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|---|---|
| Title: | Double Beta Decay |
| Author(s): | Elliott, Steven R. |
| Intended for: | Review of underground facility and double-beta decay and dark matter experiments in Korea. I am a reviewer because of my expertise in double beta decay. I will present background material at a short symposium covering material for the review. |

Los Alamos
NATIONAL LABORATORY
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Los Alamos

Steve Elliott

# Double Beta Decay

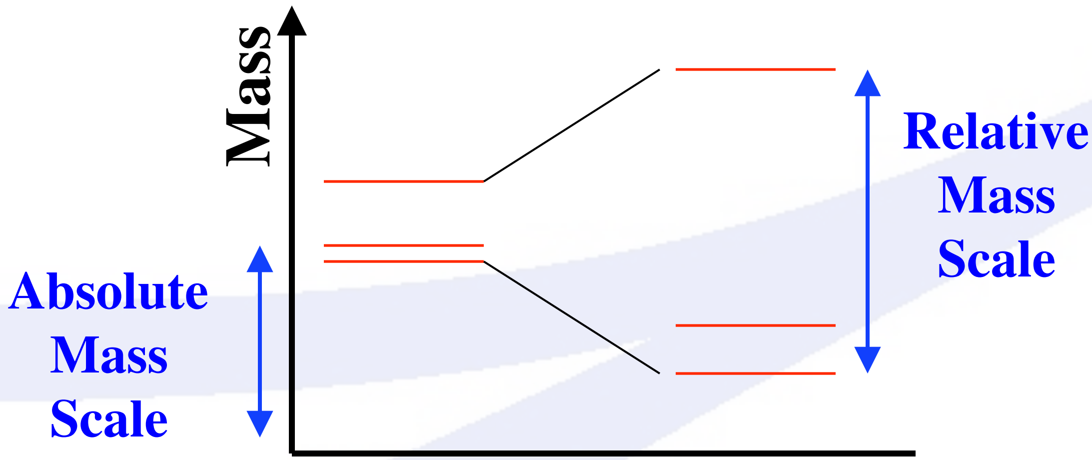
- Neutrinos
- Science of ββ
- MAJORANA DEMONSTRATOR

# Why Neutrinos?

**$\nu$ properties are critical input to many physics questions**

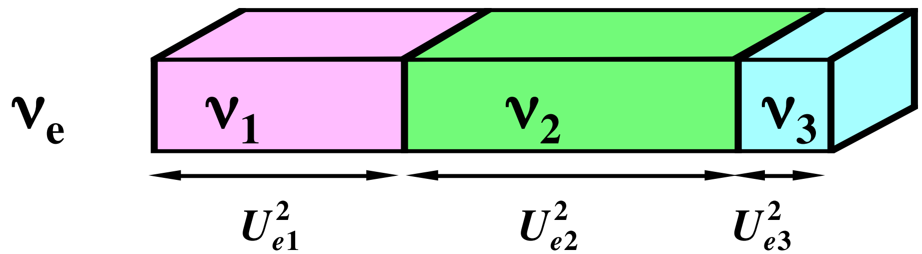
- **Particle/Nuclear Physics**
  - **Fundamental questions about standard model**
  - **Fundamental issues regarding interactions**
- **Cosmology**
  - **Large scale structure**
  - **Leptogenesis and matter-antimatter asymmetry**
- **Astrophysics**
  - **Supernova explosions**
  - **Solar burning**

# Neutrinos: What do we want to know?




## Dirac or Majorana

$$\begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \\ \bar{\nu}_{\downarrow} \\ \bar{\nu}_{\uparrow} \end{pmatrix} \text{ or } \begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \end{pmatrix}$$




## Mixing

# Neutrino Masses: What do we know?

- **The results of oscillation experiments indicate $\nu$ do have mass!, set the relative mass scale, and a minimum for the absolute scale.**

- **$\beta$ decay experiments set a maximum for the absolute mass scale.**

$$50\ \text{meV} < m_\nu < 2200\ \text{meV}$$

# We also know $\nu$ mix.

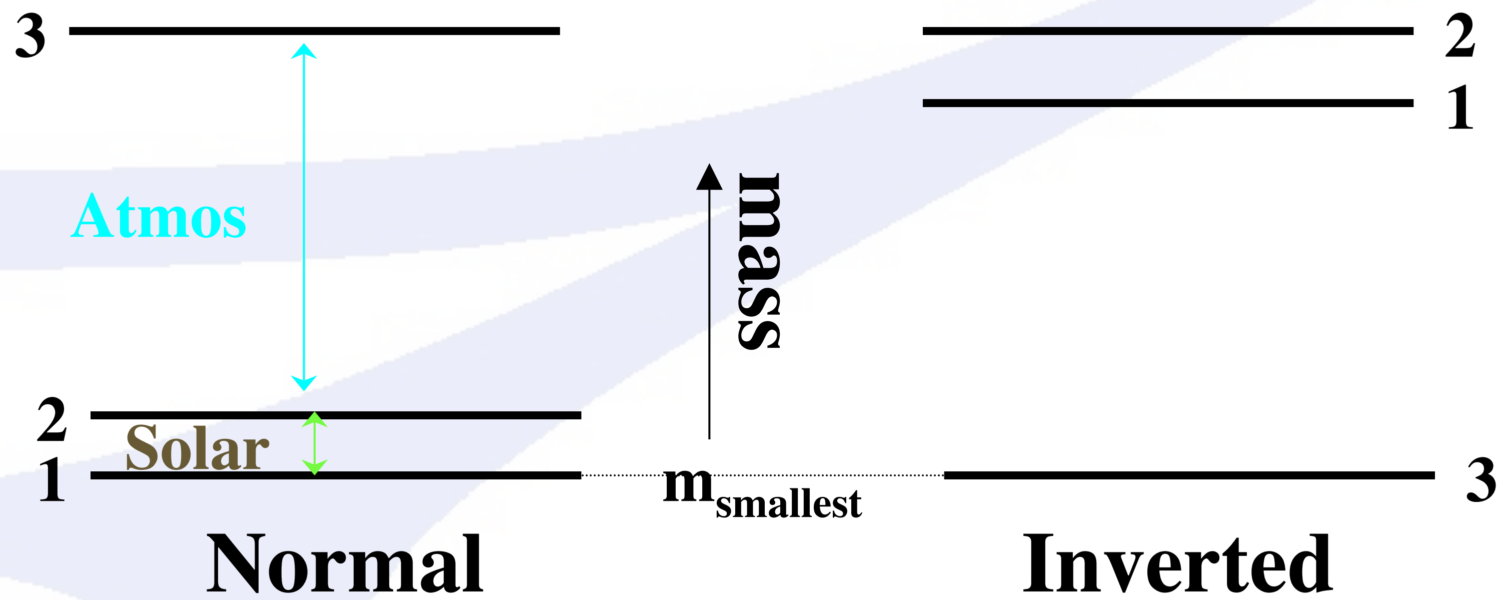
**The weak interaction produces $\nu_e$, $\nu_\mu$, $\nu_\tau$.**

