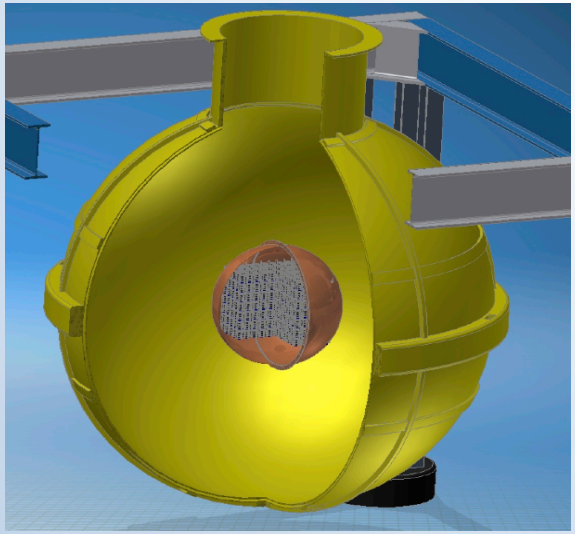
Compact high-Z shield



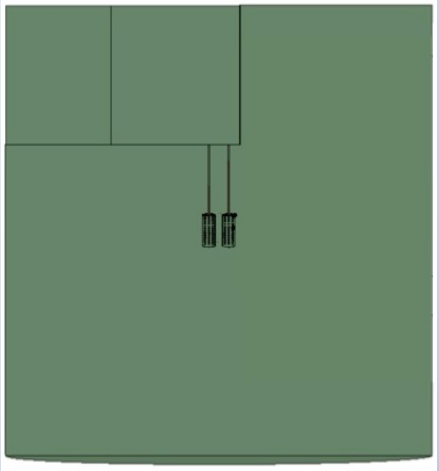
Direct Immersion in LAr/Water Shield



Vacuum Cryostat in LAr/Water Shield



Vacuum Cryostat in Water/ Scintillator Shield

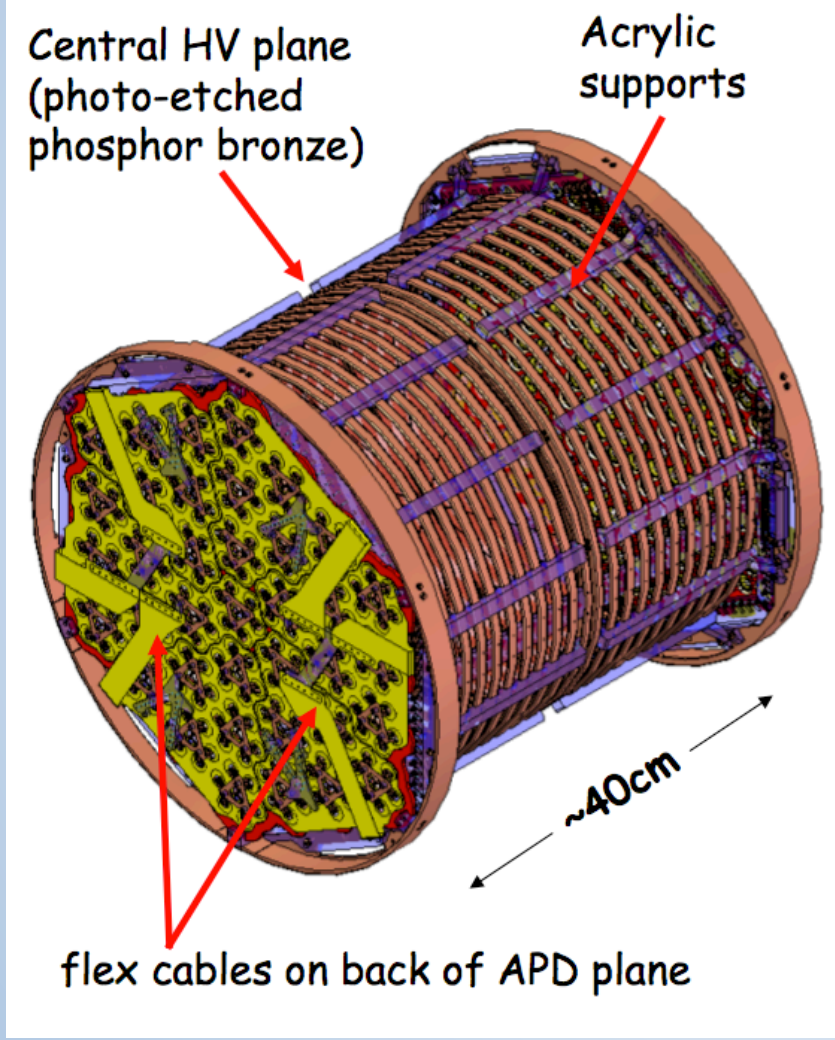


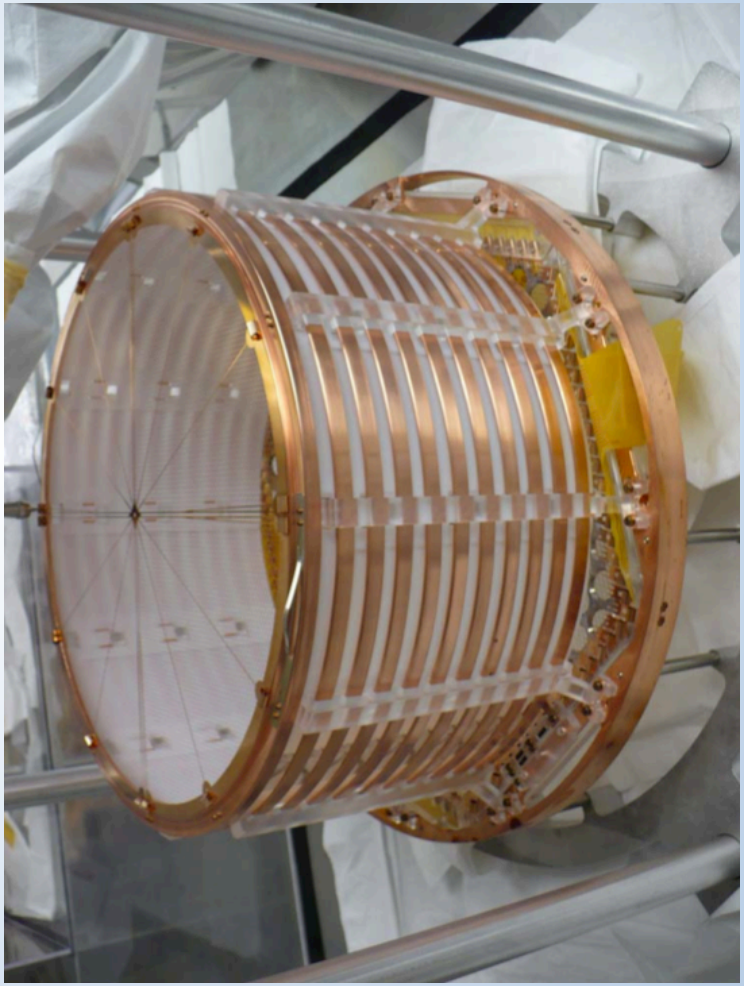
EXO Collaboration

K.Barry, E.Niner, A.Piepke
Physics Dept., U. of Alabama, Tuscaloosa AL, USA
P.Vogel
Physics Dept., Caltech, Pasadena CA, USA
A.Bellerive, M.Bowcock, M.Dixit, K.Graham, C.Hargrove, E.Rollin, D.Sinclair, V.Strickland
Carleton University, Ottawa, Canada
C.Benitez-Medina, S.Cook, W.Fairbank Jr., K.Hall, B.Mong
Colorado State U., Fort Collins CO, USA
M.Moe
Physics Dept., UC Irvine, Irvine CA, USA
D.Akimov, I.Alexandrov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Karelin, A.Kovalenko, A.Kuchenkov, V.Stekhanov, O.Zeldovich
ITEP Moscow, Russia
B.Aharmin, K.Donato, J.Farine, D.Hallman, U.Wichoski
Laurentian U., Canada

