Experimental Prospects for Direct Measurements of Neutrino Mass (Tritium Experiments)

Outline

Directness?

The Various Techniques: for completeness

Astrophysics/Cosmology (very short)

Nuclear and Particle Physics: heart of the talk

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.
- 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".

Neutrino Mass: What do we want to know?

Mass

Relative Mass Scale

Absolute Mass Scale

Dirac or Majorana

ν_e ν_1 ν_2 ν_3

Mixing

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**
- **ββ decay - hope to reach below 50 meV**
- **oscillations - great sensitivity to mass differences**

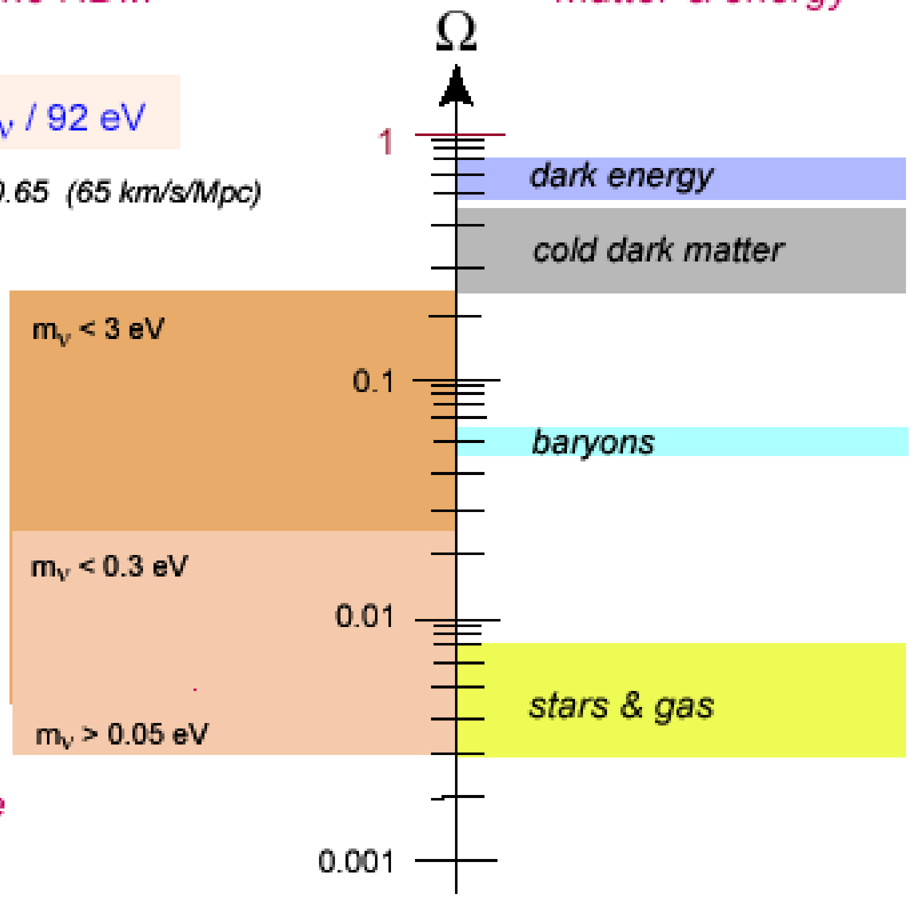
Matter Content of Universe

neutrino HDM

matter & energy

$\Omega_\nu h^{\leq} = \Sigma m_\nu / 92$ eV

Hubble Parameter $h = 0.65$ (65 km/s/Mpc)



$\Omega_\nu < 0.25$

structure formation
tritium experiments

$\Omega_\nu < 0.025$

KATRIN

$\Omega_\nu > 0.003$

Super-Kamiokande

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.

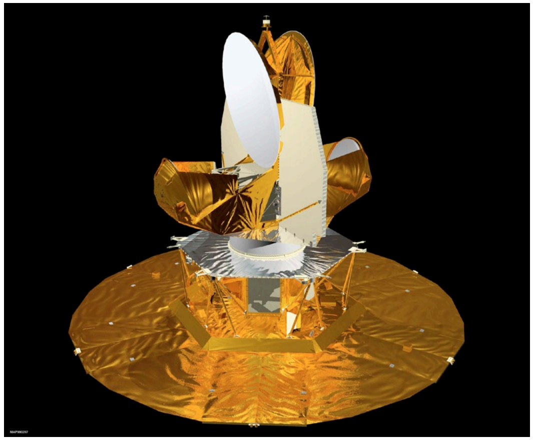
But Earth effects might be exploited for θ_{13} and sgn(δm^2) measurments

