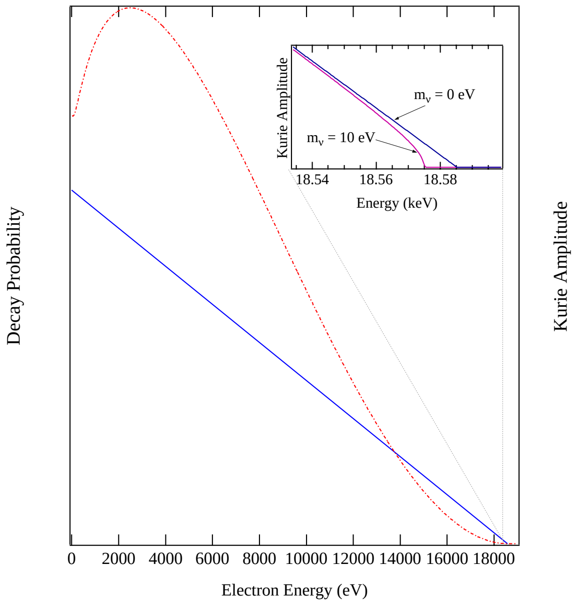
Beta-decay endpoint experiments: past, present, and future.

Direct measurements of neutrino mass

- Motivation
- Impact of ν oscillations and mixing
- Interpretation of β-decay endpoint results in terms of ν mass eigenstates



Current β-decay endpoint experiments

- INR - Troitsk
- Mainz

Future experiments and prospects for sub-eV sensitivities

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

CENPA
Center for Experimental Nuclear Physics and Astrophysics

J.F. Wilkerson
WIN02 Workshop
Christchurch, New Zealand
January 25, 2002

The absolute scale of ν masses

- Addresses key issues in particle physics
  - hierarchical or degenerate neutrino mass spectrum
  - understanding the scale of new physics beyond SM
  - potential insight into origin of fermion masses

- Impacts cosmology and astrophysics
  - early universe, relic neutrinos (HDM), structure formation, anisotropies of CMBR
  - supernovae, r-process, origin of elements
  - potential influence on UHE cosmic rays

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:

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

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

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

These experiments yield only a ***lower bound*** on absolute ν mass

$$m_i \geq \sqrt{\Delta m_{ij}^2}$$

So, from the Superkamiokande atmospheric neutrino oscillation result:

$$m_3 \geq \sqrt{\Delta m_{atm}^2} \sim (0.04 - 0.07)\ \text{eV}$$

The solar neutrino result is much smaller:

$$m_2 \geq \sqrt{\Delta m_{sol}^2} \sim (0.0001 - 0.01)\ \text{eV}$$

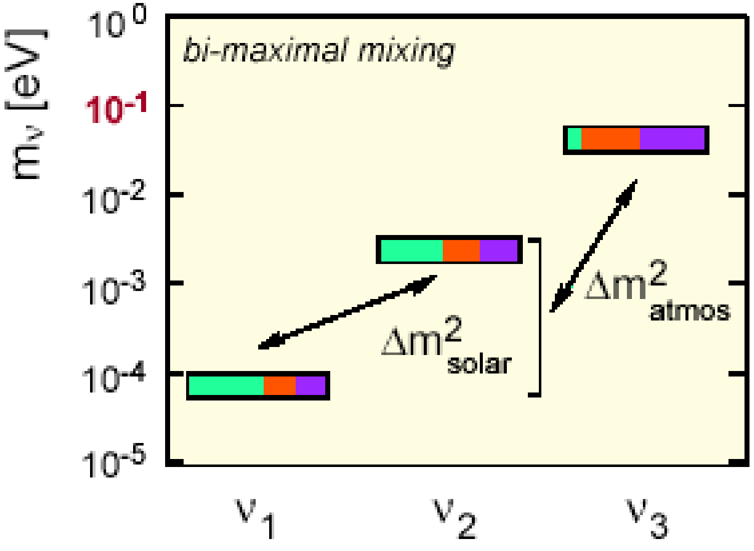
The LSND result (in a 4 neutrino scenario) would mean

$$m_4 \geq \sqrt{\Delta m_{LSND}^2} \sim 1\ \text{eV}$$

sub-eV absolute ν mass measurements

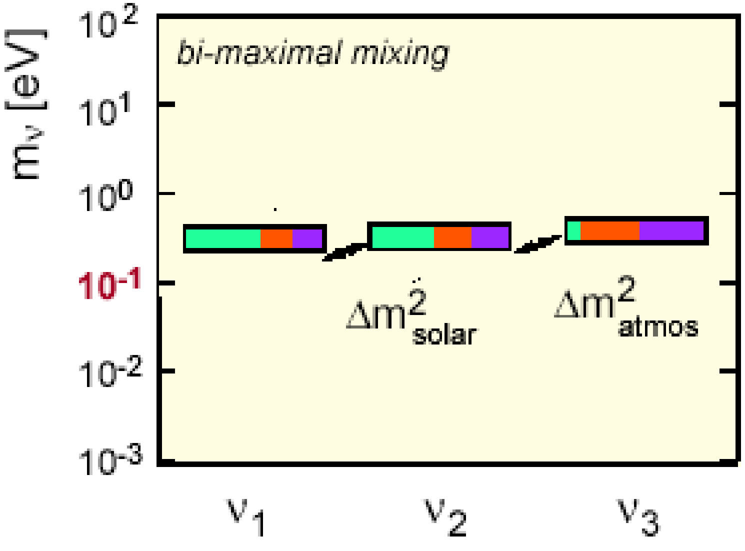
hierarchical

$m_{\nu} << m_{\nu} << m_{\nu}$



degenerate

$m_{\nu} \approx m_{\nu} \approx m_{\nu}$



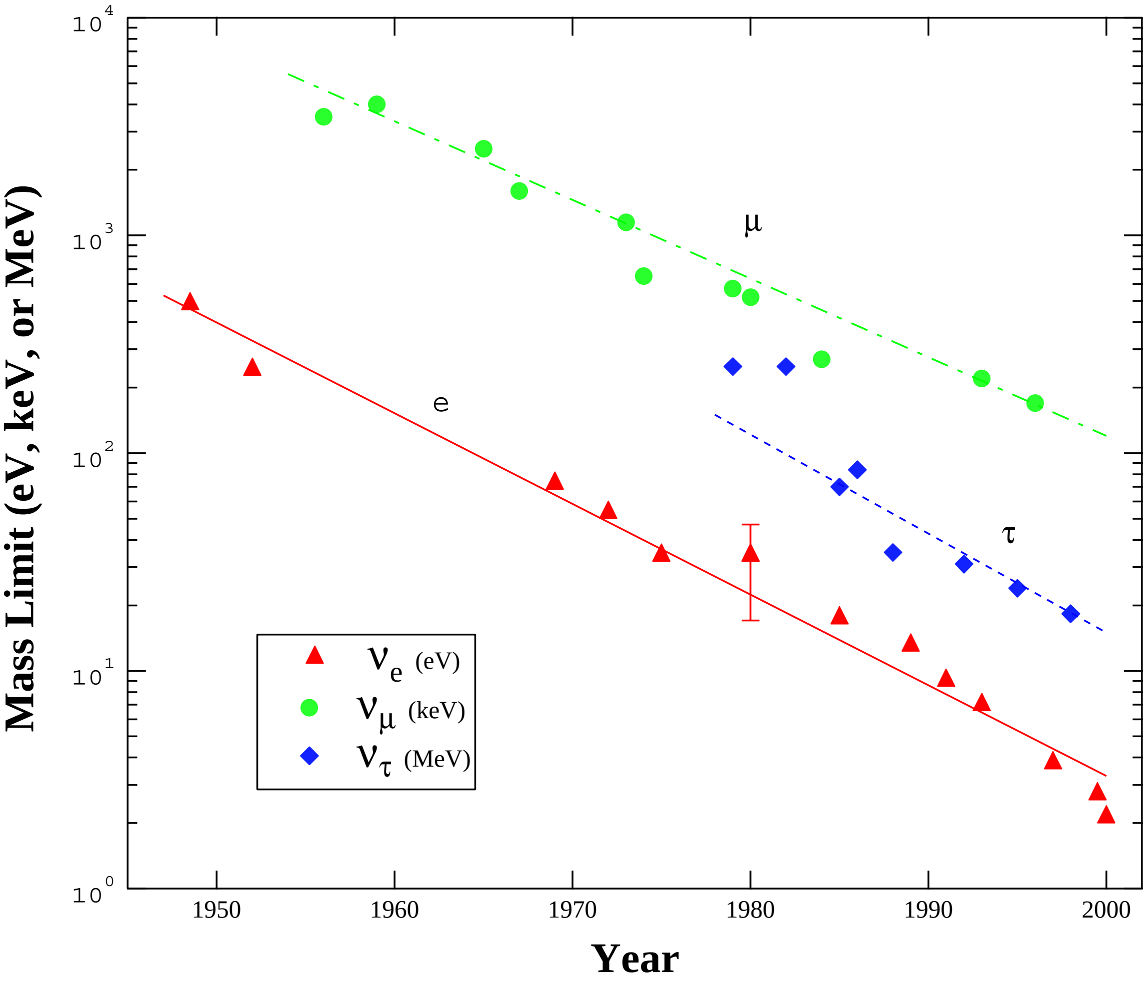
🟩 ν_e 🟥 n 🟪 n_t

Direct or indirect (0ν-ββ-decay, cosmology) mass measurements with sub-eV sensitivity are needed

Direct measurements of neutrino mass

- **Techniques**
  - time of flight (SN1987a)
  - particle decay kinematics
    - beta decay (and electron capture) spectrum shape
    - muon momentum in pion decay
    - invariant mass studies of multiparticle semileptonic decays
- **Advantages**
  - sensitive to absolute mass scale
  - purely kinematical observables
  - few, if any, assumptions about ν properties
- **Direct measurements combined with observables from oscillation & 0ν-ββ decay experiments can potentially:**
  - help distinguish 3 or 4 neutrino scenarios
  - yield understanding of hierarchy and ordering of masses
  - measure CP-violating phases in lepton sector

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

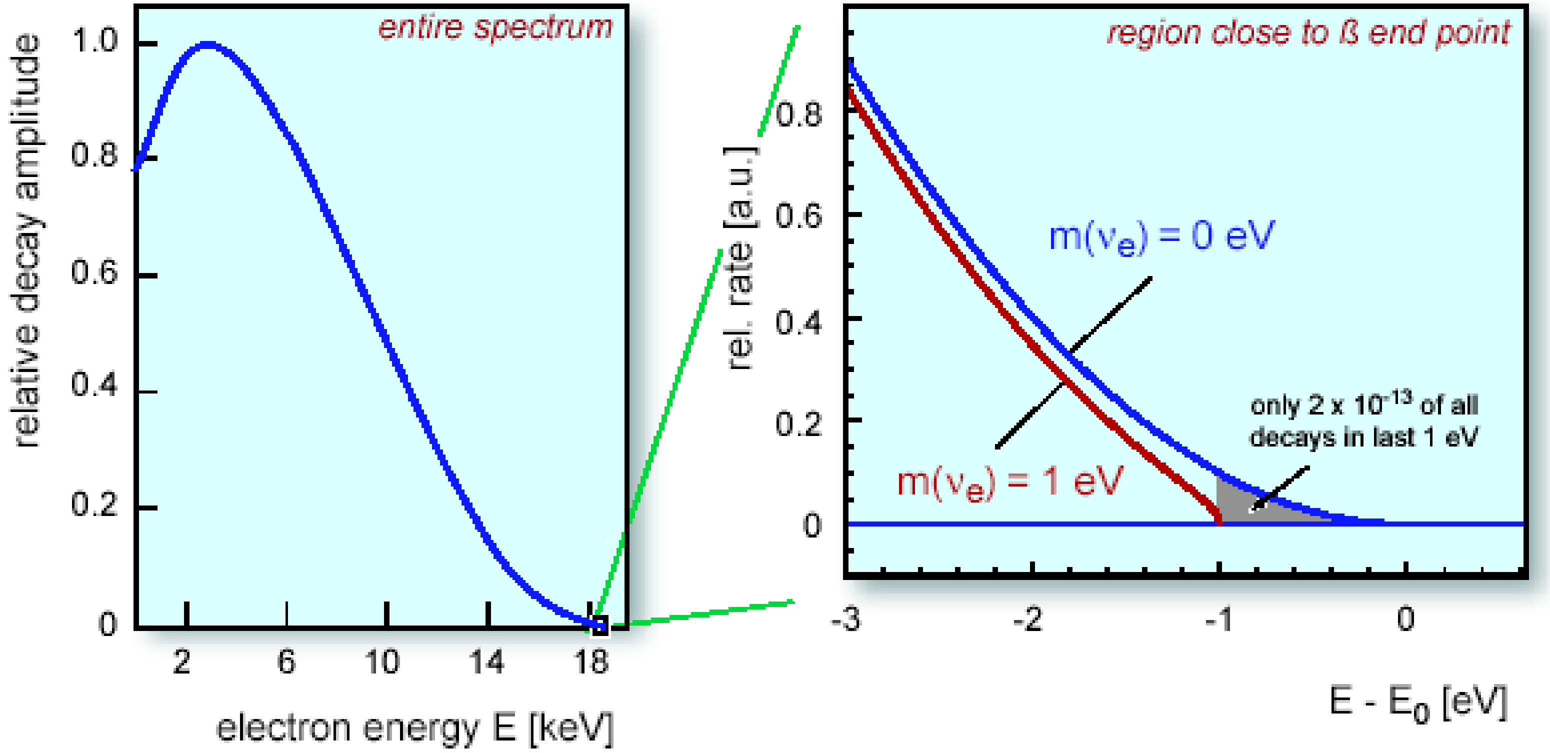


But ν oscillations with large mixing angles - forces one to consider direct techniques in terms of ν mass eigenstates!

points without error bars represent upper limits

β-decay endpoint measurement

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



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

β-decay in terms of ν mass eigenstates

Taking into account ν mass eigenstates, the original spectrum

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

becomes

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

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" : $m_\beta = \sum |U_{ei}|^2\, m^2_{\nu_i}$

