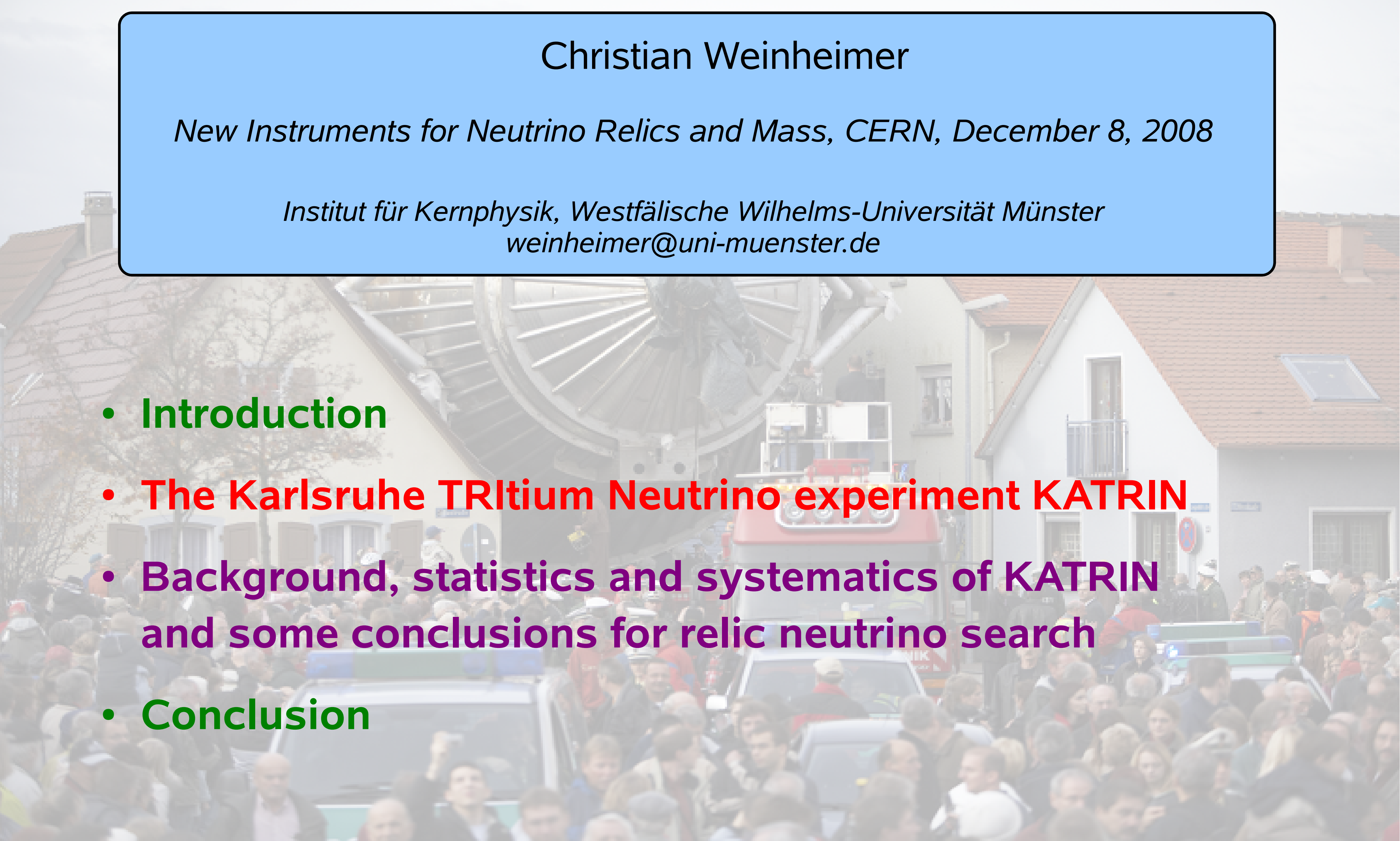
The Karlsruhe Tritium Neutrino Experiment KATRIN

Christian Weinheimer

New Instruments for Neutrino Relics and Mass, CERN, December 8, 2008

Institut für Kernphysik, Westfälische Wilhelms-Universität Münster
weinheimer@uni-muenster.de



- **Introduction**
- **The Karlsruhe TRItium Neutrino experiment KATRIN**
- **Background, statistics and systematics of KATRIN and some conclusions for relic neutrino search**
- **Conclusion**

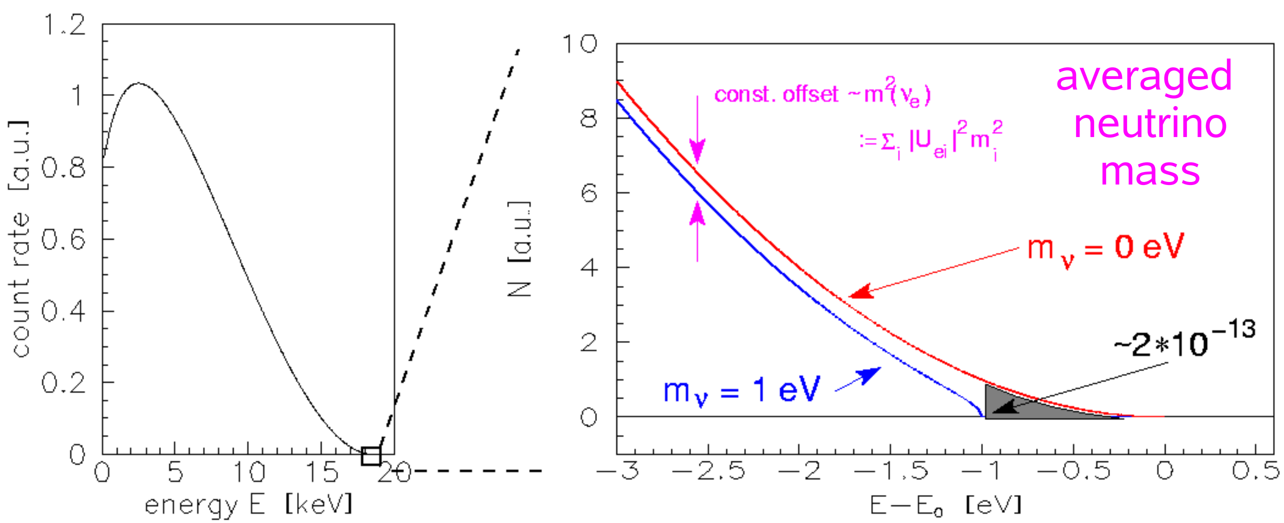
Direct determination of $m(\nu_e)$ from β decay

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)



Mainz, Troitzk experiments:
$m(\nu) < 2$ eV
e.g.: Otten & Weinheimer, Rep. Prog. Phys. 71 (2008) 086201

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

very high energy resolution &
very high luminosity &
very low background

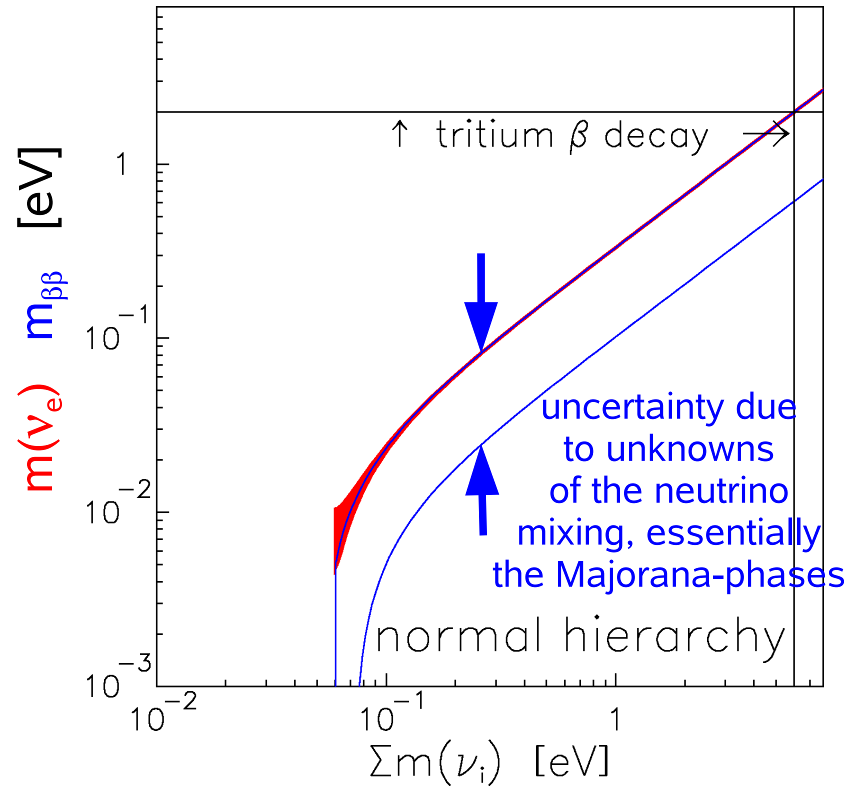
} ⇒ **MAC-E-Filter** (or bolometer for ^{187}Re)

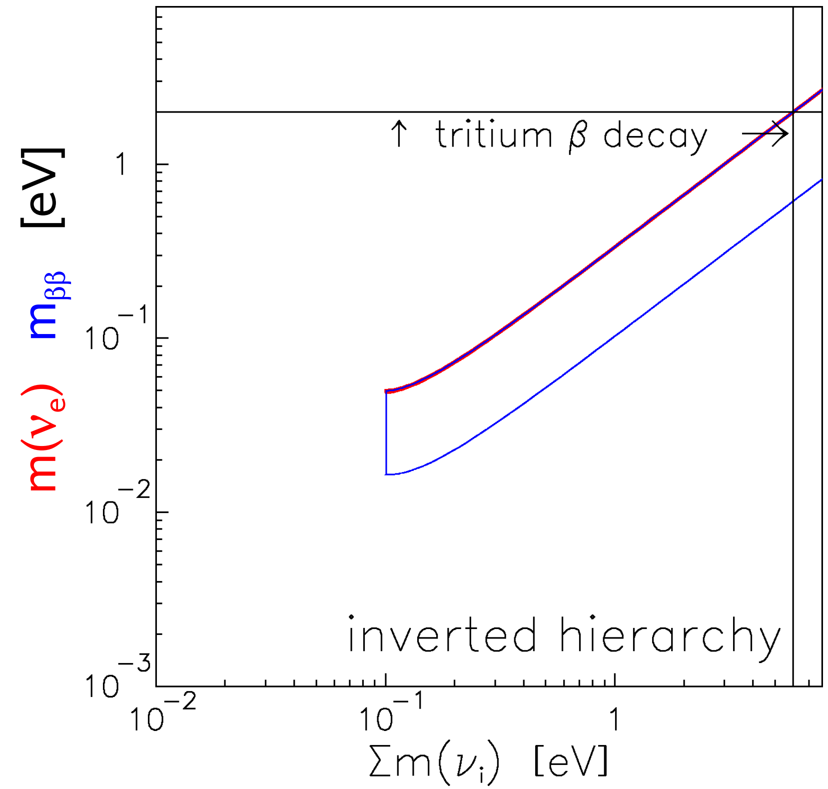
Comparison of the different approaches to the neutrino mass

Direct kinematic measurement: $m^2(\nu_e) = \Sigma\ |U_{ei}{}^2|\ m^2(\nu_i)$ (incoherent)

Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = |\ \Sigma\ |U_{ei}{}^2|\ e^{i\alpha(i)}\ m(\nu_i)|$ (coherent)

