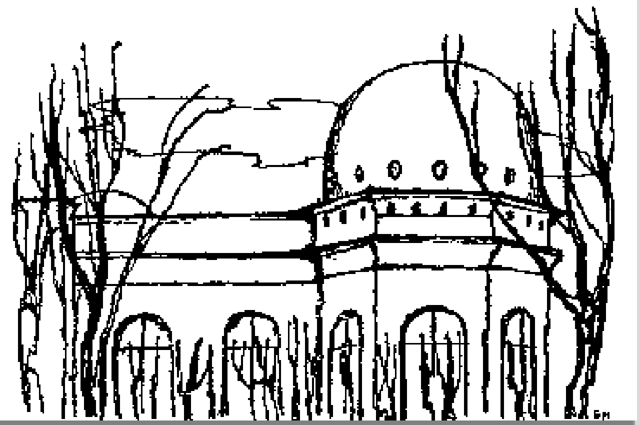
KATRIN



Ecole Internationale Daniel Chalonge

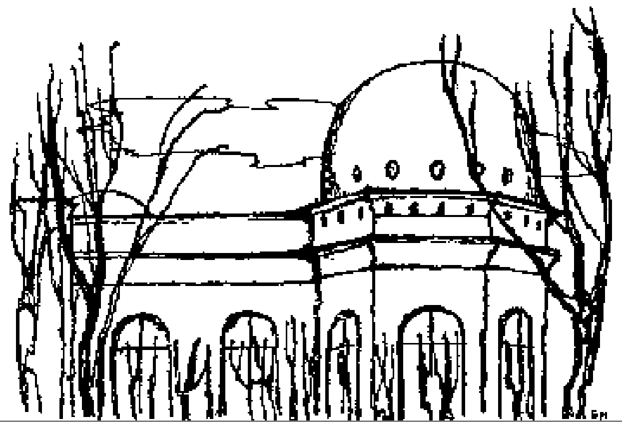
19th Paris Cosmology Colloquium July 24th, 2015

Guido Drexlin, KCETA

in memoriam of Hector J. de Vega

Karlsruhe Institute of Technology

KATRIN



Ecole Internationale Daniel Chalonge

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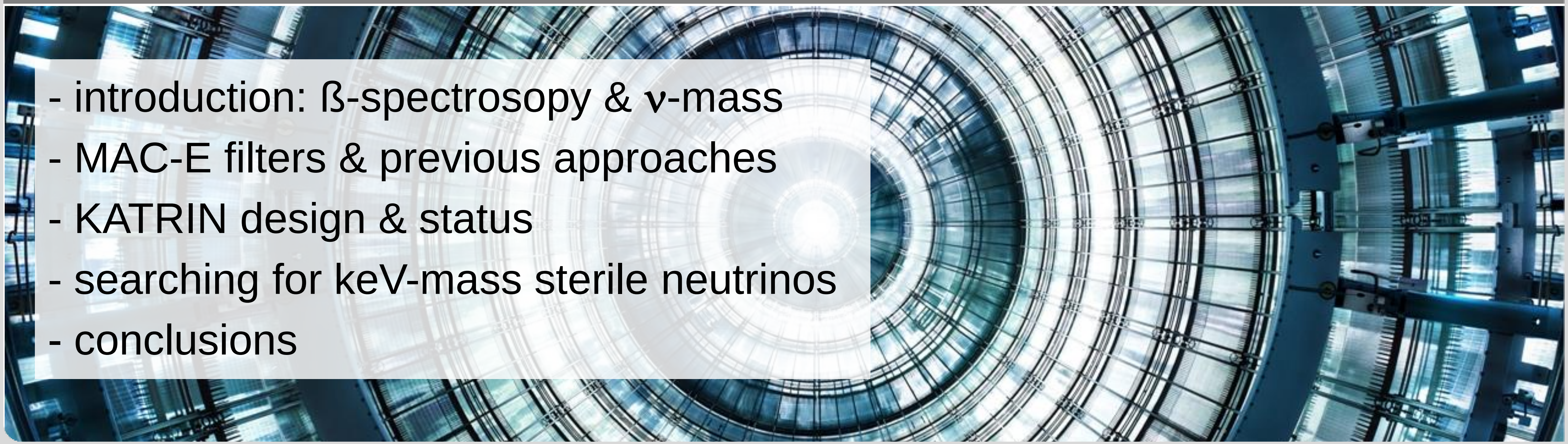


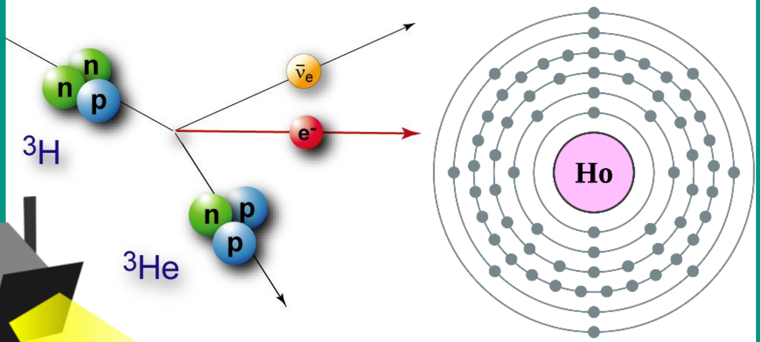
- introduction: ß-spectrosopy & ν-mass
- MAC-E filters & previous approaches
- KATRIN design & status
- searching for keV-mass sterile neutrinos
- conclusions

hunting neutrino masses

KIT Karlsruhe Institute of Technology

kinematics weak decays

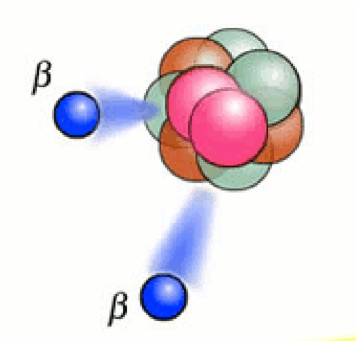
- ß-decay: ^3H, EC: ^{163}Ho
- **model-independent**



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

search for 0νßß-decay

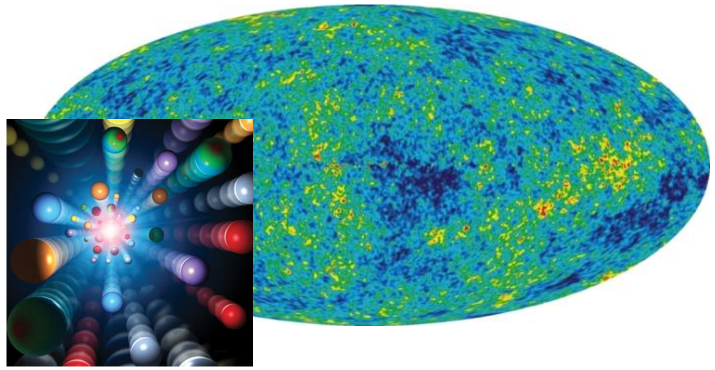
- ßß-decay ^{76}Ge, ^{130}Te,…
- model-dependent (α_i)



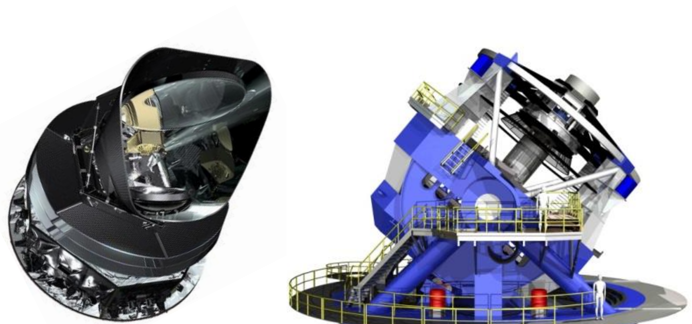
quenching of g_A?
hep-ph
1404.2616v2
strong impact
on $m_{ßß}$

cosmology

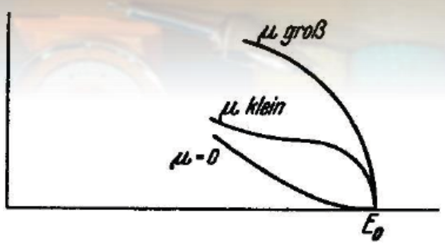
- LSS: CMB, GRS, WL,…
- model-dependent (⇔w)



$$m_{tot} = \sum_{i=1}^{3} m_i$$



ν-mass &
ß-spectroscopy



Review: G.D., V. Hannen, S. Mertens, C. Weinheimer, *Current Direct Neutrino Mass Experiments*,
Advances in High Energy Physics Vol. 2013, ID293986

ß-decay: kinematics

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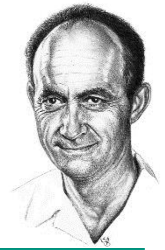
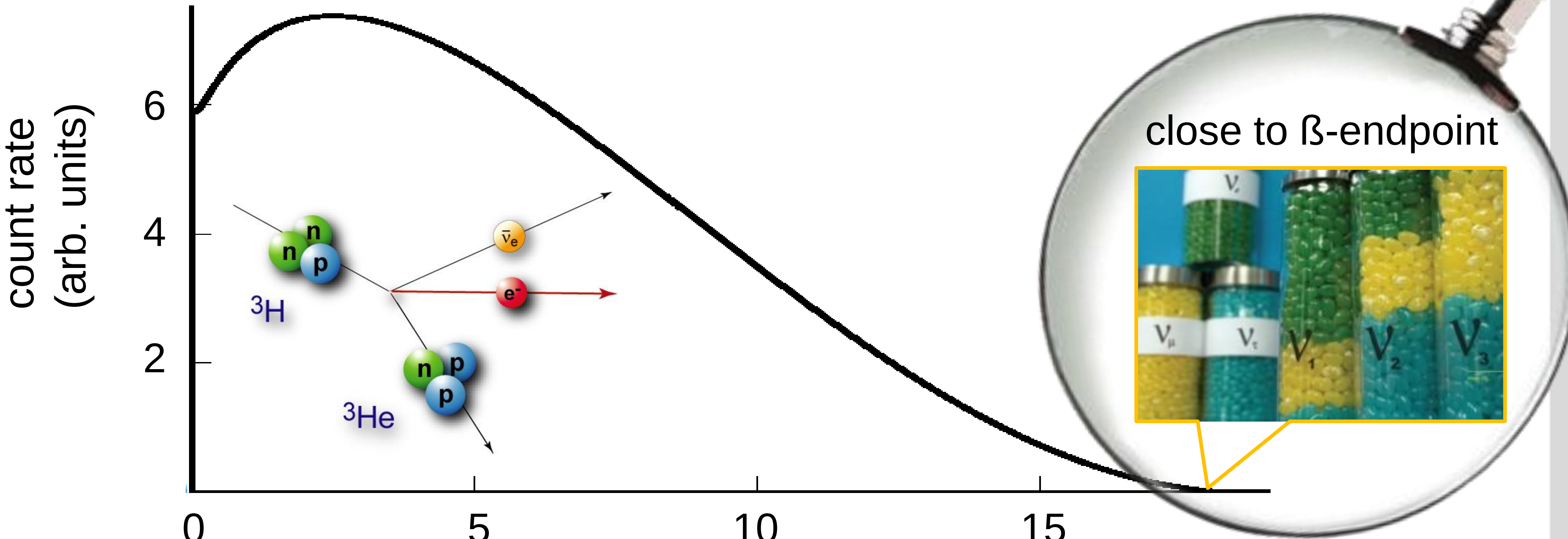
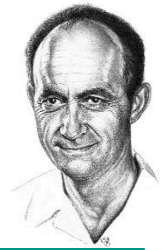


- model independent measurement of m($\boldsymbol{\nu_e}$)
  - based only on **kinematic parameters & energy conservation**

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

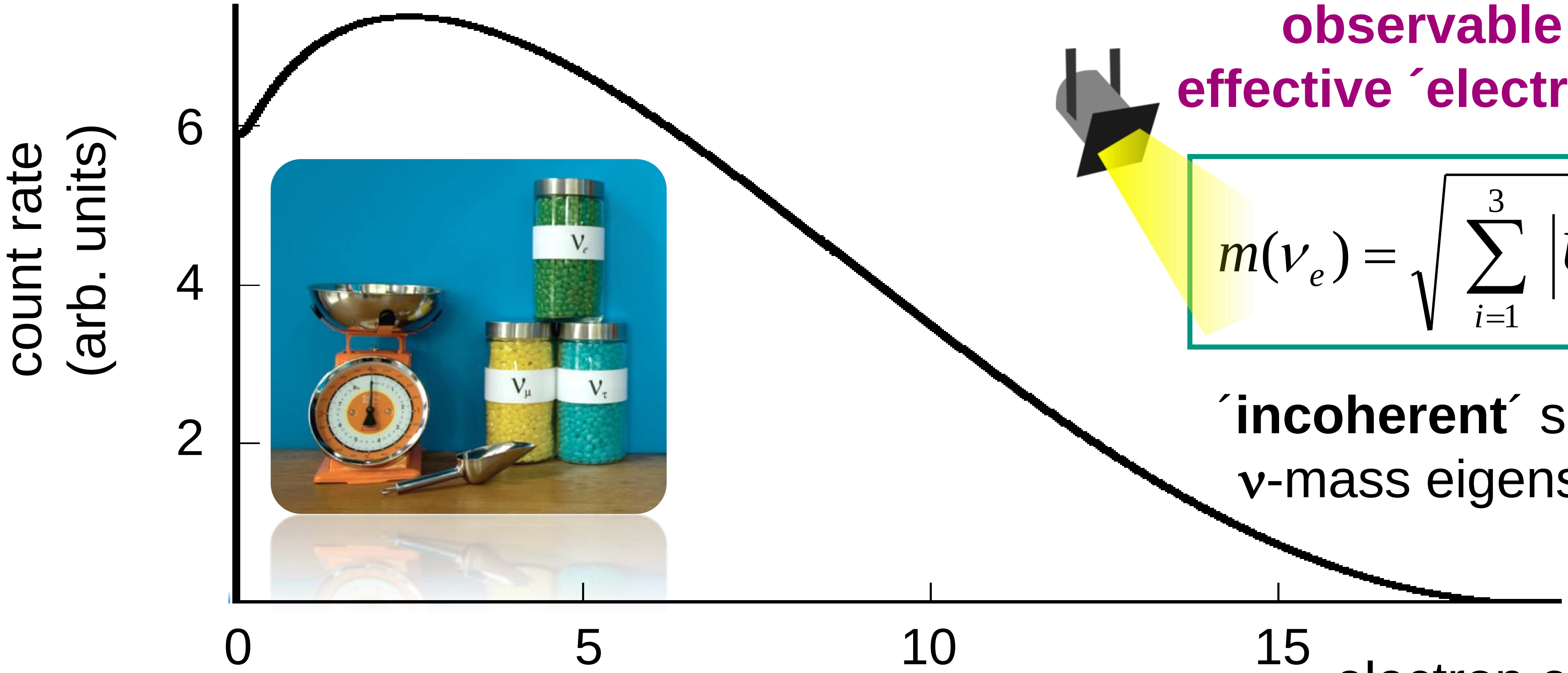


ß-decay: kinematics



- model independent measurement of m(ν_e)
  - based only on **kinematic parameters & energy conservation**

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



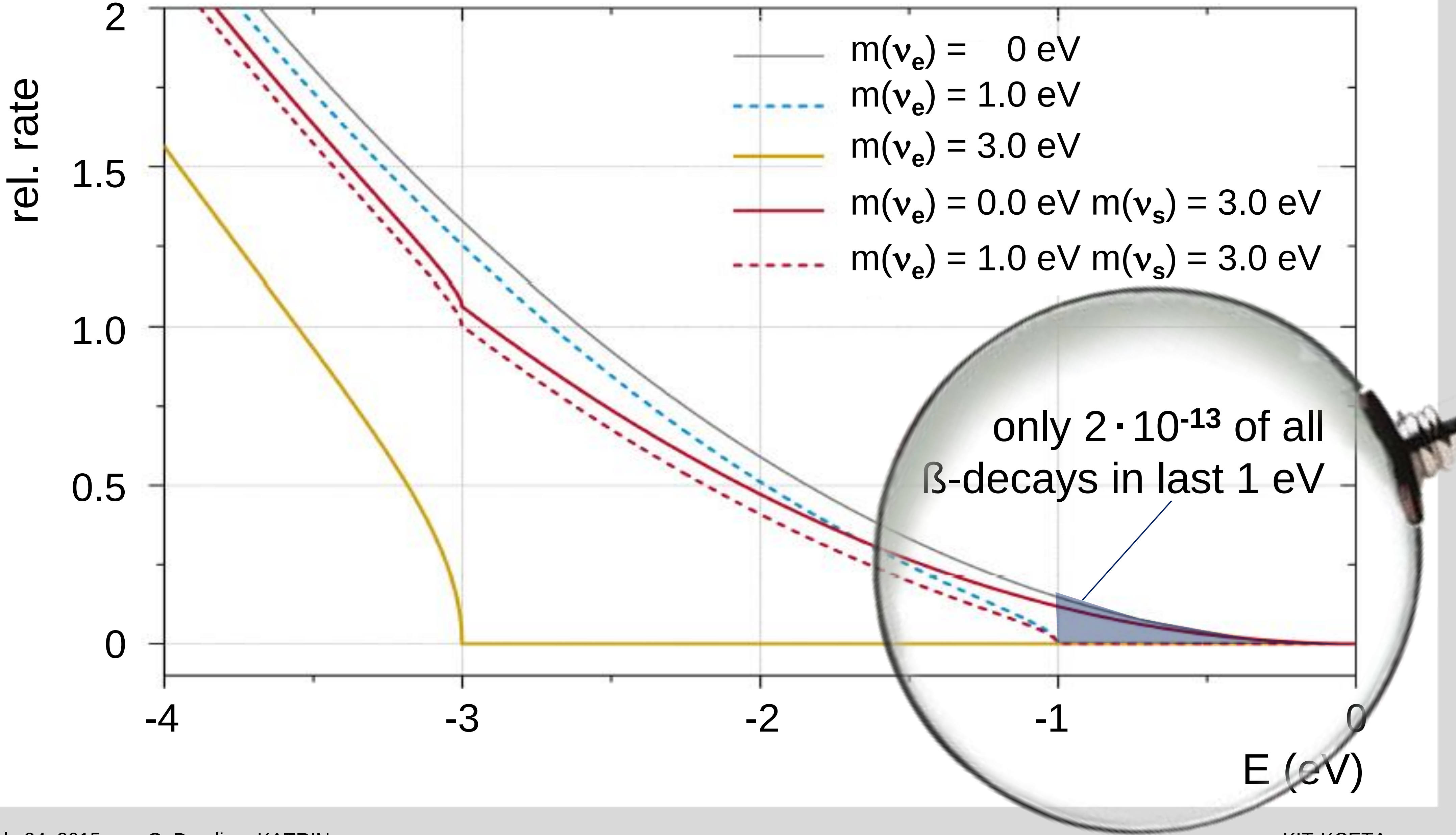
observable m²(ν_e):
effective ´electron-ν-mass´

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

´incoherent´ sum of the
ν-mass eigenstates m_i

ß-decay: relative shape modification

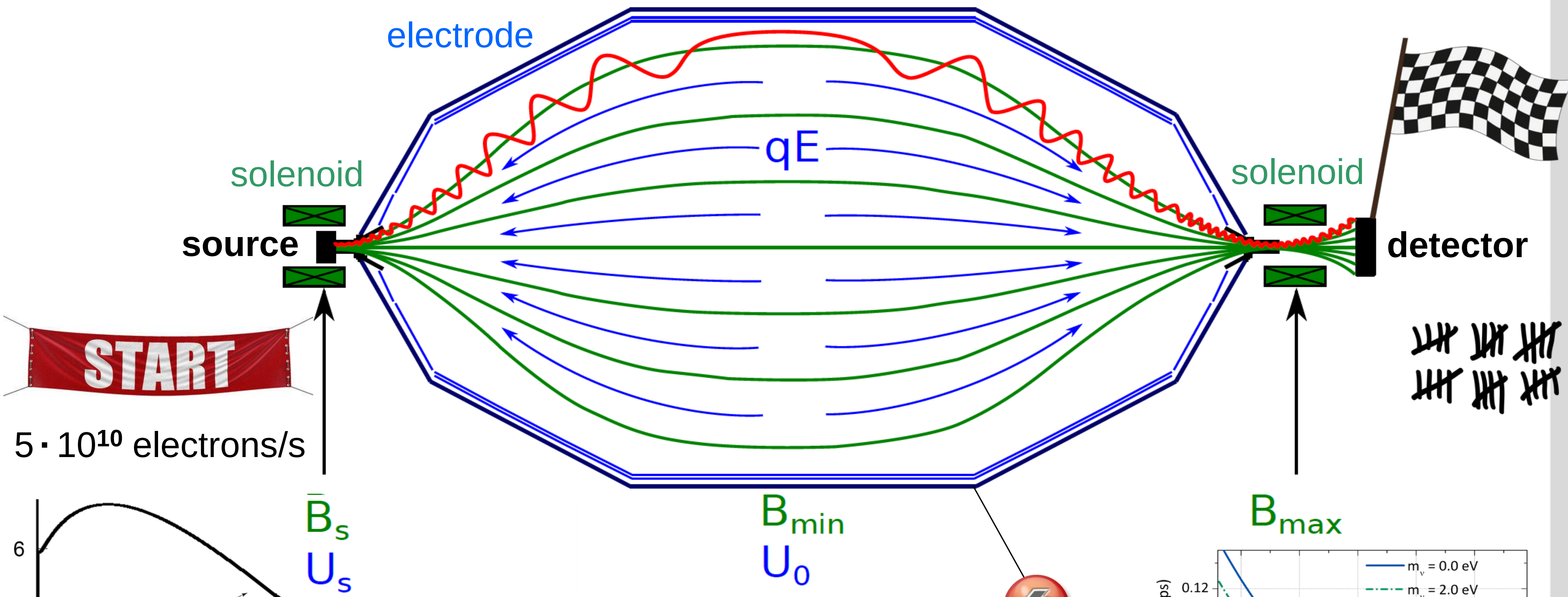
- **relative shape measurement** only, as precision of external E_0 only ~ eV

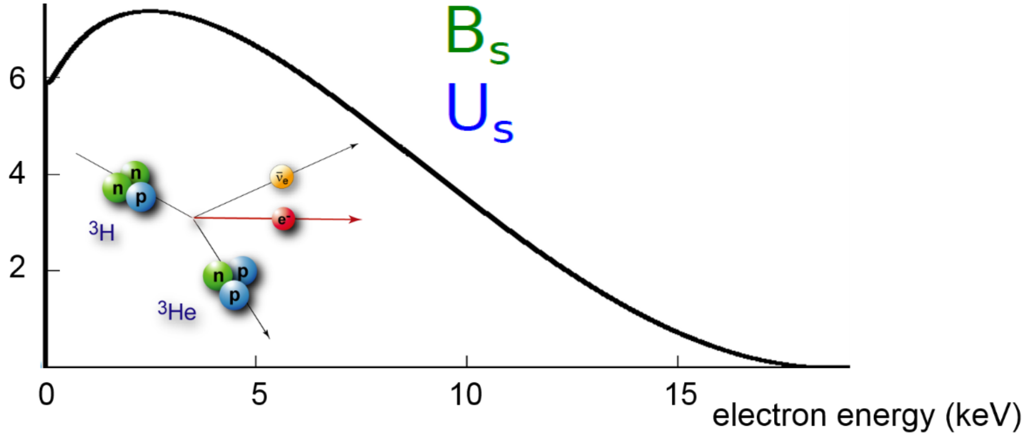


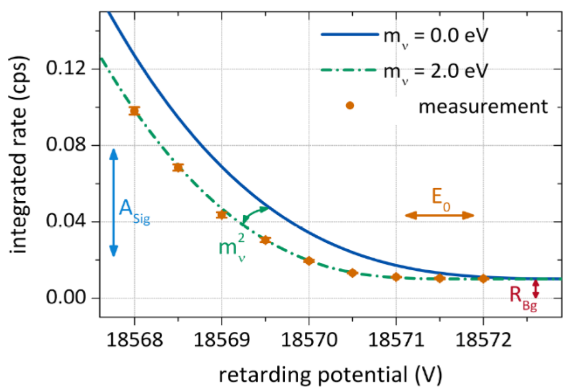
MAC-E filter & previous T2 experiments

MAC-E principle: Mainz, Troitsk, KATRIN

- **Magnetic Adiabatic Collimation & Electrostatic Filter**

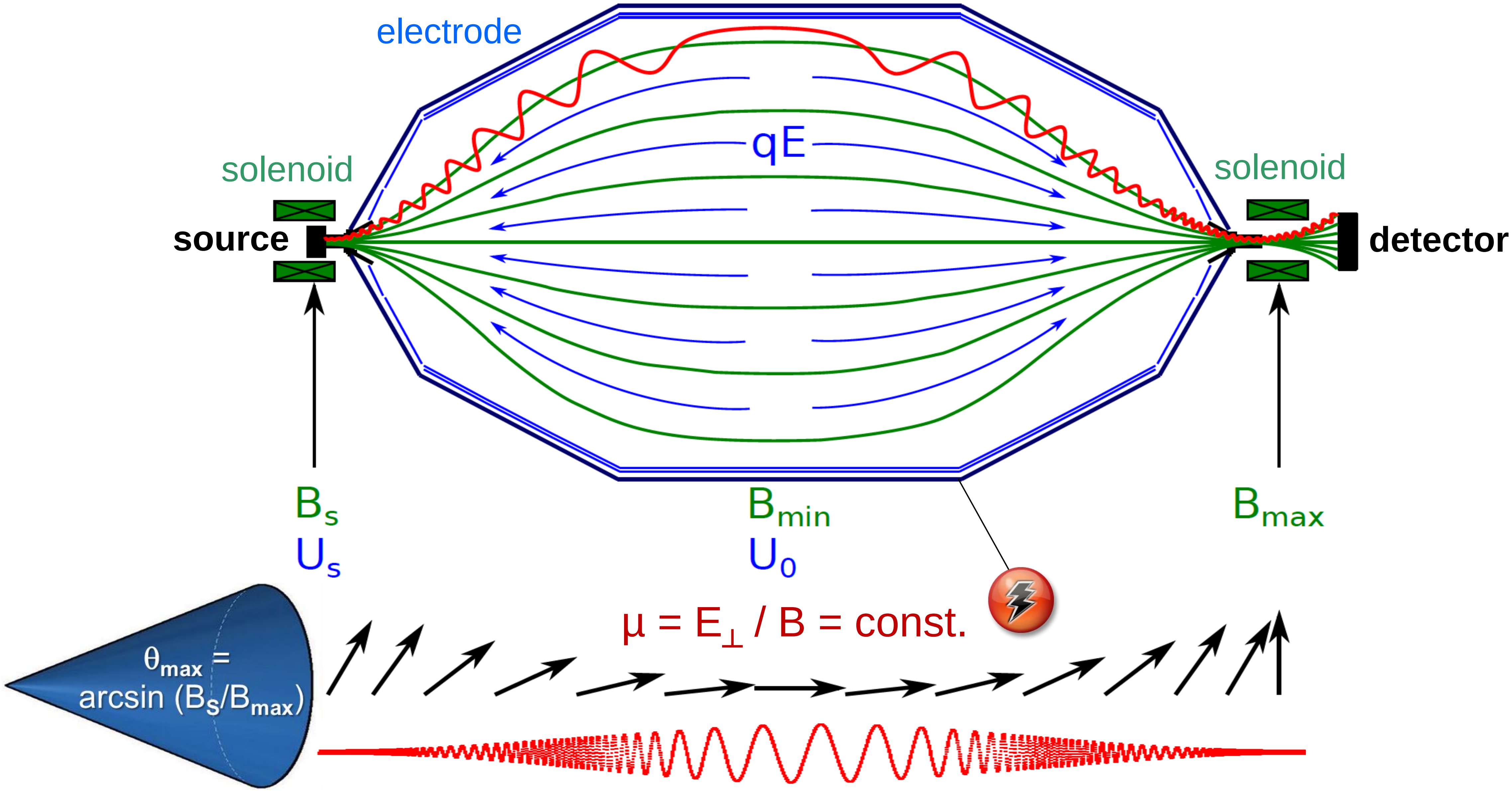






MAC-E principle: Mainz, Troitsk, KATRIN

- **Magnetic Adiabatic Collimation & Electrostatic Filter**



MAC-E principle: Mainz, Troitsk, KATRIN

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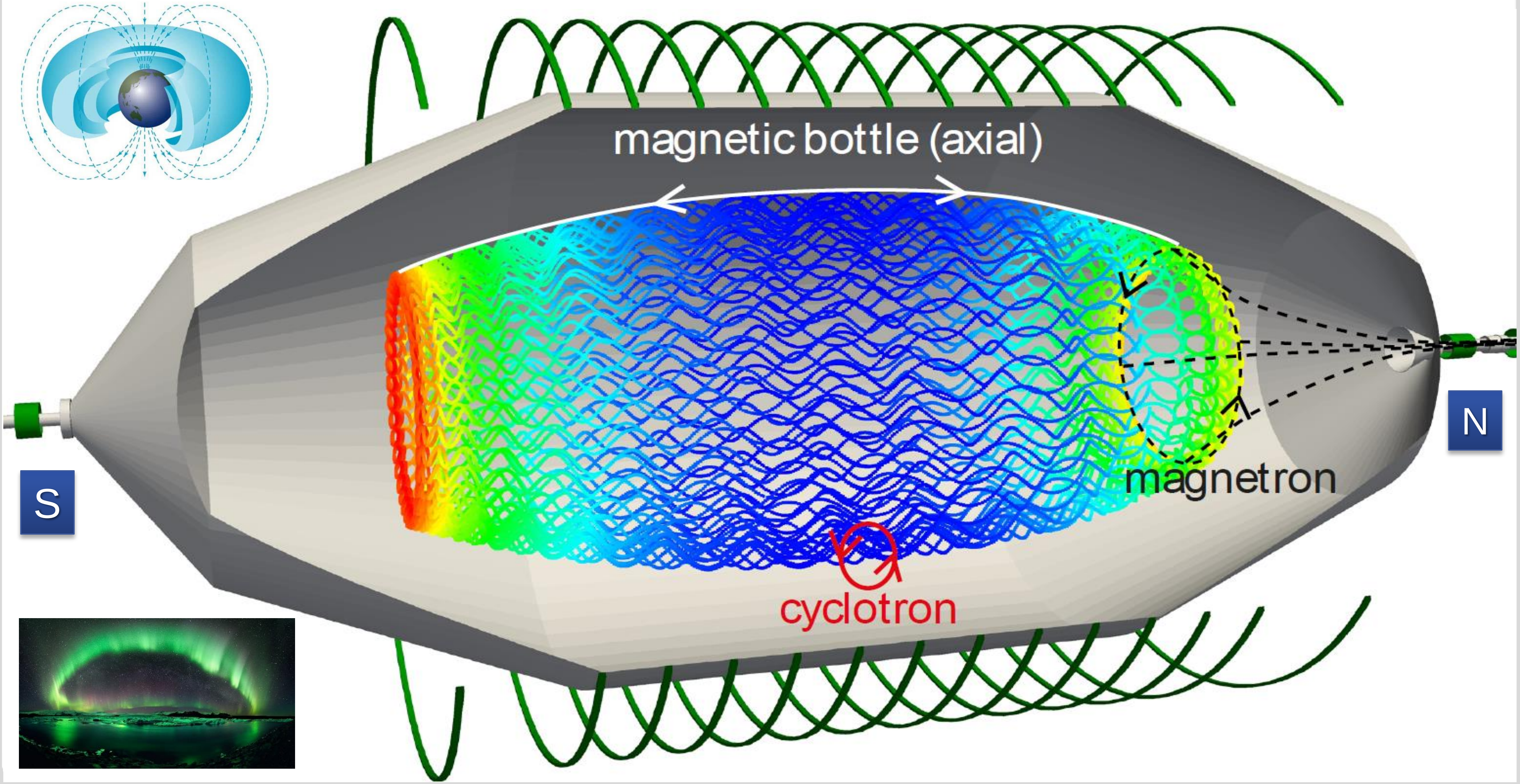
- **Magnetic Adiabatic Collimation & Electrostatic Filter = magnetic bottle**



Troitsk & Mainz experiments

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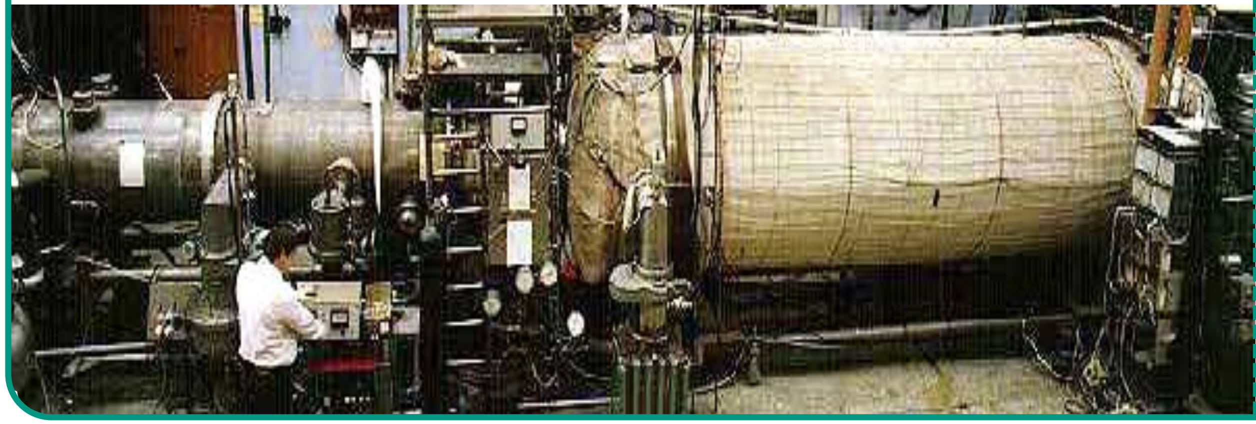
Troitsk experiment

