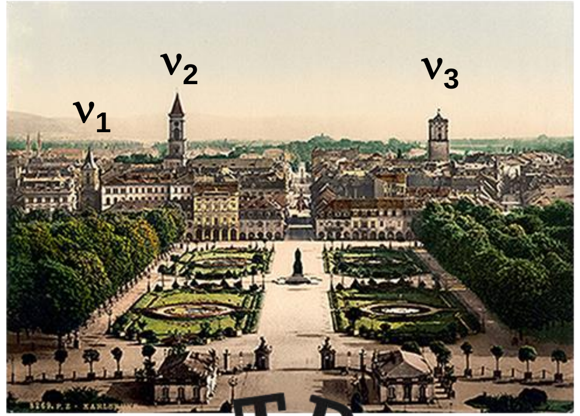
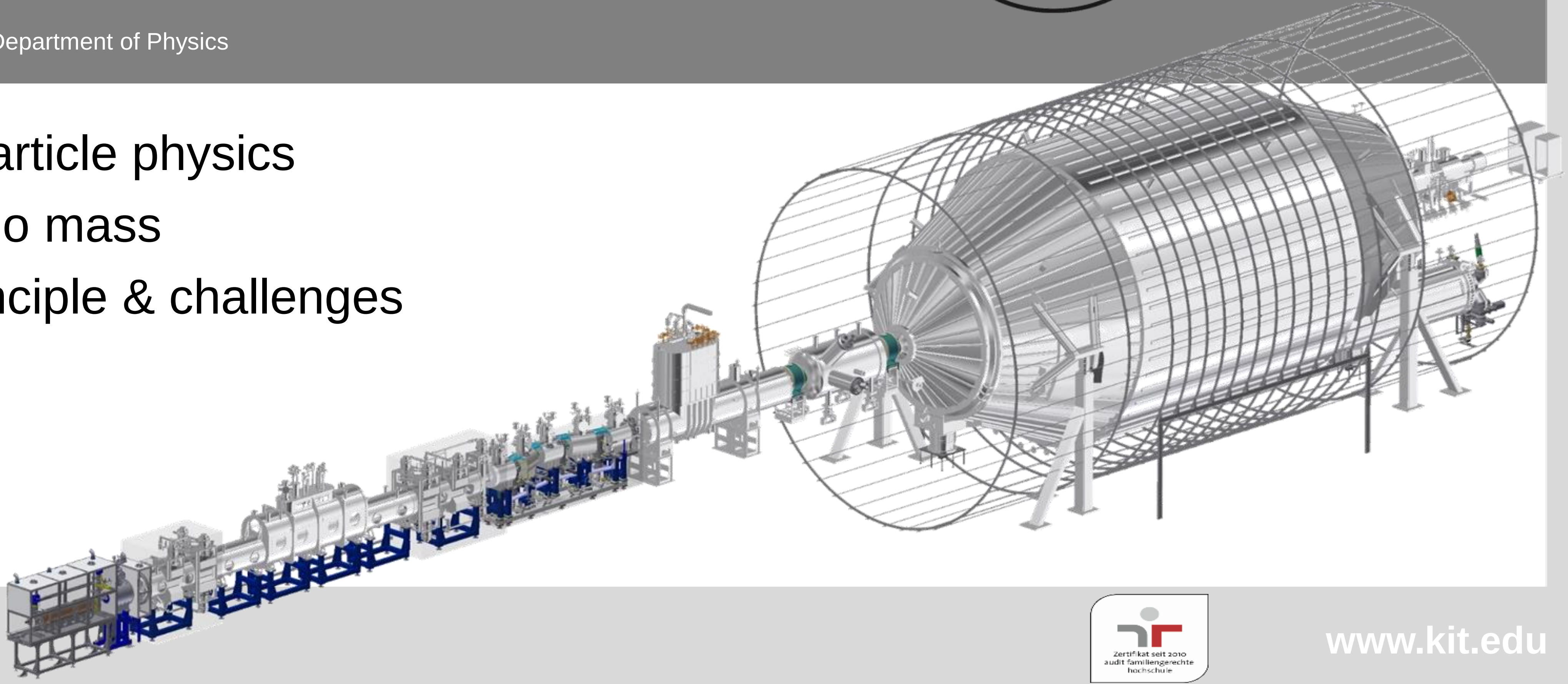
KATRIN – the most precise scale for neutrinos



Topical Workshop on Electronics for Particle Physics (TWEPP-2016)
KIT, September 26-30, 2016

Guido Drexlin, Institute for Experimental Nuclear Physics, Department of Physics

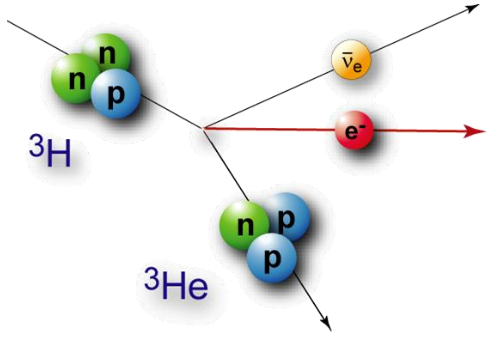
- Introduction: neutrinos in particle physics
- ß-spectroscopy and neutrino mass
- KATRIN: measurement principle & challenges
- KATRIN: main components
- KATRIN: status & future
- Conclusions

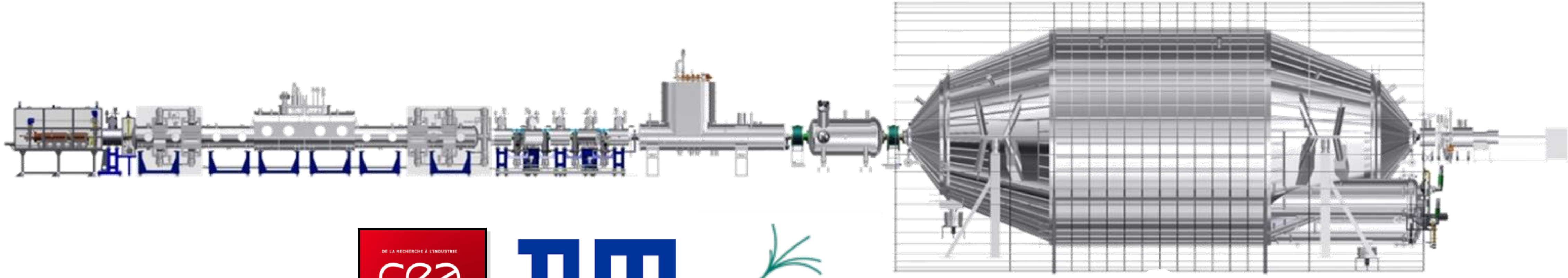


KATRIN experiment

Karlsruhe Tritium Neutrino Experiment

- **direct ν–mass experiment**: located at Tritium Laboratory (TLK) of KIT
- international collaboration ~130 members
  from 6 countries: D, US, CZ, RUS, F, ES

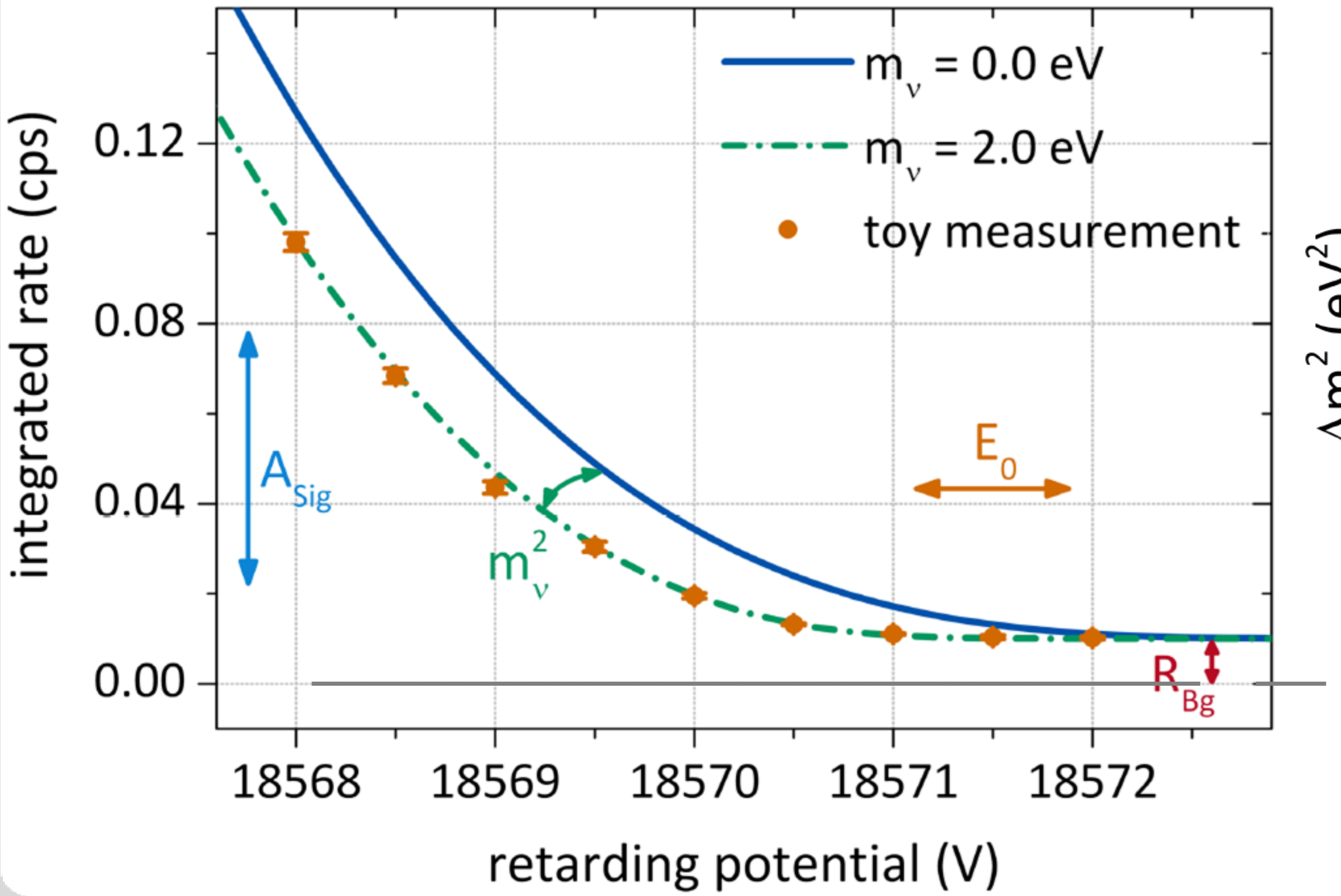


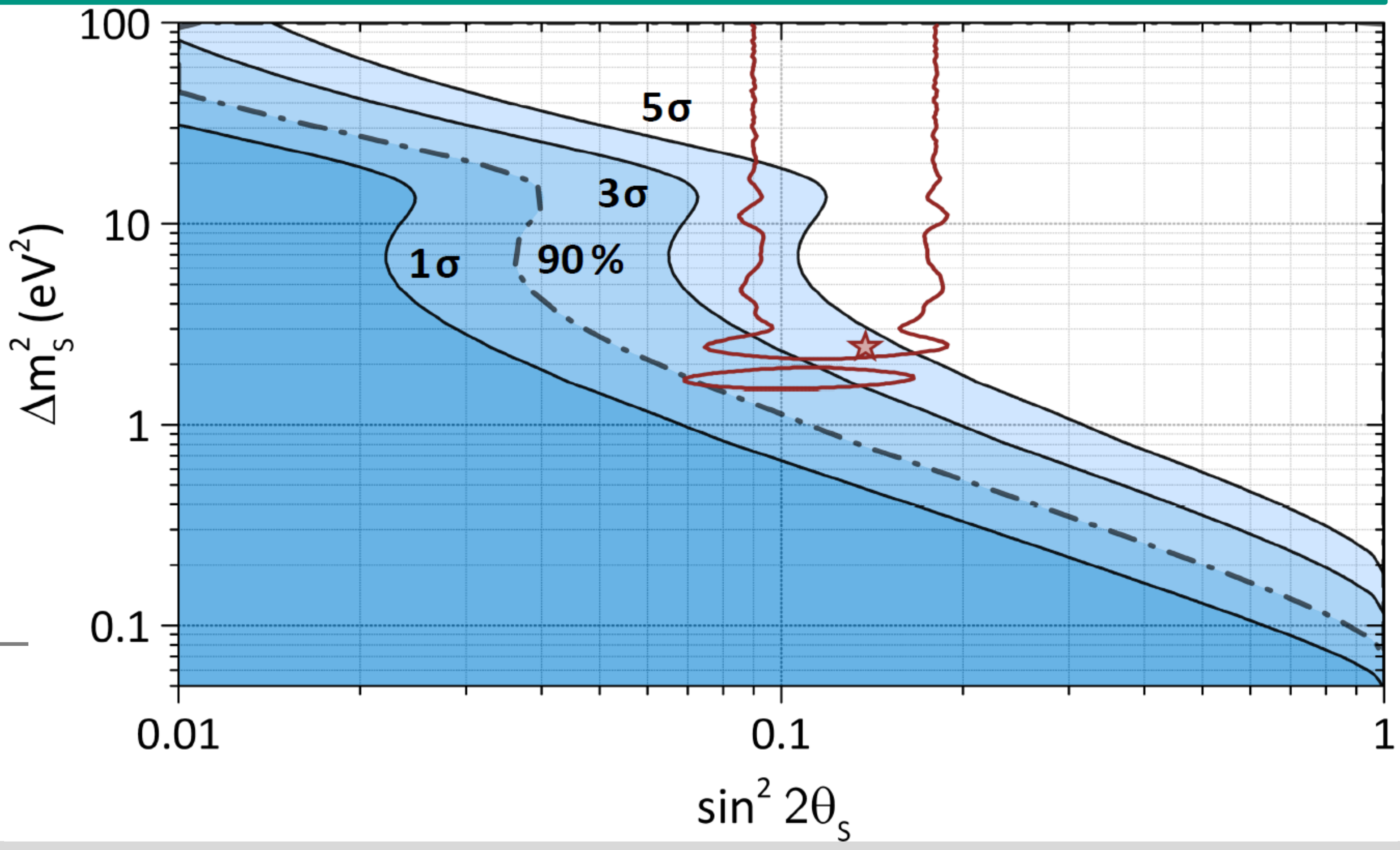


18 institutions:

KATRIN experiment – science case

- **physics programme**
  - model-independent effective electron (anti-)neutrino mass: **$m(\nu_e)$ = 200 meV** (90% CL)
  - search for light… heavy sterile neutrinos: sub-eV … keV mass scale
  - constrain local relic-ν density, search for Lorentz violation, exotic currents, BSM physics …





Introduction: neutrinos in particle physics

6.10.2015 – and the winners are:

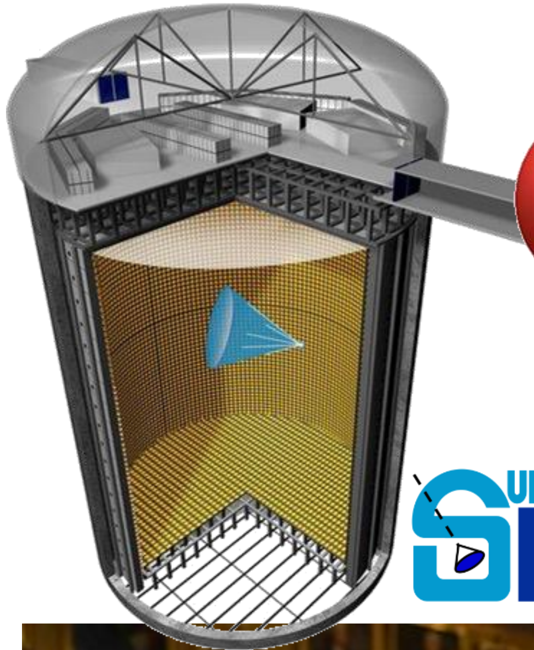
Karlsruhe Institute of Technology

Ill: N. Elmehed. © Nobel Media 2014

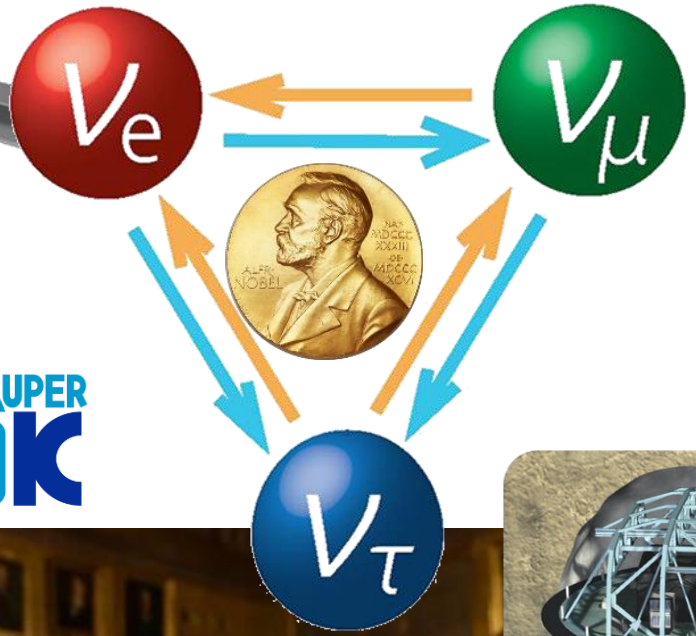
2015 Nobel Prize in Physics

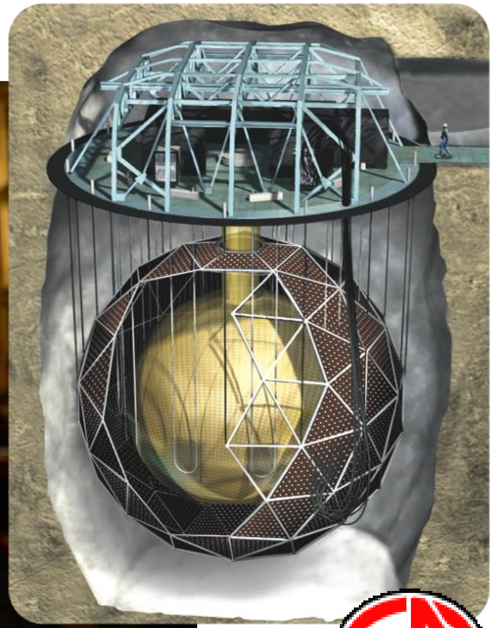
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

Nobelprize.org
The Official Web Site of the Nobel Prize



SUPER K





SNO

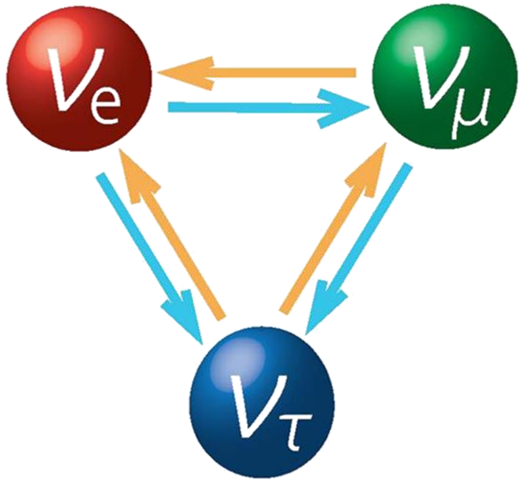
Most Popular Physics Laureates

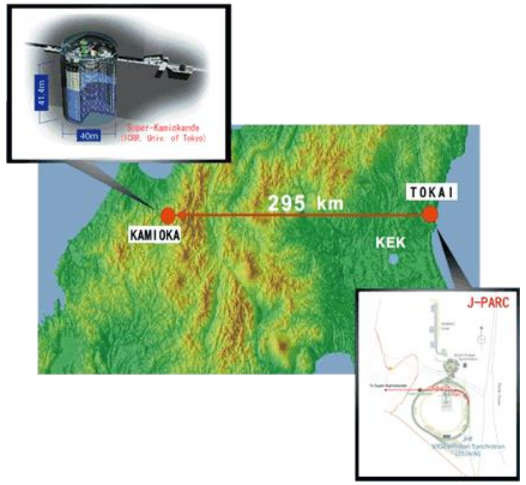
1. Albert Einstein
2. Niels Bohr
3. Marie Curie
4. James Chadwick
5. Takaaki Kajita
6. Erwin Schrödinger
7. J.J. Thomson
8. Arthur B. McDonald
9. Robert A. Millikan
10. Werner Heisenberg

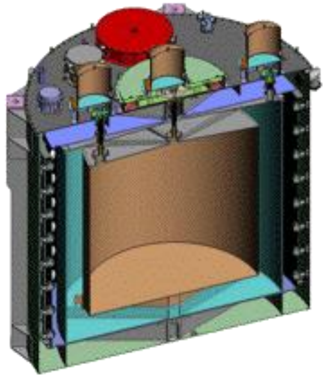
8.11.2015 – and the winners are:

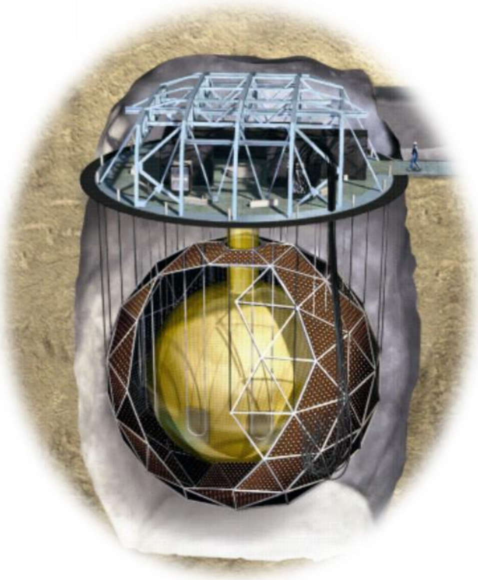
FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

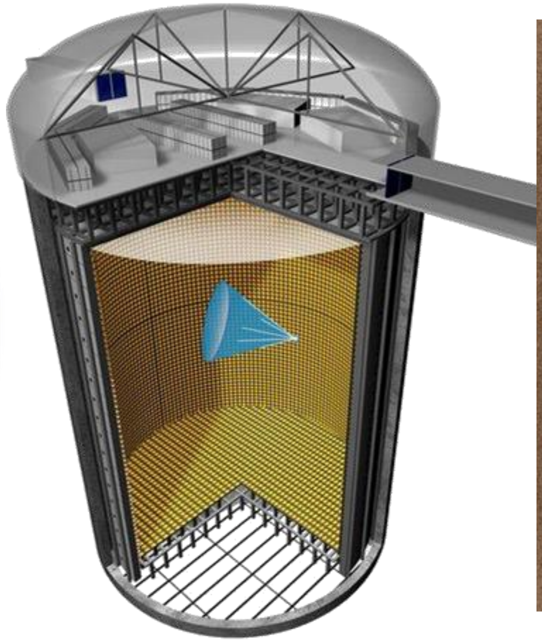
2015 „annus mirabilis" of neutrino physics

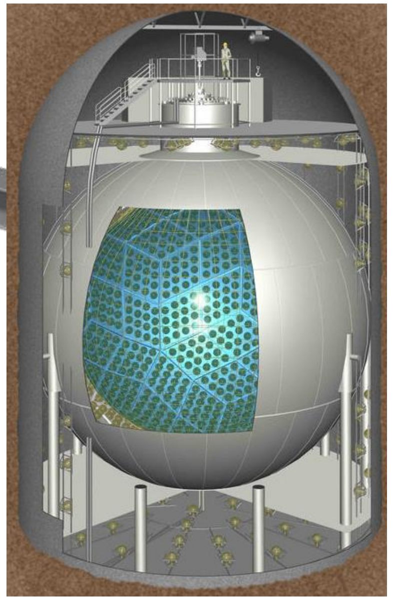












 Kam-Biu Luk and the Daya Bay Collaboration

 Yifang Wang and the Daya Bay Collaboration

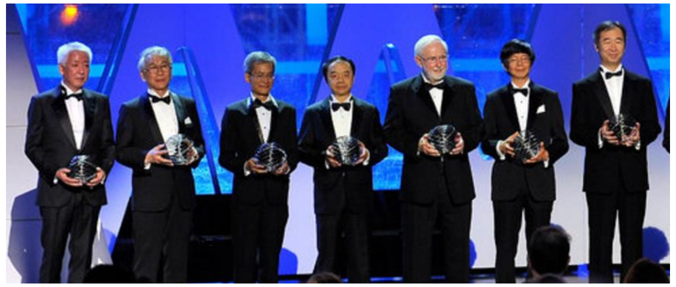
 Koichiro Nishikawa and the K2K and T2K Collaboration

 Atsuto Suzuki and the KamLAND Collaboration

 Arthur B. McDonald and the SNO Collaboration

 Takaaki Kajita and the Super K Collaboration

 Yoichiro Suzuki and the Super K Collaboration



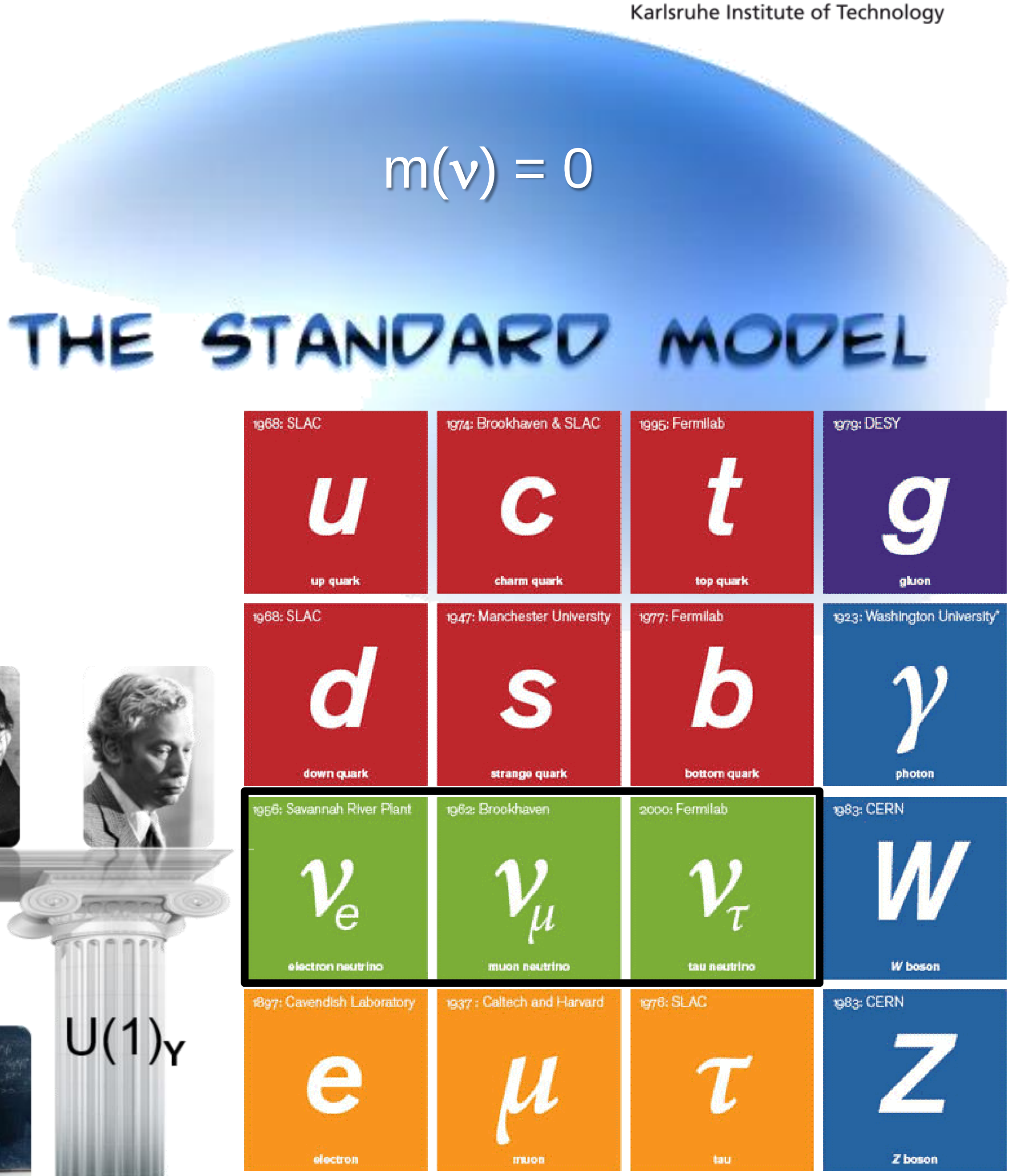
massless neutrinos in the Standard Model

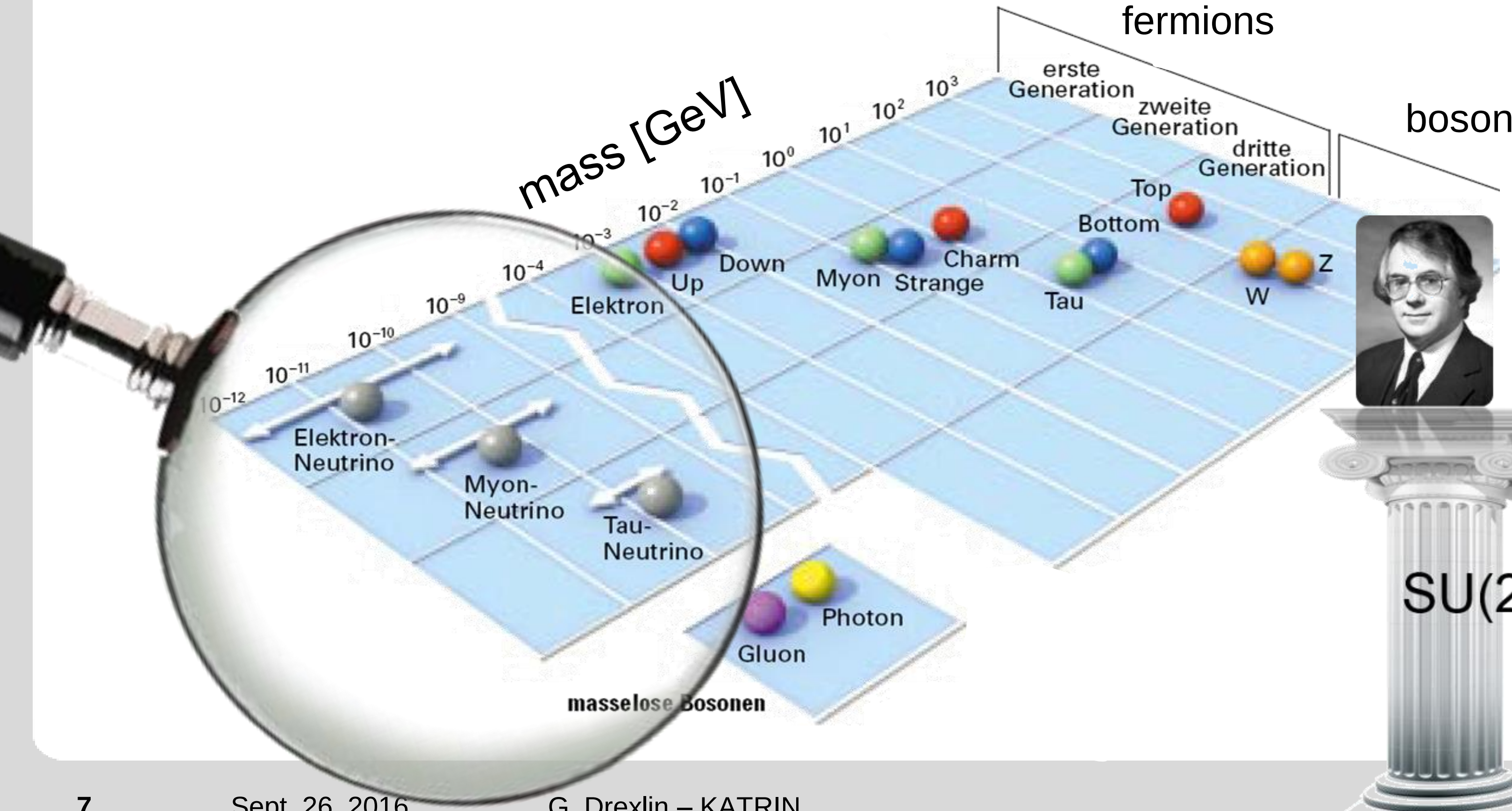
Karlsruhe Institute of Technology

$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L$$

$$\begin{pmatrix}u \\ d'\end{pmatrix}_L \quad \begin{pmatrix}c \\ s'\end{pmatrix}_L \quad \begin{pmatrix}t \\ b'\end{pmatrix}_L$$

