Neutrino Physics - Double-Beta Decay

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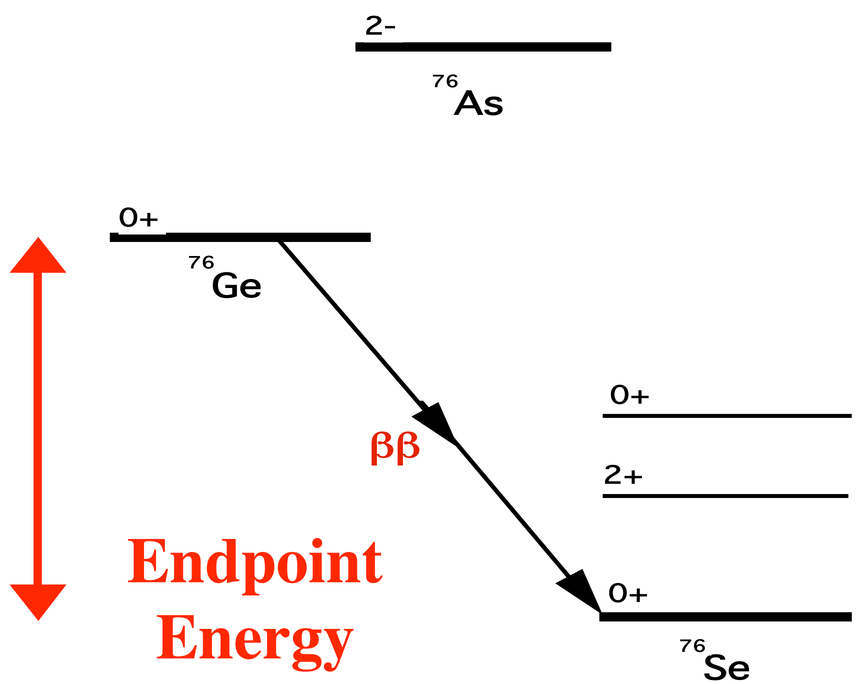
Lecture Outline

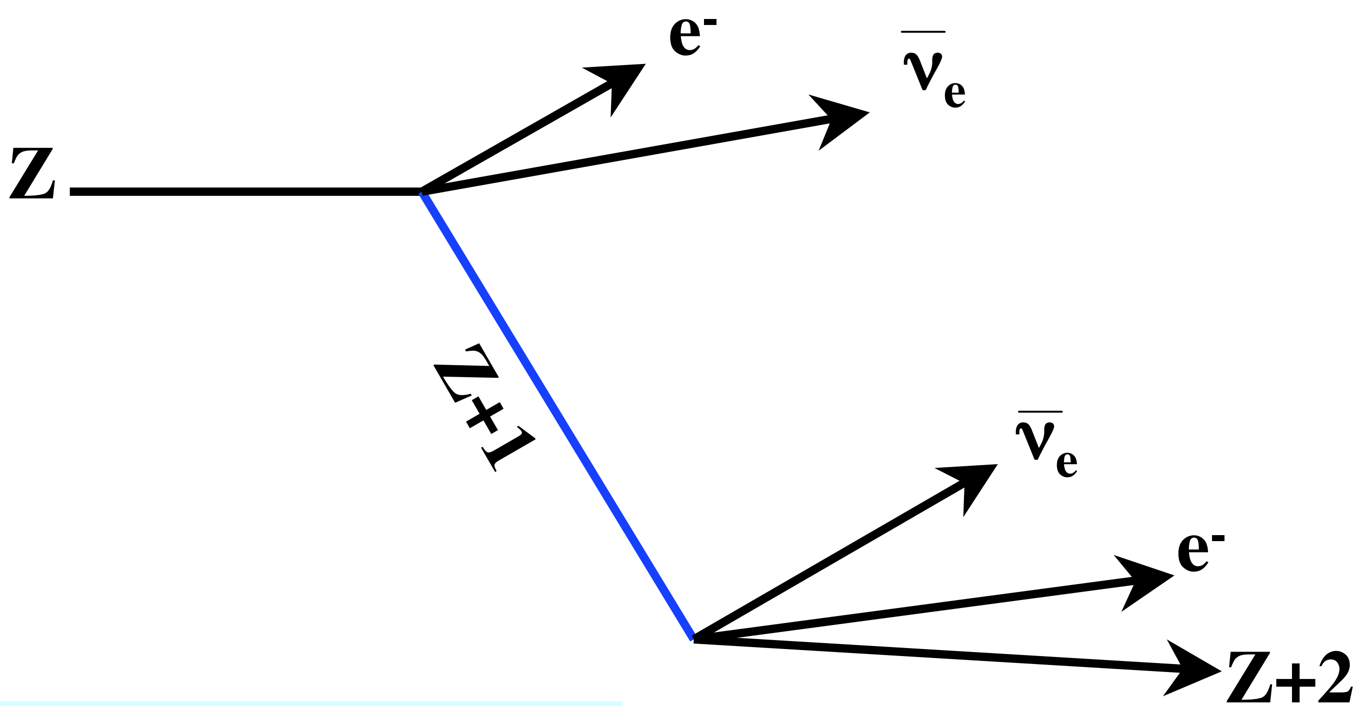
- **Double Beta Decay**
  - **Basic physics**
  - **General experimental techniques**
  - **The various experiments**

