Direct measurement of the neutrino mass: KATRIN and Troitsk

ASTROPARTICLE PHYSICS
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Introduction

Status of the KATRIN experiment

Systematic uncertainties of KATRIN & Troitsk contributions

Conclusions

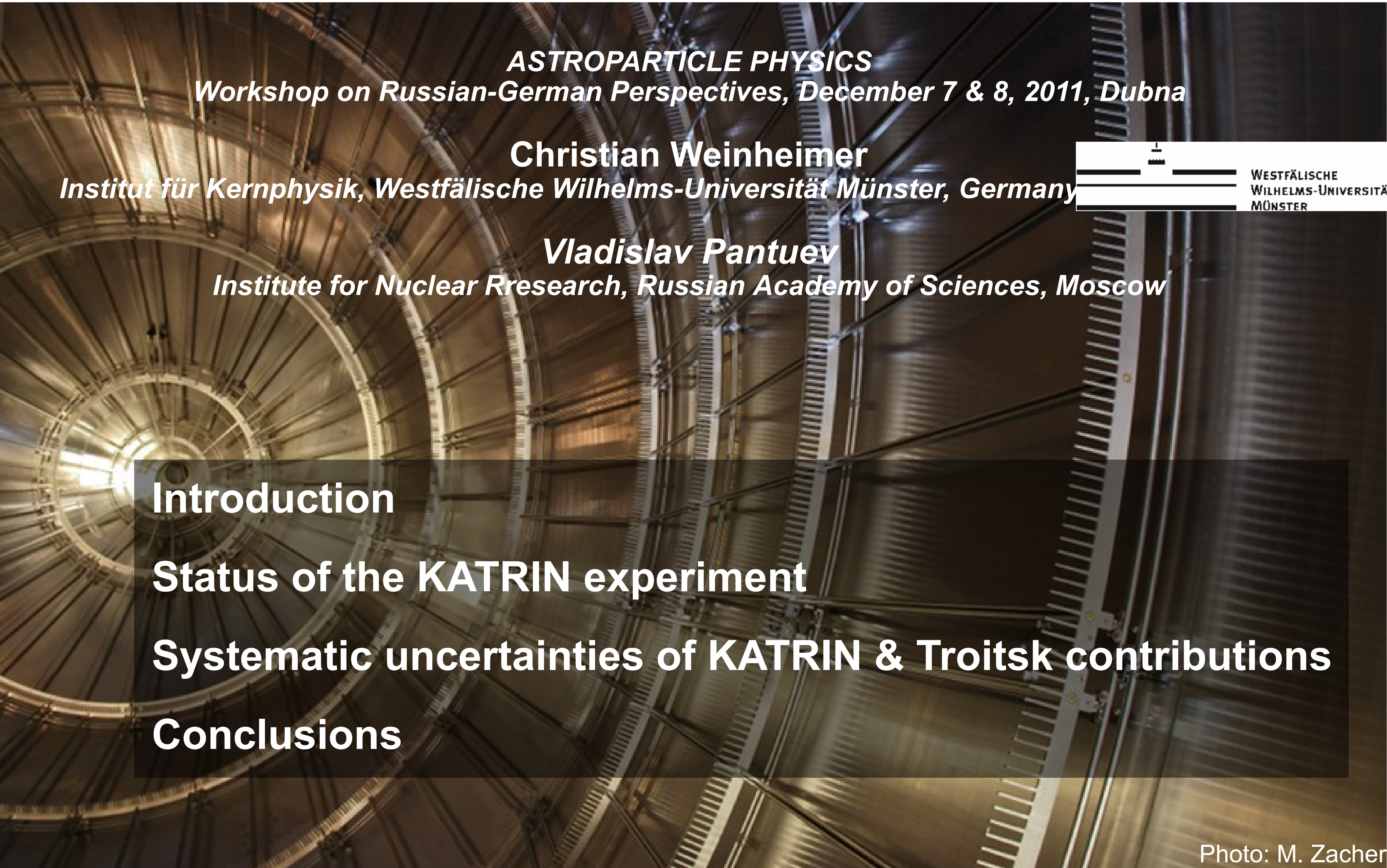
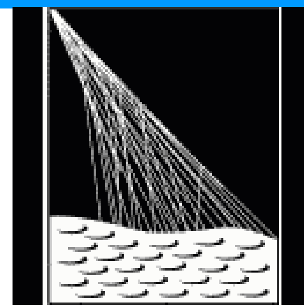


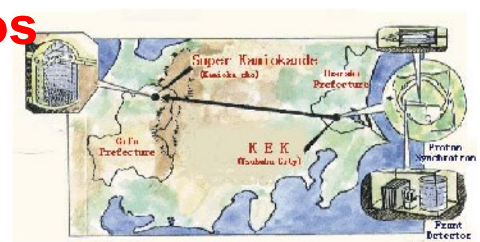
Photo: M. Zacher

Positive results from ν oscillation experiments

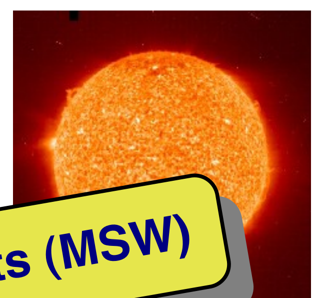
atmospheric neutrinos
(Kamiokande,
Super-Kamiokande, ...)



accelerator neutrinos
(K2K, T2K, MINOS,
OPERA, MiniBoone)

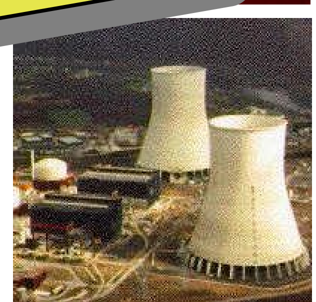


solar neutrinos
(Homestake, Gallex,
Sage, Super-Kamiokande,
SNO, Borexino)



Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ, ...)



$\Rightarrow$ **non-trivial ν-mixing**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

with:

$0 < \sin^2(2\theta_{13}) < 0.15$ (90% CL)

$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$ large !

