The Long Route to KATRIN – Neutrino Mass in β-Decay

(Ernst Otten, Mainz)

HAP-meeting 19. 9. 2012

1.) Introduction

2.) The quiet early phase (< 1980) of neutrino mass search in β-decay

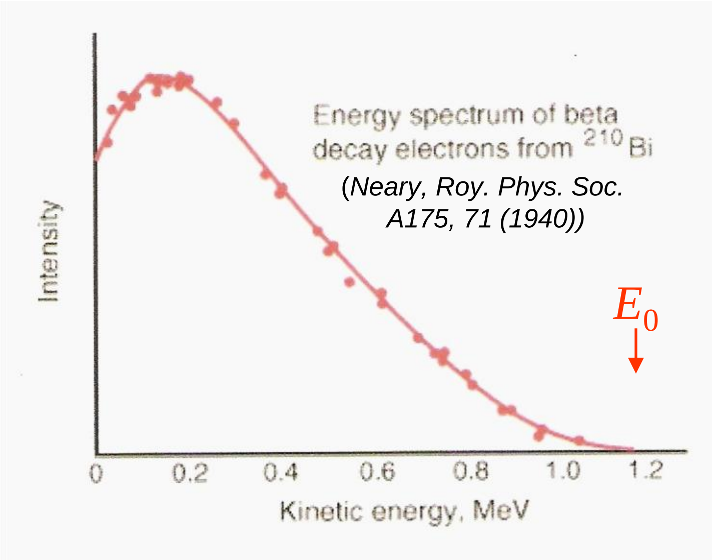
3.) The shocking Ljubimov claim of 30eV neutrino mass and reactions to it

4.) Mainz and Troitzk: **Ma**gn1etically **C**ollimated **E**lectrostatic (MAC-E)-Filters

5.) 21st Century: New demands for absolute neutrino mass challenge KATRIN

1.) Introduction:
Pauli‘s pragmatic Neutrino Proposal and Fermi‘s Weak Interaction

A century ago: Scandalous β-decay:
Decay energy missing, momenta and spins not balanced!



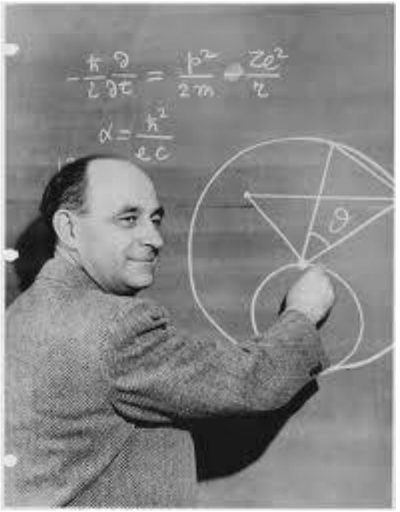
Energy spectrum of beta decay electrons from ^{210}Bi
(*Neary, Roy. Phys. Soc. A175, 71 (1940)*)

1930 Wolfgang Pauli

Encouraged experimentalists to search for hidden, neutral companion of β-particle
Should end the mystery by carrying off missing energy, momentum and spin 1/2!

Further properties:
Interaction with matter: Smaller than detection limit at the time
Mass: Smaller than known upper limits on $Q - E_0$, possibly 0

1934: Fermi: Ingenious Field Theory of Weak Interaction



- provided perfect description of beta decay kinematics.

- explained by one and the same universal weak interaction constant
  - i) why beta decay is so slow
  - ii) why the cross section for emitted neutrinos reacting with matter is so terribly small ($\approx 10^{-42}$ cm^2) that contemporary experiments failed to discover them.

Fermi's theory treats neutrino mass as free input parameter
Till today we put in only upper limits, the latest from Mainz and Troitzk[1-3]: $m_\nu < 2$ eV

Anyway, in the still „Higgs less" old days one had no chance explainig particle masses
Physics focused rather on the spectacular properties of weak interaction:
parity violation, neutral currents, vector bosons and electroweak interaction

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1) *Mainz: Kraus Ch, Bornschein B, Bornschein L, Bonn J, Flatt B, Kovalik A, Ostrick B, Otten E W, Schall J P, Thümmler Th, Weinheimer Ch 2005 Eur. Phys. J. C* ***40****, 447*
2) *Troitsk: Aseev V N, et al. 2011 Phys.Rev. D 84 (112003)*
3) *Review: Otten E W and Weinheimer Ch 2008 Rep. Prog. Phys.* ***71****, 086201*

2.) Early phase (< 1980) of neutrino mass search

In the shadow of the really big issues, quite a number of dedicated, continuously improving neutrino mass searches were performed over the years

Particularly on tritium decay because of
low endpoint, 18.6 keV and superallowed type

2 totally opposed approaches shall be presented from this era :

Hamilton‘s toy: The hemisperical electrostatic filter (Princeton,1950 – 1953)

Bergkvists perfectionated $\pi\sqrt{2}$-spectrometer (Stockholm 1971)

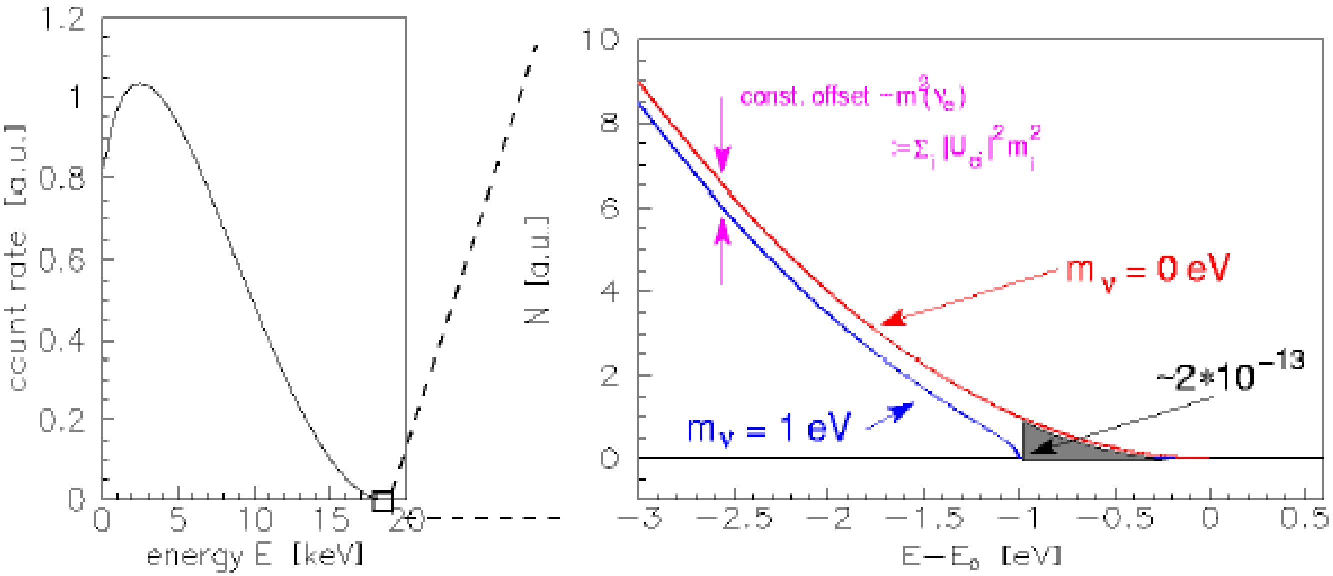
In case of a fairly relativistic neutrino one measures m_ν^2

Via the invariant: $m_\nu^2 = E_\nu^2 - p_\nu^2 \Rightarrow$

Correlation of uncertainties: $\underline{\sigma(m_\nu^2)} = \underline{2E_\nu}\sigma(E_\nu) + \underline{2p_\nu}\sigma(p_\nu)$

Very ugly upscaling factors!

Hence one likes „slow" neutrinos; To be found only near β-endpoint!



Close to endpoint: β-spectrum ~ ν-phase space $\frac{d\Gamma}{dE} \propto E_\nu \cdot p_\nu = (\underline{E_0} - E)\cdot\sqrt{(\underline{E_0} - E)^2 - \underline{m_\nu^2}\,c^4}$

With parameter correlation: $\sigma(m_\nu^2) = \underline{4(E_0 - E)}\cdot\sigma(E_0)$

In case of a fairly relativistic neutrino one measures $m_\nu{}^2$

Via the invariant: $m_\nu^2 = E_\nu^2 - p_\nu^2 \;\Rightarrow$

Correlation of uncertainties: $\underline{\sigma(m_\nu^2)} = \underline{2E_\nu}\sigma(E_\nu) + \underline{2p_\nu}\sigma(p_\nu)$

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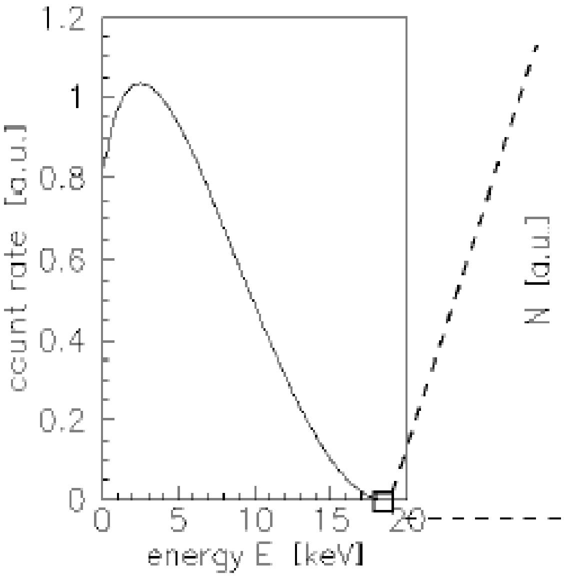

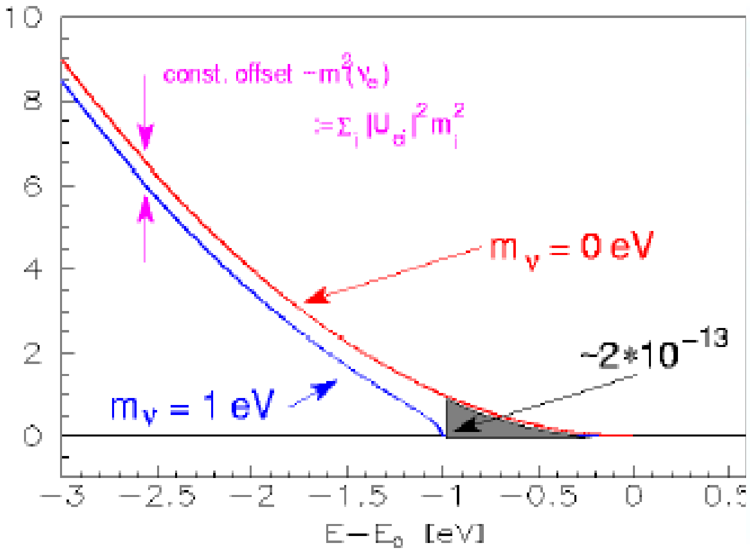

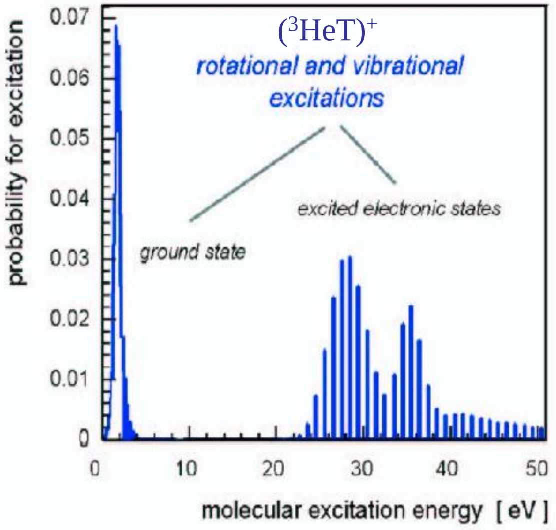

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PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Upper Limits on the Neutrino Mass from the Tritium Beta Spectrum[*]

DONALD R. HAMILTON, W. PARKER ALFORD,[†] AND LEONARD GROSS[‡]
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received August 25, 1953)

The shape of the tritium beta spectrum near the end point has been investigated in a spherical electrostatic integral spectrograph with particular reference to the possible effects of a nonzero neutrino mass. It is shown that the source thickness of 100 micrograms/cm² may be satisfactorily taken into account in the last kilovolt of the spectrum, upon which the results are based. An upper limit to the neutrino mass of 500, 250, and 150 electron volts is found for the Dirac, Majorana, and Fermi forms, respectively, of the beta interaction.

