Neutrino Mass Search in Tritium β - decay

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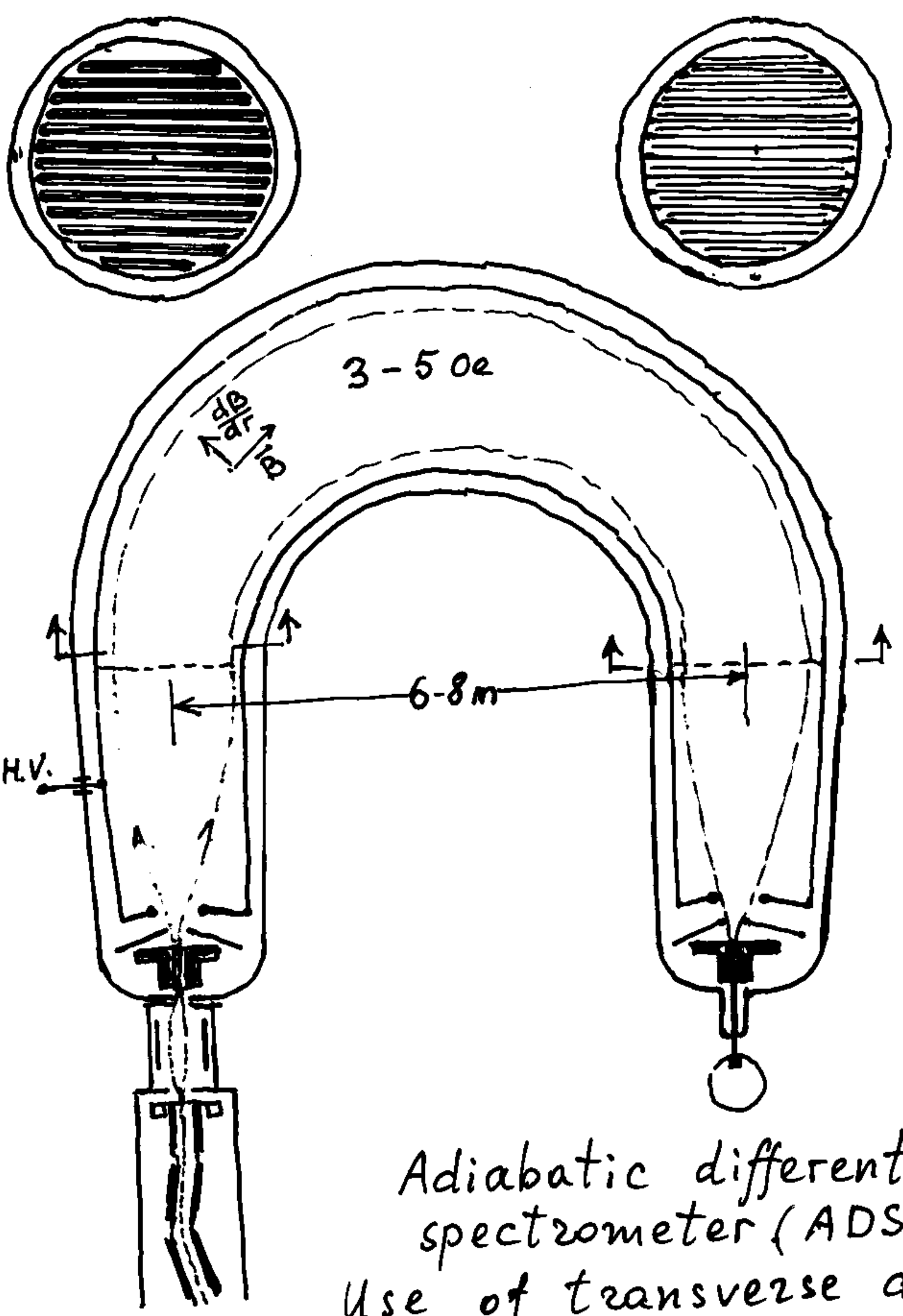
INR RAS, Moscow, KATRIN Collaboration

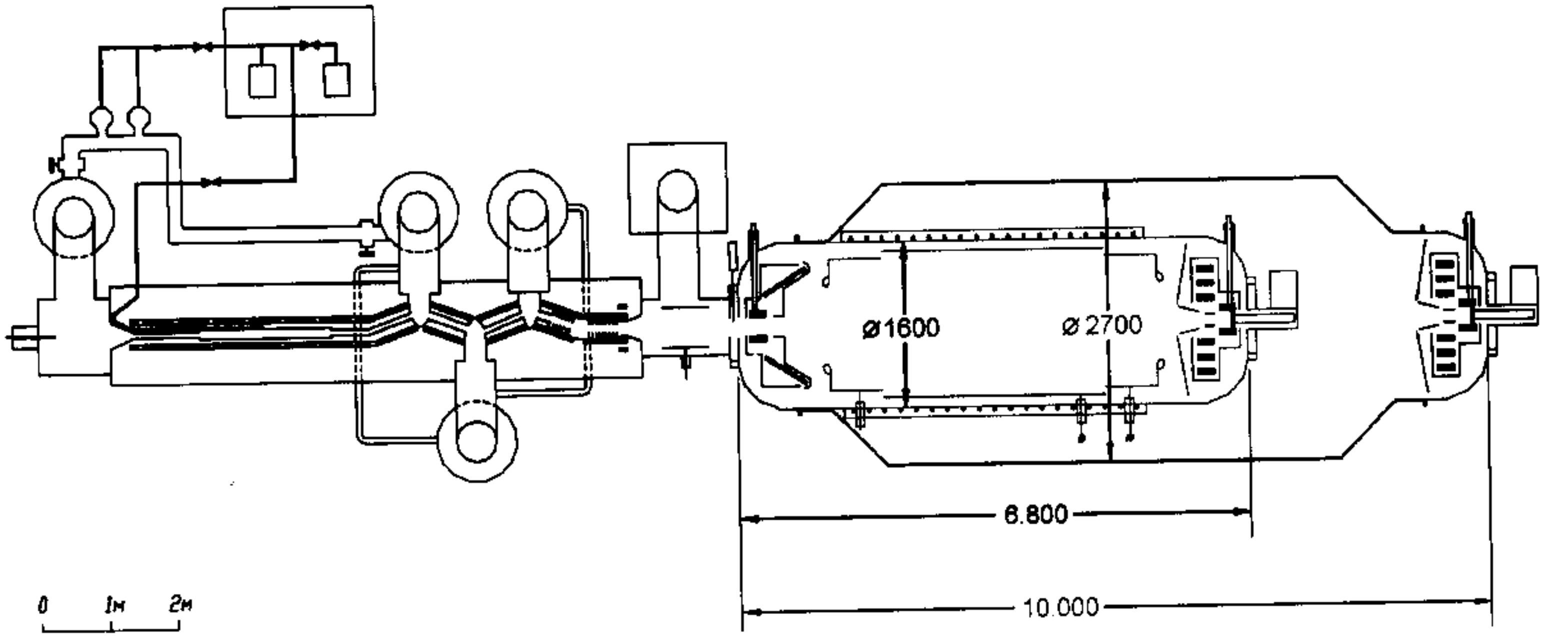
1. Introduction
2. Main feature of electrostatic spectrometer with adiabatic magnetic collimation
3. Status of experiments “Troitsk ν-mass” and “Mainz Neutrino Mass”
4. Experiment KATRIN
5. Systematics in tritium experiment
6. Diagnostic of the source by means of ^{83m}Kr
7. Fantastic vision of future



Adiabatic differential spectrometer (ADS). Use of transverse drift in inhomogenious magnetic field. between two parts of integral spectrometer.

Modernization of “Troitsk ν-mass” spectrometer.

Main goal – resolution ~1 eV and study with ^{83}Kr conversion line.



Benefit:

- Less correlation of m_ν^2 and anomaly.
- Possibility to study plasma fluctuation and energy shifts.
- Study of anomaly with about twice of luminosity.

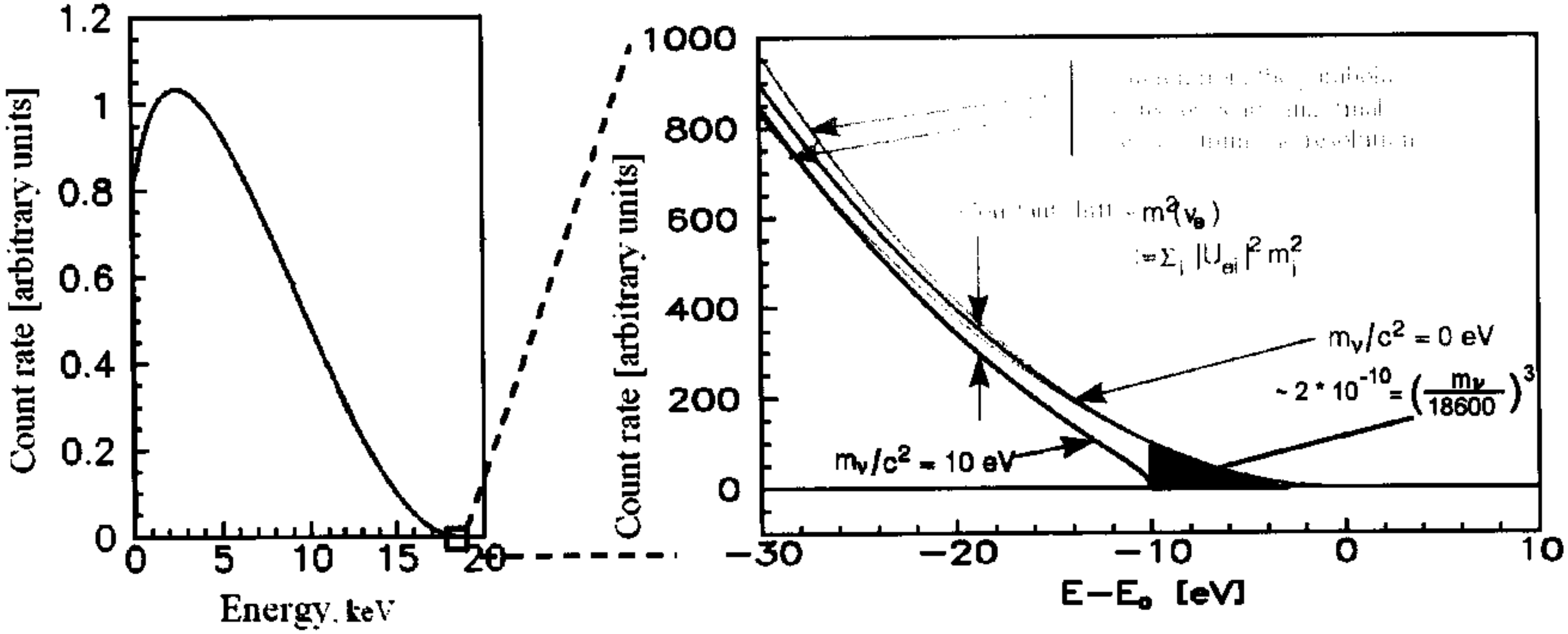
Direct search for neutrino mass ν_e

Tritium β-decay:

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

$E_0 = 18.6$ keV

$t_{1/2} = 12.3$ years



Adiabatic invariant

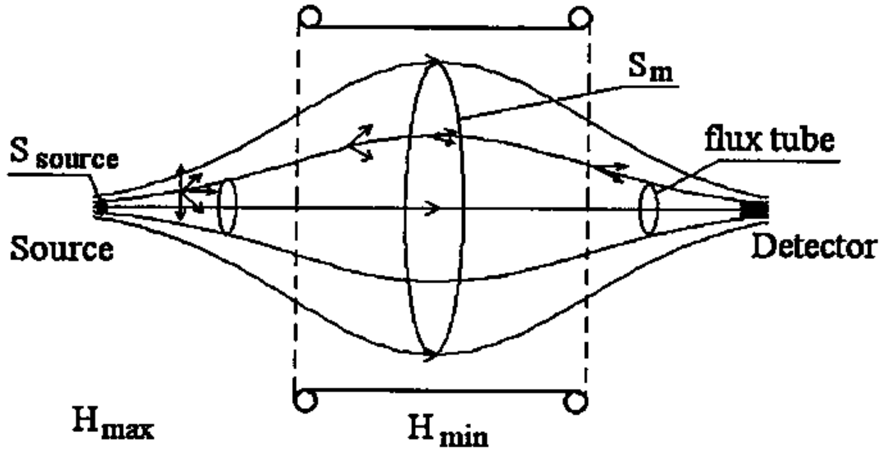
$$\frac{P_{\perp}^{2}}{H} = const$$

For movement of particles in magnetic field along the force line.

$$h = \upsilon^{2}(z) - \frac{2e}{m}\varphi(z) = const$$

For magnetic and electric field.

Integral electrostatic spectrometer with magnetic adiabatic collimation (IESMAC) (MAC-E-Filter).



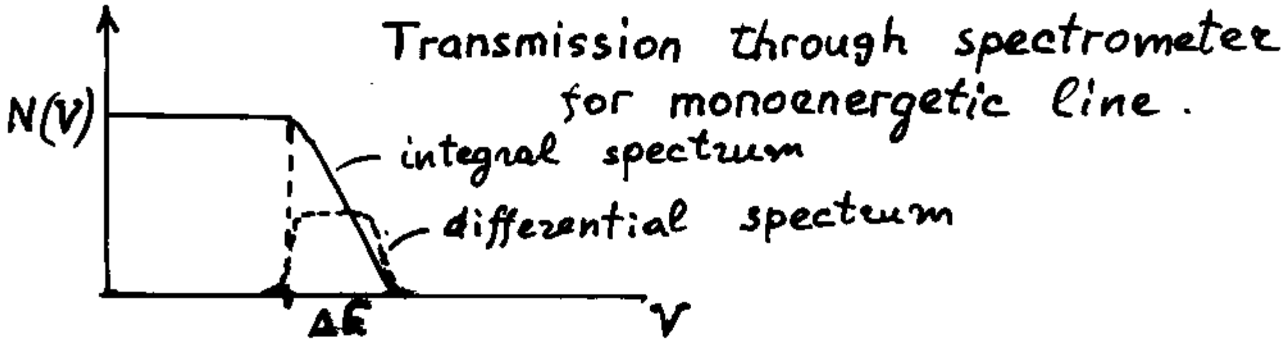
Adiabaticity: $\frac{\Delta H}{H} \leq 0.1$ spiral step along m.t.l.

$$\frac{P_{\perp}^{2}}{H} = const$$

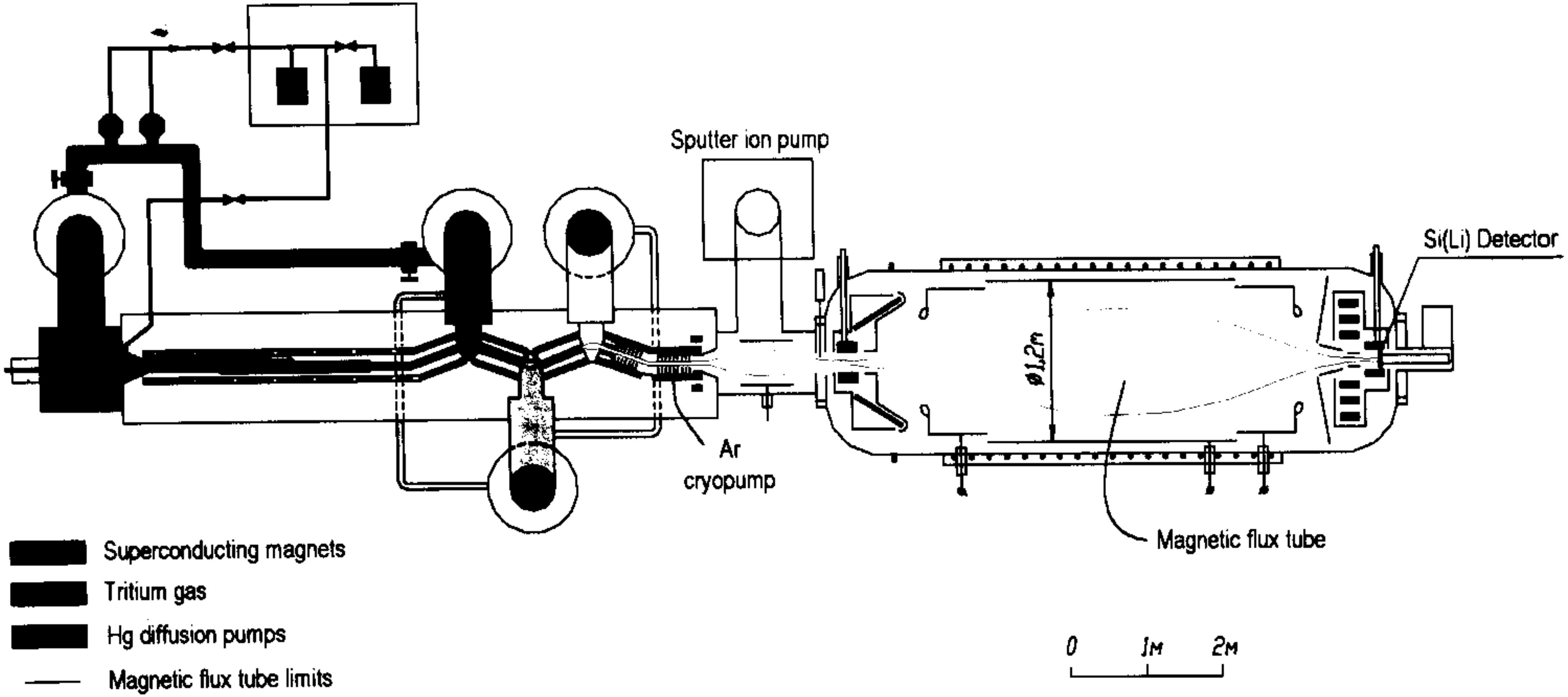
$$E_{tot} = \underbrace{\frac{P_{\perp}^{2}}{2m}}_{\downarrow} + \underbrace{\frac{P_{\parallel}^{2}}{2m} - eV}_{=0}; \qquad \frac{P_{\perp}^{2}}{P_{0}^{2}} = \frac{H_{\min}}{H_{\max}} = \frac{\Delta E}{E_{0}};$$

$L = S_S \cdot \frac{\Omega}{4\pi}$; $\Omega = 2\pi$; $L = \frac{S_S}{2}$; Flux tube $\Phi = const$