**These are not pure mass states but a linear combination of mass states.**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

**Oscillation experiments indicate that $\nu$ mix and constrain $U_{\alpha i}$.**

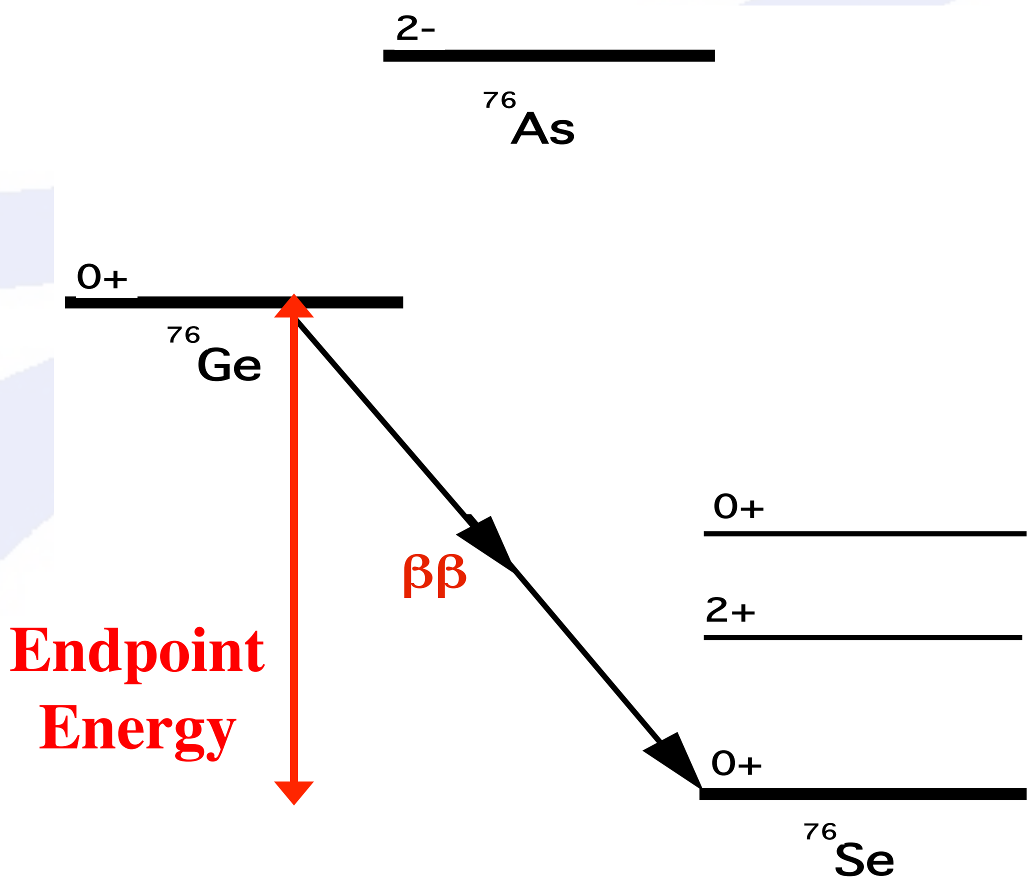
# The Neutrino Mass Spectrum: Oscillations and Hierarchy Possibilities




$\nu_e$ is composed of a large fraction of $\nu_1$.

