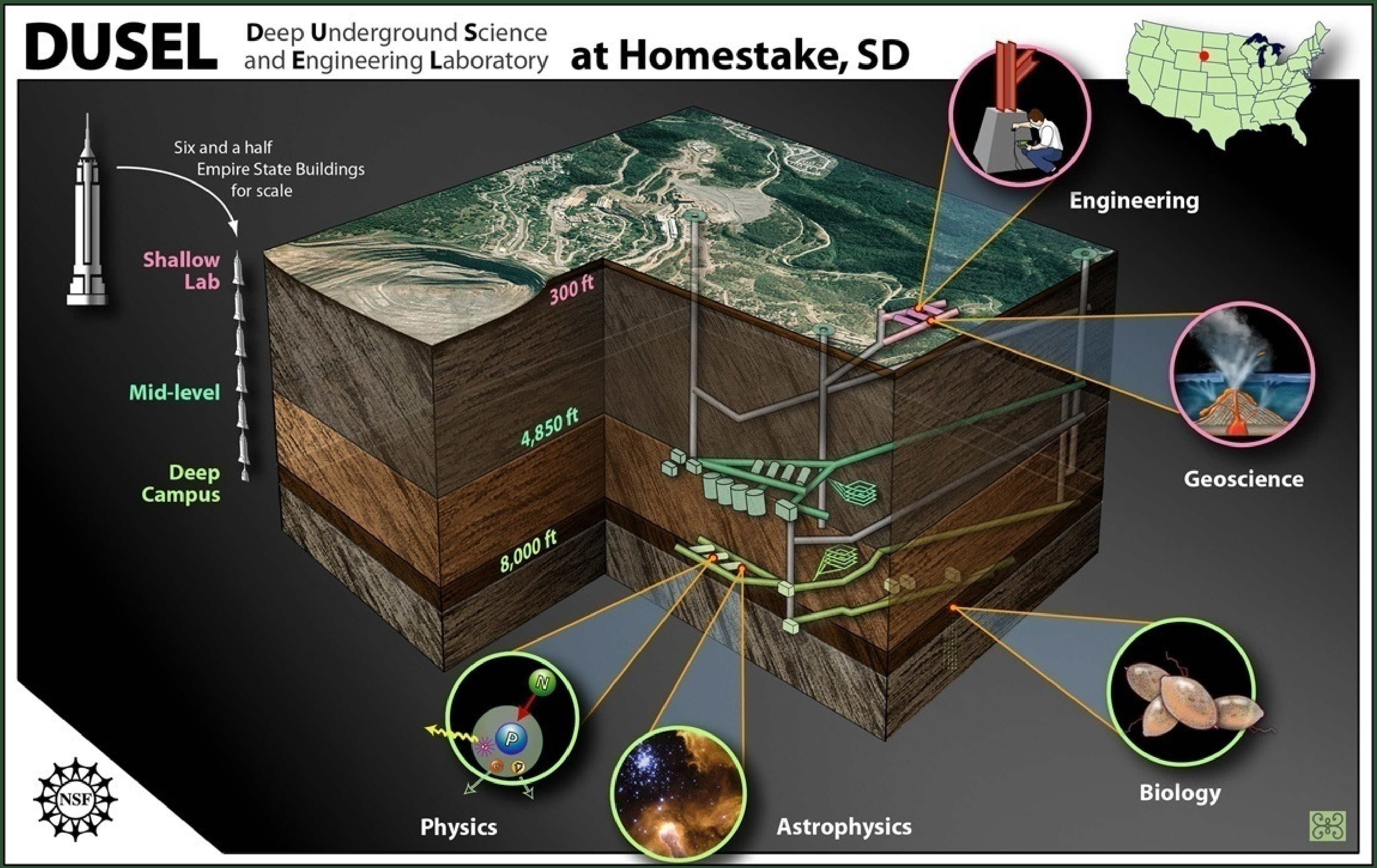
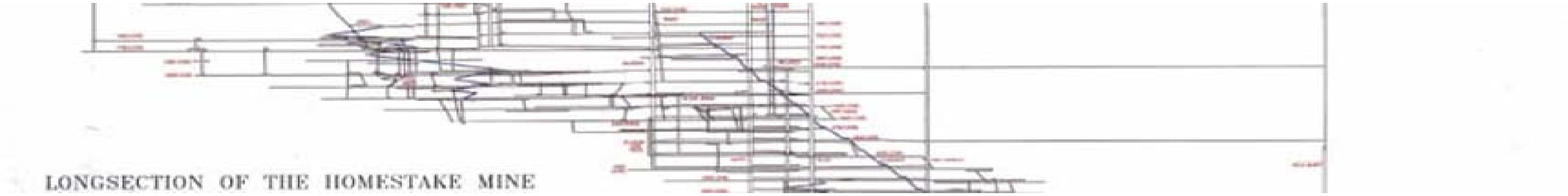
Double Beta Decay

Committee to Assess the Science Proposed for a Deep Underground Science and Engineering Laboratory (DUSEL)

December 14-15, 2010

Steve Elliott





Los Alamos

Steve Elliott

Double Beta Decay

- Neutrinos
- Double Beta Decay
- Matrix Elements
- The Need for Multiple Experiments
- Experimental Considerations
- The Future Worldwide Program

ν physics broadly impacts many areas of science

ν properties are critical input to many physics questions

- Particle/Nuclear Physics
  - Fundamental questions about standard model
  - Fundamental issues regarding interactions
- Cosmology
  - Large scale structure
  - Leptogenesis and matter-antimatter asymmetry
- Astrophysics
  - Supernova explosions
  - Solar burning

The major physics questions addressed by ββ

- **Decay can only occur if neutrinos are massive Majorana particles**
  - **This conclusion is model independent if ββ is observed.**
  - **Critical for understanding incorporation of mass into standard model**

    ββ is only practical experimental technique to answer this question

  ββ(0ν) decay rate proportional to neutrino mass
  - **Most sensitive laboratory technique (if Majorana particle)**
- **Decay can only occur if Lepton number conservation is violated**
  - **Leptogenesis?**
- **Fundamental nuclear/particle physics process**