H.Breuer, C.Hall, L.Kaufman, D.Leonard, S.Slutsky, YR.Yen
U. of Maryland, College Park MD, USA
K.Kumar, A.Pocar
U. of Massachusetts, Amherst, Amherst MA, USA
M.Auger, G.Giroux, R.Gornea, F.Juget, G.Lutter, JL. Vuilleumier
Laboratory for High Energy Physics, Bern, Switzerland
N.Ackerman, M.Breidenbach, R.Conley, W.Craddock, S.Herrin, J.Hodgson, D.Mackay, A.Odian, C.Prescott, P.Rowson, K.Skarpaas, J.Wodin, L.Yang, S.Zalog
SLAC, Menlo Park CA, USA
L.Bartoszek, R.Cooper, R.DeVoe, M.Dolinski, B.Flatt, G.Gratta, M.Green, F.LePort, M.Montero-Diez, R.Neilson, A.Reimer-Muller, A.Rivas, K.O'Sullivan, K.Twelker
Physics Dept., Stanford University, Stanford CA USA

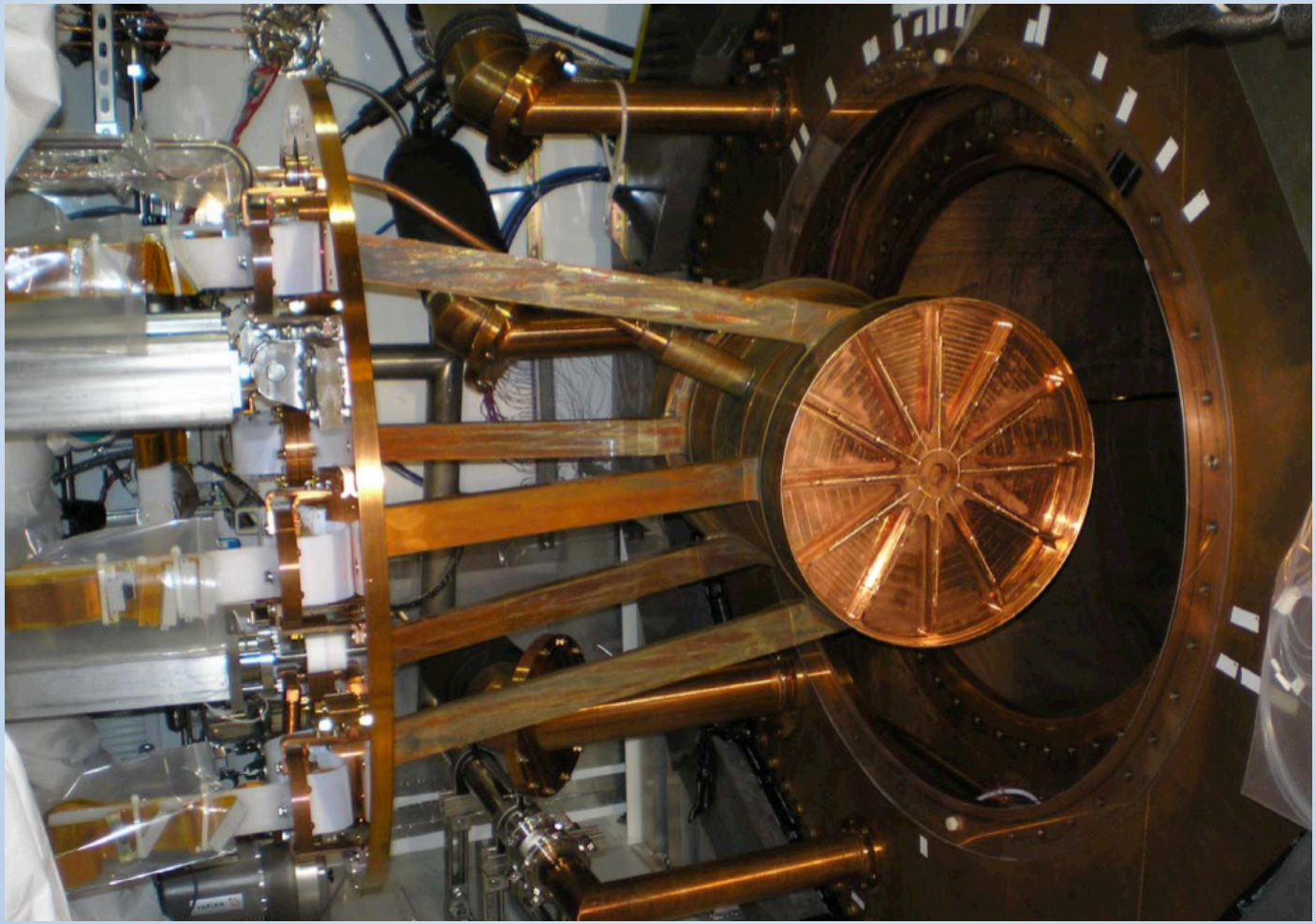
EXO-200 TPC


Central HV plane
(photo-etched
phosphor bronze)
Acrylic
supports
~40cm
flex cables on back of APD plane