3 ν mass eigenstates - degenerate spectrum

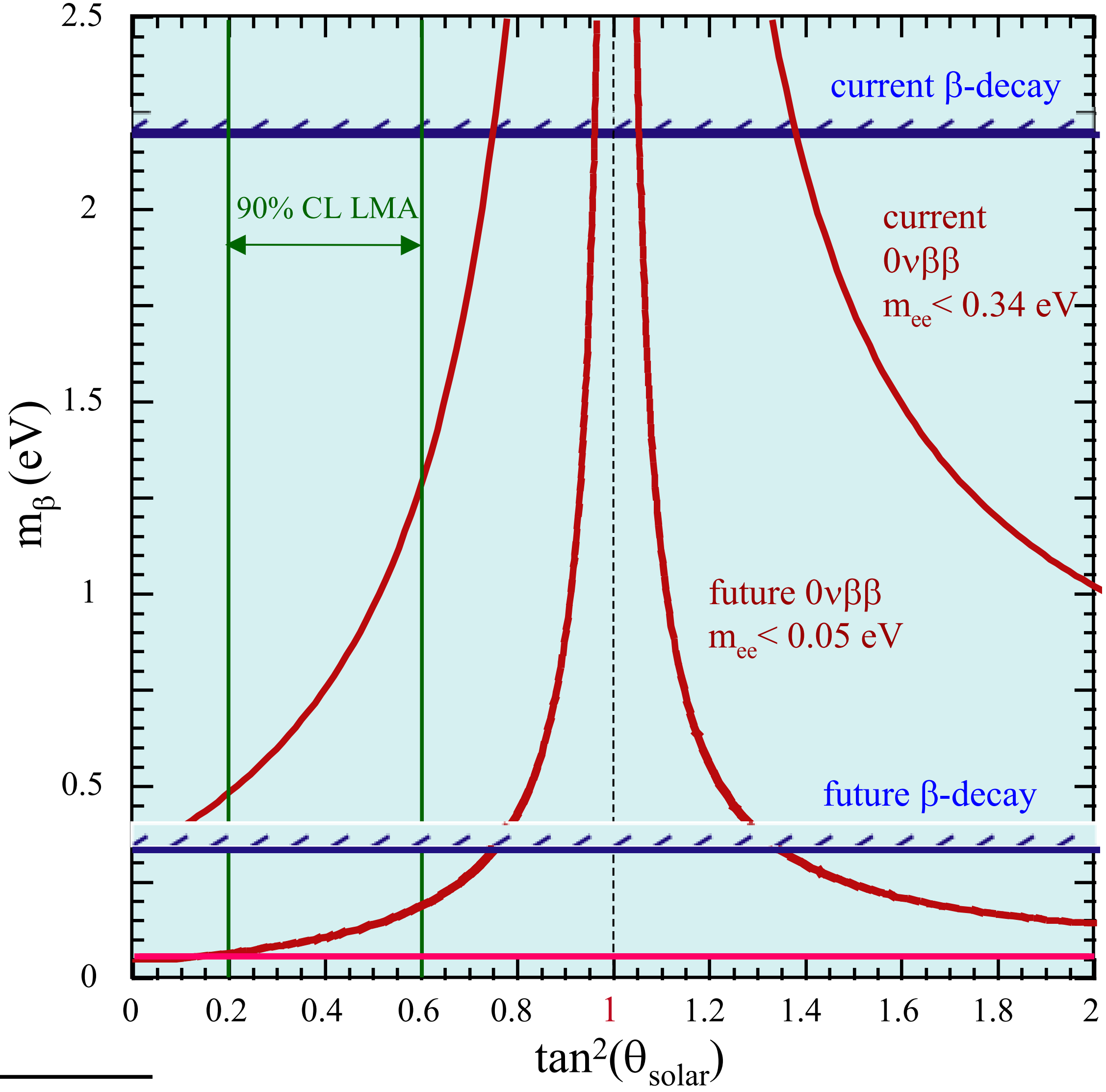
Combining β-decay, 0νββ, and neutrino matrix information can potentially distinguish various scenarios

See: Y. Farzan, O.L.G. Peres, and A. Yu. Smirnov
Nucl.Phys. **B612**, 59 (2001)
hep-ph/0105105

$$m_\beta = \sum |U_{ei}|^2 m_{\nu_i}^2$$

$$m_{ee} = \left| \sum U_{ei}^2 m_{\nu_i} \right|$$

$$m_{ee} < m_\beta < \frac{m_{ee}}{\left| |\cos 2\theta_{sol}|(1-|U_{e3}|^2) - |U_{e3}|^2 \right|}$$



0νββ curves assume $|U_{e3}| = 0$

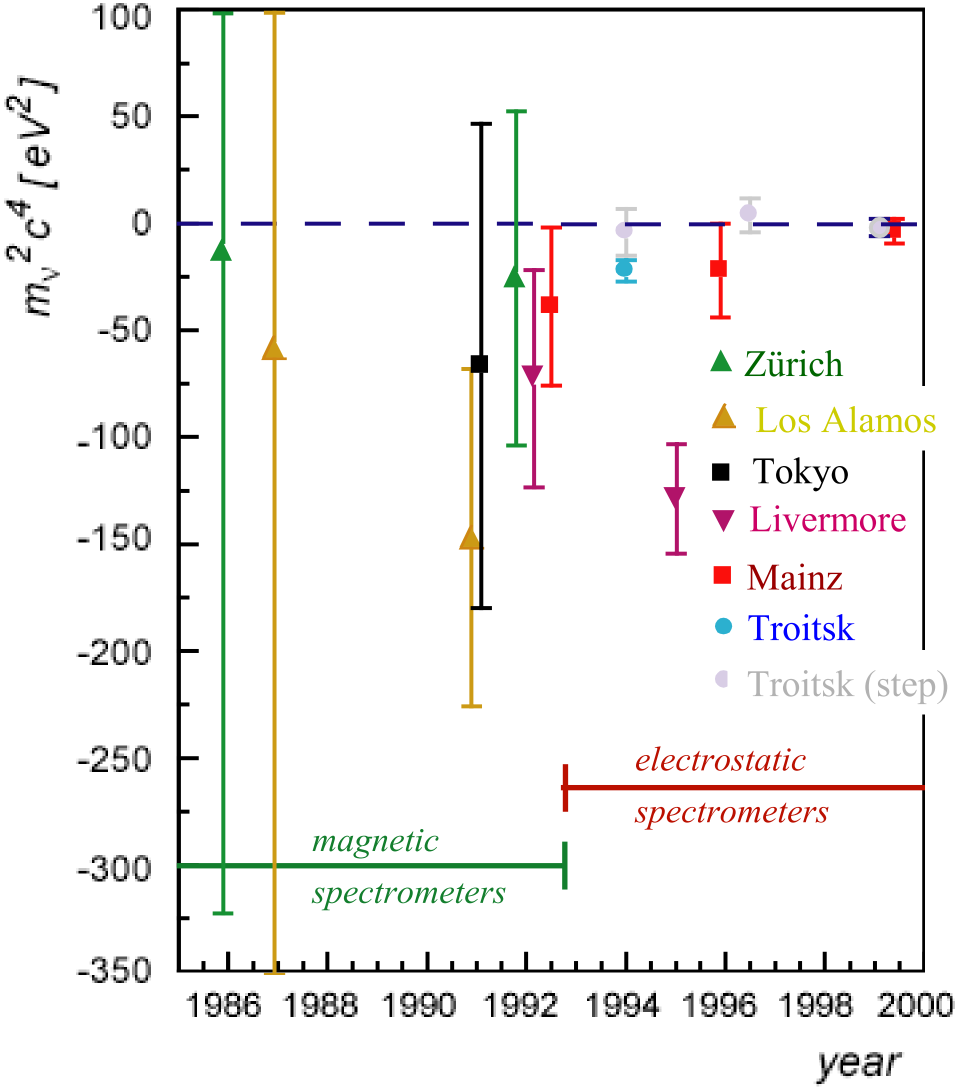
Keys to β-decay shape measurements

- **Statistics and uncertainty budget**
  - Only 2 ∑ 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 (^{3}H Æ ^{3}He + 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)

Tritium β-decay experiments

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokyo *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.2 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	(< 2.5 eV)

experimental results



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

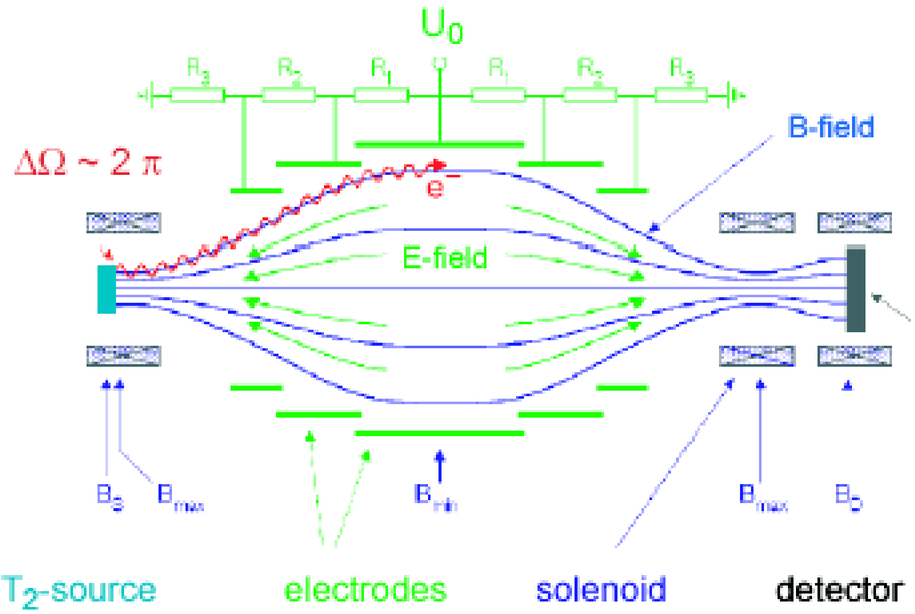
(*electrostatic filter*)

integral transmission : $E > U_0$

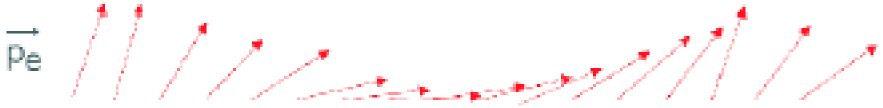
$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla})\,\vec{B} + q\,\vec{E}$$

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

adiabatic motion

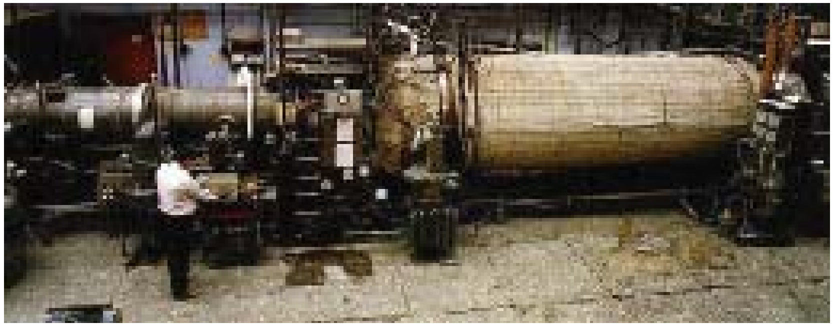


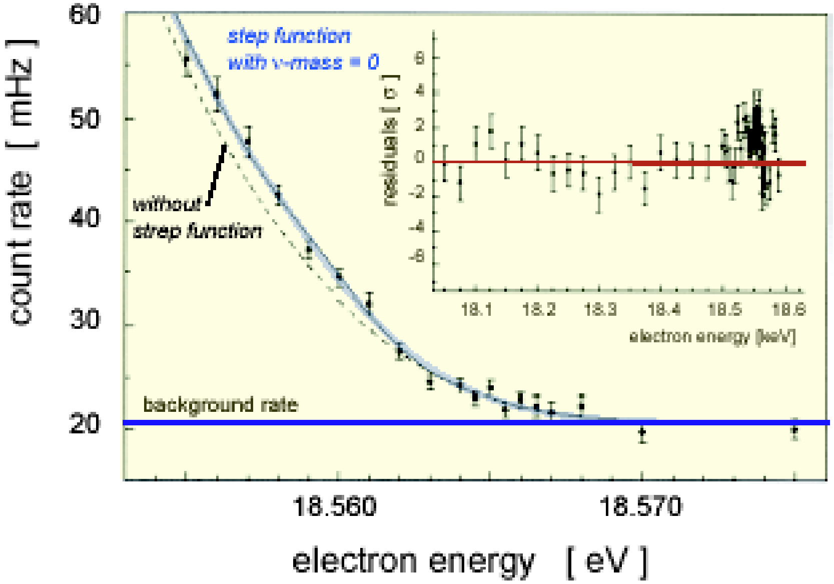
$E \parallel B$



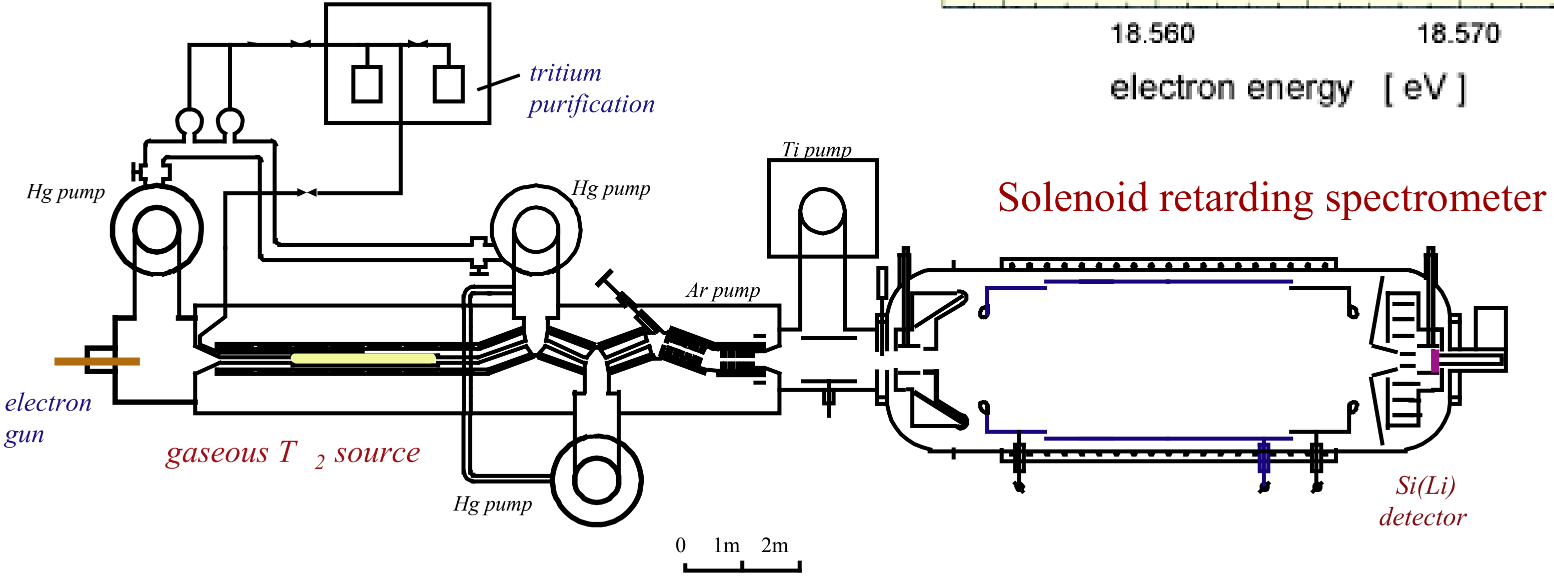
adiabatic transformation $E_\perp \rightarrow E_\parallel$