$\sin^2(2\theta_{23}) > 0.92$ (99.7% CL) max !

$7.39 \cdot 10^{-5}\ \mathrm{eV}^2 < \Delta m_{12}^2 < 7.79 \cdot 10^{-5}\ \mathrm{eV}^2$

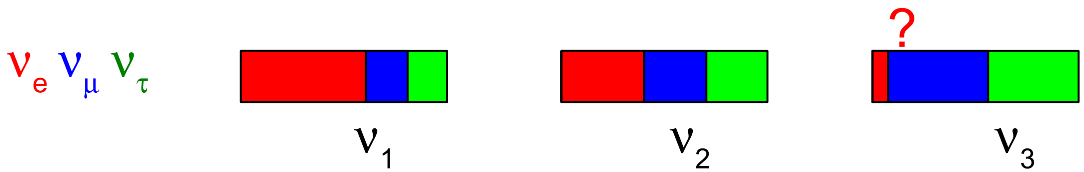
$2.30 \cdot 10^{-3}\ \mathrm{eV}^2 < |\Delta m_{23}^2| < 2.56 \cdot 10^{-3}\ \mathrm{eV}^2$

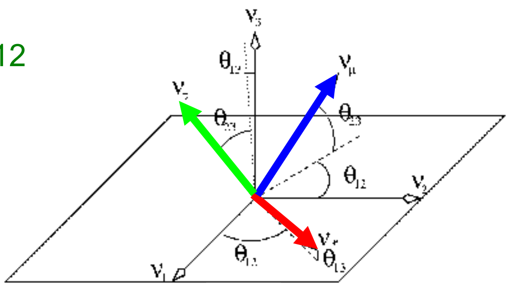
$\Rightarrow$ **$m(\nu_j) \neq 0$, but unknown !**

2011: start to require description
by 3-flavour oscillations

Need for the absolute
ν mass determination

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Δm^2_{23}, Δm^2_{12}





degenerated masses

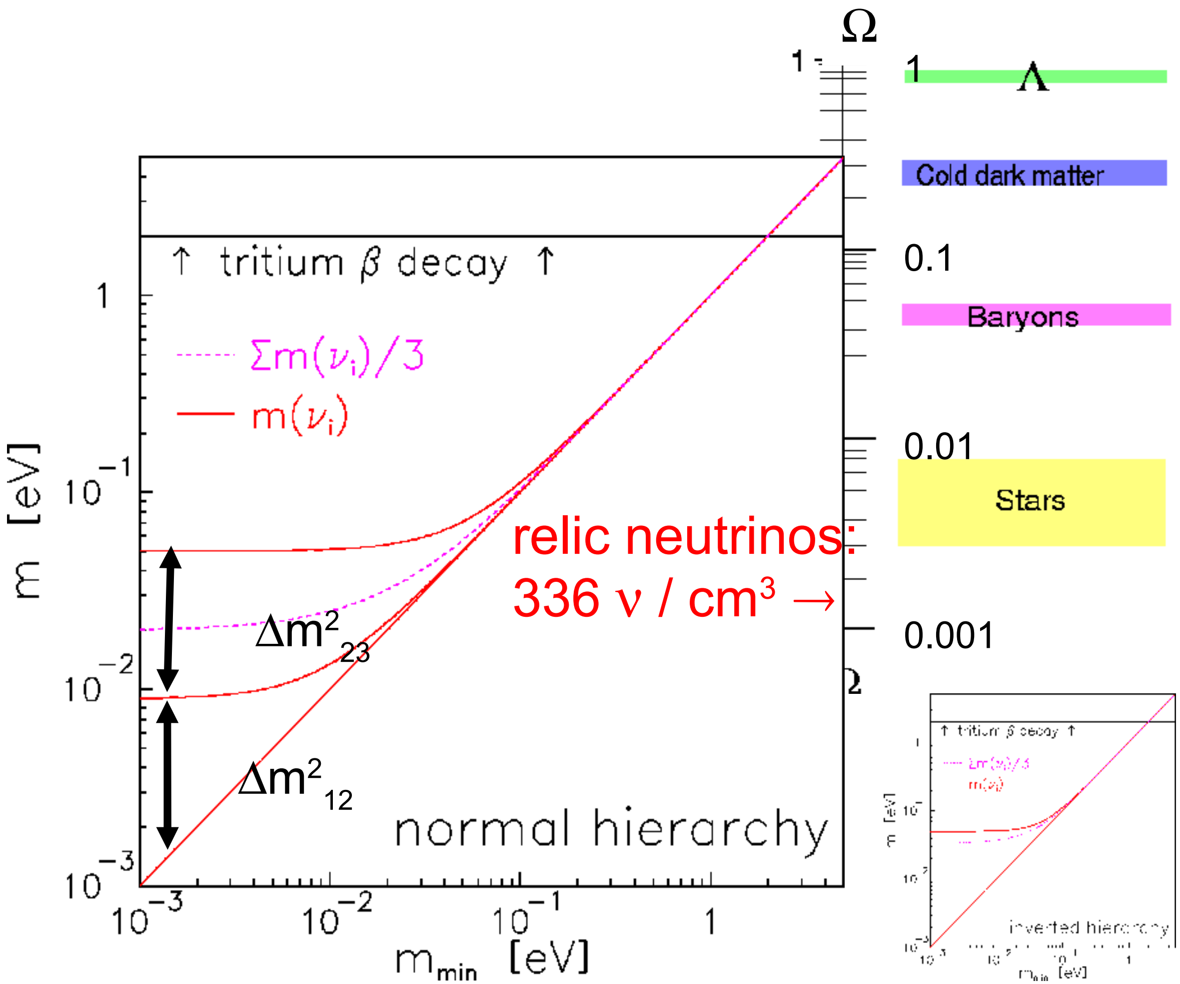
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