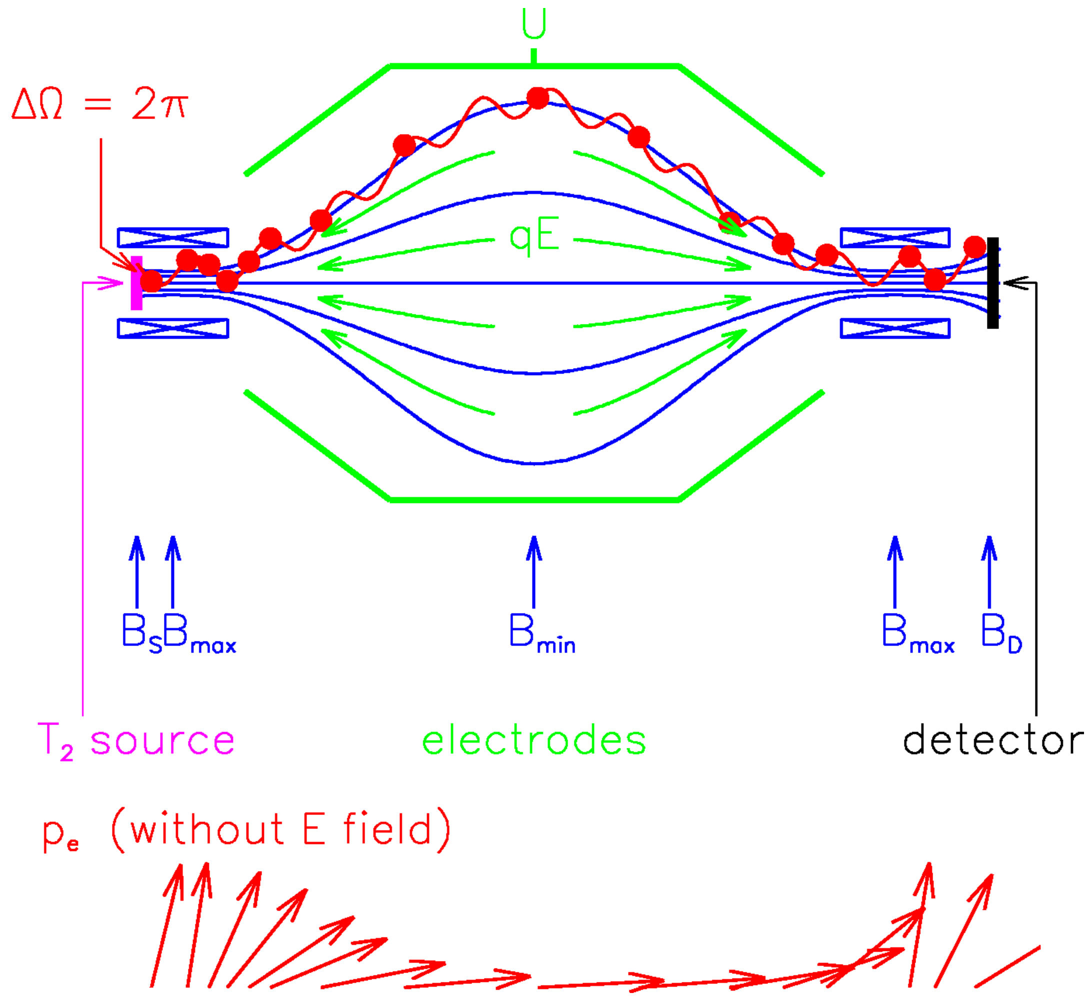
if no other particle is exchanged (e.g. R-violating SUSY)
problems with uncertainty of nuclear matrix elements





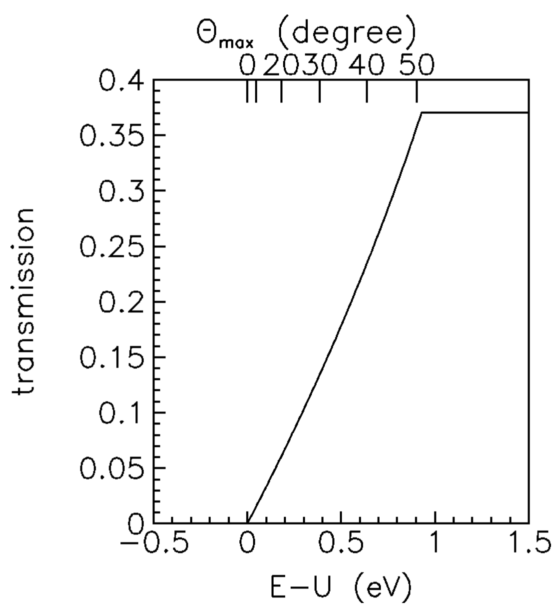
⇒ **absolute scale/cosmological relevant neutrino mass in the lab by single β decay**

Principle of the MAC-E-Filter



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

⇒ sharp integrating transmission function without tails →



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

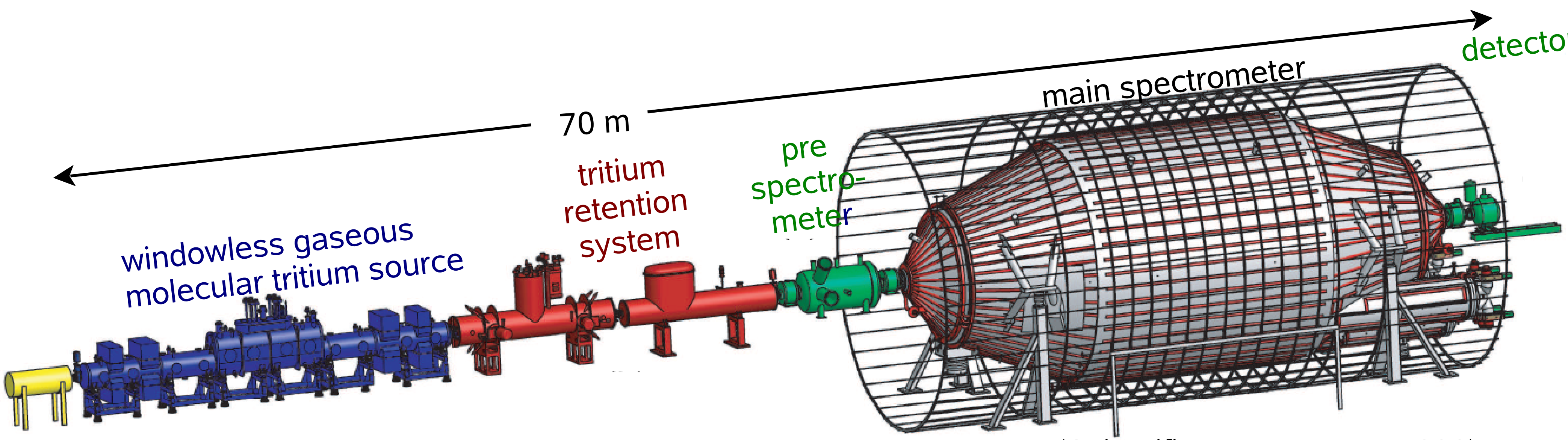
The Karlsruhe Tritium Neutrino experiment KATRIN

is being set up at the Forschungszentrum Karlsruhe

Physics Aim: $m(\nu_e)$ sensitivity of 0.2 eV

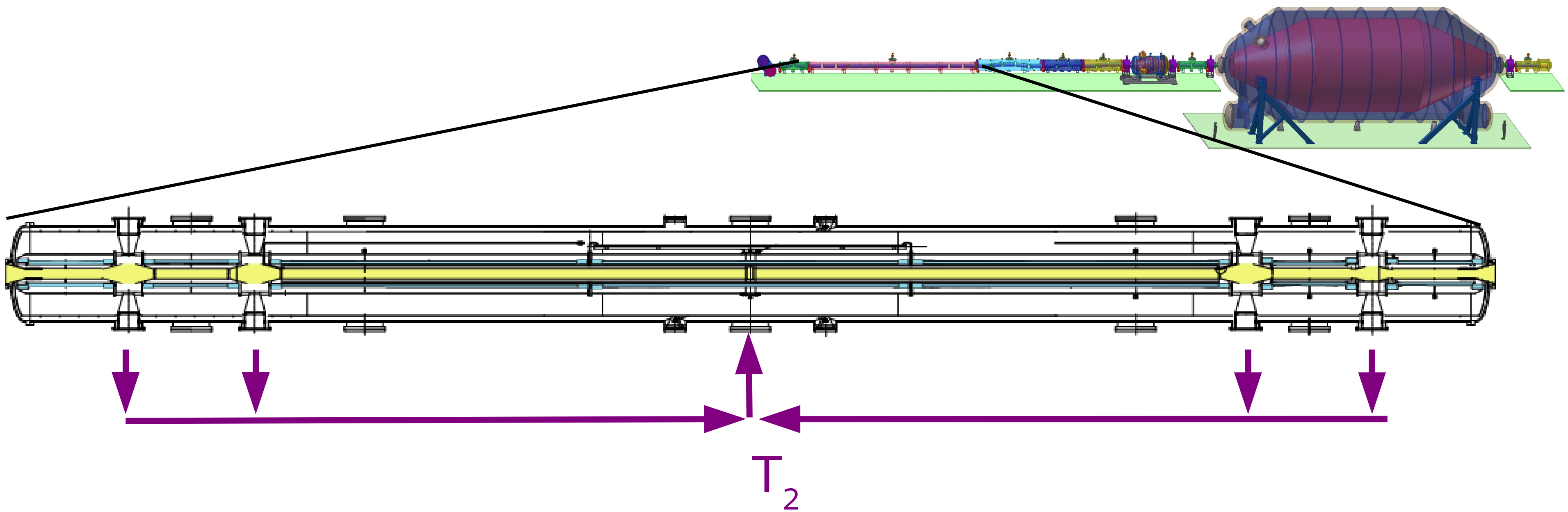
- higher energy resolution: $\Delta E \approx$ 1eV
  since $E/\Delta E \sim A_{spectrometer}$ $\Rightarrow$ larger spectrometer
- relevant region below endpoint becomes smaller
  even less rate $dN/dt \sim A_{source} \sim A_{spectrometer}$ $\Rightarrow$ larger spectrometer

  } $\varnothing$10 m
- small systematics $\Rightarrow$ windowless gaseous tritium source
- much longer measurement time: 100 d $\rightarrow$ 1000 d



(Scientific Report FZKA 7090)

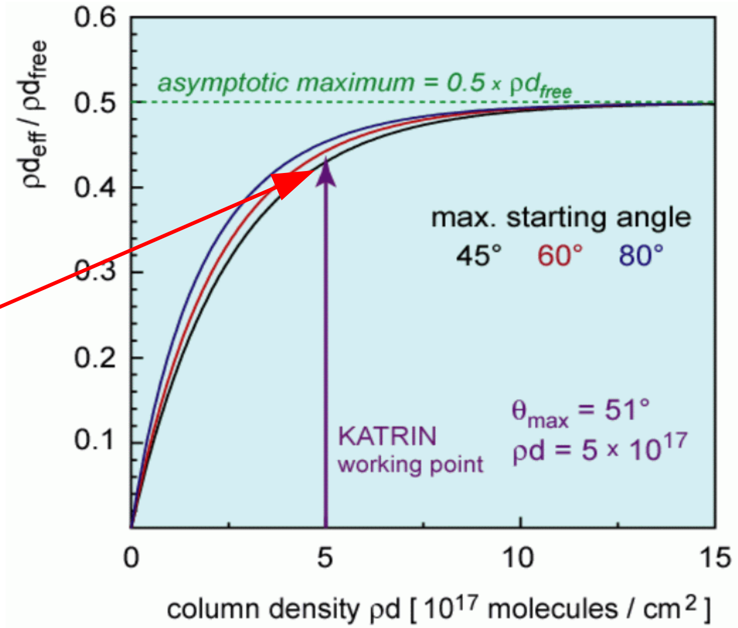
Molecular Windowless Gaseous Tritium Source WGTS



