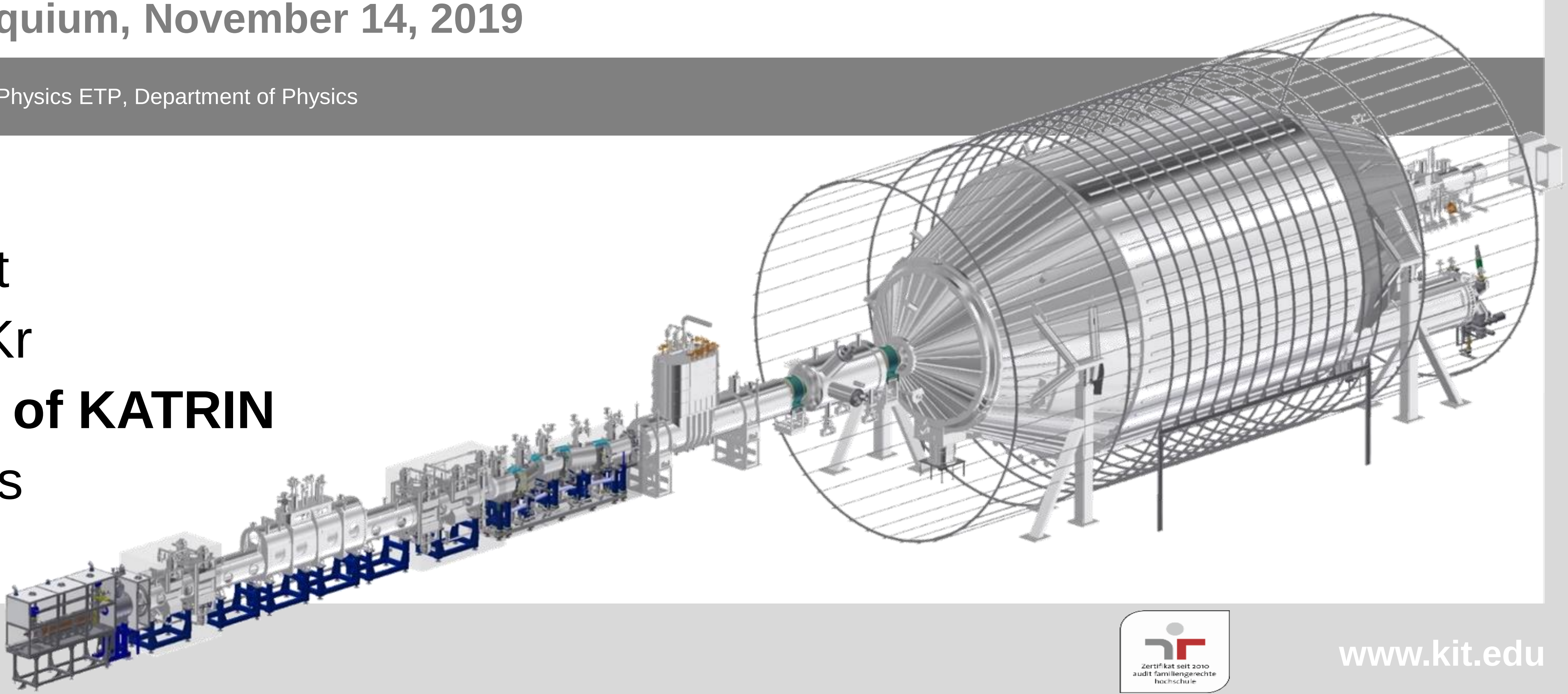
Karlsruher Institut für Technologie

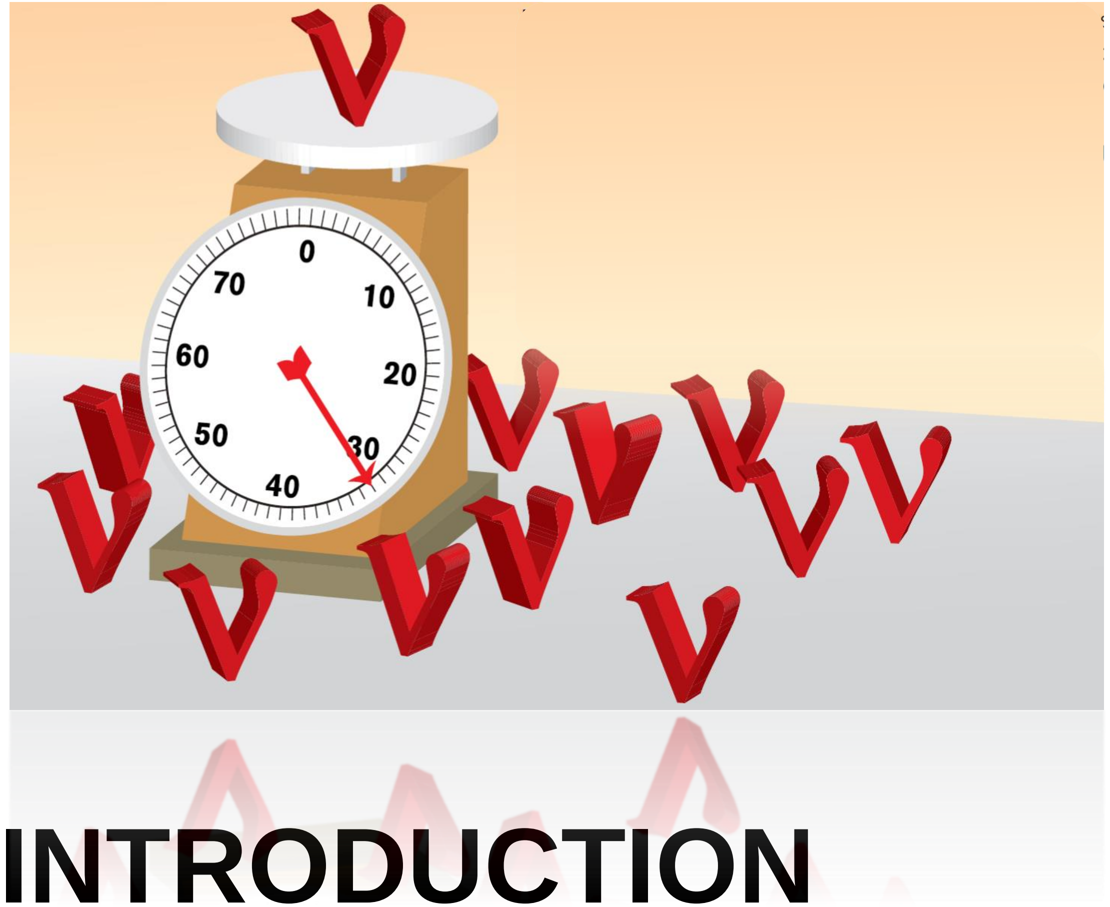
First neutrino mass results from the KATRIN experiment

LTP/PSI Thursday Colloquium, November 14, 2019

Guido Drexlin, Institute of Experimental Particle Physics ETP, Department of Physics

- introduction
- KATRIN experiment
- calibration with ^{83m}Kr
- **first ν-mass result of KATRIN**
- keV-sterile neutrinos
- conclusion

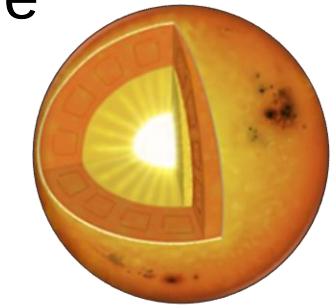




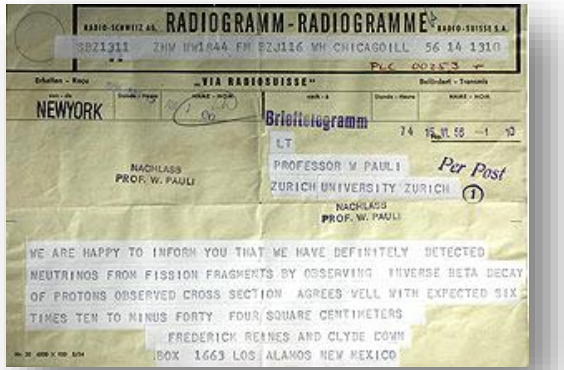
INTRODUCTION

Neutrinos – experimental milestones

- **neutrino detection:** study of neutrino properties implies interactions at the weak scale
  ⇨ very large detectors (now: kt) with extremely low background



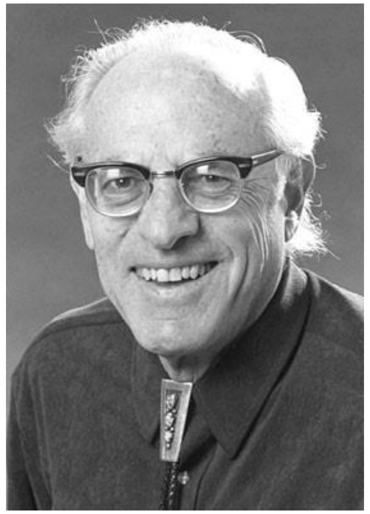
“Proved the existence of the neutrino”

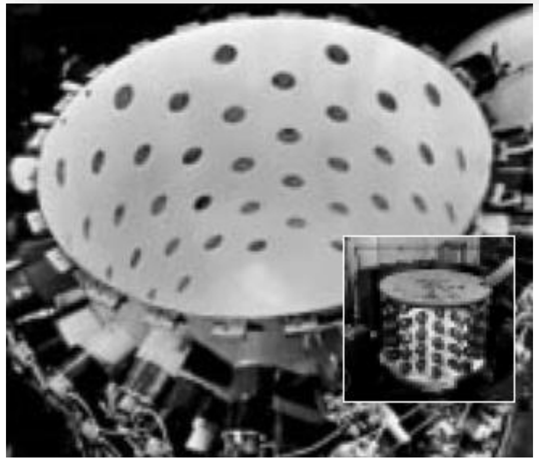

RADIOGRAMM - RADIOGRAMME
VIA RADIOSUISSE
NEWYORK
Briefelegramm
LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS PROF. W. PAULI

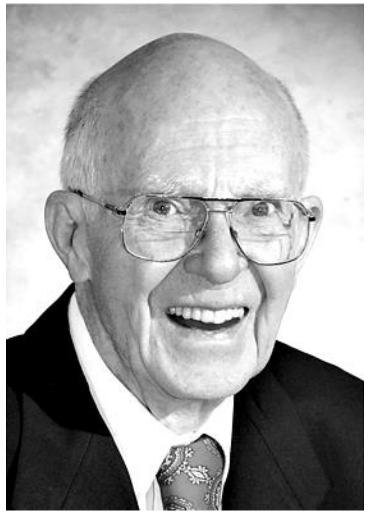
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

“Detected cosmic neutrinos"

“Caught Neutrinos in a Gold Mine”







Frederick Reines
Nobel prize 1995

Masatoshi Koshiba
Nobel prize 2002

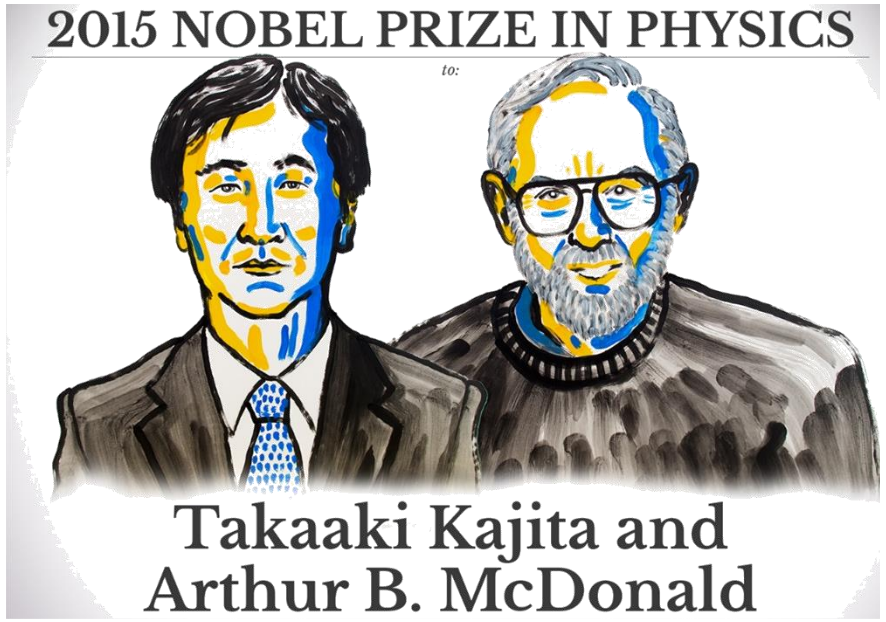
Ray Davis Jr.
Nobel prize 2002

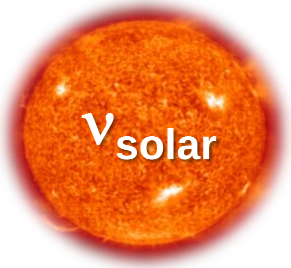
Neutrinos – experimental milestones

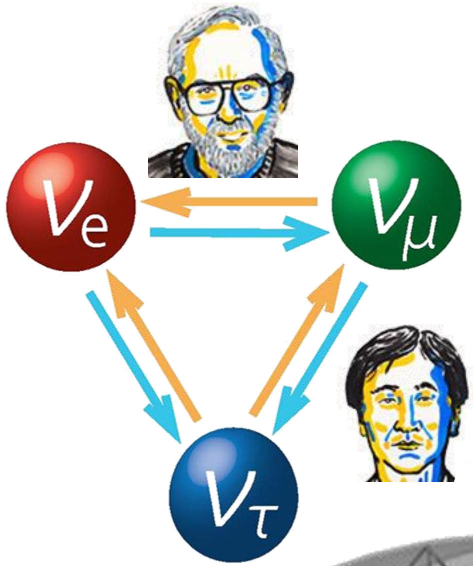
- **neutrino oscillations:** observation of flavour transitions unequivocally prove **neutrinos to be massive**

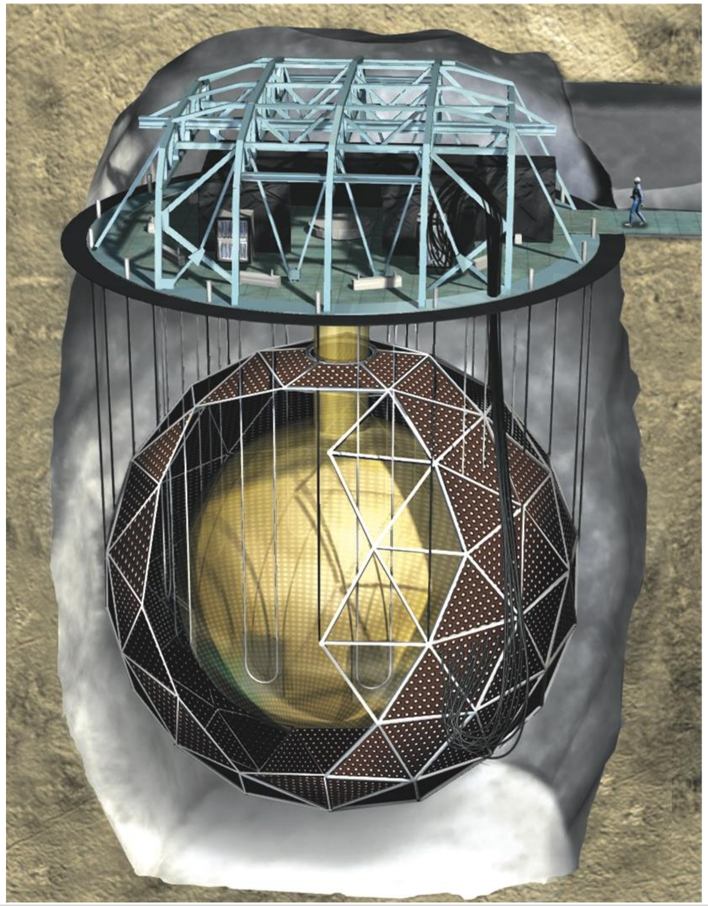
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

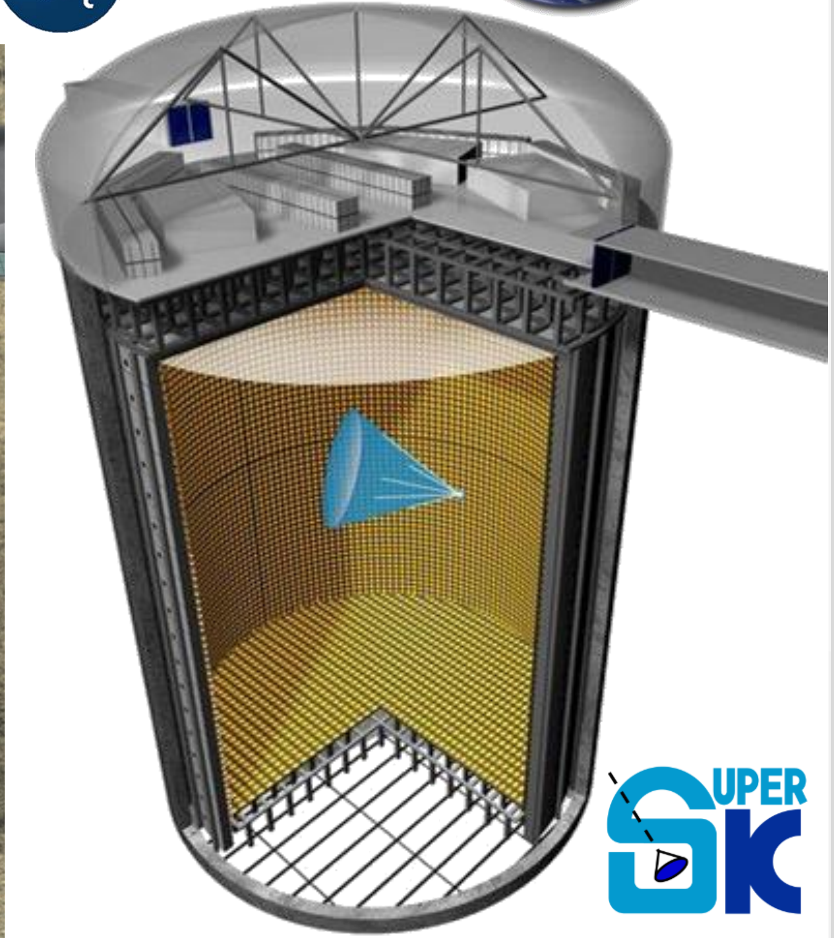
Nobelprize.org
The Official Web Site of the Nobel Prize











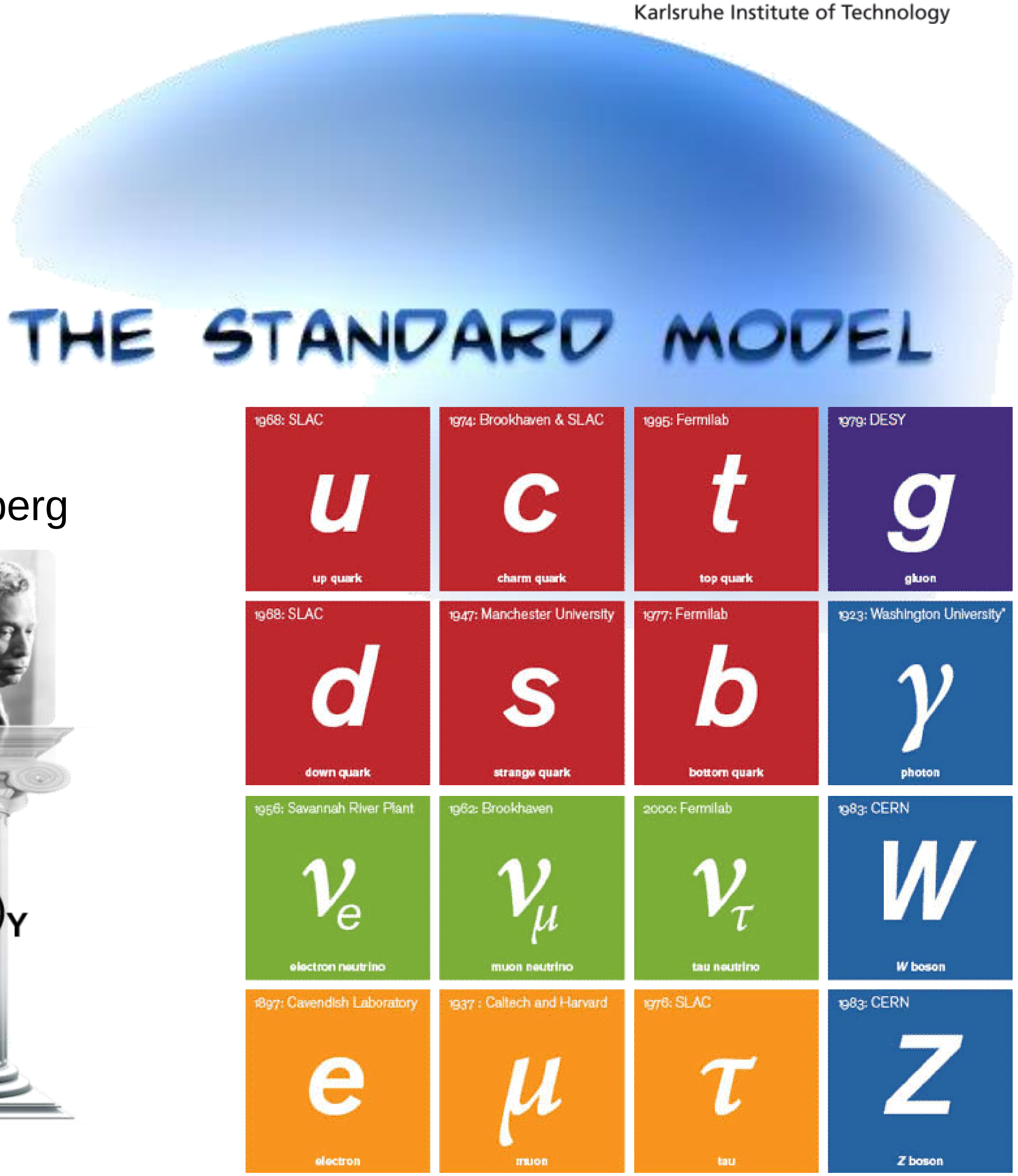
neutrino masses in particle physics

- **Standard model -** neutrinos are massless particles
  ⇨ parity violation: purely LH neutrino states

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

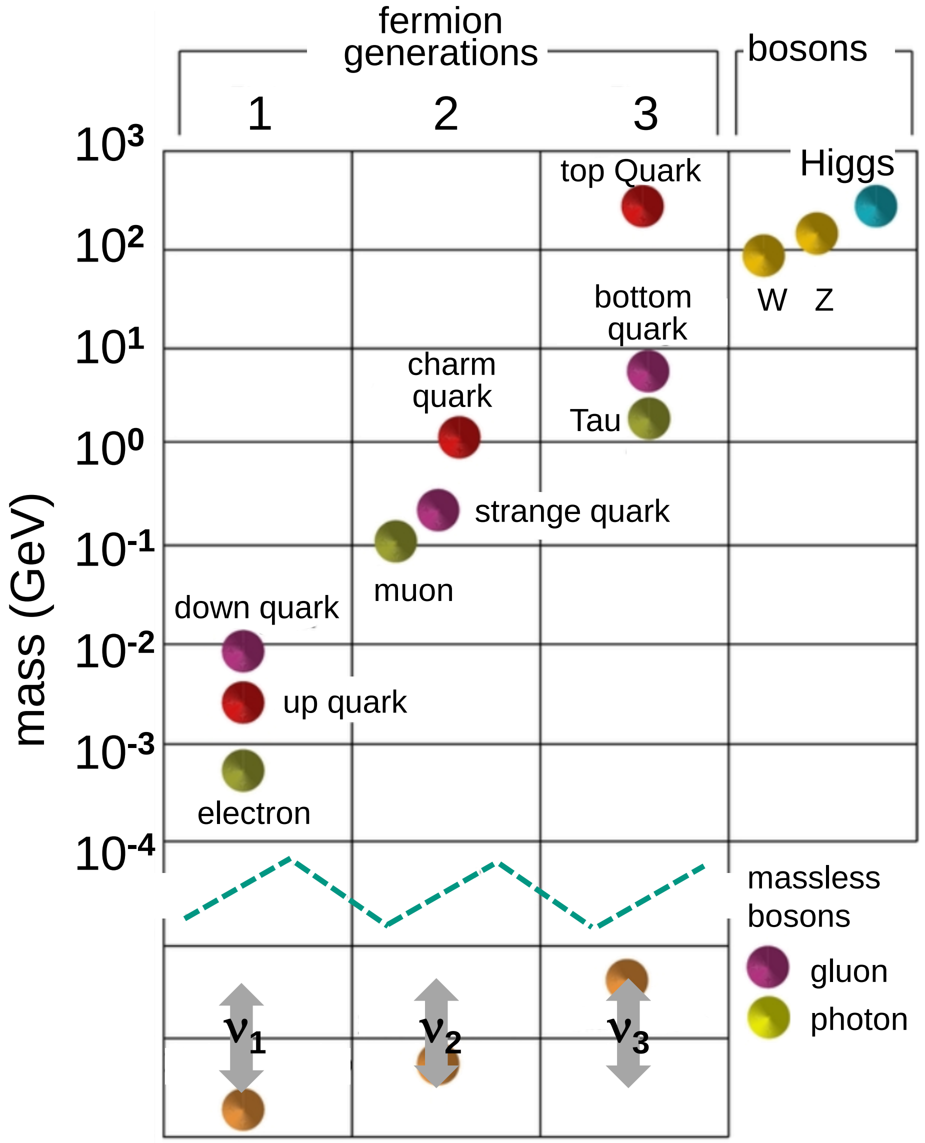
$$\begin{pmatrix}u \\ d'\end{pmatrix}_L \quad \begin{pmatrix}c \\ s'\end{pmatrix}_L \quad \begin{pmatrix}t \\ b'\end{pmatrix}_L$$

neutrino oscillations
imply massive
neutrinos



neutrino masses in particle physics

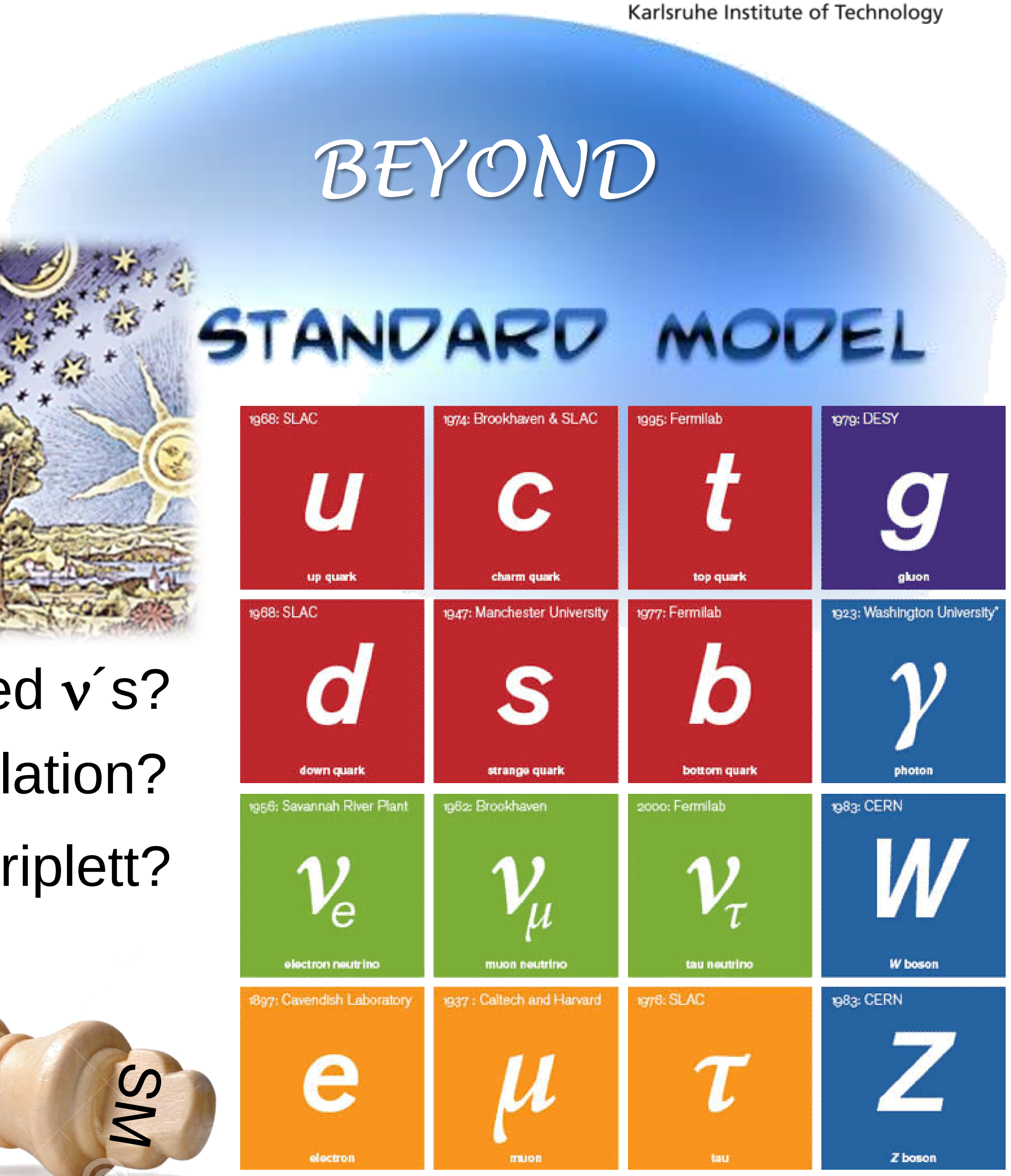
- **Neutrinos** and their unbearable lightness…



- right handed ν´s?

- lepton number violation?

- Higgs triplett?

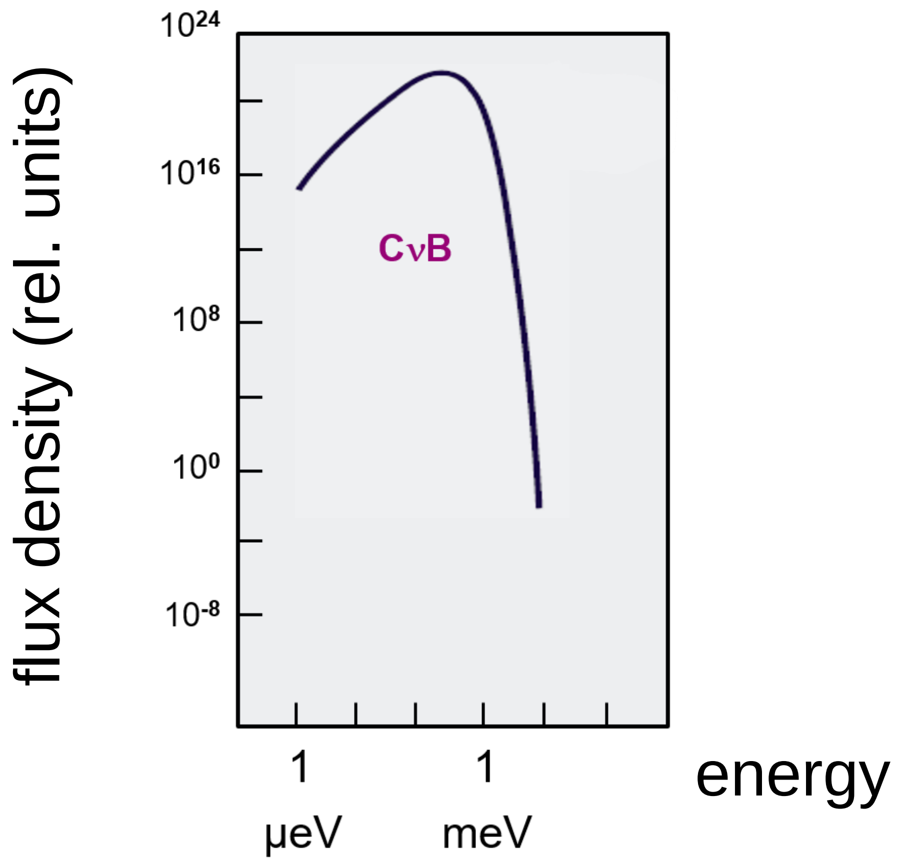


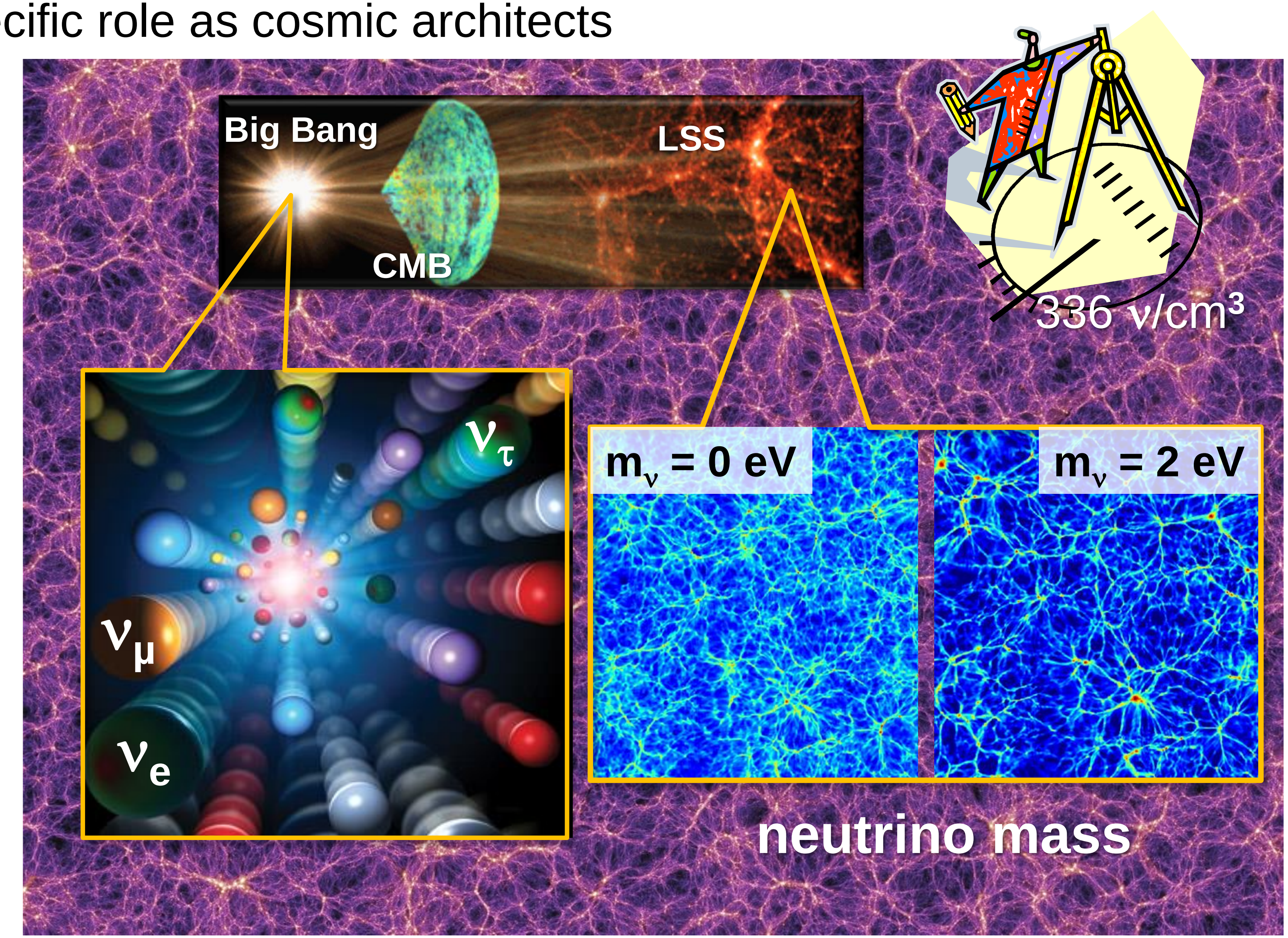
neutrino masses in cosmology

- **Neutrinos** from Big Bang play a specific role as cosmic architects

HDM (**H**ot **D**ark **M**atter)

$$T_\nu = \left(4/11\right)^{1/3} T_\gamma \approx 1.95\,\mathrm{K}$$

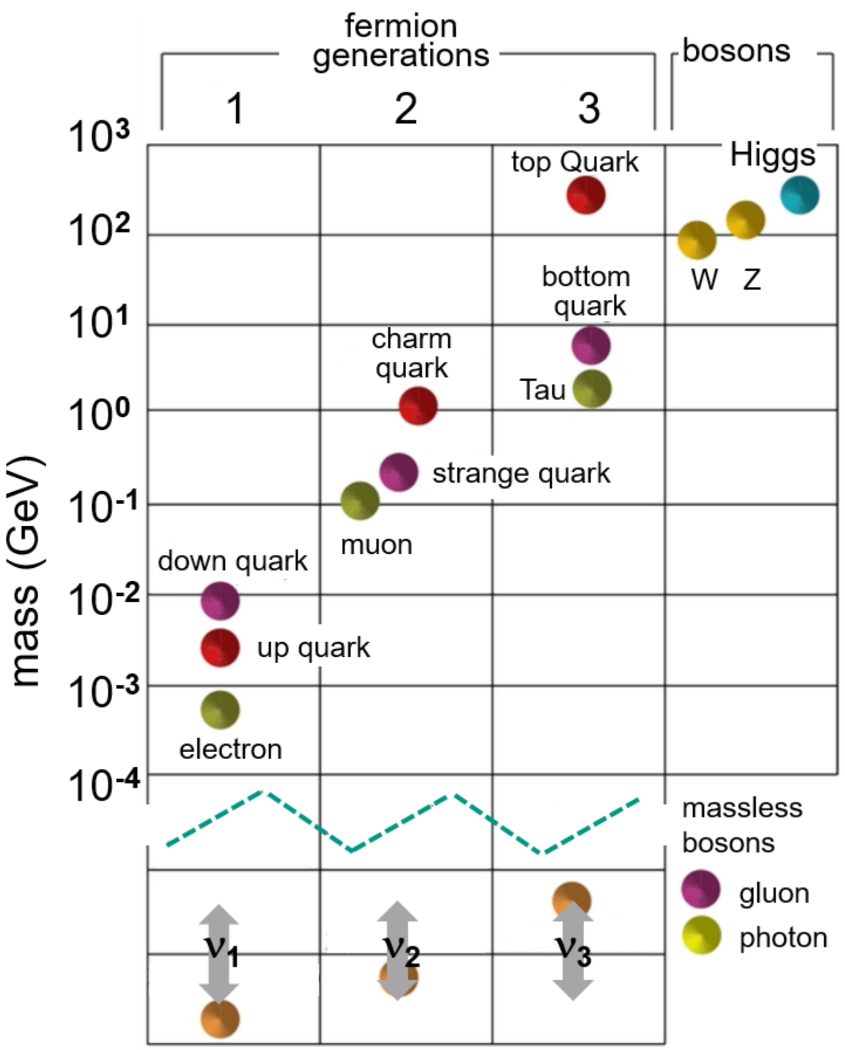


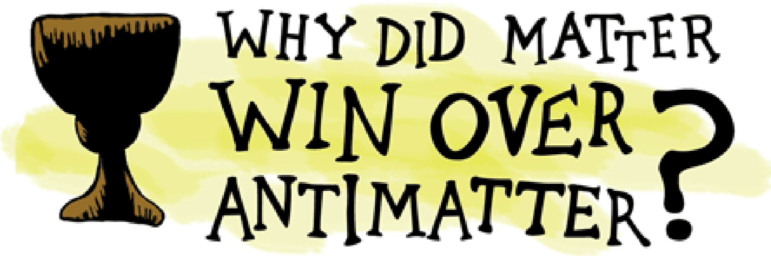


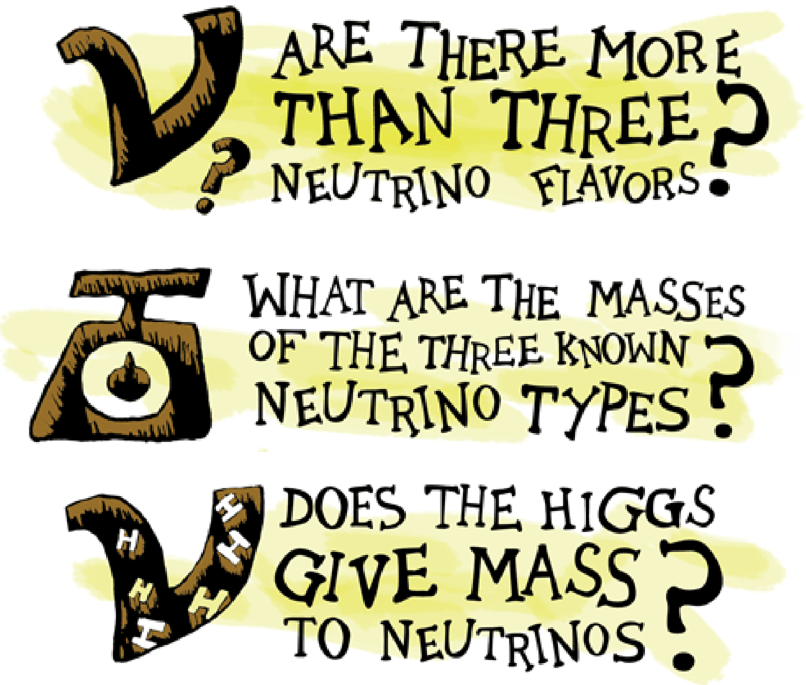
neutrino masses in astroparticle physics