Troitsk tritium β-decay experiment



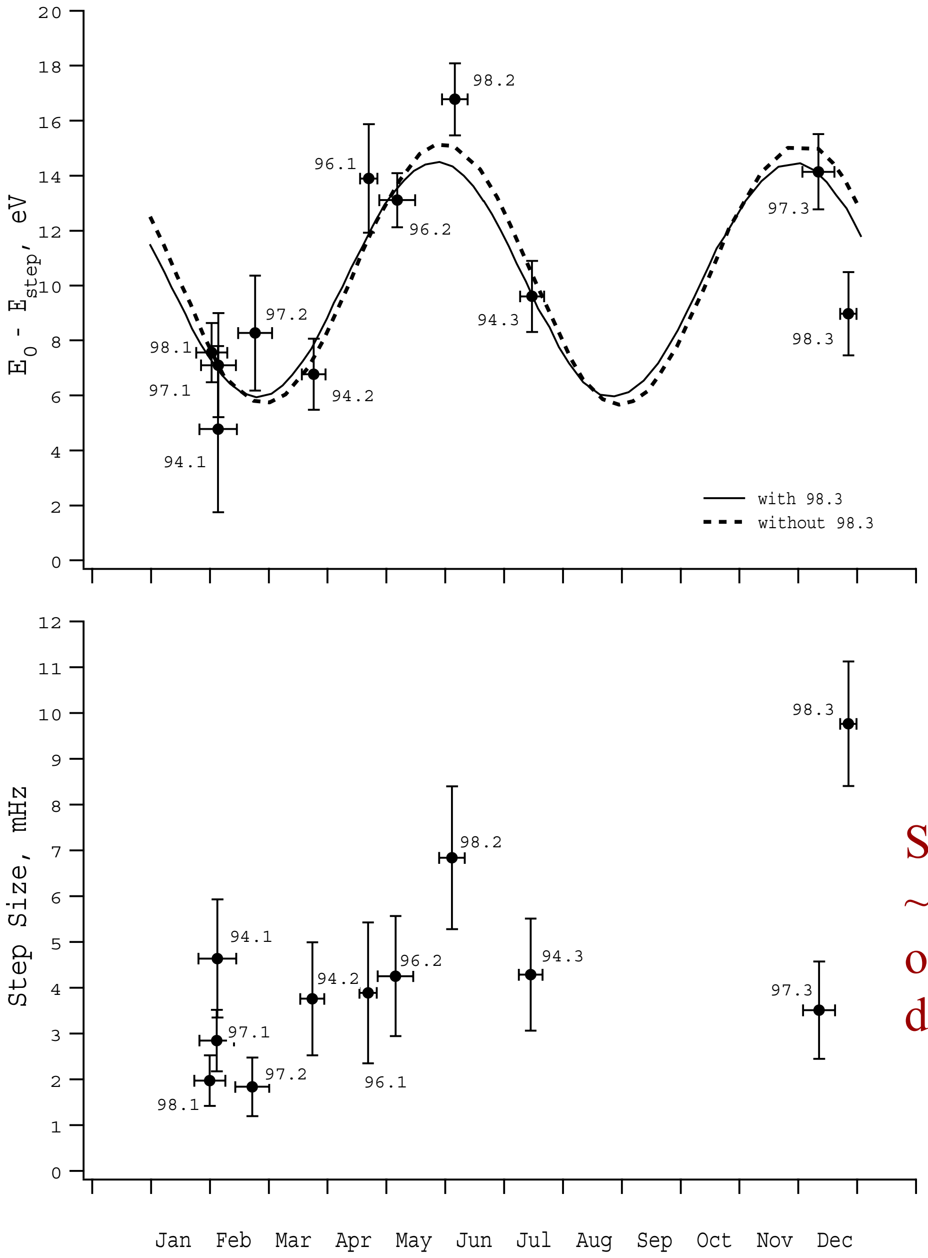


200 days of data since 1994



Troitsk Results

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



Step intensity ~ 6 ∑ 10^{-11} of total T_2 decay rate

It is difficult to have much confidence in their reported limit

$m_\beta \leq 2.5$ eV (95%CL)

since it requires removing the step function (excess counts)

Likely systematic problems

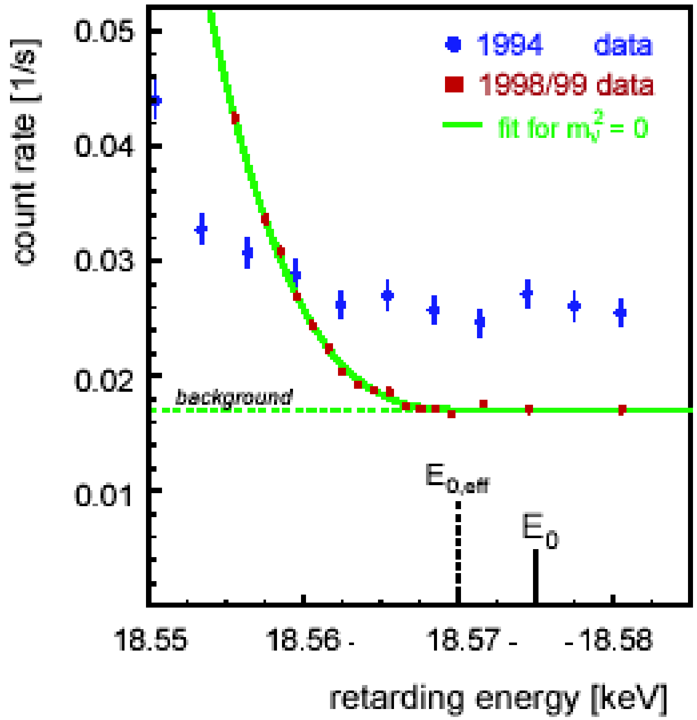
Lobashev et al., Phys. Lett. **B460** 227 (1999)

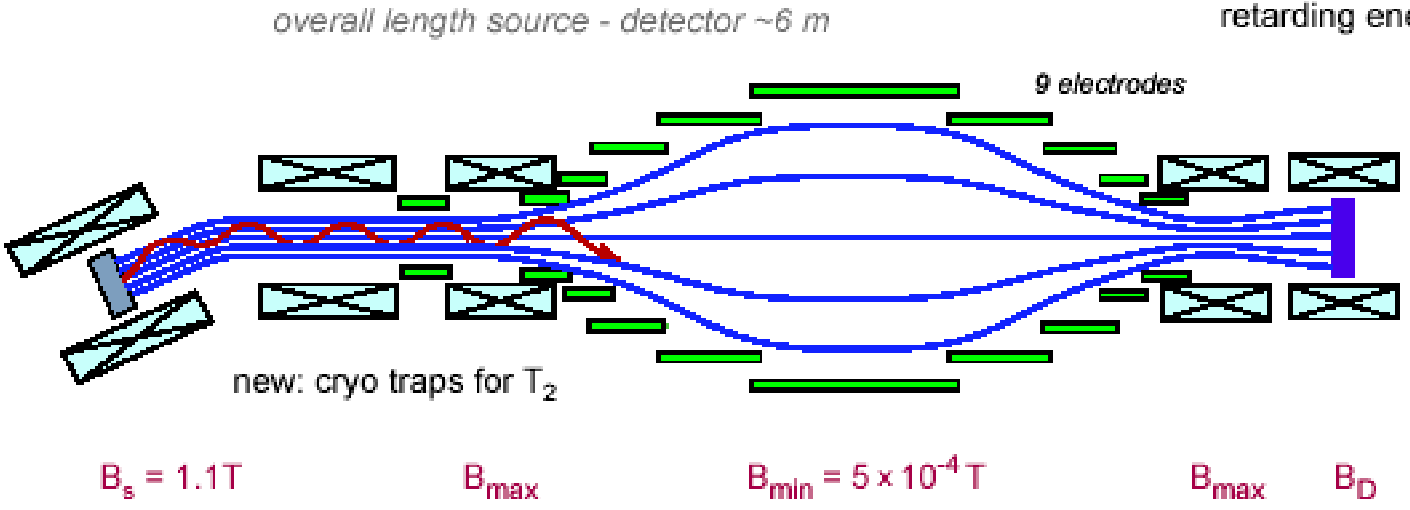
Mainz Neutrino Mass Experiment

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 Results

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

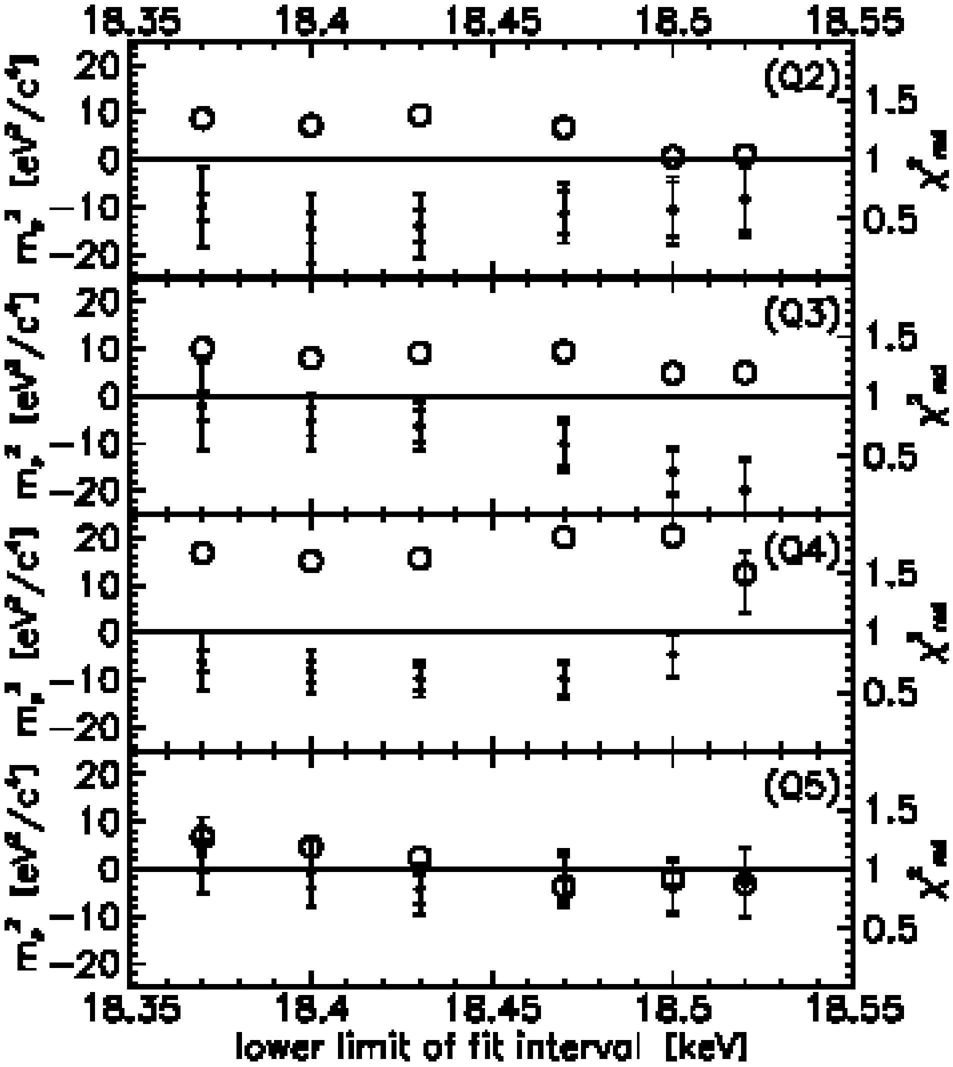
Change made to “sweep” spectrometer backgrounds between data points starting at run Q5.

Detailed studies published on source systematics.

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

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

A solid result.



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

Future β-decay endpoint measurements

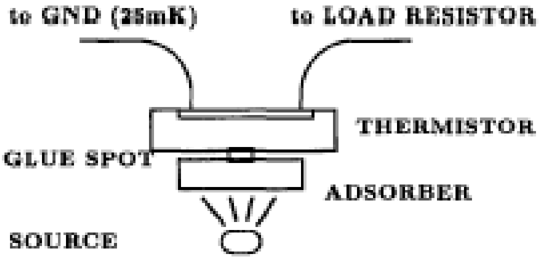
- Ultimate sensitivity of spectrometers
  - require instrumental resolution of ~ m_ν/E_o
  - spectral fraction per decay that falls in the last m_ν of the spectrum is ~ $(m_\nu/E_o)^3$
  - source thickness is set by the inelastic scattering cross-section (3.4×10^{-18} cm^2), $\sigma n \leq 1$
  - If one wants ~1 event/day in last m_ν of the spectrum
    - for a 10 m magnetic spectrometer $m_\nu \sim 1.7$ eV
    - for a 3 m dia. solenoid retarding field spectrometer $m_\nu \sim 0.3$ 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

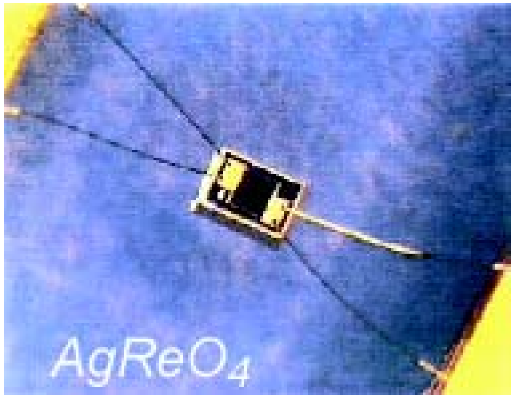
See Wilkerson and Robertson, Direct Measurements of Neutrino Mass, Sect 3.6

^{187}Re β-decay microbolometers

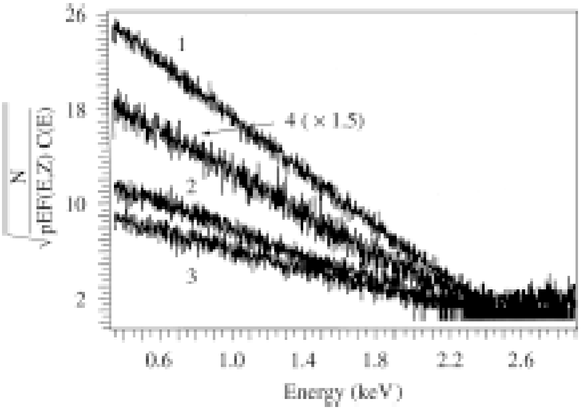
^{187}Re Æ $^{187}Os + e^{-} + \overline{\nu}_e$

- lowest Q-value: 2.6 keV
- 63% abundance
- $5/2^{+}$ Æ $1/2^{-}$ first forbidden transition (requires shape correction)