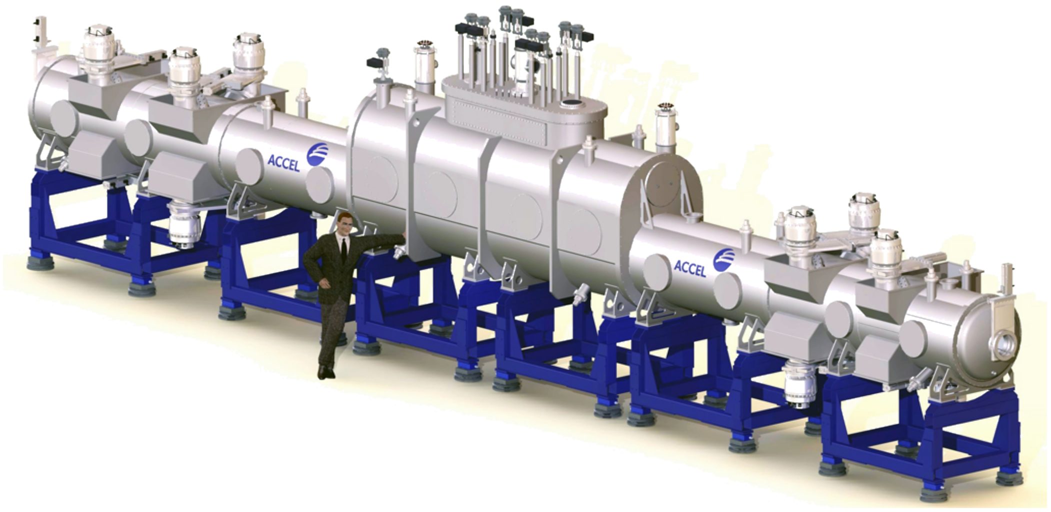
WGTS: tub in long superconducting solenoids
∅ 9cm, length: 10m, T = 30 K

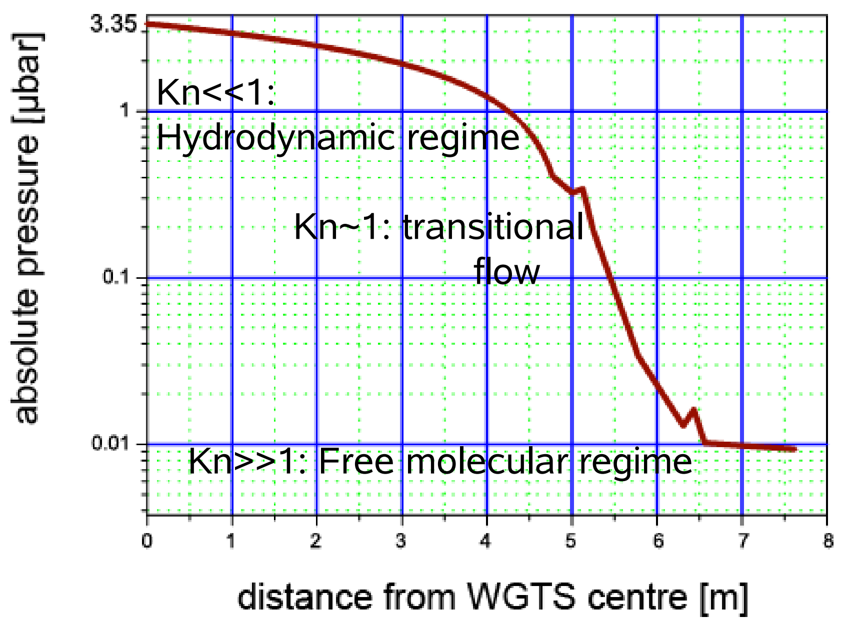
Tritium recirculation (and purification)
p_{inj} = 0.003 mbar, q_{inj} = 4.7Ci/s

allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics



Molecular Windowless Gaseous Tritium Source WGTS

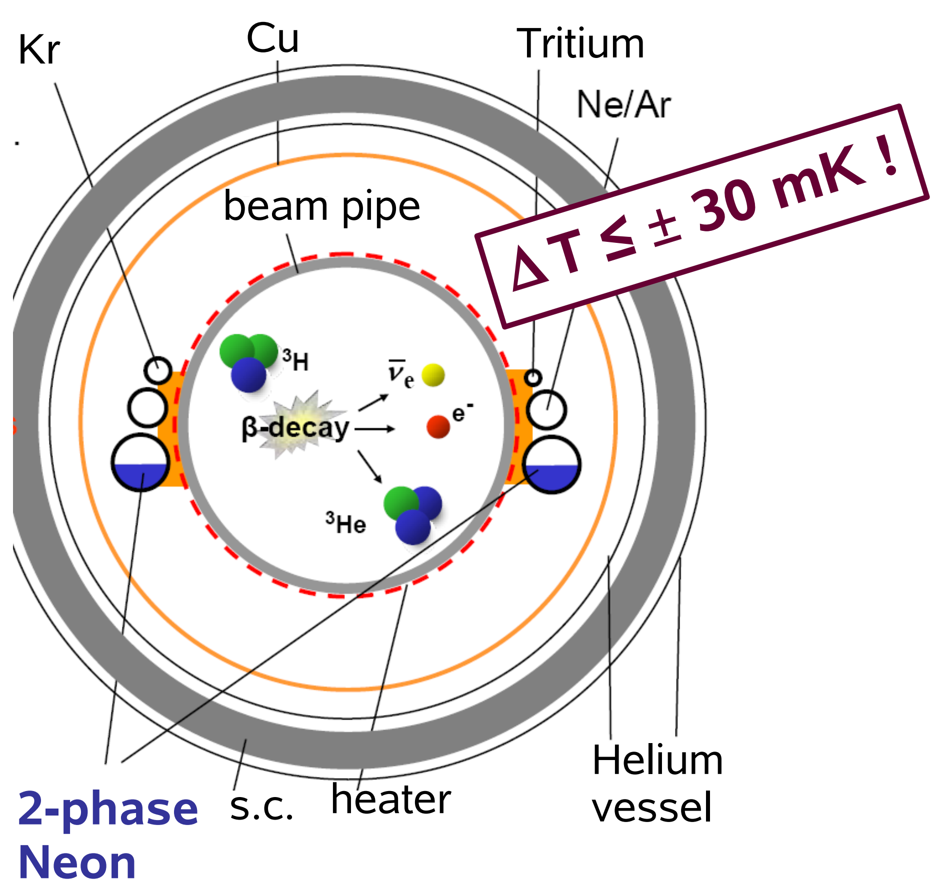




Conceptional design

2 phase Neon cooling with operating temperature: 27–28 K

- **spatial** (homogeneity): ± **0.1%**
- **time** (stability/hour): ± **0.1%**




M1,2,3 coil winding finished
2007 11 30

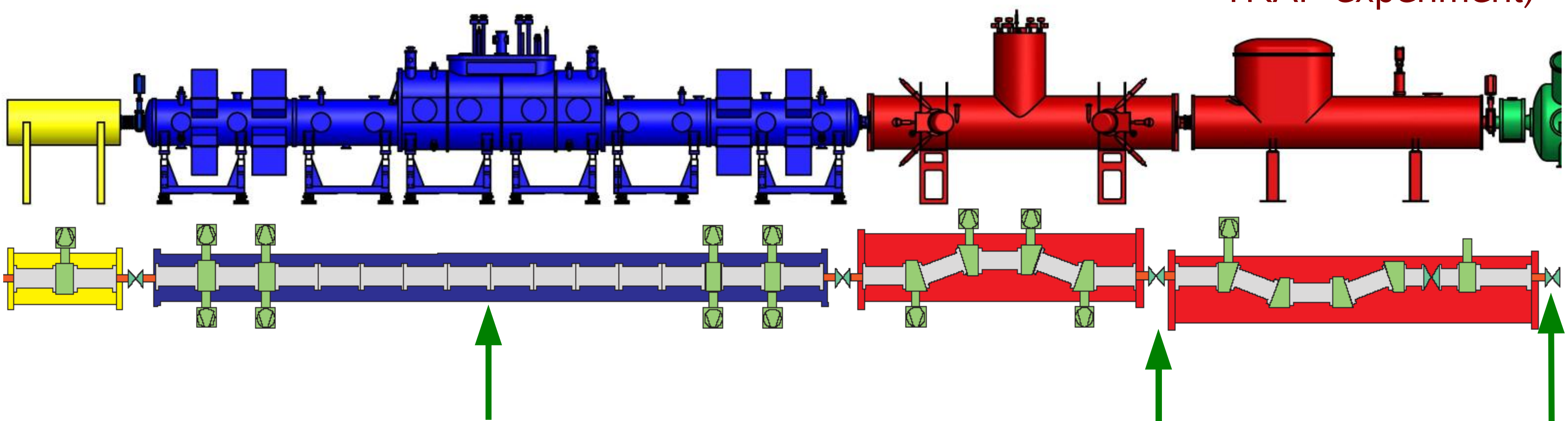

vacuum vessels DPS1
2007 8 17

Transport and differential & cryo pumping sections

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping with Argon snow at LHe temperatures (successfully tested with the TRAP experiment)