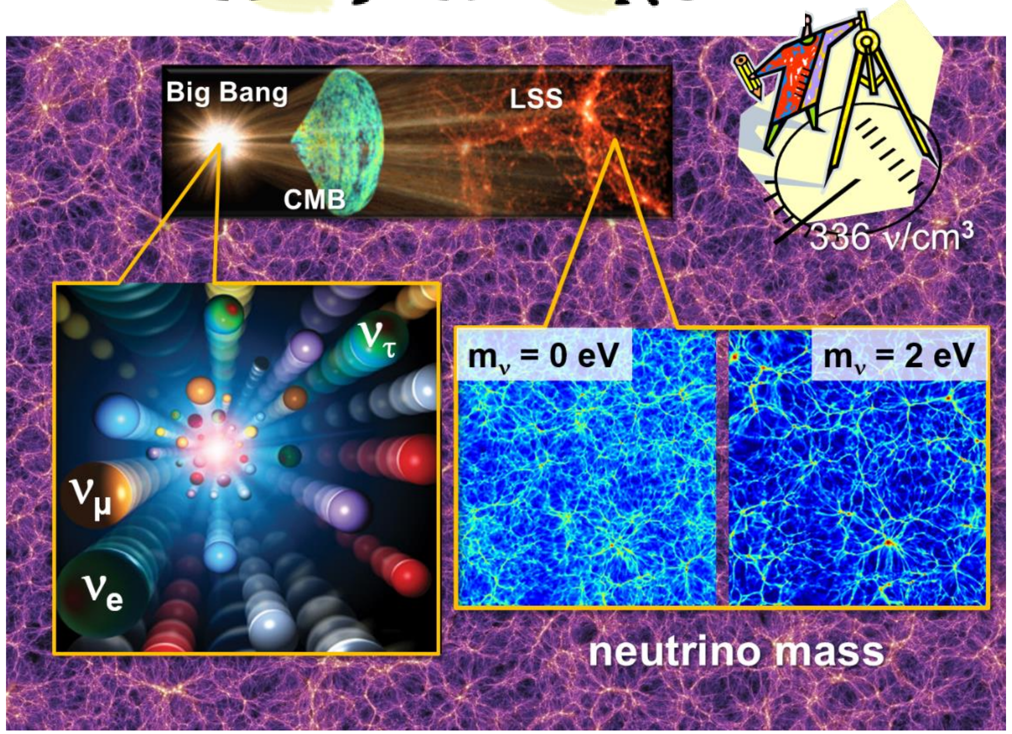
Karlsruhe Institute of Technology

- **Neutrinos** and their unbearable lightness…





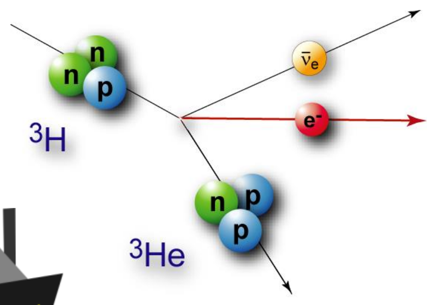


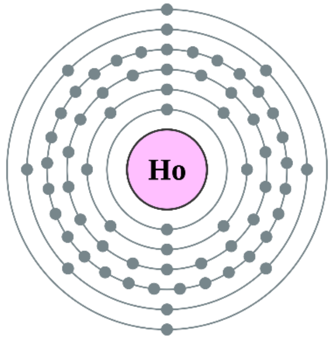


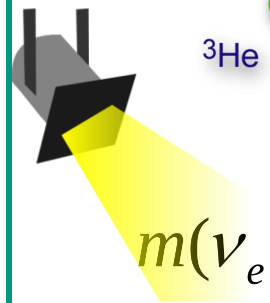
neutrino masses and experimental approaches

kinematics of weak decays

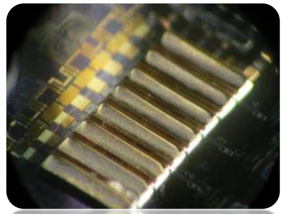
- ß-decay of ^{3}H, EC of ^{163}Ho
- **model-independent**

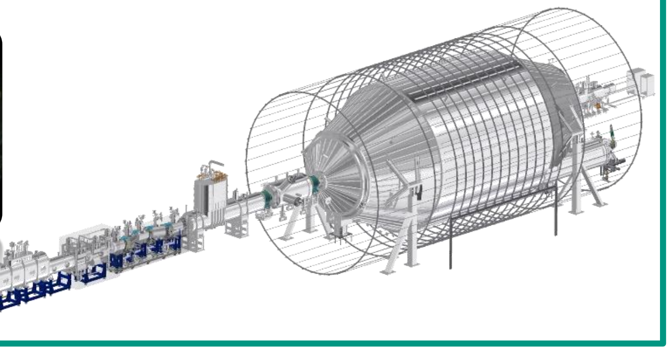






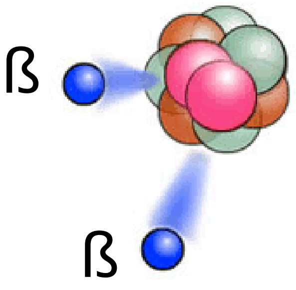
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}\right|^2 \cdot m_i^2}$$



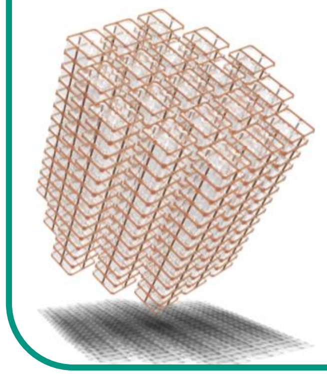


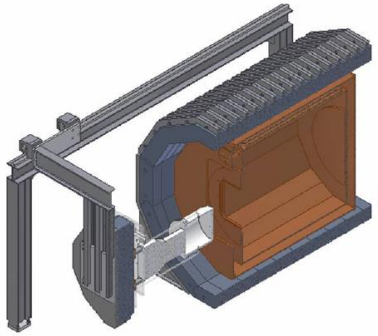
search for 0νßß-decay

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



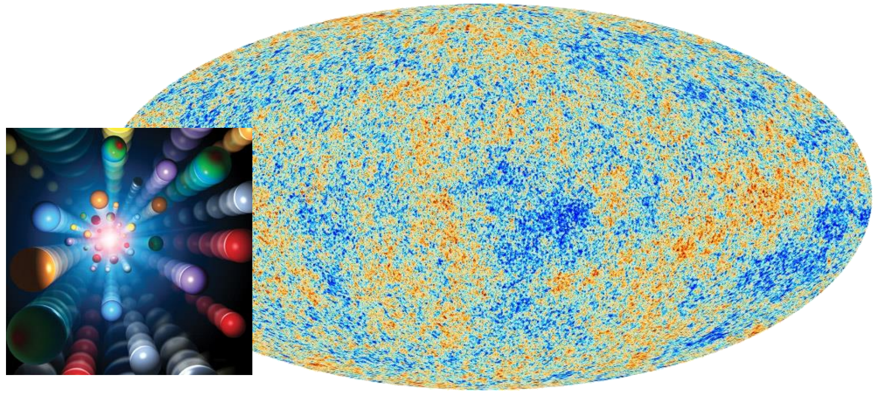
$$\langle m_{ßß} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$



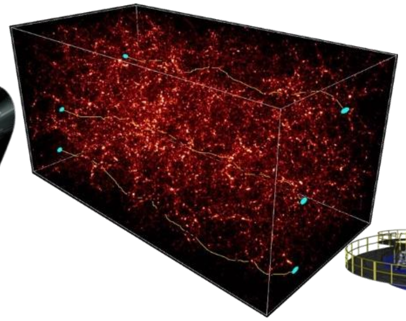


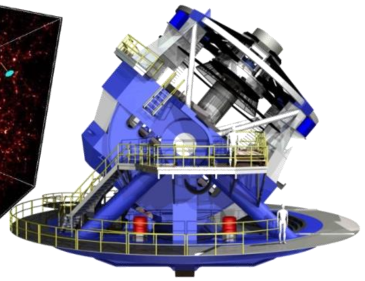
Cosmology & LSS

- CMBR, GRS, lensing,…
- model-dependent (⇔H_0,…)



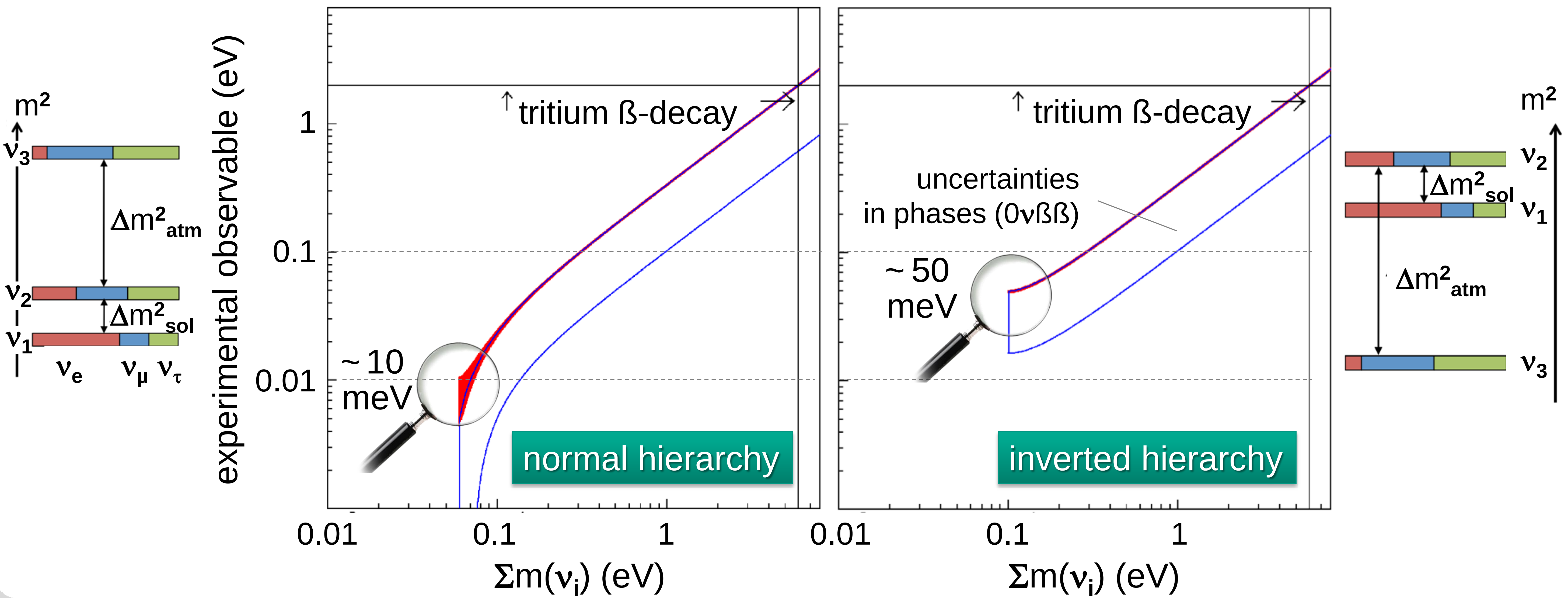
$$m_{tot} = \sum_{i=1}^{3} m_i$$





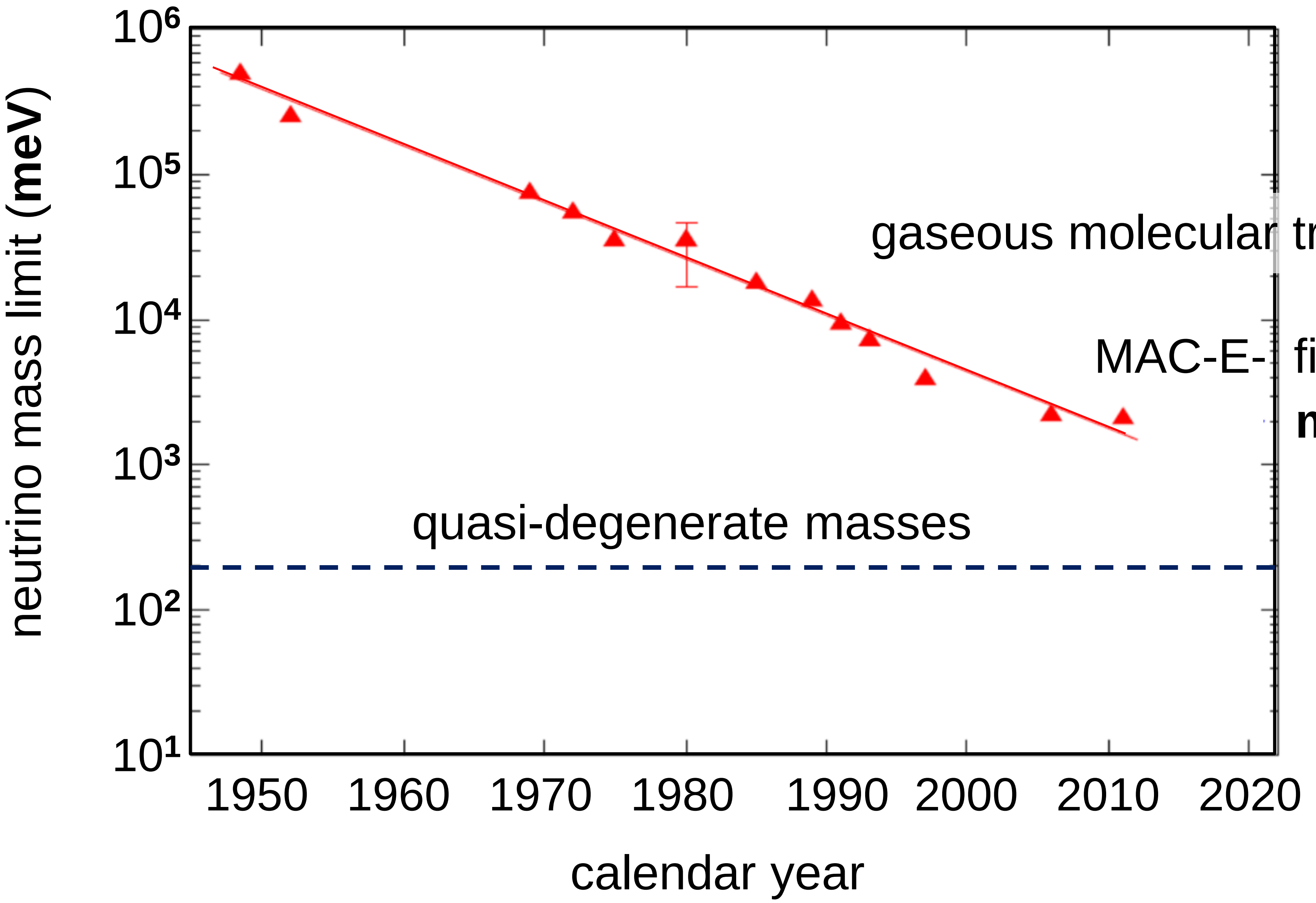
ν-masses from kinematic studies – the challenge

- **setting the stage:** experimental observables $m(\nu_e)$ in ß-decay & EC
  $m_{ßß}$ in 0νßß-searches (Majorana/CP-phases)

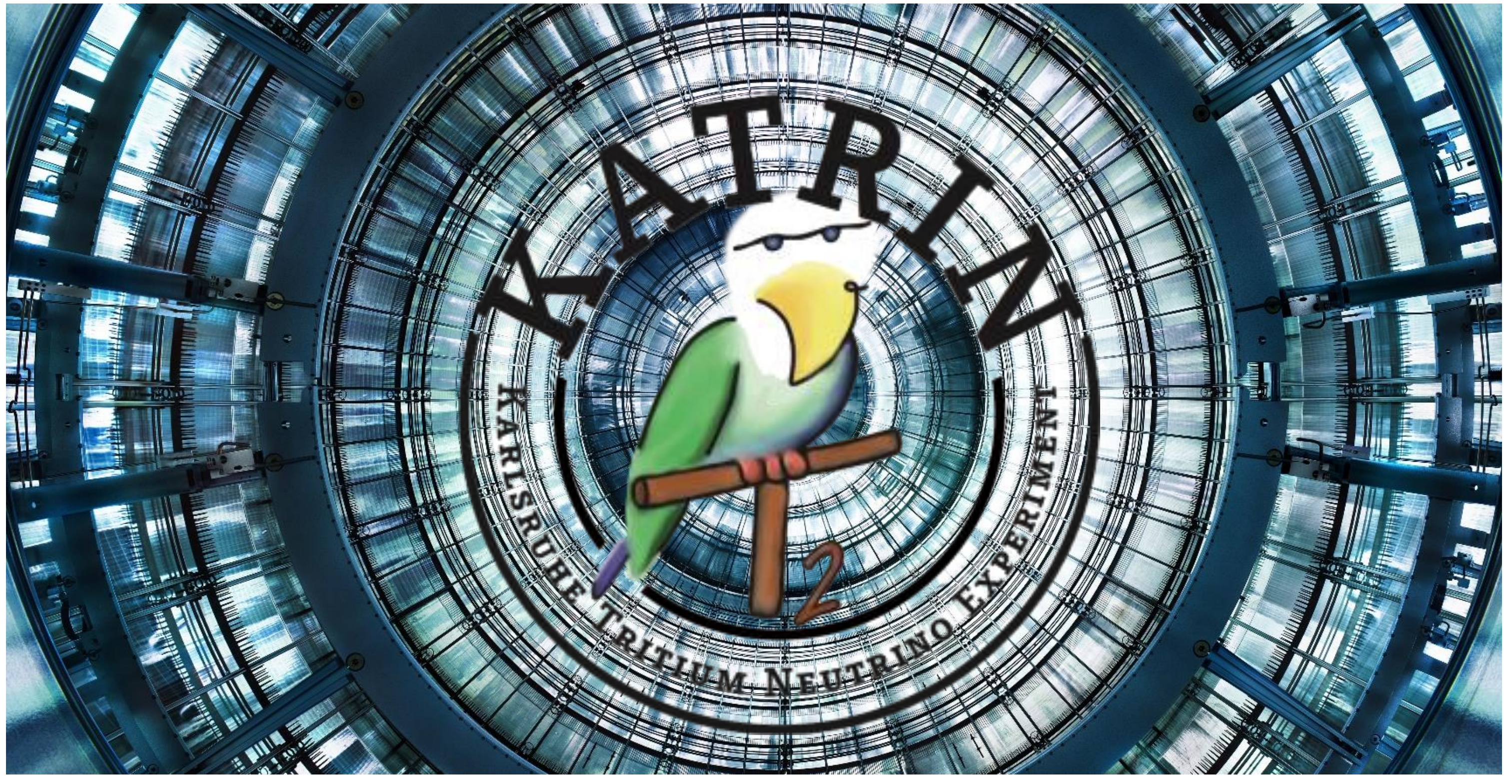


Moore´s law* of direct ν-mass sensitivities

- **setting the stage:** experimental progress over past decades due to **new technologies**



*courtesy of JF Wilkerson

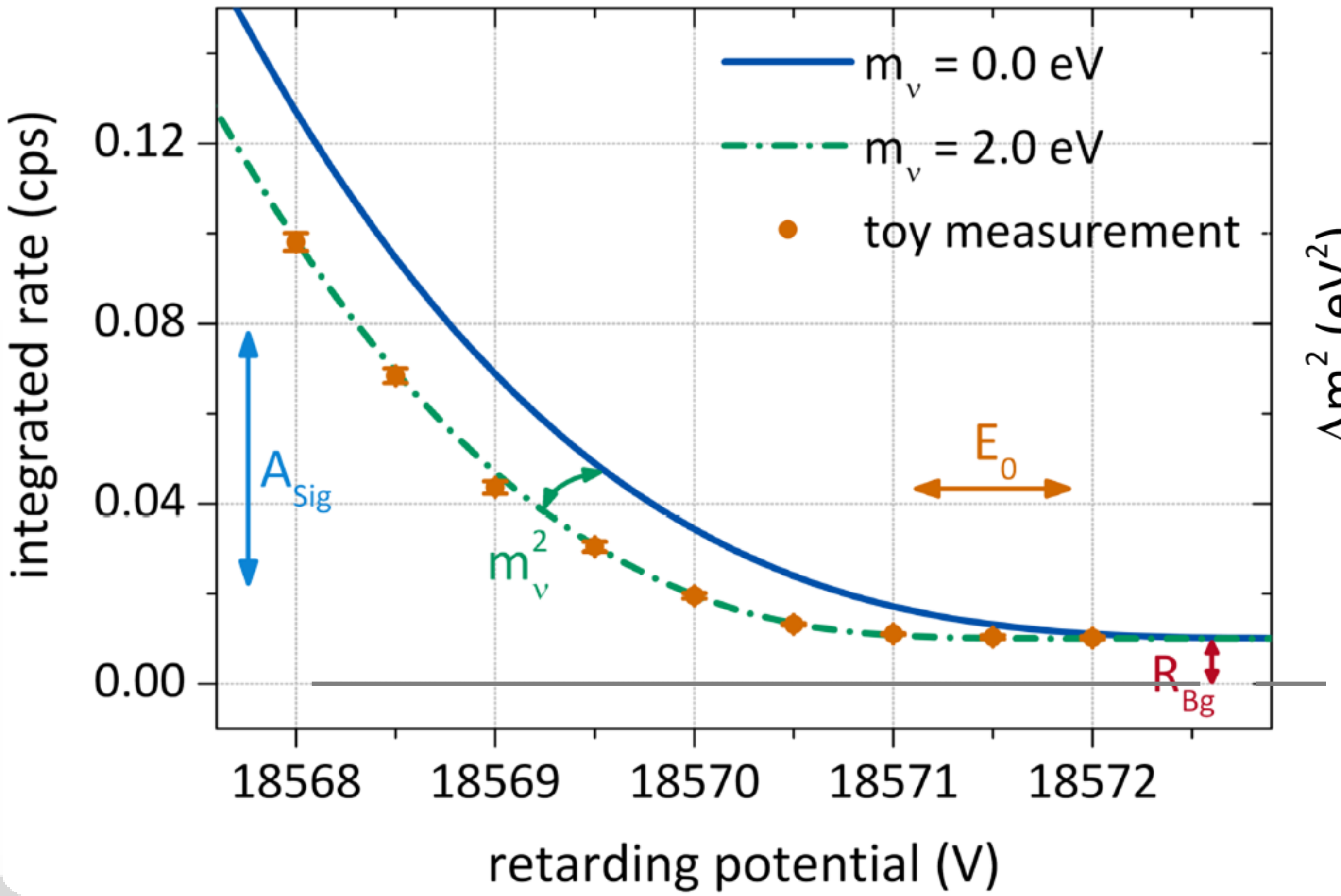


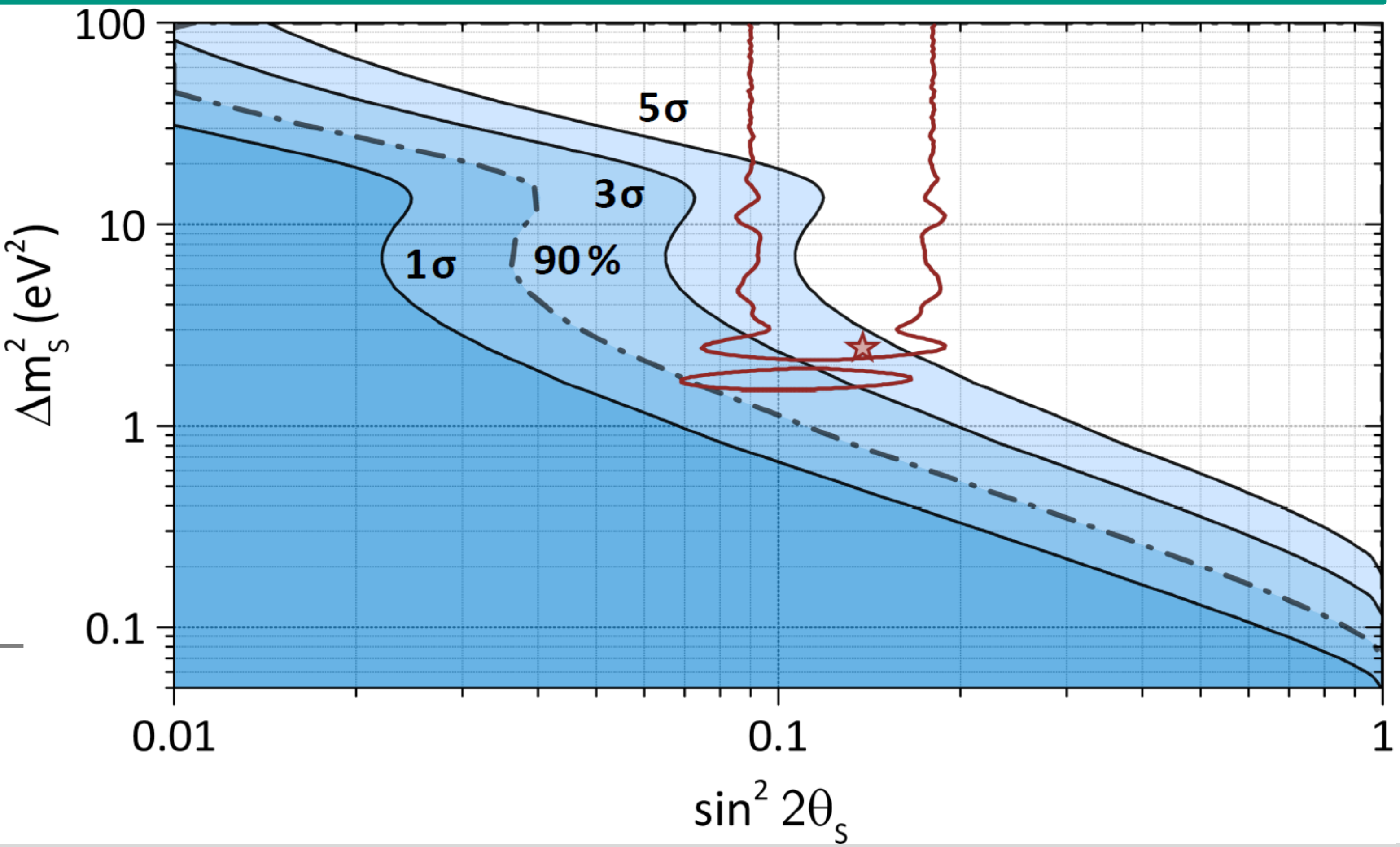
KATRIN EXPERIMENT

KATRIN experiment – science case for phase 1

■ 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 …





KATRIN Collaboration – 20 institutions

- **Karlsuhe Tritium Neutrino Experiment**
  - 6 countries (D, US, CZ, RU, F, ES)
  - 20 institutions, 150 collaborators

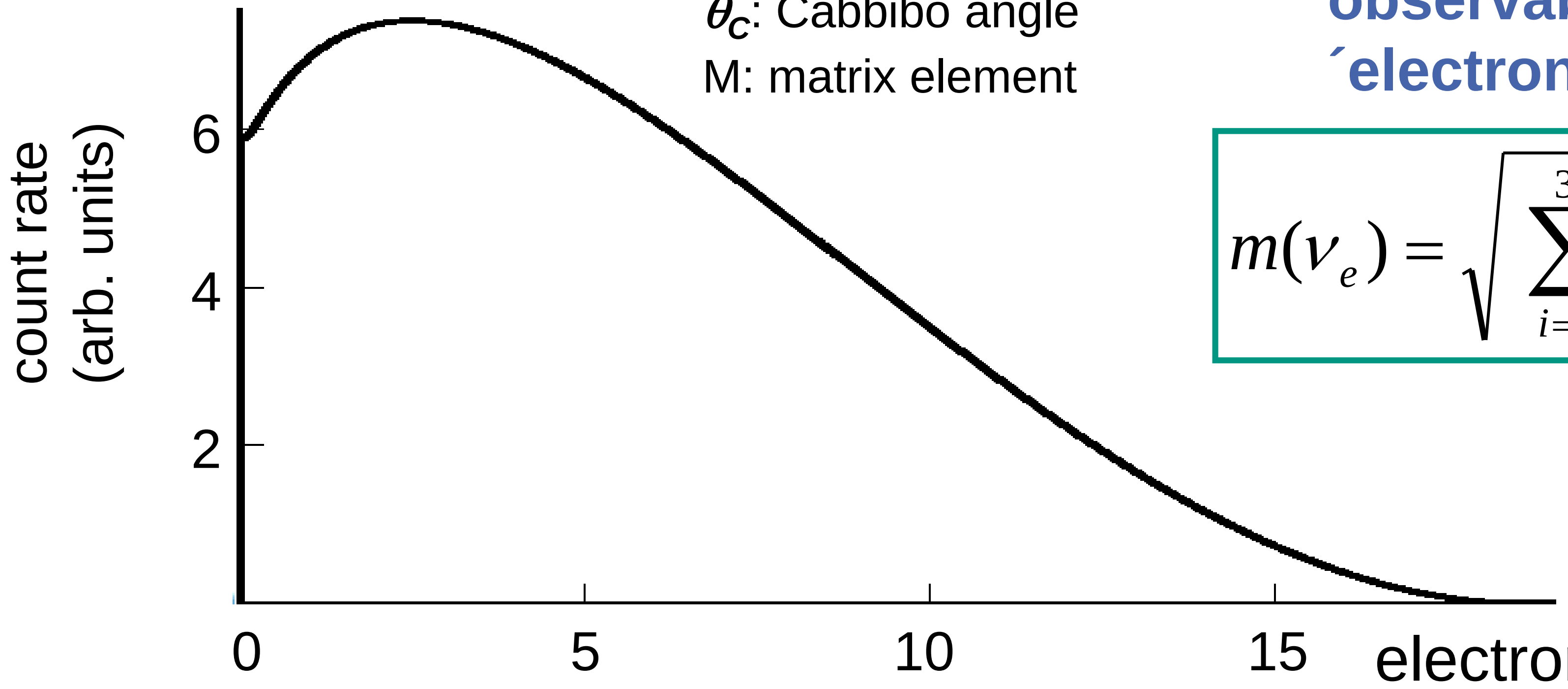
tritium ß-decay: kinematics & observable

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

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

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

$\boldsymbol{\theta_C}$: Cabbibo angle
M: matrix element

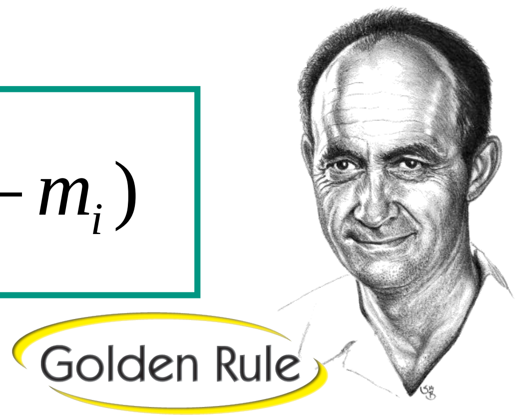


observable $m^2(\nu_e)$: ´electron-ν-mass´

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

´incoherent´ sum of the mass eigenstates m_i

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



Enrico Fermi

tritium ß-decay: kinematics & observable

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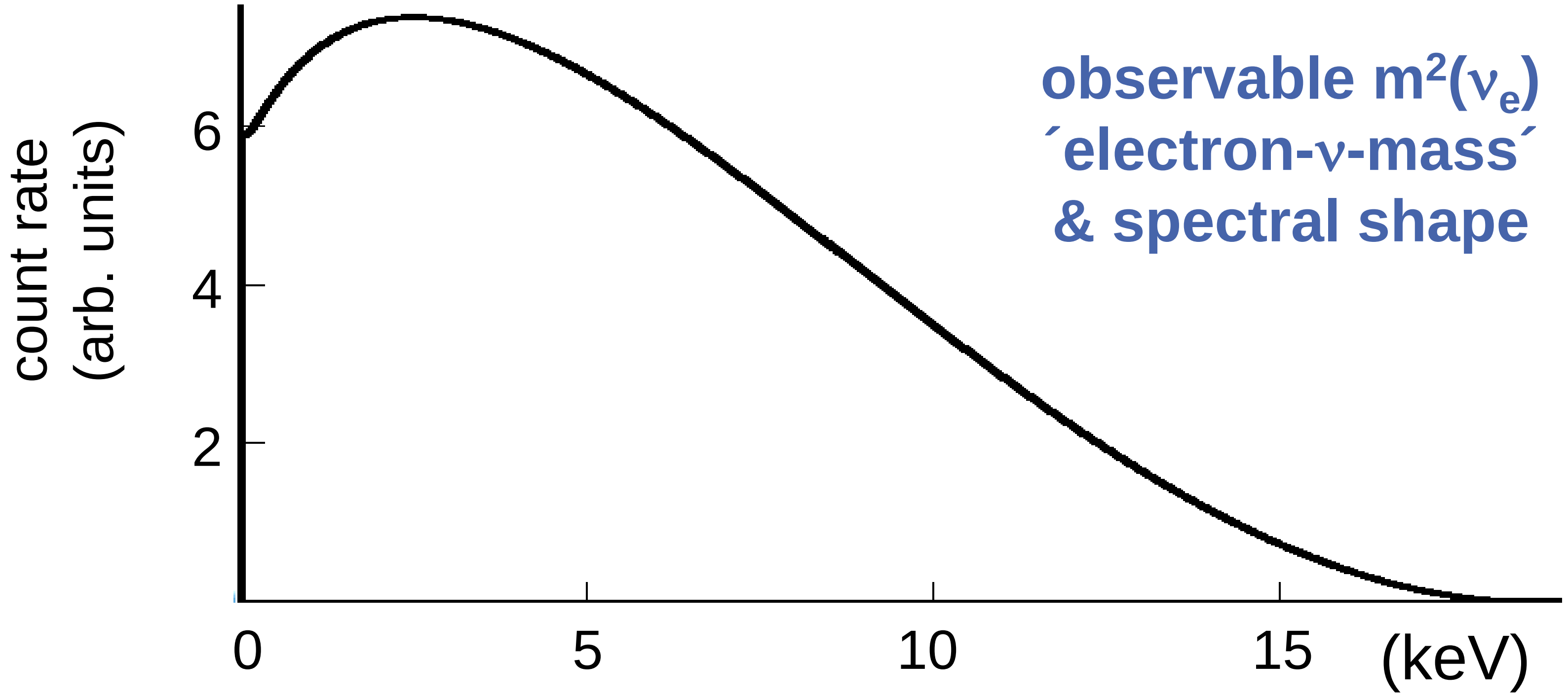
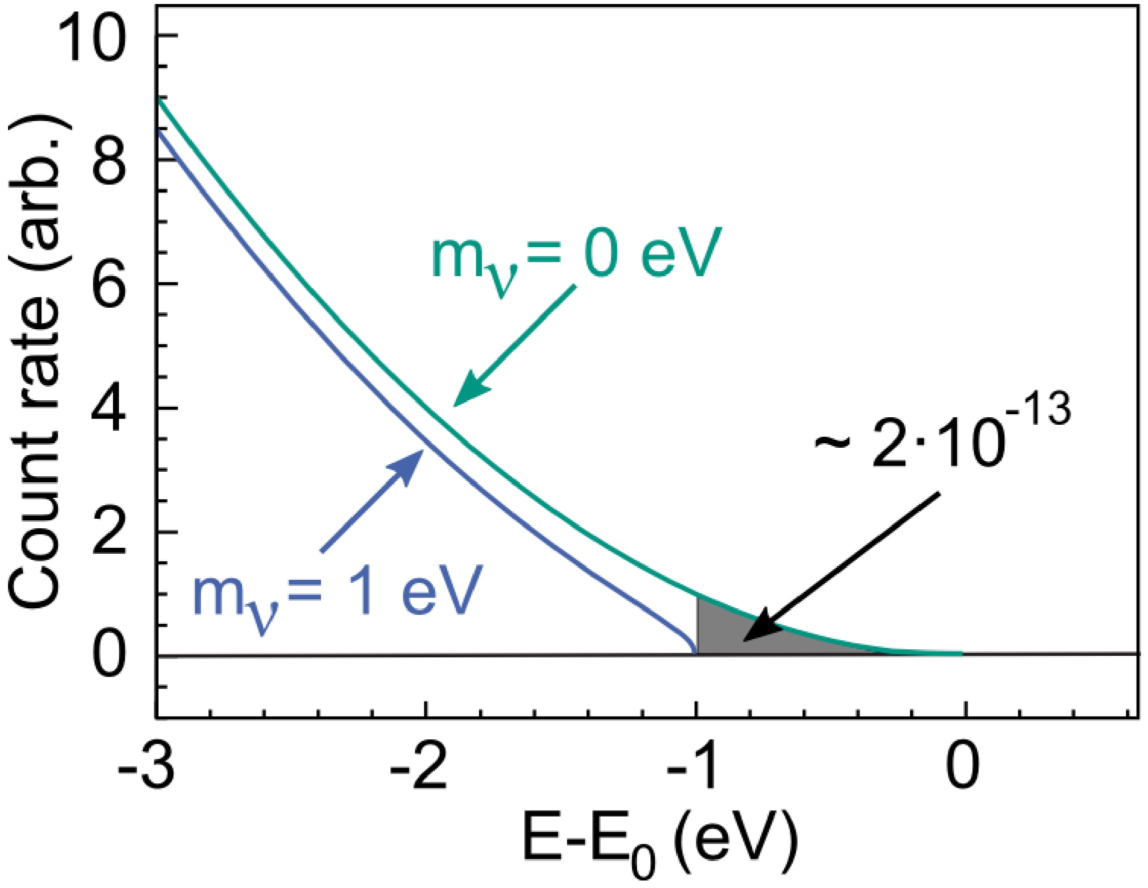
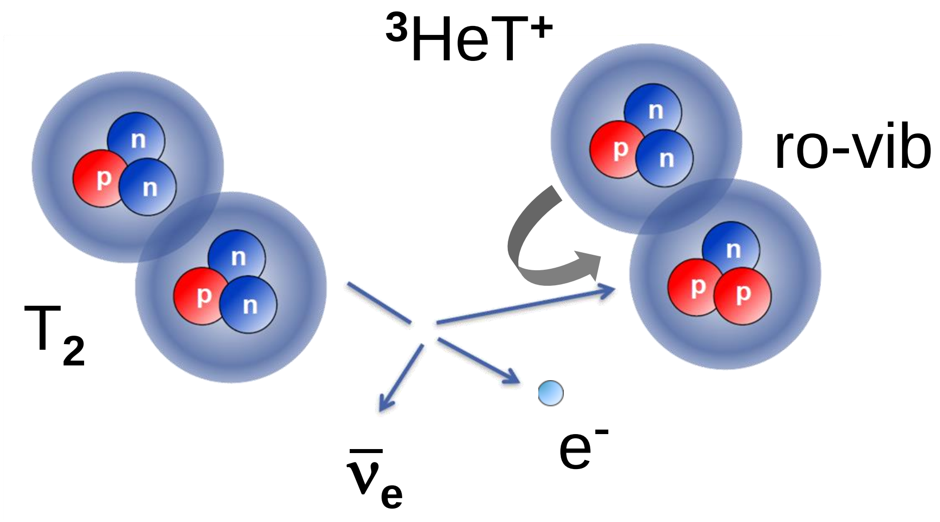


observable m²(νe)
´electron-ν-mass´
& spectral shape

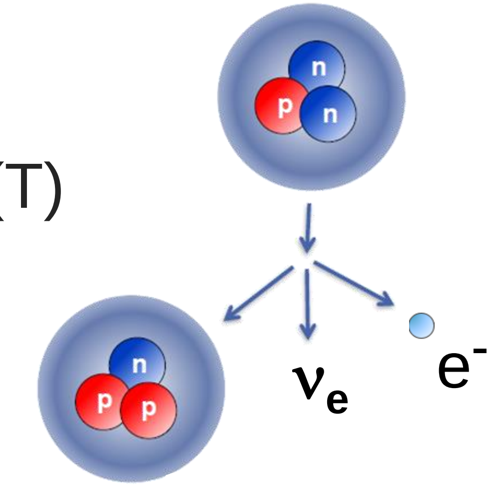


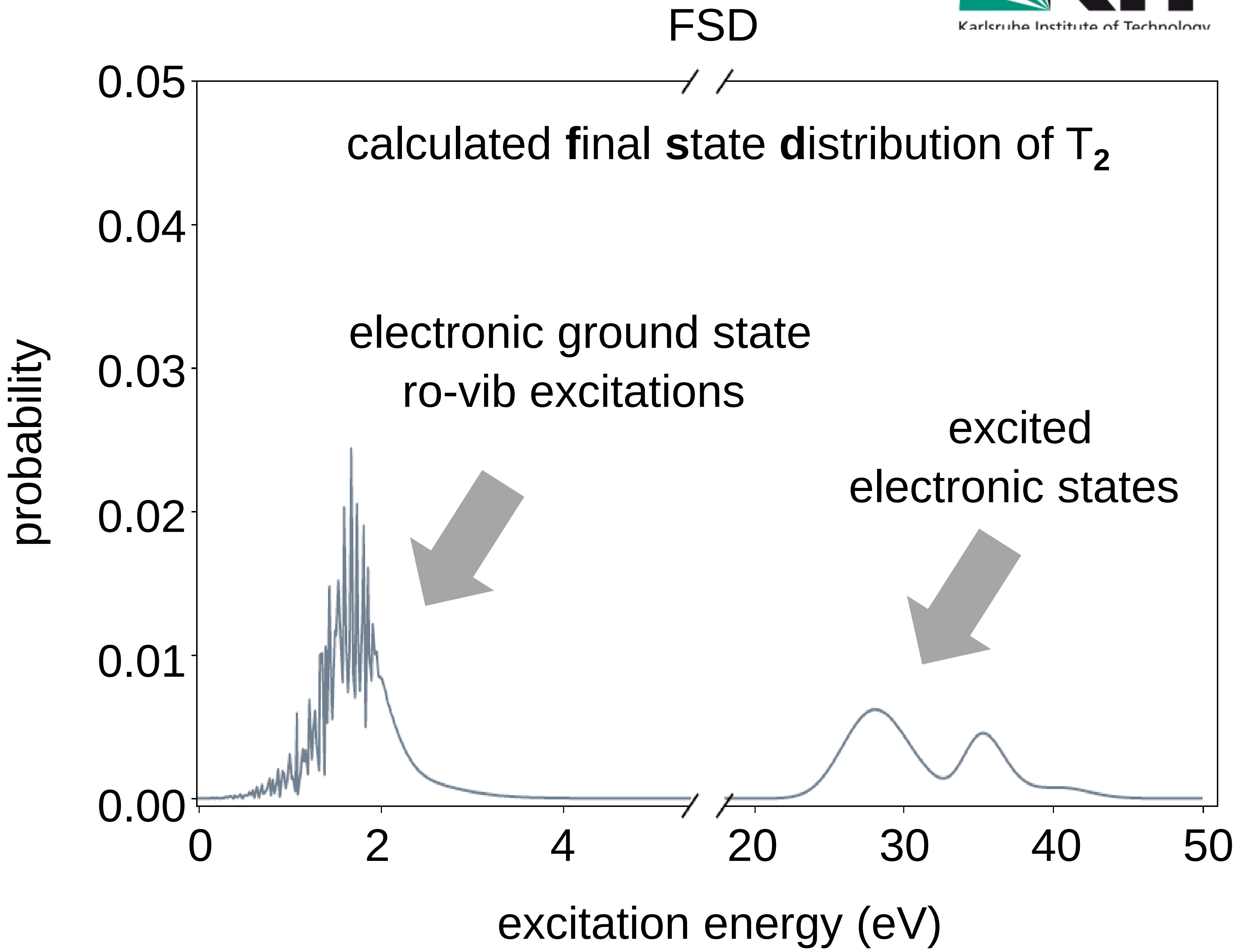
ß-spectroscopy: molecular & atomic tritium



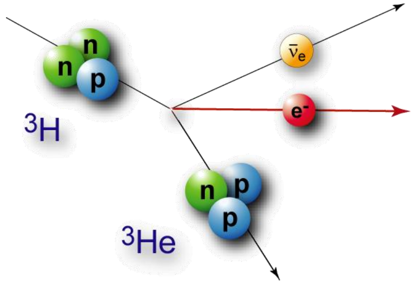
molecular source (T_2) –
sensitivity limit ~ 100 meV

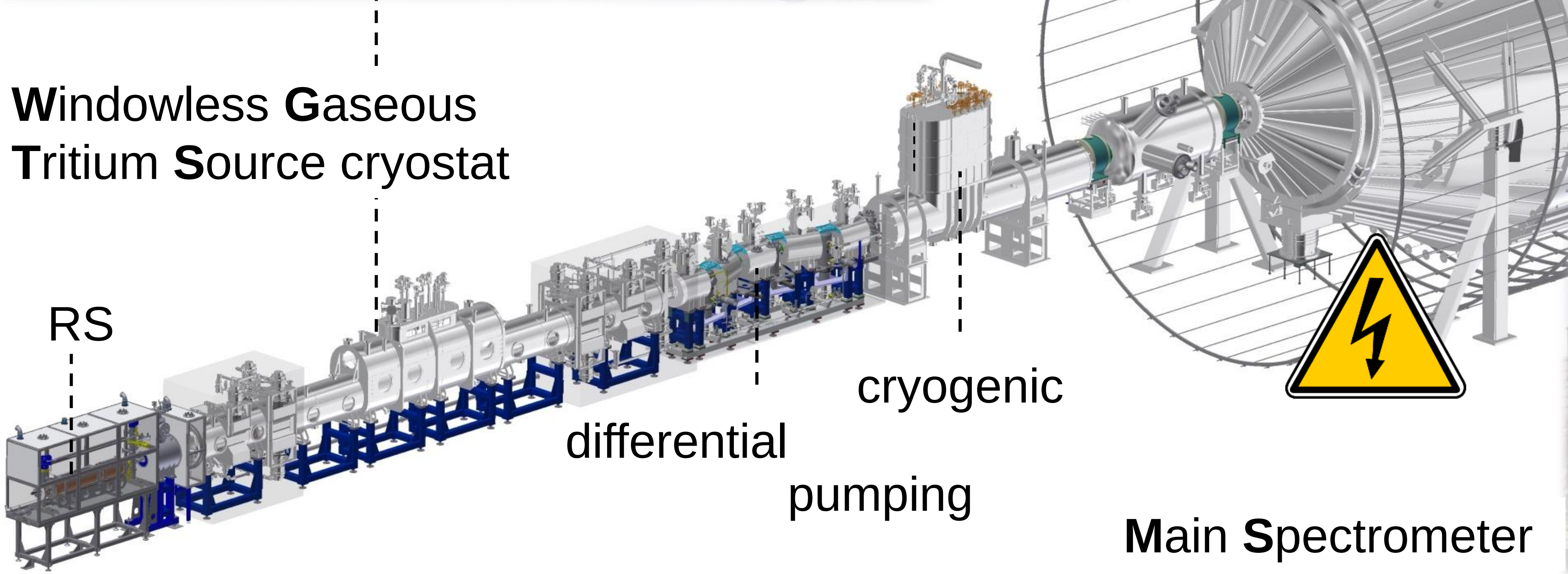
atomic source (T)
sensitivity limit
~ 40 meV (?)

