Direct neutrino mass experiments: Present and Future

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- Tritium β decay experiments at Mainz and Troitsk
- How to proceed?
  future projects
- KATRIN
  a large tritium β decay experiment with sub−eV sensitivity
- Conclusion

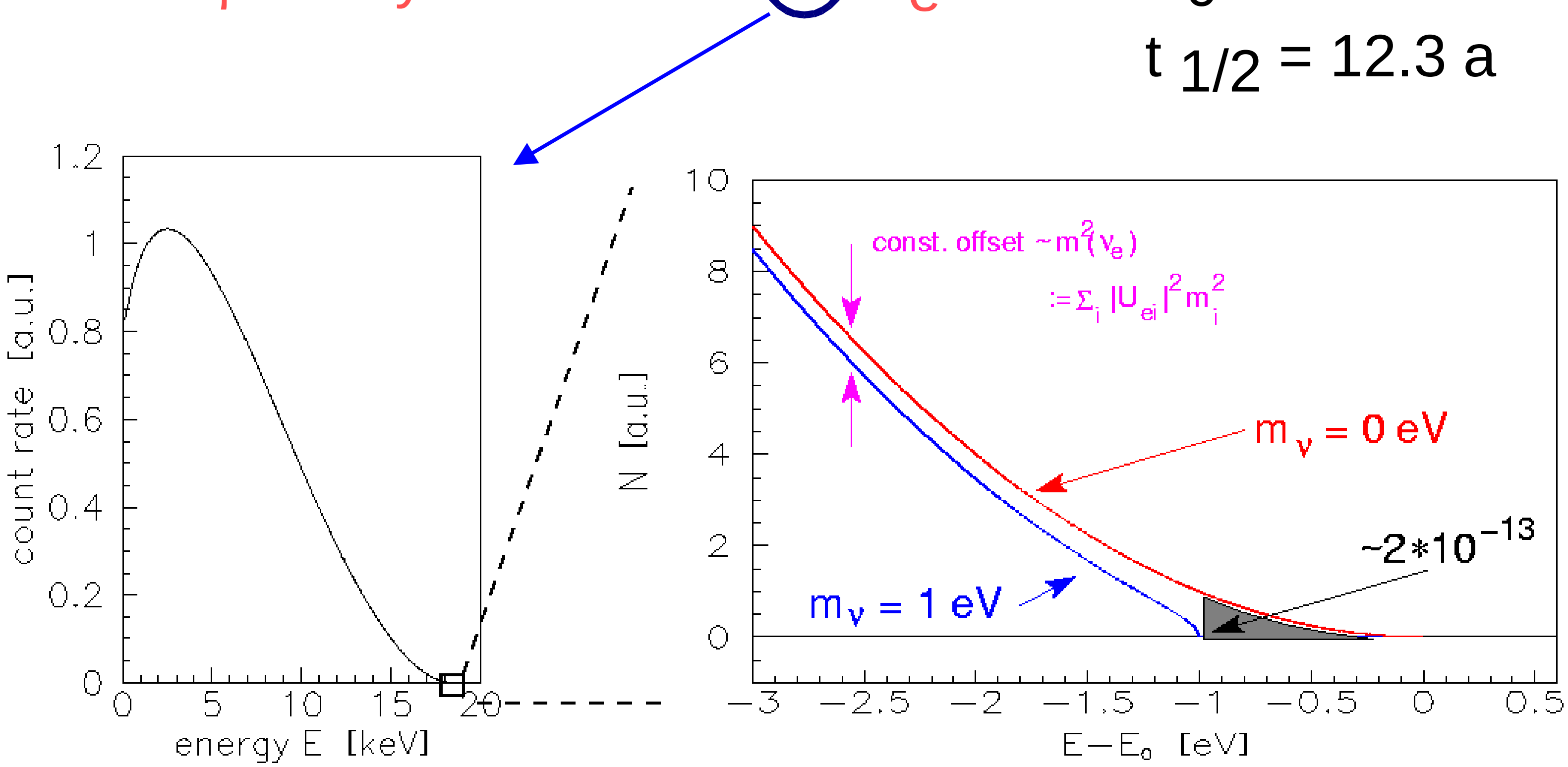
Direct measurement of $m(\nu_e)$

Tritium β decay: $^3H \rightarrow ^3He^+ + e^- + \bar{\nu}_e$

super−allowed

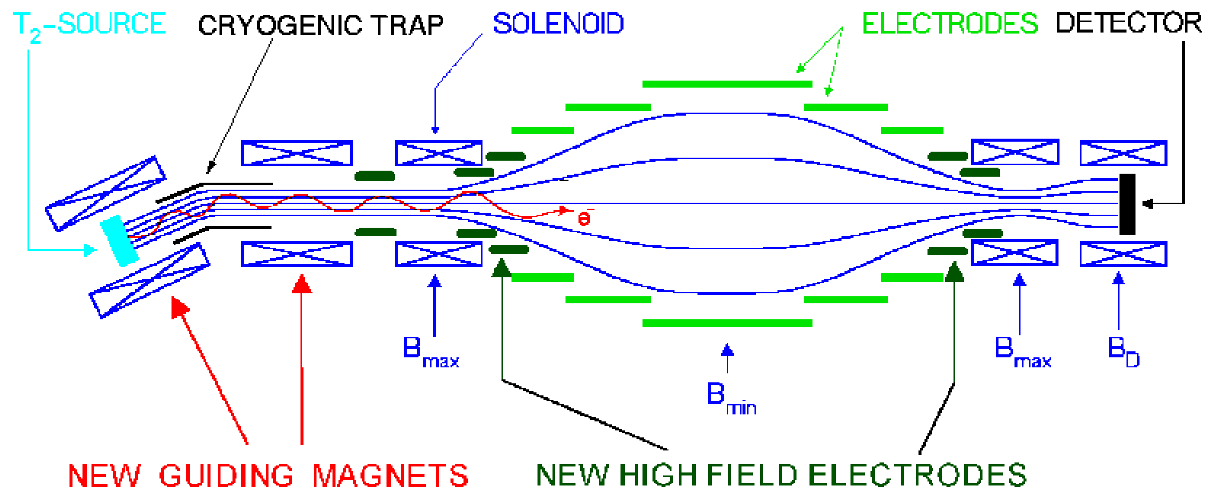
$E_0 = 18.6$ keV

$t_{1/2} = 12.3$ a



Need **very high energy resolution** &
very high signal rate &
very low background

Mainz Neutrino Mass Experiment since 1997

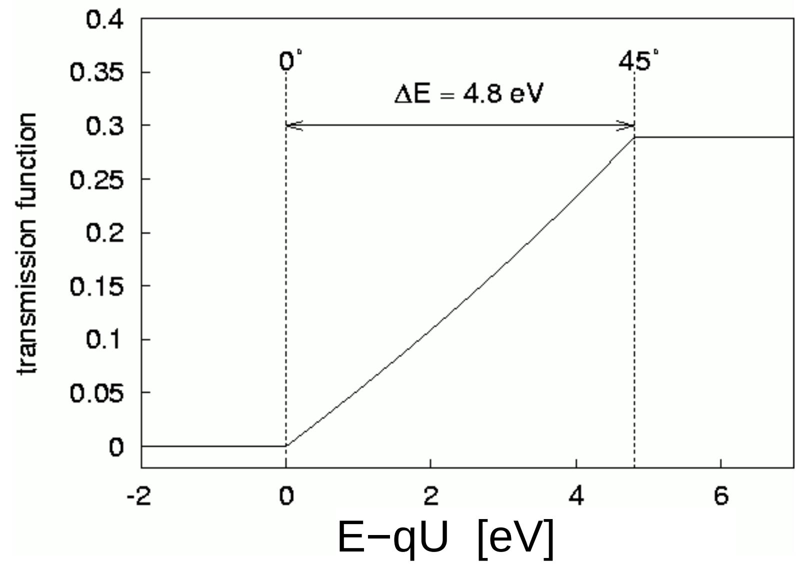


Magnetic Adiabatic Collimation + Electrostatic Filter (MAC−E−Filter)

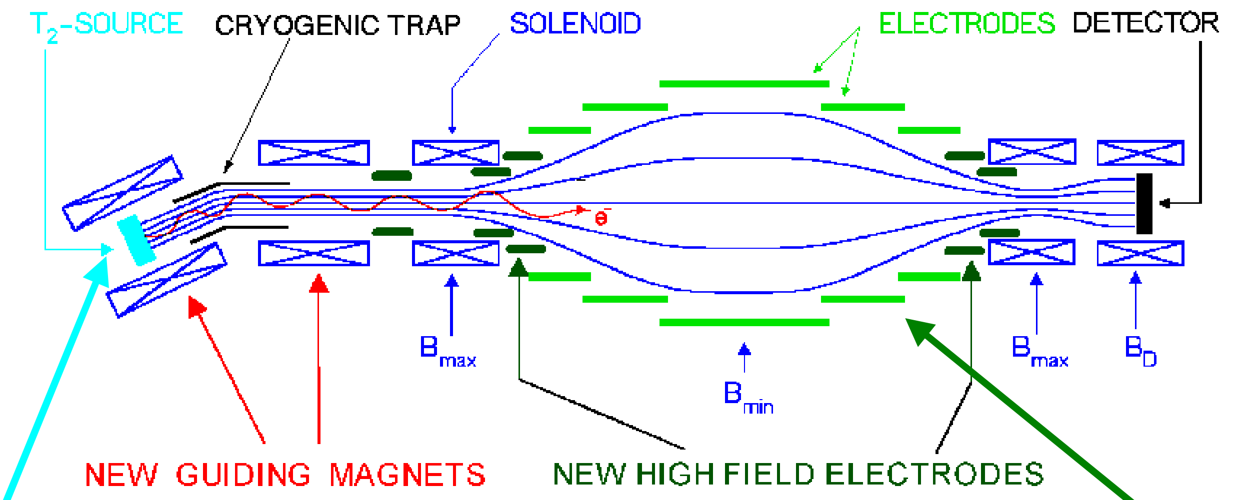
⇒ sharp integrating transmission function

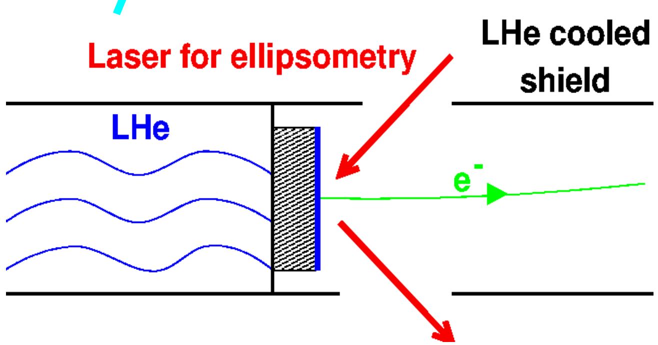
without tails:

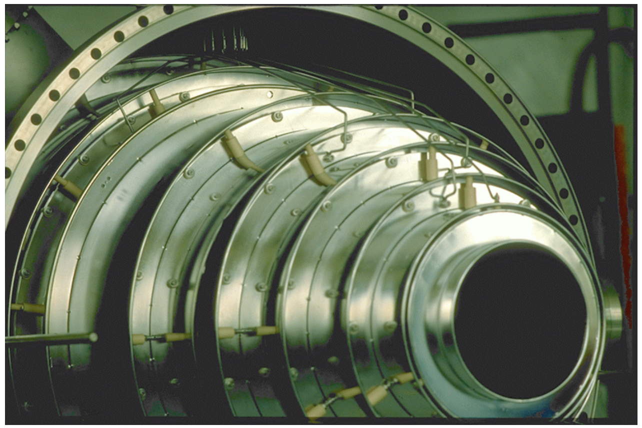
$\Delta E = E \cdot B_{min}/B_{max} = E \cdot A_{s,eff}/A_{analysis} \approx 4.8 eV$