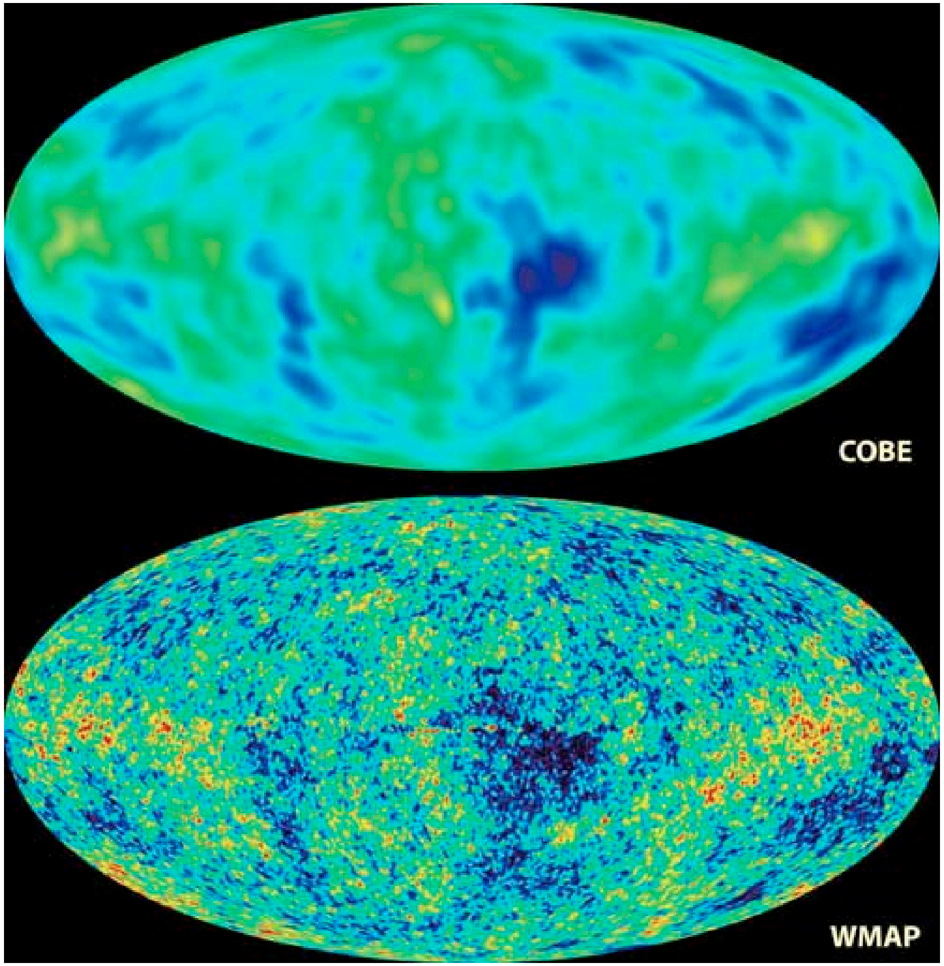
Supernova ν Experiments

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	Running
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	$M_{eff} \sim 0.4$/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): $\Sigma m_i < \sim 300$ meV

If weak lensing by LSS is also considered:

$\Sigma m_i < \sim 40$ 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 ($5\text{x}10^{19}$ 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.

Nuclear and Particle Physics Techniques

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

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

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Eur. Phys. J. C2 (1998) 3

Nuclear and Particle Physics Techniques

μ decay: π --> μ + ν

PR D53 (1996) 6065

The β Spectrum (bare nucleus)

Fund. Constants

Energy-independent Matrix Element

Fermi Function

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

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: $<m_\beta>$.

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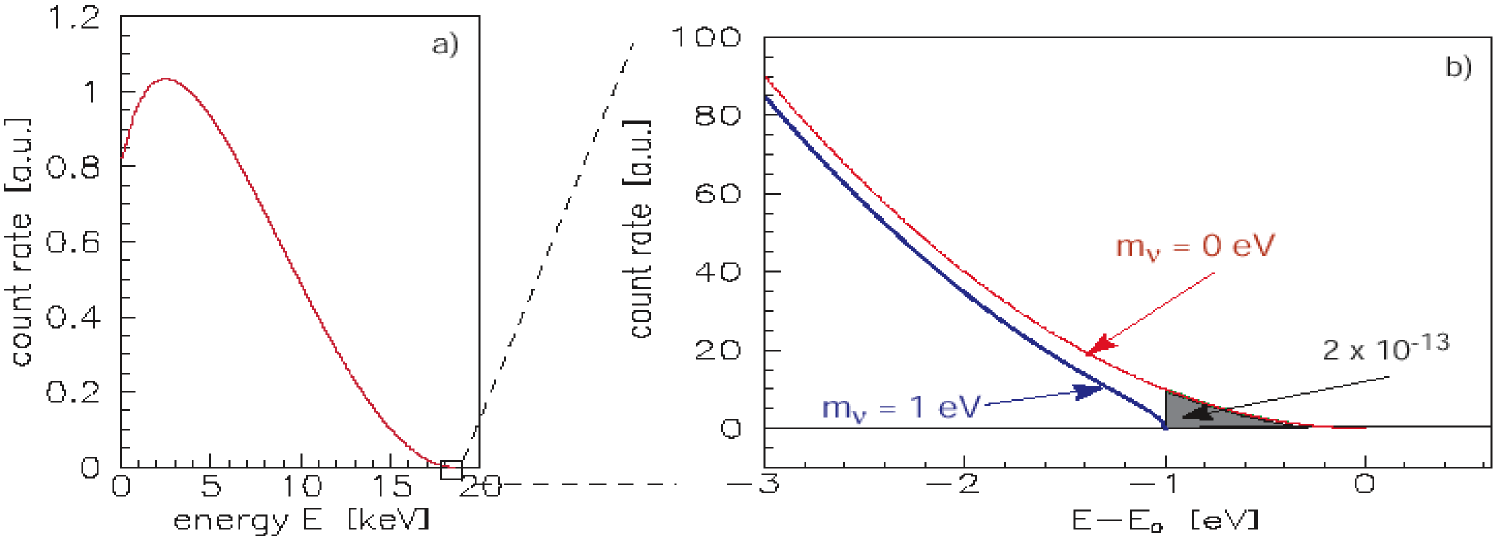
The Neutrino Mass from β decay