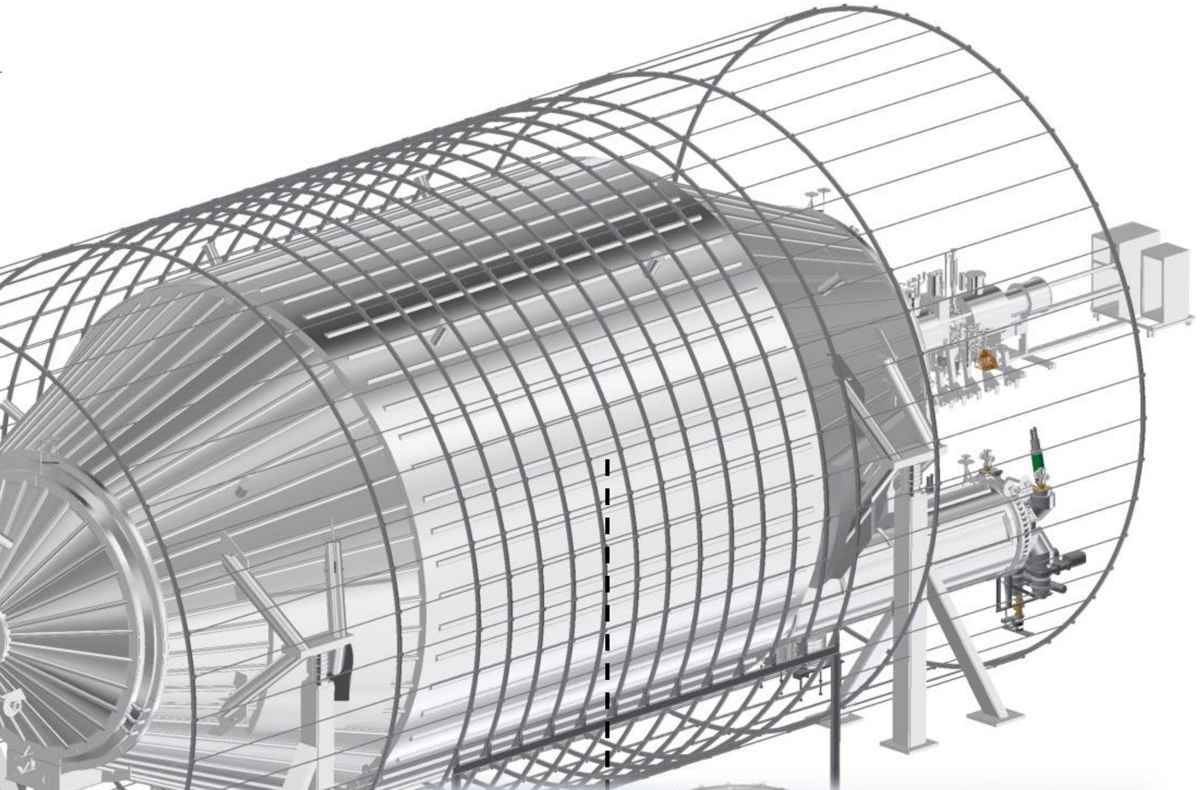




KATRIN overview: 70 m long beamline







Windowless **G**aseous
Tritium **S**ource cryostat

RS

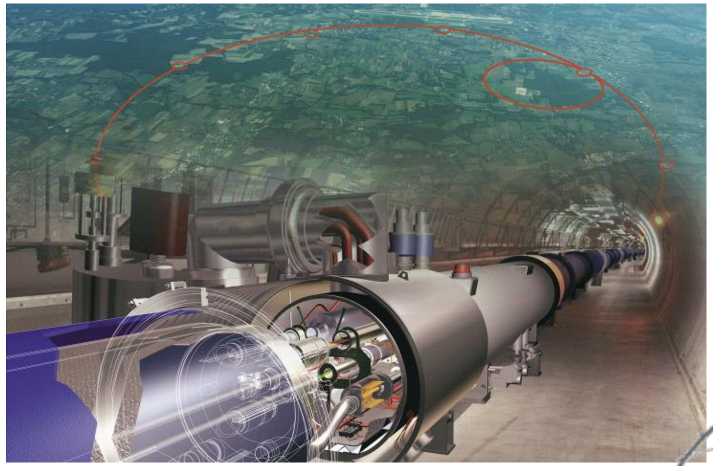
differential
pumping

cryogenic

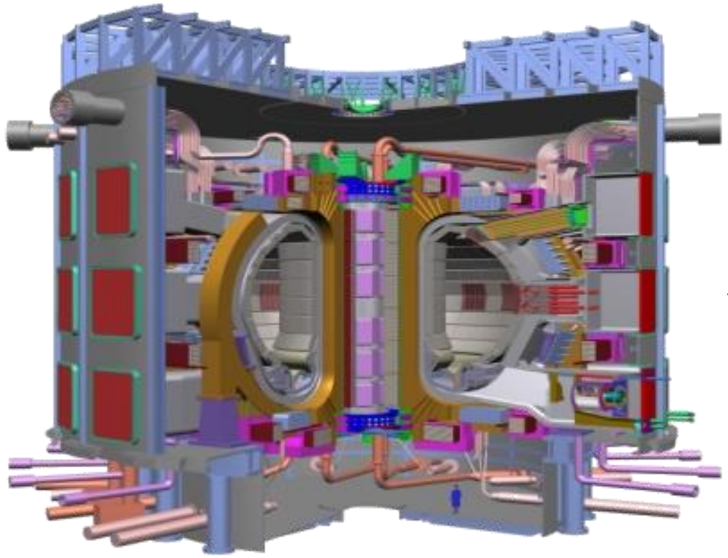
Main **S**pectrometer

KATRIN overview: challenges

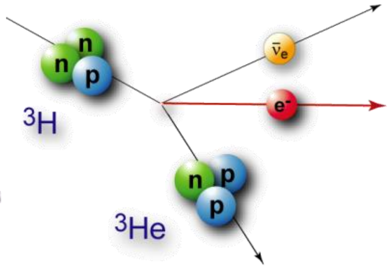
$1250\ m^3$

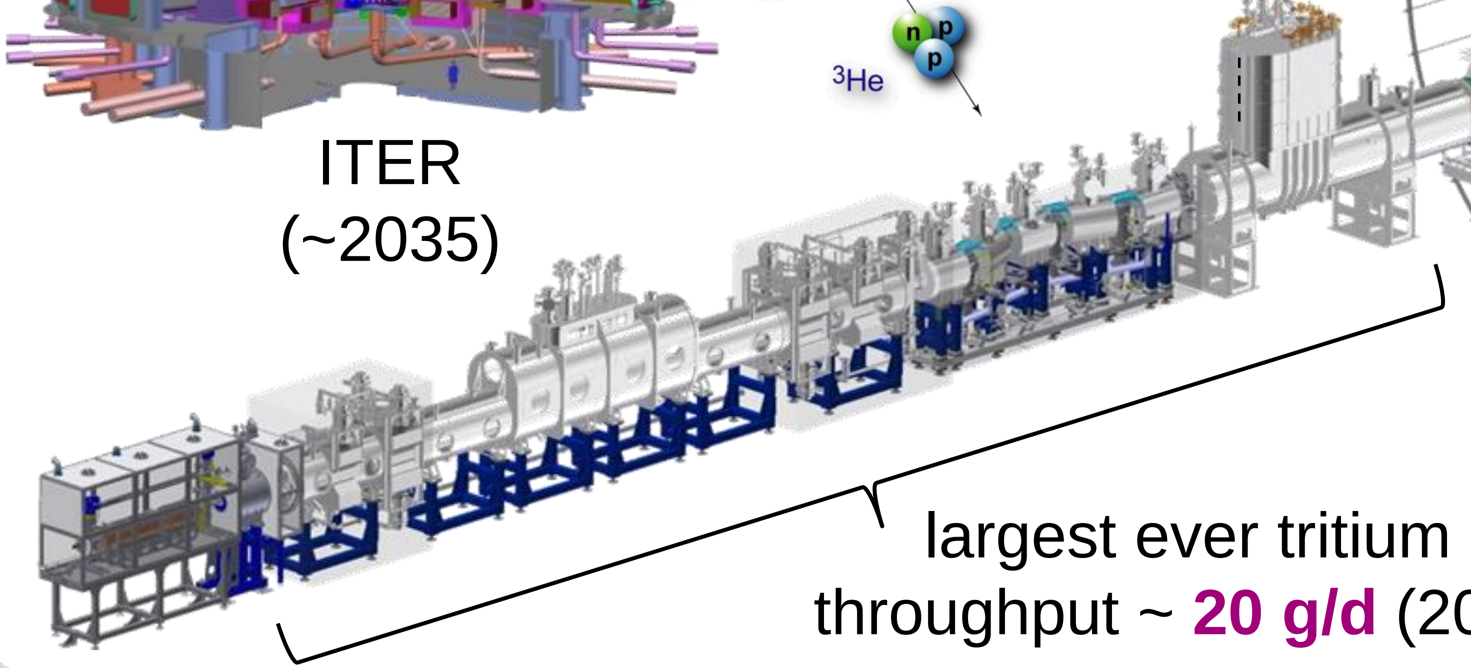


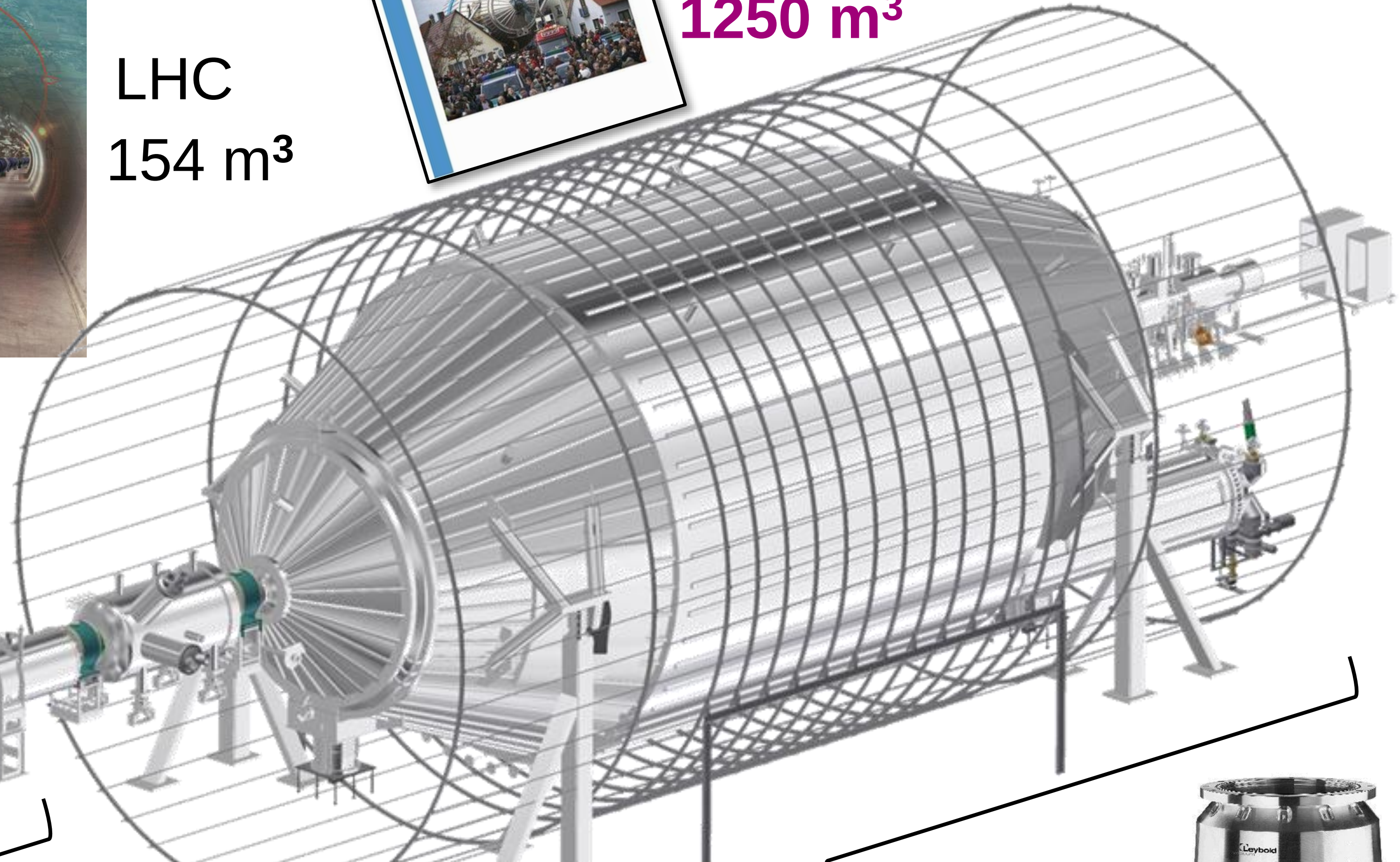
LHC
$154\ m^3$



ITER
(~2035)



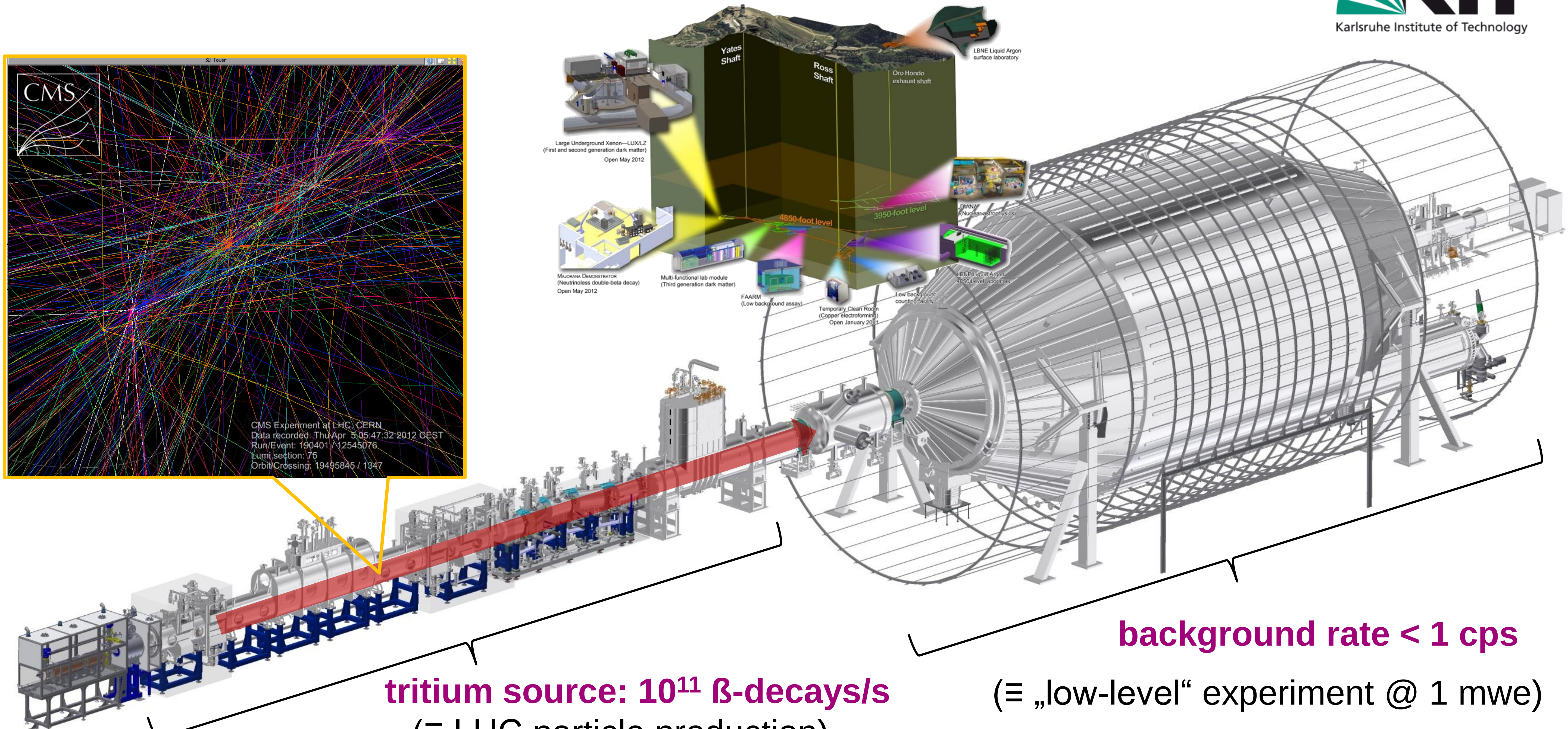




largest ever tritium throughput ~ **20 g/d** (2019)

largest ever UHV recipient: p ~ 10^{-11} mbar (since 2013)

KATRIN overview: challenges



background rate < 1 cps

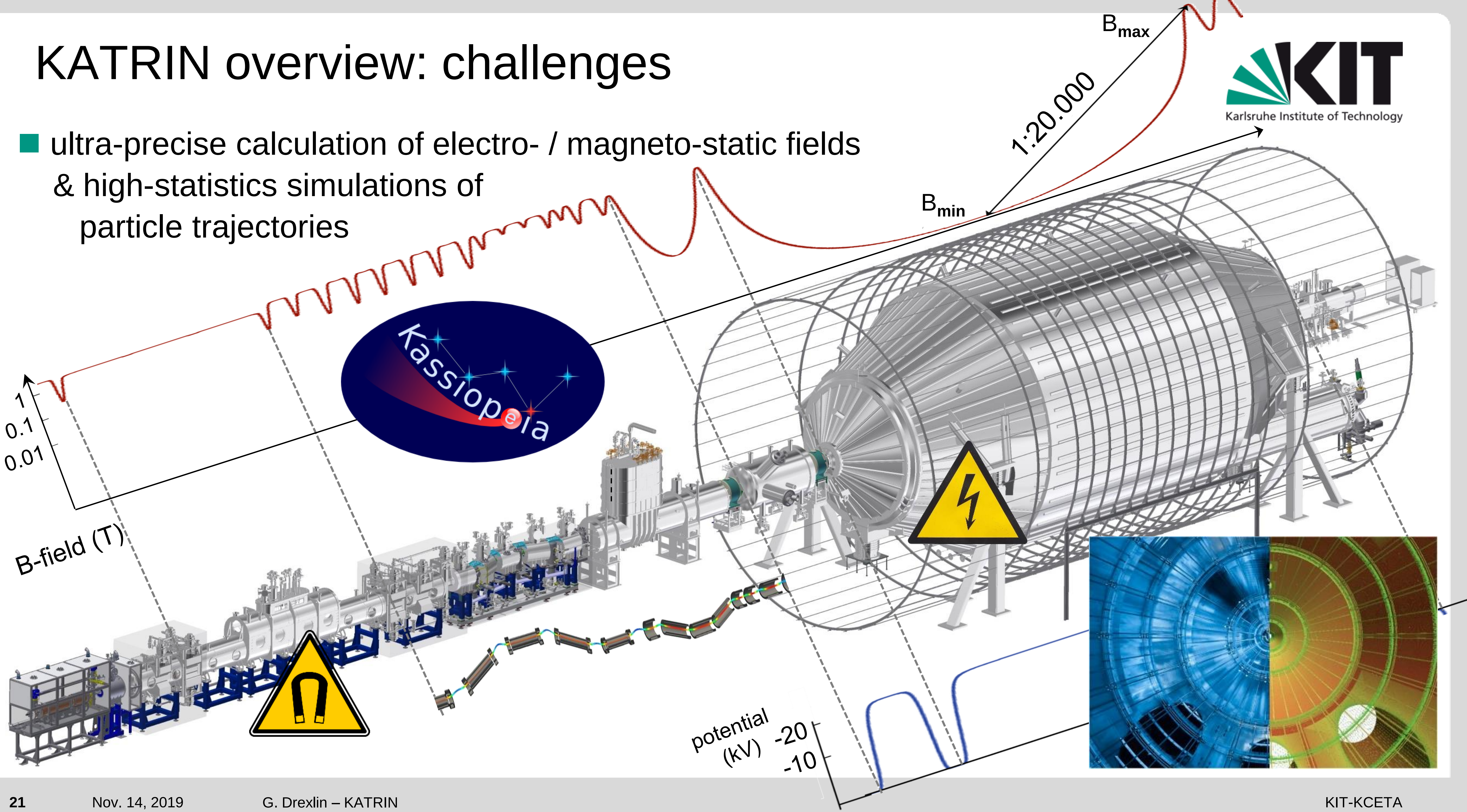
(≡ „low-level“ experiment @ 1 mwe)

tritium source: 10^{11} ß-decays/s

(≡ LHC particle production)

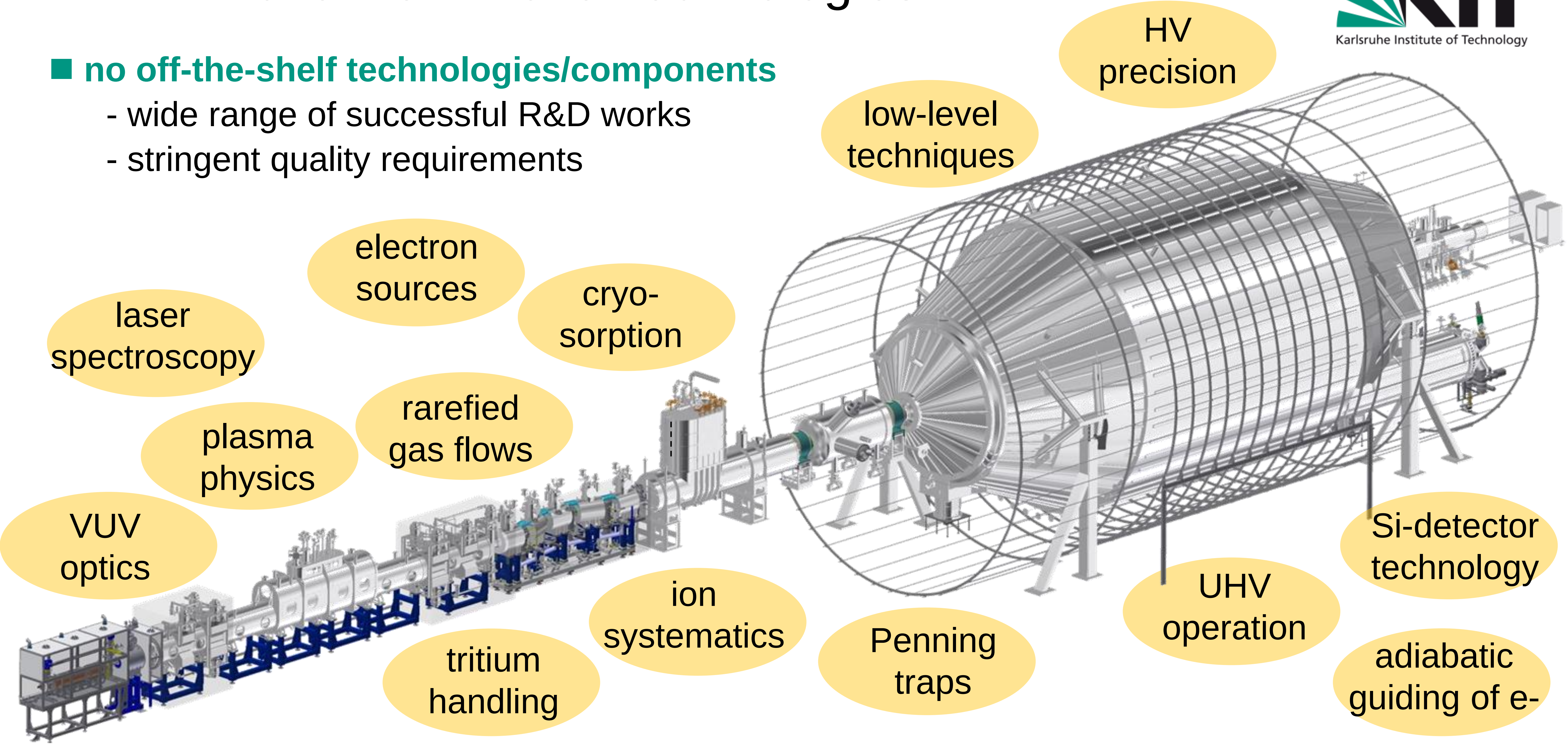
KATRIN overview: challenges

- ultra-precise calculation of electro- / magneto-static fields & high-statistics simulations of particle trajectories

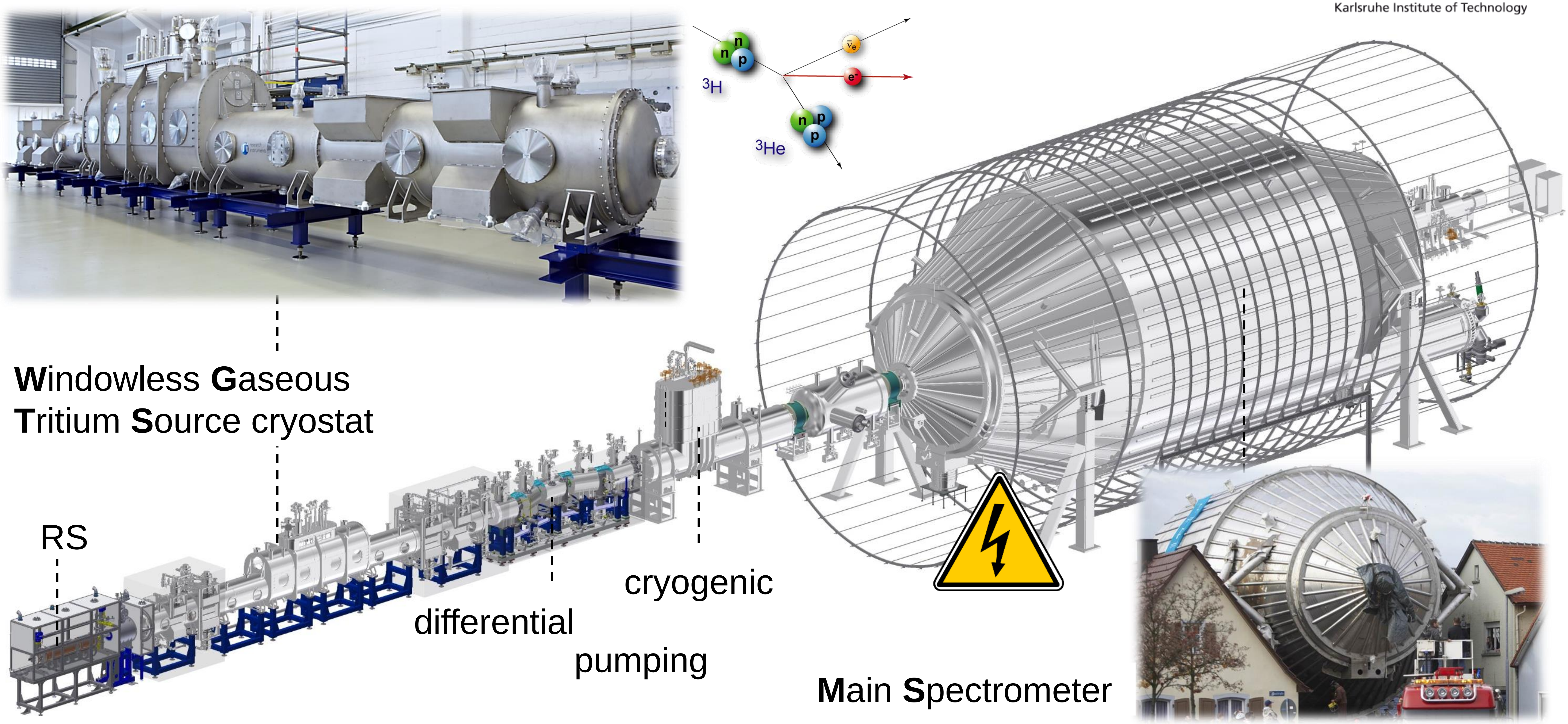


KATRIN overview: novel technologies

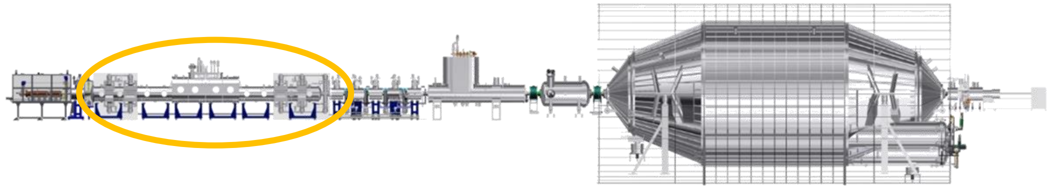
- **no off-the-shelf technologies/components**
  - wide range of successful R&D works
  - stringent quality requirements



KATRIN overview: 70 m long beamline

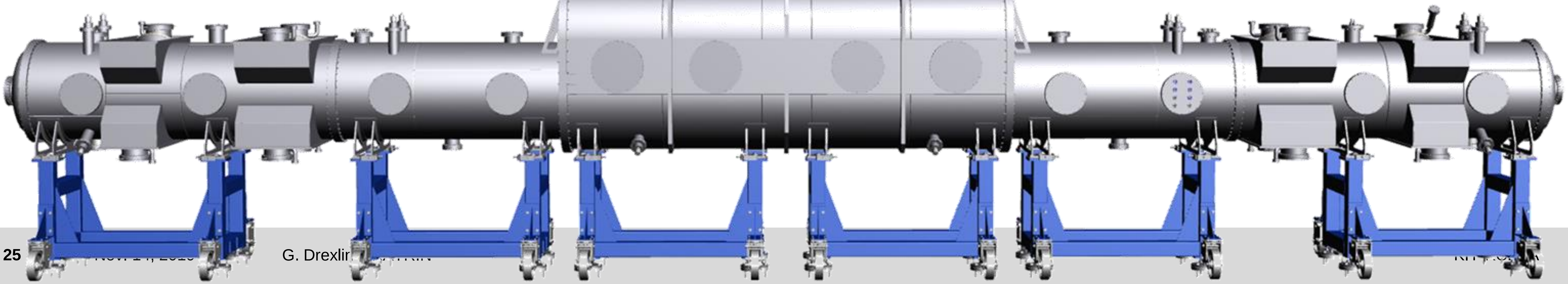


WGTS – source cryostat



WGTS – a complex cryostat

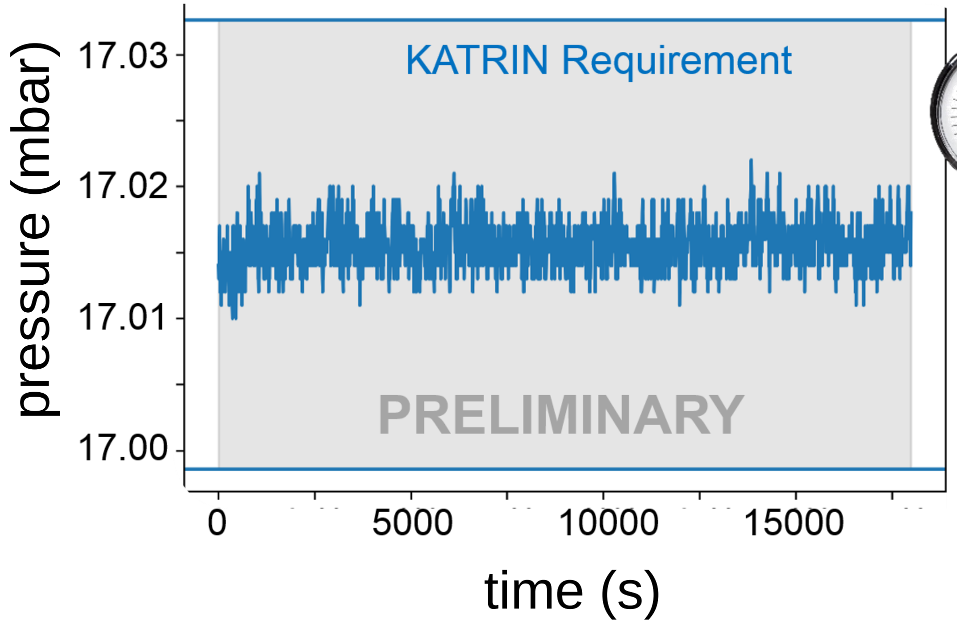
- **a unique cryostat for ultra-stable gaseous tritium source**:
  - 16 m length, 27 t total weight, ~ 40.000 pieces
  - 7 s.c. solenoids for adiabatic guiding of ß-decay electrons (3 – 5 T)
  - 7 cryogenic fluids for tritium operation (BT: 30 – 120 K) & liquid He bath for magnets (4 K)
  - tritium beam tube @30K with stability and homogeneity of 0.1%
  - extensive instrumentations: >800 sensors (B, T, p, level, flow, …)



WGTS – commissioning of a complex cryostat

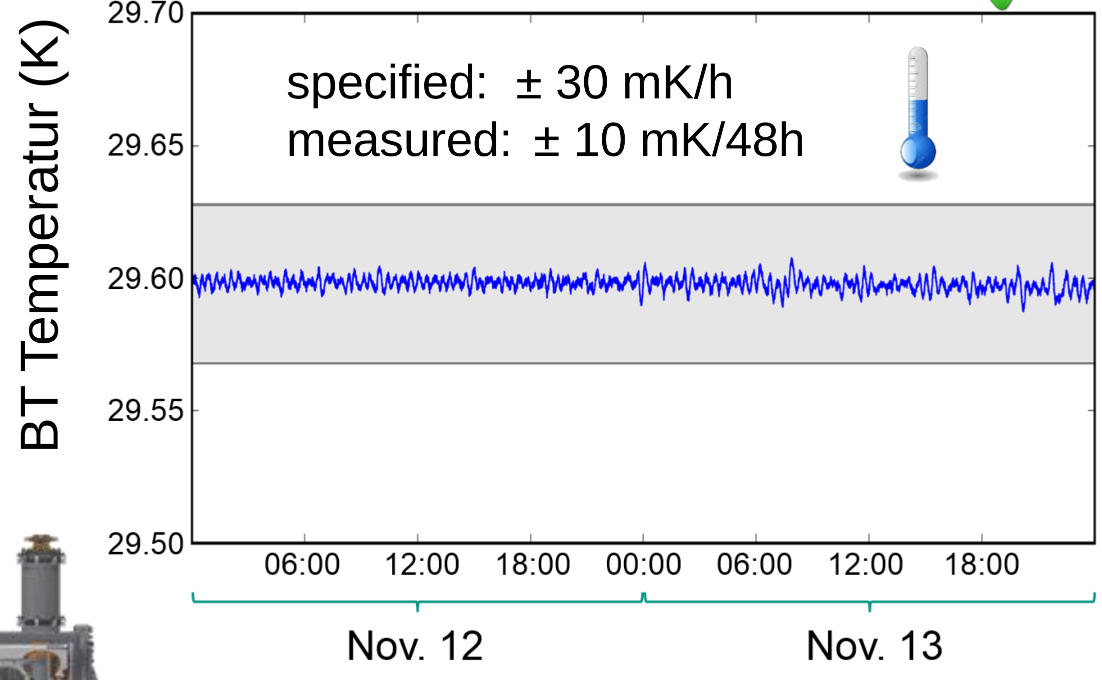
- **excellent source stability with D2 (10^{-4} level)**

