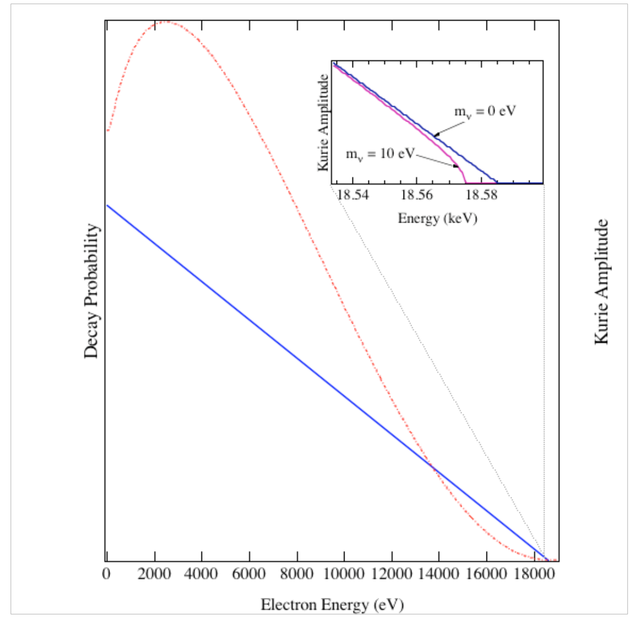
Direct ν mass measurements via beta-decay



Direct measurements of neutrino mass

- Probe of absolute mass
- ν oscillations - a major paradigm shift
- β-decay endpoint and ν mass eigenstates

Current β-decay endpoint results

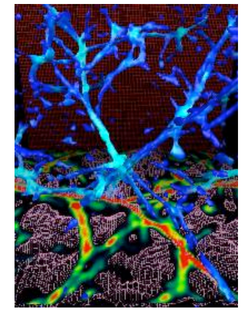
- INR - Troitsk
- Mainz

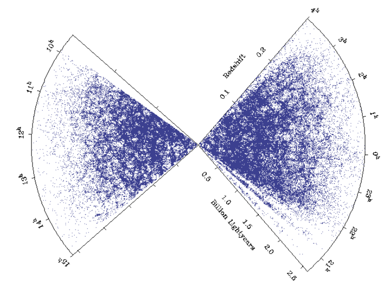
Future prospects for sub-eV sensitivities

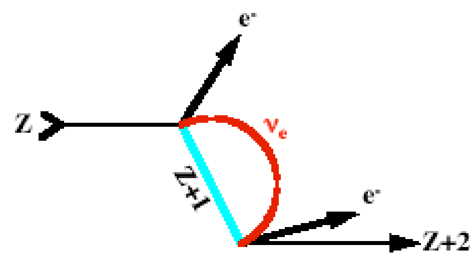
- ^{187}Re bolometers
- Karlsruhe Tritium Neutrino Experiment (KATRIN)

Probes of absolute ν mass

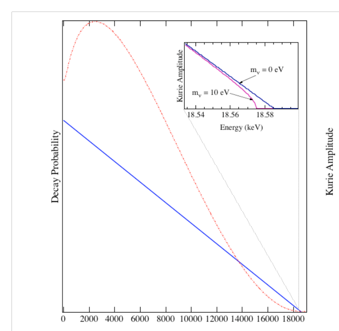
- Indirect
  - Cosmology - Hot Dark Matter
    - Galaxy clusters
    - Lyman-α forest
    - Galaxy large scale structure
  - Astrophysics
    - UHE cosmic-rays
    - Supernovae generation mechanisms
  - Neutrinoless ββ-decay







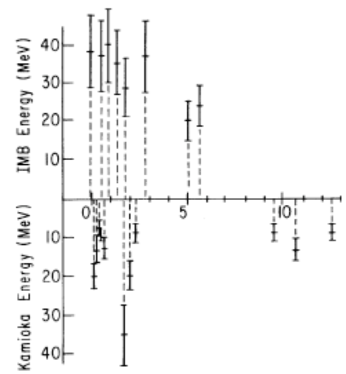
- **Direct techniques**
  - time of flight (supernovae)
  - **particle decay kinematics**



Direct measurements of neutrino mass

Techniques

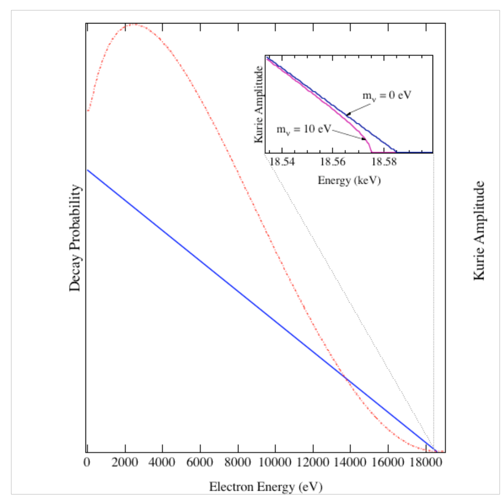
SN1987a



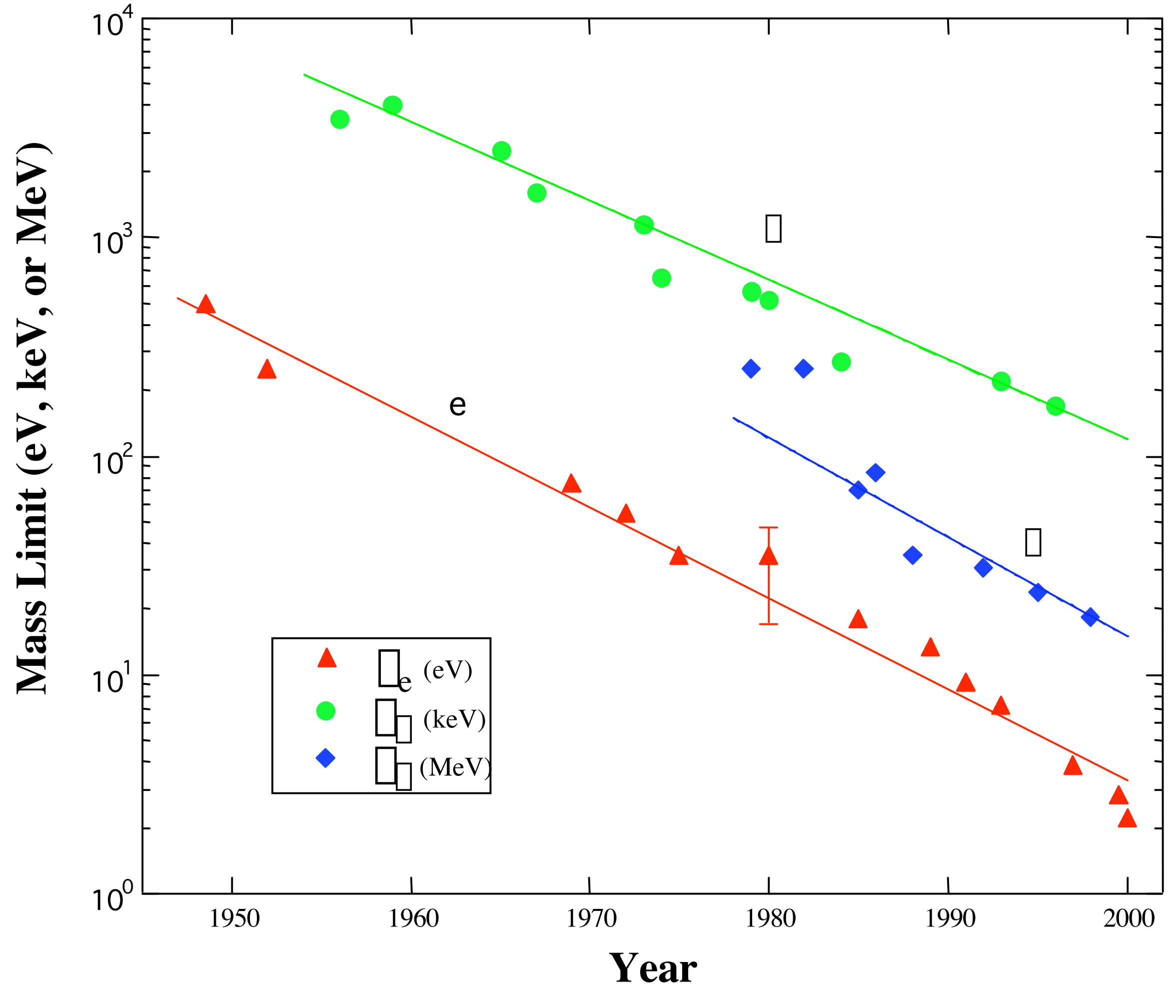
- **time of flight from supernovae**
  - not expected to reach sub-eV sensitivity

    Collapse to Black Hole: $m_{\nu} \geq 1.8$ eV (Rotation neglected)

    Beacom, Boyd, Mezzacappa PRD63 073011
  - much more likely that a direct measurement or limit will be used to help understand supernovae dynamics.
- **particle decay kinematics**
  - β-decay (and e capture) spectrum shape
  - muon momentum in pion decay
  - invariant mass studies of multiparticle semileptonic decays
  - advantages
    - purely kinematical observables
    - few, if any, assumptions about ν properties
    - free of model dependencies



Past: history of direct □ mass measurements
(□ flavor eigenstates)