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



KATRIN LOI

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

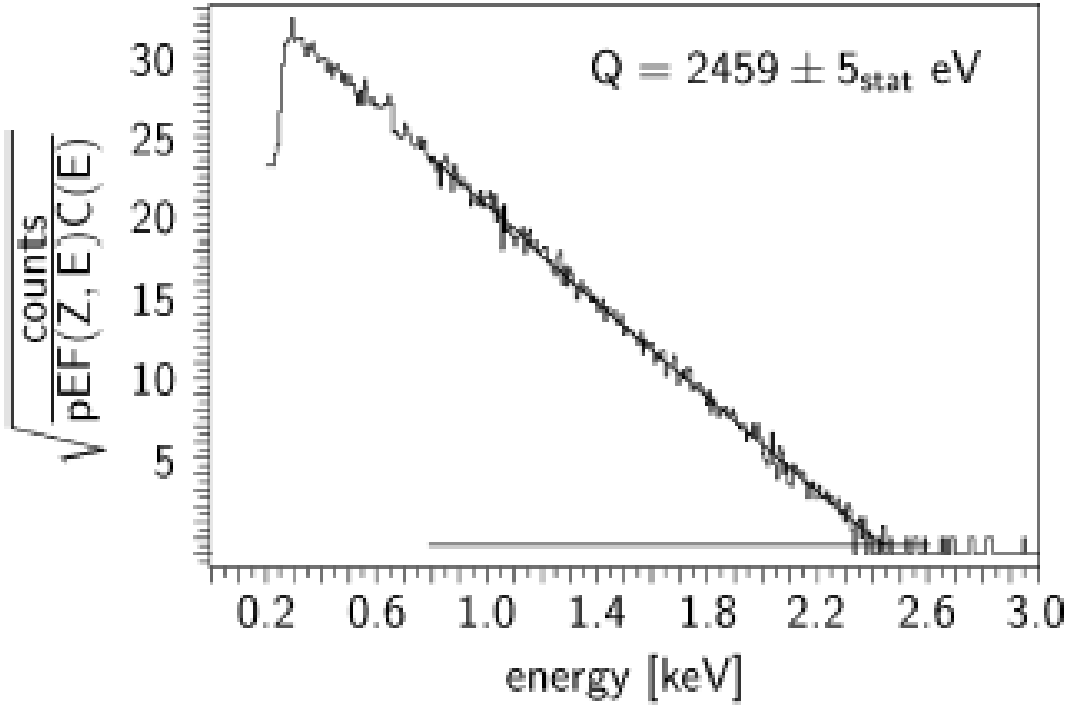
^{187}Re β Decay Experiments

- 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

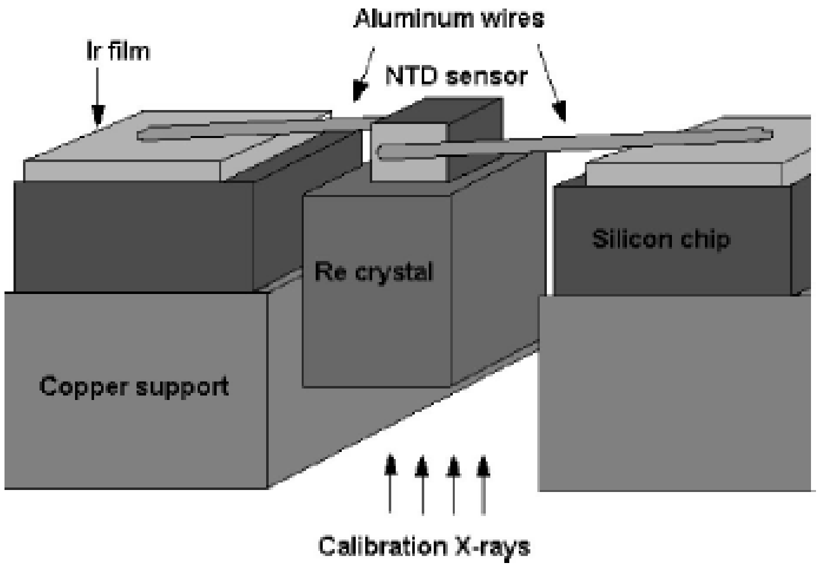
$AgReO_4$

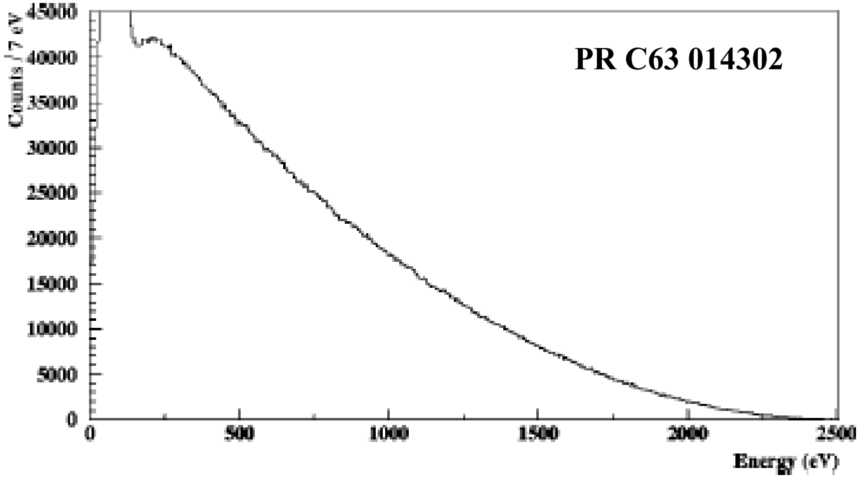
Hope for a sensitivity of 4 eV



NIM A444 (2000) 77

Genoa Re Experiment





PR C63 014302

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

Why Tritium?

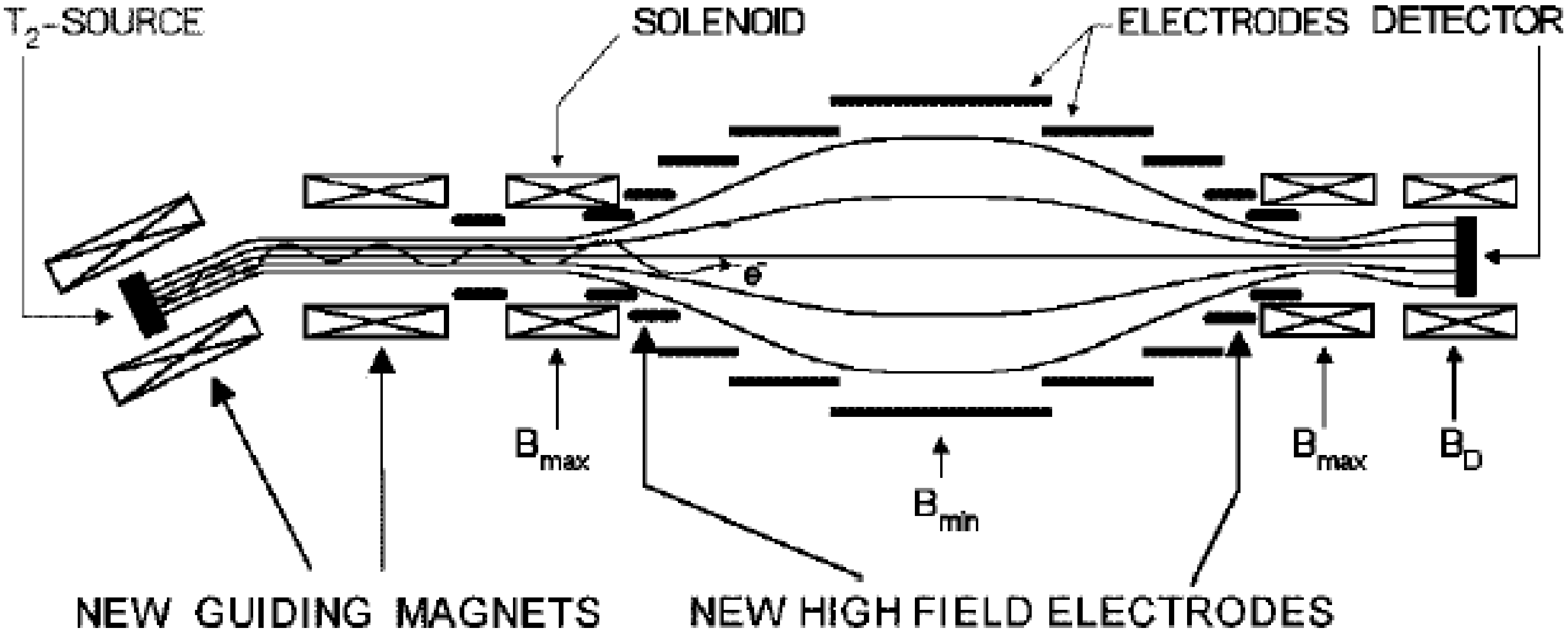
- Re bolometers (source = detector) collect whole spectrum at once: therefore need low rate to prevent pile-up.

- 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

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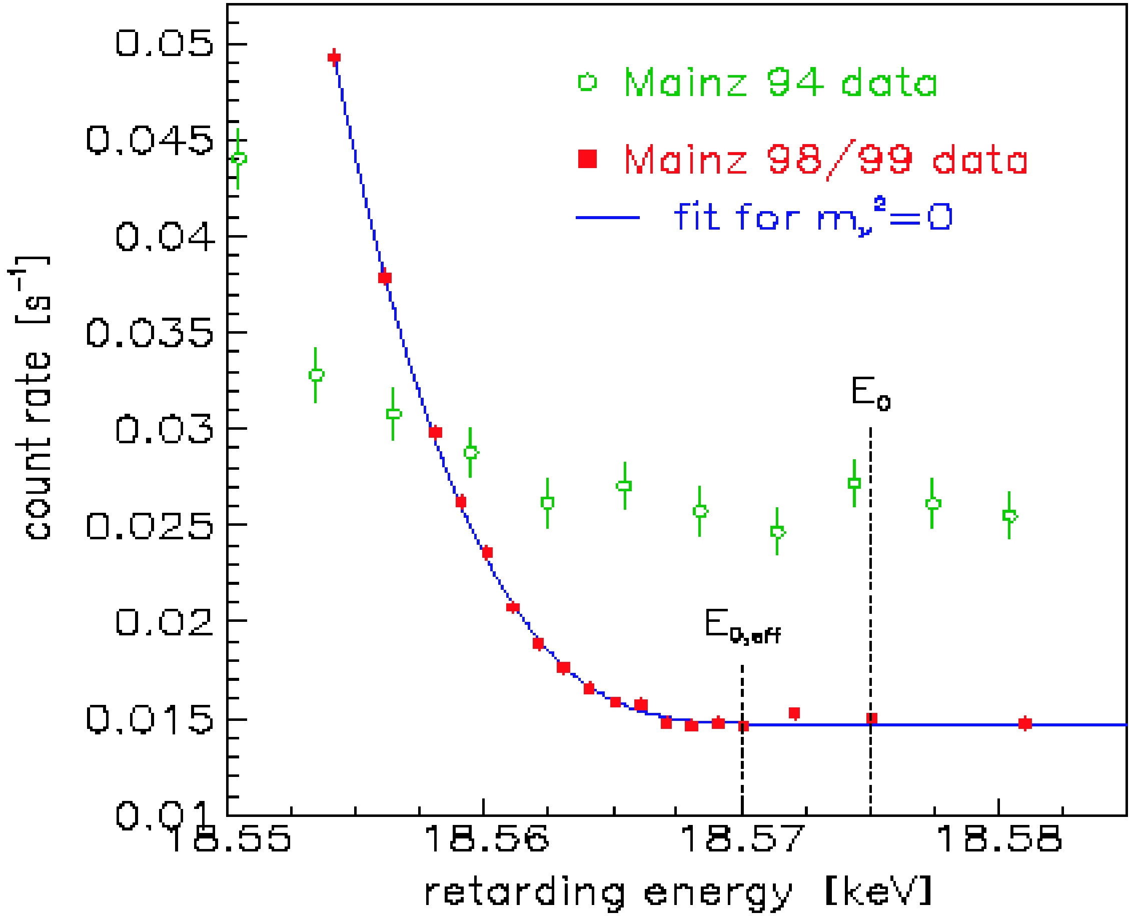
ΔE ~2-6 eV at 20 keV
Large acceptance
10-40% of 4π



<u>Improvements 94-98</u>

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

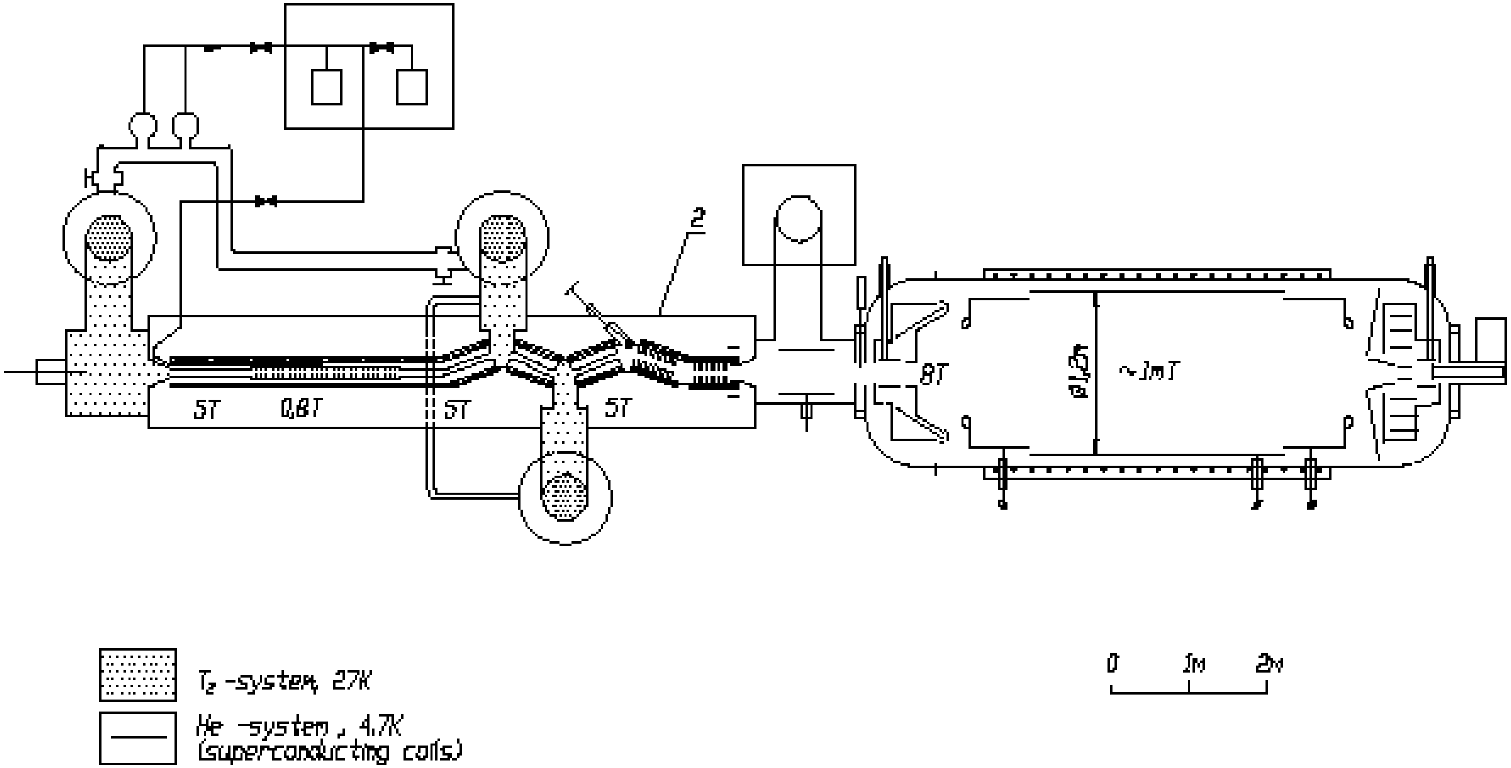
Neighbor molecule excitation

Final states in THe^+ molecule

Charging of source film

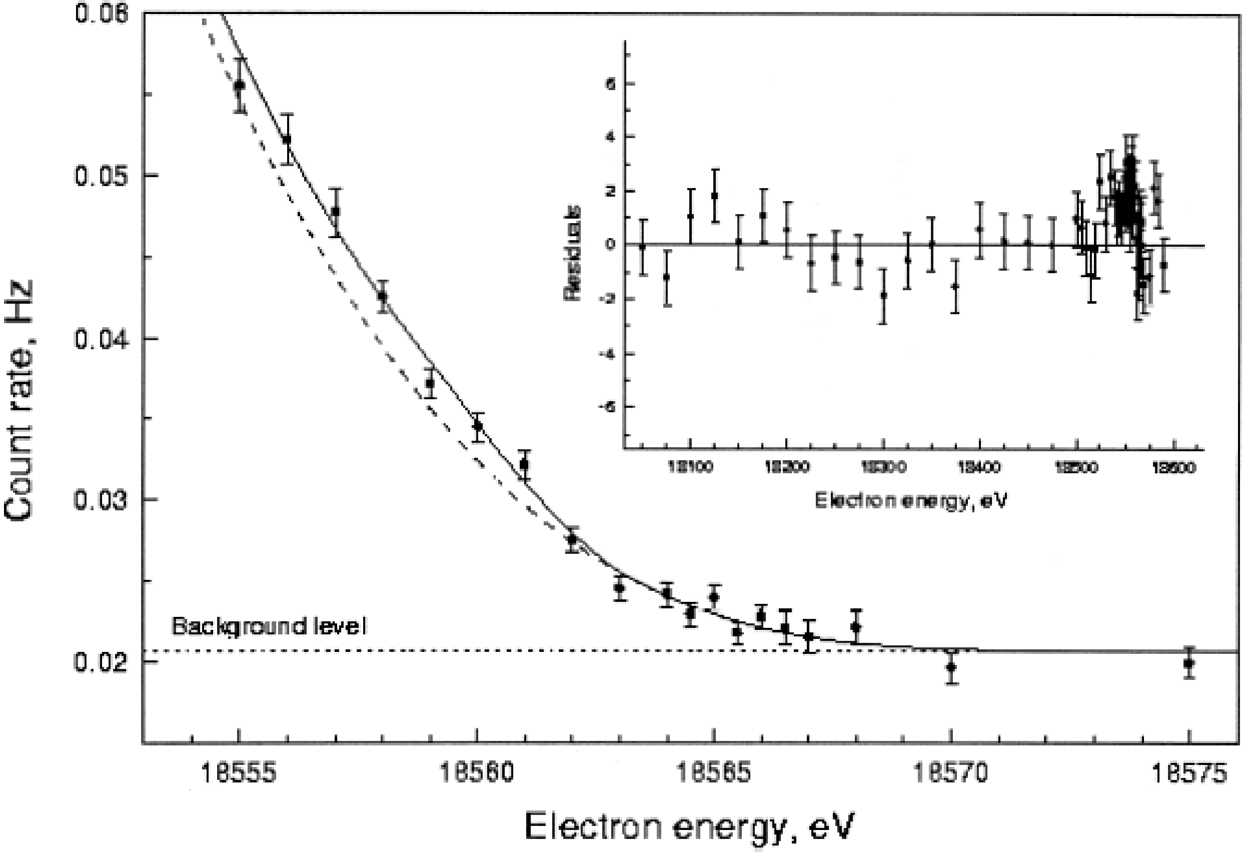
Statistical Systematic

The Troisk Experiment



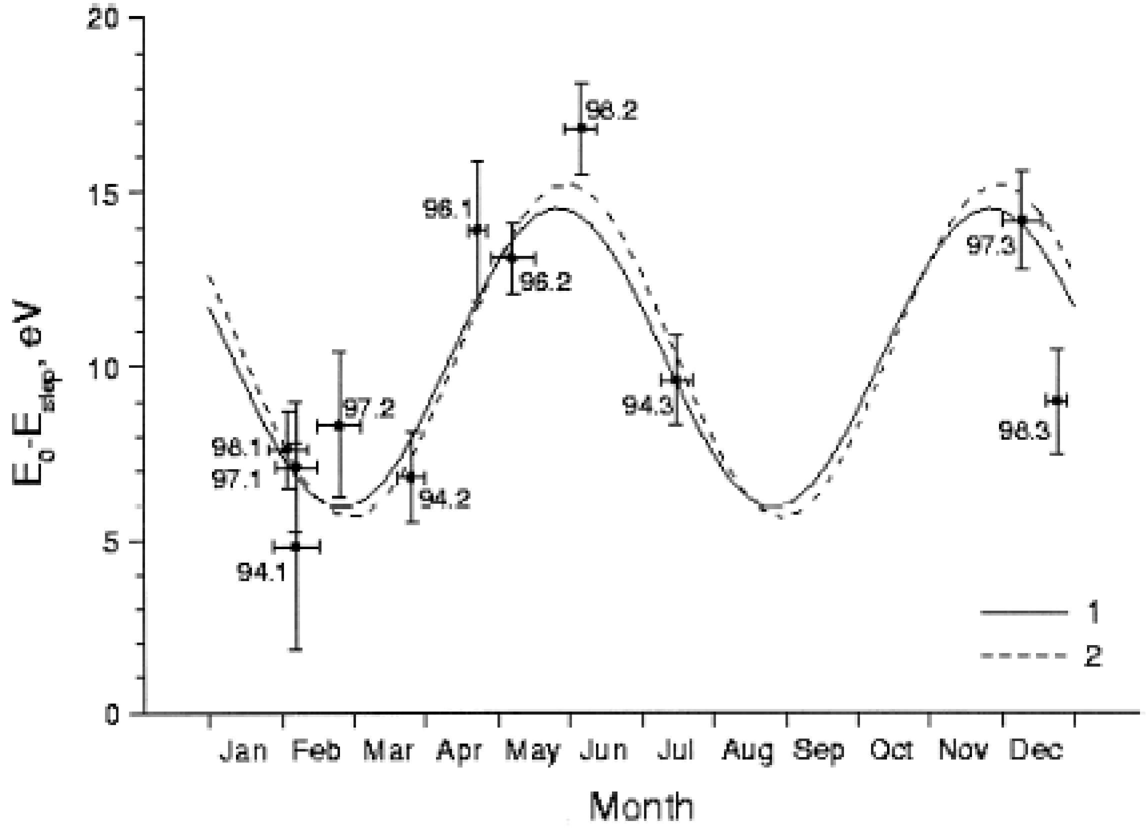
Troisk Results

Solid line is spectrum with step funcion.