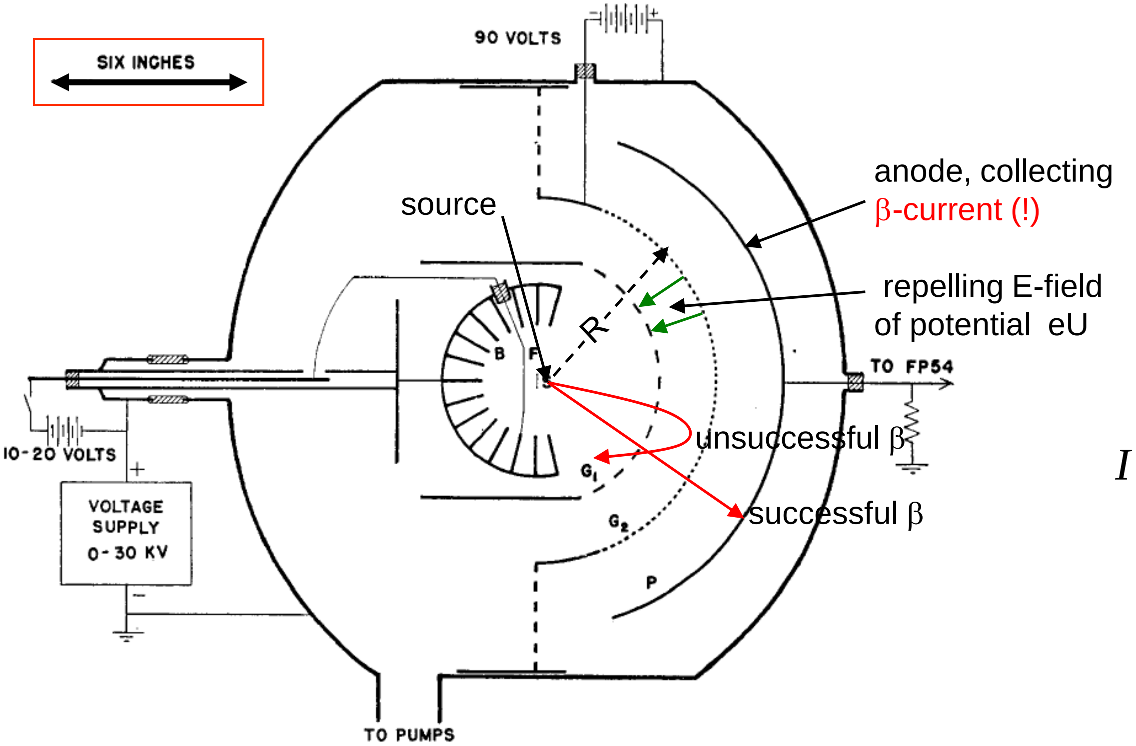


FIG. 1. Schematic diagram of electrostatic beta-spectrograph showing collector P, grids G_1 and G_2, source S, decharging filament F, and electron backstop B.

The width of the filter is:

$$\frac{\Delta E}{E} = \frac{\text{source area}}{9\text{R}^2} \approx 0.7\%$$

For an infinitely sharp filter and infinitely thin source the collected current is the integral of successful β's + background:

$$I = C \int_{E \geq |eU|} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}\,\mathrm{d}E + B$$

$$\approx A\left((E_0 - E)^3 - \frac{3}{2}(E_0 - E)m_{\nu_e}^2\right) + B$$

Result of Hamilton et al.:

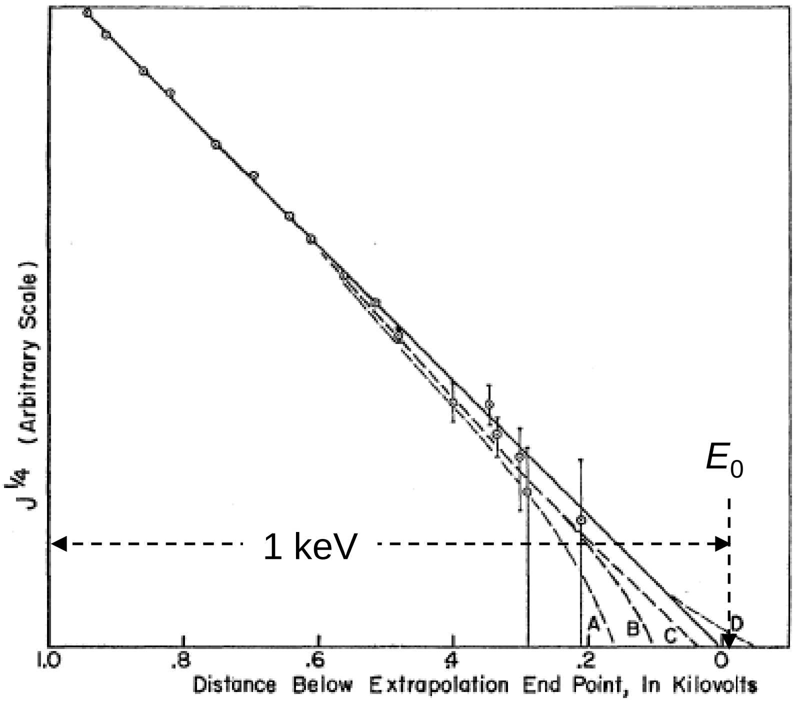


FIG. 3. Fourth root of tritium current plotted against kilovolts below end point. Dotted curves represent curves predicted on the basis of measured resolution and for various neutrino masses and interactions. Majorana, Fermi, and Dirac interactions indicated by (0) (+) (−), respectively. Neutrino mass μ in electron volts.

Curve A: $\mu=250$ (+), 350 (0).
Curve B: $\mu=150$ (+), 200 (0).
Curve C: $\mu=500$ (−).
Curve D: $\mu=0$ (0, +, −).

Comparing measured spectrum qualitatively with theoretical spectra, plotted for various neutrinomasses (0, 200 and 350 eV) the authors conclude:

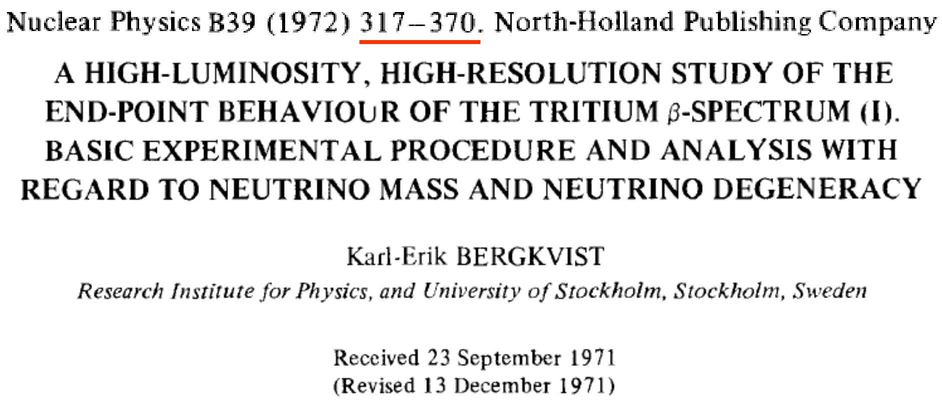
$m_\nu < 200$ eV

Comments:

The analysis of data is certainly not up to present standards

But the experimental idea is appealing:
Being focussed just to the endpoint region, the simple hemispherical filter combines high angular acceptance with reasonable energy resolution

The result, obtained from this toylike instrument was competitive at the time



Nuclear Physics B39 (1972) 317–370. North-Holland Publishing Company

A HIGH-LUMINOSITY, HIGH-RESOLUTION STUDY OF THE END-POINT BEHAVIOUR OF THE TRITIUM β-SPECTRUM (I). BASIC EXPERIMENTAL PROCEDURE AND ANALYSIS WITH REGARD TO NEUTRINO MASS AND NEUTRINO DEGENERACY

Karl-Erik BERGKVIST
Research Institute for Physics, and University of Stockholm, Stockholm, Sweden

Received 23 September 1971
(Revised 13 December 1971)

Karl Eric Bergkvist

opens the era of professional ν-mass seeking

In the light of developing particle physics and cosmology ν-mass problem becomes burning

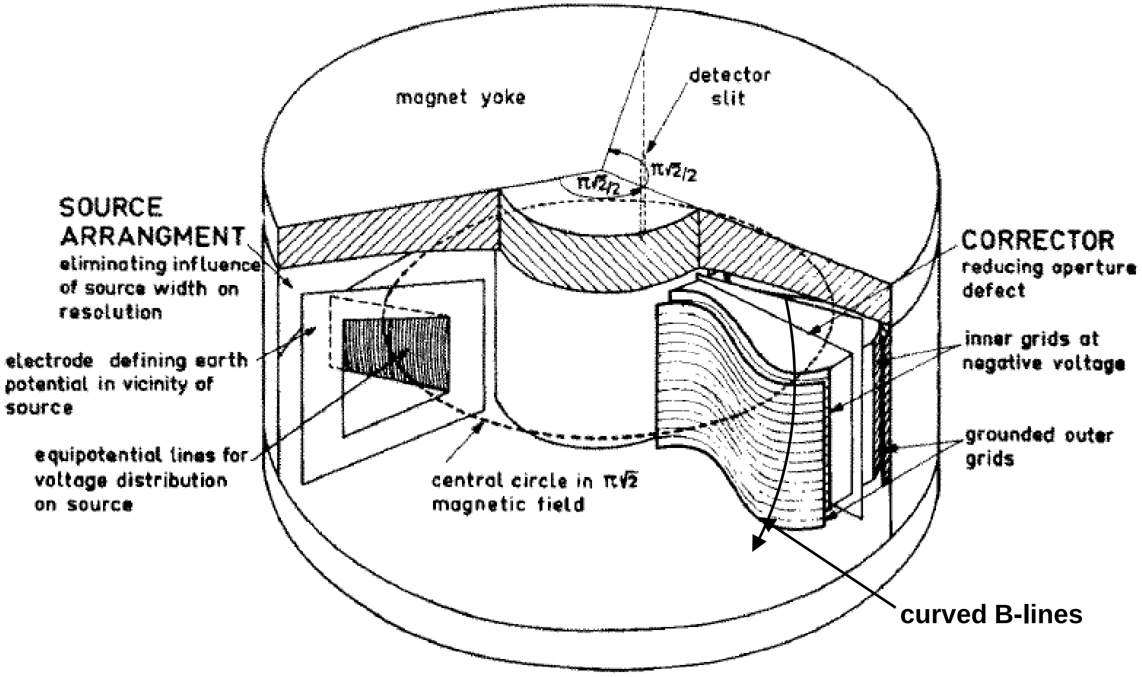


Fig. 3. Basic components of electrostatic-magnetic spectrometer employed in the present investigation of the end-point region of the tritium β-spectrum.

