Mass limits from β-decay of tritium

- General properties of tritium
- Former tritium experiments
  - Mainz experiment
  - Troitzk experiment
- Next generation experiment
  - KATRIN

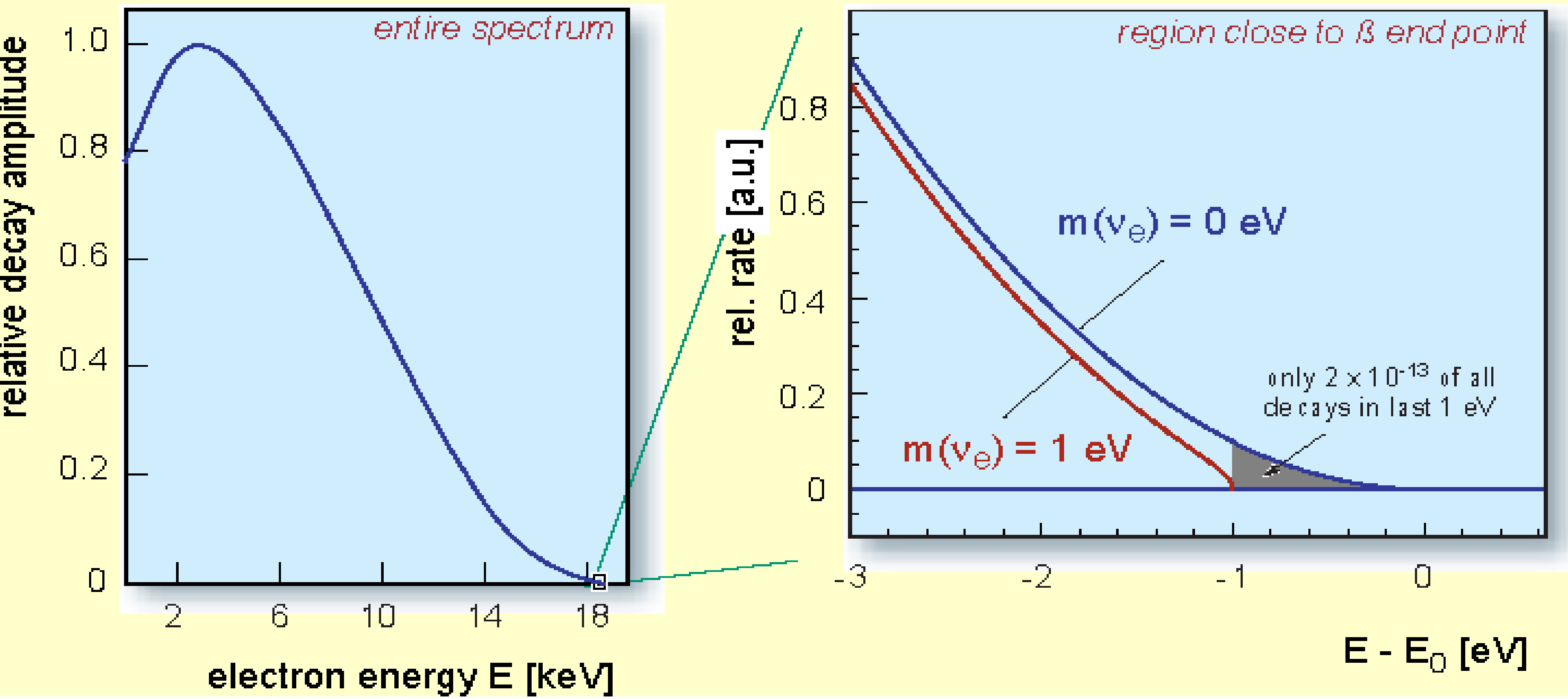
Tritium

$$^{3}H \rightarrow {}^{3}He + e^{-} + \bar{\nu}_e$$

superallowed

half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV



β-decay of tritium

- absolute value of ν mass will have crucial implications for cosmology, astrophysics and particle physics
- tritium β-deay experiments perform a high precision direct measurement of the absolute mass of the ν_e with sub-eV sensitivity
- mass of the electron anti-neutrino will be studied
  but: CPT theorem: mass of particle and anti-particle are equal
  $\Rightarrow$ mass limits can also be used for electron neutrino