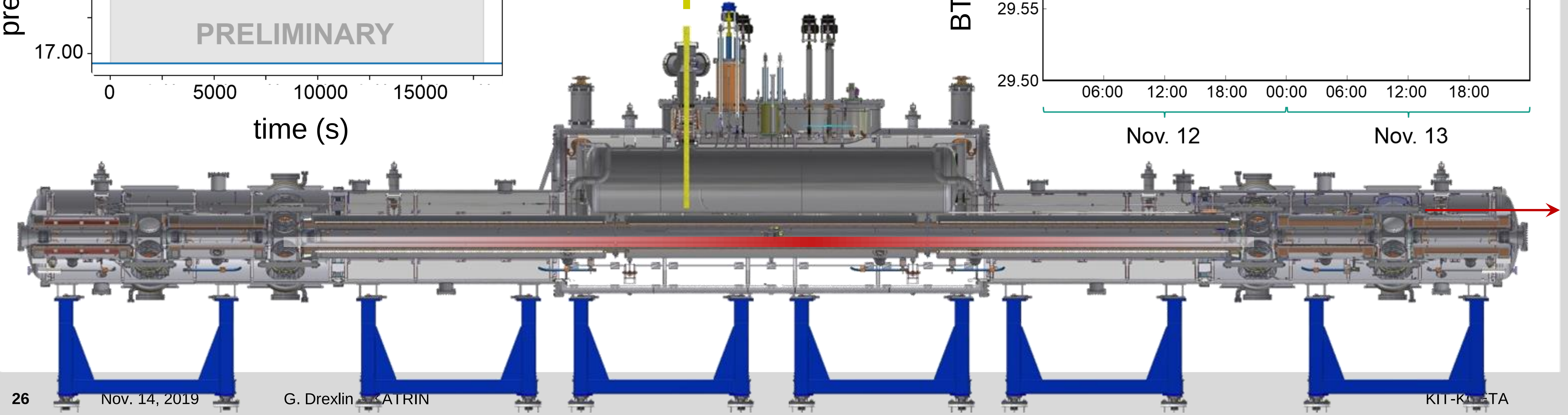
specified: Δp = ±0.1%/h
measured: Δp < ±0.1% over longer times



injection
pressure (± 0.1%)

beam tube temperature (± 0.1%)
(27-120 K)

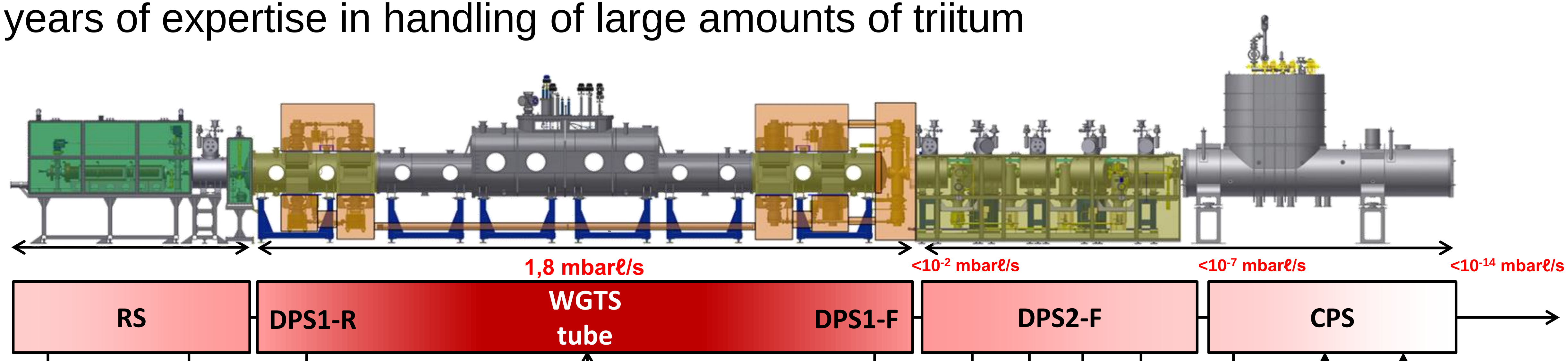




TLK – a unique research infrastructure at KIT

Karlsruhe Institute of Technology

- 20+ years of expertise in handling of large amounts of triitum

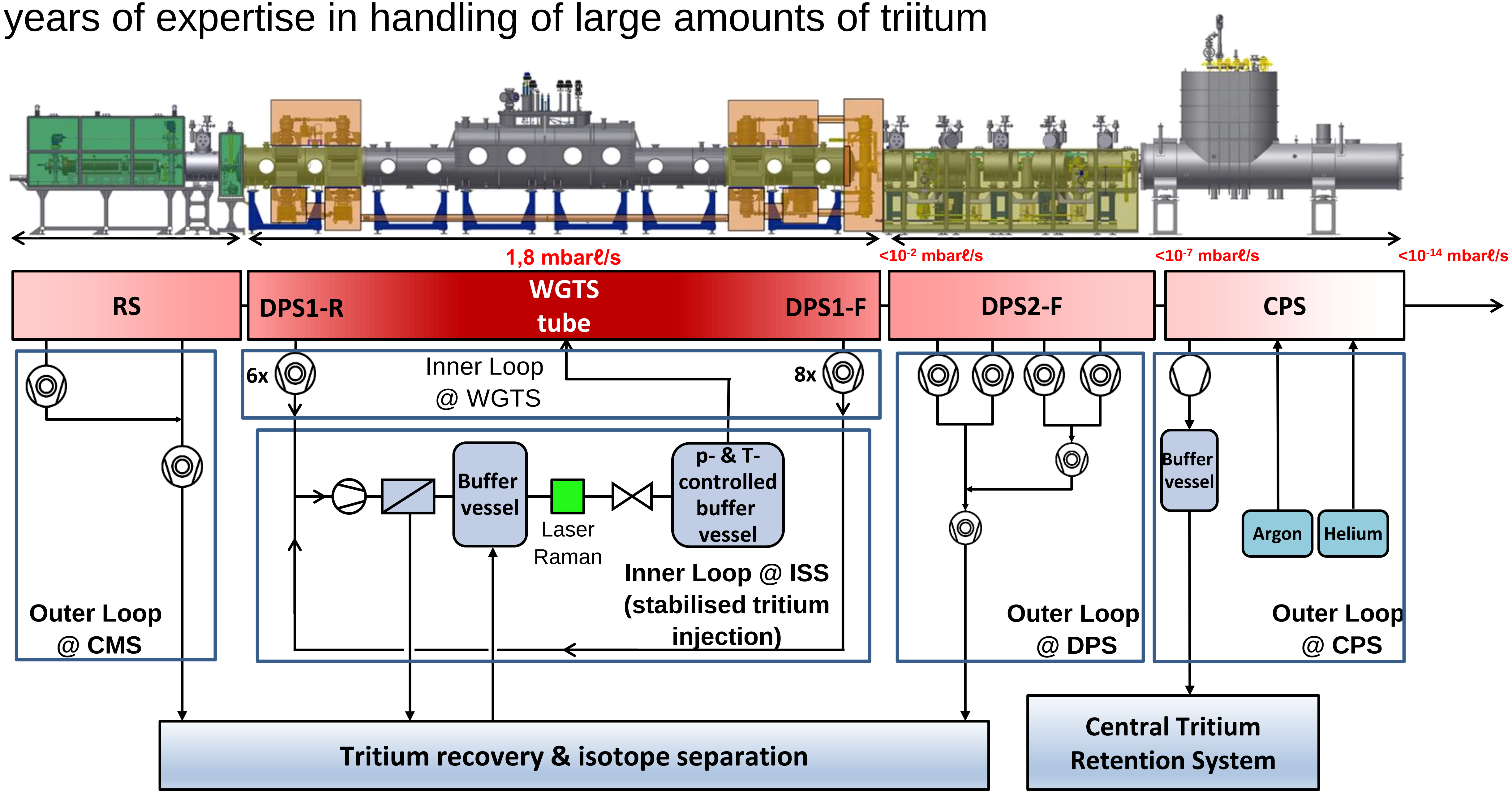


worldwide unique reseach infrastructure: 30 FTE

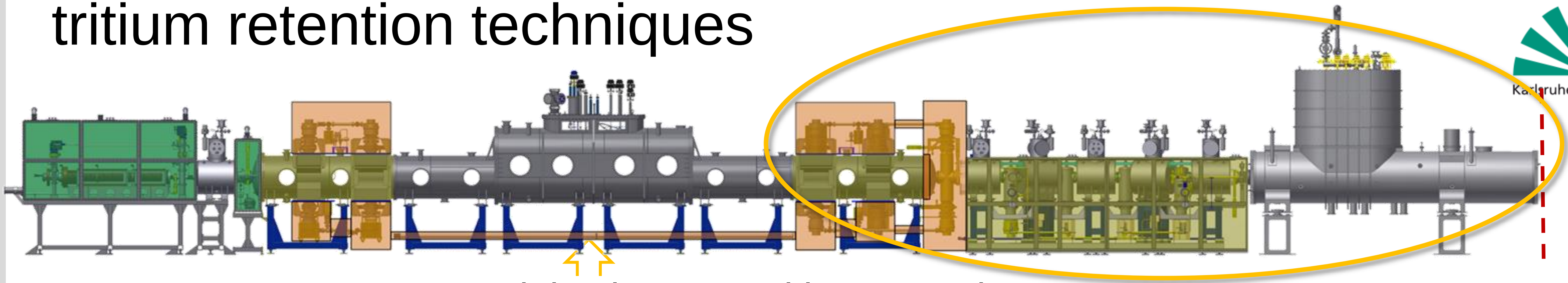
Tritium Laboratory Karlsruhe

TLK – a unique research infrastructure at KIT

- 20+ years of expertise in handling of large amounts of triitum

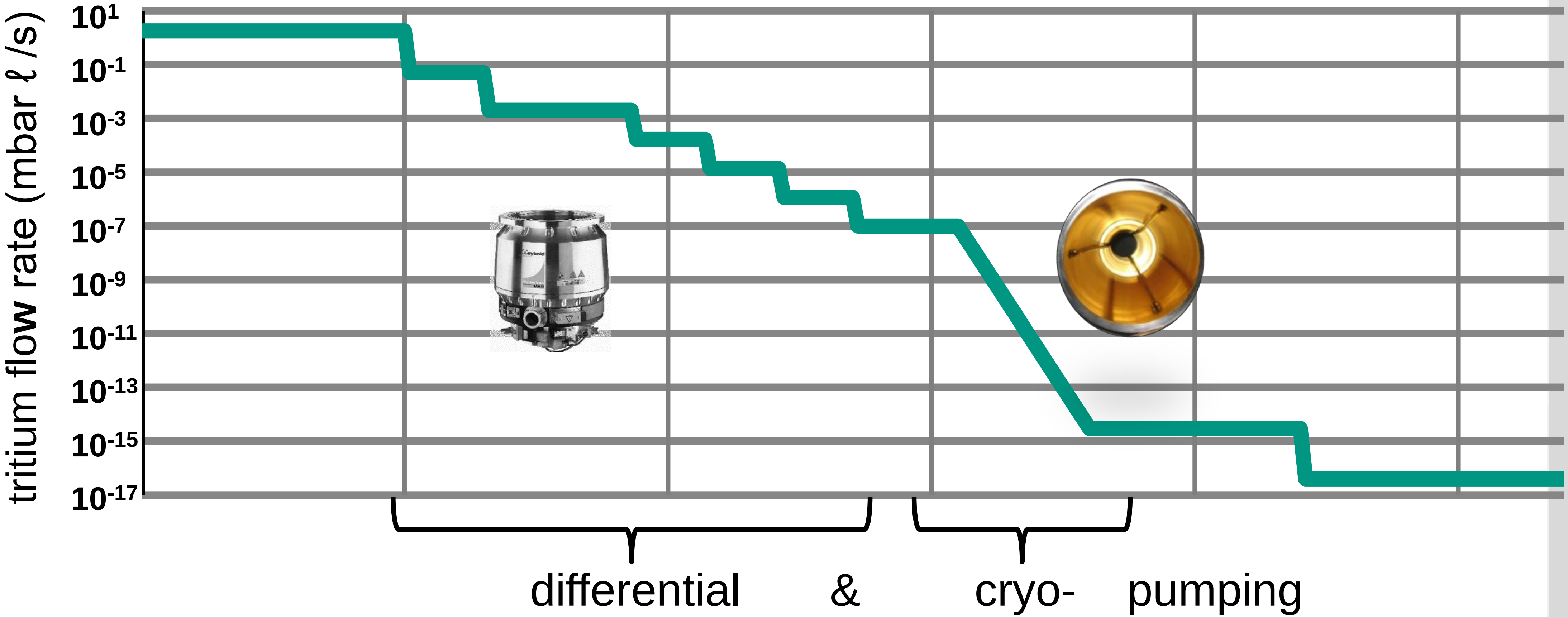


tritium retention techniques



- overall retention **factor > 10^{14}**

for overall **factor > 10^{14}**

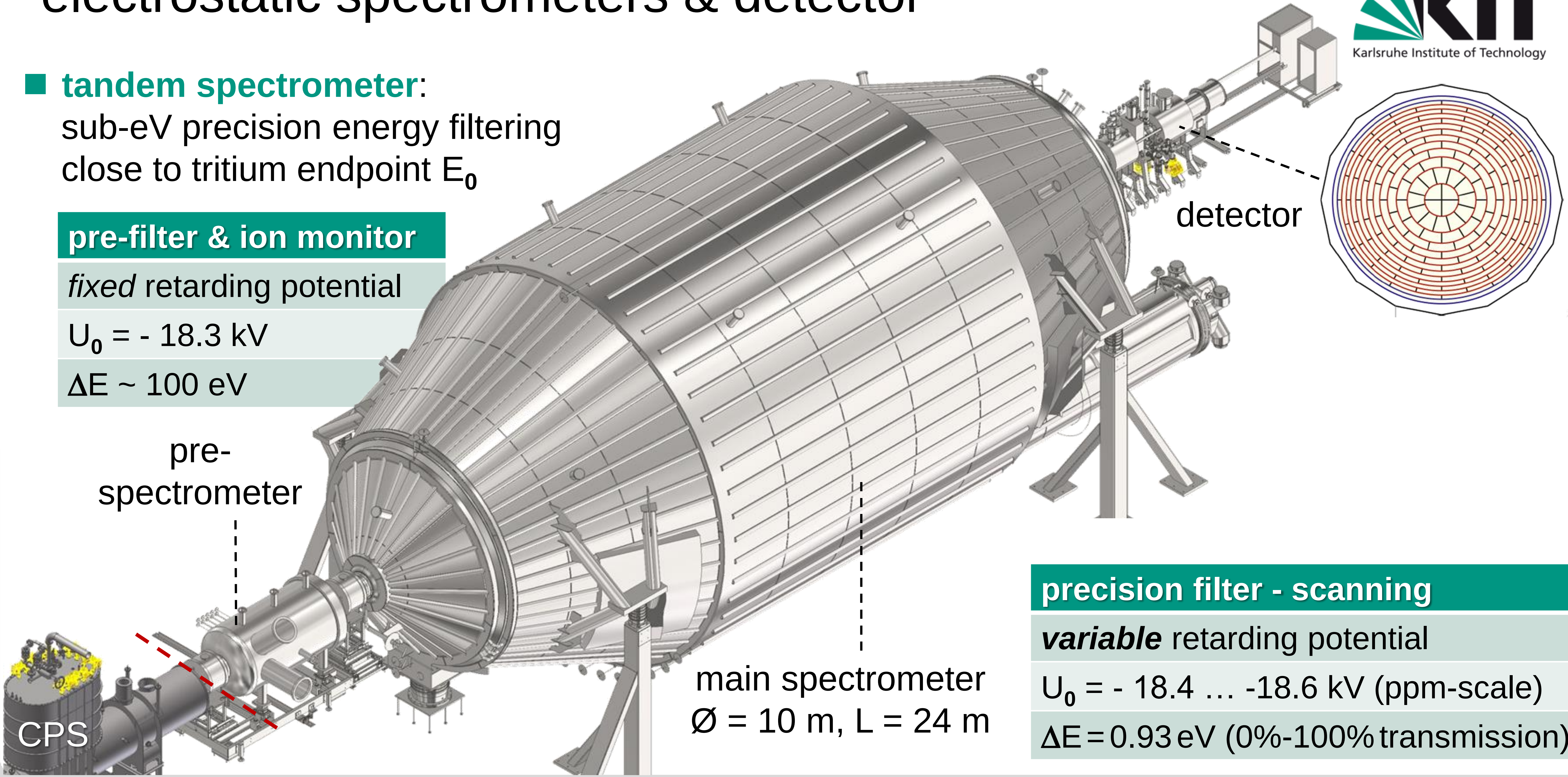


theoretical expecation
from TDR surpassed!

electrostatic spectrometers & detector

- **tandem spectrometer**:
  sub-eV precision energy filtering close to tritium endpoint E_0

pre-filter & ion monitor
fixed retarding potential
U_0 = - 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 (0%-100% transmission)

electrostatic spectrometer – a look back to 2006

- **a spectrometer** travels around Europe (8000 km) from DWE to KIT

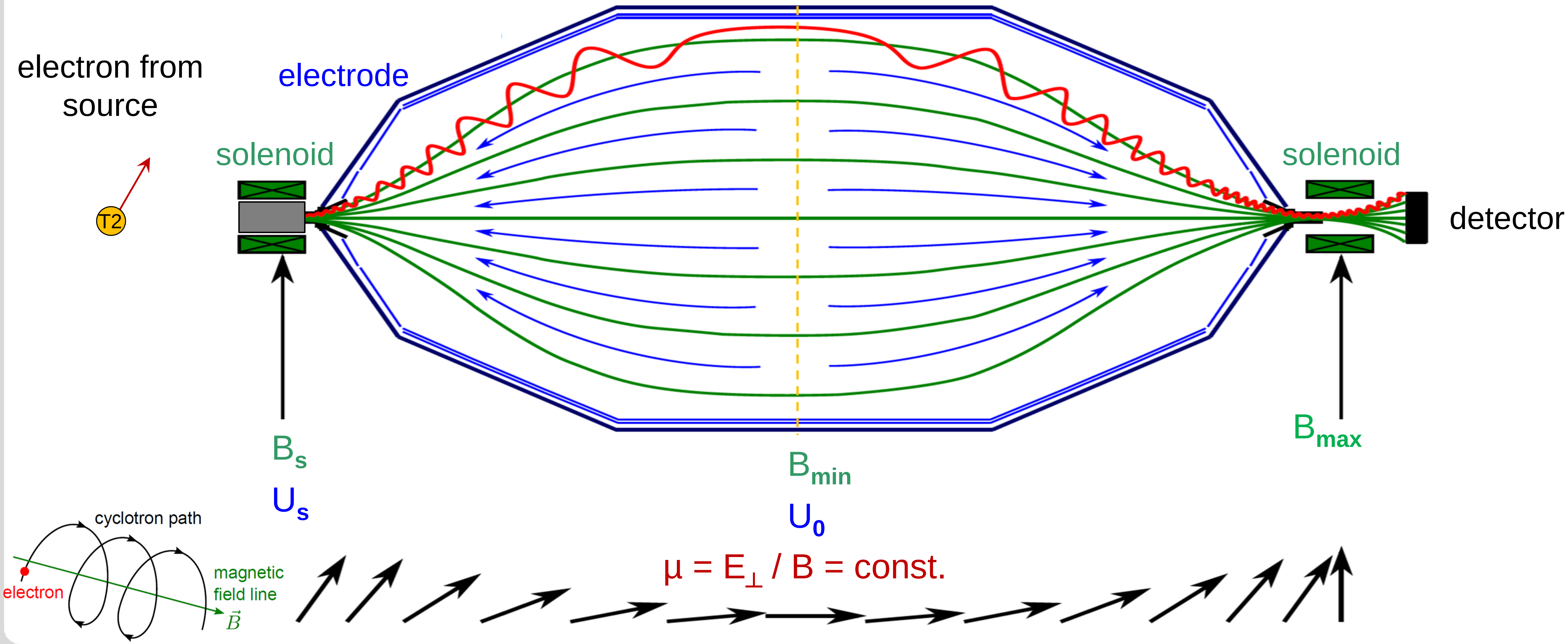
BBC NEWS

In pictures: photos of the year 2006

from wikipedia

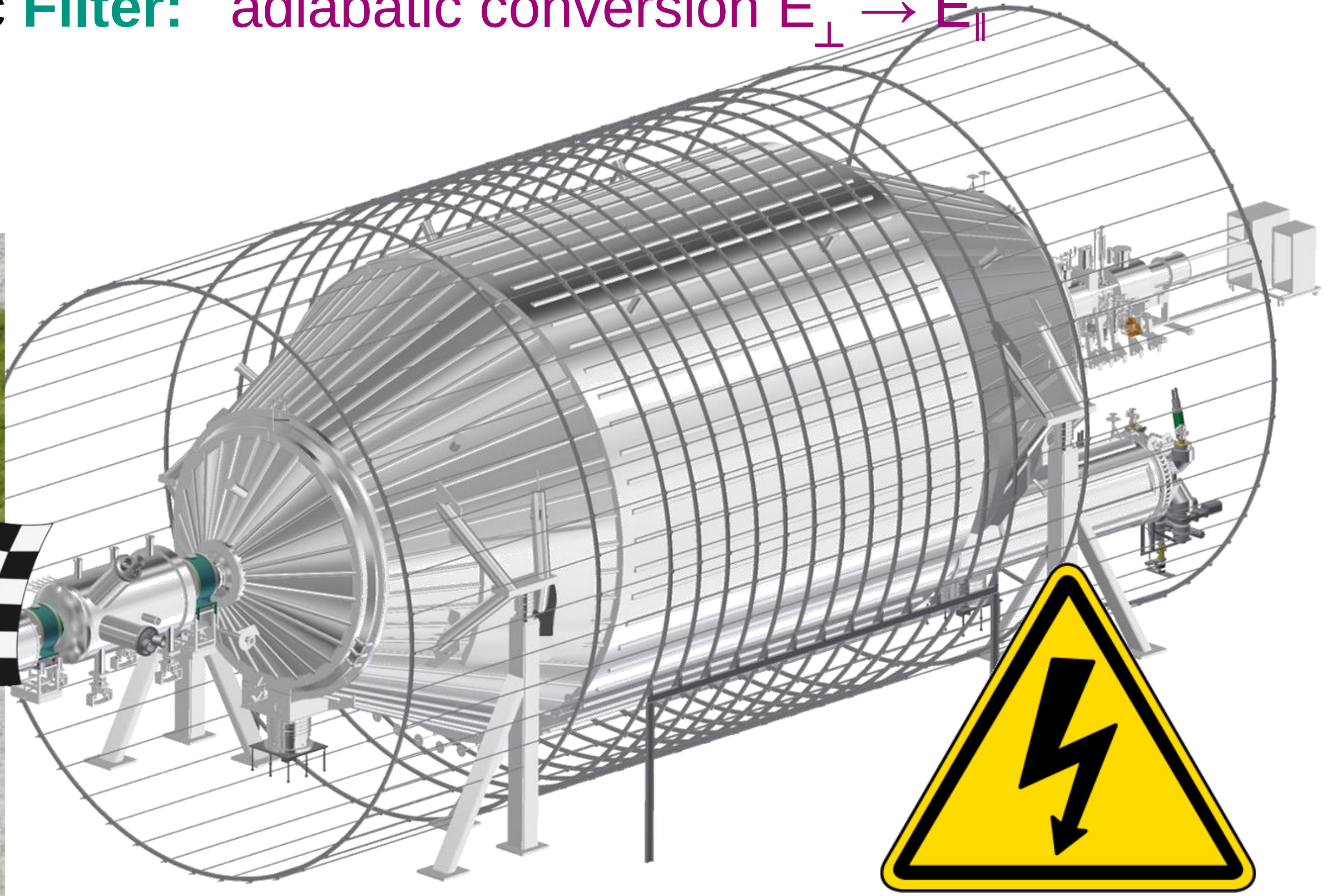
MAC-E principle: high-resolution tritium ß-spectroscopy

- **Magnetic Adiabatic Collimation & Electrostatic Filter:** adiabatic conversion $E_\perp \rightarrow E_\parallel$

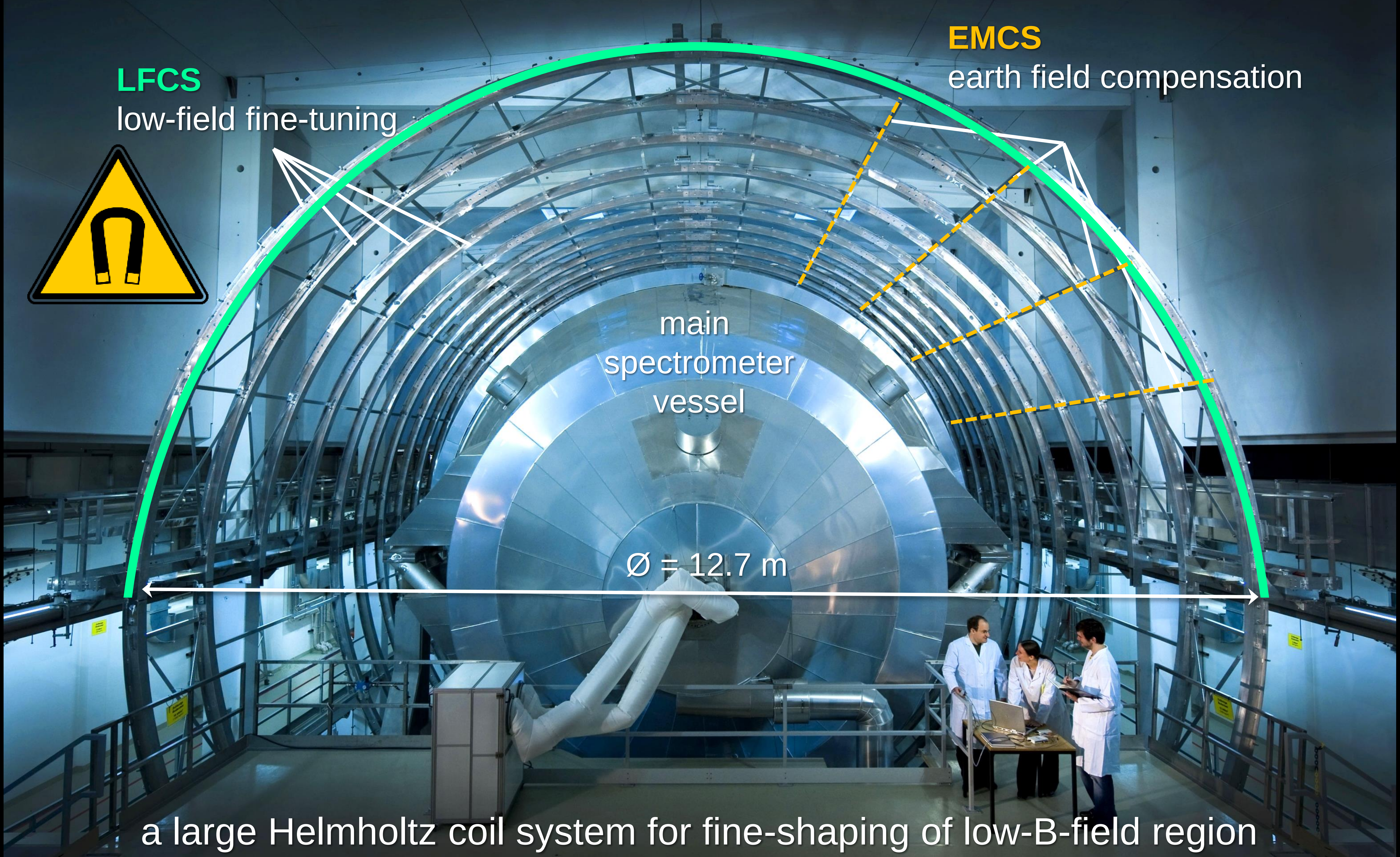


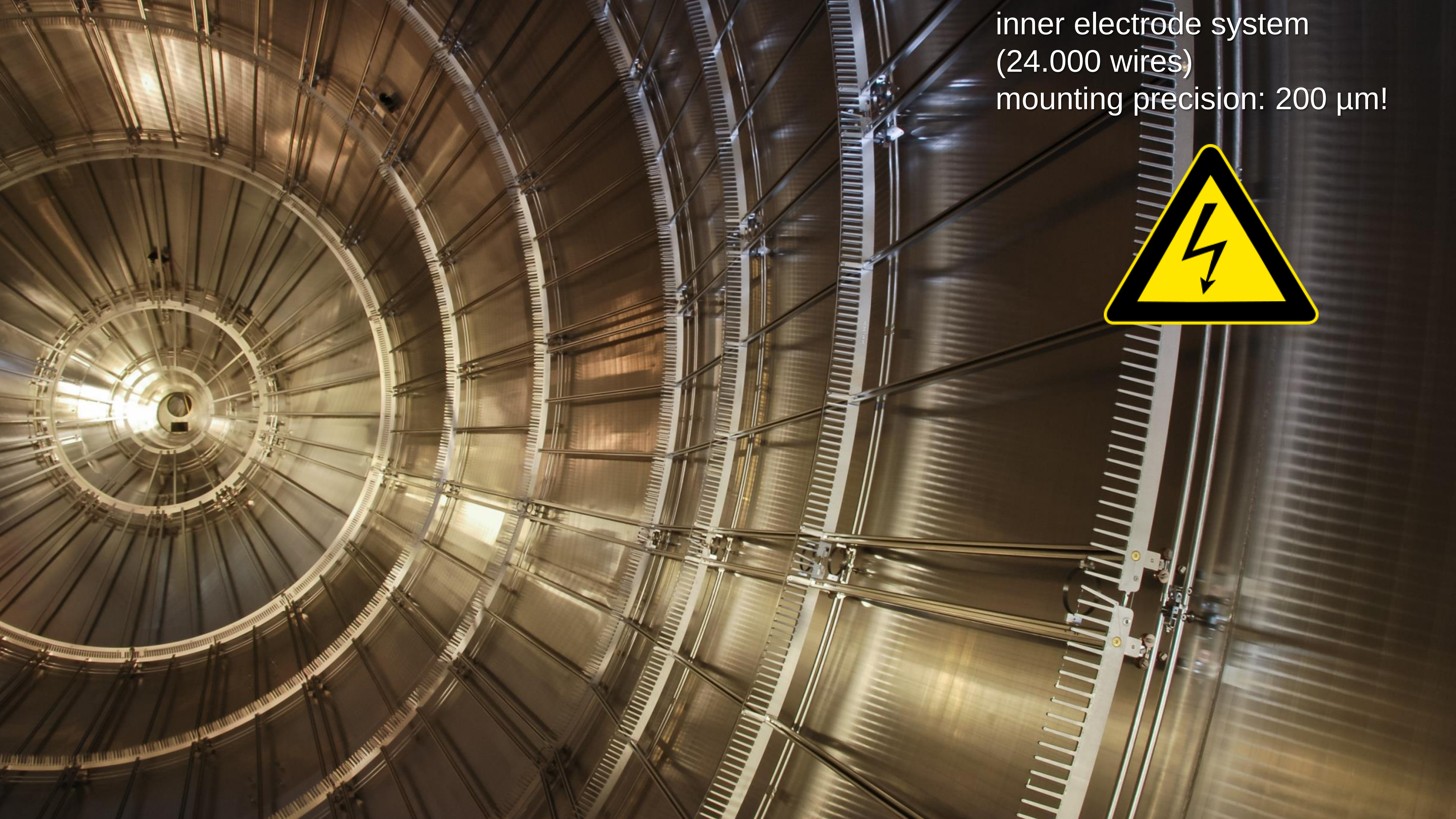
MAC-E principle: high-resolution tritium ß-spectroscopy

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



only **one signal electron per second** detected (out of 10^{11} electrons produced in source)

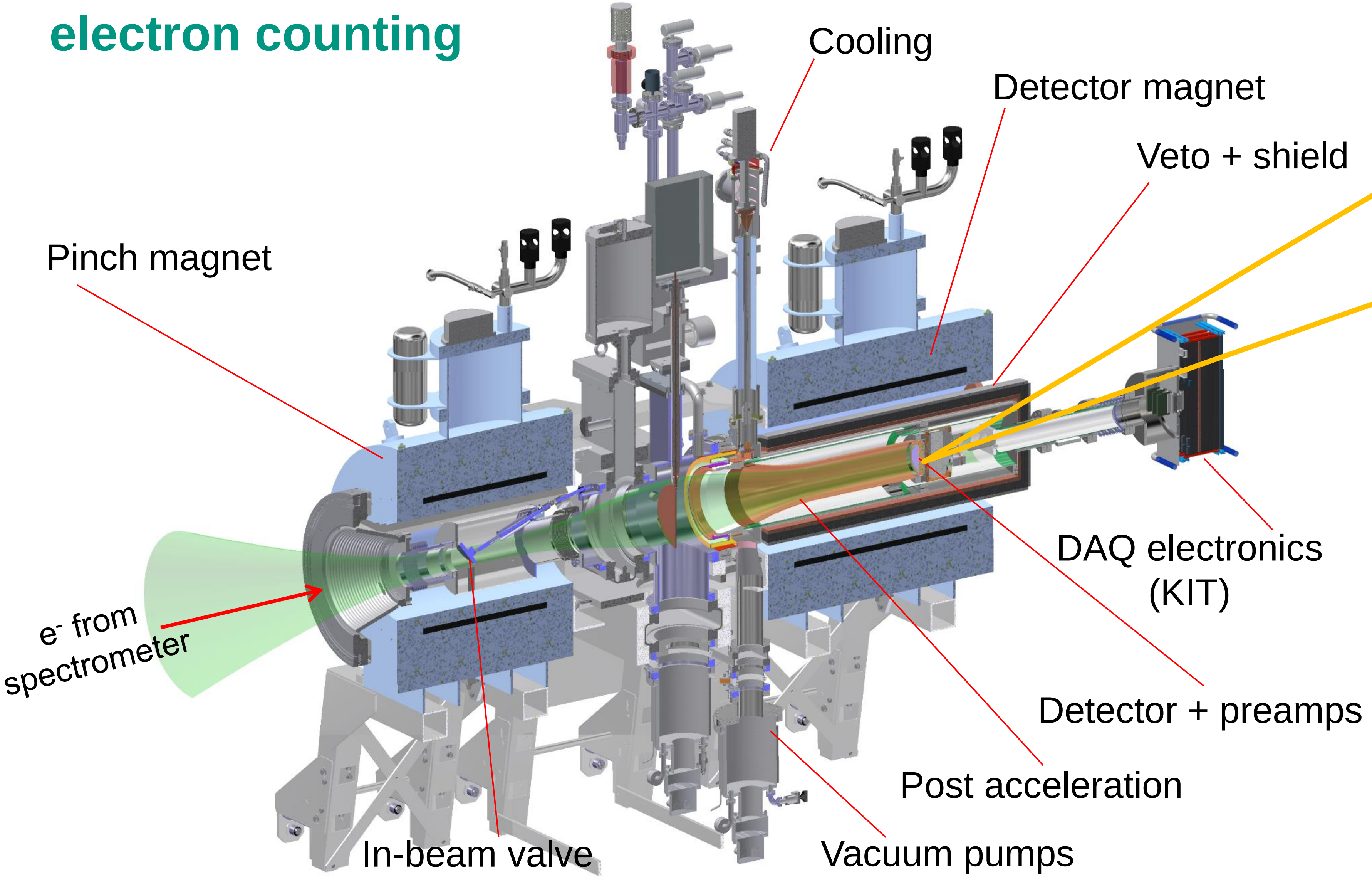

LFCS
low-field fine-tuning
EMCS
earth field compensation
main
spectrometer
vessel
Ø = 12.7 m
a large Helmholtz coil system for fine-shaping of low-B-field region

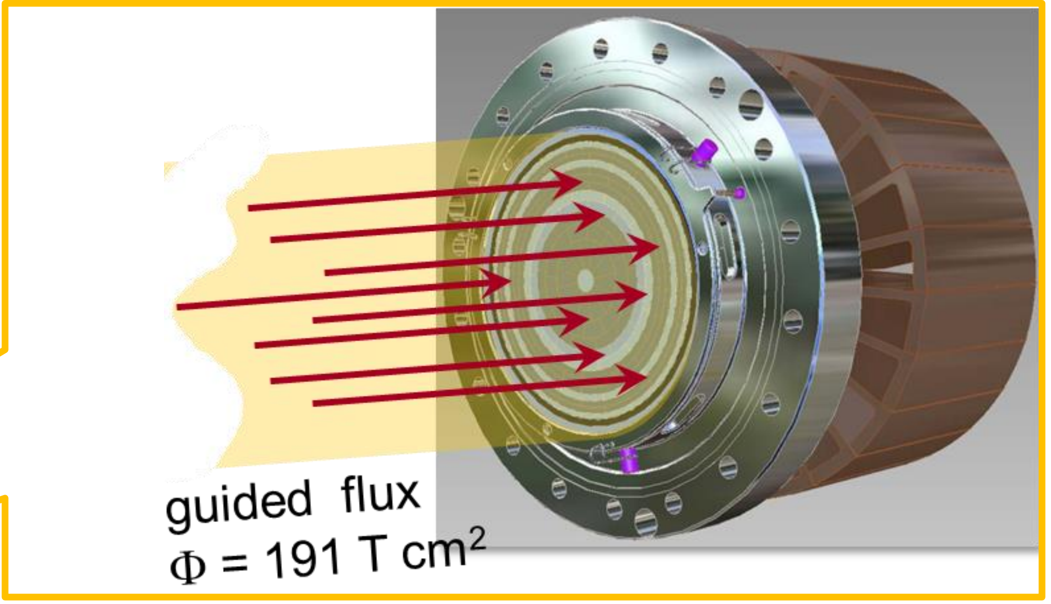

inner electrode system
(24.000 wires)
mounting precision: 200 µm!

