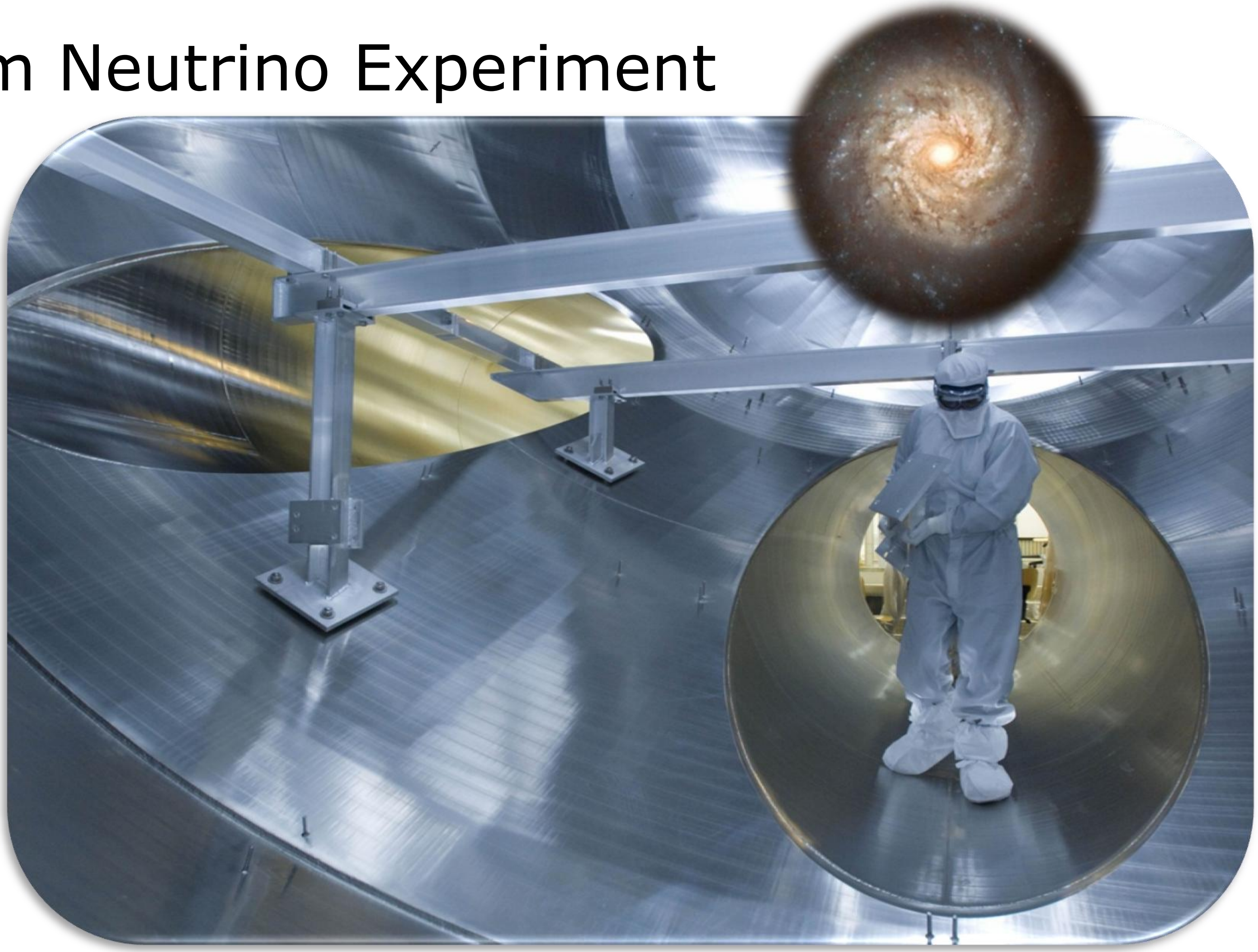
KATRIN –

Karlsruhe Tritium Neutrino Experiment



Outline of lecture:

- Introduction: massive ν´s
- ß-spectroscopy & m(ν)
- KATRIN
- Conclusions & Outlook

KIT – die Kooperation von
Forschungszentrum Karlsruhe GmbH
und Universität Karlsruhe (TH)

Universität Karlsruhe (TH)
Forschungsuniversität • gegründet 1825

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

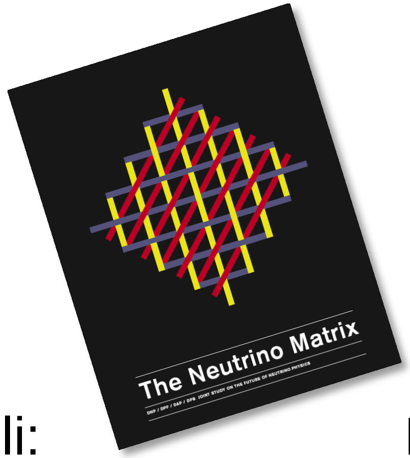
KIT Karlsruhe Institute of Technology

neutrino physics – historical review

KIT Karlsruhe Institute of Technology

´the growing excitement of neutrino physics´

The Neutrino Matrix, APS Neutrino Study



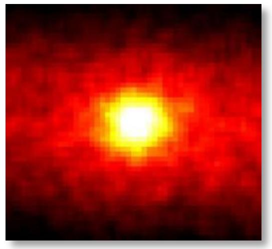
see lectures C. Hagner

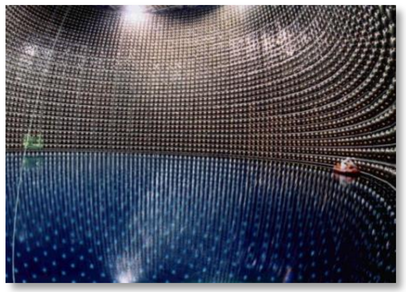
Pauli:
ν-postulate

Fermi:
theory

Reines & Cowan:
ν-detection

solar
ν-deficit
chlorine-37





Reines,
Davis &
Koshiba

neutrino properties?

LBL-experiments:
L/E variation

SNO solves problem of the deficit ν_{solar}

Super-Kamiokande:
oscillation of ν_{atm}

pp-ν s (Gallex, SAGE)

SN1987a: ν-pulse observed

LEP: Z^0 width – $N_\nu = 3$ (ν_e, ν_μ, ν_τ)

Kamiokande confirms deficit of ν_{solar}

1930 1955 1980 2000

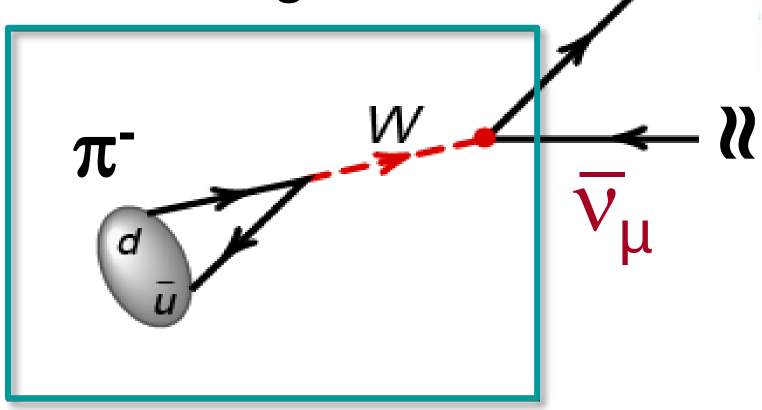
neutrino masses in particle physics

ν-oscillations (solar, atmospheric, LBL ν s): ν s have non-zero masses!

- mixing angles θ_{ij}, mass splittings Δm^2_{ij}

ν–source

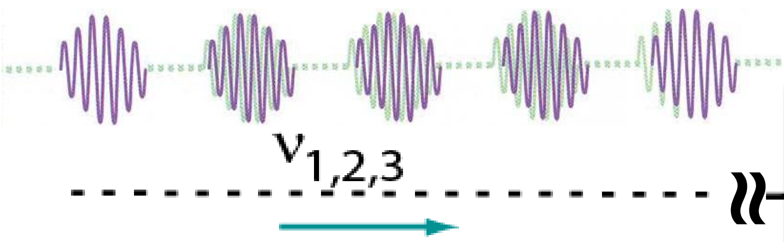
flavour eigenstate



source paramenters
to be determined:

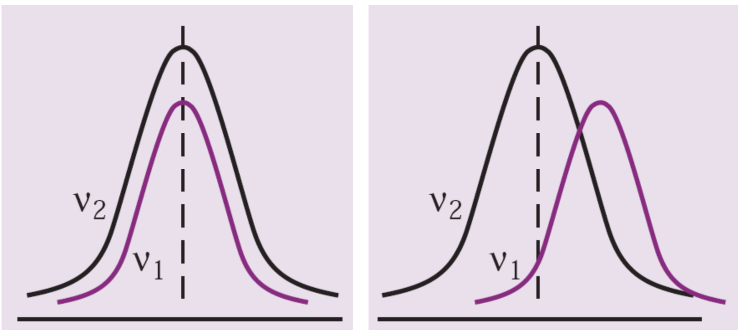
ν–energies
ν–fluxes
ν–flavours

ν–oscillations



propagation of the ν–mass eigenstates

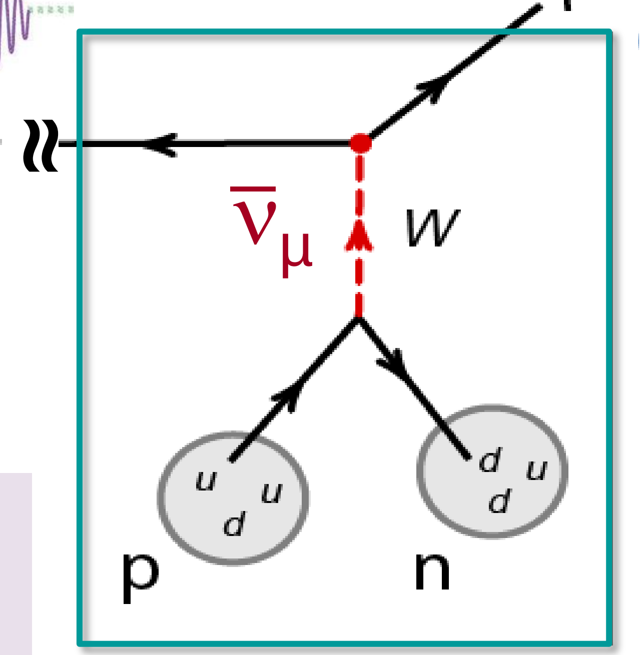
L = 10 m … 10.000 km



emission detection

ν–detection

flavour state



ν–detection efficiency
ν–energy resolution

neutrino oscillations: 3-flavour mixing

3-flavour oscillations decouple into three separate mixing terms:

δ: CP-phase

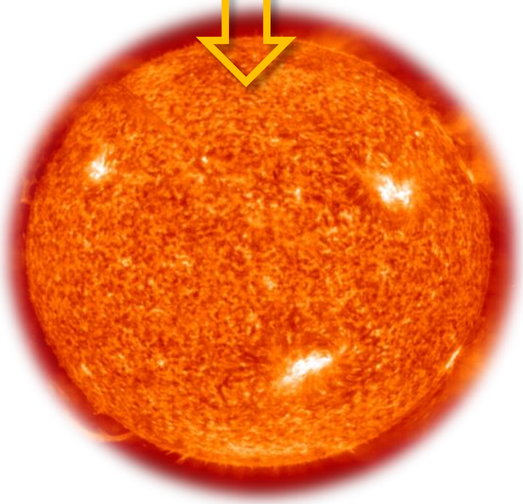
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix}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

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



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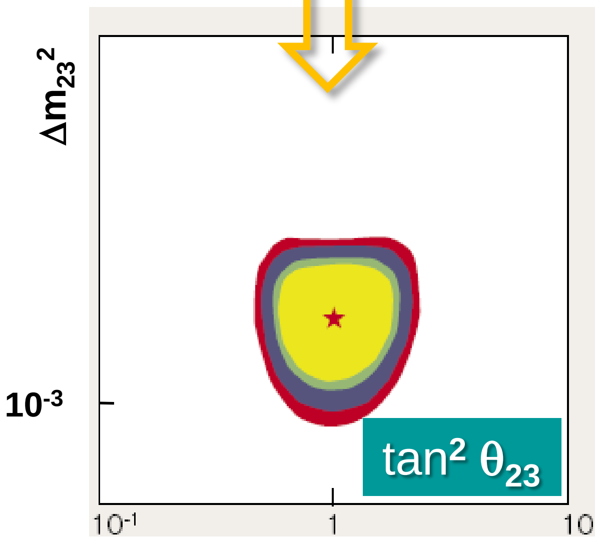
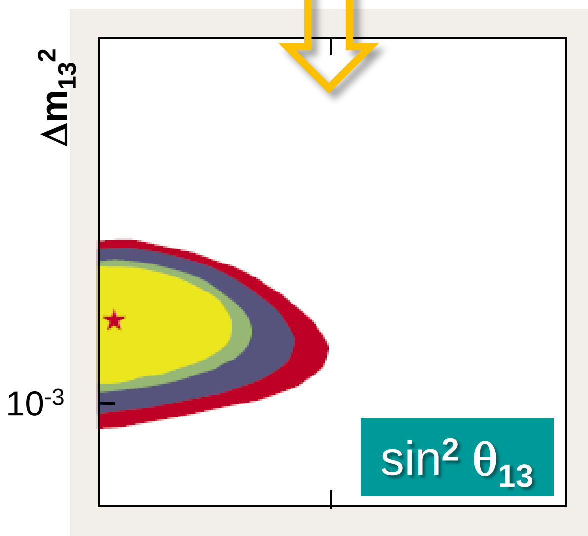
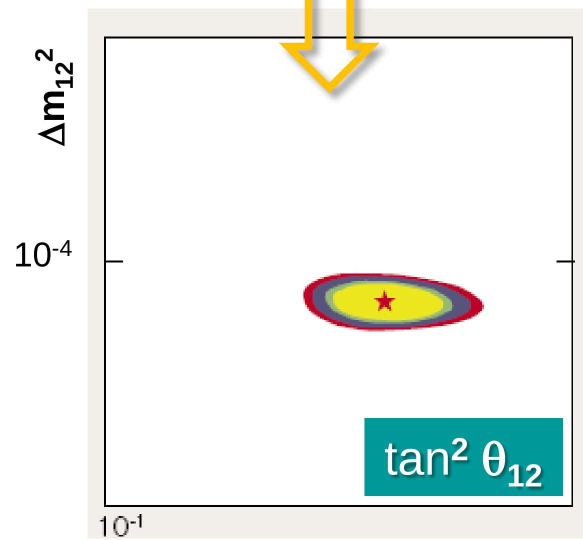
2. & 3. generation	1. & 3. generation	1. & 2. generation
$\Delta m_{23}^2 = 2.3 \times 10^{-3}$ eV²	$\Delta m_{13}^2 = 2.3 \times 10^{-3}$ eV²	$\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV²
$\theta_{23} = (45 \pm 4)°$ (maximum)	$\theta_{13} < 12°$ (very small)	$\theta_{23} = (33.7 \pm 1.3)°$ (large)

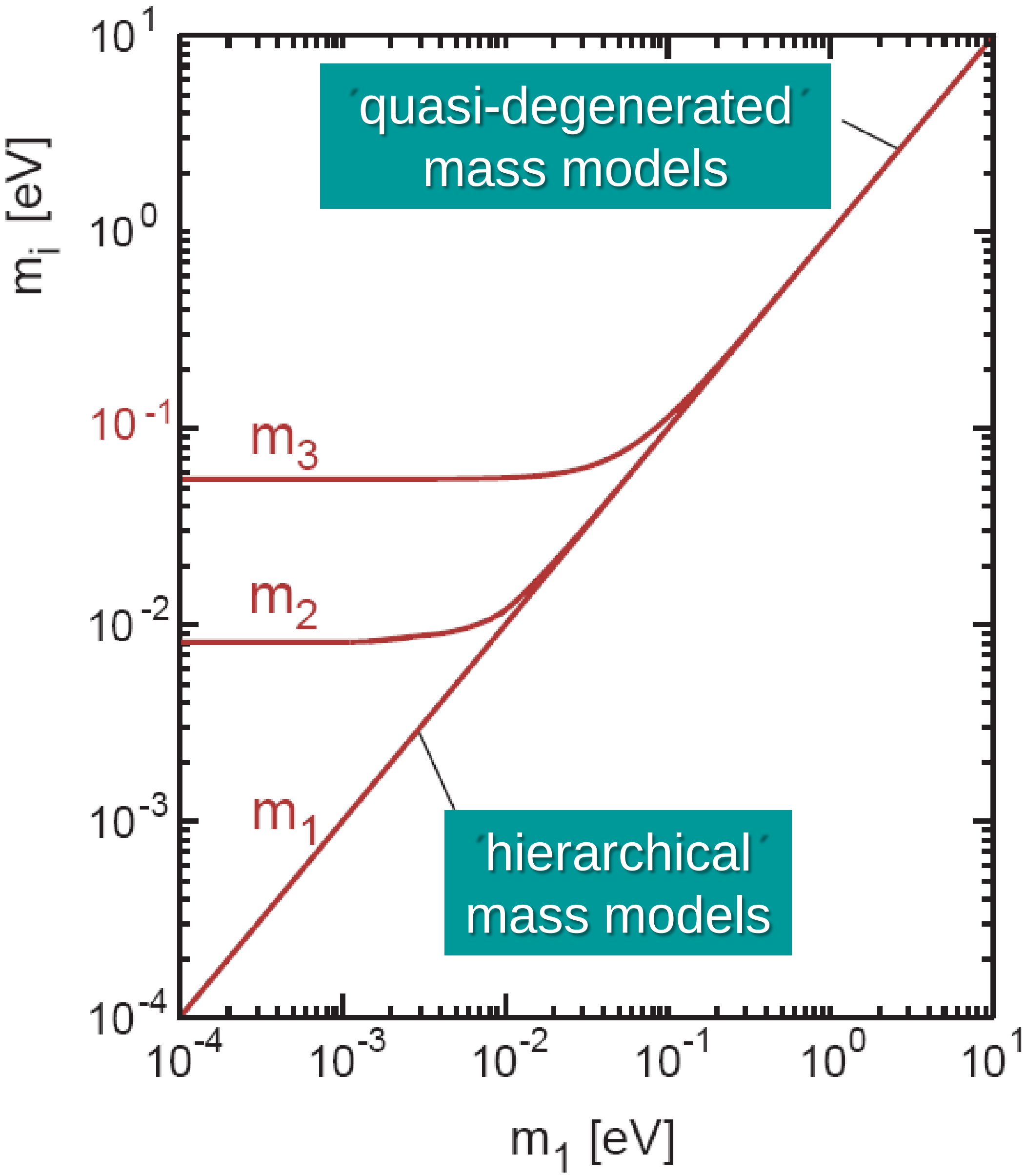


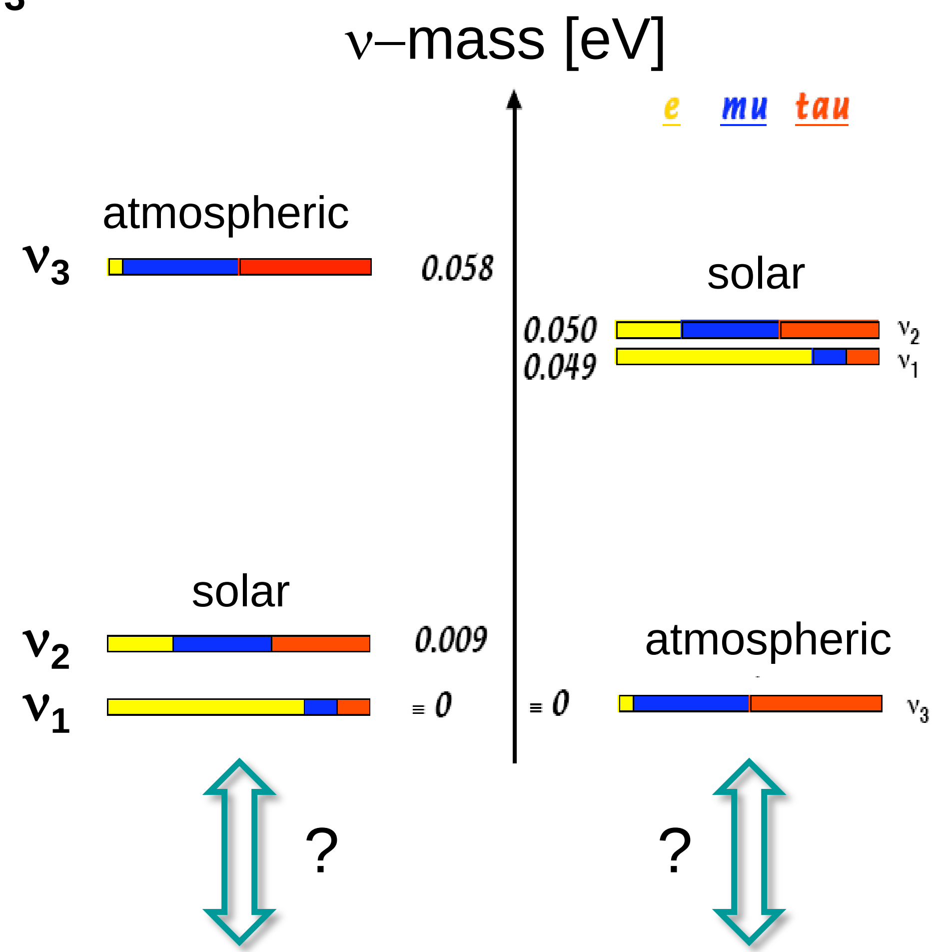




neutrino masses in particle physics

normal hierarchy scenario with $m_1 < m_2 < m_3$





ν–mass offset?
absolute scale m_1?

neutrino masses in particle physics

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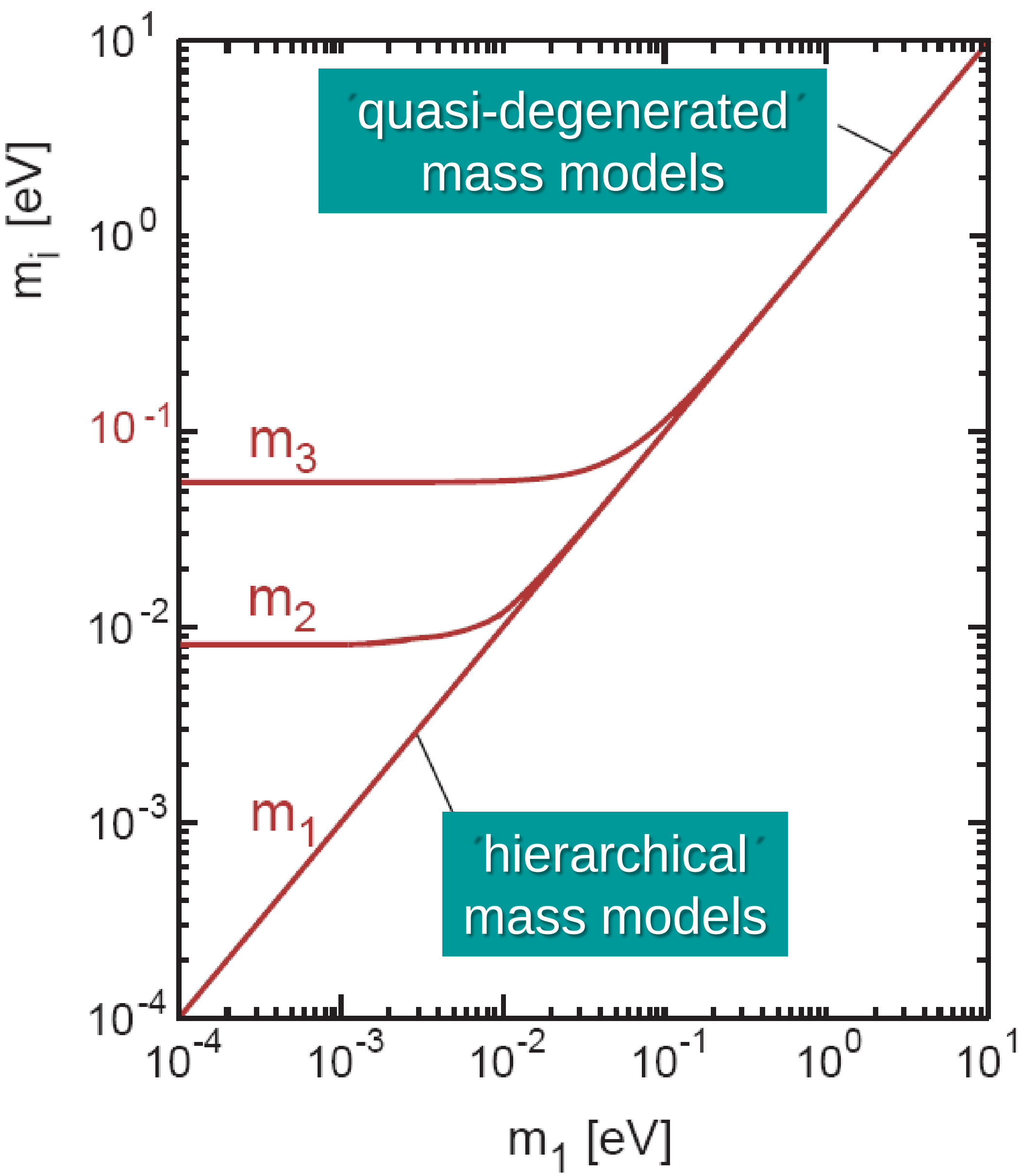

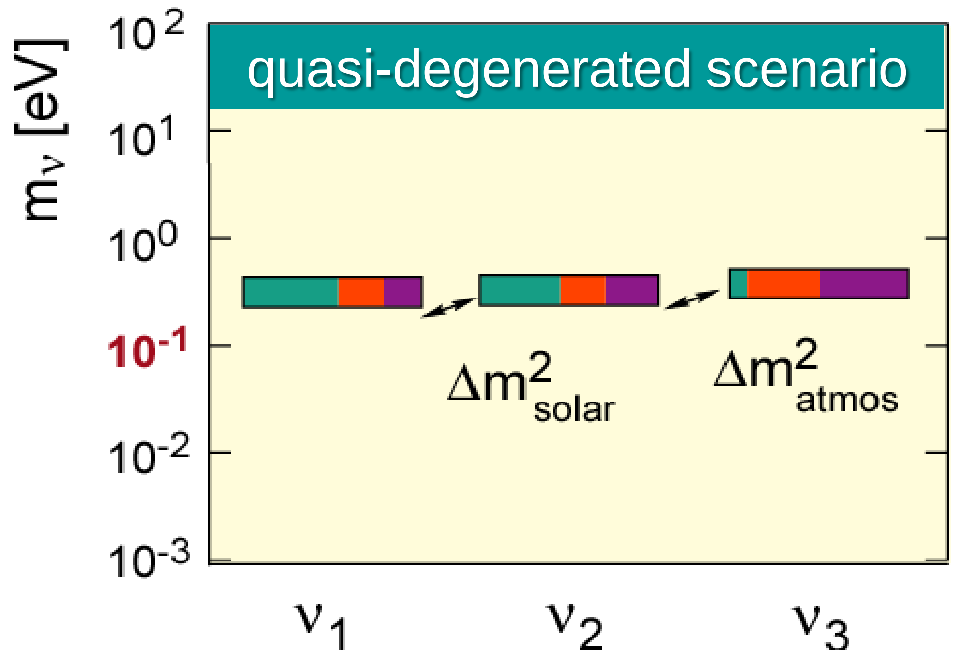

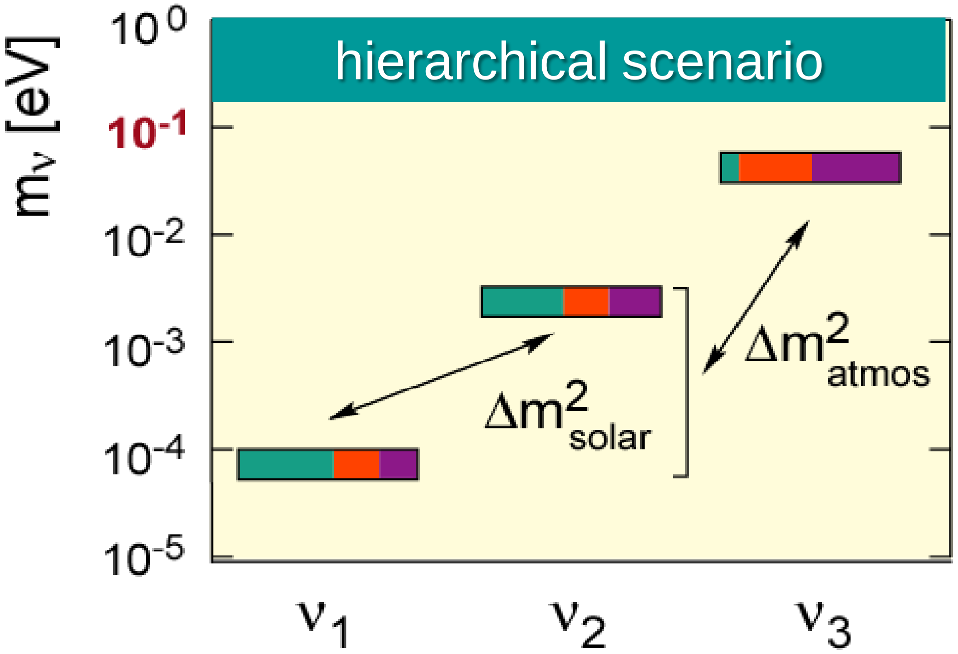

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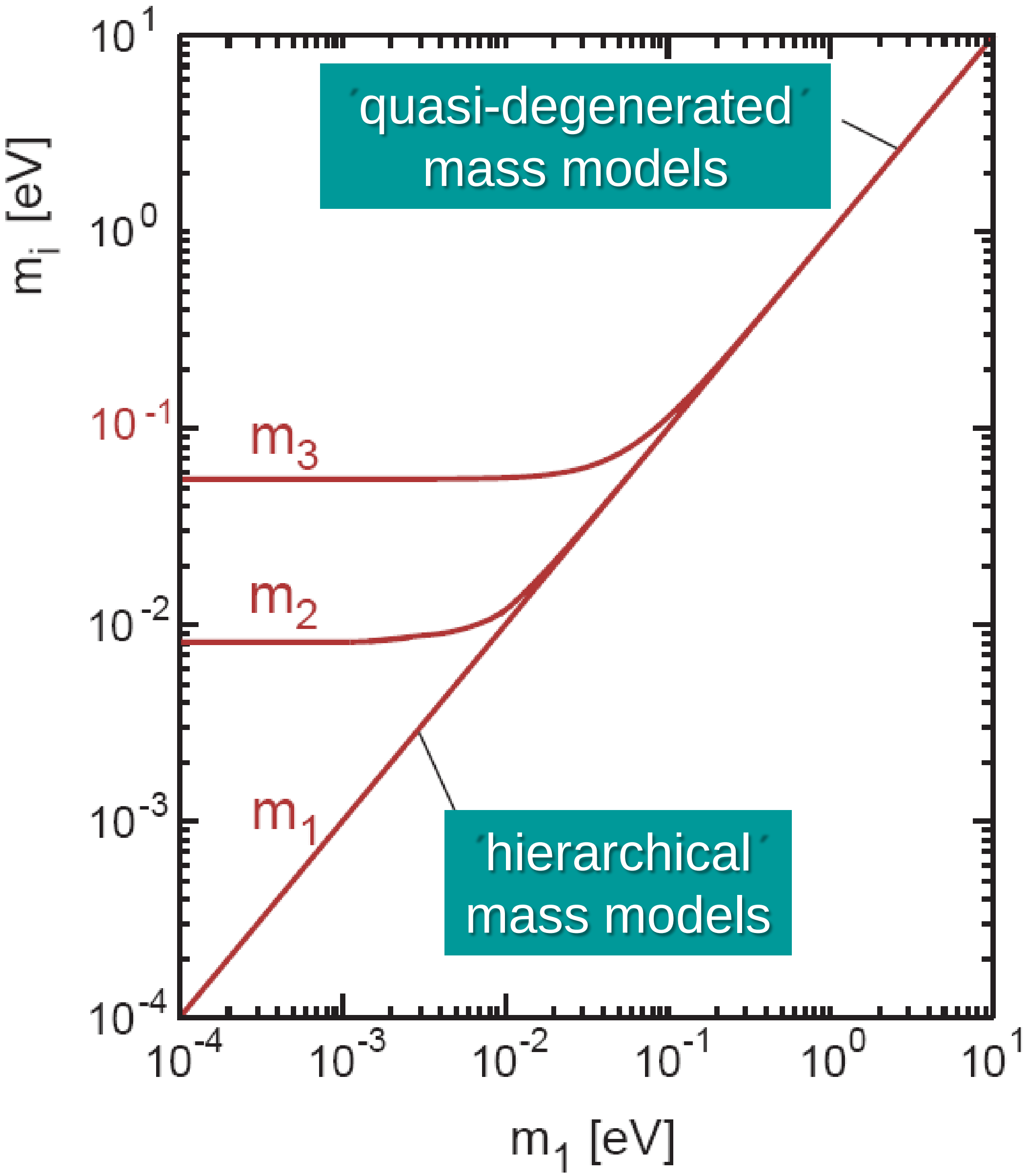
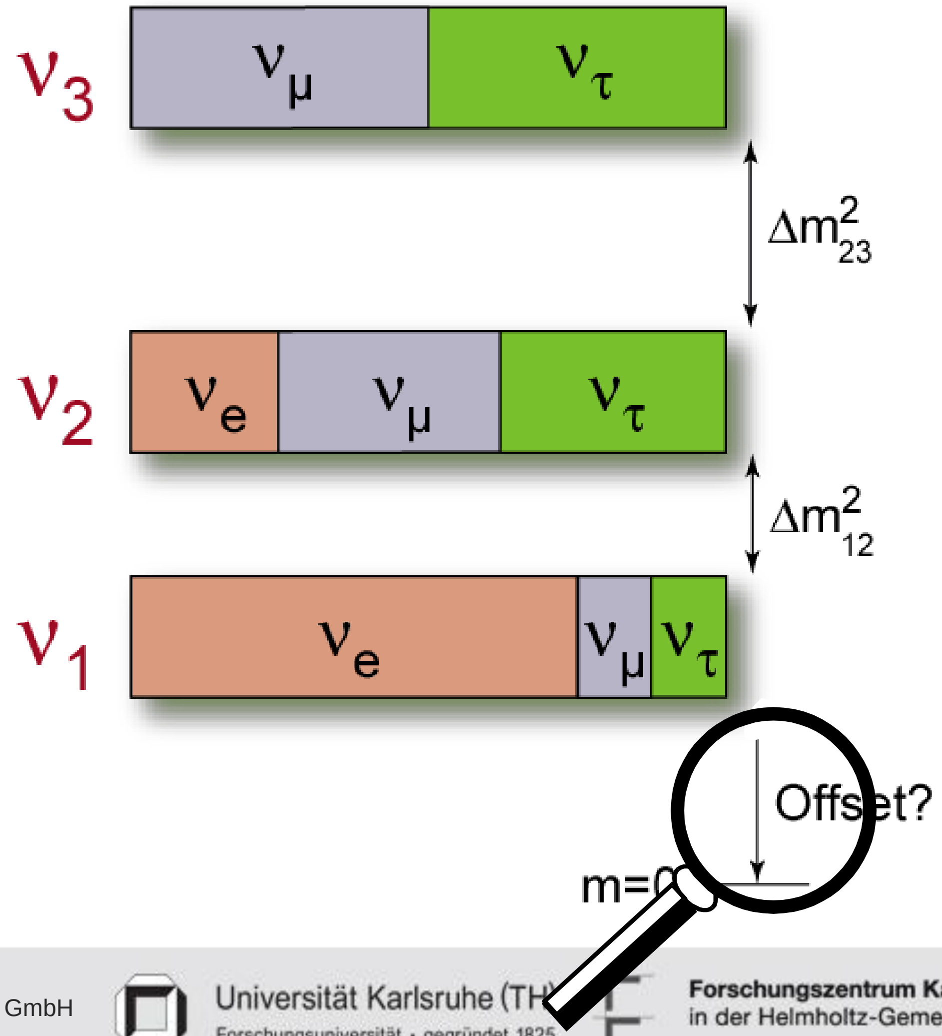
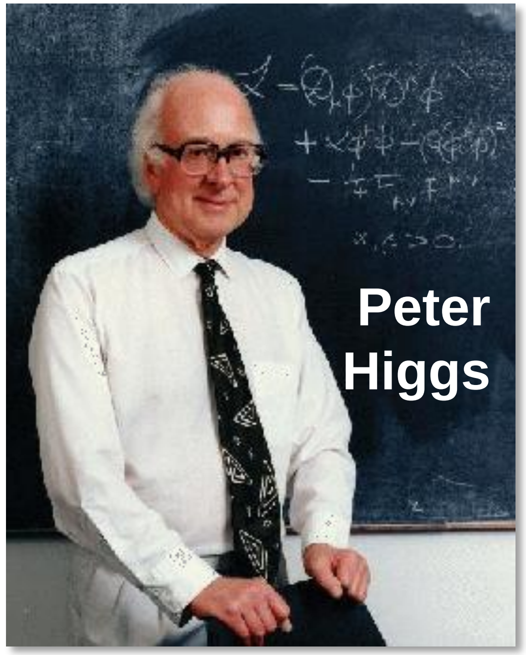


flavour composition of mass eigenstates

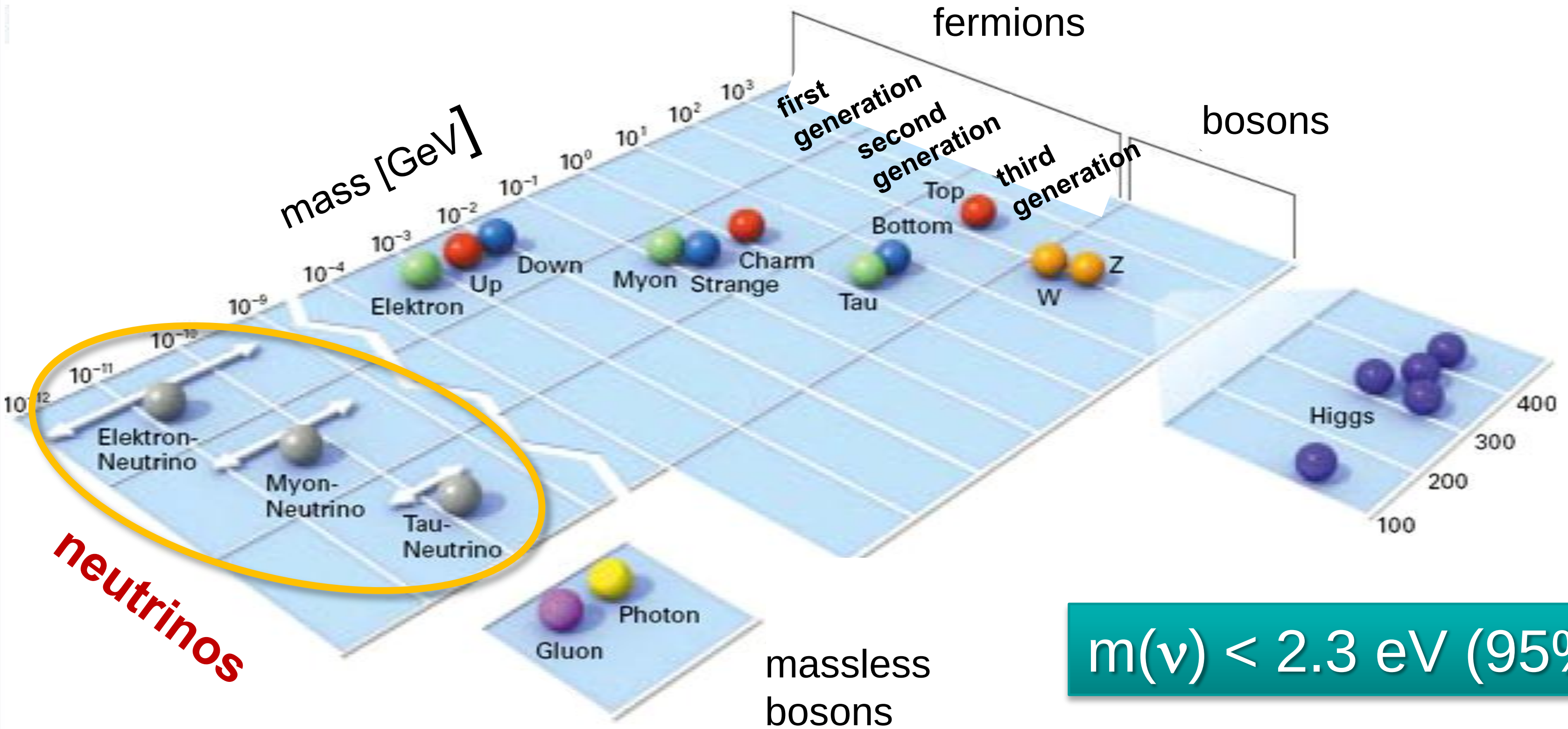


neutrino masses in particle physics

Higgs mechanism: SM particles acquire mass via interaction with the scalar Higgs boson, this coupling results in a **change of handedness** (lefthanded ↔ righthanded $\nu_{L,R} \leftrightarrow \nu_{L,R}$)



but: why are neutrino masses much smaller than
the masses of all other SM particles?



m(ν) < 2.3 eV (95% C.L.)

