



Neutrino Physics - Double-Beta Decay

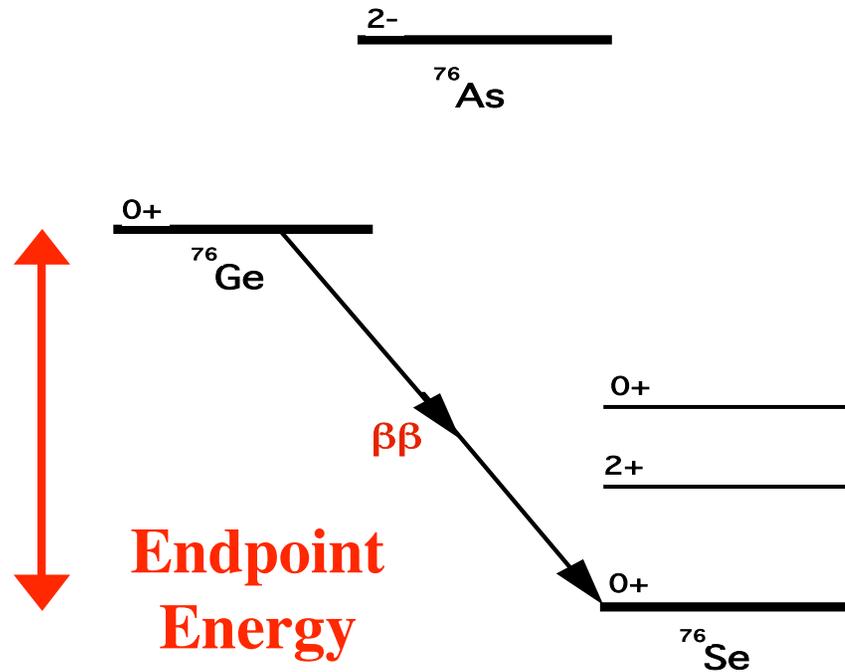
Steve Elliott

**Los Alamos National
Laboratory**

Lecture Outline

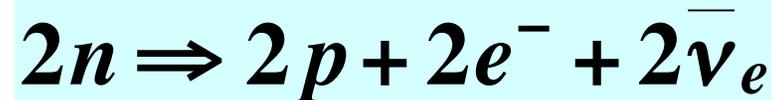
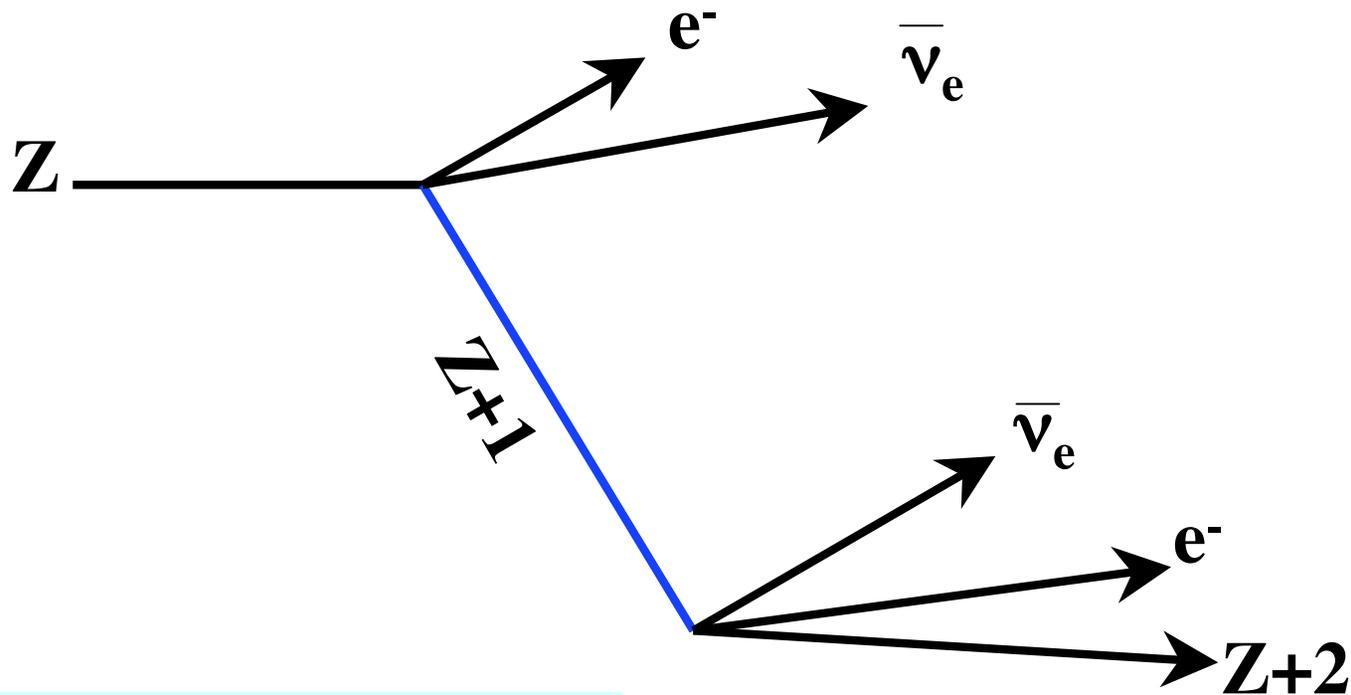
- **Double Beta Decay**
 - **Basic physics**
 - **General experimental techniques**
 - **The various experiments**

Example Decay Scheme

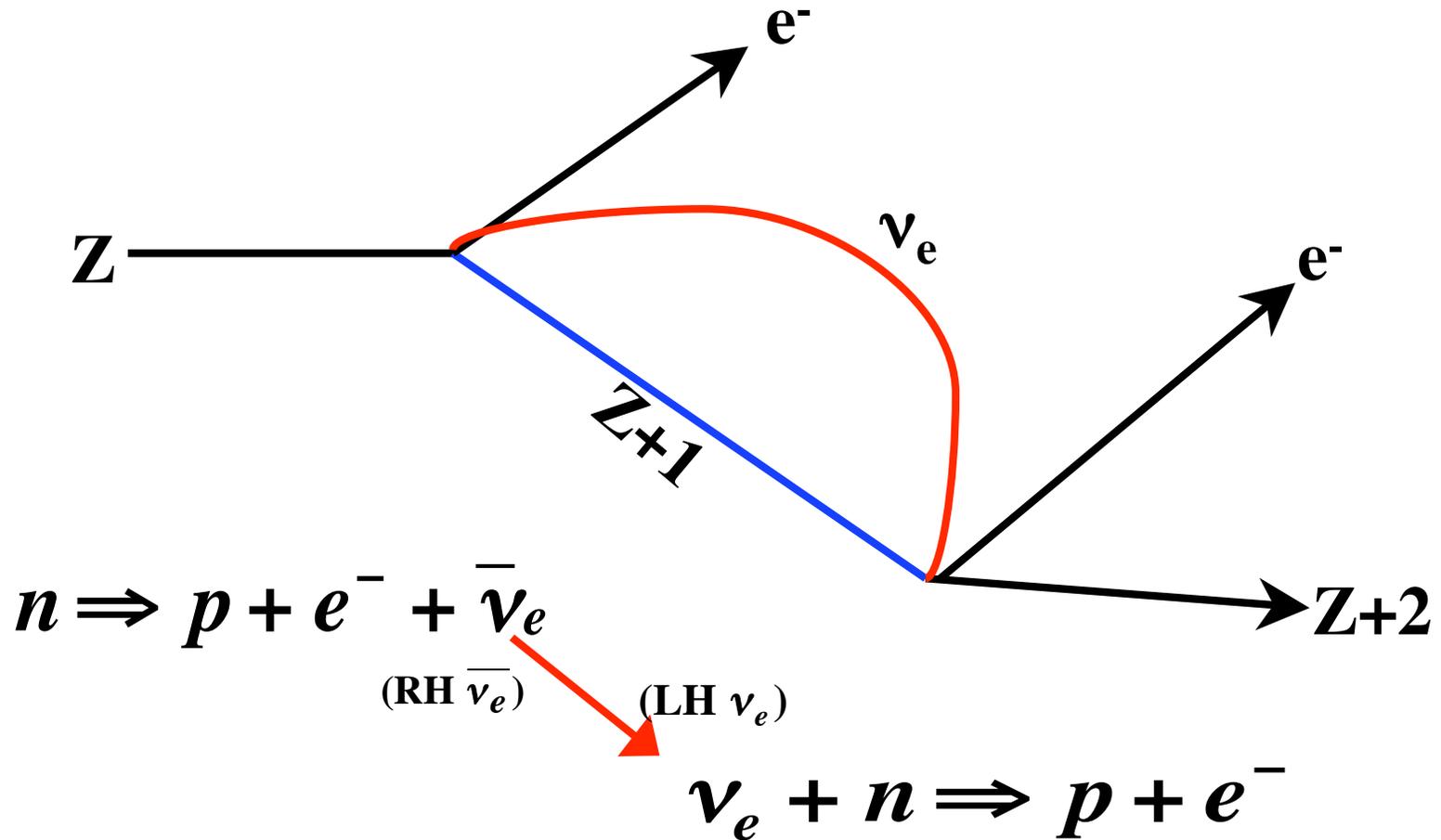


In many even-even nuclei, β decay is energetically forbidden. This leaves $\beta\beta$ as the allowed decay mode.