EXO

- EXO-200 being commissioned at WIPP



1-10t EXO for DUSEL

(G. Gratta)

Assumptions:

1) 80% enrichment in 136
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy res only used to separate the 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2.481MeV endpoint
4) Use for 2νββ $T_{1/2}>1\cdot10^{22}$yr (Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2νββ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	19	24
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	4.3	5.3

* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area

‡ F.Simkovic et al., *Phys. Rev. C79*, 055501 (2009)

\# Menendez et al., *Nucl. Phys.* A818, 139 (2009)

Conclusions

- Neutrinoless double-beta decay has a compelling physics motivation
- Confirmation of potential discovery requires more than one technique/isotope.

Backups

Majorana vs. Dirac

Majorana particles are their own anti-particles.

Dirac particles are not.

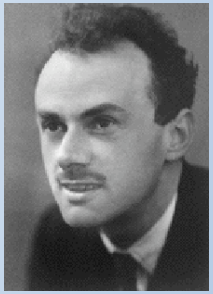
No fermions are known to be Majorana.

Experimental evidence consistent with both Majorana or Dirac neutrinos.

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

Ettore Majorana

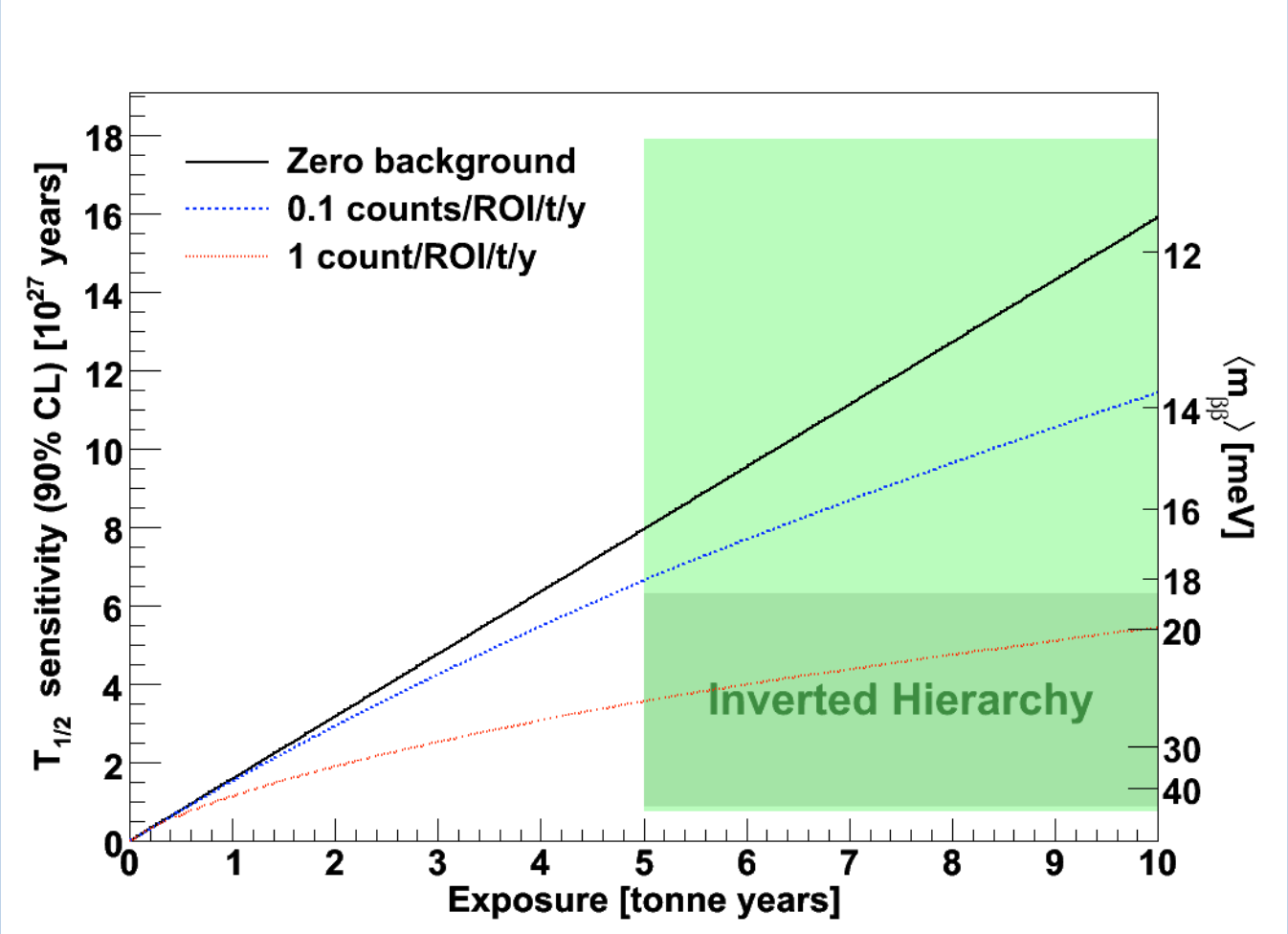
Paul Dirac



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

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)



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*

Flavor Mixing

Mass eigenstates different than flavor eigenstates.

⇒ Propagating neutrinos undergo flavor oscillations.