Example Decay Scheme



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

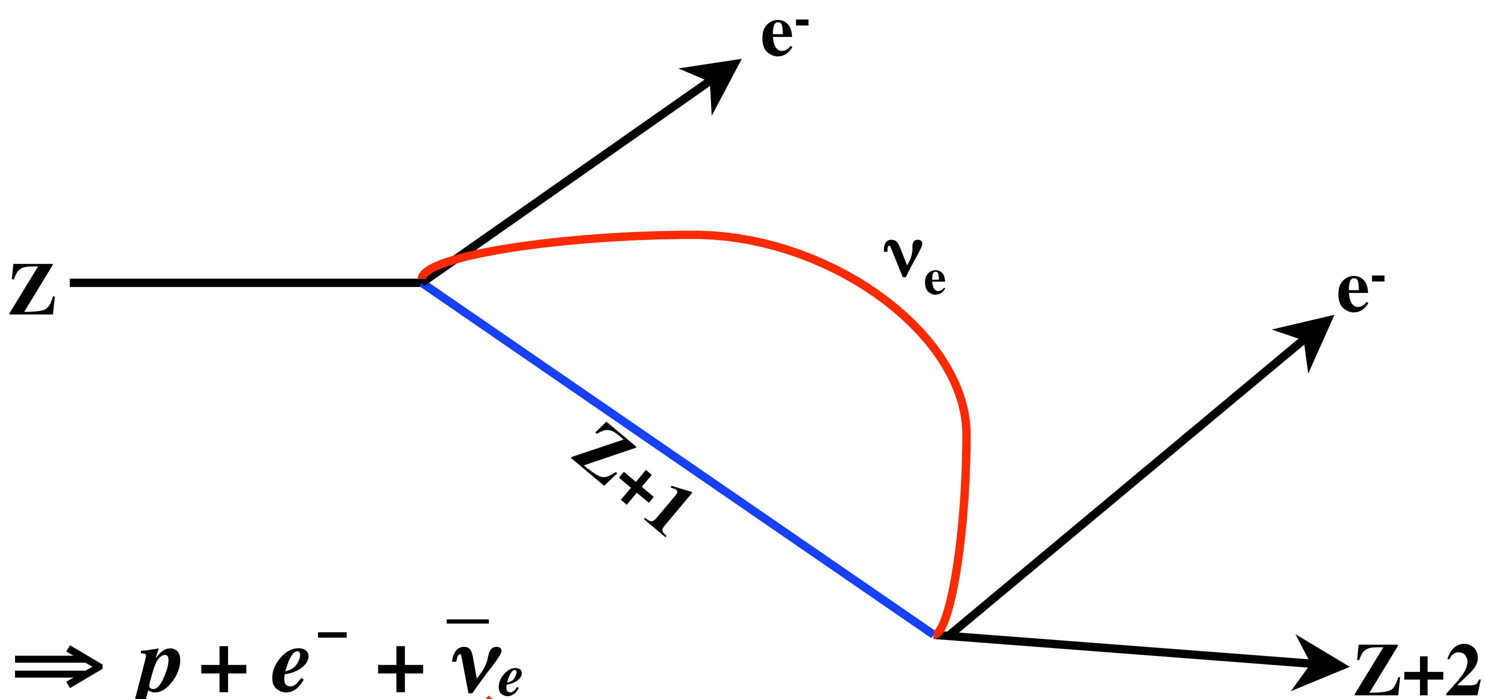
$\beta\beta(2\nu)$: Allowed weak decay



$$2n \Rightarrow 2p + 2e^- + 2\bar{\nu}_e$$

$\beta\beta(0\nu)$: requires massive Majorana ν

Only practical way to address the particle-antiparticle question

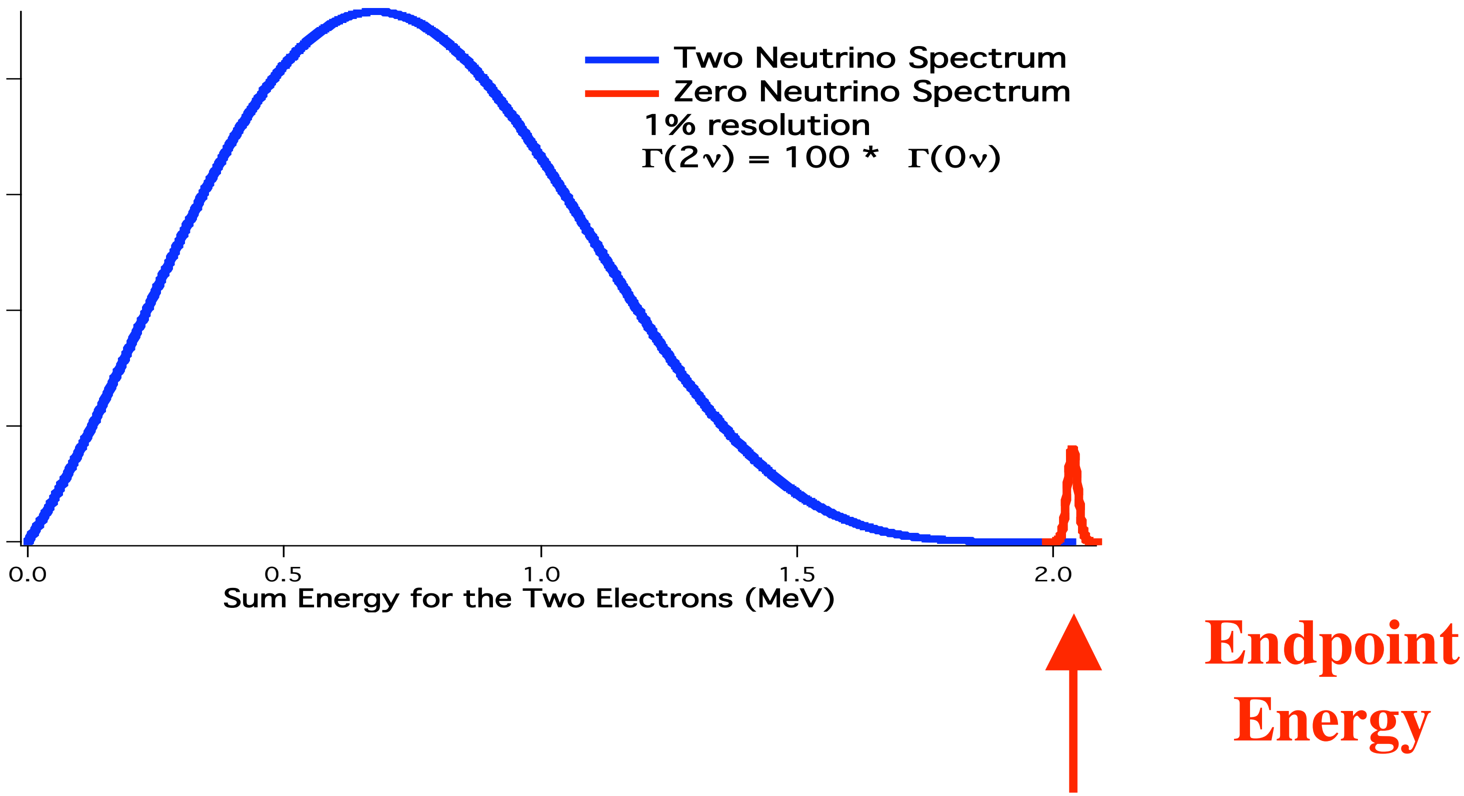


$$n \Rightarrow p + e^- + \bar{\nu}_e$$

(RH $\bar{\nu}_e$) (LH ν_e)

$$\nu_e + n \Rightarrow p + e^-$$

Energy Spectrum for the 2 e^-



ββ History

- **ββ(2ν) rate first calculated by Maria Goeppert-Mayer in 1935.**
- **First observed directly in 1987.**
- **Why so long? <u>Background</u>**

$$\tau_{1/2}(U, Th) \sim T_{universe}$$

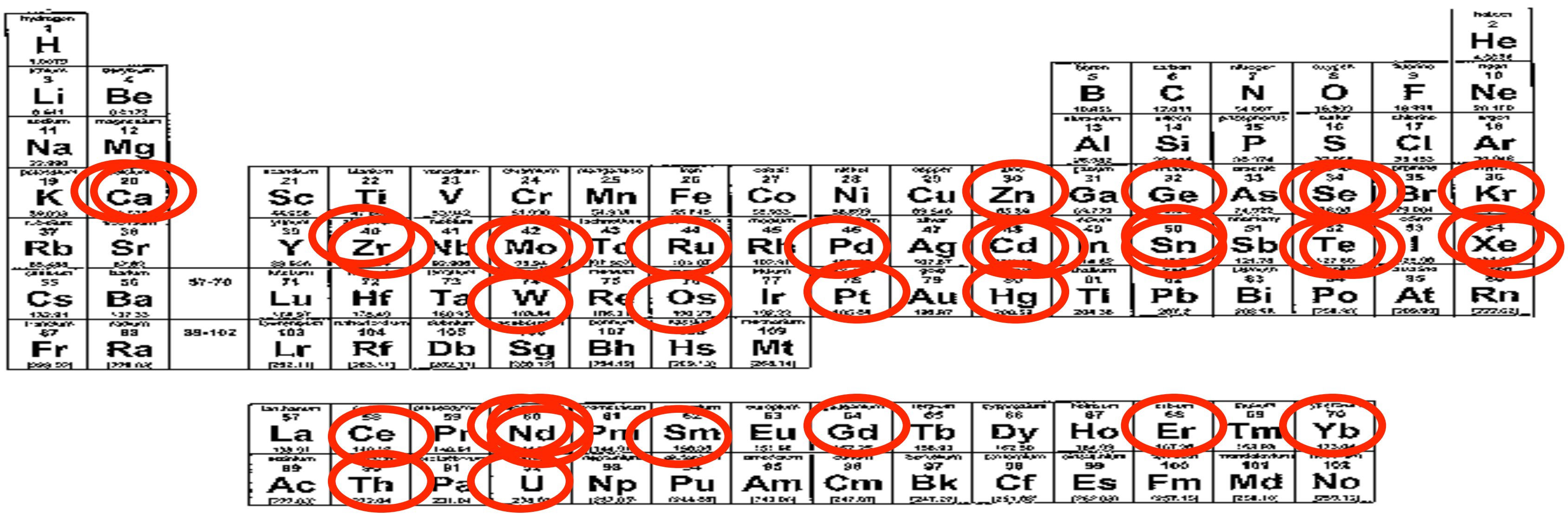
$$\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{10}\ T_{universe}$$

- **But next we want to look for a process with:**

$$\tau_{1/2}(\beta\beta(0\nu)) \sim 10^{17}\ T_{universe}$$

ββ Candidates

There are a lot of them!

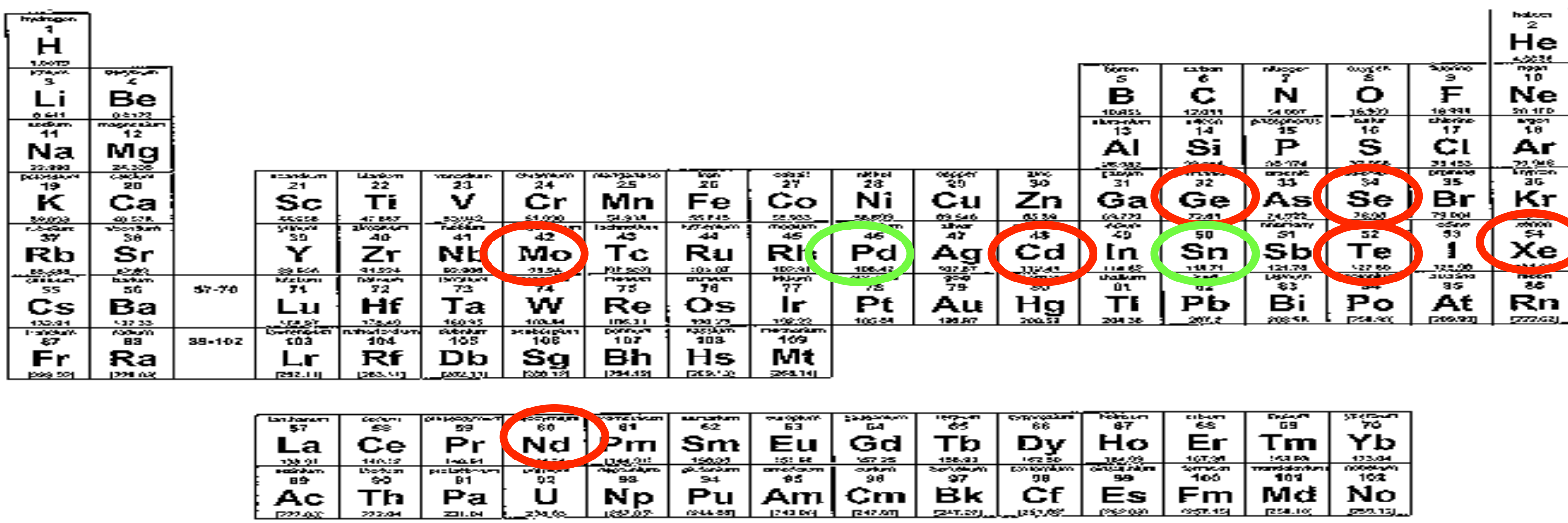


How to choose a $\beta\beta$ isotope?