ββ

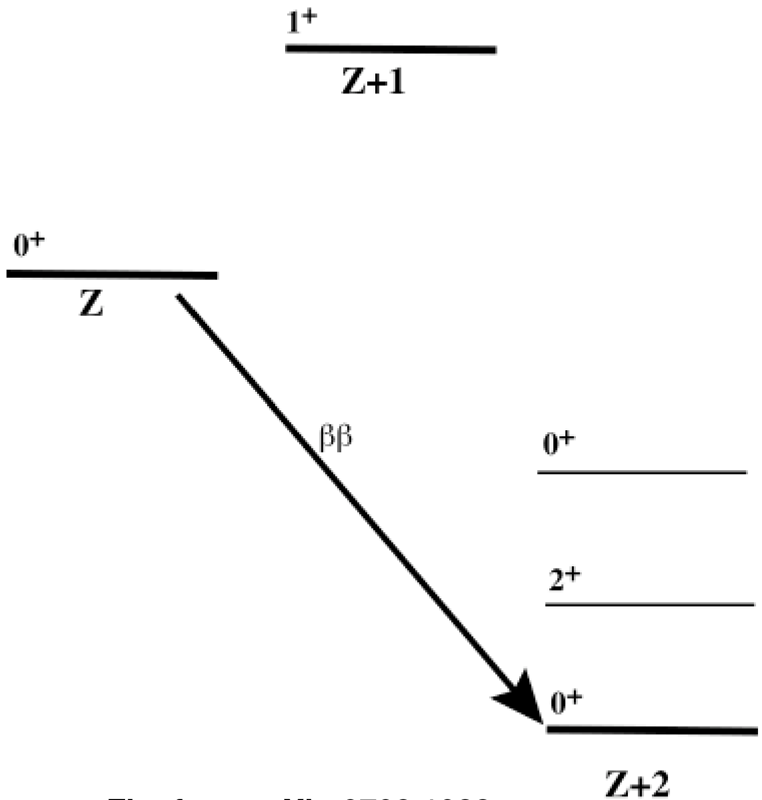


Fig. from arXiv:0708.1033

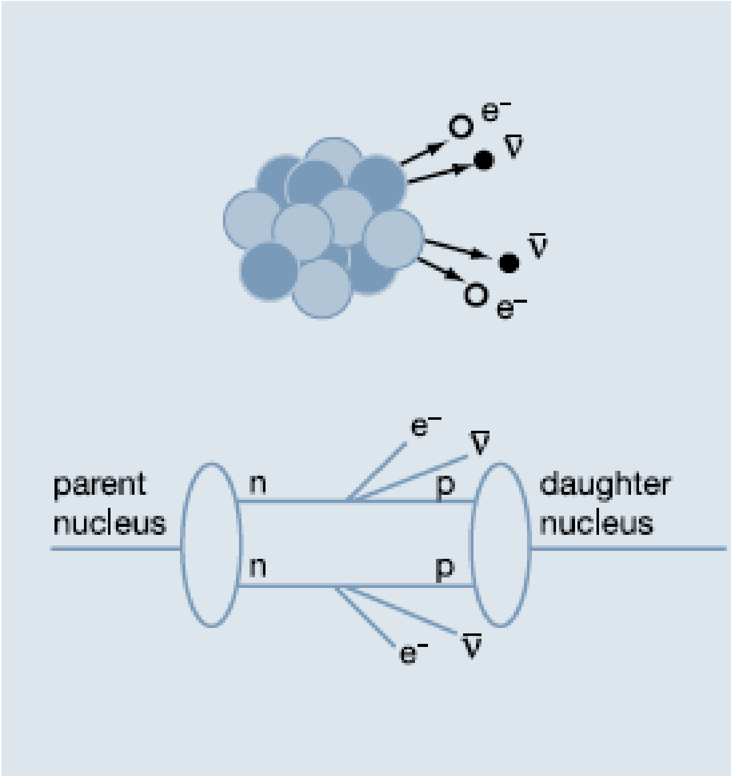
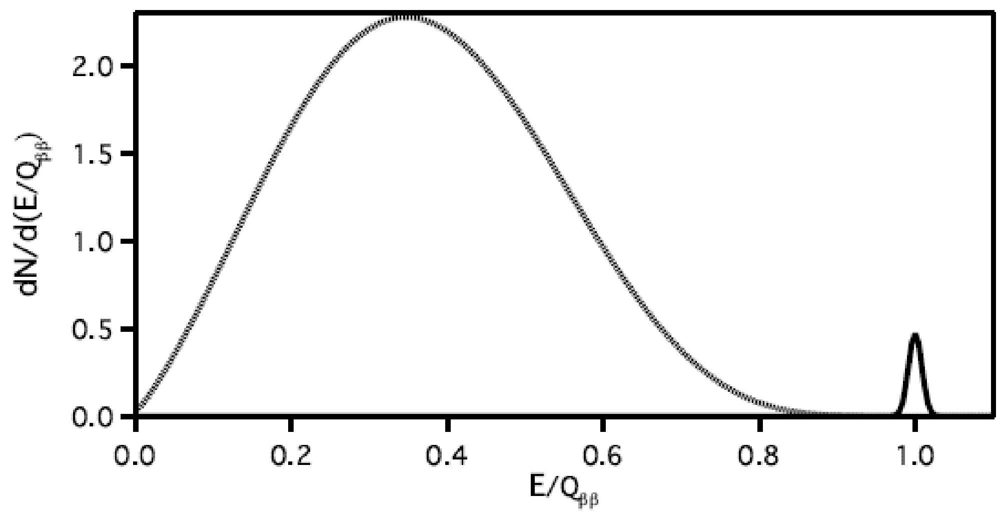


Fig. from Deep Science



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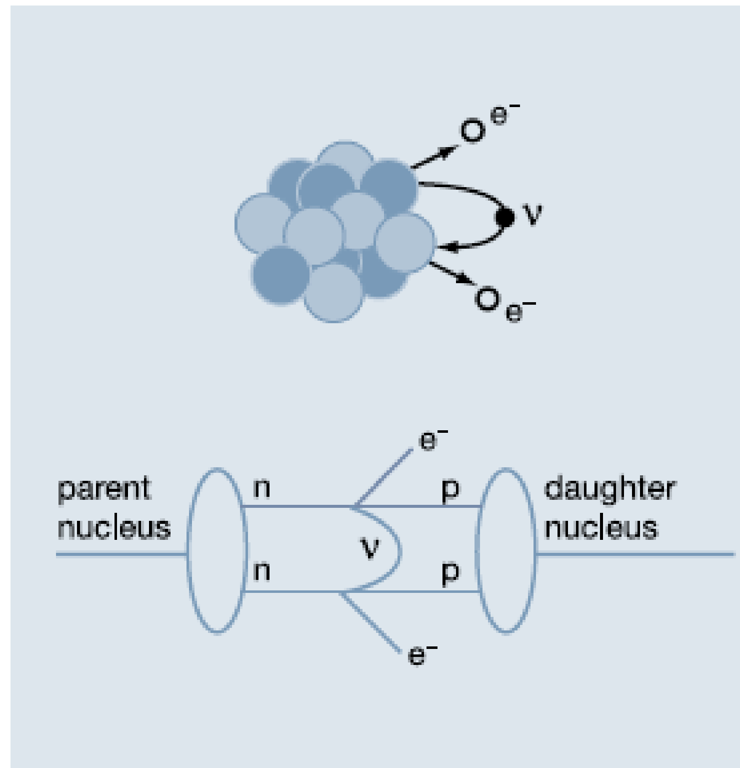


Fig. from Deep Science

ββ Decay Rates

LONGSECTION OF THE HOMESTAKE MINE

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

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

G are calculable phase space factors.

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

|M| are nuclear physics matrix elements.

Hard to calculate.

If Γ is non-zero, it implies Lepton number is not conserved and that neutrinos are massive Majorana particles.