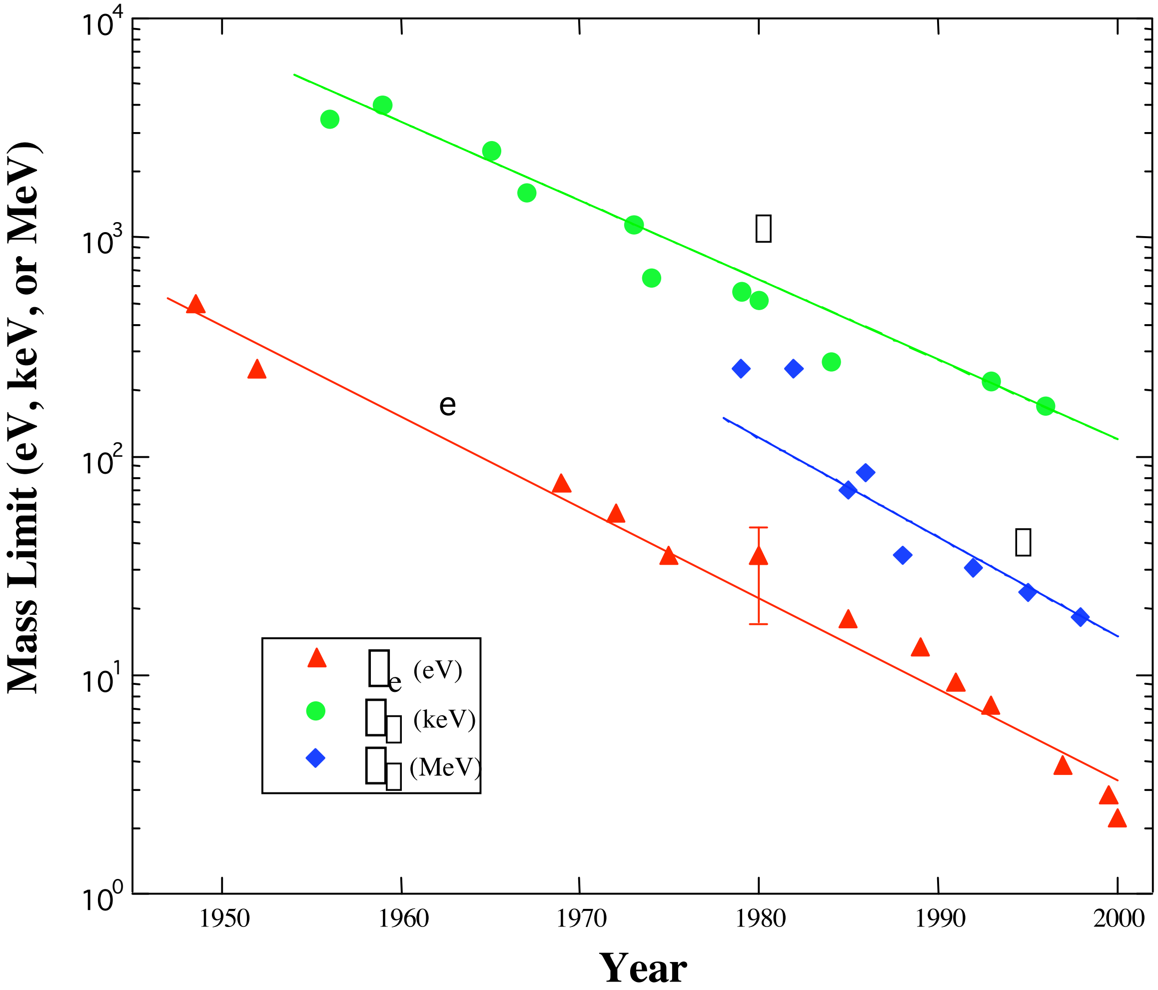
$m_{□□}$ < 170 keV (90%CL)
(PSI 1996)

$m_{□□}$ < 18.2 MeV (95% CL)
(ALEPH 1998)

$m_{□e}$ < 2.2 eV (95% CL)
(Mainz 2000)

points without error bars represent upper limits

Past: history of direct mass measurements
(flavor eigenstates)



points without error bars represent upper limits

But oscillations with large mixing angles - means one must consider direct techniques in terms of mass eigenstates!

ν mass & mixing - oscillation experiments

For a 3 neutrino scenario the lepton mixing matrix (Maki-Nakagawa-Sakata-Pontecorvo), which relates ν mass eigen-states to weak or flavor eigenstates, is:

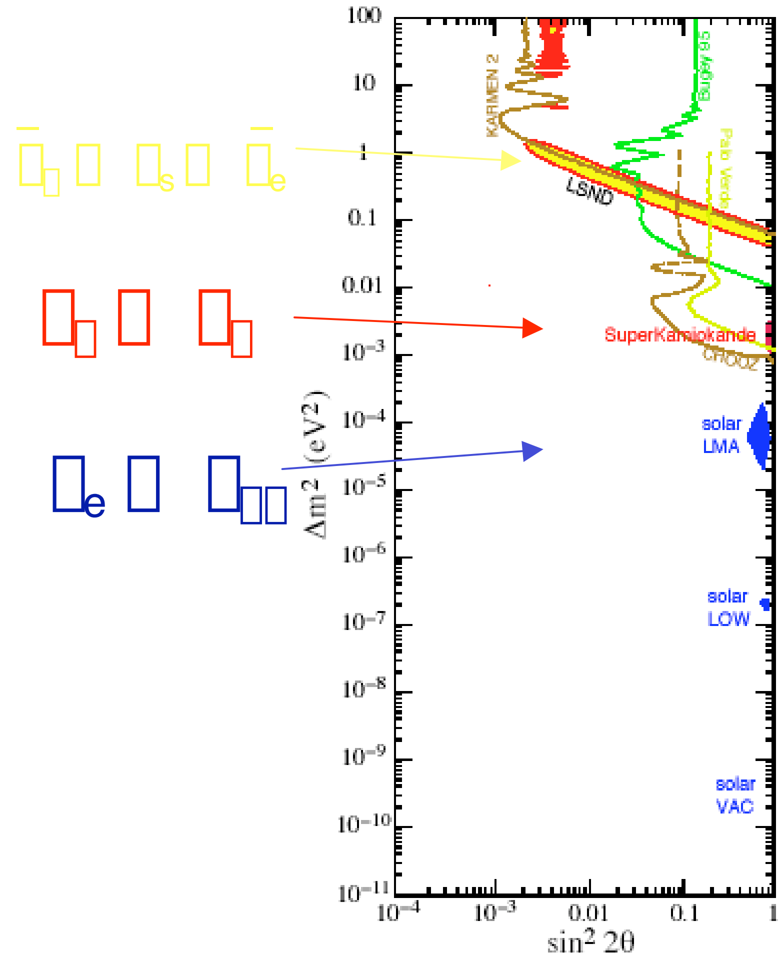
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation experiments yield mass squared differences:

$$\Delta m_{12}^2 = \left| m_{\nu_1}^2 - m_{\nu_2}^2 \right|$$

$$\Delta m_{23}^2 = \left| m_{\nu_2}^2 - m_{\nu_3}^2 \right|$$

$$\Delta m_{13}^2 = \left| m_{\nu_1}^2 - m_{\nu_3}^2 \right|$$



ν mass & mixing - oscillation experiments

Best bet for MNSP Matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \times$$

Chooz

$$\times \begin{pmatrix} \sim 1 & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \sim 1 \end{pmatrix} \times$$

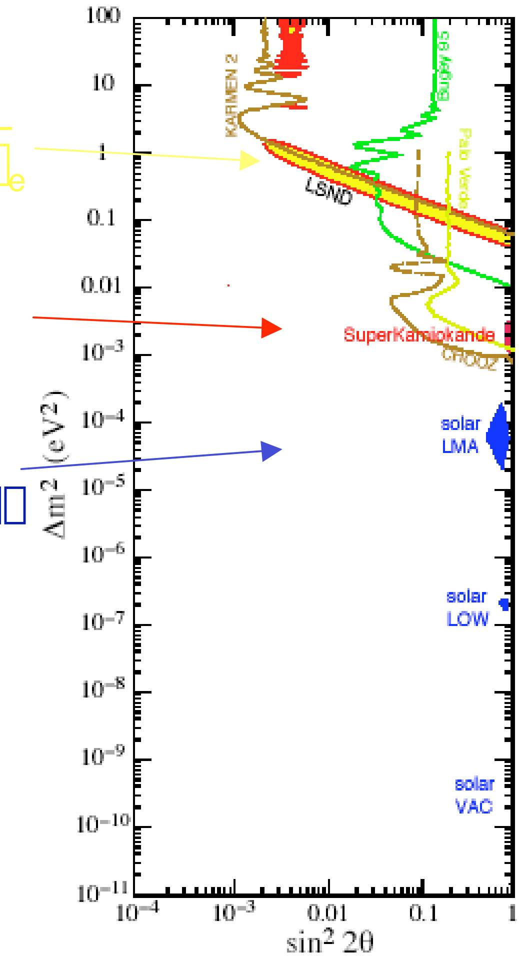
LMA

$$\times \begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\bar{\nu}_\mu \to \nu_s \to \bar{\nu}_e$