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

ββ Candidates

Abundance > 5%,Trans. Energy > 2 MeV



Frequently studied isotope.

ββ Decay Rates

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

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

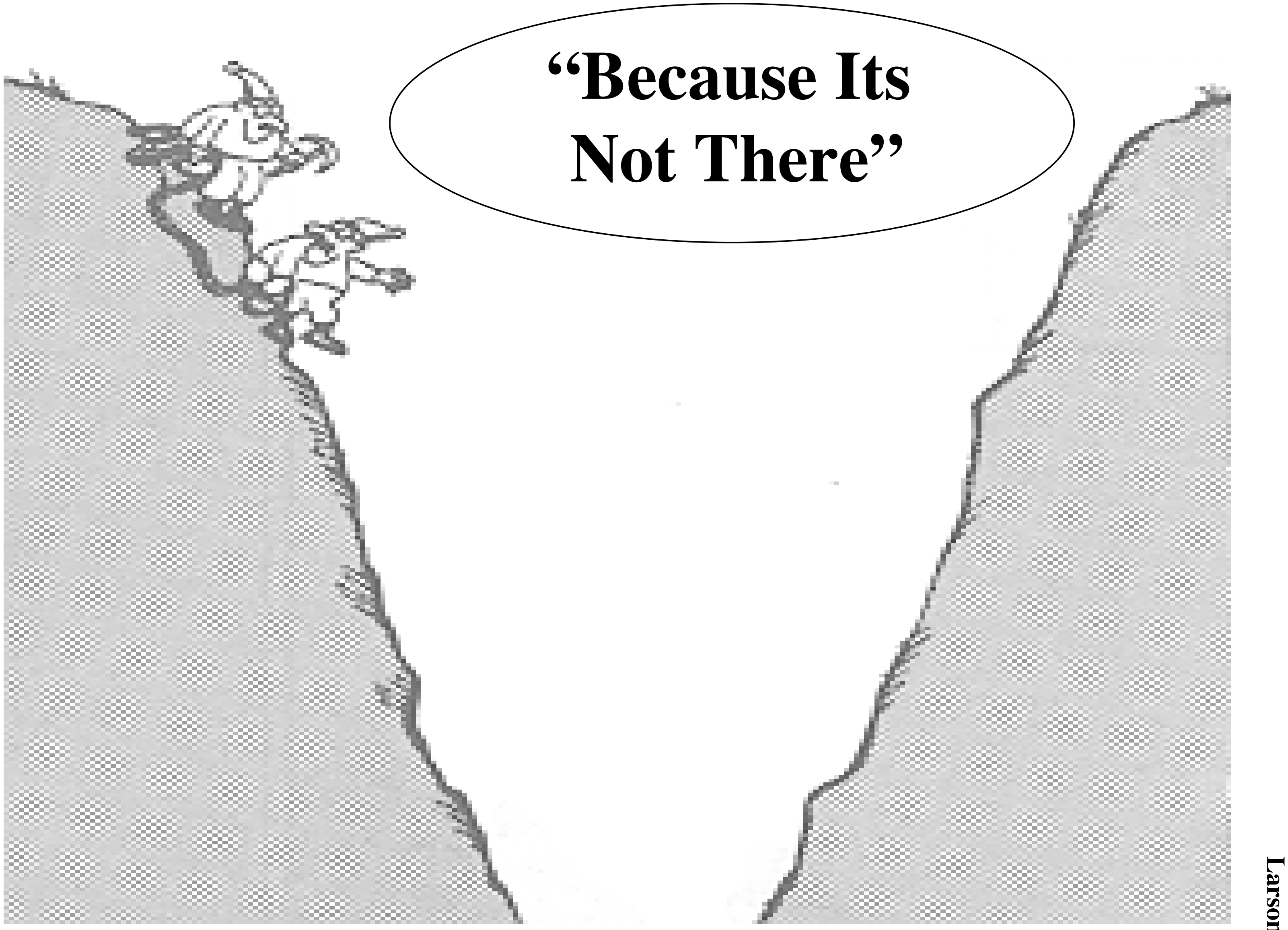
G are calculable phase space factors.

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

|M| are nuclear physics matrix elements.

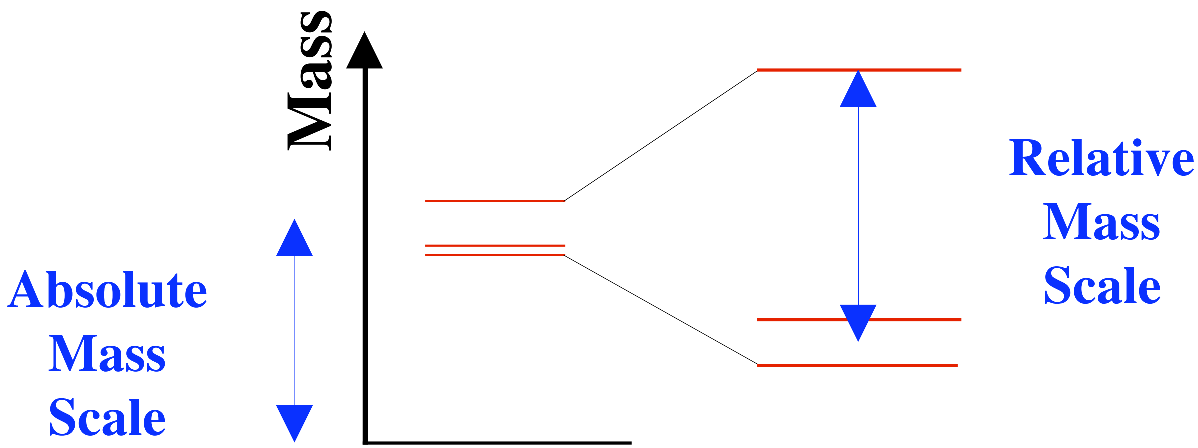
Hard to calculate.

m_ν is where the interesting physics lies.



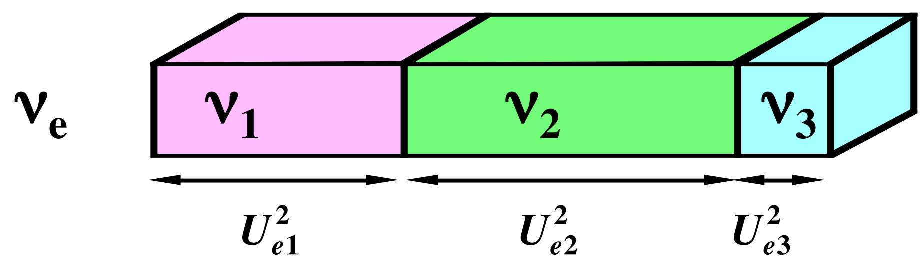
"Because Its
Not There"
Larson

Neutrino Mass: 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 Mass: How do we learn what we want to know?

	Absolute Mass Scale	Relative Mass Scale	Mixing Matrix Elements	CP nature of ν
$\beta\beta$	✓			✓
β, cosm.	✓			
Oscil.		✓	✓	

Need all 3 types of experiments.

Neutrino Masses: What do we know?

- The results of oscillation experiments **indicate ν do have mass!**, set the relative mass scale, and a minimum for the absolute scale.
- β decay experiments set a maximum for the absolute mass scale.

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

We also know ν mix.

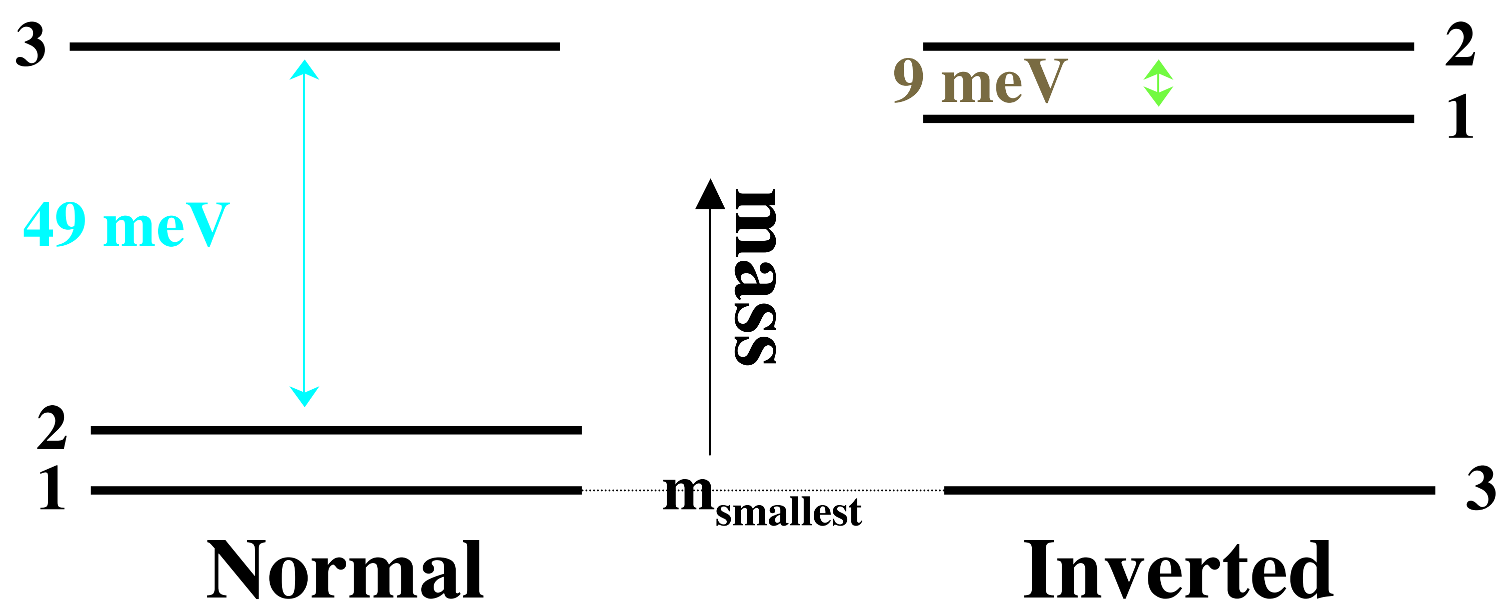
The weak interaction produces ν_e, ν_μ, ν_τ.