Troitsk
Mainz

neutrino masses in particle physics

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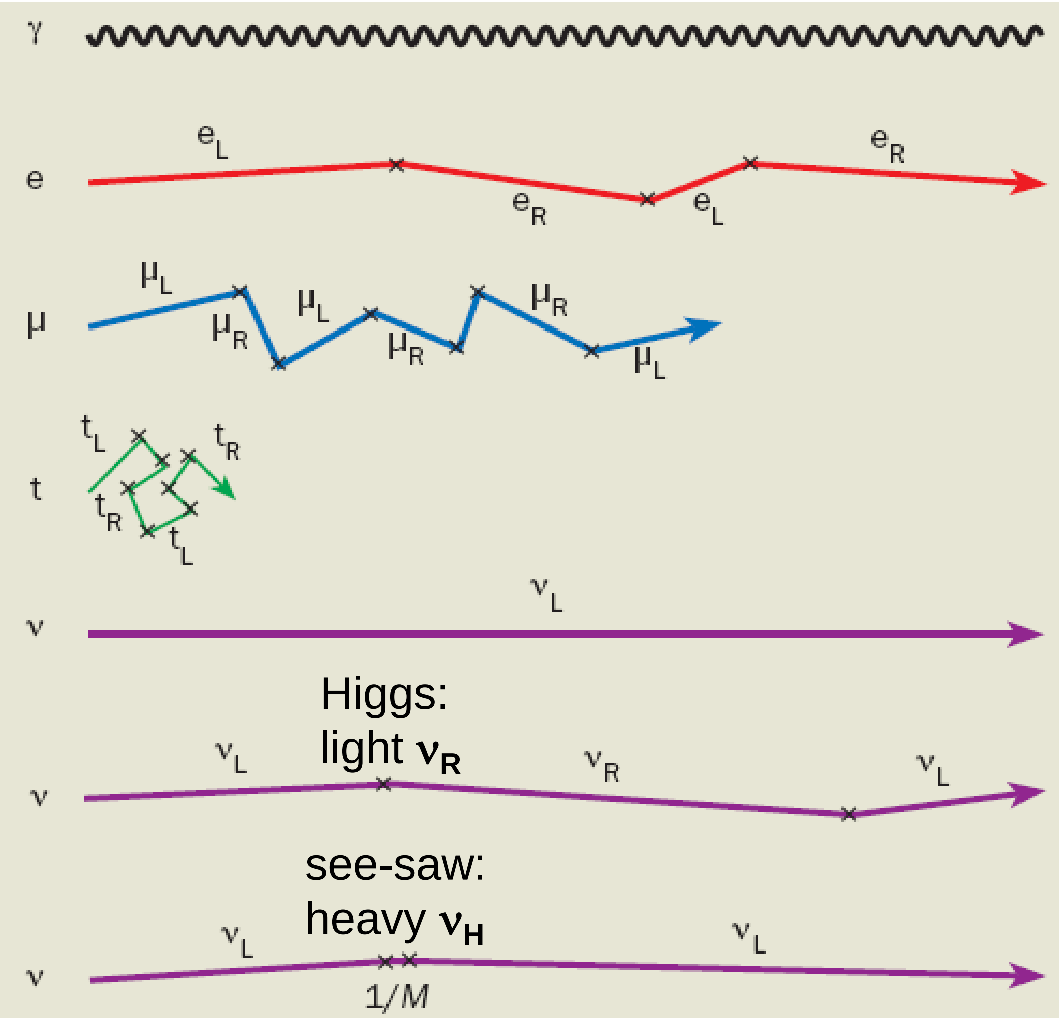


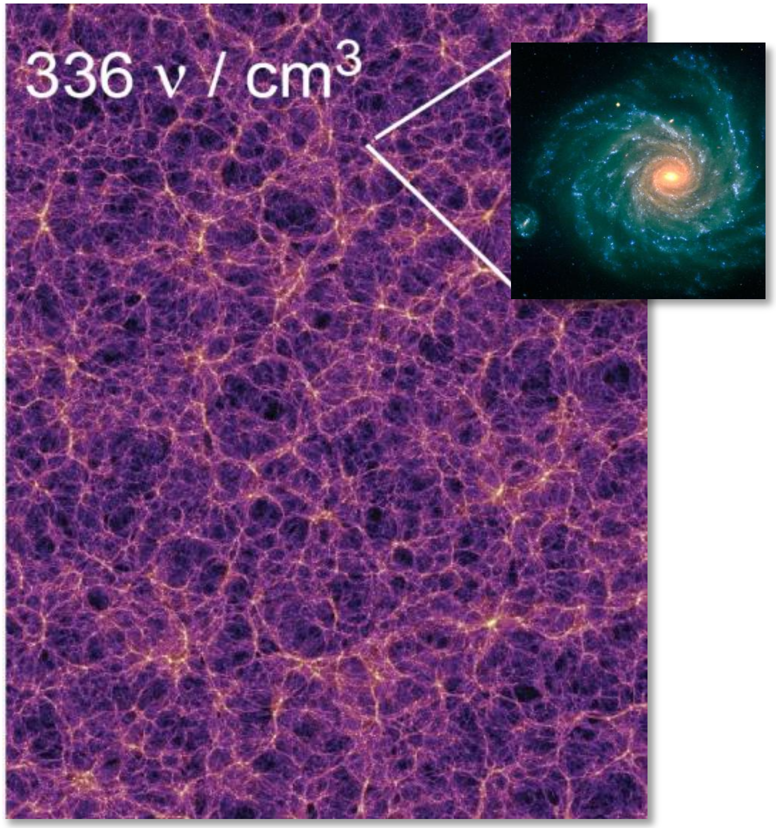
particle	scale	m [MeV]
photon γ	massless	0
electron e	light	0.511
muon μ	medium	105.6
top quark t	heavy	$1.71 \cdot 10^5$
SM neutrino ν_L	massless	0
Dirac ν ν^D	very light	$10^{-8} – 10^{-6}$
Majorana ν ν^M	**very light**	**$10^{-8} – 10^{-6}$**

relic ν background & ν-masses

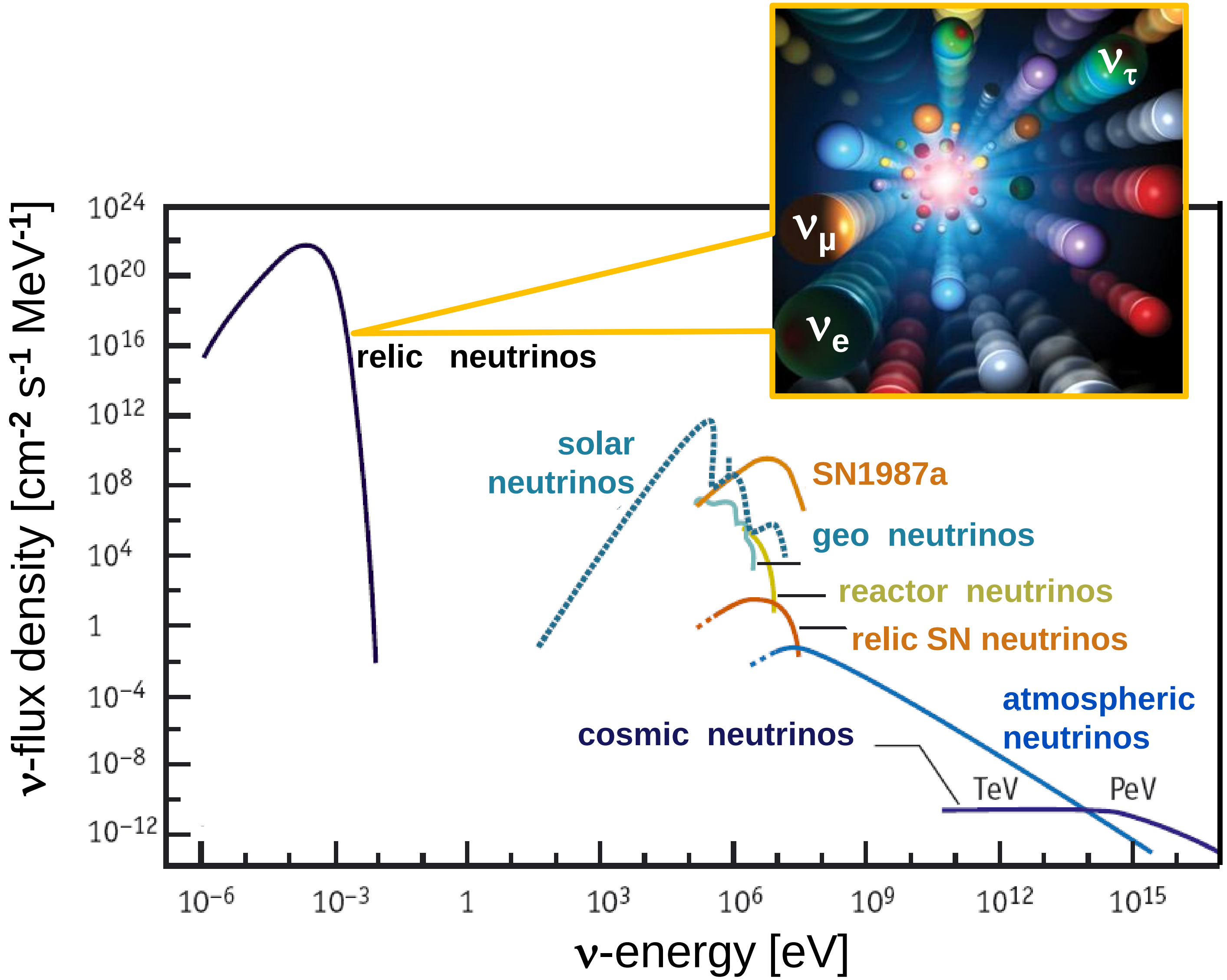
cosmic architects: what is the role of relic ν s as **hot dark matter**?

large scale structures: free streaming of ν s on Gpc scales (less small clusters)

cosmology



structure of the Universe
(Millenium Simulation)



neutrinos in cosmology

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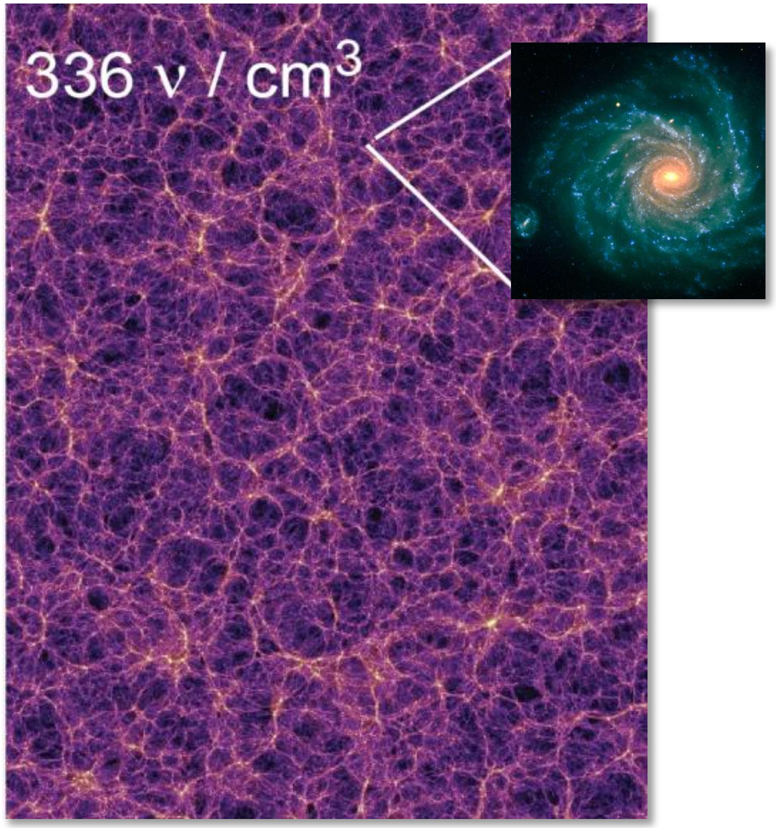

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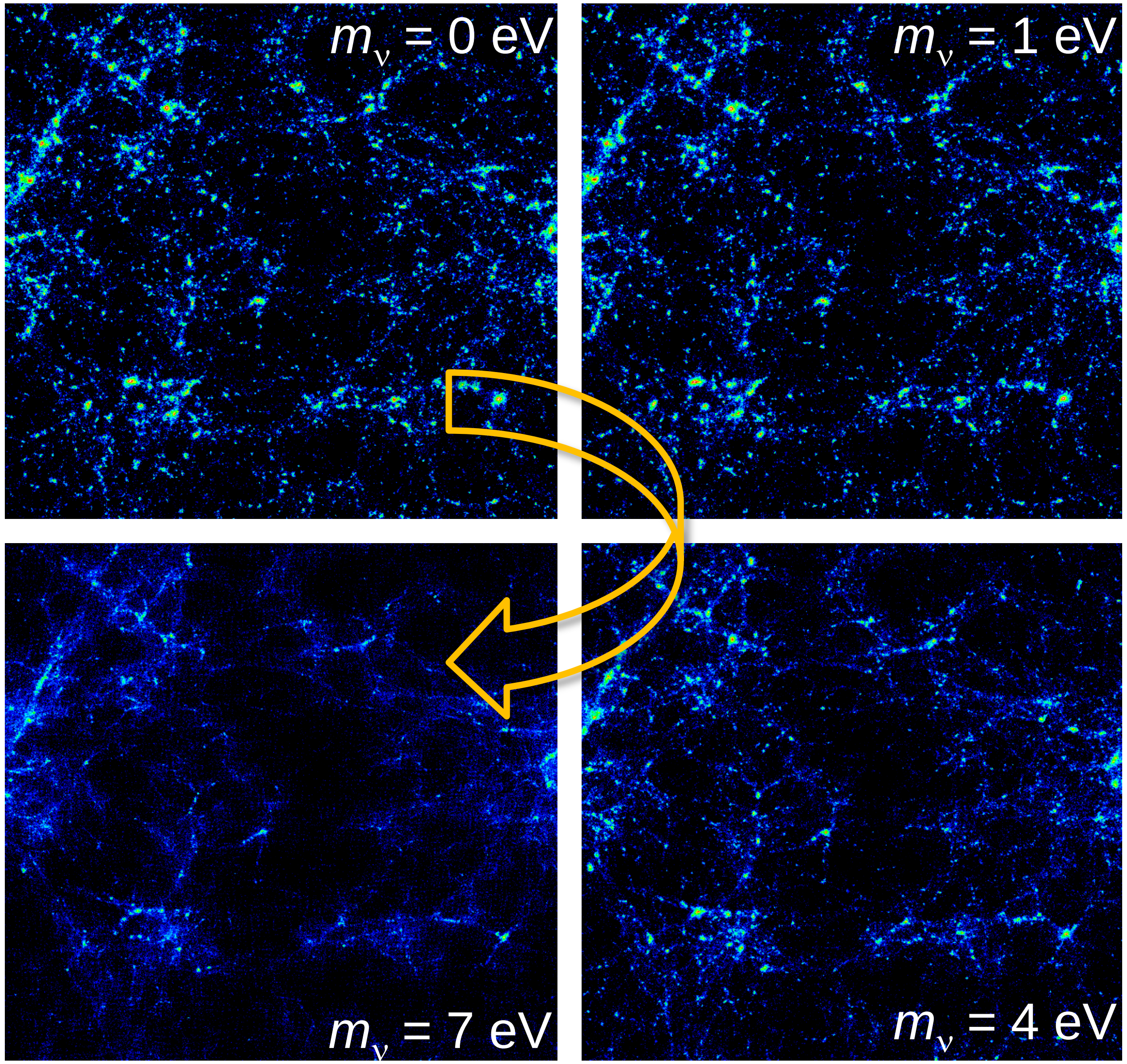

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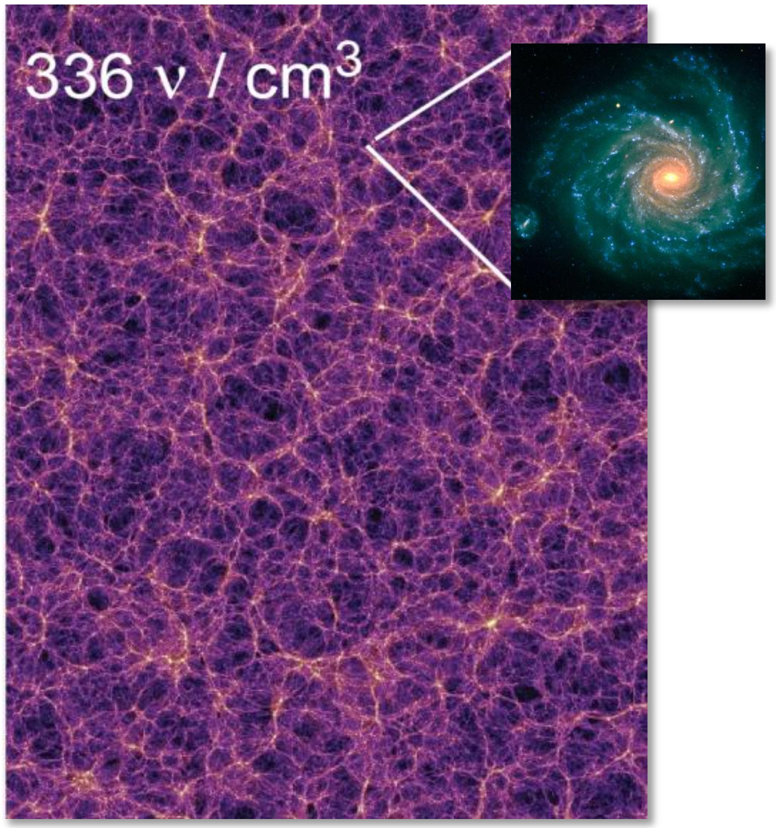

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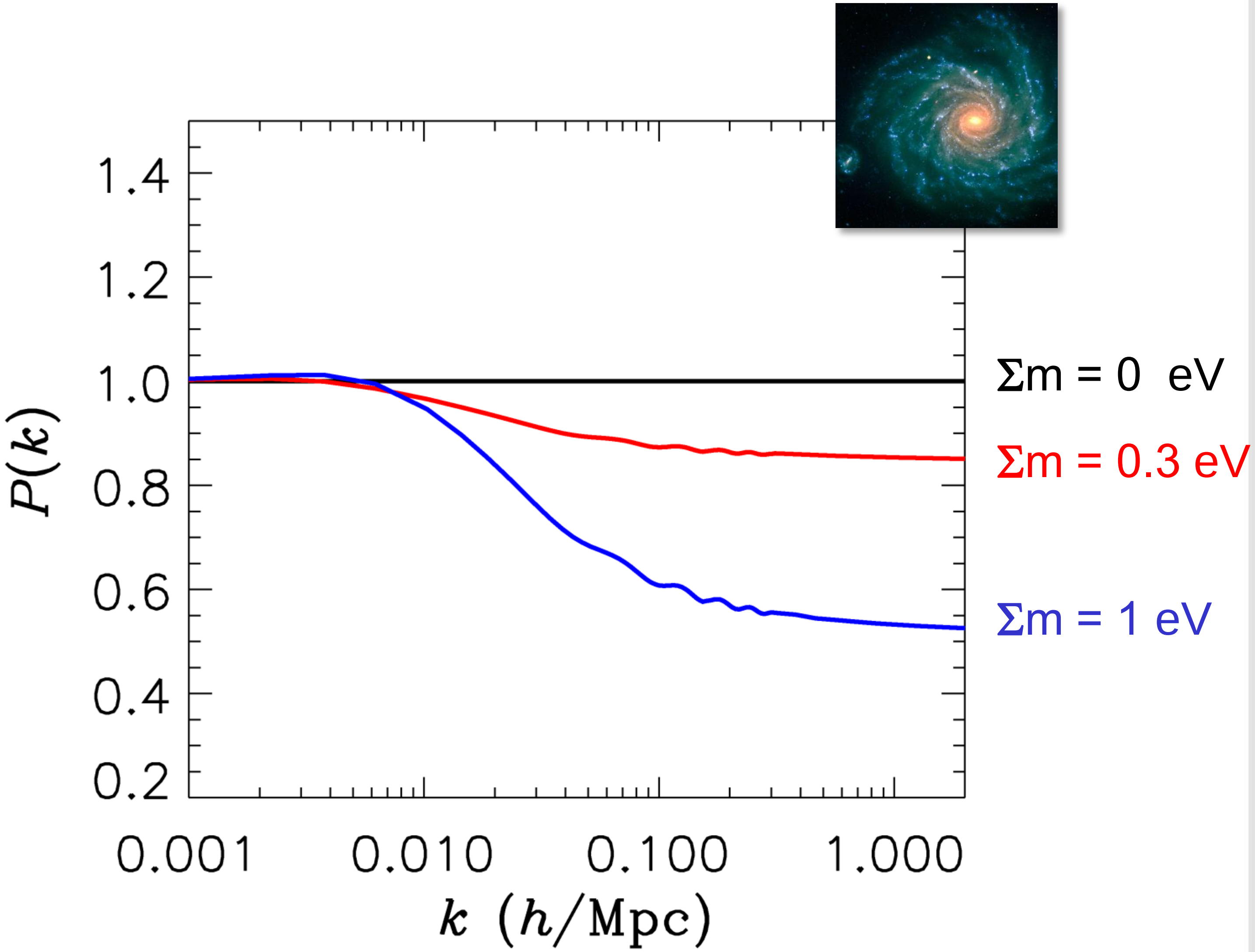
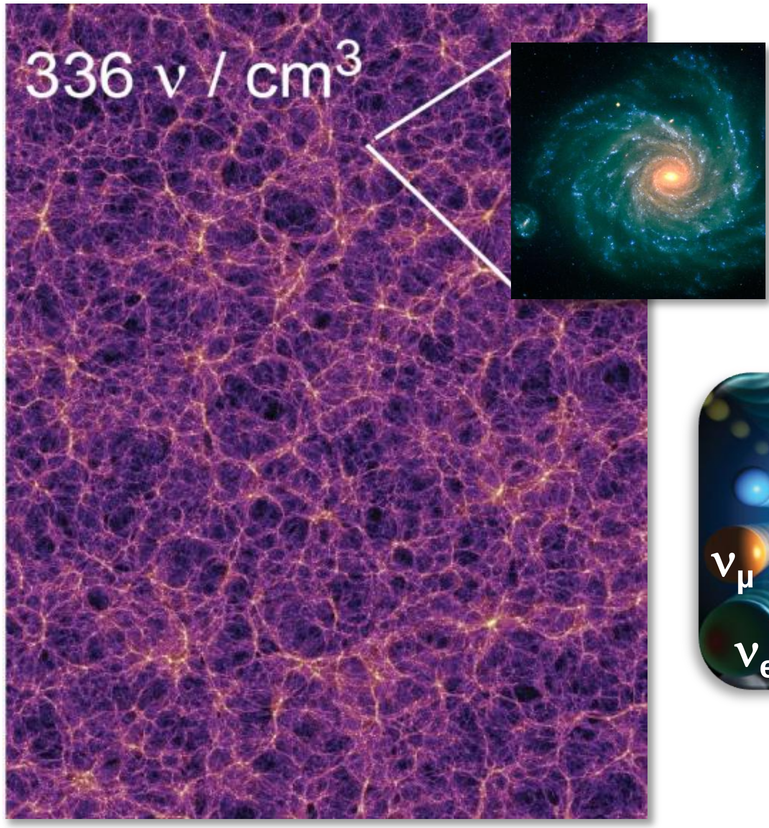


motivation: ν s in astroparticle physics

HDM contribution: 2 orders (0.1% → 10%)
lower limit: ν-oscillations upper limit: tritium ß-decay

$\Omega_\nu h^2 = \Sigma m_\nu / 92$ eV



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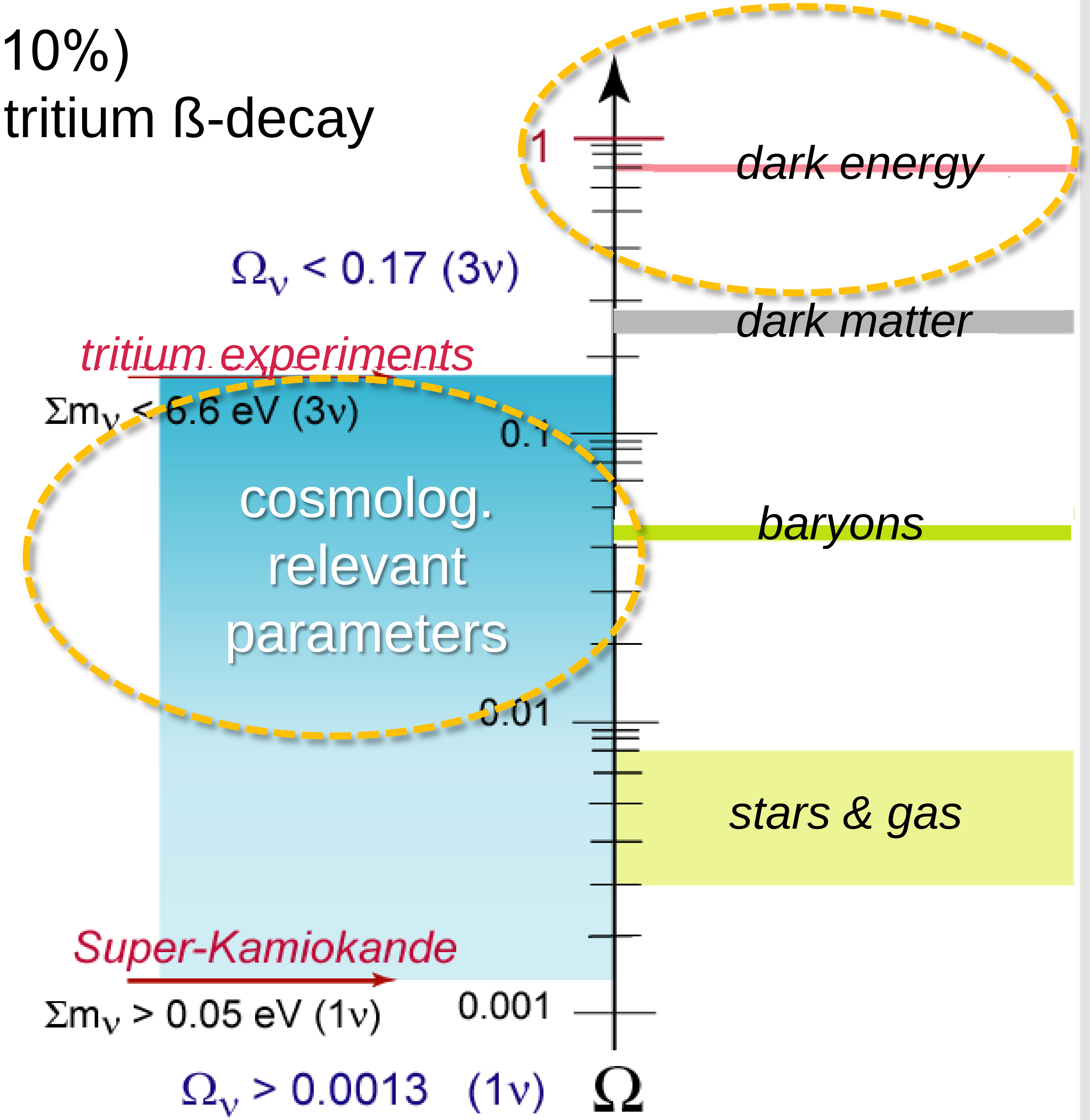
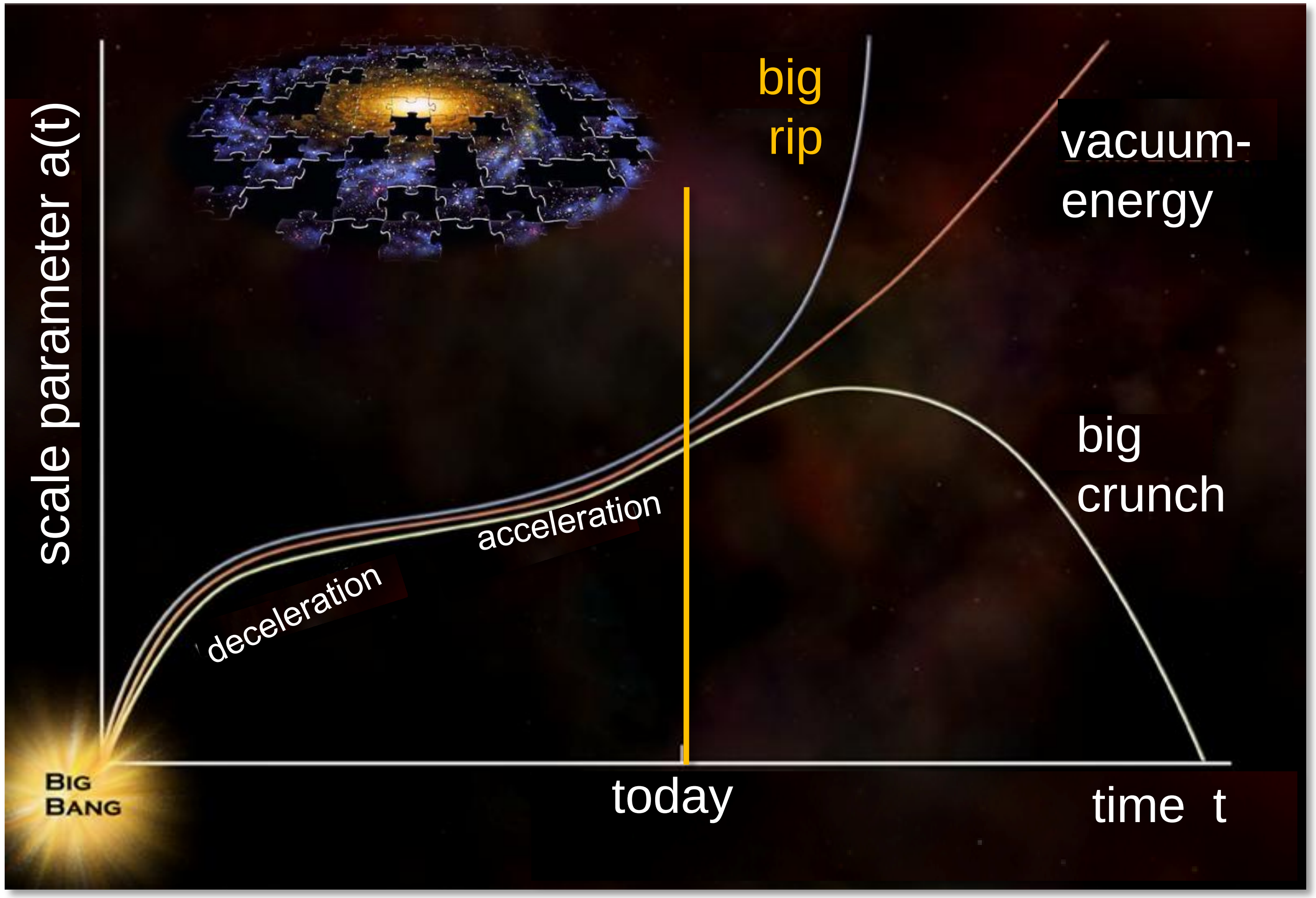
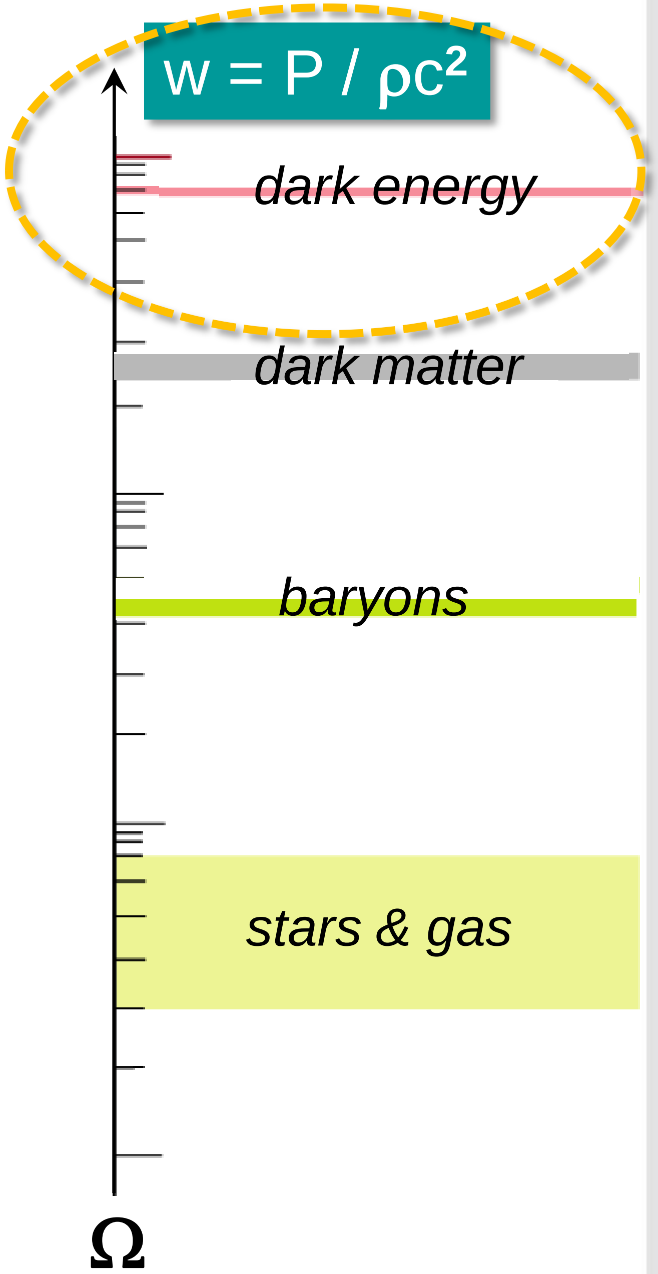


motivation: ν s in astroparticle physics

global analysis of cosmological data (CMBR & LSS):
correlation of ν–mass m(ν) & DE equation of state *w*

m_ν & dark energy equation of state *w*





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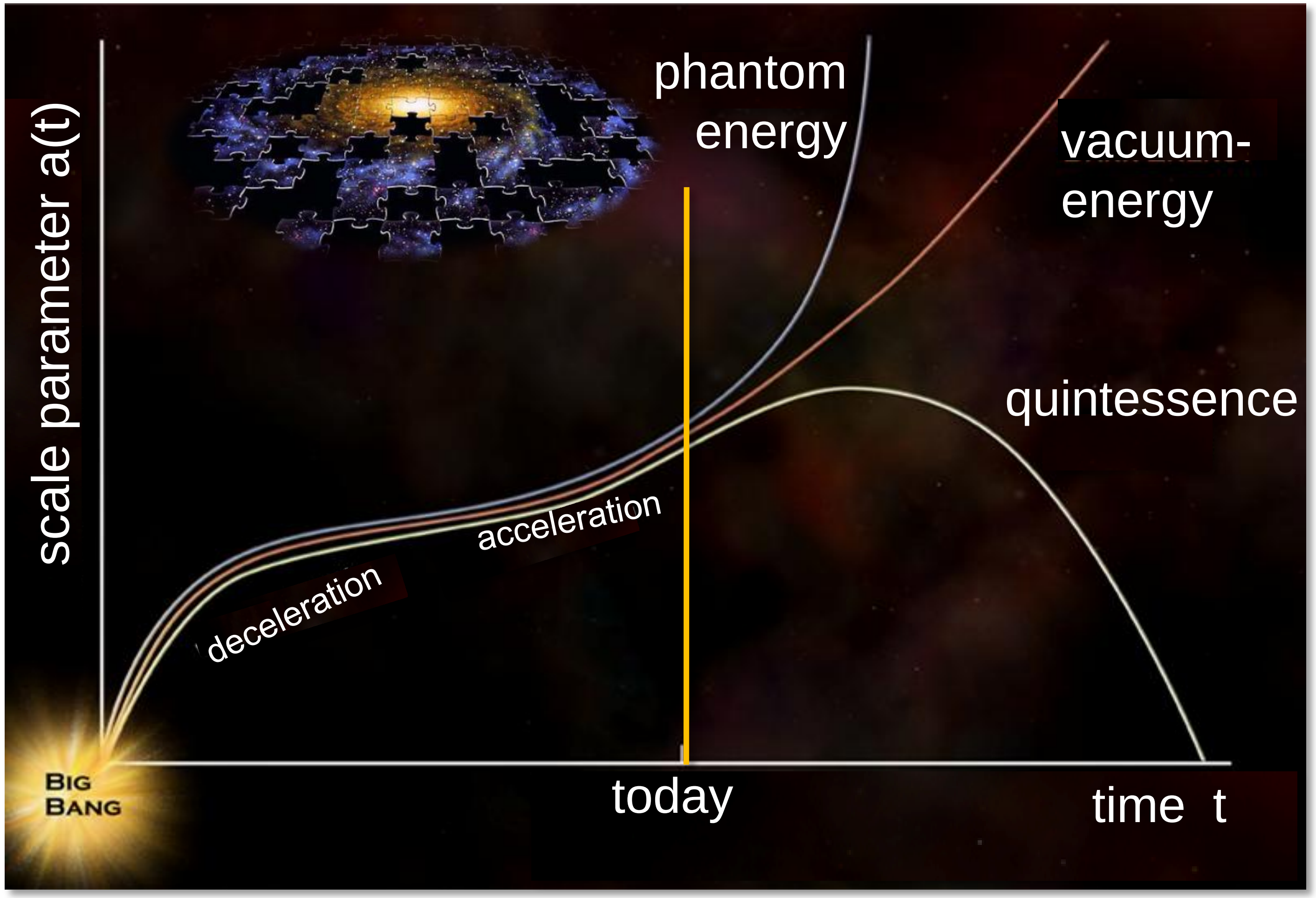
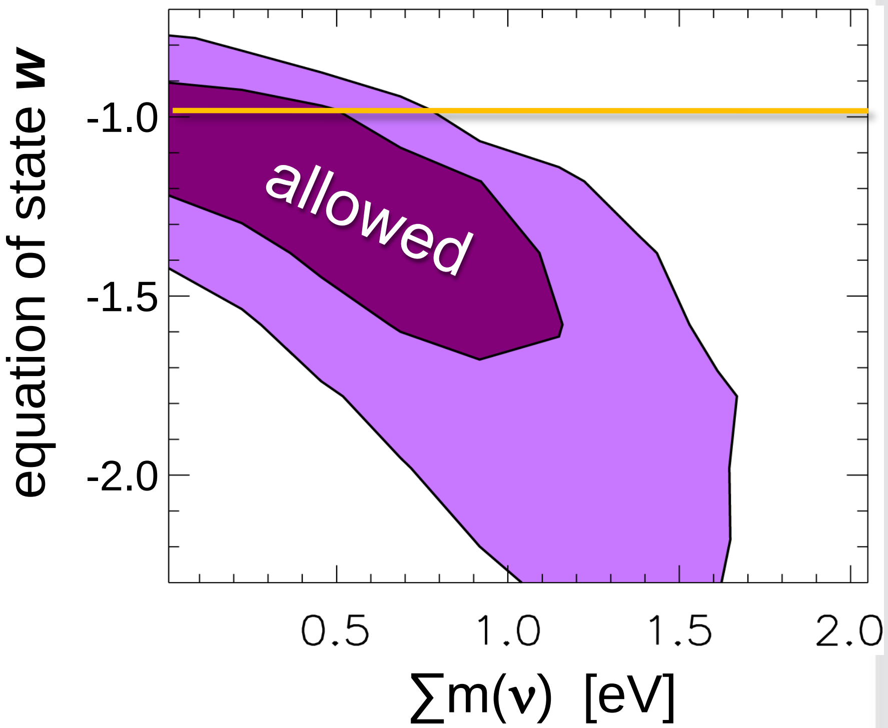
correlation of ν–mass m(ν) & DE equation of state *w*

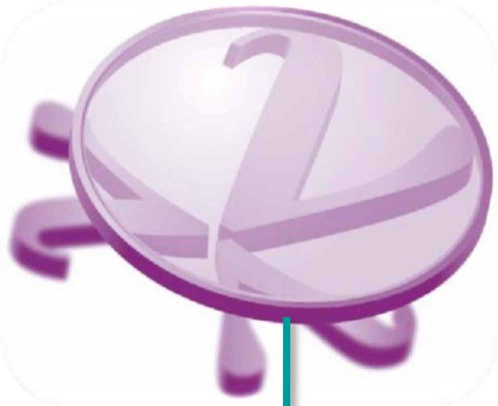
m_ν & dark energy equation of state $w = P/\rho c^2$

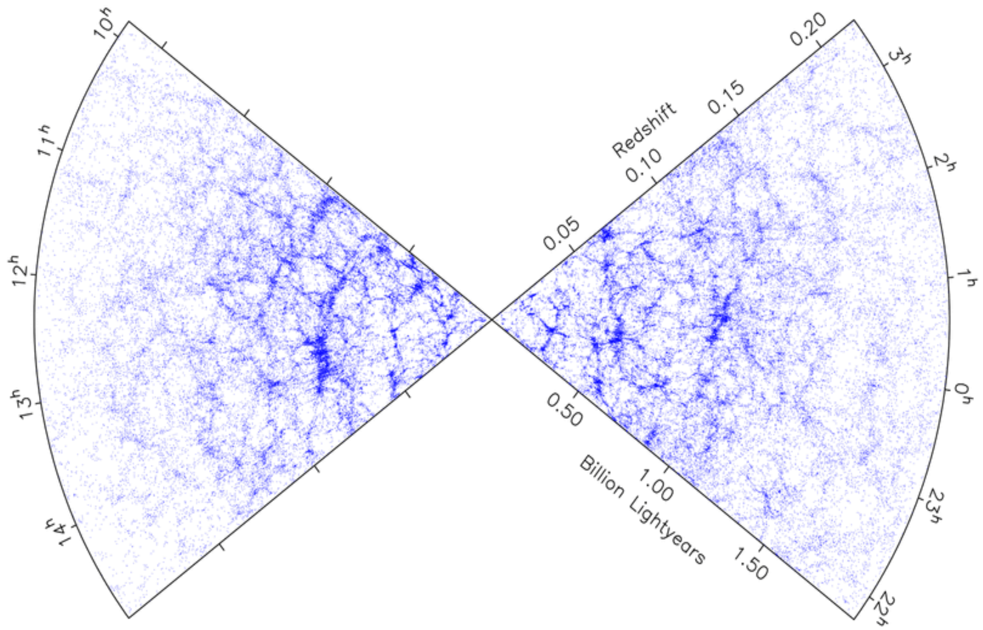


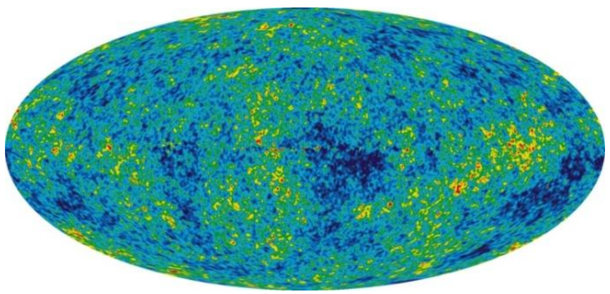
laboratory measurement of m(ν) > 0.2 eV could imply *w* < - 1 (phantom energy)



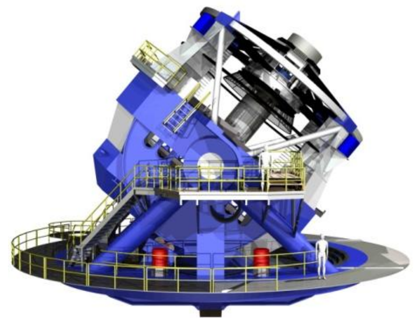
neutrino mass: status and perspectives







cosmology
sum Σm_i, HDM Ω_ν



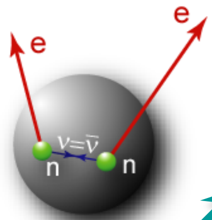
model-dependent (multi-parameter fits)

status: Σm_i < 1 eV [Hannestad et al., arXiv:0803.1585v2]

potential: Σm_i = 20-50 meV

Planck, LSST, weak lensing

neutrino mass: status and perspectives



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

model-dependent (CP-phases)
status: $m_{ßß}$ < 0.35 eV, evidence?
potential: $m_{ßß}$ = 20-50 meV
GERDA, EXO, CUORE

Dirac neutrino

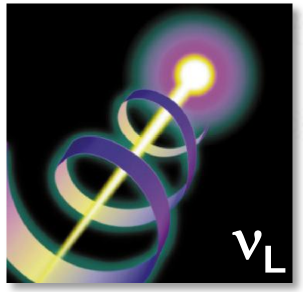
4 ν states
lepton number conservation ΔL = 0
neutrino ≠ antineutrino

Majorana neutrino

2 ν states
lepton number violation ΔL = 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?