$\nu_\mu \to \nu_\tau$

$\nu_e \to \nu_{\mu\tau}$



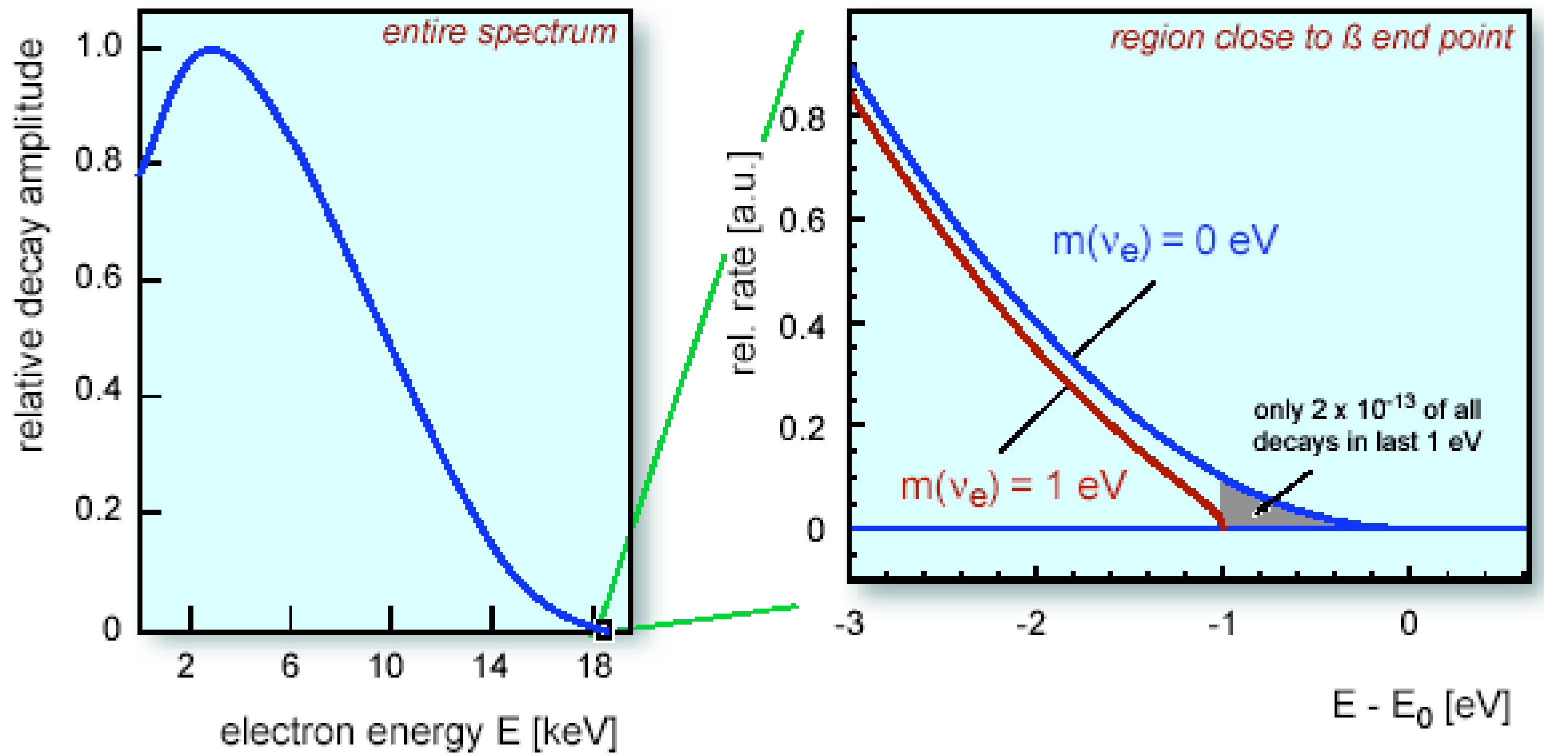
$$\nu_e = 0.85\nu_1 + 0.51\nu_2$$

$$\nu_\mu = -0.36\nu_1 + 0.60\nu_2 + 0.71\nu_3$$

$$\nu_\tau = 0.36\nu_1 - 0.60\nu_2 + 0.71\nu_3$$

□-decay endpoint measurement

Essentially a search for a distortion in the shape of the b-spectrum in the endpoint energy region



$$dN(E) = K|M|^2F(Z,R,E)\ p_eE\ (E_0\text{-}E)\ \{(E_0\text{-}E)^2\text{-}m^2_{\square e}c^4\}^{1/2}\ dE$$

β-decay in terms of ν mass eigenstates

Taking into account ν mass eigenstates, the original spectrum

$$dN(E) = K|M|^2F(Z,R,E)\ p_eE\ (E_0-E)\ \{(E_0-E)^2-m_{\nu_e}^2c^4\}^{1/2}\ dE$$

becomes

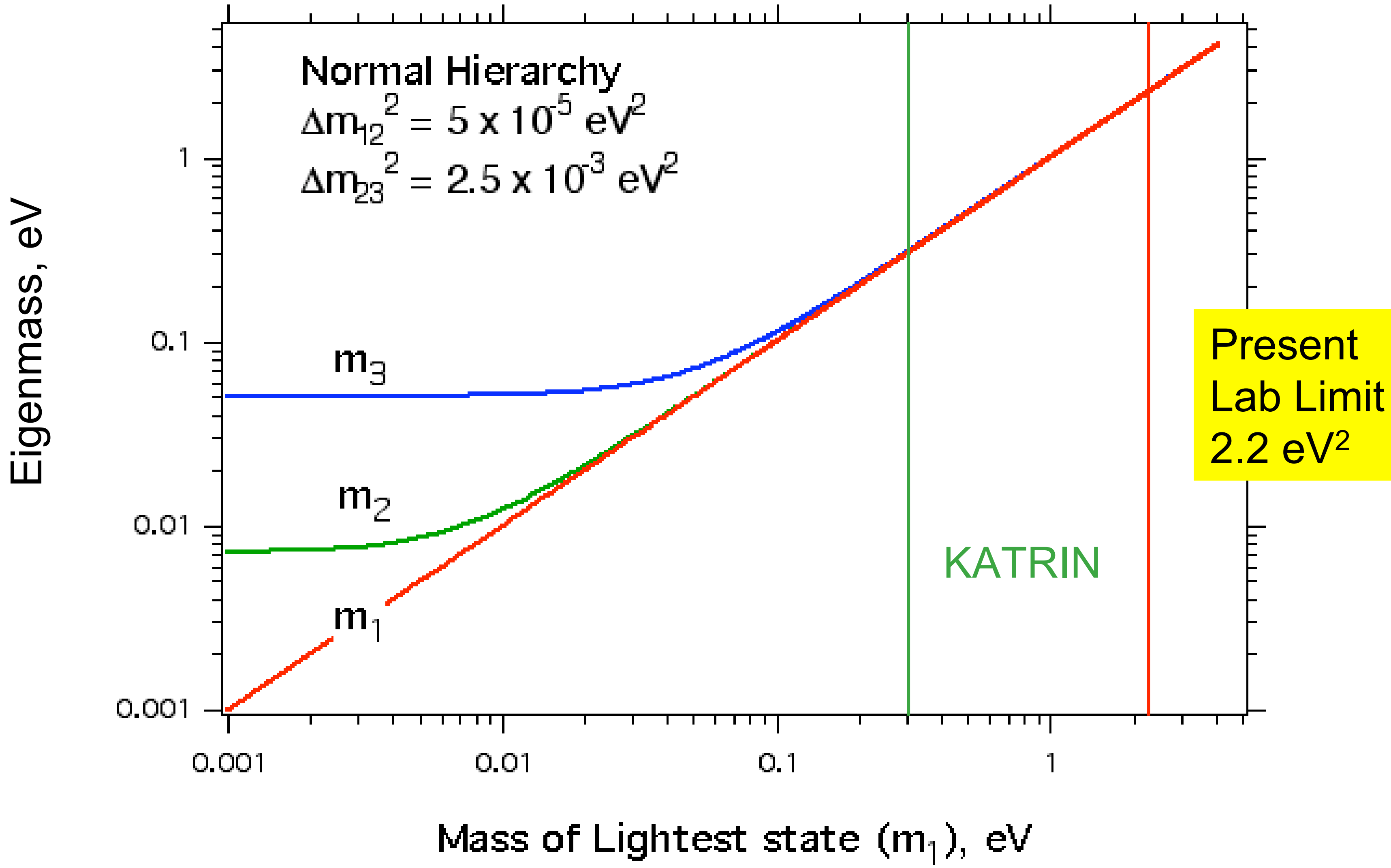
$$dN(E) = K|M|^2F(Z,R,E)\ p_eE\ (E_0-E)\ \sum_i |U_{ei}|^2\ \{(E_0-E)^2-m_{\nu_i}^2c^4\}^{1/2}\ dE$$

The observed beta spectrum shape will depend on:

- the neutrino masses
- the number of neutrino mass eigenstates
- the leptonic mixing matrix elements
- the total resolution/sensitivity of the measurement

For 3 ν mass spectrum, with degenerate states, the beta spectrum simplifies to an "effective mass" : $m_{\nu}^{2} = \sum |U_{ei}|^2\ m_{\nu_i}^2$