explains smallness of masses, but not mixing



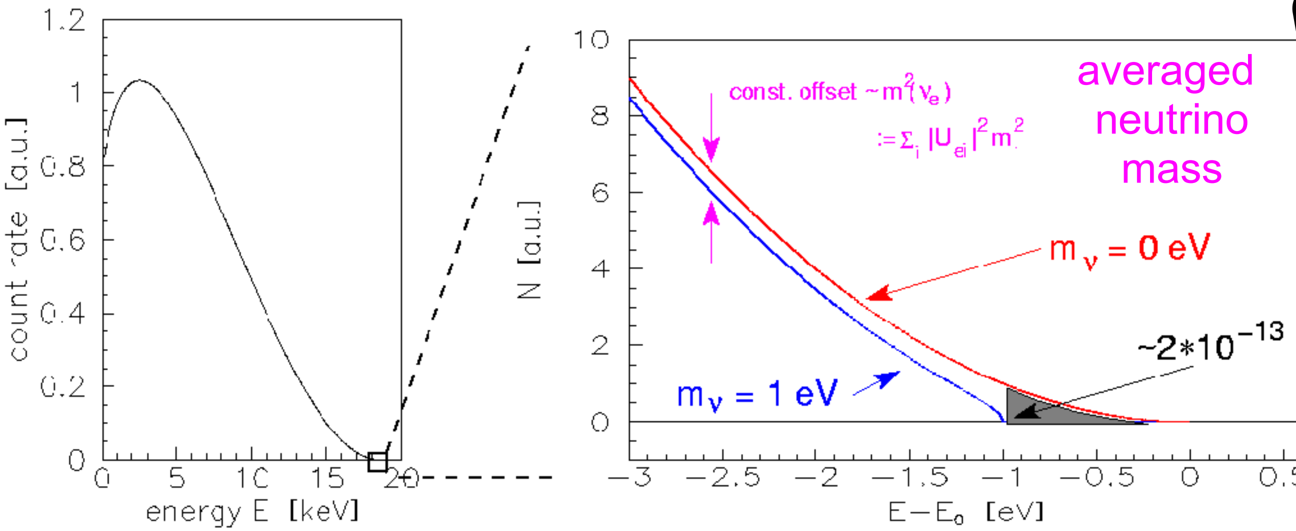
Direct determination of $m(\nu_e)$ from β decay

β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

β electron energy spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma\,|U_{ei}|^2\ \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$$

(modified by electronic final states, recoil corrections, radiative corrections)



Present limits:

V.M. Lobashev, Nucl. Phys. A719 (2003) 153c

V.N. Aseev, Phys. Rev. D 84 (2011) 112003

Ch. Kraus et al. (Mainz m_ν exp.) Eur.Phys.J.C40 (2005) 447

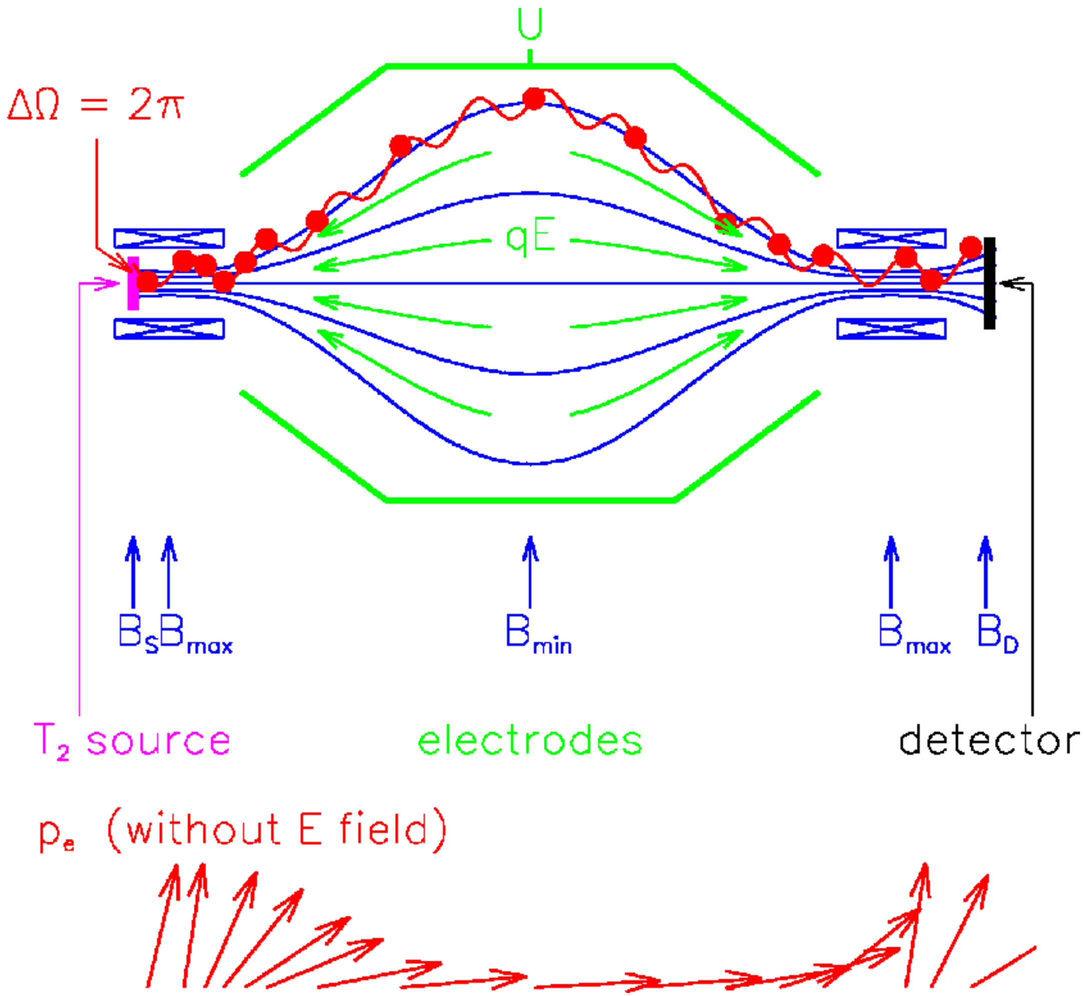
Review:

E.W. Otten & C. Weinheimer Rep. Prog. Phys., 71 (2008) 086201

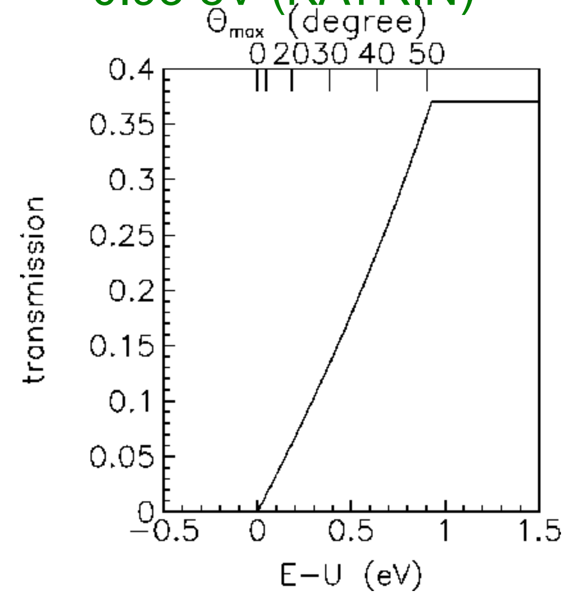
Need: **low endpoint energy** ⇒ **Tritium ^3H, (^{187}Re)**

very high energy resolution &
very high luminosity &
very low background } ⇒ **MAC-E-Filter**
(or bolometer for ^{187}Re)

Ultrahigh resolution & huge count rate MAC-E-Filter



- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E/B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)



⇒ **sharp integrating transmission function without tails →**

Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

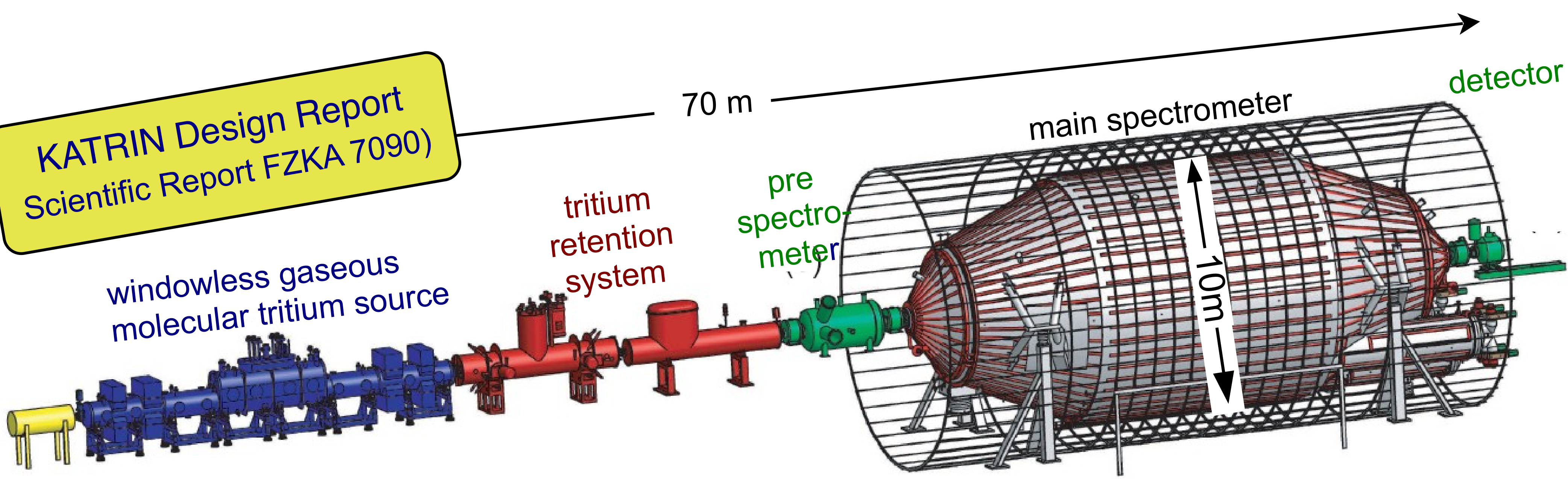
The KATRIN experiment at KIT

Aim: $m(\nu_e)$ sensitivity of 200 meV (currently 2 eV)

- very high energy resolution ($\Delta E \leq$ 1eV, i.e. σ = 0.3 eV) $\Rightarrow$ source $\neq$ spectrometer concept
- strong, opaque source $\Rightarrow dN/dt \sim A_{source}$
- magnetic flux conservation (Liouville) $\Rightarrow$ scaling law:

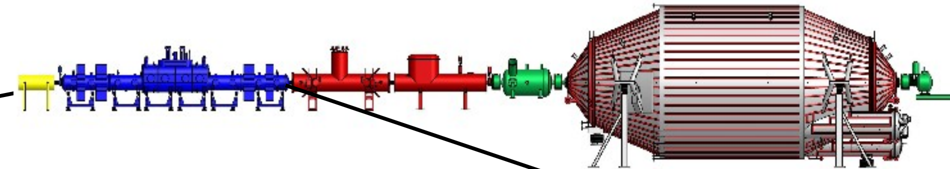
$$A_{spectrometer} / A_{source} = B_{source} / B_{spectrometer} = E / \Delta E = 20000 / 1$$