T_2-injection 1.8 mbar l/s (STP) = $1.7 \cdot 10^{11}$ Bq/s = 40 g/d

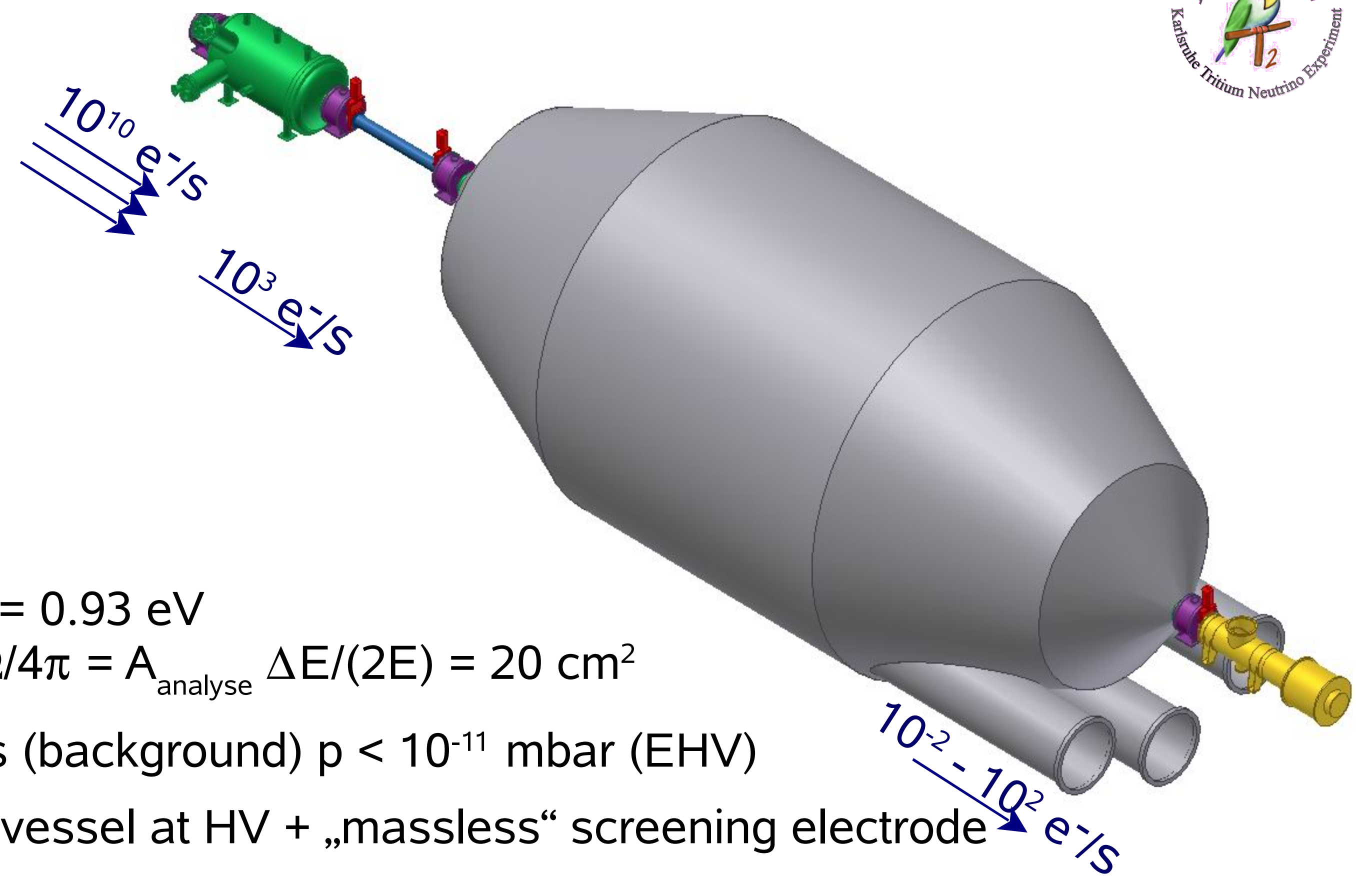
≈ 10^{-7} mbar l/s

< 2.5 10^{-14} mbar l/s

⇒ adiabatic electron guiding & T_2 reduction factor of ~10^{14}

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Pre and main spectrometer



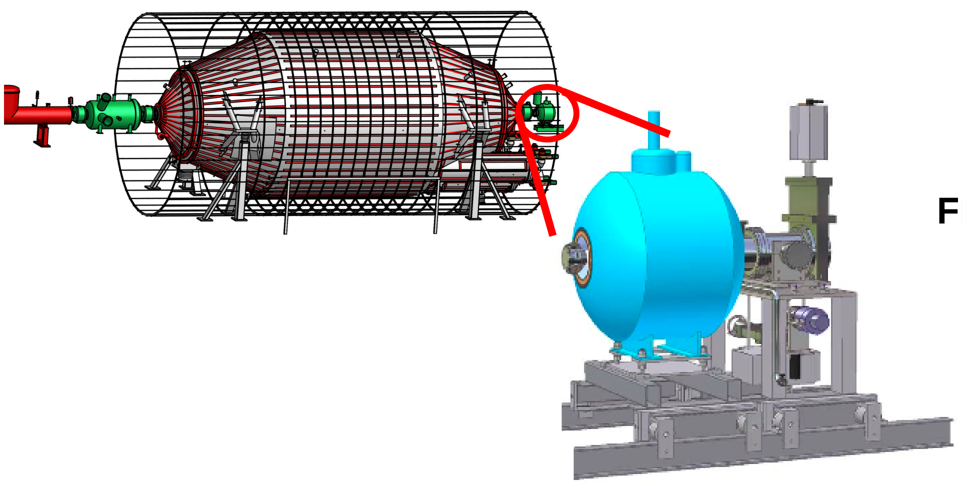
Main spectrometer:

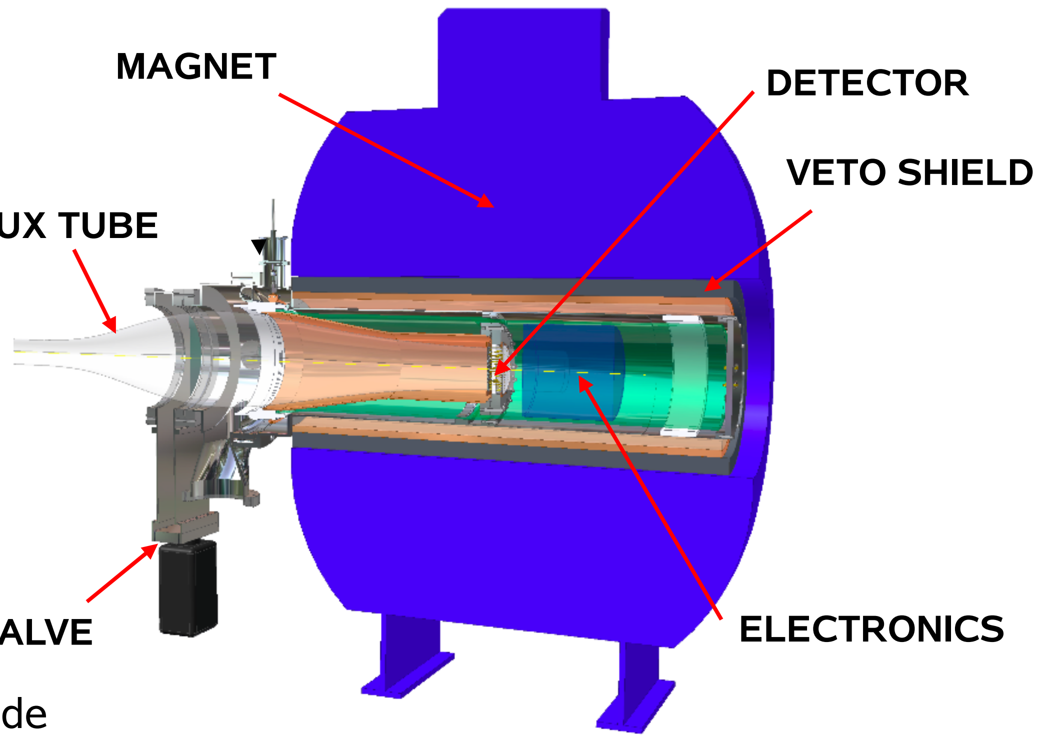
- ∅10m, length 24m
  ⇒large energy resolution: ΔE = 0.93 eV
  ⇒high luminosity: $L = A_{Seff}\ \Delta\Omega/4\pi = A_{analyse}\ \Delta E/(2E) = 20\ cm^2$
- ultrahigh vacuum requirements (background) $p < 10^{-11}$ mbar (EHV)
- „simple" construction: vacuum vessel at HV + „massless" screening electrode

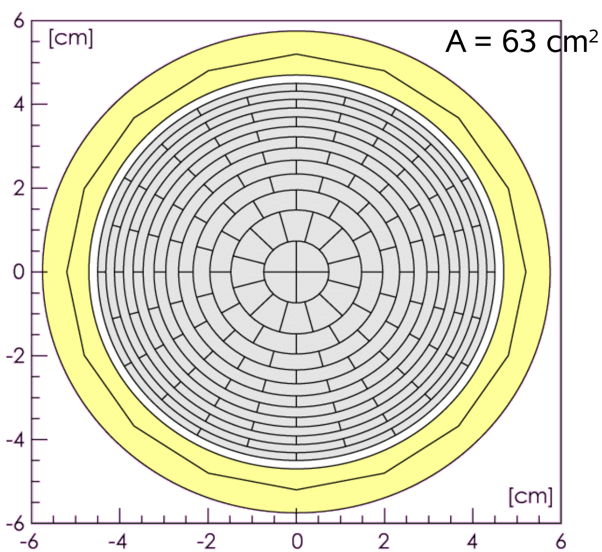
Pre spectrometer

- 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: ΔE = 80 eV
- test of new ideas (EHV, shape of electrodes, avoid and remove of trapped particles, ...)

Detector Setup



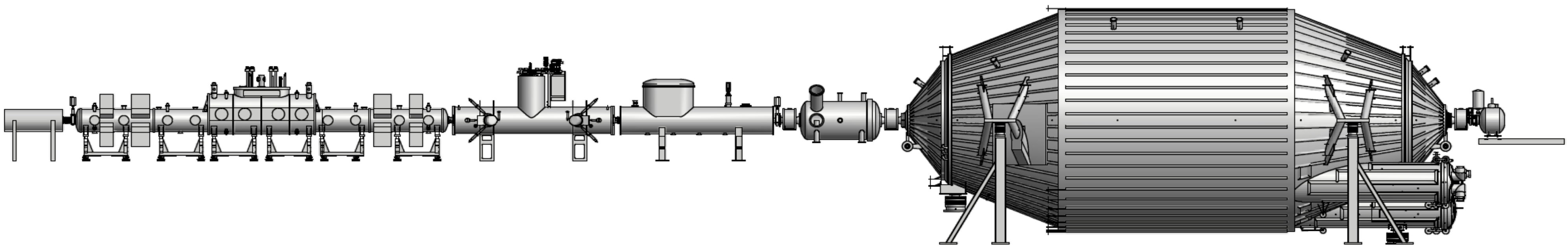


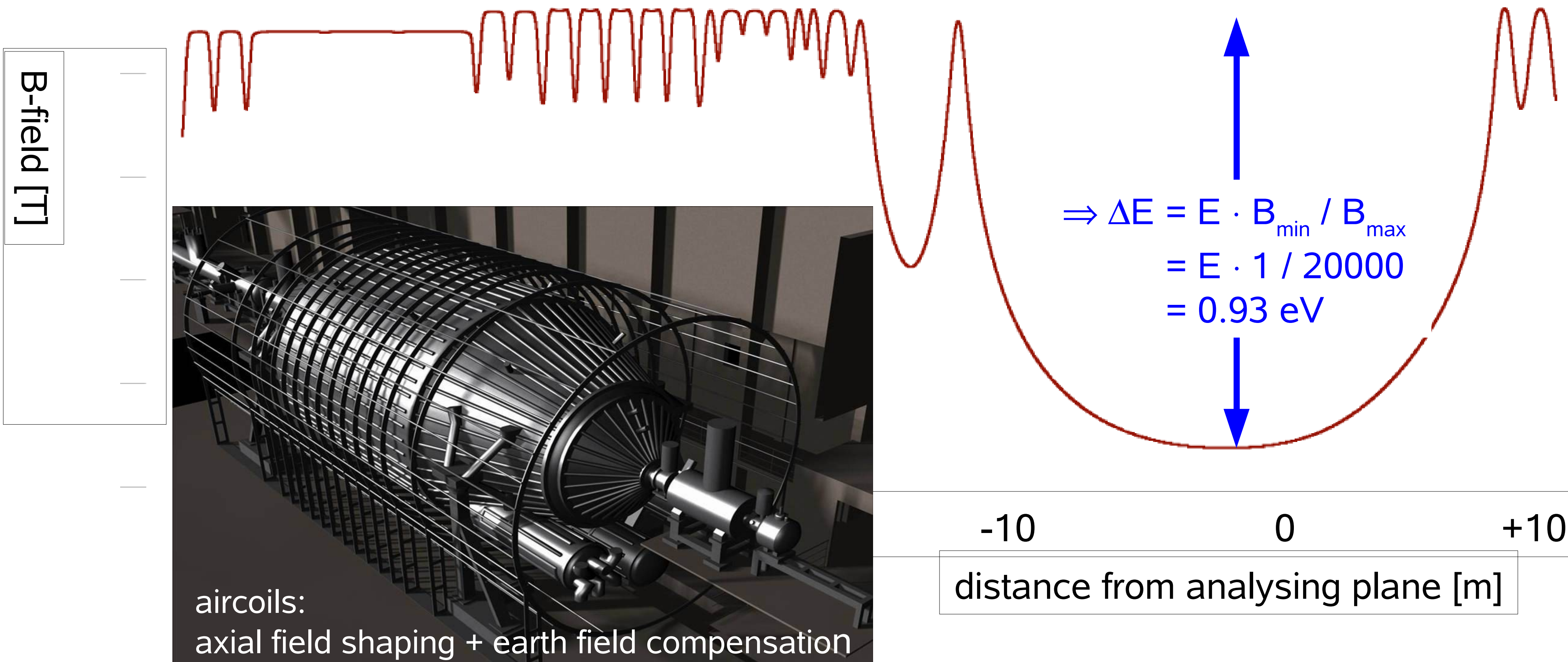


- Si-Pin diode
- Detection of transmitted β-decay electrons (mHz to kHz)
- **Low background for endpoint investigation**
- High energy resolution ΔE < 1 keV
- 12 rings with 30° segmentation + 4 fold center = **148 pixels**
  - ➔ record azimuthal and radial profile of flux tube
    - ➔ minimize background
    - ➔ investigate systematic effects
    - ➔ compensate field inhomogeneity in analyzing plane