- windowless gaseous tritium source



- **2011** re-analysis of selected data from 1994-2004: no evidence for Troitsk anomaly

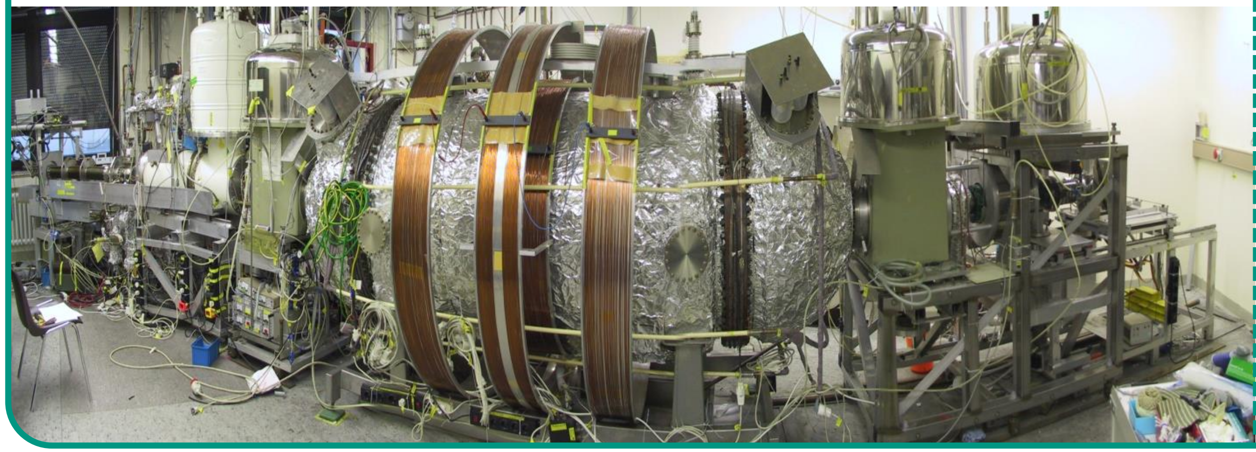
$$m^2(\nu_e) = (-0.67 \pm 1.89 \pm 1.68)\ eV^2$$

$$m(\nu_e) < 2.05\, eV$$

V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003

Mainz experiment

- quench condensed tritium source



- **2004** final analysis of Mainz phase II data from 1998-2001: analysis of last 70 eV

$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\ eV^2$$

$$m(\nu_e) < 2.3\, eV$$

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

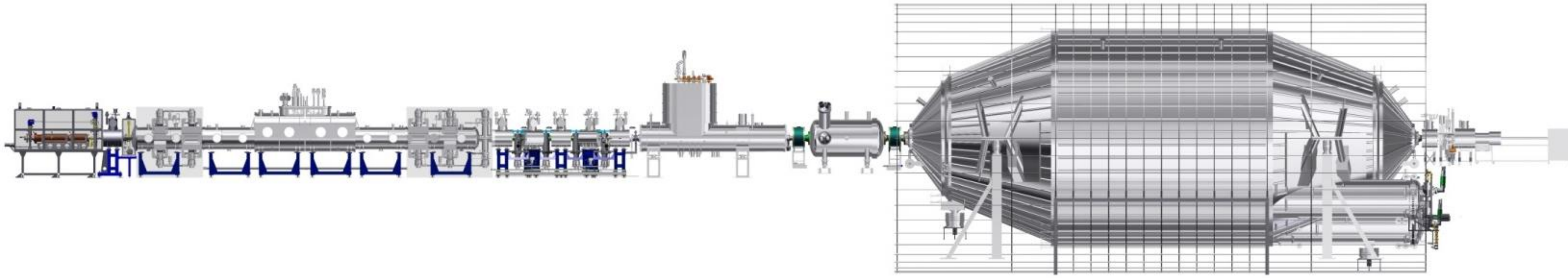
KATRIN – design & status

KATRIN experiment

Karlsruhe Tritium Neutrino Experiment

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

  15 institutions in 5 countries: D, US, CZ, RUS, ES



KATRIN member institutions

Hochschule Fulda – University of Applied Sciences

The University of North Carolina at Chapel Hill

KIT – Karlsruher Institut für Technologie

MIT

Max-Planck-Institut für Kernphysik

INR

ÚJF

Berkeley Lab

Universidad Complutense Madrid

JG|U – Johannes Gutenberg Universität Mainz

Westfälische Wilhelms-Universität Münster

UCSB

Bergische Universität Wuppertal

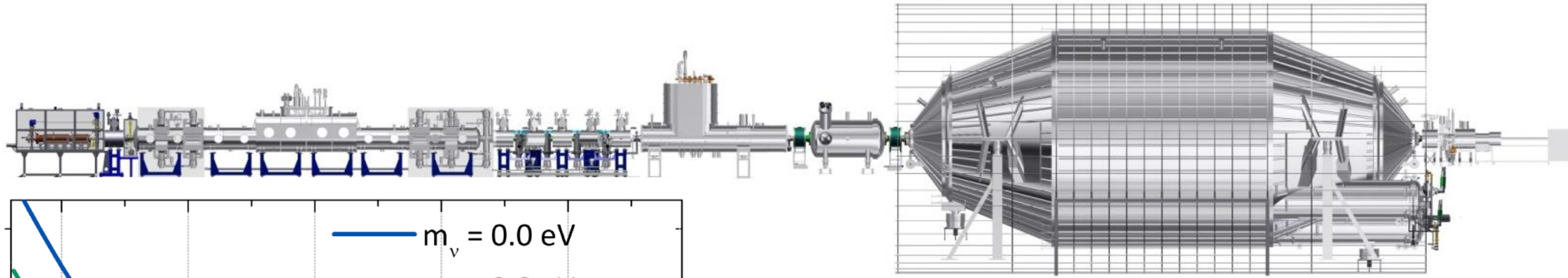
University of Washington

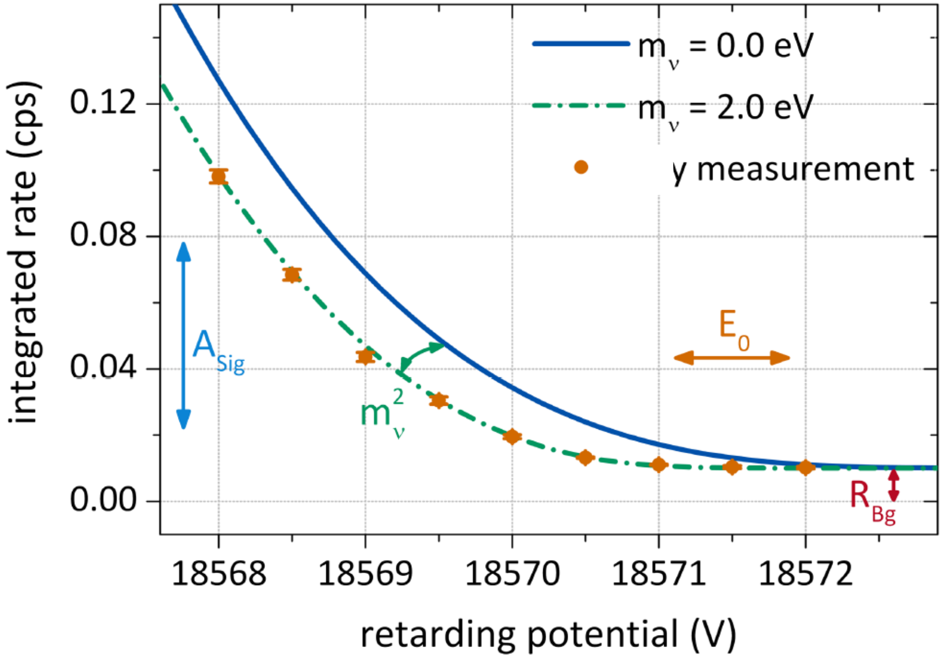
universität bonn

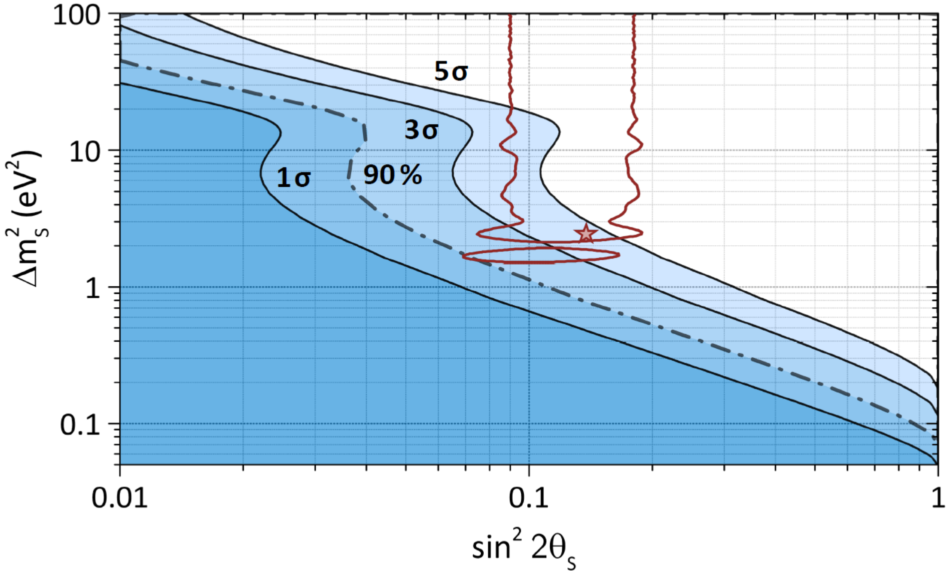
KATRIN experiment – science case

physics programme

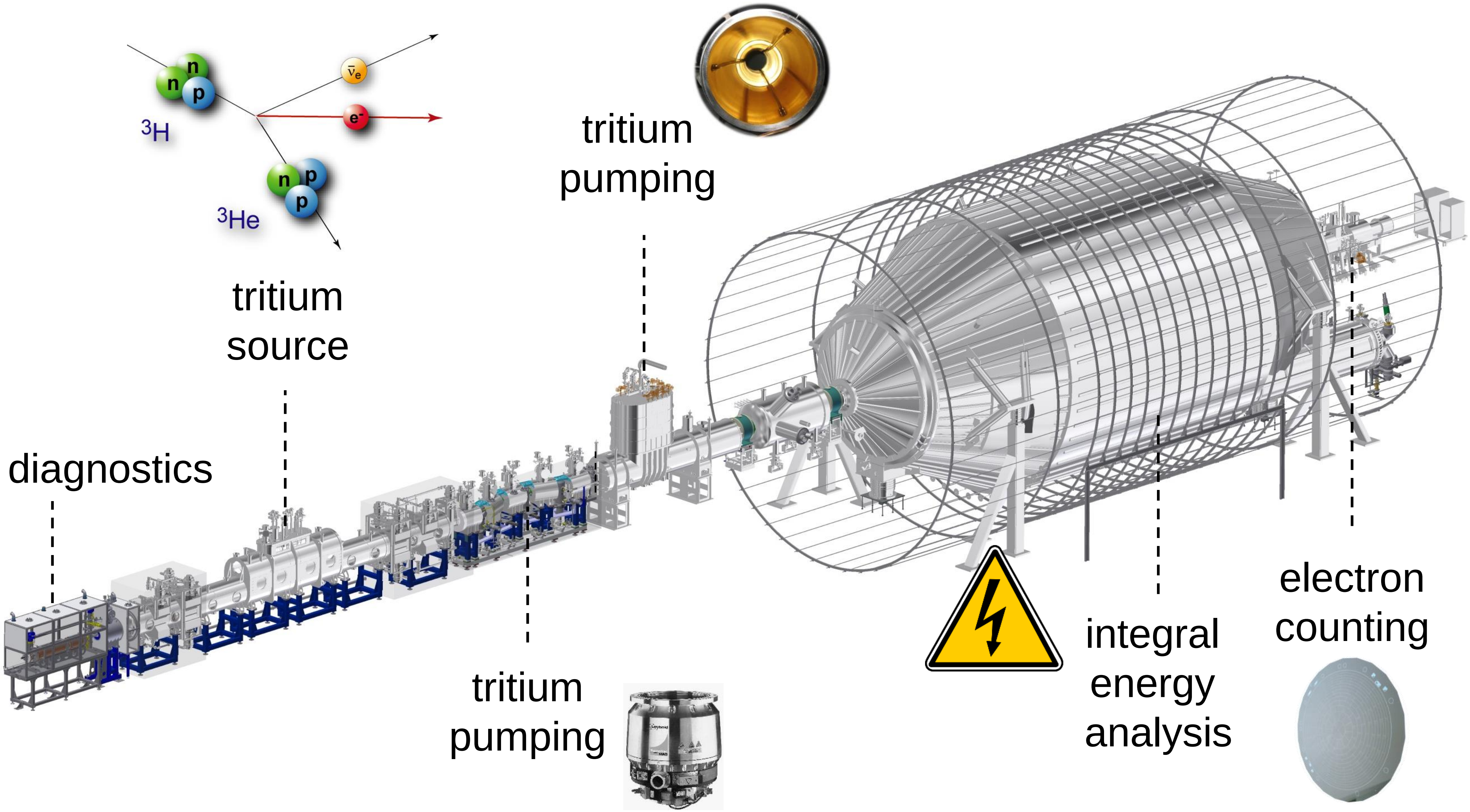
- measure effective electron neutrino mass: **$m(\nu_e)$ = 200 meV** (90% CL)
- search for sterile neutrinos from sub-eV … keV mass scale
- constrain local relic-ν density, search for RH currents/Lorentz violation





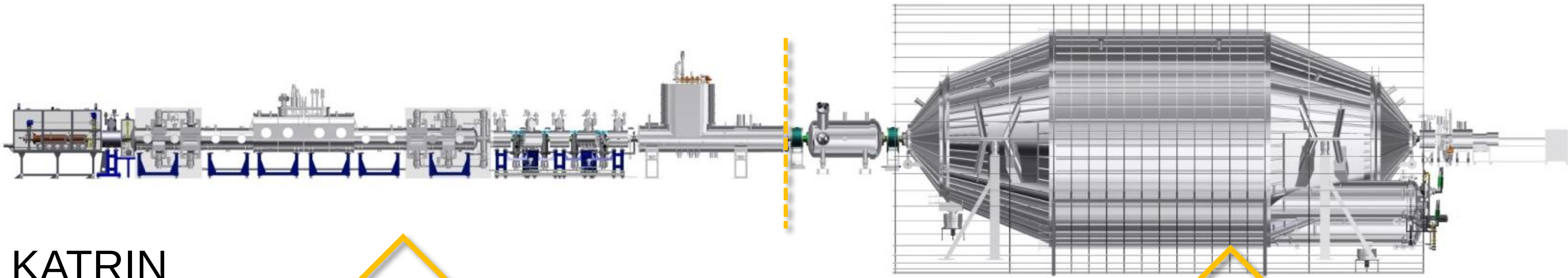


KATRIN overview: 70 m beamline



KATRIN experiment – challenges

Karlsruhe Institute of Technology

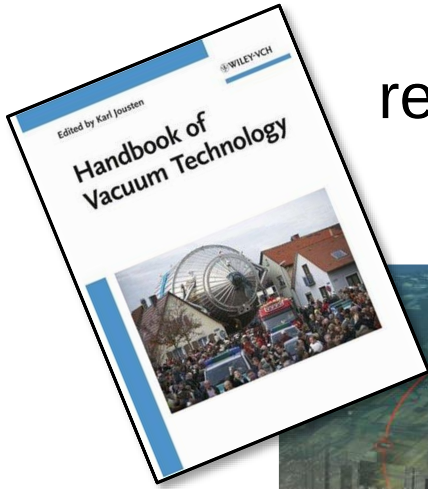


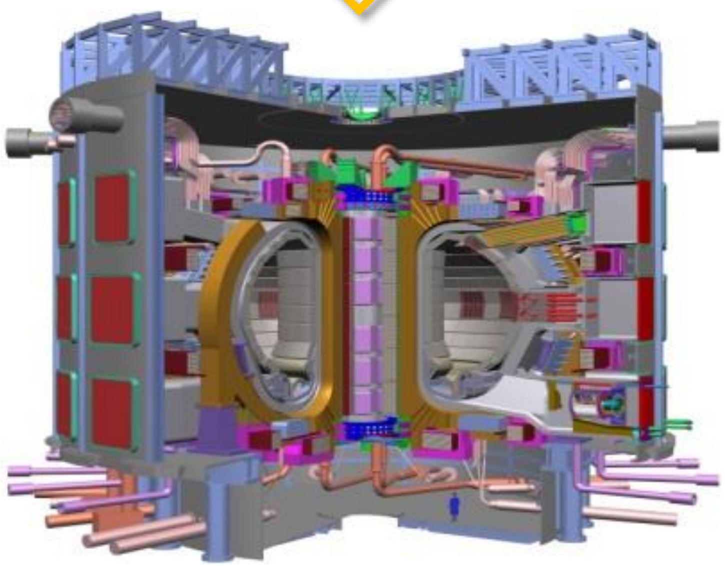
KATRIN
(2017)

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

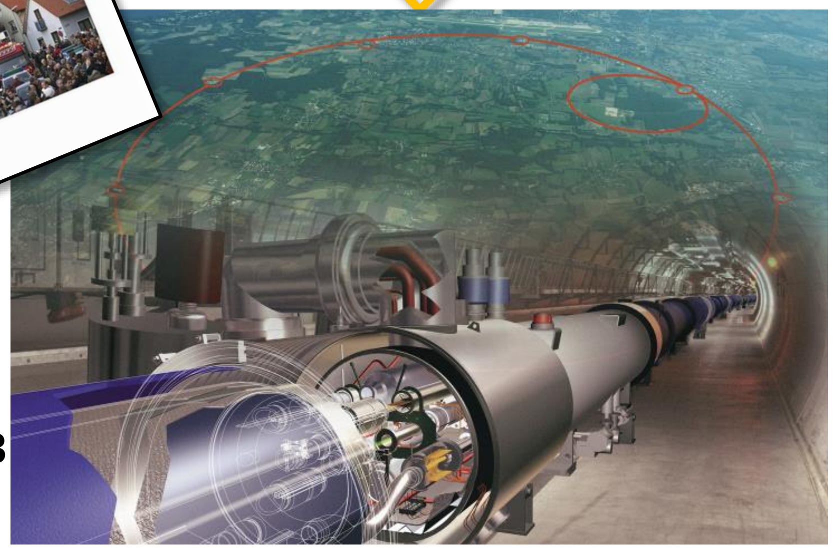
1250 m³

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



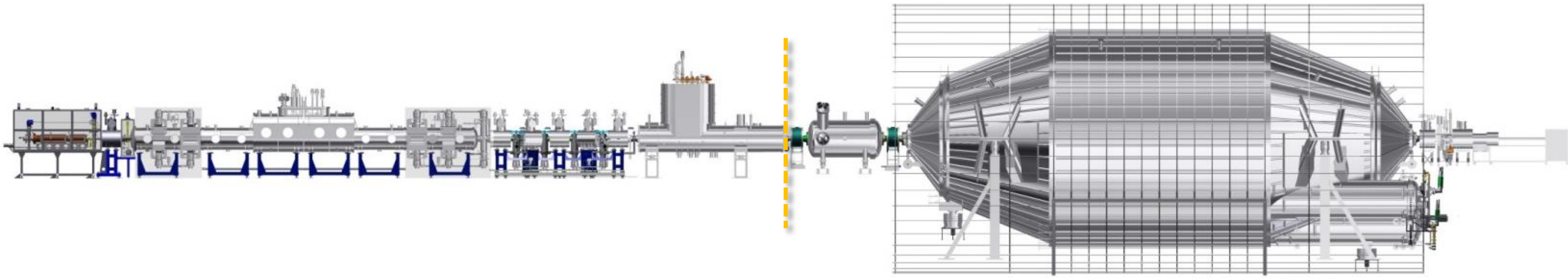


ITER
(2027)



LHC
154 m³

KATRIN – benchmark parameters

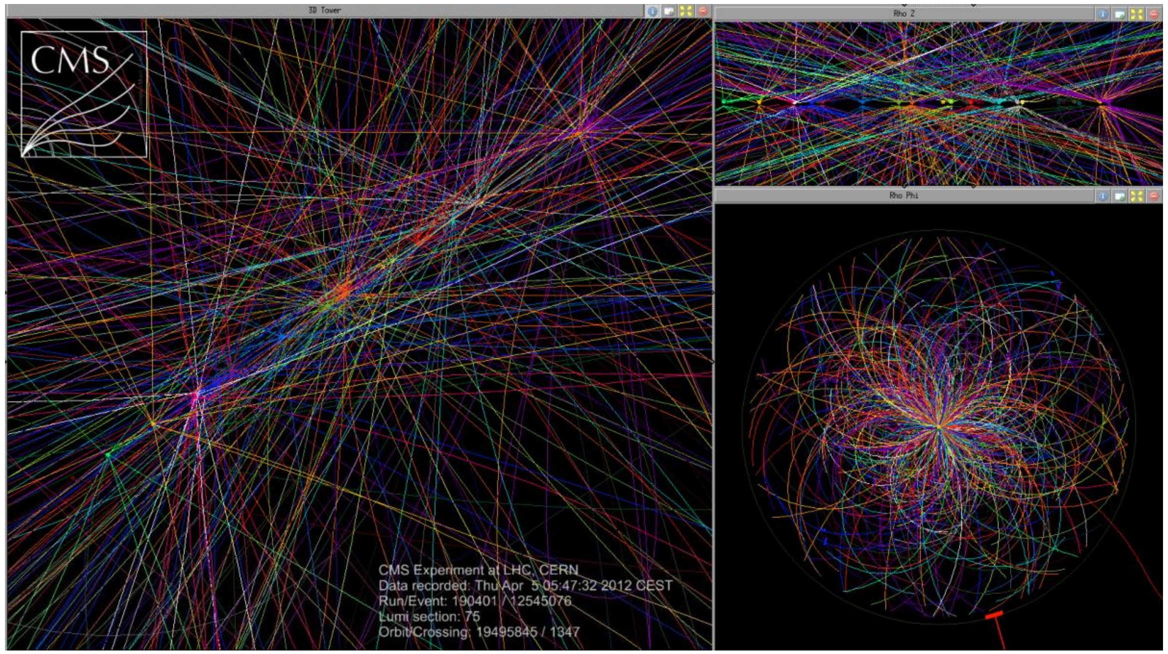


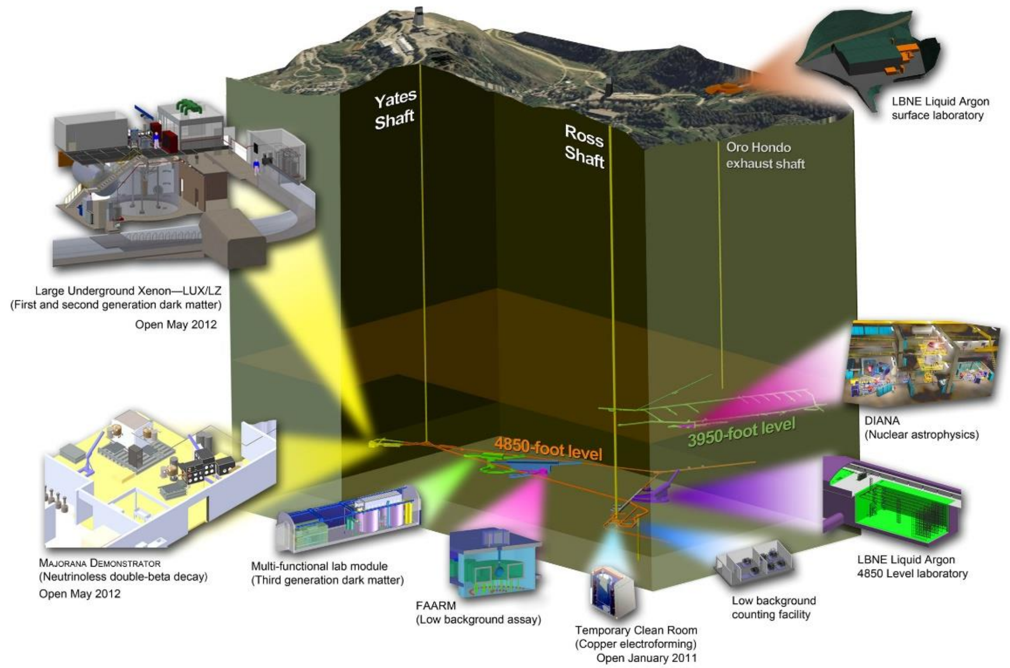
tritium source: 10^{11} ß-decays/s

(≡ LHC particle production)

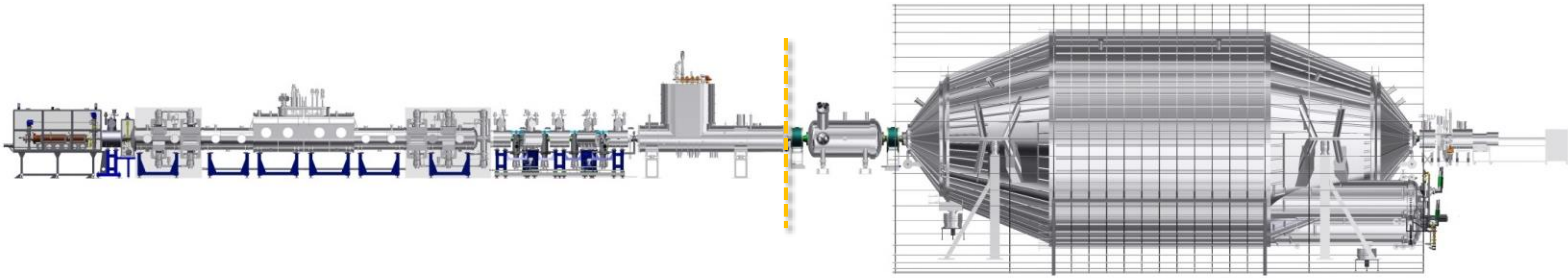
total background: 10^{-2} cps

(≡ low level @ 1 mwe)





KATRIN – benchmark parameters



tritium source: 10^{11} ß-decays/s

(≡ LHC particle production)

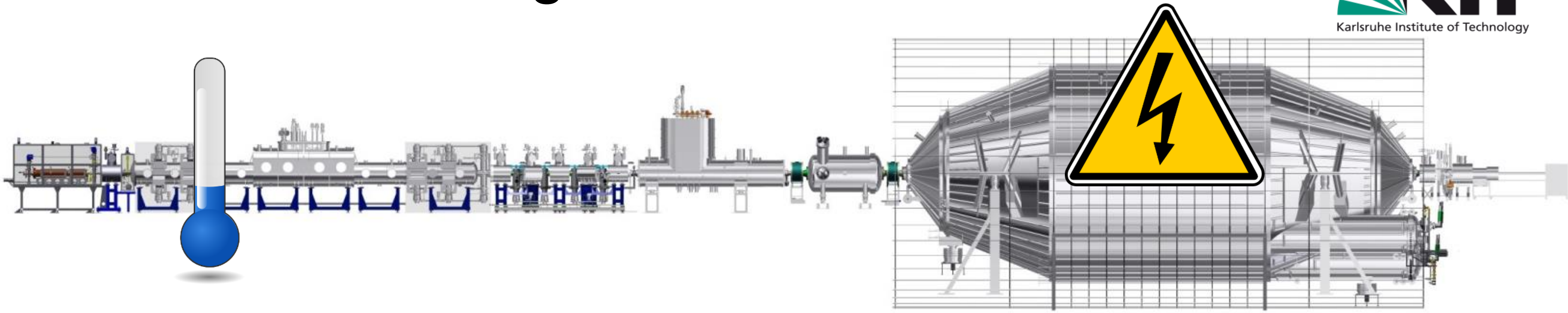
total background: 10^{-2} cps

(≡ low level @ 1 mwe)

experimental challenges

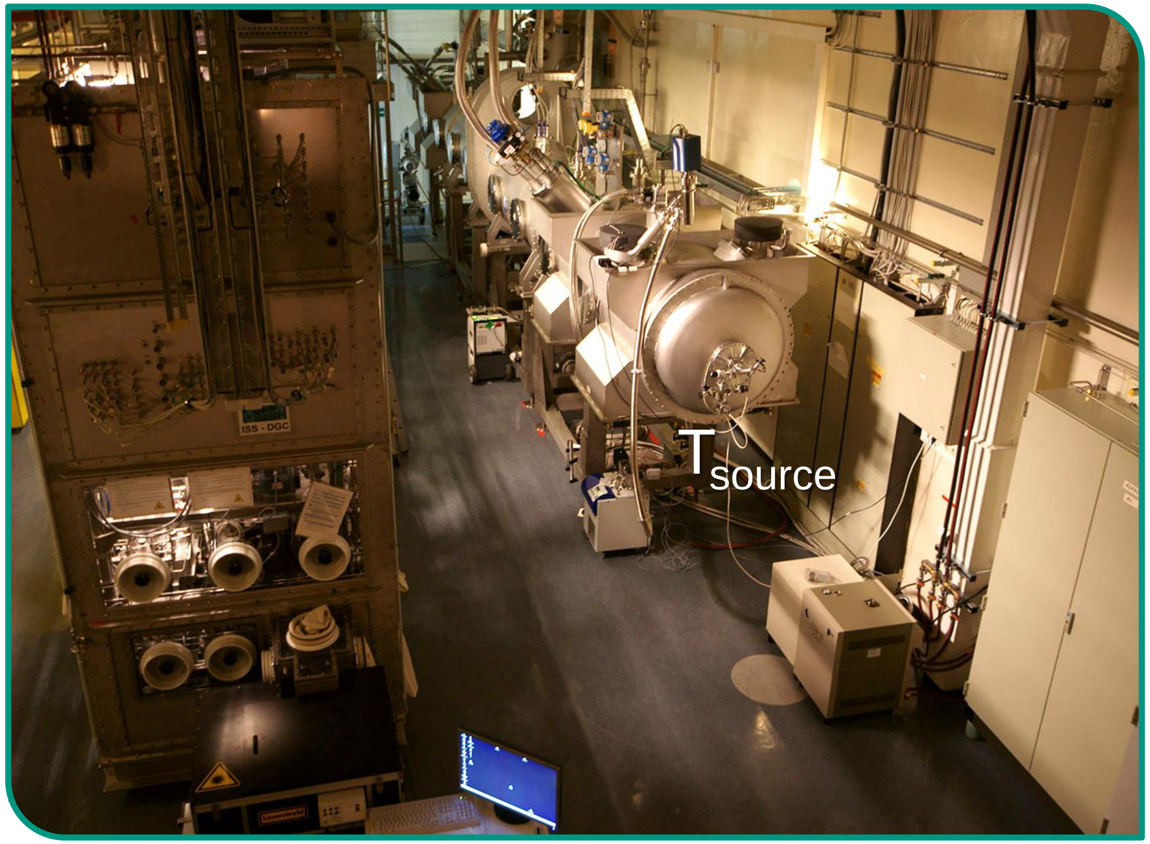
- 10^{-3} stability of tritium source column density
- 10^{-3} isotope content in source
- 10^{-5} non-adiabaticity in electron transport
- 10^{-6} monitoring of HV-fluctuations
- 10^{-8} remaining ions after source
- 10^{-14} remaining flux of molecular tritium