Bergkvist perfectionates the optics of the $\pi\cdot\sqrt{2}$-magnetic spectrometer to its very limits, improving luminosity by 10^3 at still high resolution of 0.1%.

Any parameter is checked by control experiments and analysis.

Final electronic states of the daughter are considered for the first time.

342 K-E. Bergkvist, *Triton-β-spectrum (I)*

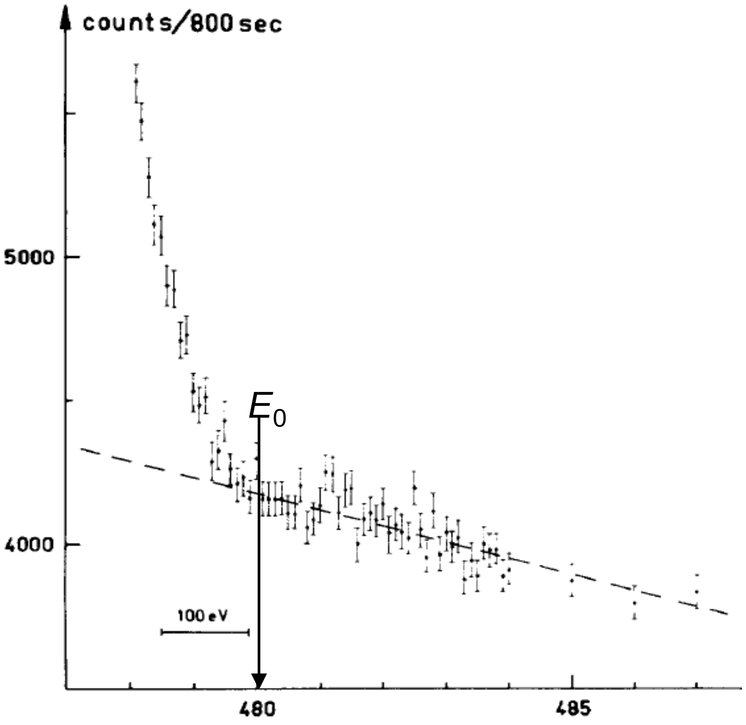


Fig. 12. A direct representation of the uppermost part of the recording Kurie plot of fig. 11.

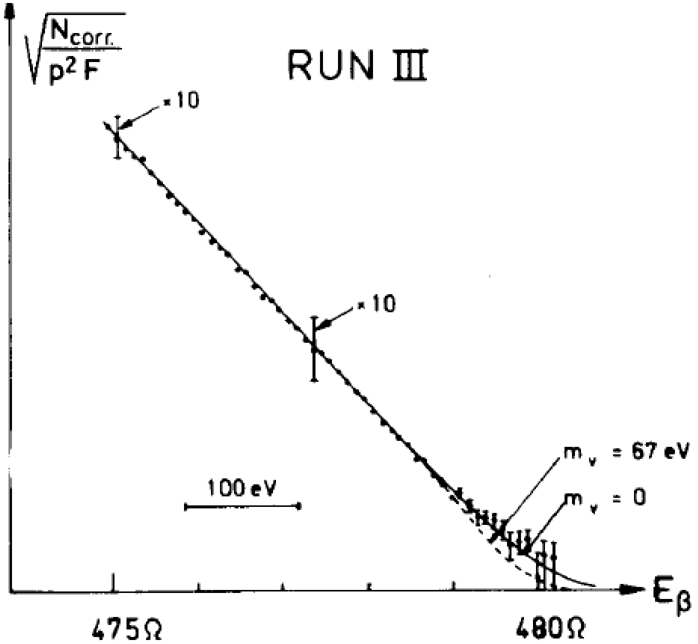


Fig. 20. Kurie plots of data from runs I–III. The data exhibited have been subjected to a very slight correction for distortion in the measured spectrum. The theoretical curves have been fitted to the data in the way discussed in connection with fig. 18.

Recorded spectrum and resulting Kurie plot

The data clearly separate from the dotted line calculated for m_ν = 67 eV
Aanalysis yields an upper limit: $m_\nu < 55$ eV ($\sigma(m_\nu^2) \approx 3000$ eV^2)

Finally Bergkvist emphazises that substantial improvements of this limit would become very hard

Nevertheless the show went on:

Present limit on $\sigma(m\nu^2) \approx 3$ eV^2; expected at KATRIN: ≈ 0,0 3eV^2

Next scene: Shocking Ljubimov claim

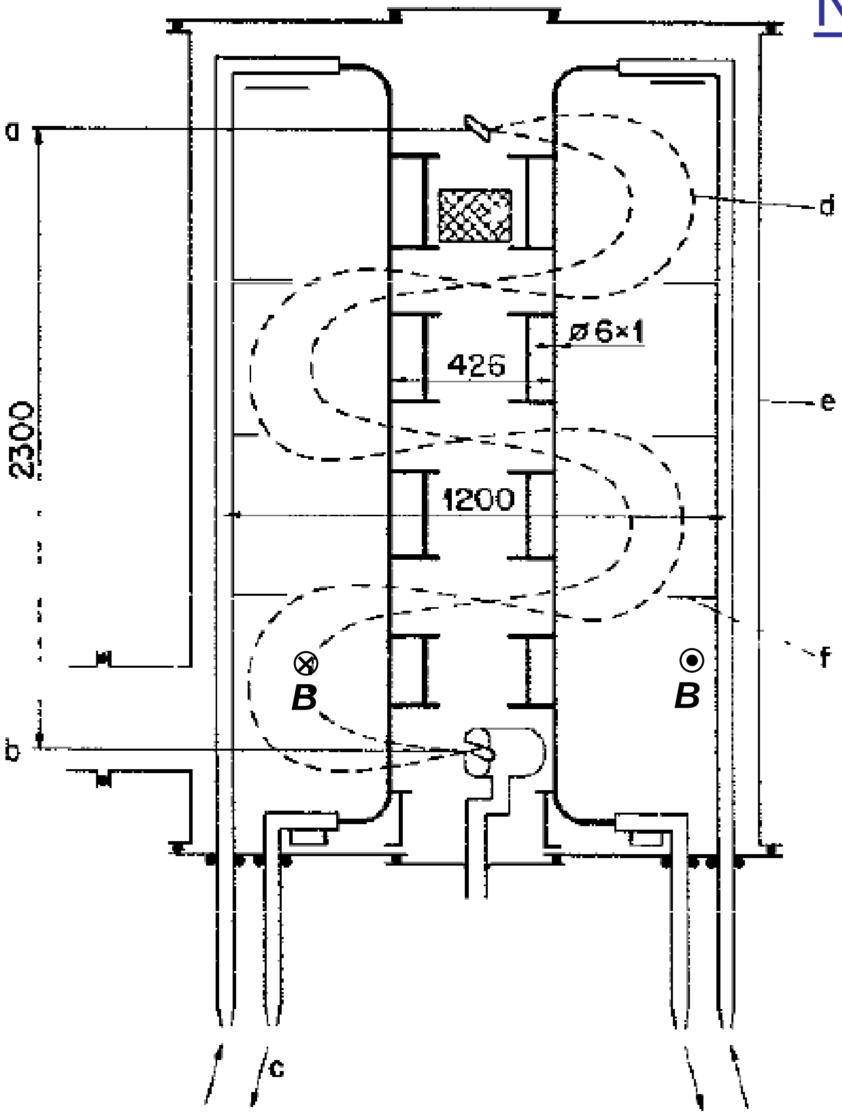


Figure 9. Cross section of the ITEP spectrometer, adopted from Tret'yakov (1975). Source a, detector b, Water-cooled current loops c, electron orbits d, vacuum tank e, baffles f. Linear dimensions in mm.

1975 Tretyakov et al.

had developed at Moscow a toroidal magnetic spectrometer imaging the source with still enhanced solid angle and deflection angle

→ higher luminosity and resolution!

E.F. Tretyakov et al., Izv. Akad. Nauk SSSR Ser. Fiz. 40 (1976) 20; Proc. Intern. Nuetrino Conf. (Aachen, 1976) pp. 663–670.

In these years interest in ν-Mass starts growing:

- Particle physics fills up Quark and Lepton Sector and uncovers their Interaction by Gluons and Weakly Interacting Bosons
- Cosmology develops Big Bang Theory and postulates Relic Neutrinos. Their rest mass might influence Cosmic Evolution dramatically

Phys. Letters **94B**, 267 (1980):

AN ESTIMATE OF THE υ_e MASS FROM THE β-SPECTRUM OF TRITIUM IN THE VALINE MOLECULE

V.A. LUBIMOV, E.G. NOVIKOV, V.Z. NOZIK, E.F. TRETYAKOV and V.S. KOSIK [1]

Institute of Theoretical and Experimental Physics, Moscow, USSR

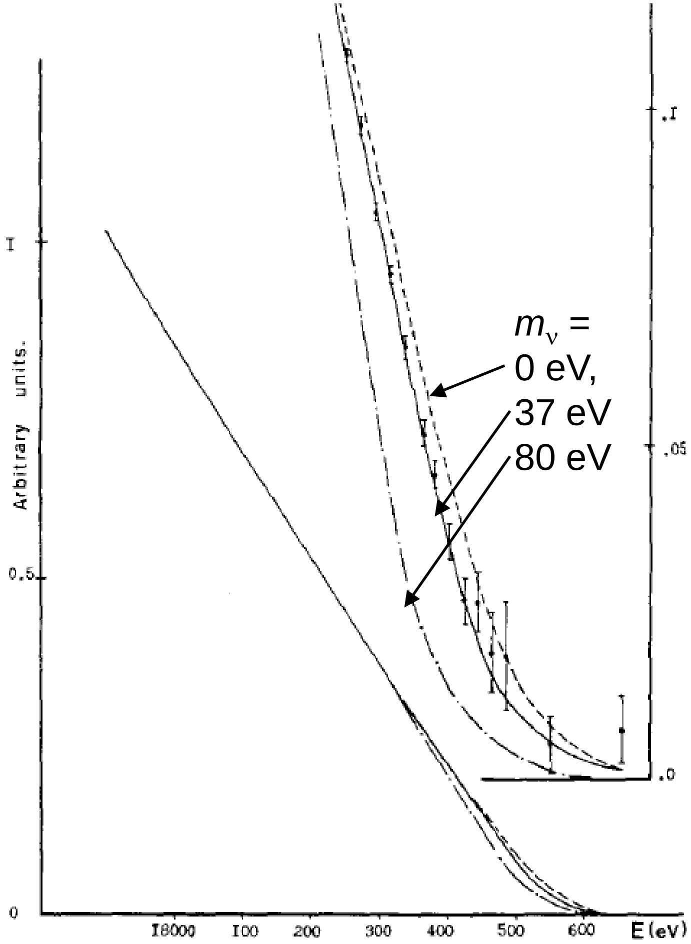


Fig. 1. The measured β-spectrum of tritium (Kurie plot). The results of the χ^2 fit (see text) for different values of M_ν for half of the statistics are shown (solid line 37 eV, E_0 = 18 578 eV; dashed line 0 eV, E_0 = 18 574 eV; dash–dotted line 80 eV, E_0 = 18 586 eV).