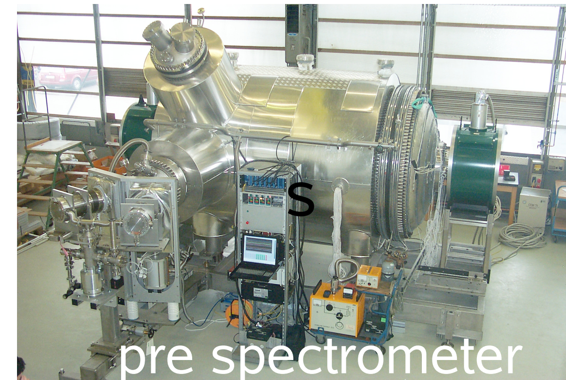
(magn. field of 3 - 6 T, active veto shield, post-accel. mode)

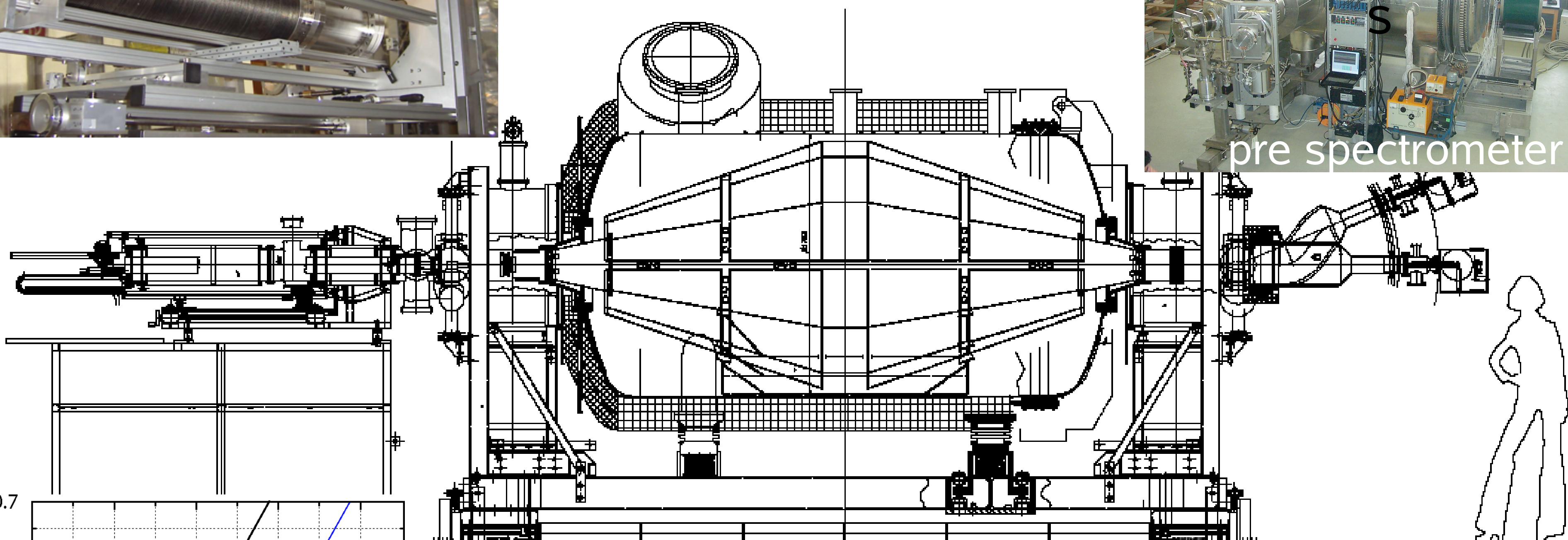
Electromagnetic design: magnetic fields

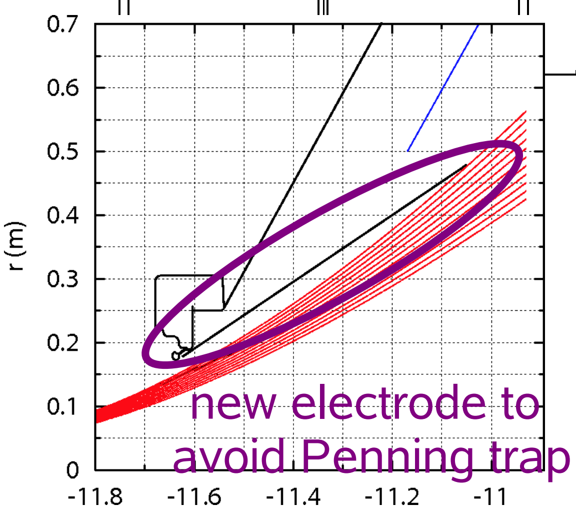


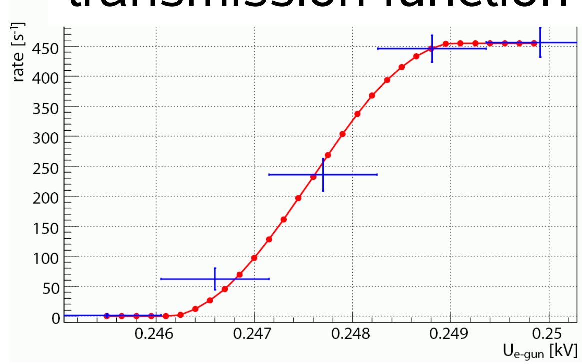


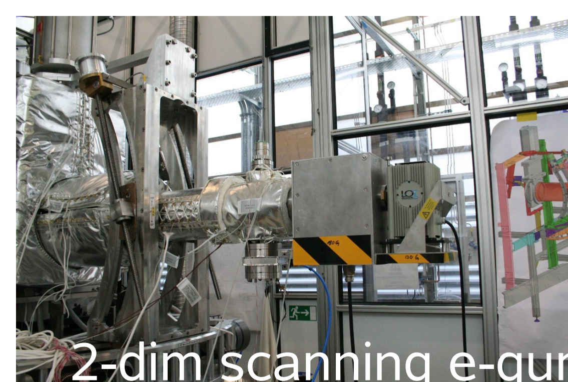
Electromagnetic design tests at the pre spectrometer



