Westfälische Wilhelms-Universität Münster

The Karlsruhe Tritium Neutrino experiment KATRIN

KATRIN Karlsruhe Tritium Neutrino Experiment

Workshop on Precision Measurements at Low Energy, PSI, Switzerland, January 18&19, 2007

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- The neutrino mass quest
- The Karlsruhe TRItium Neutrino experiment KATRIN
- KATRIN´s background suppression, statistics & systematics
- Summary

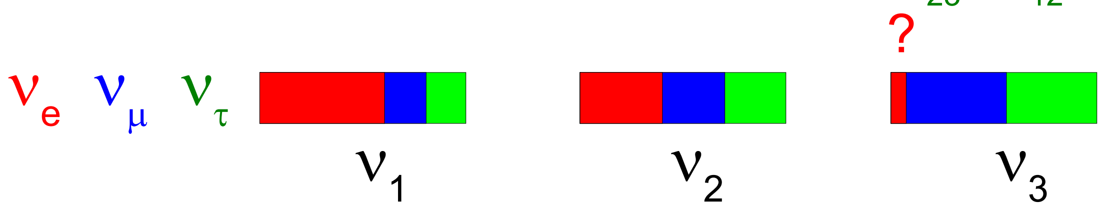
bmb+f - Förderschwerpunkt

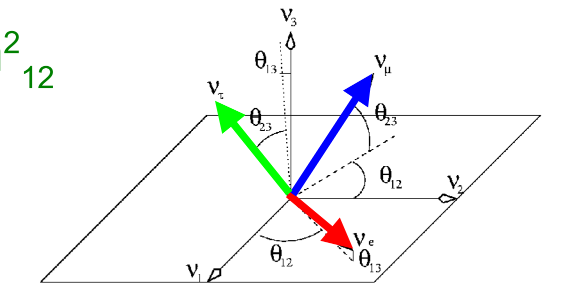
Astroteilchenphysik

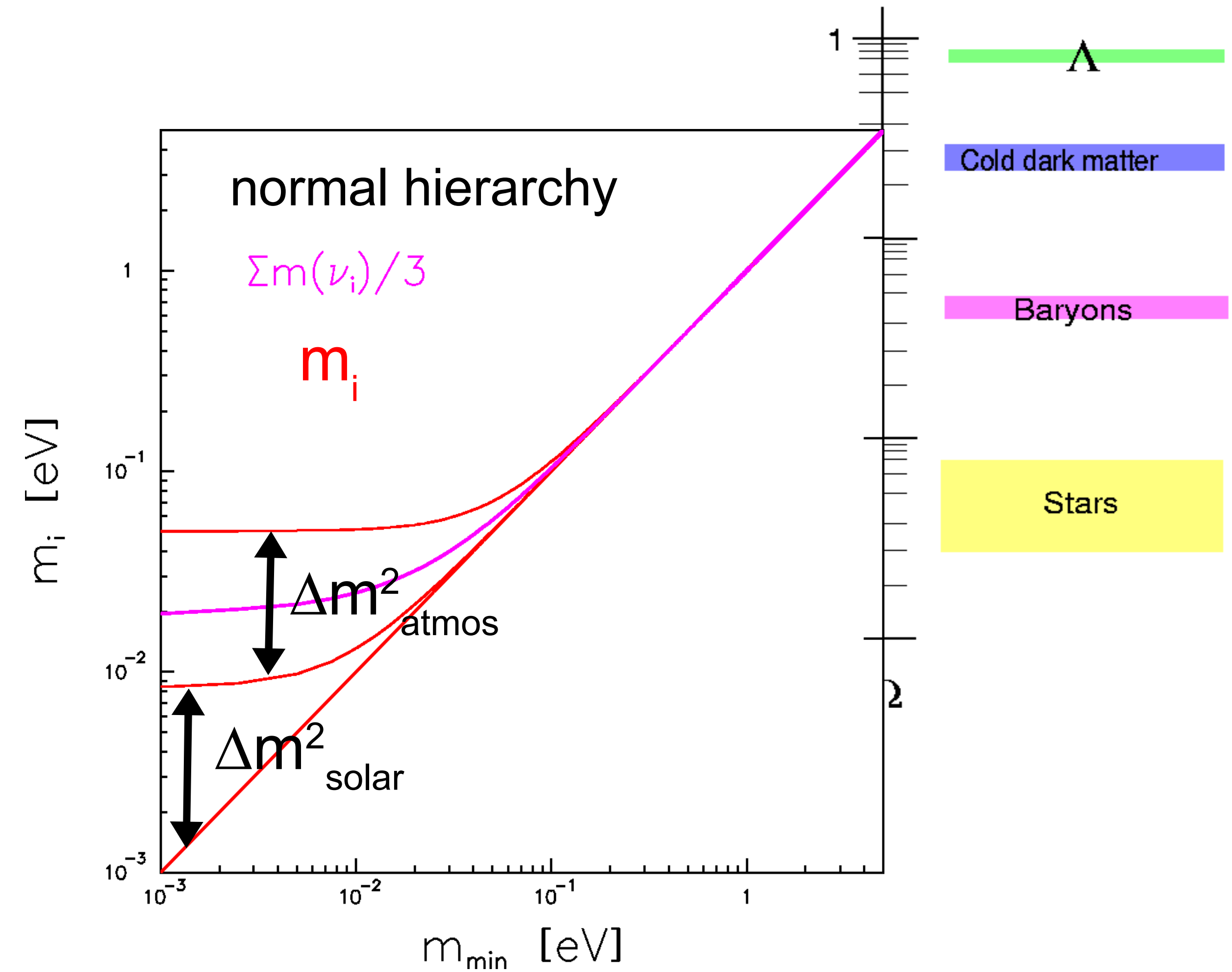
Großgeräte der physikalischen Grundlagenforschung

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

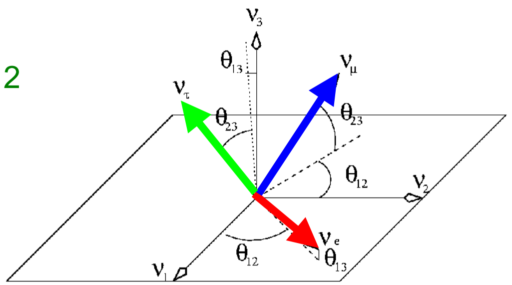
explains smallness of masses, but not mixing

Need for the absolute ν mass determination

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

?

ν_e ν_μ ν_τ — ν_1, ν_2, ν_3



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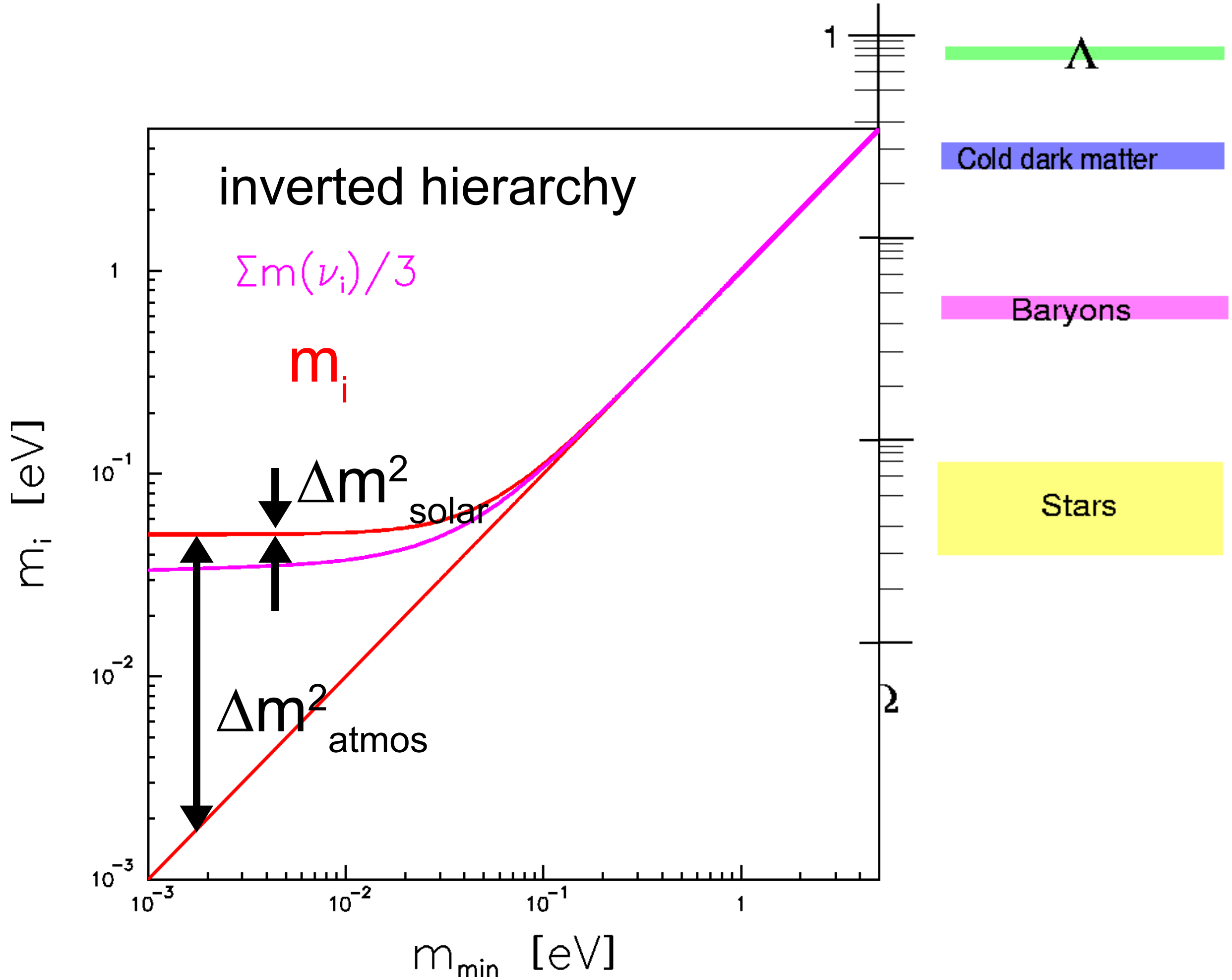

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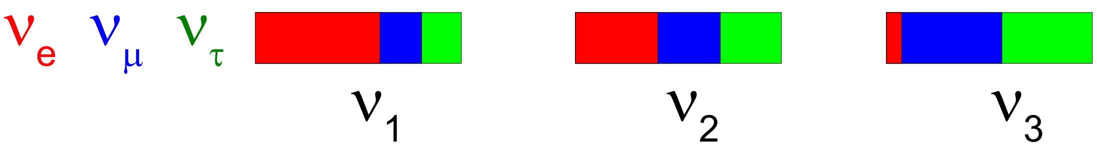
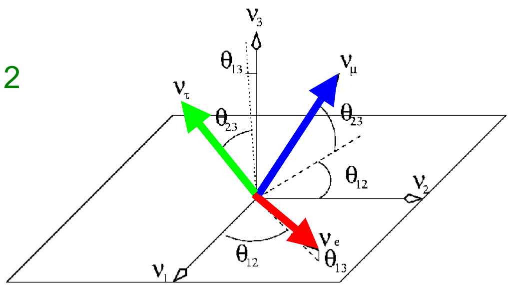
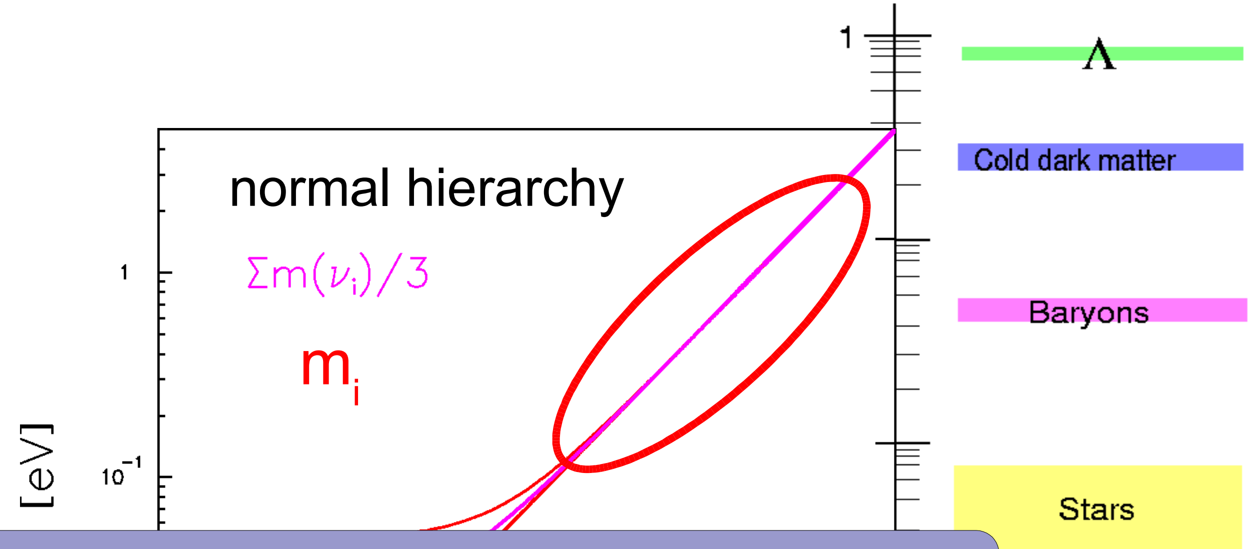




degenerated masses

cosmological relevant

e.g. seesaw mechanism type 2



hierarch

e.g. seesaw

explains sma

but

Investigate high mass region ⇒

a) distinguish hierarchical and degenerate masses

(→ theory beyond SM)

b) check cosmological relevance

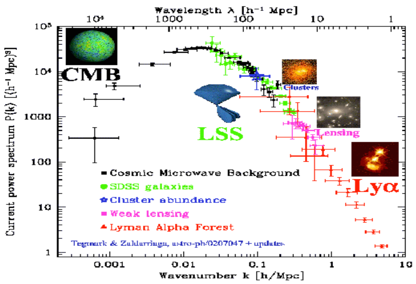
(→ ν hot Dark Matter)

Search for the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

current sensitivity: $\Sigma m(\nu_i) \approx 1$eV



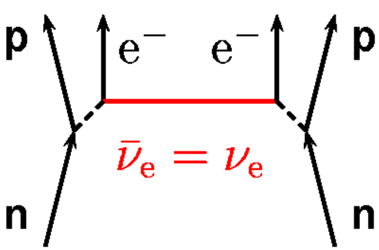
2) Search for 0νββ

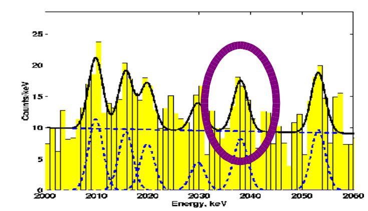
very sensitive, but needs ν to be of Majorana-type

sensitive to coherent sum: $m_{ee}(\nu) = |\, \Sigma\, |U_{ei}{}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$

$\Rightarrow$ partial cancelation possible

Evidence for $m_{ee}(\nu) \approx 0.4$ eV (Klapdor-Kleingrothaus et al.)?