# Example ββ Decay Scheme

**In many even-even nuclei, β decay is energetically forbidden. This leaves ββ as the allowed decay mode.**



# What is $\beta\beta$?

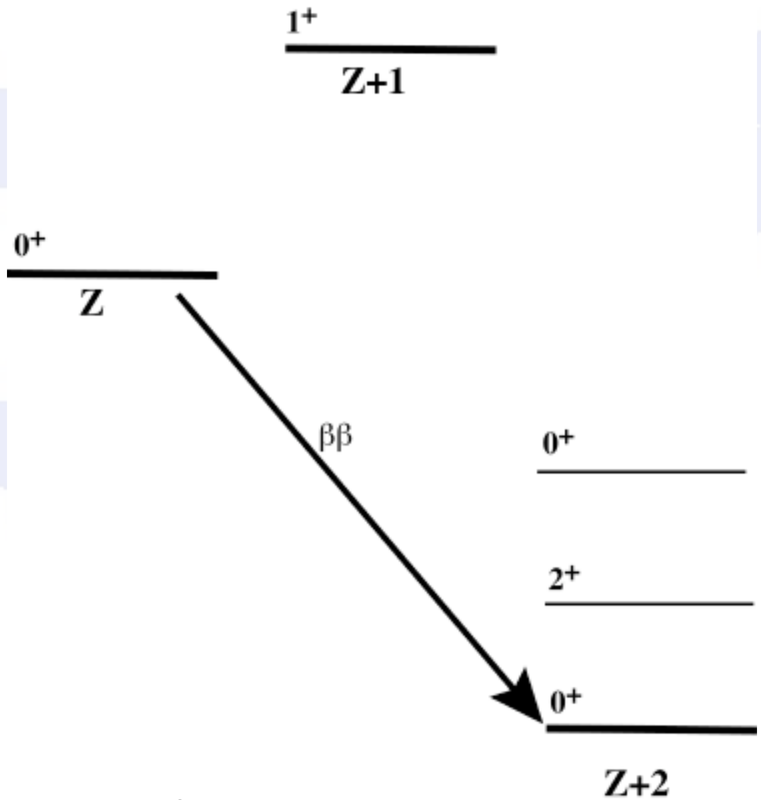



Fig. from arXiv:0708.1033

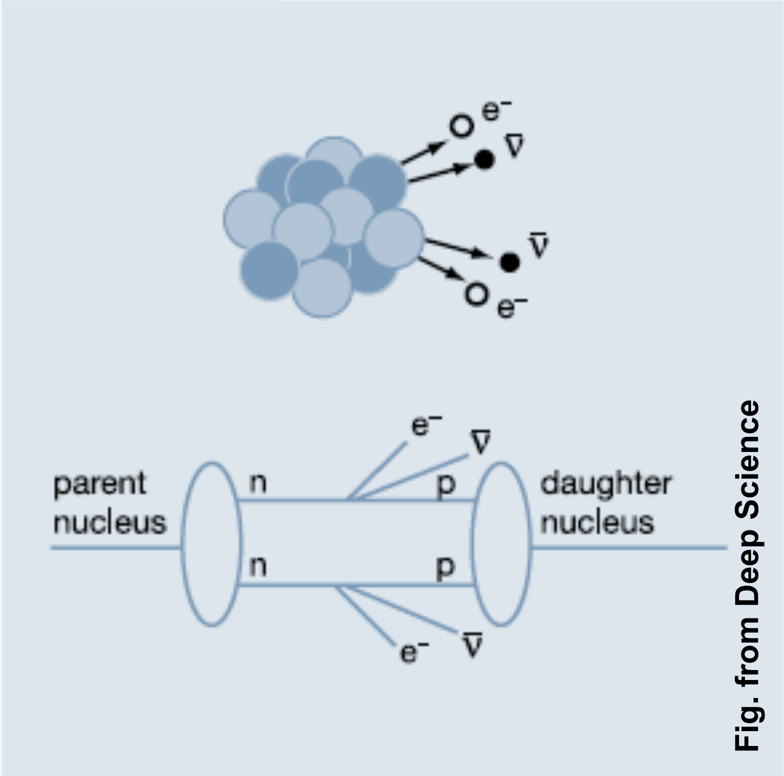



Fig. from Deep Science

# What is $\beta\beta$?

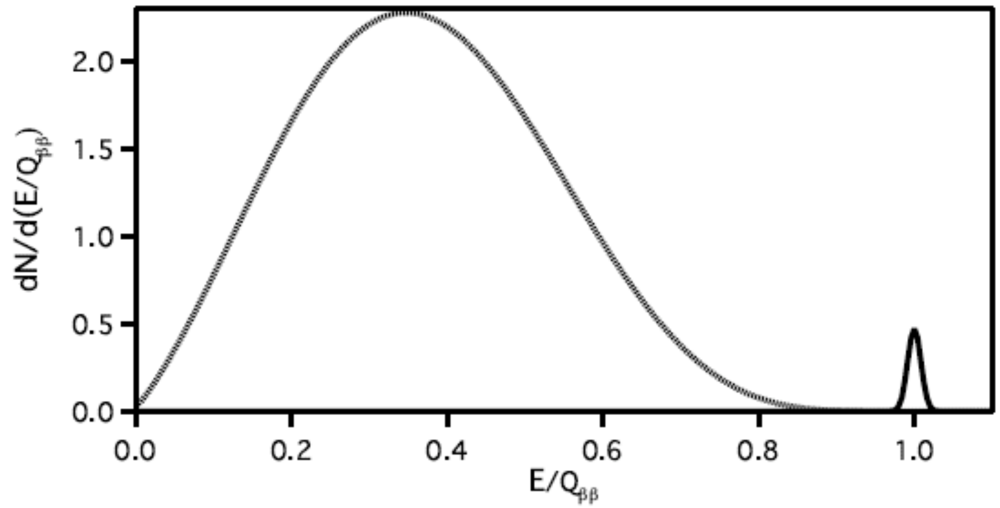



Fig. from arXiv:0708.1033

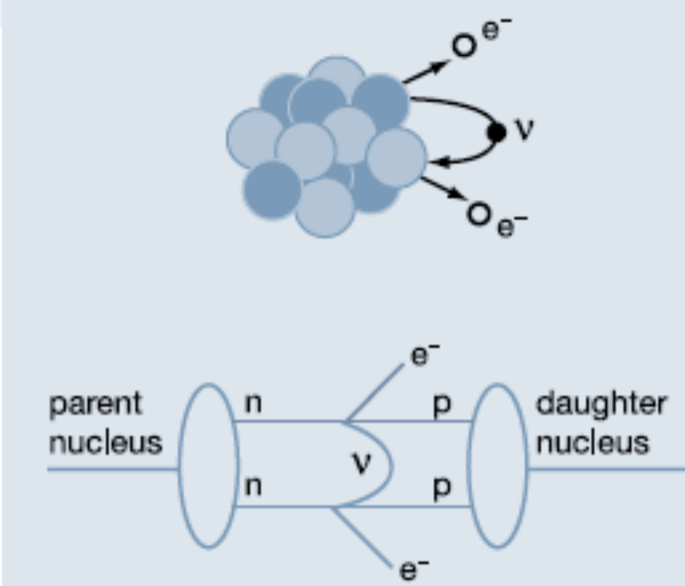



Fig. from Deep Science

# ββ Decay Rates

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

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

**G are calculable phase space factors.**

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

**|M| are nuclear physics matrix elements.**

**Hard to calculate.**

**$m_\nu$ is where the interesting physics lies.**

# What about mixing, $m_\nu$ & $\beta\beta(0\nu)$?

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

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

**virtual ν exchange**

$\varepsilon = \pm 1$, **CP cons.**

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**Compare to β decay result:**