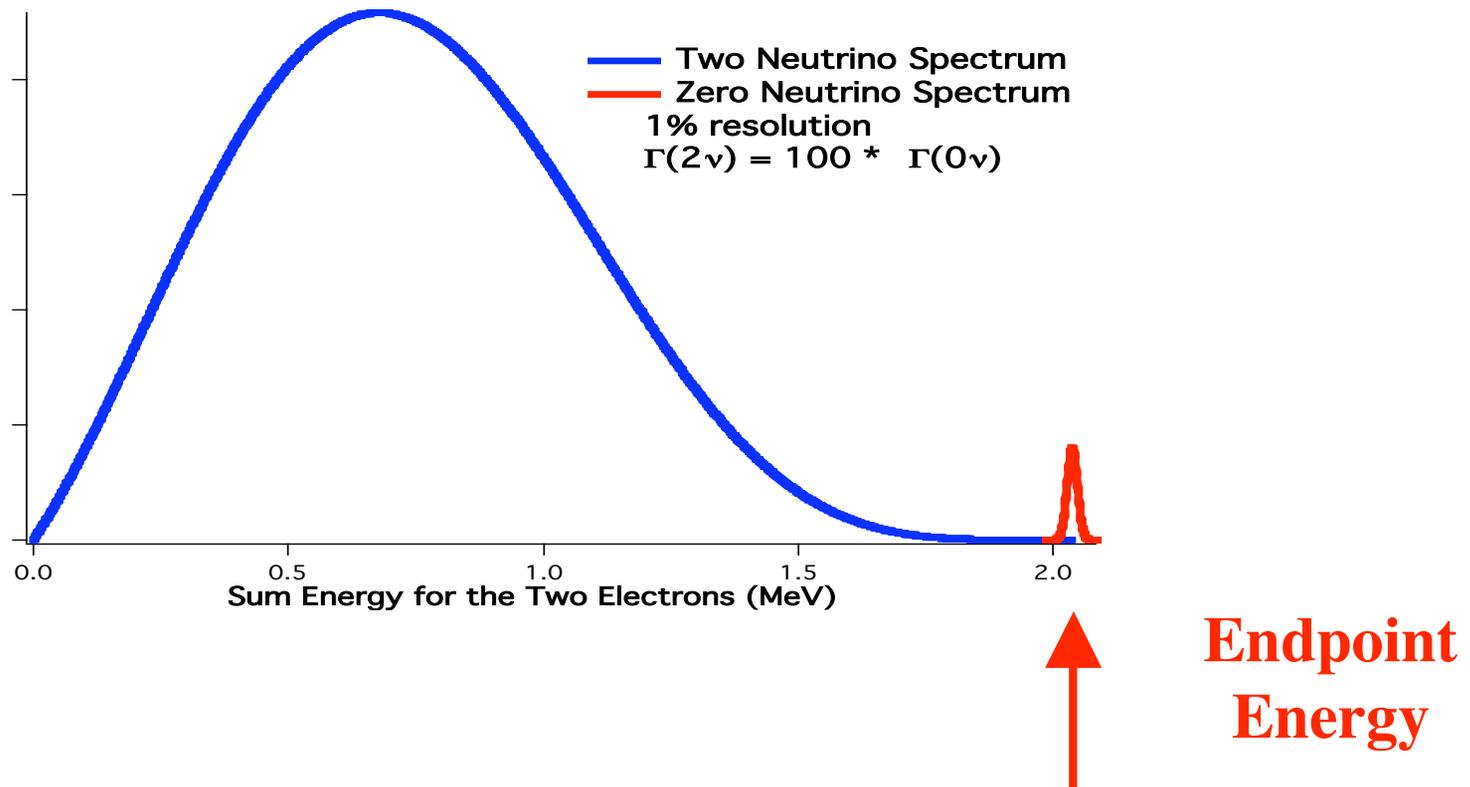
$\beta\beta(2\nu)$: Allowed weak decay



$\beta\beta(0\nu)$: requires massive Majorana ν
 Only practical way to address the particle-antiparticle question



Energy Spectrum for the $2 e^-$



$\beta\beta$ History

- $\beta\beta(2\nu)$ rate first calculated by Maria Goeppert-Mayer in **1935**.
- First observed directly in **1987**.
- Why so long? Background

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

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

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

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

$\beta\beta$ Candidates

There are a lot of them!

A periodic table of elements with red circles highlighting the following elements: Ca, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, K, Rb, Cs, Fr, Ra, Ba, Sr, Y, Lu, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn, Br, Kr, and the lanthanide series elements Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Yb.

Hydrogen 1 H 1.00794	Helium 2 He 4.002602																	Boron 5 B 10.811	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.179																				
Lithium 3 Li 6.941	Beryllium 4 Be 9.0122																	Aluminum 13 Al 26.982	Silicon 14 Si 28.086	Phosphorus 15 P 30.974	Sulfur 16 S 32.06	Chlorine 17 Cl 35.453	Argon 18 Ar 39.948																				
Sodium 11 Na 22.990	Magnesium 12 Mg 24.305	Scandium 21 Sc 44.956	Titanium 22 Ti 47.88	Vanadium 23 V 50.942	Chromium 24 Cr 51.996	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.693	Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.63	Arsenic 33 As 74.922	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.80																										
Potassium 19 K 39.098	Calcium 20 Ca 40.078	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.94	Technetium 43 Tc [98]	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 101.07	Palladium 46 Pd 106.36	Silver 47 Ag 107.868	Cadmium 48 Cd 112.411	Indium 49 In 114.818	Tin 50 Sn 118.710	Antimony 51 Sb 121.757	Tellurium 52 Te 127.60	Iodine 53 I 126.905	Xenon 54 Xe 131.29																										
Rubidium 37 Rb 85.468	Sr 38 Sr 87.62	57-70																Thallium 81 Tl 204.38	Lead 82 Pb 207.2	Bismuth 83 Bi 208.98	Polonium 84 Po [209]	Astatine 85 At [209]	Rn 86 Rn [222]																				
Cesium 55 Cs 132.91	Ba 56 Ba 137.33	89-102																Francium 87 Fr [223]	Radium 88 Ra [226]																	Mercury 80 Hg 200.59	Thallium 81 Tl 204.38	Lead 82 Pb 207.2	Bismuth 83 Bi 208.98	Polonium 84 Po [209]	Astatine 85 At [209]	Rn 86 Rn [222]	
Francium 87 Fr [223]	Radium 88 Ra [226]	89-102																Lanthanum 57 La 138.91	Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Niodymium 60 Nd 144.24	Europium 61 Eu 151.96	Gadolinium 62 Gd 157.25	Terbium 63 Tb 158.93	Dysprosium 64 Dy 162.50	Ho 65 Ho 164.93	Erbium 66 Er 167.26	Thulium 67 Tm 168.93	Ytterbium 68 Yb 173.05	Actinium 89 Ac [227]	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Neptunium 93 Np [237]	Plutonium 94 Pu [244]	Americium 95 Am [243]	Curium 96 Cm [247]	Berkelium 97 Bk [247]	Californium 98 Cf [251]	Einsteinium 99 Es [252]	Fermium 100 Fm [257]	Mendelevium 101 Md [258]	No 102 No [259]