- only LH ν, RH anti-ν
  (maximum parity violation)
- massless fermions
- carry Lepton number





massive neutrinos: beyond the Standard Model

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- neutrino oscillations imply **massive neutrinos**

PDG particle data group 2015/16

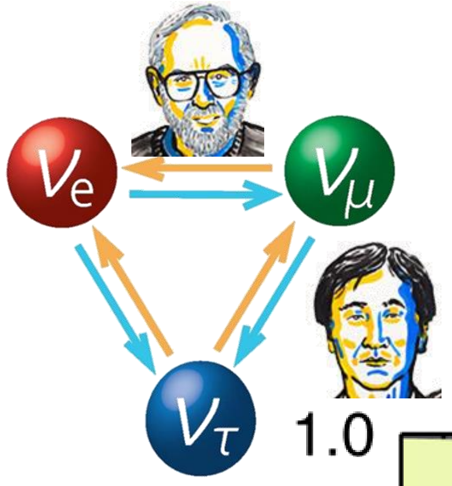
$$\sin^2 2\theta_{12} = 0.846 \,^{+0.021}_{-0.021}$$

$$\sin^2 2\theta_{23} = 0.999 \,^{+0.001}_{-0.018}$$

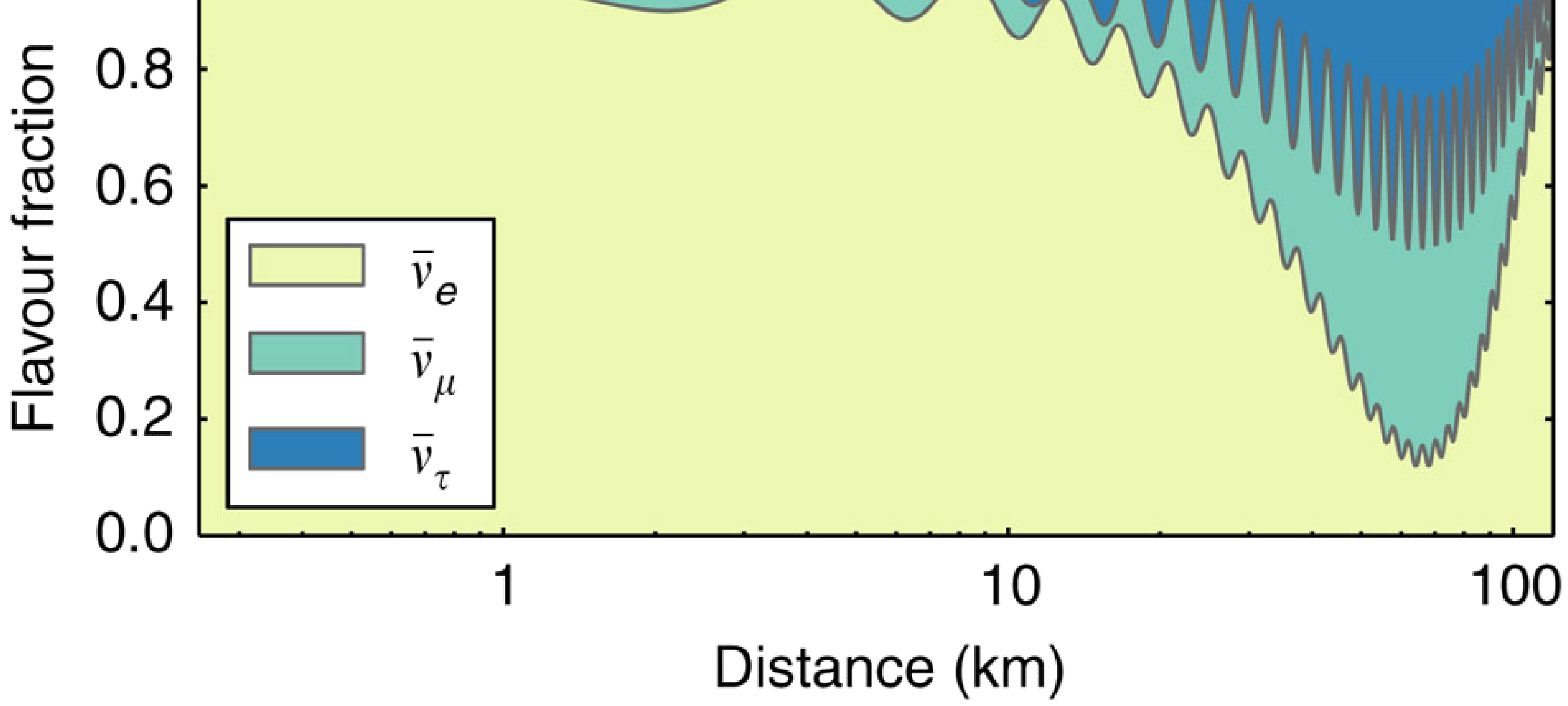
$$\sin^2 2\theta_{12} = 0.085 \,^{+0.005}_{-0.005}$$

$$\Delta m^2_{21} = (7.53 \pm 0.18) \cdot 10^{-5}\,\mathrm{eV}^2$$

$$|\Delta m^2_{23}| = (2.42 \pm 0.06) \cdot 10^{-3}\,\mathrm{eV}^2$$

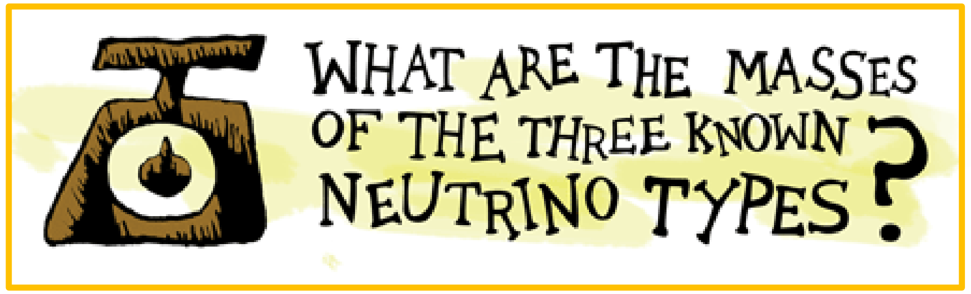


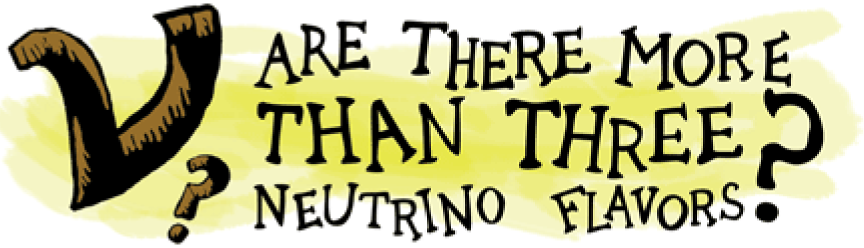
strong mixing

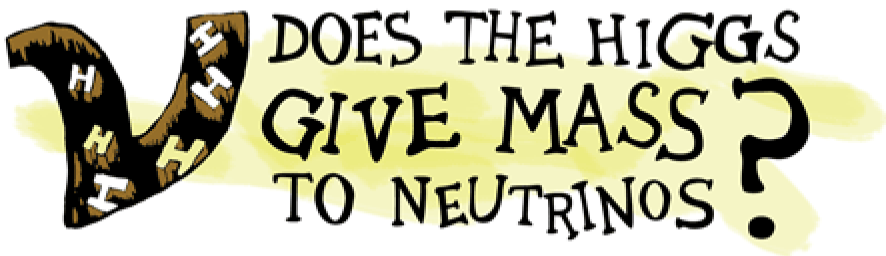


massive neutrinos: beyond the Standard Model

- neutrino oscillations imply **massive neutrinos**
- massive neutrinos imply **novel particles / processes**:
  - Lepton number violation?
  - new fundamental mass scale?
  - extended Higgs sector?
  - right handed (sterile) neutrinos?
- **open questions** in neutrino physics







neutrino mass – what is the correct pattern?

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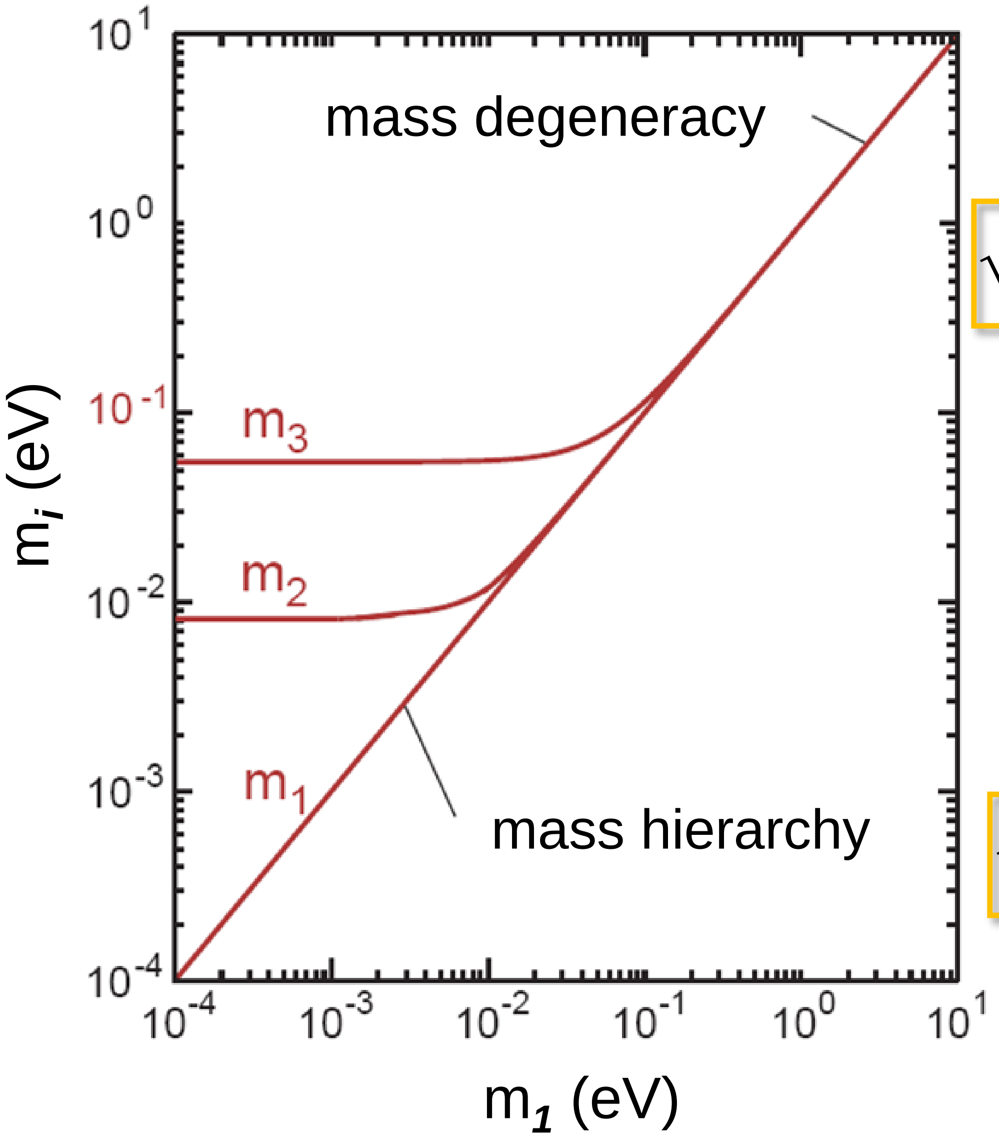
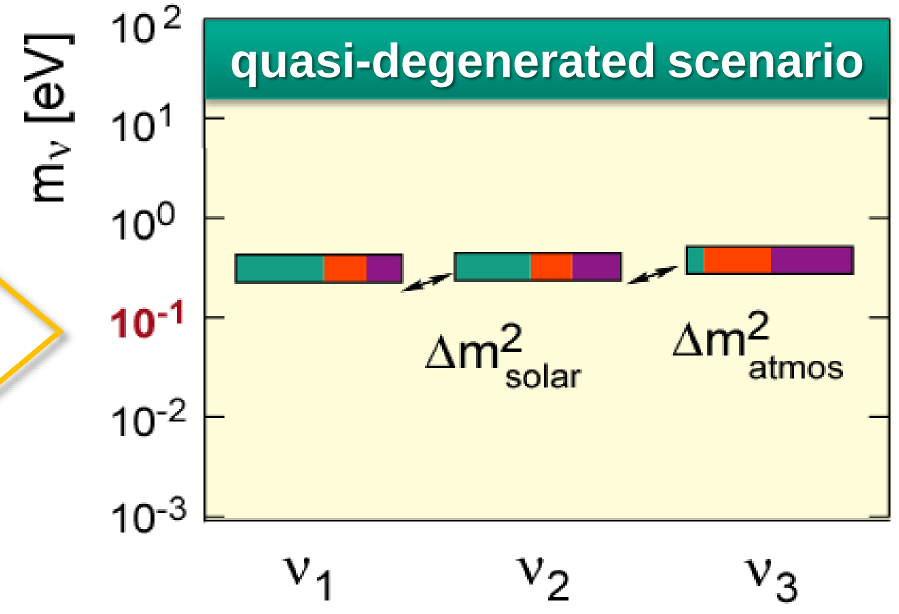
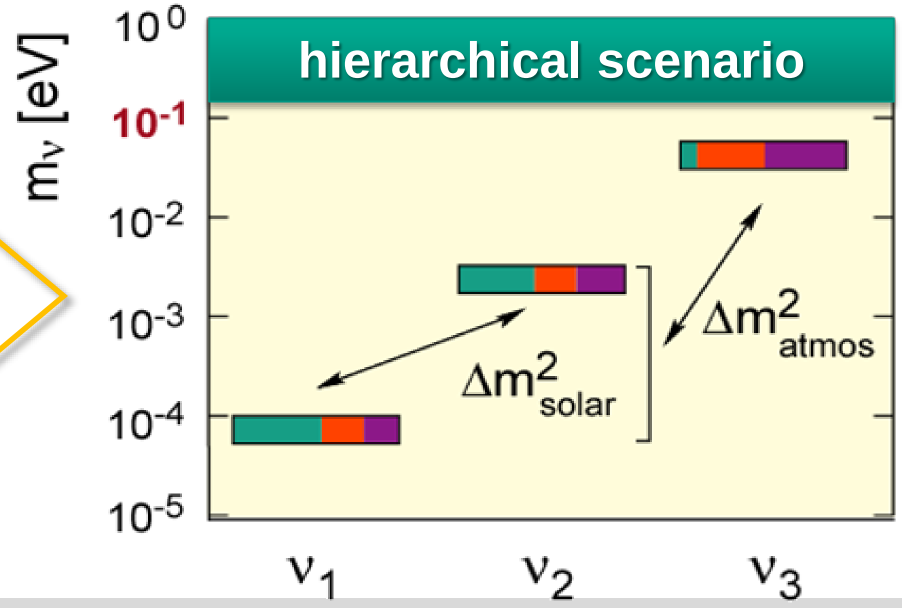
- **hierachy** – normal case: $m_1 < m_2 << m_3$, inverted case: $m_3 << m_{1,2}$
  quasi-degeneracy – $m_1 \sim m_2 \sim m_3$

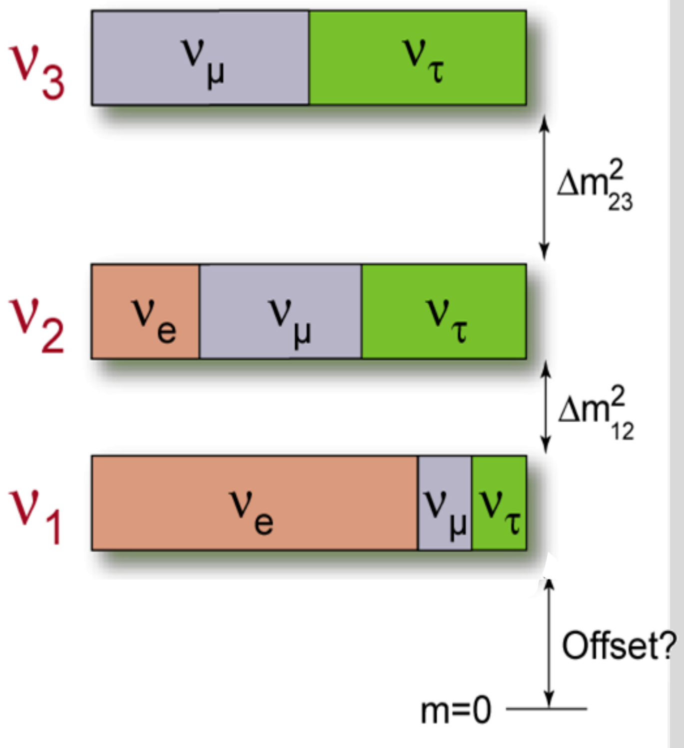


see-saw
$\sqrt{\Delta m^2} << m_i$
type II

see-saw
$\sqrt{\Delta m^2} \sim m_i$
type I





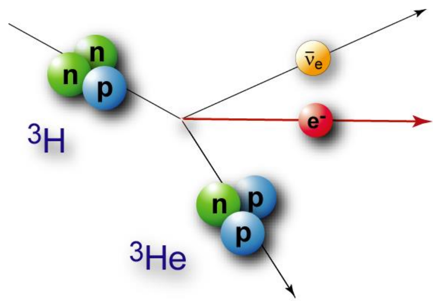


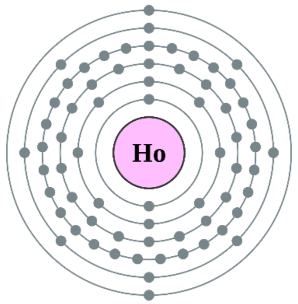
ß-spectroscopy and neutrino mass

neutrino mass: status and perspectives

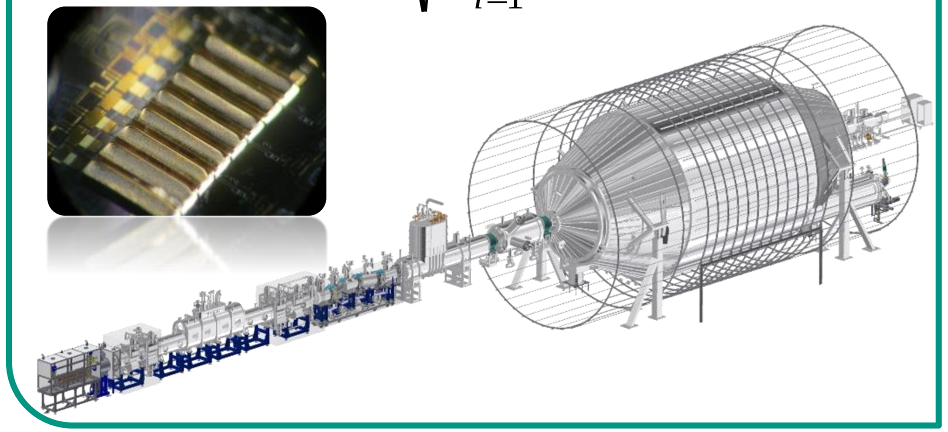
kinematics of weak decays

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



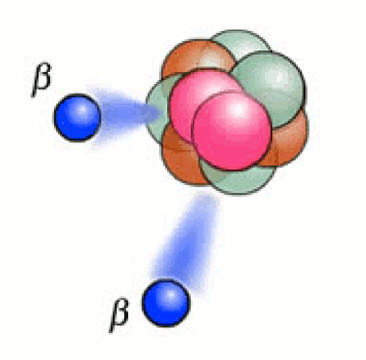


$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

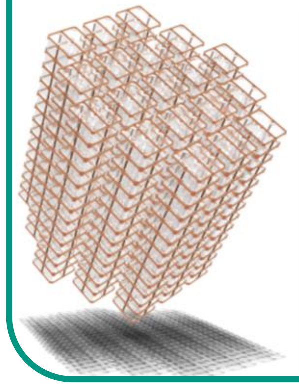


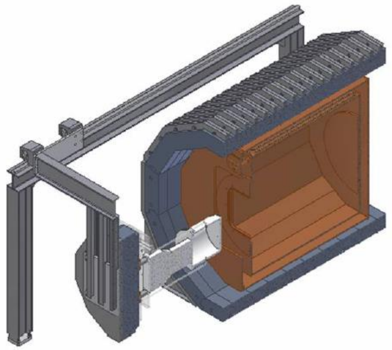
search for 0νßß-decay

- **ßß-decay**: ^{76}Ge, ^{130}Te, ^{136}Xe, …
- model-dependent (phases α_i)



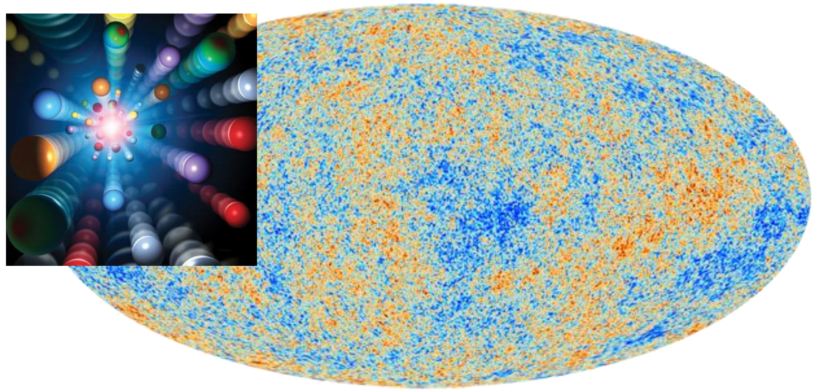
$$\langle m_{ßß} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$





cosmology

- **LSS**: CMB, GRS, WL,…
- model-dependent (w⇔H_0)



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

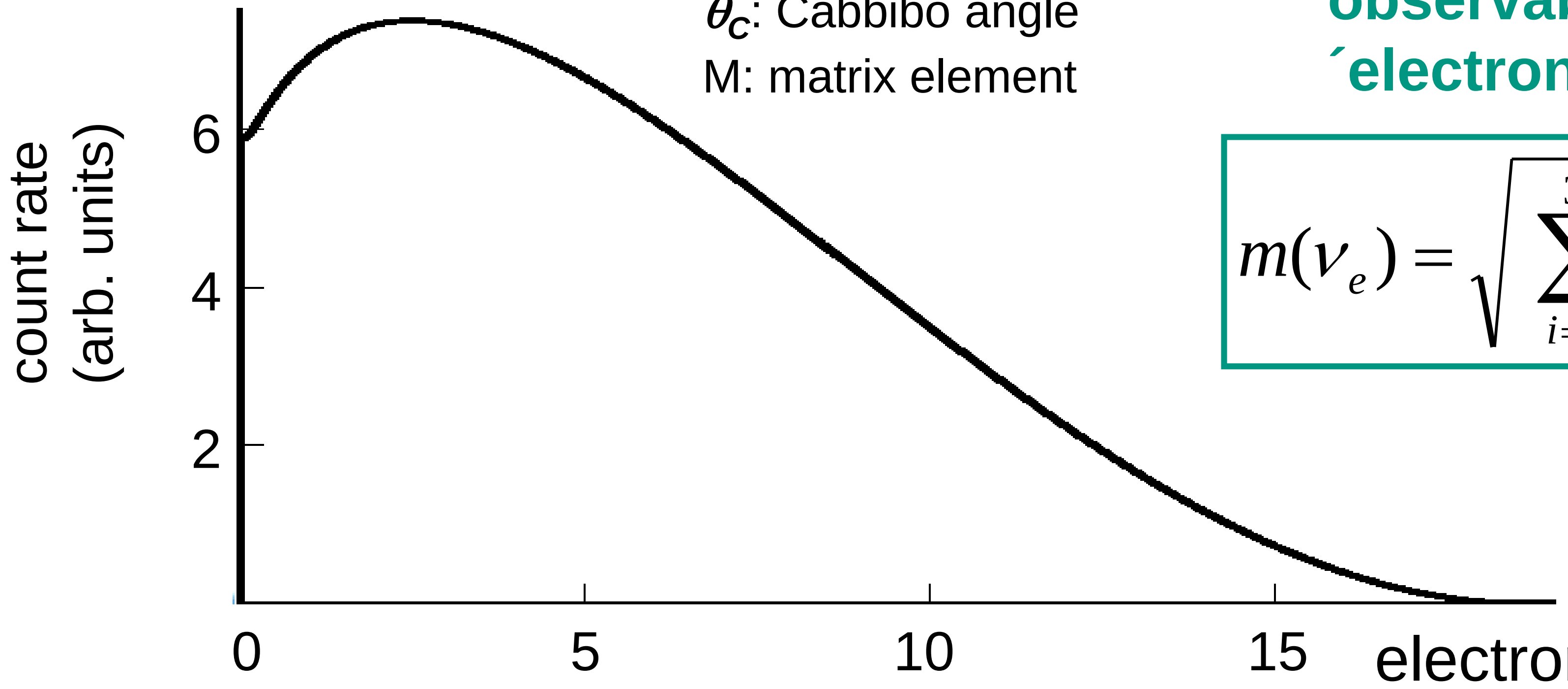
ß-decay: kinematics

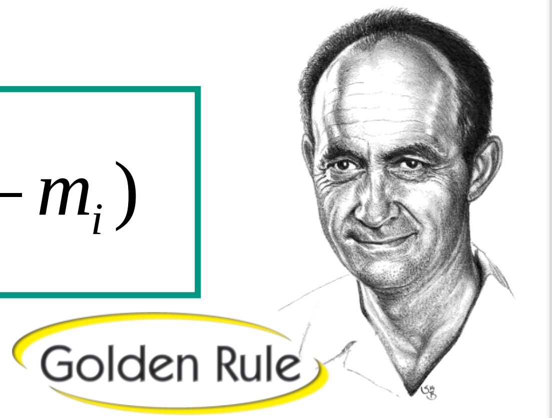
- model independent measurement of m(ν_e), based solely on **kinematic parameters & energy conservation**

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

$$G_F^2 \cdot \frac{m_e^5}{2\pi^3} \cdot \cos^2\theta_C \cdot |M|^2$$

θ_C: Cabbibo angle
M: matrix element





Enrico Fermi

observable m²(ν_e): ´electron-ν-mass´

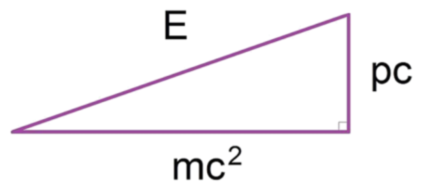
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

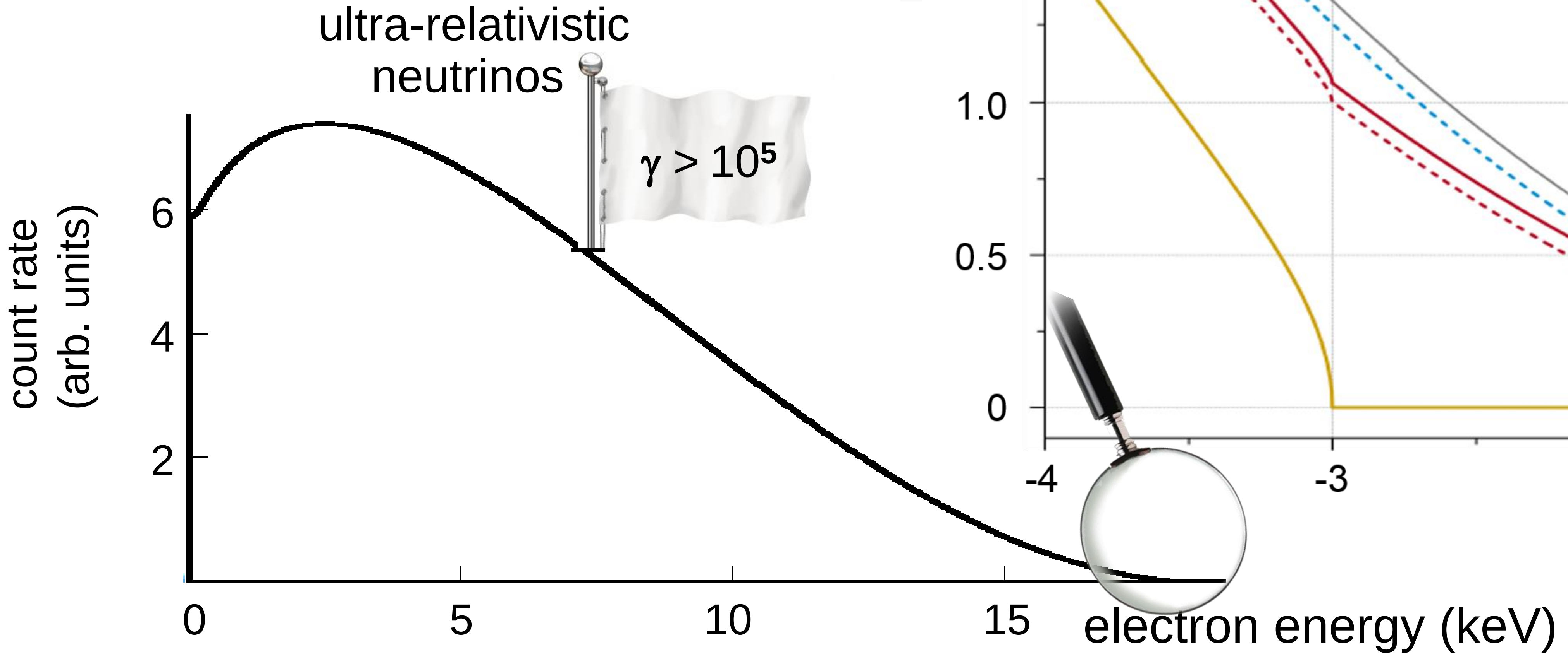
´incoherent´ sum of the mass eigenstates m_i

