Neutrino Physics - Double-Beta Decay and Beta Decay

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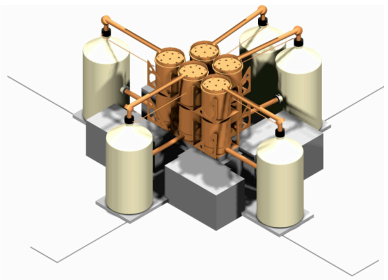
Los Alamos National Laboratory

Lecture Outline

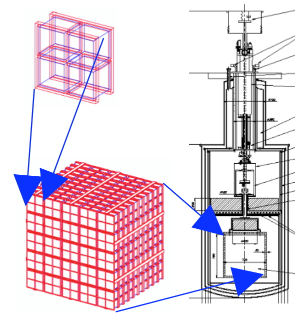
- Finish Double Beta Decay
  - Basic physics
  - General experimental techniques
  - The various experiments
- Beta Decay
  - Basic physics
  - Experimental techniques

“Selected” Projects



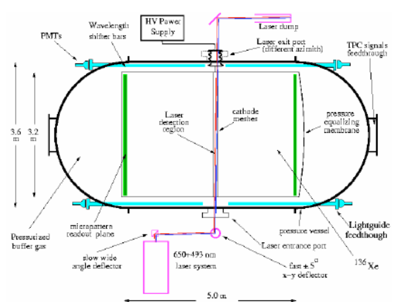
MAJORANA

CUORE	TeO_2 Crystal bolometers
EXO	Liquid Xe TPC, daughter tag
GERDA	Bare Ge detectors in LN
MAJORANA	Ge det. in traditional cryostat
MOON	Scint. sandwiching Mo foils
SuperNEMO	Foils, tracking and scint.

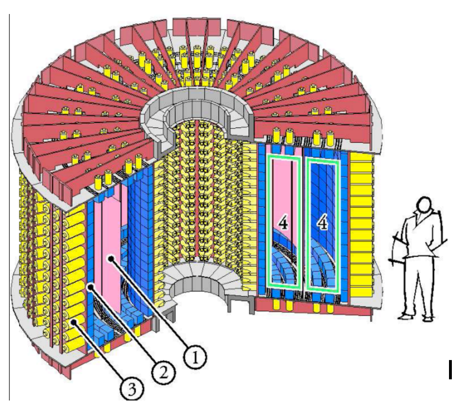


CUORE

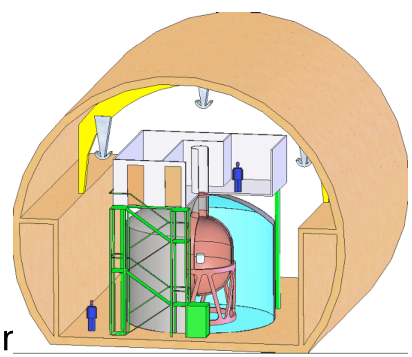
EXO



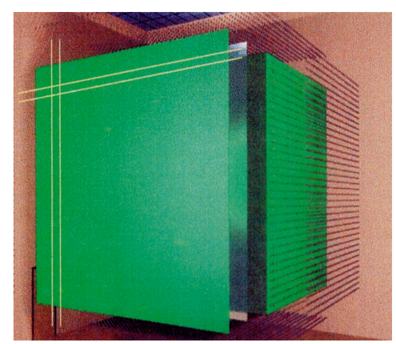
NEMO



GERDA



MOON



The MAJORANA Project

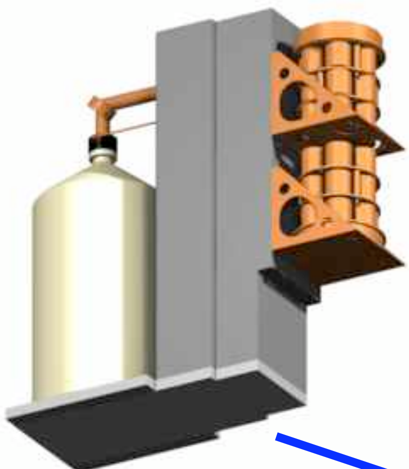
Duke U.
North Carolina State U.
TUNL
Lawrence Livermore Nat. Lab.
JINR, Dubna
ITEP, Moscow
Lawrence Berkeley Nat. Lab.
Pacific Northwest Nat. Lab.

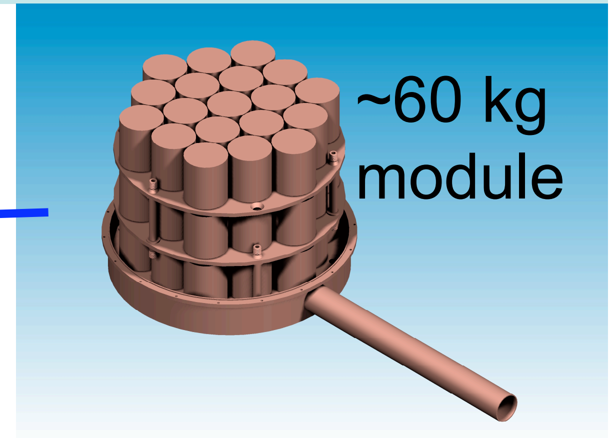
U. of Washington
Los Alamos Nat. Lab.
U. of South Carolina
Univ. of Chicago
RCNP, Osaka Univ.
Univ. of Tenn.
Oak Ridge Nat. Lab.
Queen's University

MAJORANA Overview

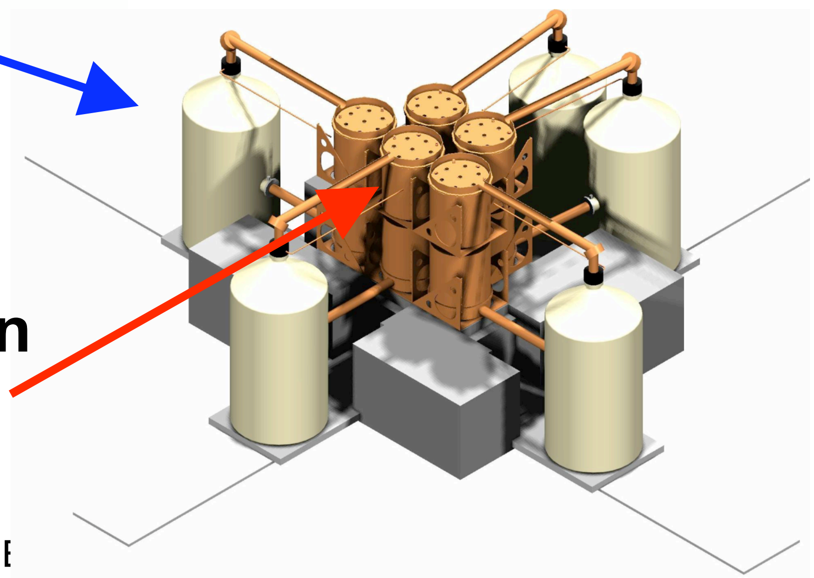
- **30-60 kg of 86% enriched ^{76}Ge**
- **Demonstrate feasibility for a 1-ton expt.**
  - **Background near 1/t-y**
  - **Technology down-select in coop. with GERDA**
- **Scalable to ton scale**
- **Segmented detectors using pulse shape discrimination for background rejection.**
- **Prototypes being assembled.**
- **Highly efficient**
- **Extensive past experience**

MAJORANA Layout: M-500 to M-1000



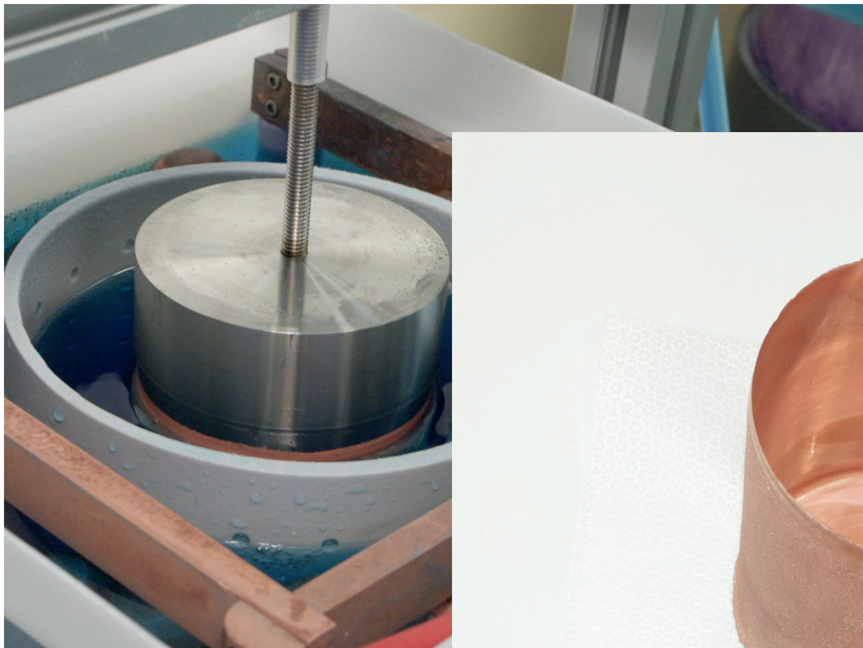


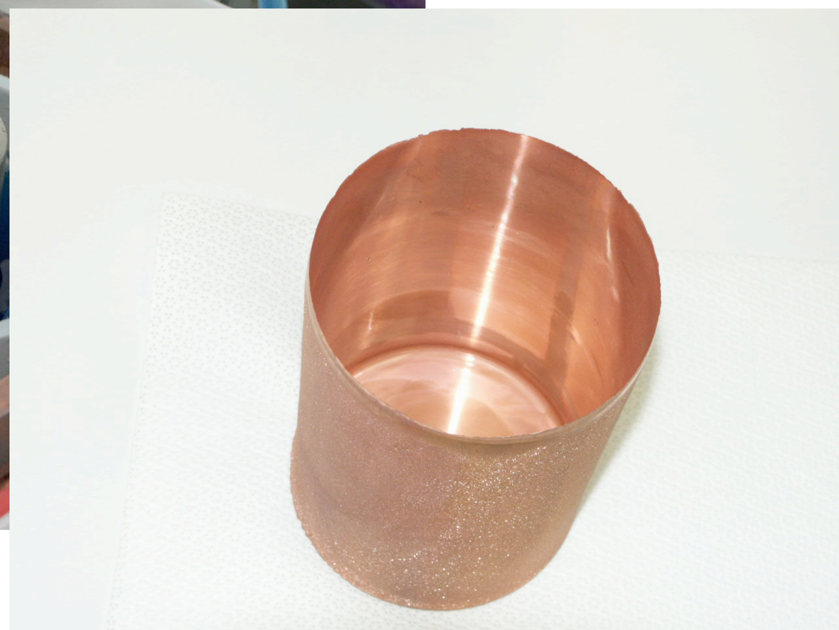
~60 kg module



M-60 would contain 1 module

Electroforming Hut Installation at WIPP





GERmanium Detector Array - GERDA

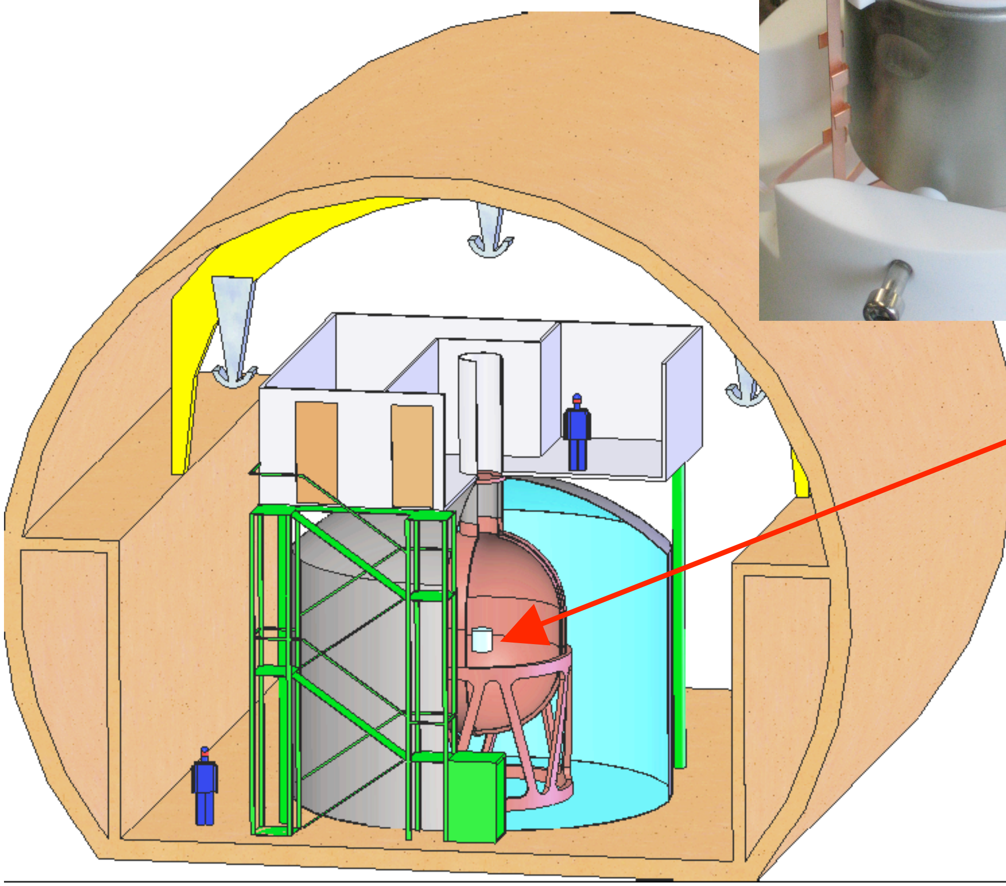
[a] INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
[b] Joint Institute for Nuclear Research, Dubna, Russia
[c] Max-Planck-Institut für Kernphysik, Heidelberg, Germany
[d] Institut für Kernphysik, Universität Köln, Germany
[e] Jagiellonian University, Krakow, Poland
[f] Università di Milano Bicocca e INFN Milano, Milano, Italy
[g] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[h] Institute for Theoretical and Experimental Physics, Moscow, Russia
[i] Russian Research Centre Kurchatov Institute, Moscow, Russia
[j] Max-Planck-Institut für Physik, München, Germany
[k] Dipartimento di Fisica dell'Università di Padova e INFN Padova, Padova, Italy
[l] Physikalisches Institut, Universität Tübingen, Germany