Prima vista, data seem compatible with

$m_\nu \approx 35$ eV

excluding zero mass safely.

But such plots can be quite deceiving!

Striking result was challenged, defended, corrected endlessly (with Bergkvist as main opponent).

Retrospect conclusion:

Analysis definitely wrong:

Energy loss in source overestimated

→ Endpoint 10 eV too high:

Resulting upshift of E_ν shifts m_ν^2 by correlation:

$$\boxed{\delta m_\nu^2 = 4(E_\nu)\times\delta(E_\nu)}$$

ITEP1987 tritium decay: $\Delta M(\mathrm{T},{}^3\mathrm{He}) = 18600(4)$ eV

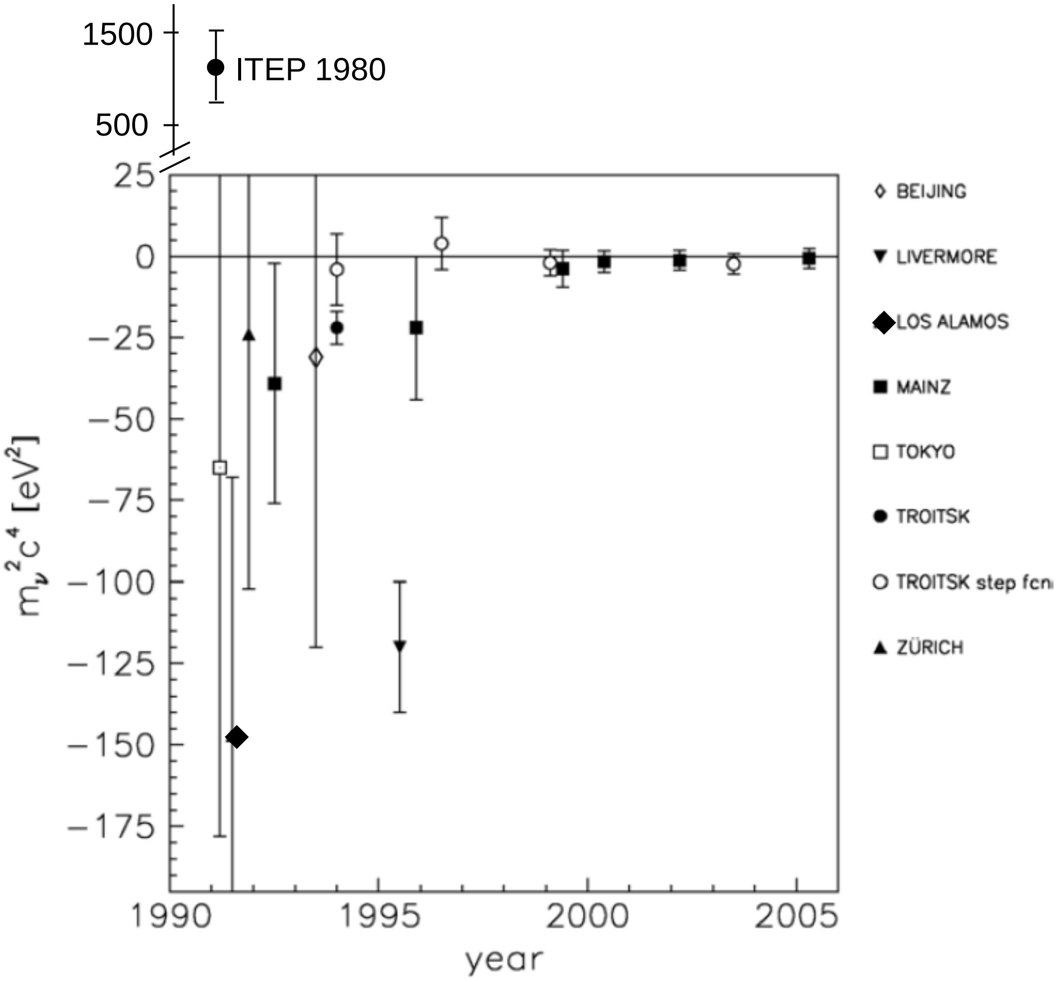
at the time backed by: $\Delta M(\mathrm{T},{}^3\mathrm{He}) = 18599(2)$ eV

(Lippmaa, 1985, cyclotron resonance)

Present: $\Delta M(\mathrm{T},{}^3\mathrm{He}) = 18589.8(1.2)$ eV

(Nagy et al.,Stockholm, 2006, Penning trap)

Neutrino mass squared values from T_2 decay from 1990 – 2005



Challenged by the ITEP result many Groups started control experiments.

Zurich, Los Alamos, Livermore have built spectrometers à la Tretyakov
but developed quite advanced sources
(monomolecular Langmuir Blodget films
(Zh), gaseous T_2 (Los Al., Liv.))

Tokyo, Beijing improved traditional ones

Looking at 1990 – 1996:
Refined sensitivity and resolution
may even turn into a curse!

They may reveal finally that your
result is unphysical ($m^2 < 0$)
and teach you pittilessly:
Experiment not properly understood!

Anyway, everybody has disproved the ITEP result!

In the course of time results tend to converge towards zero mass with dramatically narrowed uncertainenties, due to MAC-E Filters developed at Mainz and Troitsk

4.) Mainz and Troitzk: MAC-E Filters

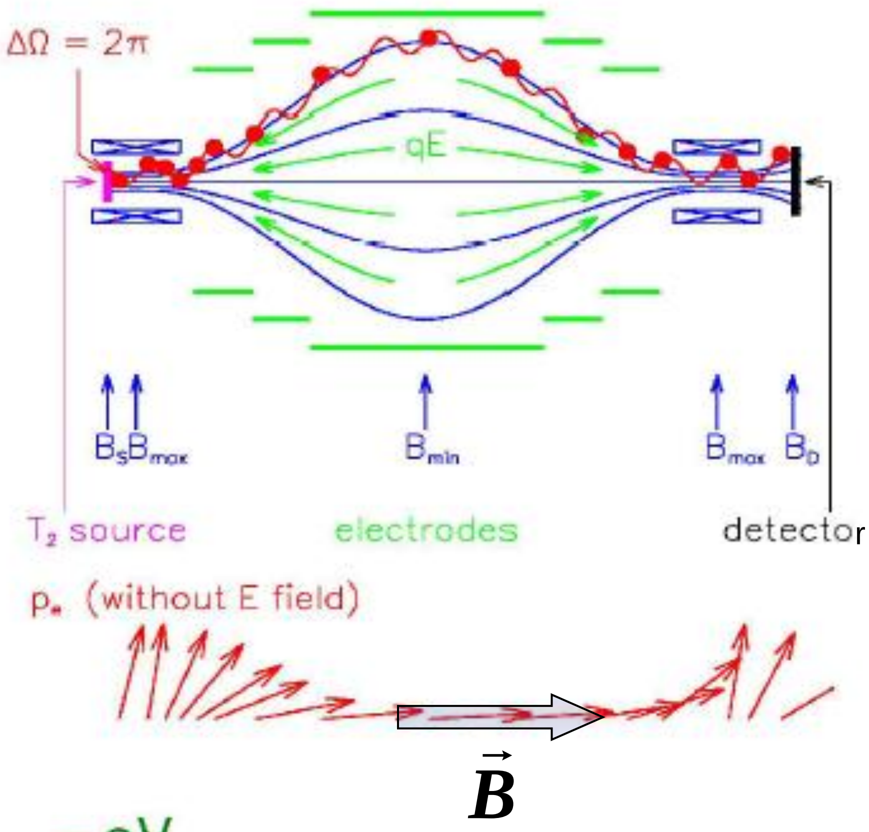
Magnetic **A**diabatic **C**ollimator with **E**lectrostatic **F**ilter

Hamilton‘s toy had proved already:Applying an electrostatic filter to the endpoint region of tritium spectrum yields promising m_ν-value

However, a much more powerful collimation principle was necessary: **MAC!**

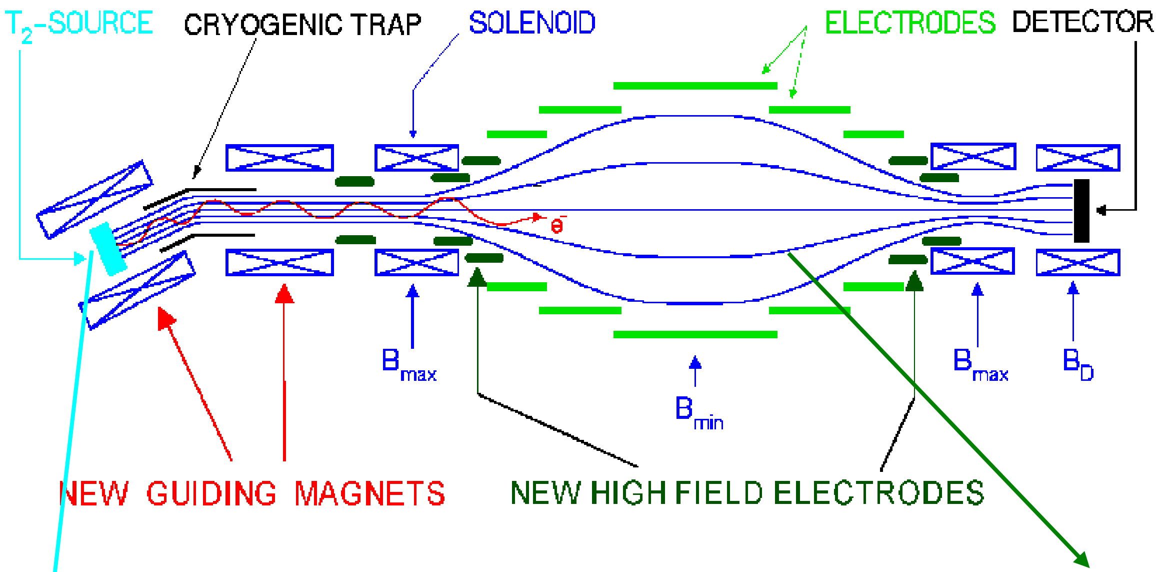
Lobashev V M and Spivak P E 1985 *Nucl. Instr. and Meth. in Phys. Res*. **A 240** *305*
Picard A *et al*. 1992 *Nucl.Instr. Meth.* **B 63** 345