Mainz Neutrino Mass Experiment since 1997







Mainz
ν group
2001:

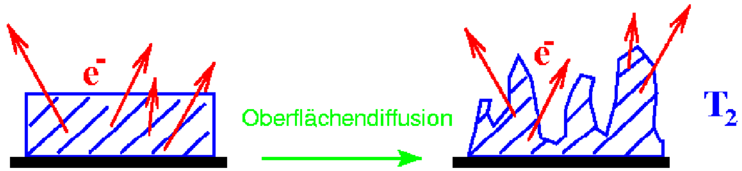
J. Bonn
B. Bornschein*
L. Bornschein
B. Flatt
Ch. Kraus
B. Müller
E.W. Otten
J.P.Schall
Th. Thümmler**
Ch. Weinheimer**

* → FZ Karlsruhe
** → Univ. Bonn

- T_2 Film at 1.86 K
- quench−condensed on graphite (HOPG)
- 45 nm thick (≈130ML), area 2cm^2
- Thickness determination by ellipsometry

Investigation and improvement of systematics

- **Roughening transition of T_2 film**

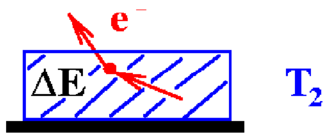


Determination of dynamics: $\Delta E = (45 \pm 6)\, k_B$ K

$\Rightarrow$ no roughening transition below 2 K

L. Fleischmann et al., J. Low Temp Phys. **119** (2000) 615, (with P. Leiderer
L. Fleischmann et al., Eur. Phys. J. **B16** (2000) 521 Konstanz)

- **Inelastic scattering**



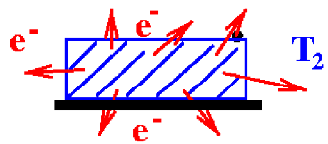
Deterimination of cross section:

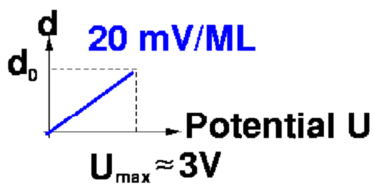
$$\sigma_{tot} = (2.98 \pm 0.16) \cdot 10^{-18}\ \text{cm}^2$$

Determination of energy loss function:

V.N. Aseev et al., Eur. Phys. J. **D10** (2000) 39

- **Self charging of T_2 film**





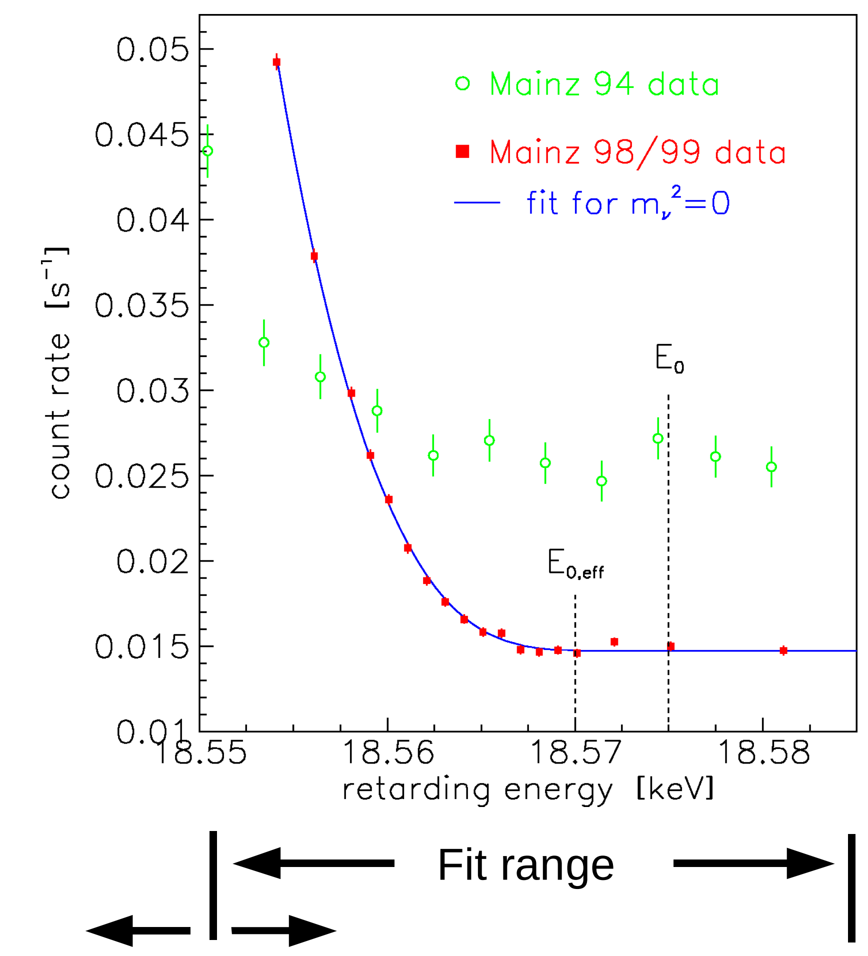
Determination of critical field:

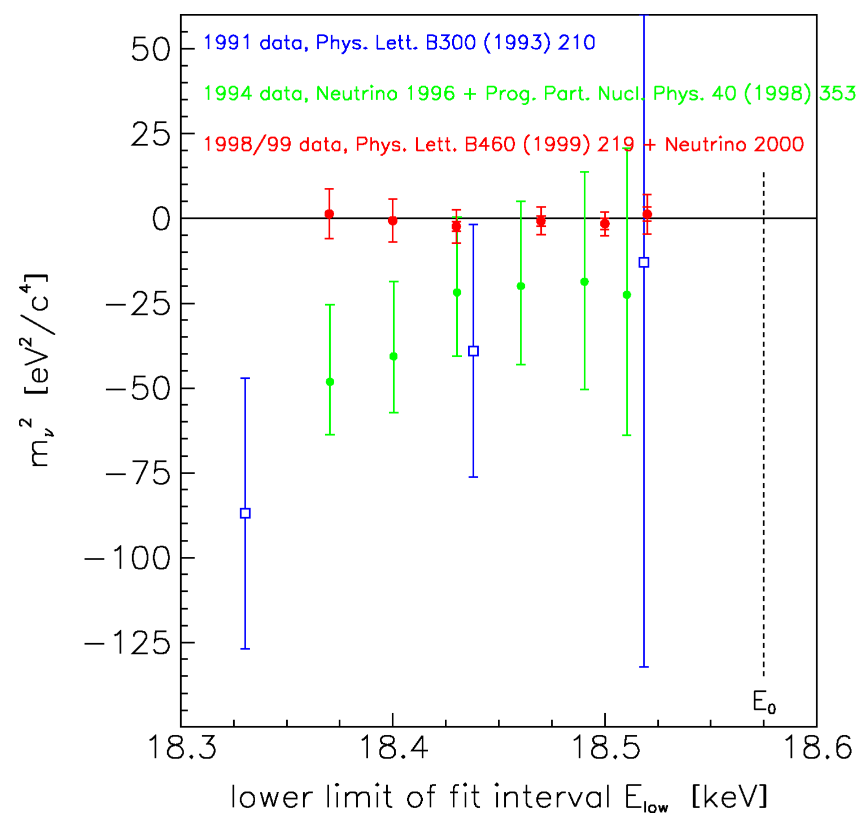
$$E_c = (63 \pm 4)\ \text{MV/m} \quad = 20\ \text{mV/monolayer}$$

$\Rightarrow$ slight broadeing of energy resolution

H. Barth et al., Prog. Part. Nucl. Phys. **40** (1998) 353,
B. Bornschein, PhD thesis, publication in preparation

Mainz data of 1998,1999

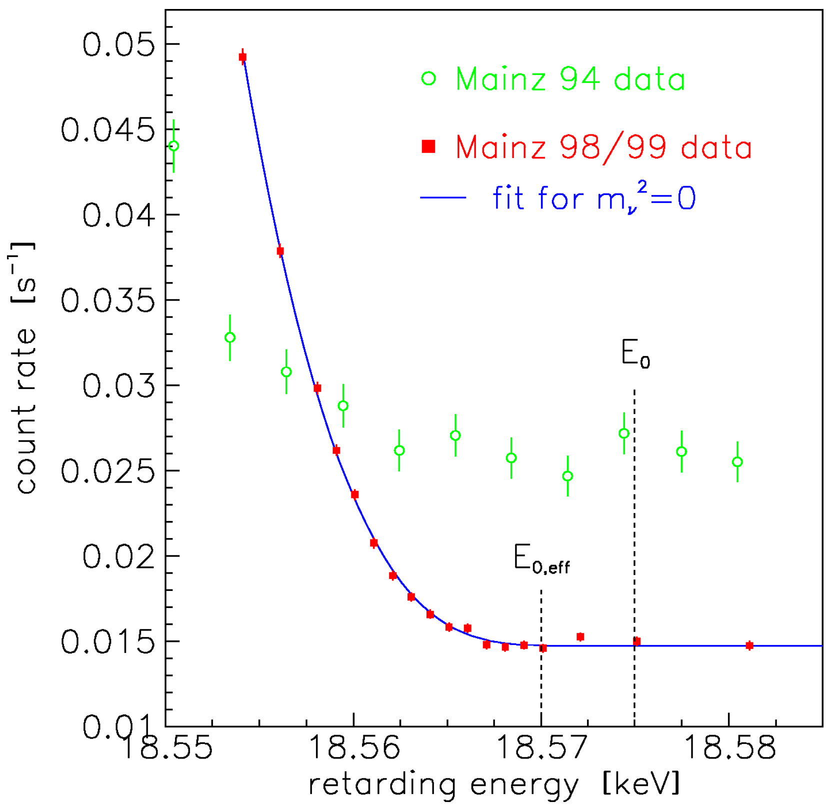


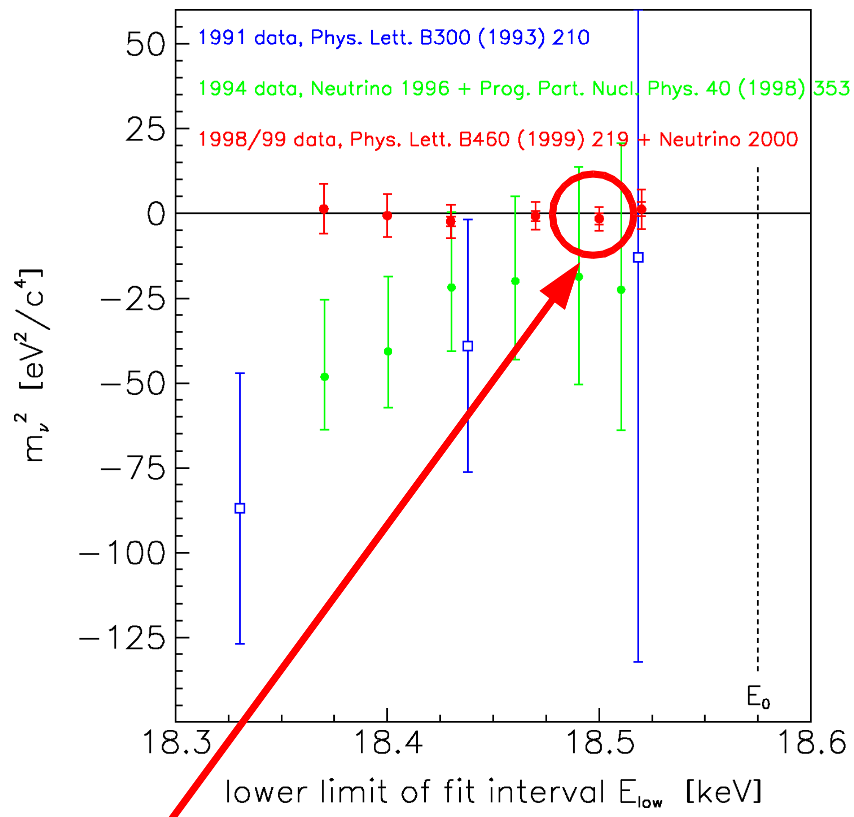


1998+1999: roughening transition avoided by T < 2 K

1998+1999: Signal/background 10 x higher

Mainz data of 1998,1999





$m^2(\nu) = -1.6 \pm 2.5 \pm 2.1$ eV^2 (χ^2/d.o.f. = 125/121)

$\Rightarrow$ $m(\nu) < 2.2$ eV (95% C.L.)