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**

$\beta\beta$ Candidates

Abundance > 5%, Trans. Energy > 2 MeV

Hydrogen 1 H 1.00794																		Helium 2 He 4.00260																	
Lithium 3 Li 6.941		Beryllium 4 Be 9.01218												Boron 5 B 10.811		Carbon 6 C 12.011		Nitrogen 7 N 14.007		Oxygen 8 O 15.999		Fluorine 9 F 18.998		Neon 10 Ne 20.179											
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Rubidium 37 Rb 85.468		Strontium 38 Sr 87.62		Yttrium 39 Y 88.906		Zirconium 40 Zr 91.224		Niobium 41 Nb 92.906		Molybdenum 42 Mo 95.94		Technetium 43 Tc [98]		Ruthenium 44 Ru 101.07		Rhodium 45 Rh 101.07		Palladium 46 Pd 106.42		Silver 47 Ag 107.865		Cadmium 48 Cd 112.411		Indium 49 In 114.818		Tin 50 Sn 118.710		Antimony 51 Sb 121.757		Tellurium 52 Te 127.60		Iodine 53 I 126.905		Xenon 54 Xe 131.29	
Cesium 55 Cs 132.905		Barium 56 Ba 137.327		Lanthanum 57 La 138.905		Cerium 58 Ce 140.12		Praseodymium 59 Pr 140.908		Neodymium 60 Nd 144.242		Promethium 61 Pm [145]		Samarium 62 Sm 150.36		Europium 63 Eu 151.964		Gadolinium 64 Gd 157.25		Terbium 65 Tb 158.925		Dysprosium 66 Dy 162.50		Holmium 67 Ho 164.930		Erbium 68 Er 167.259		Thulium 69 Tm 168.934		Ytterbium 70 Yb 173.054					
Francium 87 Fr [223]		Radium 88 Ra [226]		Actinium 89 Ac [227]		Thorium 90 Th 232.037		Protactinium 91 Pa 231.036		Uranium 92 U 238.029		Neptunium 93 Np [237]		Plutonium 94 Pu [244]		Americium 95 Am [243]		Curium 96 Cm [247]		Berkelium 97 Bk [247]		Californium 98 Cf [251]		Einsteinium 99 Es [252]		Fermium 100 Fm [257]		Mendelevium 101 Md [258]		Nobelium 102 No [259]					

 Frequently studied isotope.

$\beta\beta$ Decay Rates

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

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

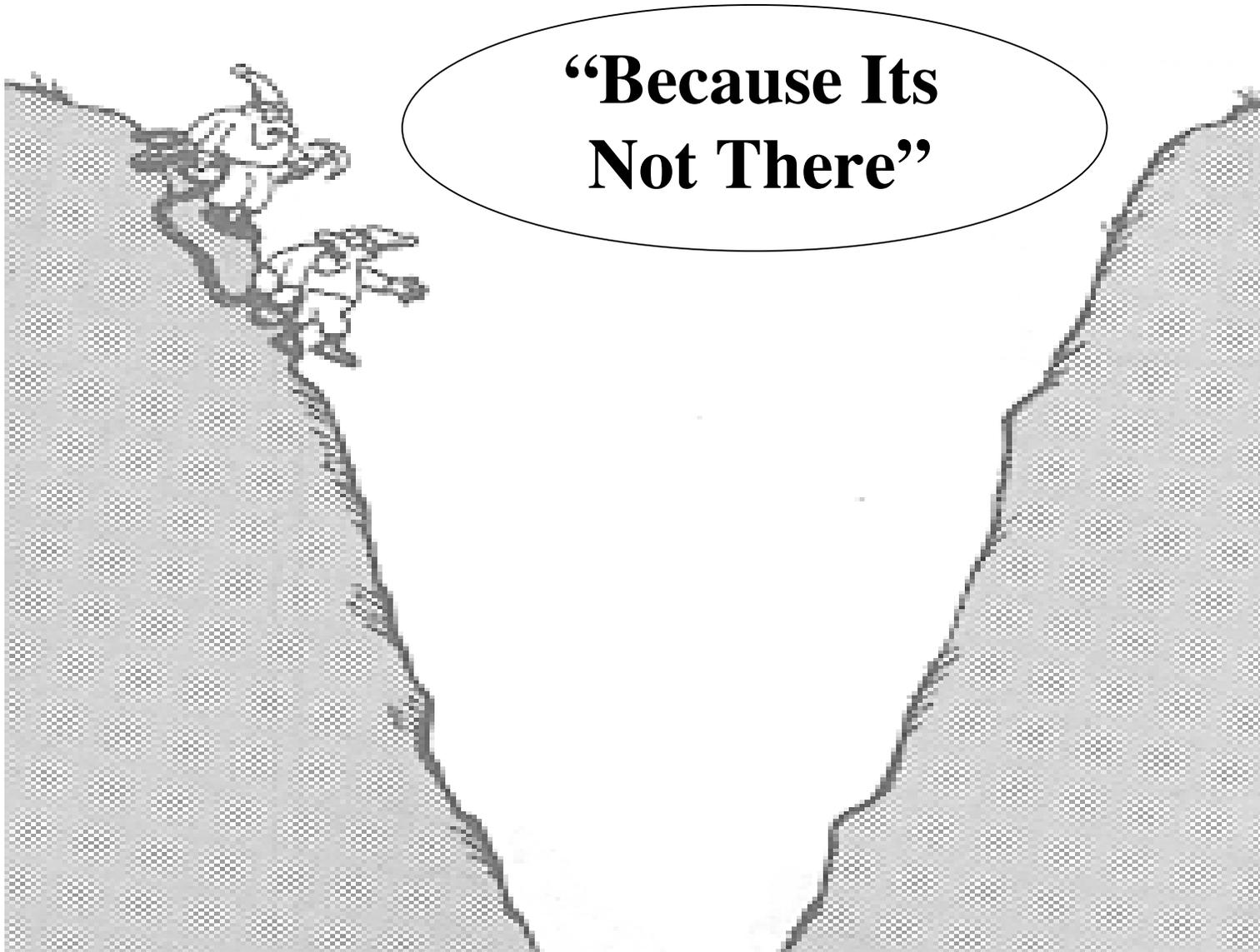
G are calculable phase space factors.

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

|M| are nuclear physics matrix elements.

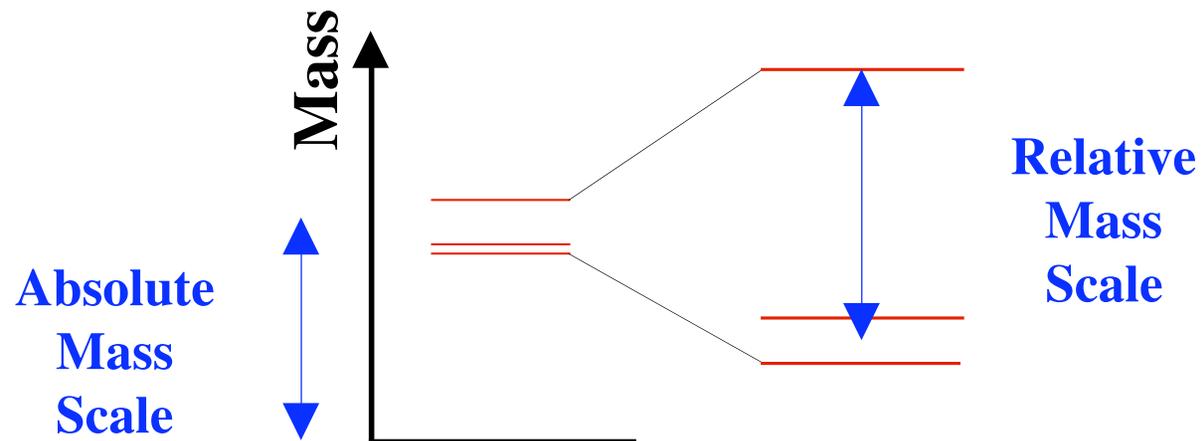
Hard to calculate.

m_ν is where the interesting physics lies.