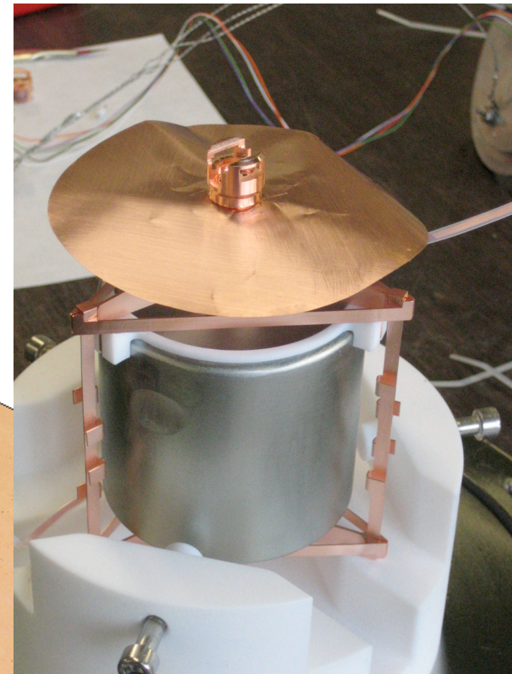
GERDA Overview

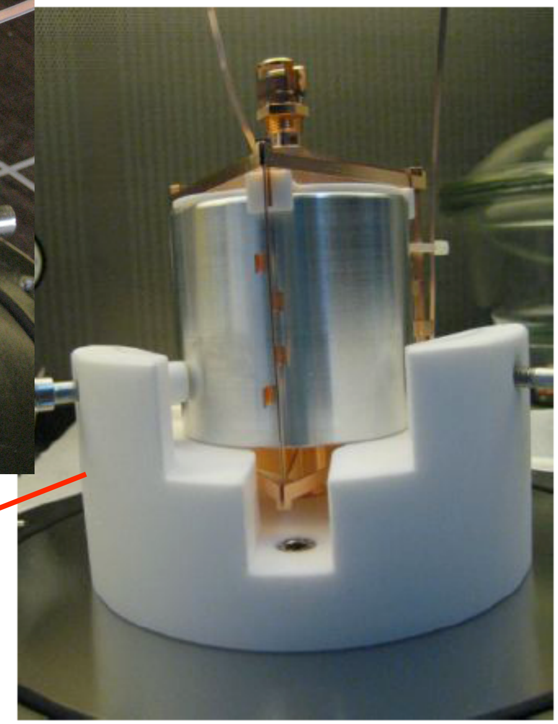
- **Phase 1: 15 kg, ~86% enriched ^{76}Ge**
- **Naked Ge crystals in LN**

  Very little material near Ge.
- **Phase 2: additional ~20 kg for ~35 kg**
- **Phase 3: scale to ~1 t scale**
  - **Coordinated effort with MAJORANA**

GERDA Layout







Mockup assembly for operation of three 'naked' Germanium detectors in liquid nitrogen. (in holder)

Molybdenum Observatory Of Neutrinos - MOON

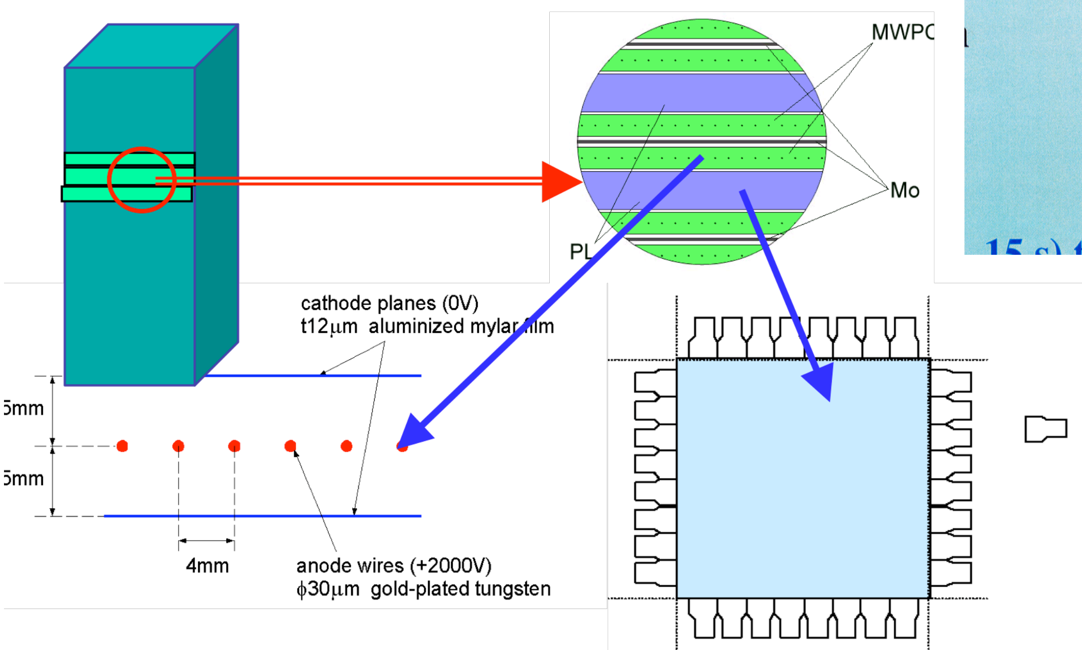
- U. of Washington
- U. of North Carolina
- U. of Wisconsin
- Research Center for Nuclear Physics, Osaka
- Plus others as collaboration is forming.

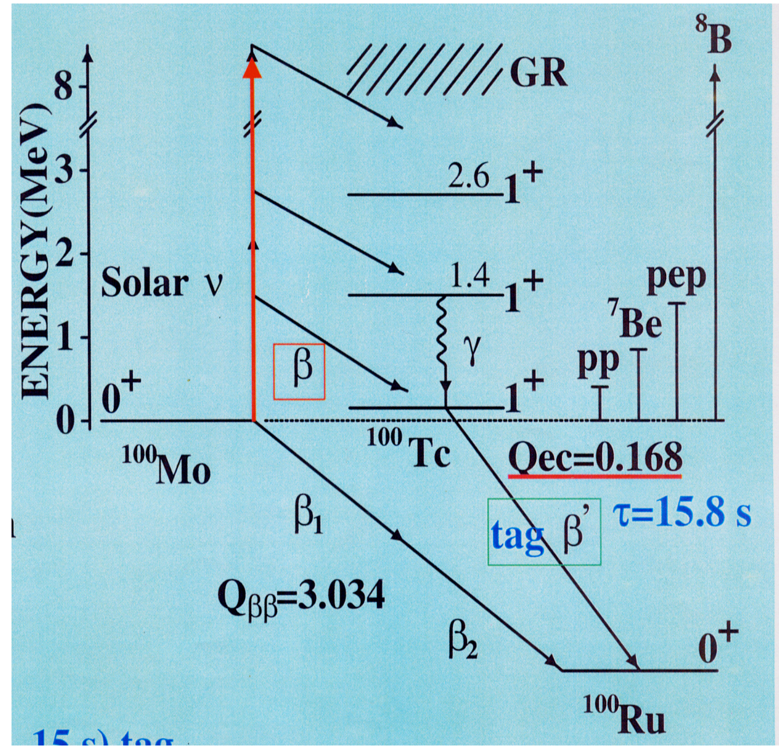
Spokesperson
Hiro Ejiri
RCNP

MOON Overview

- Few tons ^{100}Mo
- Scintillator/source sandwich
- Or possibly bolometer
- Position and single E_{β} data play big role in $\beta\beta(2\nu)$ and U, Th rejection.
- 14% efficiency
- ELEGANTS is precursor.

MOON


MWPC
Mo
PL
cathode planes (0V)
t12μm aluminized mylar film
5mm
5mm
4mm
anode wires (+2000V)
ϕ30μm gold-plated tungsten


ENERGY (MeV)
8
3
2
1
0
GR
8B
2.6 1+
1.4 1+
1+
0+
Solar ν
β
γ
pep
7Be
pp
100Mo
100Tc
Qec=0.168
β1
tag β'
τ=15.8 s
Qββ=3.034
β2
0+
100Ru

Cryogenic Underground Observatory for Rare Events - CUORE

Berkeley
Firenze
Gran Sasso
Insubria (COMO)
Leiden
Milano
Neuchatel
U. of South Carolina
Zaragoza

Spokesperson
Ettore Fiorini
Milano

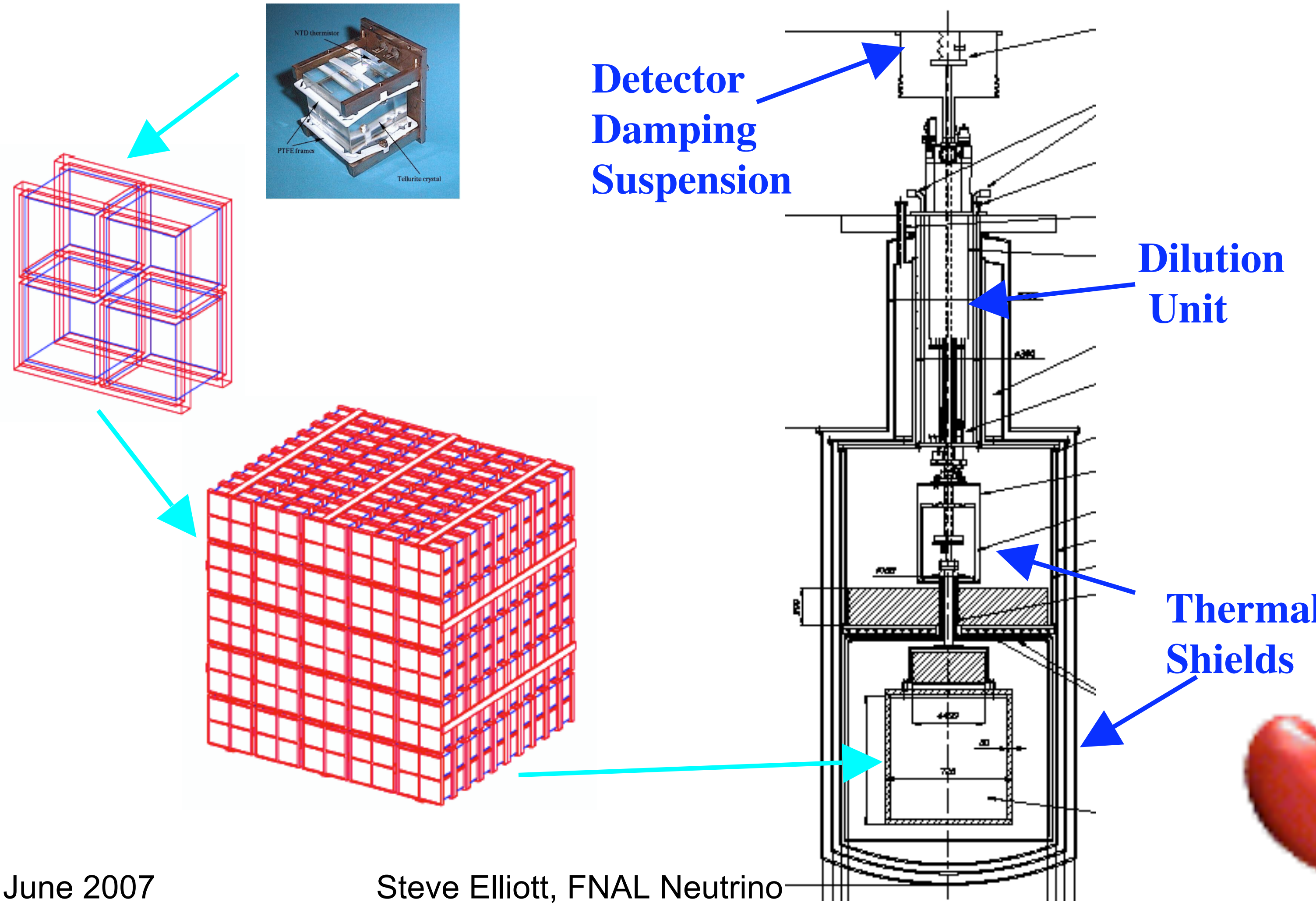
CUORE Overview

- 0.21 ton, 34% natural abundance ^{130}Te
- 741 kg of TeO_2 bolometers, 750 g crystals

