Karlsruhe Institute of Technology

Direct neutrino mass measurement

Solvay-Francqui Workshop on

Neutrinos:
from Reactors to the Cosmos

Guido Drexlin, Institut für Experimentelle Kernphysik

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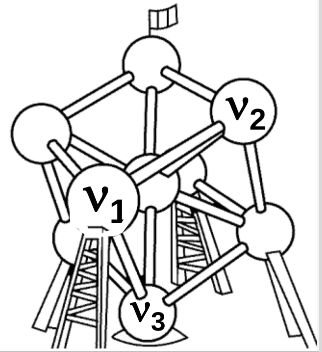

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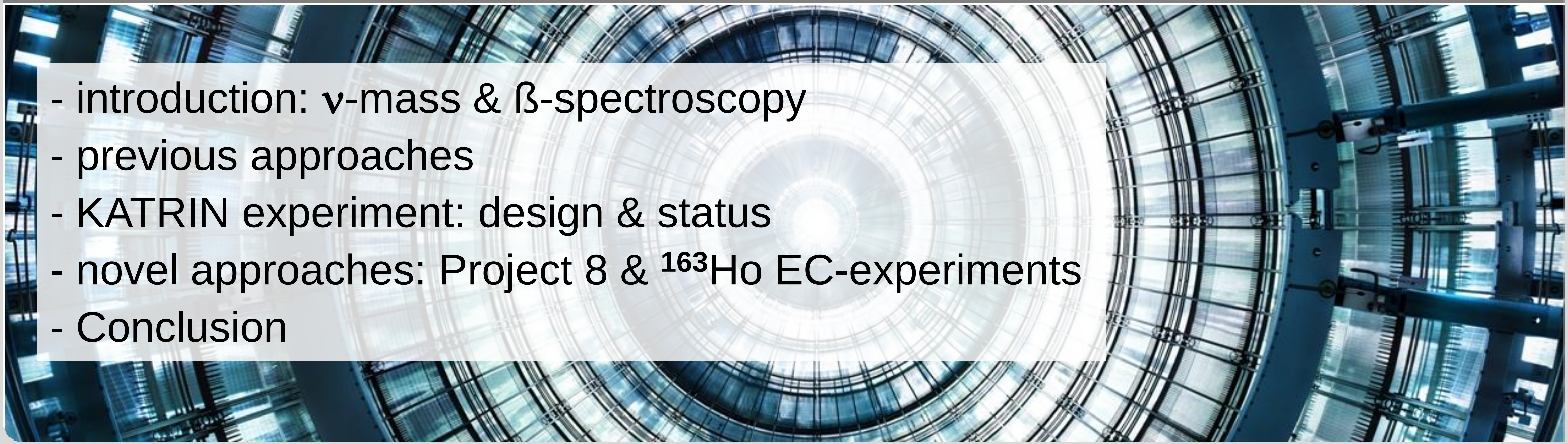
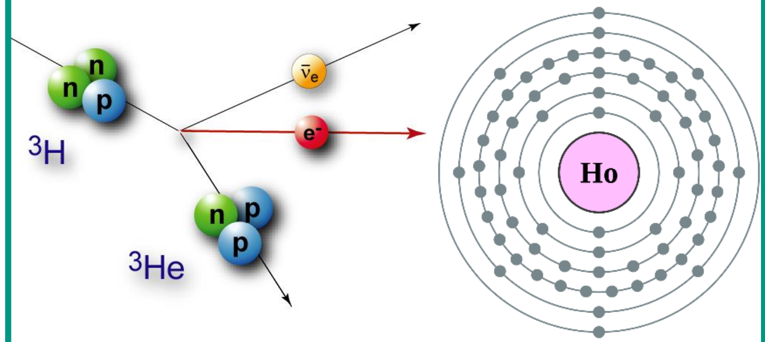


- introduction: ν-mass & ß-spectroscopy
- previous approaches
- KATRIN experiment: design & status
- novel approaches: Project 8 & ^{163}Ho EC-experiments
- Conclusion

hunting neutrino masses

kinematics weak decays

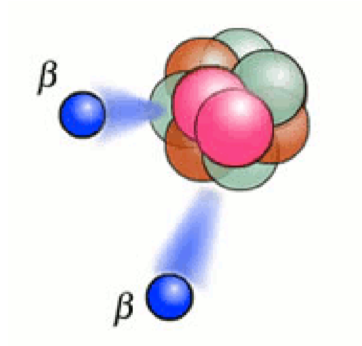
- ß-decay: ^{3}H, EC: ^{163}Ho
- **model-independent**



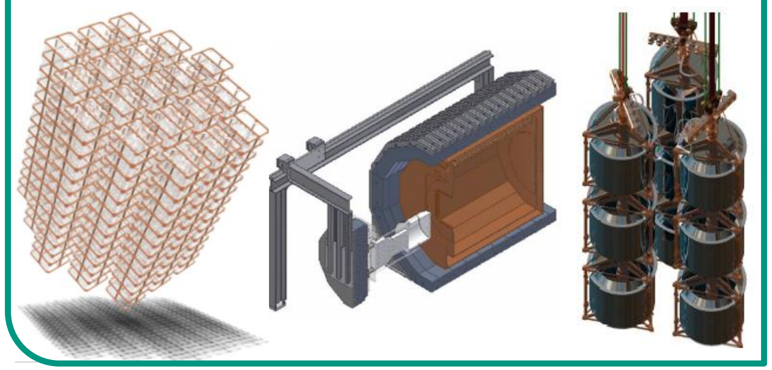
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

search for 0νßß-decay

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

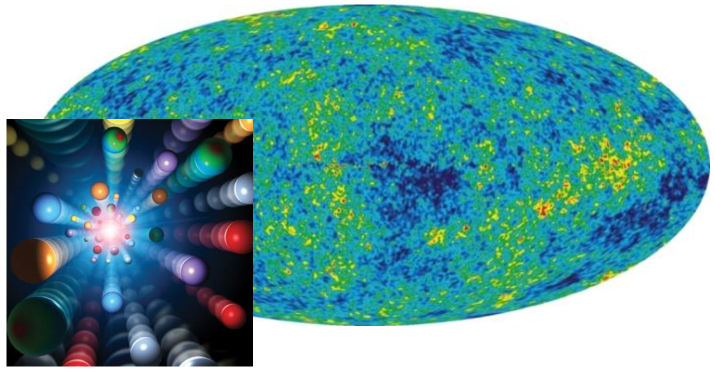


$$\langle m_{ßß} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$

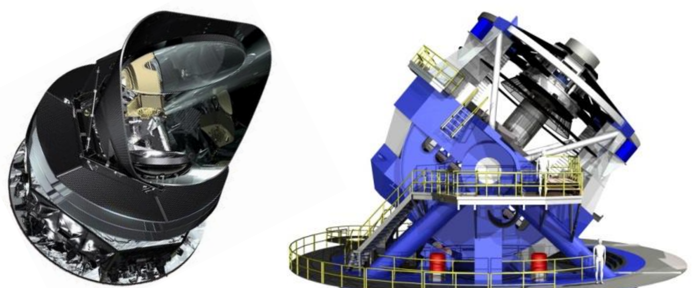


cosmology

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



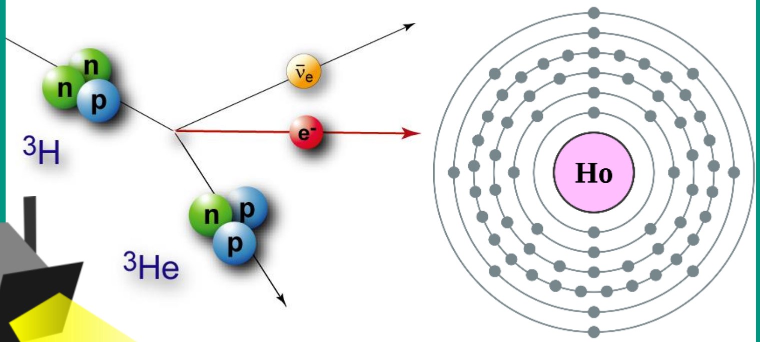
$$m_{tot} = \sum_{i=1}^{3} m_i$$



hunting neutrino masses

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

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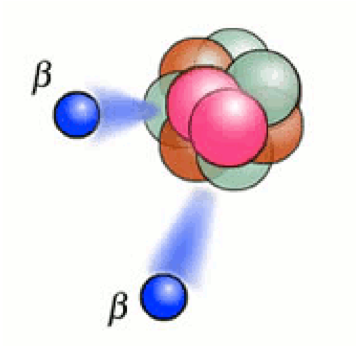
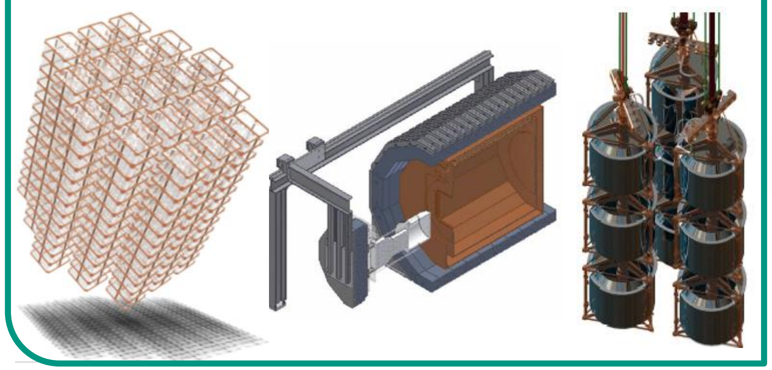


$$\left\langle m_{ßß} \right\rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$



cosmology

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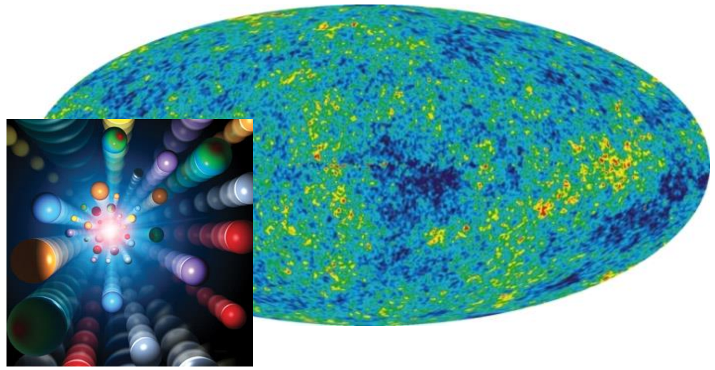

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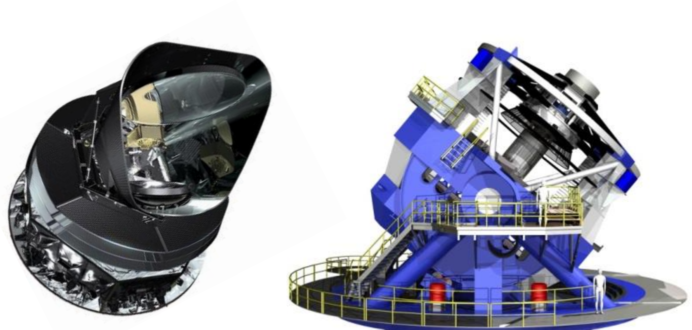
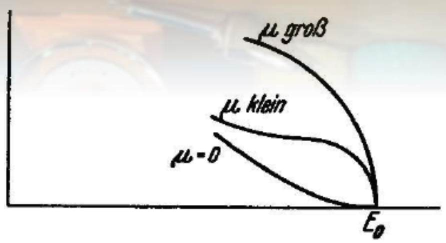


introduction: ν-mass & ß-spectroscopy



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

ß-decay: Fermi theory & ν-mass

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

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

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

Fermi function F(E,Z)

observable $m^2(\nu_e)$:
effective ´electron-ν-mass´

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

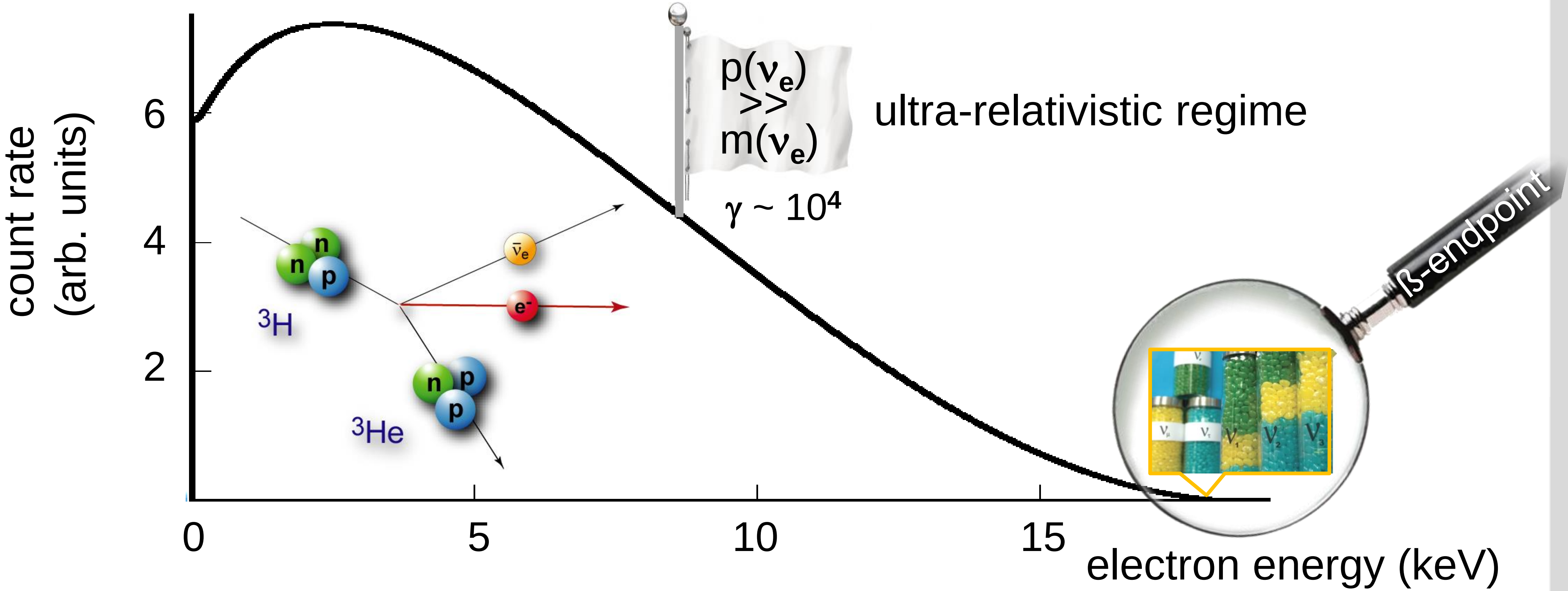
´incoherent´ sum of the ν-mass eigenstates m_i

- small shape modifications due to final states, radiative & recoil corrections

ß-decay: kinematics

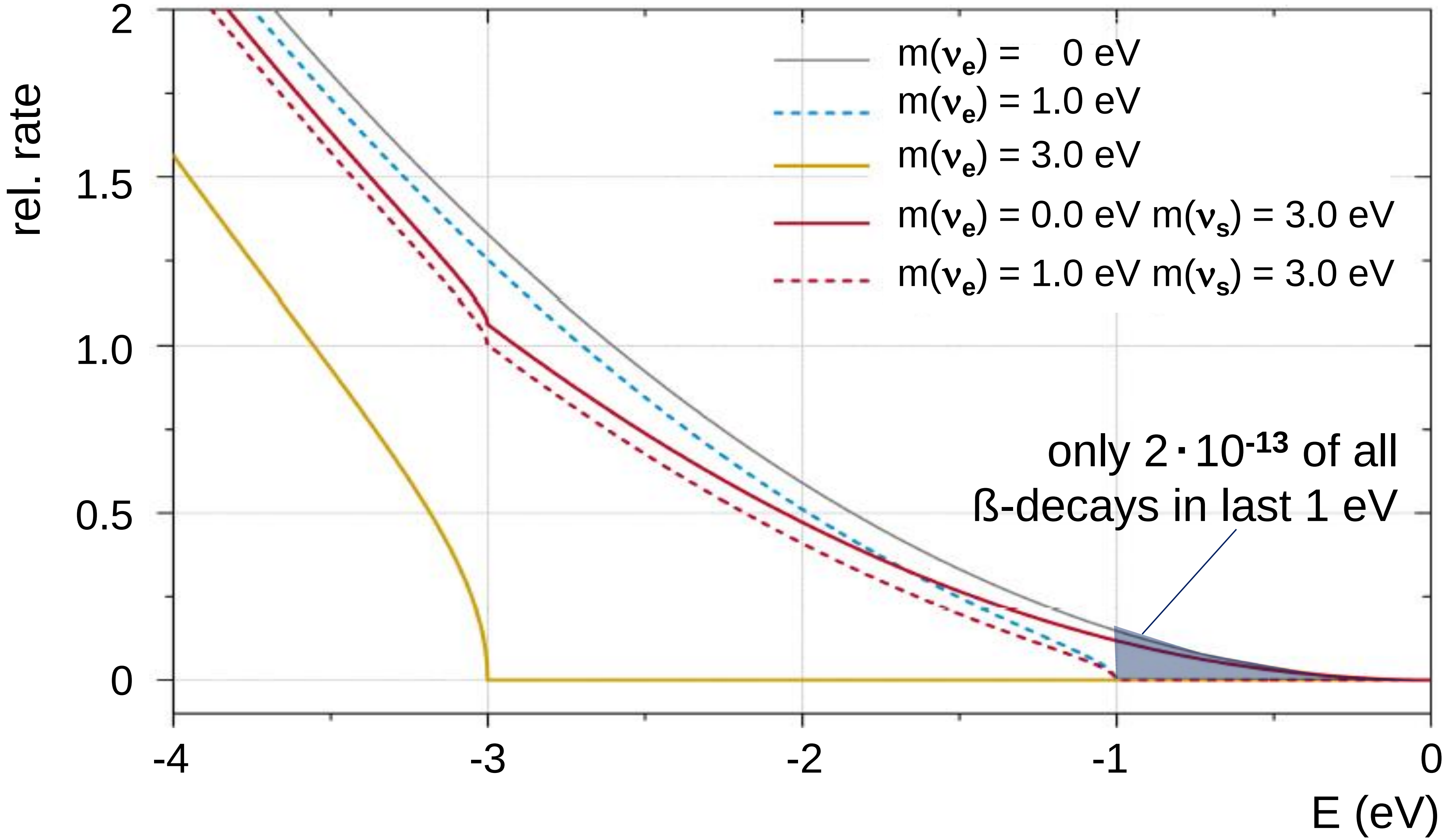
- model independent measurement of m(ν_e)
  - based solely on **kinematic parameters & energy conservation**

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



ß-decay: relative shape modification

- **relative shape measurement** only, as E_0 not known precisely (~eV)



ß-isotopes for highest ν-mass sensitivity

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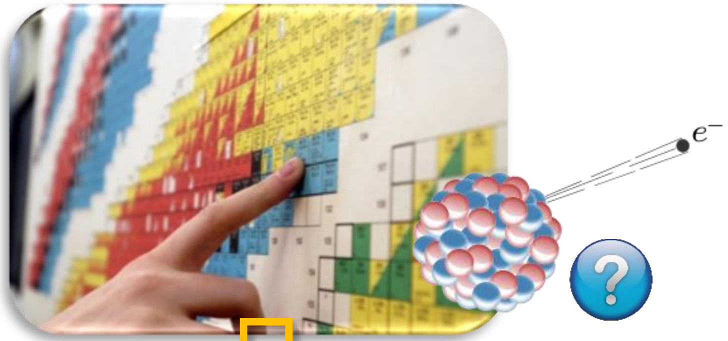
highest statistics

lowest systematics



atomic
molecular
condensed

ß-source requirements
short half life $t_{½}$
low endpoint energy E_0
superallowed/allowed transition
simple atomic/molecular structure
high purity / established procurement

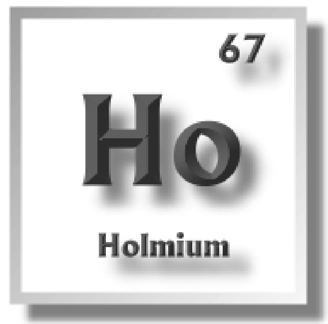
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

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

tritium

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

^{163}Dy*: line widths	
Q_{EC}	2.3 – 2.8 keV
$t_{1/2}$	**4570 y**



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

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

discontinued

ß-isotopes for highest ν-mass sensitivity

highest statistics

lowest systematics

atomic
molecular
condensed

ß-source requirements

ß-source requirements
short half life $t_{½}$
low endpoint energy E_0
superallowed/allowed transition
simple atomic/molecular structure
high purity / established procurement

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

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

KATRIN

PROJECT 8

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

^{163}Dy*: line widths	
E_0	2.3 – 2.8 keV
$t_{1/2}$	4570 y

ECHo

HOLMES

NUMECS

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

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

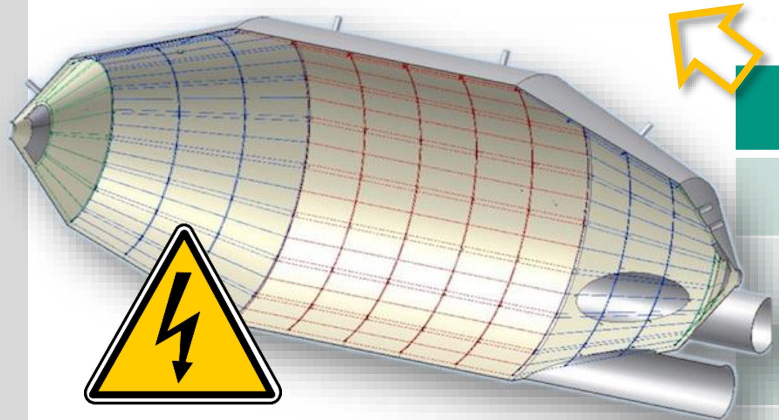
(MARE)

read-out technologies for highest sensitivity

MAC-E filter

min. longitudinal ß-energy $E_{||}$

ΔE = 0.9 eV (100%)



ß-detection requirements

cover large solid angle (~ 2π)

very low background rate at E_0

high energy resolution (~ eV)

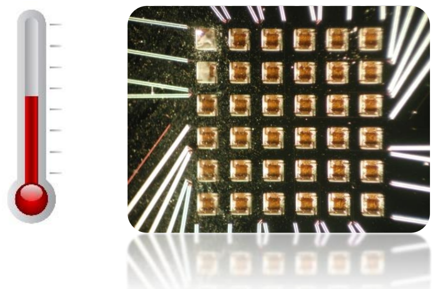
short dead time, no pile up

ΔE < 2 eV usually suffices for sub-eV sensitivity

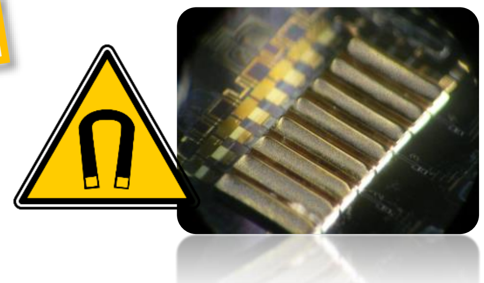
thermal µ-calorimeter

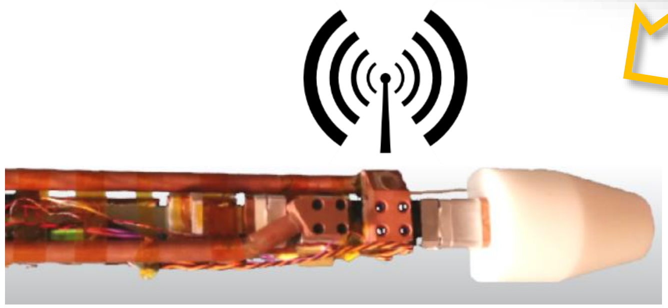
released decay-energy

ΔE ~ 10 eV (FWHM)



source ⇔ detector





cyclotron radiation

max. transversal ß-energy $E_{\perp}$

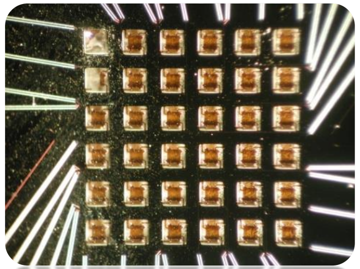
ΔE = 15 eV (FWHM)

magn.-metal. calorimeter

decay-energy

ΔE = 2-10 eV (FWHM)

experimental ν-mass data: Re-187, Mainz & Troitsk



bolometer experiments for ^{187}Re

^{187}Re-experiments (MANU, MIBETA, MARE)

^{187}Re as ß-emitter: natural isotope content = 62.8 %

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

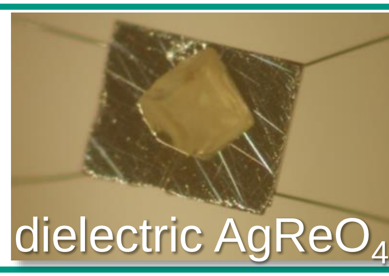
$5/2^+ \rightarrow 1/2^-$ ´unique´ 1st forbidden transition (shape factor), BEFS

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

previous ^{187}Re-experiments MANU, MIBETA

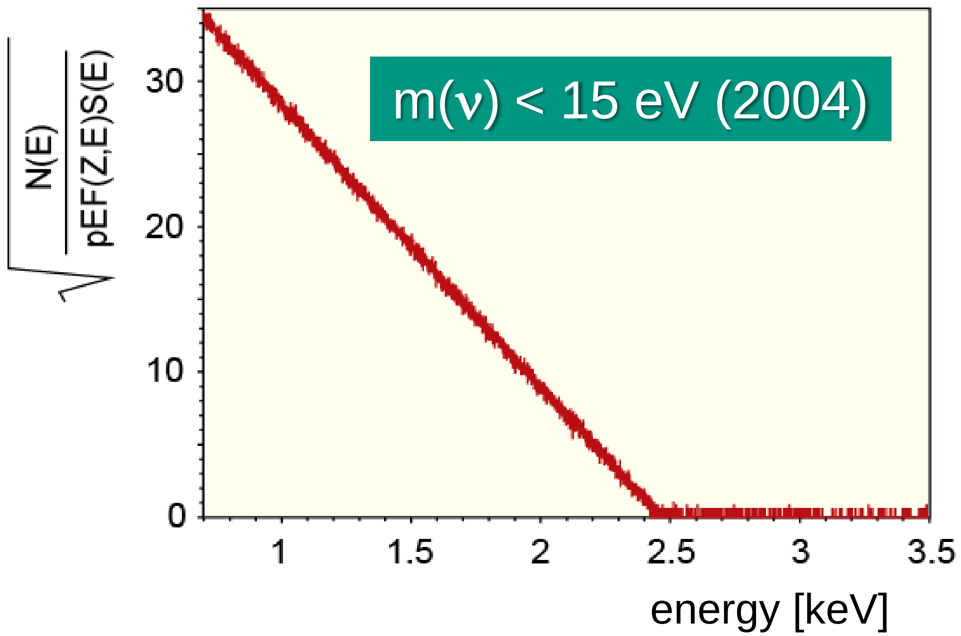
MANU: metallic Rhenium [Genova]

MIBETA: dielectric $AgReO_4$ crystals [Milano]



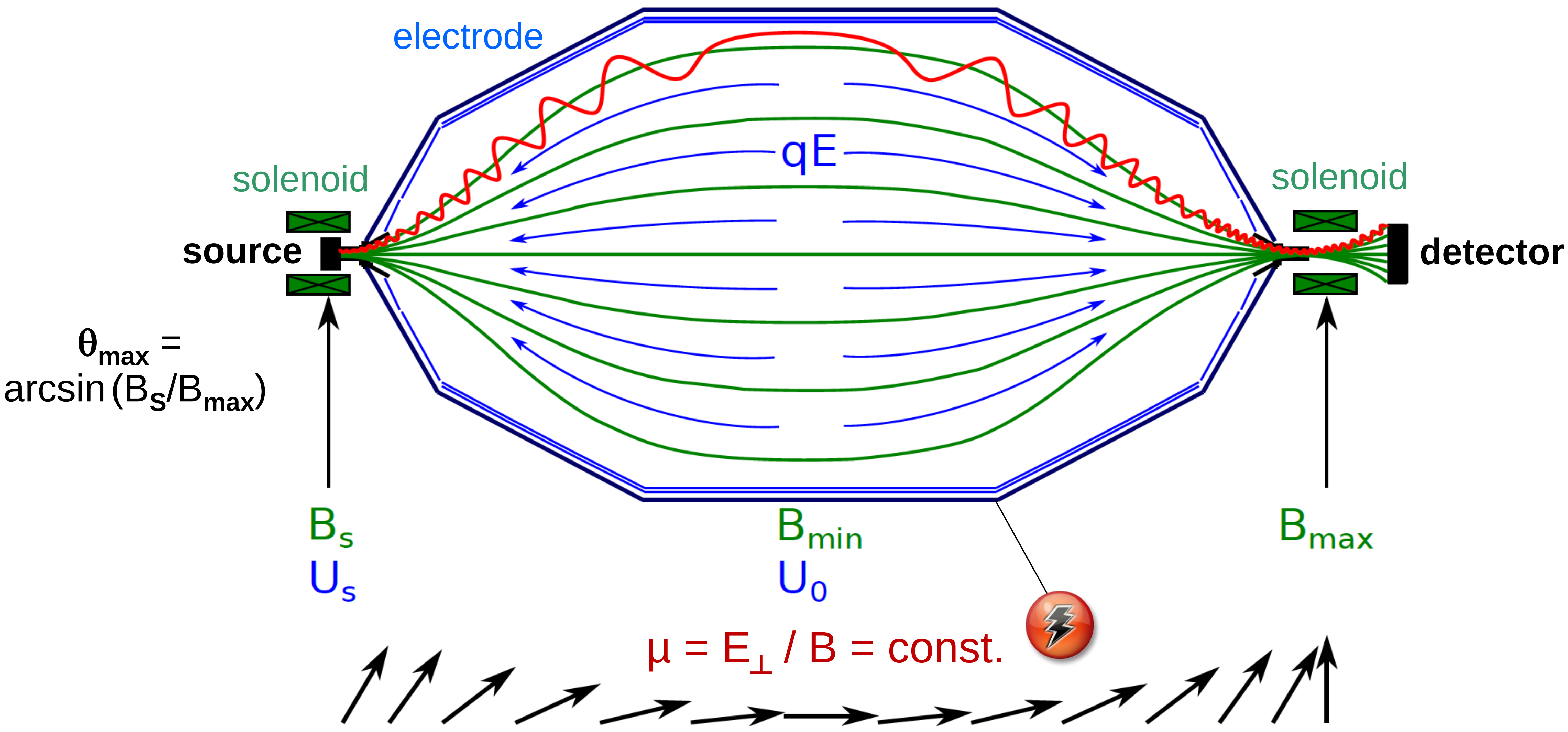
MARE [Milano, Genova]

- metallic Re absorbers (Genova) with TES-sensors, t_{rise} ~160 µs
- 6x6 arrays of $AgReO_4$ crystals Si-implanted thermistors, t_{rise} ~ 250 µs
- ΔE ~ 10-20 eV
- **focus now shifted to Ho-163**



MAC-E principle: Mainz, Troitsk, KATRIN

- **M**agnetic **A**diabatic **C**ollimation **& E**lectrostatic **Filter**

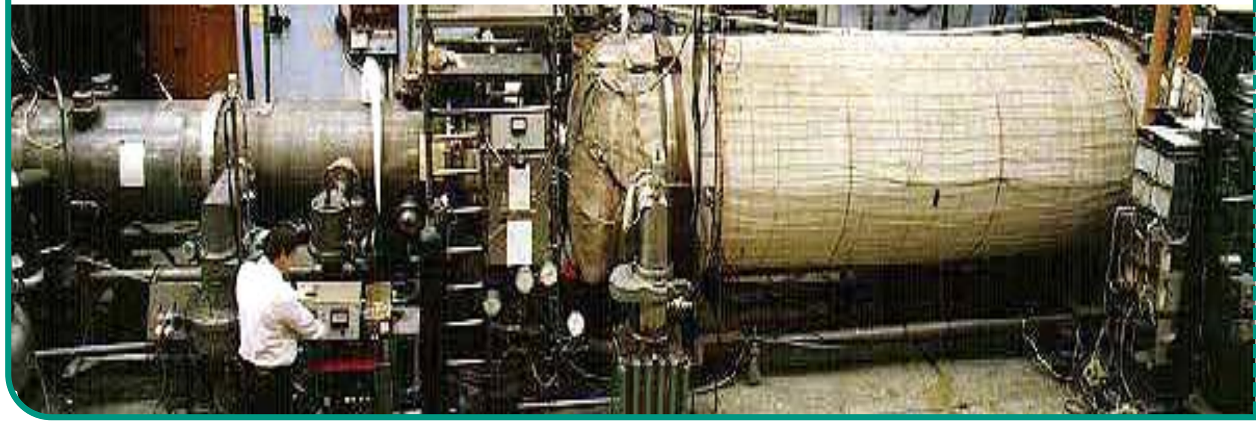


$\Delta E / E = B_{min} / B_{max}$

Troitsk & Mainz experiments

Troitsk experiment

- windowless gaseous tritium source



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

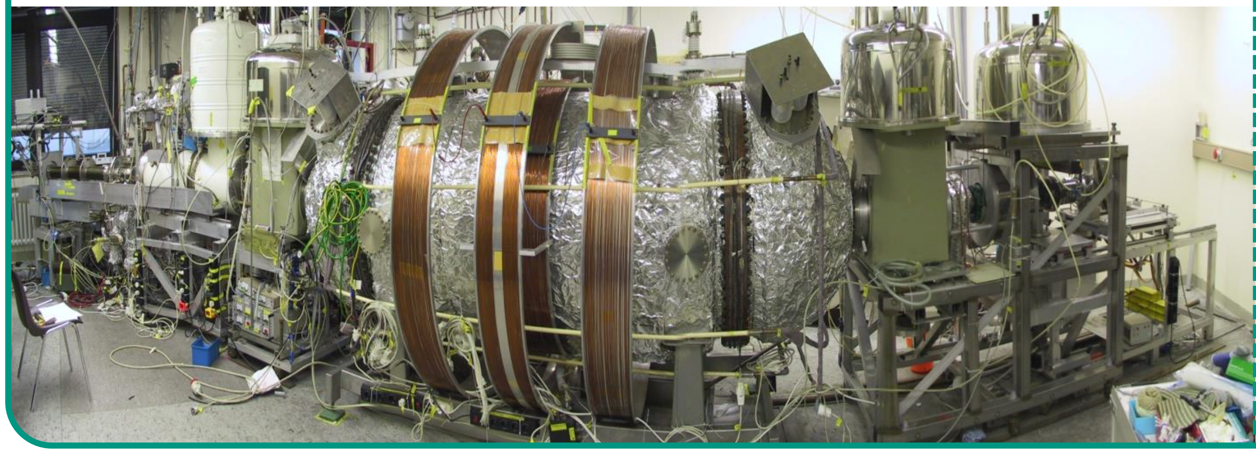
$$m^2(\nu_e) = (-0.67 \pm 1.89 \pm 1.68)\ eV^2$$

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

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

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

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

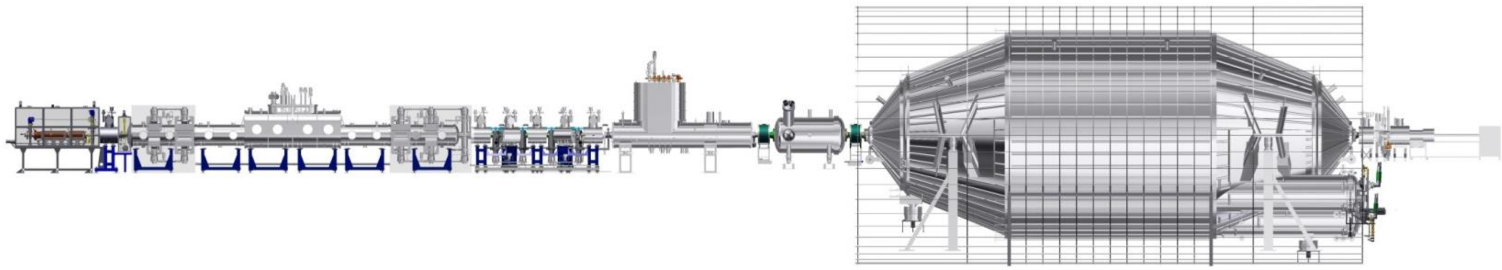
C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

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
- reference ν-mass sensitivity: **$m(\nu_e)$ = 200 meV**



■ KATRIN member institutes

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

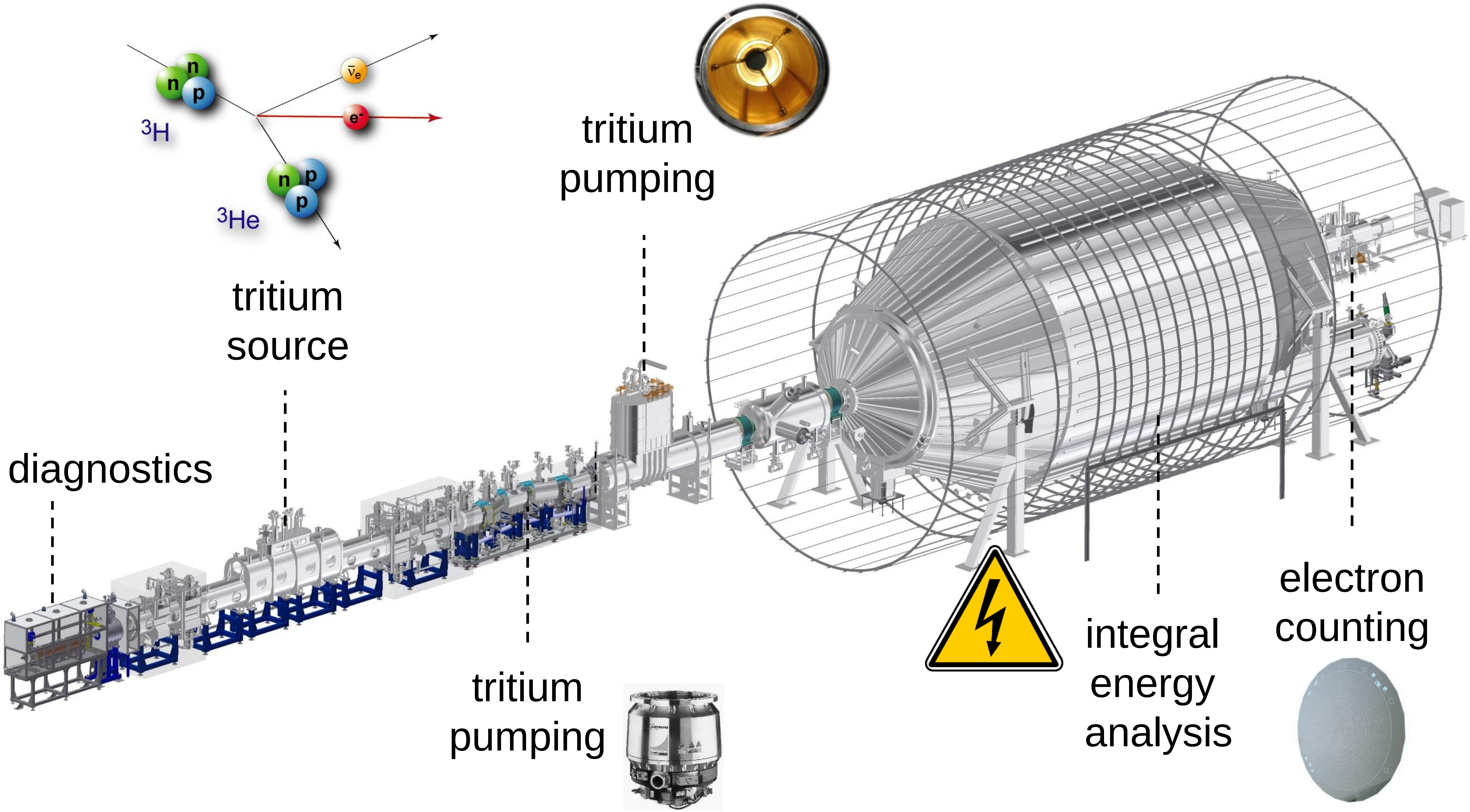
UCSB

BERGISCHE UNIVERSITÄT WUPPERTAL

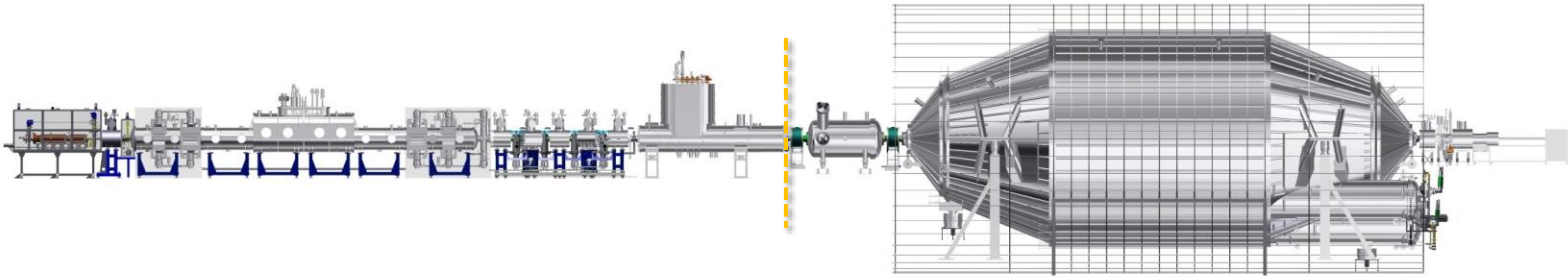
W UNIVERSITY of WASHINGTON

universitätbonn

KATRIN overview: 70 m beamline



KATRIN – benchmark parameters



tritium source: 10^{11} ß-decays/s

(≡ LHC particle production)

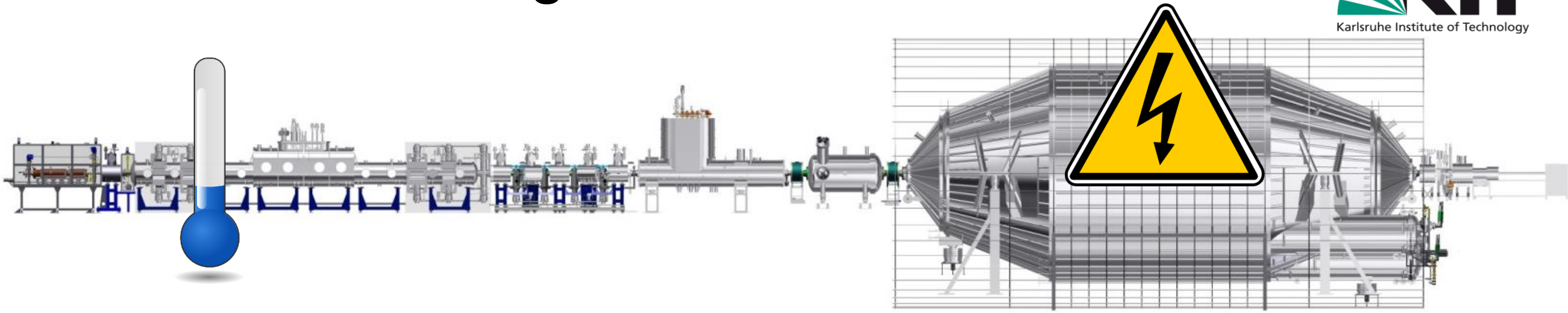
total background: 10^{-2} cps

(≡ low level @ 1 mwe)

experimental challenges

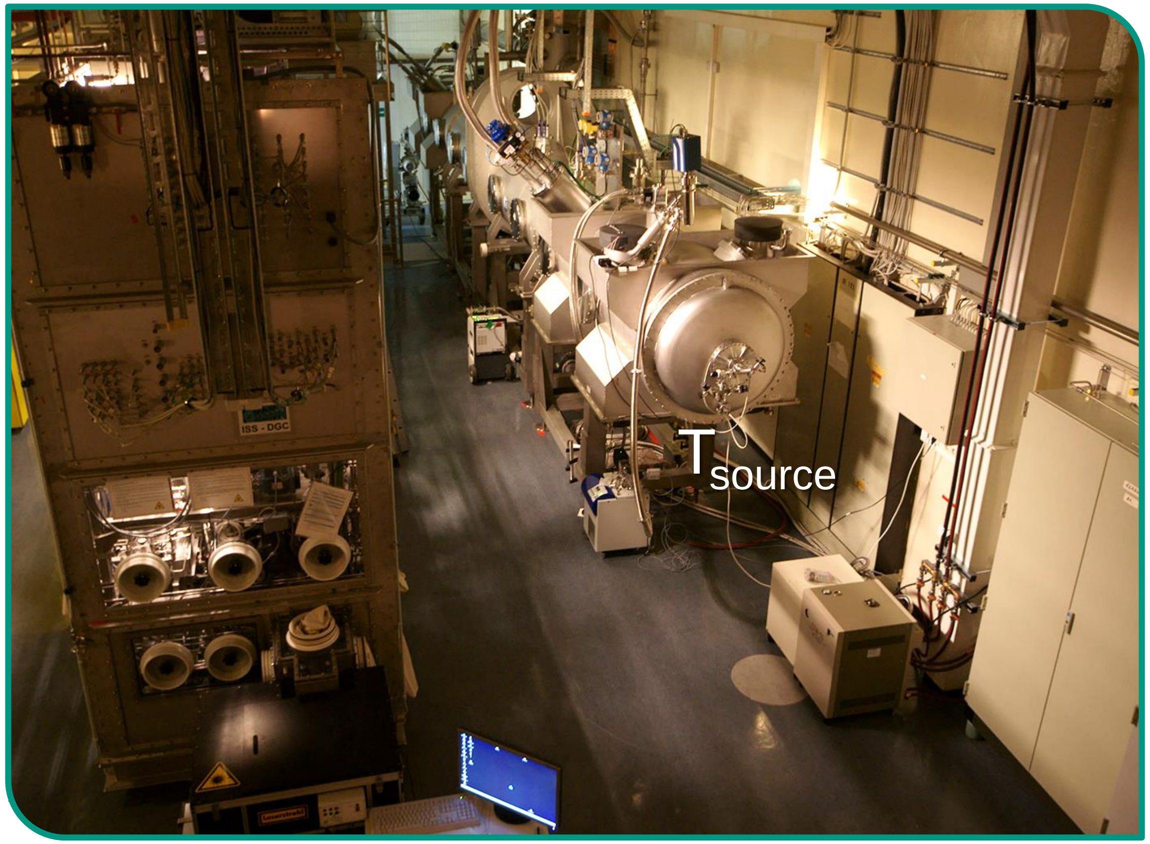
- 10^{-3} stability of tritium source column density
- 10^{-3} isotope content in source
- 10^{-5} non-adiabaticity in electron transport
- 10^{-6} monitoring of HV-fluctuations
- 10^{-8} remaining ions after source
- 10^{-14} remaining flux of molecular tritium