$$dN/dE = C \cdot F(Z,E) \cdot p \cdot E \cdot (E_0 - E) \cdot [(E_0 - E)^2 - m_\nu^2]^{1/2} \, \Theta(E_0 - E - m_\nu)$$

- F(E,Z): Fermi function which takes into account the Coulomb interaction of outgoing electron in the final state
- p : electron momentum
- E_0: maximum energy
- E : electron energy
- Θ : step function to ensure energy conservation

Troitzk

- windowless gaseous T_2-source:
  - 3m long
  - 5 mm wide
  - 26-28 K
  - $T_2 : HT : H_2 = 6 : 8 : 2$
- electrostatic spectrometer:
  - 6 m long
  - 1.2 m wide
  - $p = 10^{-9}$ mbar
- detector:
  - Si(Li)

Mainz

- quench-condensed solid T_2 film
  - 45 nm thick, area $2 cm^2$, 20 mCi activity
  - 1.86 K
- electrostatic spectrometer:
  - 2 m long
  - 0.9 m wide
  - $p < 5 \cdot 10^{-7}$ mbar
- detector:
  - segmented Si detector

Final results:

Troitzk: $m^2_\nu = -2.3 \pm 2.5 \pm 2.0\ eV^2$ $m_\nu < 2.2\ eV$

Mainz: $m^2_\nu = -0.7 \pm 2.2 \pm 2.1\ eV^2$ $m_\nu < 2.2\ eV$

limit of intrinsic sensitivity

Next-generation direct ν mass experiments

Exp. observable in β-decay is m_ν^2

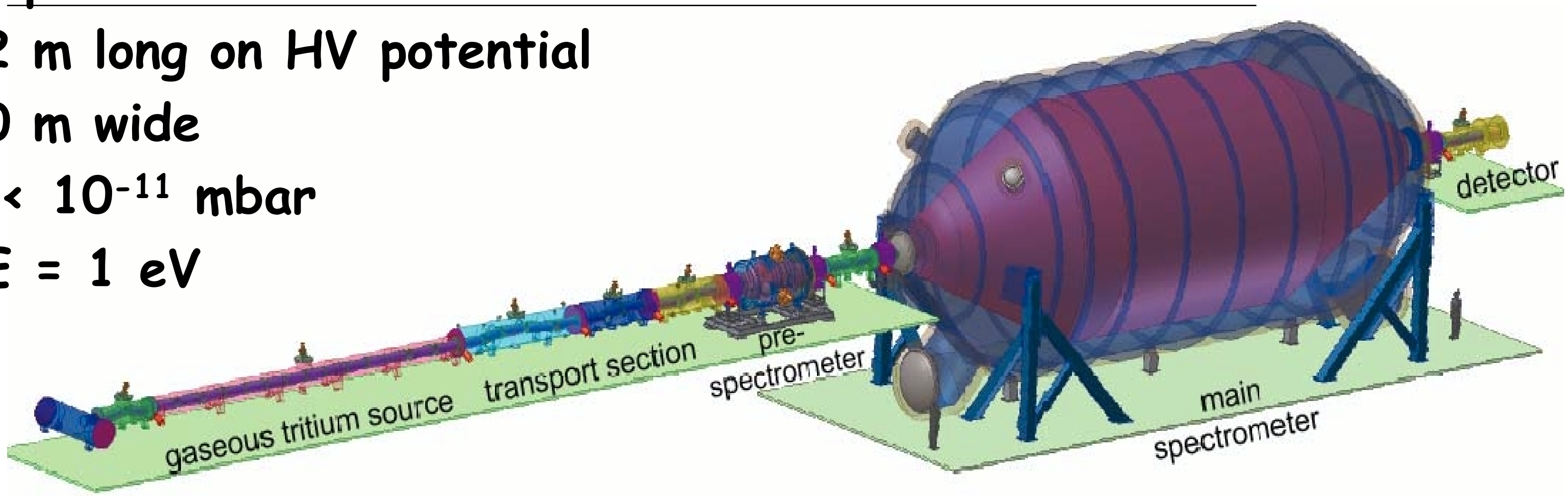
- low background
- large solid angle
- higher energy resolution: $E/\Delta E \sim A_{spec}$,
  relevant region below endpoint is smaller: $dN/dt \sim A_{spec}$
  requires: larger spectrometer
- improvement of sensitivity of m_ν by one order of magnitude ($2\ eV \rightarrow 0.2\ eV$)
  requires: improvement for m_ν^2 by two orders of magnitude
- stronger tritium source & larger analysing plane
- longer measuring period