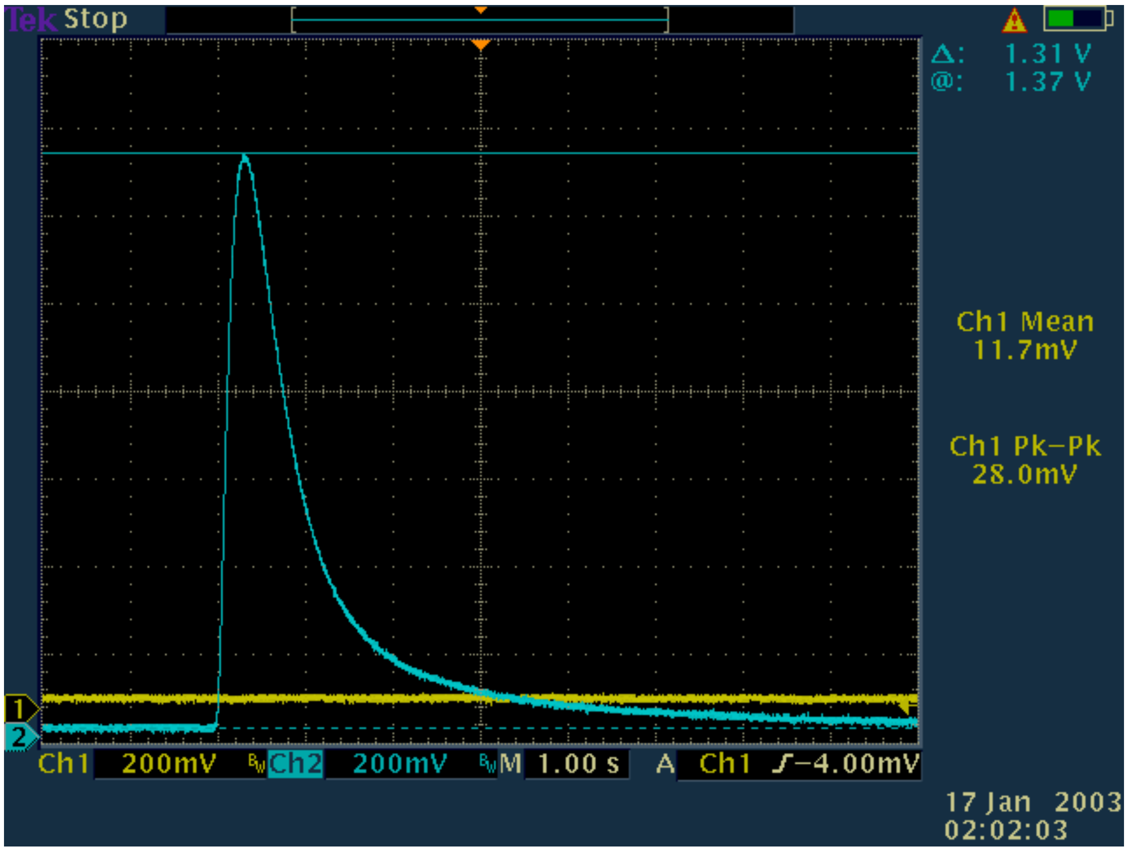
- Doesn't require enriched material.
- 988 5x5x5 cm^3 crystals
- 19 towers of 13 layers of 4 crystals

- Gran Sasso Laboratory
- CUORICINO is an approved prototype (1 tower).
- CUORICINO began operation in Feb. 2003

CUORE Detector



CUORICINO IS OPERATING



FIRST PULSE.

Data runs began In Feb. 2003

$\tau > 3.0x10^{24}$ y
Soon to be published

Enriched Xenon Observatory - EXO

U. of Alabama
Caltech
IBM Almaden
ITEP Moscow
U. of Neuchatel
INFN Padova
SLAC
Stanford U.
U. of Torino
U. of Trieste
WIPP Carlsbad

Spokesperson
Giorgio Gratta
Stanford

EXO Overview

10 ton, ~70% enriched ^{136}Xe

70% effic., LXe chamber

Optical identification of Ba ion.

- Extract ion on cold probe to optical trap.

Has achieved ~2% energy resolution

- Measure ionization and scintillation

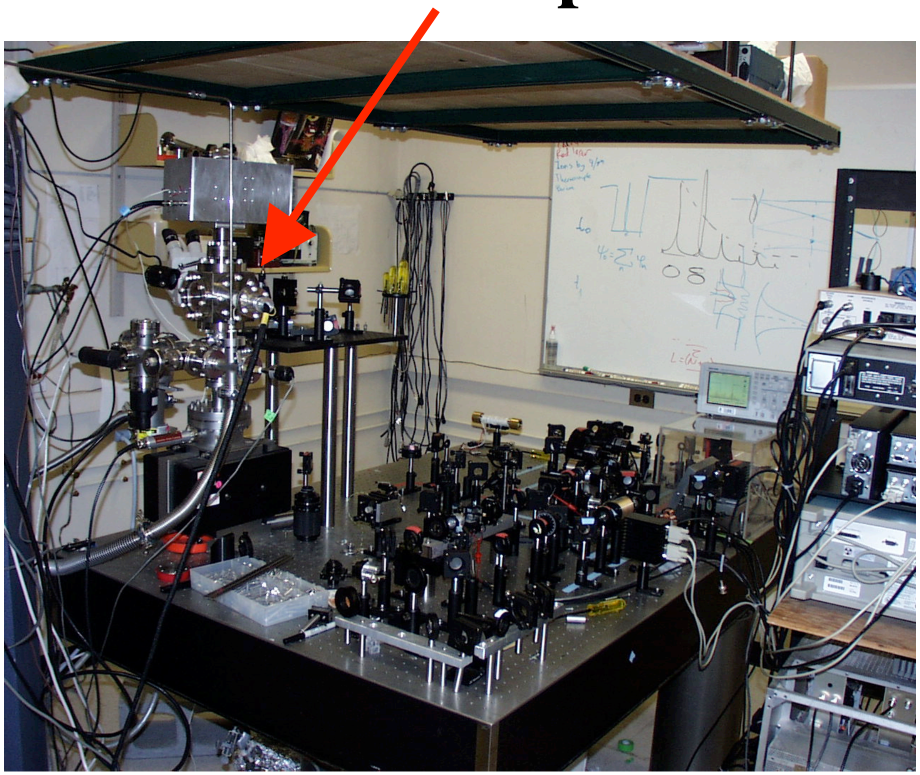
TPC performance similar to that at Gotthard.

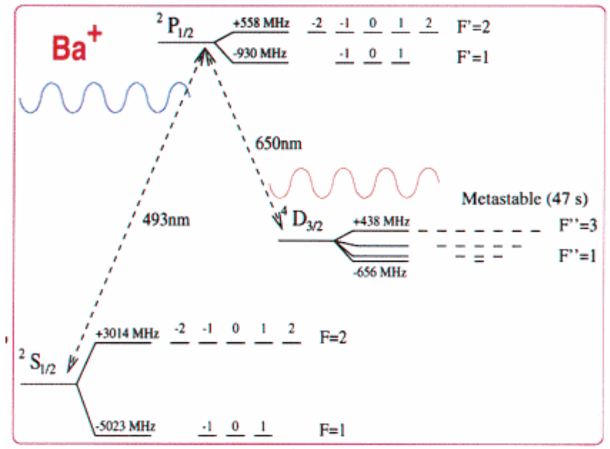
~200-kg ^{enr}Xe prototype (no Ba ID)

- Isotope in hand

Stanford Optics Lab with Ba Trap

Ba Trap

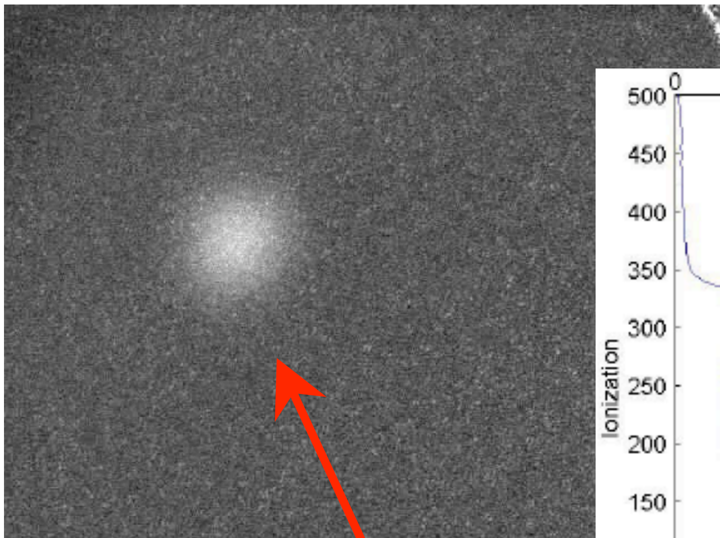


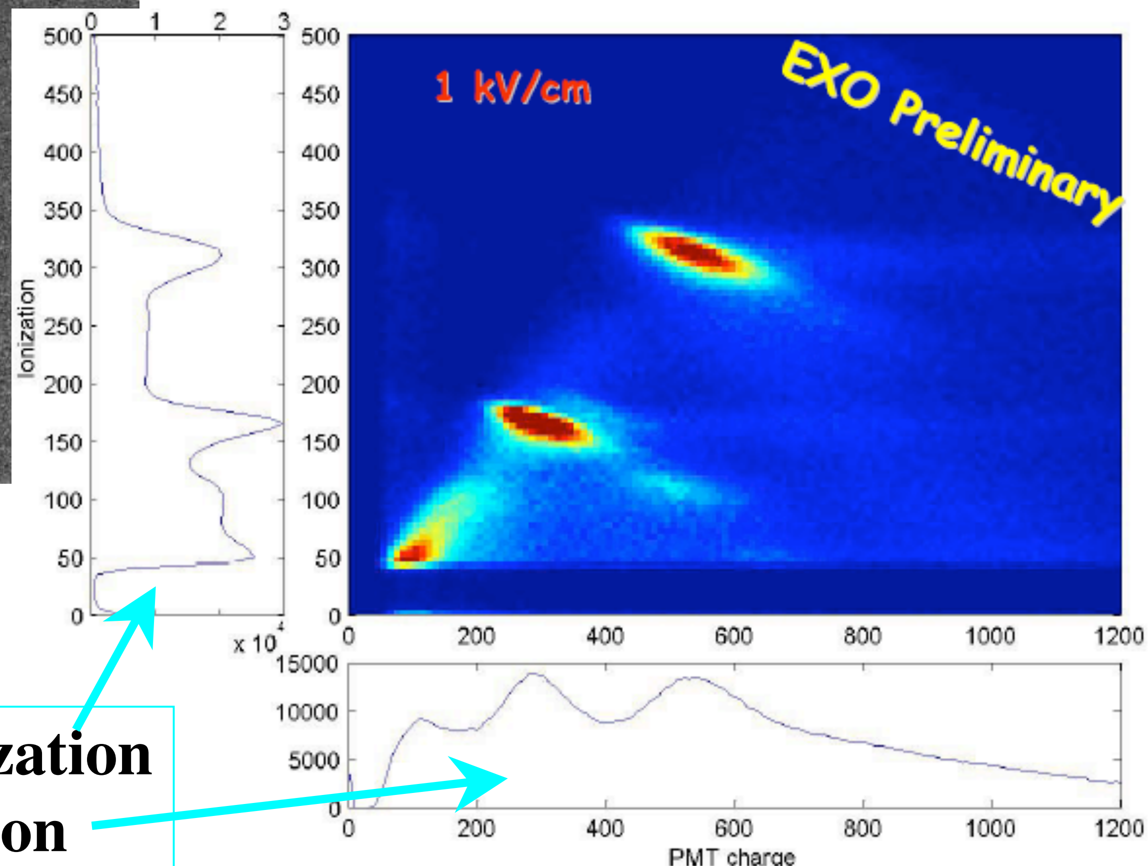


$^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^- e^- \rightarrow {}^{136}Ba^+$

Optically observe final state. (Moe, PRC44 (1991) 931)