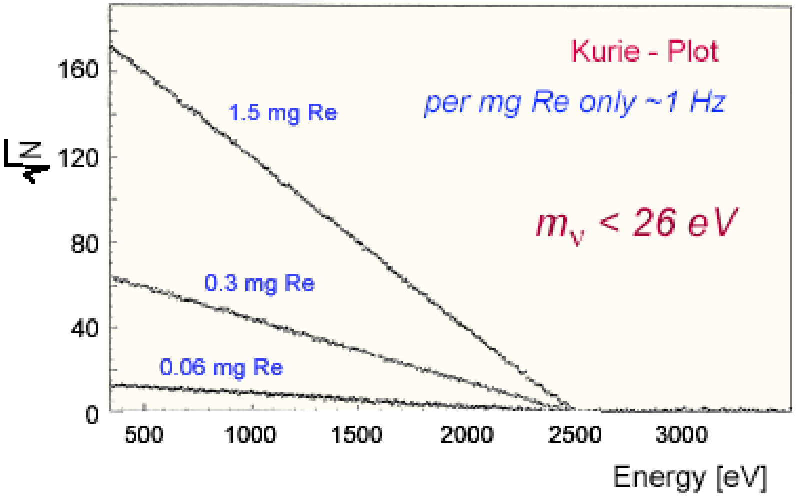




Fiorini, INFN Milano - $AgReO_4$



Gatti, INFN Genoa - Re crystal



10 μcalorimeters (250 μg, ΔE ~ 25 eV, t_{rise} ~ 1 ms) m_ν sensitivity: 10 eV in 1 year

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 $eV^2 \rightarrow 0.09\ eV^2$)

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

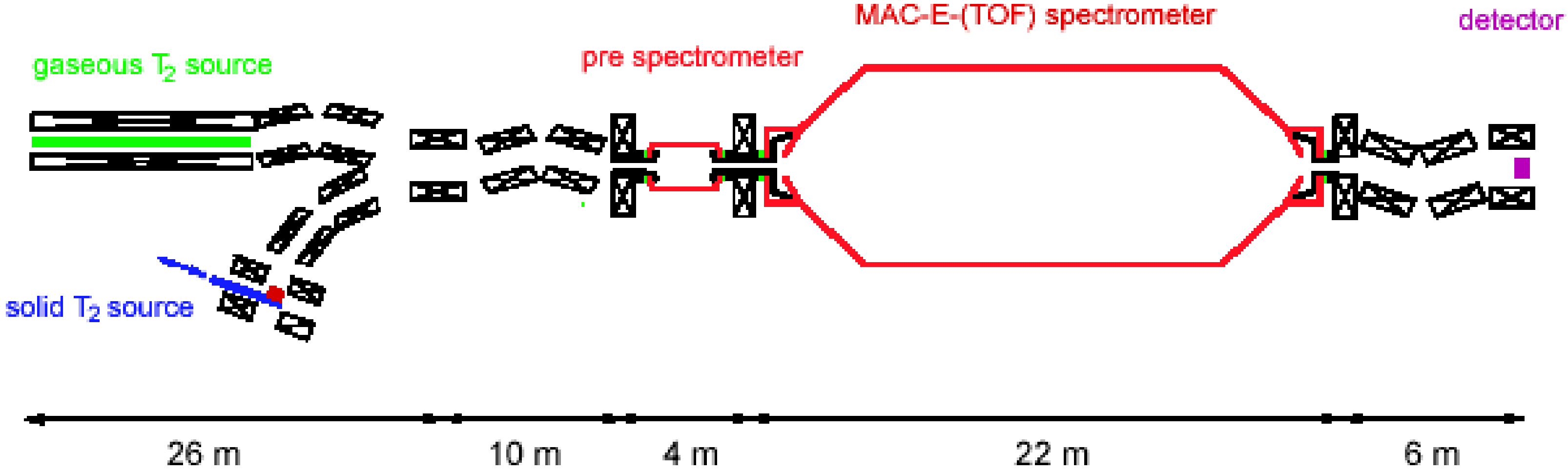
Karlsruhe Tritium Neutrino Experiment (KATRIN)

next-generation experiment with sub-eV neutrino mass sensitivity

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

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

molecular tritium source	pumping	pre-filter	energy analysis	ß-electron counting



KATRIN Collaboration

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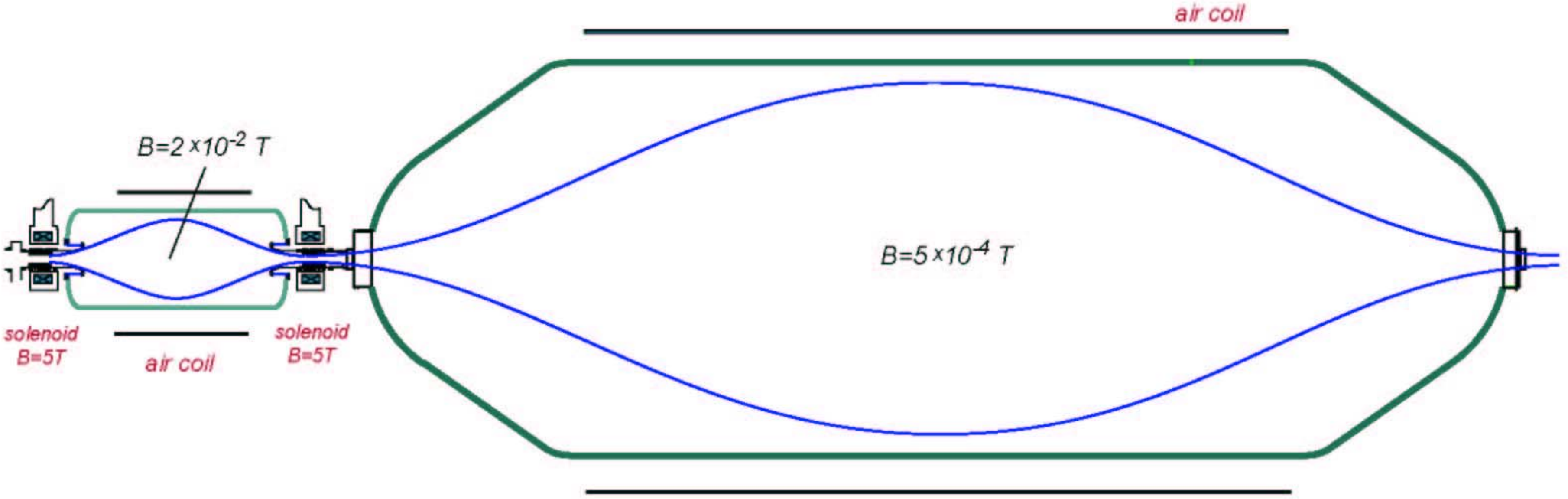
electrostatic spectrometers - properties and geometry

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

XUHV - conditions : p < 10^{-11} mbar (degassing rate 10^{-13} mbar l / cm^2 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

Technological Challenges

electrostatic spectrometer

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

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

HV control & stabilization

optimized electrode system

tritium sources

stable & safe tritium supply

high luminosity & reliability

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

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)

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

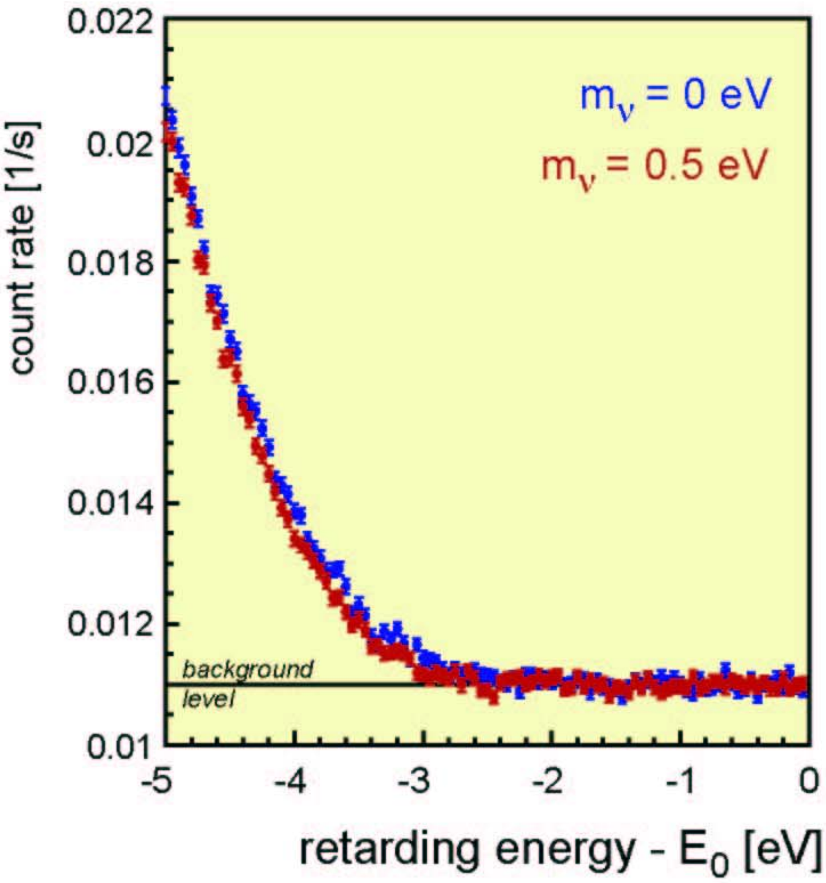
interdisciplinary solutions are required

Forschungszentrum Karlsruhe

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 5×10^{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

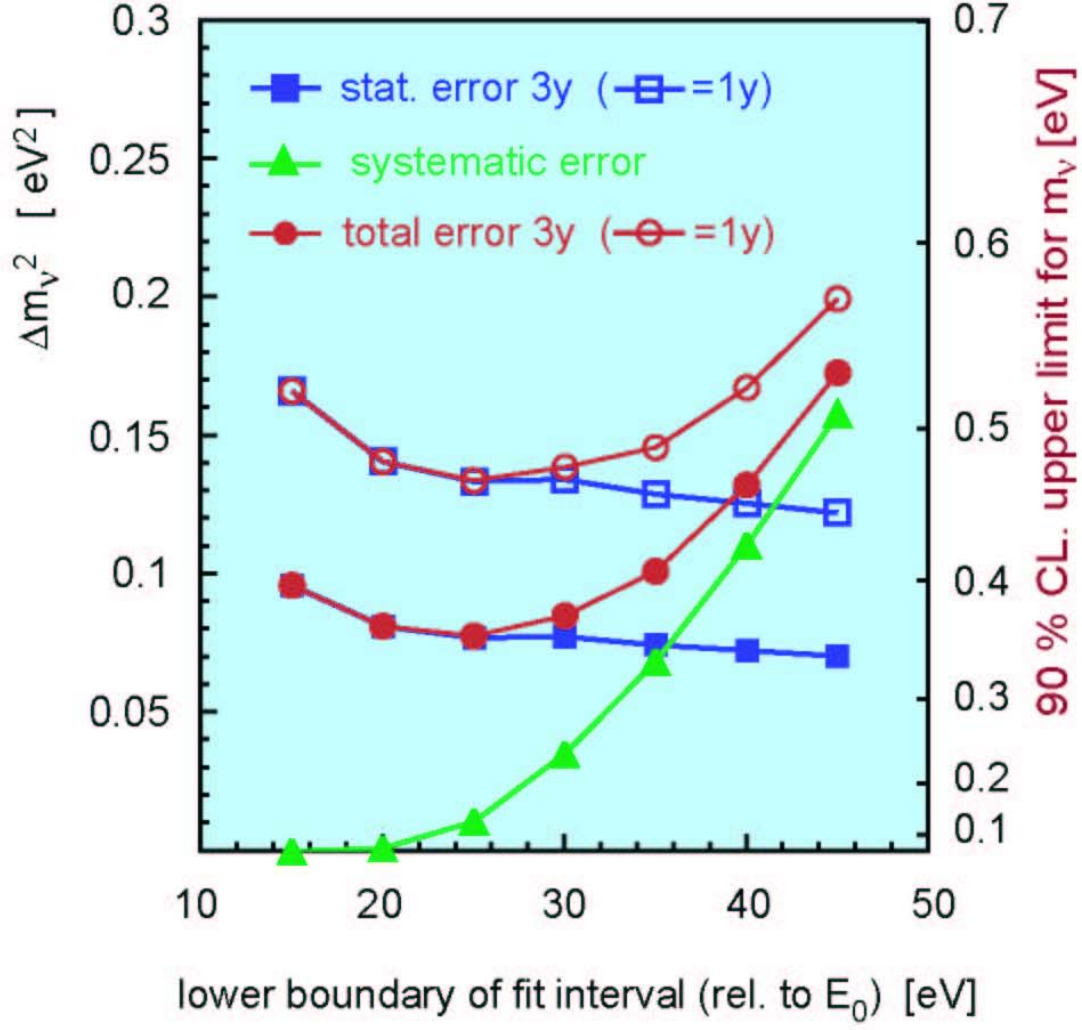
- *no contribution from excited electronic states of ^{3}He-T ($\delta E > 25$ eV)*
- *small contribution from inelastic scattering in source (for δE-Interval of 25 eV : 2% of signal from scattered electrons)*

+ 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

$m_\nu < 0.35$ eV (90% CL.)