All masses linked to lightest by oscillations

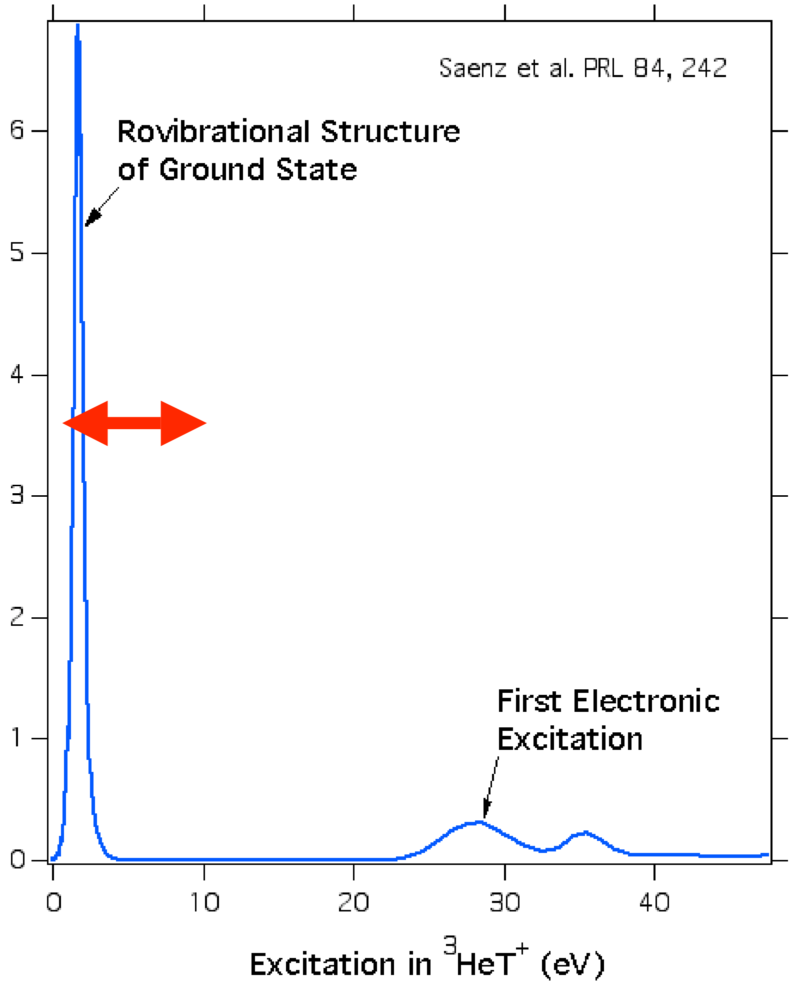


Keys to β-decay shape measurements

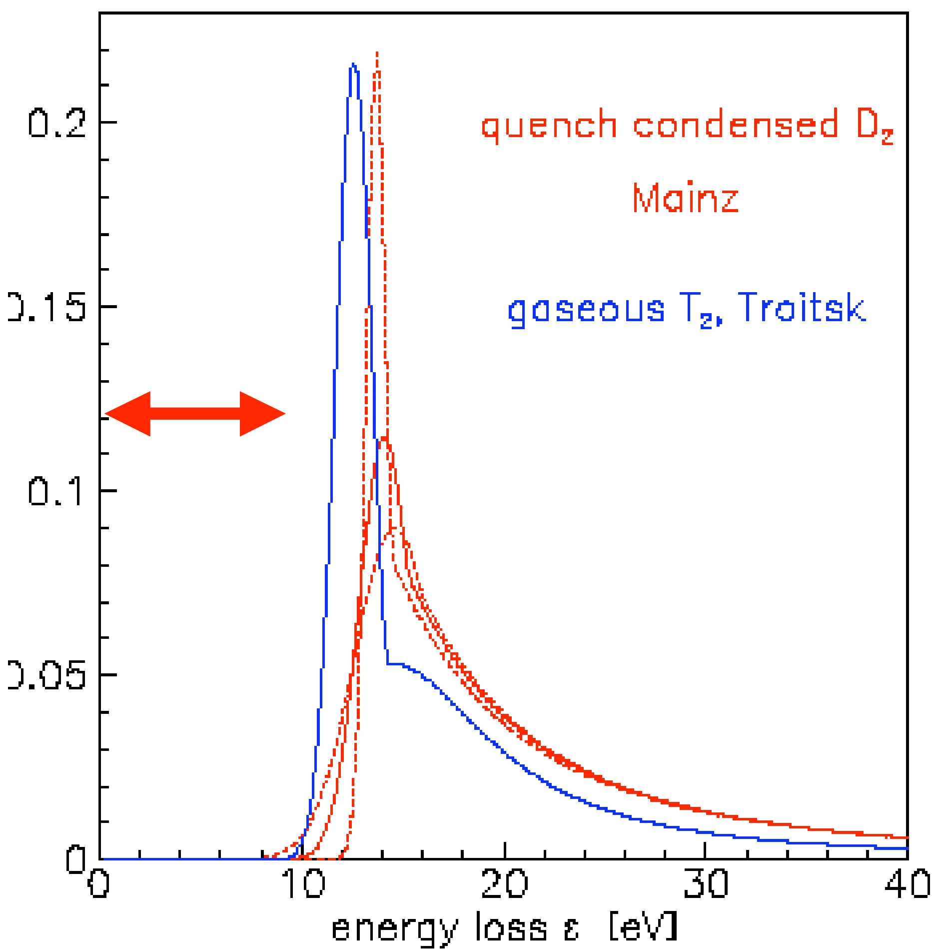
- **Statistics and uncertainty budget**
  - Only $2 \bullet 10^{-13}$ decays in last 1 eV below endpoint.
  - For 10 eV sensitivity, 100 eV^2, for 1 eV sensitivity, 1 eV^2
  - Must reduce backgrounds (~mHz) and ensure that they are very stable with time.
- **One must precisely eliminate or characterize all possible shape effects**
  - atomic final state effects
    - use atomic or molecular tritium source ($^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$)
    - utilize spectrum above atomic states (last 20 eV below endpoint)
  - energy loss shape effects
    - directly measure
    - use only no-loss portion of spectrum (last 9 eV below endpoint)
  - instrumental shape effects
    - direct measurements, using $^{83}Kr^m$
    - use integral spectrometers with very good resolution (~ eV)

A window to work in

Molecular Excitations



Energy loss function



Solenoid Retarding Spectrometer

Magnetic Adiabatic Collimation with Electrostatic Filter (MAC-E)

guiding by magnetic fields

(*magnetic adiabatic collimation*)

$\Delta\Omega \sim 2\pi$

electric (retarding-) field :

analysis of electron energies

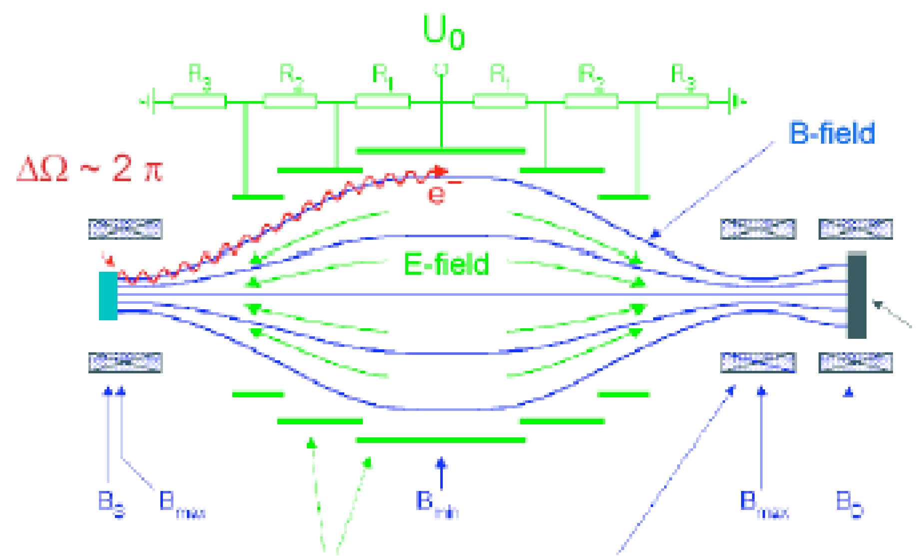
(*electrostatic filter*)

integral transmission : $E > U_0$

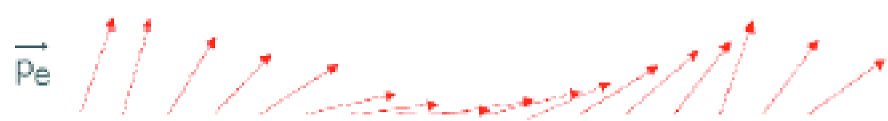
$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla})\,\vec{B} + q\,\vec{E}$$