What about mixing, m_ν & ββ(0ν)?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

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

virtual ν exchange

$\varepsilon = \pm 1$, CP conservation

Compare to β decay result:

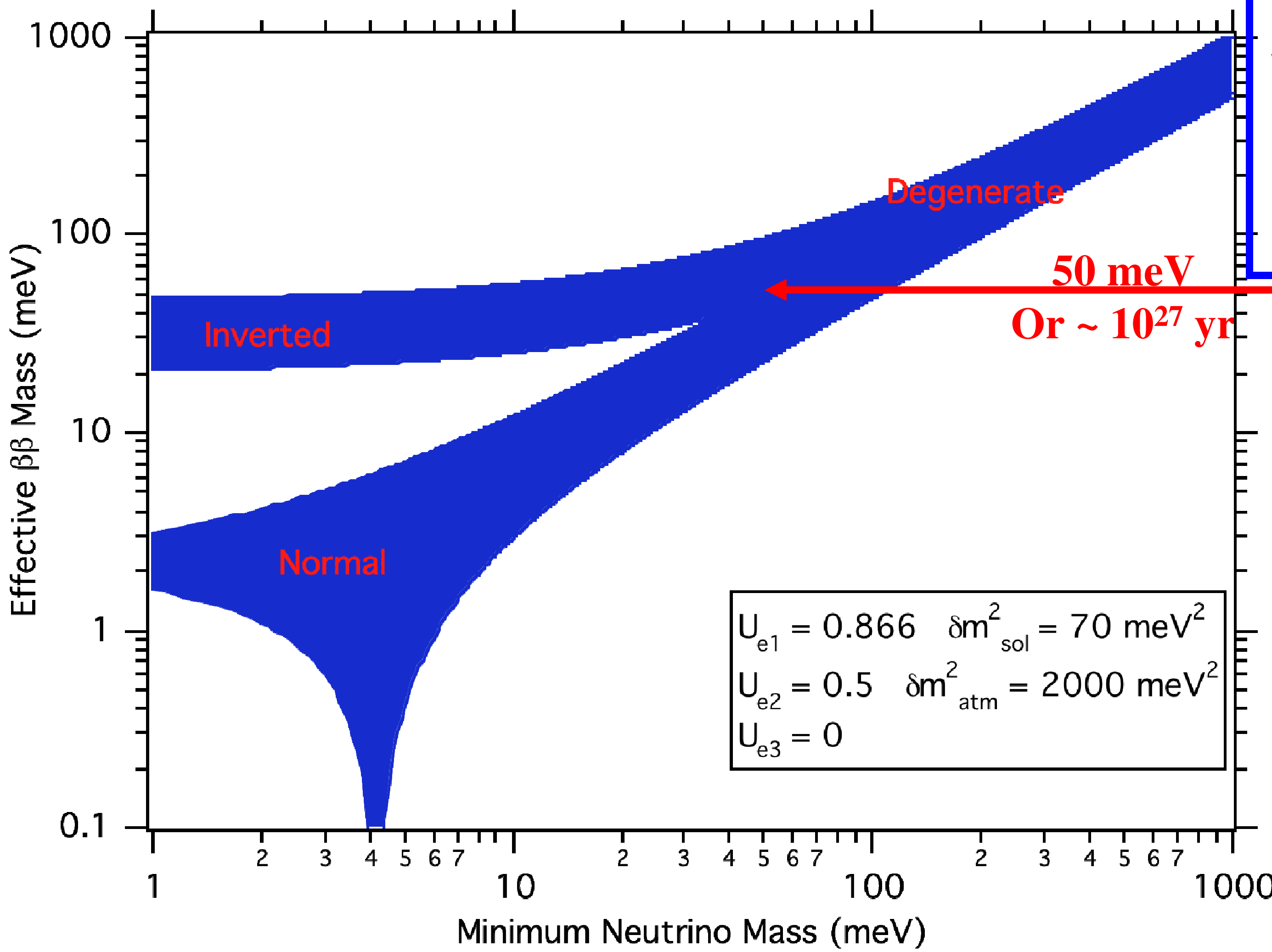
$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

real ν emission

Compare to cosmology:

$$\Sigma = \sum m_i$$

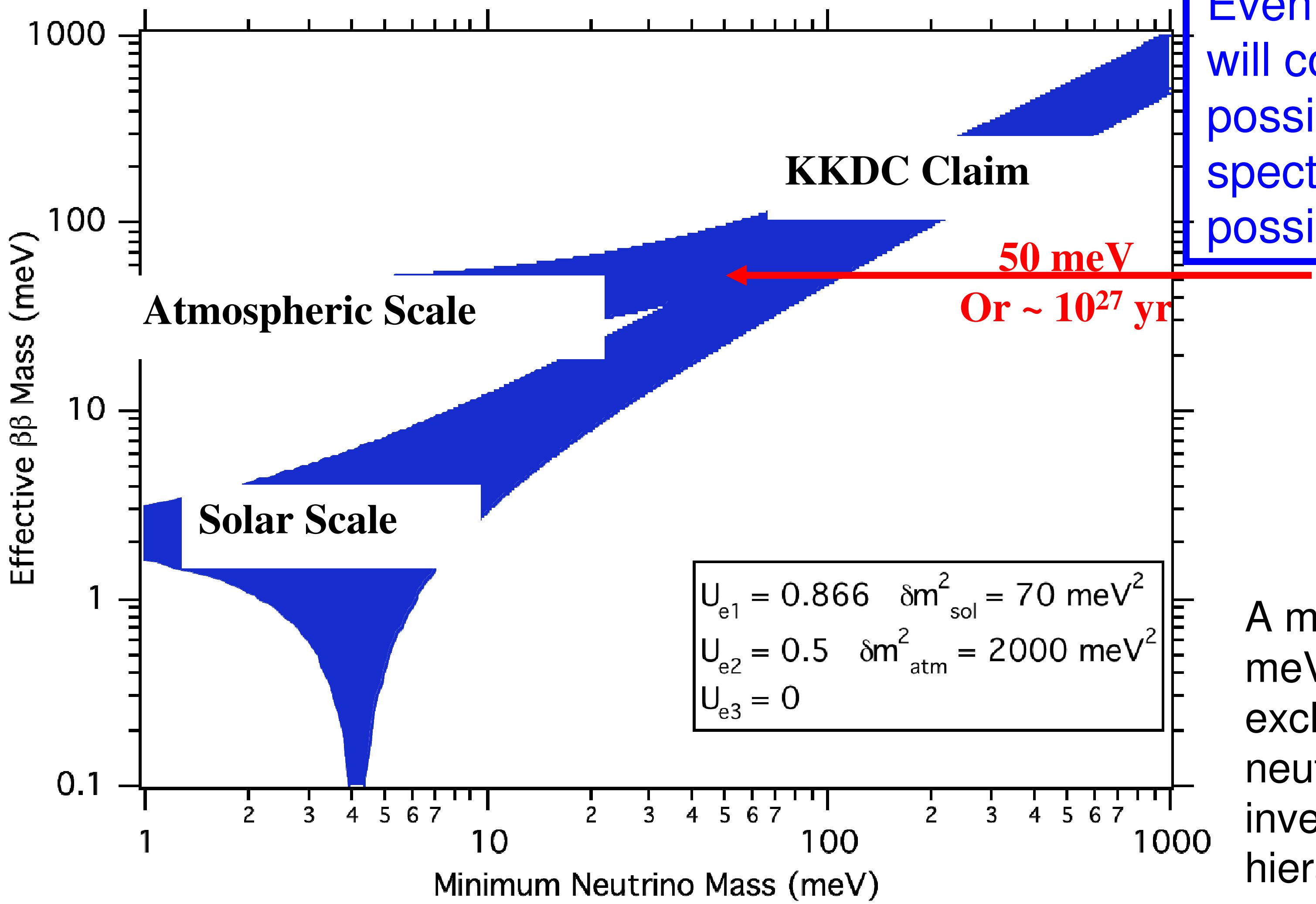
Sensitivity



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.