EXO lone Ion/Resolution

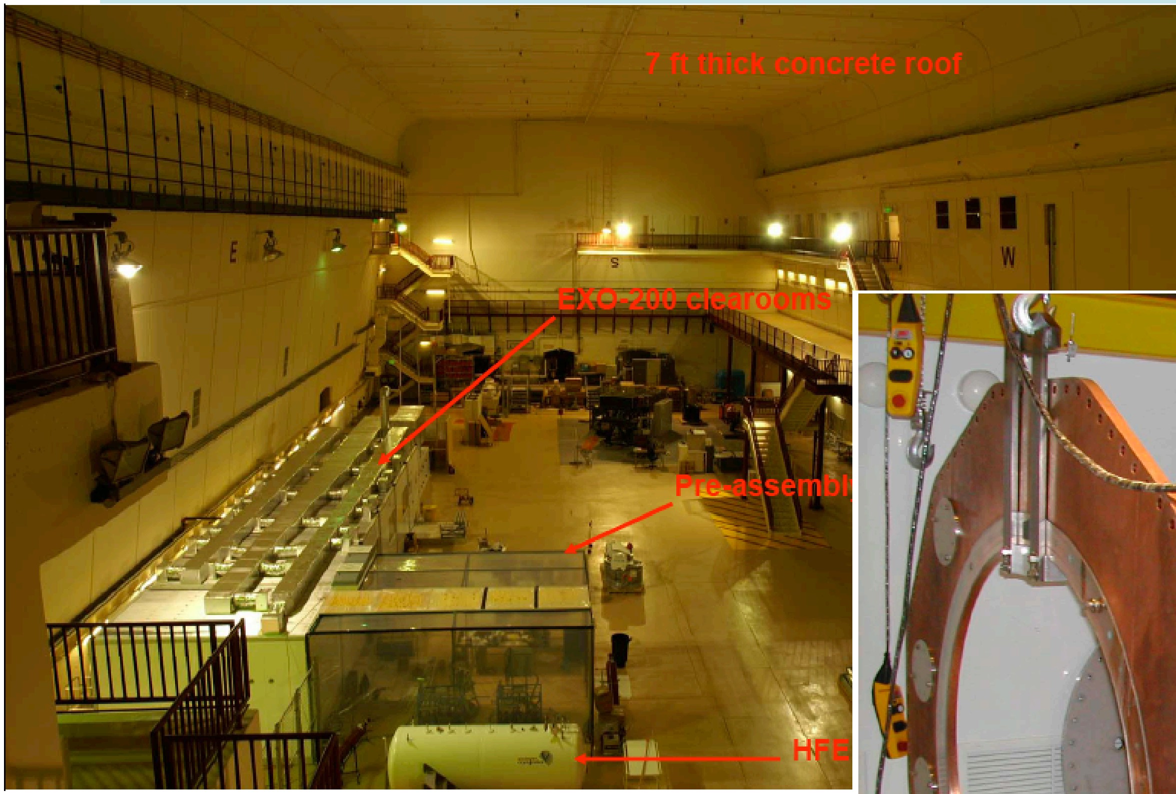


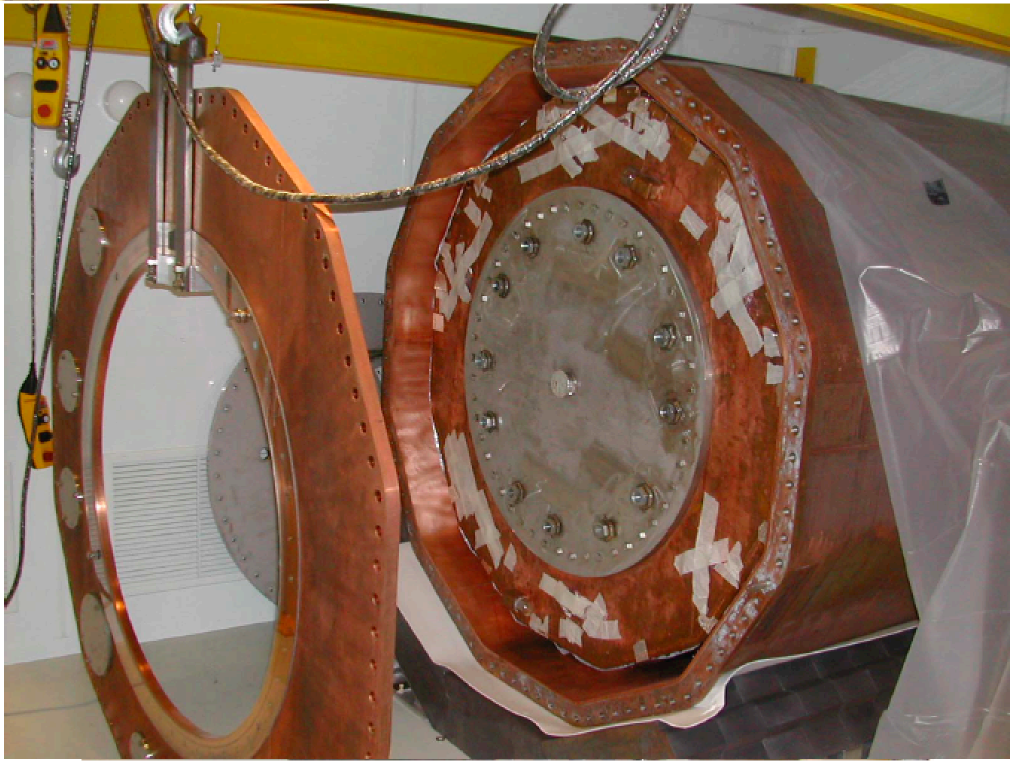


Single Ba ion

Measure ionization and scintillation

EXO-200 Photos





To deduce $m_{\beta\beta}$ from τ, one needs Matrix Elements

$$\frac{1}{\tau_{0\nu}} = G_{0\nu} \left| M_{0\nu} \right|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

- **If $\beta\beta$ is observed, the qualitative physics conclusions are profound regardless of |M|.**
- **There are many calculations of |M|. Which should be used to deduce $m_{\beta\beta}$?**
- **How do we interpret the uncertainty associated with the nuclear physics?**

Progress in Understanding the Matrix Element Uncertainty

- **Previous spread is mostly due to the various implementations of QRPA.**
- **Rodin et al. show that QRPA results tighten up (typically to ~20% uncertainty in half life):**
  - **When implementation differences are accounted for**
  - **One uses $\beta\beta(2\nu)$ to set the free parameter**
- **Recent shell model numbers are comparable (differ < factor of 2). But these calculations are still evolving.**
- **Debate continuing on the proper setting of free parameters.**

Take-home message

- **Due to the minimum neutrino mass scale implied by the neutrino oscillation experiments:**

- **The next generation ββ experiments have a good possibility of reaching an exciting $\langle m_{\beta\beta} \rangle$ region.**

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.**
- **Many laboratory experiments might 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".**

A List of Upcoming Techniques

- **Supernovas - relatively poor sensitivity**
- **Cosmology - hope of reaching below 100 meV**
- **Nuclear/Particle Physics**

  τ decay - relatively poor sensitivity

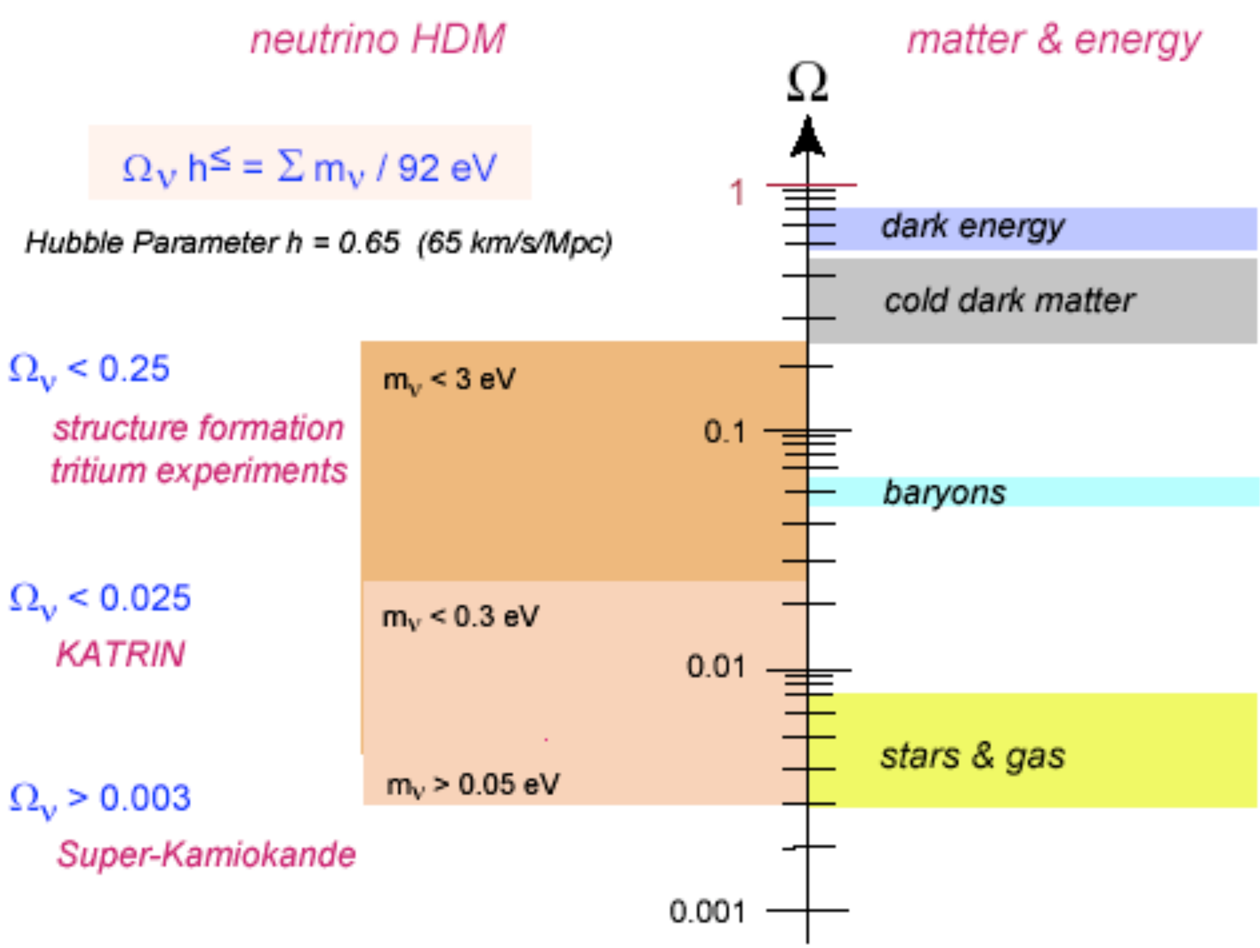
  μ decay - relatively poor sensitivity

  β decay - hope to reach below 500 meV

  $\beta\beta$ decay - hope to reach below 50 meV

  oscillations - great sensitivity to mass differences

Matter Content of Universe



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)

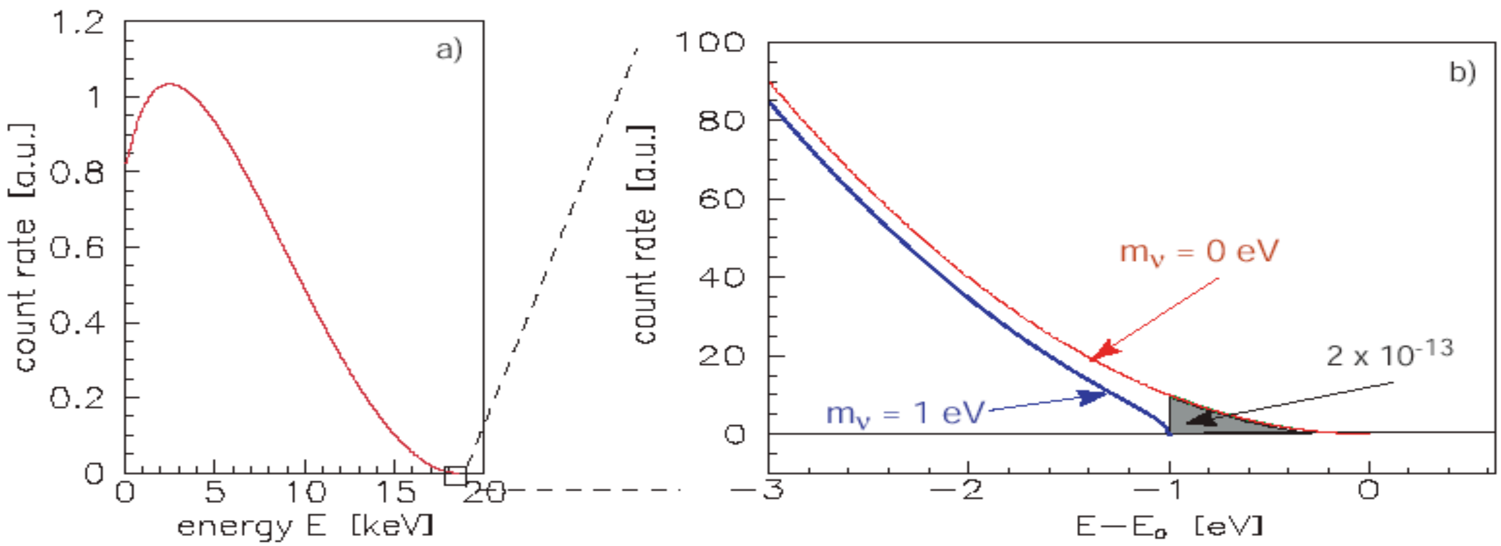
When convolved with resolution function with width > m_i, we can analyze the spectrum with one mass parameter: $\langle m_\beta \rangle$.