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

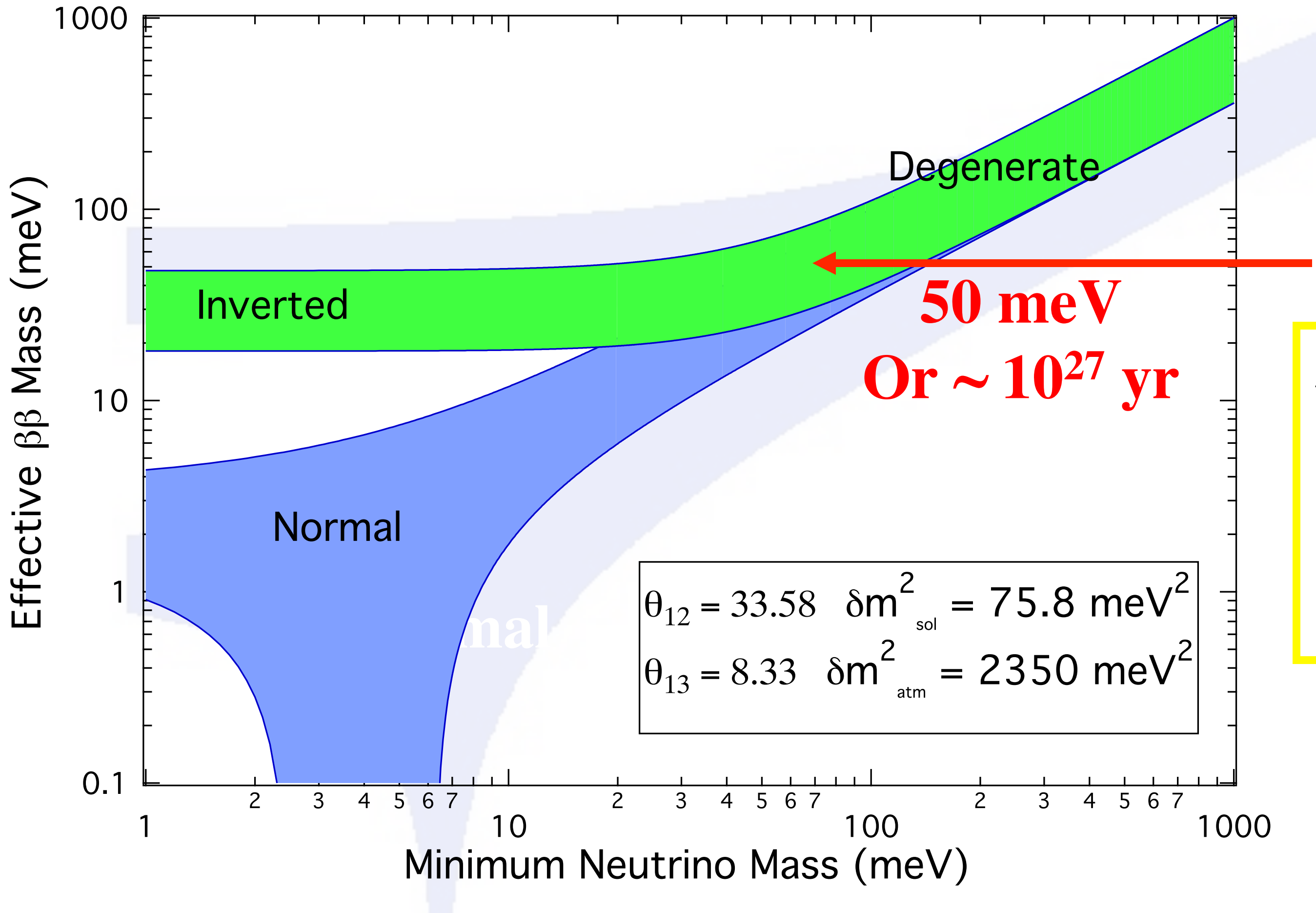
**real ν emission**

**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!

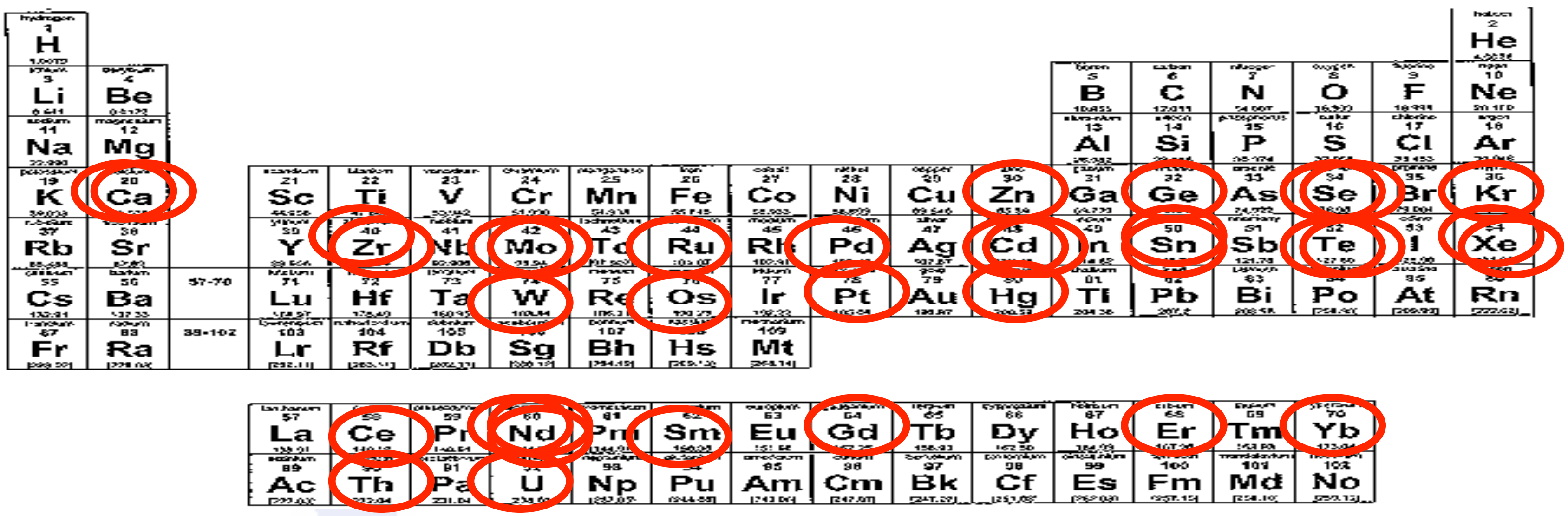
A $m_{\beta\beta}$ limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.

# ββ and the neutrino

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

# ββ Candidates

There are a lot of them!

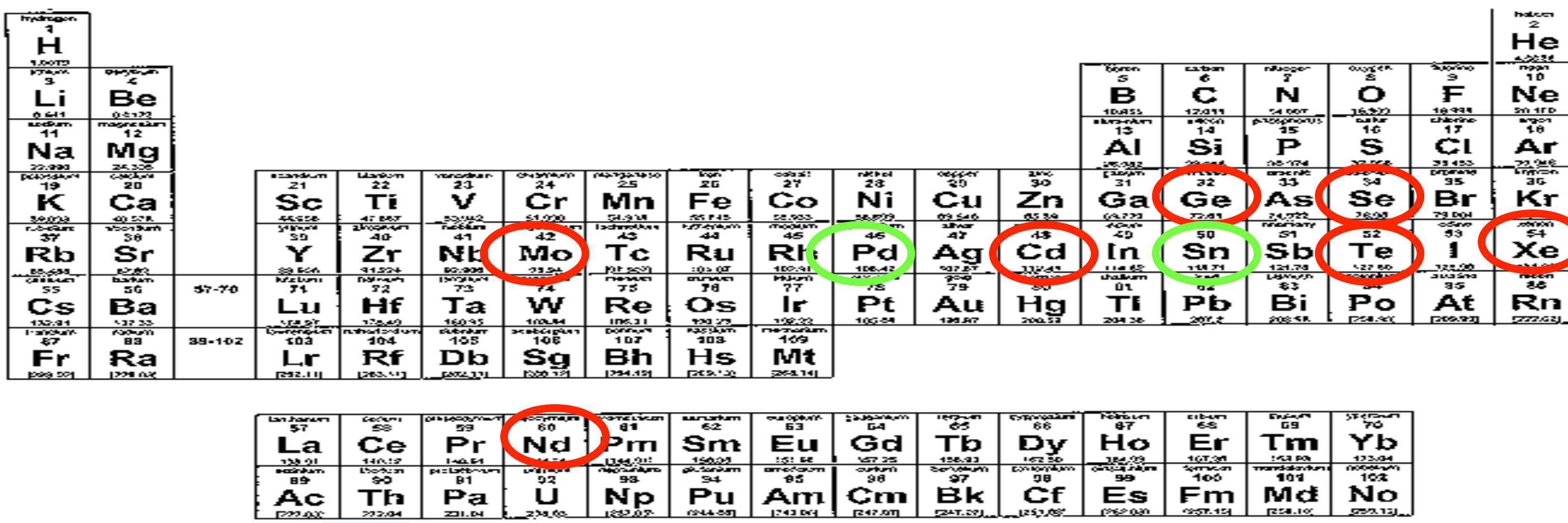


# How to choose a $\beta\beta$ isotope?

- **Detector technology exists**
- **High isotopic abundance or an enriched source exists.**
- **High energy = fast rate, above background**