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 ν mix and constrain $U_{\alpha i}$.

Oscillations and Hierarchy Possibilities



ν_e **is composed of a large fraction of** ν_1**.**

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

ε = ±1, CP cons.

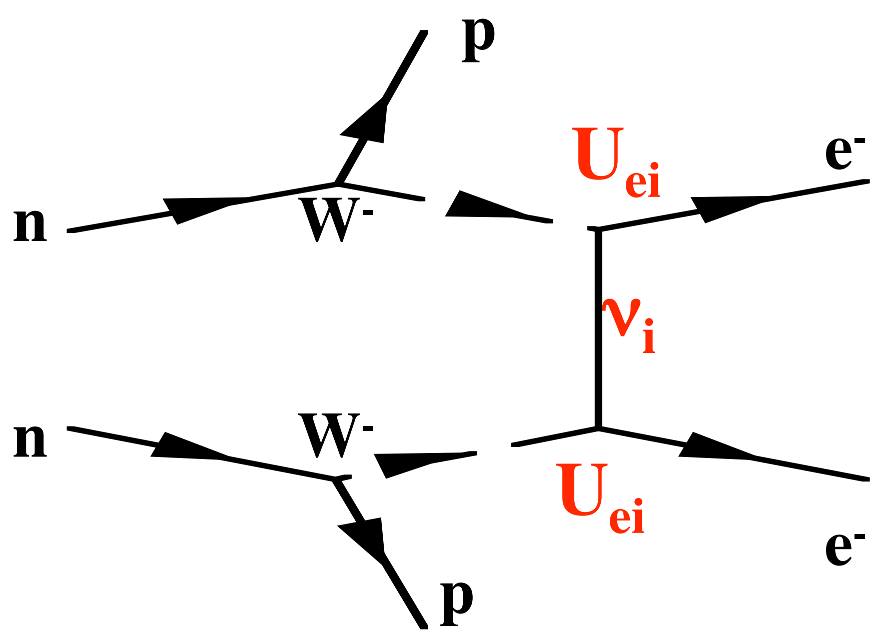
Compare to β decay result:

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

real ν emission

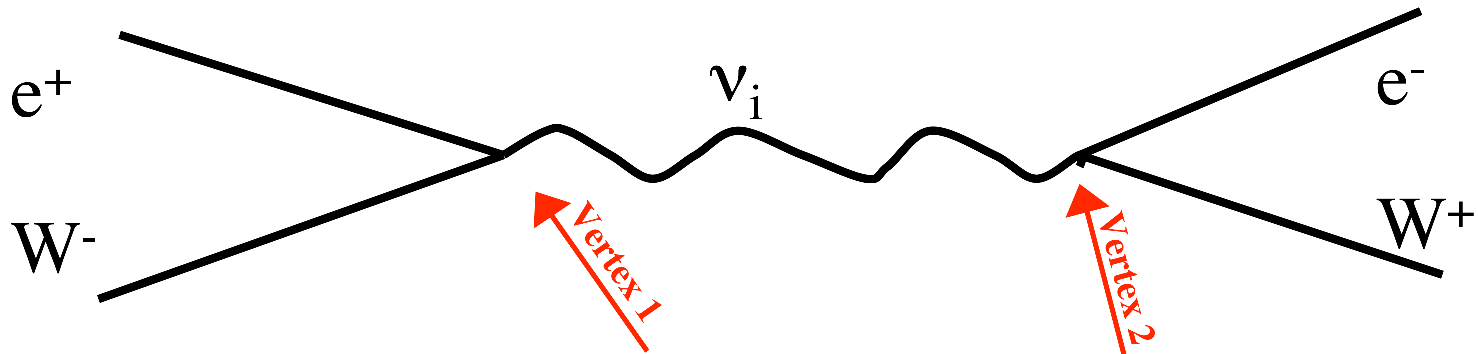
Why does the CP parity appear in $<m_{\beta\beta}>$?

$$A_{0\nu} \sim \Sigma_i$$



Look at the critical part of this diagram.

The crossed channel.



$$A \propto \sum_i U_{ei}^2 \langle e^+W^- | H_{SM} | \nu_i \rangle \langle \nu_i | H_{SM} | e^-W^+ \rangle$$

The 1st vertex creates the CP partner of the particle needed by the 2nd vertex.

$$\textbf{But } CP|\nu_i\rangle = \varepsilon_i |\nu_i\rangle$$

Upon substitution, the factor ε_i appears.

What can be learned from Oscillations & ββ?

- **From oscillations, we have:**
  Information on U_{ei}
  Information on δm^2

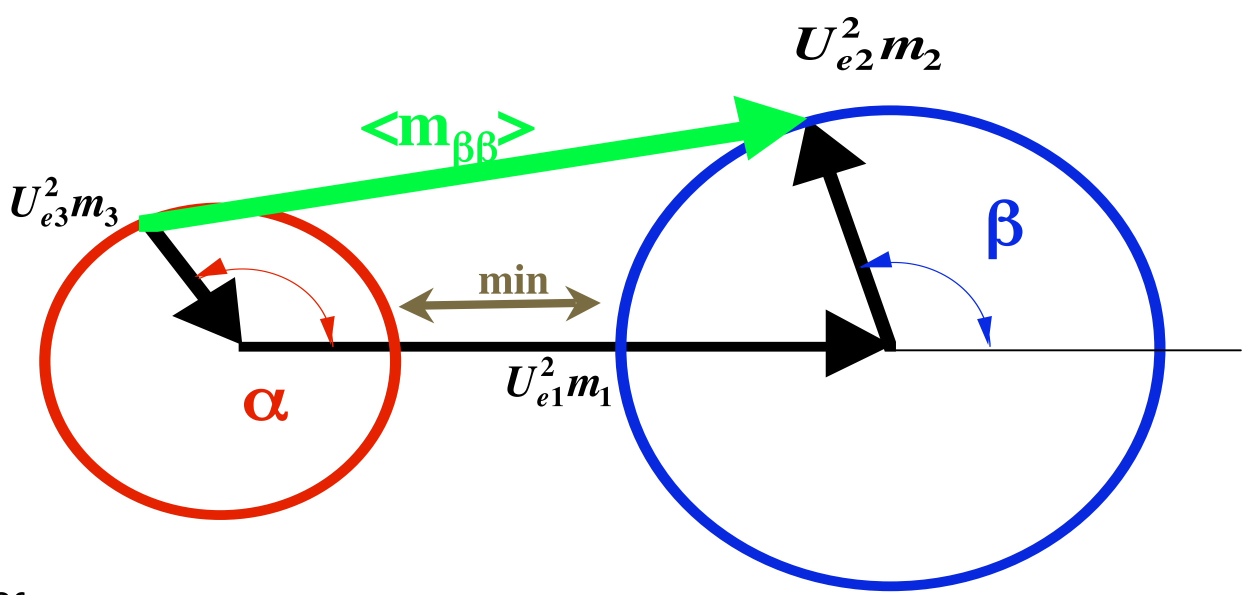
- **With $<m_{\beta\beta}>$ constraints, we can constrain m_1:**
  (2 flavor example)

$$\langle m_{\beta\beta} \rangle = \left| U_{e1}^2 m_1 + \varepsilon_{21} U_{e2}^2 \sqrt{m_1^2 + \delta m_{21}^2} \right|$$