PL B 460, 227 (1999)

Troisk Anomaly



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

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

Identifying the Systematics

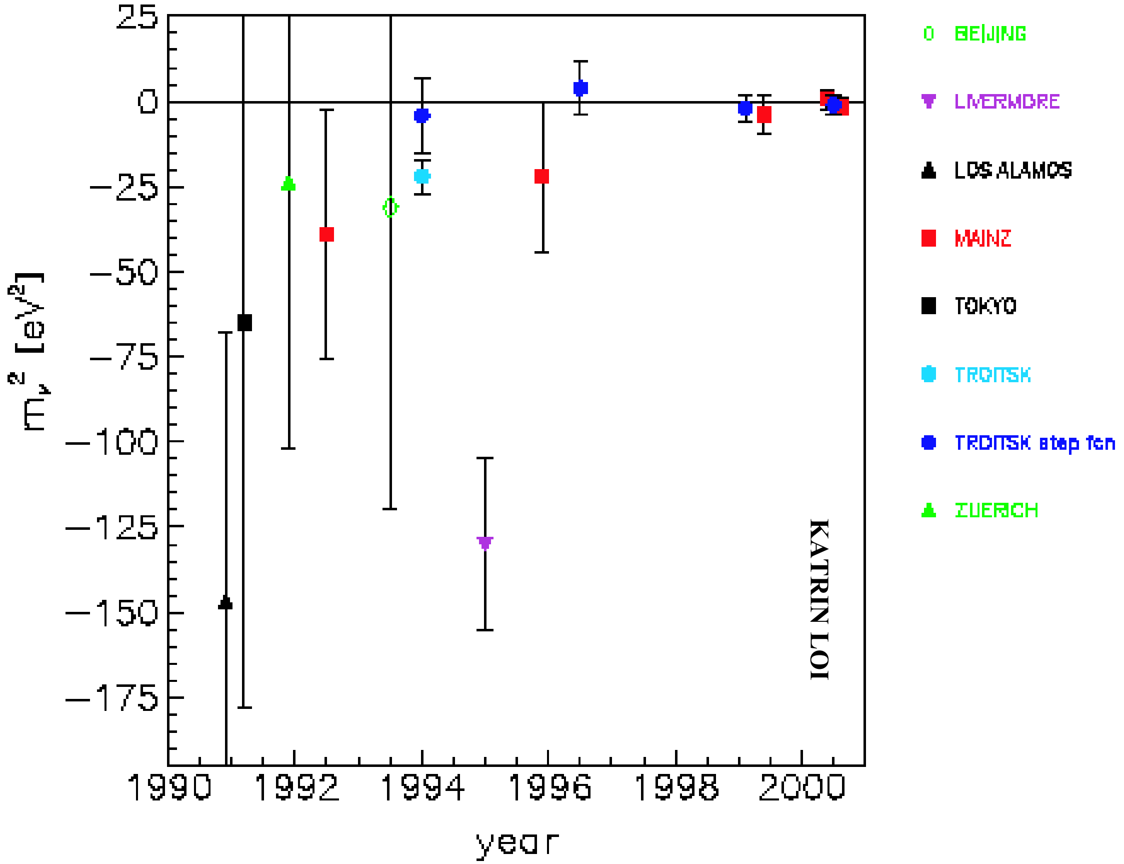
Mainz: tritium as thin film on flat surface. Temperature activated roughening led to microcrystals in turn leading to large inelastic scattering.

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



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

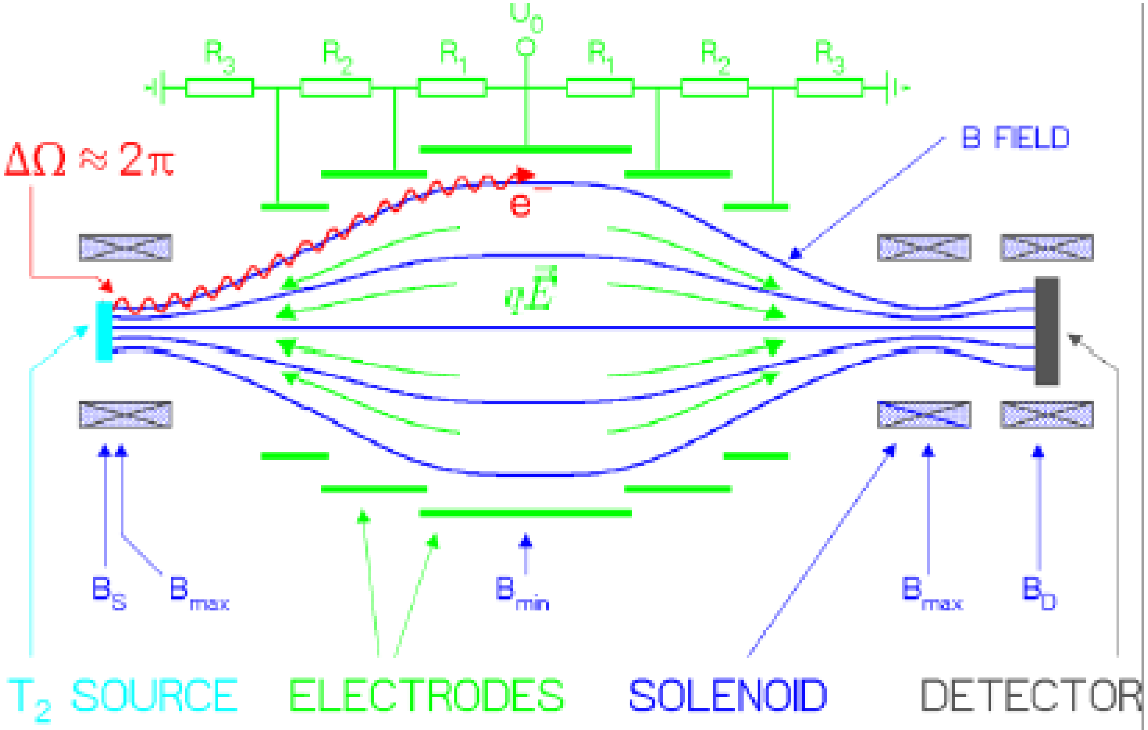
Magnetic Adiabatic Collimation followed by an Electrostat Filter

High luminosity

Low background

Good energy resolution

Integrating
high-pass filter

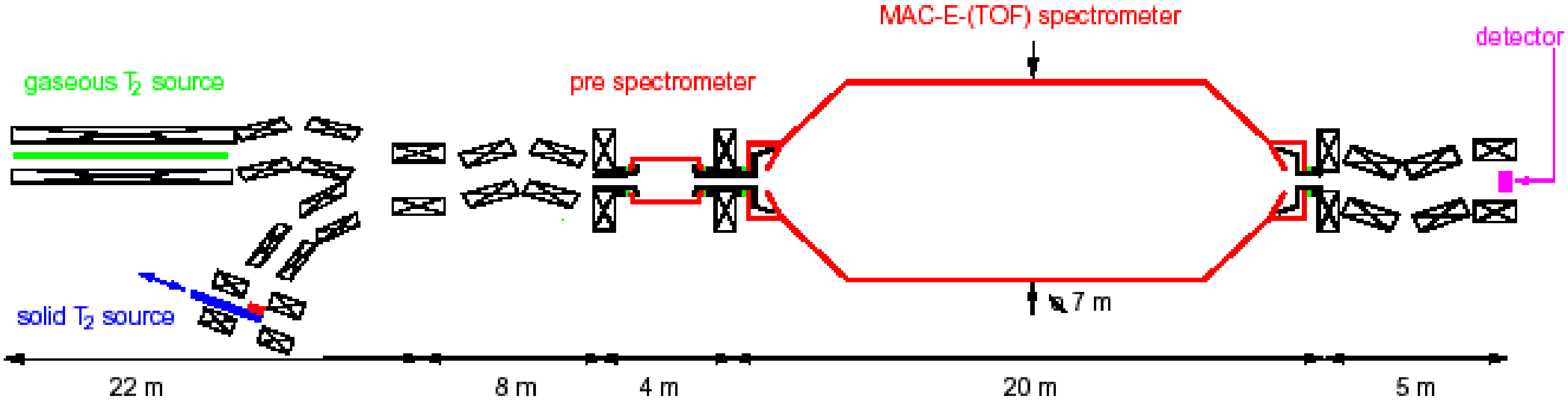


KATRIN LOI

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)



Present Mainz Setup :

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 $\langle m_\beta \rangle = m_1$.

Los Alamos
NATIONAL LABORATORY

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

Plot a la PL B532, 15 (2002)

Absolute scale measures

β: 350 meV

ββ: 50 meV

Cosmology: <100 meV

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?

References

Katrin LOI

Lobashev *et al*. PL B460 (1999) 227

Weinheimer *et al*. PL B460 (1999) 219

Bilenky Review

hep-ph/0211462 v3