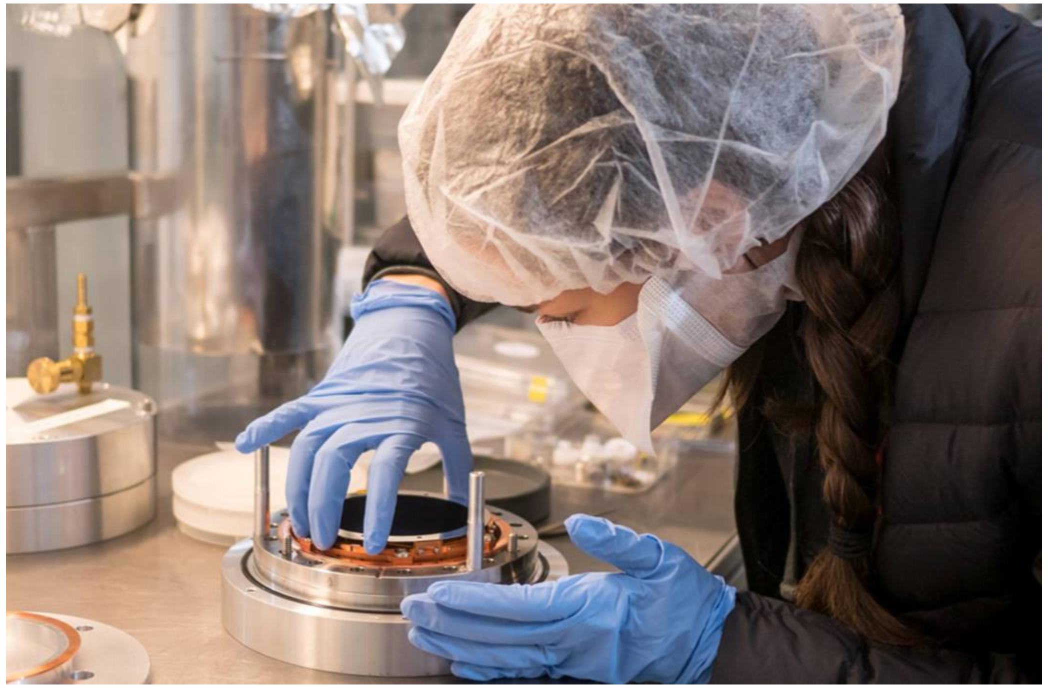
Focal plane detector to count transmitted electrons

Karlsruhe Institute of Technology

- **A monolithic 148 Si-pixel detector array (FPD) for electron counting**





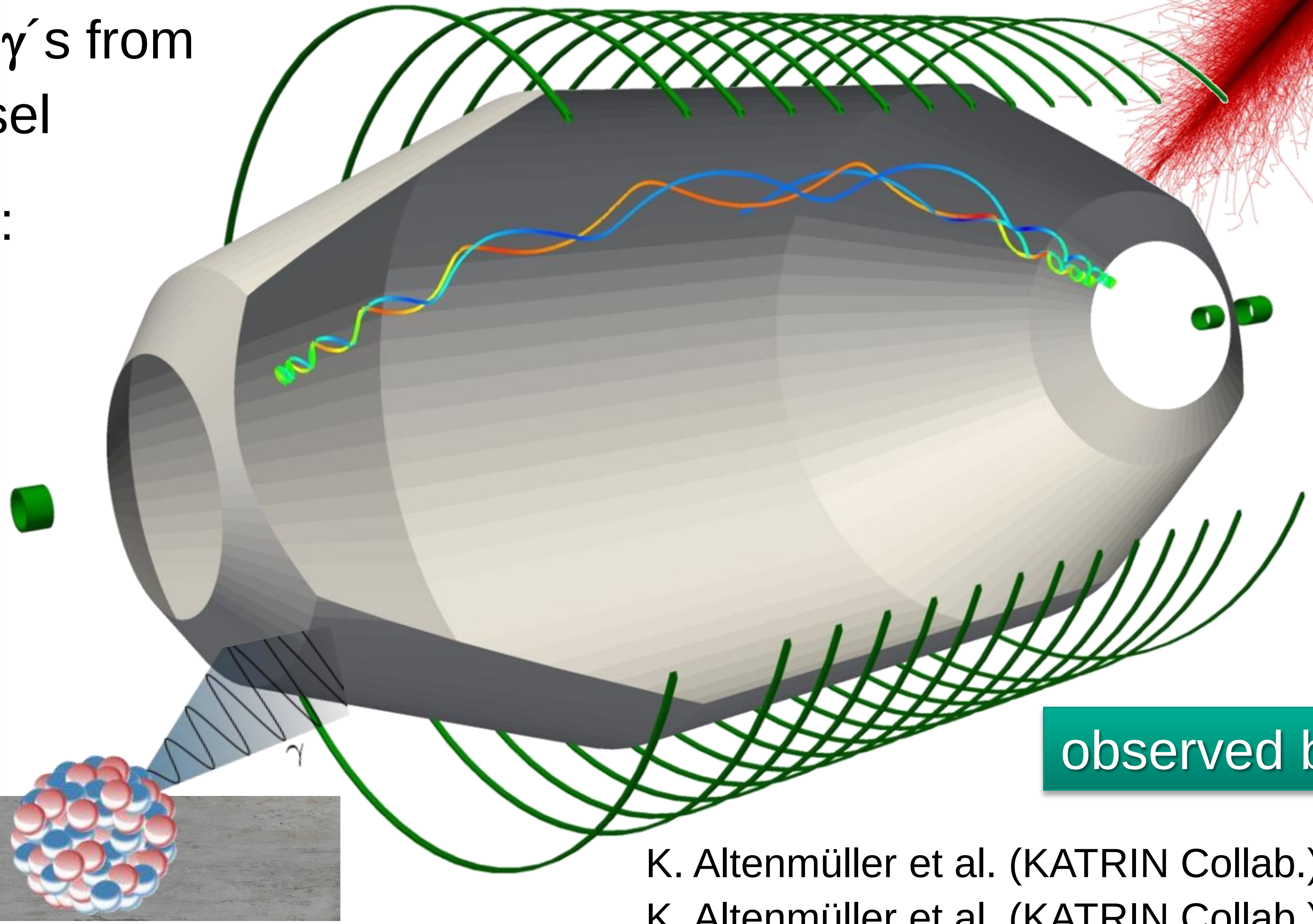


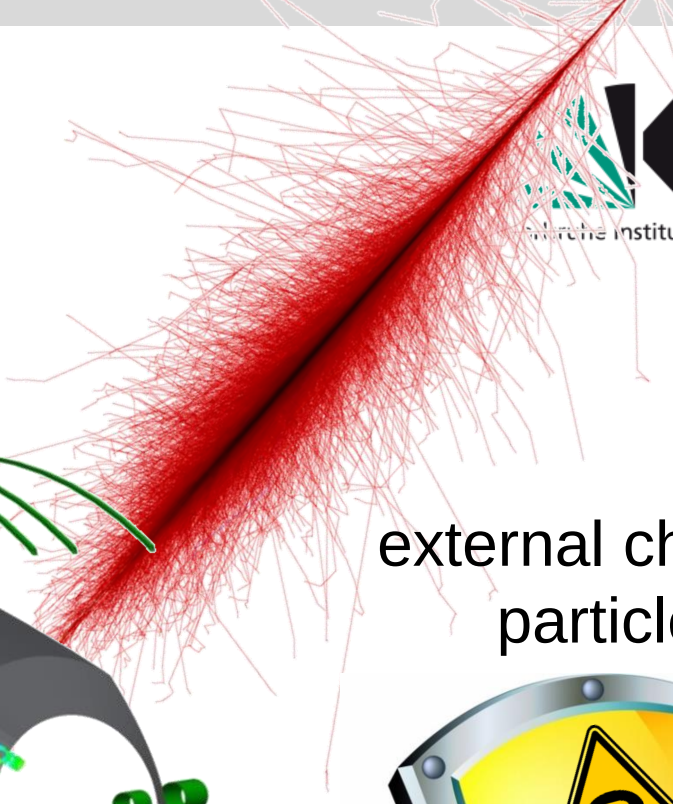
MAC-E background – external particles

- **background sources**: **<u>no</u>** contributions observed from
  - μ-induced secondaries (~10^5/s)
  - environmental γ´s from building & vessel

magnetic shielding: factor **>10^5**

electric shielding: factor >10^1





external charged particles

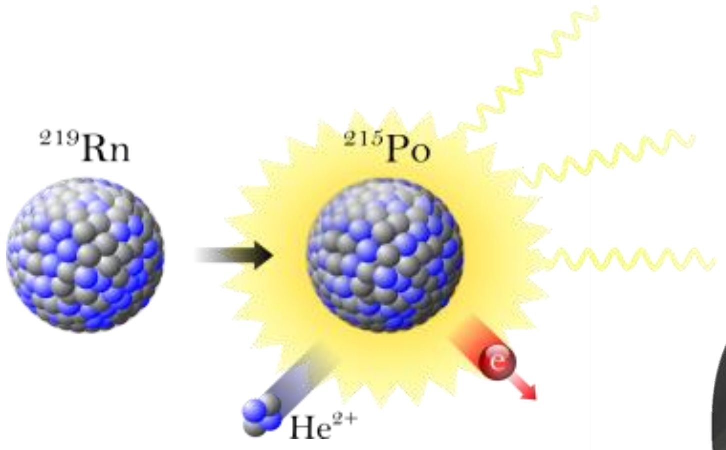
observed background rate: 0 cps

K. Altenmüller et al. (KATRIN Collab.), Eur. Phys. J. C79 (2019) 807

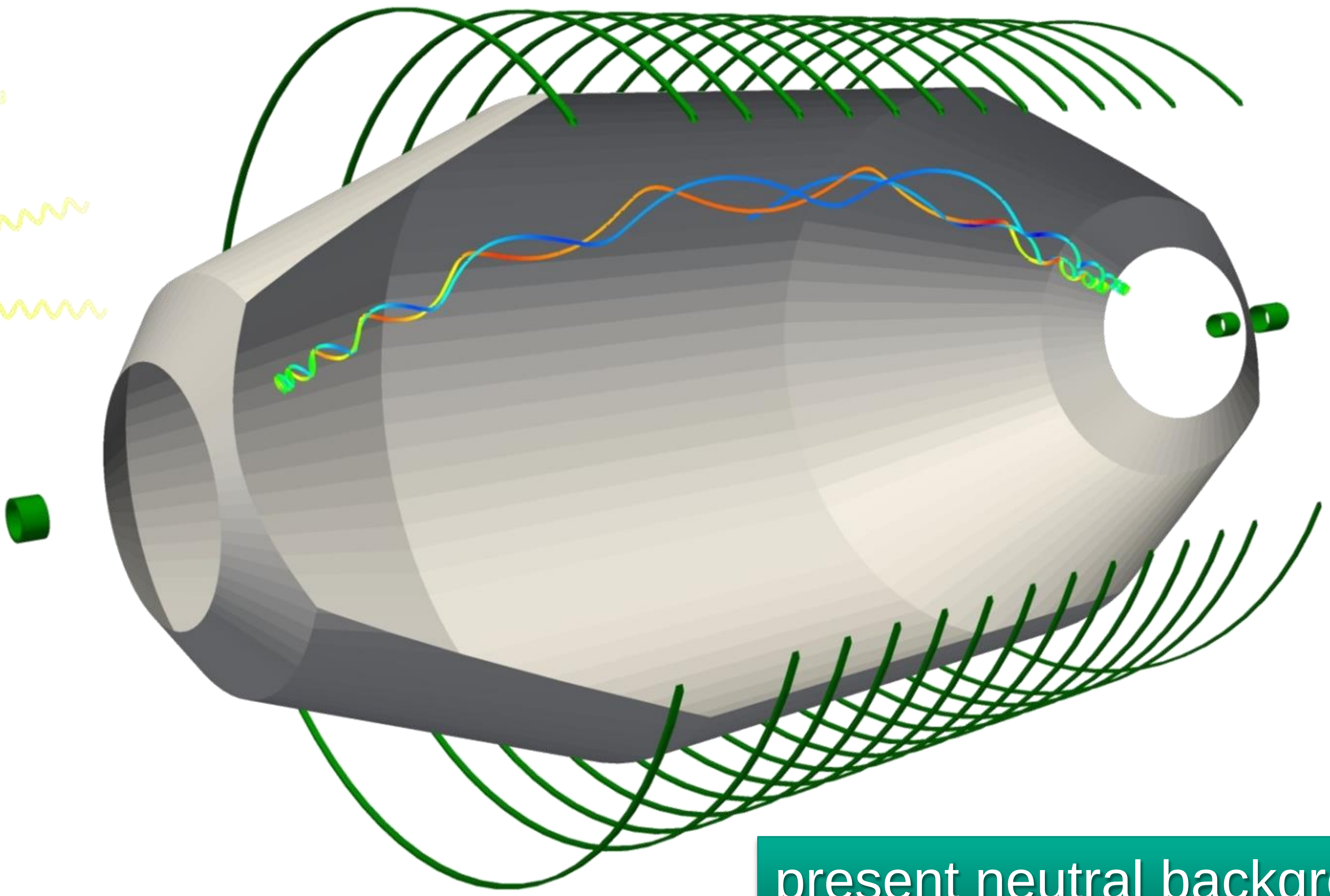
K. Altenmüller et al. (KATRIN Collab.), Astropart. Phys. 108 (2019) 40

MAC-E background – internal neutral atoms

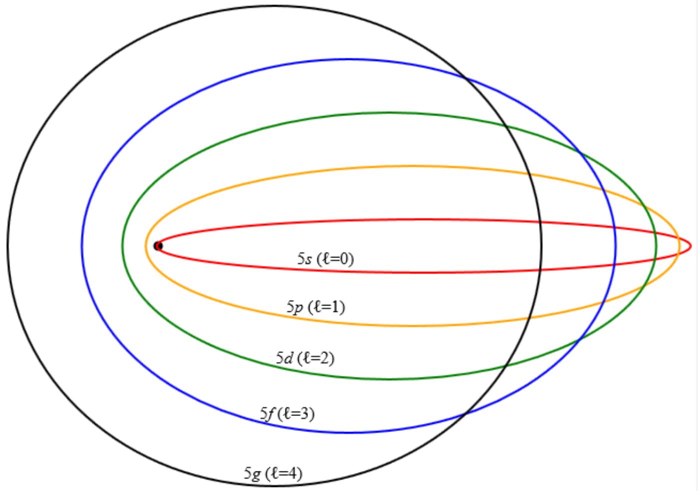
- **background sources**: neutral, excited atoms with long lifetime can de-excite in flux tube



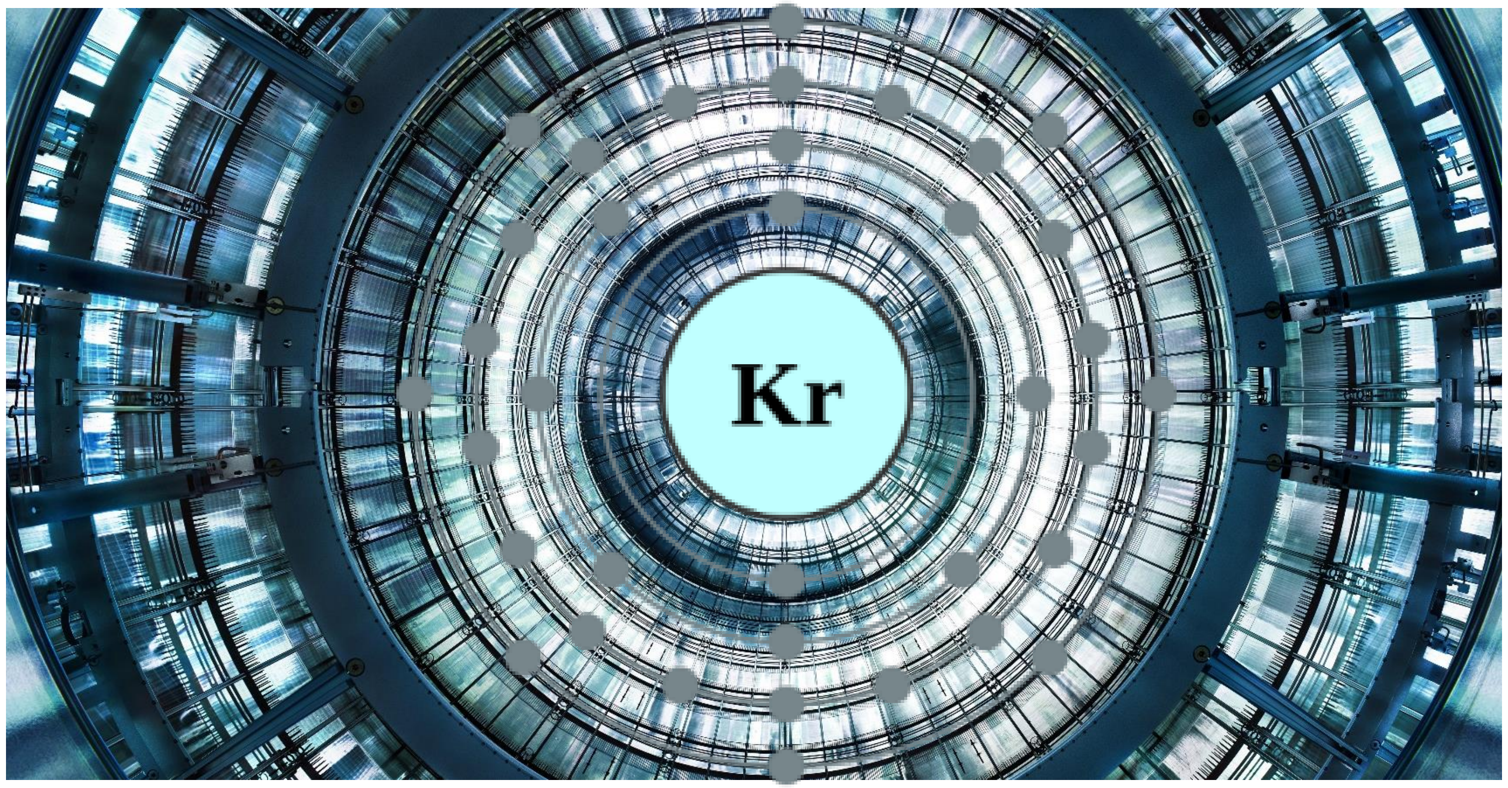
- radioactive atoms Rn-219 from NEG

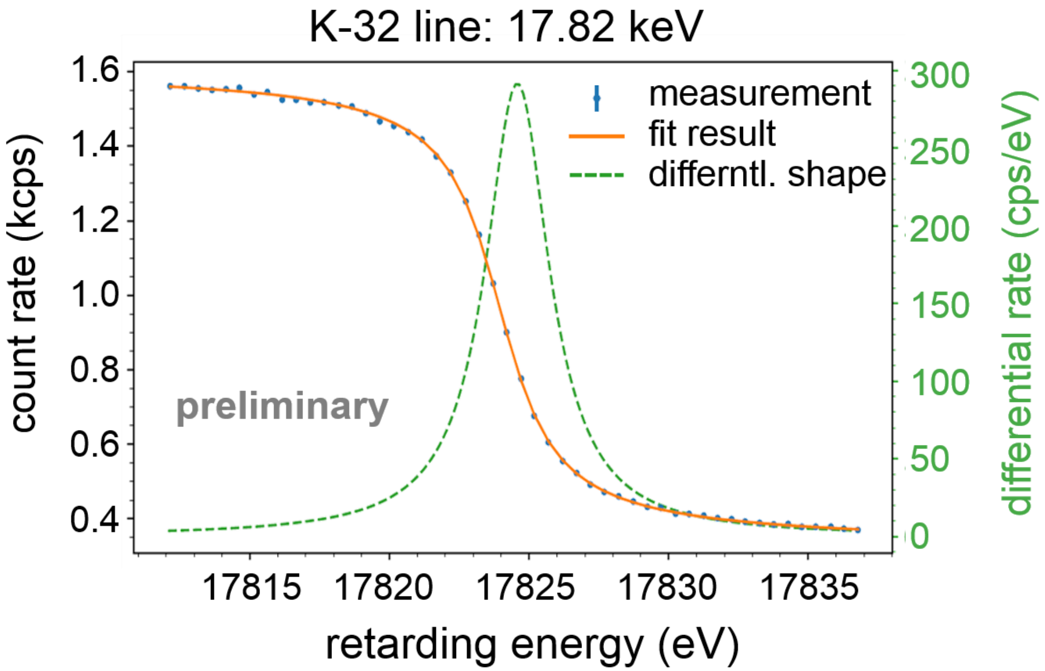


- Rydberg states from Pb-206 ions



present neutral background rate ~ 0.2 cps



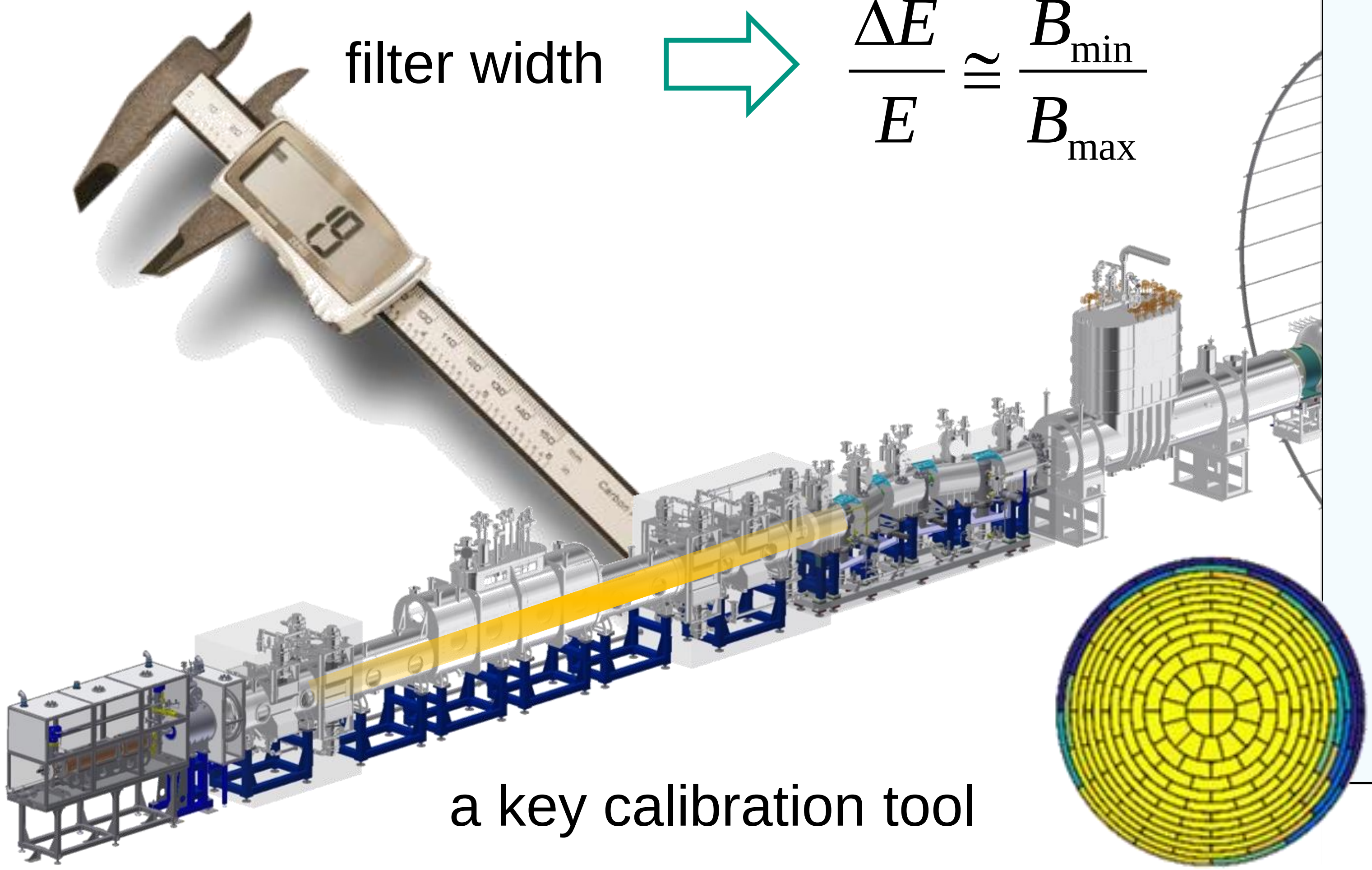


CALIBRATION WITH KR-83m

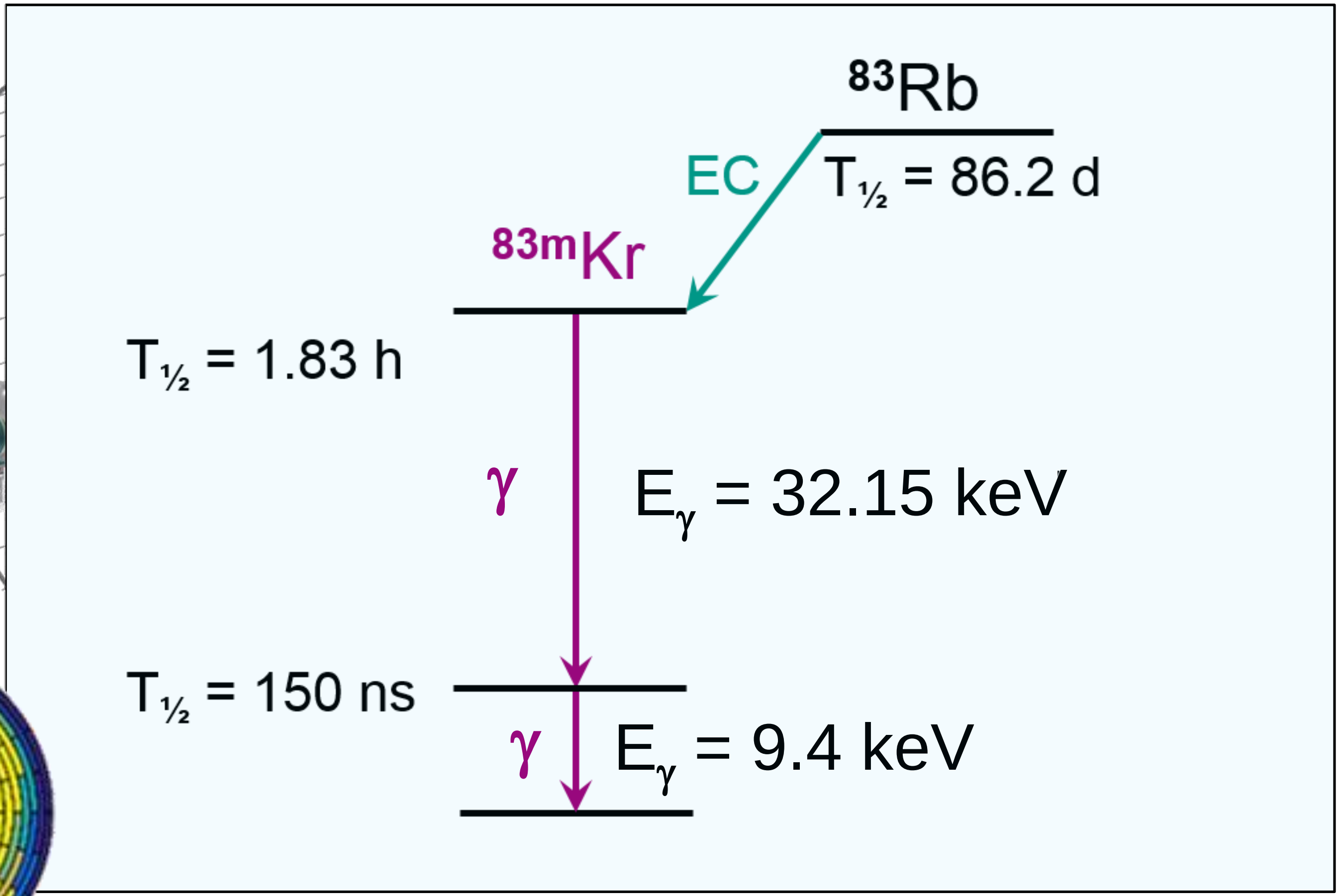
adding ^{83m}Kr to tritium – a key spectroscopic test

- world-leading expertise of NPI Rez/Prague in electron & gamma spectroscopy of ^{83m}Kr
  - exact energies and line widths of **conversion electron lines** (K-32, L-32, M-32,…)

filter width ⇒ $$\frac{\Delta E}{E} \cong \frac{B_{min}}{B_{max}}$$



a key calibration tool



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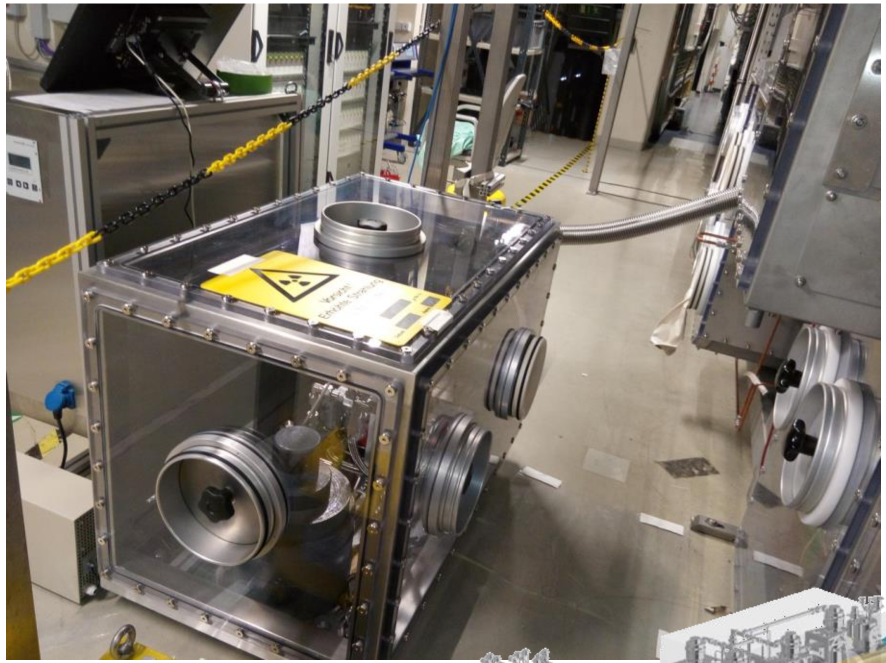
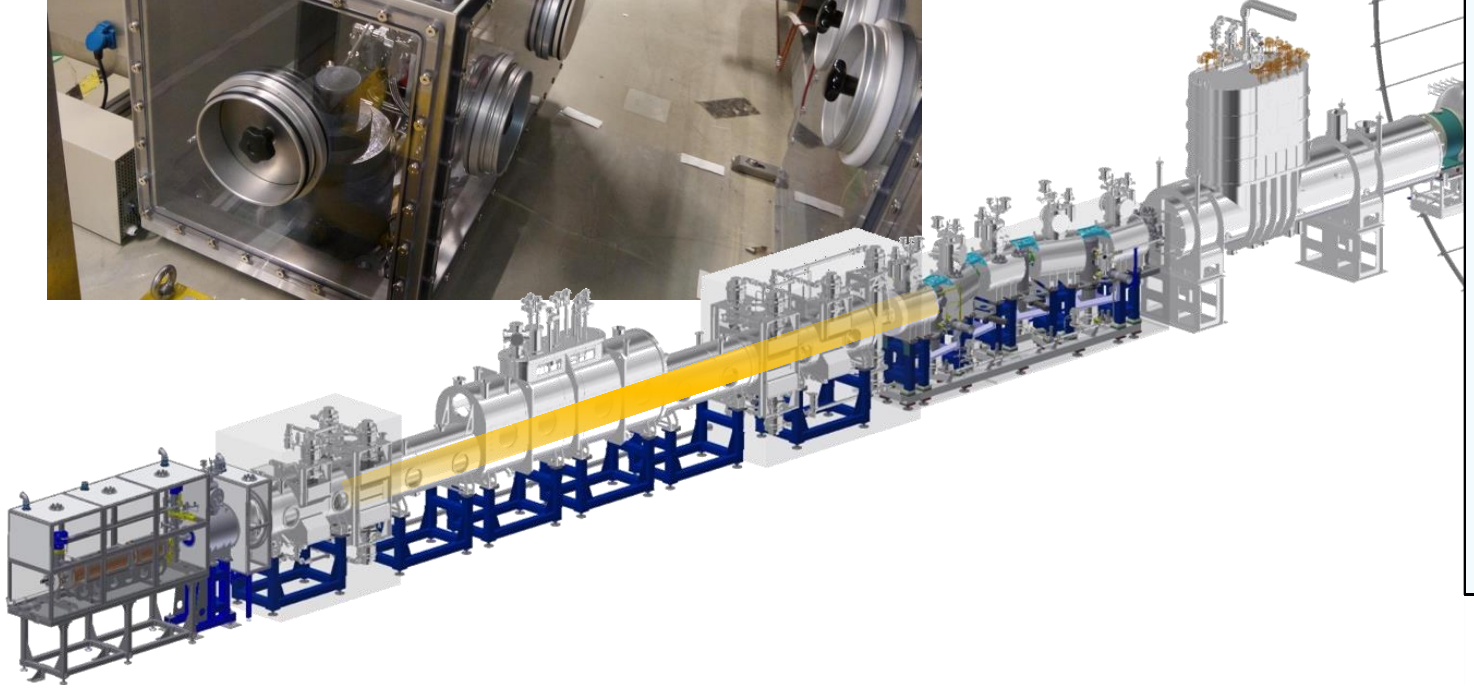
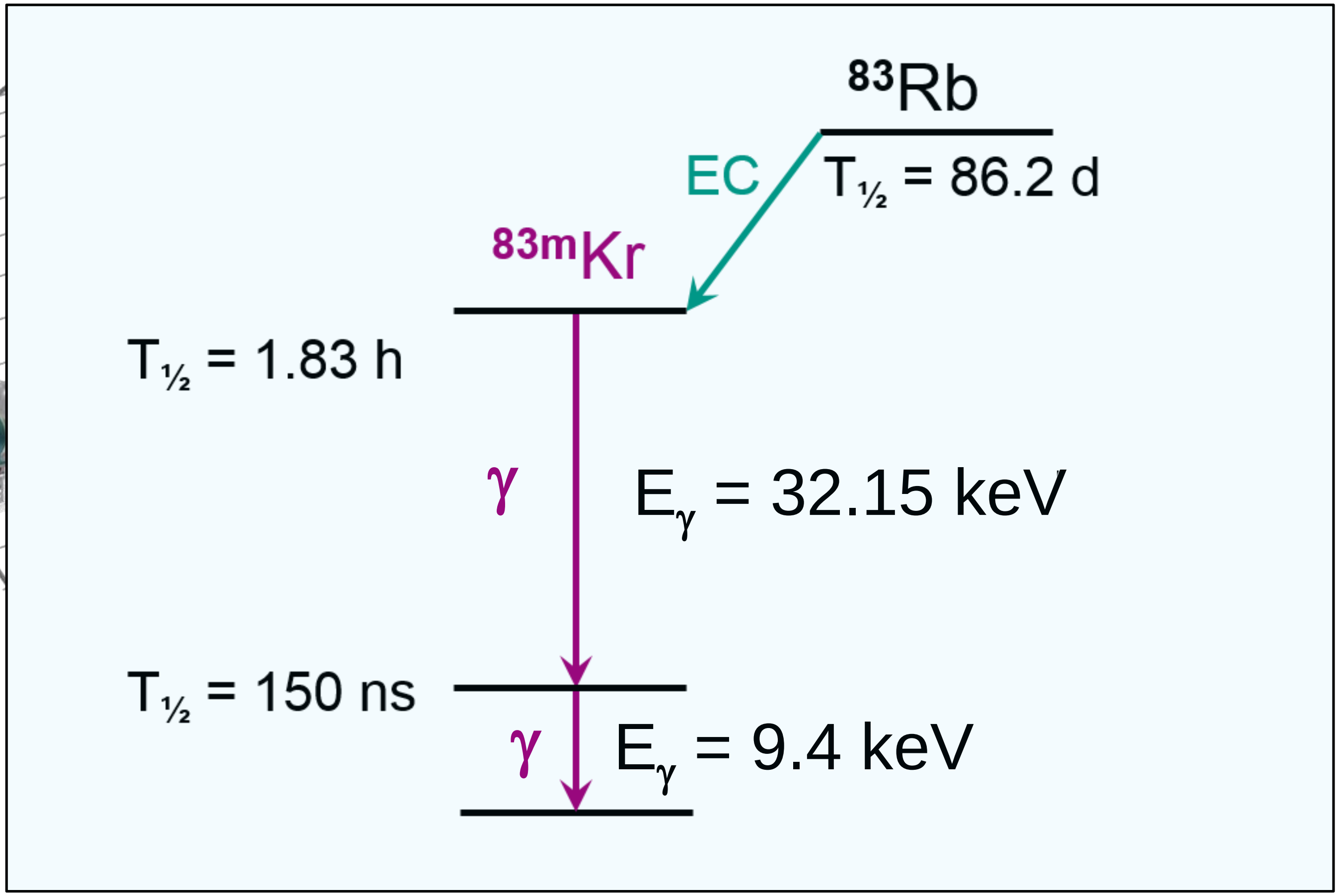


Kr-generator

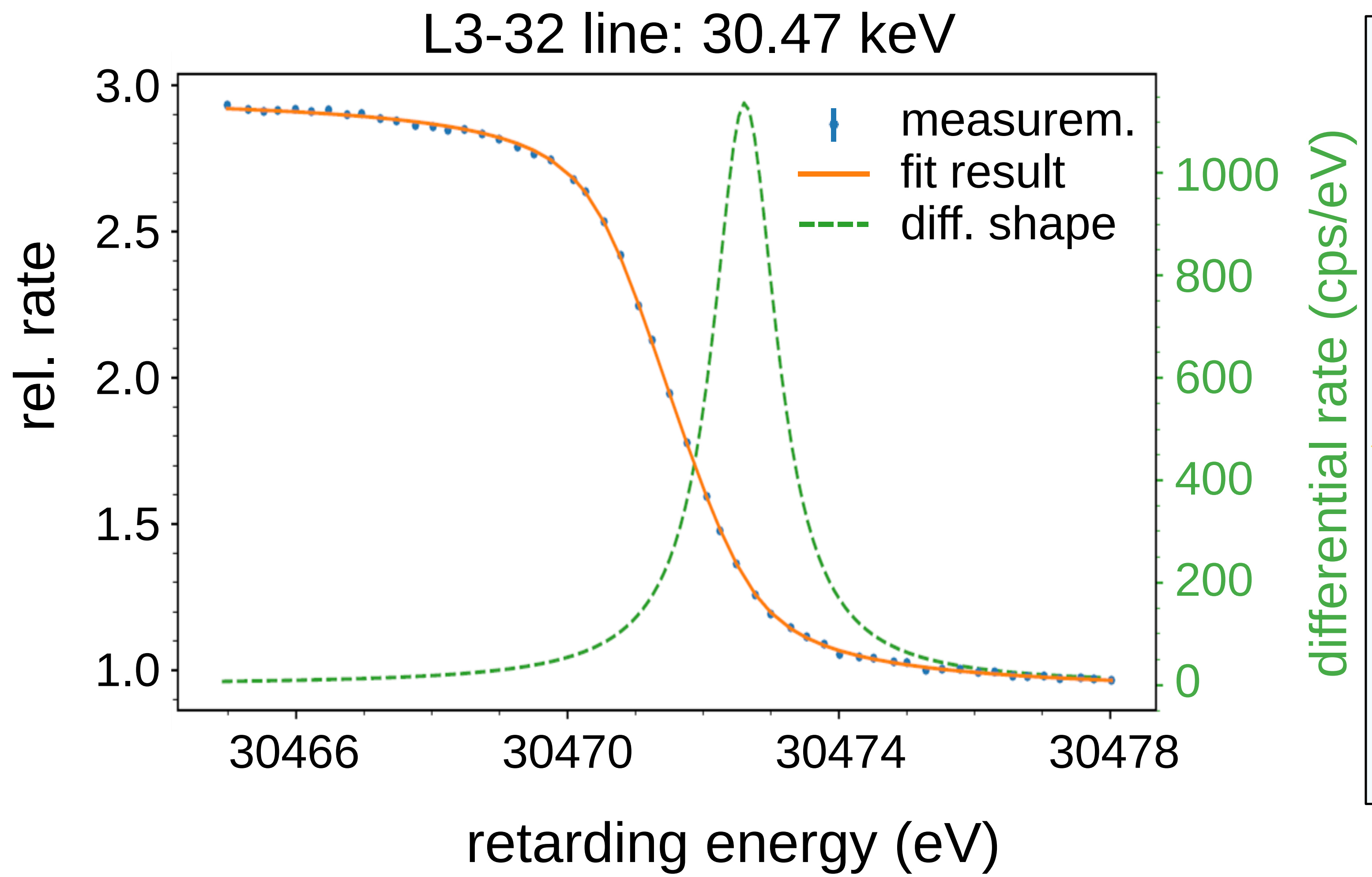


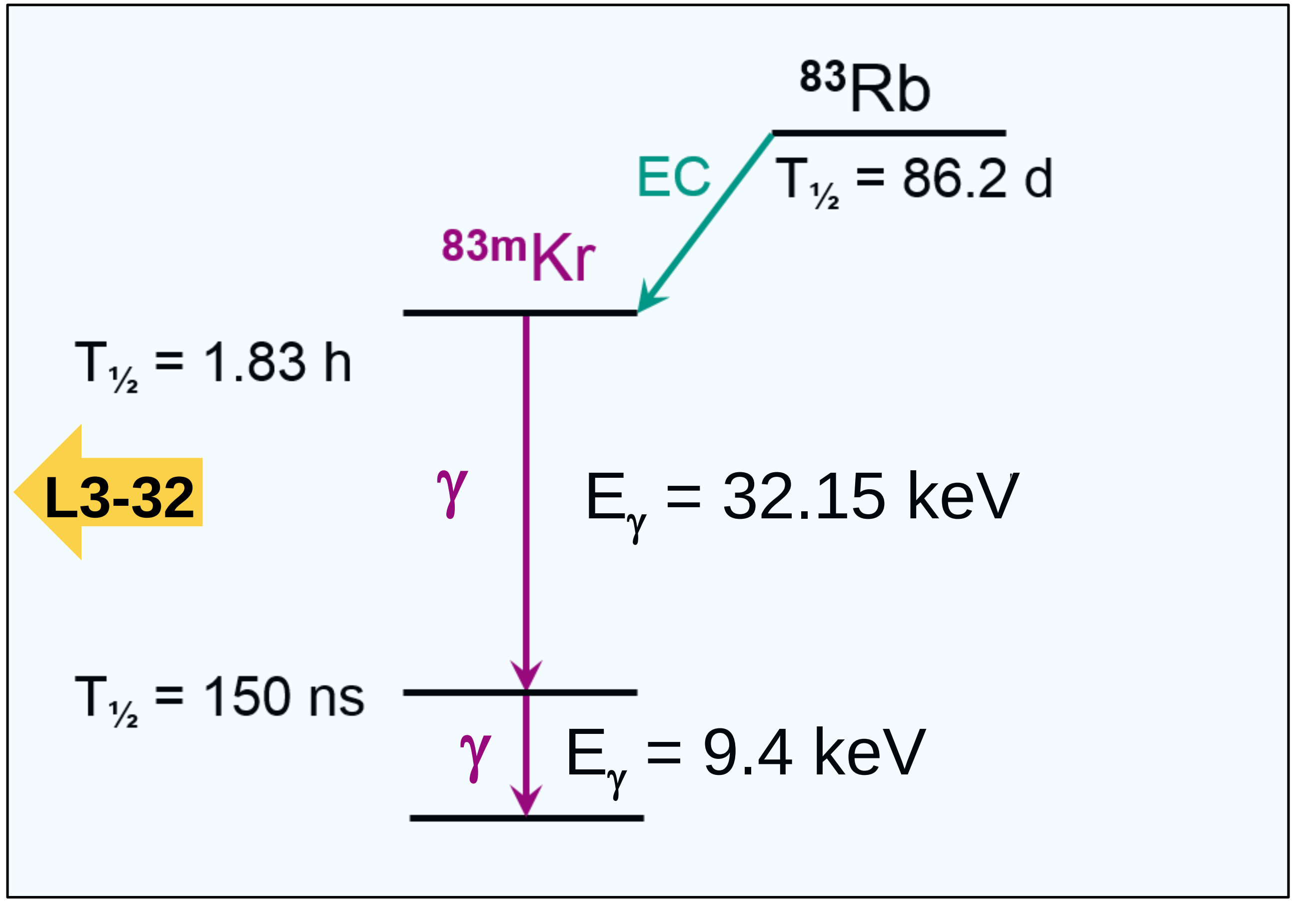


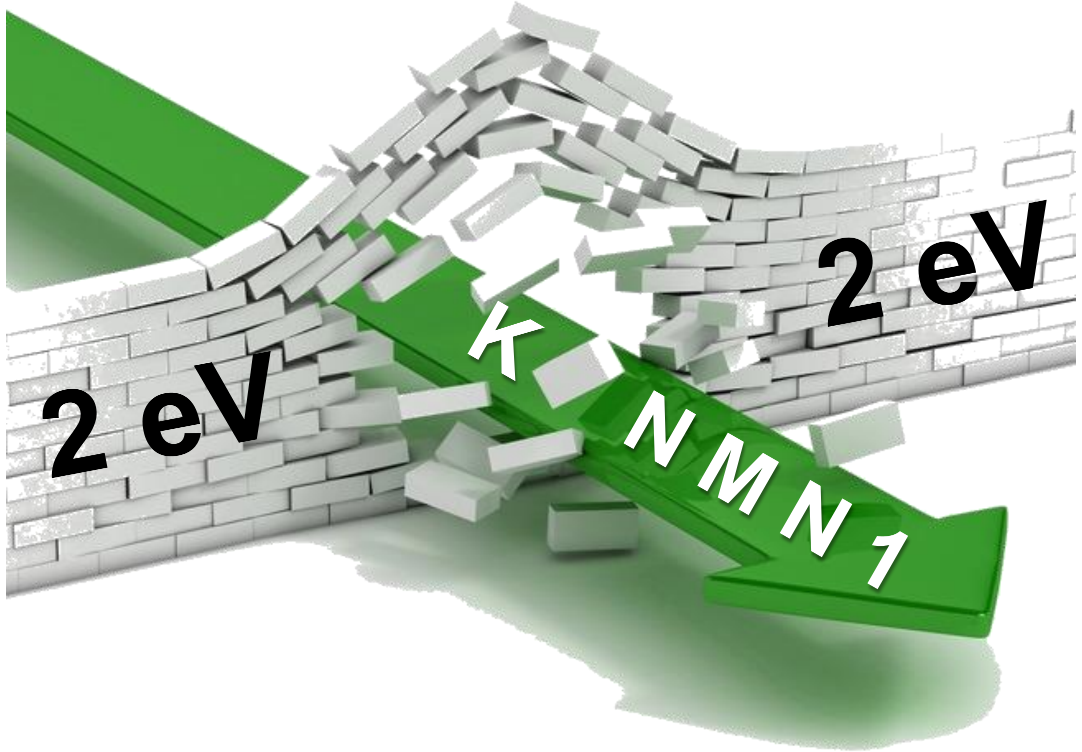
adding ^{83m}Kr to tritium – a key spectroscopic test