Sensitivity



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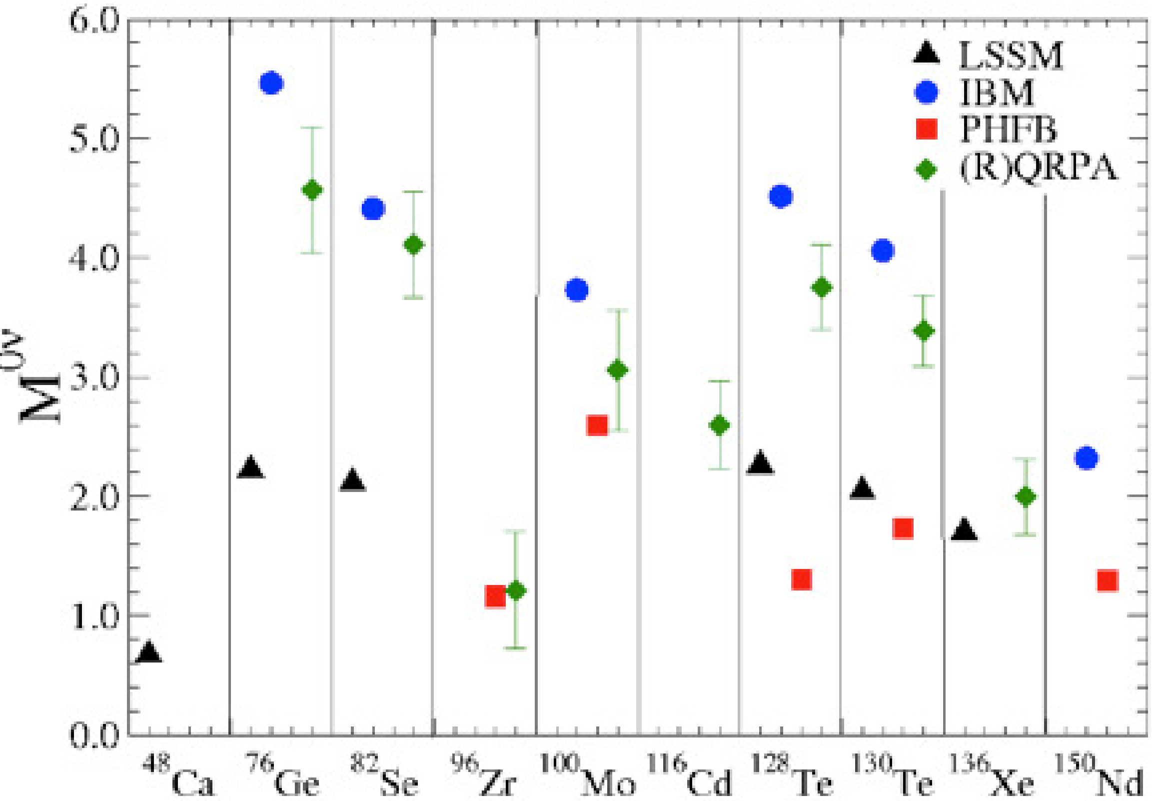
Nuclear Matrix Elements

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

Recent progress NSM-QRPA:
- 2005 within x 5
- 2010 agree within x 2

Does agreement between methods provide an estimate of theoretical uncertainty?

NME are calculated using different approximate methods: Shell Model; Quasi-random phase approximation (QRPA); Interacting Boson Model; Projected Hartree-Fock-Bogoliubov



Barea and Iachello, PRC 79 (2009), IBM approach
Menedez, Poves, Caurier, Nowacki NPA 818 (2009), NSM
K. Chaturvedi et al, PRC 78 (2008), PHFB approach
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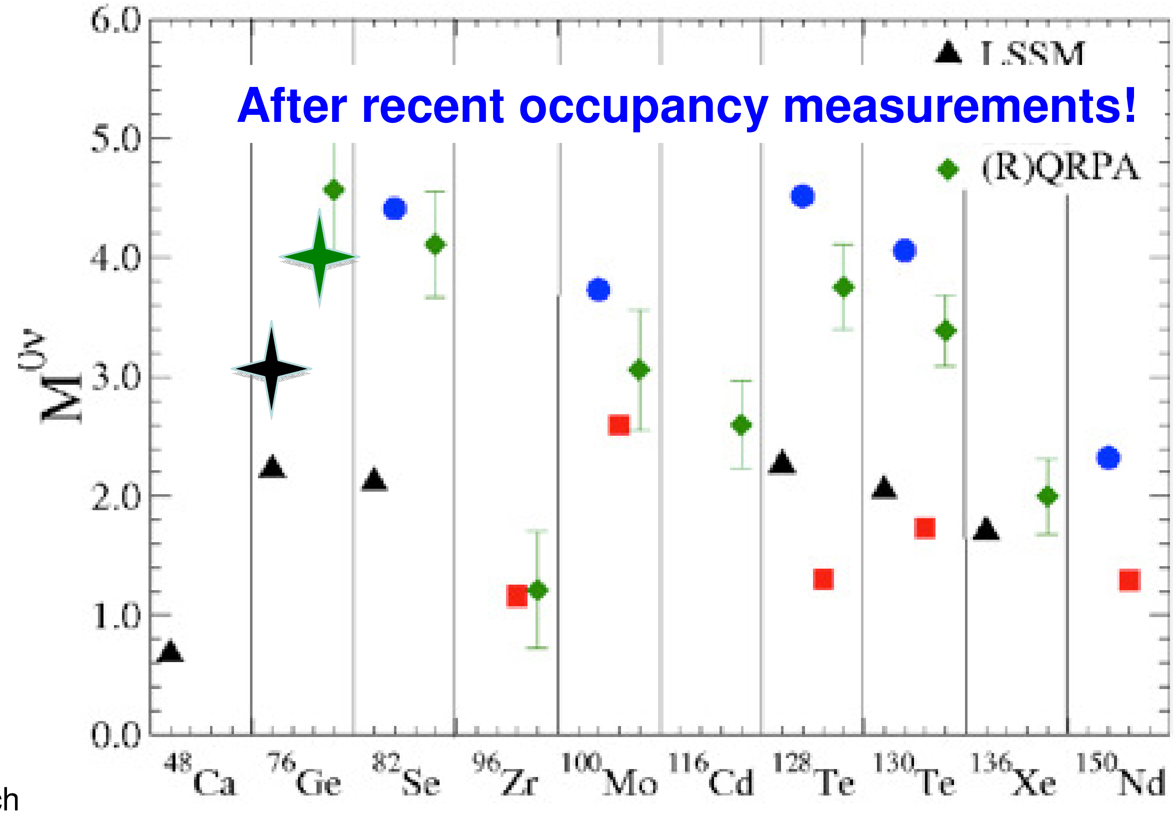

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Need Several Experiments to Fully Deduce Underlying Physics

If $\Gamma^{0\nu}$ is non-zero, ν's are massive Majorana particles, but…

$$\Gamma^{0\nu} = G^{0\nu} \left| M_{0\nu} \eta \right|^2 \quad \text{or} \quad G^{0\nu} \left| M_{0\nu} \right|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

- There are many physics models that lead to Lepton Number Violation (η), |M| can change with the model
  - Light neutrino exchange
  - Heavy neutrino exchange
  - R-parity violating supersymmetry
  - RHC
  - etc.