KATRIN - KArlsruhe TRItium Neutrino Experiment

- much longer measuring time: 1000 d
- 70 m linear setup with 40 sc solenoids
- pre-spectrometer:
  - transmition of electrons with highest energies only (10^{10} e/s $\rightarrow$ 10^3 e/s)

  $\Rightarrow$ reduction of scattering probability in main spectrometer

  $\Rightarrow$ reduction of background
- main spectrometer:
  - 22 m long on HV potential
  - 10 m wide
  - $p < 10^{-11}$ mbar
  - $\Delta E = 1$ eV

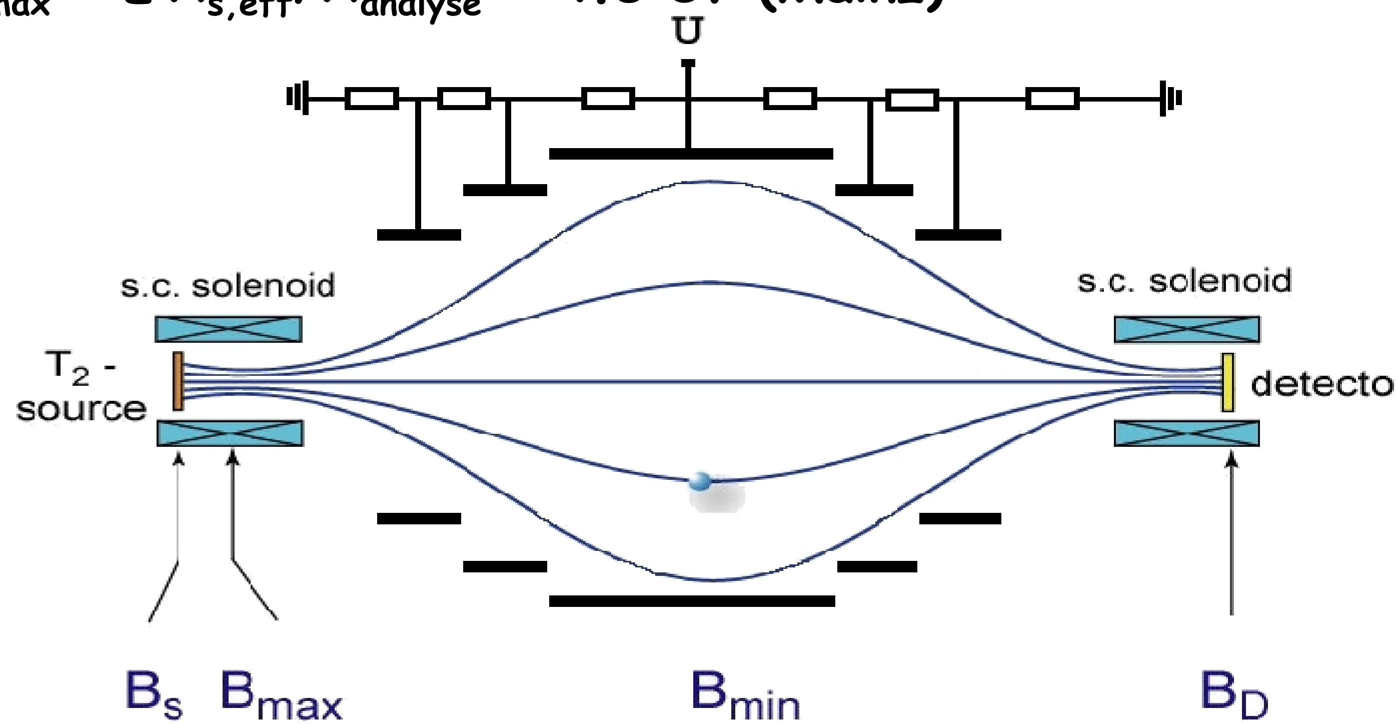


MAC-E-Filter

Magnetic Adiabatic Collimation + Electrostatic Filter

- two superconducting solenoids compose magnetic guiding field
- tritium (electron source) in left solenoid