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

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

The Neutrino Mass from β decay

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



KATRIN LOI

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

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

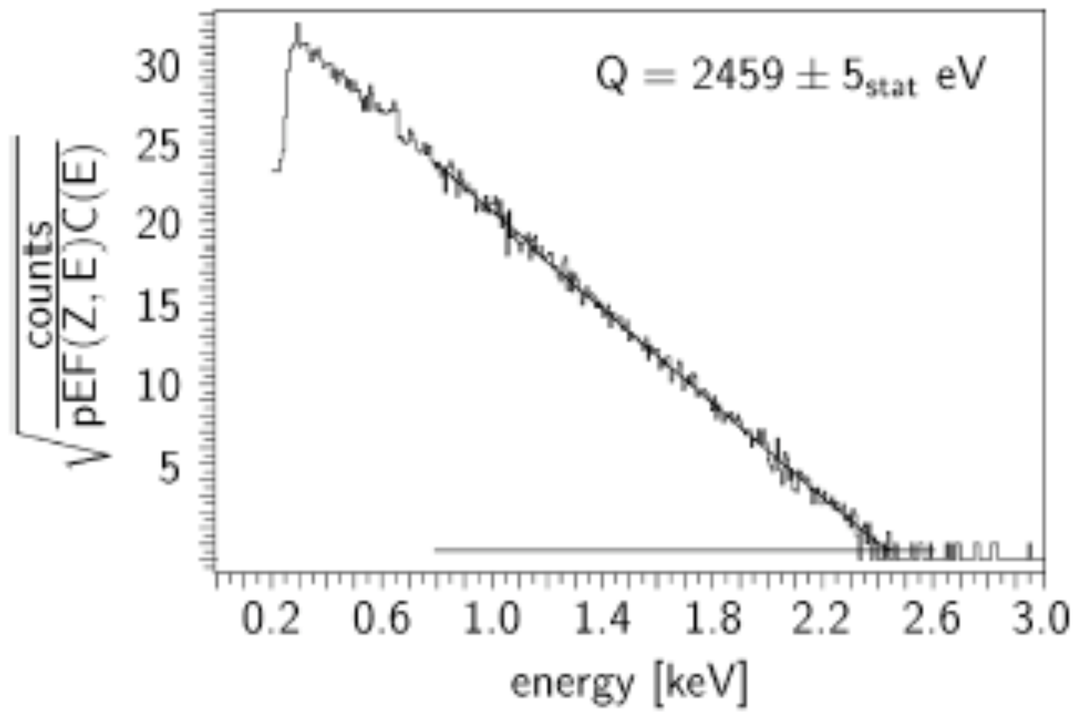
^{187}Re β Decay Experiments

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

Milano Re Experiment

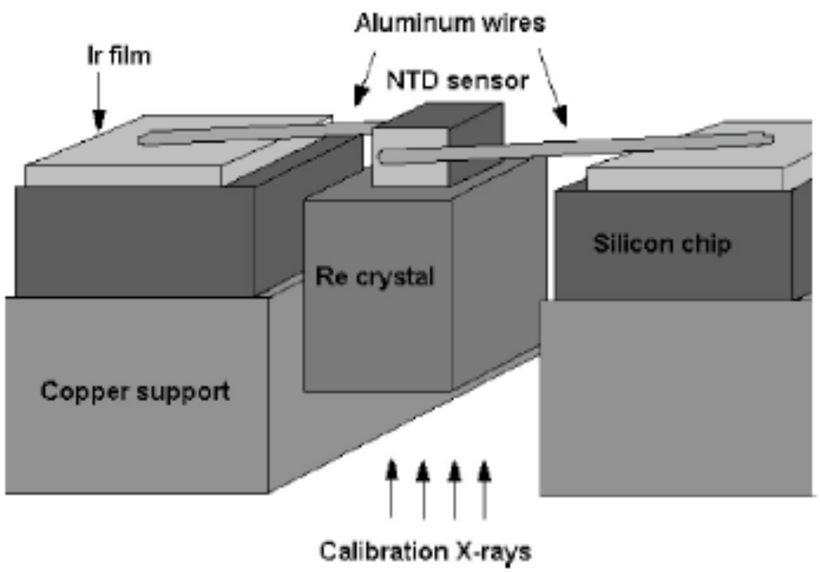
$AgReO_4$

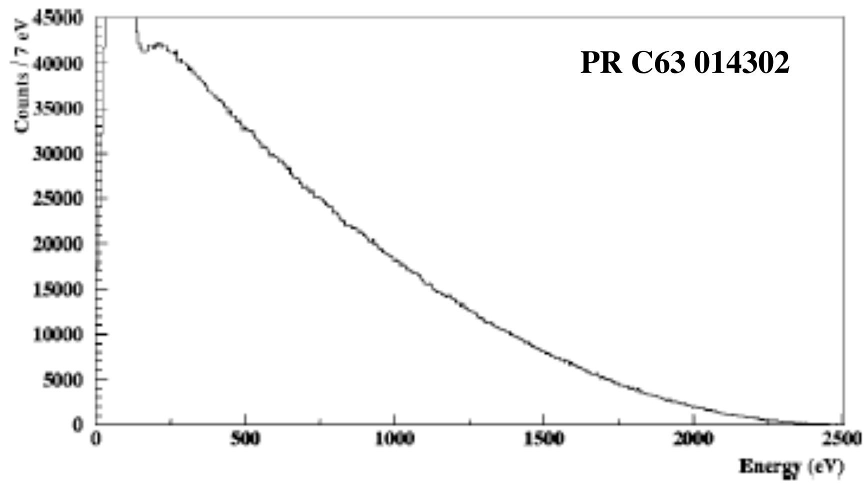
Hope for a sensitivity of 4 eV



NIM A444 (2000) 77

Genoa Re Experiment





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

MARE

http://crio.mib.infn.it/wig/silicini/proposal/proposal_MARE_v2.6.pdf

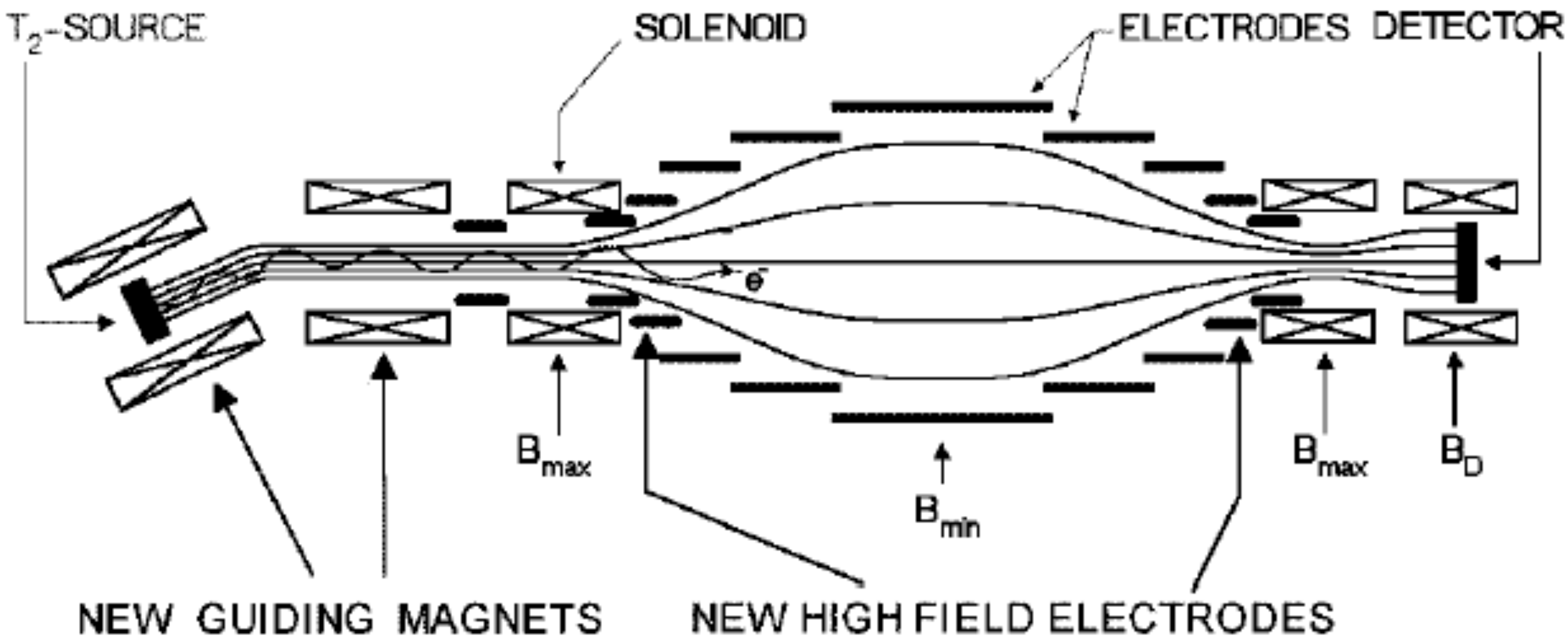
- **Requires 10^{14} β decays to reach 200 meV**
- **To prevent pile-up requires $3x10^5$ detector-years**
- **Hope to start data taking in ~2011**

Why Tritium?

- **Re bolometers (source = detector) collect whole spectrum at once: therefore need low rate to prevent pile-up.**
- **Very low Q-value (2.5 keV)**

- **With source ≠ detector, one can just analyze end of spectrum: much higher activities.**
- **Low Q-value (18 keV)**

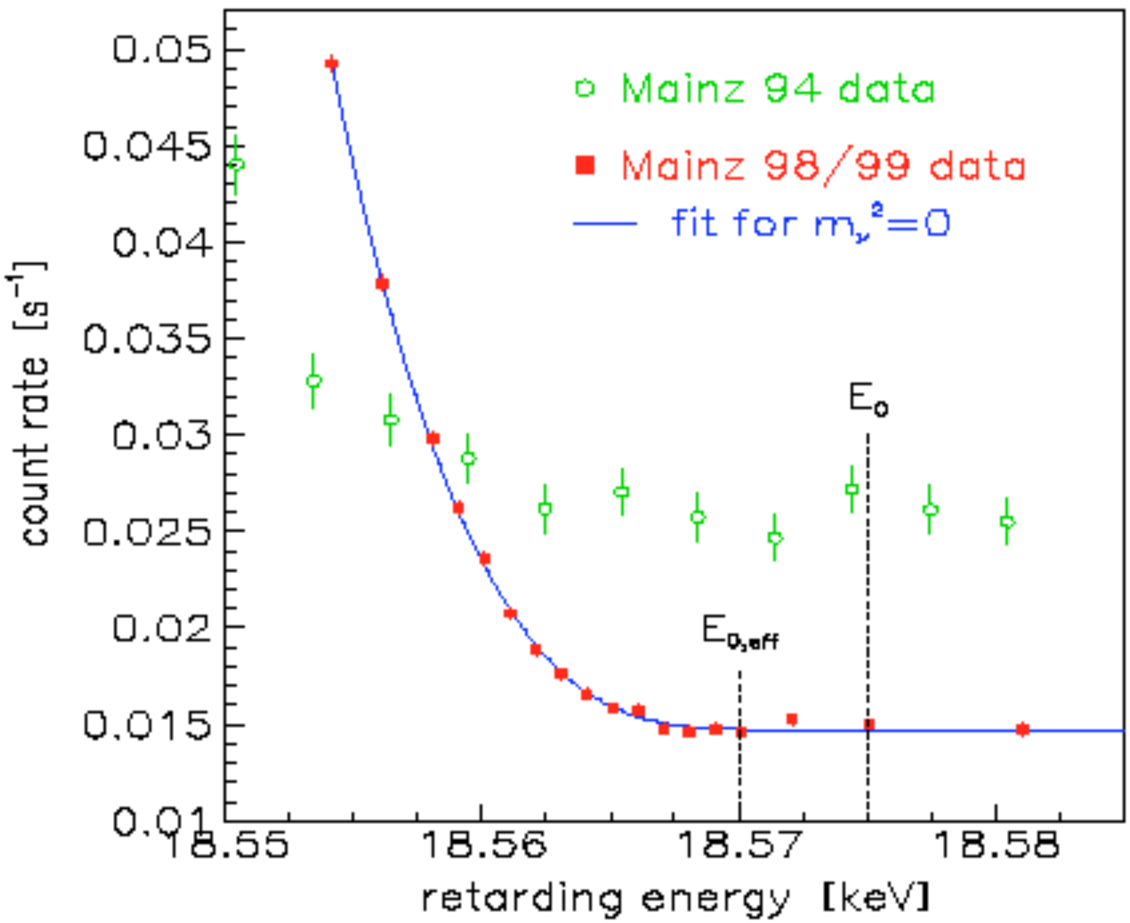
Mainz Experiment Setup



Mainz Results

$m_\nu < 2.8$ eV (95% CL)

ΔE ~2-6 eV at 20 keV
Large acceptance
10-40% of 4π



Improvements 94-98

Lower temp source
no dewetting

T_2 evaporating into spectrometer stopped by tilted solenoids.

Fit Function

- Fit Parameters: Free Amplitude, Endpoint energy, neutrino mass squared, and background
- Response function depends on: Potential distribution within source, backscattering from source substrate, spectrometer transmission, and energy dependence of detection efficiency.

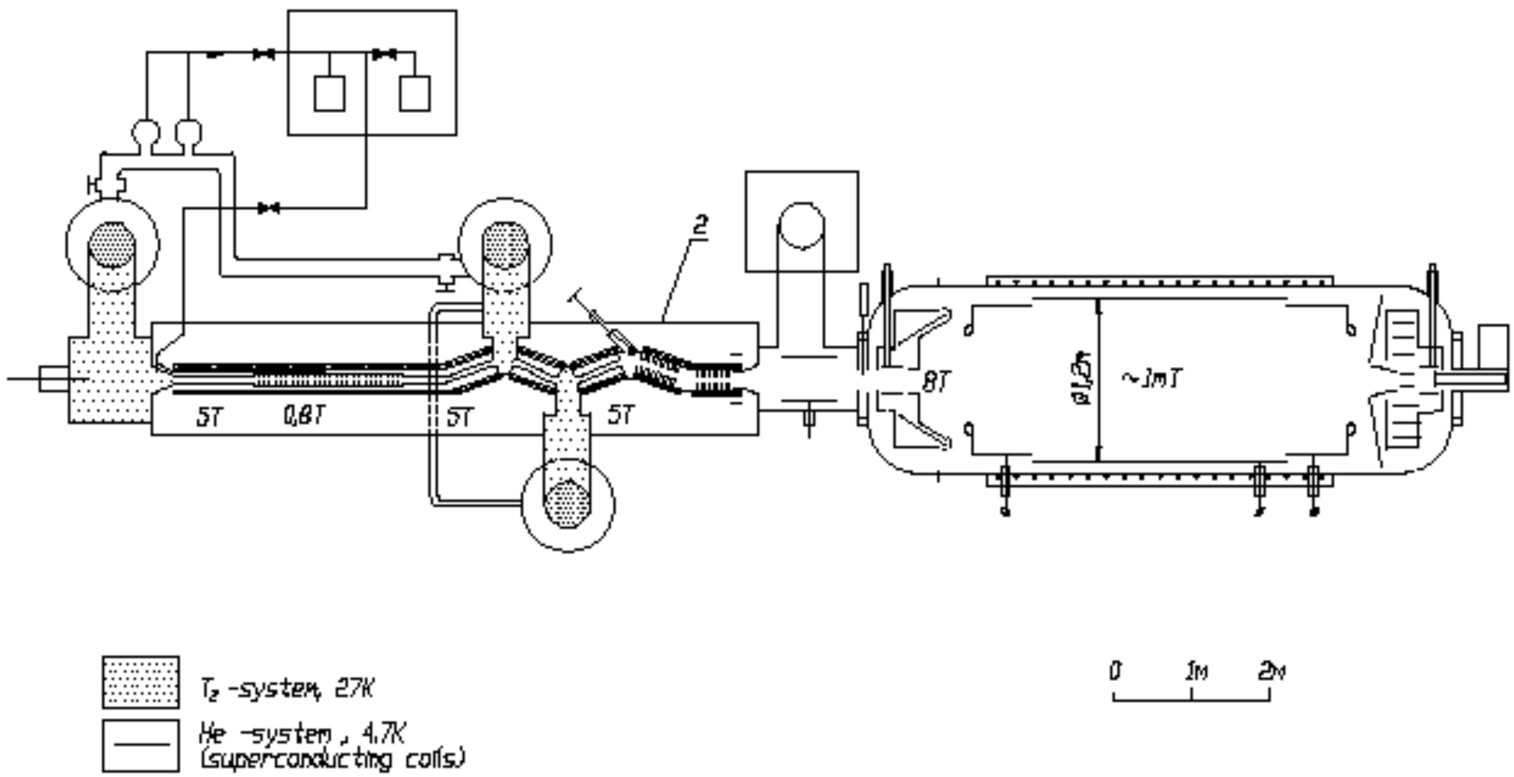
Systematic Uncertainties

- **Inelastic scattering in tritium film**
- **Neighbor molecule excitation**
- **Final states in THe^+ molecule**
- **Charging of source film**