# $\beta\beta$ Candidates

## Abundance > 5%,Trans. Energy > 2 MeV



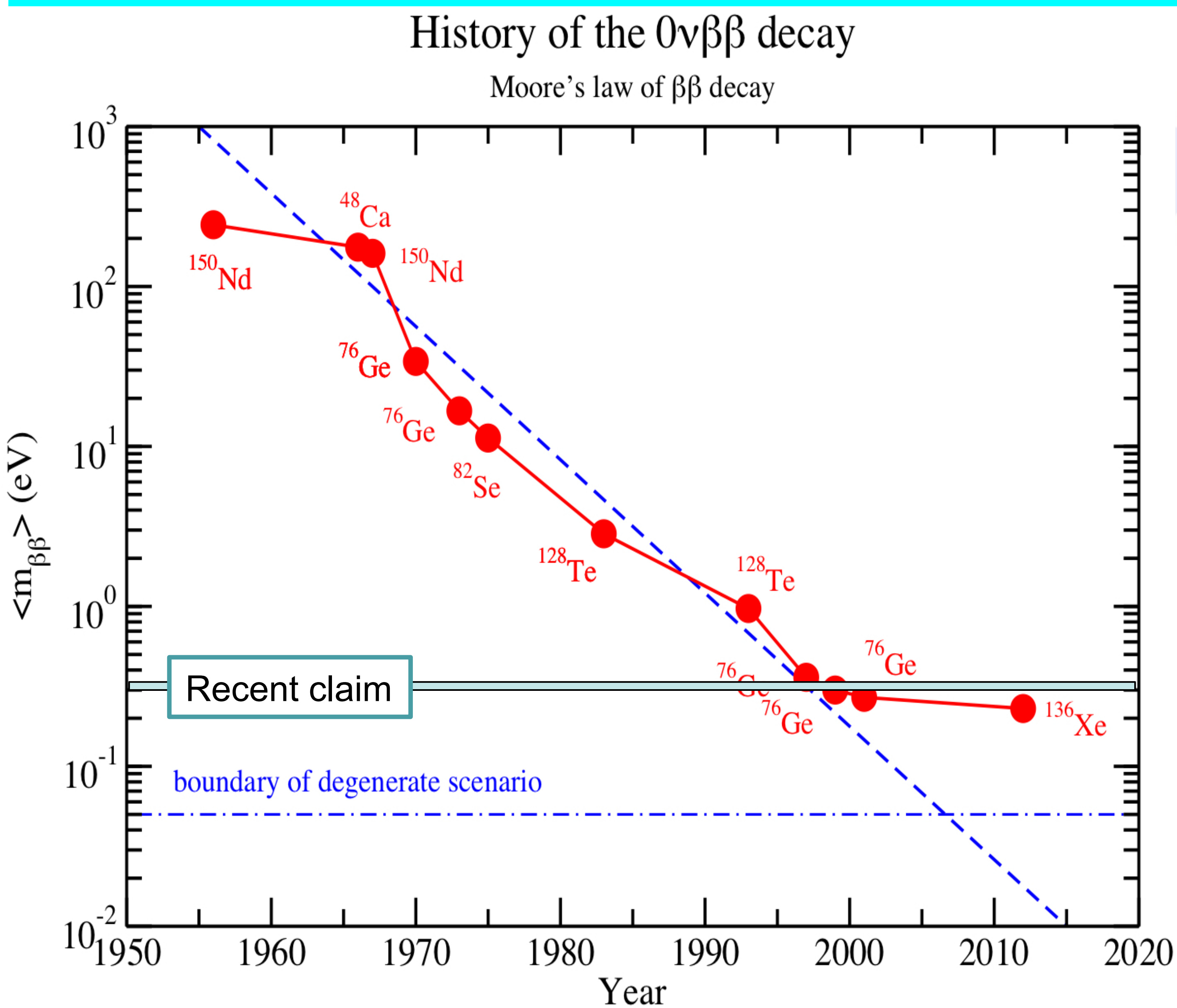

Frequently studied isotope.

# $\beta\beta$ History

- $\beta\beta(2\nu)$ rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why so long? Background
  - $\tau_{1/2}$(U, Th) ~ $T_{universe}$
  - $\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{10}\ T_{universe}$

- But next we want to look for a process with:
  - $\tau_{1/2}(\beta\beta(0\nu)) \sim 10^{17}\ T_{universe}$

# 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 $<m_{\beta\beta}>$ 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.