Karlsruhe Institute of Technology

- world-leading expertise of NPI Rez/Prague in electron & gamma spectroscopy of ^{83m}Kr
  - exact energies and line widths of **conversion electron lines** (K-32, L-32, M-32,…)







FIRST NEUTRINO MASS RESULT OF KATRIN

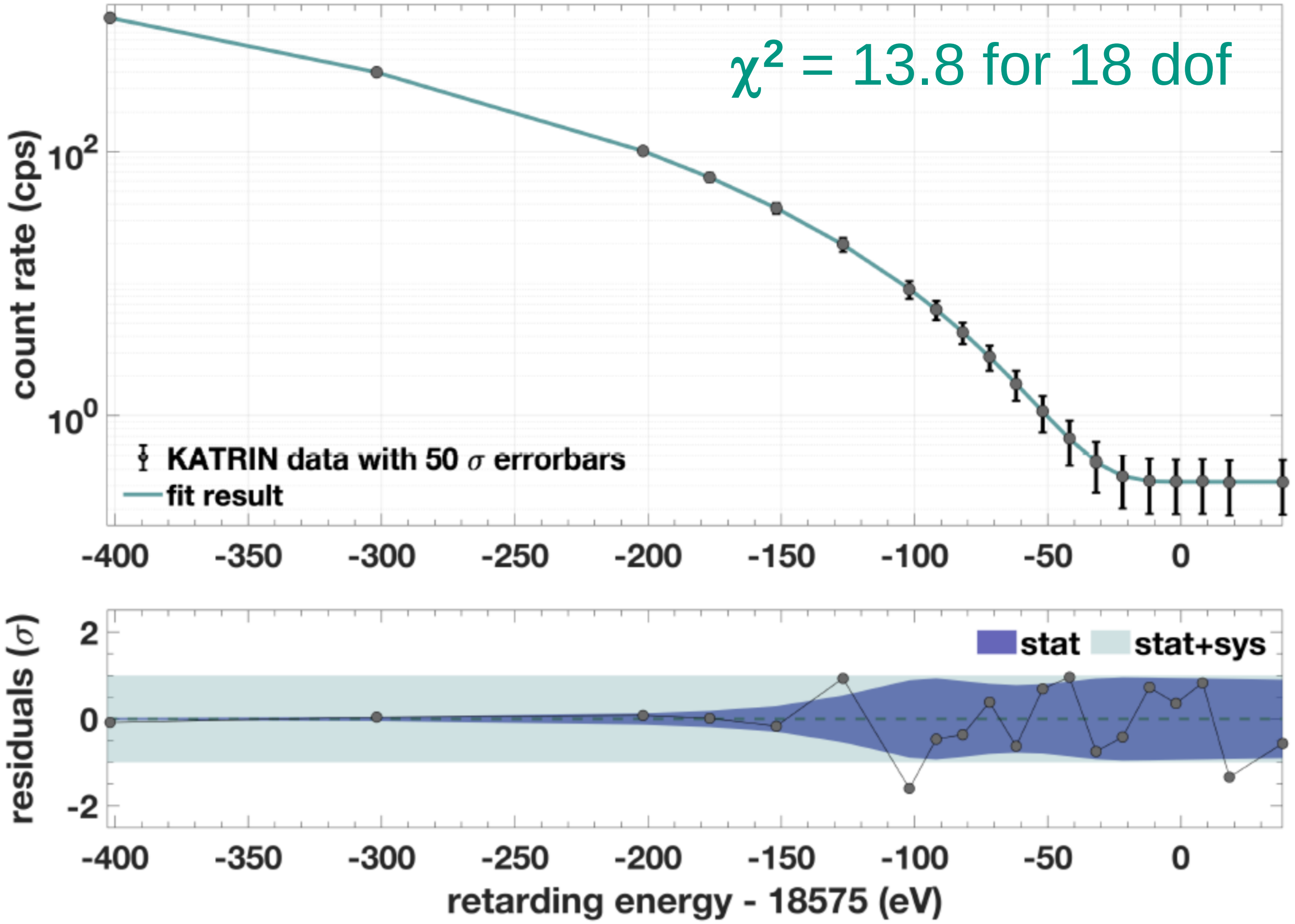
„First Tritium“ FT (2-week engineering run in mid-2018)

- First Tritium:

  - **low tritium concentration**:
    ~1% DT and ~99% D2

  - functionality of all system components ☑
    at nominal ρd ($5 \cdot 10^{17}$ cm^{-2})

deep scan possible due to „low“ ß-activity



M. Aker et al. (KATRIN Collab.), “First operation of the KATRIN experiment with tritium”, acc. for publ. in Eur. Phys. J. C

KATRIN neutrino mass campaign #1

- **4-week long measuring campaign in spring 2019 with high-purity tritium**

  - April 10 – May, 13 2019 780 h

  - high-purity tritium (ε_T = 97.5 %) laser-Raman

  - high source activity: $2.45 \cdot 10^{10}$ Bq

  - high-quality data collected

  - **full analysis chain using two independent methods**

  - target: first neutrino mass result at TAUP 2019

KATRIN neutrino mass campaign #1

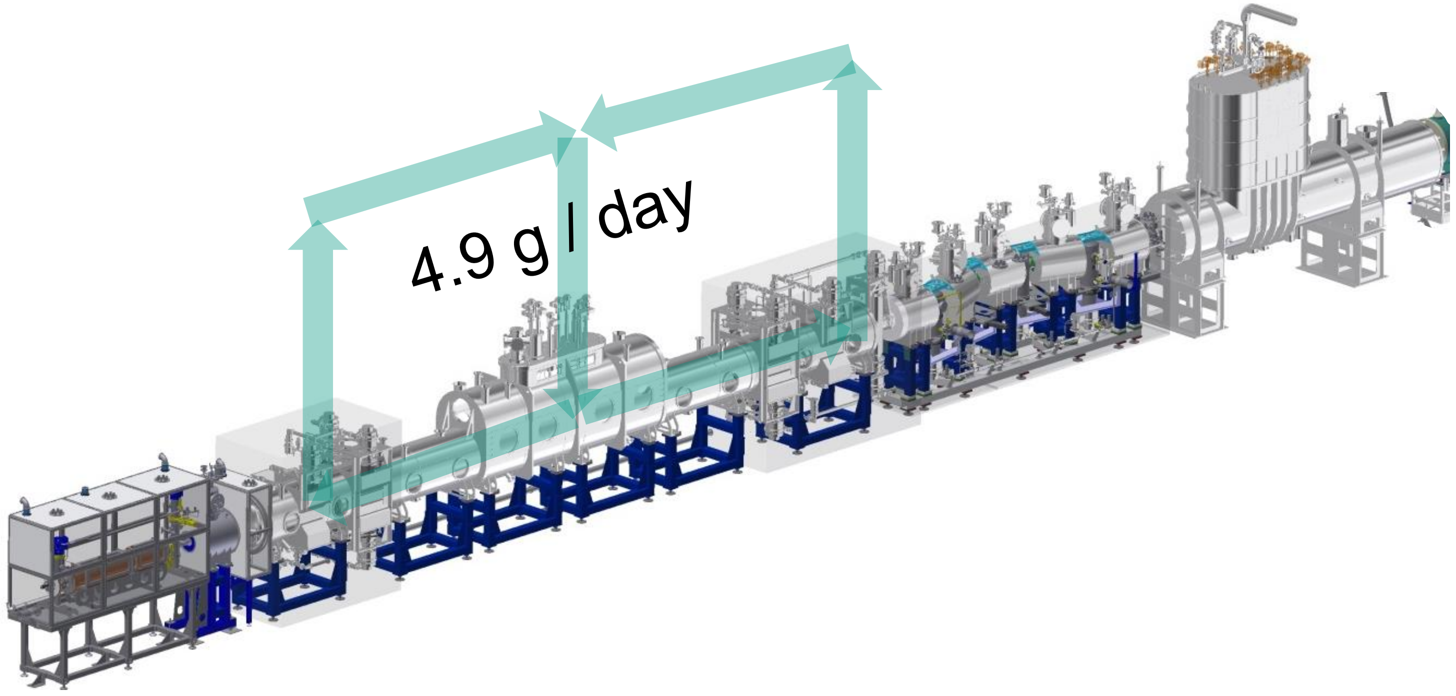
- **first ever large-scale throughput of high-purity tritium in closed loops**

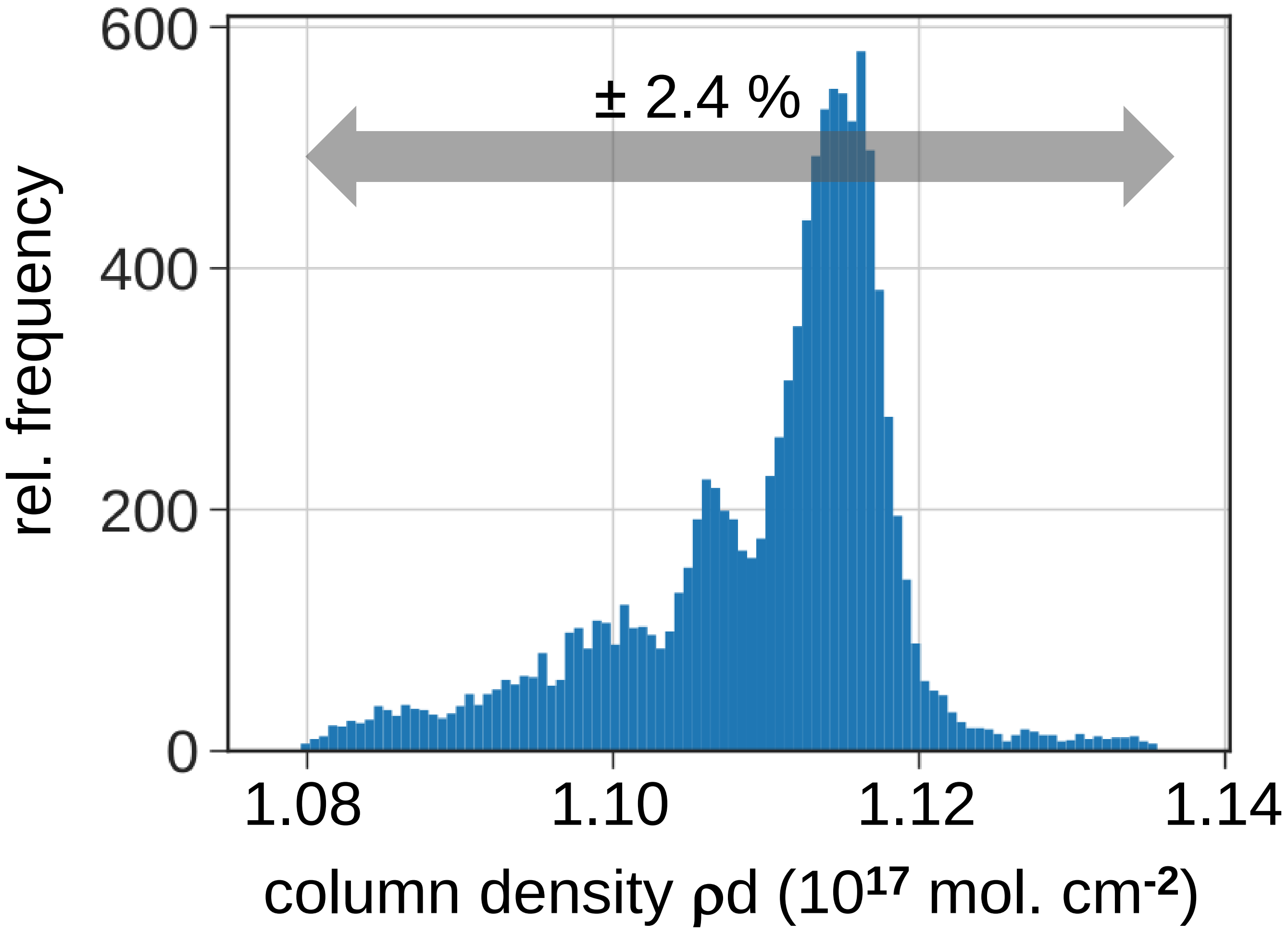
  - 22% of nominal source activity (column density)

    ⇨ limits effects due to radiochemical reactions of T_2 (initial „burn in“ effect)

  - high isotopic tritium purity

    ⇨ T_2 (95.3 %), HT (3.5 %), DT (1.1 %)



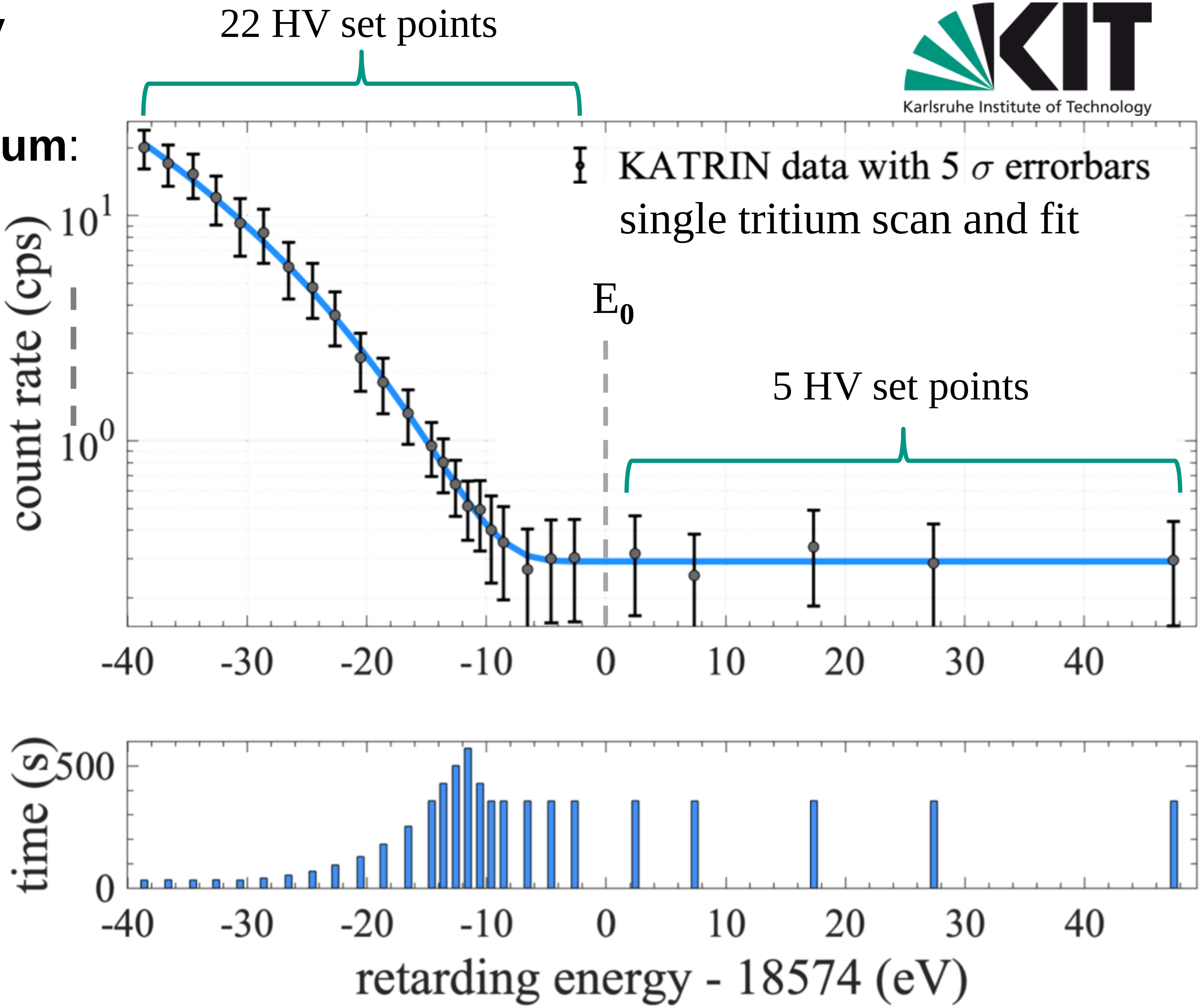


tritium scanning – strategy

- **274 scans of tritium ß-decay sepctrum**:
  - alternating up- / down- scans
  - 2 h net scanning time
  - analysis: 27 HV set points
  - [E_0 – 40 eV , E_0 + 50 eV]

FSD   bg-slope

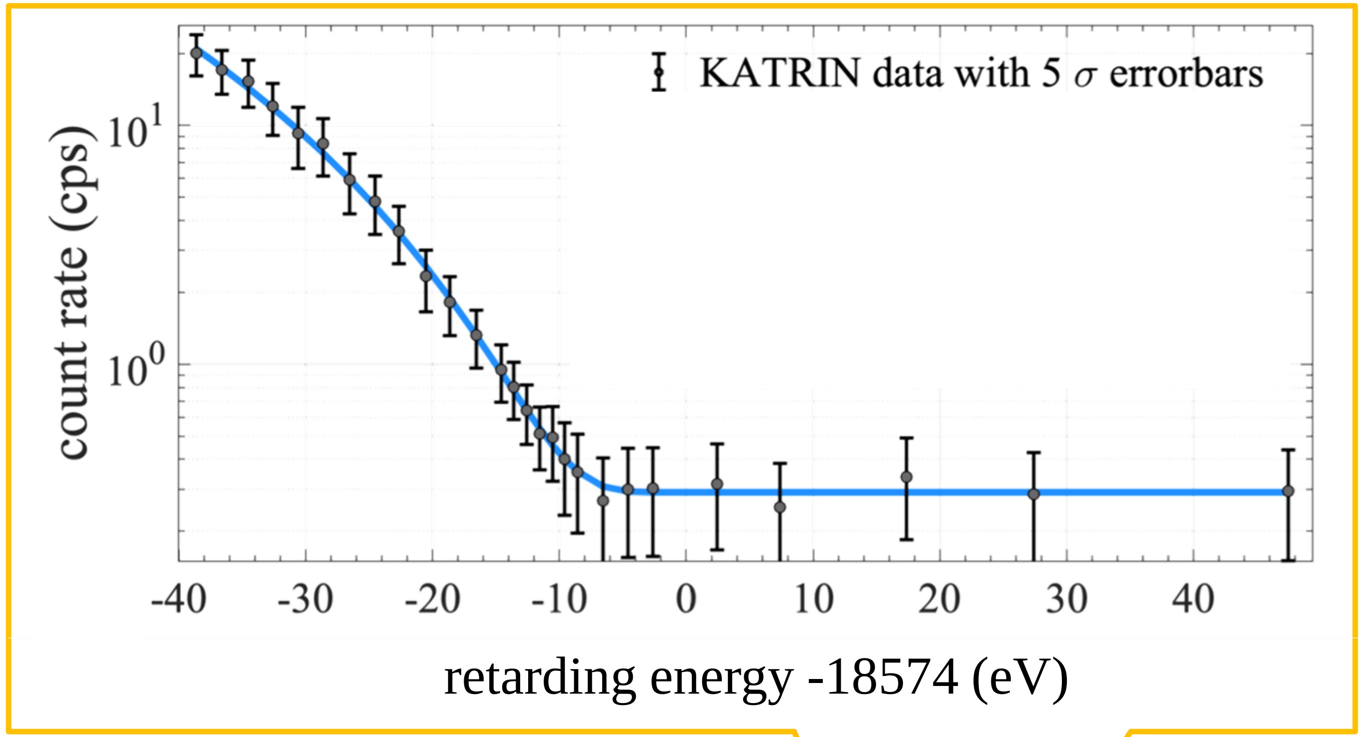
- **MTD maximises ν-mass sensitivity**
  - focus on region close to E_0

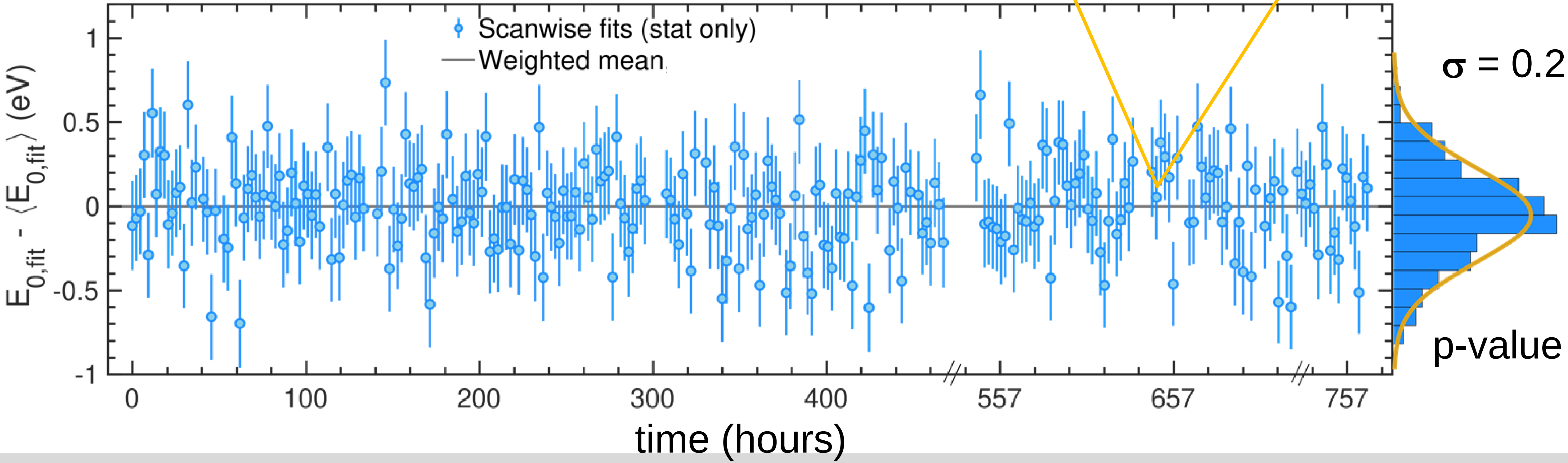


tritium scanning

- **excellent stability of scanning over entire 4-week period**

  - fits to ß-decay endpoints E_0 of all 274 tritium scans:
    ⇨ Gaussian distribution





σ = 0.254 eV

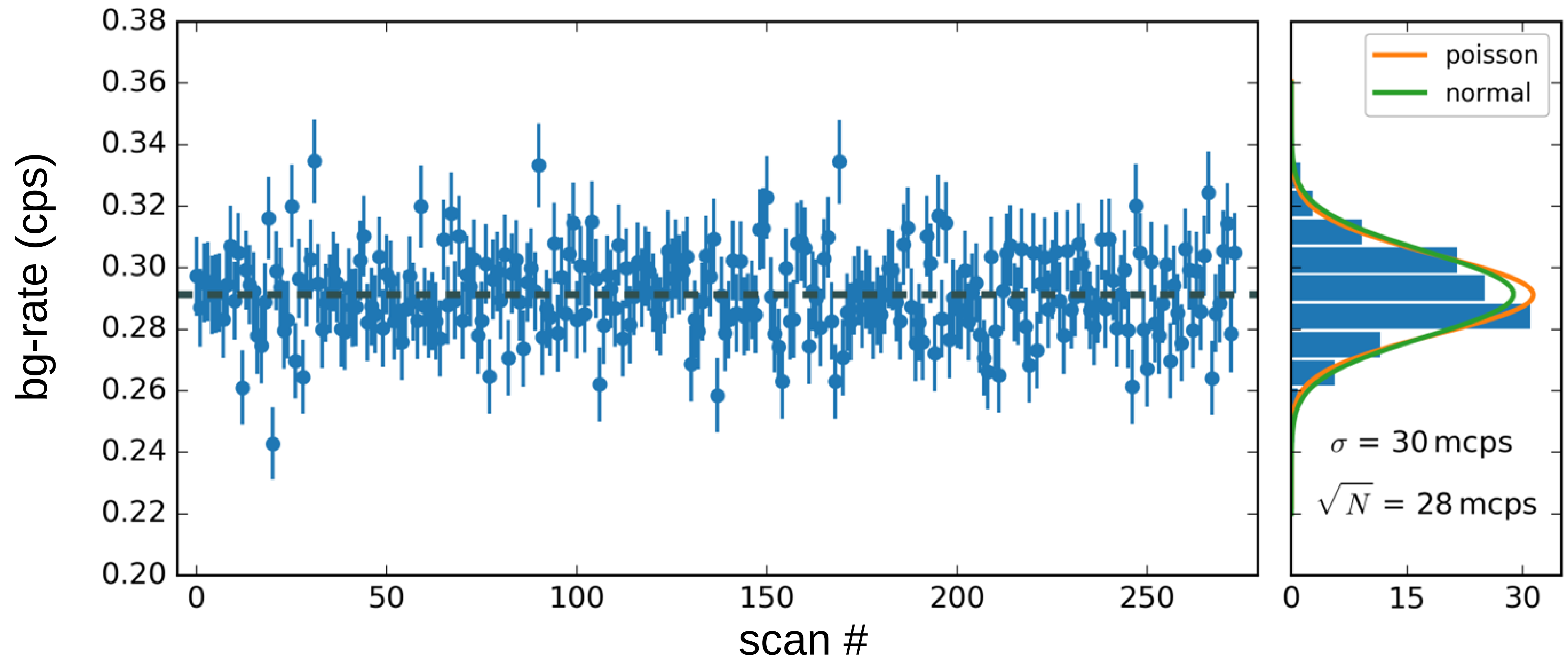
p-value = 0.51

systematics: background

- **background due to neutral, excited atoms in active flux-tube volume**

  - ionisation of Rydberg states due to BBR ⇨ purely Poisson component

  - α-decays of ^{219}Rn atoms from NEG pump ⇨ with small non-Poisson part



Integral tritium ß-decay spectrum - merged

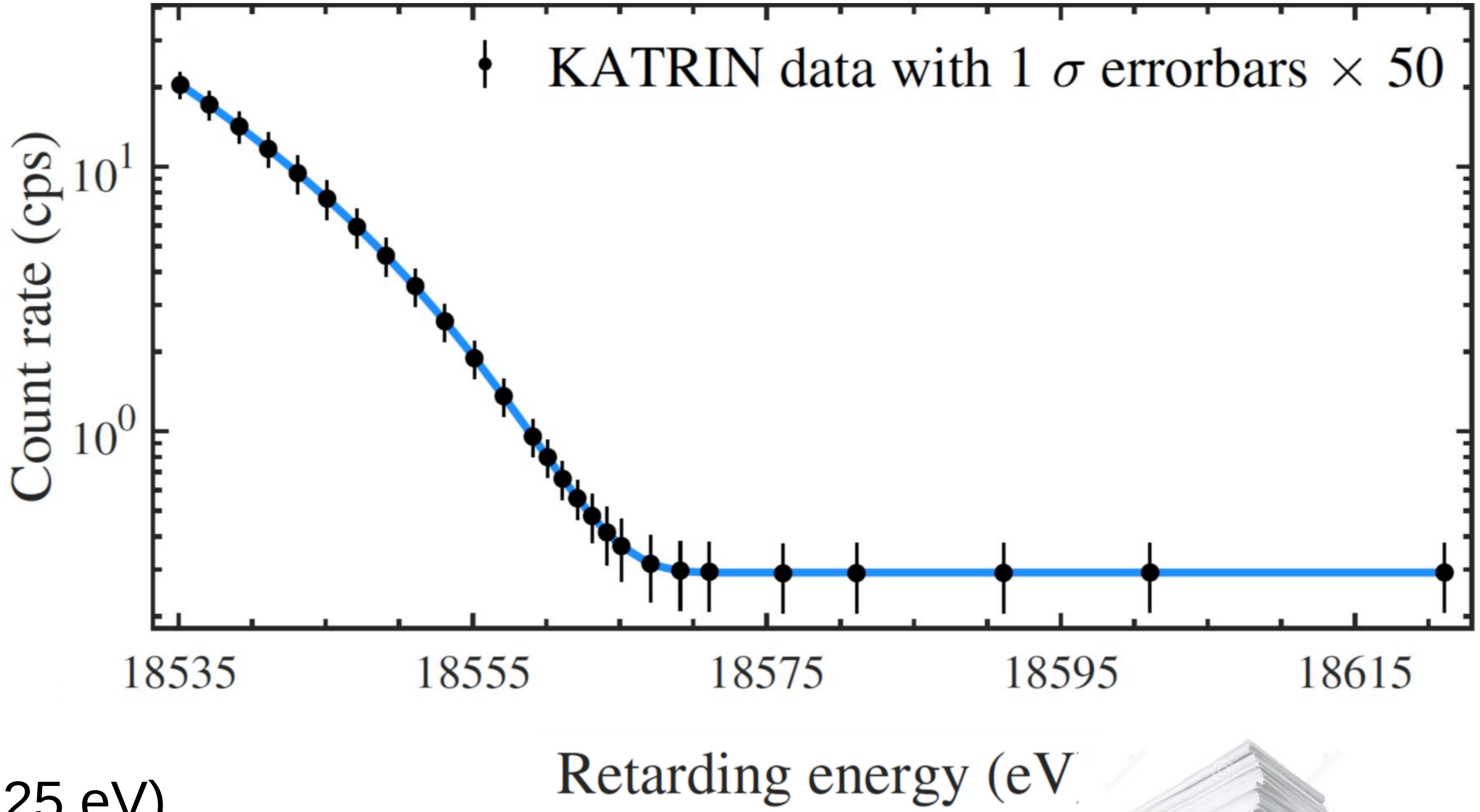
- **High-statistics ß-spectrum**

  - 2 million events in
    in 90-eV-wide interval
    (522 h of scanning)

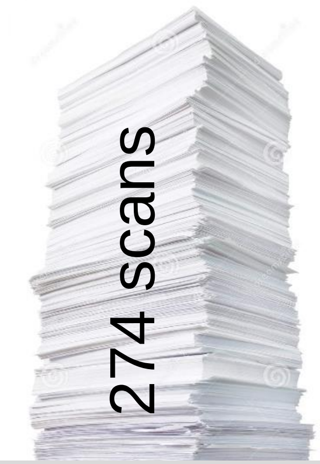
- **merged data set**

  - combine all 274 scans:
    excellent stability of all
    fitted ß-decay endpoints E_0 (σ = 0.25 eV)

  ⇨ “stacking“ of events at mean HV set-point
     (excellent reproducibility: RMS = 34 mV)

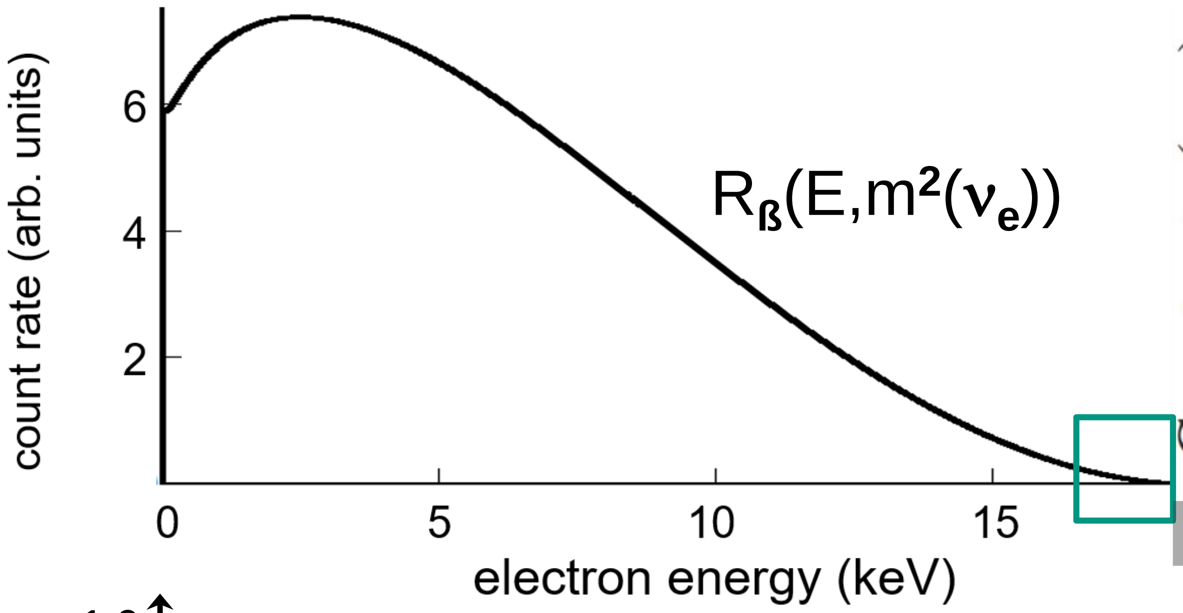


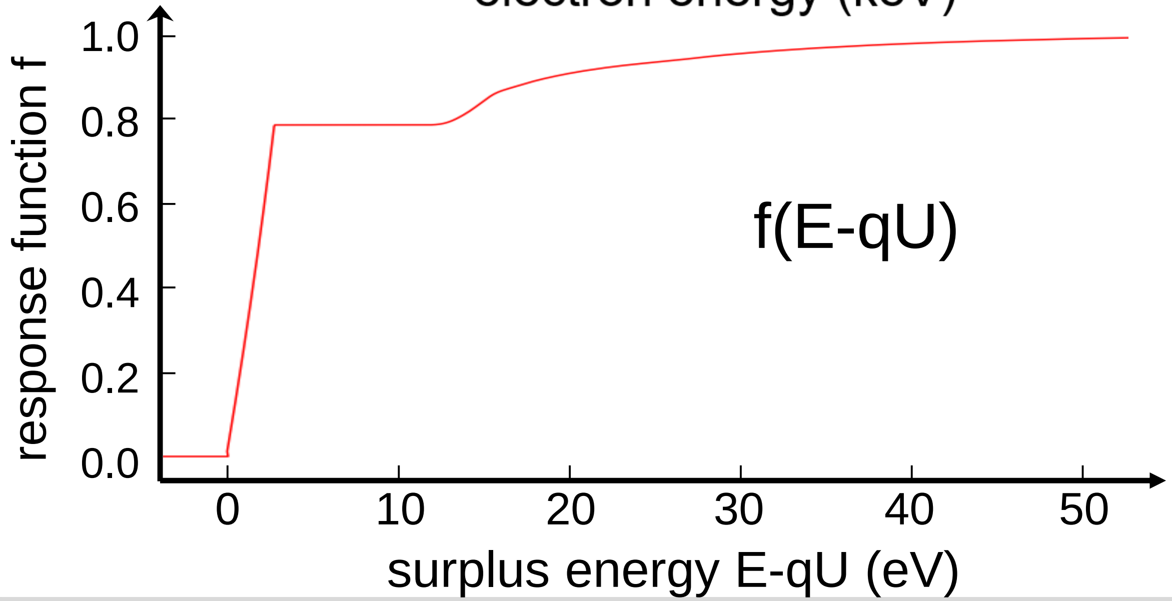
„50σ errorbars“

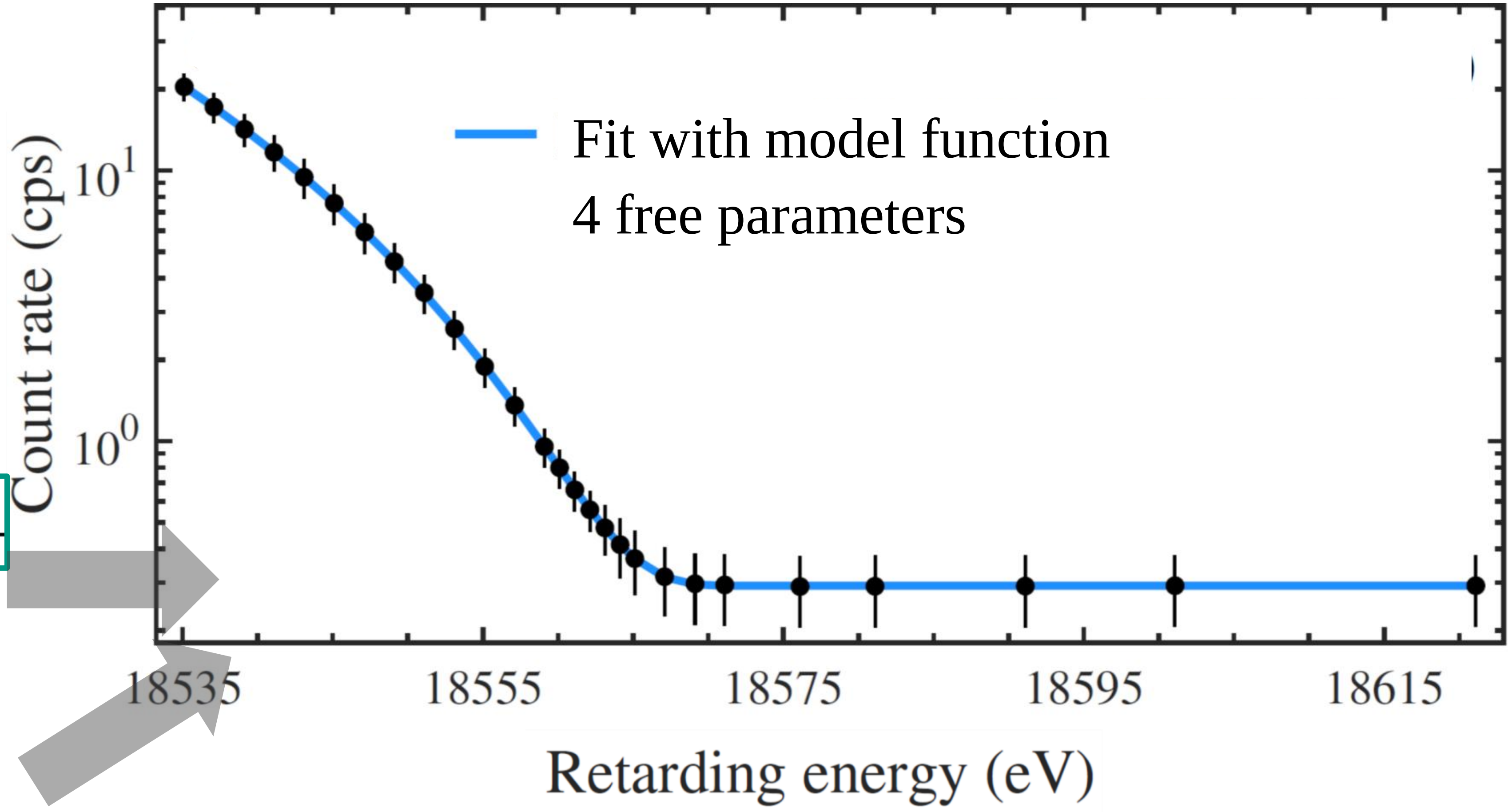


modelling of experimental data

- **ß-spectrum ⊗ response function**







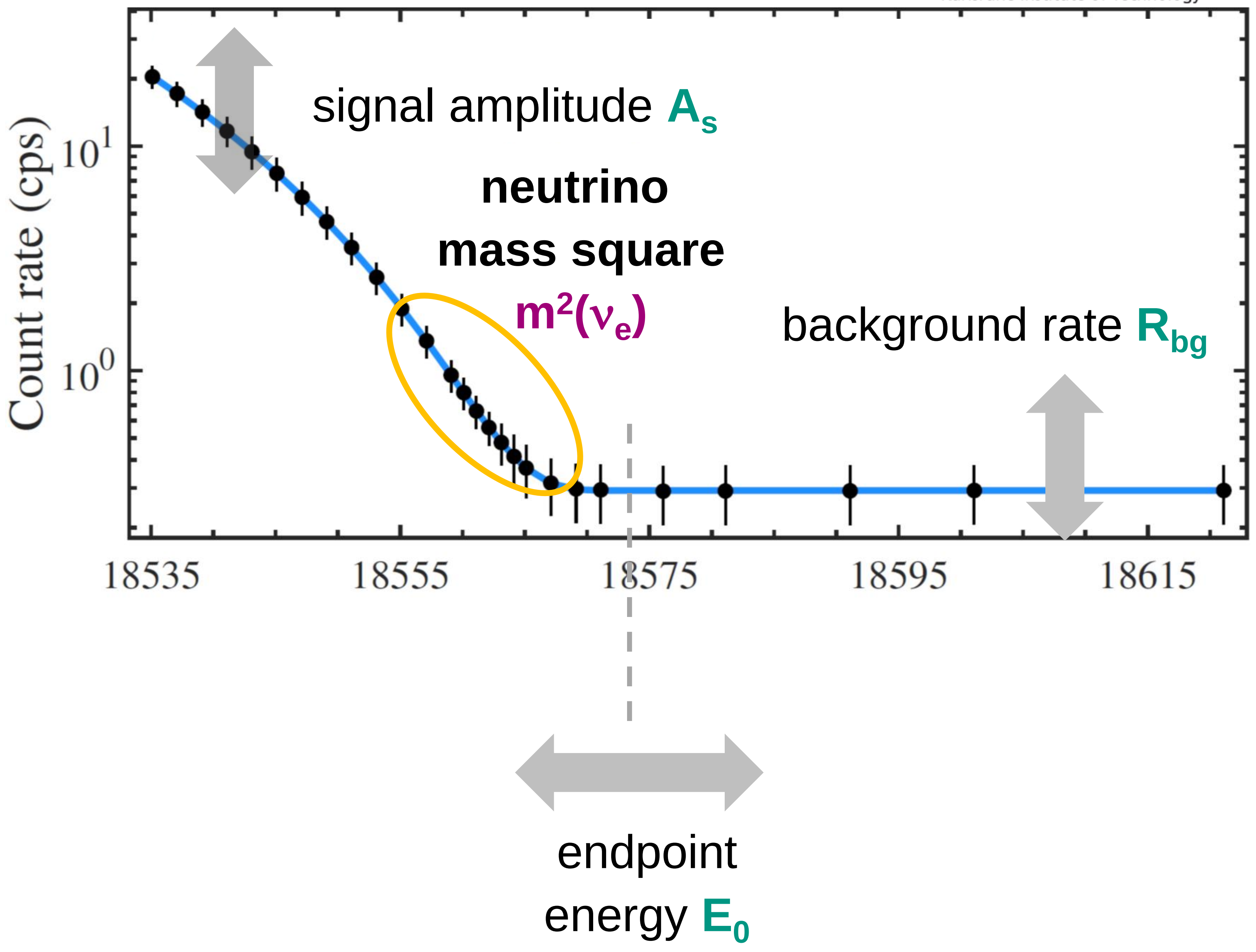
$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_{ß}(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

tritium scanning – fitting of spectrum

- **fit of integrated experimental energy spectrum** to theoretical model with **4 free parameters**