Statistical Systematic

$$m_\nu^2 = -3.7 \pm 5.3 \pm 2.1 \text{ eV}^2$$

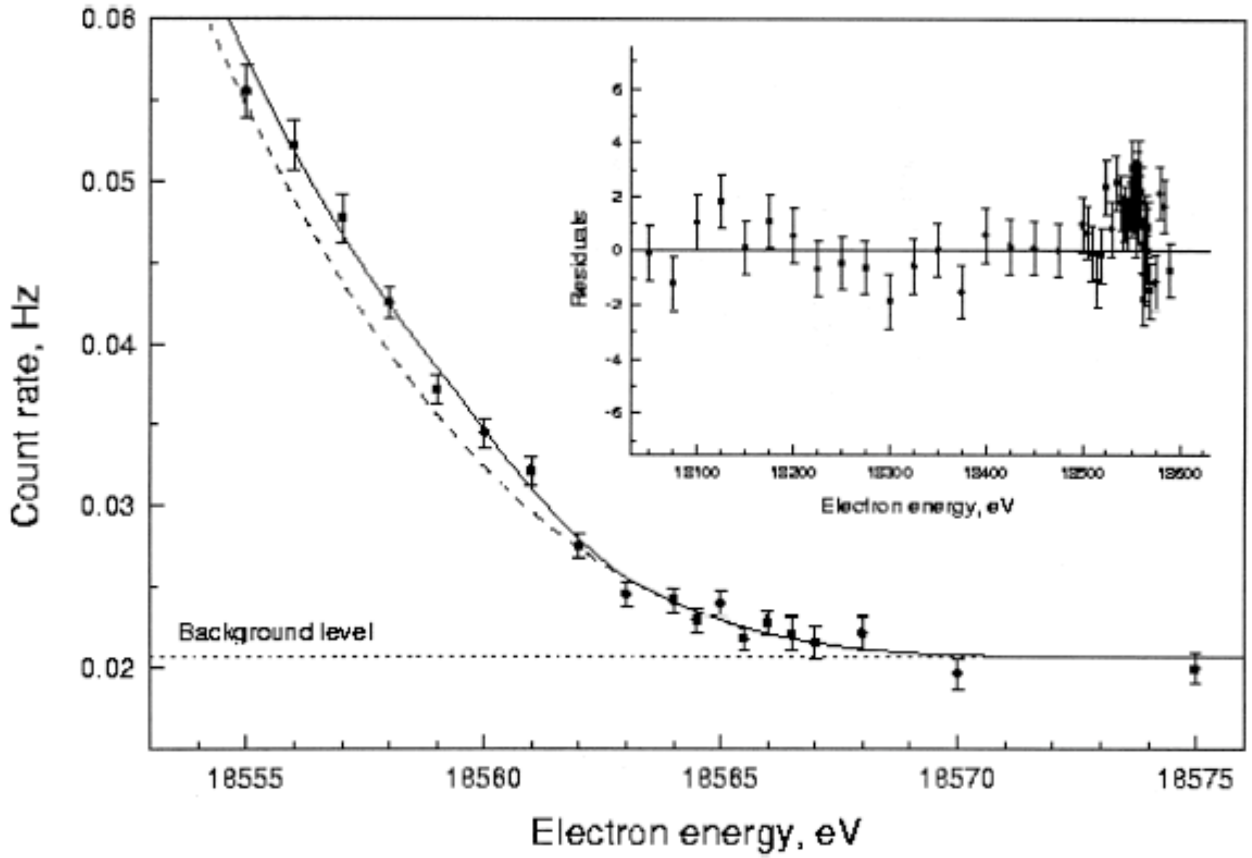
The Troisk Experiment



Troisk Results

$m_\nu < 2.5$ eV (95% CL)

Solid line is spectrum with step funcion.



PL B 460, 227 (1999)

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.**

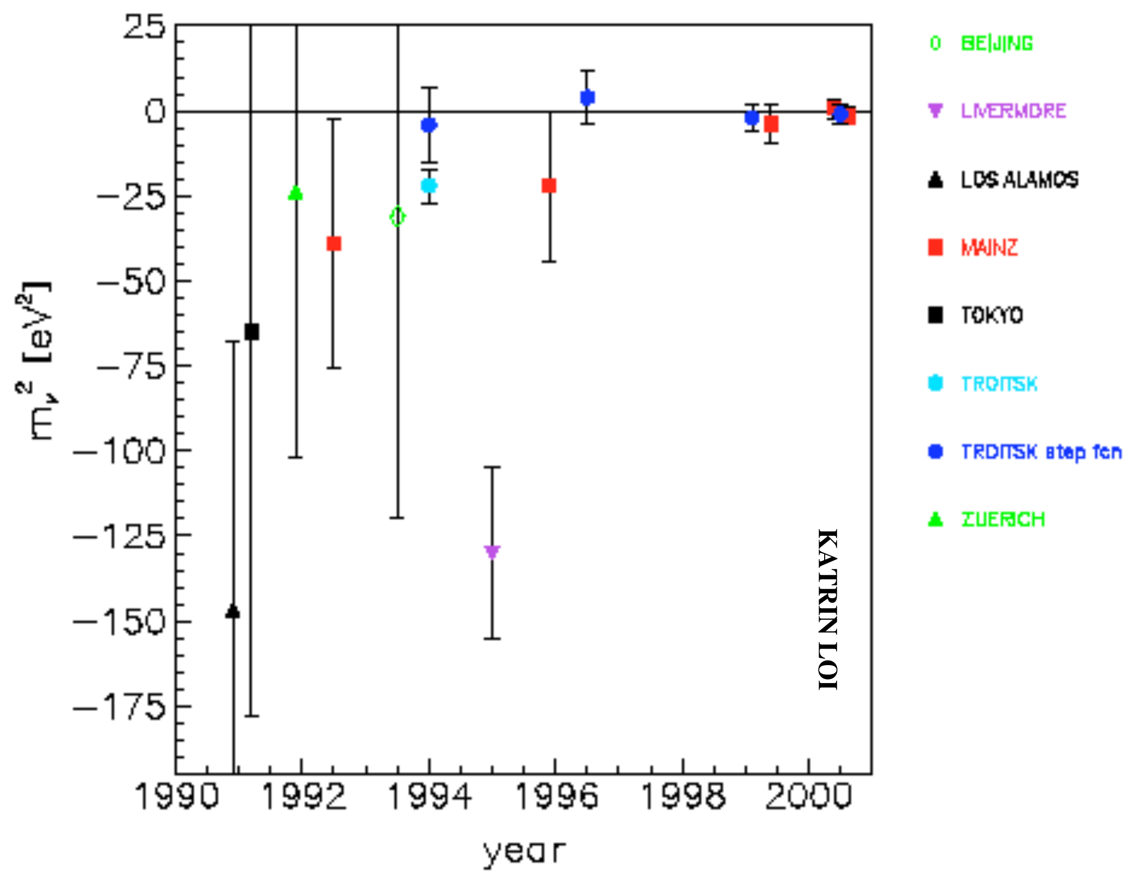
Primary Systematic Uncertainties

- **Resolution error leads to m_ν error**

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

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

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



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.

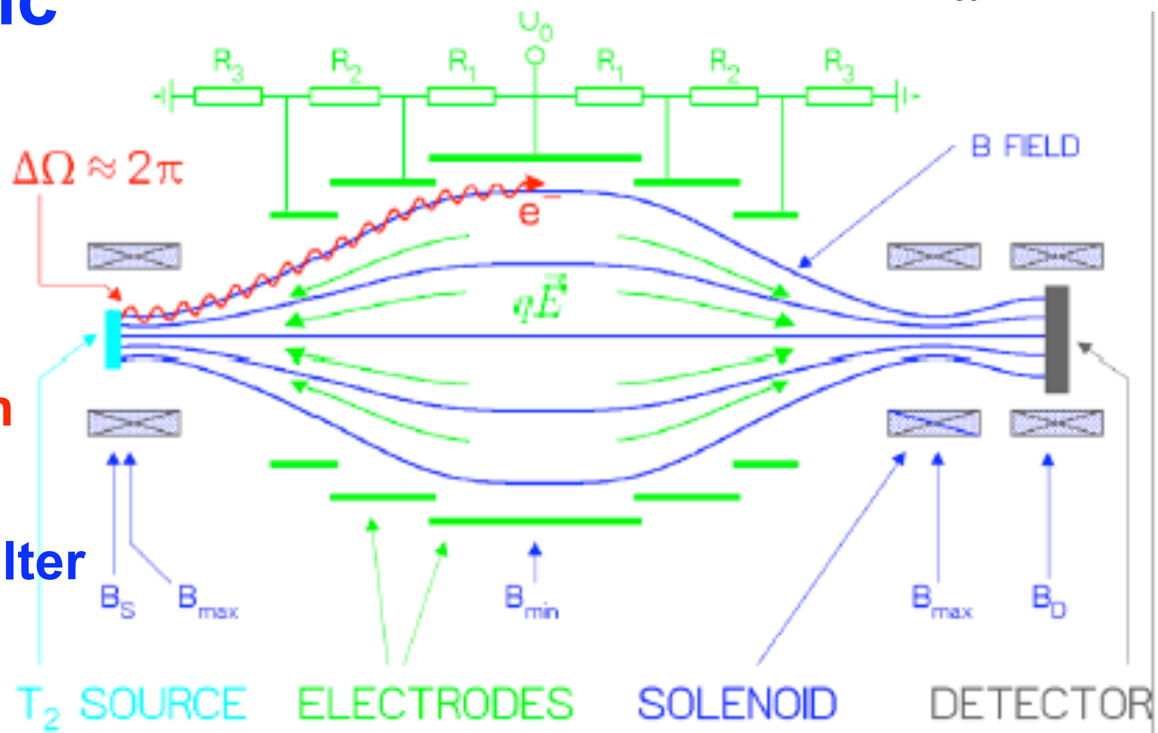
The MAC-E Filter

- Magnetic Adiabatic Collimation followed by an Electrostatic Filter

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

- High luminosity
- Low background
- Good energy resolution

- Integrating high-pass filter

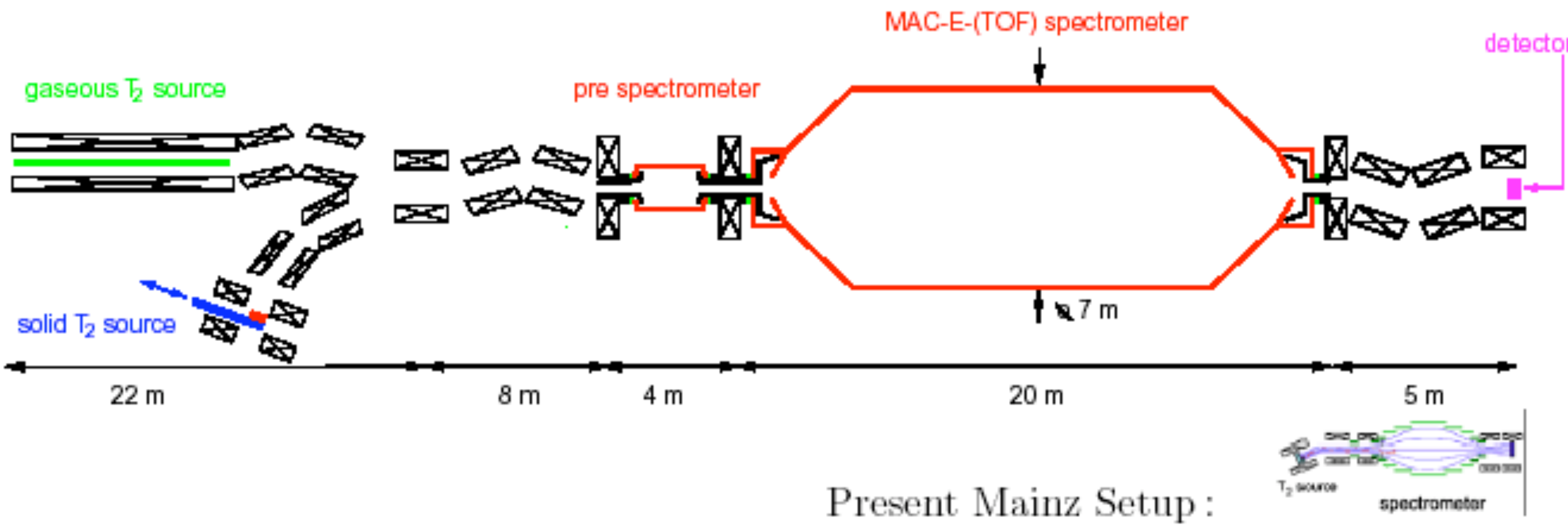


KATRIN LOI

KATRIN

- **1-eV resolution (x4 better) - larger spectrometer**
- **Longer run time**
- **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 200 meV. Thus if the m_i follow a degenerate pattern and m_1 is within the sensitivity, the experiment may see $\langle m_\beta \rangle = m_1$.

It is very big and heavy ⇒ a 8500 km long detour

Arrival of the Main Spectrometer Vessel: October 2006

A summary of the questions

- Are neutrinos Majorana or Dirac?
- What is the absolute mass scale?
- How small is θ_{13}?
- How maximal is θ_{23}?
- Is there CP violation in the neutrino sector?
- Is the mass hierarchy inverted or normal?
- Is the LSND evidence for oscillation true? Are there sterile neutrinos? Do we know the answer to this yet?