KATRIN – challenges and solutions

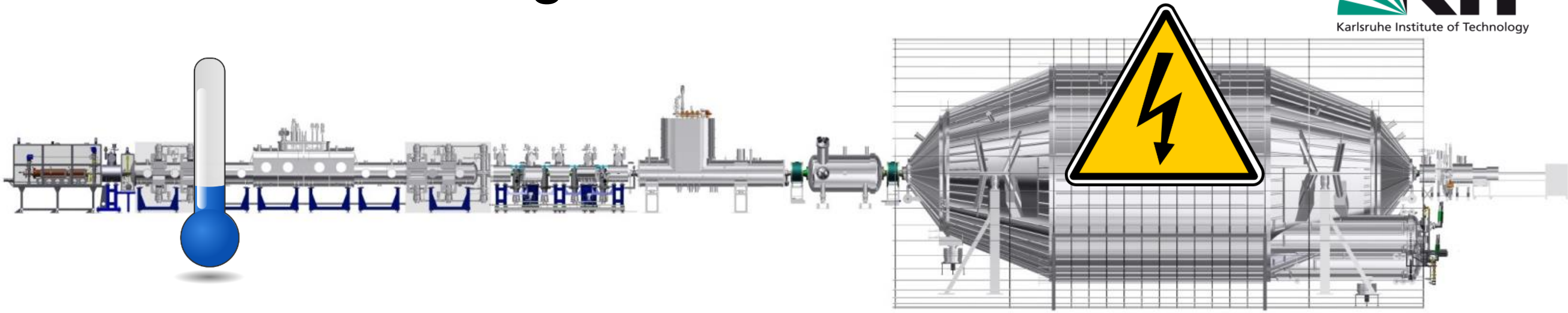


required: source fluctuation: $\Delta T < 10^{-3}$

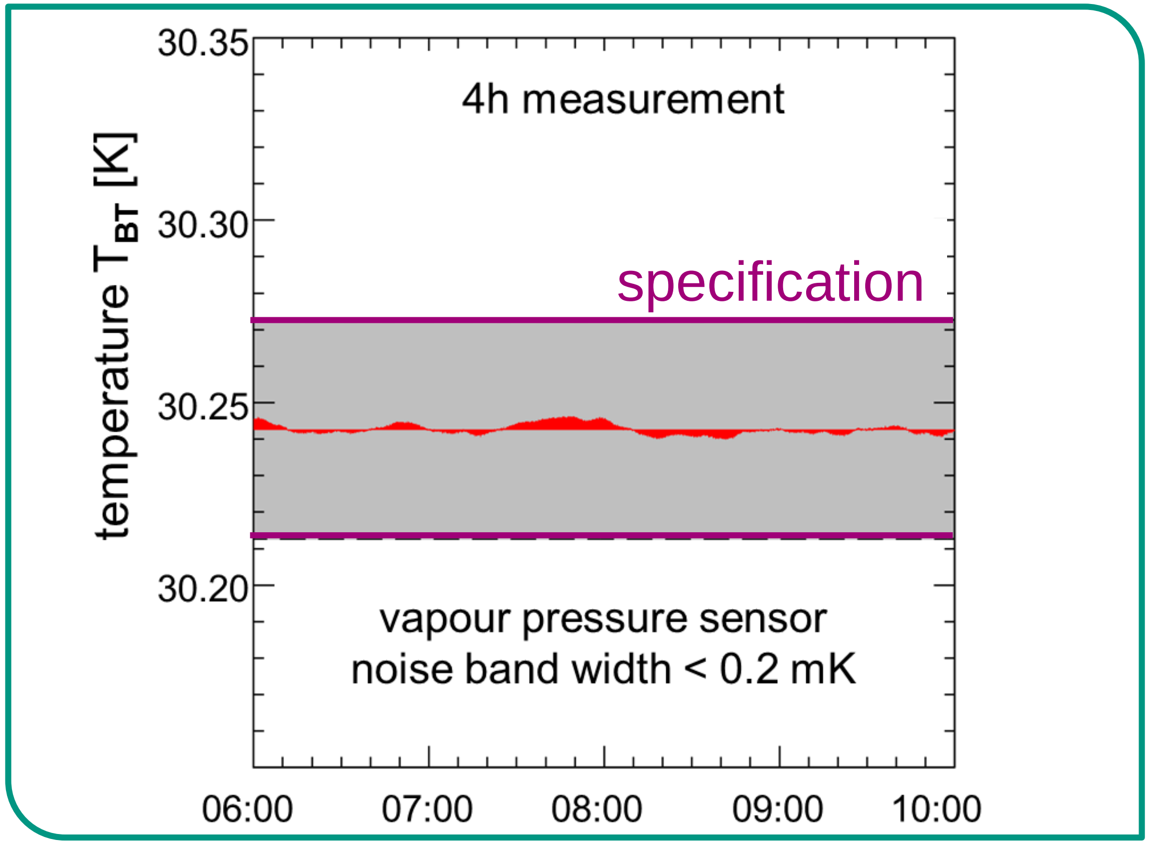
required: HV-fluctuations: $\Delta U < 60$ mV



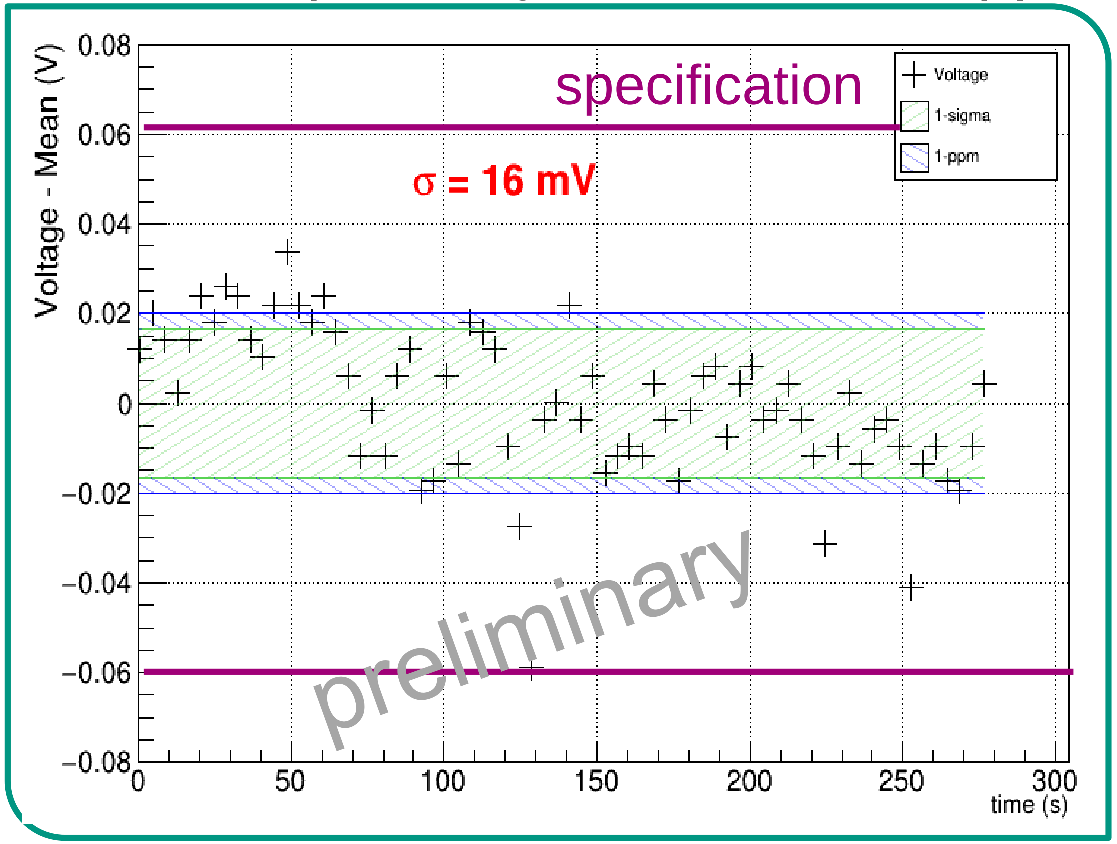
KATRIN – challenges and solutions



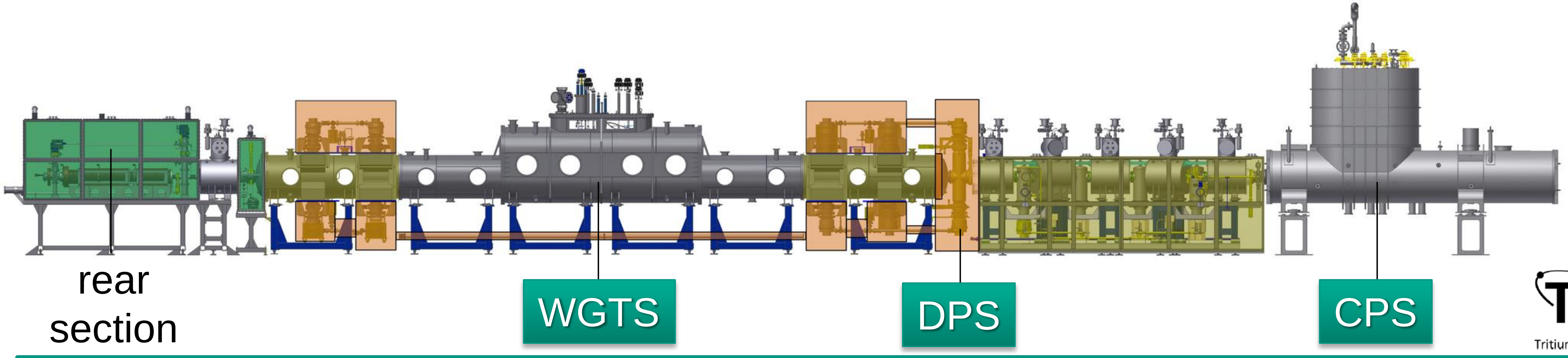
WGTS demonstrator: $\Delta T \sim 10^{-4}$



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



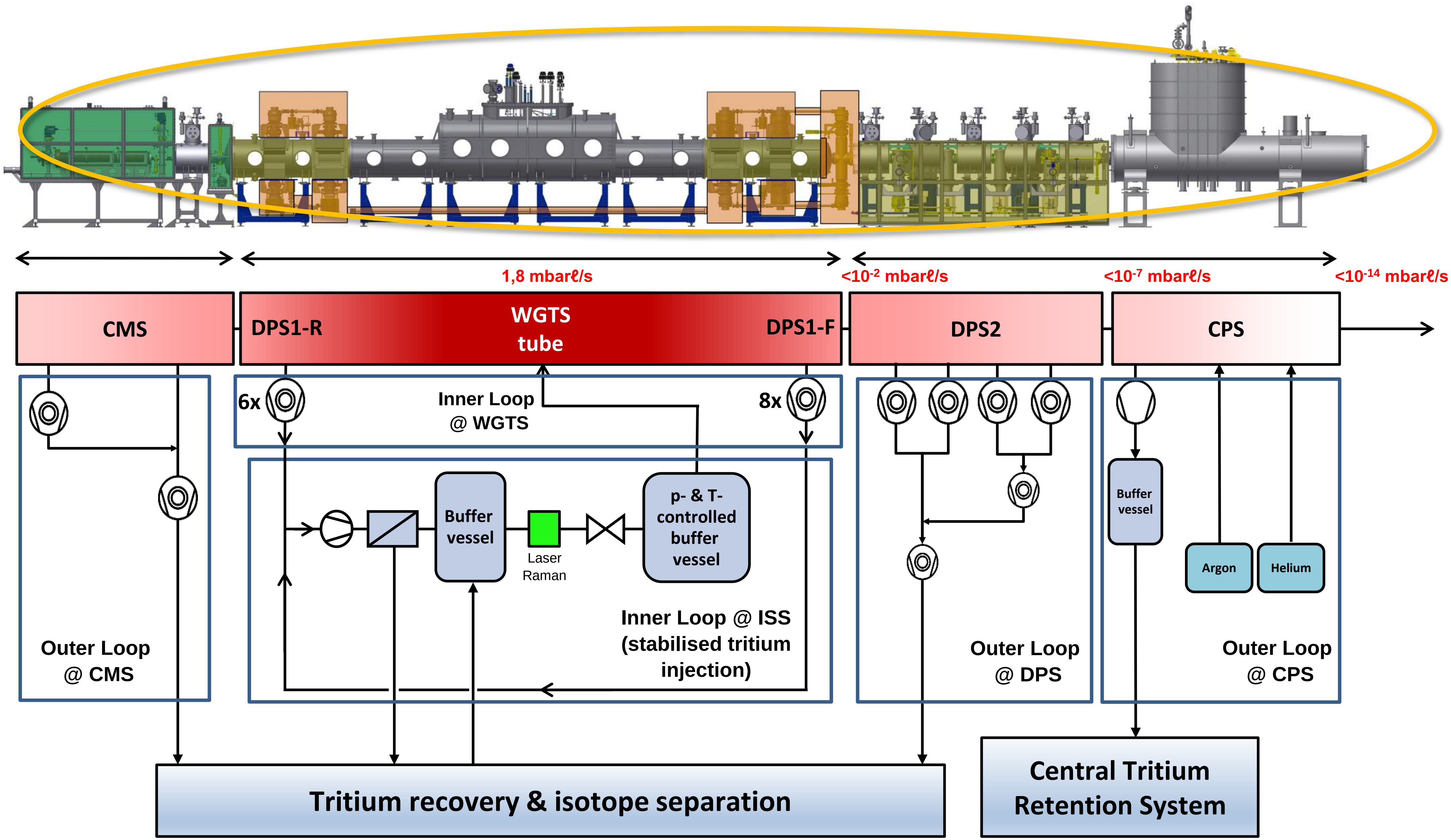
Tritium Laboratory Karlsruhe – TLK



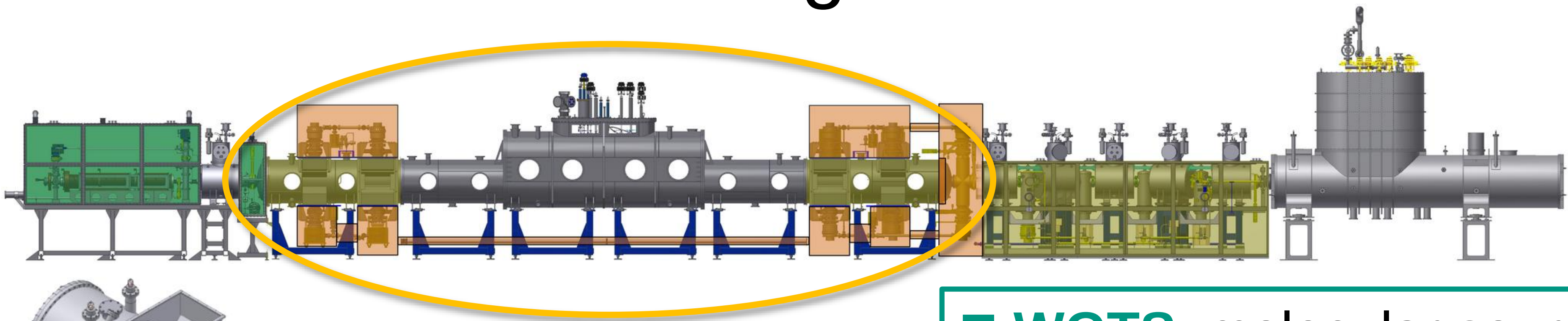
- **TLK**: unique large research facility at KIT for KATRIN and fusion (ITER)
  20 years of experience in tritium handling and processing, > 20 FTE

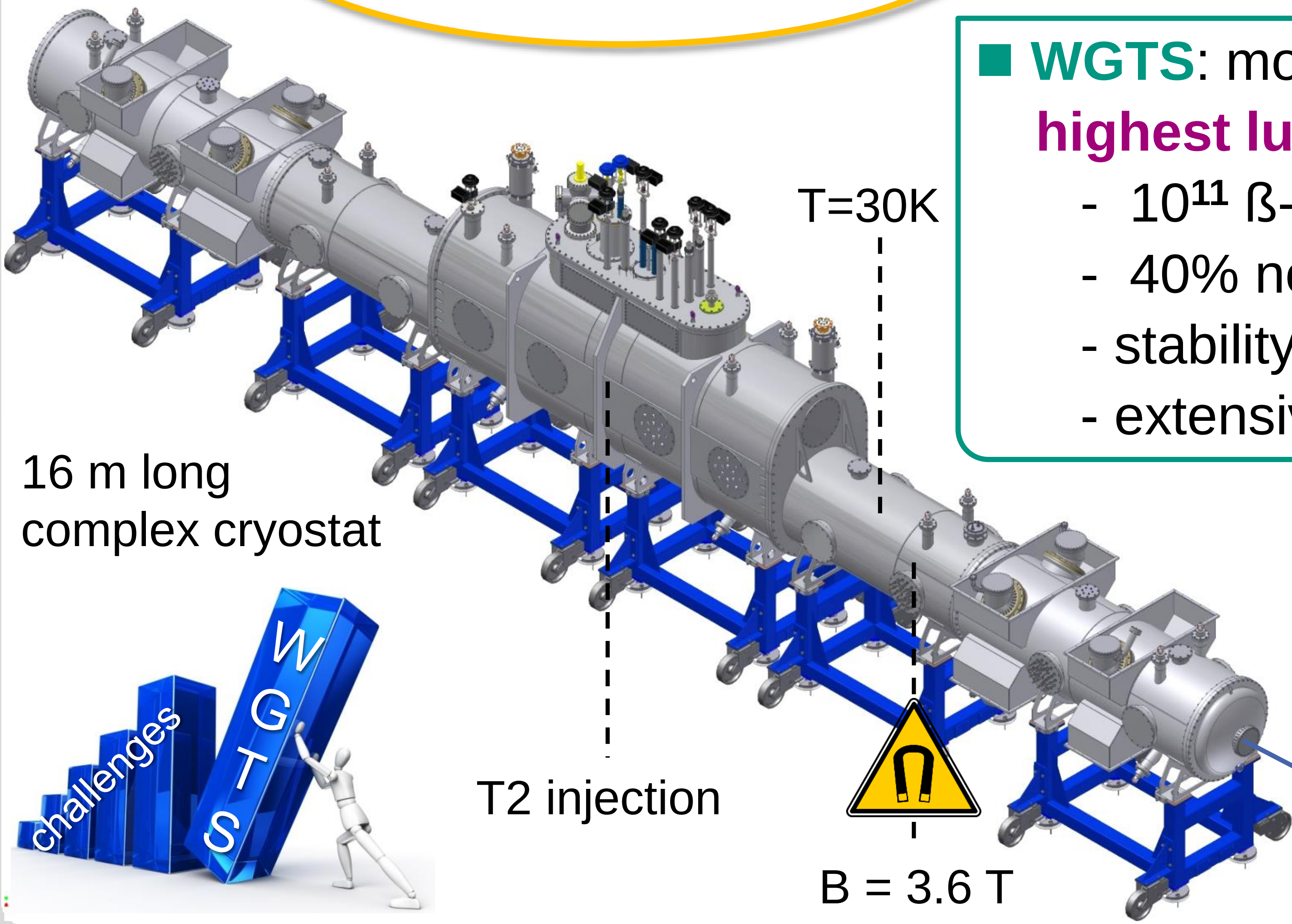
B. Bornschein et al., Fusion Sci. Techn. 60 (2011) 1088

TLK – closed tritium loop system



WGTS – windowless gaseous source

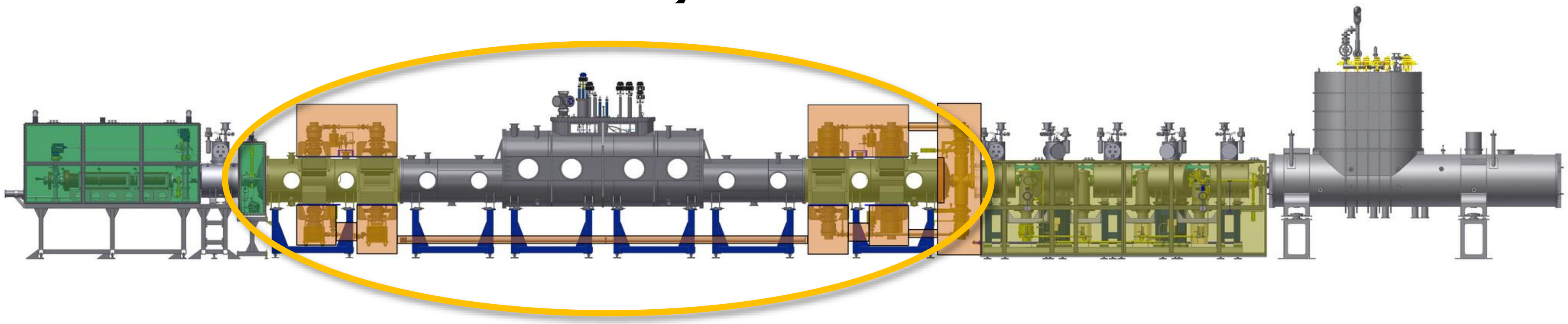




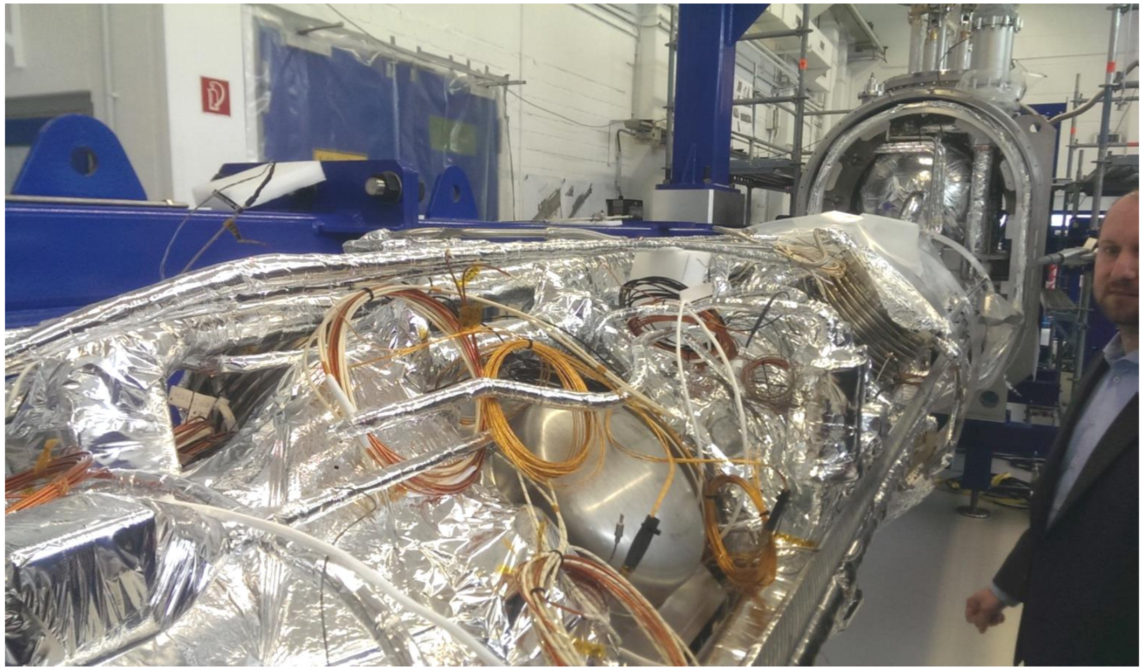
- **WGTS**: molecular source (>90% T_2)
  highest luminosity & **stability**
  - 10^{11} ß-decays / s
  - 40% no-loss electrons
  - stability at level 10^{-3}
  - extensive control of systematics

need very good temperature stability and homogeneity $\Delta T < 30$ mK (at 30 K)

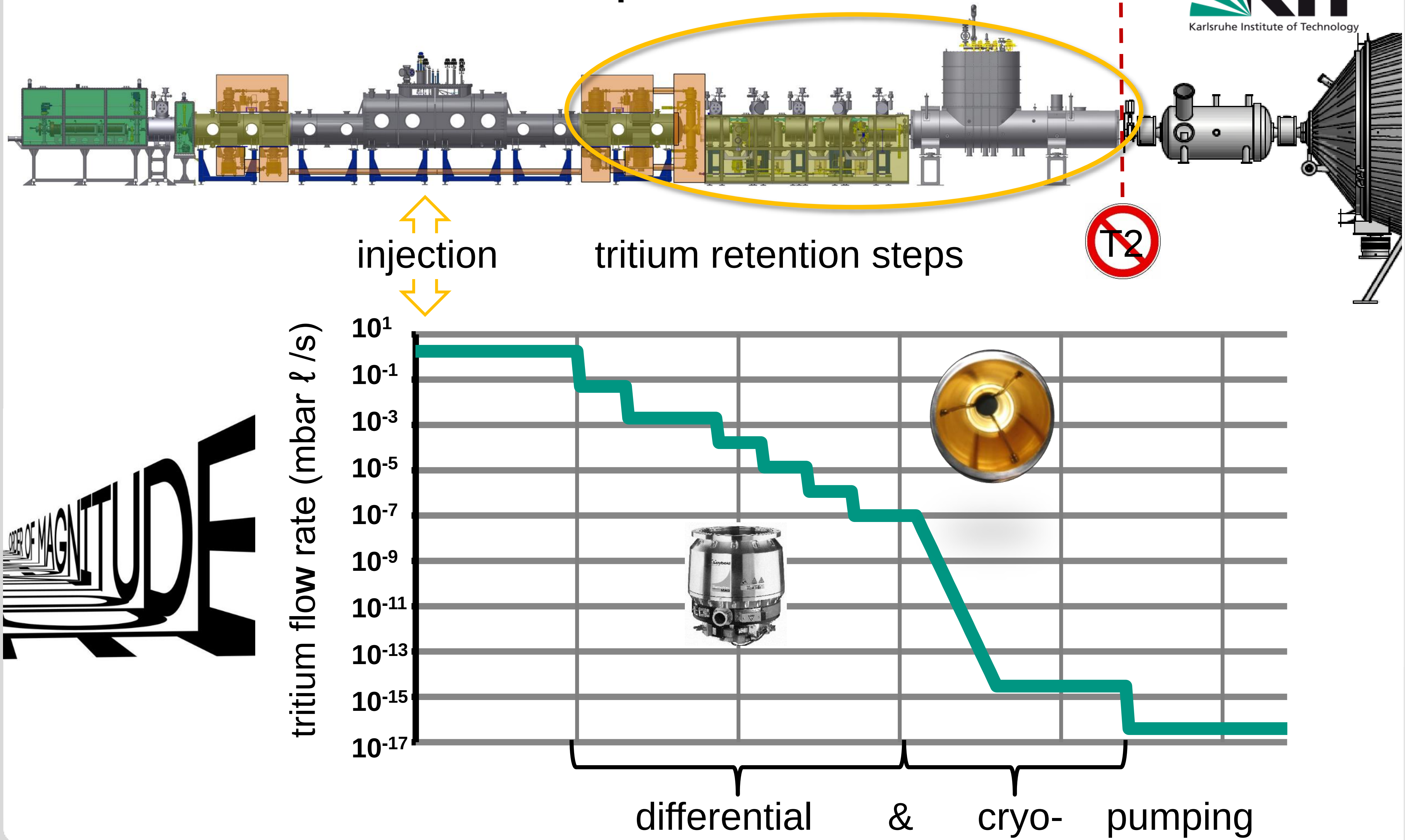
WGTS – assembly status



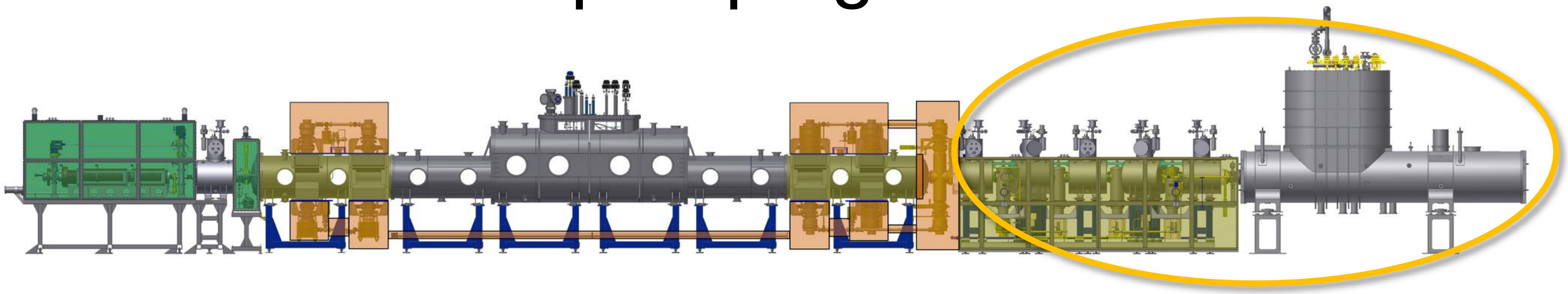
- **cryostat assemby at ri GmbH progressing well and on schedule**
  - arrival at KIT (TLK) expected in mid-August 2015
  - WGTS system integration with tritium loops is on the critical path



tritium retention techniques

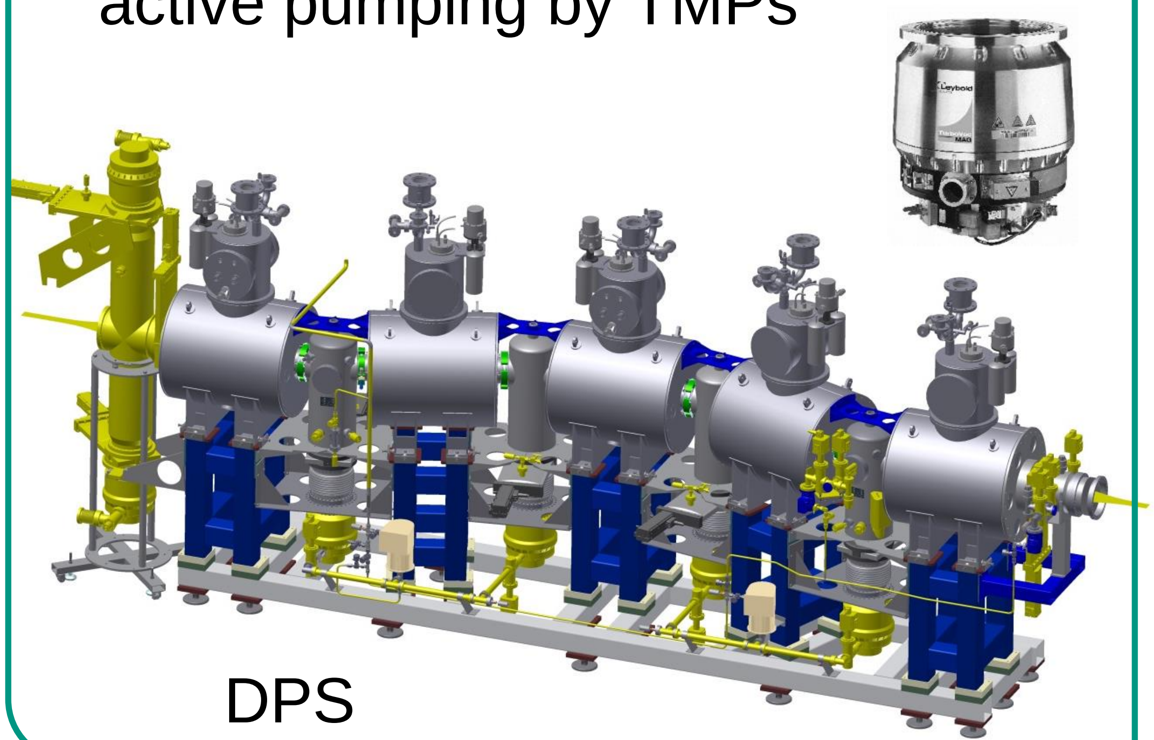


units for tritium pumping

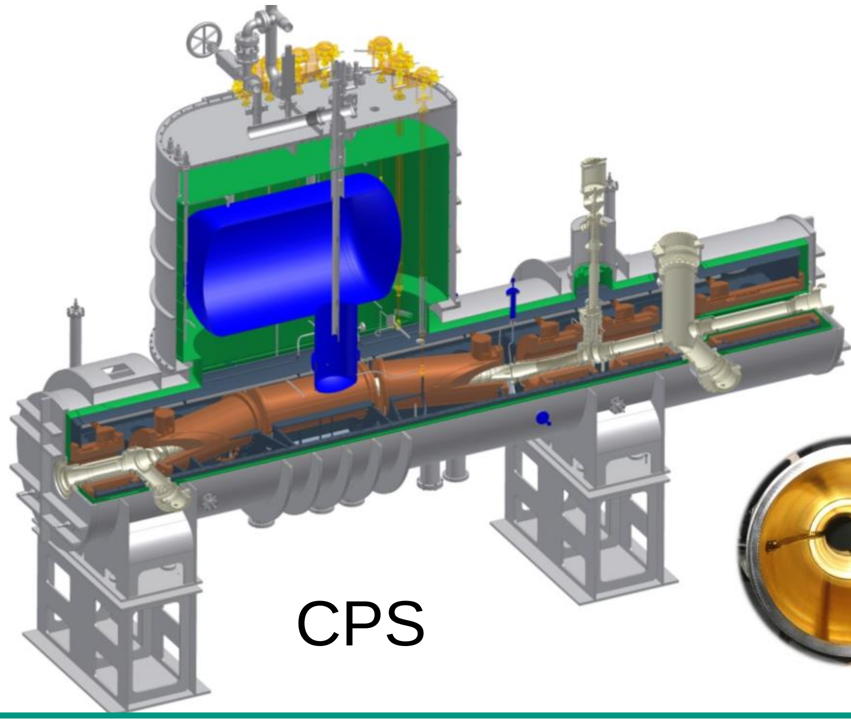


- DPS & CPS: two large cryostat systems for overall retention **factor > 10^{14}**

- **Differential Pumping Section DPS**
  active pumping by TMPs



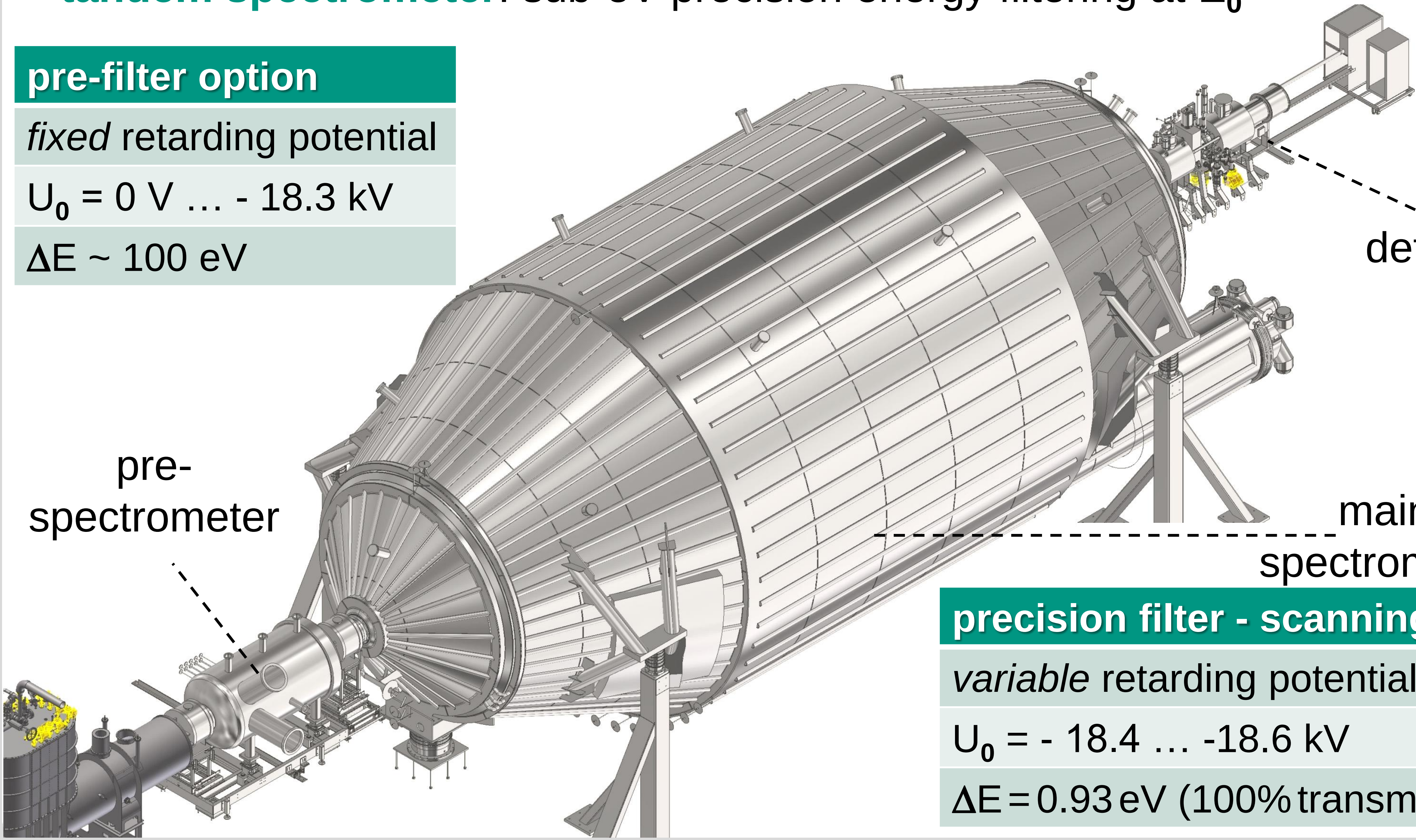
- **Cryogenic Pumping Section CPS**
  cryosorption on Ar-frost



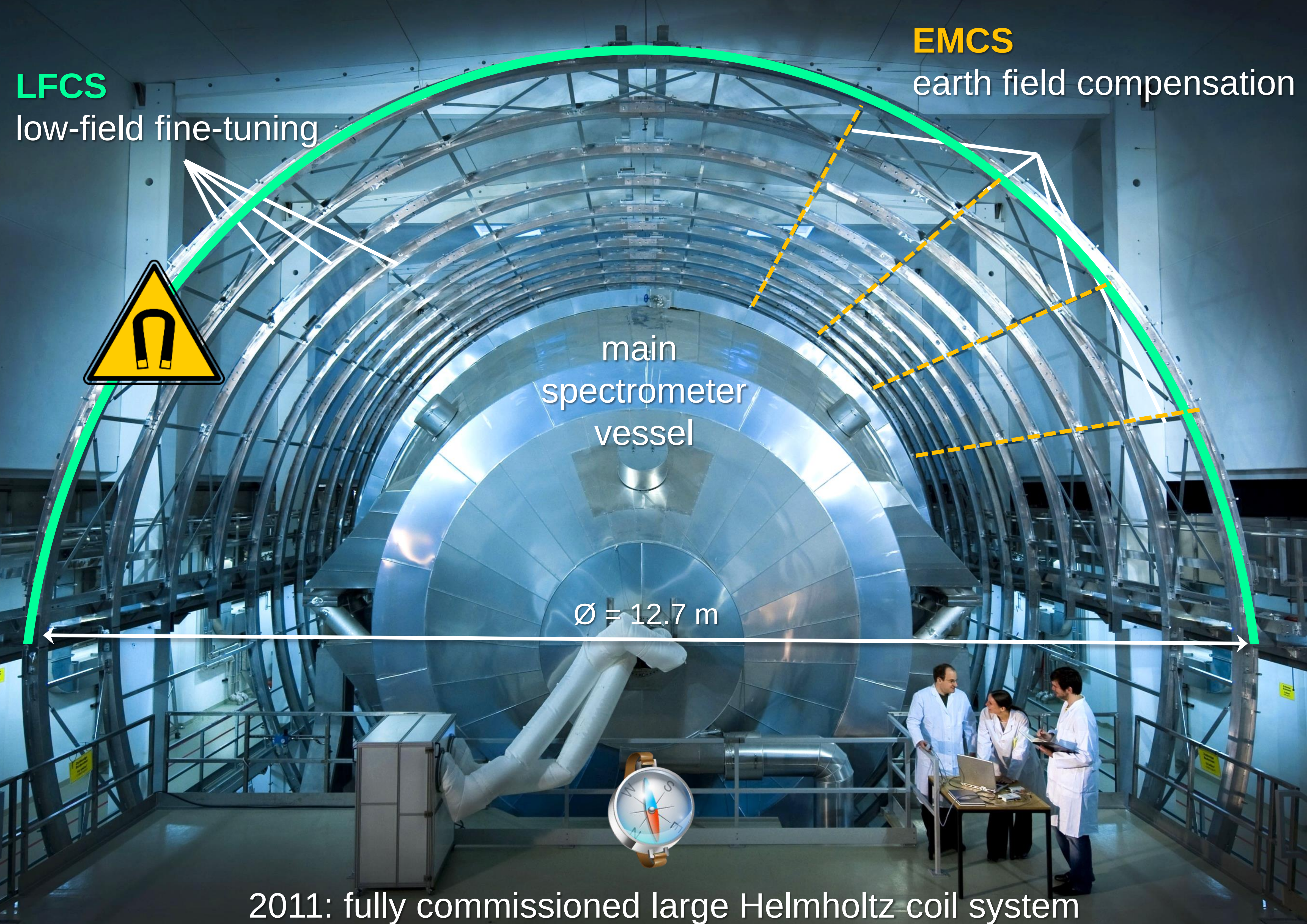
electrostatic spectrometers & detector

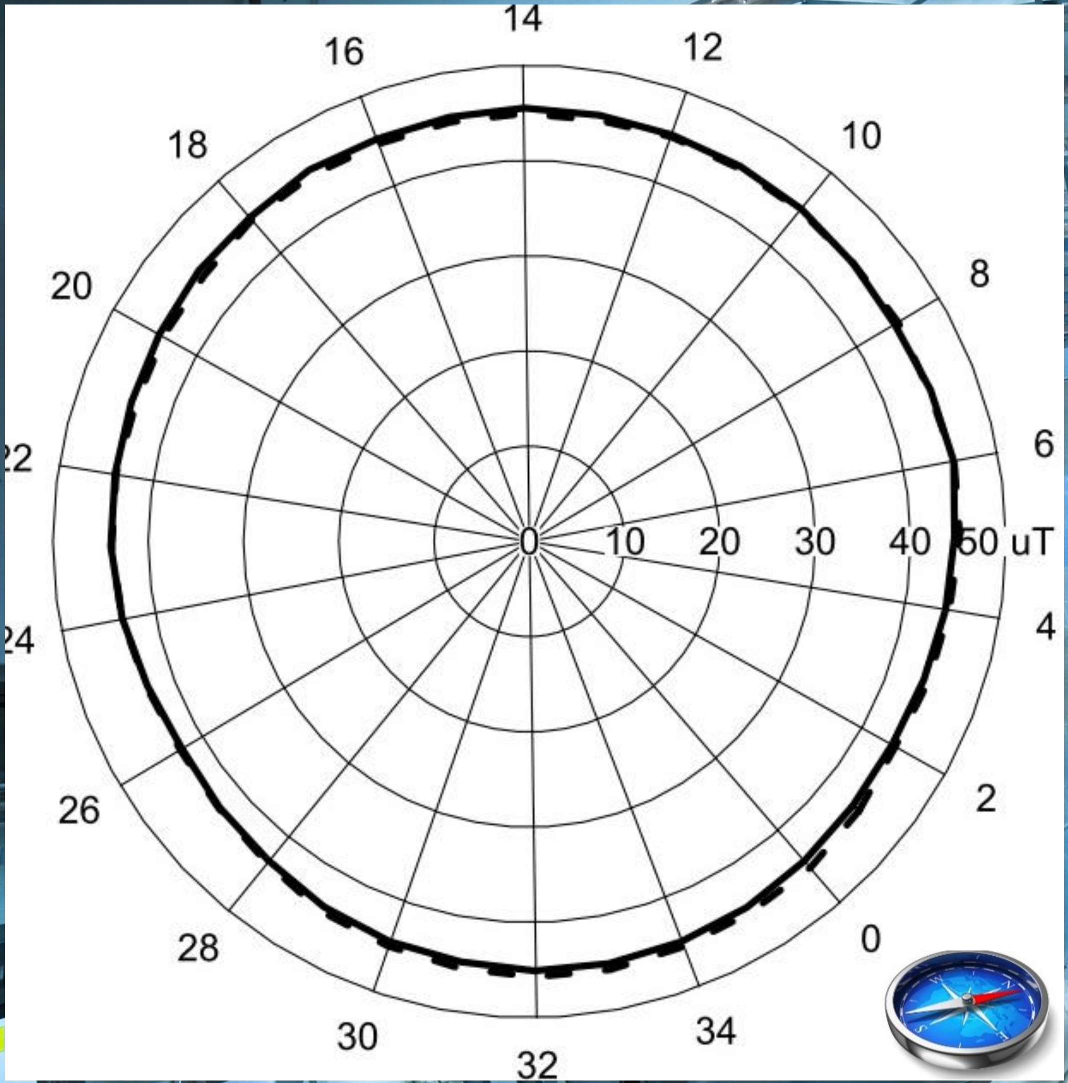
- **tandem spectrometer**: sub-eV precision energy filtering at E_0

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

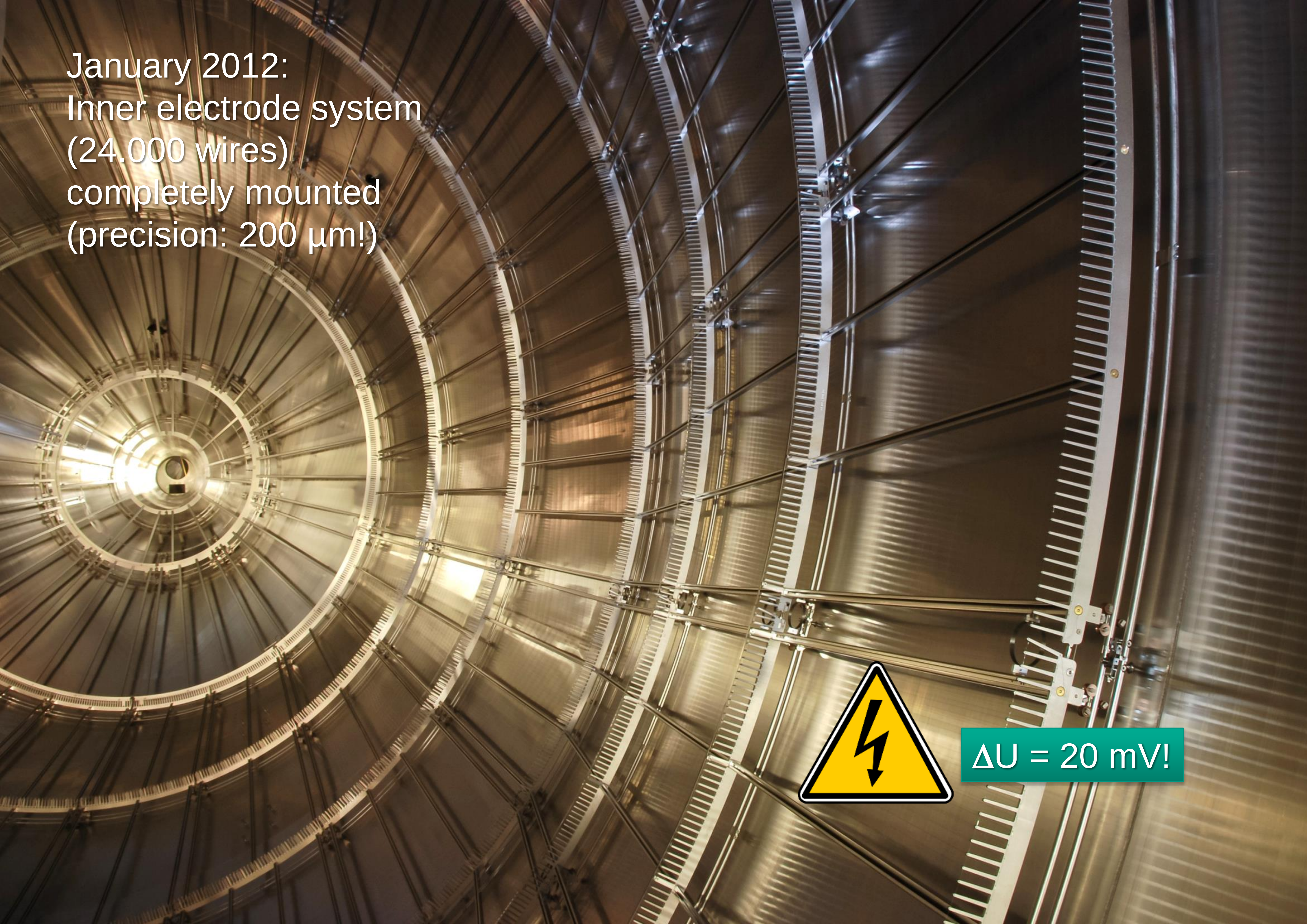


precision filter - scanning
variable retarding potential
U_0 = - 18.4 … -18.6 kV
$\Delta E = 0.93$ eV (100% transmission)


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

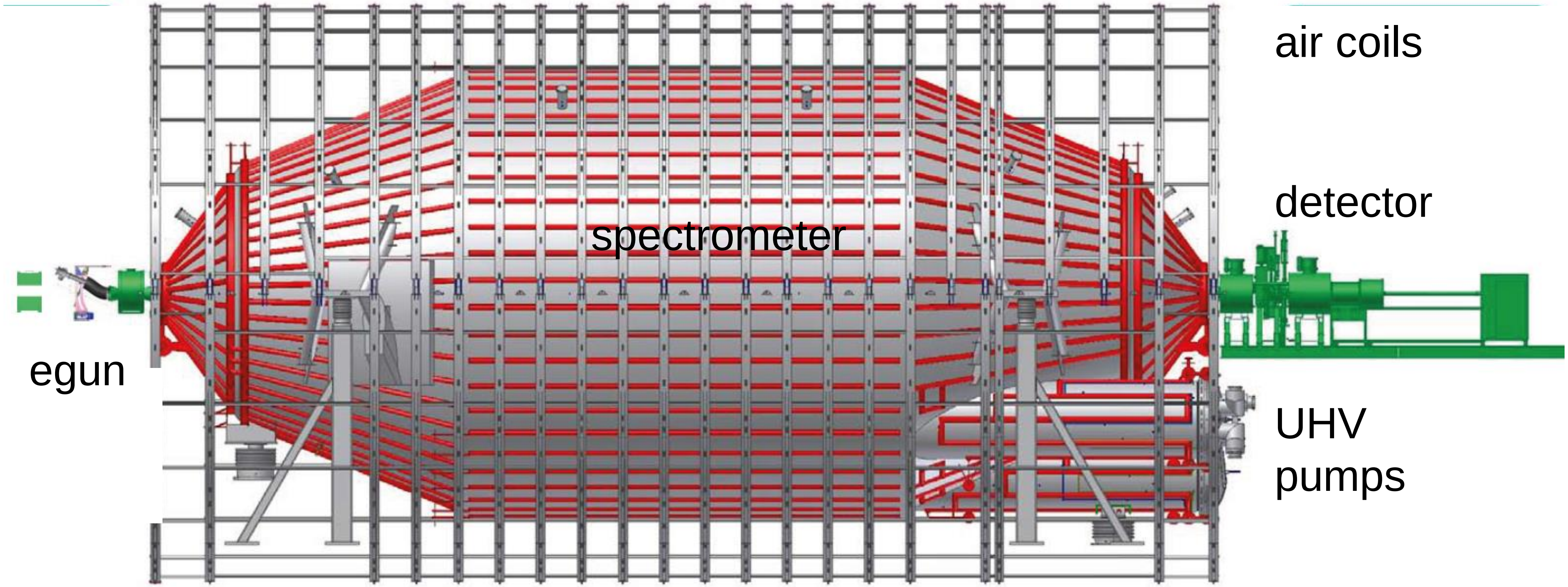


9/2014: successfull de-gaussing of experimental hall

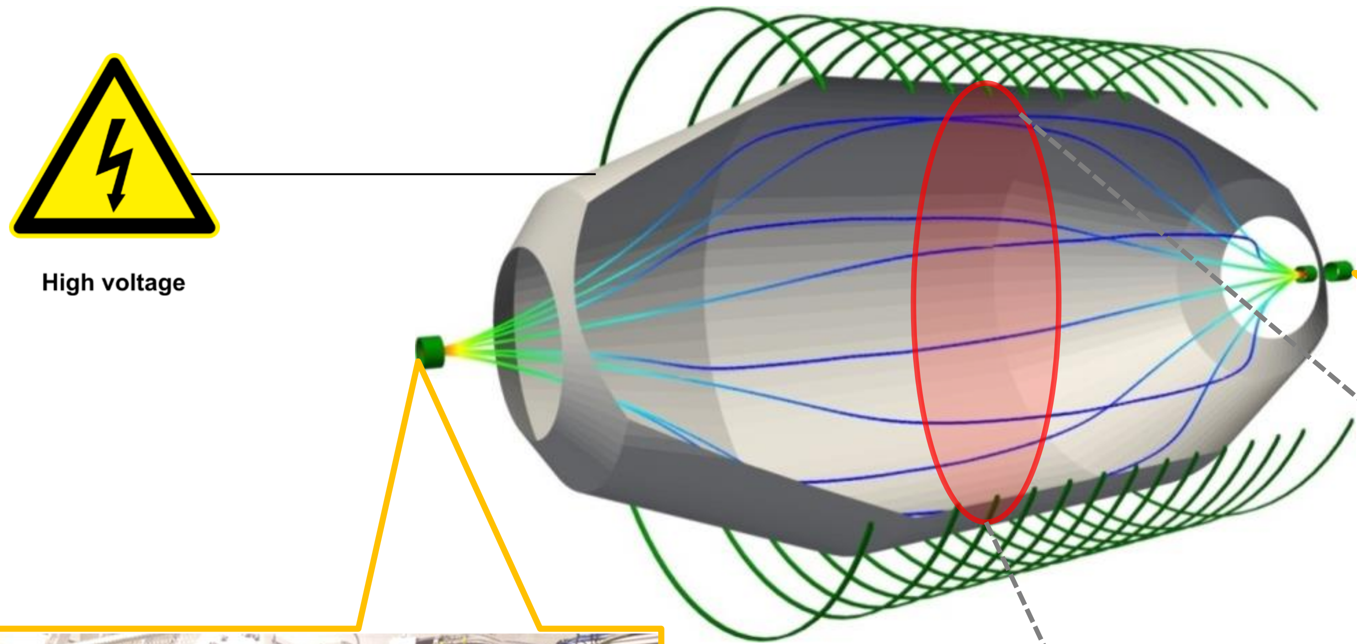

January 2012:
Inner electrode system
(24.000 wires)
completely mounted
(precision: 200 µm!)
ΔU = 20 mV!