3) Direct neutrino mass determination:

No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$

- **Time-of-flight measurements** (ν from supernova)

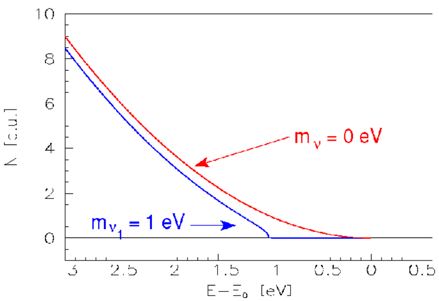
  SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV (PDG 2003)

- **Kinematics of weak decays**

  measure charged decay prod., energy/momentum conserv. $\Rightarrow m^2(\nu)$

  β-decay searchs for $m(\nu_e)$ - tritium β decay spectrometers

  \- ^{187}Re bolometers



3 complementary ways to the absolute ν mass scale

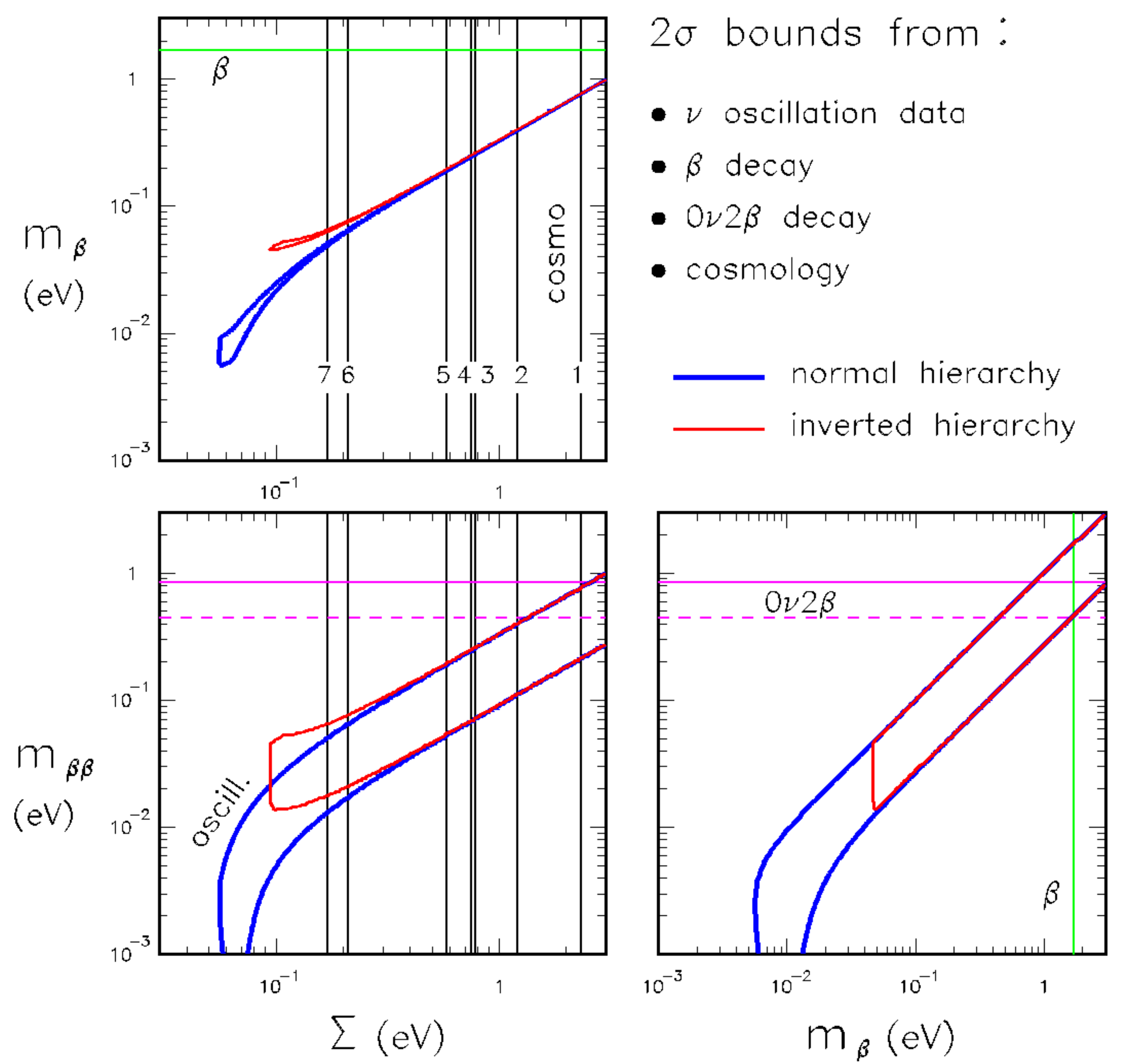
1) cosmology:
very sensitive $\Sigma m(\nu_i)$
but model dependent

2) $0\nu\beta\beta$:
evidence?
Majorana neutrinos

$$m_{ee}(\nu) = |\Sigma |U_{ei}^2| e^{i\alpha(i)} m(\nu_i)|$$

3) direct neutrino mass determination:
no further assumptions
no cancellations:

$$m^2(\nu_e) = \Sigma |U_{ei}^2| m^2(\nu_i)$$



Fogli et al., hep-ph/0608060

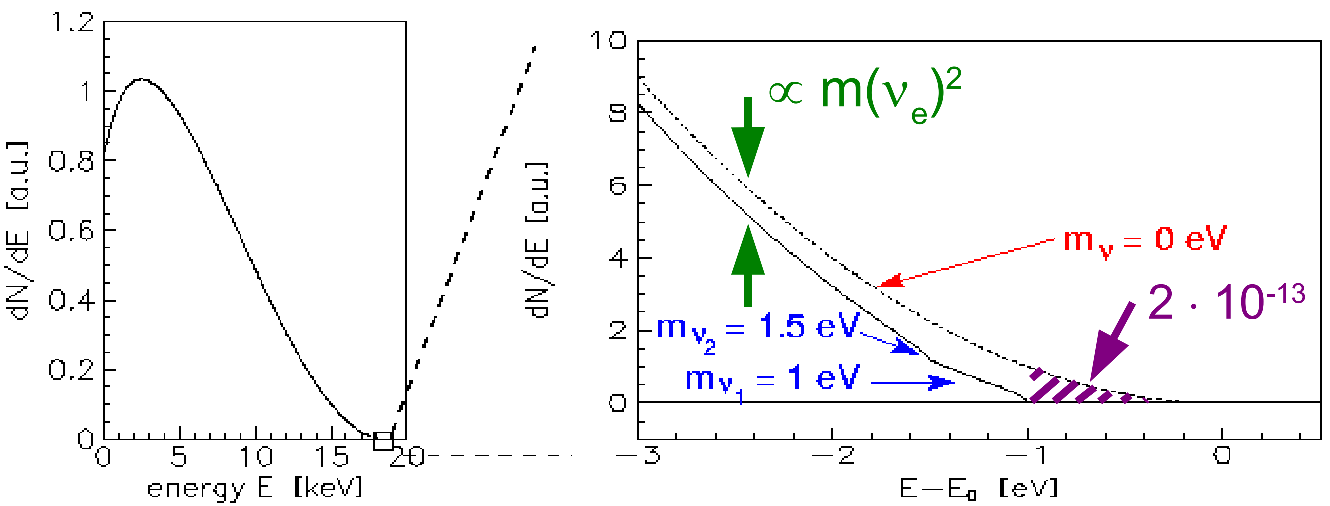
Direct determination of $m(\nu_e)$ from β decay

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

β electron energy spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma\, |U_{ei}|^2 [\, (E_0-E_e)^2 - \mathbf{m(\nu_i)^2}\,]^{1/2}$$

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



oscillation exp: small Δm_{ij}^2

$\Rightarrow$ see only average neutrino mass squared:

$m(\nu_e)^2 := \Sigma\, |U_{ei}|^2\, \mathbf{m(\nu_i)^2}$

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

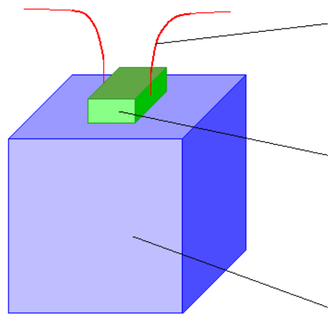
very high energy resolution &
very high luminosity &
very low background
} $\Rightarrow$ **MAC-E-Filter** **(or bolometer for ^{187}Re)**

Cryo bolometer experiments with ^{187}Re

Multiple purpose, scalable new detector technology

basic idea: β emitting crystal = cryodetector

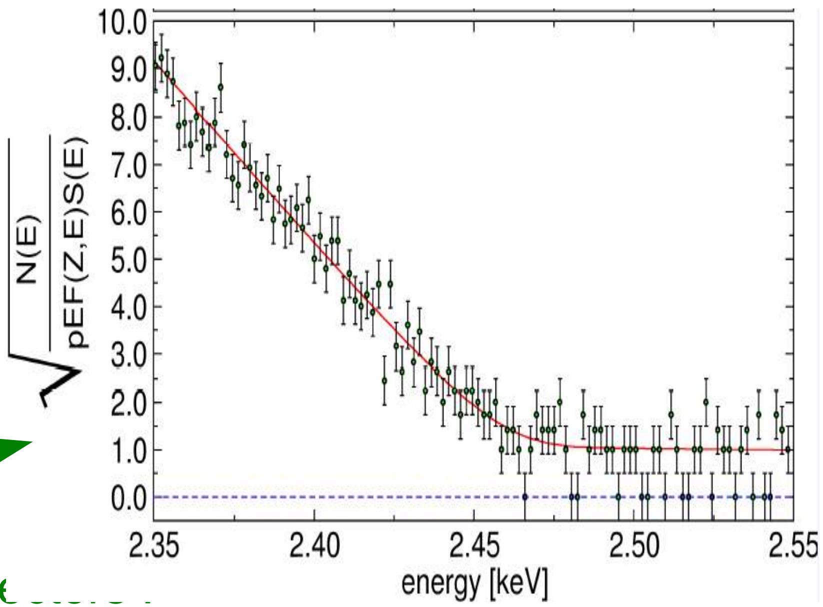
⇒ single final state: detection of total energy except ν



Choice of β emitter: ^{187}Re: E_0 = 2.47 keV ($t_{1/2}$ = 4.3 10^{10}y)

MANU2 (F. Gatti et al., Genua)

- Re metalic crystal (1.5 mg)
- BEFS observed (F.Gatti et al., Nature 397 (1999) 137)
- sensitivity:
  now: m(ν) < 26 eV (.F.Gatti, Nucl. Phys. B91 (2001) 293)
  future: eV resolution by s.c. transition sensors.
  (now typically: ΔE = 30 eV)



MiBeta (E. Fiorini et al., Mailand,Como)

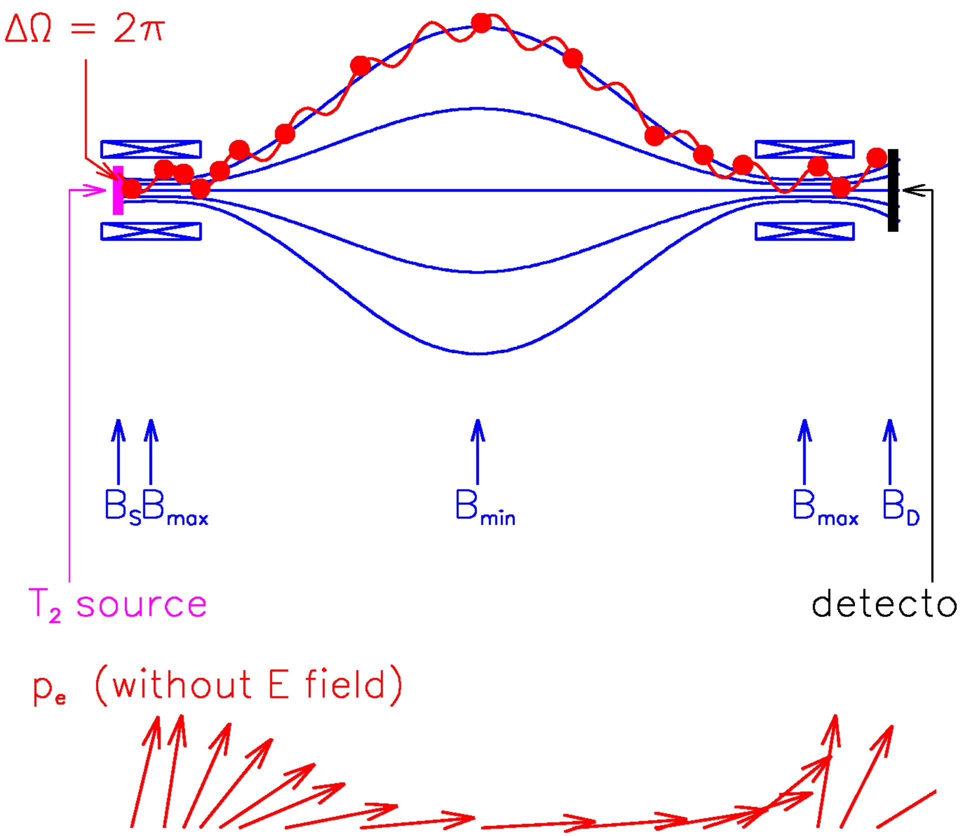
- $AgReO_4$ (10 * 250 -350 mg)
- Final result of Mibeta after 1 year data taking with 10 dete...
  (M. Sisti et al., NIMA520 (2004) 125)
  $m_\nu^2 = -112 \pm 207 \pm 90$ eV^2 ⇒ **m_ν < 15 eV (90%CL)**

„Common future: MARE I: sensitivity 2-3 eV expected by 300 detectors
MARE II: better DE, Dt, 50000 detectors: sub-eV sensitivity

Principle of the MAC-E-Filter

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



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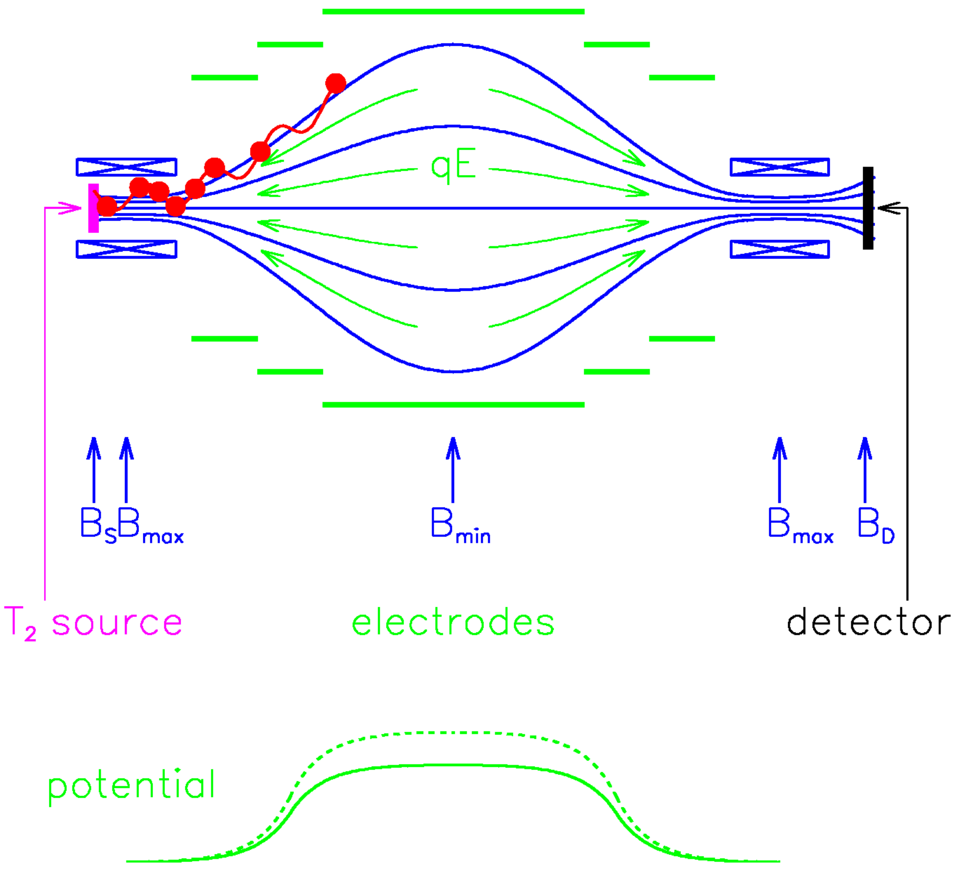
- adiabatic transformation: $\mu = E_\perp / B = \text{const.}$
  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max} = E \cdot A_{s,eff}/A_{analyse}$ ≈ 4.8 eV (Mainz) = 0.93 eV (KATRIN)