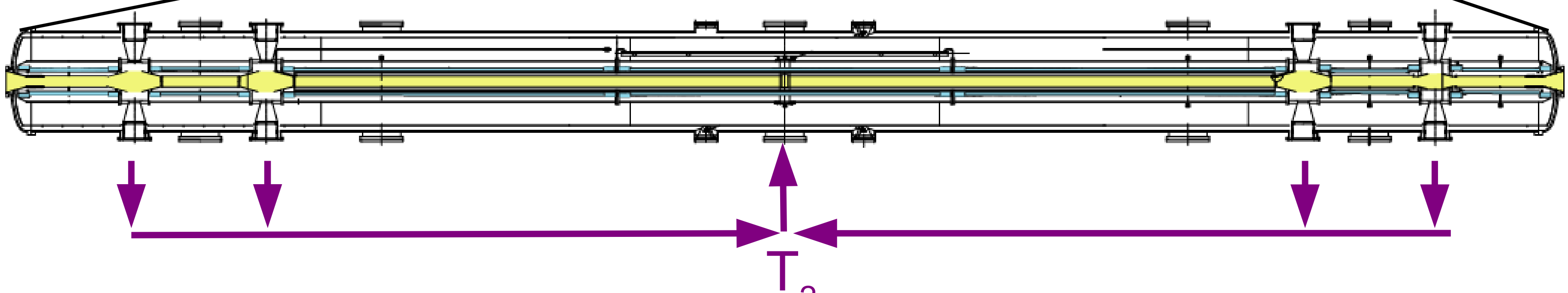
KATRIN Design Report
Scientific Report FZKA 7090)



Molecular Windowless Gaseous Tritium Source WGTS

Principle like Troitsk, LANL, LLNL
Basic design: V.M. Lobashev, O. Kazachenko





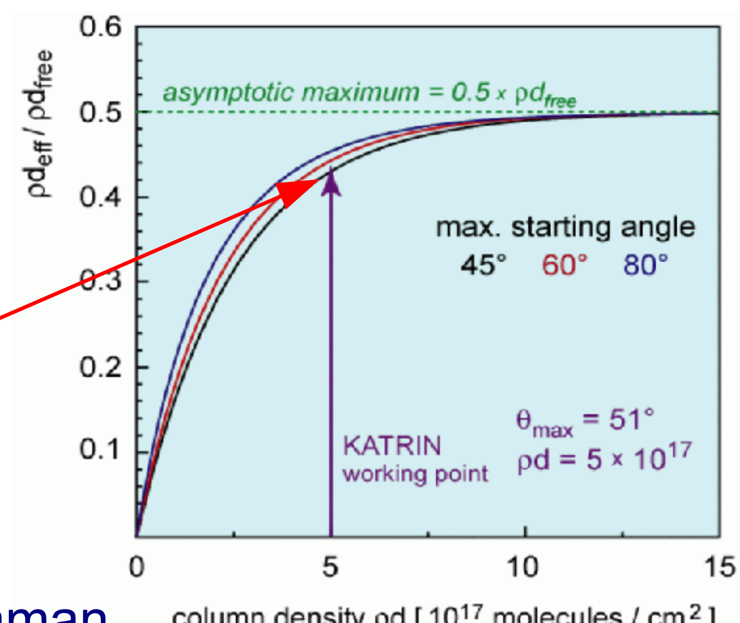
WGTS: tub in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