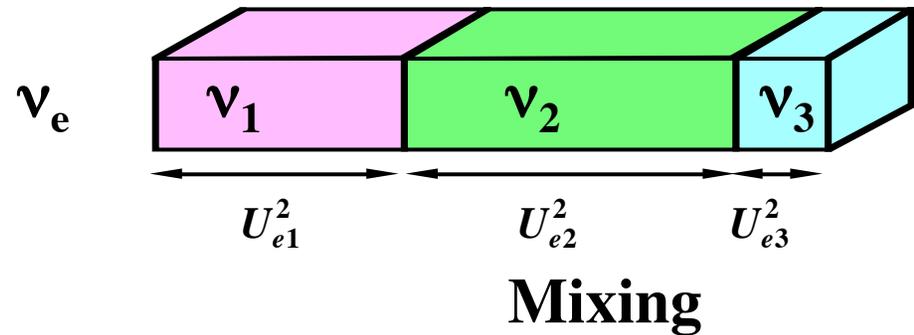
Larson

Neutrino Mass: What do we want to know?



Dirac or Majorana

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



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.

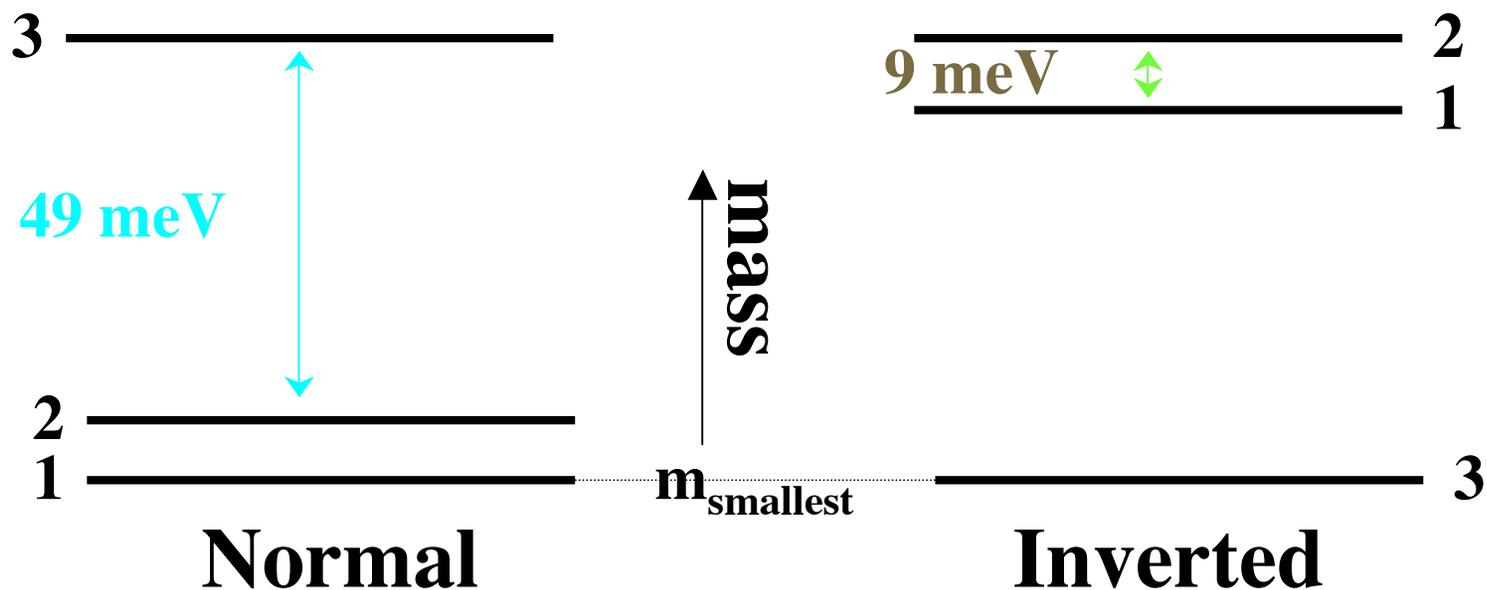
The weak interaction produces ν_e, ν_μ, ν_τ .

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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 & $\beta\beta(0\nu)$?

No mixing:

$$\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$$

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

**virtual ν
exchange**

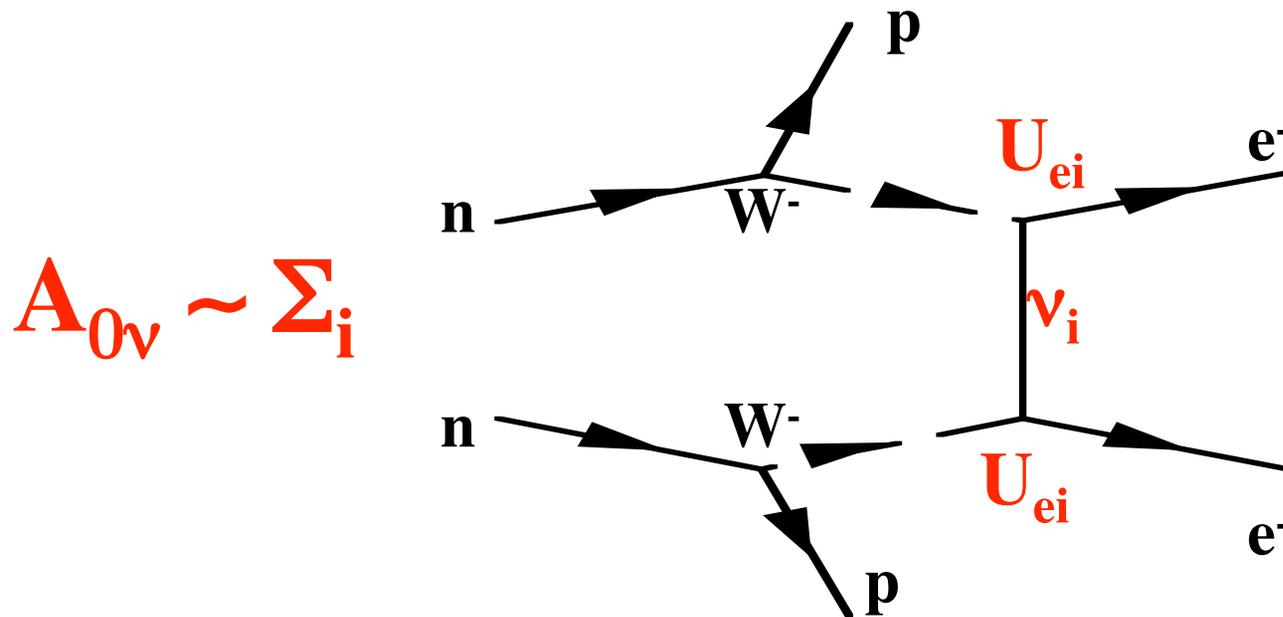
$\varepsilon = \pm 1$, CP cons.

Compare to β decay result:

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

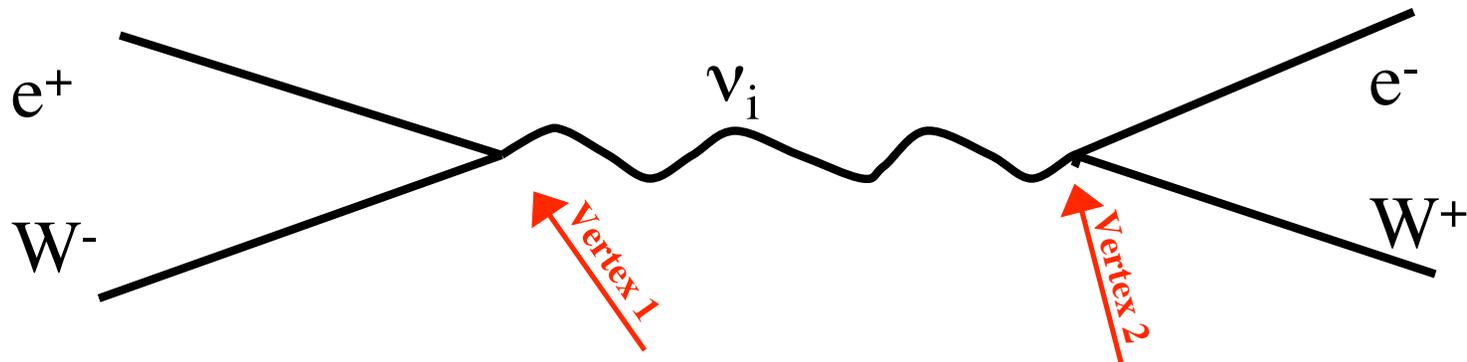
**real ν
emission**

Why does the CP parity appear in $\langle m_{\beta\beta} \rangle$?