Extra Slides

References

- **Elliott & Vogel; Elliott & Engel**

  Recent reviews, many references

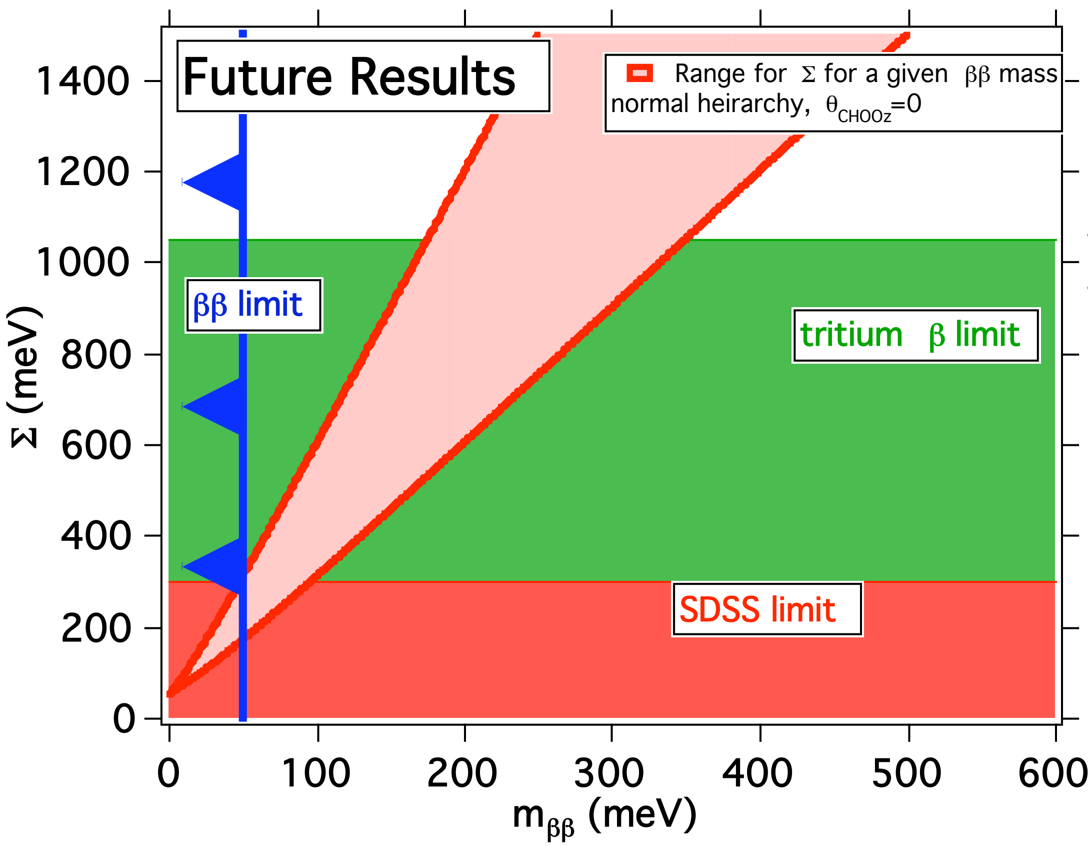
- **Haxton & Stephenson**

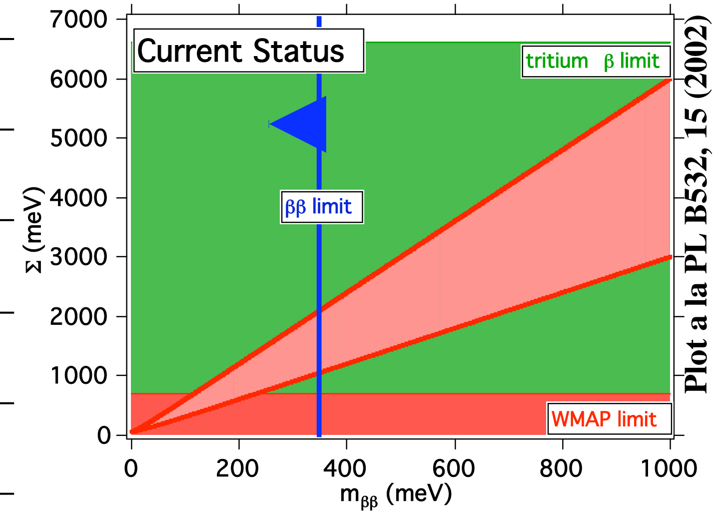
  Classic paper

References

- **Katrin LOI**
- **Lobashev *et al*. PL B460 (1999) 227**
- **Weinheimer *et al*. PL B460 (1999) 219**
- **Bilenky Review**
- **hep-ph/0211462 v3**

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





Absolute scale measures

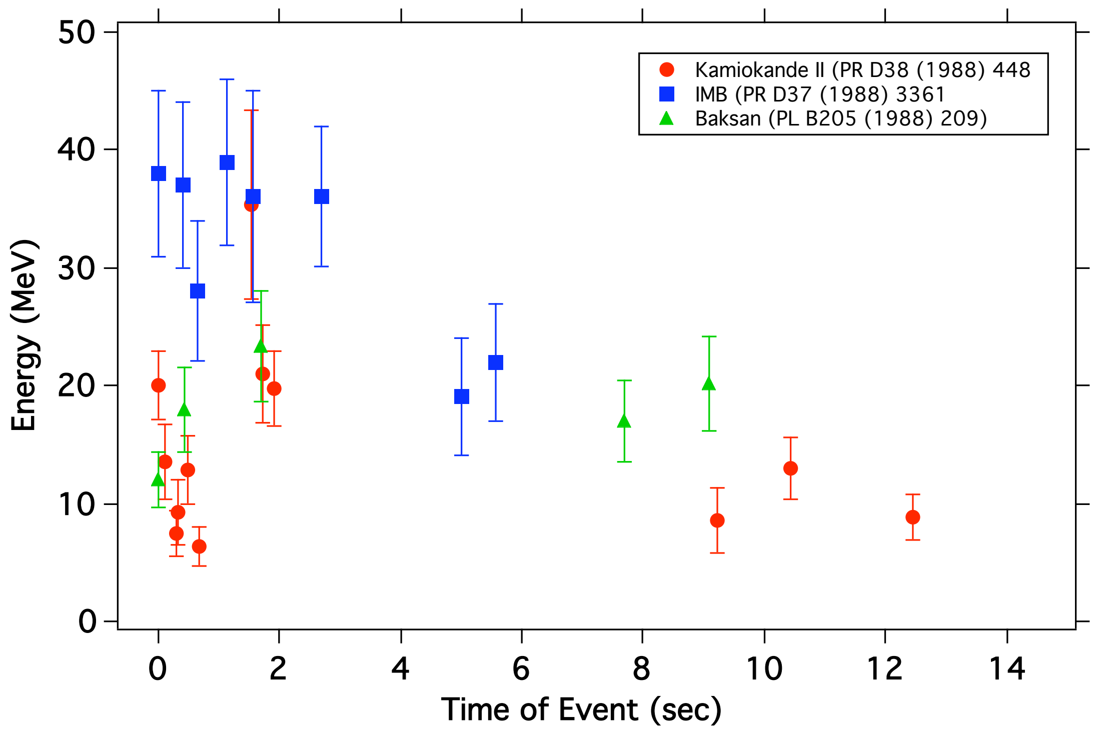
β: 350 meV

ββ: 50 meV

Cosmology: <100 meV

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.**



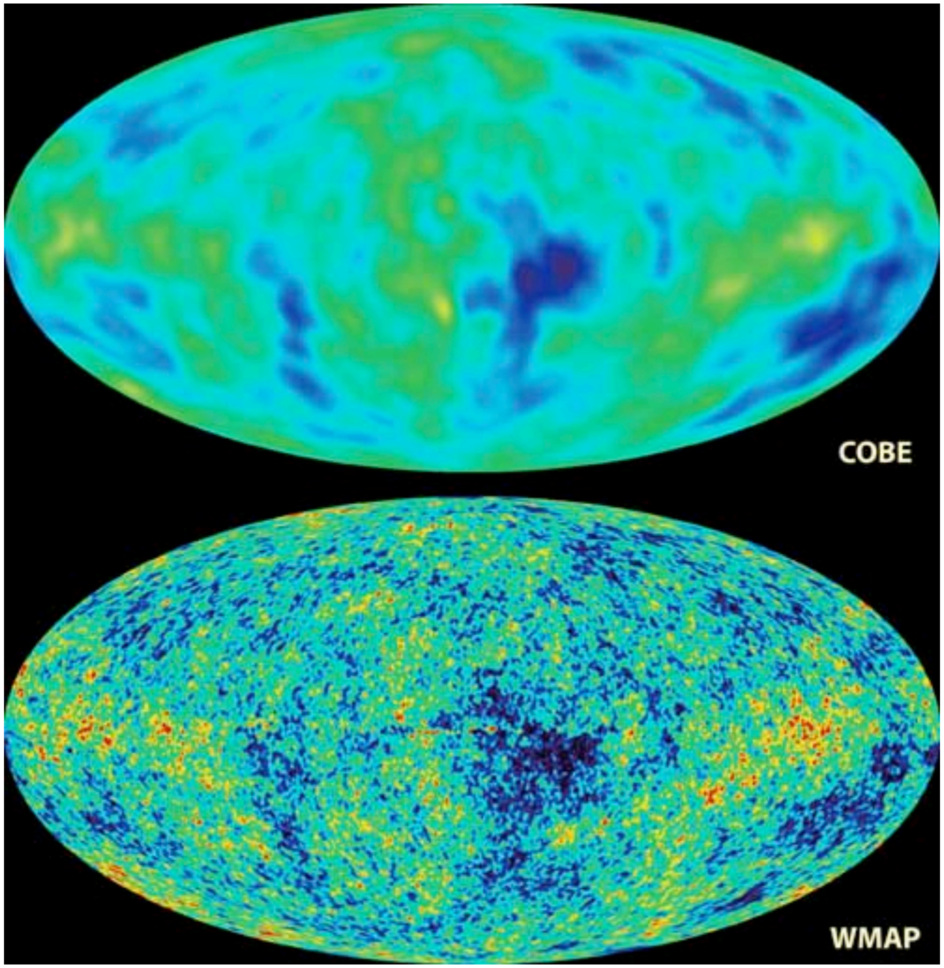
But Earth effects might be exploited for θ_{13} and sgn(δm^2) measurments

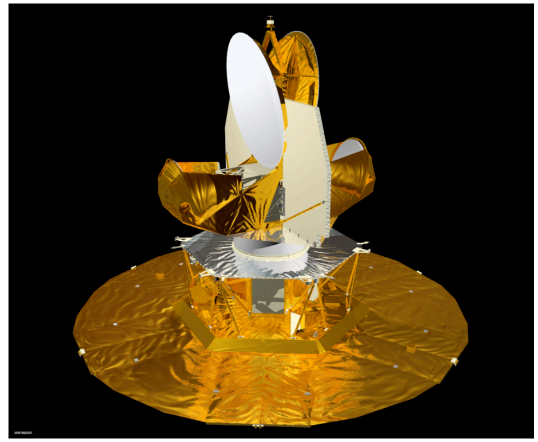
Supernova ν Experiments

Detector	Type	Mass (kton)	Location	# events at 10 kpc	status
Super-K	H_2O Cerenkov	32	Japan	7000	Running
SNO	Heavy Water (salt)	1.4 H_2O / 1 D_2O	Canada	350, 450	Stopped
LVD	Scintillator	1	Italy	200	Running
KamLAND	Scintillator	1	Japan	300	Running
Borexino	Scintillator	0.3	Italy	100	Soon?
Baksan	Scintillator	0.33	Russia	50	Running
MINIBooNE	Scintillator	0.7	USA	200	Running
AMANDA	Ice	M_{eff} ~ 0.4/PMT	South Pole	N/A	Running
Icarus	Liquid Ar	2.4	Italy	250	Soon
OMNIS	Pb, Fe	4, 1	USA	2000	Proposed
LANNDD	Liquid Ar	70	USA	6000	Proposed
UNO	H_2O Cerenkov	600	USA	>100,000	Proposed
Hyper-K	H_2O Cerenkov	1000	Japan	>100,000	Proposed
LENA	Scintillator	30	Europe	15,000	Proposed

Table aby Scholberg (NESS)

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. (one interpretation claims $\Sigma m_i = 0.64$ eV!)
- But, correlations between parameters result in assumption dependent 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.

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

- 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

- **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

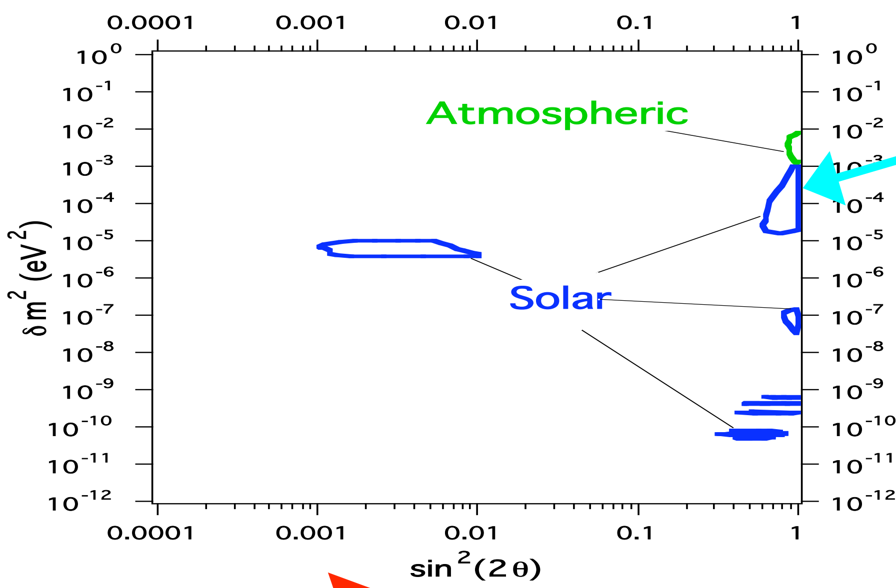
Why is m_ν interesting?