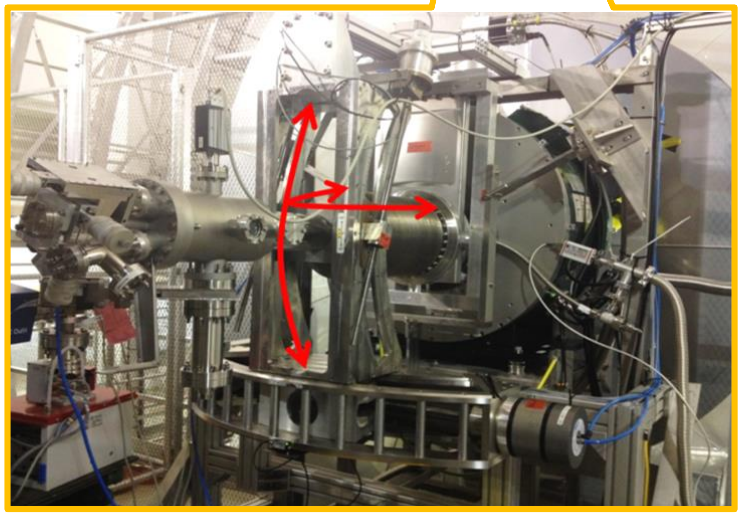
spectrometer commissioning

- 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



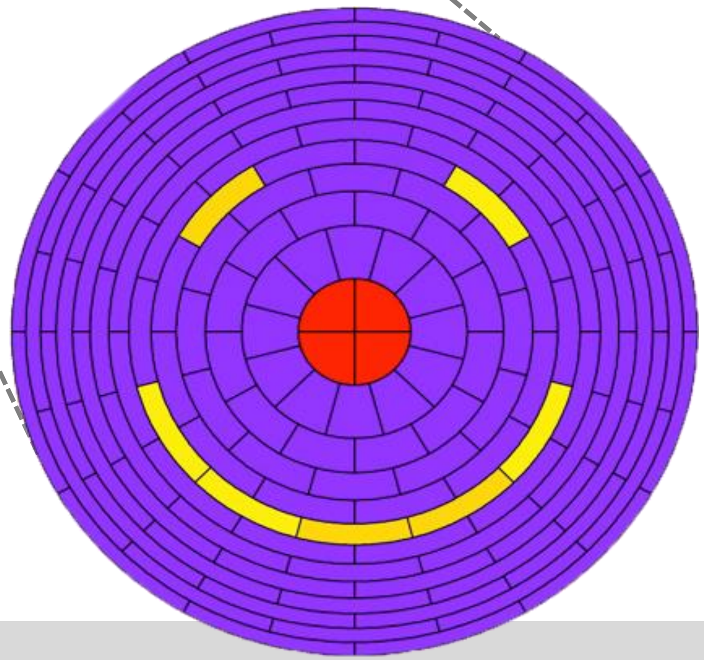
Transmission studies & mapping



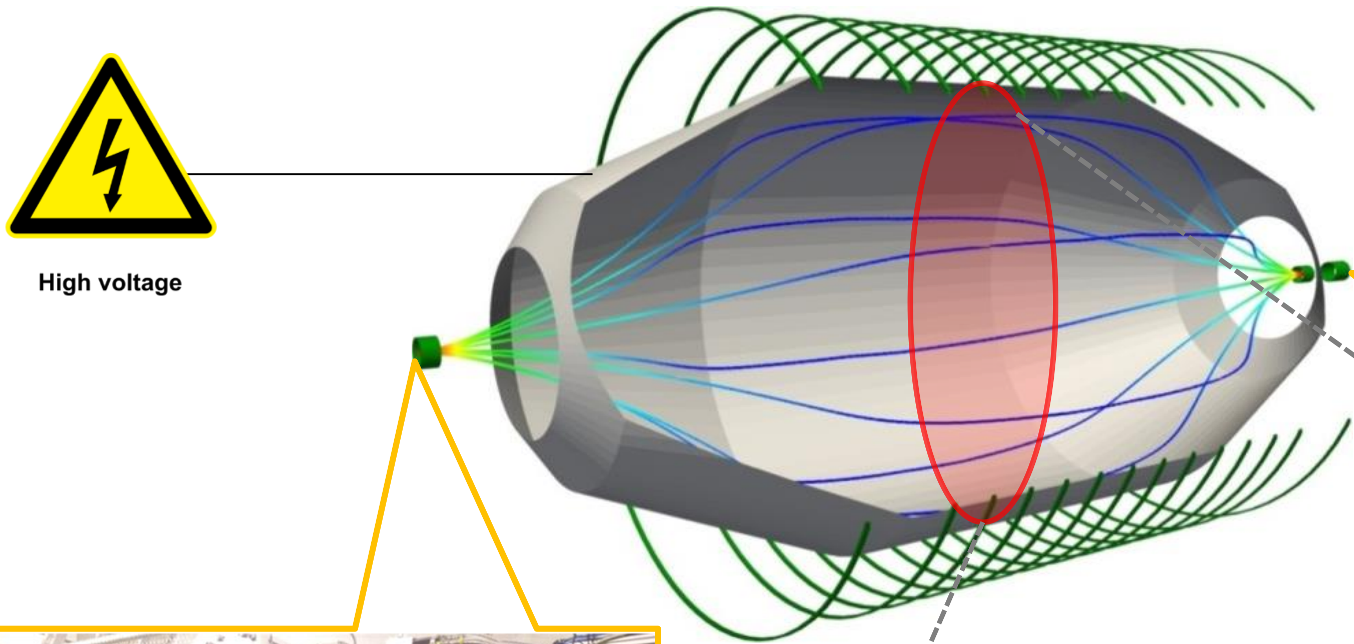


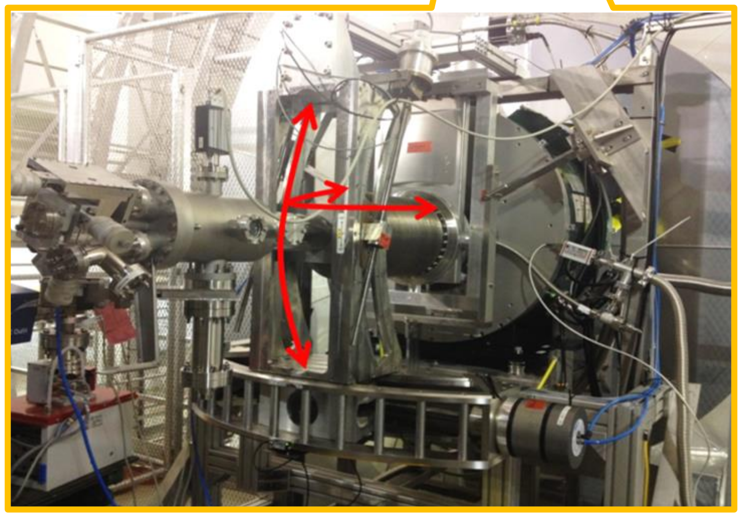
angular selective electron gun

focal plane detector



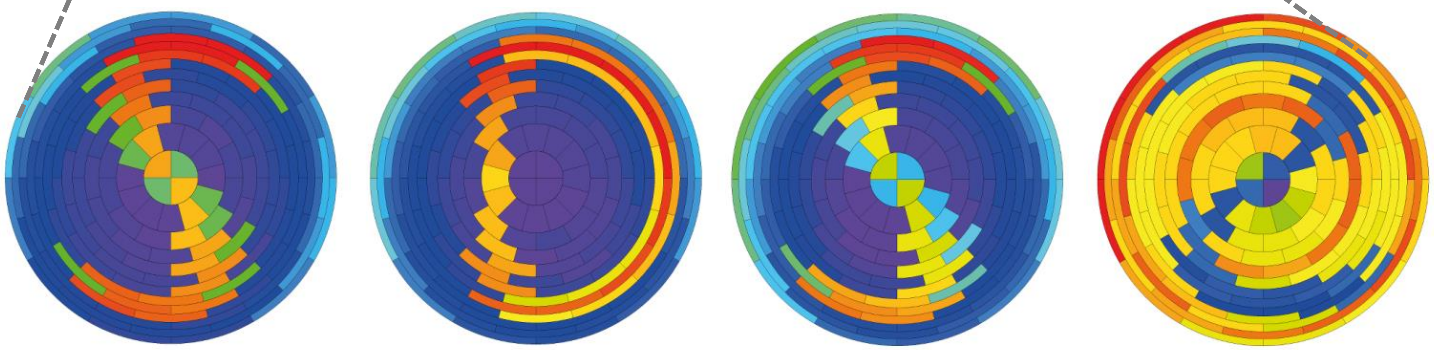
Transmission studies & mapping





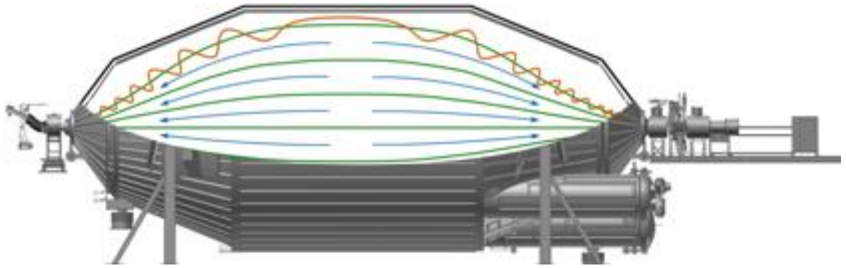
angular selective electron gun

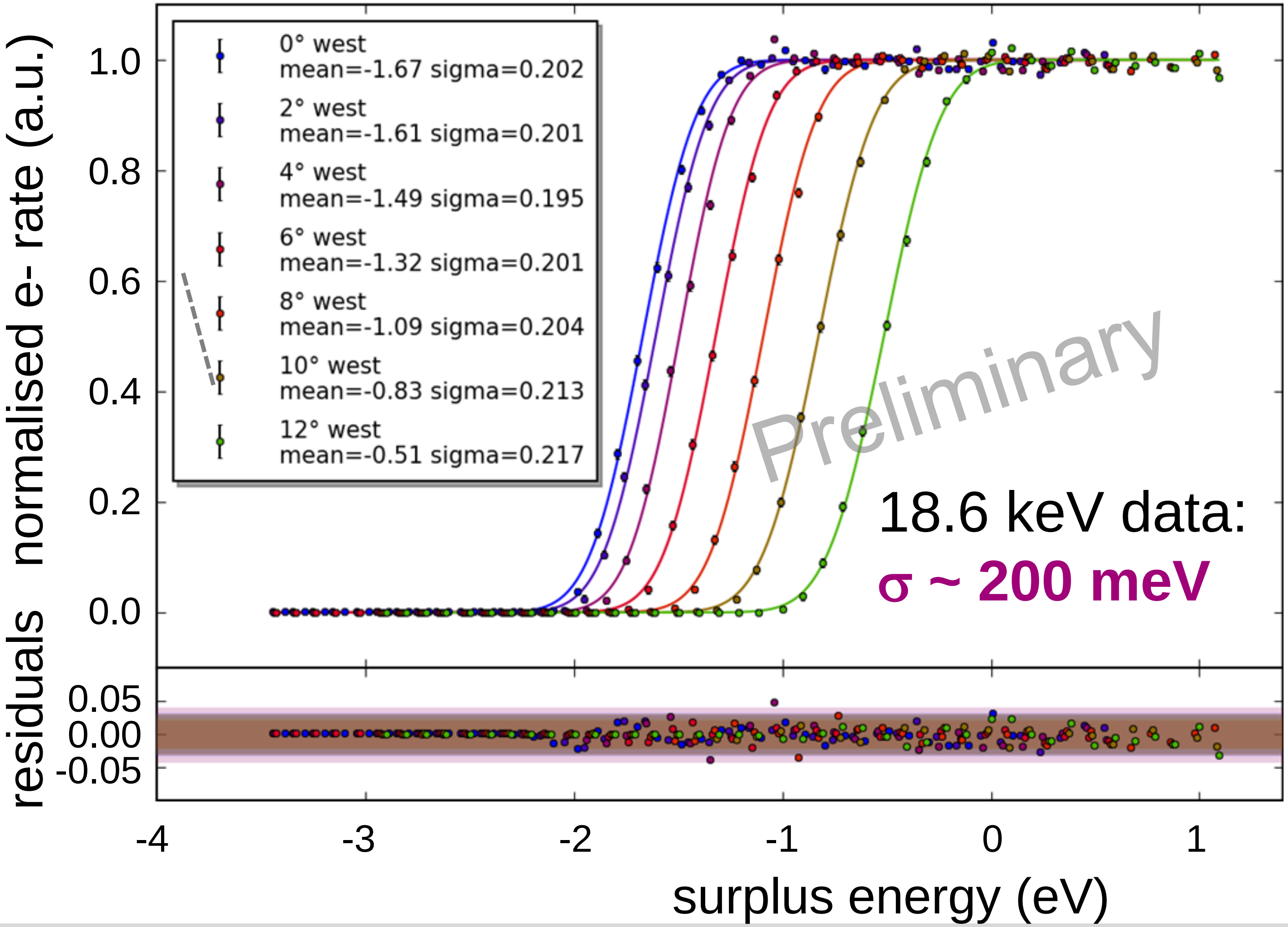
focal plane detector



Transmission studies & mapping

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

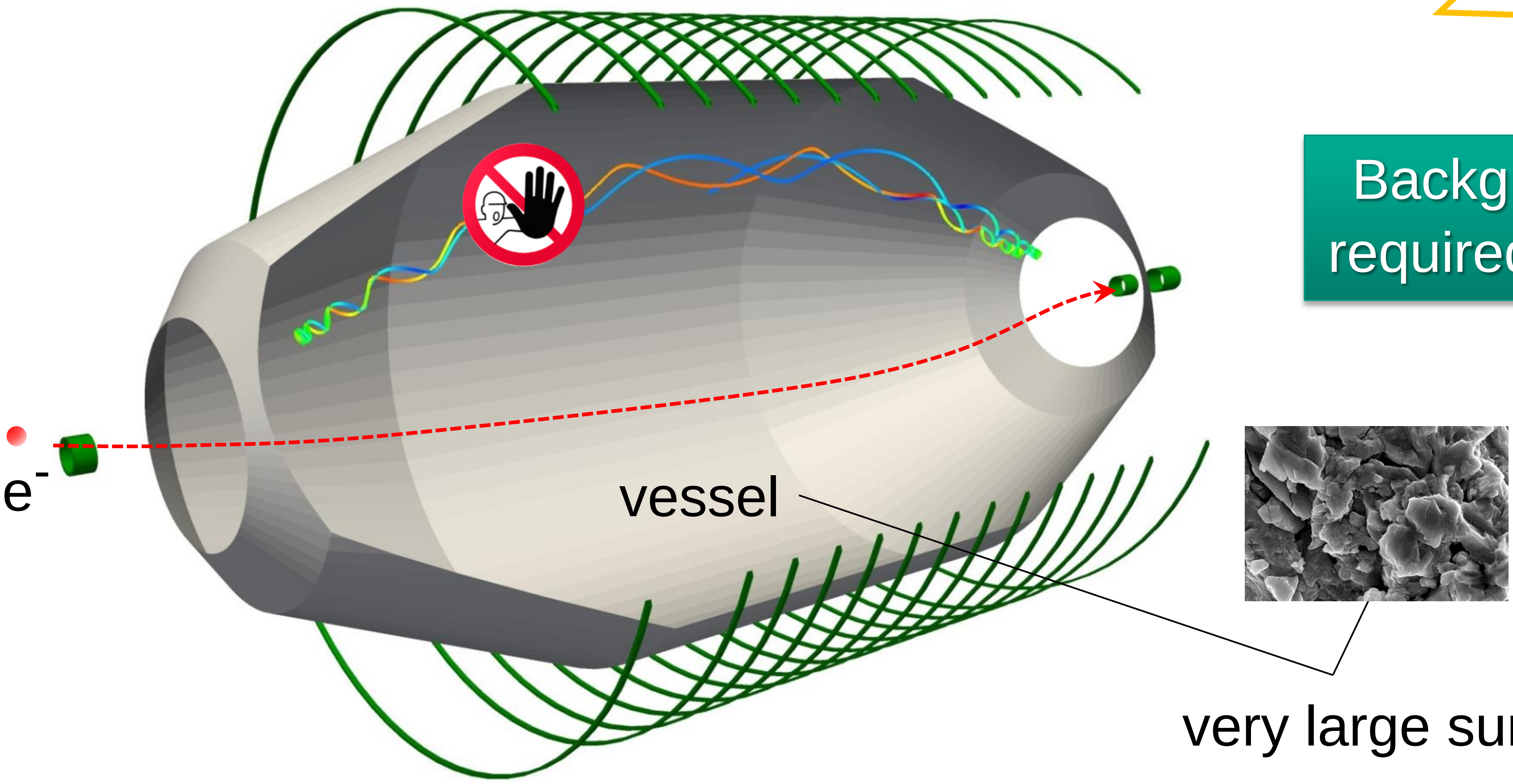




backgrund – status

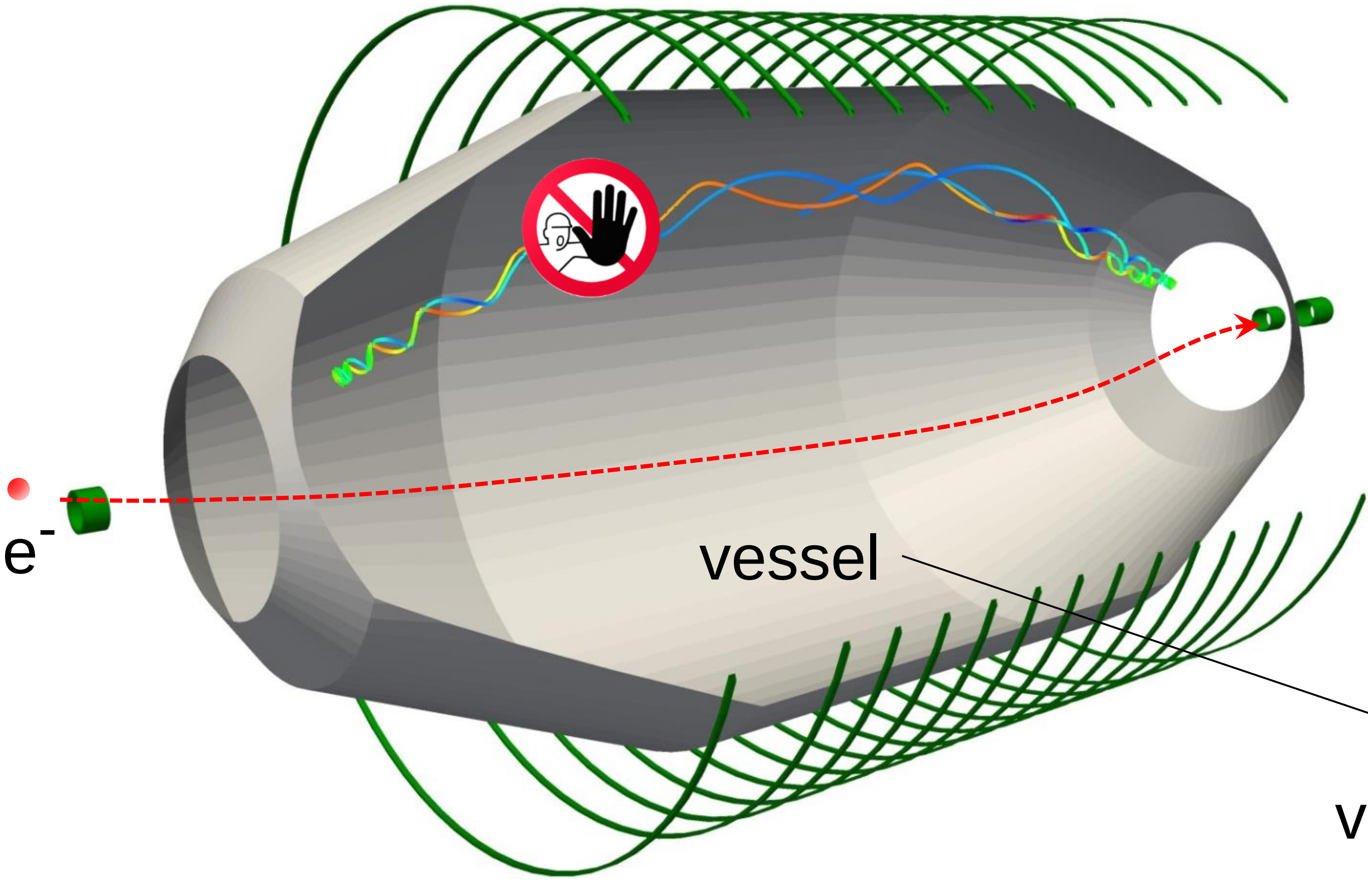
- reference value: R_{bg}(total) ~ 10 mcps
  experimental value: R_{bg}(total) ~ 1050 mcps

Background reduction required by factor ~ 100

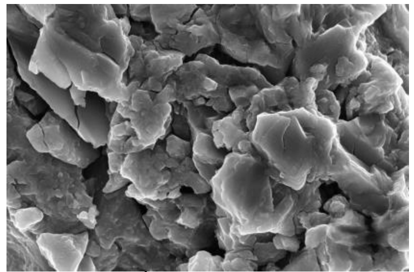


backgrund – status

- reference value: R_{bg}(total) ~ 10 mcps
  experimental value: R_{bg}(total) ~ 1050 mcps



Background reduction required by factor ~ 100



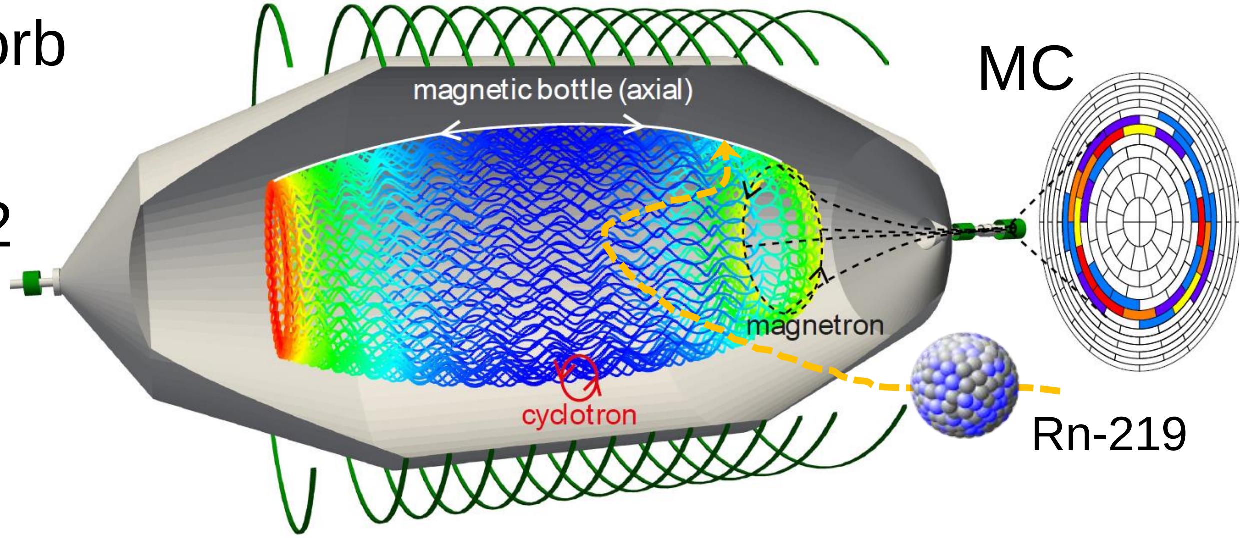
NEG-pump

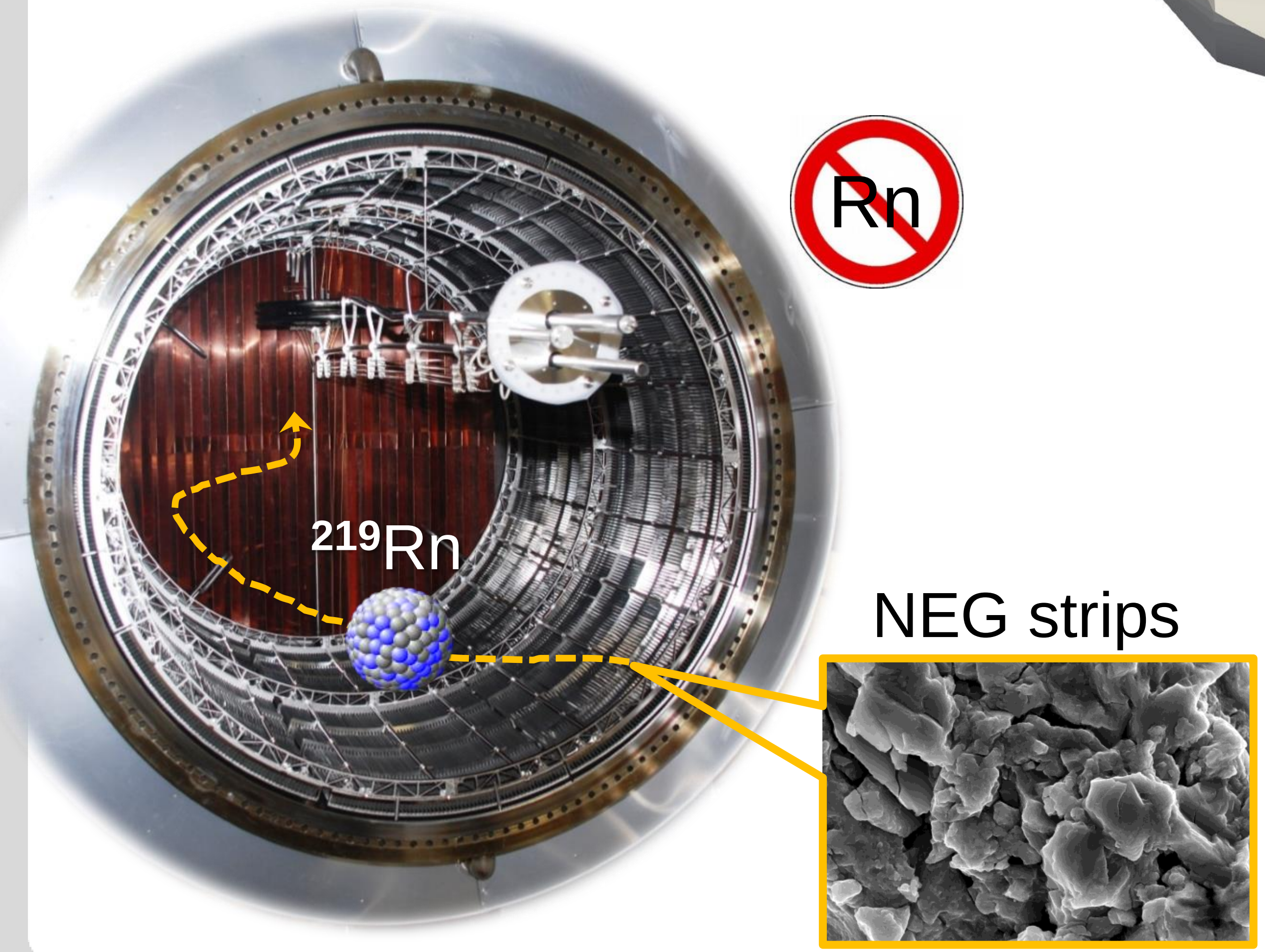
very large surfaces

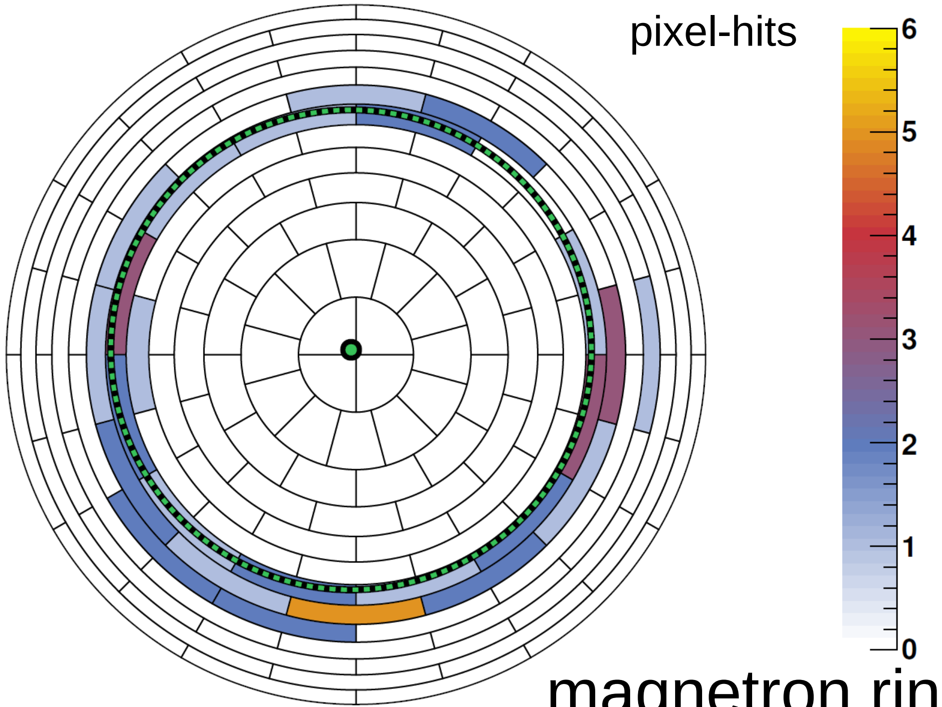
- magnetic & electrostatic shielding only against charged particles: e^- & H^-
- **neutral, unstable atoms** (^{219,220}Rn, H*) can penetrate to inner flux tube

Rn-background & LN2-cooled baffles

- **3 large-area Cu-baffles** to adsorb emanated ^{219,220}Rn-atoms, requires cooling to 77K with LN2

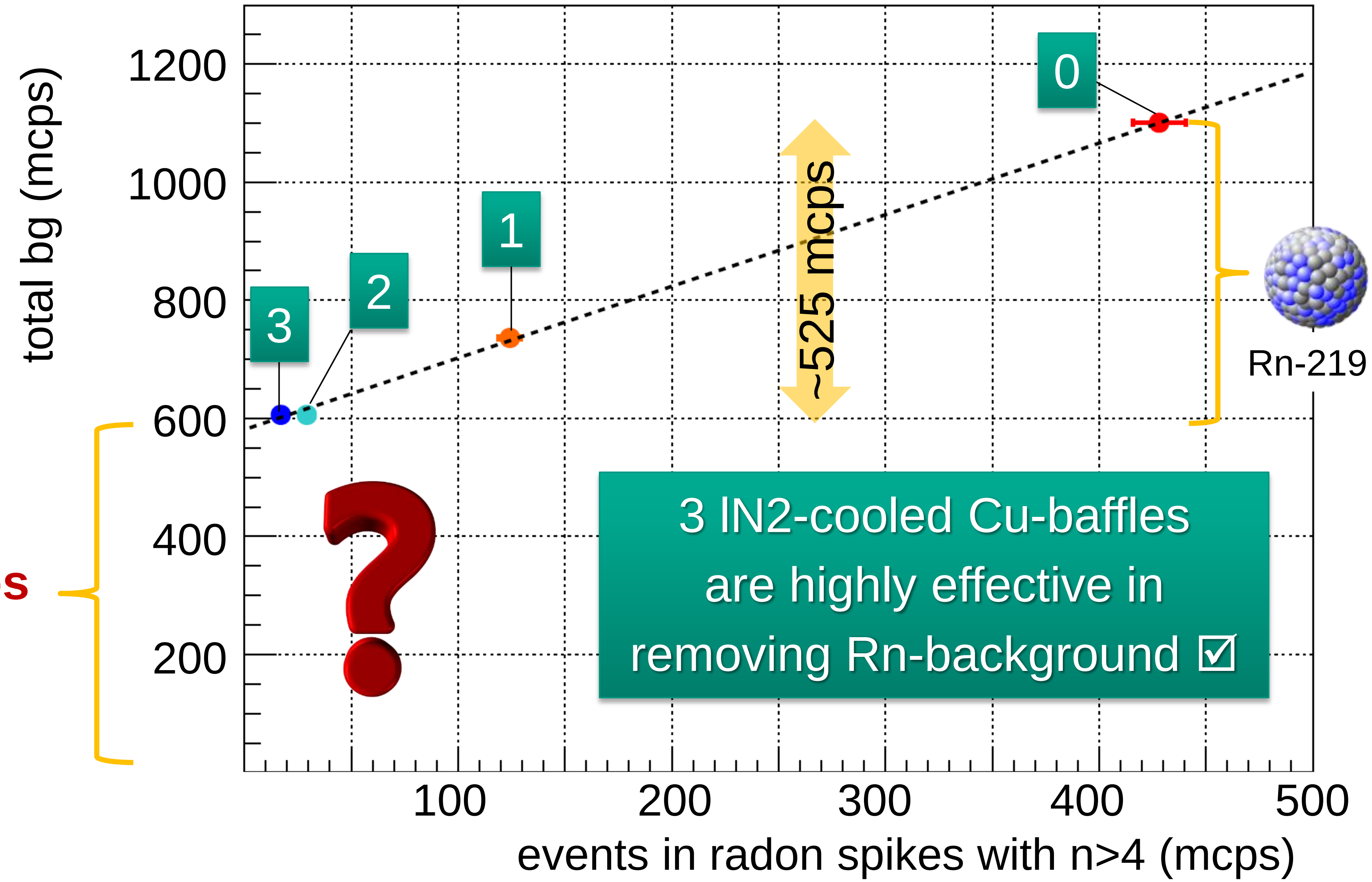






efficiency of lN2-cooled Cu-baffles

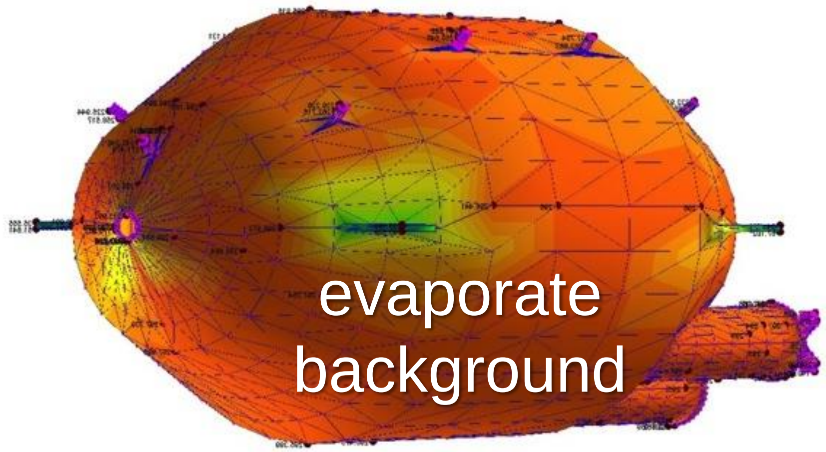
- efficiency of the 3 large-area Cu-baffles **ε = (97± 2)%**
  no indication for ^{219,220}Rn emanation from vessel walls ☑



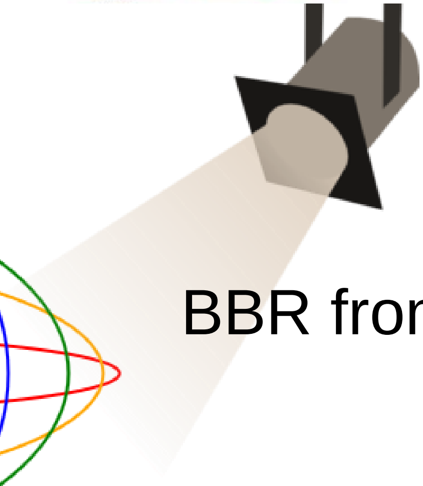
remaining:
R_{bg} = 525 mcps

Rydberg model of background

- Model of **neutral H* Rydberg atoms** can explain bg characteristics
  formation by ESD and PSD, ionisation by BBR
  - only passive countermeasures will work:
    spectrometer bakeout (ongoing)
    improved gamma shielding

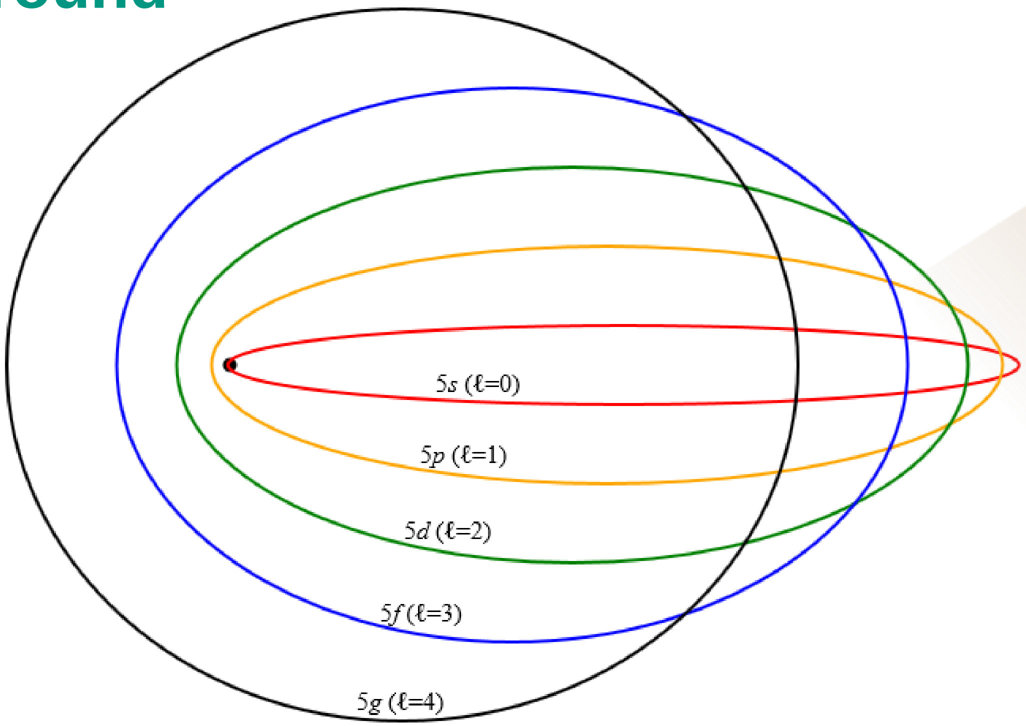


- expect very low bg-level after
  removal of H* background



BBR from walls

remaining:
R_{bg} = 525 mcps



KATRIN neutrino mass sensitivity

- **first explorative T2 data in mid-2016**
  - small column density ρd allows first search for **sterile keV neutrinos**
  - ramp up to nominal ρd-values until end of 2016
  - early 2017: start T2 with nominal ρd
- **reference ν-mass sensitivity**
  for 3 ´full beam´ (5 calendar) years:

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

350 meV (5σ)

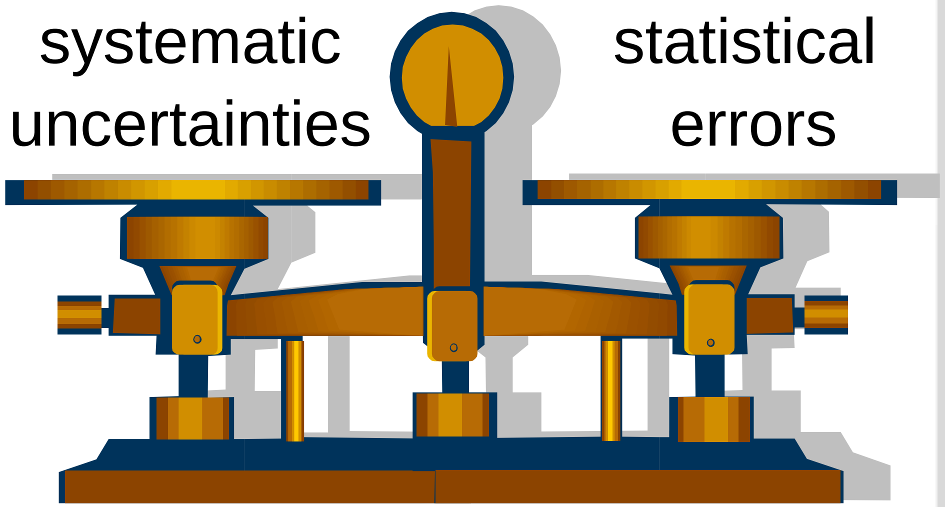
- **explore fully differential read-out**
  recent **ToF-studies** very promising!!