(J. Bonn et al., Nucl. Phys. B (Proc. Suppl.) 91 (2001) 273)

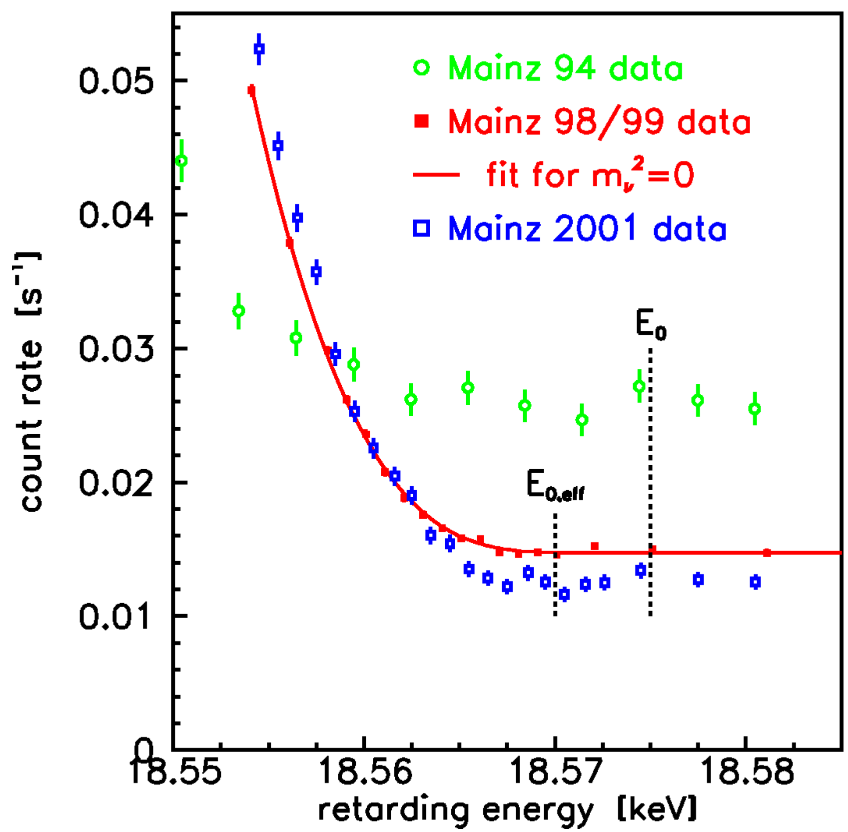
Mainz measurements in 2001

(In 2000 two measurements (Q9,Q10) with background problems
due to trapped particles: hysteresis effect in dependence of scanning direction)

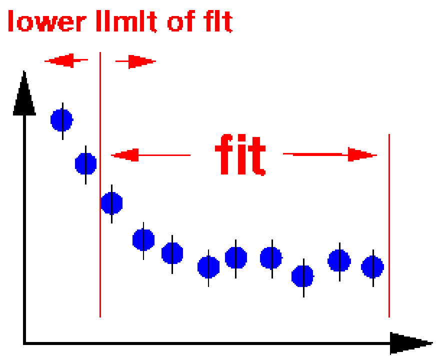
Before Q11,Q12: optimal preparation

- Vacuum: baken out, getter activated:
  - tritium source
  - spectrometer
  - detector
- T_2 source, HV: new:
  - source substrate
  - tritium ampula
  - HV divider oil
- Conditioning at high pressure (10^{-7}mbar)

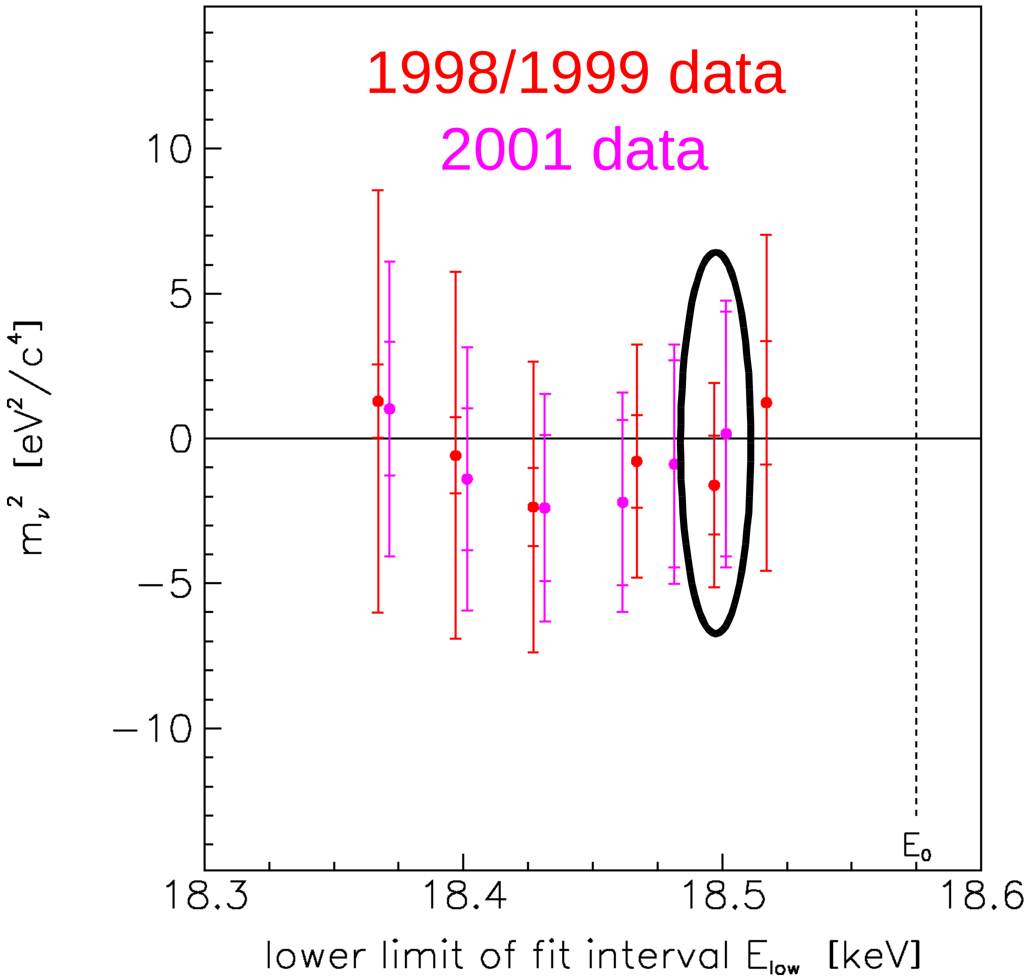
⇒ **Low and stable background,**
no Troitsk−like anomalies



Results of 1998/1999, 2001 data



(see poster E2)



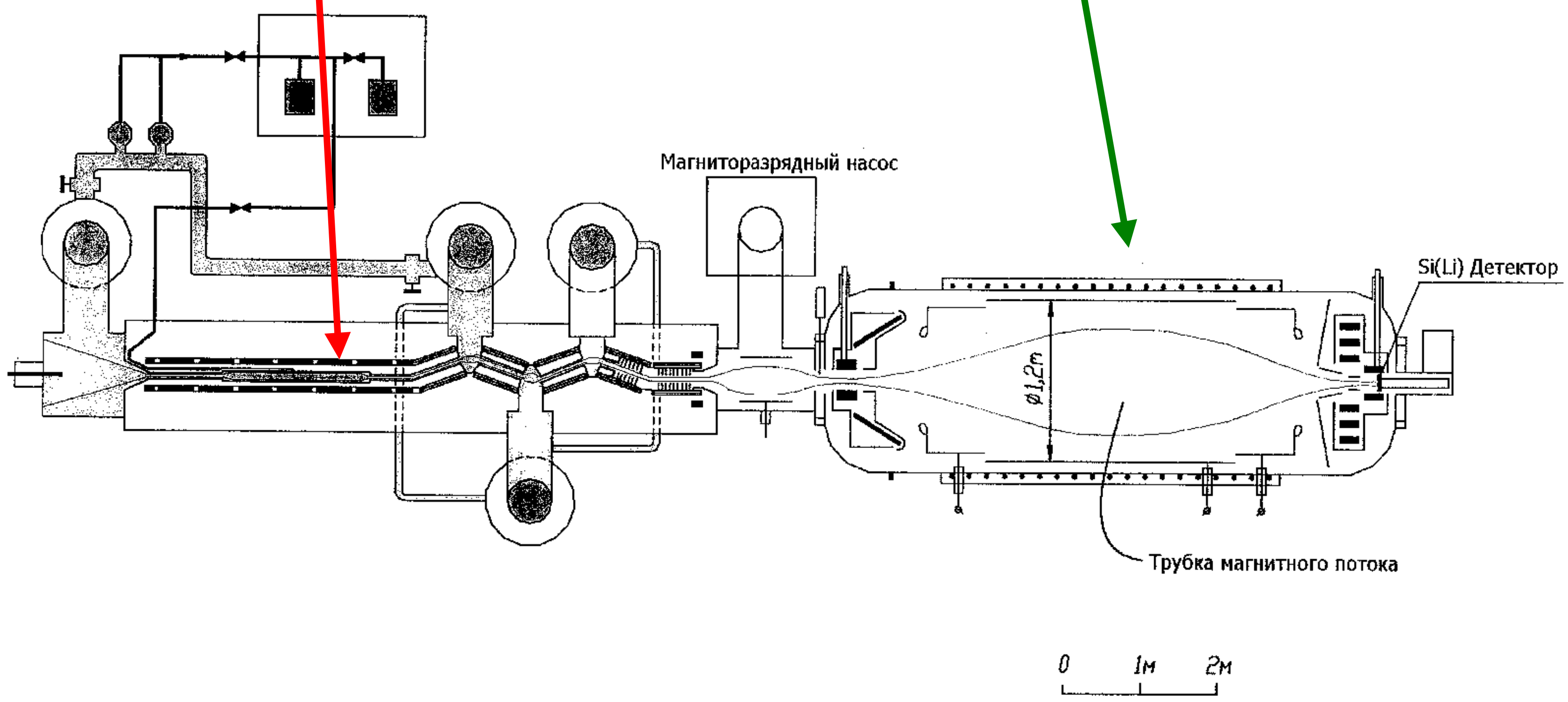
1998/1999:	$m^2(\nu) = -1.6 \pm 2.5 \pm 2.1$ eV²	$\Rightarrow$	$m(\nu) < 2.2$ eV (95% C.L.)
2001:	$m^2(\nu) = +0.1 \pm 4.2 \pm 2.0$ eV²		
1998/1999/2001:	$m^2(\nu) = -1.2 \pm 2.2 \pm 2.1$ eV²	$\Rightarrow$	$m(\nu) < 2.2$ eV (95% C.L.)