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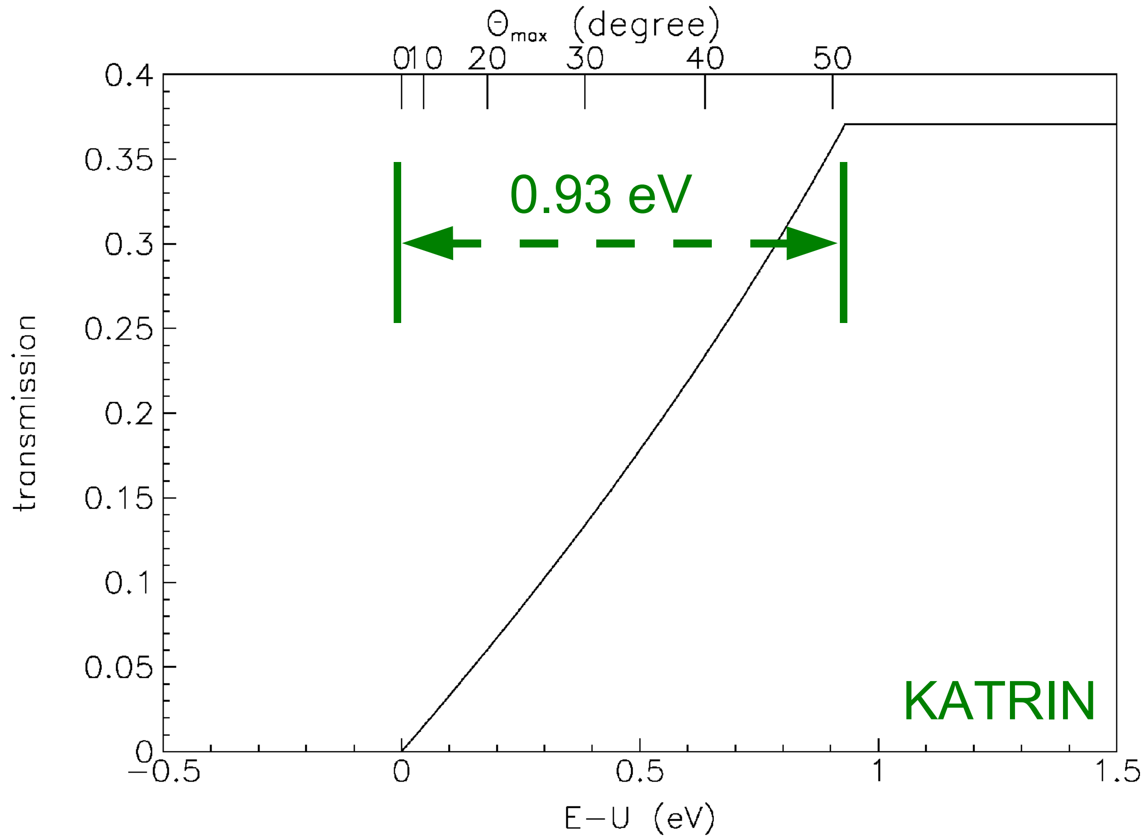
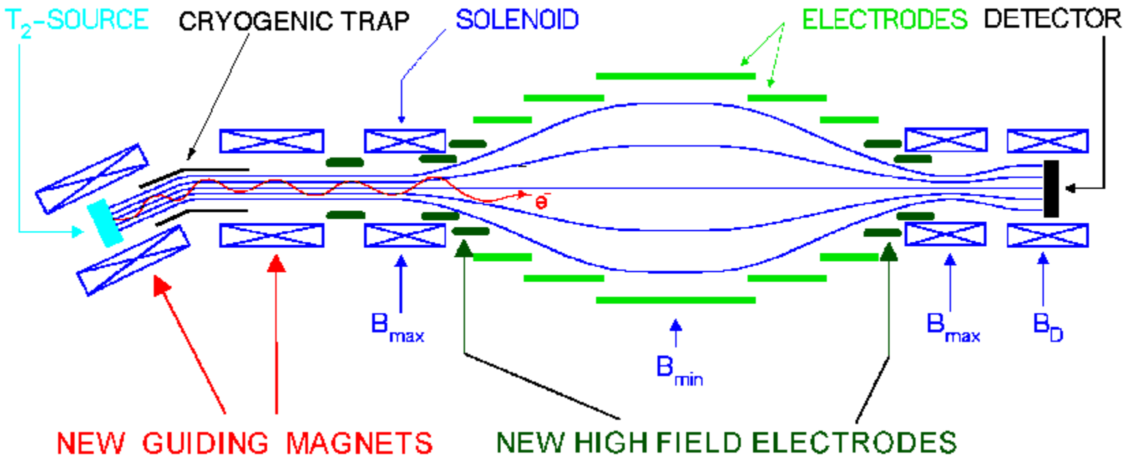
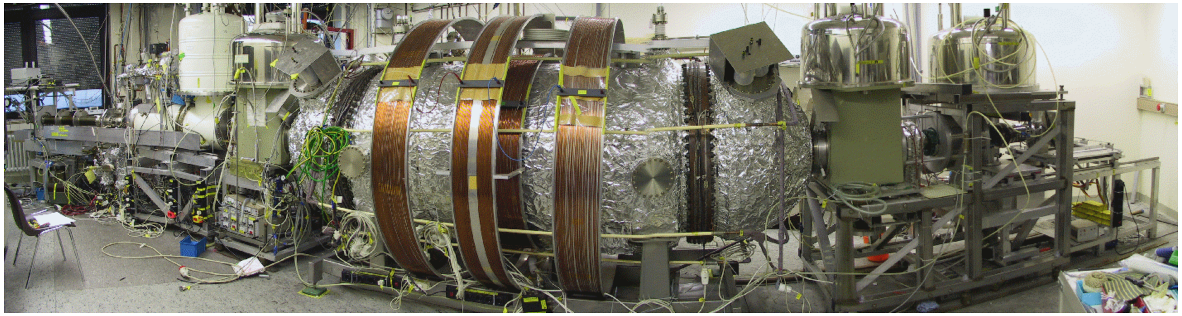


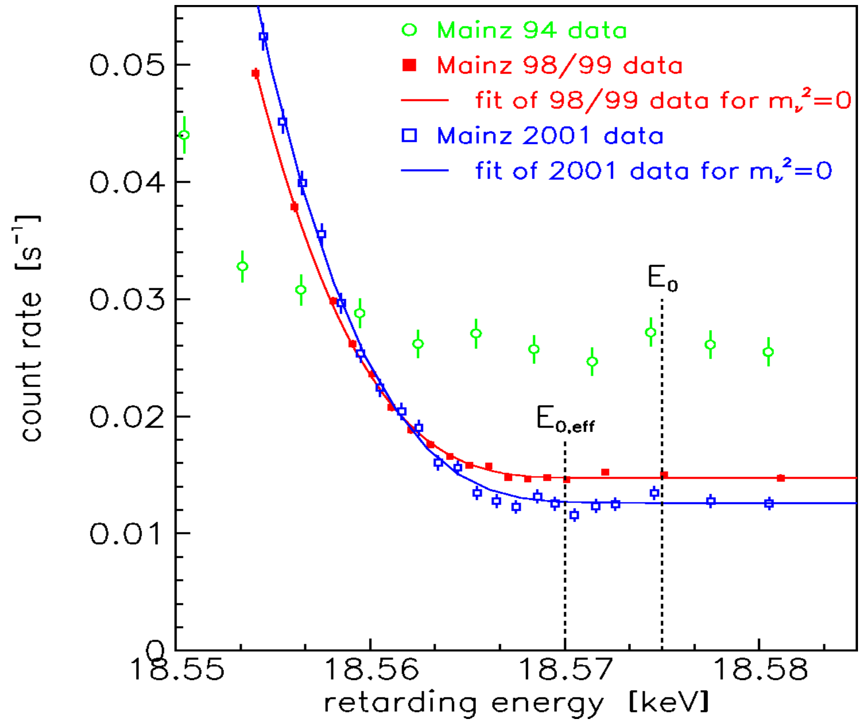
⇒ sharp integrating transmission function without tails:

$\Delta E = E \cdot B_{min}/B_{max} = E \cdot A_{s,eff}/A_{analyse} = 0.93$ eV, KATRIN (4.8 eV, Mainz)

The Mainz Neutrino Mass Experiment Phase 2: 1997-2001







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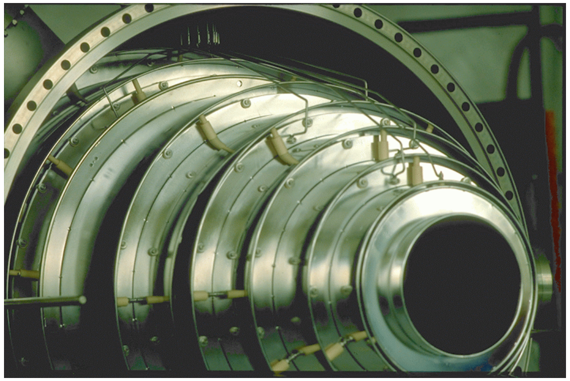


After all critical systematics measured by own experiment (inelastic scattering, self-charging, neighbor excitation):

$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ eV^2 \Rightarrow m(\nu) < 2.3\ eV$ (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

The Karlsruhe Tritium Neutrino experiment KATRIN

is being set up at the Forschungszentrum Karlsruhe

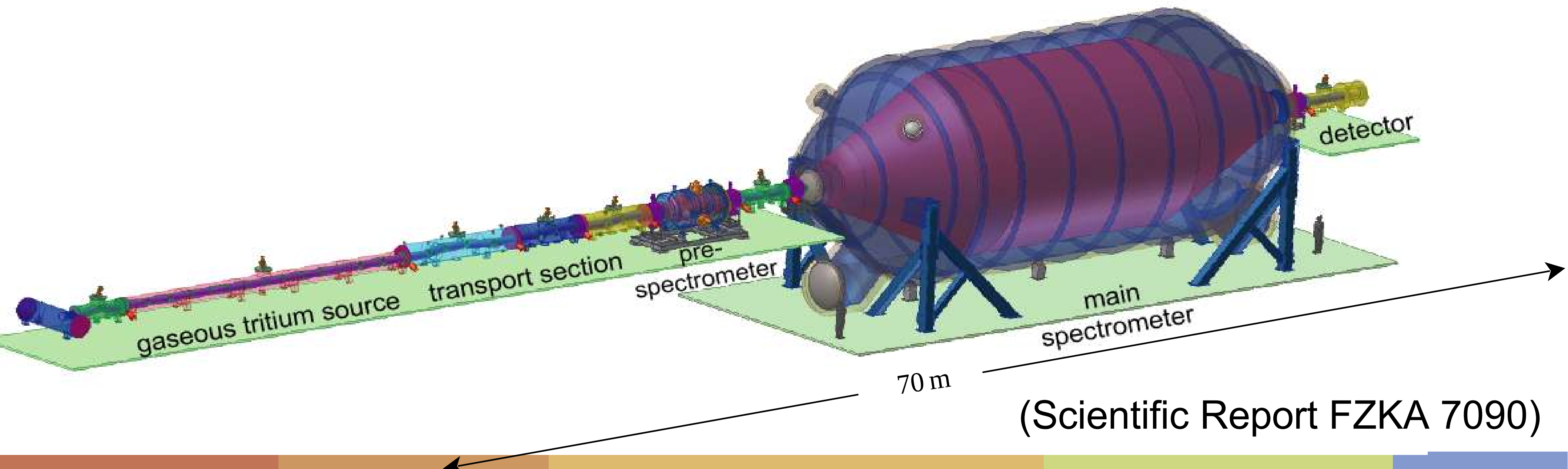
Physics Aim:

Improvement of sensitivity by 1 order of magnitude: 2.2 eV $\rightarrow$ 0.2 eV

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

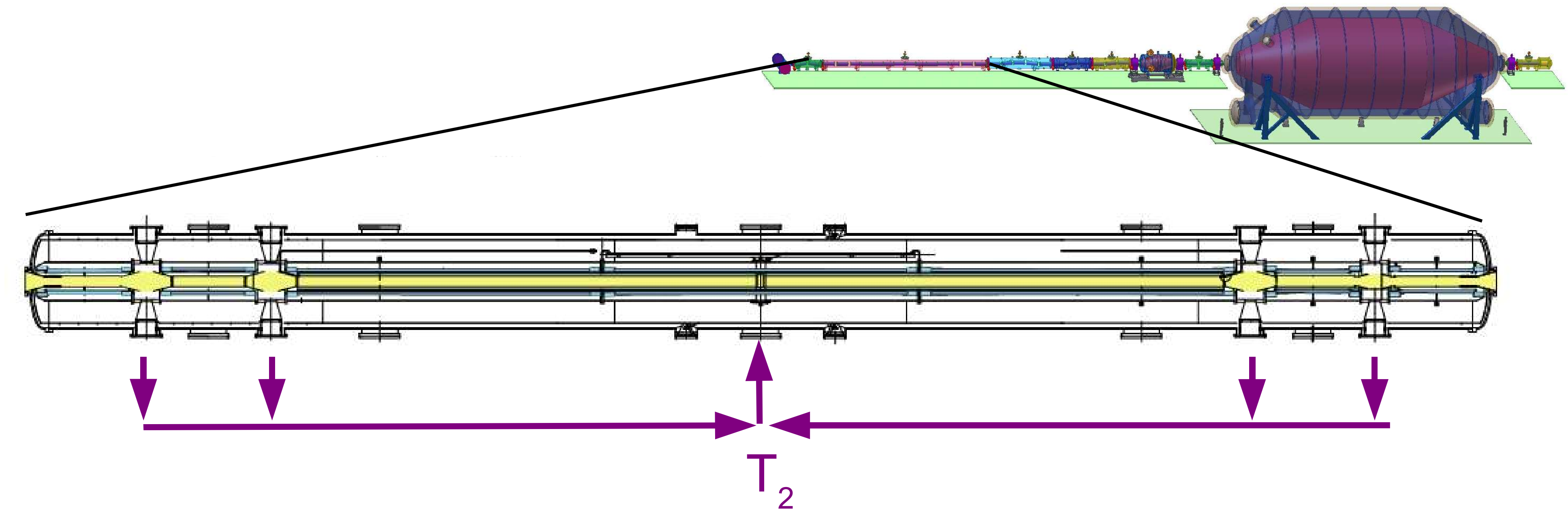
} $\varnothing$10m

- 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

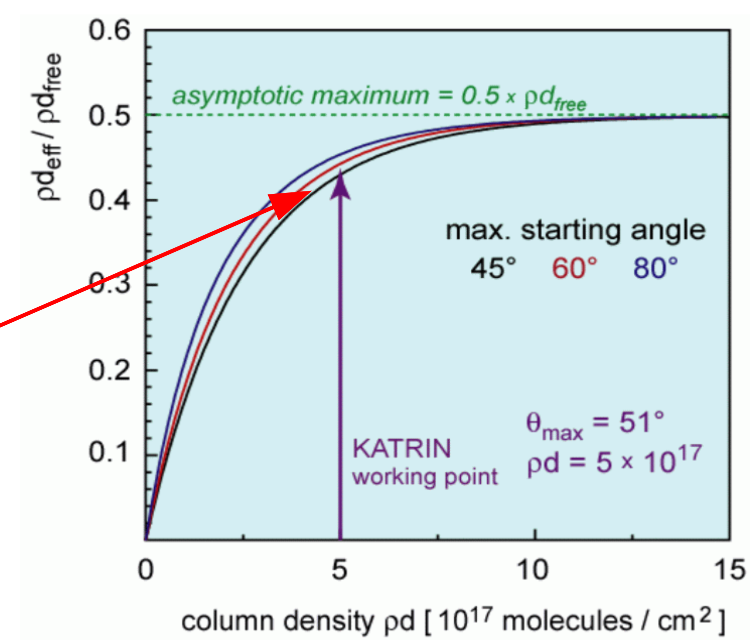
Tritium recirculation (and purification)