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_\perp / B = \text{const.} \Rightarrow$ parallel e^- beam
- energy analysis by electrostatic retarding field

  $\Delta E = E \cdot B_{min}/B_{max} = E \cdot A_{s,eff}/A_{analyse} \approx 4.8$ eV (Mainz)



Molecular tritium sources: WGTS & QCTS

2 sources: independent measurements with different systematic effects

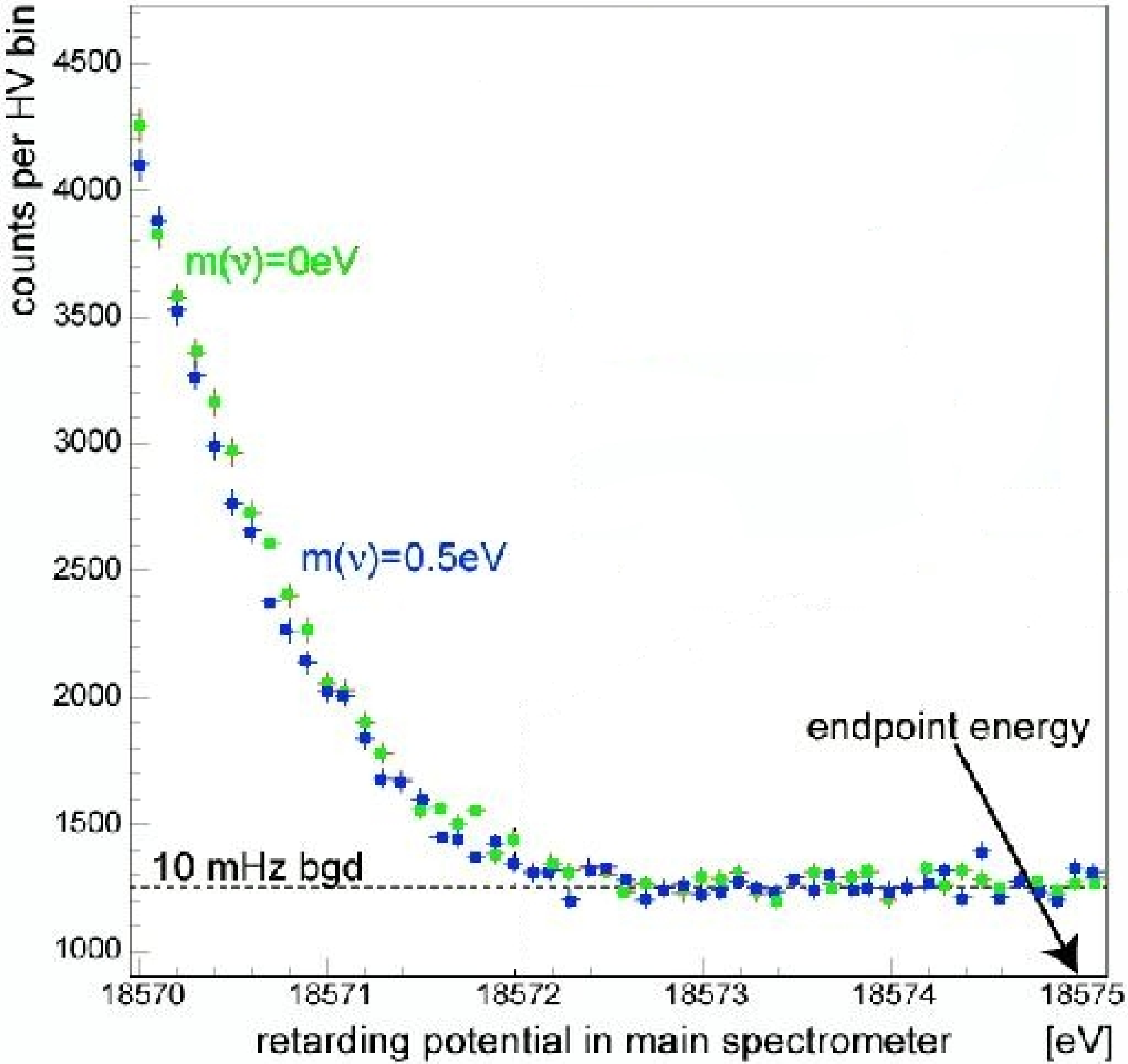
- WGTS - Windowless Gaseous Tritium Source
  - 10 m tritium tube with 90 mm diameter operated at 30 K
  - high-purity molecular tritium (95 %)
  - injection rate 2.1 Ci/s (20 g T_2 per day)
  - allows to measure near to maximum count rate