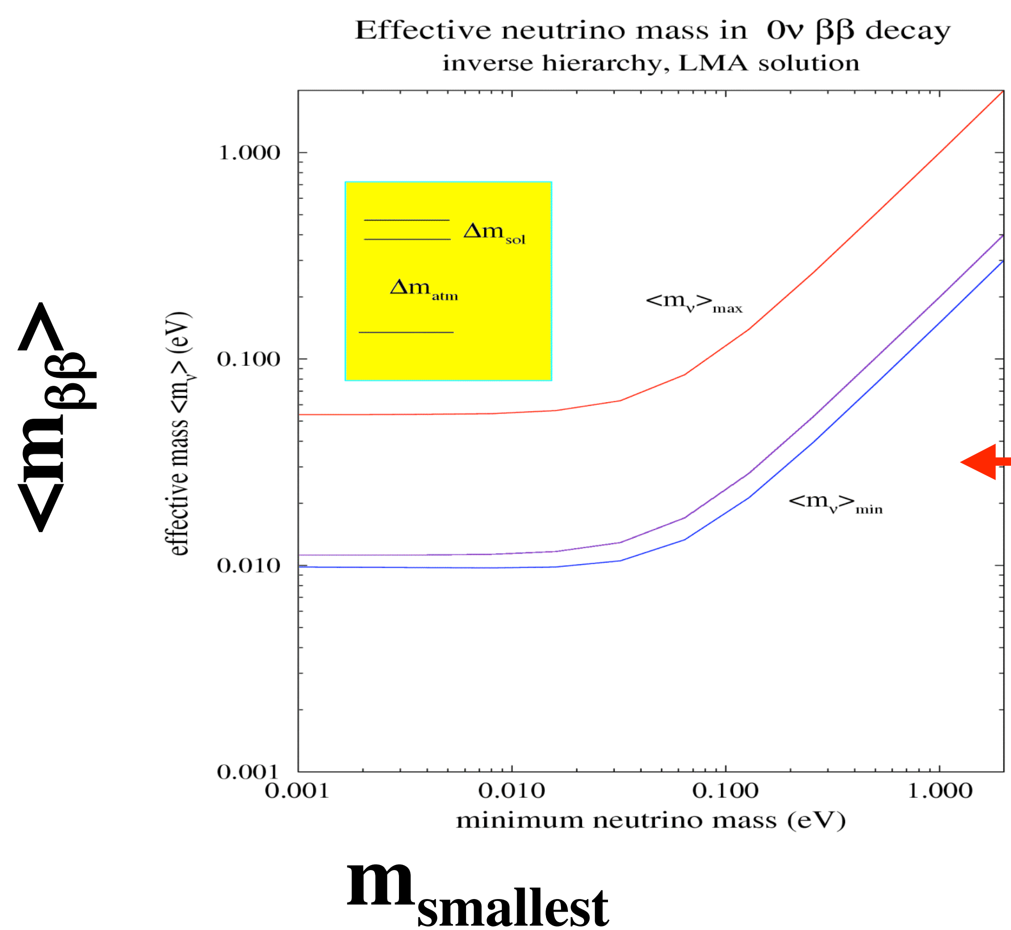
Min. <m$_{\beta\beta}$> as a vector sum.
General Case

$$\langle m_{\beta\beta}\rangle = \left\| U_{e1}\right|^2 m_1 + e^{i\beta}\left|U_{e2}\right|^2 m_2 + e^{i\alpha}\left|U_{e3}\right|^2 m_3 \right\|$$

<m$_{\beta\beta}$> is the modulus of the resultant.
In this example, <m$_{\beta\beta}$> has a min. It cannot be 0.



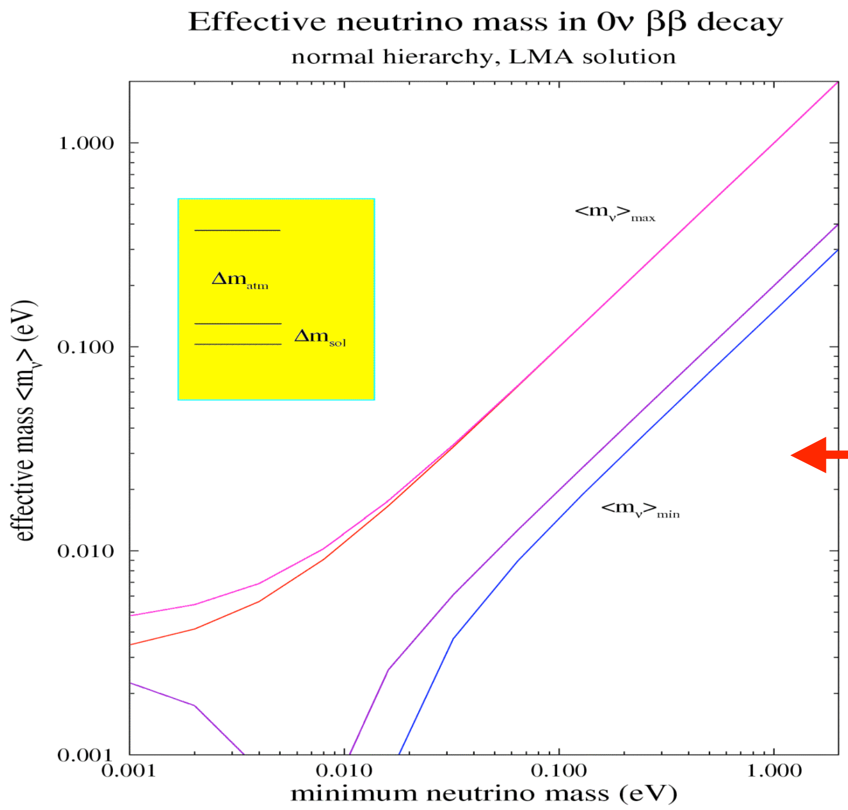
More General: 3 ν



50 meV or few x 10^{27} yr

Plot Thanks to Petr Vogel

More General



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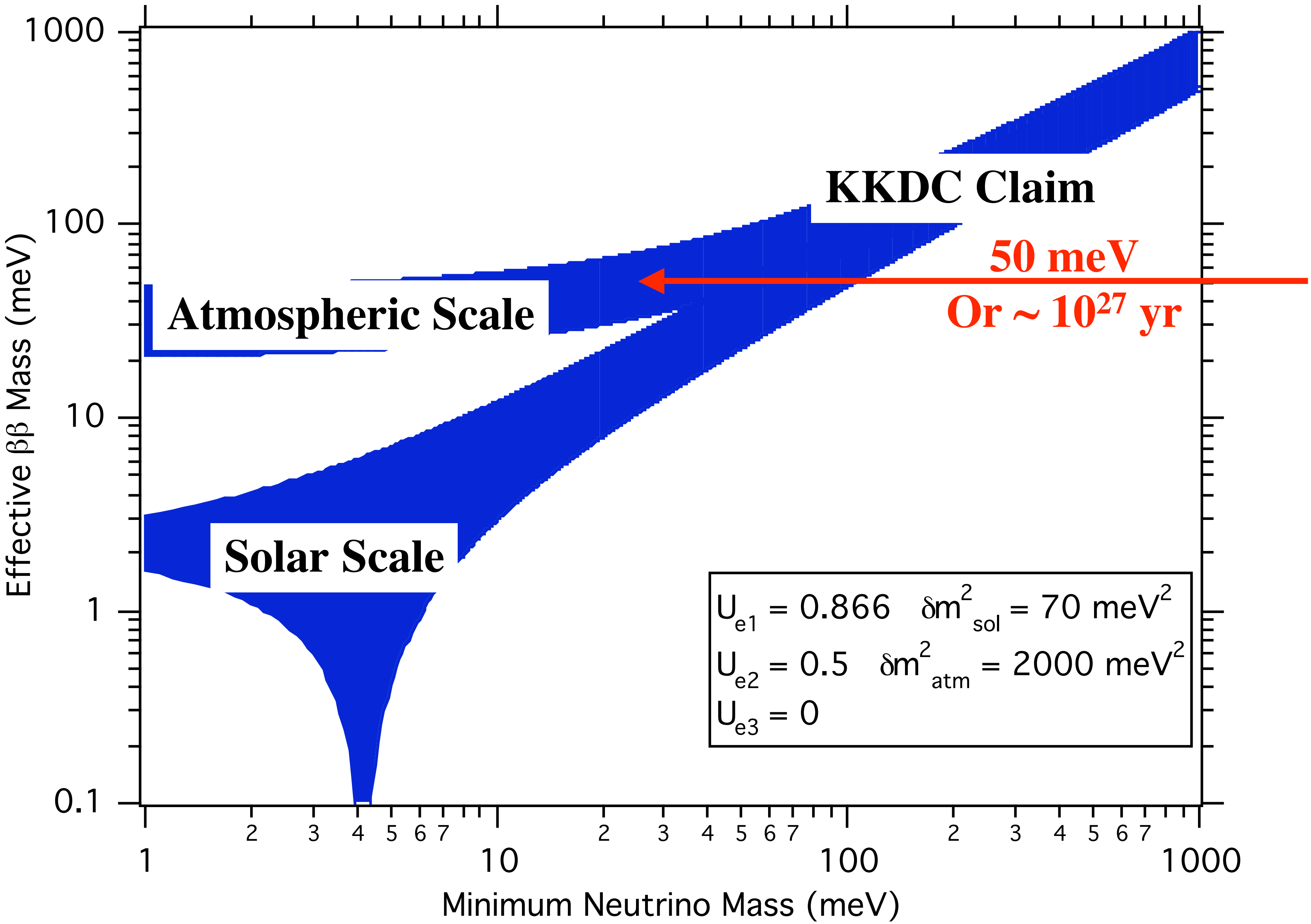
Plot Thanks to Petr Vogel


1000
100
10
1
0.1
Effective ββ Mass (meV)
1
2
3
4
5
6
7
10
100
1000
Minimum Neutrino Mass (meV)
KKDC Claim
Atmospheric Scale
Solar Scale
50 meV
Or ~ 10^27 yr
U_e1 = 0.866 δm^2_sol = 70 meV^2
U_e2 = 0.5 δm^2_atm = 2000 meV^2
U_e3 = 0

An exciting time for ββ!