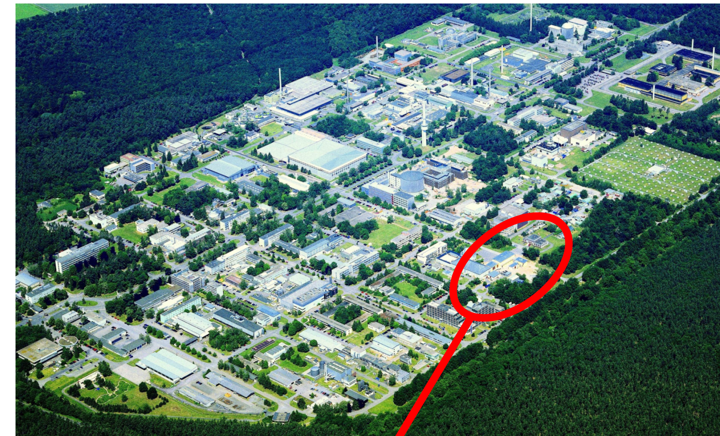


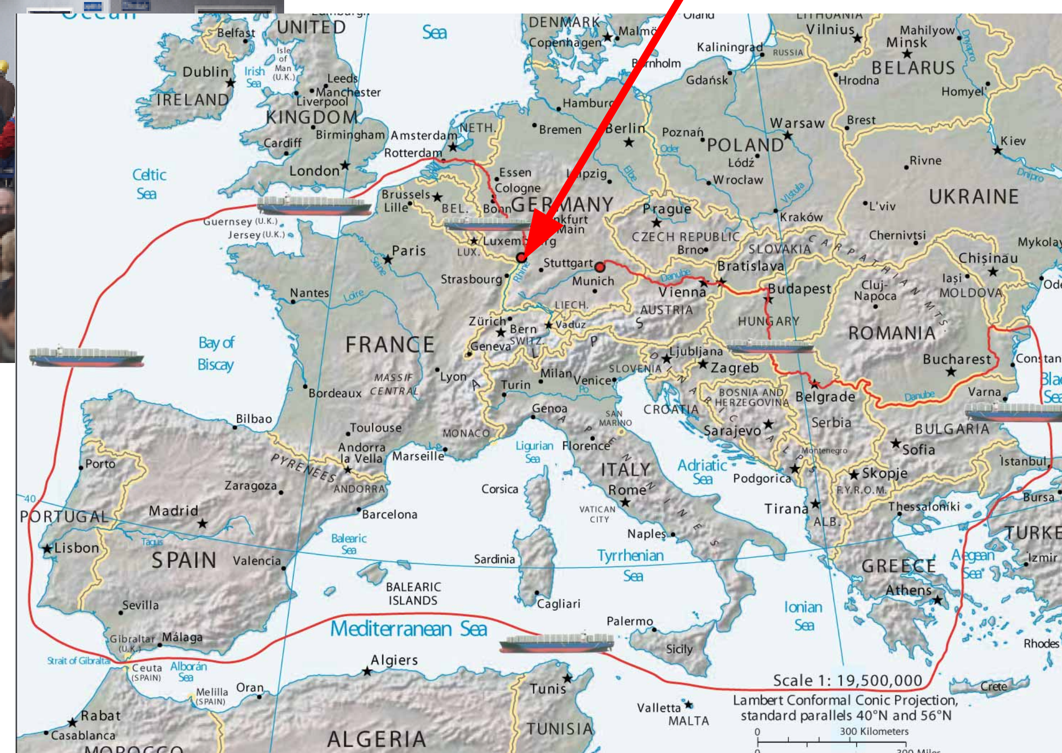




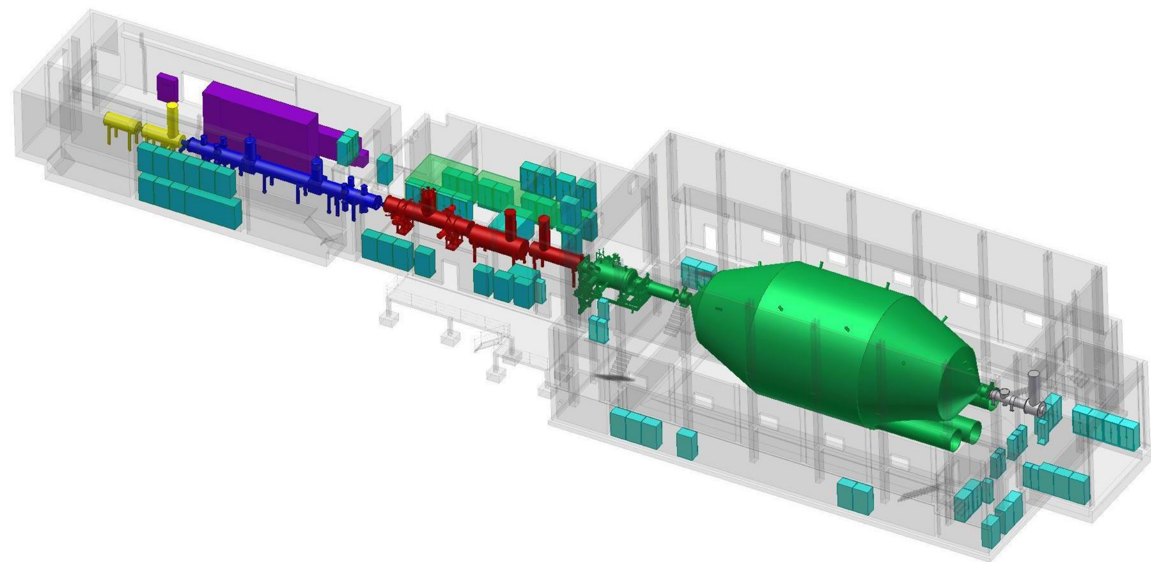


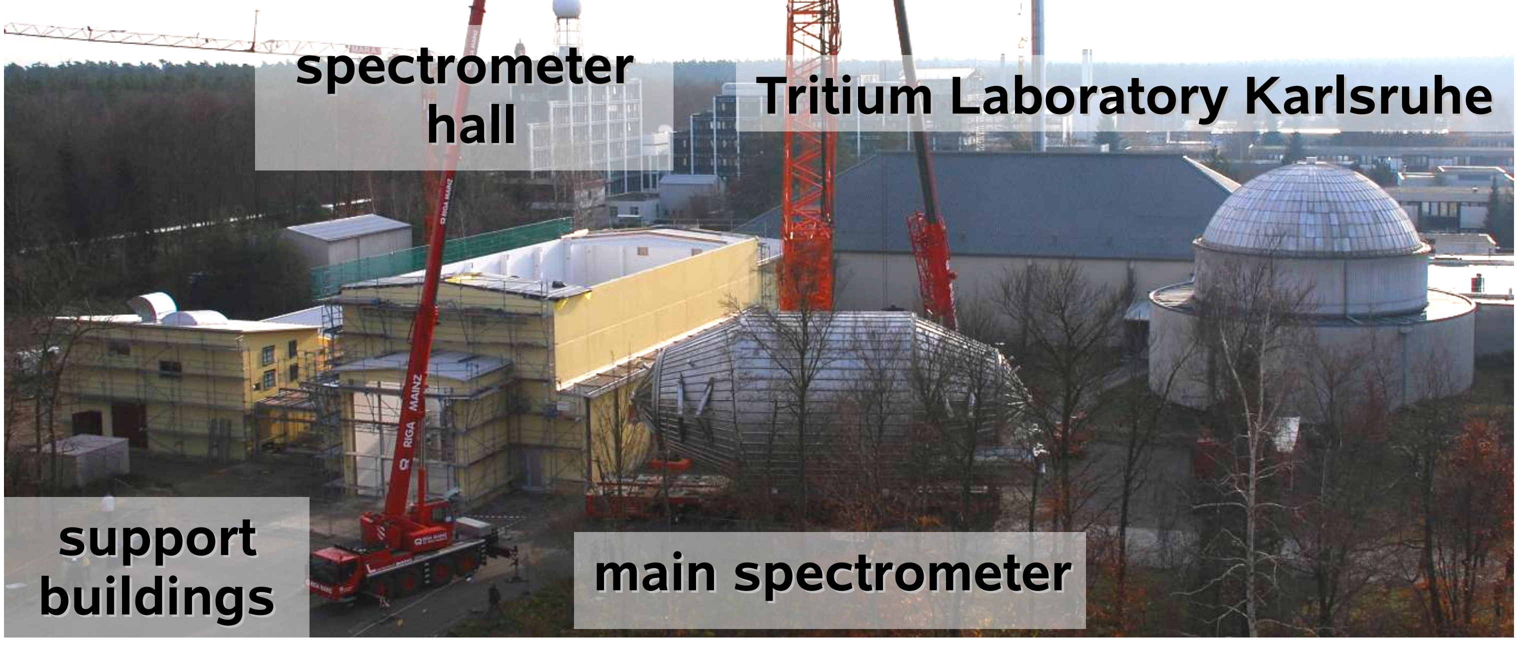
Main Spectrometer – Transport to Forschungszentrum Karlsruhe





KATRIN`s location at Forschungszentrum Karlsruhe





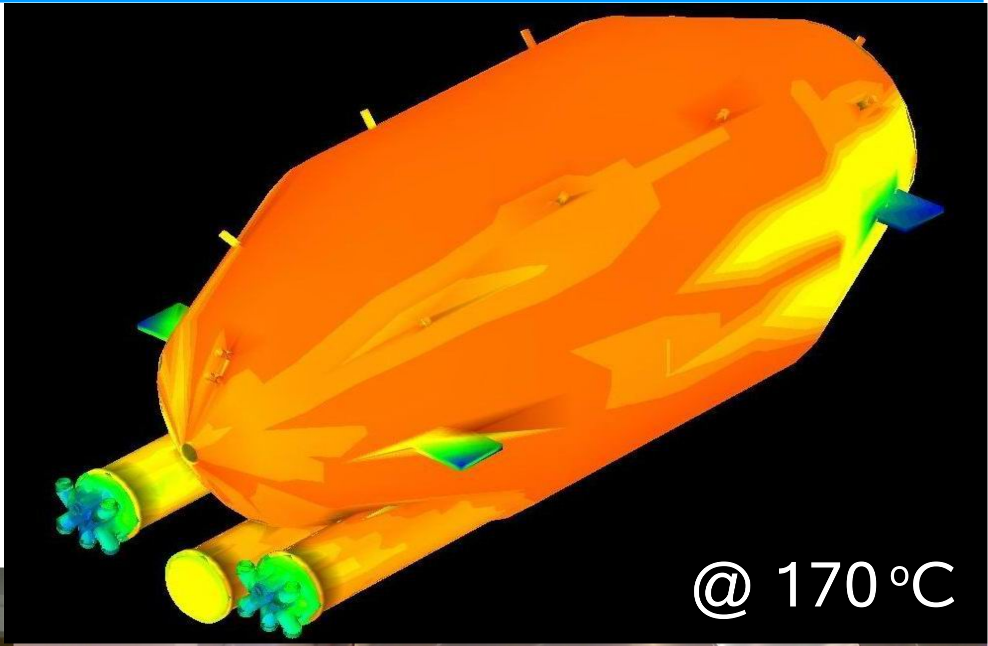
Westfälische Wilhelms-Universität Münster

Installation of heating/cooling system and first out-baking at 350 °C

After out-baking (with only 6 TMPs):

a) $p = 5 * 10^{-10}$ mbar, (but pumping speed will still be increased by 2 orders of magnitude by NEGs)

b) out-gasing rate is about KATRIN´s design value of $q<10^{-12}$ mbar l/s cm^2



Sensitivity requirements

1) Huge statistics: optimized source & large spectrometer

2) Low background: Mainz experiment:
most background from spectrometer
but KATRIN spectrometer is much bigger!
⇒ need something new !

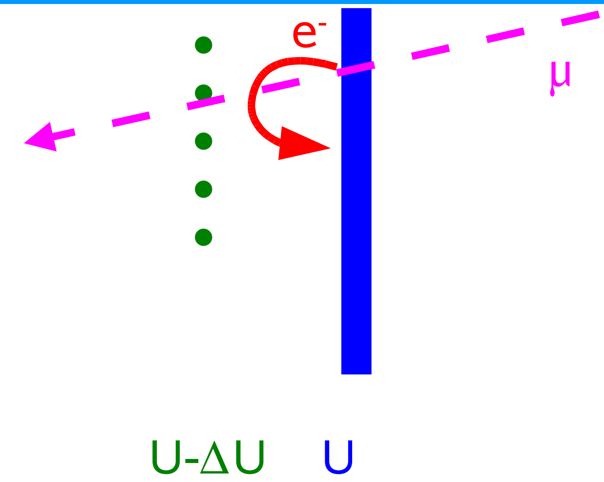
3) Systematic uncertainties:
need to be very small !

Background reduction: shielding by „massless“ wire electrode

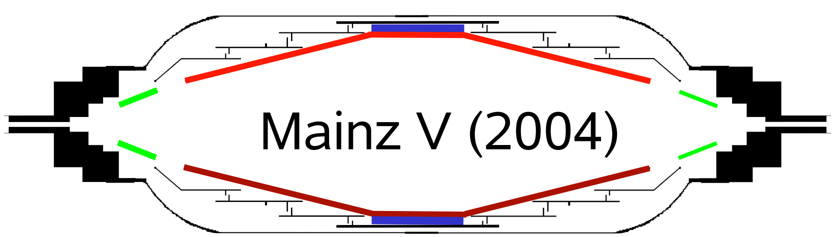
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

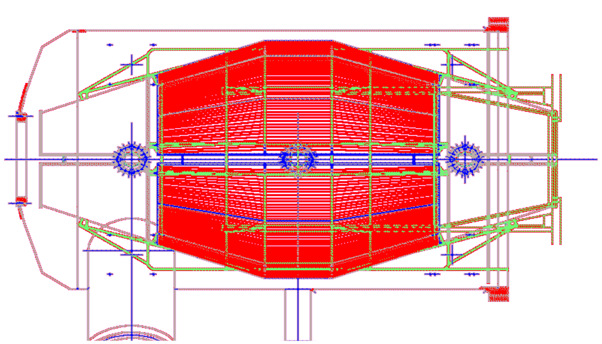
wire electrode on slightly more negative potential



First realisation:
Mainz III

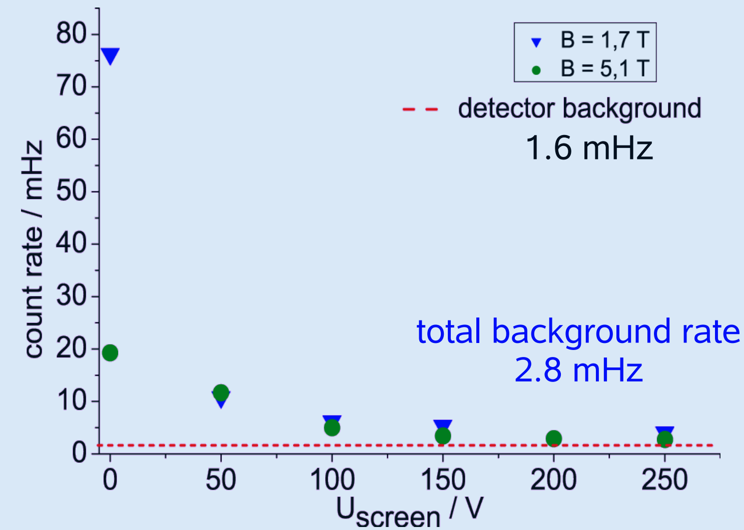


New record !
April 04



KATRIN pre spectrometer

Background suppression successfully tested at the Mainz MAC-E filter:



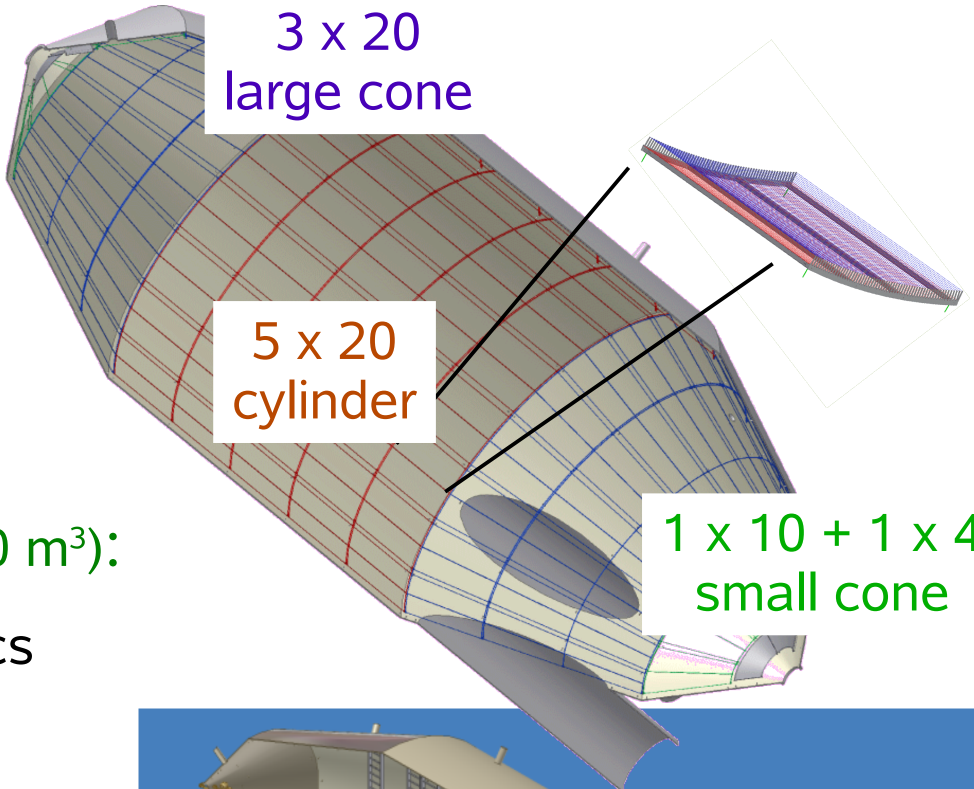
Dipl. thesis B. Ostrick (U Mainz, 2002),
PhD thesis B. Flatt (U Mainz, 2004)