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

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

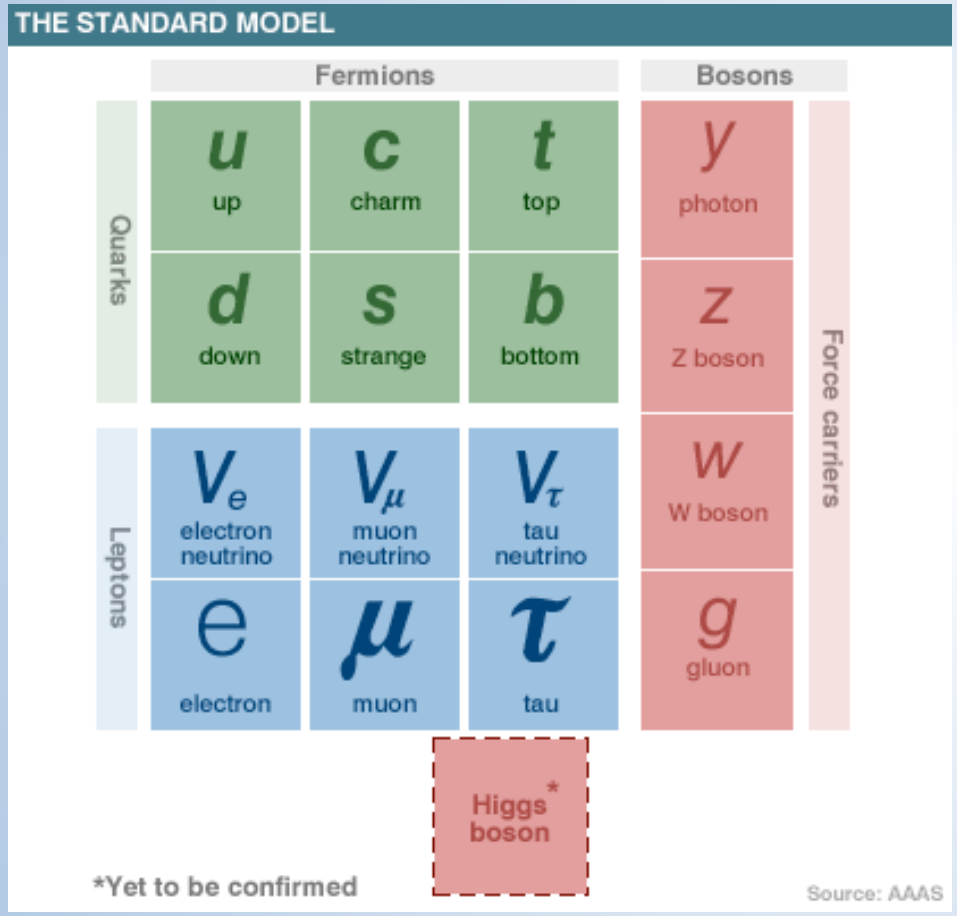
CP Phase

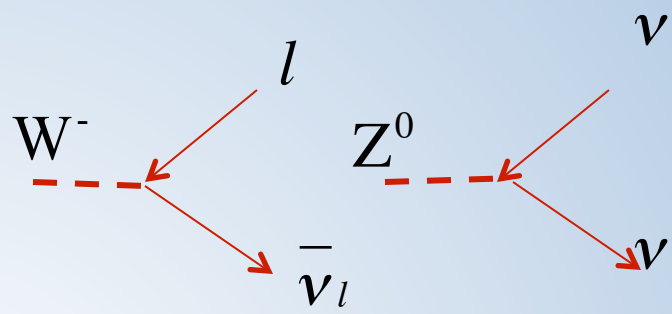
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}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