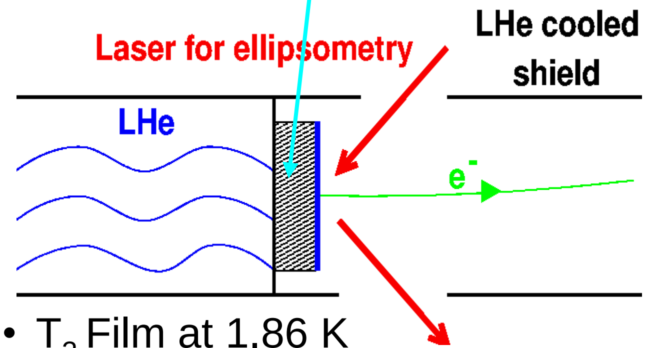
- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_\perp/B = \text{const.}$
  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field $\Delta E = E \cdot B_{min}/B_{max} = E \cdot A_{s,eff}/A_{analyse} \approx eV$



Mainz Neutrino Mass Experiment, Phase II (1997-2001)

Kraus Ch, Bornschein B, Bornschein L, Bonn J, Flatt B, Kovalik A, Ostrick B, Otten E W, Schall J P, Thümmler Th, Weinheimer Ch 2005 *Eur. Phys. J.* C **40**, 447

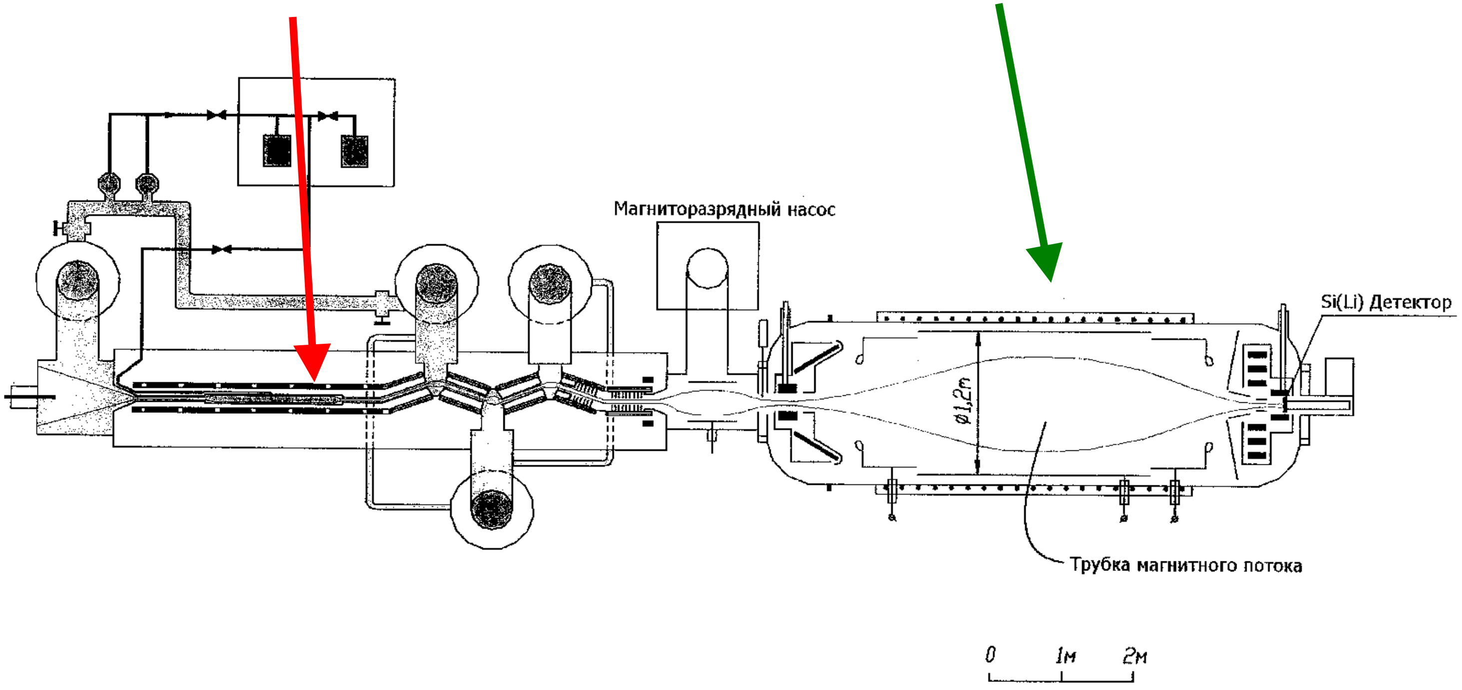




- T_2 Film at 1.86 K
- quench-condensed on graphite (HOPG)
- 45 nm thick (≈130ML), area 2cm^2
- Thickness determination by ellipsometry

Belesev A I *et al.* 1995 *Physics Letters* **B 350** *263*

The Troitsk Neutrino Mass Experiment (1994 – present)



Gaseous T_2 source

MAC-E-Filter

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

luminosity: $L = 0.6 cm^2$

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

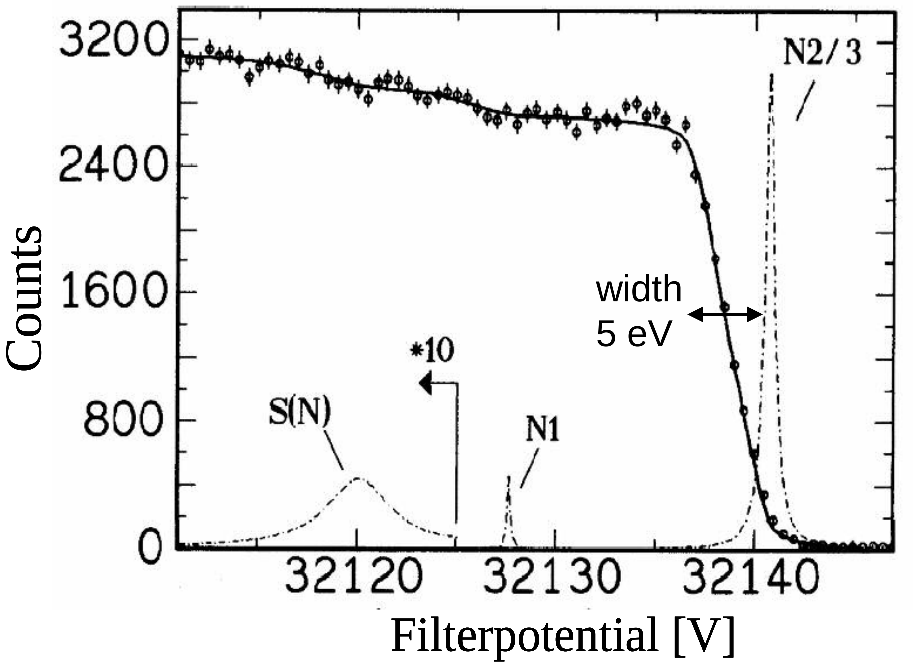
energy resolution: $\Delta E = 3.5 eV$

3 electrode system in 1.5m

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

Test of spectrometer resolution at Mainz on ^{83m}Kr conversion lines

(Picard A *et al*. 1992 *Nucl.Instr. Meth.* **B 63** 345)

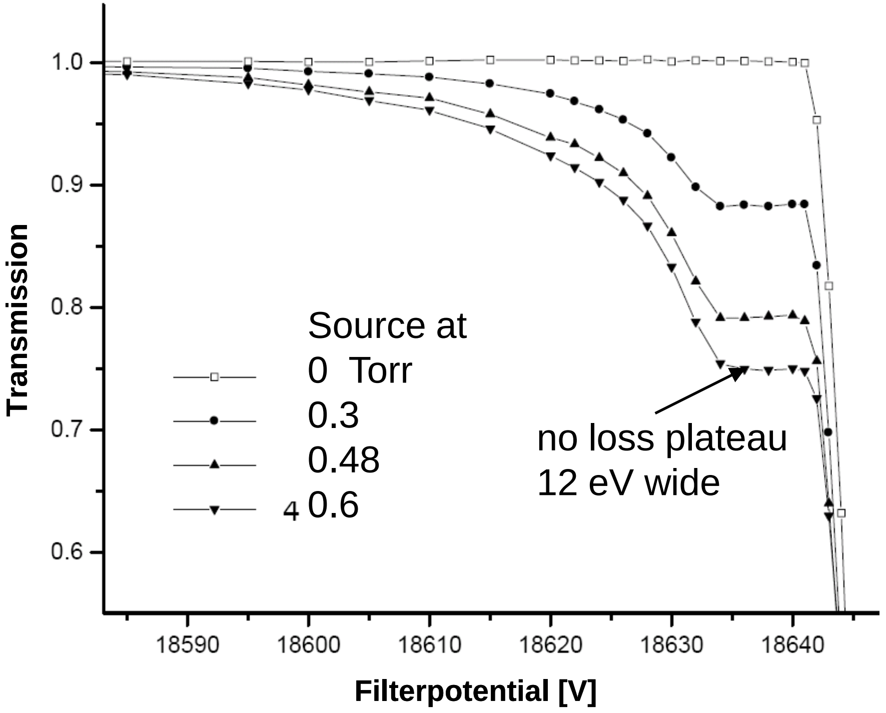


Scan of the N-conversion electron lines of ^{83m}Kr by an integrating electrostatic filter of MAC-E type. The full line shows the convolution of a sum of Lorentzians with the transmission function, fitted to the data. The Lorentzian components found by the fit are shown by *dotted lines.* The elastic peak of the unresolved N2/3-doublet dominates. S(N) represents qualitatively shake up/shake off events.