  - leave parameters A_s and E_0 unconstrained ´**shape-only**´ fit

  - excellent goodness-of-fit $\chi^2 = 21.4$ for 23 d.o.f. (p-value = 0.56)



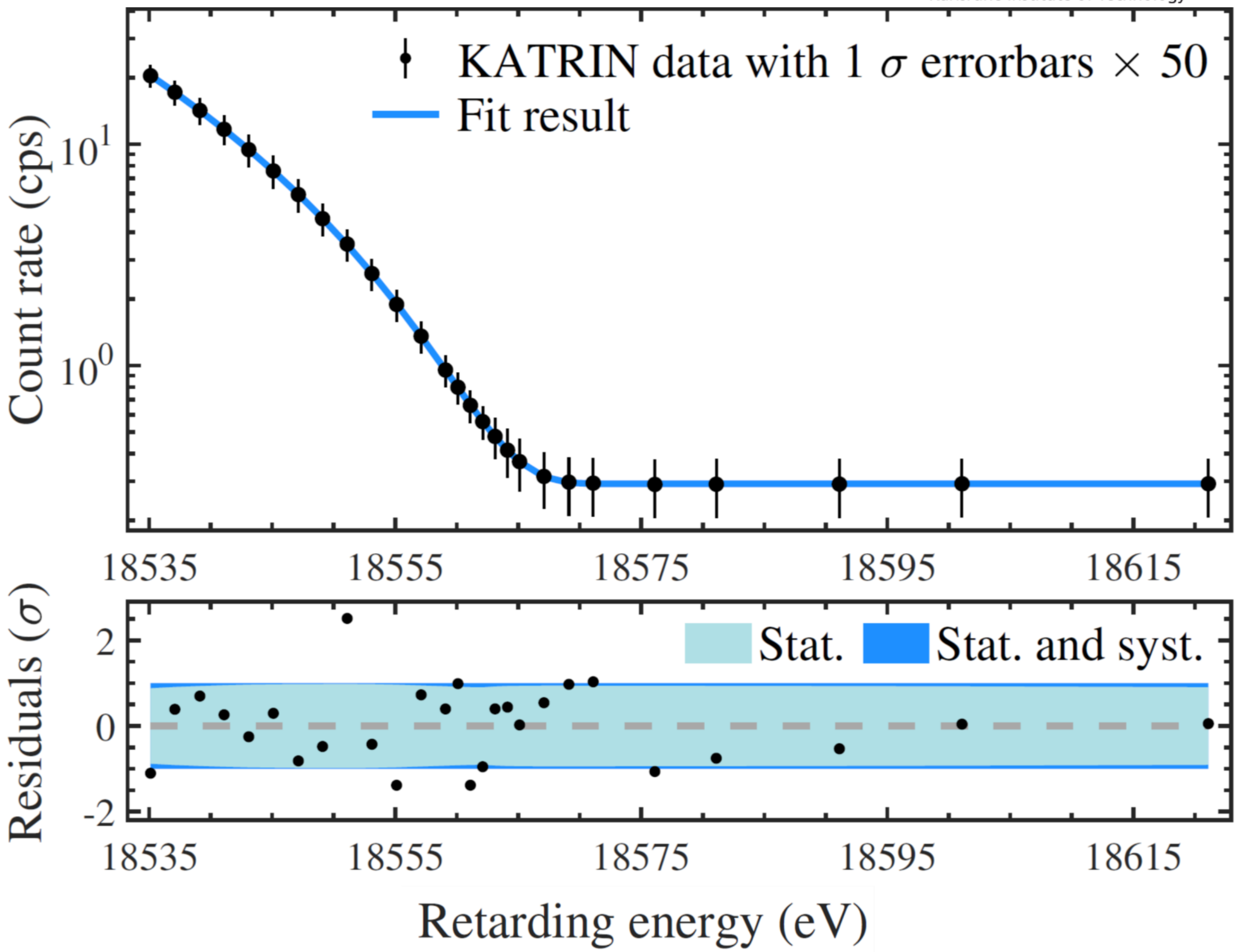
Integral tritium ß-decay spectrum

- **bias-free analysis**

  - blinding of FSD
    (Final State Distribution)
    important: data are
    left untouched
    blinding only on model !

  - full analysis chain first on
    MC data sets
    (MC twins for each ß-scan)

  - final step: unblinded FSD
    for experimental data

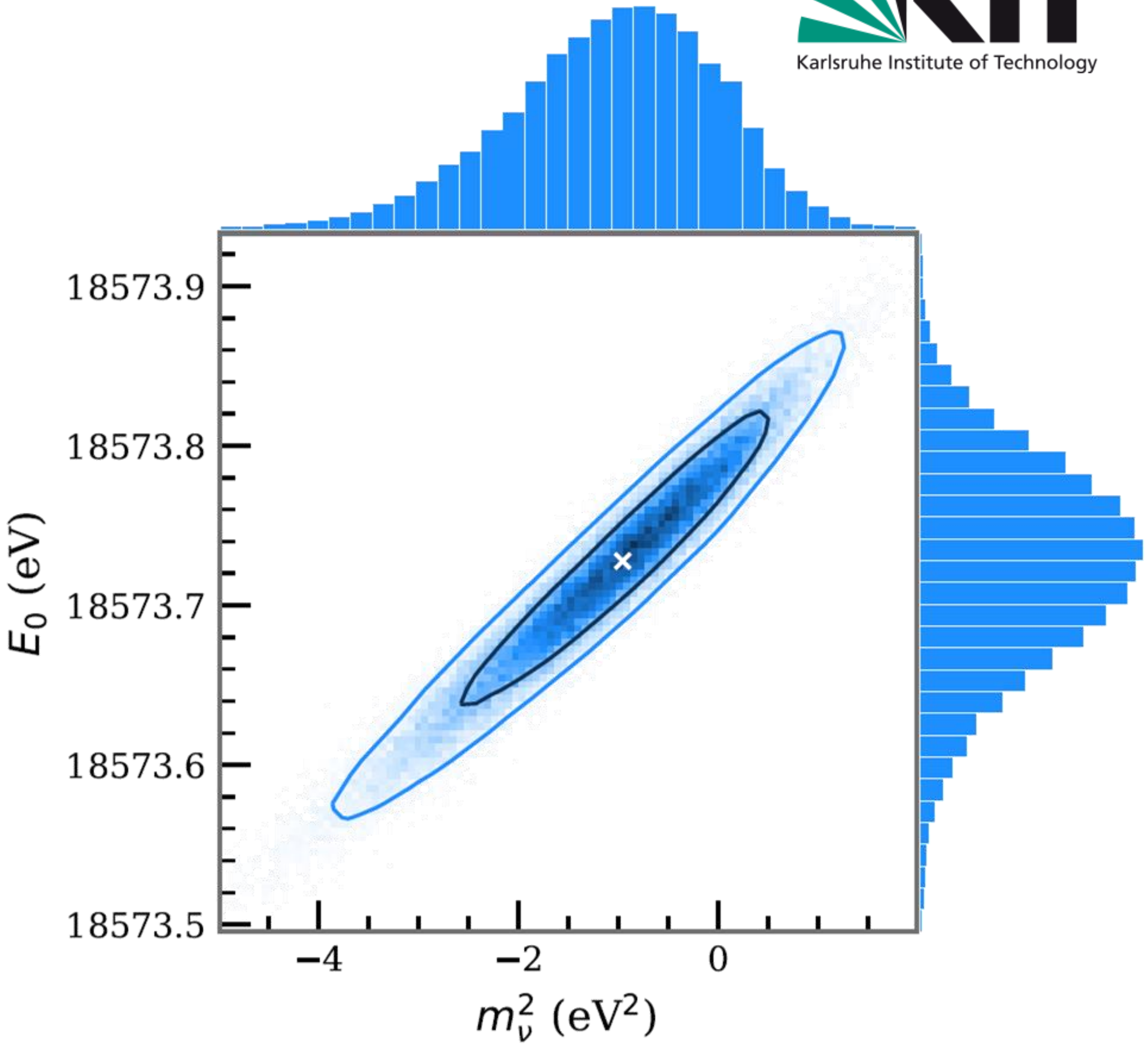


analysis chain & ν-mass result

- **two independent analysis methods**
  to propagate uncertainties & infer parameters
  - Covariance matrix:
    covariance matrix + χ^2-estimator
  - MC propagation:
    10^5 MC samples + likelihood (-2 ln $\mathcal{L}$)
  - both methods agree to a few percent

- **ν-mass and E_0: best fit results**

$$m^2(\nu_e) = \left(-1.0 \begin{array}{l} +\,0.9 \\ -\,1.1 \end{array}\right) \text{eV}^2 \ (90\%\ \text{CL})$$



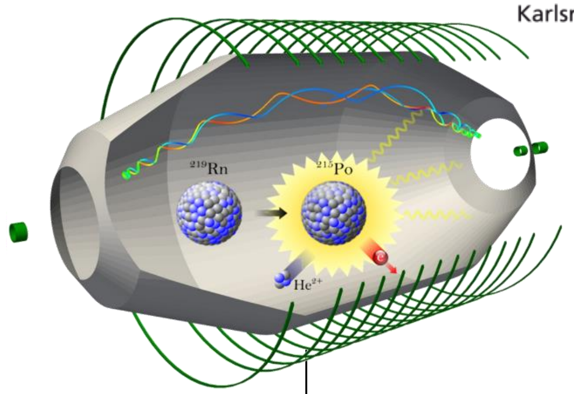
E_0 = (18573.7 ± 0.1) eV ⇨ Q-value : (18575.2 ± 0.5) eV Q-value [$\Delta M(^3H,^3He)$]: (18575.72 ± 0.07) eV

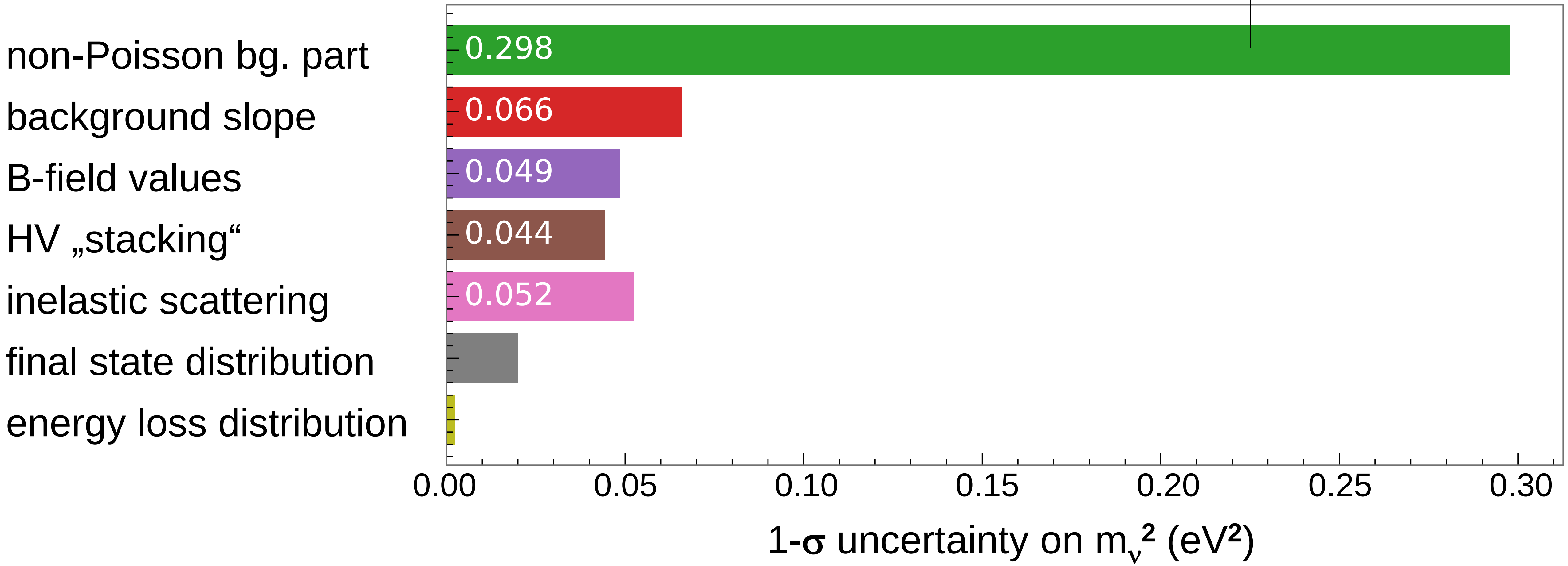
systematics breakdown

- **well-understood systematics budget σ_{syst} (with $\sigma_{syst} < \sigma_{stat}$)**

  - total statistical uncertainty budget σ_{stat} = 0.97 eV^2

  - total systematic uncertainty budget σ_{syst} = 0.32 eV^2



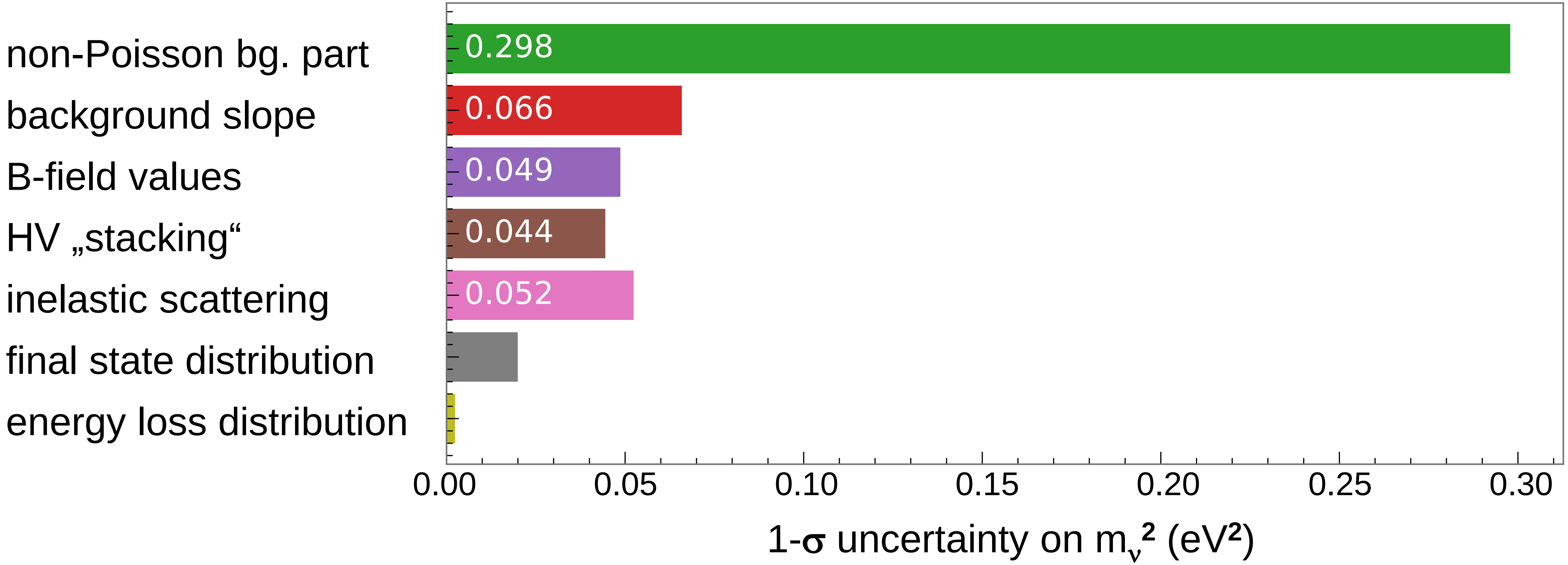


systematics breakdown

- **well-understood systematics budget σ_{syst} based on only 4 weeks of data**

  - total statistical uncertainty budget σ_{stat} = 0.97 eV²
  - total systematic uncertainty budget σ_{syst} = 0.32 eV²

  improves on Mainz/Troitsk by **factor 2** (statistical) and **factor 6** (systematic)

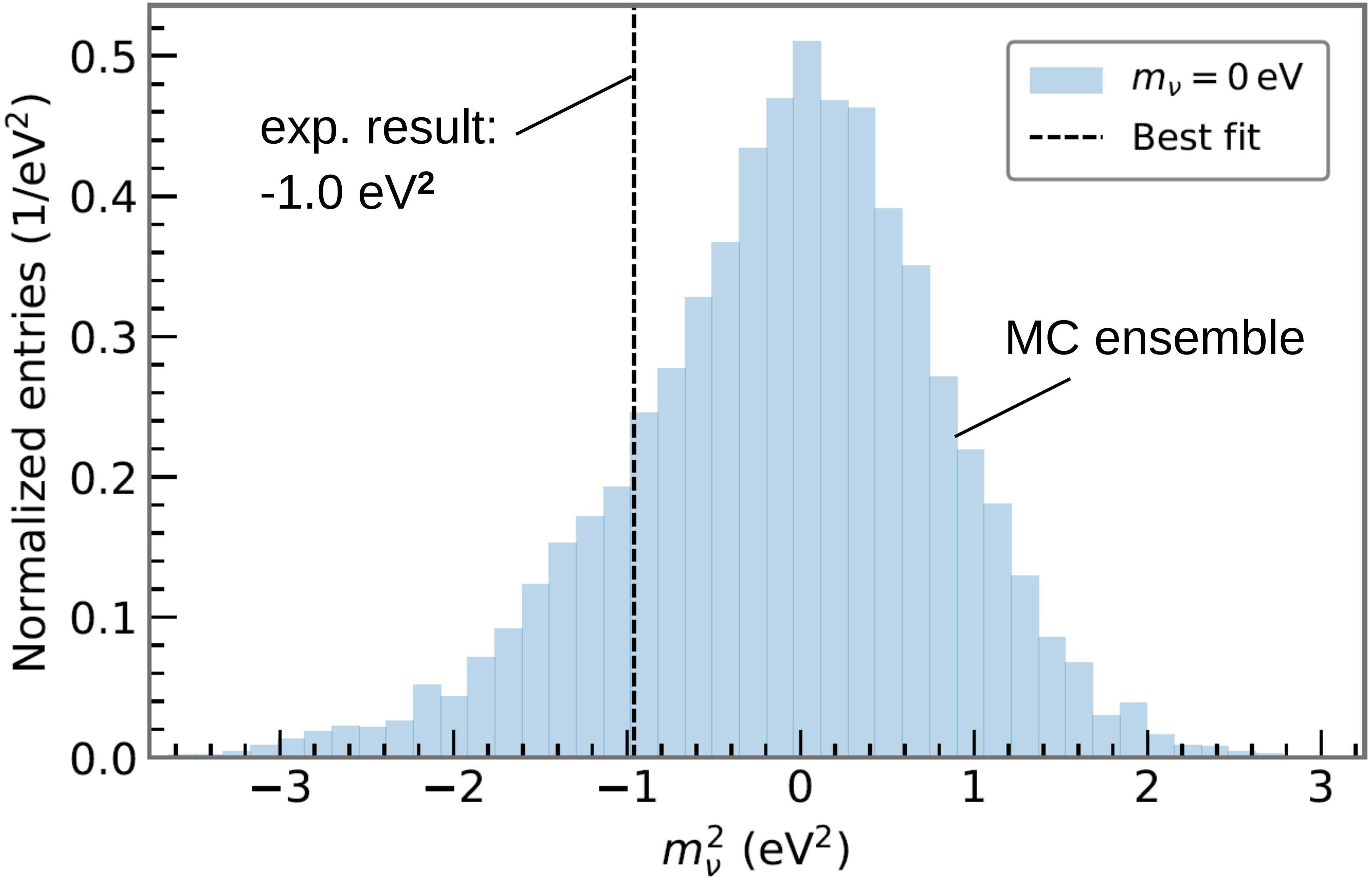


KATRIN result and expectation

- **best-fit result corresponds to a 1-σ statistical fluctuation to negative $m^2(\nu_e)$**

  - p-value is derived from 13 000 MC samples with $m^2(\nu_e)$ = 0 and properly fluctuated σ_{stat} and σ_{syst}

p-value = 0.16



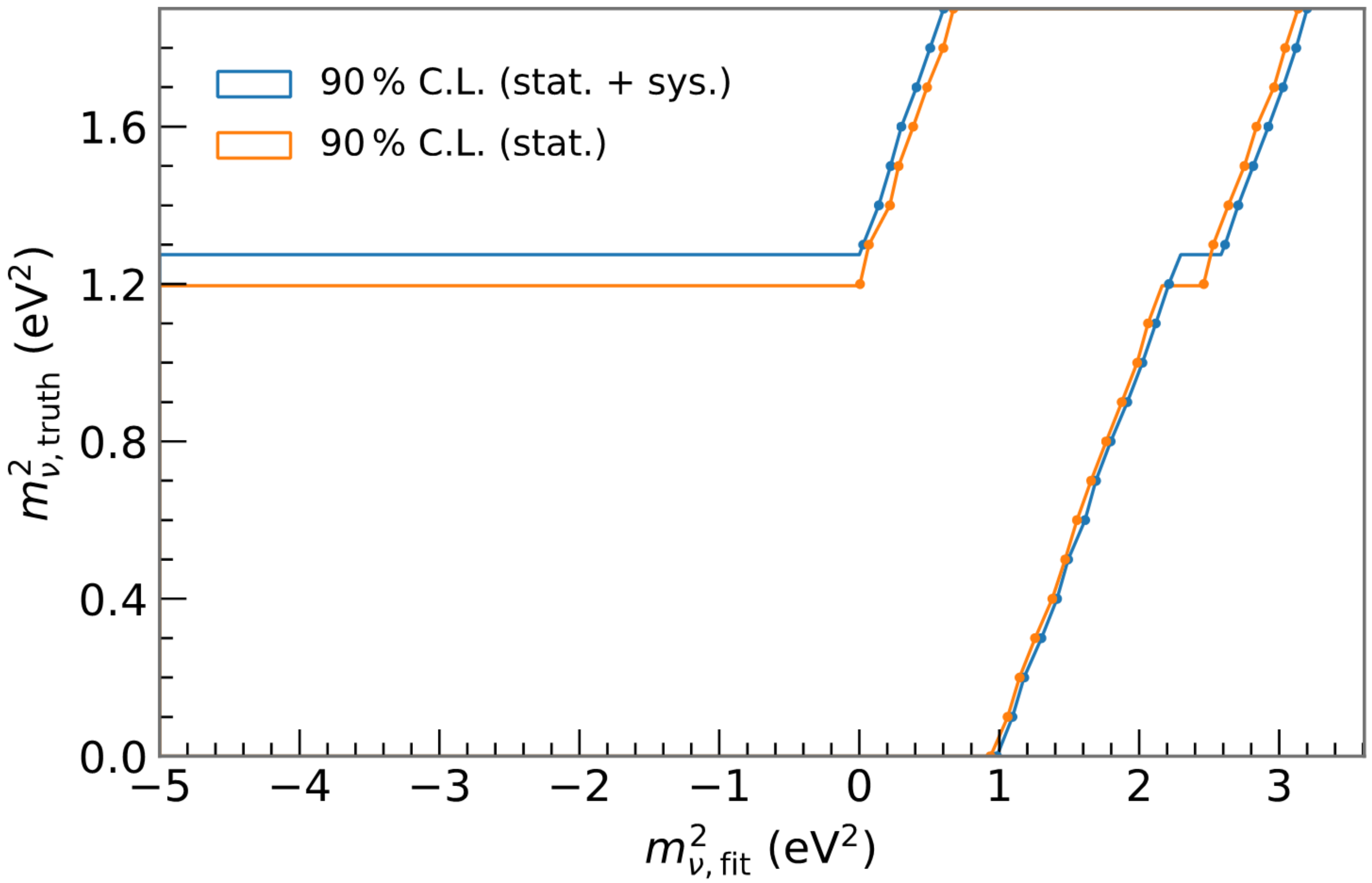
neutrino mass upper limit

- **confidence belts:** procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC)

  - for this first result we follow the robust LT method
  - LT yields experimental sensitivity by construction for $m^2(\nu_e) < 0$
  - **KATRIN upper limit on neutrino mass:**

LT $m(\nu) < 1.1$ eV (90% CL)

FC $m(\nu) < 0.8$ eV (90% CL)
< 0.9 eV (95% CL)



A.V. Lokhov, F.V. Tkachov, Phys. Part. Nucl. 46 (2015) 347

neutrino mass upper limit

- **confidence belts:** procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC)

  - for this first result we follow the robust LT method
  - LT yields experimental sensitivity by construction for $m^2(\nu_e) < 0$
  - **KATRIN upper limit on neutrino mass:**

LT $m(\nu) < 1.1$ eV (90% CL)

FC $m(\nu) < 0.8$ eV (90% CL)
< 0.9 eV (95% CL)

M. Aker et al. (KATRIN Collab.), *An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN*, acc. for publ. in PRL

arXiv:1909.06048v1 [hep-ex] 13 Sep 2019

An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN

M. Aker,[1,2] K. Altenmüller,[10,3,4] M. Arenz,[5] M. Babutzka,[6] J. Barrett,[7] S. Bauer,[8] M. Beck,[8,12] A. Beglarian,[9] J. Behrens,[6,1,8] T. Bergmann,[10,3,9] U. Besserer,[1,2] K. Blaum,[11] F. Block,[6] S. Bobien,[2] K. Bokeloh (née Hugenberg),[8] J. Bonn,[12,*] B. Bornschein,[1,2] L. Bornschein,[1] H. Bouquet,[9] T. Brunst,[10,3] T. S. Caldwell,[13,14] L. La Cascio,[6] S. Chilingaryan,[9] W. Choi,[6] T. J. Corona,[13,14,7] K. Debowski,[15,6] M. Deffert,[6] M. Descher,[6] P. J. Doe,[16] O. Dragoun,[17] G. Drexlin,[6,1] J. A. Dunmore,[16] S. Dyba,[8] F. Edzards,[10,3] L. Eisenblätter,[9] K. Eitel,[1] E. Ellinger,[15] R. Engel,[1,6] S. Enomoto,[16] M. Erhard,[6] D. Eversheim,[5] M. Fedkevych,[8] A. Felden,[1] S. Fischer,[1,2] B. Flatt,[12] J. A. Formaggio,[7] F. M. Fränkle,[1,13,14] G. B. Franklin,[18] H. Frankrone,[9] F. Friedel,[6] D. Fuchs,[10,3] A. Fulst,[8] D. Furse,[7] K. Gauda,[8] H. Gemmeke,[9] W. Gil,[1] F. Glück,[1] S. Görhardt,[1] S. Groh,[6] S. Grohmann,[2] R. Grössle,[1,2] R. Gumbsheimer,[1] M. Ha Minh,[10,3] M. Hackenjos,[1,2,6] V. Hannen,[8] F. Harms,[6] J. Hartmann,[9] N. Haußmann,[15] F. Heizmann,[6] K. Helbing,[15] S. Hickford,[1,15] D. Hilk,[6] B. Hillen,[8] D. Hillesheimer,[1,2] D. Hinz,[1] T. Höhn,[1] B. Holzapfel,[2] S. Holzmann,[2] T. Houdy,[10,3] M. A. Howe,[13,14] A. Huber,[6] A. Jansen,[1] A. Kaboth,[7] C. Karl,[10,3] O. Kazachenko,[21] J. Kellerer,[6] N. Kernert,[1] L. Kippenbrock,[16] M. Kleesiek (né Haag),[6] M. Klein,[1,6] C. Köhler,[10,3] L. Köllenberger,[1] A. Kopmann,[9] M. Korzeczek,[6] A. Kosmider,[1] A. Kovalík,[17] B. Krasch,[1,2] M. Kraus,[6] H. Krause,[1] L. Kuckert (née Neumann),[1] B. Kuffner,[1] N. Kunka,[9] T. Lasserre,[4,3,10] T. L. Le,[1,2] O. Lebeda,[17] M. Leber,[16] B. Lehnert,[19] J. Letnev,[20] F. Leven,[6] S. Lichter,[1] V. M. Lobashev,[21,*] A. Lokhov,[8,21] M. Machatschek,[6] E. Malcherek,[1] K. Müller,[1] M. Mark,[1] A. Marsteller,[1,2] E. L. Martin,[13,14,16] C. Melzer,[1,2] A. Menshikov,[9] S. Mertens,[10,3,19,1] L. I. Minter (née Bodine),[16] S. Mirz,[1,2] B. Monreal,[22] P. I. Morales Guzmán,[10,3] K. Müller,[1] U. Naumann,[15] W. Ndeke,[25] H. Neumann,[2] S. Niemes,[1,2] M. Noe,[2] N. S. Oblath,[7] H.-W. Ortjohann,[8] A. Osipowicz,[20] B. Ostrick,[8] E. Otten,[12,*] D. S. Parno,[18,16] D. G. Phillips II,[13,14] P. Plischke,[1] A. Pollithy,[10,3] A. W. P. Poon,[19] J. Pouryamout,[15] M. Prall,[8] F. Priester,[1,2] M. Röllig,[1,2] C. Röttele,[1,6,2] P. C.-O. Ranitzsch,[8] O. Rest,[8] R. Rinderspacher,[1] R. G. H. Robertson,[16] C. Rodenbeck,[8] P. Rohr,[9] Ch. Roll,[25] S. Rupp,[1,2,6] M. Ryšavý,[17] R. Sack,[8] A. Saenz,[25] P. Schäfer,[1,2] L. Schimpf,[6] K. Schlösser,[1] M. Schlösser,[1,2] L. Schlüter,[10,3] H. Schön,[2] K. Schönung,[11,1,2] M. Schrank,[1] B. Schulz,[25] J. Schwarz,[1] H. Seitz-Moskaliuk,[6] W. Seller,[20] V. Sibille,[7] D. Siegmann,[10,3] A. Skasyrskaya,[21] M. Slezák,[10,17] A. Špalek,[17] F. Spanier,[1] M. Steidl,[1] N. Steinbrink,[8] M. Sturm,[1,2] M. Suesser,[2] M. Sun,[16] D. Tcherniakhovski,[9] H. H. Telle,[23] T. Thümmler,[1,8] L. A. Thorne,[18] N. Titov,[21] I. Tkachev,[21] N. Trost,[1] K. Urban,[10,3] D. Vénos,[17] K. Valerius,[1,8] B. A. VanDevender,[16] R. Vianden,[5] A. P. Vizcaya Hernández,[18] B. L. Wall,[16] S. Wüstling,[9] M. Weber,[9] C. Weinheimer,[8] C. Weiss,[24] S. Welte,[1,2] J. Wendel,[1,2] K. J. Wierman,[13,14] J. F. Wilkerson,[13,14,†] J. Wolf,[6] W. Xu,[7] Y.-R. Yen,[18] M. Zacher,[8] S. Zadorozhny,[21] M. Zbořil,[8,17] and G. Zeller[1,2]

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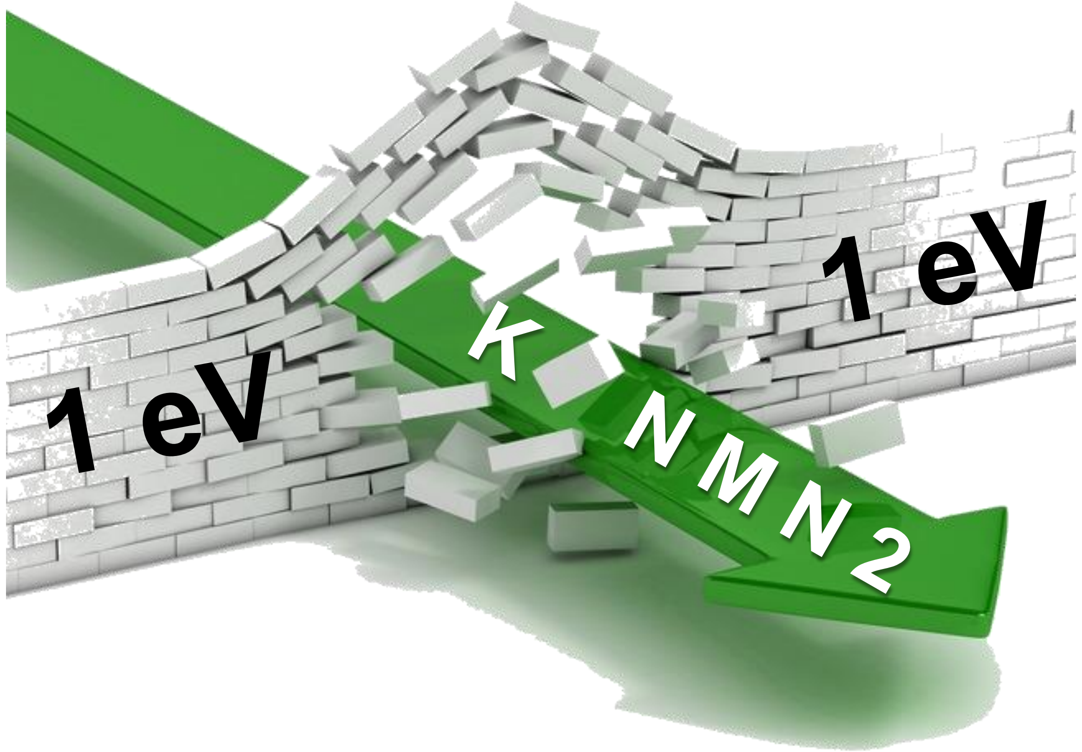
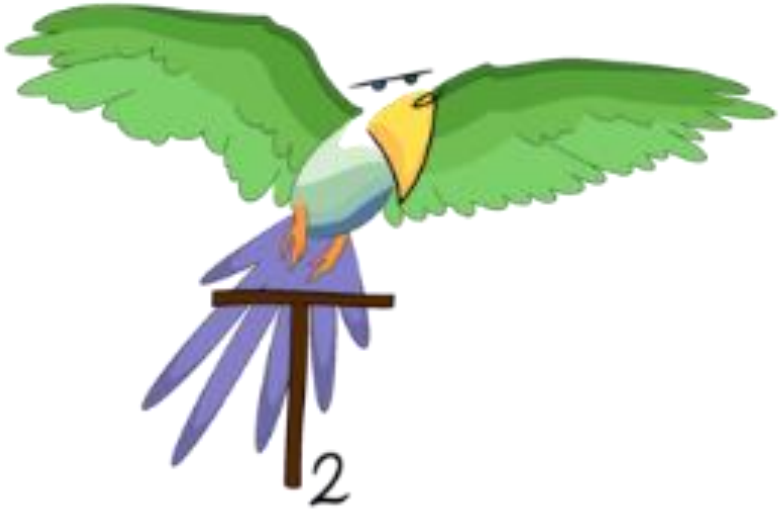




KATRIN FUTURE

actual KNM2 measurement campaing

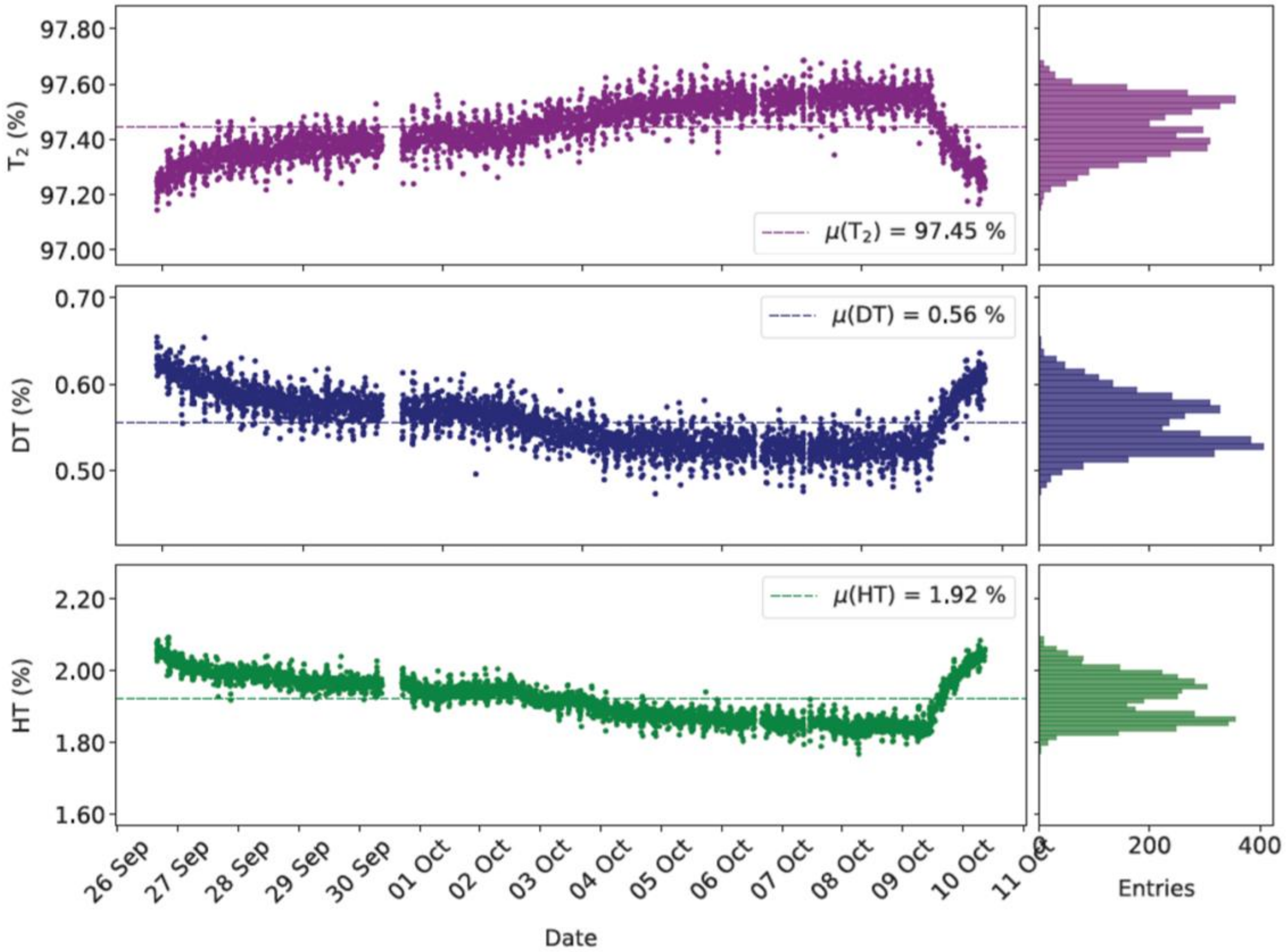
- **KNM2**: since Sept. 27, 2019

  - first campaign with quasi-nominal column density (~60 days)