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

Majorana Phases

The weak force and neutrinos





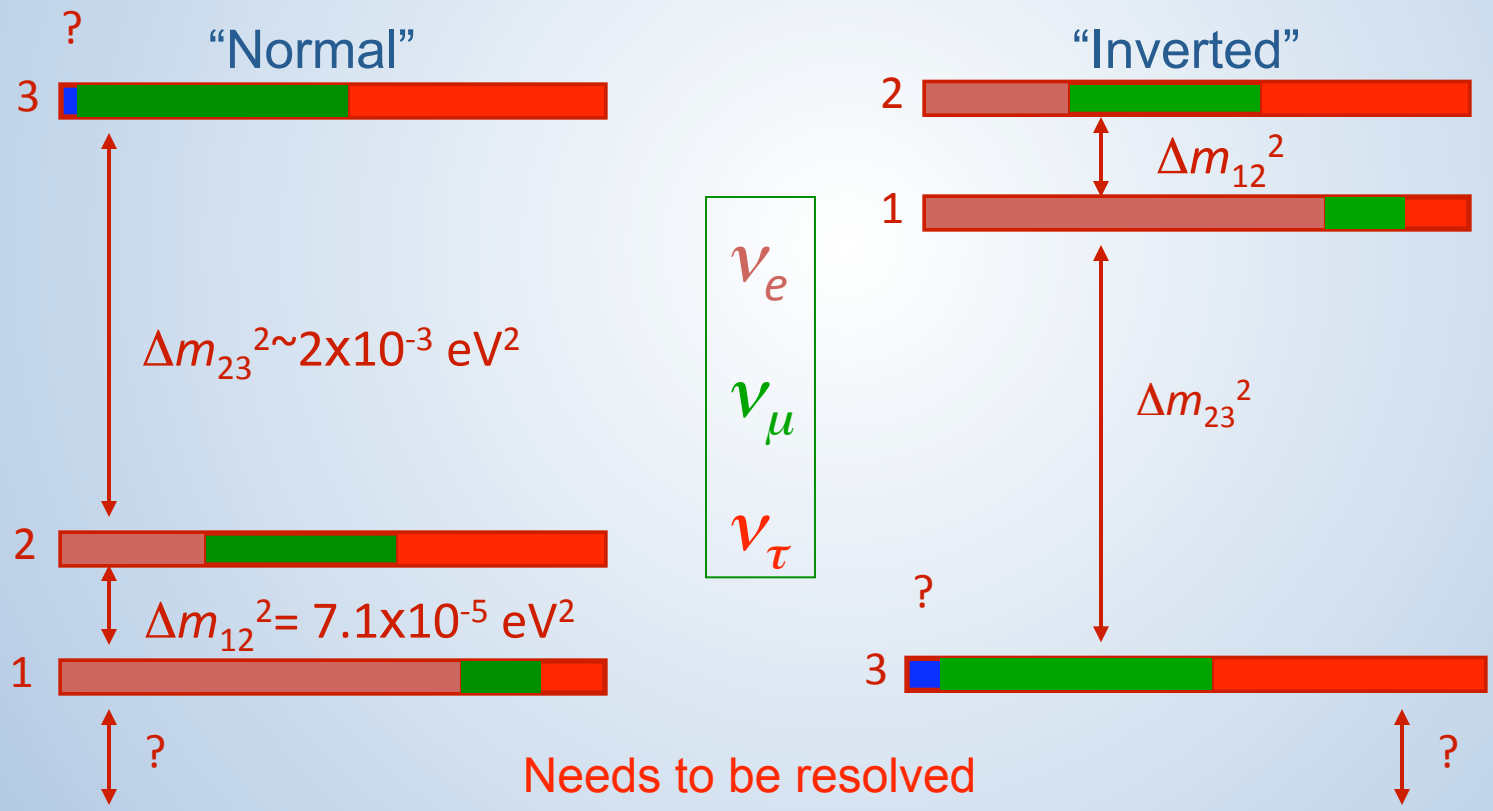
- Three flavors that undergo only weak interactions.
- Electrically neutral
- Neutrinos are massive, but very light
- Compelling evidence neutrinos undergo flavor oscillations.