Tritium recirculation (and purification)
p_{inj} = 0.003 mbar, q_{inj} = 4.7Ci/s

allows to measure with near to maximum count rate using

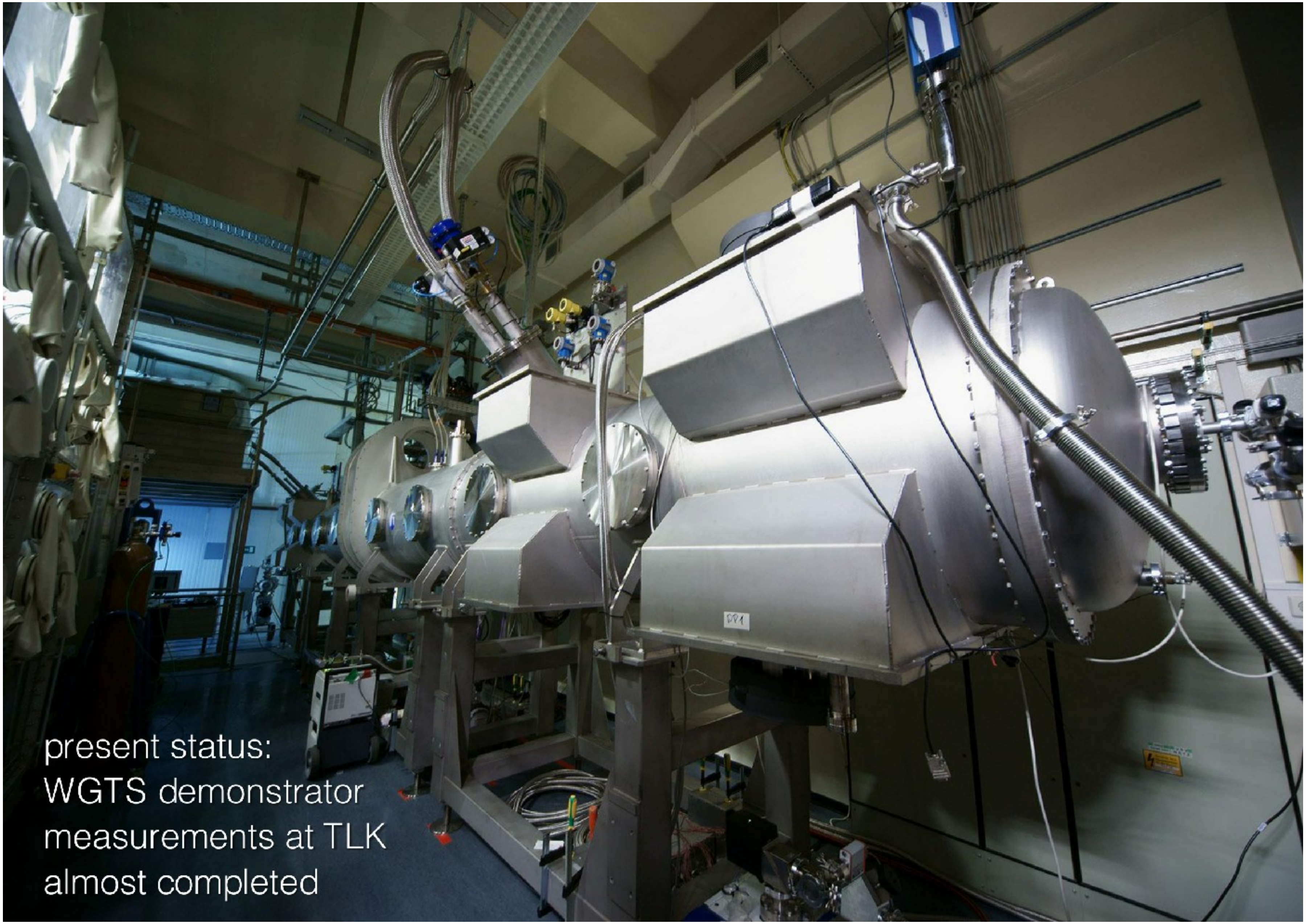
$\rho d = 5 \cdot 10^{17}/cm^2$

with small systematics

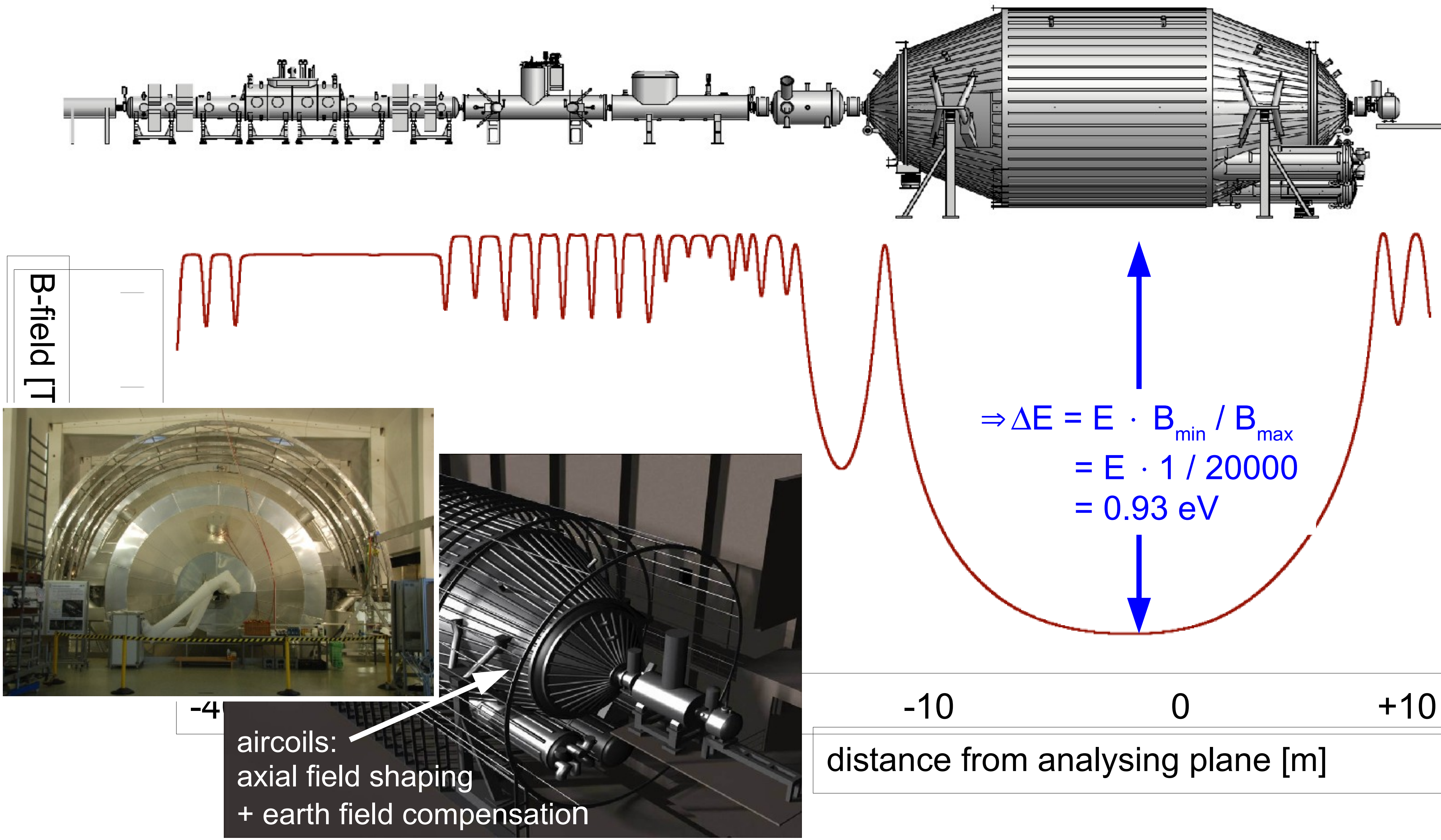


check column density by e-gun, T_2 purity by laser Raman

The windowless gaseous tritium source demonstrator



Electromagnetic design: magnetic fields



Inside main spectrometer: wire electrode system & LN2 baffles

Avoid background by secondary electrons from cosmic rays, environmental gammas & from Radon decays

The electron detector (US contribution)

Requirements

- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (1 mHz)
  (passive and active shielding)
- good energy resolution (1 keV)

Properties

- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV)
  (to lower background in signal region)
- segmented wafer (148 pixels)
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities

Systematic uncertainties

A) As smaller m(ν) as smaller the region of interest below endpoint E_0

B) Any unaccounted variance σ^2 leads to negative shift of m_ν^2: $\Delta m_\nu^2 = -2\sigma^2$

1. inelastic scatterings of ß´s inside WGTS
   - **dedicated e-gun measurements**, unfolding of response fct.