Observation of ββ(0ν) implies massive Majorana neutrinos, but:

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

Effective comparisons require experimental uncertainties to be small wrt theoretical uncertainties. Correlations between |M| calculations are important.

Require 3-4 results in different isotopes.

Total uncertainty, experimental/theoretical, 20-50%.

Deppish/Pas Phys. Rev. Lett. 98, 232501 (2007)
Gehman/Elliott J. Phys. G 34, 667 (2007) [Erratum G35, 029701 (2008)
Fogli/Lisi/Rotunno Phys. Rev. D 80, 015024 (2009)

The need for more than 1 experiment

It is very important to understand that a healthy neutrinoless double-beta decay program requires more than one isotope. This is because:

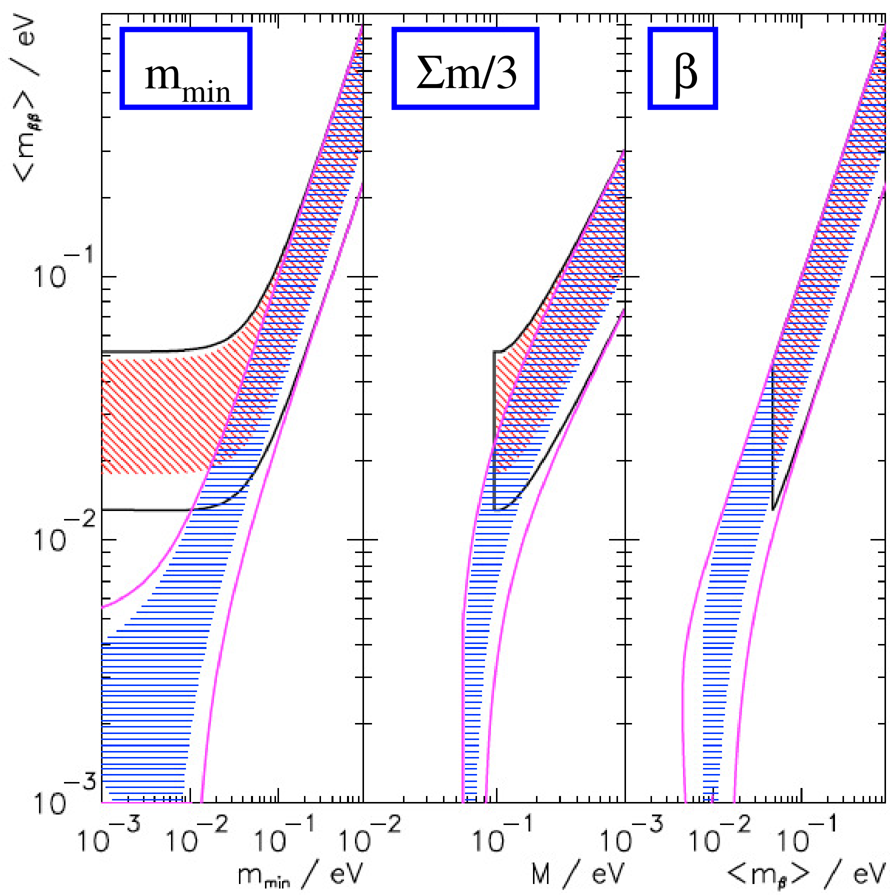
- **There are many unknown gamma transitions and a line observed at the "end point" in one isotope does not necessarily imply that $0\nu\beta\beta$ decay was discovered (daughter tagging and exceptional energy resolution help)**
- **Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities**
- **Different isotopes correspond to vastly different experimental techniques**
- **2 neutrino background is different for various isotopes (low rates in some isotopes and energy resolution)**
- **The elucidation of the mechanism producing the decay requires the analysis of more than one isotope**

3 neutrino mass measurements
ββ, cosmology, β

- Because we know ν's have mass, even null results constrain the mass spectra.
- No m_ν measurement directly determines a mass eigenvalue.
- The 3 techniques measure different combinations of neutrino parameters. All 3 play critical roles.
- In degenerate region, all m_ν techniques measure a value approximately equal to the average mass eigenvalue.

ββ might lead to Majorana phase data. Cosmology is model dependent. β decay is least model dependent.