Neutrino Masses

Absolute masses weakly constrained, < 1eV.

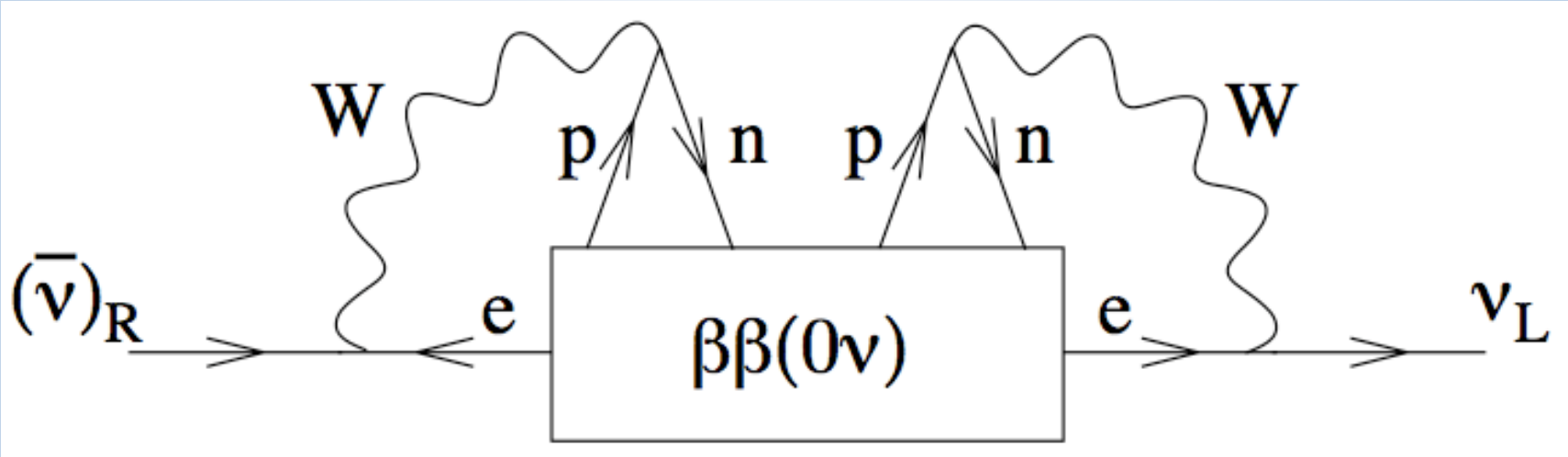
Relative mass-squared differences known.

Three possible scenarios: Quasi-degenerate, also:



Needs to be resolved

$0\nu\beta\beta$–decay and Majorana Neutrinos



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

Majorana nature verification ***independent*** of process that mediates $0\nu\beta\beta$ decay!

Nuclear structure approaches

In NSM (Madrid-Strassbourg group) a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states. Technically difficult, thus only few 0νββ-decay calculations

In QRPA (Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata groups) a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more 0νββ–decay calculations

In IBM (Iachello, Barea) the low lying states of the nucleus are modeled in terms of bosons. The bosons have either L=0 (s boson) or L=2 (d boson). The bosons can interact through one and to body forces giving rise to bosonic wave functions.

In PHFB (India/Mexico groups) w.f. of good angular momentum are obtained by making projection on the axially symmetric intrinsic HFB states. Nuclear Hamiltonian contains only quadrupole interaction.

Differences: i) mean field; ii) residual interaction; iii) size of the model space iv) many-body approximation

F. Simkovic, Neutrino 2010