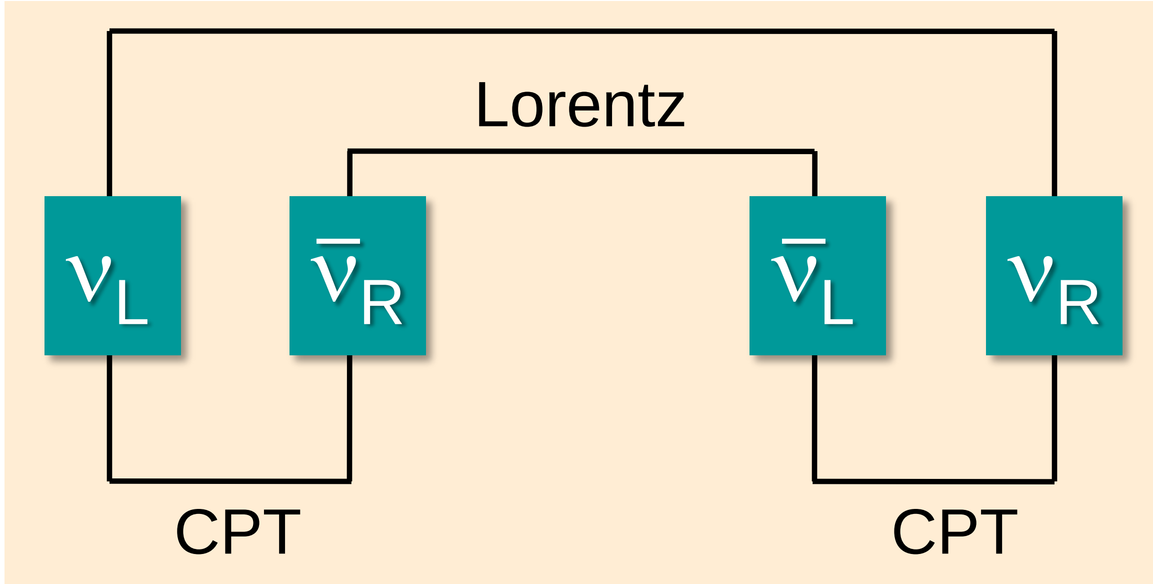
Dirac neutrino

ν^D

4 ν states

lepton number conservation $\Delta L = 0$

neutrino ≠ antineutrino



Majorana neutrino

ν^M

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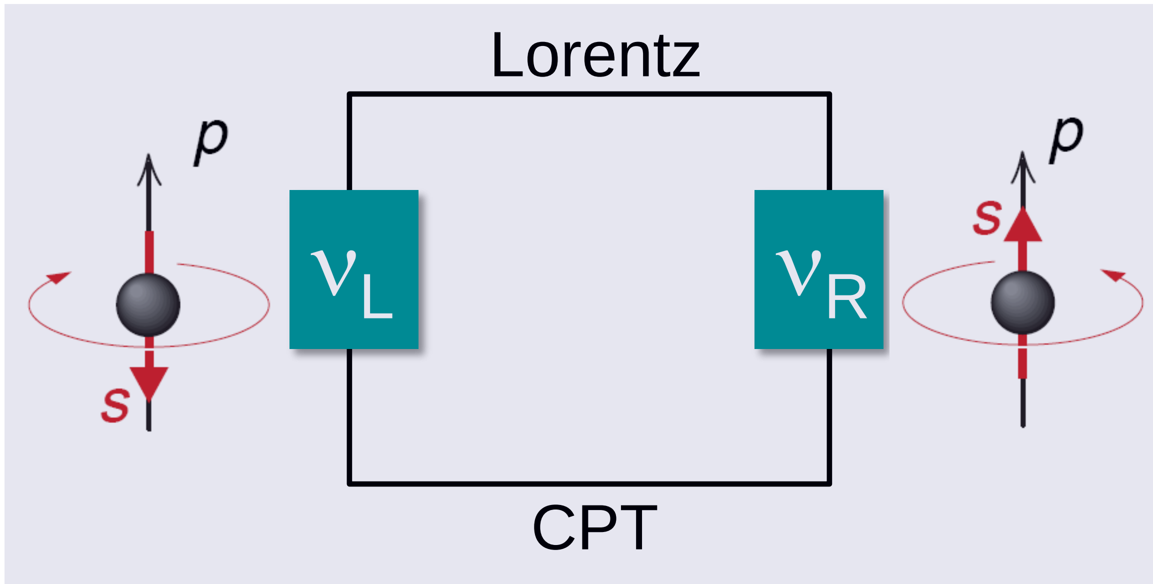
lepton number violation $\Delta L = 2$



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

KIT – die Kooperation von Forschungszentrum Karlsruhe GmbH und Universität Karlsruhe (TH)

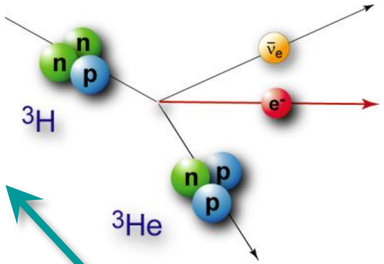
Universität Karlsruhe (TH)
Forschungsuniversität · gegründet 1825

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

neutrino mass: status and perspectives

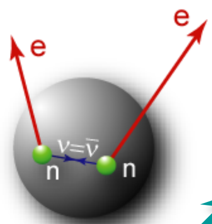
KIT Karlsruhe Institute of Technology

kinematics of ß-decay absolute ν_e-mass: m_ν



model-independent

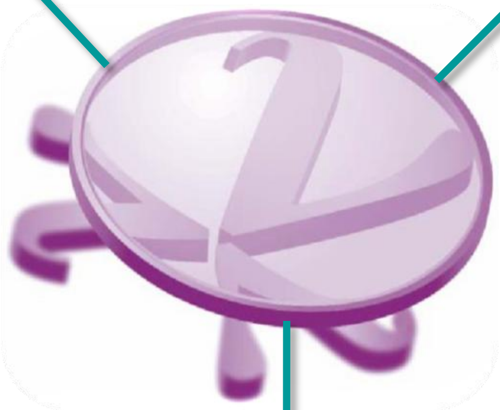
status: $m_\nu < 2.3$ eV
potential: $m_\nu = 200$ meV
KATRIN (MARE-II)

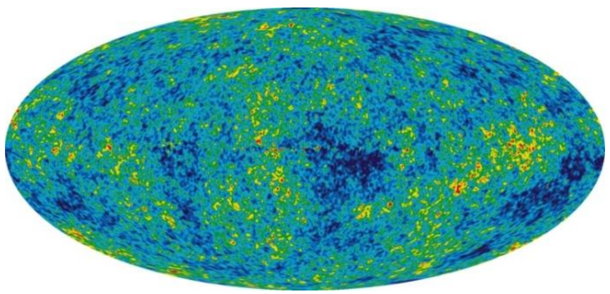


search for 0νßß eff. Majorana mass $m_{ßß}$

model-dependent (CP-phases)

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





cosmology sum Σm_i, HDM Ω_ν

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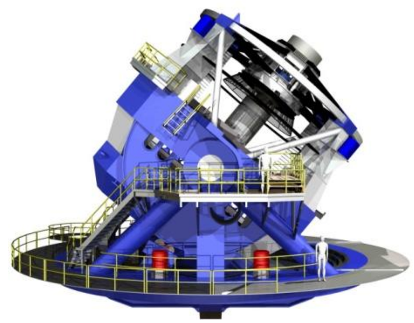
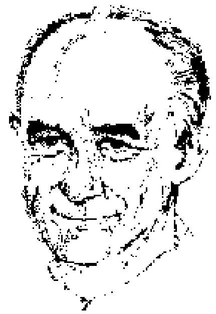
Planck, LSST, weak lensing



ß-decay: Fermi s theory & ν-mass



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

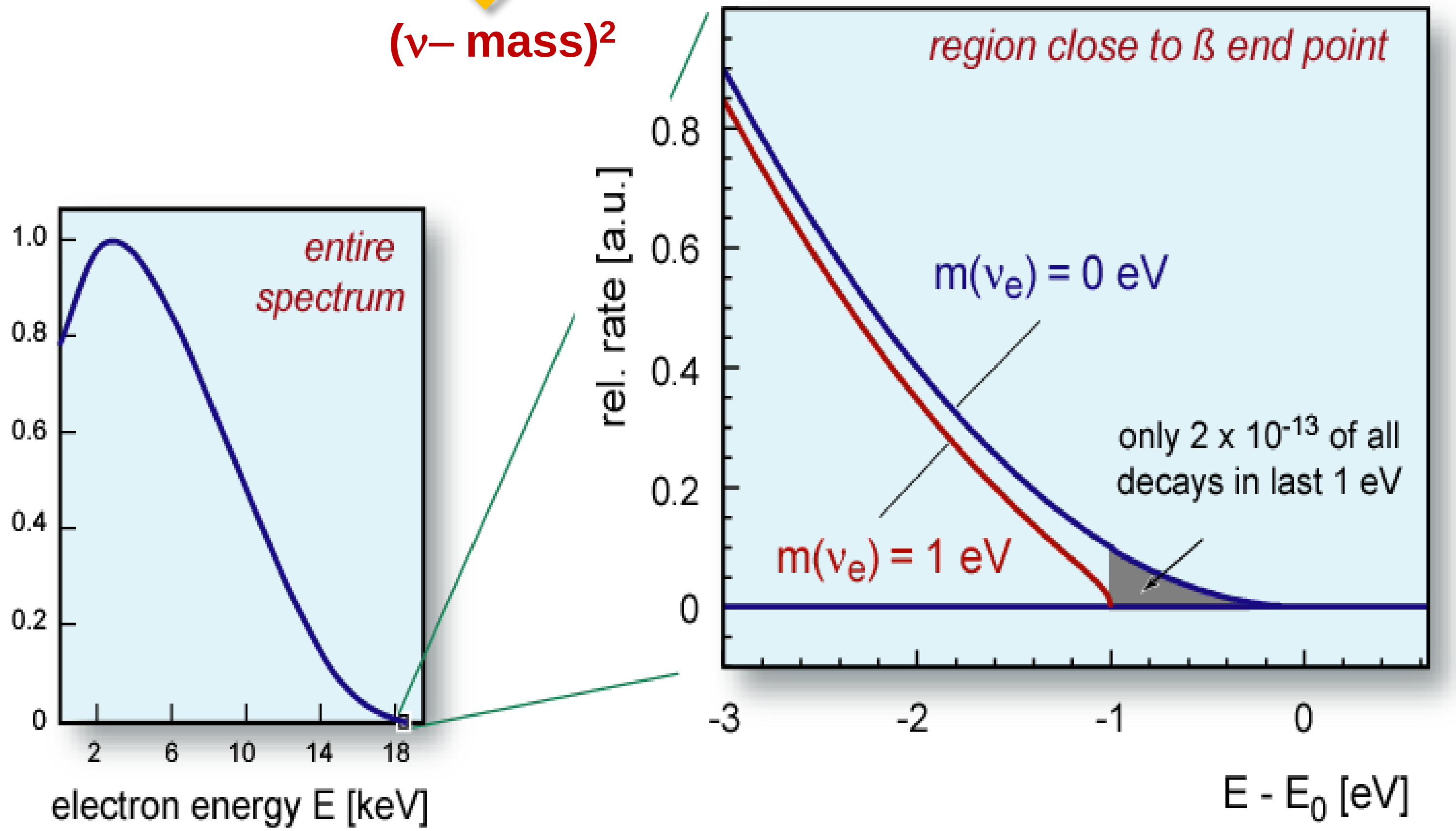
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

incoherent sum

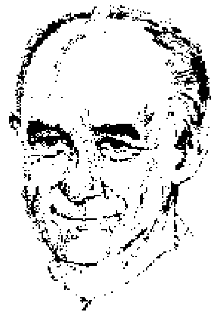
$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

which isotope?

(ν– mass)²



ß-decay: energy spectrum



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based on kinematics & energy conservation

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

incoherent sum of m_i

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

(ν– mass)²

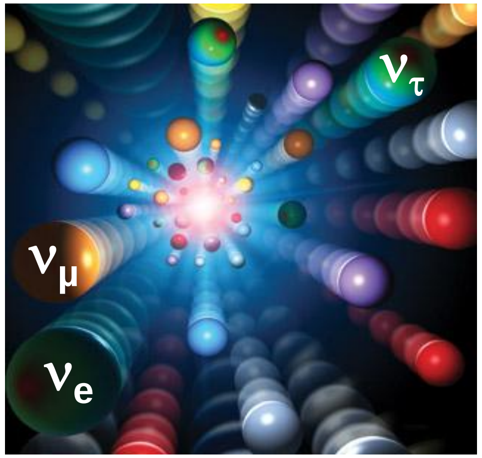
ß-source requirements	ß-detection requirements
short half life $t_{1/2}$ ⇘ high luminosity	large solid angle (~2π)
low endpoint energy E_0	low background rate
superallowed/allowed transition	high energy resolution (~eV)
simple atomic/molecular structure	short dead time, no pile up

^{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

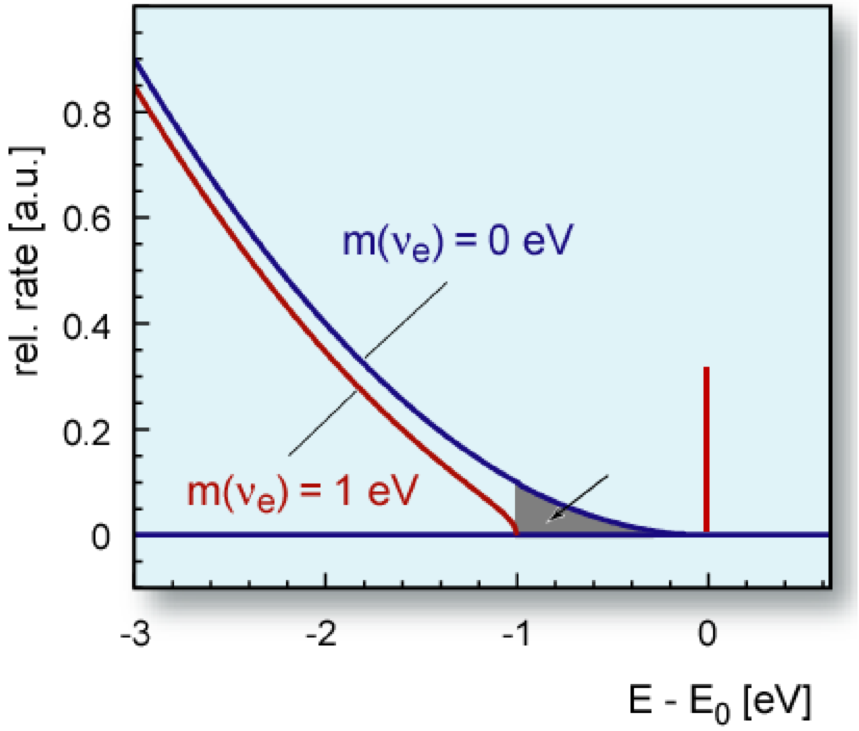
relic ν background CνB

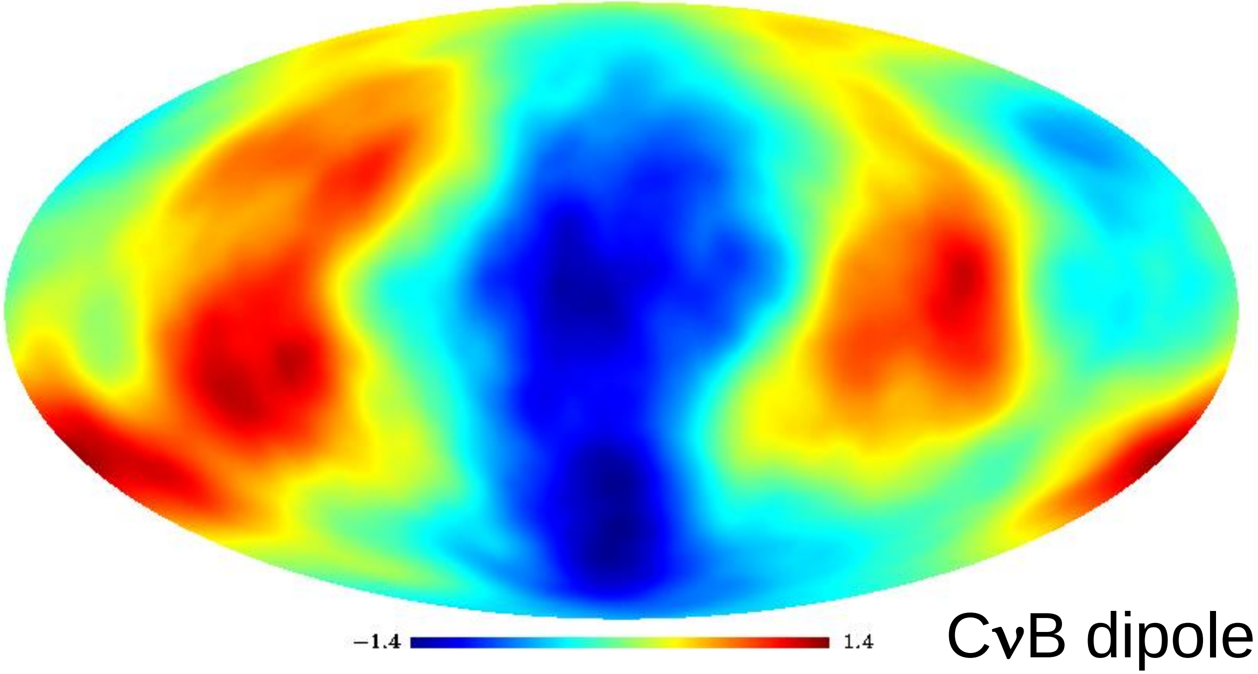


capture of relic neutrinos on a ß-unstabile isotope (^3H):

$\nu_e + {}^3H \rightarrow {}^3He + e^-$ advantage: no threshold!

drawbacks: ~10^6 KATRIN T_2 target mass required
improve resolution for 18.6 keV ß s to ΔE = 50 meV





CνB dipole

calculated anisotropies of the CνB
for m_ν = 10 meV (S. Hannestad)

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

MARE experiment

Microcalorimeter **A**rrays for a **R**henium **E**xperiment

^{187}Re as ß-emitter: isotopic abundance 62.8%

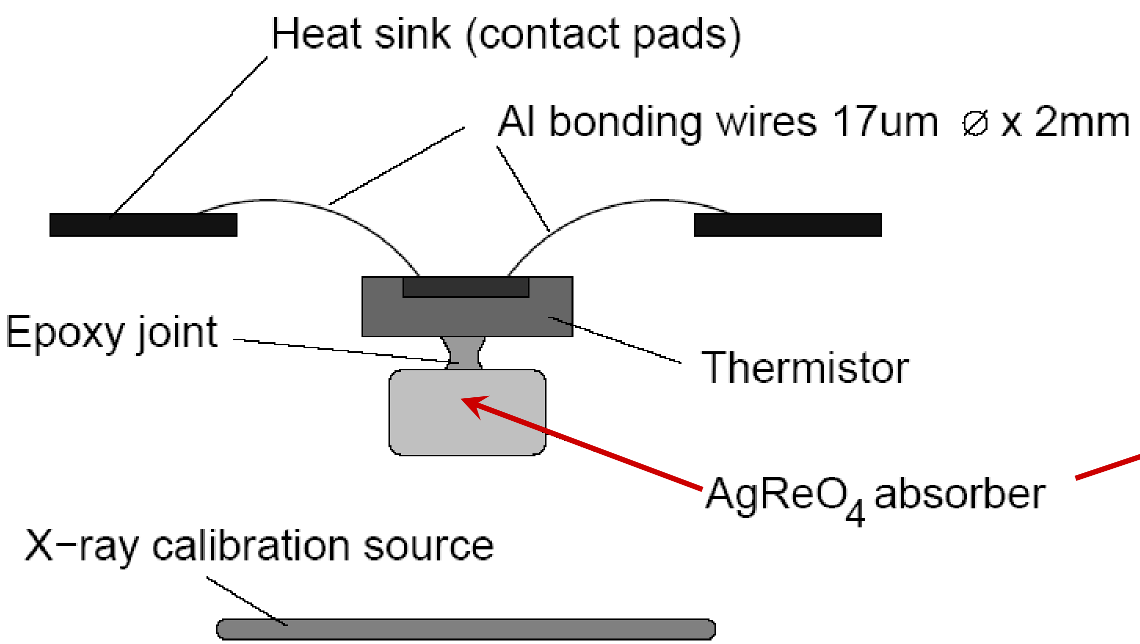
$^{187}_{85}Re \rightarrow ^{187}_{86}Os + e^- + \bar{\nu}_e$

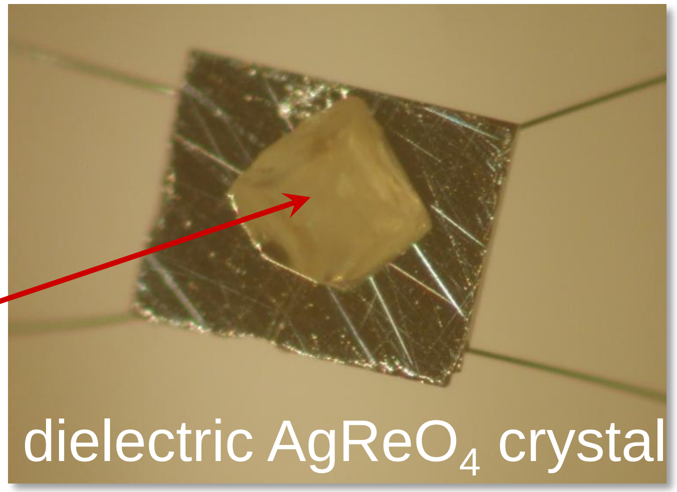
$5/2^+ \rightarrow 1/2^-$ unique first forbidden transition (shape factor)

previous experiments:

Genova: metallic Re (MANU)
Milano: $AgReO_4$ (MIBETA)

6.2 10^6 ^{187}Re ß-decays:
m(ν) < 15 eV (2004)





MIBETA:
10 crystals

MARE experiment: Phase-I

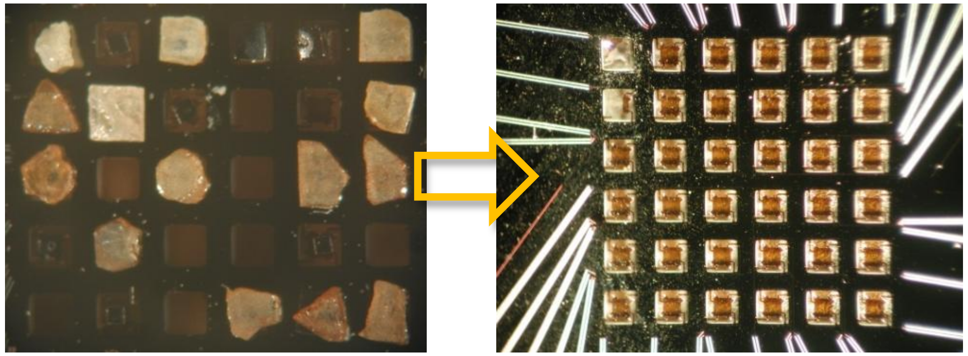
Phase-I objective: improve sensitivity for m(ν) by factor 10
increase statistics to 10^{10} ß-decays ⇨ m(ν) ~ 2 eV

Phase-I detectors: Genova: metallic Re, superconducting at T = 1.6 K
absorber mass 1 mg

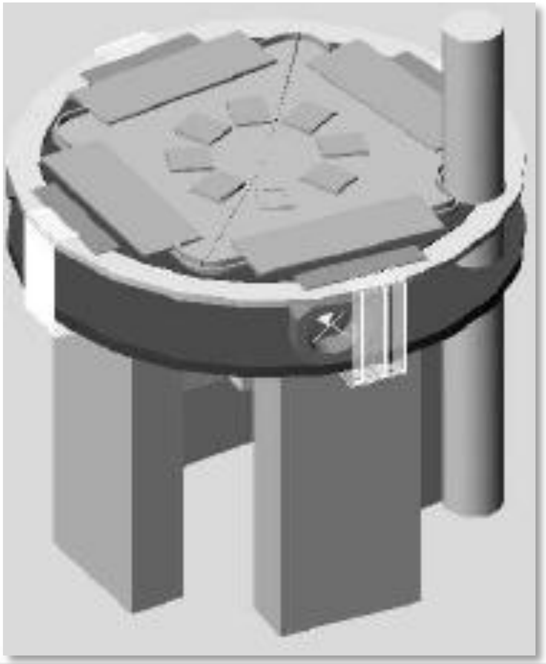
Milan: new $AgReO_4$ crystals, dielectric perrhenates
absorber mass 500 µg at T ~ 85 mK, τ_{rise} ~200 µs
6   6 pixel arrays: 1st operational, 2nd: funded
energy resolution: ΔE = 34 eV @ 2.5 keV

ΔE = 15 eV
Δt = 50 µs
3 years

Genova: Re metal

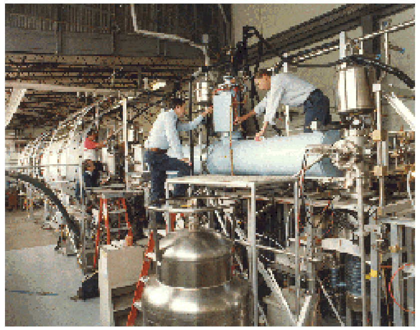


Milano: pixel arrays of $AgReO_4$



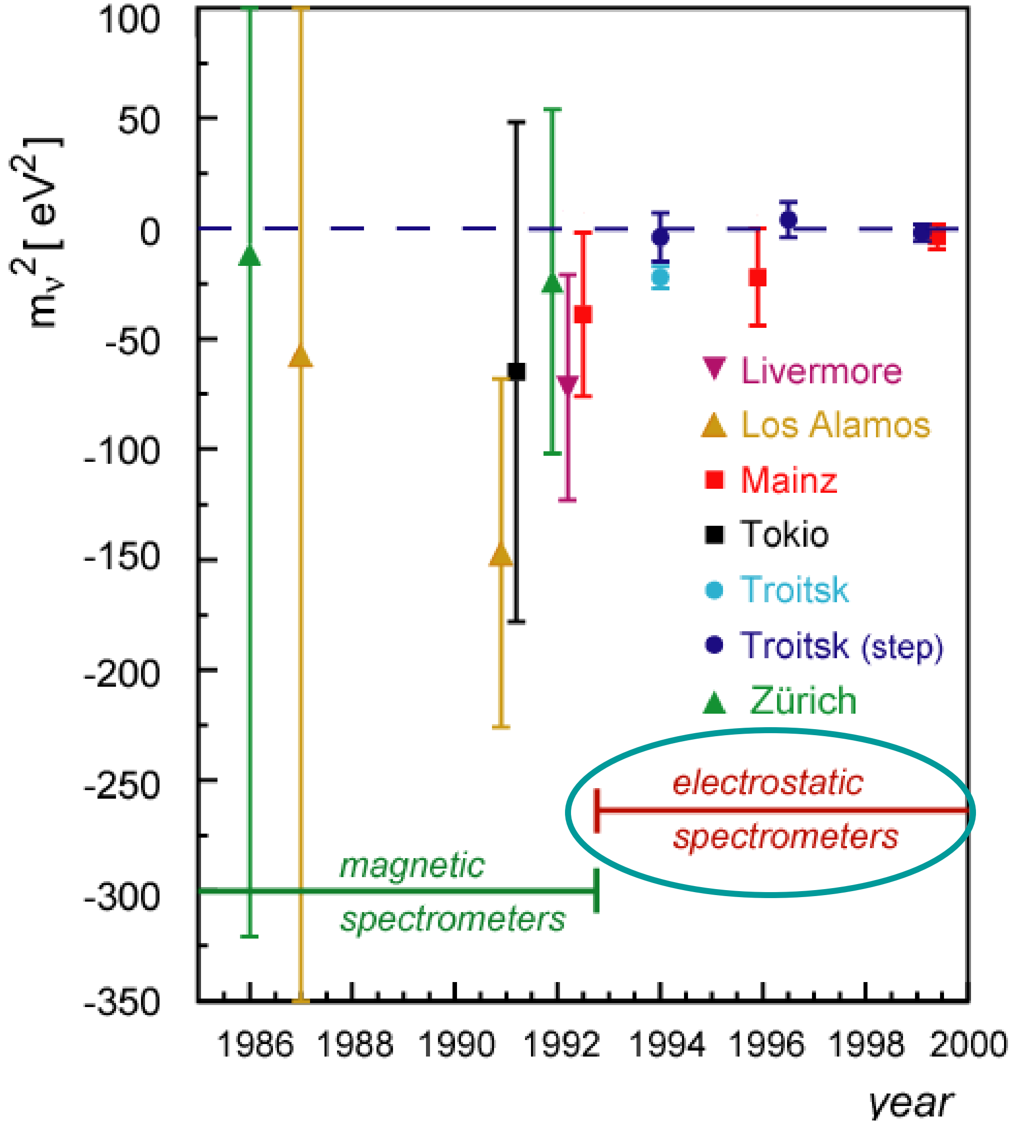
MARE-I cryostat layout for 288 elements (4 72)

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

results m_ν^2



Troitsk & Mainz experiments

Troitsk experiment

windowless gaseous tritium source

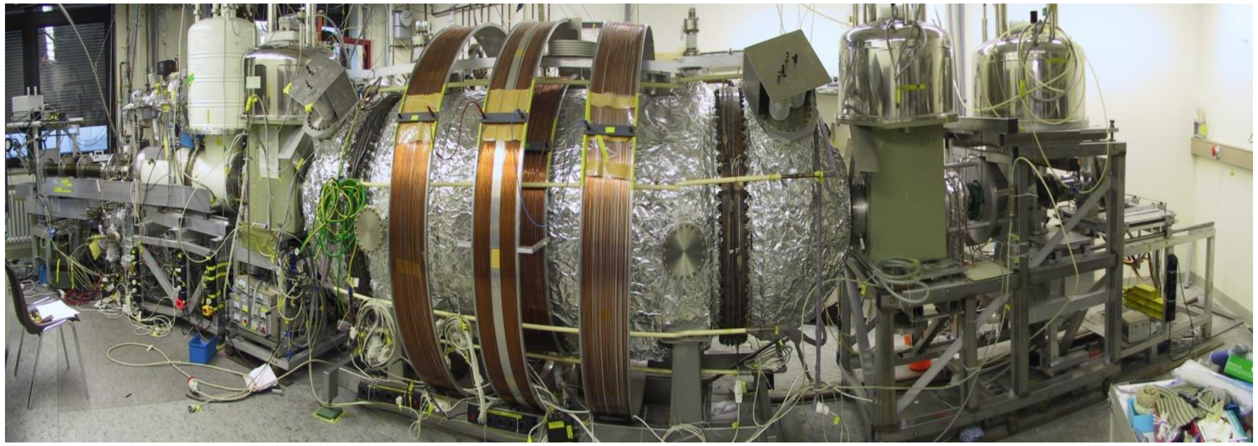
analysis of data 1994-99, 2001

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

$m_\nu \leq 2.2\ eV\ (95\%\ CL.)$

Mainz experiment

quench condensed tritium source



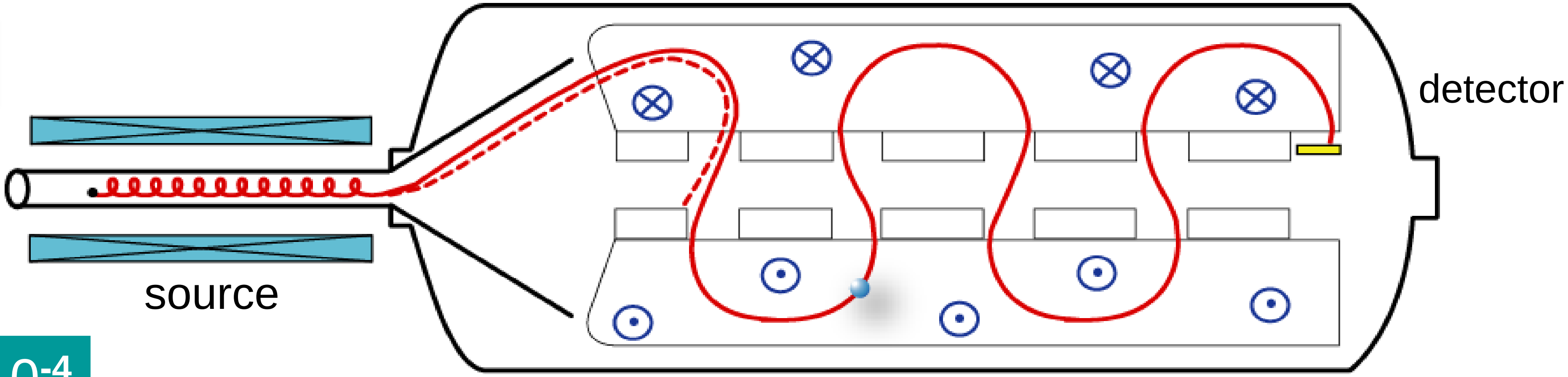
analysis of data 1998-99, 2001

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

$m_\nu \leq 2.2\ eV\ (95\%\ CL.)$

spectrometers – comparison of techniques

Tret´yakov

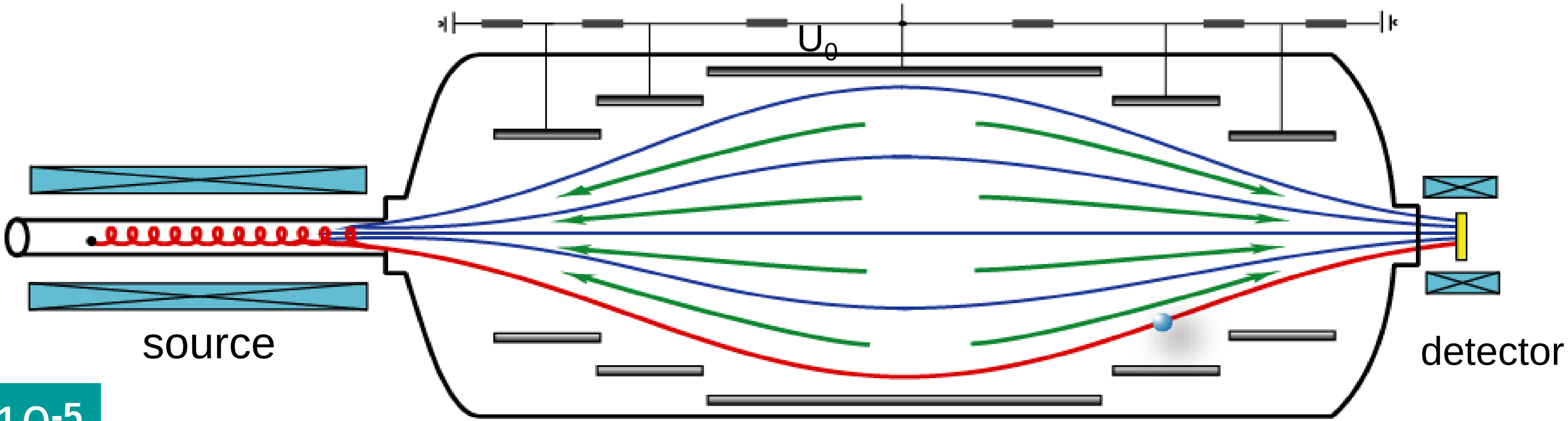


$\Delta p/p = 7 \quad 10^{-4}$

$\delta\Omega = 10^{-3}$

magnetic guiding field: momentum analysis

MAC-E



$\Delta E/E = 1 \quad 10^{-5}$

$\delta\Omega \sim 2\pi$

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

MAC-E filter – principle

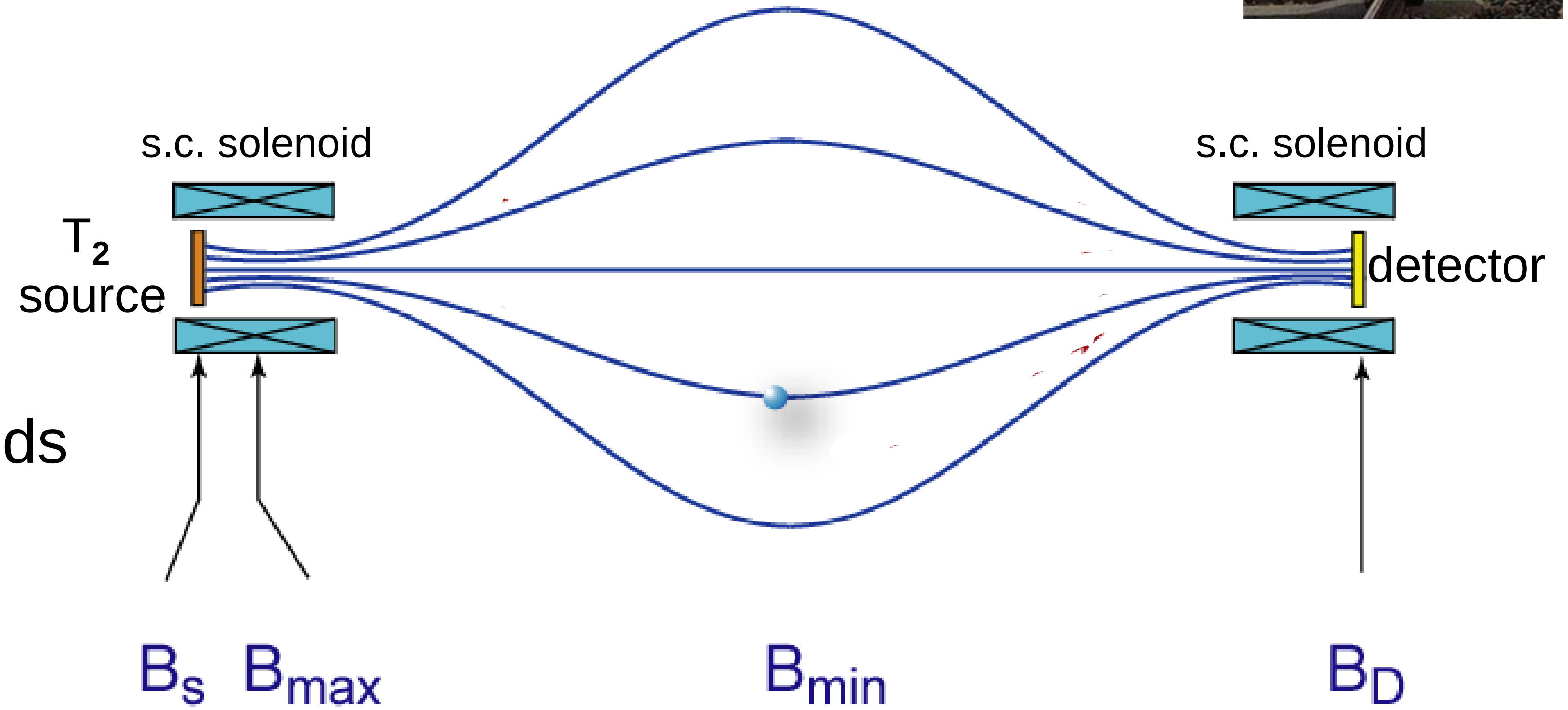
MAC – Magnetic Adiabatic Guiding

adiabatic guiding
of electrons along
magnetic field lines

inhomogenous B-field:
superconducting solenoids
$B_{max} = 3 – 6$ T
$B_{min} < 1$ mT
solid angle dΩ ~ 2π