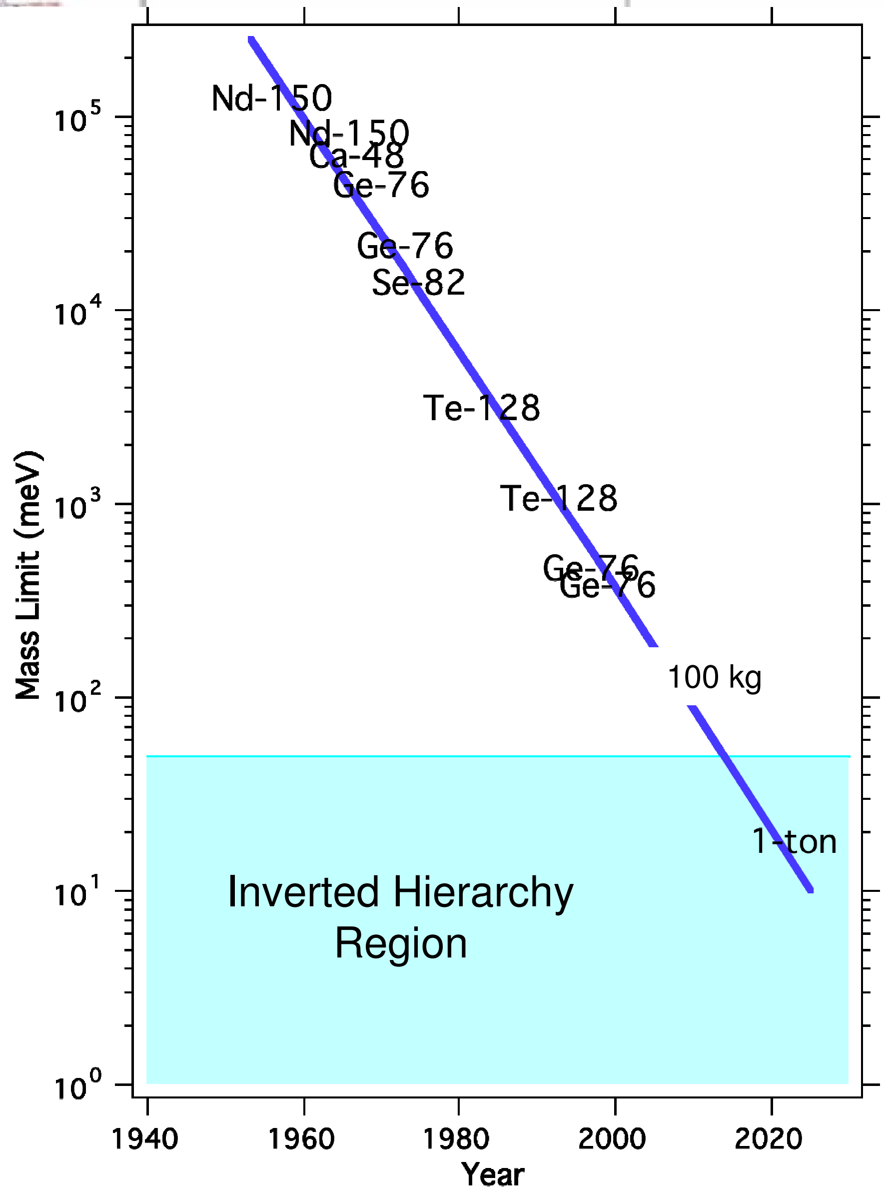
Vogel, Piepke, Particle Data Book



Past Results: Very long US History

^{48}Ca CaF$_2$	>5.8x10^{22} y	<(3.5-22) eV
^{76}Ge H-M	>1.9x10^{25} y	<0.35 eV
^{76}Ge IGEX	>1.6x10^{25} y	<(0.33-1.35) eV
^{76}Ge KDHK	=1.2x10^{25} y	=0.44 eV
^{82}Se NEMO	>3.6x10^{23} y	<(0.89-1.61) eV
^{96}Zr NEMO	>9.2x10^{21} y	<(7.2-19.5) eV
^{100}Mo NEMO	>1.1x10^{24} y	<(0.45-0.93) eV
^{116}Cd Kiev	>1.7x10^{23} y	<1.7 eV
^{128}Te geochem	>7.7x10^{24} y	<(1.1-1.5) eV
^{130}Te (CUORE)	>2.94x10^{24} y	<(0.21-0.70) eV
^{136}Xe Gotthard	>4.4x10^{23} y	<(1.8-5.2) eV
^{150}Nd NEMO	>1.8x10^{22} y	<(1.7-7.6) eV

Elliott & Vogel
Annu. Rev. Part. Sci. 2002 52:115



Great Number of Proposed Experiments Worldwide

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
COBRA	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORICINO	^{130}Te	11 kg	TeO_2 bolometers	Complete - 2008	Gran Sasso
CUORE	^{130}Te	200 kg	TeO_2 bolometers	Construction - 2012	Gran Sasso
DCBA	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Construction - 2011	WIPP
EXO	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	DUSEL
GEM	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	
GENIUS	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Construction - 2012	Gran Sasso
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
KamLAND-Zen	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Contruction - 2011	Kamioka
MAJORANA	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2013	SUL
MOON	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
NEXT	^{136}Xe	80 kg	gas TPC	Development	Canfranc
SNO+	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2012	SNOLab
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Frejus
Xe	^{136}Xe	1.56 t	^{enr}Xe in liq. scint.	Development	
XMASS	^{136}Xe	10 ton	liquid Xe	Inactive for $\beta\beta$	Kamioka
HPXe	^{136}Xe	tons	High Pressure Xe gas	Development	

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Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka

Of these efforts, EXO and 1TGe are trying to reach tonne scale.

- **Both are major US efforts**
- **Both propose to go to DUSEL**
- **Both have significant foreign participation**
- **Both include many university groups**
- **Both include many young investigators**

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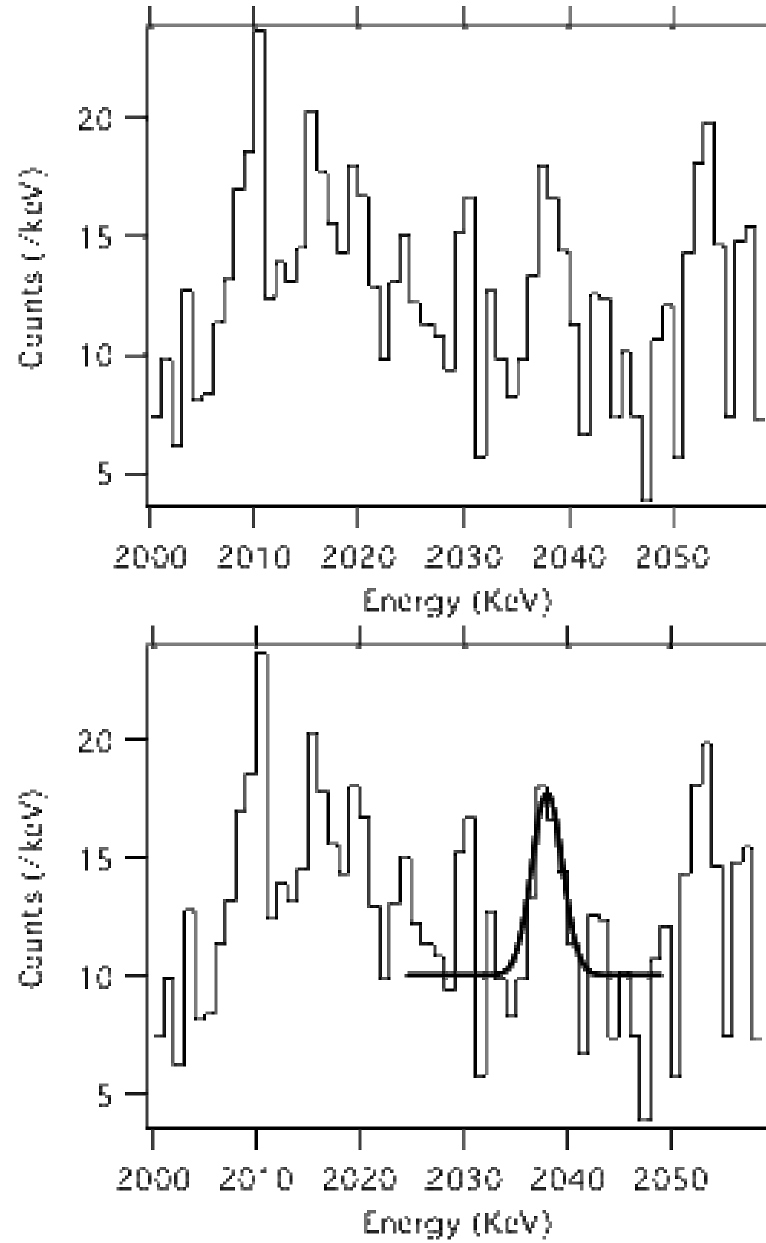
A Recent Claim
has become a litmus test for future efforts

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)

Future Data Requirements

Why wasn't this claim sufficient to avoid controversy?