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
7/2002	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
2007	commissioning and begin of data taking

Summary

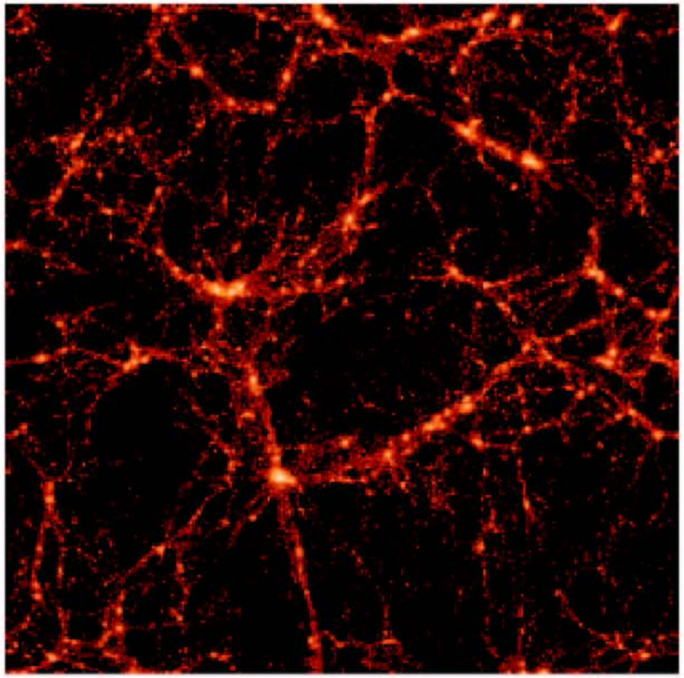
- **There are compelling reasons to attempt sub-eV sensitivity absolute neutrino mass measurements.**
  - Understanding neutrino properties.
  - Impact on cosmology and astrophysics
- **Large leptonic matrix mixing angles make sub-eV β-decay endpoint measurements an ideal method to directly probe neutrino mass.**
- **Direct measurements combined with oscillation and 0νββ decay results can discriminate between a variety of 3 and 4 neutrino mass spectrum scenarios.**
- **KATRIN should be able to achieve a mass sensitivity of 0.35 eV, nearly an order of magnitude improvement over current experiments.**

neutrino masses in cosmology

primordial neutrinos as hot dark matter

$$\Omega_\nu h^2 = \Sigma m_\nu / 92 \text{ eV}$$

Hubble parameter h= 0.65 (65 km/s/Mpc)

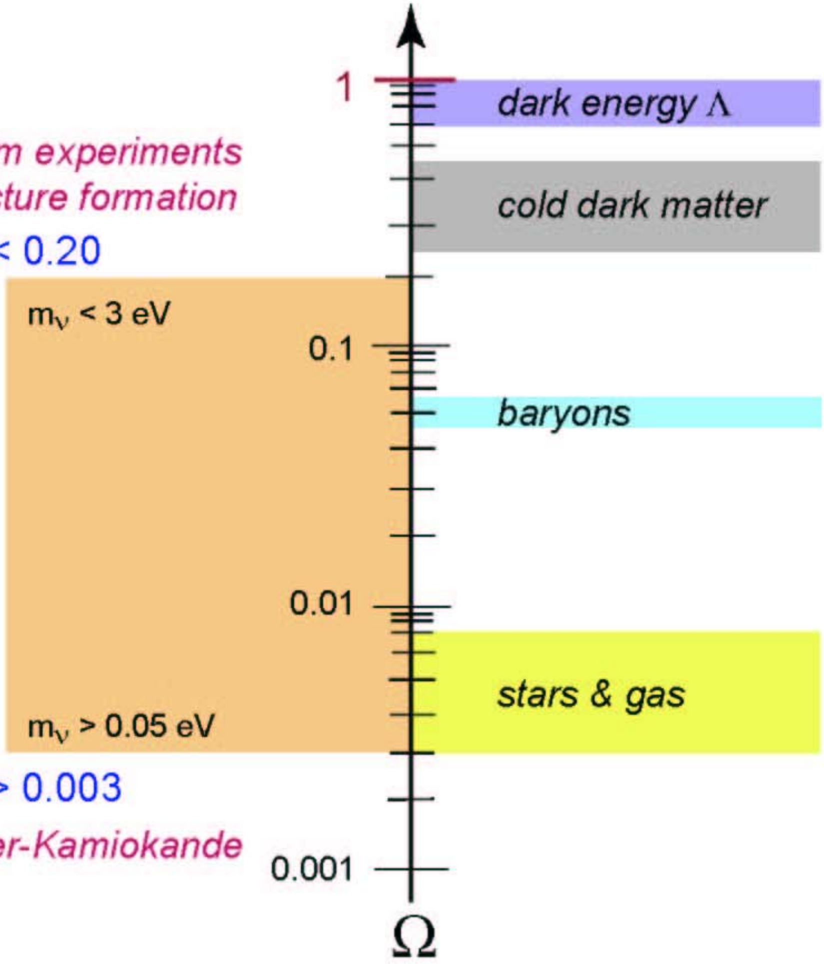


evolution of large scale structures

$\Omega = 1$ *critical density & flat universe (inflation)*

tritium experiments
structure formation

$\Omega_\nu < 0.20$



dark energy Λ

cold dark matter

$m_\nu < 3$ eV

baryons

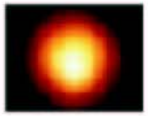
stars & gas

$m_\nu > 0.05$ eV

$\Omega_\nu > 0.003$

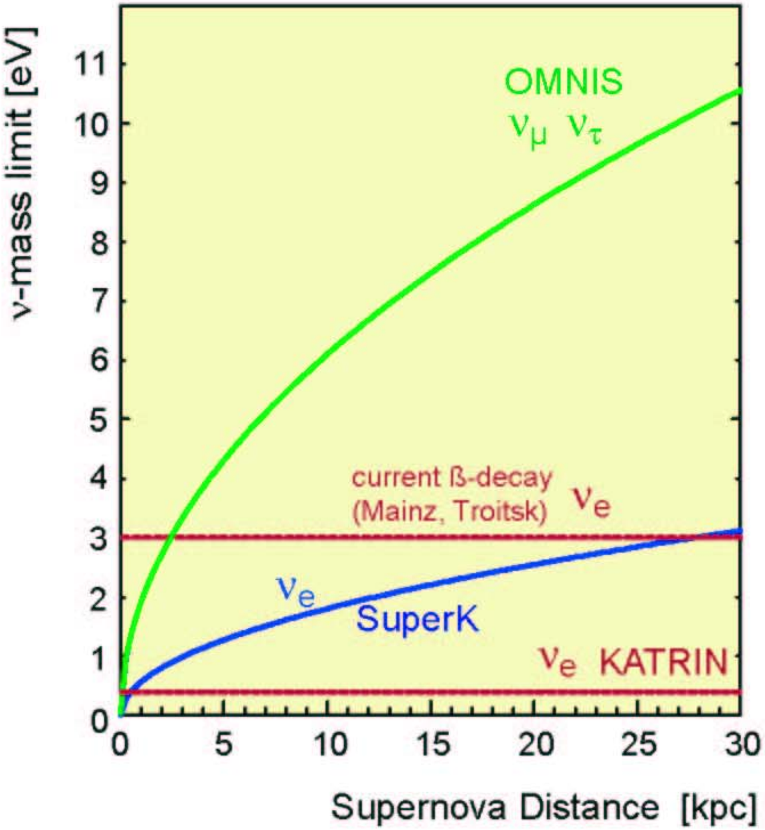
Super-Kamiokande

ν–masses: sensitivity from a SN ν – signal



SN20xx

future m_ν limits expected from SN-ν
cutoff due to early black hole formation



'standard' method :
use time delay due to rest mass: f (E_ν, Δt_ν)

$$\boxed{\Delta t_\nu \text{ [sec]} = 0.026 \cdot d \text{ [50 kpc]} \cdot m_\nu \text{ [1eV]} \cdot E_\nu^{-2} \text{ [10 MeV]}}$$

limit from SN1987a :
11 ν's in Kamiokande and 9 ν's in IMB-3

$m(\nu_e) < 23$ eV

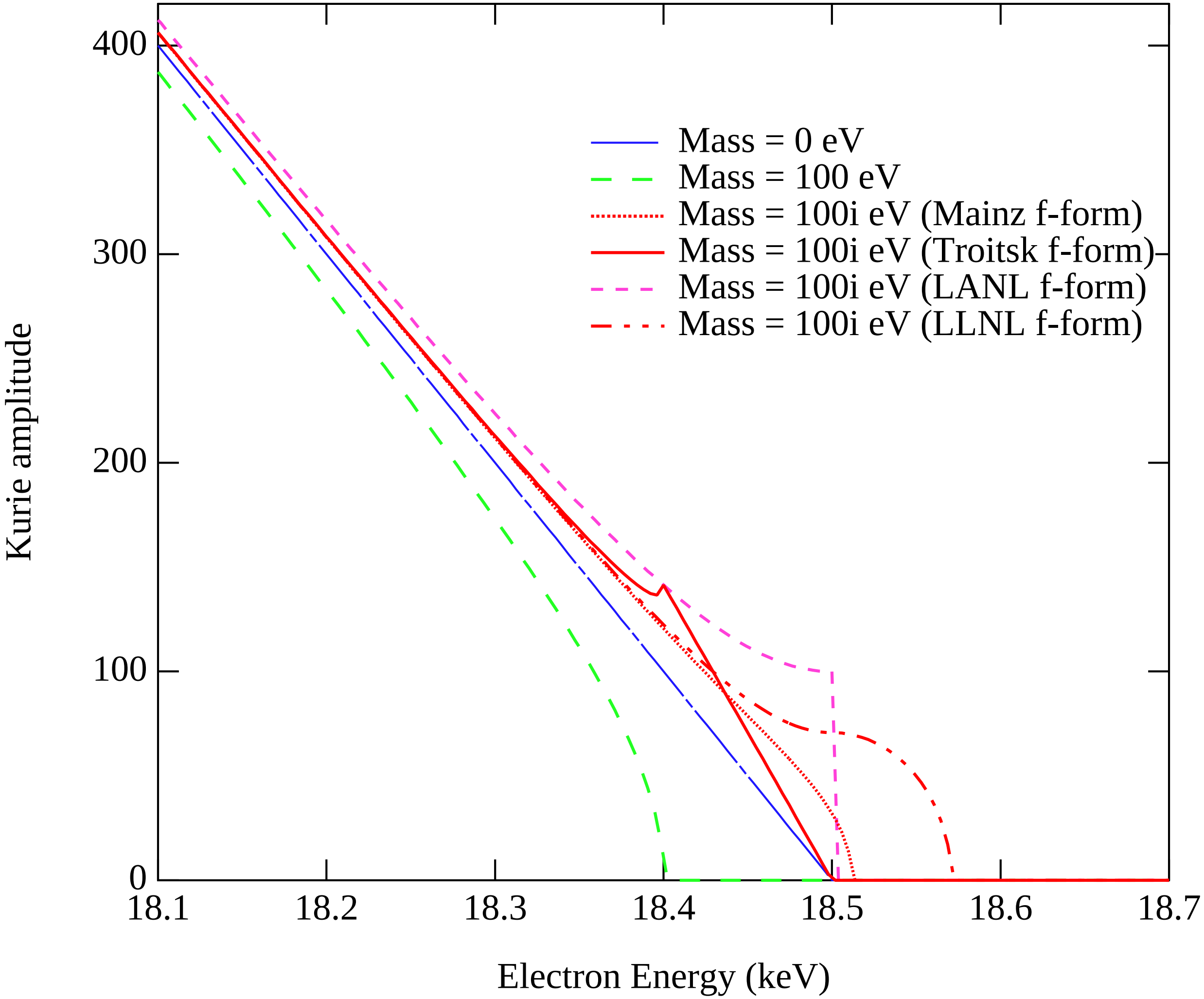
improved methods (SN - network) :

a) cutoff due to early black hole formation (problem : neutron star - black hole ratio uncertain)

b) correlation of ν-signal with gravitational waves (Virgo,Ligo)

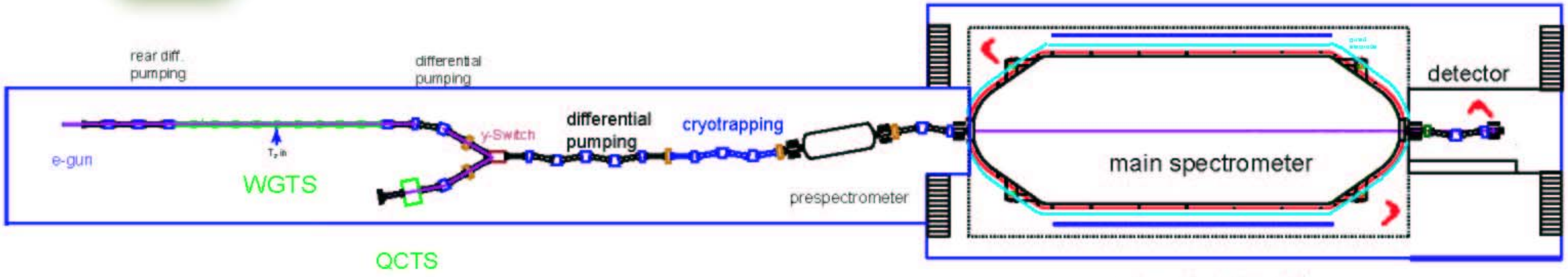
Dealing with excess counts near the endpoint

Directly comparing results with excess counts is impossible since each experiment uses different functional forms to accommodate excess counts near the endpoint.

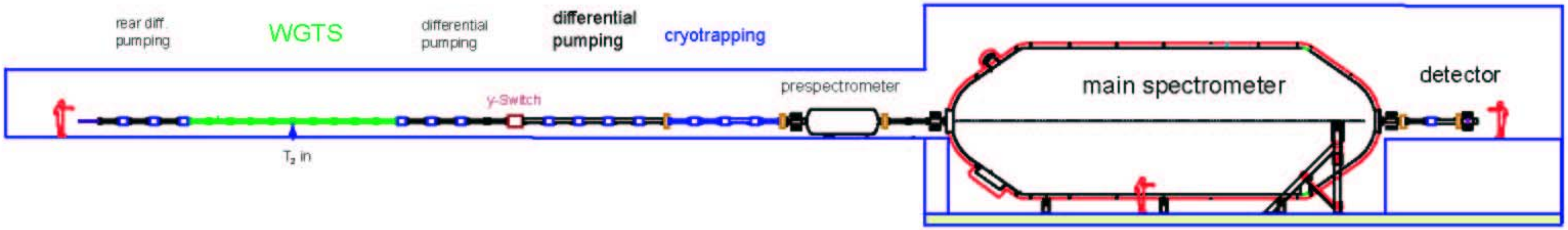


KATRIN experiment in linear configuration

top view



spectrometer hall l = 30 m



side view

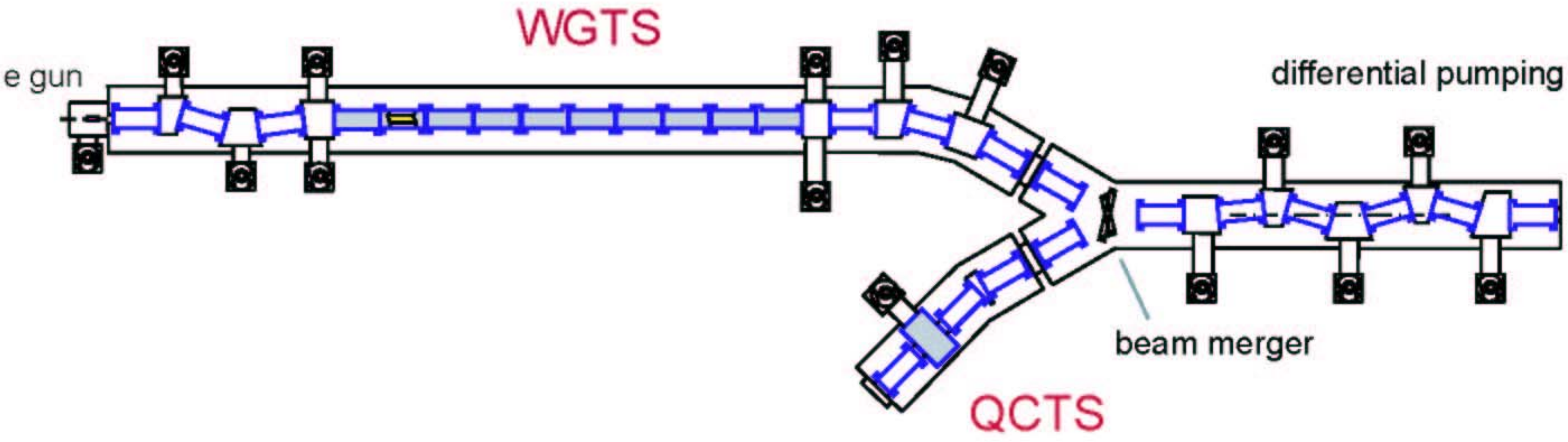
total length of KATRIN experimental hall
in linear set up ~ 70 m