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.

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

Upon substitution, the factor ε_i appears.

What can be learned from Oscillations & $\beta\beta$?

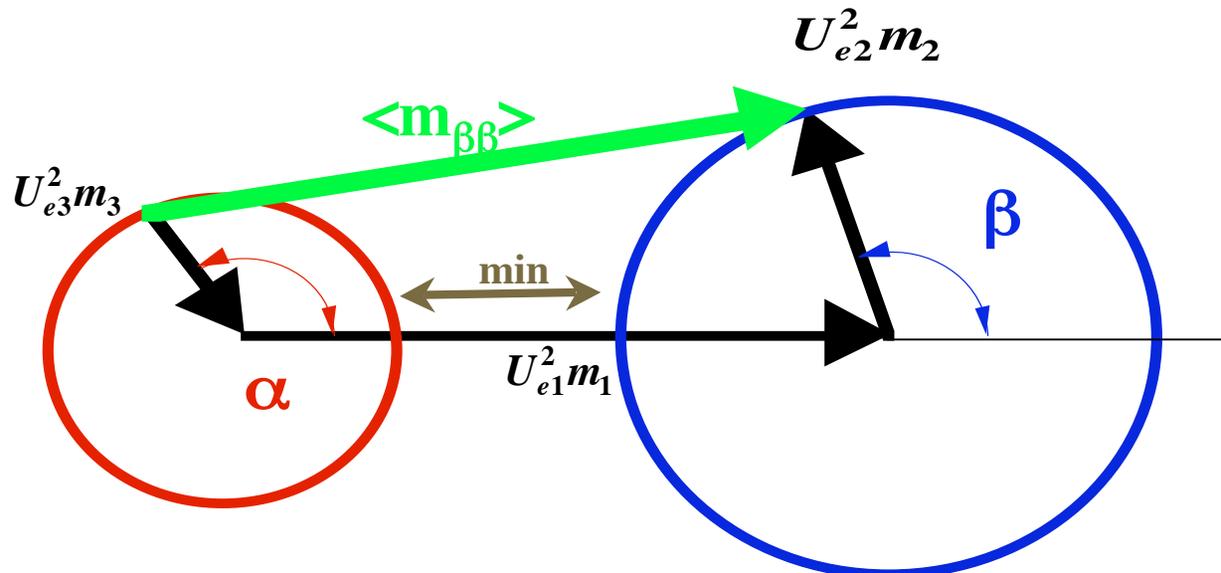
- **From oscillations, we have:**
Information on U_{ei}
Information on δm^2
- **With $\langle m_{\beta\beta} \rangle$ constraints, we can constrain m_1 :**
(2 flavor example)

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

Min. $\langle m_{\beta\beta} \rangle$ as a vector sum. General Case

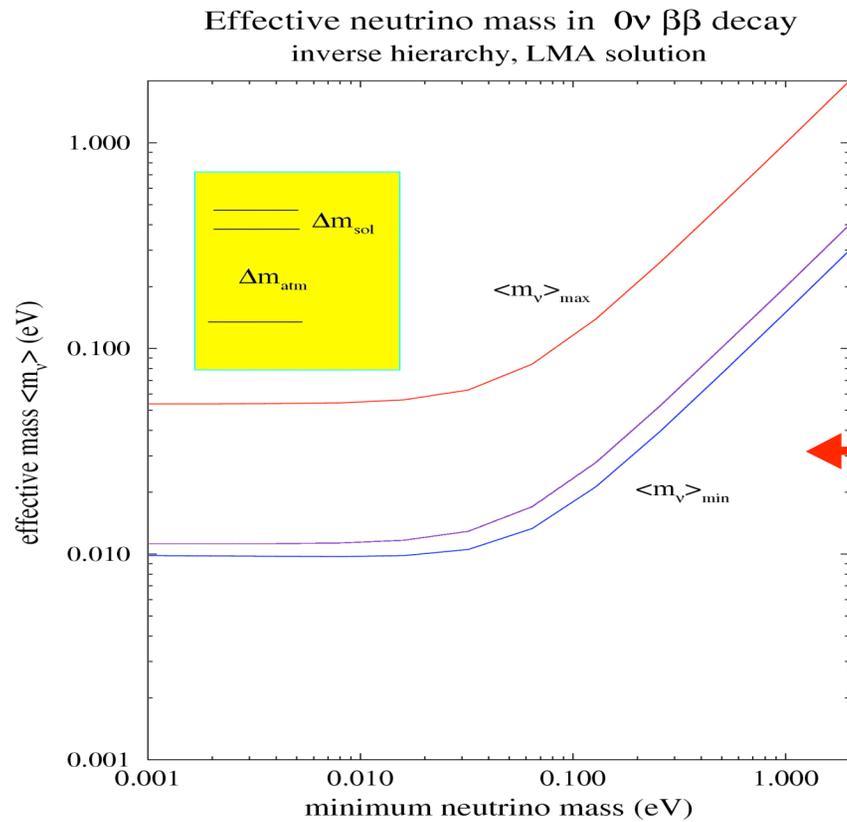
$$\langle m_{\beta\beta} \rangle = \left| U_{e1}^2 m_1 + e^{i\beta} U_{e2}^2 m_2 + e^{i\alpha} U_{e3}^2 m_3 \right|$$

$\langle m_{\beta\beta} \rangle$ is the modulus of the resultant.
In this example, $\langle m_{\beta\beta} \rangle$ has a **min**. It cannot be 0.



