

# direct neutrino mass measurements

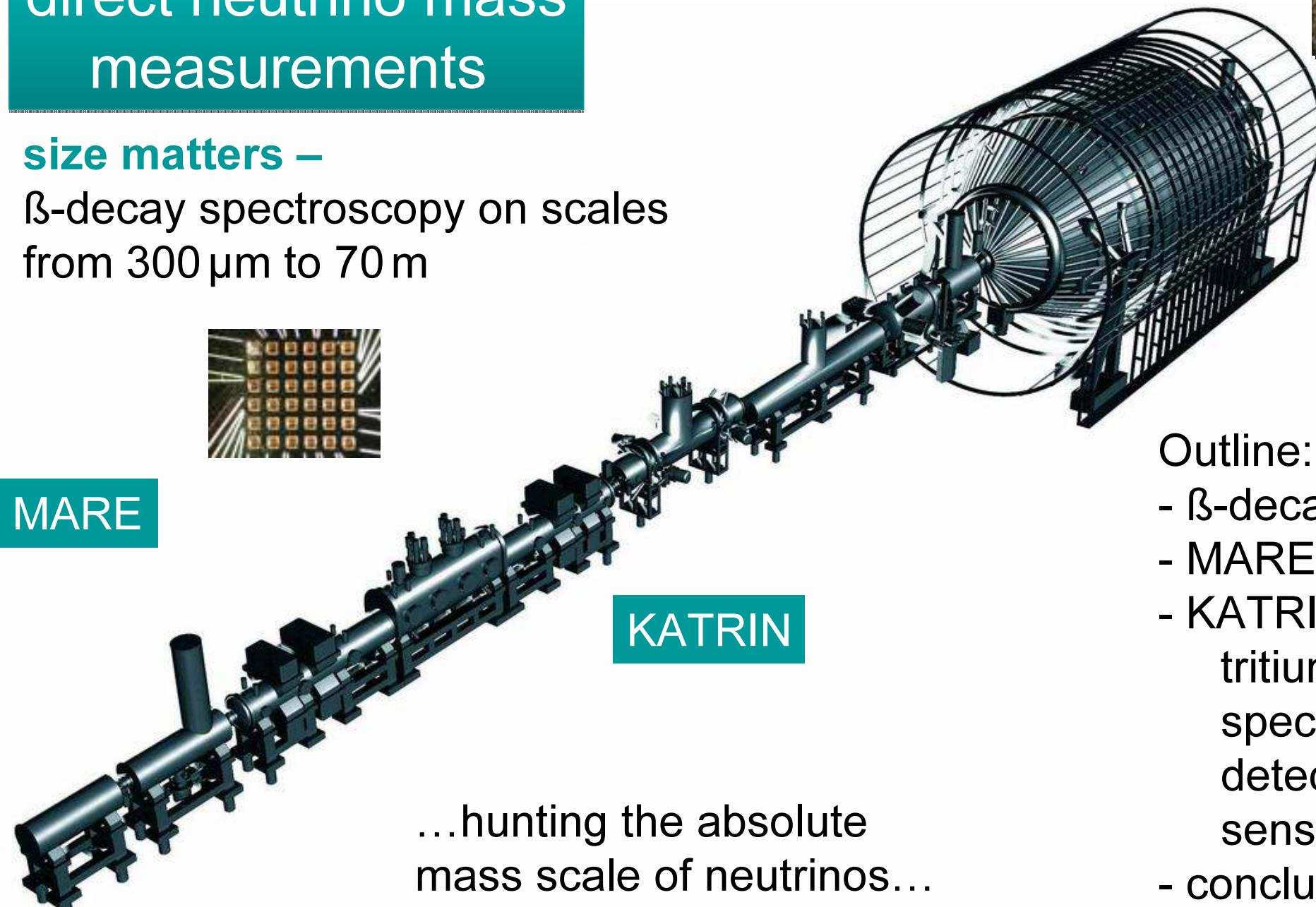


**size matters –**  
 $\beta$ -decay spectroscopy on scales  
from 300  $\mu\text{m}$  to 70 m



MARE

KATRIN

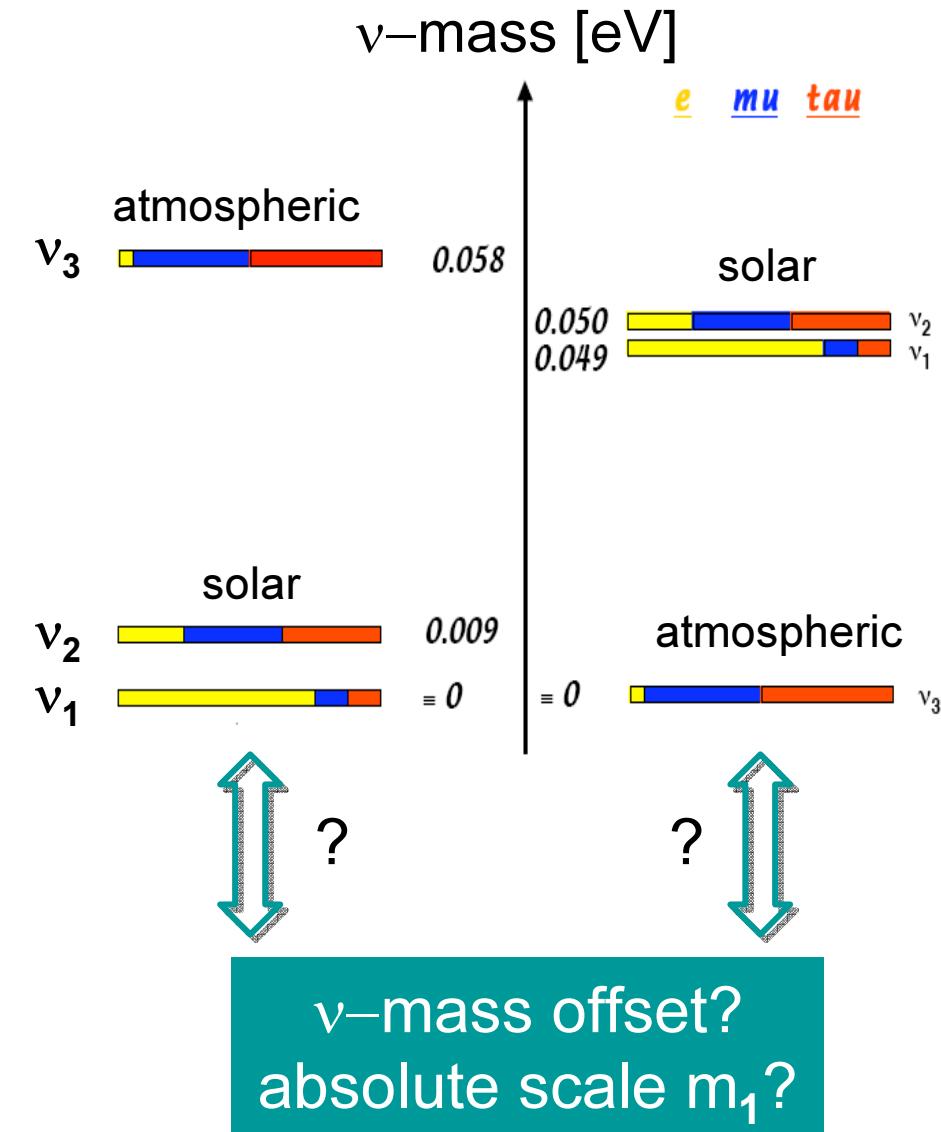
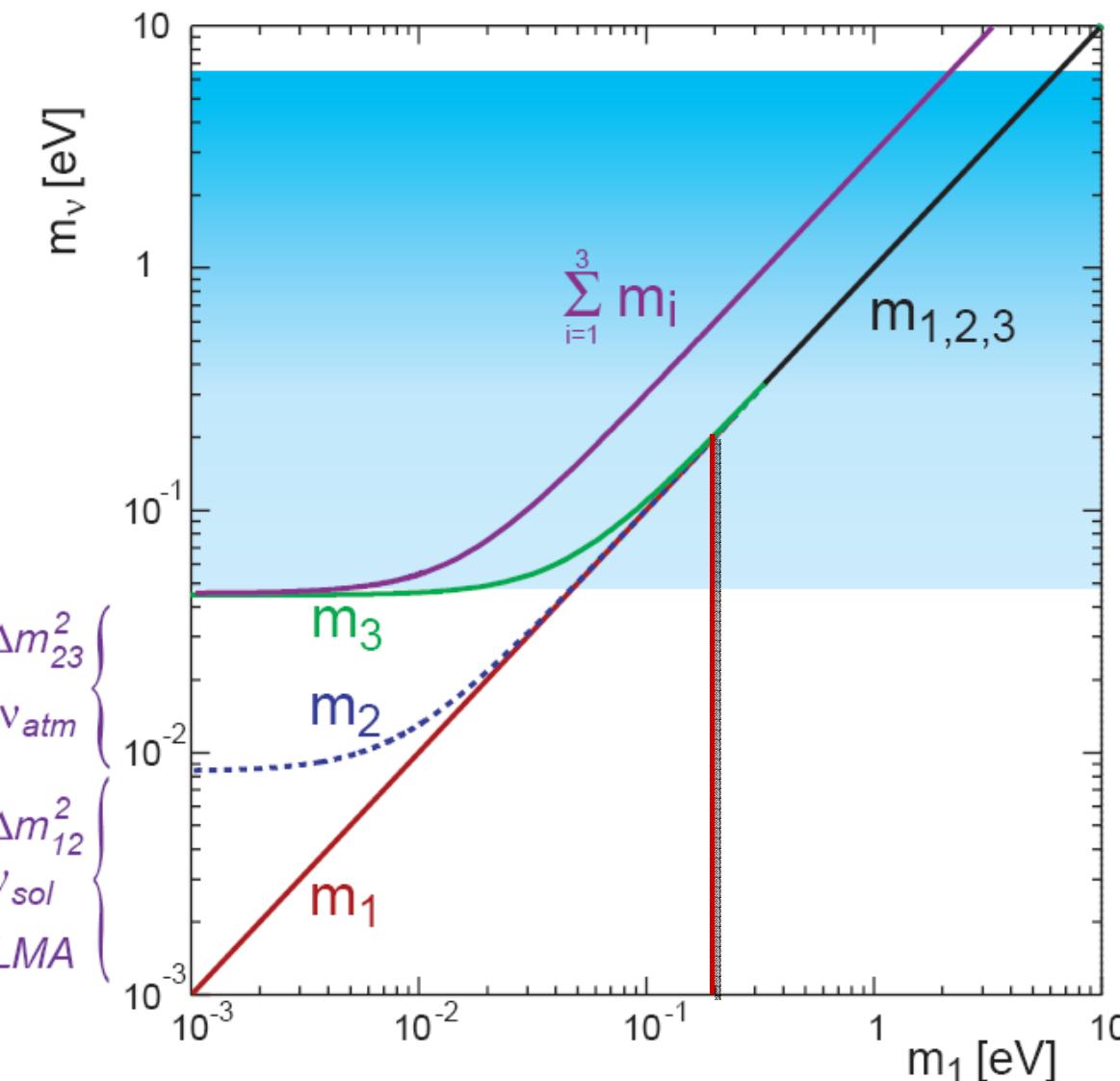


...hunting the absolute  
mass scale of neutrinos...

Outline:  
-  $\beta$ -decay techniques  
- MARE  
- KATRIN  
tritium source  
spectrometers  
detector  
sensitivity  
- conclusion

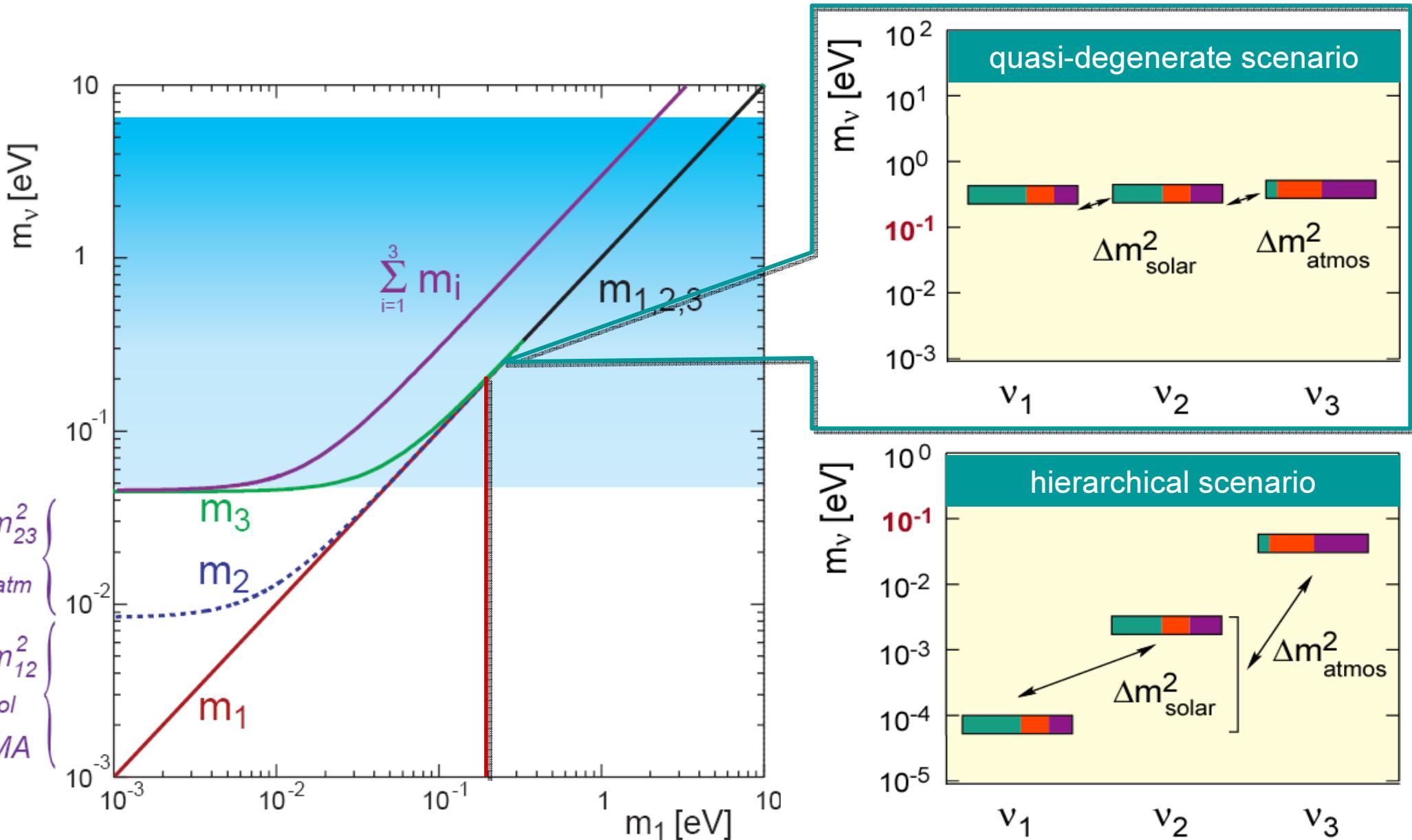
# absolute mass scale of neutrinos

**particle physics:**  $\nu$ -mass pattern? (hierarchy, degenerate)



# absolute mass scale of neutrinos

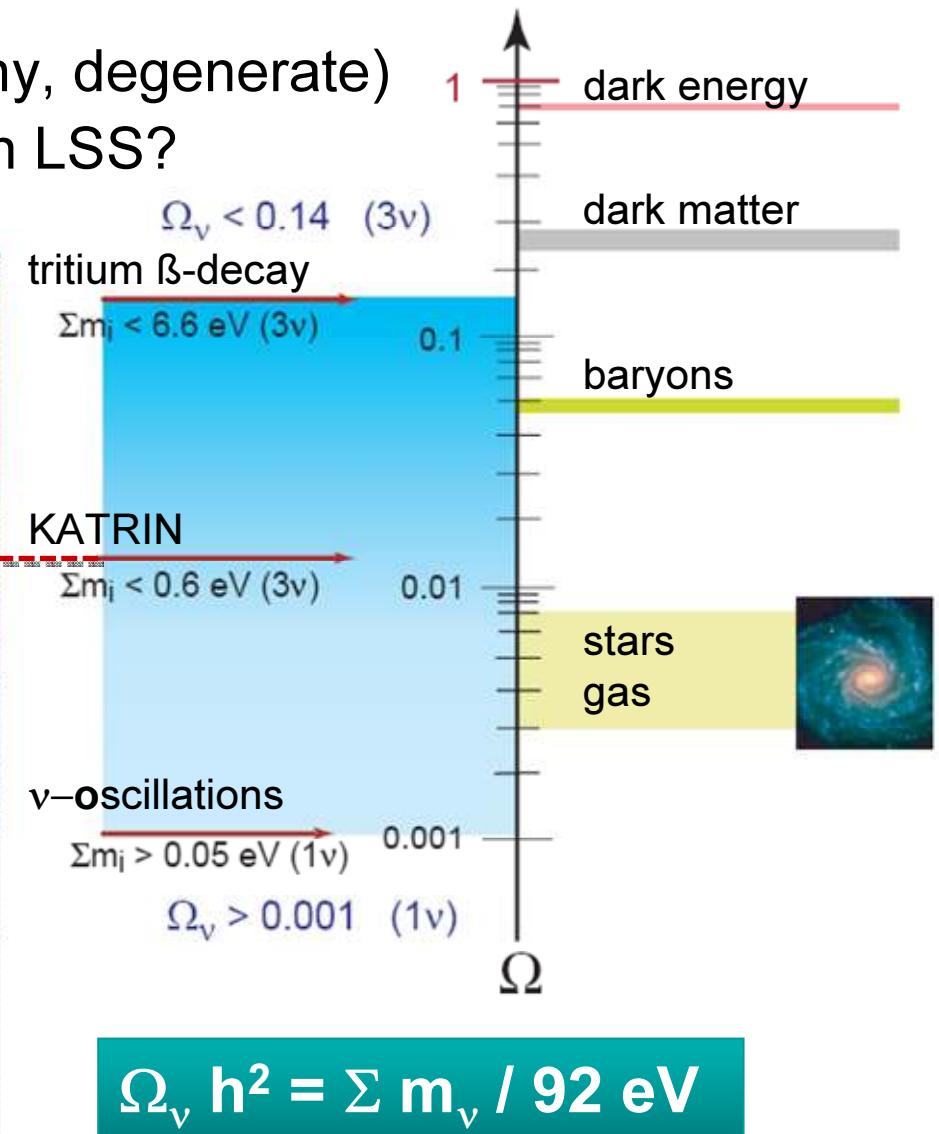
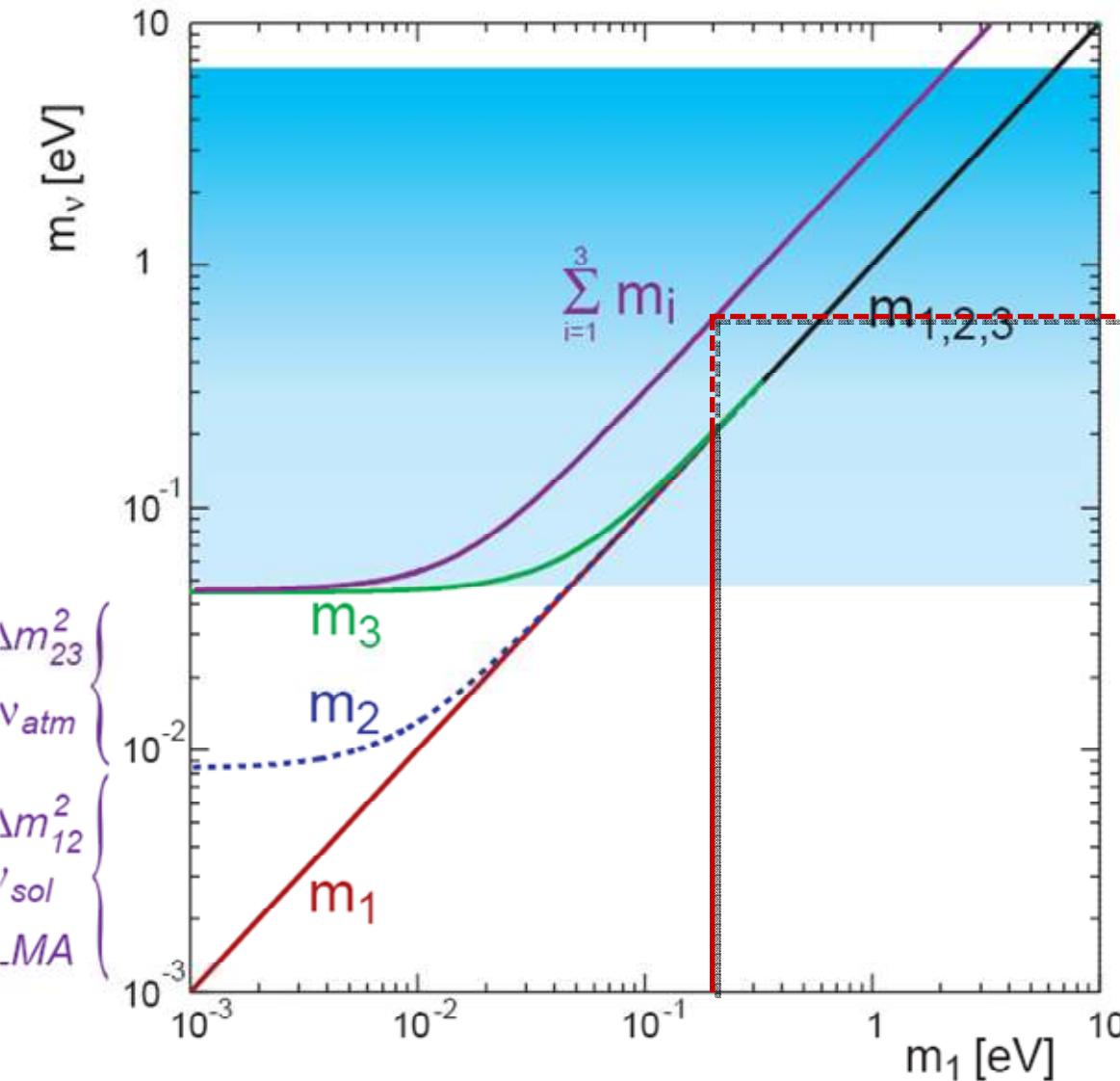
**particle physics:**  $\nu$ -mass pattern? (hierarchy, degenerate)



# absolute mass scale of neutrinos

**particle physics:**  $\nu$ -mass pattern? (hierarchy, degenerate)

**cosmology:** rôle of  $\nu$ 's as hot dark matter in LSS?



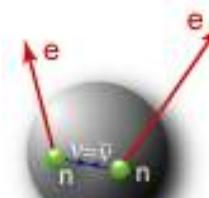
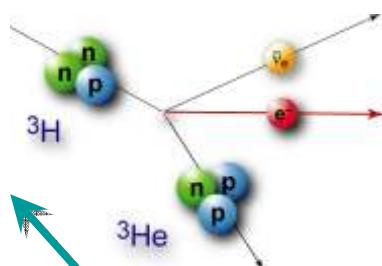
336 relic  $\nu$ 's/cm<sup>3</sup>

# neutrino mass: status and perspectives

kinematics of  $\beta$ -decay  
absolute  $\nu_e$ -mass:  $m_\nu$

## model-independent

status:  $m_\nu < 2.3$  eV  
potential:  $m_\nu = 200$  meV  
KATRIN, MARE-II



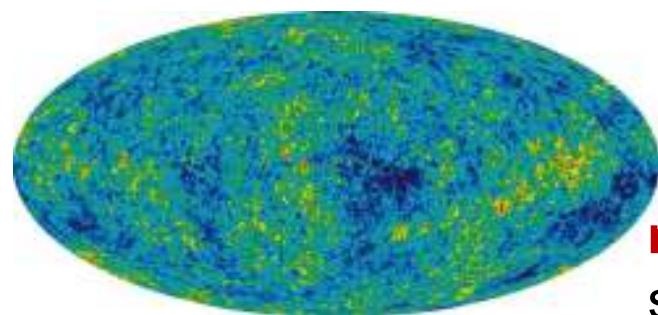
search for  $0\nu\beta\beta$   
eff. Majorana mass  $m_{\beta\beta}$

## model-dependent (CP-phases)

status:  $m_{\beta\beta} < 0.35$  eV, evidence  
potential:  $m_{\beta\beta} = 20-50$  meV  
GERDA, EXO, CUORE



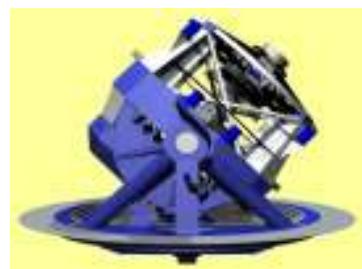
neutrino masses  
experimental techniques:  
status & potential



cosmology  
 $\sum \Sigma m_i$ , HDM  $\Omega_\nu$

## model-dependent (multi-parameter fits)

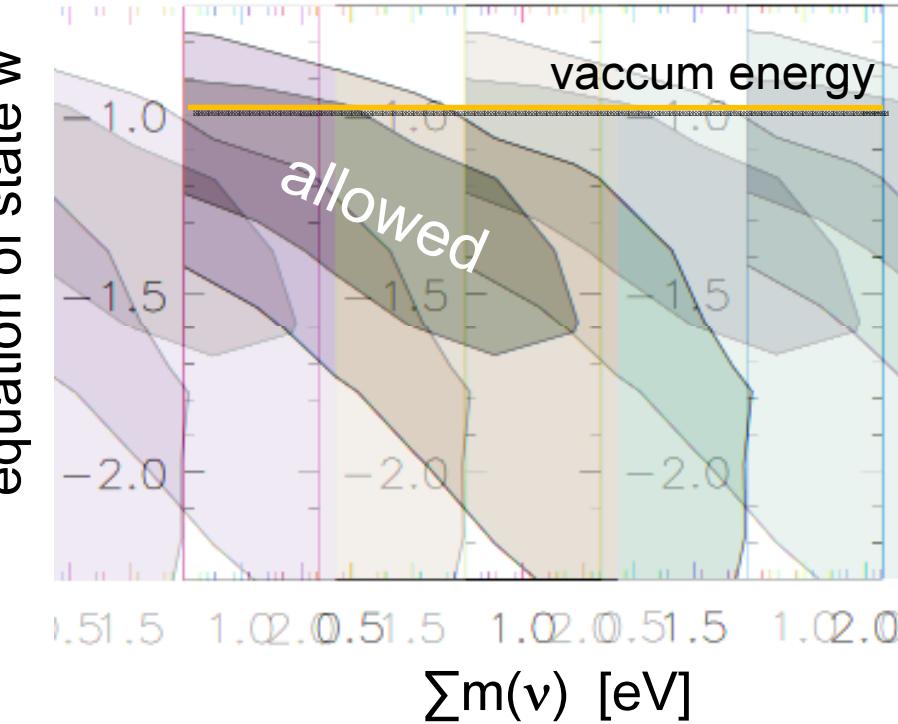
status:  $\sum m_i < 1$  eV [Hannestad et al., arXiv:0803.1585v2]  
potential:  $\sum m_i = 20-50$  meV  
Planck, LSST, weak lensing



# neutrino mass & dark energy

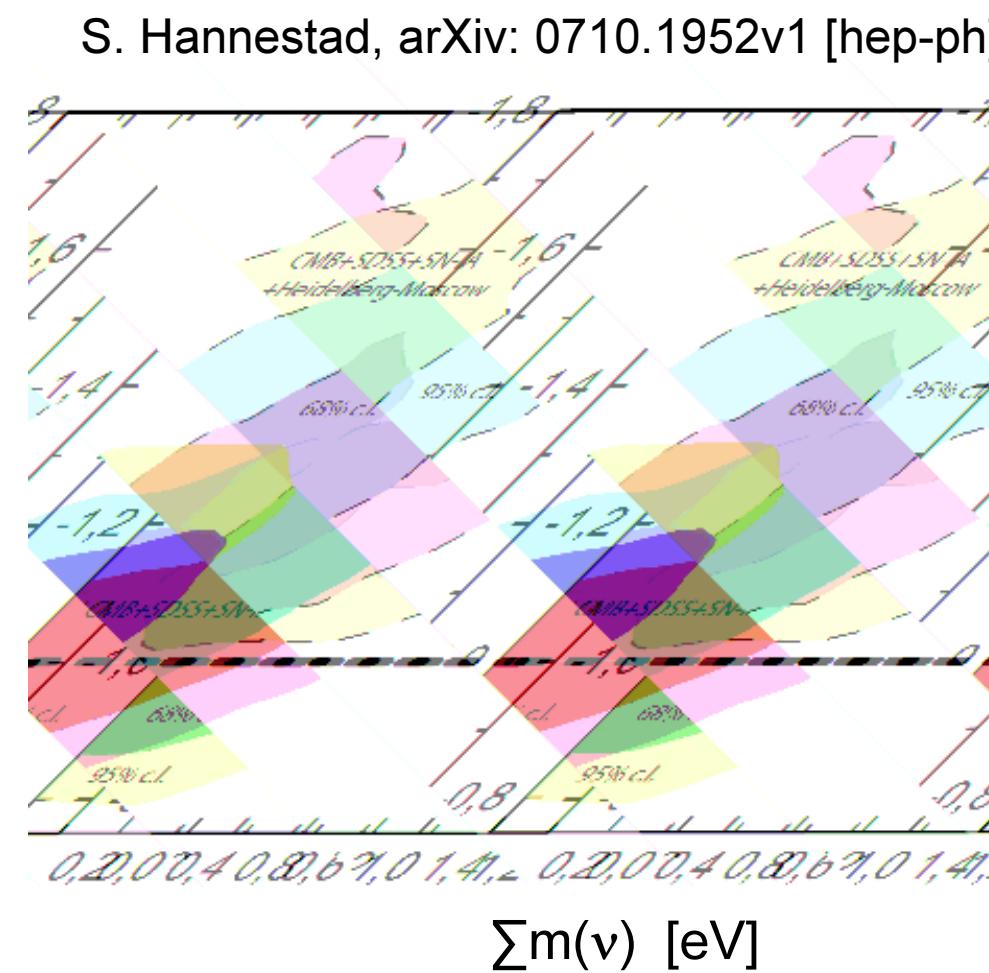
global analysis of cosmological data (CMBR & LSS):  
 correlation of  $\nu$ -mass  $m(\nu)$  & equation of state  $w$   
 of dark energy (degeneracy of parameters)

**laboratory measurement of  $m(\nu) > 0.2$  eV  
 could imply  $w < -1$  (quintessence)**



equation of state  $w$

$$w = P / \rho c^2$$



# $\beta$ -decay: energy spectrum

a model-independent measurement of  $m(\nu_e)$   
based on kinematics & energy conservation

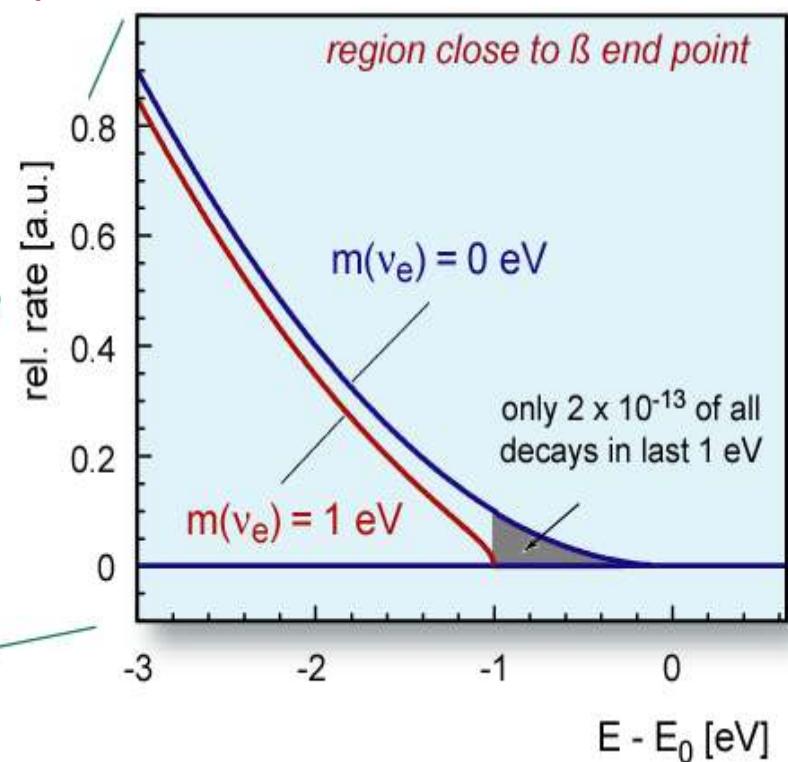
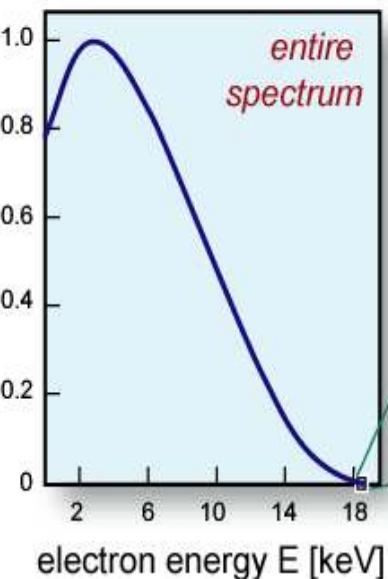
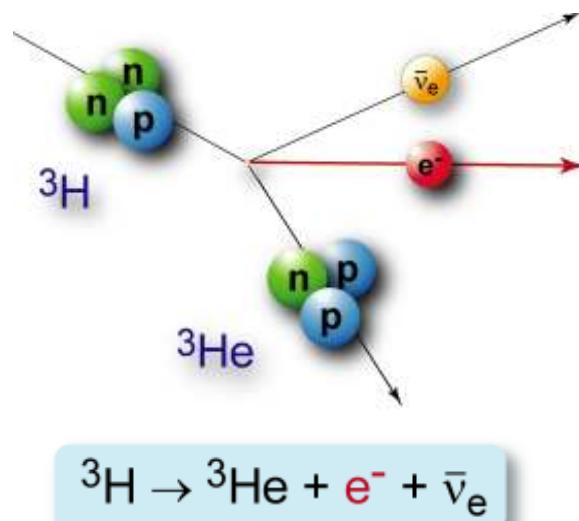


$$m(\nu_e) = \sqrt{\sum_{i=1}^3 |U_{ei}|^2 \cdot m_i^2}$$

incoherent sum

$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E, Z) \cdot \theta(E_0 - E - m_i)$$

$\frac{m^5}{3} G_F^2 \frac{s^2 \theta_W}{2\pi} G_F^2 M_p^2 \frac{m_e^5}{2\pi^3 C} \phi ds^2 \gamma^2$ 
(ν-mass)<sup>2</sup>
Fermi function



# $\beta$ -decay: energy spectrum



a model-independent measurement of  $m(\nu_e)$   
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$$m(\nu_e) = \sqrt{\sum_{i=1}^3 |U_{ei}^2| \cdot m_i^2}$$

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$(\nu\text{- mass})^2$

## $\beta$ -source requirements

short half life  $t_{1/2}$  high luminosity

low endpoint energy  $E_0$

superallowed/allowed transition

simple atomic/molecular structure

## $\beta$ -detection requirements

large solid angle ( $\sim 2\pi$ )

low background rate

high energy resolution ( $\sim$ eV)

short dead time, no pile up

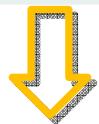
${}^3\text{H}$ : super-allowed		${}^{187}\text{Re}$ : unique 1 <sup>st</sup>	
$E_0$	18. 6 keV	$E_0$	2.47 keV
$t_{1/2}$	12.3 y	$t_{1/2}$	43.2 Gy

calorimeter	spectrometer
$\beta$ -source = detector	external $\beta$ -source
$\beta$ -source: ${}^{187}\text{Re}$	$\beta$ -source: ${}^3\text{H}$

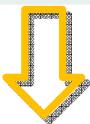
# techniques in $\beta$ -decay

the two different techniques are complementary due to different systematics

	calorimeter	spectrometer
source	metallic Re / dielectric AgReO <sub>4</sub>	windowless gaseous / condensed T <sub>2</sub>
activity	low: <10 <sup>5</sup> $\beta$ /s, ~ 1 Bq/mg Re	high: ~10 <sup>11</sup> $\beta$ /s, 4.7 Ci/s injection
energy	single crystal bolometers	electrostatic spectrometer
response	entire $\beta$ -decay energy	kinetic energy of $\beta$ -decay electrons
interval	entire spectrum	very narrow interval close to E <sub>0</sub>
method	differential energy spectrum	integrated energy spectrum
set-up	modular size, scaling factors	integral design, size limits
resolution	$\Delta E_{\text{expected}} \sim 5\text{-}10 \text{ eV (FWHM)}$	$\Delta E_{\text{expected}} \sim 0.93 \text{ eV (100%)}$



MARE

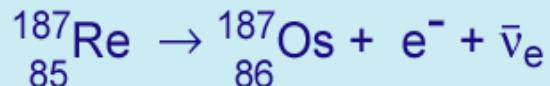


KATRIN

# MARE experiment

## Microcalorimeter Arrays for a Rhenium Experiment

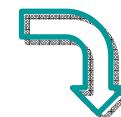
$^{187}\text{Re}$  as  $\beta$ -emitter: isotopic abundance 62.8%



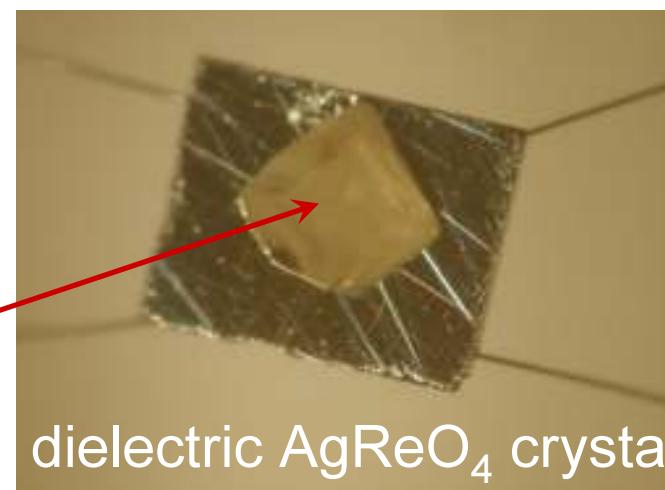
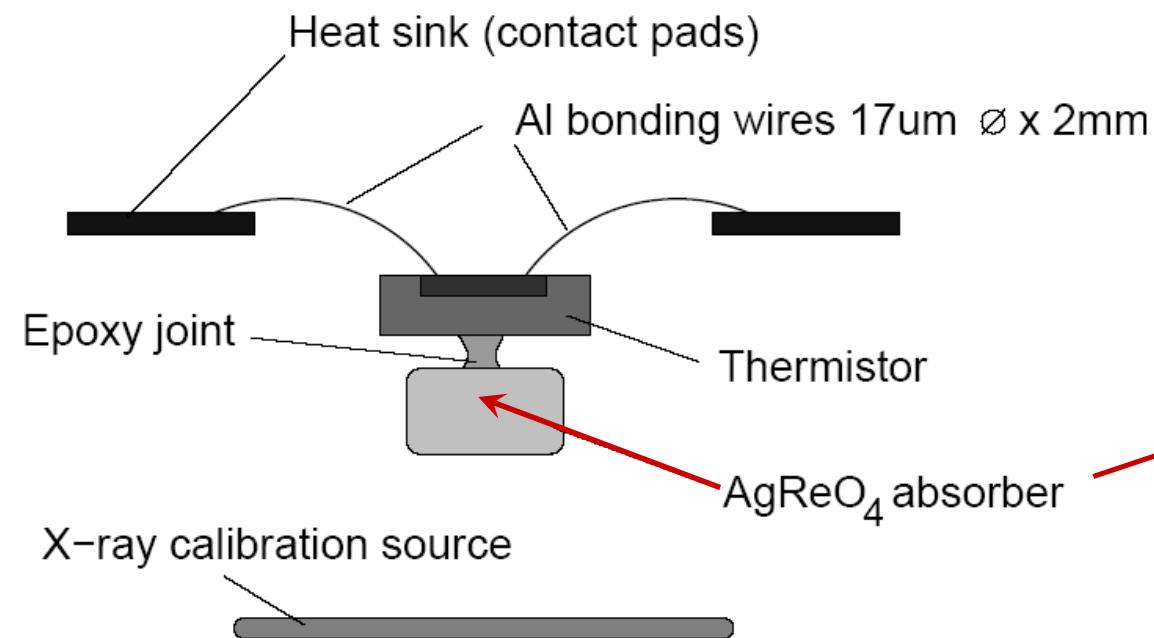
$5/2^+ \rightarrow 1/2^-$  unique first forbidden transition (shape factor)

previous experiments:

Genova: metallic Re (MANU)  
 Milano:  $\text{AgReO}_4$  (MIBETA)

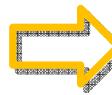


$6.2 \times 10^6$   $^{187}\text{Re}$   $\beta$ -decays:  
 $m(\nu) < 15$  eV (2004)



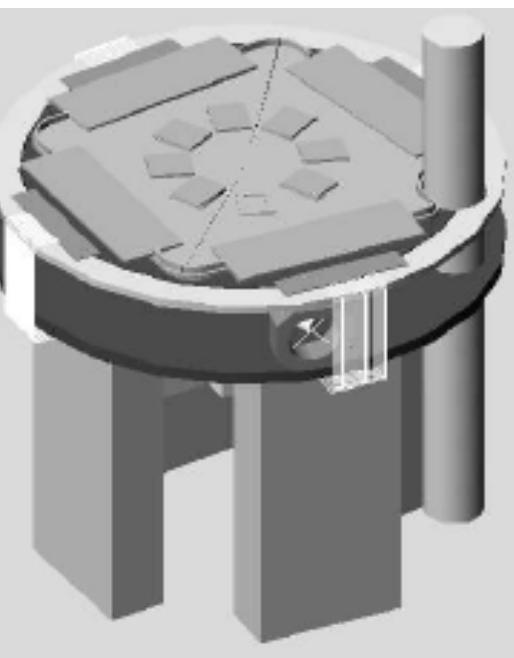
MIBETA:  
 10 crystals

# MARE experiment: Phase-I

**Phase-I objective:** improve sensitivity for  $m(\nu)$  by factor 10  
 increase statistics to  $10^{10}$   $\beta$ -decays   $m(\nu) \sim 2$  eV

**Phase-I detectors:** Genova: metallic Re, superconducting at  $T = 1.6$  K  
 absorber mass 1 mg  
 Milan: new  $\text{AgReO}_4$  crystals, dielectric perrhenates  
 absorber mass 500  $\mu\text{g}$  at  $T \sim 85$  mK,  $\tau_{\text{rise}} \sim 200$   $\mu$ s  
 $6 \times 6$  pixel arrays: 1<sup>st</sup> operational, 2<sup>nd</sup>: funded  
 energy resolution:  $\Delta E = 34$  eV @ 2.5 keV

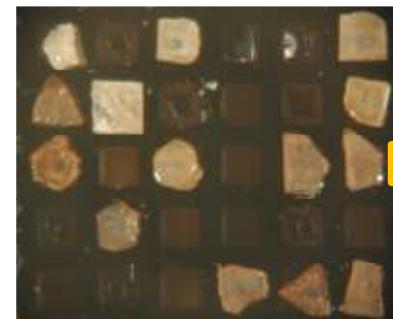
$\Delta E = 15$  eV  
 $\Delta t = 50$   $\mu\text{s}$   
 3 years



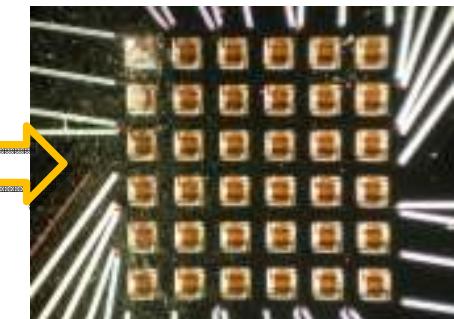
MARE-I cryostat for  
 288 elements ( $4 \times 72$ )  
 under construction



Genova: Re metal



Milan: pixel arrays of  $\text{AgReO}_4$



see poster Saskia Kraft-Bermuth:  
**'The MARE project for  $\nu$ -mass measurements  
 from the  $\beta$ -decay of  $^{187}\text{Re}$ - status &  
 perspectives'**

# MARE experiment: Phase-II

**Phase-II objective:** improve sensitivity for  $m(\nu)$  by another factor 10

increase statistics to  $10^{14}$   $\beta$ -decays

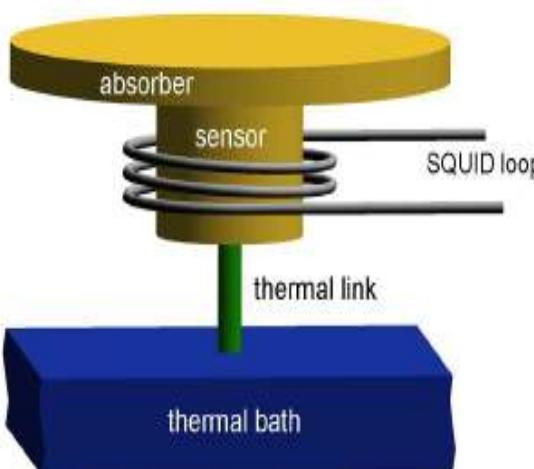
$$\Rightarrow m(\nu) \sim 0.2 \text{ eV}$$

**Phase-II detectors:** R&D efforts for new detectors

magnetic micro-calorimeters with paramagnetic sensor  
 $\delta T$  in absorber  $\Rightarrow$  change in magnetism  $\delta M$  of sensor

$$\delta M = \frac{\partial M}{\partial T} \cdot \delta T$$

read out by SQUID



if R&D for MMC or other detectors successful:

- operate a pilot array with 5000 bolometers
- sensitivity of  $m(\nu) = 0.2 \text{ eV}$  would require an array of  $\sim 50.000$  bolometers in several cryostats and a measuring time of  $> 5$  years



# history of tritium $\beta$ -decay experiments

TEP

$T_2$  in complex molecule  
magn. spectrometer (Tret'yakov)

Los Alamos

Gaseous  $T_2$  - source  
magn. spectrometer (Tret'yakov)

Tokio

$T^-$  - source  
magn. spectrometer (Tret'yakov)

Livermore

Gaseous  $T_2$  - source  
magn. spectrometer (Tret'yakov)

Zürich

$T_2$  - source impl. on carrier  
magn. spectrometer (Tret'yakov)

Troitsk (1994-today)

Gaseous  $T_2$  - source  
electrostat. spectrometer

Mainz (1994-today)

Frozen  $T_2$  - source  
electrostat. spectrometer

$m_\nu$   
17-40 eV

< 9.3 eV

< 13.1 eV

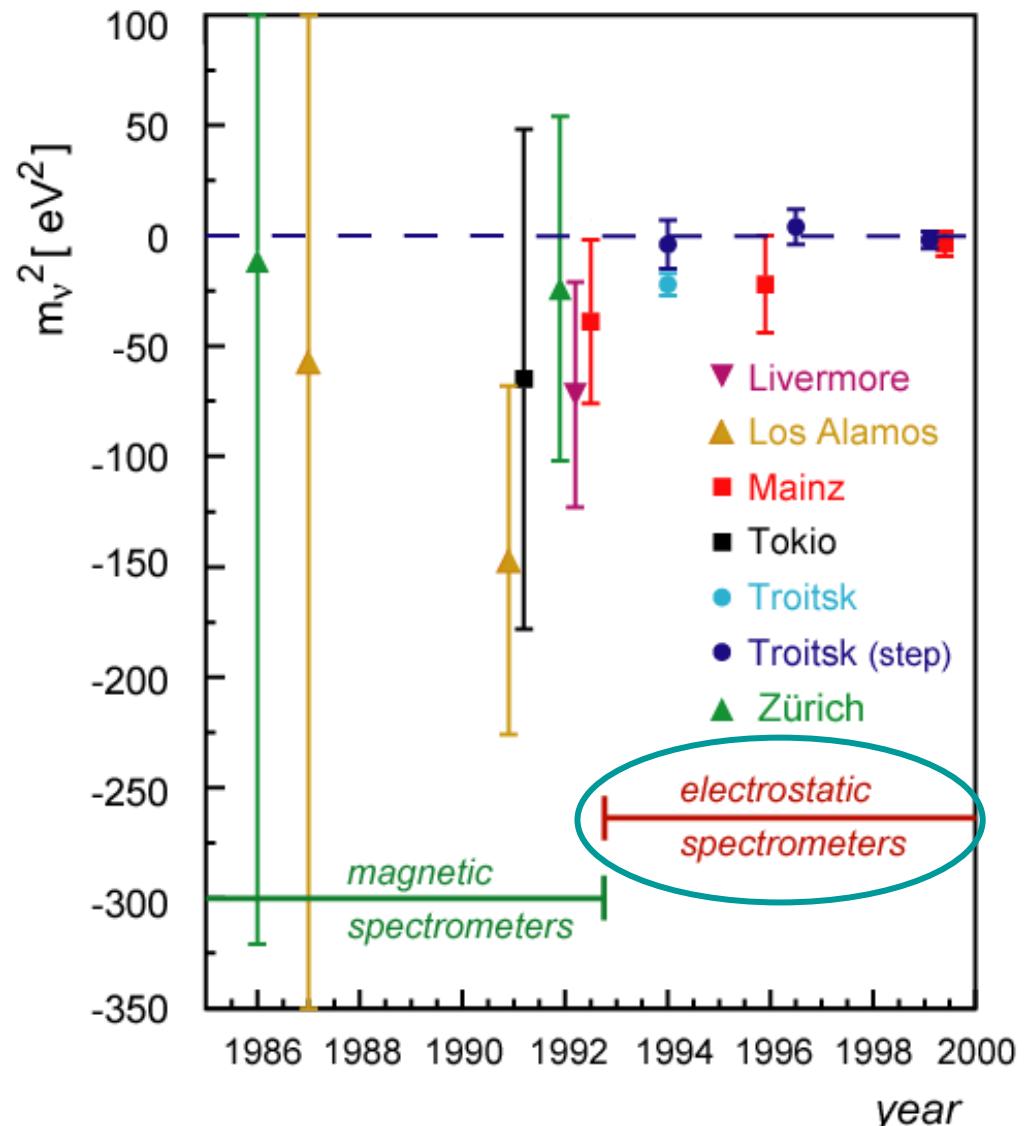
< 7.0 eV

< 11.7 eV

< 2.3 eV

< 2.3 eV

## experimental results for $m_\nu^2$



# MAC-E filter – principle

MAC – Magnetic  
Adiabatic Guiding

adiabatic guiding  
of electrons along  
magnetic field lines

inhomogenous B-field:  
superconducting solenoids

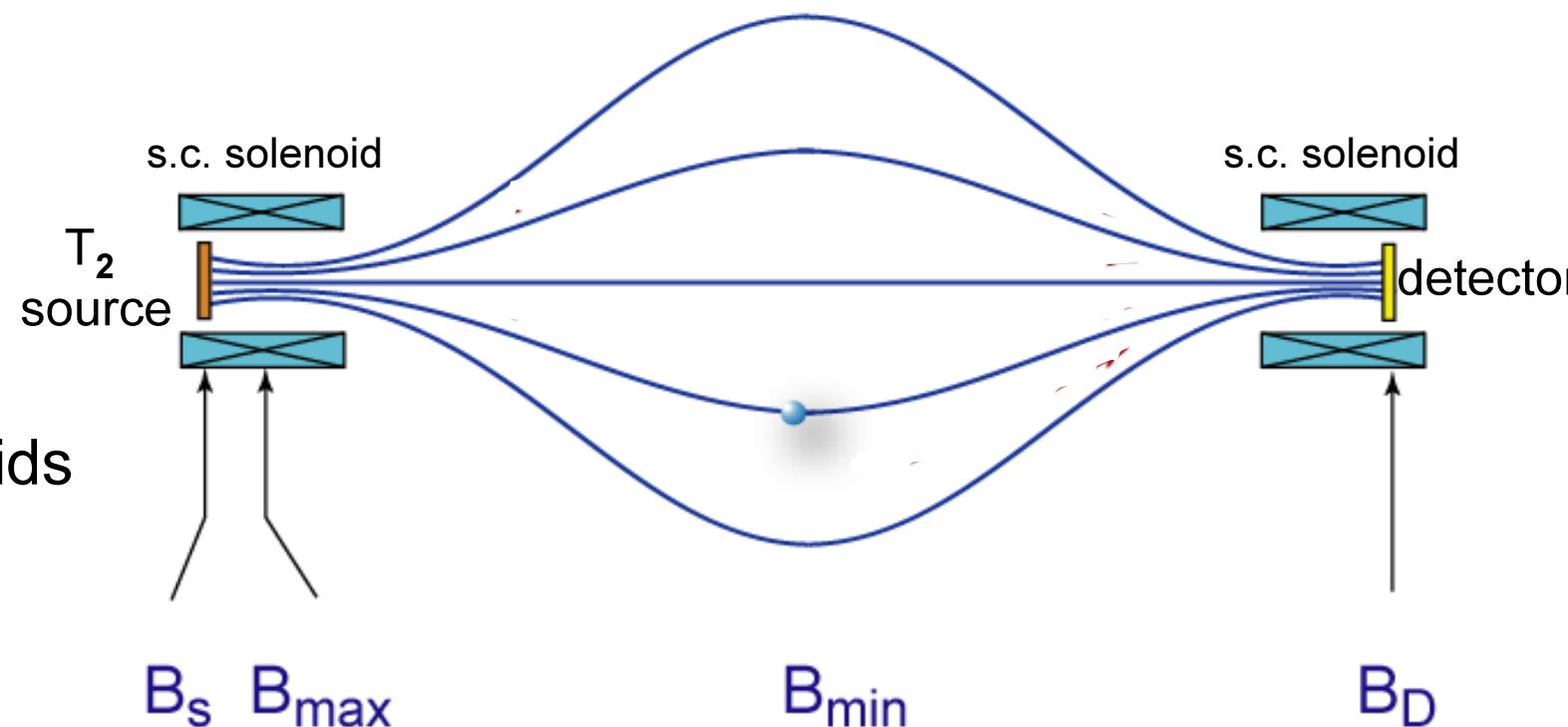
$$B_{\max} = 3 - 6 \text{ T}$$

$$B_{\min} < 1 \text{ mT}$$

**solid angle  $d\Omega \sim 2\pi$**

$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla}) \vec{B} + q \cdot \vec{E}$$

$$\mu = E_{\perp} / B = \text{const.}$$



adiabatic transformation  $E_{\perp} \rightarrow E_{||}$

# MAC-E filter – principle

E Filter – Electrostatic filter

energy analysis by an electrostatic retarding field

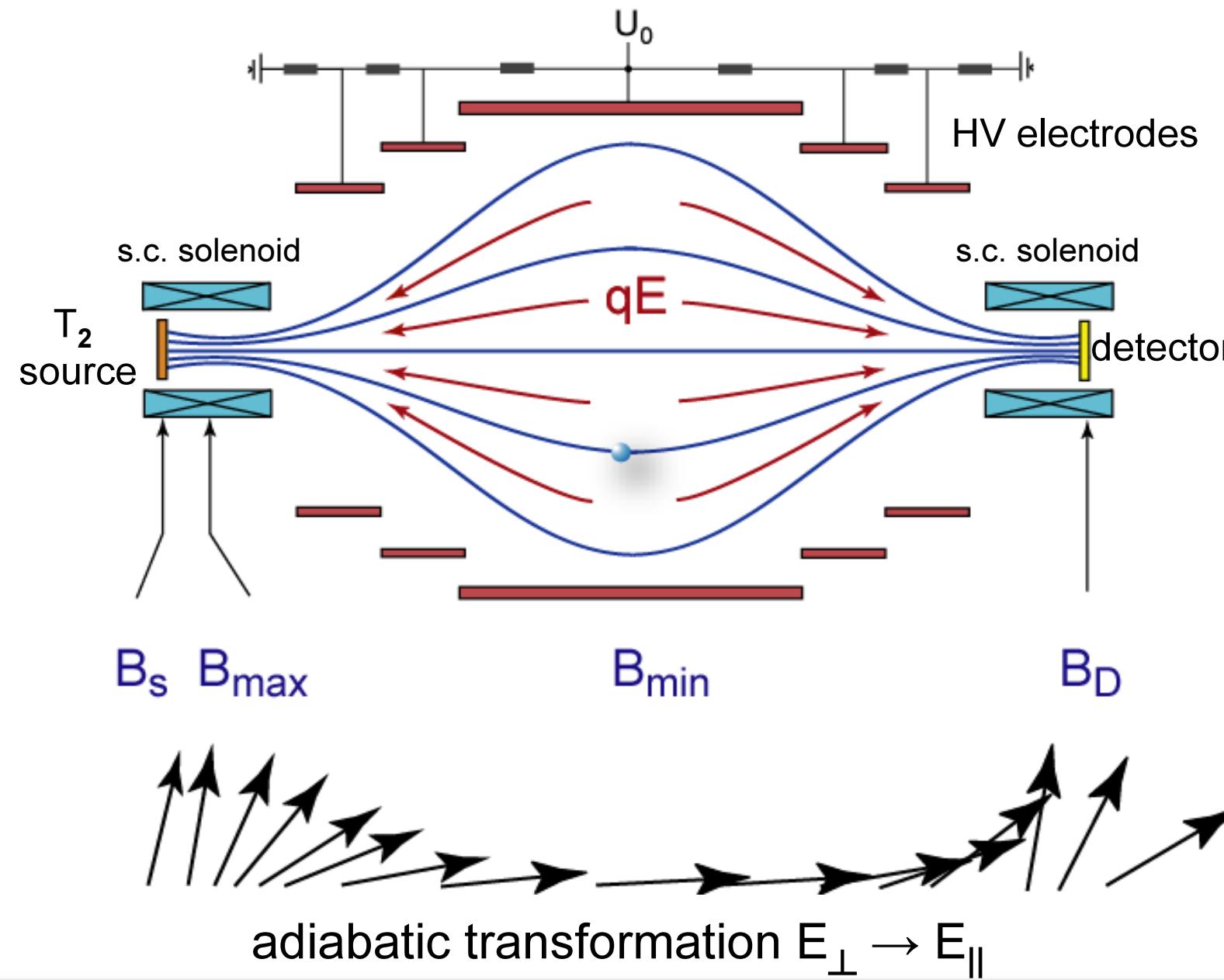
variable E-field:  
inner electrodes

$J_0 = 18.5 - 18.7 \text{ kV}$

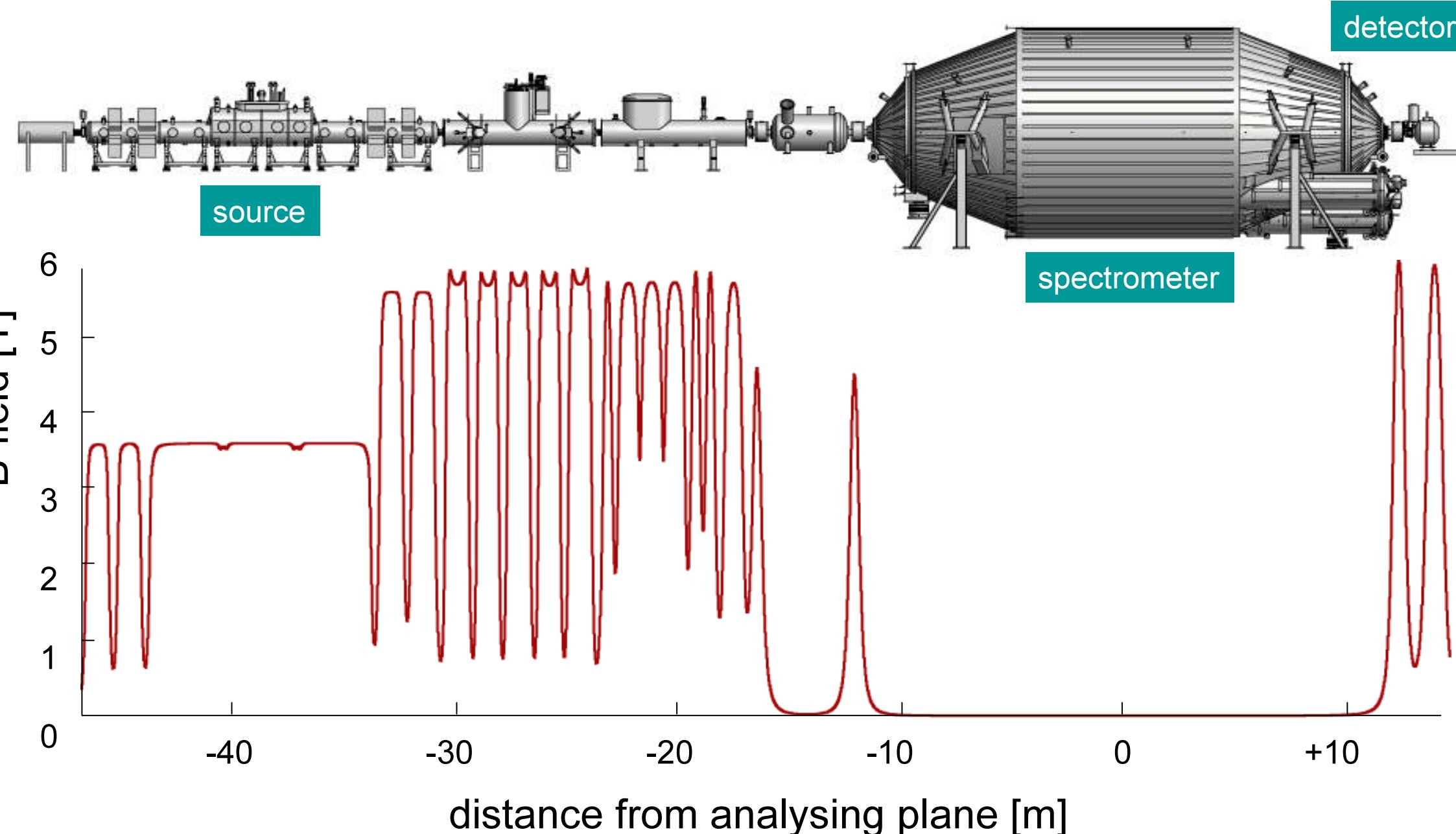
integral transmission  
for  $E > U_0$   
high pass filter

E Feld  $\parallel$  B-Feld

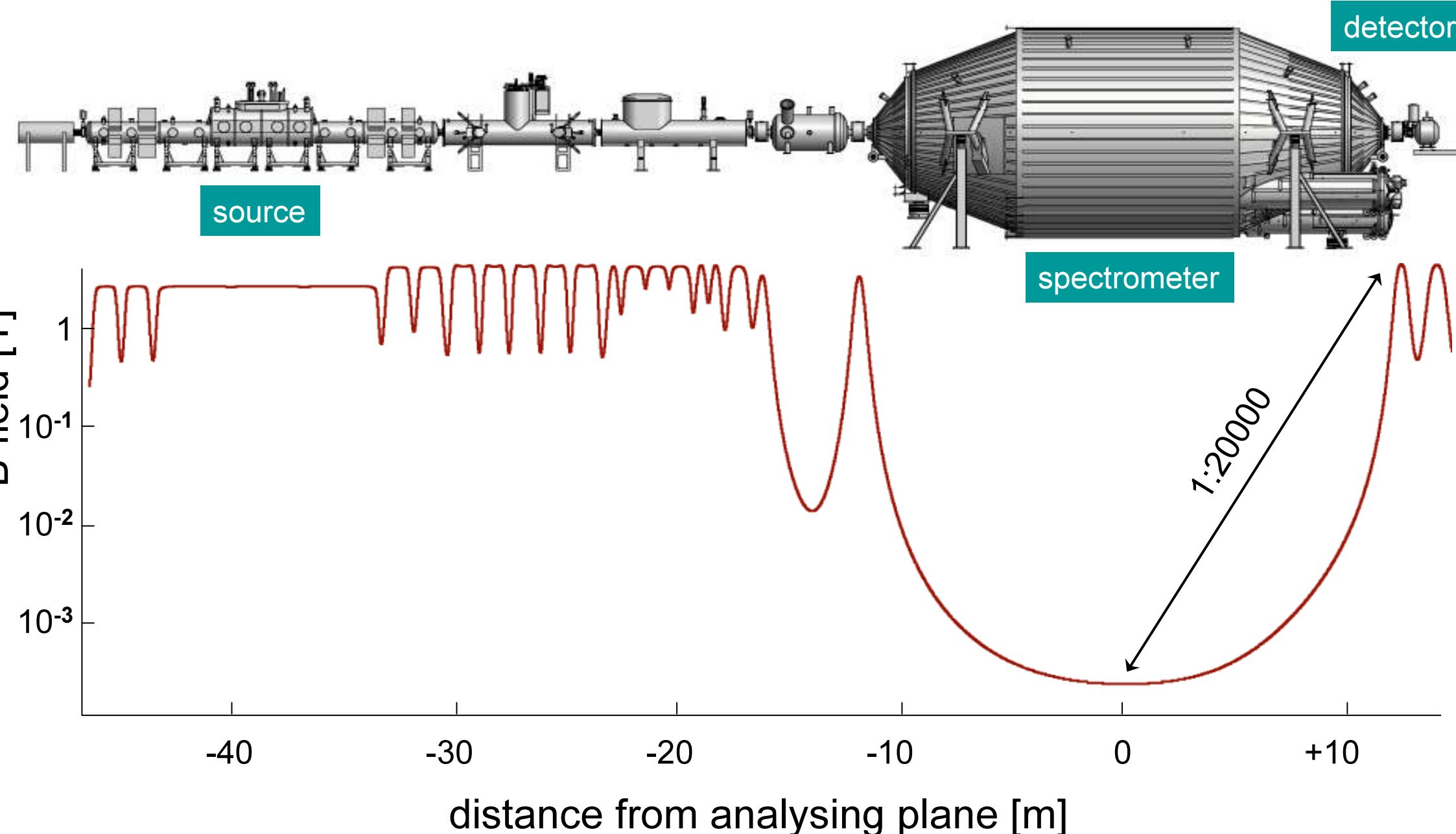
conversion  $\rightarrow$  retarding



# KATRIN – magnetic field map (linear)



# KATRIN – magnetic field map (logarithmic)



# KATRIN – design considerations

experimental observable in  $\beta$ -decay is square of  $\nu$ -mass  $m_\nu^2$

**aim:** improve sensitivity for  $m_\nu$  by 1 order of magnitude ( $2 \text{ eV} \rightarrow 0.2 \text{ eV}$ )  
requires improvement for  $m_\nu^2$  by 2 orders of magnitude ( $4 \text{ eV}^2 \rightarrow 0.04 \text{ eV}^2$ )

## statistics

count rate at  $\beta$ -endpoint falls off very steeply ( $\sim \delta E^3$ ), small background!

### Improvement of statistics ( $\times 10^3$ ):

- stronger tritium source (factor 80)  $\Rightarrow$  larger analysing plane ( $\varnothing = 10 \text{ m}$ )
- longer measuring period ( $\sim 100 \text{ days} \rightarrow \sim 1000 \text{ days}$ )

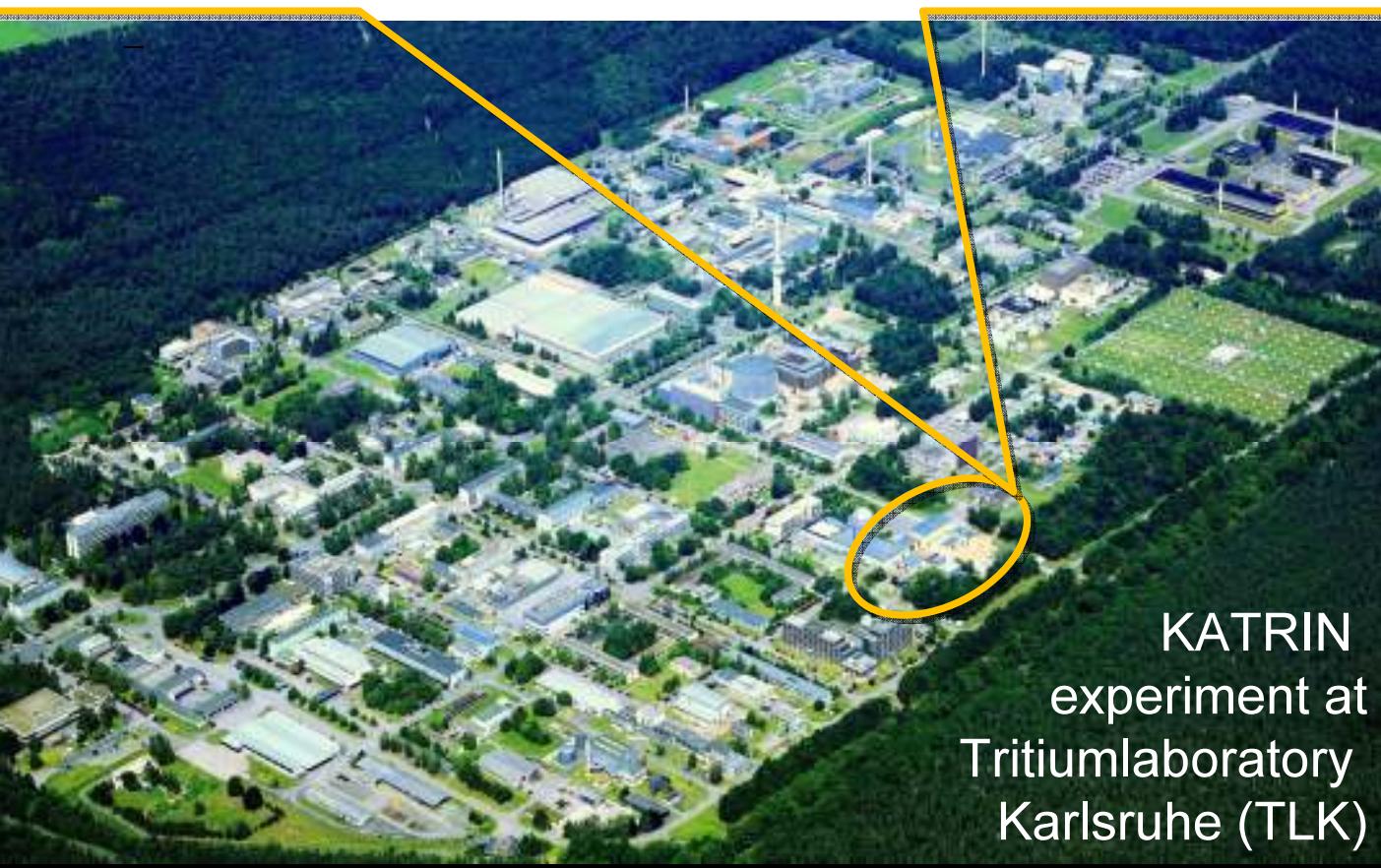
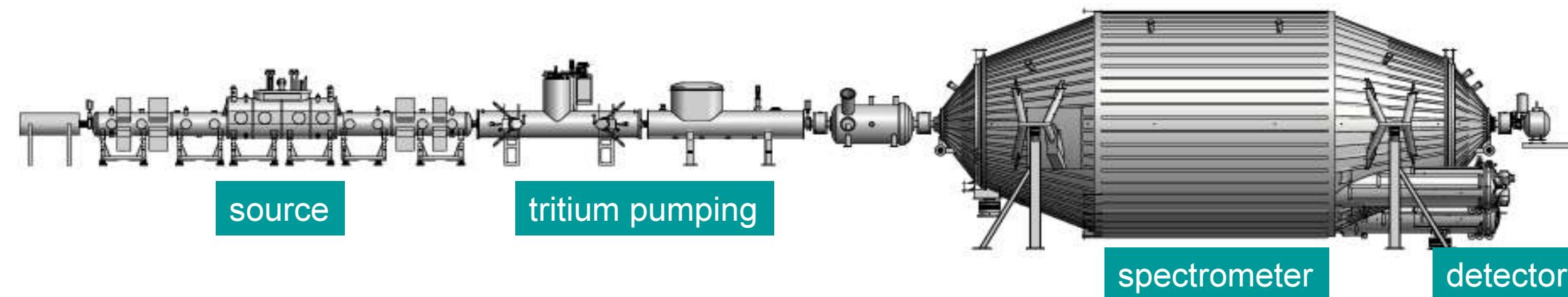
## systematics

**aim:** systematic uncertainties  $\equiv$  statistical errors

### Improvement of systematics ( $\times 0.1$ )

- improved energy resolution spectrometer with  $\Delta E = 0.93 \text{ eV}$  (factor 4)
- reduced systematic errors for energy losses in source, slow control, HV, ...

# KATRIN at Tritium Laboratory Karlsruhe



TLK offers unique expertise  
in tritium handling techniques  
required for closed cycles of  
- ITER  
- KATRIN

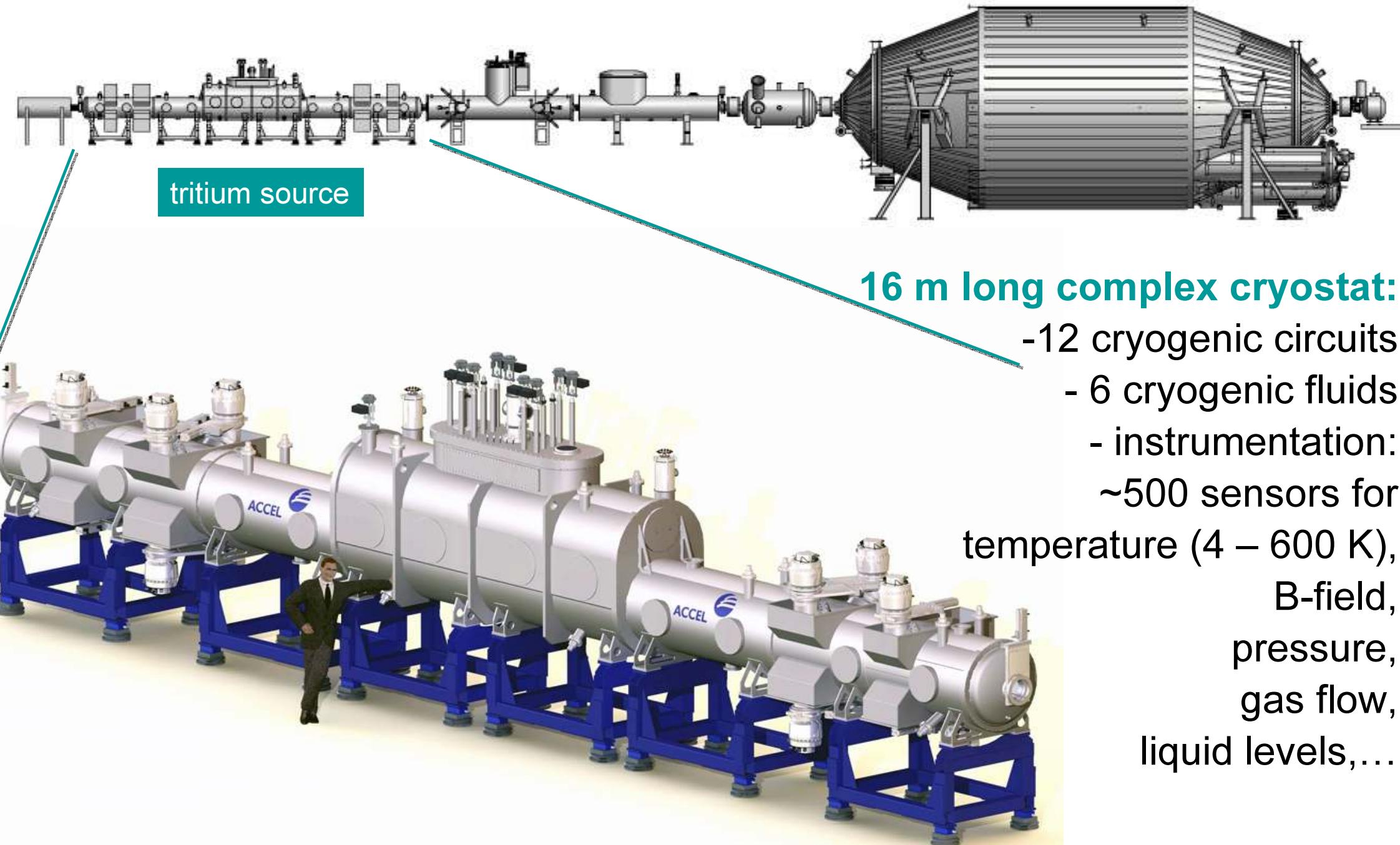
# KATRIN at Tritium Laboratory Karlsruhe



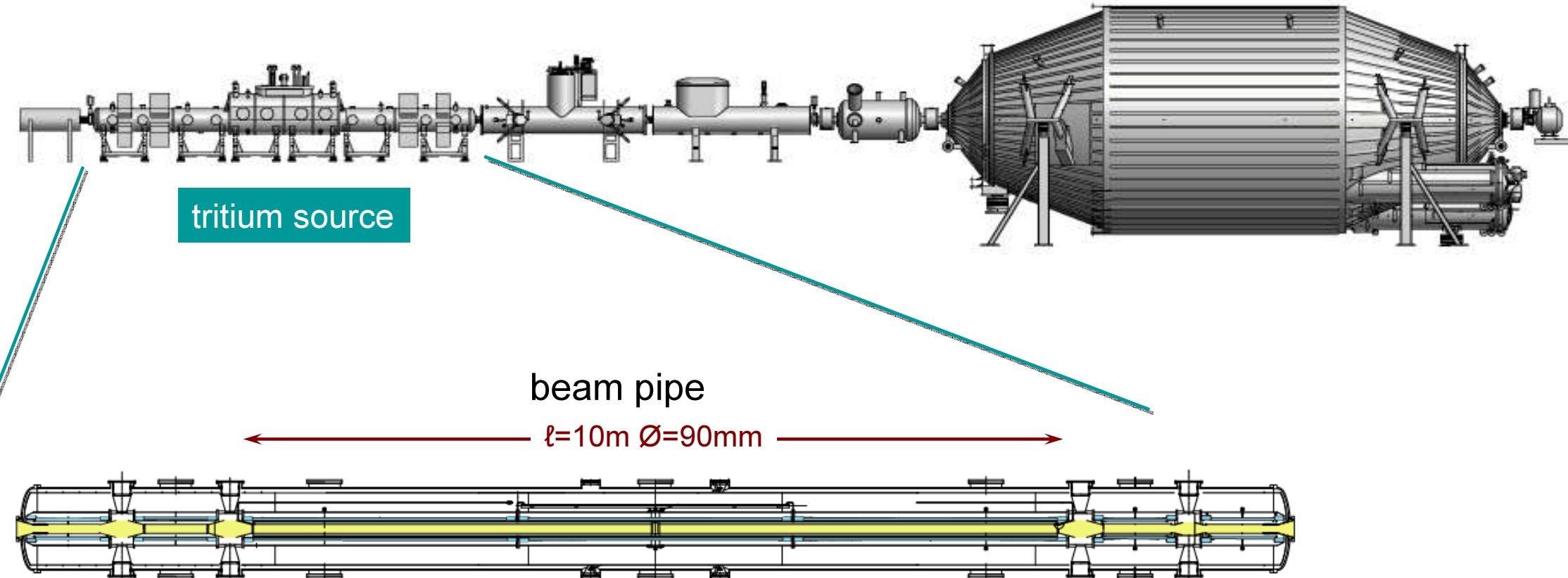
TLK offers unique expertise  
in tritium handling techniques  
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- ITER
- KATRIN

# KATRIN – windowless gaseous source



# KATRIN – windowless gaseous source



## WGTS

## design value

## precision

luminosity	$1.7 \times 10^{11} \text{ Bq}$	
injection rate	$5 \times 10^{19} \text{ mol/s}$	$\pm 0.1 \%$
column density pd	$5 \times 10^{17} \text{ mol/cm}^2$	$\pm 0.1 \%$
tritium purity	> 95%	
magnetic field	3.6 T	$\pm 2\%$

key technological challenge:  
precise cooling of beam tube

temperature stabilisation  
of beam tube of  $10^{-3}$

# beam tube cooling concept & demonstrator



stainless steel  
beam tube  
 $\varnothing=90\text{mm}$

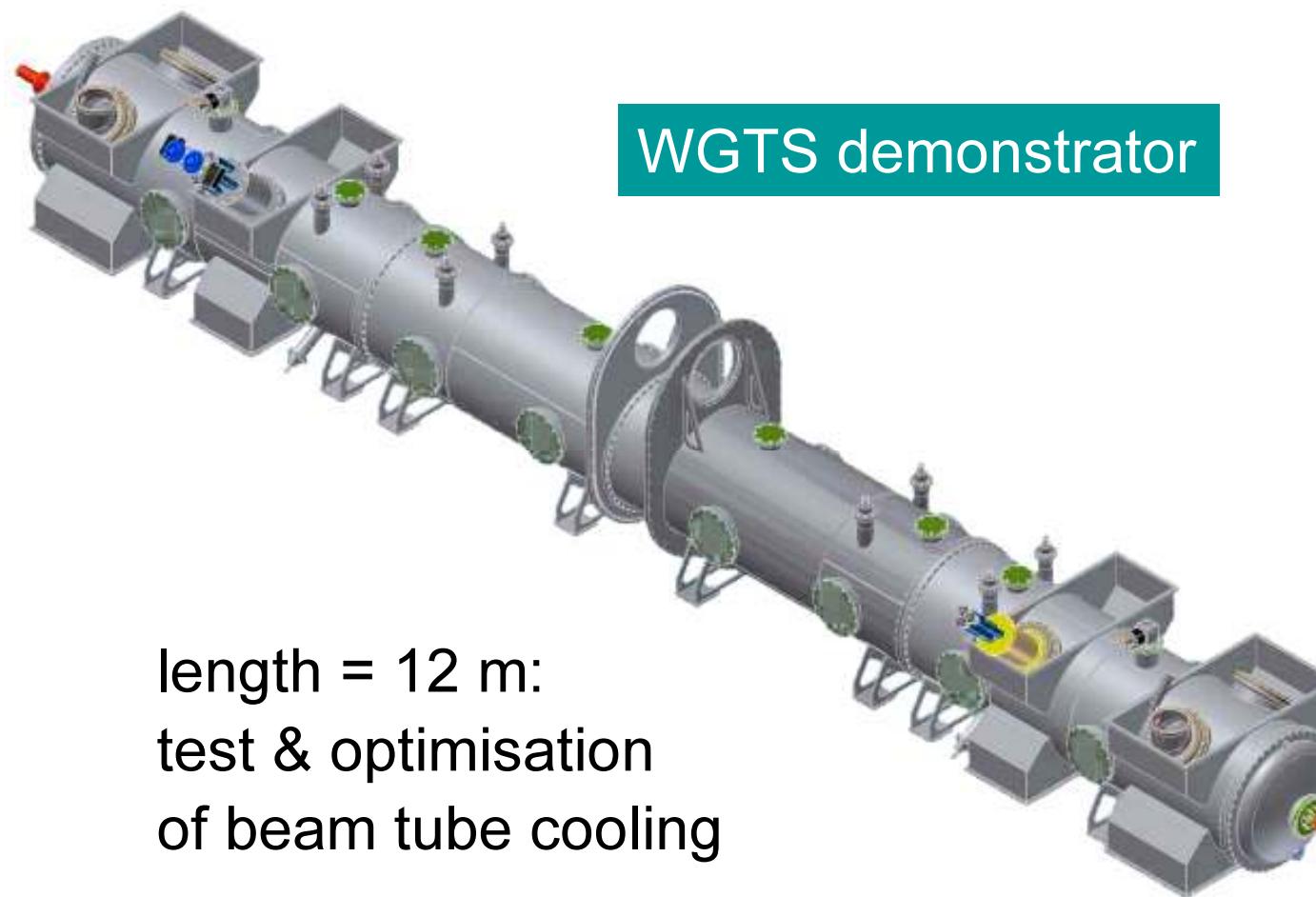
-phase  
Neon

2-phase  
Neon

principle for stabilisation at  $T = 27 \text{ K}$

$\Delta T < \pm 30 \text{ mK}$ : spatial homogeneity, time stability (1h)

2 separate cooling pipes ( $\varnothing=16\text{mm}$ ) with  
boiling LNe at  $p = 1 \text{ bar}$  (thermosiphon



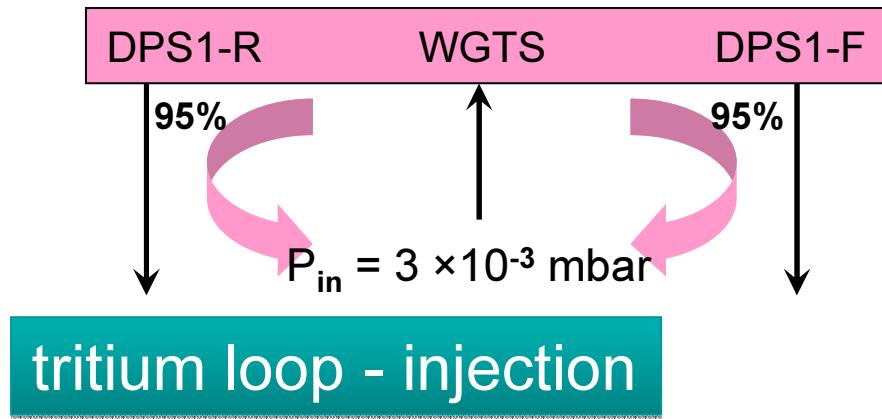
WGTS demonstrator

length = 12 m:  
test & optimisation  
of beam tube cooling

# WGTS cryostat – manufacture

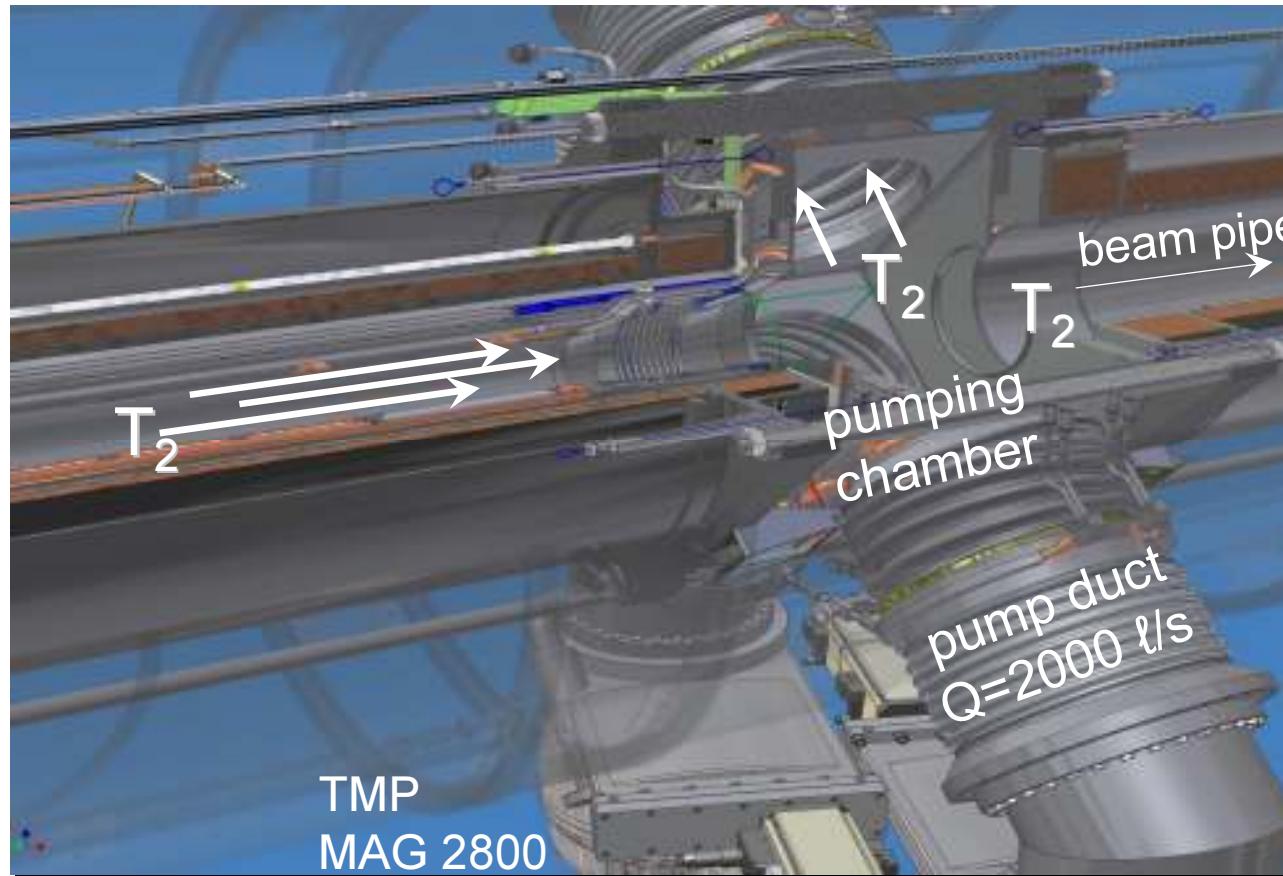
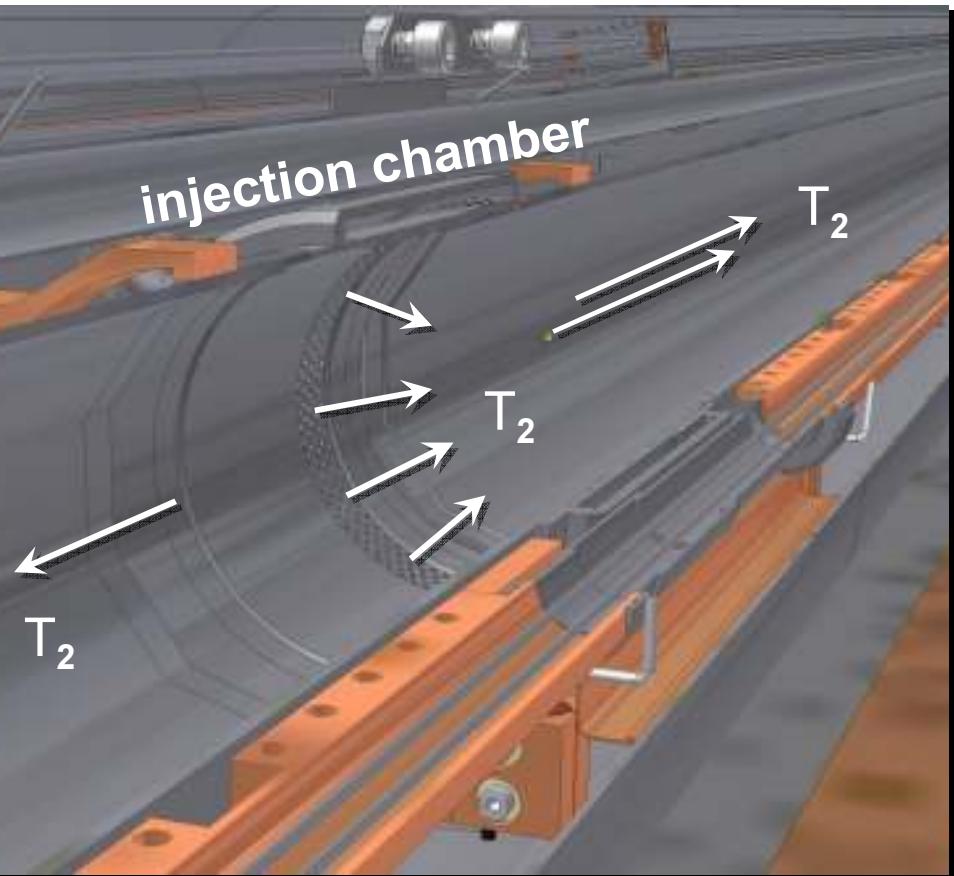


# WGTS – tritium injection & pumping

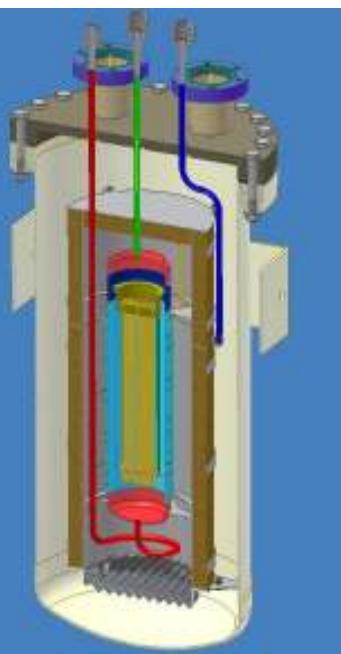
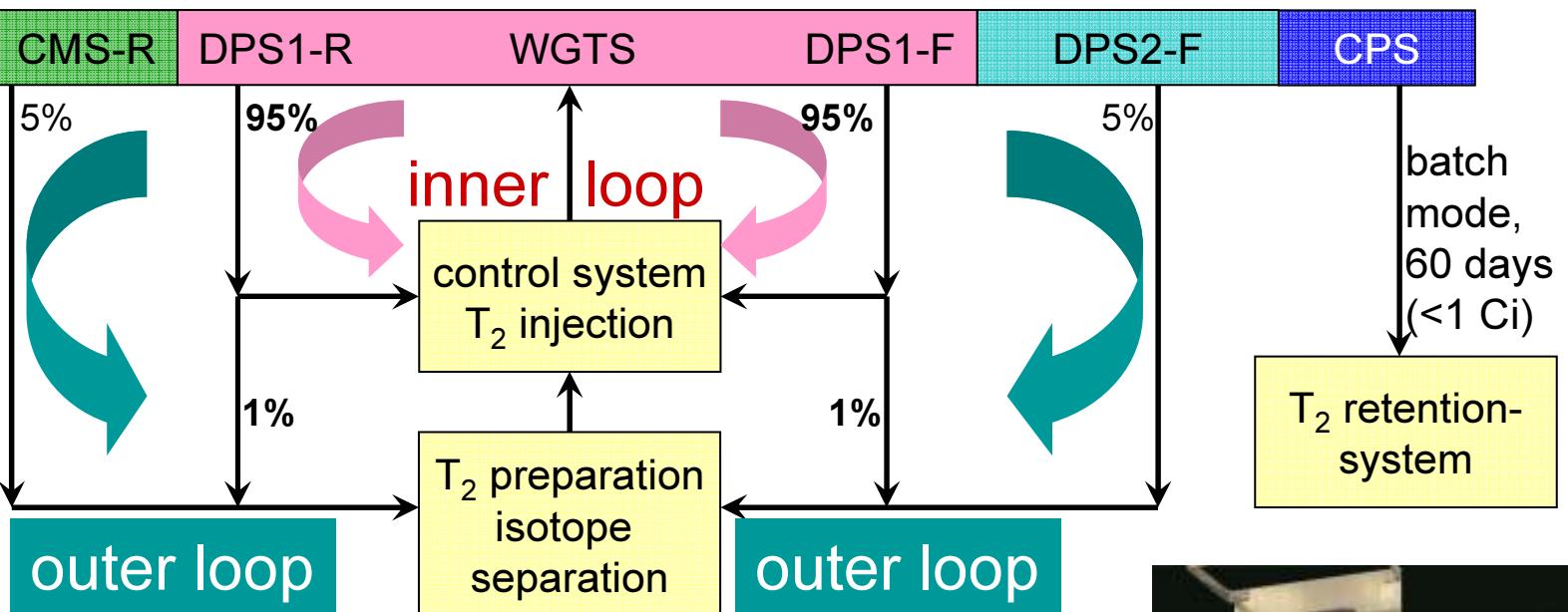


**injection rate:**  $5 \times 10^{19}$  molecules/s  
 $= 40\text{ g T}_2/\text{day}$  ( $\sim 2$  TLK inventory/day)  
 **$\beta$ -intensity:**  $= 4.7 \text{ Ci/s} = 1.7 \times 10^{11} \text{ Bq}$

**tritium loop – first pumping port**



# WGTS – closed tritium cycle



permeator

- 27 pumps
- 109 valves
- 62 sensors
- 2 permeators
- 6 pressure vessels

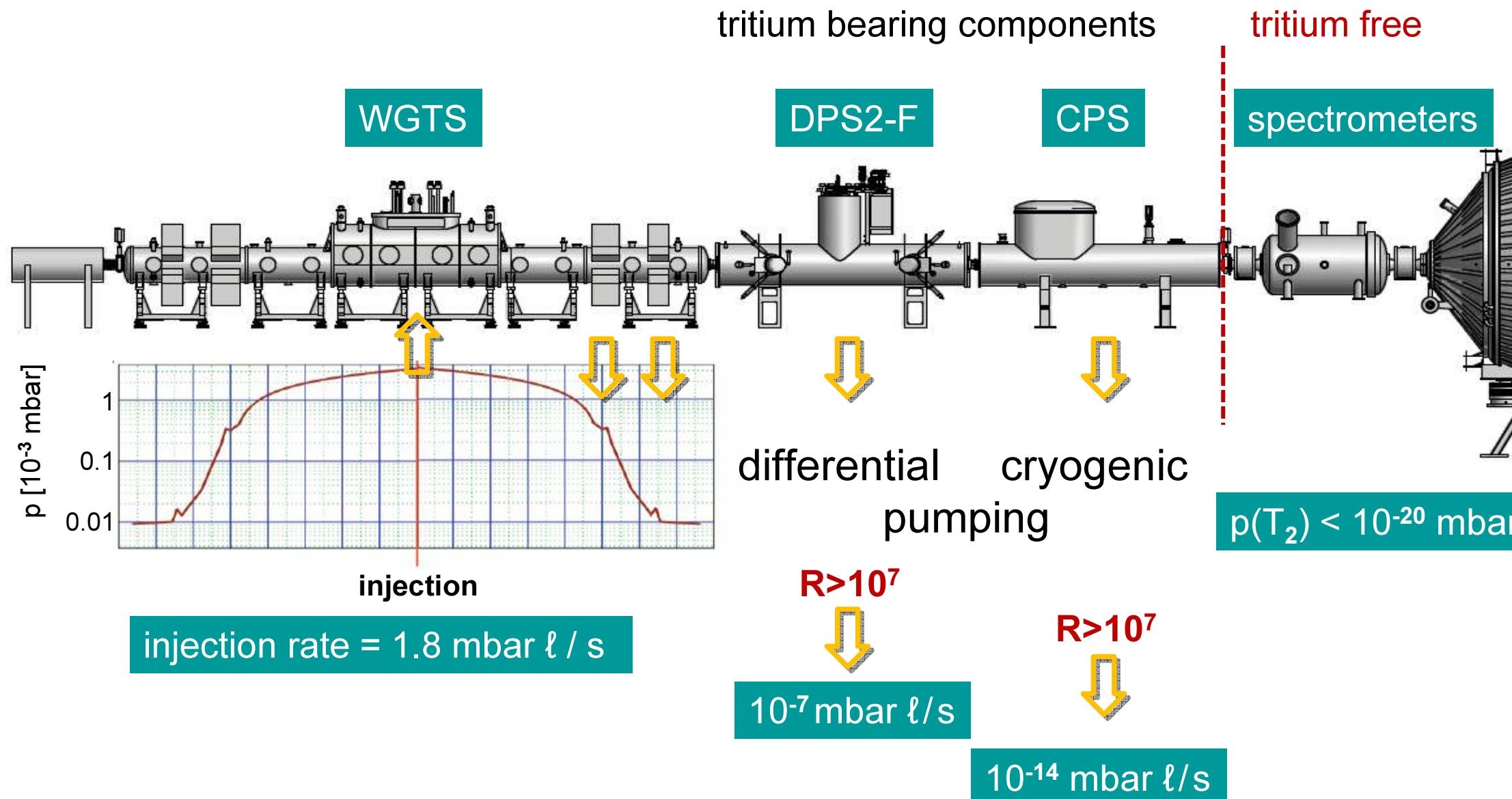


ISS glove box

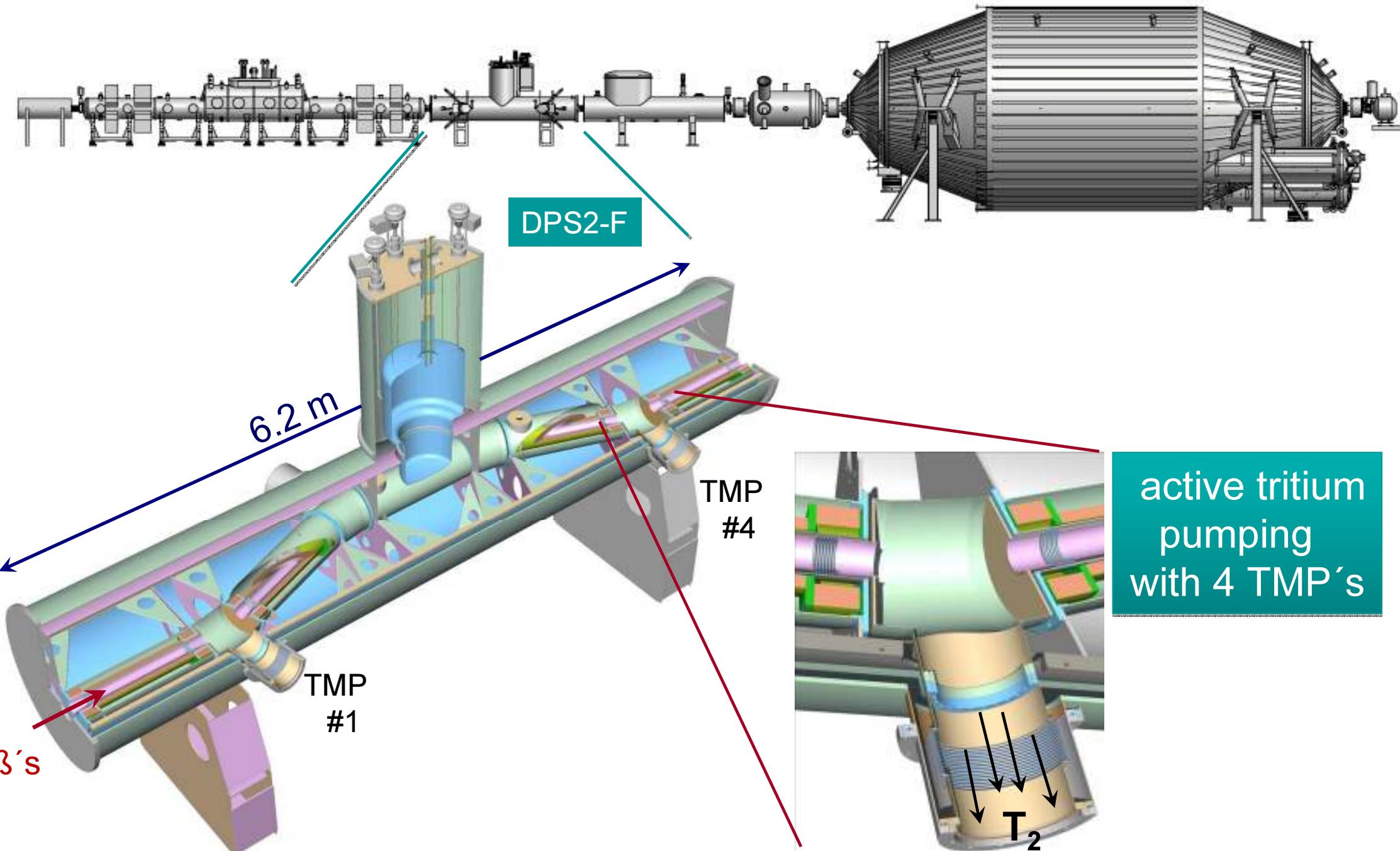


# tritium reduction

the tritium flow out of the WGTS has to be reduced by **factor  $\sim 10^{14}$**



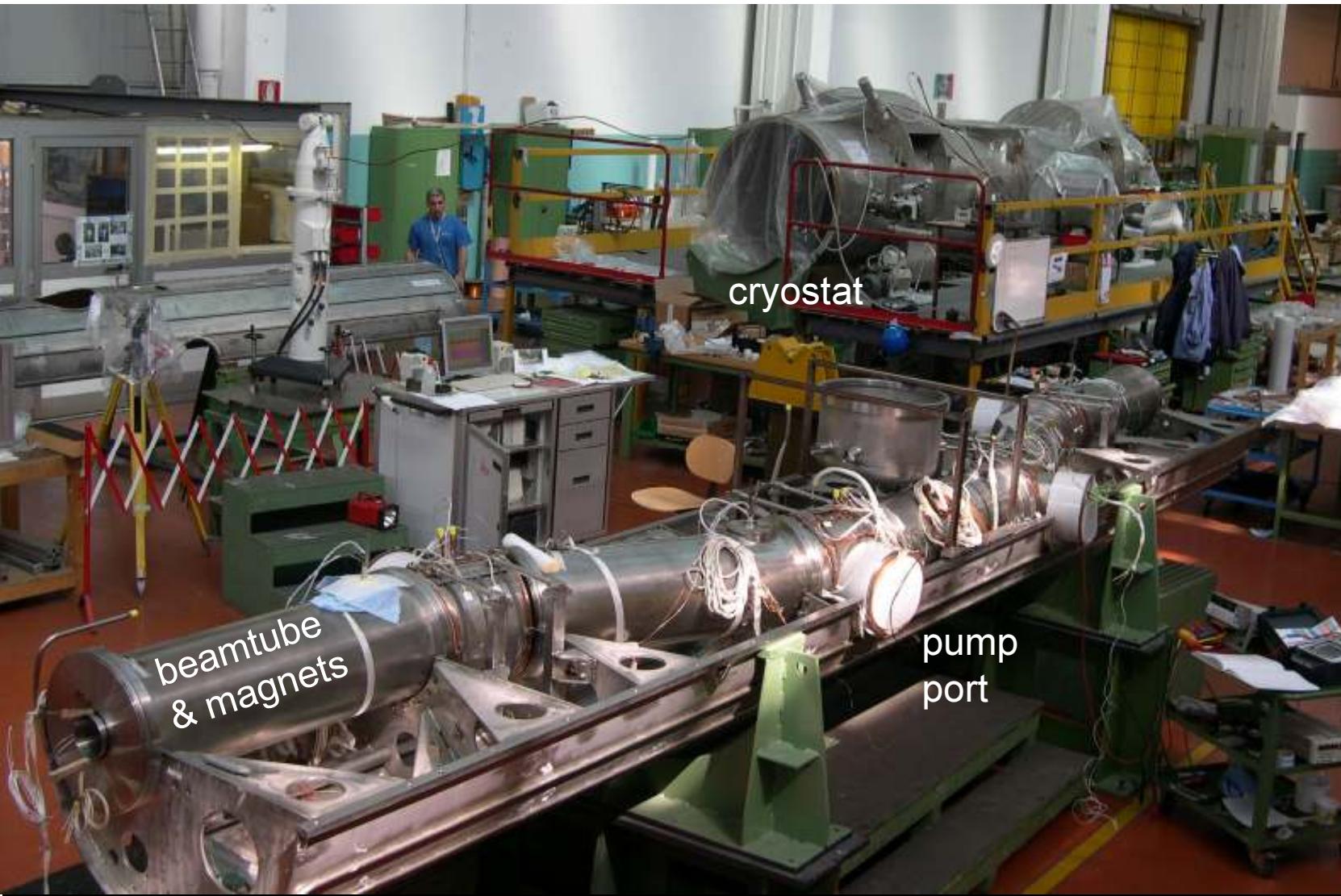
# differential pumping section DPS2-F



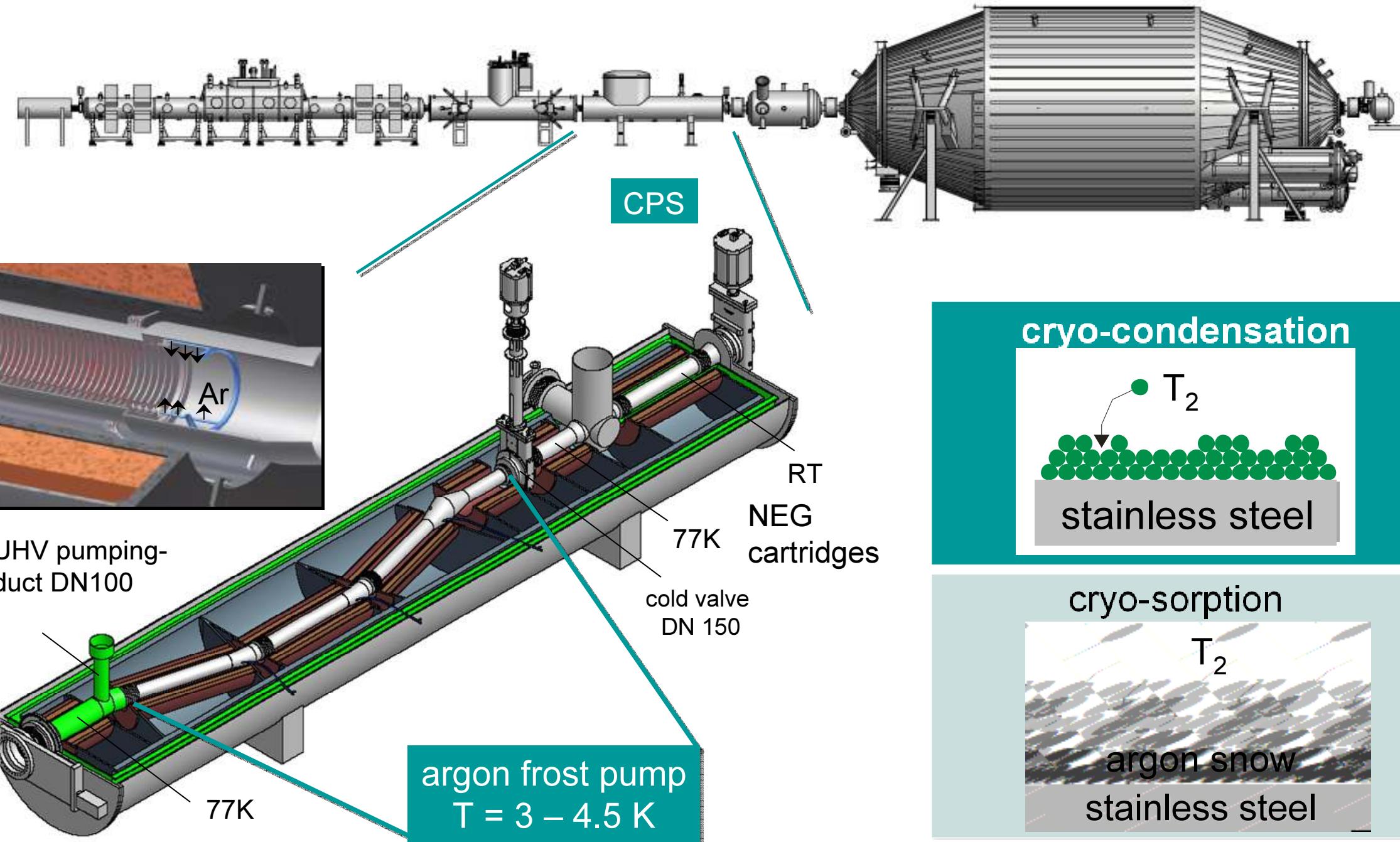
# DPS2-F: manufacture

**status DPS2-F:** cryostat: final assembly & cold test at ASG (Genua)

**delivery to TLK:** September 2008, tests of pumping & electron optics



# cryogenic pumping section CPS



# cryogenic pumping section CPS

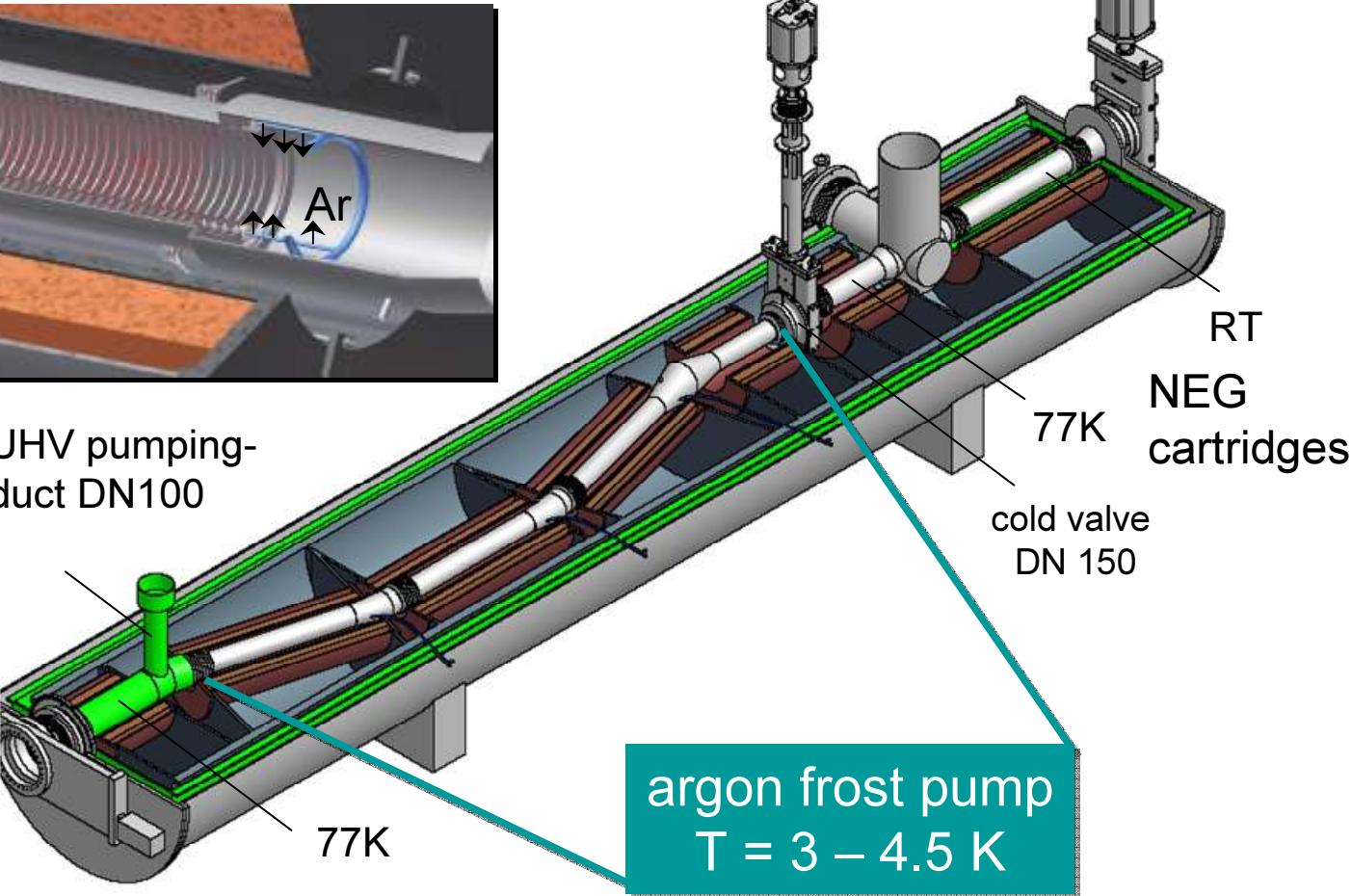
**objective:** reduction of  $T_2$ -flux by factor  $10^7$  :  $10^{-7}$  mbar l/s  $\rightarrow 10^{-14}$  mbar l/s

↳  $T_2$ -partial pressure in spectrometer:  $p < 10^{-20}$  mbar

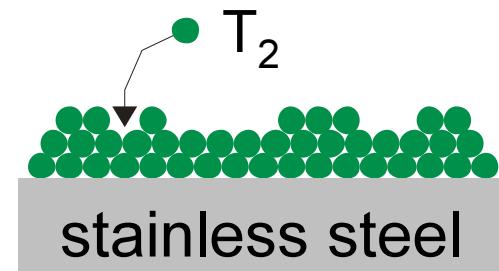
**method:** cryo-sorption on condensing Ar-frost

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

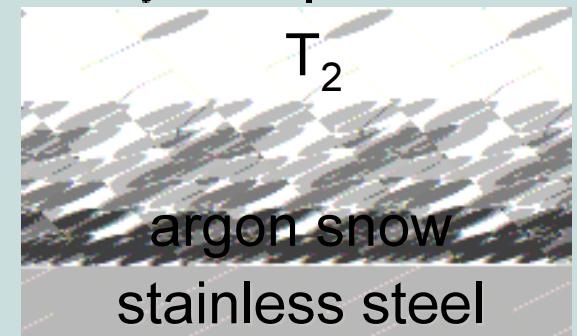
order placed  
May, 19



**cryo-condensation**

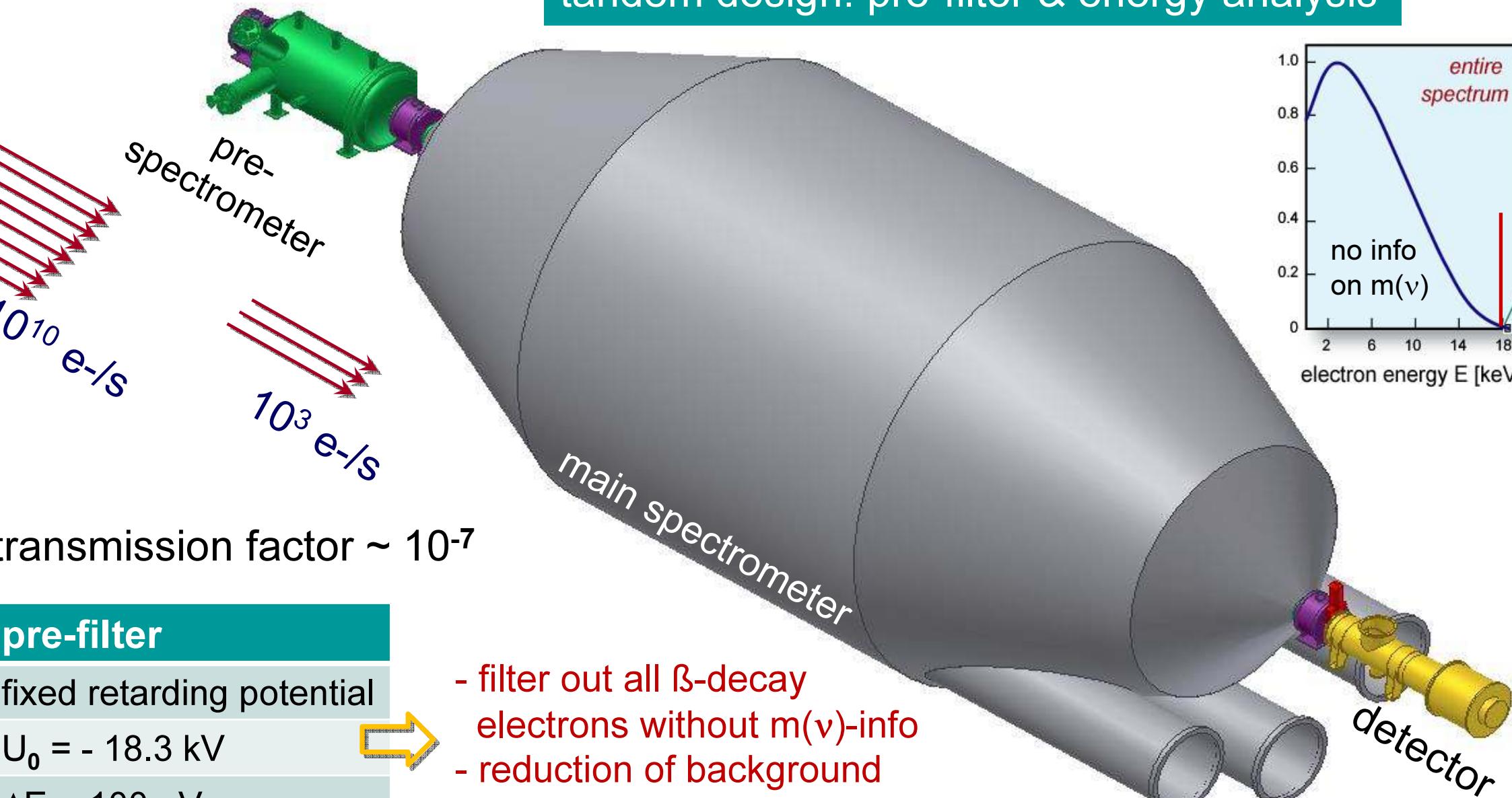


**cryo-sorption**



# electrostatic spectrometers

tandem design: pre-filter & energy analysis



transmission factor  $\sim 10^{-7}$

## pre-filter

fixed retarding potential

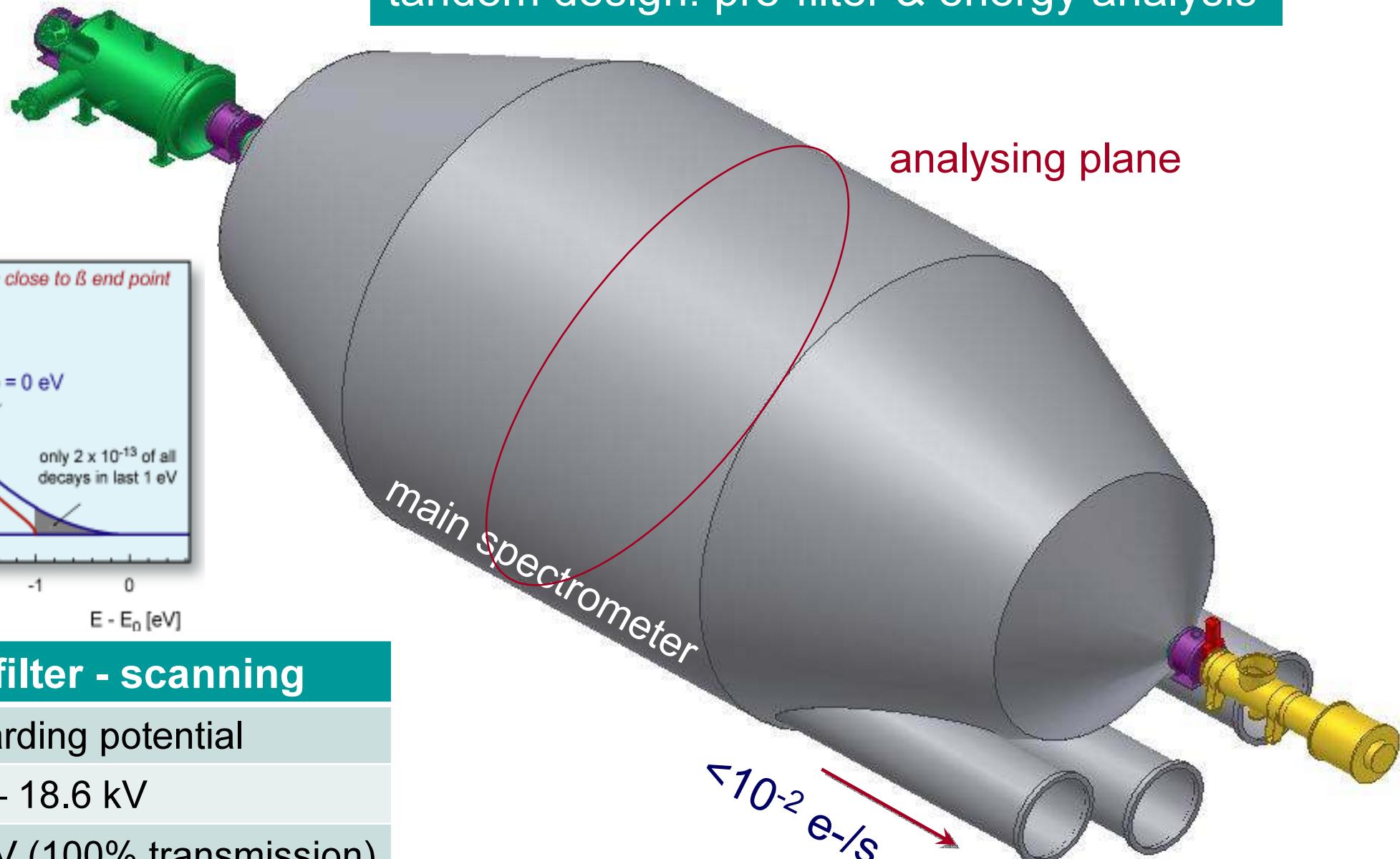
$$U_0 = -18.3 \text{ kV}$$

$$\Delta E \sim 100 \text{ eV}$$

- filter out all  $\beta$ -decay electrons without  $m(v)$ -info
- reduction of background from ionising collisions

# electrostatic spectrometers

tandem design: pre-filter & energy analysis



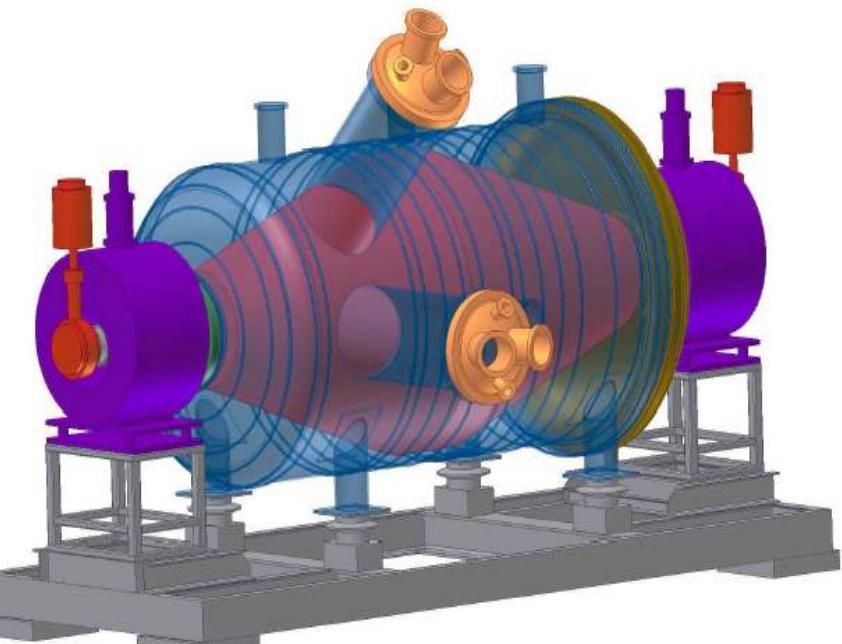
## precision filter - scanning

variable retarding potential

$U_0 = -18.4 - 18.6 \text{ kV}$

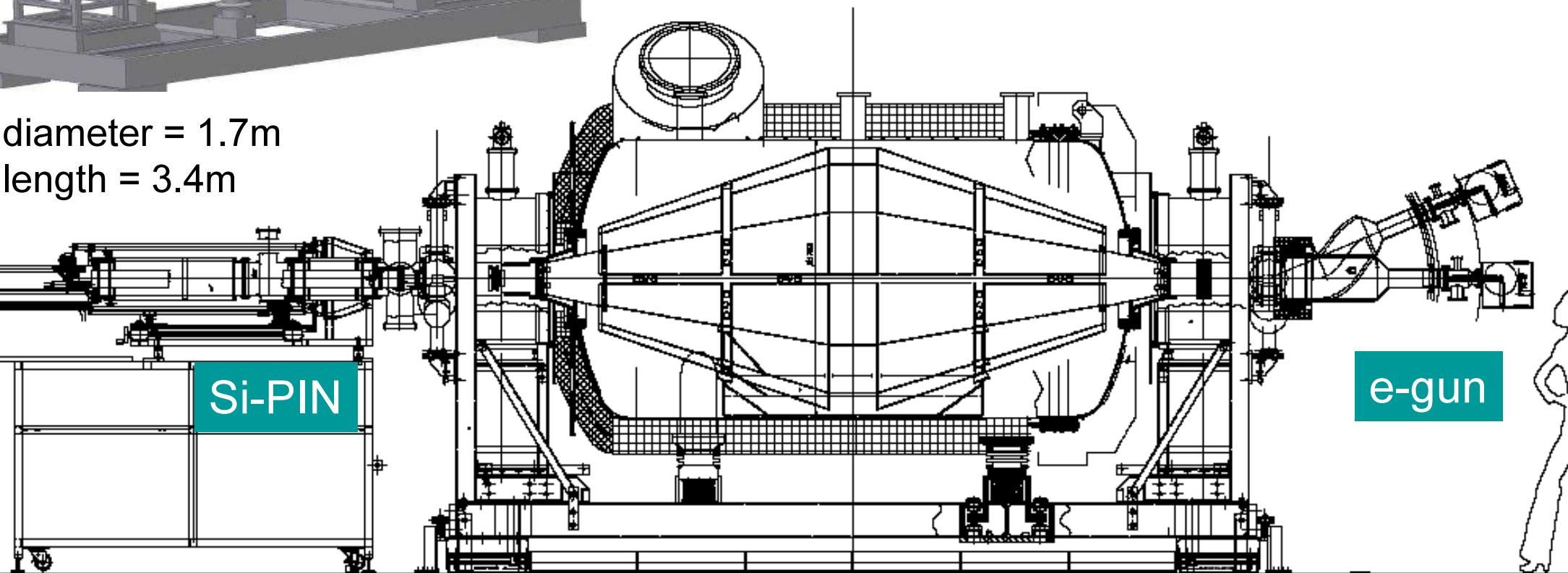
$\Delta E \sim 0.93 \text{ eV}$  (100% transmission)

# pre-spectrometer: electromagnetic tests



diameter = 1.7m  
length = 3.4m

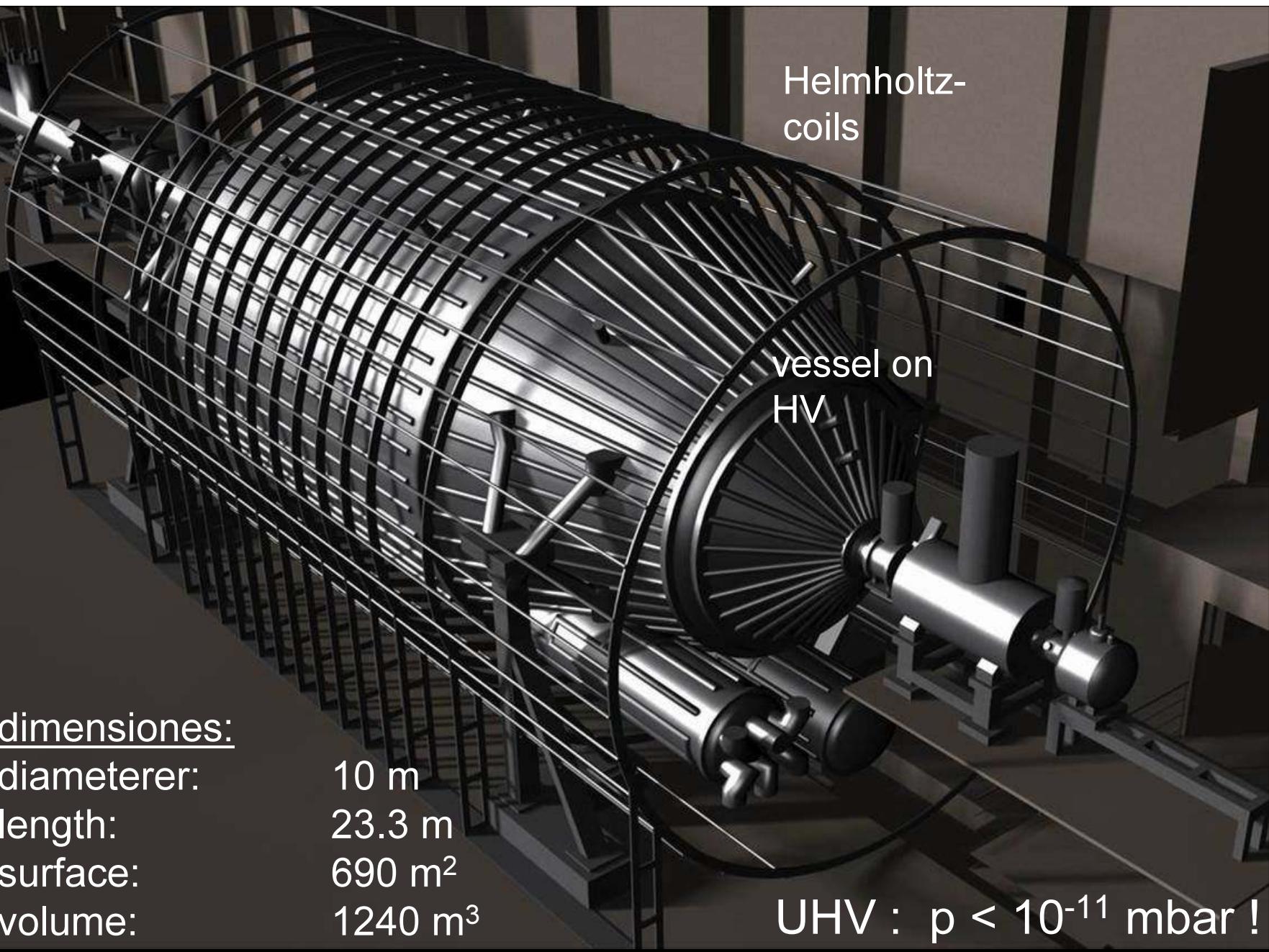
since 2006:  
optimisation of electromagnetic design  
- measurement of transmission function  
- study of Penning traps  
- background reduction



# main spectrometer: world's largest UHV recipient



MAN DWE GmbH



# main spectrometer: pre-acceptance tests

initial integral He-leak test and pressure test at manufacturer MAN-DWE



August 2006

1 TMP (WMAG2800)

$p < 6 \times 10^{-8}$  mbar



# main spectrometer: transport



# main spectrometer: transport



# main spectrometer: transport



# main spectrometer: transport



# main spectrometer: transport



# main spectrometer: transport



# the final 7km

November 25, 2006: after 8800 km only another 7km to the final destination at the KATRIN experimental halls...  
(30.000 visitors)



Arrival at Leimersheim ferry & reloading  
onto SPMT with heavy-duty crane



BBC NEWS

## In pictures: photos of the year 2006

The main spectrometer of the Karlsruhe Tritium Neutrino Experiment (KATRIN) is manoeuvred through Leopoldshafen in southern Germany.



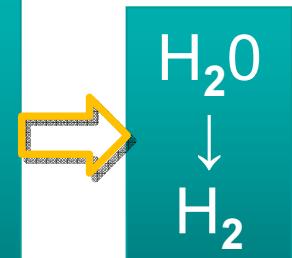
# the final 7m, initial out-baking & UHV



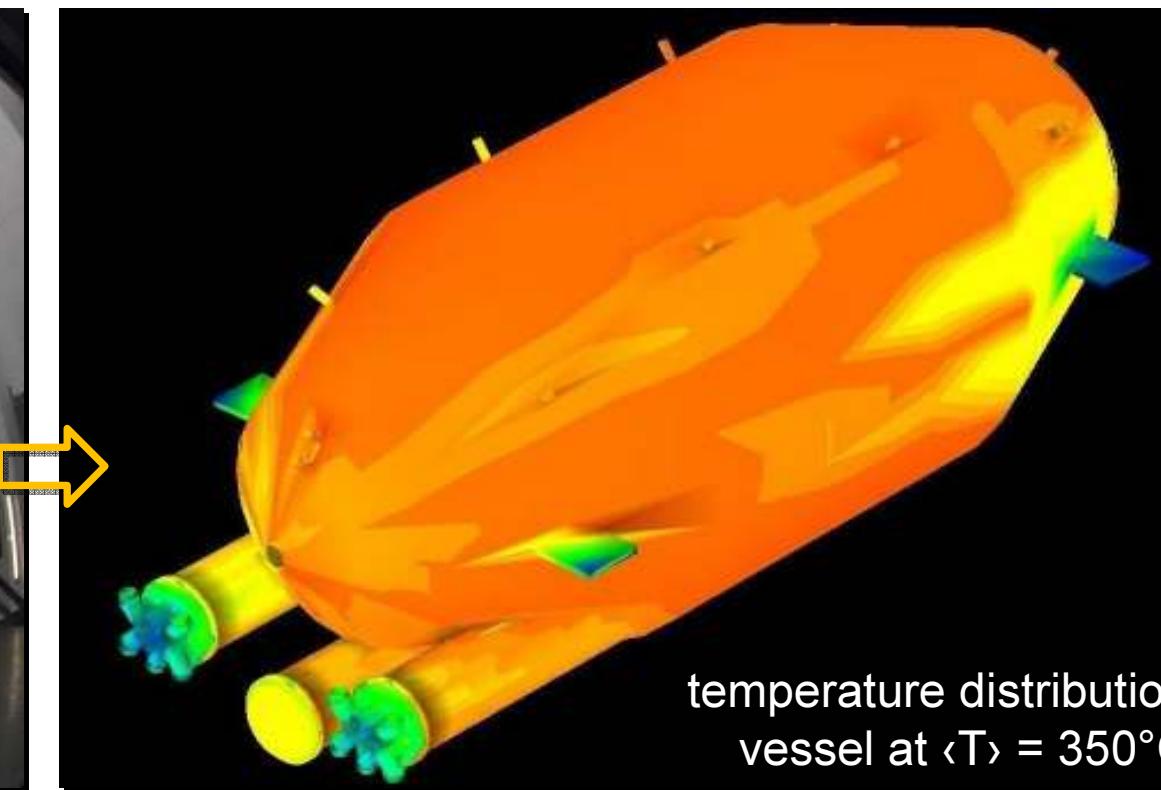
steam  
blasting

July 2007: initial UHV tests of vessel  
after out-baking with 6 TMPs

outgassing rate [  $T = 20^\circ\text{C}$  ]  
 $1.18 \times 10^{-12} \text{ mbar l / cm}^2 \text{ s}$   
 $p = 10^{-10} \text{ mbar}$



November 29, 2006



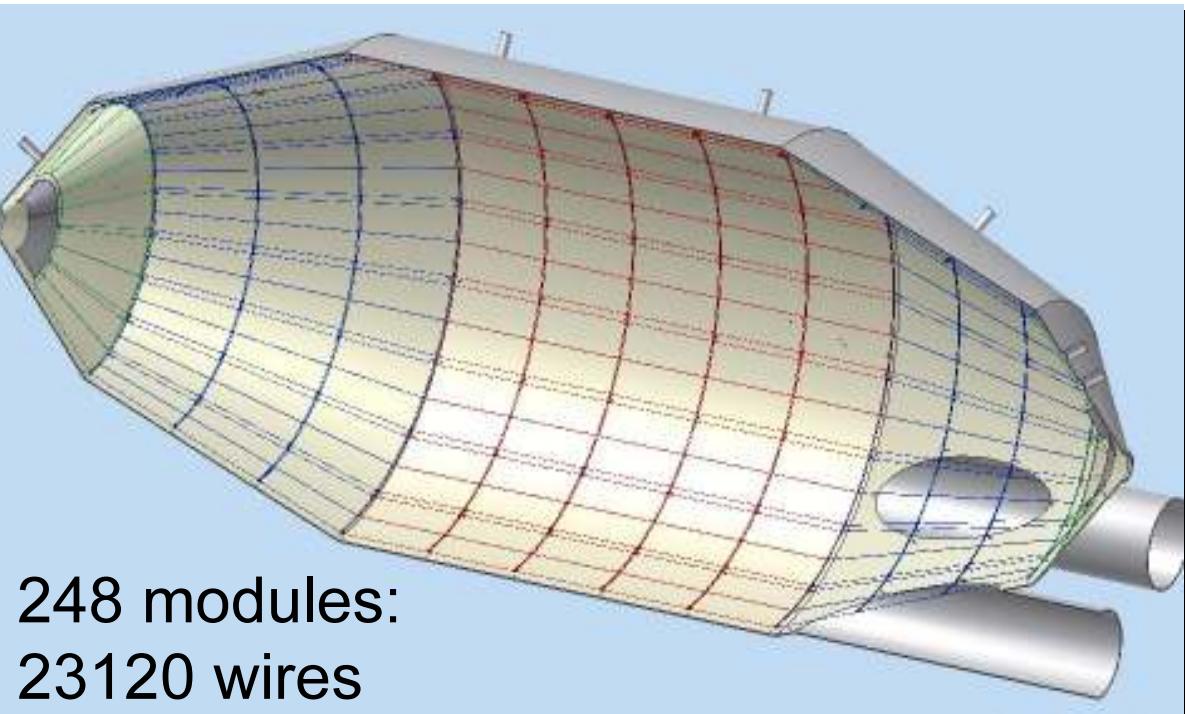
temperature distribution  
vessel at  $\langle T \rangle = 350^\circ\text{C}$

# inner electrode system

spectrometer inner surface: covered by a 'massless' inner wire-based electrode

## #1: fine forming electric field

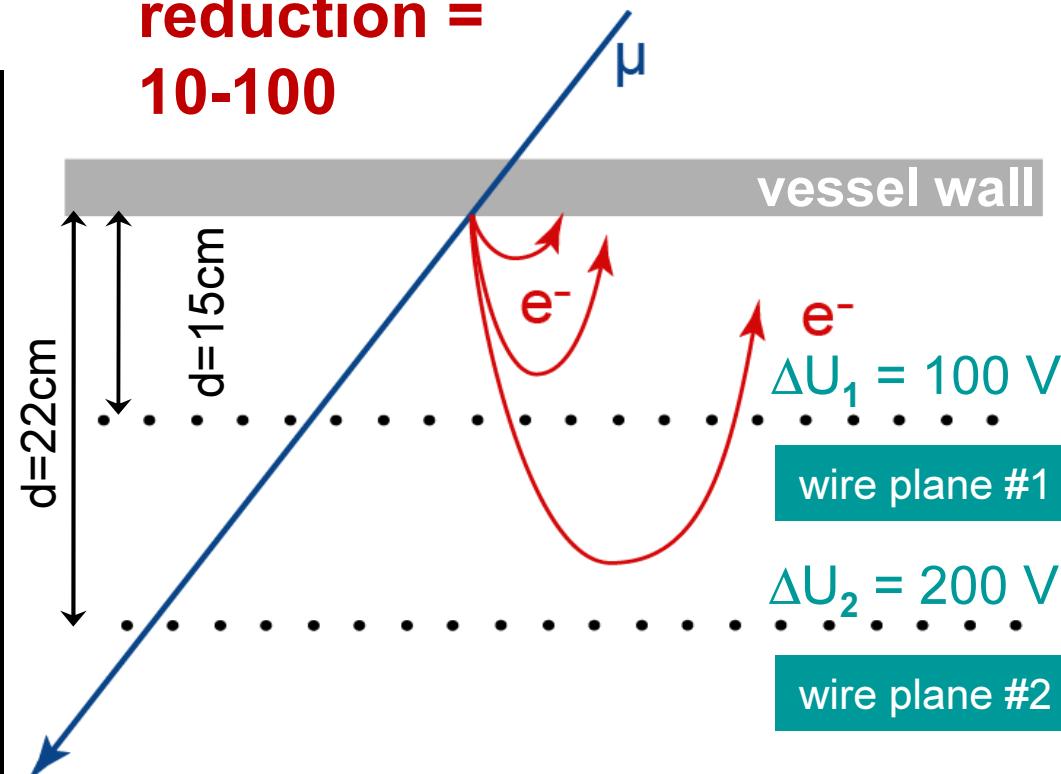
- precision-HV-supplies
- measurements with 1ppm
- dipole mode to empty stored
- electrons in Penning traps



## #2: background suppression

- inelastic reactions of cosmic muons
- ↳ low-energy secondary electrons
- from 690 m<sup>2</sup> large inner surface

**reduction =  
10-100**



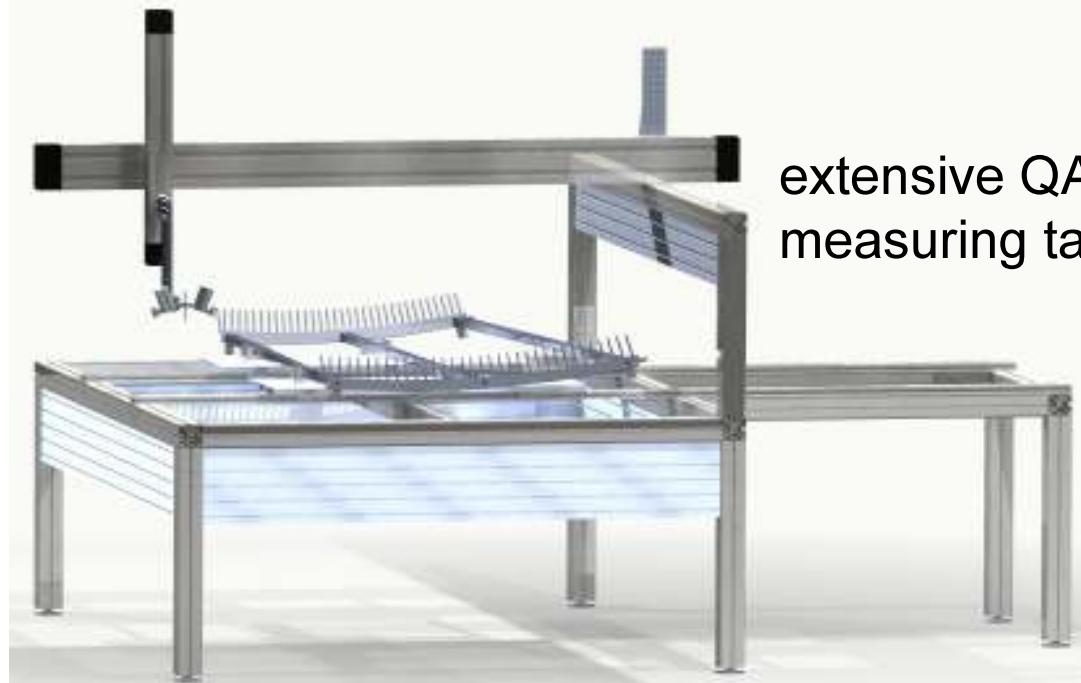
# inner electrode system: manufacture

design, manufacture, assembly & QA of frames at University of Münster



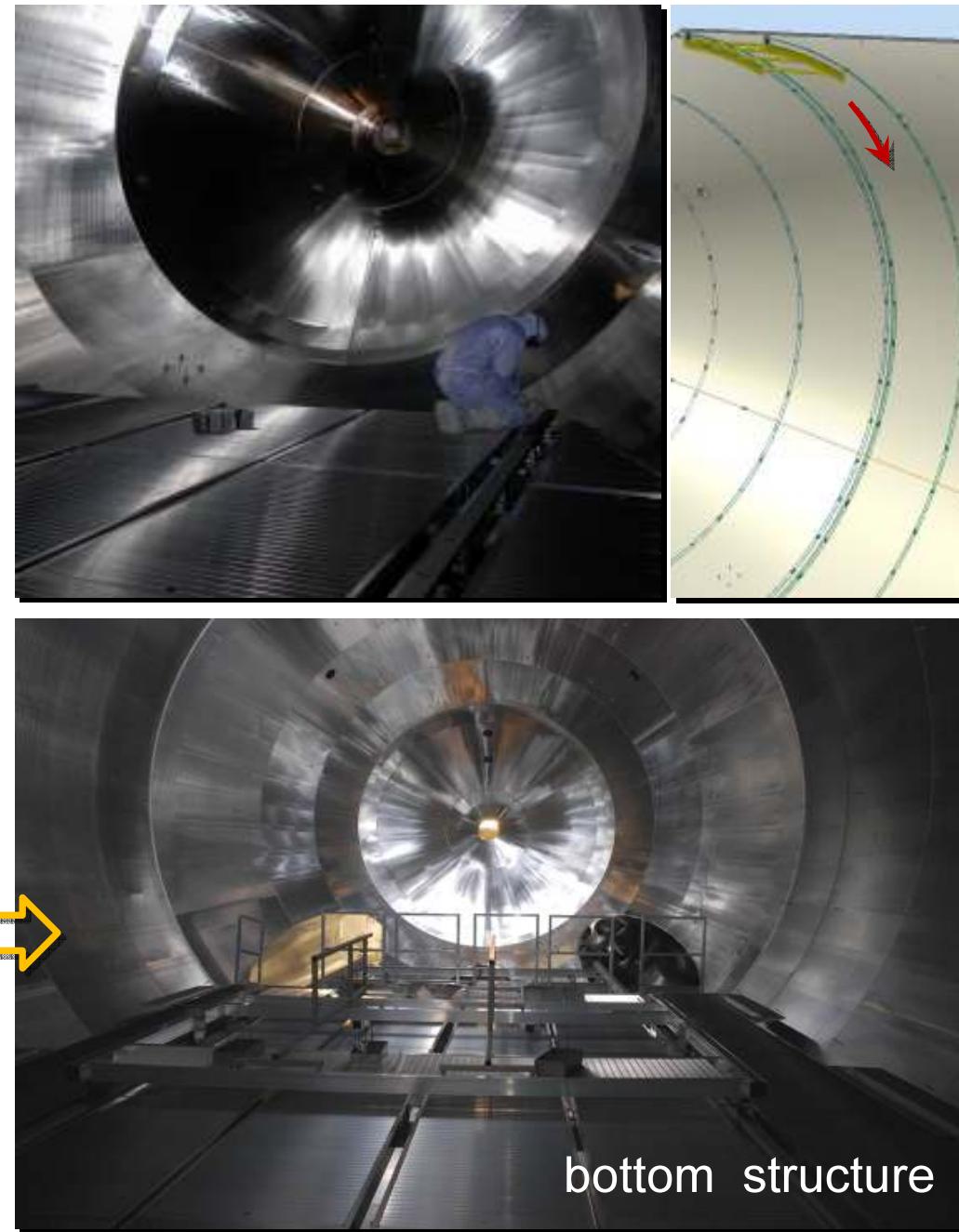
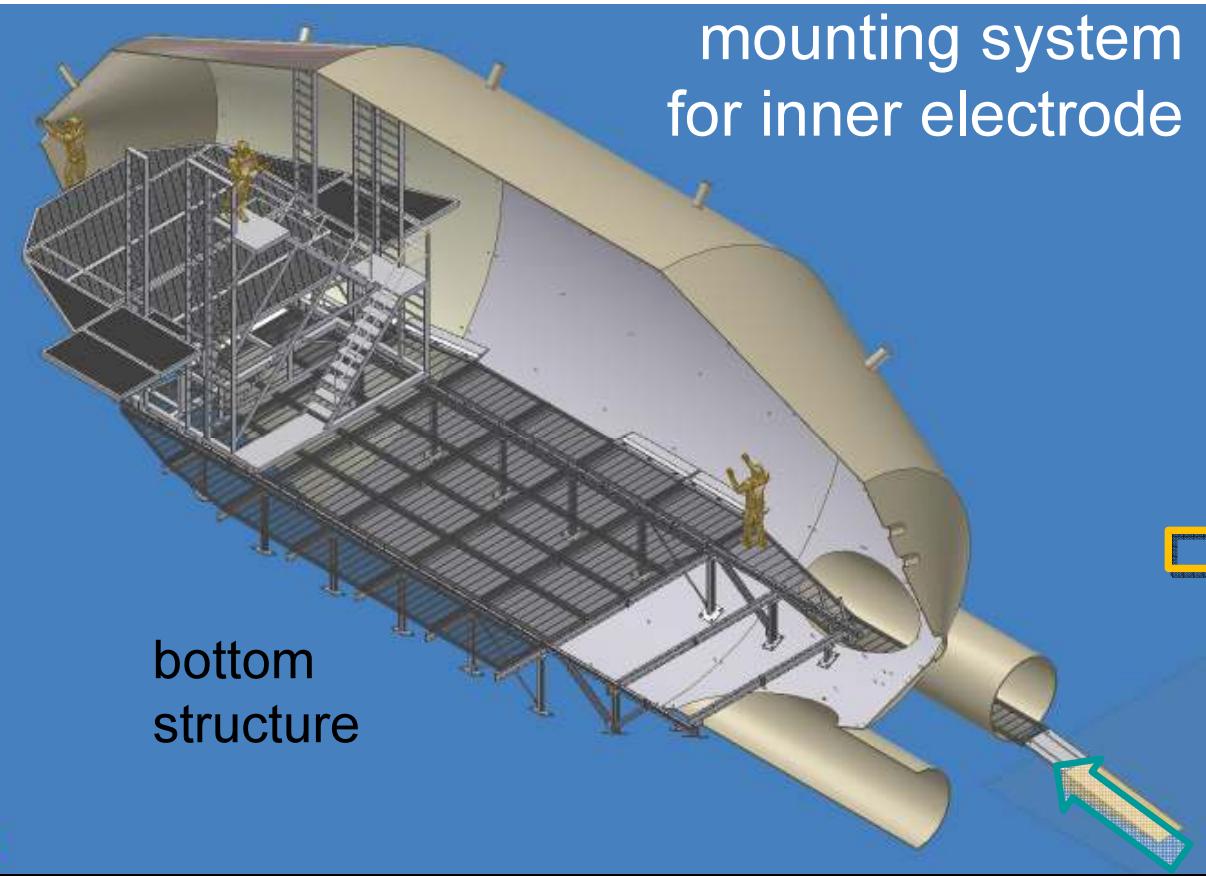
- three different geometries (2 cones, 1 cylinder)
- UHV compatibility
- low intrinsic wire radioactivity
- positioning accuracy  $\pm 200 \mu\text{m}$ , sag  $< 200 \mu\text{m}$

see poster Matthias Prall:  
**“the wire electrode of the KATRIN experiment”**



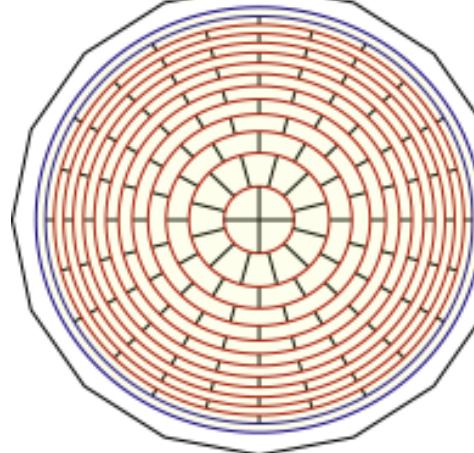
# mounting system for inner electrodes

- access to main spectrometer via 85 m<sup>2</sup> clean room at rear end
- specially cleaned & electropolished mounting system with large-area platform for precision mounting of inner electrodes



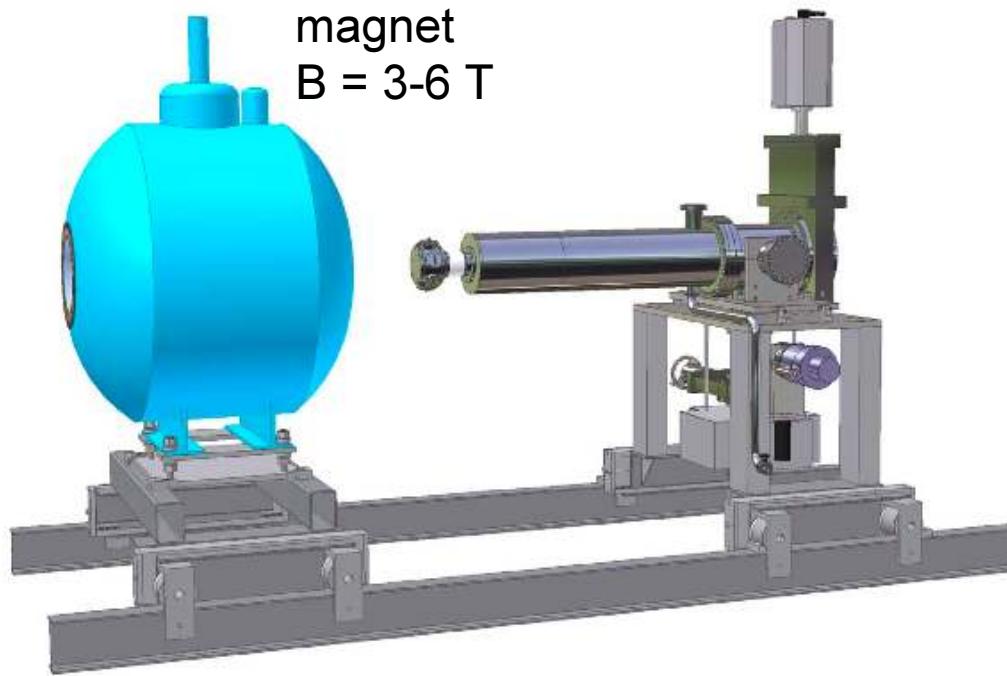
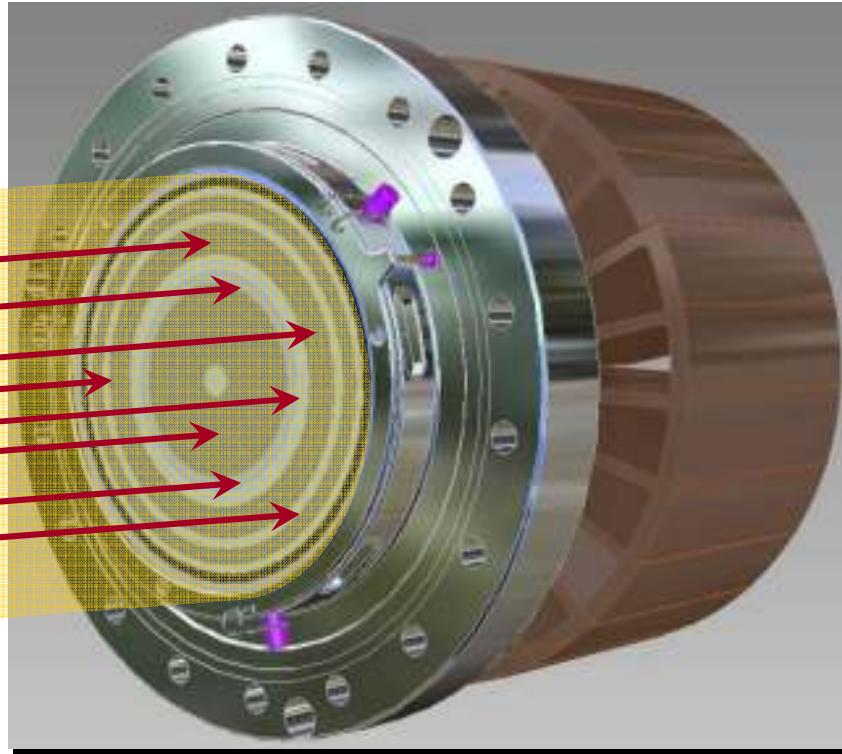
# focal plane detector

- monolithic segmented Si-PIN diode array:
  - counting of transmitted electrons (very low background!)
  - determination of radial position and azimuth angle
  - compensation of field inhomogeneities in the analysing plane
  - will be supplied by US Collaborators together with s.c. pinch & detector magnets



see poster Michelle Leber:  
'status of the detector for the  
**KATRIN neutrino mass experiment'**

guided flux  
 $\Phi = 191 \text{ T cm}^2$



# measurement intervals & spectra

optimised HV scanning procedure, parameter decorrelation by 3 regions

**Region I:**  $E \ll E_0$

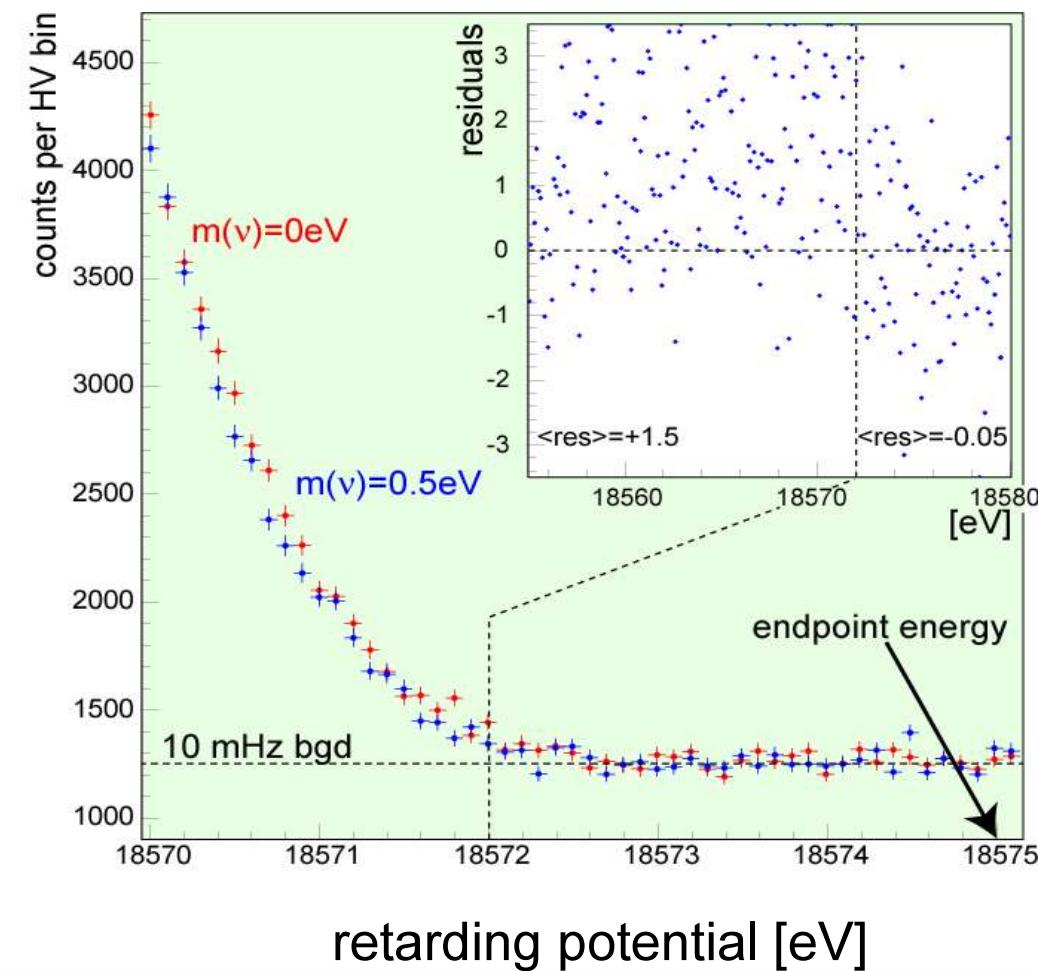
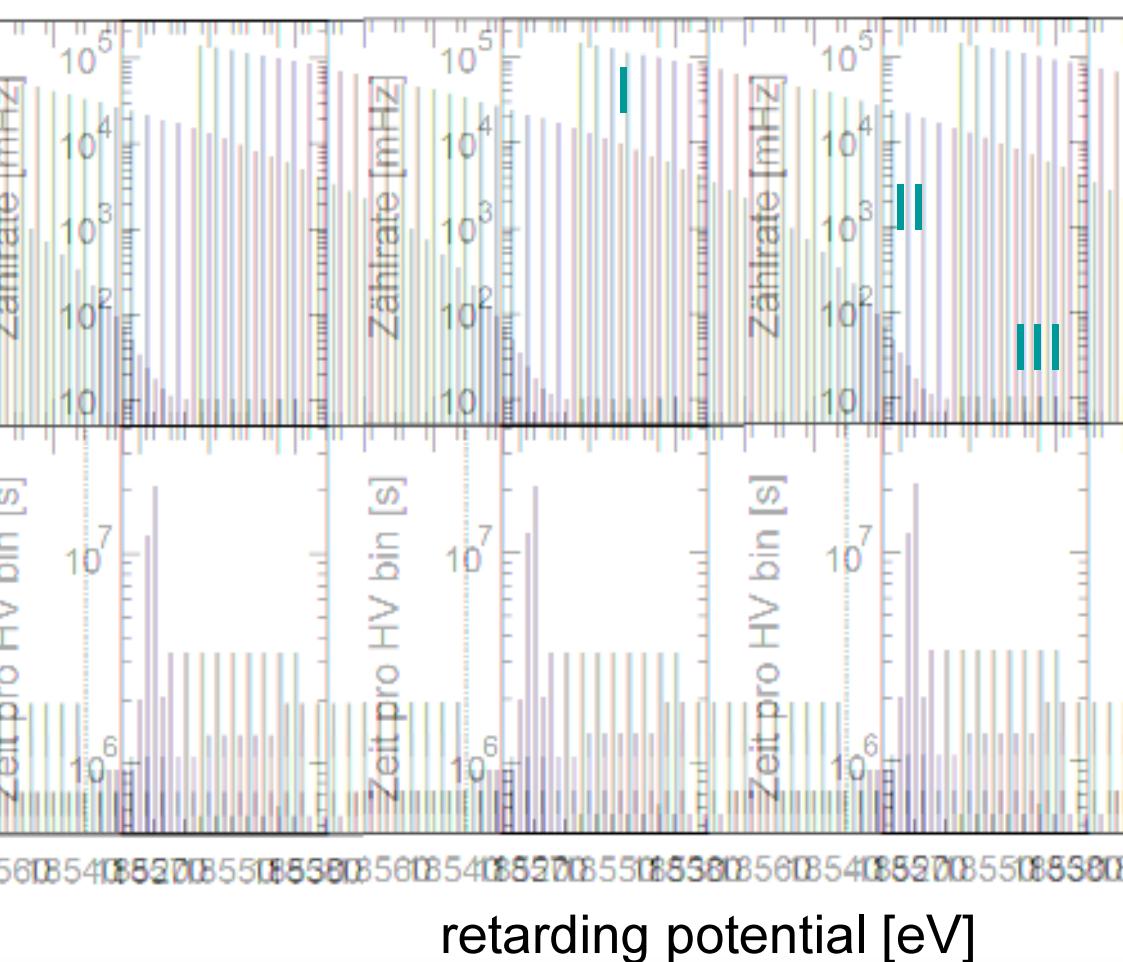
determine  $E_0$  from fit procedure ( $\Delta E_0 \sim 3$  meV)

**Region II:**  $E \sim 18570$  eV

maximum sensitivity for  $m(\nu)$  with S/B-ratio~2

**Region III:**  $E > E_0$

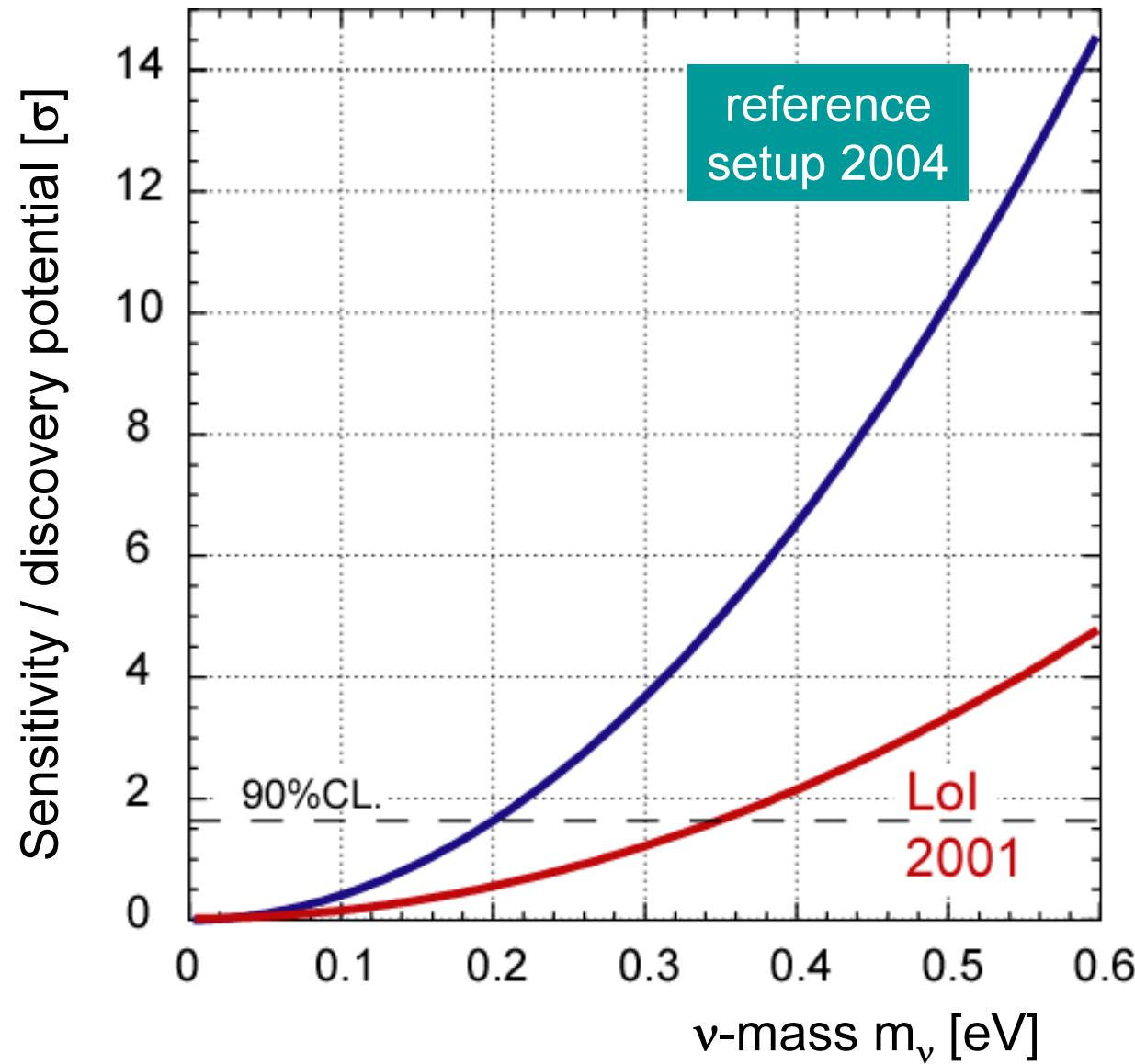
determine background rate (aim for 10 mHz)



# KATRIN sensitivity



- $\nu$ -mass sensitivity for 3 'full beam' measuring years



statistical & systematic errors contribute equally:

- statistical error  $\sigma_{\text{stat}} = 0.018 \text{ eV}^2$
- systematic error  $\sigma_{\text{syst}} < 0.017 \text{ eV}^2$

sensitivity (90% CL)  
 $m(\nu) < 200 \text{ meV}$

discovery potential  
 $m(\nu) = 350 \text{ meV} (5\sigma)$

# KATRIN Collaboration

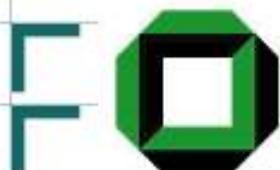
focusing the world-wide expertise in tritium  $\beta$ -decay experiments:

> 125 collaboration members (12 institutions from D, USA, GB, CZ, Russia)



## KATRIN time line

- 2008: inner electrode mounting
- 2009: DPS2-F elmagn. tests  
demonstrator tests  
spectrometer elmagn. Tests
- 2010: WGTS, tritium loops & CPS  
commisioning, system  
integration & initial  $T_2$  runs
- 2011: long-term measurements  
sub-eV sensitivity



# Conclusions

investigation of the kinematics of  $\beta$ -decay = only model-independent measurement of the absolute mass scale of neutrinos

**MARE:** staged approach based on microcalorimeters  $^{187}\text{Re}$   $\beta$ -decay

MARE-I ~300 detectors with  $m(\nu) \sim 2$  eV

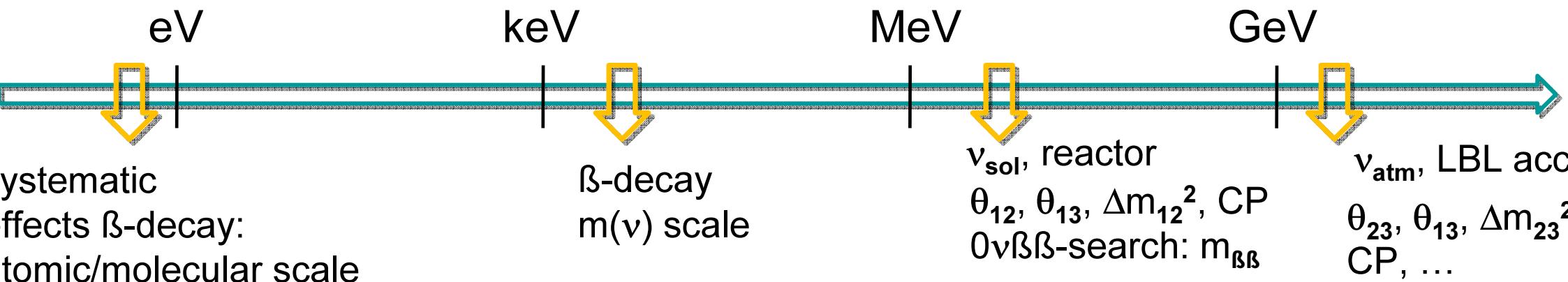
MARE-II ~50.000 detectors with  $m(\nu) \sim 0.2$  eV  
if successful R&D & if funded

**KATRIN:** integral approach based on MAC-E filter technique

designed as ‘ultimate’ tritium  $\beta$ -decay experiment

many experimental challenges, initial runs Q4/2010

sensitivity  $m(\nu) = 0.2$  eV



# additional slides

# pre-spectrometer

## UHV concept: TMP`s & NEG-getters

### 1. outgassing rate @ -20°C

specified:  $1 \times 10^{-12}$  mbar l / cm<sup>2</sup> s

measured:  $7 \times 10^{-14}$  mbar l / cm<sup>2</sup> s

gas charge: ~50% vessel, ~50% TMP&QMS

### 2. final pressure

specified:  $p < 10^{-11}$  mbar @ -20°C

measured:  $p < 10^{-11}$  mbar @ RT

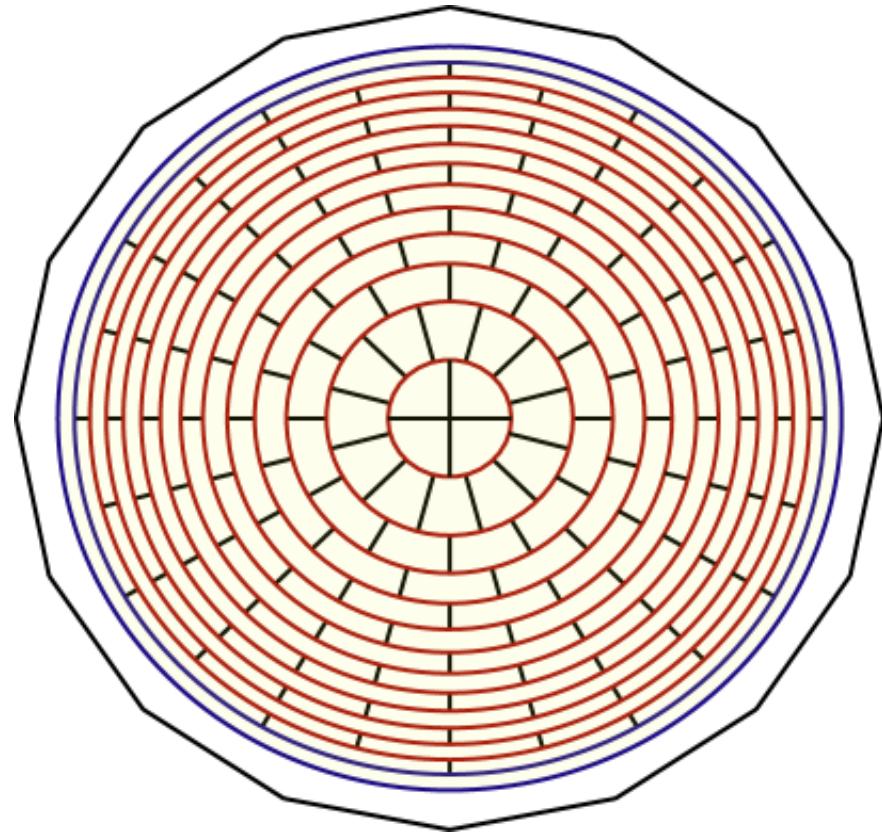


→KATRIN needs low-level getters (radon emanation!)

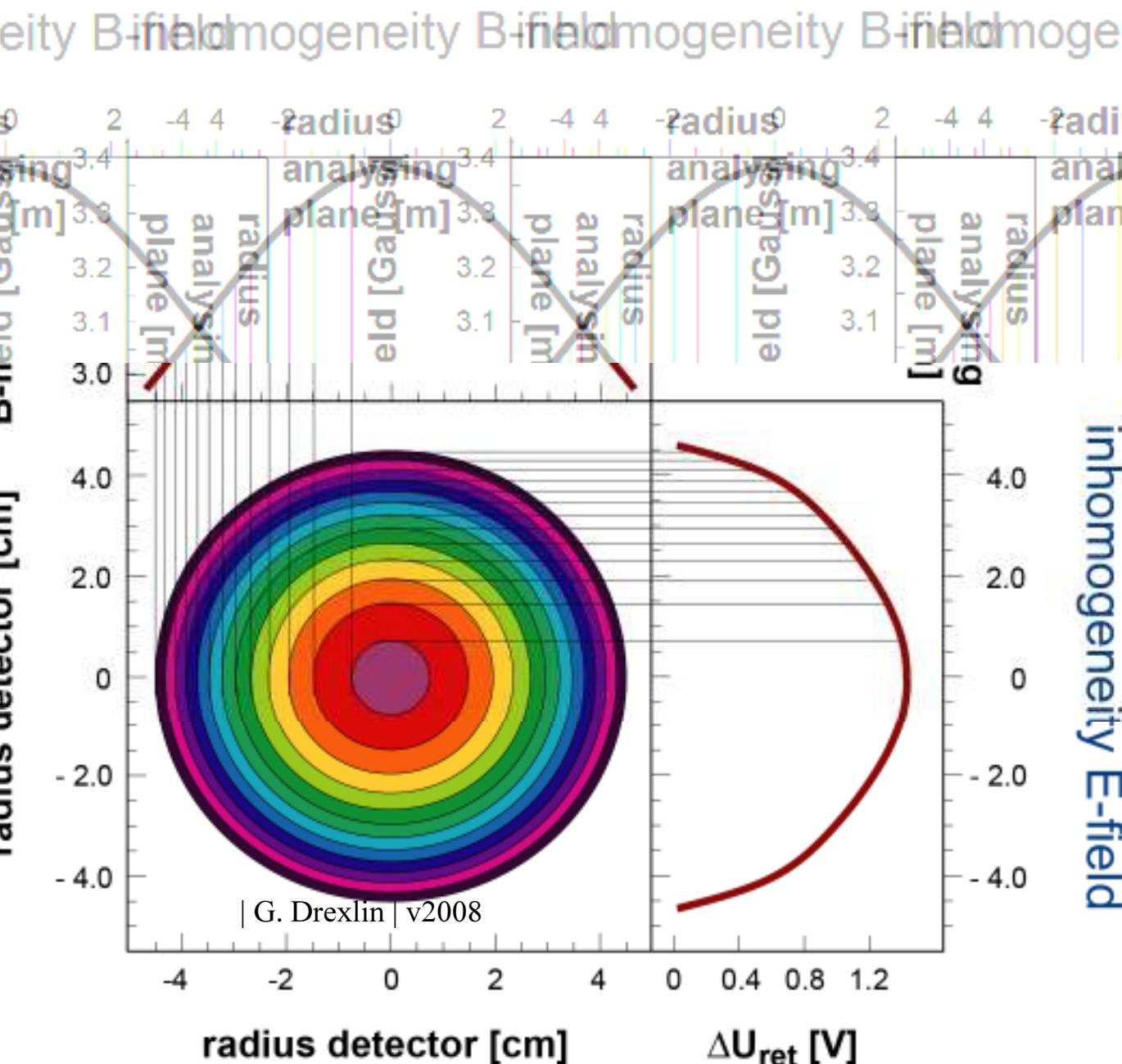
# focal plane detector

parameter	requirements
electron energy	5 - 100 keV
background rate	< $10^{-3}$ mHz in RoI
efficiency	>90 % (with veto)
sensitive area	>6300 mm <sup>2</sup> Ø = 10 cm
segmentation	148 Pixel
single pixel	~ 50 mm <sup>2</sup>
time resolution	$\Delta t < 0.5 \mu\text{s}$
dead layer	< 100 nm
dark currents	< 2 nA / cm <sup>2</sup>
magnetic field	3 T → 6 T
temperature	100 K → 250 K

**12 rings with 12 pixels each  
central circle 4 pixels**



# compensation of field inhomogeneities

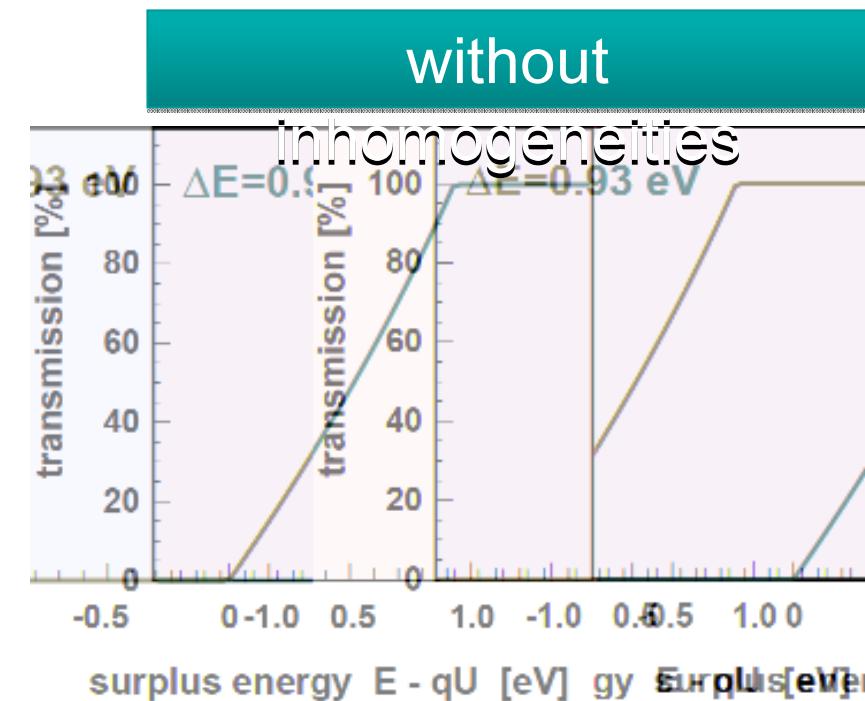


$B(\text{detector}) \approx 3 \text{ T}$

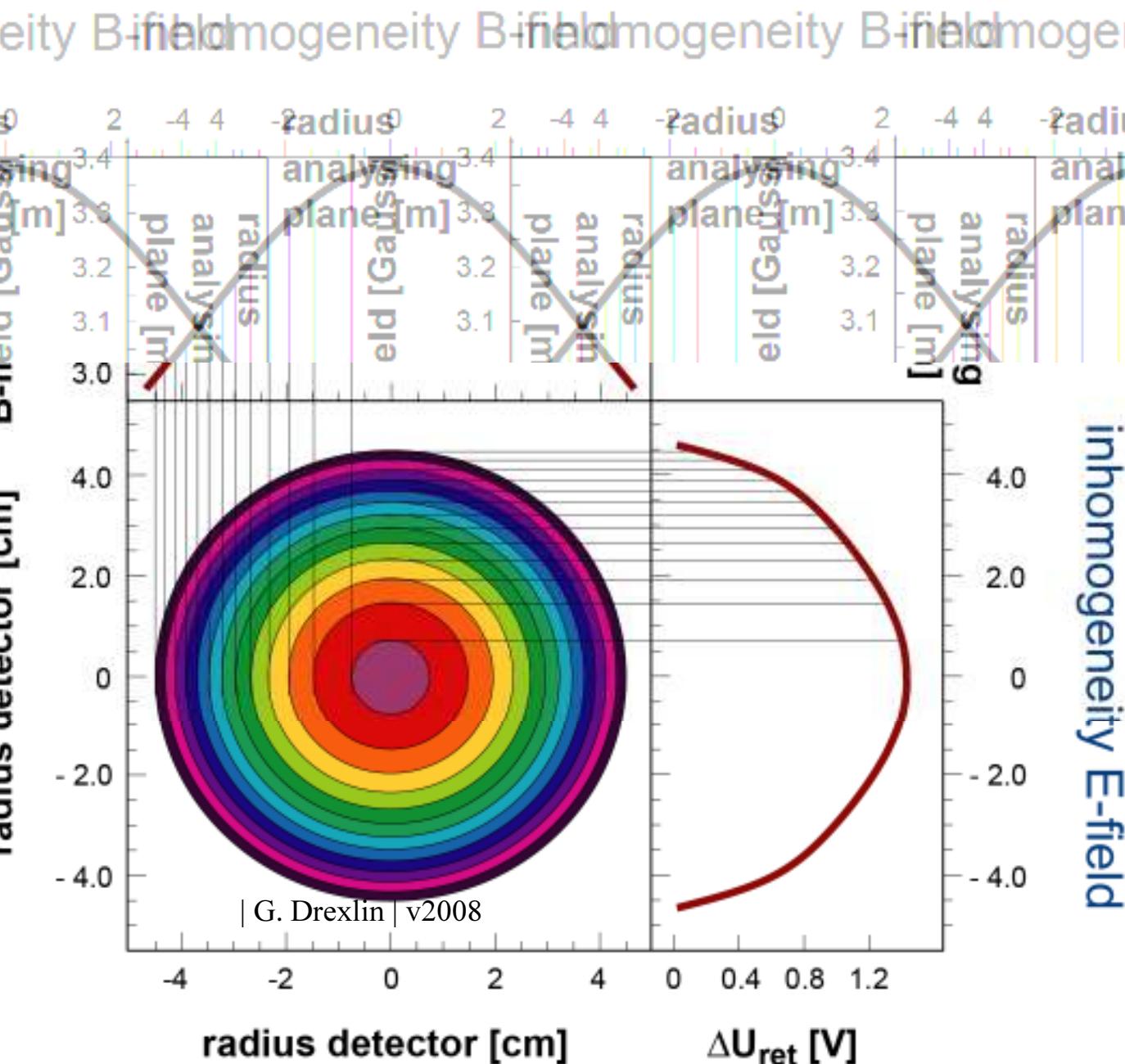
$B(\text{analys. plane}) \approx 3 \times 10^{-4} \text{ T}$

to first order

$$\frac{r(\text{analys. plane})}{r(\text{detector})} = \frac{100}{1}$$



# compensation of field inhomogeneities



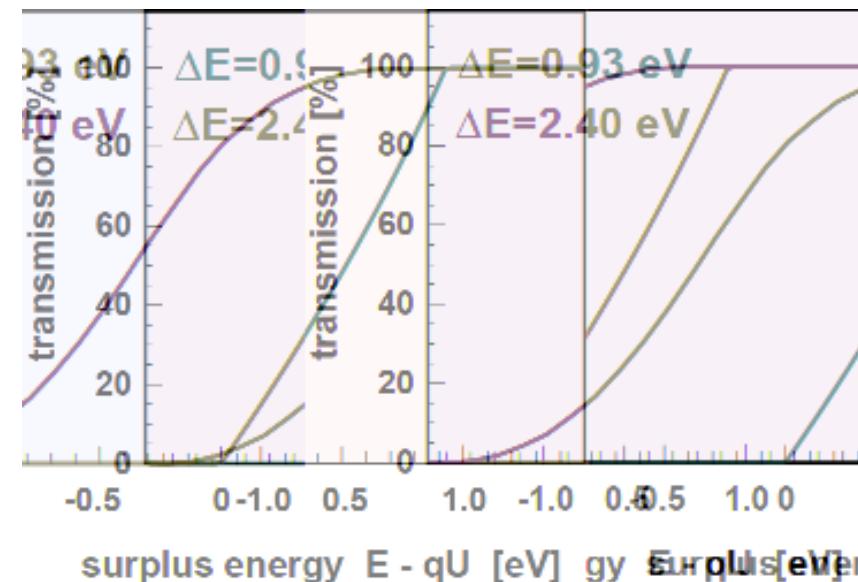
$B(\text{detector}) \approx 3 \text{ T}$

$B(\text{analys. plane}) \approx 3 \times 10^{-4} \text{ T}$

to first order

$$\frac{r(\text{analys. plane})}{r(\text{detector})} = \frac{100}{1}$$

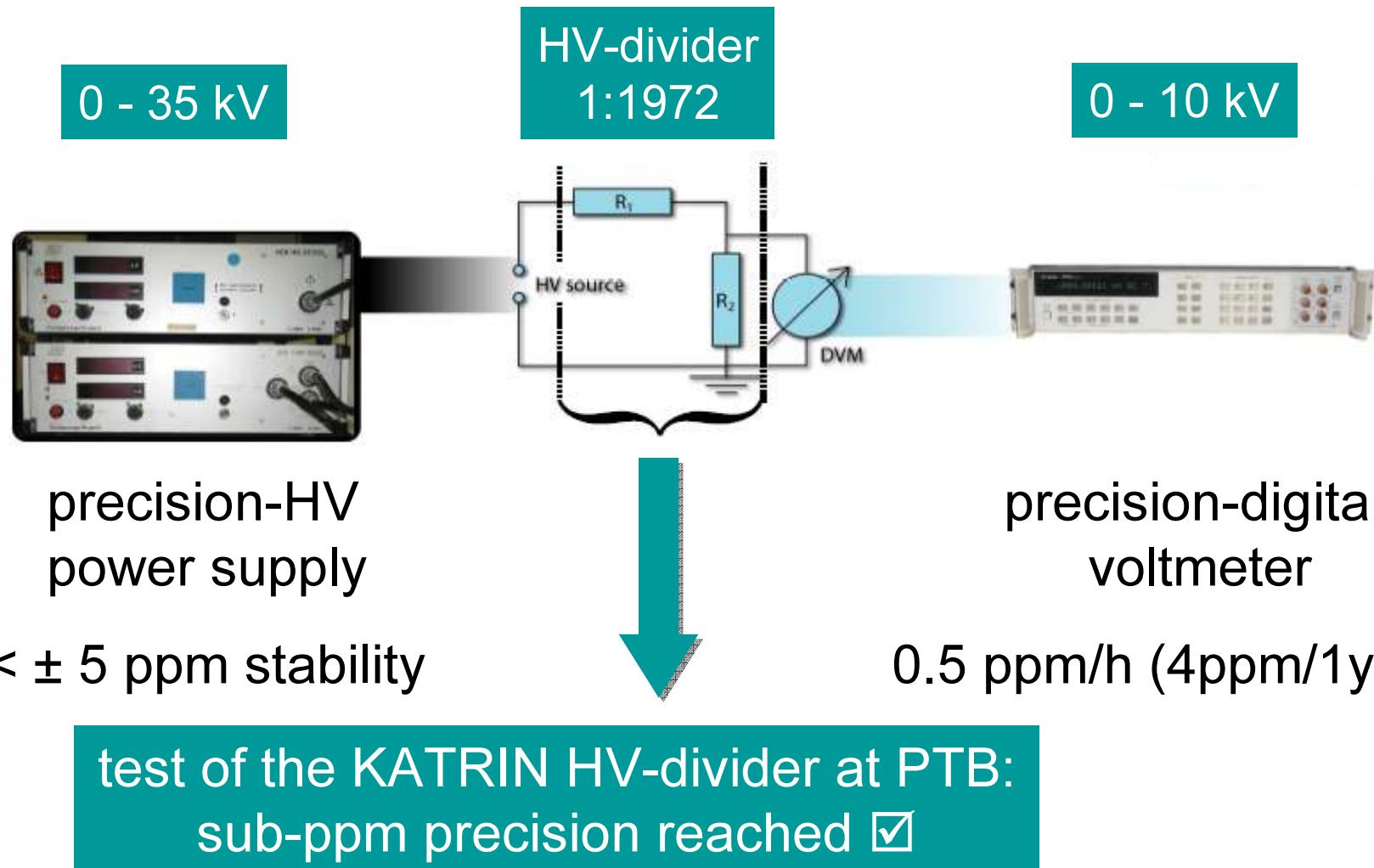
with inhomogeneities



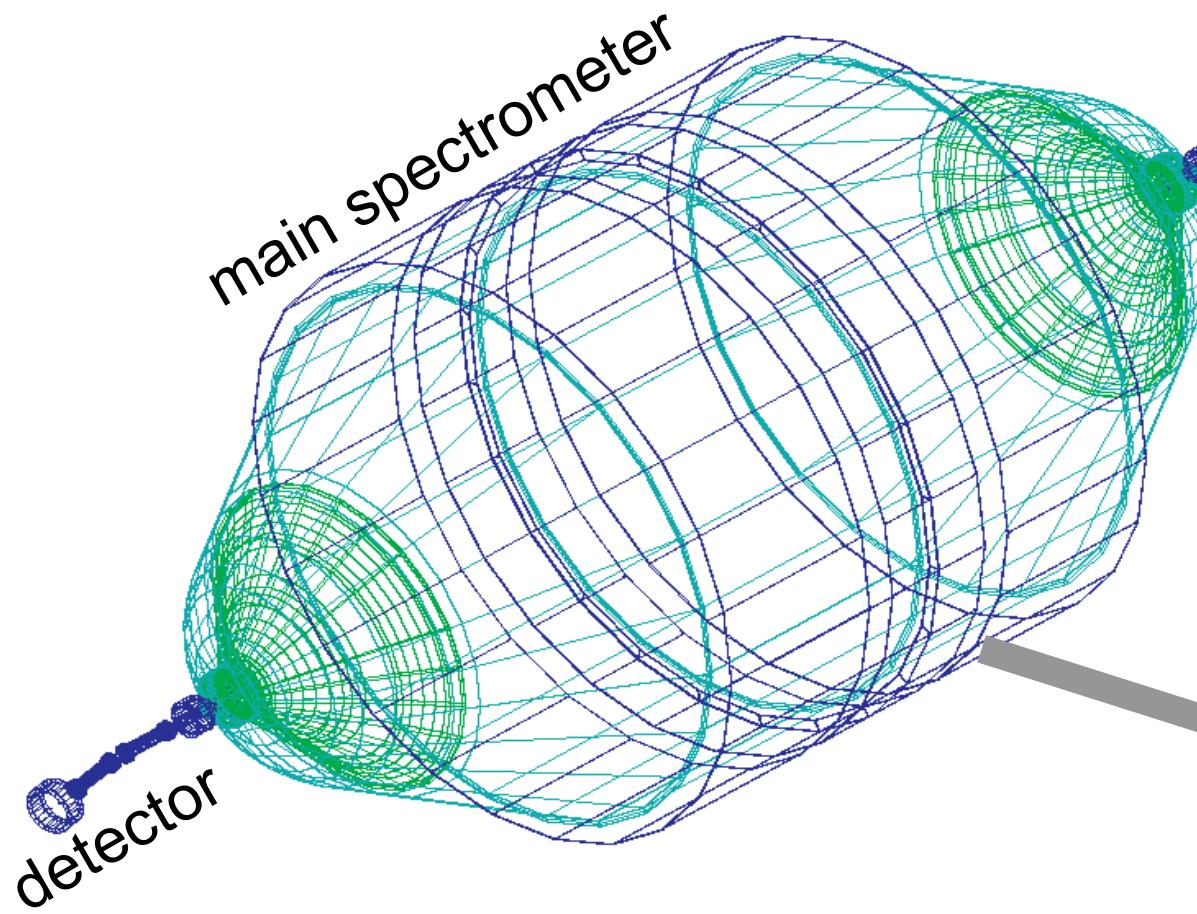
# HV - world's most precise HV-divider



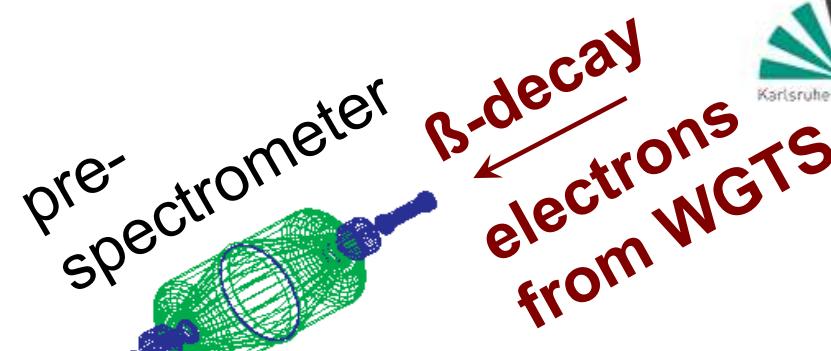
measurements require knowledge of actual HV-potential  
on the 1 ppm level (broad band: from DC to MHz)  
HV-stabilisation & HV-monitoring



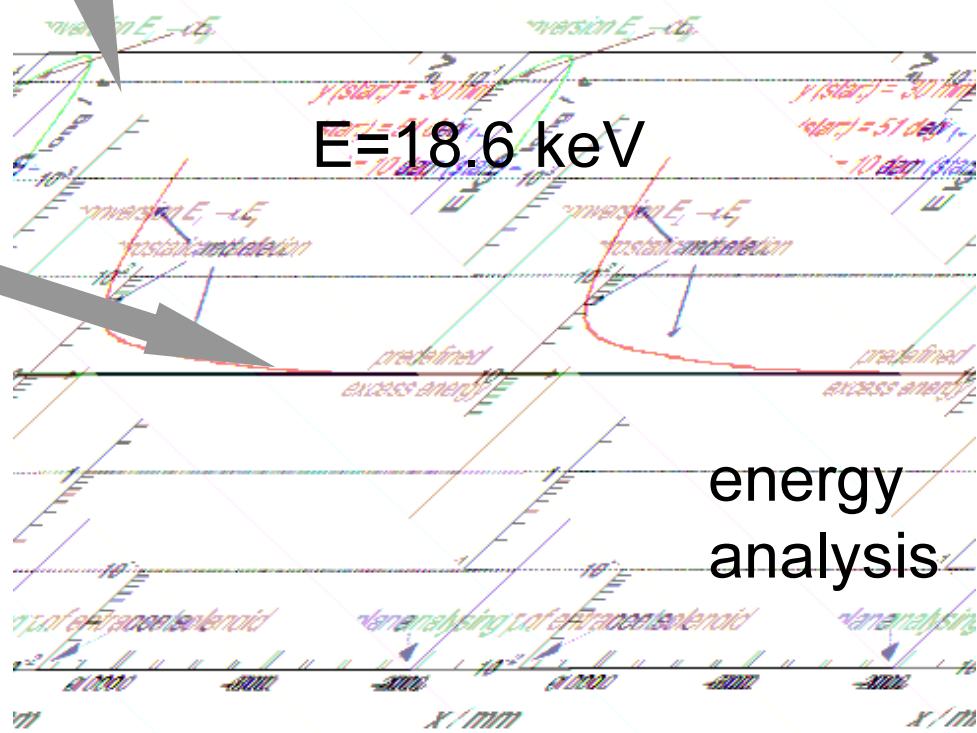
# transmission



transported magnetic  
flux  $191 \text{ T cm}^2$



- electromagnetic transmission
- 1. magnetic conversion
- 2. electrostatic retardation



# systematic effects

$$\Delta m_\nu^2 = -2\sigma_{\text{syst}}^2$$



general relation for tritium- $\beta$ -decay

## inelastic scattering of $\beta$ -decay electrons in the WGTS

- dedicated measurements with electron gun, special unfolding techniques

## HV-stabilisation of spectrometer retarding potential

- precision-HV-divider (calibrated by PTB) & digital voltmeter
- monitor spectrometer (Mainz) & atomic/nuclear standard (Rb/Kr-source)

## fluctuations of the WGTS column density pd (required $< 10^{-3}$ )

- stabilisation of pd: injection pressure, beam tube T=27K, Laser-Raman
- measurements electron gun, rear monitor detector/system

## charging effects in the WGTS

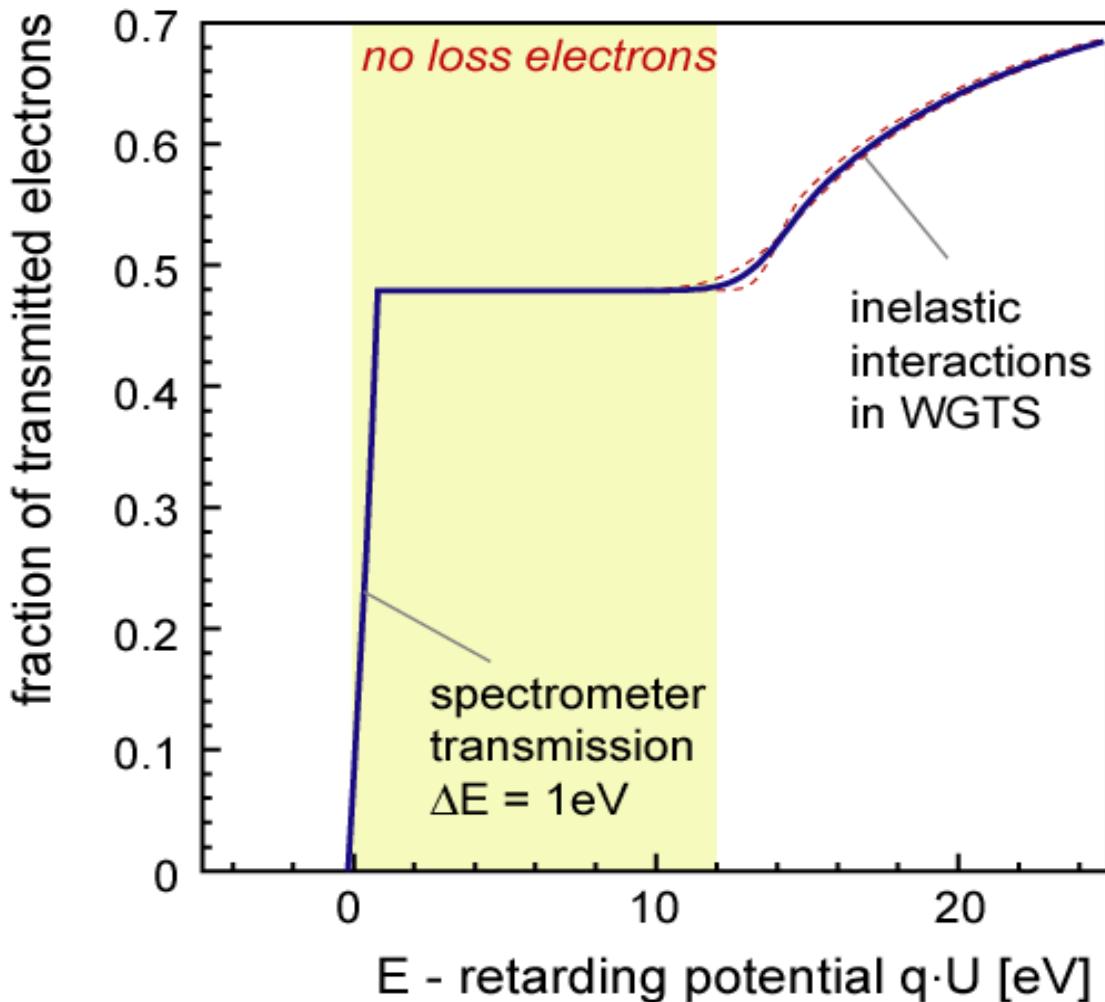
- neutralise remaining ions in WGTS ( $\Phi < 20 \text{ mV}$ ), injection of meV-e-

## distribution of final states (molecular excitations in ${}^3\text{H}{}^3\text{He}$ )

- reliable quantumchemical calculations, very good agreement

# measurement window

*calculated response function for monoenergetic electrons (energy  $E$ ) emitted isotropically from WGTS close to tritium  $\beta$ -endpoint at 18.6 keV*



## electrostatic spectrometer

*analytical transmission function  $T$  :*

*depends only on  $B_S / B_A$  and  $B_A / B_{max}$*

*no tails of resolution !!*

## molecular source WGTS

*calculation of energy losses :  $\sigma \times L(\theta)$*

*total cross section  $\sigma = 3.4 \times 10^{-18} \text{ cm}^2$*

*parameters:  $\rho d = 5 \times 10^{17} \text{ mol/cm}^2$*

*max. accepted angle  $51^\circ$*

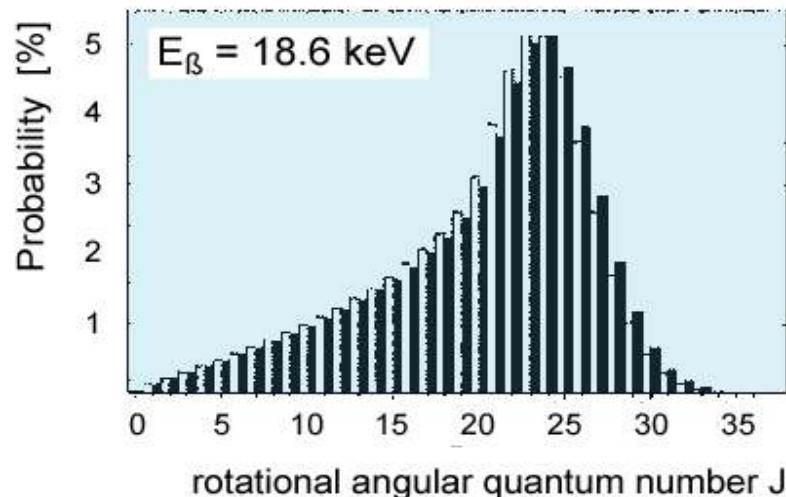
*last 12 eV below  $E_0$  :  
only 'no loss' electrons !*

# molecular excitations

quantenchemical modelling of the  $\beta$ -decay of molecular  $T_2$ :  
 recoil energy, electronic & rotational- / vibrational excitations

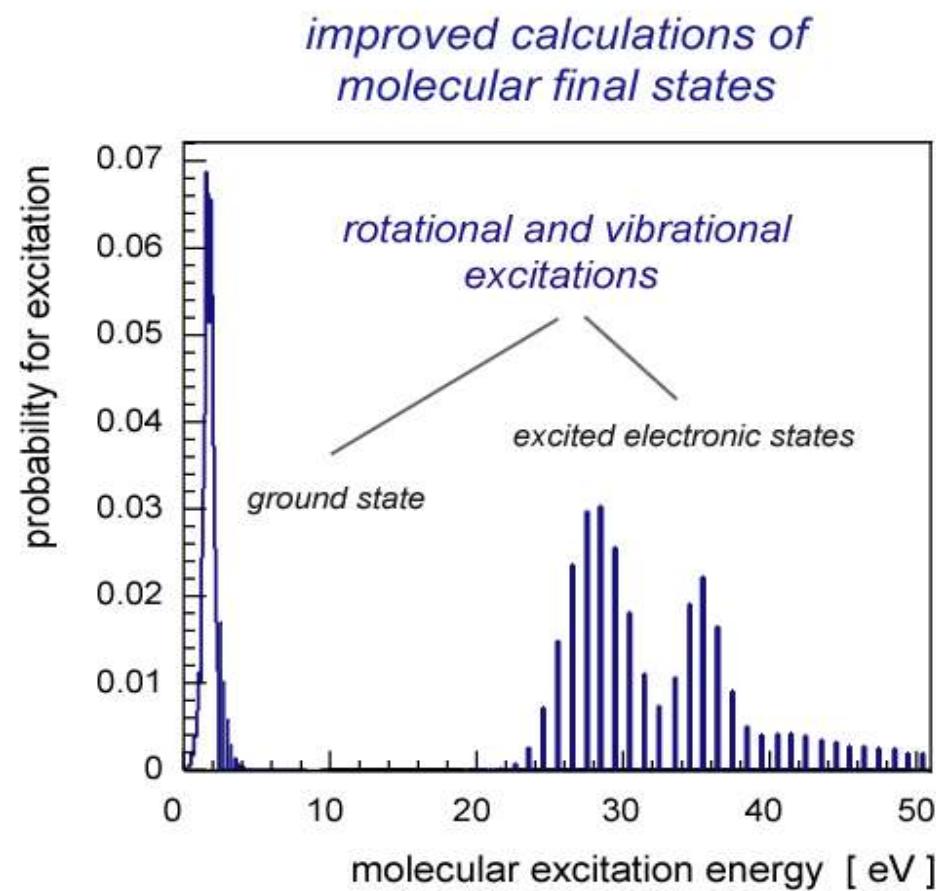
$$E_R = 1.72 \text{ eV} @ 18.6 \text{ keV}$$

Be	final state
14%	continuum
29%	excited electronic states
57%	ground state



*absolute accuracy of theory = 0.2 %*

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



*integration of spectrum yields 99.93% of total population probability*

# energy calibration & -monitoring

- absolute calibration of energy

K-32 conversion  $e^-$  line of gaseous  $^{83m}\text{Kr}$

$$E = [(17824.35 \pm 0.75) - (\phi_{\text{spec}} - \phi_{\text{spec}})] \text{ eV}$$

based on

difference in  
work functions

$$E_\gamma \text{ (gamma energy)} = (32\,151.55 \pm 0.75) \text{ eV}$$

$$E_b \text{ (bind. energy of K-elec.)} = (14\,327.09 \pm 0.39) \text{ eV}$$

& atomic recoil energy corrections

precision for E can be further improved !

$\phi_{\text{spec}} - \phi_{\text{spec}}$  measurement

- long-term monitoring  
of retarding energy

use separate monitor source &  
separate monitor spectrometer

QCMS : *quench condensed*  
monitor source of  $^{83m}\text{Kr}$   
either  $^{83}\text{Rb} / ^{83}\text{Kr}$  source or  
repeated condensation of  $^{83}\text{Kr}$

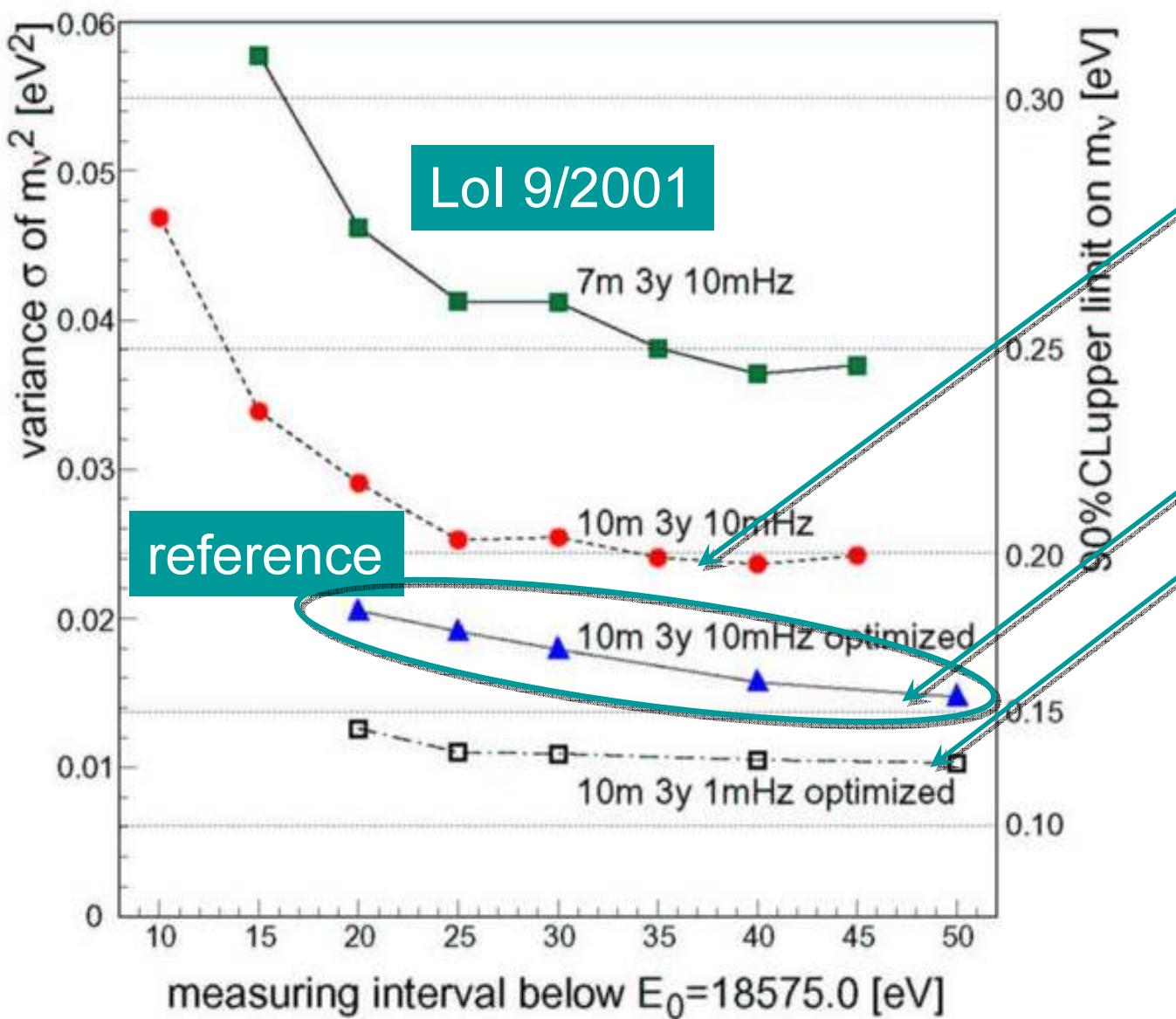
monitor spectrometer :

transfer Mainz spectrometer  
to KATRIN experimental hall  
fed by *same HV as spectrometer*

need to accelerate electrons  
from  $^{83m}\text{Kr}$  ( $\sim 800$  V, high prec.)

# statistical errors

design optimisation 2002-2004: improved sensitivity



luminosity upgrade WGTS  
by factor 2  
( $\varnothing = 75$  mm  $\rightarrow \varnothing = 90$  mm)  
 $\Rightarrow$  spectrometer  $\varnothing = 10$  m

optimised distribution of  
scanning, scan  $E_0 - 5$  eV

active background reduction:  

- inner electrode system
- low activity detector

 $\Rightarrow$  requires extensive tests

# background rate

total background rate at Mainz/Troitsk: ~10 mHz, aim for same rate at KATRIN

- detector: aim for bg-rate in few mHz range, environmental  $\gamma$ 's / X-rays & cosmics, , larger area: better energy resolution & better shielding, thinner detector, material selection develop background model on GEANT4.4 simulations
- spectrometer: aim for bg-rate in few mHz range
  - a) low energy shake off electrons from tritium  $\beta$ -decays  
T<sub>2</sub> 1mHz bg-rate from  $\sim 10^{-20}$  mbar tritium partial pressure (cryotrapping section)
  - b)  $\beta$ -decay electrons in keV-range that get trapped (-> ionising collisions)  
stringent XHV conditions  $< 10^{-11}$  mbar & active removal of trapped particles
  - c) cosmic ray induced  $\delta$ -electrons (muons, elmag. showers, hadronic component)  
CR can create ions, -> tertiary reactions: electrons & H<sup>-</sup> ions,  
stringent XHV conditions  $< 10^{-11}$  mbar & active removal of trapped particles
  - d) trapped  $\beta$ -electrons (from 'normal' tritium decays in WGTS)  
 $\beta$ 's stringent XHV conditions  $< 10^{-11}$  mbar & active removal of trapped particles
- sources:
  - a)  $\beta$ -electrons from tritium decays in areas with different source potential
  - b)  $\beta$ -electrons from T<sup>-</sup> ions (higher end-point) careful electromag. design