- **Neutrino mass is physics beyond the standard model of particle physics. The mass and mixing provides clues to the underlying structure of particle physics.**

- **Neutrino mass and mixing play an important role in astrophysics and cosmology.**
  - **light nuclei formation in big bang**
  - **large scale structures in the universe**
  - **supernova explosion dynamics**
  - **R-process production of nuclei**
  - **dark matter**

The Relative m_ν Scale

$$\delta m^2 = m_2^2 - m_1^2$$



LMA:

This region is preferred by the solar ν and KamLAND results.

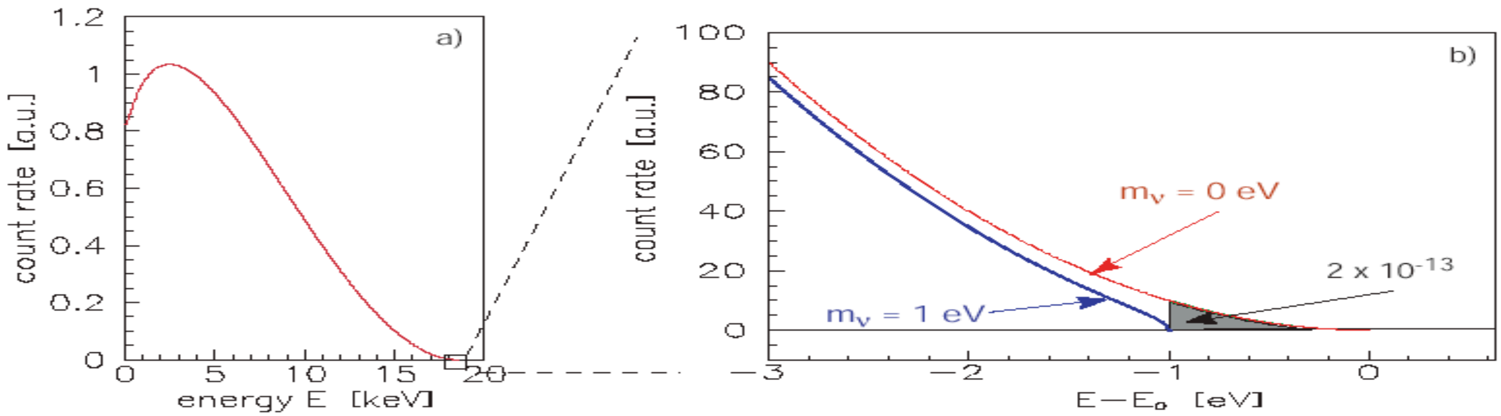
Related to $U_{\alpha i}$

$$\delta m^2_{atm} \approx 2.4x10^{-3}\, eV^2 = (49\ meV)^2$$

$$\delta m^2_{LMA} \approx 8x10^{-5}\, eV^2 = (9\ meV)^2$$

The Neutrino Mass from β decay

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

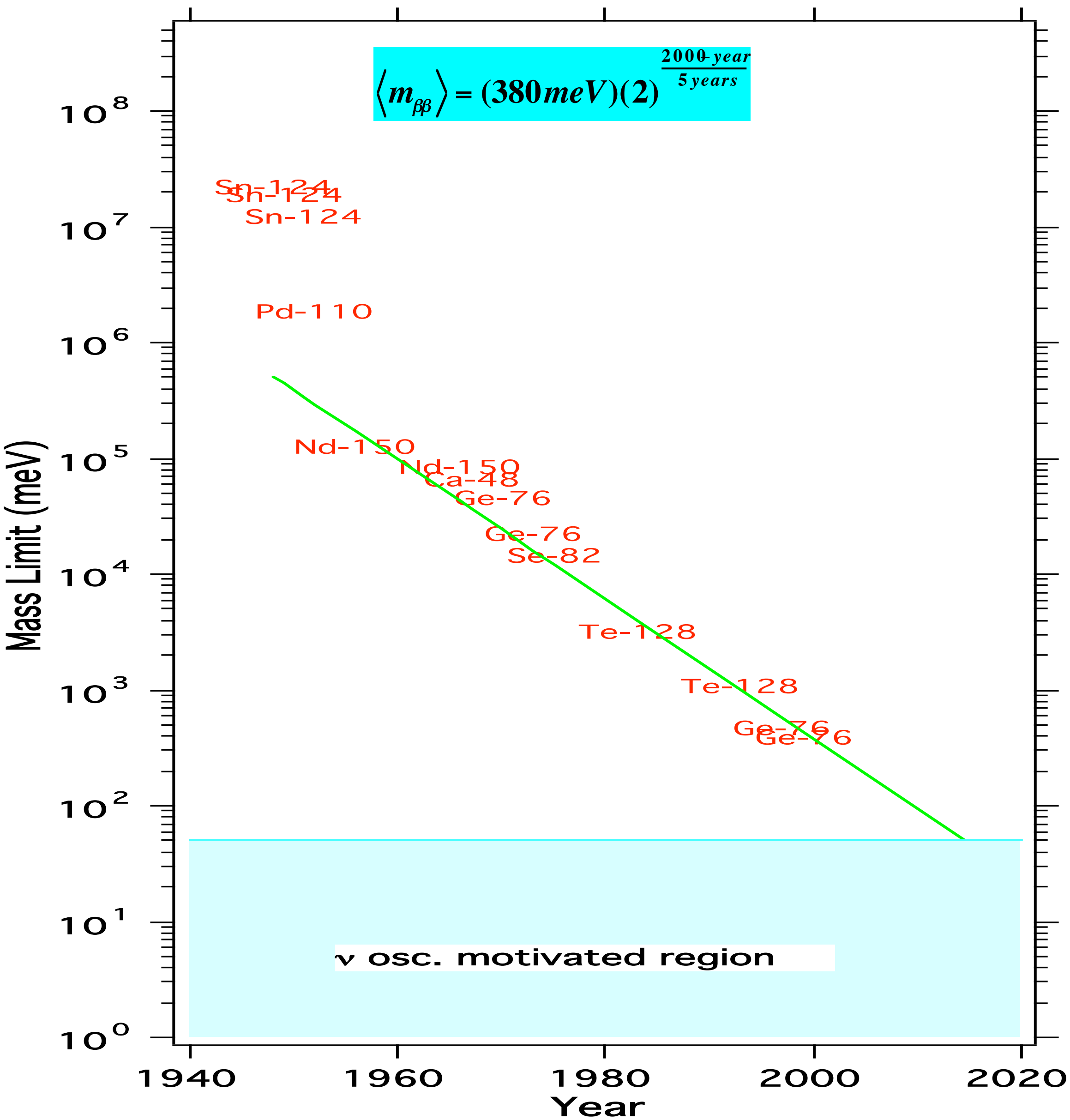


KATRIN LOI

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

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

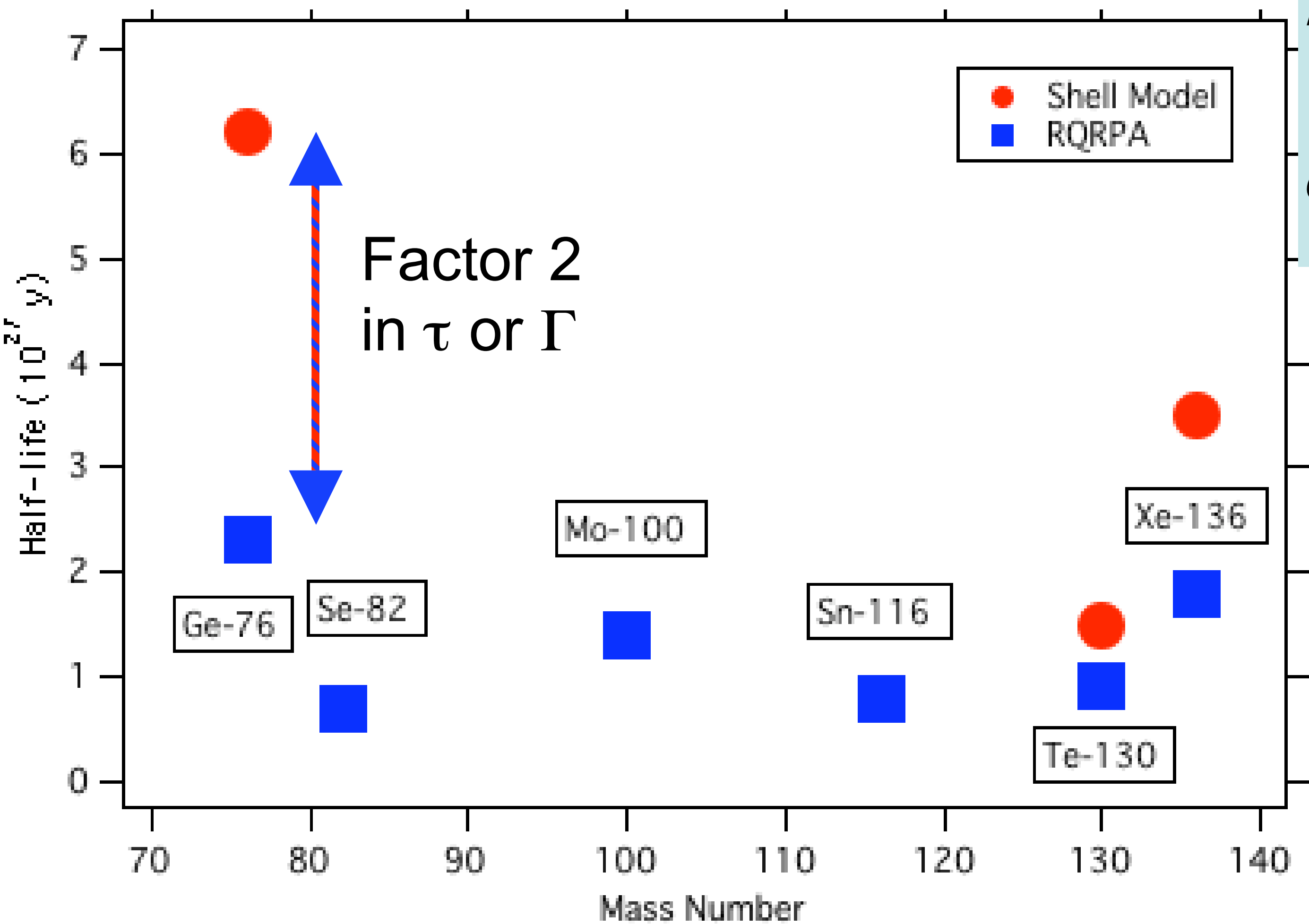
$<m_{\beta\beta}>$ History



|M| Reference
Eur. Lett. 13, 31 (1990)

Presently
$<m_{\beta\beta}> < 300$ meV

RQRPA* and Shell Model Predictions

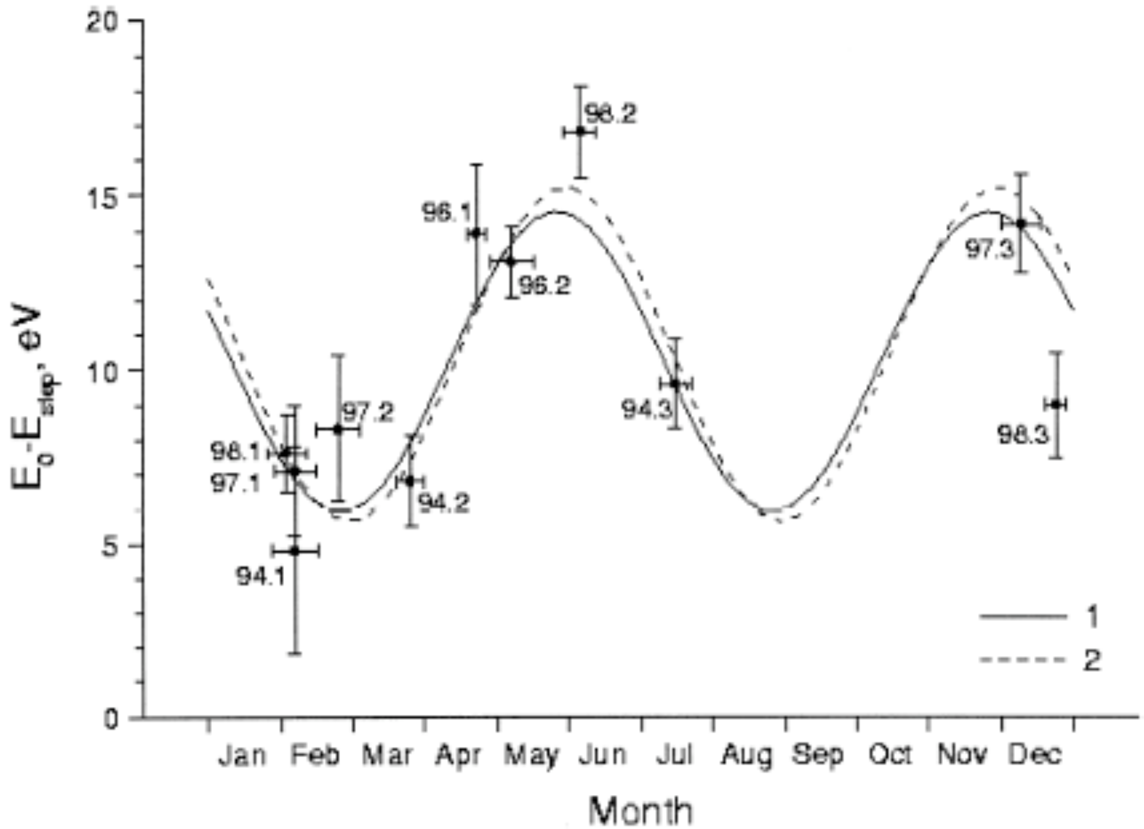


$$m_{\beta\beta} \approx \sqrt{\Gamma}$$

$$\partial m_{\beta\beta} \approx \frac{1}{2}\partial\Gamma$$

*renormalized quasiparticle random phase approximation

Troisk Anomaly



A "peak" shifting periodically in time would match the data.

In a integrating spectrum, a peak would appear as a step.