Molecular Tritium Sources : WGTS & QCTS

two sources : independent measurements with different systematic effects

Windowless Gaseous Tritium Source

Quench Condensed Tritium Source



WGTS

design parameters : length 10 m
diameter : 70 mm
temperature : 30 K

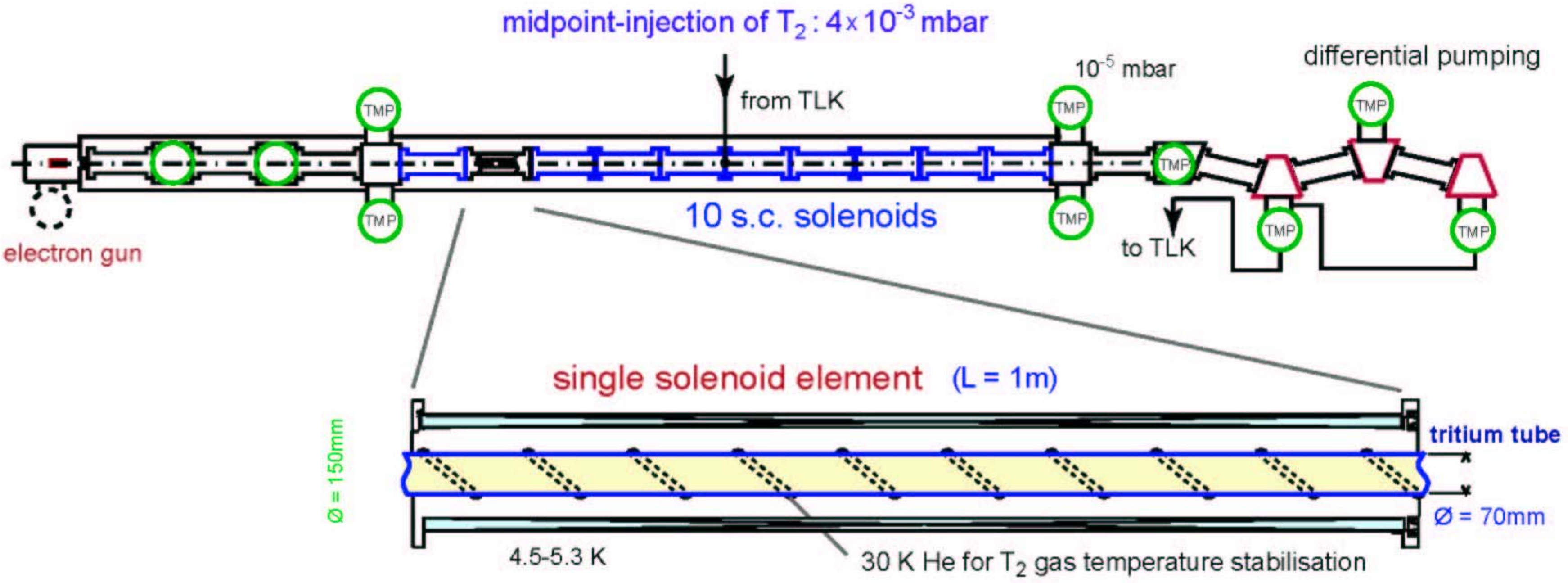
QCTS

design parameters : thickness ~35 nm
diameter : 70 mm
temperature : 1.6 K

WGTS - Windowless Gasous Tritium Source

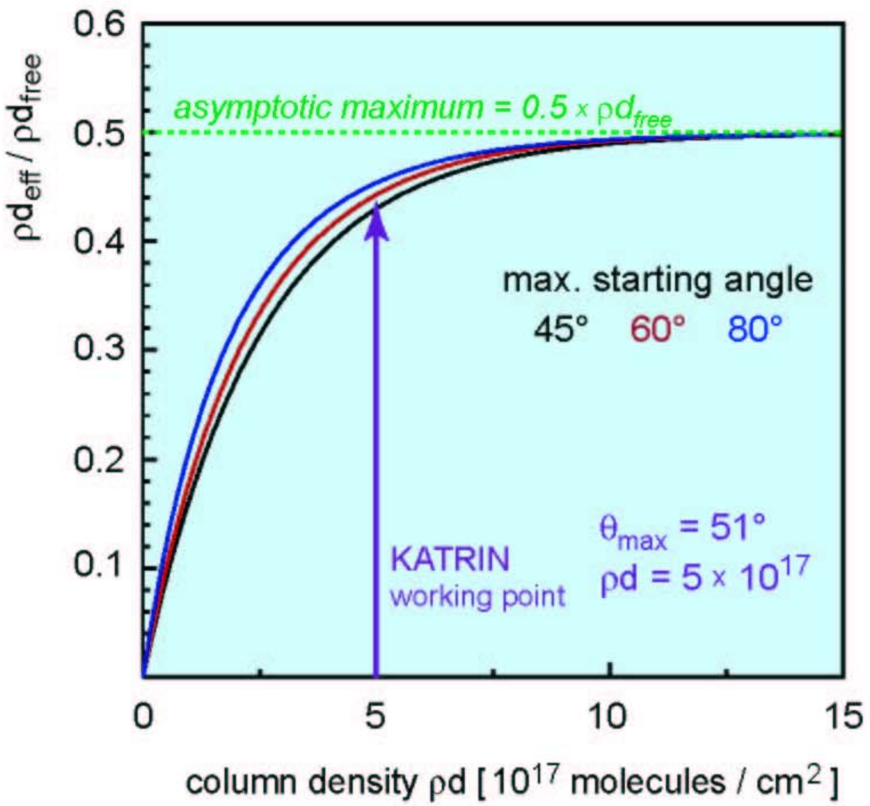
WGTS : maximum T_2 luminosity & smallest possible systematic errors
adiabatic electron transport in strong magnetic field & tritium diffusion

source parameters : L = 10 m, Ø = 70 mm, $B_S = 6$ T, gas purity > 99.5% T_2
T = 30 K (± 0.2°), column density ρd : 5×10^{17} T_2 / cm²



WGTS parameters: column density ρd

choice of column density ρd and θ_{max} to maximise ß-count rate



Signal rate S close to ß-end point ('no loss' electrons : no inelastic scattering in WGTS)

$$S \sim \underbrace{(A_s \times \rho d)}_{N(T_2)} \cdot \underbrace{(1-\cos\theta_{max})}_{d\Omega} \cdot \underbrace{P_0(\rho d, \cos\theta_{max})}_{\text{no loss}}$$

$$\boxed{S \sim A_A \cdot \Delta E/E \cdot \rho d_{eff}}$$

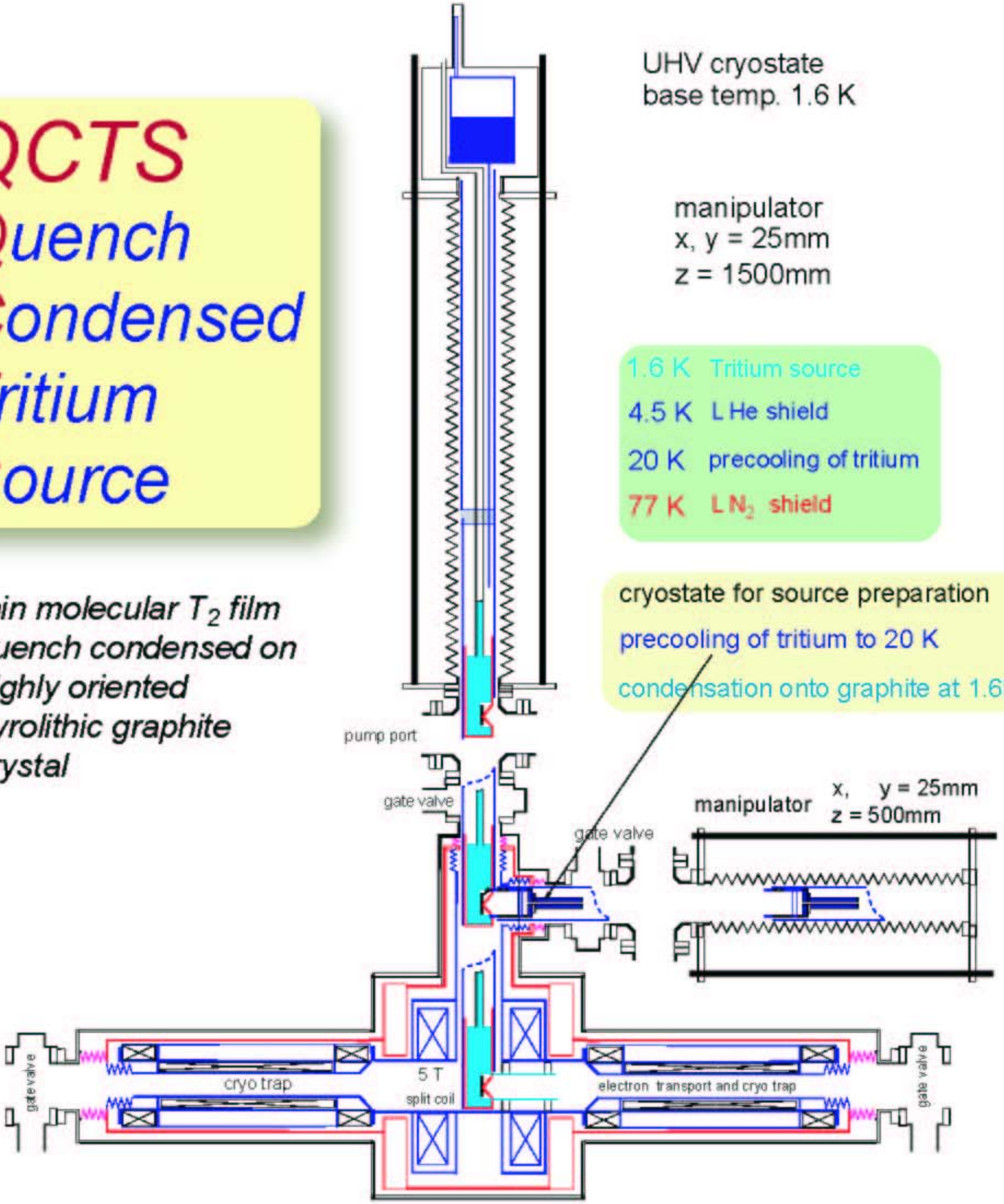
'effective' column density ρd_{eff}

virtual source of no loss ß-electrons at B_{max}

KATRIN WGTS delivers almost maximum count rate close to E_0

QCTS
Quench
Condensed
Tritium
Source

thin molecular T_2 film quench condensed on highly oriented pyrolithic graphite crystal



UHV cryostate
base temp. 1.6 K

manipulator
x, y = 25mm
z = 1500mm

1.6 K	Tritium source
4.5 K	L He shield
20 K	precooling of tritium
77 K	L N$_2$ shield

cryostate for source preparation

precooling of tritium to 20 K

condensation onto graphite at 1.6K

manipulator x, y = 25mm
z = 500mm

QCTS design parameters :

thickness : 340 Å (100 monolayers)

source diameter : 70 mm

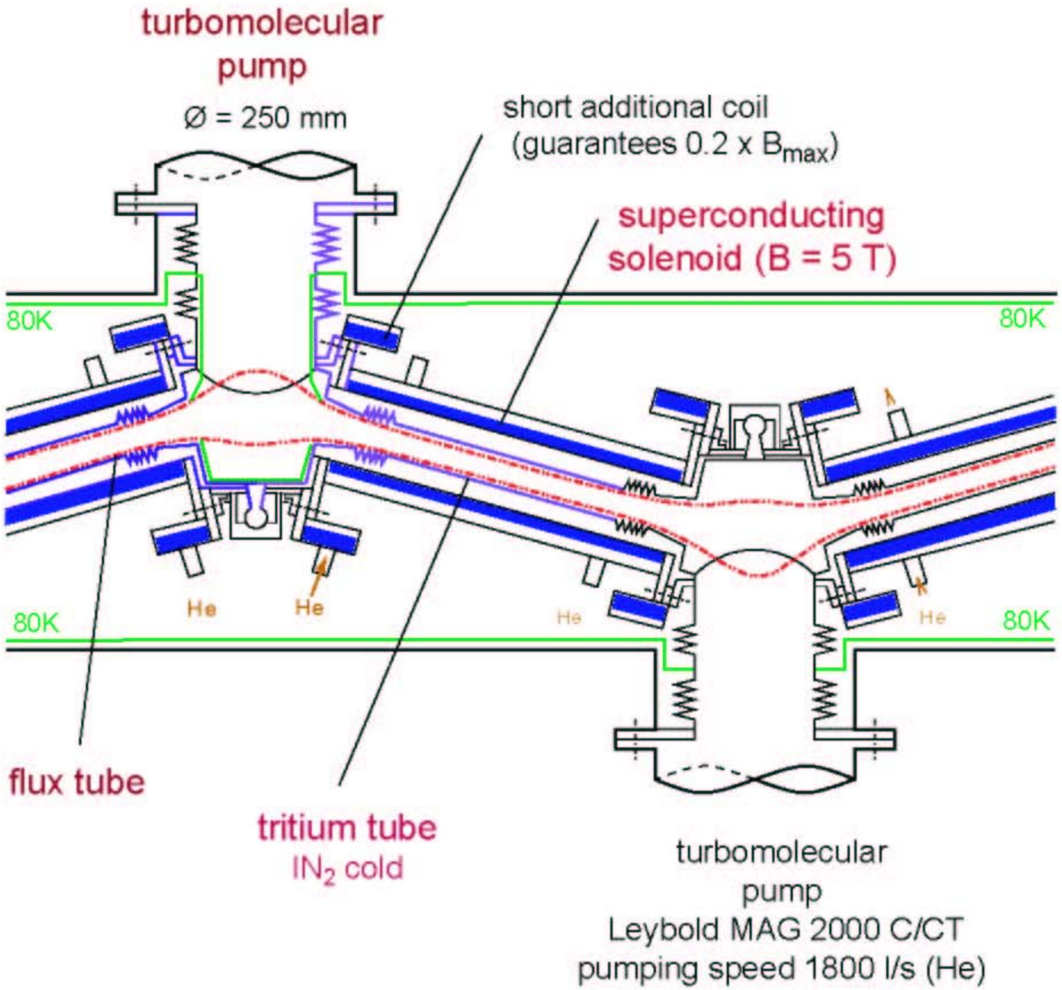
energy resolution : 2-3 eV

temperature :1.6 K (avoid roughening transitions)

effective lifetime : ~300 days (due to tritium evaporation)

The QCTS will provide results with independent systematic effects

layout of the differential pumping



differential pumping by turbo molecular pumps

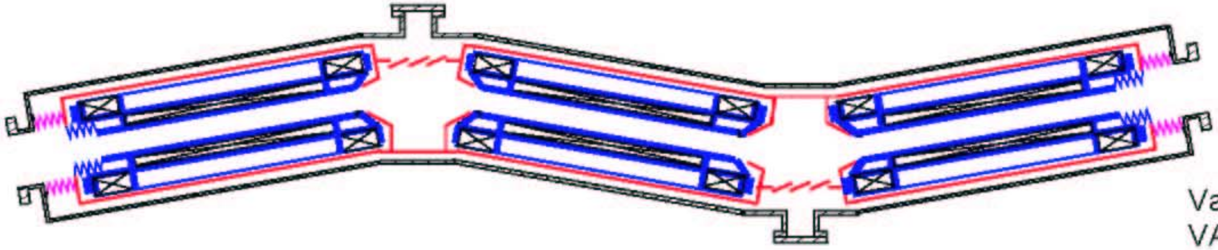
task :
tritium extinction by factor 10^9
transfer of used gas to TLK :
T_2 purification (>99.5%)

upstream :
tritium pressure < 10^{-7} mbar

tritium tubes and solenoids :
1 m long sections tilted by 20°

Electron transport and cryotrapping

tasks : transport of electrons to the spectrometer (B = 5 T)
inner tritium tube d = 90mm
cryotrapping of tritium & residual gases on lHe-cold bore



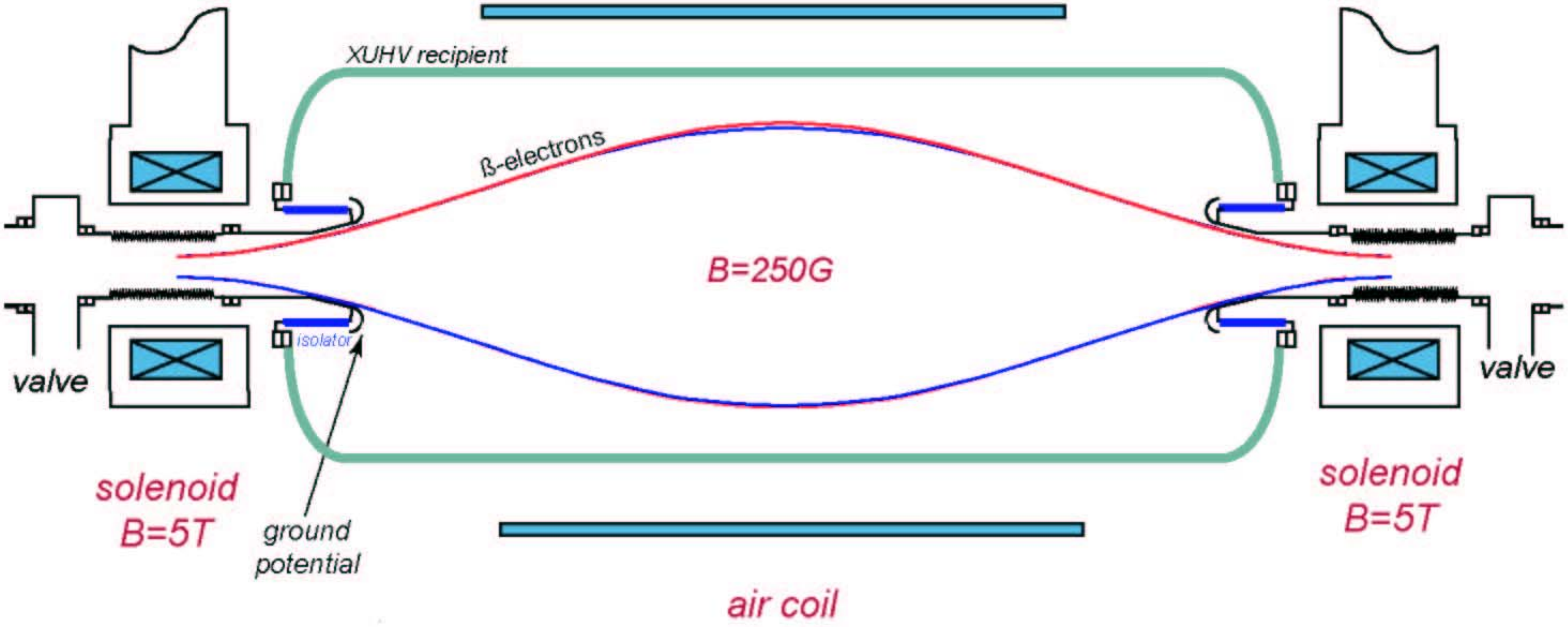
guided magnetic flux ~ 190 Tcm²
indvidual solenoids and pipes are tilted by 20° relative to each other
no direct line of sight !

cryptrapping part guarantees non-contamination of the spectrometer with tritium

KATRIN electrostatic pre-spectrometer

purpose : reject all ß-electrons with $E<18.45$ keV to suppress background in main spectrometer

ß-electron transmission factor : ~10^{-7} with $\Delta E < 80$ eV

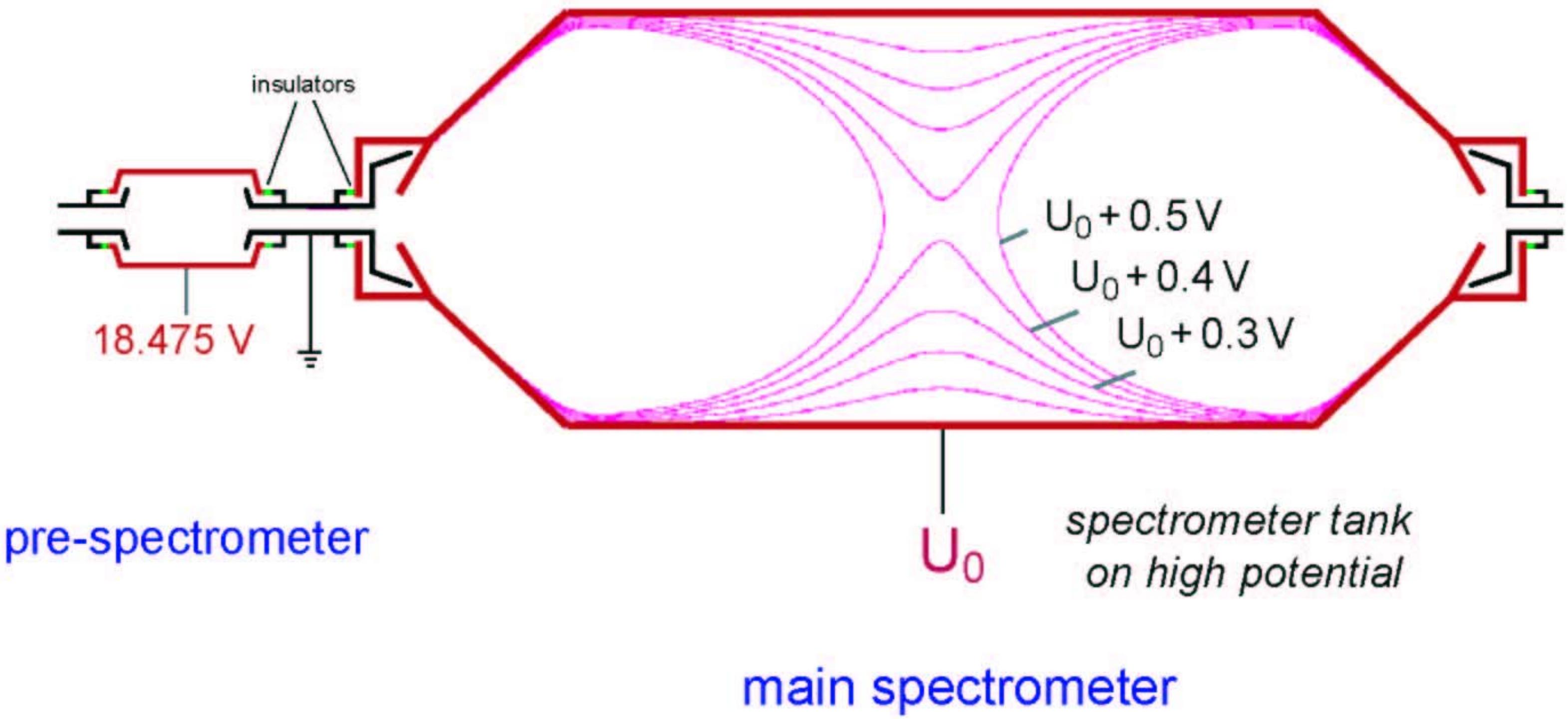


pre-spectrometer parameters: $l = 4.0$ m $Ø = 1.7$ m $p < 10^{-12}$ mbar

pumping by getters and TMPs

Optimization of the electrode design for the central spectrometer

symmetric drop of electrostatic potential in central plane
requirement: $\Delta U < 1$ V is met !

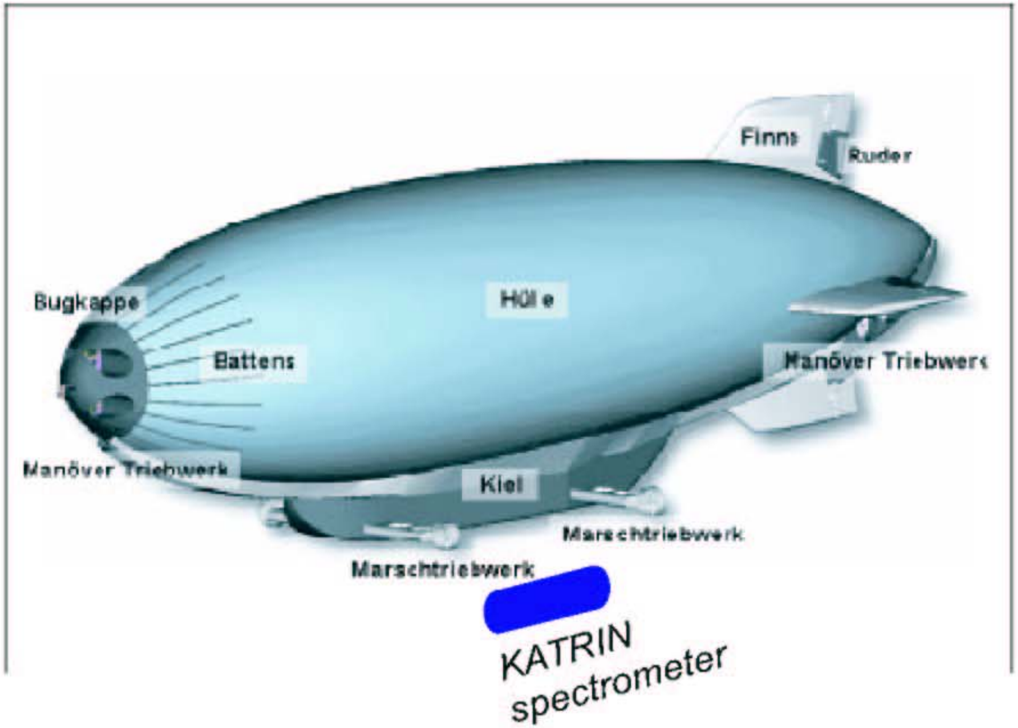


spectrometer tank on high potential

transport of the spectrometer to FZK

possible option : Cargolifter CL160

with 160 t transport capacity



Length 260 m , d = 65 m

cruising altitude :
maximum 2000 m

traveling speed :
80-100 km/h

costs : central european
manufacturer to FZK

~60 kEuro

Detector Requirements

large sensitive area (Ø = 100 mm, i.e. $\sim 10^4$ mm^2)

high efficiency for <20 keV e^- (minimum dead layer)

good spatial resolution to measure source profile
background studies ($\Delta x \times \Delta y \sim 5\text{-}10$ mm^2)

good time resolution for ToF mode ($\tau_{rise} < 0.1$ μs)

good energy res. / low el. noise ($\Delta E < 250\text{-}300$ eV)

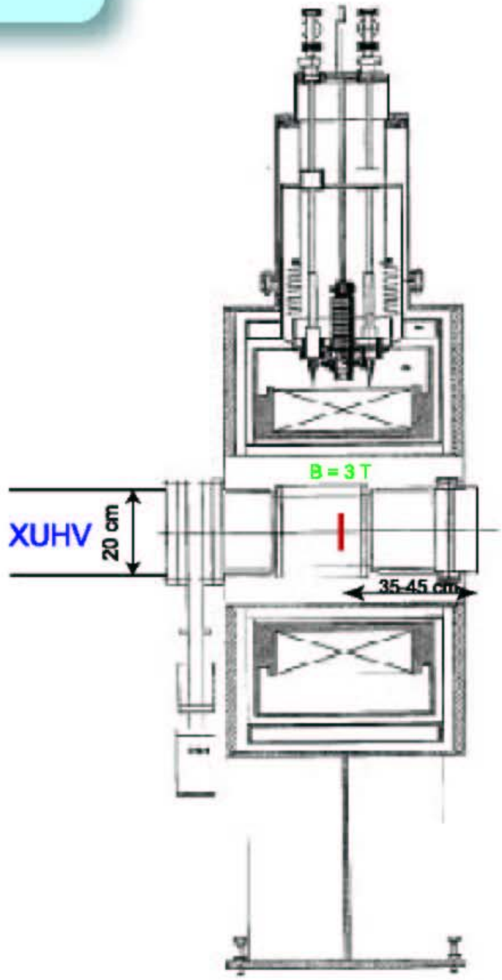
low γ-efficiency (thickness ≤ 300 μm)

small backscatter prob. for ß's (low Z, small angles)

low intrinsic background (bg rate ~ 1 mHz)

long-term operation a) strong B-fields (~ few T)
b) XUHV conditions

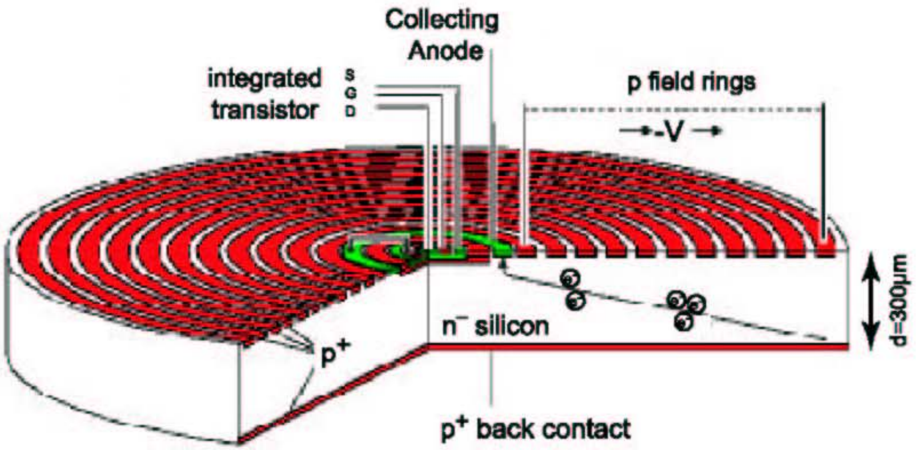
no LHC/Tesla radiation hardness required (rate ~ few mHz)