- Low statistics of claimed signal - hard to repeat measurement
- Background model uncertainty
- Unidentified lines
- Insufficient auxiliary handles

Result needs confirmation or refutation

Various Levels of Confidence in a Result

- Preponderance of the evidence: a combination of
  - Correct peak energy
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
- Beyond a reasonable doubt: include the following
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay
- Smoking Gun
  - See the process in several isotopes

International Program in $\beta\beta$

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

SUL/DUSEL will play a significant role far into the future!

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

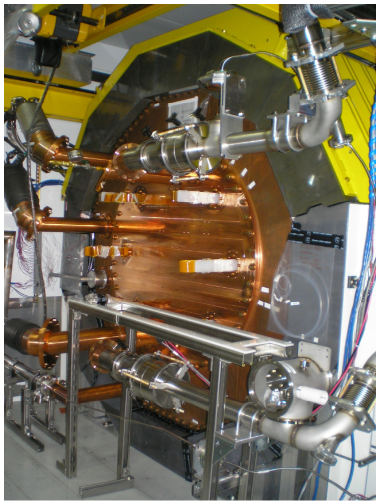
Solar Scale: Showstoppers?

- 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

Double Beta Decay in the US

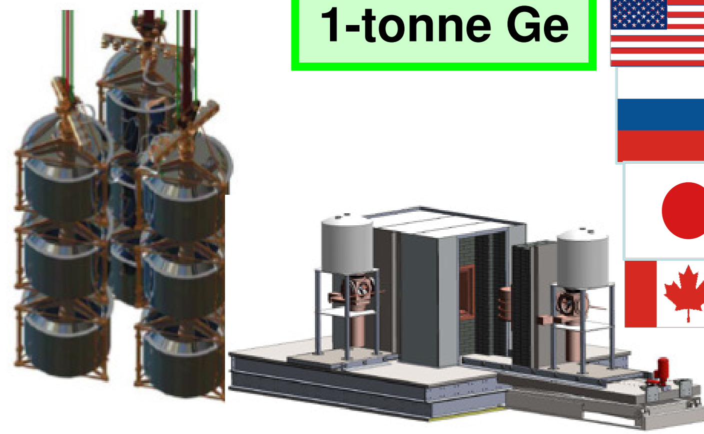
two collaborations that are led by US groups and proposing to work at DUSEL

EXO



$$\Gamma_{0\nu} = G_{0\nu}|M_{0\nu}|^2 m_\nu^2$$

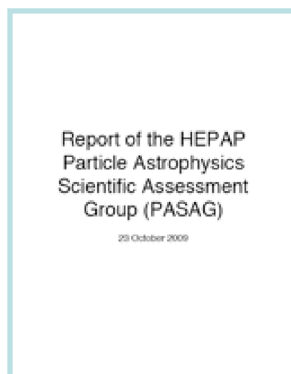
At least one neutrino has a mass >50 meV. These experiments will have a sensitivity below 50 meV.

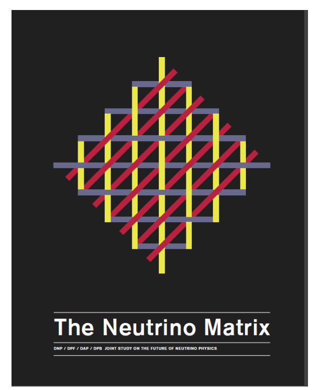


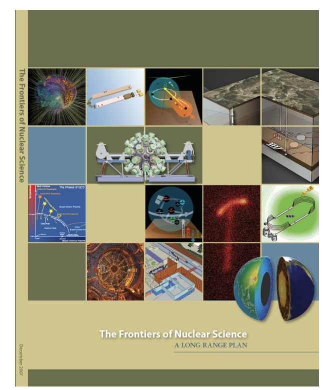
1-tonne Ge

Two detectors proposed for DUSEL: EXO and 1TGe, which use isotopes of ^{136}Xe and ^{76}Ge with very different and complementary techniques. Both are currently building prototypes for tonne-scale experiment.

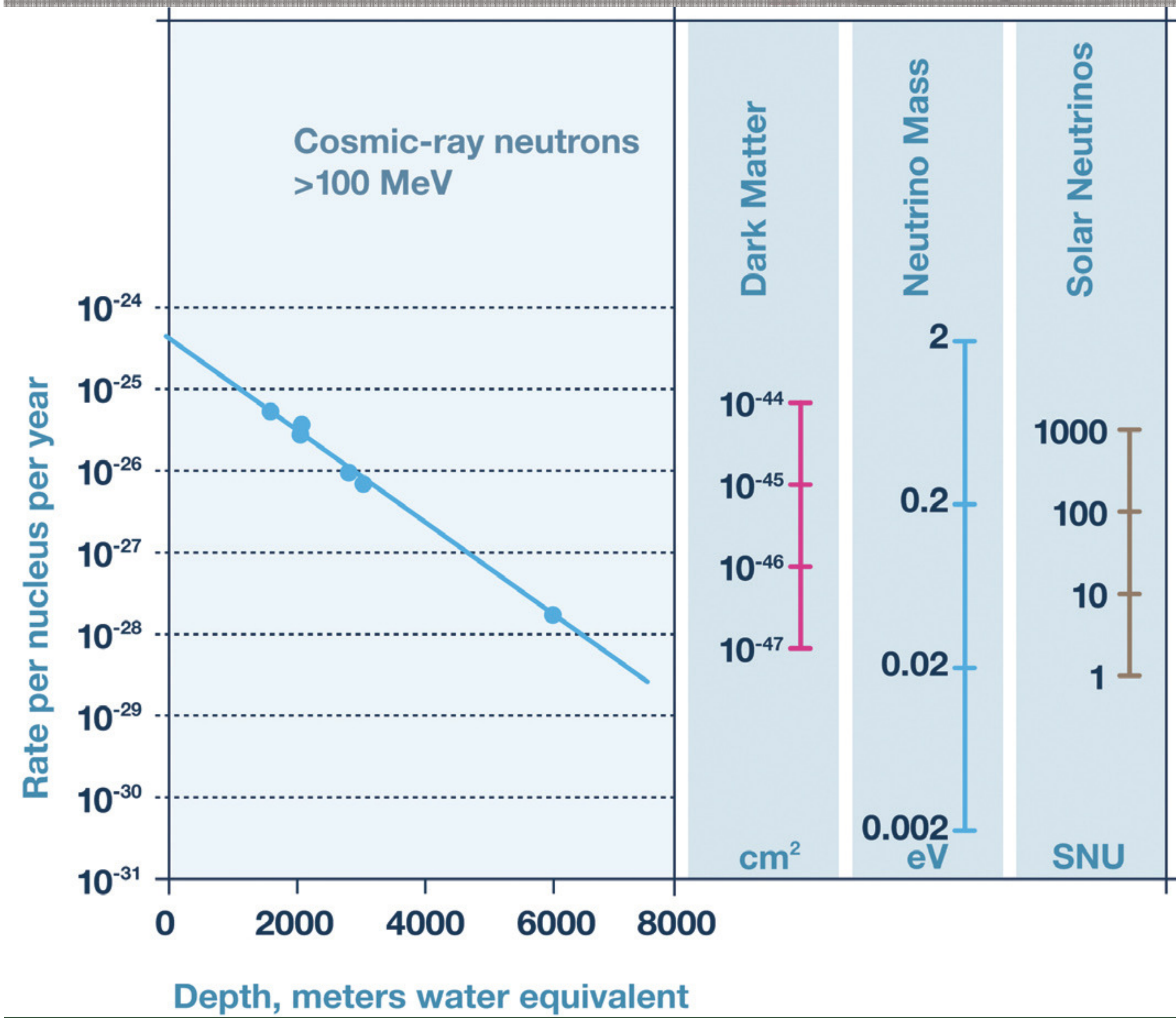
These reports call out the need for ββ in general and these experiments in particular. CUORE was also well recommended.