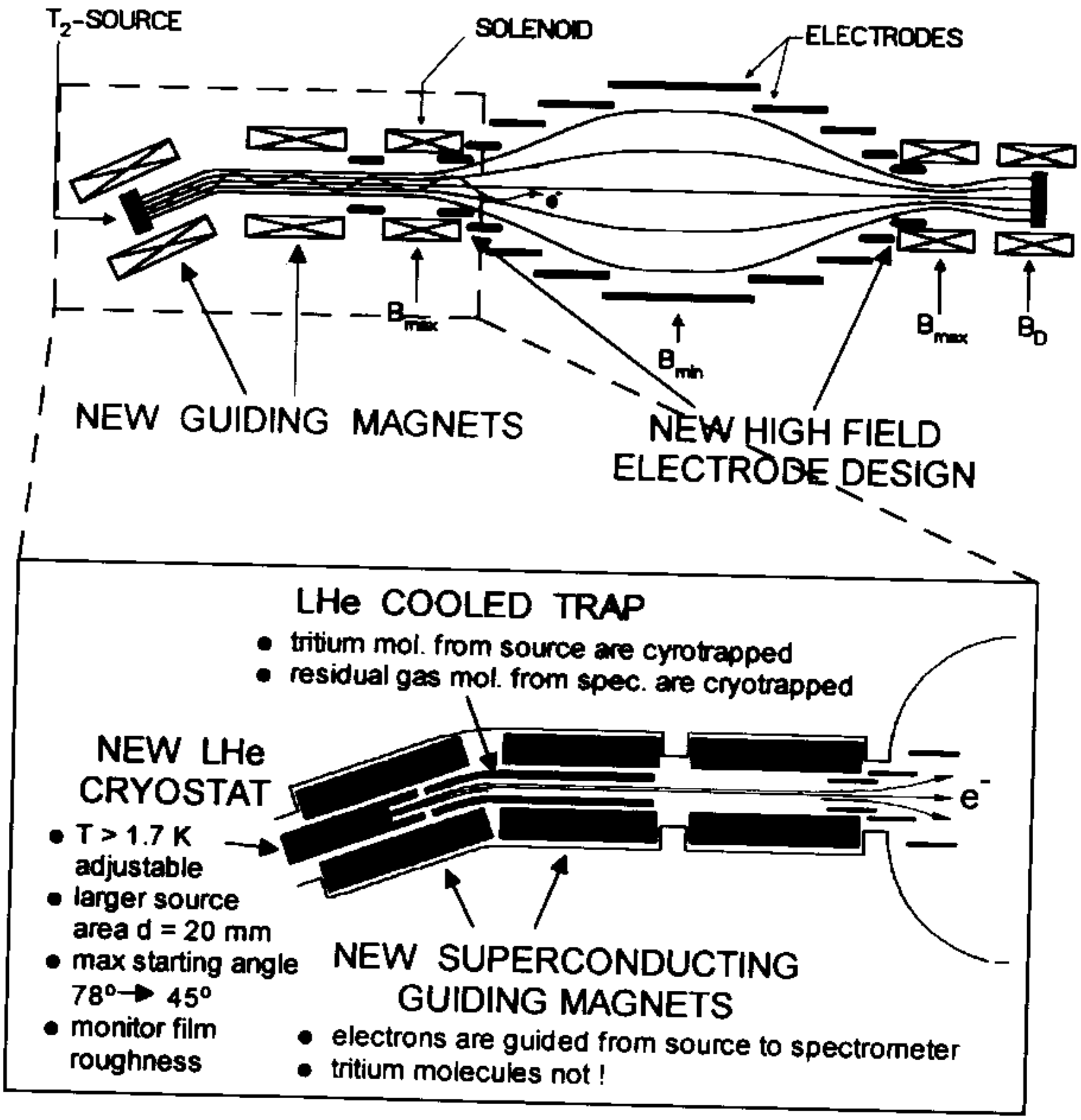
$\underbrace{\frac{\Delta E}{E_0} = \frac{S_S}{S_m};}_{\gtrsim 5m}$ Magnetic focusing sp. $\underbrace{\frac{\Delta E}{E} \sim \frac{\sqrt{S_S}}{R}}_{equivalent \quad size \sim 50m}$


Transmission through spectrometer for monoenergetic line.

Institute for Nuclear Research RAS
Troitsk ν-mass set-up



The improved Mainz Setup



NEW GUIDING MAGNETS

NEW HIGH FIELD ELECTRODE DESIGN

LHe COOLED TRAP

- tritium mol. from source are cyrotrapped
- residual gas mol. from spec. are cryotrapped

NEW LHe CRYOSTAT

- T > 1.7 K adjustable
- larger source area d = 20 mm
- max starting angle 78° → 45°
- monitor film roughness

NEW SUPERCONDUCTING GUIDING MAGNETS

- electrons are guided from source to spectrometer
- tritium molecules not !

KATRIN main spectrometer: industrial design study

- Stainless steel vessel ($\varnothing = 10$ m, $l = 24$ m) on HV potential
- Minimization of background rate: $p < 10^{-11}$ mbar (XHV!)

KATRIN COLLABORATION

Зависимость тритиевого спектра вблизи граничной точки от массы нейтрино (квадрата массы).

$$N(E)dE = A\cdot F(E,E_0,Z)|M|^2 p_e E_e \sum_i W_i \underline{(E_{0i}-E)\sqrt{(E_{0i}-E)^2 - m_\nu^2 c^4}}\,dE$$

Энергия нейтрино $\varepsilon_\nu = E_{0e} - E_e$

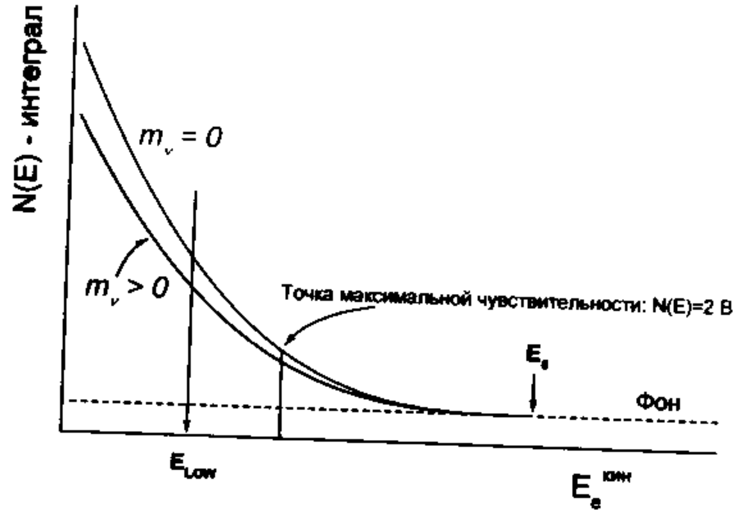
где E_e, p_e – полная энергия и импульс электрона

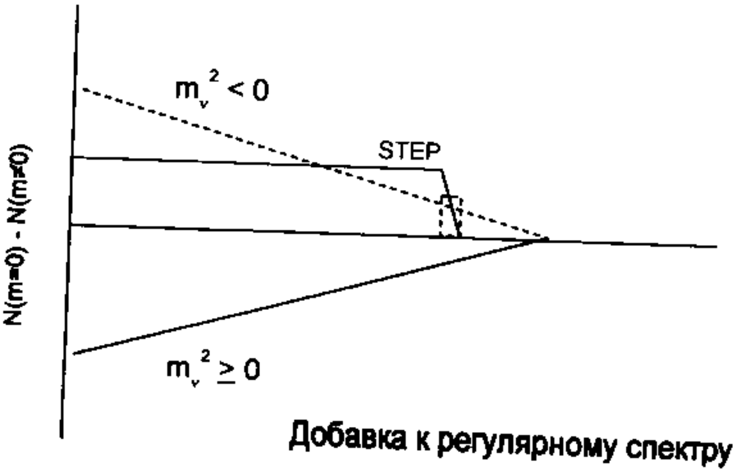
Вблизи граничной точки, но при $\varepsilon_\nu \gg m_\nu$:

$$\boxed{N(E)\sim A\left[\varepsilon^2-\frac{m_\nu^2}{2}\right]+B \qquad \textit{Дифференциальный спектр}}$$

$$\boxed{N(E)\sim C\left[\varepsilon^3-\frac{3}{2}m_\nu^2\cdot\varepsilon\right]+B \qquad \textit{Интегральный спектр}}$$