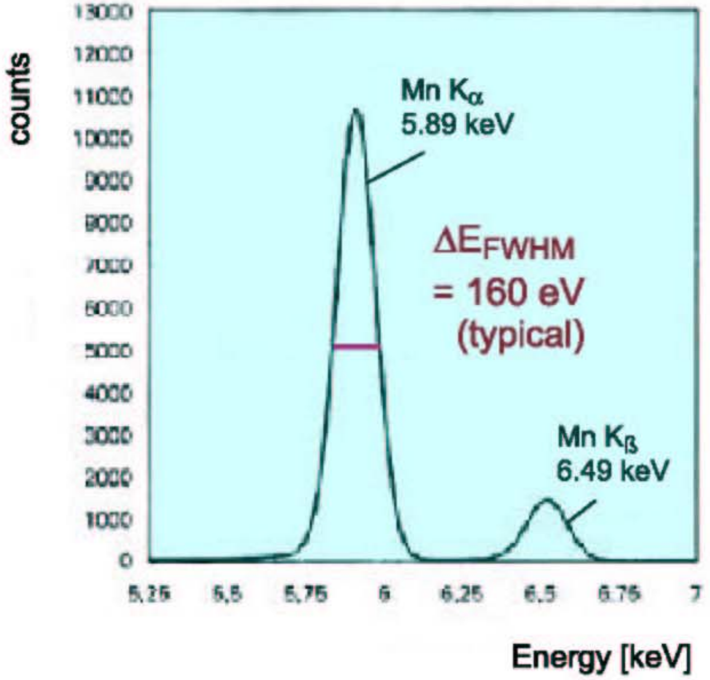
detector environment

Silicon Drift Diodes for detection of keV ß-electrons

manufacturers : Halbleiterlabor Garching & KETEK, Canberra



energy resolution from Fe-55 source



layout : active area 5-10 mm^2
small collect. anode diameter 100-400 µm
segmented p^+ junctions

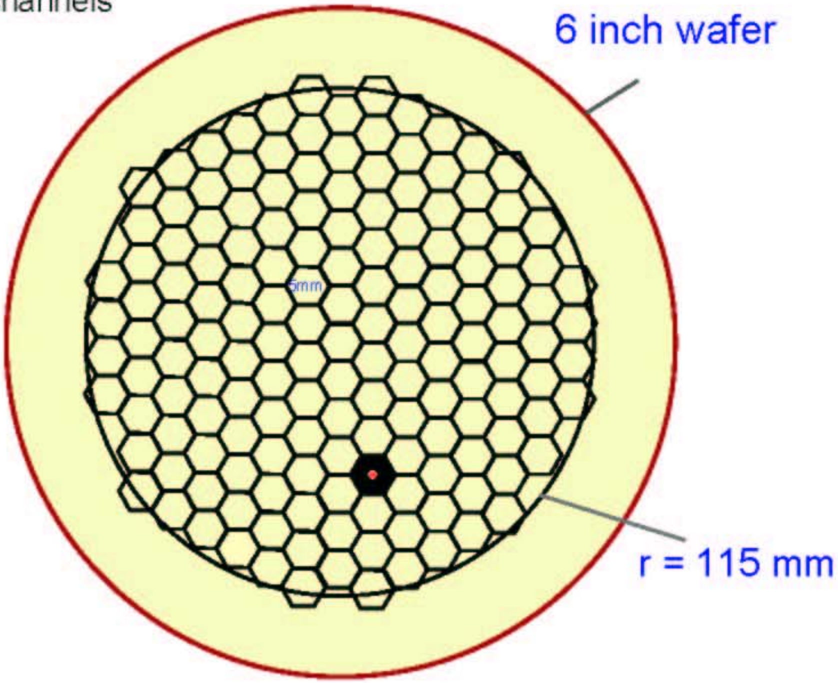
advantages : low capacitance ~ 0.1 pF
red. electronics noise (~90eV)
thin dead layer (30-50 nm)
integrated jFET
Peltier cooling sufficient

expected energy resolution @ 18.6 keV
ΔE (FWHM) = ~ 230 eV

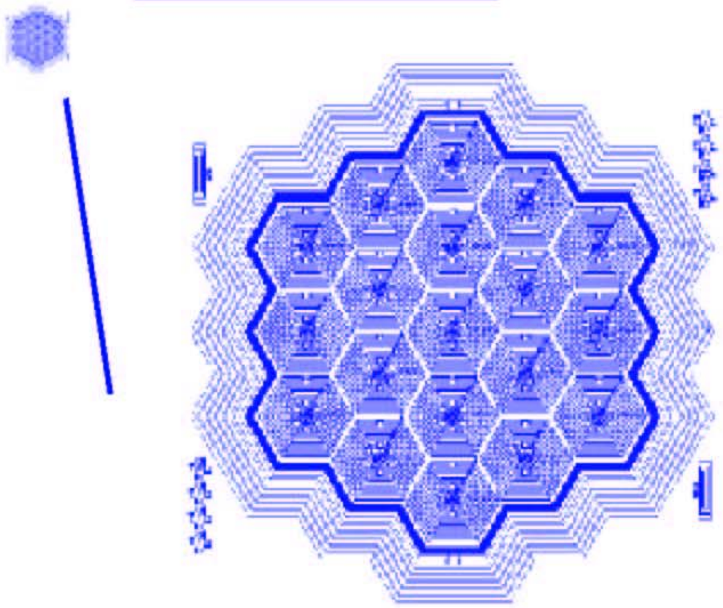
Multichannel Silicon Drift Diodes

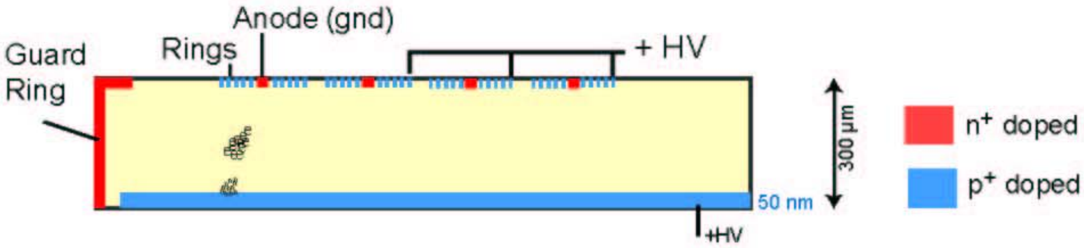
Monolithic Array *(very prelim.)*

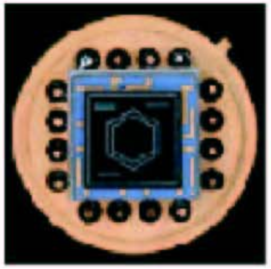
154 channels



current arrays of 19 SDDs (each 5 mm2)

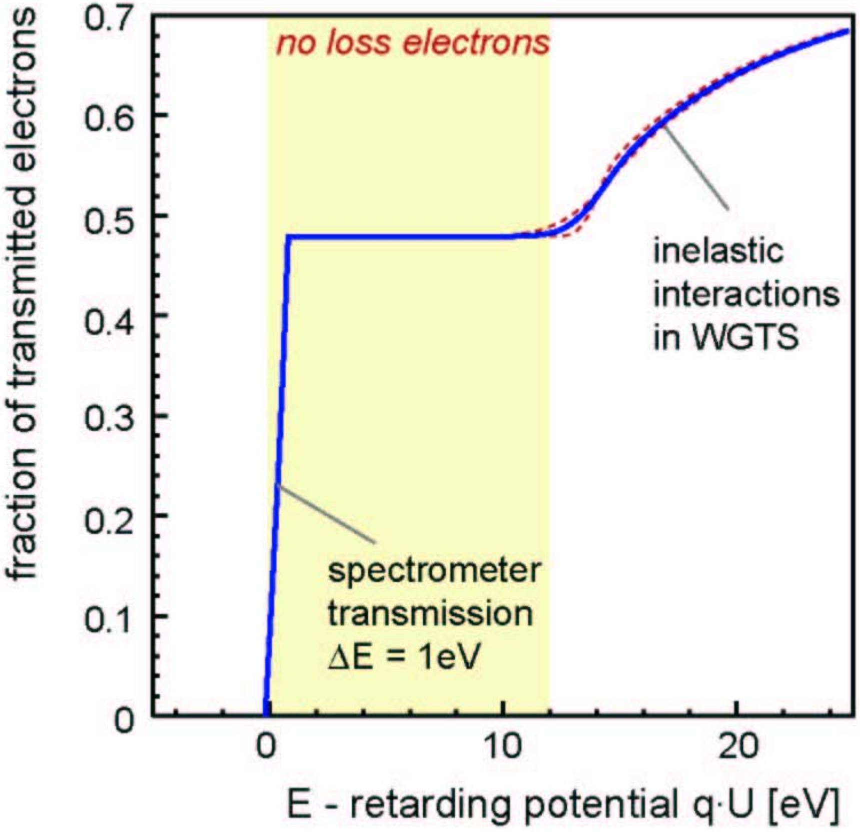






KATRIN response function

calculated response function for monoenergetic electrons (energy E)
emitted isotropically from WGTS close to tritium ß-endpoint at 18.6 keV



electrostatic spectrometer

analytical transmission function T :

depends only on B_S / B_A and B_A / B_{max}

no tails of resolution !!

molecular source WGTS

calculation of energy losses : $\sigma \times L(\theta)$

total cross section $\sigma = 3.4 \times 10^{-18}$ cm^2

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

max. accepted angle 51°

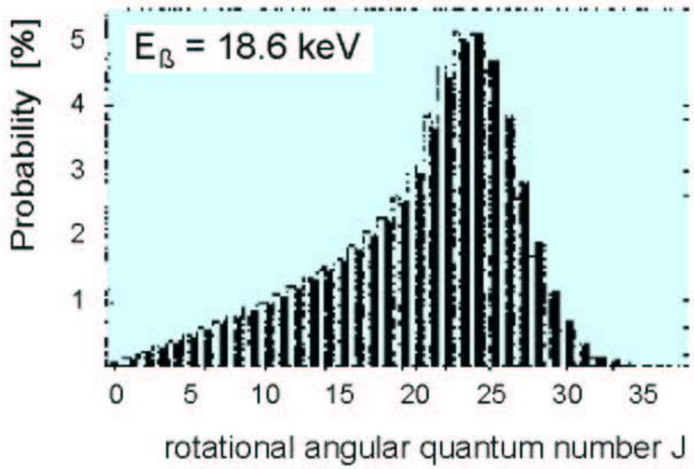
last 12 eV below E_0 :
only 'no loss' electrons !

Molecular Excitations of $^3HeT^+$

ß-decay of molecular T_2 : recoil energy, electronic & rotational-vibrational excitations

E_R = 1.72 eV @18.6 keV

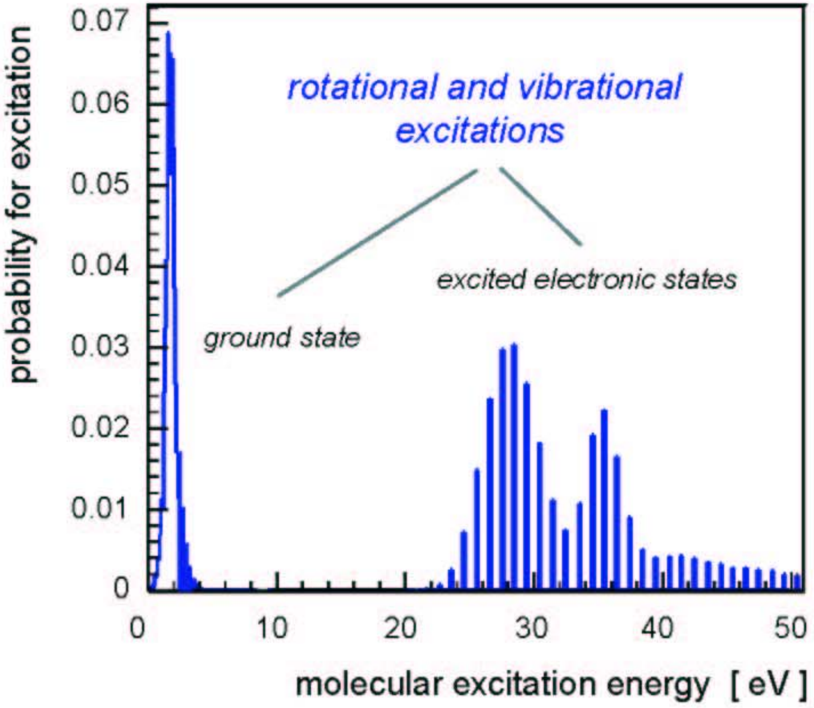
final state probability	*electronic final state*
14 %	continuum
29 %	excited states
57 %	ground state



absolute accuracy of theory = 0.2 %

A. Saenz, S. Jonsell, P. Froelich, Phys. Rev. Lett. 84 (2000) 242

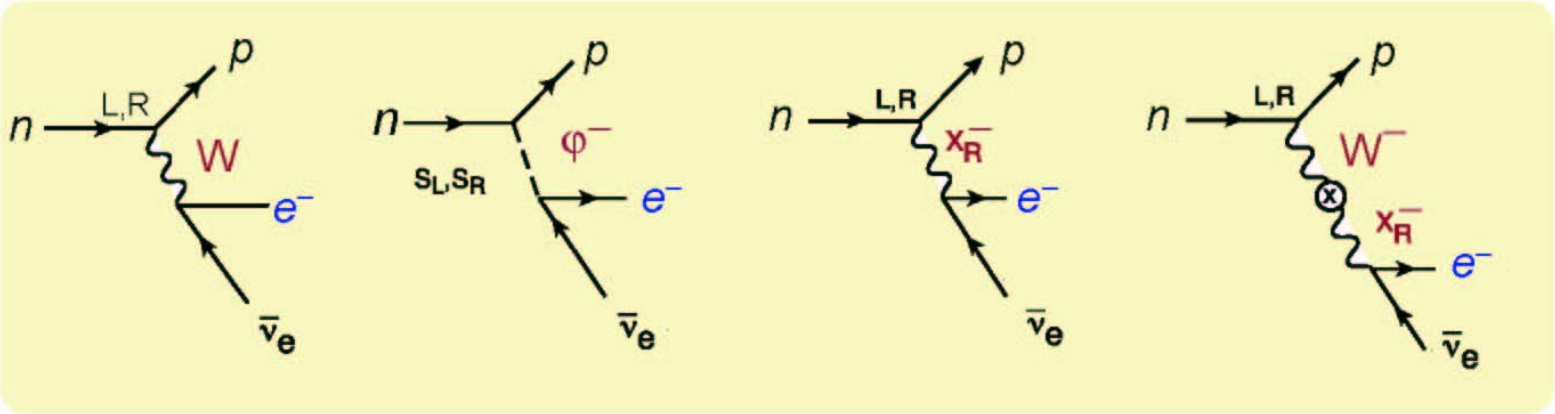
improved calculations of molecular final states



integration of spectrum yields 99.93% of total population probability

‚non ν-mass' physics with KATRIN

- tritium ß-decay as test for non-SM interactions :



SM process — scalar exchange — direct RH current — mixing

G.J. Stephenson, T. Goldman, B.H.J. McKellar, Phys.Rev. D62 (2000) 093013

- tritium ß-decay as test of tachyonic neutrinos

J. Ciborowski, J. Rembielinski, Eur.Phys.J. C8 (1999) 157