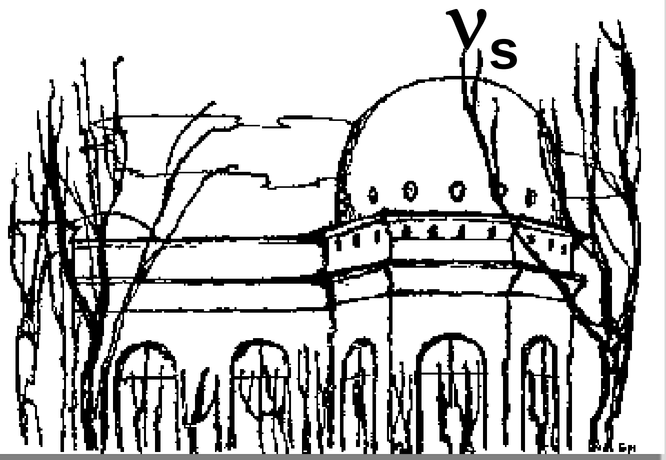
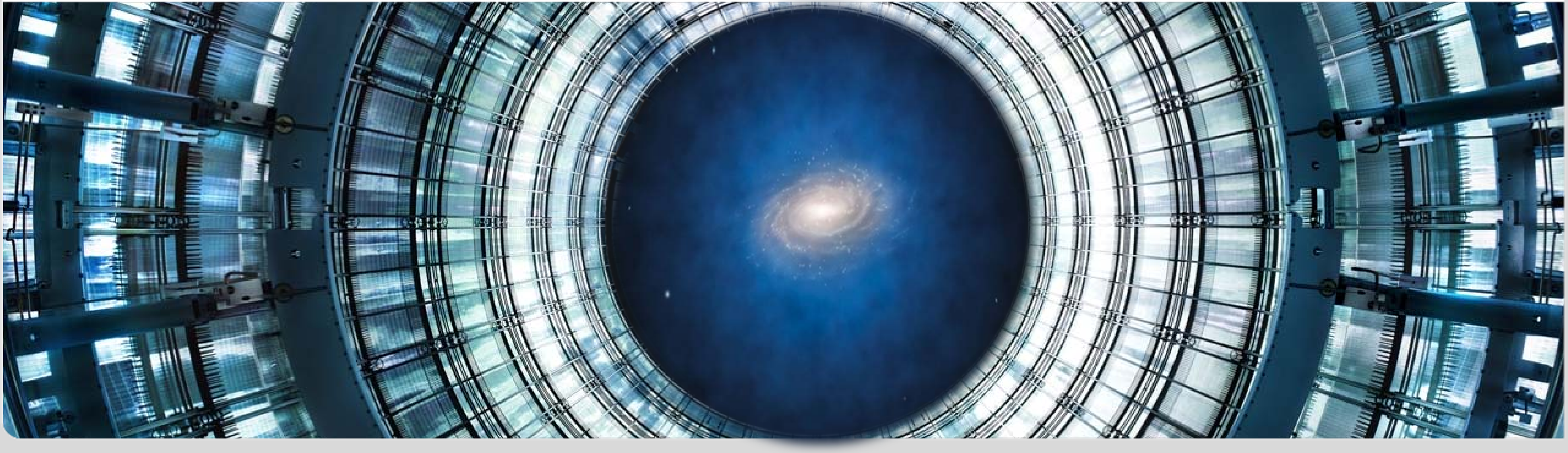


KATRIN

Ecole Internationale Daniel Chalonge 2013

July 26th, 2013

Guido Drexlin, KCETA



KIT – University of the State of Baden-Württemberg and
National Research Center of the Helmholtz Association

www.kit.edu

Outline

- **Introduction**

  - Scientific goals

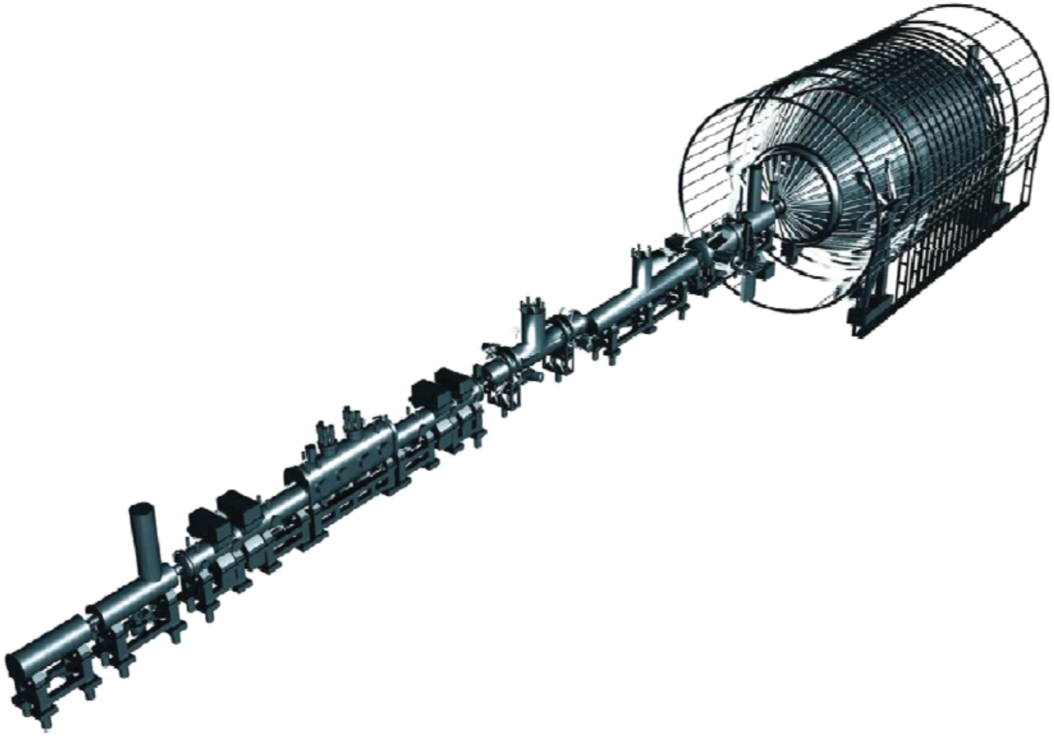
- **Tritium source**

  - challenges:
    temperature stability

- **Electrostatic spectrometer**

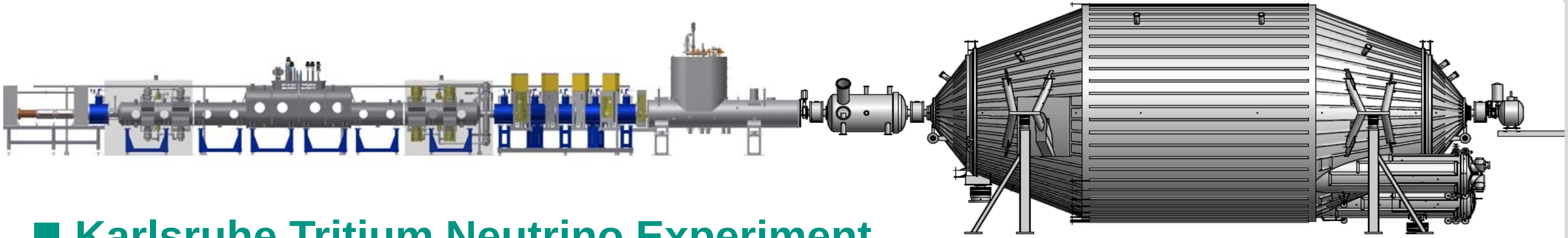
  - challenges:
    radon-induced background

- **Conclusion**



KATRIN experiment

Karlsruhe Institute of Technology



■ Karlsruhe Tritium Neutrino Experiment

- next-generation **direct ν-mass experiment** at KIT
- International Collaboration: 120 members

  15 institutions in 5 countries: D, US, UK, CZ, RUS
- reference ν-mass sensitivity: **$m(\nu_e) = 200$ meV**

■ KATRIN member institutes

Karlsruhe Institute of Technology

universitätbonn

UCSB

Westfälische Wilhelms-Universität Münster

Max-Planck-Institut für Kernphysik

universität mainz

University of Washington 1861

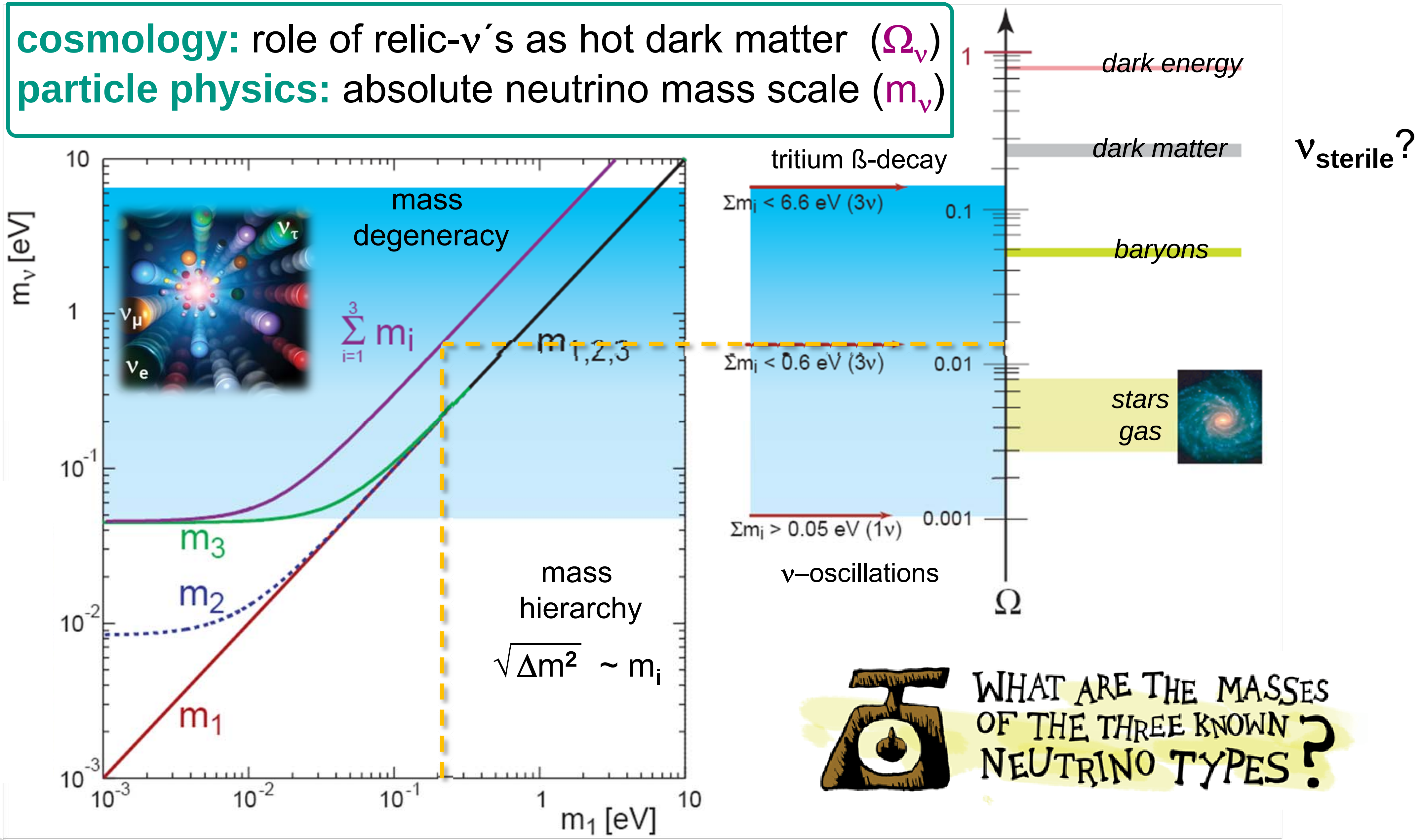
The University of North Carolina at Chapel Hill

Berkeley Lab

absolute ν-mass scale

cosmology: role of relic-ν´s as hot dark matter (Ω_ν)

particle physics: absolute neutrino mass scale (m_ν)



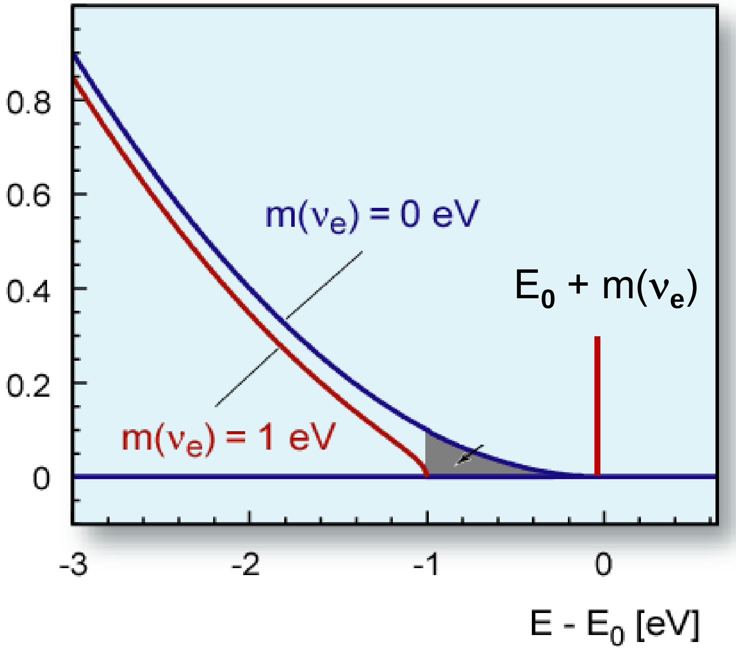
motivation: ν´s in astroparticle physics

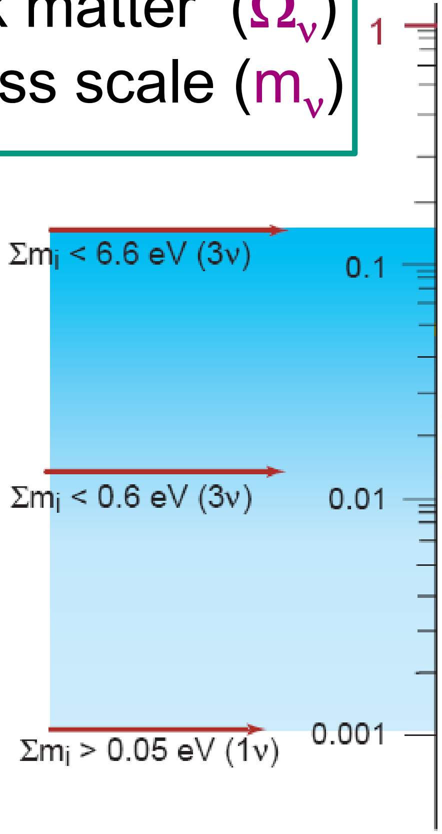
cosmology: role of relic-ν´s as hot dark matter (Ω_ν)
particle physics: absolute neutrino mass scale (m_ν)

- idea: capture of relic neutrinos on ß-unstabile isotope (^3H, ^{187}Re):

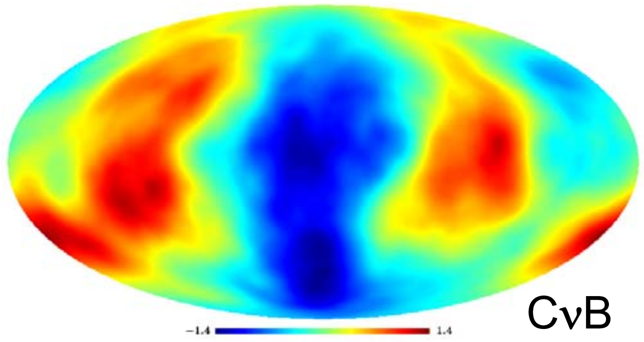
  e.g. $\nu_e + {}^3H \rightarrow {}^3He + e^-$

  advantage: no threshold!





calculated anisotropies of the CνB for m_ν = 10 meV (S. Hannestad, 2009)



CνB dipole

- **experimental challenges in case of ^3H:**

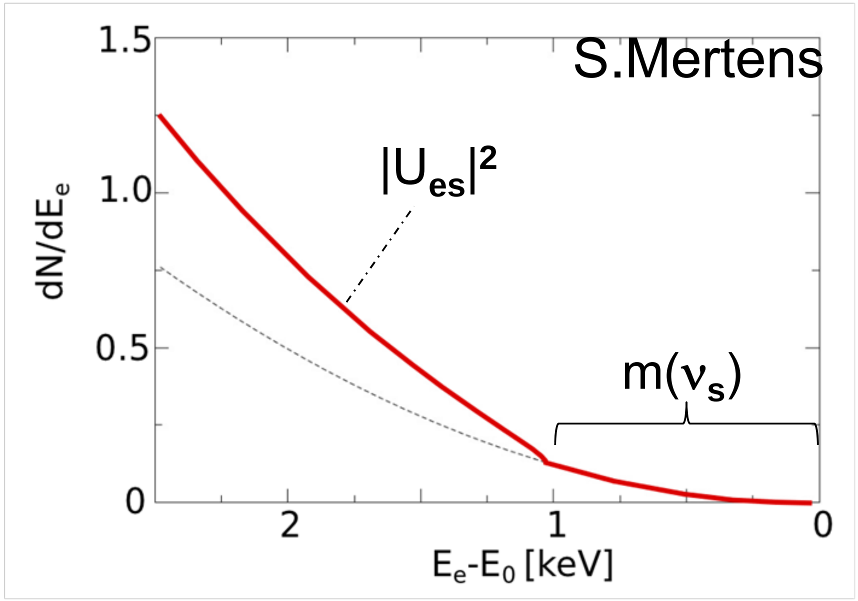
  a) >10^6 KATRIN T_2 target mass required (~100 g), 24 g T_2 are on site at TLK

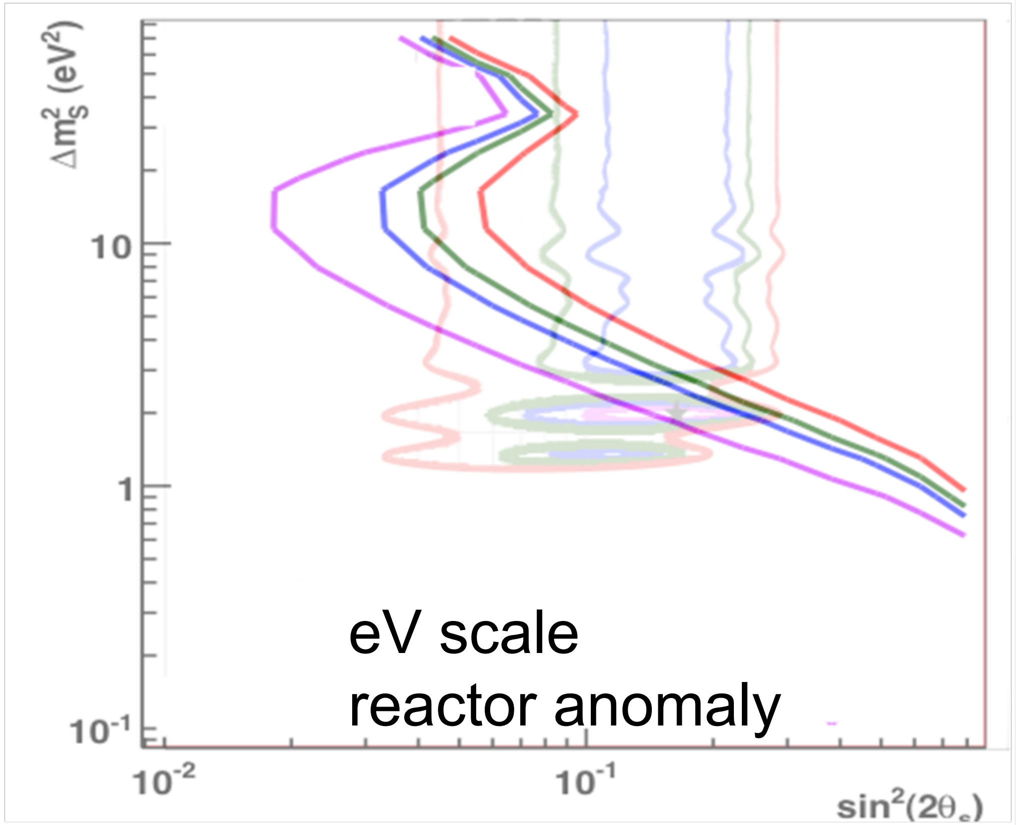
  b) resolution ΔE < 50 meV for 18.6 keV ß´s strongly limits accepted source solid angle

motivation: searching for sterile neutrinos

cosmology: role of relic-ν´s as hot dark matter (Ω_ν)
particle physics: absolute neutrino mass scale (m_ν)

- idea: **detect kinks in ß-decay spectrum** when mass of sterile species is accessible kinematically in ß-decay (sub-eV to keV scale)

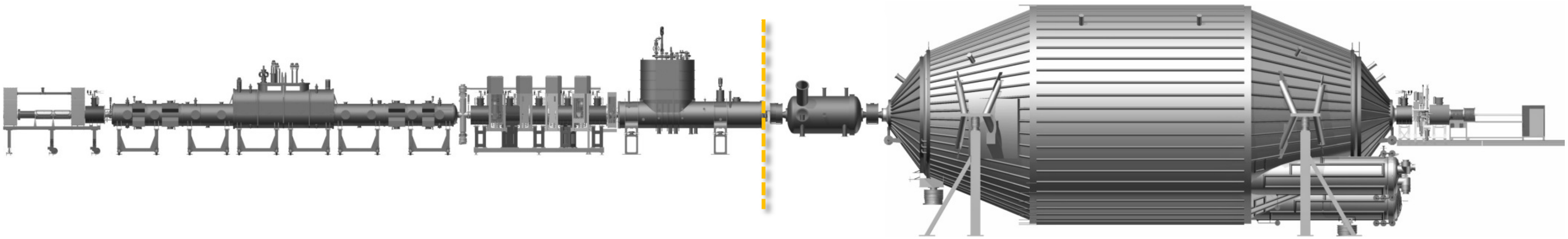




eV scale
reactor anomaly

- see also talk by C. Weinheimer

KATRIN experiment – overview



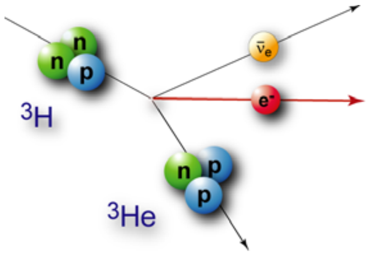
Source & Transport Section (STS)

Spectrometer & Detector Section (SDS)

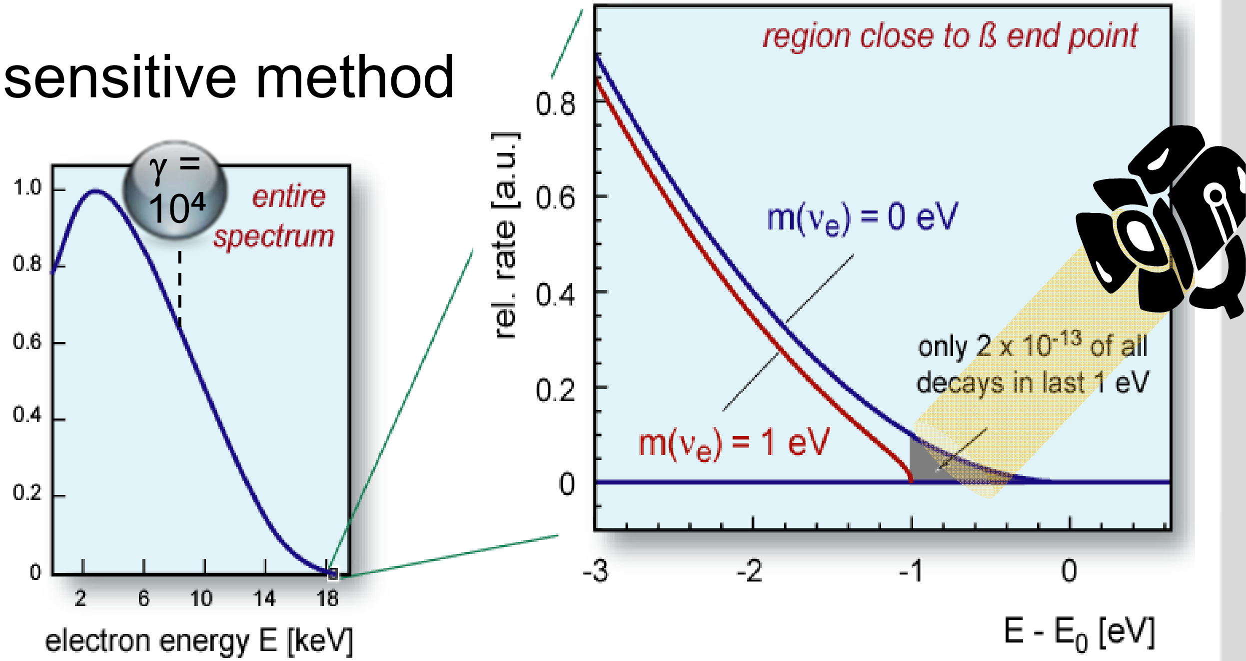
ideal
ß-emitter

^3H: super-allowed	
E_0	**18.6 keV**
$t_{1/2}$	**12.3 y**

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

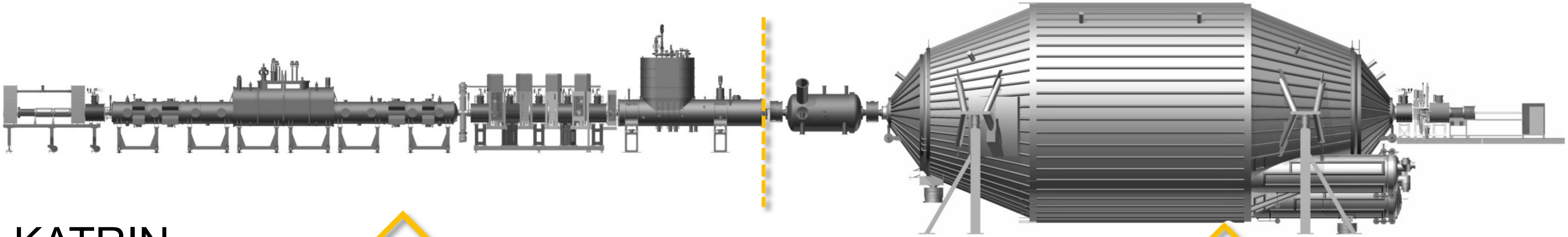


most sensitive method



G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, Current Direct Neutrino Mass Experiments (Review)
Advances In High Energy Physics (2013) 293986

KATRIN experiment – overview

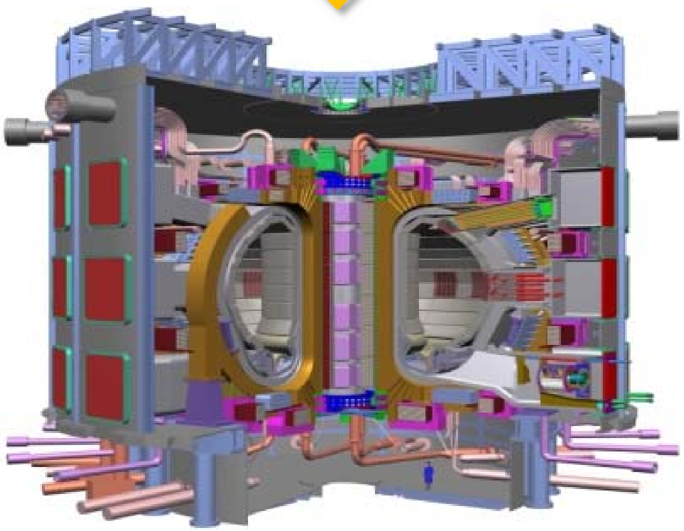


KATRIN
(2015)

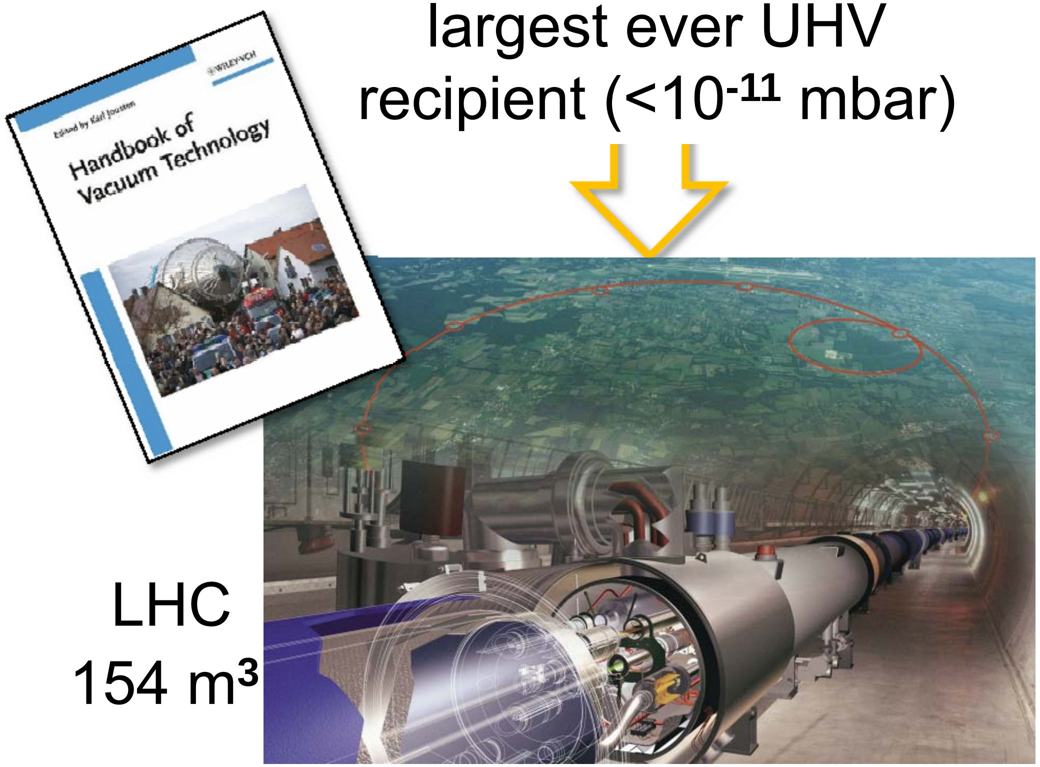
1250 m^3

largest ever tritium throughput ~ **10 kg/a**

largest ever UHV recipient (<10^{-11} mbar)



ITER
(2027)



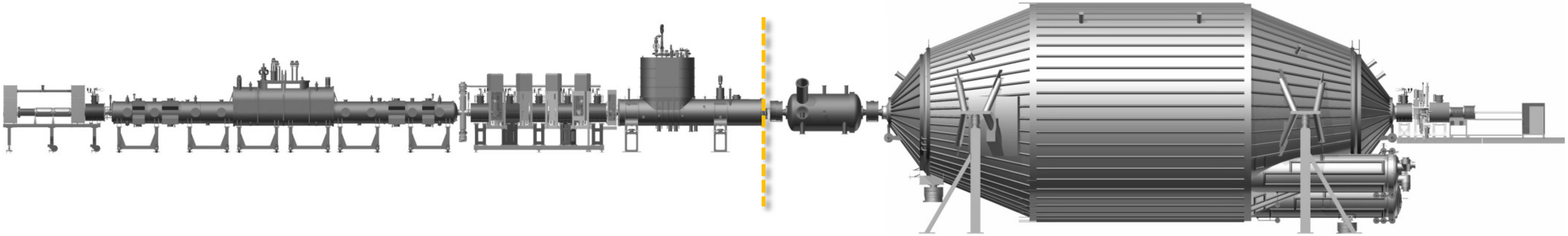
WILEY-VCH

Edited by Karl Jousten

Handbook of Vacuum Technology

LHC
154 m^3

KATRIN – benchmark parameters



tritium source: 10^{11} ß-decays/s

(≡ LHC particle production)

total background: 10^{-2} cps

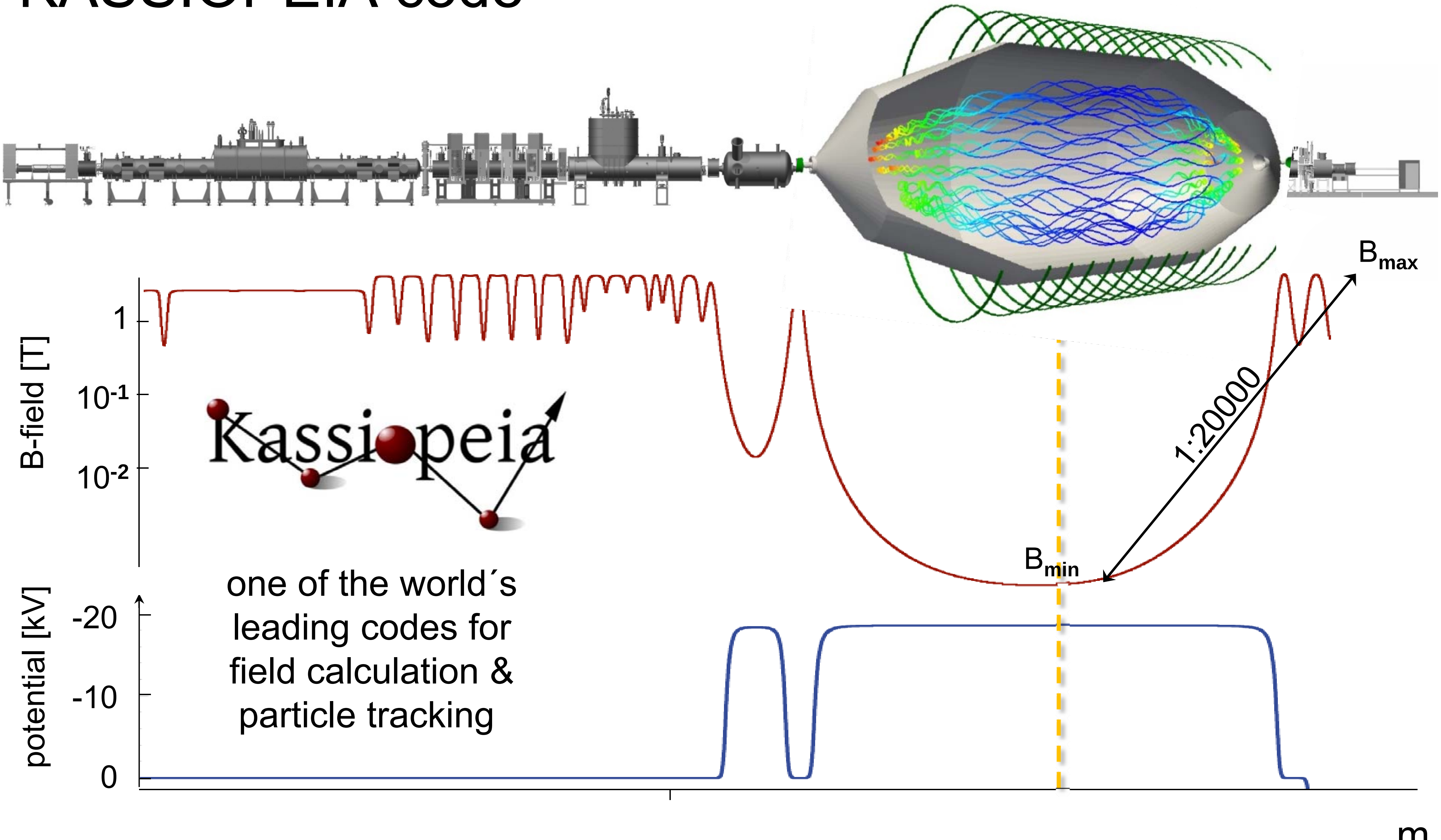
(≡ low level @ 1 mwe)

experimental challenges

- 10^{-3} stability of tritium source column density
- 10^{-3} isotope content in source
- 10^{-5} non-adiabaticity in electron transport
- 10^{-6} monitoring of HV-fluctuations
- 10^{-8} remaining ions after source
- 10^{-14} remaining flux of molecular tritium

many benchmark parameters reached or exceeded

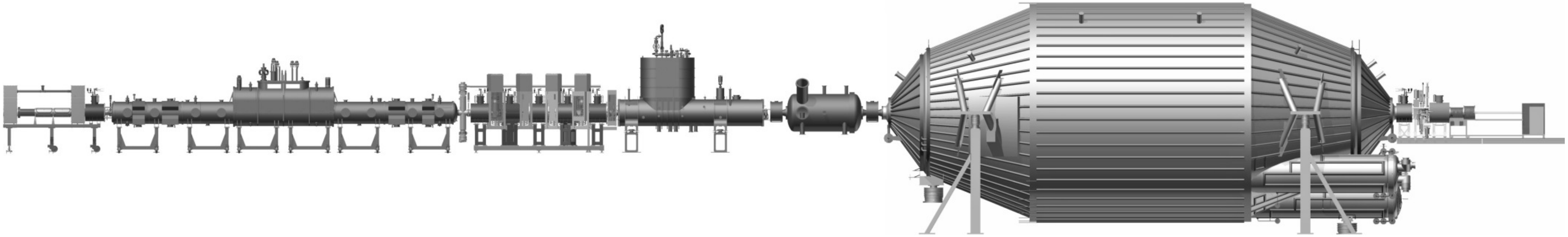
KASSIOPEIA code



one of the world´s leading codes for field calculation & particle tracking

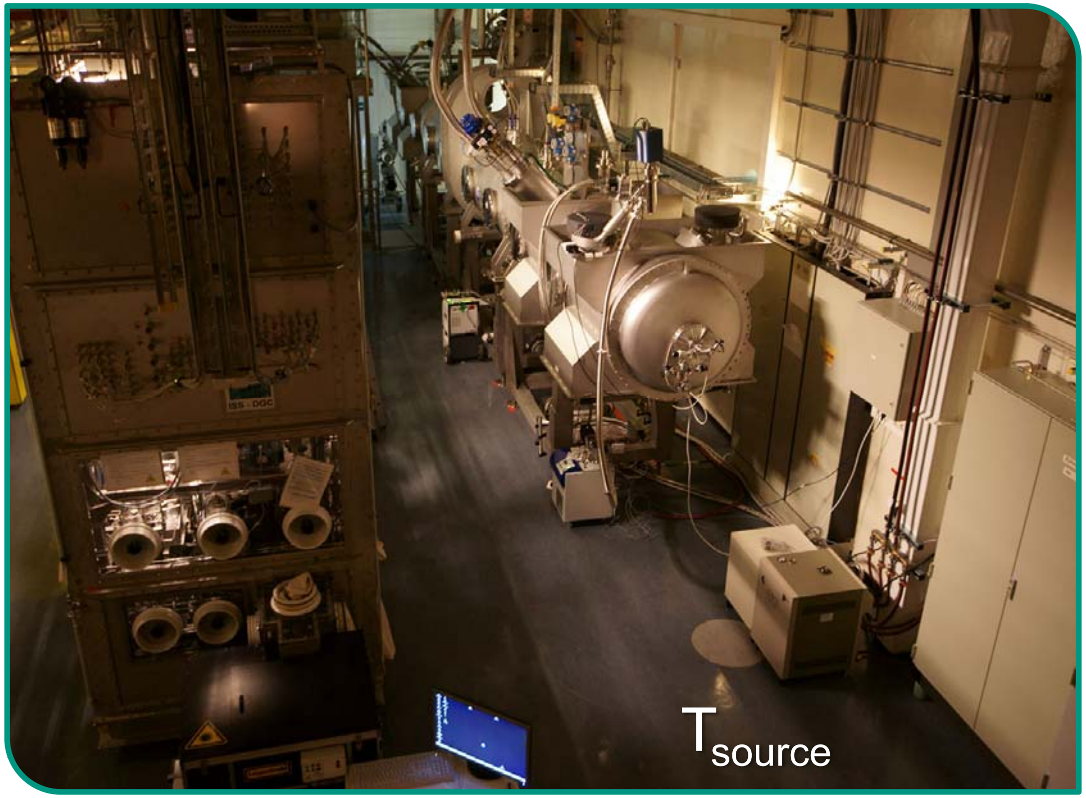
F. Glück, Prog. in Electromagnetics Research B, 32 (2011) 351-388 & 319-350

KATRIN – challenges and solutions

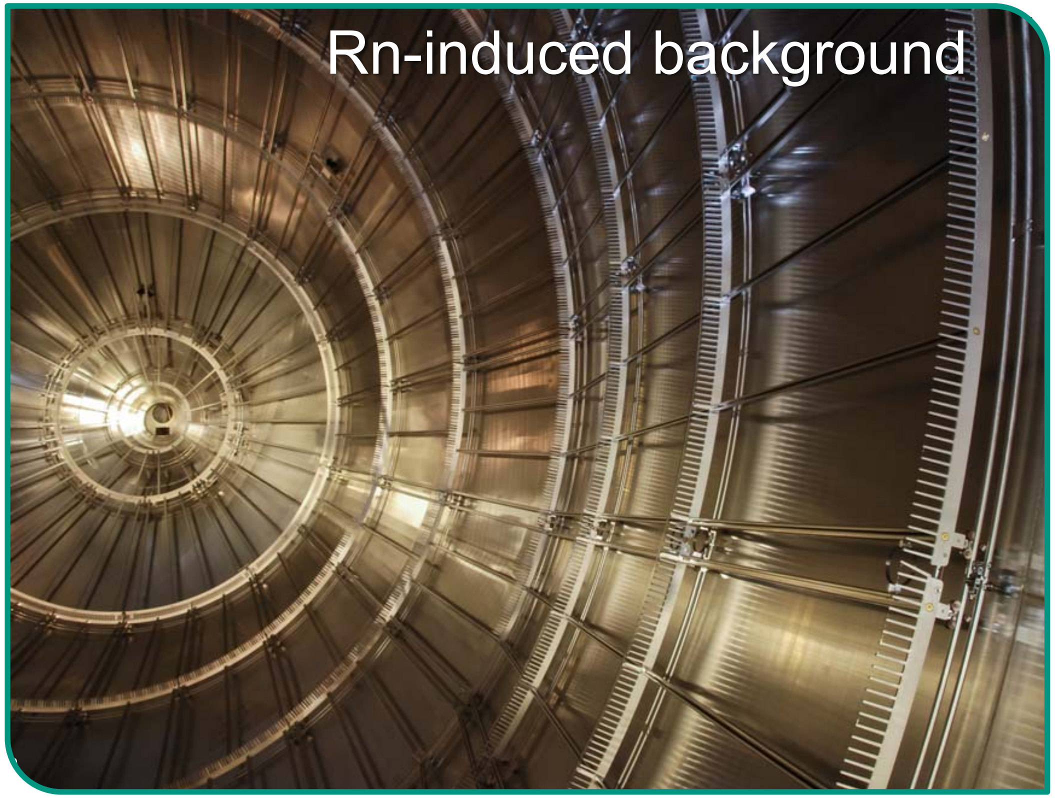


WGTS demonstrator

main spectrometer



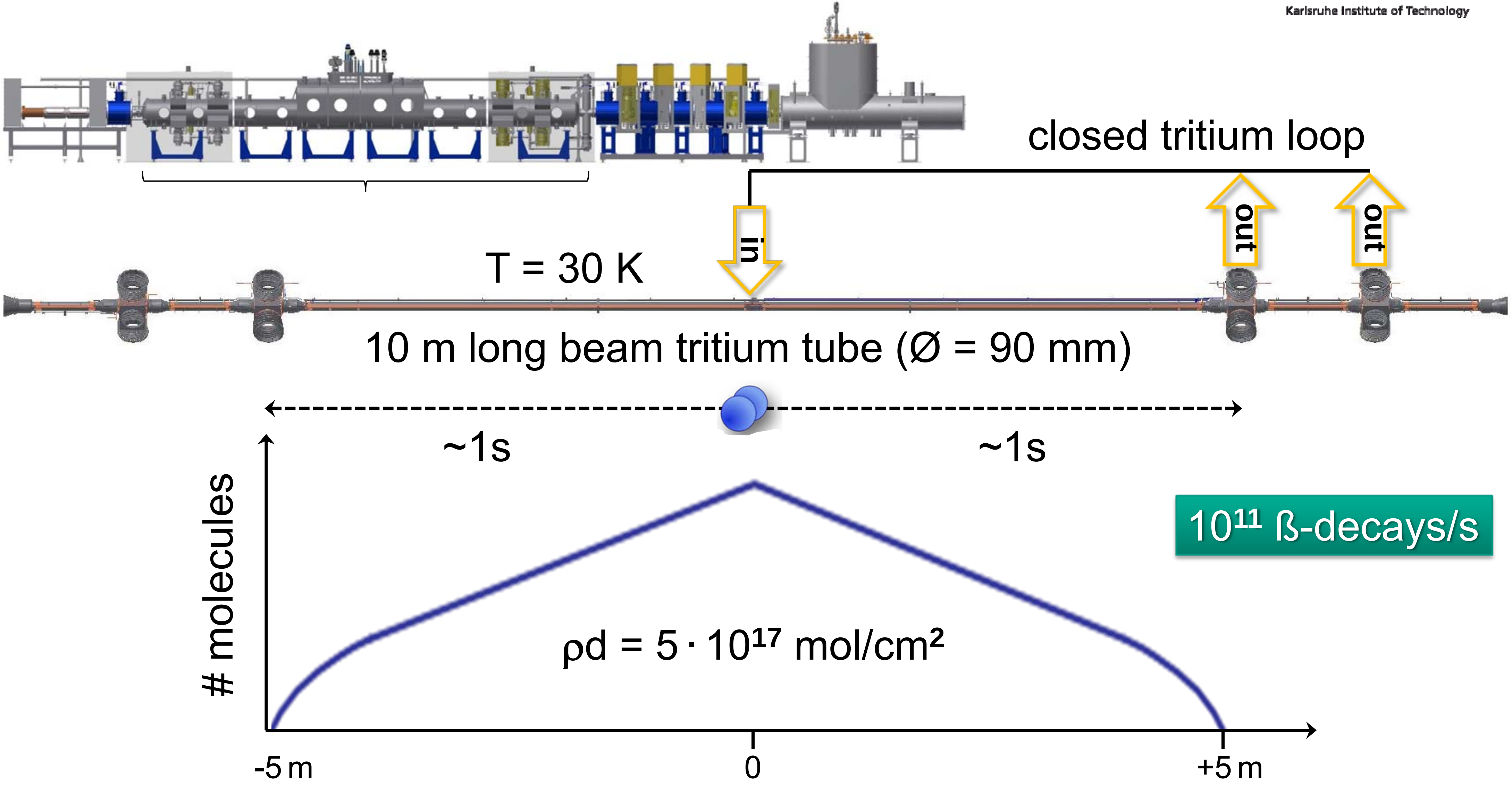
T_{source}



Rn-induced background

Why is the gaseous tritium source so challenging when measuring m(ν_e) and hunting for keV-mass ν_s?

WGTS – principle

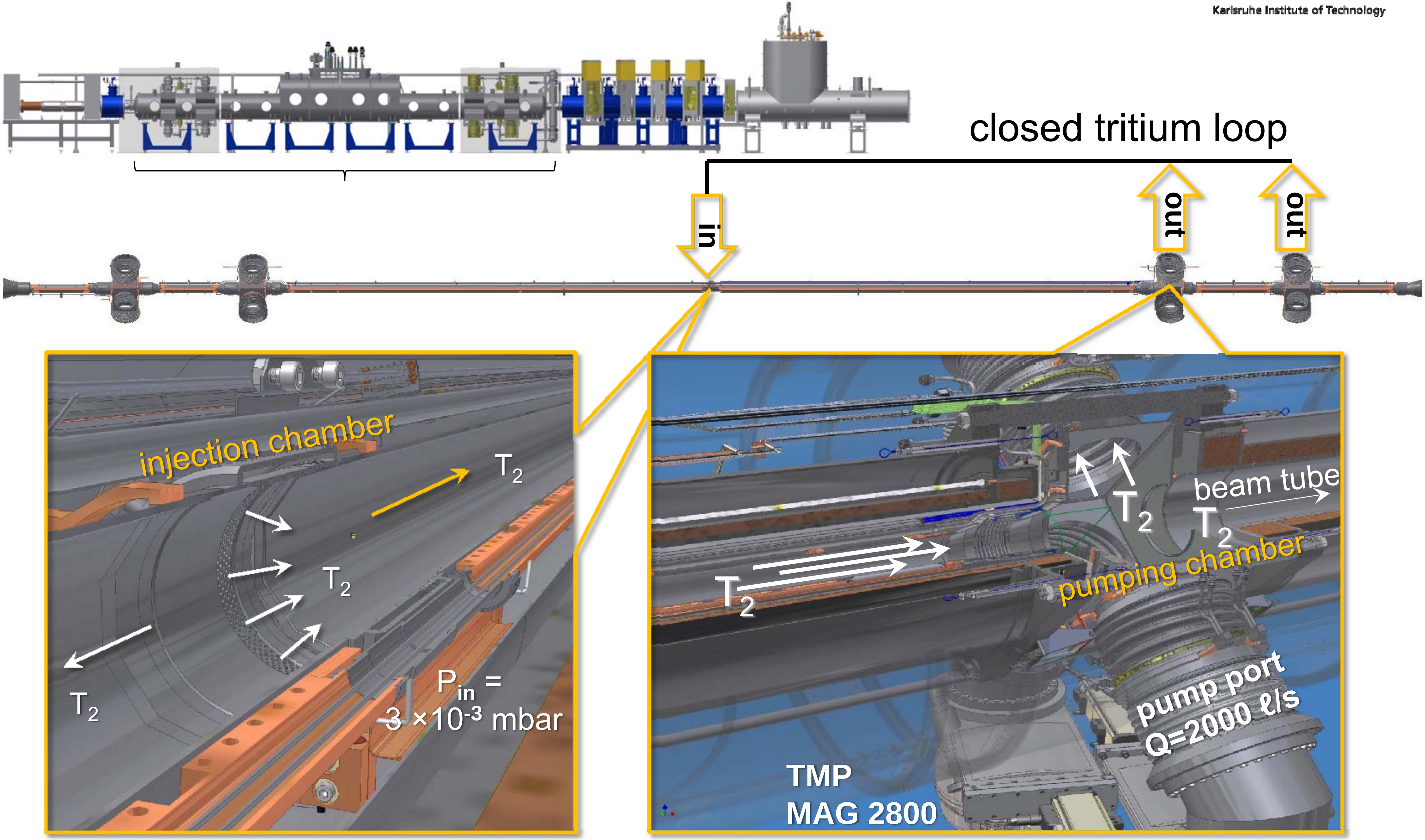


$\rho d = 5 \cdot 10^{17}$ mol/cm²

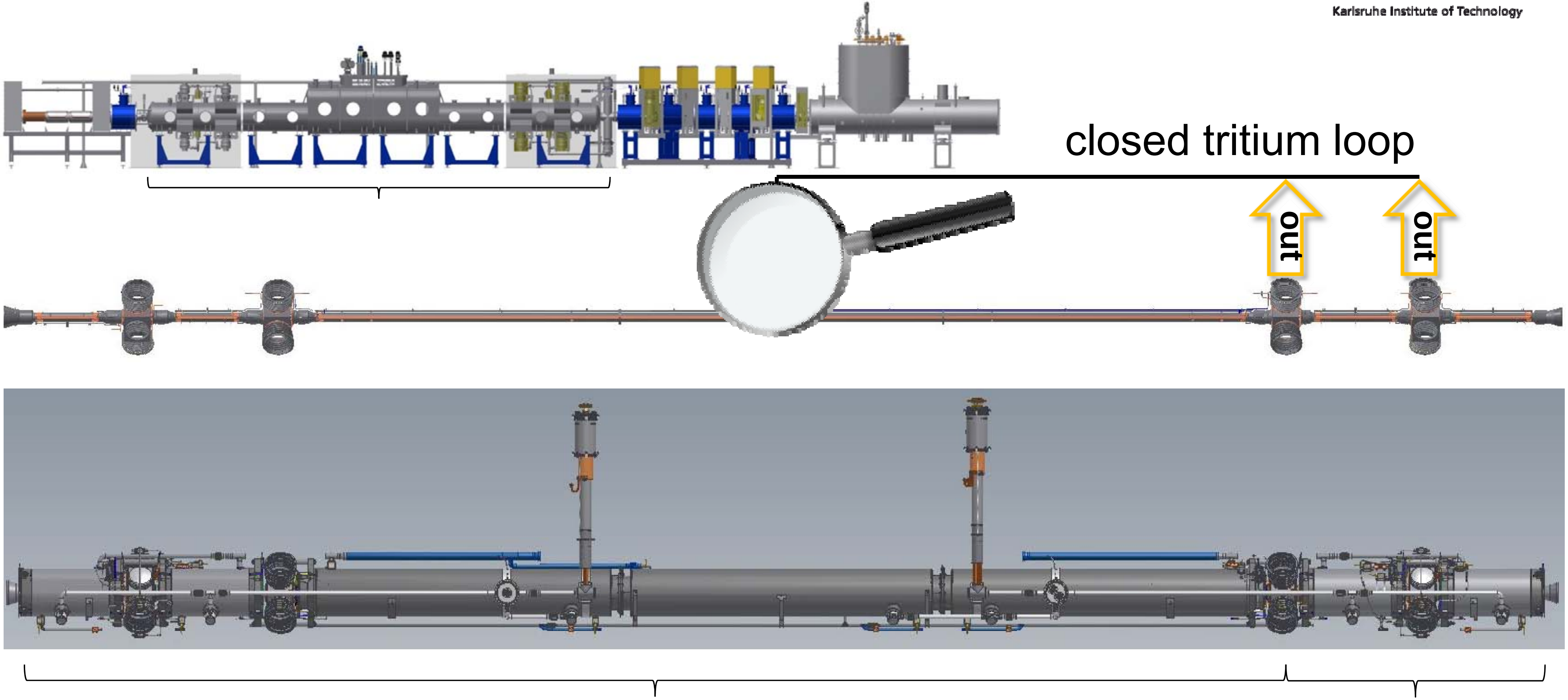
10^{11} ß-decays/s

Windowless Gaseous Tritium Source

WGTS – injection & pumping chamber



WGTS – s.c. magnet system



closed tritium loop

out

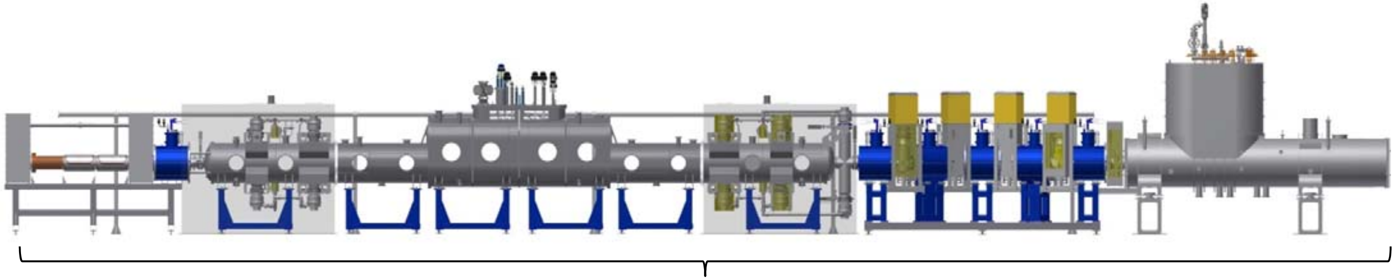
out

B = 3.6 T

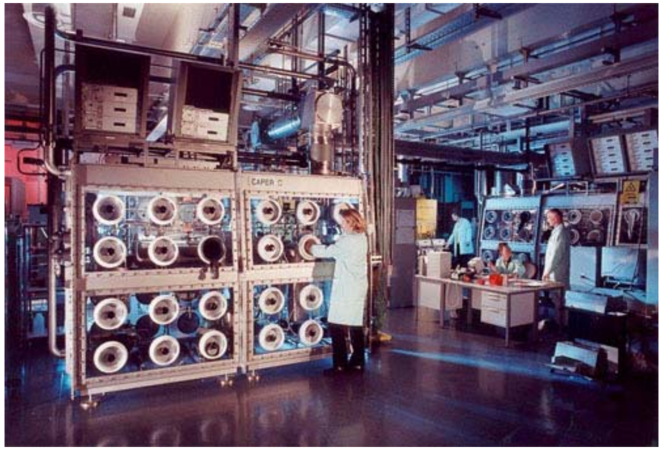
B = 5.6 T

superconducting magnet system for adiabatic guiding of ß-decay electrons

Tritium Laboratory Karlsruhe – TLK



tritium bearing components



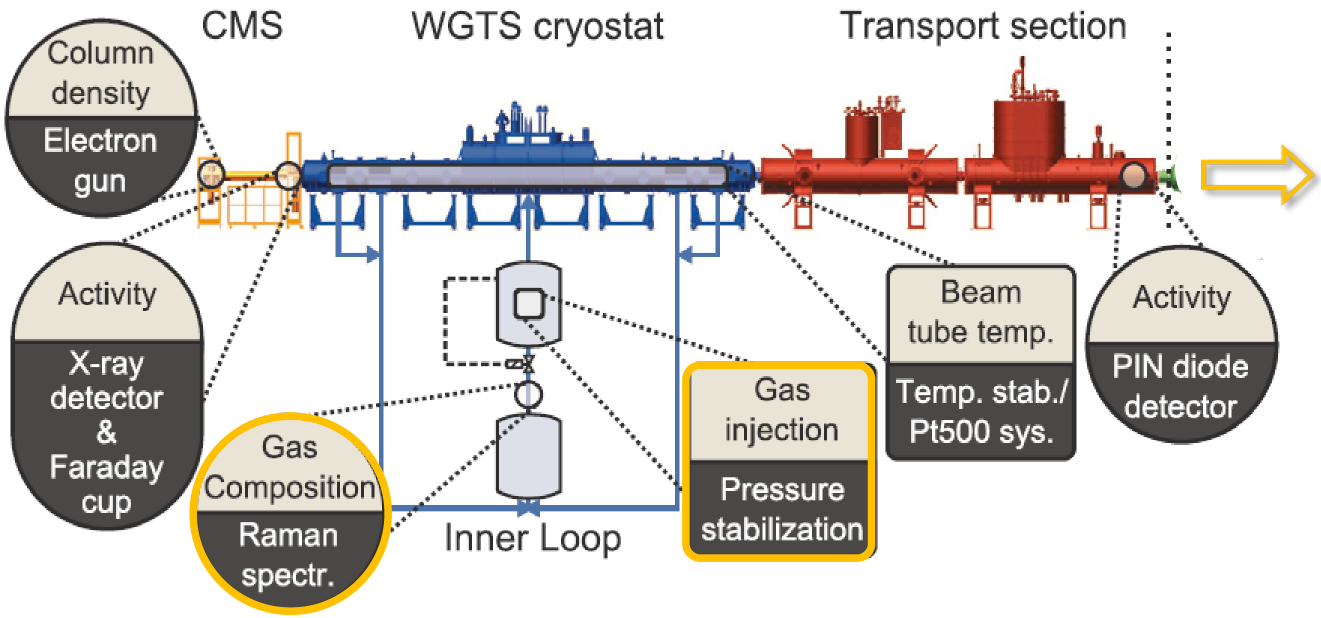
- **TLK**: unique large research facility at KIT for KATRIN and fusion (ITER)
  20 years of experience in tritium handling and processing, 24 g on-site

Tritium Laboratory Karlsruhe

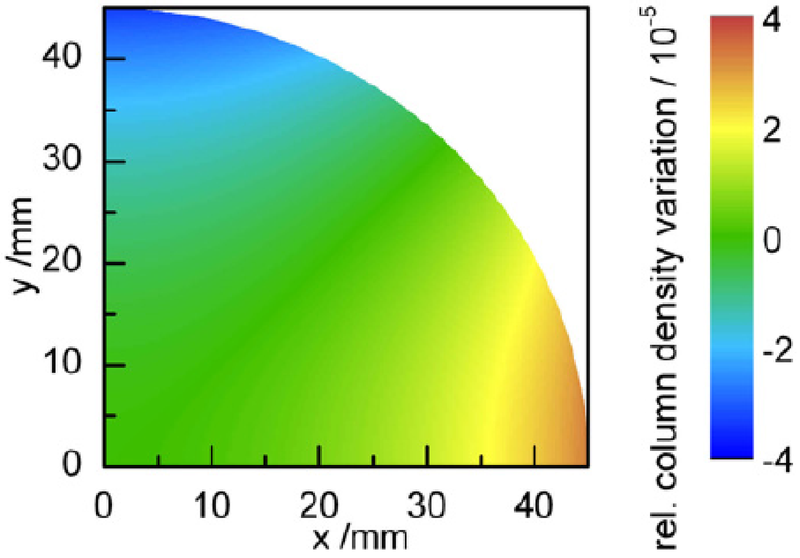
B. Bornschein et al., **Fusion Sci. Techn. 60 (2011) 1088**

Investigation of source systematics

- **control of source systematics:**
  - near-time control/monitoring systems for key parameters ☑
  - successful large-scale test experiments (WGTS demonstrator) ☑
  - improved source modelling: quasi-3D gas flow ☑

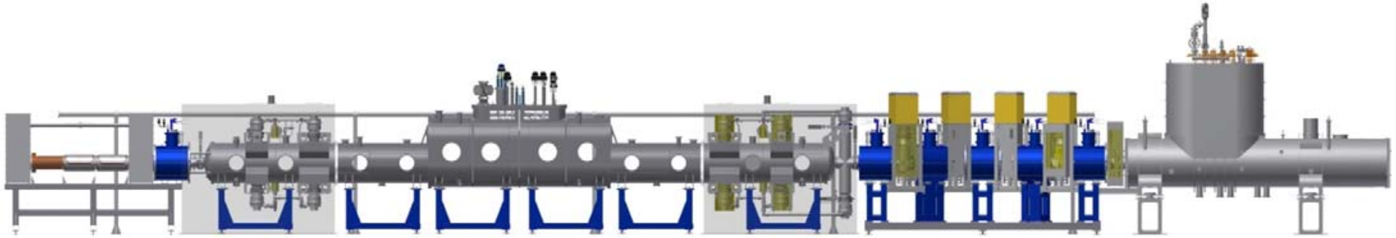


column density profile



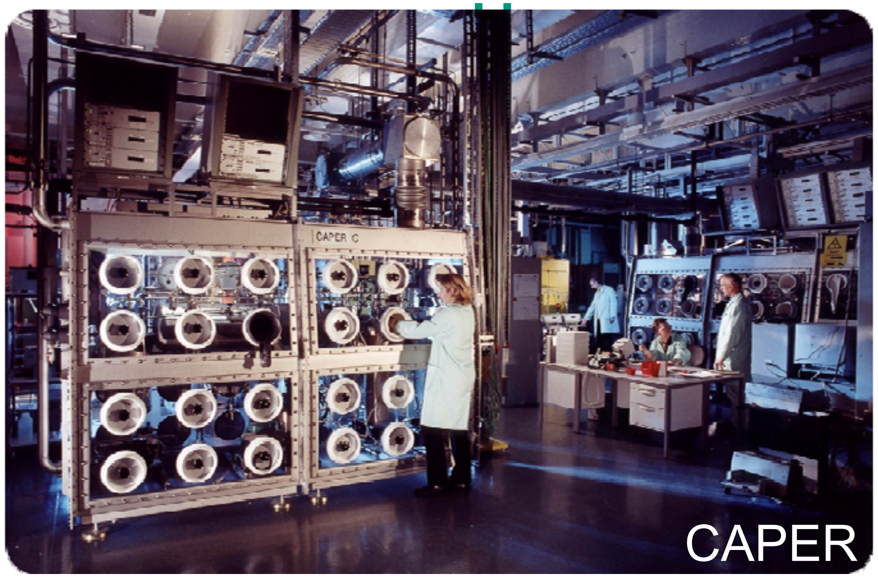
M. Babutzka et al., **New Journal of Physics 14 (2012) 103046**

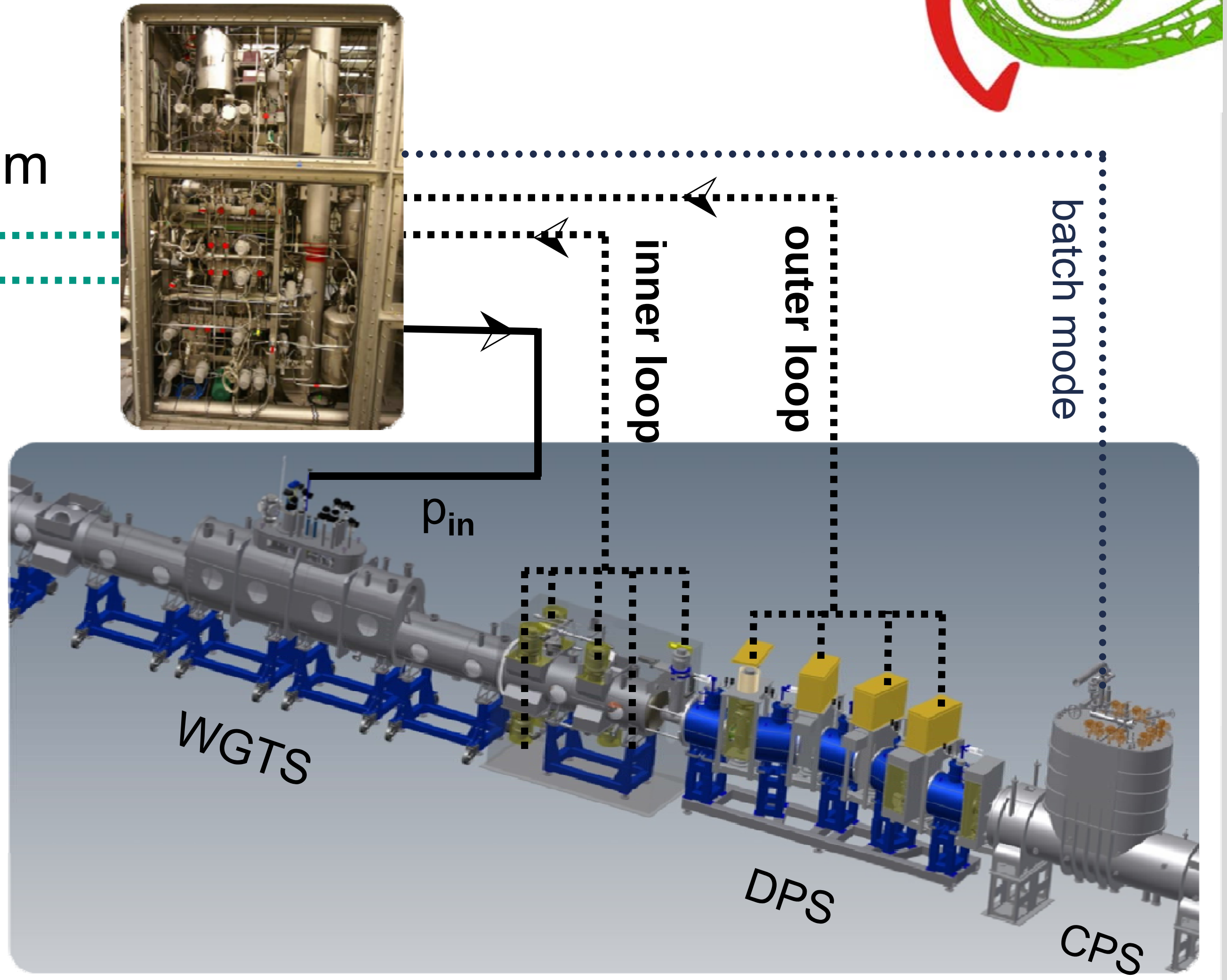
Closed loops and high-purity tritium source



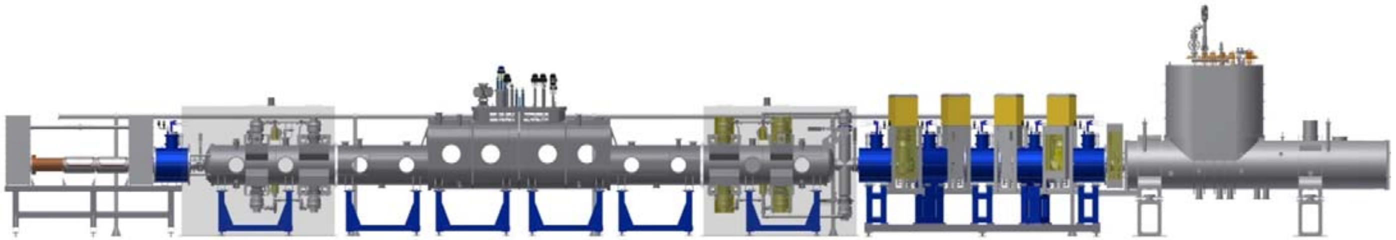
- **continuous purification**
  with **I**sotope **S**eparation **S**ystem

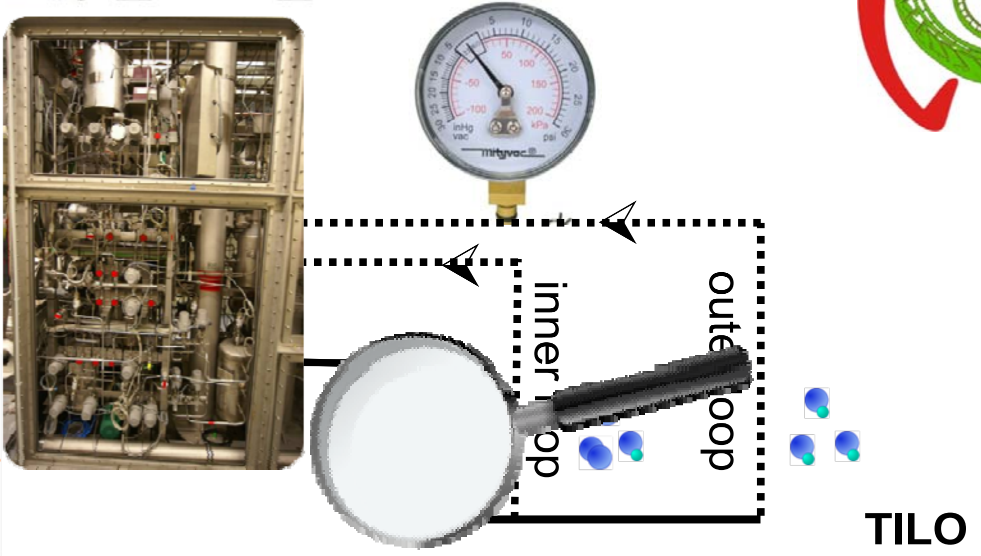
extensive
TLK infrastructure



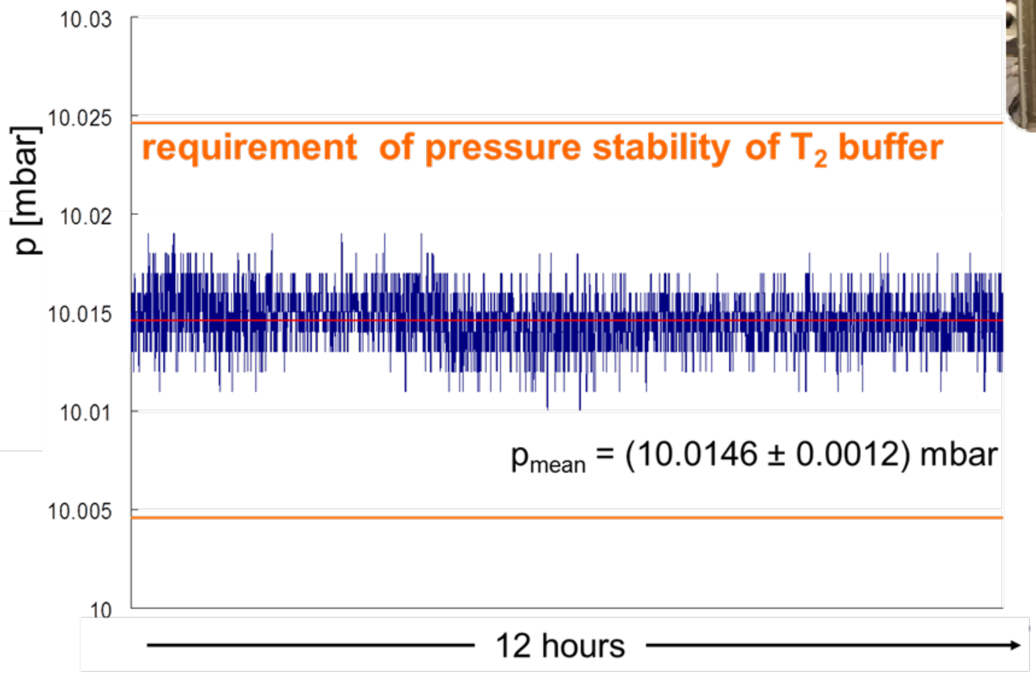


Test of Inner Loop (TILO)



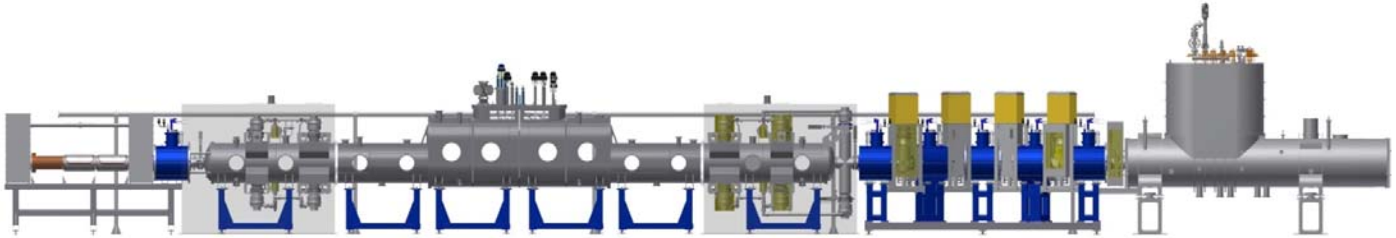


- **demonstrate stability of tritium flow in closed loop system**

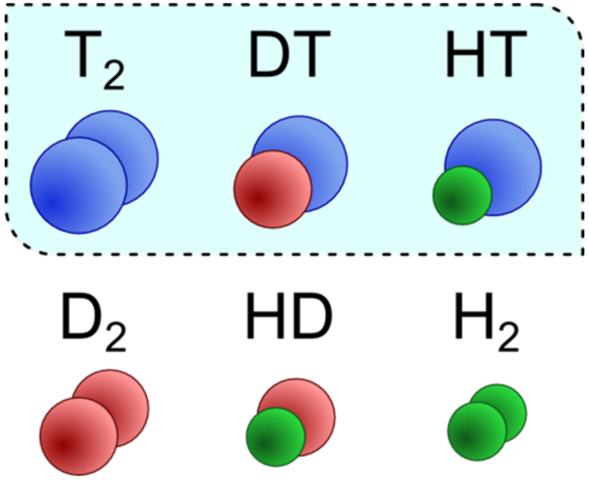


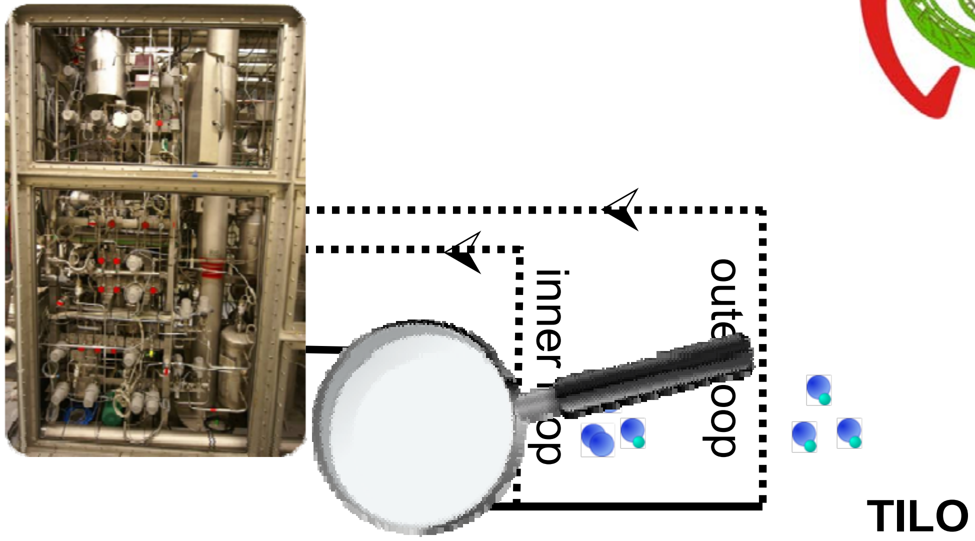
- **TILO achievements**
  - successful commissioning ☑
  - stability: required: 10^{-3}
    achieved: 10^{-4} ☑
  - reduced source systematics ☑

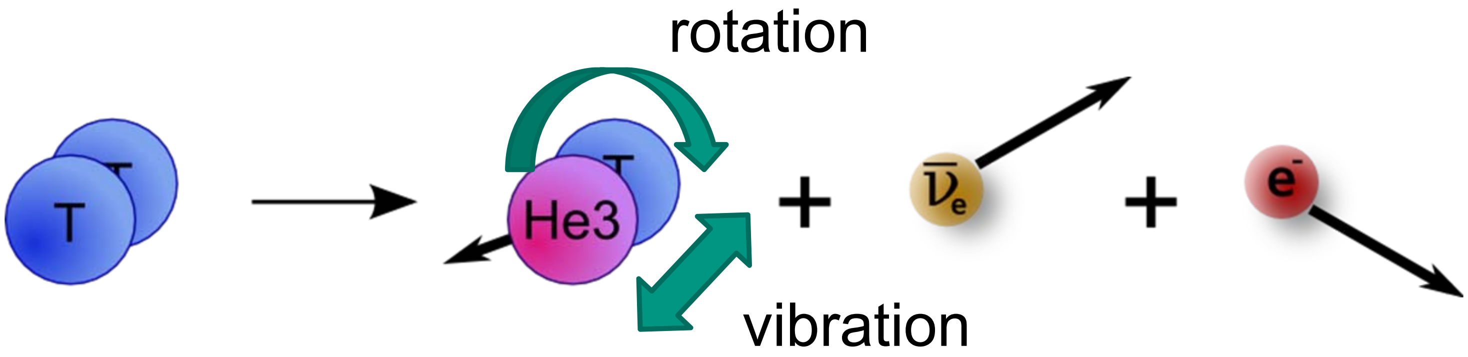
Hydrogen Isotopologues



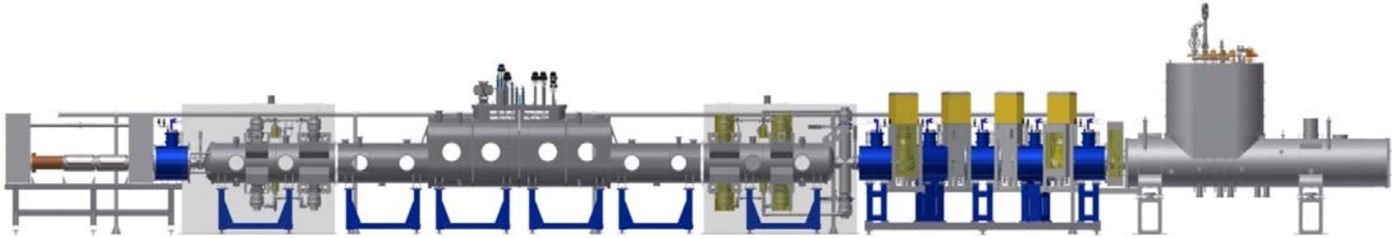
6 Hydrogen isotopologues



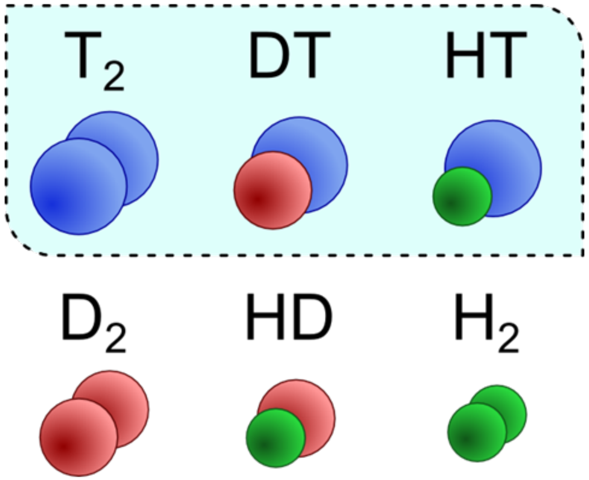


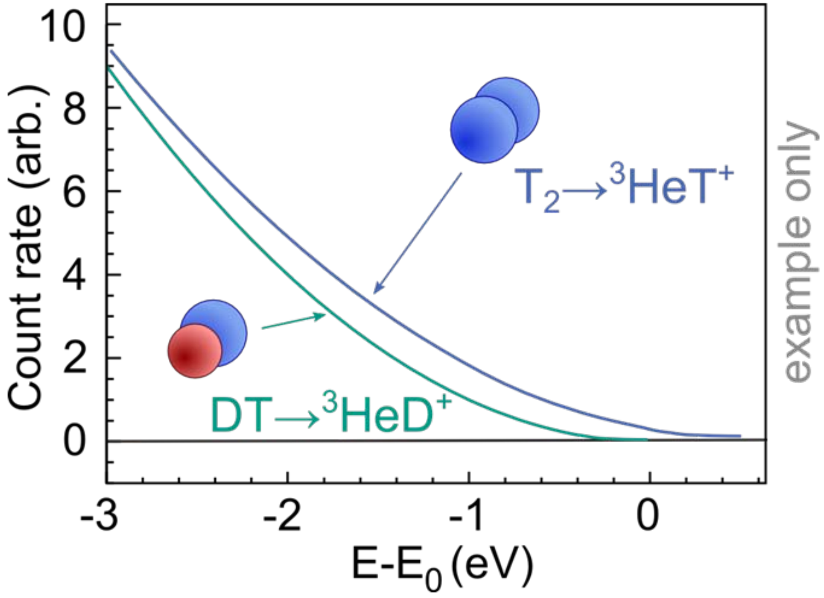


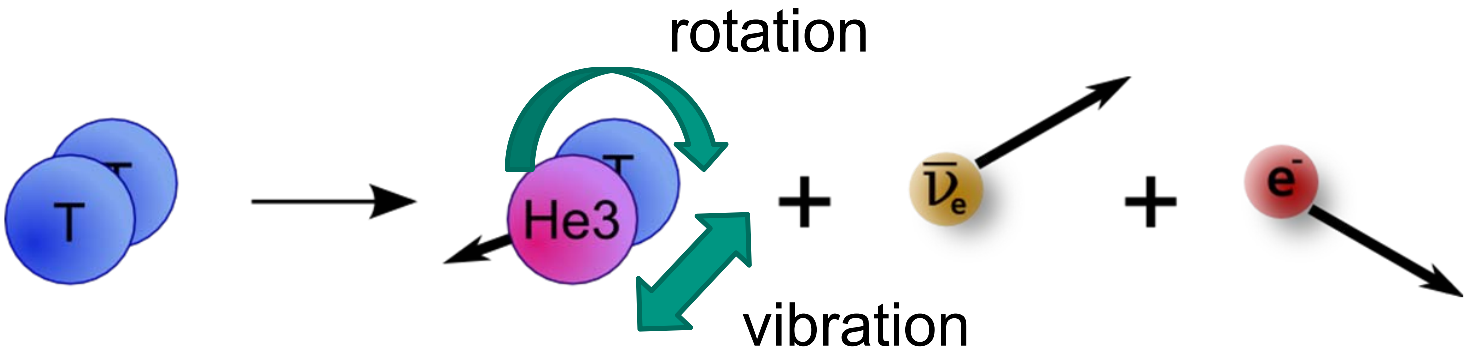
Hydrogen Isotopologues



6 Hydrogen isotopologues

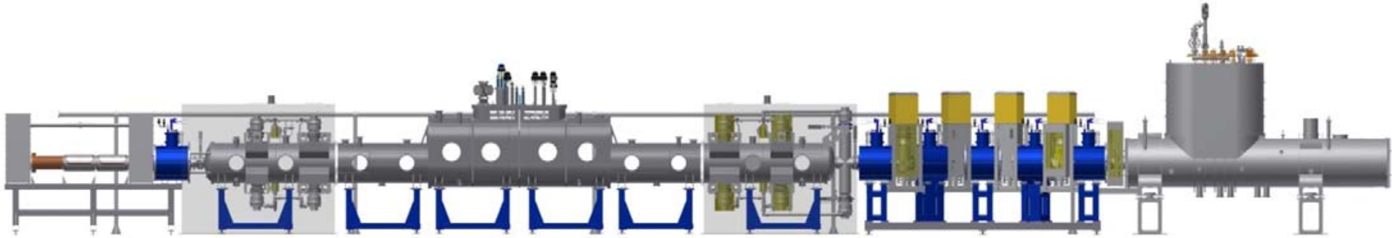




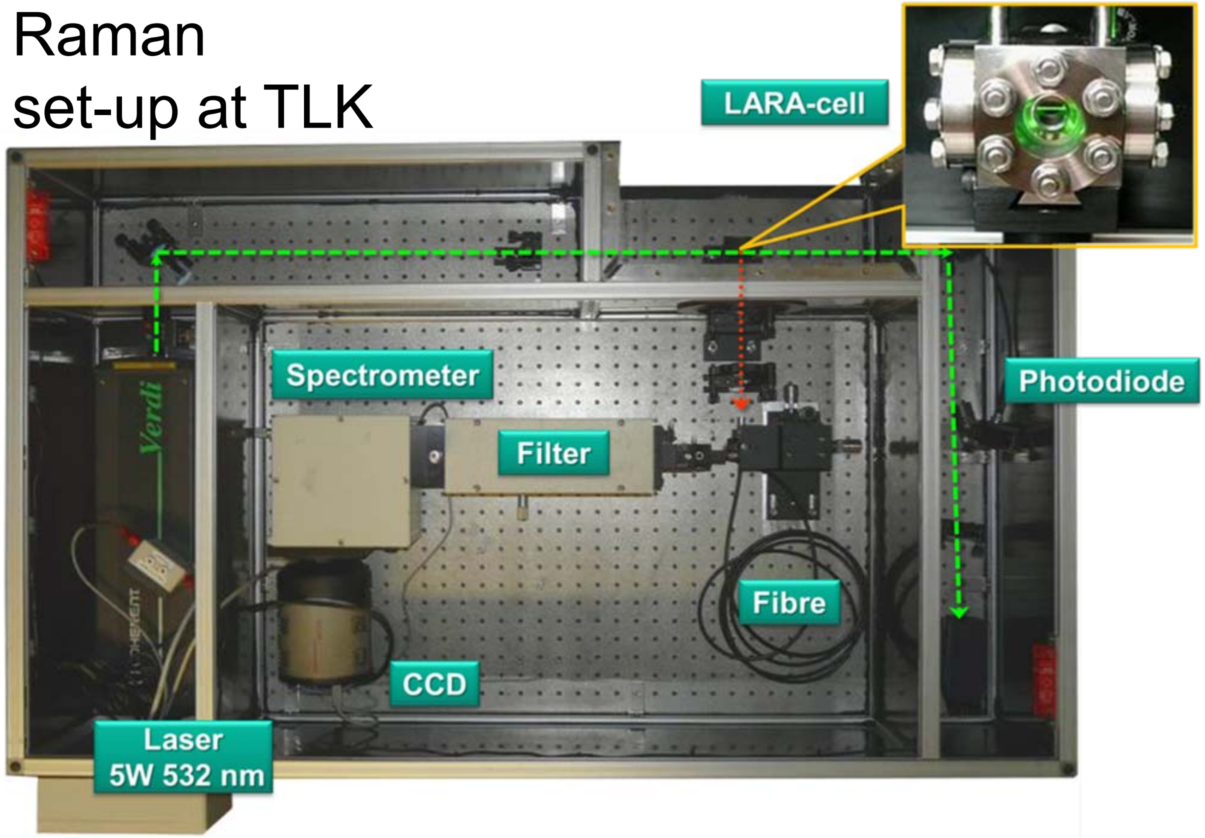


- recoil effects
- molecular excitation (final states)

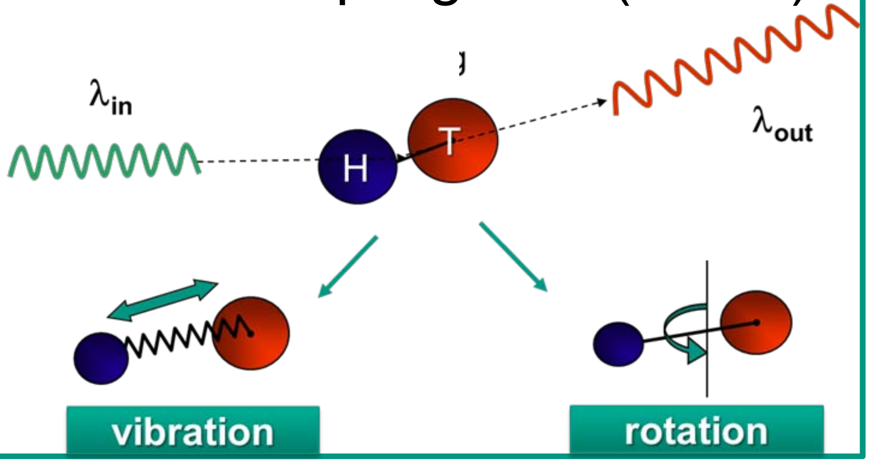
Laser Raman (LARA) spectroscopy



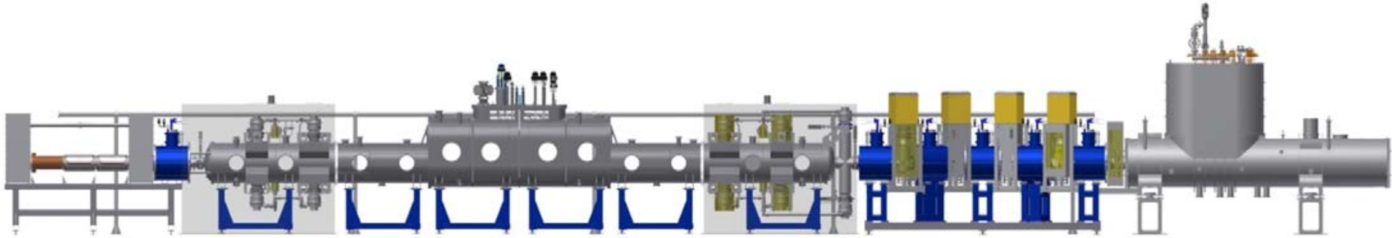
Raman
set-up at TLK



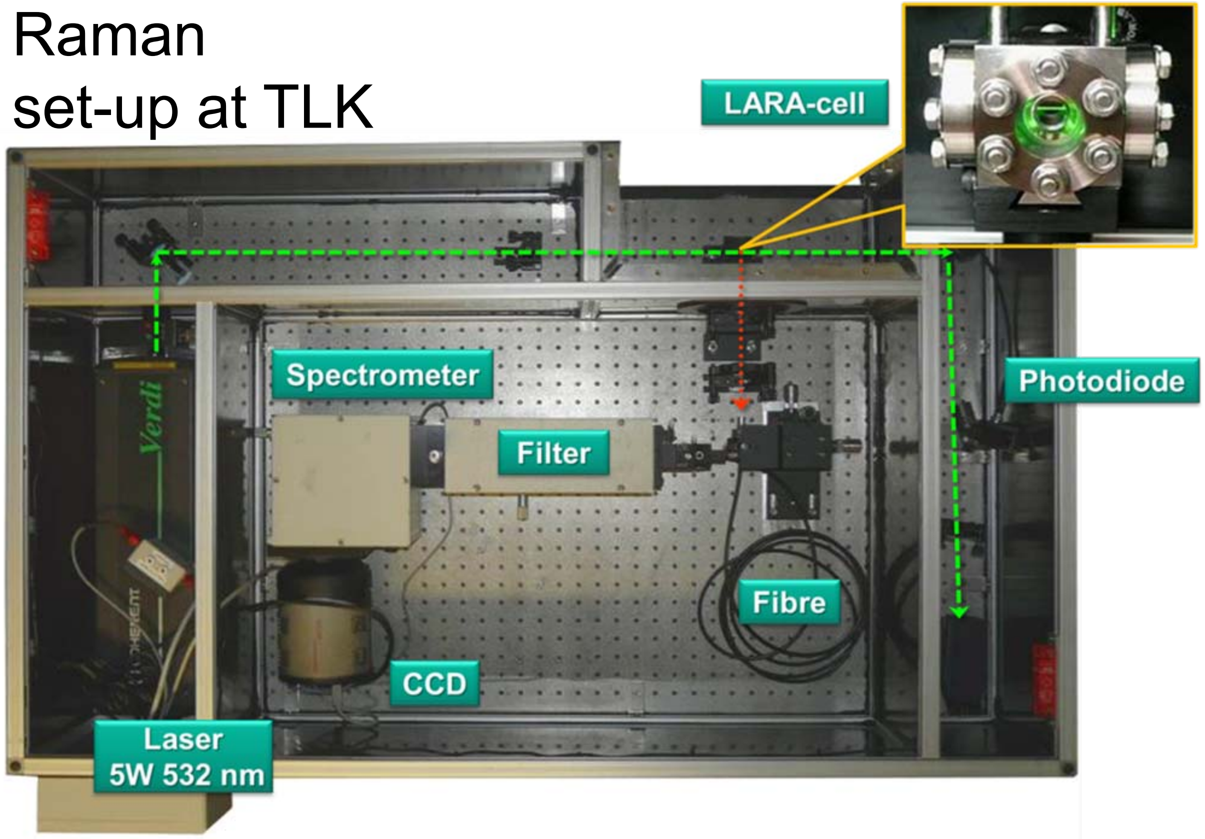
- **LARA task:**
  continuous monitoring of actual H-isotopologue composition
  - high precision (~0.1%)
  - short sampling time (~min.)



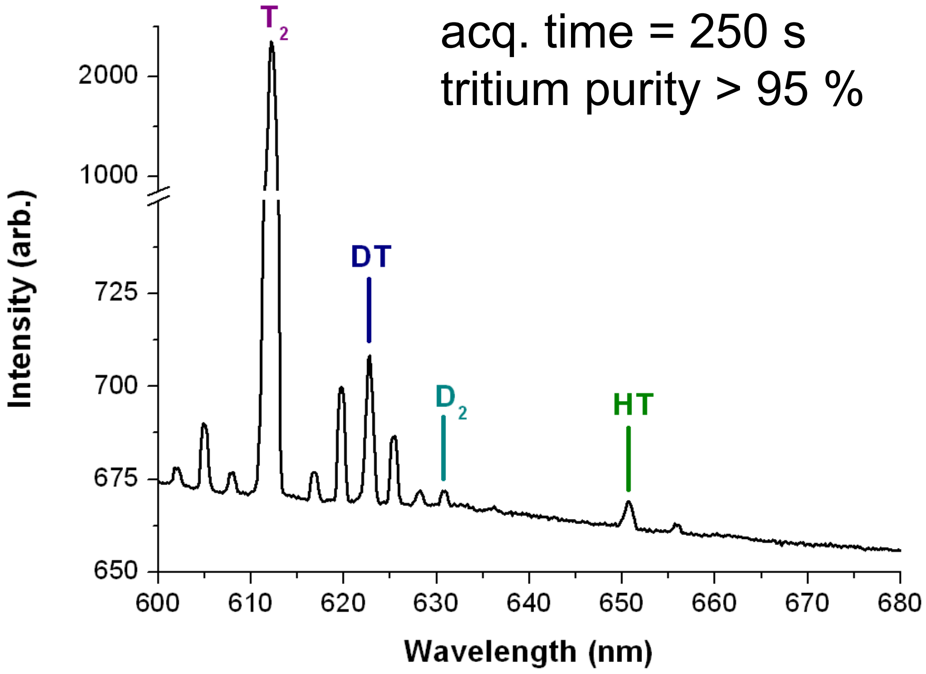
Laser Raman (LARA) spectroscopy



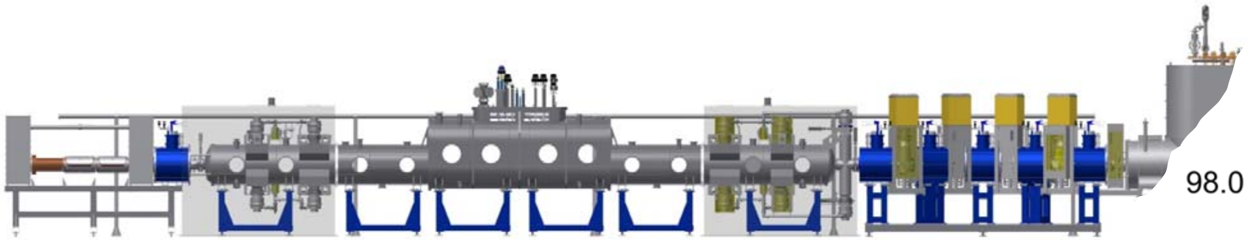
Raman
set-up at TLK

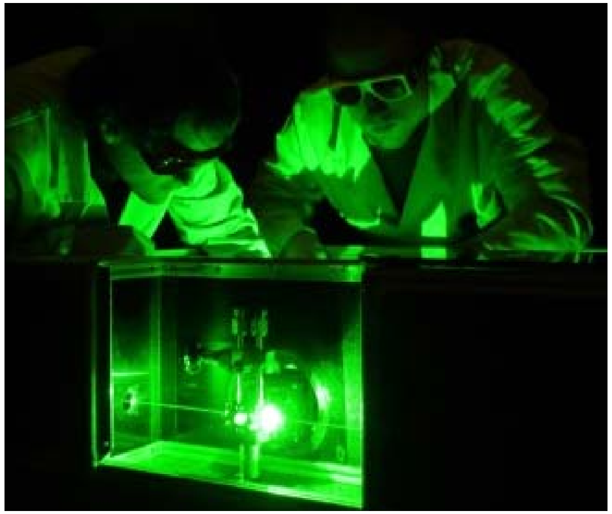


p_{cell} = 200 mbar
laser power = 5 W
acq. time = 250 s
tritium purity > 95 %

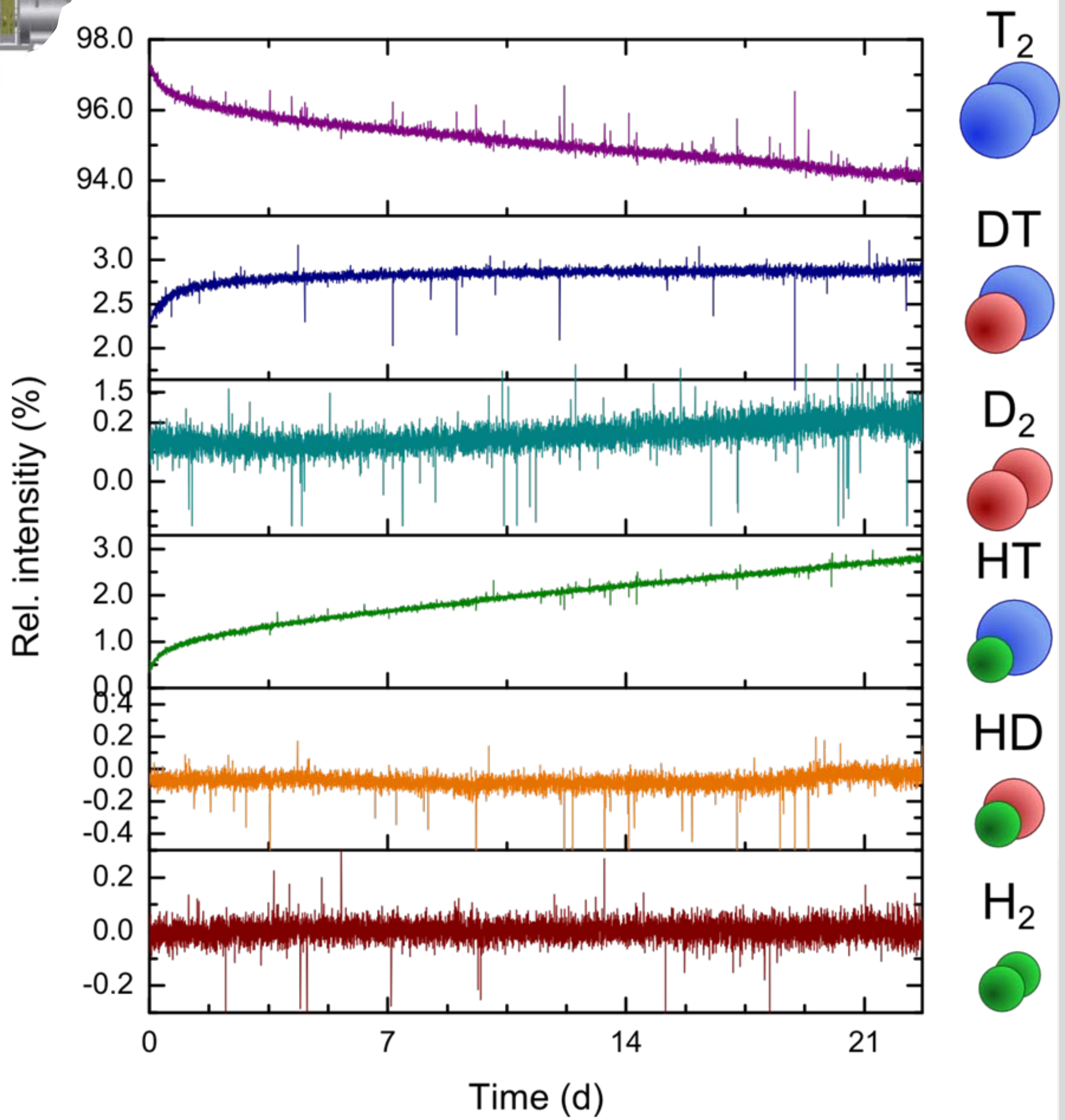


LARA – Laser Raman Spectroscopy



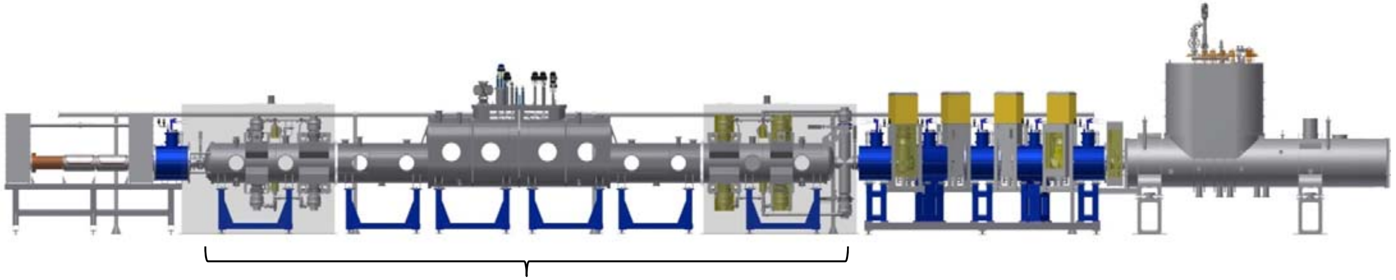


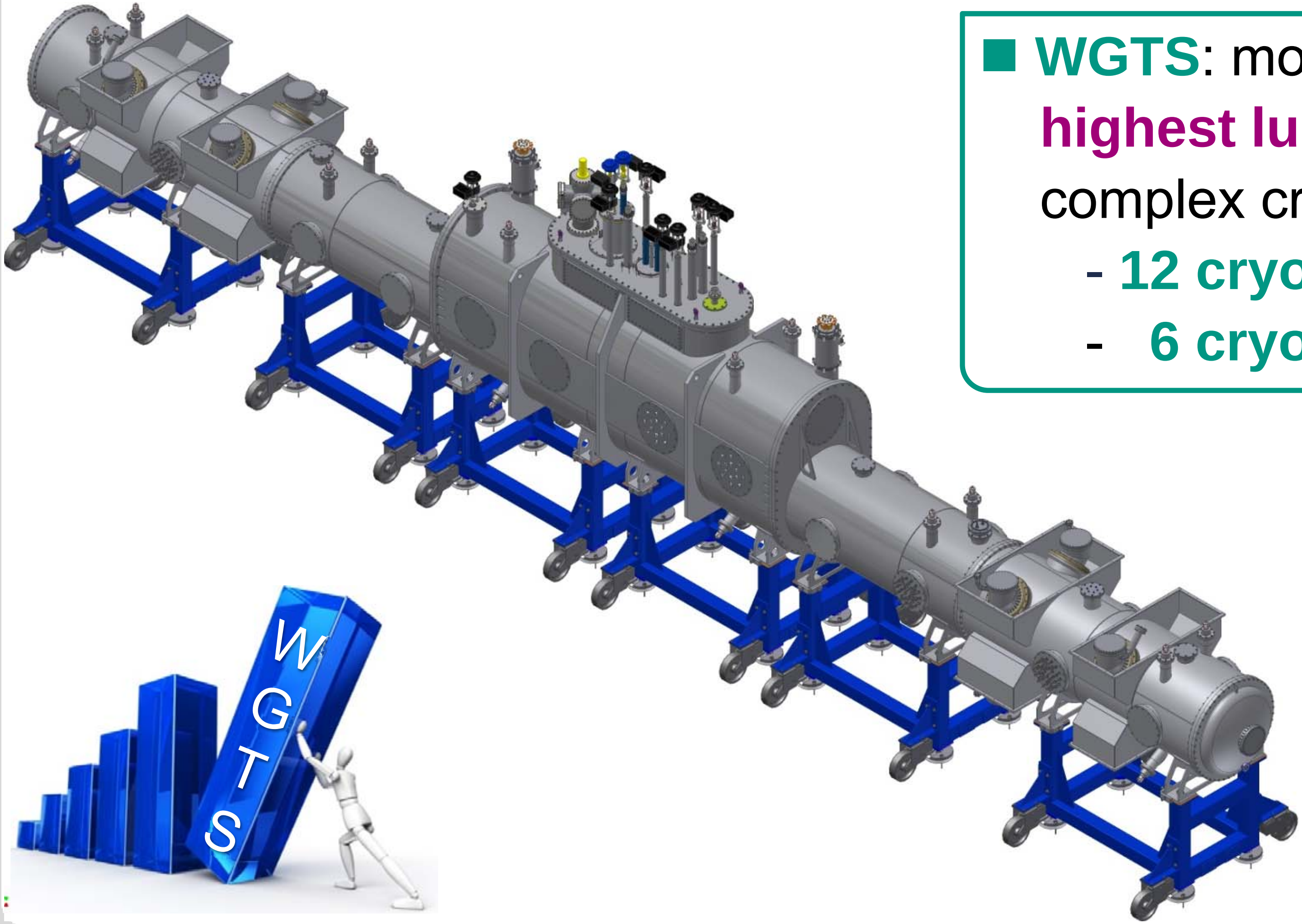
5W
Nd-YAG laser



- **LARA achievements**
  - sampling time reduced to
    $\Delta t = 60$ s for 0.1% precision ☑
  - trueness: required < 10%
    achieved: < 3% ☑
  - systematic investigations ☑

WGTS – windowless gaseous source



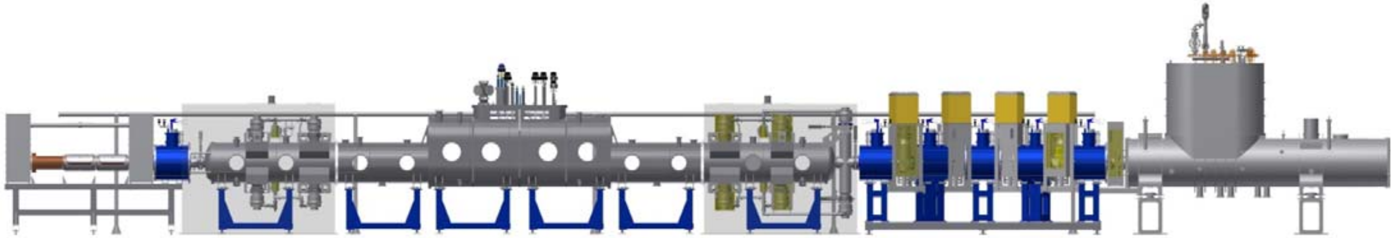


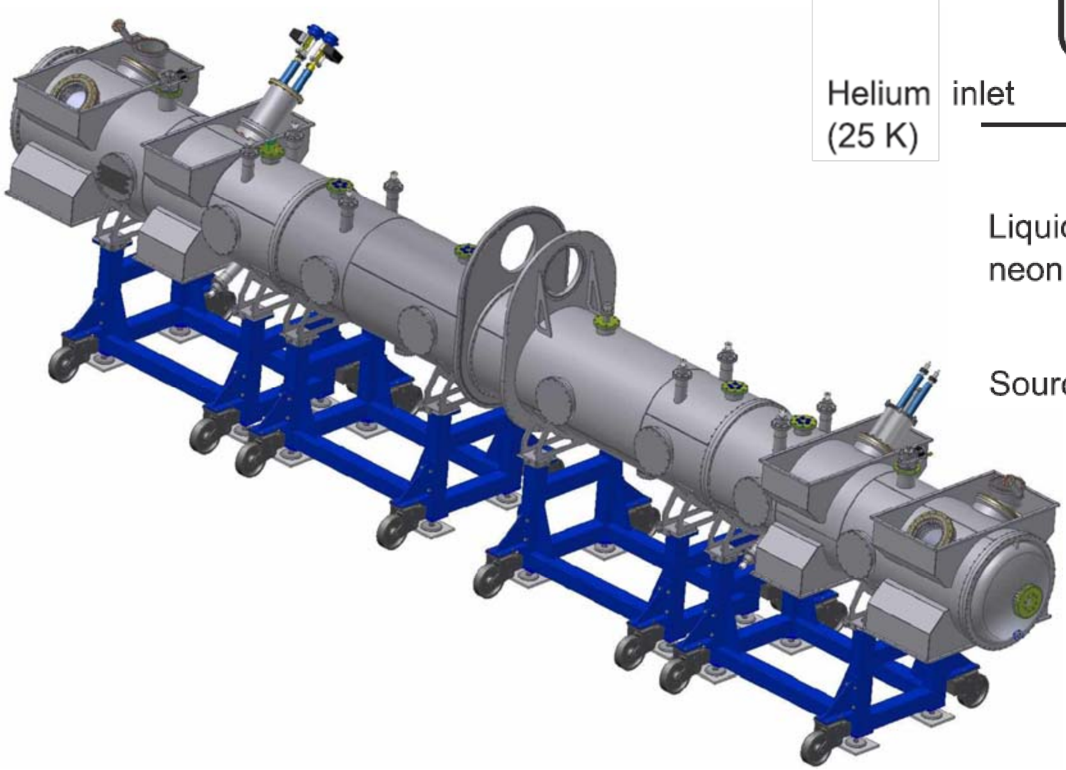
- **WGTS**: molecular tritium source of **highest luminosity** & **stability** complex cryostat with:
  - **12 cryogenic circuits**
  - **6 cryogenic fluids**

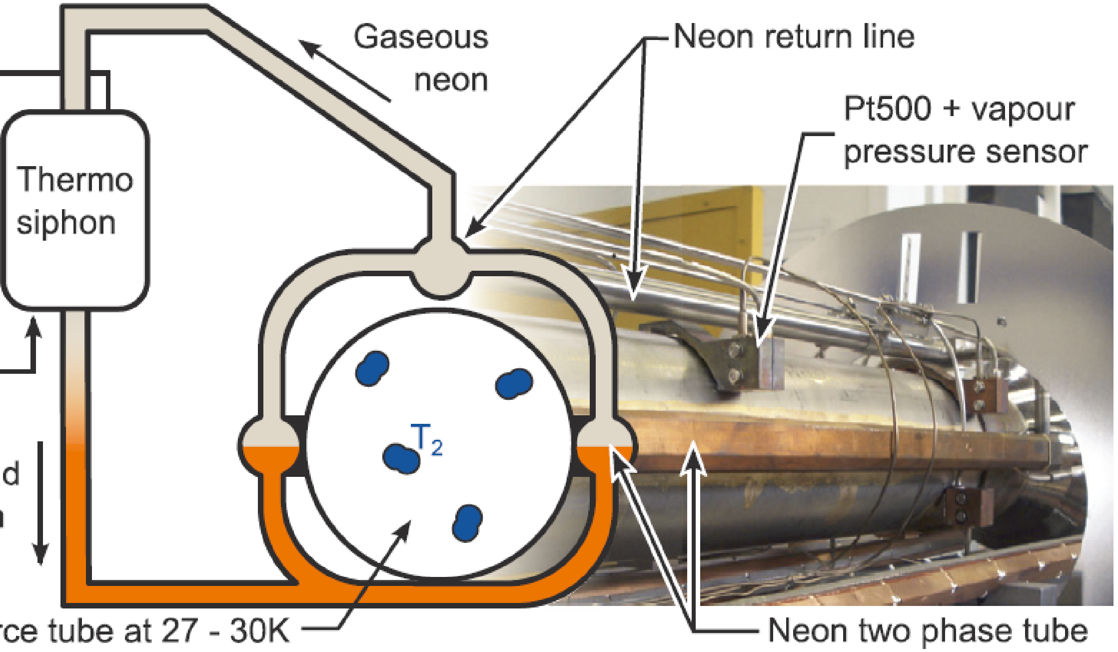
need very good temperature stability and homogeneity better than 10^{-3} at 30K

16 m long cryostat

WGTS – demonstrator



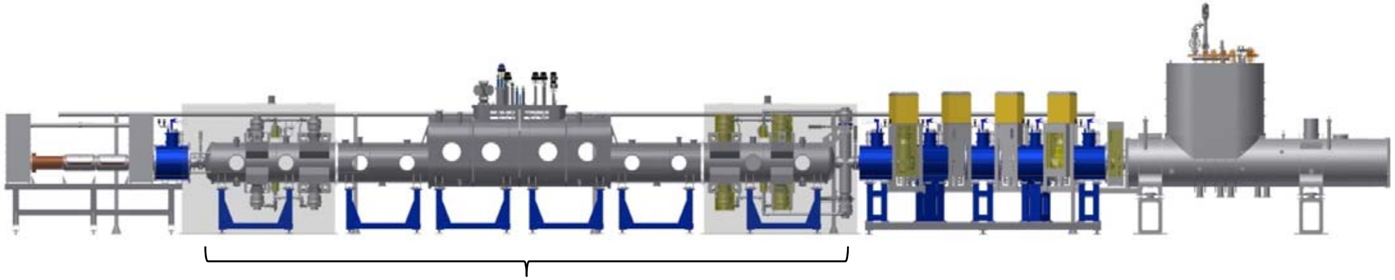


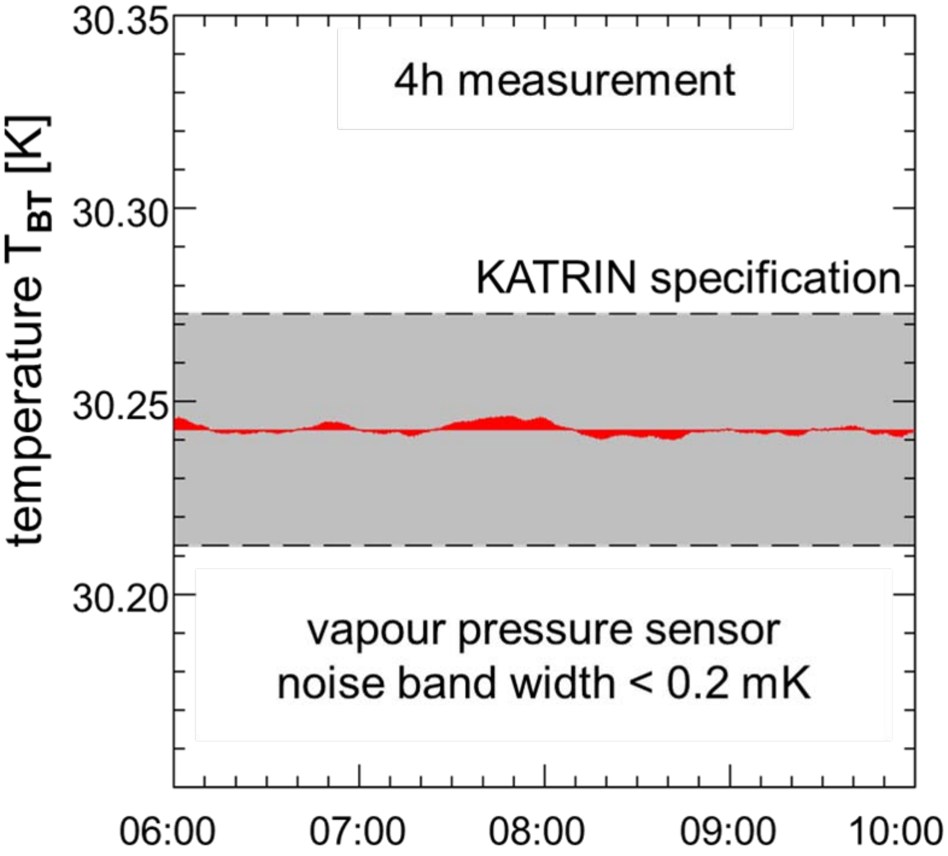


- **WGTS demonstrator**:
  - proof-of-principle of 2-phase beam tube cooling principle

S. Grohmann et al., Cryogenics 51, 8 (2011) 438

WGTS demonstrator – BT stability at 30K

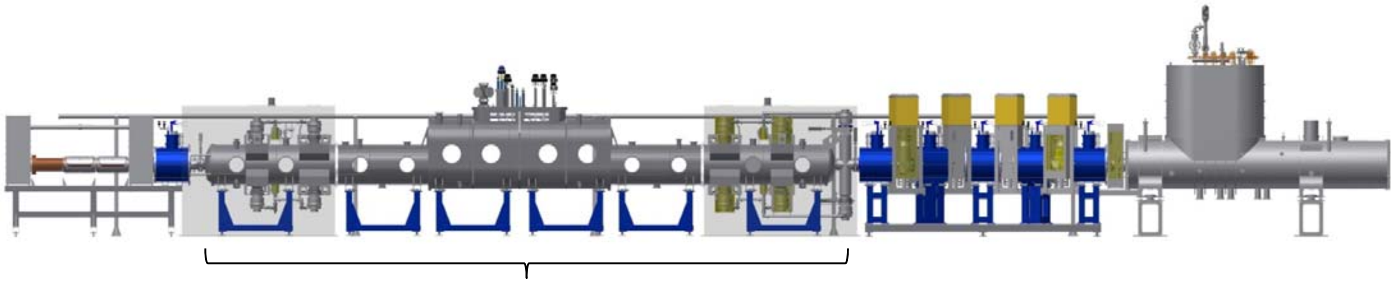


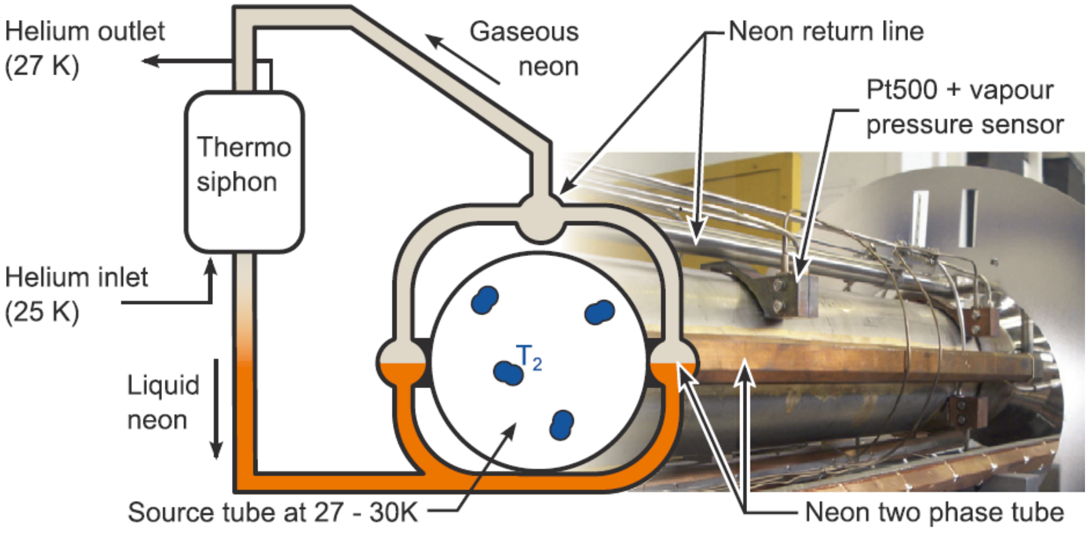


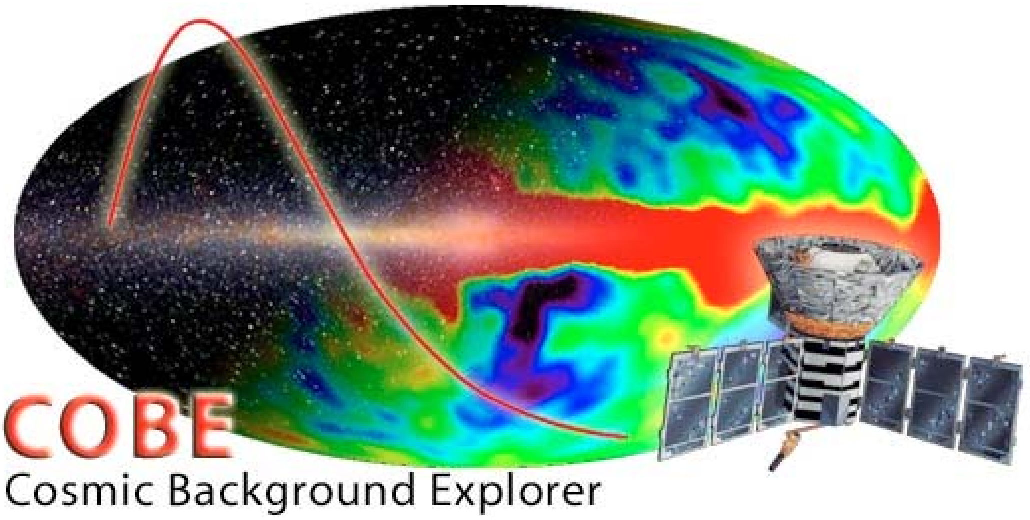
- **Technology highlight:**
  successful proof-of-principle of novel WGTS beam tube cooling system
  - data: **$\Delta T = 1.5$ mK (1σ)** (1 h)
  - required: **$\Delta T = 30$ mK (1σ)** (1 h)
  - implications:
    significantly reduced systematic errors from source fluctuations
    $\Delta\rho d/\rho d \sim \Delta T/T = 5 \cdot 10^{-5}$

S. Grohmann et al., The thermal behaviour of the tritium source in KATRIN, Cryogenics 55 (2013) 5

WGTS – demonstrator



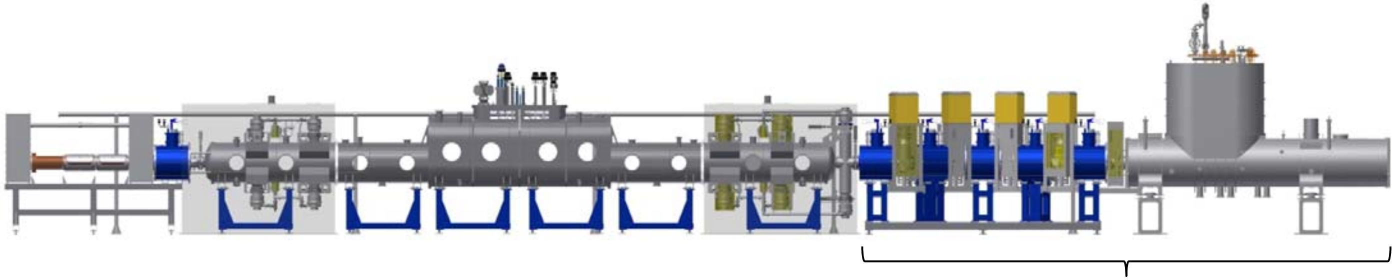




$\Delta\rho d/\rho d \sim \Delta T/T \sim 5 \cdot 10^{-5}$
per hour

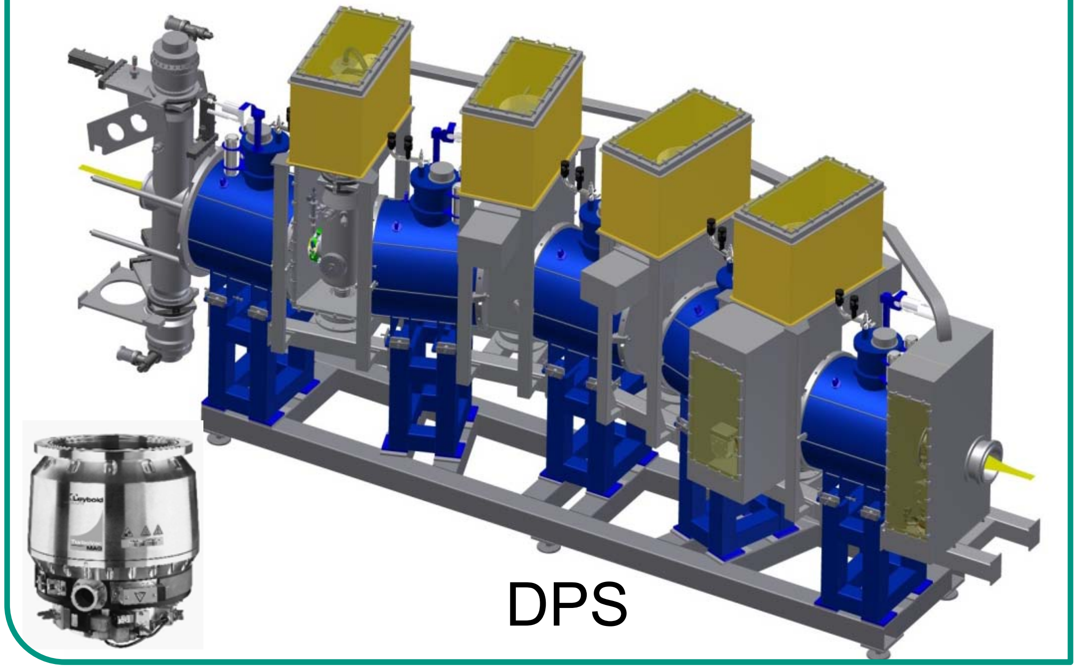
$\Delta\rho/\rho \sim \Delta T/T \sim 10^{-5}$

tritium retention techniques

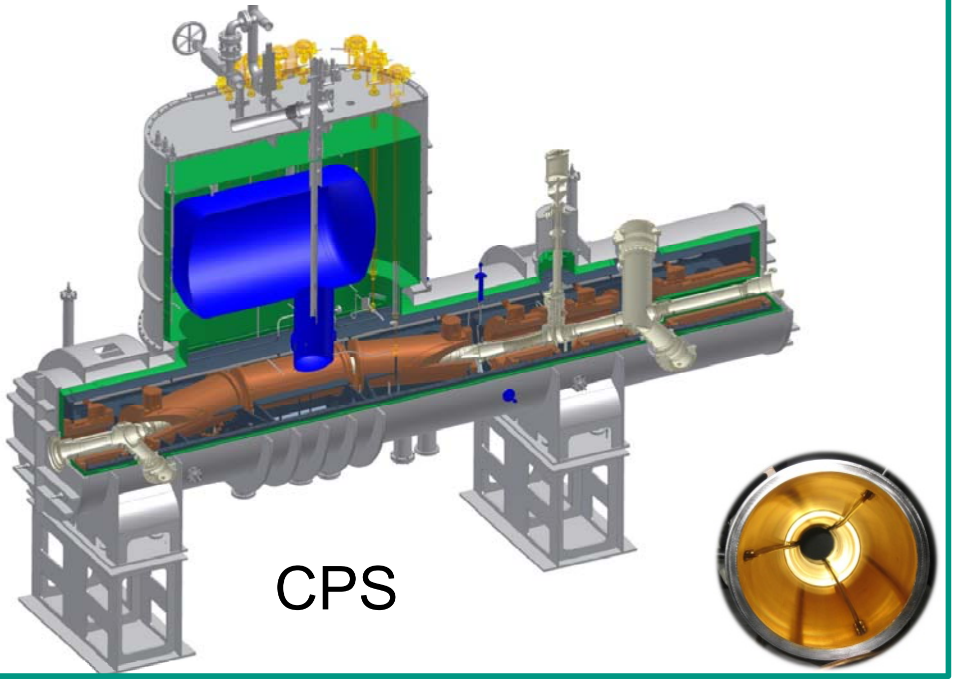


- DPS & CPS: two large cryostat systems for overall retention **factor > 10^{14}**

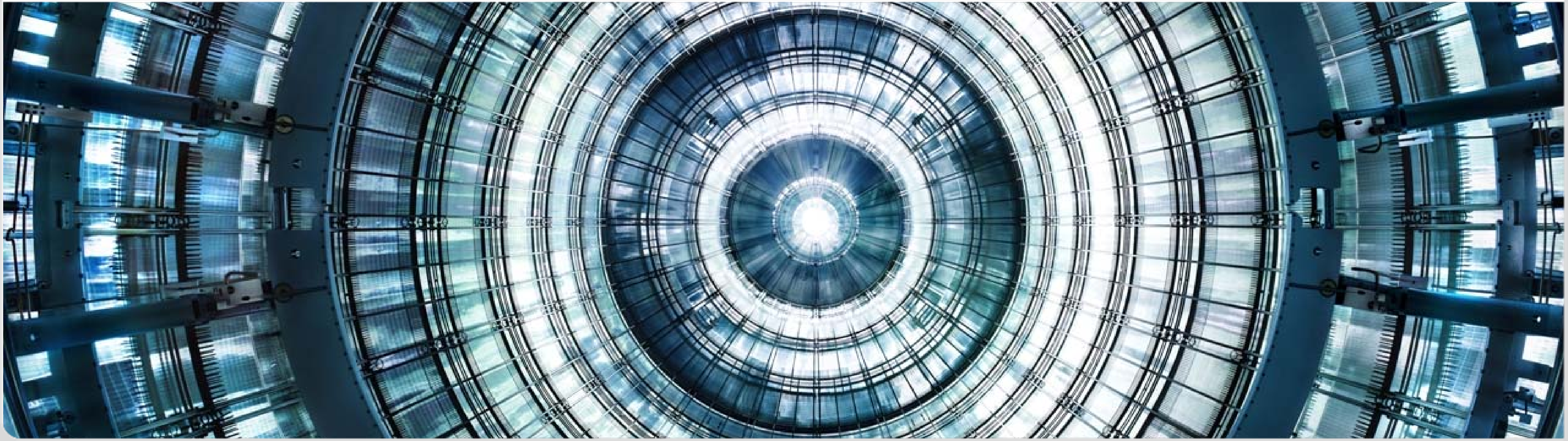
- **differential pumping section DPS**
  active pumping by TMPs



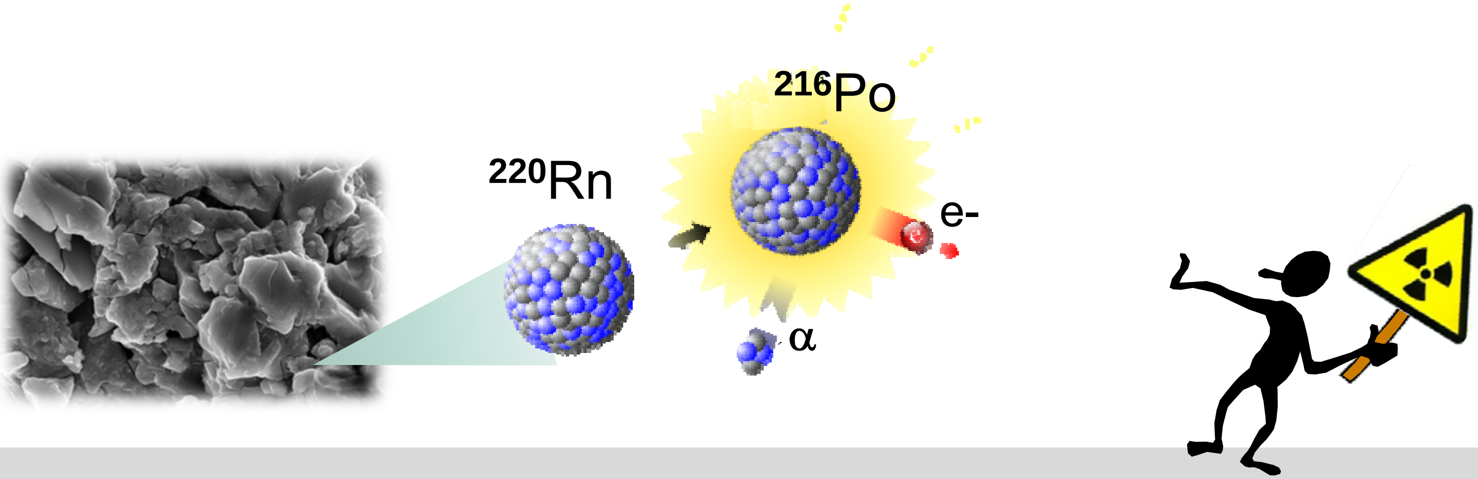
- **cryogenic pumping section CPS**
  cryosorption on Ar-frost



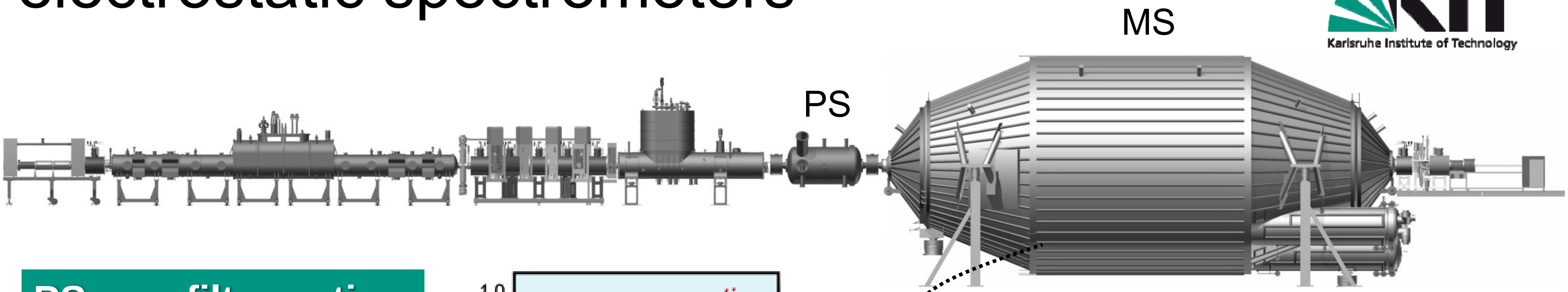
Guido Drexlin, KCETA



Why is a single nuclear α-decay in the spectrometer so dangerous when measuring $m(\nu_e)$?



electrostatic spectrometers



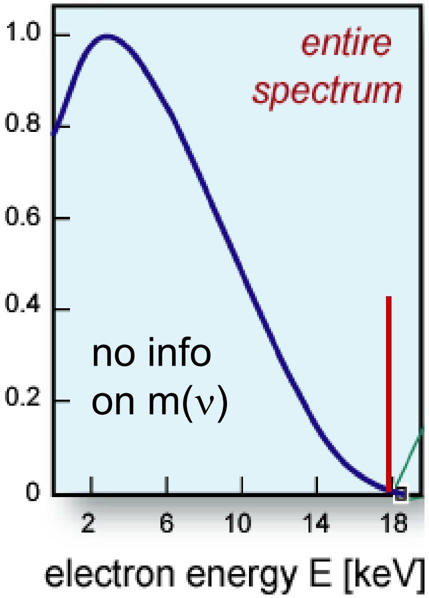
PS: pre-filter option

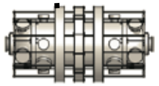
fixed retarding potential

U_0 = - 18.3 kV

ΔE ~ 100 eV

- option to filter out low ß-decay electrons
- reduce background from ionising collisions





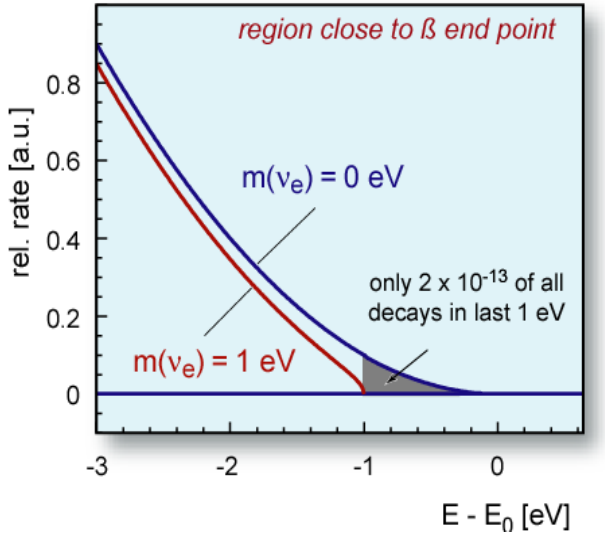
MoS: in operation ☑

MS: precision filter - scanning

variable retarding potential

U_0 = - 18.4 … -18.6 kV

ΔE ~ 0.93 eV (100% transmission)



MoS: HV monitoring

MS retarding potential

nuclear standard (^{87m}Kr)

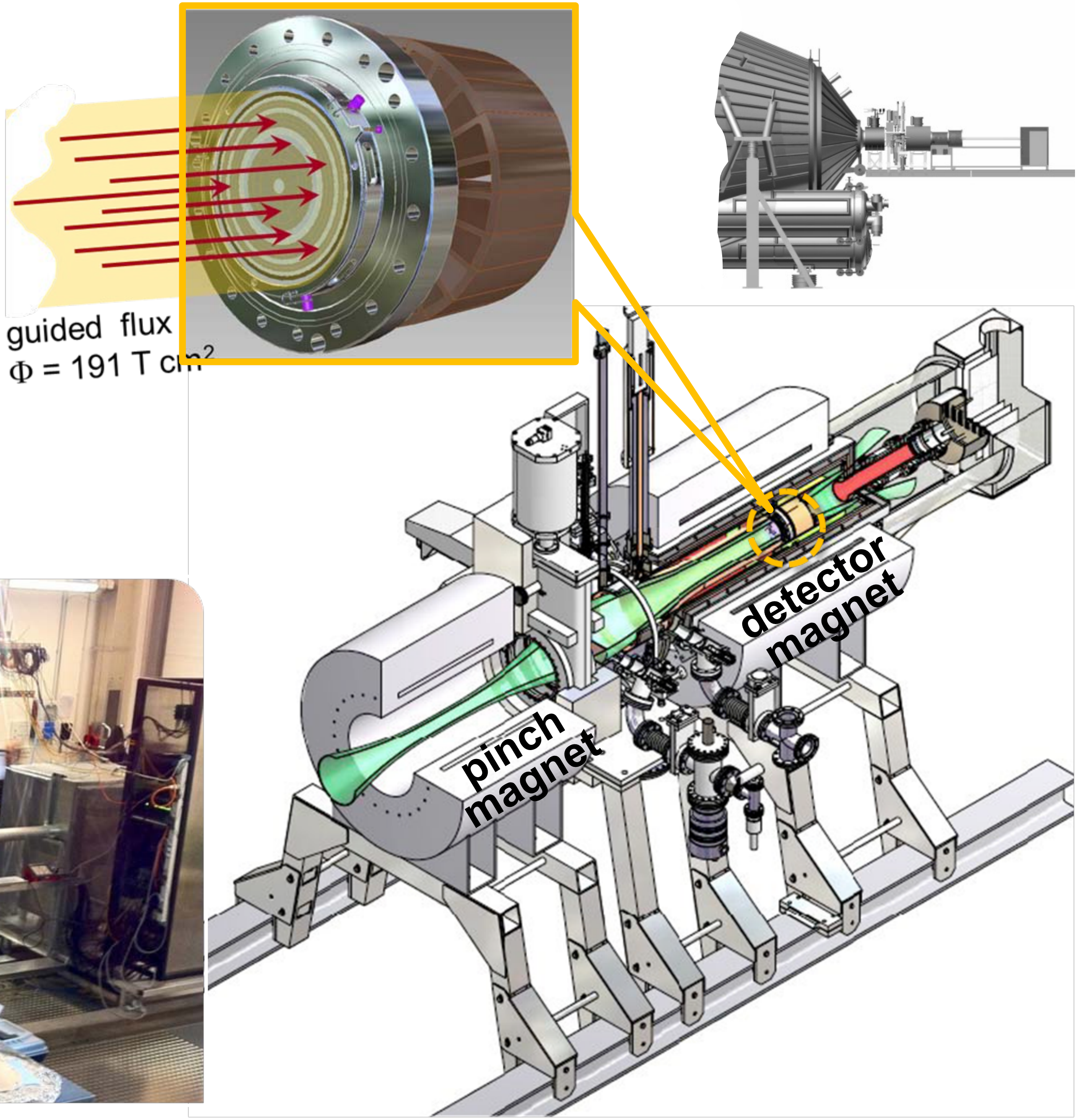
separate beam line

focal plane detector system

- **focal plane detector**

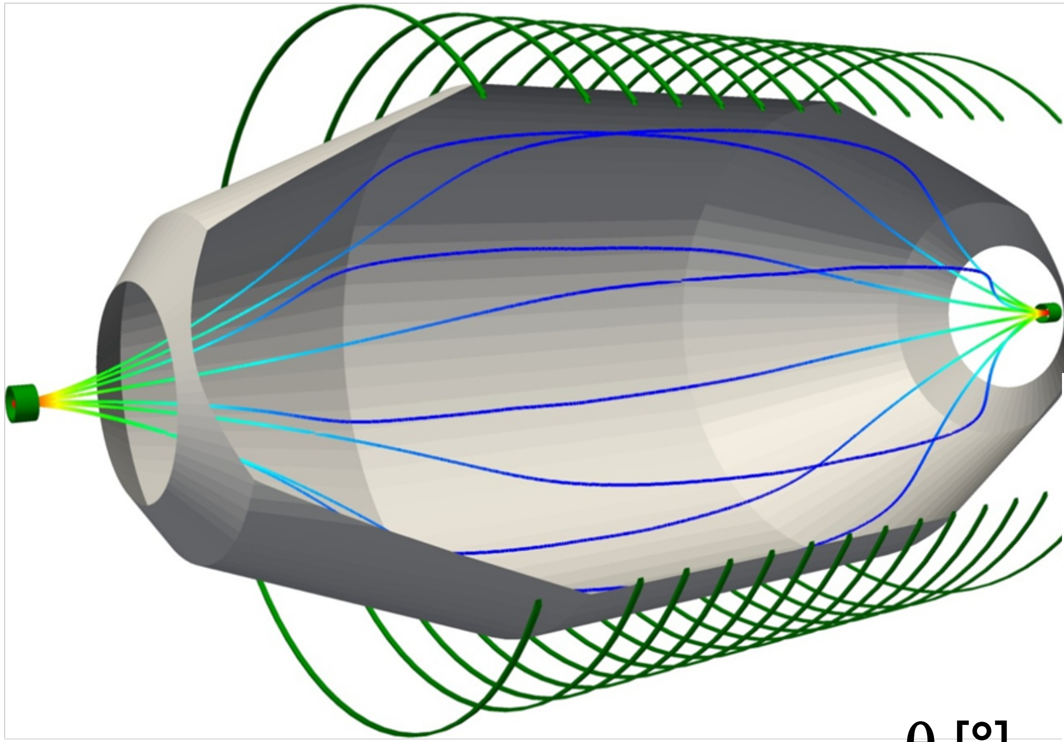
  segmented Si-PIN diode array:

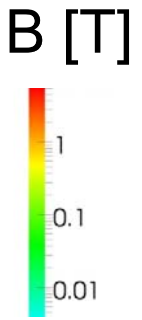
  - count transmitted electrons
  - radial & azimuthal mapping
  - arrival time of electron
  - study of systematics
  - s.c. magnets for guiding



spectrometer: signal & background

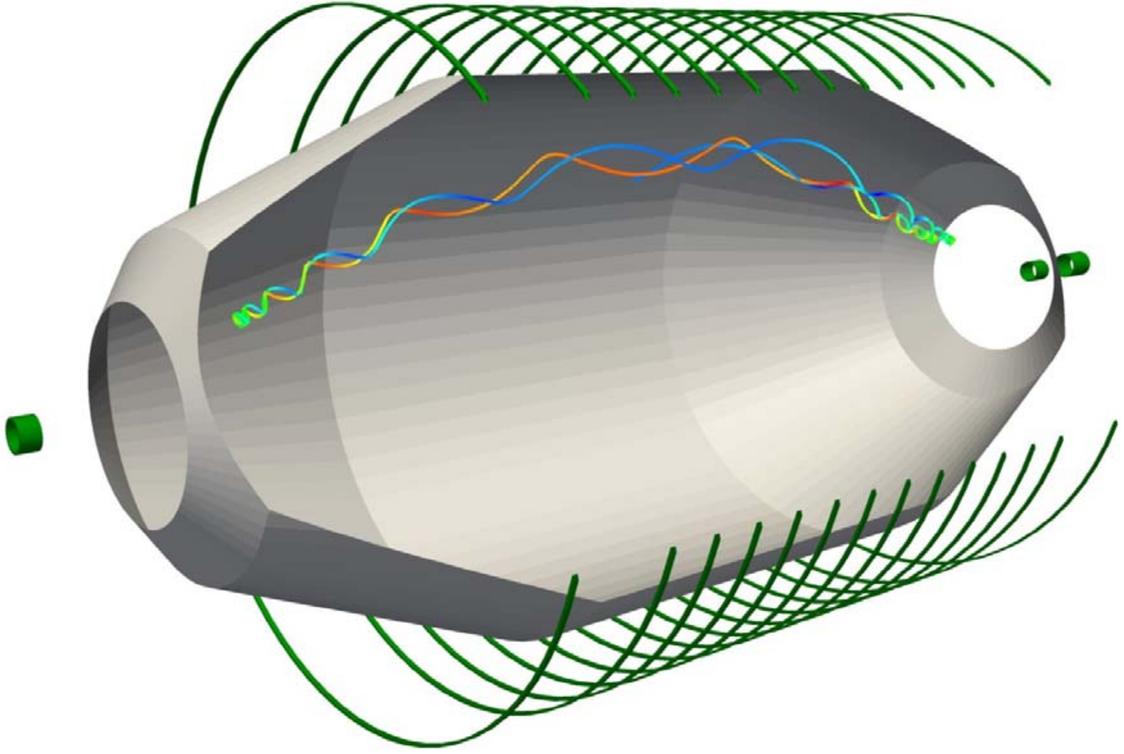
- **KASSIOPEIA:** detailed simulation of electron trajectories





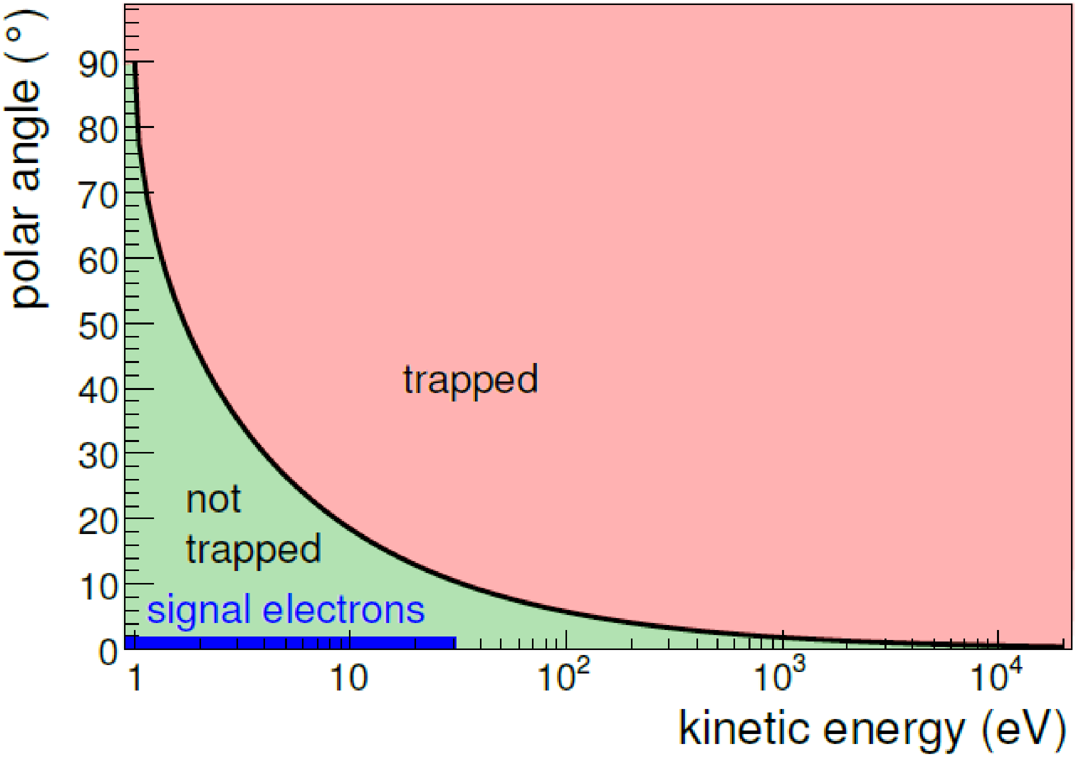
- **transmission of ß-electrons**:
  magnetic guiding &
  electrostatic retardation

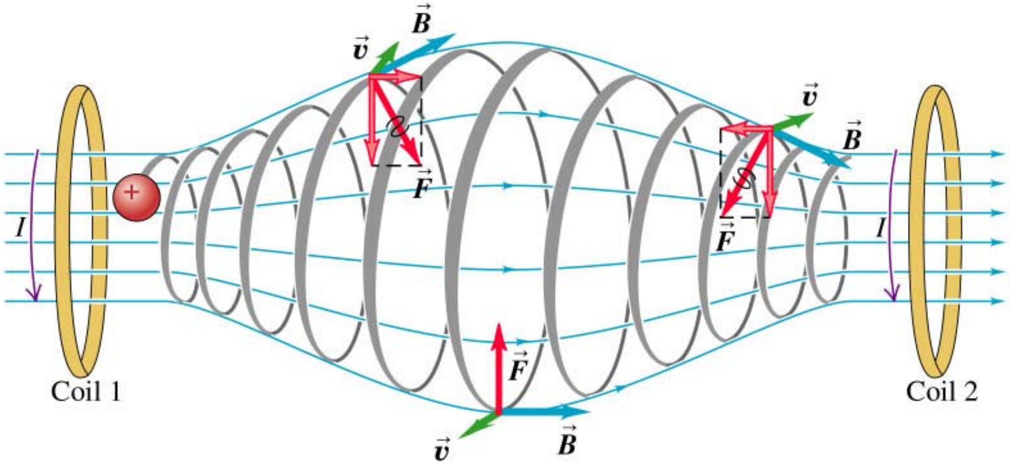
- **trapping of bg-electrons**:
  spectrometer acts as
  a magnetic bottle,
  long storage (h)

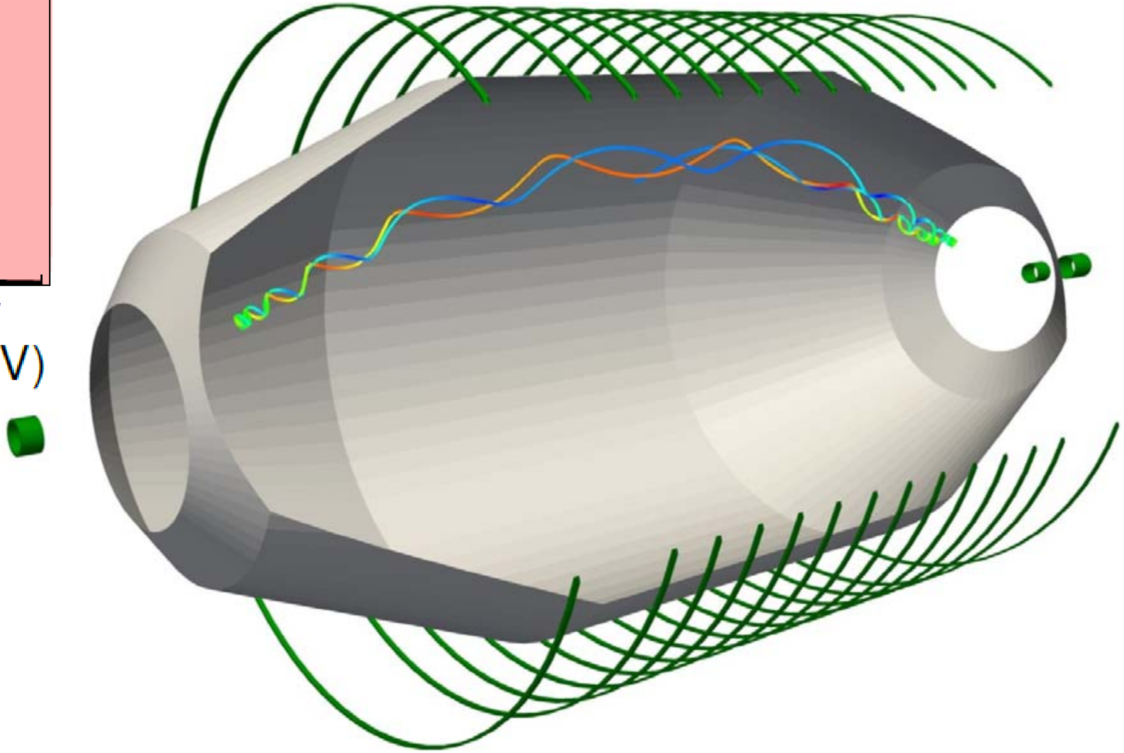


spectrometer: signal & background

- **KASSIOPEIA:**







- **trapping of bg-electrons**:
  spectrometer acts as
  a magnetic bottle,
  long storage (h)

radon induced background

- ^{219}Rn emanation from St707 NEG getter strips (3 · 1 km) in pump ports of spectrometers

S. Mertens, PhD thesis KIT (2012)

^{219}Rn

^{215}Po

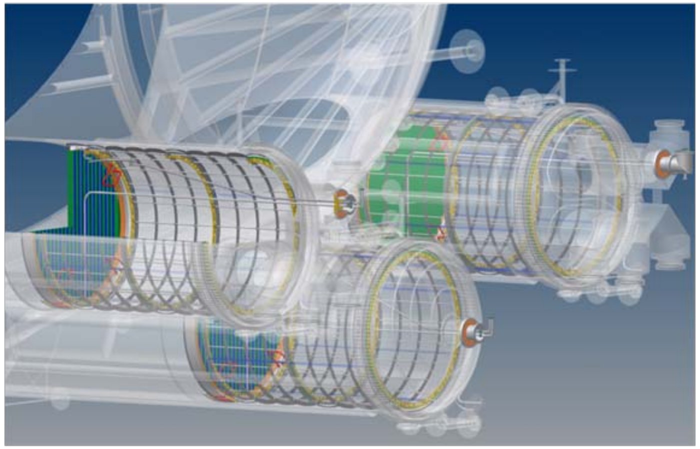
He^{2+}

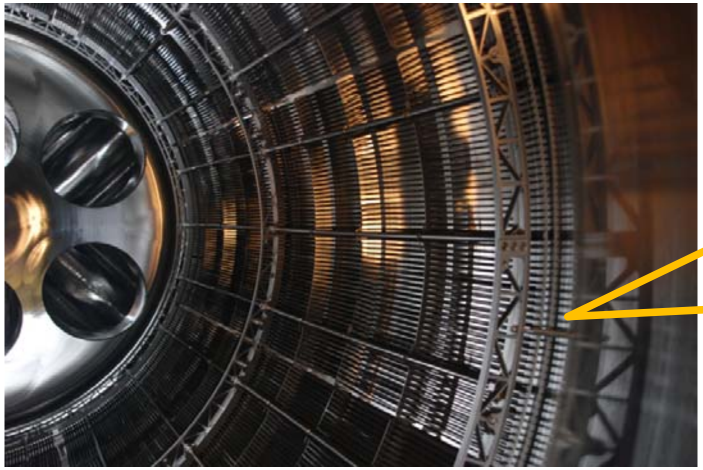
shake-off electrons

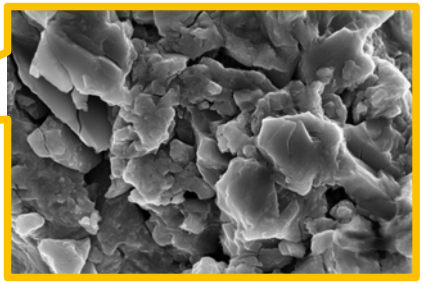
conversion electrons

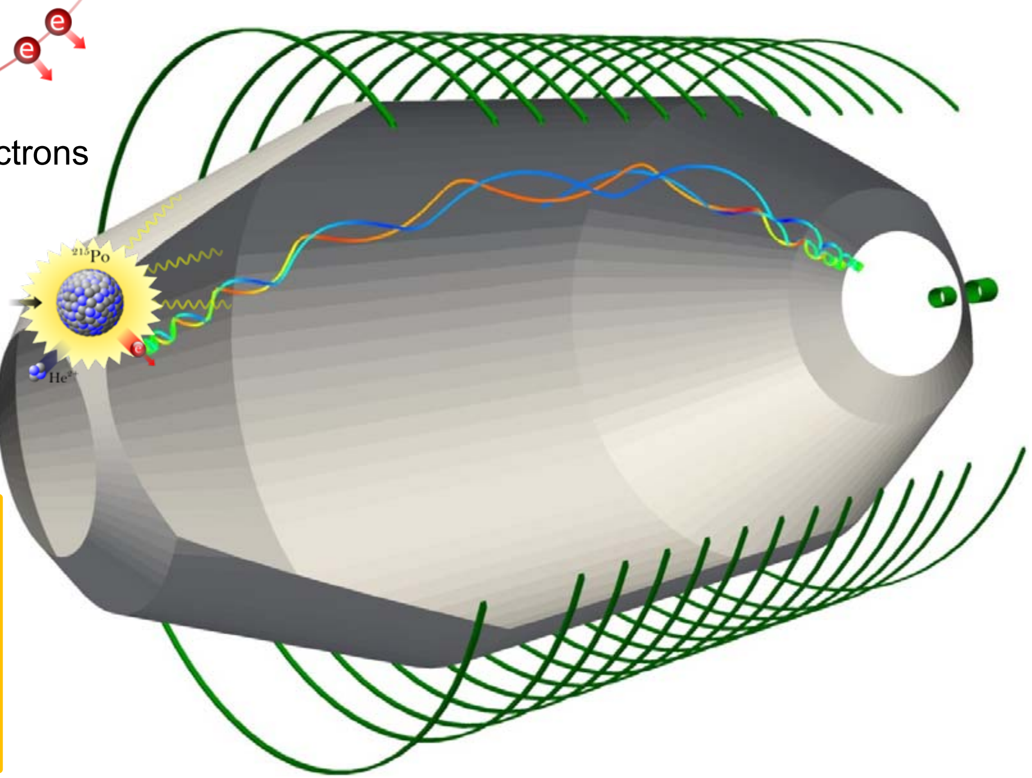
Auger electrons

shell reorganisation electrons

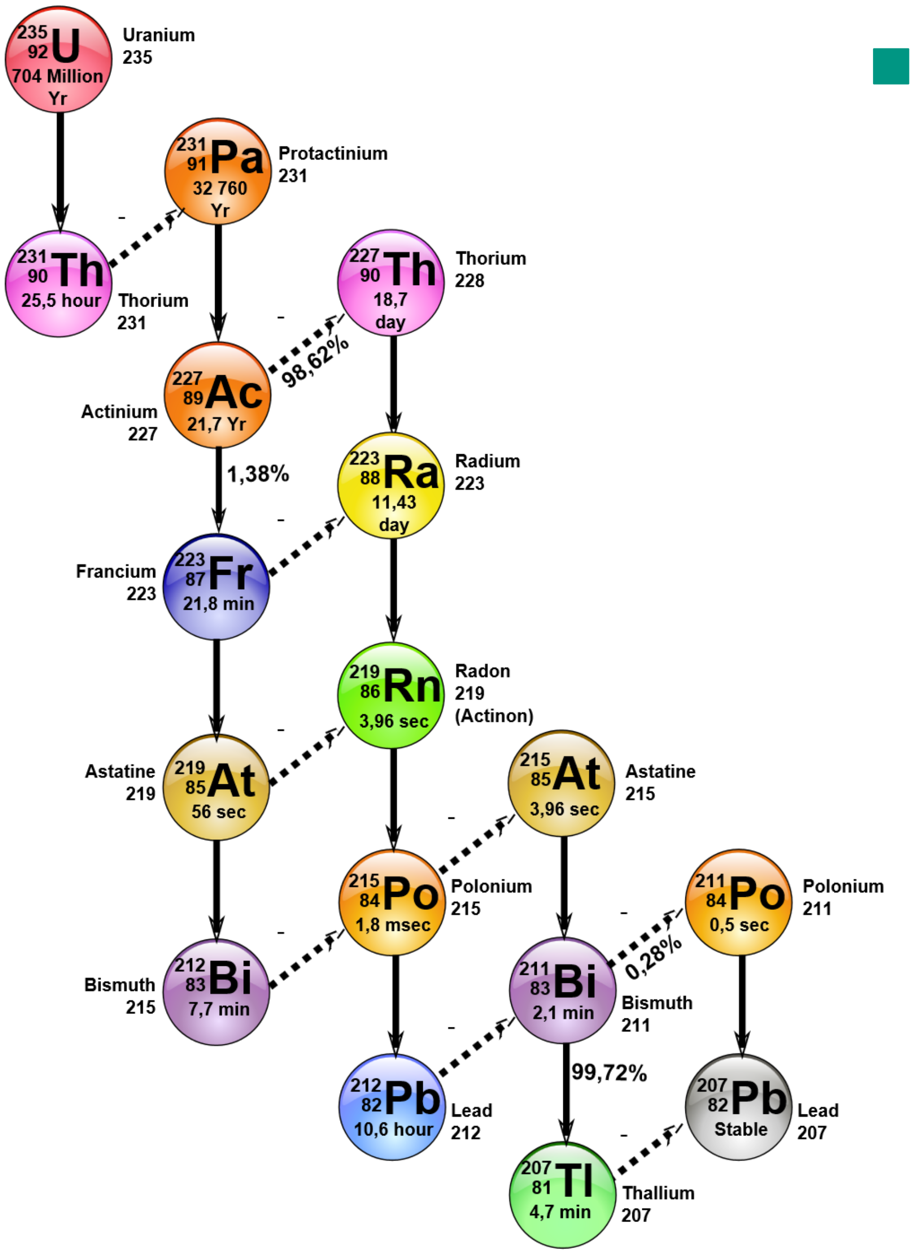








radon induced background

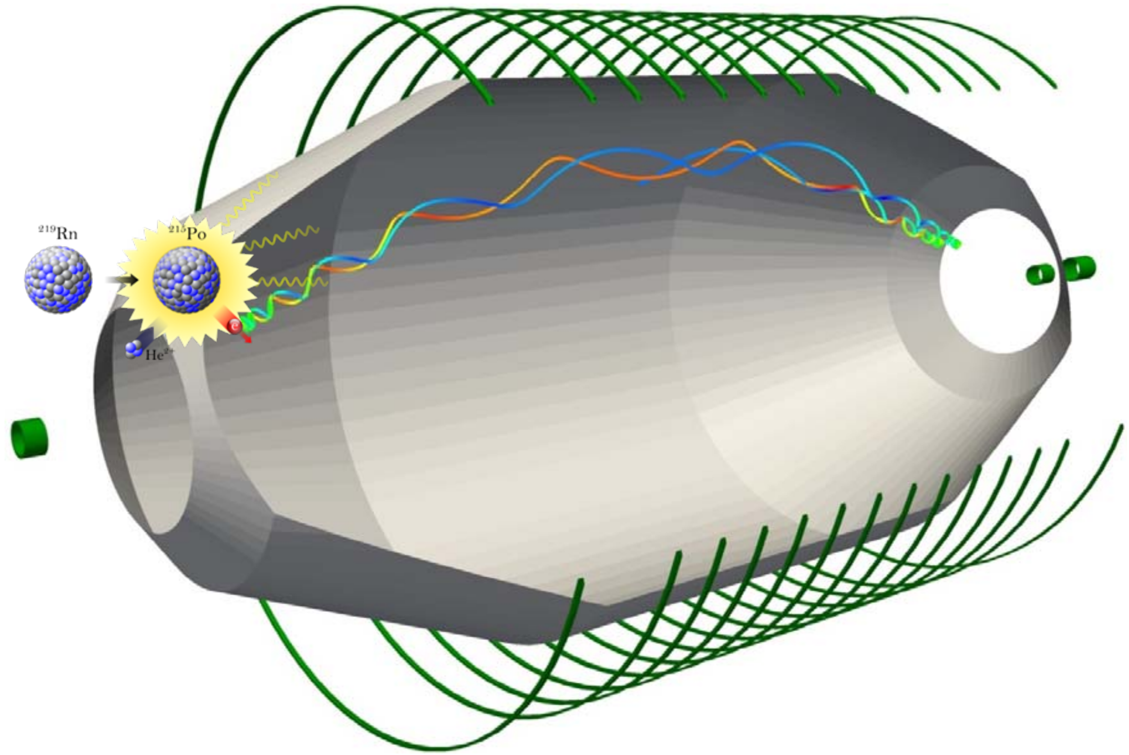


- ^{219}Rn produced during primordial ^{235}U decay chain

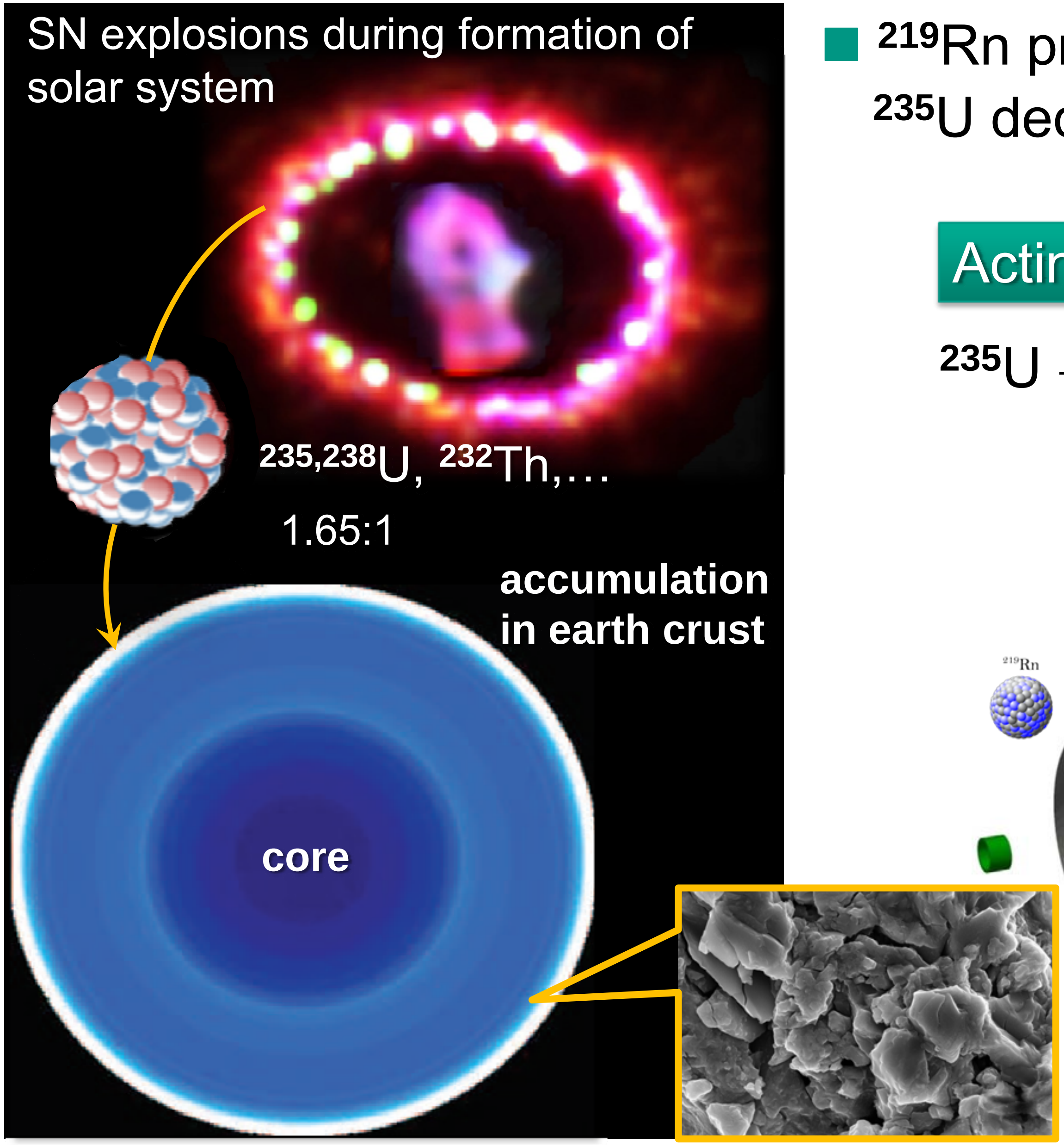
Actinium series ^{235}U

$A = 4 \cdot j + 3$

$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb}$, $t_{½} = 7.1 \cdot 10^{8}$ a



radon induced background



SN explosions during formation of solar system

^{235,238}U, ^{232}Th,…

1.65:1

accumulation in earth crust

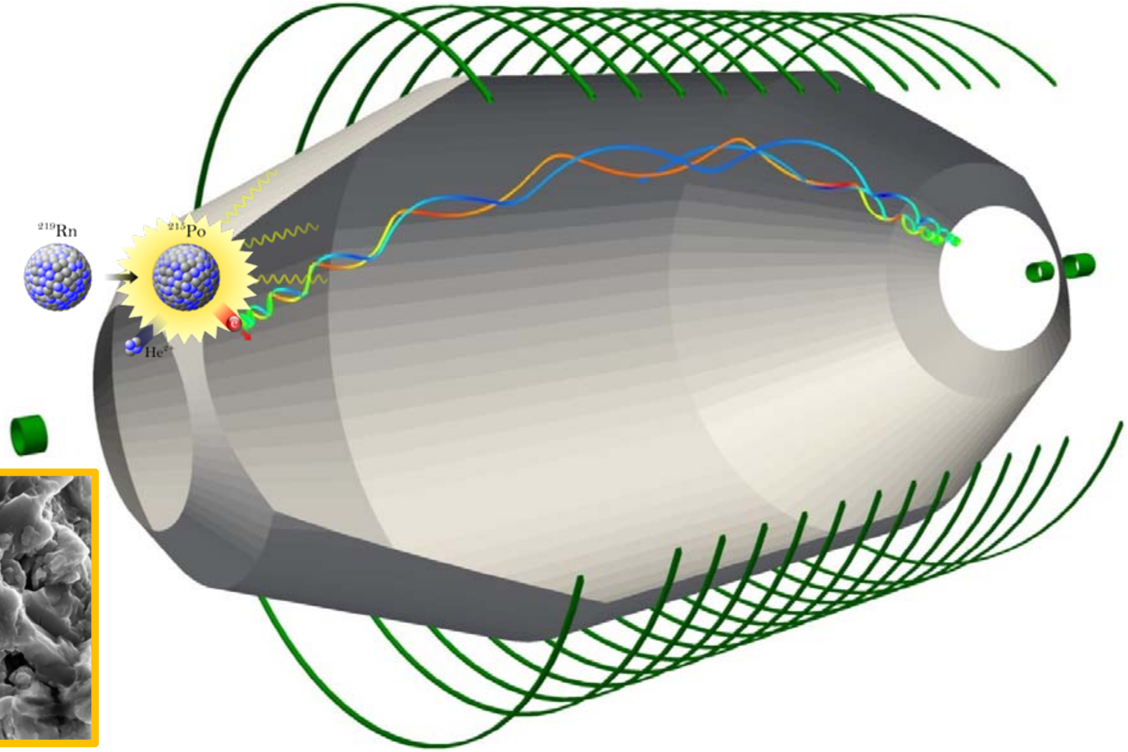
core

- ^{219}Rn produced during primordial ^{235}U decay chain

Actinium series ^{235}U

$A = 4 \cdot j + 3$

$^{235}\text{U} \rightarrow {}^{207}\text{Pb}$, $t_{½} = 7.1 \cdot 10^{8}$ a



pre-spectrometer – measurements

pre-spectrometer background investigations

- novel bg-source: ^{219,220}Rn produce electrons in the keV-range, which are trapped & generate **enhanced bg-levels for up to several hours**

ISSN 0954-3899

Journal of Physics G

Nuclear and Particle Physics

Volume 40 Number 8 August 2013

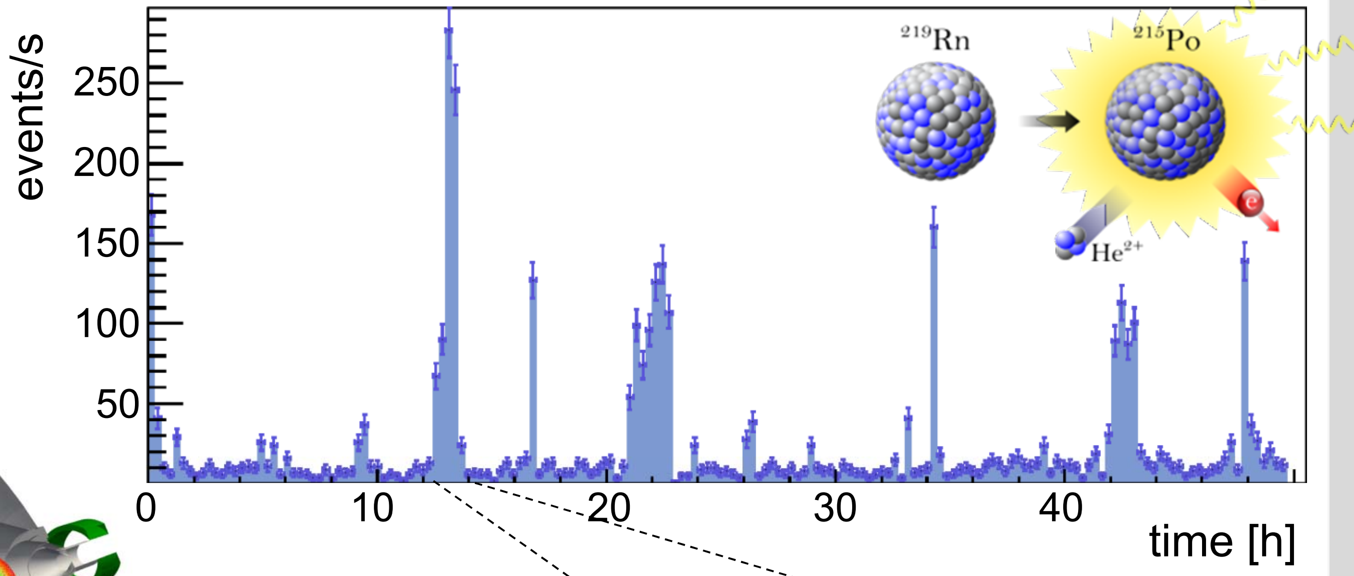
Topical Review

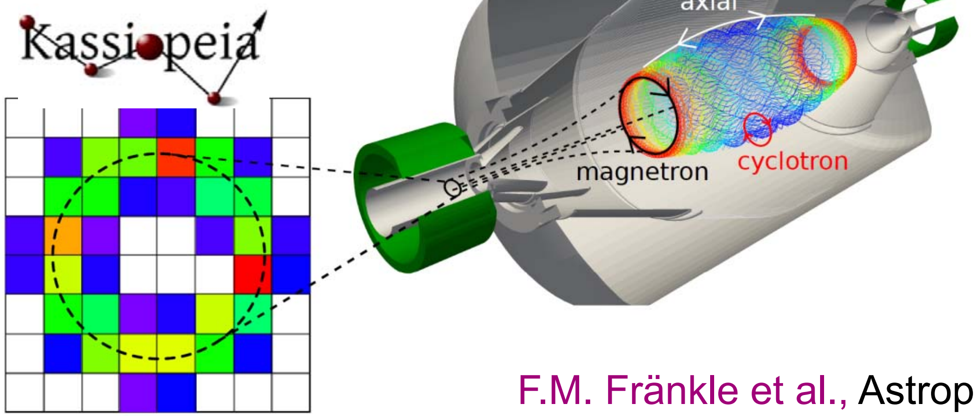
Element synthesis in the supernova environment and neutrino oscillations

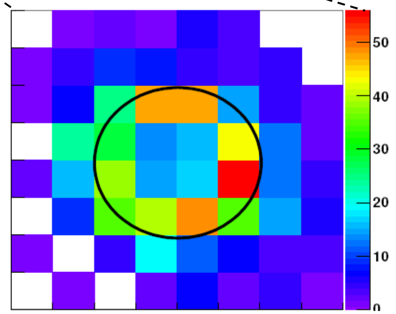
Toshio Suzuki and Toshitaka Kajino

iopscience.org/jphysg

IOP Publishing







data

F.M. Fränkle et al., Astropart. Phys. **35** (2011) 128

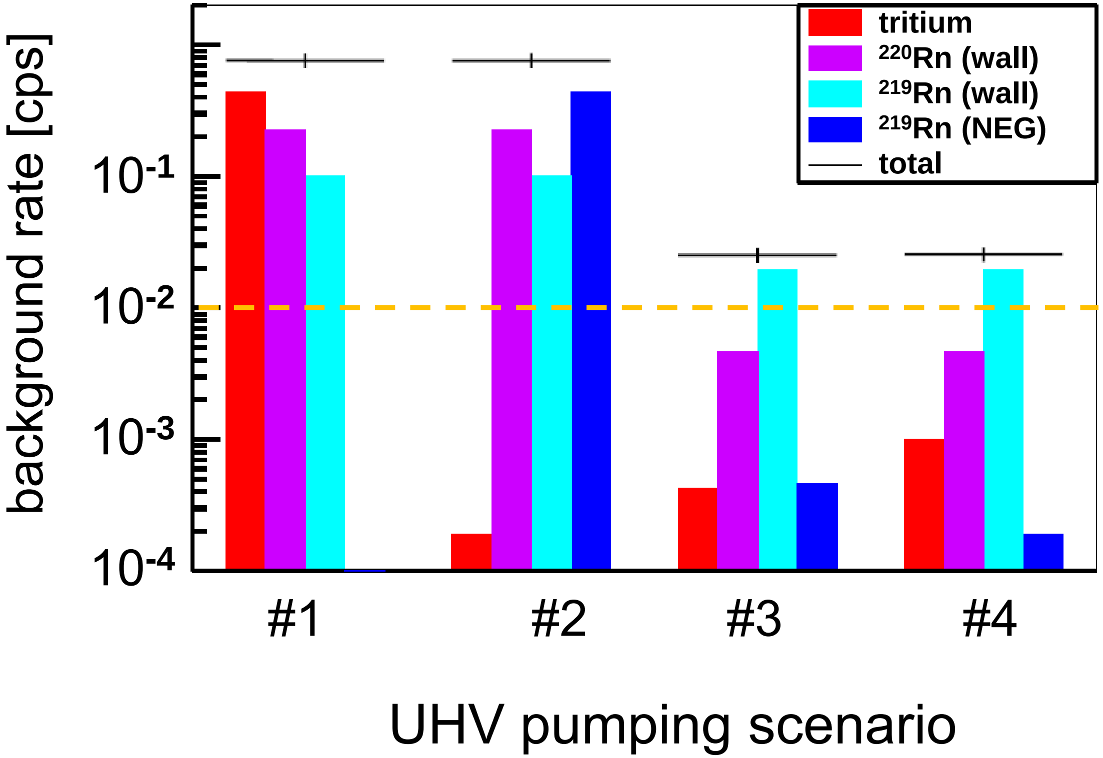
pre-spectrometer – measurements

Implications for main spectrometer

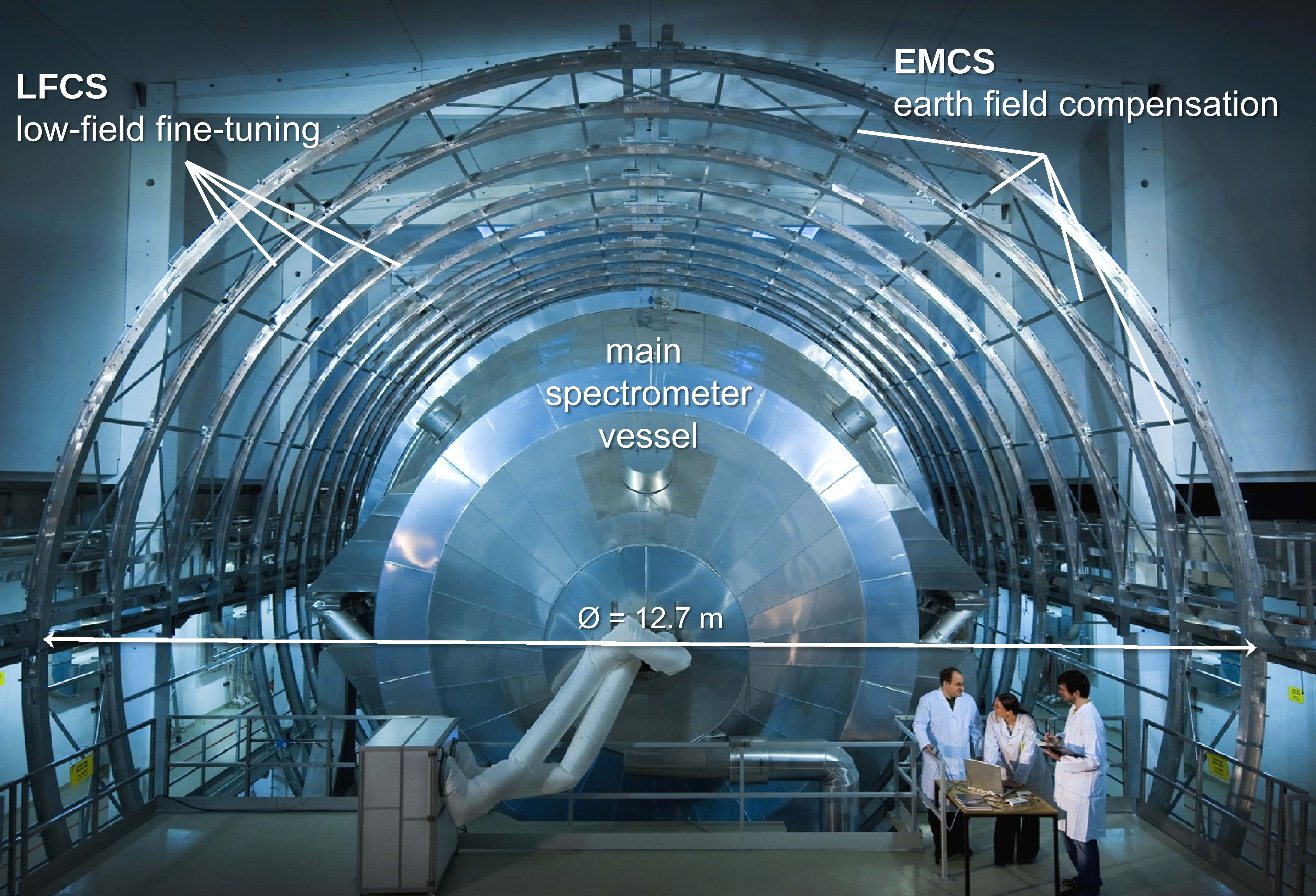
non-Poissonian nature of Rn-induced background has the potential to limit neutrino mass sensitivity of KATRIN

need novel background reduction techniques

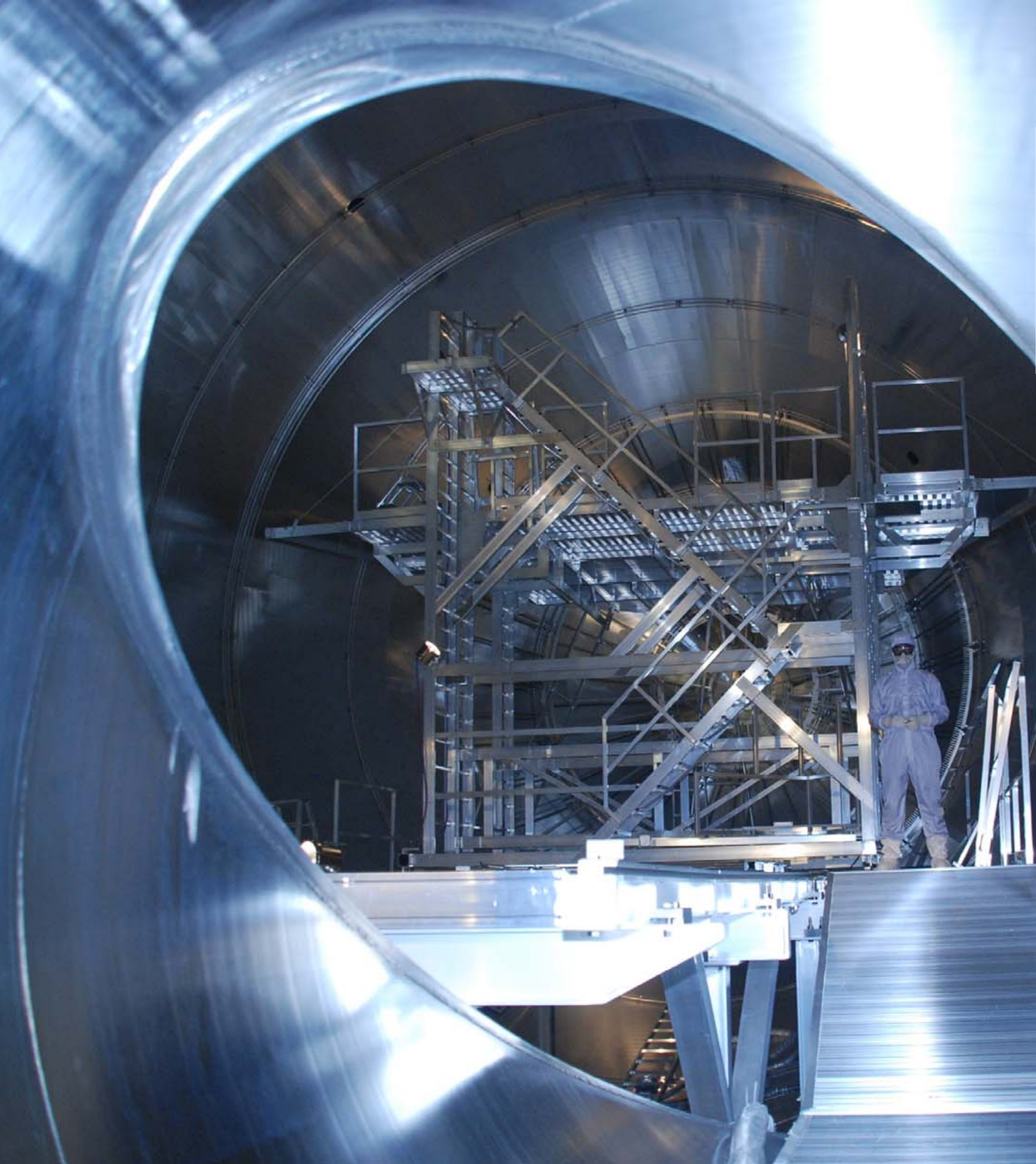
TDR-benchmark: r_{bg} = 0.01 cps



S. Mertens et al., Astropart. Phys. 41 (2013) 52



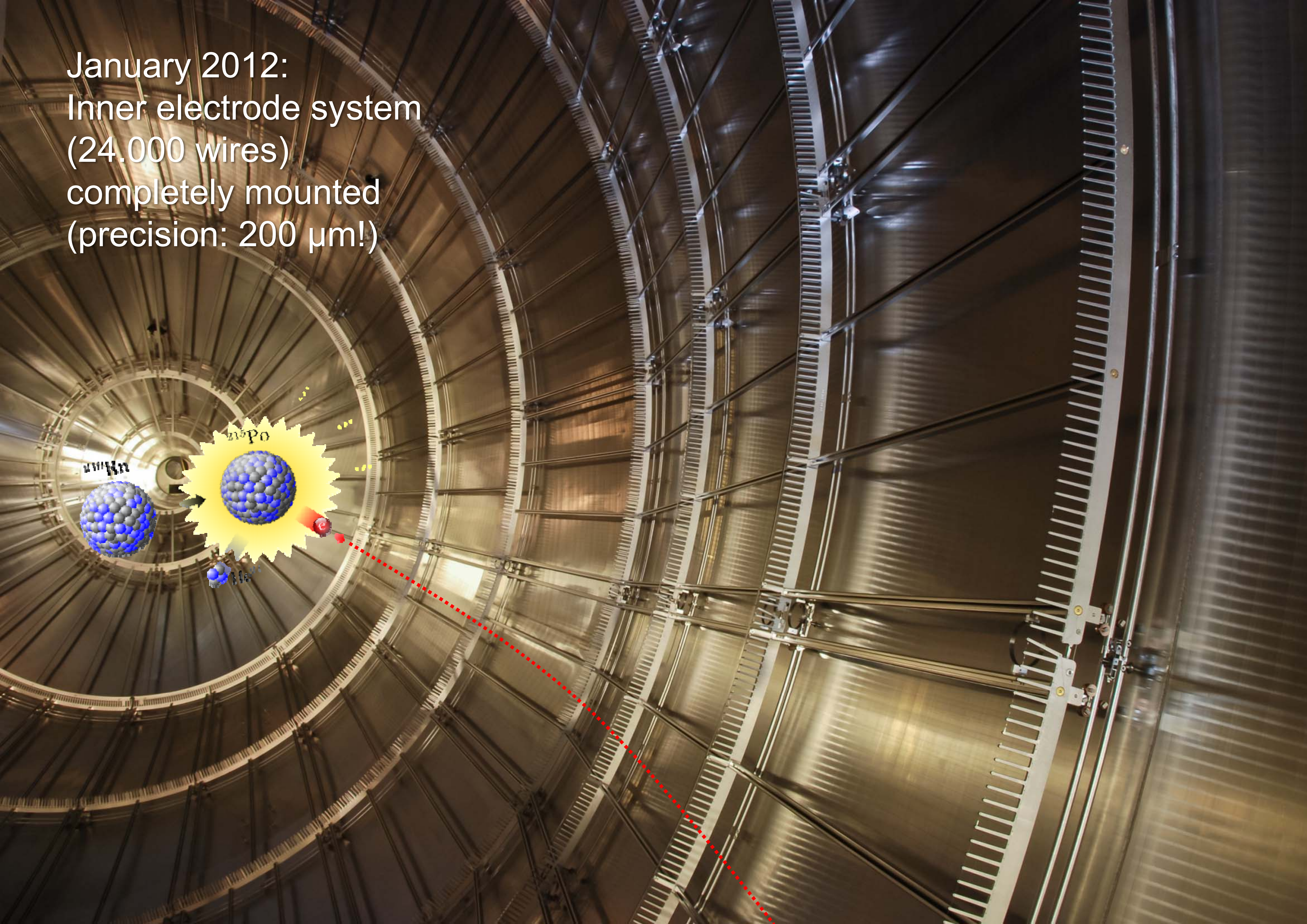
2011: fully commissioned large Helmholtz coil system



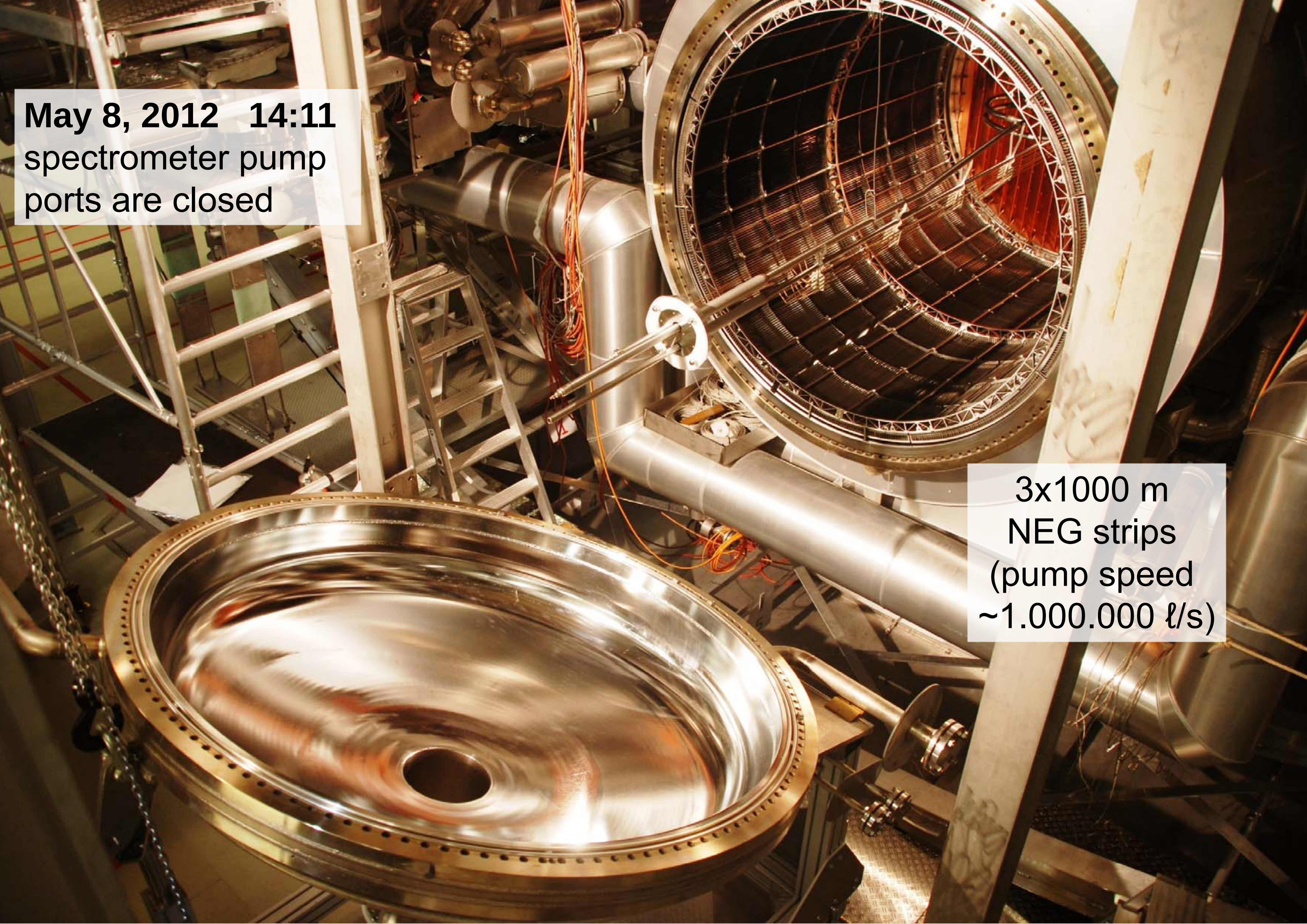
measurement of
magnetic inhomogeneities:

$\Delta B/B < 2\%$

May 2010:
first wire
modules installed



January 2012:
Inner electrode system
(24.000 wires)
completely mounted
(precision: 200 µm!)

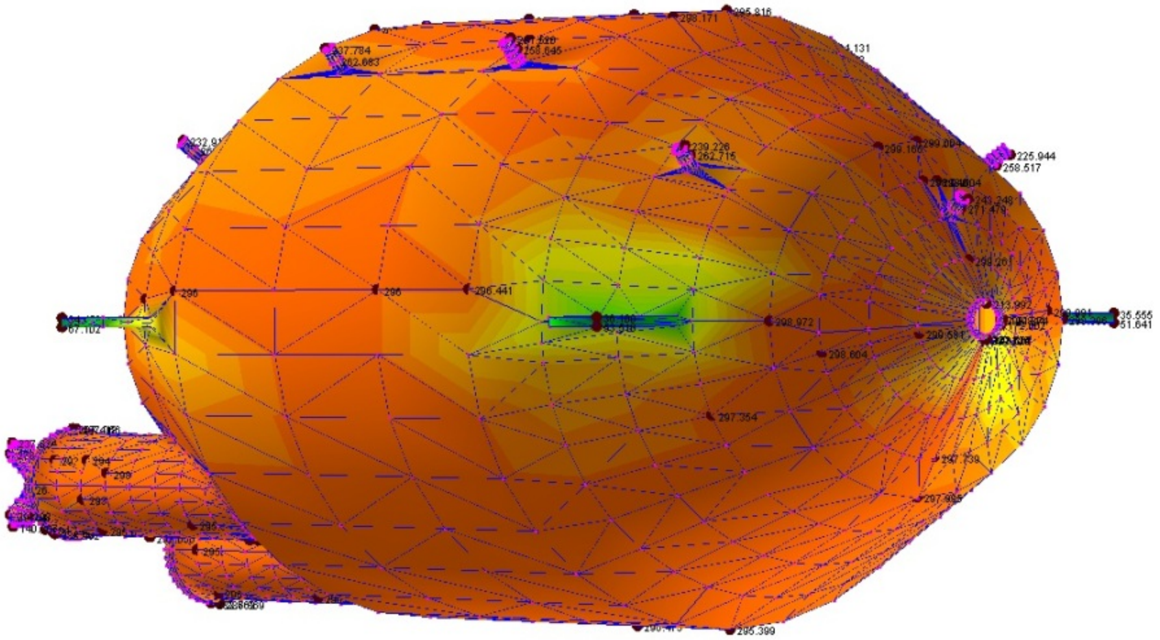


May 8, 2012   14:11
spectrometer pump
ports are closed

3x1000 m
NEG strips
(pump speed
~1.000.000 ℓ/s)

Spectrometer commissioning

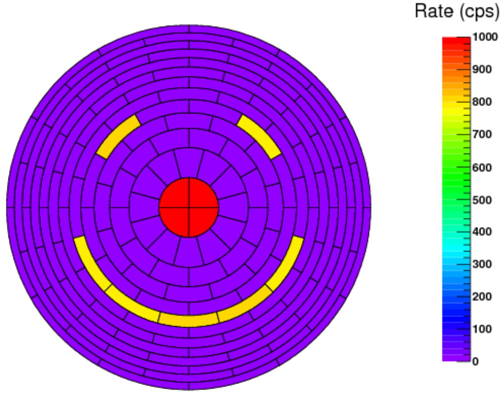
- **2013 first period of data-taking with entire spectrometer/detector**
  - successful bake-out of spectrometer vessel at 300°C
  - NEG pump activated
  - inner electrode system: no broken wire
  - **first light achieved May 31st**
  - extensive commissioning measurements started

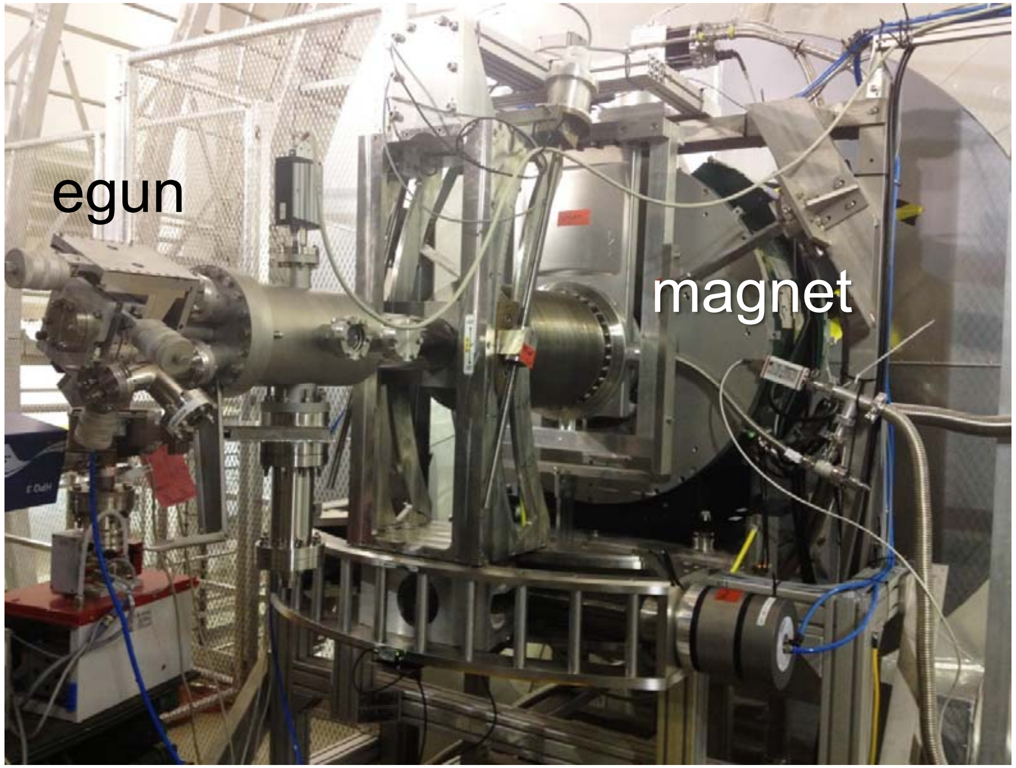


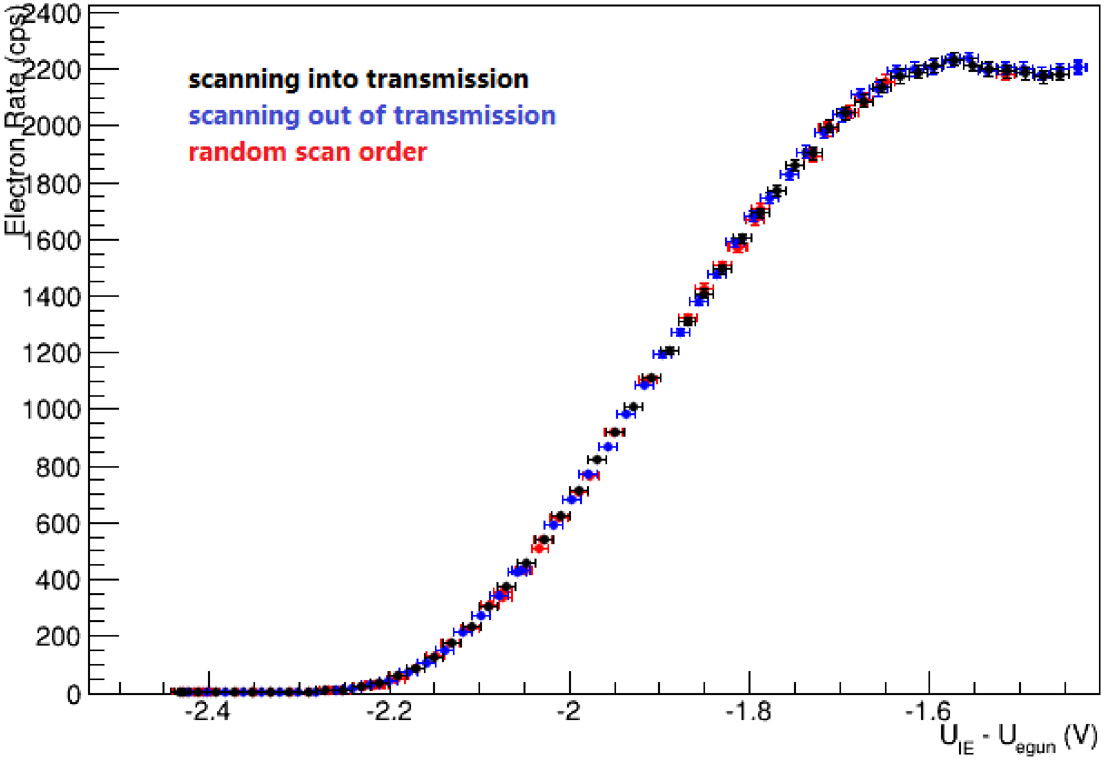
commissioning measurements

Commissioning measurements

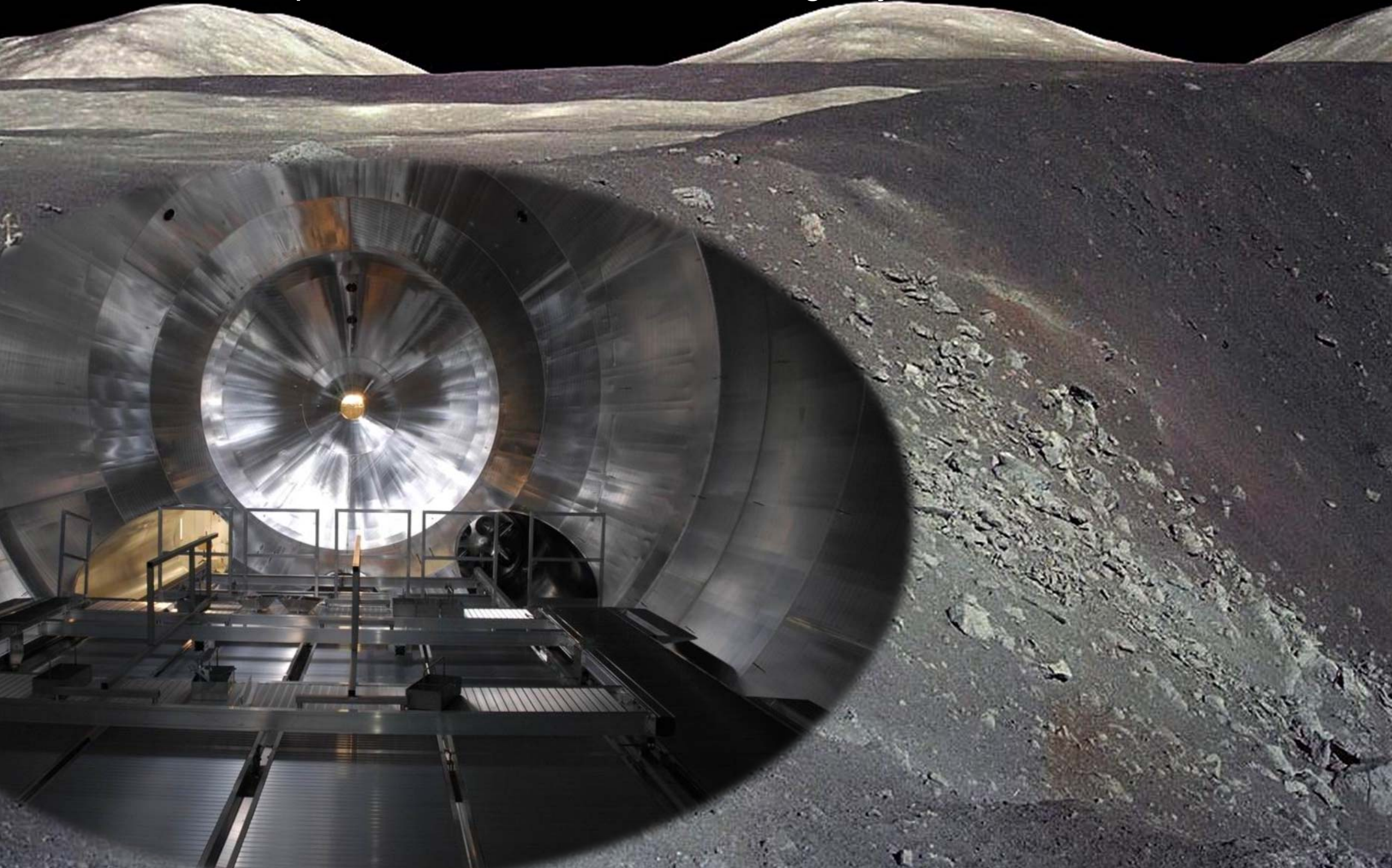
- study background characteristics
- study of optimisied electromagnetic layout
- first measurement of transmission curve with egun
- test active background removal methods







spectrometer pressure **$p \sim 5 \cdot 10^{-11}$ mbar**
= pressure at lunar surface during day time



Background reduction techniques

- **Passive methods: pump out & cryotrap radon atoms**
  - minimise background generation mechanisms due to ionisation

Radon pump-out

- fast pump-out time for radon atoms

non-getterable species

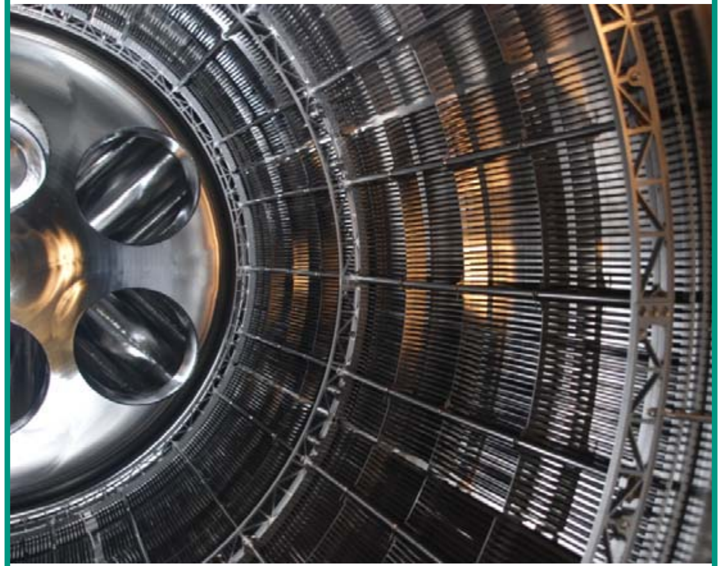
Cryogenic Cu-Baffle

- cryotrap radon atoms onto LN2 cooled baffle

cryotrap gas species

Excellent UHV

- keep stable UHV with $p < 1 \cdot 10^{-11}$ mbar (~5 a)



getterable gas species

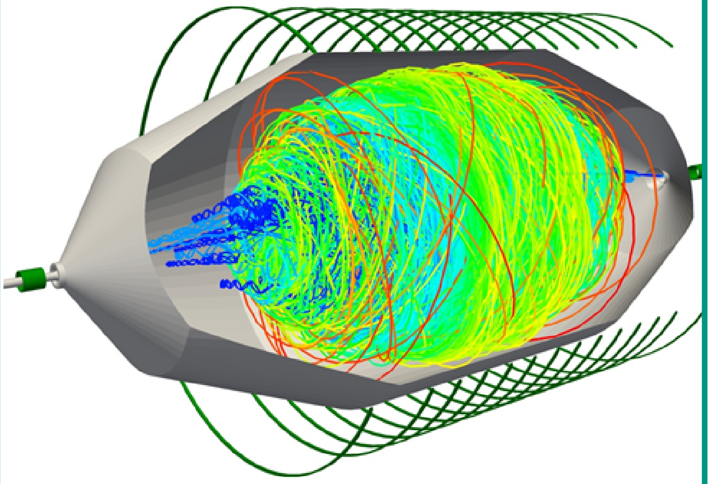
Background reduction techniques

- **Active methods**

  - fast removal of stored electrons by breaking of trapping condition

Cylclotron Resonance

- apply RF-field tuned to cyclotron frequency

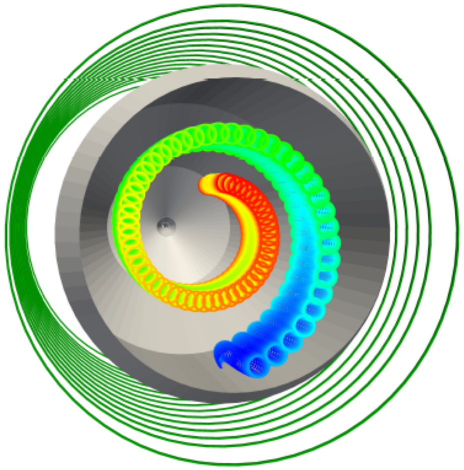


$\omega_{RF} = \omega_{cycl}$

all electron energies

Magnetic Pulse

- zero central B field to induce drift to wall

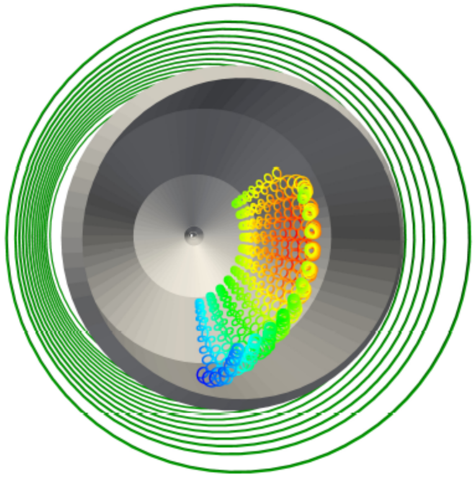


$r = m \cdot v / q \cdot B$

high energies (E > 1 keV)

Electrostatic Dipole

- apply transversal dipole to drift electrons to wall



$\vec{v} = {}^{c}/_{B^2} \cdot \vec{E} \times \vec{B}$

low energies (E < 1 keV)

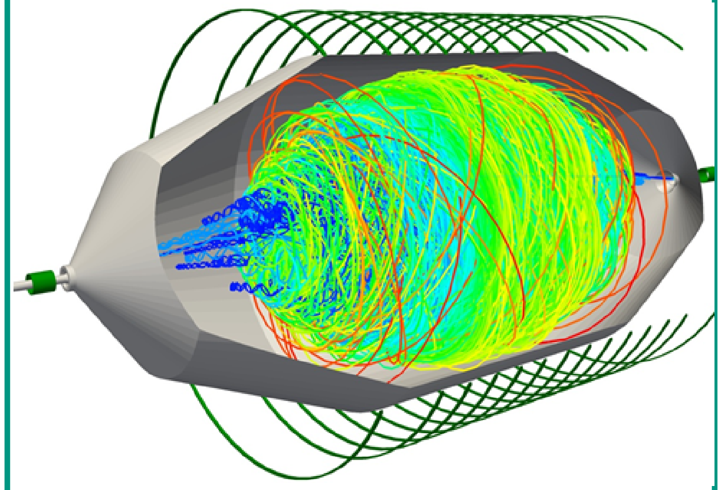
Background reduction techniques

Active methods

- fast removal of stored electrons by breaking of trapping condition

Cyclotron Resonance

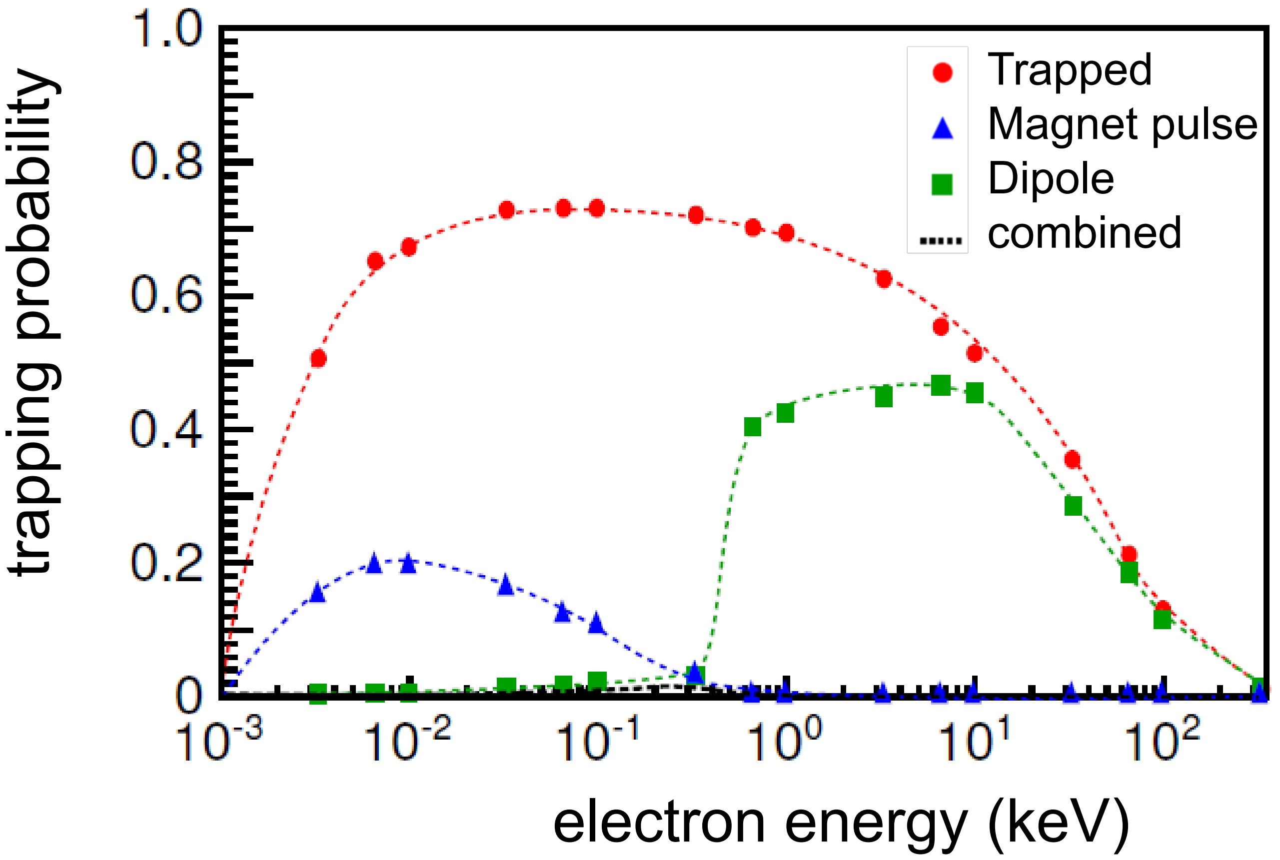
- apply RF-field tuned to cyclotron frequency



$\omega_{RF} = \omega_{cycl}$

all electron energies

Magnetic Pulse + Electrostatic Dipole

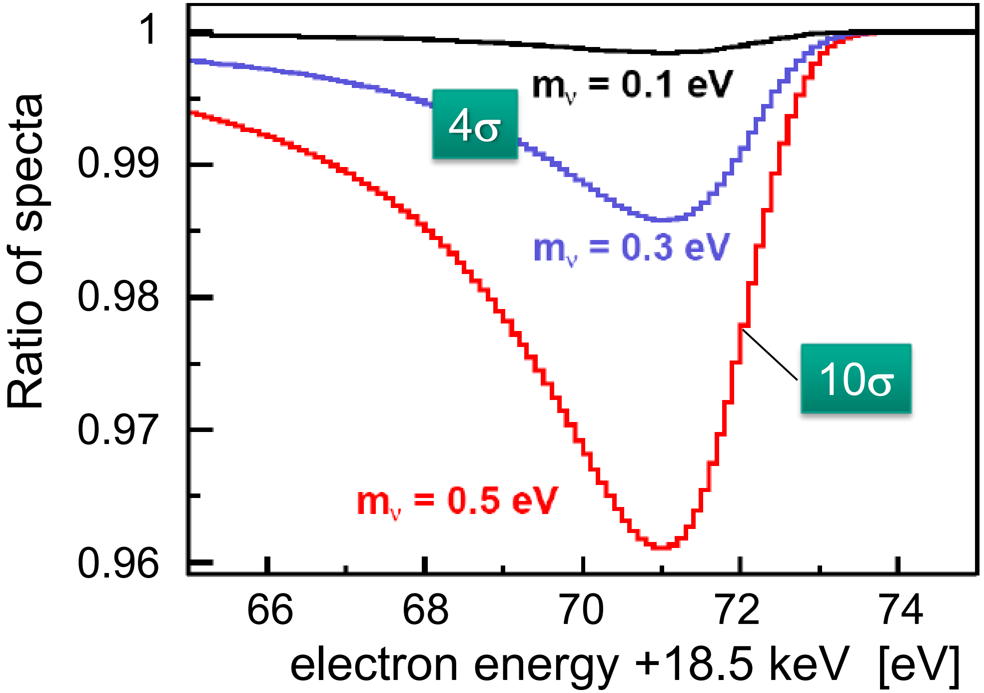


KATRIN sensitivity

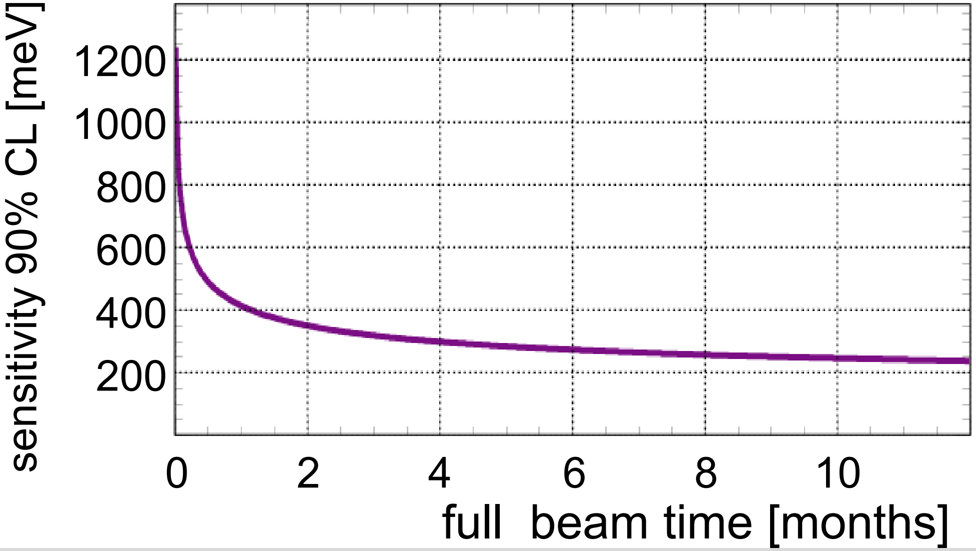
- **reference ν-mass sensitivity**
  for 3 ´full beam´ years:
  - statistical & systematic errors contribute equally:
    statistics $\sigma_{stat} = 0.018\ \text{eV}^2$
    systematics $\sigma_{syst} < 0.017\ \text{eV}^2$

sensitivity m(ν) = 200 meV (90% CL)

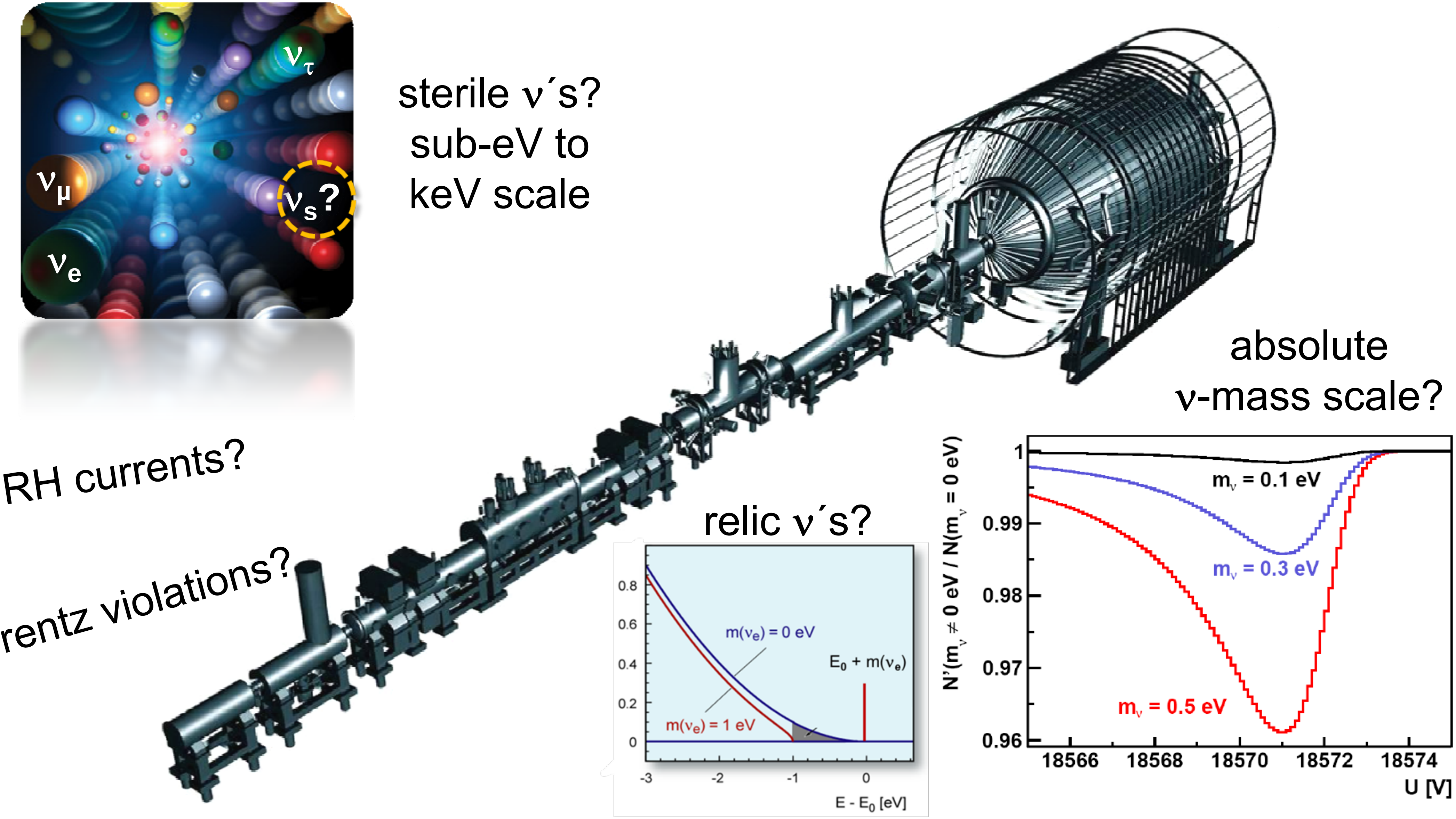
350 meV (5σ)



- **other physics**
  - light sterile neutrinos (eV-scale)
    reactor anomaly
  - heavy sterile neutrinos (keV-scale)
    warm dark matter
  - non-V-A interactions, Lorentz violation



Conclusion



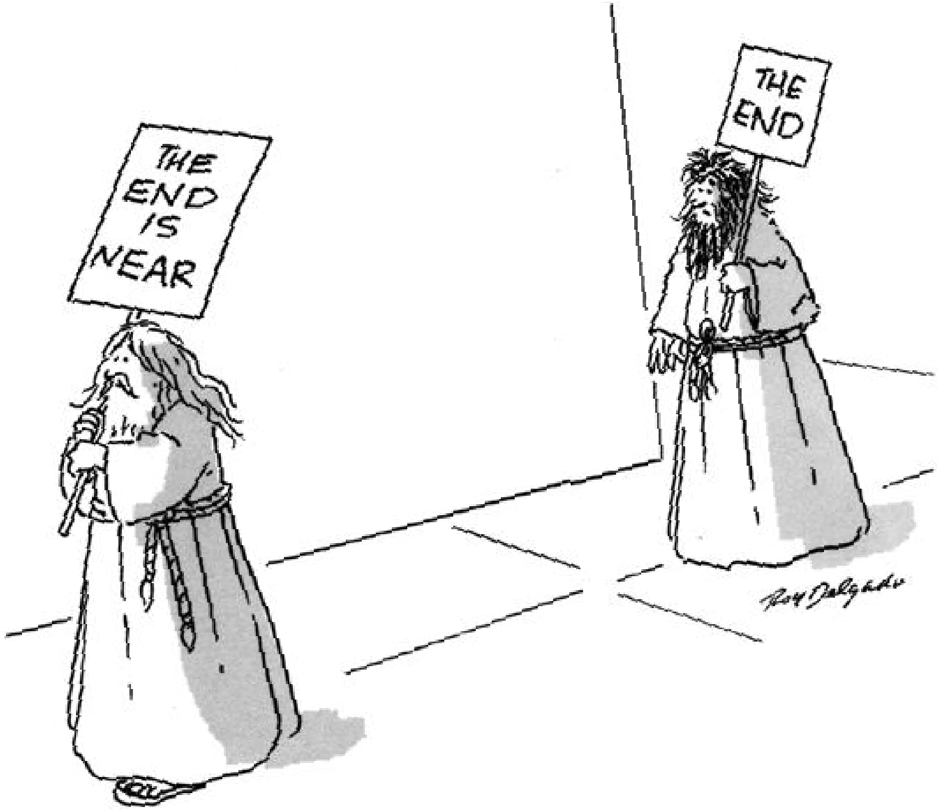
sterile ν´s?
sub-eV to
keV scale

RH currents?

Lorentz violations?

relic ν´s?

absolute
ν-mass scale?


THE END IS NEAR
THE END
Roy Delgado