2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, e-gun measurements

3. transmission function
   - spatial resolved e-gun measurements

4. WGTS charging due to remaining ions (MC: φ < 20mV)
   - inject low energy meV electrons from rear side, diagnostic tools available, **check with Troitsk tritium source**

5. final state distribution
   - reliable quantum chem. calculations

6. HV stability of retarding potential on ~3ppm level required
   - precision HV divider (PTB), monitor spectrometer beamline

} a few contributions with $\Delta m_\nu^2 \leq 0.007\ eV^2$ each

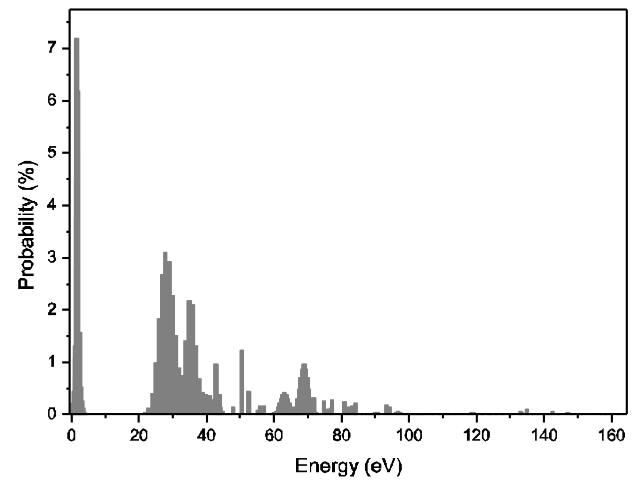
Long way from measured data/numbers to physical result:

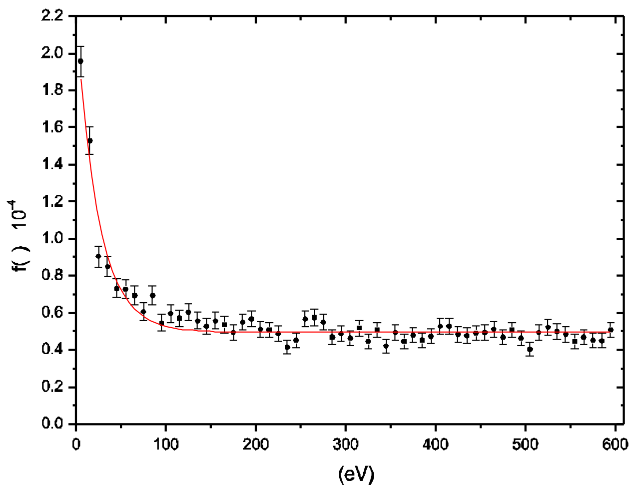
- Simulation
- Data reconstruction
- Calibrations
- Corrections
- Systematic effects
- Estimation of systematic errors

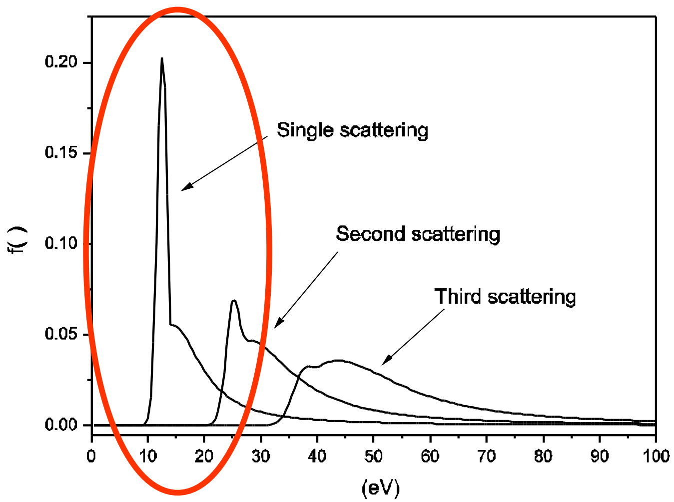
What experience at Troitsk ν-mass tell us?
Our estimate is $m^2 = -0.67 \pm 1.89_{stat} \pm 1.68_{syst}$ eV^2

Systematic effects and errors are the major problems

- Column density calibration and monitoring
- Correction on final states of $T_2 \to T\,{}^3He$
- Electron energy losses by multiple scattering
- Effect of magnetic trapping