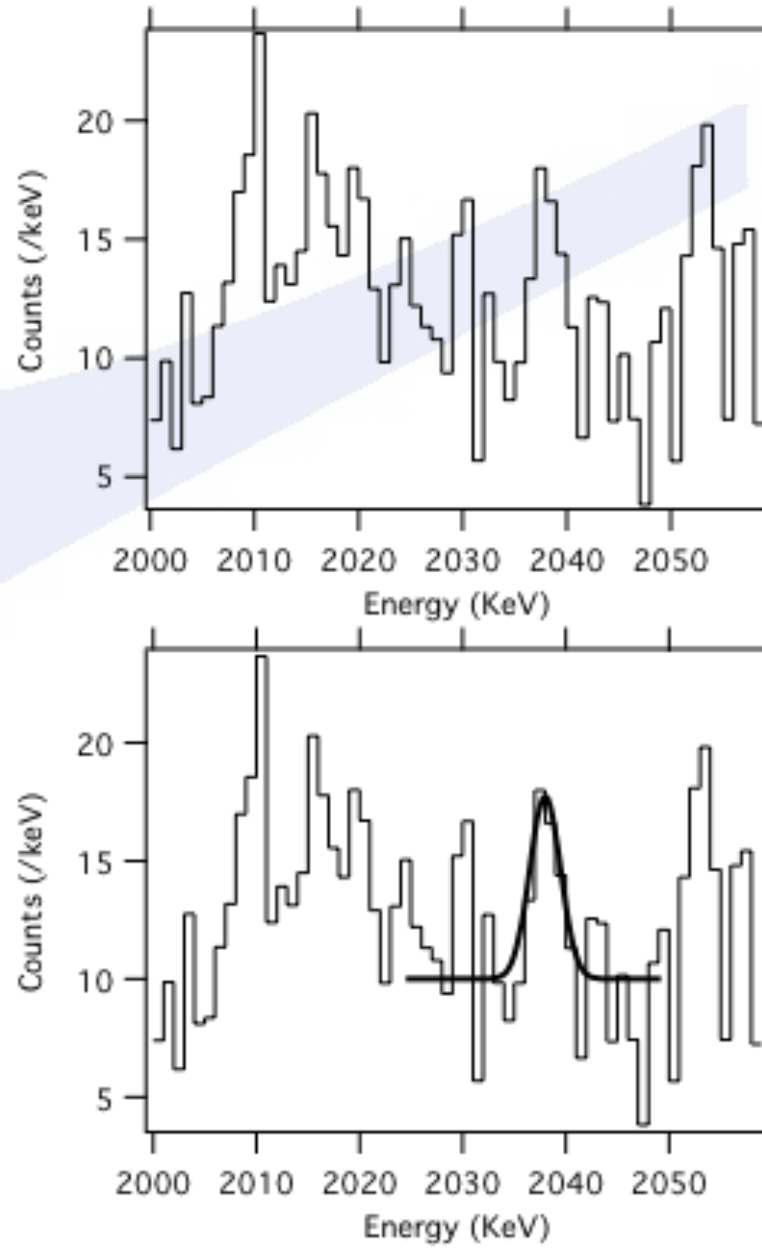
# A Claim

has become a litmus test for future efforts

**ββ is the search for a *[very](#)* rare peak on a continuum of background.**

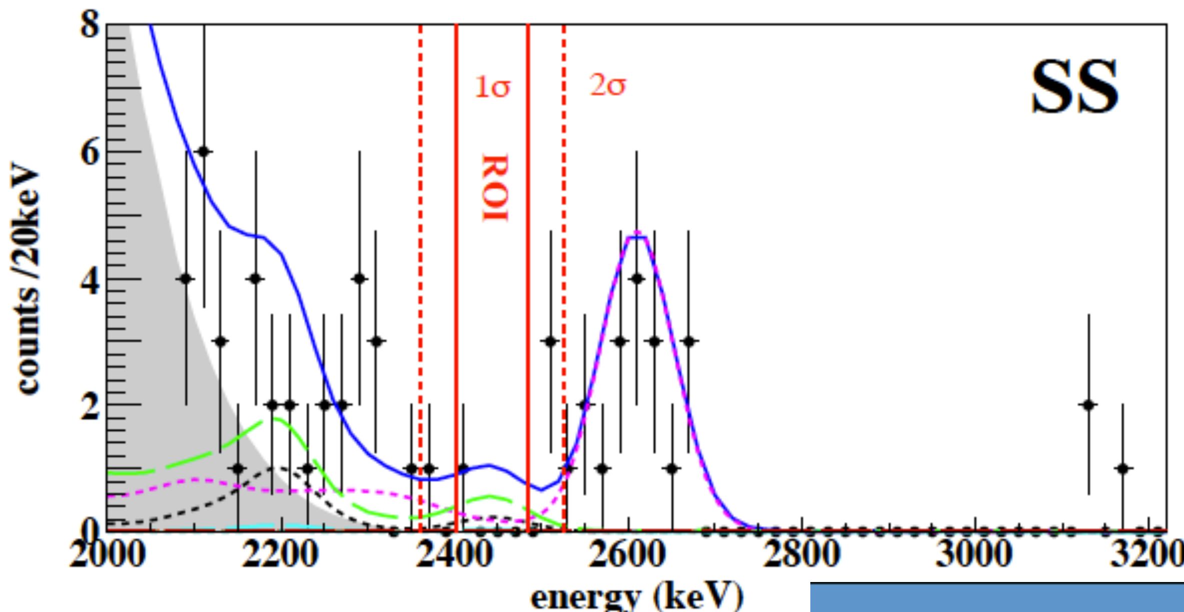
**~70 kg-years of data**
**13 years**

**The “feature” at 2039 keV is arguably present.**




NIM A522, 371 (2004)

# EXO result




Joint analysis with KamLAND-Zen gives $3.4 \times 10^{25}$ 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 ($kg^{-1}yr^{-1}keV^{-1}$) | $1.5 \cdot 10^{-3} \pm 0.1$ | | $1.4 \cdot 10^{-3} \pm 0.1$ | |

# Future Data Requirements

**Why wasn't the 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 repudiation**

# 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 $\beta\beta(0\nu)$**
**Good source radiopurity**
**Demonstrated technology**
**Ease of operation**
**Natural isotope**
**Small volume, source = detector**
**Good energy resolution**
**Slow $\beta\beta(2\nu)$ rate**
**Identify daughter in real time**
**Event reconstruction**
**Nuclear theory**

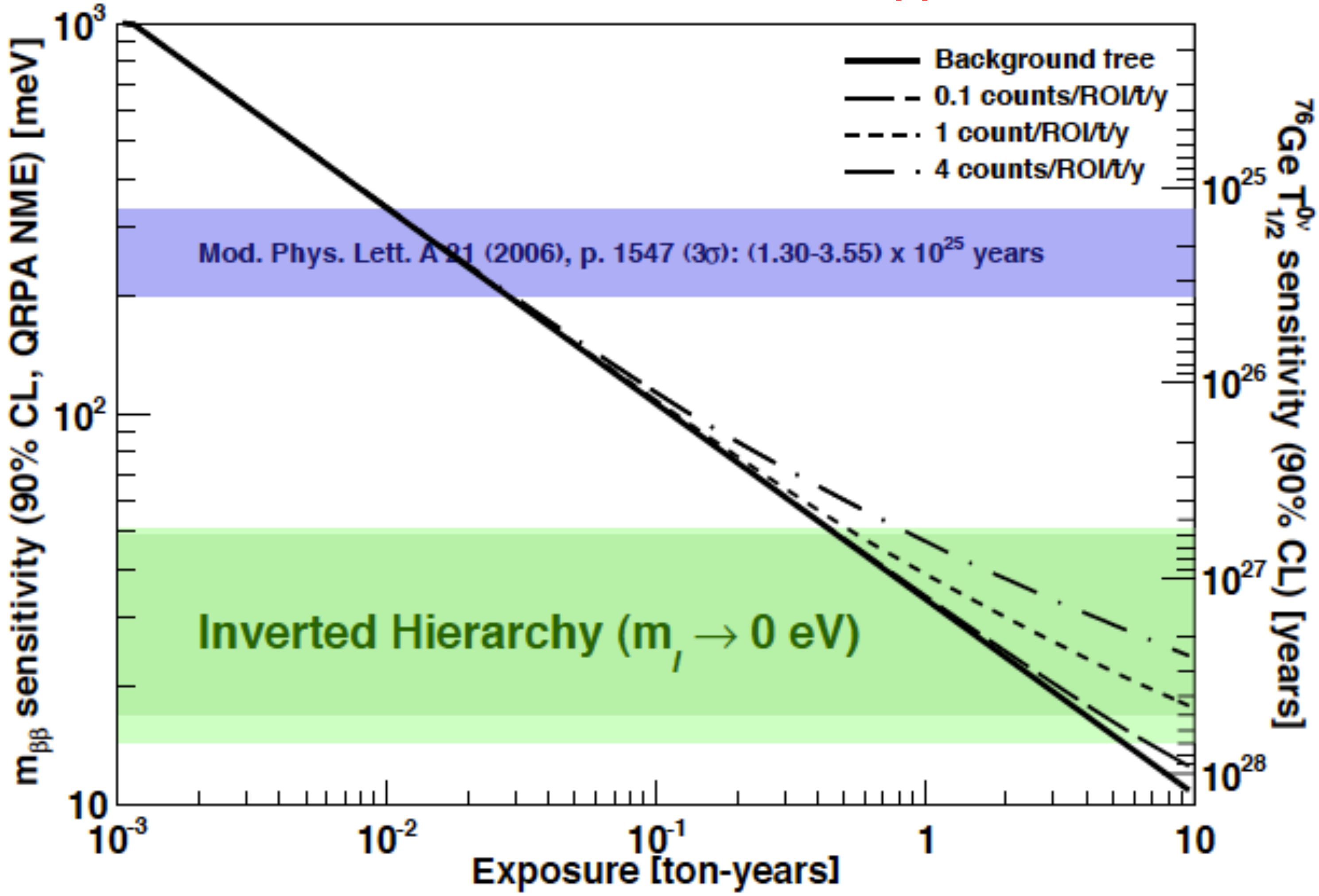
# Signal:Background ~ 1:1

## Its all about the background

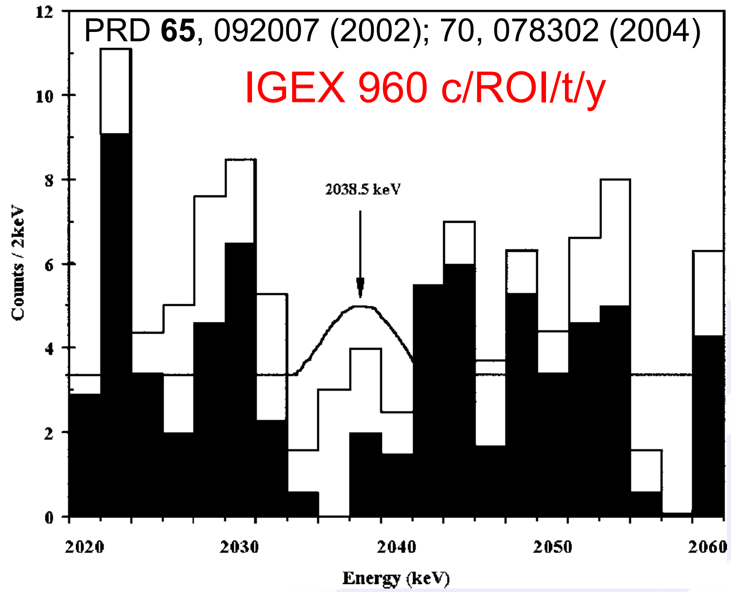
| Half life (years) | ~Signal (cnts/ton-year) | ~Neutrino mass scale (meV) | |
|---|---|---|---|
| $10^{25}$ | 530 | 400 | Degenerate |
| $5 \times 10^{26}$ | 10 | 100 | |
| $5 \times 10^{27}$ | **To reach atmospheric scale need BG on order 1/t-y.** | 40 | Atmospheric |
| $>10^{29}$ | <0.05 | <10 | Solar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

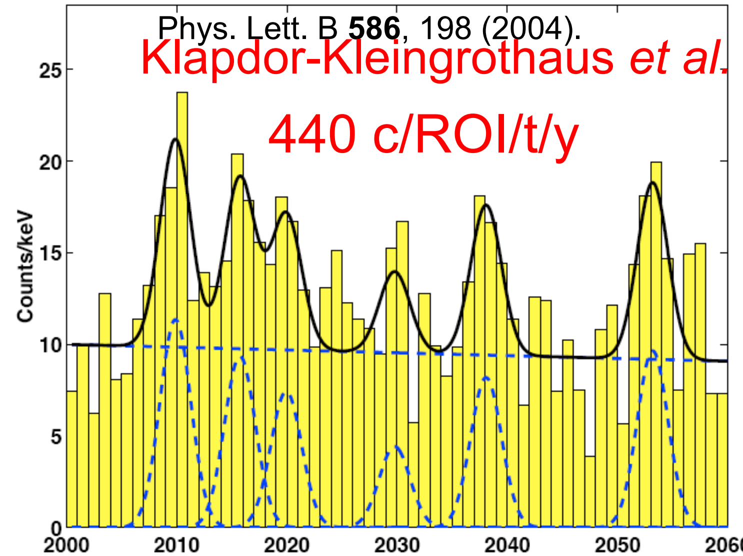
# Sensitivity, Background and Exposure

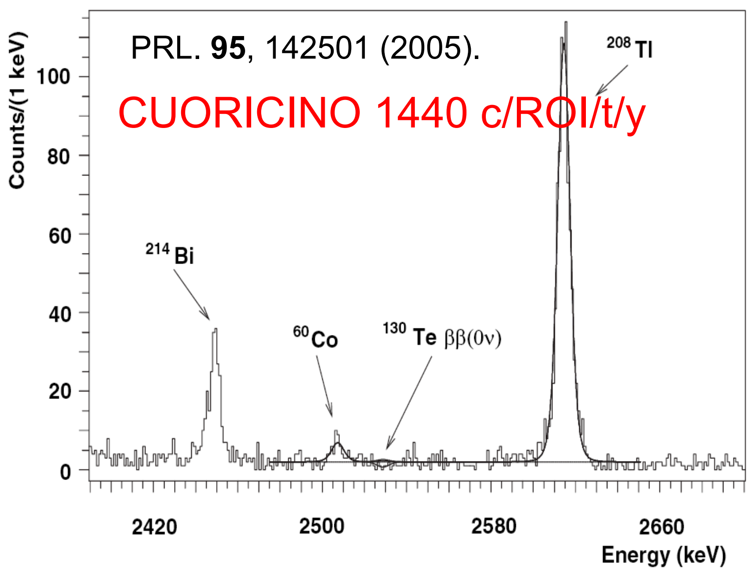
**Goal is to achieve ultra-low backgrounds of less than 1 count per ton of material per year in the ROI about the ββ(0ν) Q-value energy.**

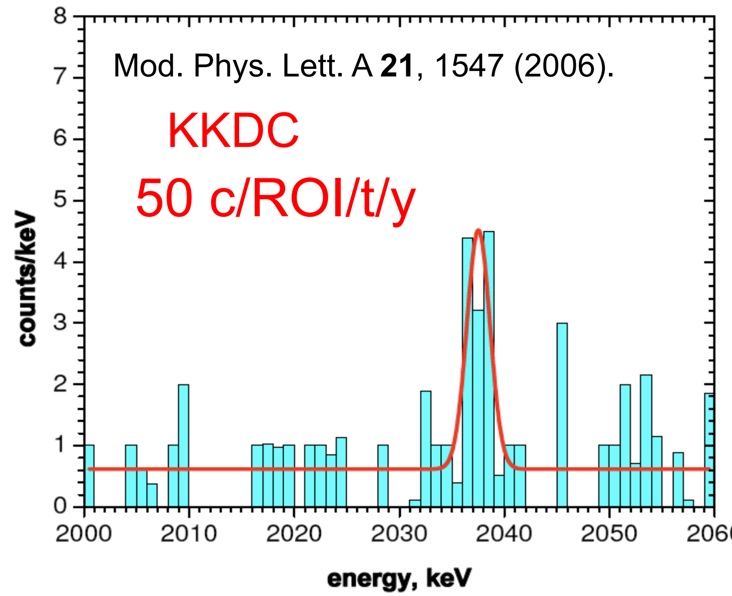


# Background in Recent Experiments

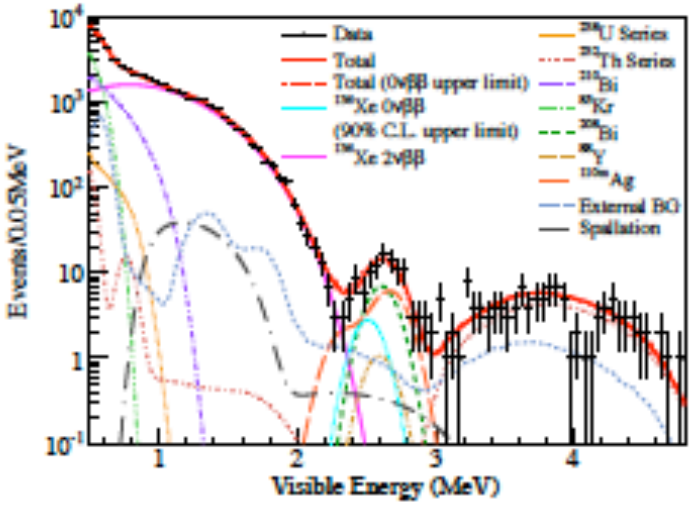


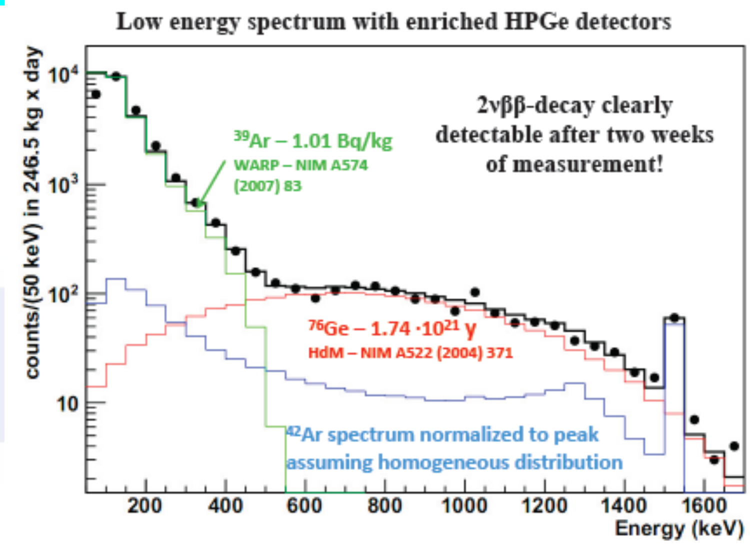



# Background in Recent Experiments



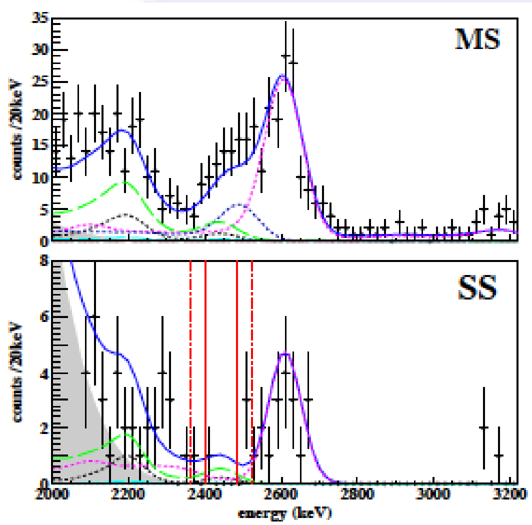

PRC 85, 045504



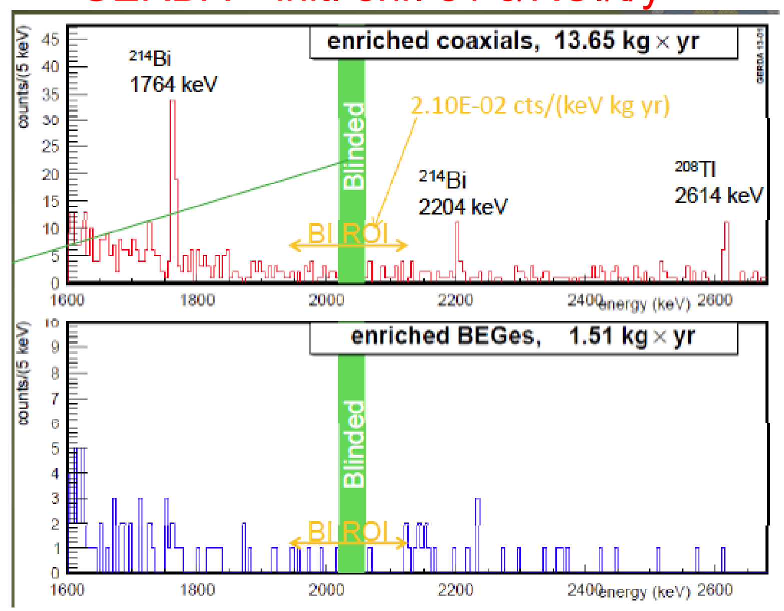

KamLAND-Zen 2400 c/ROI/t(Xe)/y

EXO-200 129 c/ROI/t/y

GERDA – init. enr. 81 c/ROI/t/y




PRL 109, 032505



# Previous Background Levels

| Experiment | Background (cnts/ ROI-t-y) | Width (1 FWHM) |
|---|---|---|
| IGEX | 960 (400 with PSD) | 4 keV ROI |
| Heid-Moscow | 440 (50 with PSD) | 4 keV ROI |
| CUORICINO | 1440 | 8 keV ROI |
| GERDA | 81 (no PSD) | 4 keV ROI |
| EXO-200 | 130 | 106 keV ROI (1.8% 1 sig resol.) |
| KamLAND-Zen | ~55(~2400per t(Xe)) | Width not explicitly given |

Background is per tonne of material – big difference for KamLAND-Zen

# Background Considerations

**At atmospheric scale, expect a signal rate on the order of 1 count/tonne-year**

- $\beta\beta(2\nu)$
- **natural occurring radioactive materials**
- **neutrons**
- **long-lived cosmogenics**

# 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 |
| Super | | | | | jus |
| Su | | | | | jus |
| C | | | | | Sasso |
| N | | | | | RF |
| A | | | | | Yang |
| Mo | | | | | |
| | | | | | Sasso |
| C | | | | | Sasso |
| C | | | | | Sasso |
| E | | | | | PP |
| | | | | | franc |
| Kam | | | | | ioka |
| DCBA | Nd | 20 kg | 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.**

# 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 $\beta\beta$ 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.**