$$\mu = E_\perp / B = \text{const}$$

adiabatic motion

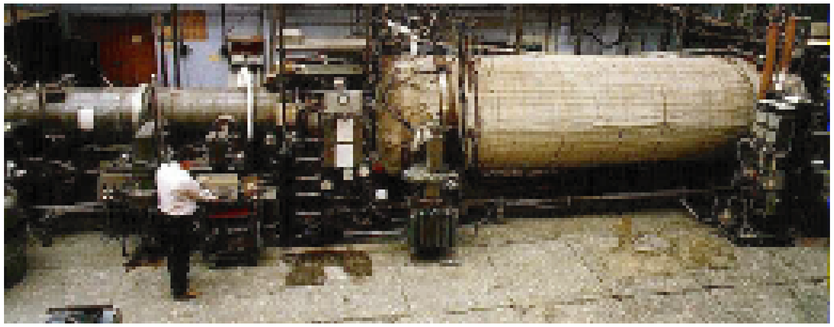


$E \parallel B$

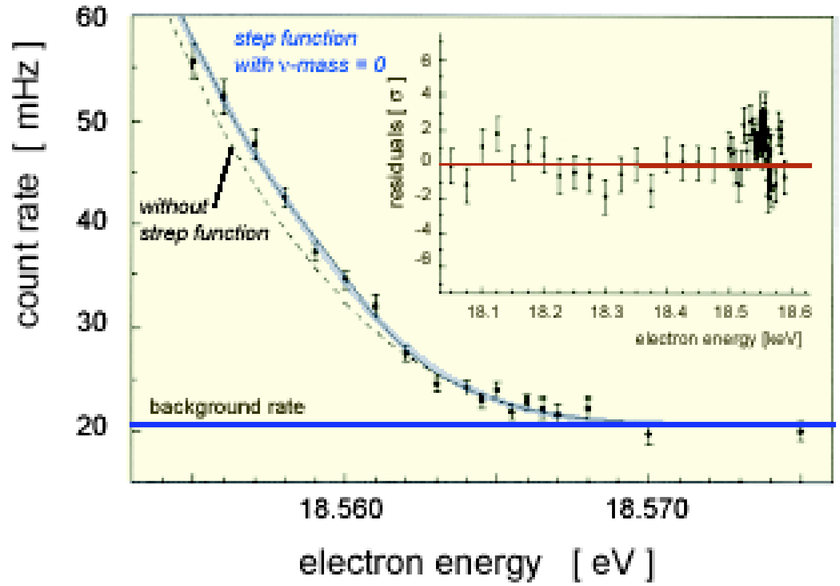


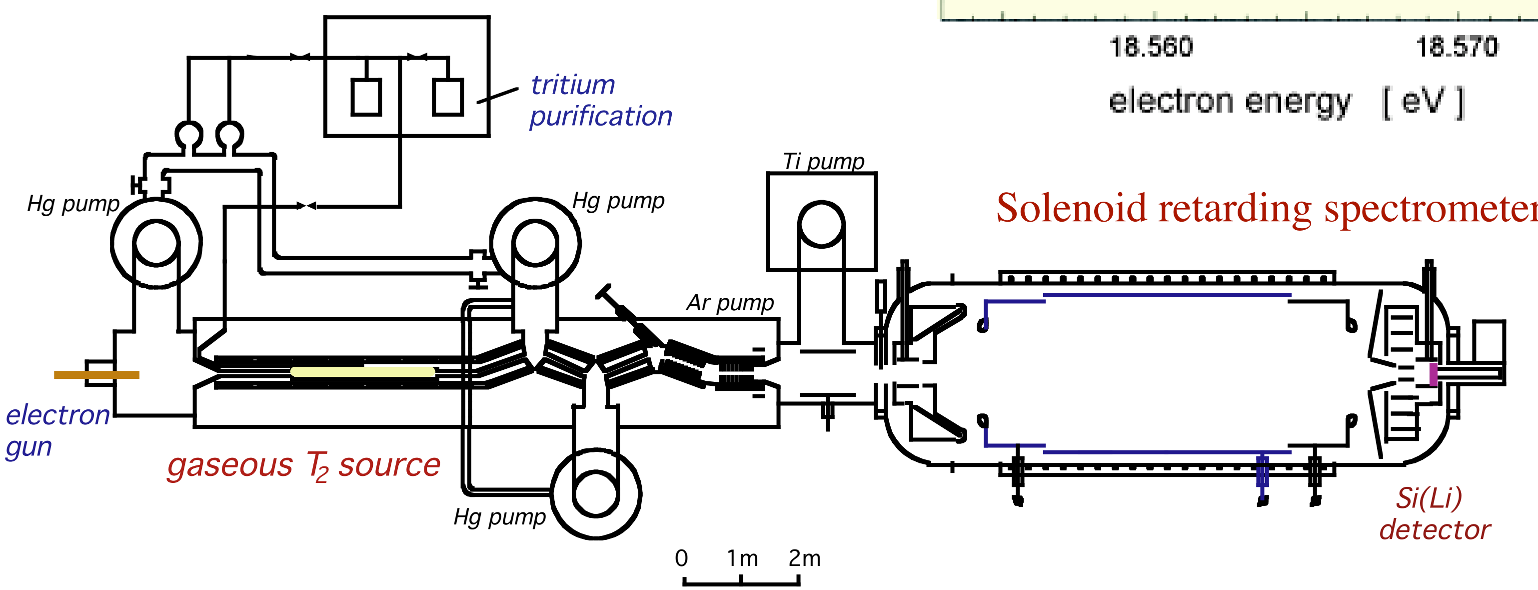
adiabatic transformation $E_\perp \rightarrow E_\parallel$

Troitsk tritium β-decay experiment



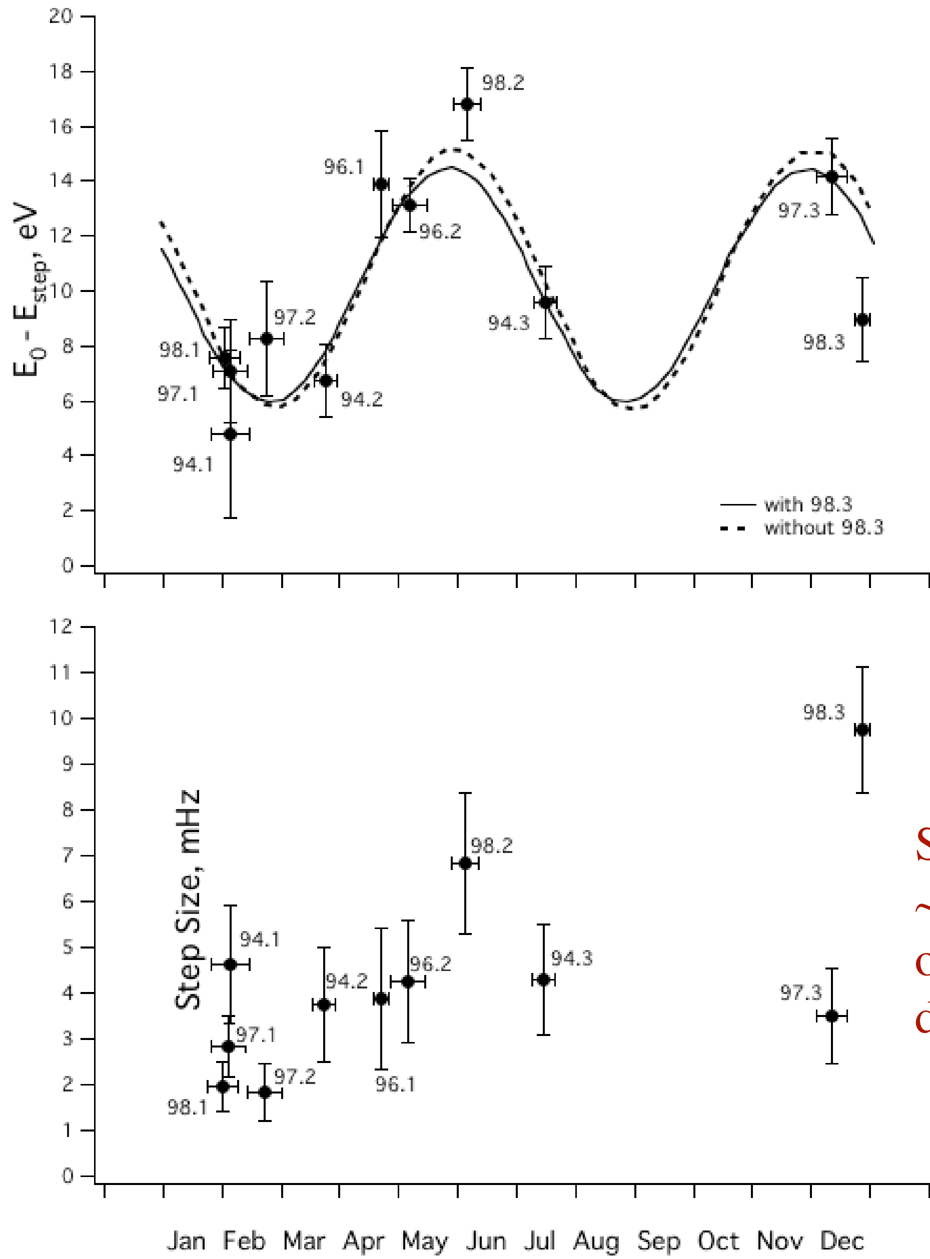
200 days of data since 1994





Troitsk Results

Claims there is a step function anomaly that varies in **both** amplitude and position above the endpoint.



It is difficult to have much confidence in their reported limit

$m_{\nu} \leq 2.5$ eV (95%CL)

since it requires removing the step function (excess counts)

Step intensity ~ $6 \bullet 10^{-11}$ of total T_2 decay rate

Likely systematic problems

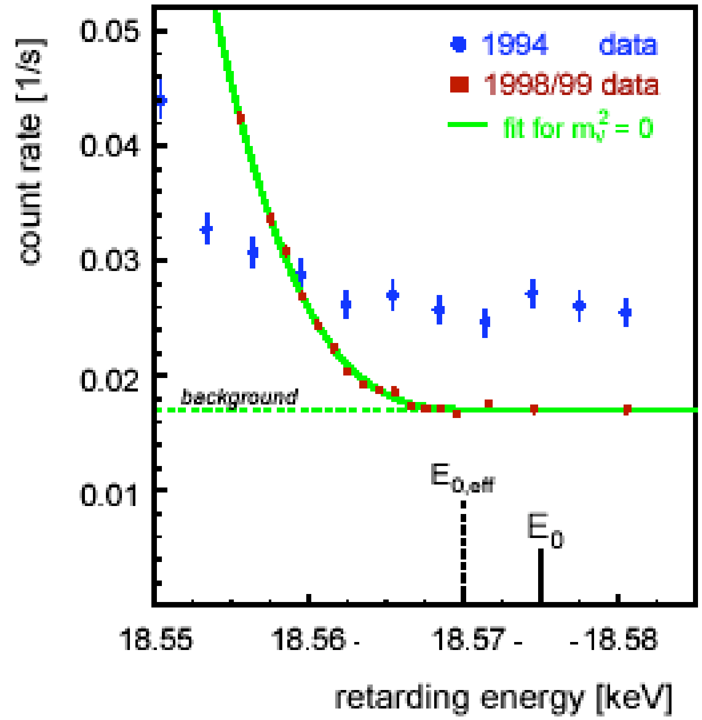
Lobashev et al., Phys. Lett. **B460** 227 (1999)

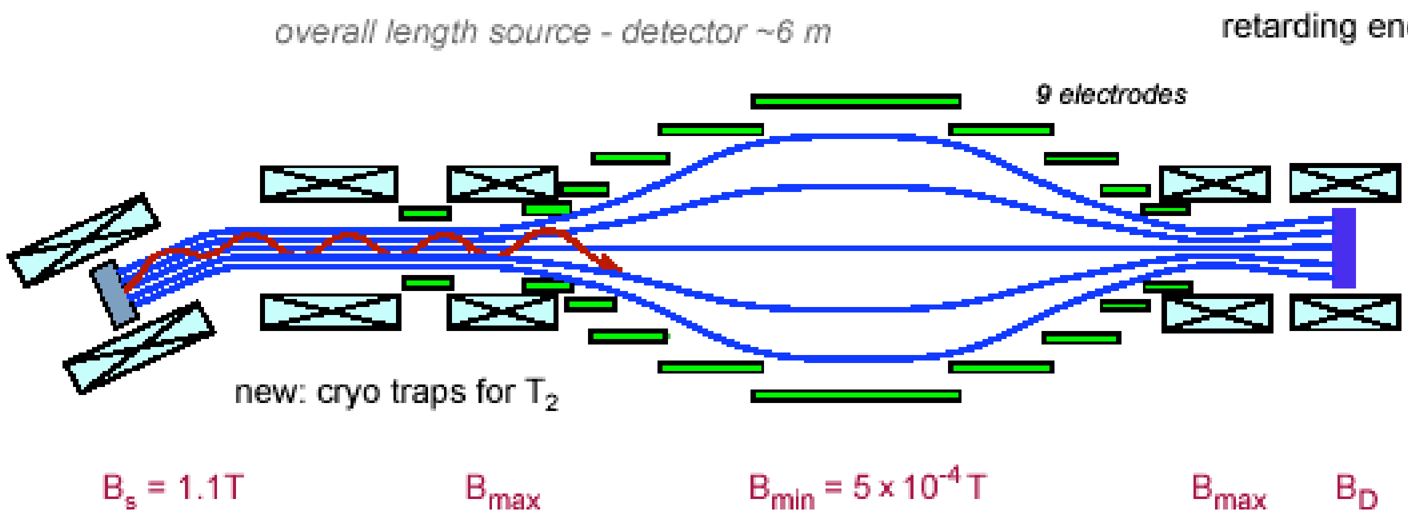
Mainz Neutrino Mass Experiment

Quench condensed solid T_2 source

Early results (94) showed systematic effects, traced to source film roughening transition. (fixed by lowering temperature)