KATRIN – challenges and solutions

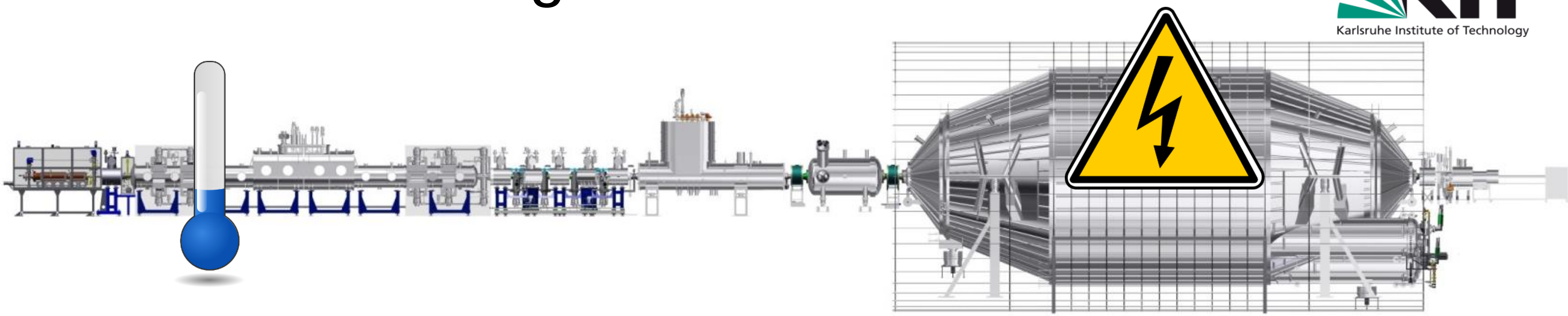


required: source fluctuation: $\Delta T < 10^{-3}$

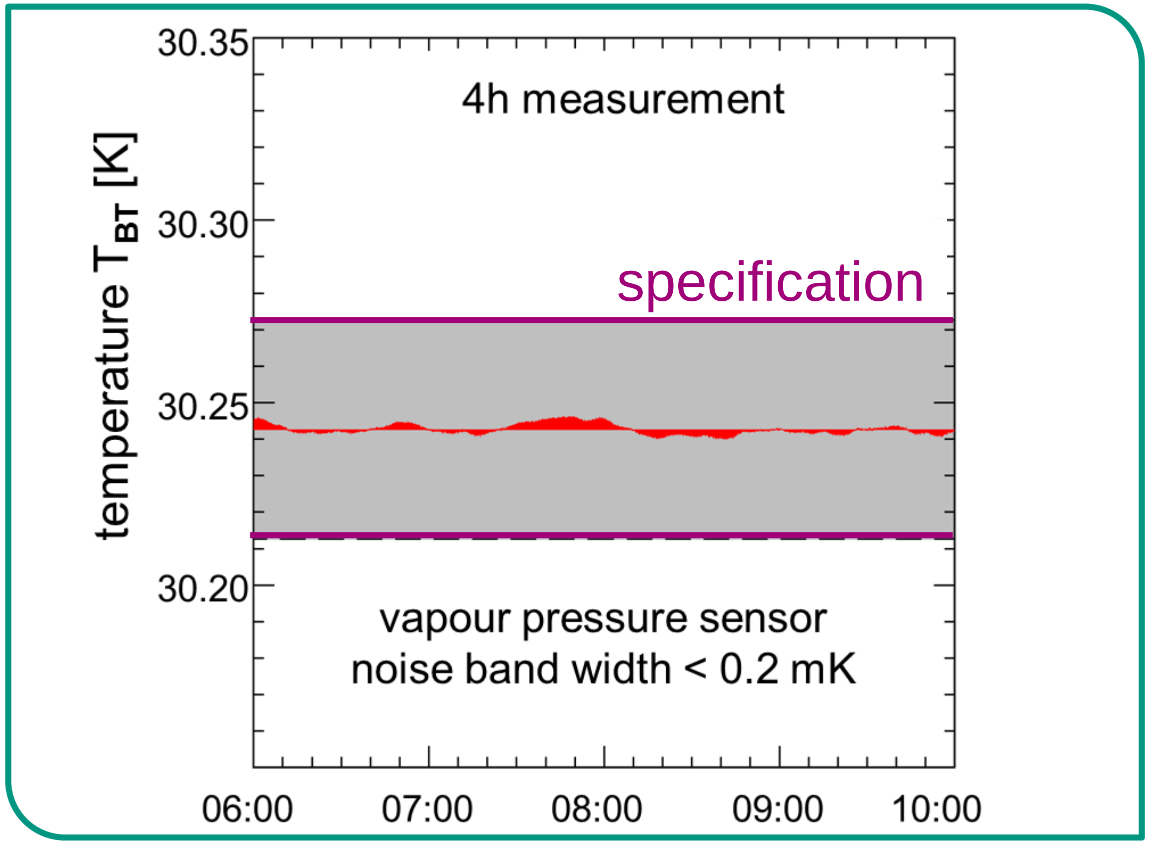
required: HV-fluctuations: $\Delta U < 60$ mV



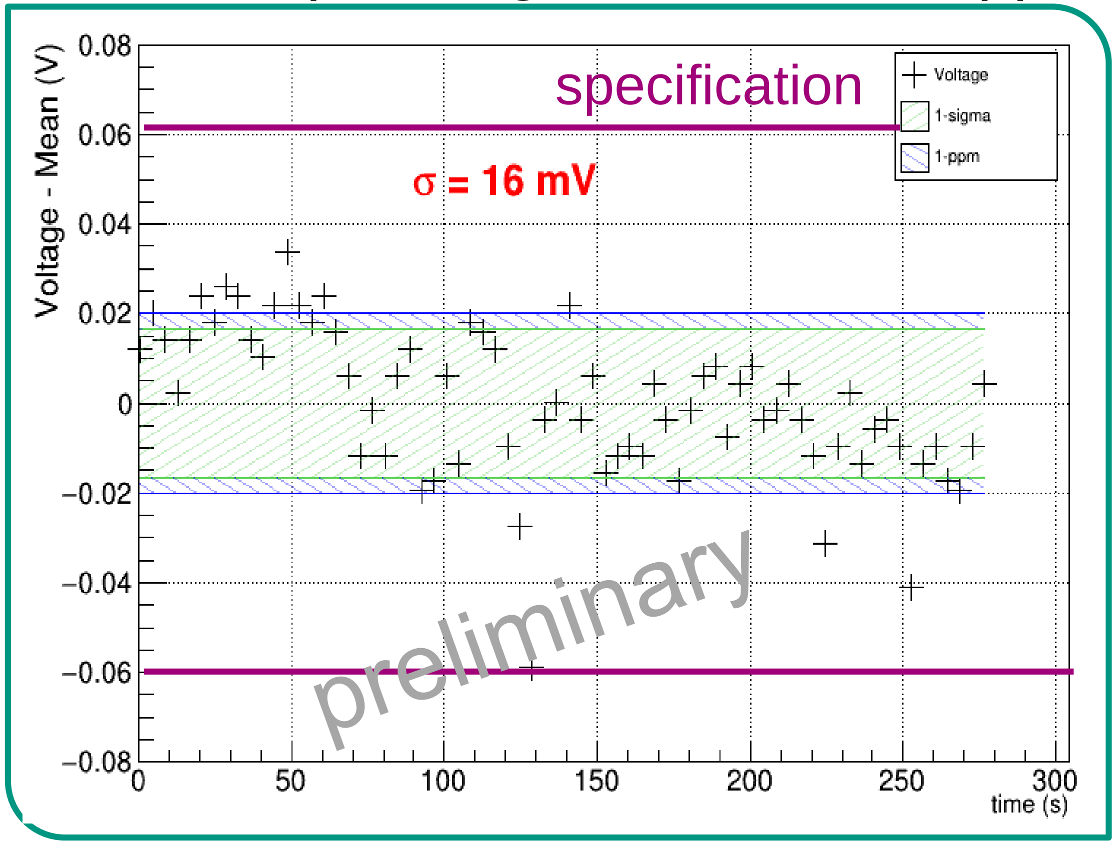
KATRIN – challenges and solutions



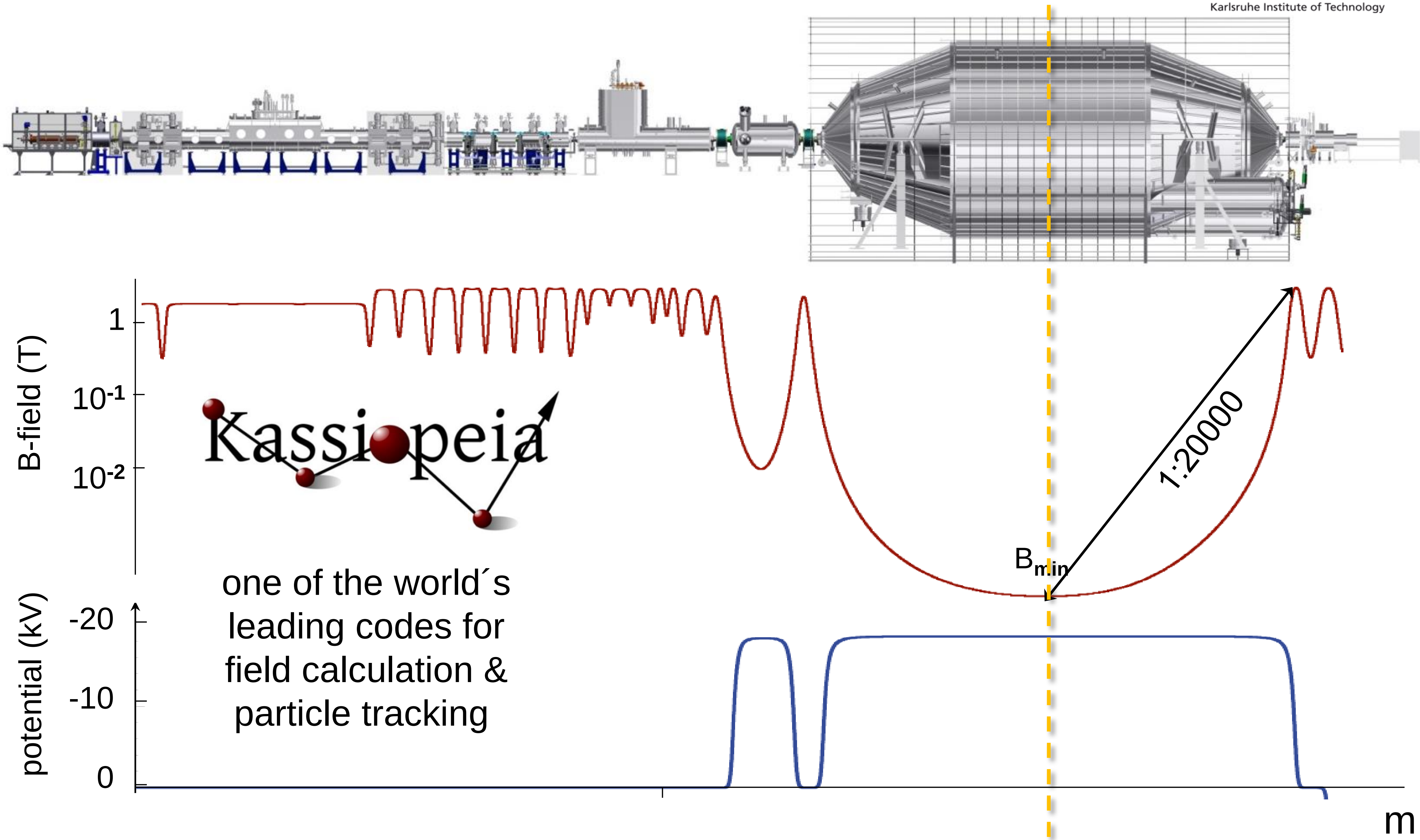
WGTS demonstrator: $\Delta T \sim 10^{-4}$



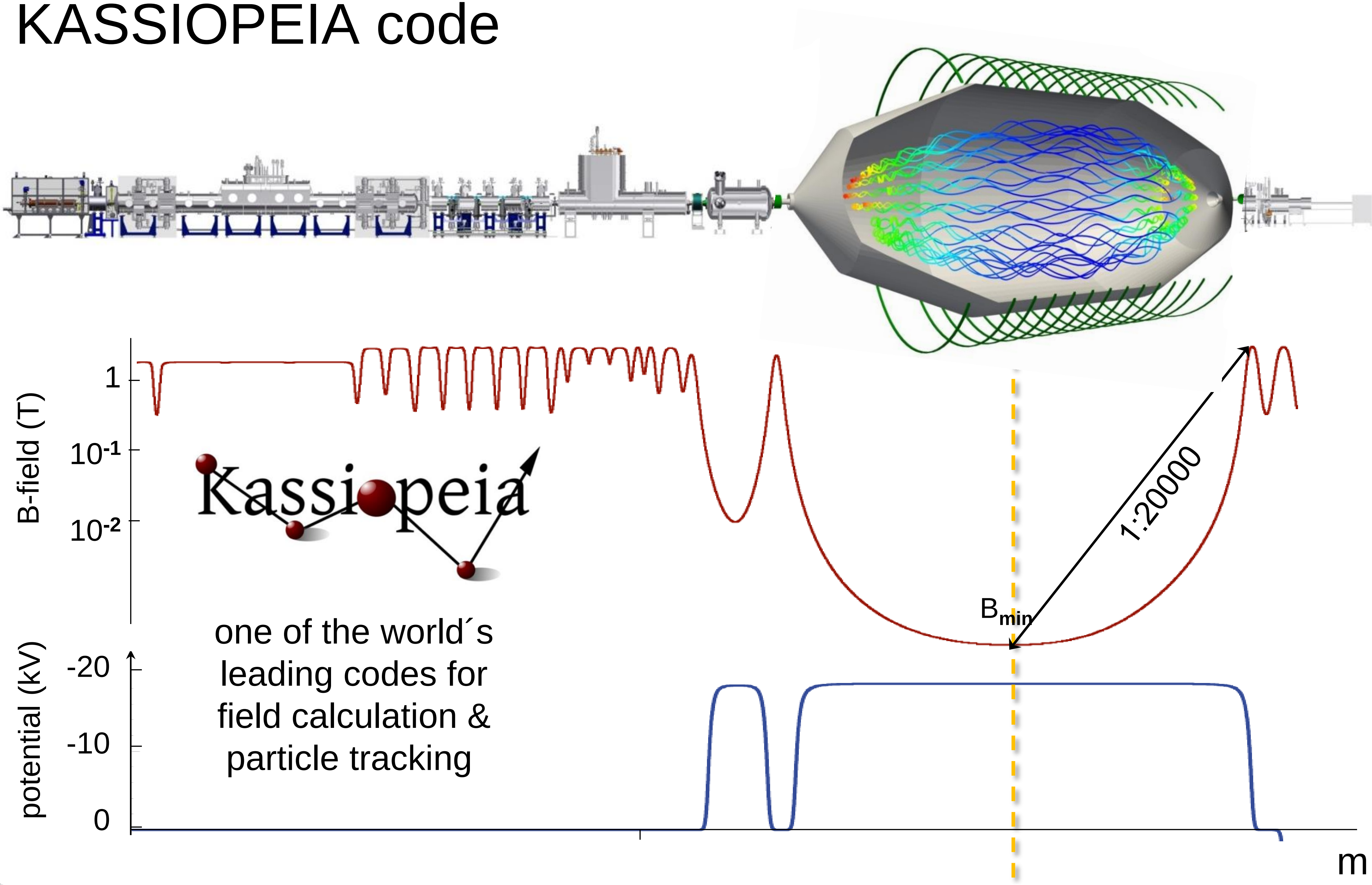
SDS2: HV post-regulation: $\Delta U \sim 1$ ppm



electron beam line

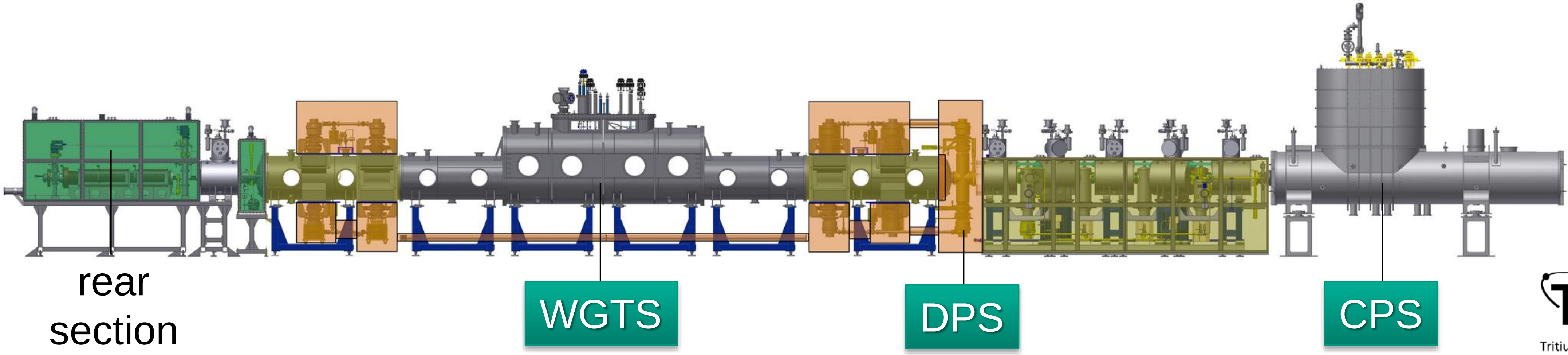


KASSIOPEIA code



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

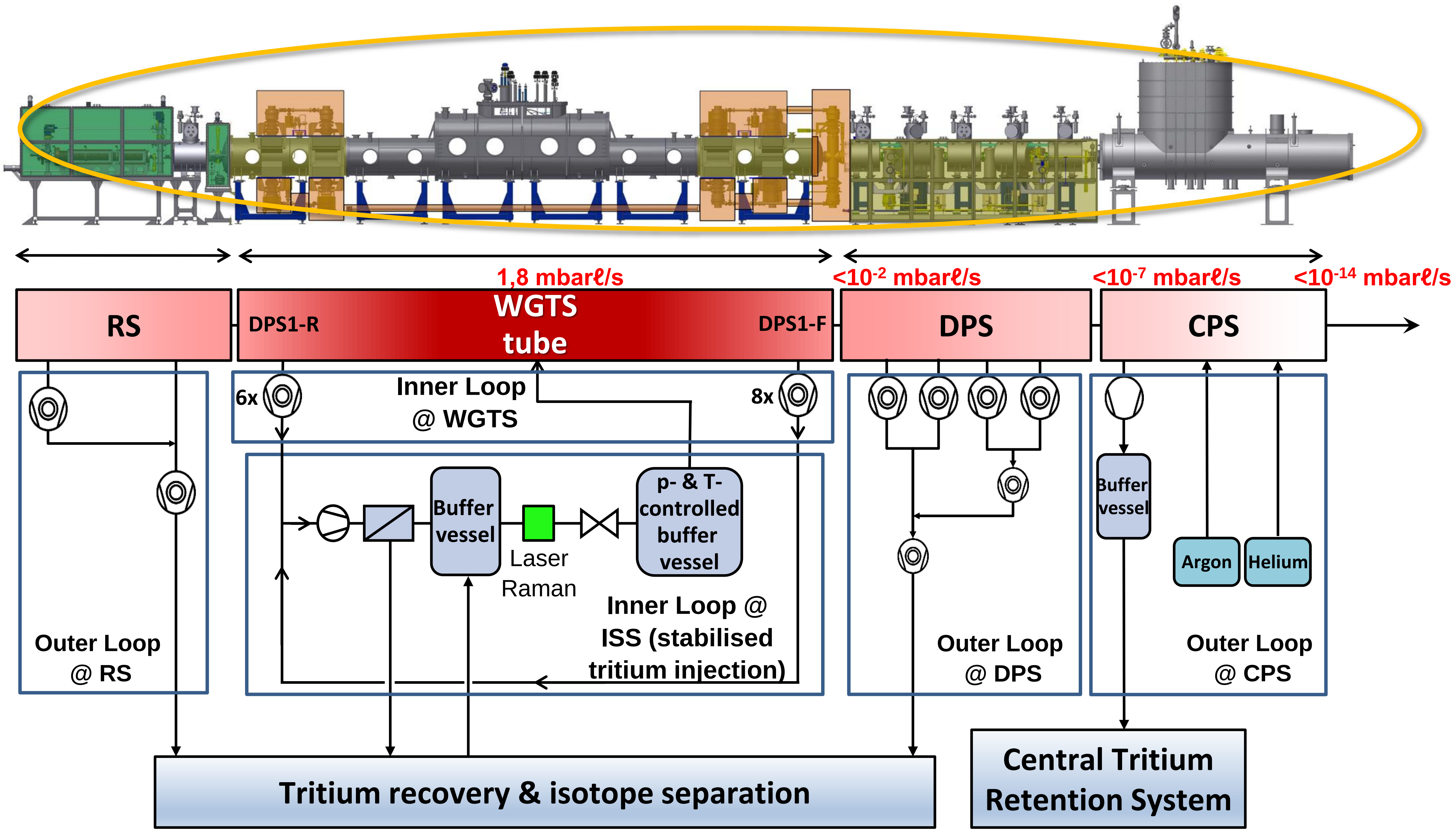
Tritium Laboratory Karlsruhe – TLK



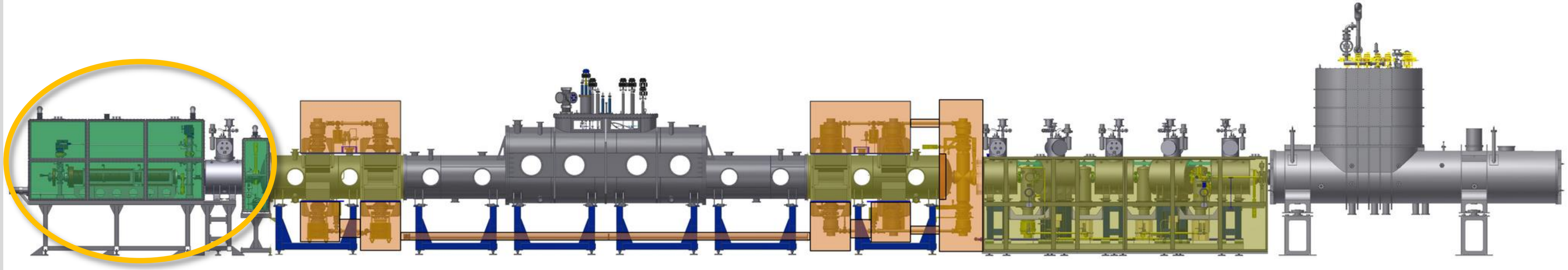
- **TLK**: unique large research facility at KIT for KATRIN and fusion (ITER)
  20 years of experience in tritium handling and processing, 20 g on-site

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

TLK – closed tritium loop system



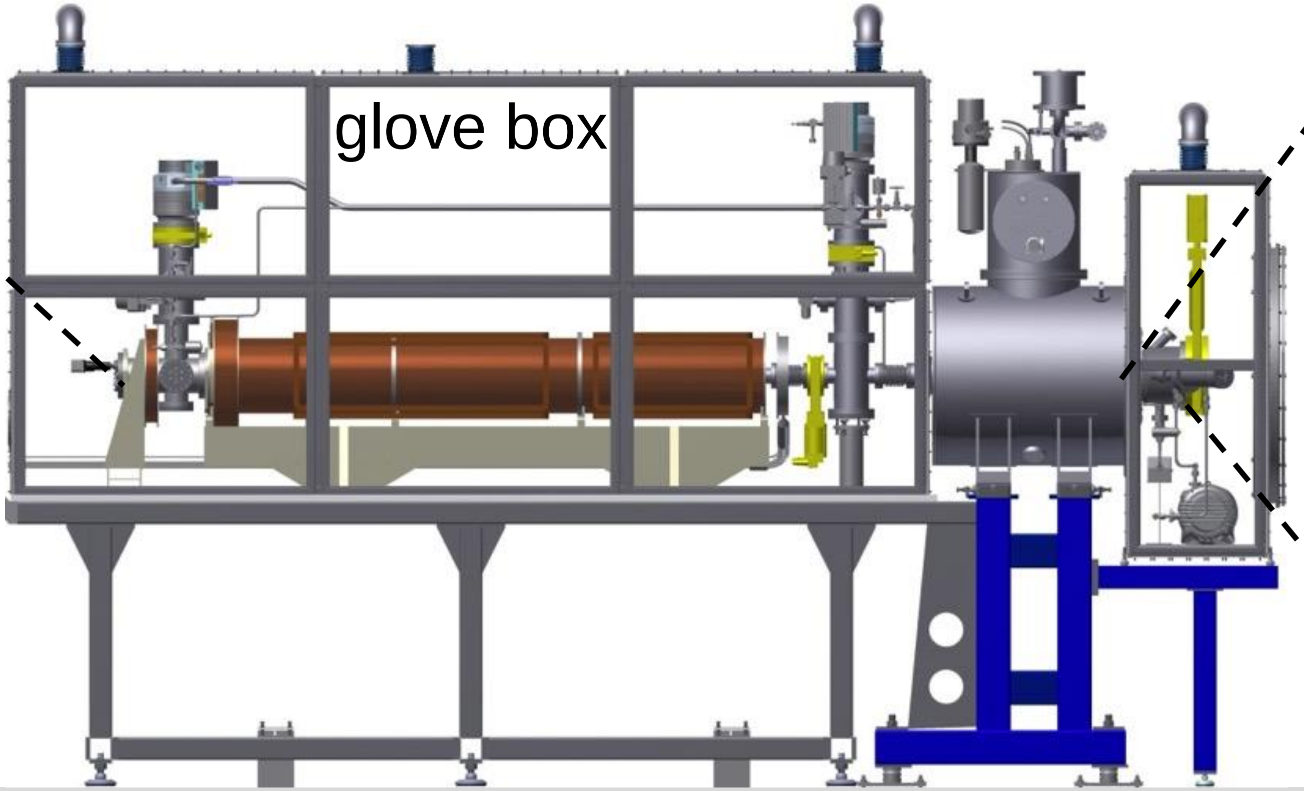
Rear Section – science goals



- RS of major importance for studying & monitoring **source systematics**

electron gun:
measure σ_{inel} & column density ρd

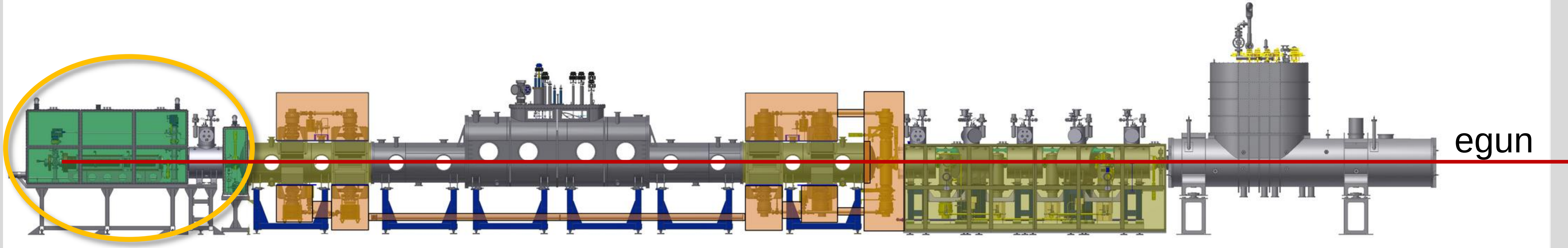
- angular selective
- pulsed mode
- high rate
- high stability