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

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



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

MAC-E filter – principle

E Filter – Electro-static filter

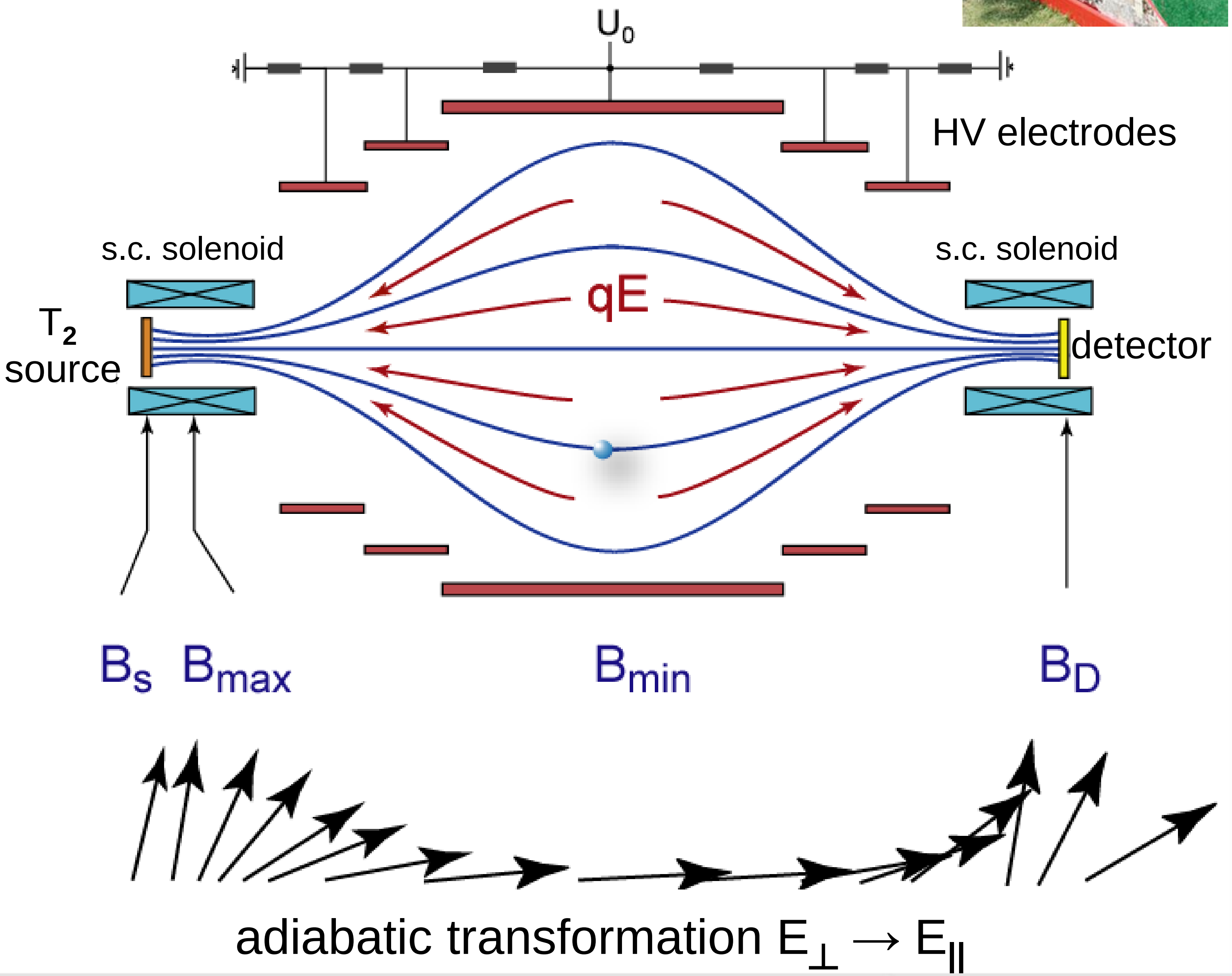
energy analysis by an electrostatic retarding field

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



KATRIN – design considerations

Karlsruhe Institute of Technology

experimental observable in ß-decay is square of ν-mass m_ν^2

aim: improve sensitivity for m_ν by 1 order of magnitude (2 eV → 0.2 eV)
requires improvement for m_ν^2 by 2 orders of magnitude (4 eV² → 0.04 eV²)

statistics

count rate at ß-endpoint falls off very steeply (~δE³), small background!

improvement of statistics (10³):

- stronger tritium source (factor 80) ⤷ larger analysing plane (Ø=10m)
- longer measuring period (~100 days → ~1000 days)

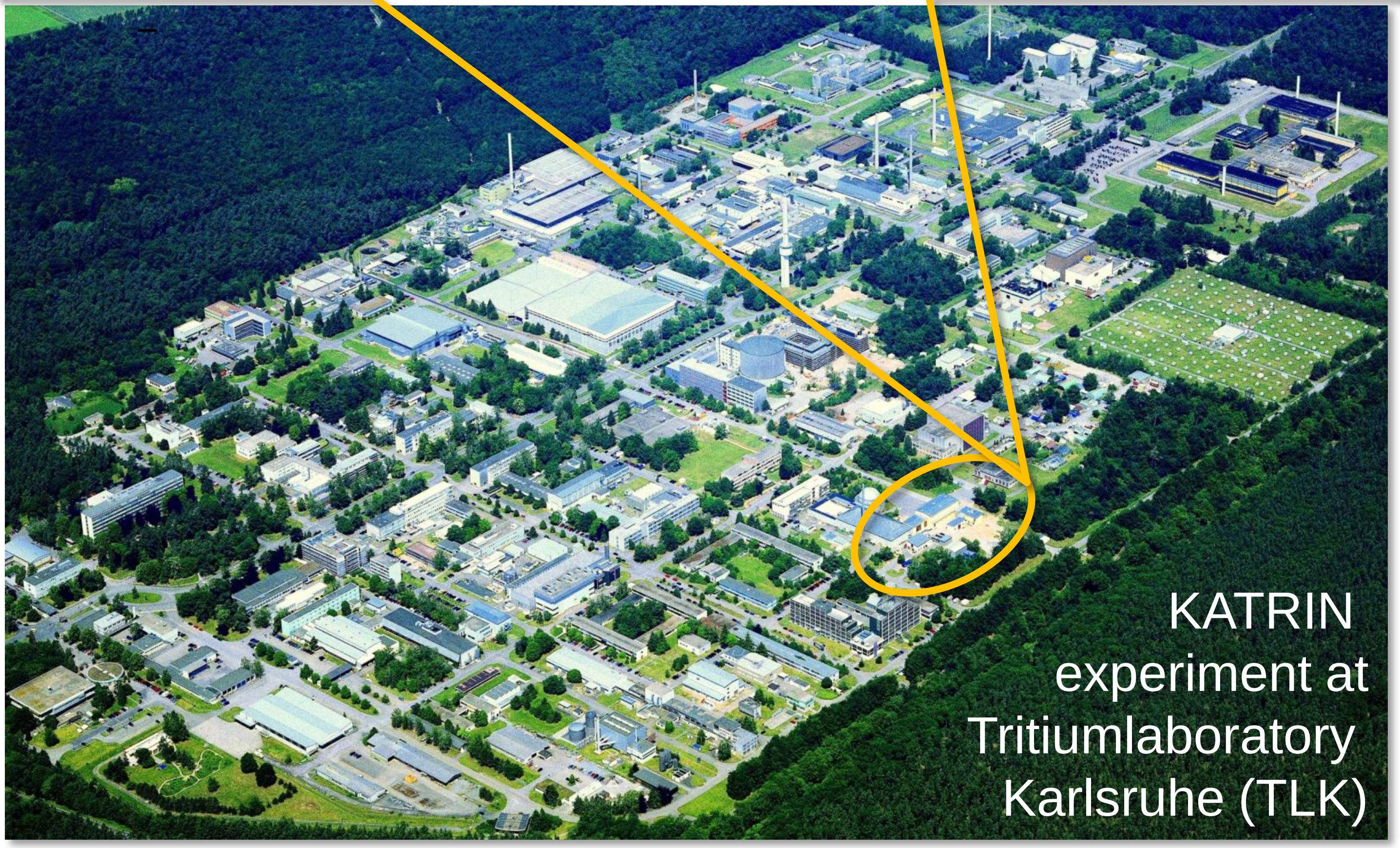
systematics

aim: systematic uncertainties ≡ statistical errors

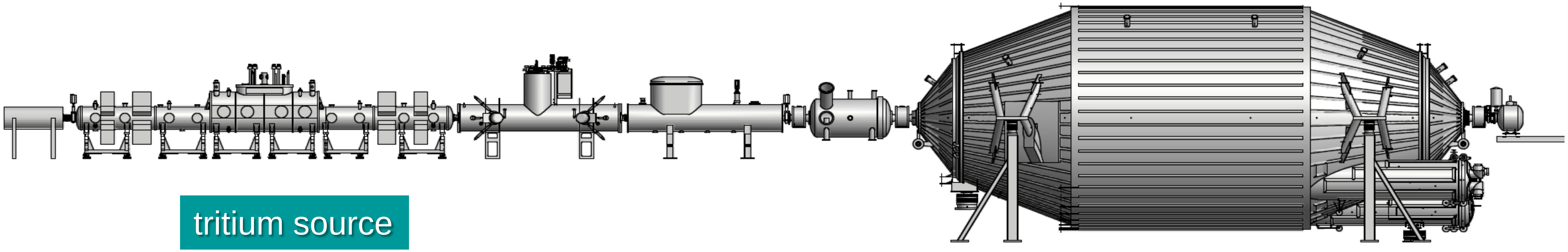
Improvement of systematics (0.1)

- improved energy resolution spectrometer with ΔE = 0.93 eV (factor 4)
- reduced systematic errors for energy losses in source, slow control, HV,…

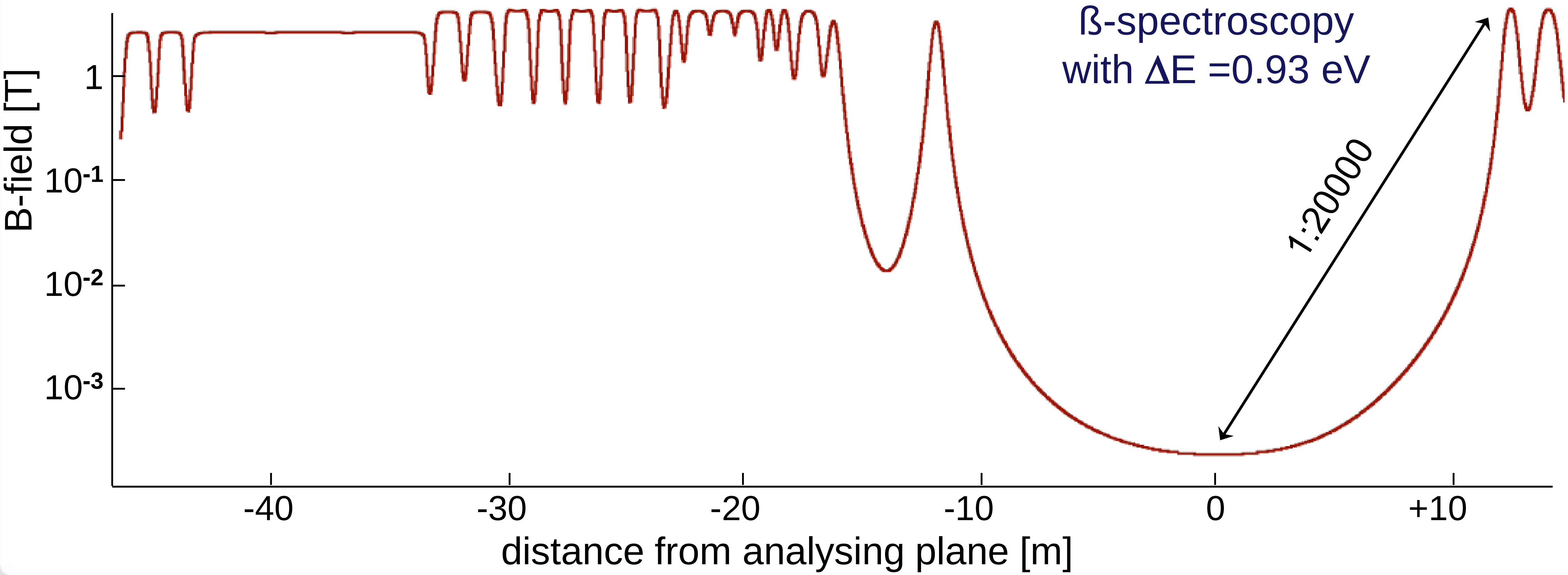
KATRIN experiment



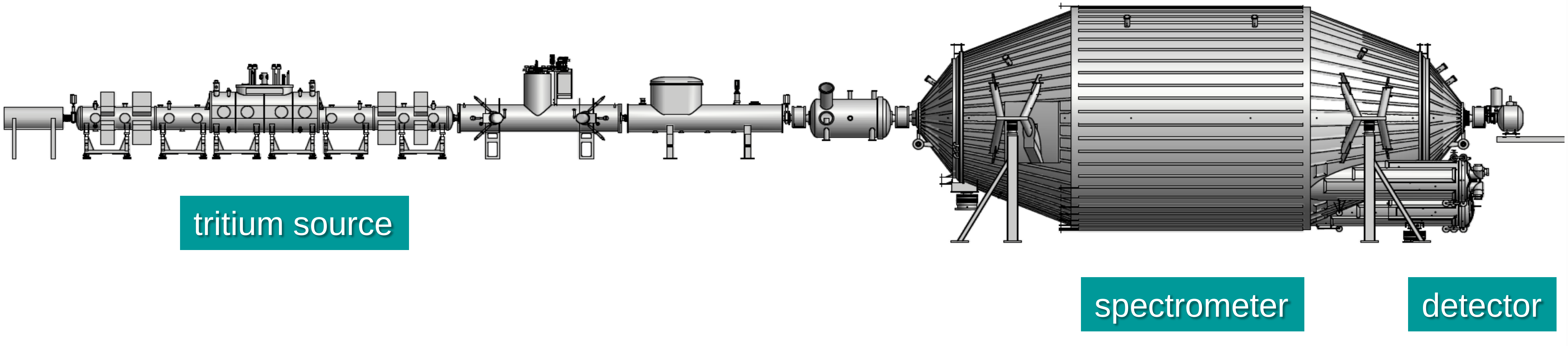
KATRIN – a MAC-E filter system

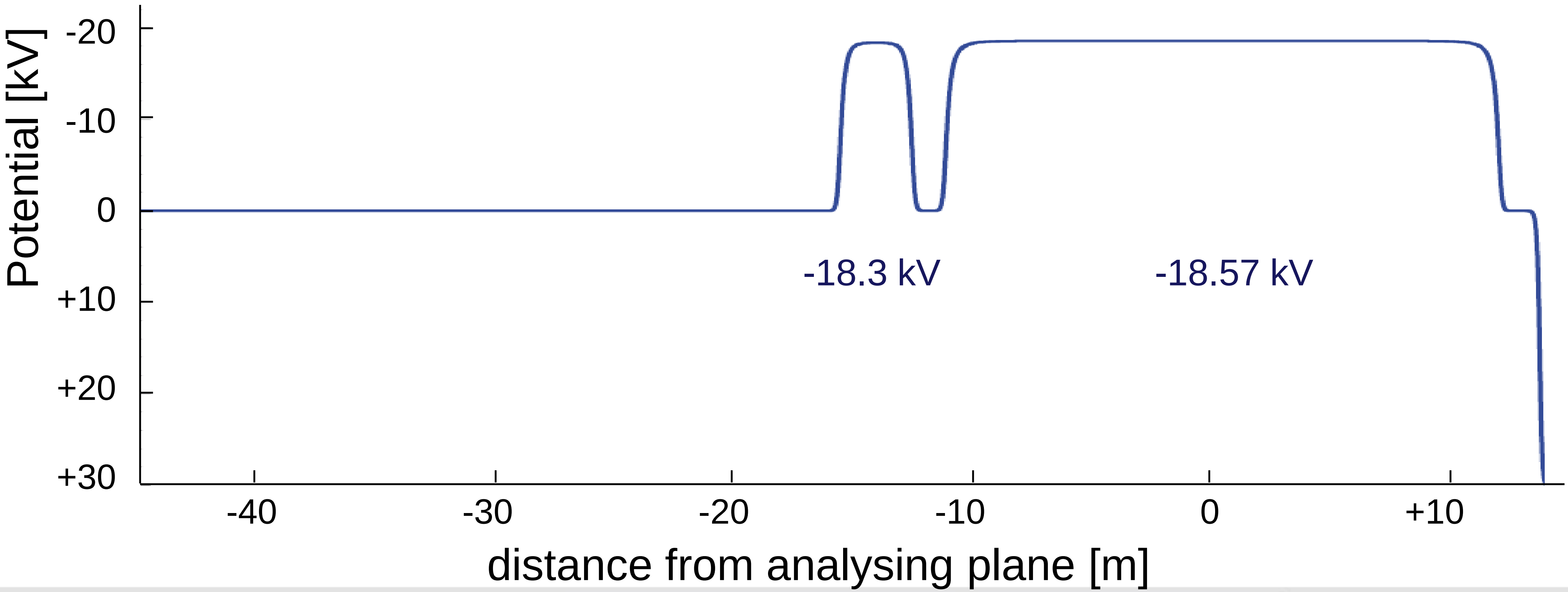


adiabatic particle transport over 70 m

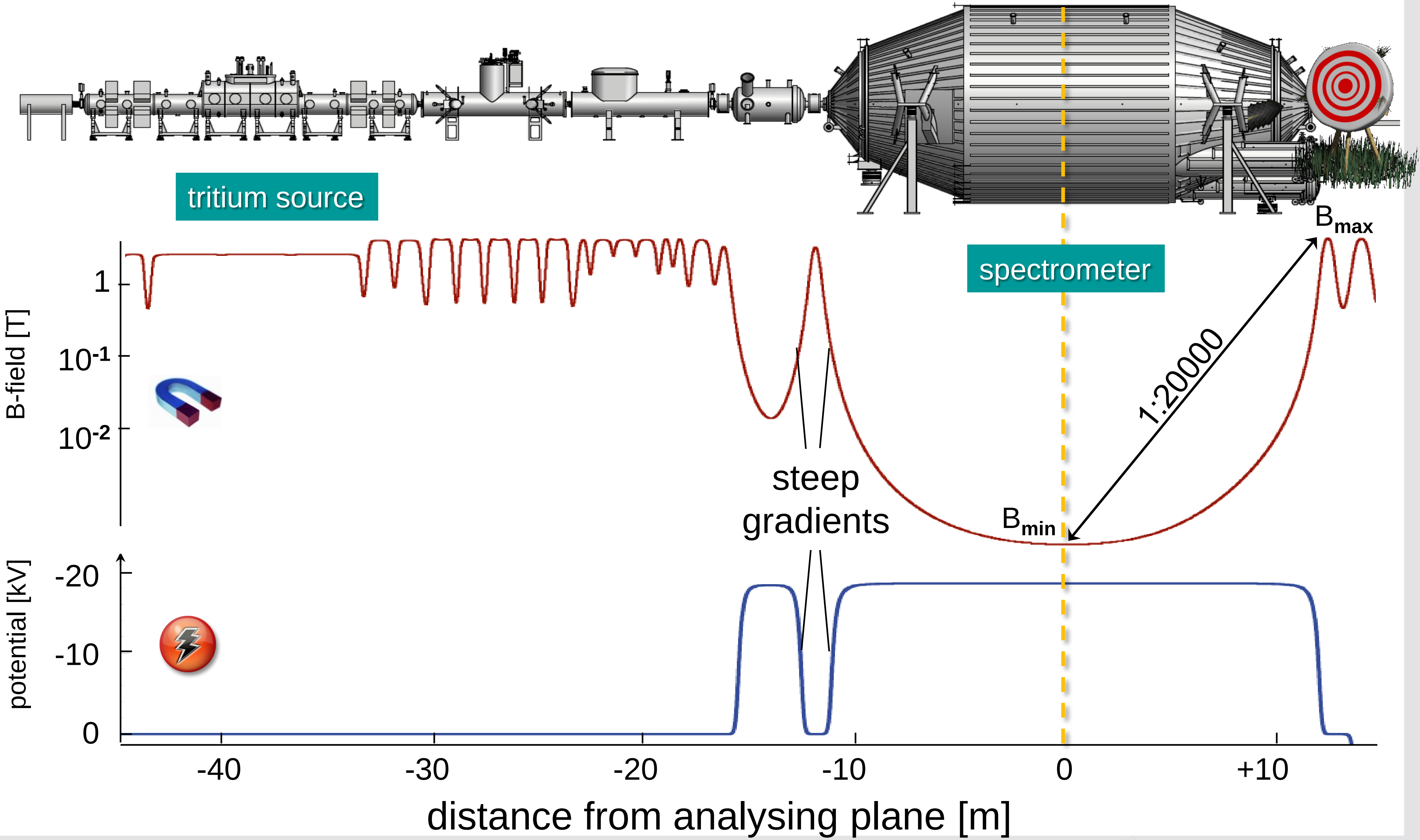


KATRIN – electrostatic potential (linear)

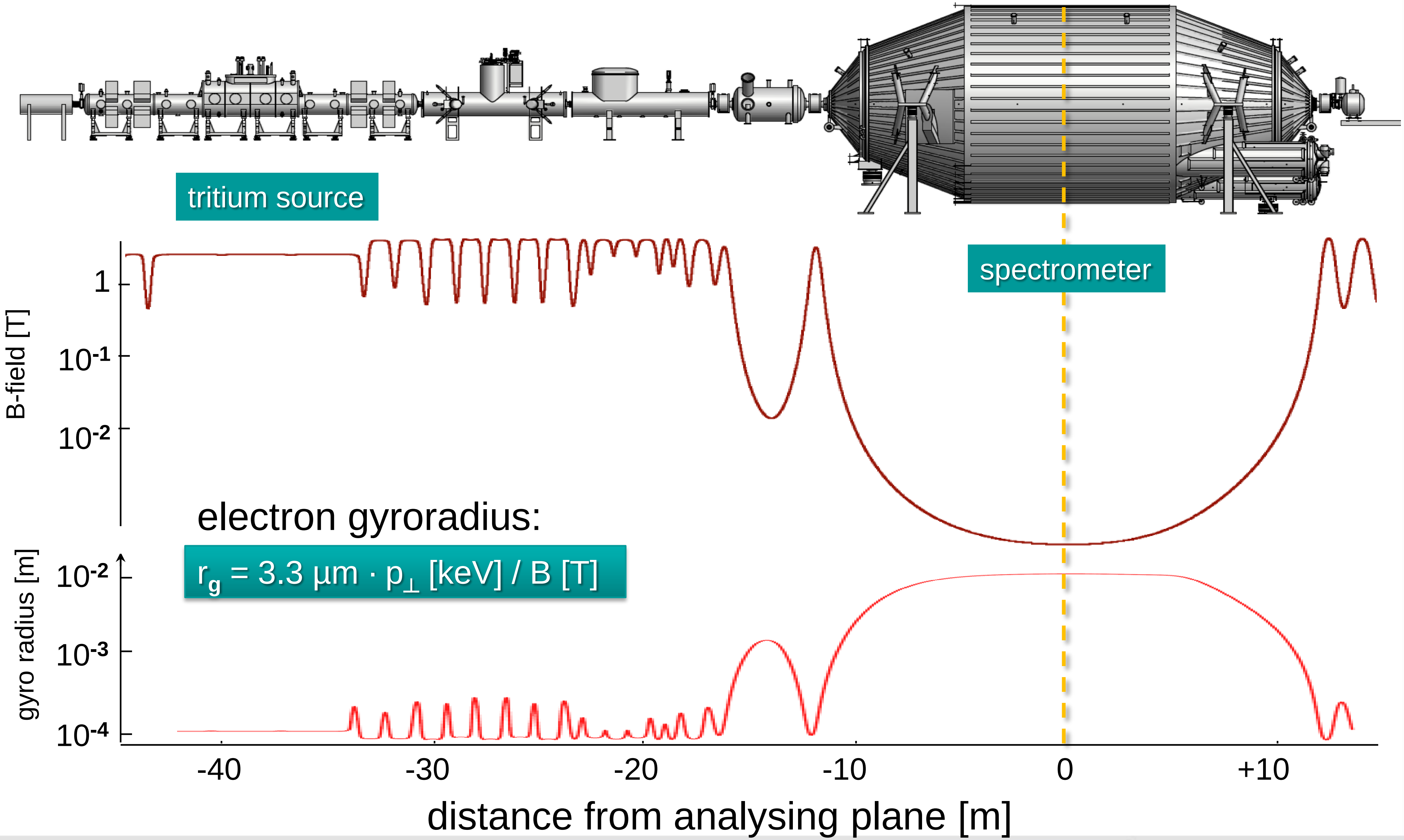




KATRIN – B-field & electrostatic potential

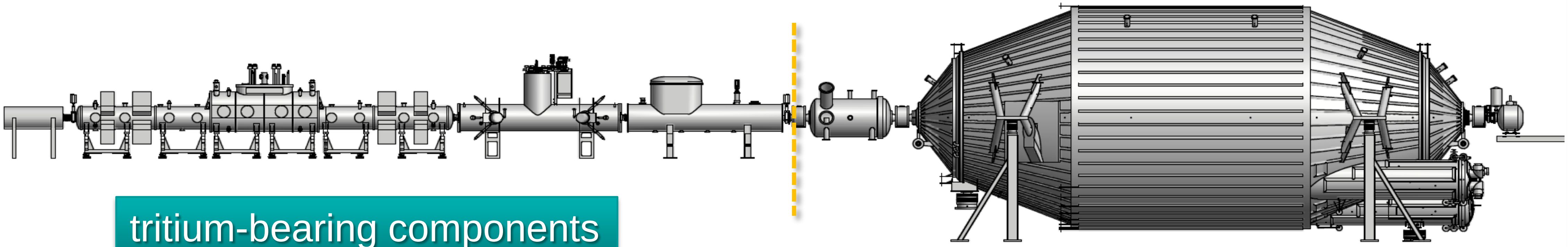


KATRIN – B-field & gyroradius



r_g = 3.3 µm · $p_\perp$ [keV] / B [T]

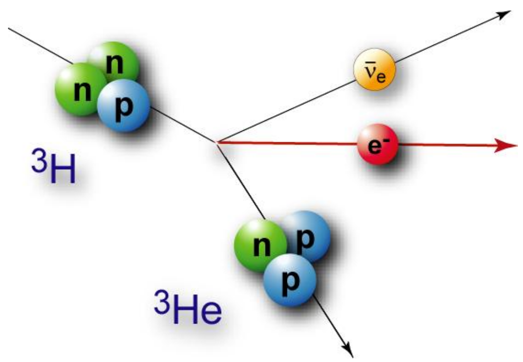
KATRIN experiment - overview

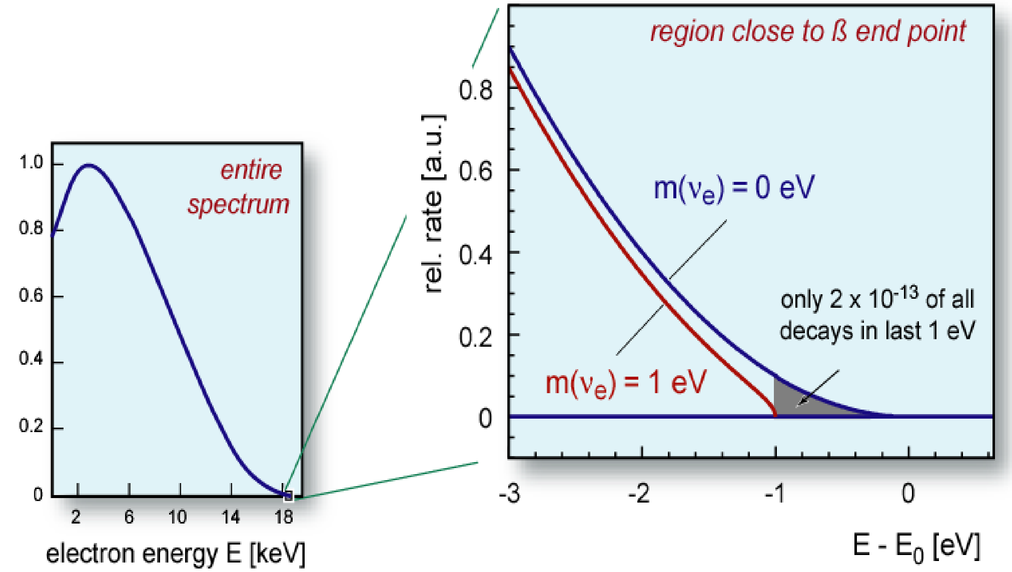


tritium-bearing components

electrostatic spectrometers & detector

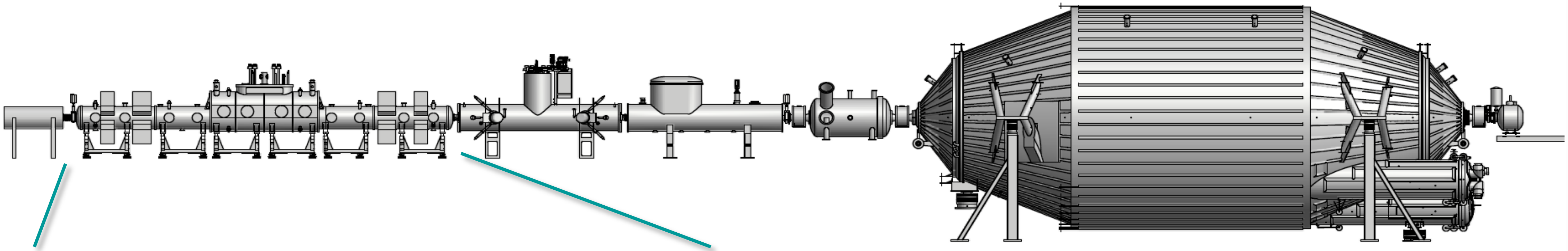
$^{3}H \rightarrow {}^{3}He + e^{-} + \bar{\nu}_e$





- 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

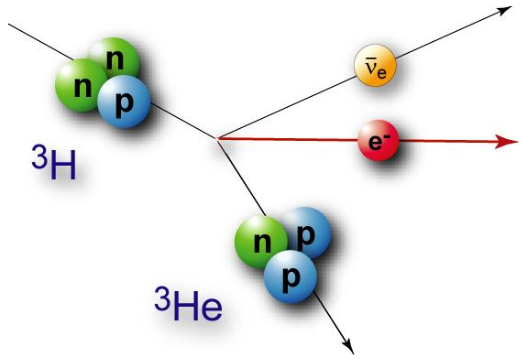
KATRIN – closed tritium cycle & TLK

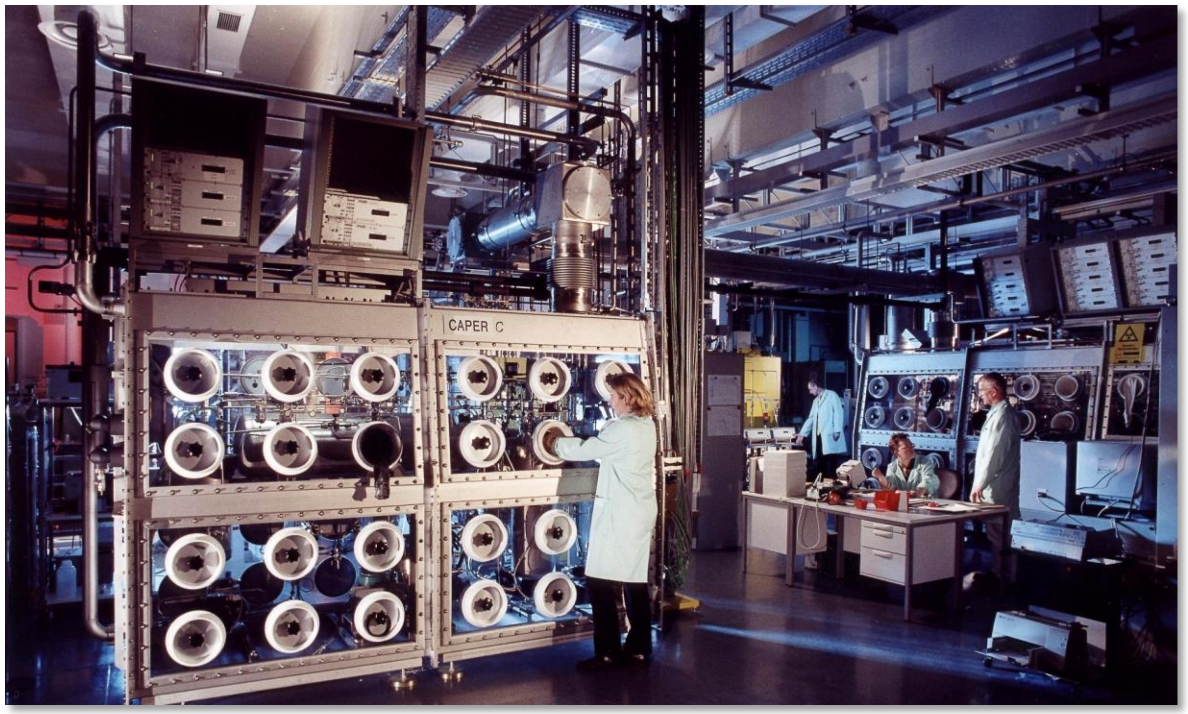


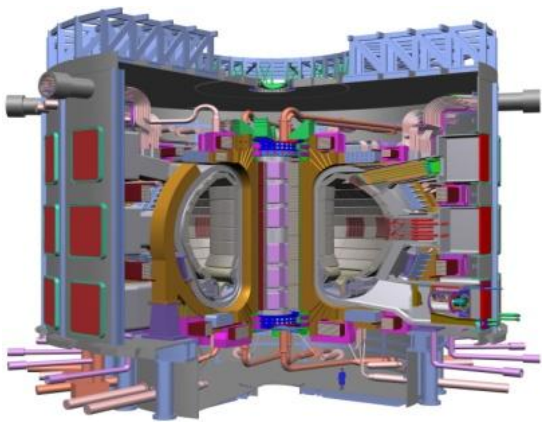
KATRIN tritium throughput per year equivalent to fusion facility ITER

KATRIN closed cycle operational in 2012

⇔ first D-T operation of ITER in 2026





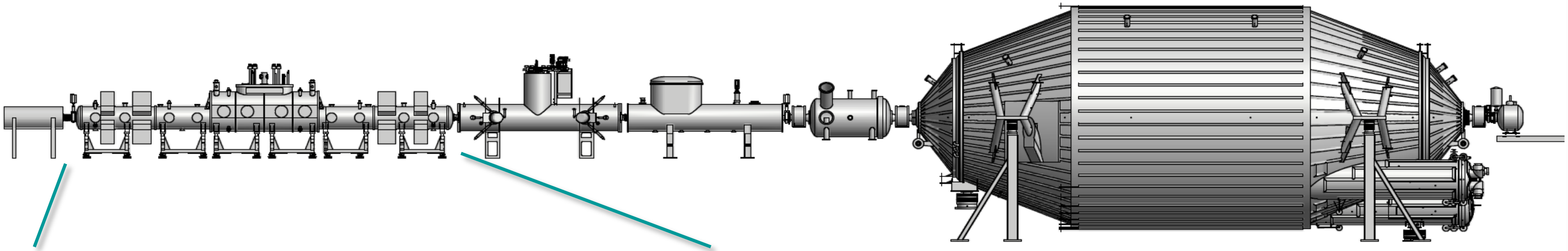


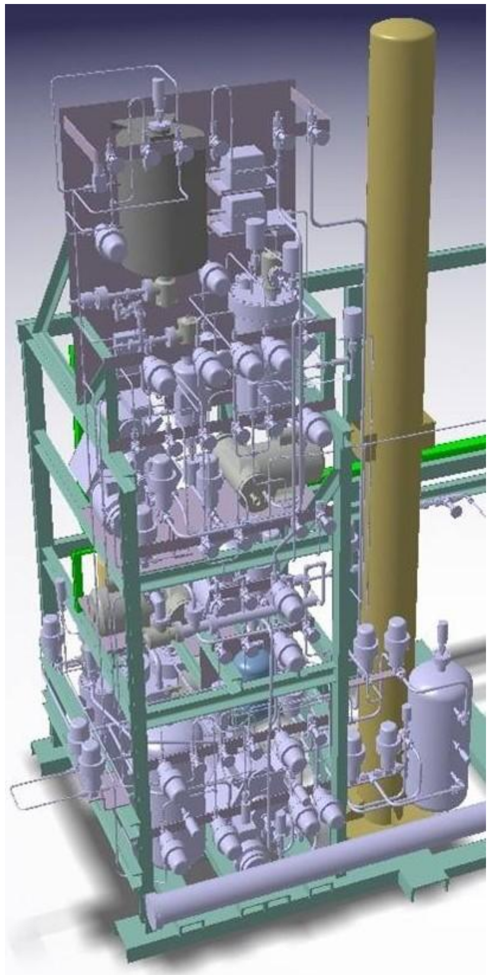
TLK – Tritium Laboratory Karlsruhe

a unique research facility in Europe

licensed for storage of 20 g tritium

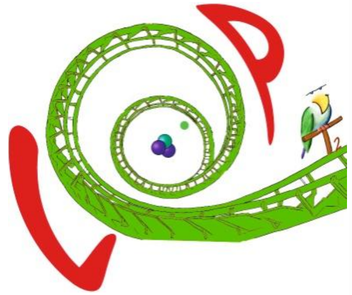
KATRIN – closed tritium cycle

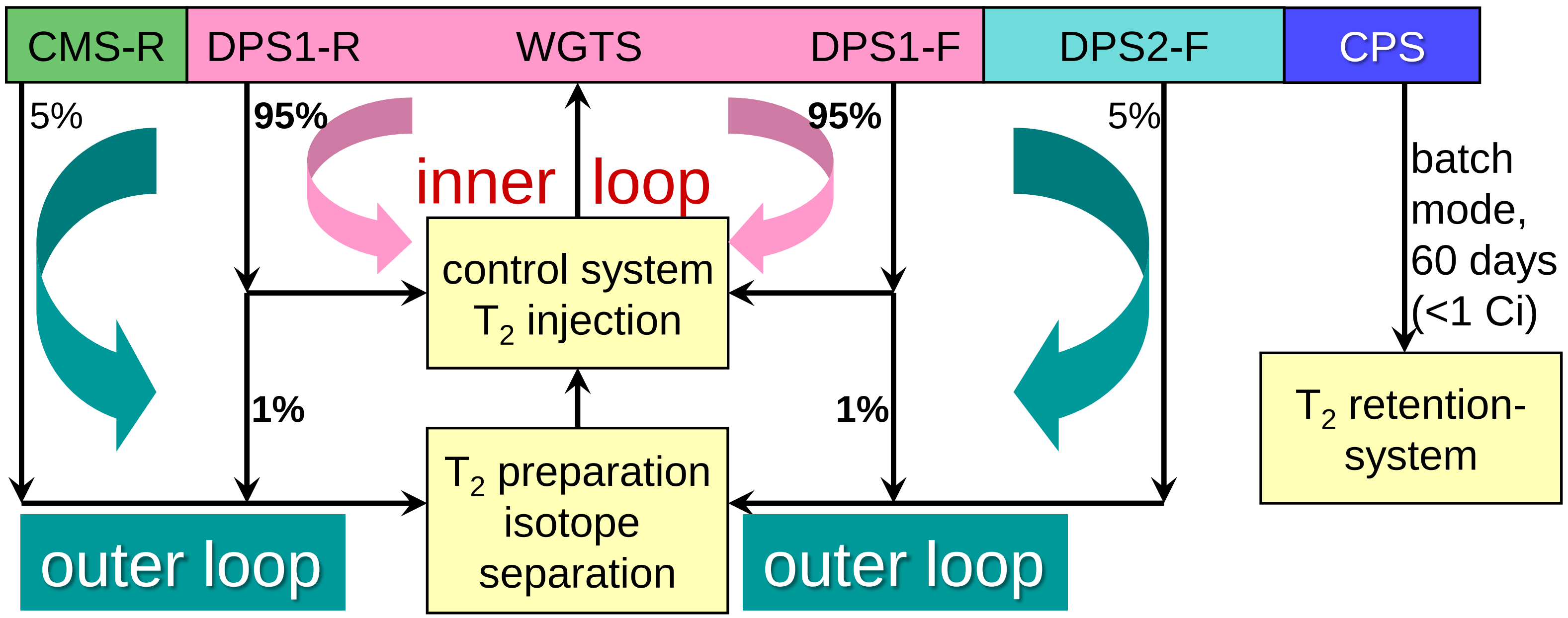




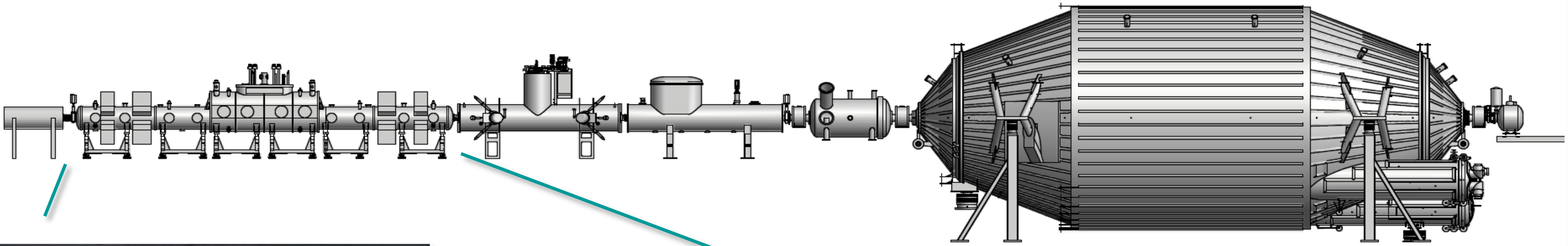
KATRIN tritium loop system

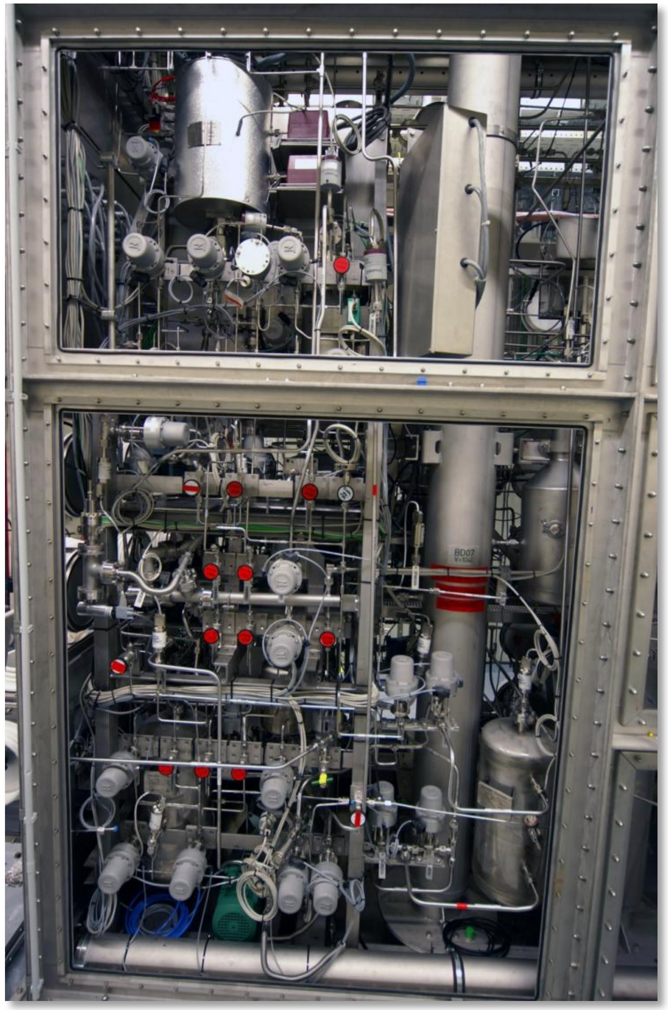
27 pumps, 109 valves, 62 sensors,
6 buffer vessels, 2 permeators