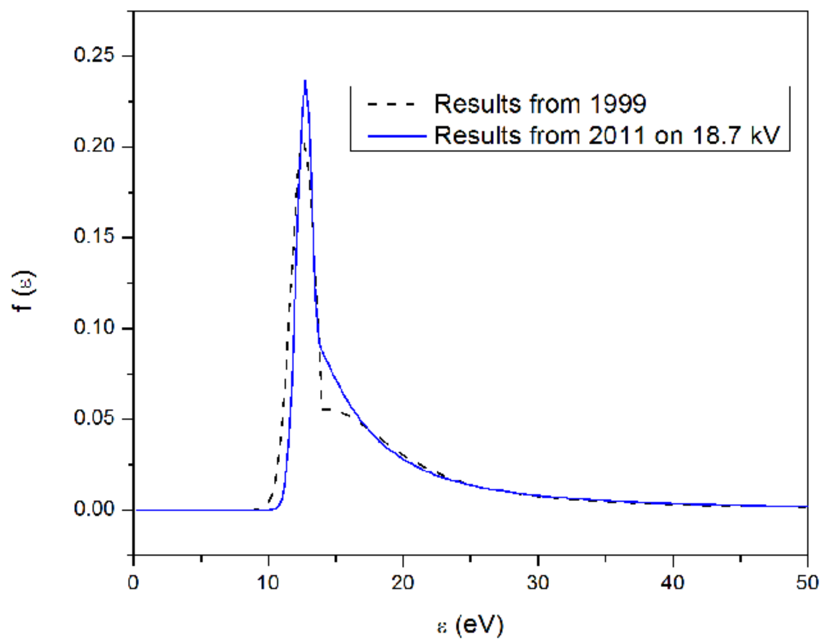




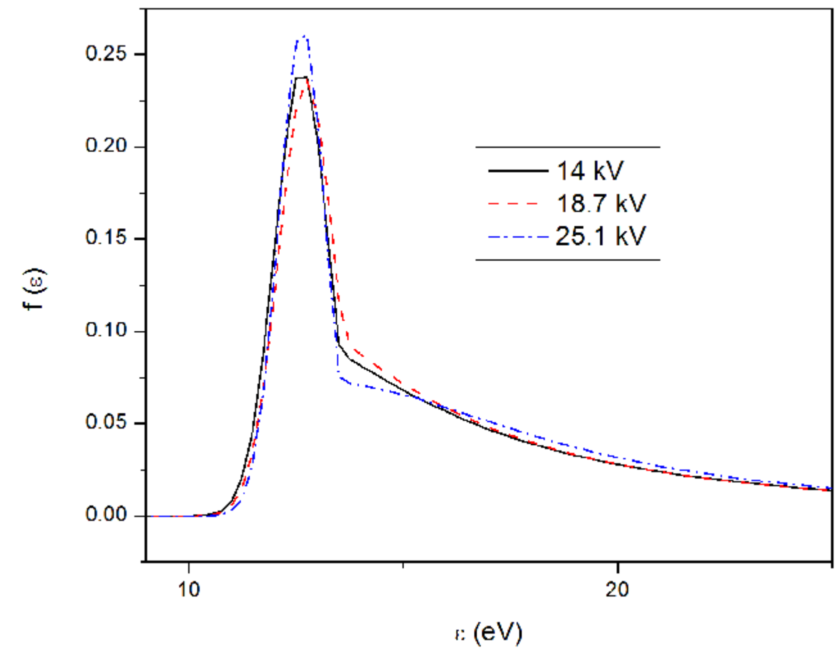


Recently achieved results at Troitsk

Measurement of electron scattering on H_2 at 14, 18, and 25 keV. New data on excitation and ionization spectra obtained with spectrometer resolution of about 1 eV.



Electron energy losses by scattering in H_2

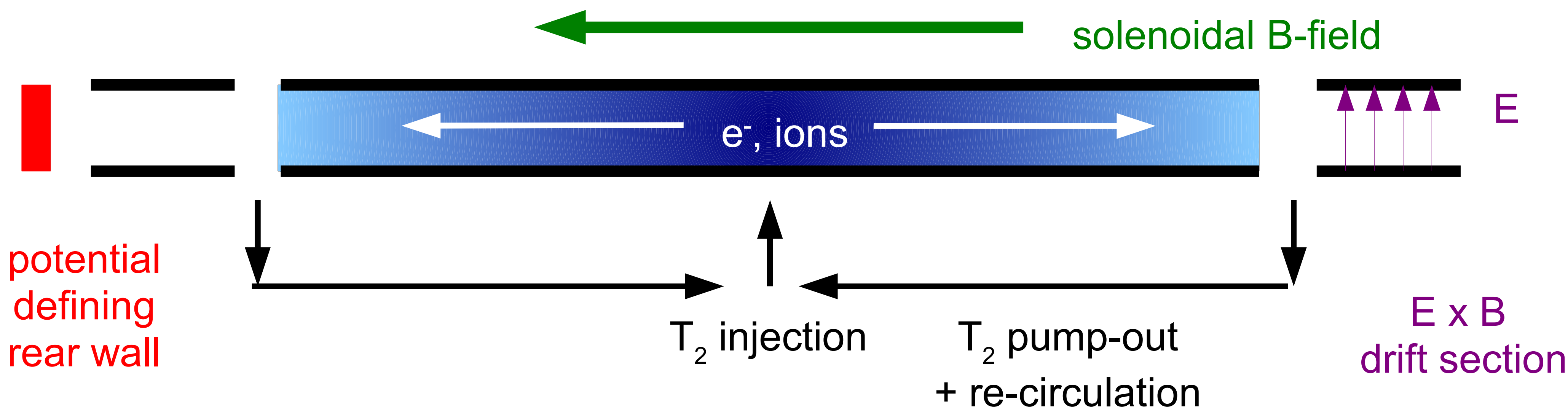


The same, at different energies

Recently achieved results at Troitsk

- Recently achieved results:
  - Measurement of electron scattering on H_2 at 14 keV, 18 keV, 25 keV. New data on excitation and ionization spectra obtained with spectrometer resolution of about 1 eV.
  - Preliminary measurement of a possible shift of 30.5 keV ^{83m}Kr lines in WGTS filled with H2.

Plasma potential within windowless gaseous tritium source



- Plasma is radially confined by the longitudinal B-field (no transverse mobility)
- There is a very good longitinal confinement by magnetic field lines ("short-cut")
- Plasma is neutralized by low energy electrons (from inelastic scattering)
- Potential in source is defined by "potential defining rear wall"
- Escaping non-neutralized ions are drifted out by transversal E-field

Russian-German cooperation within KATRIN:

A.F. Nastoyashchii, N.A. Titov, I.N. Morozov, F. Glück and E.W. Otten, Fusion Science and Technology, 48 (2005) 743

Another serious concern and its possible solution to be checked at Troitsk

Another serious systematics for Troitsk/KATRIN-type of the Windowless Gaseous Tritium Source are possible effects in charged plasma:

Tritium decay produces fast electrons and slow moving positive daughter ions.

Large positive charge and potential would build up in WGTS.

How well it will be compensated by primary and secondary electrons could be investigated by small admixture of ^{83m}Kr isotope with mono energetic electrons.

Planned activities in Troitsk in 2012

- Complete measurements of electron scattering on H_2, D_2 and T_2 in 14-30 keV electron energy range.
- Investigation of systematic effects of a possible shift 30.5 keV L_3 ^{83m}Kr line in WGTS filled with H_2, D_2 and T_2.
- Such measurements are extremely useful for future KATRIN measurements and corrections

Conclusions

Neutrino mass is very important for particle, astrophysics and cosmology

KATRIN is a direct neutrino mass experiment

for particle and astroparticle physics with 0.2 eV sensitivity

complementary to $0\nu\beta\beta$ searches and cosmological analyses

2012/13 - commissioning of spectrometer & detector

- commissioning of tritium source & elimination lines

2013 (?)- regular data taking for 5-6 years (3 full-beam-years)

The Troitsk nu mass setup plus the Troitsk group could contribute strongly to investigate the systematics !