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



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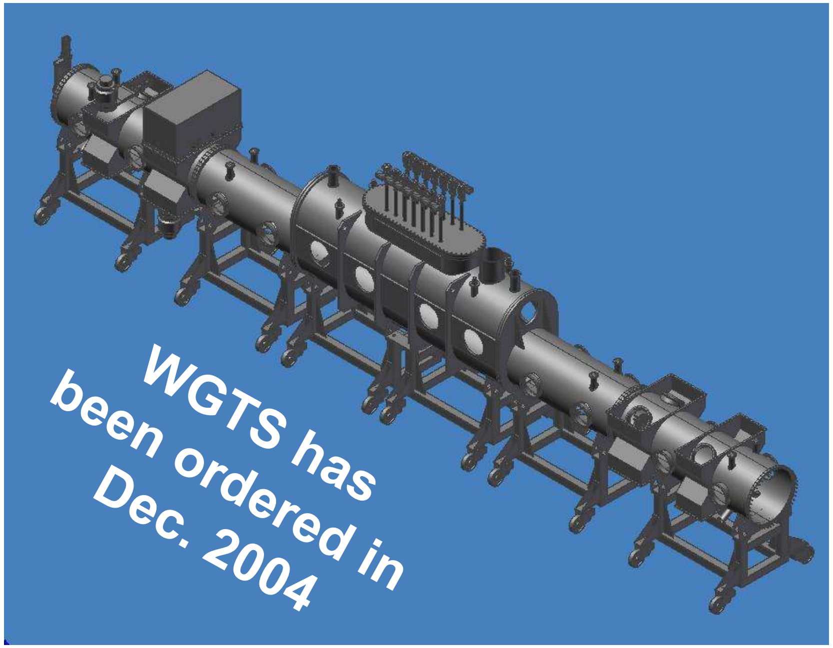
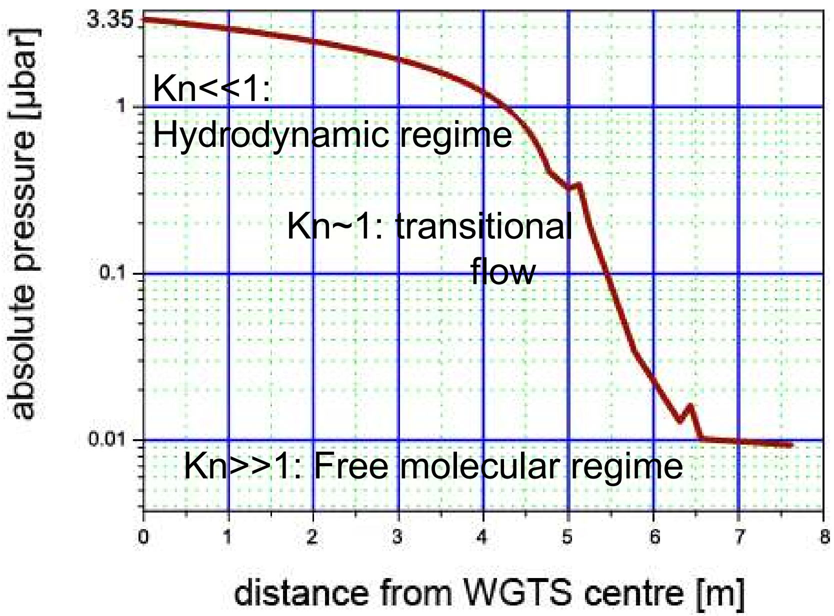
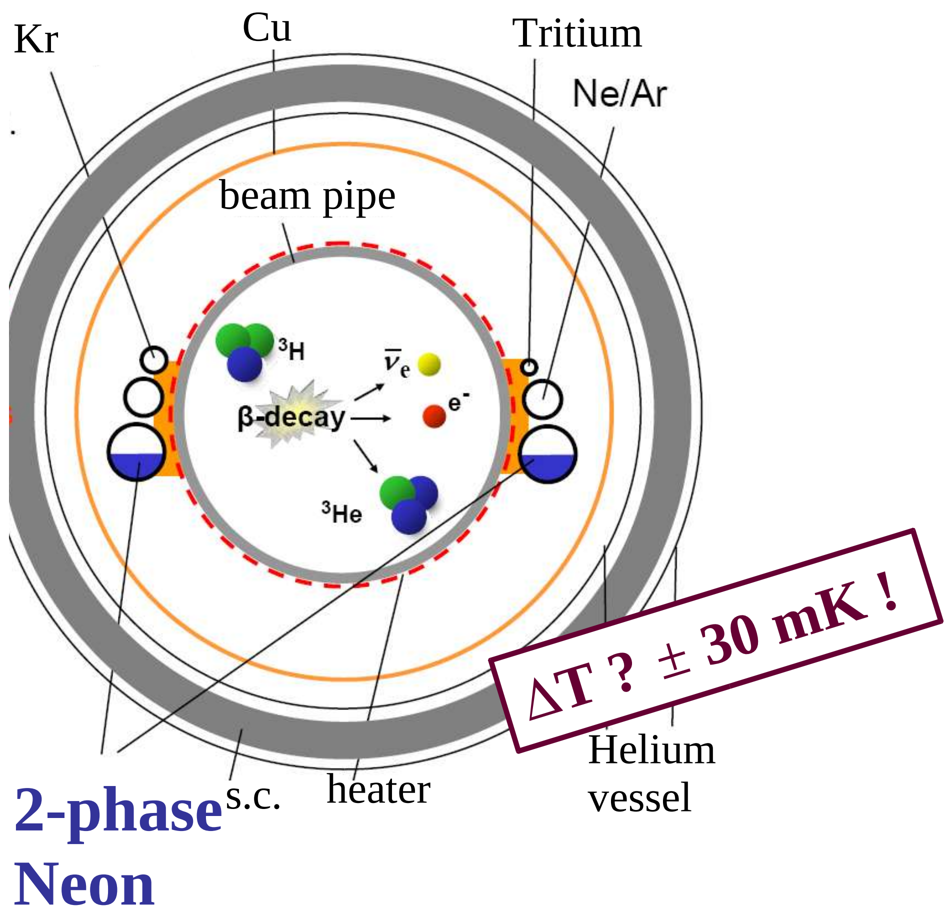




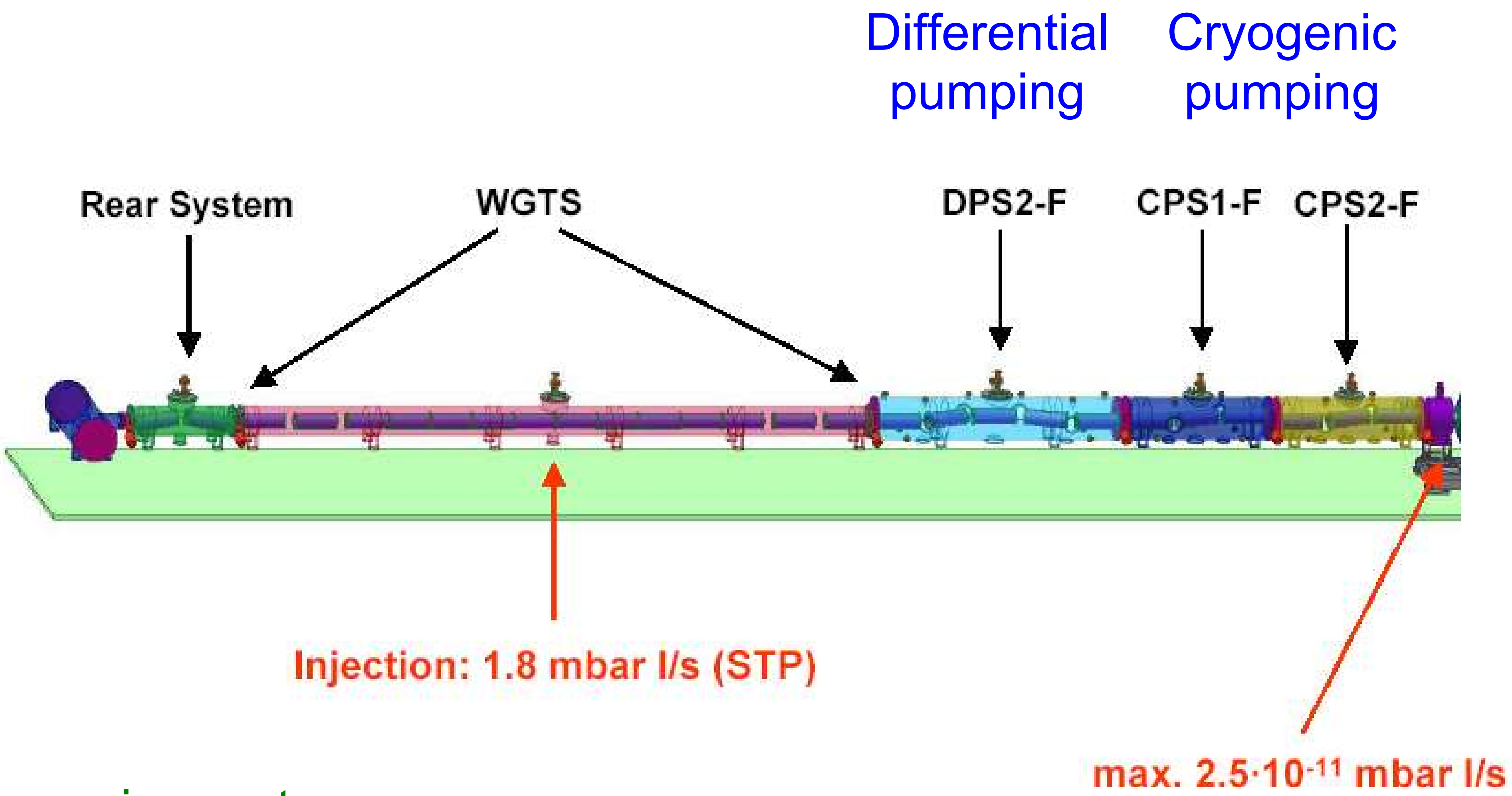
Conceptional design

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

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



Transport and differential & cryo pumping sections



requirements:

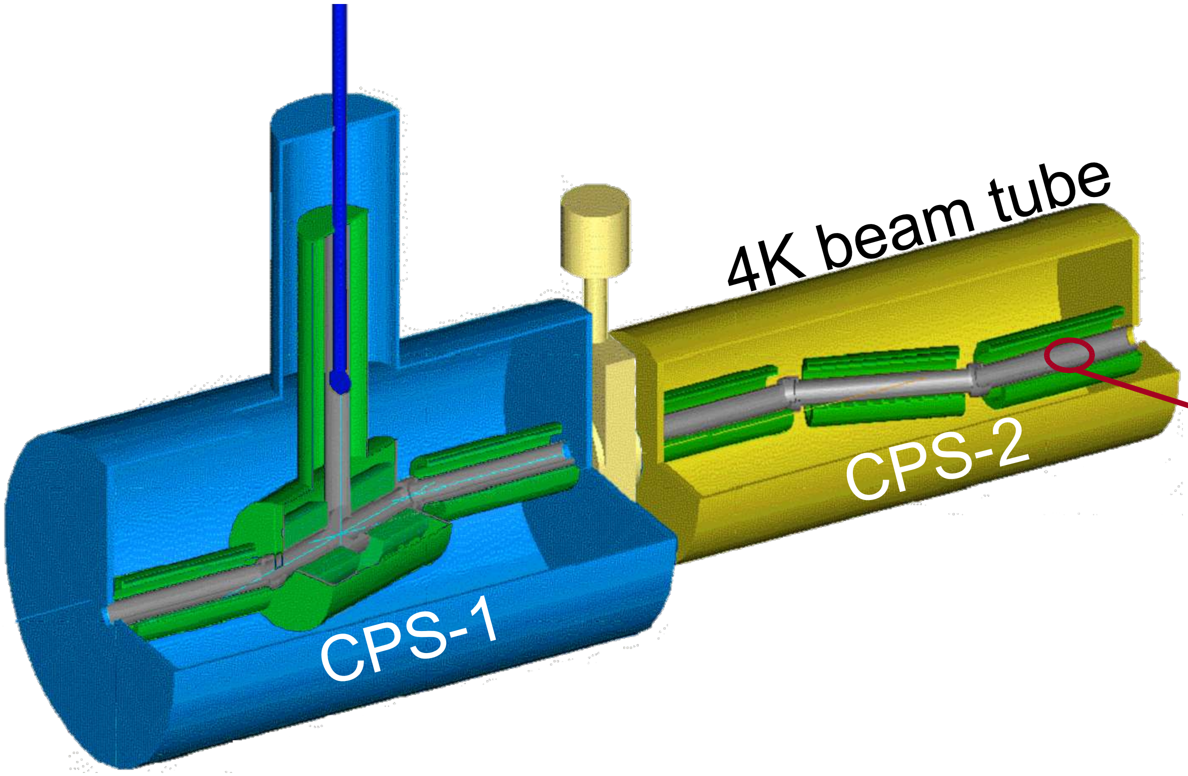
- adiabatic electron guiding
- T_2 reduction factor of ~10^{11}

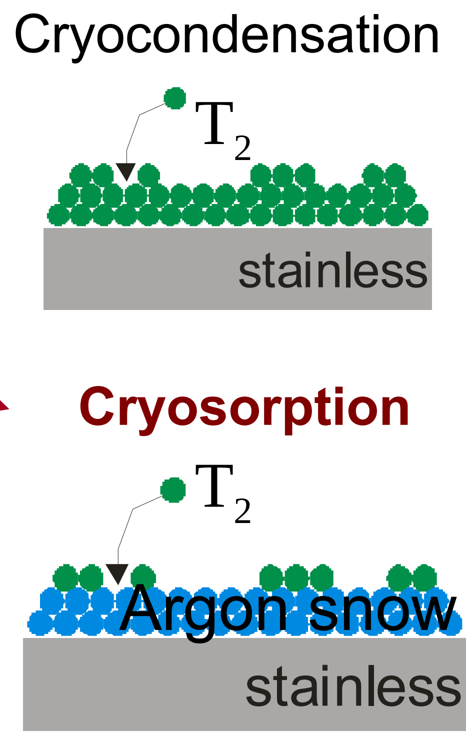
Cryogenic pumping section

Objective: retention of remaining tritium flux
tritium partial pressure spectrometer $p < 10^{-20}$ mbar

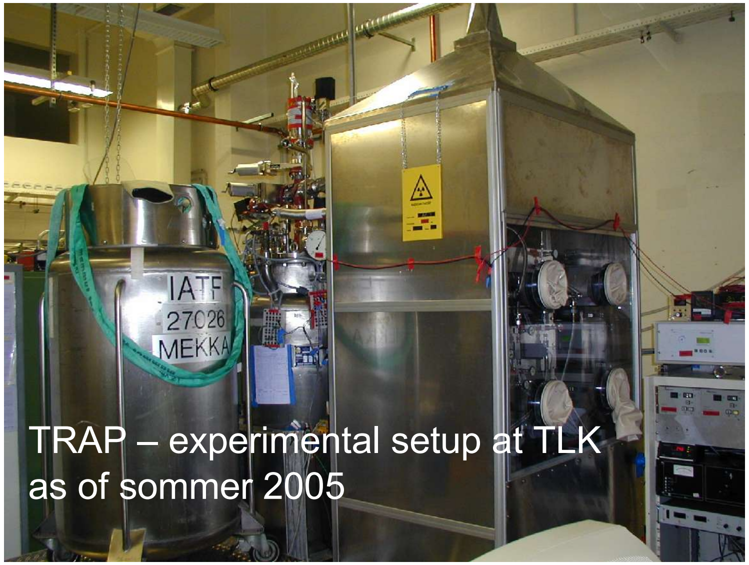
method: cryo-sorption on condensing Ar-frost

rate: <1 Ci T_2 in 60 days (regeneration with warm He-gas)





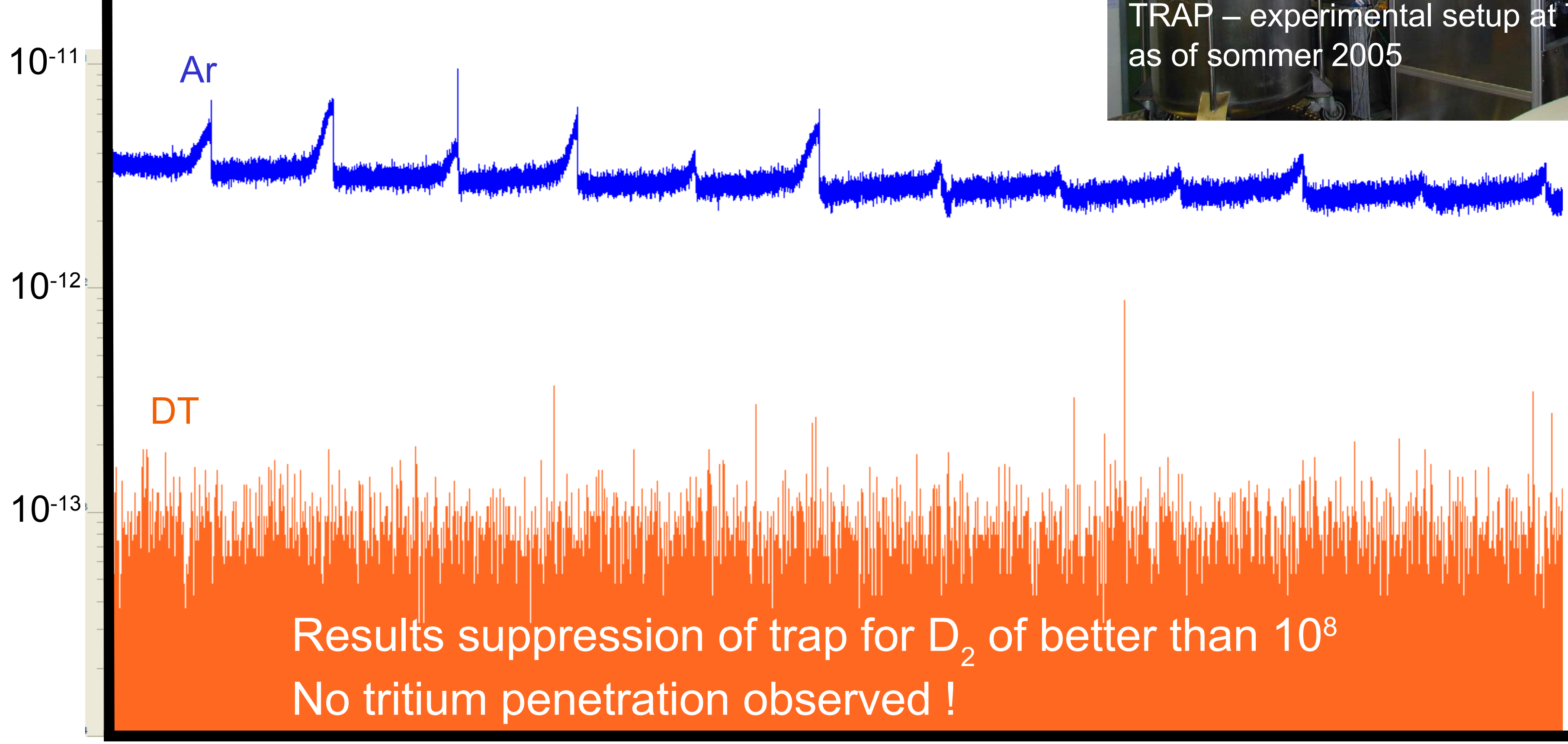
TRAP - TRitium Argon Frost Pump at FZK

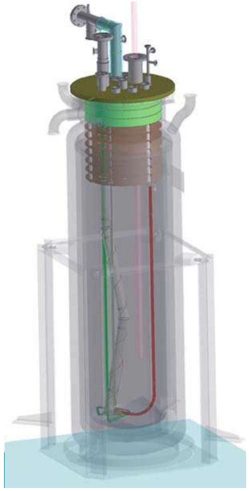


Inlet flow rate: ≈ 10^{-6} mbar l/s

Isotopic composition (CAPER-GC):