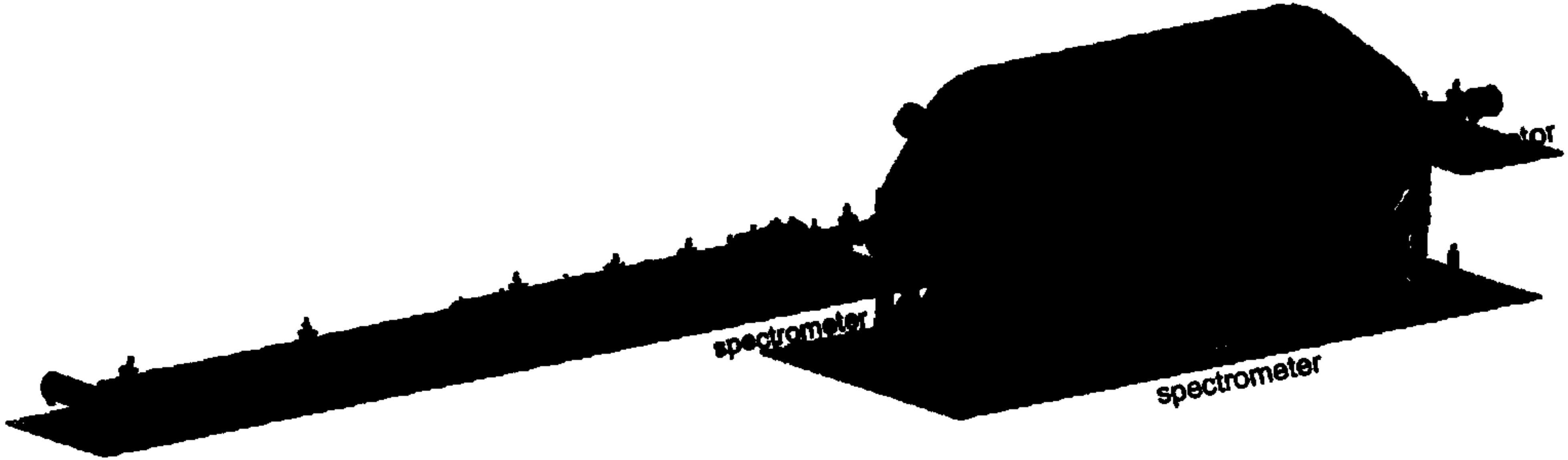
B – Фон





Добавка к регулярному спектру

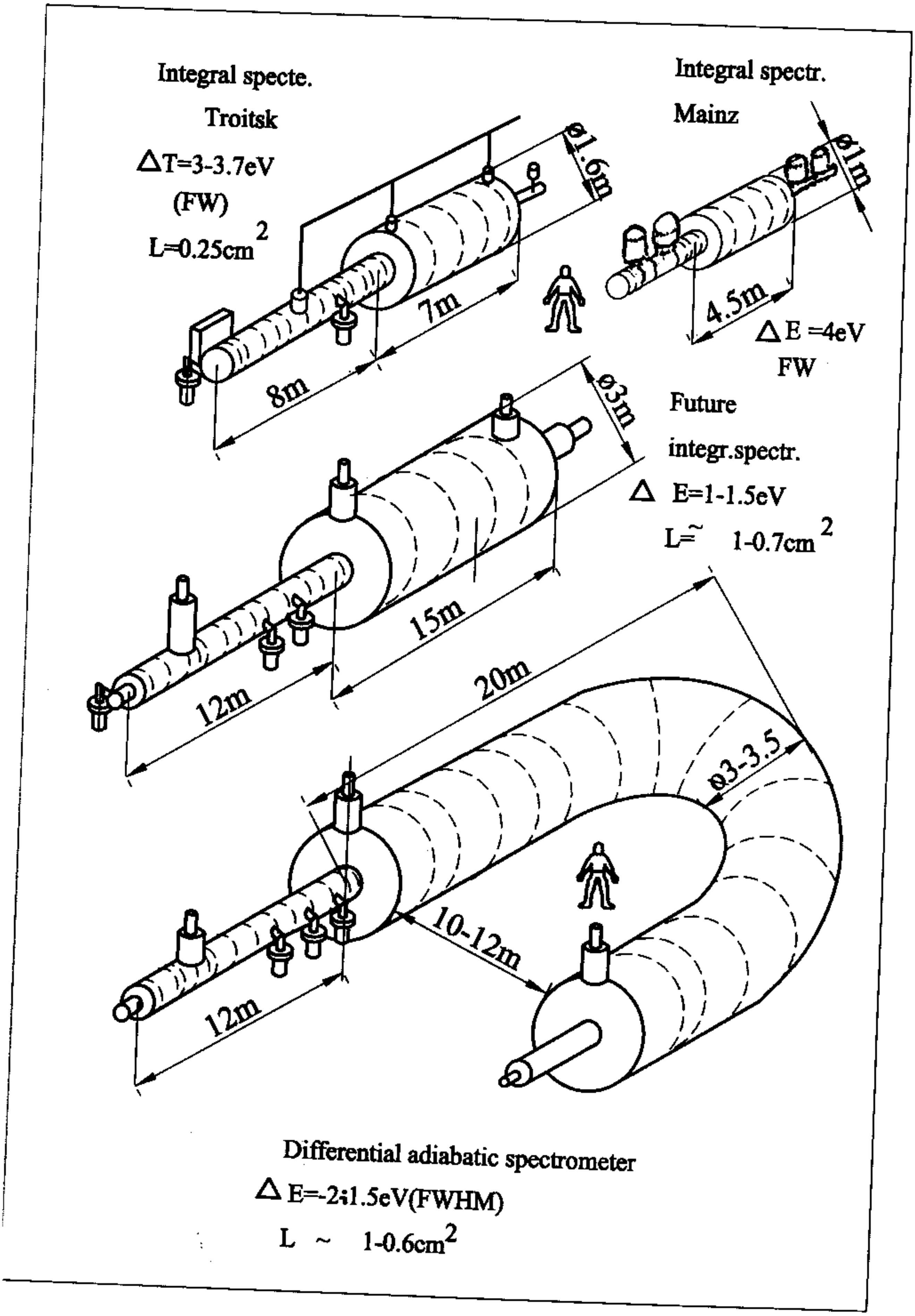
KArlsruhe **TRI**tium **N**eutrino Experiment



Benefit of spectrometer increase.

1. Energy resolution increase. $\frac{\Delta E}{E} = \frac{\Delta H_p}{H_M}$; H_p - pinch, H_m middle
2. Tritium soure ϕ increase.
3. Shift of maximal sensitivity point to end point due to condition $N(E)_{Max} = 2Bkg$. This allowes to cut measured interval and supress significant part of systematics.

Disadventage: long tritium source.


Integral specte.
Troitsk
ΔT=3-3.7eV
(FW)
L=0.25cm²
ø1.6m
7m
8m
Integral spectr.
Mainz
ø1m
4.5m
ΔE =4eV
FW
ø3m
Future
integr.spectr.
Δ E=1-1.5eV
L≃ 1-0.7cm²
15m
12m
20m
ø3-3.5
10-12m
12m
Differential adiabatic spectrometer
Δ E=-2÷1.5eV(FWHM)
L ~ 1-0.6cm²

Ultimate results of the search for neutrino mass

Troitsk
1994-2001

$$m_\nu^2 = -2.3 \pm 2.5(fit) \pm 2.0(syst) eV^2/c^4$$

$$m_\nu < 2.05 eV/c^2$$

At 95% C.L. (universal approach)