For at least one neutrino:

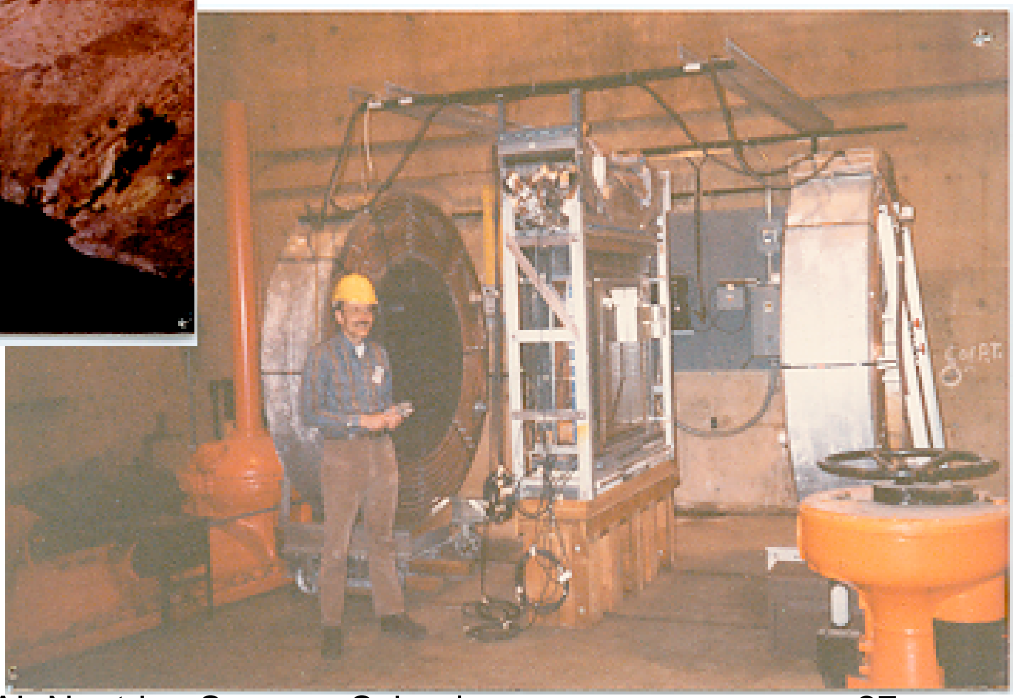
$$m_i > \sqrt{\delta m^2_{atmos}} \approx 50 meV$$

For the next experiments:

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

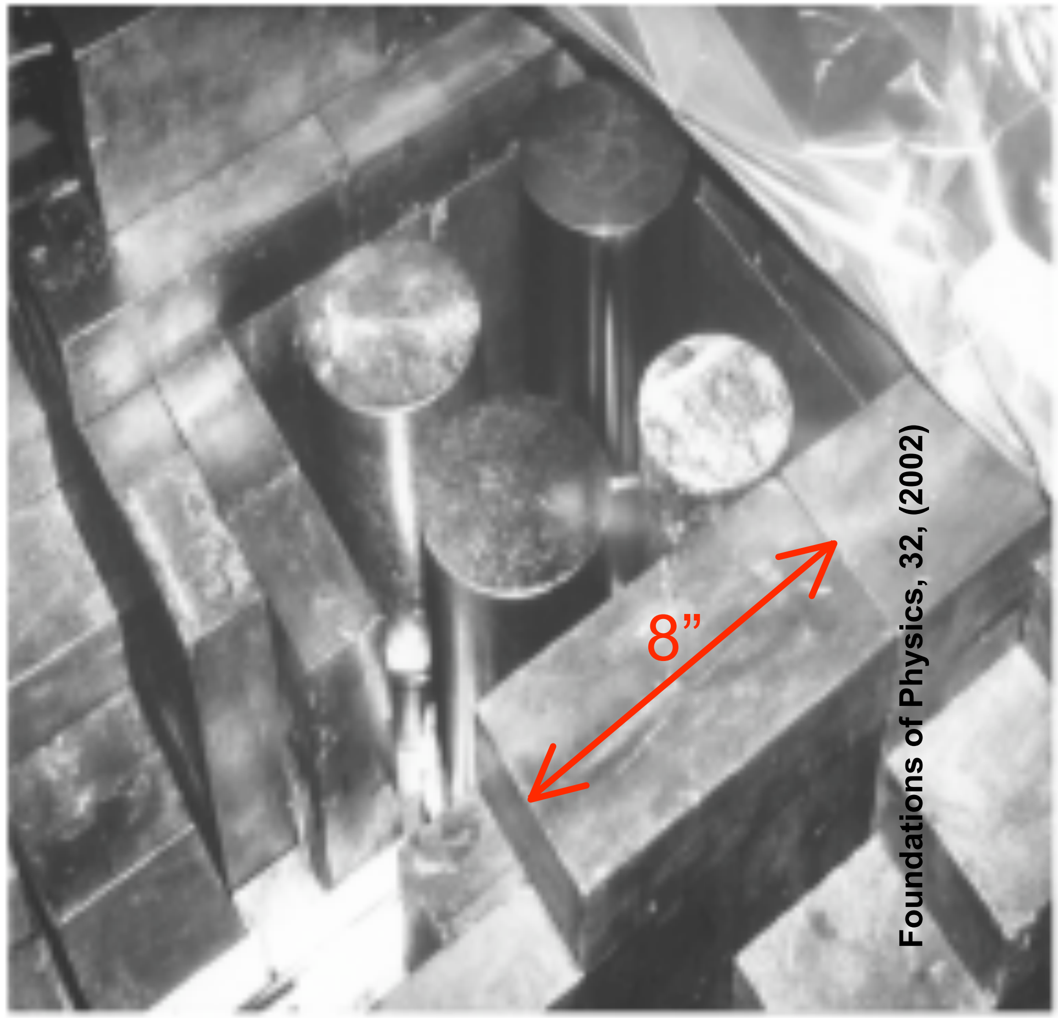
$< m_{\beta\beta} >$ in the range of 10 - 50 meV is very interesting.

The 1st Observation



The Heidelberg-Moscow Experiment

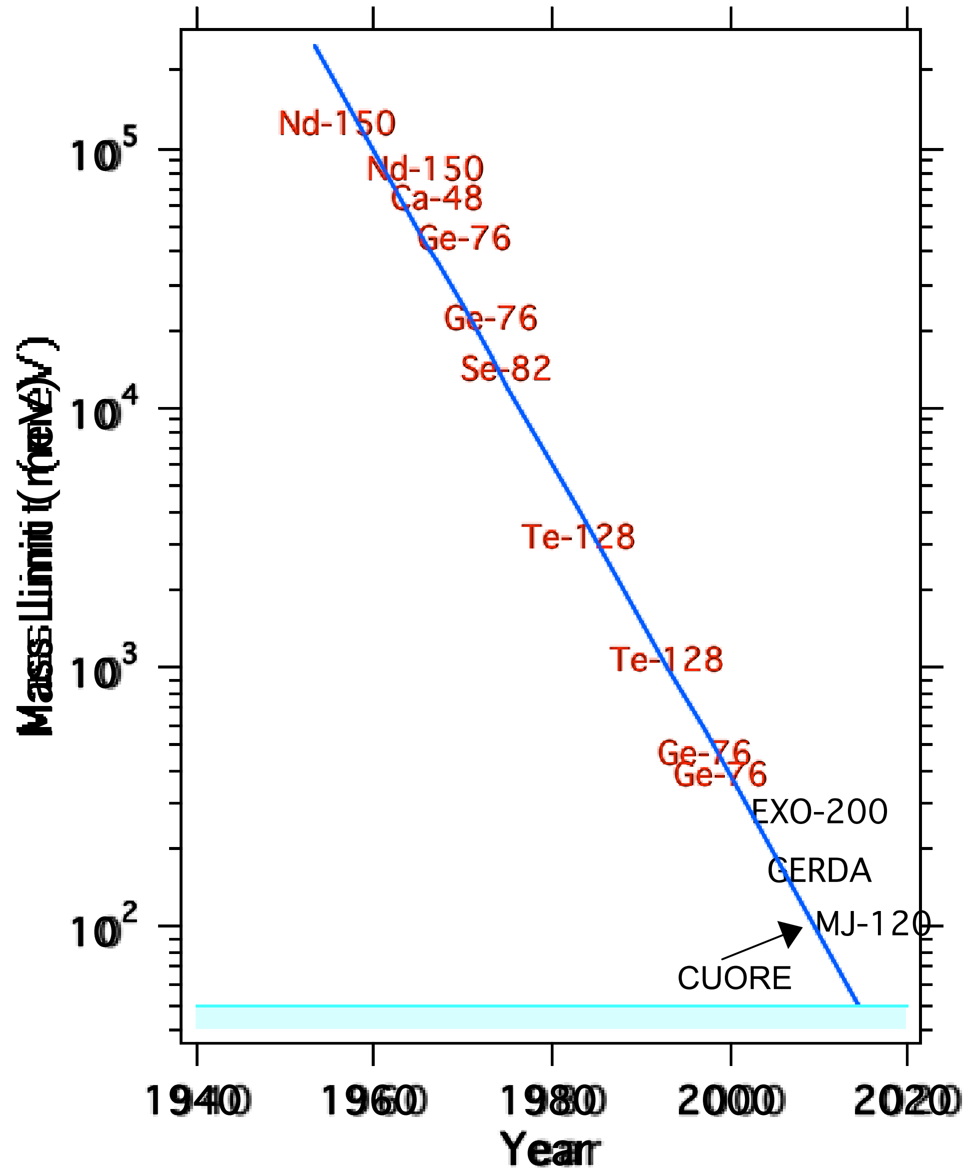
~10 kg of ^{76}Ge
13 years of data



$$\langle m_{\beta\beta} \rangle \propto \left(\frac{1}{|M|\sqrt{G_{0\nu}\tau_{1/2}}} \right)$$