Integral energy loss spectra

of monochromatic electrons passing the gaseous T_2-source at Troitsk at different pressures

(V.N. Aseev et al. 2000 *Euro. Phys. J.* **D 10** 39)

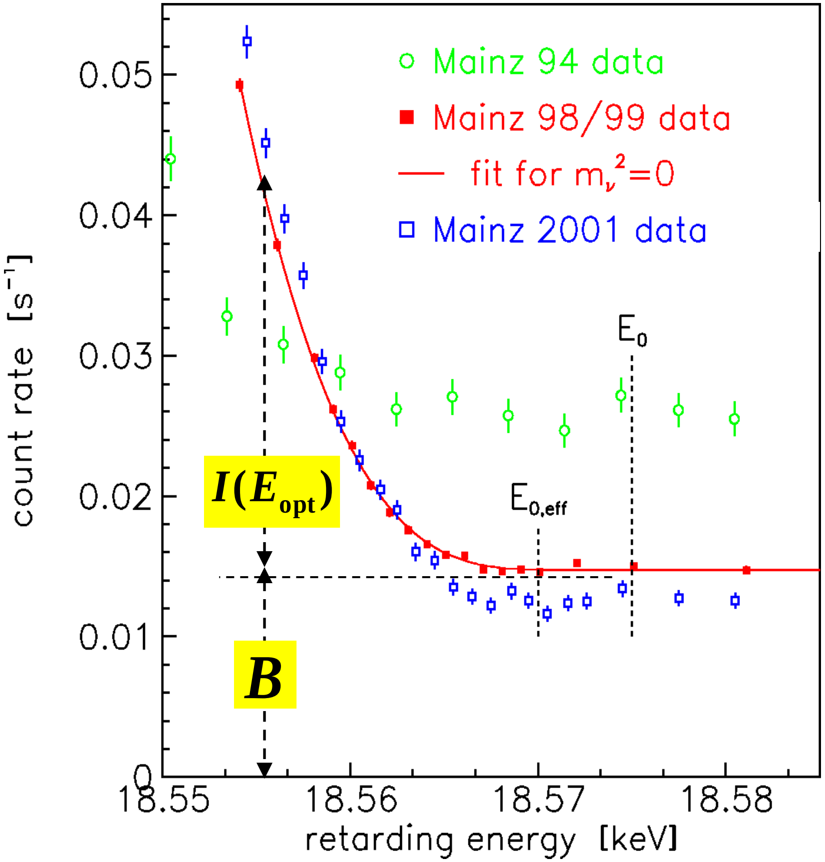


Spectra taken with Mainz Spectrometer

$$I(E) \approx \underline{A}\Big(\big(\underline{E_0} - E\big)^3 - (3/2)\big(E_0 - E\big)\underline{m^2(\nu_e)}\Big) + \underline{B}$$ (— parameters to be fitted)

Optimal sensitivity on $m^2(\nu_e)$
reached at

$$\boxed{I(E_{opt}) = 2B}$$



Final results

$$\text{Mainz 2005: } m^2(\nu_e) = \left(-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}}\right)\text{eV}^2 \Rightarrow m(\nu_e) \leq 2.2\,\text{eV}$$

$$\text{Troitzk 2011: } m^2(\nu_e) = \left(-0.67 \pm 2.5\right)\text{eV}^2 \Rightarrow m(\nu_e) \leq 2.1\,\text{eV}$$

Vladimir Lobashew (left) hosting the KATRIN collaboration at Troitsk (2004)

Vladimir Lobashew
† August 3, 2011

Jochen Bonn
† August 27, 2012

21st Century: ν-Oscillations re-stimulate interest in neutrino mass:

- Demand for sub-eV ν-mass sensitivity in β- and 2β0ν-decay

The new situation:

3 ν–flavors (*e*, *μ*, *τ*) created as superposition of 3 mass eigenstates:

$$\left|\nu_{(e,\mu,\tau)}\right\rangle = \sum_{i=1}^{3} U_{(e,\mu,\tau)\,i}\left|m_i\right\rangle \Rightarrow$$

Components propagate with different phase velocities

$$\left(c_\varphi\right)_i = \frac{\omega}{k_i} = \frac{E}{p_i} \approx \left(1+m_i^2/2E^2\right) \Rightarrow$$

Wave packet starts beating between different flavors on the length scale

$$L = \frac{1}{\Delta k} \approx \frac{m_i^2 - m_j^2}{2E}$$

β-decay measures a mean squared mass

$$m_{\nu_e}^2 = \sum \left|U_{e\,i}\right|^2 m_i^2$$

2β0ν-decay measures coherent sum of masses sqaured

$$1\big/T_{1/2}^{0\nu} \propto m_{ee}^2 = \left|\sum_j m(\nu_j)\left|U_{ej}\right|^2 \mathrm{e}^{\mathrm{i}\varphi_\mathrm{j}}\right|^2$$

Already at the Erice school in 1997 first ideas for a more powerful MAC-E-Filter were put forward by Mainz and Troitzk.

But only after the firm discovery of neutrino oscillations in 1998 they were heard.

The same year I approached Manfred Popp, director general of FZ-Karlsruhe and convinced him easily that physics needs a new Tritium Beta Spectrometer, 10 times larger in each dimension than the present, 6 m long instrument at Mainz and that this new instrument wouldn‘t fit neither into the labs nor into the budget of our physics institute at Mainz university.

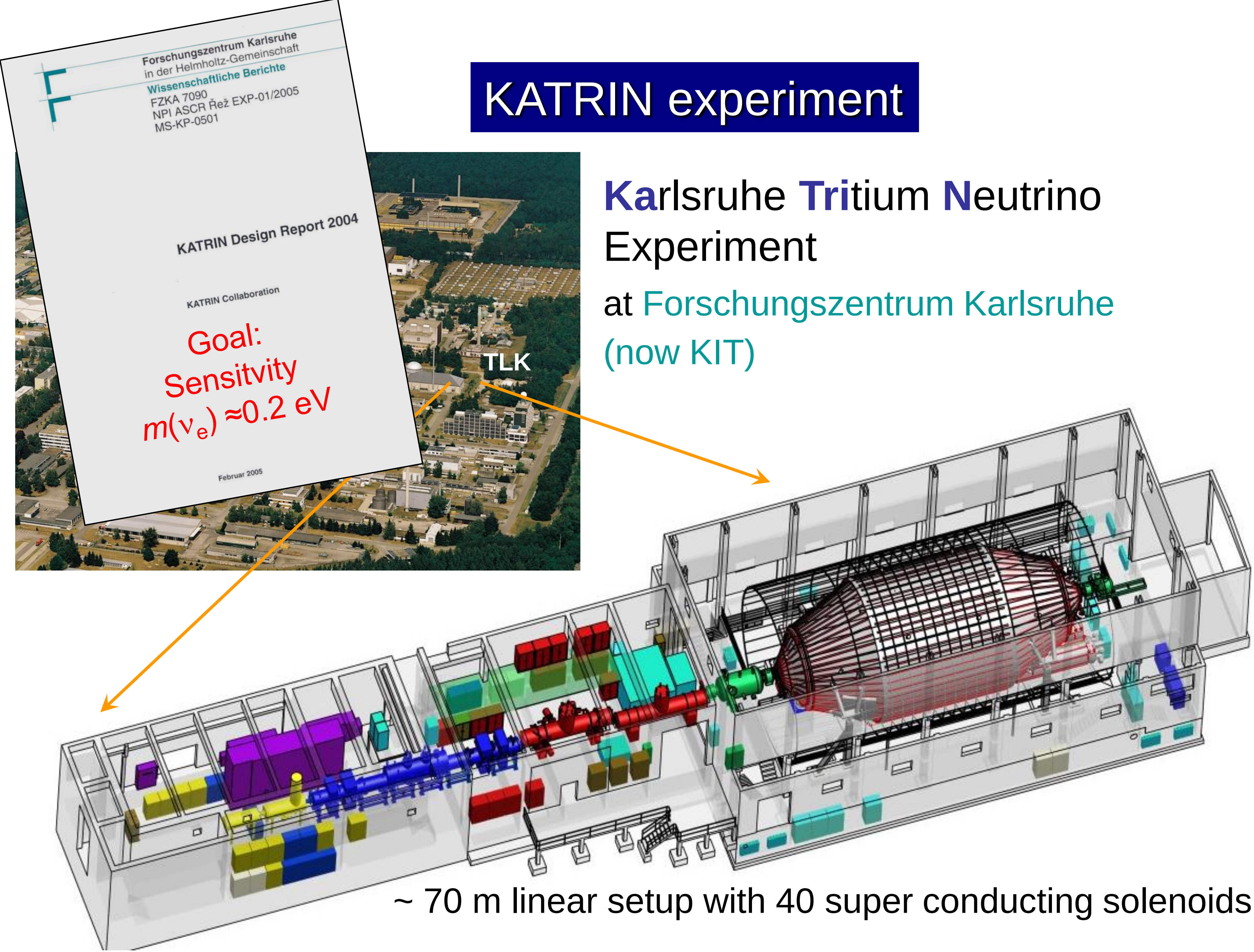
However, his centre would be the right place
with the right resources and
with a well known group of neutrino physicists (KARMEN)
which could form the nucleus of a large international collaboration

.

Popp answered right away that he might find the money within a couple of years and encouraged the interested groups to set up a collaboration.

This happened in 2001 at the romantic Burg Liebenzell in the Black Forest where the principal founding groups from Karlsruhe, Mainz, Troitzk and Seattle presented a letter of intent to an international advisory group.

KATRIN experiment



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft
Wissenschaftliche Berichte
FZKA 7090
NPI ASCR Řež EXP-01/2005
MS-KP-0501

KATRIN Design Report 2004

KATRIN Collaboration

Februar 2005

Goal:
Sensitivity
$m(\nu_e) \approx 0.2$ eV

Karlsruhe **Tri**tium **N**eutrino
Experiment

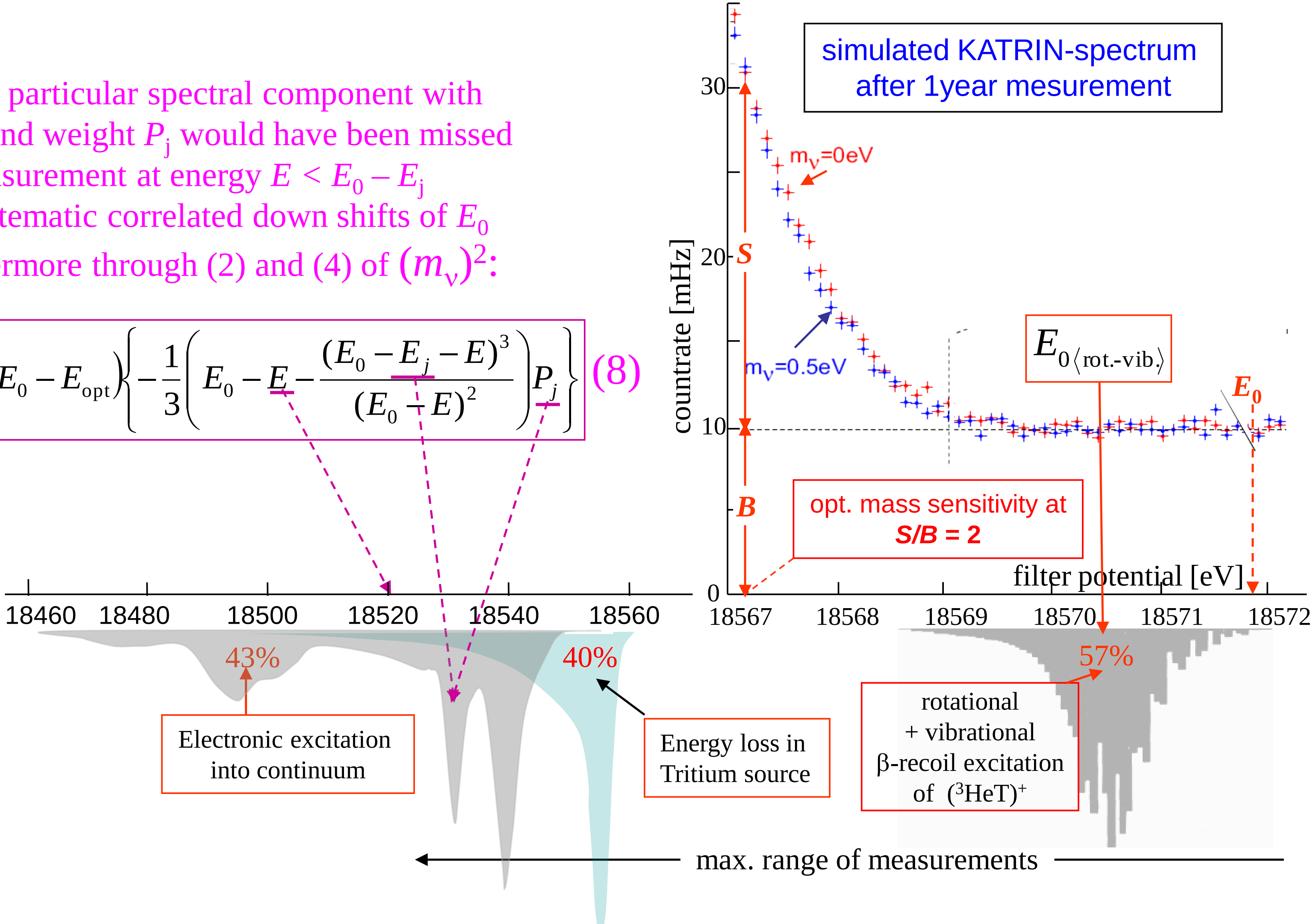
at Forschungszentrum Karlsruhe
(now KIT)