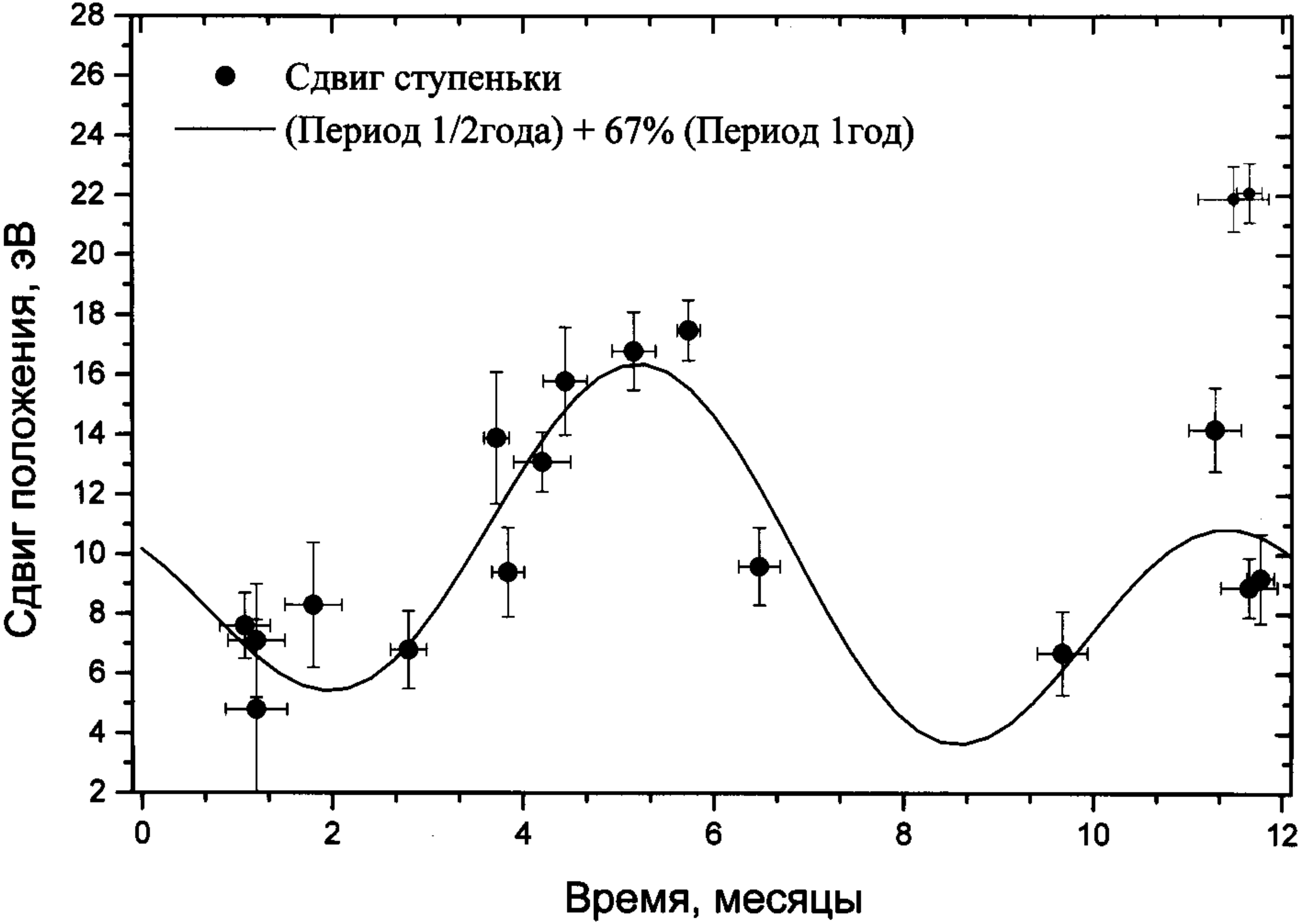
Mainz Neutrino mass Experiment

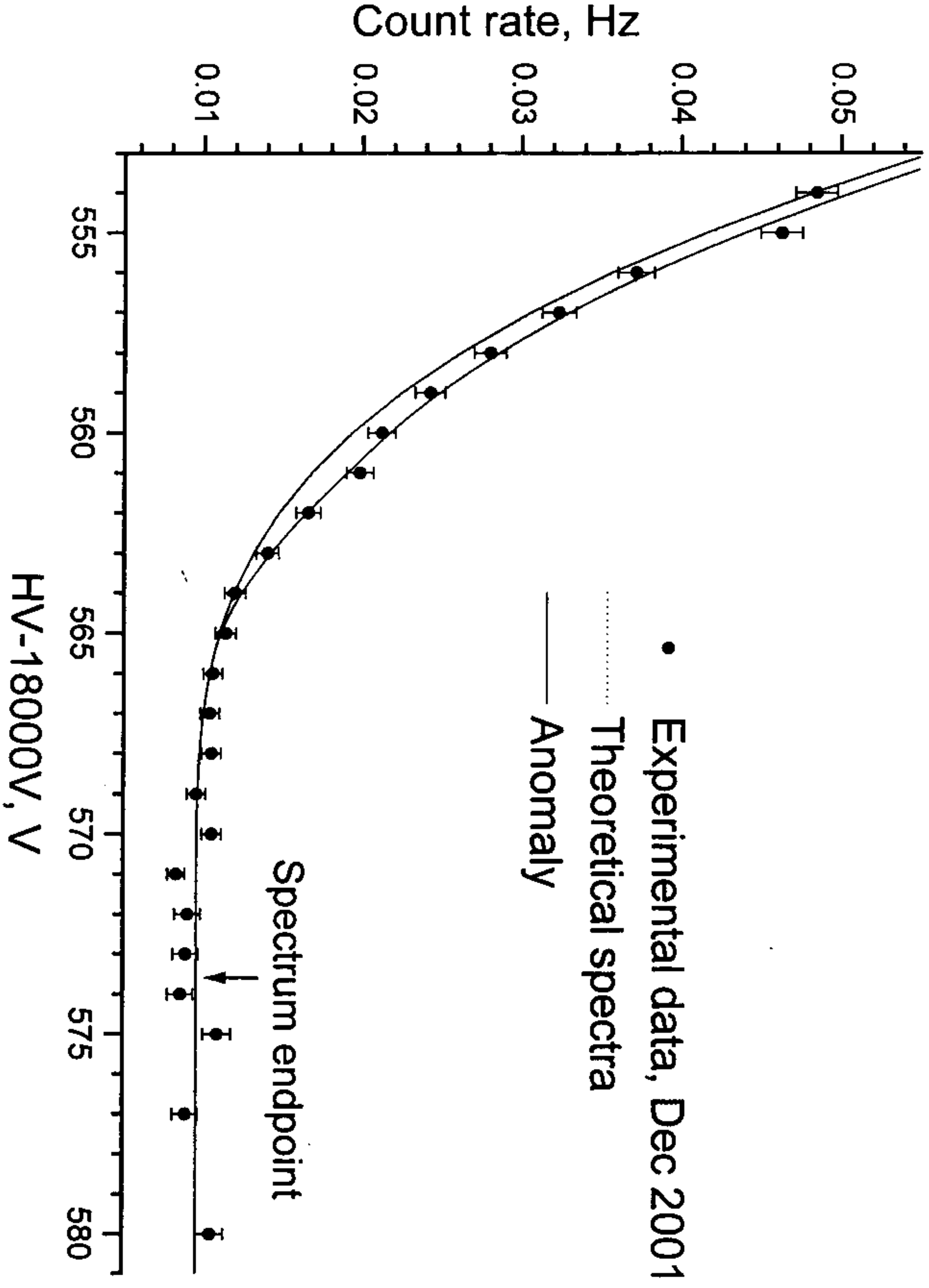
1998-2001

$$m_\nu^2 = -1.2 \pm 2.2_{stat} \pm 2.1_{syst} eV^2/c^4$$

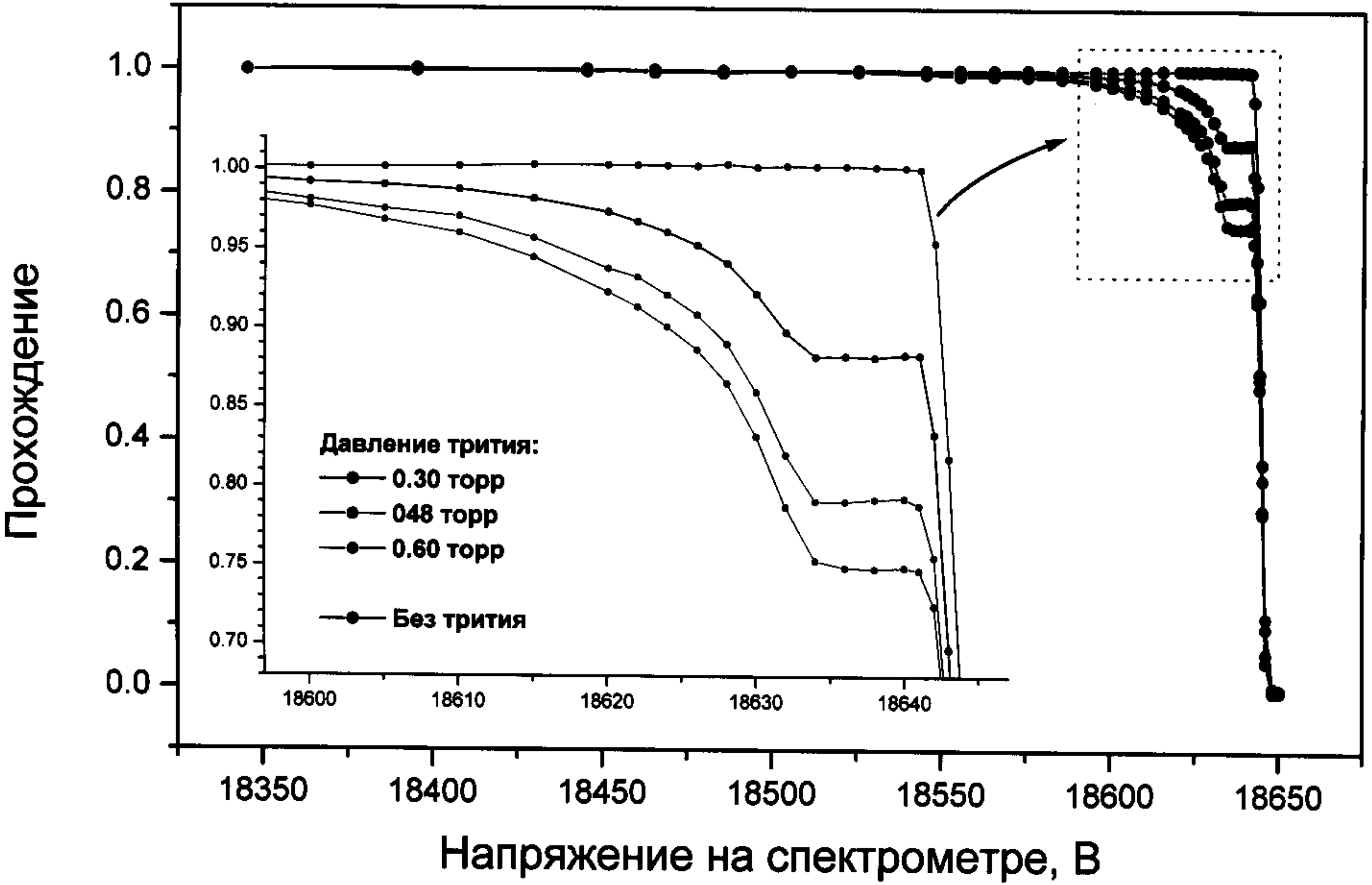
$$m_\nu < 2.2 eV/c^2$$

At 95% C.L. (universal approach)

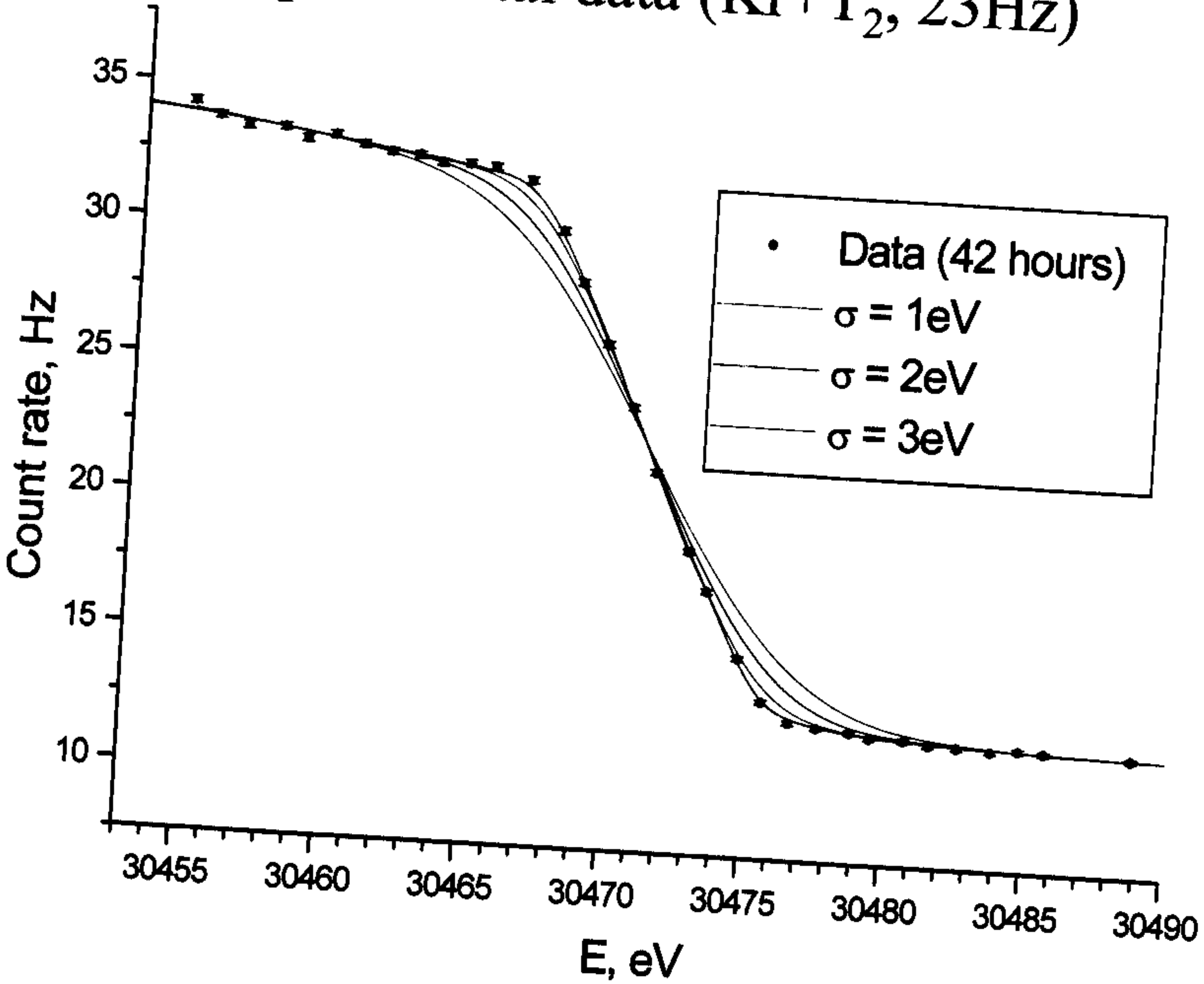

Сдвиг ступеньки
(Период 1/2года) + 67% (Период 1год)
Сдвиг положения, эВ
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
2
4
6
8
10
12
Время, месяцы


Count rate, Hz
0.01
0.02
0.03
0.04
0.05
555
560
565
570
575
580
HV-18000V, V
Experimental data, Dec 2001
Theoretical spectra
Anomaly
Spectrum endpoint

Функция прохождения



Experimental data (Kr+T_2, 23Hz)



Plasma effects in WGTS

Measurement of energy shift and width enlargement of ^{83}Kr conversion line

$E_e = 17\ 830$ eV.   Width 2.9 eV (HWFM)

Space charge and wall effects may produce an energy shift and width enlargement

Fluctuation of space charge (micro fluctuation) causes enlargement of width.