$\Rightarrow$ **Mainz sensitivity limit reached, final analysis of all Mainz data soon**

The Troitsk Neutrino Mass Experiment

Gaseous T_2 source

MAC−E−Filter



column density: 10^{17} cm^{-2}

luminosity: $L = 0.6 cm^2$

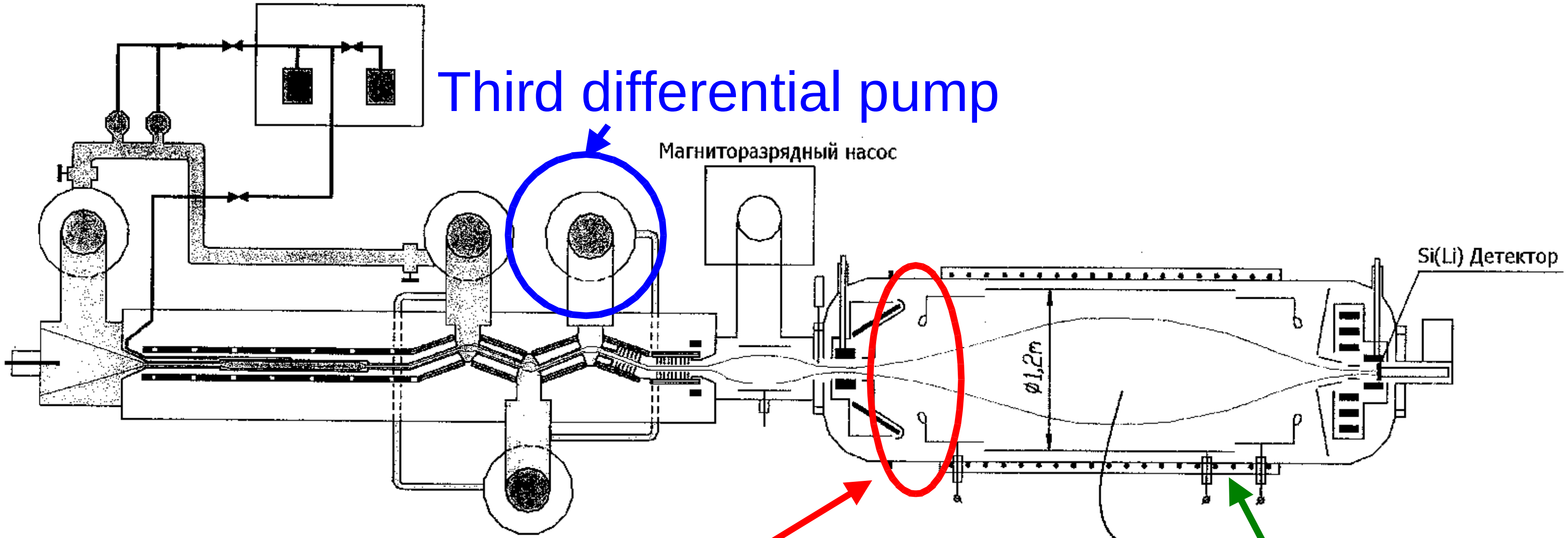
($L = \Delta\Omega/2\pi * A_{source}$)

energy resolution: $\Delta E = 3.5 eV$

3 electrode system in 1.5m

diameter UHV vessel ($p<10^{-9}$ mbar)

Troitsk improvements in 2001



Third differential pump

increasing distance

$\Rightarrow$ smaller electrical field

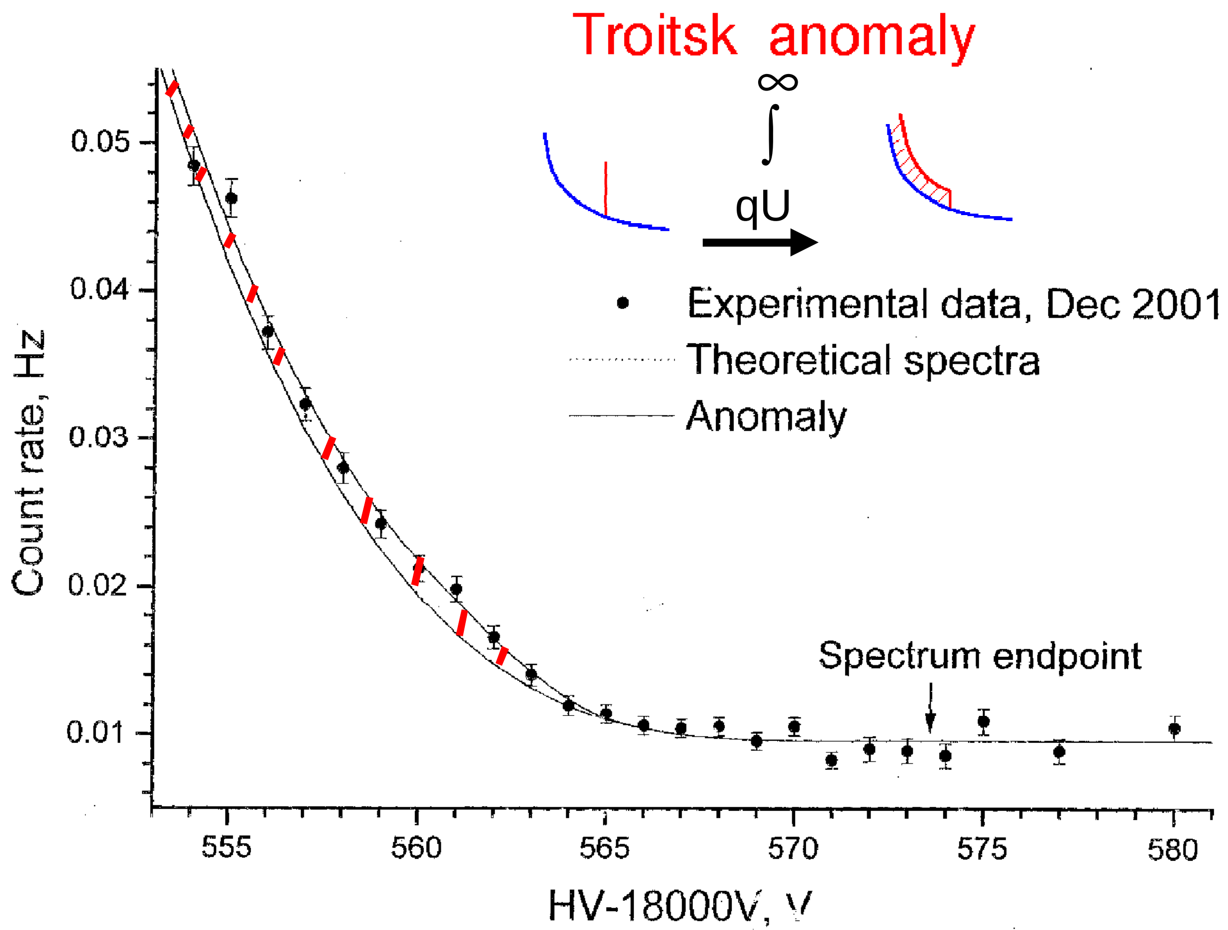
vacuum:

lowering temperature of spectrometer:

30°C $\rightarrow$ 13°C

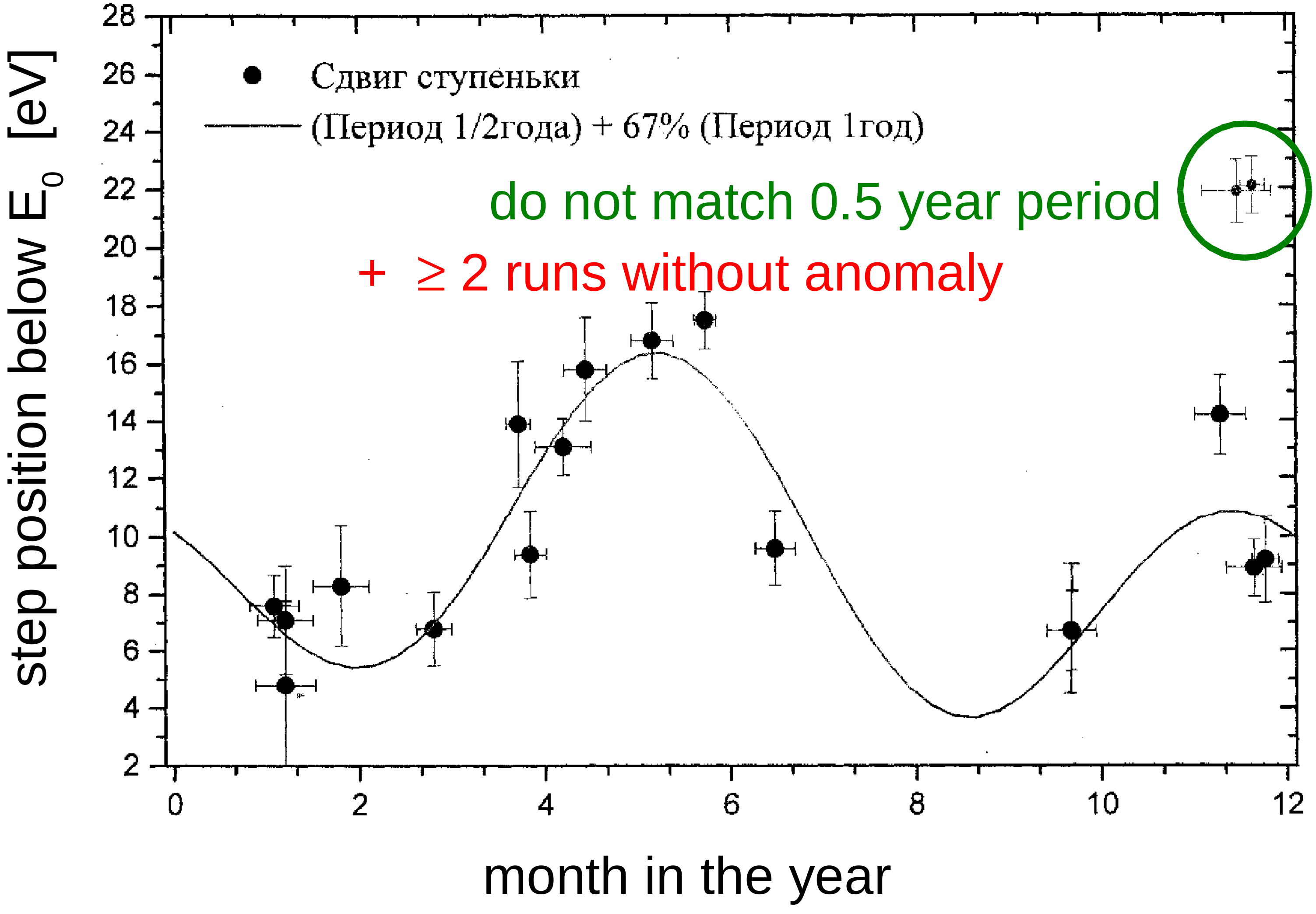
$\Rightarrow$ 3 times lower background
less depedent on tritium source activity

Troitsk anomaly



Troitsk anomaly: monoenergetic line in β spectrum of 10^{-10} amplitude origin ?