HT: 7%	**T_2: 19%**
DT: 43%	**H_2,D_2,HD: 31%**





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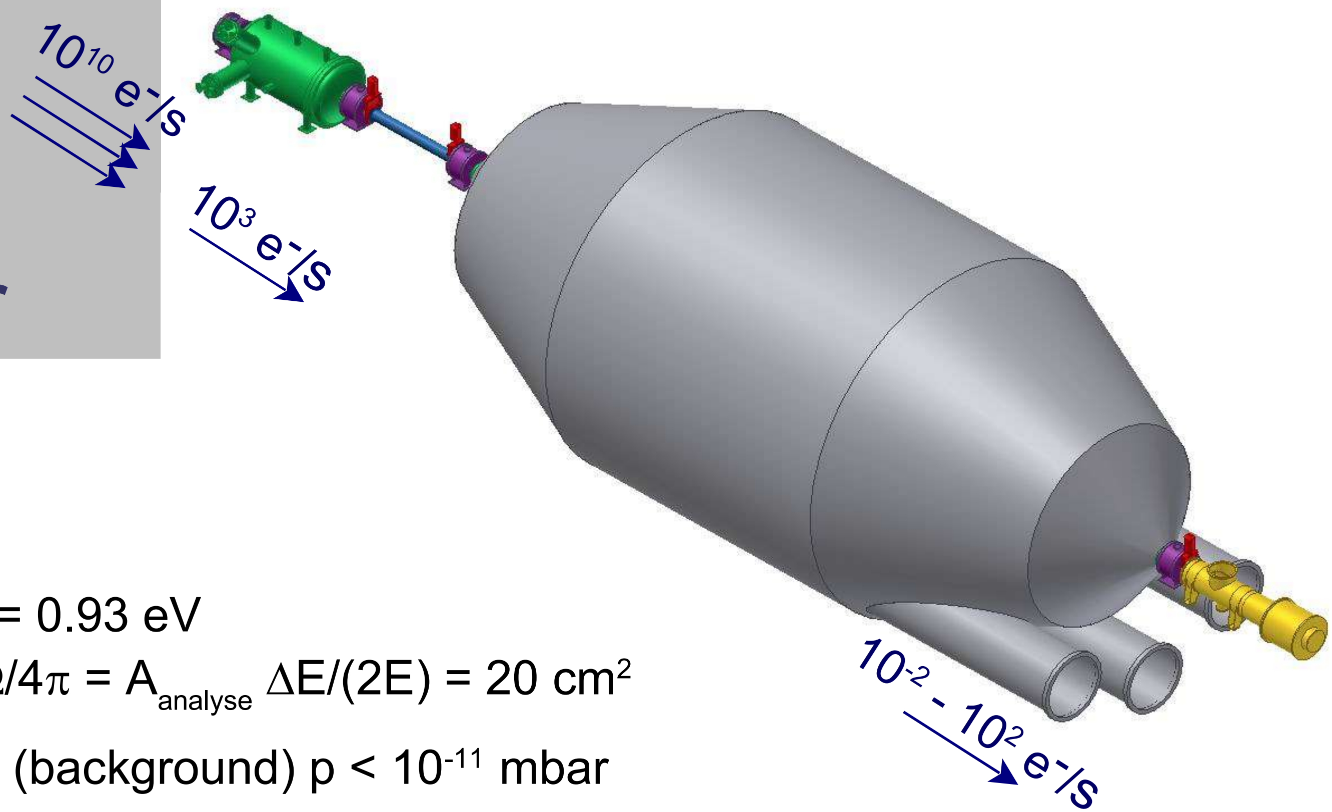
Pre and main spectrometer



Main spectrometer:

- ∅10m, length 24m
  ⇒ large energy resolution: $\Delta E = 0.93$ 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
- „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: $\Delta E = 80$ eV
- test of new ideas (XHV, shape of electrodes, avoid and remove of trapped particles, ...)

Detector

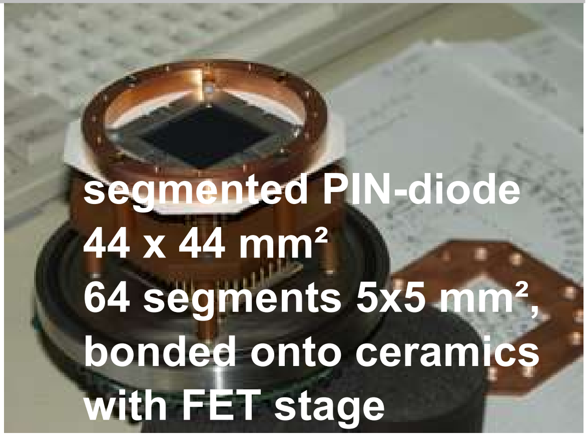
task: detection of transmitted ß-decay electrons

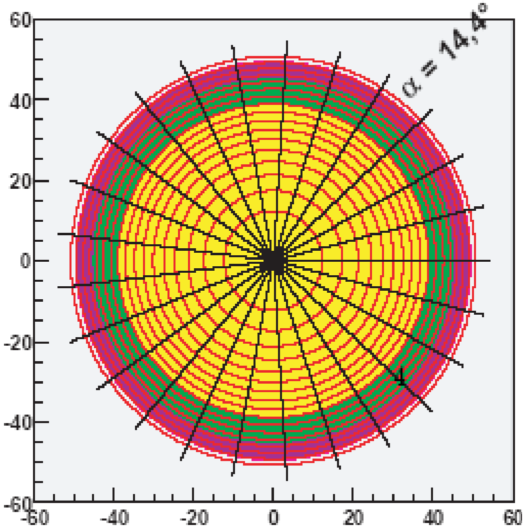
with high energy resolution (ΔE =1 keV)

record radial profile of flux tube

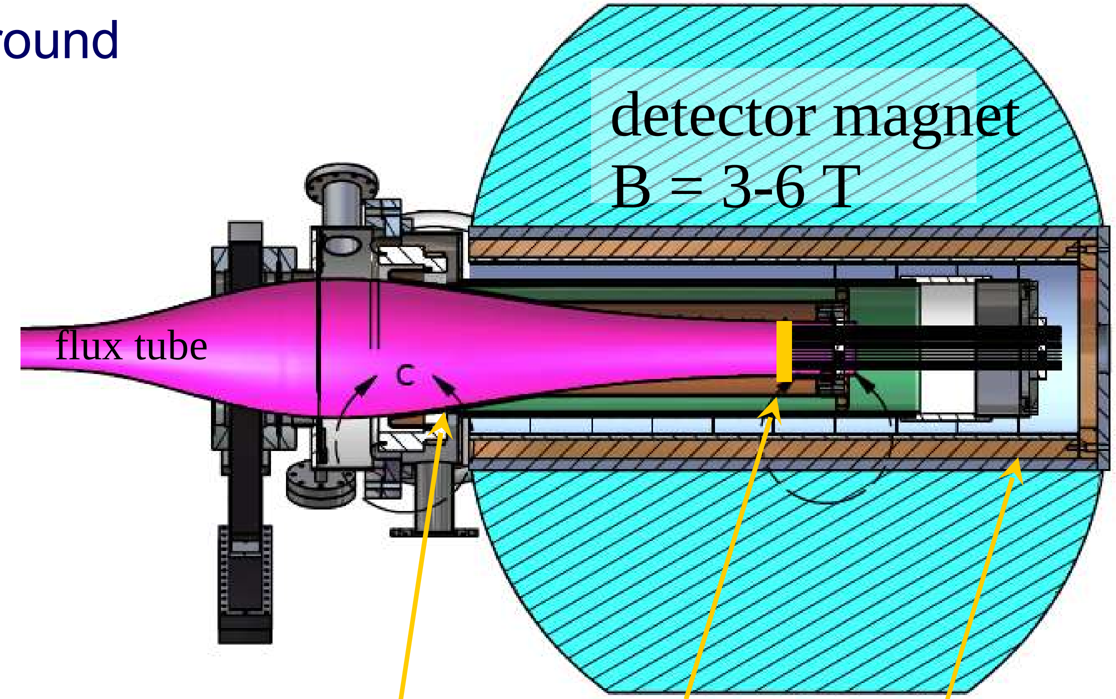
aim: background minimisation, systematic effects

⇒ post-acceleration to place signal line at lower intrinsic background





design: radially segmented Si-PIN diode array ~150 pixels with A=100 cm²

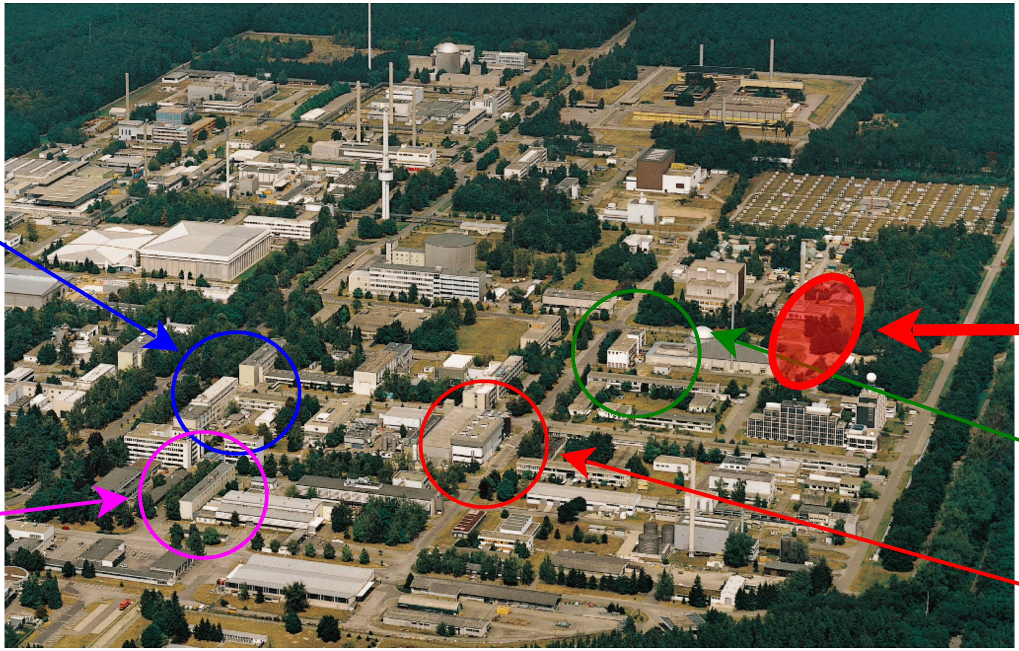


electrode (kV-acceleration) | low-level detector | shielding & veto

Technical challenges

- Recirculation and purification of tritium to a large extent (kCi)
- ≈ 30 superconducting solenoids
- UHV (< 10^{-11} mbar) in huge volume (1000m^2)
- HV calibration and stability on ppm level
- High resolution detectors
- ....

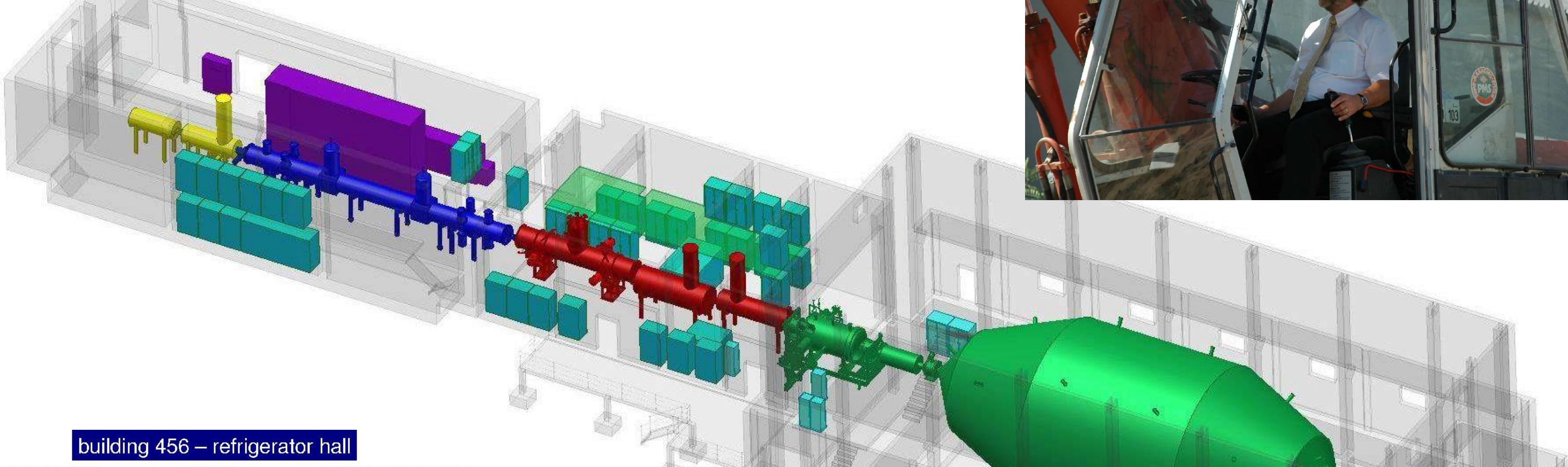
⇒ ideal place: Forschungszentrum Karlsruhe/Germany