Tritium background at 17830 eV is:

~ 6 kHz at column density 5 10^{14} m/cm^2

^{83}Kr must provide ~ 6 kHz

To provide Kr/T signal ~ 1:1 it is necessary a source of Kr (Rb)

~ 1 mC   T ~ 50 – 80 K

ist. Durch die hohe Zerfallsrate benötigt man weniger als eine Monolage ^{83m}Kr. Selbstabsorption in der Quelle kann daher ausgeschlossen werden.

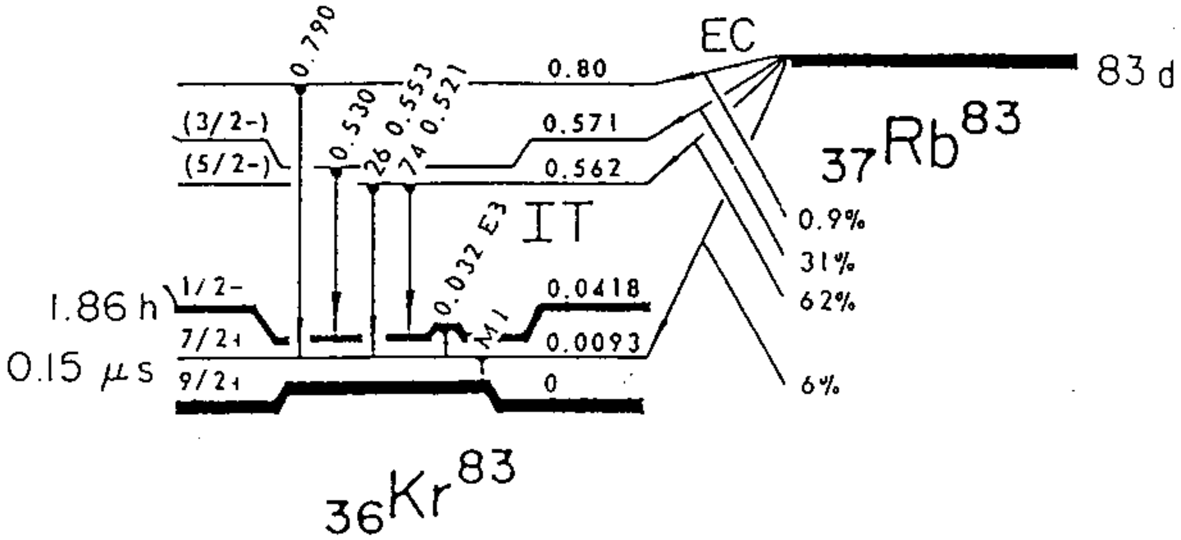
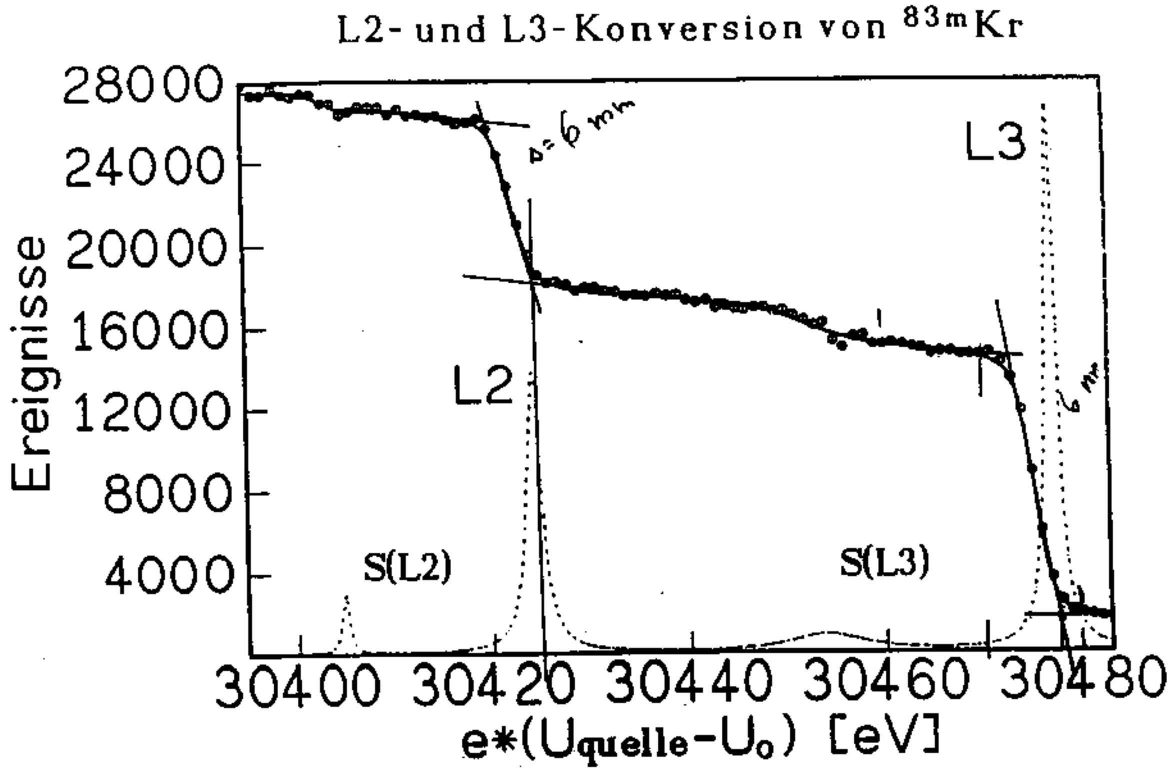


Bild 6-4 *Das Zerfallsschema des ^{83}Rb über EC in ^{83m}Kr [Led78].*



Goals and Schedule of KATRIN

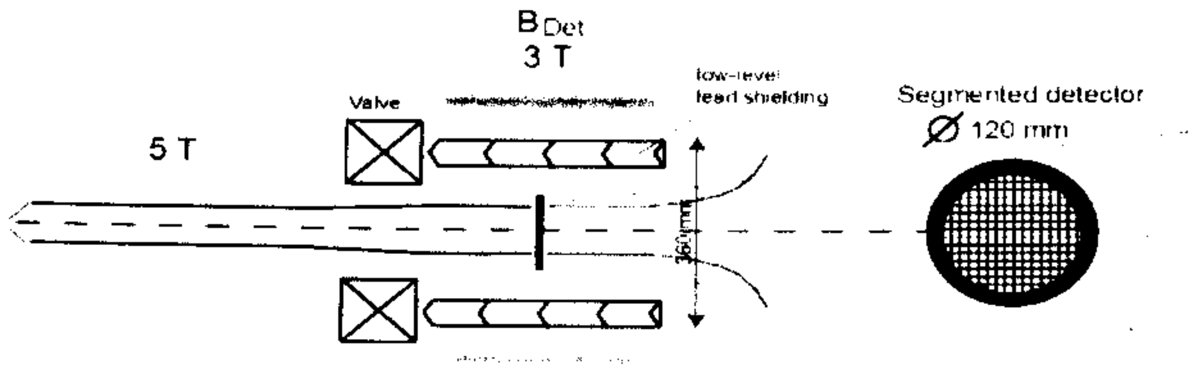
KATRIN sensitivity after 3 years of measuring:

- sensitivity: $m_\nu < 0.2$ eV (90%CL)
- discovery potential: $m_\nu = 0.35$ eV with 5σ ($m_\nu = 0.3$ eV with 3σ)
- statistical and systematic uncertainties contribute about equally

KATRIN schedule:

- since 2001: prototype studies to improve:
  - background suppression (Mainz, Troitsk)
  - vacuum ($< 10^{-11}$ mbar)
  - e-m design and calibration (electrodes, magnets, e-gun)
  - Si-detector (SDD, APD, PIN)
- September 2003: delivery of the pre-spectrometer
- 2005/2006: construction of the main spectrometer and WGTS
- 2007: start of measurements