Key Infrastructure Need is Depth



1TGe and EXO have written depth requirement documents for the DOE-NSF JOG. Both conclude that background risks to experiments at the tonne scale, related to cosmic rays, are eliminated by going to 7400'.

An exciting time for ββ!

For at least one neutrino:

$$m_i > \sqrt{\delta m^2_{atmos}} \approx 50 meV$$

Capability of the technologies:

$$\langle m_{\beta\beta} \rangle \leq 50 meV$$

$< m_{\beta\beta} >$ in the range near 50 meV is very interesting.

Conclusions

- The present technology is ready for atmospheric scale sensitivity and we can at least discuss it for the solar scale.
- Even null results will be interesting.
- Need several measurements with a total uncertainty (experiment & theory) of ~50% or less, and eventually even better (20%).
- The worldwide program will support several experiments and DUSEL is well poised to house 2 experiments on a very timely schedule.

If we see ββ, the qualitative physics results are profound, but next we'll want to quantify the underlying physics. We need space underground to pursue this program.

EXTRAS

Background Considerations

$\beta\beta(2\nu)$

- natural occurring radioactive materials
- neutrons
- long-lived cosmogenics

Some of the usual suspects

LONGSECTION OF THE HOMESTAKE MINE

$\beta\beta(2\nu)$

- For the current generation of experiments, resolutions are sufficient to prevent tail from intruding on peak. Becomes a concern as we approach the ton scale
- Resolution, however, is a very important issue for signal-to-noise

- Natural Occurring Radioactive Materials
  - Solution mostly understood, but hard to implement
    - Great progress has been made understanding materials and the U/Th contamination, purification
    - Elaborate QA/QC requirements
  - Future purity levels greatly challenge assay capabilities
    - Some materials require levels of 1μBq/kg or less for ton scale expts.
    - Sensitivity improvements required for ICPMS, direct counting, NAA

The other usual suspects

LONGSECTION OF THE HOMESTAKE MINE

- Long-lived cosmogenics
  - material and experimental design dependent
  - Minimize exposure on surface of problematic materials
- Neutrons (elastic, inelastic, short-lived cosmogenics)
  - (α,n) up to 10 MeV can be shielded
  - High-energy-μ generated n are a more complicated problem
    - Depth and/or well understood anti-coincidence techniques
    - Rich spectrum and hence difficult at these low rates to discern actual process, e.g. (n,n'γ) reactions
    - Simulation codes not entirely accurate wrt low-energy nuclear physics
    - Low energy nuclear physics is tedious to implement and verify

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
5×10^{26}	10	100	
5×10^{27}	**To reach atmospheric scale need BG on order 1/t-y.**	40	Atmospheric
$>10^{29}$	<0.05	<10	Solar

An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b \Delta E}{M t_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)
Large Q value, fast ββ(0ν)
Good source radiopurity
Demonstrated technology
Ease of operation
Natural isotope
Small volume, source = detector
Good energy resolution
Slow ββ(2ν) rate
Identify daughter in real time
Event reconstruction
Nuclear theory

Key Past Experimental Limitations

- Scintillators: Resolution and internal radioactivity
- Tracking Detectors: Source mass
- Calorimeters: External background
  - Most sensitive techniques to date

How many experiments?

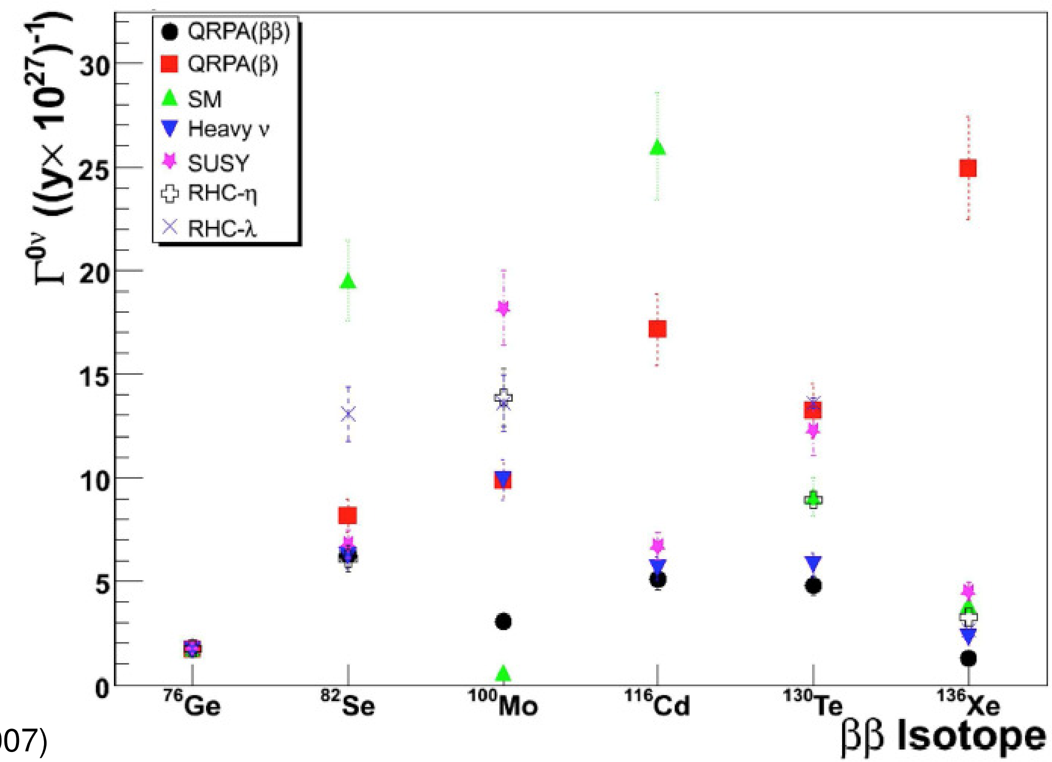
Requires results from 3-4 isotopes & calculation of NME to ~20%

Compare theories

- Even though theory is uncertain, one can estimate the number of required experiments by using the theoretical calculations at face value to compare the spread.

Is there a preferred set of isotopes?

- Perhaps, but this a dangerous stretch for the theory.



Gehman, Elliott, J. Phys. G: Nucl. Part. Phys. 34, 667 (2007)
Deppish, Pas, Phys. Rev. Lett. 98 232501

Why a precision measurement?

If $\langle m_{\beta\beta} \rangle$ is near the degenerate scale:

- We will want to compare results from several isotopes to fully understand the underlying physics.
- A 10-20% decay rate measurement will allow effective comparisons between isotopes, when the matrix element uncertainty nears ~20%.