- QCTS - Quench Condensed Tritium Source
  - thin molecular T_2 film quench condensed on highly oriented pyrolithic graphite crystal
  - thickness 35 nm, source diameter 80 mm, temperature 1.6 K
  - energy resolution 2-3 eV
  - effective lifetime 300 days
  - activity 0.95 Ci

Detector requirements

- large sensitive area
- high efficiency for 18.57 keV electrons
- good energy resolution
- low electronic noise
- longterm operation
- strong magnetic fields
- for test + calibration: high count rates

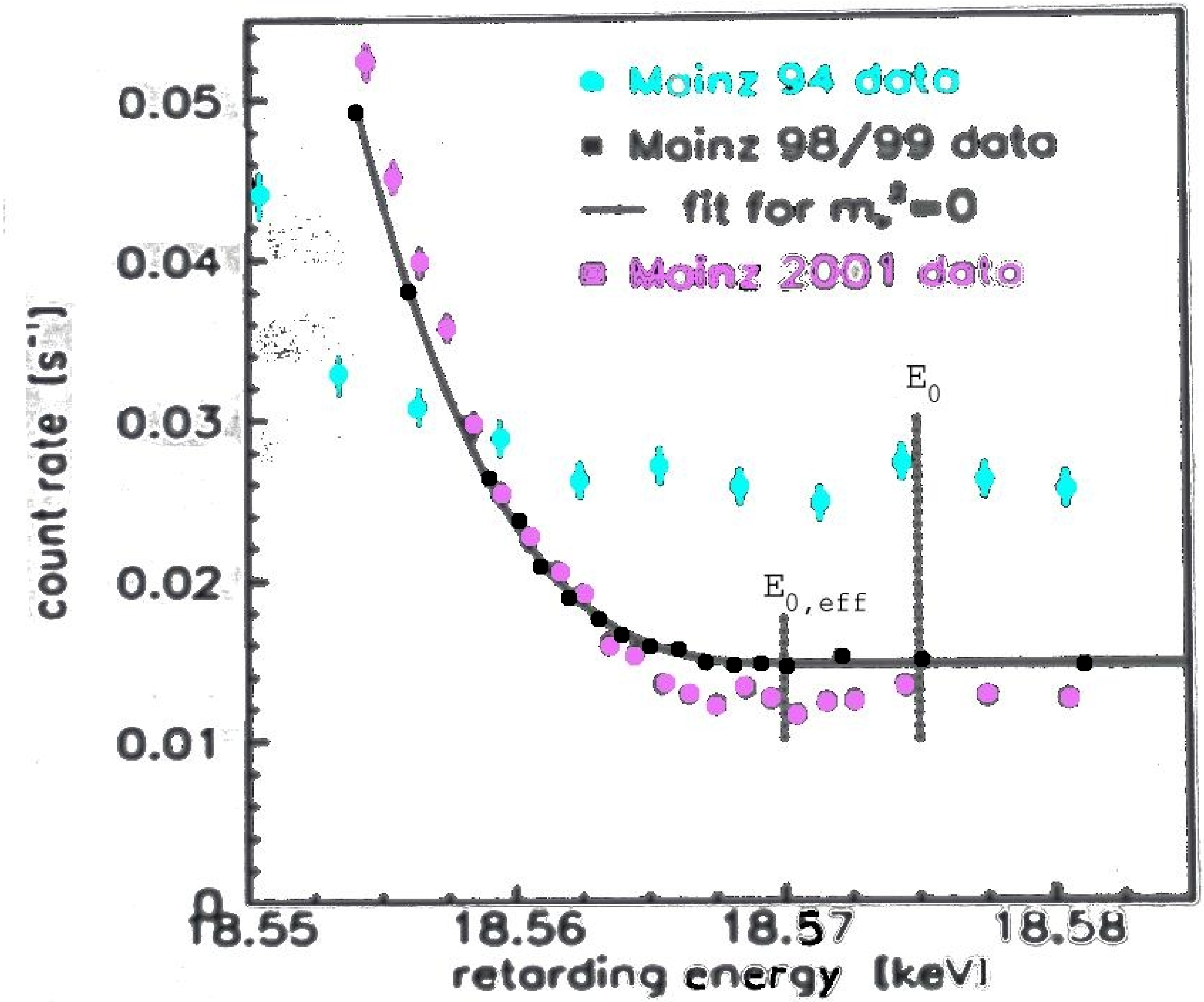
- silicon drift diodes
  - thin dead layer in order to reduce energy loss
  - segmented detector of 120 mm diameter
  - expected resolution at 18.6 keV: ΔE=230 eV


counts per HV bin
4500
4000
3500
3000
2500
2000
1500
1000
m(ν)=0eV
m(ν)=0.5eV
10 mHz bgd
endpoint energy
18570
18571
18572
18573
18574
18575
retarding potential in main spectrometer
[eV]