^{48}Ca	$>1.4\text{x}10^{22}$ y	<(7.2-44.7) eV
^{76}Ge	$>1.9\text{x}10^{25}$ y	<0.35 eV
^{76}Ge	$>1.6\text{x}10^{25}$ y	<(0.33-1.35) eV
^{76}Ge	$=1.2\text{x}10^{25}$ y	=0.44 eV
^{82}Se	$>2.1\text{x}10^{23}$ y	<(1.2-3.2) eV
^{100}Mo	$>5.8\text{x}10^{23}$ y	<(0.6-2.7) eV
^{116}Cd	$>1.7\text{x}10^{23}$ y	<1.7 eV
^{128}Te	$>7.7\text{x}10^{24}$ y	<(1.1-1.5) eV
^{130}Te	$>3.0\text{x}10^{24}$ y	<(0.41-1.) eV
^{136}Xe	$>4.5\text{x}10^{23}$ y	<(0.8-5.6) eV
^{150}Nd	$>3.6\text{x}10^{21}$ y	

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



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)**
- **Good source radiopurity**
- **Demonstrated technology**
- **Natural isotope**
- **Small volume, source = detector**
- **Good energy resolution**
- **Ease of operation**
- **Large Q value, fast ββ(0ν)**
- **Slow ββ(2ν) rate**
- **Identify daughter**
- **Event reconstruction**
- **Nuclear theory**

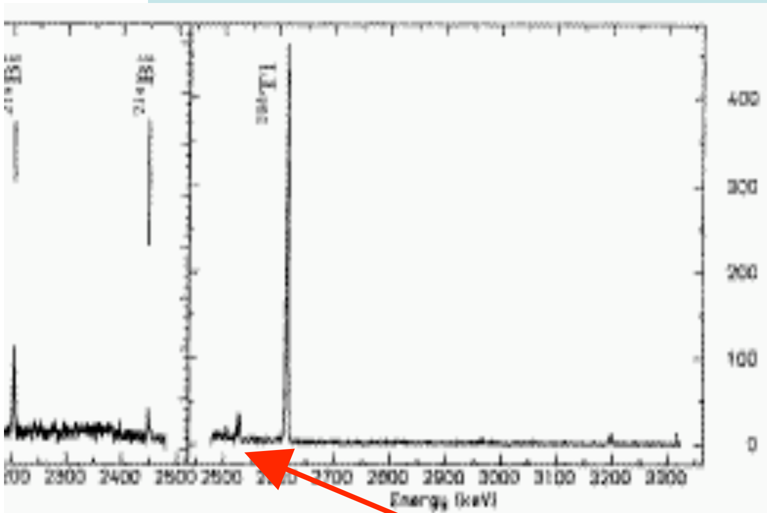
Great Number of Proposed Experiments

Experiment	Isotope	Mass	Technique	Present Status
CANDLES	^{48}Ca	few tons	CaF_2 scint. crystals	Prototype
CARVEL	^{48}Ca	1 ton	$CaWO_4$ scint. crystals	Development
COBRA	^{116}Cd	418 kg	CZT semicond. det.	Prototype
SuperNEMO	Se	100 kg	Se foils/tracking	Proposal
Xe	^{136}Xe	1.56 t	^{enr}Xe in liq. scint.	Development
XMASS	^{136}Xe	10 ton	liquid Xe	Prototype
HPXe	^{136}Xe	tons	High Pressure Xe gas	Development

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

"Found" Peaks

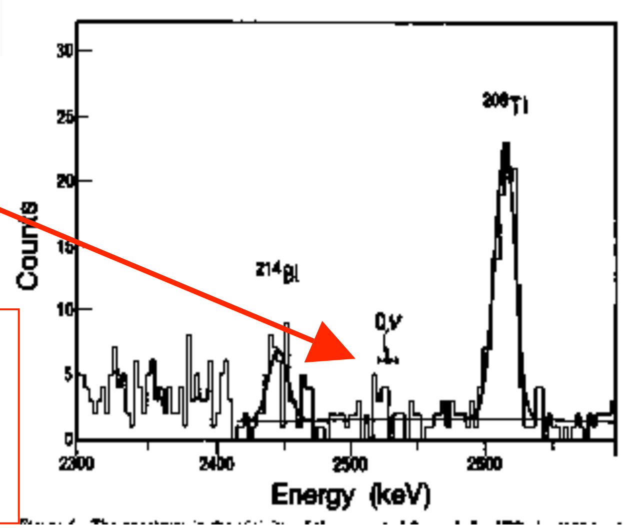
PR D45, 2548 (1992)



Need more than one experiment

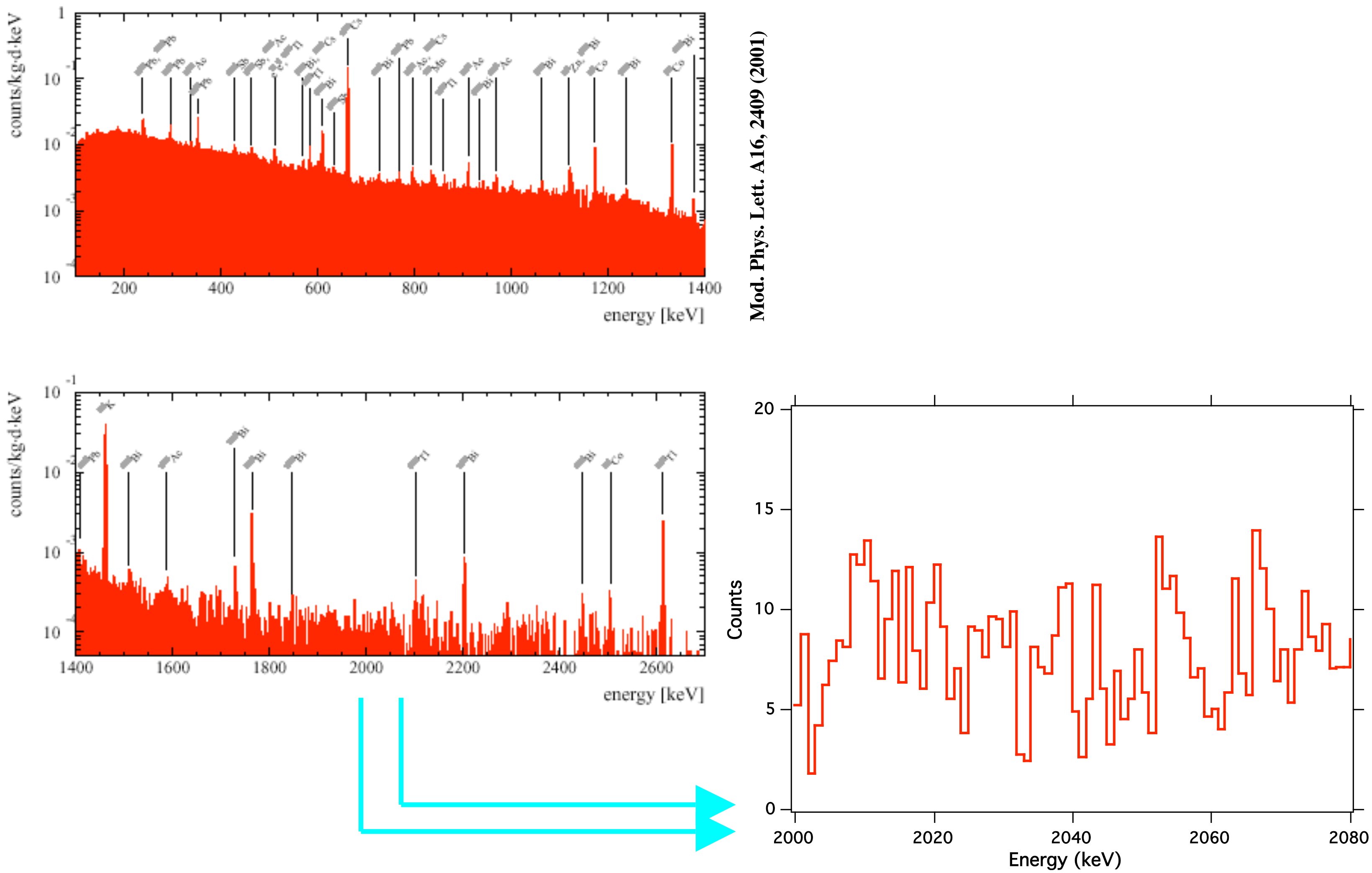
A 2527-keV Ge-det. peak that was an electronic artifact.