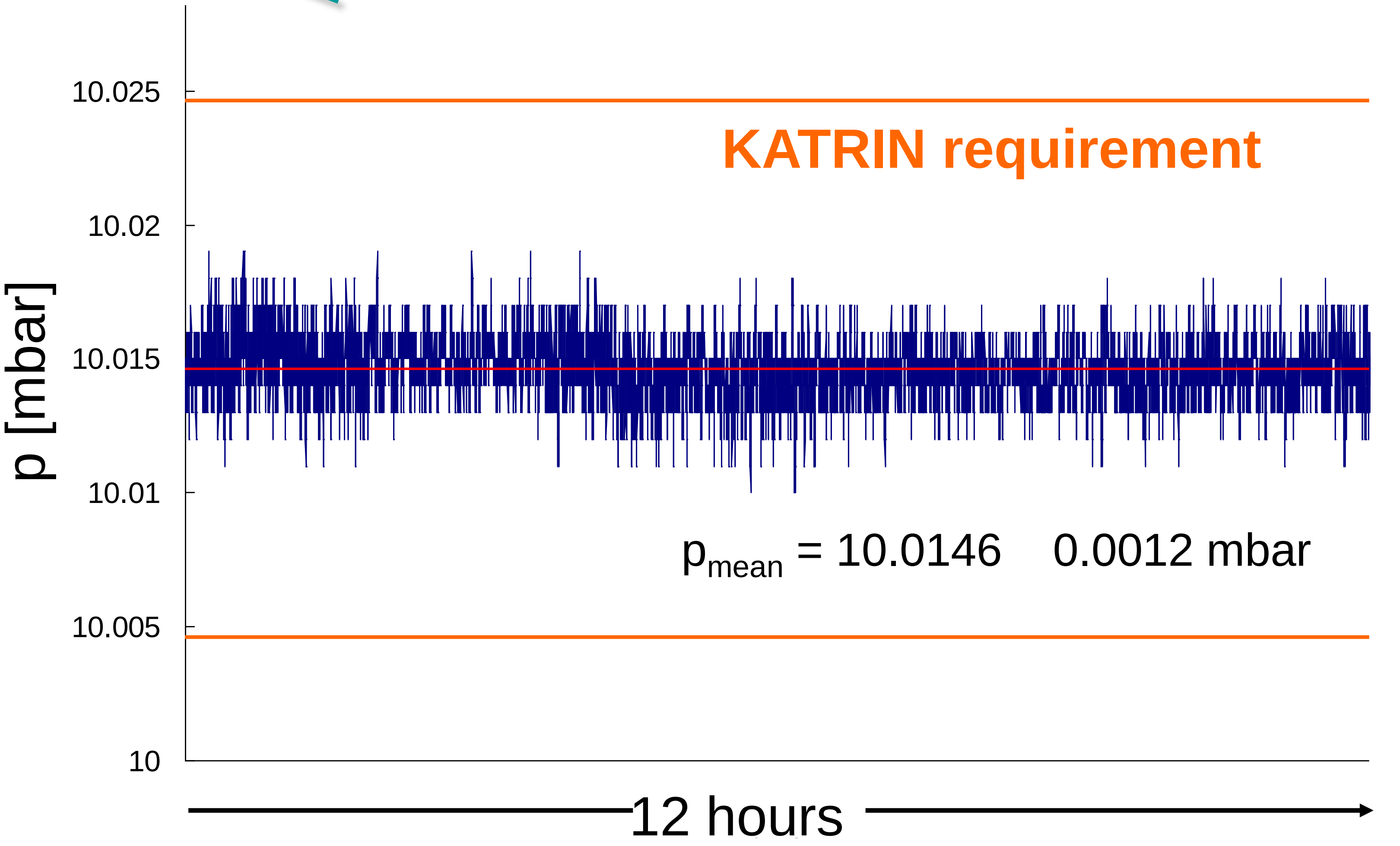




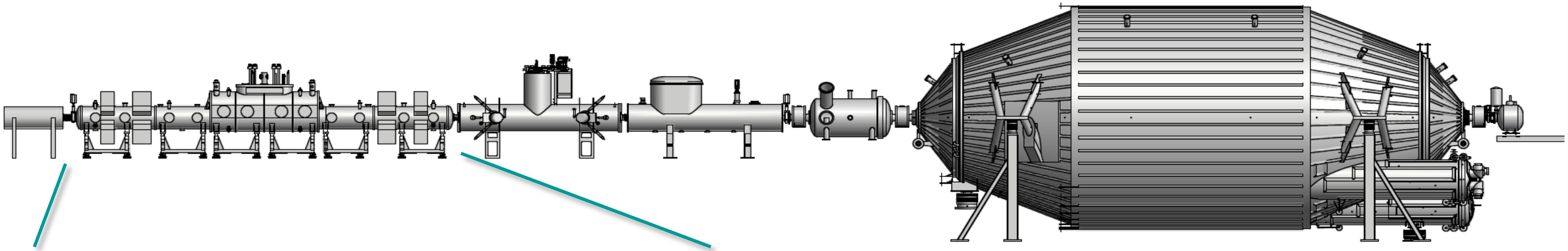
KATRIN – closed tritium cycle



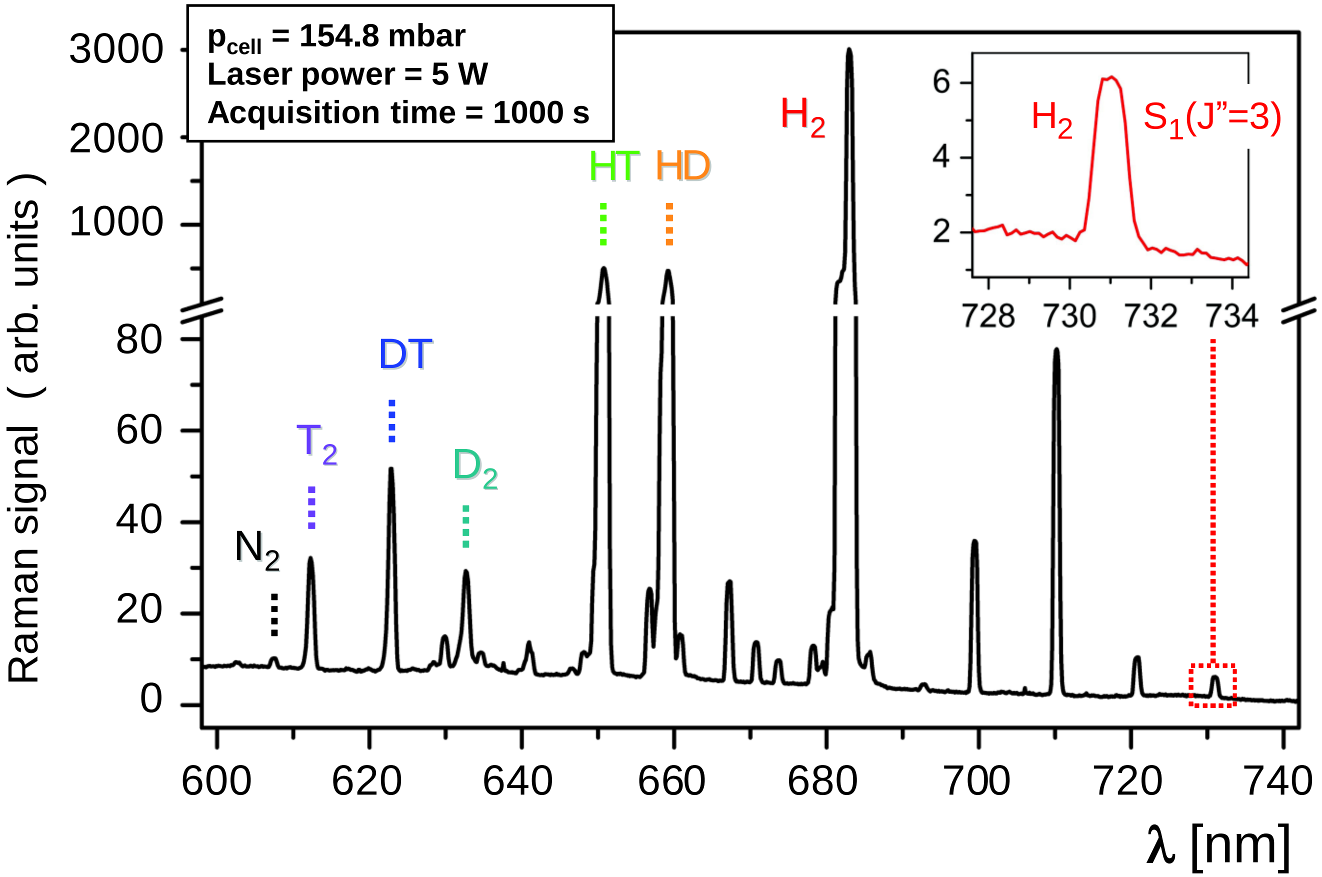




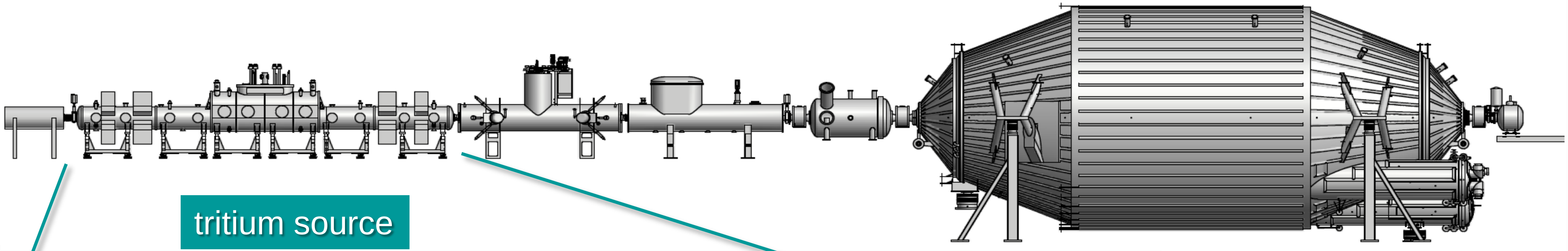
KATRIN – Laser Raman Spectroscopy



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

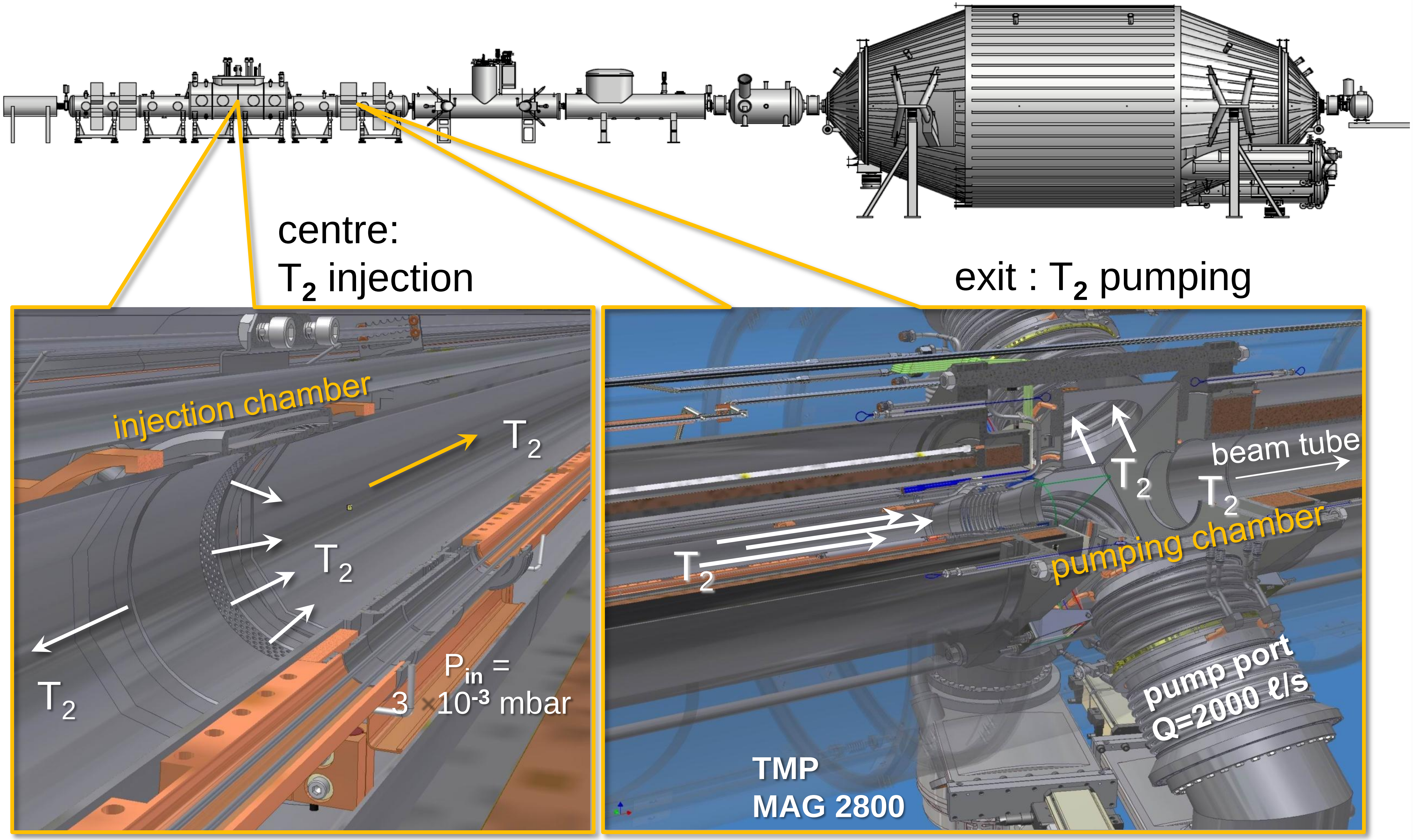


WGTS – windowless gaseous source

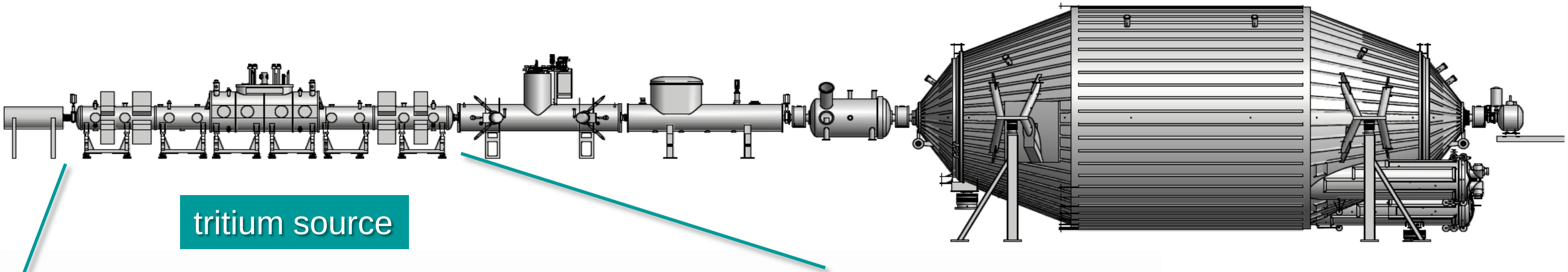


WGTS	design value	precision
luminosity	$1.7 \quad 10^{11}$ Bq	
injection rate	$5 \quad 10^{19}$ mol/s	±0.1 %
column density ρd	$5 \quad 10^{17}$ mol/cm^2	±0.1 %
tritium purity	> 95%	±0.1 %
magnetic field	3.6 T	± 2%

KATRIN – windowless gaseous source

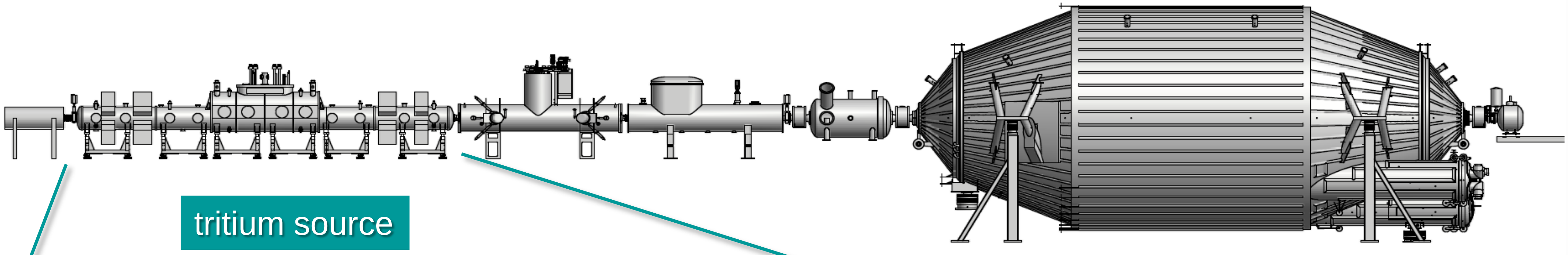


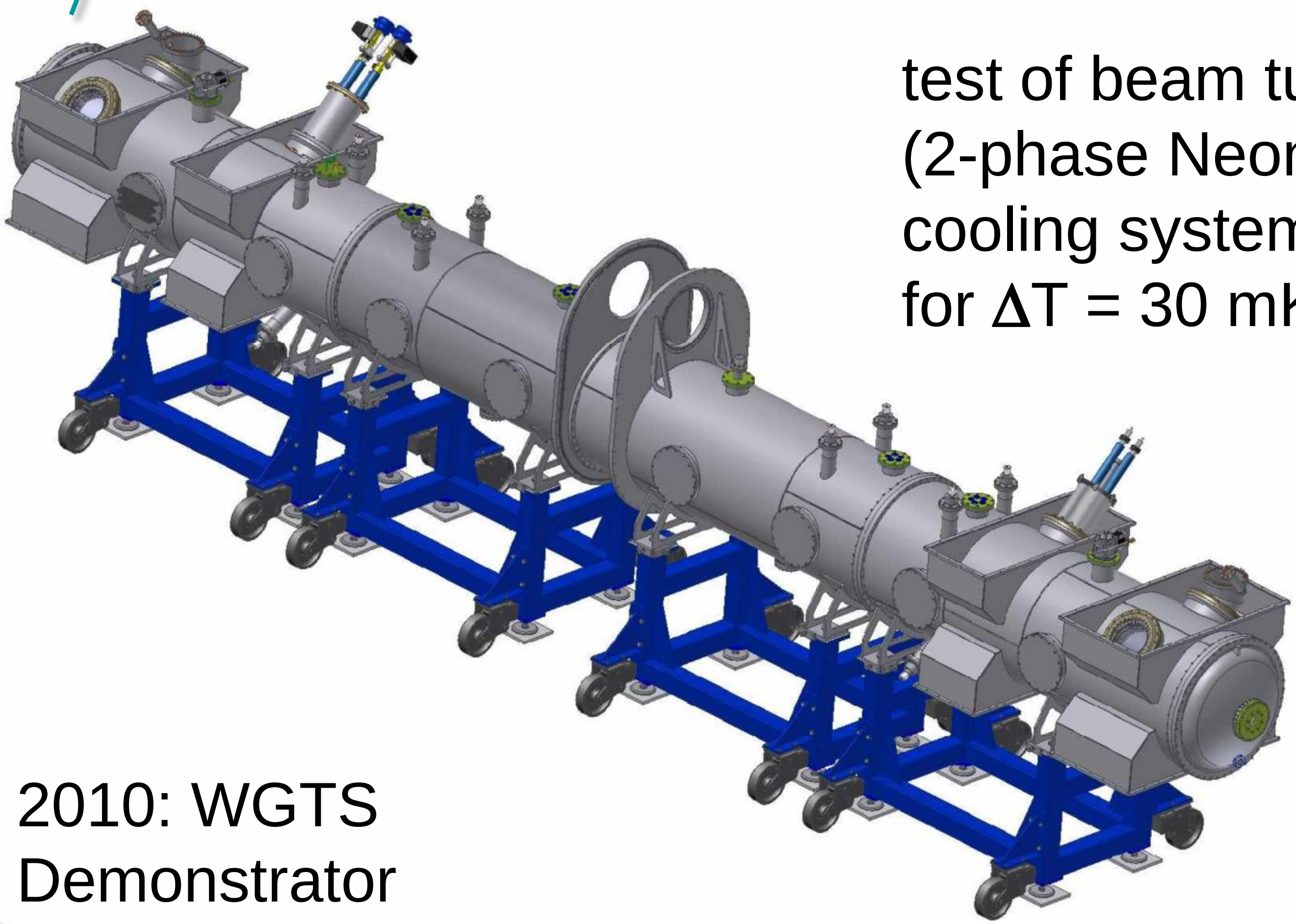
WGTS – windowless gaseous source



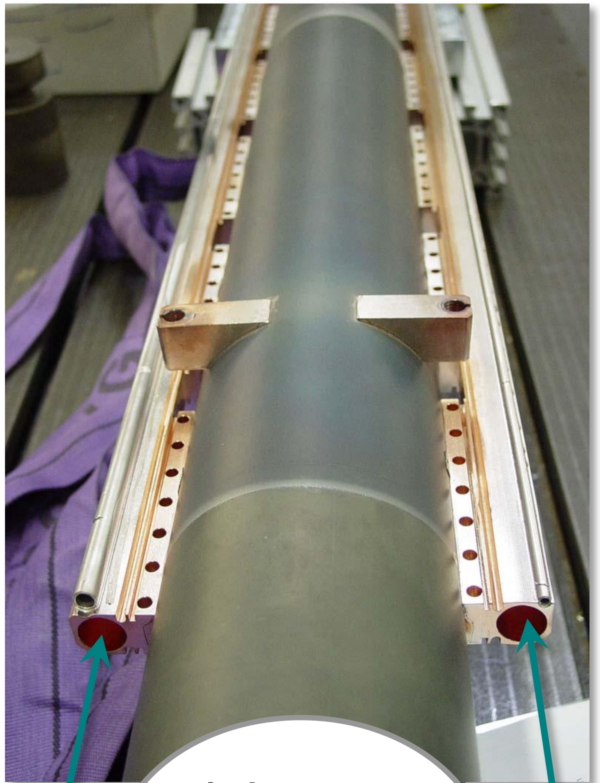
12 cryogenic circuits
6 cryogenic fluids
- instrumentation:
~ 500 sensors for temperature (4 – 600 K), B-field, pressure, gas flow, liquid levels

WGTS – windowless gaseous source



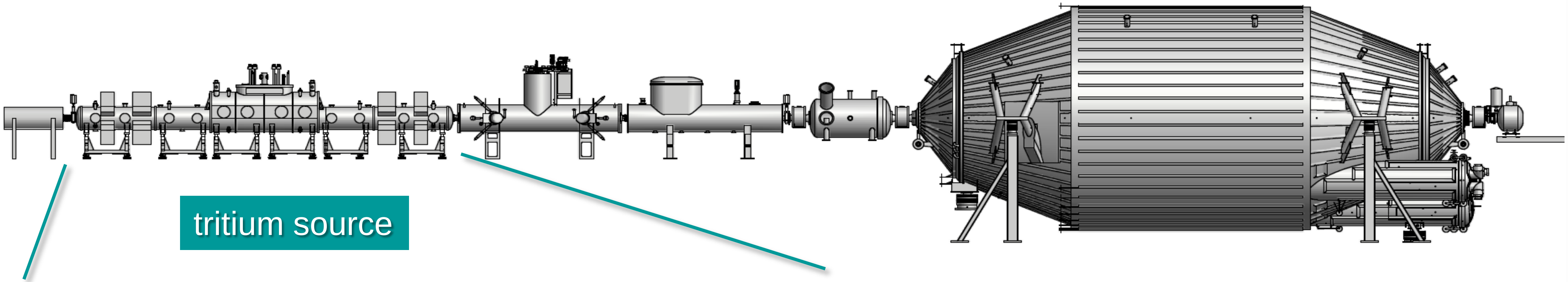


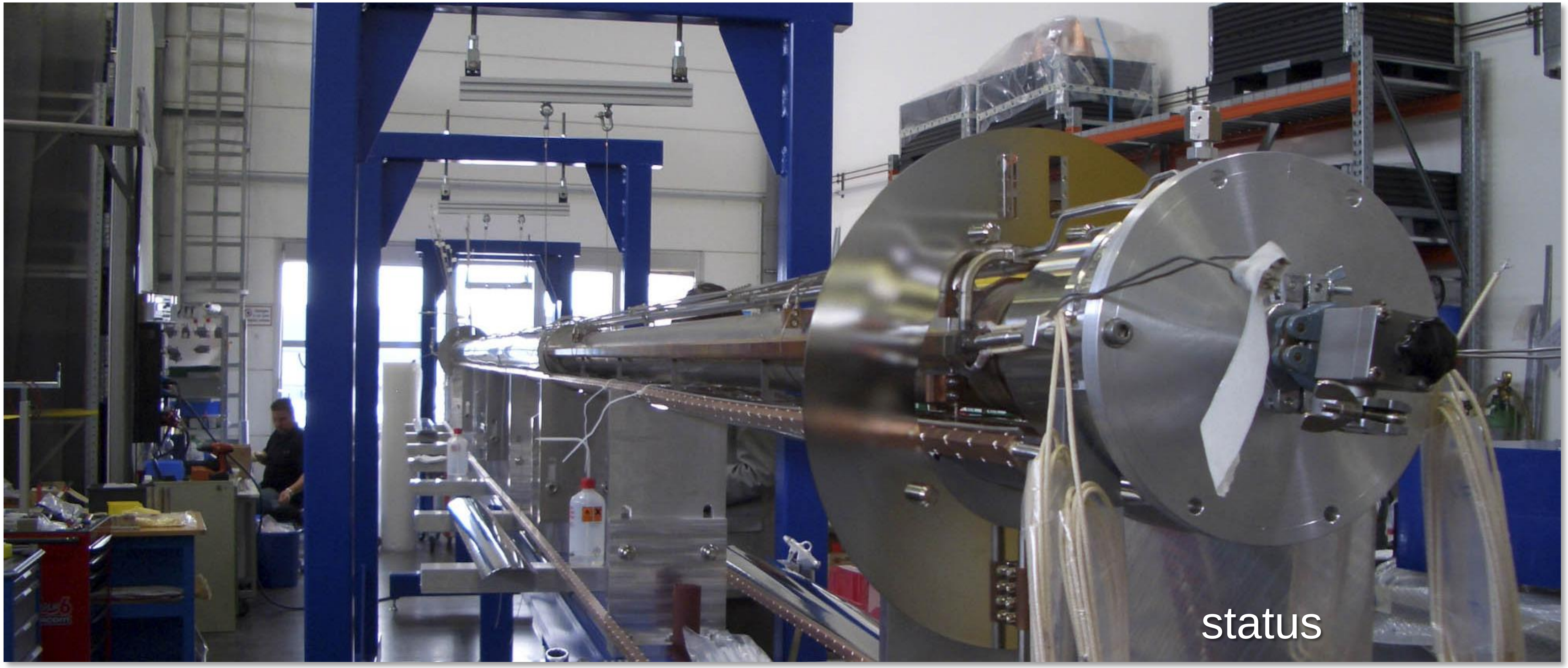
test of beam tube
(2-phase Neon)
cooling system
for ΔT = 30 mK



2010: WGTS Demonstrator

WGTS – windowless gaseous source



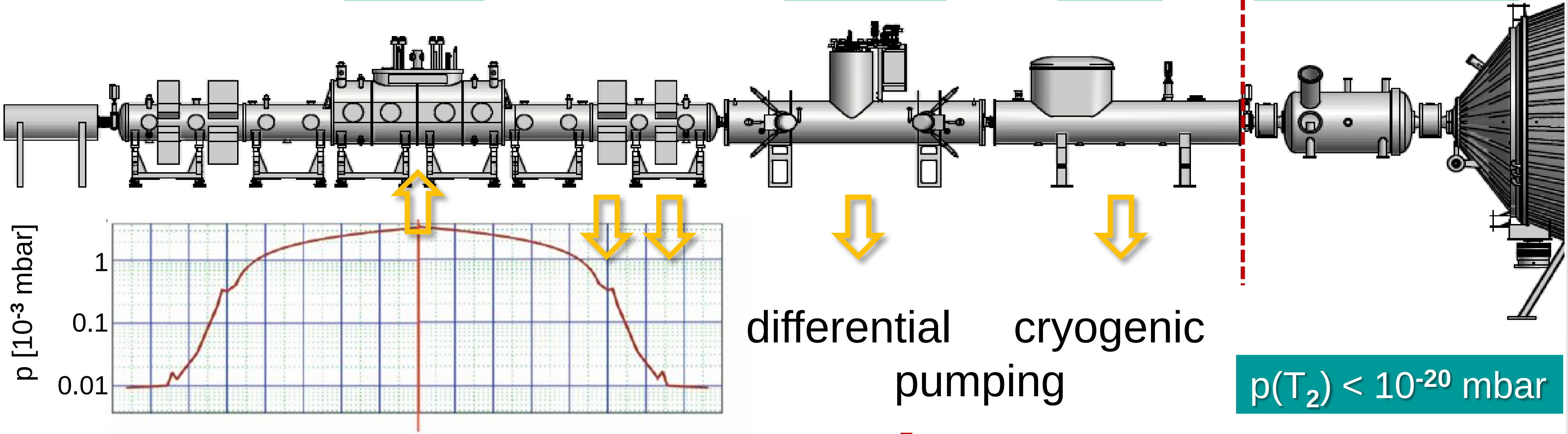


KATRIN – tritium retention

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



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

injection

injection rate = 1.8 mbar ℓ / s

R>10^7

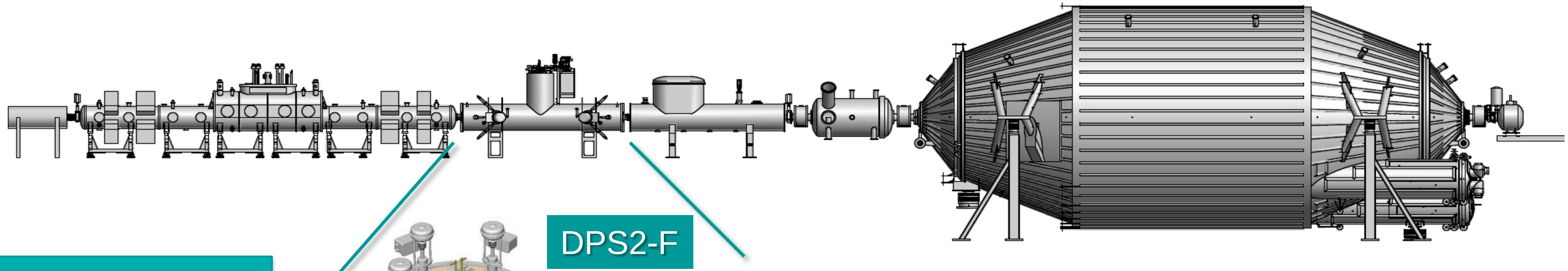
10^{-7} mbar ℓ/s

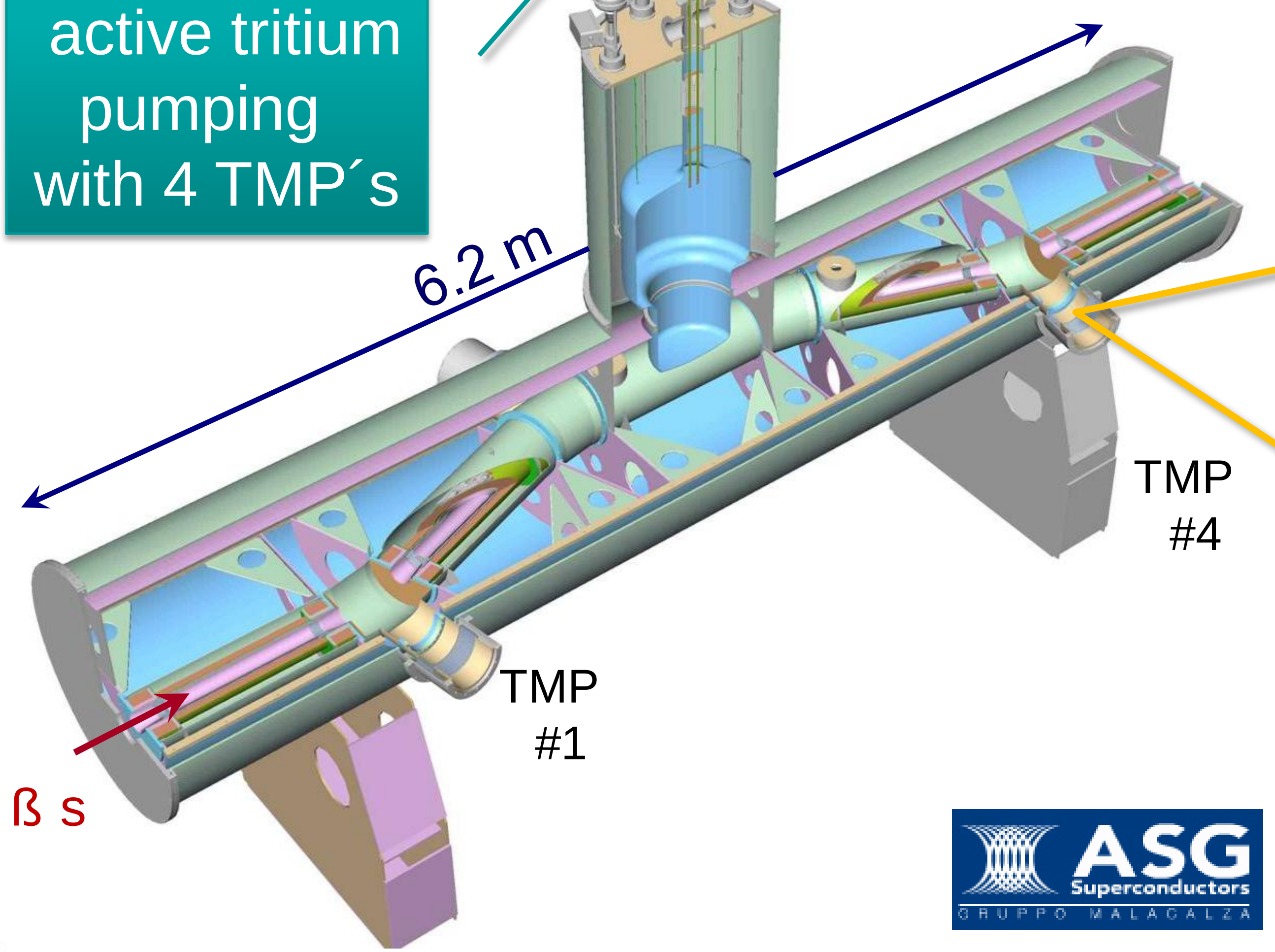
R>10^7

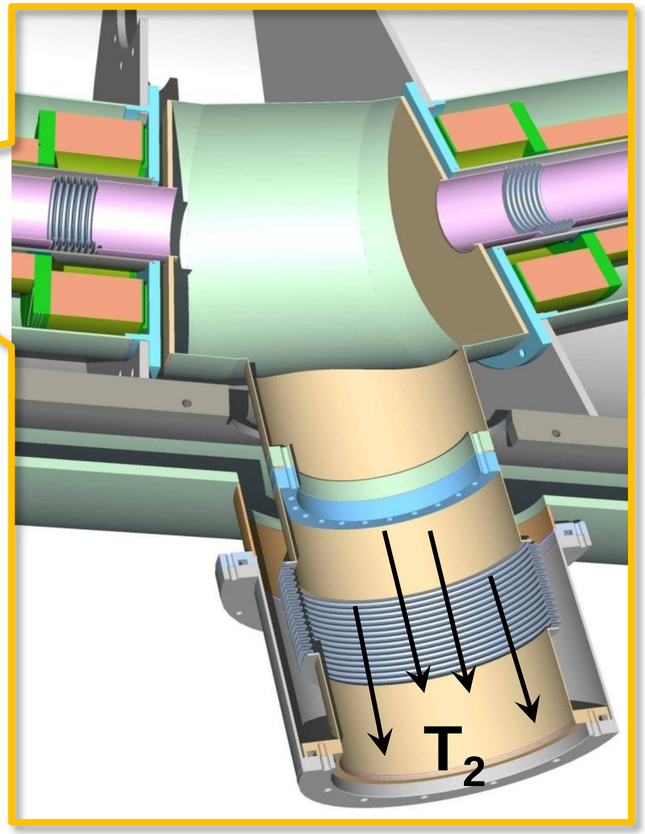
10^{-14} mbar ℓ/s

differential pumping section DPS2-F

active tritium pumping with 4 TMP´s

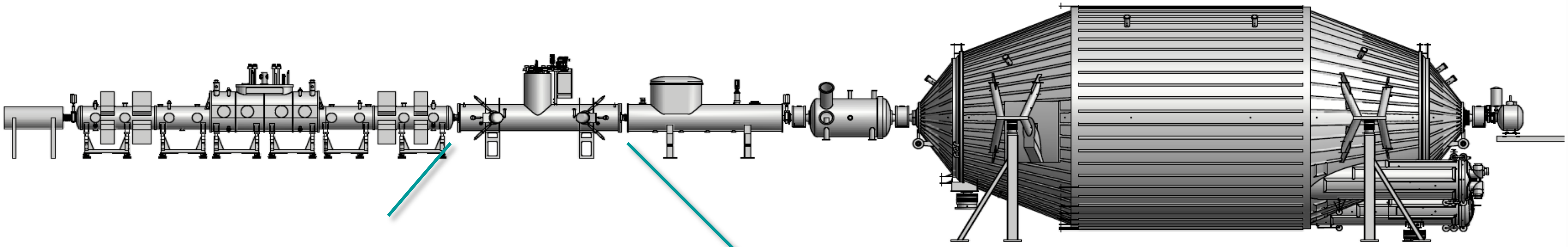


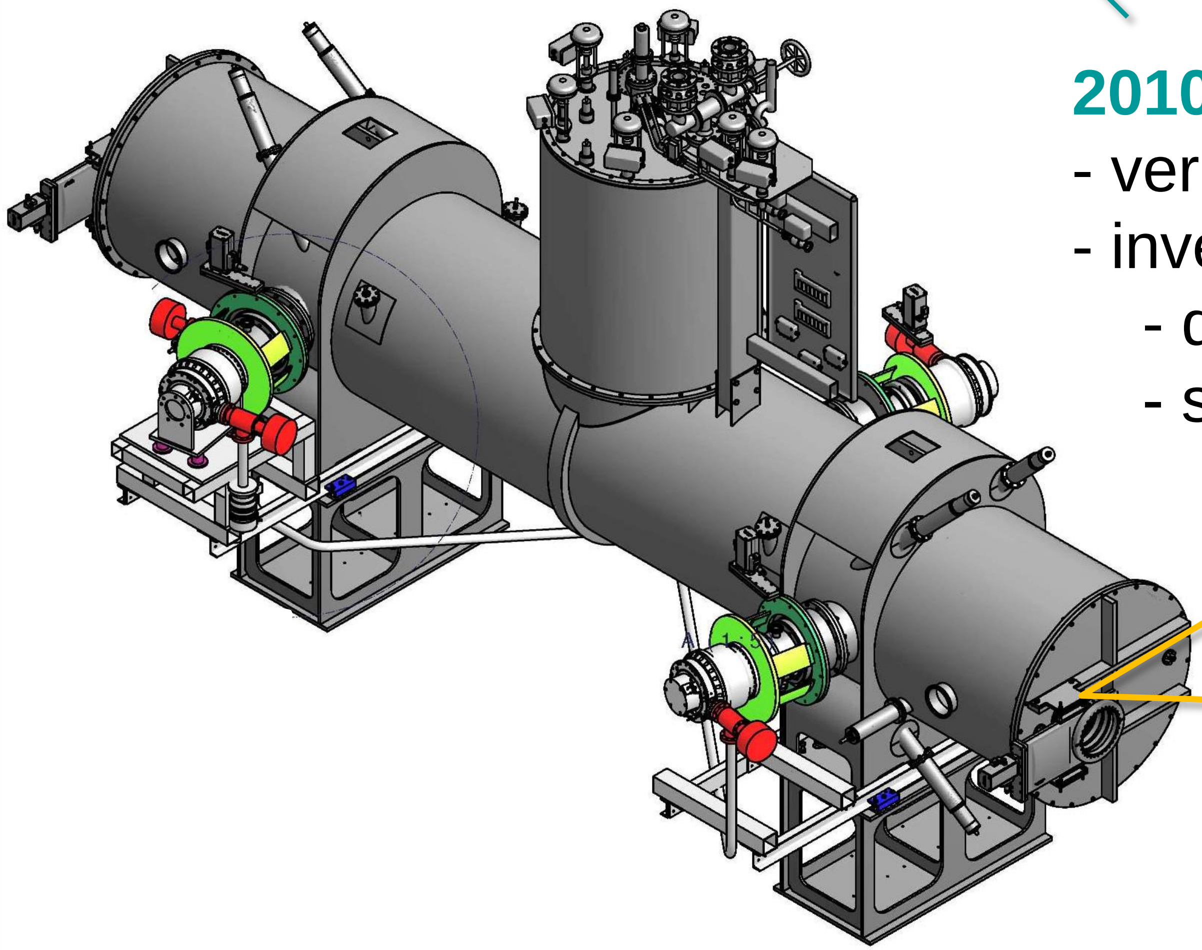





July 14, 2009:
DPS2-F cryostat has arrived
at KIT campus north
DETECTOR SIDE
KIT

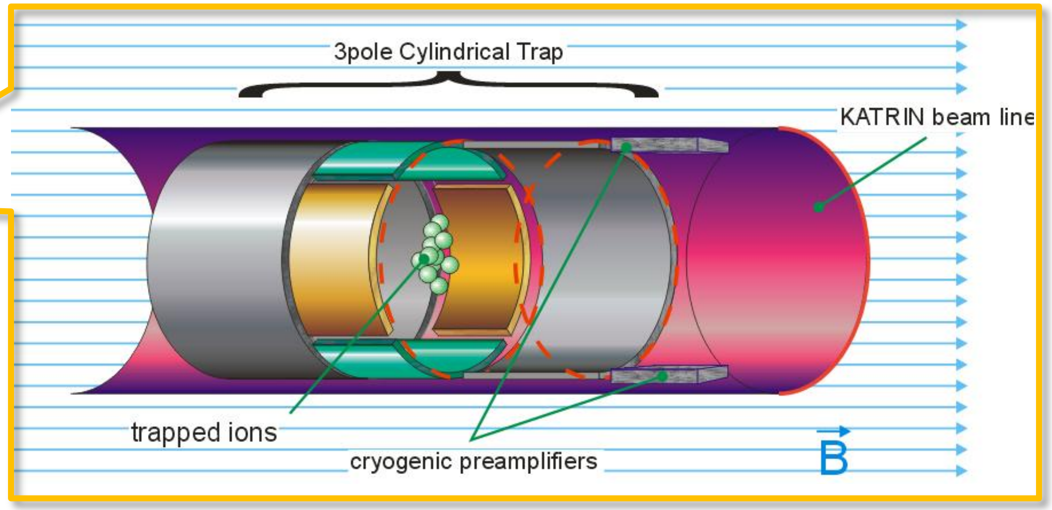
differential pumping section DPS2-F



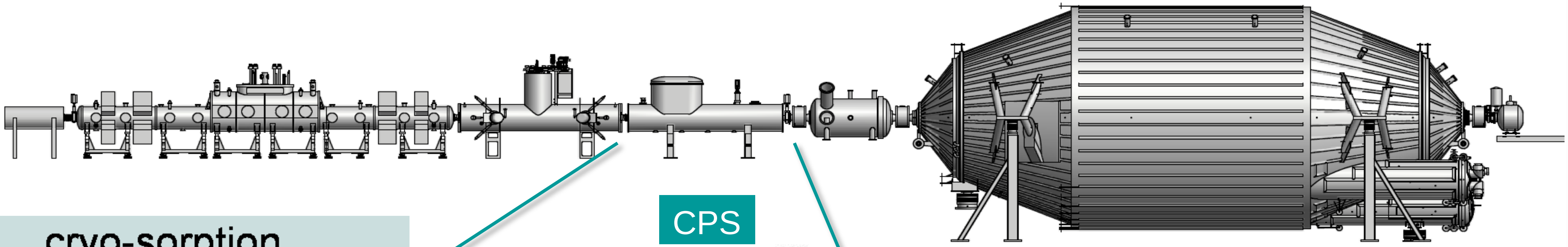


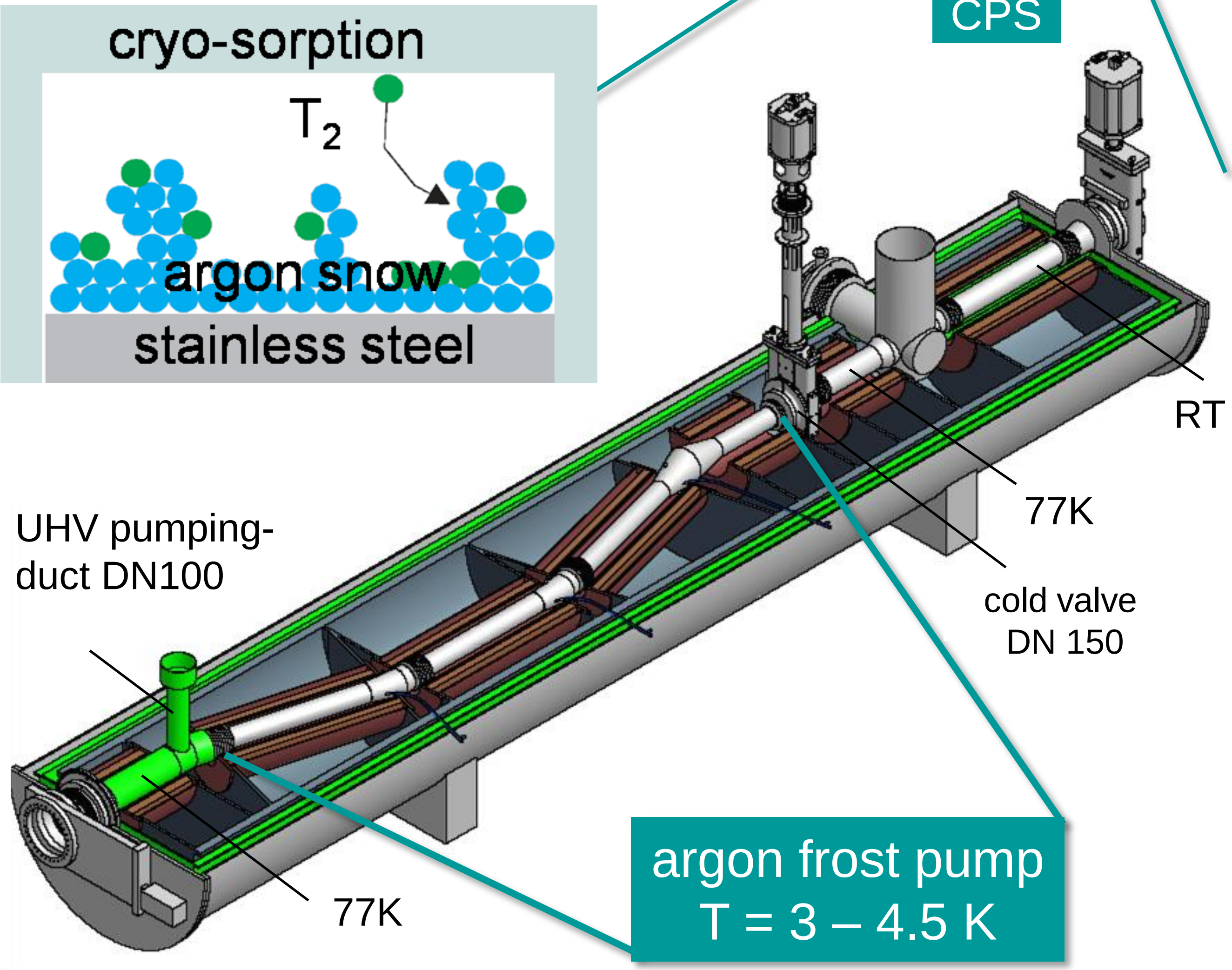
2010 DPS2-F experimental programme

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

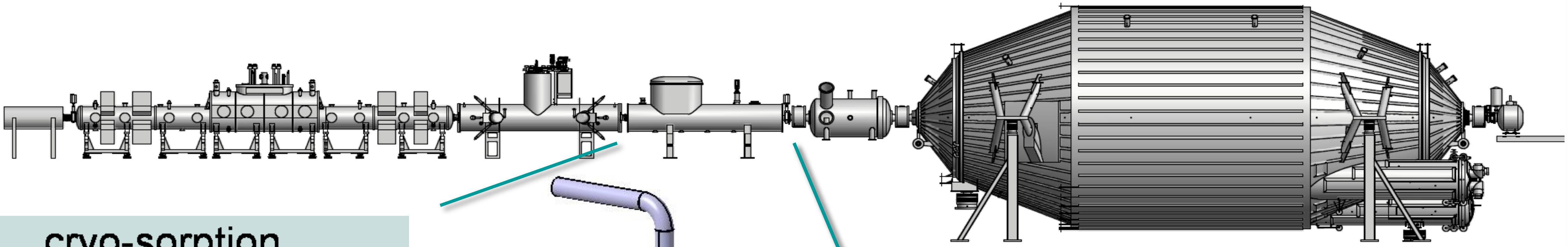
method: cryo-sorption on condensing Ar-frost

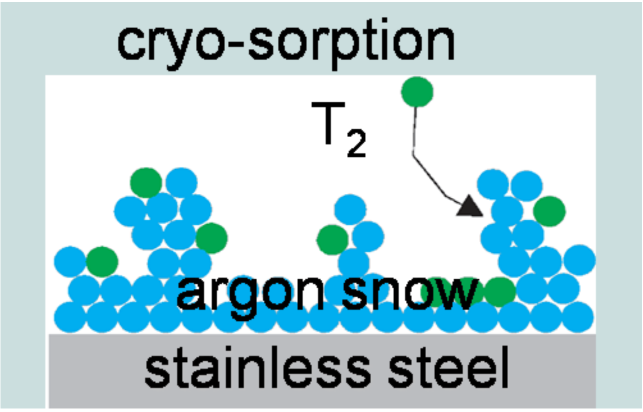
T_2-rate: <1 Ci T_2 in 60 days
= 1 KATRIN run

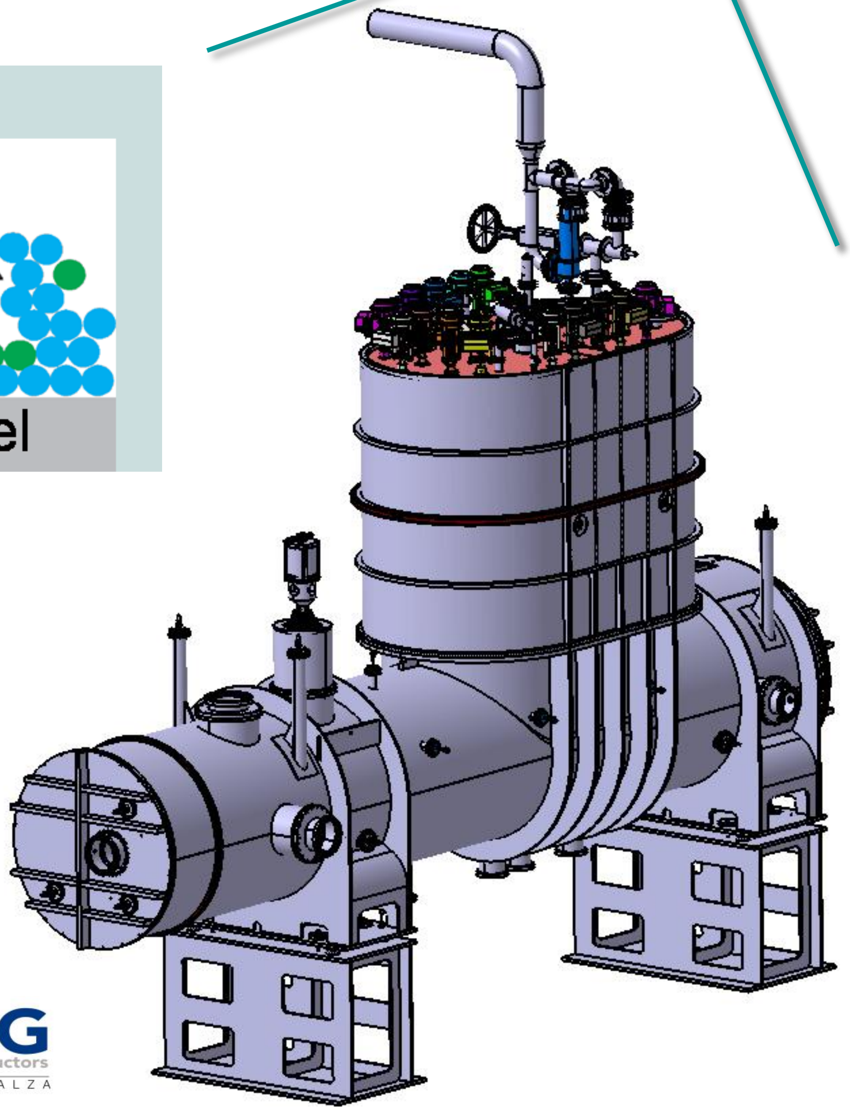
(regeneration with warm He-gas)

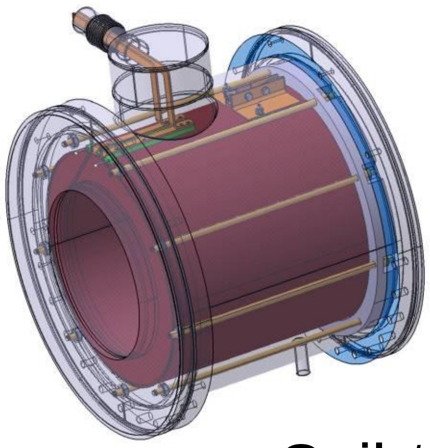
presently being manufactured by ASG

cryogenic pumping section CPS



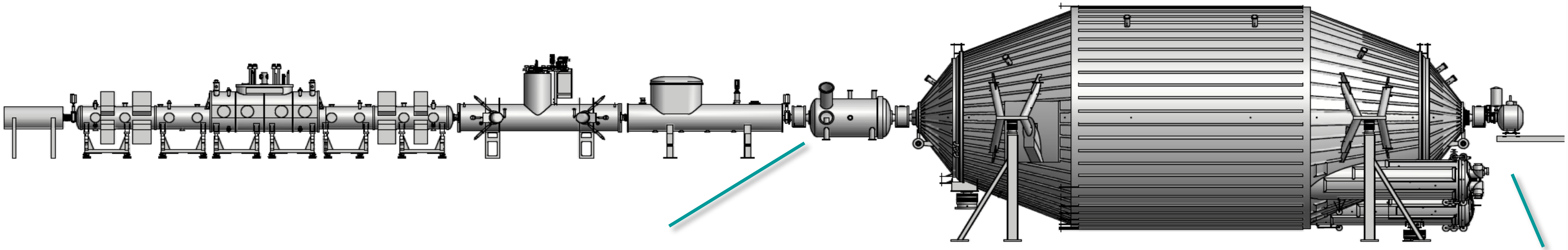






Coil #1

electrostatic spectrometers



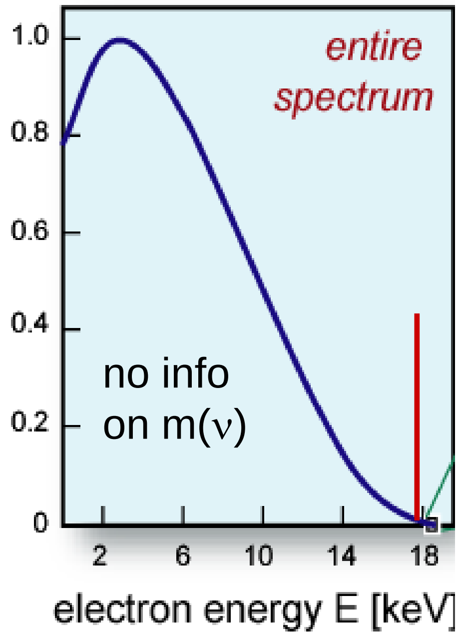
pre-filter

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

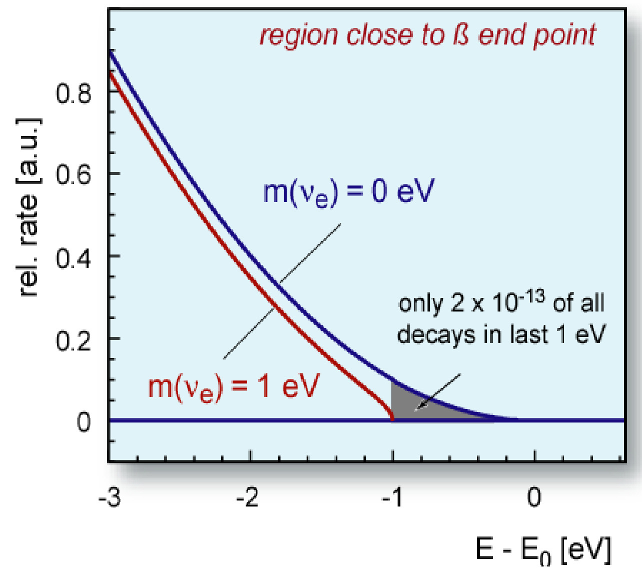


precision filter - scanning

variable retarding potential

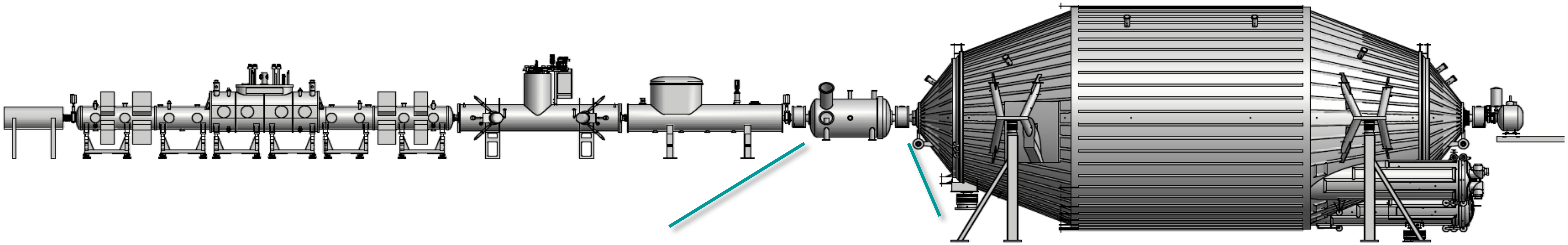
U_0 = - 18.4 … -18.6 kV

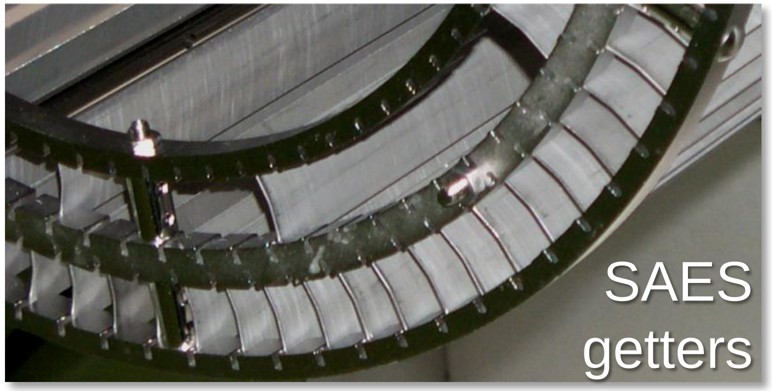
ΔE ~ 0.93 eV (100% transmission)



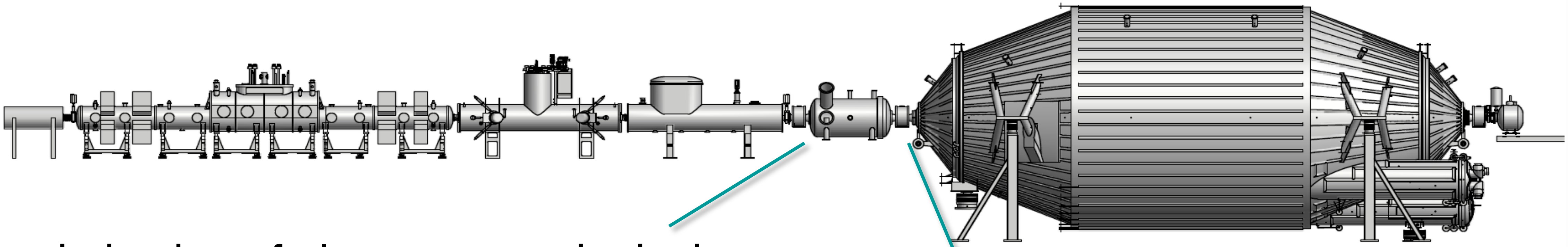
tandem design: pre-filter & energy analysis

pre-spectrometer – UHV





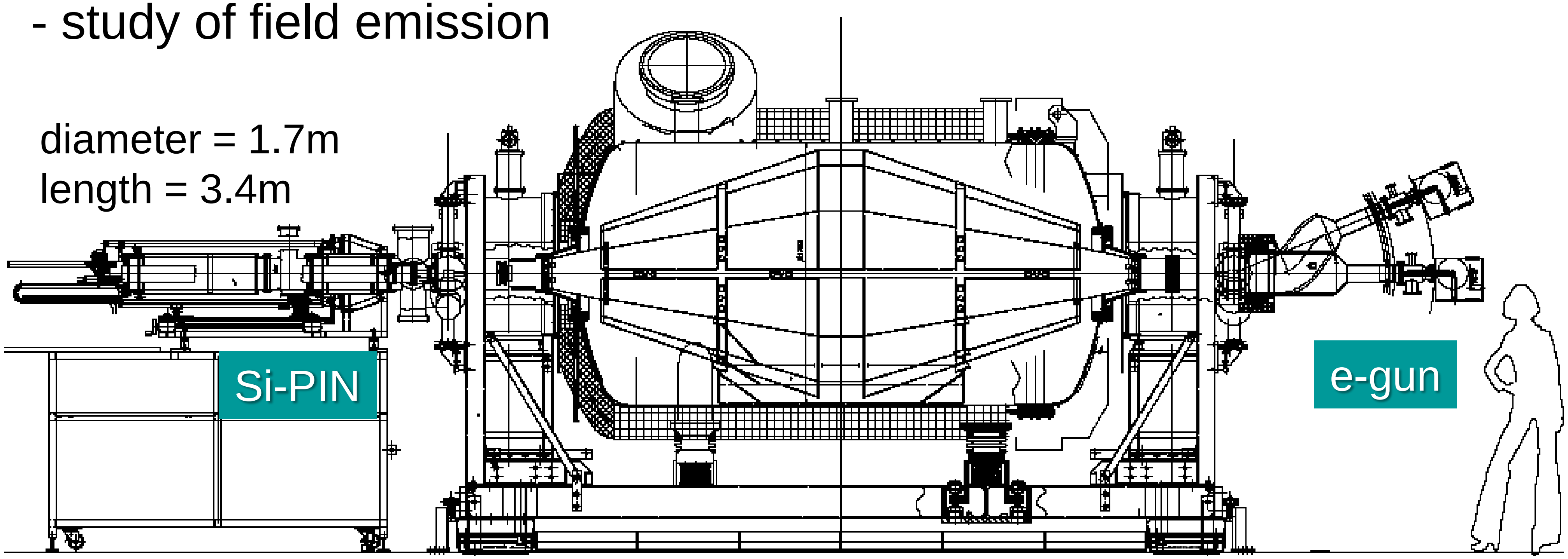
pre-spectrometer: electromagnetic tests



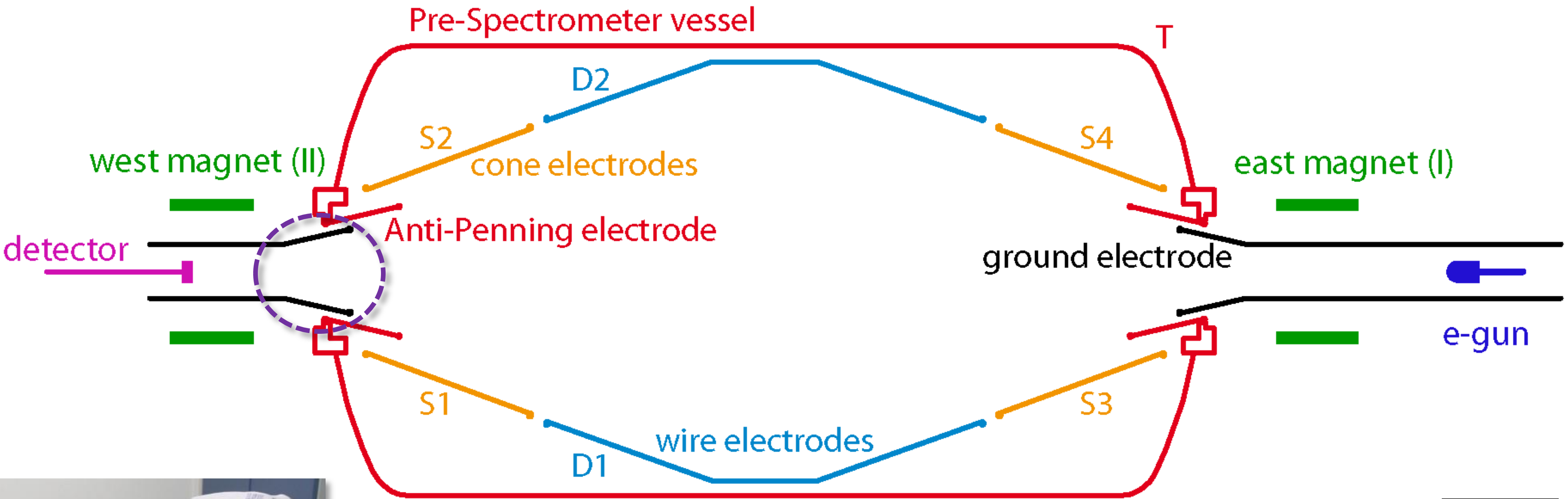
optimisation of electromagnetic design

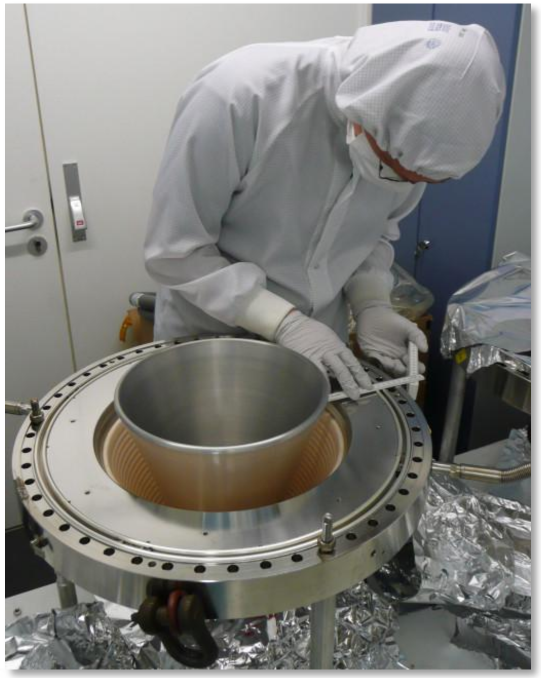
- minimisation of Penning traps
- background reduction techniques (dipole fields)
- study of field emission

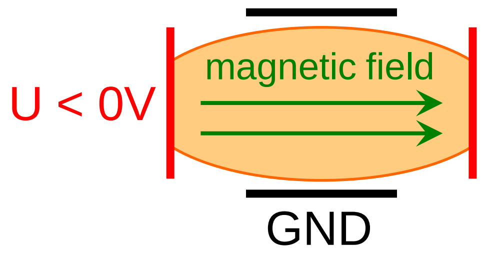
diameter = 1.7m
length = 3.4m



pre-spectrometer: electromagnetic tests



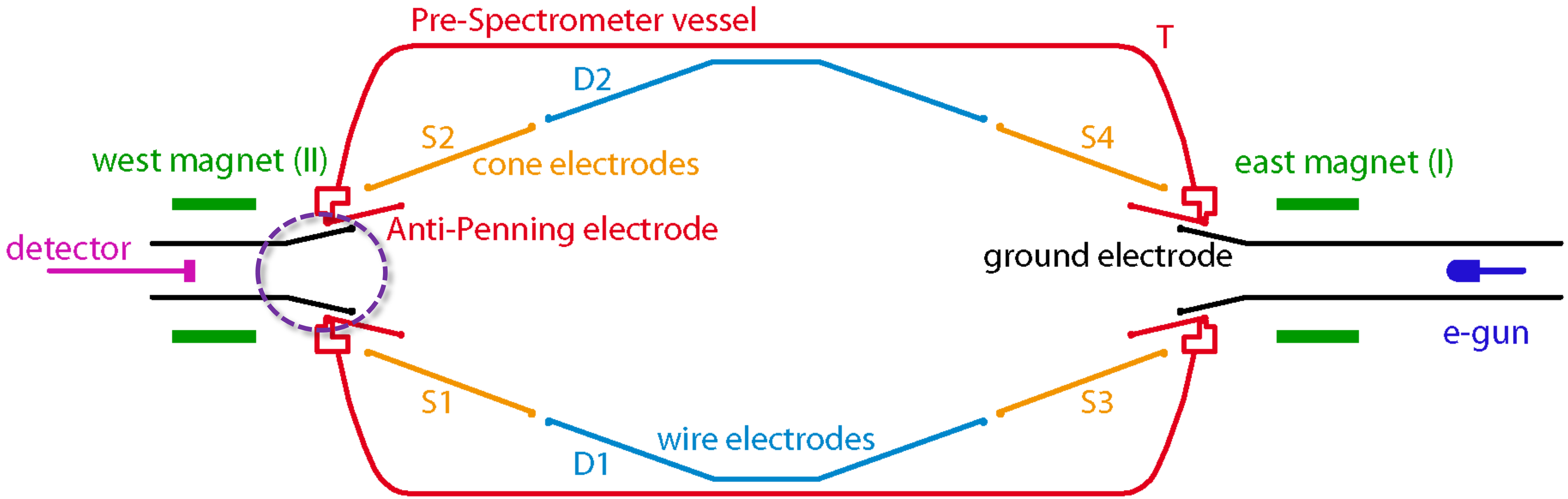




optimisation of electromagnetic design

- design of geometry of ground & Anti-Penning electrodes
- detailed study of characteristics of Penning traps as function of electrostatic potential, B-field, pressure
- 4^{th} generation layout implemented

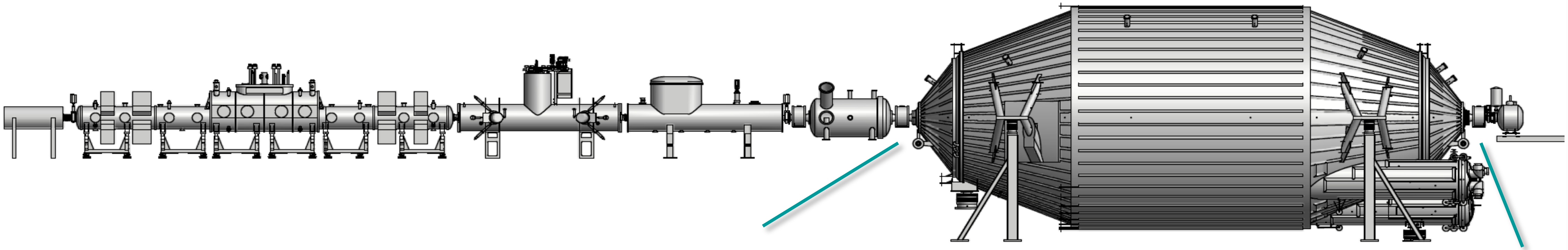
pre-spectrometer: electromagnetic tests



ground electrode geometries: generations # 1 - 4

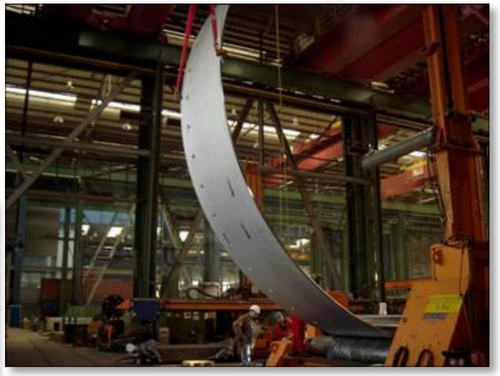
Penning background:
#1: MHz range &
major discharges
#4: mHz range &
long-term stability ☑
huge effort (MC+experiment)

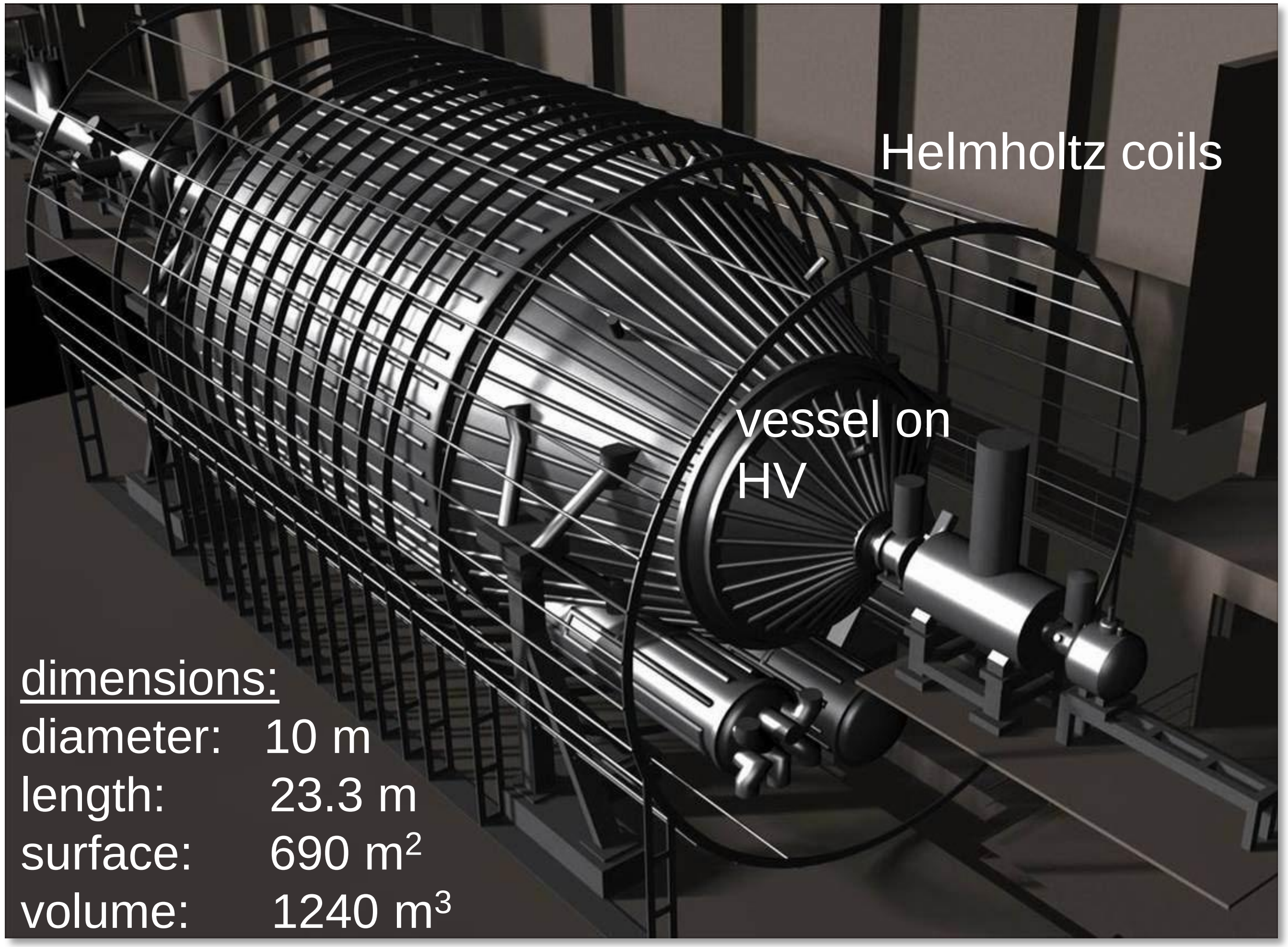
main spectrometer: world s largest UHV recipient



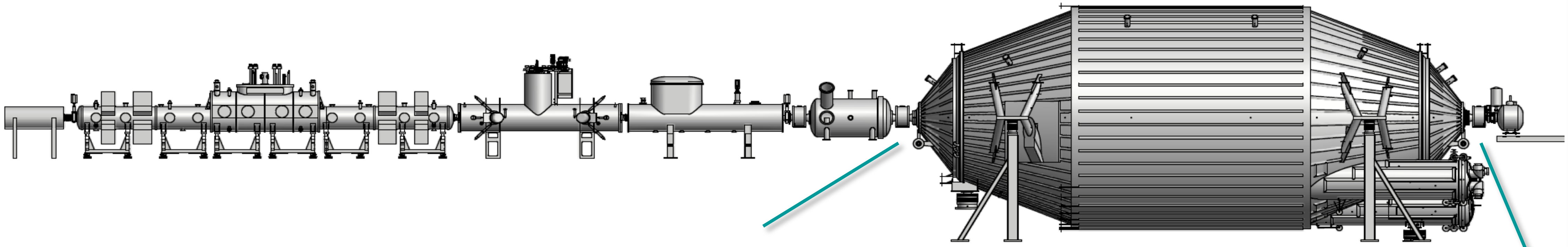
UHV : p < 10^{-11} mbar !

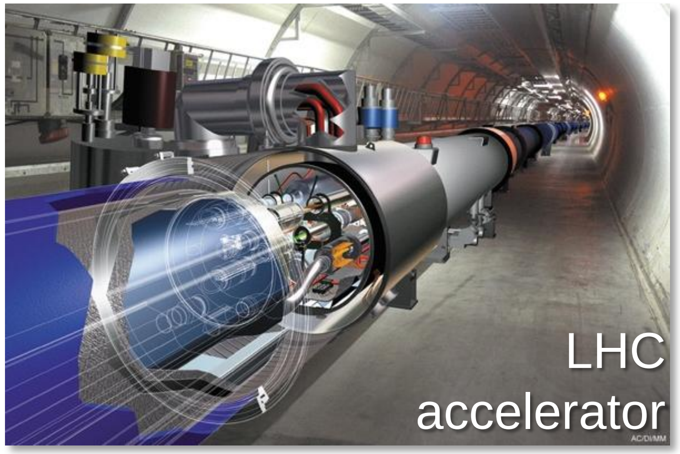
MAN DWE GmbH





main spectrometer: world s largest UHV recipient





KATRIN	Volume	pressure	method
spectrometer	**1250 m³**	**10^{-11} mbar**	turbomolecular pumps / nonevaporable getters

LHC	Volume	pressure	method
storage ring	154 m³	10^{-11} mbar	cryocondensation on beam screen/magnet bore (1.9K)
cryogenic insulation	640 m³	10^{-6} mbar	cryocondensation on magnet cold mass

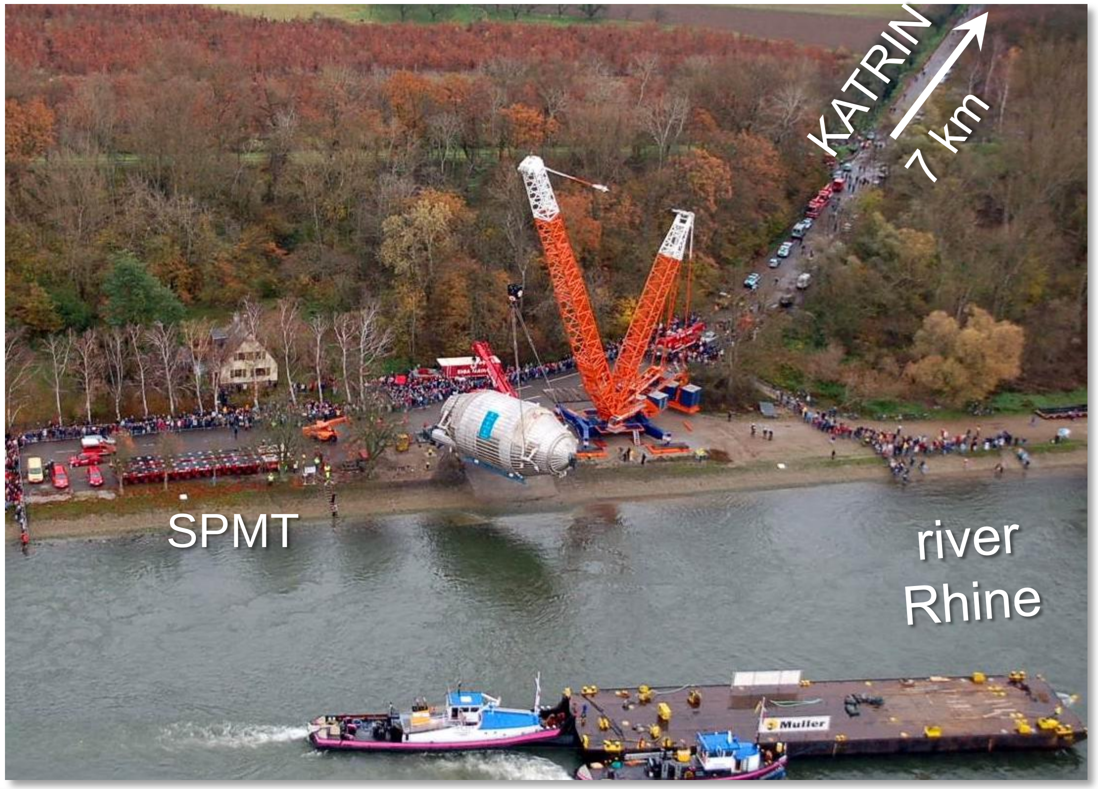
LIGO	Volume	pressure	method
2x4km arms	8000 m³	~10^{-8} mbar	ion pumps & cold traps

VIRGO	Volume	pressure	method
2x3km arms	6800 m³	<10^{-9} mbar	titanium & ion pumps

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)

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



the final 7m, initial out-baking & UHV

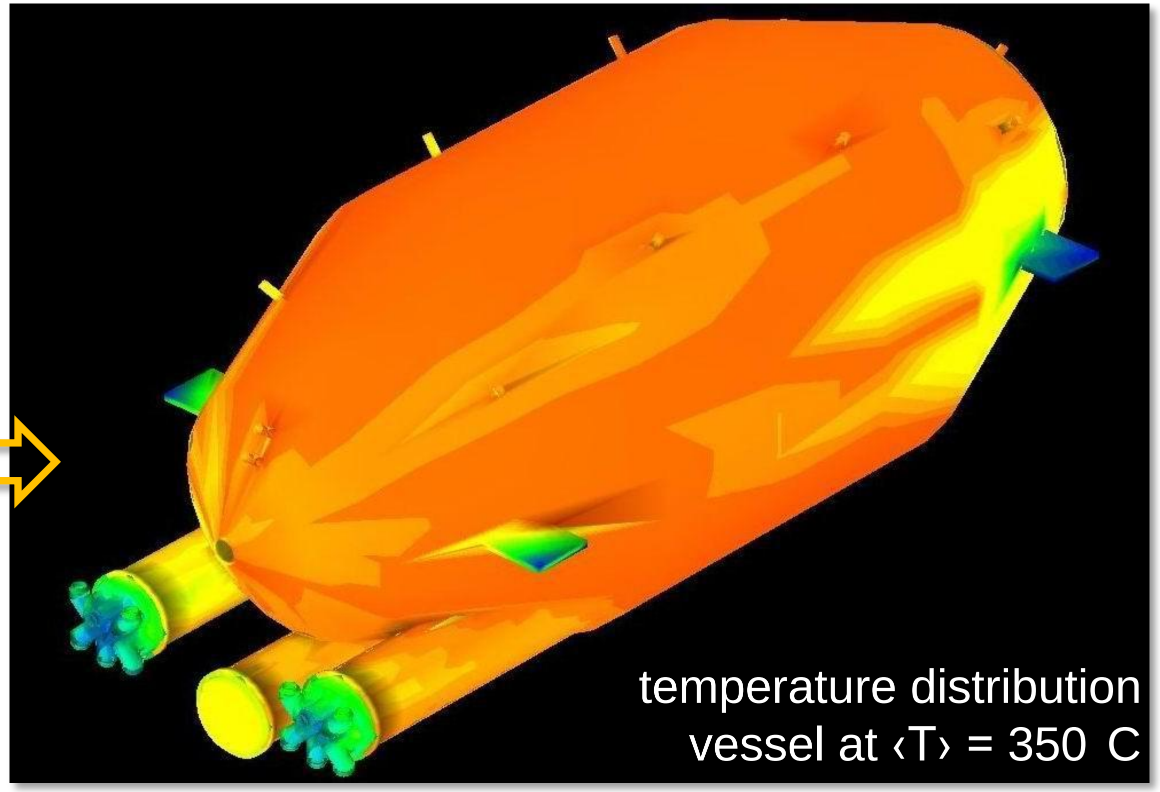
steam
blasting

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_2O
↓
H_2

November 29, 2006



temperature distribution
vessel at ‹T› = 350 C

inner electrodes: motivation & tasks

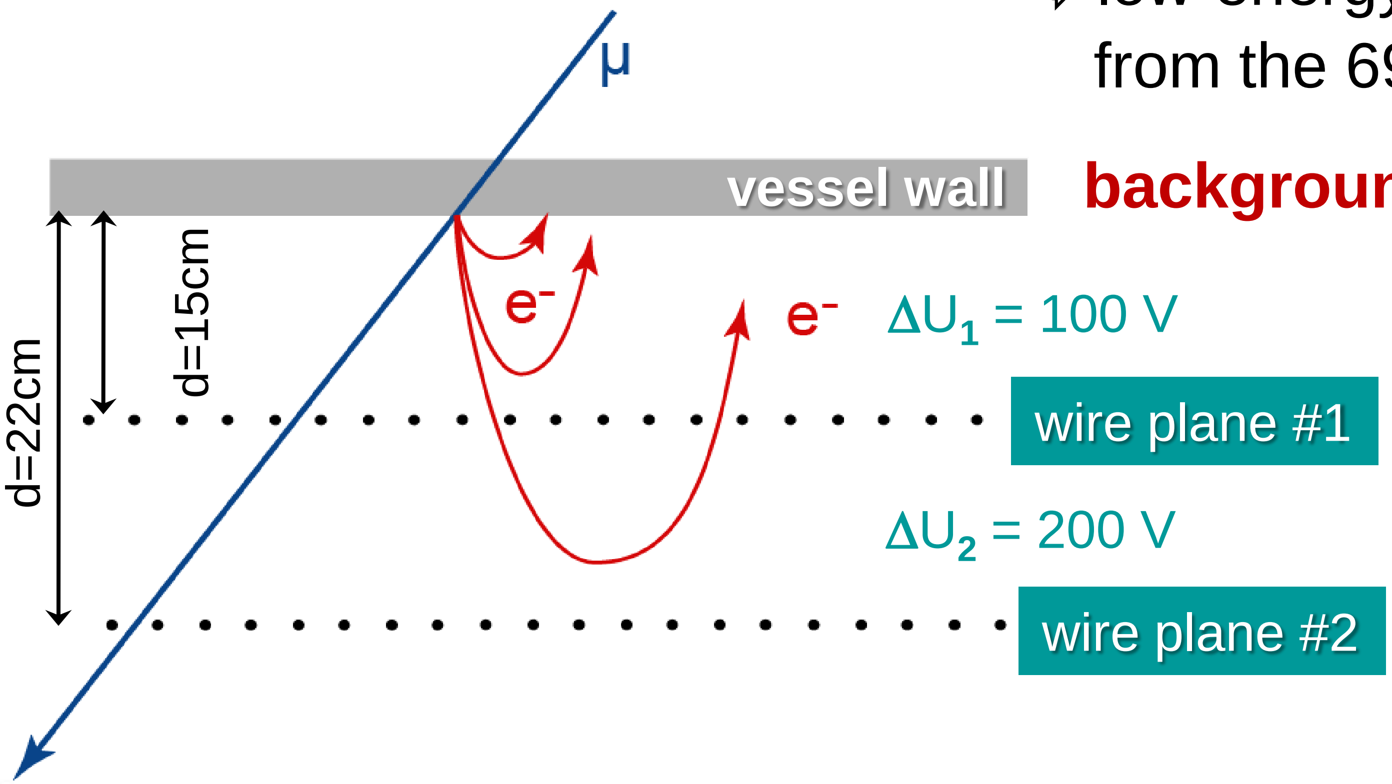
#1: fine forming of electrostatic retarding field

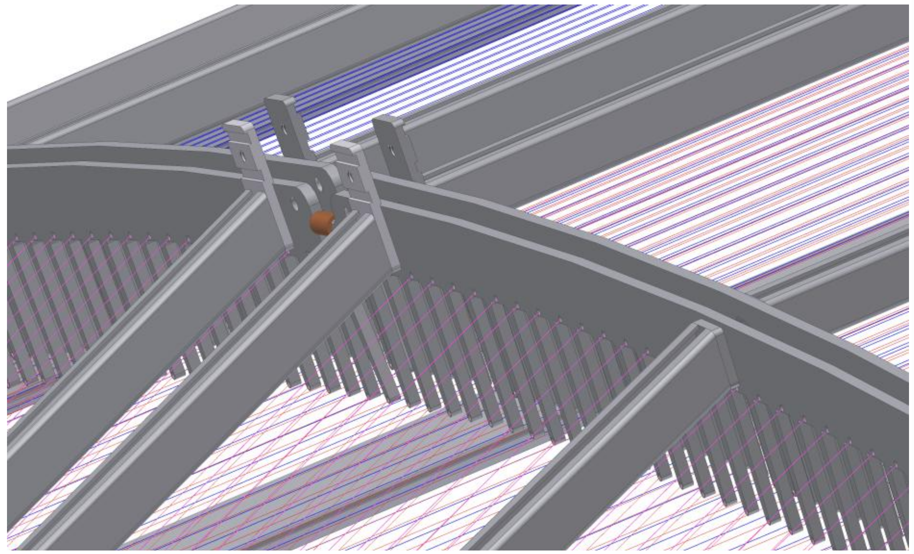
- precision HV power supplies: intrinsic HV precision ~1 ppm
- dipole mode: emptying of particles stored in Penning traps

#2: background suppression

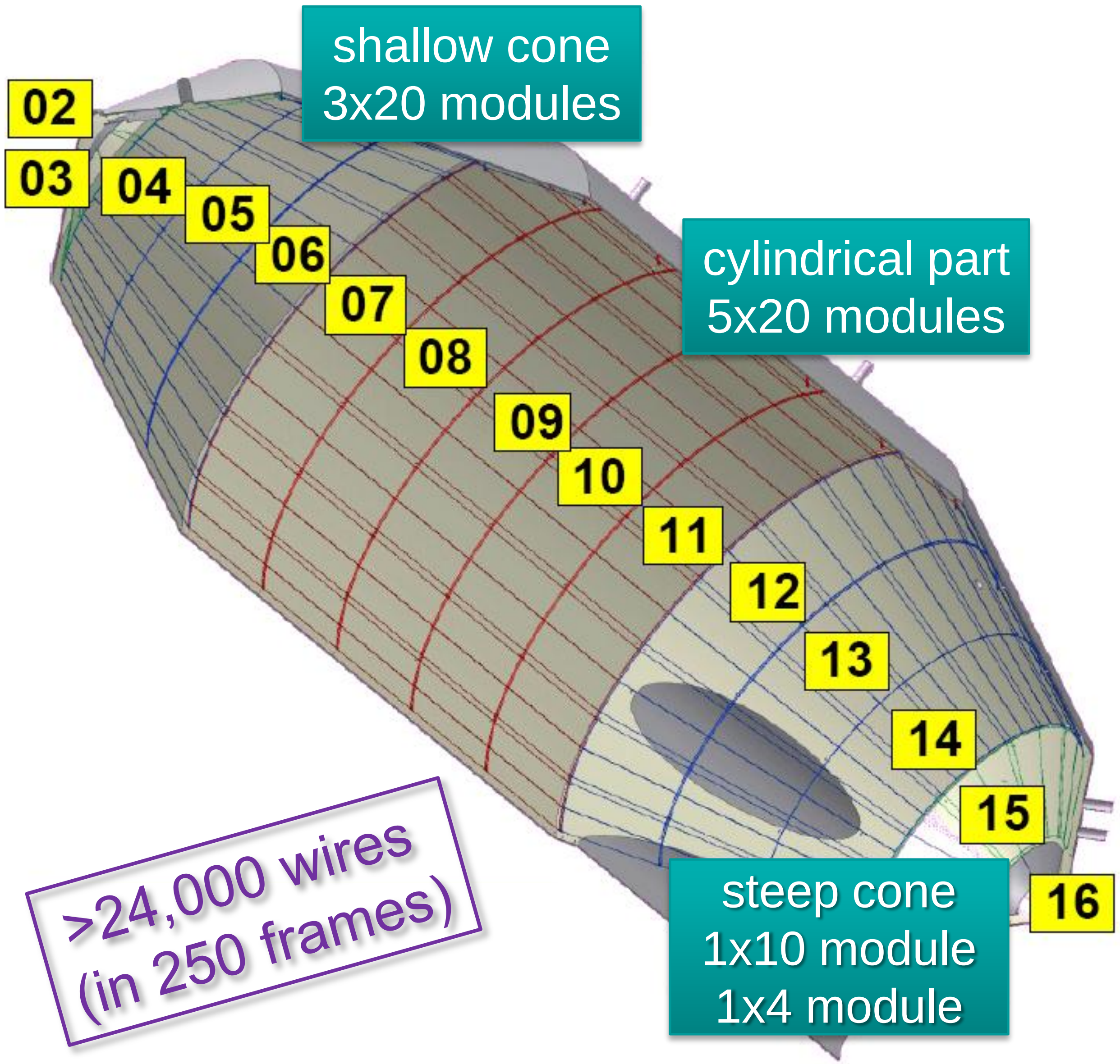
inelastic reactions of cosmic muons
↳ low-energy secondary electrons
from the 690 m^2 inner surface

background reduction: factor 10-100



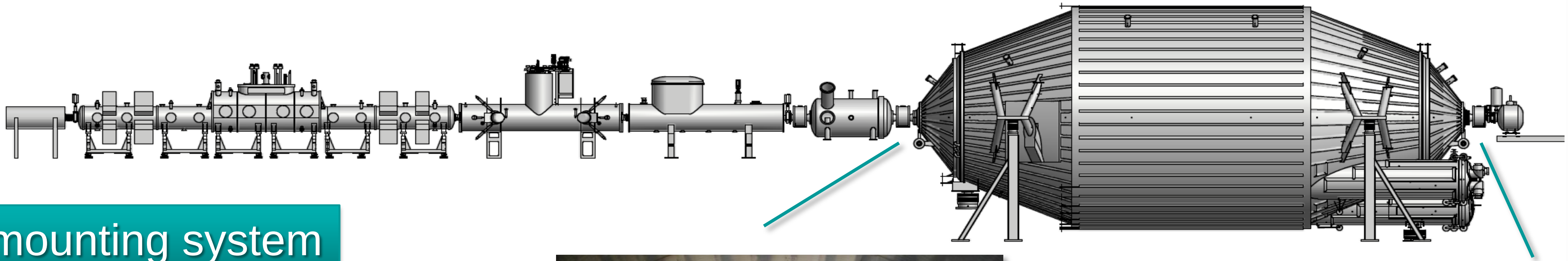


inner electrodes: overall system layout



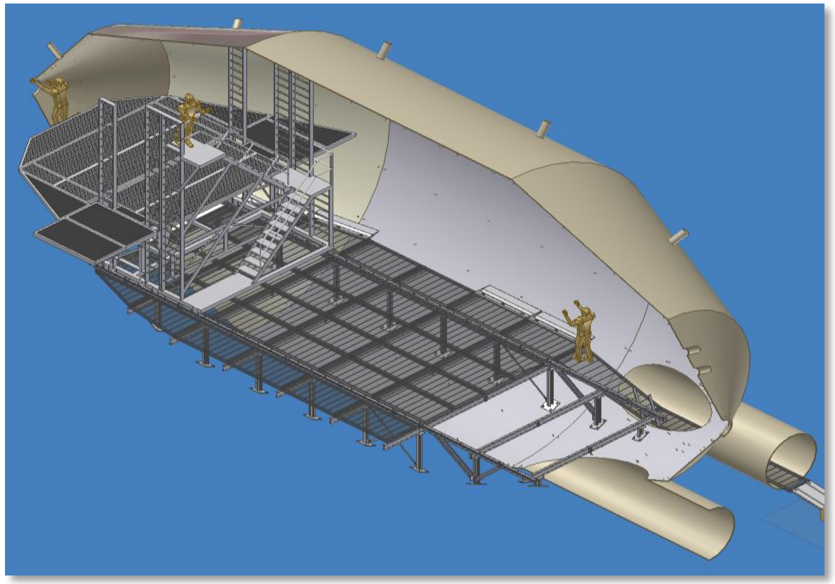
module manufacture at U Münster

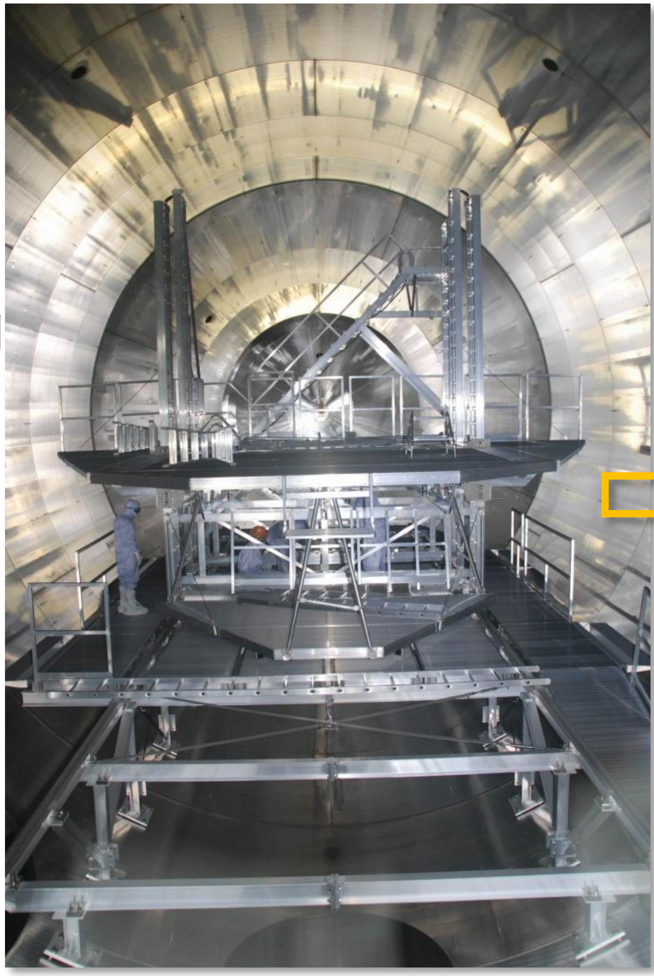
inner electrodes: mounting system



mounting system

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

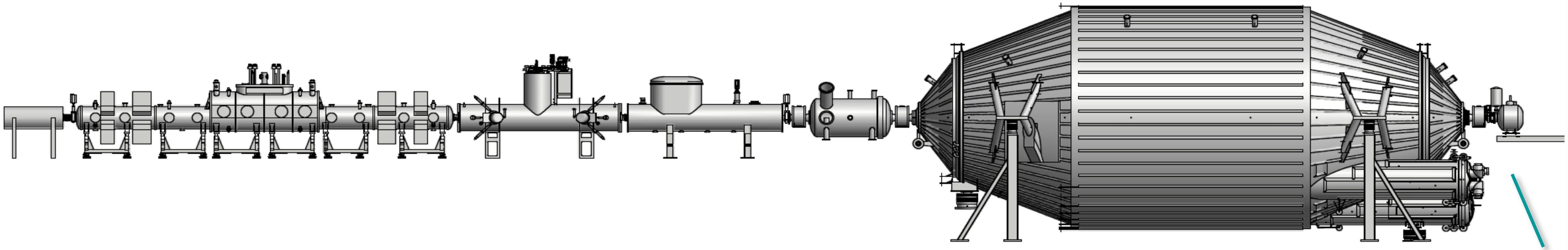


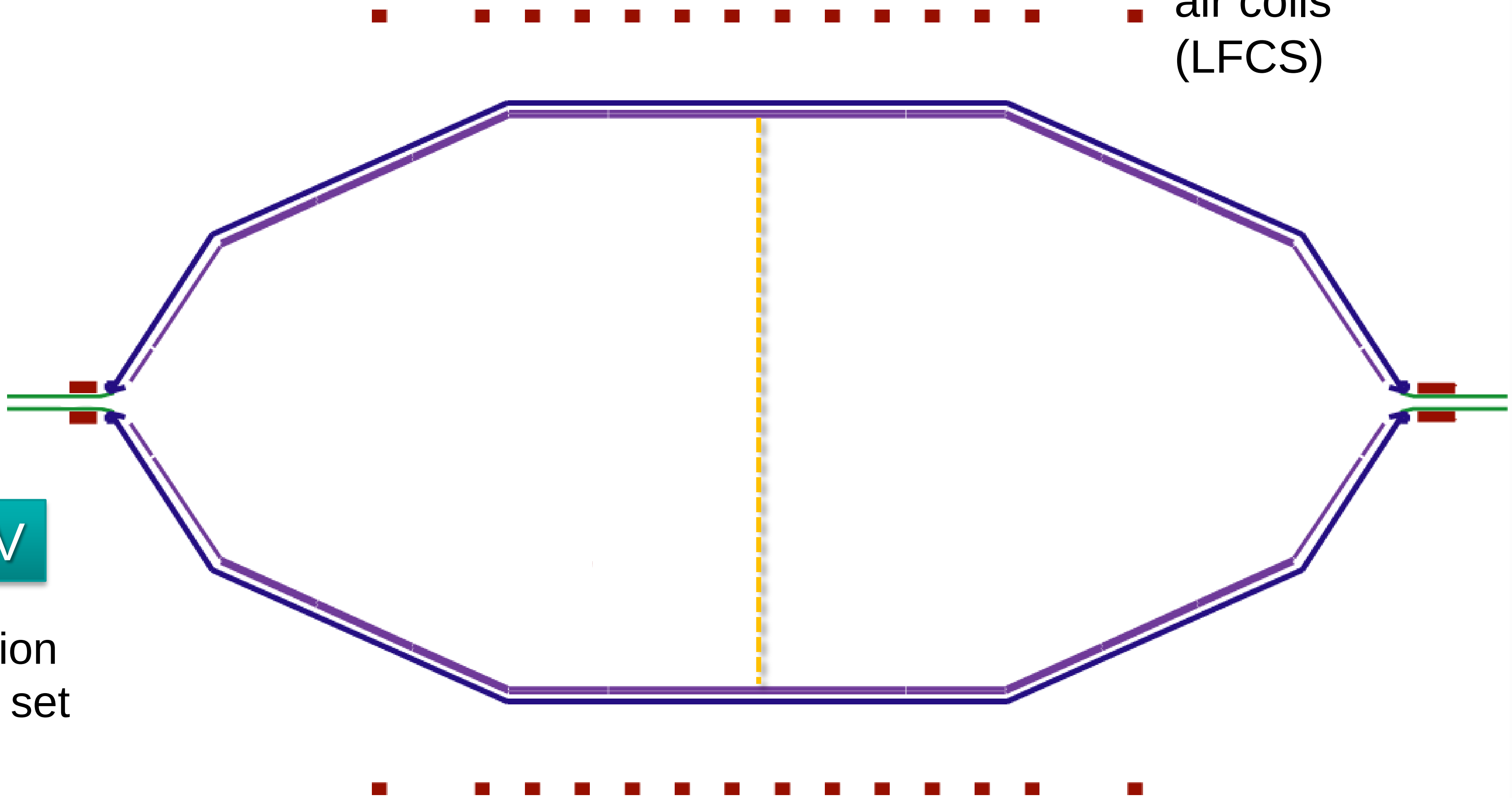


- laser tracker alignment with 100 µm over entire inner surface


July 2009: first wire
modules installed
successfully

main spectrometer

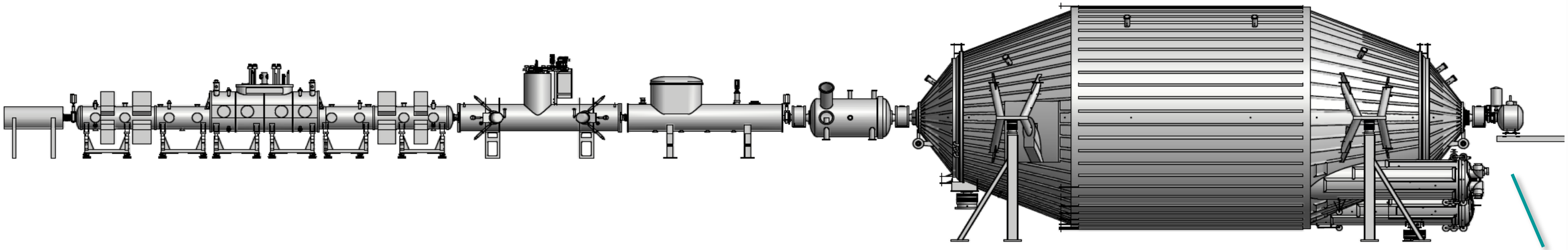


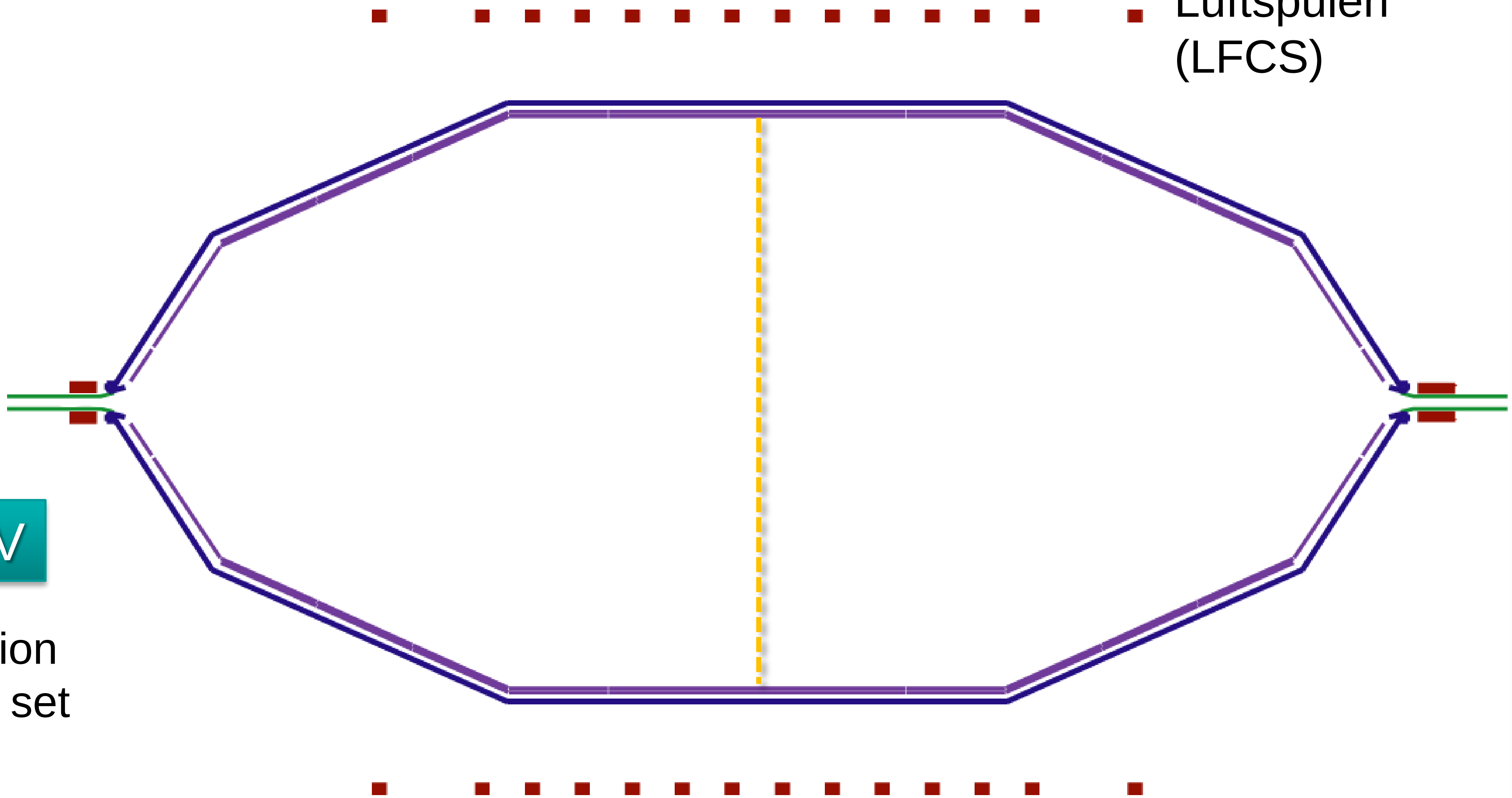


$E(e^-) = U_0 - 1\ \mathrm{eV}$

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

main spectrometer

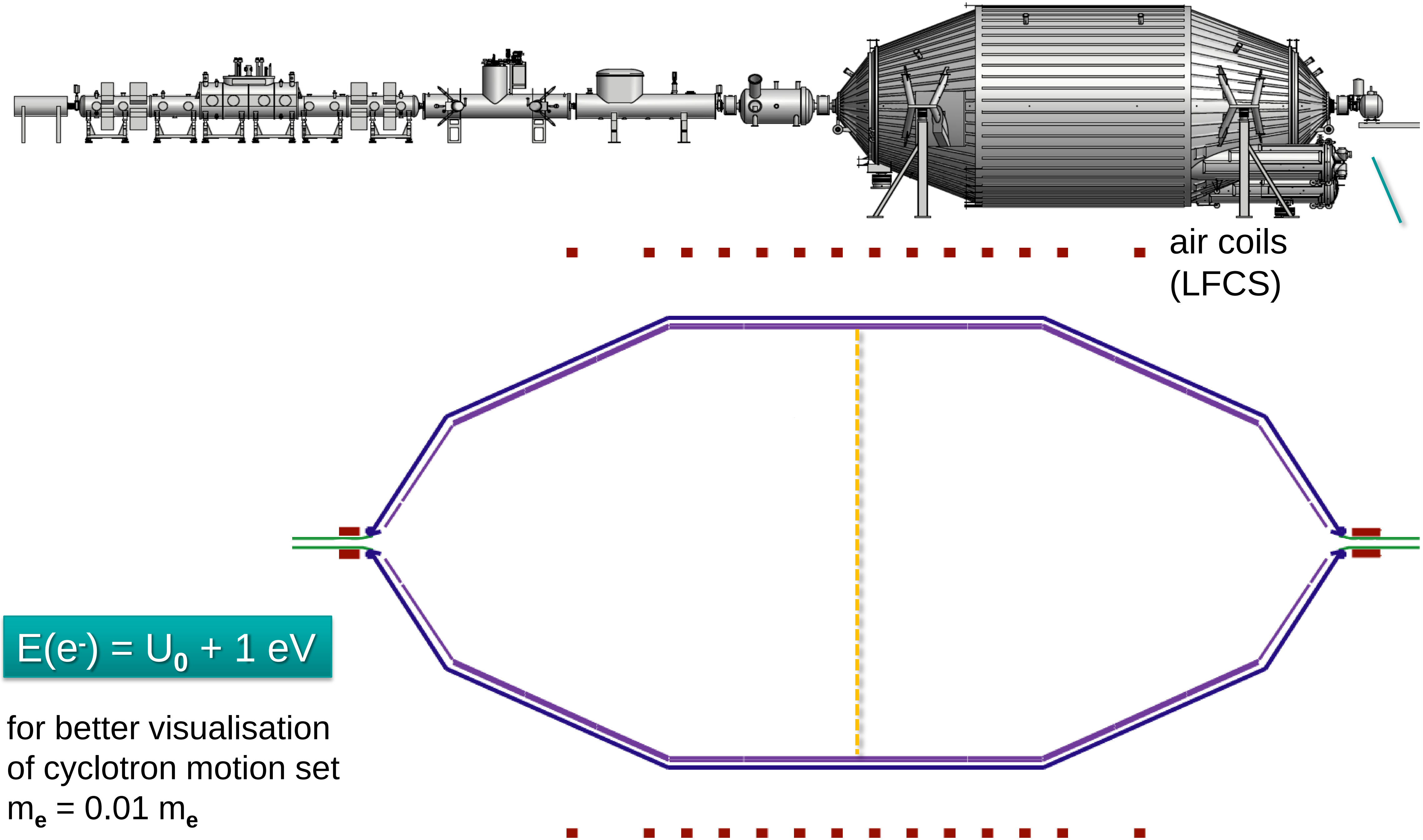




$E(e^-) = U_0 - 1$ eV

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

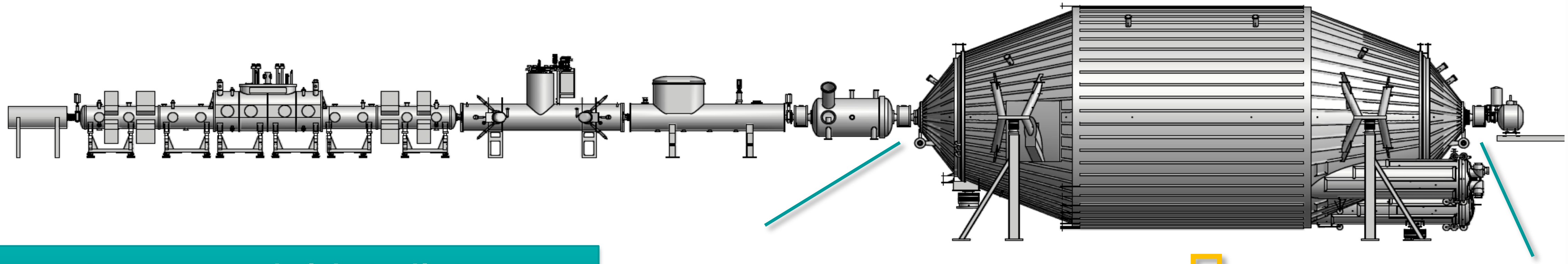
main spectrometer



$E(e^-) = U_0 + 1$ 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:

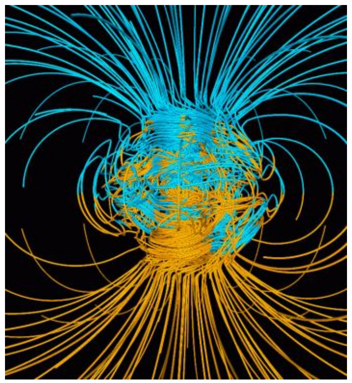
- constrain magnetic flux tube (2.4 G→3.4 G)
- reduce field inhomogeneities (33%→13%)

EMCS – Earth Magnetic Field Coil System

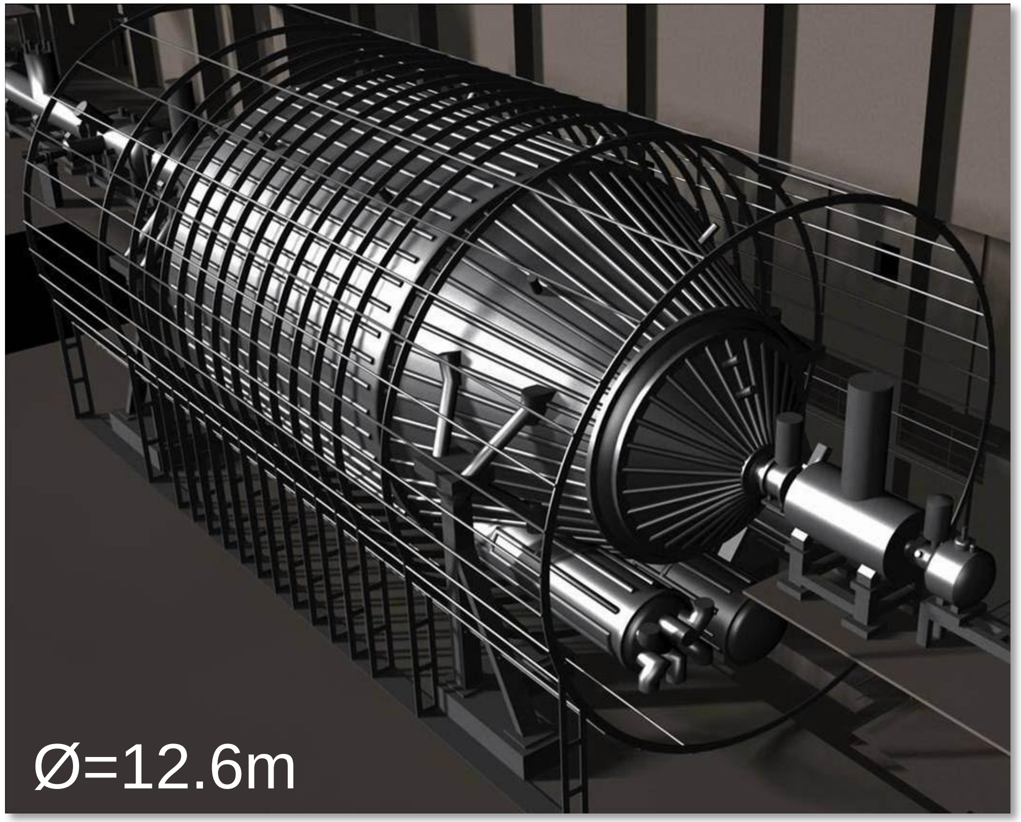
cosine coils

tasks:

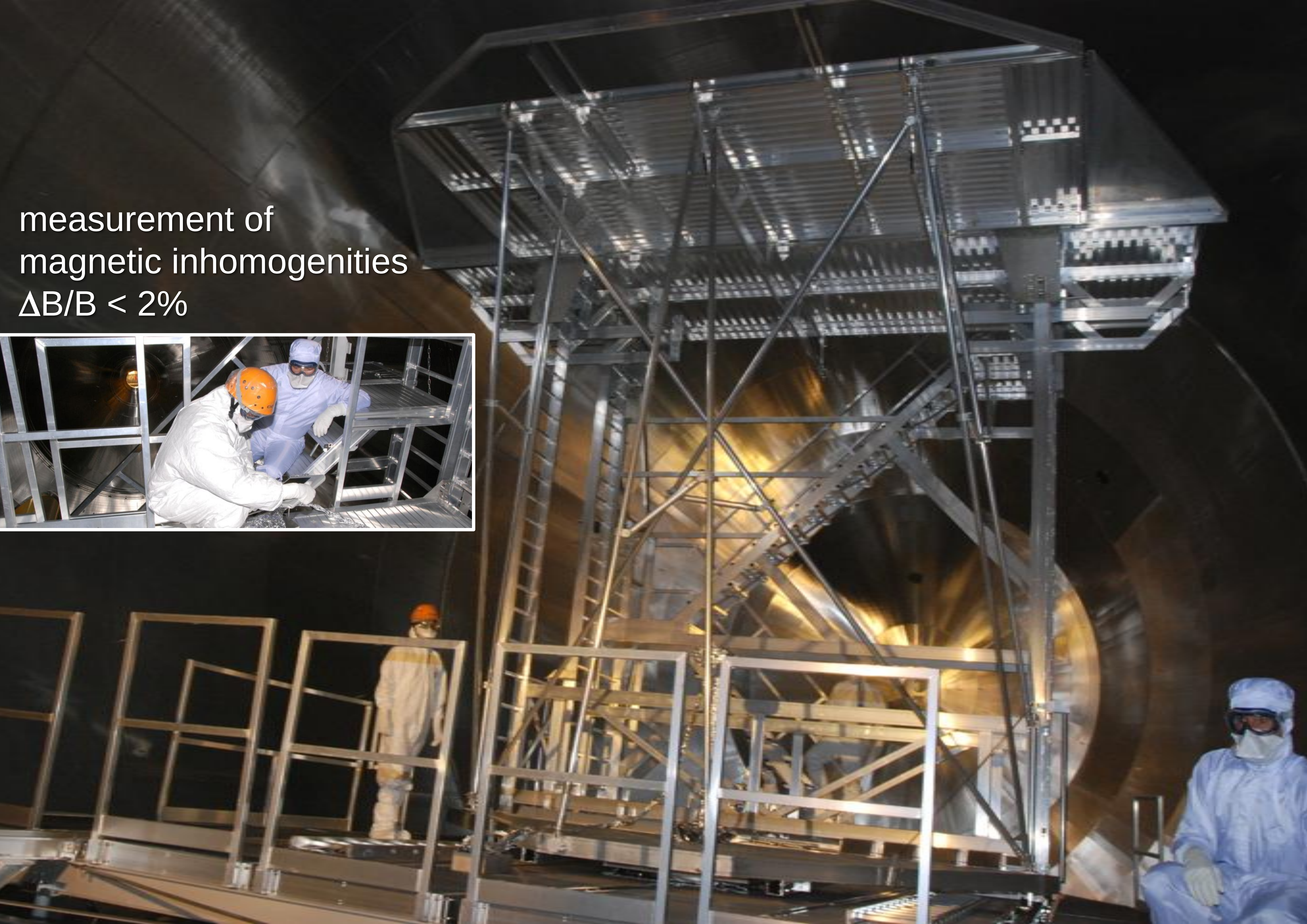
- compensate earth magnetic field (500 mG) or B-field distortions



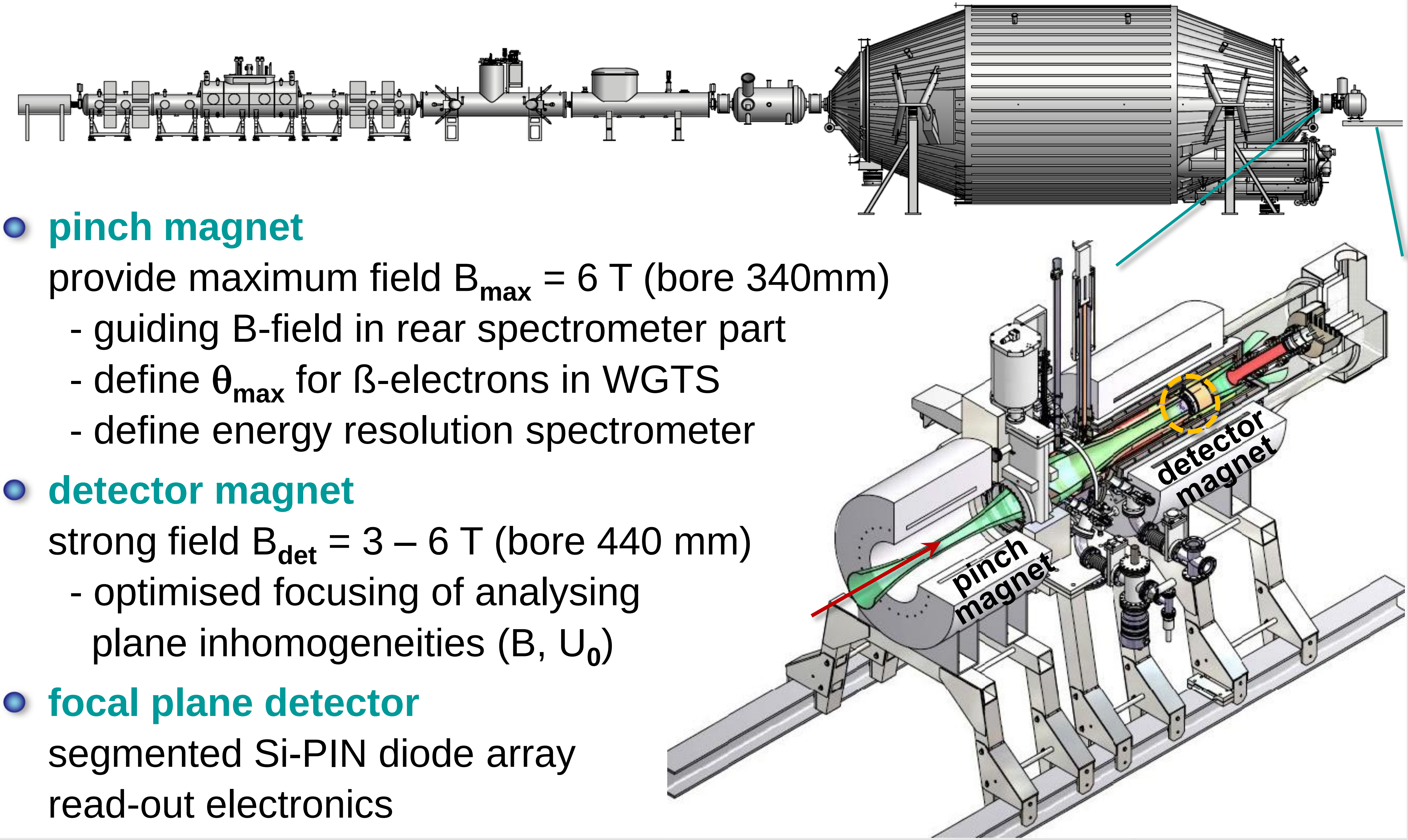
02/09-08/09: assembly




LFCS
EMCS
Ø = 12.7 m
largest Helmholtz
coil system

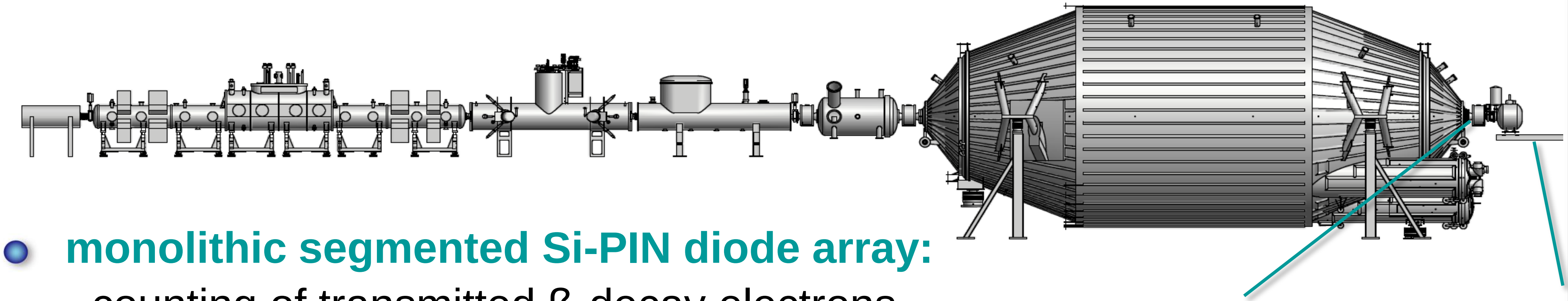

measurement of
magnetic inhomogenities
ΔB/B < 2%

focal plane system

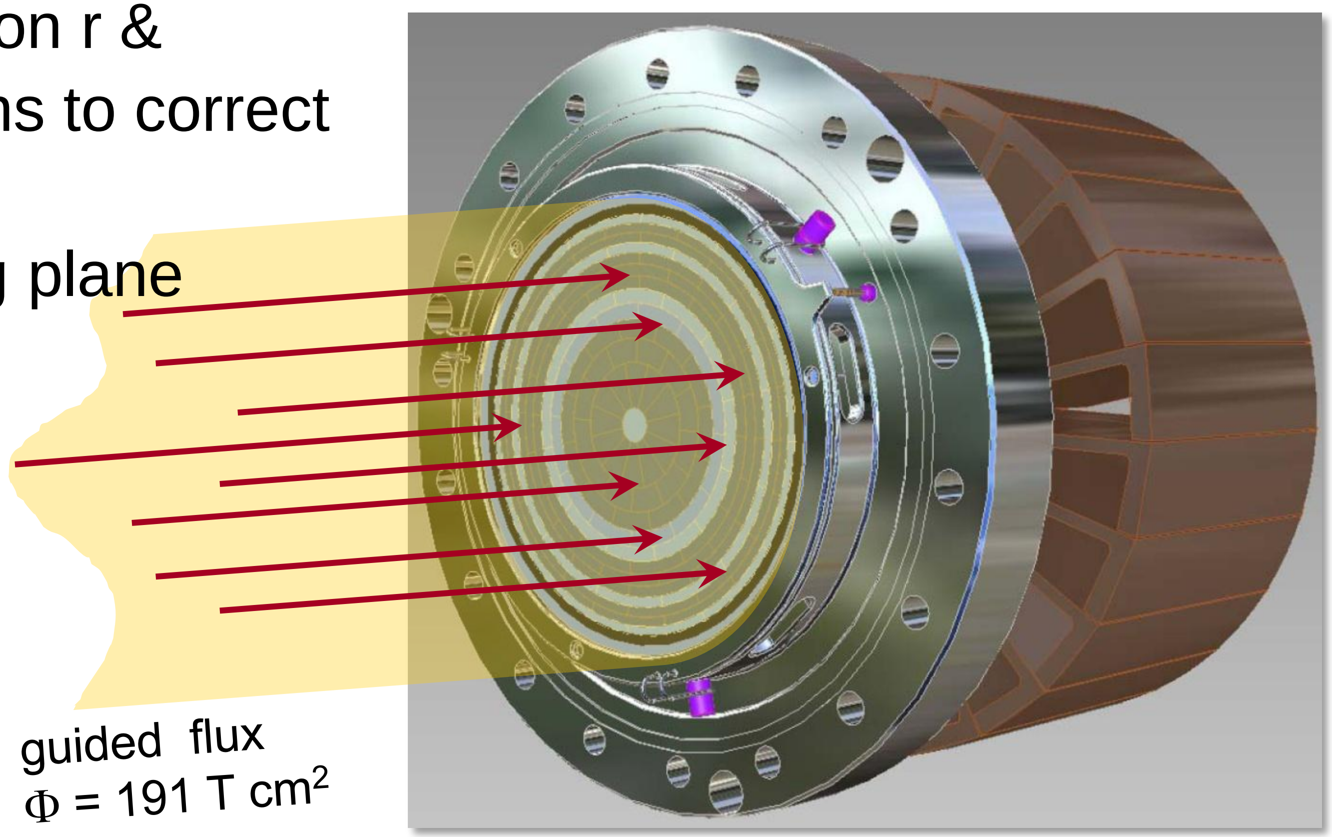


- **pinch magnet**
  provide maximum field B_{max} = 6 T (bore 340mm)
  - guiding B-field in rear spectrometer part
  - define θ_{max} for ß-electrons in WGTS
  - define energy resolution spectrometer
- **detector magnet**
  strong field B_{det} = 3 – 6 T (bore 440 mm)
  - optimised focusing of analysing plane inhomogeneities (B, U_0)
- **focal plane detector**
  segmented Si-PIN diode array
  read-out electronics

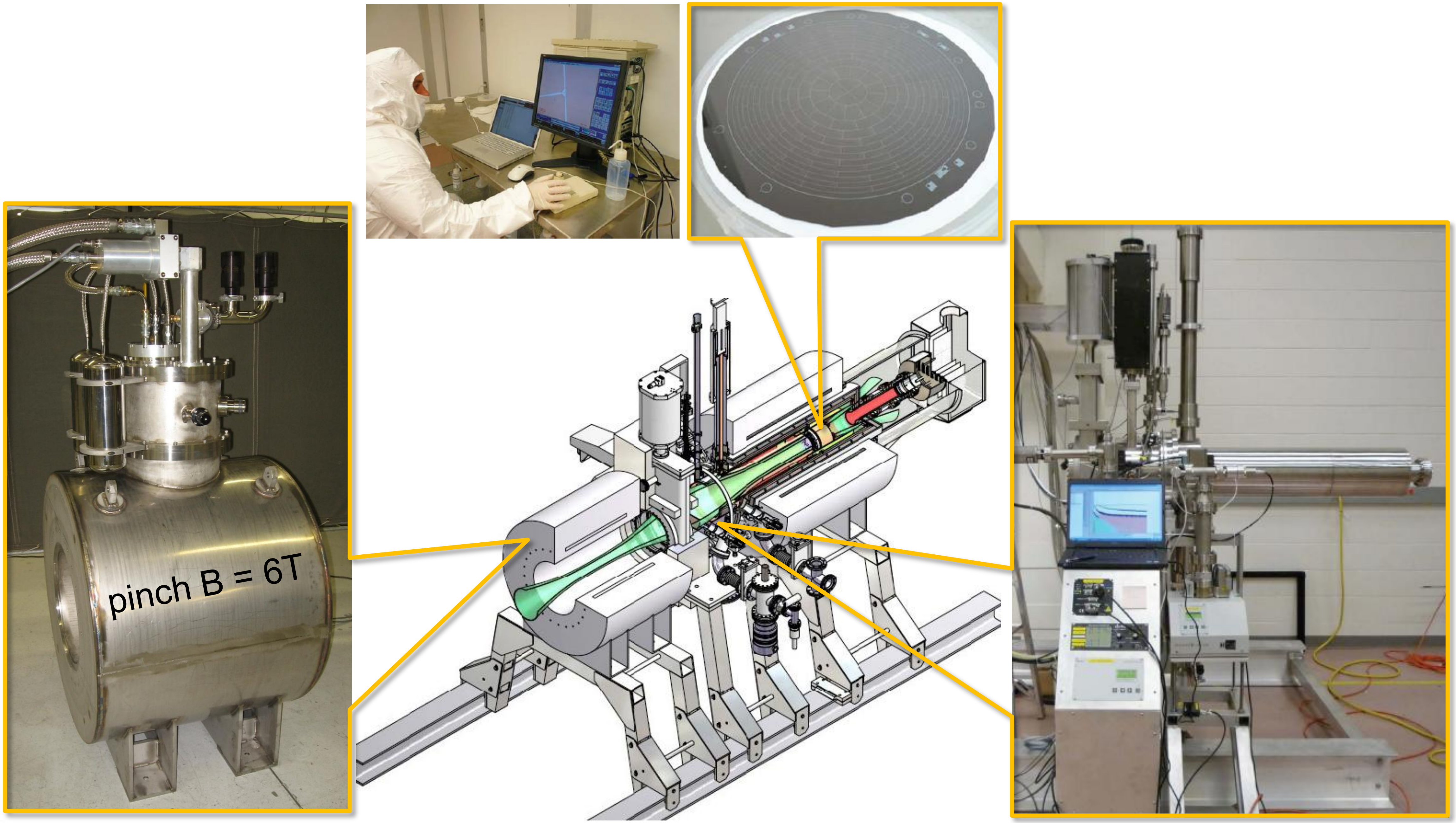
focal plane detector



- **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



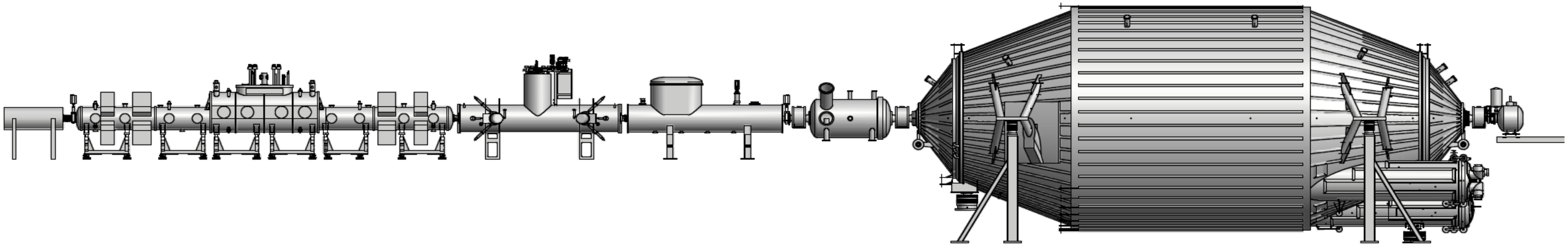
background sources

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)



total bg - rate
R_{bg} = 10 mHz

spectrometer

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

systematic effects

$\Delta m_\nu^2 = -2\sigma_{syst}^2$ ⟺ 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 (Φ < 20 mV), injection of meV-e^-

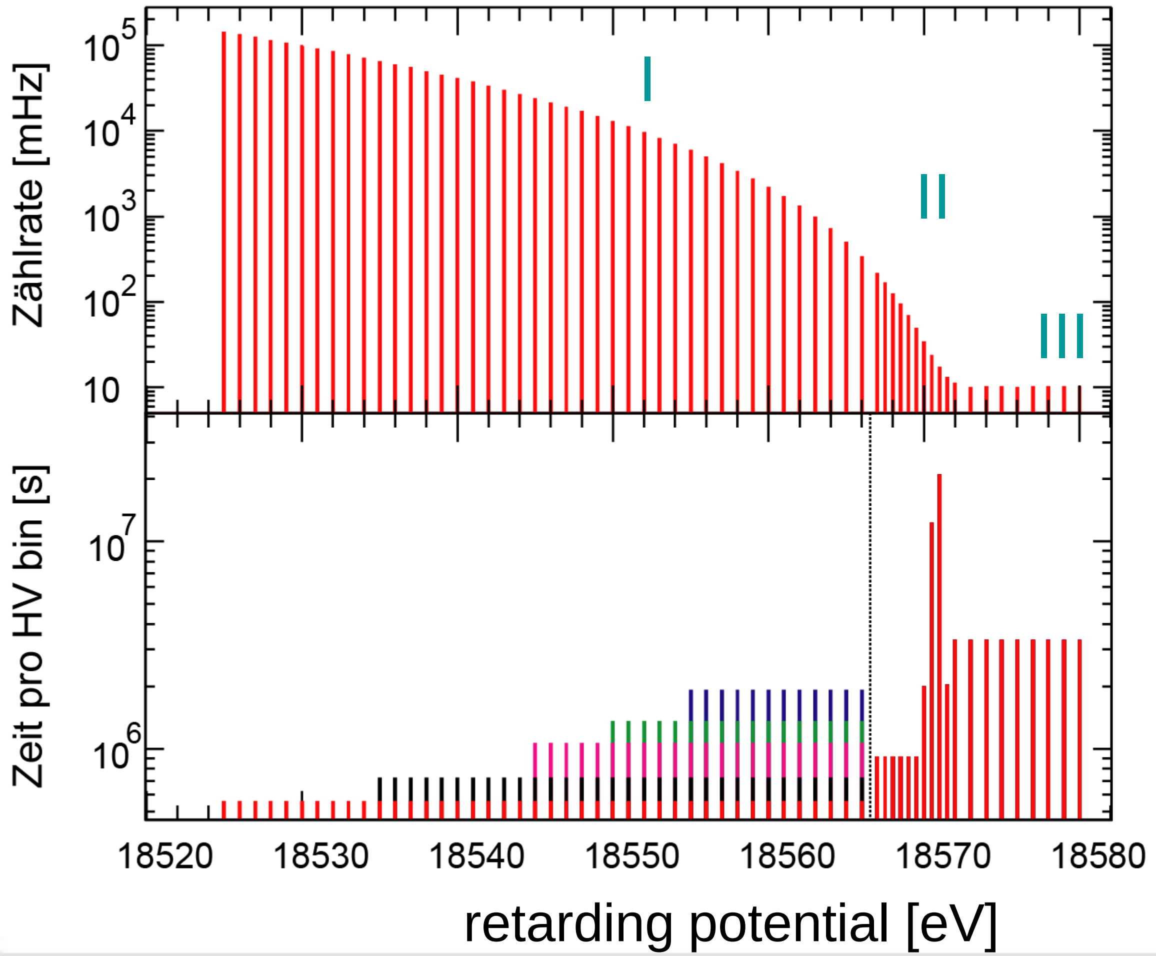
distribution of final states (molecular excitations in $^3H^3He$)

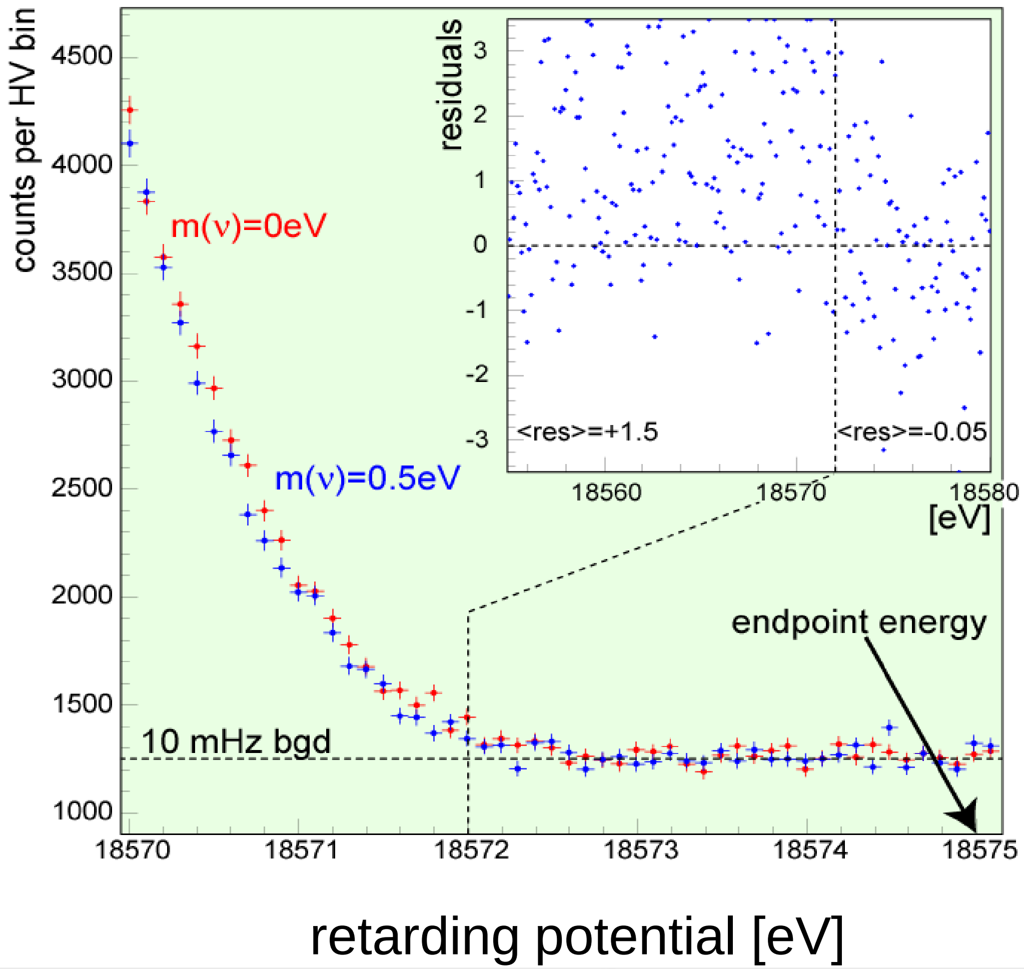
- reliable quantumchemical calculations, very good agreement

measurement intervals & spectra

optimised HV scanning procedure, parameter decorrelation by 3 regions

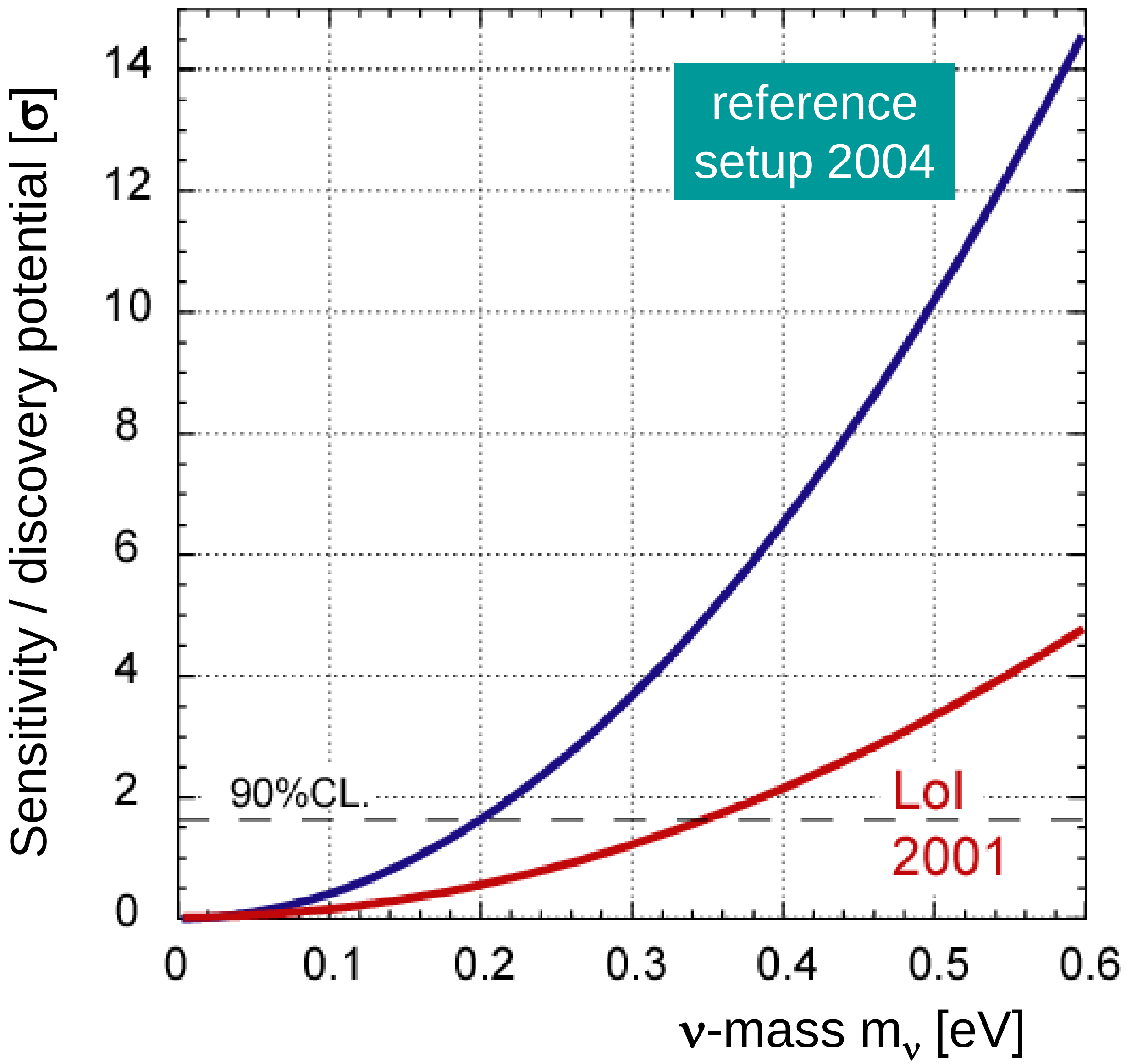
Region I: $E \ll E_0$	determine E_0 from fit procedure (ΔE_0 ~ 3 meV)
Region II: E ~ 18570 eV	maximum sensitivity for m(ν) with S/B-ratio~2
Region III: $E > E_0$	determine background rate (aim for 10 mHz)





KATRIN sensitivity

- ν-mass sensitivity for 3 full beam measuring years



statistical & systematic errors contribute equally:

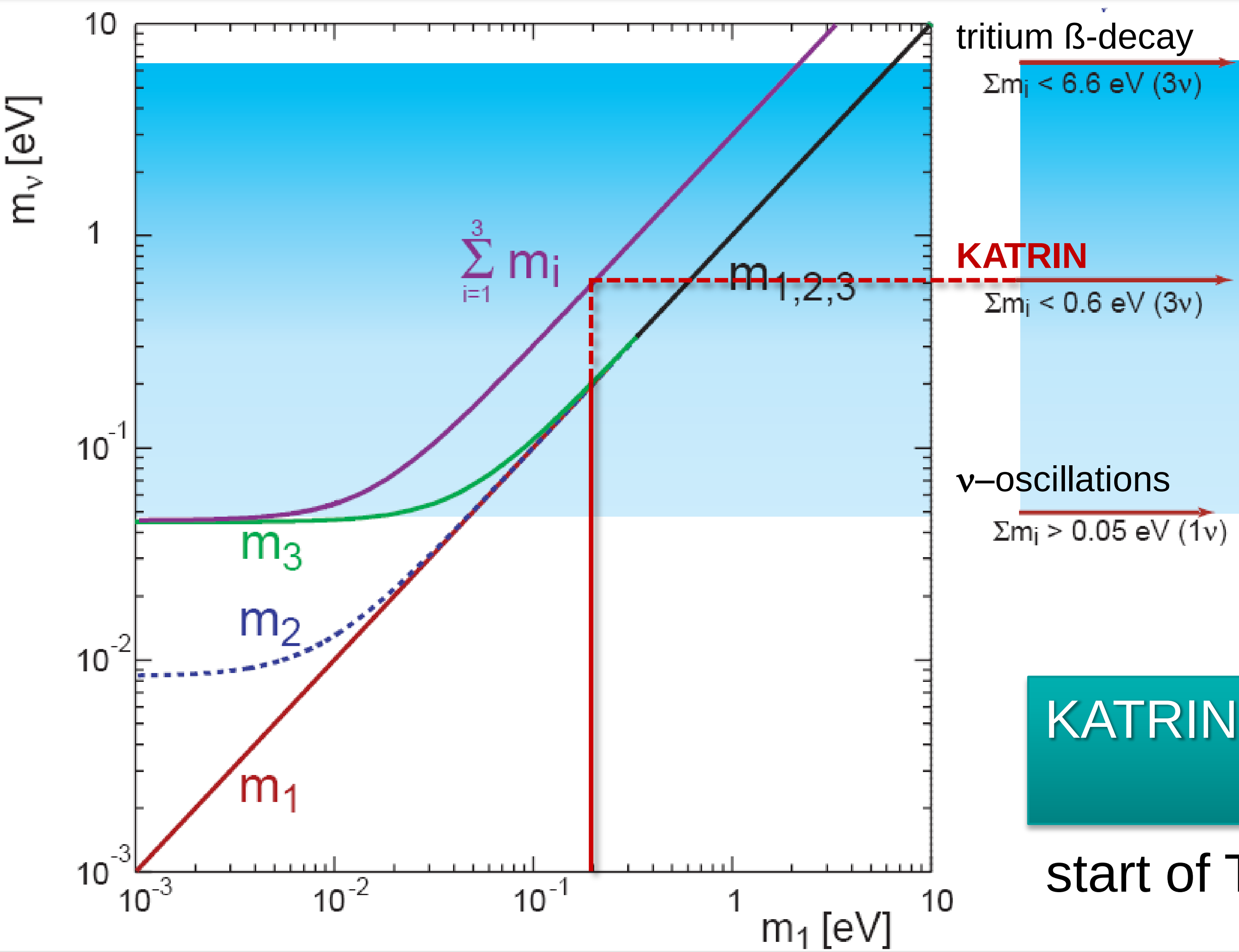
- statistical error σ_{stat} = 0.018 eV²
- systematic error σ_{syst} < 0.017 eV²

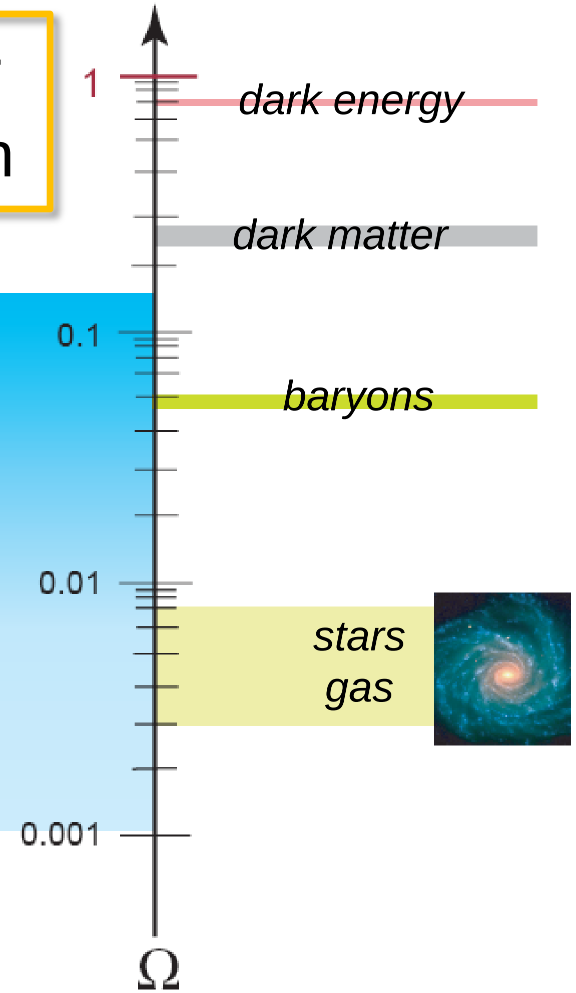
sensitivity (90% CL)
m(ν) < 200 meV

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

KATRIN impact on astroparticle physics

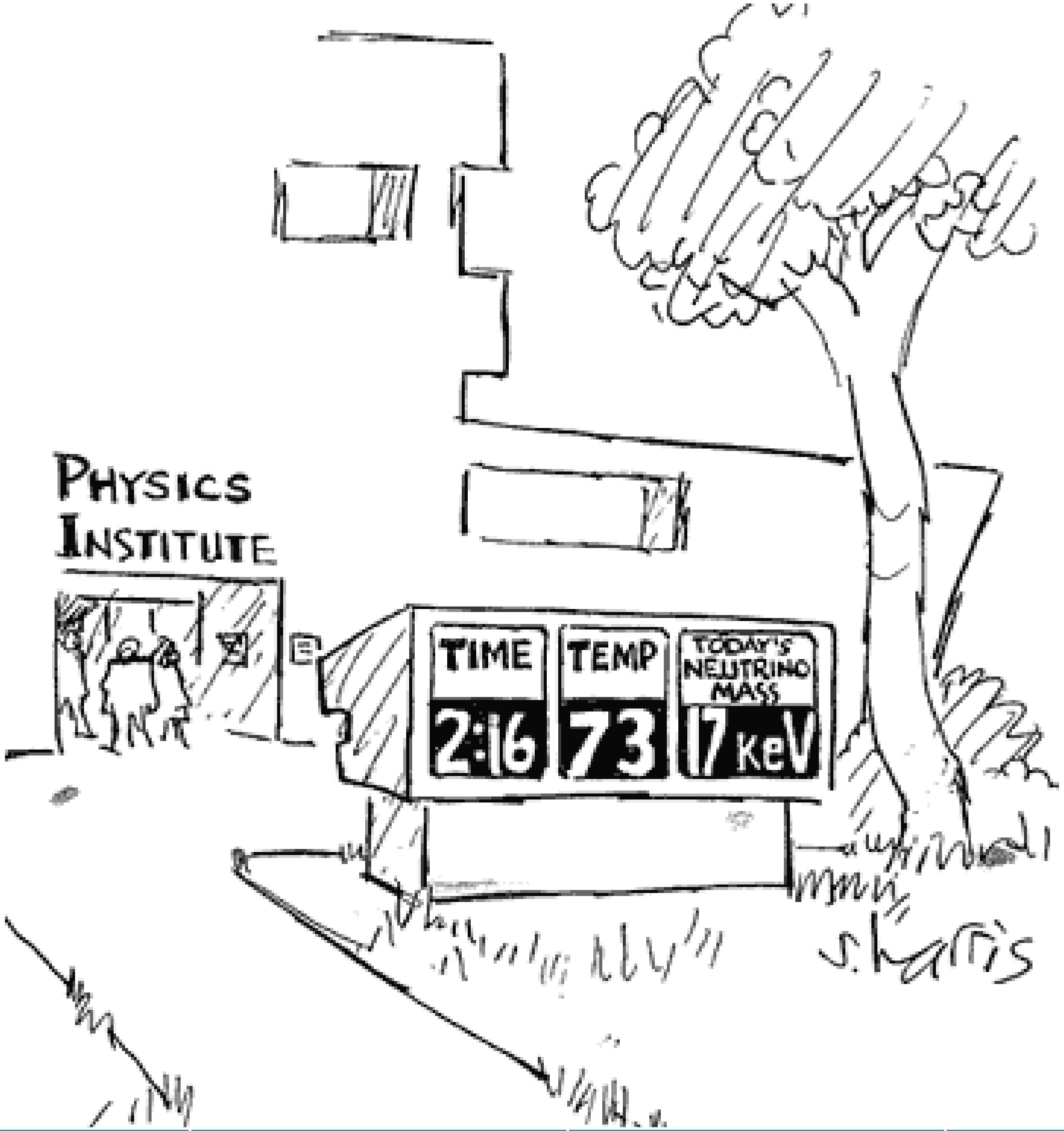
cosmic architects: fix relic-ν role as hot dark matter
microscopic keys: fix generic neutrino mass pattern



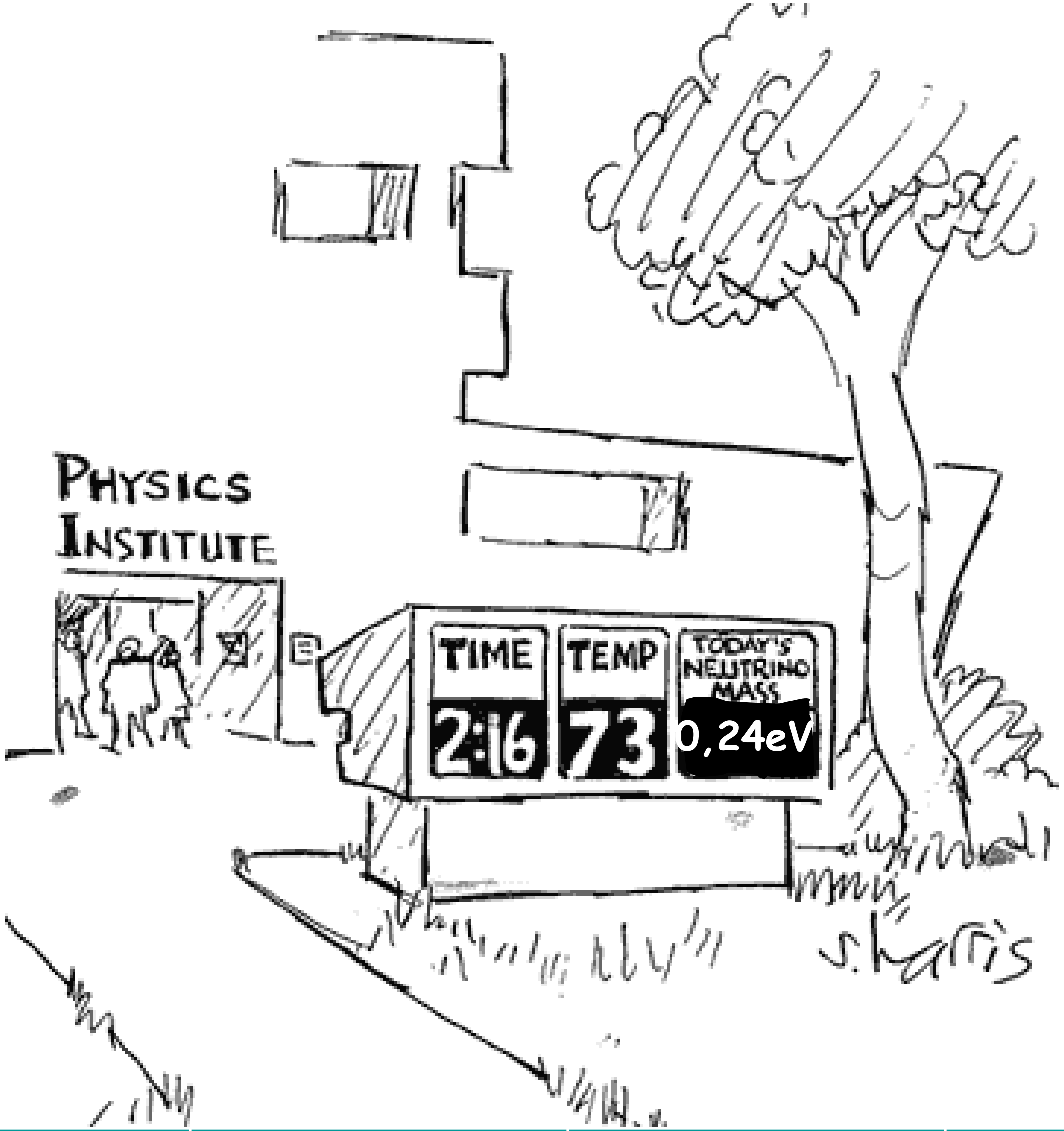


KATRIN : a key experiment for astroparticle physics

start of T2-measurements: 2012



1985	1986	1987	1988	1989	1990



2009	2010	2011	2012	2013	2014