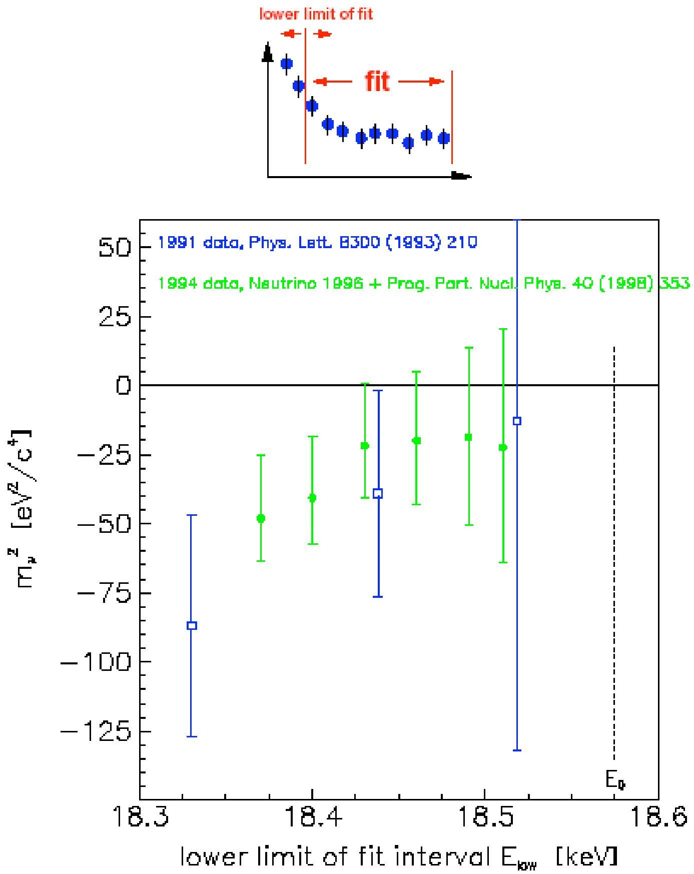
95-97 significant background reduction, signal improvement





Mainz Systematics Resolved

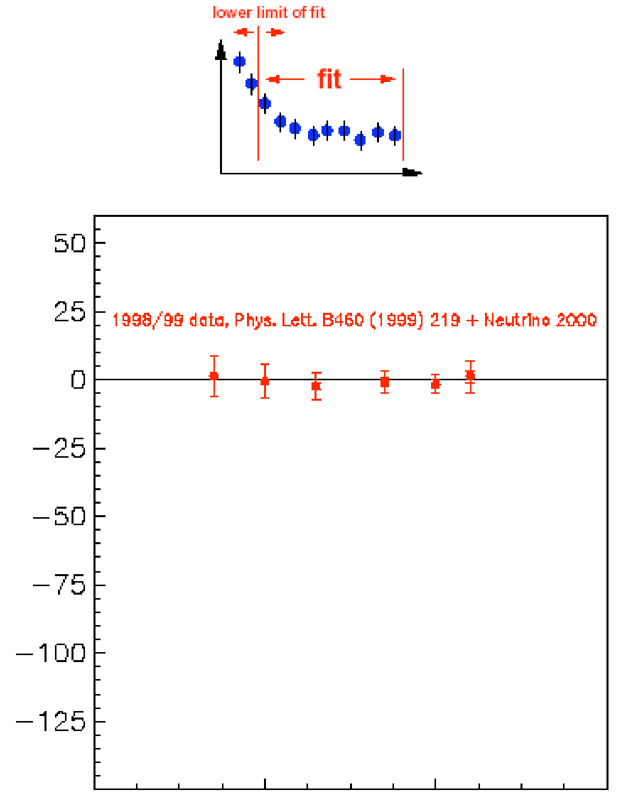
Former problem of negative m_ν^2 at Mainz



⇒ Problem of missing energy loss was caused by roughening transition

⇒ should be solved by much lower T_2 temperatures

Former problem of negative m_ν^2 at Mainz



T_{source} = 1.8 K

Trap pulsing on

Mainz Results

Recent runs (Q5 and greater) exhibit good reduced χ^2 and are stable over a varying fit interval.

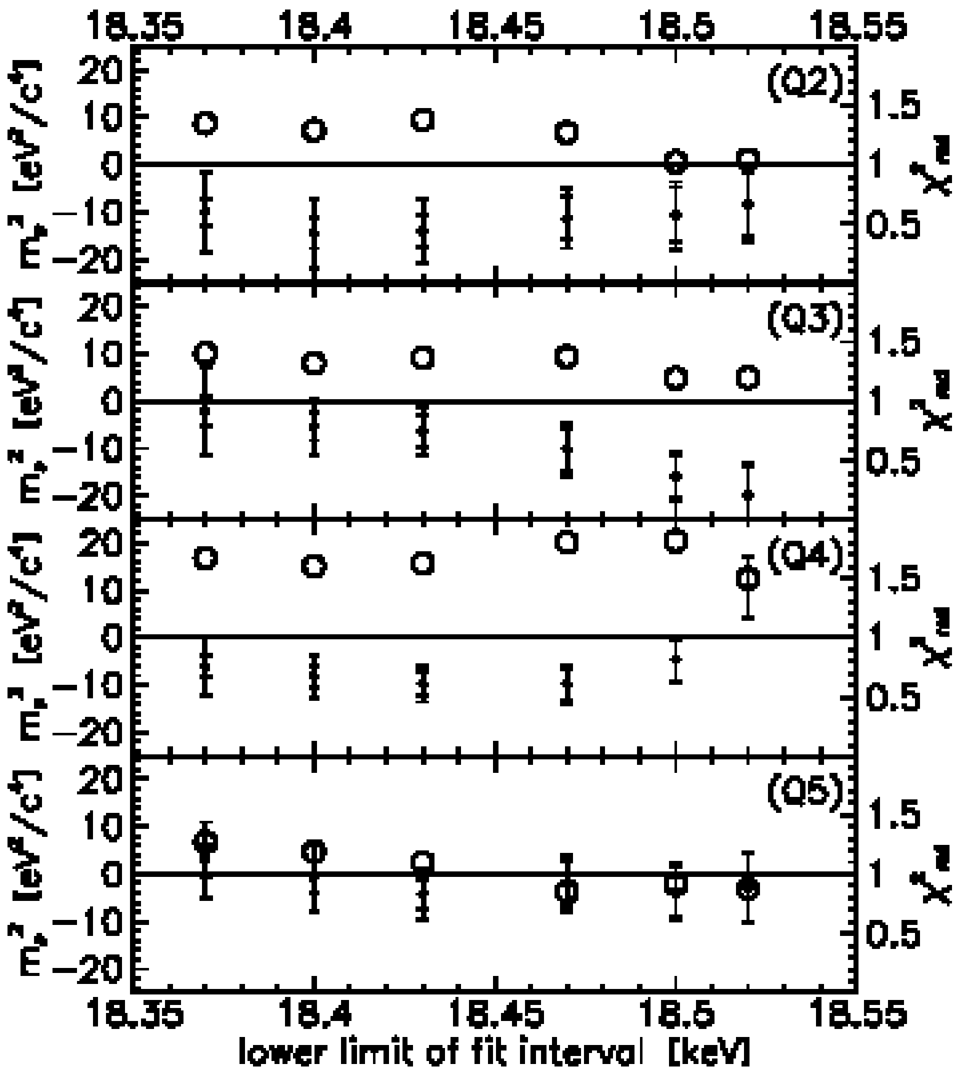
Change made to "sweep" spectrometer backgrounds between data points starting at run Q5.

Detailed studies published on source systematics.

$m_\nu^2 = -1.6 \pm 2.5 \pm 2.1$ eV^2

$m_\nu \leq 2.2$ eV (95%CL)

A solid result.



Weinheimer et al., Phys. Lett. **B460** 219 (1999)

Future β-decay endpoint measurements

- Ultimate sensitivity of spectrometers
  - require instrumental resolution of ~ m_ν/E_o
  - spectral fraction per decay that falls in the last m_ν of the spectrum is ~ $(m_\nu/E_o)^3$
  - source thickness is set by the inelastic scattering cross-section (3.4×10^{-18} cm^2), $\sigma n \leq 1$
  - If one wants ~1 event/day in last m_ν of the spectrum
    - for a 10 m magnetic spectrometer m_ν ~ 1.7 eV
    - for a 3 m dia. solenoid retarding field spectrometer m_ν ~ 0.3 eV
- Calorimetic detector sensitivity
  - evade source-thickness limit, because no e-loss problem
  - limited by response time, and eventually pileup
    - requires fine segmentation, many detectors

See Wilkerson and Robertson, Direct Measurements of Neutrino Mass, Sect 3.6

planning the next-generation direct ν mass experiment

experimental observable in ß-decay is m_ν^2

aim : improvement of m_ν by one order of magnitude (3 eV → 0.3 eV)

requires : improvement of m_ν^2 by two orders of magnitude (9 eV^2 → 0.09 eV^2)

improve statistics :

- stronger tritium source (factor 40) (& larger analysing plane)
- longer measuring period (~100 days → ~1000 days)

improve energy resolution :

- large electrostatic spectrometer with ΔE=1 eV (factor 4 improvement)

but : count rate close to ß-end point drops very fast ($\sim\delta E^3$)

last 10 eV : 2×10^{-10} *of total ß-intensity*
last 1 eV : 2×10^{-13}

Karlsruhe **Tri**tium **N**eutrino **E**xperiment (KATRIN)

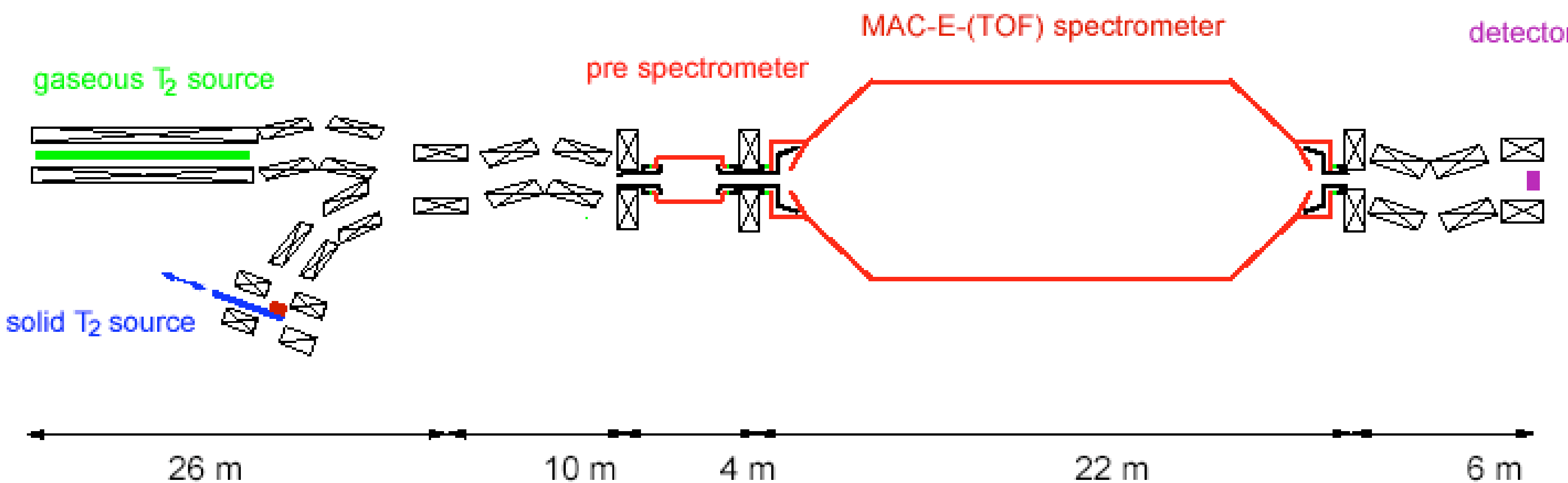
arXiv:hep-ex/0109033

next-generation experiment with sub-eV neutrino mass sensitivity

FH Fulda - FZ & U Karlsruhe - U Mainz - INP Prague - INR Troitsk - U Washington

high luminosity — *background suppression* — *high energy resolution* — *control of systematics*

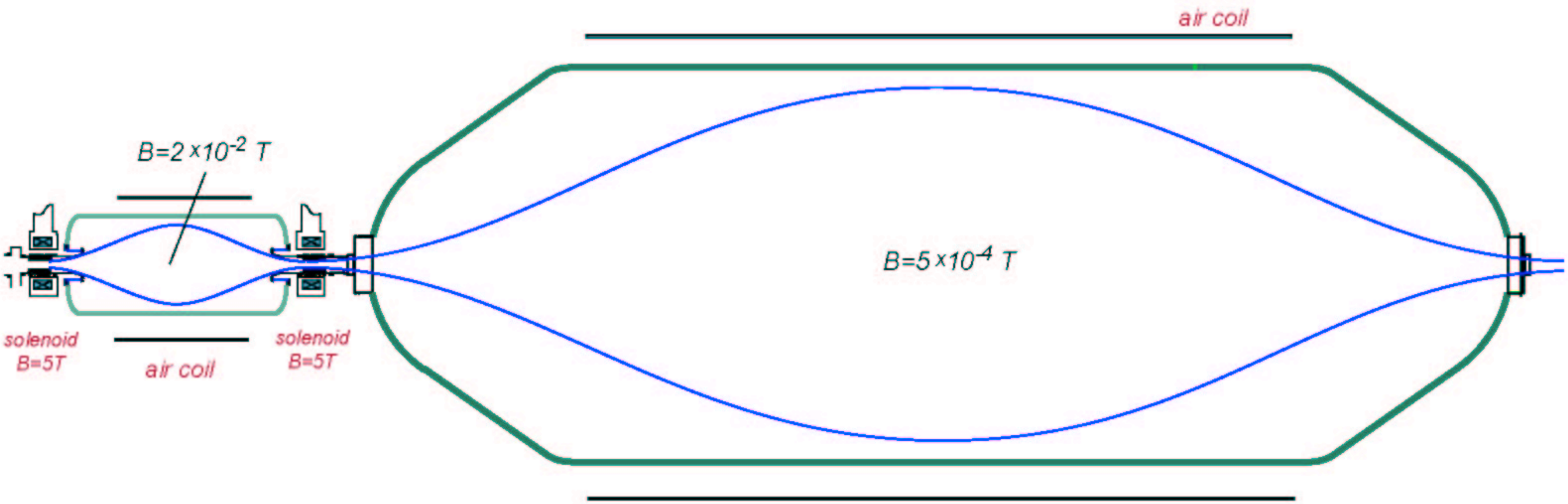
molecular tritium source — pumping — pre-filter — energy analysis — fl-electron counting



electrostatic spectrometers - properties and geometry

electrostatic analysis of tritium ß-decay electrons (electrode system)

XUHV - conditions : $p < 10^{-11}$ mbar (degassing rate 10^{-13} mbar l / cm² s)



pre-spectrometer

fixed retarding potential 18.4 kV

Ø = 1.7 m / L = 4.0 m

ΔE = 80 eV

main spectrometer

variable retarding potential 18.5-18.6 kV

Ø = 7 m / L = 20 m

ΔE = 1 eV

KATRIN

Technological Challenges

electrostatic spectrometer

construction large vessel (Ø=7m, l=20m)

XHV ($p < 10^{-11}$ mbar)

HV control & stabilization

optimized electrode system

electron transport

> 30 superconducting solenoids

lHe and lN_2 supply (200W cooling power)

optimized particle tracking (l > 60 m)

reliable extinction of tritium (freeze out)

tritium sources

stable & safe tritium supply

high luminosity & reliability

control of syst. effects (TOF op., calib.)

solid state detector

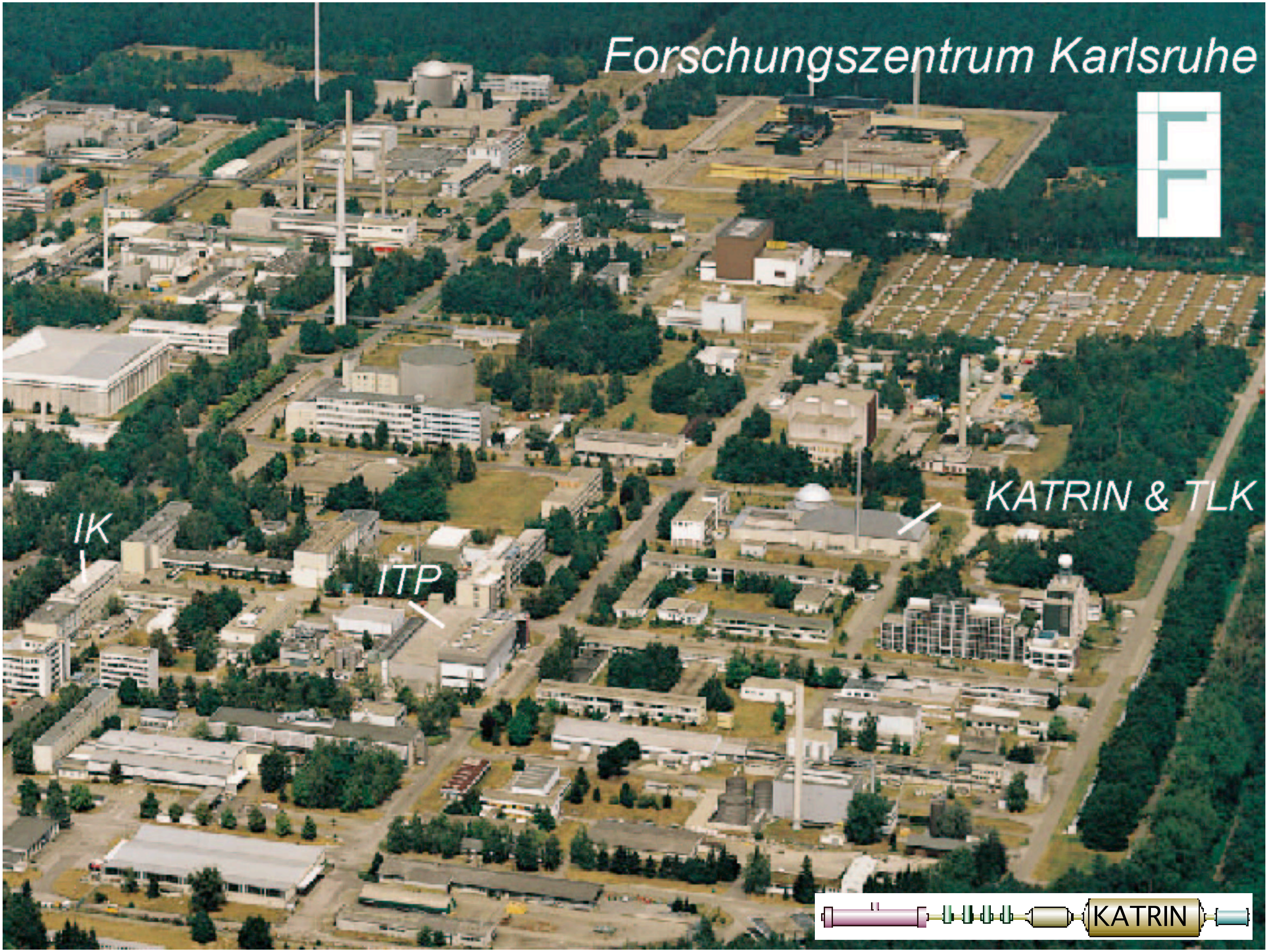
excellent $\Delta E/E$ in high B-field (< 1keV)

good position resolution

mK operation of bolometer

experiment will be operational for several years

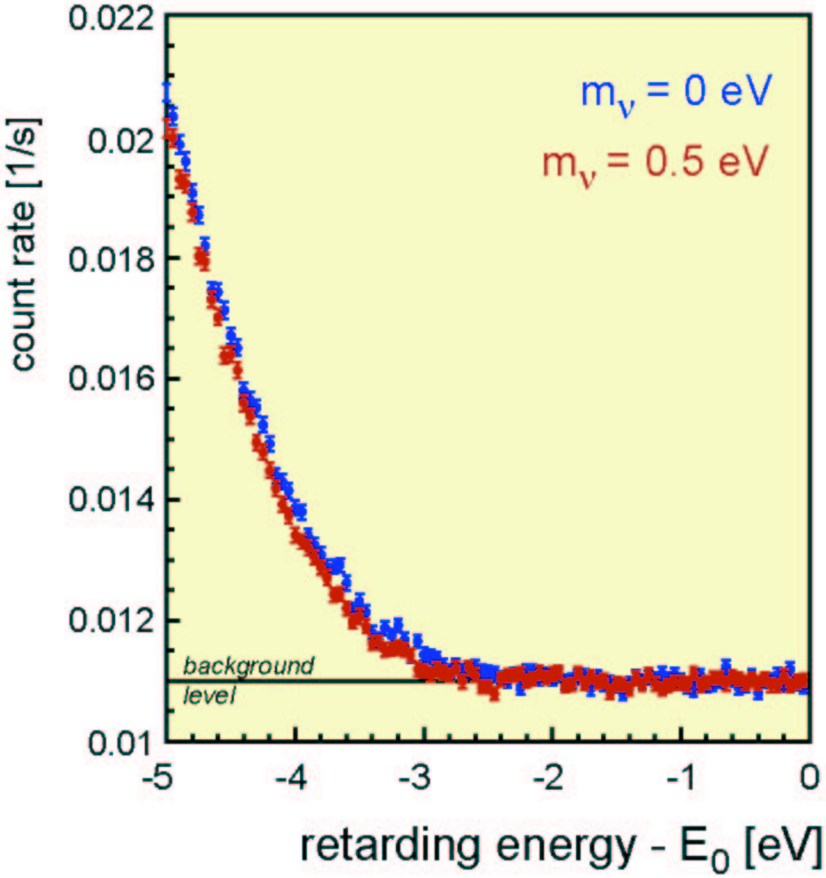
interdisciplinary solutions are required


Forschungszentrum Karlsruhe
KATRIN & TLK
IK
ITP
KATRIN

Estimated KATRIN sensitivity for neutrino masses

realistic MC simulation of sub-eV ν-mass signal close to sensitivity limit

narrow interval close to ß end point (last 5 eV) from WGTS



input paramters for simulation :

measuring time : 3 years

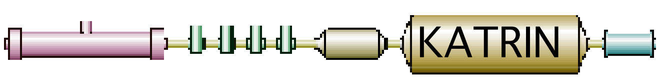
ΔE = 1 eV (spectrometer)

background rate = 11 mHz

WGTS :
column density 5 x 10^{17} / cm^2

max. accepted angle 51°

molecular excitations included



Systematic Uncertainties

δE-interval = 15-20 eV

KATRIN focuses on very narrow region below E_0
(ΔE=1eV, high T_2 luminosity): many systematic uncertainties reduced

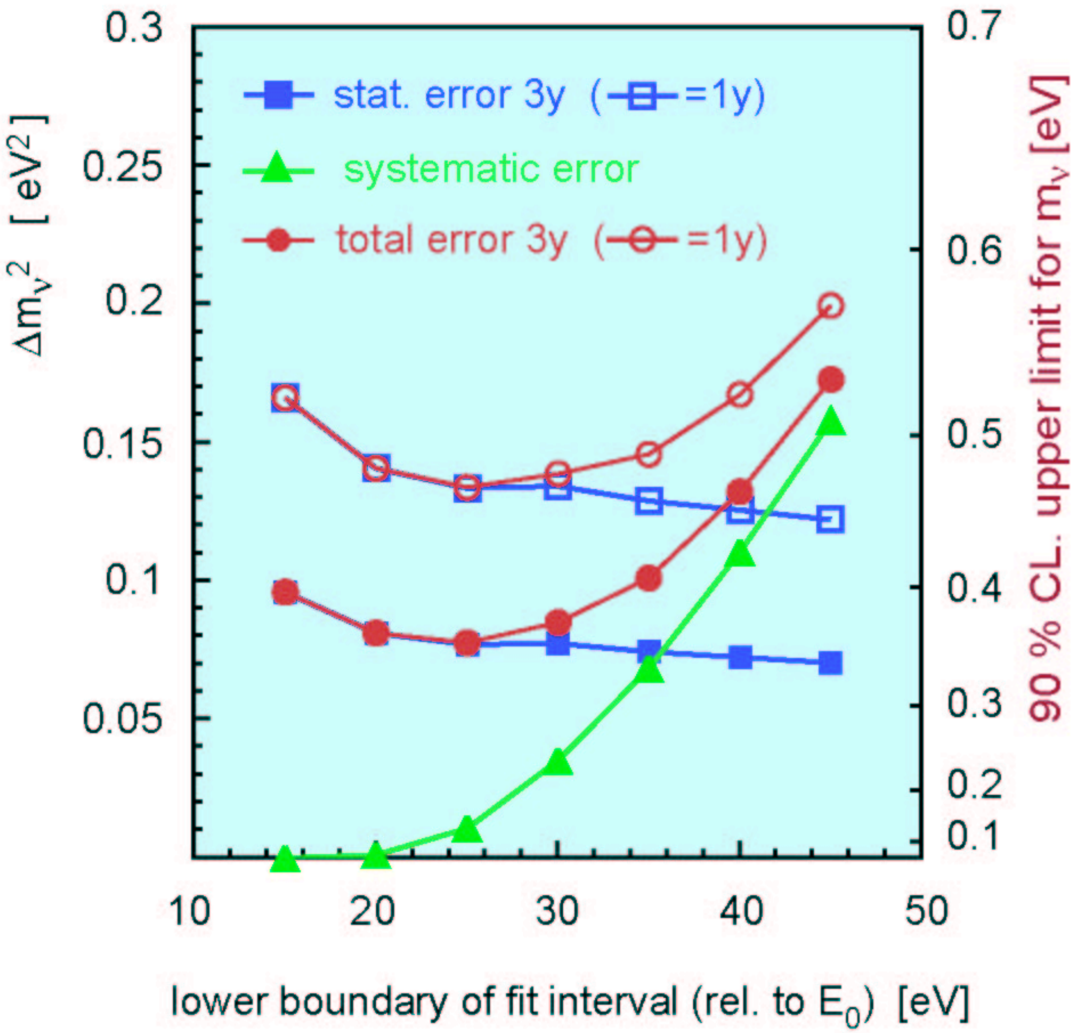
- *no contribution from excited electronic states of ^{3}He-T (δE > 25 eV)*
- *small contribution from inelastic scattering in source (for δE-Interval of 25 eV : 2% of signal from scattered electrons)*

+ better vacuum & higher T_2 purity

remaining uncertainties :

- *calculations of rotational-vibrational excitations of ^{3}He-T ground state (0.2% theory uncertainty)*
- *inelastic scattering of ß-electrons in WGTS (2% uncertainty on σ_{tot}, can be improved)*
- *solid state effects (self-charging of film, neighbour excitations, ...) only QCTS*
- *stability of settings : HV calibration and stabilisation*
  WGTS activity and T_2 -purity

estimates of KATRIN sensitivity for m_ν



assumptions for simulation:

ΔE = 1 eV (spectrometer)

background rate = 11 mHz

WGTS : $\rho d = 5 \times 10^{17} / cm^2$

area = 29 cm^2

max. accepted angle 51°

systematic error :
2% energy loss in WGTS

m_ν < 0.35 eV (90% CL.)

KATRIN

KATRIN - time schedule

1/2001	first presentation at international workshop at Bad Liebenzell
6/2001	formal founding of KATRIN collaboration
9/2001	Letter of Interest (LoI) submitted hep-ex/0109033 BMBF funding 'astroparticle physics' for german universities
5/2002	Complete successful FZK International Panel Review
12/2002	Submission of proposal
2002-03	sytematic studies of background processes and design optimisation funding requests (HGF, DOE, ...) and reviews pre-spectrometer measurements and R&D studies
2004-06	set up of spectrometer, solenoid system, transport system, detector and tritium sources, hall construction, cryo supply
2006	commissioning and begin of data taking

Summary

- All 3 ν masses can be probed through the electron neutrino
- Present direct limit on mass of ν_1, ν_2, and ν_3
  - 2.2 eV
  - Sum $\leq$ 6.6 eV
- Direct measurements combined with oscillation and $0\nu\beta\beta$ decay results can discriminate between a variety of 3 and 4 neutrino mass spectrum scenarios.
- KATRIN should be able to achieve sub-eV mass sensitivity of 0.30 eV, nearly an order of magnitude improvement over current direct measurements.
- Sub-eV direct lab limits yield model independent results that will likely be serve as strong constraints on astrophysics.