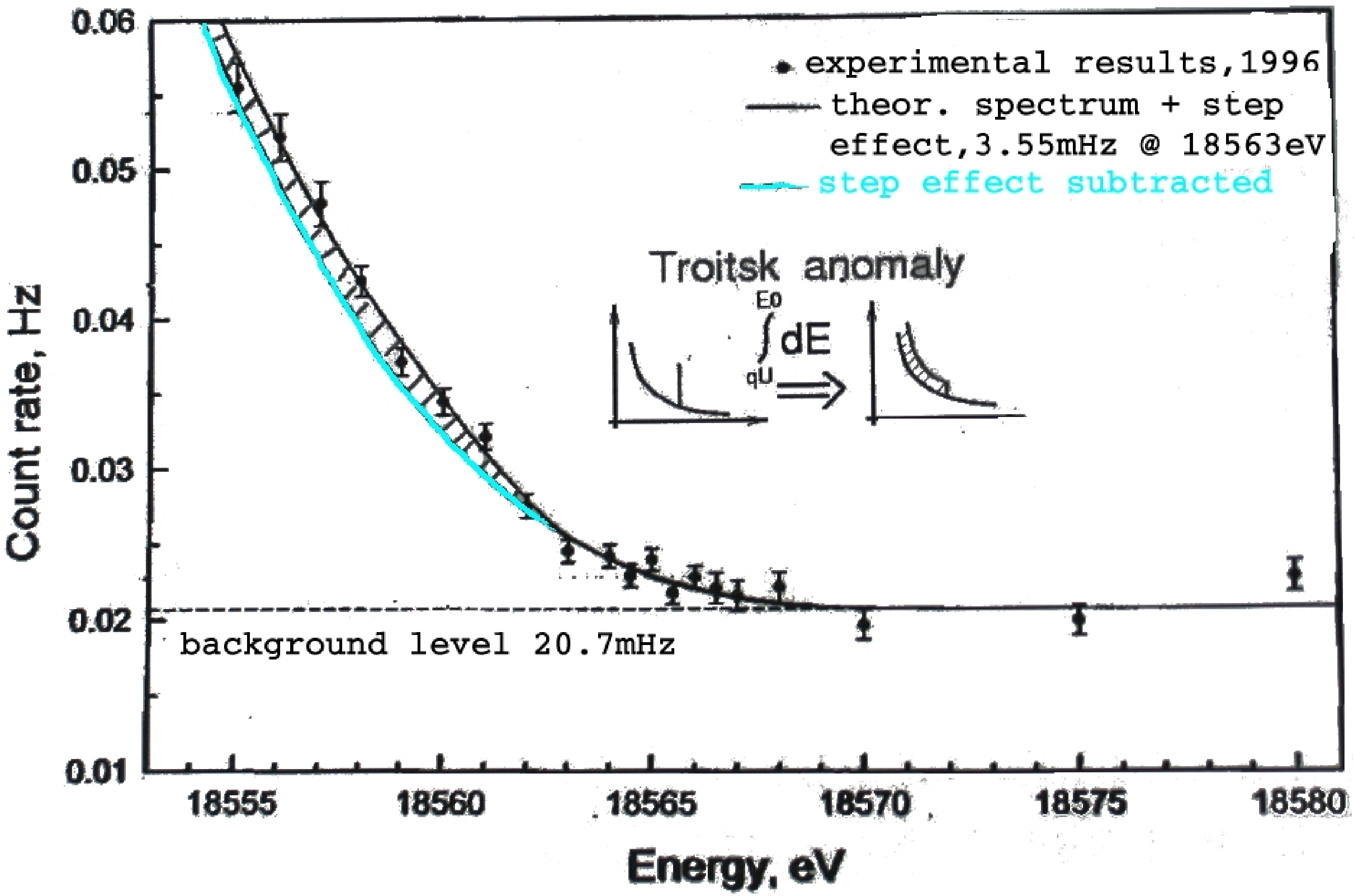
KATRIN discovery potential

- estimated total systematic error $\sigma=0.016\ eV^2$
- statistical & systematic errors will contribute almost equally
- KATRIN sensitivity if no neutrino mass signal + 3 year measuring time
  - $m_\nu < 0.2$ eV (90 % CL)
- KATRIN discovery potential if evidence for neutrino mass signal
  - $m_\nu = 0.35$ eV (5σ)
  - $m_\nu = 0.30$ eV (3σ)

Mainz results



Troitz results



History of tritium β-decay exp.

- Zürich < 11.7 eV
  - T_2 source on carbon film put onto aluminium foil
- Los Alamos < 9.3 eV
  - gaseous T_2 source
  - reduction of systematic errors (no energy loss in solid source)
- Tokio < 13.1 eV
  - T doped salt, magnet. spectr.

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- Troitzk < 2.2 eV
  - gaseous T_2 source
- Mainz < 2.2 eV
  - frozen T_2 source
  - electrostatic filter with very high energy resolution