Periodicity of Troitsk anomaly

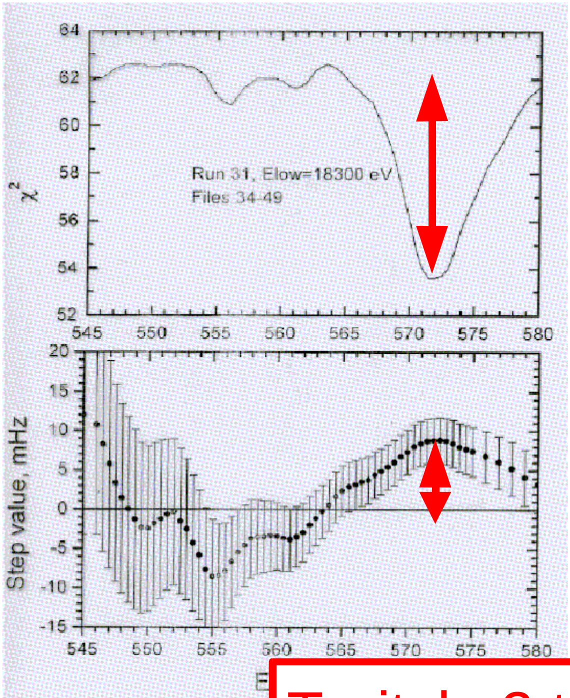


Decribing anomaly phenomenologically by additional line, different run−by−run
Troitsk 1994−1999,2001 data: $m^2(\nu) = -2.3 \pm 2.5 \pm 2.0\ eV^2$ ⇒ $m(\nu) < 2.2\ eV$ (95% C.L.)

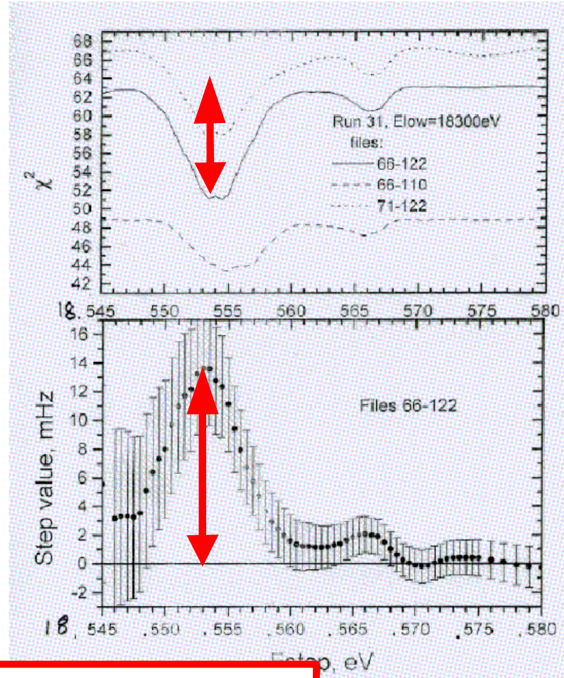
Coincident measurements Troitsk and Mainz

06. – 13. Dec. 2000 | 22.–28. Dec. 2000

Troitsk

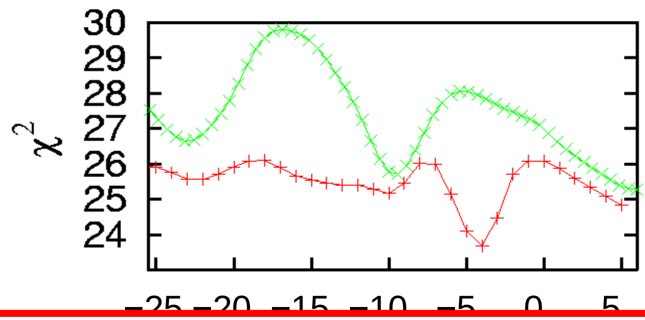


V.M. Lobashev
NANP2001

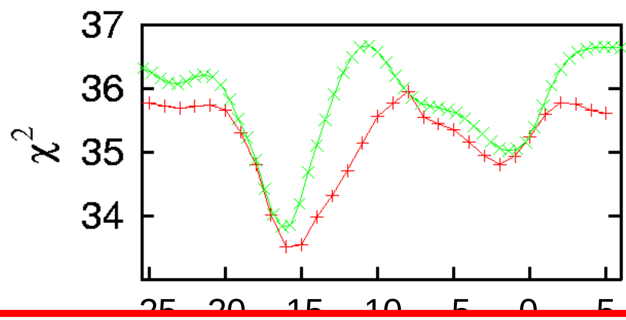


Troitsk: 2 times sizeable anomaly

Mainz



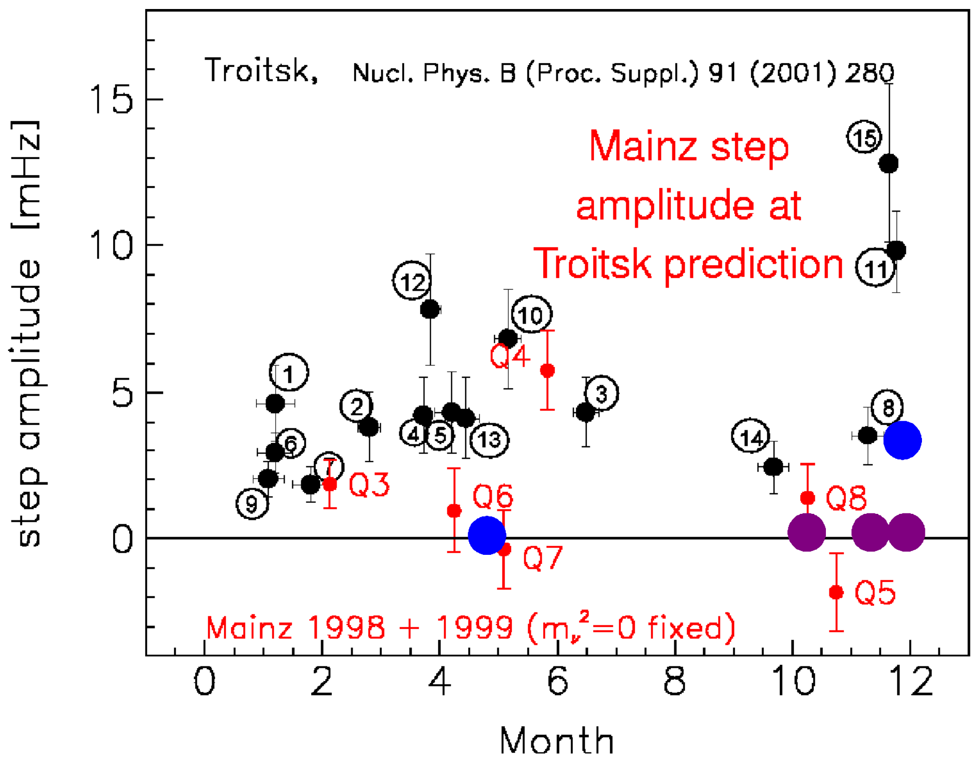
$m_\nu^2 = 0$ fixed
m_ν^2 free



Mainz: no significant change of χ^2 $\Rightarrow$ no indication of an anomaly

Status of Troitsk anomaly

Amplitude of anomaly: Troitsk, Mainz



Troitsk 2001:

- **No anomaly in May 2001**
- **Only small anomaly in Dec. 2001**

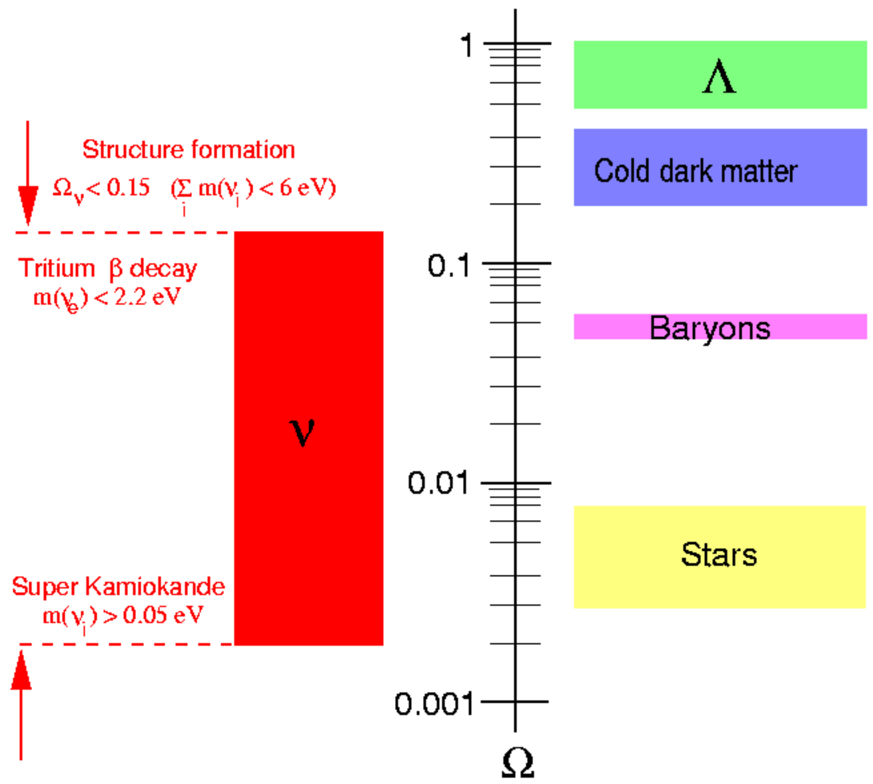
Mainz:

- **Clear contradiction to 0.5 y period**
- Similiar effect observed only once (Q4 1998)
- **Does not show up in in newest Mainz data:** of 2000 (Q9,Q10, partially in parallel with Troitsk) and of 2001 (Q11,Q12)