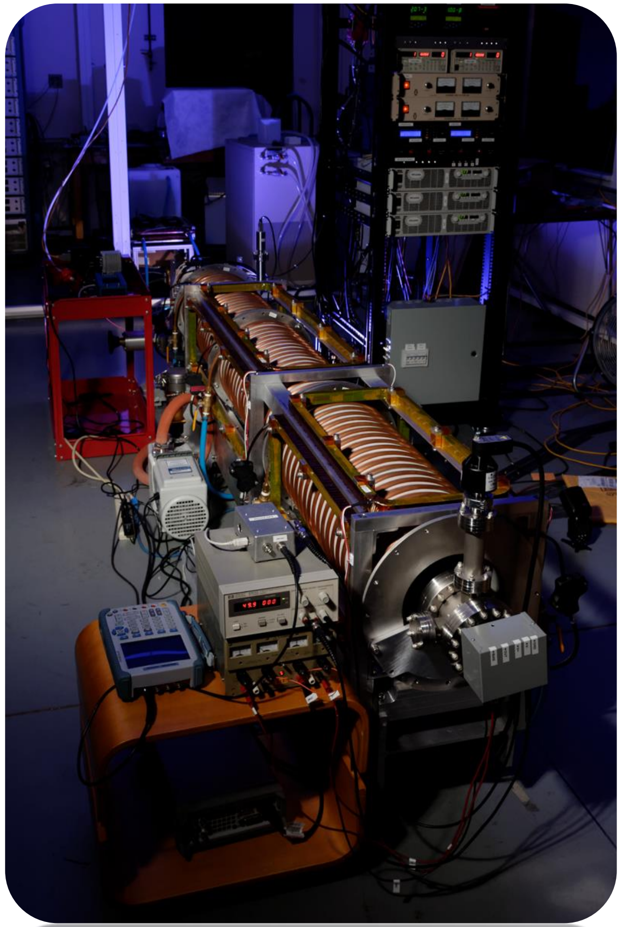


rear wall:
define source potential

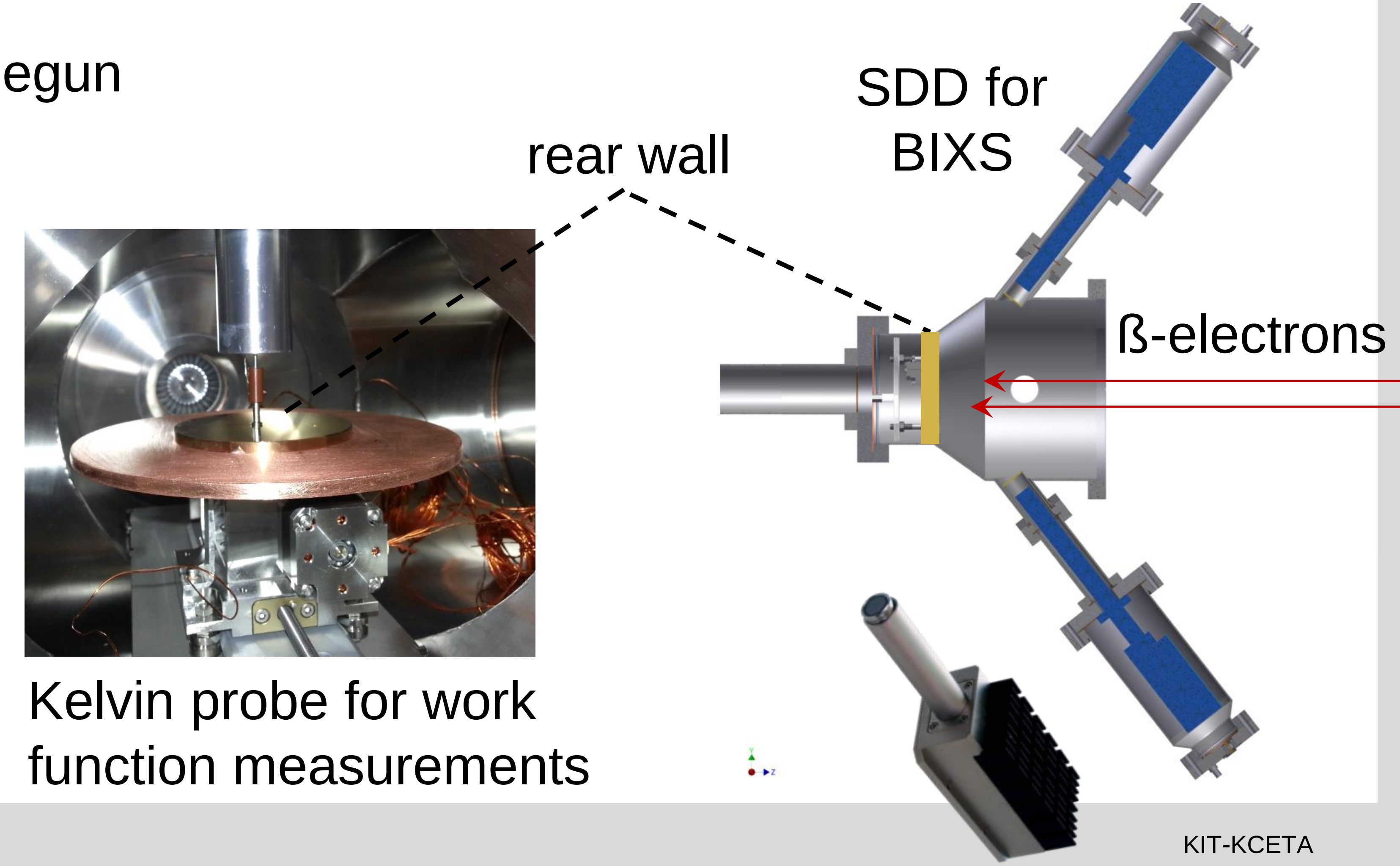
BIXS:
monitor source ß-activity

Rear Section – egun & rear wall



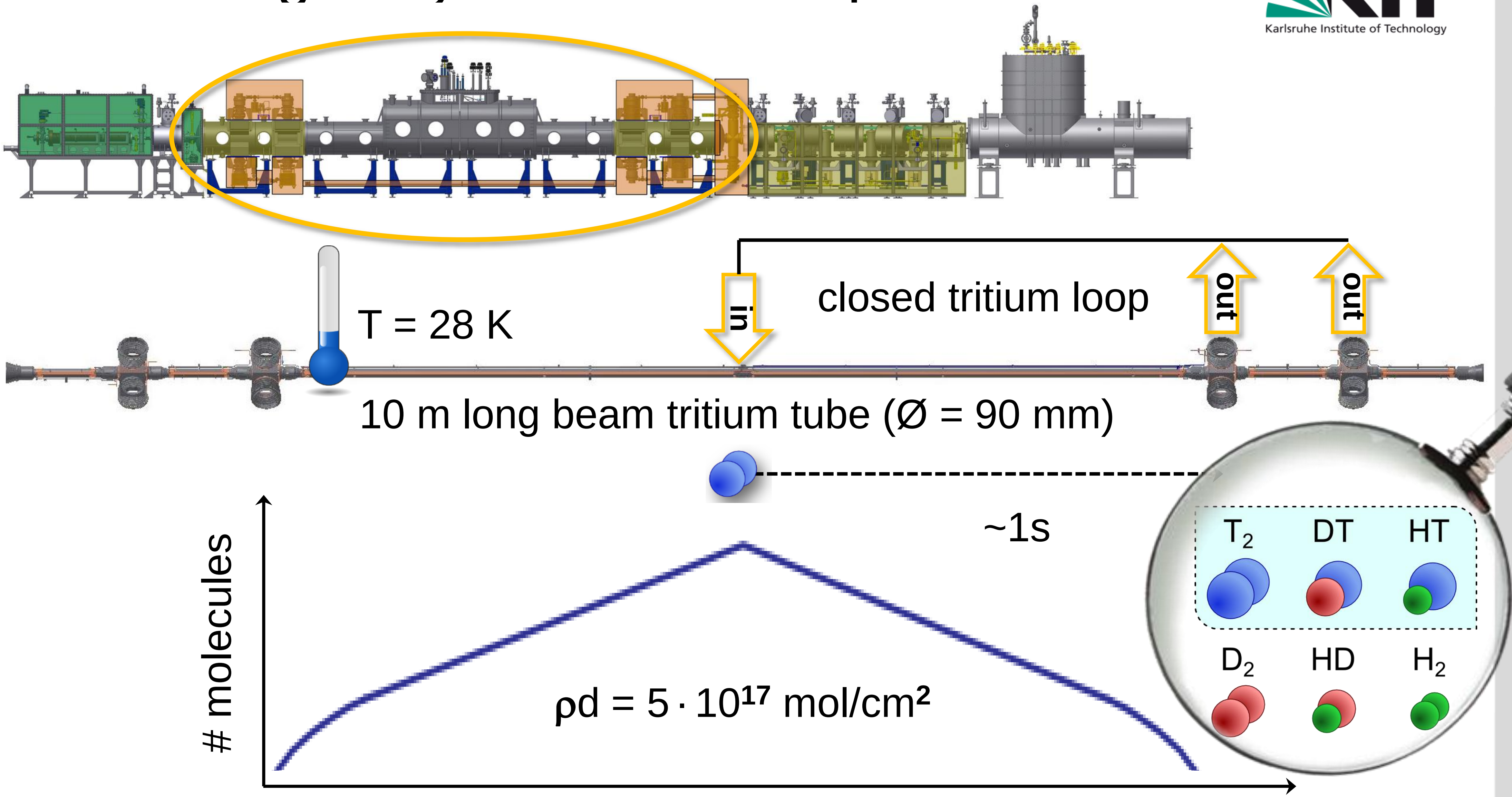


egun



Kelvin probe for work function measurements

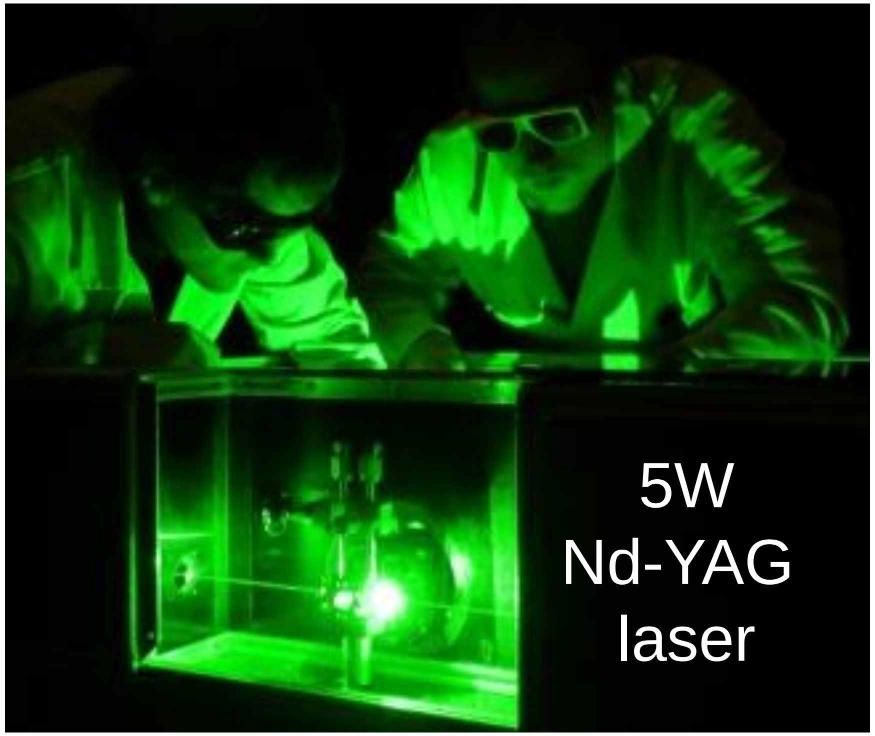
WGTS – gas dynamics & composition

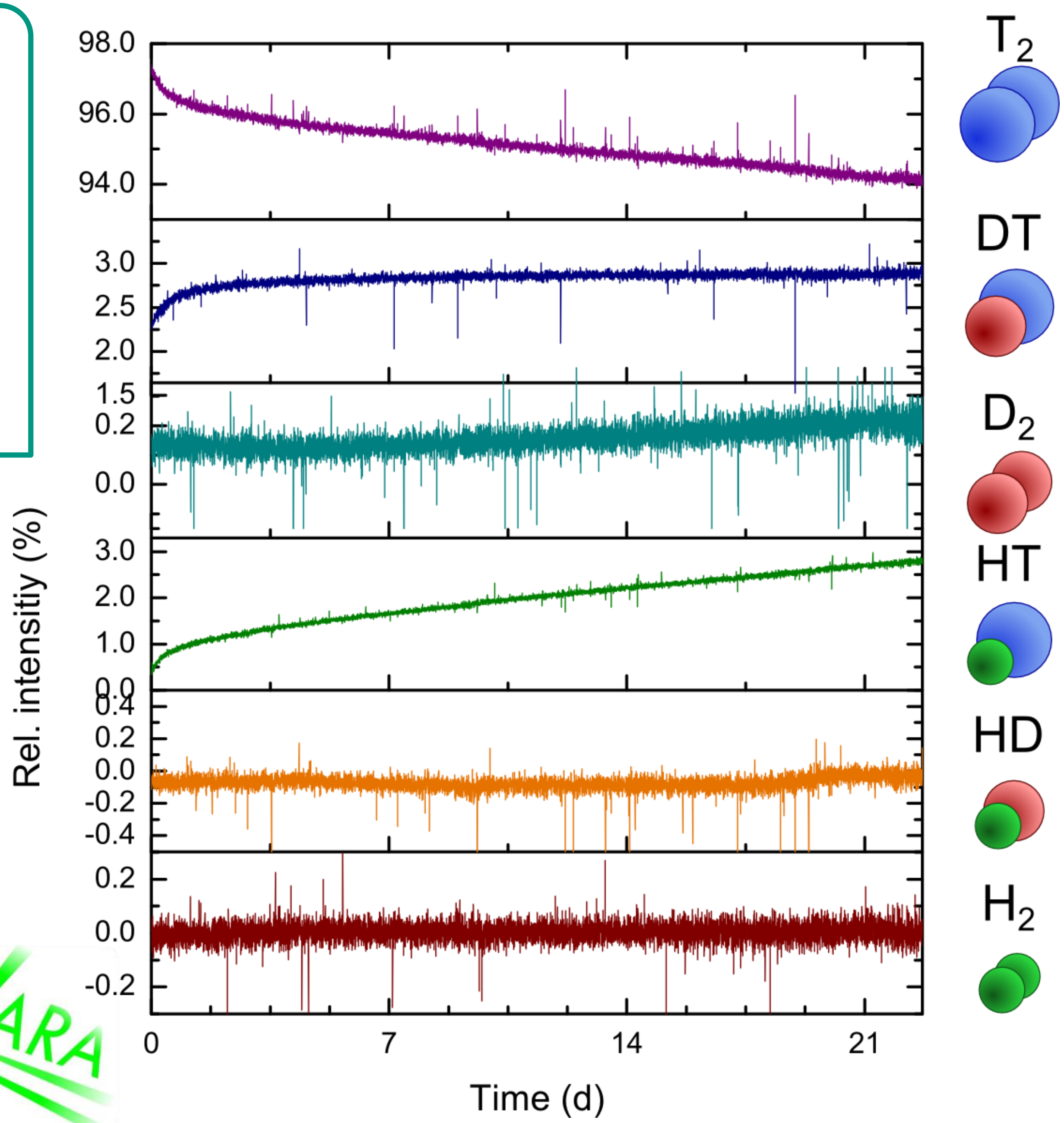


Windowless Gaseous Tritium Source

LARA – Laser Raman Spectroscopy

- **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

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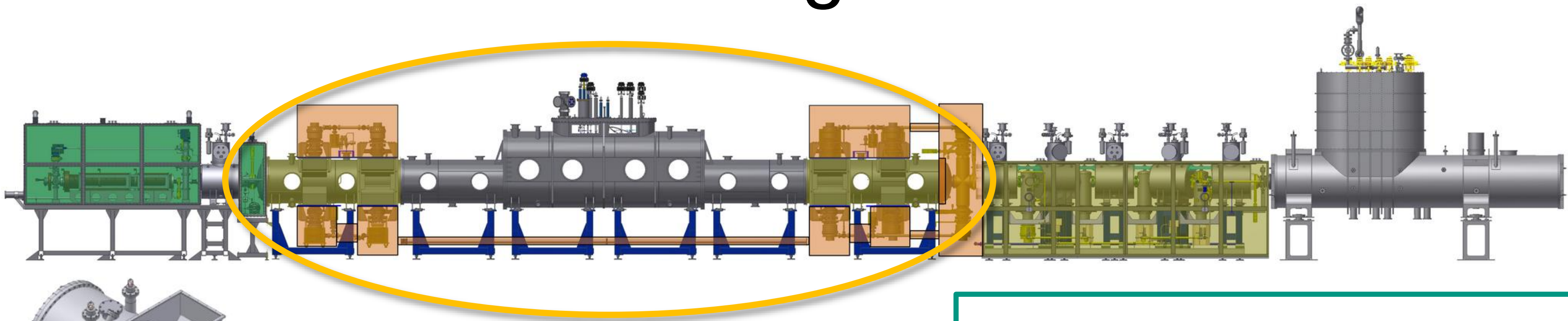
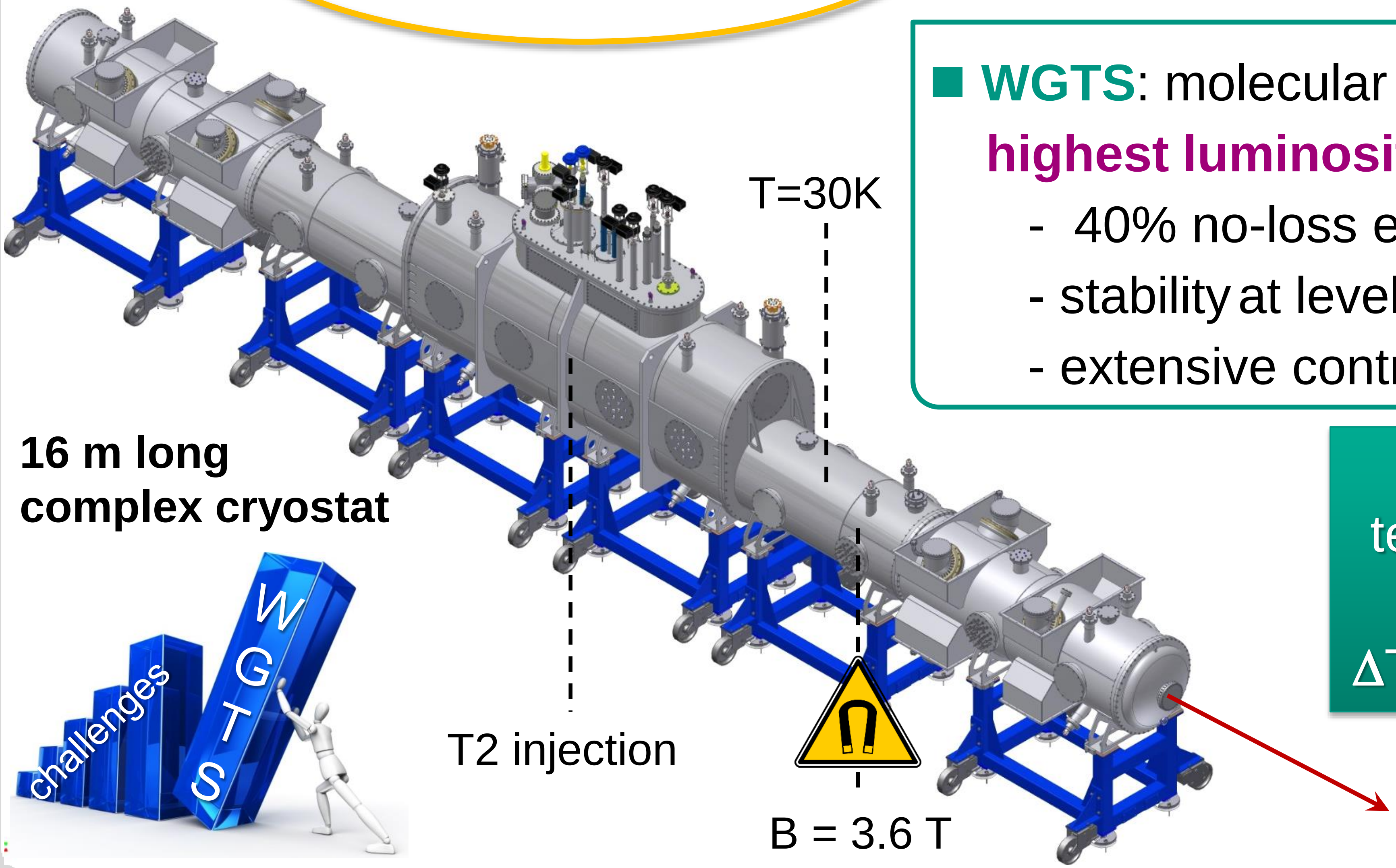




■ **WGTS**: molecular source (> 90% T_2)

highest luminosity & **stability**

- 40% no-loss electrons
- stability at level 10^{-3}
- extensive control of systematics

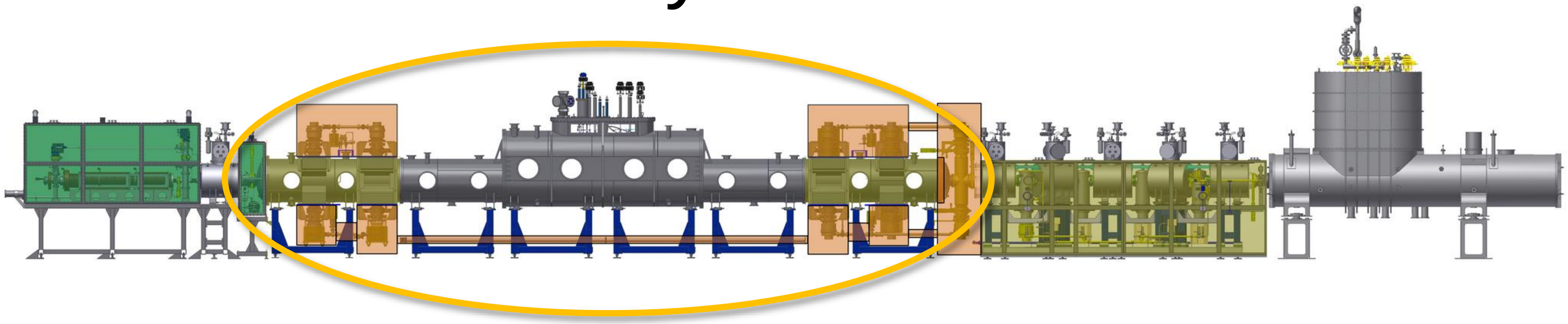
need very good temperature stability and homogeneity
ΔT < 30 mK (at 30 K)

16 m long complex cryostat

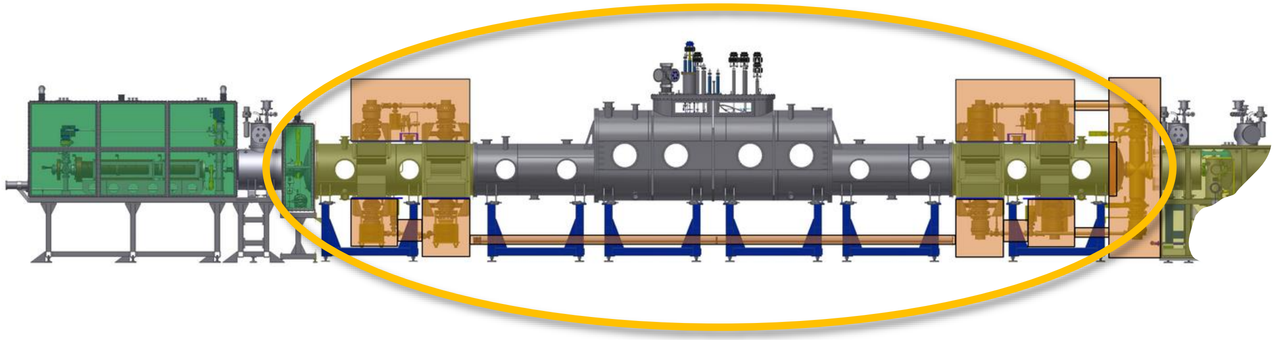
WGTS – assembly

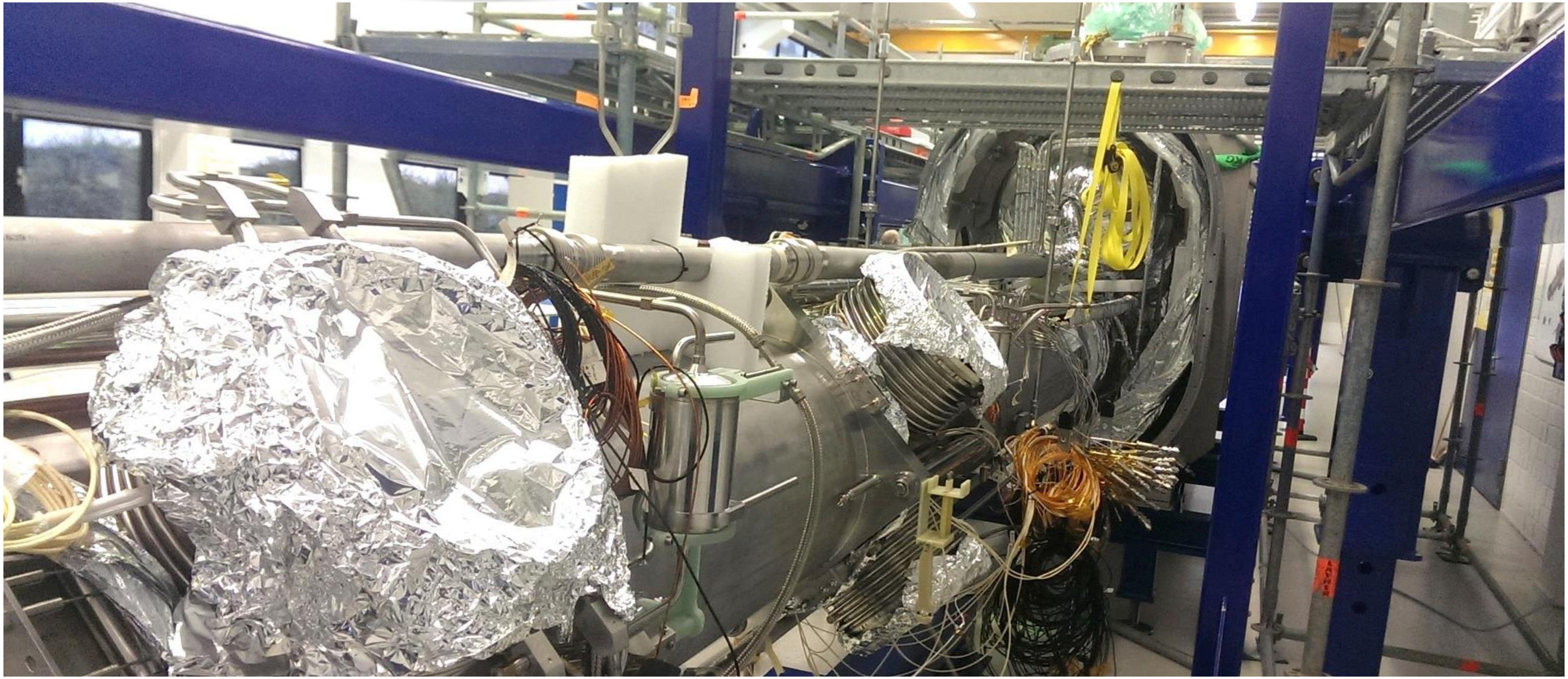
Karlsruhe Institute of Technology

research instruments

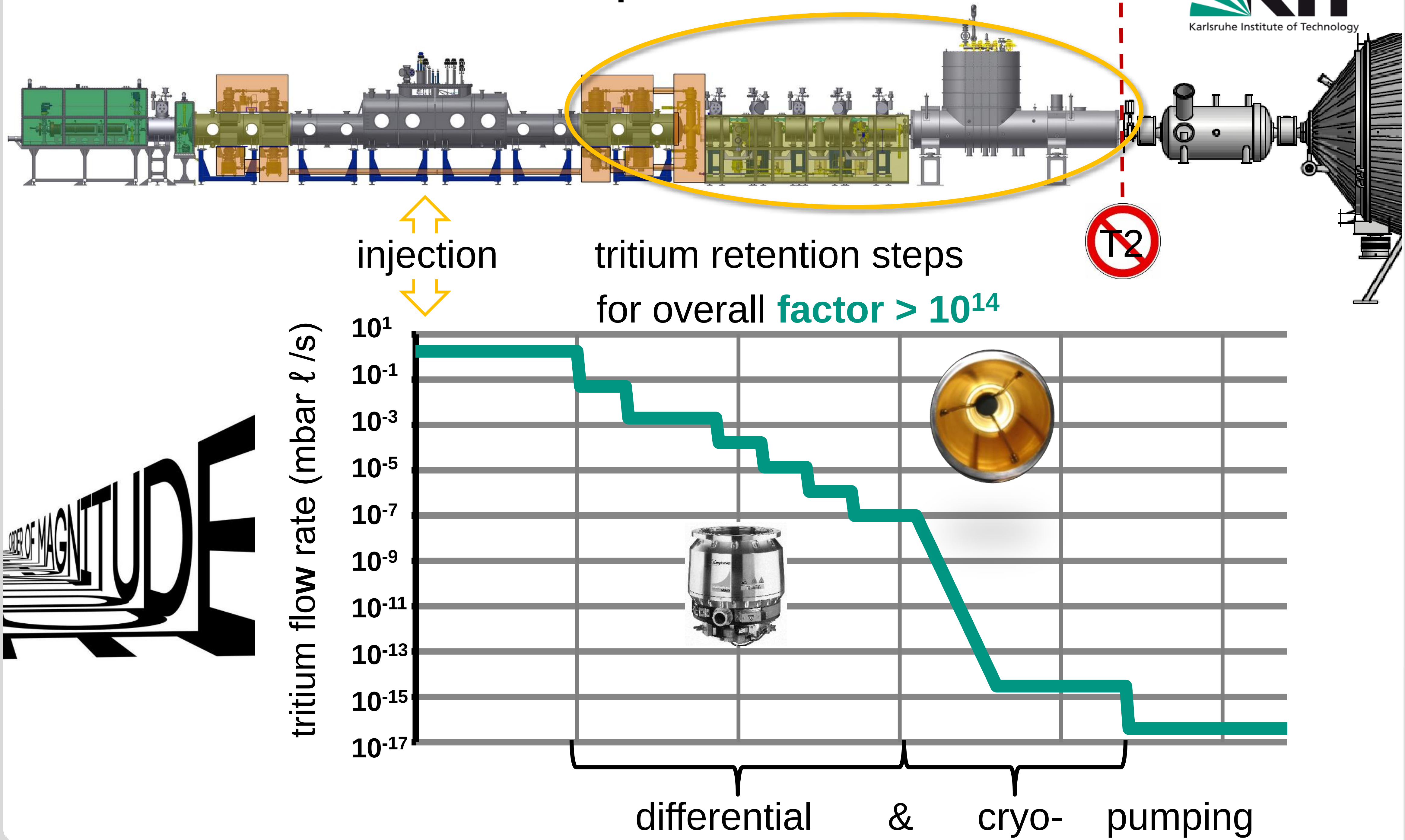


WGTS – assembly & delivery to TLK

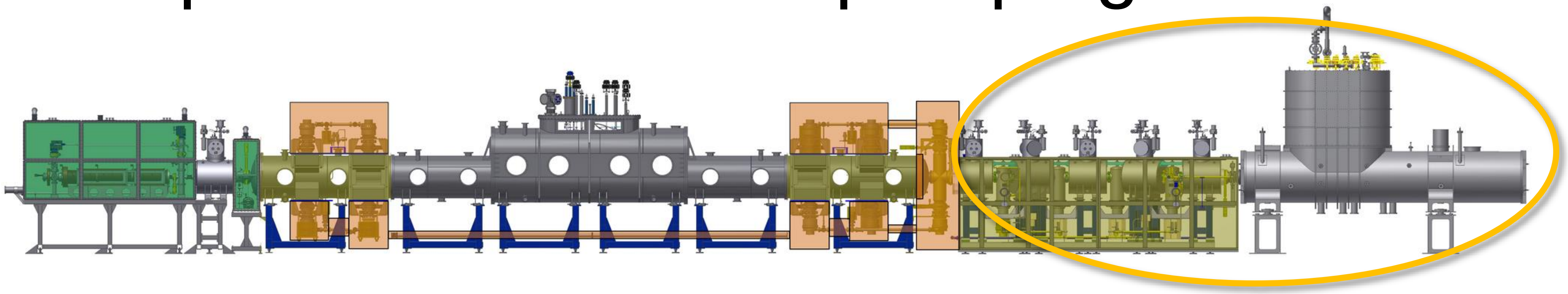




tritium retention techniques



components for tritium pumping

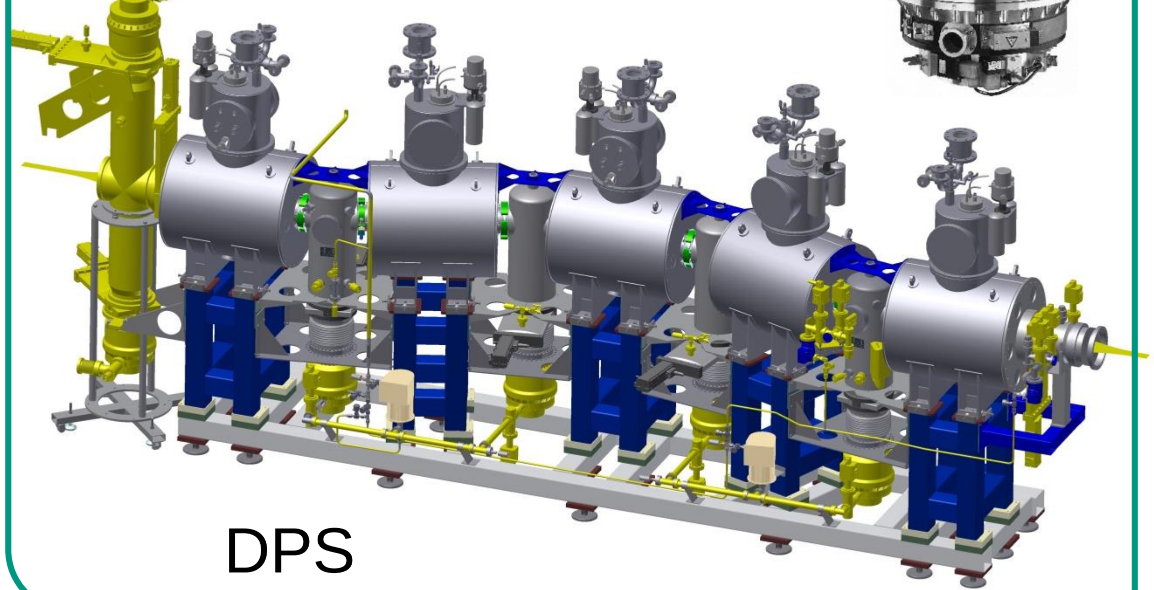


tritium free

- **Differential Pumping Section DPS:** active (serial) pumping by TMPs

- **DPS pump ports**

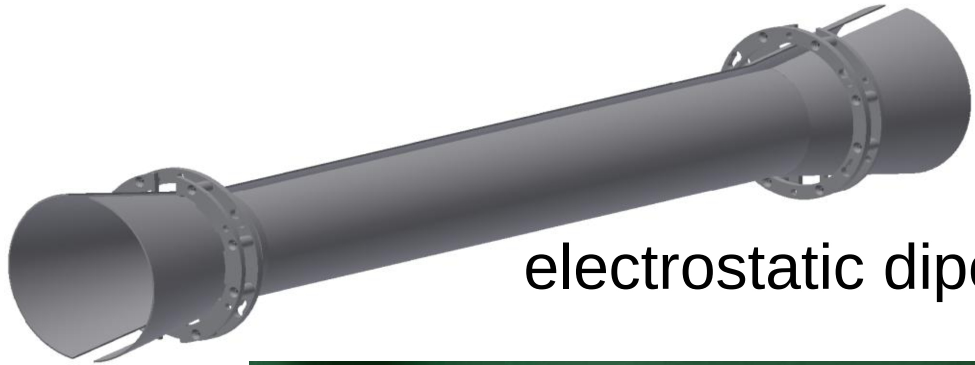
  tritium retention factor ~10^5



DPS

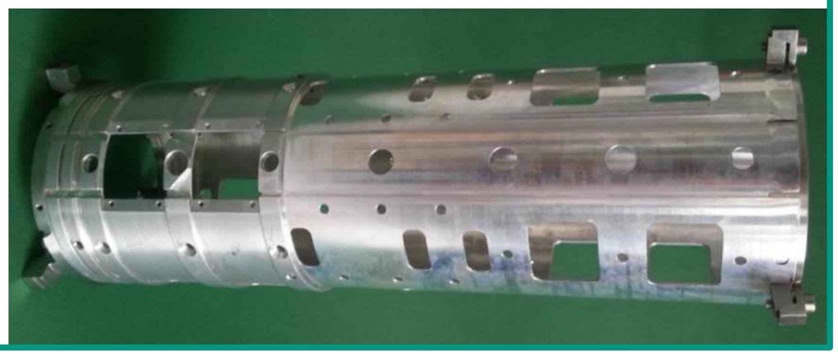
- **DPS beam tube instrumentation**

  measurement & removal of ions

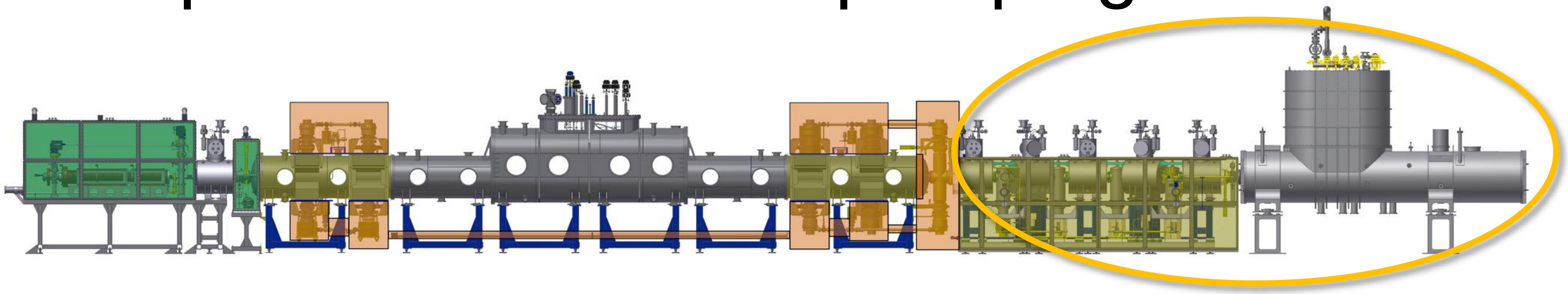


electrostatic dipole

FT-ICR

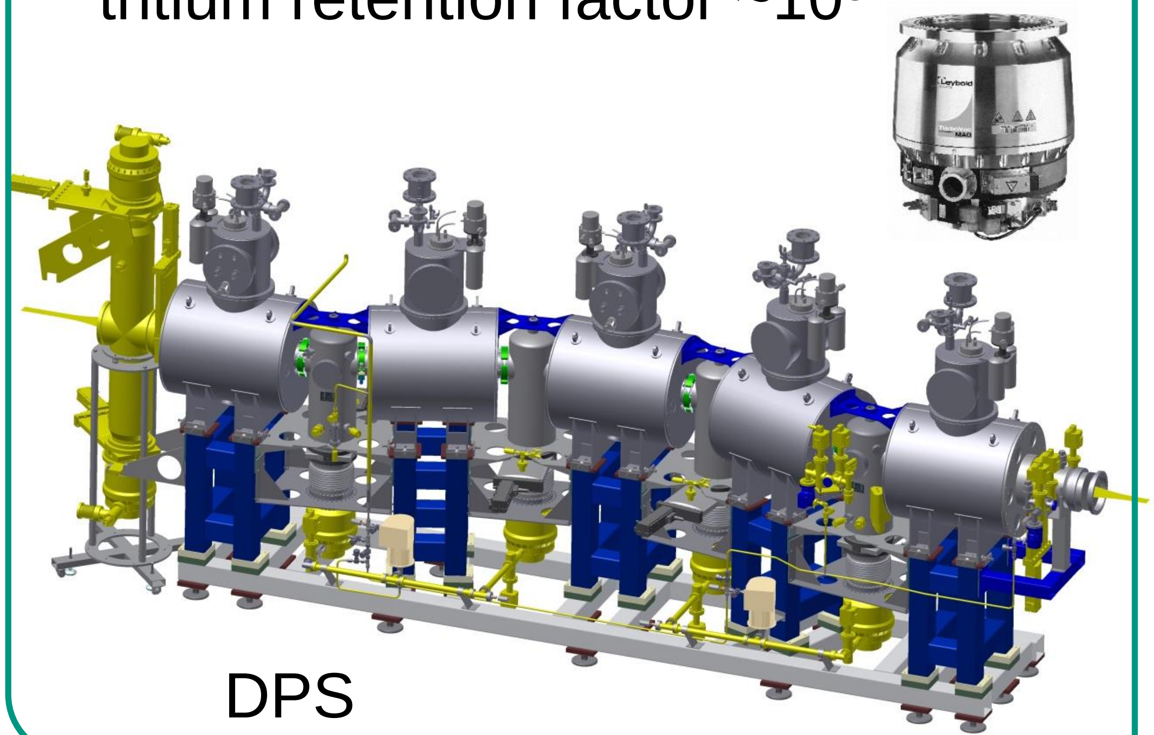


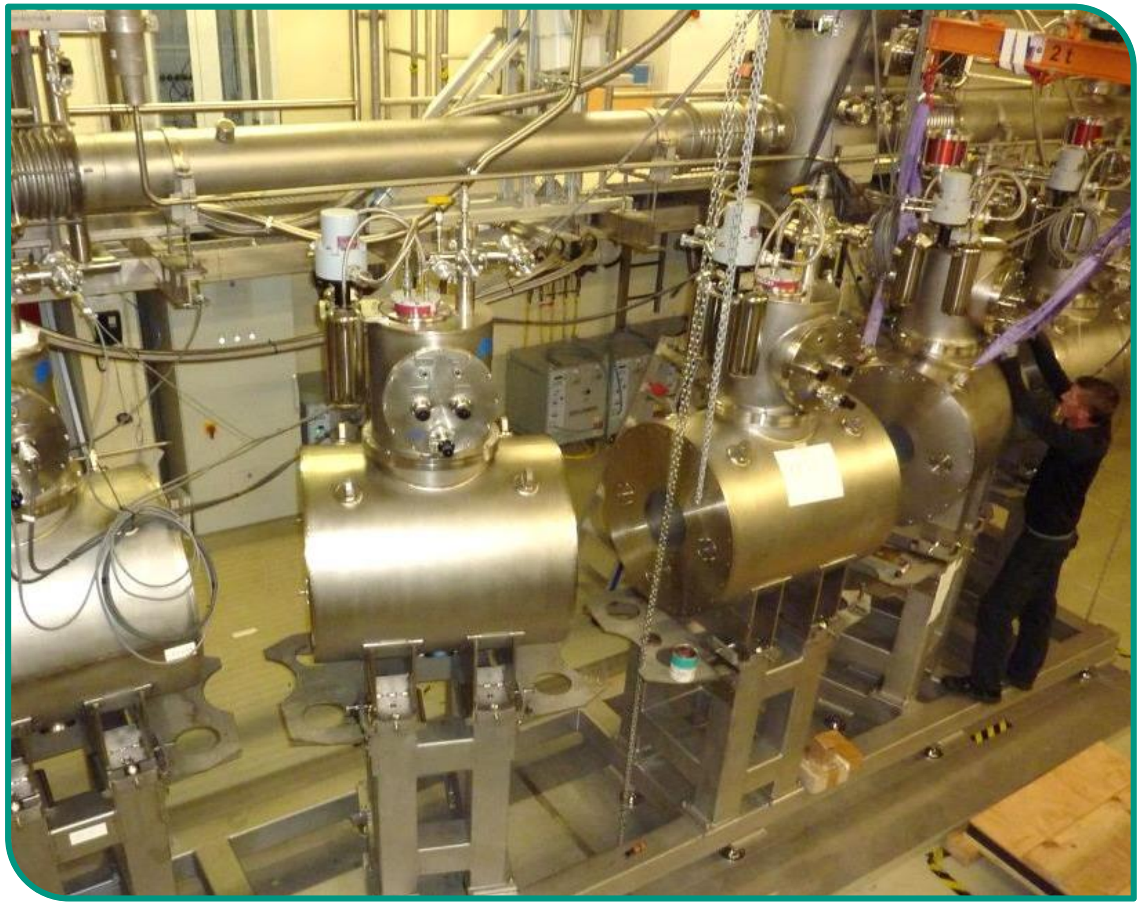
components for tritium pumping



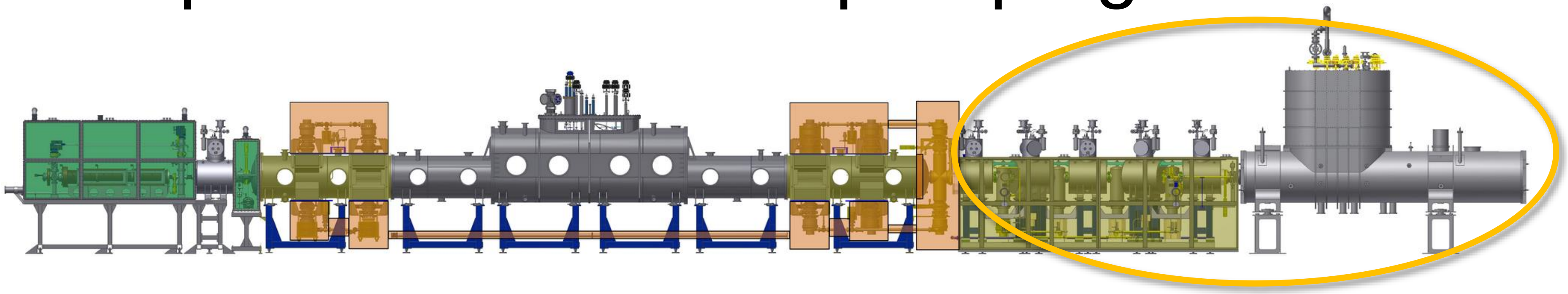
- **Differential Pumping Section DPS:** SAT of s.c. magnets successful

- **DPS pump ports**
  tritium retention factor ~10^5



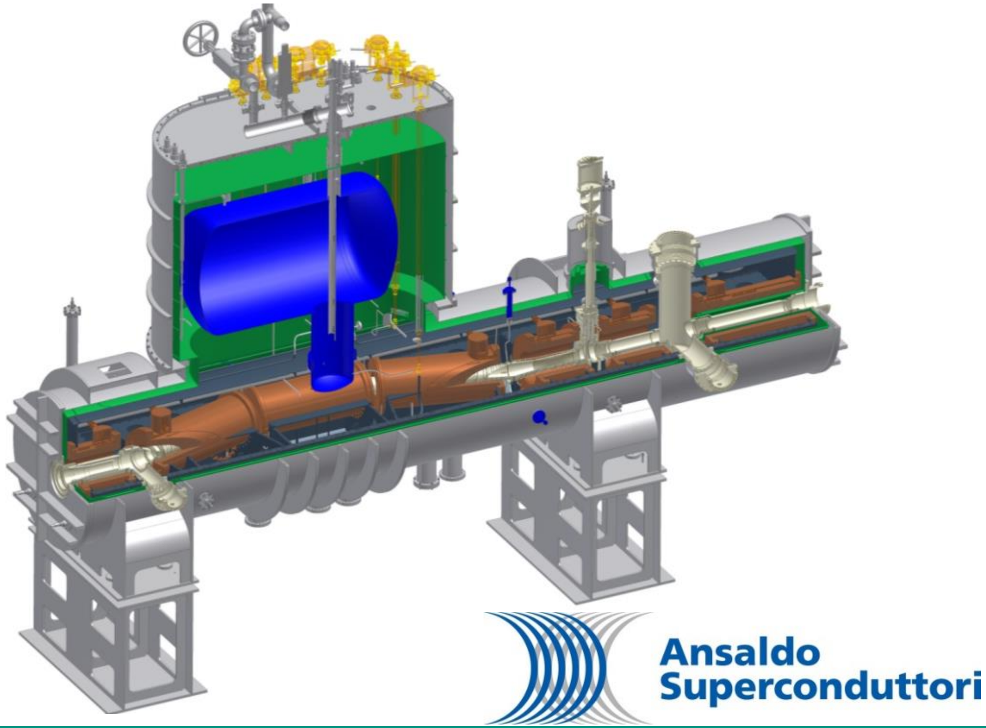


components for tritium pumping

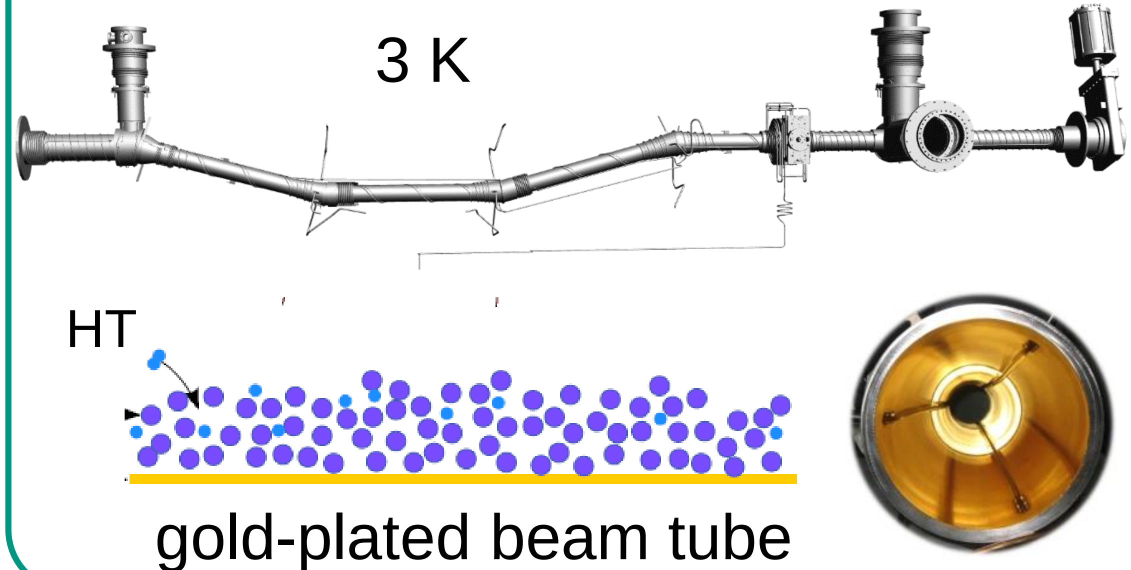


■ **Cryogenic Pumping Section CPS:** cryosorption on Ar-frost

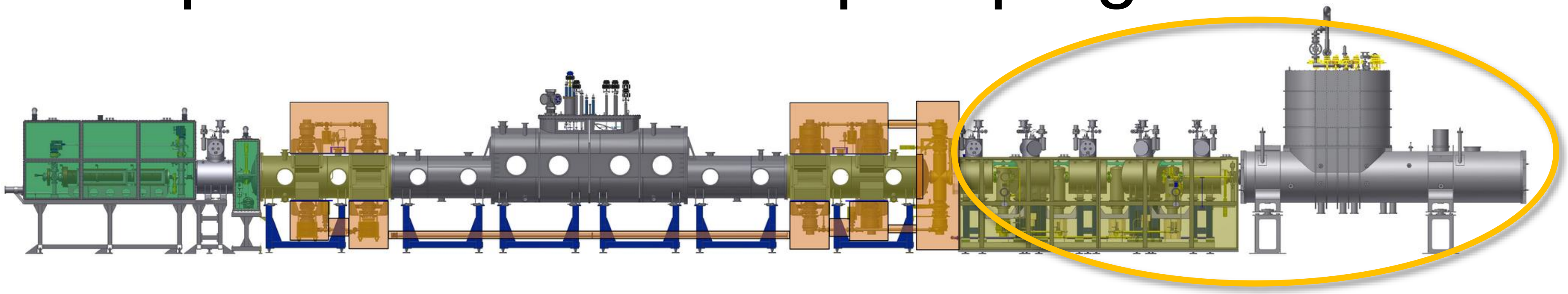
■ **CPS beam tube system**
tritium retention factor < 10^7



■ **CPS beam tube system**
argon frost pump: up to 1 Ci T2



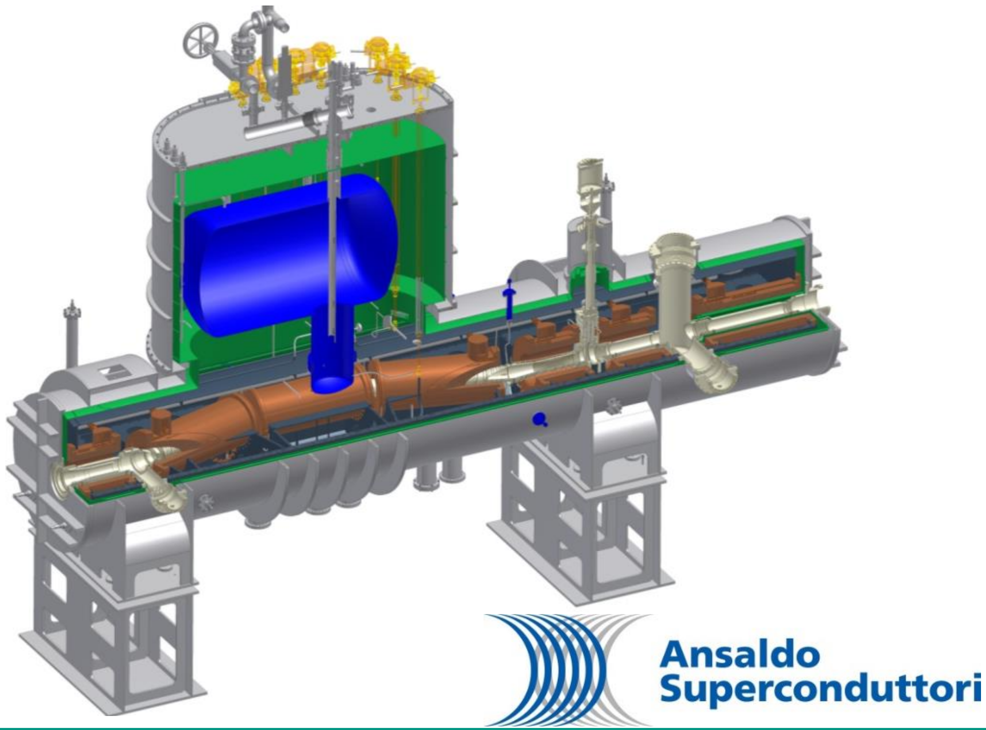
components for tritium pumping



■ **Cryogenic Pumping Section CPS:** FAT successful, arrival at TLK: July 30

■ **CPS beam tube system**

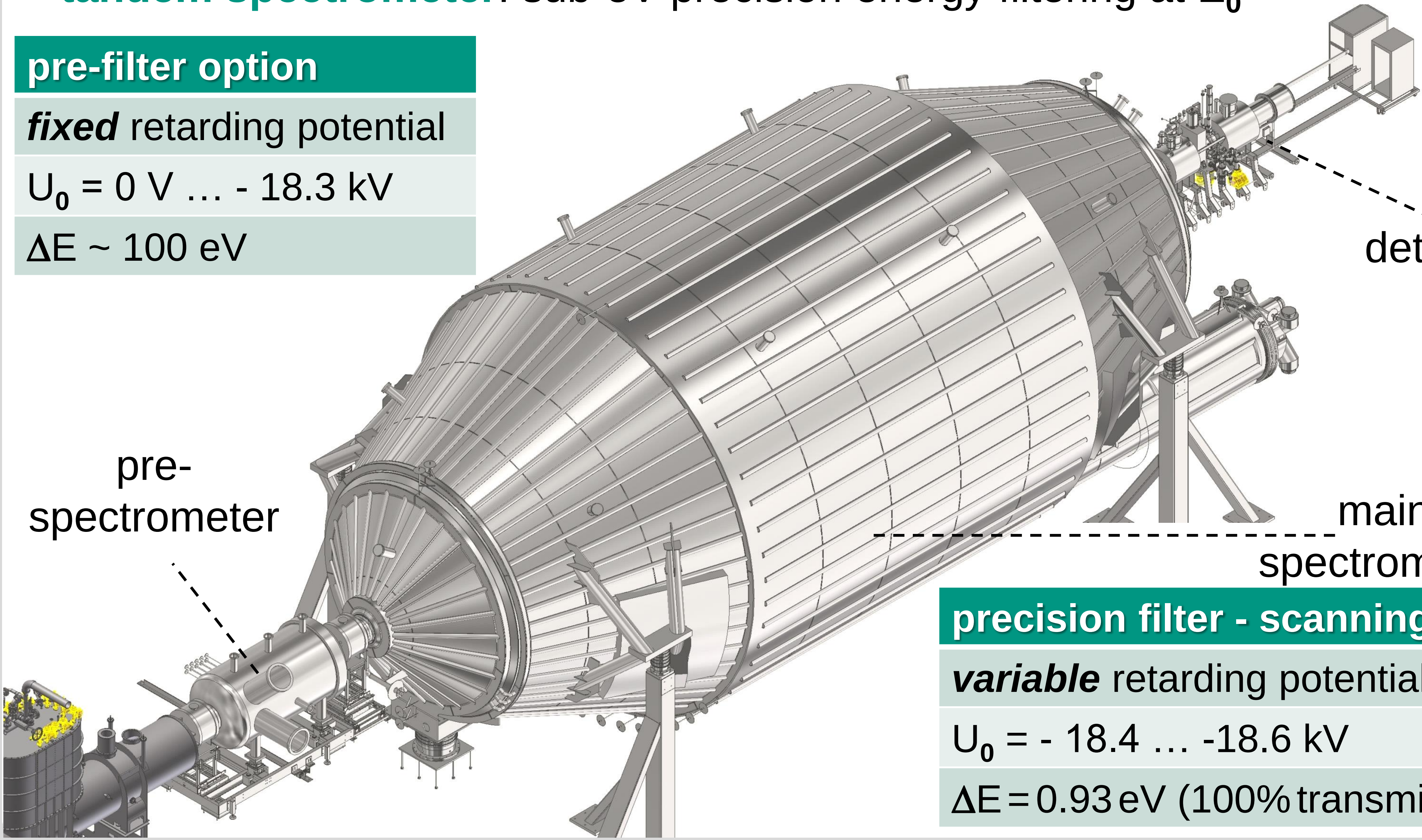
tritium retention factor < 10^7



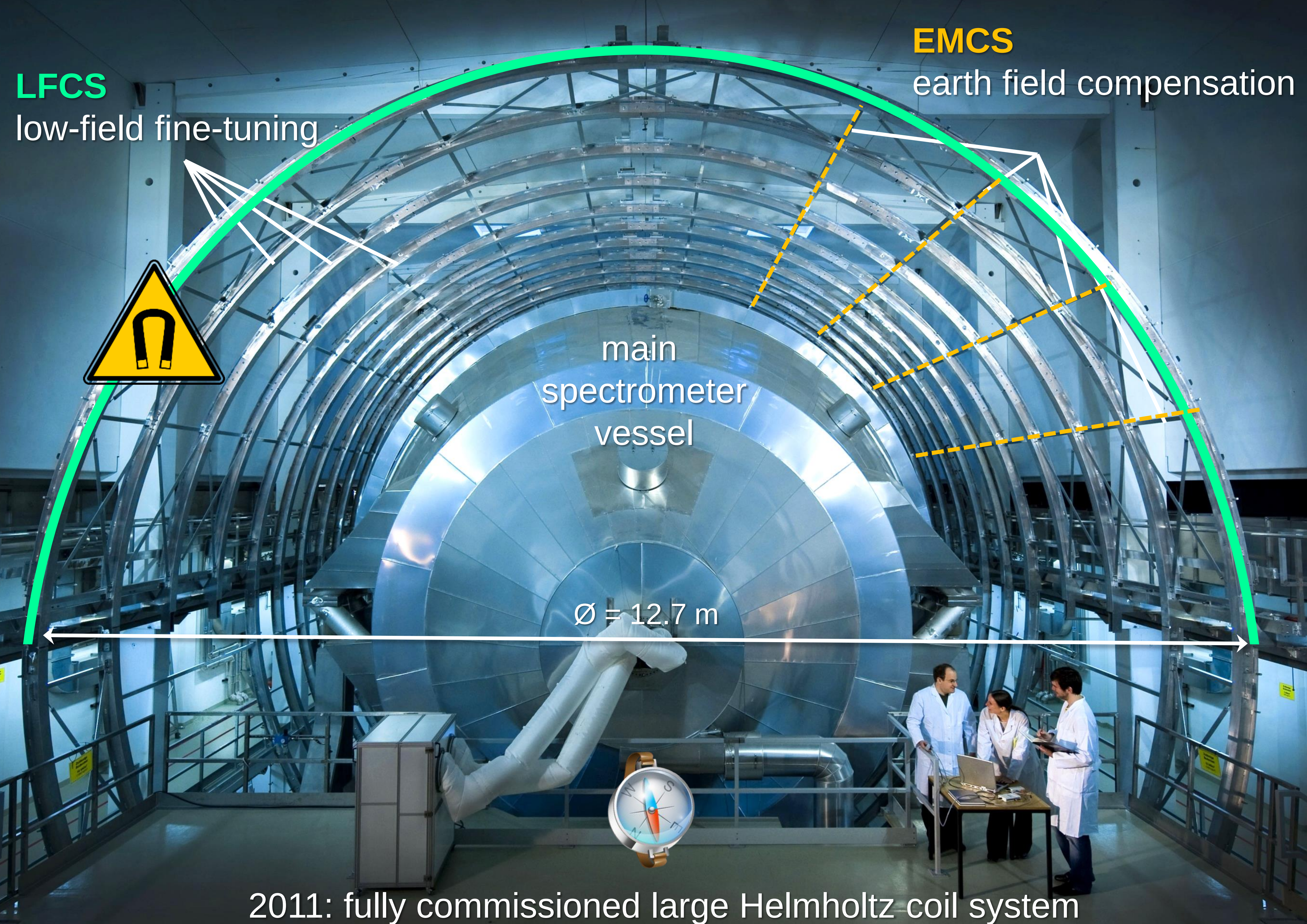
electrostatic spectrometers & detector

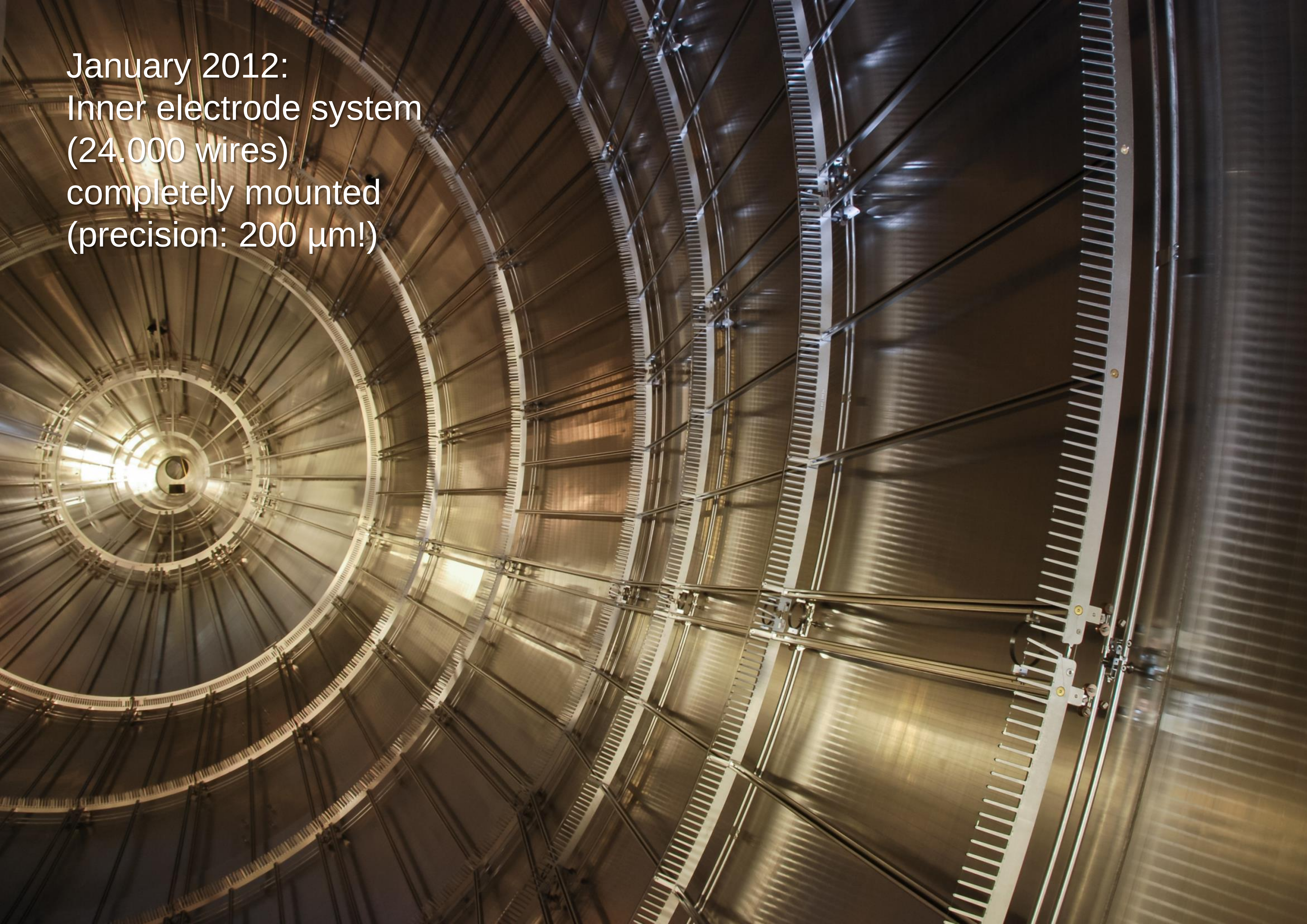
- **tandem spectrometer**: sub-eV precision energy filtering at E_0

pre-filter option
fixed retarding potential
U_0 = 0 V … - 18.3 kV
ΔE ~ 100 eV



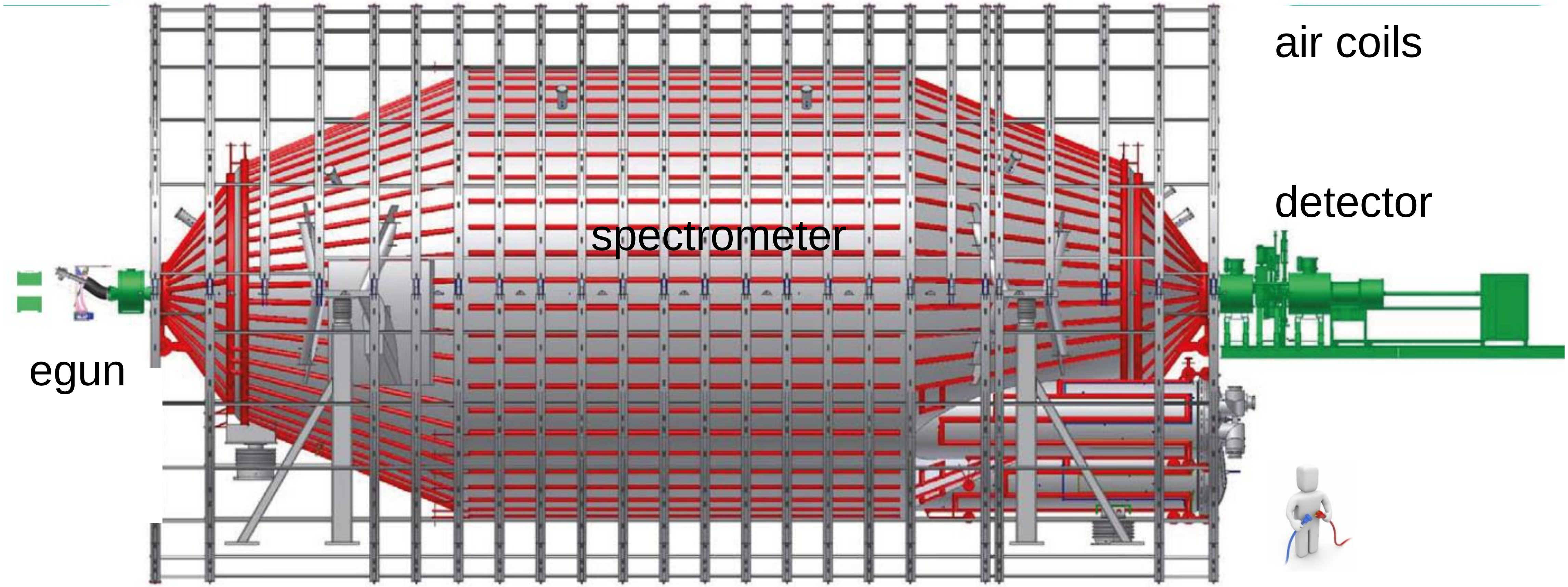
precision filter - scanning
variable retarding potential
U_0 = - 18.4 … -18.6 kV
ΔE = 0.93 eV (100% transmission)


LFCS
low-field fine-tuning
EMCS
earth field compensation
main spectrometer vessel
Ø = 12.7 m
2011: fully commissioned large Helmholtz coil system


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

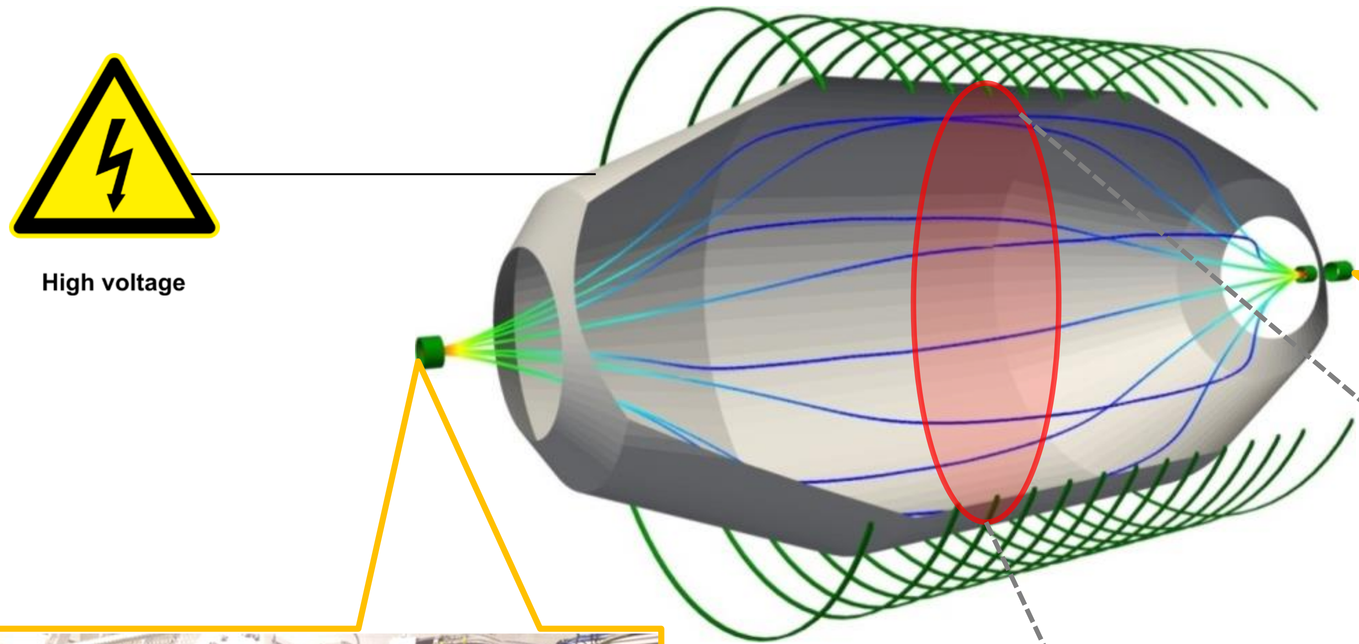
spectrometer commissioning

- two long-term commissioning phases **SDS-I/SDS-II** in 2013-15 to verify:
  - concepts & functionality of all components: UHV, HV, SC, DAQ,…
  - MAC-E filter characteristics via egun-transmission studies
  - background model (electrons) & optimise bg-suppression methods

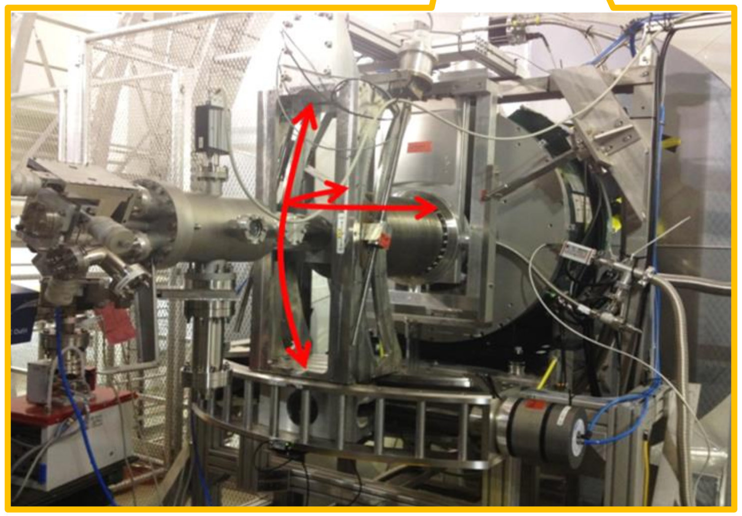


transmission studies & mapping

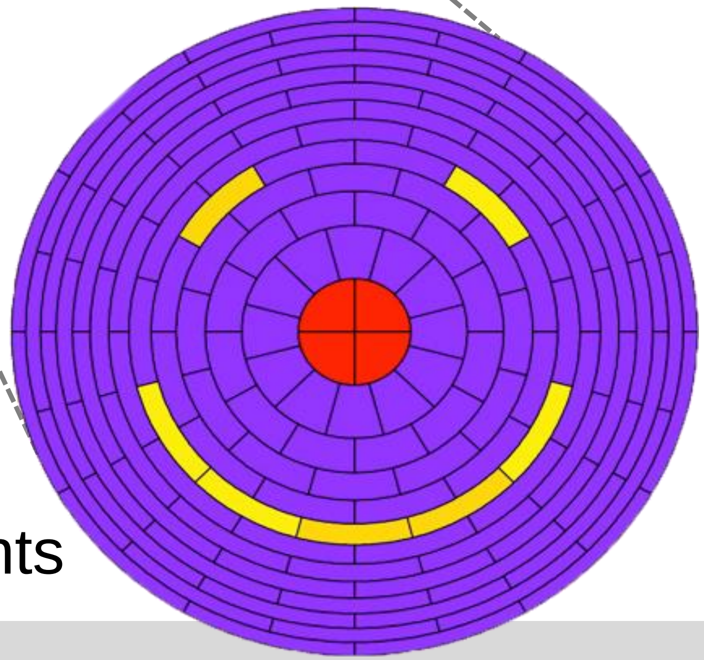
Karlsruhe Institute of Technology



focal plane detector

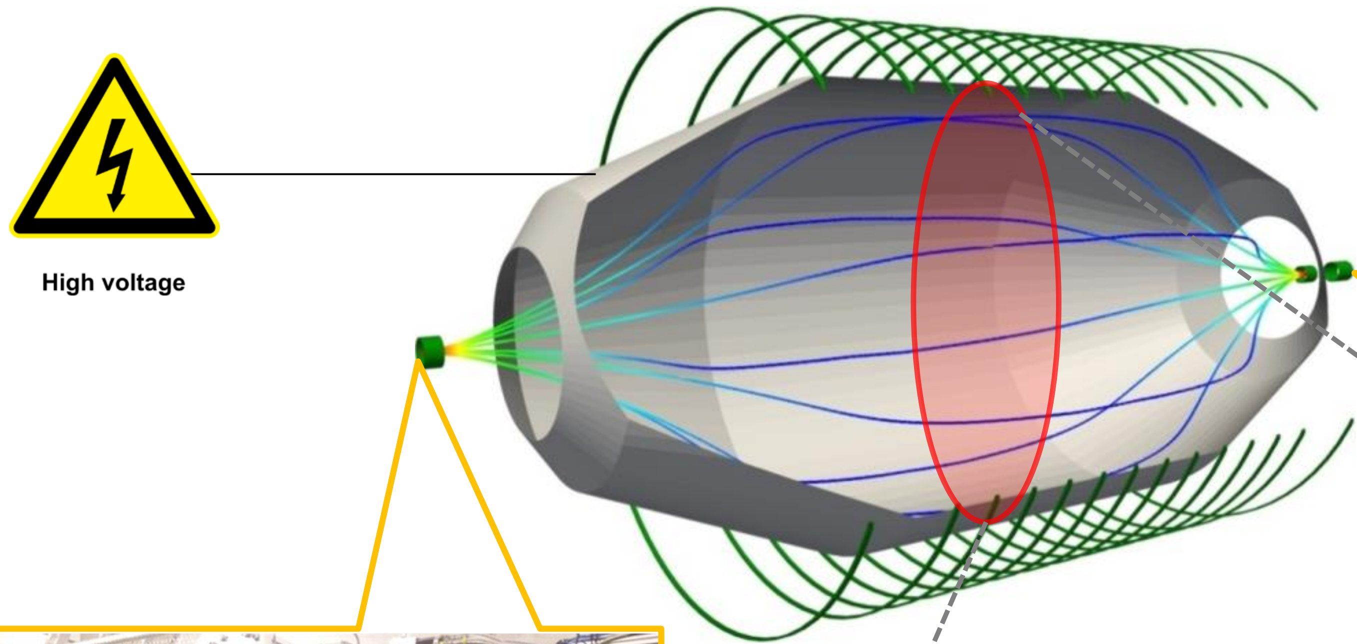


angular selective electron gun

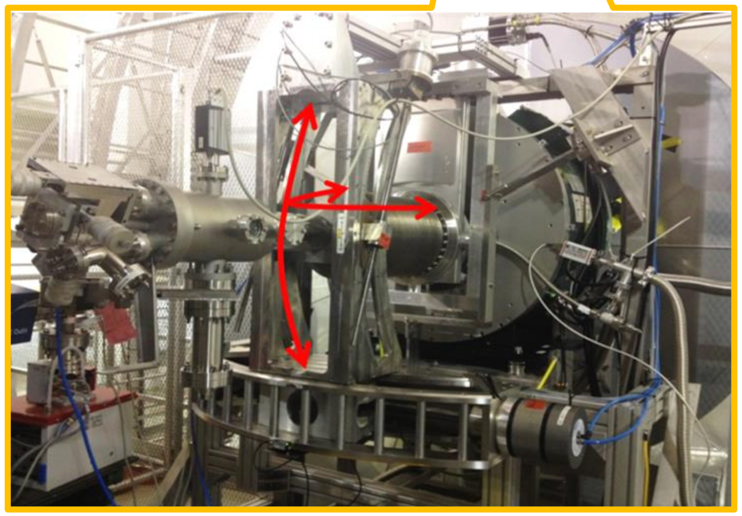


SDS1 measurements

transmission studies & mapping

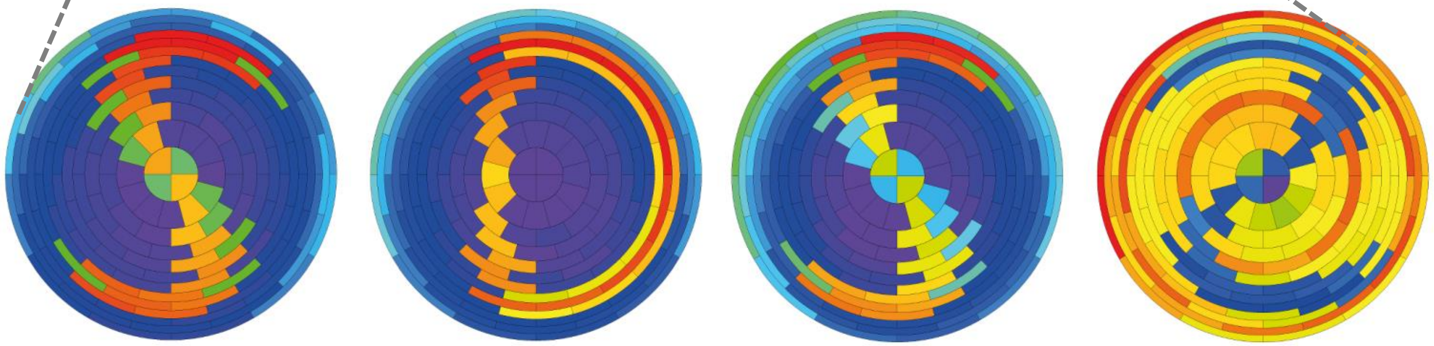


focal plane detector



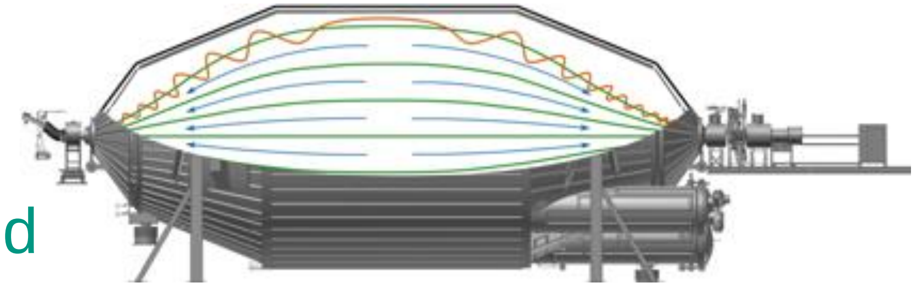
angular selective electron gun

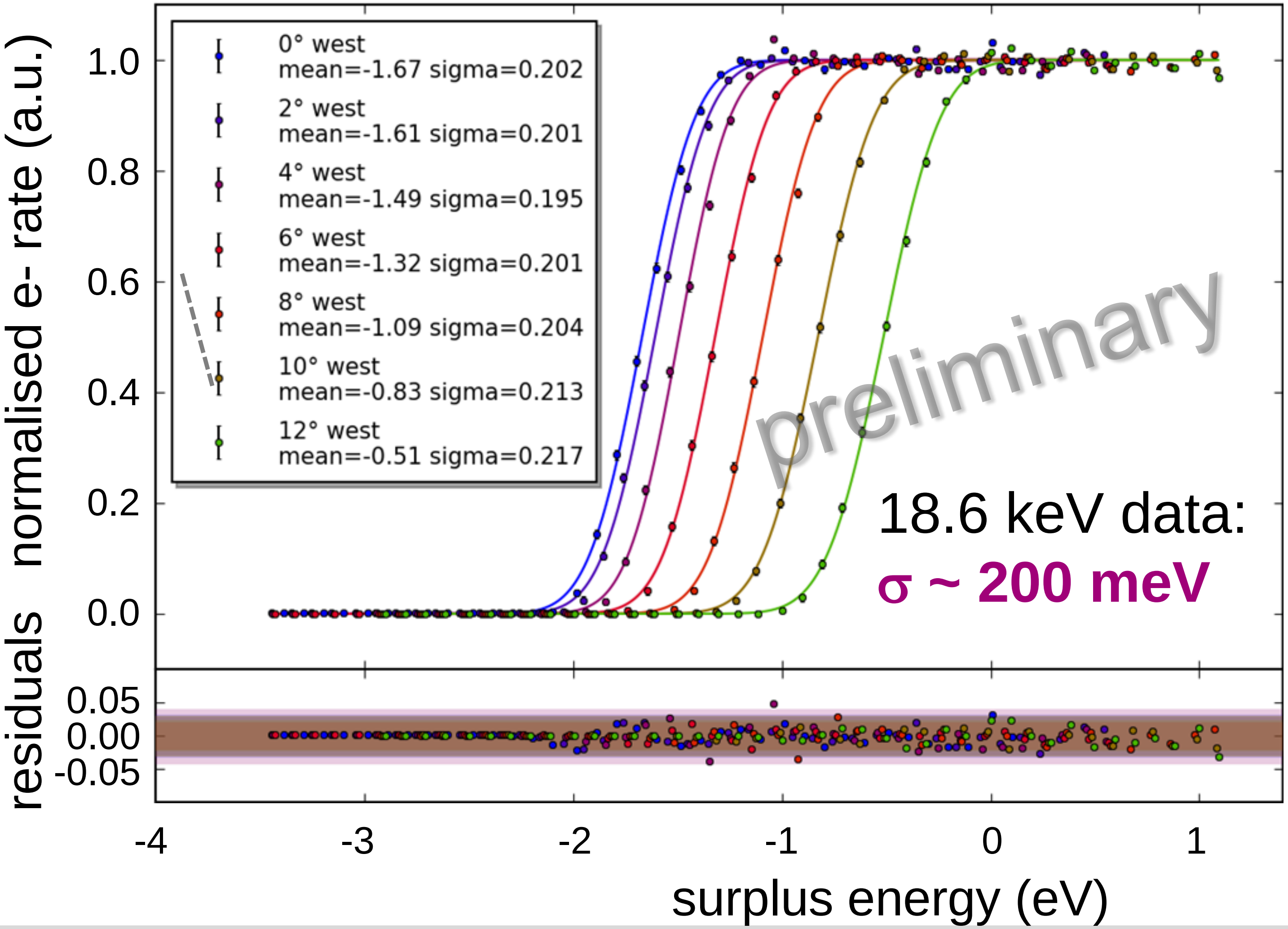
SDS2 measurements



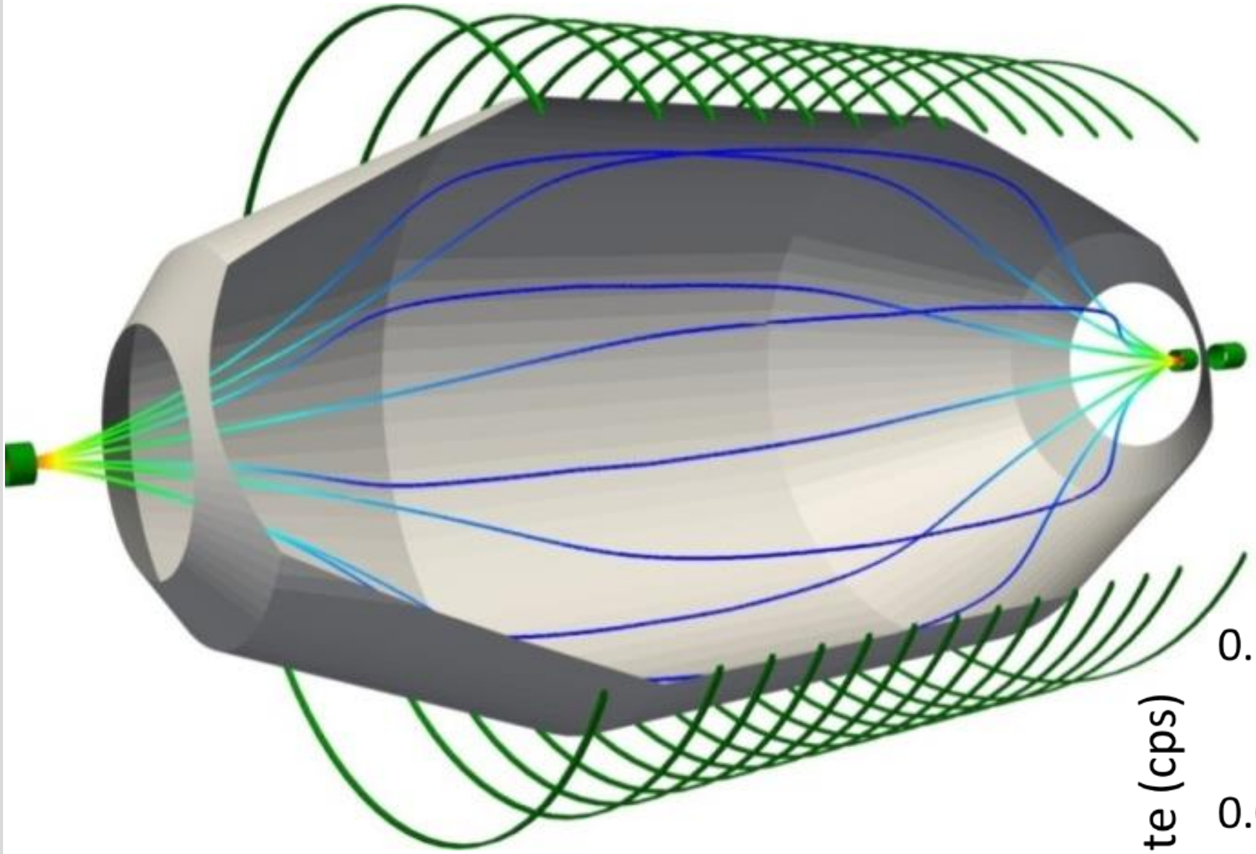
Transmission studies & mapping

- spectrometer works as MAC-E filter ☑
  - magnetic collimation verified
  - potential map in analysing plane as expected



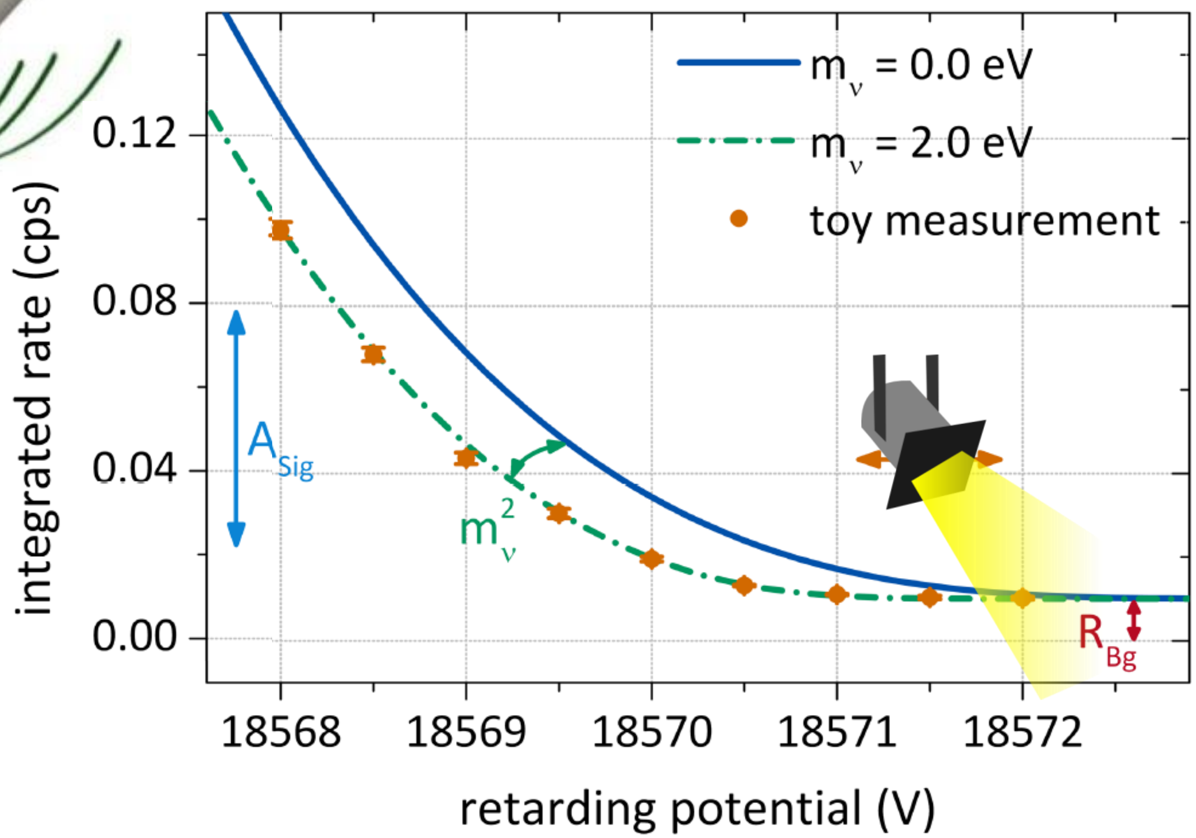


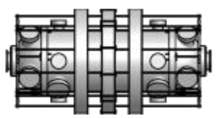
signal and background



KATRIN main spectrometer:
- volume V = 1250 m^3
- nominal background: 10 mcps

background reduction factor ~ 400 required

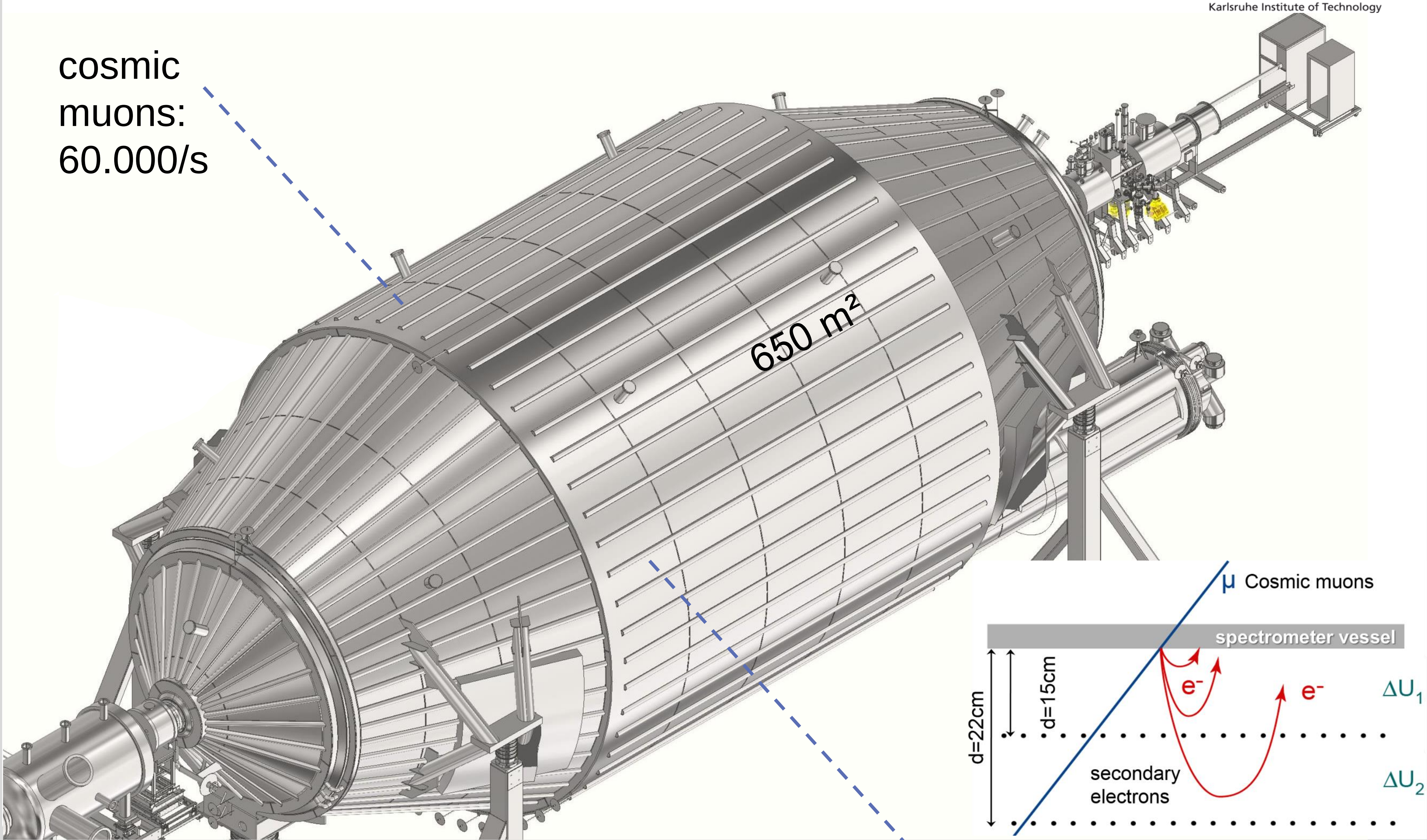




Mainz spectrometer:
- volume V ~ 3 m^3
- background level: 10 mcps

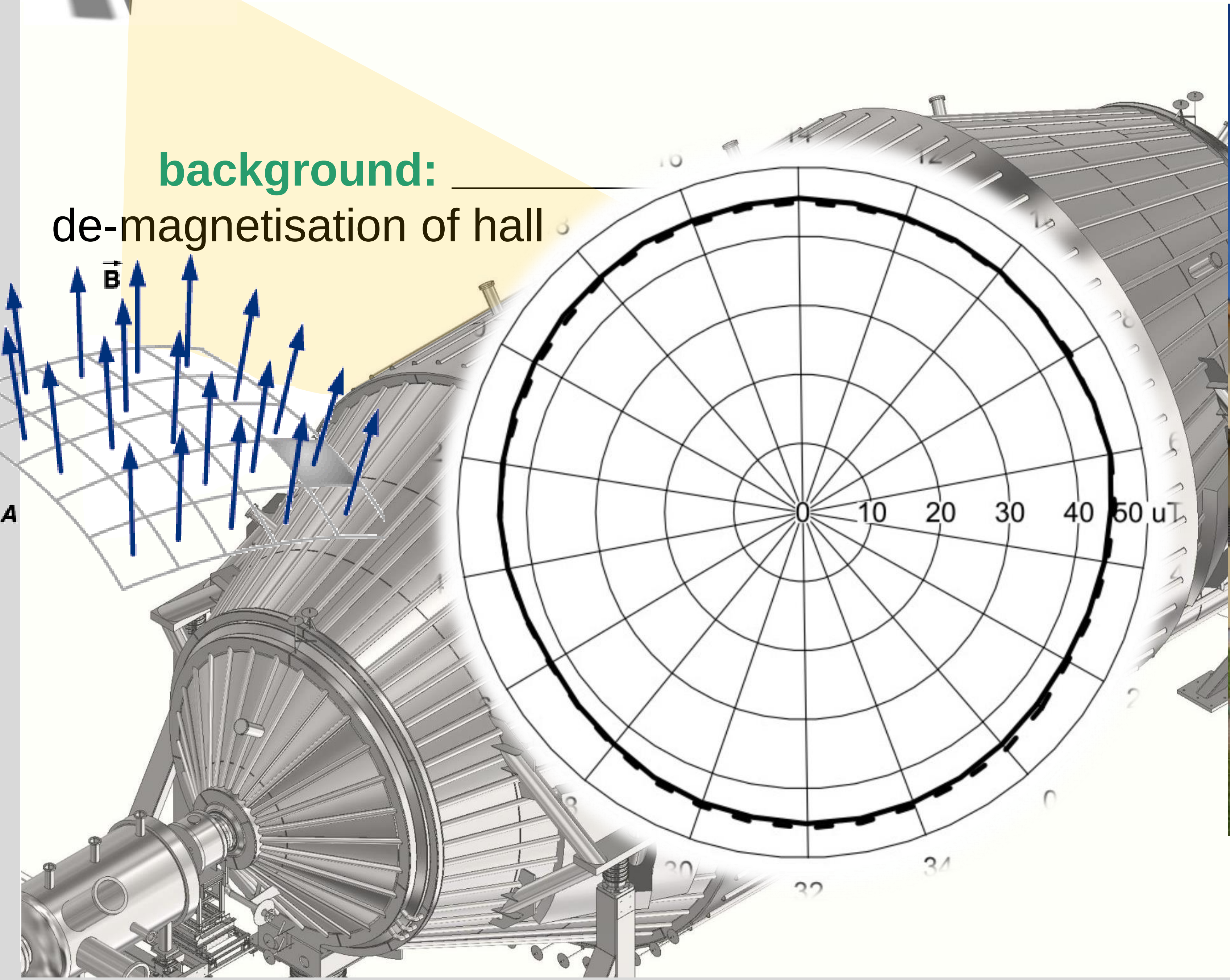
Background processes: secondary electrons

cosmic
muons:
60.000/s



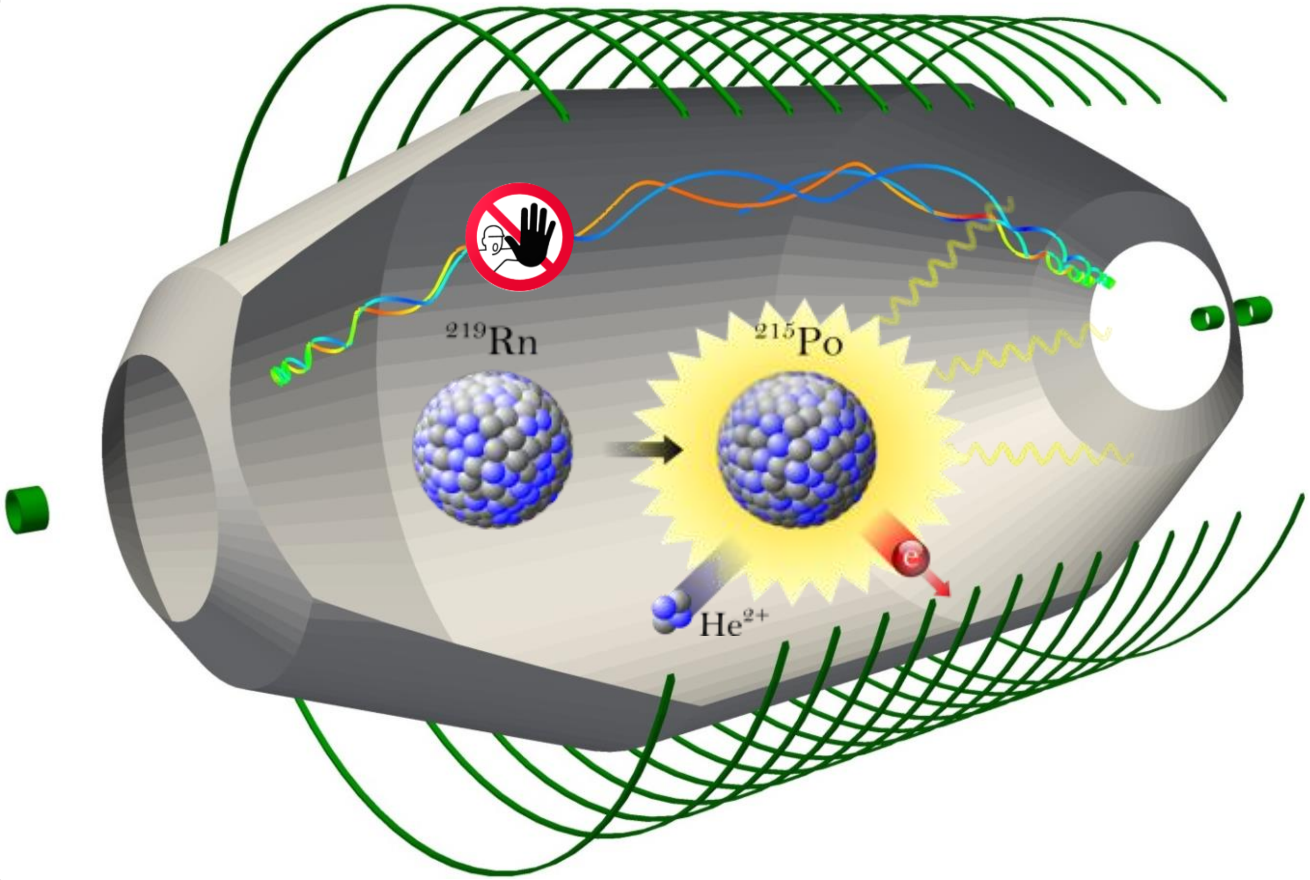
de-magnetisation of hall

background: ___________
de-magnetisation of hall



axi-symmetric
magnetfic field

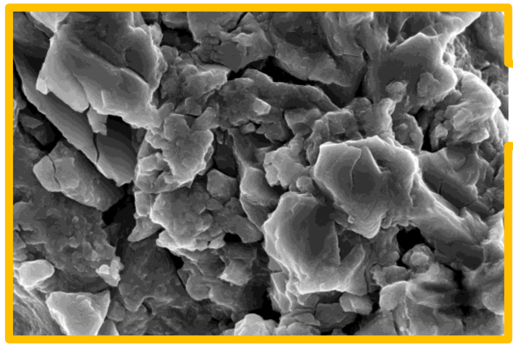
background sources - I



known unknowns:

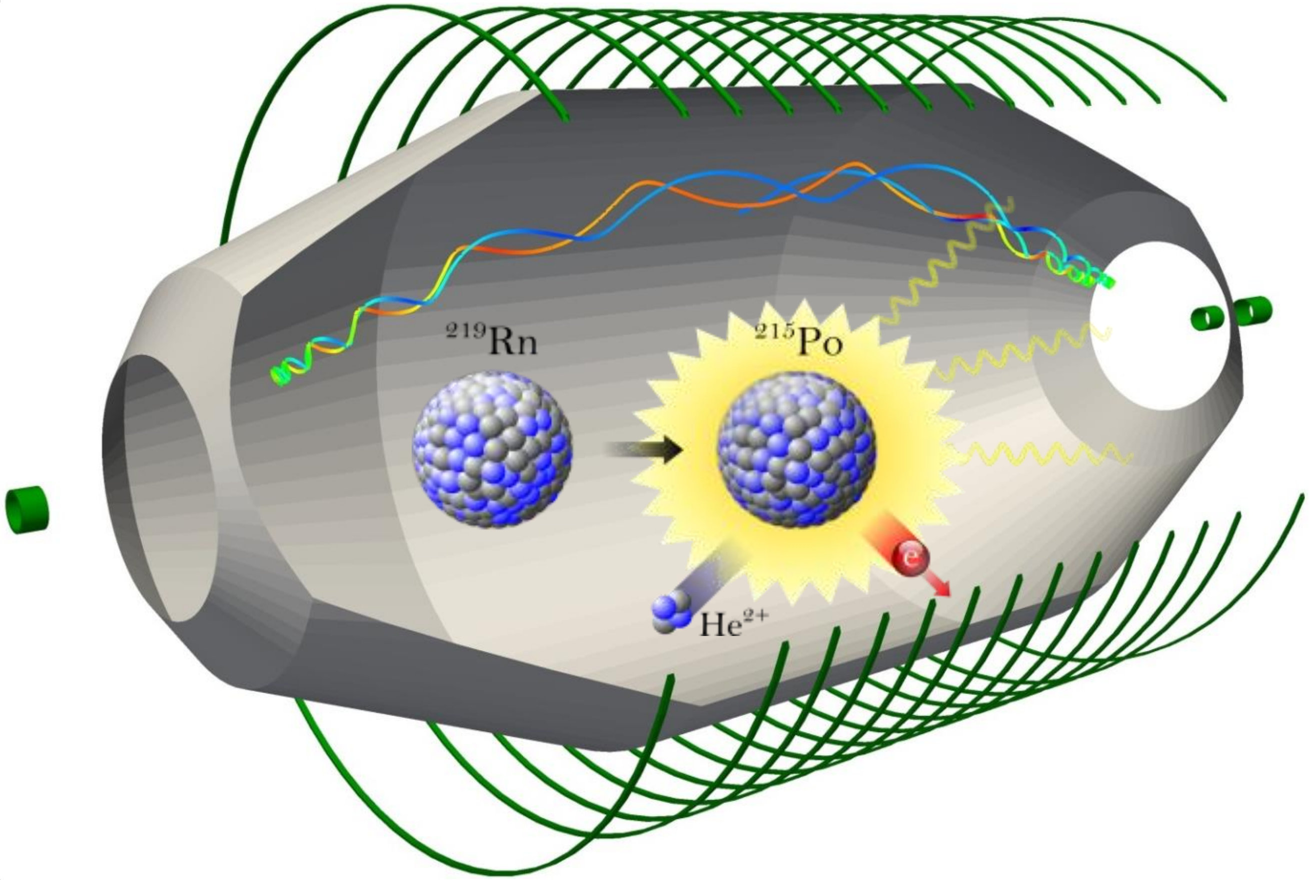
500 mcps due to emanation of ^{219}Rn from NEG pump

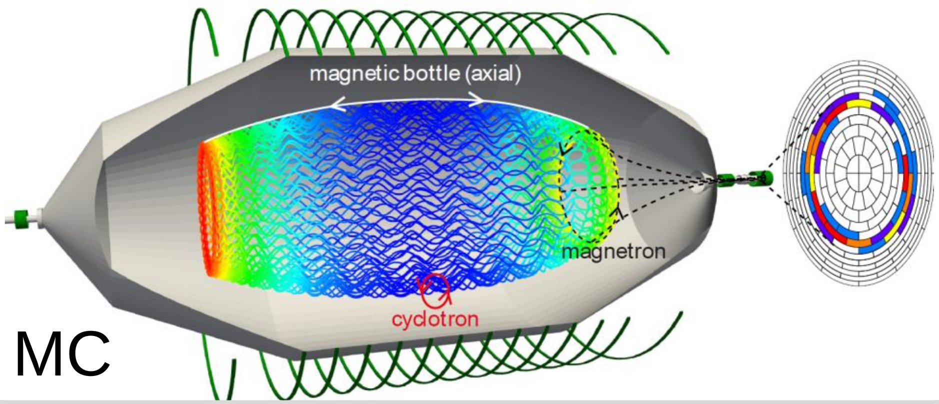
3 km NEG strips



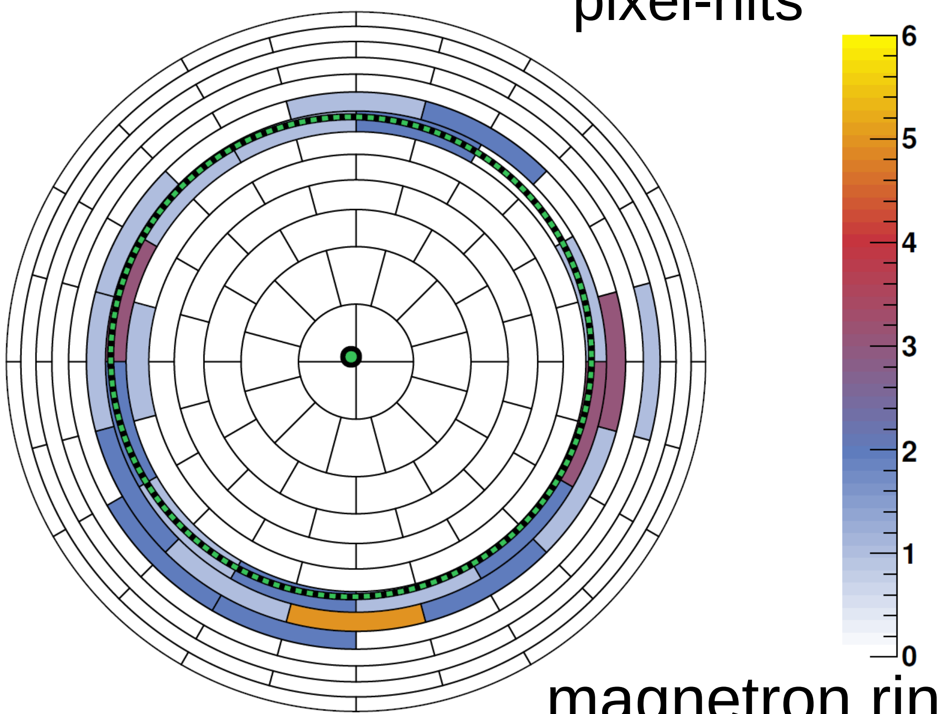
background sources - I

known unknowns:
500 mcps due to emanation of ^{219}Rn from NEG pump



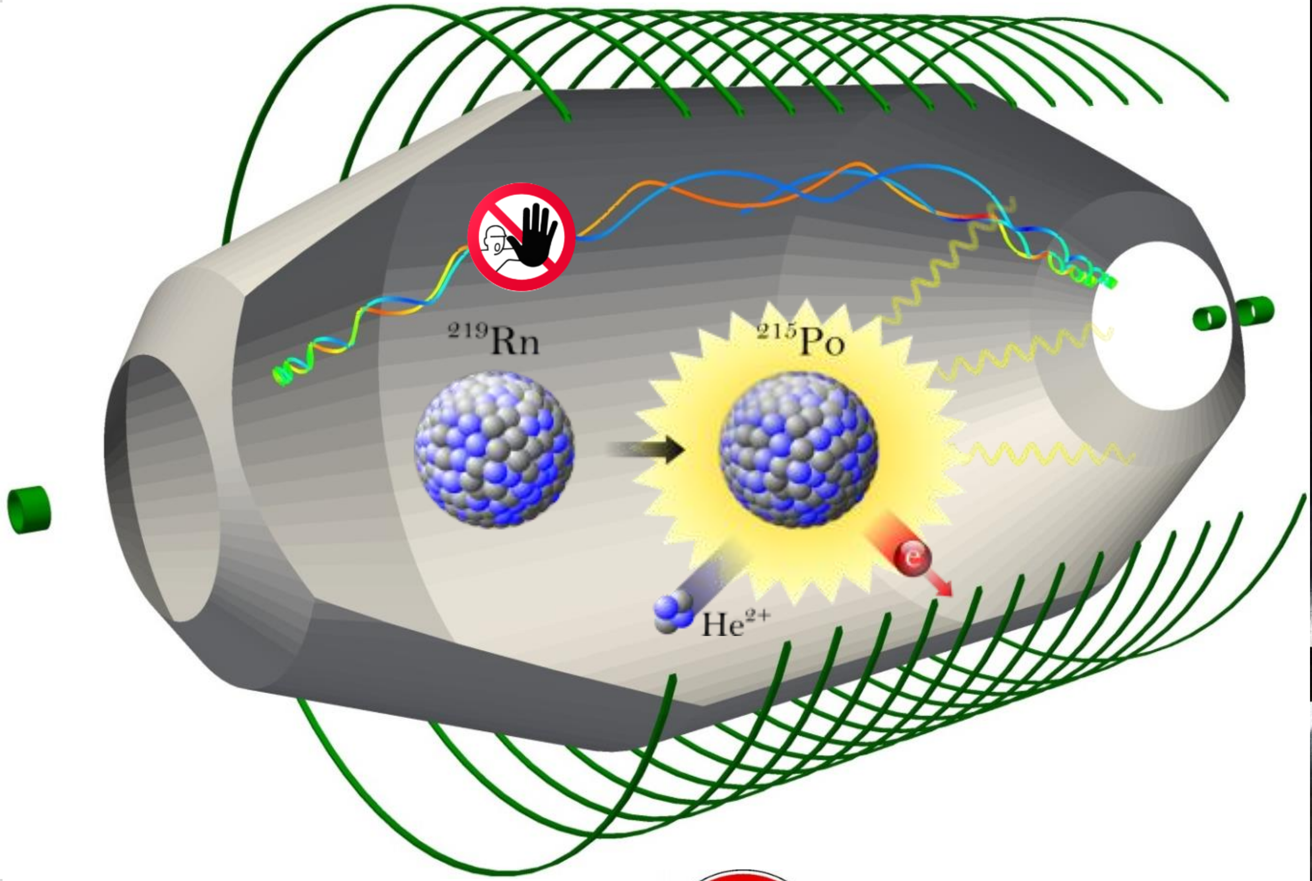


MC



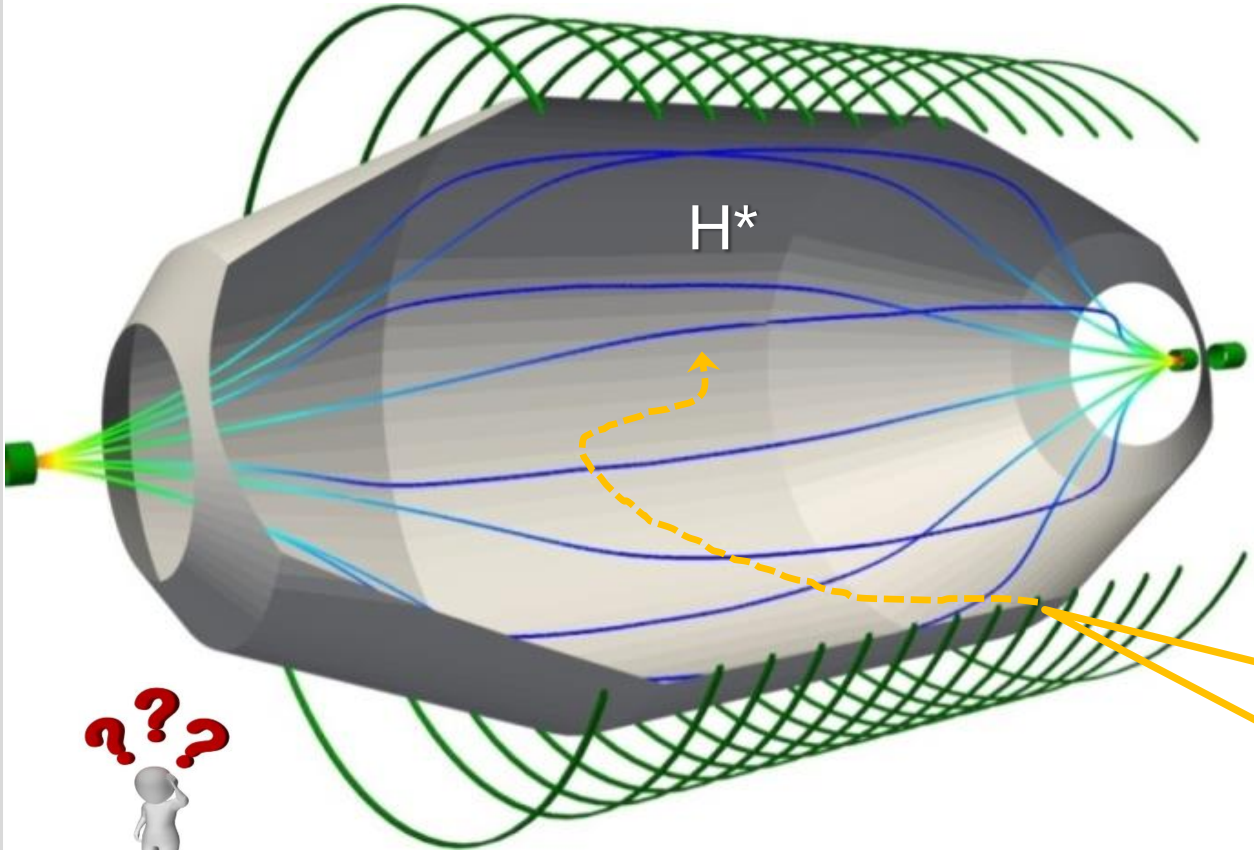
magnetron ring

background sources - I

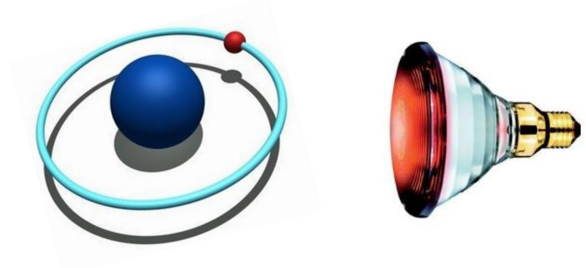


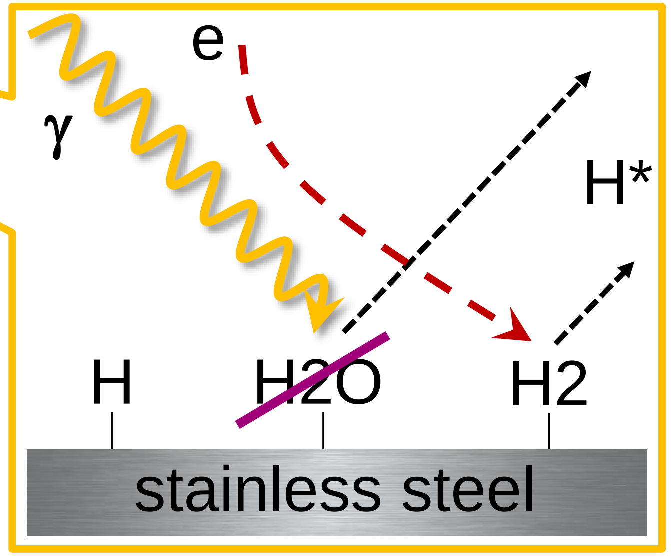
solution:
LN2-cooled baffles
ε = (97 ± 2)%

background sources - II

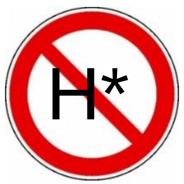


unknown unknowns:
500 mcps due to
photon-stimulated desorption
of hydrogen Rydberg states

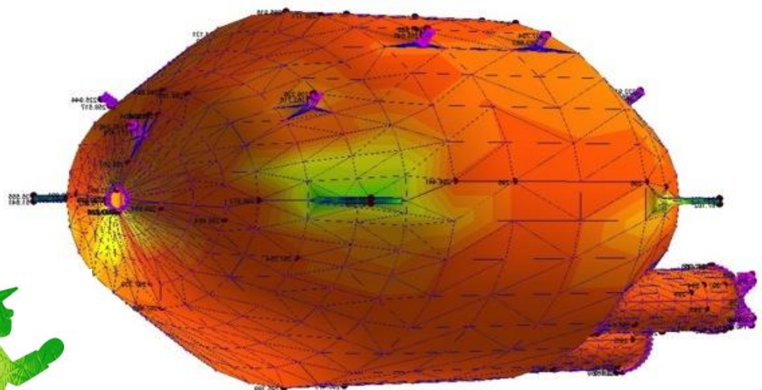




650 m²



solutions:
- proper bakeout
- reduced gamma
  levels in hall

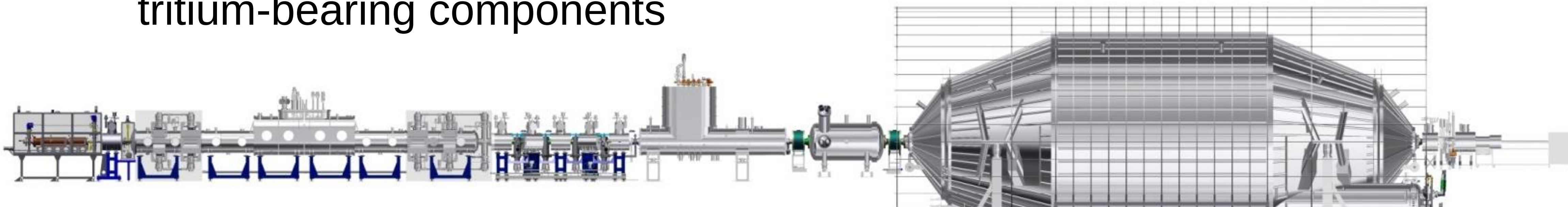


KATRIN – future steps

end ´15: cryo/magnet commissioning — final modifications, gamma shielding

mid ´16: tritium loops completed, first T_2 — operate with nominal bg-level

tritium-bearing components

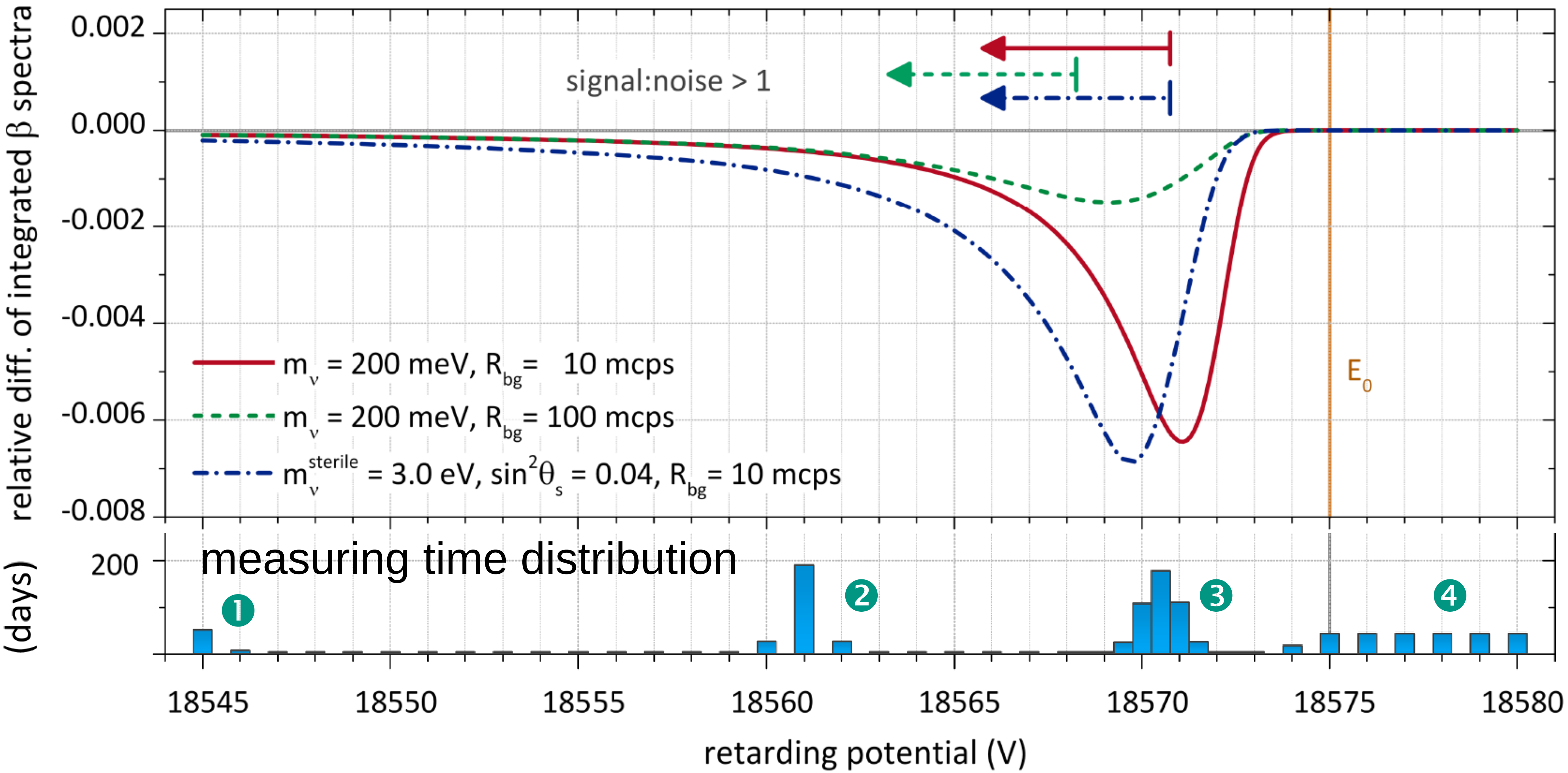


mid-end ´16: first exploratory with small T2 column densities, ramp up

early ´17: operate with nominal T2 column densities, egun runs, ν-mass, ...

spectral shape modification & MTD

- **shape modification**: information on $m^2(\nu_e)$ mainly from region 4 eV below E_0
  ↳ optimized scanning strategy for 4 parameters (statistics only)

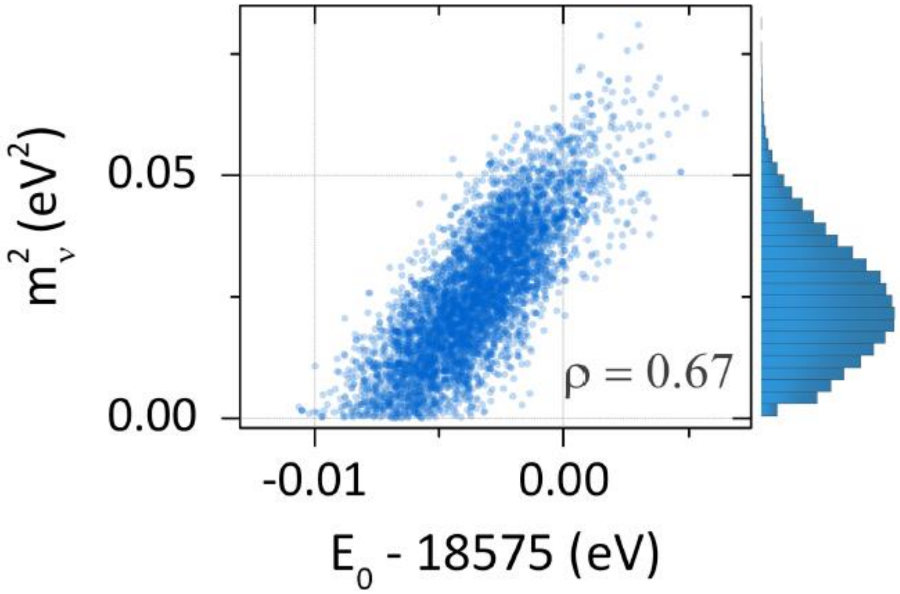


spectral shape – integral measurement

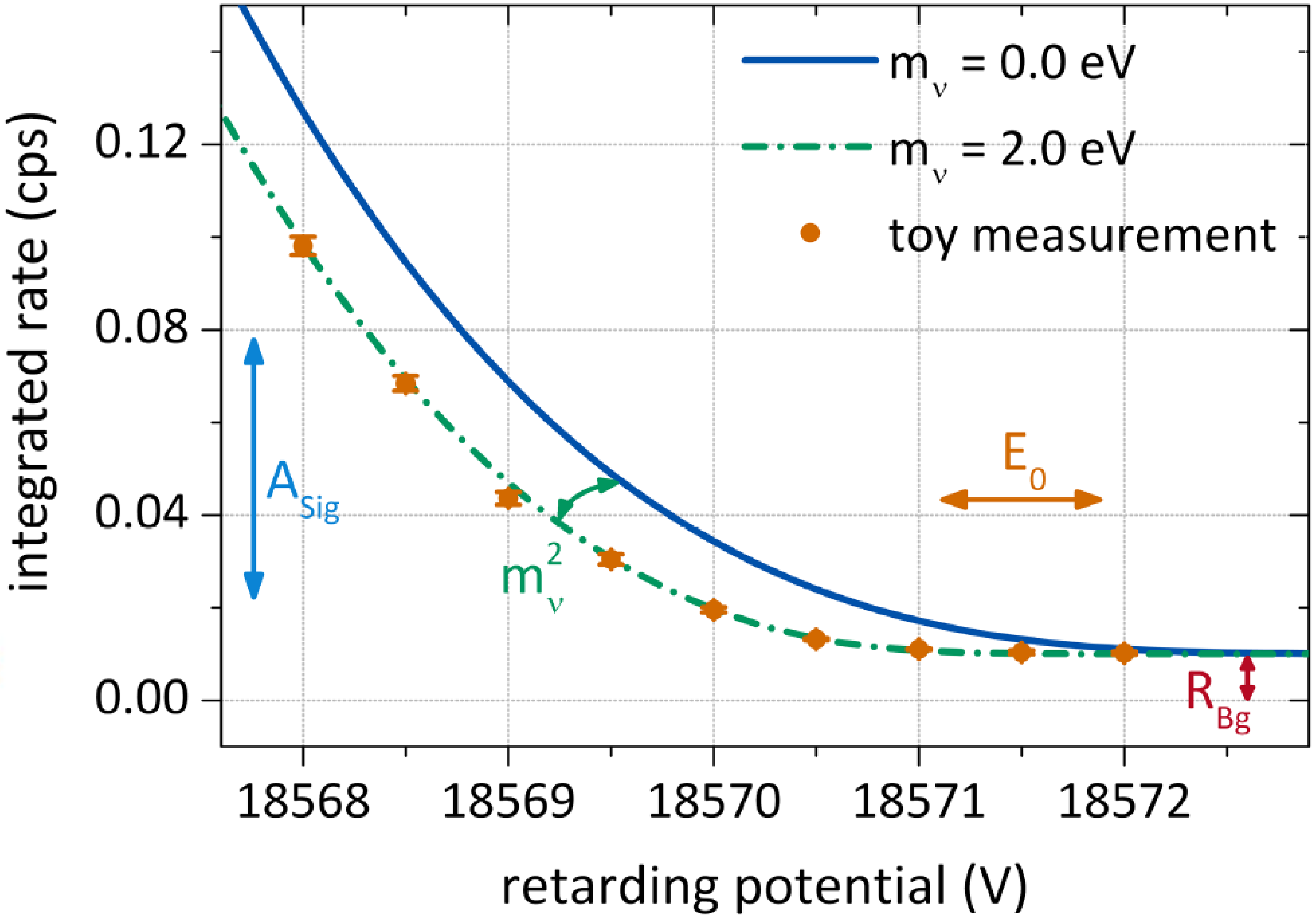
- only **relative spectral shape** is measured, no absolute measurement

4 parameters:
- background rate R_{bg}
- signal amplitude A_{sig}
- endpoint energy E_0
- neutrino mass $m^2(\nu_e)$

- parameter correlations:

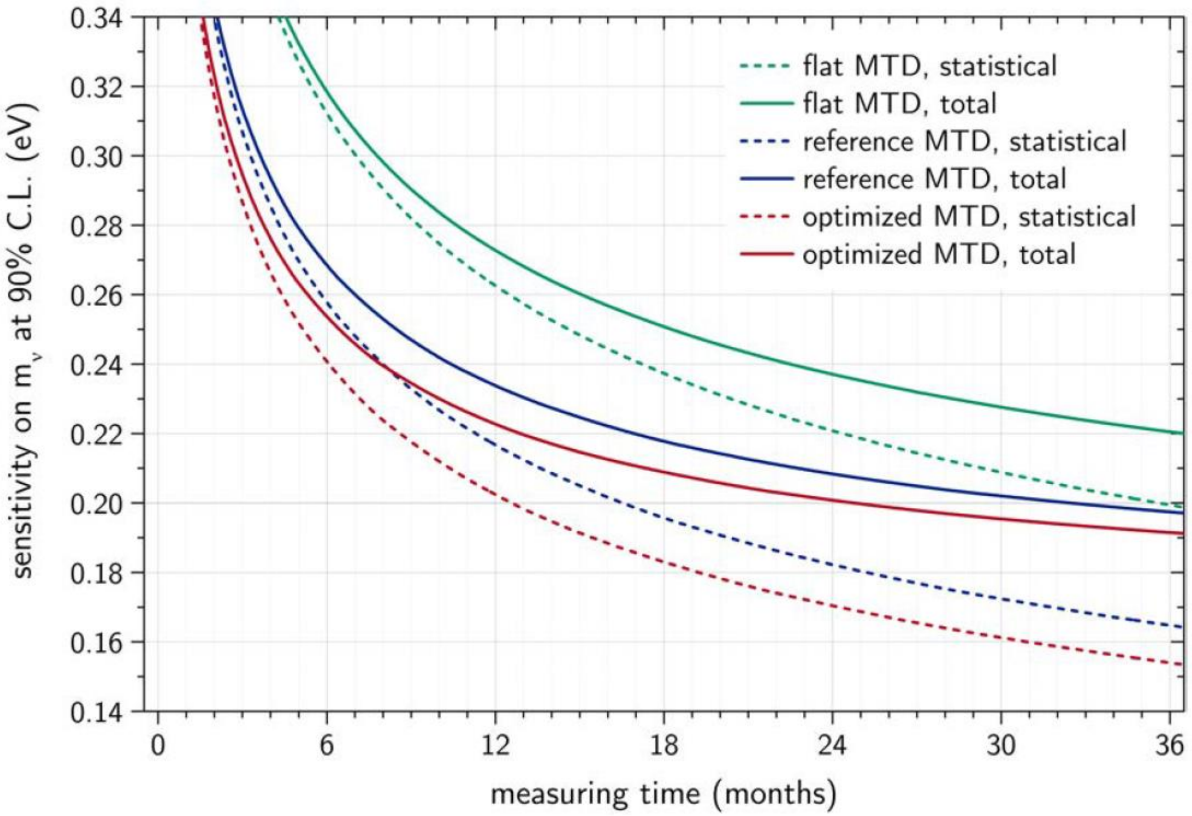


first month of nominal KATRIN data-taking



KATRIN neutrino mass sensitivity

- **reference ν-mass sensitivity**
  for 3 ´full beam´ (5 calendar) years:



sensitivity $m(\nu_e)$ = 200 meV (90% CL)

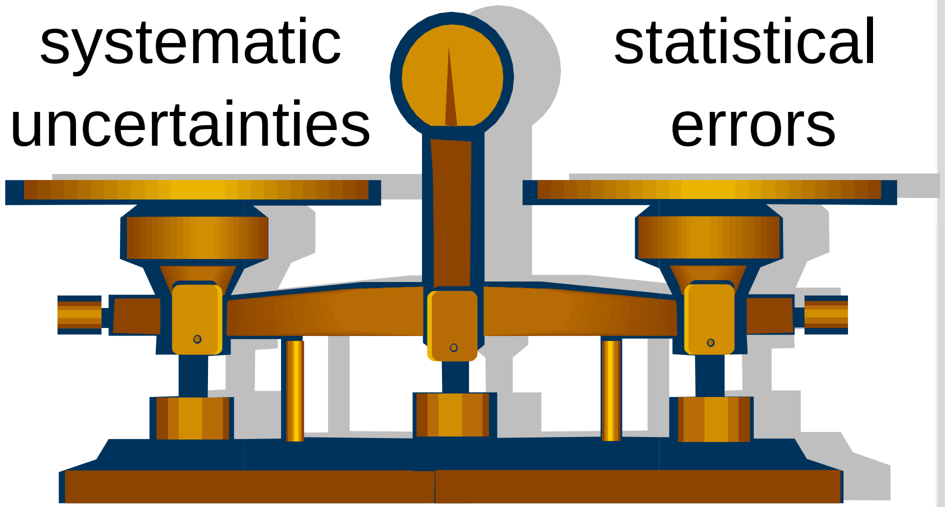
350 meV (5σ)

statistics: σ_{stat} = 0.018 eV²

Σ 5 systematics: σ_{syst} < 0.017 eV²

systematic uncertainties

statistical errors

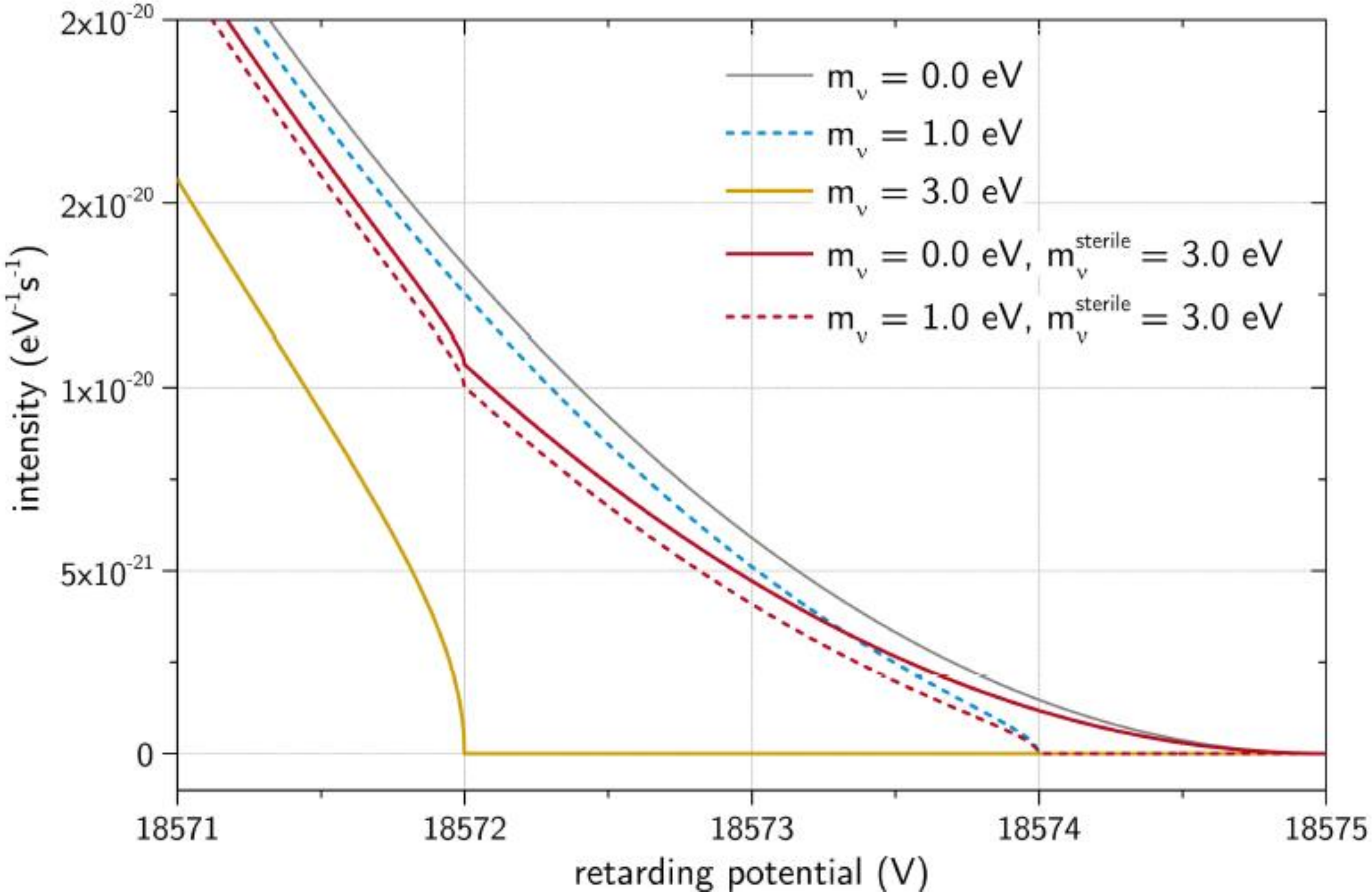


light sterile neutrinos: reactor anomaly

- shape modification below E_0 by active $(m_a)^2$ and sterile $(m_s)^2$ neutrinos

$$\frac{dN}{dE} = \cos^2\theta_s \cdot \frac{dN}{dE}(m_a) + \sin^2\theta_s \cdot \frac{dN}{dE}(m_s)$$

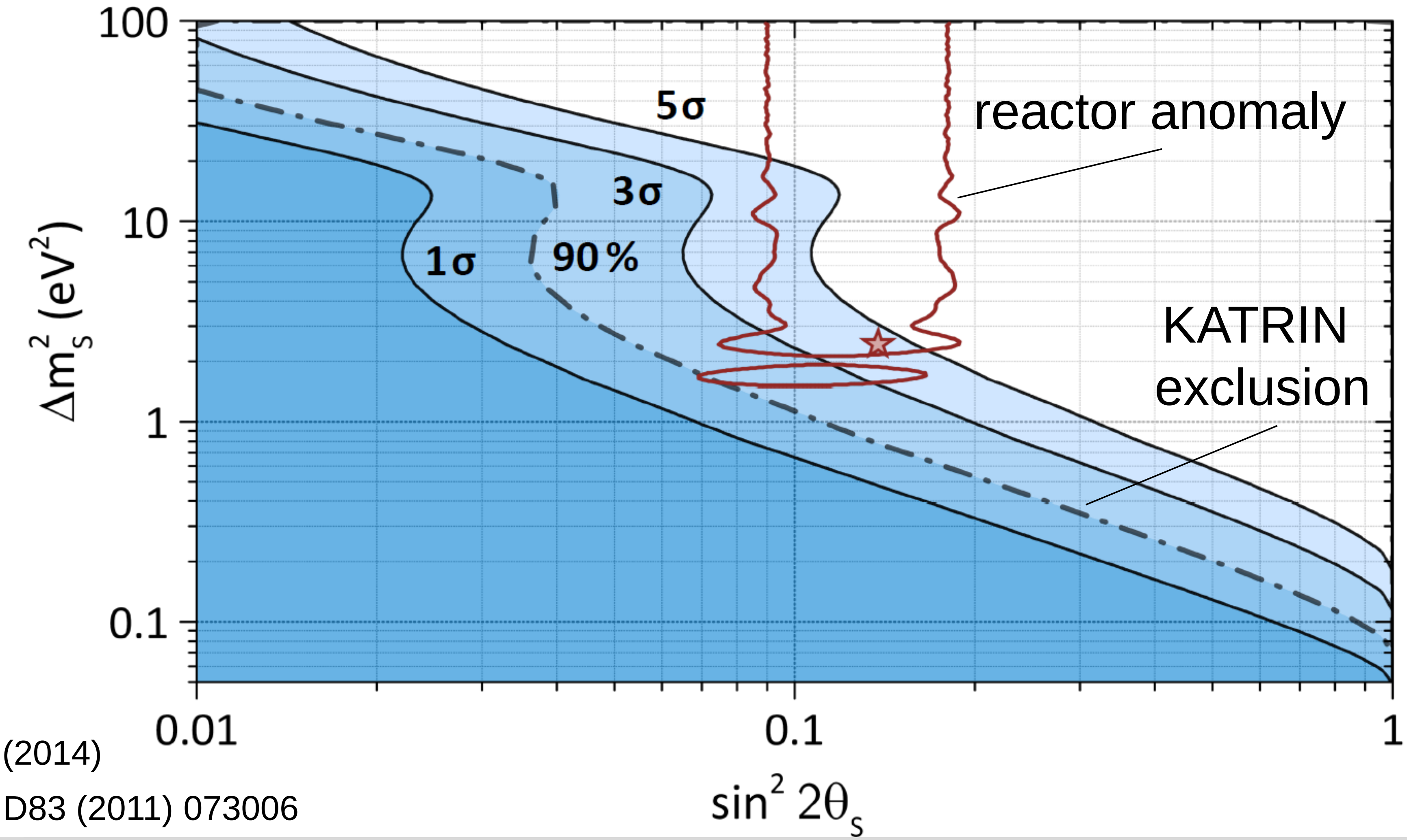
additional kink would appear in the electron energy spectrum at $E = E_0 - m_{sterile}$



light sterile neutrinos: reactor-ν-anomaly

- KATRIN sensitivity reevaluated for light (ev-scale) sterile neutrinos
  parameter region $\Delta m^2 \sim 1$ eV, $\sin^2 2\theta_s \sim 0.1$ has been suggested
  by **reactor anti-neutrino anomaly**

- KATRIN covers large part of allowed Δm^2 - $\sin^2 2\theta$ region within 3 net years

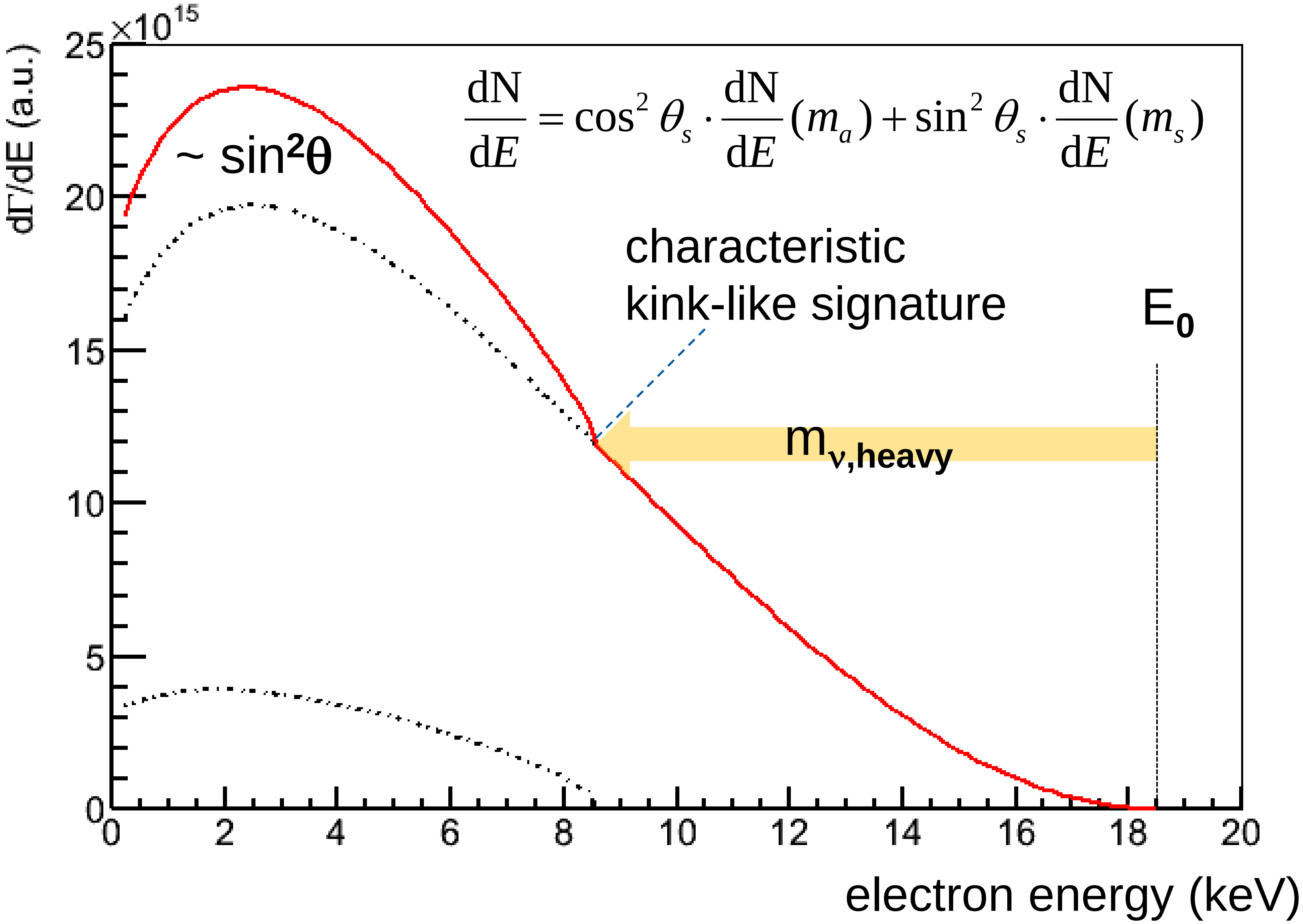


M. Kleesiek, PhD thesis, KIT (2014)

G. Mention et al., Phys. Rev. D83 (2011) 073006

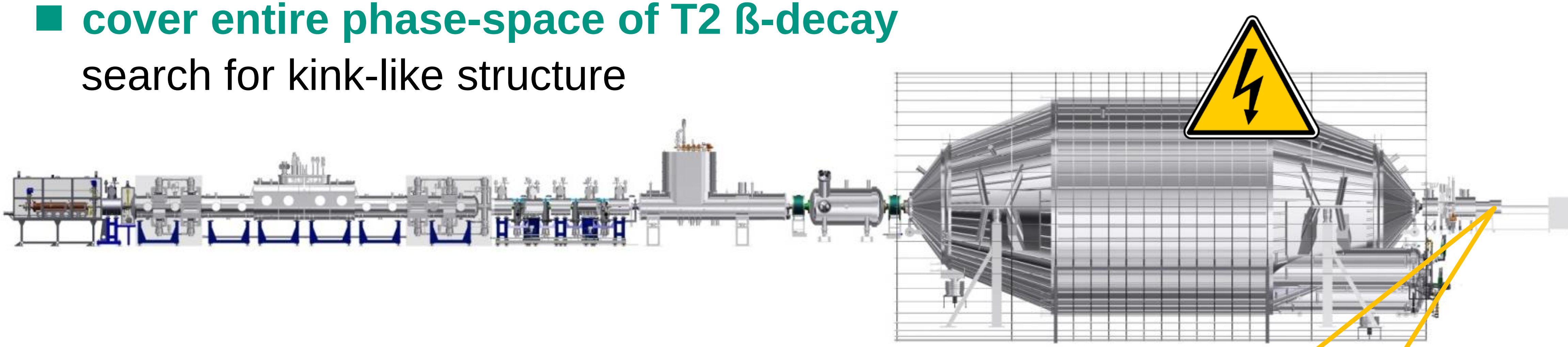
keV-mass sterile neutrinos

- shape modification by keV-mass sterile neutrino with mass m_s



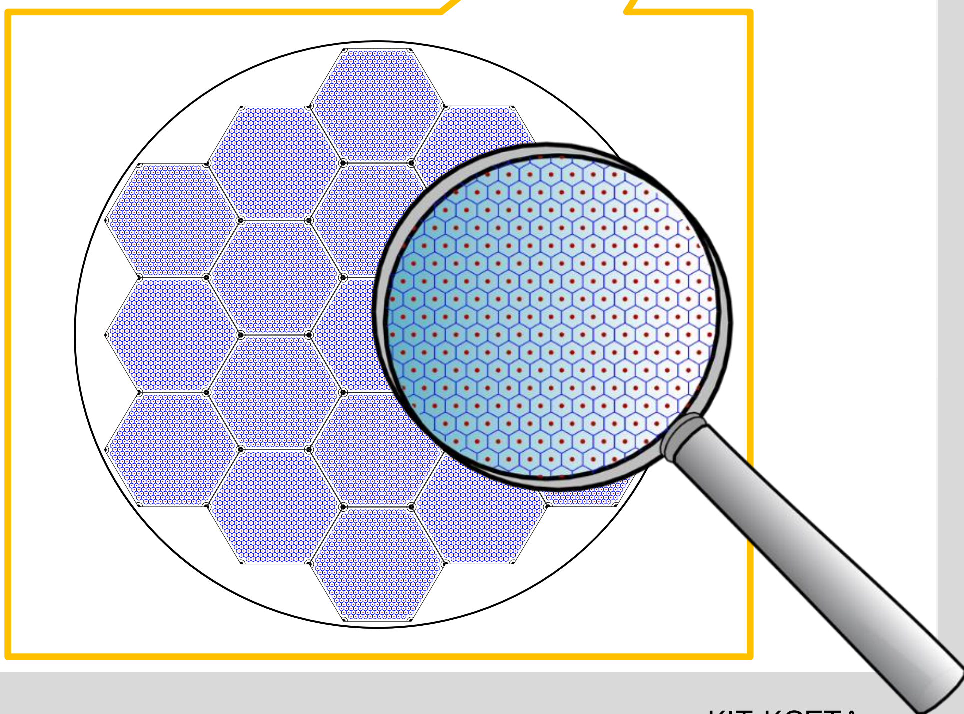
KATRIN – a novel detector system (TRISTAN)

- **cover entire phase-space of T2 ß-decay**
  search for kink-like structure

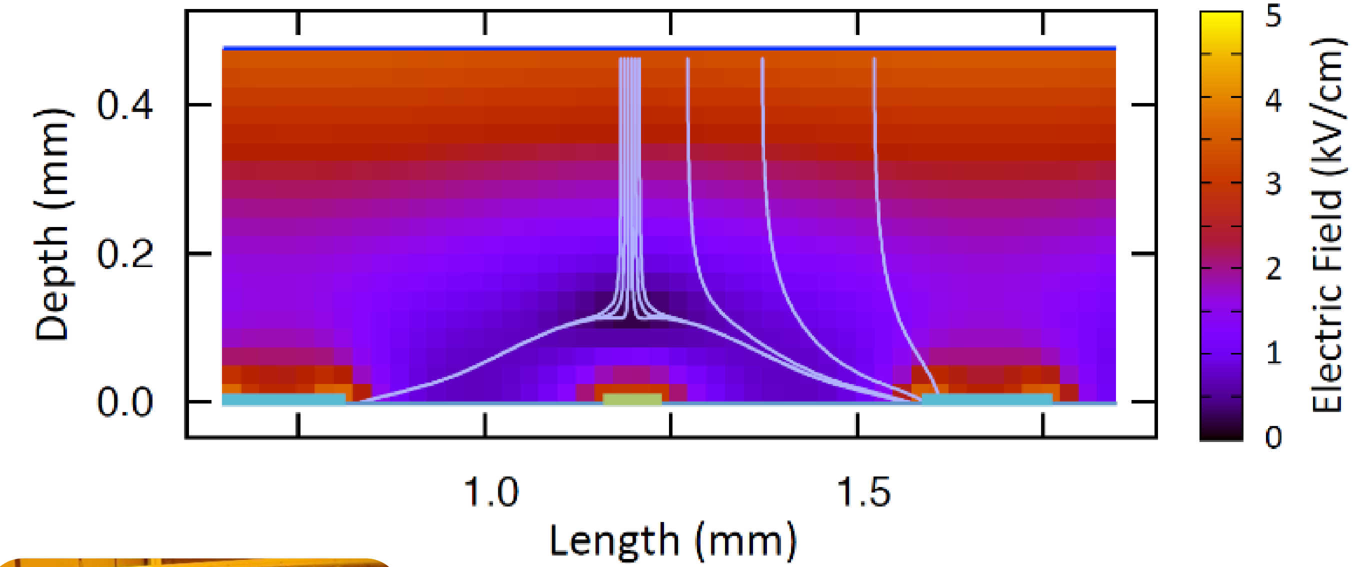


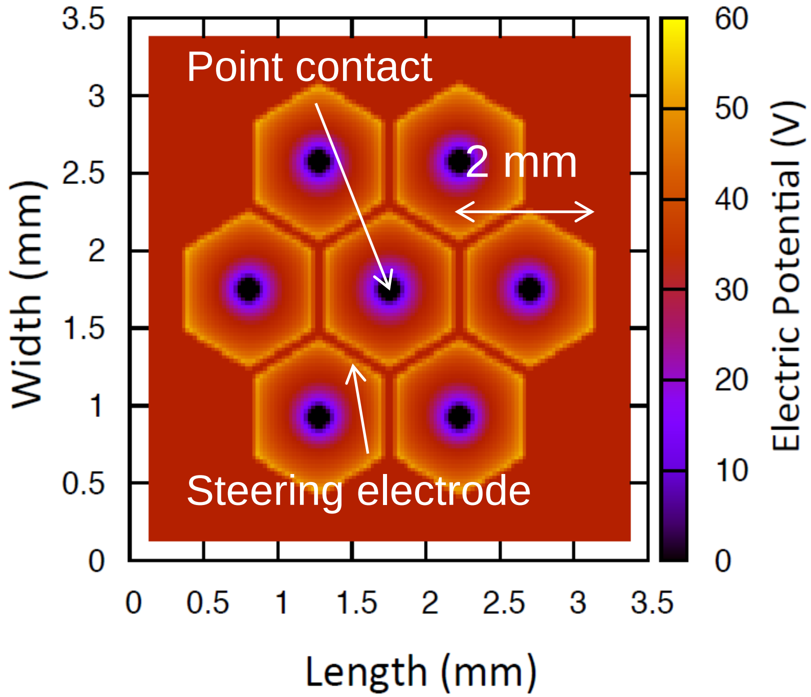
- main spectrometer operated at
  variable retarding potential (0-18.6 keV)
  huge signal rates $\mathcal{O}(10^{10}$ cps)

- need detectors with energy resolution
  of ΔE ~ 300 eV for kink identification

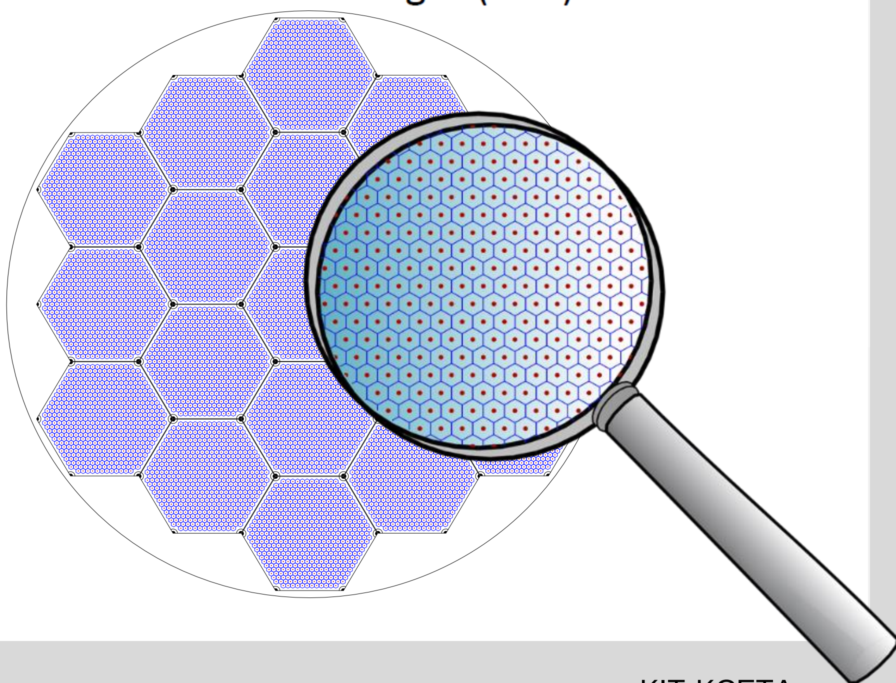


KATRIN – a novel detector system (TRISTAN)





- promising **differential read-out** technology for kink-search: p-type point contact detectors (miniaturized from 0νßß)
  ↳ array with ~10^4 pixels

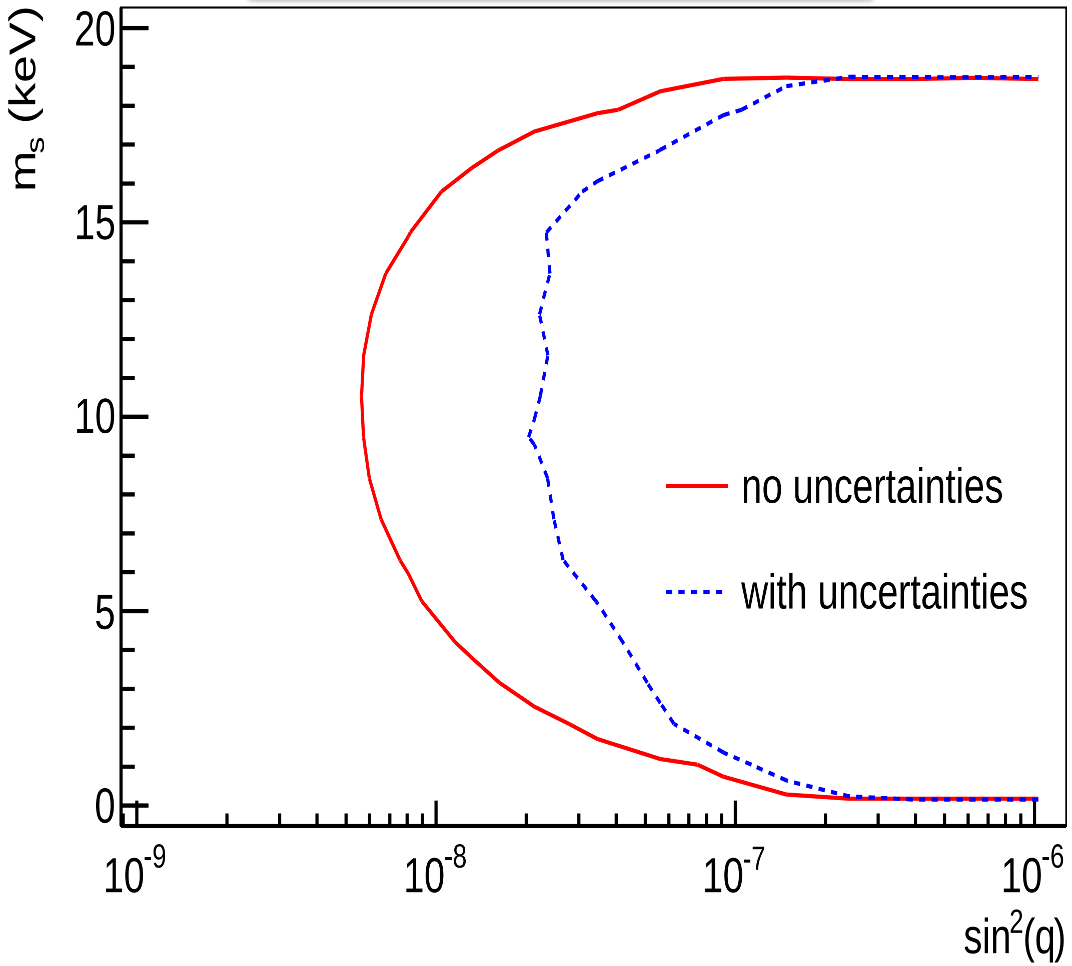


Sensitivity studies (S. Mertens et al.)

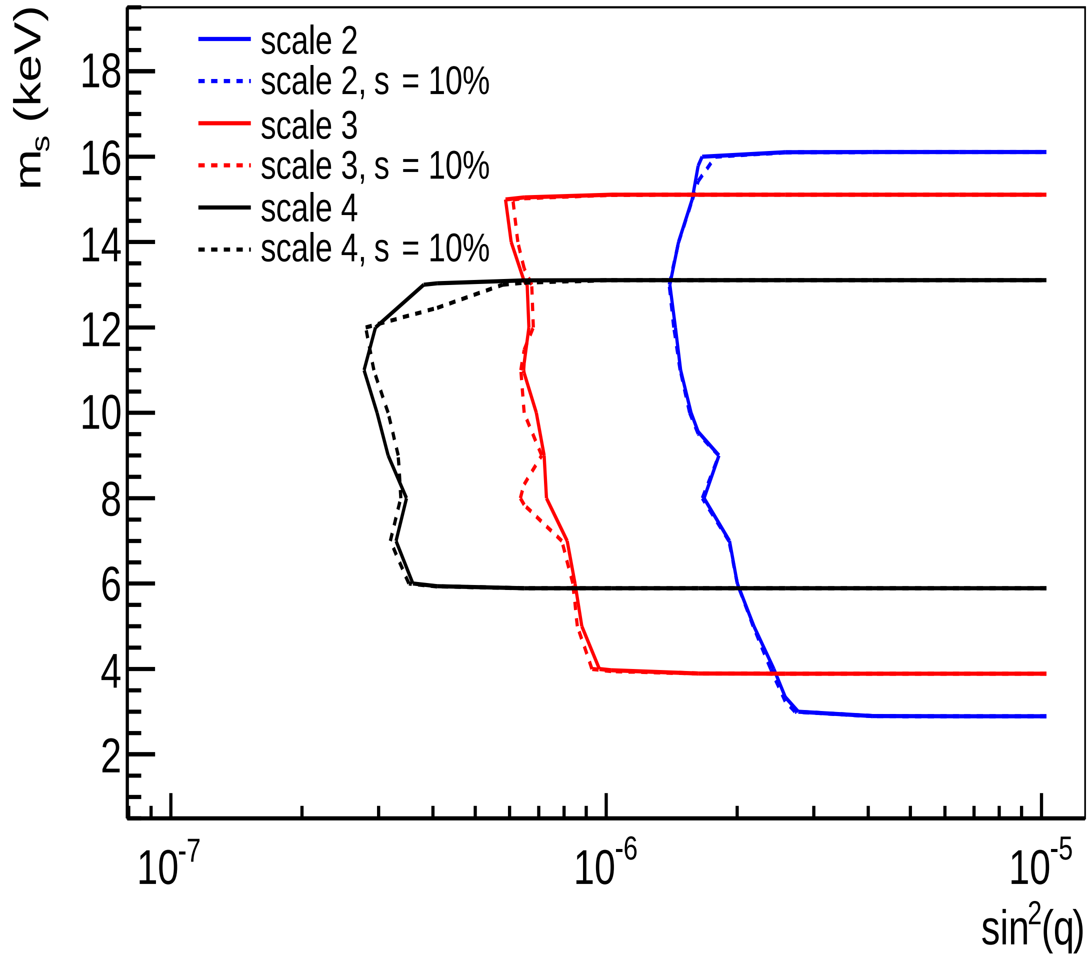
Karlsruhe Institute of Technology

- Investigation of theoretical uncertainties (state-of-the-art description of tritium ß-spectrum) on spectral fit & novel wavelet transform (indep. of shape)

spectral fit approach



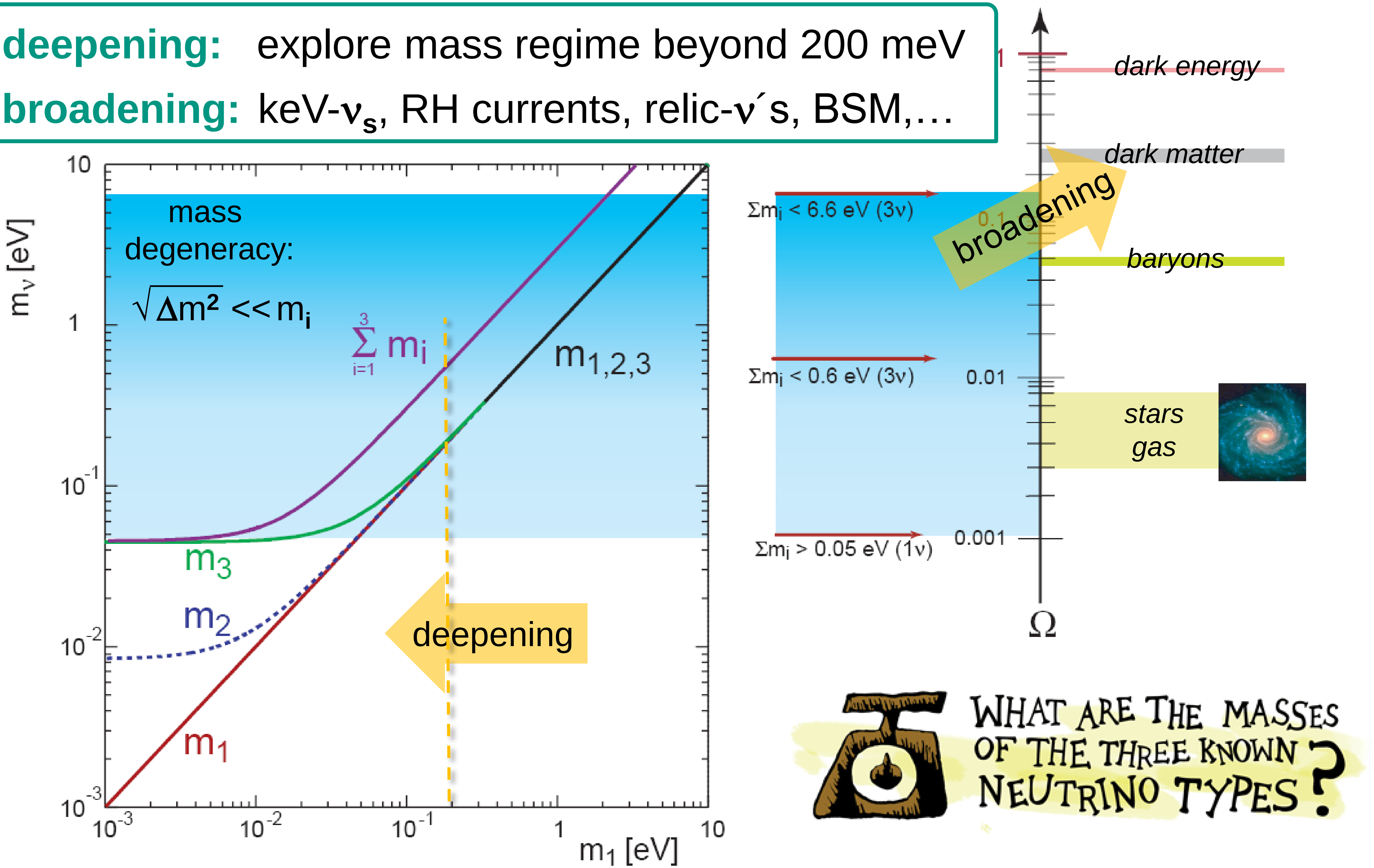
wavelet approach



KATRIN long-term goals

deepening: explore mass regime beyond 200 meV

broadening: keV-ν_s, RH currents, relic-ν´s, BSM,…



Conclusion

2015/16: integration of source components – lots of work to be done…

2016: initial runs as preparation of long-term data taking (2017-…)

R&D on detection of kink-like structure in T2 ß-spectrum

exciting times ahead in measuring neutrino masses from meV-keV