statistics: σ_{stat} = 0.018 eV²

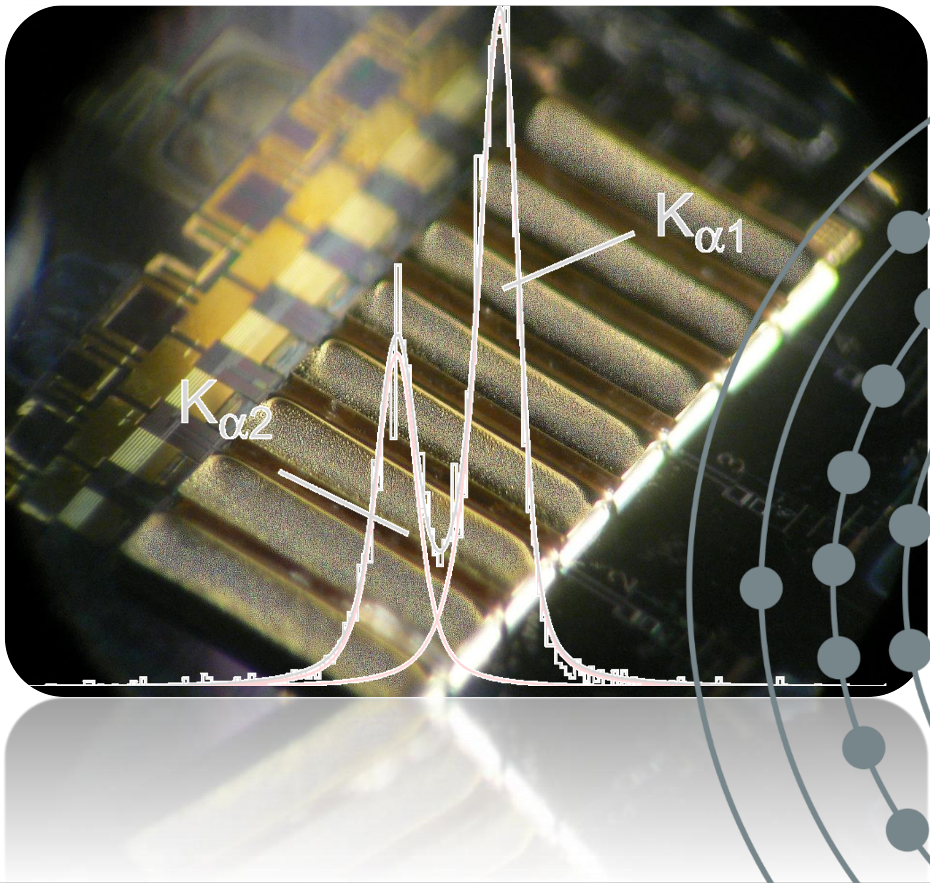
Σ 5 systematics: σ_{syst} < 0.017 eV²

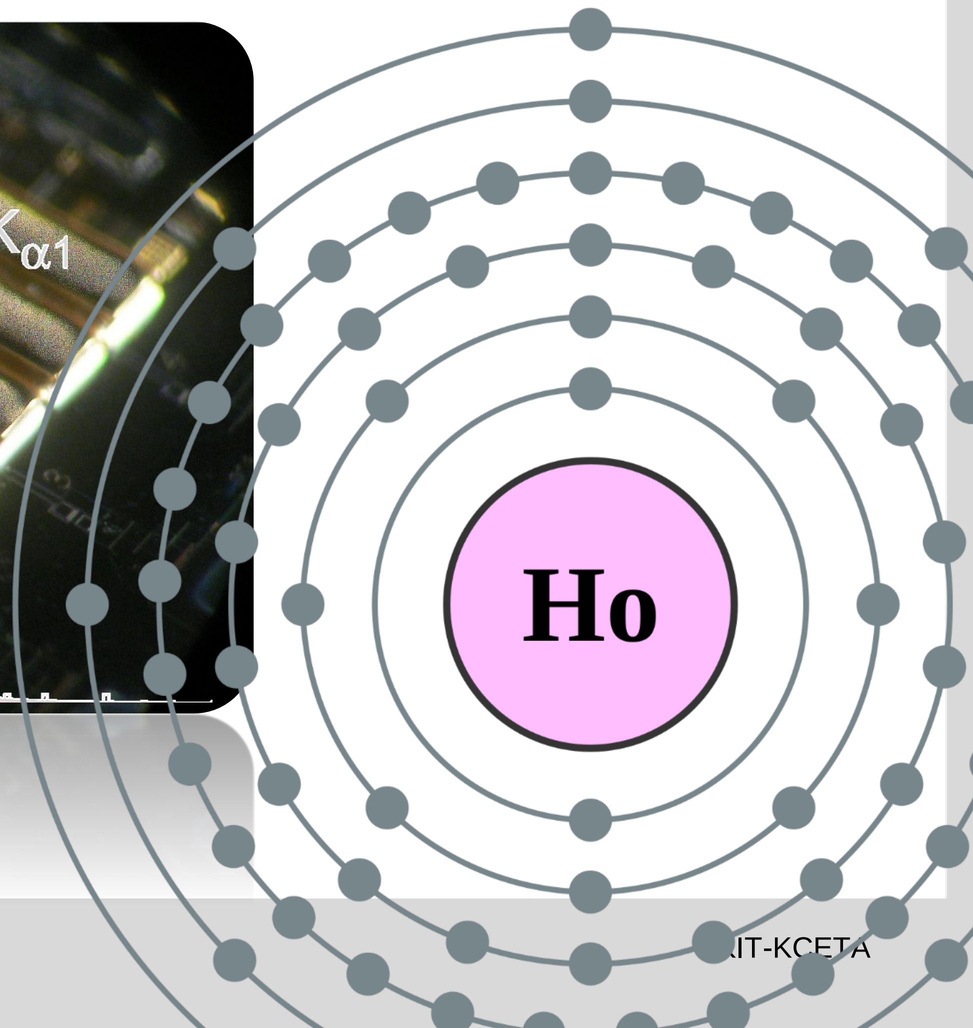
systematic uncertainties

statistical errors



novel approaches: Project 8 & ^{163}Ho EC-experiments





Project 8 – a novel spectroscopic approach

Cyclotron Radiation Emission Spectroscopy (CRES)

- observe coherent cyclotron radiation of ß-decay electrons in homogeneous magnetic field of B = 1 T

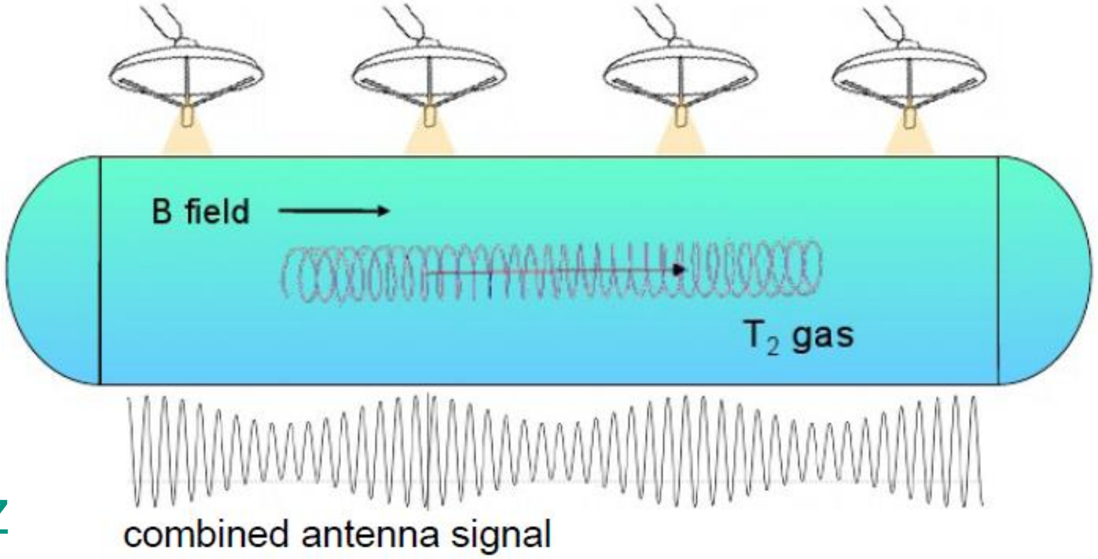
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{e \cdot B}{m_e + E_{e,kin}}$$

- precise measurement of ω yields electron kinetic energy

$E_{e,kin}$ = 18.575 keV

B = 1 T

$f_0 = \omega_0 / 2\pi \approx$ 27 GHz



ΔE = 1 eV

$\Delta\omega \sim 1/t_s$

sampling time

t_s ~ several µs

(magnetic bottle)

B. Monreal, J. Formaggio, Phys. Rev. D 80, 051301(R) (2009)

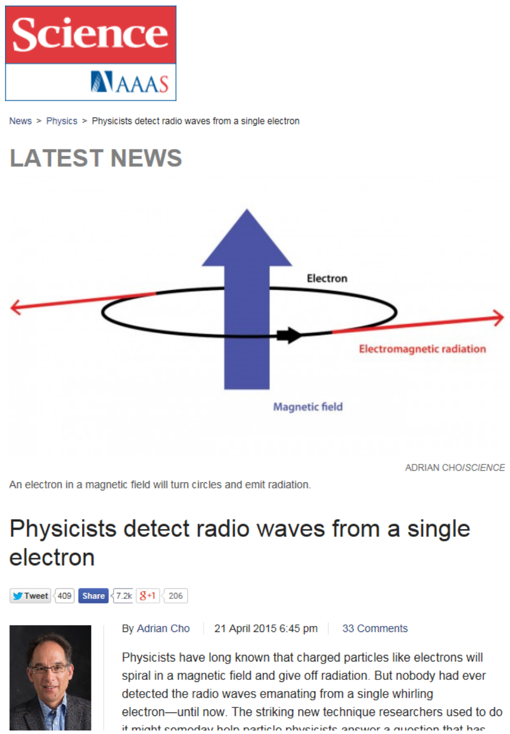
Project 8 – recent technology breakthrough

Karlsruhe Institute of Technology

Single electron detection

- electron source: ^{83m}Kr-decay (E = 17.83 keV / 30.2-30.4 keV / 31.9 keV)
- s.c. solenoid B = 1 T with weak harmonic magnetic trap of up to 8.2 mT
- 1 m WR42 waveguide for TE_{10} mode to receiver (pre-amps)

D.M. Asner et al., Single electron detection and spectroscopy via relativistic cyclotron radiation, Phys. Rev. Lett. 114, 162501 (2015)


Science AAAS

News > Physics > Physicists detect radio waves from a single electron

LATEST NEWS

An electron in a magnetic field will turn circles and emit radiation.

Physicists detect radio waves from a single electron

By Adrian Cho | 21 April 2015 6:45 pm | 33 Comments

Physicists have long known that charged particles like electrons will spiral in a magnetic field and give off radiation. But nobody had ever detected the radio waves emanating from a single whirling electron—until now. The striking new technique researchers used to do


IOP Physics World - the member magazine of the Institute of Physics

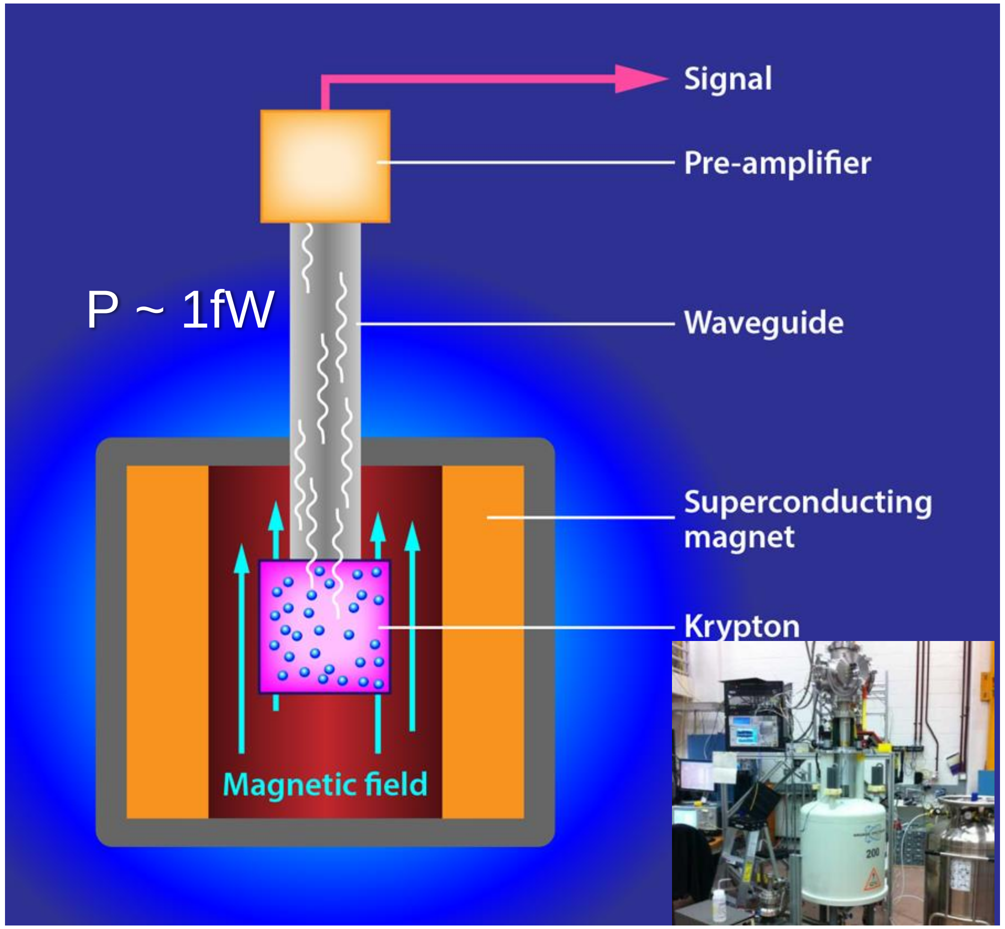
physicsworld.com

Cyclotron radiation from a single electron is measured for the first time

Apr 27, 2015 29 comments

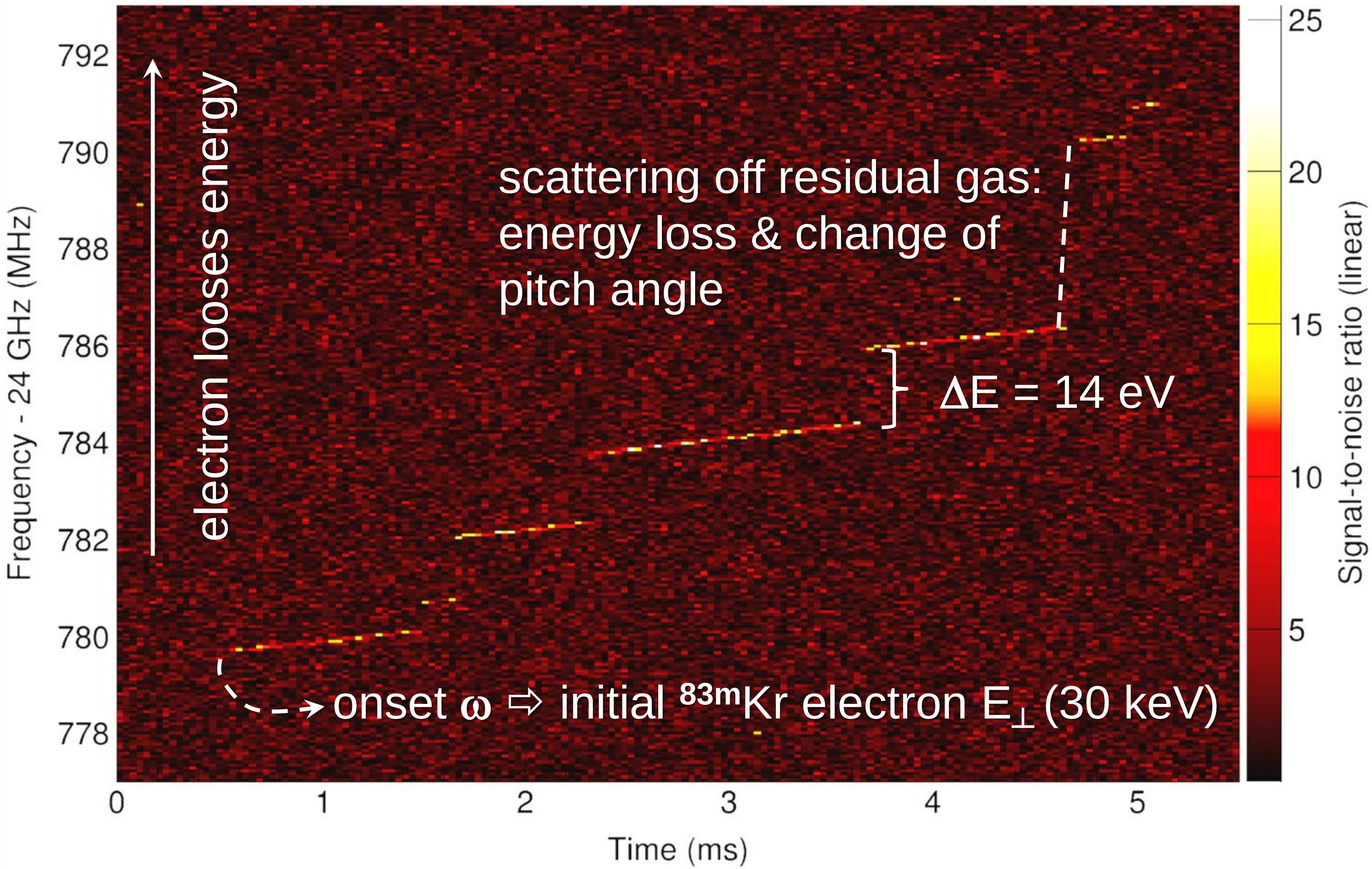
Going in circles: the Project 8 experiment

The cyclotron radiation emitted by a single electron has been measured for the first time by a team of physicists in the US and Germany. The research provides a new and potentially more precise



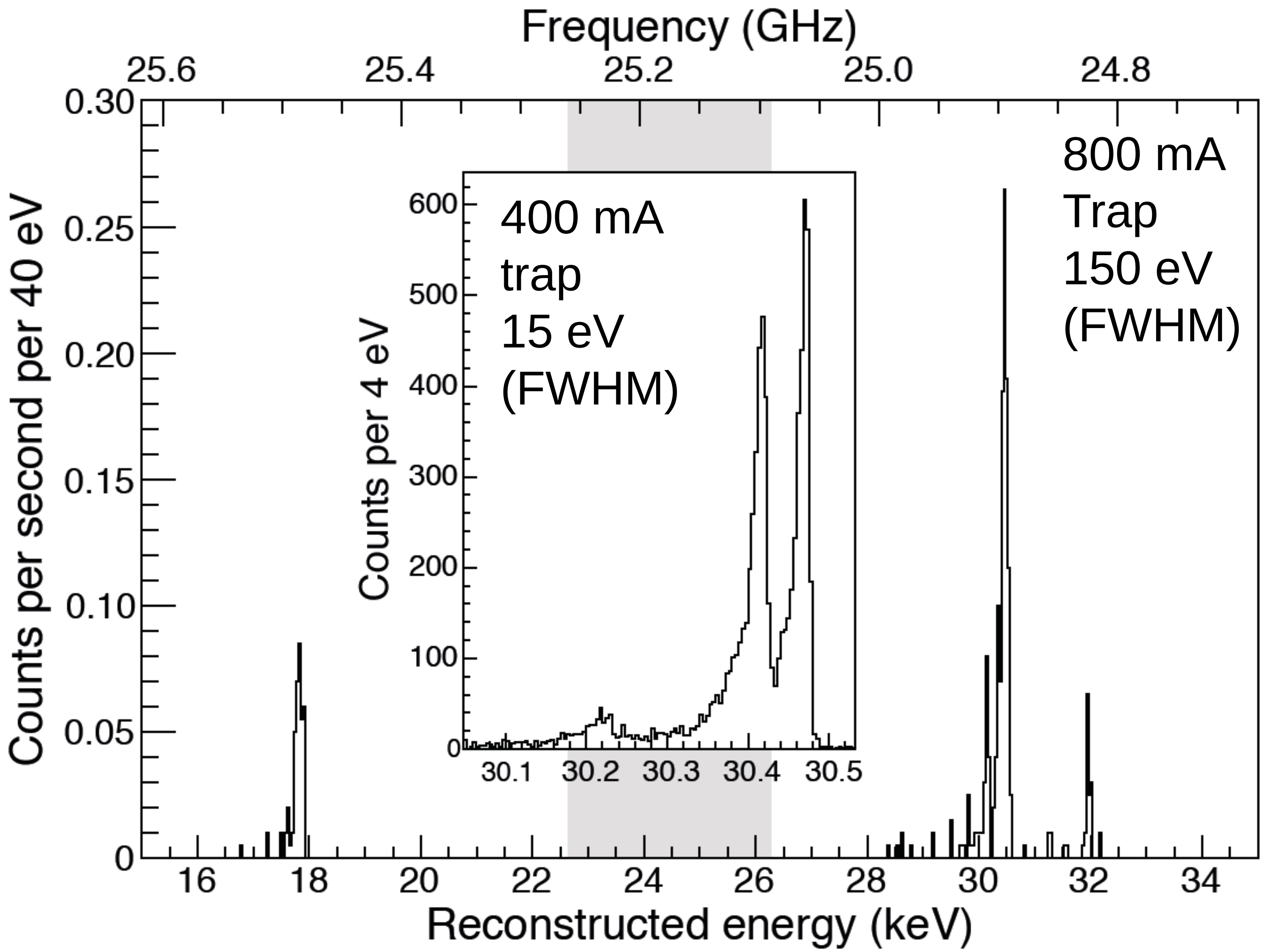
Project 8 – single electron

- **first detection of cyclotron radiation from a single keV electron**



Project 8 – ^{83m}Kr spectrum

- **energy resolution**:
  - increase resolution ΔE at expense of statistics
  - shallower trap depth:
    - a) different field gradients sampled
    - b) steeper pitch angles
    - c) less trapping



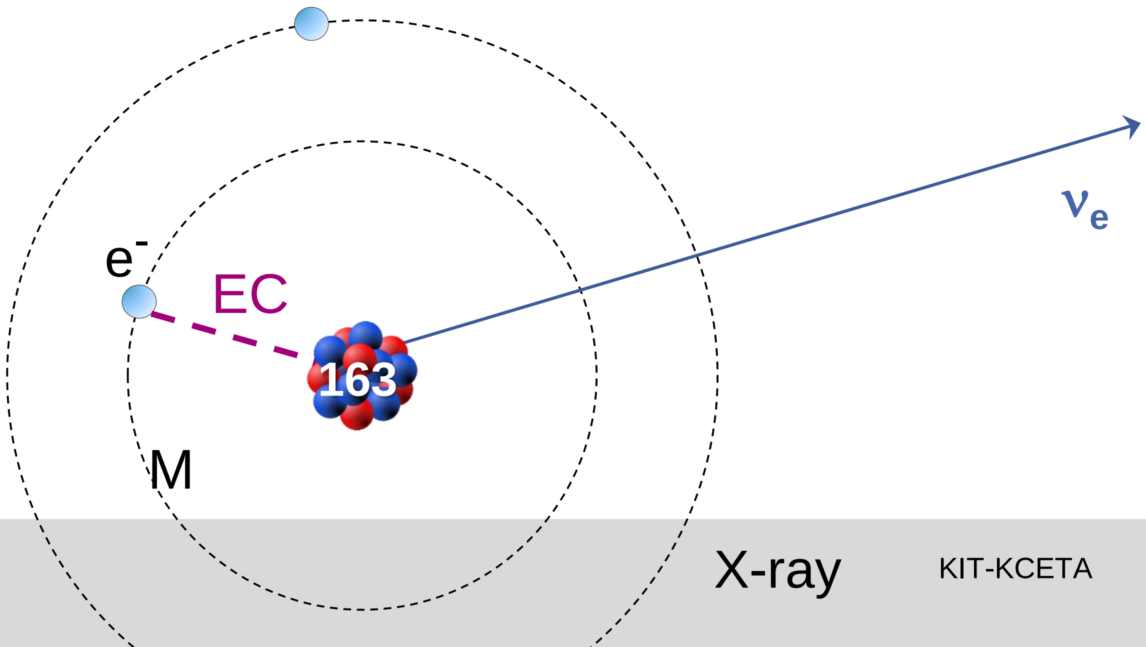
- **future** :
  - further improve ΔE
  - first T2 runs, larger 1 cm³ cell then 10 cm³ cell
  - plan for an atomic tritium source??

electron capture & ν-mass

- **EC-process of ^{163}Ho :** $^{163}Ho + e^- \rightarrow \nu_e + {}^{163}Dy^*$ (only from $s_{½}$ or $p_{½}$ orbitals)
  1 – after EC, ν_e carries away energy

Q_{EC}: Q-value of EC-process
$M(^{163}Ho) – M(^{163}Dy) \sim 2.5$ keV

atomic de-excitations (⇨T_C)

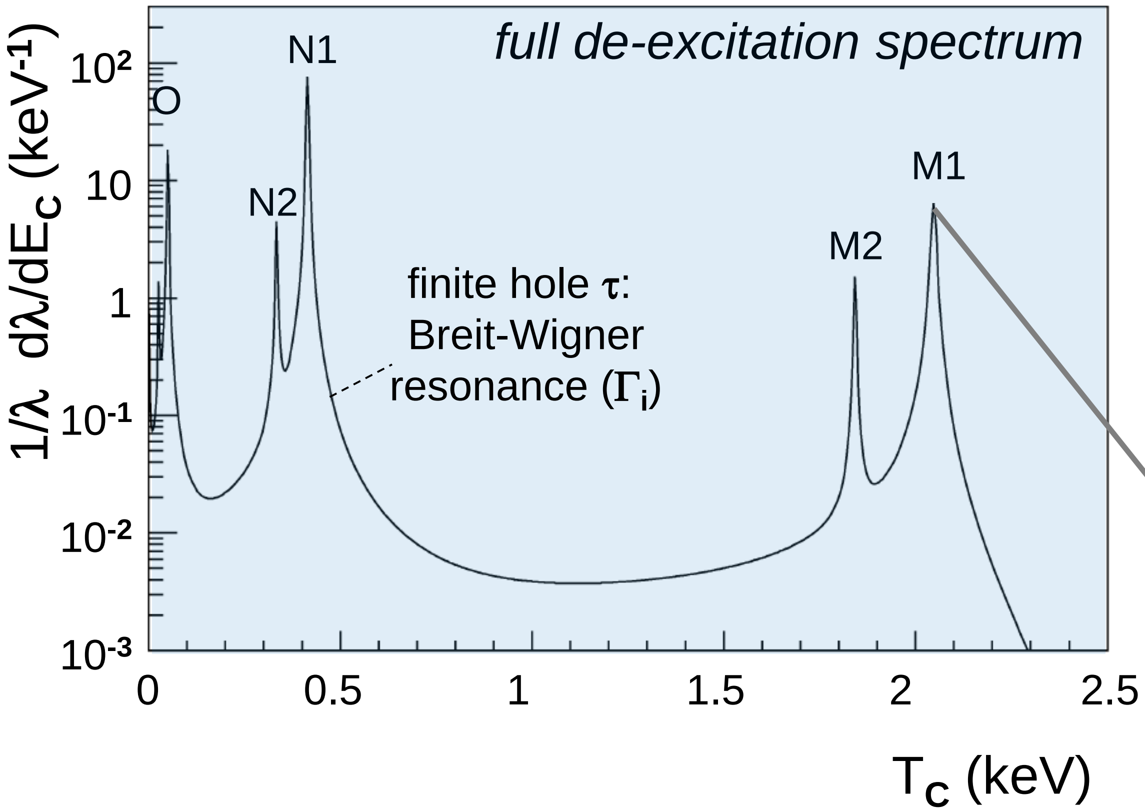


electron capture & ν-mass

- **EC-process of ^{163}Ho :** $^{163}\mathrm{Ho} + e^- \rightarrow \nu_e + {}^{163}\mathrm{Dy}^* \rightarrow {}^{163}\mathrm{Dy} + T_C$

  2 – atomic hole state de-excites to g.s.

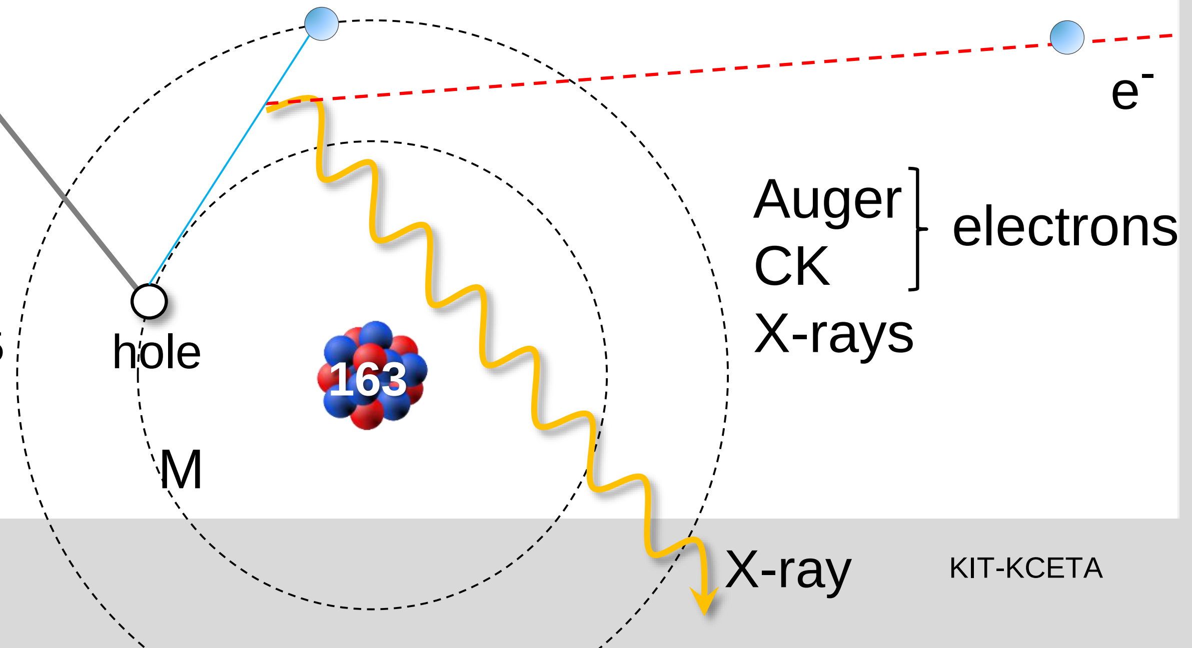
$$\frac{d\lambda_{EC}}{dT_C} \sim (Q_{EC} - T_C) \cdot \sqrt{(Q_{EC} - T_C)^2 - m^2(\nu_e)} \cdot \sum_i n_i \cdot C_i \cdot \beta_i^2 \cdot B_i \cdot \frac{\Gamma_i}{2\pi} \cdot \frac{1}{(T_C - E_i)^2 + \Gamma_i^2/4}$$



Q_{EC}: Q-value of EC-process $M(^{163}\mathrm{Ho}) - M(^{163}\mathrm{Dy}) \sim 2.5$ keV

T_C: calorimetric energy

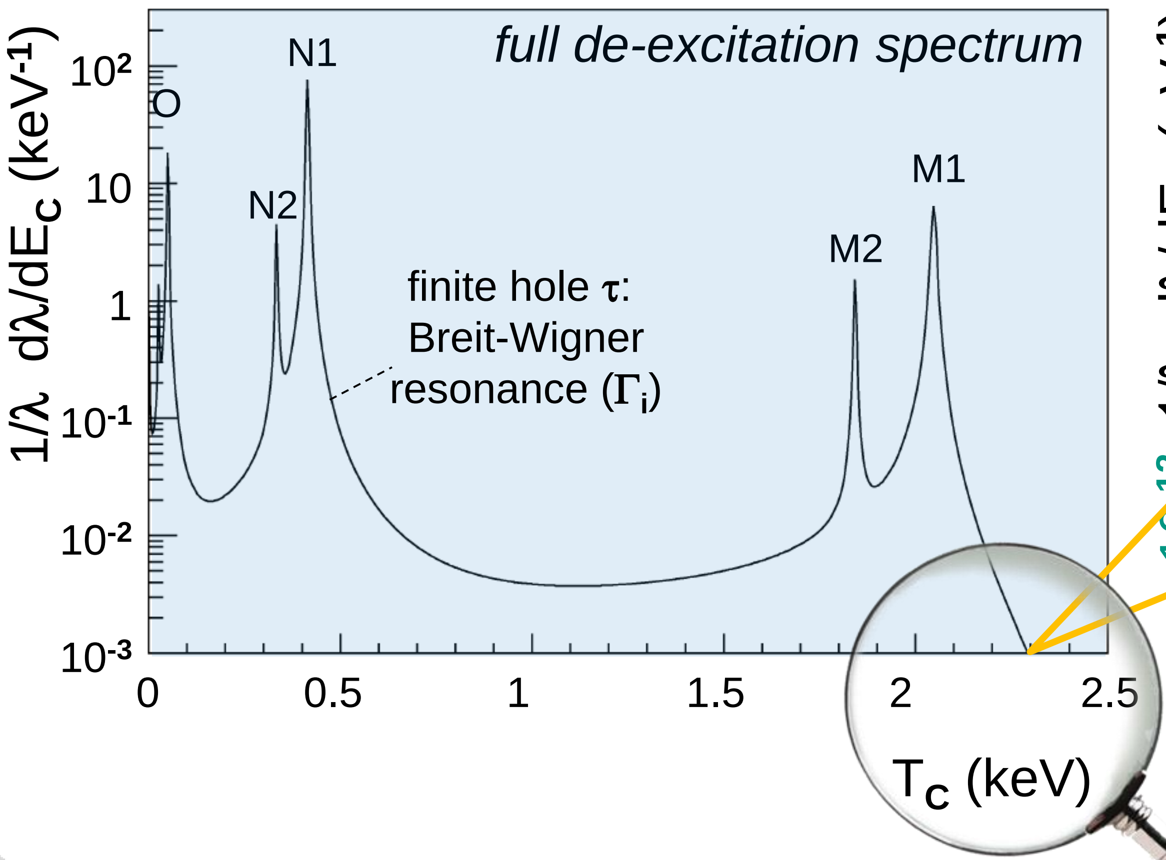
atomic de-excitations (⇨T_C)

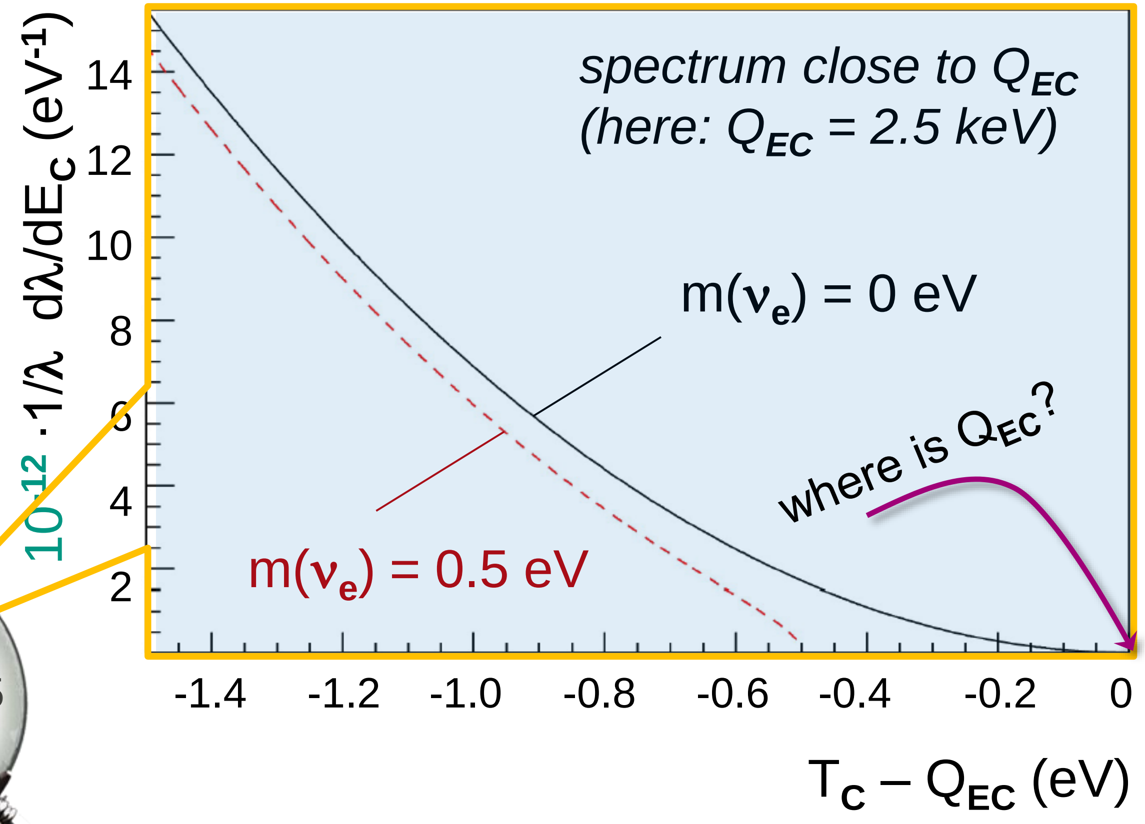


electron capture & ν-mass

- Region close to Q-value Q_{EC}: ν_e carries away energy and momentum, allows to measure $m^2(\nu_e)$

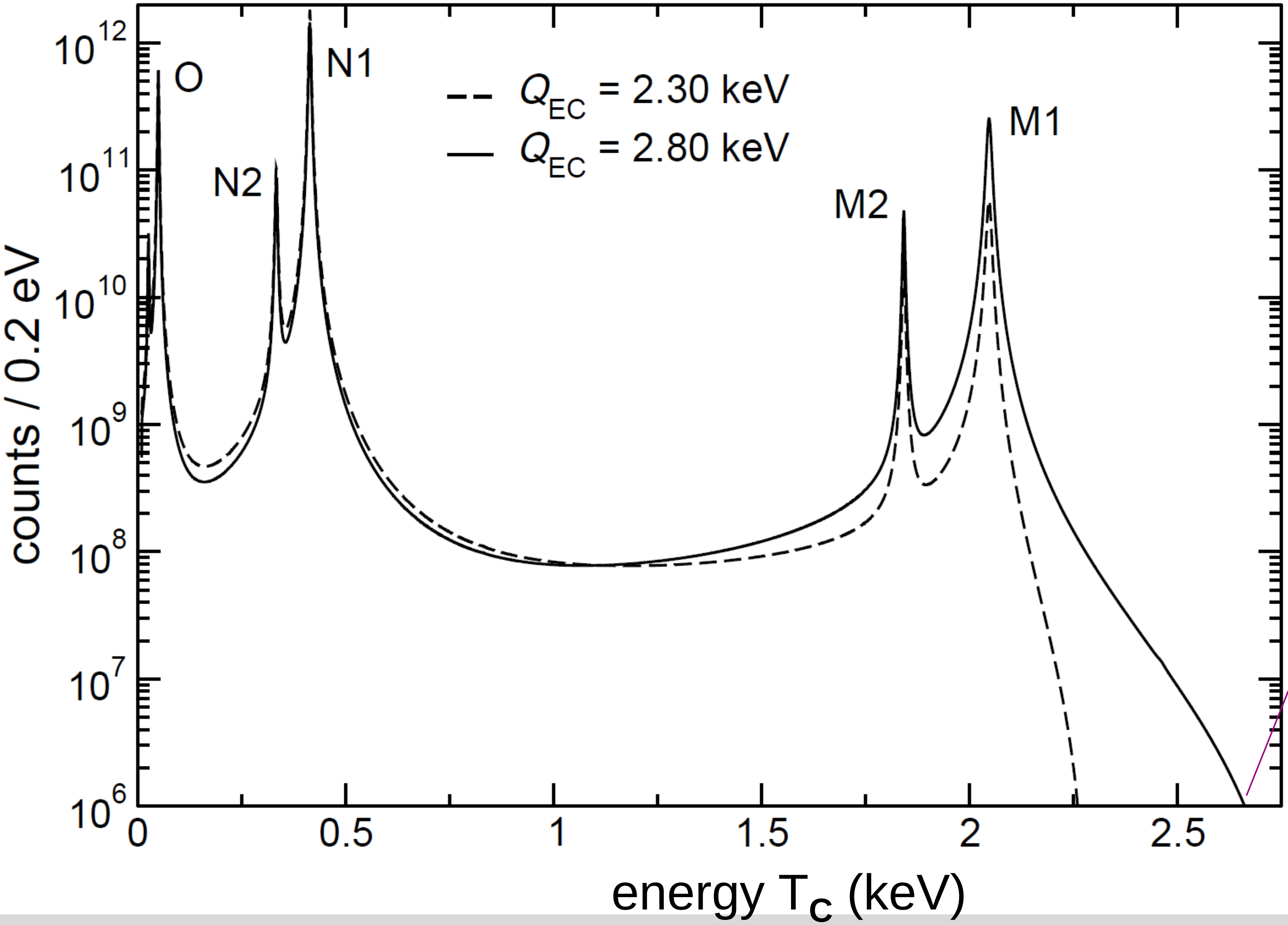
$$\frac{d\lambda_{EC}}{dT_C} \sim (Q_{EC} - T_C) \cdot \sqrt{(Q_{EC} - T_C)^2 - m^2(\nu_e)} \sum_i n_i \cdot C_i \cdot \beta_i^2 \cdot B_i \cdot \frac{\Gamma_i}{2\pi} \cdot \frac{1}{(T_C - E_i)^2 + \Gamma_i^2/4}$$





^{163}Ho-EC: description of the spectrum

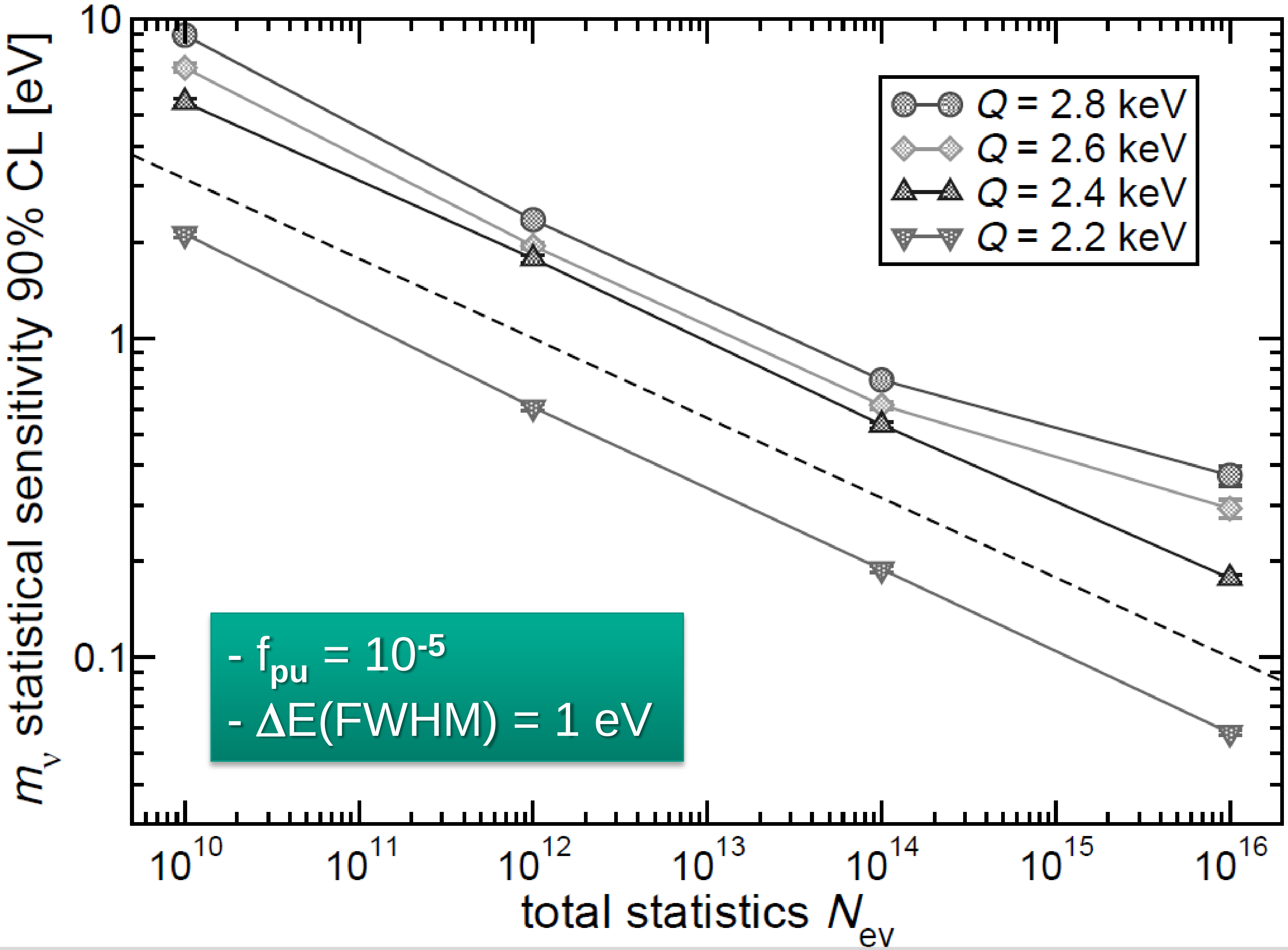
- **exact Q-value** (2.5…2.8 keV): ideal, if Q_{EC} is very close to M1 resonance



2.8 keV endpoint: less statistics for ν-mass analysis

^{163}Ho-EC: description of the spectrum

- **exact Q-value** (2.5…2.8 keV): ν-mass sensitivity can change by factor 3-4



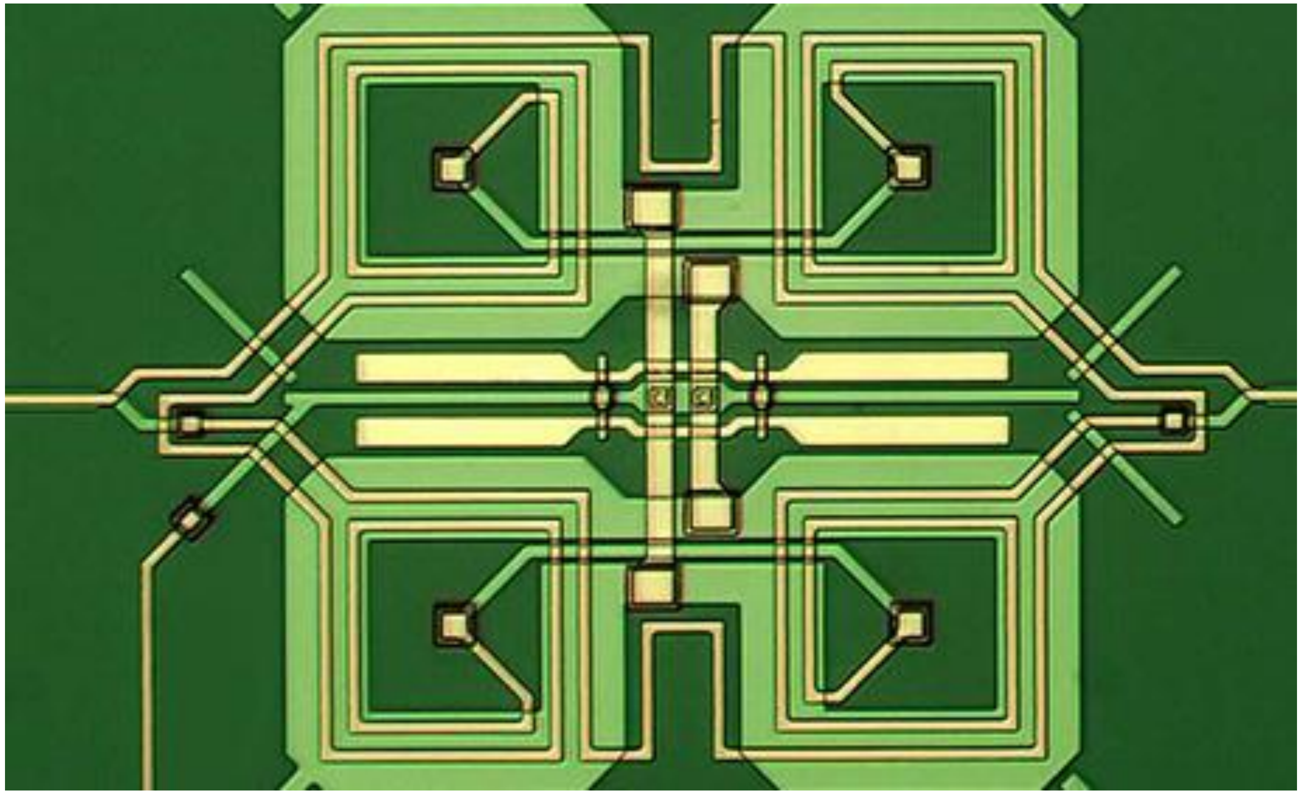
$\sim N_{ev}^{-1/4}$

^{163}Ho electron capture & statistics

- **Required setups for sub-eV sensitivity**
  - design of final experiment: independent measurement of Q_{EC} required
    Penning trap mass spectroscopy: SHIPTRAP (GSI) 30-100 eV, MPIK
  - # of events $N_{ev} > 10^{14}$
  - for 10^{14} events / year need
    10^5 detectors (100 Bq each)

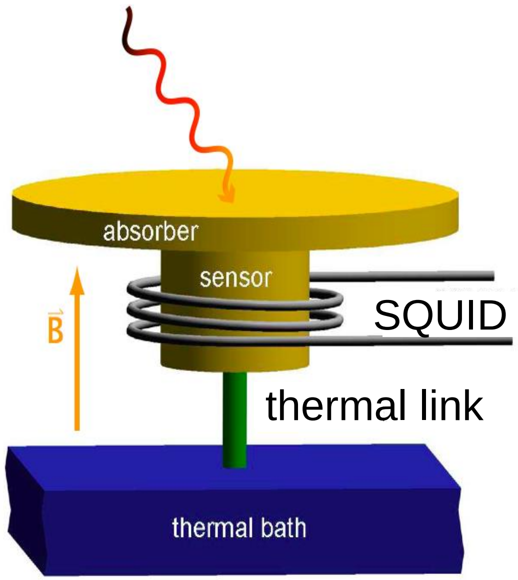
- **typical detector parameters**:
  - small pile up $f_{pu} < 10^{-5}$
  - short rise time $t_r < 1$ µs
  - ΔE(FWHM) < 5 eV

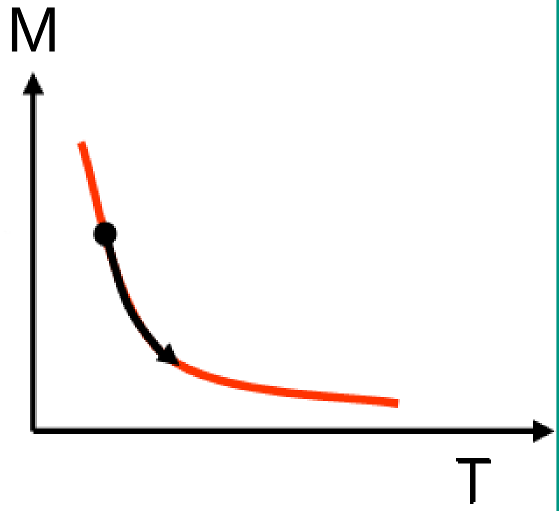
arrays of low-temperature micro-calorimeters



low-temperature μ-calorimeters

- **MMC**: **m**agnetic **m**icro-**c**alorimeters with paramagnetic sensor Au:Er





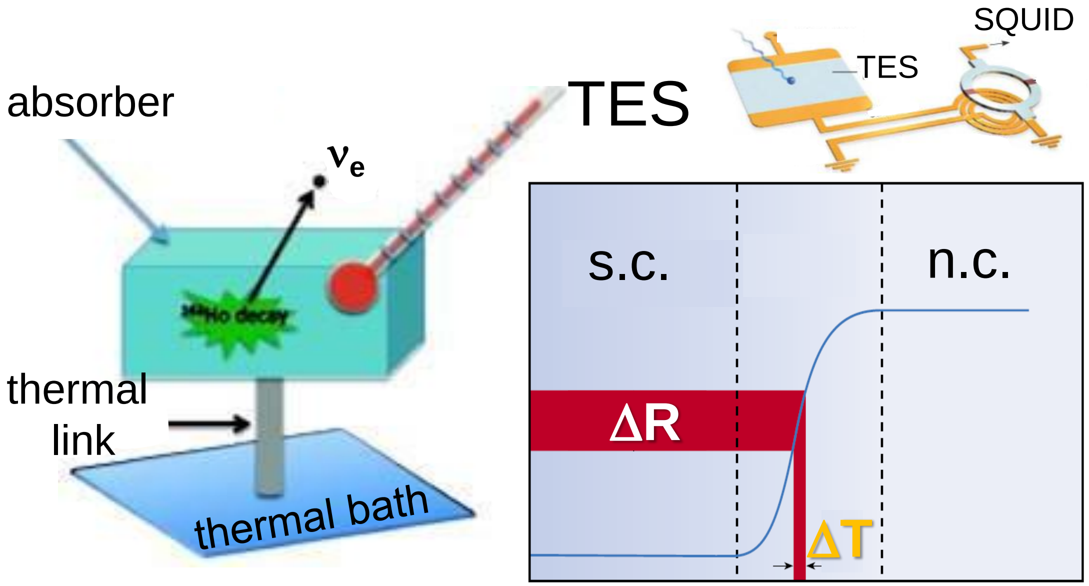
δT in absorber from EC-decay

⇨ change in magnetism δM of sensor

calorimeter signal:

$$\delta\Phi_S \sim \frac{\partial M}{\partial T}\cdot\Delta T \sim \frac{\partial M}{\partial T}\cdot\frac{1}{C_{tot}}\cdot\delta E$$

- **thermal m**icro-**c**alorimeters with TES read-out



δT in absorber from EC-decay

⇨ change in temp. T of TES thermistor

calorimeter signal:

$$\Delta T = \frac{\delta E}{V\cdot C_V}$$

^{163}Ho-experiments: the fever is on

Karlsruhe Institute of Technology

- **Common experimental challenges to reach sub-eV sensitivity:**
  - high purity ^{163}Ho source (production)
  - excellent detector performance (arrays)
  - background reduction

ECHo

- Comenius University, Bratislava, Slovakia
- Dept. of Physics, IIT Roorkee, India
- JGU Mainz
- INR, Hungarian Acad. of Sciences
- ITEP, Moscow, Russia
- Univ. of Tübingen, Germany
- KIP, Heidelberg University, Germany
- MPIK Heidelberg, Germany
- PNPI Petersburg, Russia
- Saha Institute of Nuclear Physics, Kolkata, India

HOLMES

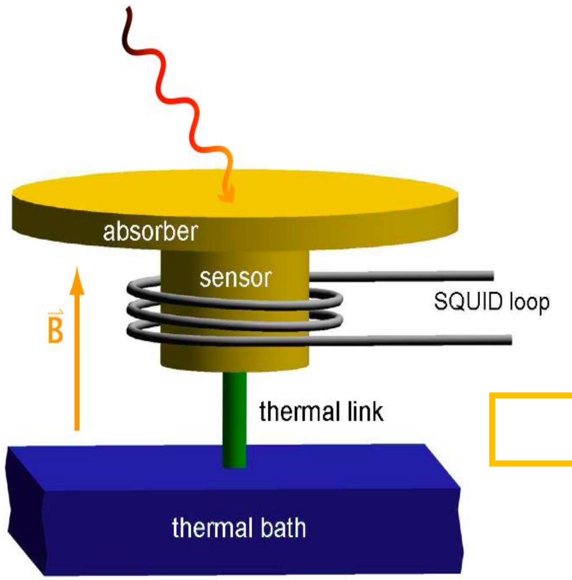
- Milano-Bicocca University, Italy
- INFN Sez. Milano-Bicocca, Italy
- INFN Sez. Genova, LNGS, Italy
- INFN Sez. Roma, Italy
- Lisboa University, Portugal
- Miami University, USA
- NIST, Boulder, USA
- JPL, Pasadena, USA

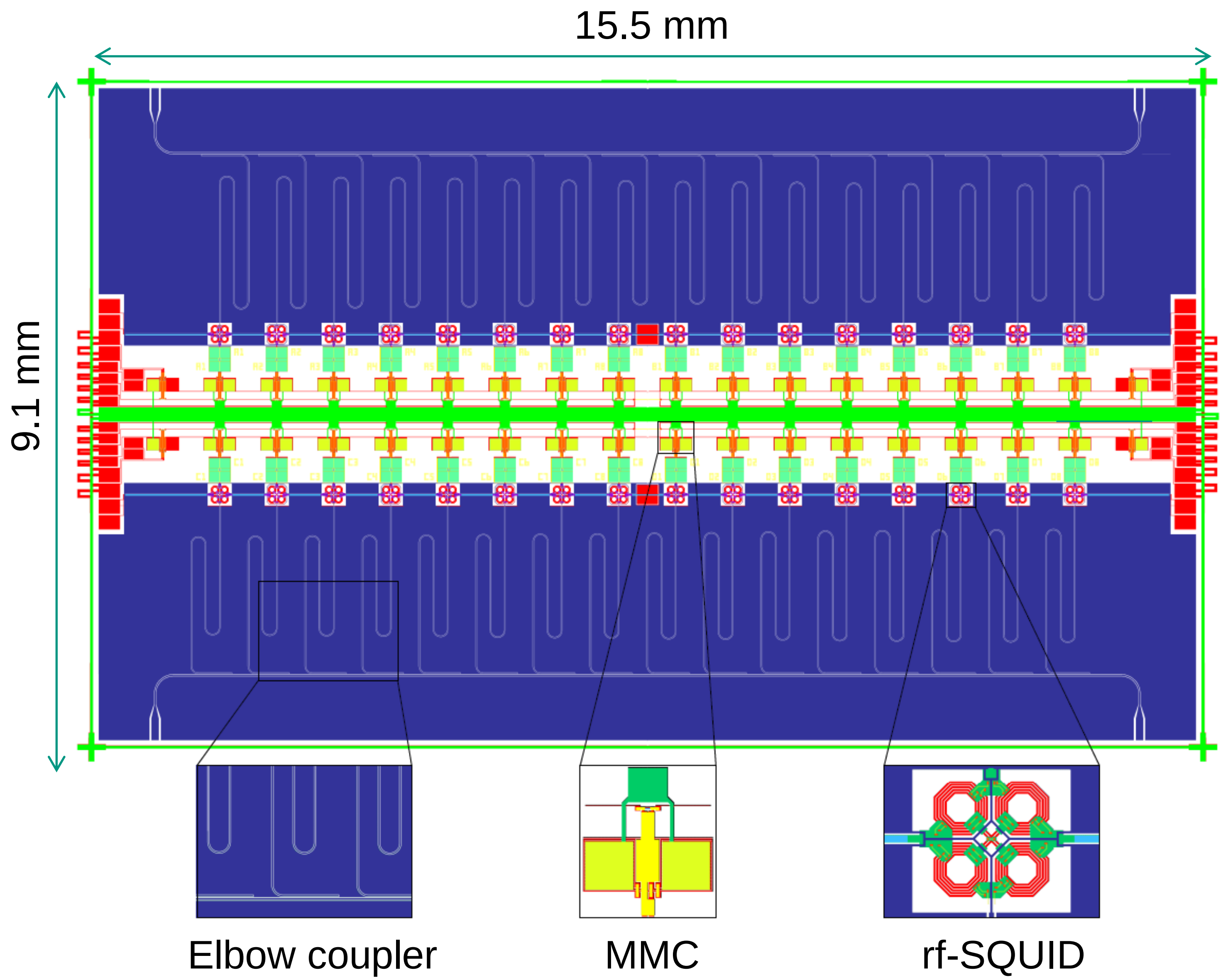
NuMECS

- LANL, Los Alamos, USA
- NIST, Boulder, USA
- Univ. of Wisconsin, Md., USA

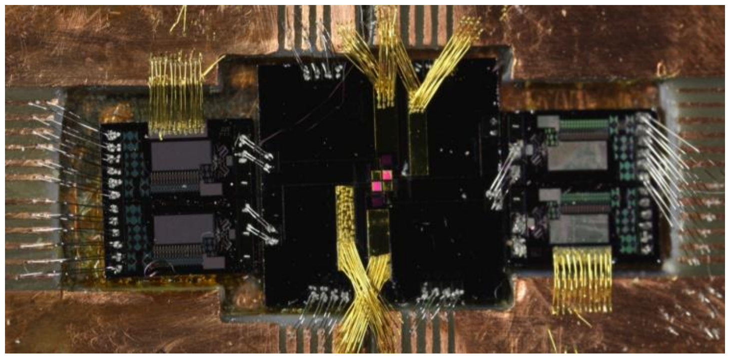
ECHo – from pixels to arrays

- increase number of pixels and make use of microwave SQUID multiplexing





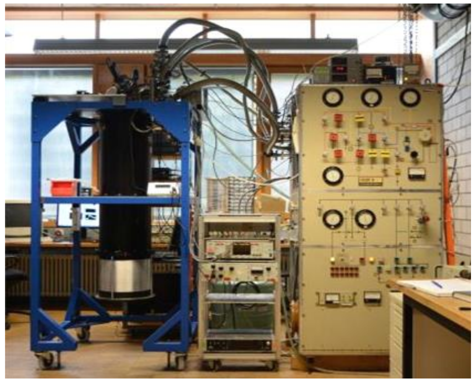
prototype



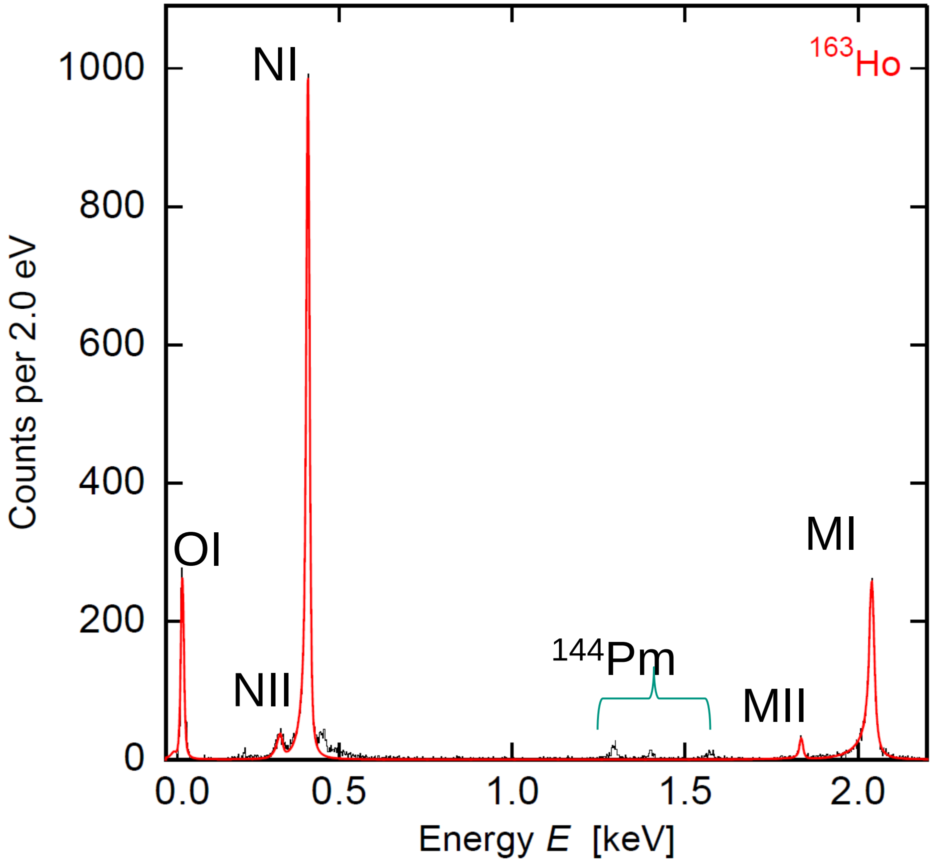
ECHo – recent results

- most precise calorimetric ^{163}Ho spectrum obtained
  - rise time t = 130 ns
  - ΔE = 7.6 eV @ 6 keV (2013)
  - ΔE = 2.4 eV @ 0 keV (2014)

2015: DFG research unit funding



- **Future steps**
  - background: material screening
  - bg-level: 5×10^{-5} counts/eV/det/day
  - high-purity ^{163}Ho sources: mass separation at CERN-ISOLDE



phase-1: 2015 – 2018

1000 Bq and 1 y: $m(\nu_e) < 10$ eV

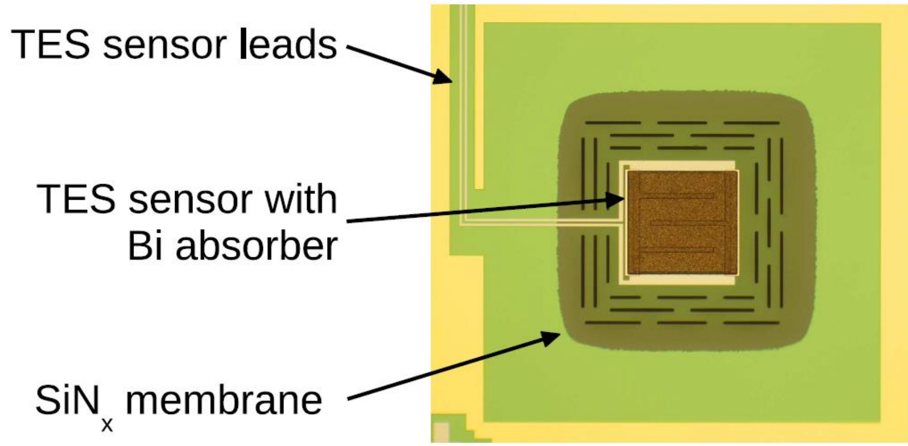
phase-2: 2018 – …

10^6 Bq and 3 y: $m(\nu_e)$ in sub-eV range

HOLMES – technology

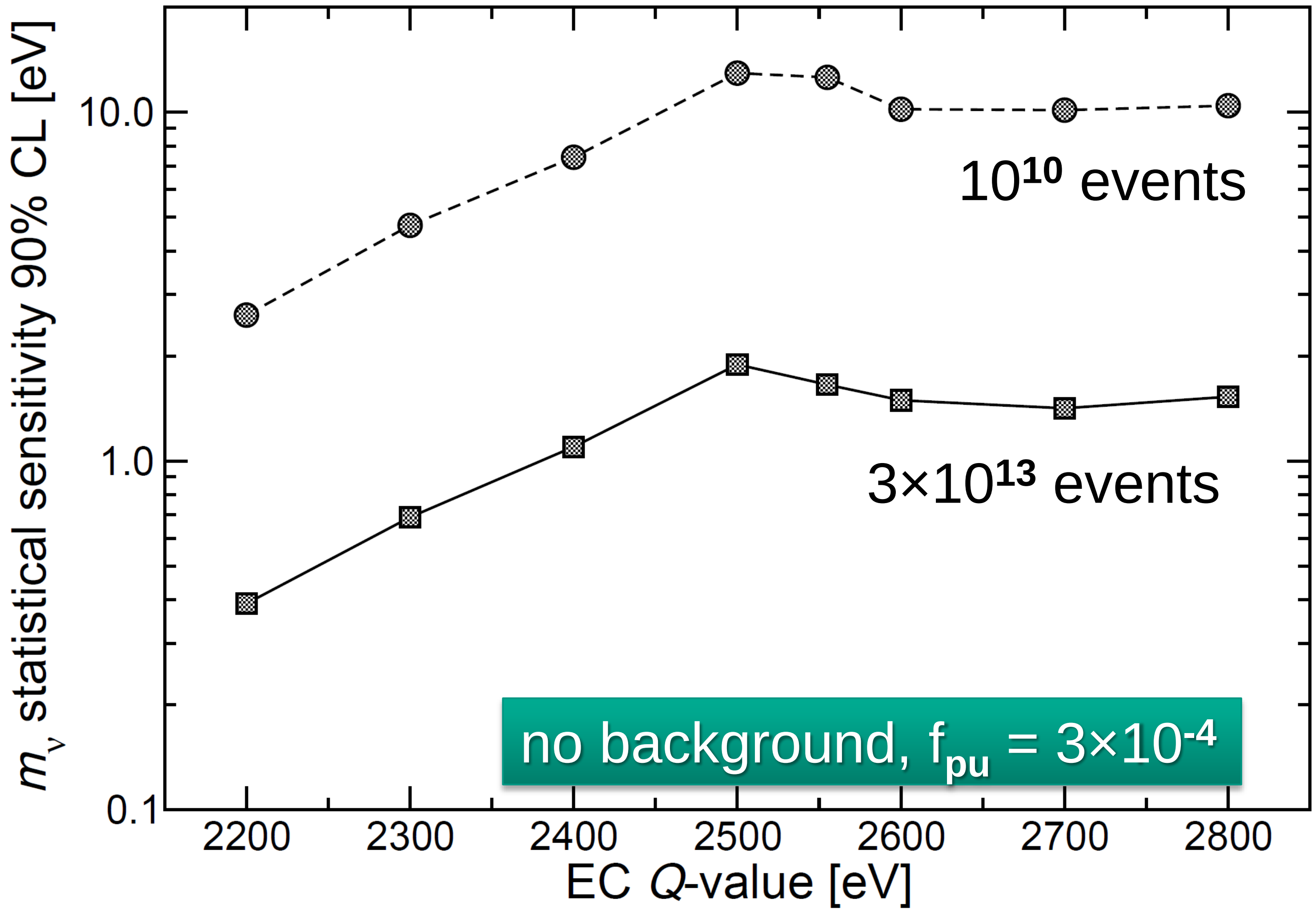
- 2013: funding via ERC Advanced Grant (2014-2019)
- array 1000 TES-based microcalorimeters,
  each with 300 Bq of Ho-163 fully embedded
- key tasks:
  - ^{163}Ho isotope production: n-irridiation of $^{162}Er_2O_3$ @ILL
  - ^{163}Ho source embedding: ion implanter
  - optimisation of single pixels:
    Mo/Cu TES on SiNx membrane with bismuth absorbers
  - array engineering:
    2x32 sub-arrays
  - multiplexed read-out:
    microwave multiplexing (µMUX)
  - data handling:
    FPGAs for 3×10^5 Bq

successor to MARE



HOLMES – overview

- baseline targets:
  - collect 3×10^{13} events over 3 years: **sensitivity m(ν) = 0.4 – 1.8 eV (90%CL)**
  - total Ho-163 activity:
    3×10^5 Bq
    (1000 pixels à 300 Bq)
    = 6.5×10^{16}
    Ho-163 nuclei
    = 18 µg
  - energy resolution:
    ΔE = 1eV
    timing: τ_r = 1 µs



first prototype detectors mid-2015

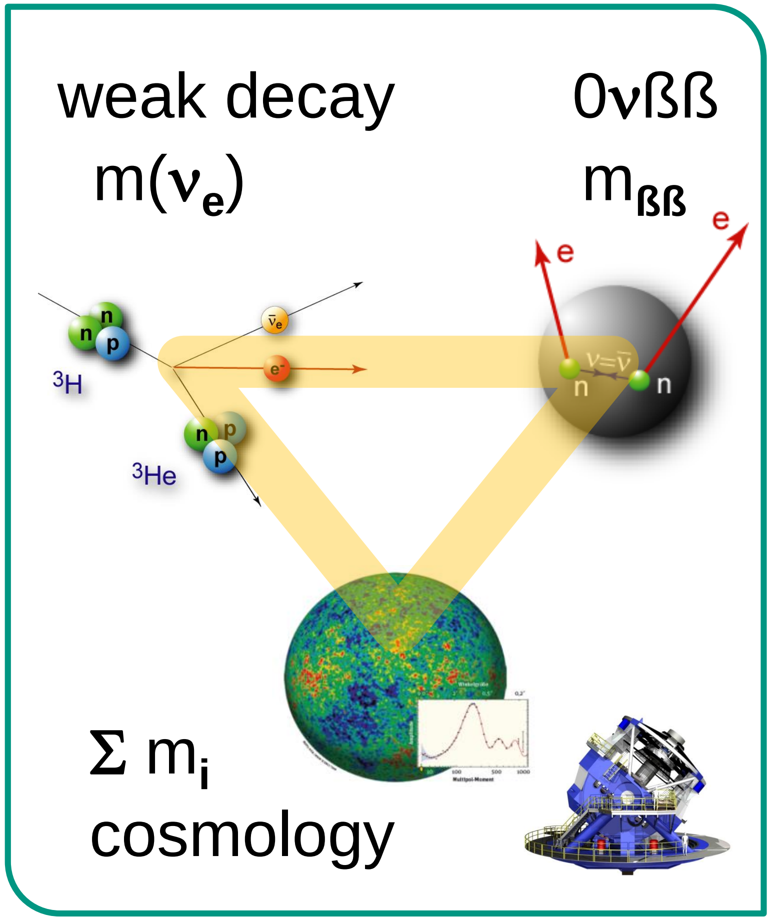
Conclusions

- **kinematic studies** of ß-decay/EC : the only model-independent method to determine the absolute ν-mass scale
- **KATRIN** will probe quasi-degenerate mass scale down to **$m(\nu_e)$ = 200 meV**
  - first tritium runs expected in mid-2016
  - studies for KATRIN phase II to go beyond this value, search keV-steriles

- **Project 8** – promising read-out technology (CRES), first single electron seen long R&D expected for planned atomic tritium source for sub-eV sensitivity
- **Ho-163 renaissance & excitement** (ECHo, HOLMES)
  - advantage: scalable approach
  - large amount of work in Europe and the US, goal: reach sub-eV sensitivity

Conclusions

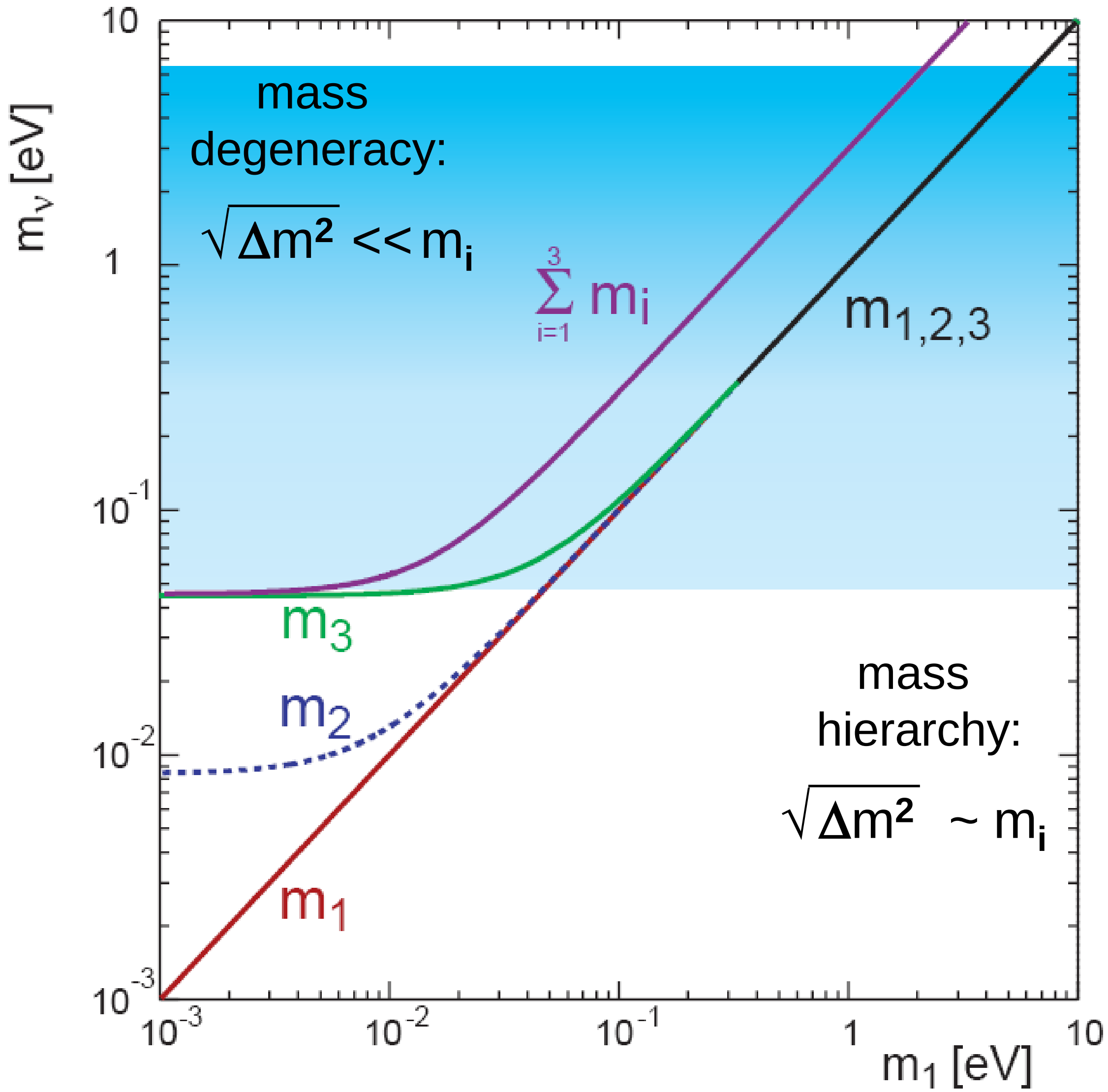
the complete picture of neutrino masses is obtained only
by comparing high-precision results from direct neutrino mass searches
with 0νßß experiments and cosmological studies

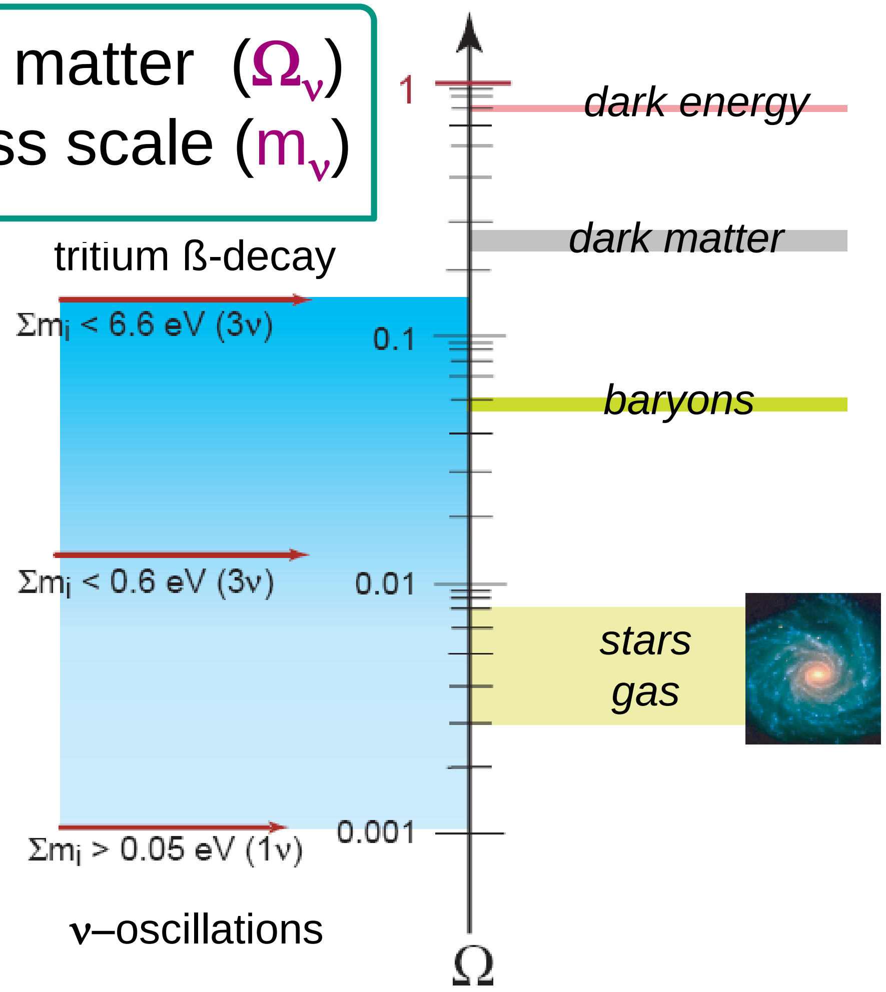


backup slides

absolute ν-mass scale

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



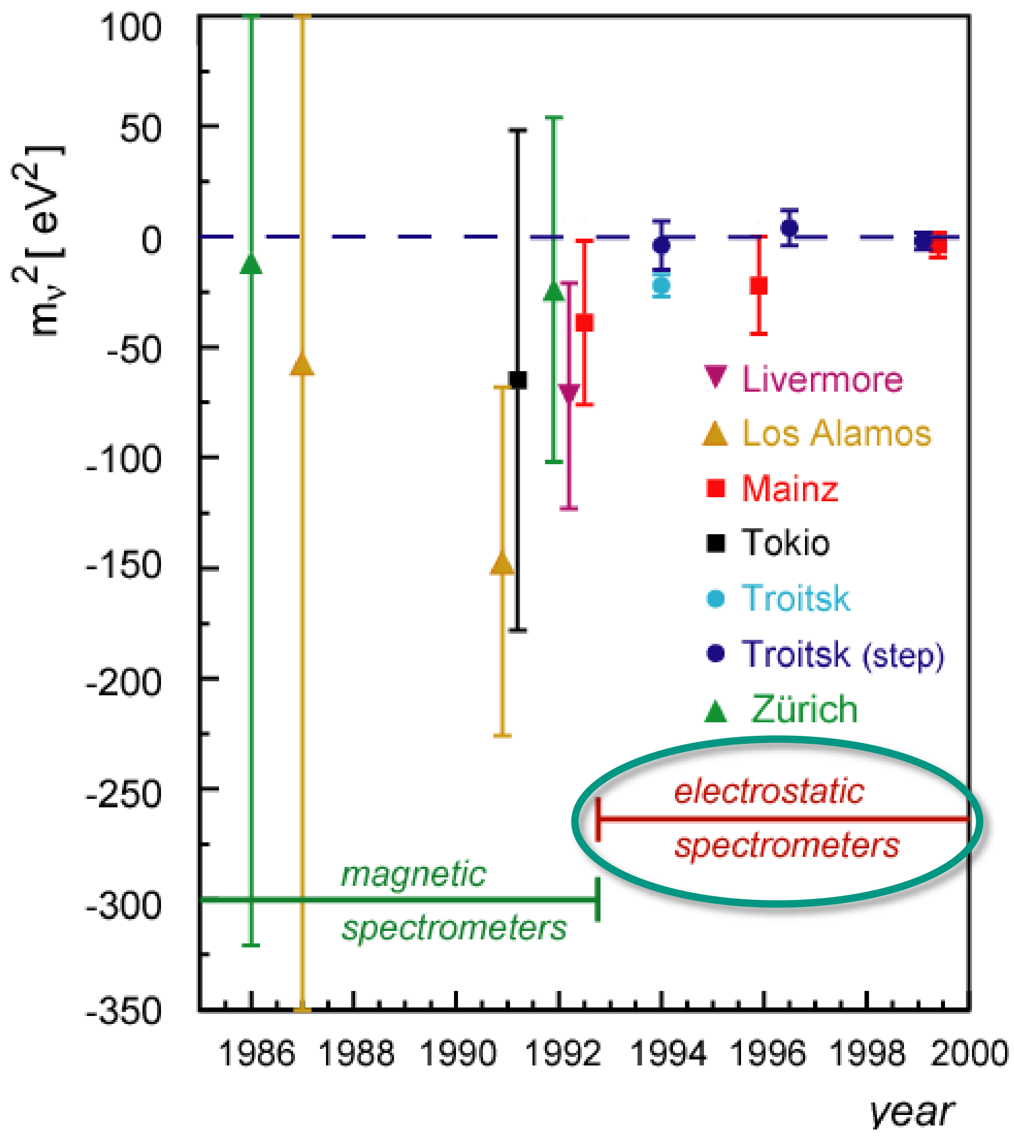


experimental sensitivity to quasi-degenerate ν-mass scenarios (and beyond?)

history of tritium ß-decay experiments

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.05 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV

experimental results for m_ν^2

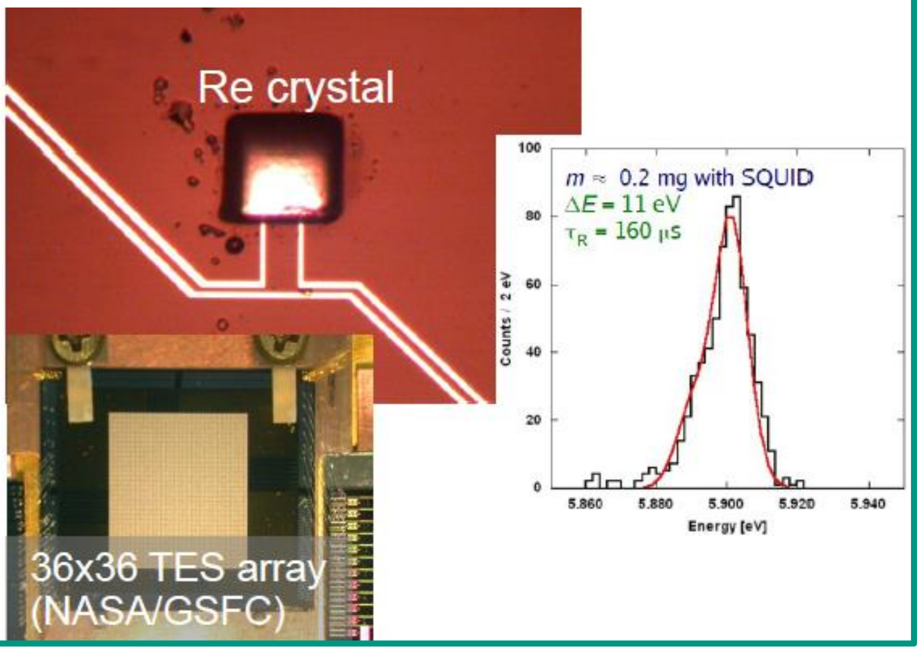


MARE experiment: R&D for Re-187

M A R E
The Microcalorimeter Arrays for a Rhenium Experiment

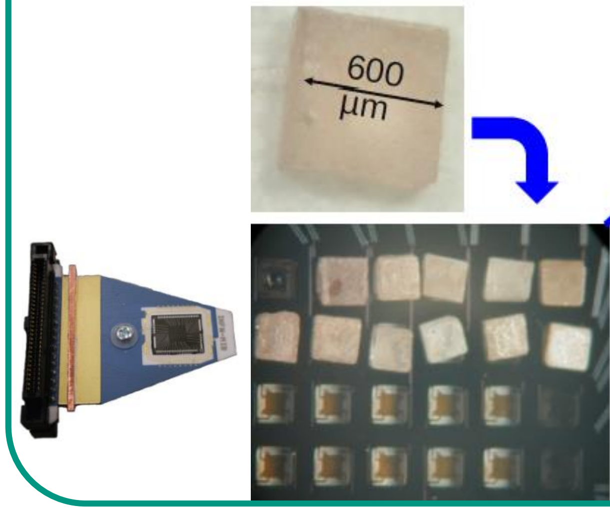
Genova, U Miami, U Lisbon/ITN

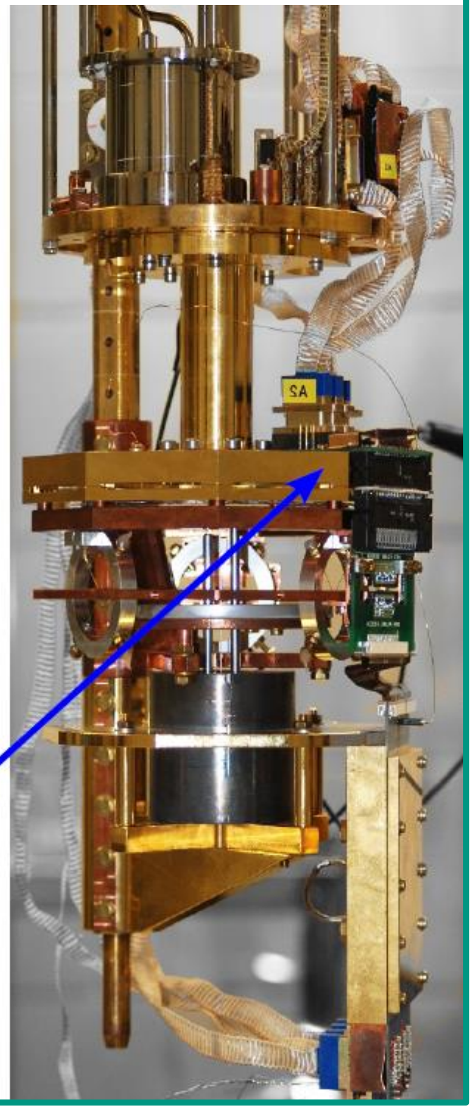
- metallic Re absorbers (up to 300)
- m = (0.2-0.3) g ➭ ~0.25 Bq
- TES sensors (Ir-Au bi-layer), multiplexed SQUID read-out
- ΔE ~ 11 eV
- τ_{rise} ~ 160 µs



Milano, NASA/GSFC, U Wisconsin

- 6x6 arrays of $AgReO_4$ crystals (up to 8 arrays can be housed in cryostat)
- m = 0.5 mg ➭ 0.27 Bq
- Si-impl. thermistors
- ΔE ~ 25 eV
- τ_{rise} ~ 250 µs





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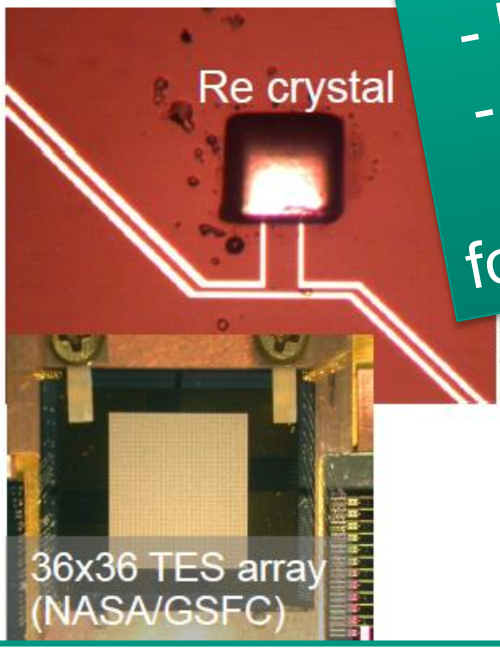
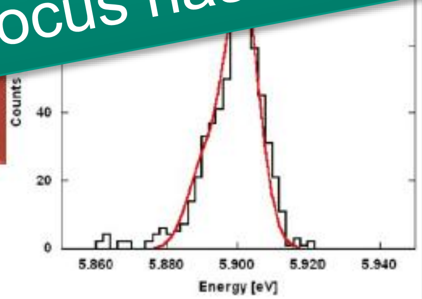


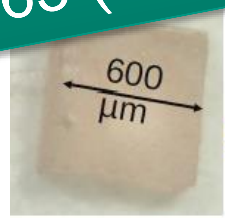


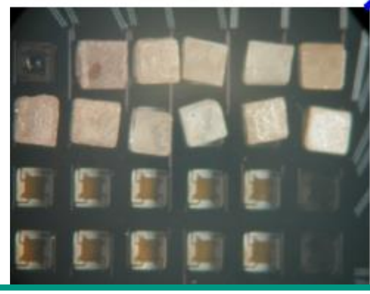
Milano, NASA/GSFC, U Wisconsin

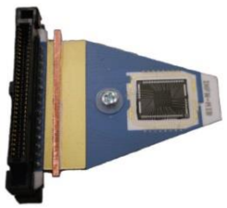
- 6x6 arrays of $AgReO_4$ crystals (up to 8 arrays can be housed in cr… at)

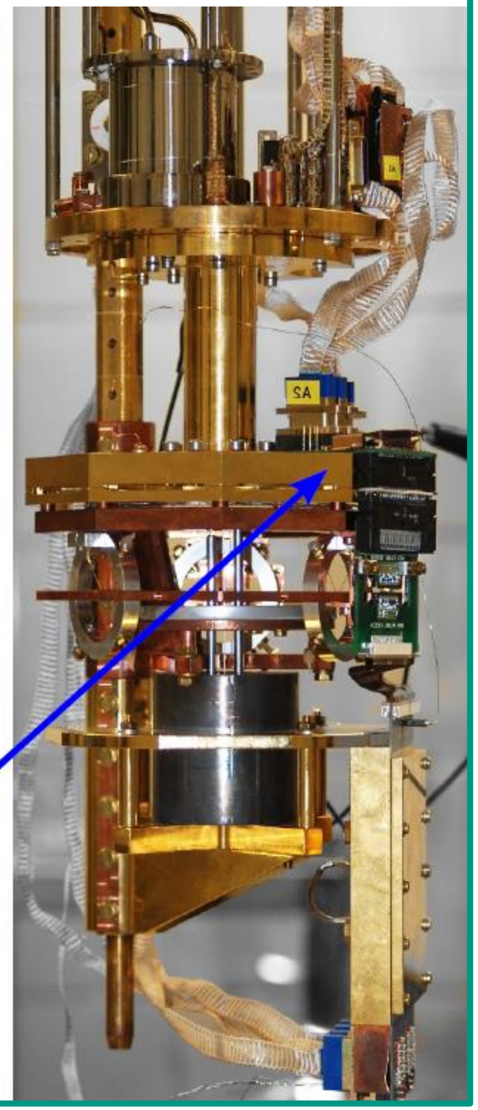
… Bq

… s







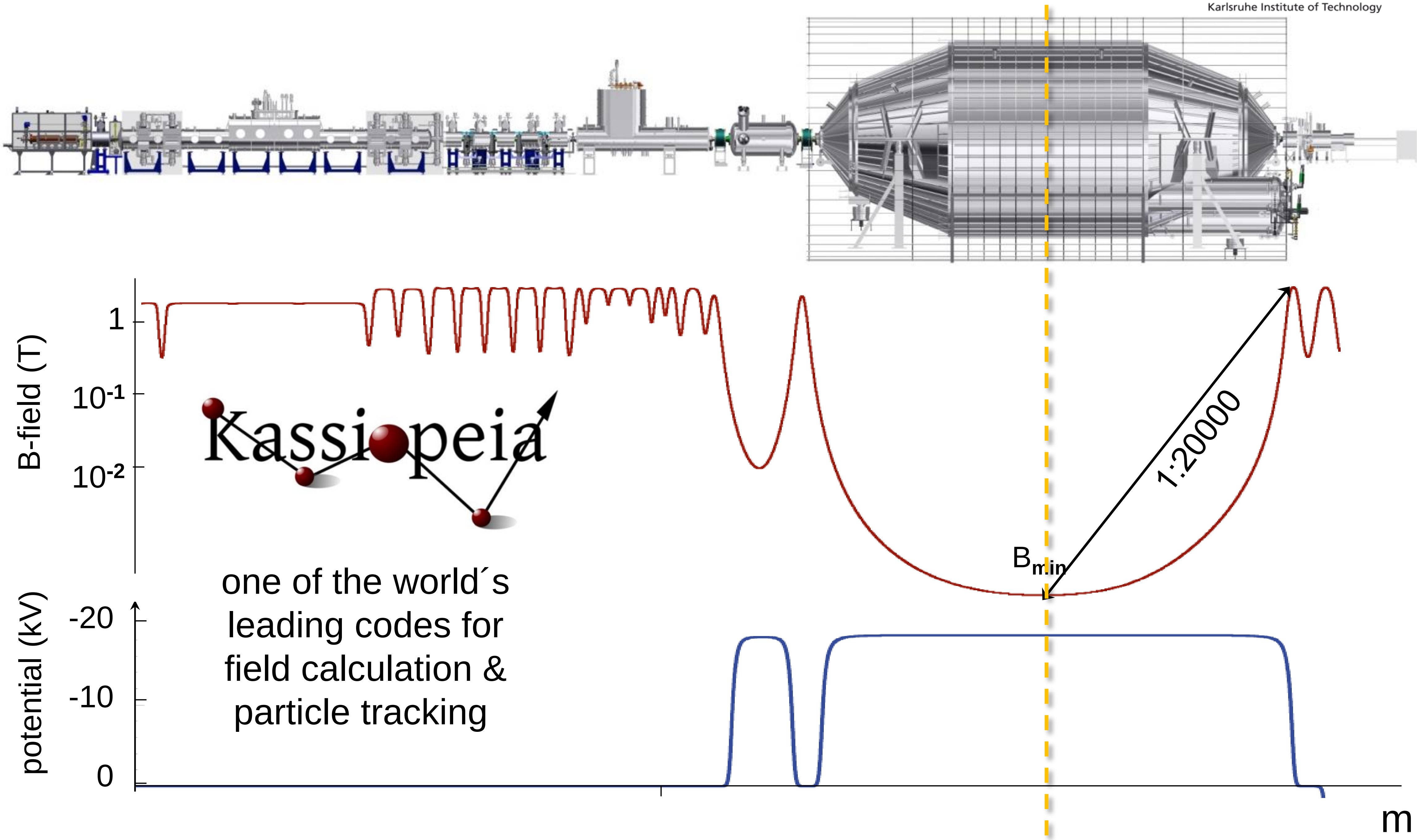


Rh-187 disadvantages:

- low specific activity ~1 Bq/mg
- slowness of thermalization process

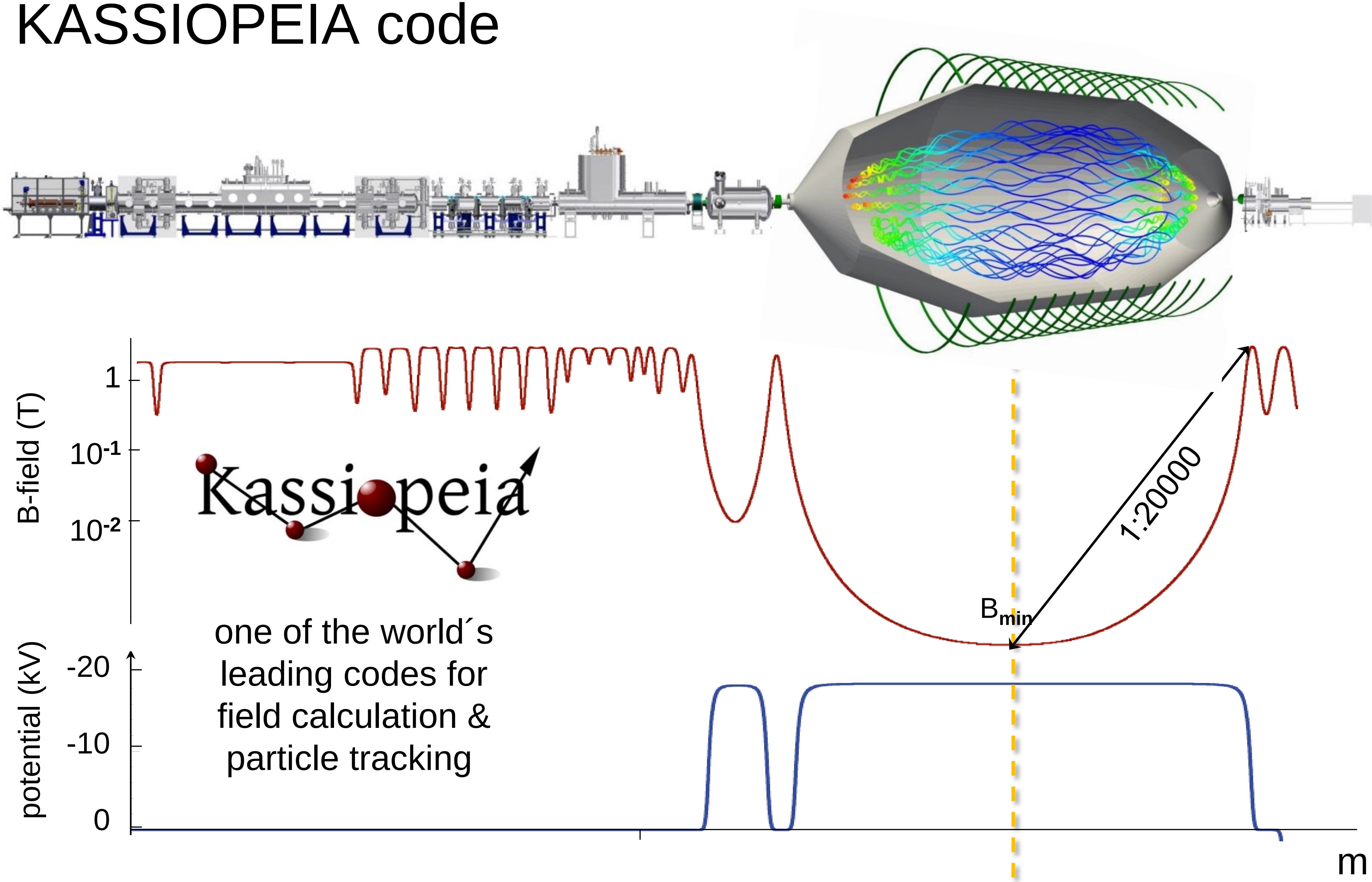
focus has shifted to Ho-163 (see later)

KASSIOPEIA code

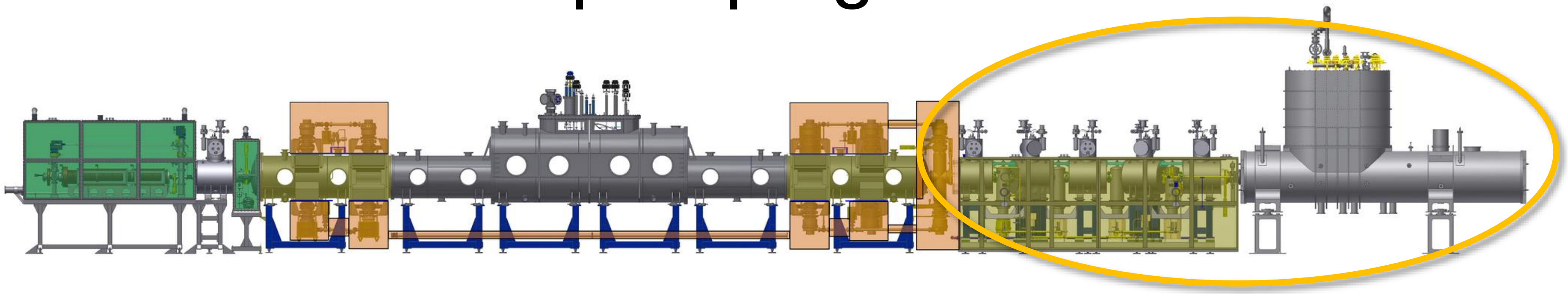


one of the world´s leading codes for field calculation & particle tracking

KASSIOPEIA code



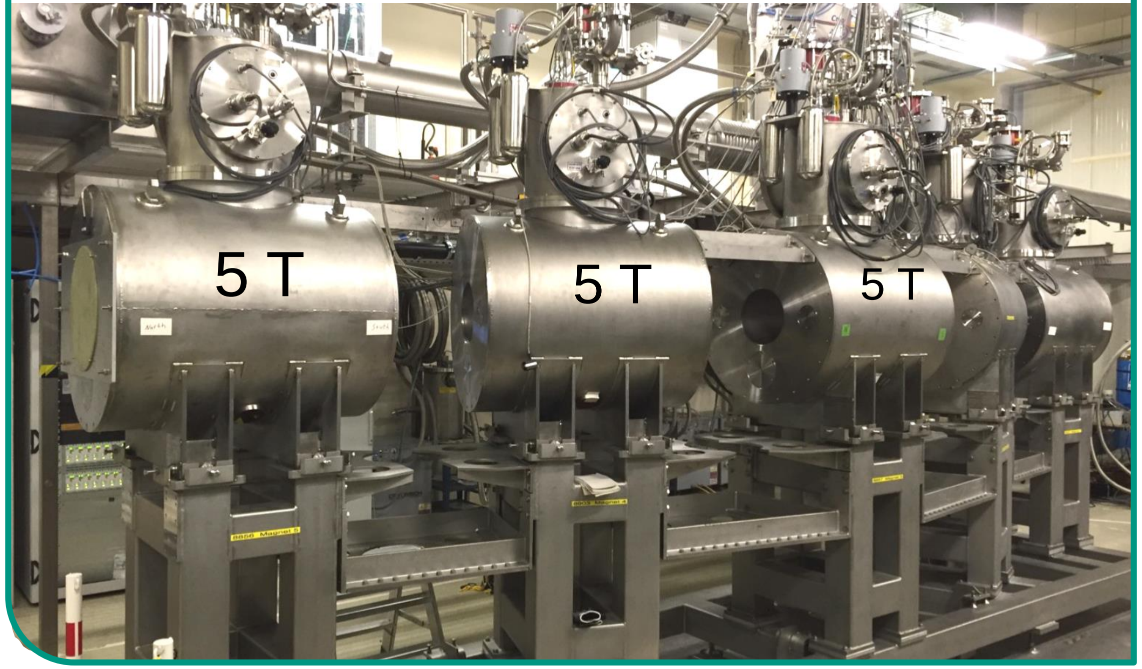
units for tritium pumping – status



■ **Differential Pumping Section DPS**

site acceptance tests at TLK almost completed

CRYOMAGNETICS, INC.



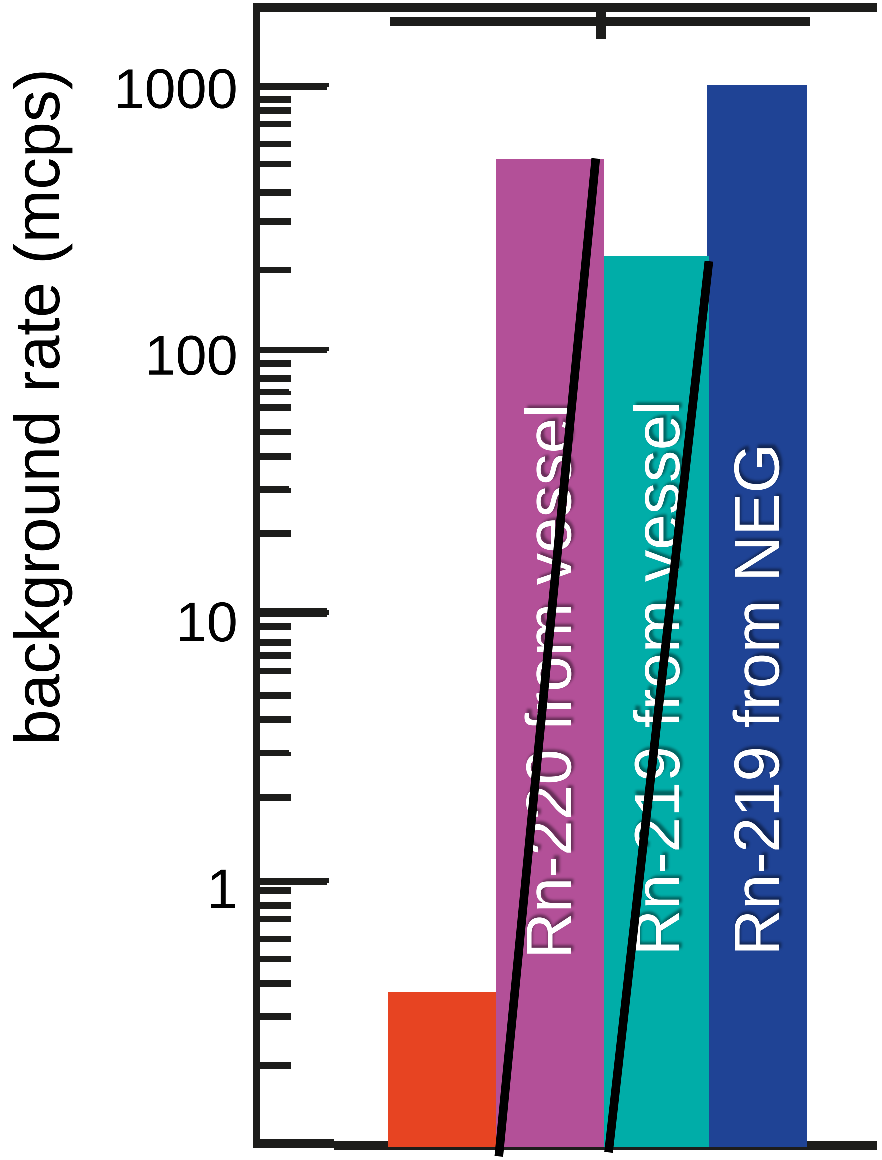
■ **Cryogenic Pumping Section CPS**

arrival of cryostat after FAT at KIT in June 2015

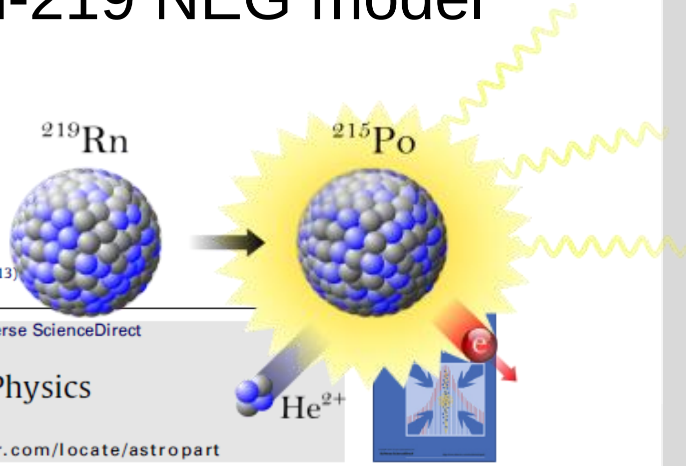
Ansaldo Superconduttori

radon background – data & model

excellent agreement of data & earlier Rn-model



- scaling by factor ~100 from pre-spectrometer:
  - model for ^{219}R(3 NEG) ~ 1000 mcps
  - model for ^{219}R(2 NEG) ~ **670 mcps**
- **experimental data SDS-2**
  - data (elevated pressure) ~ **525 mcps**
  - ⇨ validation of the Rn-219 NEG model



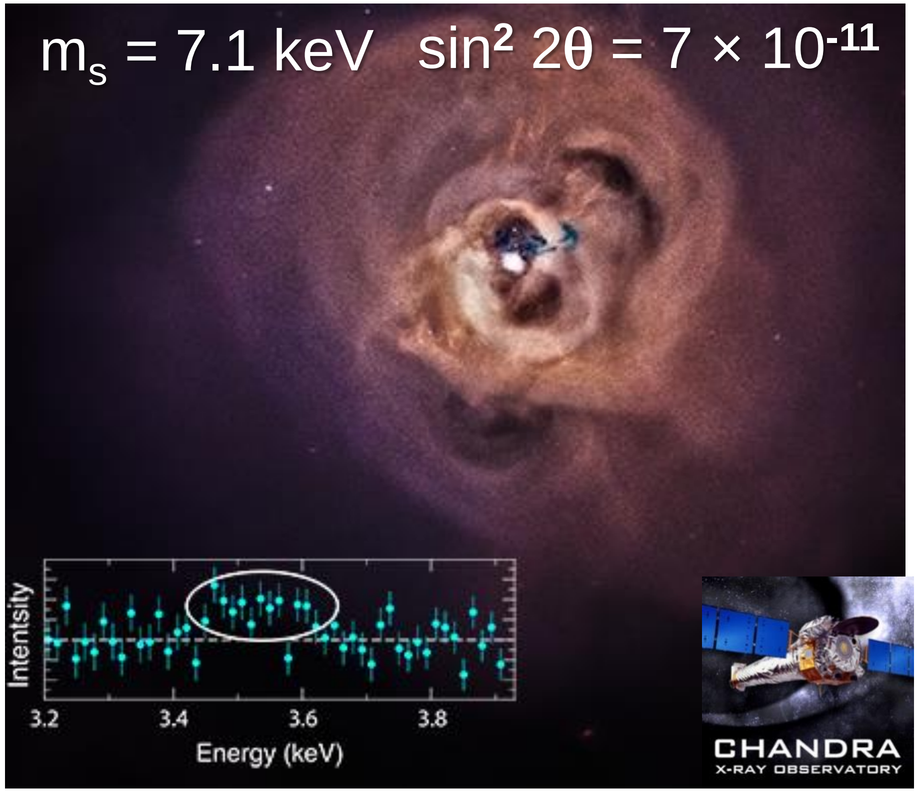
Astroparticle Physics 41 (2013)
Contents lists available at SciVerse ScienceDirect
ELSEVIER
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart

Background due to stored electrons following nuclear decays in the KATRIN spectrometers and its impact on the neutrino mass sensitivity

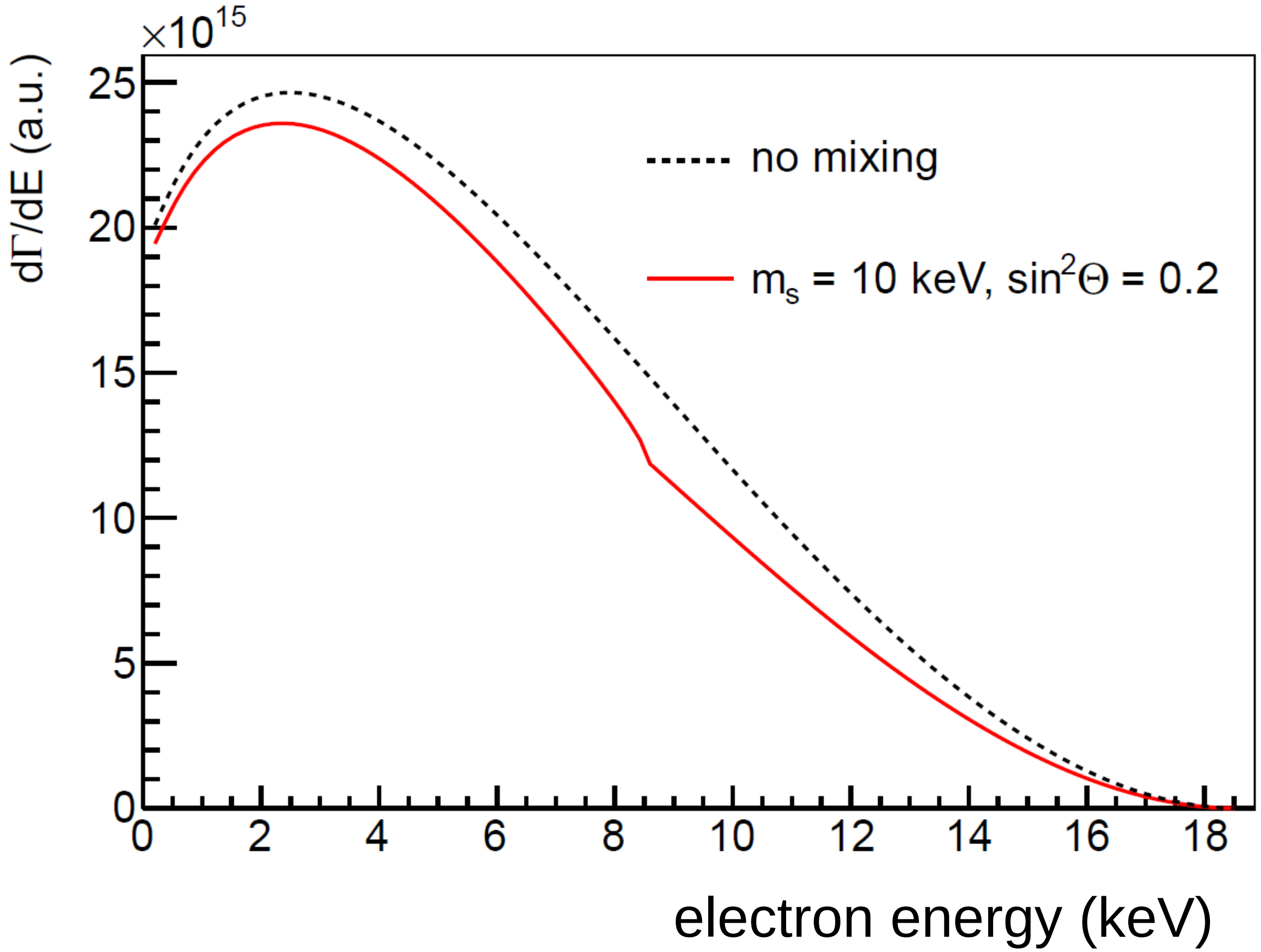
S. Mertens[a,*], G. Drexlin[a], F.M. Fränkle[a,b], D. Furse[d], F. Glück[a,c], S. Görhardt[a], M. Hötzel[a], W. Käfer[a], B. Leiber[a], T. Thümmler[a], N. Wandkowsky[a], J. Wolf[a]

keV-mass sterile neutrinos: WDM

- exploratory studies to search for **keV-mass scale sterile neutrinos** (WDM)
  - WDM: may mitigate problems of ΛCDM paradigm at smaller scales (kpc)
  - tritium ß-decay allows to search for keV sterile ν´s up to m(ν) ~ 18 keV

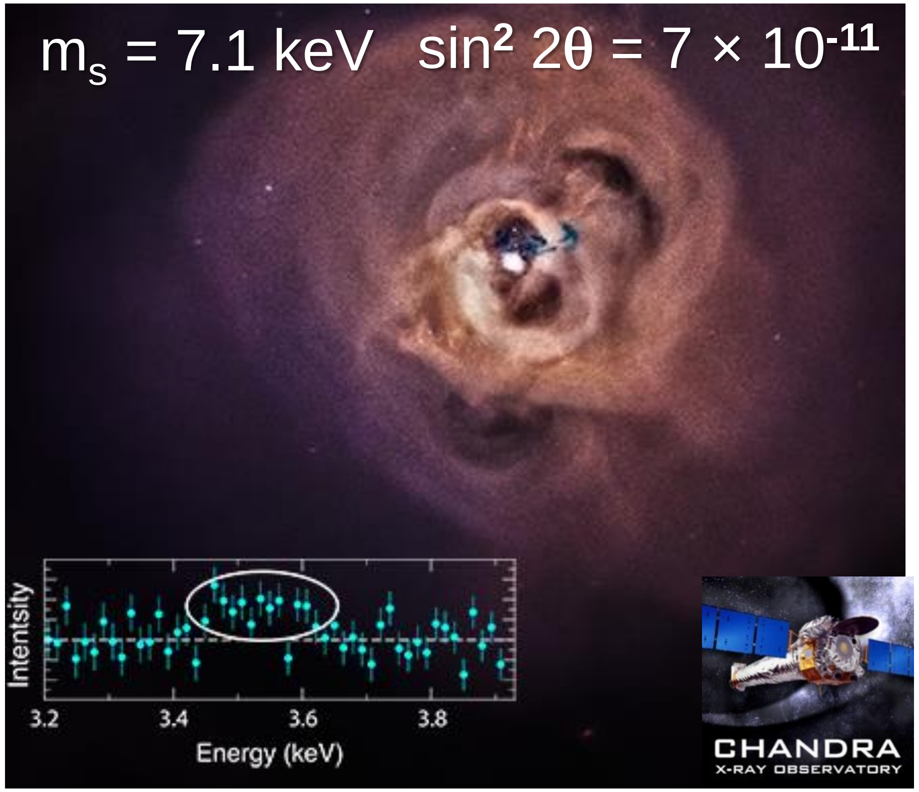


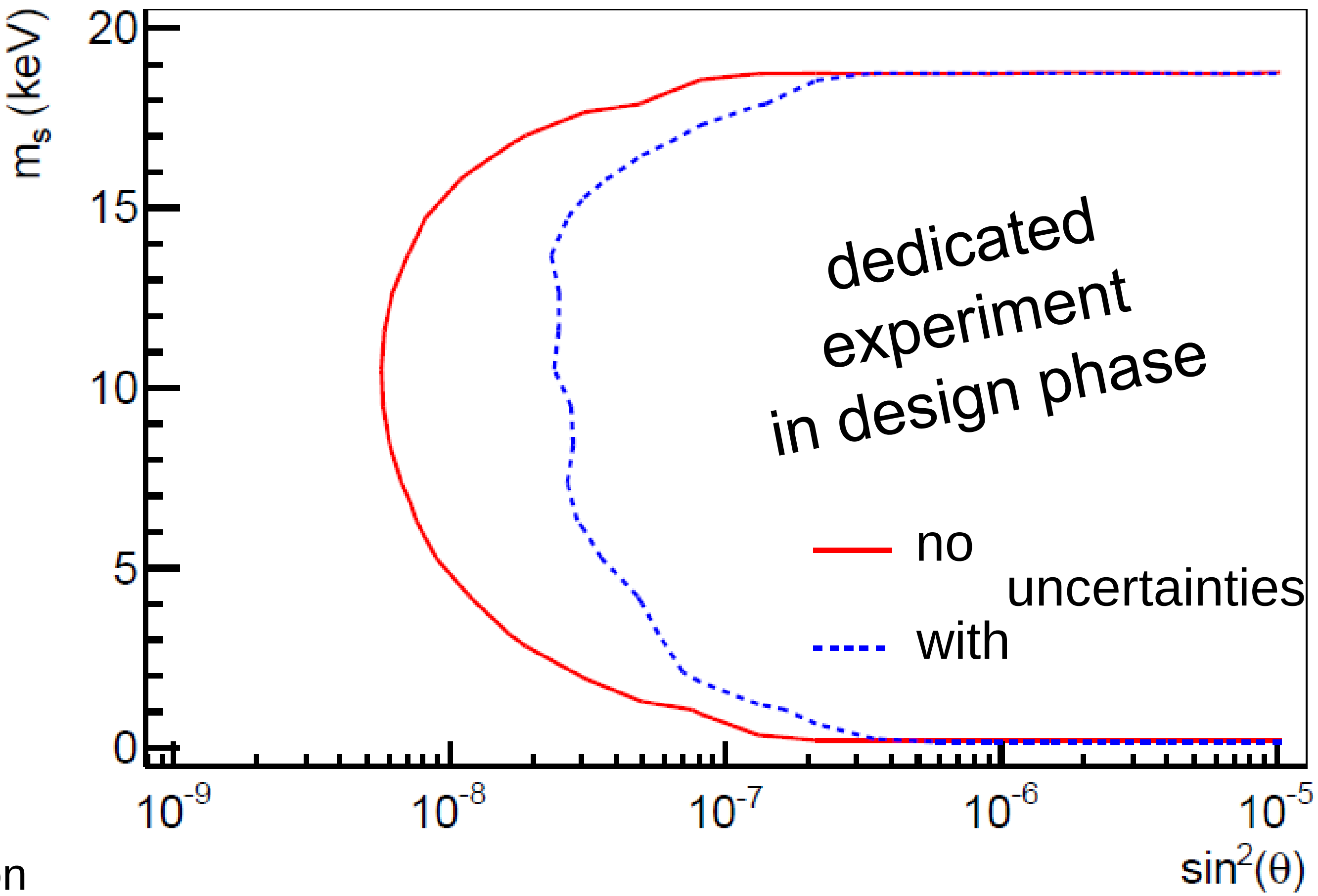
E. Bulbul et al., Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters, ApJ 789 (2014) 13



keV-mass sterile neutrinos: WDM

- exploratory studies to search for **keV-mass scale sterile neutrinos** (WDM)
  - WGTS source luminosity plus new differential read-out scheme
  - sensitivity down to $\sin^2\theta \sim 10^{-7}$ seems possible, if control of systematics

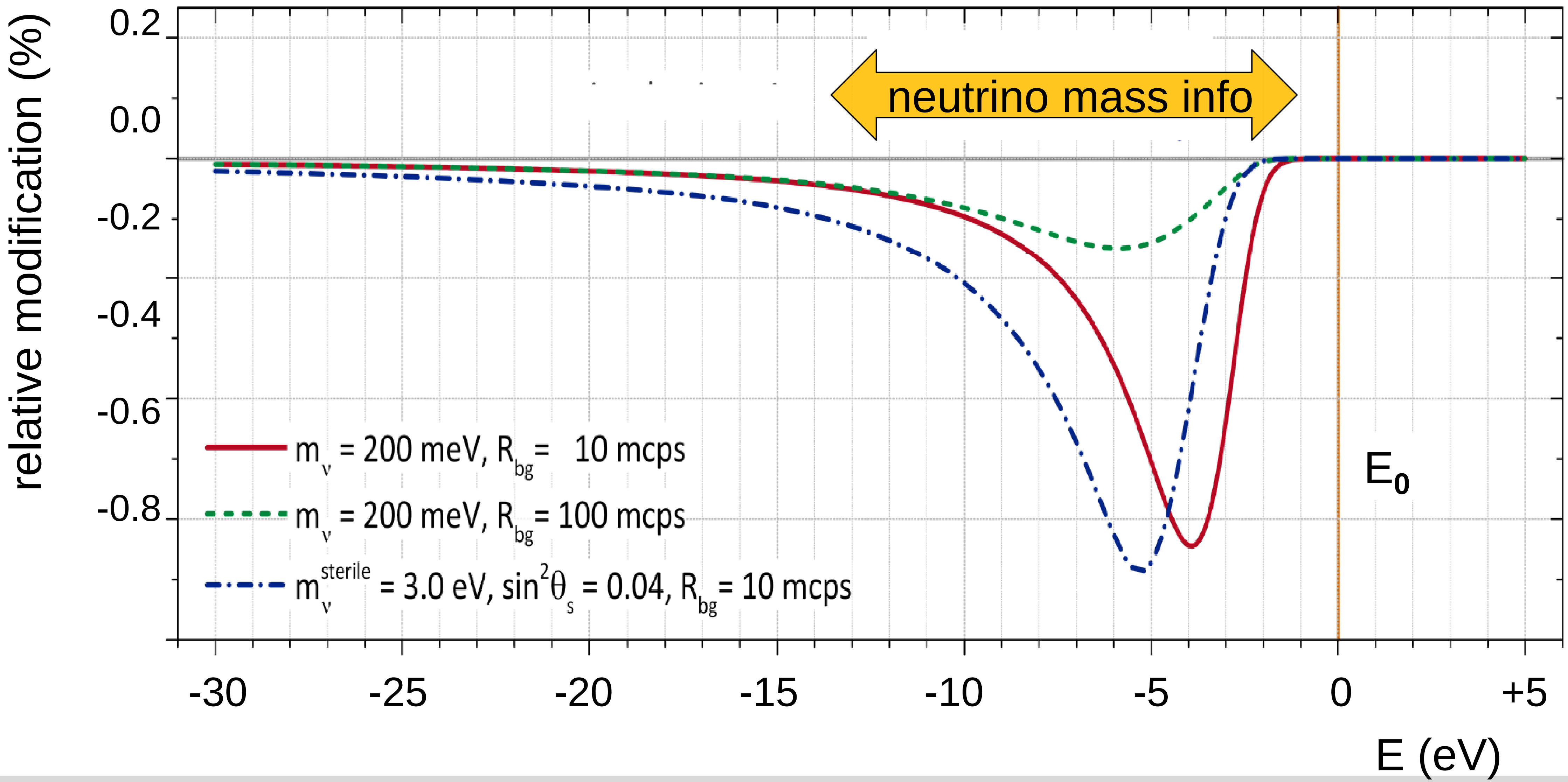




S. Mertens et al., Sensitivity of Next Generation Tritium-ß-decay Experiments for keV-Scale Sterile Neutrinos, *JCAP* 1502 (2015) 02

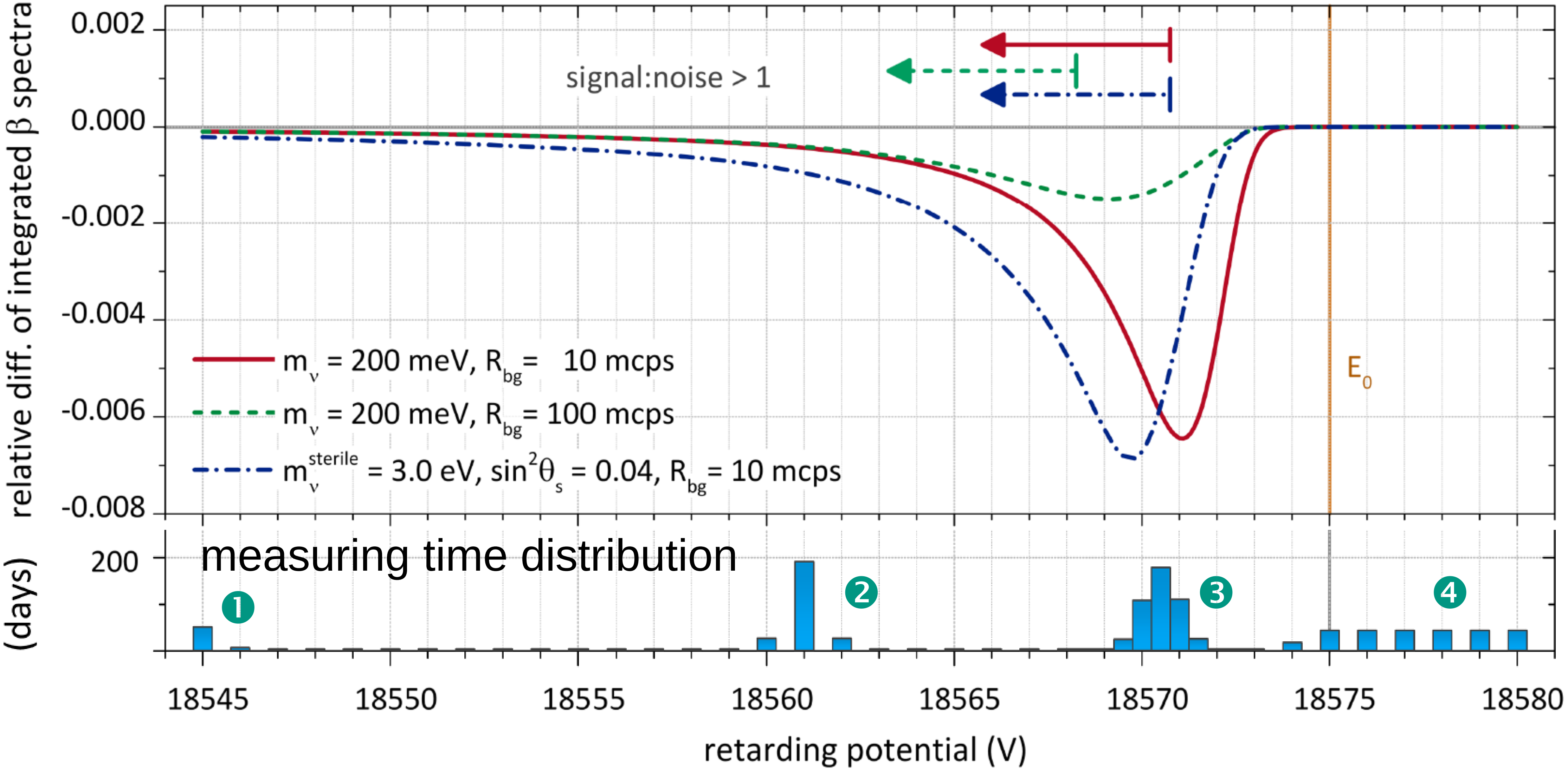
shape modification due to ν-masses

- Information in integrated spectrum from rather broad interval
  analysis uses 4 fit parameters: mass $m(\nu_e)$, R_{bg}, endpoint E_0, amplitude A_{sig}



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)

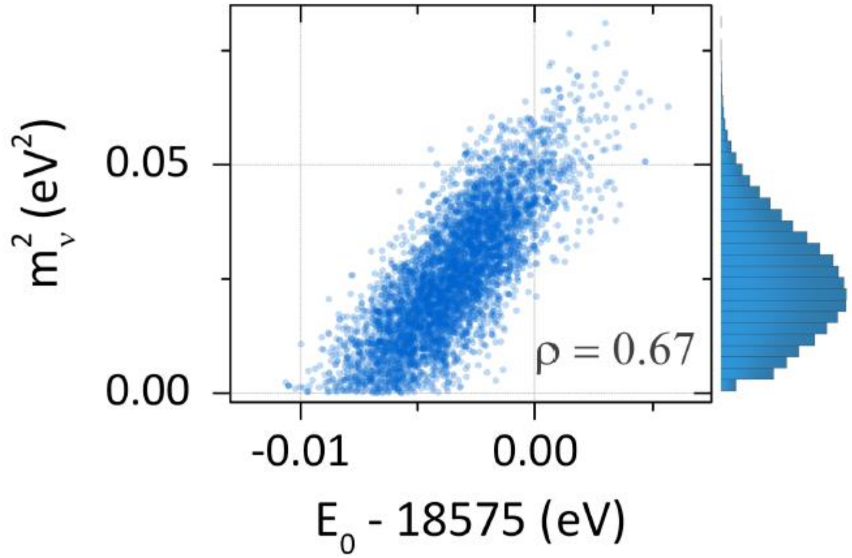


spectral shape – integral measurement

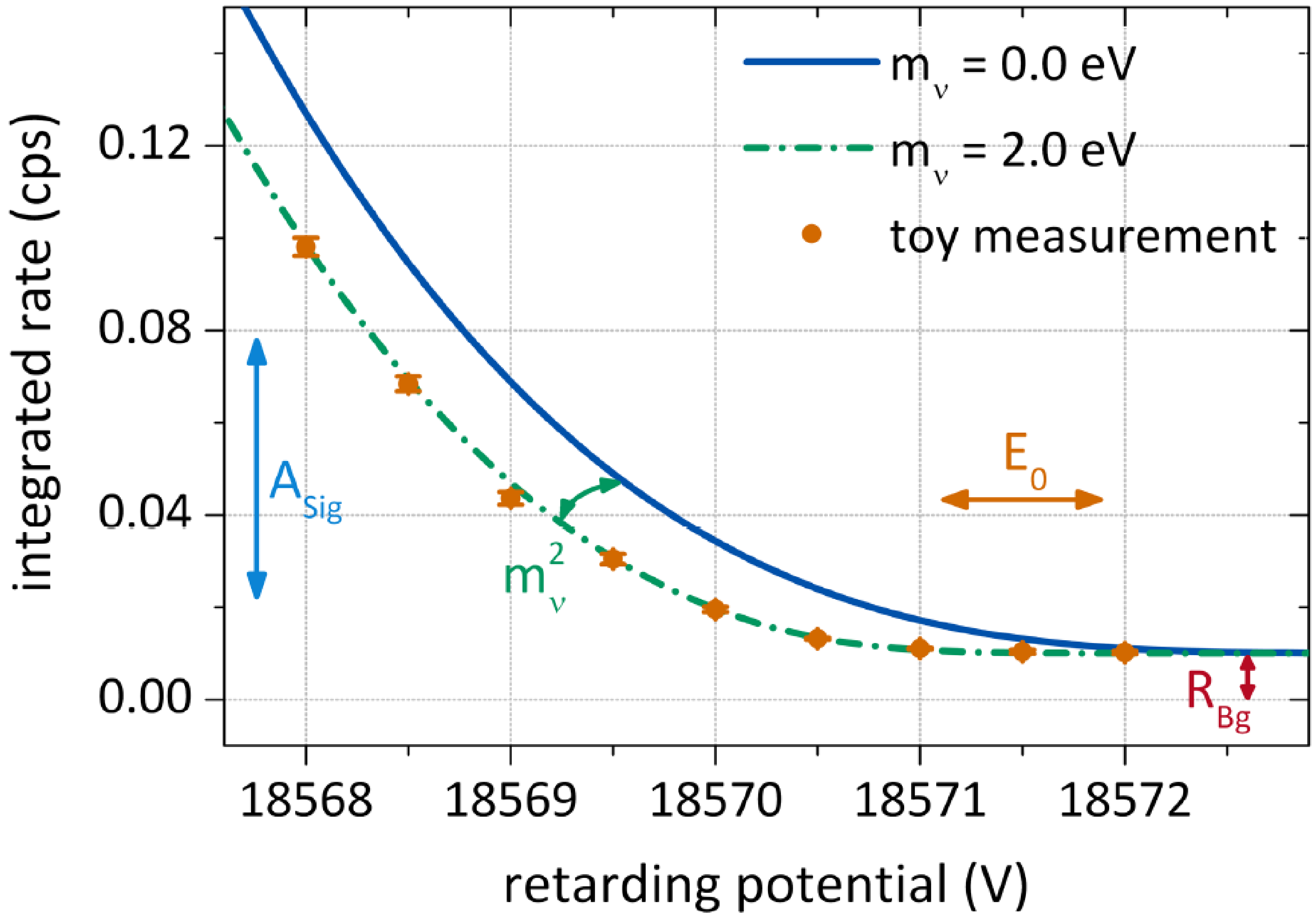
- only **relative spectral shape** is measured, no absolute measurement

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

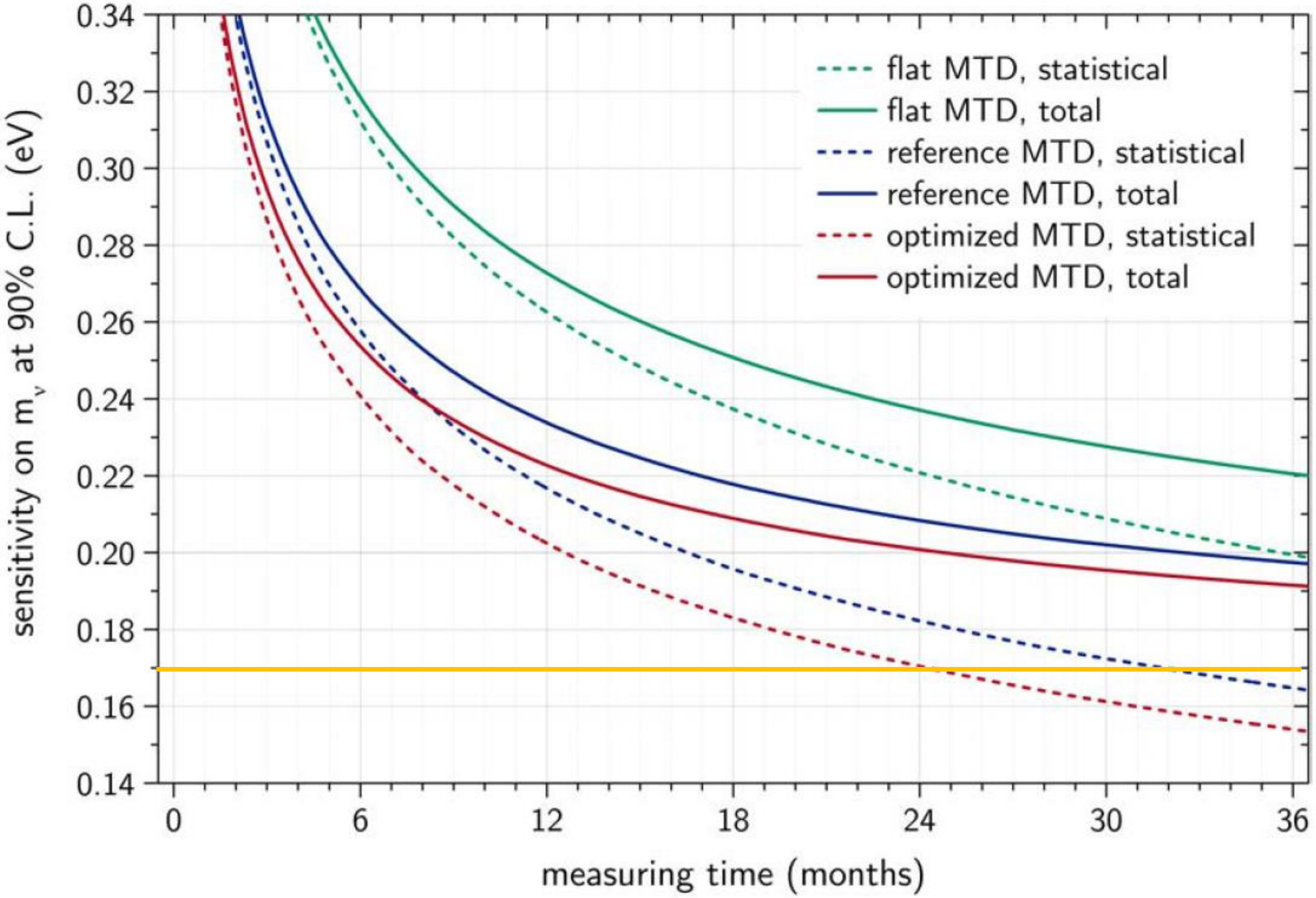


KATRIN ν-mass sensitivity & MTD

- **sensitivity as a function of measuring time**: in case systematics is constrained to σ_{syst} = 0.017 eV² ⇨ very fast progress in sensitivity

important:

- systematics
- optimized MTD
- background



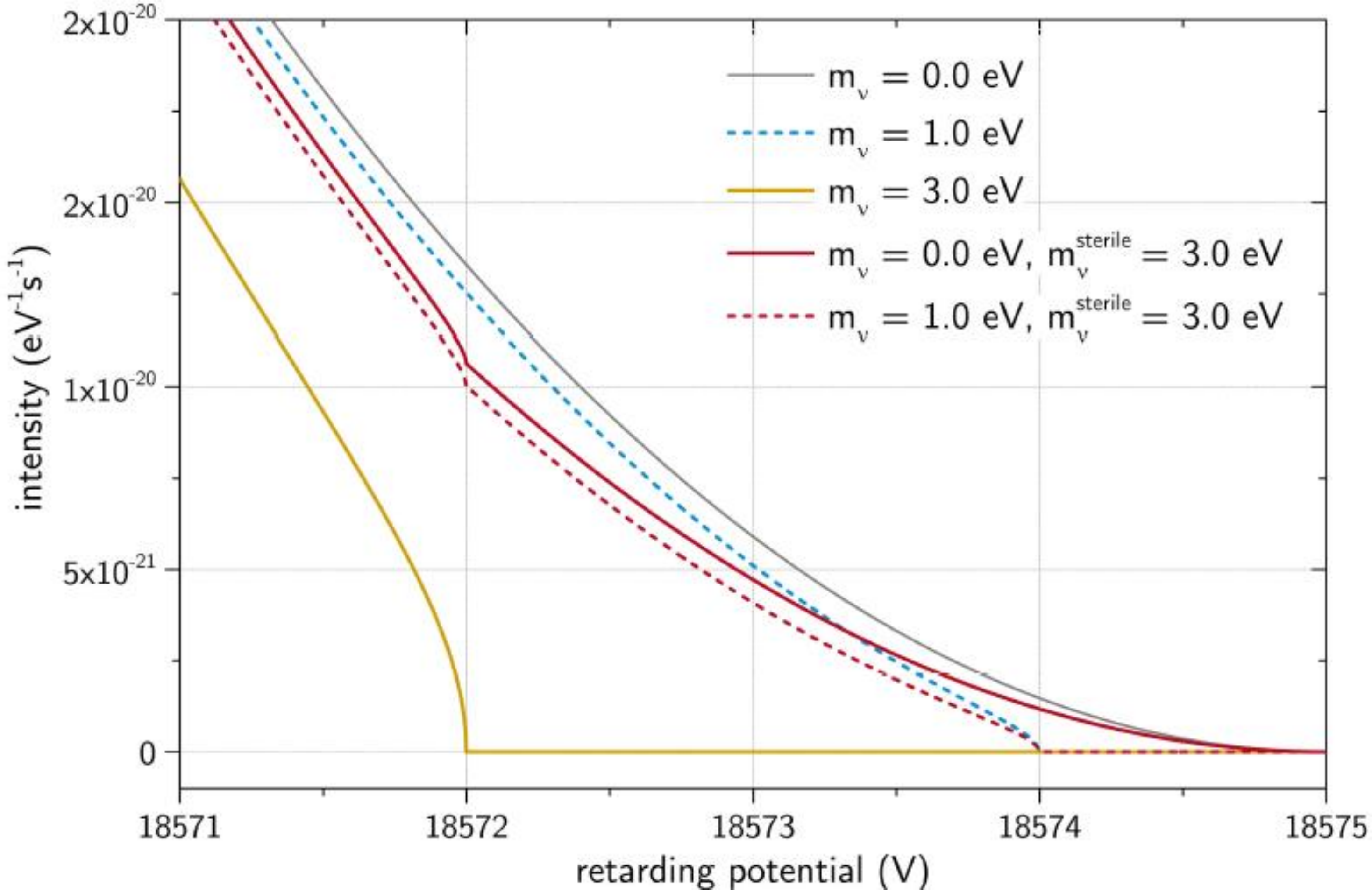
M. Kleesiek, PhD thesis, KIT (2014)

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 $E = E_0 - m_{\text{sterile}}$

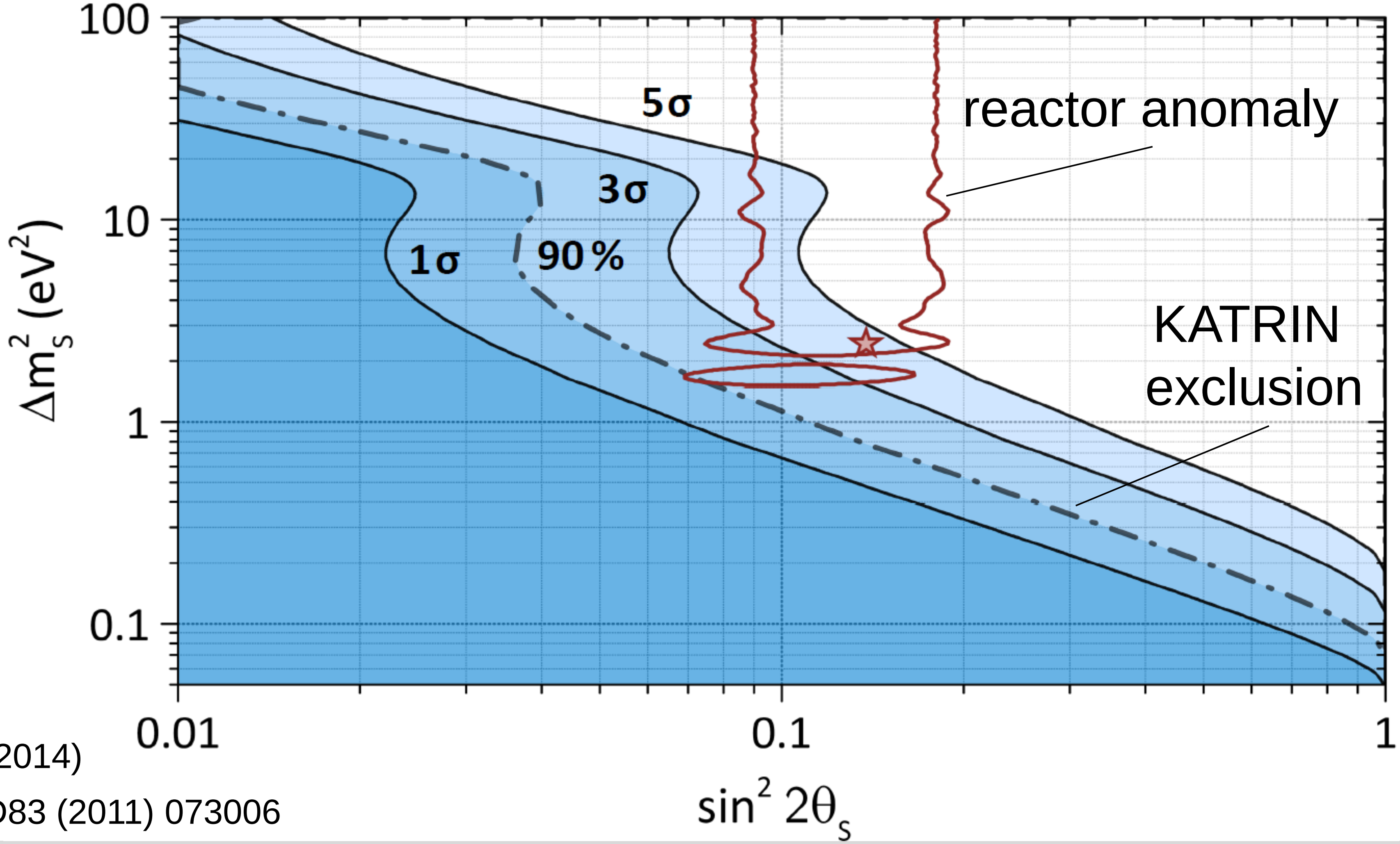


light sterile neutrinos: reactor-ν-anomaly

Karlsruhe Institute of Technology

- 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



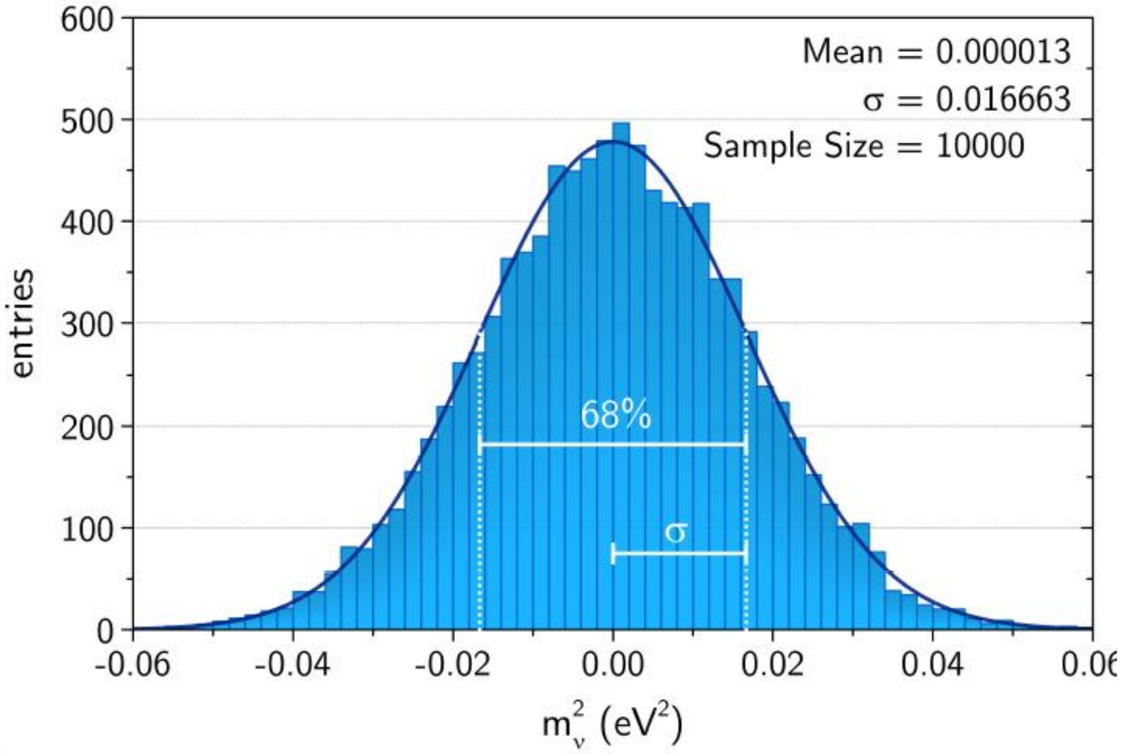
M. Kleesiek, PhD thesis, KIT (2014)

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

ensemble testing – no bias for m_ν

- bias-free neutrino mass analysis

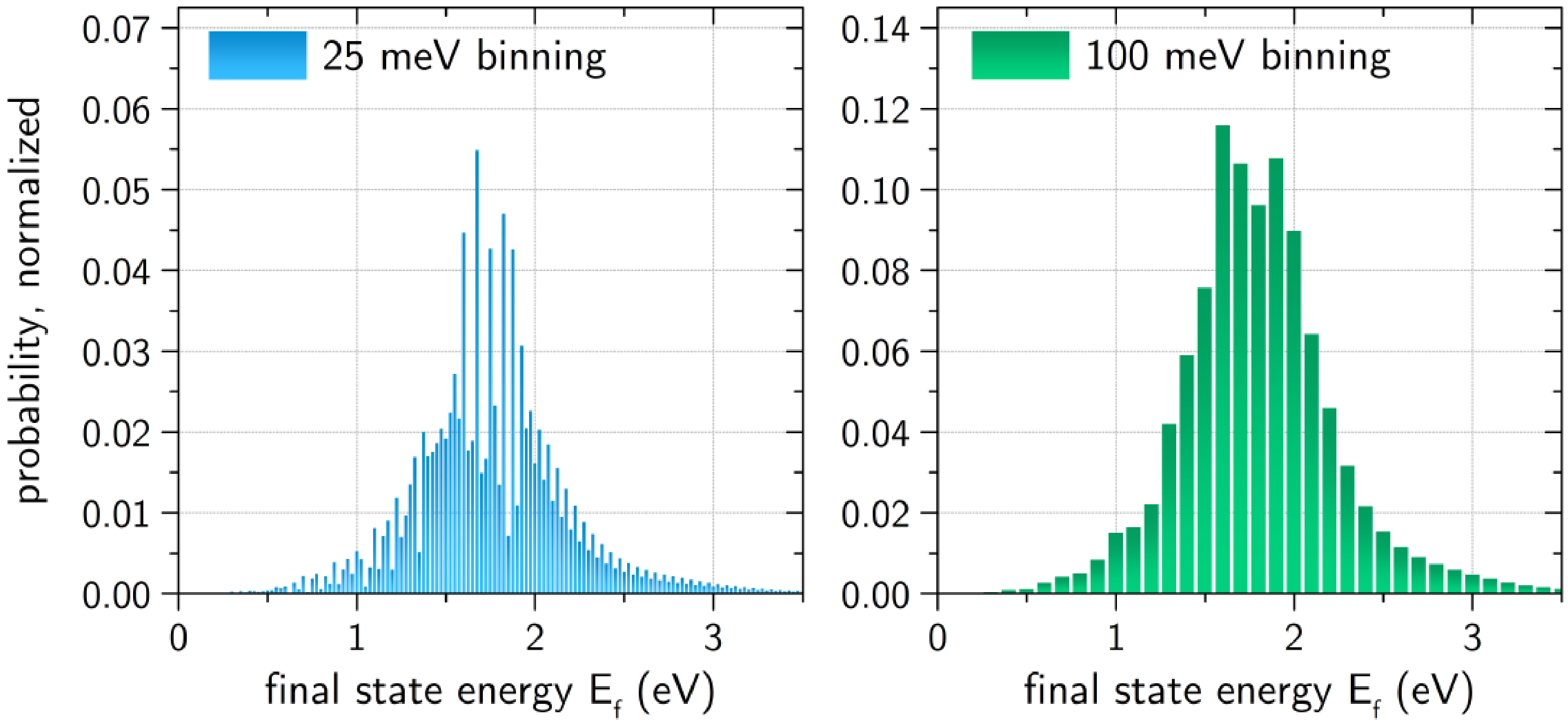
$$\sigma_{\text{stat}}(m_\nu^2) = (0.0162 \pm 0.0001)\,\text{eV}^2$$



parameter	setting
column density	$\rho d = 5 \cdot 10^{17}\,\text{cm}^{-2}$
scattering probabilities	$P_0 = 0.413339$
	$P_1 = 0.292658$
	$P_2 = 0.167331$
	$P_3 = 0.079129$
	$P_4 = 0.031776$
active source cross-section	$A_S = 53.3\,\text{cm}^2$
magnetic field strengths	$B_S = 3.6\,\text{T}$
	$B_{\text{max}} = 6.0\,\text{T}$
	$B_A = 3 \cdot 10^{-4}\,\text{T}$
tritium purity	$\varepsilon_T = 0.95$
background rate	$\dot{N}_{\text{bg}} = 0.01\,\text{cps}$
detection efficiency	$\varepsilon_{\text{det}} = 0.9$
measurement interval	$[E_0 - 30\,\text{eV}, E_0 + 5\,\text{eV}]$
Doppler effect	neglected
physical boundaries	extrapolation to negative m_ν^2
tritium endpoint energy	$E_0 = 18\,575\,\text{eV}$

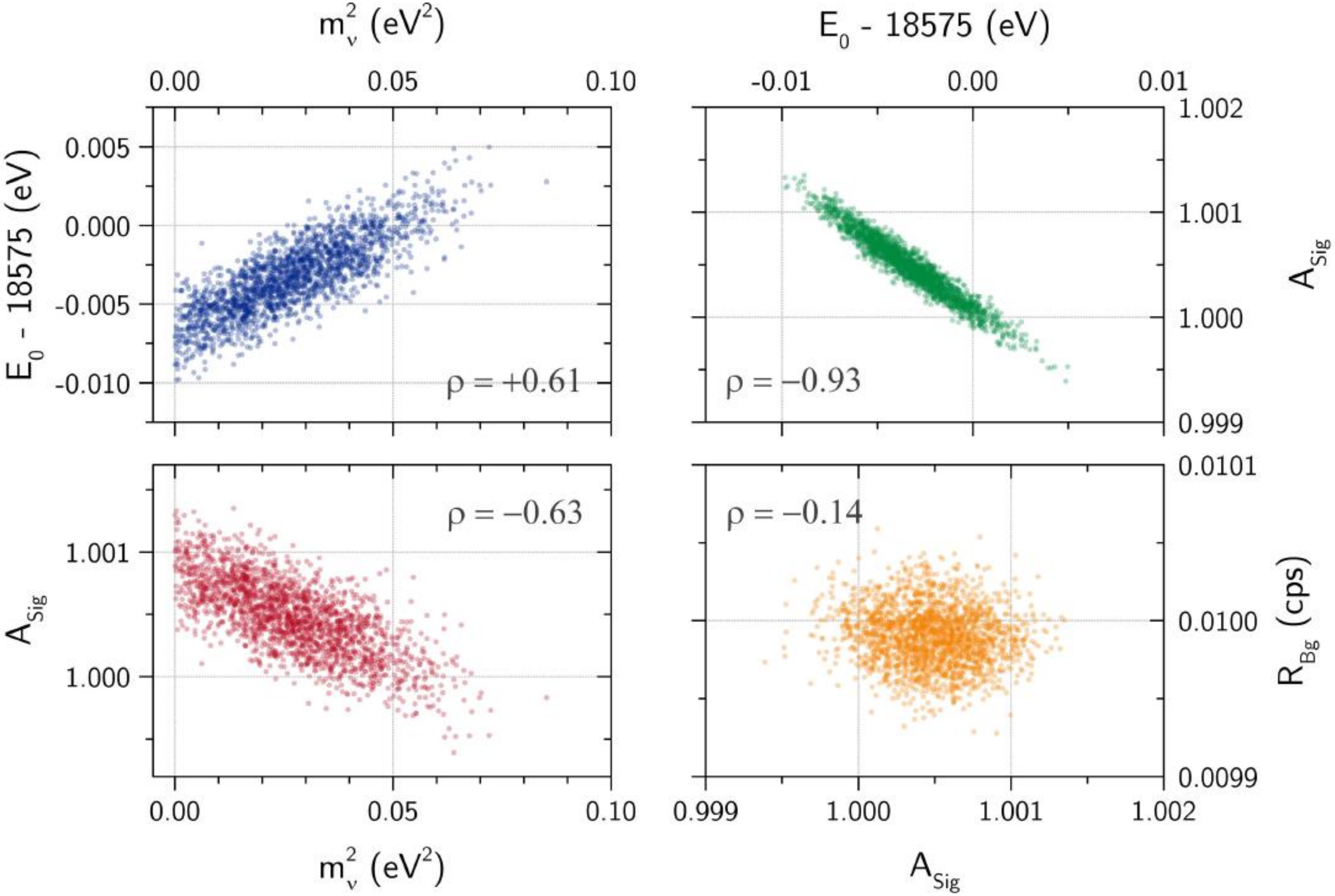
tritium ß-decay: final states

- molecule $(^3HeT)^+$ in final state is left in an excited state:
  - rotational-vibrational exciations
  - electronic excitations (discrete levels up to continuum)
  - excellent theoretical calculations available
  - close cooperation with A. Saenz, experimental: TRIMS @ UW Seattle



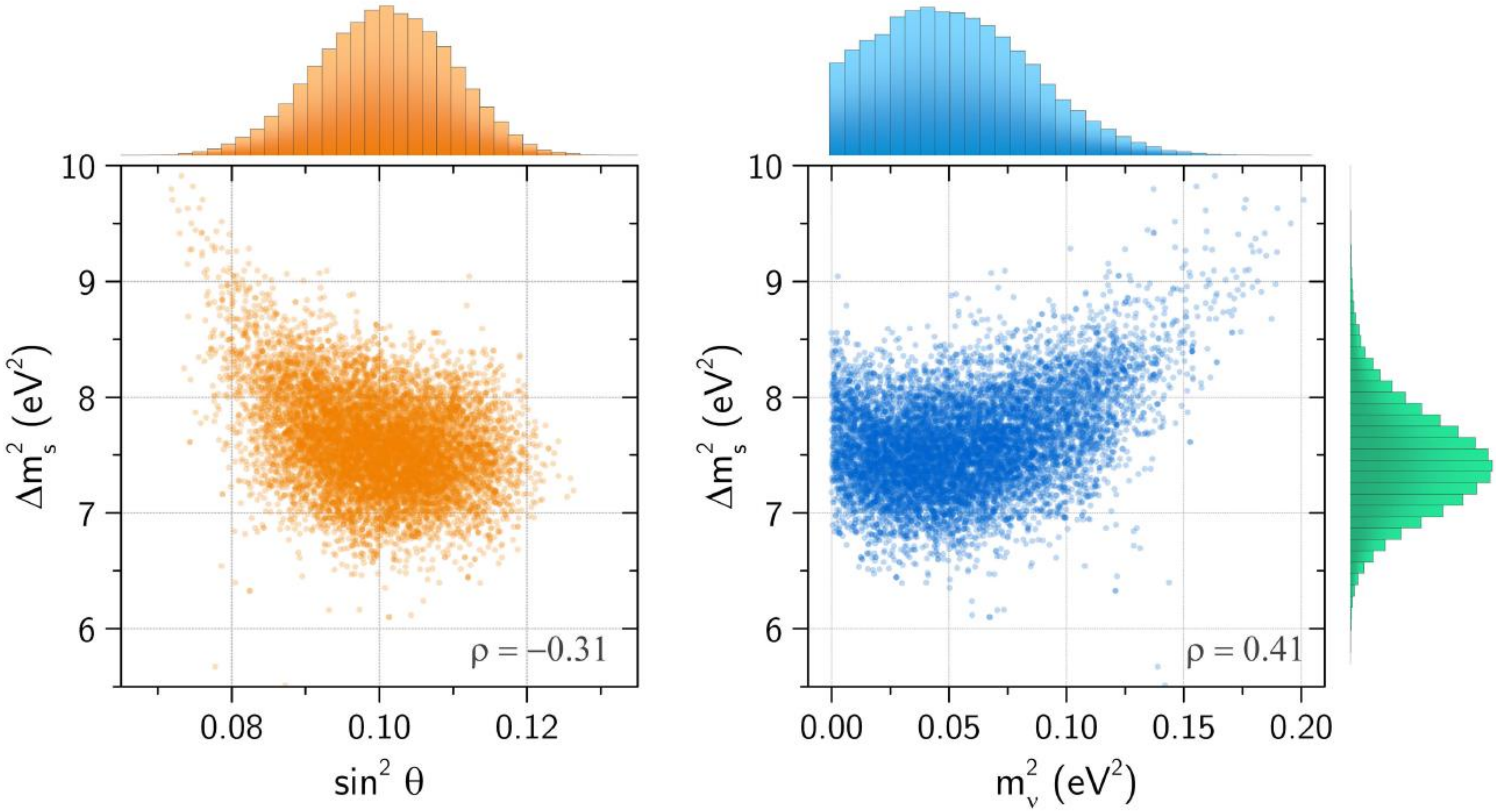
parameter correlations

- correlations of the 4 parameters E_0, $m(\nu_e)$, A_{sig}, R_{bg} in the ν-mass analysis



disentangling active-sterile neutrinos

- correlation of parameters in the search for light (eV-scale) neutrinos

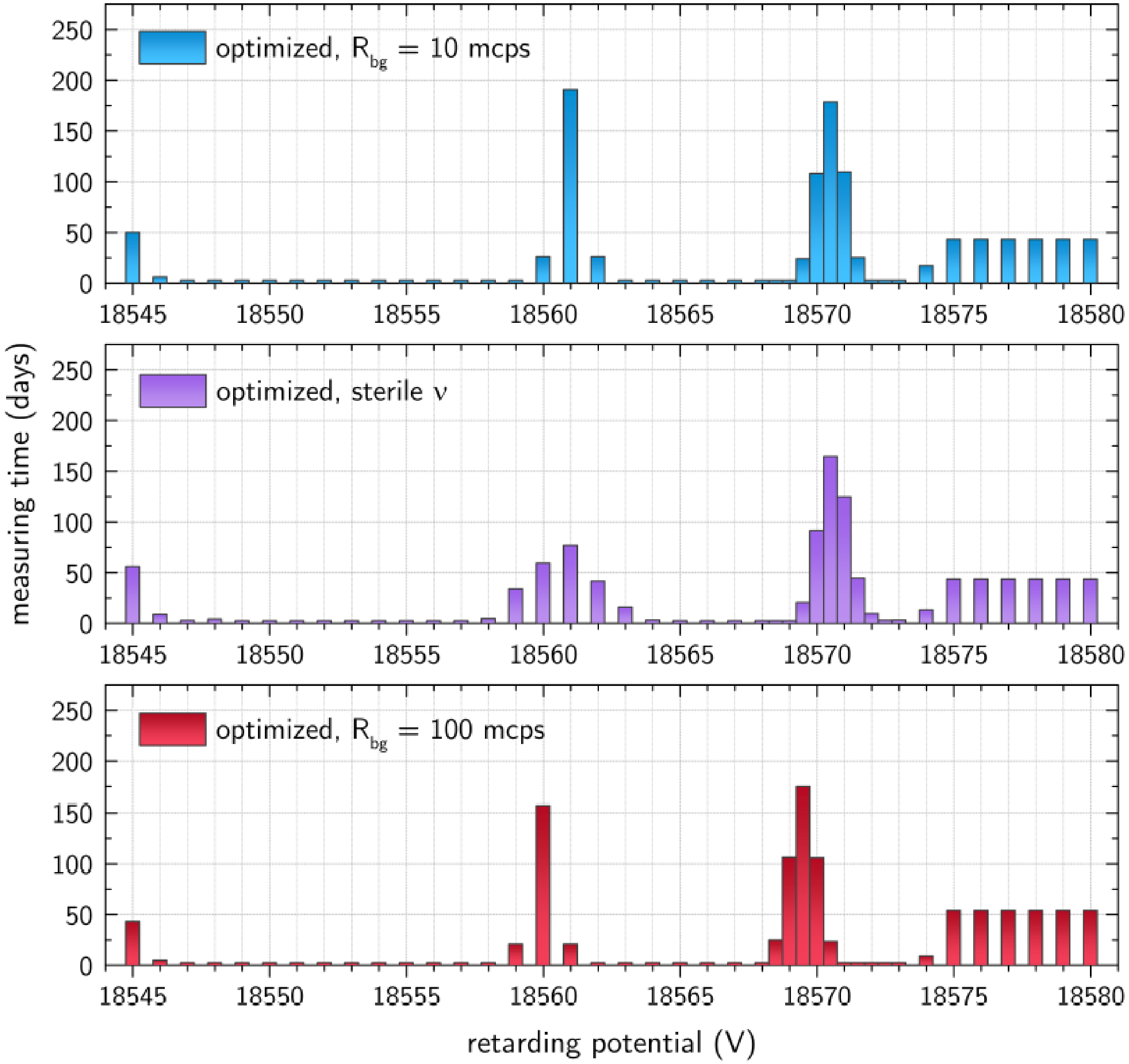


optimized scanning strategies

nominal:
active neutrinos

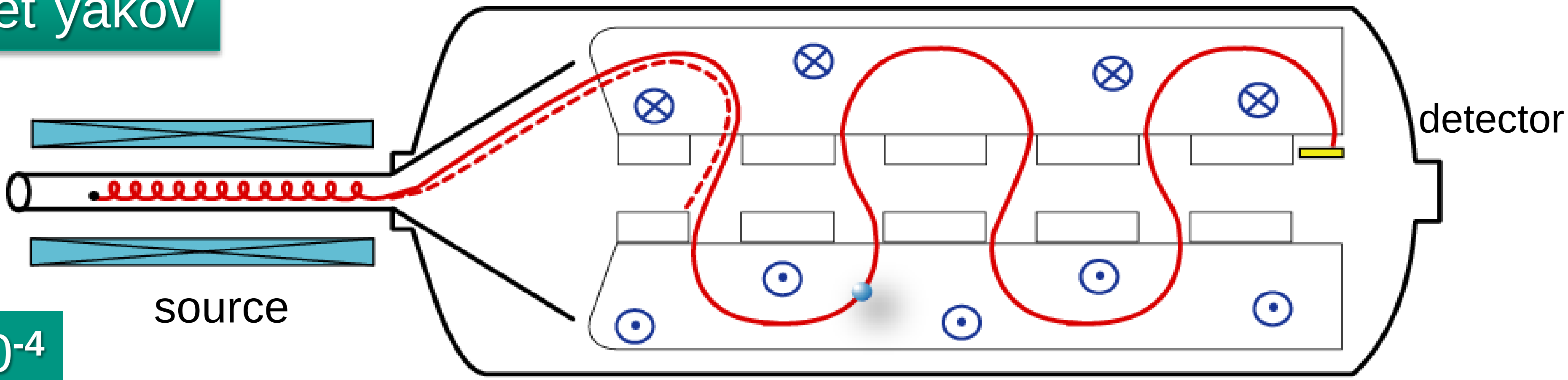
specific for
sterile neutrinos

in case of
enhanced
background



techniques in ß-spectroscopy

magnetic: Tret´yakov

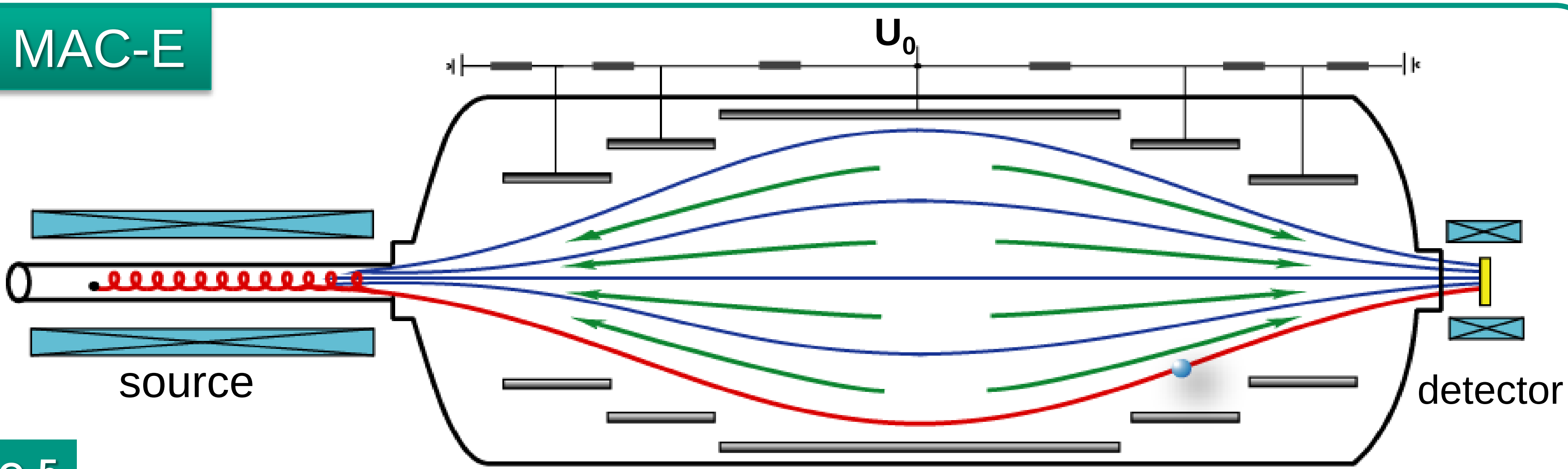


$\Delta p/p = 7 \times 10^{-4}$

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

principle: analysis of electron ***momentum*** by magnetic field

electrostatic: MAC-E

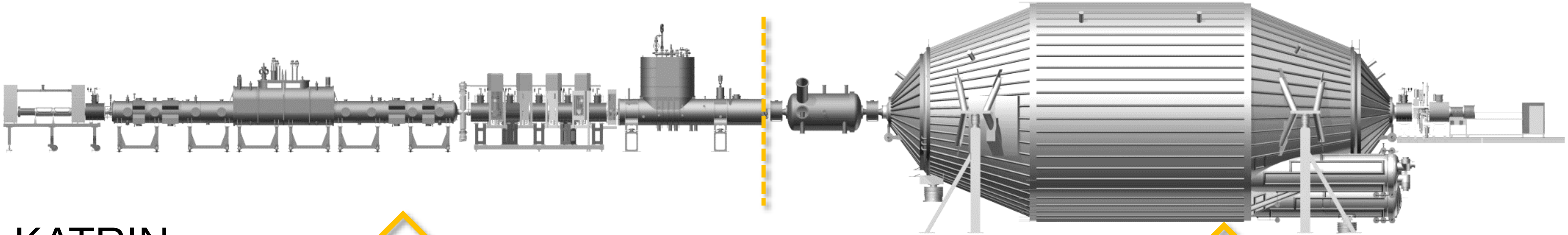


$\Delta E/E = 1 \times 10^{-5}$

$\delta\Omega \sim 2\pi$

principle: analysis of electron ***energy*** by electrostatic retardation

KATRIN experiment – overview

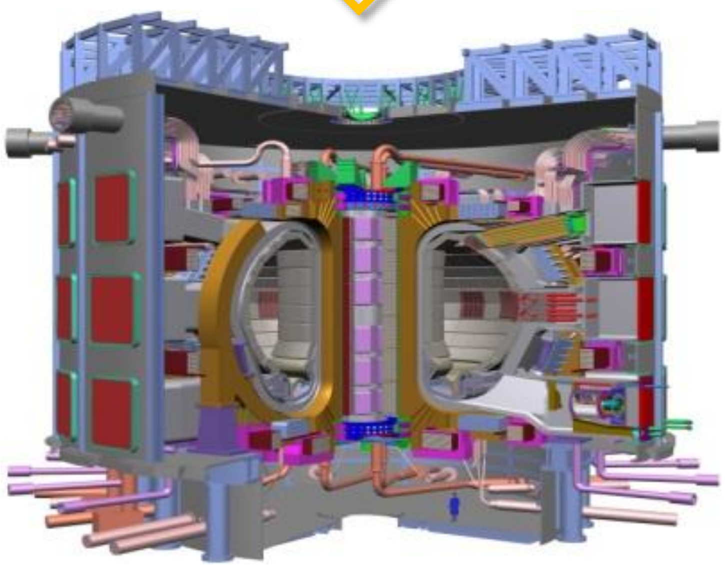


KATRIN
(2016)

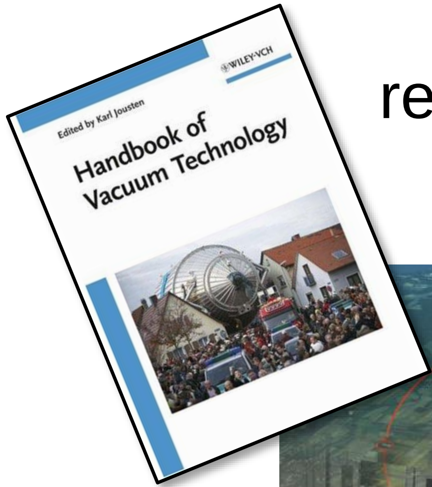
largest ever tritium throughput ~ **10 kg/a**

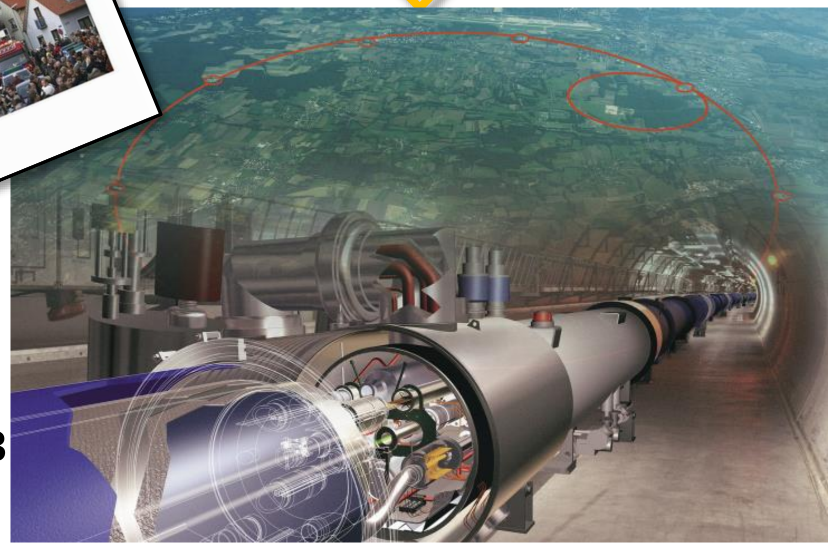
1250 m³

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

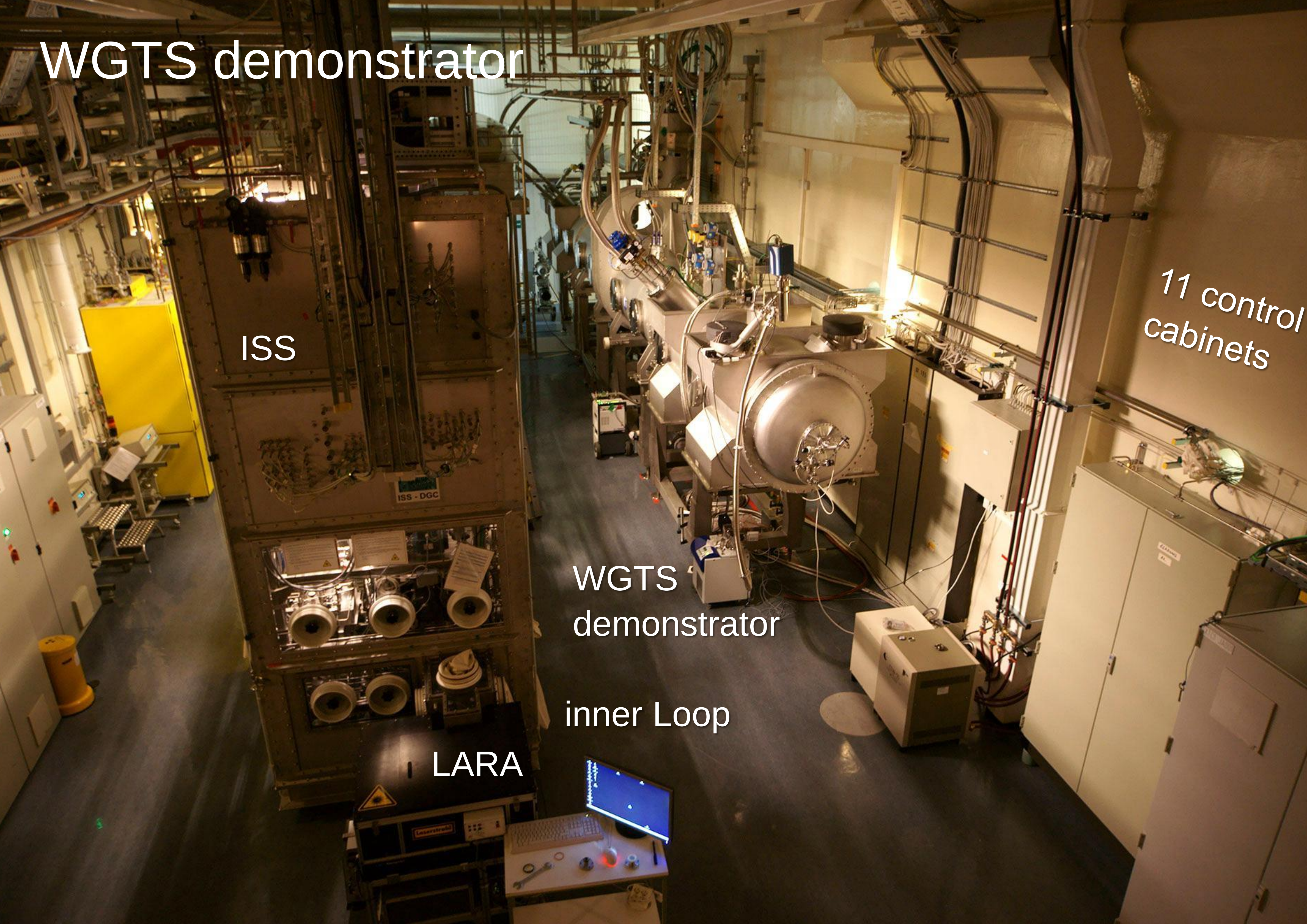


ITER
(2027)

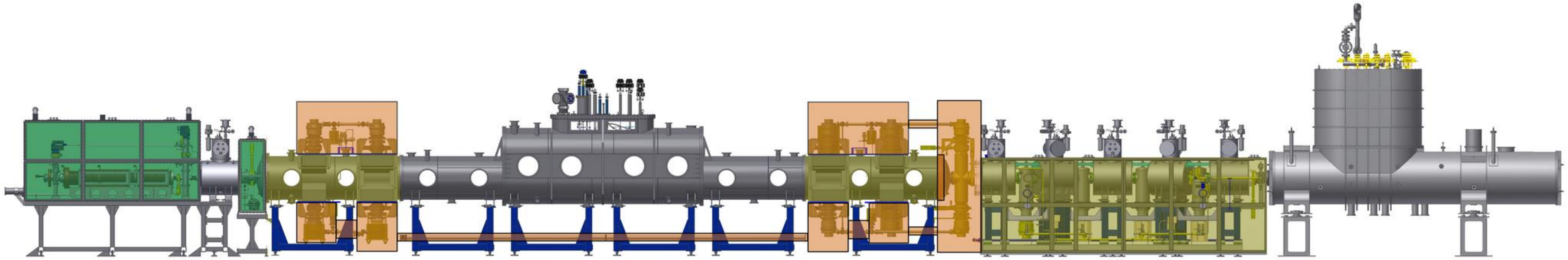


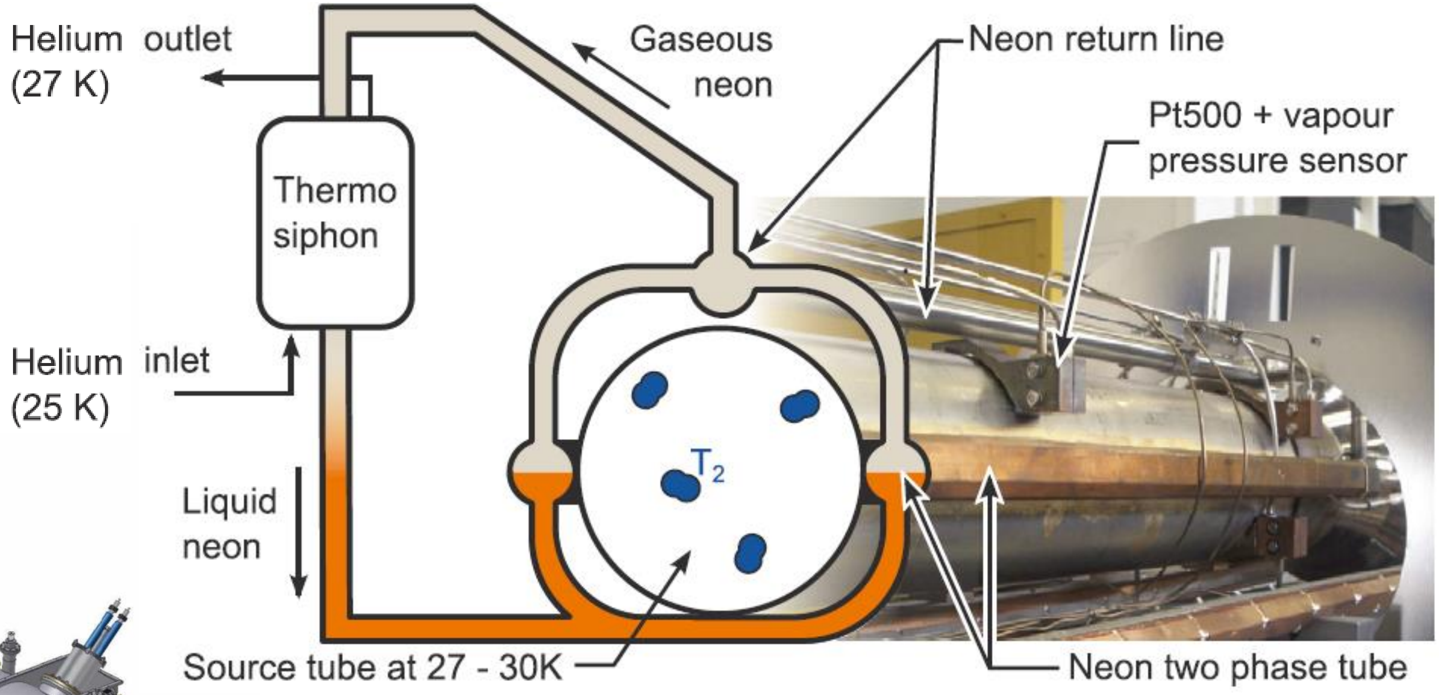


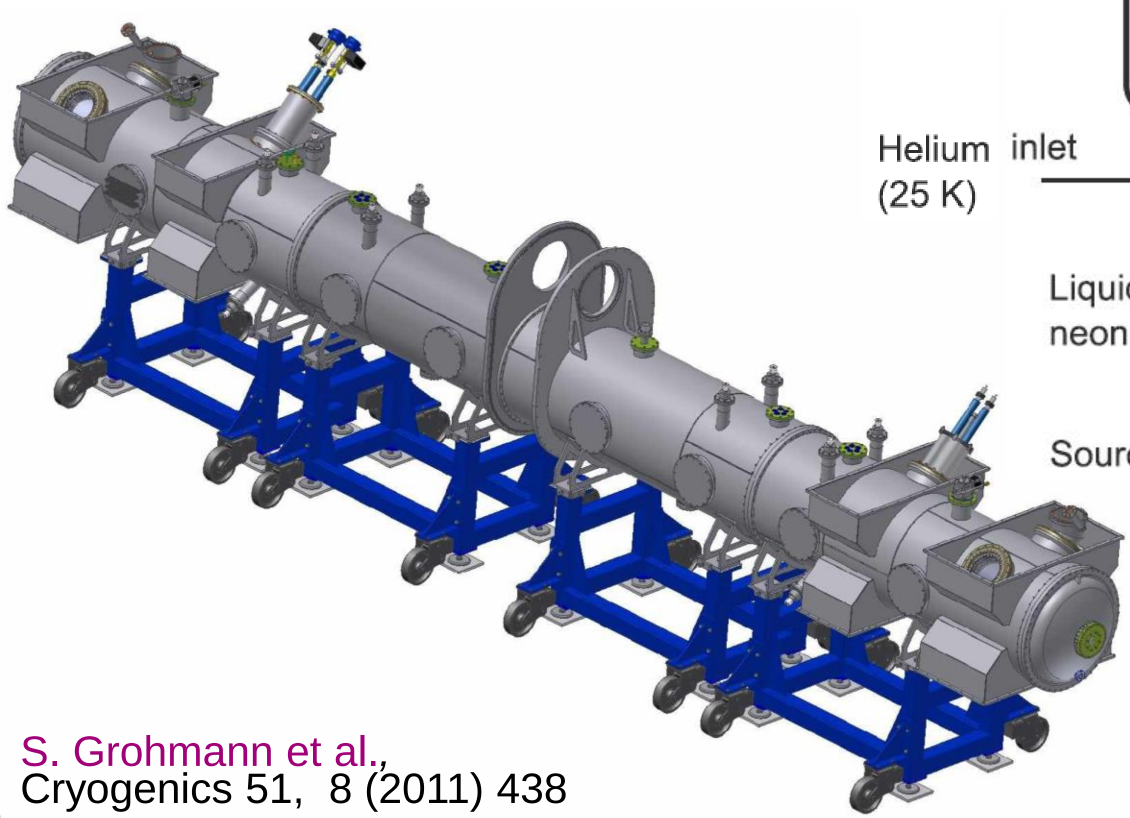
LHC
154 m³


WGTS demonstrator
ISS
11 control cabinets
WGTS demonstrator
inner Loop
LARA

WGTS – demonstrator



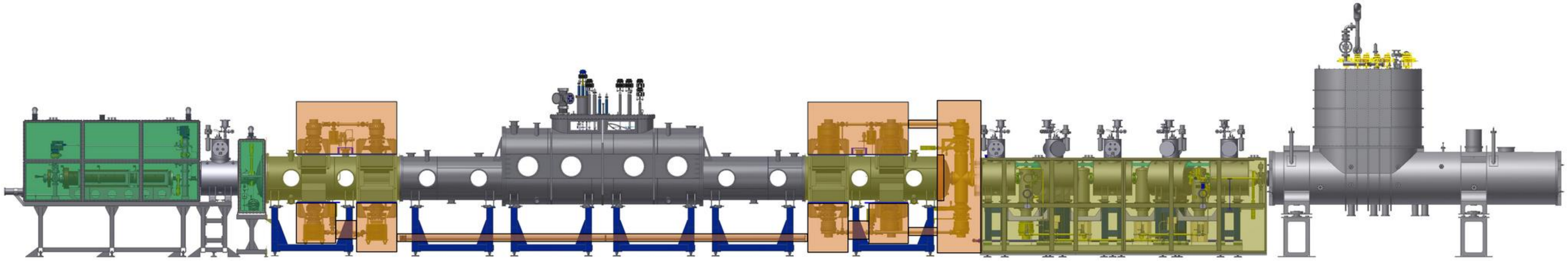


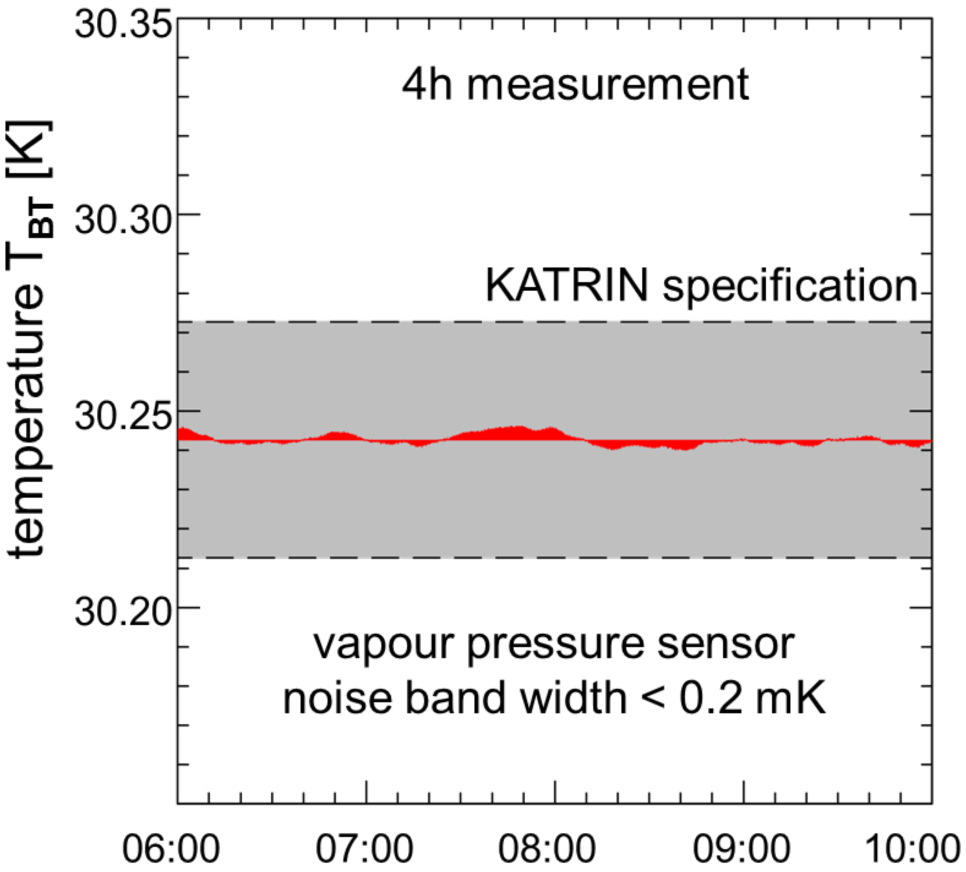


- **WGTS demonstrator**:
  - proof-of-principle of 2-phase beam tube cooling principle

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

technology highlight – stability at 30K

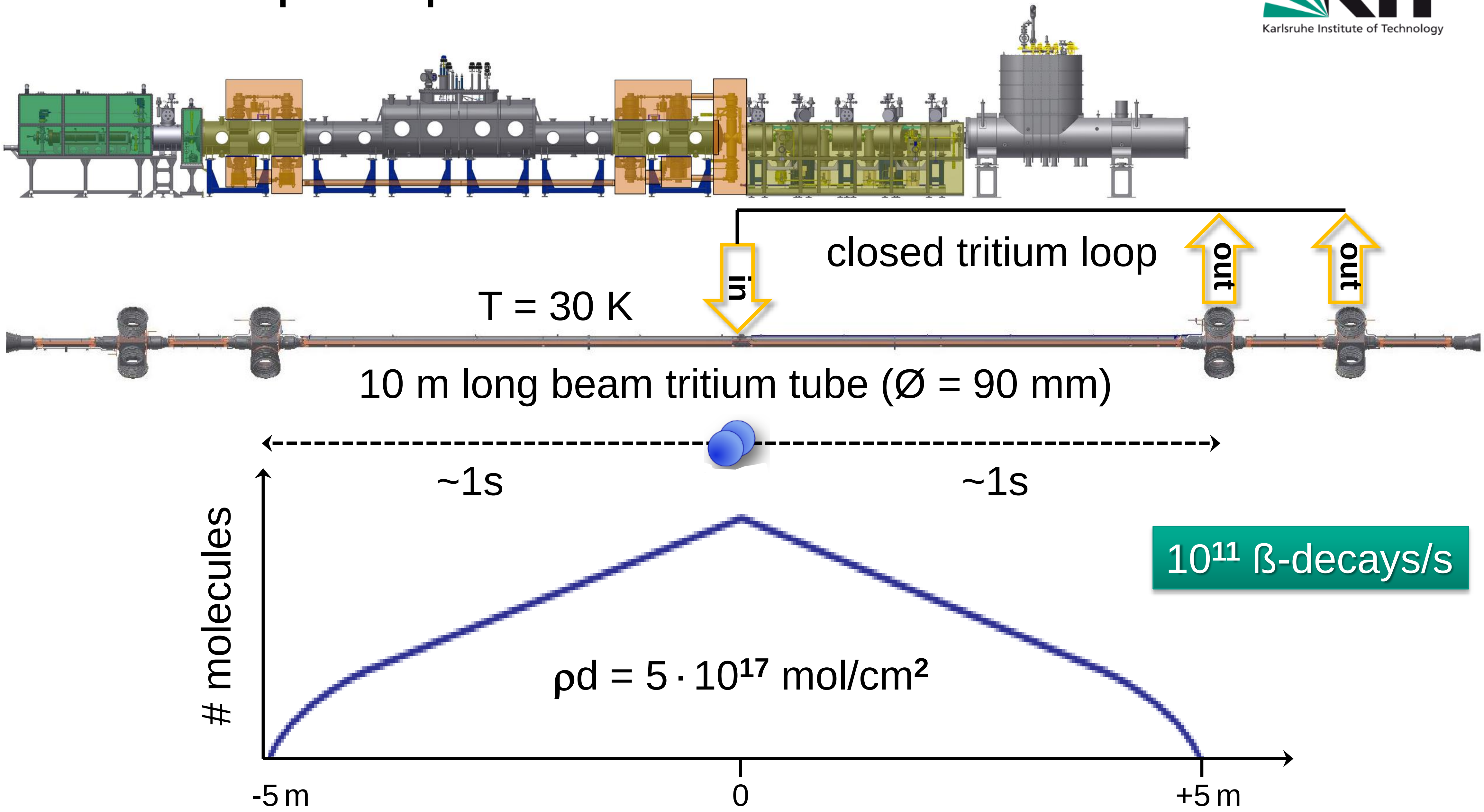




- **Technology highlight:**
  successful proof-of-principle of novel WGTS beam tube cooling system
  - data: **ΔT = 1.5 mK (1σ)** (1 h)
  - required: **ΔT = 30 mK (1σ)** (1 h)
  - implications:
    significantly reduced systematic errors from source fluctuations
    $\Delta\rho d/\rho d \sim \Delta T/T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

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

WGTS – principle

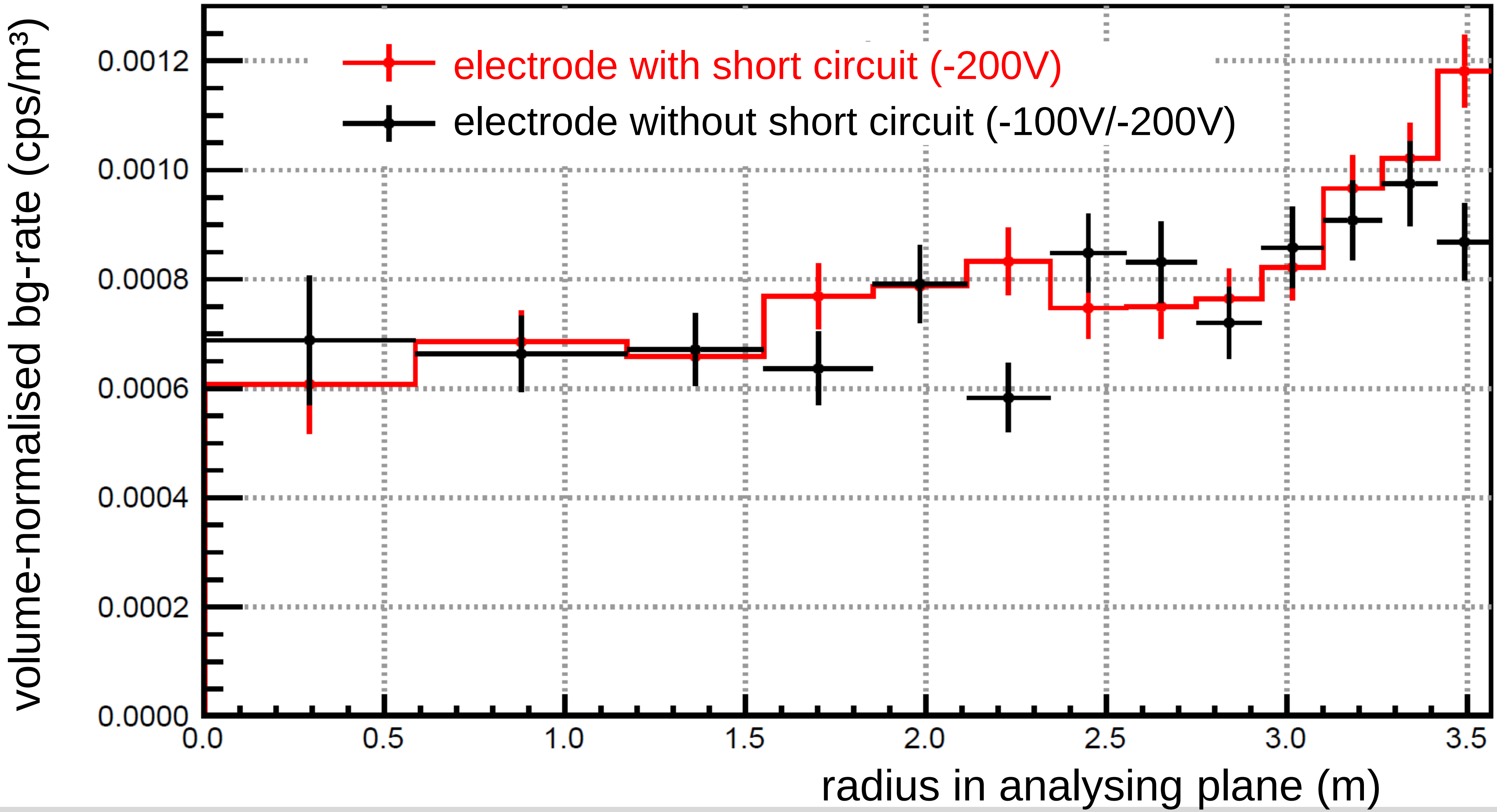


10^{11} ß-decays/s

Windowless Gaseous Tritium Source

background with 2-layer electrode

- **March 2, 2015: IE with full functionality does not further reduce bg !!**

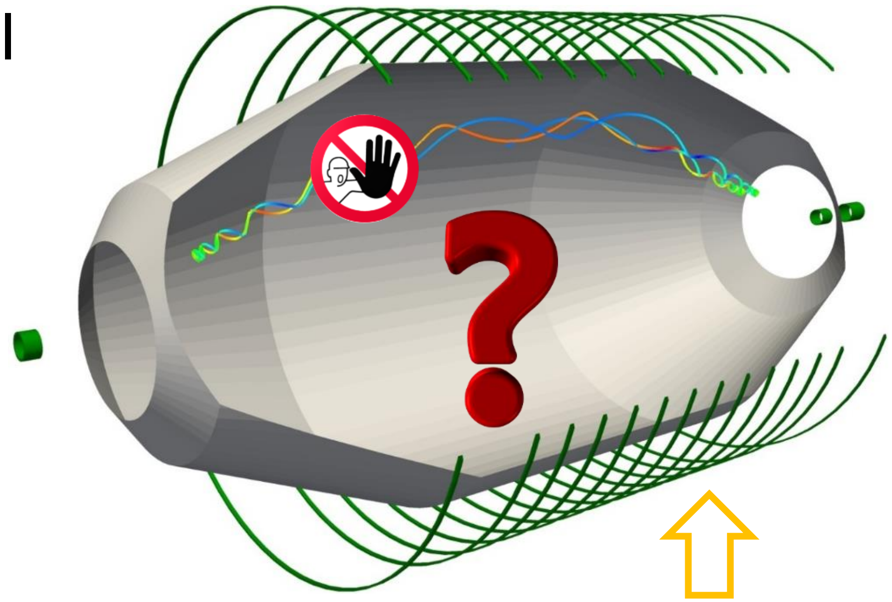


countermeasures against background

- **conventional countermeasures have no impact:** all active and passive methods seem to fail

PRELIMINARY

isotropic background electrons with $E \leq 1$ eV

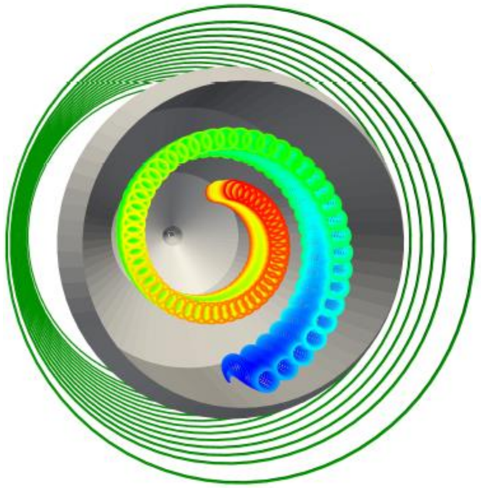


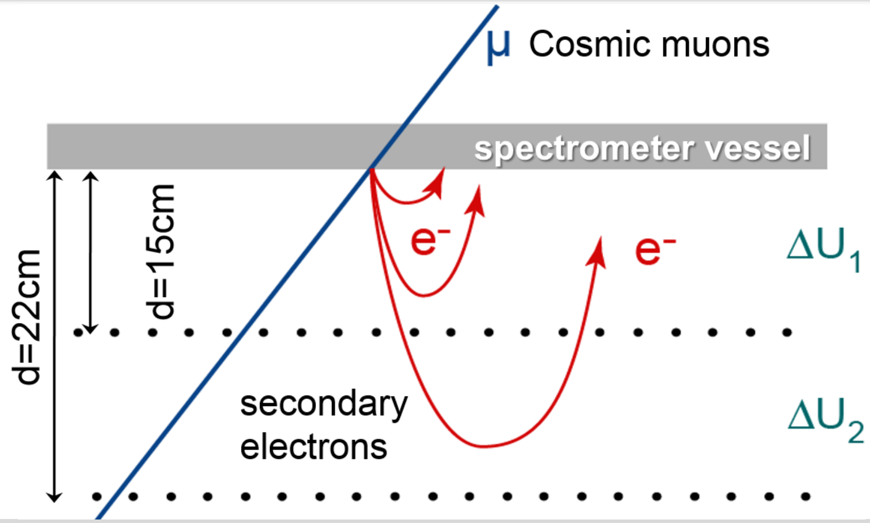
UHV conditions

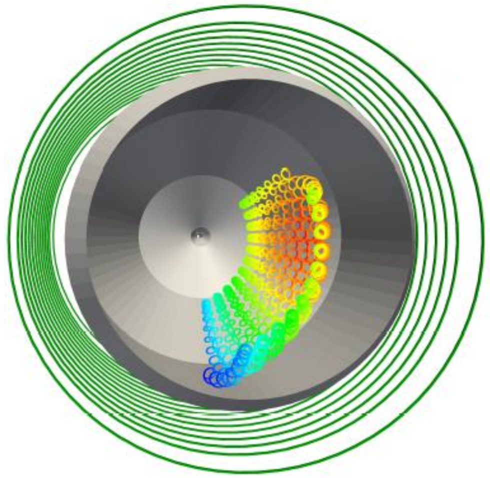
magnetic pulse

fully functional electrode with 2 offsets

electrostatic dipole



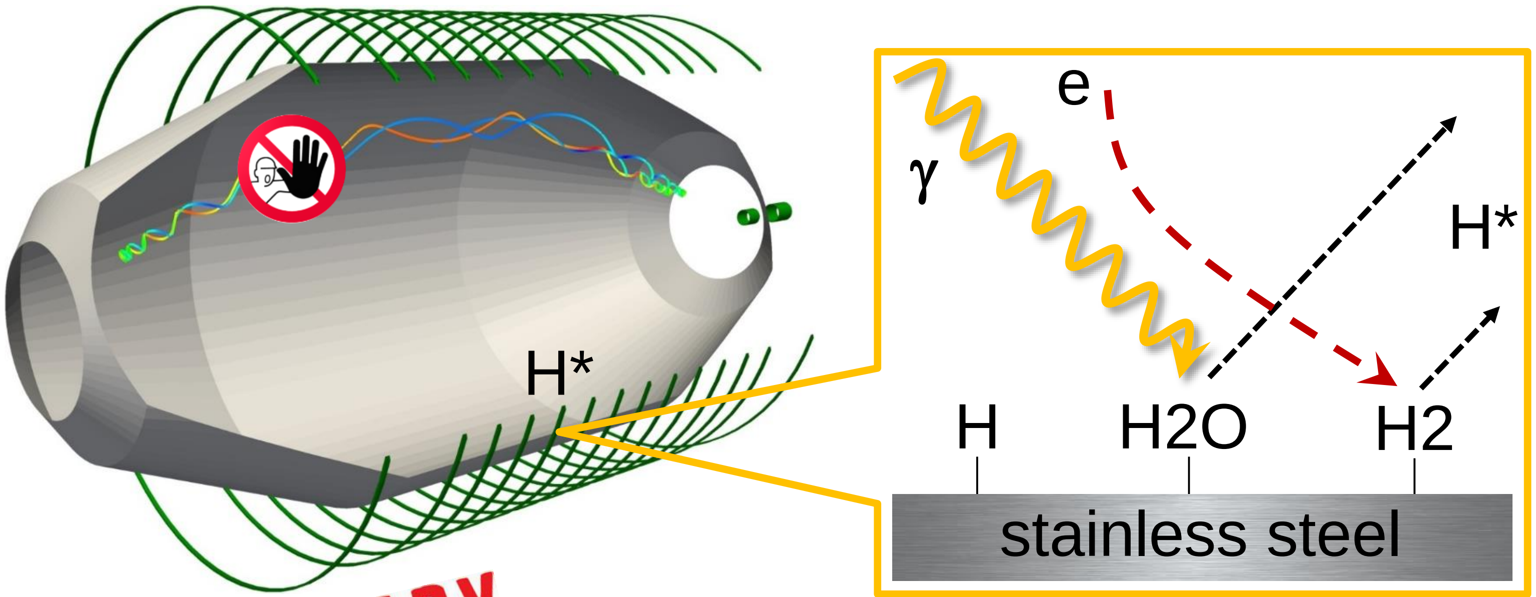




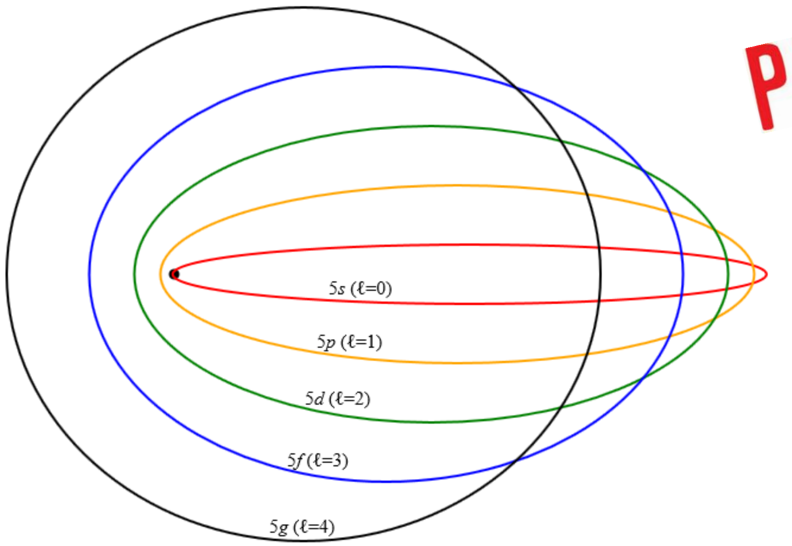
a novel background model: H* atoms

- **formation of highly excited hydrogen Rydberg atoms H* at walls**

  via PSD (photon)
  and ESD (electron)
  stimulated desorption
  - long-lived (ms)
    ↳ long paths (>10 m)
  - small E_b (meV)
    ↳ easily ionised



PRELIMINARY



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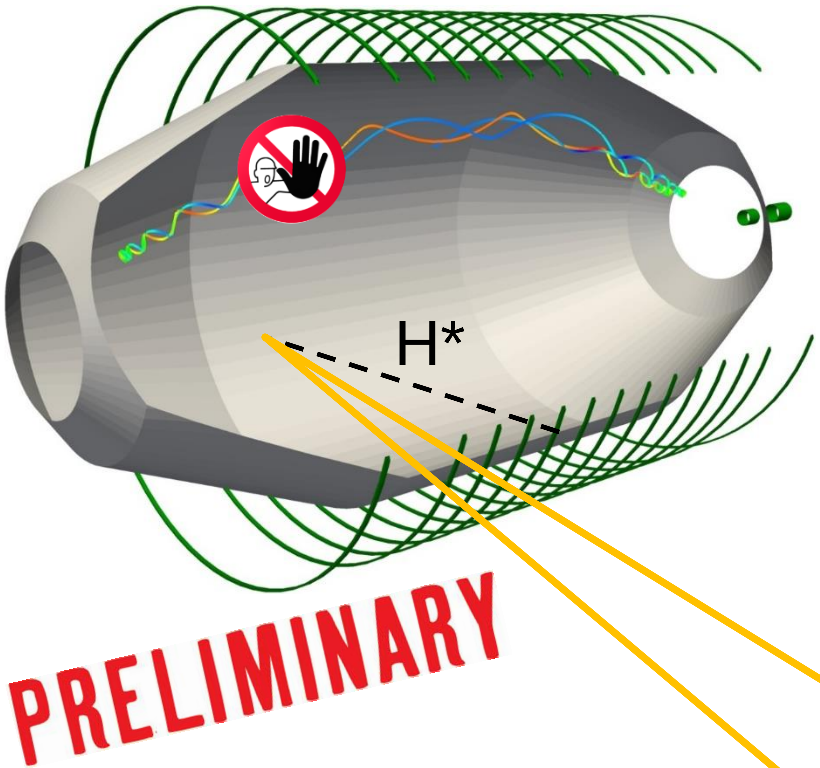
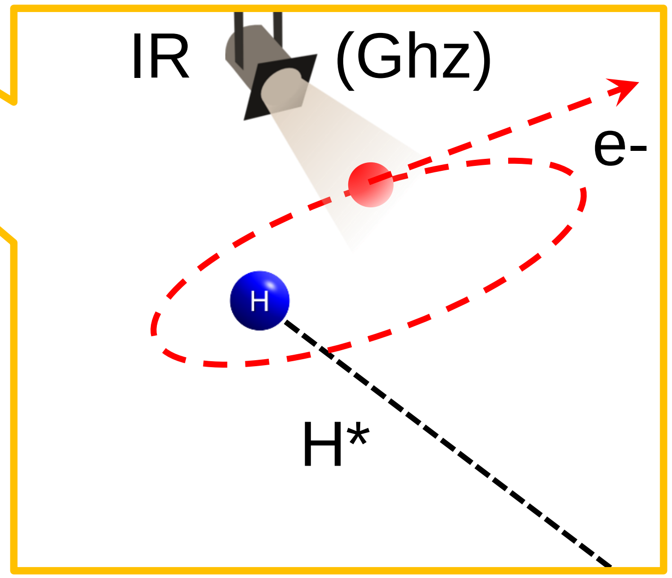
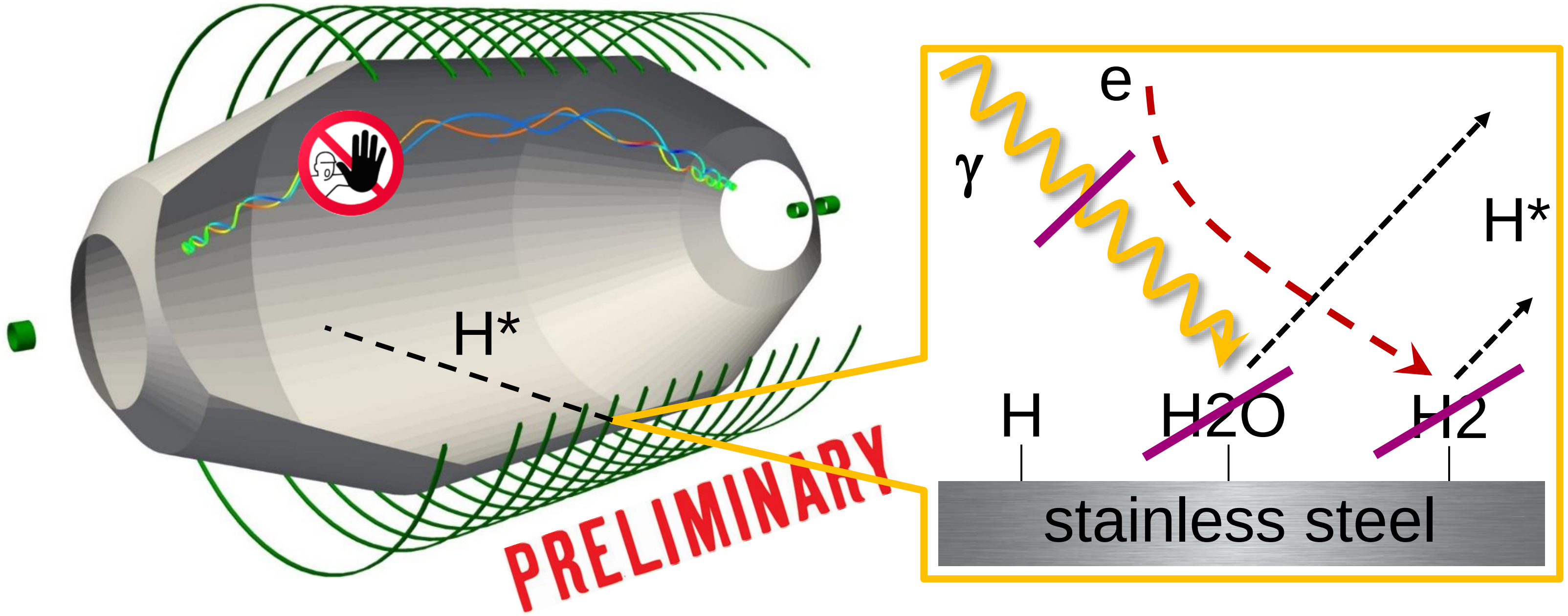




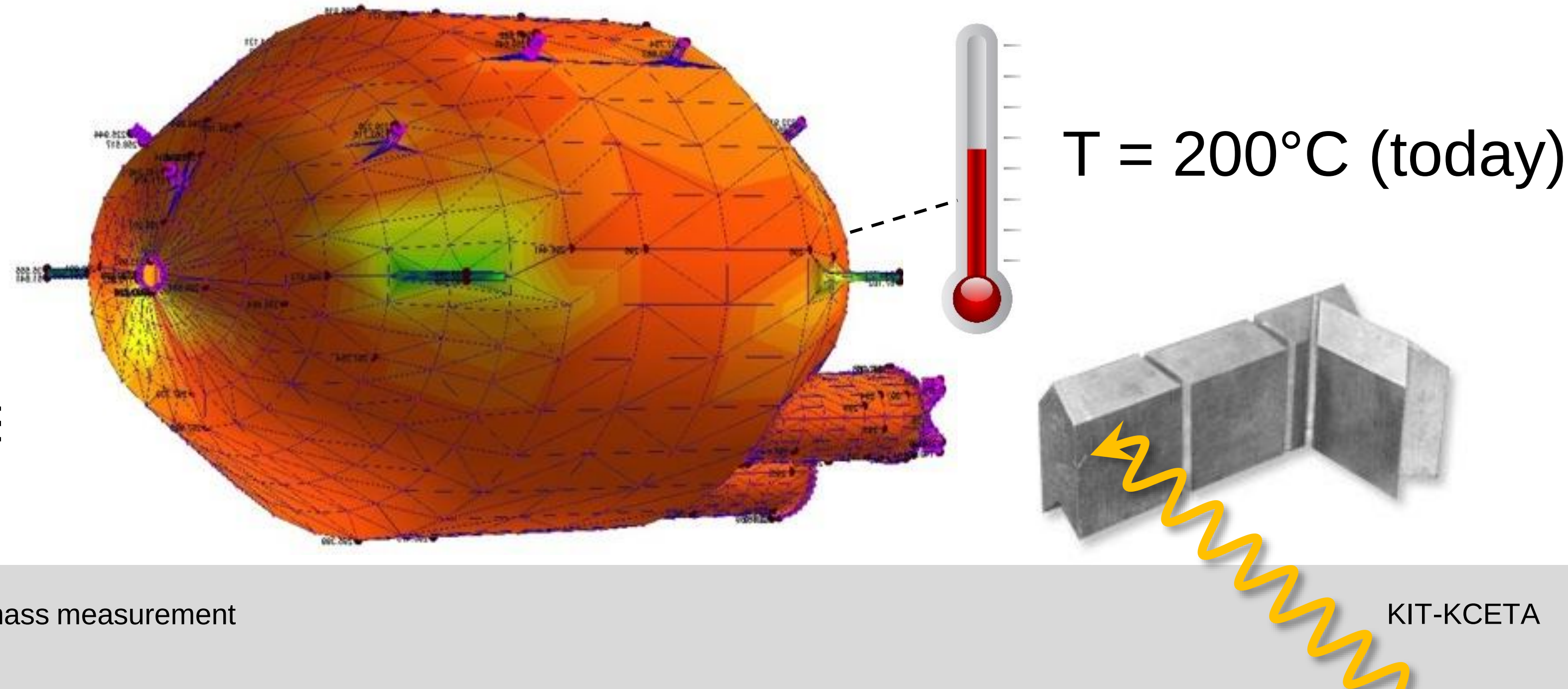
- **ionisation of highly excited hydrogen Rydberg atoms H* by BBR**
  ↳ isotropic low-energy electrons on meV-scale
  ↳ MC simulations can reproduce data
  ↳ electrode field-ionises part of H*-atoms

a novel background model: H* atoms

- **efforts to eliminate long-lived H* atoms from surface:**
  - remove hydrogen ($H2O$ and $H2$) from wall by long bake-out procedure 200°C



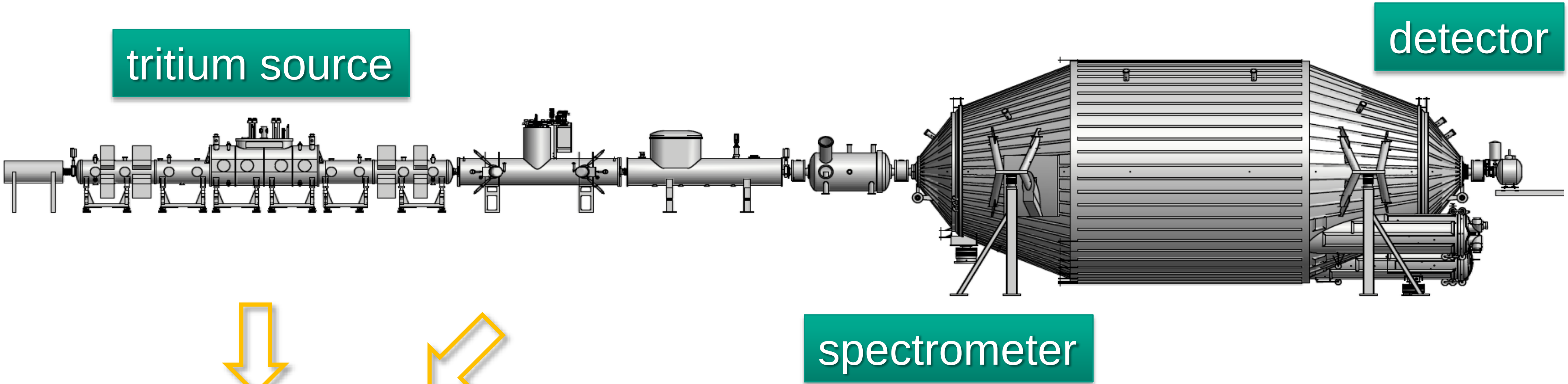
- **ongoing bake-out**:
  - mid-June: new measurements with imporved surface conditions
  - also: improved shielding against γ´s (suppress PSD)



background sources

- ß-decay electrons from areas with different electrostatic potentials
- ß-decays from T^-/T^+ ions, clusters

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



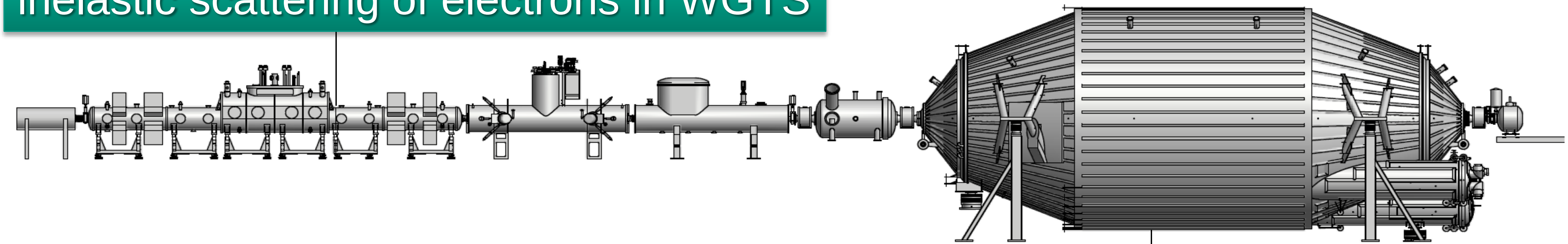
total bg - rate
$R_{bg} < 10^{-2}$ cps

- stored ß-electrons (Penning traps, scattering)
- trapped electrons from ^{219,220}Rn α-decays / T_2-ß-decays in central spectrometer area
- cosmic µ-induced secondary electrons

systematic effects – I

- precise measurement of experimental response function
- special unfolding technique to derive cross section σ_{inel} at E = 18.6 keV
- narrow analysis window around E_0 to maximise no-loss electron fraction

inelastic scattering of electrons in WGTS



fluctuations of spectrometer retarding HV potential

$$\Delta m_\nu^2 = -2\sigma_{syst}^2$$

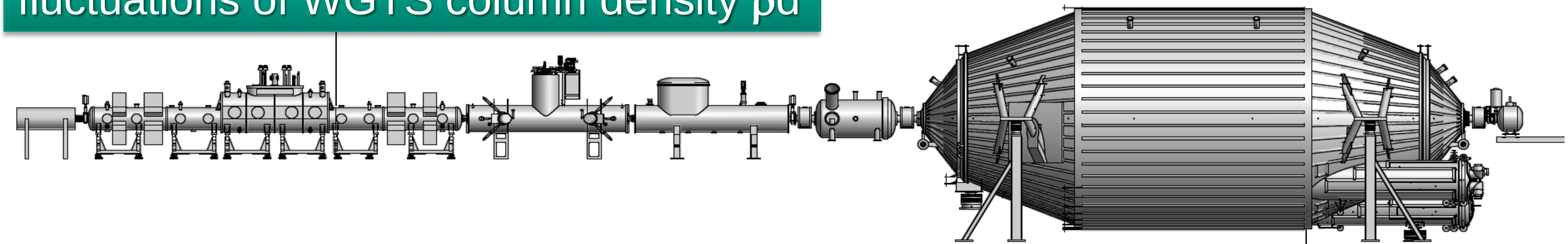
general relation for tritium-ß-decay

- stabilisation of HV: precision HV units
- monitoring of HV:
  1. ultra-stable HV-divider & precise digital voltmeter
  2. Rb/Kr-source & separate monitor spectrometer

systematic effects – II

- stabilisation of ρd: injection pressure, beam tube T = 27K, Laser-Raman
- cyclic scans of ρd: high-intensity electron gun
- monitoring of ρd: rear detector/system, forward beam monitor

fluctuations of WGTS column density ρd



hysteresis effects from HV and ρd scanning

$$\Delta m_\nu^2 = -2\sigma_{syst}^2$$

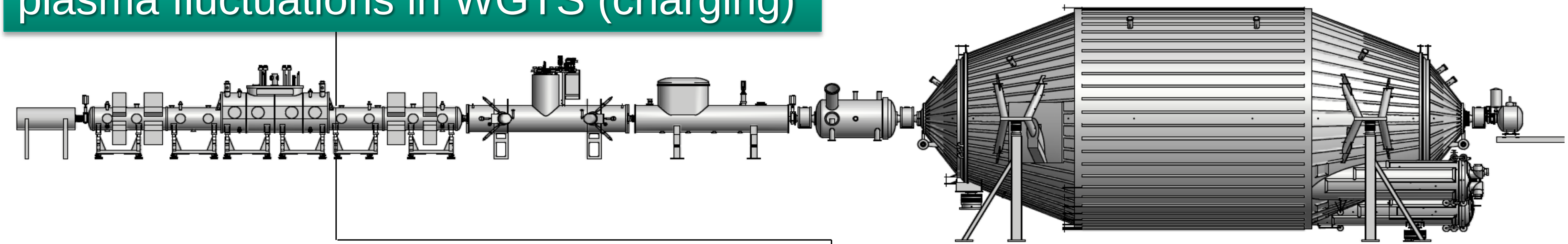
general relation for tritium-ß-decay

- minimisation of trapped particles from scanning of column density ρd
- optimised scanning strategy
- randomized steps of HV

systematic effects – III

- stabilisation of plasma: neutralise ions (Φ < 20 mV), injection of meV-e^-
- cyclic scans of plasma: high-intensity electron gun runs at different ρd
- monitoring of plasma: rear detector/system

plasma fluctuations in WGTS (charging)



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

$$\Delta m_\nu^2 = -2\sigma_{syst}^2$$

general relation for tritium-ß-decay

- reliable quantum-chemical calculations for all isotopologues available (up to continuum)
- very good agreement among the different calculations, sum rules correct

MARE experiment

- **M**icrocalorimeter **A**rrays for a **R**henium **E**xperiment

- **general strategy to increase sensitivity to sub-eV regime**:
  - deploy large arrays of cryogenic micro-bolometers
    up-scaling of source intensity with 1 mg Re ≈ 1 decay/s
  - avoid pulse pile-up: develop faster detectors
  - develop multiplexed read-out technologies
  - improve energy resolution to 1 eV-level

MARE-I ~ 10^9-10^{10} ß-decays

- set-up small bolometer array: ν-mass sensitivity $m(\nu_e)$ ~ few eV
- test & select different isotopes (^{163}Ho-EC/^{187}Re-ß-decay)
  and read-out/sensor techniques (TES, Si-thermistor, MMC, …)

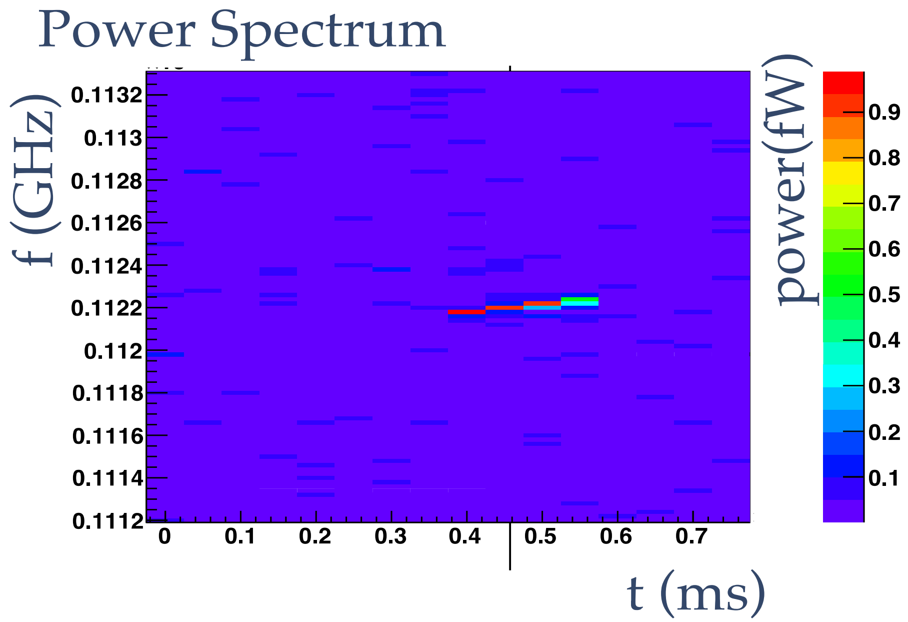
MARE-II ~ 10^{14} ß-decays

- full set-up, large bolometer array with 10^4-10^5 pixels
- aim for statistical ν-mass sensitivity $m(\nu_e)$ ~ 0.1-0.2 eV

Project 8 – a novel technology ansatz

- **experimental status end of 2013**:
  - prototype experiment running at UW Seattle
  - aim: detect cyclotron emission from ***single*** electron
  - source: 17.8 keV electrons from ^{83m}Kr (K32-line)
  - cryostat: B = 1T, small magnetic bottle (V = 1 mm³)

- **R&D 2014 on**:
  - antenna technology
  - receiver & DAQ technology
  - study Doppler shifts



- Project 8 ultimately aims for

  sensitivity m(ν) = 100 meV (90% CL)

- **a lot of R&D work still to be performed**

Project 8 – power consideration

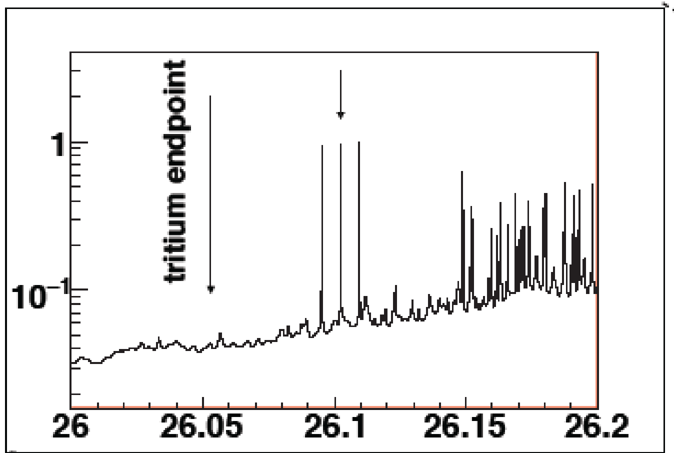
Karlsruhe Institute of Technology

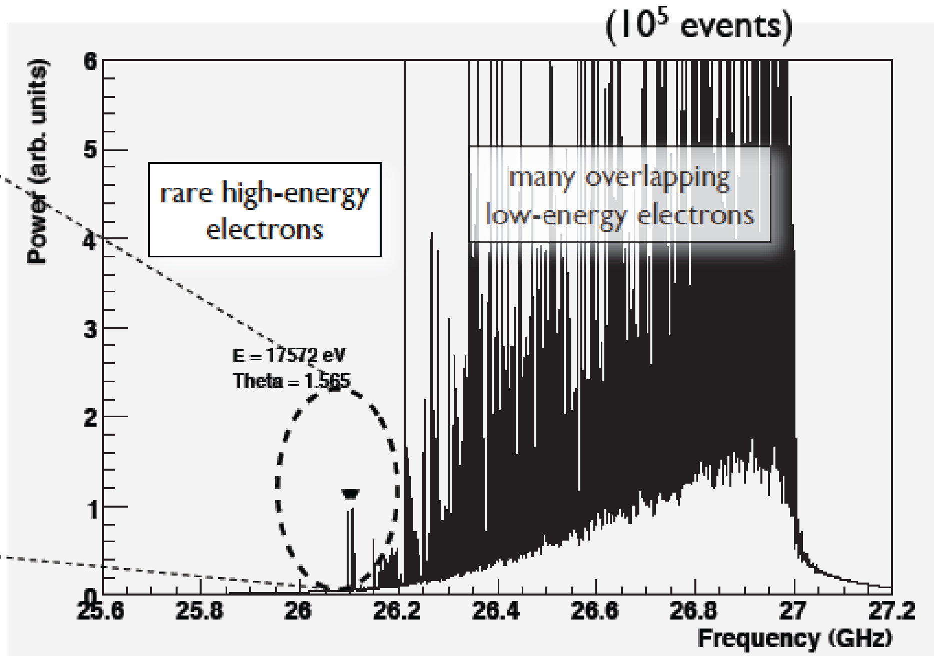
- **experimental challenges**:
  - very small power P of emitted synchrotron radiation by ***single*** keV-electron, requires adequate antennae & amplifier technologies

$$P(\beta,\gamma) = \frac{1}{4\pi\varepsilon_0}\cdot\frac{2e^2\cdot\omega_0^2}{3c}\cdot\frac{\beta^2\cdot\sin^2\theta}{1-\beta^2}$$

P_{signal} ~ 10^{-15} W (1T, 18.6 keV)
P_{noise} ~ 10^{-17} W (thermal noise ampl.)

- **MC simulation**: 30 µs measuring interval with 10^5 ß-decay electrons





signal: 3 lines (triplet)
1 unshifted (central) coherent line
2 side bands (incoherent Doppler)

Project 8 – future steps

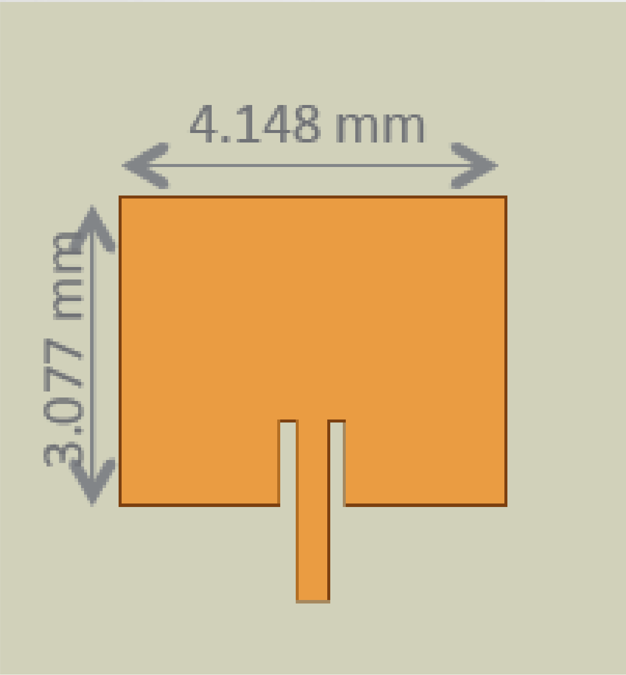
- **next steps in CRES**

  - improve (fiducial) detection volume to 1 cm^3
  - improve energy resolution to ΔE = 1 eV
    by applying more shallow „bathtub“ trap

  - **first measurements with molecular T2**
    cell design under development

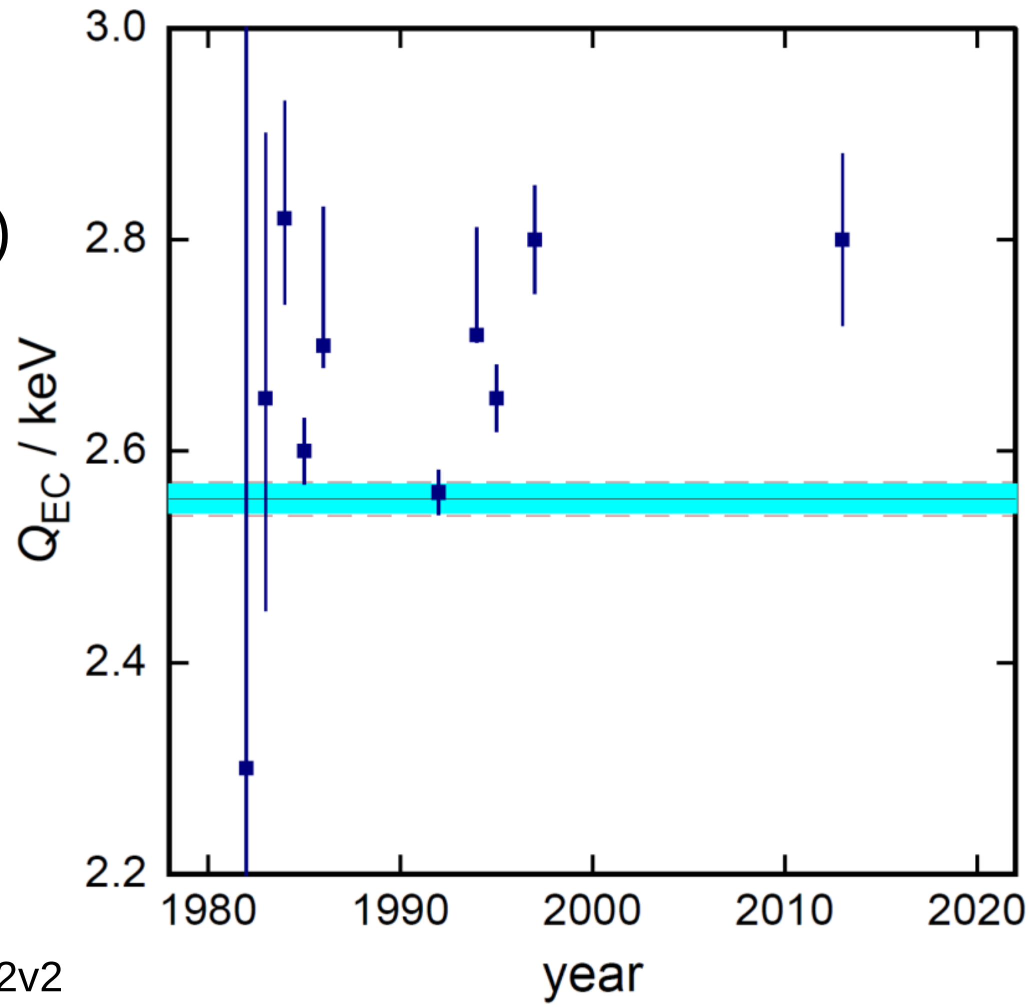
  - expand fiducial volume to 10 cm^3
    with patch antenna array

  - R&D on atomic tritium source
  - ultimate dream: go beyond KATRIN sensitivity (needs a lot of R&D)



^{163}Ho-EC: description of the spectrum

- **exact Q-value** (2.5…2.8 keV): ν-mass sensitivity can change by factor 3-4
- recent theoretical investigations on role of two- & three-hole states in ^{163}Dy* (Robertson, Faessler et al.)*
  - Dirac-Hartree-Fock approach to 2 holes
  - different shape of 2h resonance & $m(\nu_e)$
- **4 parameters in shape analysis:**
  - neutrino mass $m(\nu_e)$
  - distance of leading resonance (M1) to Q_{EC}
  - width of resonance
  - intensity of resonance



*RGH Robertson, Phys. Rev. C91, 035504 (2015)
*A Faessler et al., Phys. Rev. C91, 045505 and arXiv:1503.02282v2

- Use TES arrays with 32x32 pixels
- Resolution 1 – 2 eV FWHM
- Need 5 TES arrays for 0.2 eV/c^2 sensitivity
  - Makes **5000 pixels** (vs. 50000 for Re)

- ^{163}Ho production has been demonstrated
- Embedding process is under investigation
- Readout developed and tested as prototype
- Next: TDR for funding

F. Gatti, ISAPP 2011 and
J Low Temp Phys (2008) 151