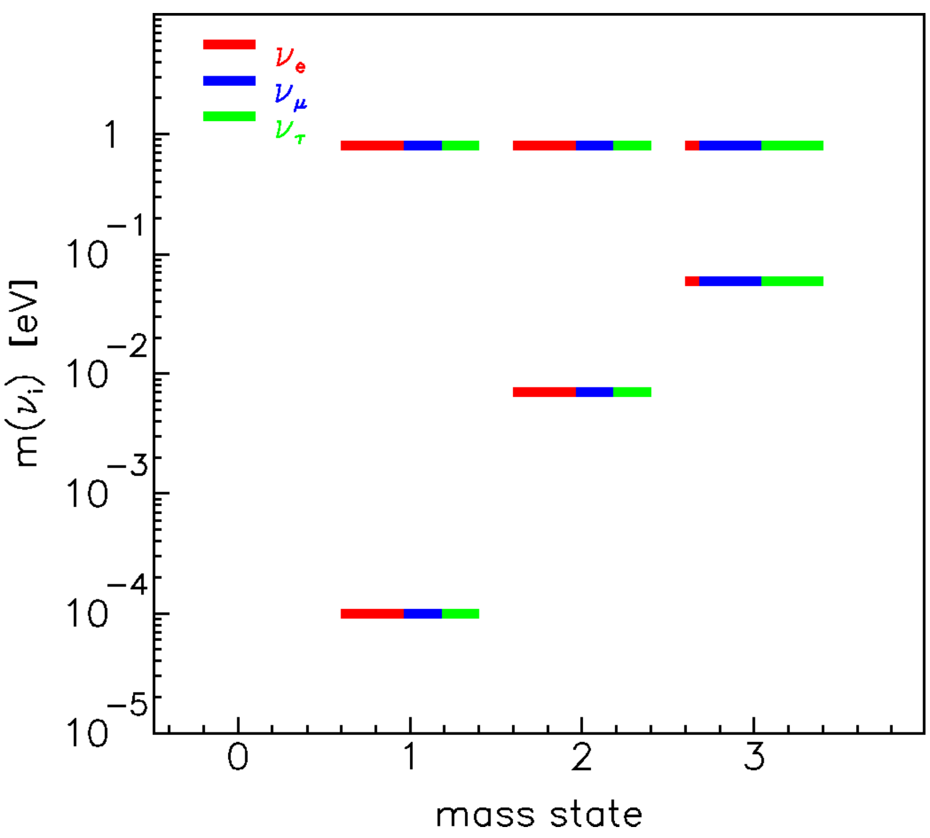
$\Rightarrow$Troitsk anomaly is very likely experimental artefact, which can be avoided (Mainz)

Motivation for a sub−eV direct neutrino mass search

Cosmological relevant neutrino mass



Neutrino mass scale
quasi−degenerate vs hierarchical



What can we learn from β decay w.r.t. $0\nu\beta\beta$?

Direct neutrino mass determination

If neutrino masses are not resolved $\Rightarrow$ average neutrino mass, e.g.:

$m^2(\nu_e) = \Sigma\, |U_{ei}{}^2|\, m^2(\nu_i)$ (incoherent sum, real average, since $0 \leq |U_{ei}{}^2| \leq 1$)

Sensitivity of β decay: check degenerate neutrino mass scenarios

$0\nu\beta\beta$ (only possible for Majorana neutrinos)

$m_{ee}(\nu) = |\, \Sigma\, |U_{ei}{}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$ (coherent sum)

$\Rightarrow$ partial cancelation possible (not fully since SNO says: no max solar mixing)

Future experiments very sensitive $m_{ee}(\nu) < 0.1$ eV

$m(\nu_e)$ vs $m_{ee}(\nu)$: complementary information, differences due to:

- Dirac neutrino
- CP−phases
- Other processes (right−handed currents, Susy−particles, ...)
- Problems with nuclear matrix elements

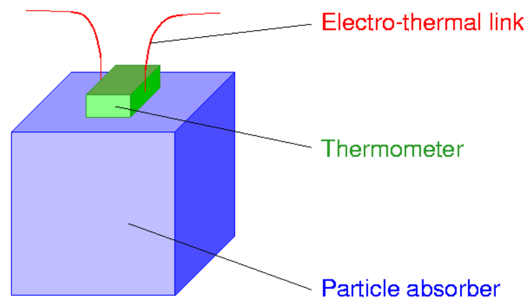
Cryogenic Bolometer Rhenium Experiments

Multi−purpose, scalable new detector technology

Basic idea: β emitting crystal = cryodetector

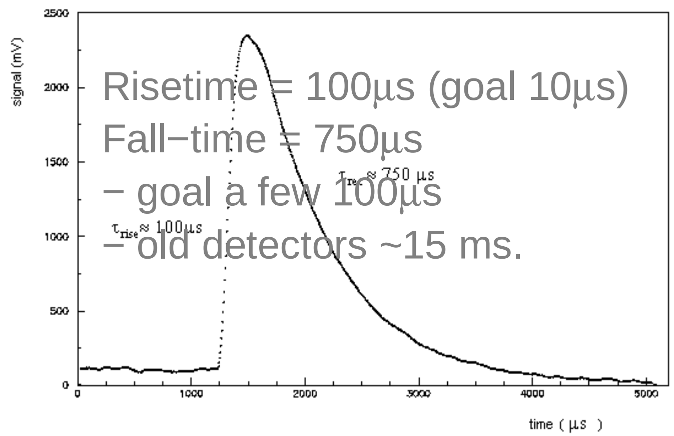
⇒ single final state: excitation by excited electronic states and inelastic scattering is collected

free choice of β emitter: ^{187}Re: E_0 = 2.5keV ($t_{1/2}$ = 5 10^{10}y)

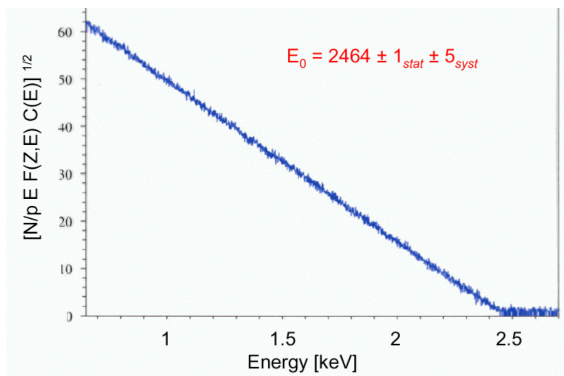


Current experiments:

MANU2 (F. Gatti et al., Genova)
- Re metallic crystal (1.5 mg)
- BEFS measured (F.Gatti et al., Nature 397 (1999) 137)
- Sensitivity:
  current: m(ν) < 26 eV
  near future: sensitivity of 10 eV expected
  future: eV resolution by s.c. sensors



MiBeta (E. Fiorini et al., Milano,Como)
- $AgReO_4$ (250 −350 μg)
- Sensitivity: similar to MANU2
  (see poster E4)



UTA neutrino rest mass experiment

M. Fink et al., University of Texas, Austin (see poster E5)

Double deflecting electrostatic
deflector aiming for $\Delta E \geq 1$eV (FWHM)

Windowless gaseous tritium source
$\rho d \approx 10^{17}/cm^2$ (as Mainz/Troitsk)

Luminosity: at least one order of
magnitude less w.r.t. Mainz/Troitsk

Very low background (cnts/day) ?

Aim: $\Delta m(\nu)$ = 1.4 eV (3σ) ?

Response function:
no tails beyond Gaussian?

Background from tritium?

Competion for Mainz and Troitsk

2

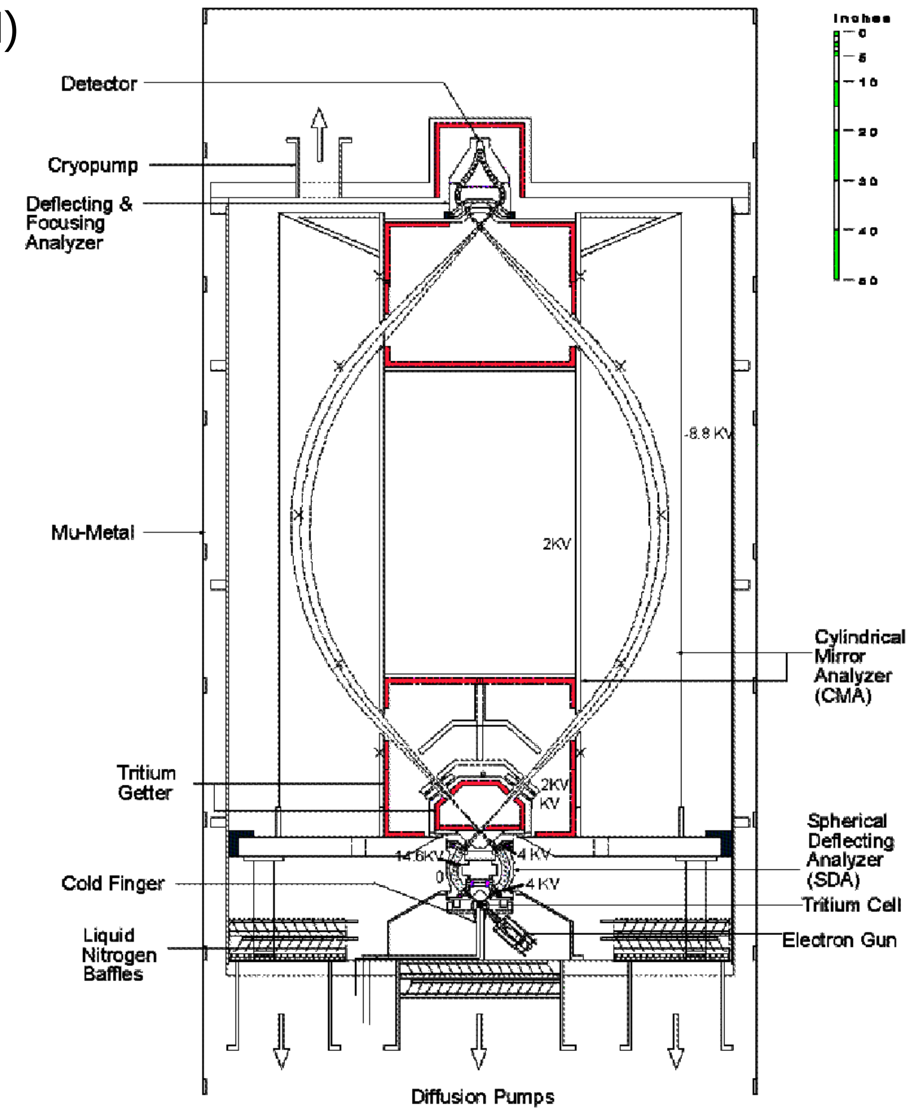


Fig. 1a. The whole electron spectrometers with T_2 cell and detector

Which way to sub−eV neutrino masses?