KATRIN detector

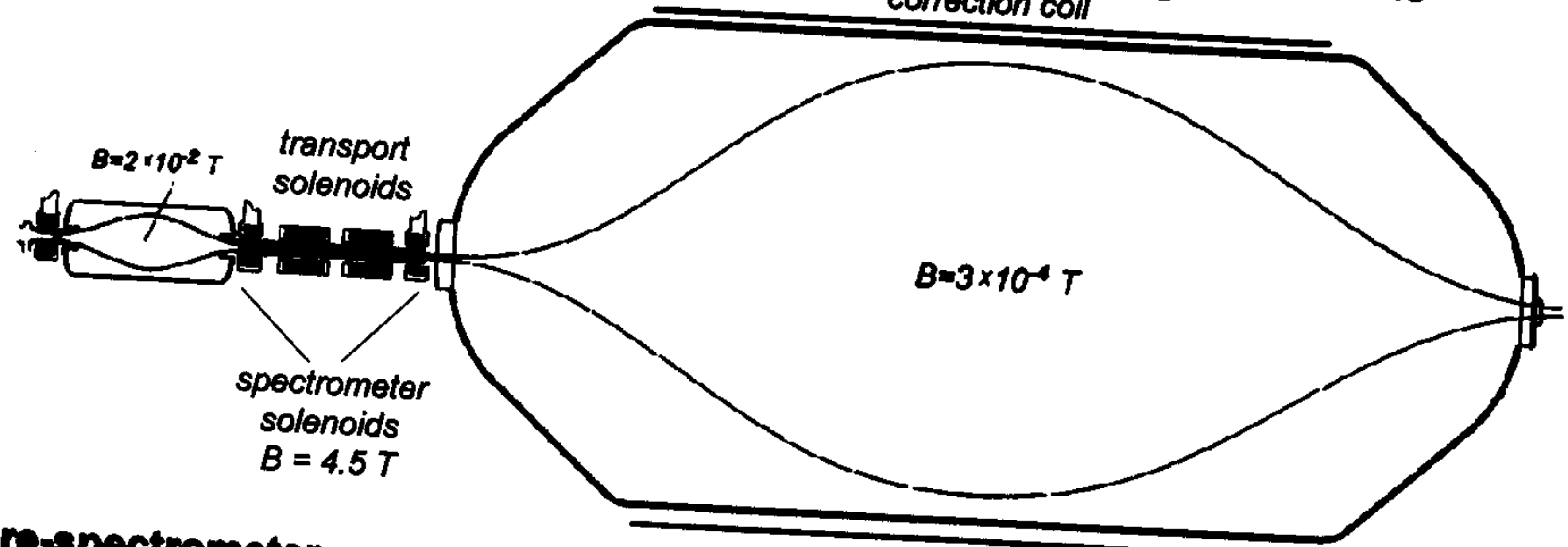


- **Detection of β-electrons** ⇒ **high efficiency (>90%)**
- **Monitoring of source density** ⇒ **pixel detector (400 pixel)**
- **Background suppression** ⇒ **good passive and active shielding**
  ⇒ **high energy resolution (ΔE < 600 eV)**
- **MAC-E-TOF Mode** ⇒ **high time time resolution: Δt < 1 ms**
- **Calibration measurements** ⇒ **high count rate: ≤ 1 MHz**

KATRIN COLLABORATION

Electro-static Spectrometer: Tandem Design

electro-static pre-filter and energy analysis of T_2 β–electrons



pre-spectrometer

fixed retarding potential: 18.4 keV

Ø= 1.7 m, L = 3.5 m

ΔE = 70 eV

main spectrometer

variable retarding potential: 18.5 – 35 kV

Ø= 10 m, L = 24 m

ΔE = 1 eV

Design Parameters

- Sectrometer diameter.................................. 10 m
- Spectrometer length.................................... 24 m
- Energy resolution for 20 keV electrons ....1 eV
- Source diameter .... 90 mm
- Maximum magnetic field strangth ....6 T
- Minimum magnetic field strangth ....0.3 mT
- Source column density .... $5x10^{17}$ mol cm^{-2}
- Acceptance angle .... 51 degrees

Systematic Error

- **Influence of systematic uncertainties on sensitivity under detailed investigation**
- **Total systematic error after 3 years of data taking should be about the same size as the statistical error**
- **Possible sources of systematic errors:**
  - Energy loss due to excitation of the daughter molecule
  - Energy loss due to inelastic scattering on gas molecules in the source
  - Density profile in the source; space charge within the source
  - T_2-purity (T2, TH, H_2)
  - HV fluctuations
  - Stability of the background rate
  - charged plasma effects in spectrometer and T_2 source

Systematic uncertainties

The smaller the neutrino mass, $A\varepsilon^3 \sim 2 Bkgr$
the smaller the region of interest below the β endpoint

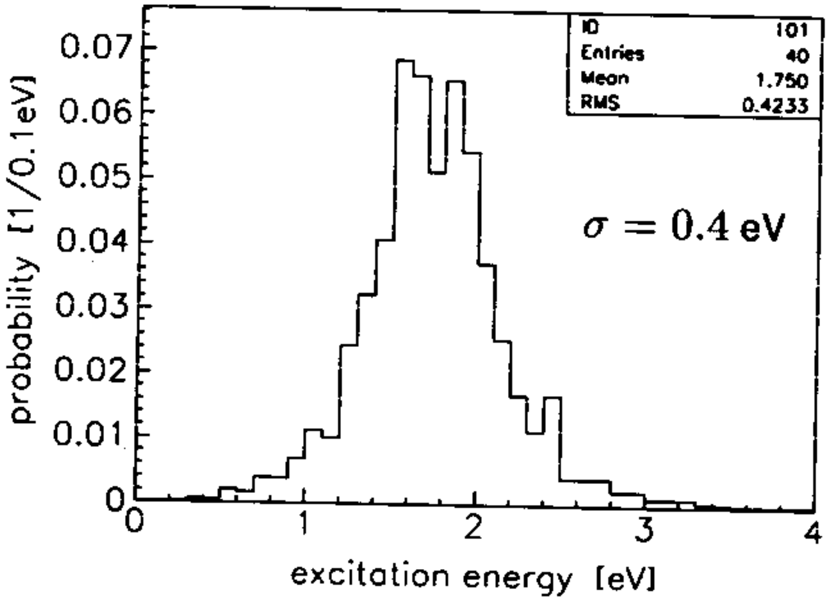
⇒ Excited electronic final states ($\Delta E_{exc} \geq 27 eV$) do not play a role !

⇒ Inelastic scattering in the T_2 source ($\Delta E_{sca} \geq 13 eV$) is not big !
is relevant since MAC-E-filter response function has no tails!

⇒ one well-defined final state similar to cryogenic detectors

Systematic uncertainties

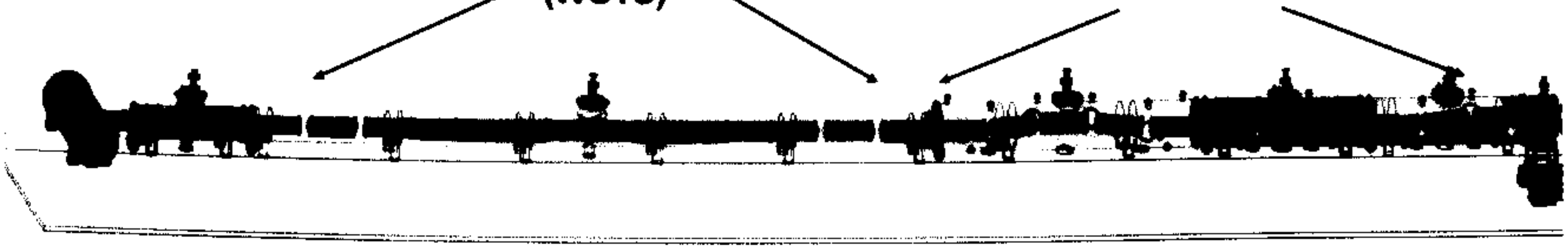
- Rotation-vibration excitation of final ground state



- Inelastic scattering (sys. uncert.: Troitsk: ≈ 3 %, Mainz: ≈ 6 %)
- Solid state effects (for quench-condensed source only)
- Stability of settings (HV, source activity, source purity, ...)

KATRIN COLLABORATION

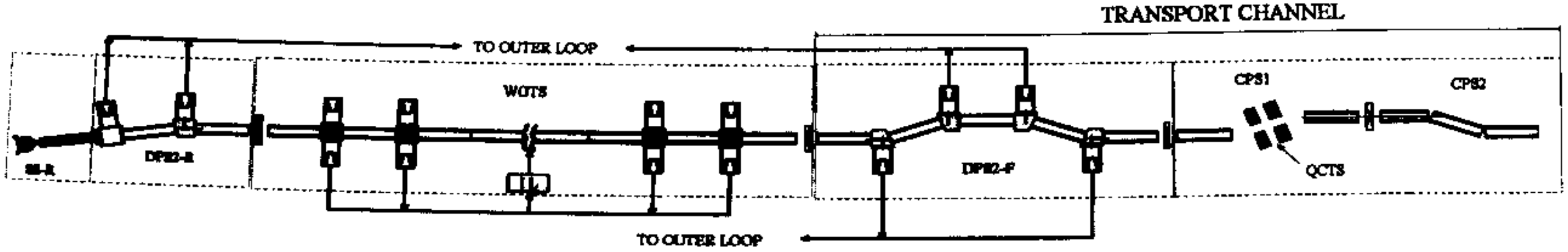
TRITIUM RELATED PARTS of KATRIN



Rear System

Windowless Gaseous Tritium Source (WGTS)