Westfälische Wilhelms-Universität Münster

Concept for KATRIN: 690 m² surface: 2-layer wire modules

Two layers:

- to increase background shielding
- to increase electrical shielding
- to allow mechanical precision

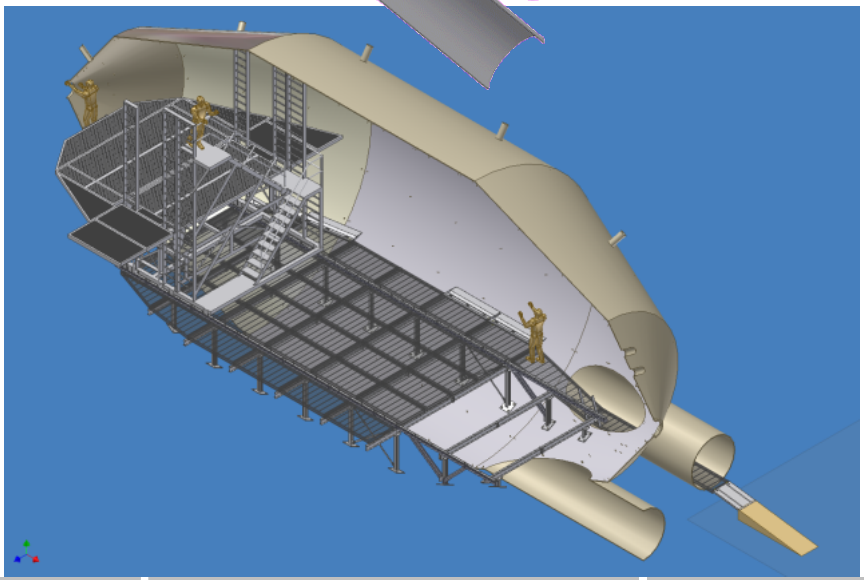


Wire electrode system of KATRIN main spectrometer (A=690 m², V=1240 m³):

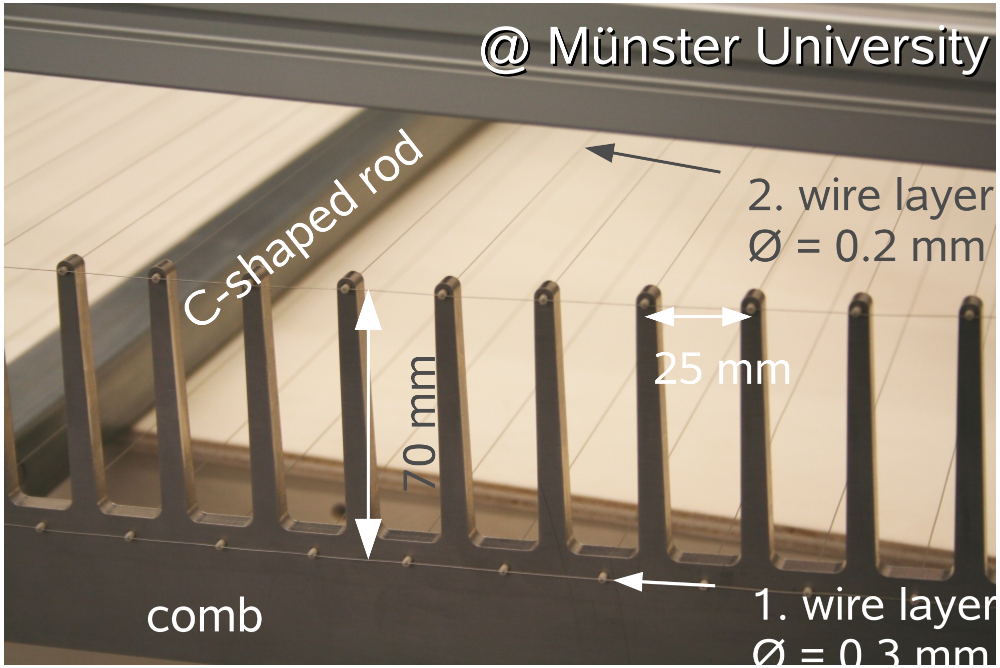
248 modules, 23120 wires, 46240 ceramics

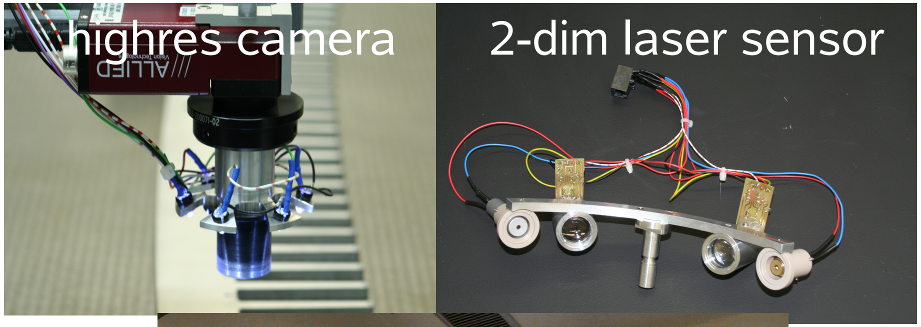
Technical requirements:

- modules have to withstand bake-out at 350°C
- module design needs to be compatible with UHV requirements (10^{-11} mbar)
- exact relative wire position (Δx = 200 µm)
- non-magnetic, non-radioactive, ...



Wire electrode design and mass production at Münster

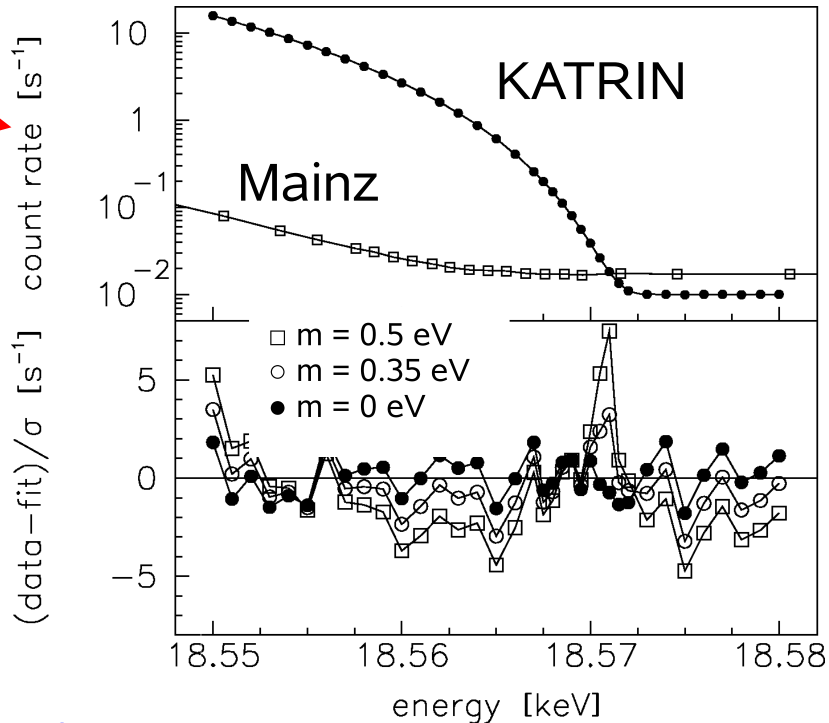


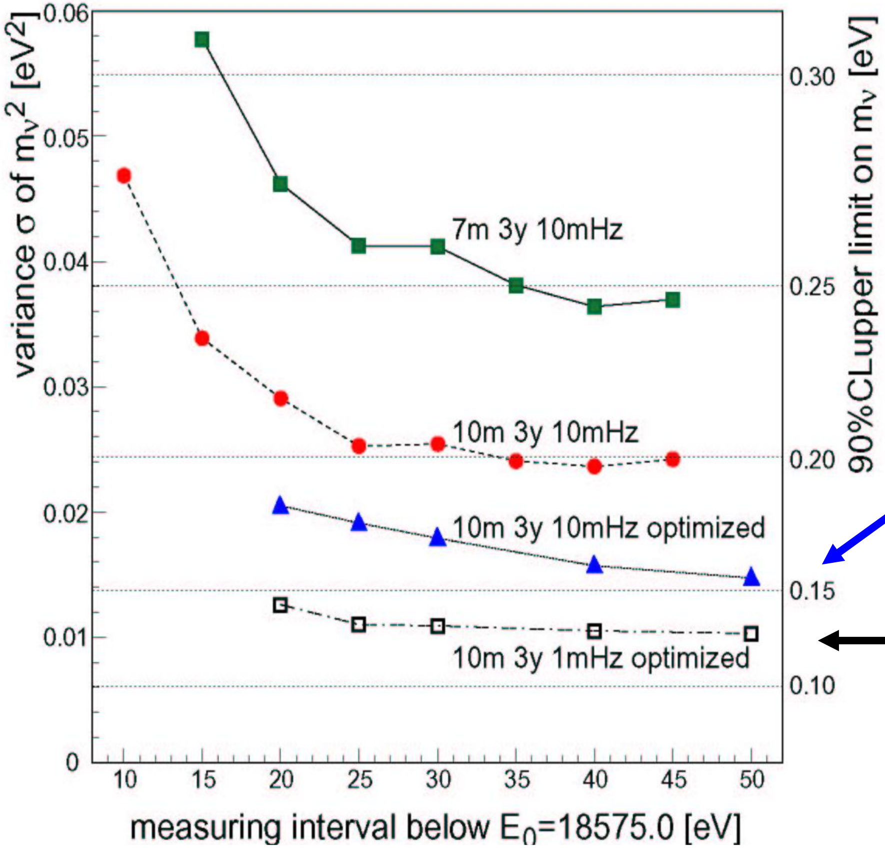


Electrode module installation: a flexible scaffold inside „cleanroom“

KATRIN´s statistical uncertainty

example of KATRIN simulation & fit
(last 25eV below endpoint, reference):





reference:
optimised measuring point distribution
expected background of 10mHz

further reduced background to 1mHz
is this possible ?