Neutrinos of galactic supernova (s. talk by J. Beacom)

- galactic SN only every 40 years
- not sensitive below 1eV (uncertainty in time spectrum of neutrino emission)

Large scale structure (s. talk by S. Hannestad)

- model depedent
- neutrino mass from lab can serve as input for astrophysics

complementary

Search for $0\nu\beta\beta$ (s. talk by O. Cremonesi)

Direct neutrino mass determination

– **^{187}Re β decay with cryogenic bolometers**

– **Tritium β decay with electrostatic deflector (UTA−exp.)**

– **Tritium β decay with MAC−E−Filter**

- first MAC−E−Filters (Mainz/Troitsk) are very successful
- no material in beam line, no tails of resolution function
- quasi „single final state“ experiment
- also: not−integrating MAC−E−TOF mode

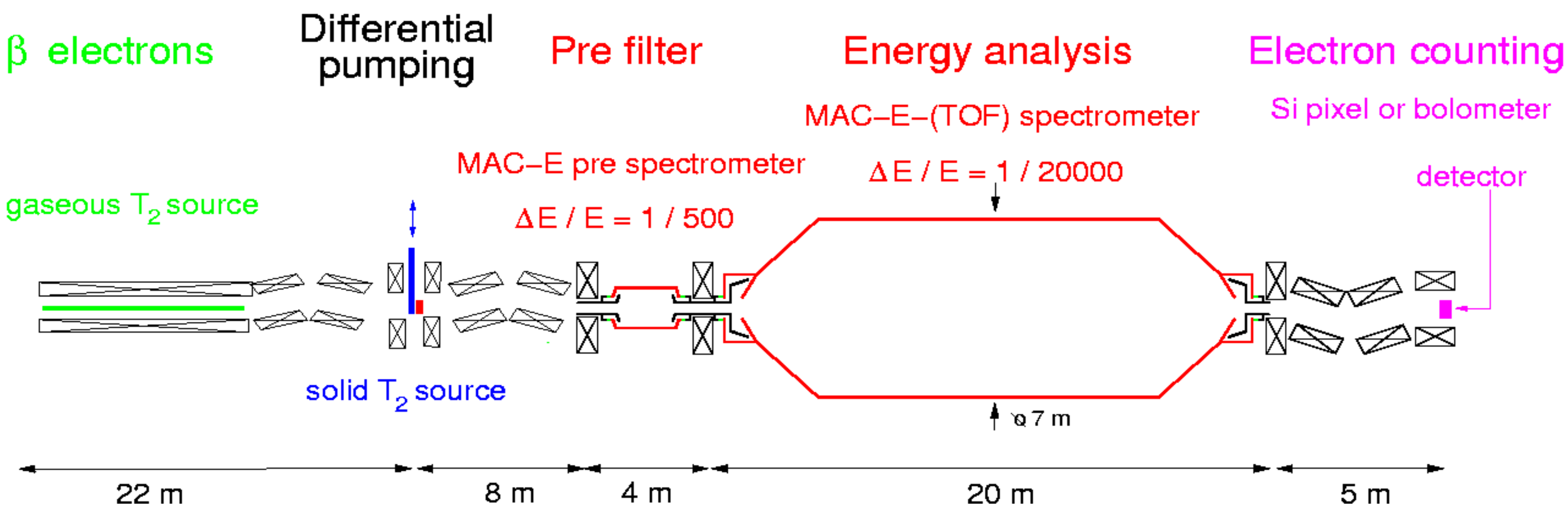
The Karlsruhe Tritium Neutrino experiment KATRIN

Physics aim:

Sensitivity on neutrino mass scale: $m(\nu) << 1eV$

- Higher energy resolution: $\Delta E \approx 1eV$
  since $E/\Delta E \sim A_{spectrometer}$ $\Rightarrow$ larger spectrometer
- Relevant region below endpoint is smaller
  even less count rate $d\dot{N}/dt \sim A_{spectrometer}$ $\Rightarrow$ larger spectrometer

} $\varnothing$7m



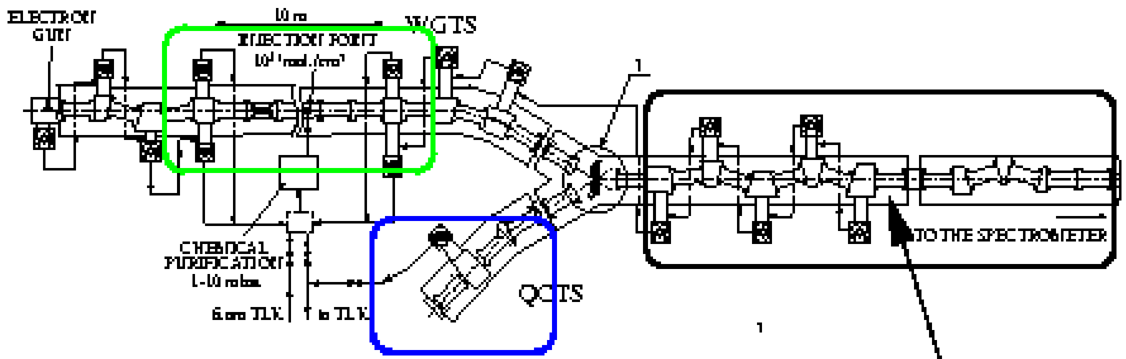
(hep−ex/0109033)

Molecular tritium sources

Windowless gaseous molecular tritium source

(pionieered by LANL (Seattle), adapted to MAC–E by Troitsk)

10 m length, 70 mm diameter, 5 10^{17} T_2 / cm^2



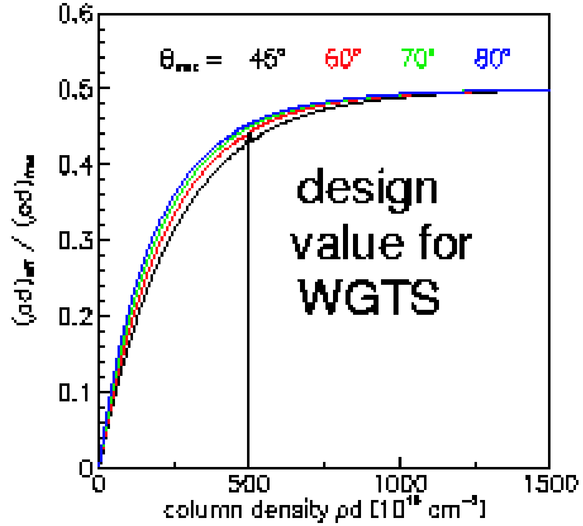
Quench condensed tritium source (QCTS)

(pioneered by Mainz)

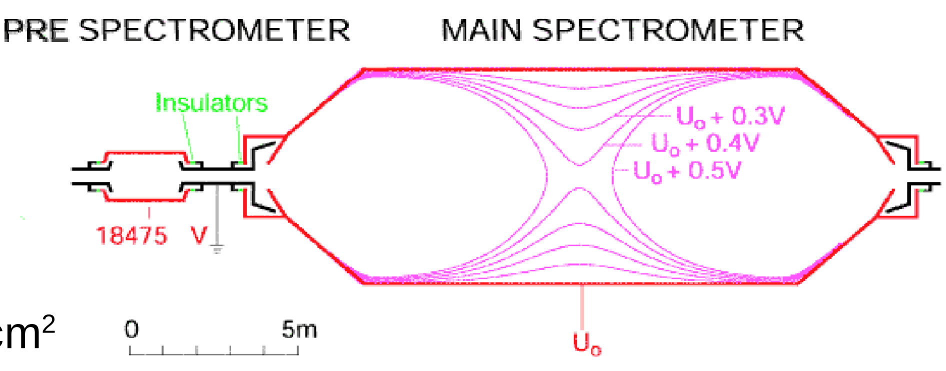
larger but complementary sys. uncert.

Differential pumping and cryo stations

WGTS allows almost maximum count rate without large sys. uncertainties:



Pre and main spectrometer



Main spectrometer

- Energy resolution:
  $\Delta E = 1eV$
- high luminosity:
  $L = A_{Seff}\ \Delta\Omega/4\pi = A_{analysier}\ \Delta E/(2E) = 10\ cm^2$
- Ultrahigh vacuum requirements (Background) $p < 10^{-11}$ mbar
- „simple“ construction: vacuum vessel at HV = electrode

Pre spectrometer:

(see poster E3)

- Transmission of electron with highest energy only
  (10^{-7} part in last 100 eV)
  ⇒ Reduction of scattering probaility in main spectrometer
  ⇒ Reduction of background
- only moderate energy resolution required:
  $\Delta E = 50$ eV
- Test of new ideas (shape of electrodes, removal of trapped particles, ...)

Systematic uncertainties

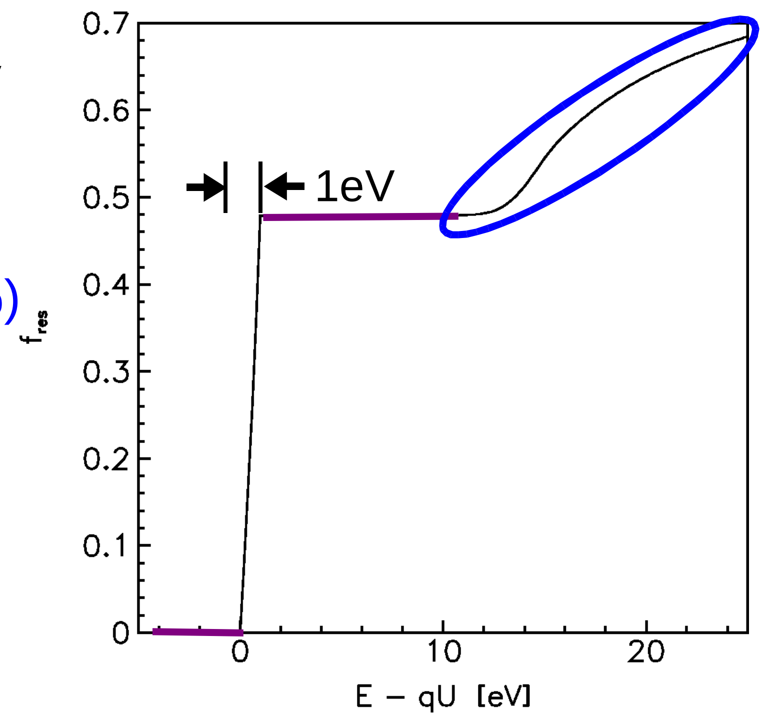
As smaller m(ν),
as smaller the region of interest below endpoint

⇒ Excited electronic final states does not play a role (ΔE_{exc} > 27 eV)

⇒ Inelastic scattering in T_2 is small ($\Delta E_{inel.}$ > 12eV ⇒ largest interval 25eV: 2%)

⇒ One well−defined final state (similiar to cryo detectors)

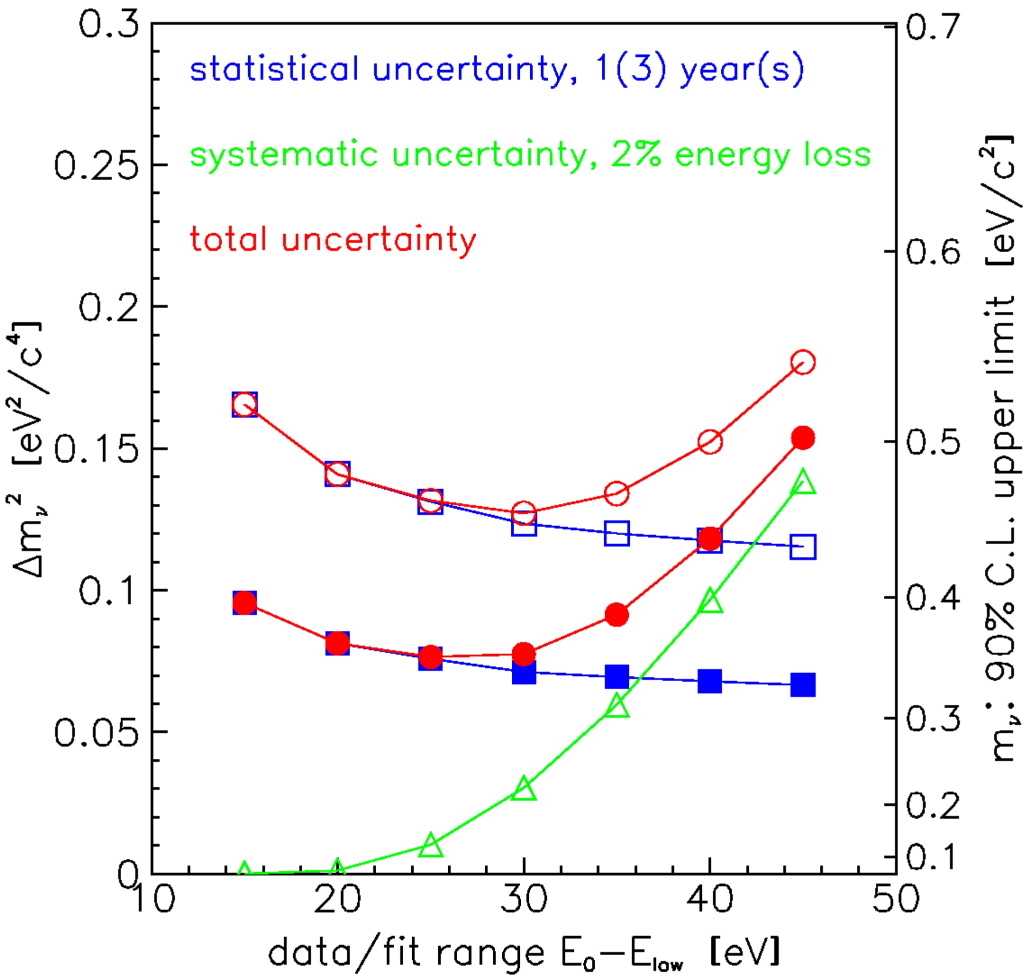
Is only true, since MAC−E−Filter response function has no tails



Systematic uncertainties

- Rotation−vibration excitation of final state
- Inelastic scattering
  (systematic uncertainty: Troitsk 2%, Mainz 6%)
- electrical potential distribution over source
- Solid state effects (for QCTS only)
- Stability of parameters (HV, T_2 partial pressure, T_2 purity, ...)