KATRIN location at Forschungszentrum Karlsruhe

KATRIN hall groundbreaking
5. Sept. 2005

Research Director FZK R. Maschuw



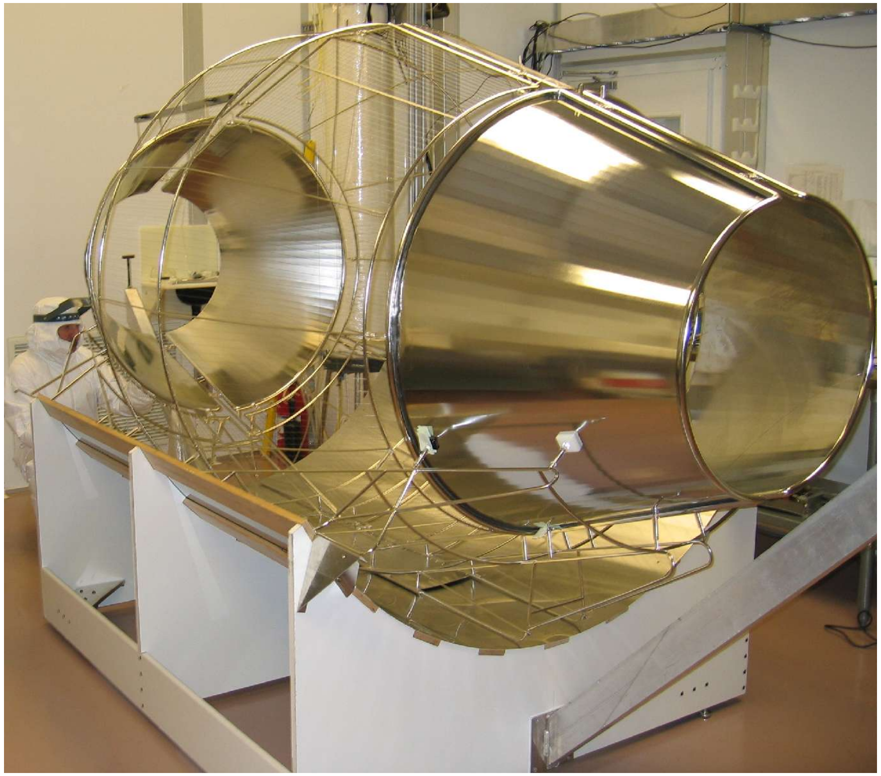
building 456 – refrigerator hall

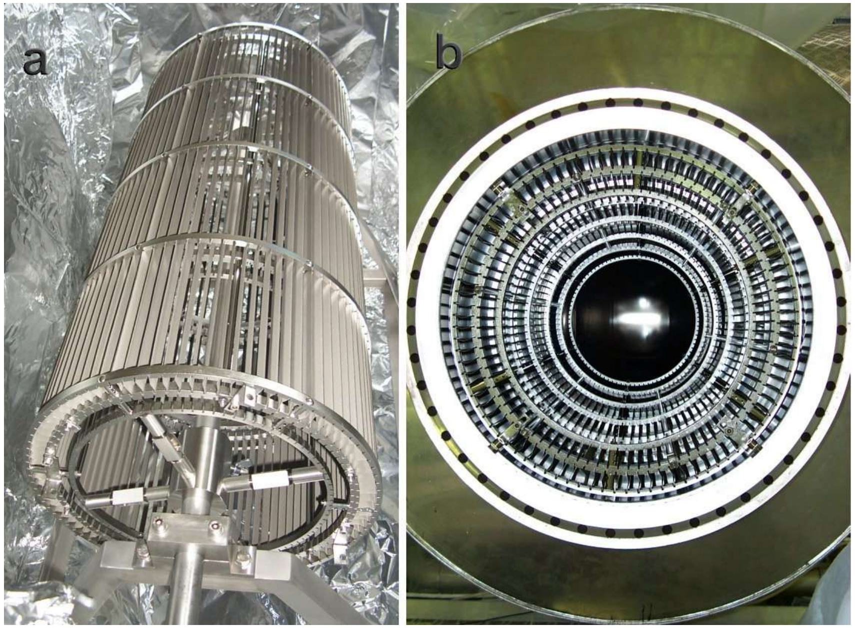
summer 2006

Vacuum tests and inner electrode system of pre spectrometer

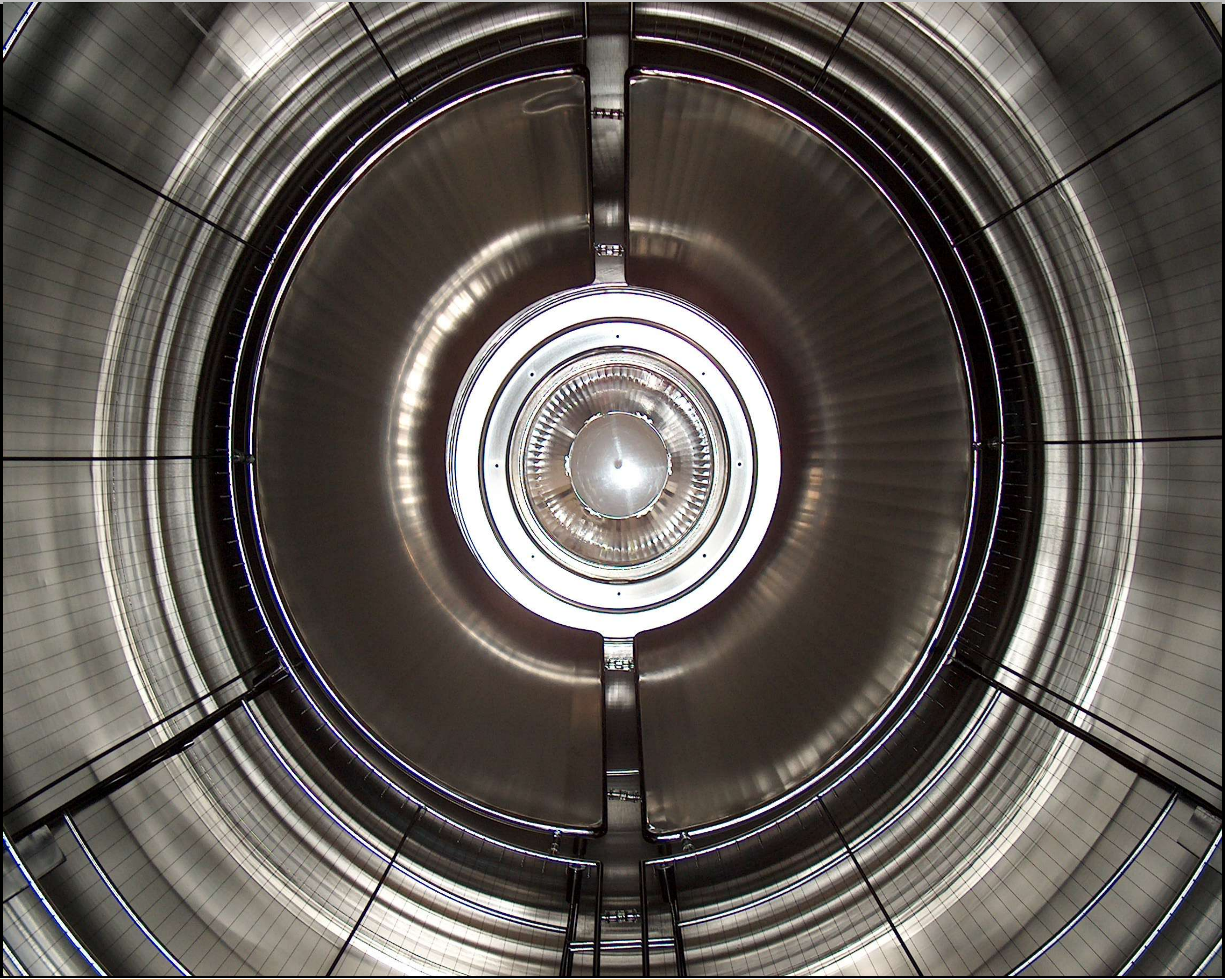
ground electrode
wire electrode + solid cones

dry air compartment to allow cooling
at -20°C: outgasing rate < 10^{-13} mbar l/s cm^2
with getter pumps (NEG, 10000 l/s): p< 10^{-11}mbar
⇒ better than KATRIN requirements

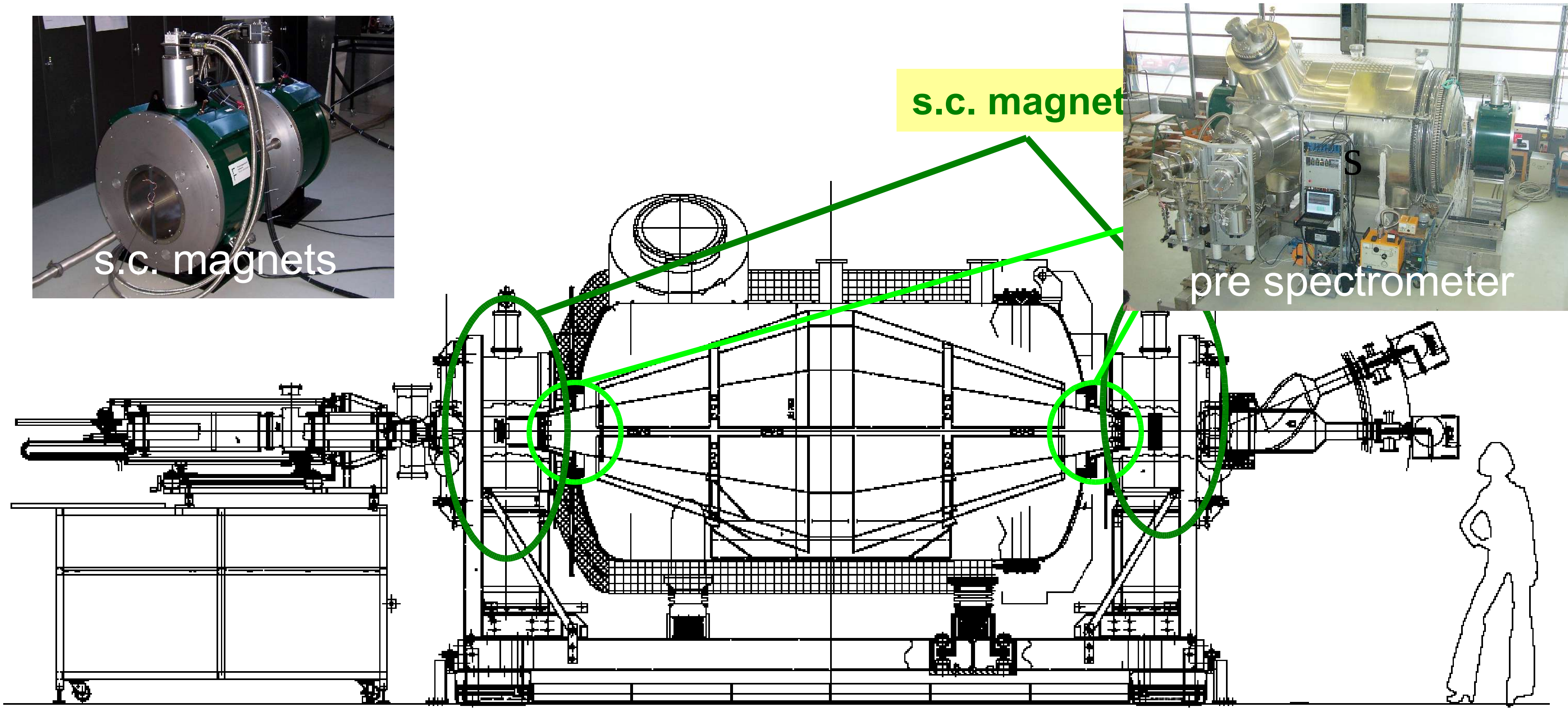


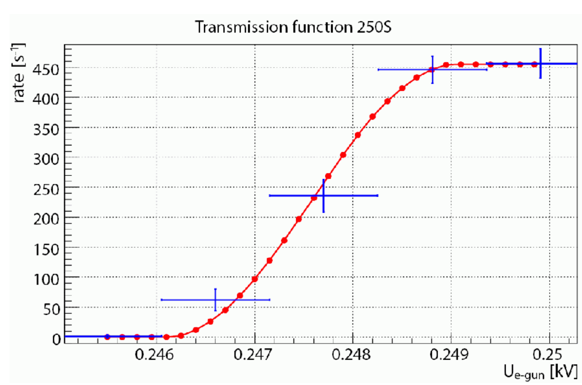


Wire electrode in pre spectrometer



Electromagnetic design tests at the pre spectrometer have just started





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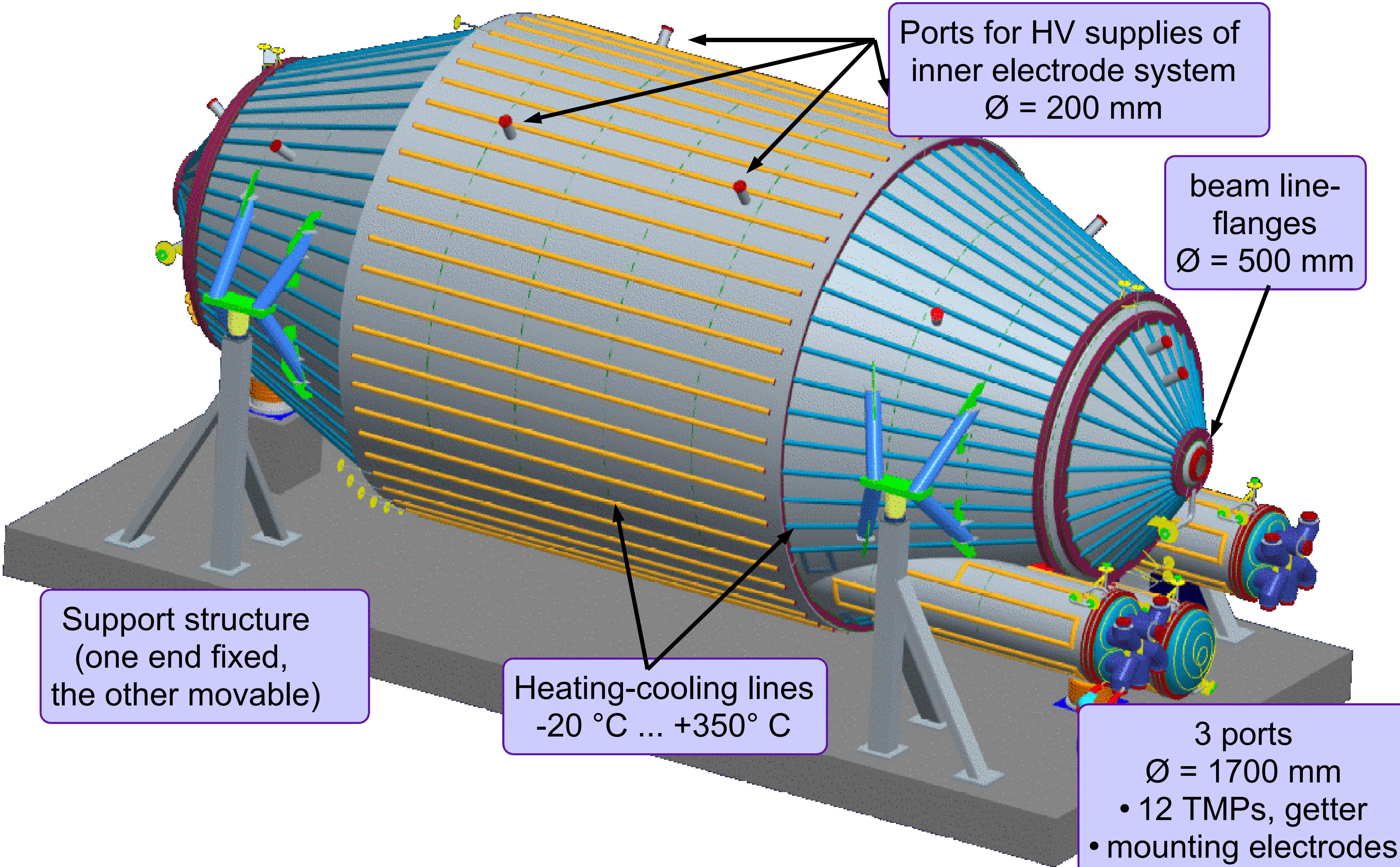
Main spectrometer 3dim model with heating-cooling system

KATRIN Karlsruhe Tritium Neutrino Experiment



Main spectrometer vessel construction at MAN DWE

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August 2006:

- construction of main spectrometer vessel has been finished
- vessel has passed leak test successfully !

⇒ world`s biggest XHV vessel ever been build !

It is very big and heavy ...
⇒ a 8500 km long detour

Arrival of the Main Spectrometer Vessel: October 2006

Sensitivity requirements for KATRIN:

1) Low background: Mainz experiment:

most background from spectrometer

but KATRIN spectrometer is much bigger!

$\Rightarrow$ need something new !

2) Huge statistics: optimized source &

large spectrometer

3) Systematic uncertainties:

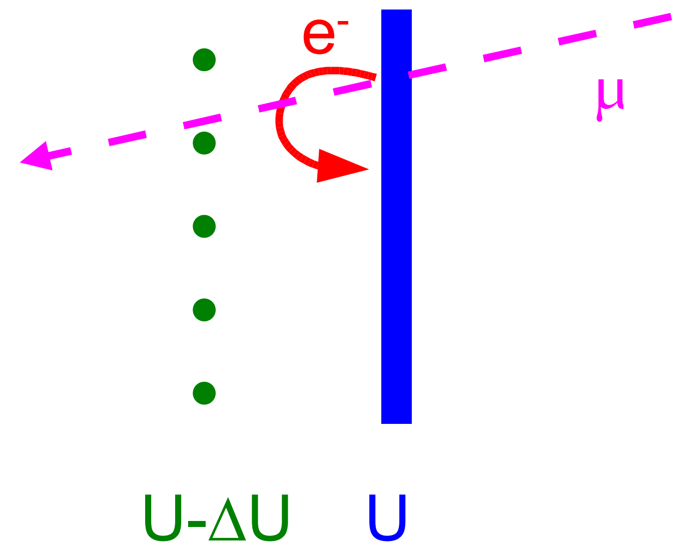
need to be very small !

Background reduction by a „massless“ wire electrode

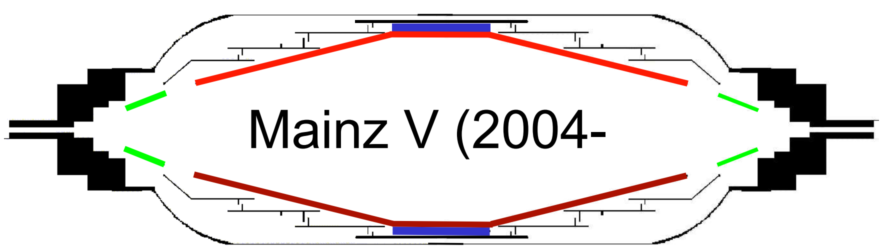
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

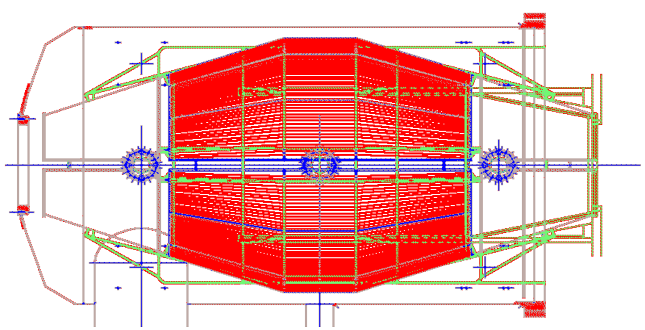
wire electrode on slightly more negative potential



First realisation:
Mainz III

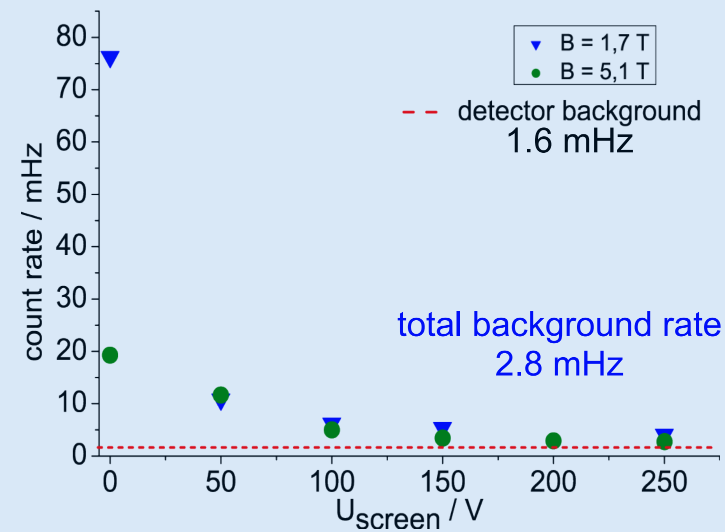


New record !
April 04



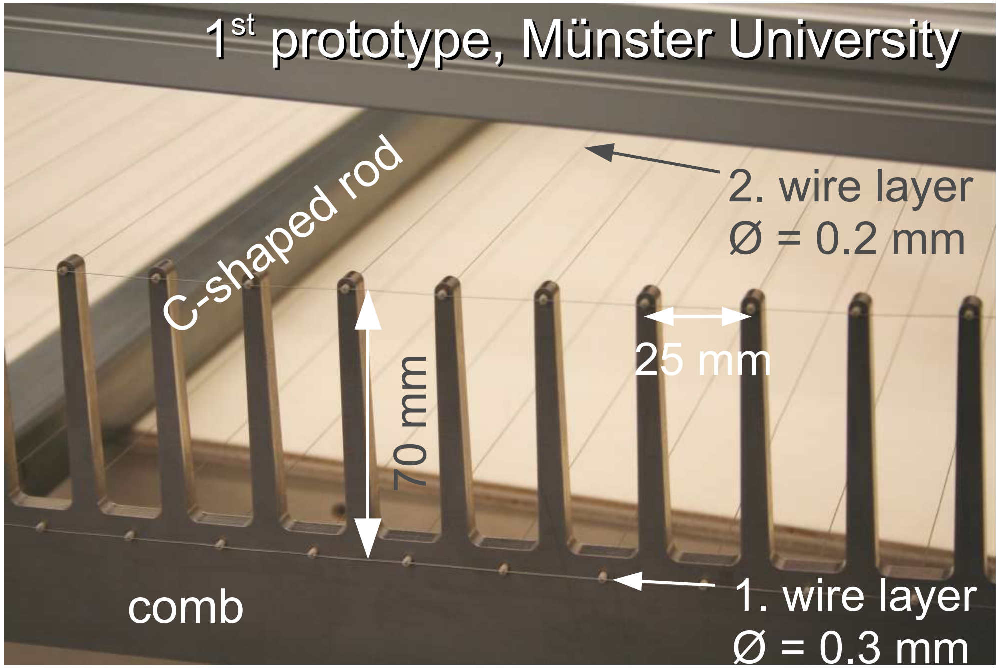
KATRIN pre spectrometer

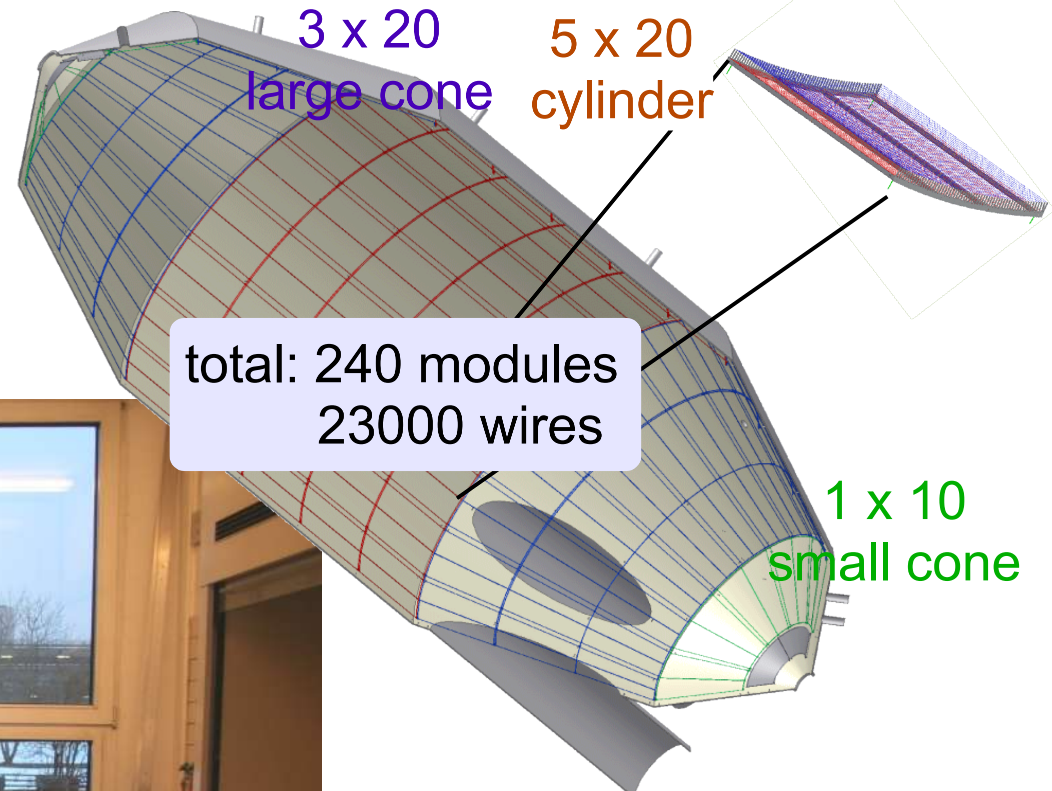
Background suppression successfully tested at the Mainz MAC-E filter:

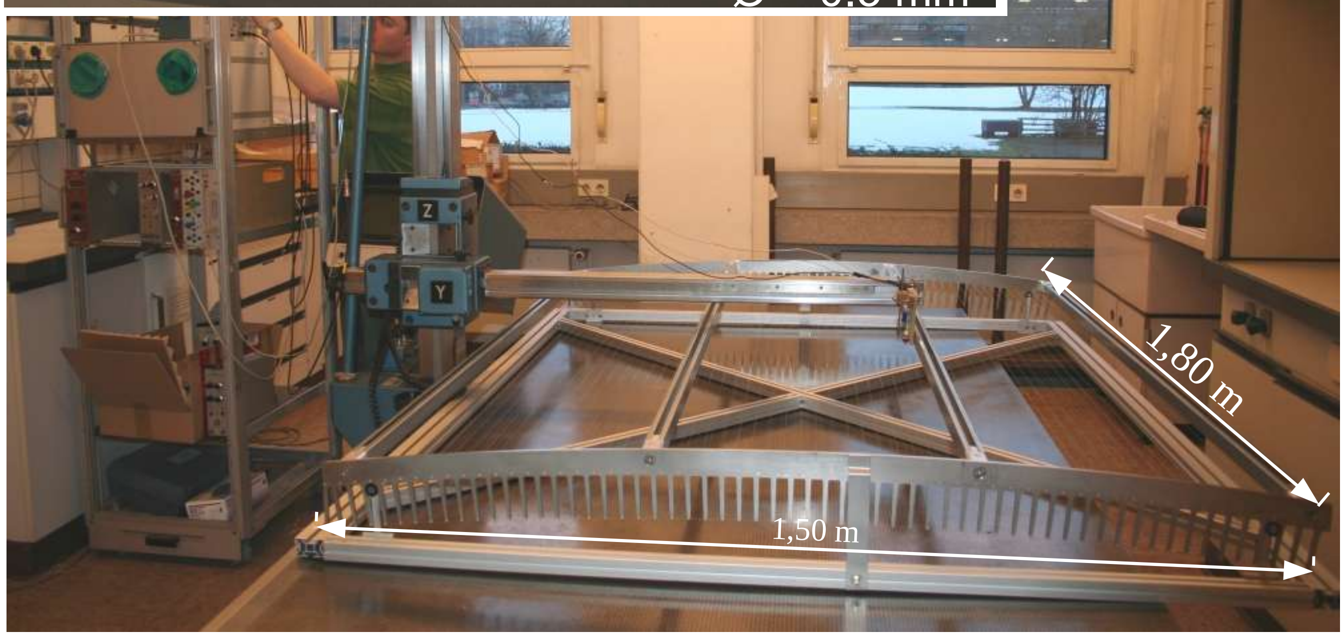


Dipl. thesis B. Ostrick (U Mainz, 2002),
PhD thesis B. Flatt (U Mainz, 2004)

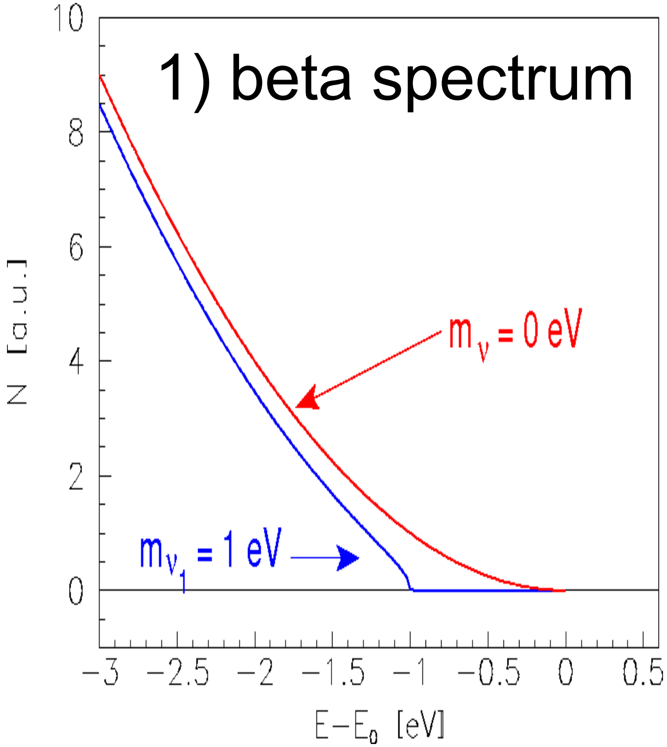
KATRIN: ≈ 240 double layer wire electrode modules



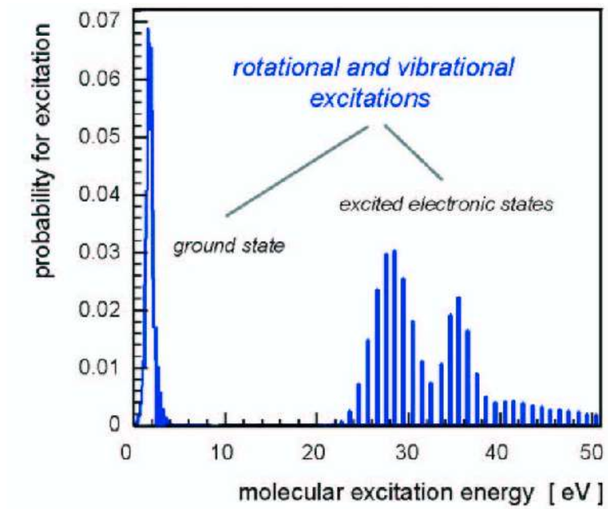


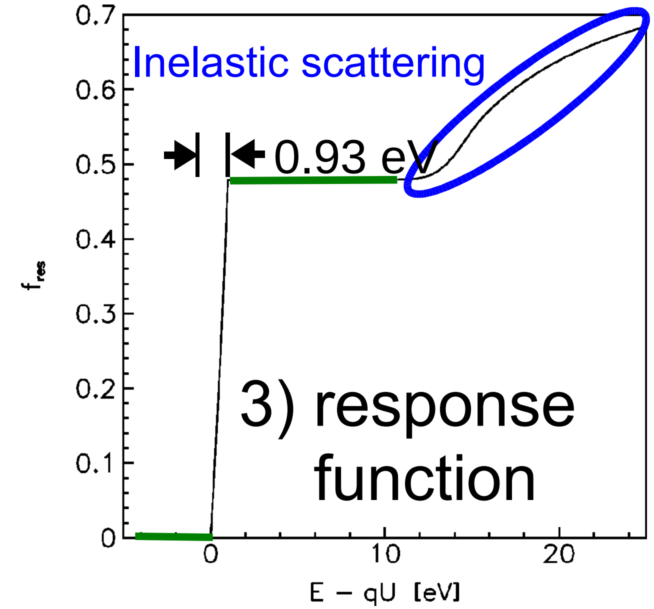


2) Statistics

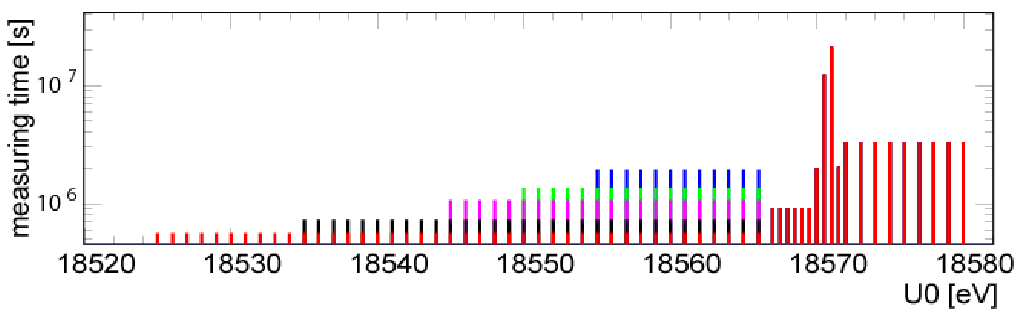


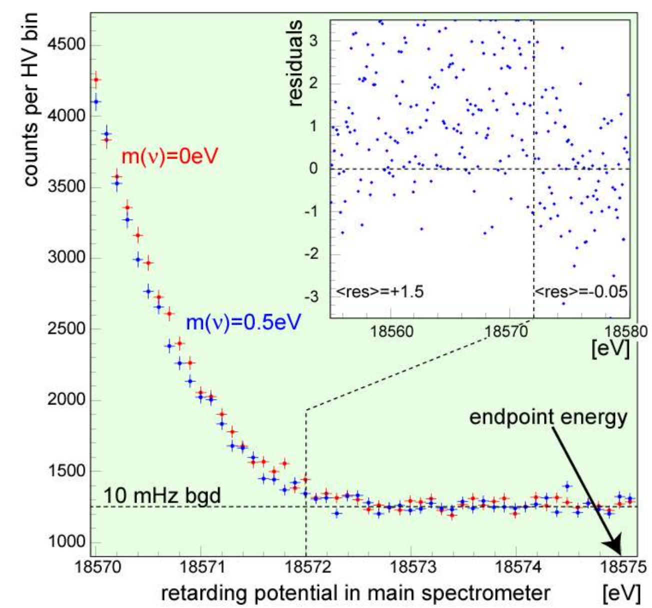
2) final states



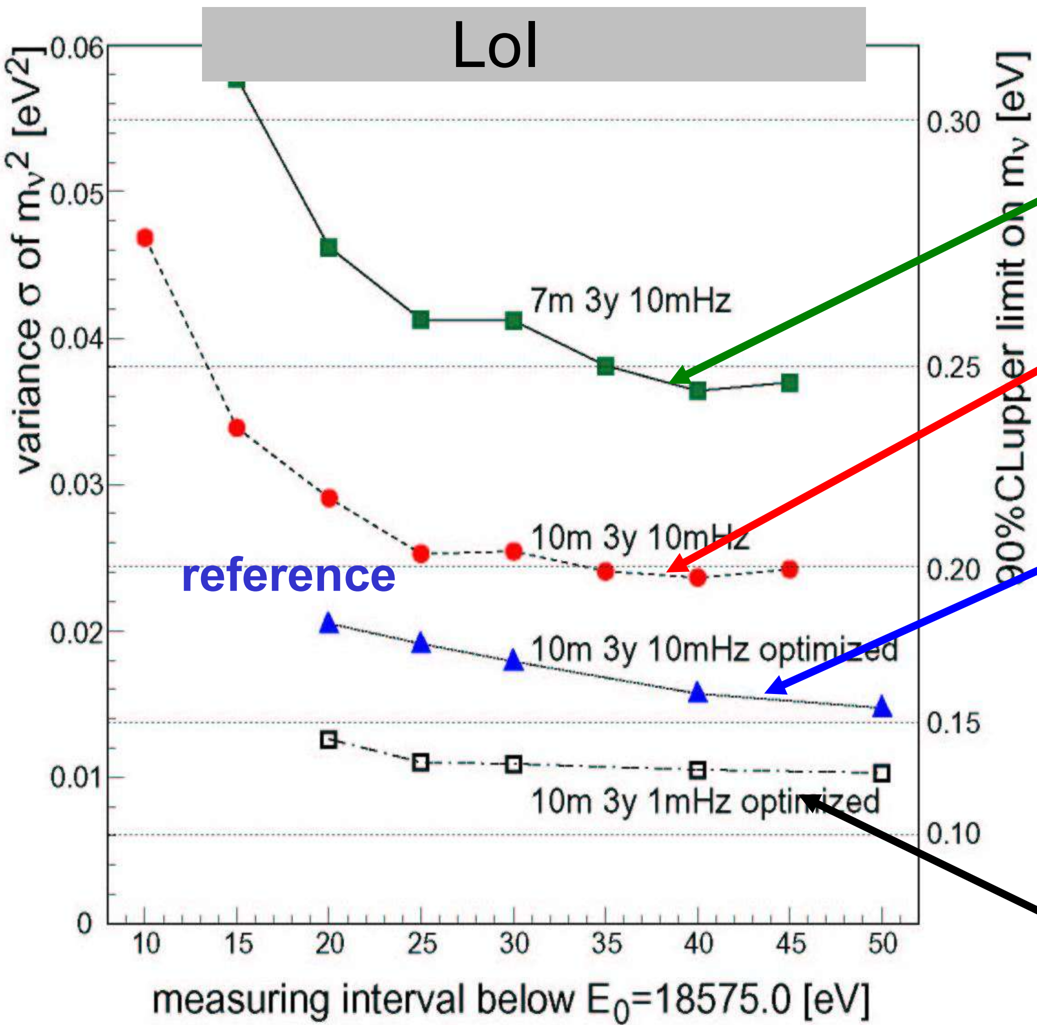


4) measurement point distrib. ⇒ MC data





KATRIN´s statistical uncertainty



design optimisation ´01 -´03

- tritium purity by tritium laboratory (>95%)

2× stronger gaseous source (Ø=75mm → Ø=90mm) requires Ø=10m spectrometer)

optimised measuring point distribution (~5 eV below E_0)

- active background reduction by inner electrode system, low background detector (needs further detailed tests)

3) Systematic uncertainties

As smaller $m(\nu)$

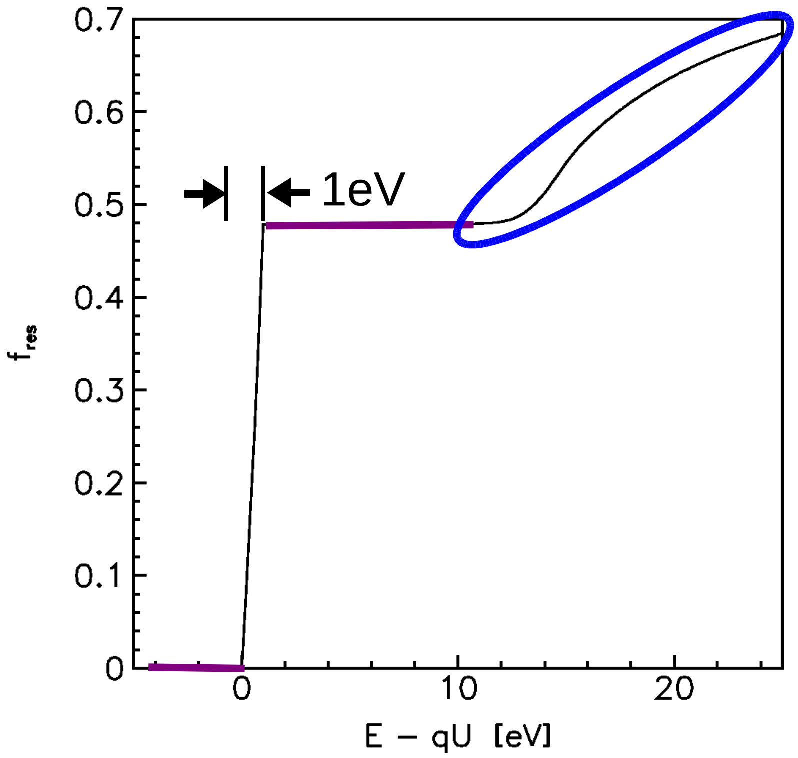
as smaller the region of interest below endpoint E_0

⇒ Excited electronic final states does not play a role (ΔE_{exc} > 27 eV)

⇒ Inelastic scattering in T_2 is small ($\Delta E_{inel.}$ > 12eV

⇒ largest interval 25eV: 2%)

⇒ One well-defined final state (similiar to cryo detectors)



Is only true, since MAC-E-Filter response function has no tails

3) Systematic uncertainties

any not accounted 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
   - requires dedicated e-gun measurements, unfolding techniques for 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

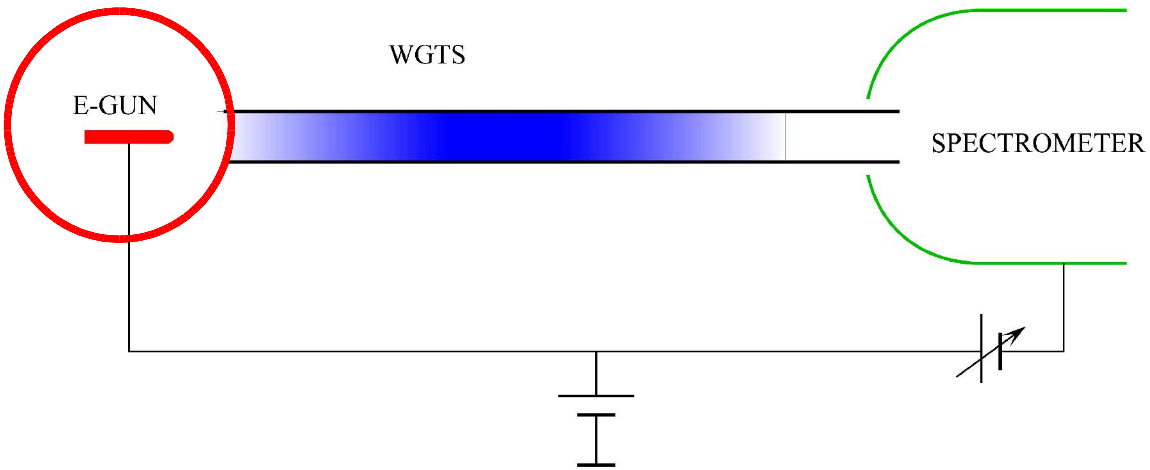
6. HV stability of retarding potential on ~3ppm level required
   - precision HV divider (PTB), monitor spectrometer beamline

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

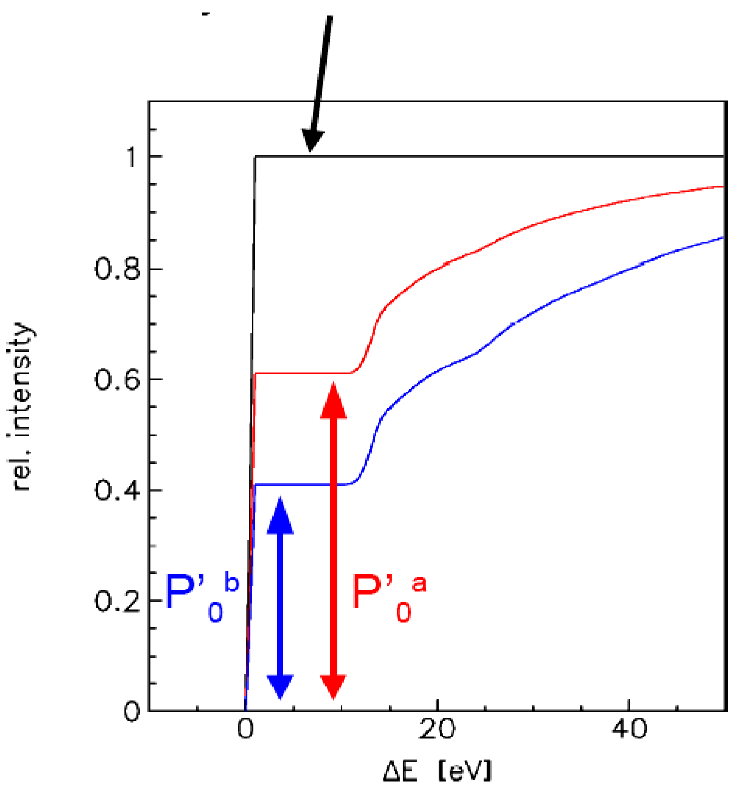
Determine energy loss function and source column density ρ d

main idea: measure ρd in terms of ρd_{free}

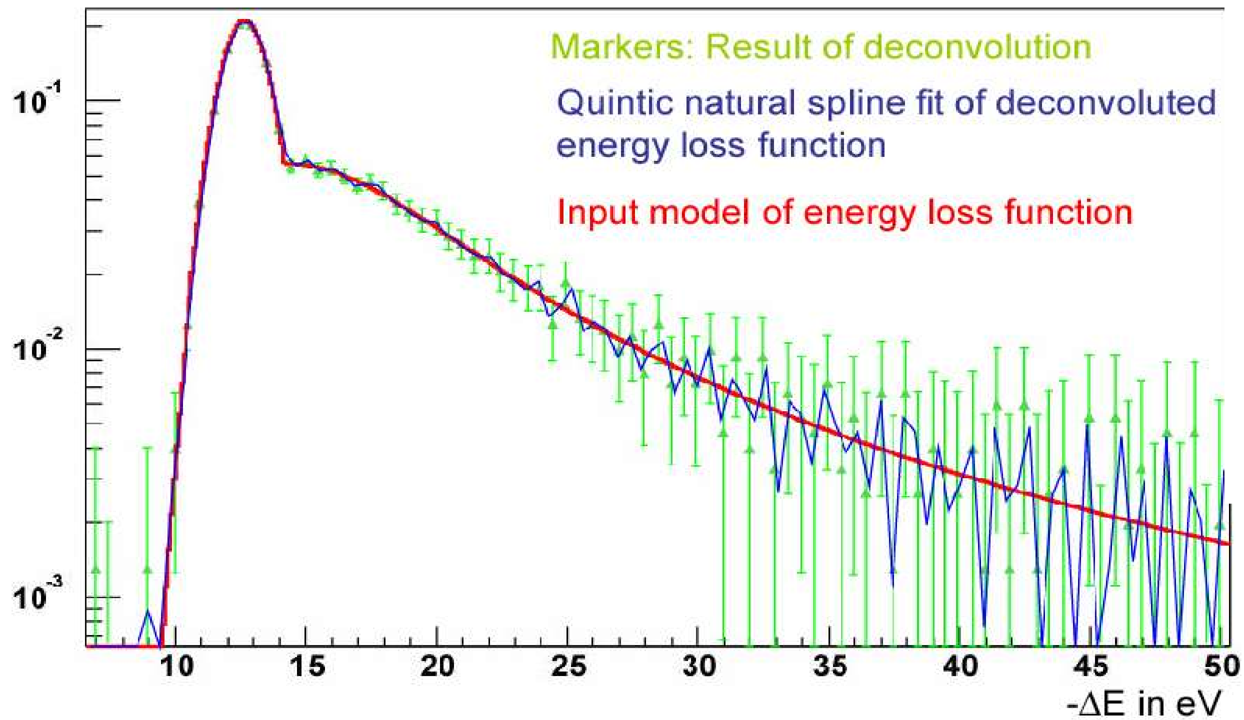
scheme of measurement



measure response function for 18.6 keV electrons for diff. ρd

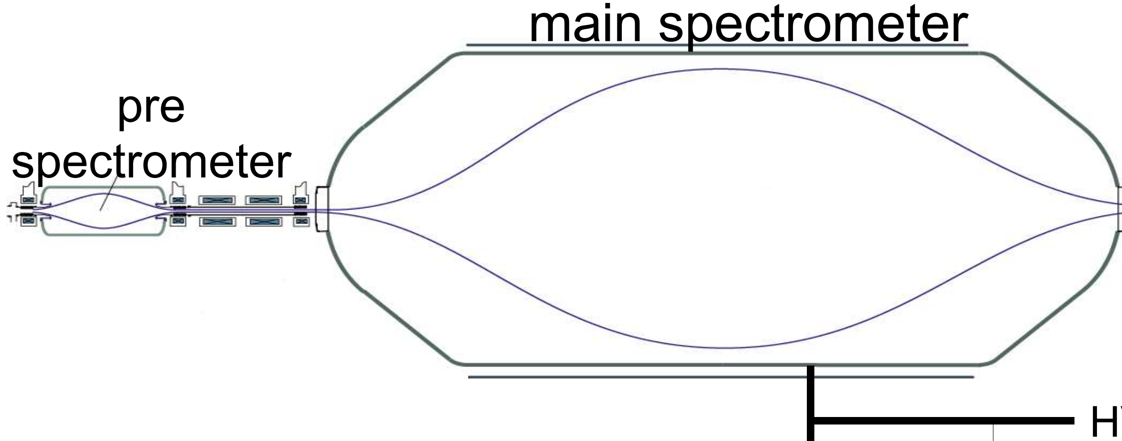
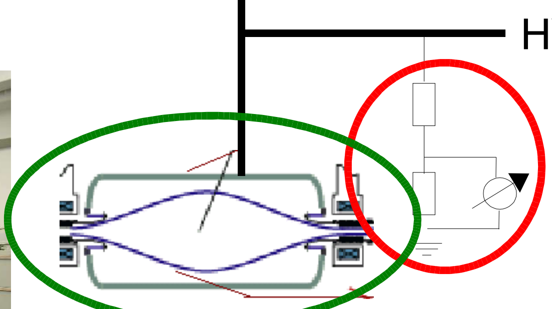


➔ deconvolution of energy loss function



Long term stability of the retarding HV

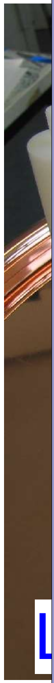
- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined (atomic/nuclear standard) and sharp electron line with monitor spectrometer

continuously calibration source: ^{83m}Kr, $^{241}Am/Co$

condensed ^{83m}Kr source at Münster

KATRIN precision high voltage divider (in cooperation with PTB Braunschweig)



KATRIN's sensitivity:

- higher T2 purity
- larger statistics
- optimized measurement point distribution
- smaller systematic uncertainties

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

$\approx 0.20\ eV/c^2$

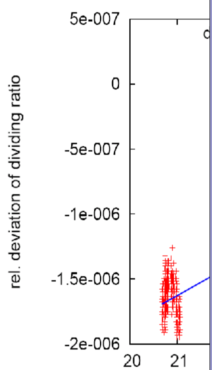
(about equal contribution from stat. and syst. uncertainties)

(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

tempera



$\Rightarrow$ TO

Measurements at PTB Braunschweig

Summary & Outlook

Absolute neutrino mass scale is needed

for particle physics & astrophysics/cosmology
by direct neutrino mass measurement
(less model dependent & complementary)

KATRIN will become sensitive on the $m(\nu_e)$

down to 0.2 eV:

$m(\nu_e) < 0.2$ eV or

$m(\nu_e) > 0$ eV (for $m(\nu_e) \geq 0.30$ eV @ 3σ)

2009/10	complete setup and commisioning
2010	start of data taking
2011	first results
2015	finish data taking

the KATRIN colloaboration as of 2005