~ 70 m linear setup with 40 super conducting solenoids

Correlation of final state and energy loss spectrum with endpoint and $(m_\nu)^2$

If, e. g., a particular spectral component with energy E_j and weight P_j would have been missed a measurement at energy $E < E_0 - E_j$ yields systematic correlated down shifts of E_0 and furthermore through (2) and (4) of $(m_\nu)^2$:

$$\delta(m_\nu^2) \approx 2\left(E_0 - E_{\text{opt}}\right)\left\{-\frac{1}{3}\left(E_0 - \underline{E} - \frac{(E_0 - \underline{E_j} - E)^3}{(E_0 - E)^2}\right)\underline{P_j}\right\} \quad (8)$$



simulated KATRIN-spectrum after 1year mesurement

opt. mass sensitivity at **S/B = 2**

Electronic excitation into continuum

Energy loss in Tritium source

rotational + vibrational β-recoil excitation of $(^3\text{HeT})^+$

max. range of measurements

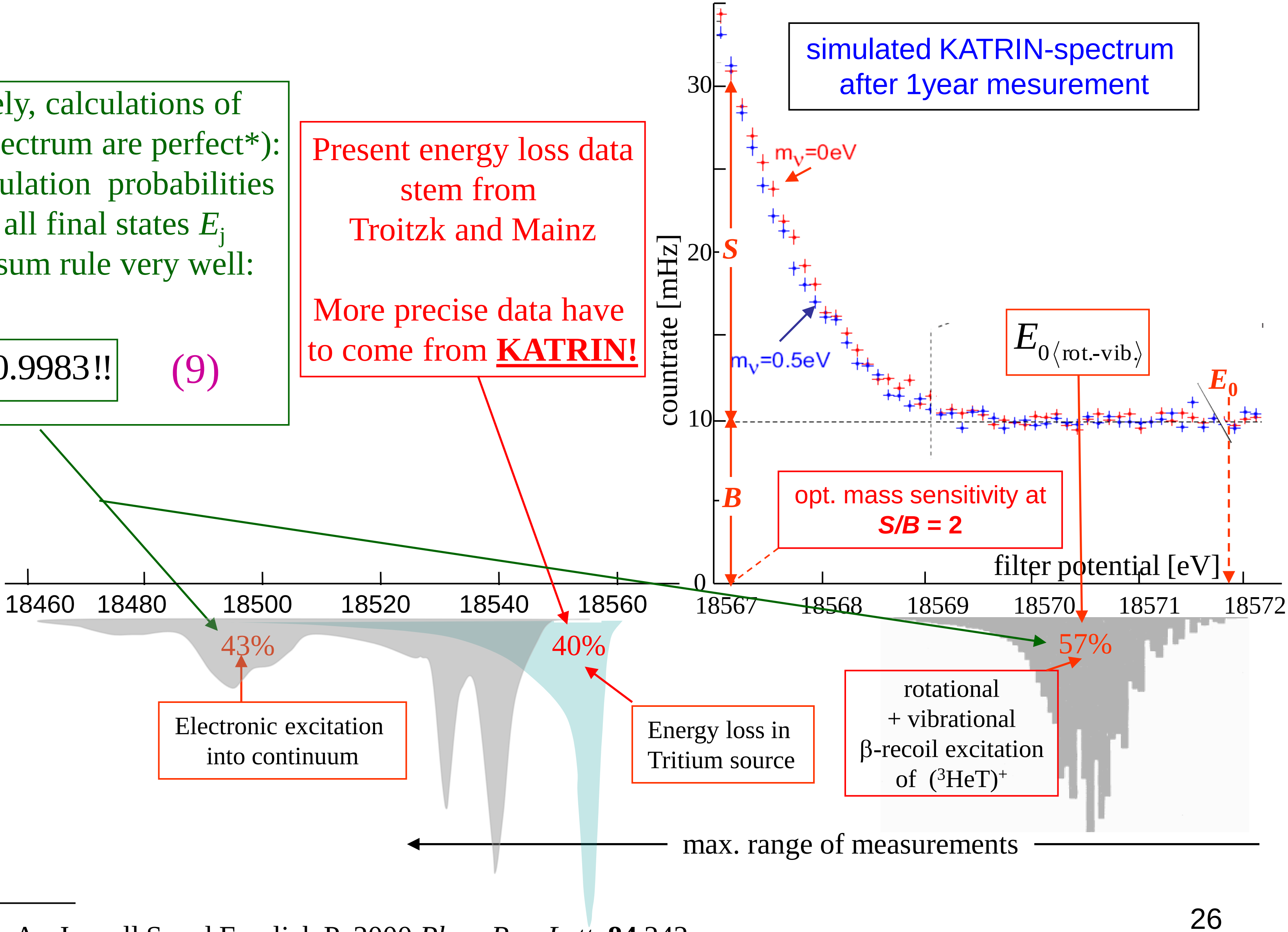
Correlation of final state and energy loss spectrum with endpoint and $(m_\nu)^2$

Fortunately, calculations of daughter spectrum are perfect*): Sum of population probabilities P_j over all final states E_j exhausts sum rule very well:

$$\sum P_j = 0.9983!! \qquad (9)$$

Present energy loss data stem from Troitzk and Mainz

More precise data have to come from **KATRIN!**



opt. mass sensitivity at ***S/B* = 2**

Electronic excitation into continuum

Energy loss in Tritium source

rotational + vibrational β-recoil excitation of $(^3\text{HeT})^+$

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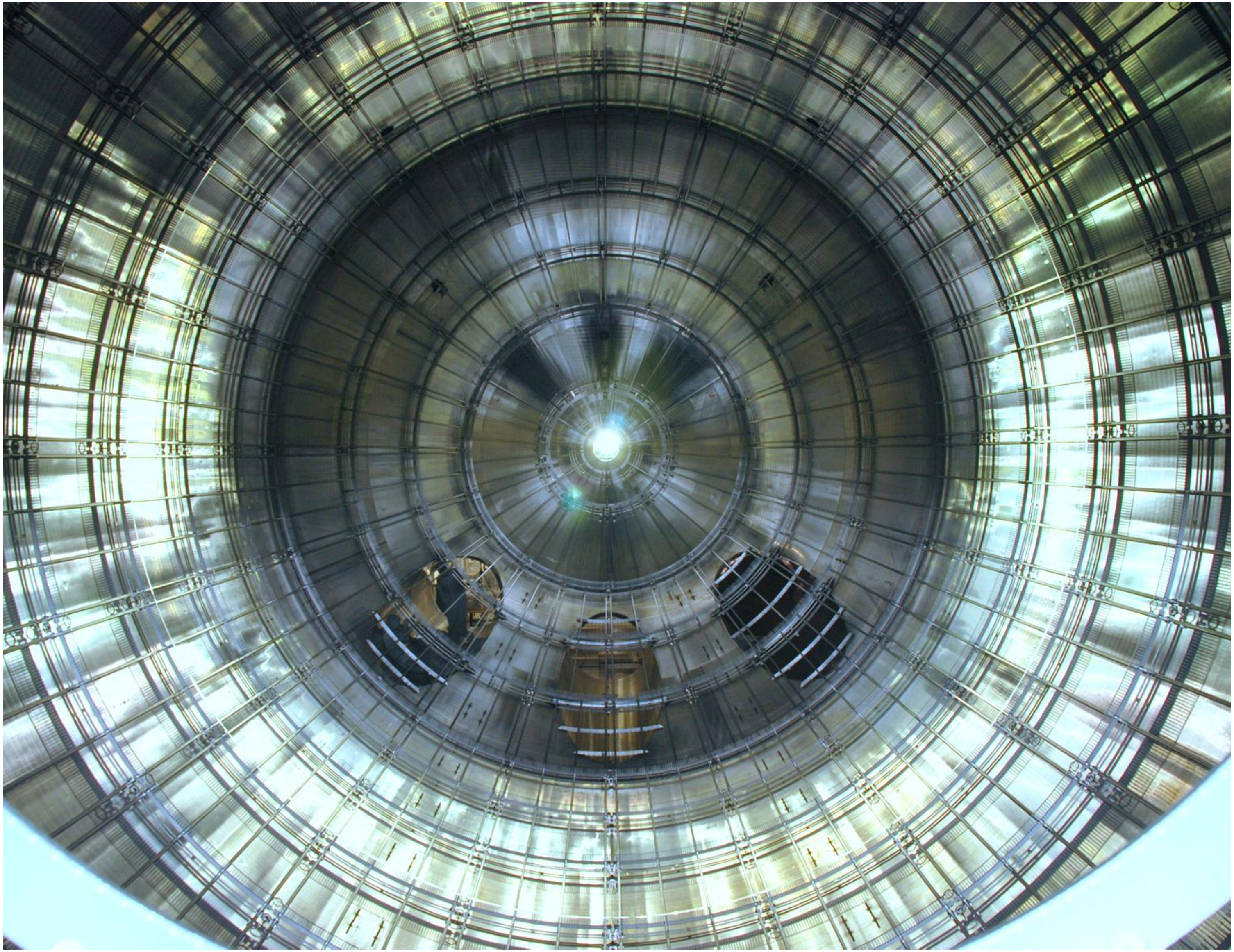
*) Saenz A, Jonsell S and Froelich P 2000 *Phys. Rev. Lett.* **84** 242

Look into KATRIN Spectrometer, fully lined with electrodes

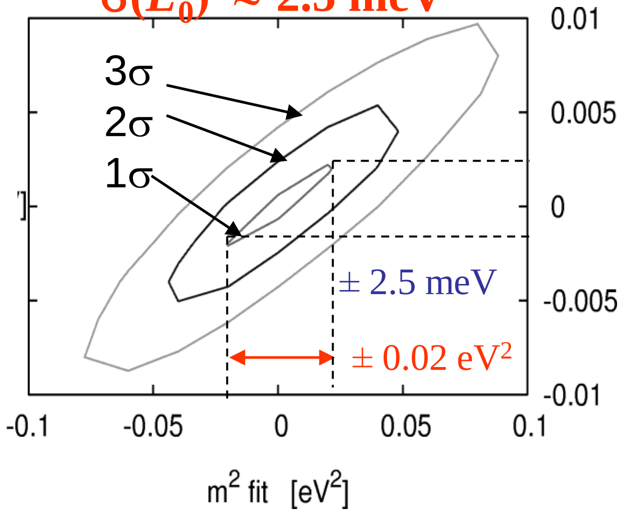


Control of filter potential

Simulation of 3y measurement
at *B* = 10 mHz predicts 1 σ uncertainties:

$\sigma((m_\nu)^2) \approx 0.02\ \mathrm{eV}^2$

$\sigma(E_0) \approx 2.5\ \mathrm{meV}$



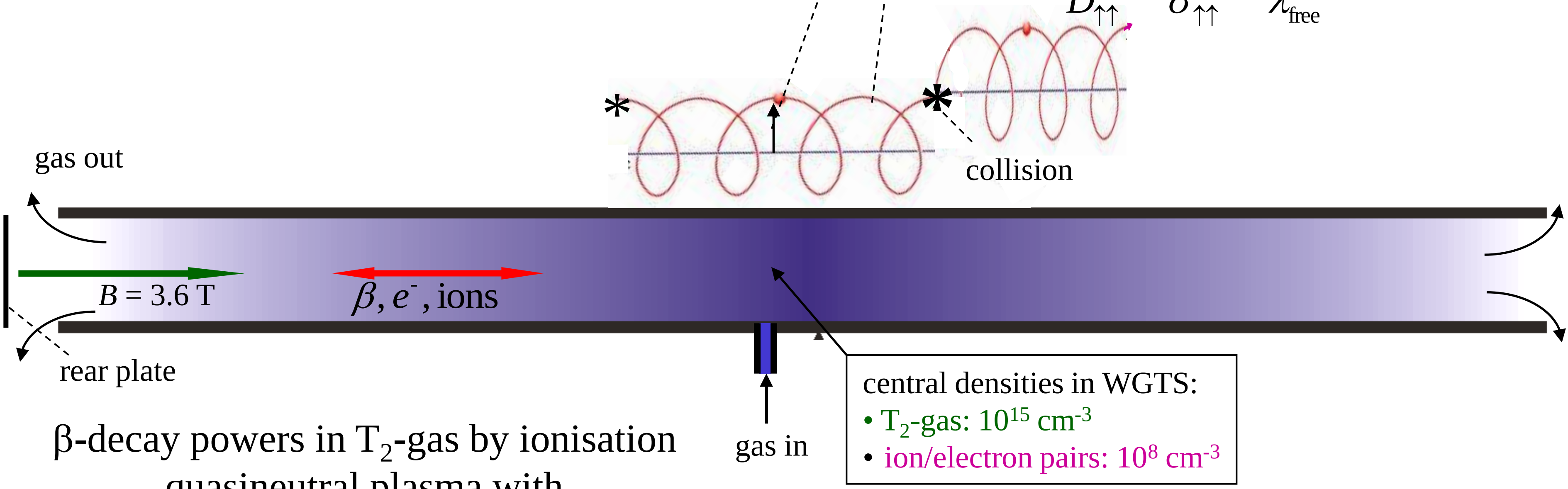
Any **fluctuation of filter** potential
in space or time during data taking
must be known and controlled precisely!
If undiscovered,
systematic downshift of $(m_\nu)^2$ occurs:

$$-\delta(m_\nu^2)_U = 2e^2\left\langle\left(U-\langle U\rangle\right)^2\right\rangle < 0.007\,\mathrm{eV}^2$$

$$\Rightarrow\quad \sigma(U) < 60\,\mathrm{mV}$$

Mechanism and consequences of magnetic confinement in WGTS

$$R_c / \lambda_{\text{free}} \ll 1 \Rightarrow \frac{D_\perp}{D_{\uparrow\uparrow}} = \frac{\sigma_\perp}{\sigma_{\uparrow\uparrow}} \approx \frac{R_c^2}{\lambda_{\text{free}}^2} \approx 10^{-7}$$



central densities in WGTS:
- T_2-gas: 10^{15} cm^{-3}
- ion/electron pairs: 10^8 cm^{-3}

β-decay powers in T_2-gas by ionisation quasineutral plasma with

high longitudinal longitudinal conductivity $\sigma_{\uparrow\uparrow}$

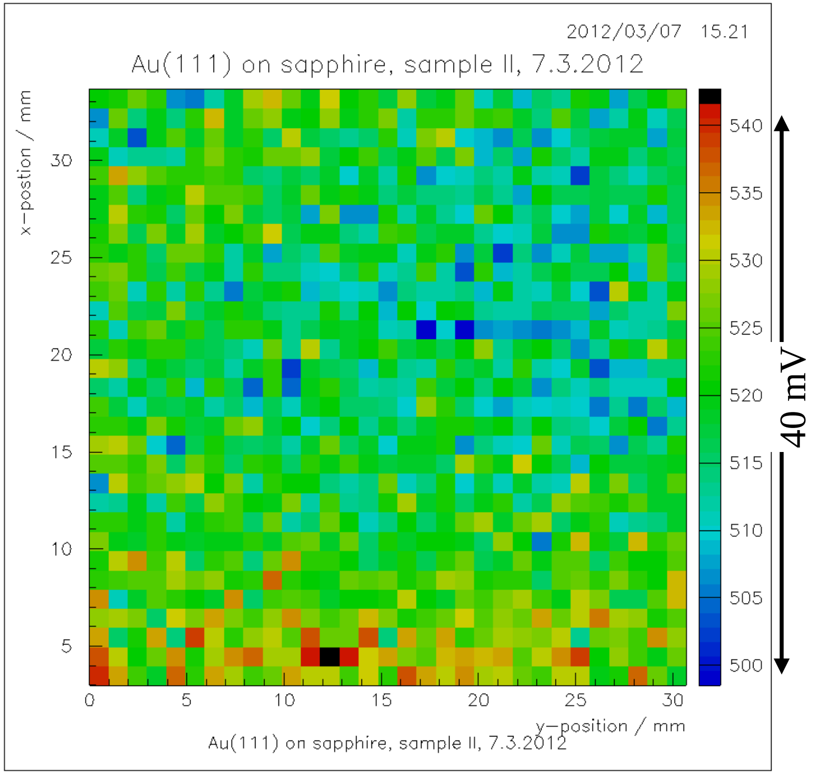
and very low transverse conductivity $\sigma_\perp$

→ charged particles have to leave the source along magnetic field lines!

→ electric potential is constant along magnetic fild lines and can be defined by a conductive plate which crosses the flux tube at the rear end of WGTS !

Macroscopic pattern of surface potential of epitaxial gold layer on sapphire

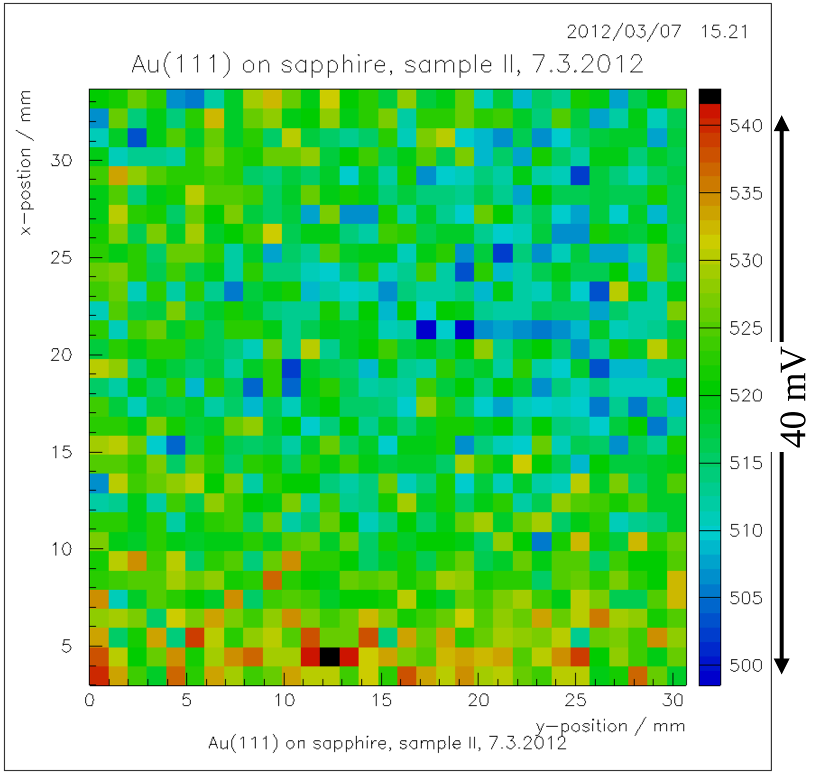
False color plot (30 x30) mm^2
Full scale 40 mV
Taken with Kelvin probe (in Lab atmosphere)
Scatter < fluctuation limit of 60 mV!

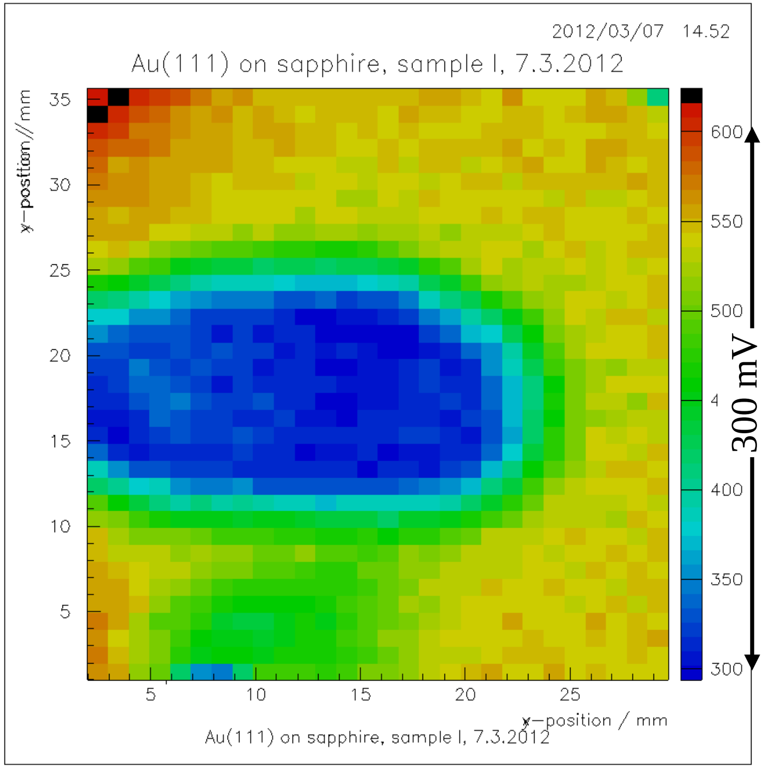


Macroscopic pattern of surface potential of epitaxial gold layer on sapphire

False color plot (30 x30) mm^2
Full scale 40 mV
Taken with Kelvin probe (in Lab atmosphere)
Scatter < fluctuation limit of 60 mV!

300 mV deep finger print
on the surface potential of gold
Obtained by a slightly careless experimentalist!





Fazit

KATRIN is not only a huge set-up
It also requires subtle expertise and care in many details!

Thanks to gracaeful nature
for providing us with this tricky ,but still playable neutrino game

Thanks to HAP
for encouraging me to play the game further on as senior fellow

Thanks to my KATRIN colleagues
for still keeping the old fellow in their playing team

Thanks to the audience in the room
for listening patiently up to the end of this nice afternoon