A ~2528-keV Te-det. peak that was a 2σ Statistical flucuation.

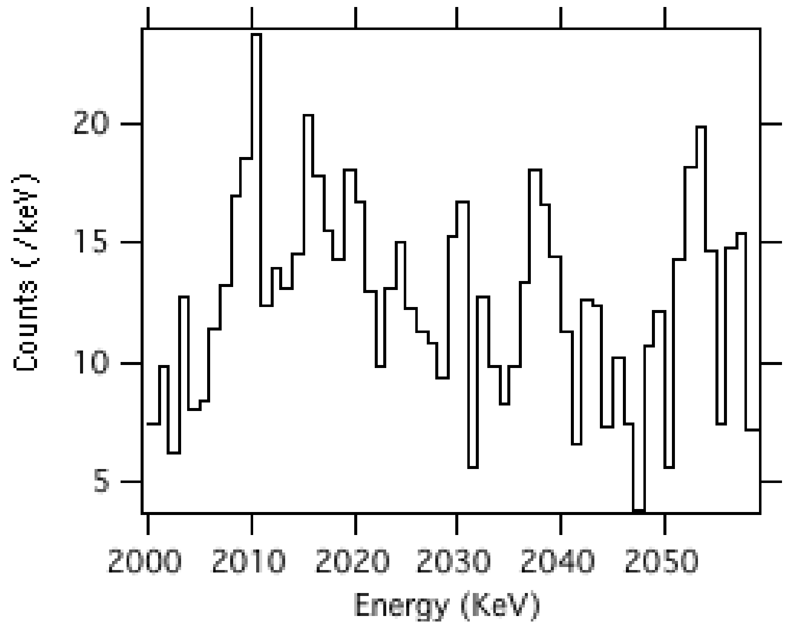


NP B35 (Proc. Supp.), 366 (1994).

A Recent Claim for ββ(0ν)

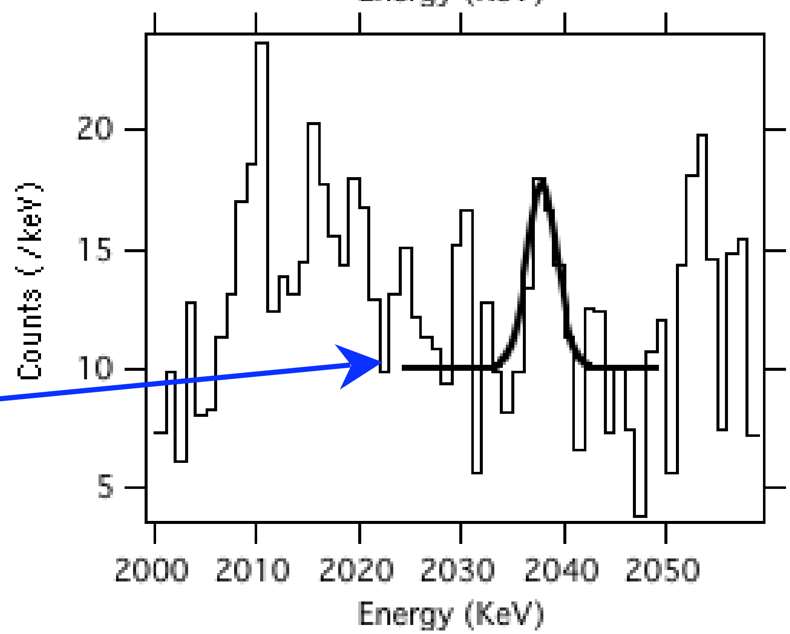


The ROI



The "feature" at 2038 keV is arguably present. This will probably require experimental testing.

Background level depends on intensity fit to other peaks.



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 repudiation

Various Levels of Confidence

- **A 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**
- **Open and shut case: the smoking gun**
  - **See the process in several isotopes**

Classes of Background for $\beta\beta(0\nu)$

- $\beta\beta(2\nu)$ tail

  Need good energy resolution.

- Natural U, Th in source and shielding

  Pure materials, segmentation, pulse shape.

- Cosmic ray activation

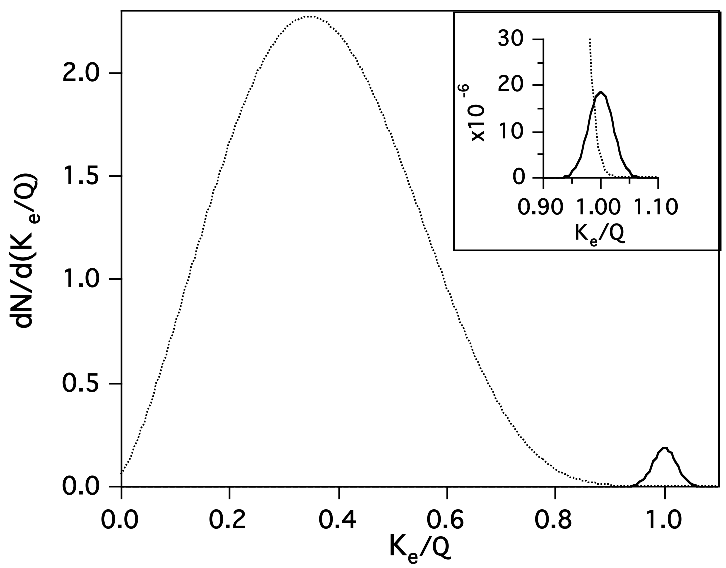
  Store and prepare materials underground.

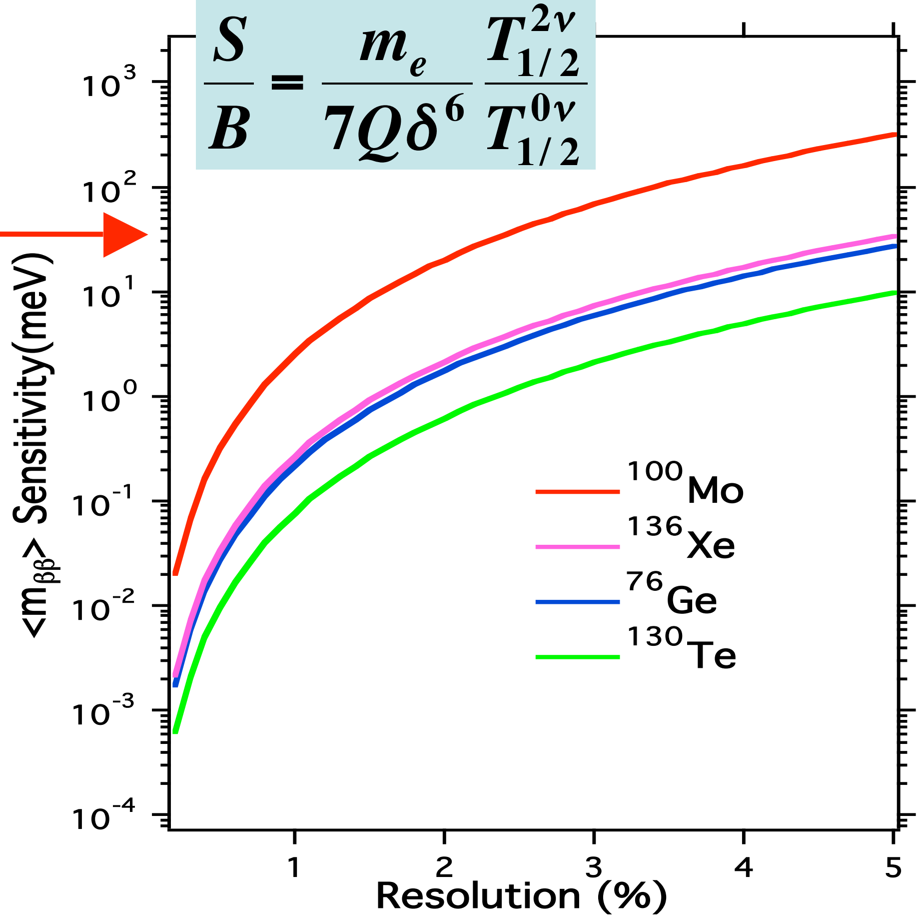
ββ(2ν) as a Background.

Sum Energy Cut Only

next generation experimental goal

$$\frac{S}{B} = \frac{m_e}{7Q\delta^6}\frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$





Natural Activity

- **The Problem:**
  τ(U, Th) ~ 10^{10} years
  Goal: $\tau(\beta\beta(0\nu))$ ~ 10^{27} years

- **Detector: Intrinsic Ge is very pure**
- **Cryostat: Electro-formed Cu**
- **Shielding: Roman Pb**
- **Front End Electronics: behind shield**

Cosmic Ray Induced Activity

- **Material dependent.**

  Lots of experience with Ge.

- **Need for depth to avoid activation.**

- **Need for storage to allow activation to decay.**

Pb(n,n'γ) and ^{76}Ge: an example