More General: 3 ν

$\langle m_{\beta\beta} \rangle$



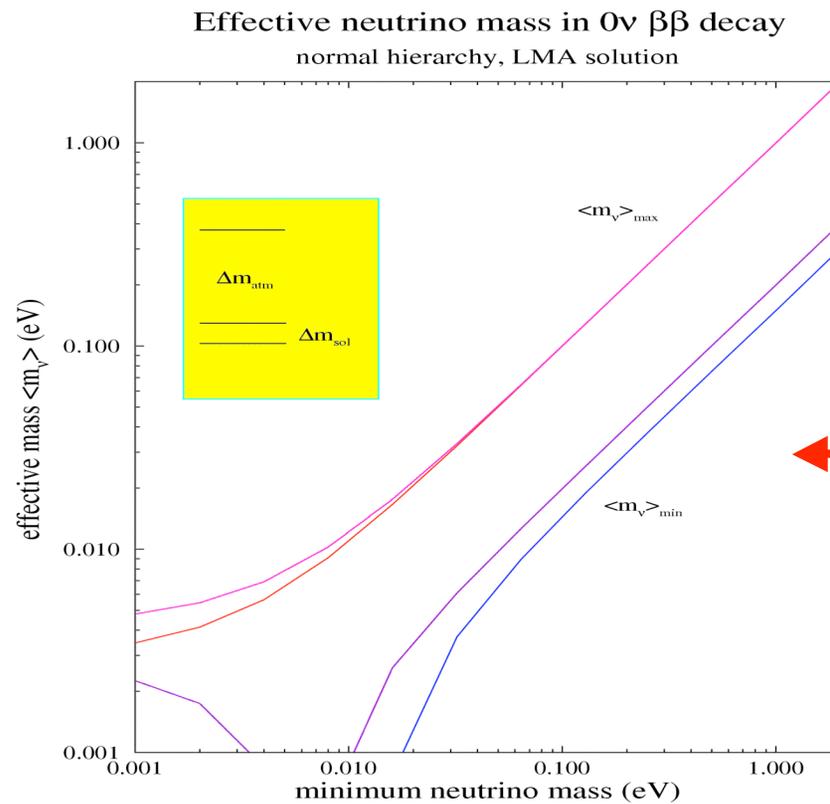
50 meV or
few $\times 10^{27}$ yr



m_{smallest}

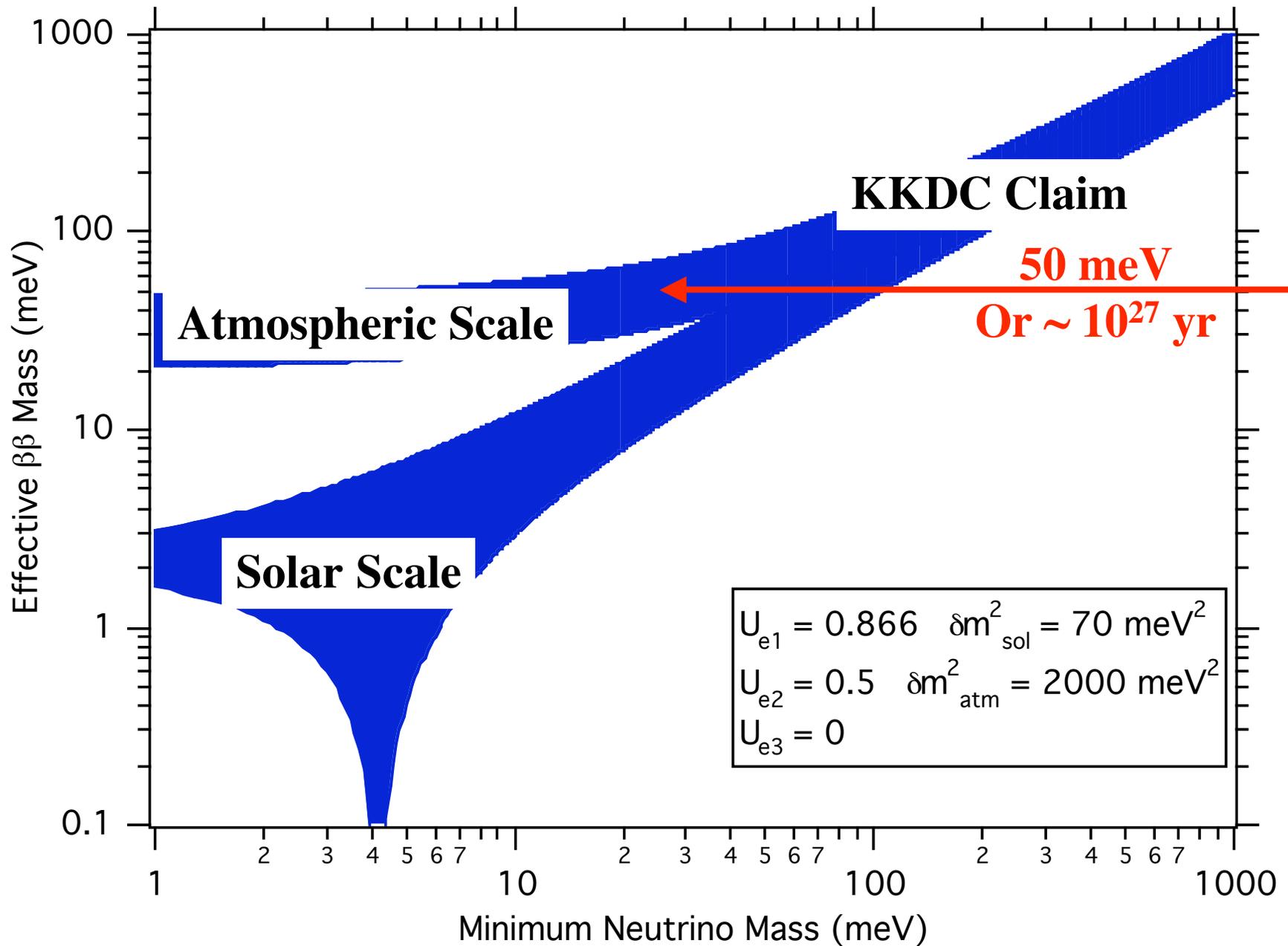
Plot
Thanks to
Petr Vogel

More General



**50 meV or
few $\times 10^{27}$ yr**

Plot
Thanks to
Petr Vogel



An exciting time for $\beta\beta$!

For at least
one
neutrino:

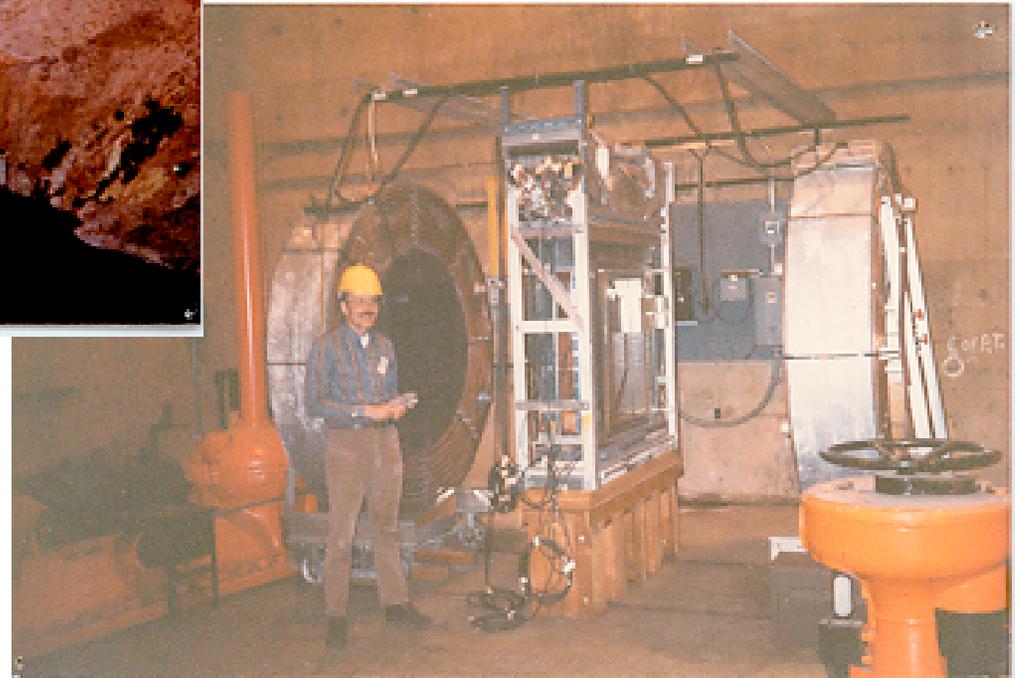
$$m_i > \sqrt{\delta m_{atmos}^2} \approx 50 \text{ meV}$$

For the next experiments:

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

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

The 1st Observation



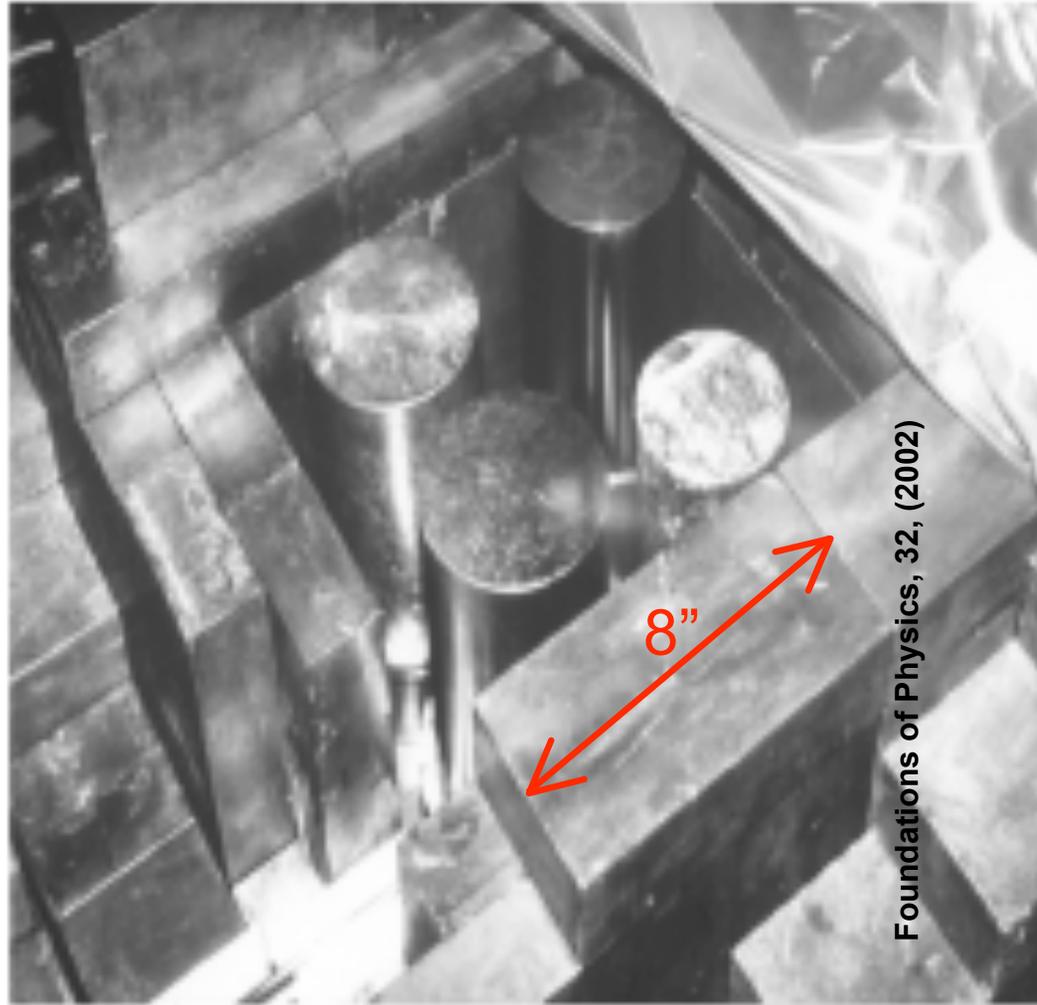
June 2007

Steve Elliott, FNAL Neutrino Summer School

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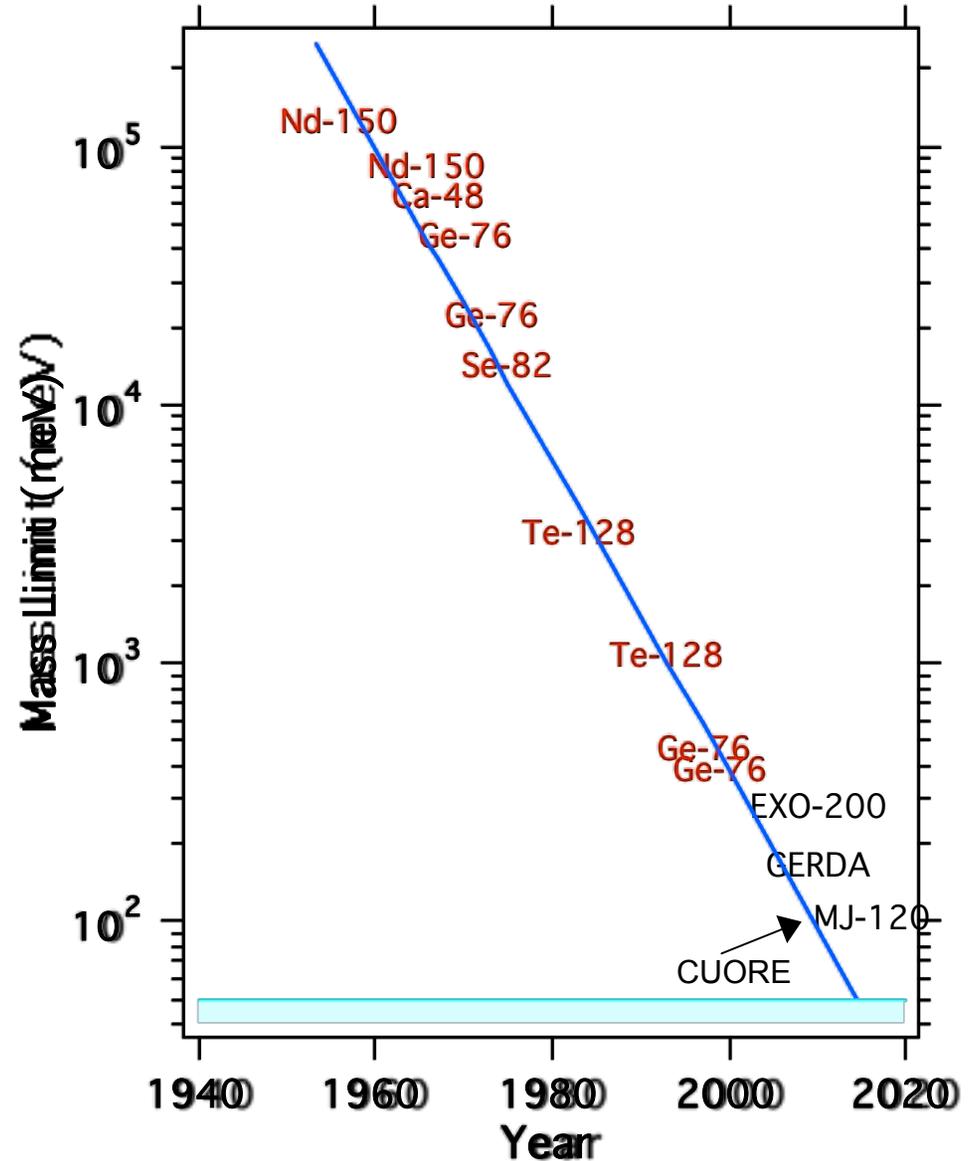
The Heidelberg-Moscow Experiment

~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	>1.4x10 ²² y	<(7.2-44.7) eV
⁷⁶ Ge	>1.9x10 ²⁵ y	<0.35 eV
⁷⁶ Ge	>1.6x10 ²⁵ y	<(0.33-1.35) eV
⁷⁶ Ge	=1.2x10 ²⁵ y	=0.44 eV
⁸² Se	>2.1x10 ²³ y	<(1.2-3.2) eV
¹⁰⁰ Mo	>5.8x10 ²³ y	<(0.6-2.7) eV
¹¹⁶ Cd	>1.7x10 ²³ y	<1.7 eV
¹²⁸ Te	>7.7x10 ²⁴ y	<(1.1-1.5) eV
¹³⁰ Te	>3.0x10 ²⁴ y	<(0.41-1.) eV
¹³⁶ Xe	>4.5x10 ²³ y	<(0.8-5.6) eV
¹⁵⁰ Nd	>3.6x10 ²¹ y	



An Ideal Experiment

Maximize Rate/Minimize Background

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

- 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 $\beta\beta(0\nu)$
 - Slow $\beta\beta(2\nu)$ rate
 - Identify daughter
 - Event reconstruction
 - Nuclear theory

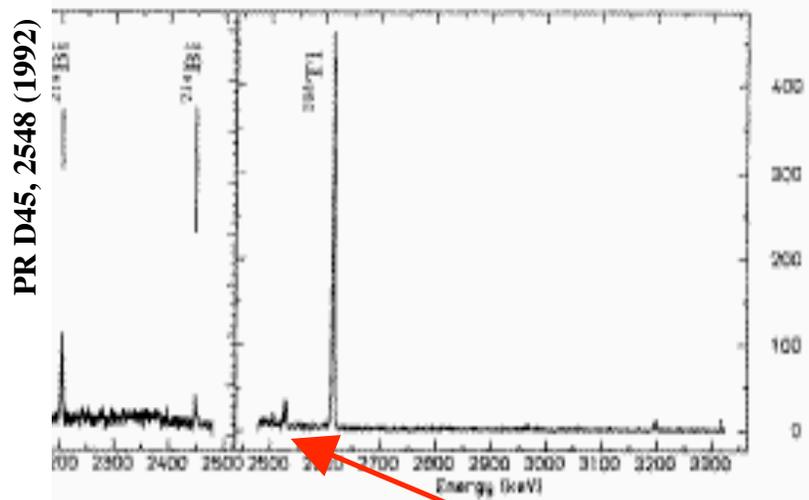
Great Number of Proposed Experiments

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

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

SuperNEMO	^{136}Xe	100 kg	Se ions/tracking	Proposal
Xe	^{136}Xe	1.56 t	^{136}Xe in liq. scint.	Development
XMASS	^{136}Xe	10 ton	liquid Xe	Prototype
HPXe	^{136}Xe	tons	High Pressure Xe gas	Development

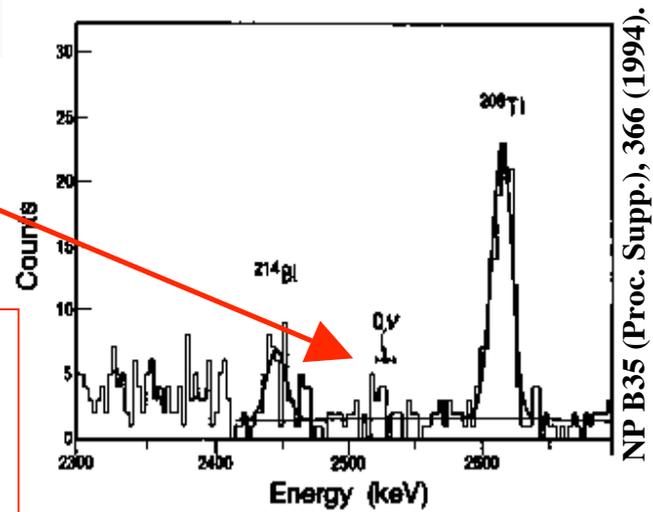
“Found” Peaks



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

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

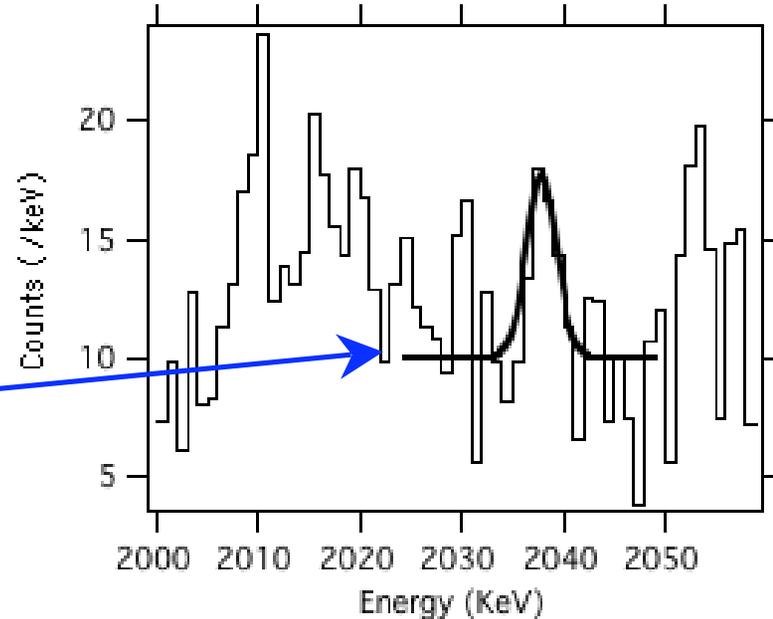
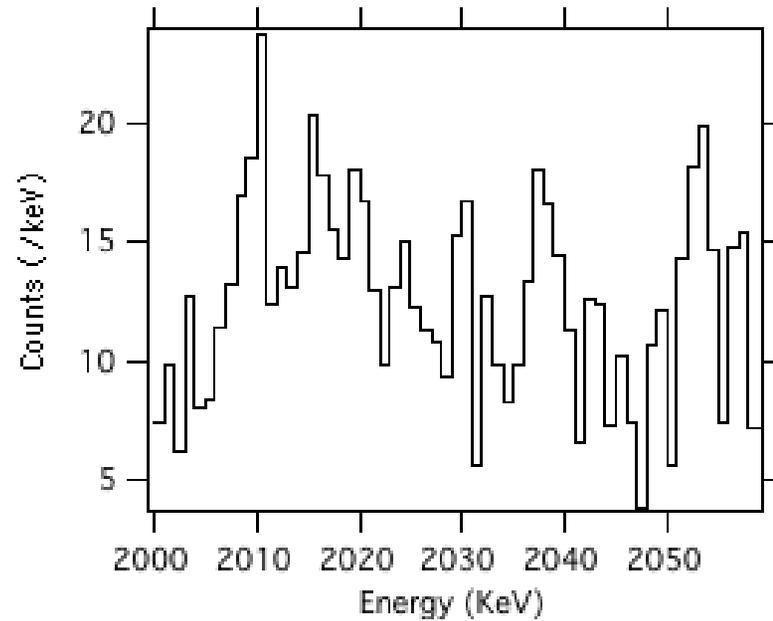
Need more than one experiment



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

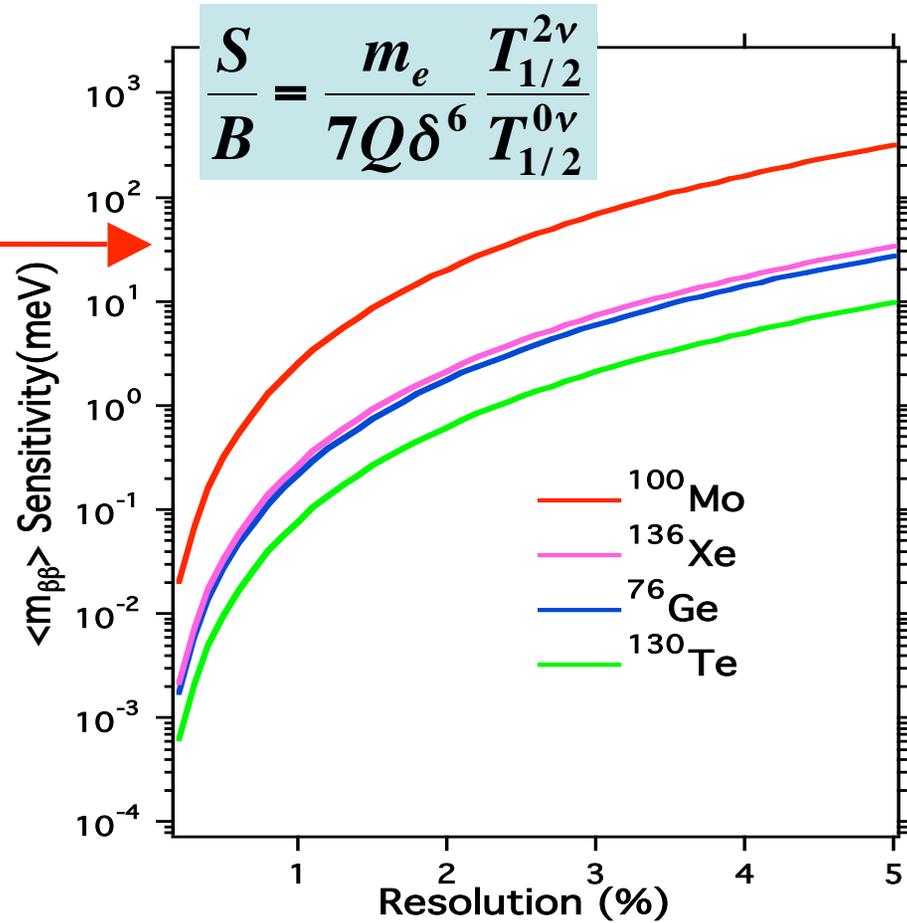
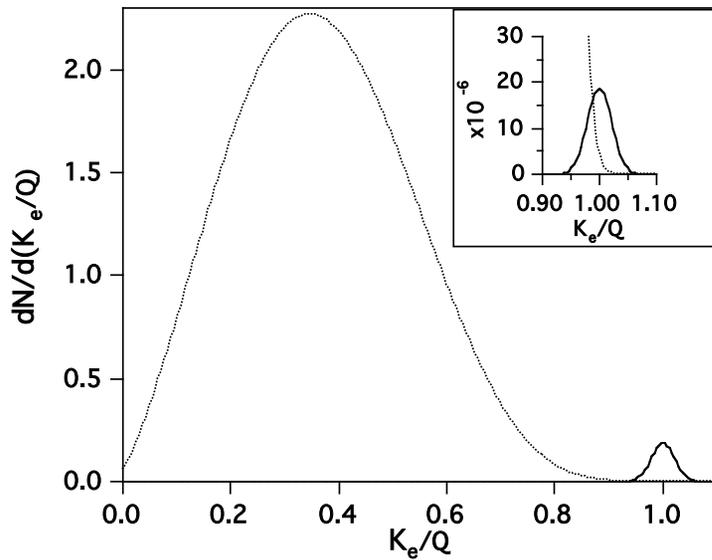
Classes of Background for $\beta\beta(0\nu)$

- **$\beta\beta(2\nu)$ 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.

$\beta\beta(2\nu)$ 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:**
 $\tau(\text{U, Th}) \sim 10^{10} \text{ years}$
Goal: $\tau(\beta\beta(0\nu)) \sim 10^{27} \text{ years}$
- **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