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

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 each: $\Delta m_\nu^2 \leq 0.007$ eV²

KATRIN's sensitivity

- large statistics
- high energy resolution
- low background
- small systematic uncertainties

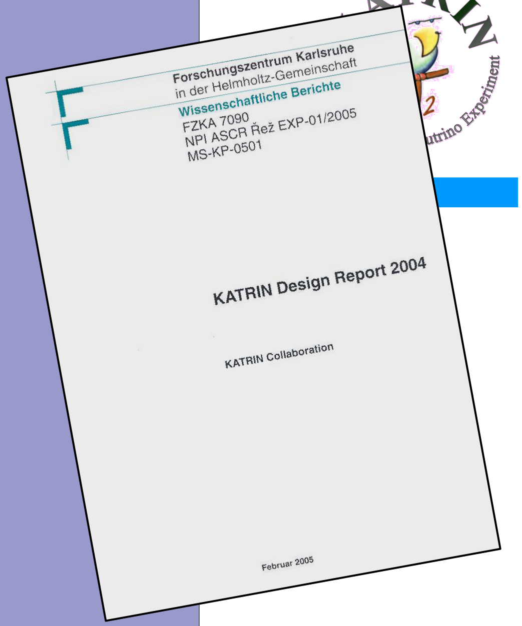
$\Rightarrow$ sensitivity on $m(\nu_e)$

$\approx$ 0.20 eV/c^2

(about equal contribution from stat. and syst. uncertainties)
(90% C.L. upper limit for $m(\nu_e) = 0$)

$m(\nu_e)$ = 0.30eV observable with 3σ

$m(\nu_e)$ = 0.35eV observable with 5σ


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

• Me

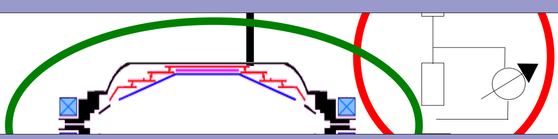
• Loc
ene

tritiun
or alt
cali
sc

ctor

ply

continuously
^{83m}Kr conversion
electron source:



precision
HV divider

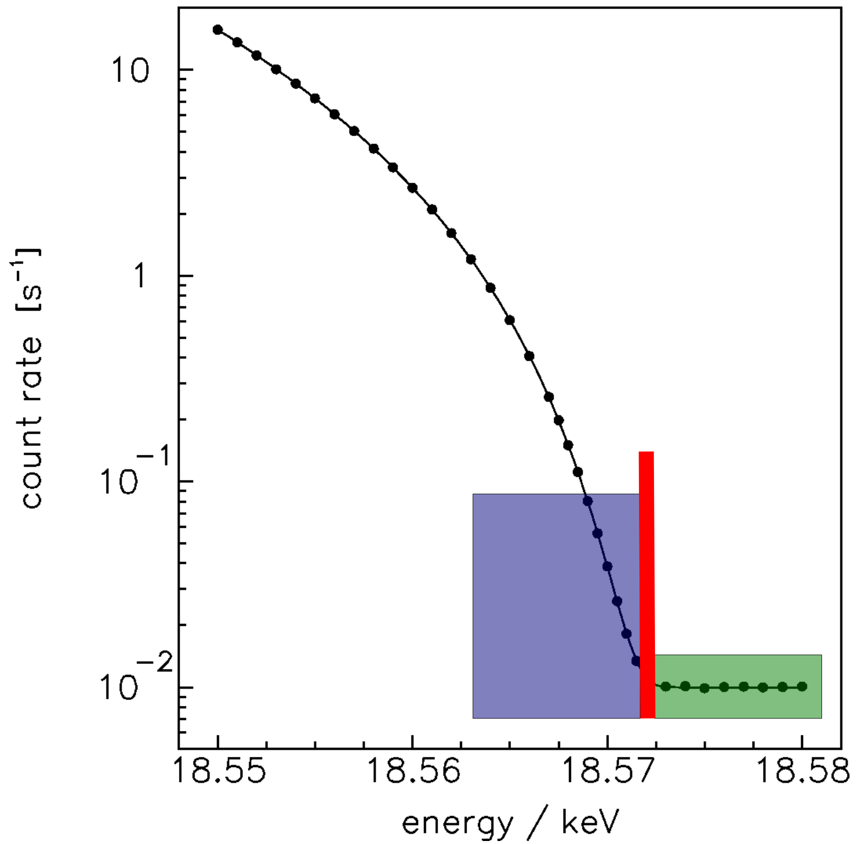
$\Rightarrow$ **KATRIN will improve the sensitivity by 1 order of magnitude**
will check the whole cosmological relevant mass range
will detect degenerate neutrinos (if they are degen.)

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Relic neutrino detection with KATRIN

$\nu_e + {}^3H \rightarrow {}^3He^+ + e^-$ has no threshold $\Rightarrow$ ideal reaction to detect relic n:eutrinos
(A.G. Cocco, G. Mangano and M. Messina, hep-ph/0703075)

Signature: monoenergetic electron at endpoint (at $E = E_0 + m_\nu$)



$\Rightarrow$ Need to distinguish from normal β electrons
and from experimental background

Relic neutrino detection with KATRIN

Capture rate of relic neutrinos for 100g T_2 (A.G. Cocco, G. Mangano and M. Messina, hep-ph/0703075):

Table 3. The number of NCB events per year for 100 g of ^{3}H, taking into account the effect of gravitational clustering in the neighborhood of the earth, compared to the case of a standard homogenous Fermi-Dirac distribution with $T_\nu = 1.7 \cdot 10^{-4}$ eV (FD). We show for some value of neutrino mass the results for a Navarro, Frenk and White profile (NFW) and for present day mass distribution of the Milky Way (MW), using the local neutrino densities computed in [36].

m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yrs^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

100 g tritium corresponds to $1*10^{25}$ T_2 molecules, they yield about 10 events/year !

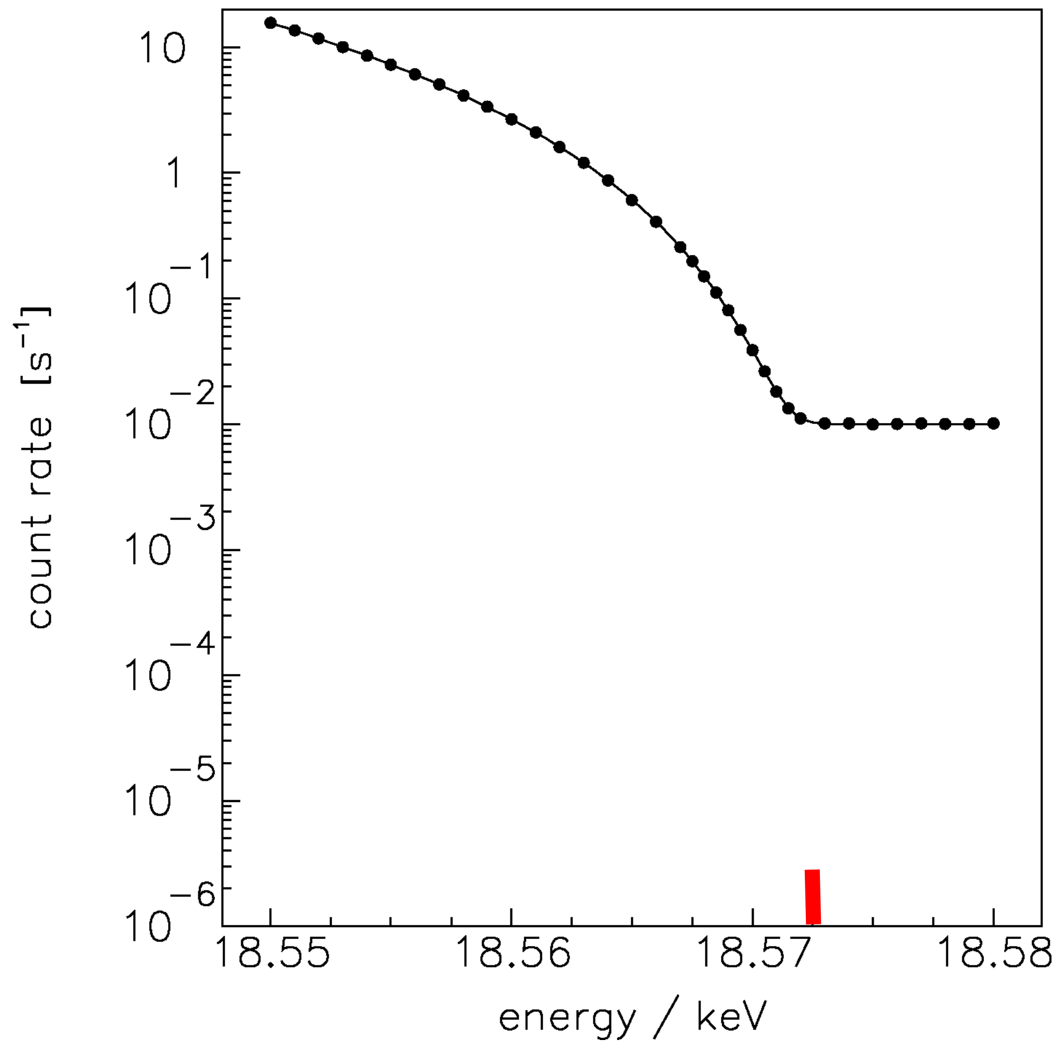
But KATRIN has a column density of $5*10^{17}$ molecules/cm^2 and
a cross section of A= 53 cm^2 $\Rightarrow$ $2.65 * 10^{19}$ T2 molecules

Taken into account the acceptance of the KATRIN spectrometer there are effectively
$5 * 10^{18}$ T_2 molecules, which are $2 * 10^6$ less than 100 g!

$\Rightarrow$ Expected rate is more like $5 * 10^{-6}$ events/year ! (completely hopeless)

Relic neutrino detection with KATRIN

⇒ Expected rate is more like 5 * 10^{-6} events/year !



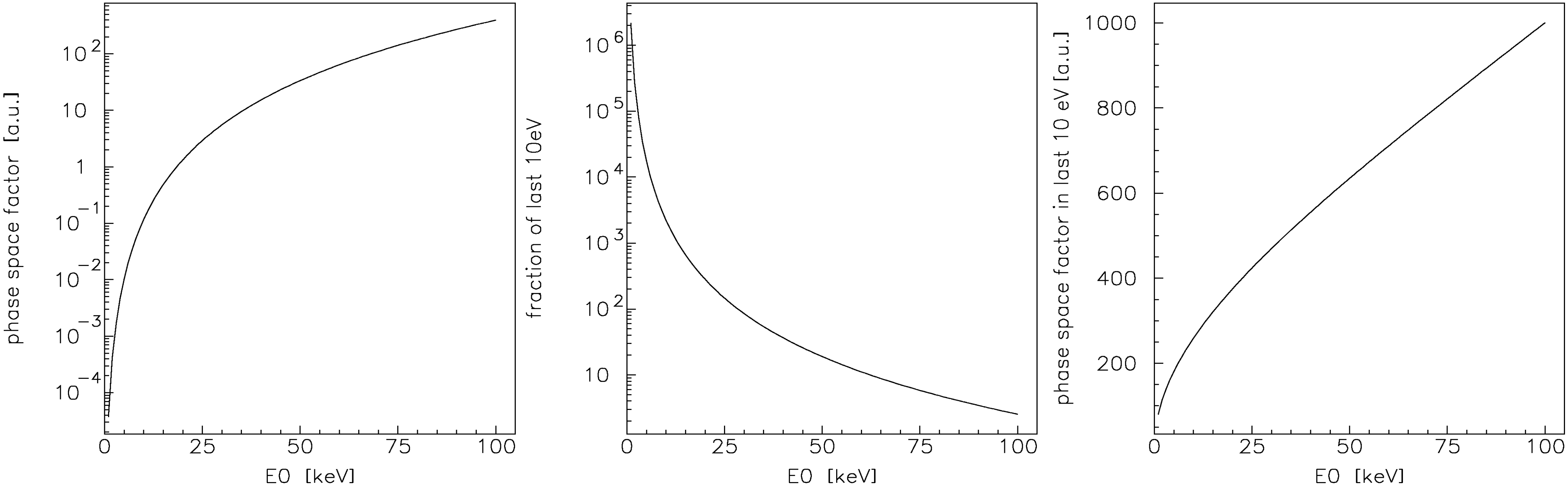
(completely hopeless, if not
much higher relic neutrino density
or
non-standard cross section)

Optimal „Q-value" E_0: count rate in last 10eV below endpoint E_0

total count rate per atom: $\Gamma \sim E_0^4$ (E_0^5) for low (high) E_0 (for super-allowed decay)

relative fraction in last 10 eV below E_0

total count rate per atom in last 10 eV below E_0



⇒ count rate per atom in last 10 eV is nearly independent on Q-value E_0: choice of β-emitter does not help much for relic ν detection !

Usually the choice depends on:
- systematics (e.g. low Z),
- feasibility (low energy for achieving ΔE)
- background by low energy electrons

Status & Outlook

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

2008/09 - mounting of inner electrode, source demonstrator on-site,
- start of el. mag. and background test of pre and main spectrometer

2011/12 - commissioning of WGTS, tritium loops, system integration,
- study of systematic effects
- first test runs with tritium
- regular data taking for 5-6 years (3 full-beam-years)

KATRIN is at present the ultimate tritium experiments,
no hope to detect "standard" relic neutrinos

KATRIN collaboration of 2007

bmb+f - Förderschwerpunkt Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung