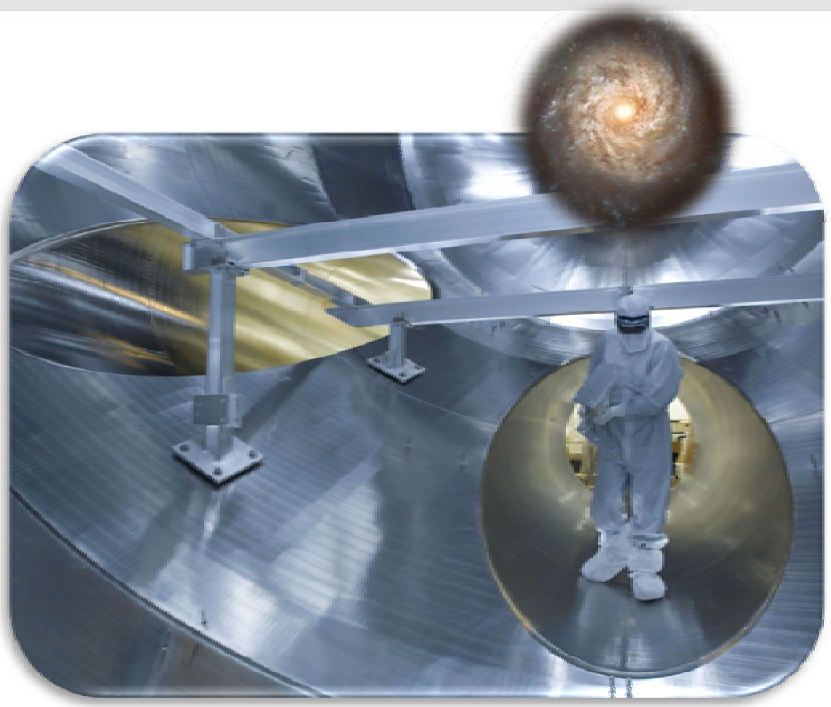


single ß-decay experiments: overview and KATRIN

ß-decay & ν-mass
tritium experiments

KATRIN – a MAC-E filter
project status

neutrino oscillations: 3-flavour mixing

3-flavour oscillations ´decouple´ into three separate mixing terms:

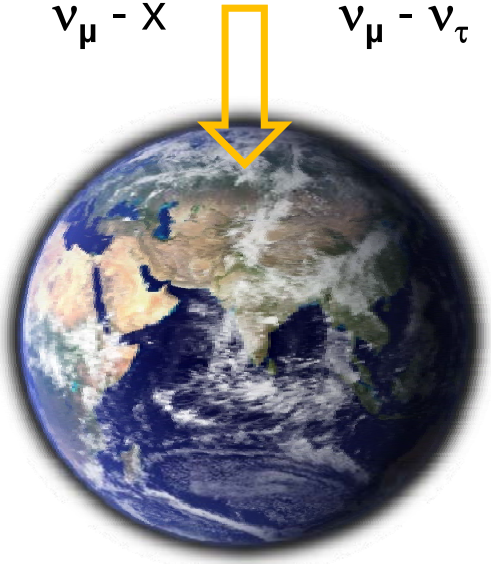
δ: CP-phase

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

2. & 3. generation	1. & 3. generation	1. & 2. generation
atmospheric ν´s	solar / reactor neutrinos	solar neutrinos
long baseline accelerators	long baseline reactor/accelerators	reactor experiments

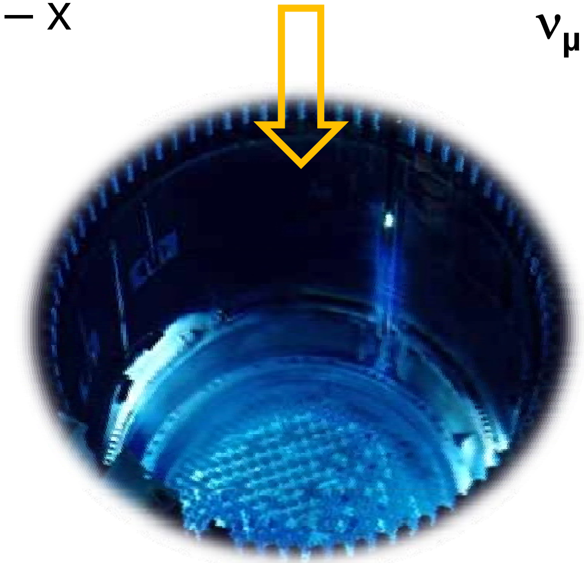
ν_μ - X

ν_μ - ν_τ



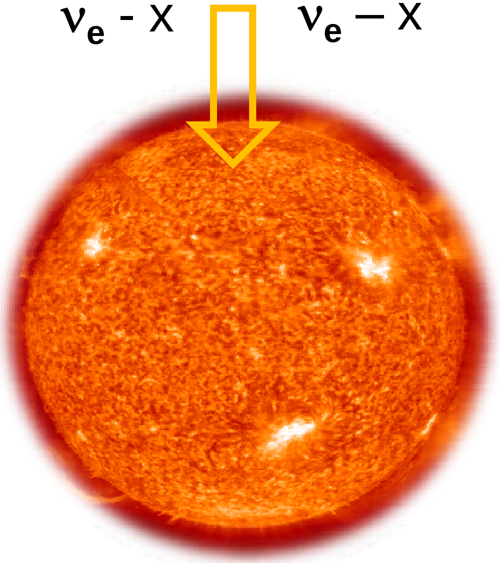
$\bar{\nu}_e$ – X

ν_μ - ν_e



ν_e - X

$\bar{\nu}_e$ – X



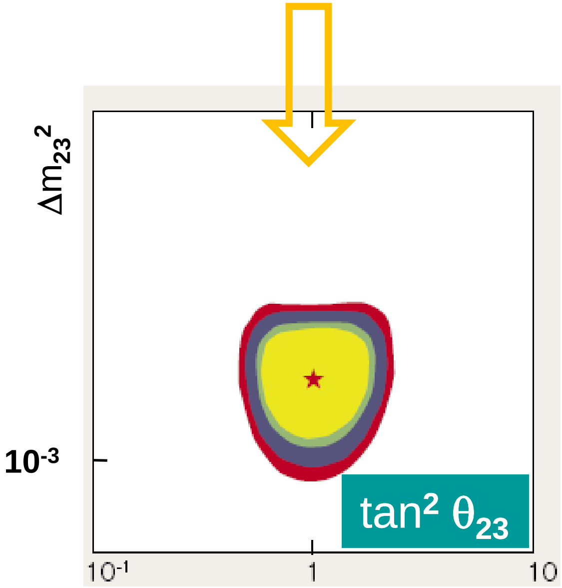
neutrino oscillations: 3-flavour mixing

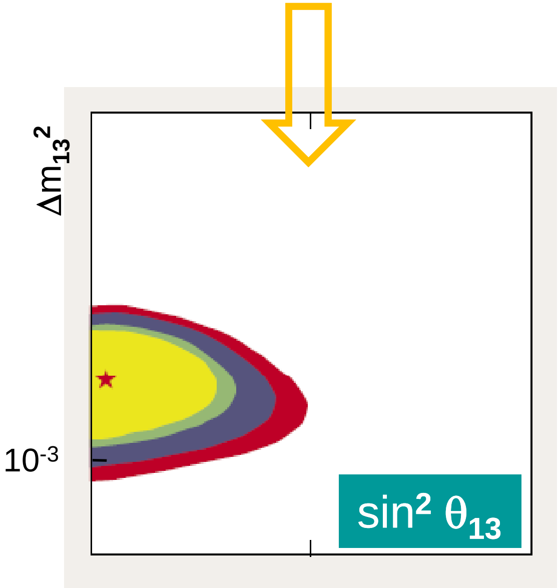
3-flavour oscillations ´decouple´ into three separate mixing terms:

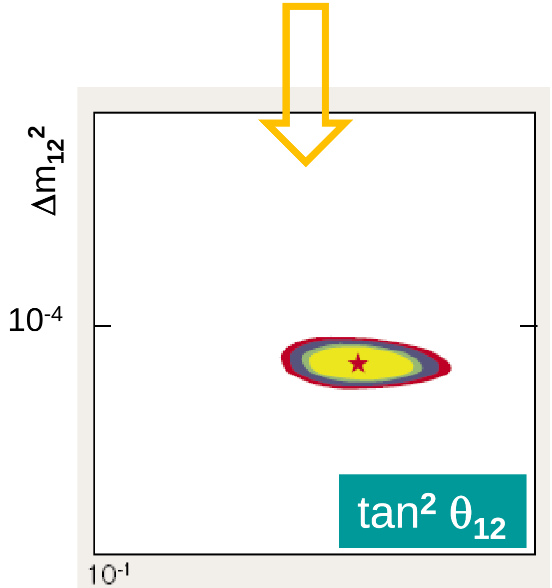
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

δ: CP-Phase

2. & 3. generation	**1. & 3. generation**	**1. & 2. generation**
$\Delta m_{23}^2 = 2.3 \times 10^{-3}$ eV²	$\Delta m_{13}^2 = 2.3 \times 10^{-3}$ eV²	$\Delta m_{12}^2 = 7.9 \times 10^{-5}$ eV²
$\theta_{23} = (45 \pm 4)°$ (maximum)	$\theta_{13} < 15°$ (very small)	$\theta_{23} = (33.7 \pm 1.3)°$ (large)

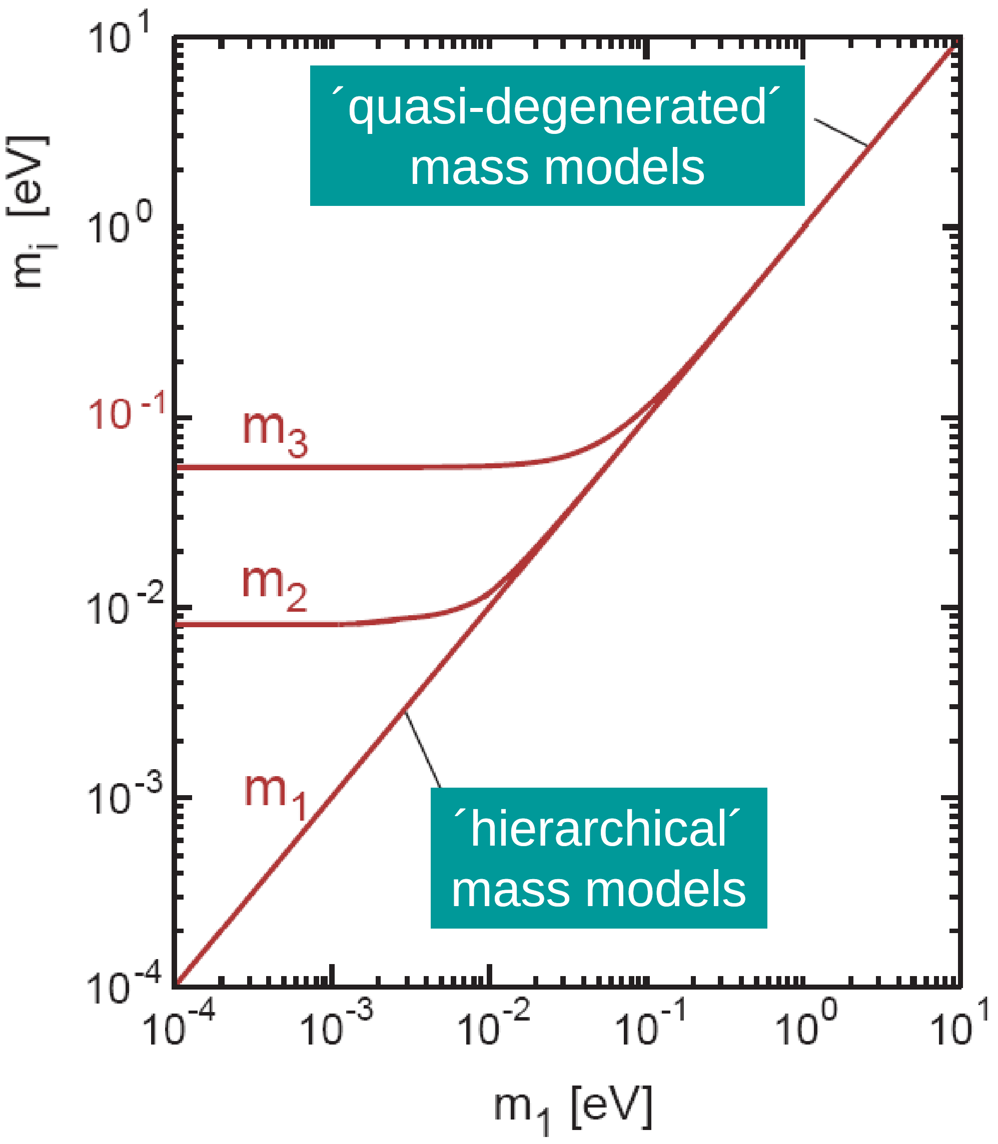


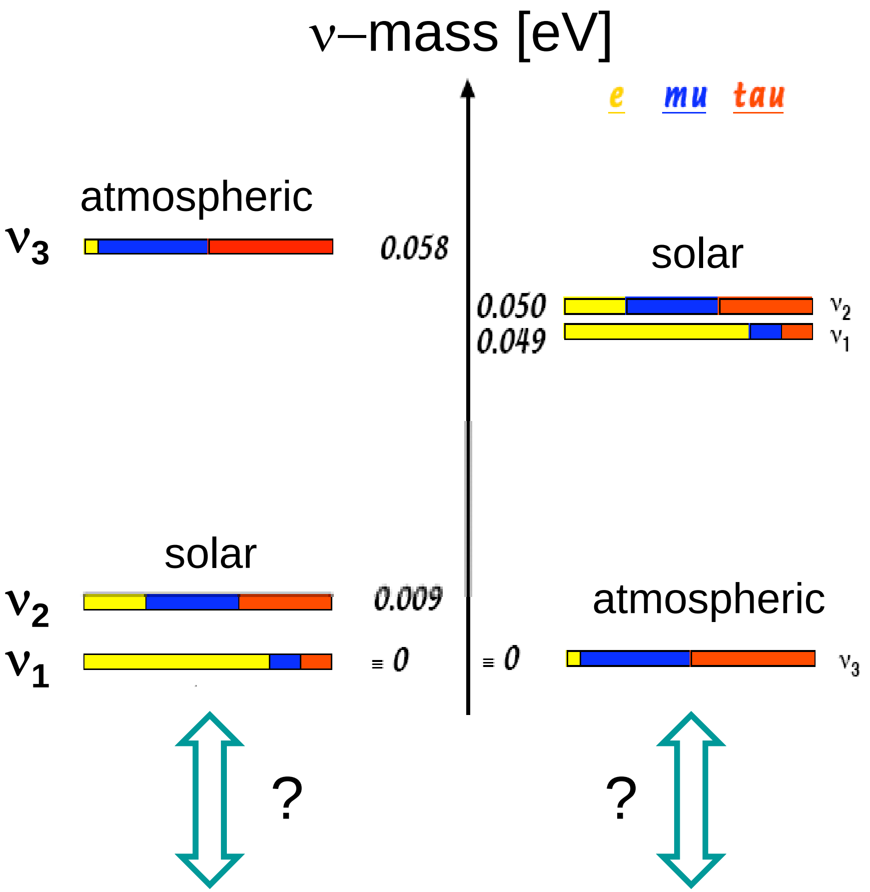




neutrino masses in particle physics

normal hierarchy with $m_1 < m_2 < m_3$

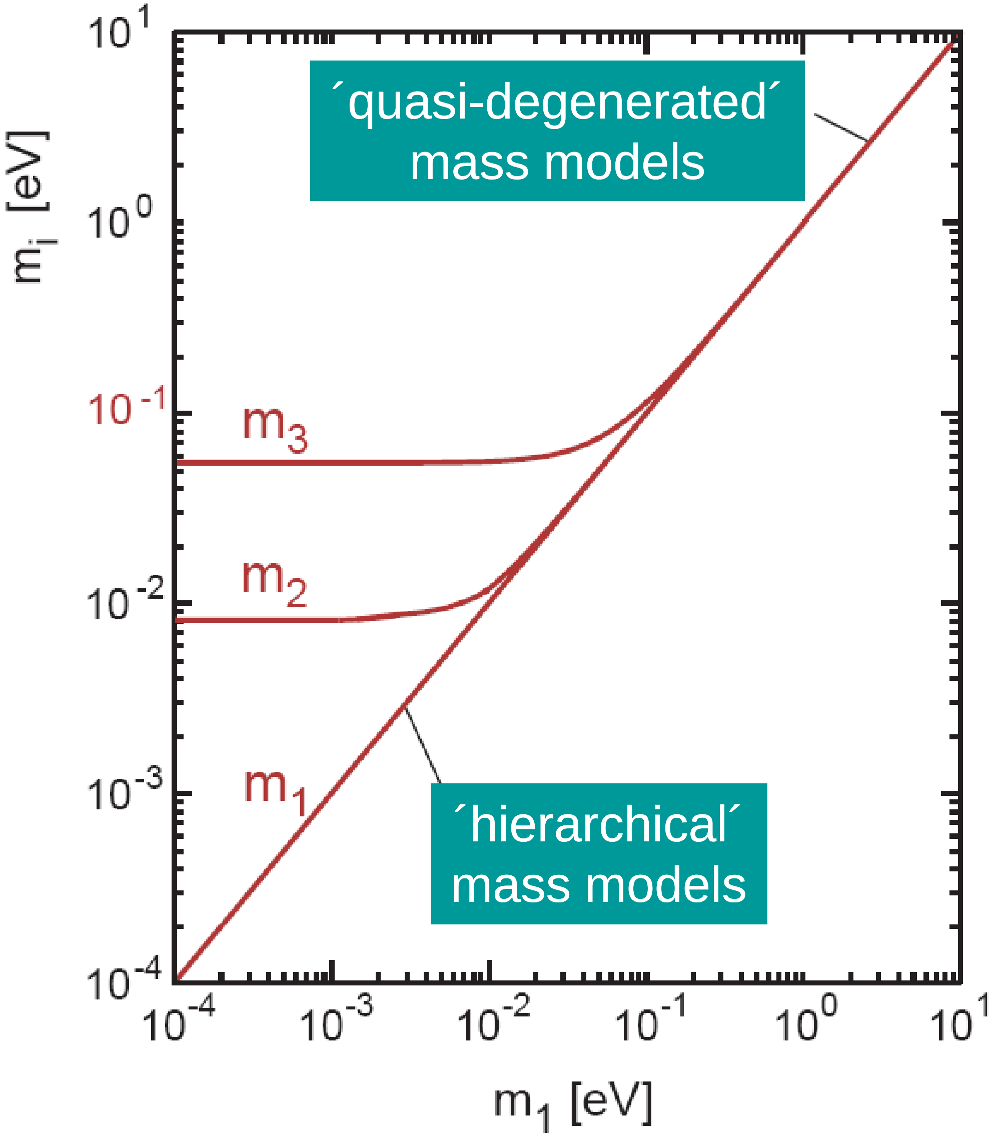


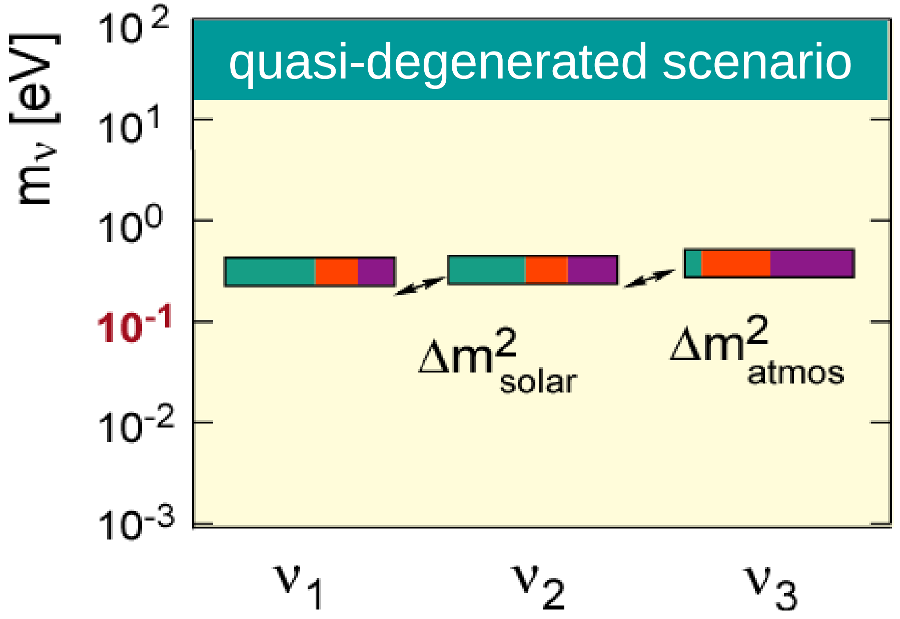


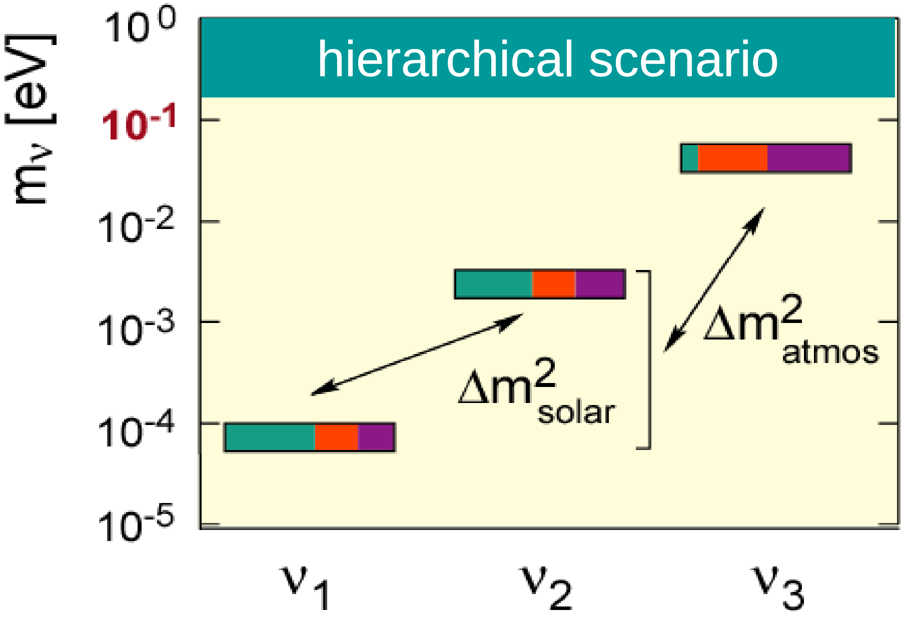
ν–mass offset?
absolute scale m_1?

neutrino masses in particle physics

normal hierarchy with $m_1 < m_2 < m_3$

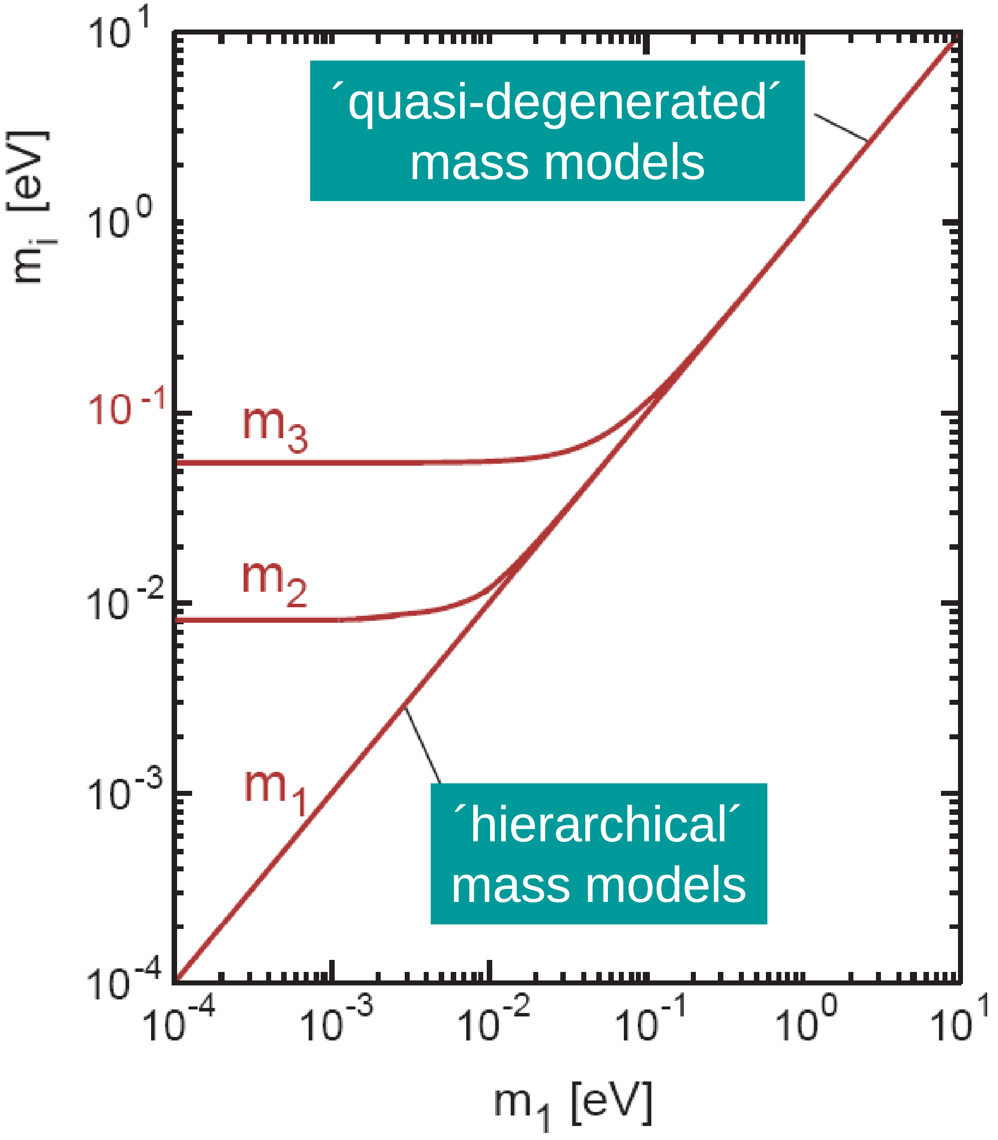






neutrino masses in particle physics

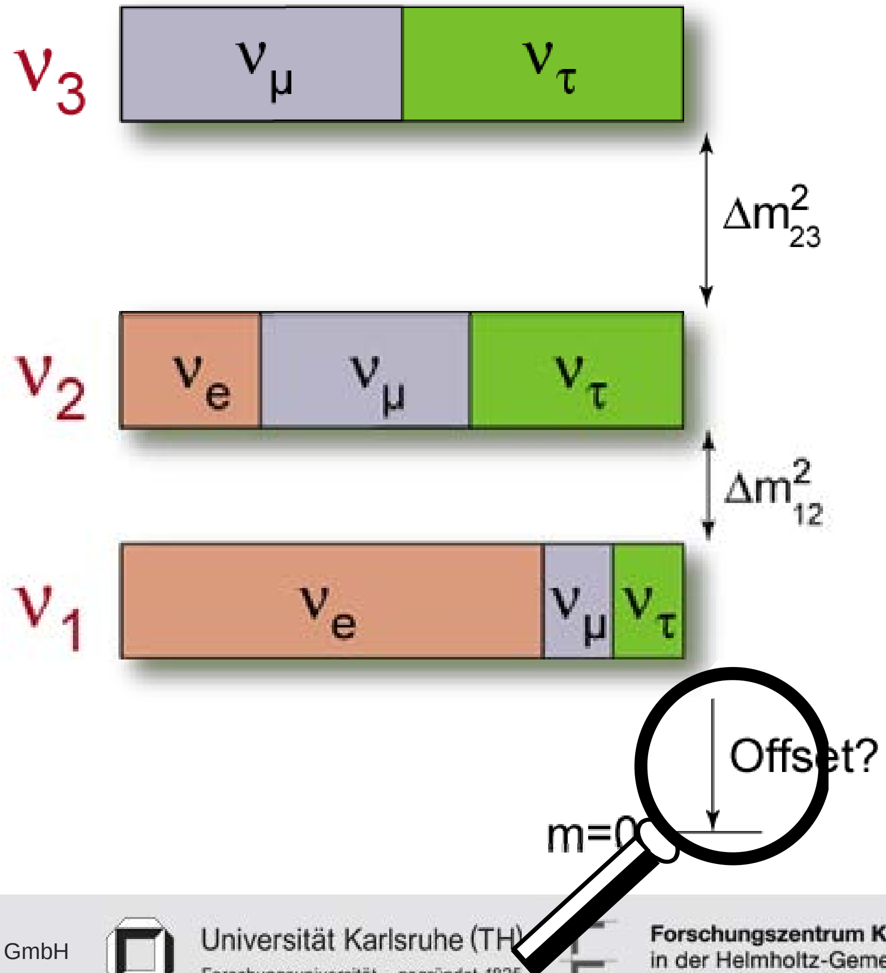
normal hierarchy with $m_1 < m_2 < m_3$



´quasi-degenerated´ mass models

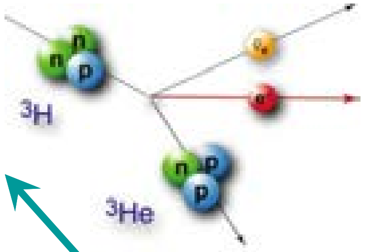
´hierarchical´ mass models

flavour composition of mass eigenstates



neutrino mass: status and perspectives

kinematics of ß-decay
absolute ν_e-mass: m_ν



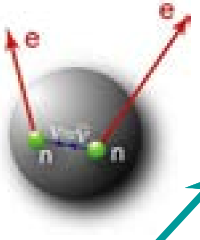
model-independent

status: $m_\nu < 2.3$ eV

potential: $m_\nu = 200$ meV

KATRIN (MARE-II)

search for 0νßß
eff. Majorana mass $m_{ßß}$



model-dependent (CP-phases)

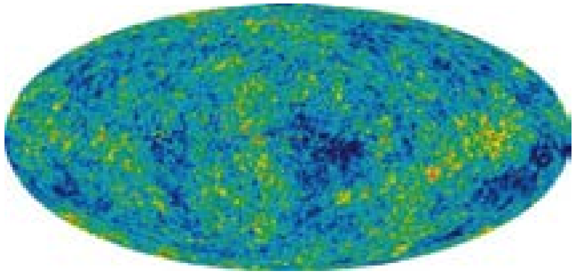
status: $m_{ßß} < 0.35$ eV, evidence?

potential: $m_{ßß} = 20\text{-}50$ meV

GERDA, EXO, CUORE

neutrino masses
experimental techniques:
status & potential

cosmology
sum Σm_i, HDM Ω_ν



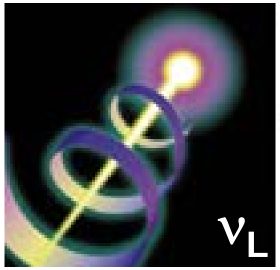
model-dependent (multi-parameter fits)

status: $\Sigma m_i < 1$ eV [Hannestad et al., arXiv:0803.1

potential: $\Sigma m_i = 20\text{-}50$ meV

Planck, LSST, weak lensing

Majorana and Dirac neutrinos



what is the intrinsic **particle-antiparticle symmetry** of neutrinos?

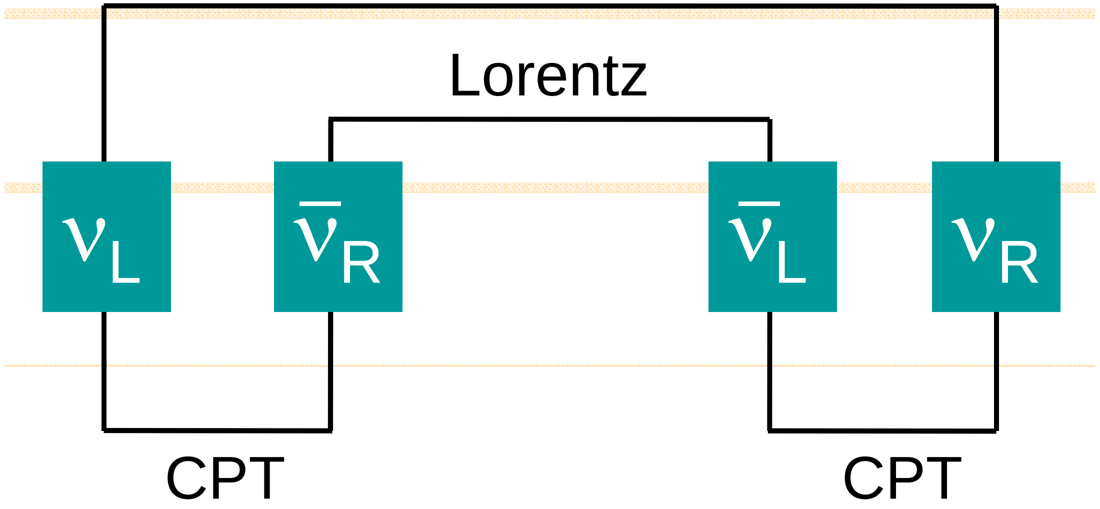
Dirac neutrino

ν^D

4 ν states

lepton number conservation $\Delta L = 0$

neutrino ≠ antineutrino

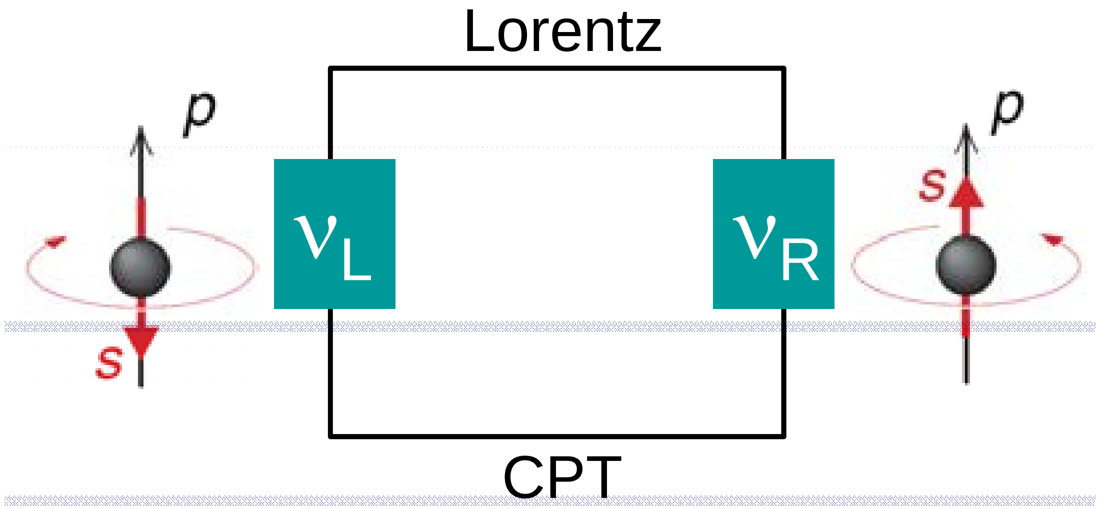


Majorana neutrino

ν^M

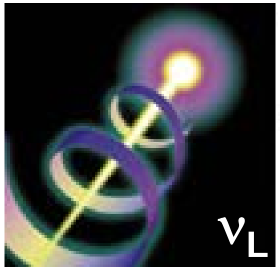
2 ν states

lepton number violation $\Delta L = 2$

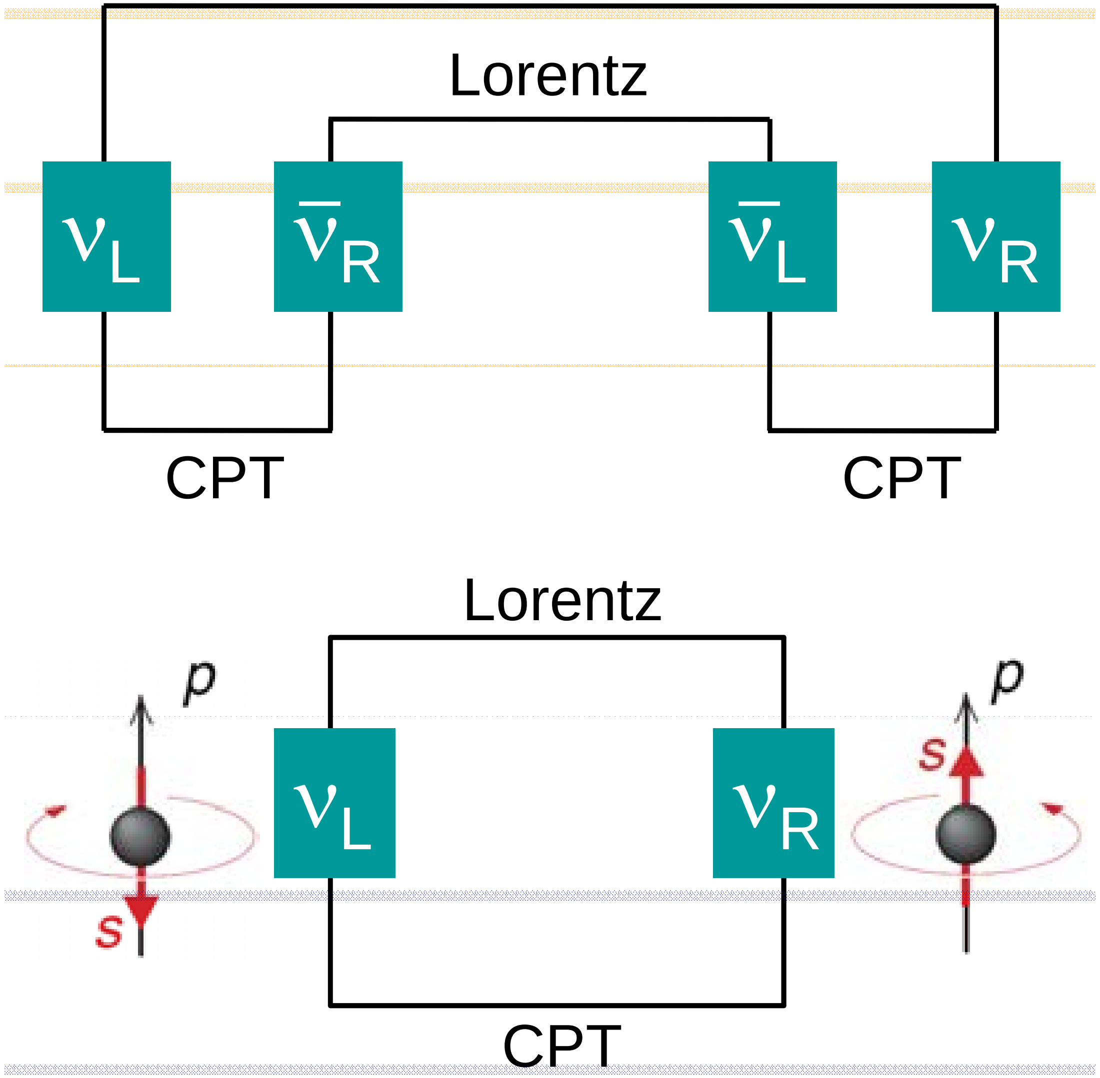


ν^D and ν^M only distinguishable if $m_\nu \neq 0$

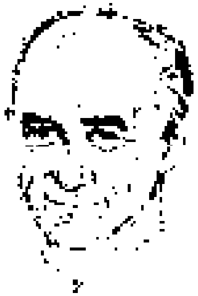
Majorana and Dirac neutrinos



what is the intrinsic **particle-antiparticle symmetry** of neutrinos?



ß-decay: Fermi´s theory & ν-mass



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

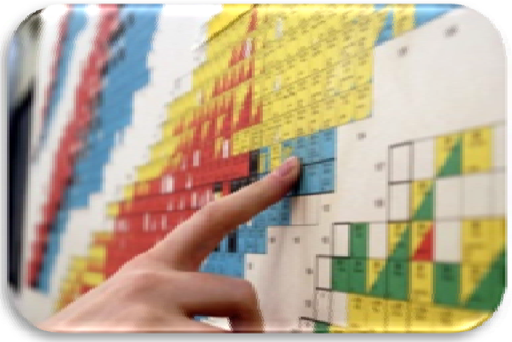
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

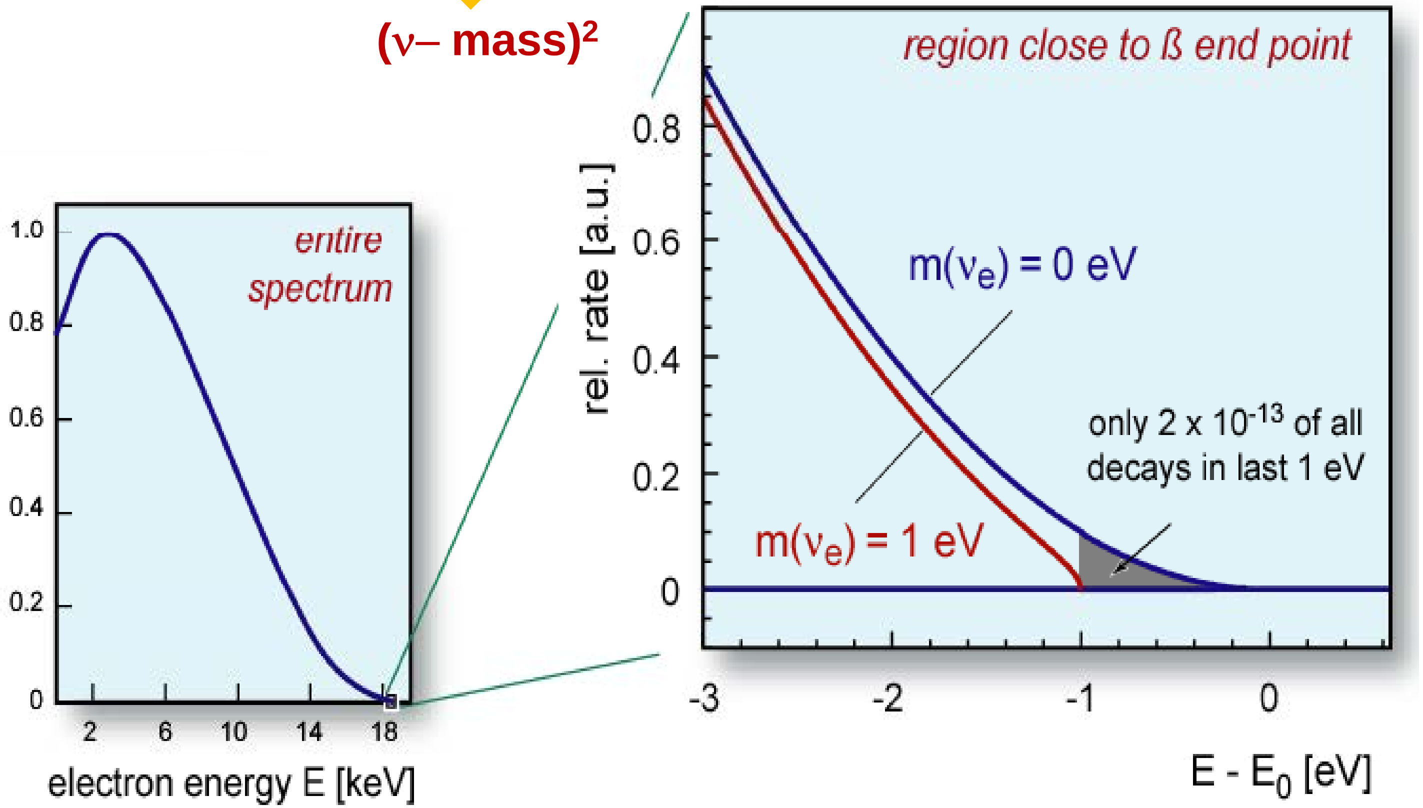
incoherent sum

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

which isotope?

(ν– mass)²





ß-decay: energy spectrum

a model-independent measurement of m(ν_e)
based on kinematics & energy conservation

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

incoherent sum

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

(ν– mass)^2

ß-source requirements	**ß-detection requirements**
short half life $t_{1/2}$ ⇨ high luminosity	large solid angle (~2π)
low endpoint energy E_0	low background rate
superallowed/allowed transition	high energy resolution (~eV)
simple atomic/molecular structure	short dead time, no pile up

^{3}H: super-allowed	
E_0	18. 6 keV
$t_{1/2}$	12.3 y

^{187}Re: unique 1st	
E_0	2.47 keV
$t_{1/2}$	43.2 Gy

calorimeter	**spectrometer**
ß-source = detector	external ß-source
ß-source: ^{187}Re	ß-source: ^{3}H

techniques in ß-decay

the two different techniques are complementary due to different systematics

	calorimeter	spectrometer
source	metallic Re / dielectric $AgReO_4$	windowless gaseous / condensed T_2
activity	low: <10^5 ß/s, ~ 1 Bq / mg Re	high: ~10^{11} ß/s, 4.7 Ci/s injection
energy	single crystal bolometers	electrostatic spectrometer
response	entire ß-decay energy	kinetic energy of ß-decay electrons
interval	entire spectrum	very narrow interval close to E_0
method	differential energy spectrum	integrated energy spectrum
set-up	modular size, scaling factors	integral design, size limits
resolution	$\Delta E_{expected}$ ~ 5-10 eV (FWHM)	$\Delta E_{expected}$ ~ 0.93 eV (100%)

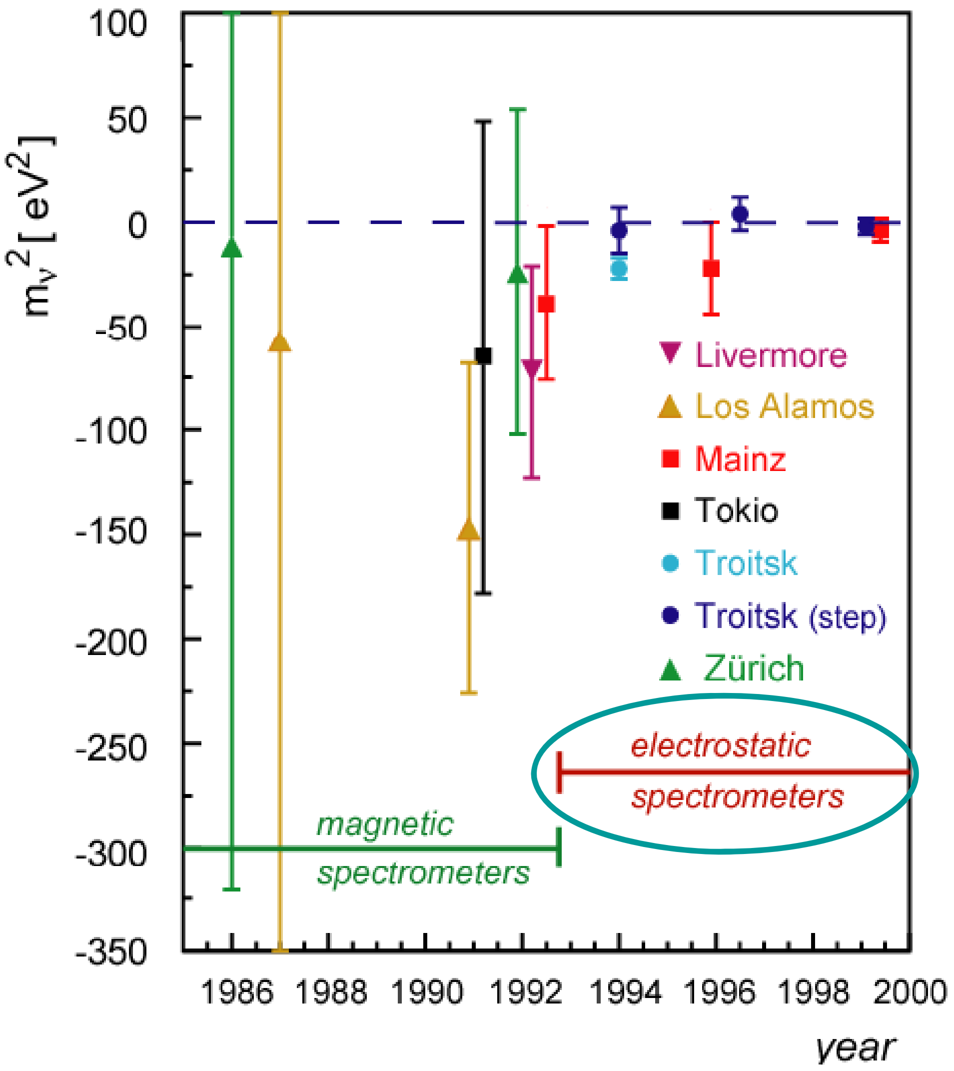
MARE

KATRIN

history of tritium ß-decay experiments

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.3 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV

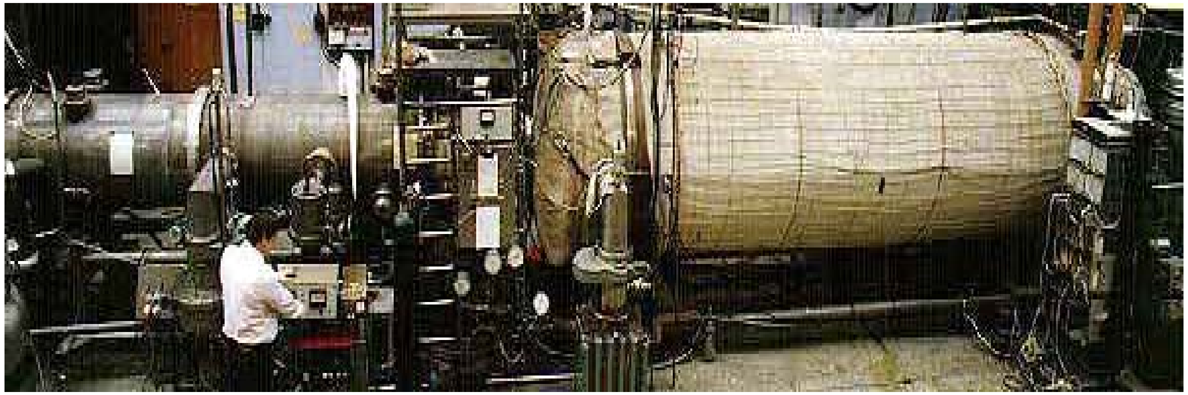
experimental results for m_ν^2



Troitsk & Mainz experiments

Troitsk experiment

windowless gaseous tritium source



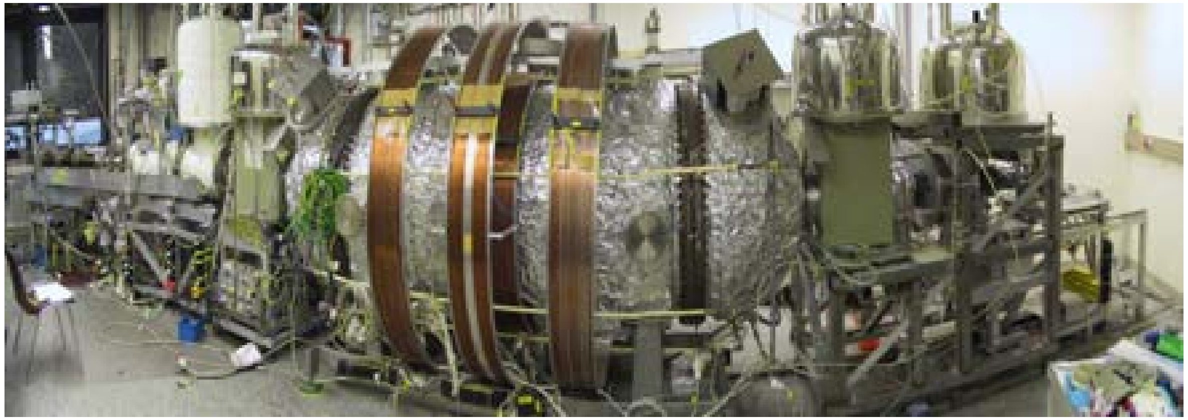
analysis of data 1994-99, 2001

$$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2$$

$$m_\nu \leq \quad 2.2 \text{ eV} \quad (95\% \text{ CL.})$$

Mainz experiment

quench condensed tritium source



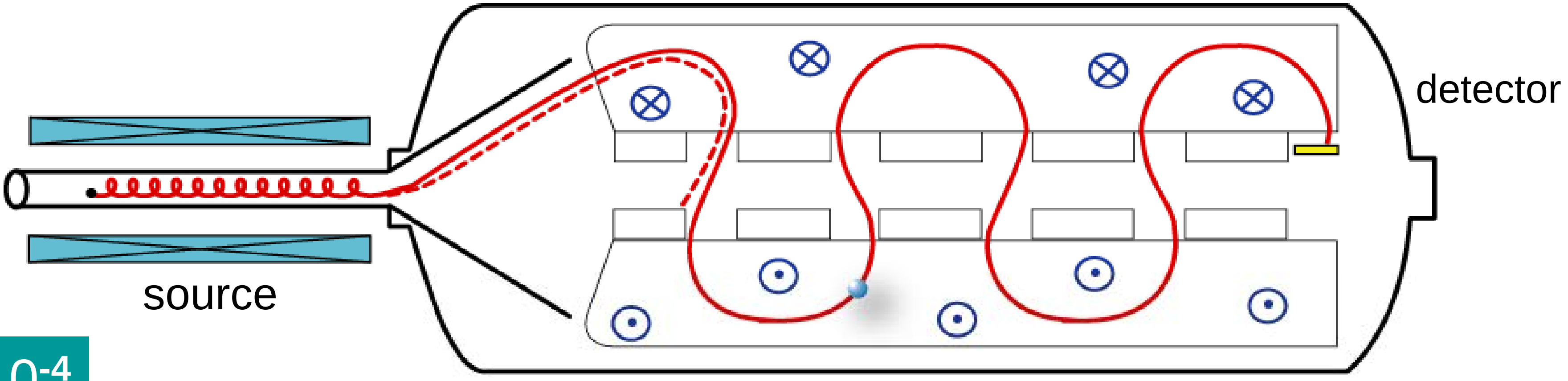
analysis of data 1998-99, 2001

$$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2$$

$$m_\nu \leq \quad 2.2 \text{ eV} \quad (95\% \text{ CL.})$$

spectrometers – comparison of techniques

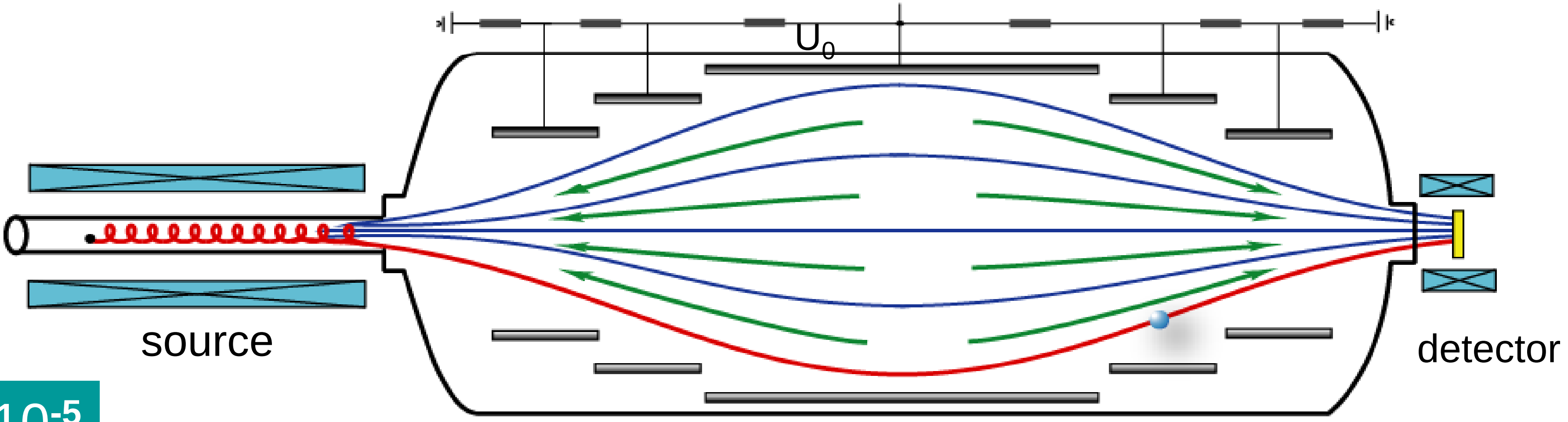
Tret´yakov



$\Delta p/p = 7 \times 10^{-4}$
$\delta\Omega = 10^{-3}$

magnetic guiding field: momentum analysis

MAC-E



$\Delta E/E = 1 \times 10^{-5}$
$\delta\Omega \sim 2\,\pi$

magnetic guiding field & conversion, cyclotron motion
electric retarding field: energy analysis

MAC-E filter – principle

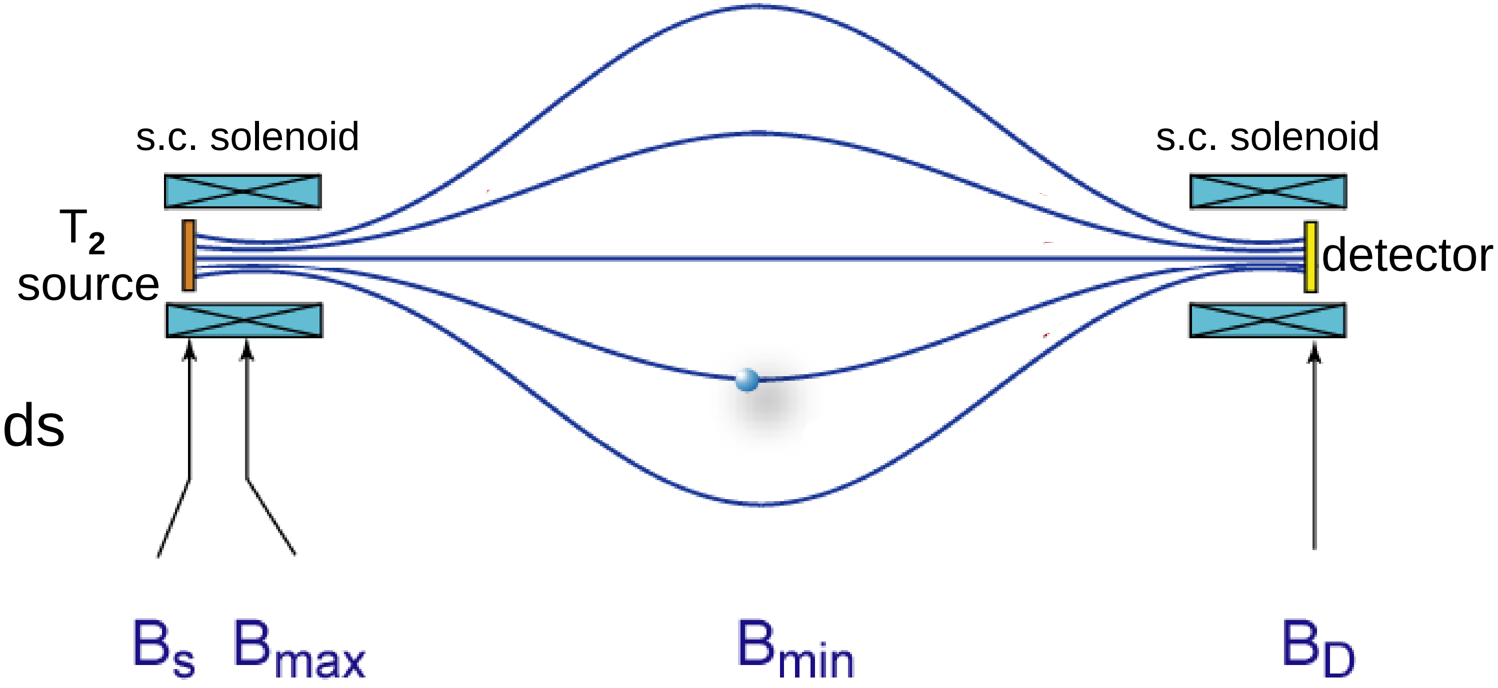
MAC – Magnetic Adiabatic Guiding

adiabatic guiding
of electrons along
magnetic field lines

inhomogenous B-field:
superconducting solenoids
$B_{\mathbf{max}} = 3 - 6$ T
$B_{\mathbf{min}} < 1$ mT
solid angle $d\Omega \sim 2\pi$

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

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



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

MAC-E filter – principle

E Filter – Electro-static filter

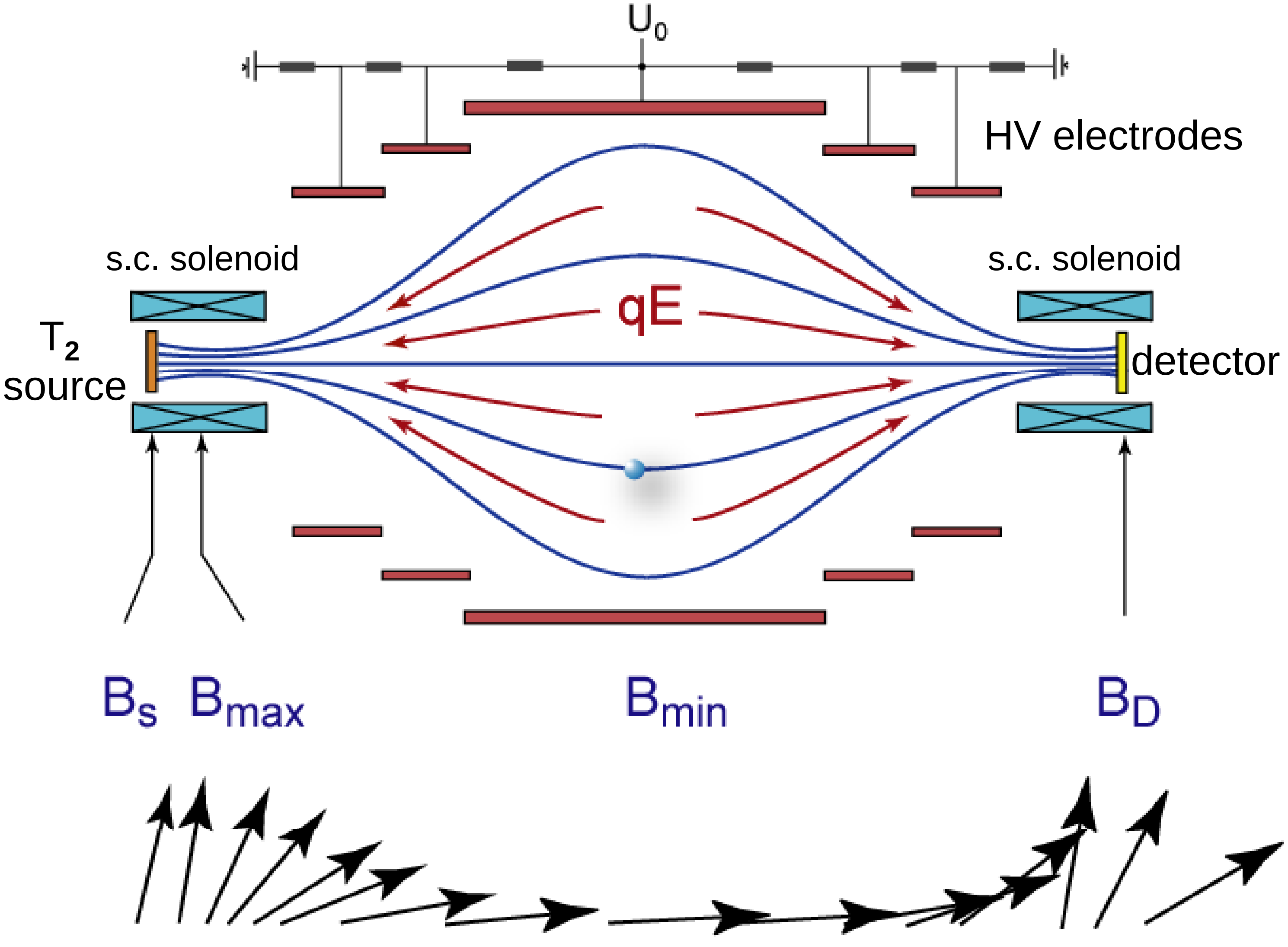
energy analysis by an electrostatic retarding field

variable E-field:
inner electrodes
U_0 = 18.5 – 18.7 kV

integral transmission for E > U_0
high pass filter

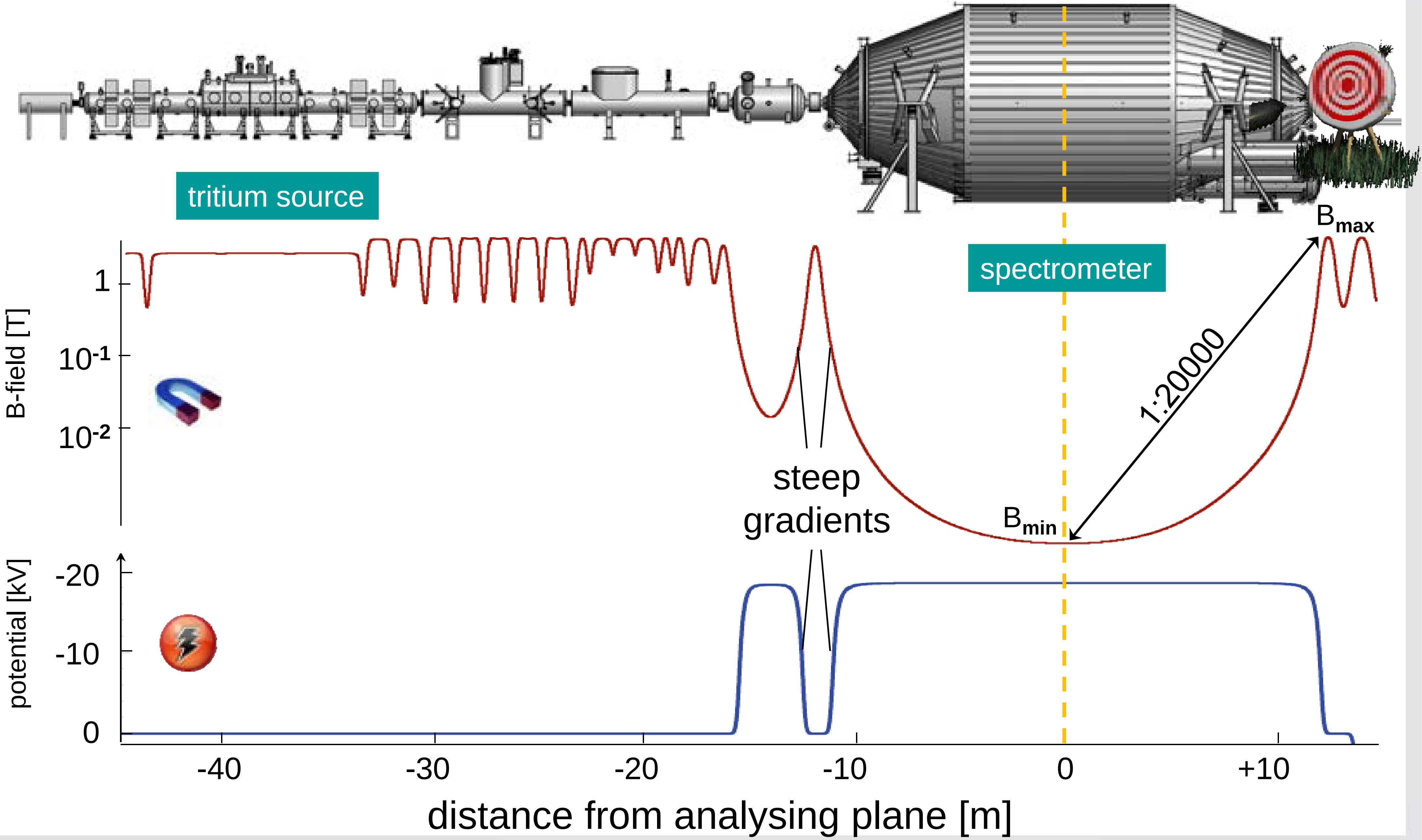
E field || B-field

conversion → retarding

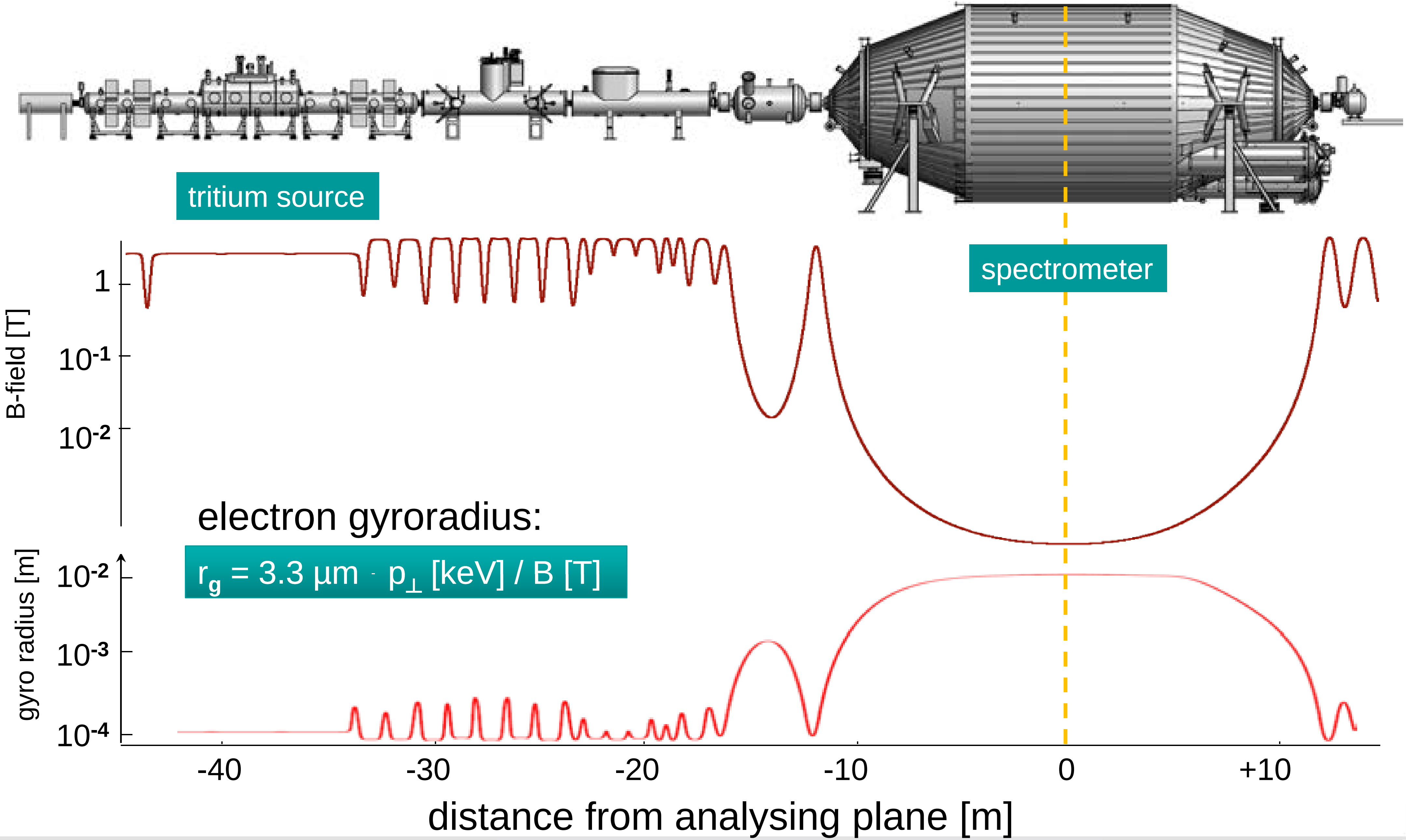


adiabatic transformation $E_\perp \rightarrow E_{||}$

KATRIN – B-field & electrostatic potential



KATRIN – B-field & gyroradius



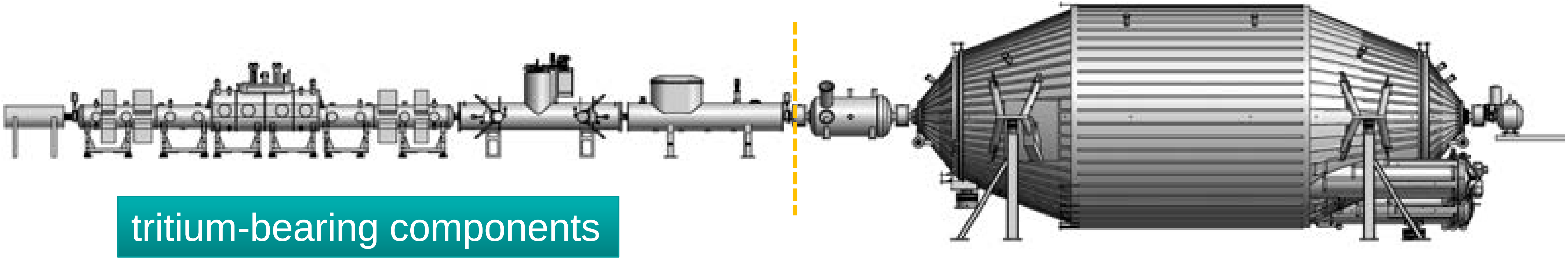
tritium source

spectrometer

electron gyroradius:

$r_g = 3.3\ \mu m \cdot p_{\perp}\ [keV] / B\ [T]$

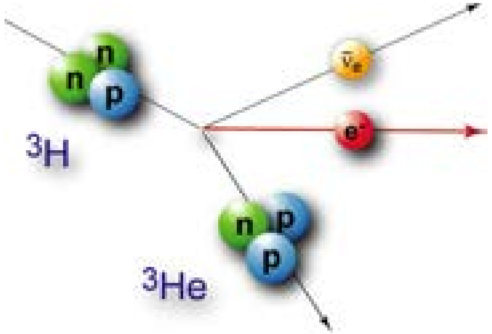
KATRIN experiment - overview

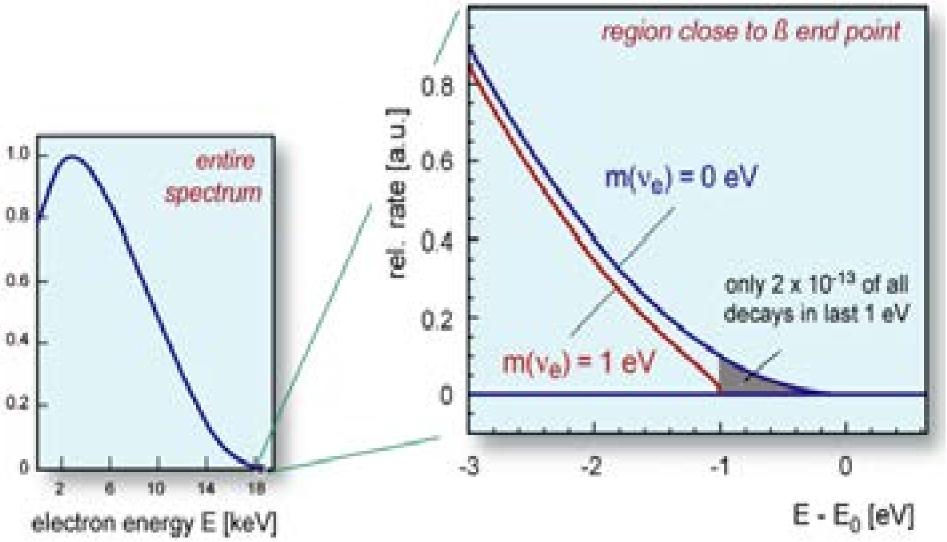


tritium-bearing components

electrostatic spectrometers & detector

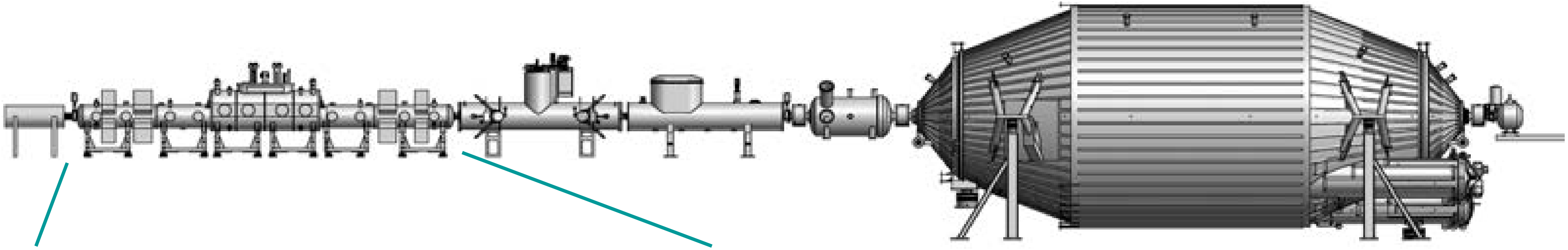
$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e}$





- improve experim. precision by factor 100 (´*go to the technological limits*´)
- fully adiabatic (meV-Skala) particle transport over > 50 m
- 10^{11} Bq tritium source ⇔ 10^{-2} Bq total background

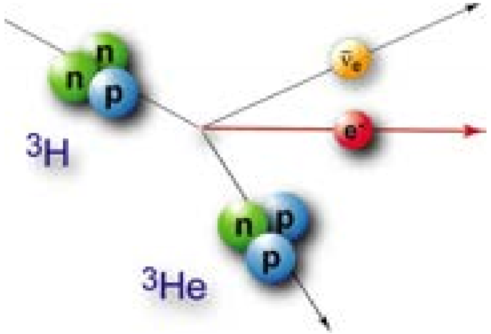
KATRIN – closed tritium cycle & TLK

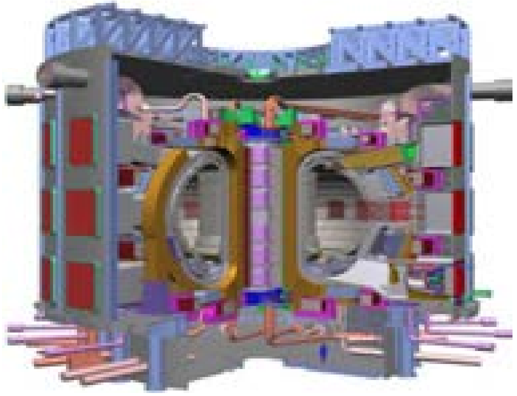


KATRIN tritium throughput per year equivalent to fusion facility ITER

KATRIN closed cycle operational in 2012

⇔ first D-T operation of ITER in 2026



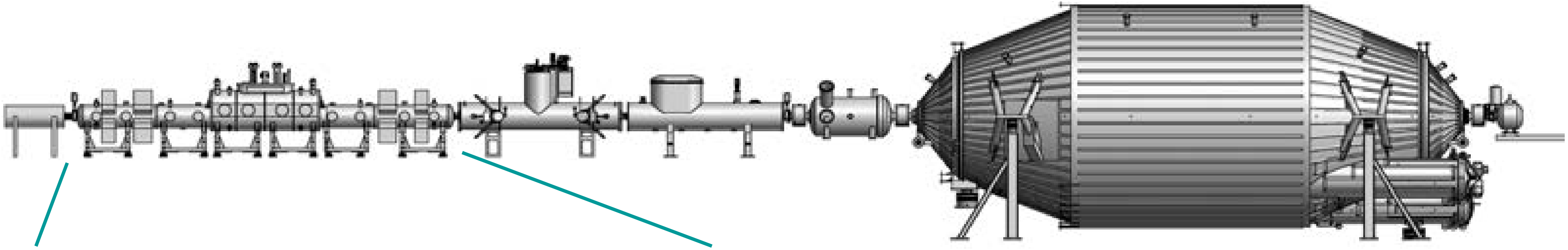


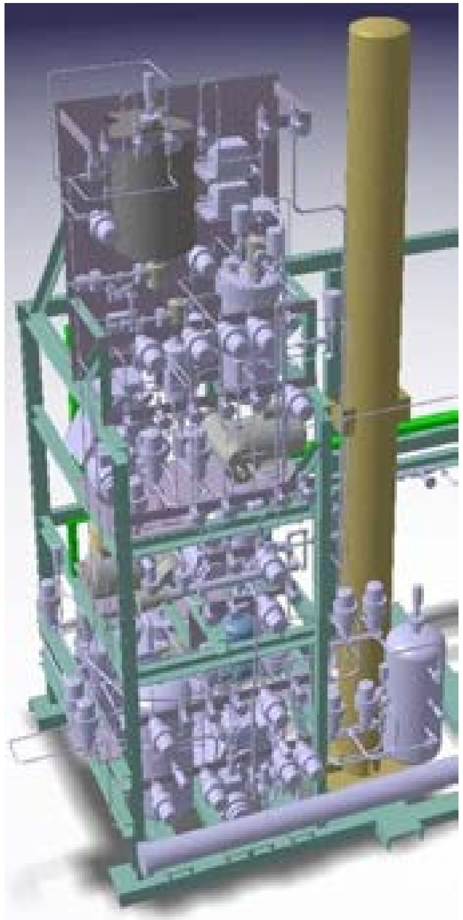
TLK – Tritium Laboratory Karlsruhe

a unique research facility in Europe

licensed for storage of 20 g tritium

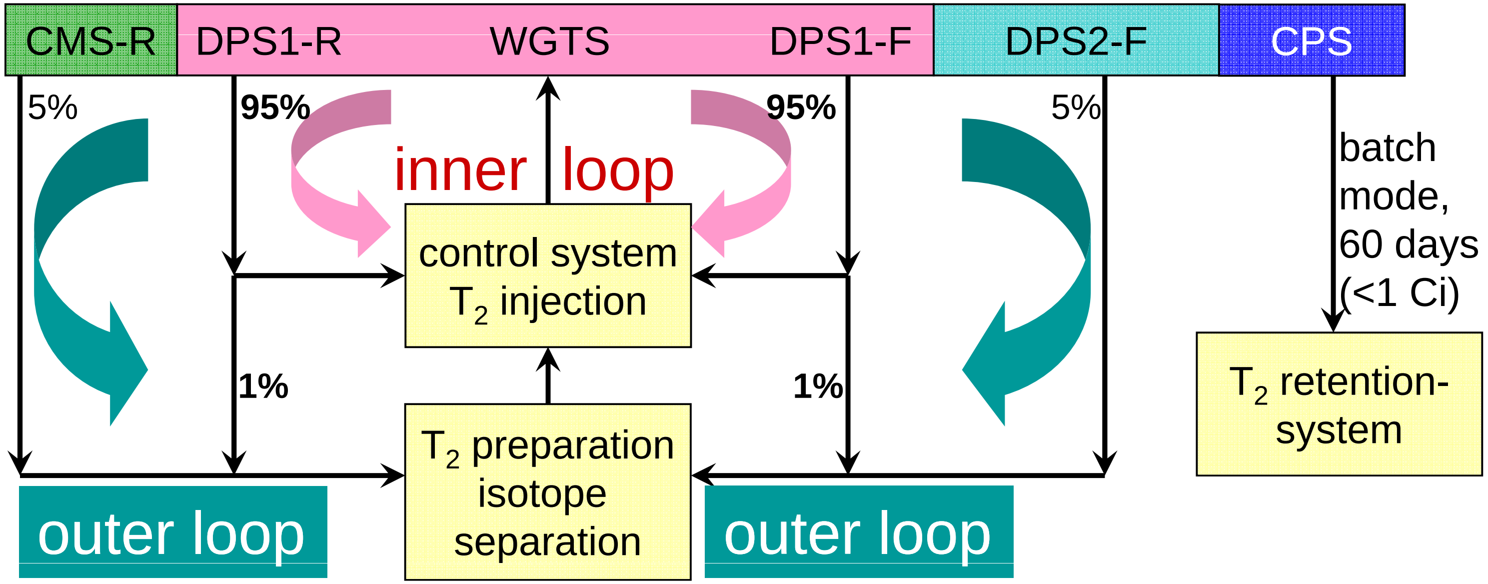
KATRIN – closed tritium cycle



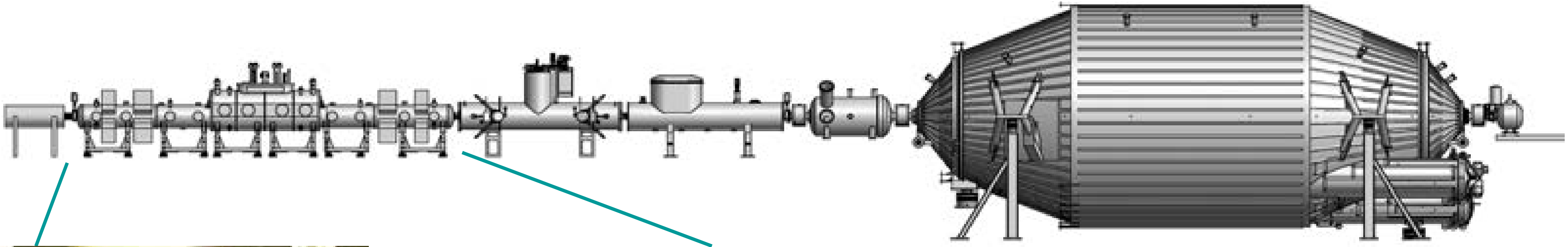


KATRIN tritium loop system

27 pumps, 109 valves, 62 sensors,
6 buffer vessels, 2 permeators

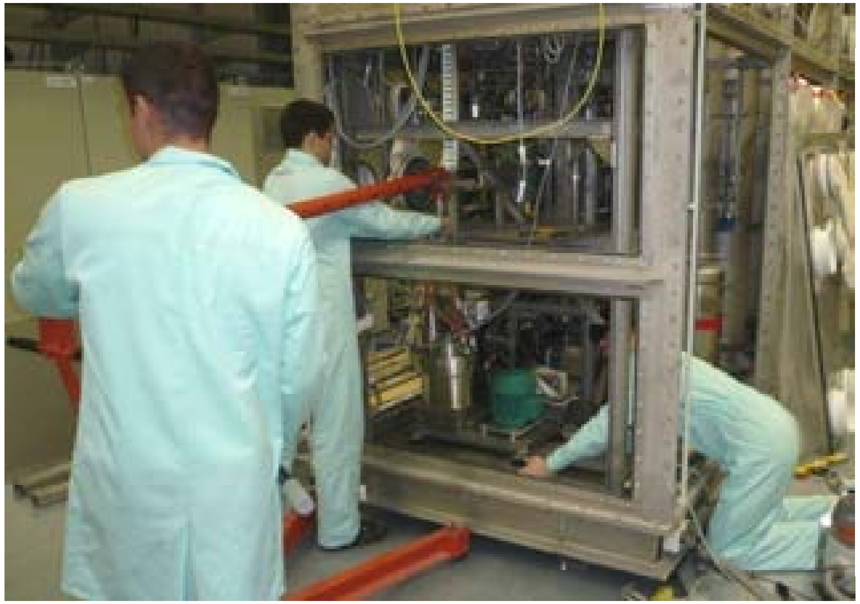


KATRIN – closed tritium cycle



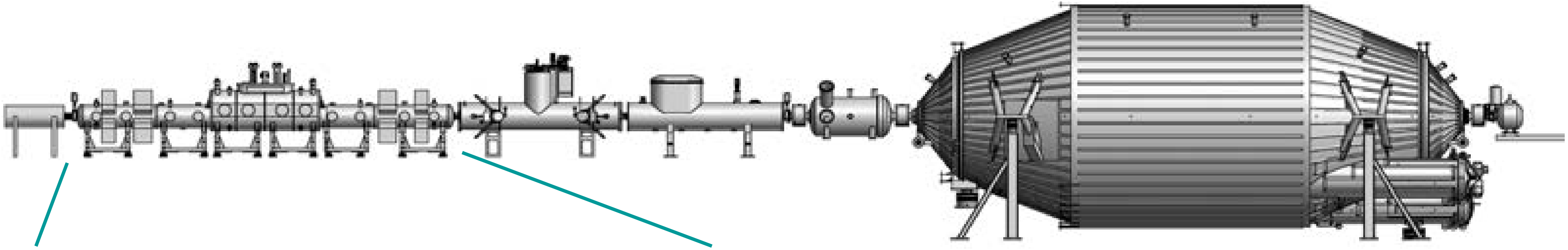
KATRIN tritium loop system

27 pumps, 109 valves, 62 sensors,
6 buffer vessels, 2 permeators

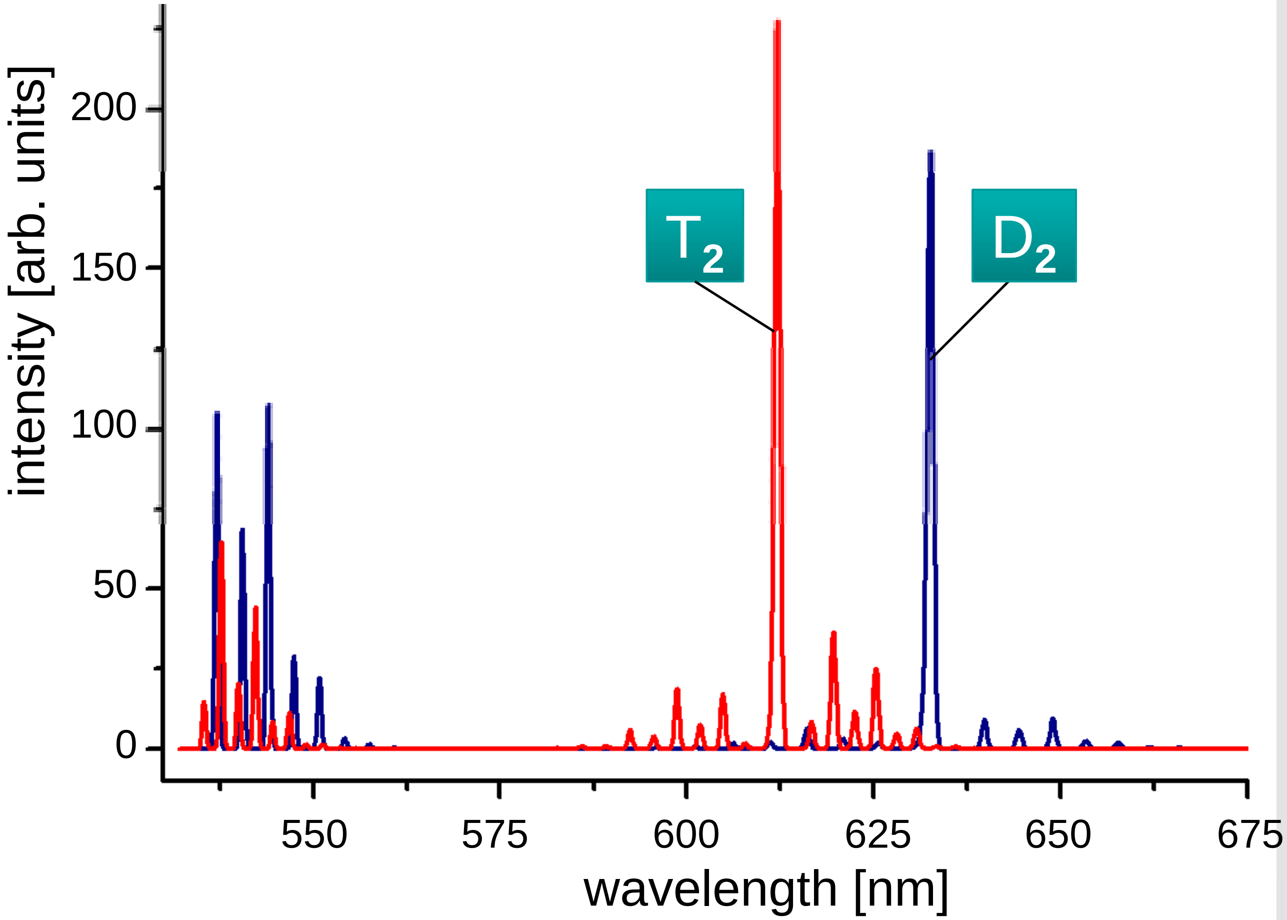


set-up of inner loop system
in progress ☑

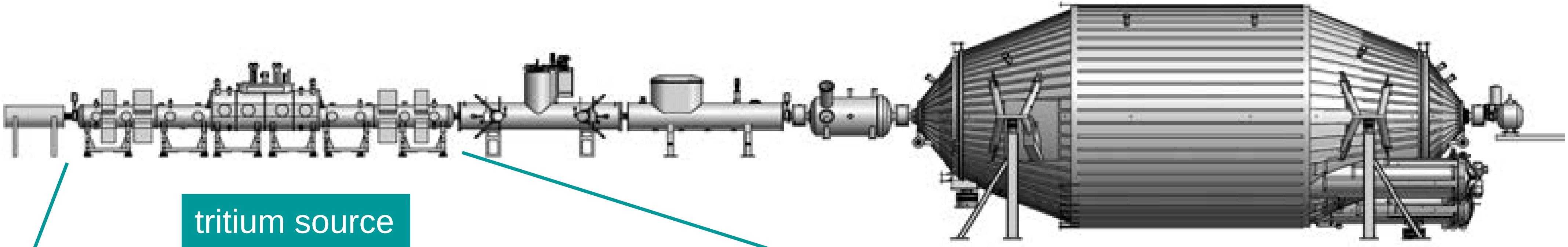
KATRIN – Laser Raman Spectroscopy



high-precision (~0.1%)
in-situ measurement of
actual H-isotopologue
composition in the WGTS



WGTS – windowless gaseous source

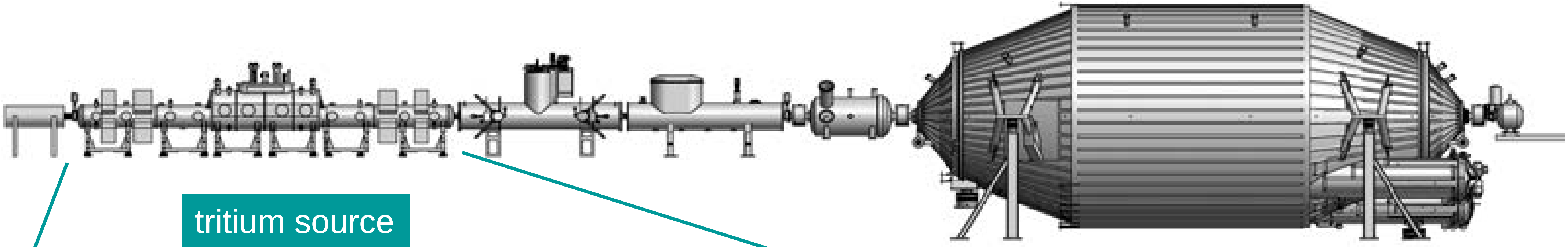


tritium source

WGTS	design value	precision
luminosity	1.7 × 10^{11} Bq	
injection rate	5 × 10^{19} mol/s	±0.1 %
column density ρd	5 × 10^{17} mol/cm^2	±0.1 %
tritium purity	> 95%	±0.1 %
magnetic field	3.6 T	± 2%

16 m long cryostat

WGTS – windowless gaseous source

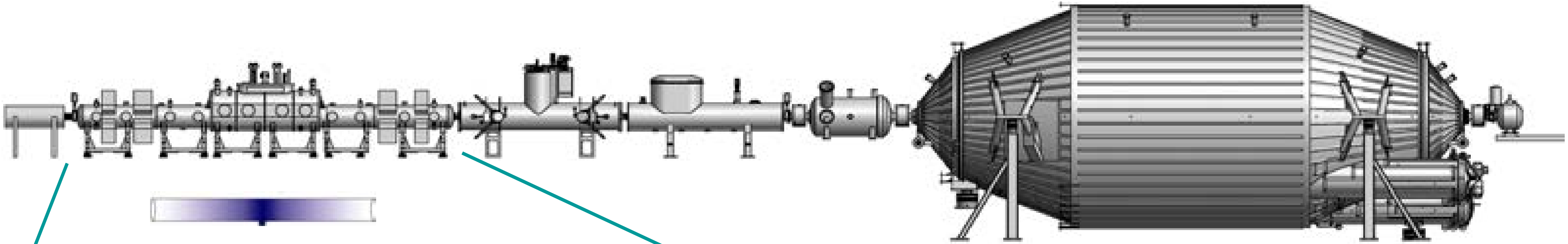


12 cryogenic circuits

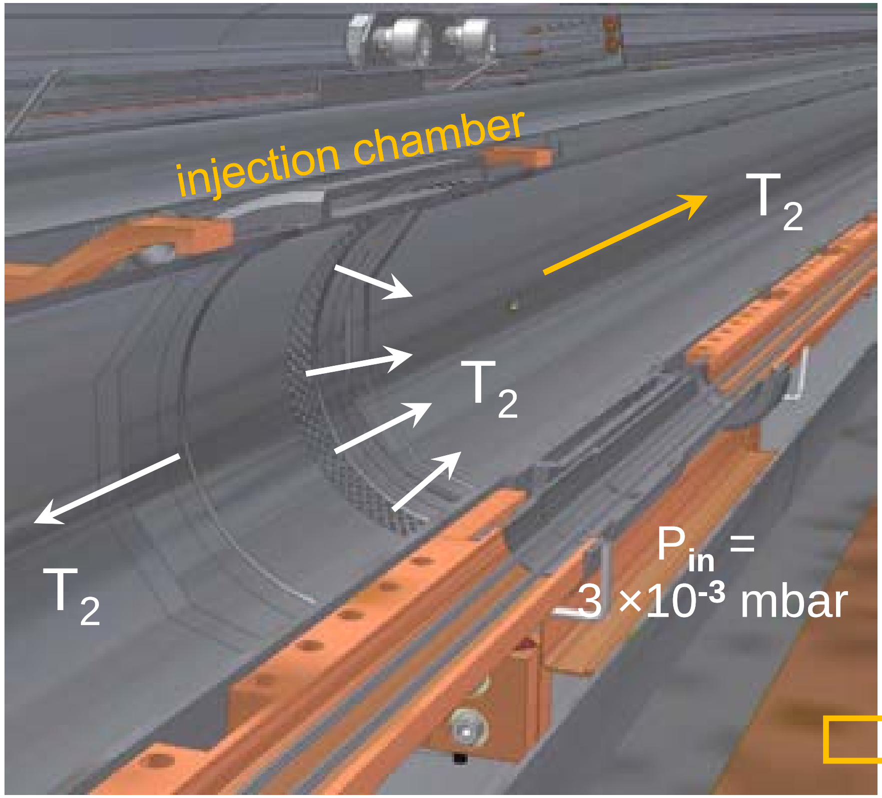
6 cryogenic fluids

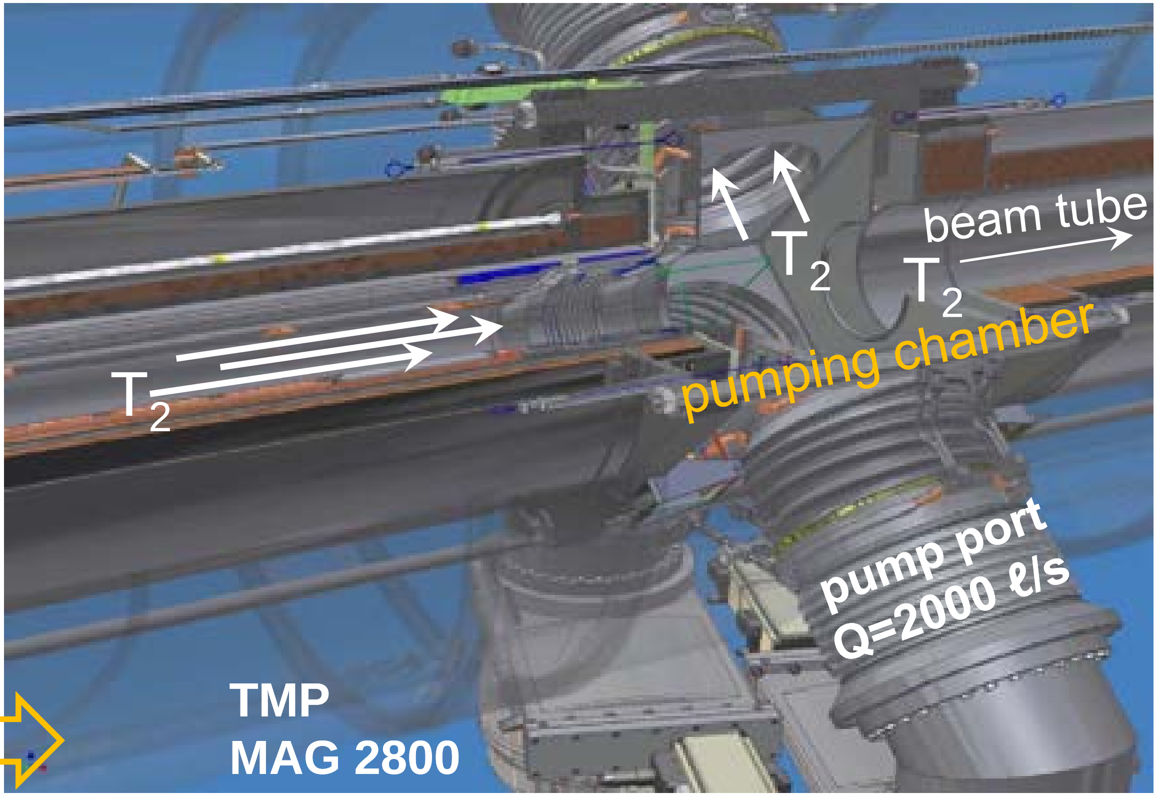
- instrumentation:
~ 500 sensors for
temperature (4 – 600 K),
B-field, pressure,
gas flow,
liquid levels

KATRIN – windowless gaseous source



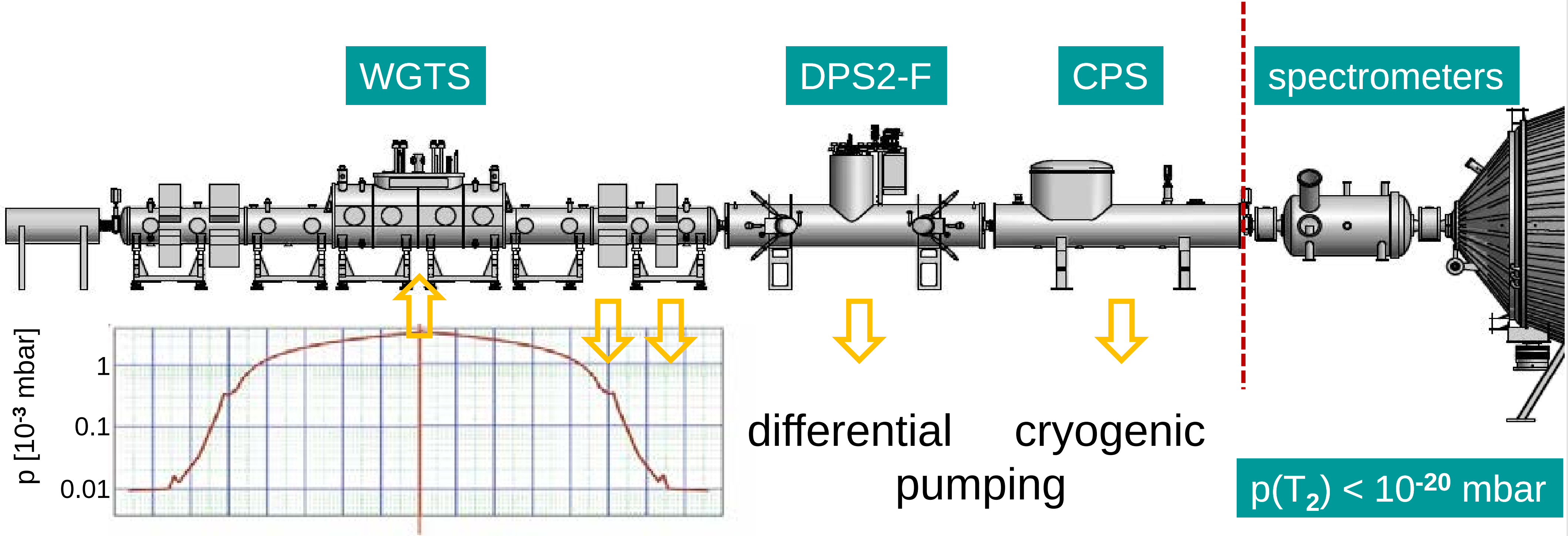
WGTS gasdynamics: on-going detailed modelling of molecular velocities





KATRIN – tritium retention

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



tritium bearing components

tritium free

WGTS

DPS2-F

CPS

spectrometers

differential cryogenic pumping

$p(T_2) < 10^{-20}$ mbar

injection

injection rate = 1.8 mbar ℓ / s

R>10^7

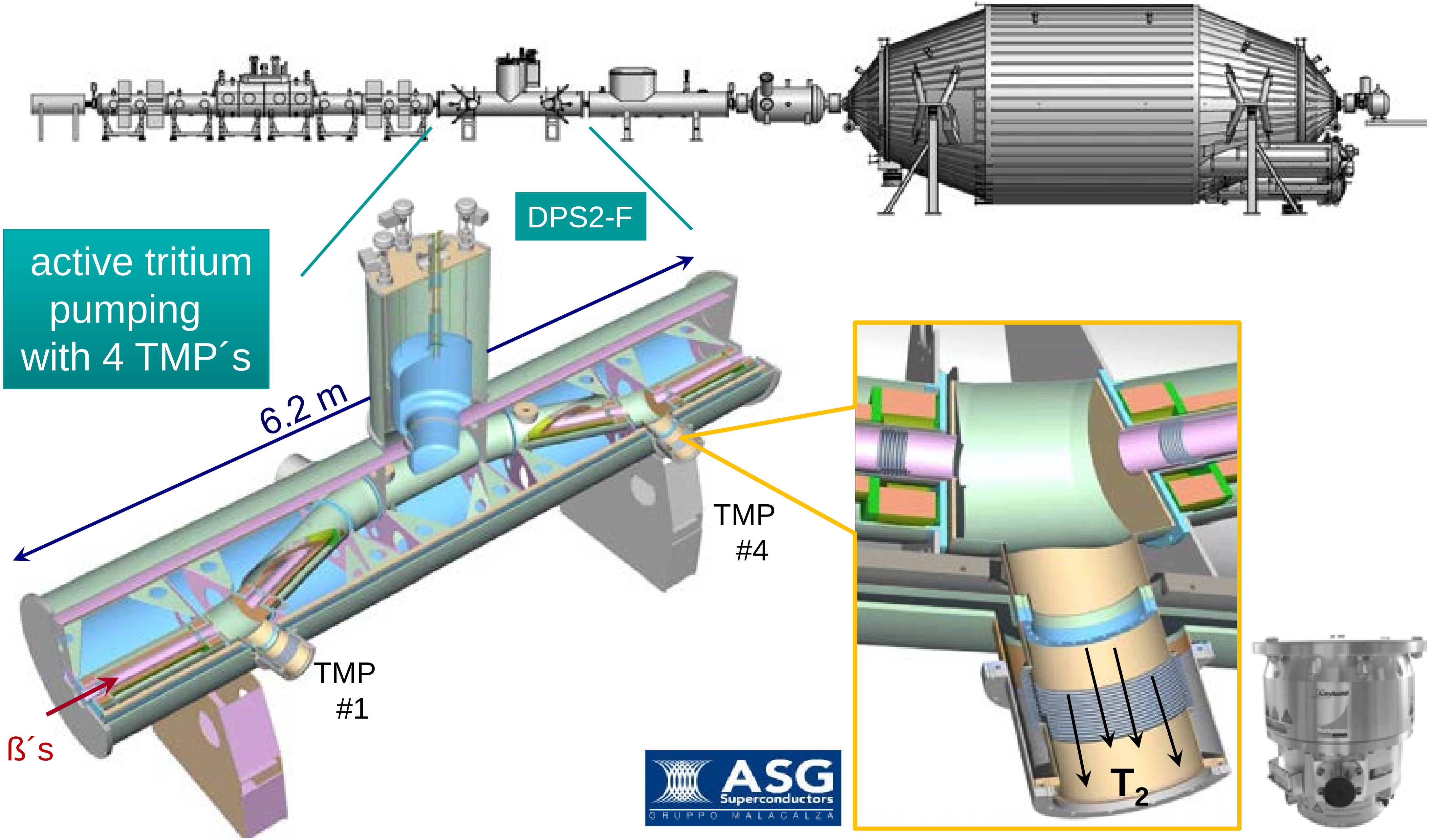
10^{-7} mbar ℓ/s

R>10^7

10^{-14} mbar ℓ/s

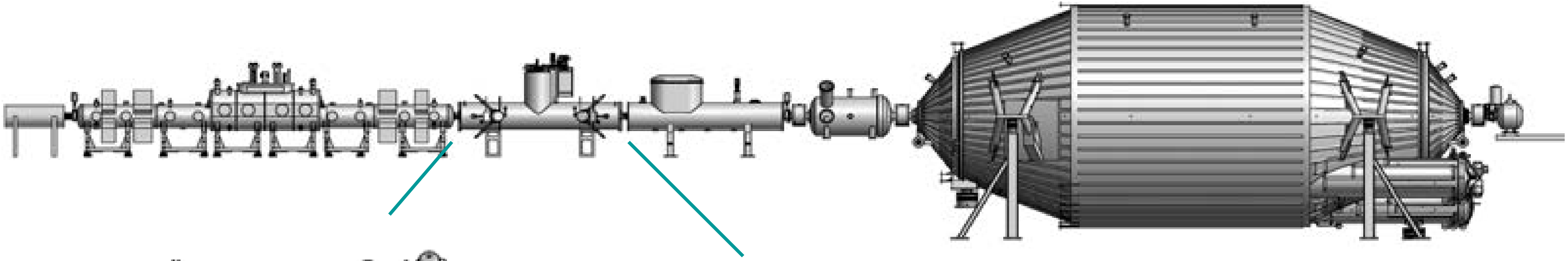
differential pumping section DPS2-F

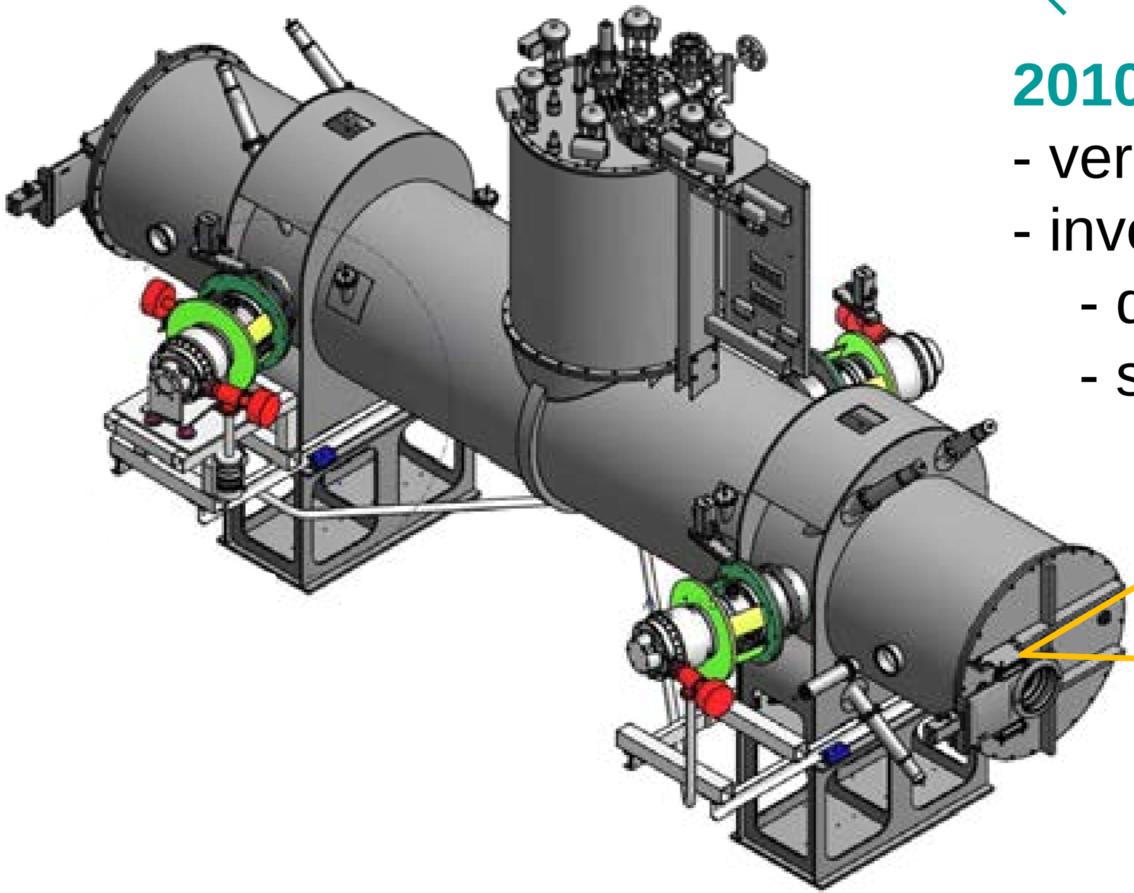
active tritium pumping with 4 TMP´s



July 14, 2009:
DPS2-F cryostat has arrived
at KIT campus north

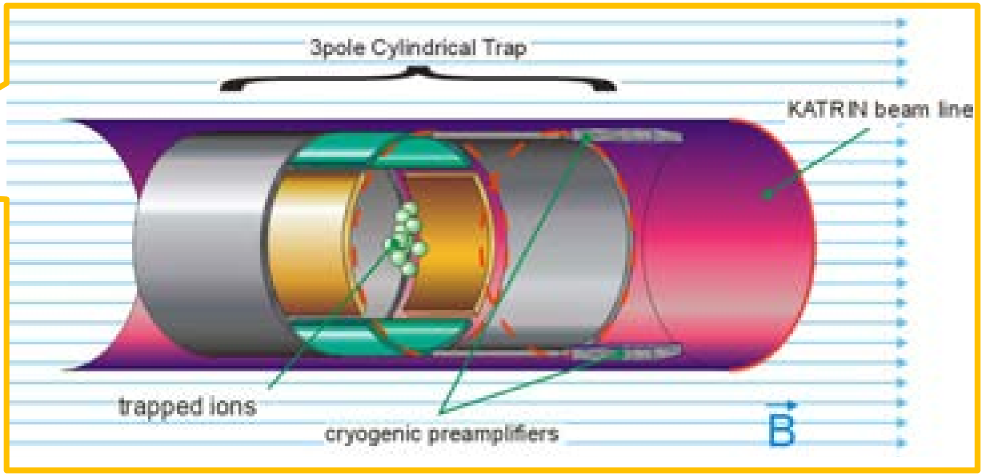
differential pumping section DPS2-F



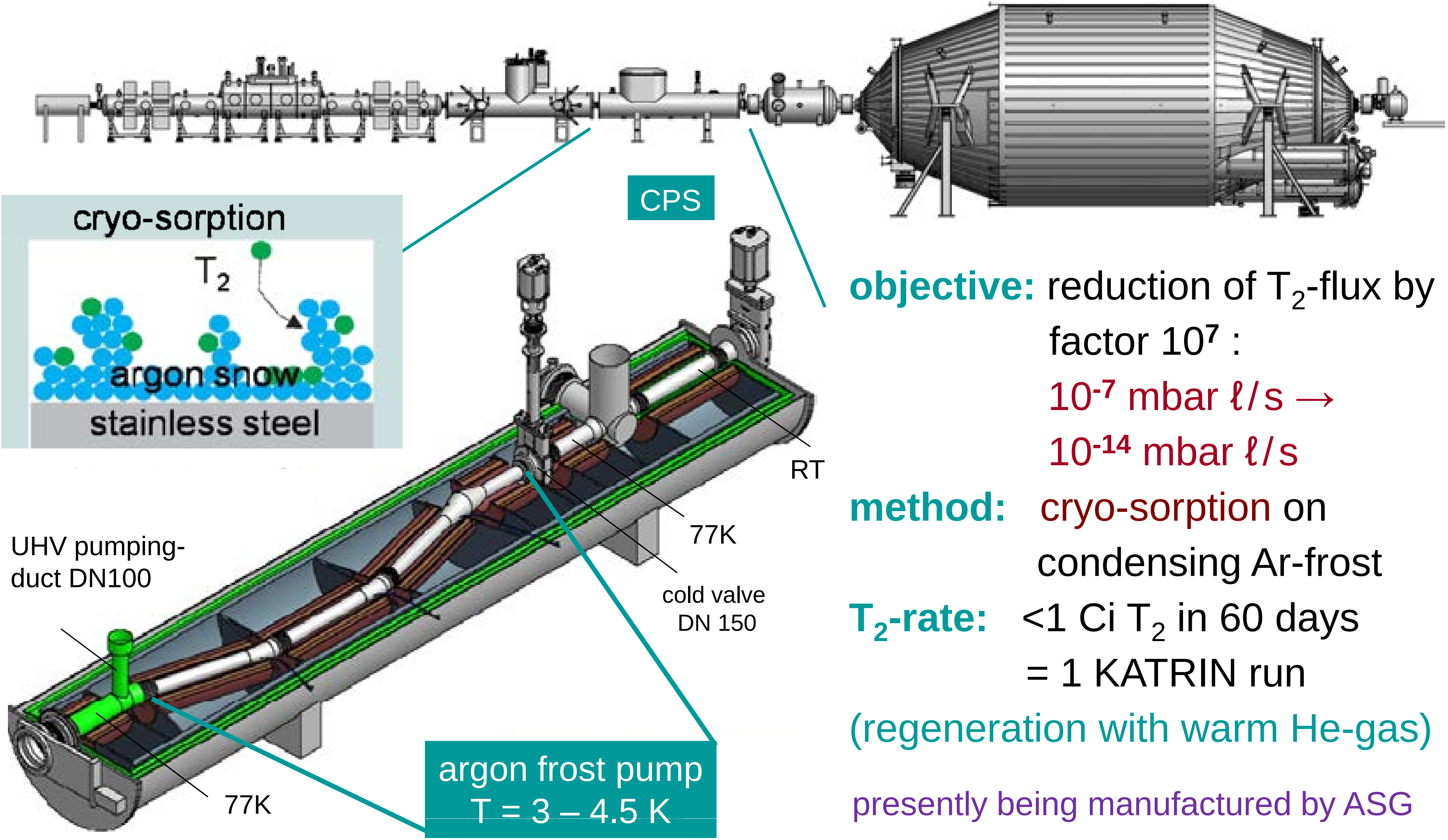


2010 DPS2-F experimental programme

- verify H-isotopologue retention $R = 10^5$
- investigations of ion properties:
  - diagnostics with FT-ICR measurements
  - suppression with dipoles



cryogenic pumping section CPS



objective: reduction of T_2-flux by factor 10^7 :

10^{-7} mbar ℓ/s →

10^{-14} mbar ℓ/s

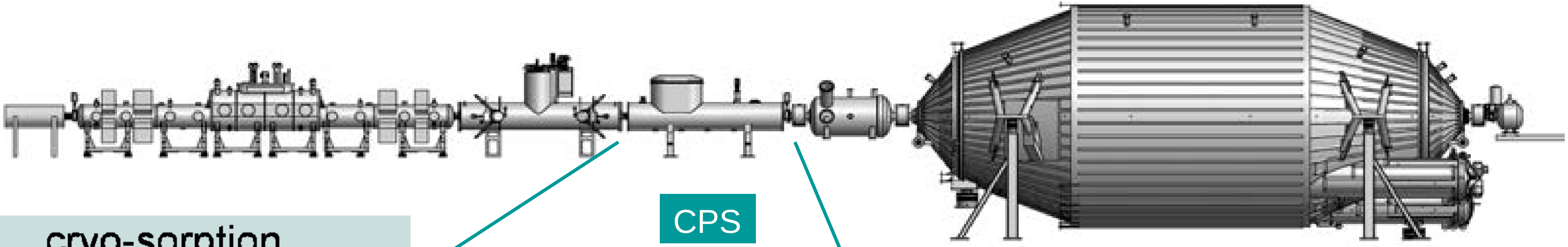
method: cryo-sorption on condensing Ar-frost

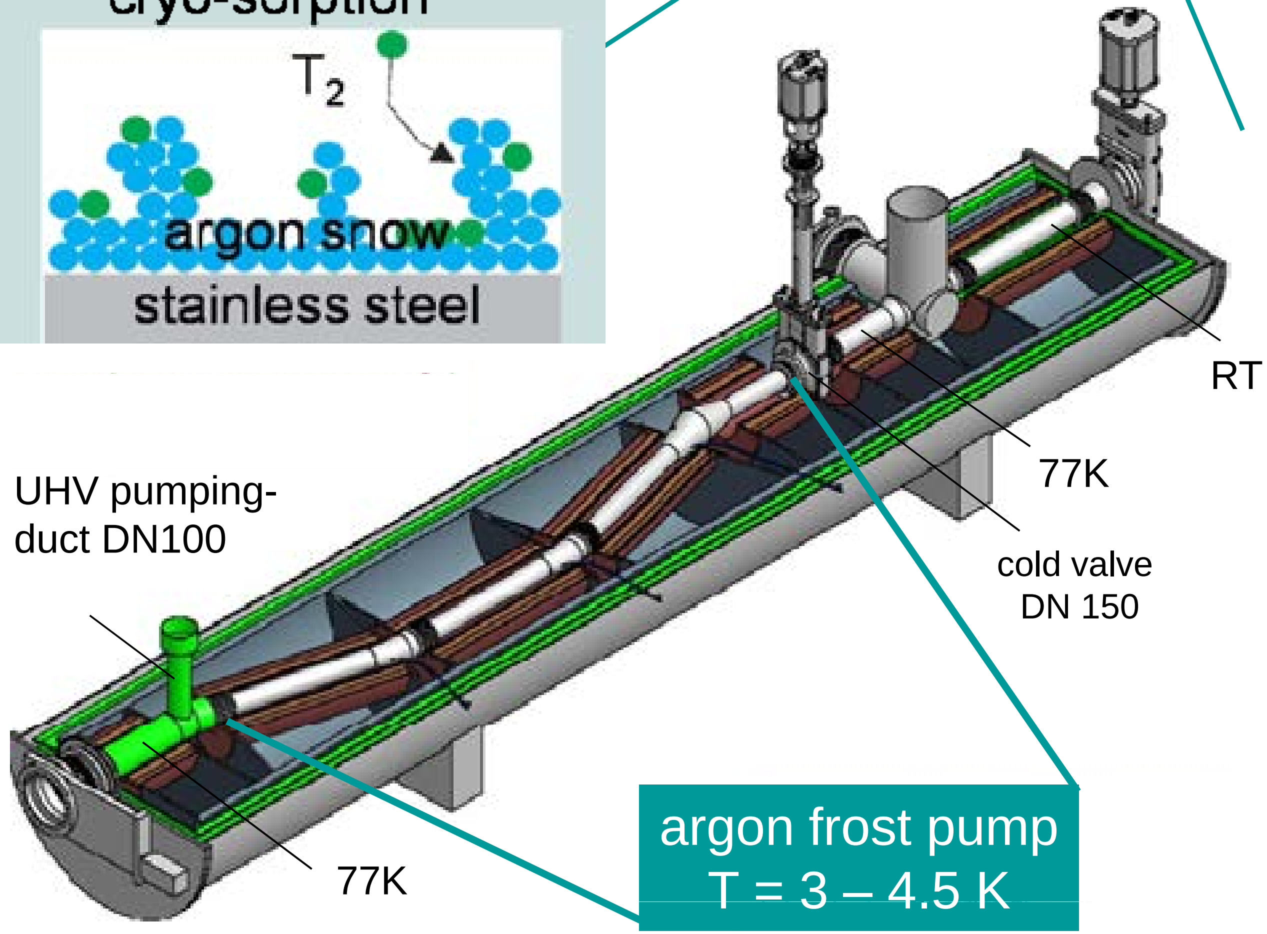
T_2-rate: <1 Ci T_2 in 60 days = 1 KATRIN run

(regeneration with warm He-gas)

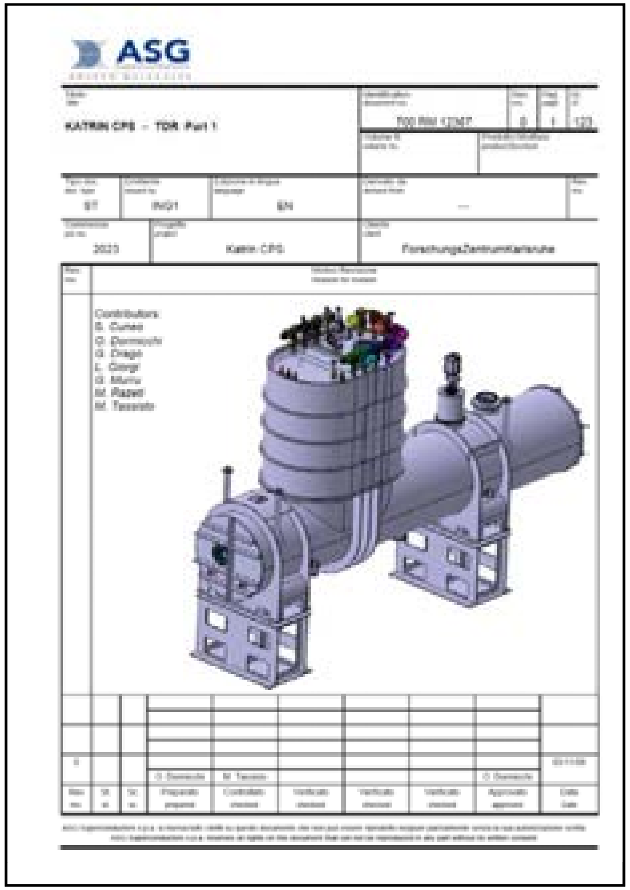
presently being manufactured by ASG

cryogenic pumping section CPS





argon frost pump
T = 3 – 4.5 K



ASG

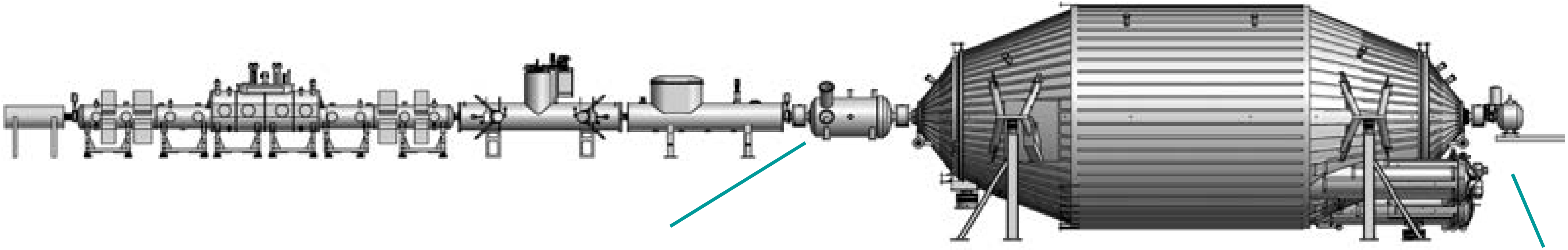
KATRIN CPS – TDR Part 1

Katrin CPS

ForschungsZentrumKarlsruhe

Contributors:

electrostatic spectrometers



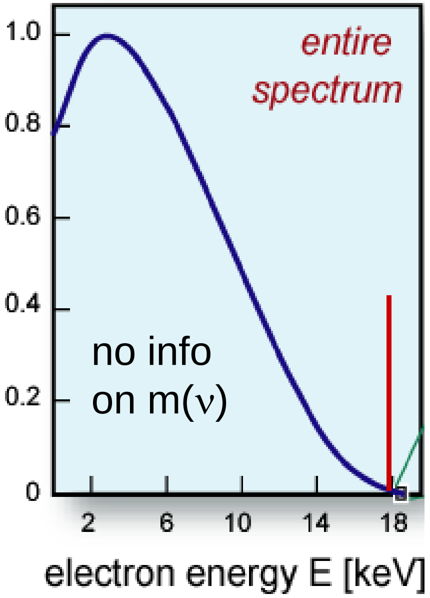
pre-filter

fixed retarding potential

U_0 = - 18.3 kV

ΔE ~ 100 eV

- filter out all ß-decay electrons without m(ν)-info
- reduce background from ionising collisions

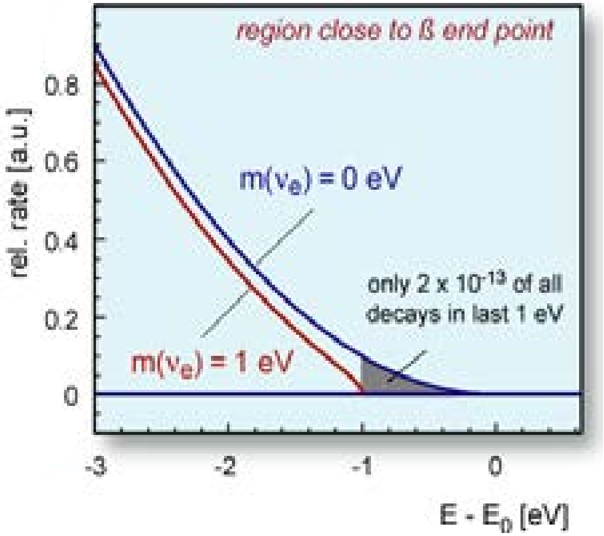


precision filter - scanning

variable retarding potential

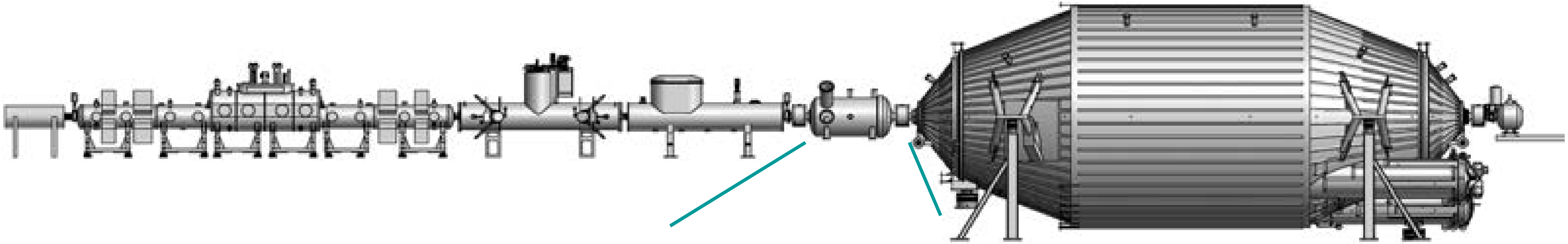
U_0 = - 18.4 … -18.6 kV

ΔE ~ 0.93 eV (100% transmission)

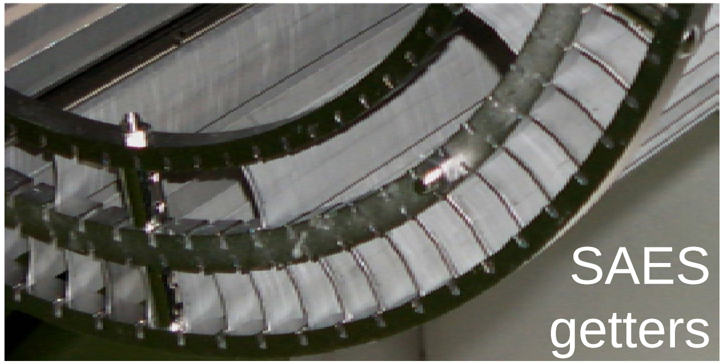


tandem design: pre-filter & energy analysis

pre-spectrometer – UHV

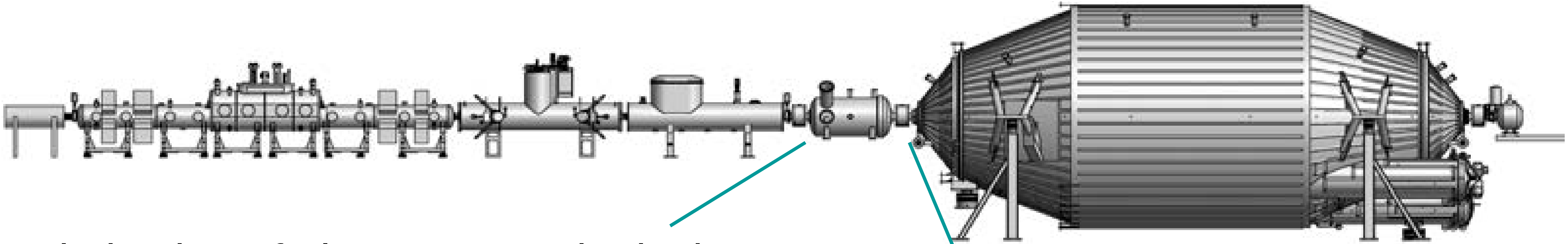


successful verification of UHV concept



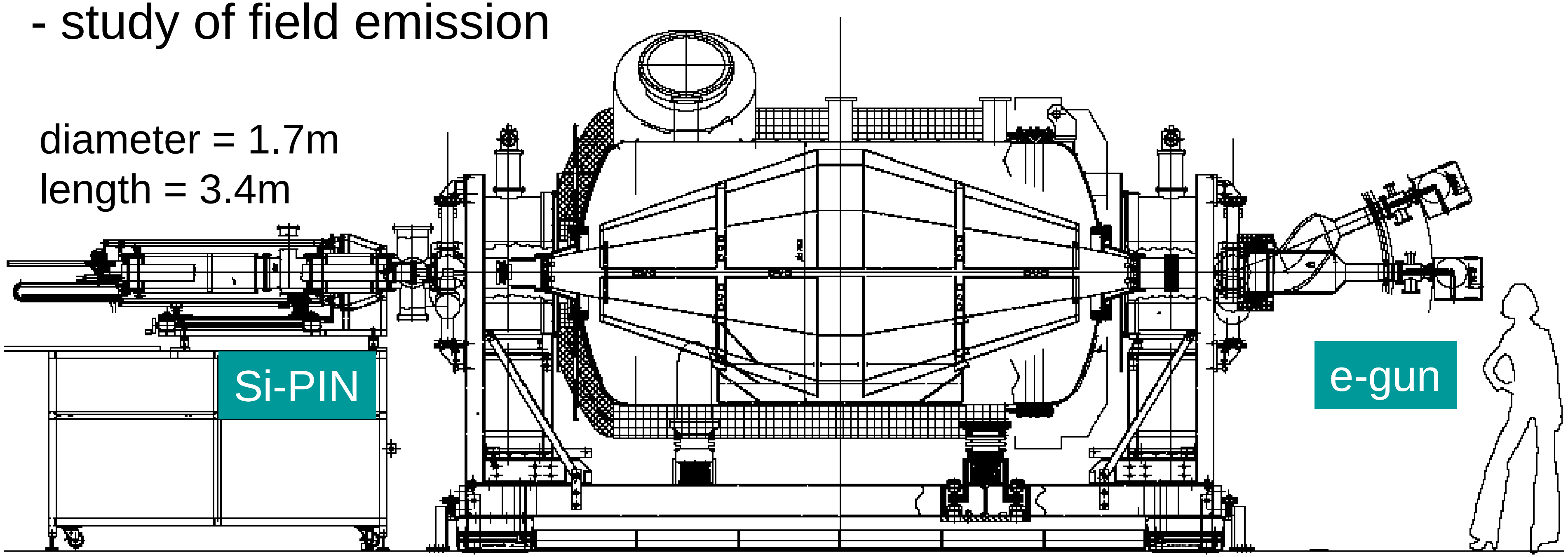
SAES getters

pre-spectrometer: electromagnetic tests



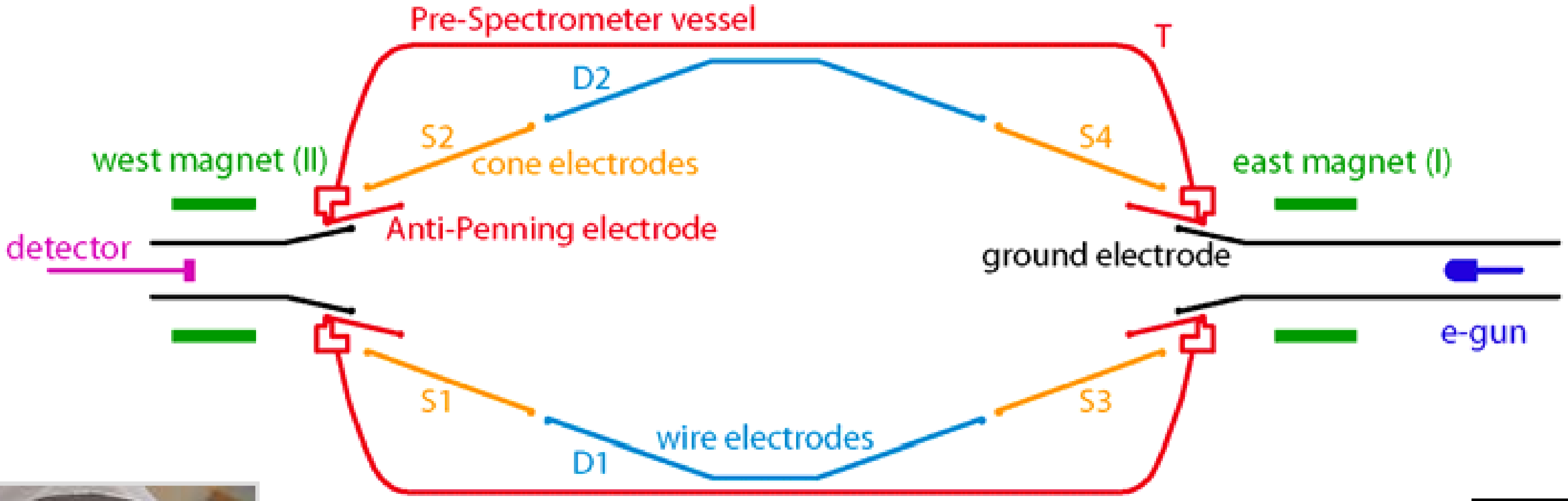
optimisation of electromagnetic design

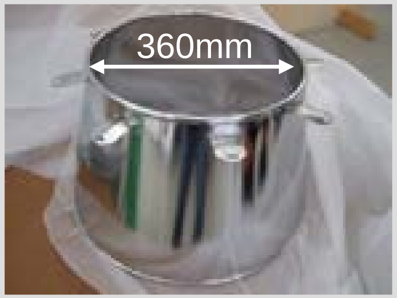
- minimisation of Penning traps
- background reduction techniques (dipole fields)
- study of field emission

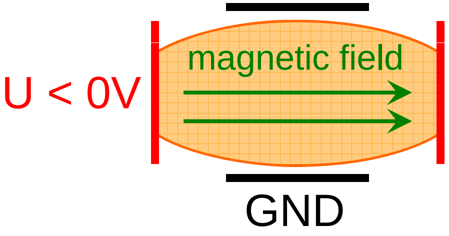


diameter = 1.7m
length = 3.4m

pre-spectrometer: electromagnetic tests



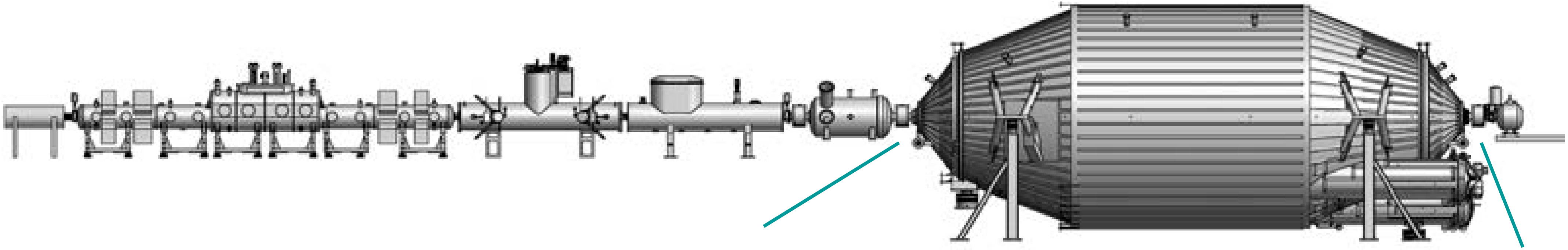




optimisation of electromagnetic design

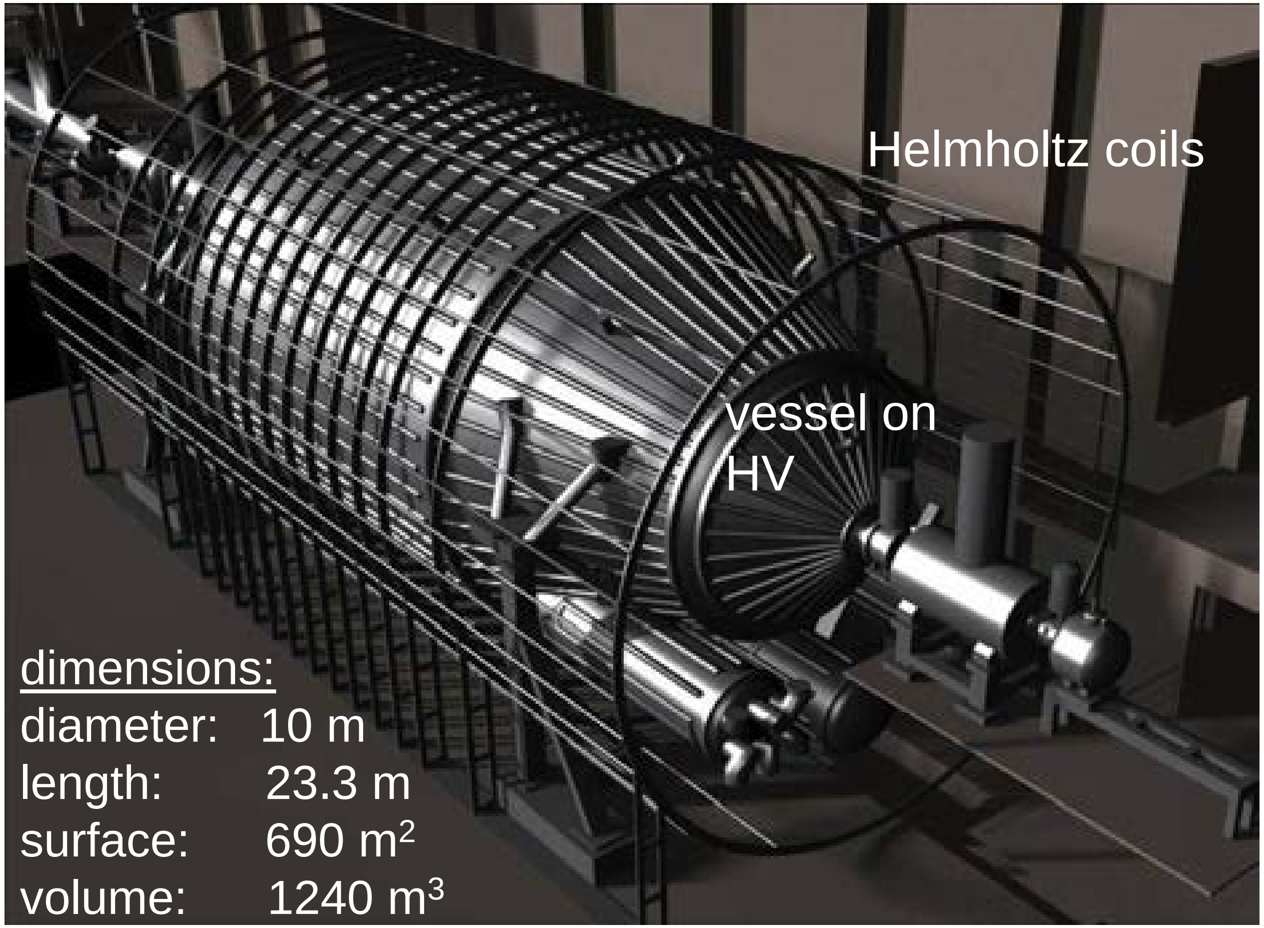
- design of geometry of ground & Anti-Penning electrodes
- detailed study of characteristics of Penning traps as function of electrostatic potential, B-field, pressure
- 3rd generation layout is being implemented

main spectrometer: world´s largest UHV recipient



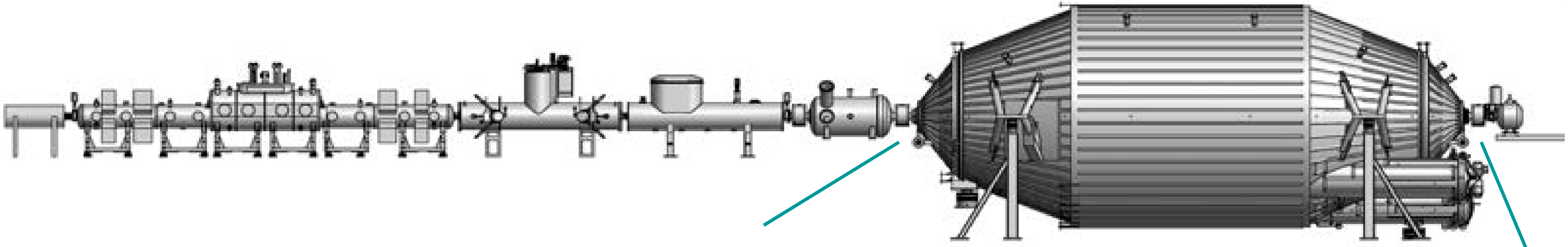
UHV : $p < 10^{-11}$ mbar !

MAN DWE GmbH



dimensions:
diameter: 10 m
length: 23.3 m
surface: 690 m^2
volume: 1240 m^3

main spectrometer: world´s largest UHV recipient



LHC
accelerator

VIRGO
antennae

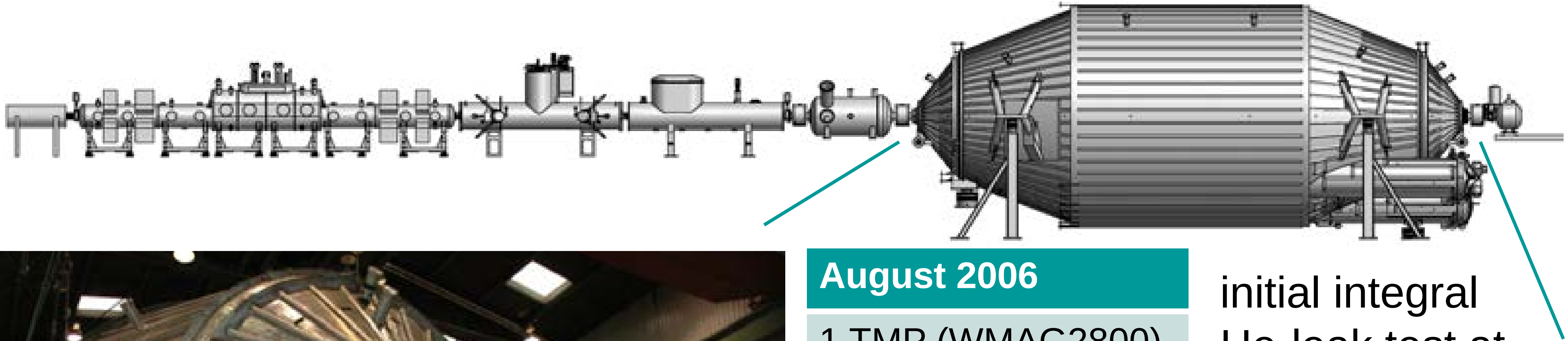
KATRIN	**Volume**	**pressure**	**method**
spectrometer	**1250 m^3**	**10^{-11} mbar**	turbomolecular pumps / nonevaporable getters

LHC	**Volume**	**pressure**	**method**
storage ring	154 m^3	10^{-11} mbar	cryocondensation on beam screen/magnet bore (1.9K)
cryogenic insulation	640 m^3	10^{-6} mbar	cryocondensation on magnet cold mass

LIGO	**Volume**	**pressure**	**method**
2x4km arms	8000 m^3	~10^{-8} mbar	ion pumps & cold traps

VIRGO	**Volume**	**pressure**	**method**
2x3km arms	6800 m^3	<10^{-9} mbar	titanium & ion pumps

main spectrometer: pre-acceptance tests



August 2006

1 TMP (WMAG2800)

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

initial integral He-leak test at MAN-DWE ☑

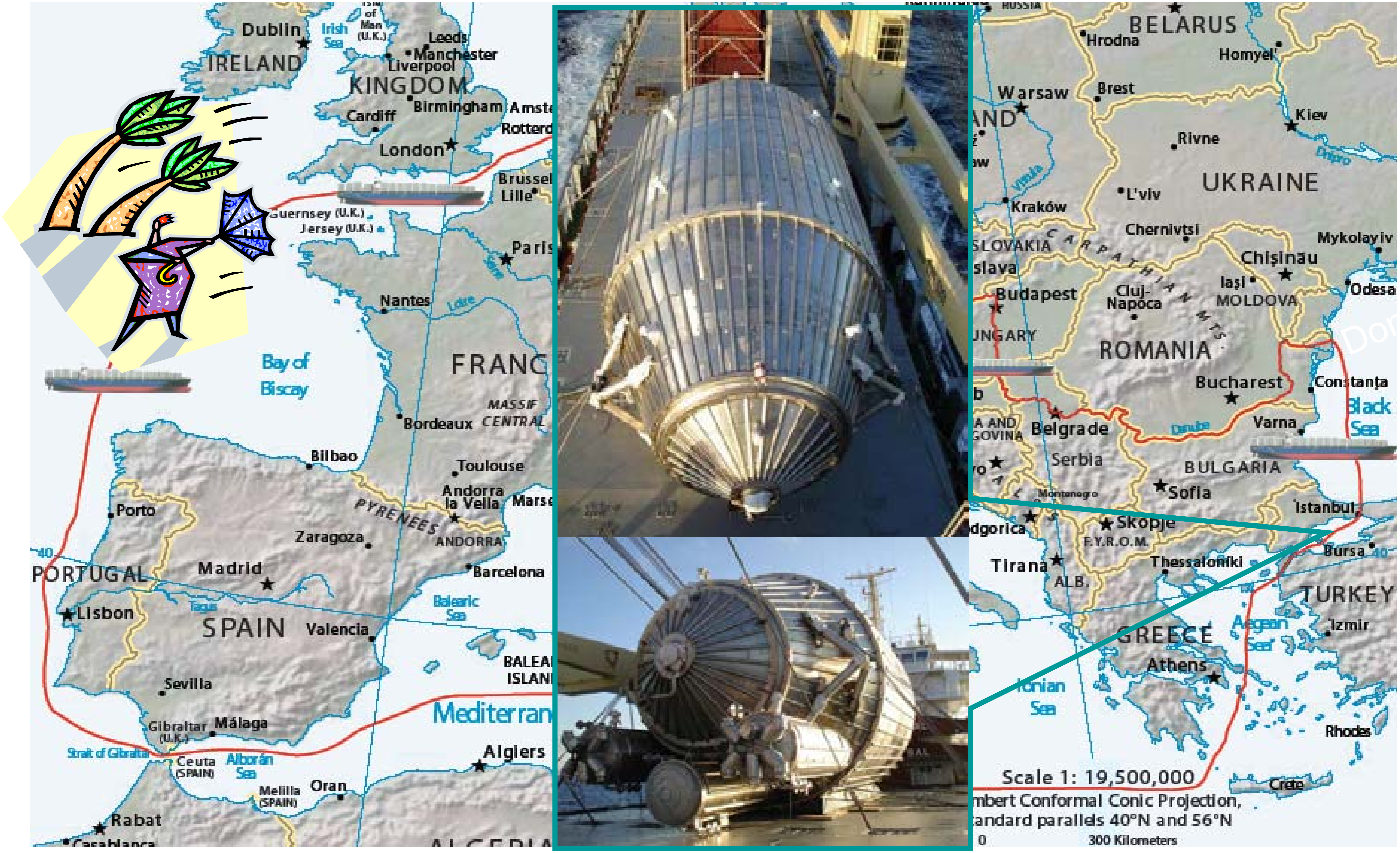
main spectrometer: transport

main spectrometer: transport

start: Oct 2006 Deggendorf MAN-DWE

main spectrometer: transport

main spectrometer: transport



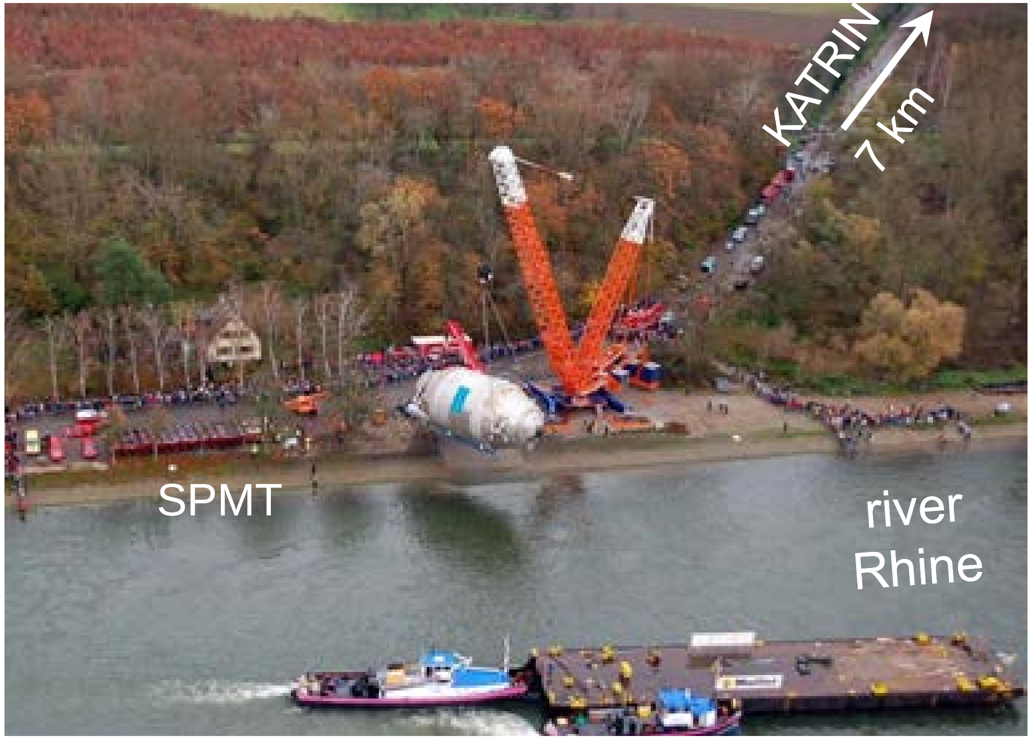
the final 7km: passing Leopoldshafen

November 25, 2006: after an 8800 km sea-going voayge the main Spectrometer was manoeuvred by an SPMT over 7km to the final destination at the KATRIN experimental halls…
(30.000 visitors)

BBC NEWS

In pictures: photos of the year 2006

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



the final 7m, initial out-baking & UHV

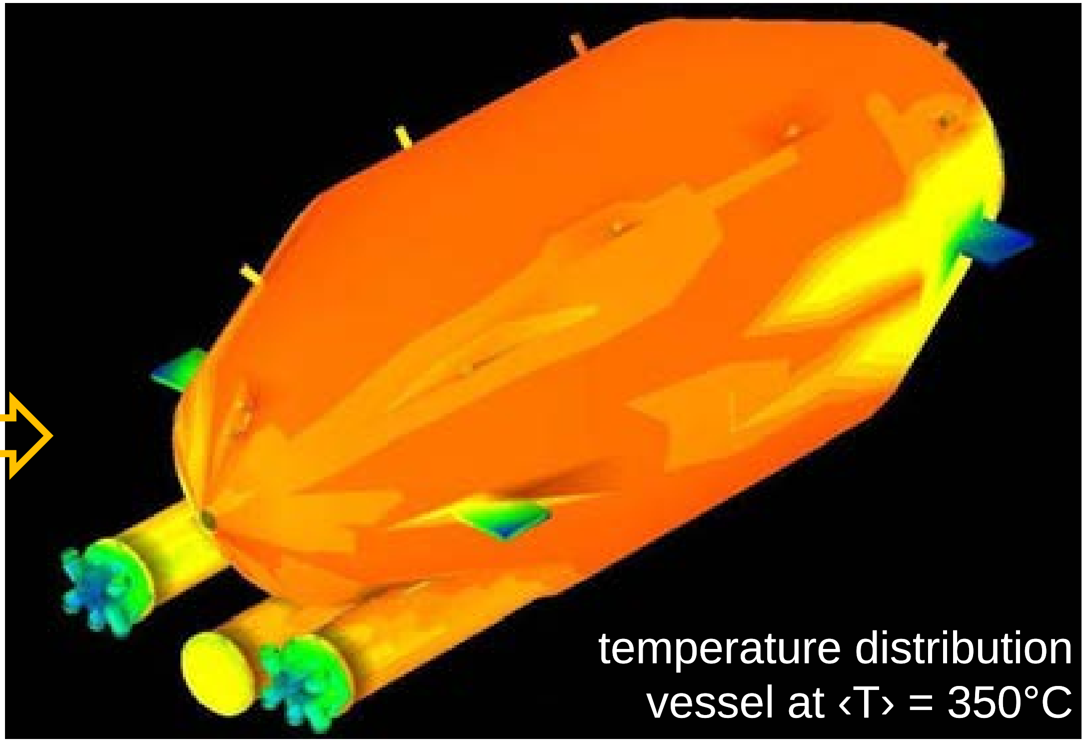
steam
blasting

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

outgassing rate [T = 20°C]
1.18×10^{-12} mbar ℓ / cm^2 s
p = 10^{-10} mbar

H_20
↓
H_2

November 29, 2006



temperature distribution
vessel at ‹T› = 350°C

inner electrodes: motivation & tasks

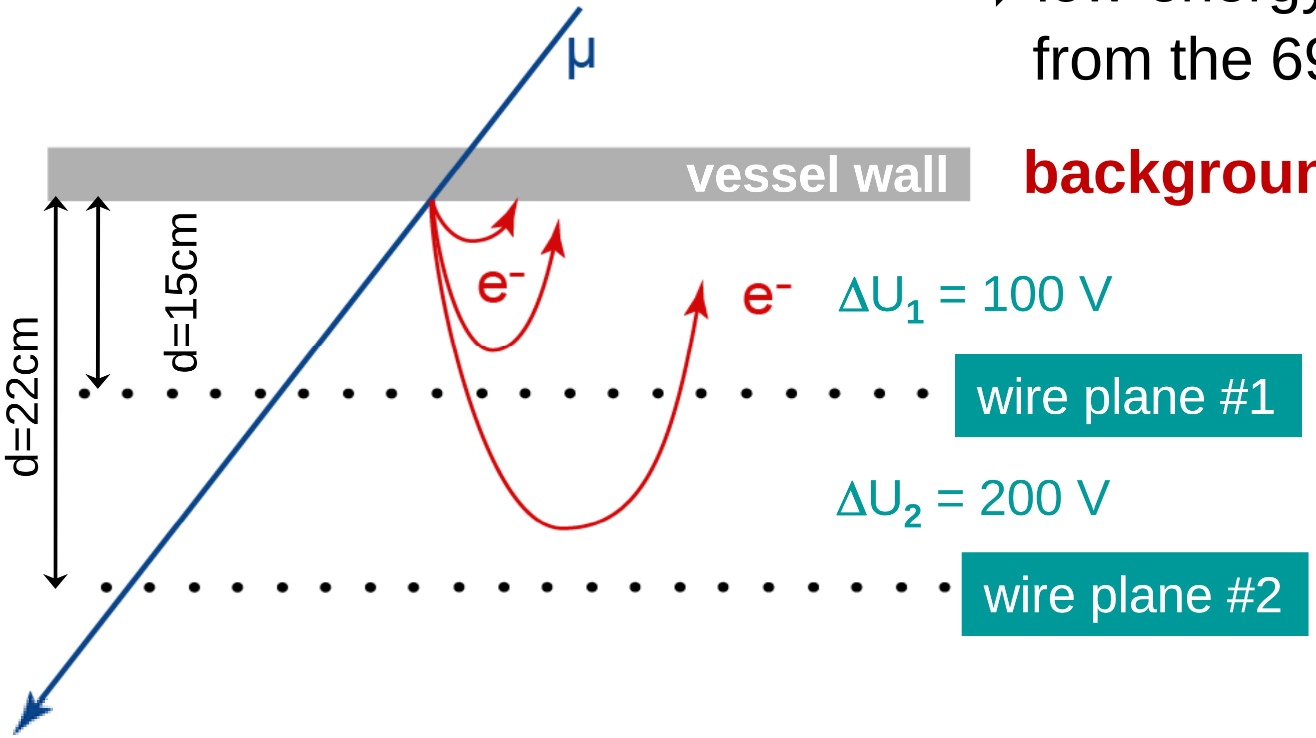
#1: fine forming of electrostatic retarding field

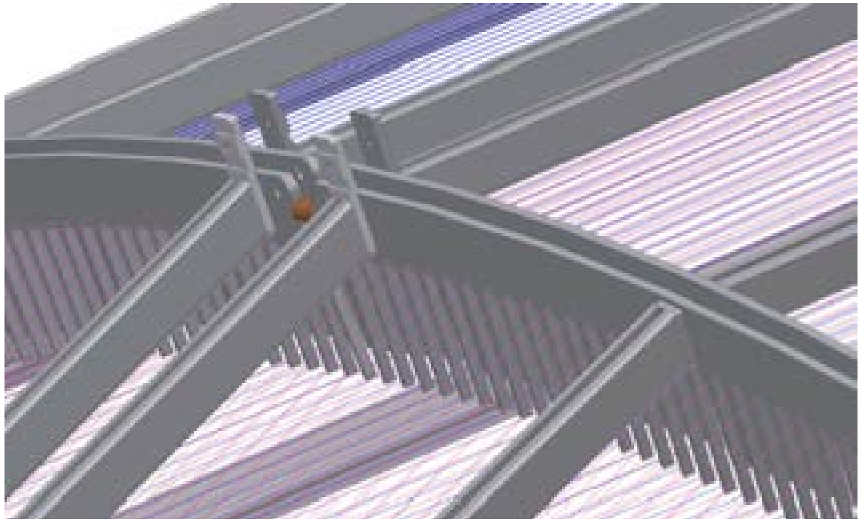
- precision HV power supplies: intrinsic HV precision ~1 ppm
- dipole mode: emptying of particles stored in Penning traps

#2: background suppression

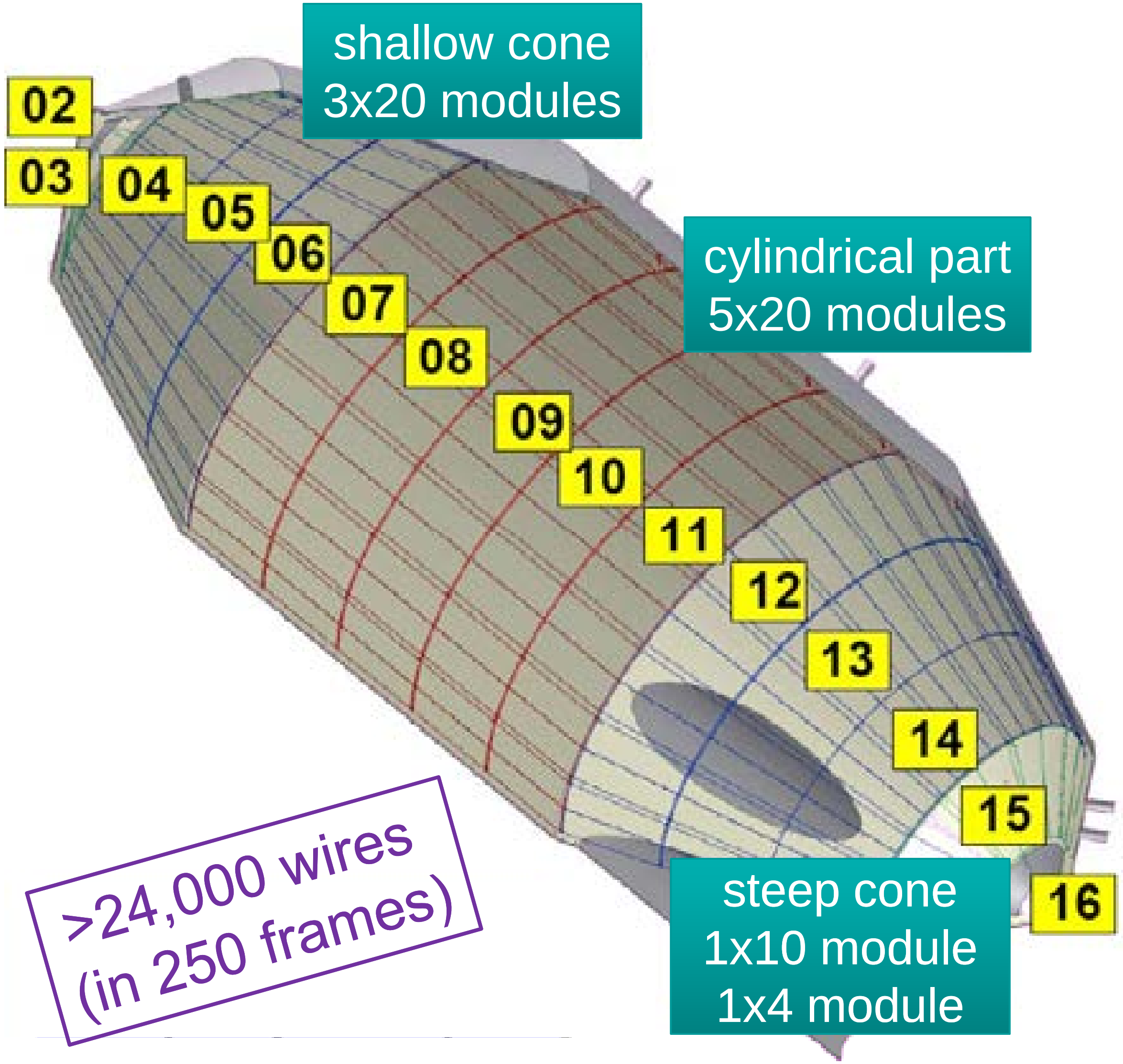
inelastic reactions of cosmic muons
↳ low-energy secondary electrons
from the 690 m² inner surface

background reduction: factor 10-100





inner electrodes: overall system layout



shallow cone
3x20 modules

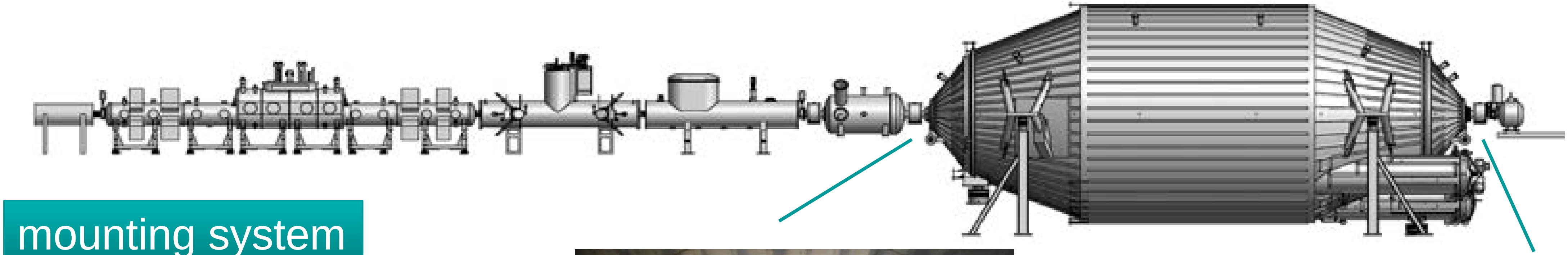
cylindrical part
5x20 modules

steep cone
1x10 module
1x4 module

>24,000 wires
(in 250 frames)

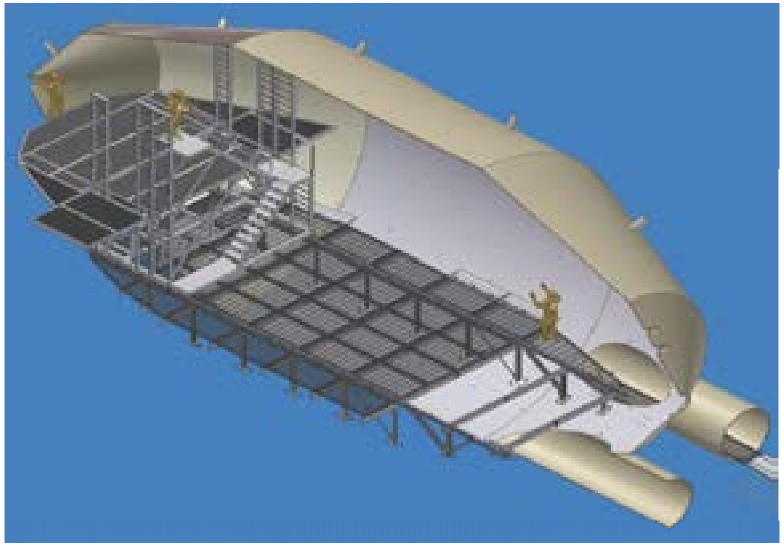
module manufacture at U Münster

inner electrodes: mounting system



mounting system

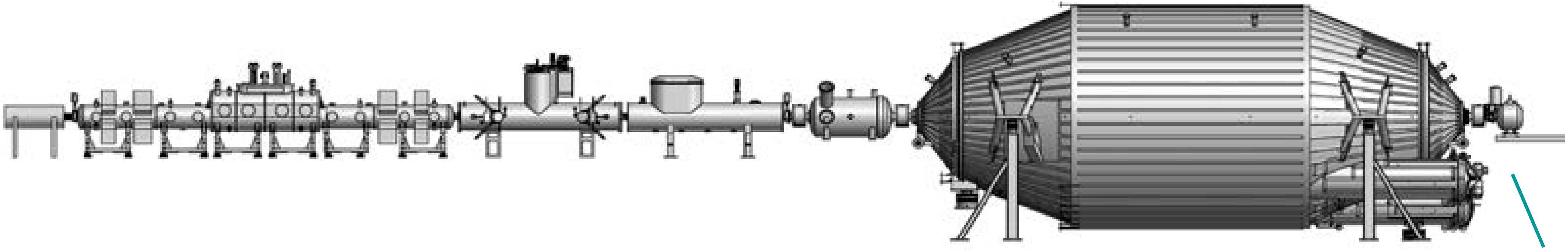
- access via 85 m² clean room at rear end
- electropolished mounting system for precise mounting

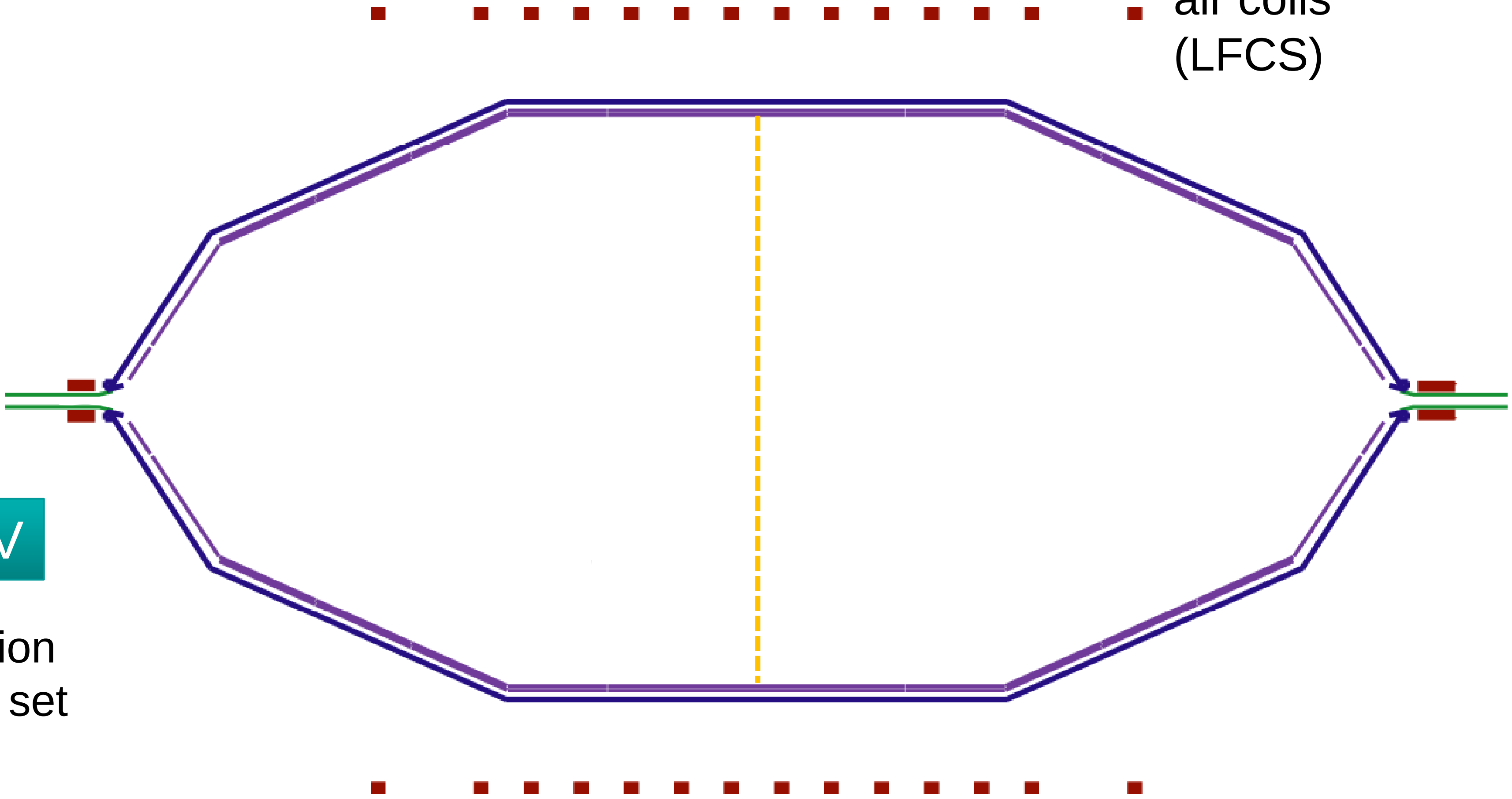


- laser tracker alignment with 100 µm over entire inner surface

July 2009: first wire modules installed successfully

main spectrometer

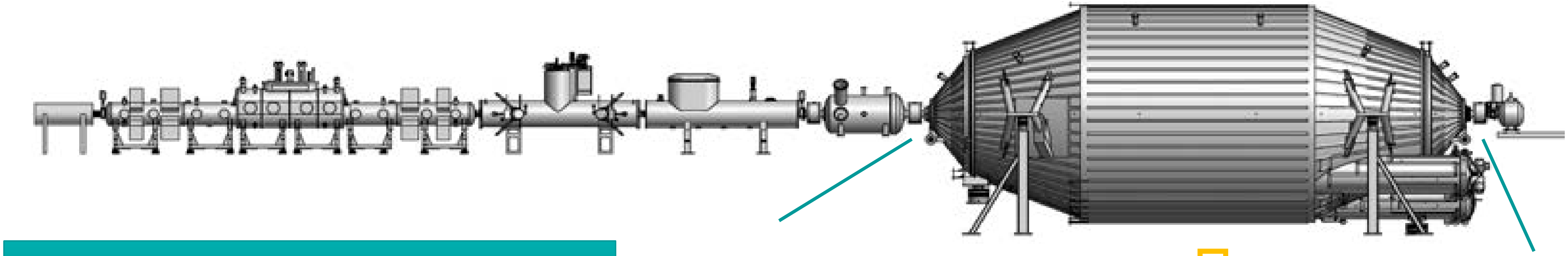




E(e$^-$) = U$_0$ - 1 eV

for better visualisation
of cyclotron motion set
$m_e = 0.01\ m_e$

main spectrometer: Helmholtz coil system



LFCS – Low Field Coil System

radial coils

tasks:

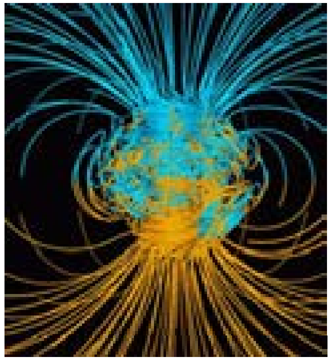
- constrain magnetic flux tube (2.4 G→3.4 G)
- reduce field inhomogeneities (33%→13%)

EMCS – Earth Magnetic Field Coil System

´cosine´ coils

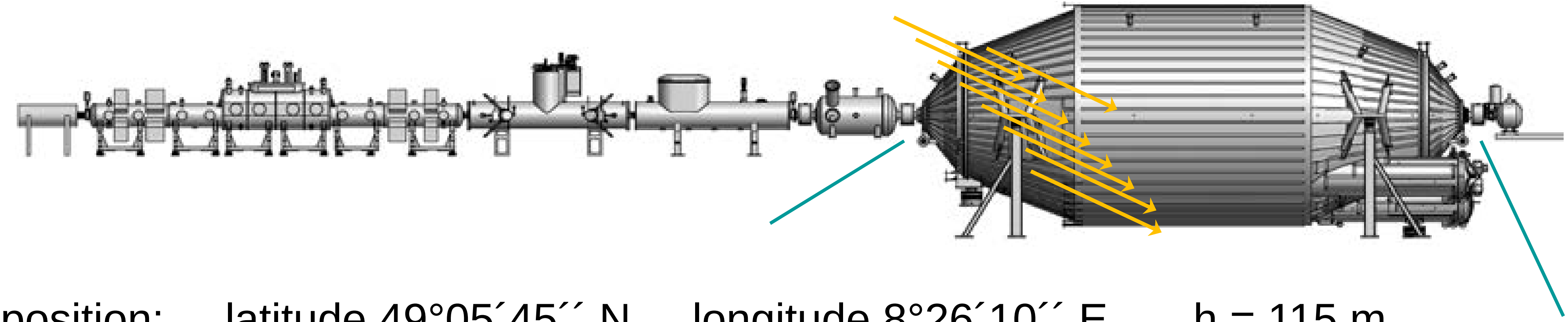
tasks:

- compensate earth magnetic field (500 mG) or B-field distortions



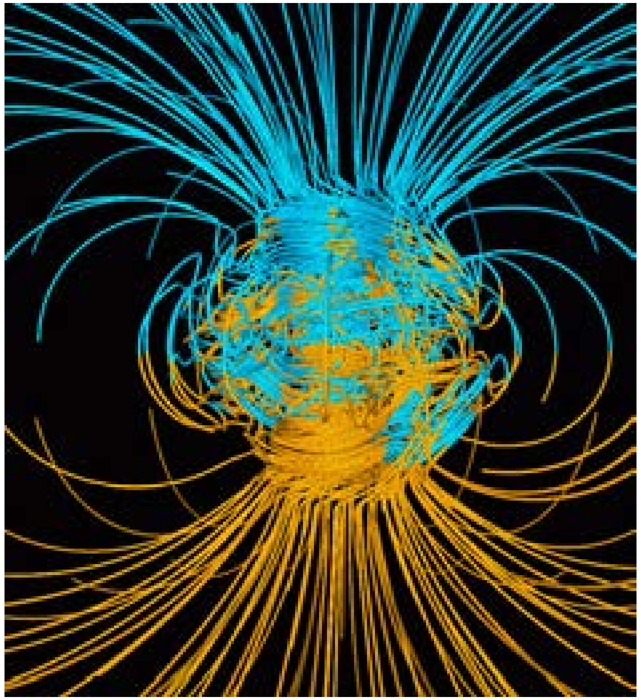
02/09-08/09: assembly

earth magnetic field



position: latitude 49°05´45´´ N longitude 8°26´10´´ E h = 115 m

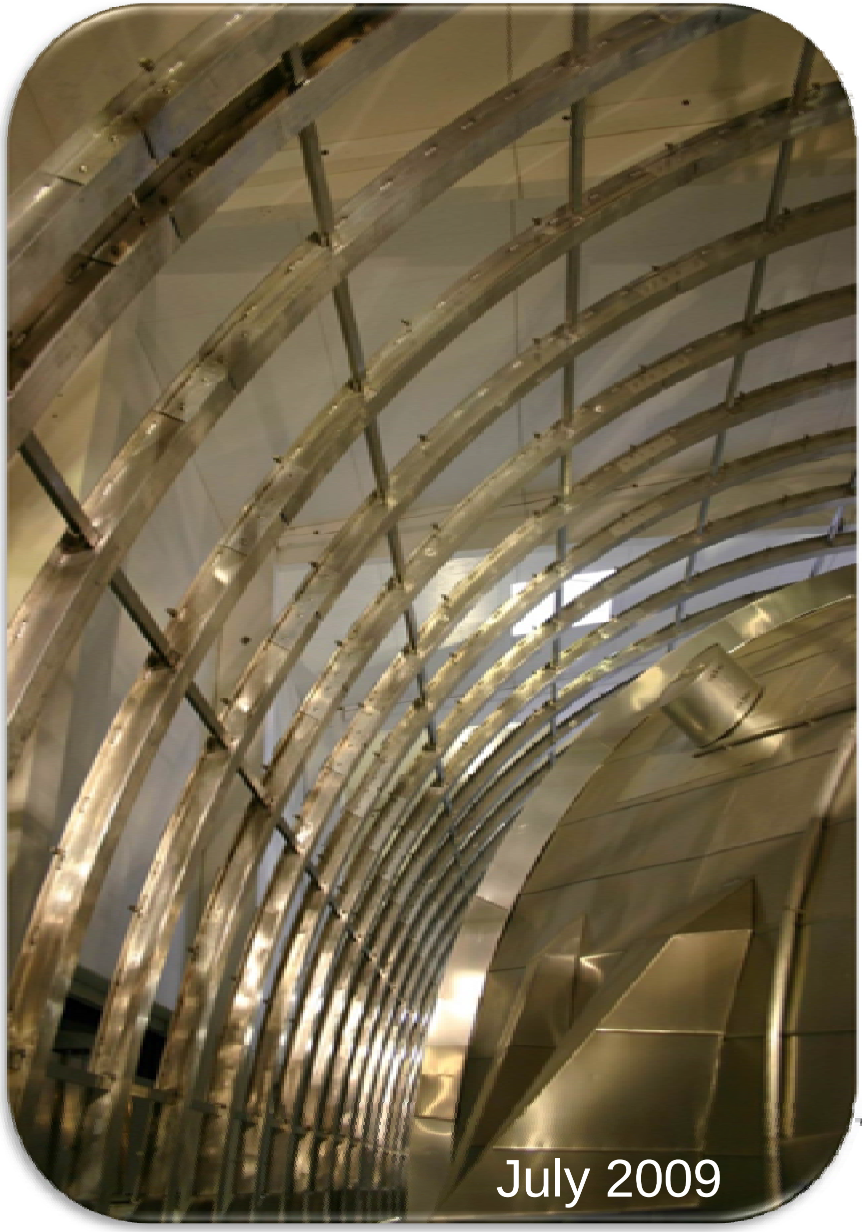
earth magnetic field: **I**nternational **G**eomagnetic **R**eference **F**ield (IGRF 10)

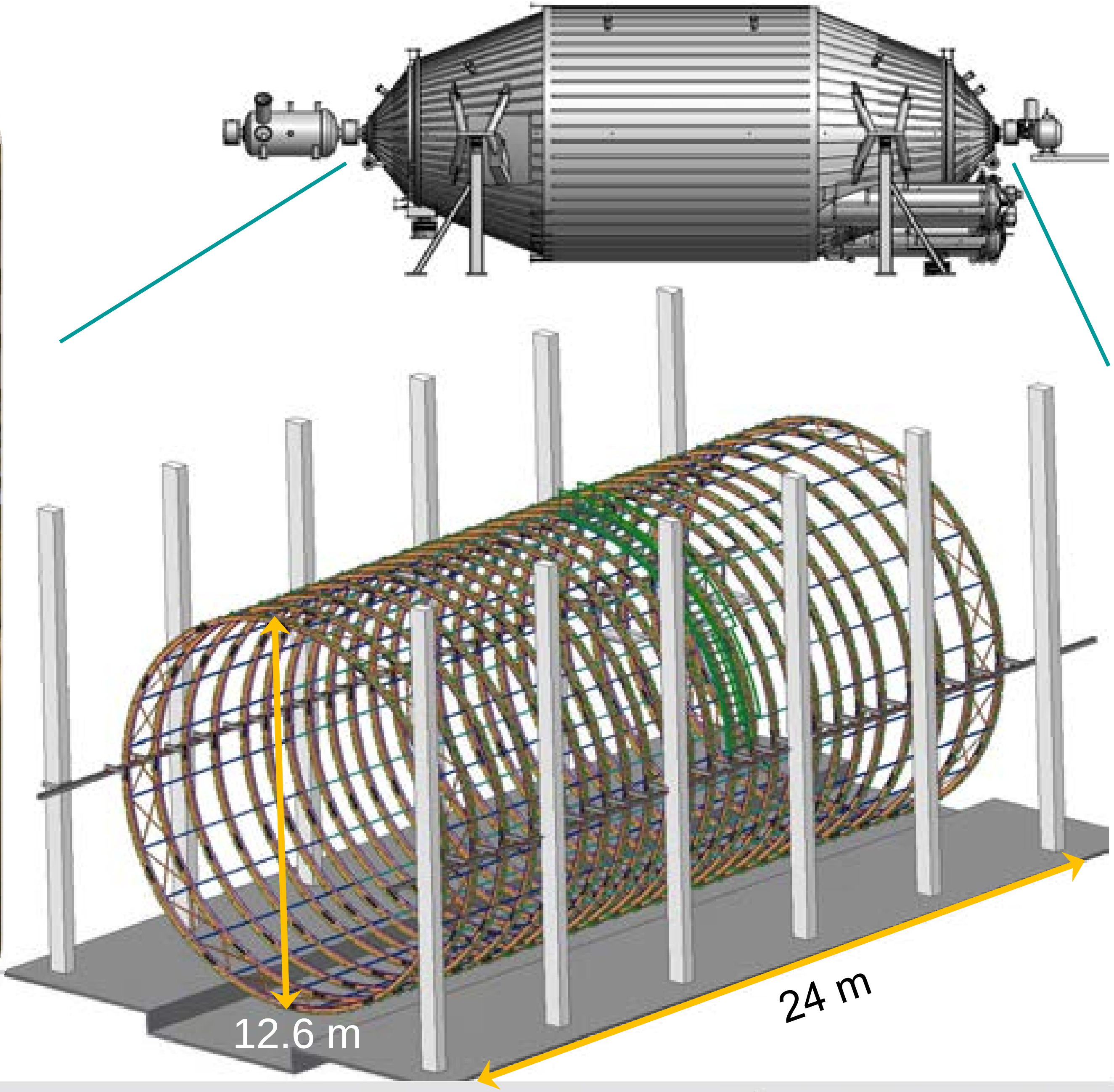


field parameter	value for 7/2009	yearly change
inclination	64° 49´	0´
declination	1° 11´	7´
absolute field strength	48 231.1 nT	34.3 nT
vertical component	43 648.8 nT	32.1 nT
horizontal component	20 518.8 nT	12.3 nT
horizontal field – north	20 514.5 nT	11.3 nT
horizontal field – east	422.5 nT	42.9 nT

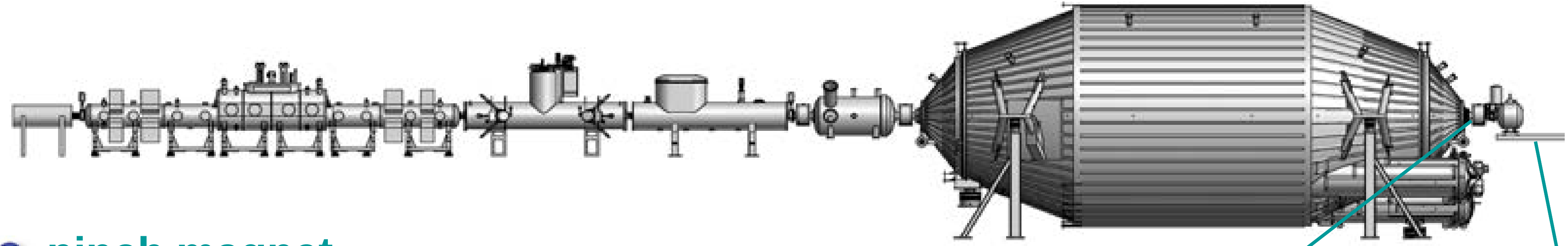
1 G = 100 000 nT 1% of 3 G = 3000 nT

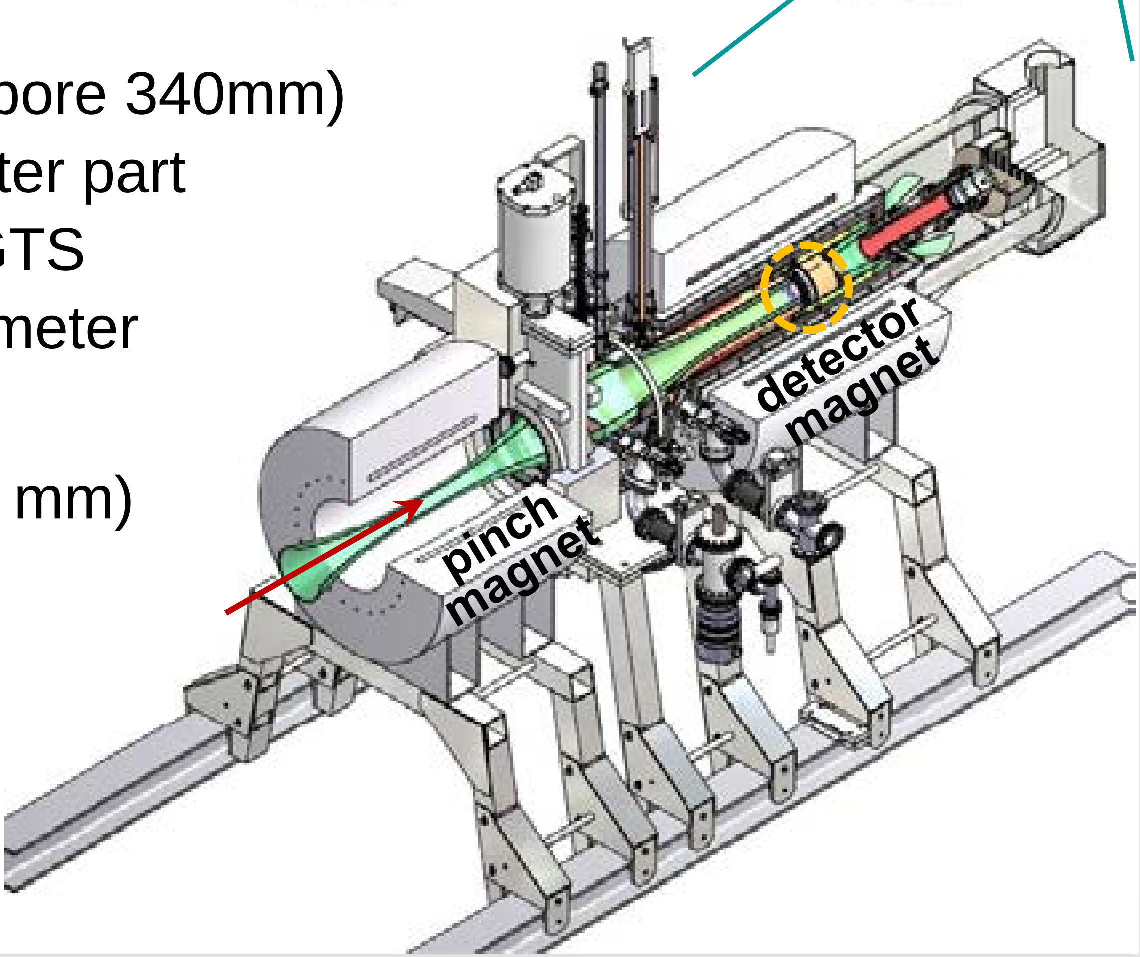
Helmholtz coil system – status





focal plane system





- **pinch magnet**

  provide maximum field B_{max} = 6 T (bore 340mm)
  - guiding B-field in rear spectrometer part
  - define θ_{max} for ß-electrons in WGTS
  - define energy resolution spectrometer
- **detector magnet**

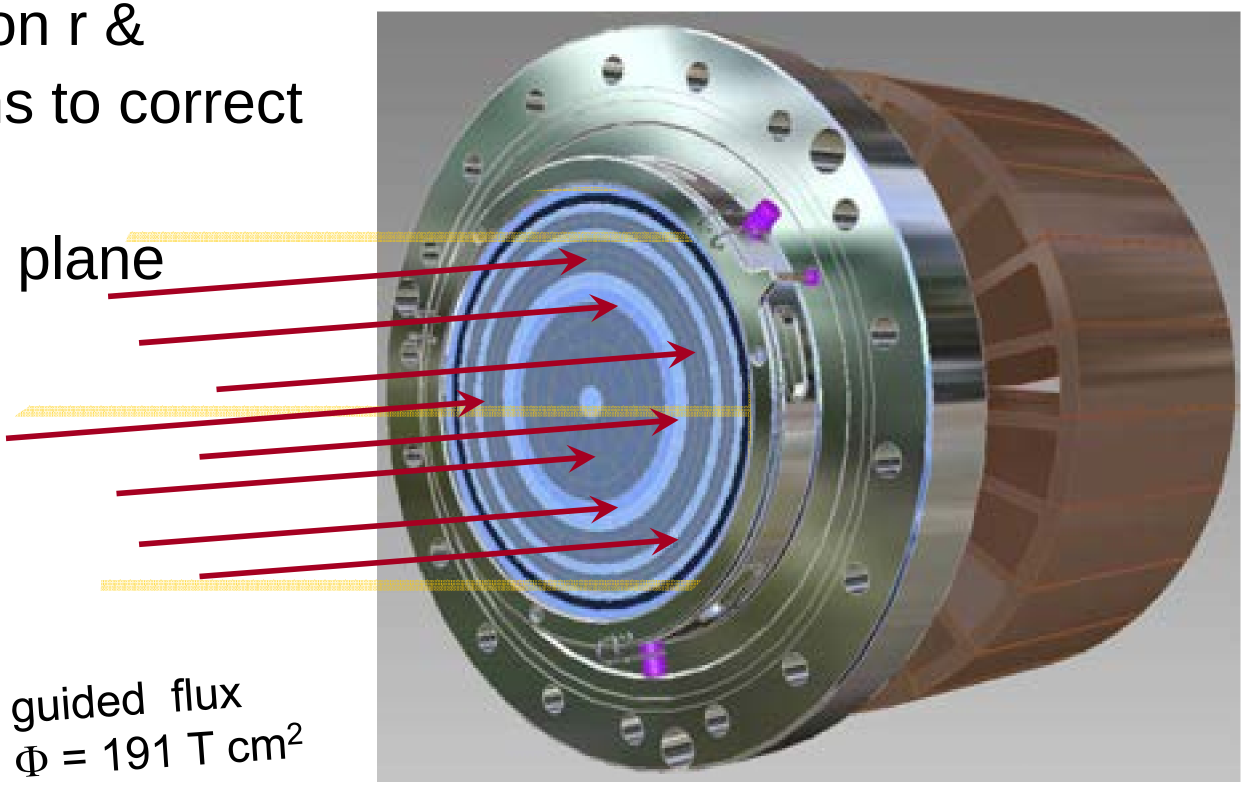
  strong field B_{det} = 3 – 6 T (bore 440 mm)
  - optimised focusing of analysing plane inhomogeneities (B, U_0)
- **focal plane detector**

  segmented Si-PIN diode array

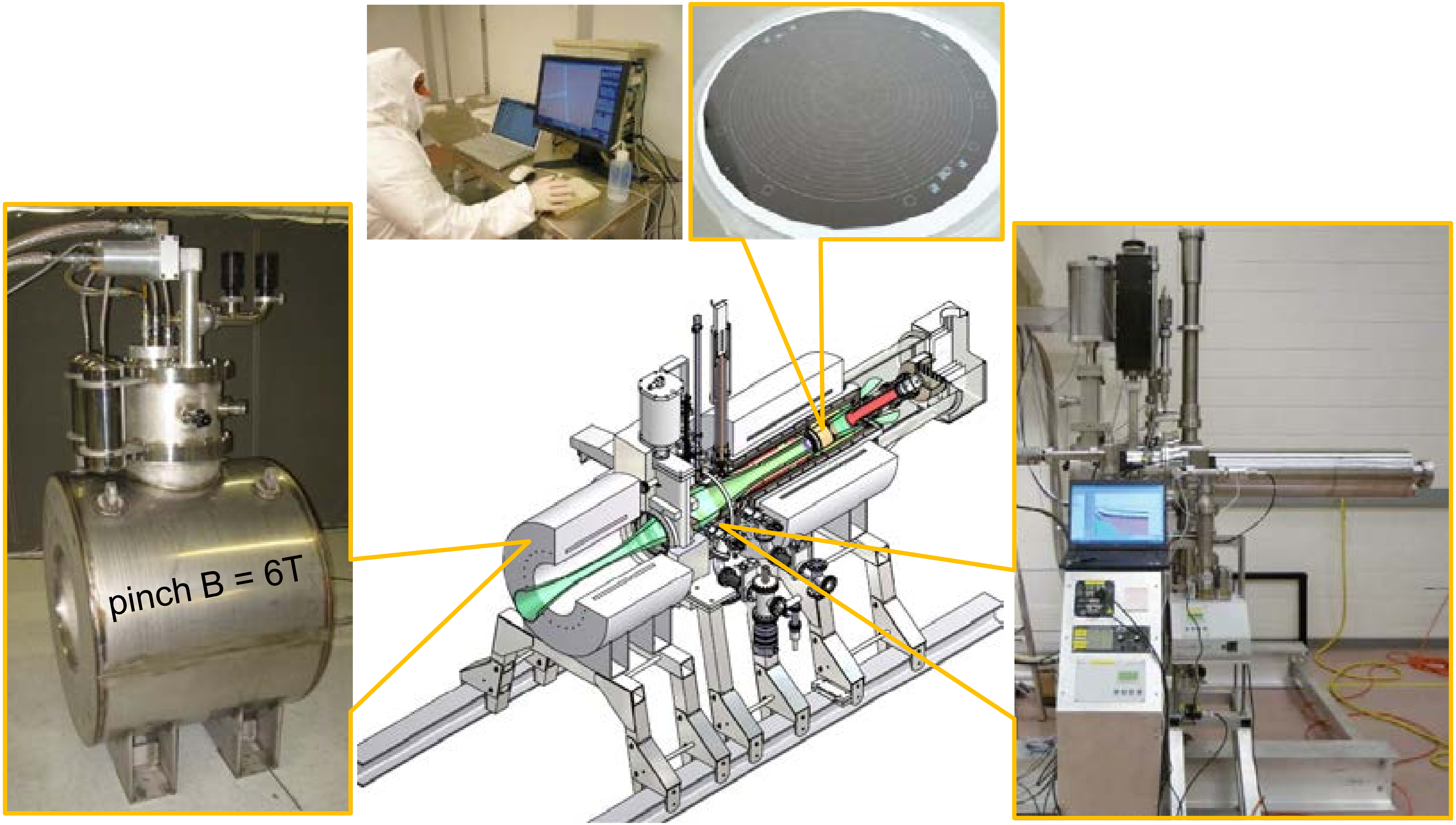
  read-out electronics

focal plane detector

- **monolithic segmented Si-PIN diode array:**
  - counting of transmitted ß-decay electrons
  - determination of radial position r & azimuth angle ϕ of ß-electrons to correct for electrostatic & magnetic inhomogeneities in analysing plane



detector system – present hardware status



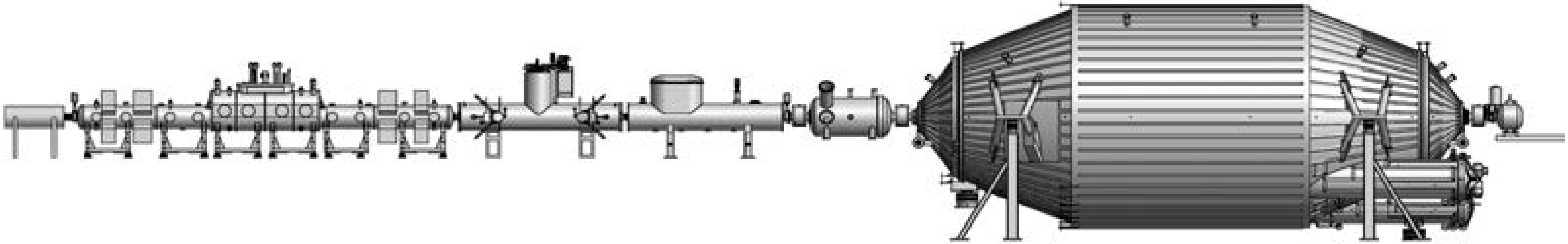
background sources

tritium source

- ß-decay electrons from areas with different electrostatic potentials
- ß-decays from T^-/T^+ iones

detector

- X-rays, gammas & electrons from natural radioactivity or scattered ß-decay electrons (beam-halo)



spectrometer

- stored ß-electrons (Penning traps)
- low-energy ´shake off´ electrons from T_2-ß-decays in central spectrometer area
- cosmic induced secondary electrons

total bg - rate
R_{bg} = 10 mHz

systematic effects

$\boxed{\Delta m_\nu^2 = -2\sigma_{syst}^2}$ ⇔ general relation for tritium-ß-decay

inelastic scattering of ß-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 densitiy ρd (required $< 10^{-3}$)

- stabilisation of ρd: 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 ($\Phi < 20$ mV), injection of meV-e^-

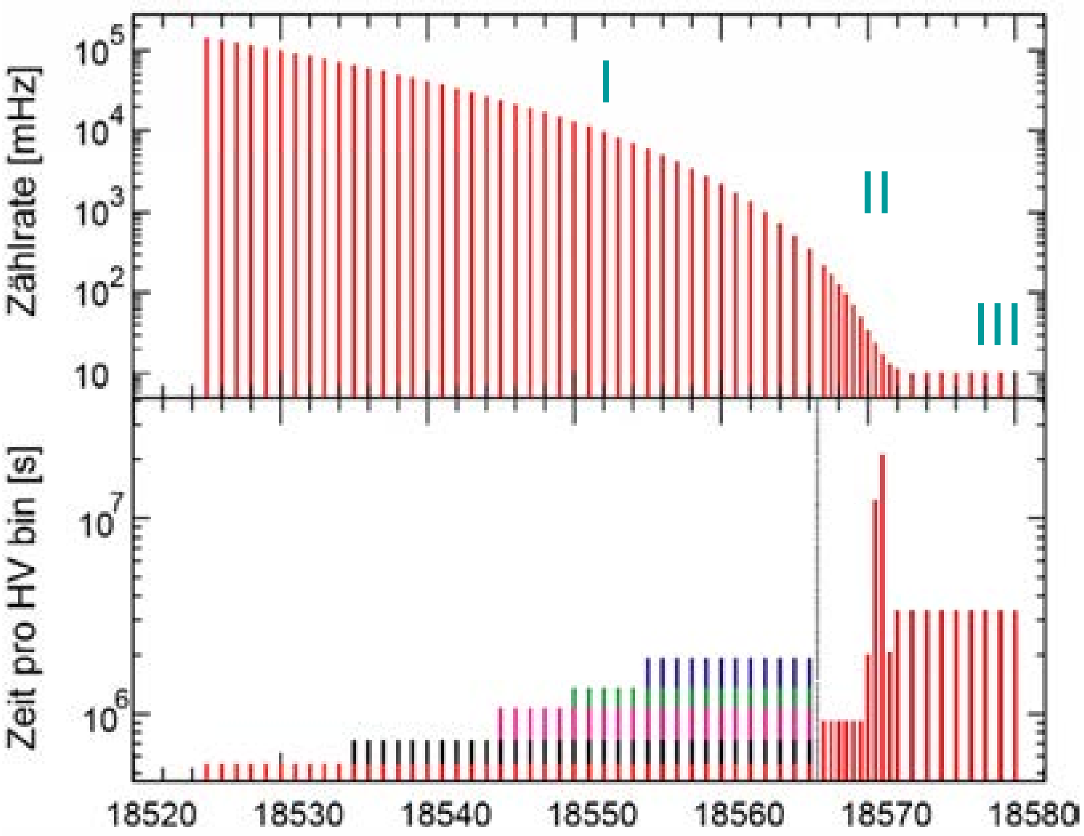
distribution of final states (molecular excitations in $^3H^3He$)

- reliable quantumchemical calculations, very good agreement

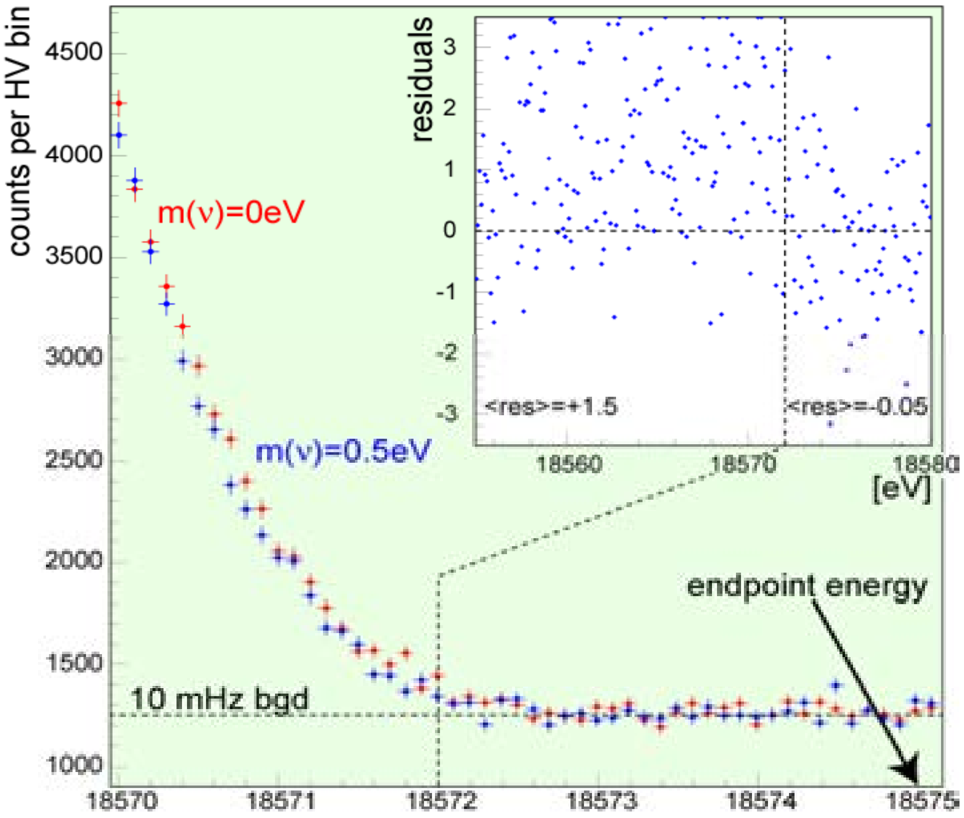
measurement intervals & spectra

optimised HV scanning procedure, parameter decorrelation by 3 regions

Region I: $E \ll E_0$	determine E_0 from fit procedure (ΔE_0 ~ 3 meV)
Region II: E ~ 18570 eV	maximum sensitivity for $m(\nu)$ with S/B-ratio~2
Region III: $E > E_0$	determine background rate (aim for 10 mHz)



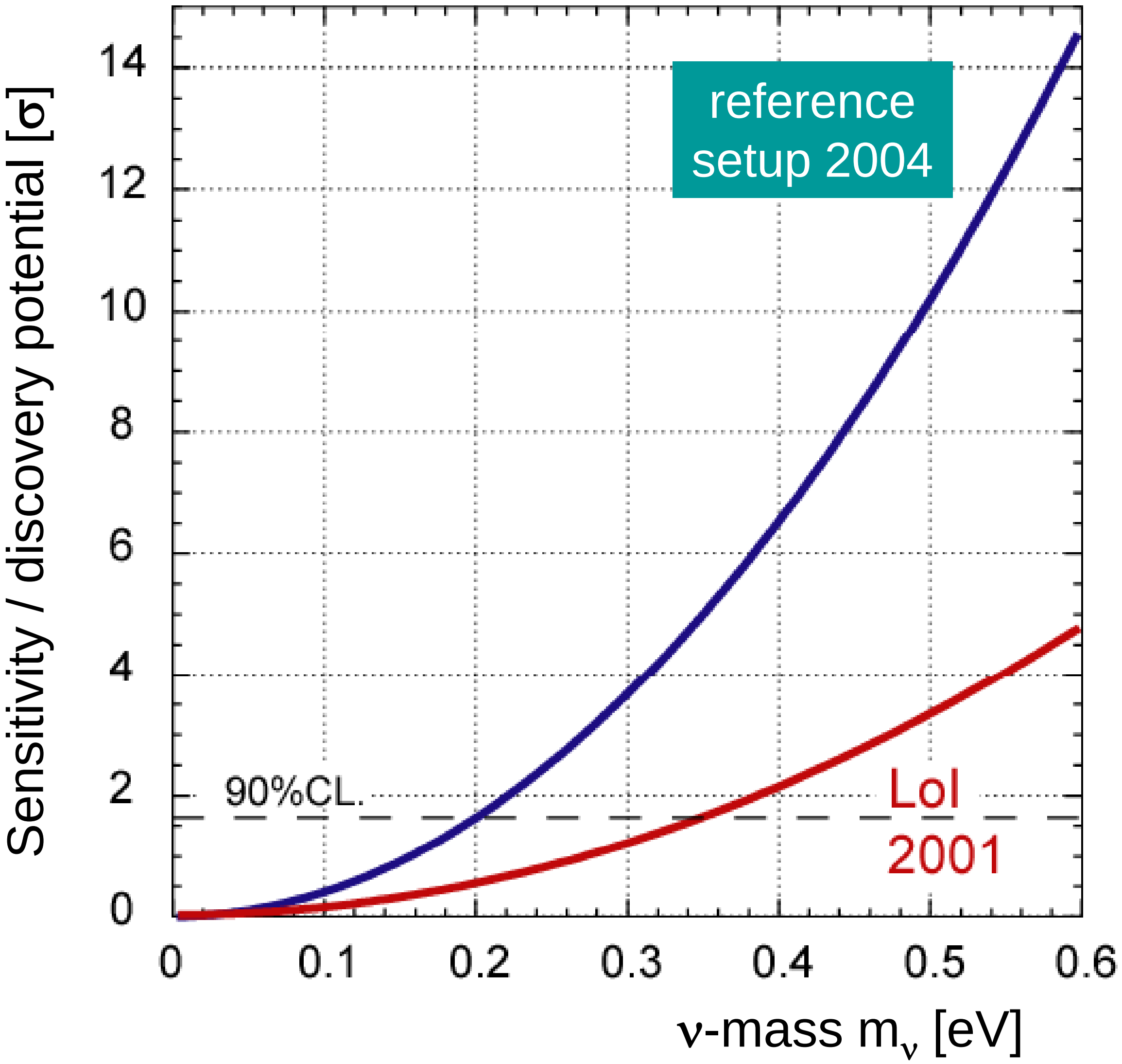
retarding potential [eV]



retarding potential [eV]

KATRIN sensitivity

- ν-mass sensitivity for 3 ´full beam´ measuring years



statistical & systematic errors contribute equally:

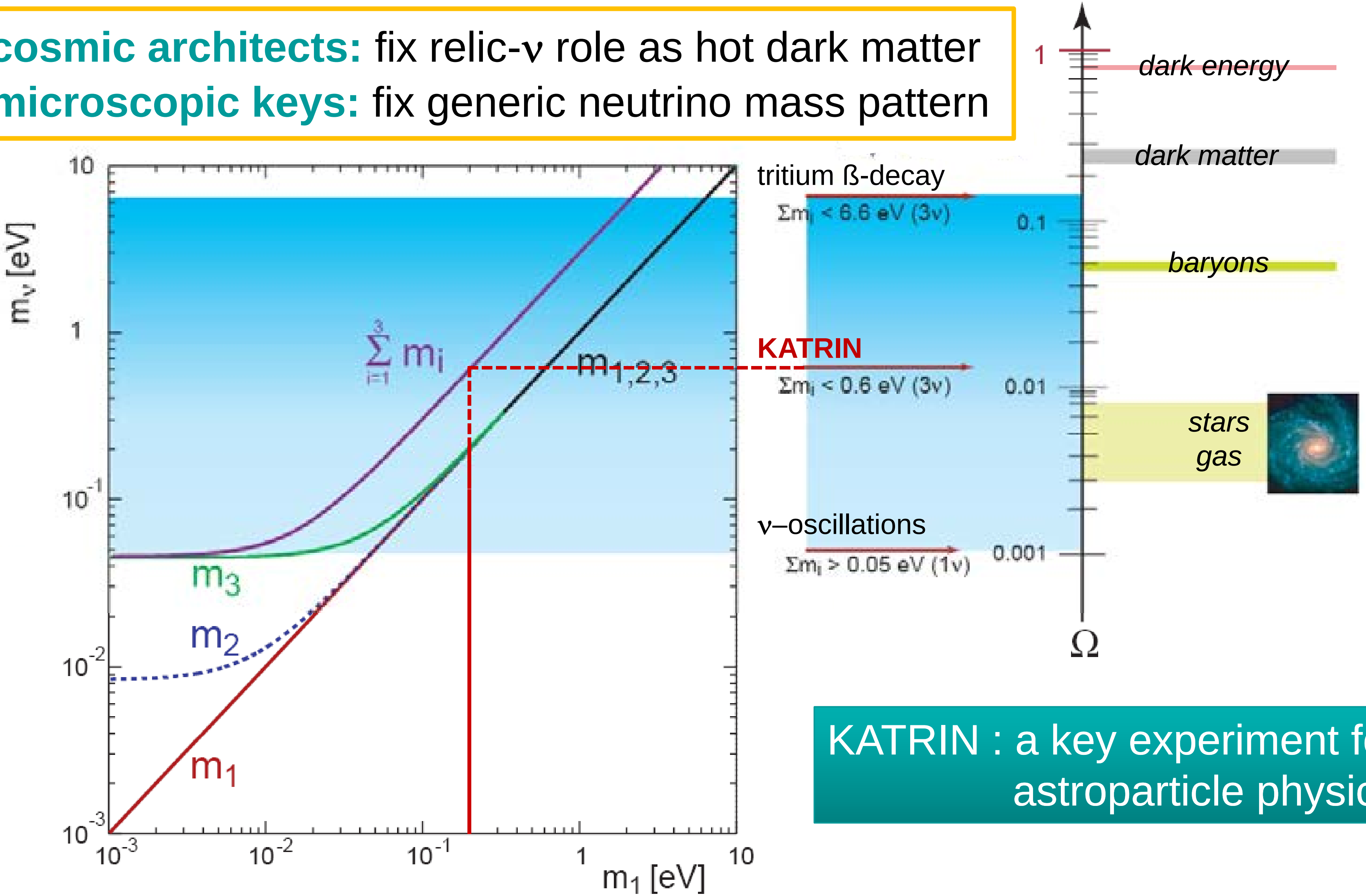
- statistical error $\sigma_{stat} = 0.018\ eV^2$
- systematic error $\sigma_{syst} < 0.017\ eV^2$

sensitivity (90% CL)
m(ν) < 200 meV

discovery potential
m(ν) = 350 meV (5σ)

KATRIN impact on astroparticle physics

cosmic architects: fix relic-ν role as hot dark matter
microscopic keys: fix generic neutrino mass pattern



KATRIN : a key experiment for astroparticle physics

KATRIN Collaboration

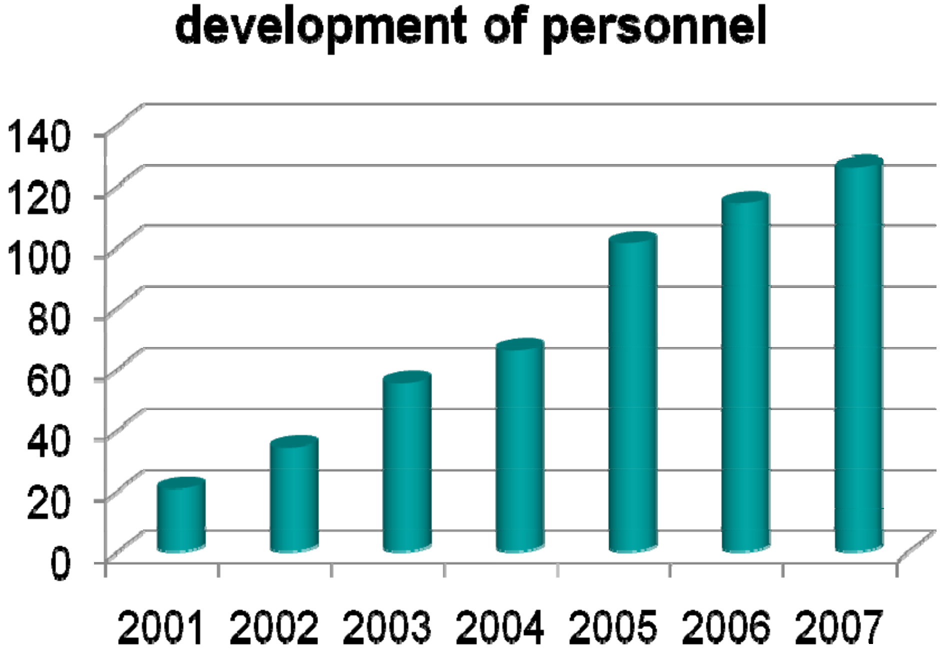
uniting the world-wide expertise in tritium ß-decay experiments:

~140 Collaboration members (12 institutions from D, USA, GB, CZ, Russia)

~ **60% from KIT pool of expertise** (IK, EKP, ITP/TLK, IPE)


2008

2012: begin of T_2 measurements



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