Experimental Prospects for Direct Measurements of Neutrino Mass

Outline

- **Directness?**
- **The Various Techniques: for completeness**
- **Astrophysics/Cosmology (very short)**
- **Nuclear and Particle Physics: heart of the talk**
  - **beta decay**
  - **double-beta decay**

Steve Elliott

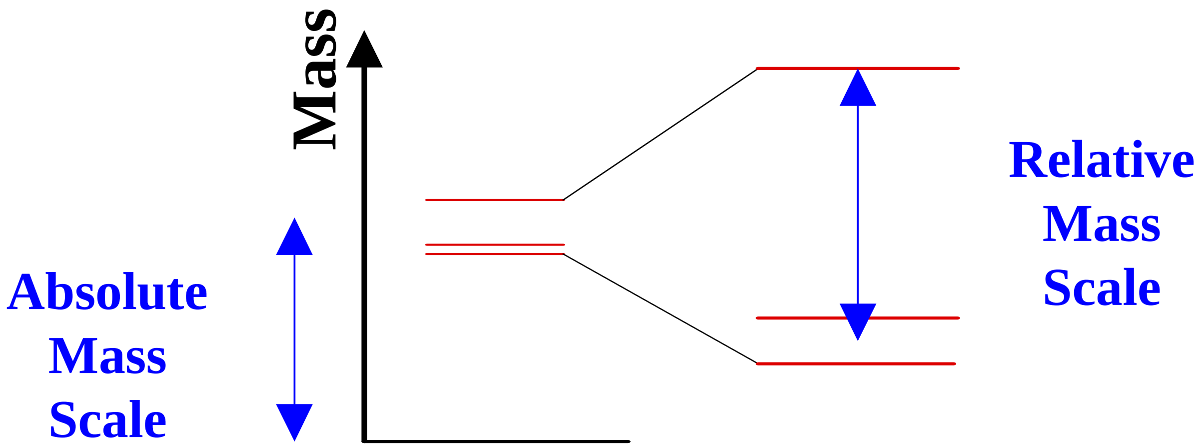
Nuclear Physics

Los Alamos

Direct vs. Indirect
Absolute vs. Relative
Kinematic vs. Interference

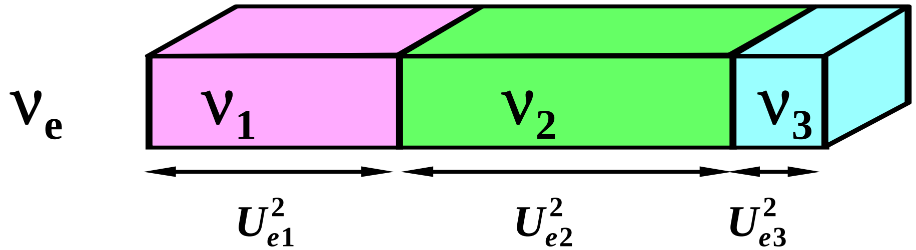
- **No m_ν experimental technique is direct in that it measures one of the m_i. All experiments measure parameters that depend on the mass eigenvalues.**
- **So, I took my assignment to be a discussion of laboratory experiments that indicate the "absolute scale of ν mass".**
- **These are experiments that search for a kinematic effect due to mass.**
- **These are not experiments that search for an interference effects. Oscillation experiments provide data on the "relative mass scale".**

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

A List of Upcoming Techniques

Present focus in red.

Supernovas - previous speaker, **relatively poor sensitivity**

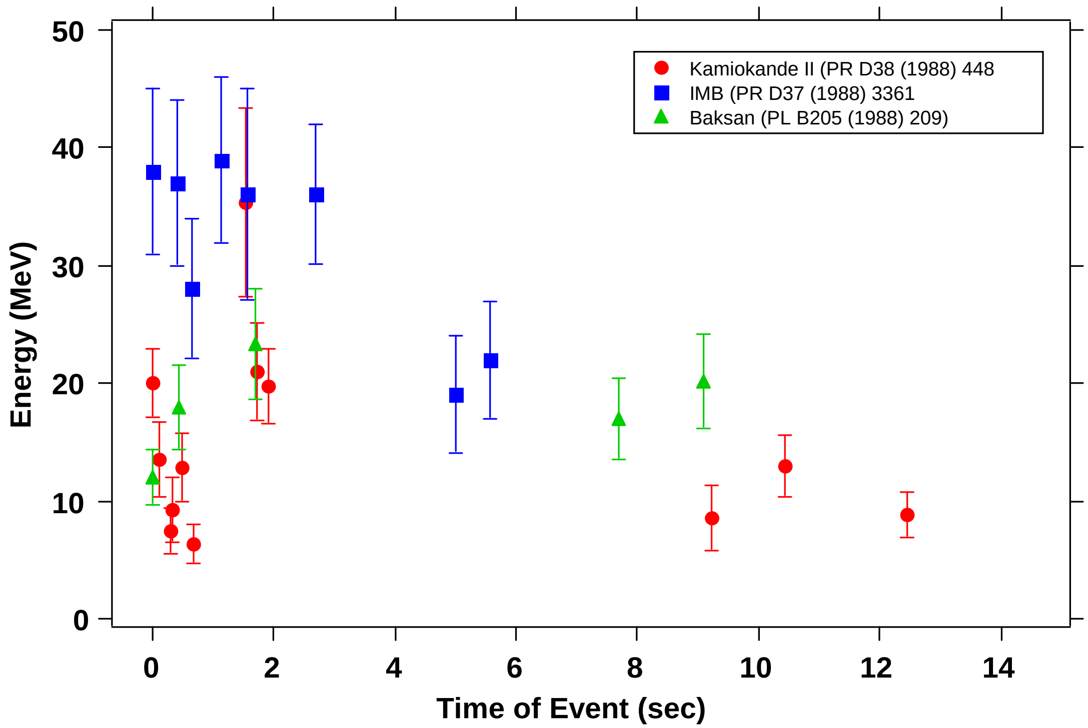
Cosmology - previous speaker, hope of reaching below 100 meV

Nuclear/Particle Physics

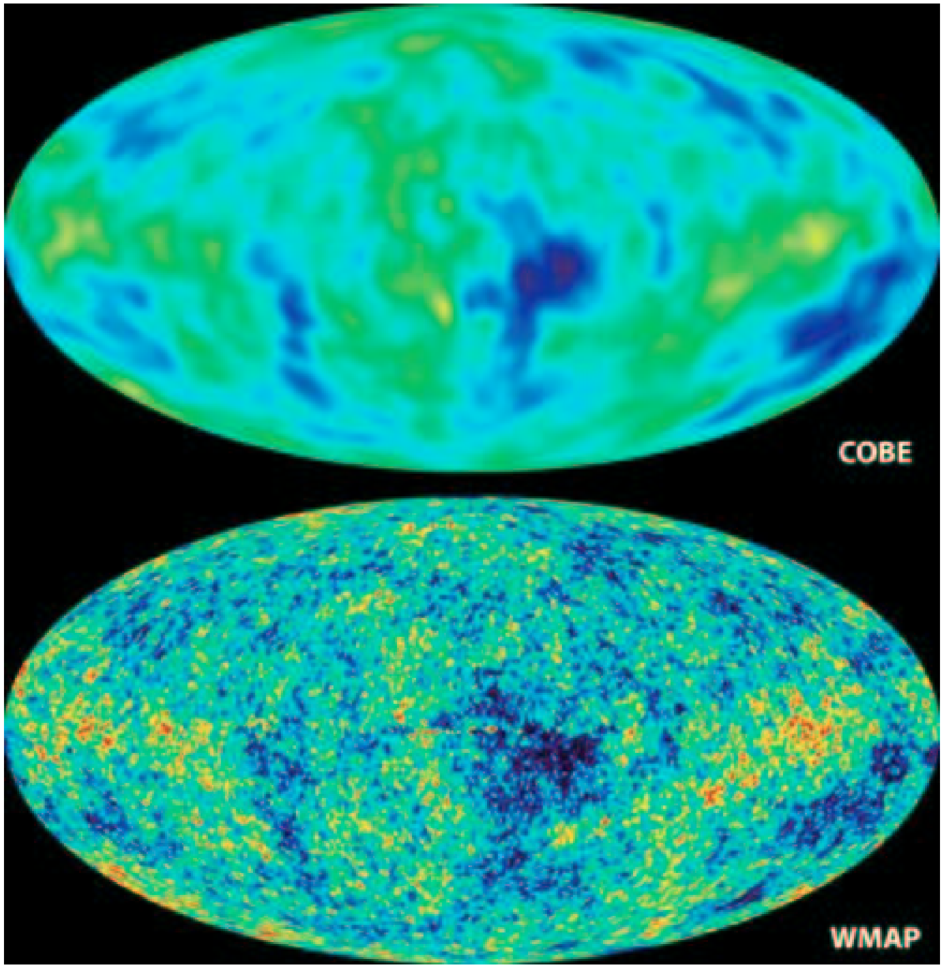
- **τ decay - relatively poor sensitivity**
- **μ decay - relatively poor sensitivity**
- **β decay - hope to reach below 500 meV**
- **$\beta\beta$ decay - hope to reach below 50 meV**
- **oscillations - other speakers, great sensitivity**

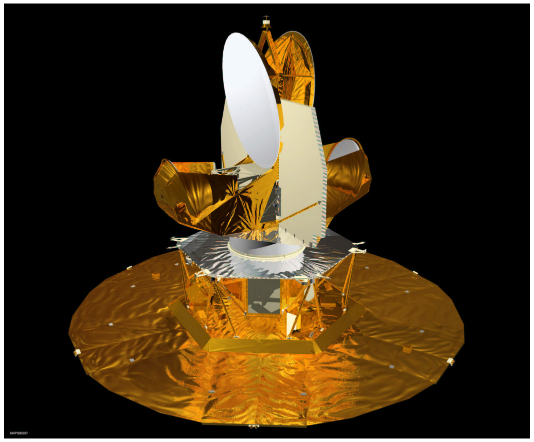
Supernova Tests

- Spread of neutrino arrival times can give indication of mass.
- SN1987a: about 20 eV limit but conclusions varied.
- SN dynamics makes for model dependencies.
- Future sensitivity might be a few eV.



Cosmology
Measure $\Omega_\nu h^2$





- WMAP measured cosmological parameters very precisely. This allowed precise estimates of $\Omega_\nu h^2$ from LSS measurements.
- WMAP results indicate $\Sigma m_i <$ about 1 eV. A very competitive result.
- But, correlations between parameters result in "arguable" conclusions.
- Want laboratory experiments.

Cosmology - Future Measurements

MAP/PLANCK CMB measurements with high precision galaxy surveys (Sloan Digital Sky Survey): Σm_i < ~300 meV

If weak lensing by LSS is also considered: Σm_i < ~40 meV

Even with the correlations, cosmology will play an important role in the interpretation of neutrino mass.

Z-burst and high-energy ν

- **Requires, as yet unknown (and unneeded?) flux of UHE ν with energy > Greisen-Zatsepin-Kuzmin (GZK) energy (5×10^{19} eV).**
- **Although could explain existence of cosmic rays with $E > E_{GZK}$, it doesn't explain source of proposed UHE ν.**
- **UHE ν + cosmic relic ν --> Z --> hadrons, γs**
- **m_i near 500 meV could produce p or γ just above GZK cutoff. Model can be "tweaked" to get lower masses.**
- **Detect p or γ : their multiplicity and energies relate to E^R and hence m_i.**

Hope you saw Sarcevic talk.

$$E_{\nu_i}^{R} \approx 4.2\left(\frac{eV}{m_i}\right)\times 10^{21}\ \mathrm{eV}$$

Nuclear and Particle Physics Techniques

τ decay: decays into 5 or 6 π most sensitive because of restricted phase space for ν.

$$\tau \rightarrow n\pi + \nu_\tau$$

$$E^* = \frac{m_\tau^2 + m_h^2 - m_i^2}{2m_\tau}$$

m_h is invariant mass of n π.
E* is total π energy in τ rest frame.
Obtain data on degenerate scale m_1.

$$m_{\nu_1} < 18.2 \text{ MeV}$$

Eur. Phys. J. C2 (1998) 3

Nuclear and Particle Physics Techniques

μ decay: π --> $\mu + \nu$

$$m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2m_\pi\sqrt{m_\mu^2 + p_\mu^2}$$

$$m_{\nu_\mu}^2 = \sum \left|U_{\mu i}^2\right| m_i^2$$

$$m_{\nu_\mu} < 190 \text{ keV}$$

PR D53 (1996) 6065

^{187}Re β Decay Experiments

- Low Q-value: 2.6 eV
- Long half-life = low specific activity
- Bolometric techniques = measure whole spectrum
- Measure 10^{-10} of decays near endpoint, but bolometer response time is 100s μs.
- Future sensitivity should be about 10 eV.

Milano: $AgReO_4$ NIM A444 (2000) 77

Genoa: Metallic Re, $m_\nu < 26$ eV NP B (proc. Suppl.) 91 (2001) 293

The β Spectrum (bare nucleus)

Fund. Constants

Energy-independent Matrix Element

Fermi Function

$$\frac{dN}{dE} = \frac{G_F^2}{2\pi^3\hbar^7}\cos^2\theta_C |M|^2 F(E, Z+1)$$

$$p(E+m_e)\varepsilon\sqrt{\varepsilon^2 - m_\nu^2}\,\Theta(\varepsilon - m_\nu)$$

Electron momentum, Energy, mass

$\varepsilon = E_0 - E$

Step Function

β Spectrum (atom or molecule) plus neutrinos mix

Many possible final states.

ε_j for state j

$$\frac{dN}{dE} = A|M|^2 F(E, Z+1)\, p(E+m_e)$$

$$\sum_j W_j \varepsilon_j \sum_i |U_{ei}|^2 \sqrt{\varepsilon_j^2 - m_i^2}\,\Theta(\varepsilon_j - m_i)$$

W_j - probability for transition to state j

U_{ei} - mixing matrix elements

m_i - ν mass eigenstate

β Spectrum (atom or molecule)

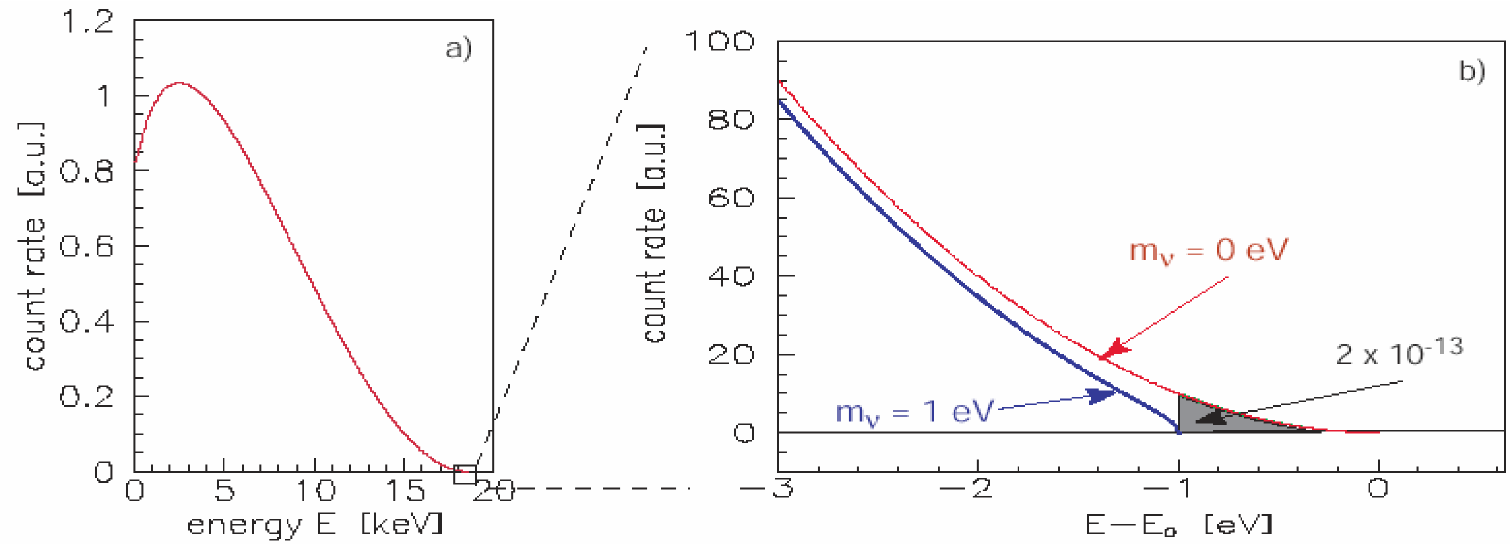
When convolved with resolution function with width > m_i, we can analyze the spectrum with one mass parameter: $\langle m_\beta \rangle$.

$$\frac{dN}{dE} = A|M|^2 F(E, Z+1) p(E+m_e)$$

$$\sum_j W_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_\beta^2}\,\Theta(\varepsilon - m_\beta)$$

The Neutrino Mass from β decay

The shape of the β energy spectrum near the endpoint depends on m_ν.



KATRIN LOI

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} < 2.2\ \mathrm{eV}$$

NP B (Proc. Suppl.) 91 (2001), 273

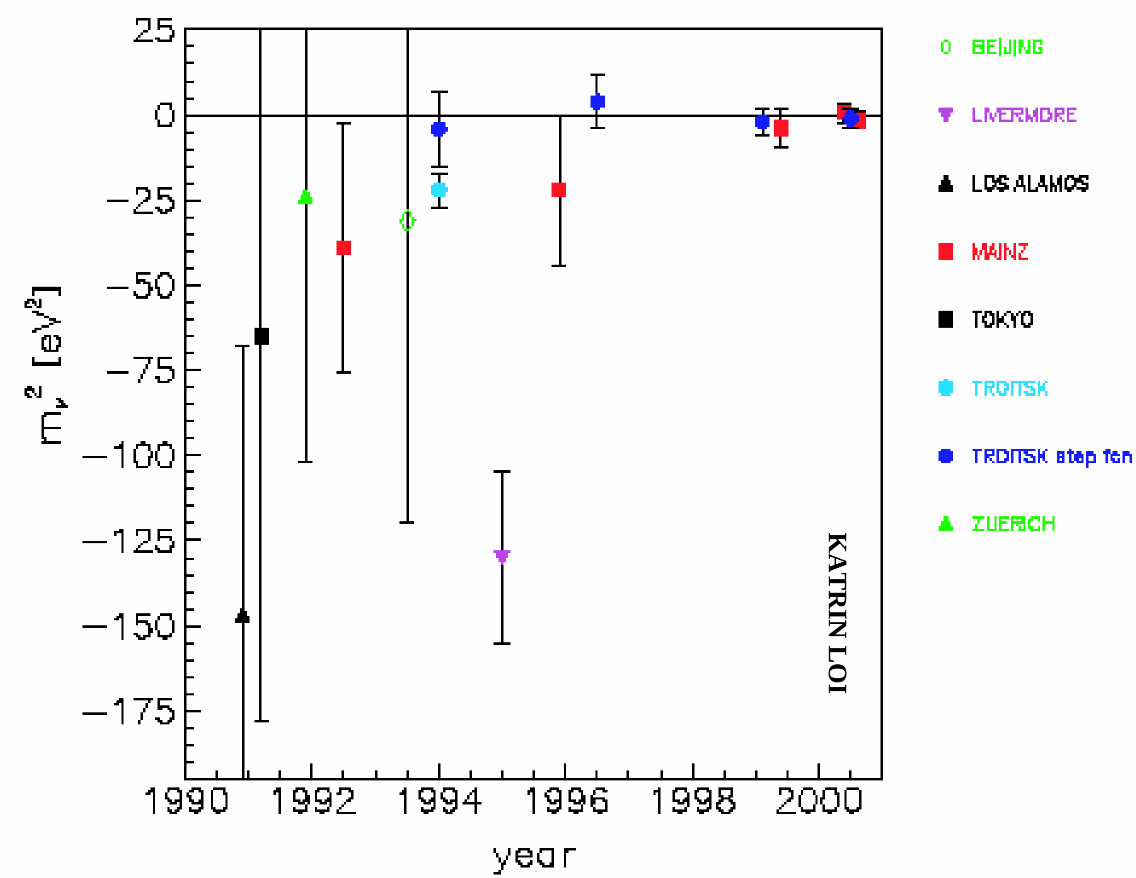
Primary Systematic Uncertainties

Resolution error leads to m_ν error

$$\frac{dN}{dE} \propto \varepsilon^2 - \frac{\langle m_\beta \rangle^2}{2}$$

$$\frac{dN}{dE} \propto \varepsilon^2 + \sigma^2$$

$$\delta \langle m_\beta \rangle^2 \approx -2\sigma^2$$



Identifying the Systematics

Mainz: tritium as thin film on flat surface. Temperature activated roughening led to microcrystals in turn leading to large inelastic scattering.

Troisk: Gaseous tritium. Large angle scattering of electrons trapped in source.

Addressing these issues removed the "negative mass squared" in those experiments.

Tritium β decay Experiments

KATRIN

Very big spectrometer using gaseous and thin sources. A big step forward.

Univ. of Texas-Austin

t_2 source in magnetic free environment.

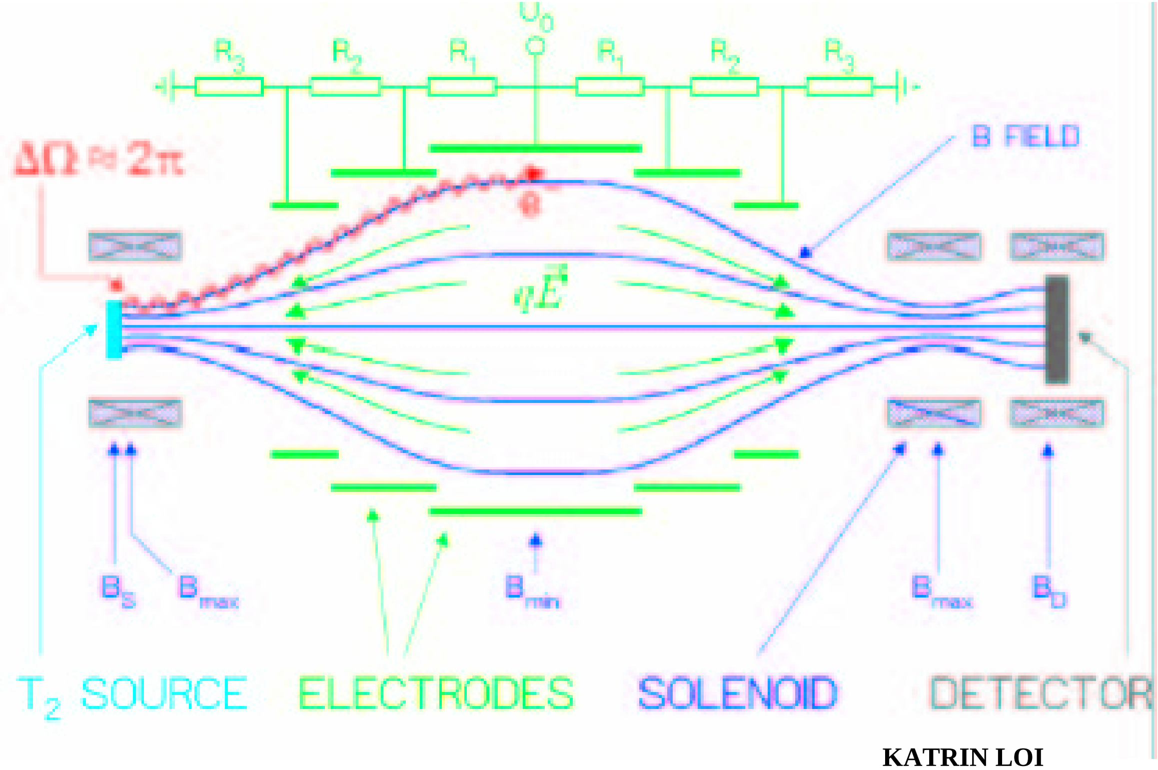
The MAC-E Filter

$$\frac{\delta E}{E} = \frac{B_{min}}{B_{max}}$$

Magnetic Adiabatic Collimation followed by an Electrostat Filter

High luminosity
Low background
Good energy resolution

Integrating
high-pass filter

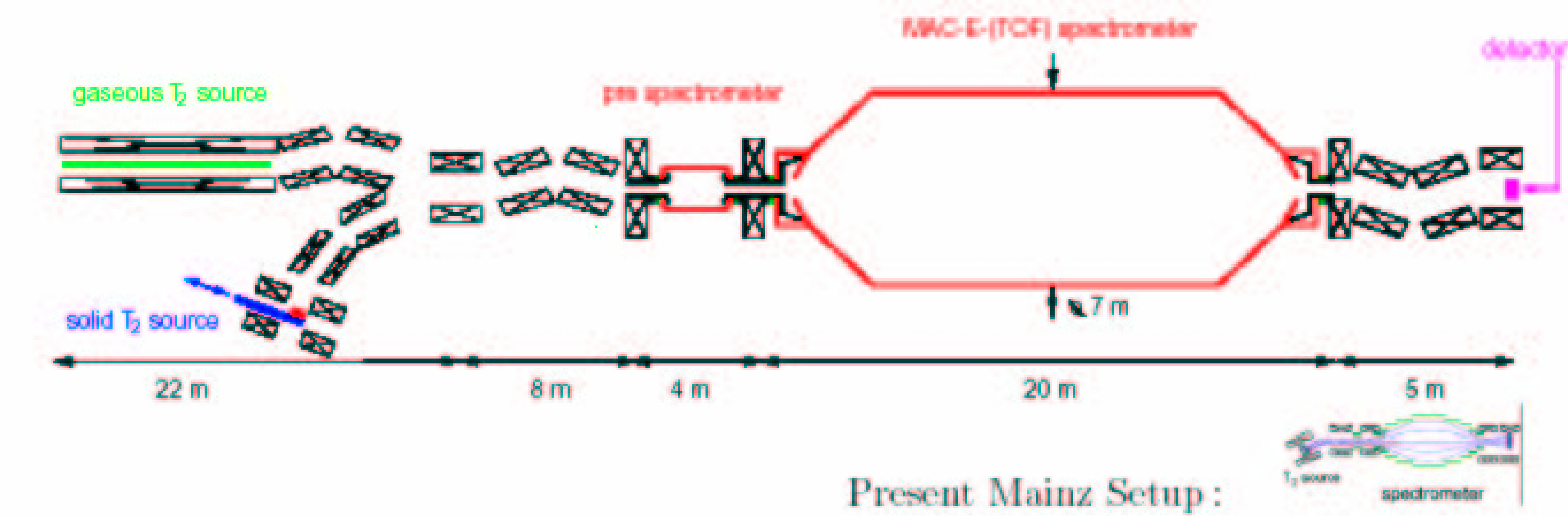


KATRIN LOI

KATRIN

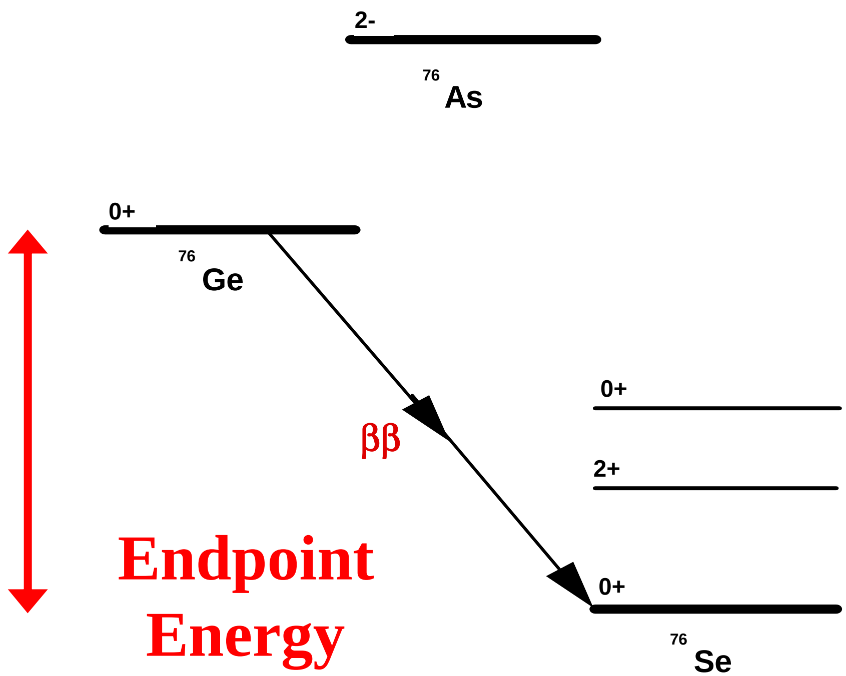
- 1-eV resolution (x4 better)
- Electron transport system guides β to pre-spectrometer while preventing tritium flow to spectrometers.
- Pre-spectrometer filters out all β except those near endpoint. Keeps residual ionization minimized hence reducing background.
- Large analyzing plane increases signal rate
- Si drift detectors. 600 eV resolution for 18.6 keV β. Good electron sensitivity but low efficiency for γ.

KATRIN (LOI version)



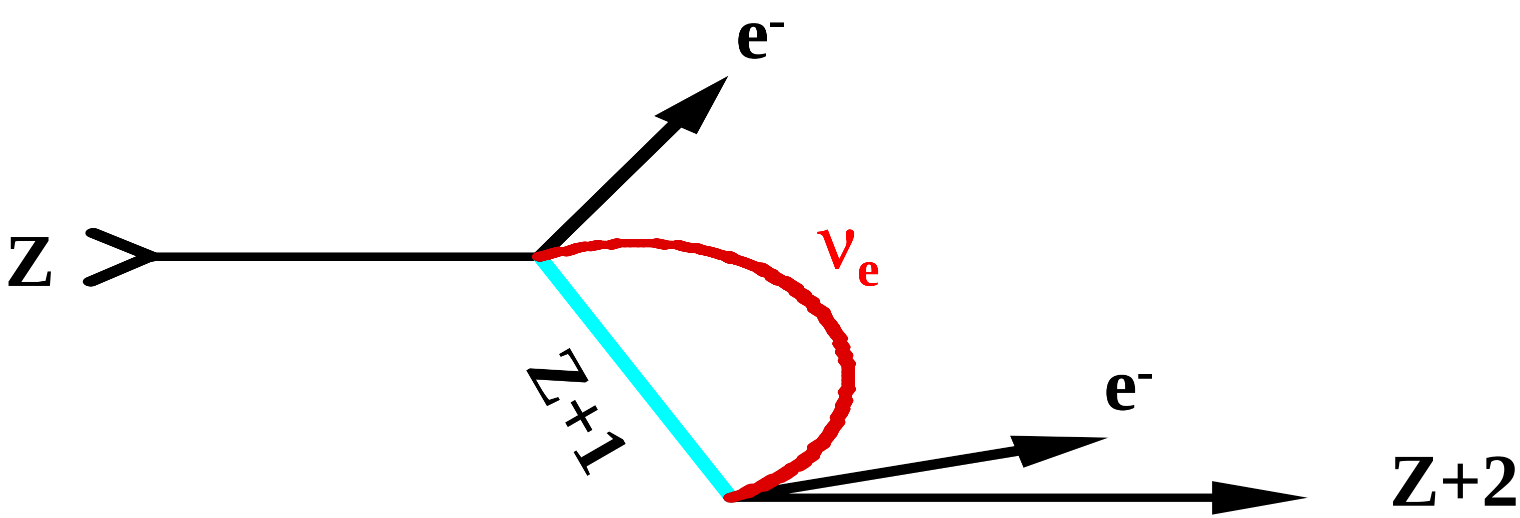
KATRIN will be sensitive to about 350 meV. Thus if the m_i follow a degenerate pattern and m_1 is within the sensitivity, the experiment may see $\langle m_\beta \rangle = m_1$.

Example ββ Decay Scheme



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

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



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

(RH $\overline{\nu_e}$)   (LH ν_e)

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

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.

What about mixing, m_ν & ββ(0ν)?

No mixing:

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

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

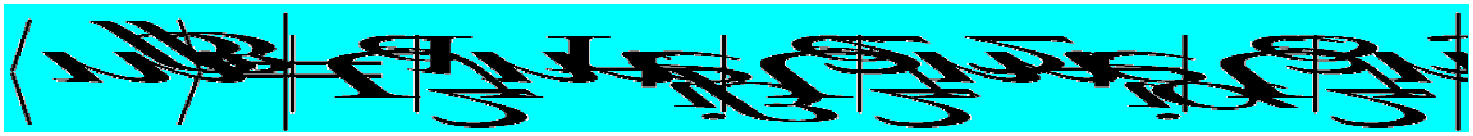
virtual ν exchange

ε = ±1, CP cons.

Compare to β decay result: real ν emission

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

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



$\langle m_{\beta\beta} \rangle$ is the modulus of the resultant vector in the complex plane. (In this example, $\langle m_{\beta\beta} \rangle$ has a min. It cannot be 0.)

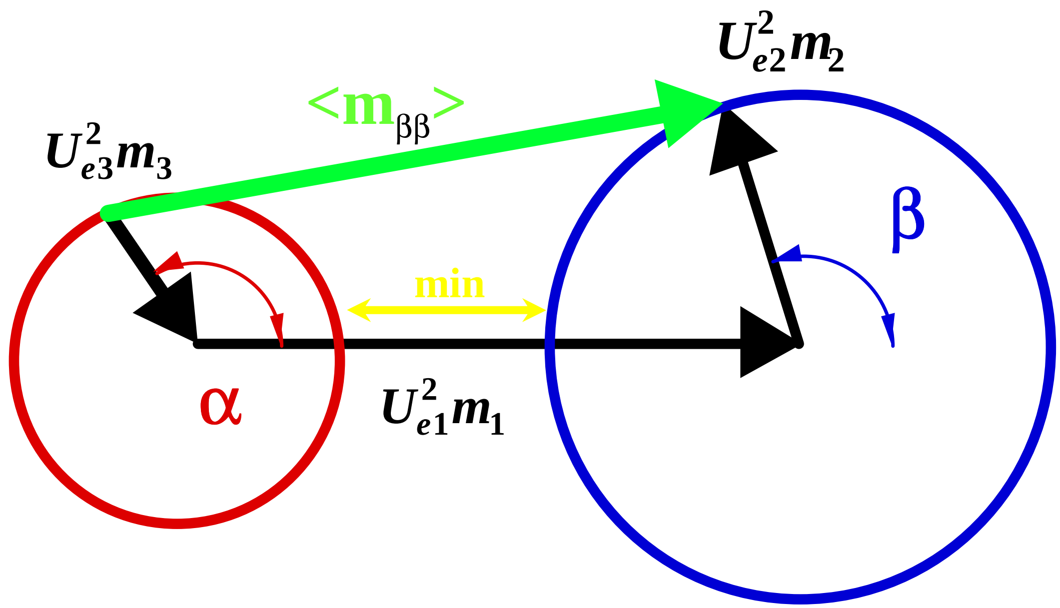
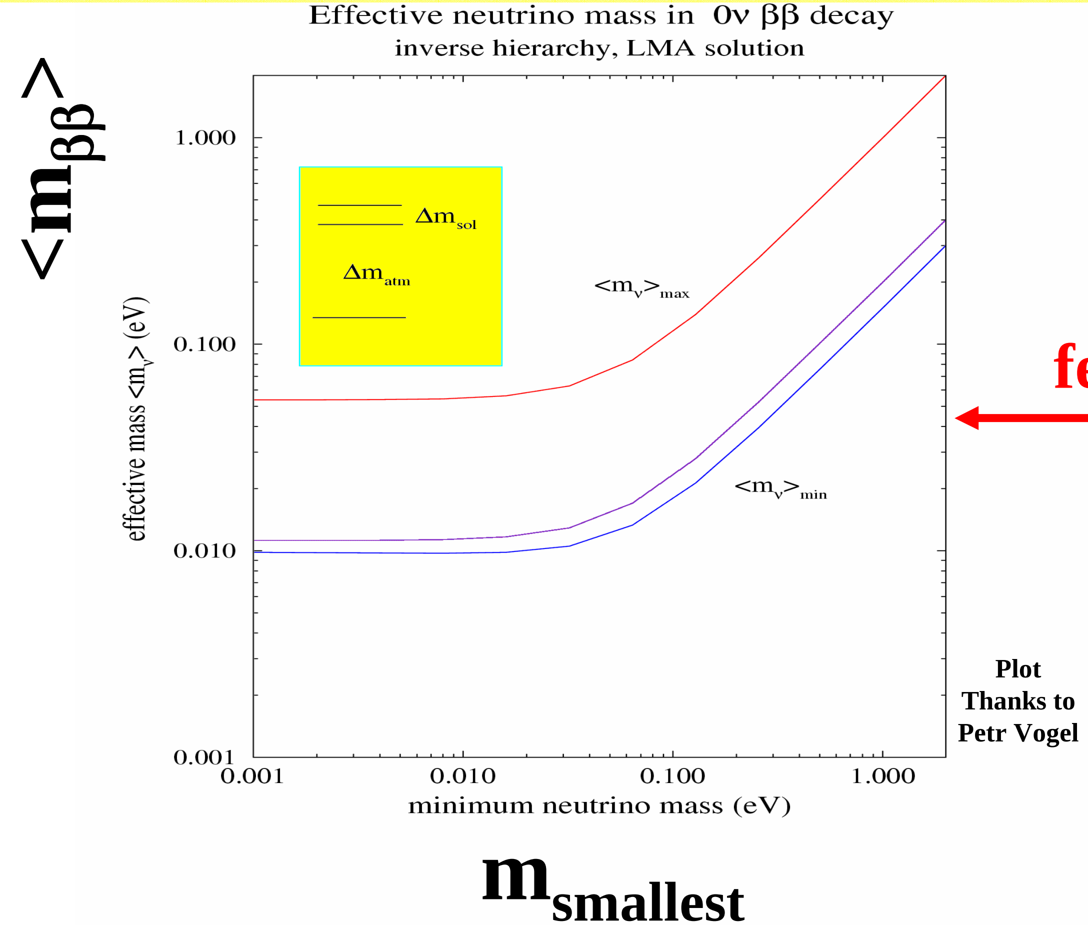


Figure from: PR D63, 073005

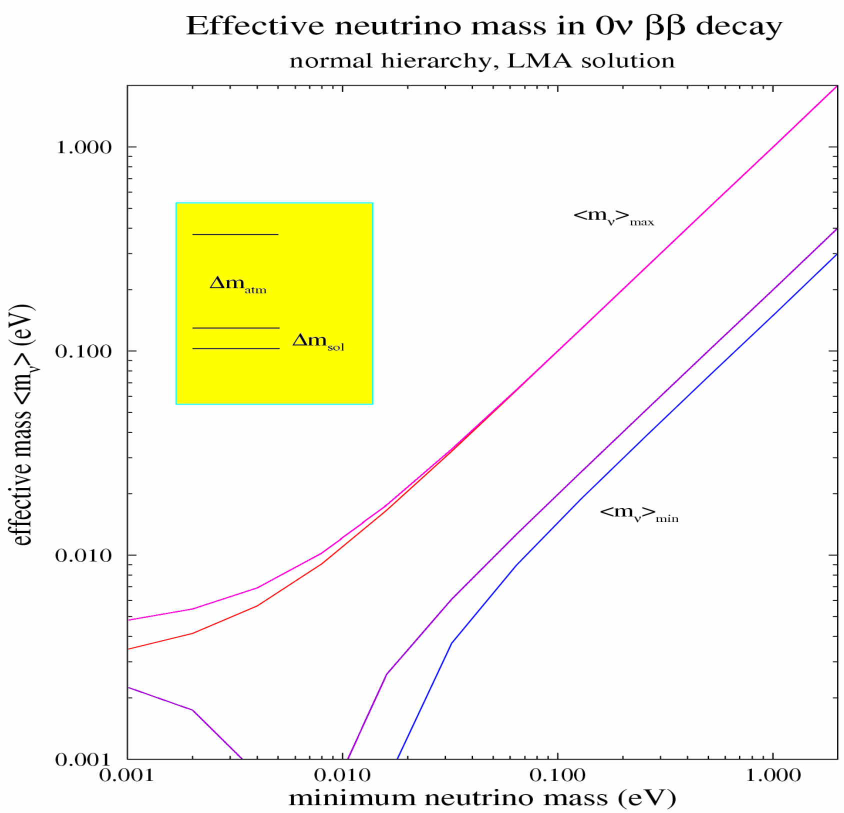
More General: 3 ν (Inverted Heir.)



30 meV
or
few x 10^{27} yr

Plot Thanks to Petr Vogel

More General: (Normal Heir.)



30 meV
or
few x 10^{27} yr

Plot Thanks to Petr Vogel

Summary of Physics Reach

Even null results have implications!

Normal Hierarchy	Inverted Hierarchy	Degenerate
$m_1 \sim 0$ meV	~55 meV	= M > about 100 meV
$m_2 \sim 7$ meV	~55 meV	M
$m_3 \sim 55$ meV	~0 meV	M
$<m_{\beta\beta}> \sim 5$ meV	28 or 55 meV	M/2 or M

Solar + KamLAND + Atmospheric (U_{e3}~ 0)

$$\langle m_{\beta\beta} \rangle \approx (0.5)^2 m_1 + \varepsilon_{21} (0.866)^2 \sqrt{m_1^2 + \delta m_{21}^2}$$

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 $\beta\beta(0\nu)$

Slow $\beta\beta(2\nu)$ rate

Identify daughter

Event reconstruction

Nuclear theory

Classes of Background

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

Need good energy resolution.

Natural U, Th in source and shielding

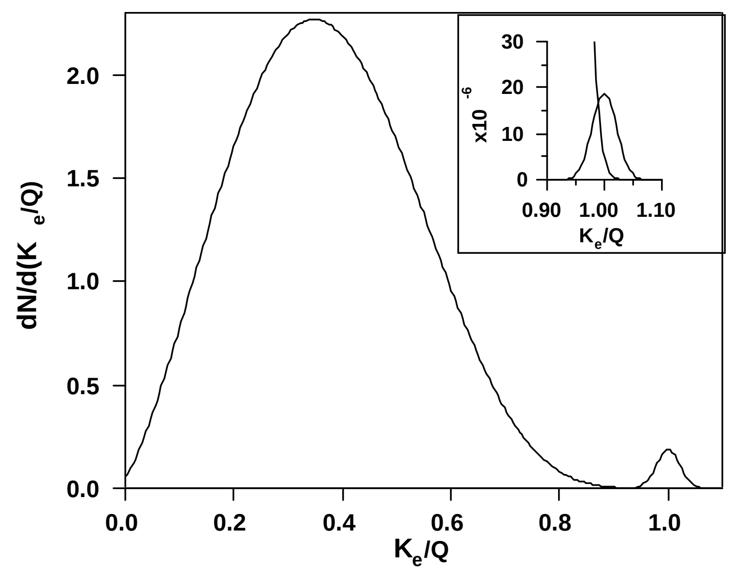
Pure materials, identify $\beta\beta$ daughter, pulse shape, timing, position.

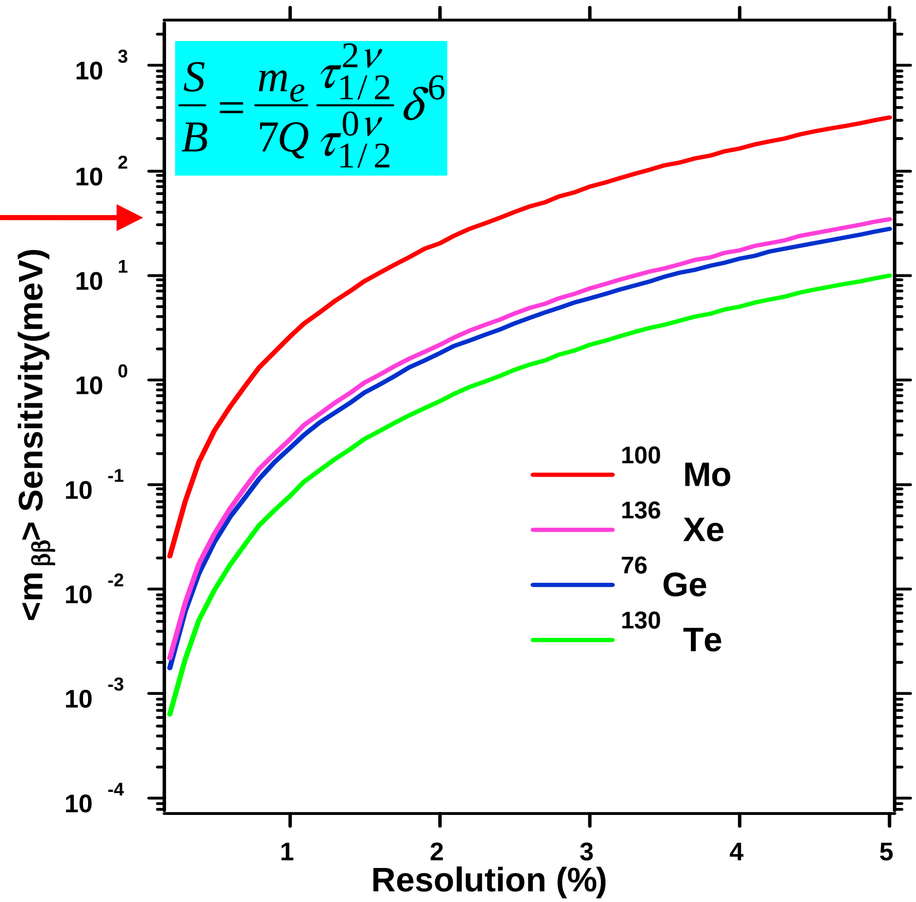
Cosmic ray activation

Store and prepare materials underground.

ββ(2ν) as a Background.
Sum Energy Cut Only

next generation experimental goal →





Evidence of ^{68}Ge

From: NIM A292 (1990) 337-342.

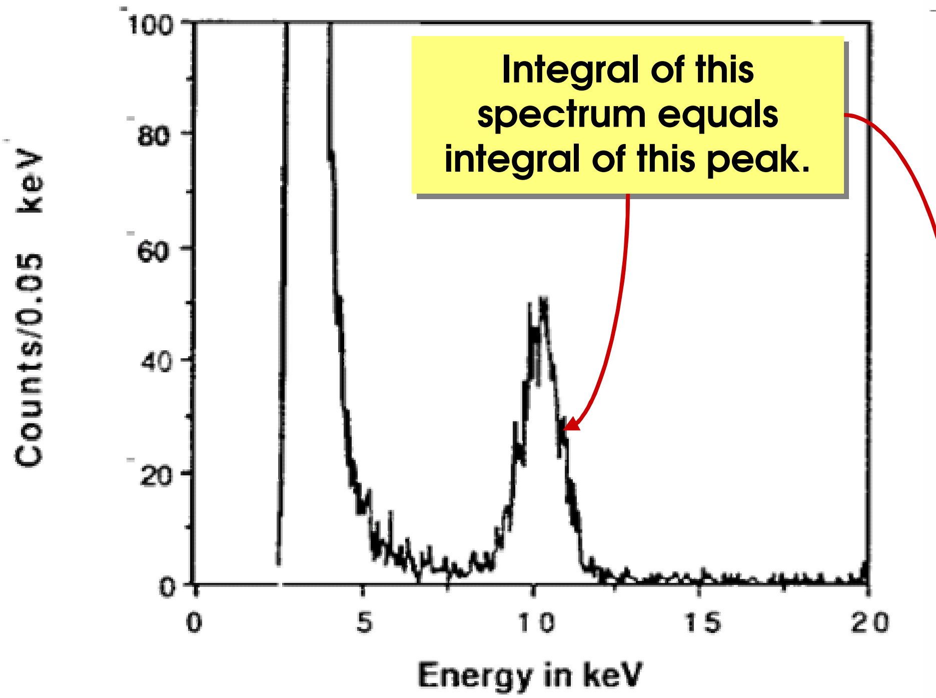


Fig. 7. 10.367 keV gallium K-shell binding energy in one of our current detectors.

This peak decays with the right half life.

Experimental data from two 1.05 kg natural detectors

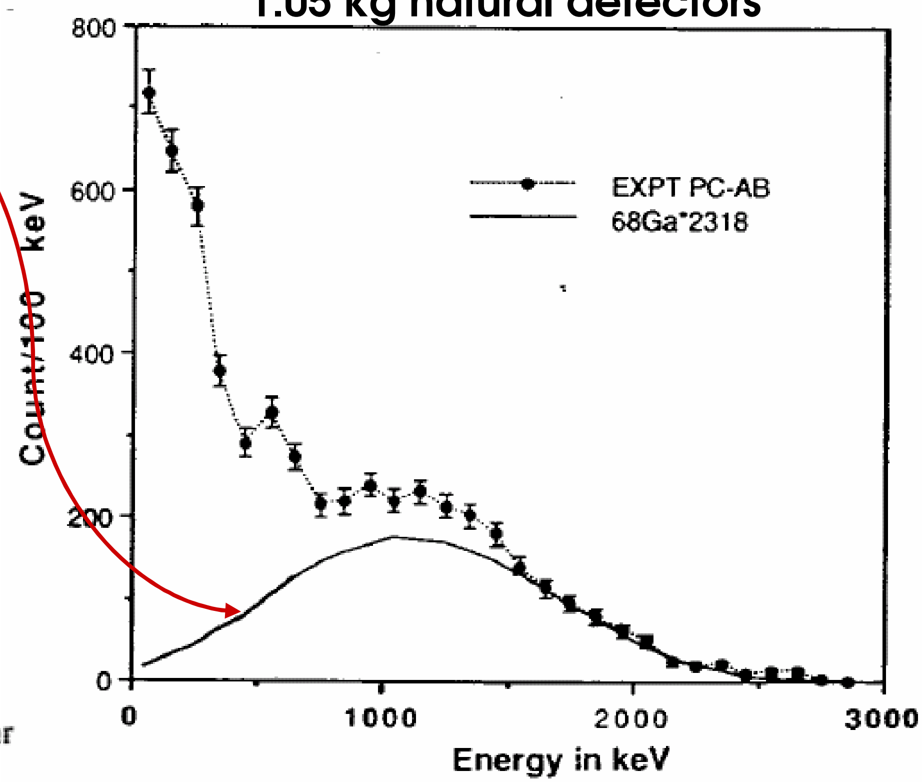


Fig. 8. Current detector data summed into 100-keV bins and compared to a Monte Carlo calculated ^{68}Ga spectrum normalized to ^{68}Ga X-rays.

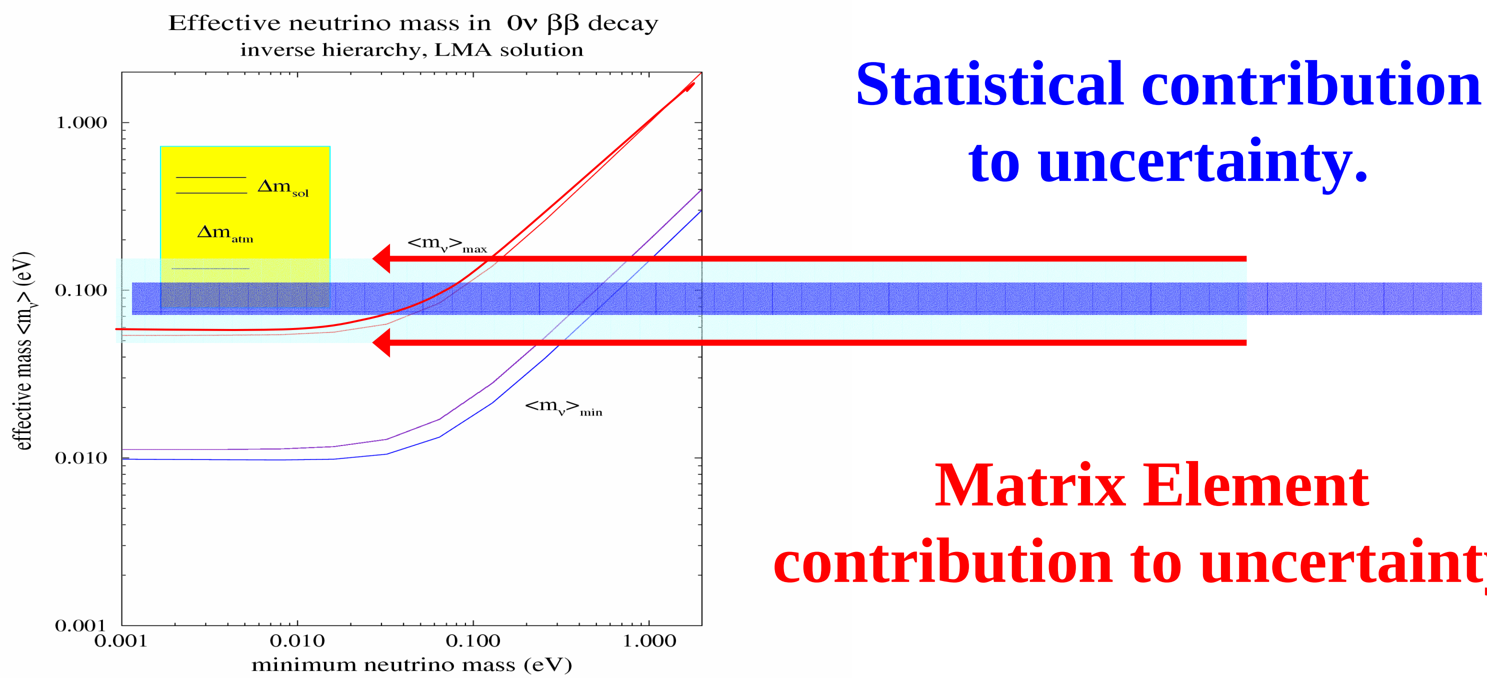
Matrix Elements

There are many calculations.

Most authors quote mass limits derived from all or at least representatives of the whole range.

How do we interpret the uncertainty associated with the mass due to the nuclear physics?

Consider a 100 meV result.



Statistical contribution to uncertainty.

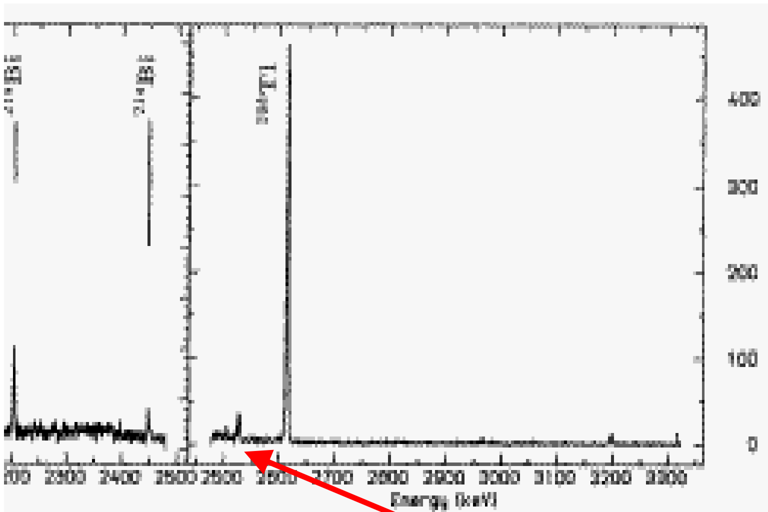
Matrix Element contribution to uncertainty.

Would this exclude the inverted hierarchy with small $m_{smallest}$?

Need improvement in the Theory.

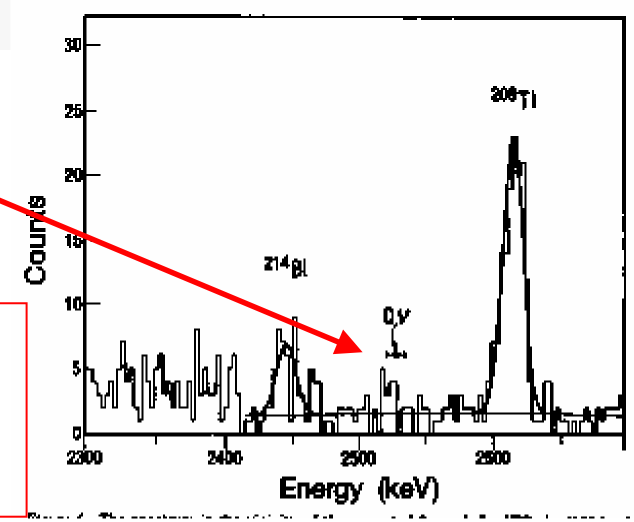
“Found” Peaks

PR D45, 2548 (1992)



Need more than one experiment

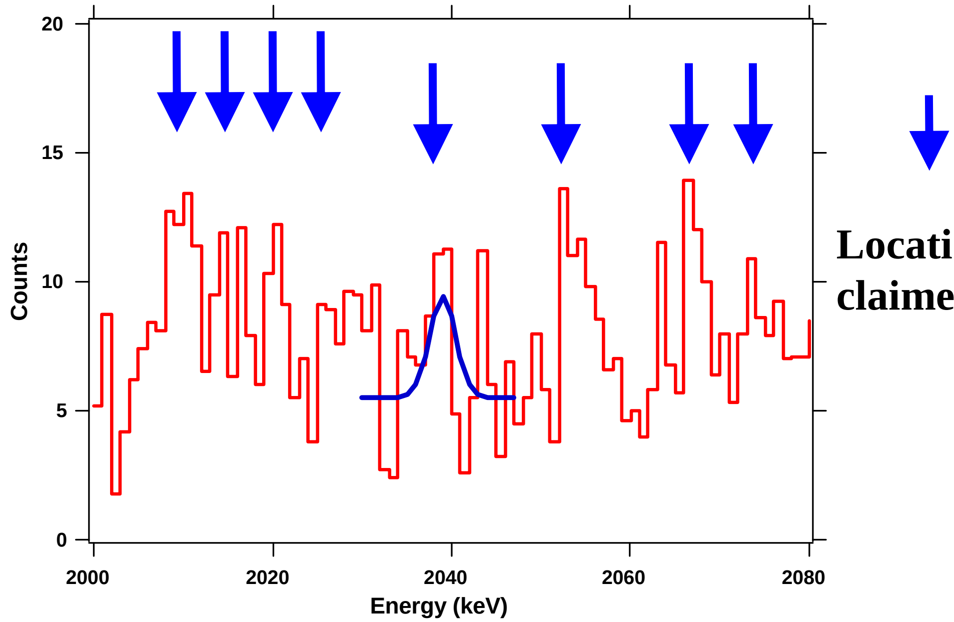
A 2527-keV Ge-det. peak that was an electronic artifact.



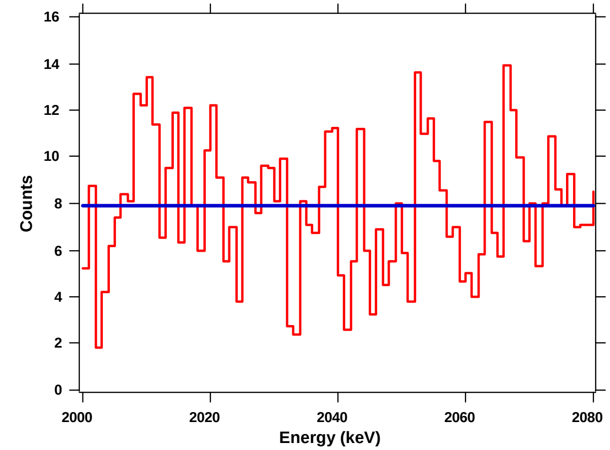
NP B35 (Proc. Supp.), 366 (1994).

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

The Controversy.



Locations of claimed peaks



Mod. Phys. Lett. A16, 2409 (2001)

If one had to summarize the controversy in a <u>short</u> statement:
Consider two extreme background models:

1. **Entirely flat in 2000-2080 keV region.**
2. **Many peaks in larger region, only ββ peak in small region.**

These 2 extremes give very different significances for peak at 2039 keV.
KDHK chose Model 2 but did not consider a systematic uncertainty associated with that choice.

A Great Number of Proposed Experiments

COBRA	**Te-130**	**10 kg CdTe semiconductors**
DCBA	**Nd-150**	**20 kg Nd layers between tracking chambers**
NEMO	**Mo-100, Various**	**10 kg of ββ isotopes (7 kg of Mo)**
CAMEO	**Cd-114**	**1 t $CdWO_4$ crystals**
CANDLES	**Ca-48**	**Several tons CaF_2 crystals in liquid scint.**
CUORE	**Te-130**	**750 kg TeO_2 bolometers**
EXO	**Xe-136**	**1 ton Xe TPC (gas or liquid)**
GEM	**Ge-76**	**1 ton Ge diodes in liquid nitrogen**
GENIUS	**Ge-76**	**1 ton Ge diodes in liquid nitrogen**
GSO	**Gd-160**	**2 t Gd_2SiO_5:Ce crystal scint. in liquid scint.**
Majorana	**Ge-76**	**500 kg Ge diodes**
MOON	**Mo-100**	**Mo sheets between plastic scint., or liq. scint.**
Xe	**Xe-136**	**1.56 t of Xe in liq. Scint.**
XMASS	**Xe-136**	**10 t of liquid Xe**

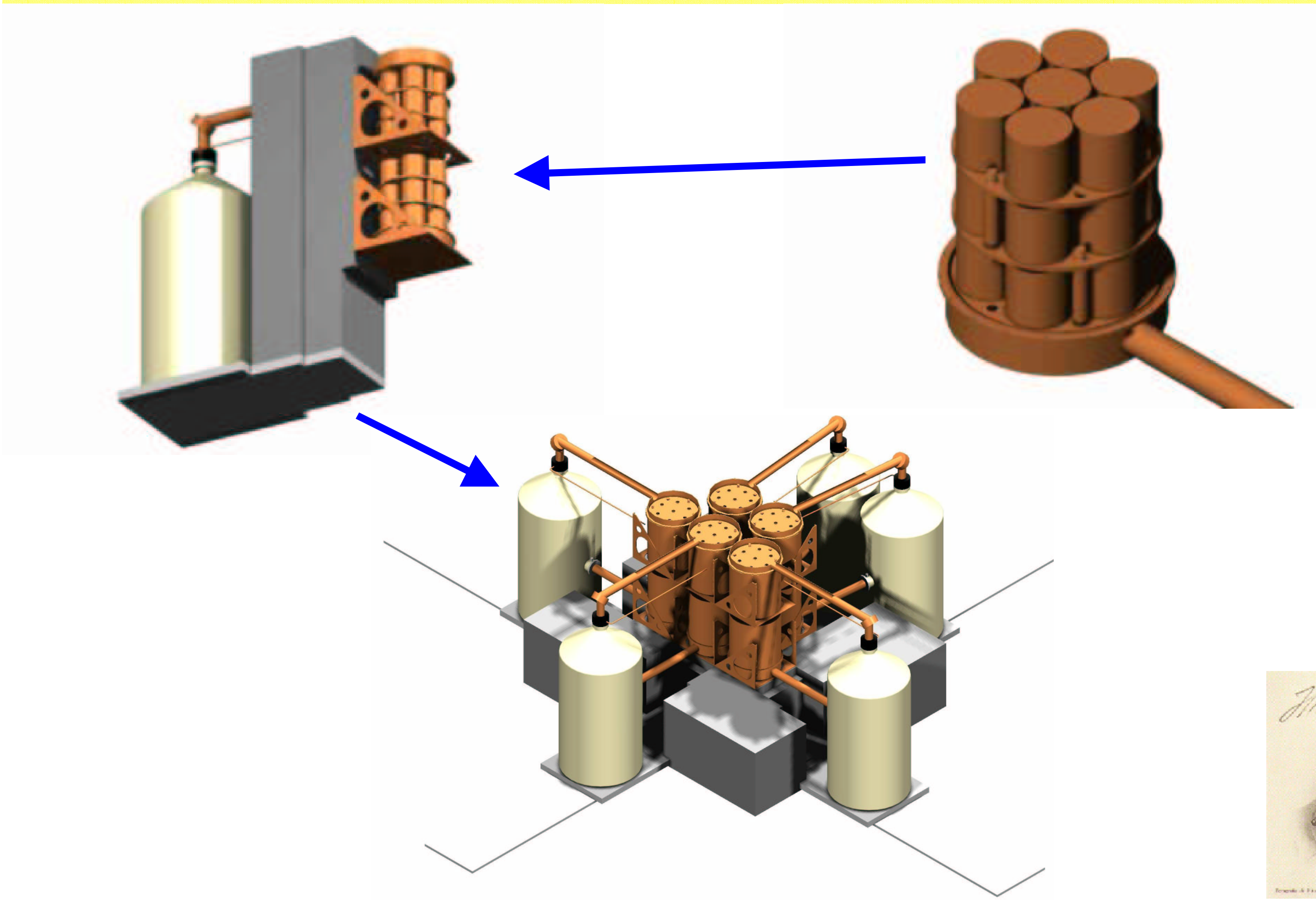
The Majorana Project

Duke U.
North Carolina State U.
TUNL
Argonne Nat. Lab.
JINR, Dubna
ITEP, Moscow
New Mexico State U.
ORNL
Pacific Northwest Nat. Lab.
U. of Washington
LANL
U. of South Carolina
Brown
Univ. of Chicago
RCNP, Osaka Univ.
Univ. of Tenn.

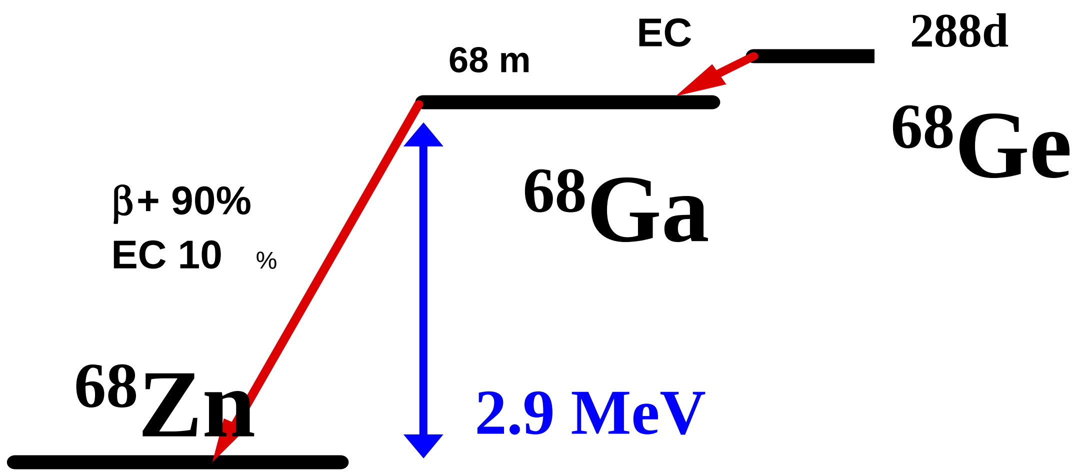
Ge Basics

Large Mass (~ 1 ton):	500 kg of ^{enr}Ge
Good source radiopurity:	Intrinsic Ge
Demonstrated technology:	"Ready to Go"
Natural isotope	
Small volume, source = det:	Fiorini "internal source method
Good energy resolution:	3-4 keV at 2039 keV, 0.2%
Ease of operation	Ge detectors are relatively simple
Large Q value, fast $\beta\beta(0\nu)$	2039 keV, above most radioactivities
Slow $\beta\beta(2\nu)$ rate	10^{21} yrs
Identify daughter	
Event reconstruction	segmentation, modularity, PSD
Nuclear theory	Low A - Shell Model and QRPA

Majorana Layout



^{A}Ge + fast n -> ^{68}Ge + X

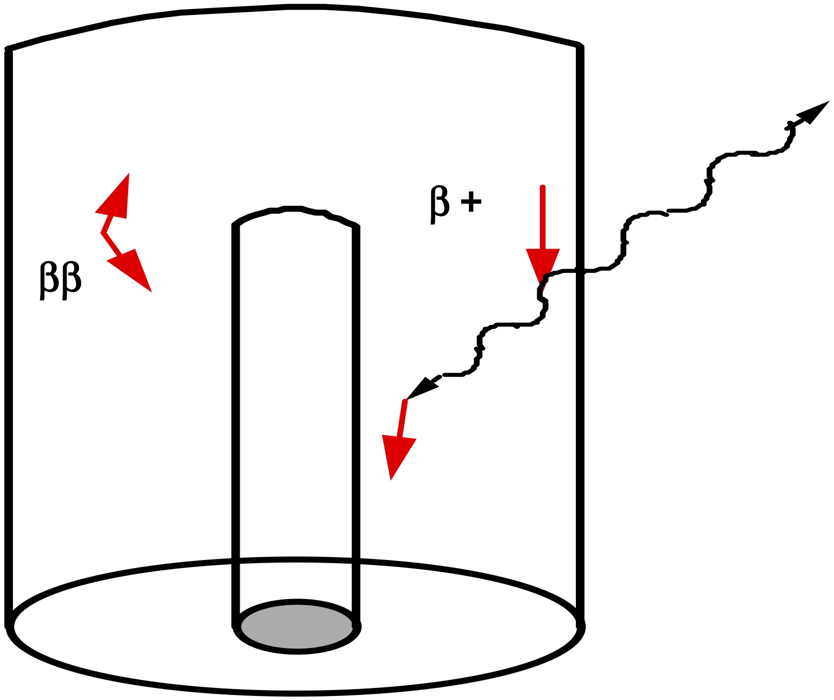


^{68}Ge is the dominate background.

For 500-kg enriched detector, initially expect ~500 ^{68}Ge decays/day. $\tau_{1\backslash 2}$ = 288 d

The naturally occurring ^{40}K in the human body decays at a rate of 12000 decays/second.

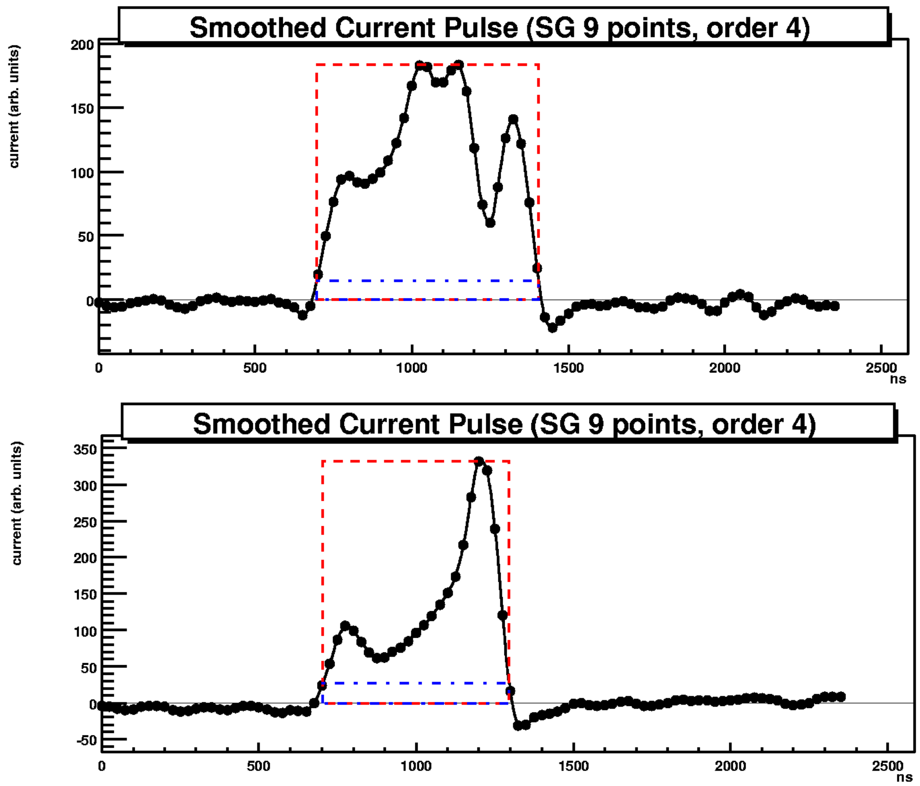
Why Segmentation and Pulse Shape Analysis?



ββ is pointlike.
β^+ or Compton scattered γ rays deposit energy in multiple locations.

Segmentation and PSD help reduce these Backgrounds.

Experimental Examples



Full-energy 1621-keV γ (top) and 1592-keV DEP (bottom) reconstructed current pulses from 120% P-type Ortec HPGe detector (experimental data)

- **Commercial digital spectroscopy hardware is available with fast (40 MHz), high-resolution (14-bit) digitization**
- **Significant developments in pulse-shape discrimination techniques for HPGe have been made in the past 10 years and are ready to apply to new hardware**

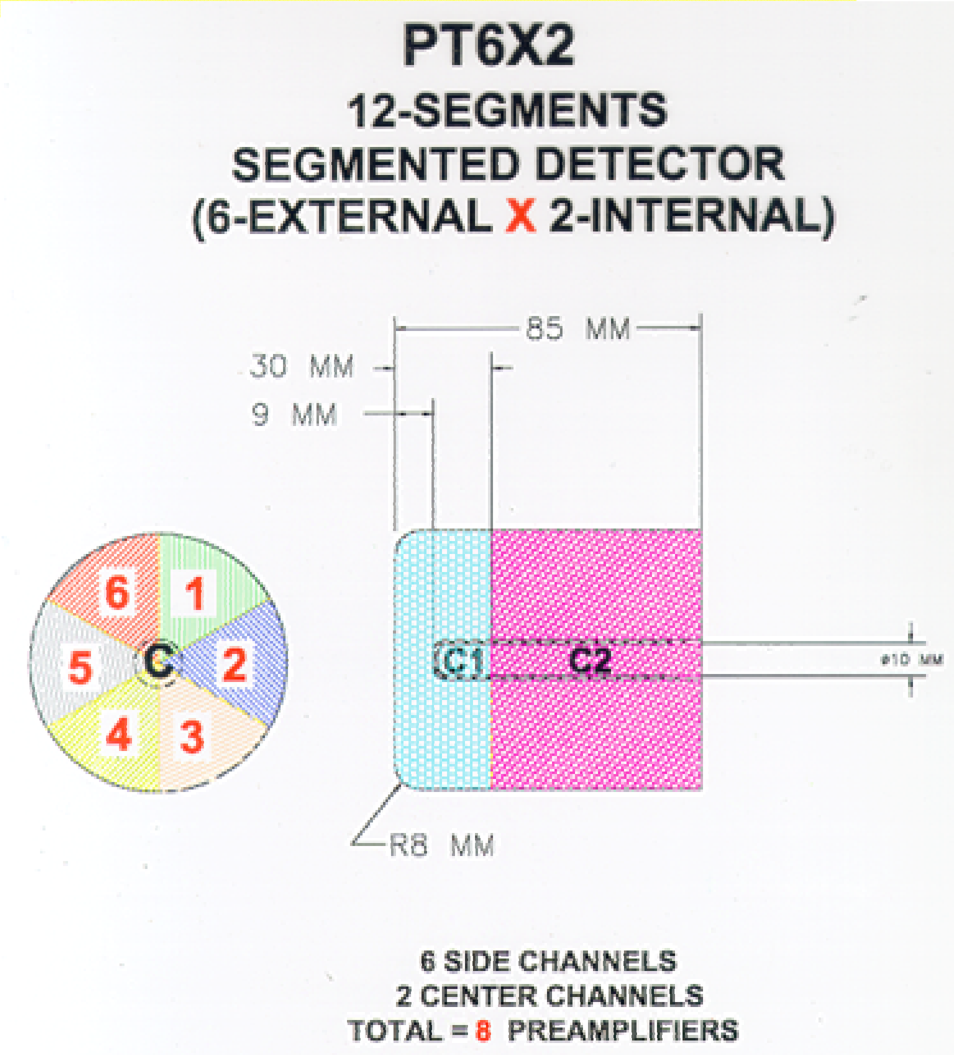
Detector Segmentation

Sensitive to axial and azimuthal separation of depositions

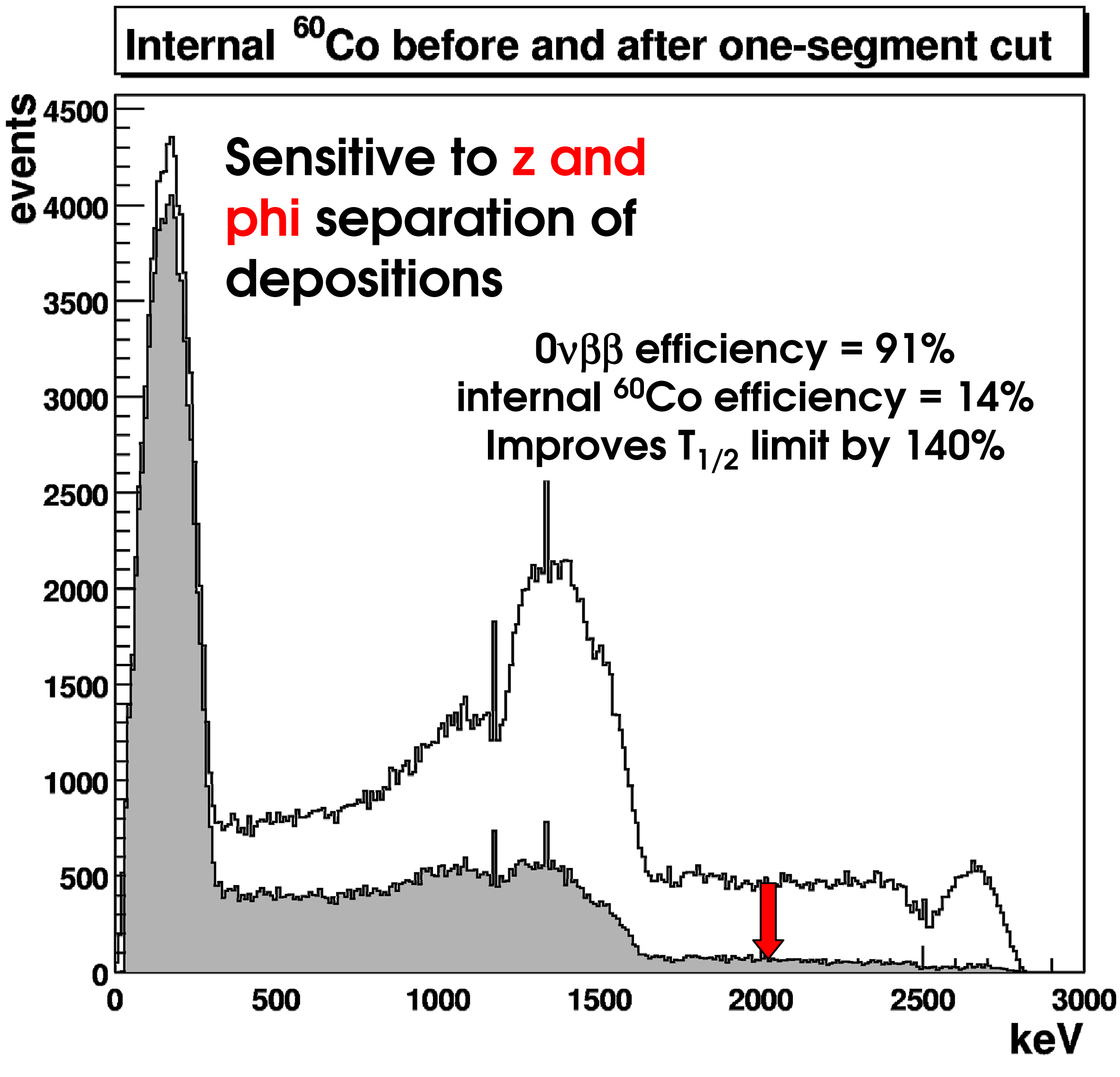
Reference design with six azimuthal and two axial contacts is low risk

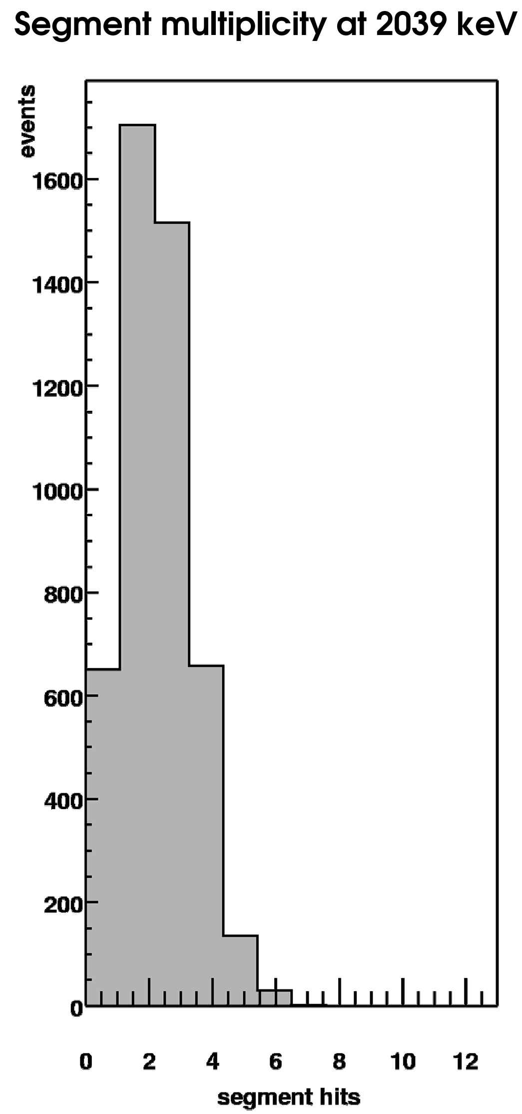
This level of segmentation gives good background rejection

This segmentation gives us ~2500 segments of 200 g or 40 cc

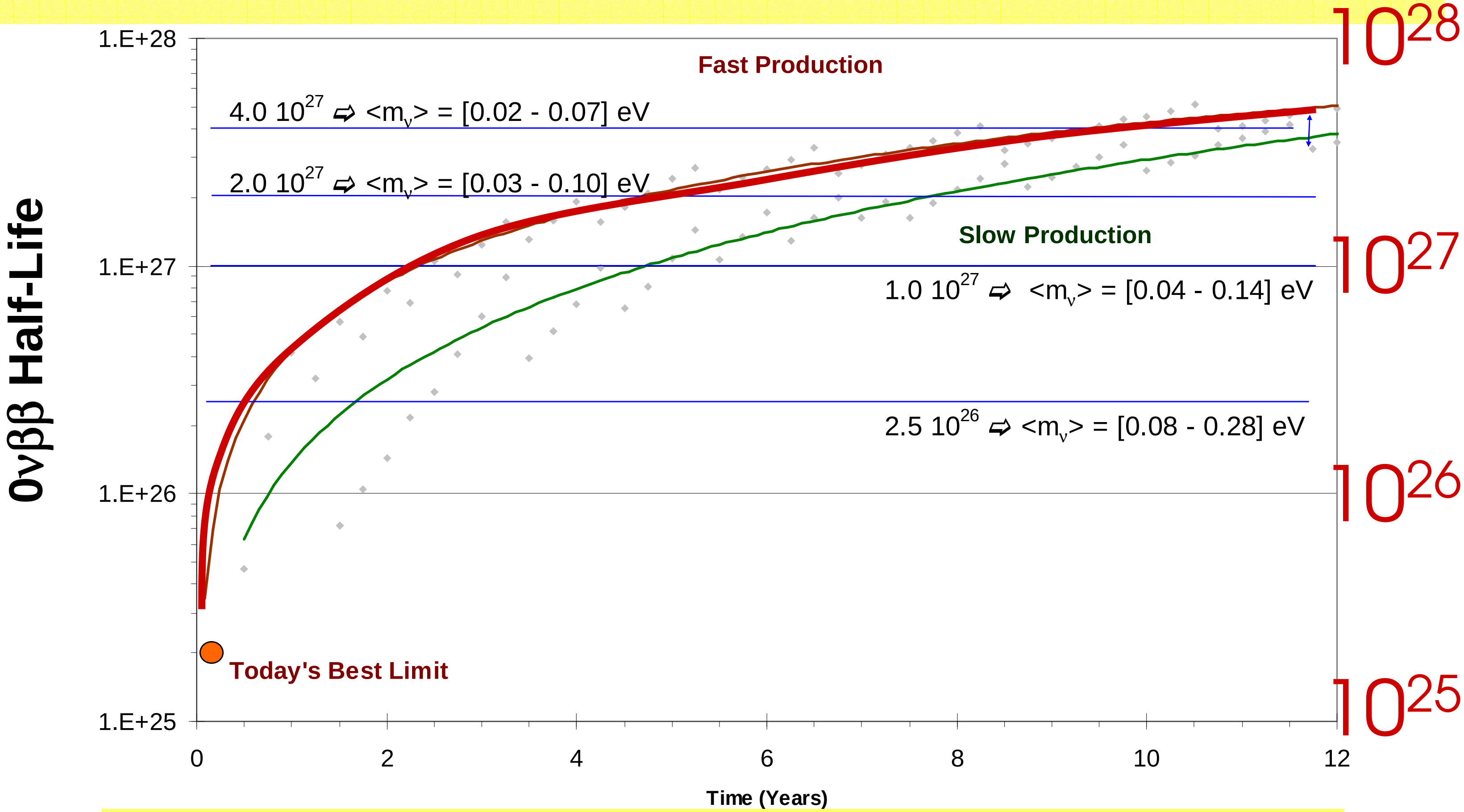


Monte-Carlo Example





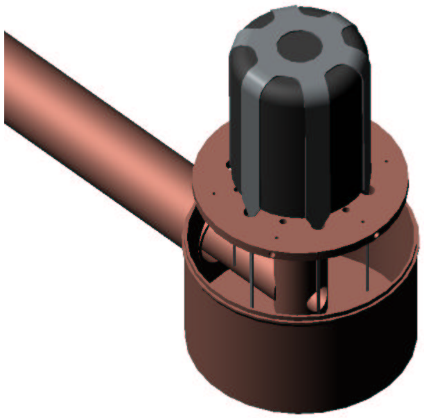
Sensitivity vs. Time



Based on early IGEX background levels with reasonable background reduction and cutting methods applied

Steve E

Collaboration Progress:
Optimization and Prep for Full Experiment



Segmented Enriched Germanium Array (SEGA):
Segmented Ge

1 to 5 Crystals

High energy n bkg

Pulse analysis test

Materials screening

Multi Element Germanium Assay (MEGA):
16+2 natural Ge

High density

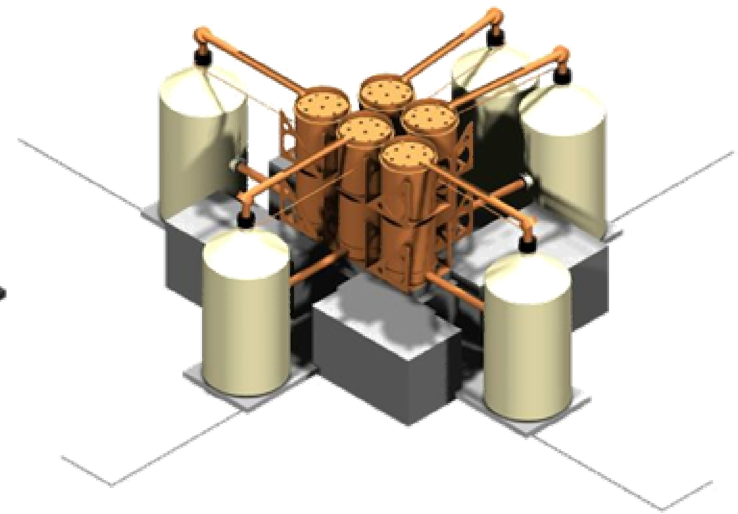
Materials qualification

Cryo design test

Geometry test

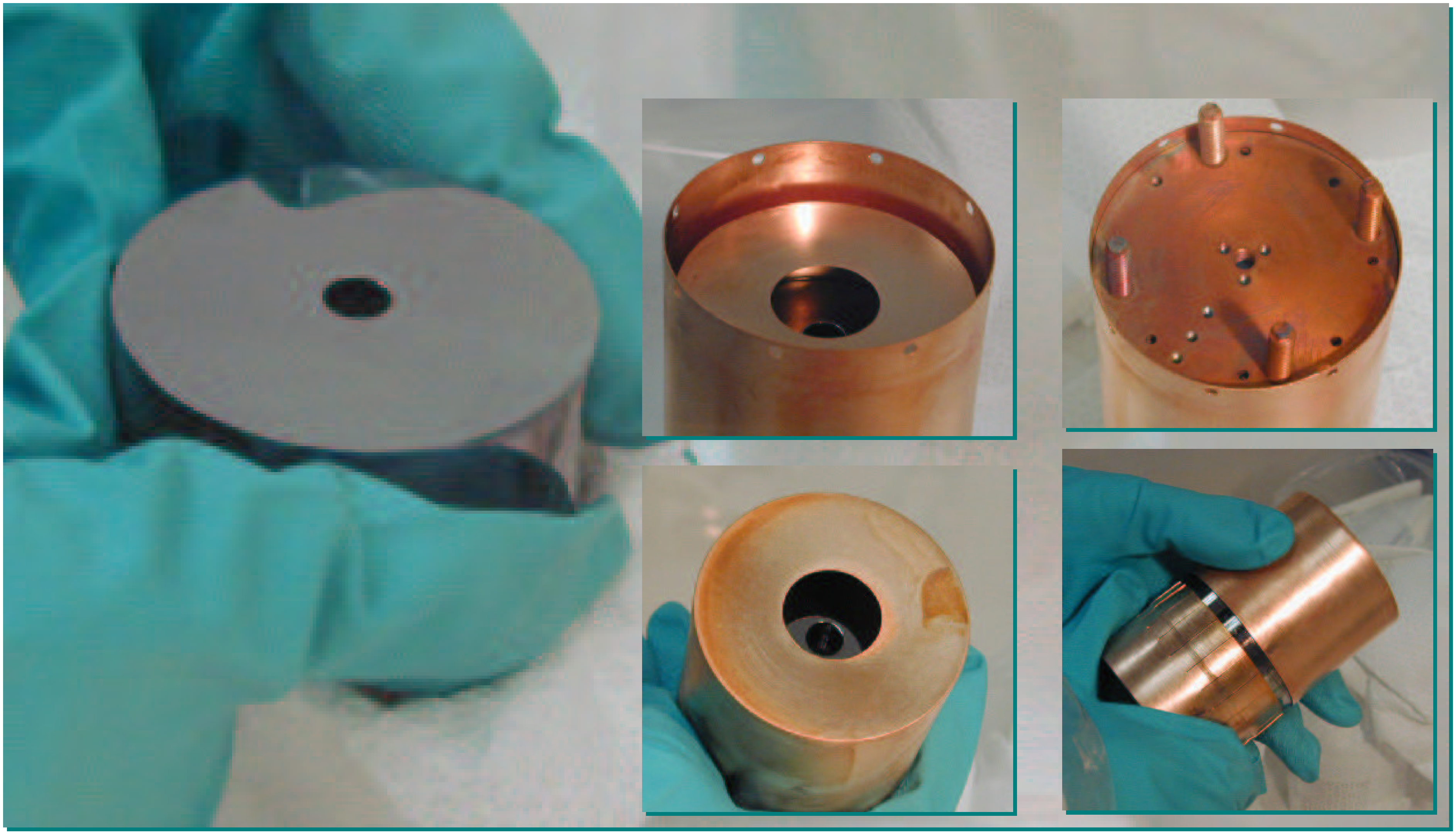
Powerful screening tool

MAJORANA:
Few hundred Ge det.
All enriched/segmented
Ten multi-crystal modules



Full Experiment

Recent Crystal Packaging Test
(MEGA)



Summary of Proposals

	Proposed ton-year = M * T * ε	Anticipated <m$_{ee}$>, (QRPA)
CUORE	0.21*5*1 = 1	60 meV
EXO	6.5*10*0.7 = 45	13 meV
GENIUS	1*2*1 = 2	20 meV
MAJORANA	0.5*10*1 = 5	25 meV
MOON	3.3*3*0.14 = 1.4	30 meV

The $\langle m_{\beta\beta} \rangle$ limits depend on background assumptions and matrix elements which vary from proposal to proposal.

An exciting time for ββ!

For at least one neutrino:

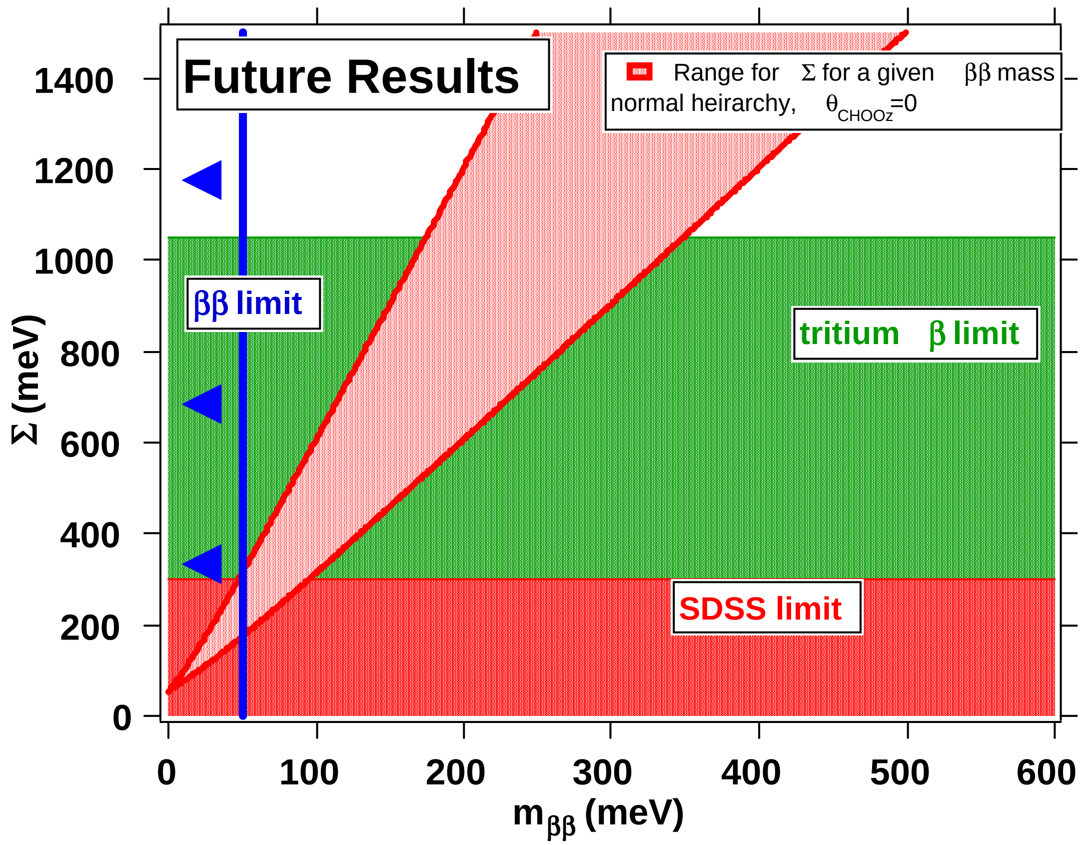
$$m_i > \sqrt{\delta m^2_{atmos}} \approx 50 meV$$

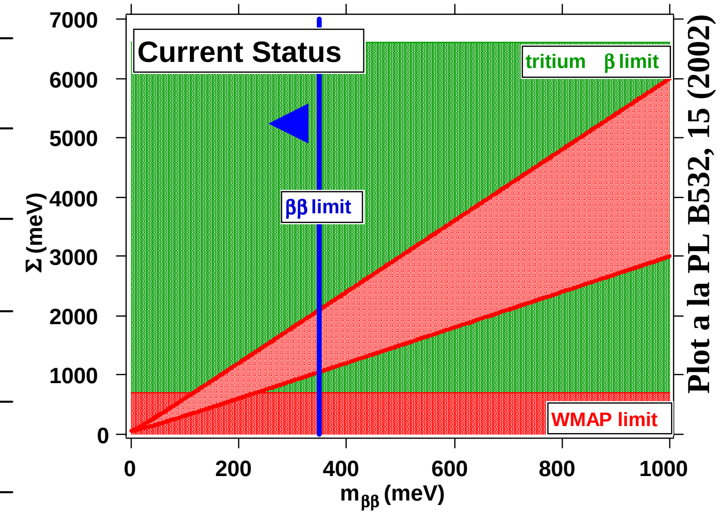
For the next experiments:

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

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

Summary of Mass Measurements (with a guess at the future)





Absolute scale measures

β: 350 meV

ββ: 50 meV

Cosmology: <100 meV