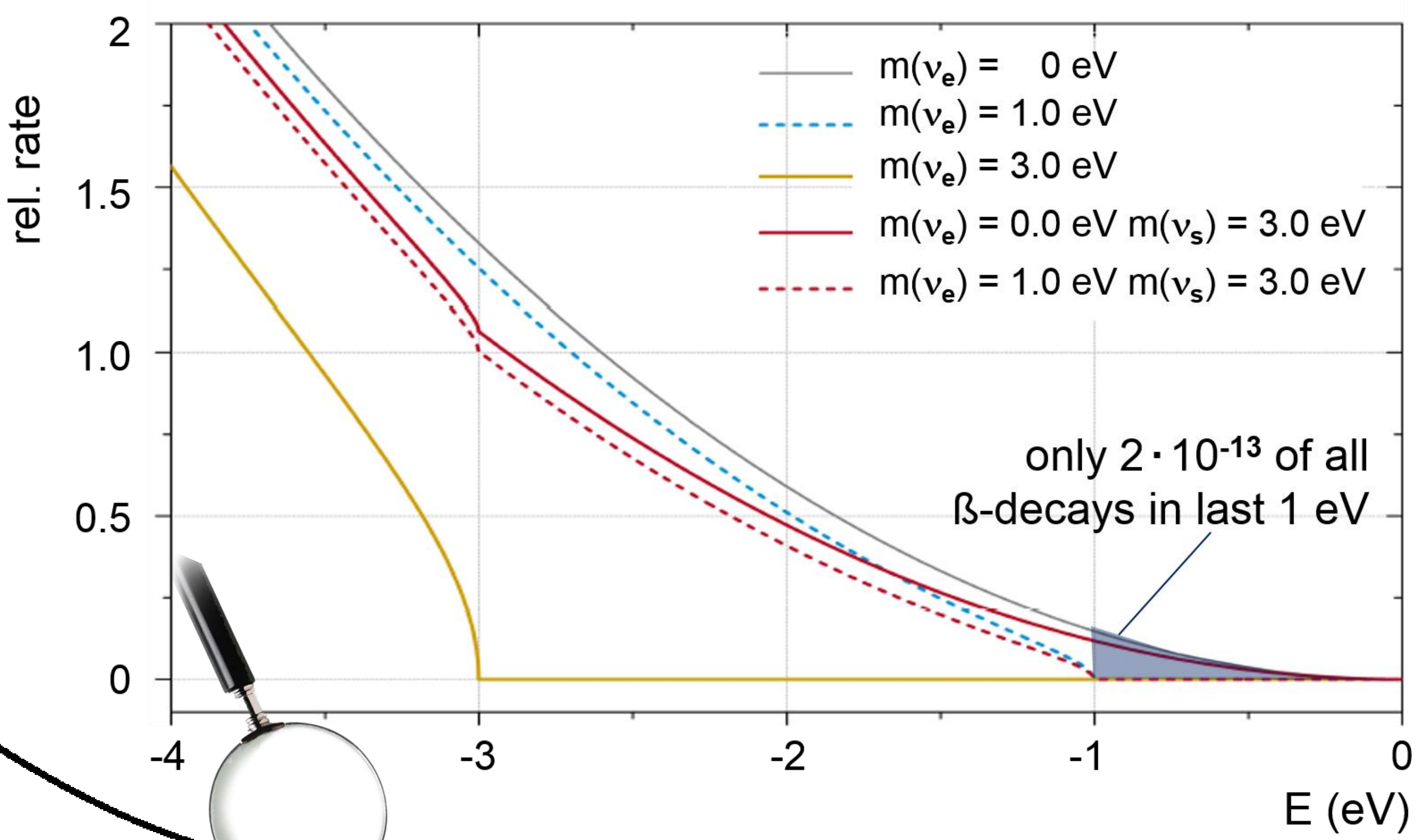
mass splittings Δm^2_{ij} cannot be observed as $\Delta E >> \sqrt{\Delta m^2_{ij}}$

ß-decay: kinematics

- neutrino mass manifests itself only close to endpoint at E_0, as neutrinos there are only „mildly relativistic“ [$E^2 = p^2c^2 + (mc^2)^2$]







KATRIN: measurement principle & challenges

MAC-E principle: high-intensity tritium ß-spectroscopy

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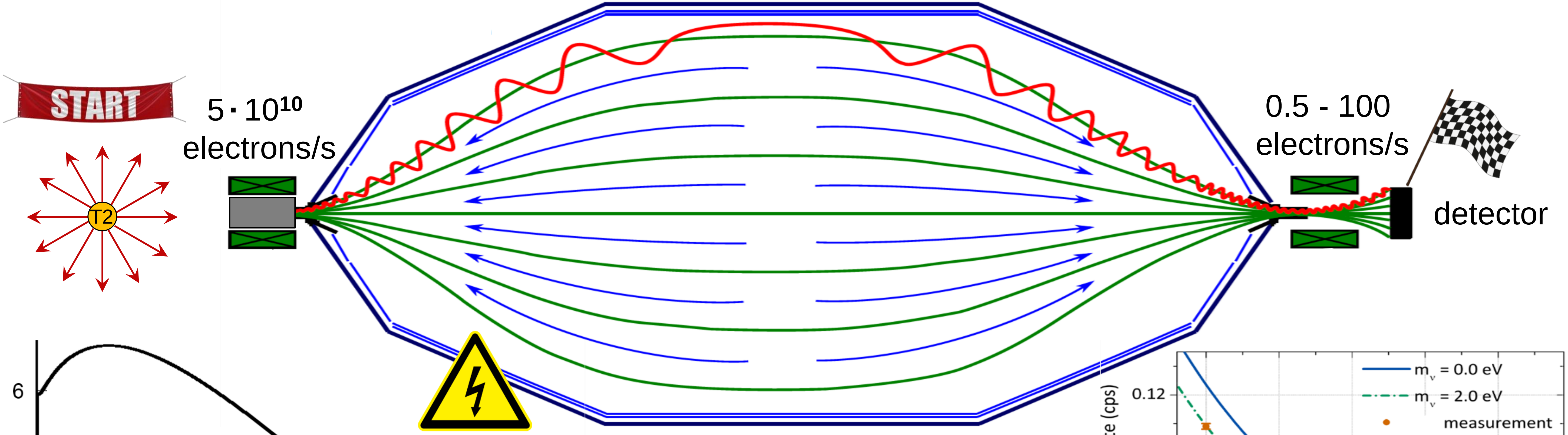
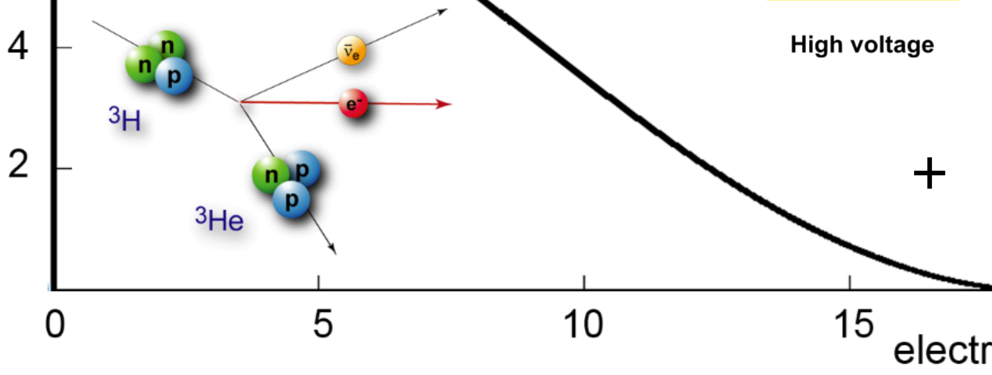
- **Magnetic Adiabatic Collimation & Electrostatic Filter:** scan high-intensity T2 source





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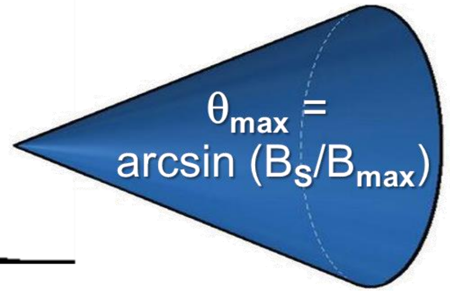
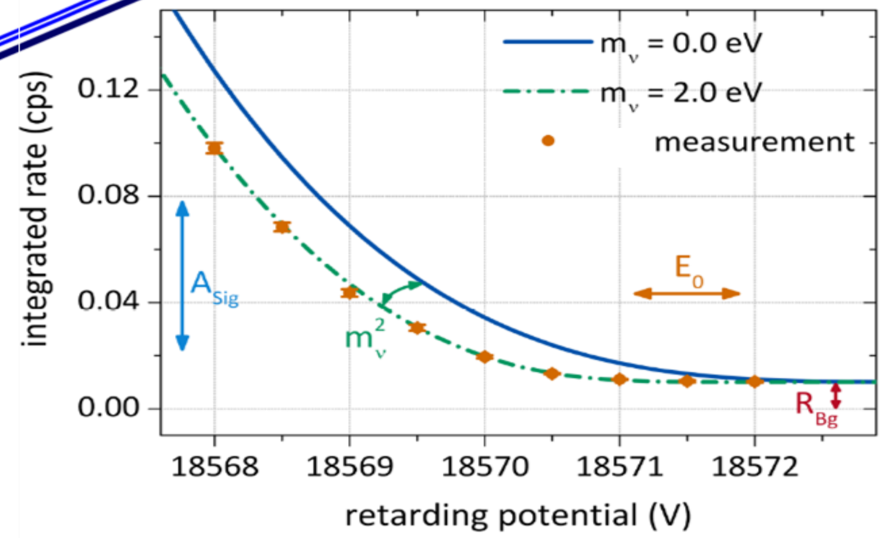
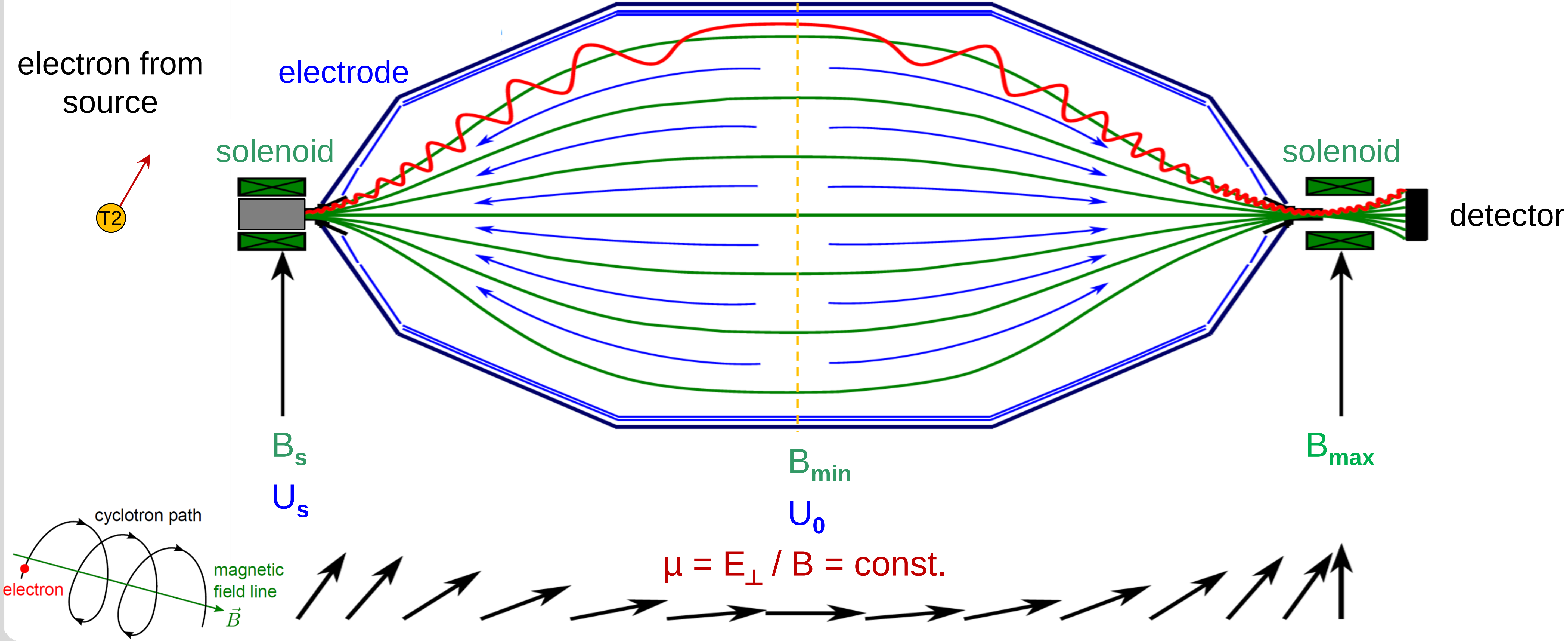


large acceptance angle ⇨



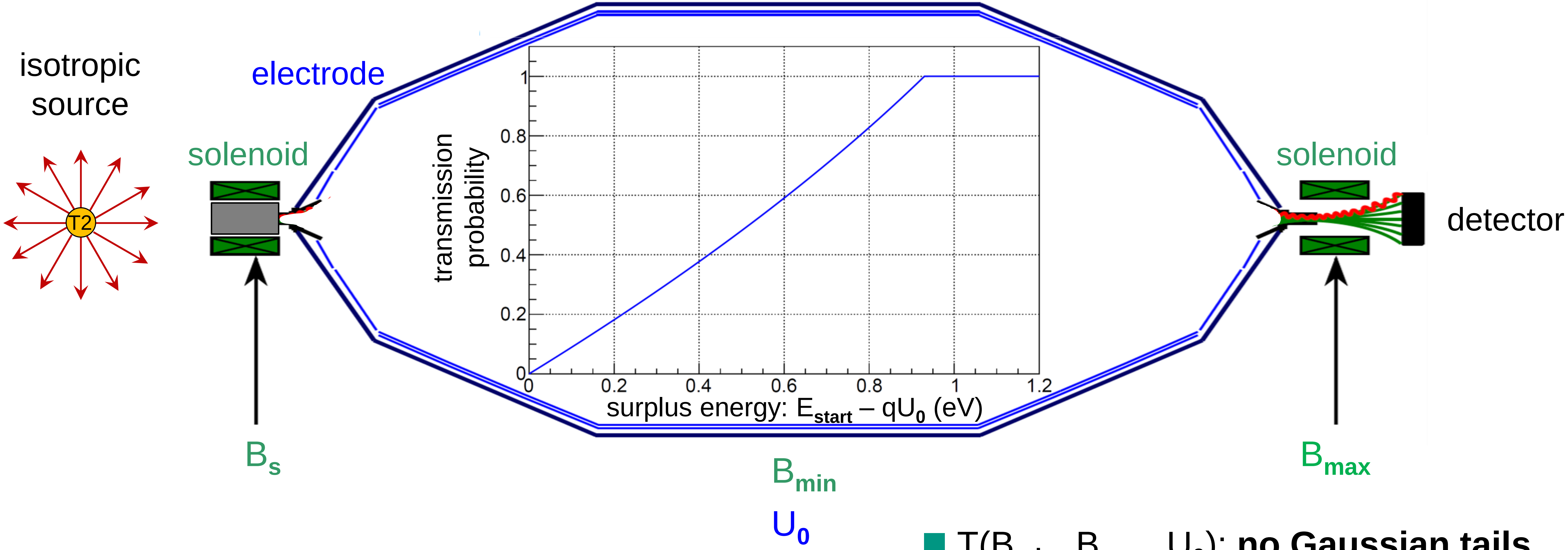
MAC-E principle: high-resolution tritium ß-spectroscopy

- **M**agnetic **A**diabatic **C**ollimation **& E**lectrostatic **Filter:** adiabatic conversion $E_\perp \rightarrow E_\parallel$



MAC-E principle: high-resolution tritium ß-spectroscopy

- **Magnetic Adiabatic Collimation & Electrostatic Filter:** *analytic* transmission function T



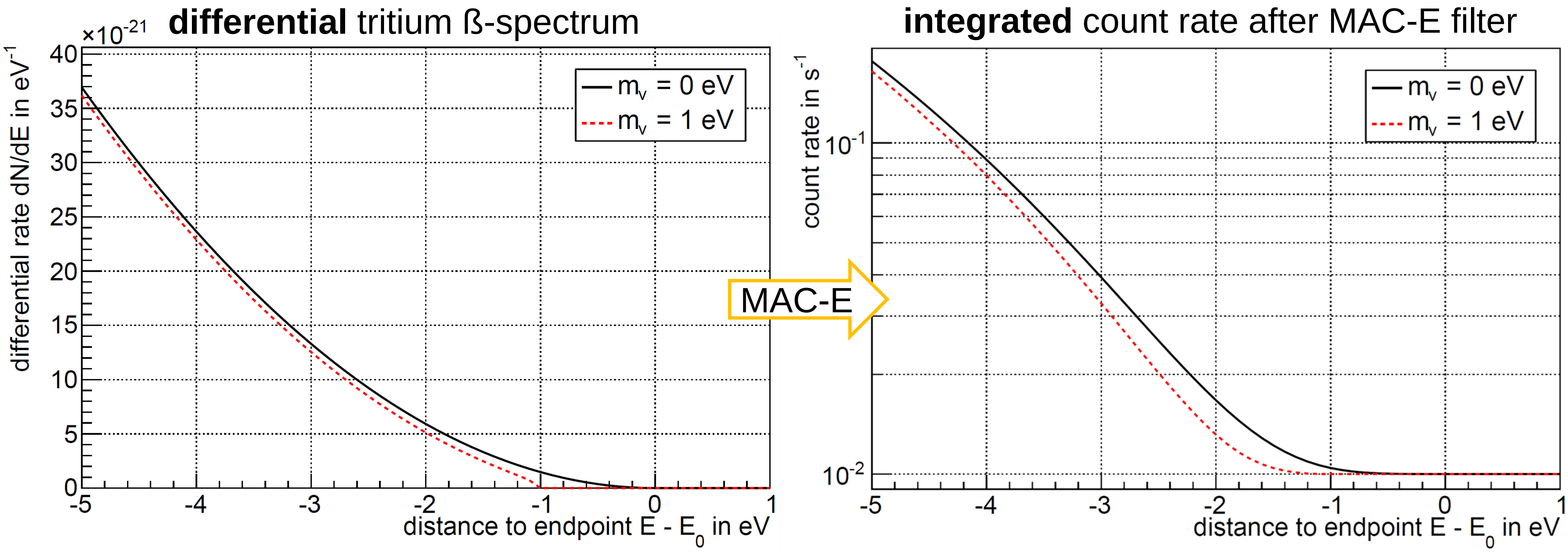
$\Delta E / E = B_{min} / B_{max}$ ⇨ $\Delta E = 0.93$ eV

3×10^{-4} T / 6 T @18.6 keV

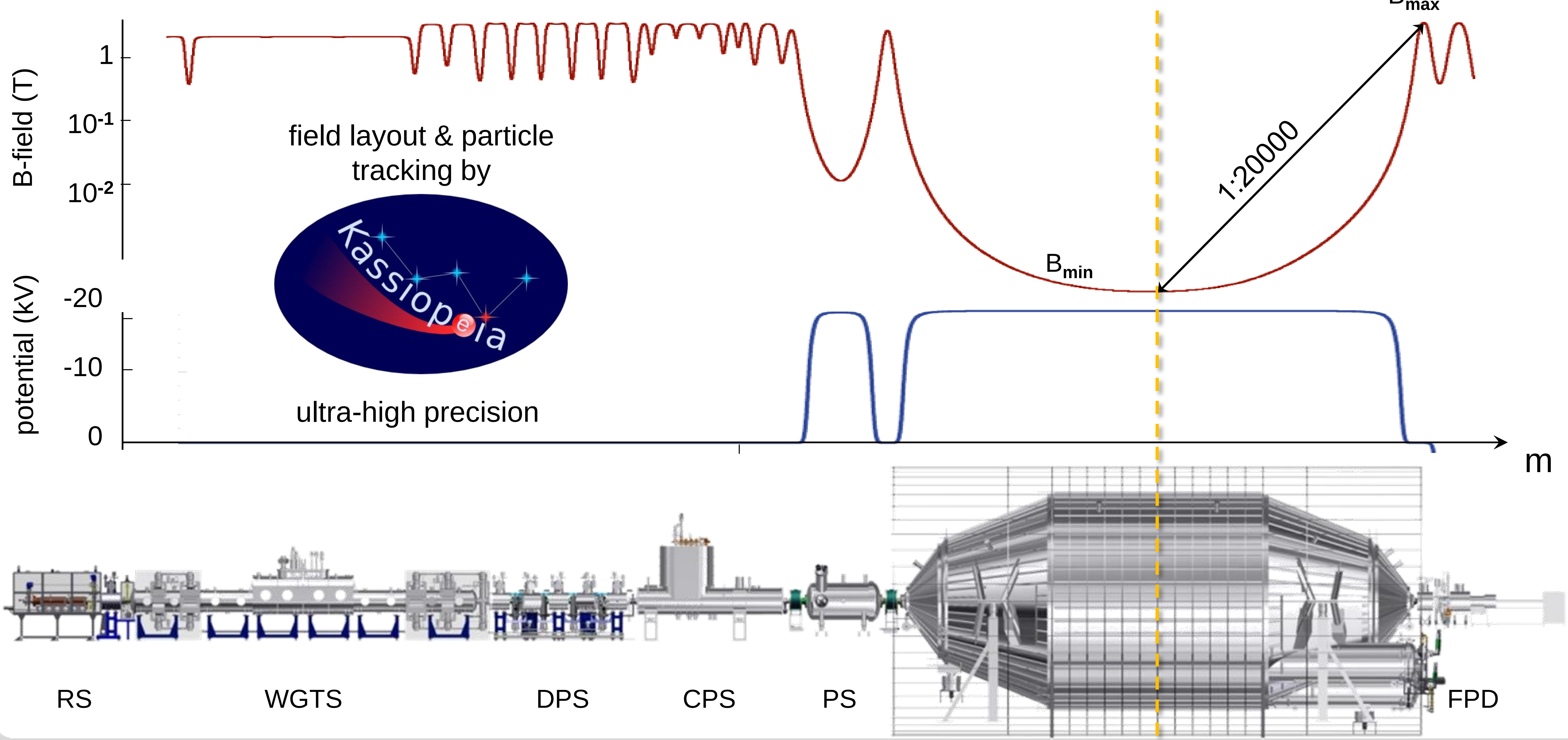
- $T(B_{min}, B_{max}, U_0)$: **no Gaussian tails**
  but: U_0 on ppm-scale for sub-eV $m(\nu_e)$!

MAC-E principle: integrated ß-spectrum close to E0

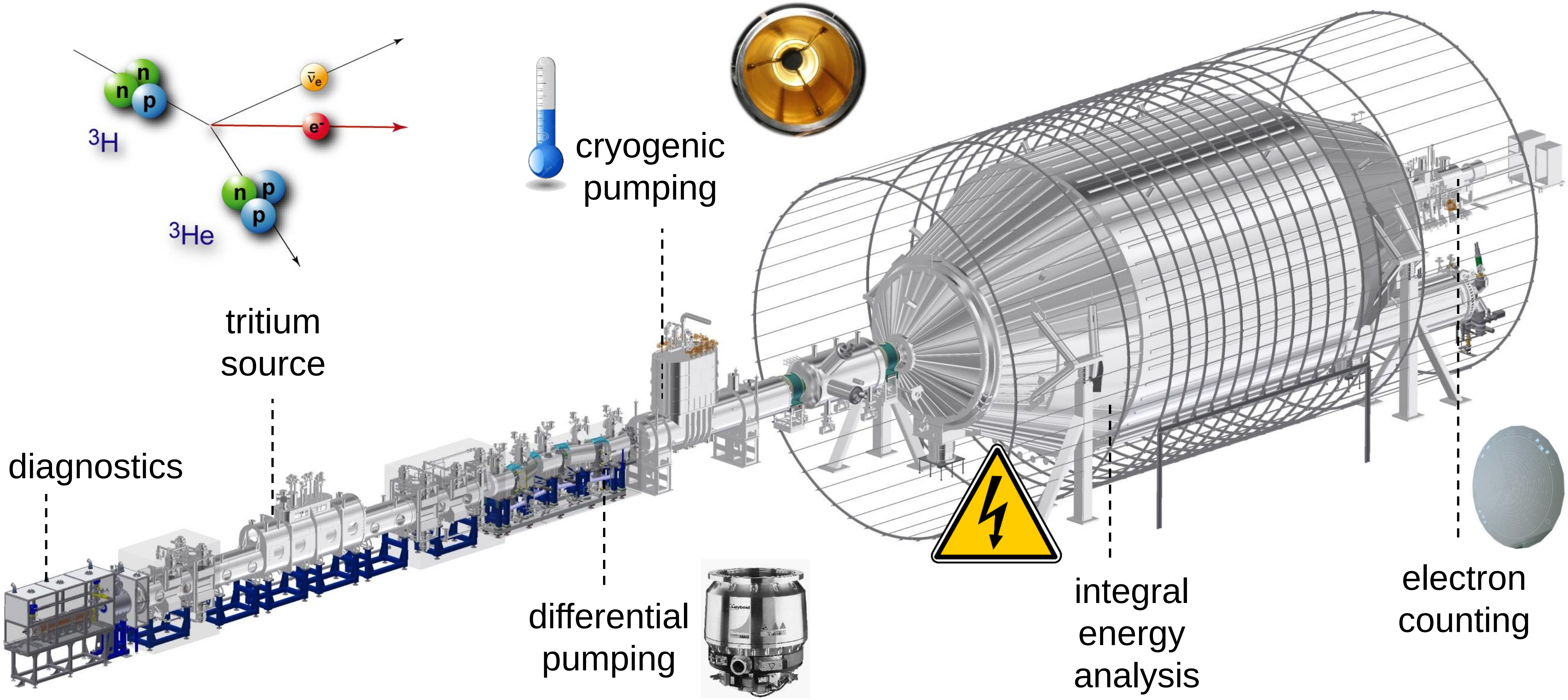
- **MAC-E filter**: count all ß-decay electrons with E > U_0 in focal plane detector
  - requires excellent source stability (and diagnostics), **R&D on differential read-out ongoing**



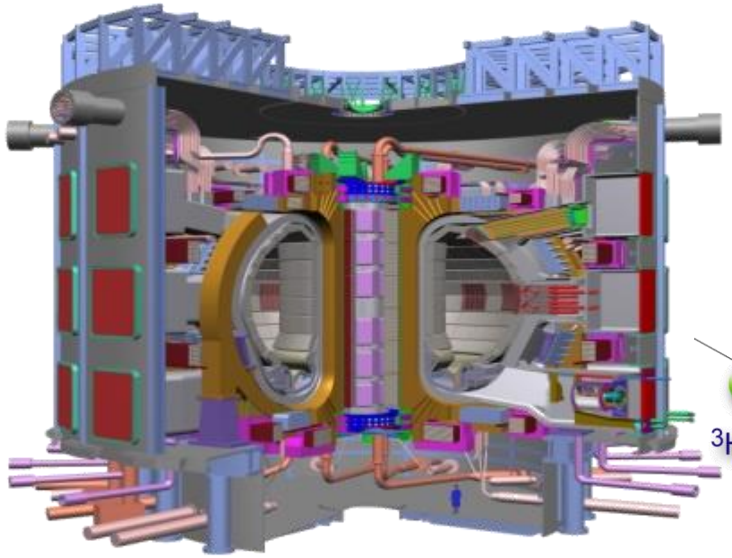
MAC-E principle: B and U_0 from source to detector



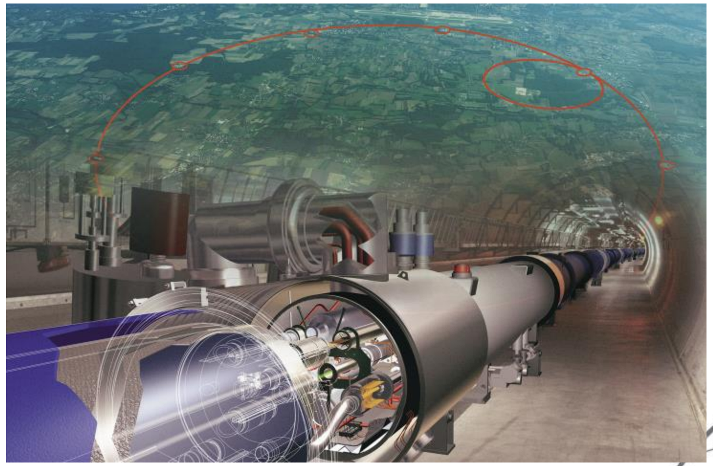
KATRIN overview: 70 m long beamline



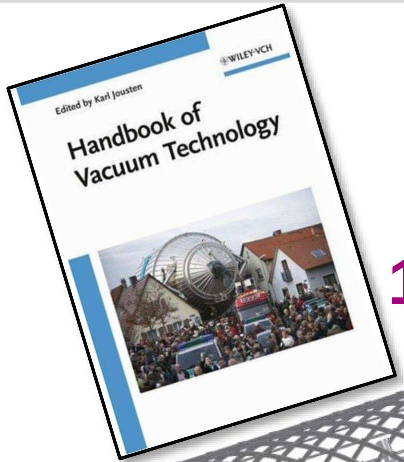
KATRIN overview: challenges-I



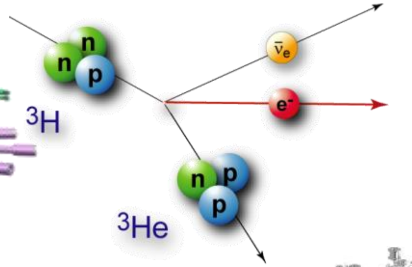
ITER
(>2030)

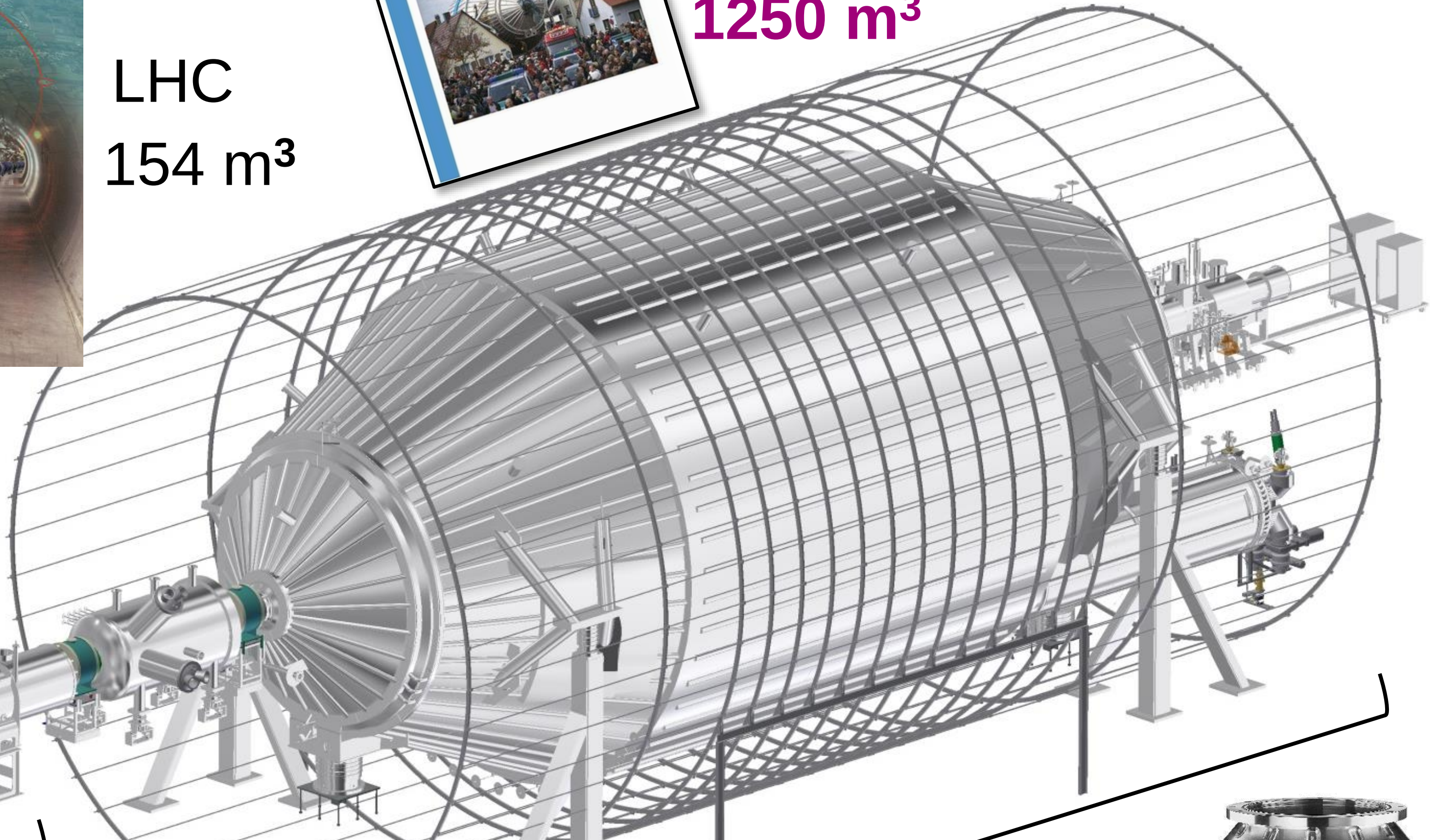


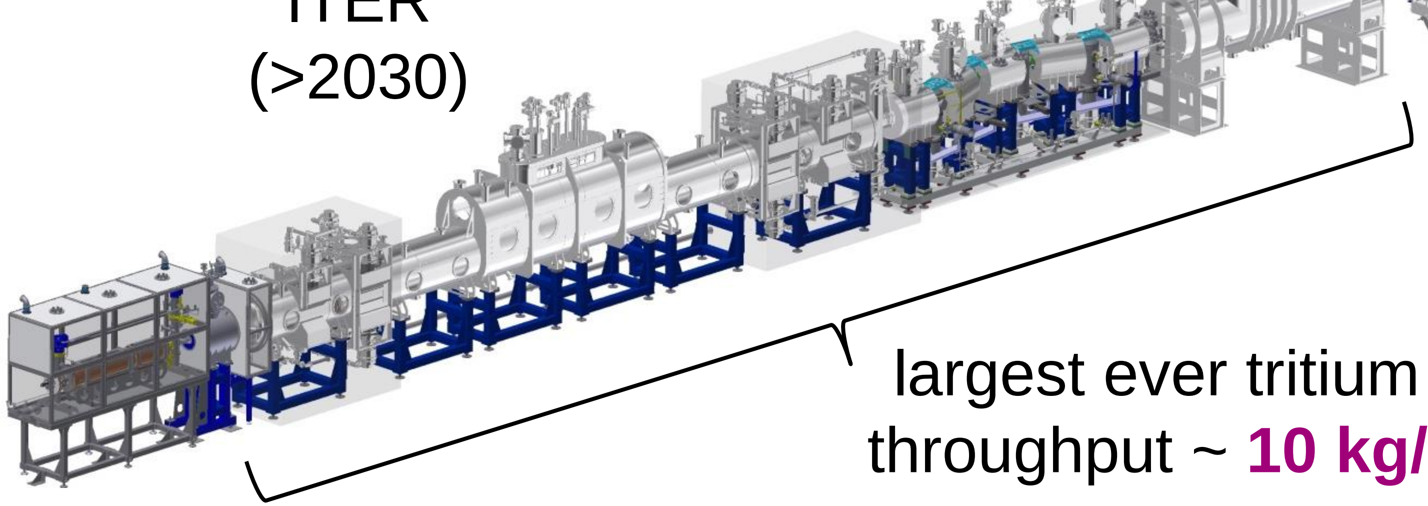
LHC
154 m³



1250 m³



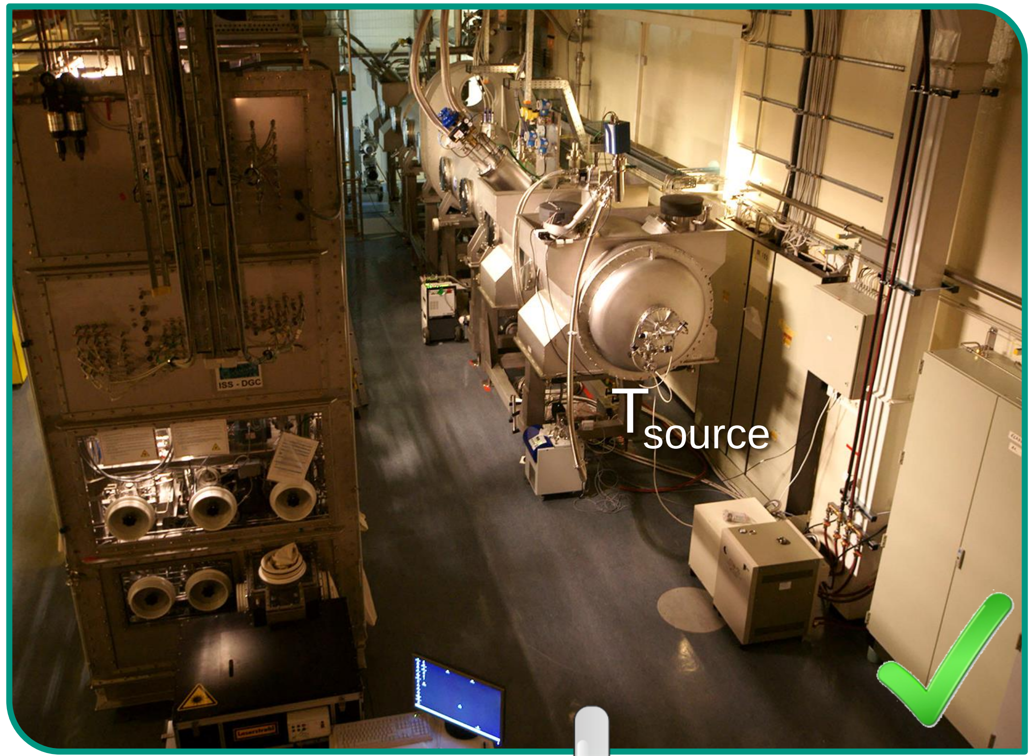


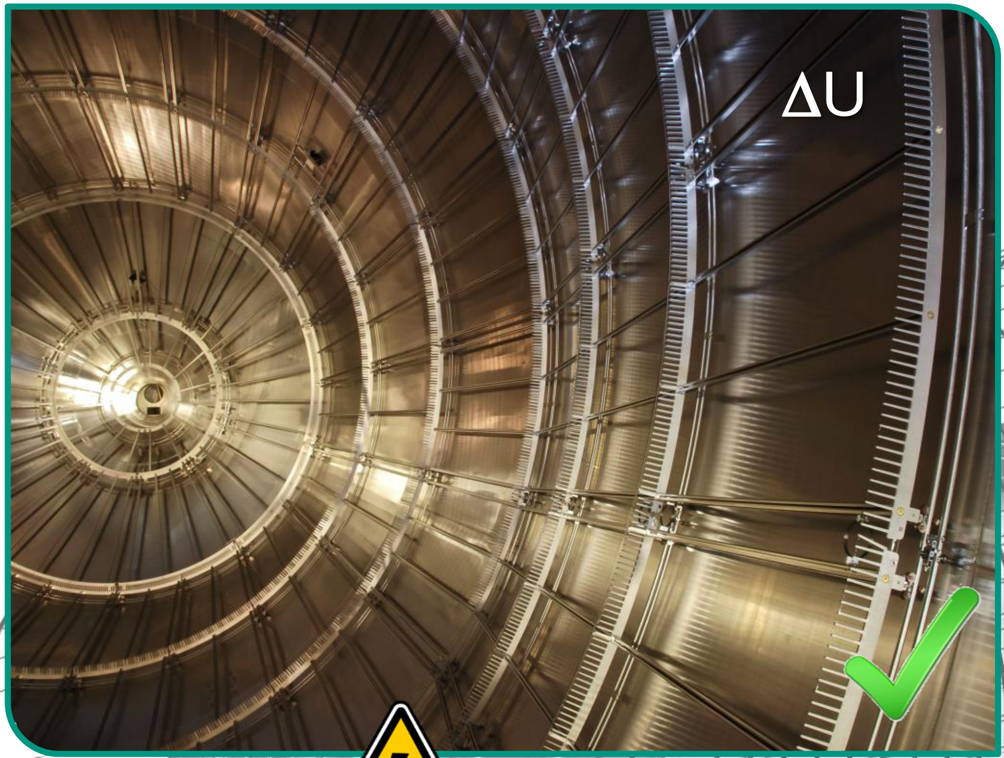


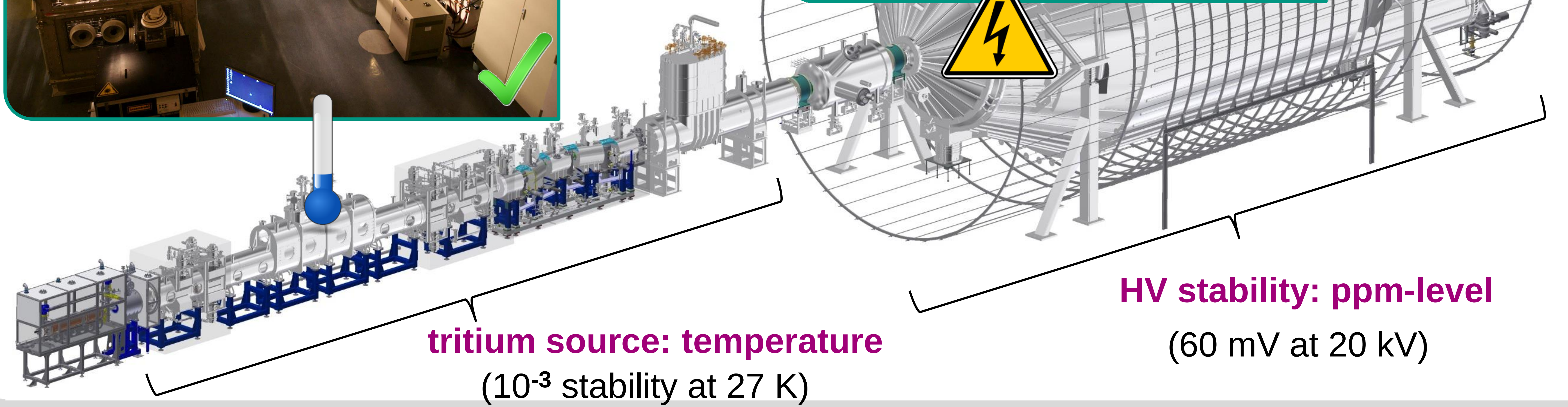
largest ever tritium throughput ~ **10 kg/a**

largest ever UHV recipient (<10⁻¹¹ mbar)

KATRIN overview: challenges-II







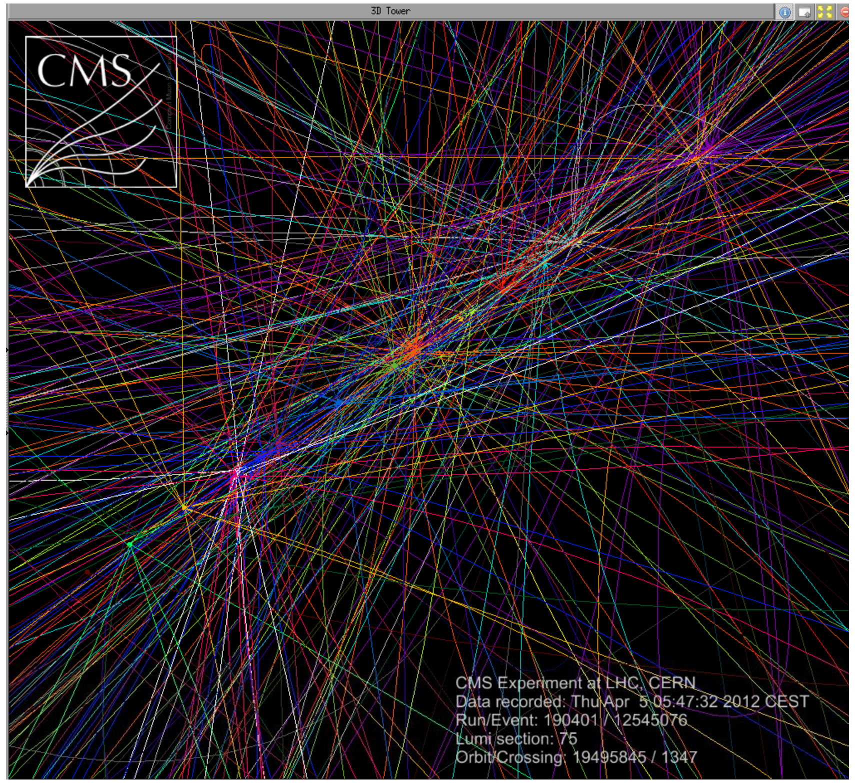
HV stability: ppm-level

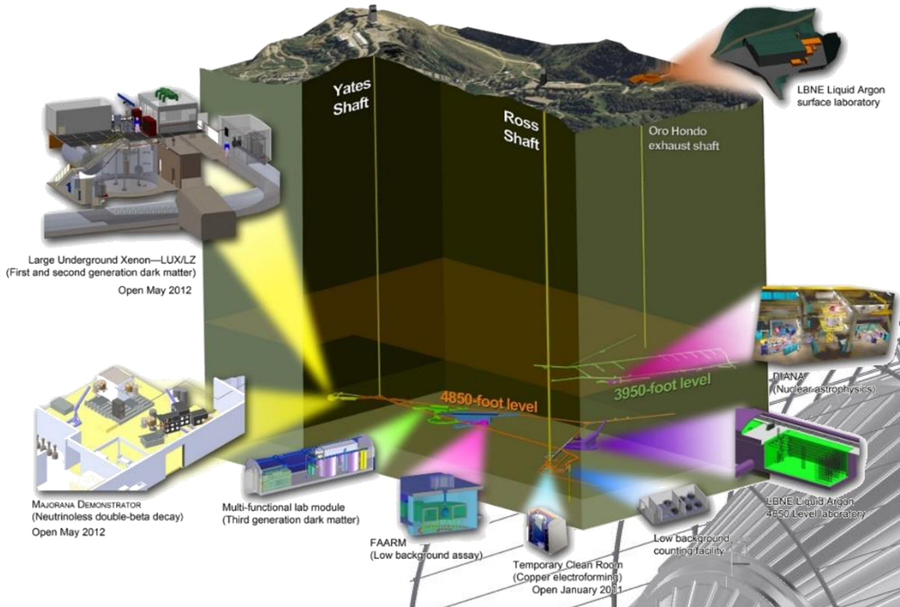
(60 mV at 20 kV)

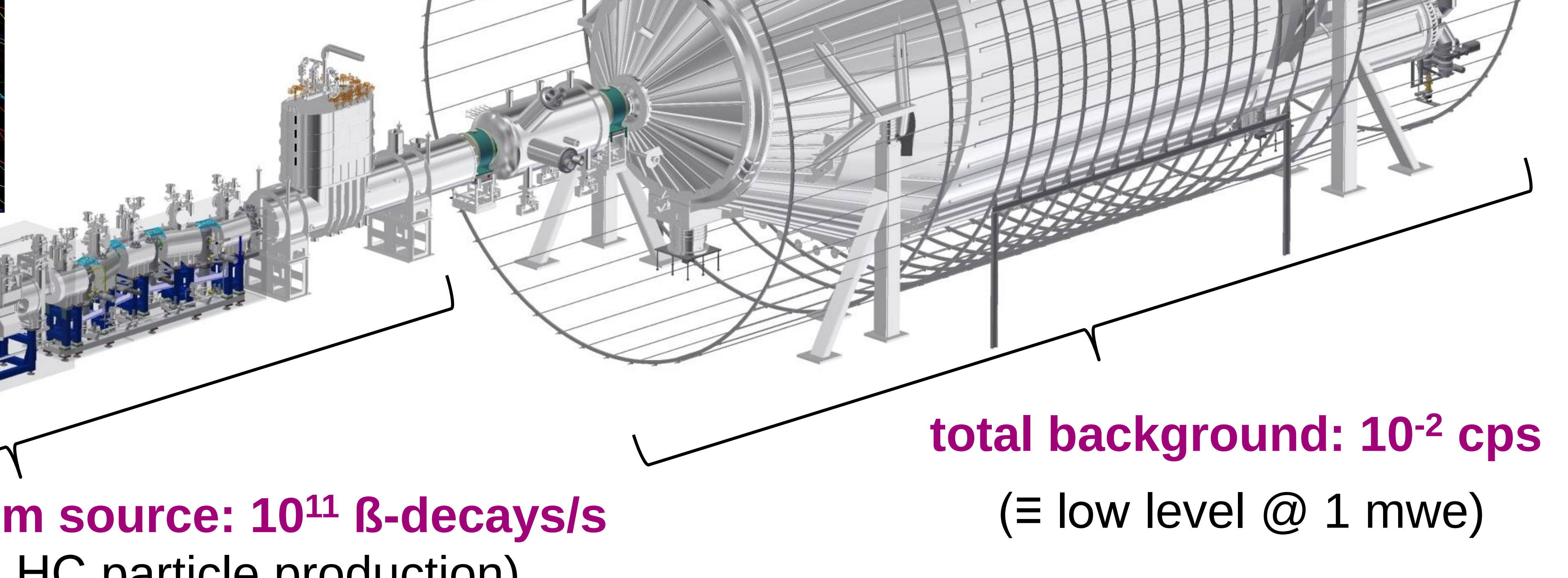
tritium source: temperature

(10^{-3} stability at 27 K)

KATRIN overview: challenges-III







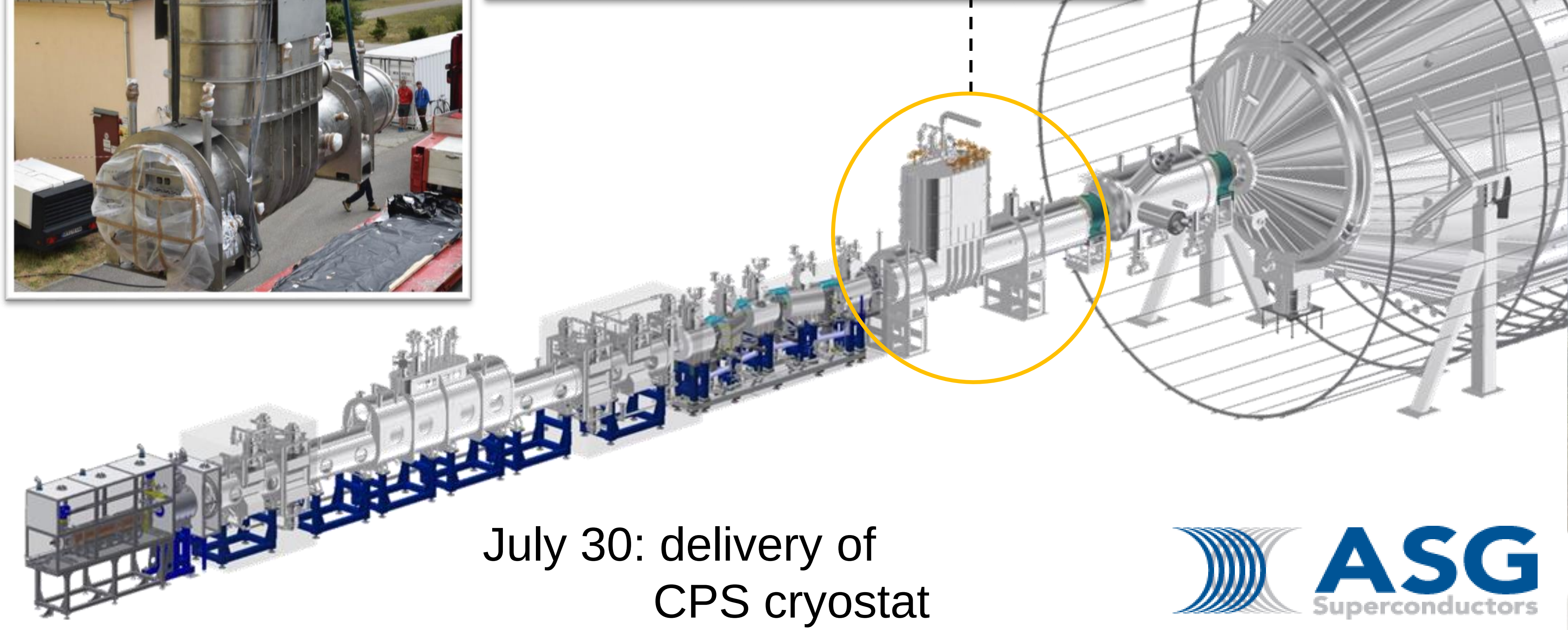
total background: 10^{-2} cps

(≡ low level @ 1 mwe)

tritium source: 10^{11} ß-decays/s

(≡ LHC particle production)

Project milestones 2015 - CPS



July 30: delivery of
CPS cryostat

ASG Superconductors

Project milestones 2015 - WGTS

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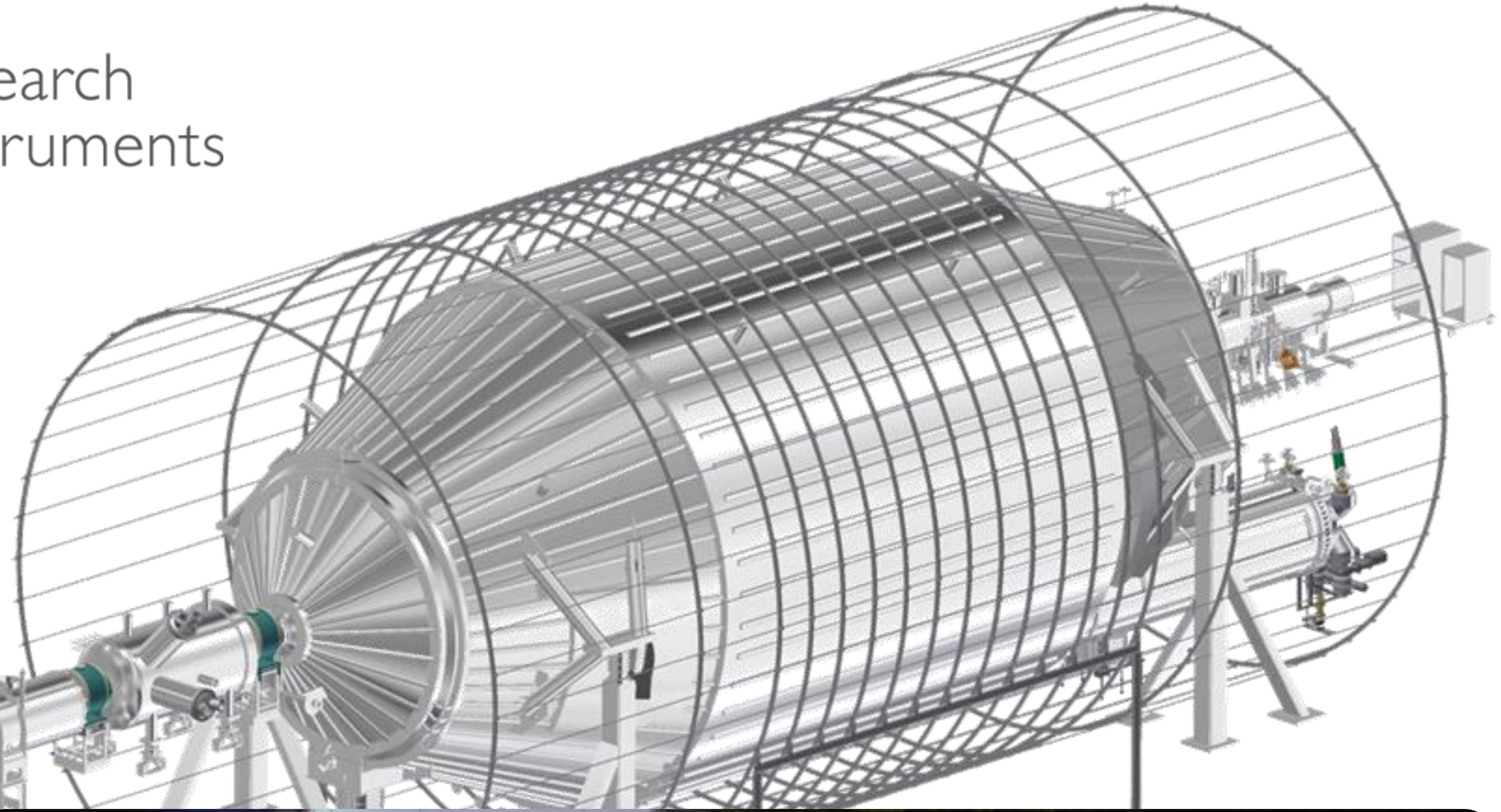
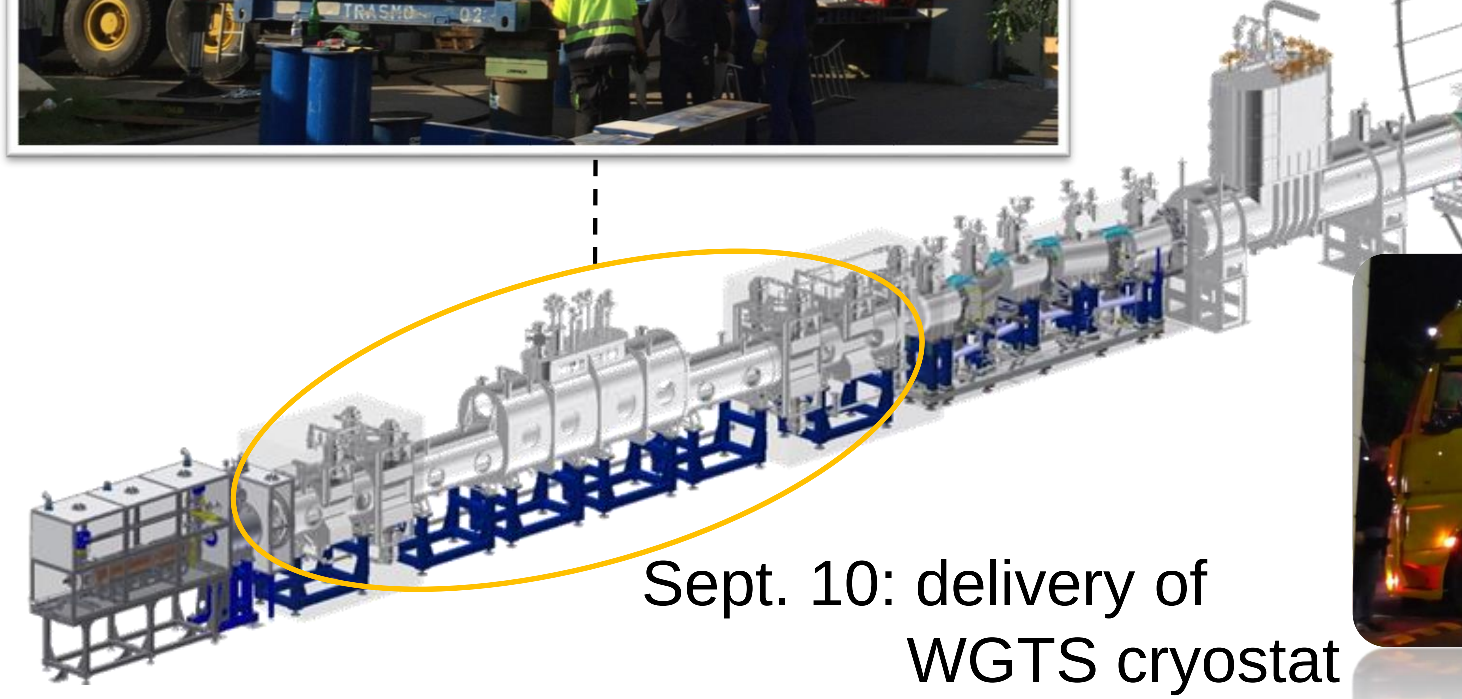
research instruments

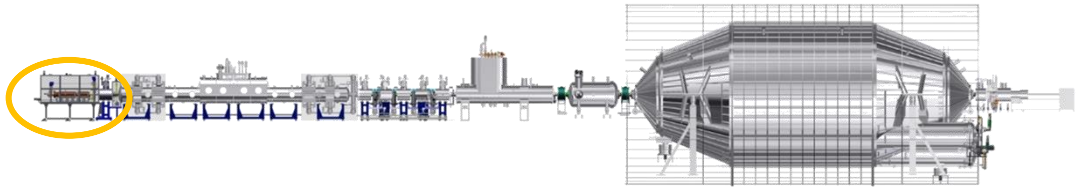




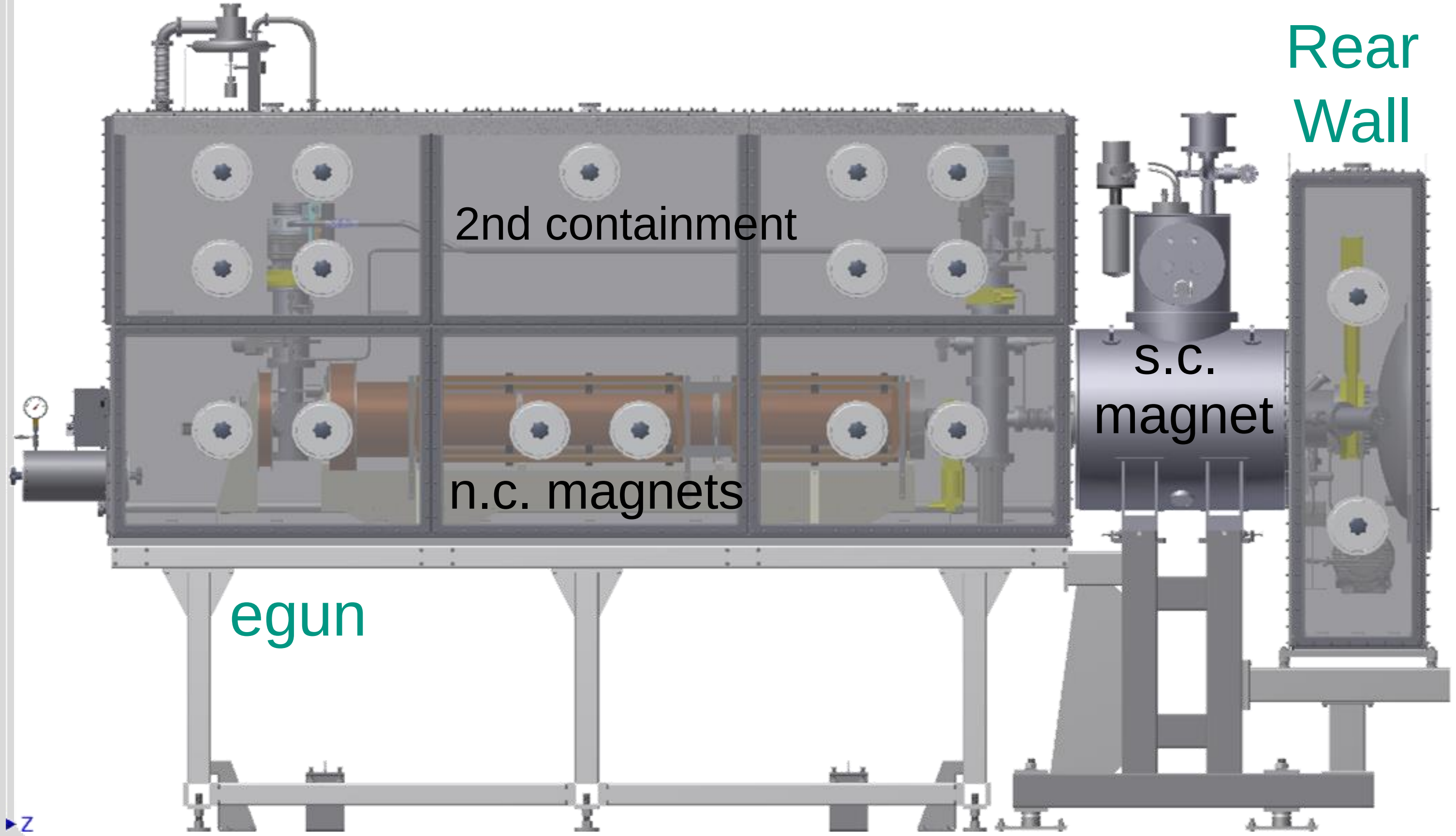
Sept. 10: delivery of WGTS cryostat

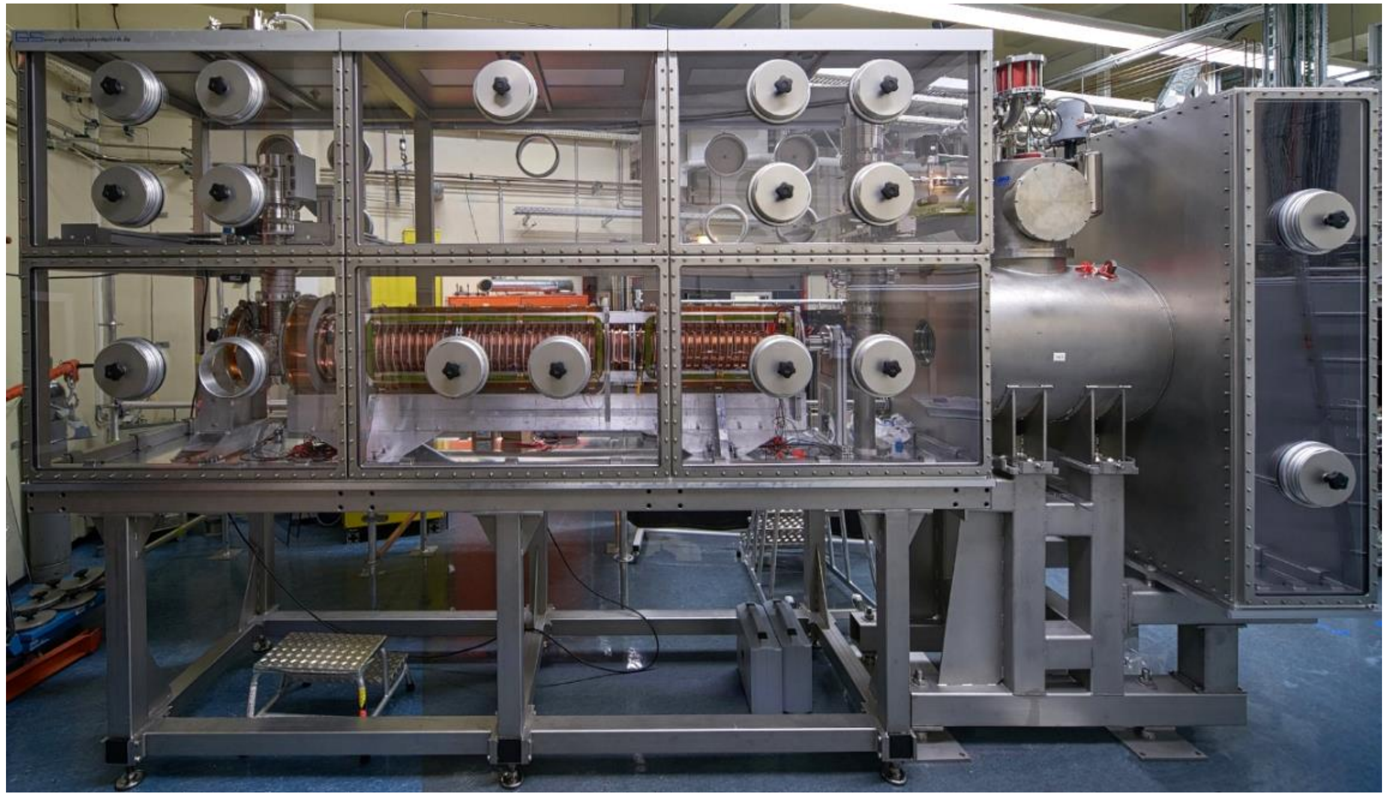
KATRIN: main components

Rear Section for diagnostics

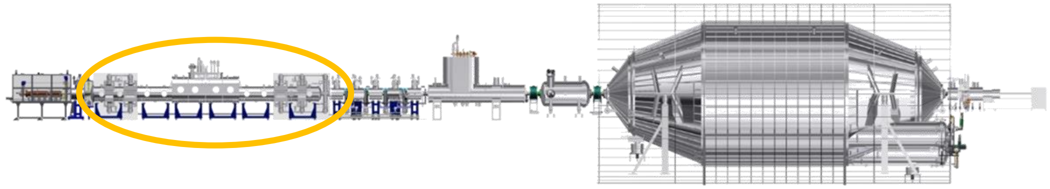


- **Rear Section:** an indispensible tool for diagnostics of source & spectrometer
  - **angular selective photoelectron gun**: spectrometer transmission & energy losses in source
  - **Rear Wall**: definition of source potential, neutralization of cold WGTS tritium plasma, online monitoring of tritium ß-decay activity via X-rays (BIXS)





WGTS – source cryostat



Windowless **G**aseous **T**ritium **S**ource cryostat

WGTS – source cryostat

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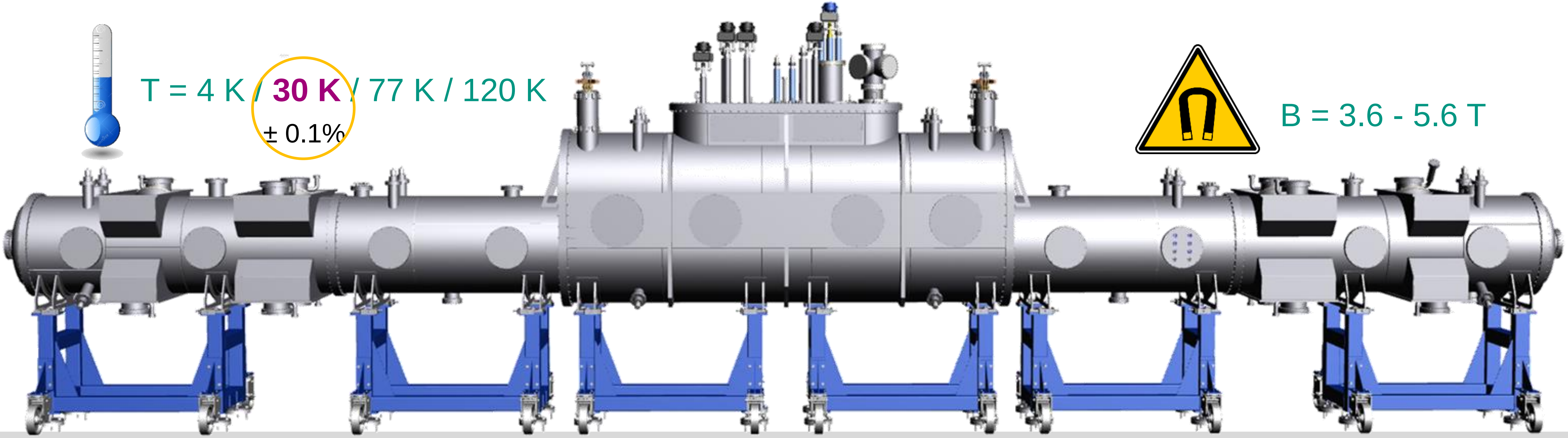
- **complex tritium source cryostat**: 16 m length, 27 t total weight, ~ 40.000 pieces
  - 7 s.c. solenoids for adiabatic guiding of ß-decay electrons (3.6 – 5.6 T)
  - 7 cryogenic fluids for tritium operation (BT: 30-120K) & liquid He bath for magnets (4 K)
  - tritium beam tube @30K with stability and homogeneity of 0.1%
  - extensive instrumentations: >800 sensors (B, T, p, level, flow, …)



source-related challenges - overview

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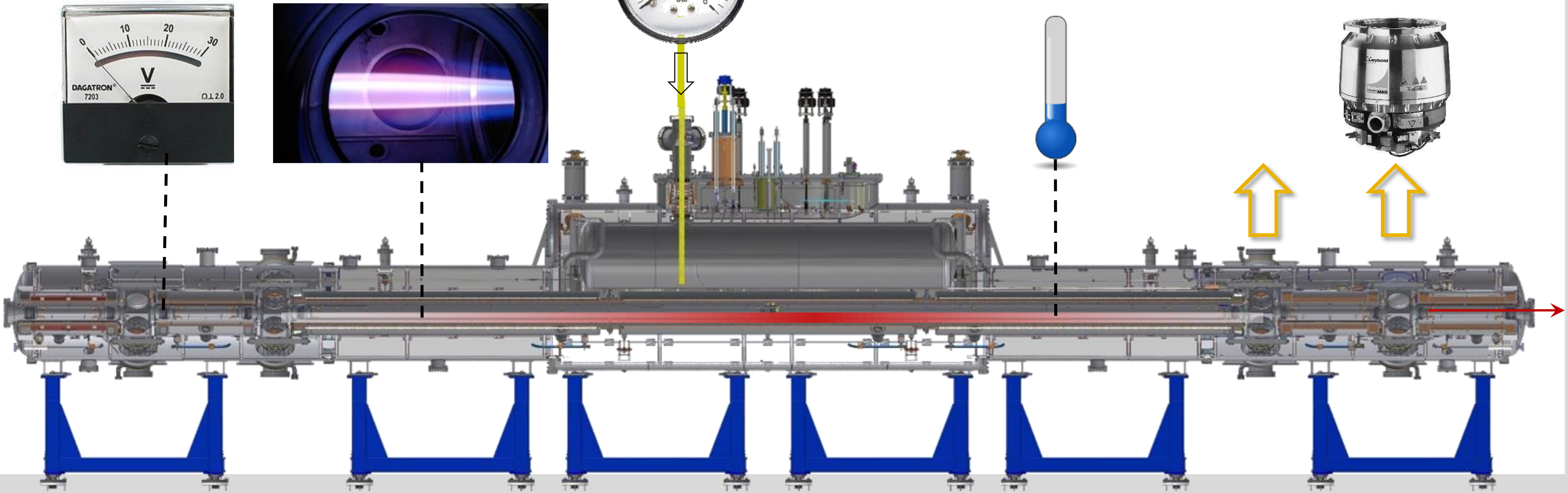
① injection pressure (± 0.1%)
② isotopic content (0.1% in < 60 s)
(also: add ^{83m}Kr)

④ source potential (mV-scale)

⑤ plasma properties (10^{11} T-ions/s)

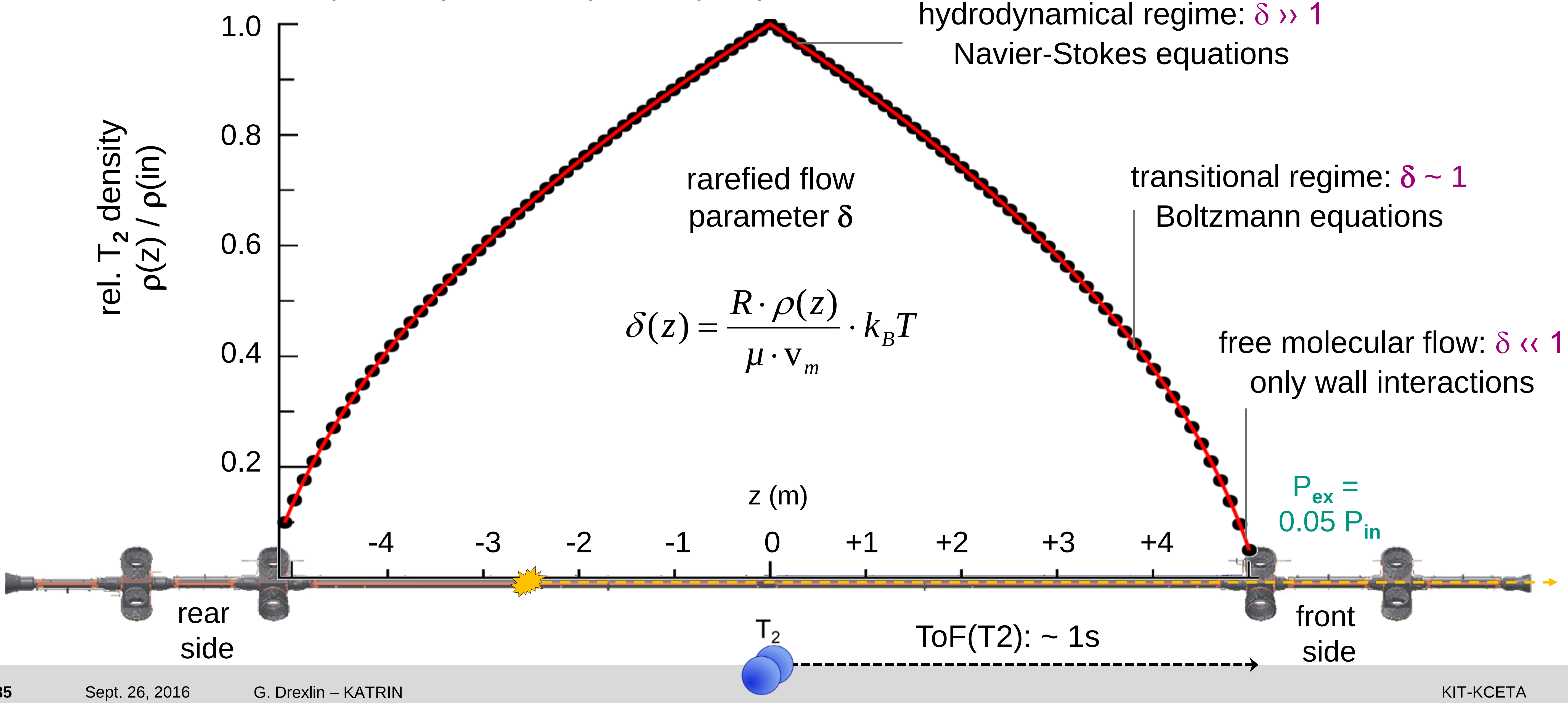
③ beamtube temperature (27-125 K)

⑥ tritium retention (12 TMPs)

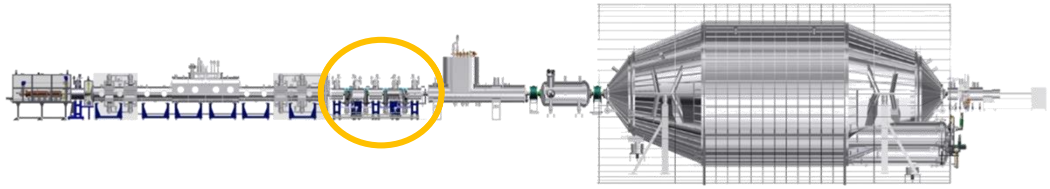


source challenges: injection & gas flow calculation

① injection pressure (± 0.1%): 3 µbar

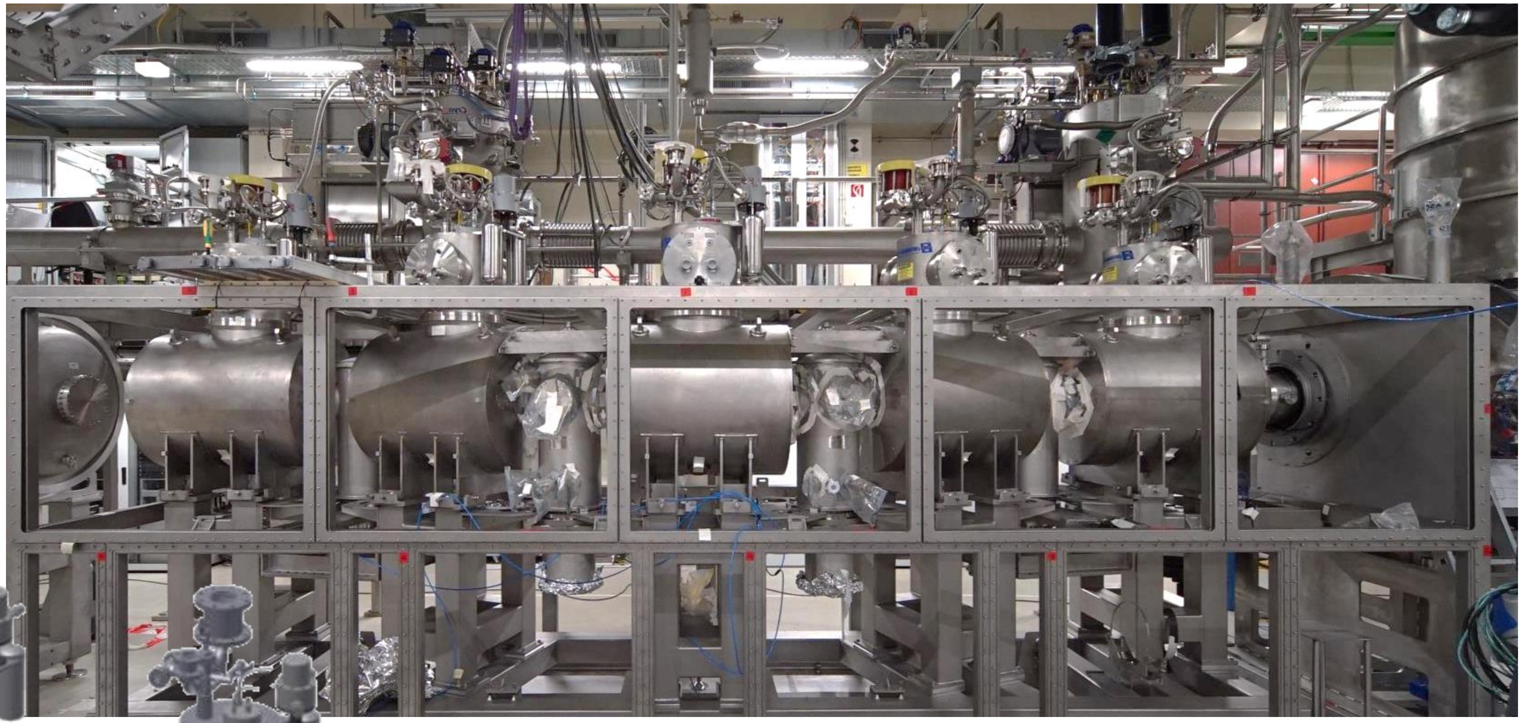


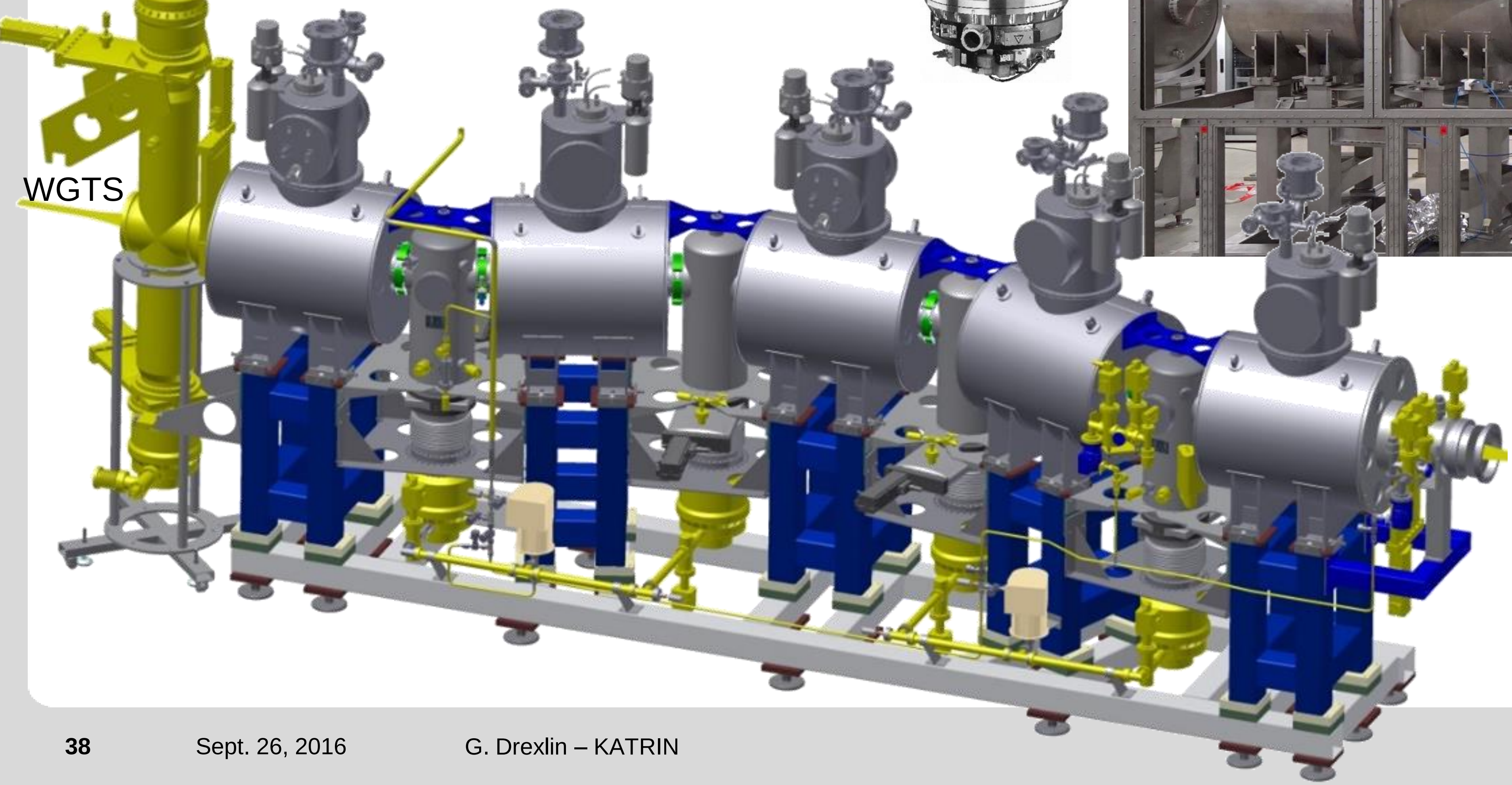
differential pumping - DPS



■ differential pumping section DPS2-F:

- serial pumping with TMPs → 10^5 reduction
- ion elimination with E × B → 10^7 reduction

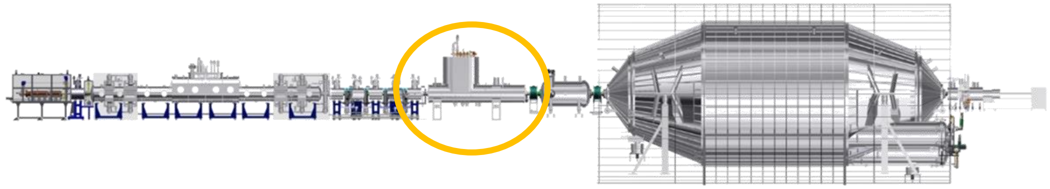




■ DPS instrumentation for ions:

- FT-ICR (ion diagnostics)
- dipoles (ion elimination)
- ring electrode (ion blocking)

cryogenic pumping - CPS



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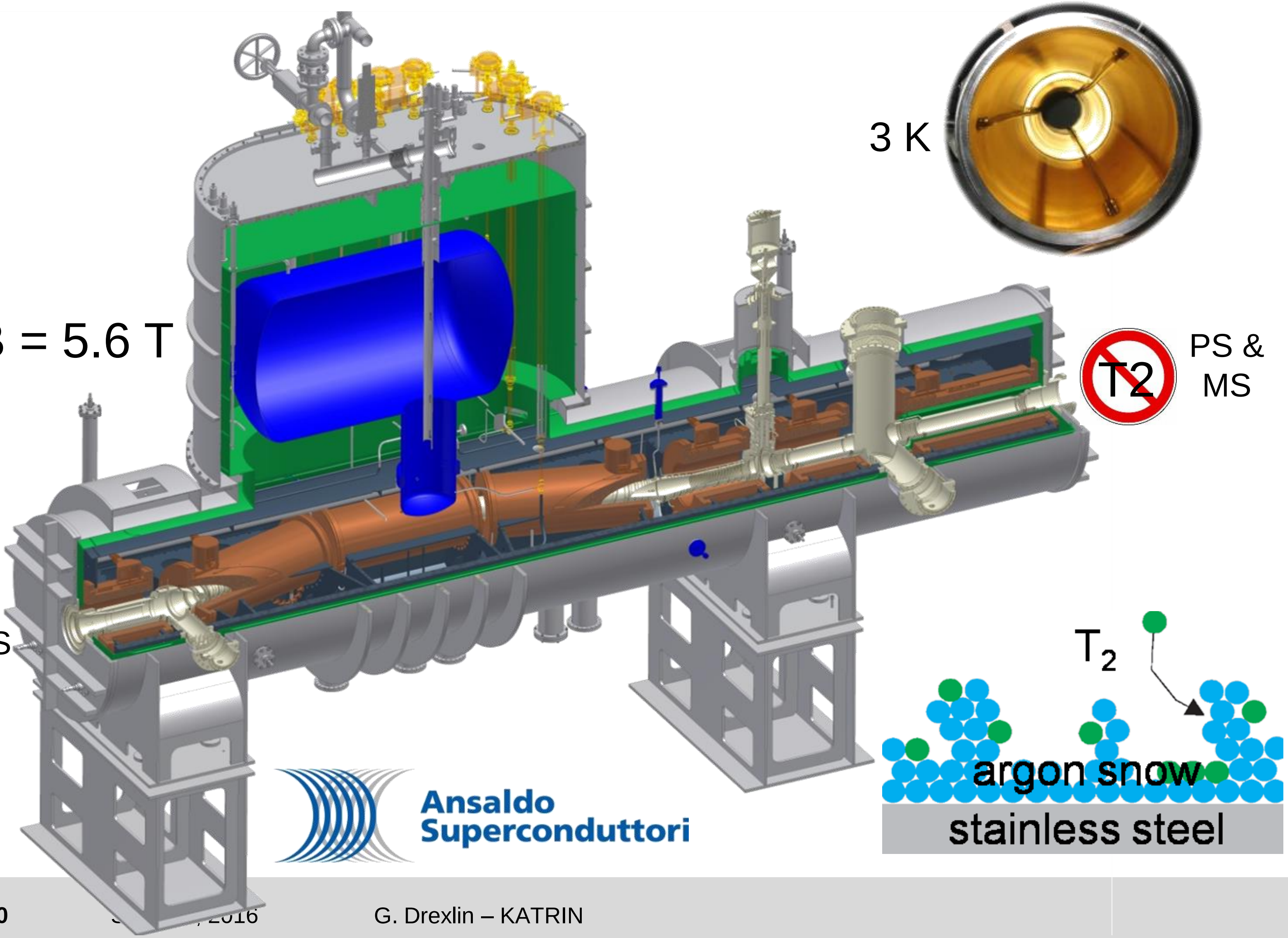
cryogenic pumping section CPS:

- 3K section with Ar-frost layer → >10^7 reduction of T2



Ansaldo Superconduttori

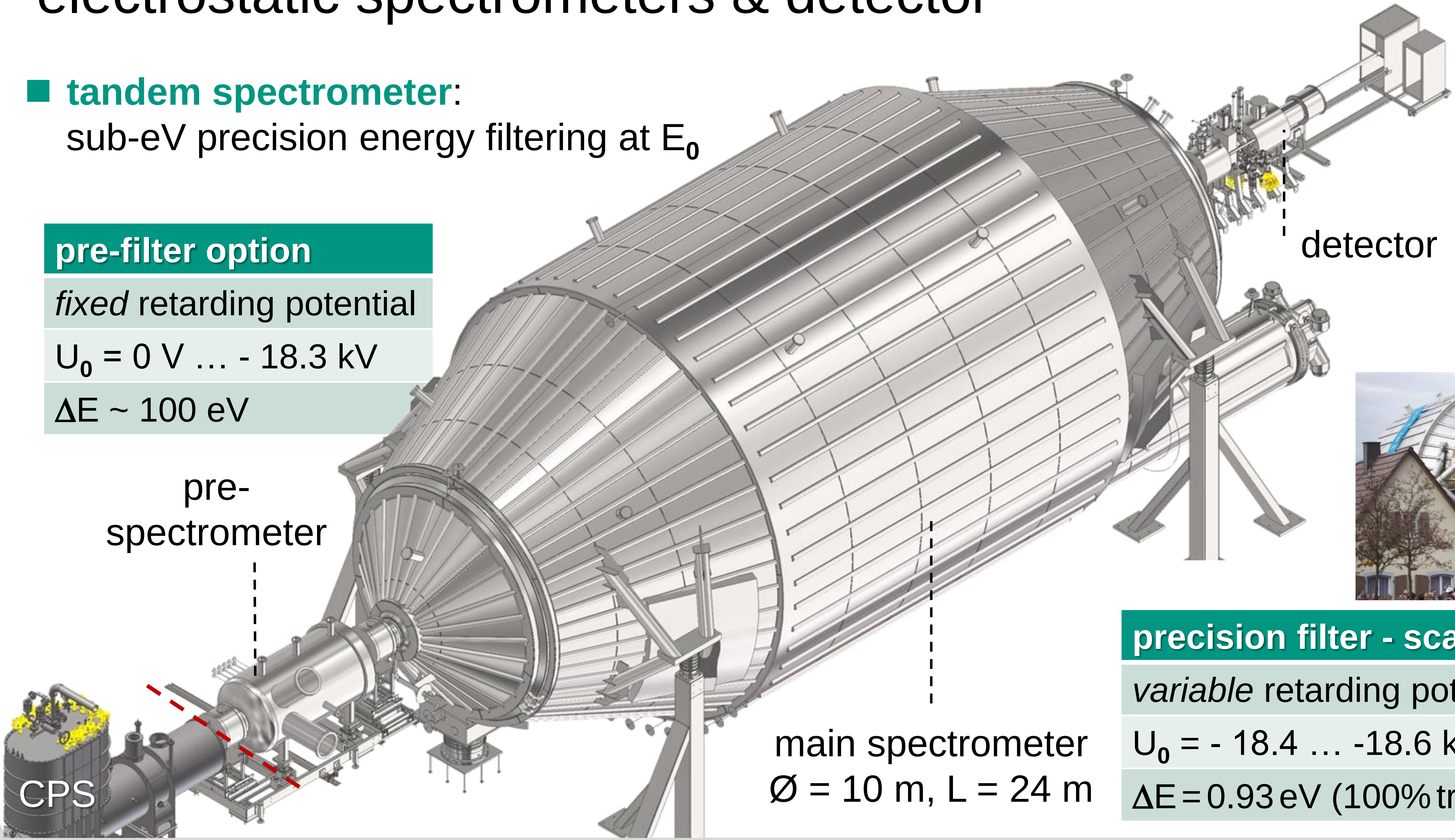
CPS instrumentation:

- condensed ^{83m}Kr-source (calibration)
- forward beam monitor (ß-activity)

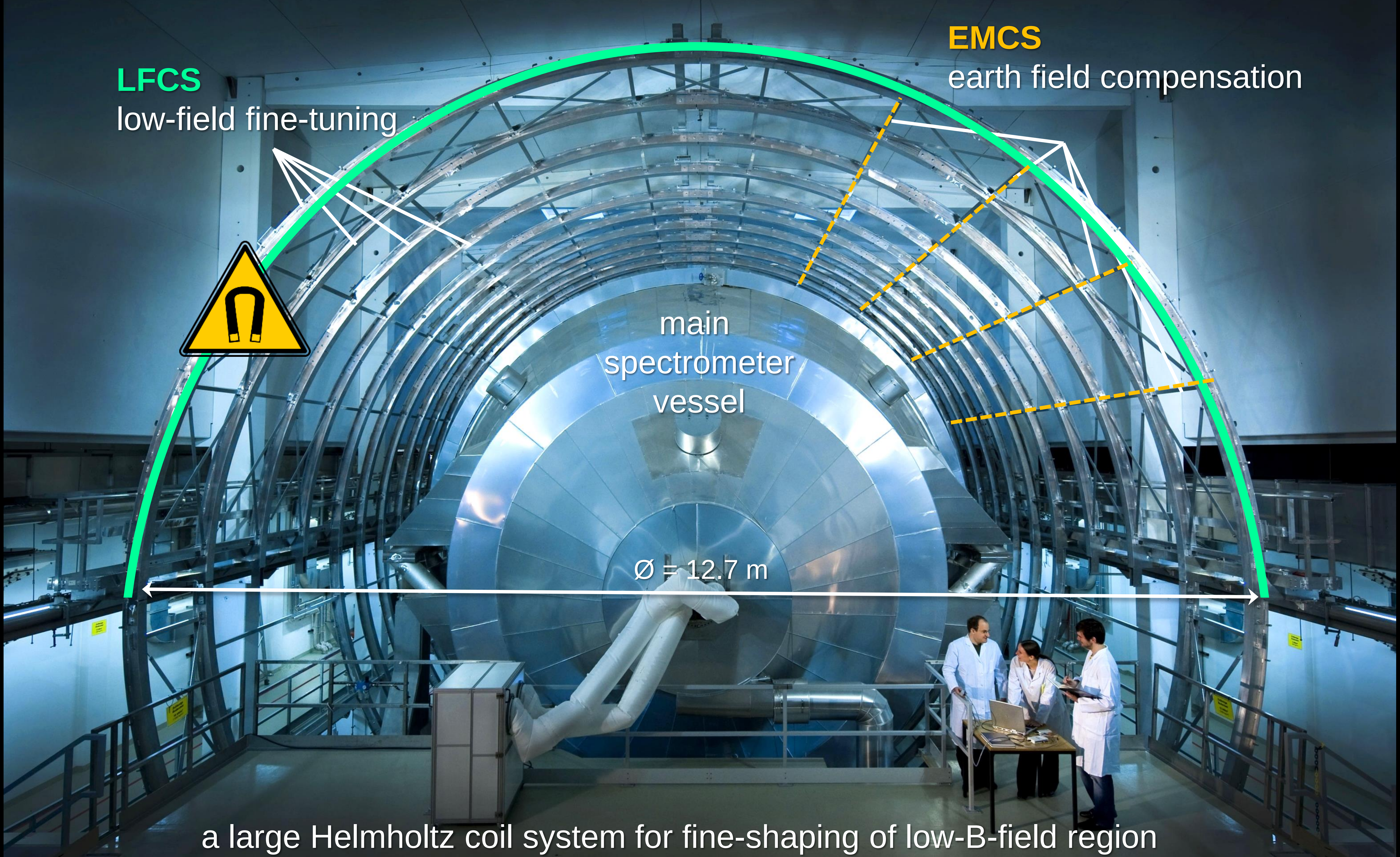
electrostatic spectrometers & detector

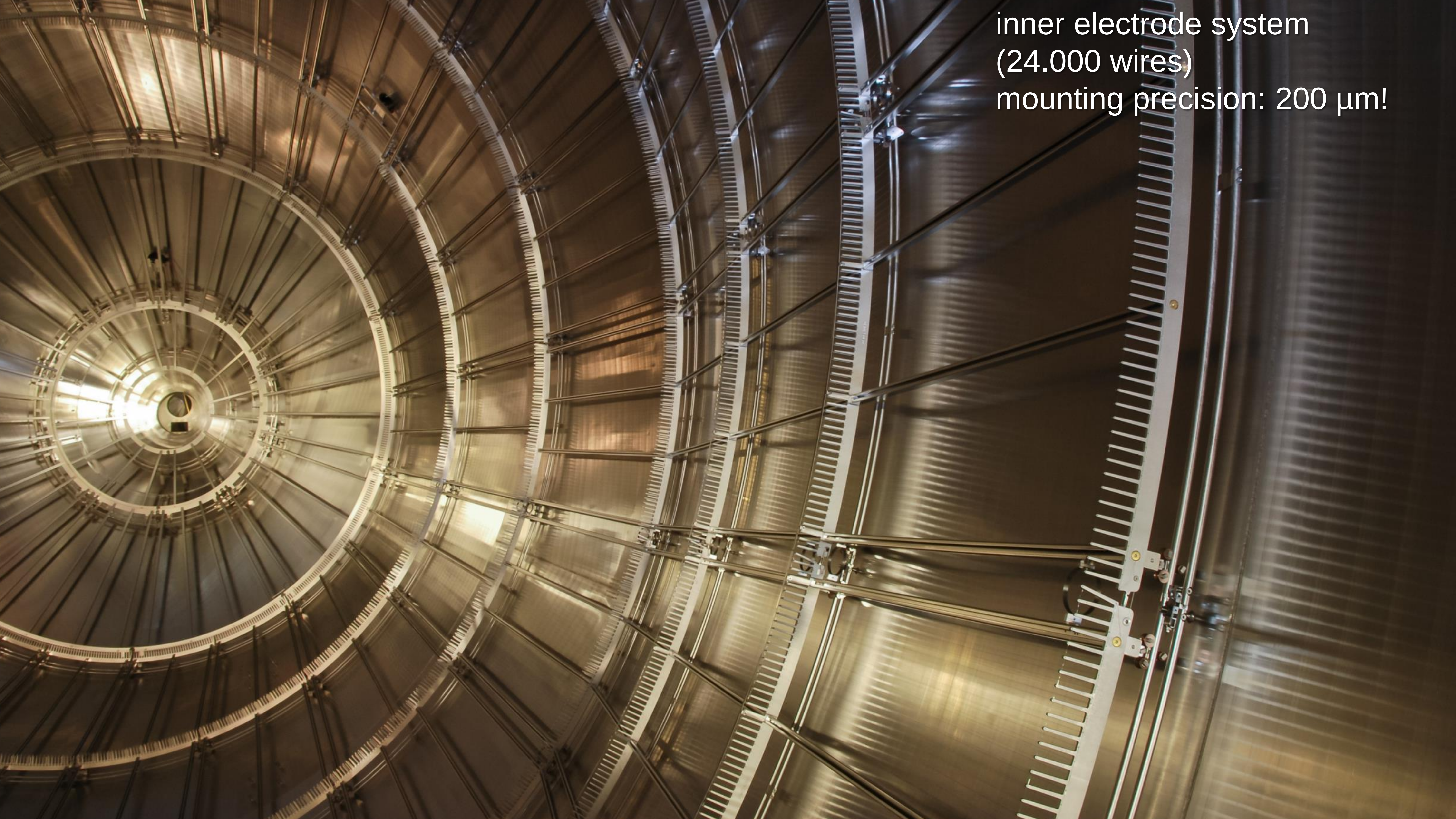
- **tandem spectrometer**:
  sub-eV precision energy filtering at E_0

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

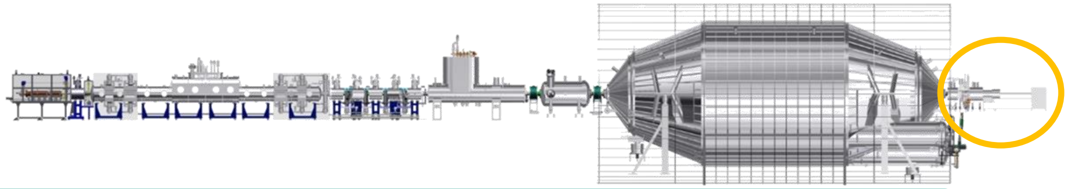


precision filter - scanning
variable retarding potential
U_0 = - 18.4 … -18.6 kV (ppm-scale)
ΔE = 0.93 eV (100% transmission)

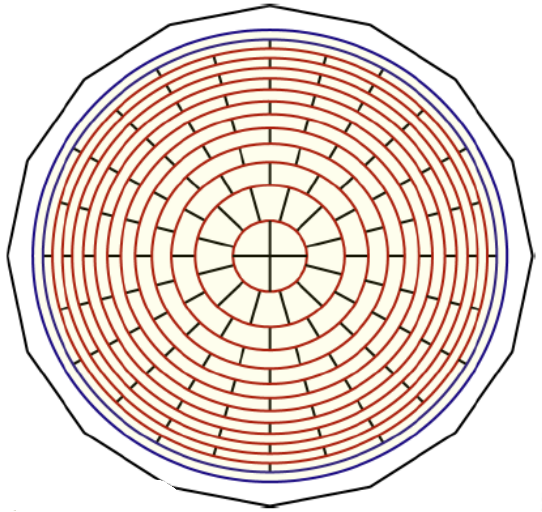

LFCS
low-field fine-tuning
EMCS
earth field compensation
main
spectrometer
vessel
Ø = 12.7 m
a large Helmholtz coil system for fine-shaping of low-B-field region

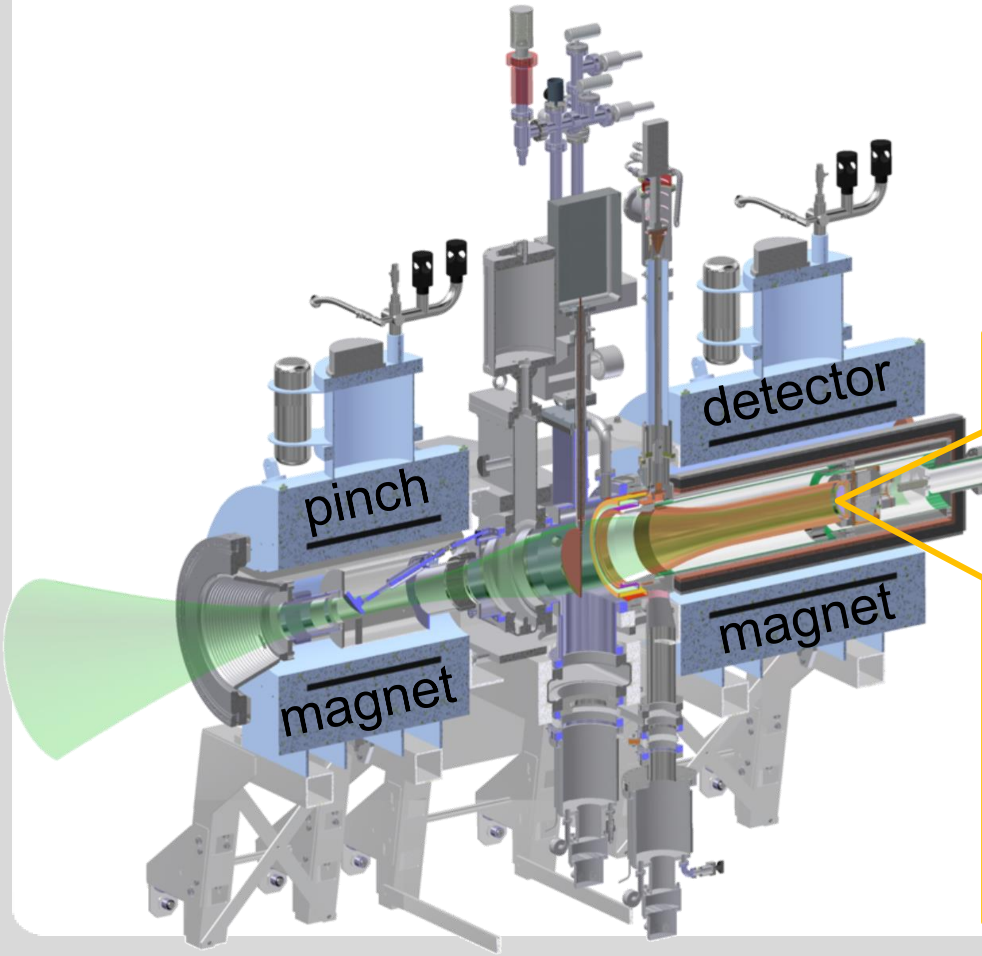

inner electrode system
(24.000 wires)
mounting precision: 200 µm!

Focal Plane Detector system

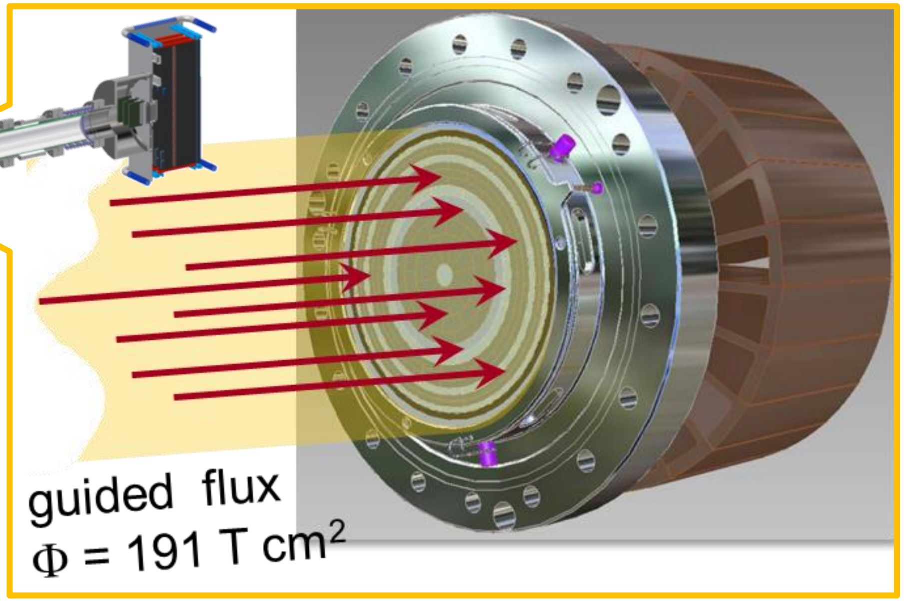


- Detection of transmitted electrons with **Si-PIN detector array**
  - 148 pixels (A = 44 mm^2 each) with ~ 100 nm top deadlayer in 500 µm wafer
  - 12 rings, each consisting of 12 pixels each, central 4-pixel bullseye
  - active scintillator µ-veto & passive (Pb, Cu) shielding, PAE: + 10 kV

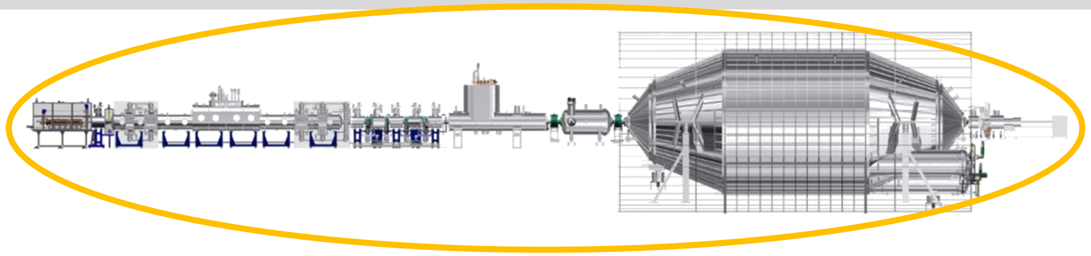




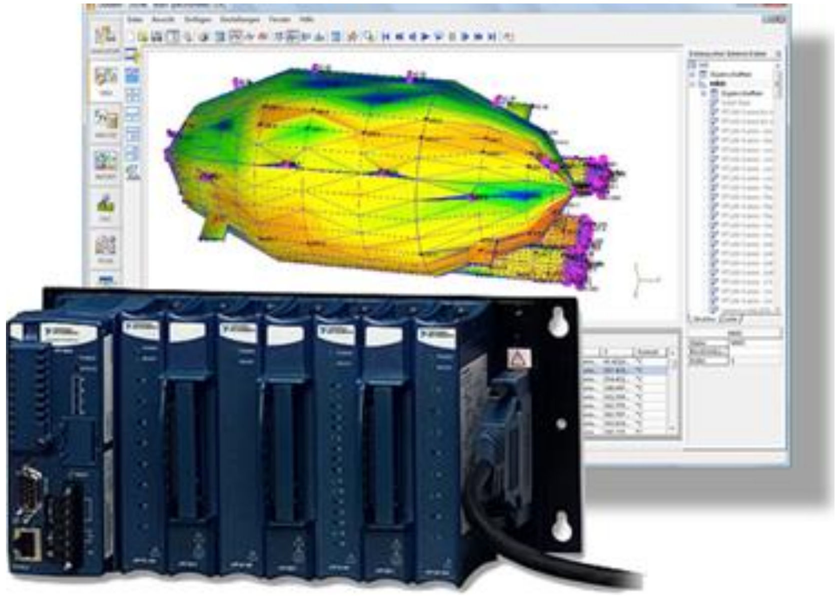
position resolution over entire flux tube (radius, azimuth)

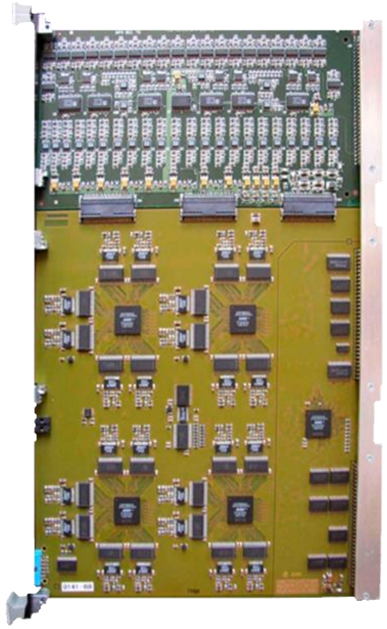


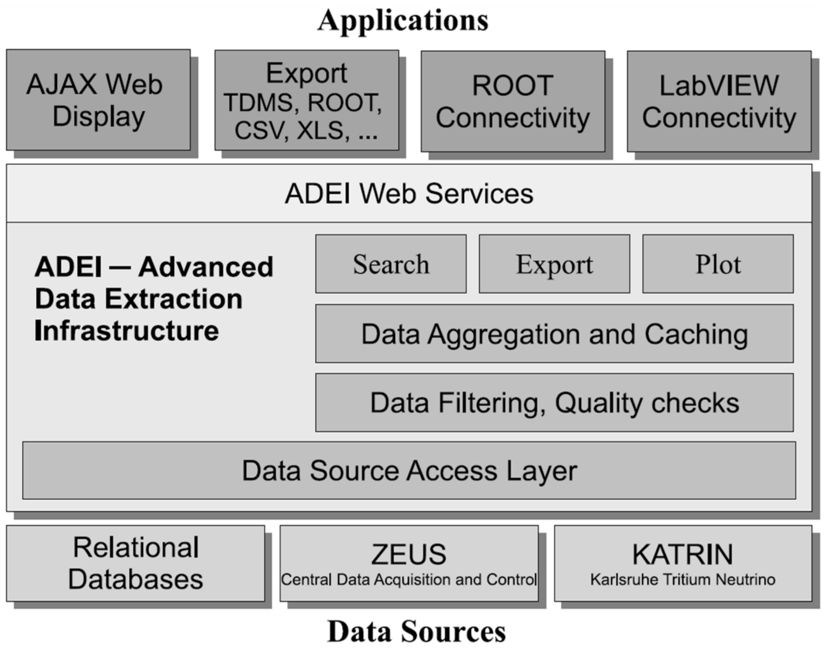
IPE contributions to KATRIN

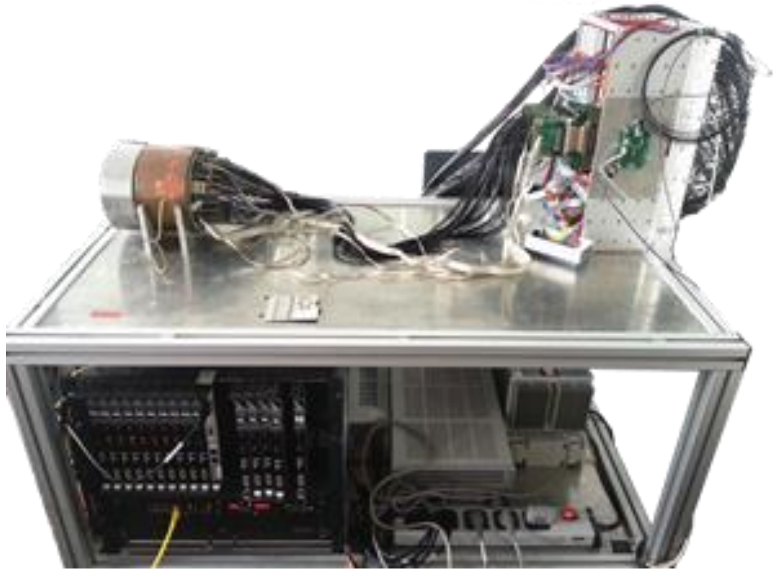


- **Important contributions from IPE** to KATRIN experiment
  - electronics: read-out chain for 148 Si-pixels
  - slow control, automatisation, data base (ADEI)
  - HV stabilisation (post-regulation)
  - FPGA-based DAQ system, data visualization
  - s.c. magnet safety system





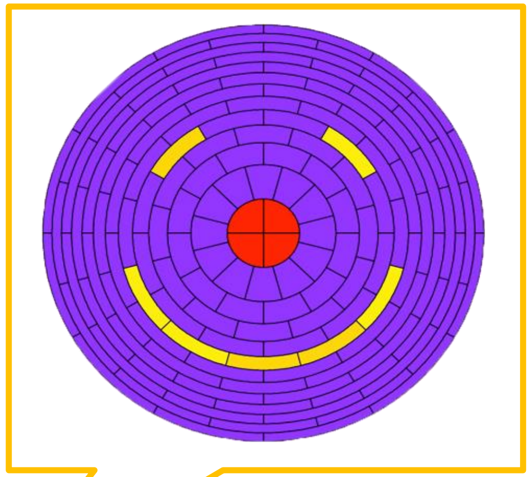


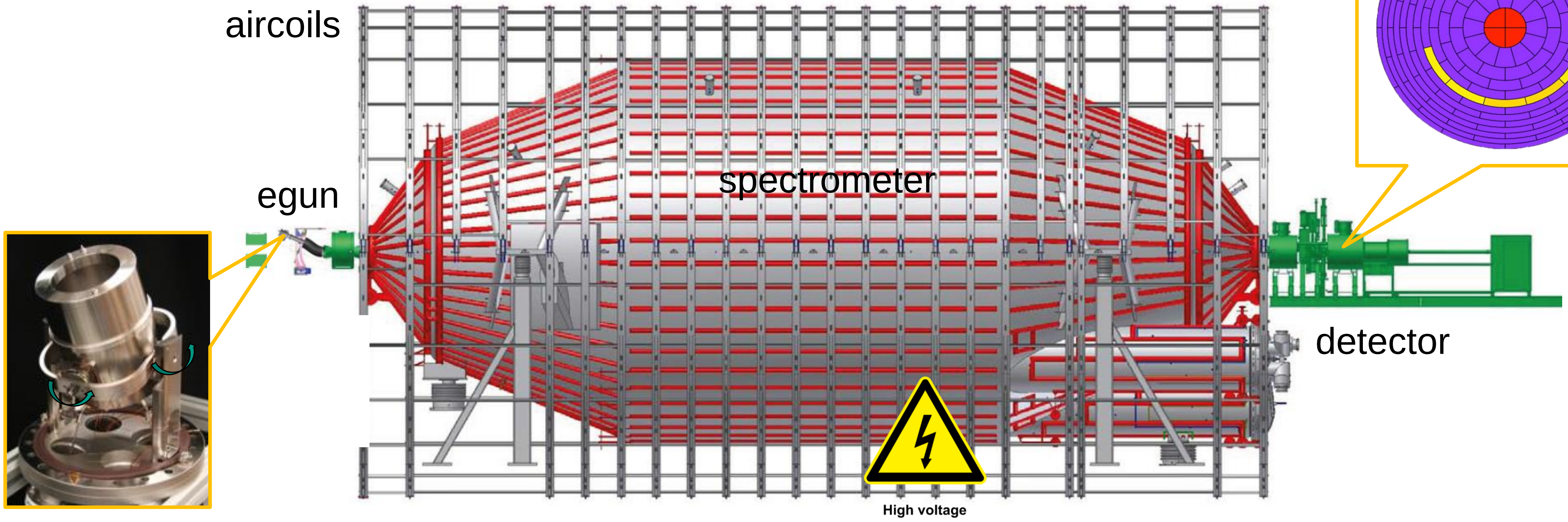


KATRIN: status & future

spectrometer commissionng measurements 2013-15

- **over 12 months of continuous spectrometer measurements** to verify:
  - functionality of all components: UHV, HV, B-fields, SC, DAQ,…
  - MAC-E filter characteristics via egun transmission studies
  - refine background model & optimisation of bg-reduction methods

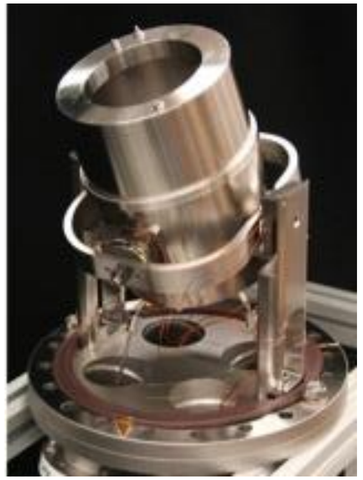


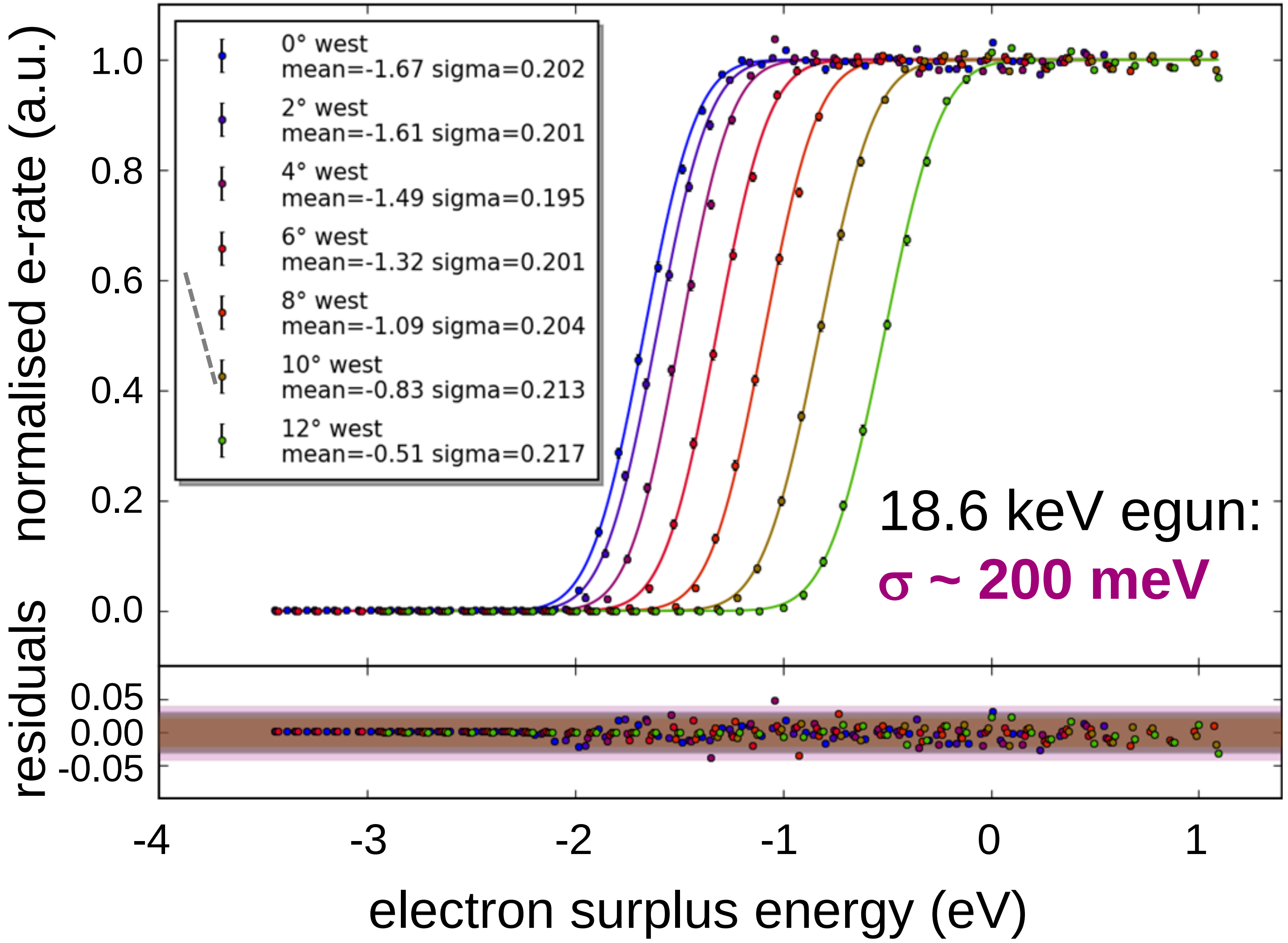


Main spectrometer: MAC-E characteristics

- **Main spectrometer** works as high-resolution MAC-filter:
  - sharp transmission function for 18.6 keV electrons from egun, HV precision on 10 mV scale

small
angular
spread





width still limited by finite egun emission energy spectrum

Radon-induced background

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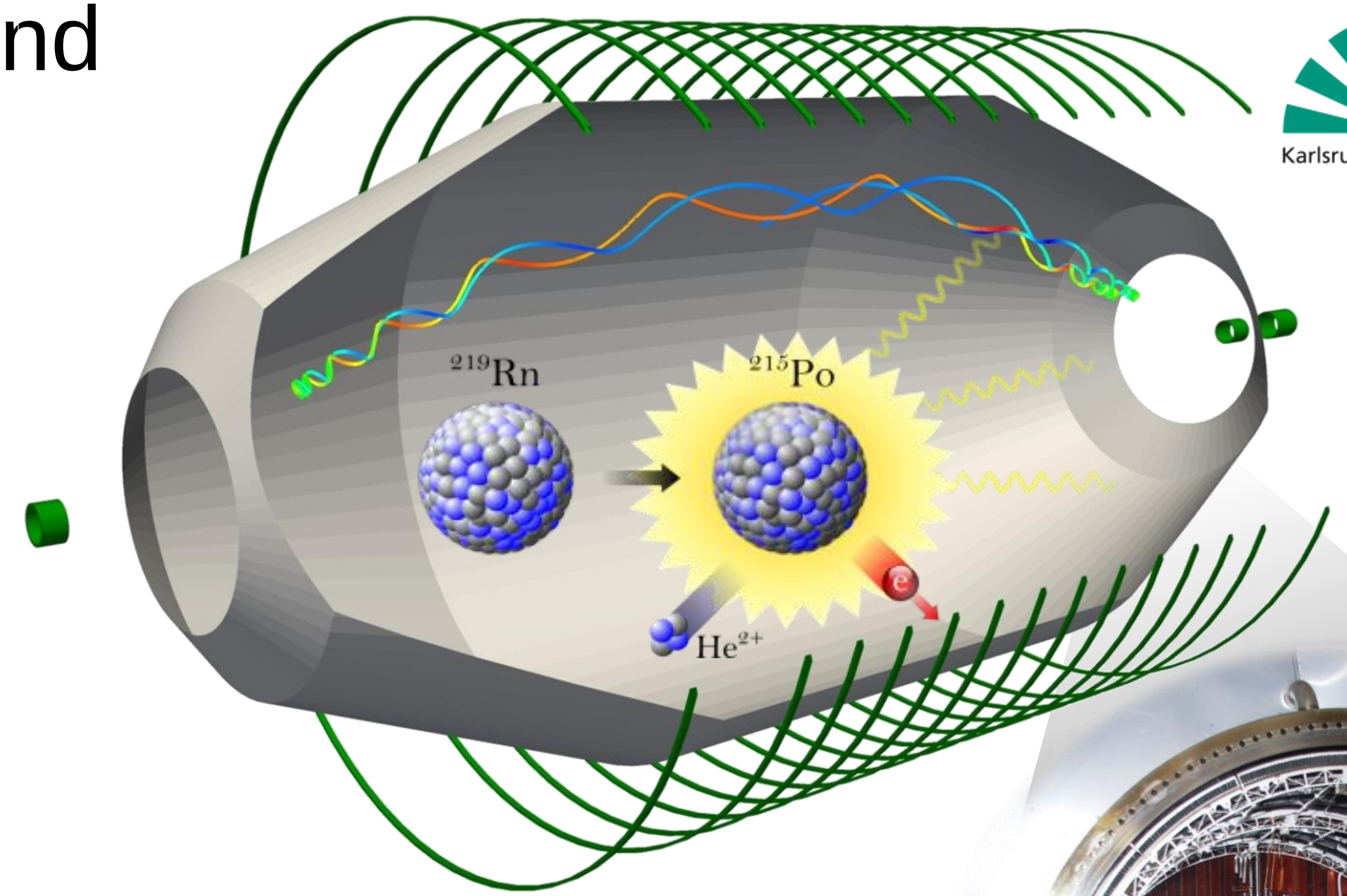
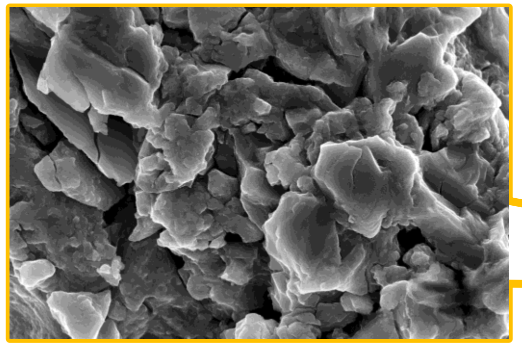
- **main spectrometer** background:
  no contributions observed from
  - μ-induced secondaries
  - environmental γ´s
- Background stems only from
  neutral, unstable atoms in UHV
- ^{219}Rn atoms emanate from large
  surface of NEG pumps (2 km strips)
  - eV…keV electrons from α-decay
  - correspnding bg-rate: ~0.5 cps
- countermeasure (factor 20):
  - 3 LN2-cooled Cu-baffles in front of NEG
  - cryotrap eliminates ^{219}Rn-propagation
  - remaining bg level: ~0.5 cps

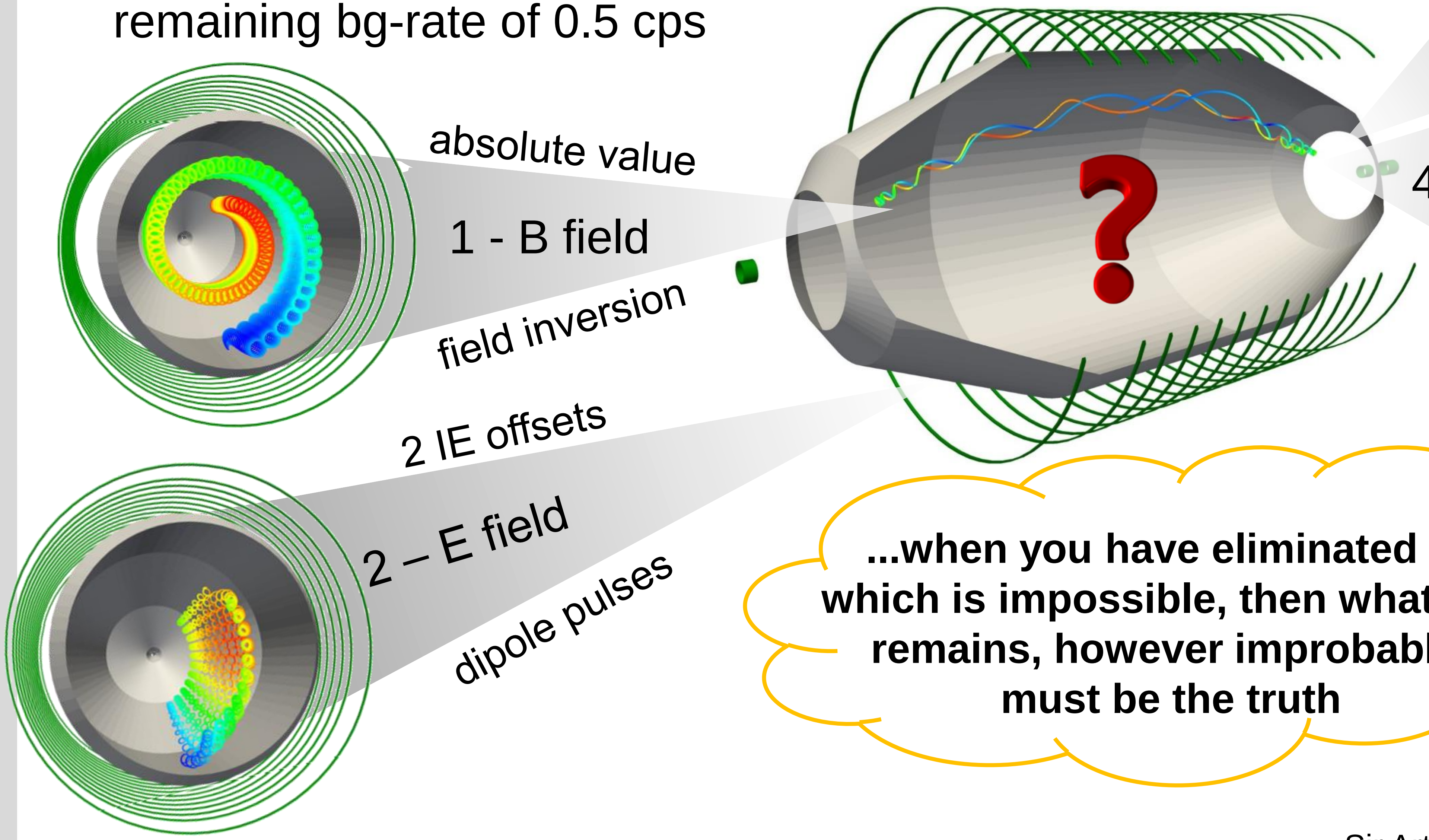




NEG strips

MAC-E filter background: a new model

- **4 conventional countermeasures have no impact on** remaining bg-rate of 0.5 cps

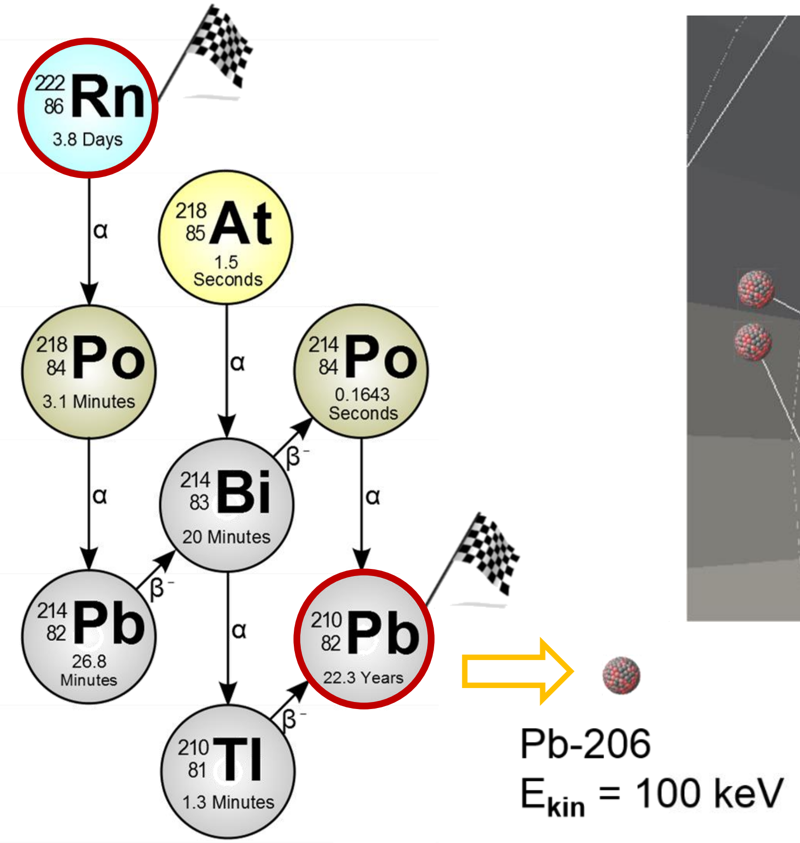


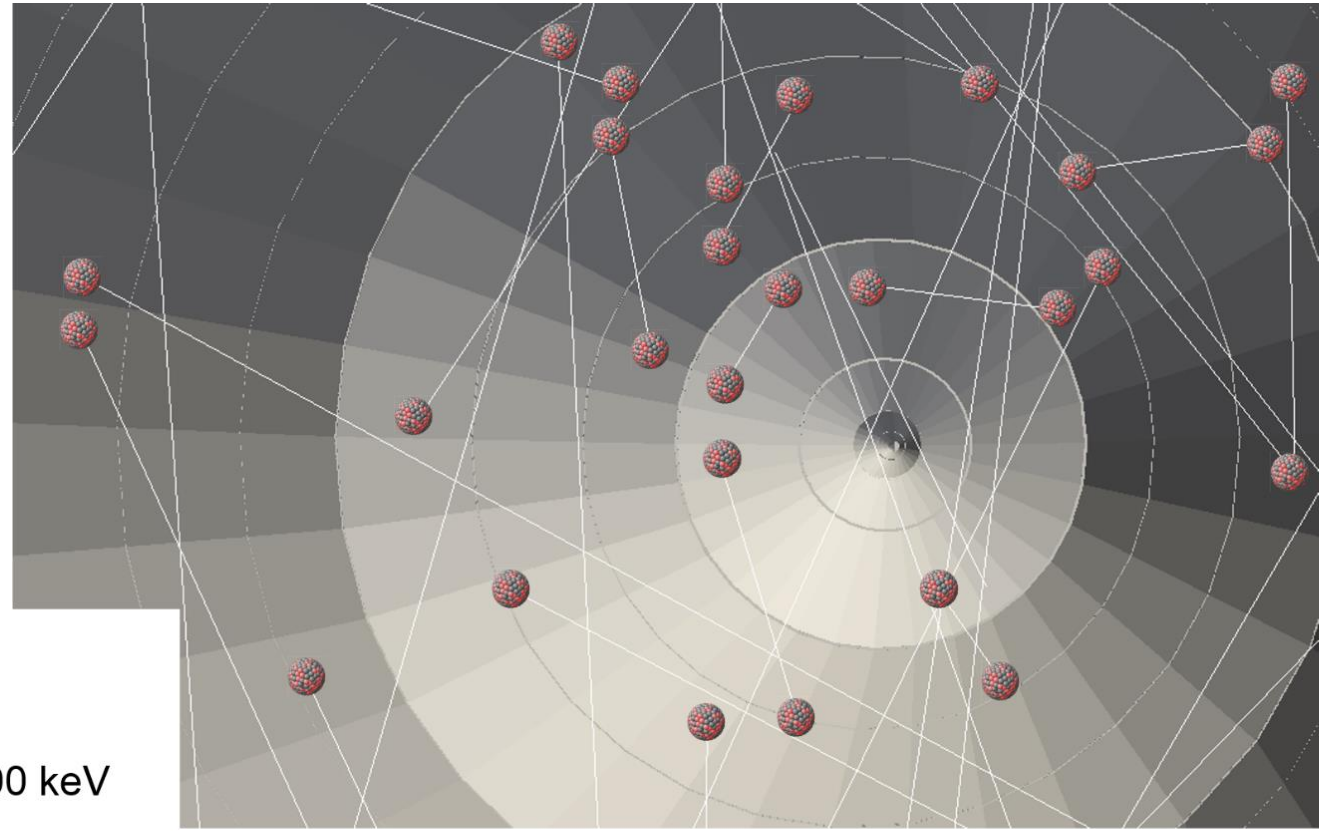
...when you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth

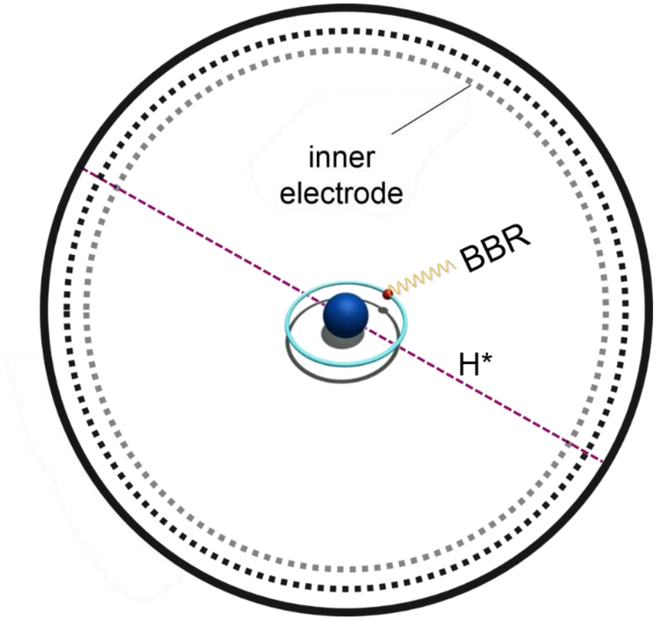
Sir Arthur Conan Doyle
The Sign of the Four

^{206}Pb-recoil induced H-Rydberg states

- **highly excited H-atoms (Rydberg states) produced by Pb-206 recoils**
  - long-term forced ventilation of spectrometer, ^{222}Rn α-decays results in ^{210}Pb implantation
  - single ^{206}Pb recoil ions generate large clouds of H-Rydberg states, which propagte in UHV
  - small number of H*- atoms is ionized in UHV by thermal BBR from spectrometer
  - isotropic generation of low-energy (<1 eV) electrons in active flux tube volume







- **countermeasures**
  - spectrometer bake-out
  - UV illumination

KATRIN First Light: Alignment & Ion Systematics

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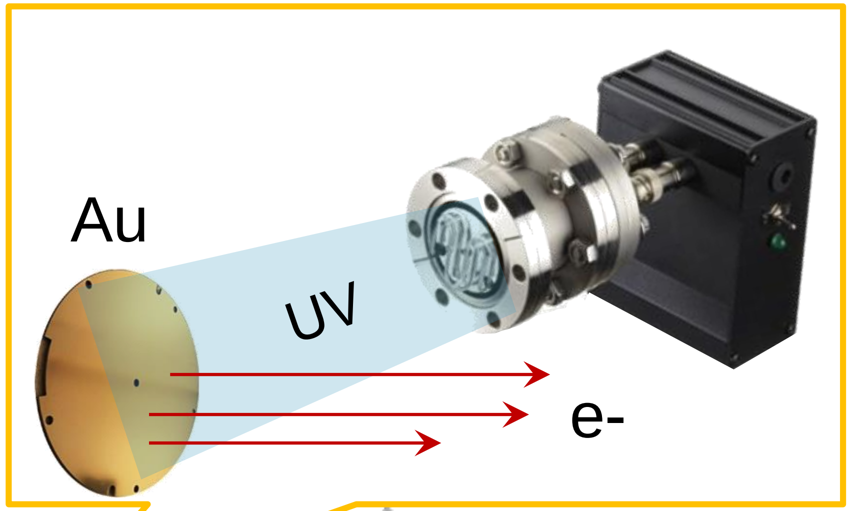
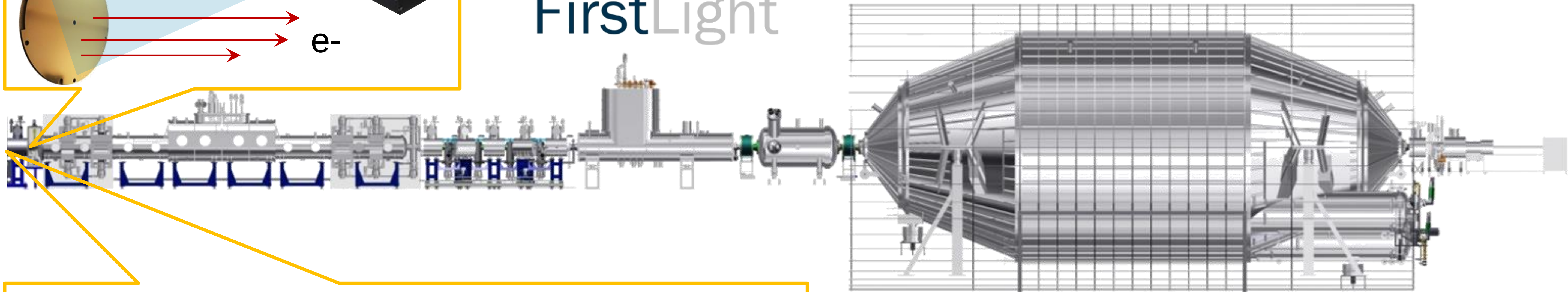
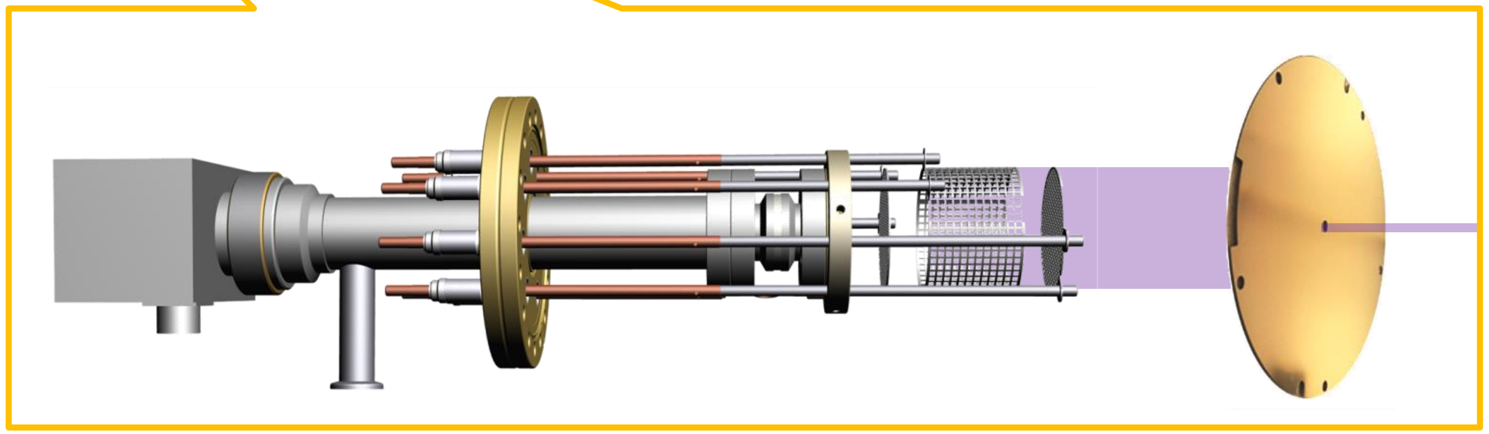


- **Alignment Measurements:** collisionless & adiabatic transport of low-energy electrons in flux-tube of 191 T cm² (start: Oct, 14 2016)

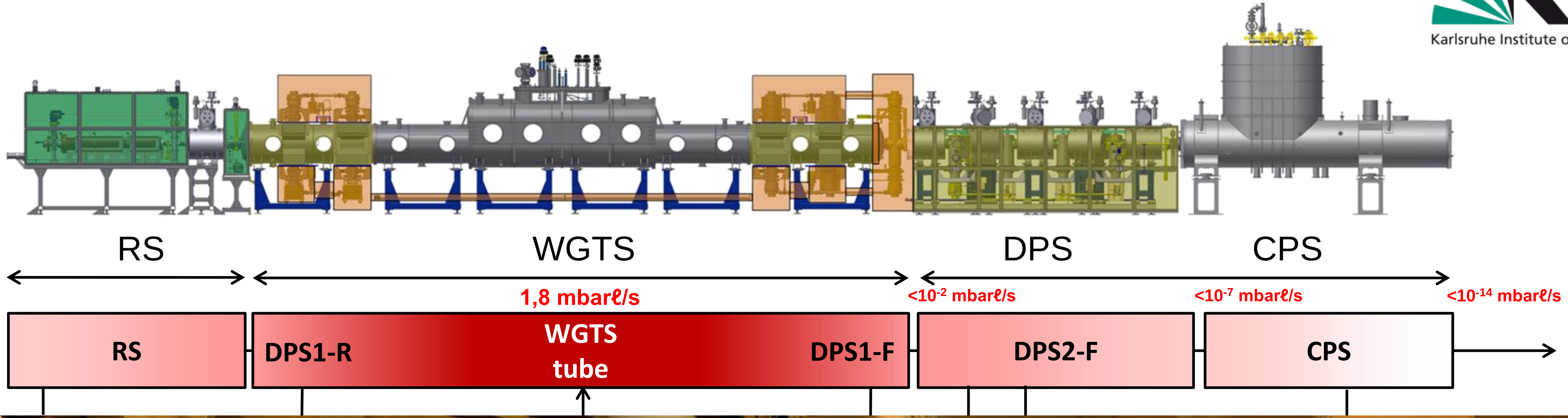
FirstLight





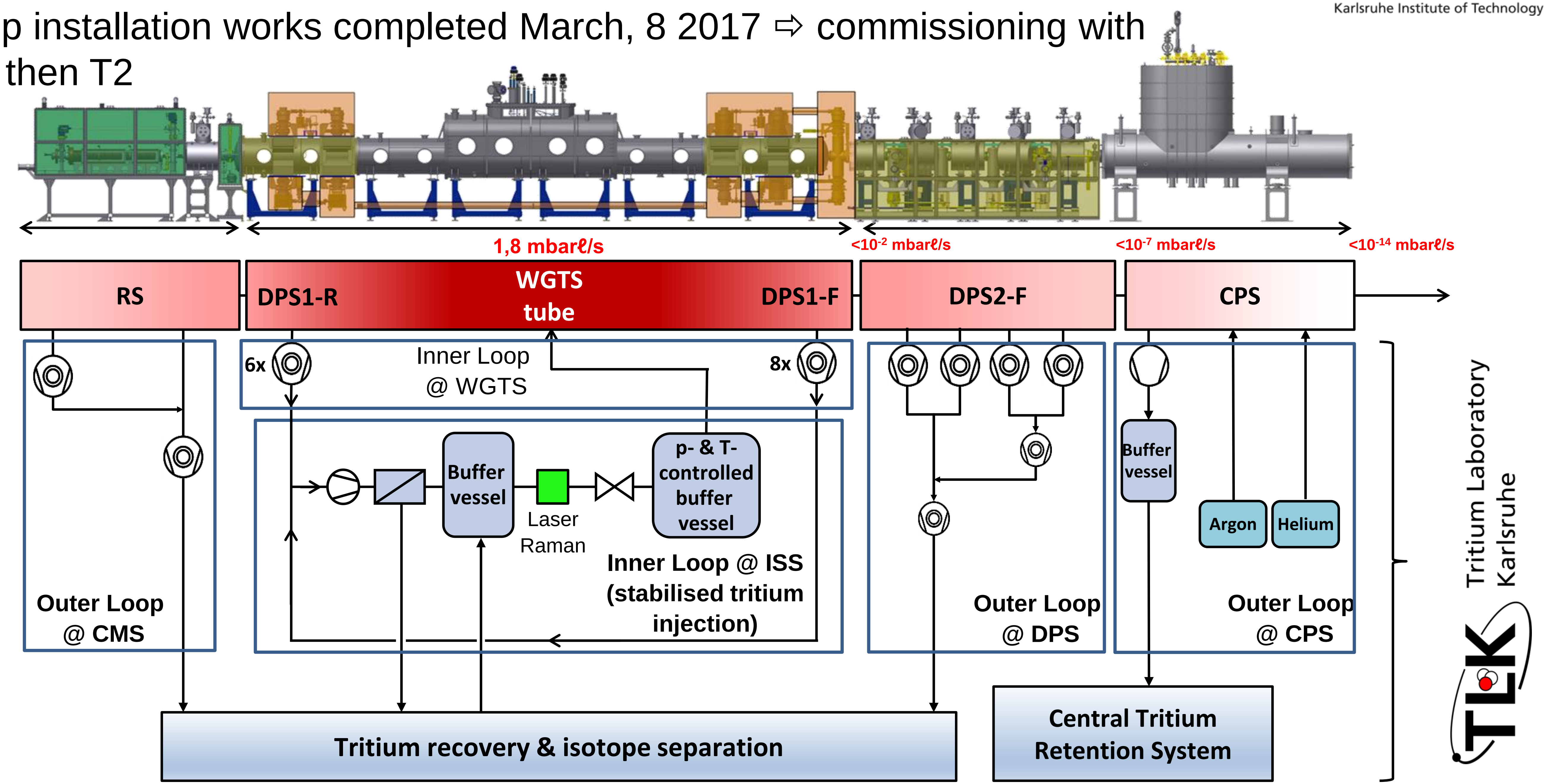
- **Ion systematics:** low-energy pencil beam of deuterium ions to study ion blocking & ion removal via E × B drift

KATRIN future: commissioning of tritium loops at TLK



KATRIN future: tritium loops in Q1-Q2/2017

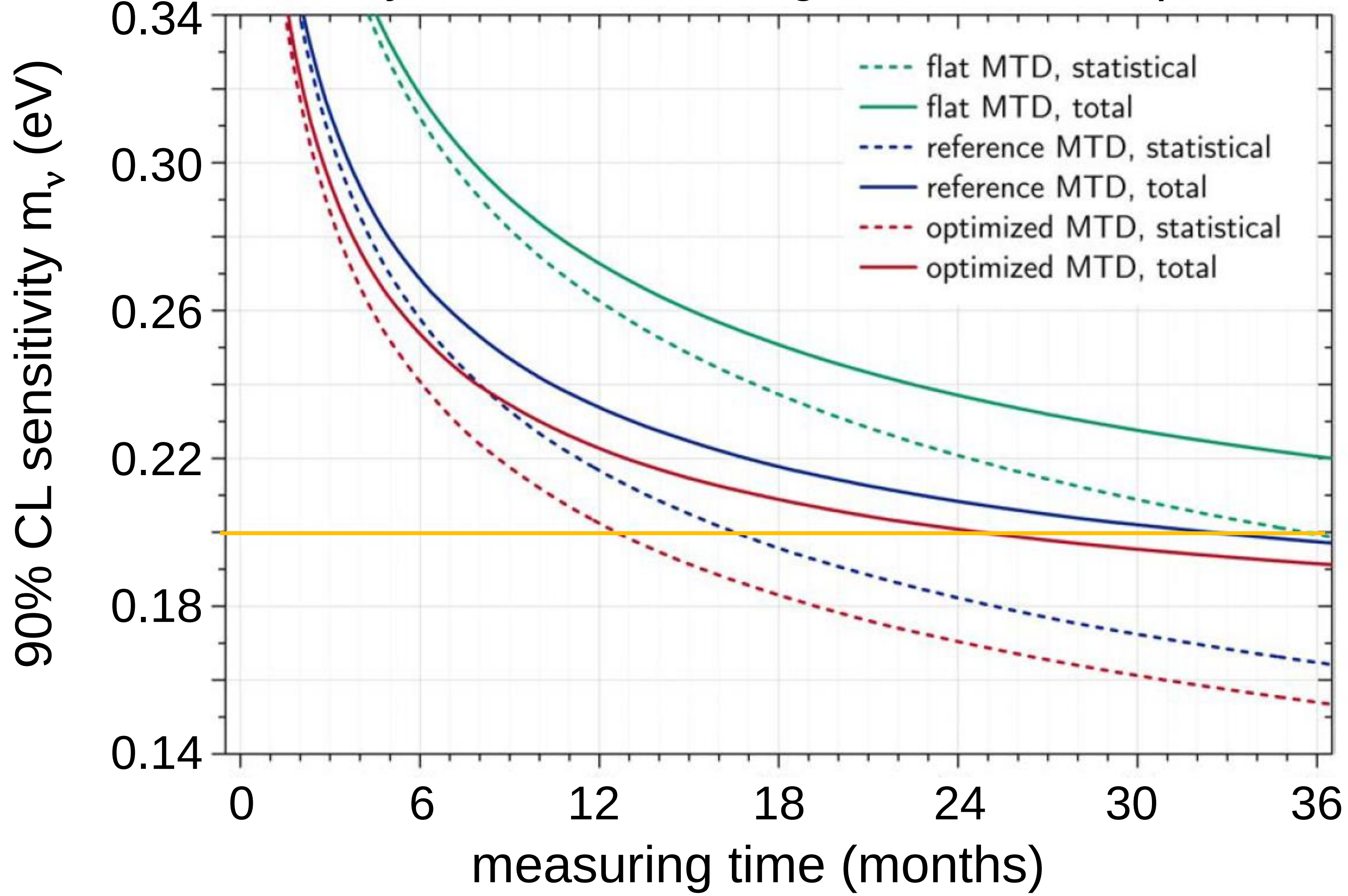
- Loop installation works completed March, 8 2017 ⇨ commissioning with D2, then T2



KATRIN - reference neutrino mass sensitivity

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

analysis for nominal bg-level of 10 mcps



sensitivity $m(\nu_e)$ = 0.2 eV (90% CL)

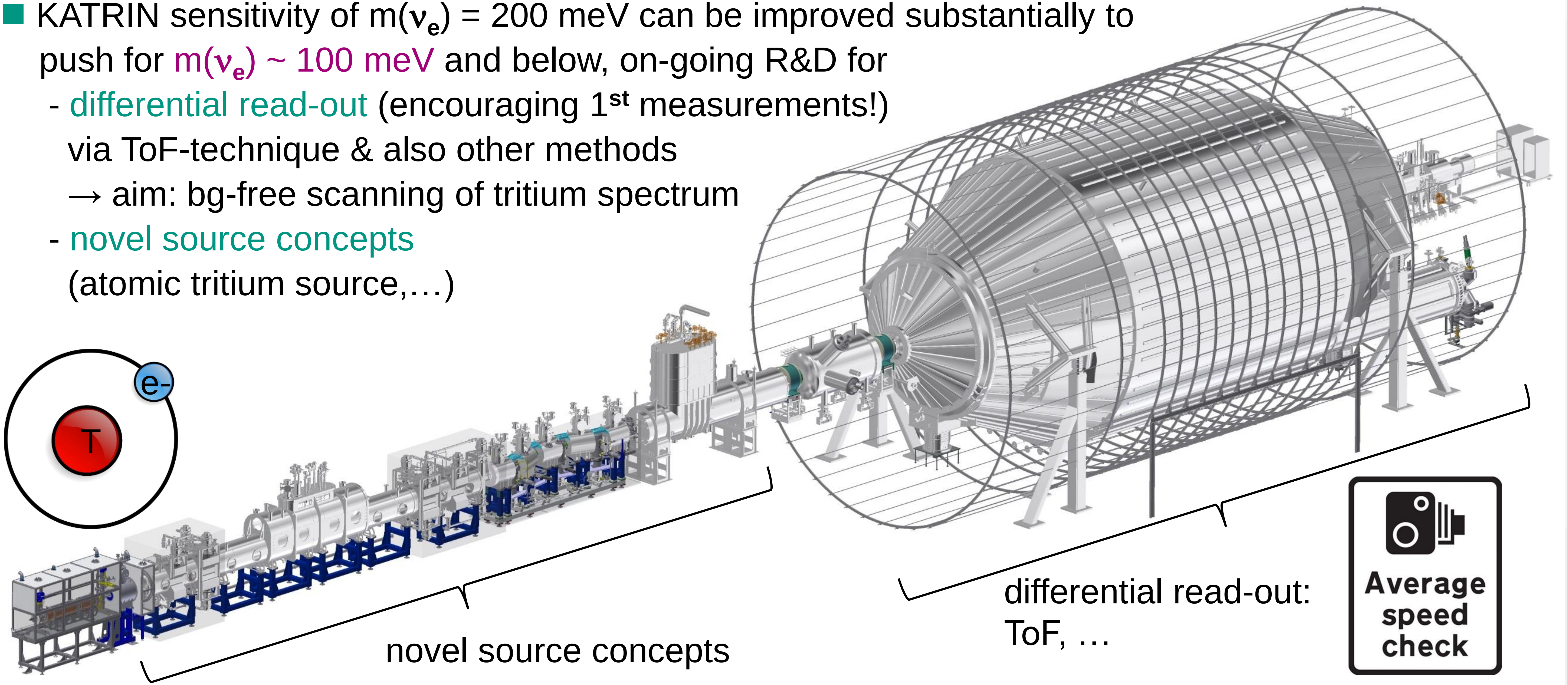
0.35 eV (5σ)

- very moderate impact of enhanced background level due to shape analysis & specific coutermeasures:
  - optimized scanning strategy
  - range of spectral analysis
  - reduced flux tube volume

  for bg-level of 2015 with 0.5 cps:
  $m(\nu_e)$ = 0.24 eV (90%) CL
  expect further bg-reduction!

KATRIN: Upgrade plans to improve sensitivity for m(ν_e)

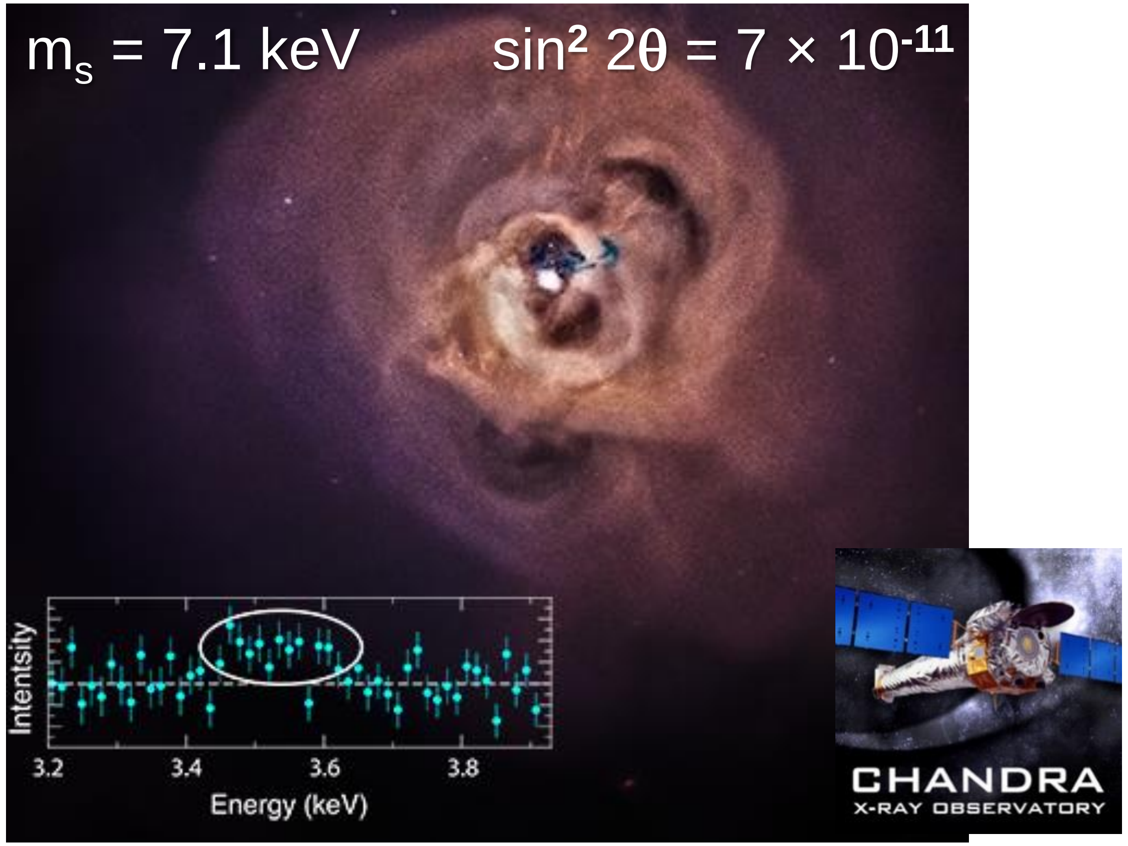
- KATRIN sensitivity of m(ν_e) = 200 meV can be improved substantially to push for m(ν_e) ~ 100 meV and below, on-going R&D for
  - differential read-out (encouraging 1st measurements!) via ToF-technique & also other methods → aim: bg-free scanning of tritium spectrum
  - novel source concepts (atomic tritium source,…)

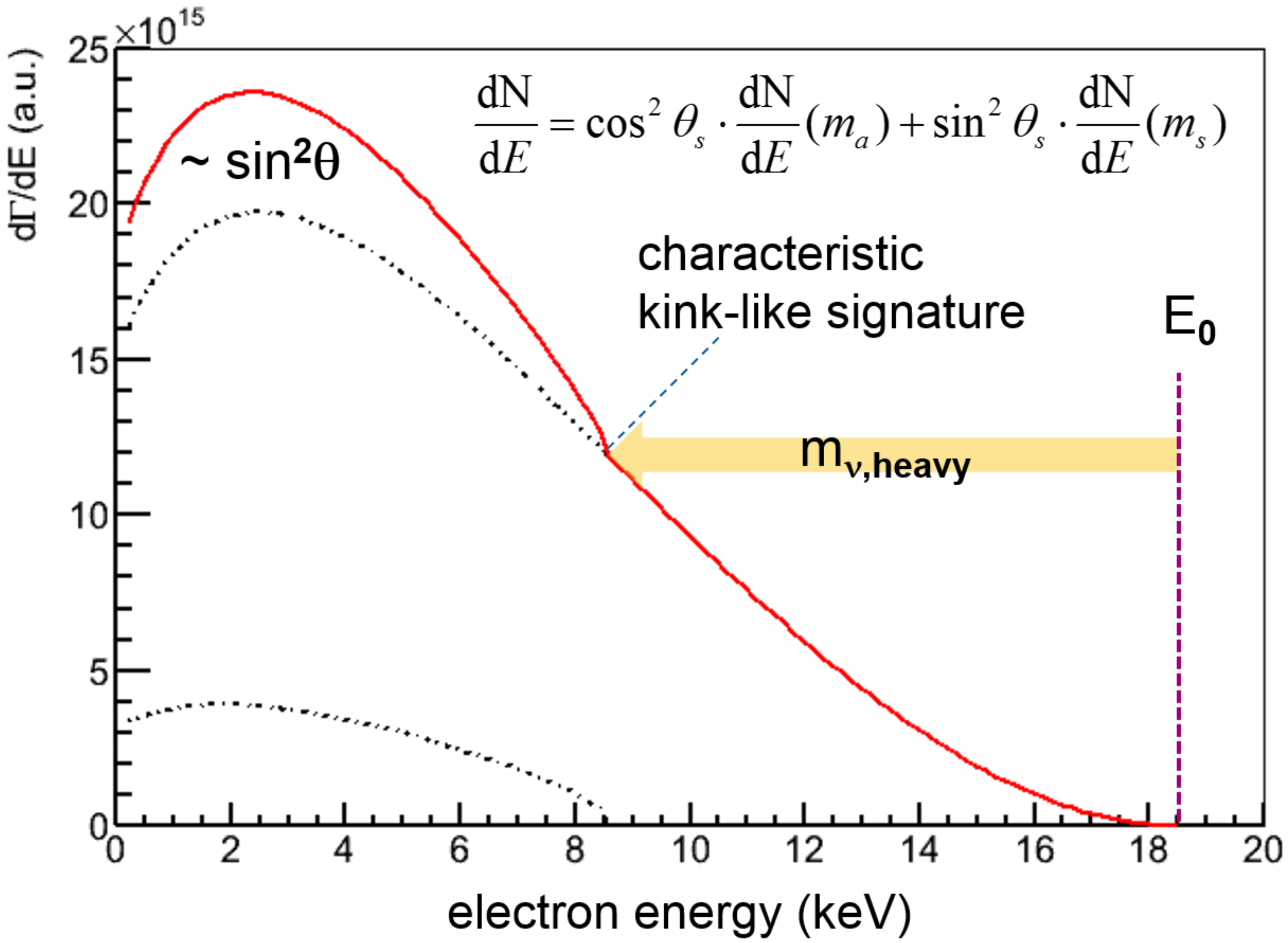


KATRIN: Upgrade plans to hunt for keV-scale ν´s

- ß-decay shape modification by **keV-mass sterile neutrinos** with mass m_s
  TRISTAN: a novel Si-pixel detector array to cover entire tritium phase space

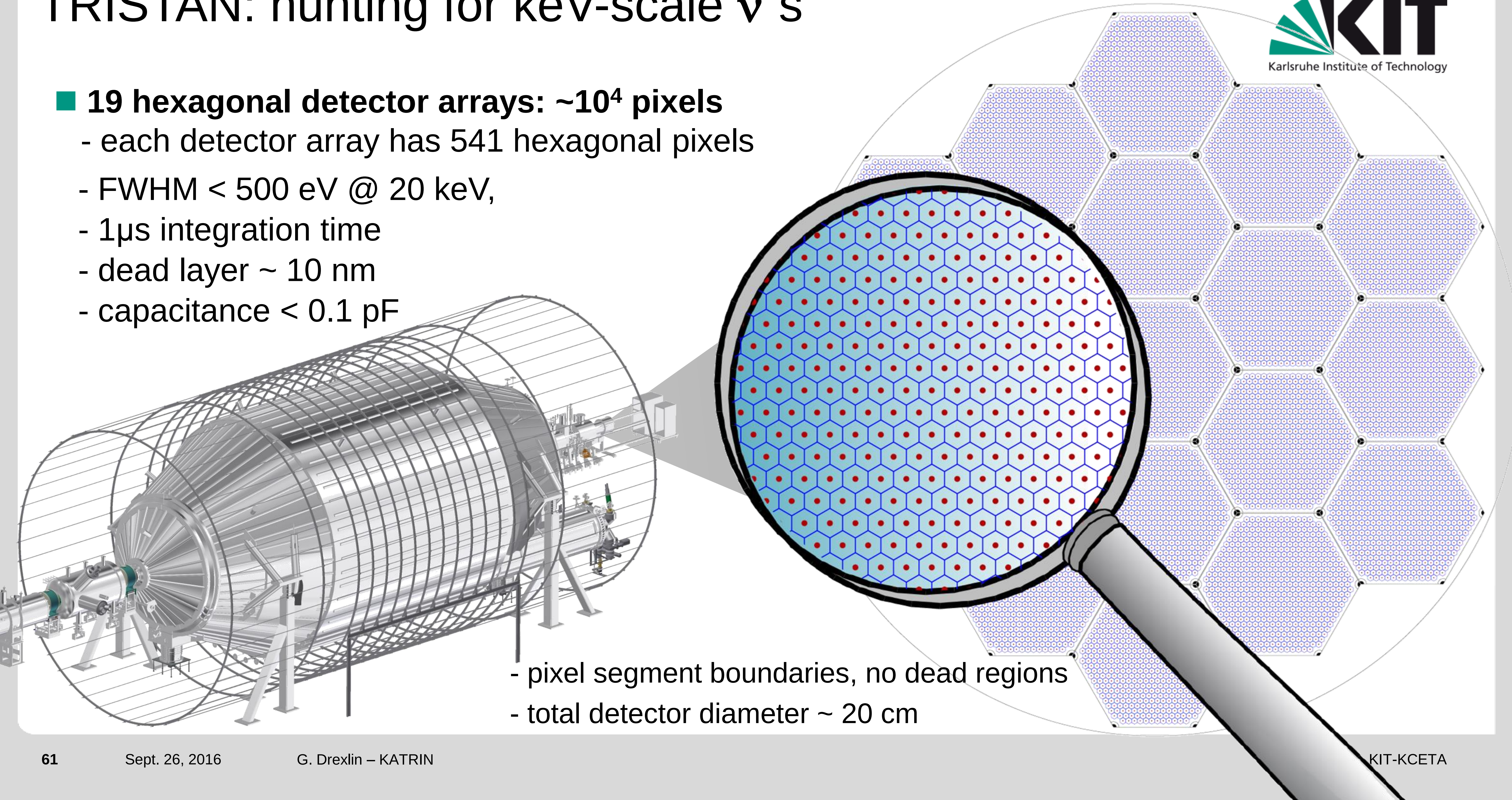
- **keV-mass sterile neutrinos** would
  be non-thermal Dark Matter particles
  - cosmological observations inconclusive





TRISTAN: hunting for keV-scale ν´s

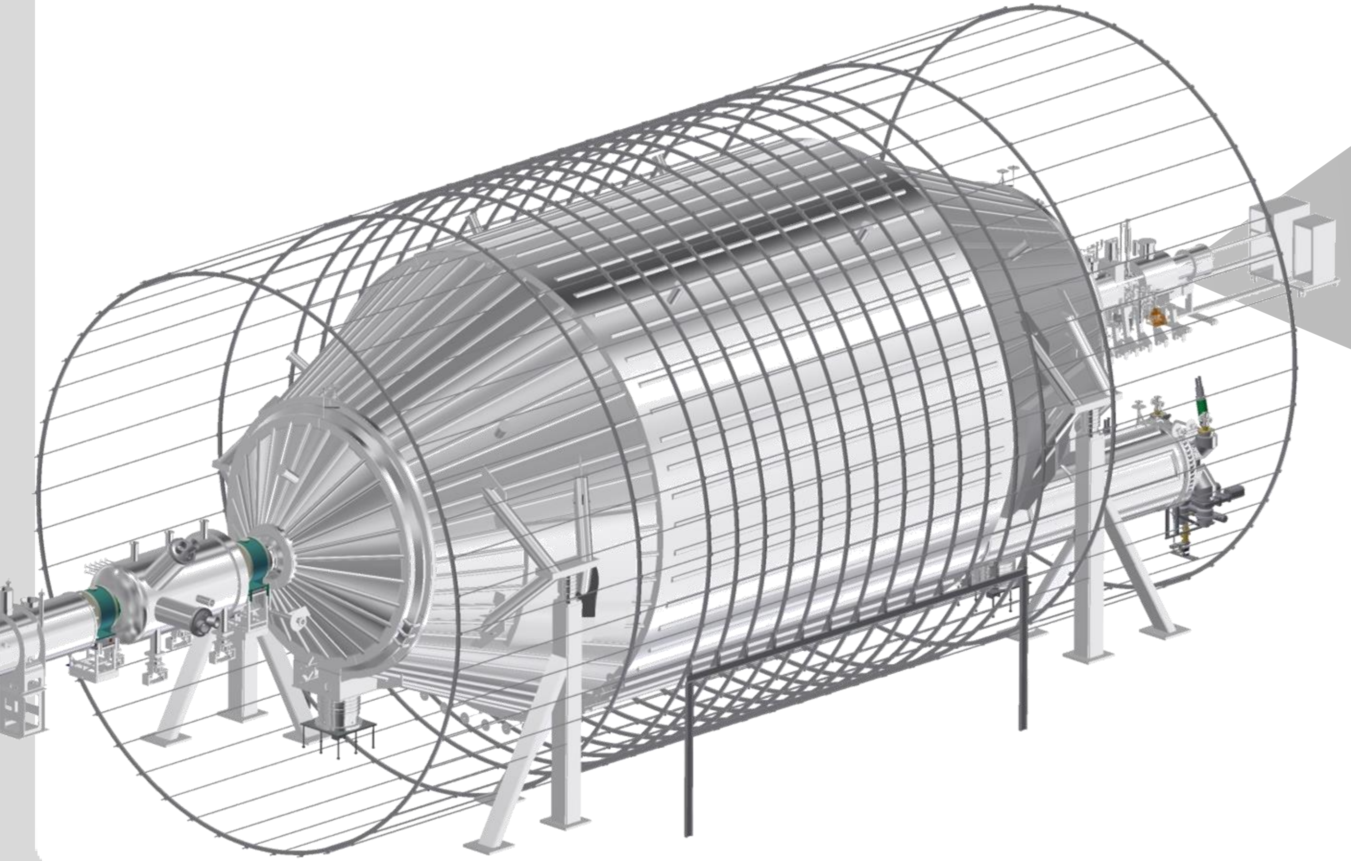
- **19 hexagonal detector arrays: ~10^4 pixels**
  - each detector array has 541 hexagonal pixels
  - FWHM < 500 eV @ 20 keV,
  - 1µs integration time
  - dead layer ~ 10 nm
  - capacitance < 0.1 pF

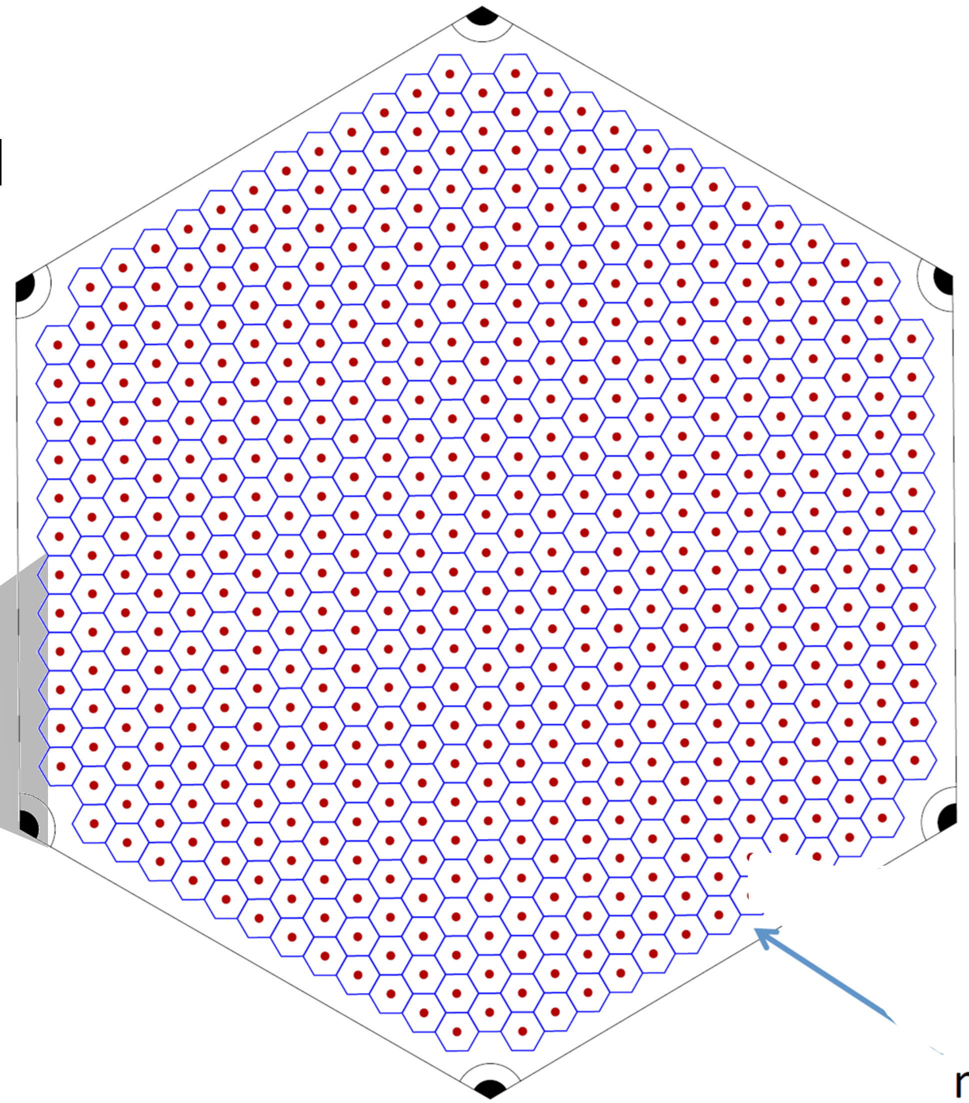


- pixel segment boundaries, no dead regions
- total detector diameter ~ 20 cm

TRISTAN: single detector array & prototyping

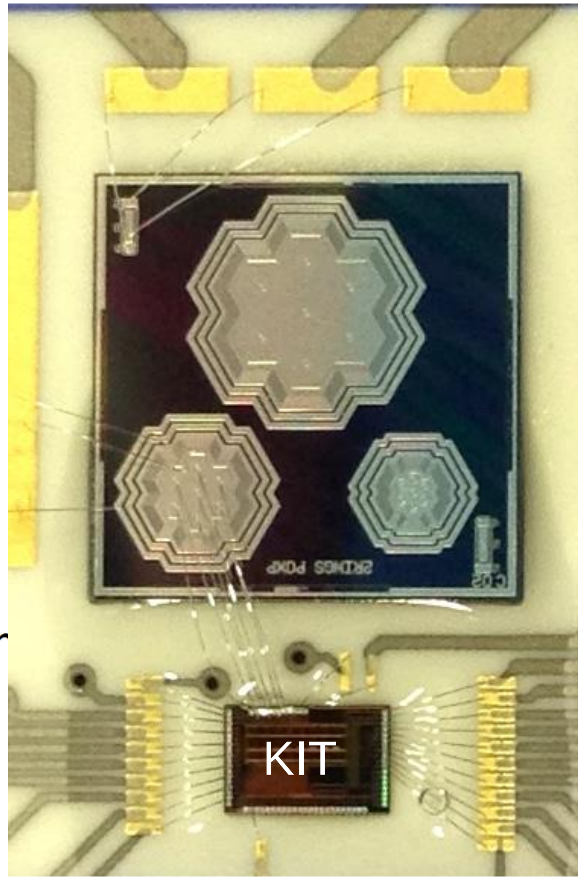
- **hexagonal detector array**
  - 541 hexagonal pixels, each with individual preamps & read-out, DC-coupled
  - pixel diamater: ~ 2 mm
  - Si thickness: 0.3-0.5 mm





- Si wafer diameter ~ 60 mm

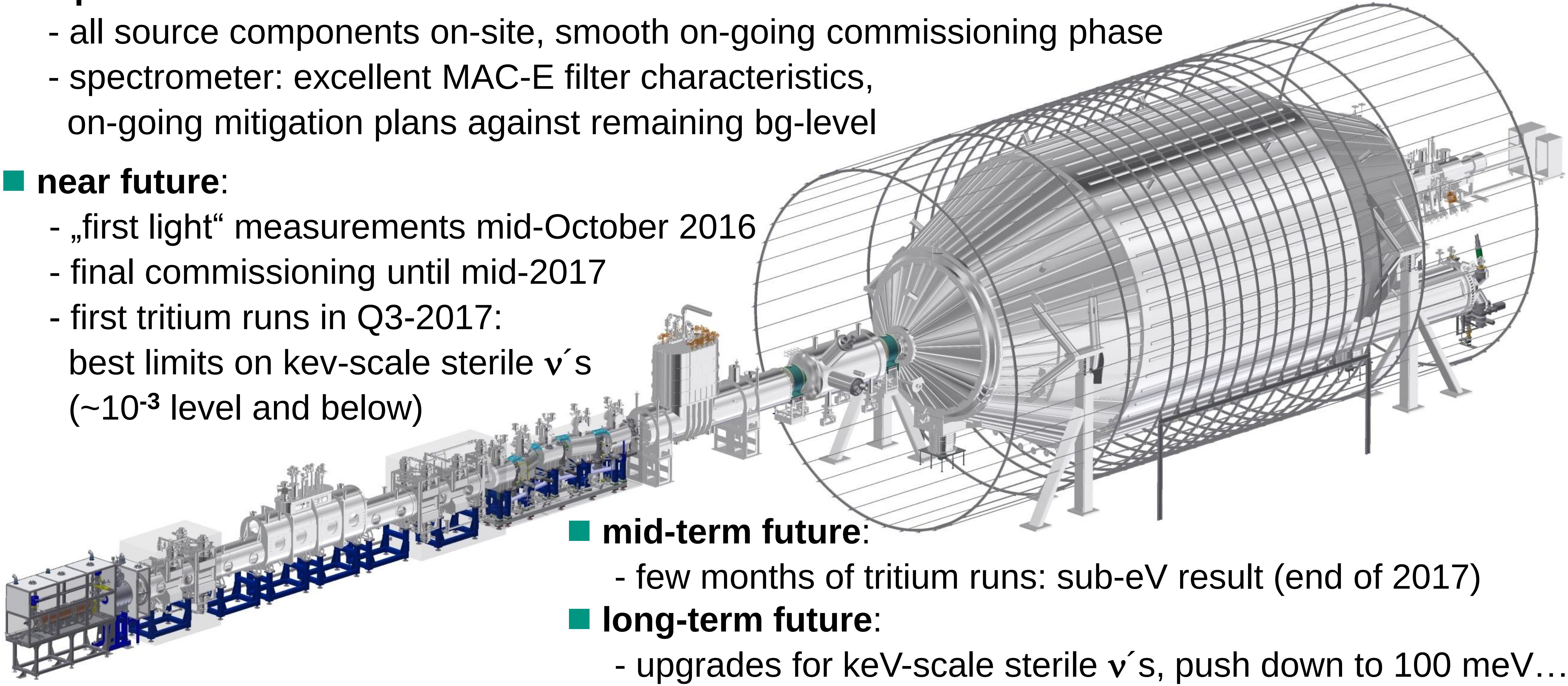
- HLL prototype
- IPE read-out



Conclusions & Outlook

- **experimental status**:
  - all source components on-site, smooth on-going commissioning phase
  - spectrometer: excellent MAC-E filter characteristics,
    on-going mitigation plans against remaining bg-level

- **near future**:
  - „first light“ measurements mid-October 2016
  - final commissioning until mid-2017
  - first tritium runs in Q3-2017:
    best limits on kev-scale sterile ν´s
    (~10^{-3} level and below)



- **mid-term future**:
  - few months of tritium runs: sub-eV result (end of 2017)
- **long-term future**:
  - upgrades for keV-scale sterile ν´s, push down to 100 meV…