Estimation of sensitivity



energy resolution: 1eV
source area: 29 cm^2
gaseous source column density: 5 $10^{17}/cm^2$
max accepted starting angle: 51°
background rate: 11 mHz

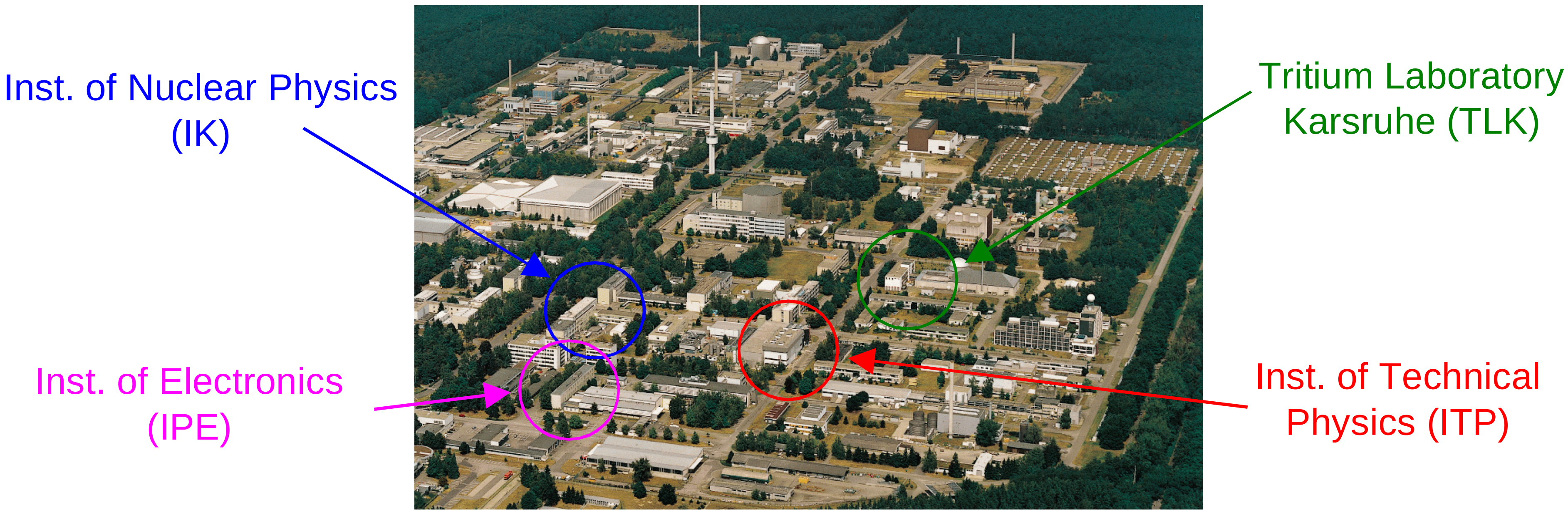
First simulations with conservative assumptions

⇒ Sensitivity on $m(\nu_e)$ ≈ 0.35eV/c^2

Technical challenges

- Recirculation and purification of tritium to a large extent (kCi)
- ≈ 30 superconducting solenoids
- UHV (< 10^{-11}mbar) in huge volume ($1000 m^2$)
- HV calibration and stability on ppm level
- High resolution detectors
- ....

⇒ ideal place: Forschungszentrum Karlsruhe/Germany



Status and schedule of Katrin

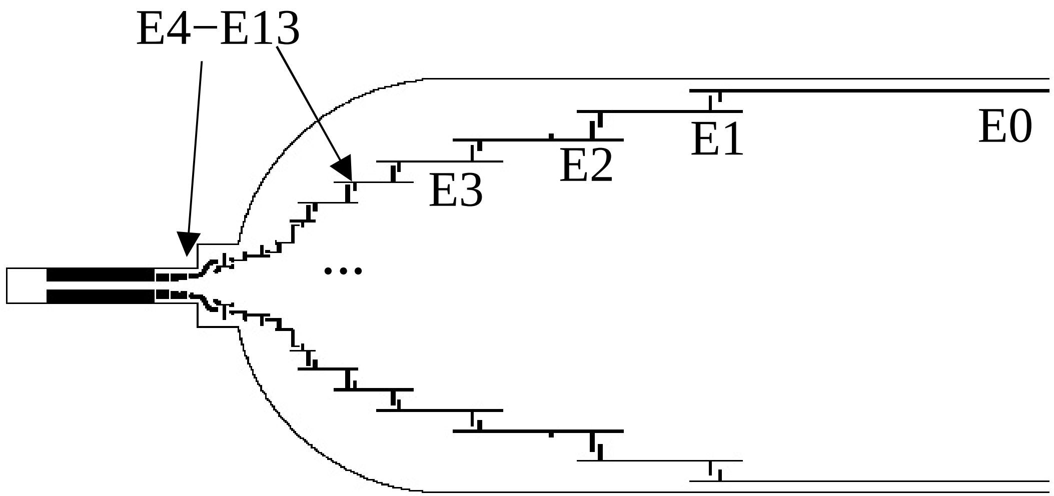
1999/2000	First discussions
1/2001	***Neutrino Masses in the sub−eV Range*** *International workshop on future direct measurements of the electron neutrino mass and their implications* Bad Liebenzell / Schwarzwald , Germany, January 18 – 21, 2001

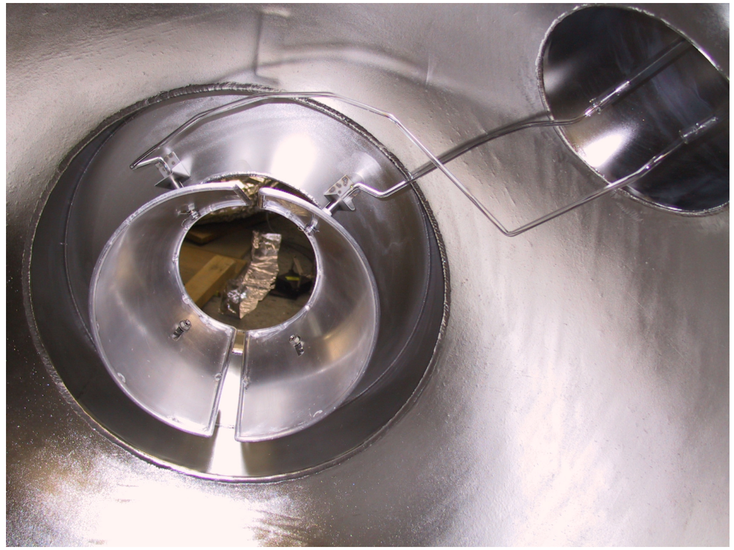
transperencies:
http://www−ik1.fzk.de/tritium/liebenzell

6/2001	KATRIN collaboration founded:
	Fulda, Karlsruhe, Mainz, Prag, Seattle, Troitsk + Bonn (12/01)
9/2001	Letter of Intent (hep−ex/0109033)
	First founding by BMBF/Germany
5/2002	International review panel
2002	Discussion with other groups to enlarge collaboration Proposal and application for major funding
	Construction of pre spectrometer at FZK
	Background investigations at Mainz
2007	Start of data taking

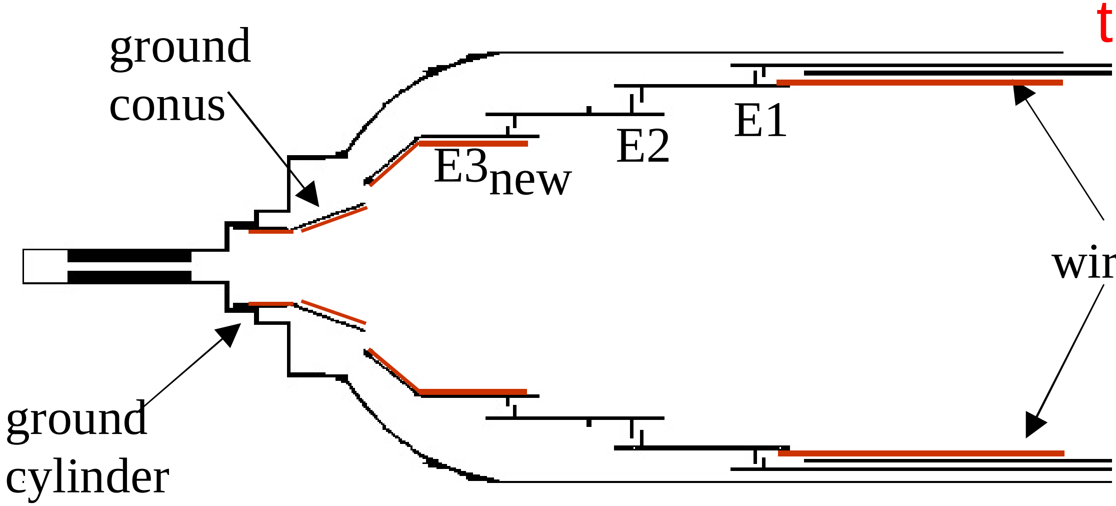
Modification of the Mainz Spectrometer 01−05/02

(see poster E1)





electrical dipoles to remove trapped particles by ExB drift



Summary

Current tritium β experiments: Final sensitivity reached

- Mainz: All problems solved by intensive studies of systematics and optimal preparation of experiment
  $\Rightarrow m(\nu_e) < 2.2$ eV
- Troitsk: Experimental improvements $\Rightarrow$ lower background
  anomaly is becoming less stable, probably experimental artefact
  by substraction of anomaly run−by−run: $m(\nu_e) < 2.2$ eV

How to proceed?

Need future direct sub−eV neutrino mass experiment

- UTA experiment: electrostatic deflector
- Cryogenic detectors with Rhenium: challenging new approach
  how far can they go?
- KATRIN: A large tritium β decay neutrino mass experiment at FZ Karlsruhe
  with sub−eV sensitivity (<0.35 eV)
  probes degenerate neutrino masses and cosmologically relevant mass
  $\Rightarrow$ key experiment w.r.t. neutrino mass