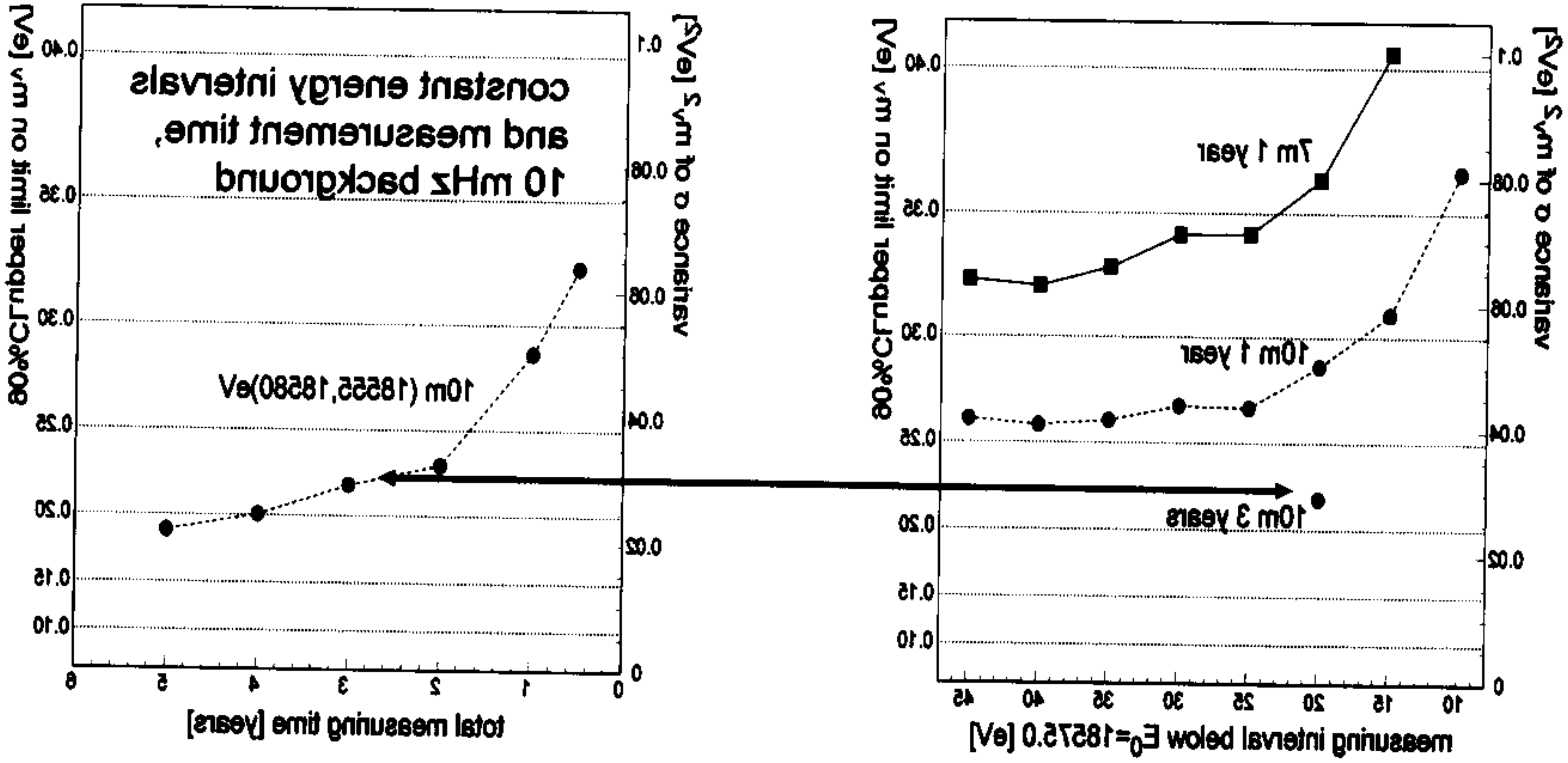
Transport System (Electron Transport + Tritium Retention)



KATRIN COLLABORATION

Sensitivity on Neutrino Mass

(statistical error only)



Motivation

1.KATRIN specification $\delta m_\nu^2 < .007\ \mathrm{eV}^2$

$\sigma < 0.06\ \mathrm{eV}$

2.Troitsk $m_\nu^2 = -10 \div -20\ \mathrm{eV}^2$

Step effect

$\sigma = 2 \div 3\ \mathrm{eV}$

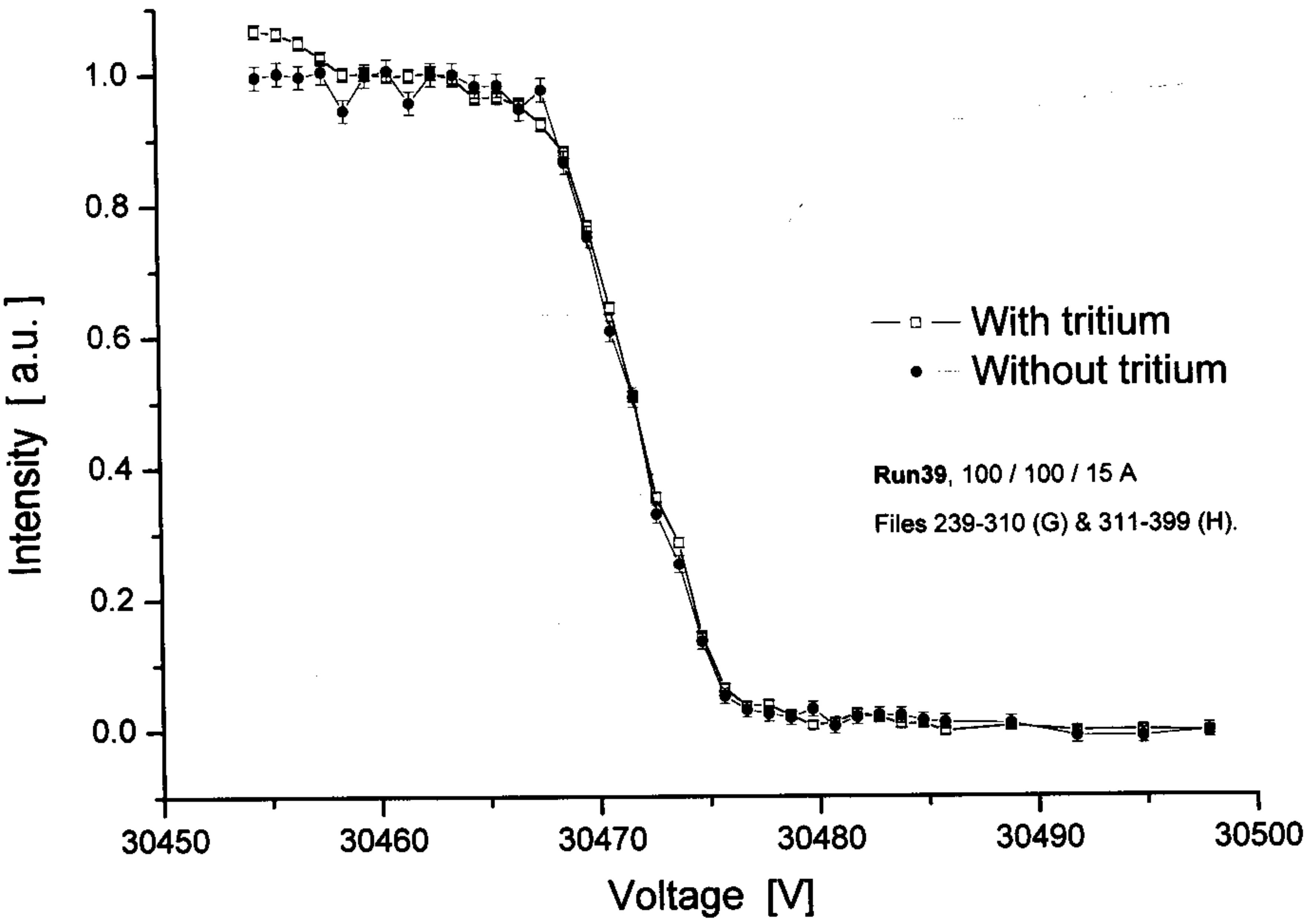
Motivation

WGTS space charge problem was pointed by international KATRIN evaluation panel

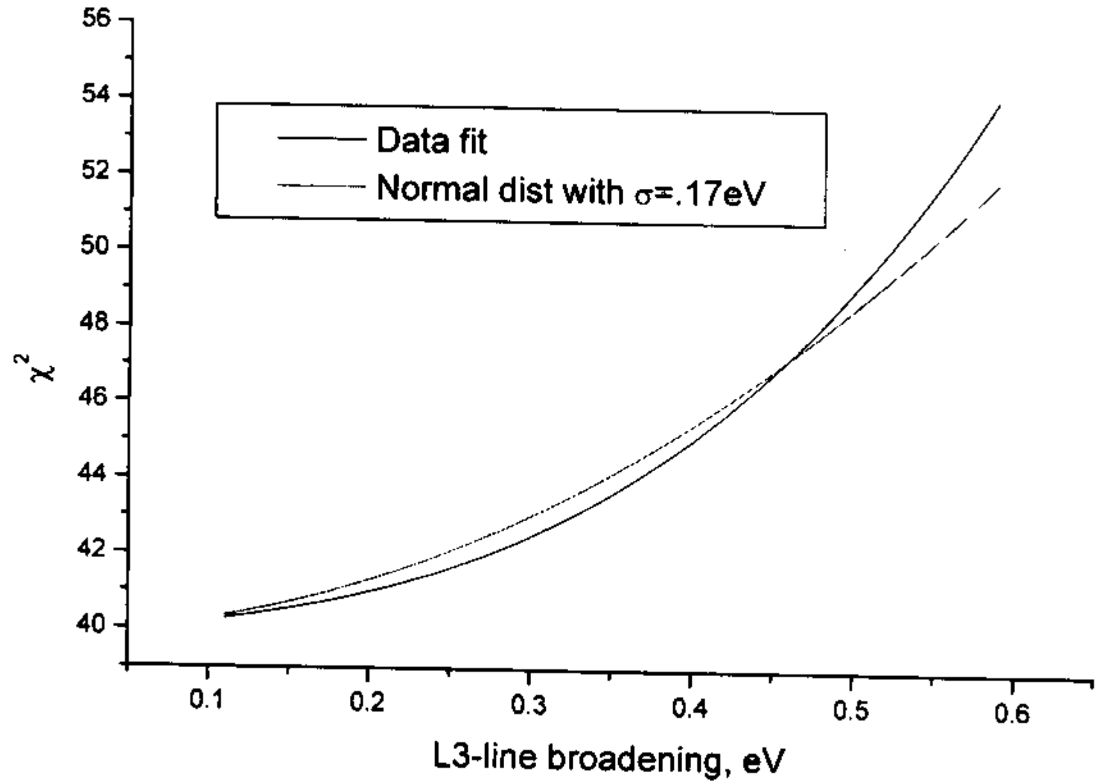
$$\delta m_\nu^2 = -2\sigma^2$$

^{83m}Kr lines broadening in the presence of T_2 in WGTS is a measure of space charge variation.

Spectrum of the ^{83m}Kr L3 conversion line.



Broadening sensitivity



Broadening error about
0.17 eV
but is not parabolic!

About 10^2 higher
statistics
is required to check
KATRIN specifications:
broadening < .06 eV