  - improved HV-reproducability (34 mV → few mV) ☑

  - reduced background rate after spectrometer bake-out ☑

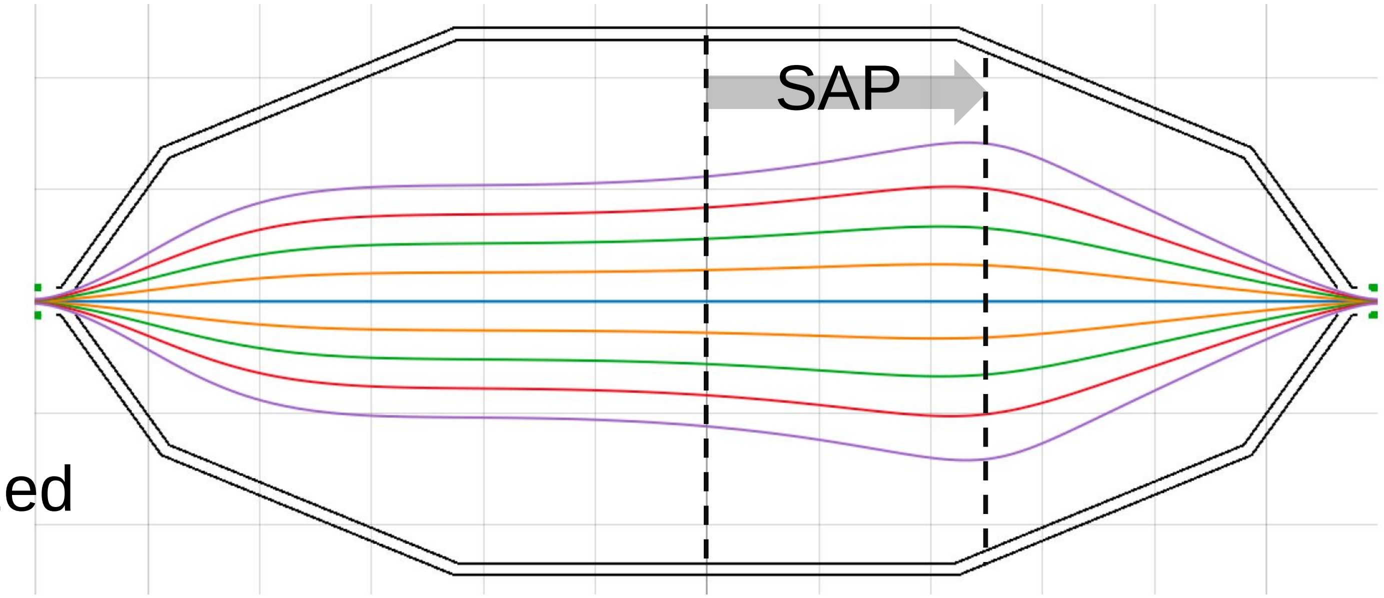
  - **significantly improved S/B relative to KNM1 (goal: factor 10)**



KATRIN – future plans

■ **KATRIN near- and long-term future** :

- even further reduction of background
from decays of Radon & Rydberg atoms
⇨ upgraded aircoil system ☑
„shifted analysis plane“ (SAP)
bg-studies & tritium scans being analyzed



- **further reduction of systematics**
energy loss via egun in ToF modus, …

R&D works on ToF-technique for differential tritium scanning

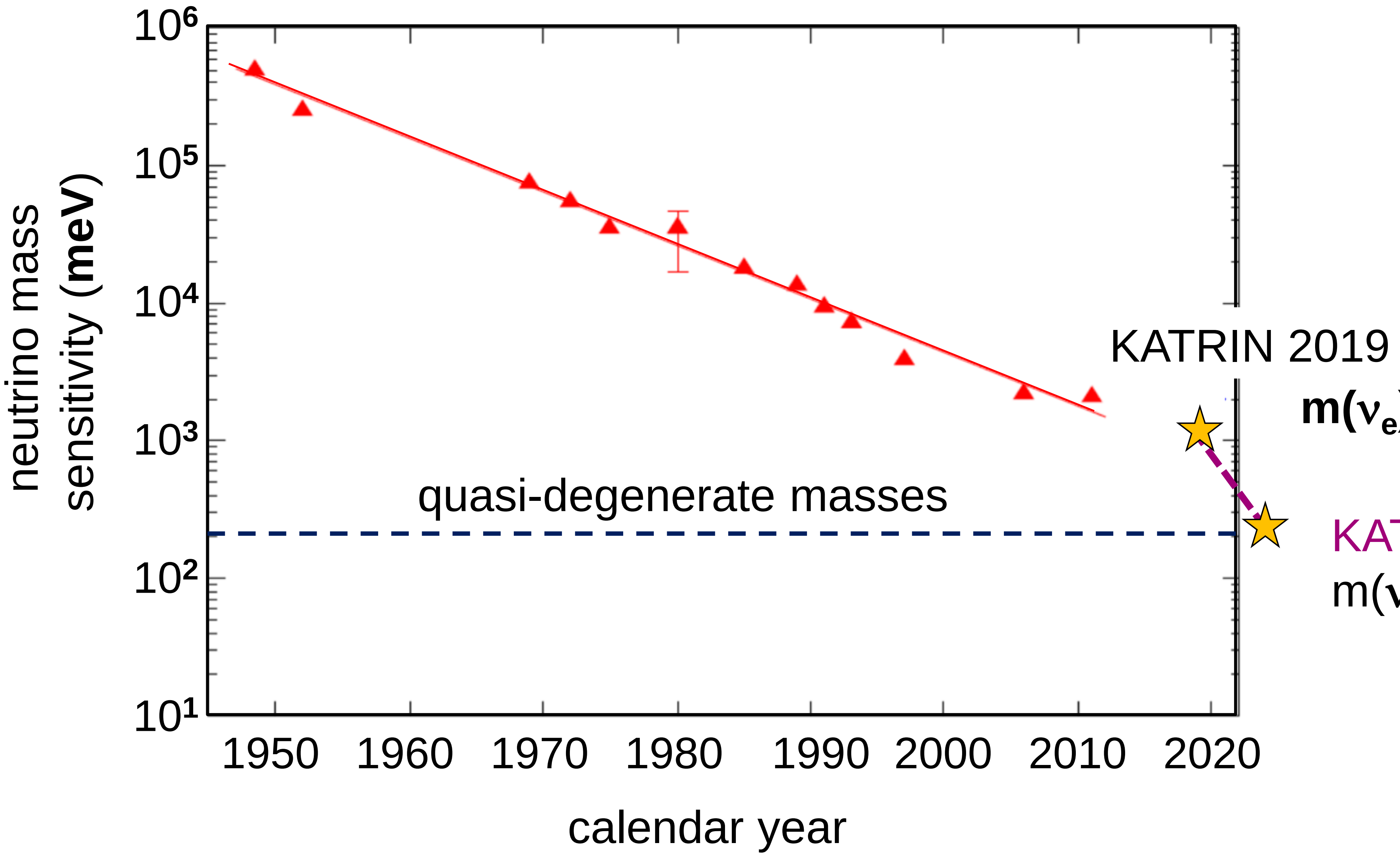
- **1000 days of measurements** at nominal ρd ($5 \cdot 10^{17}$ molecules cm^{-2})
3 tritium campaigns (65 days each)
per calendar year over next 5 years

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

0.35 eV (5σ)

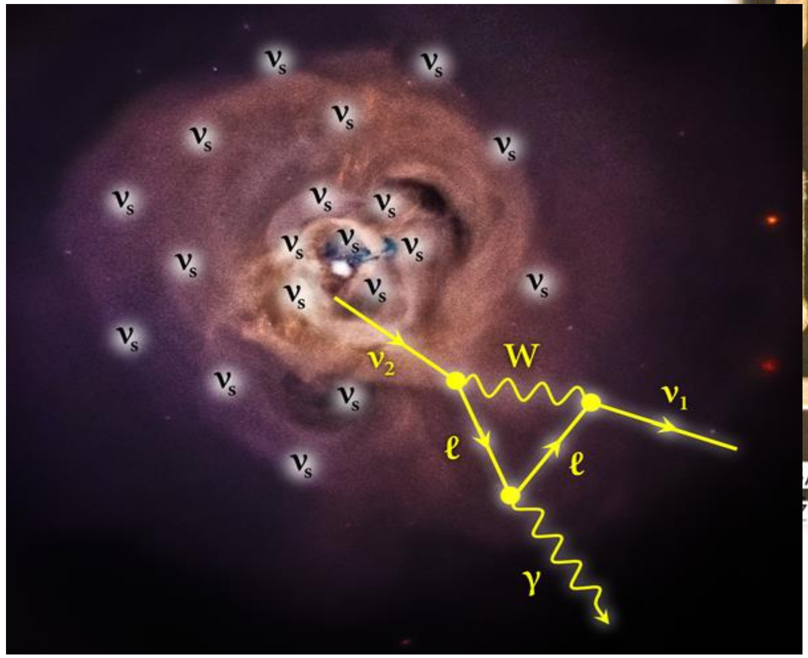
future Moore´s law of direct ν-mass sensitivities

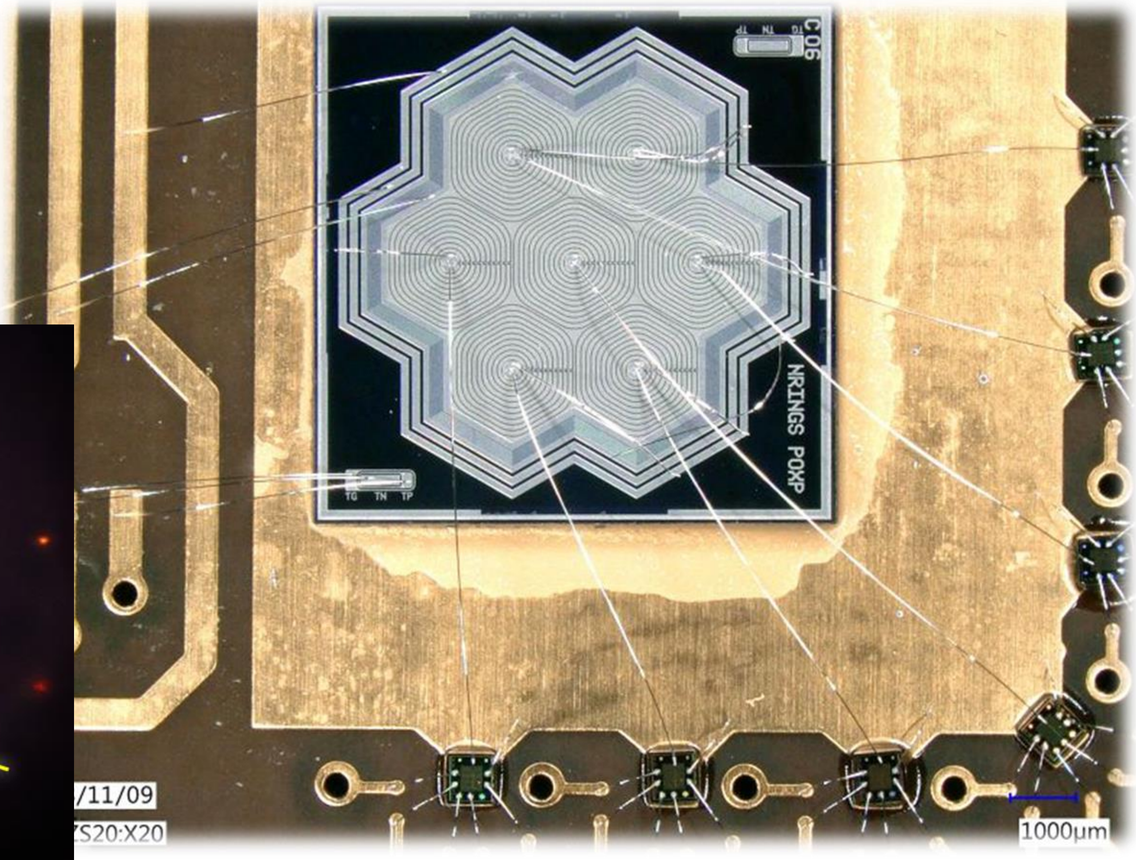
- KATRIN 2019 – 2024: **a new, much steeper slope for Moore´s law**



$m(\nu_e)$ < 1.1 eV (90% CL)

KATRIN 2024:
$m(\nu_e)$ < 0.2 eV (90% CL)
or = 0.35 eV (5 σ)



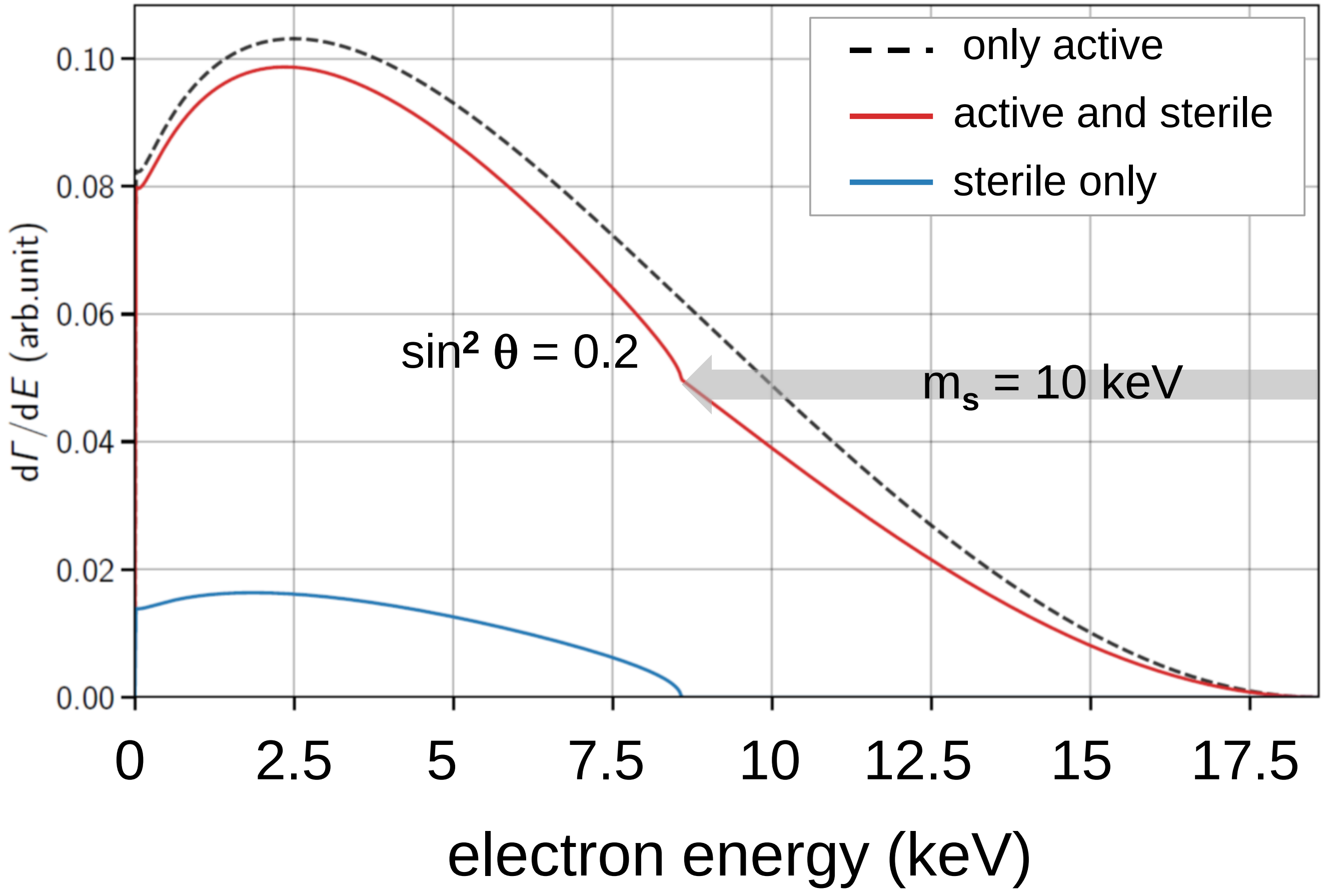


SEARCH FOR KEV STERILE NEUTRINOS

Tritium ß-decay and dark fermions

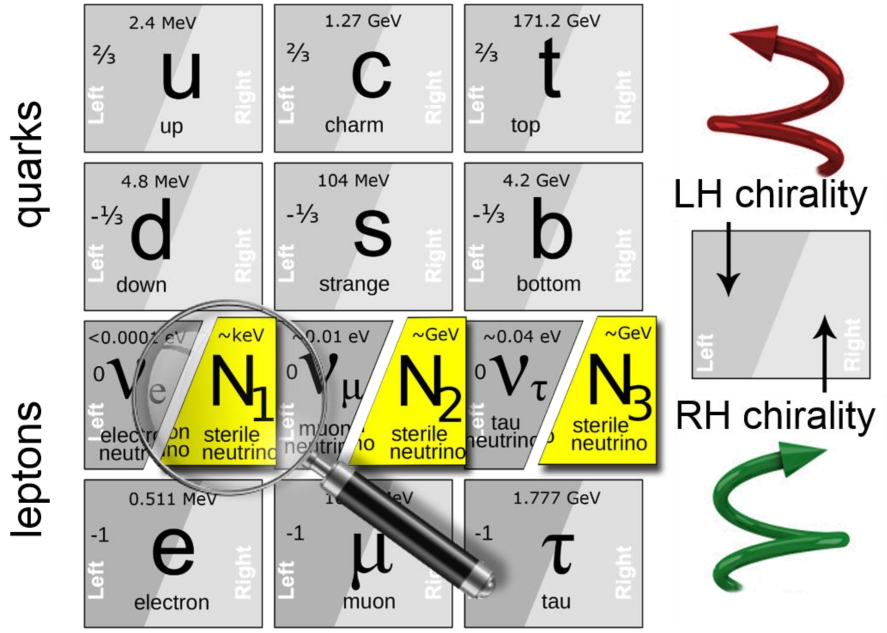
- **BSM particles (sterile neutrinos, light fermionic DM)**
  in keV-mass scale would produce a **´kink´ in the ß-spectrum**

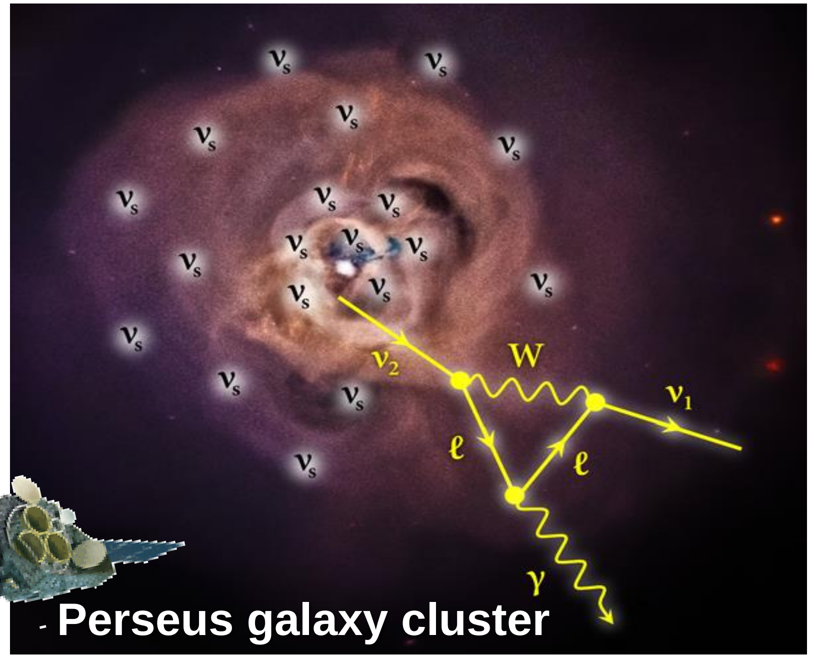
  - cover entire phase space (masses up to 18 keV)
  - cover tiny couplings (~10^{-7}) ⇨ left-right coulings (Rodejohann)



$$\frac{dN}{dE} = \cos^2\theta_s \cdot \frac{dN}{dE}(m_{active}) + \sin^2\theta_s \cdot \frac{dN}{dE}(m_{sterile})$$

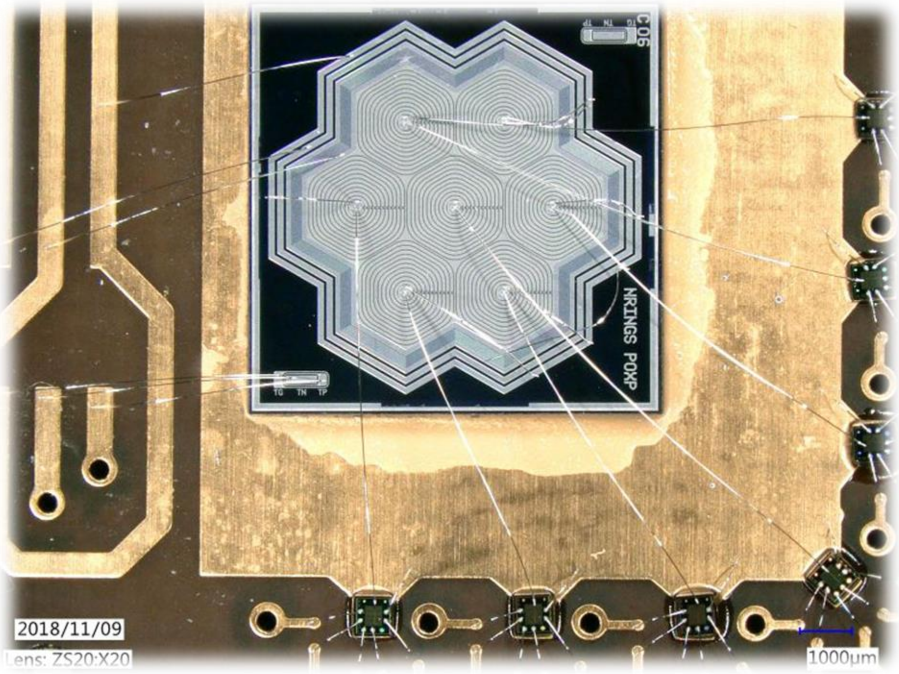
νMSM



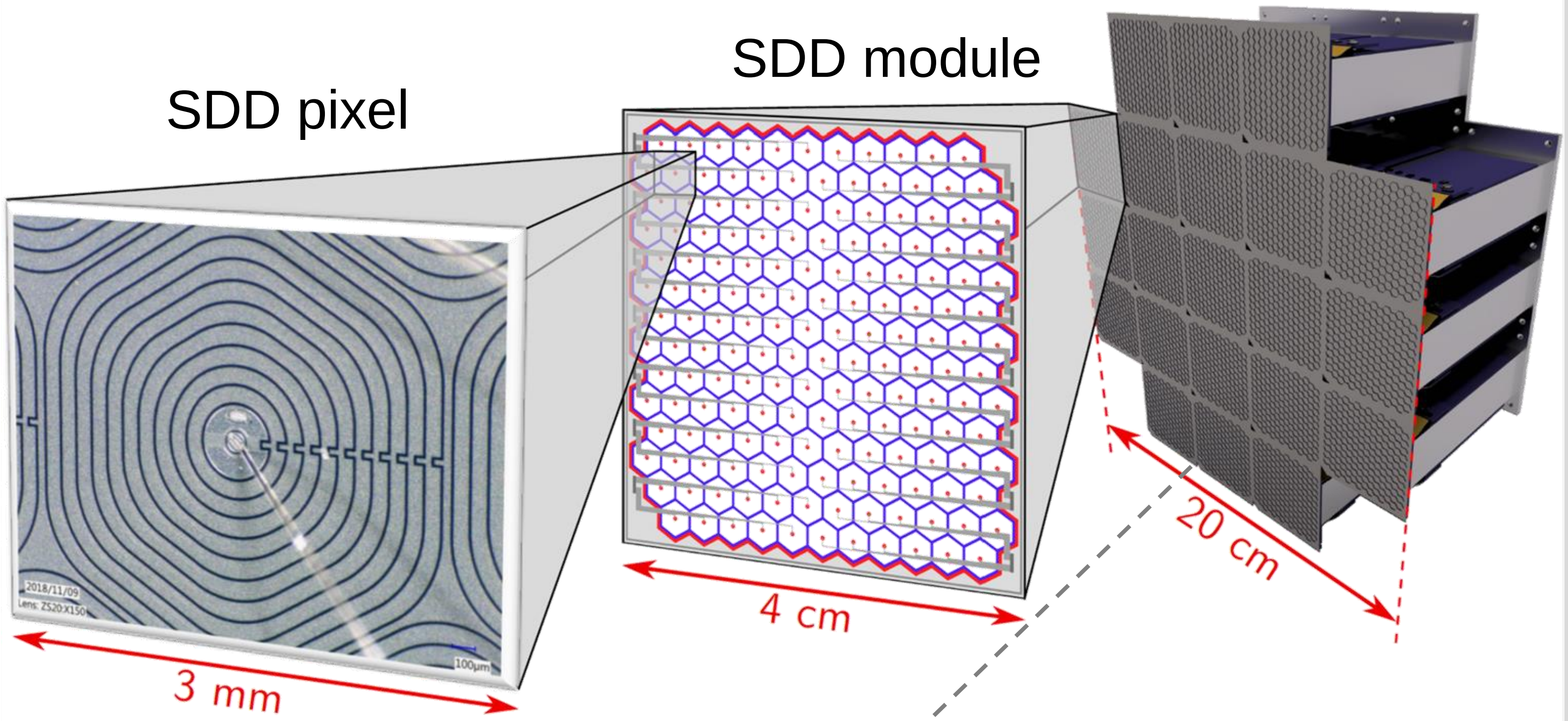


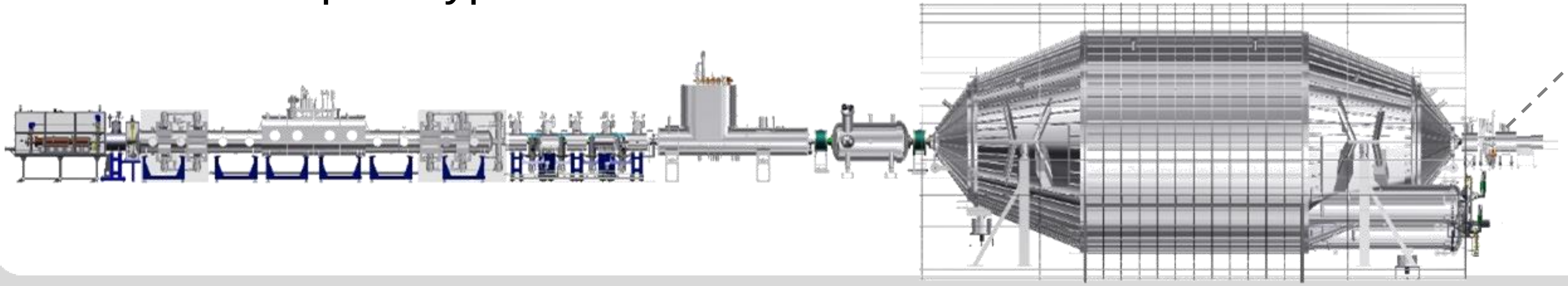
KATRIN with new detector array for entire ß-spectrum

- SDD layout of TRISTAN detector for KATRIN



prototype

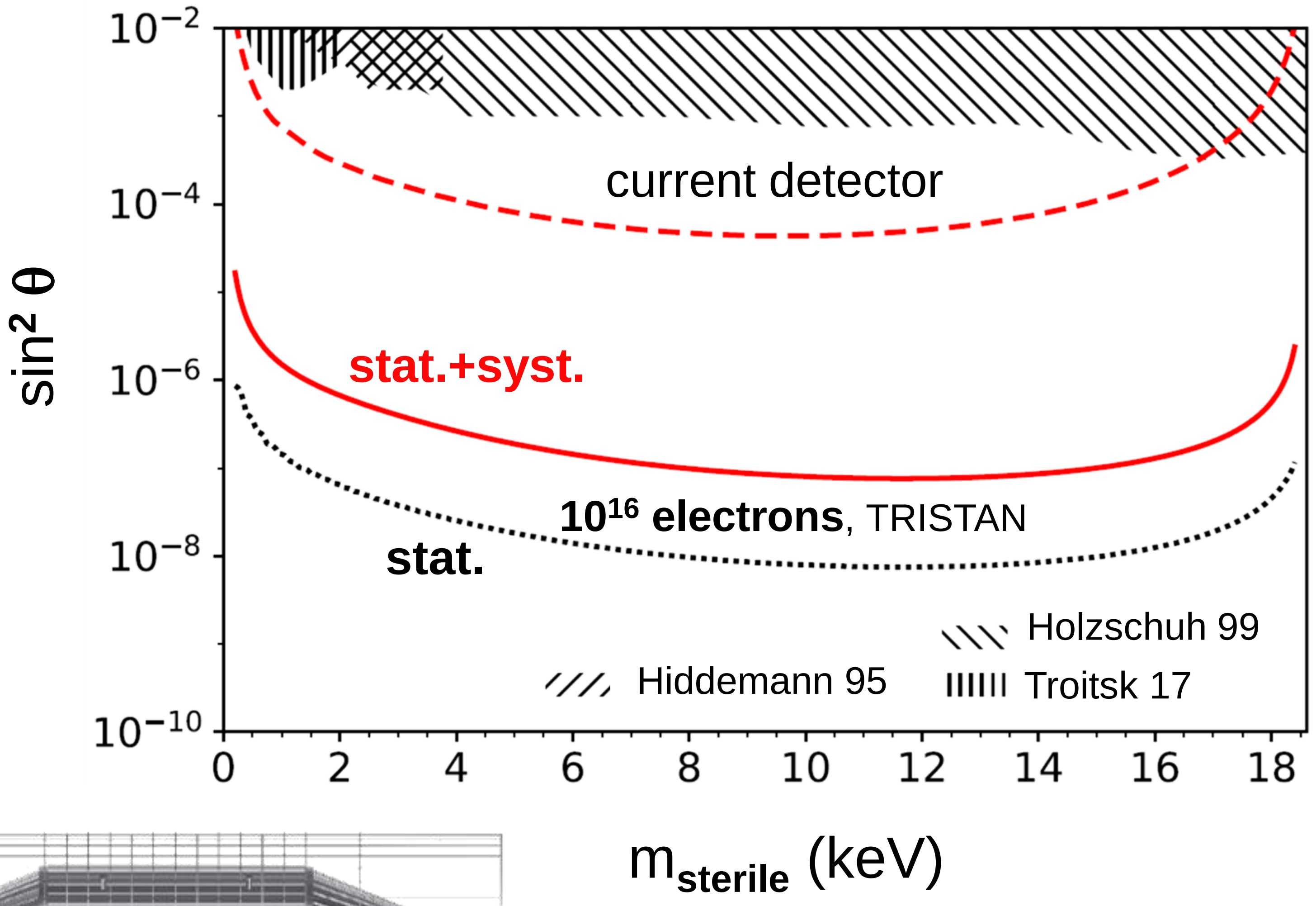


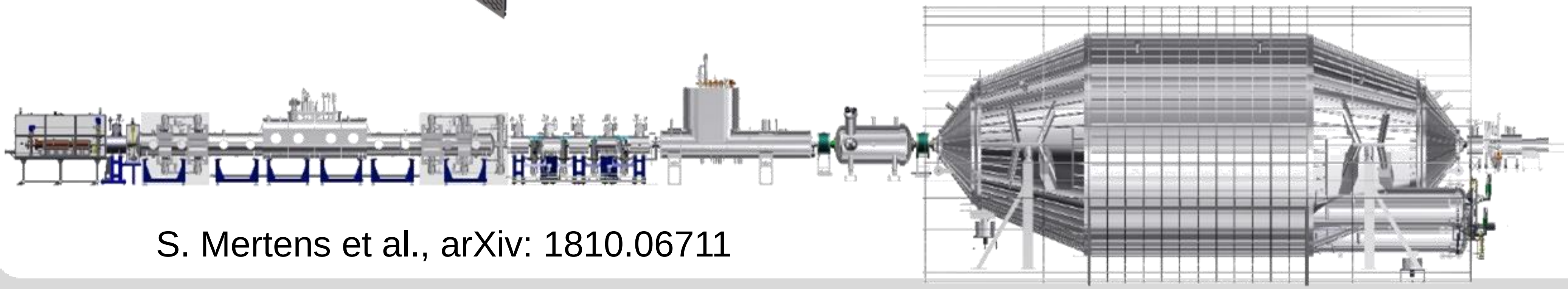


TRISTAN –
TRitium **I**nvestigation on **ST**erile
(**A**) **N**eutrinos

Science reach of KATRIN with new detector array

- estimated **KATRIN sensitivity for** keV-scale sterile neutrinos



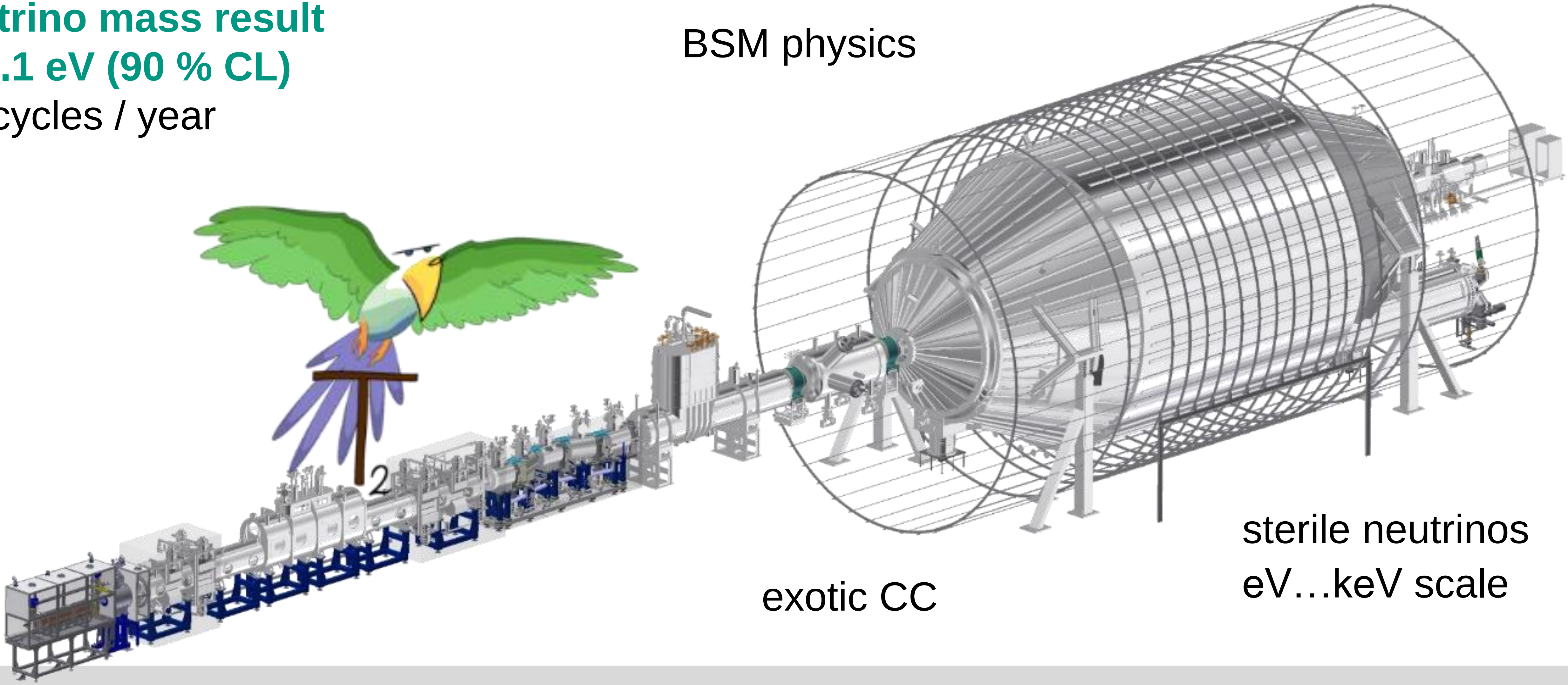


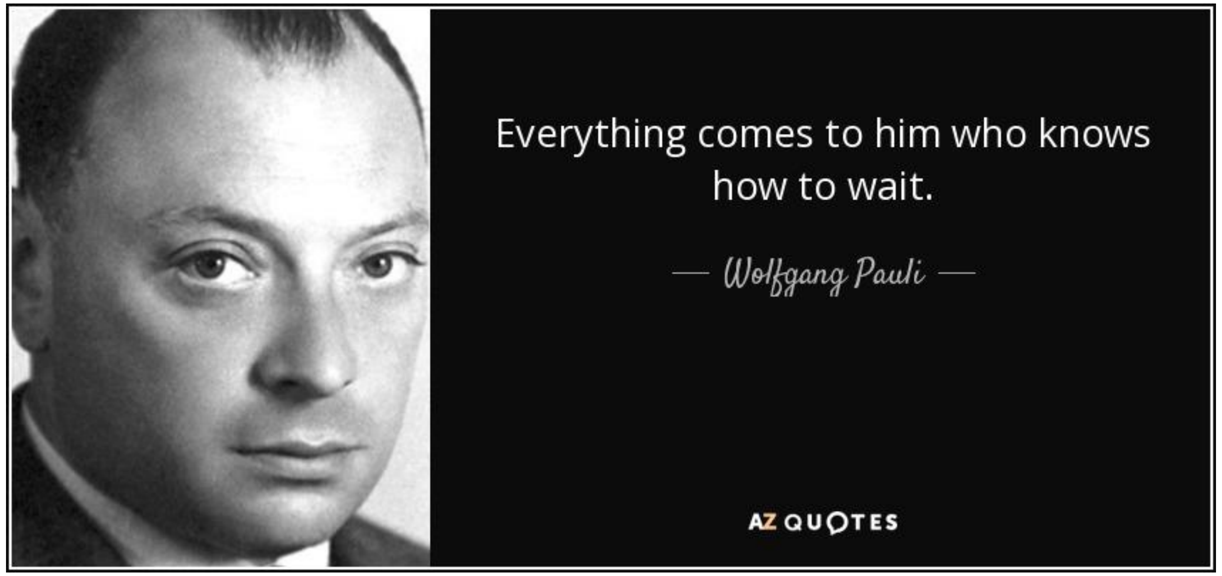
S. Mertens et al., arXiv: 1810.06711

Conclusion

- **major experimental progress of KATRIN & future improvements**

KATRIN:
first neutrino mass result
m_ν < 1.1 eV (90 % CL)
3 cycles / year

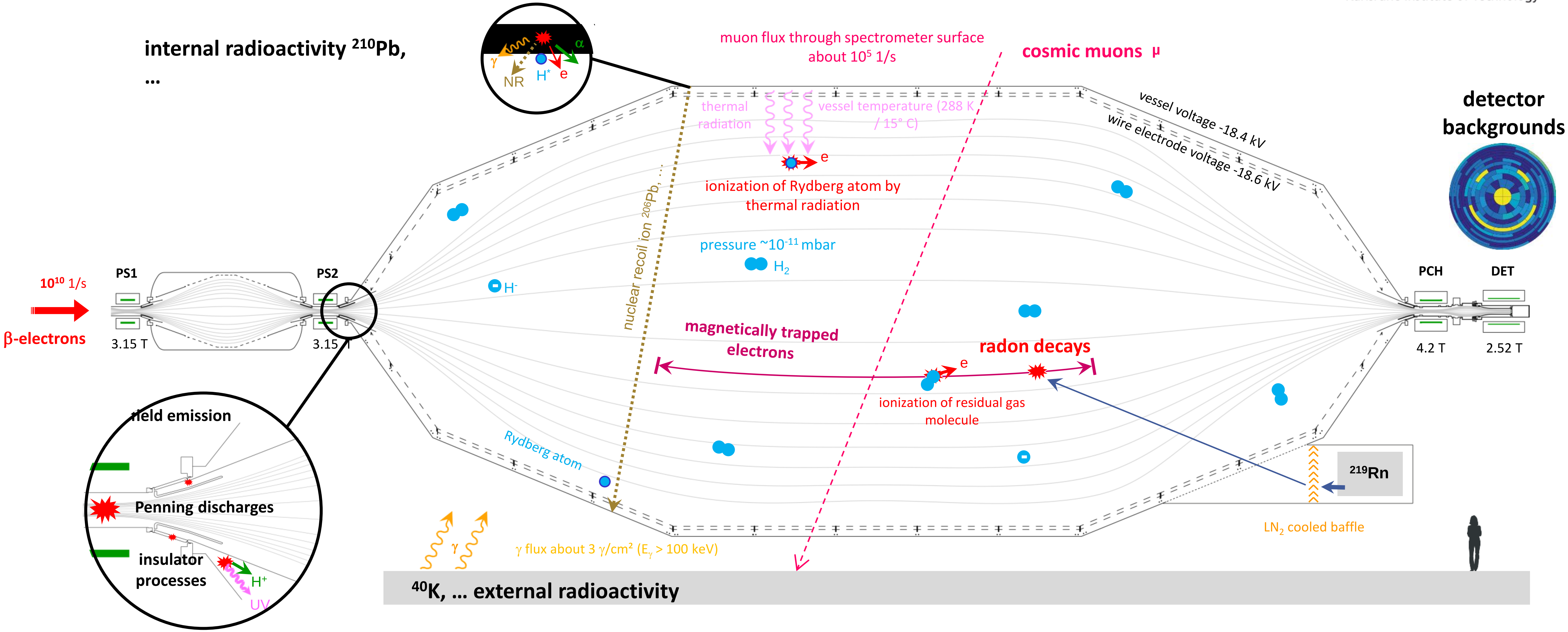



Everything comes to him who knows how to wait.
— Wolfgang Pauli —
AZ QUOTES

THANK YOU!

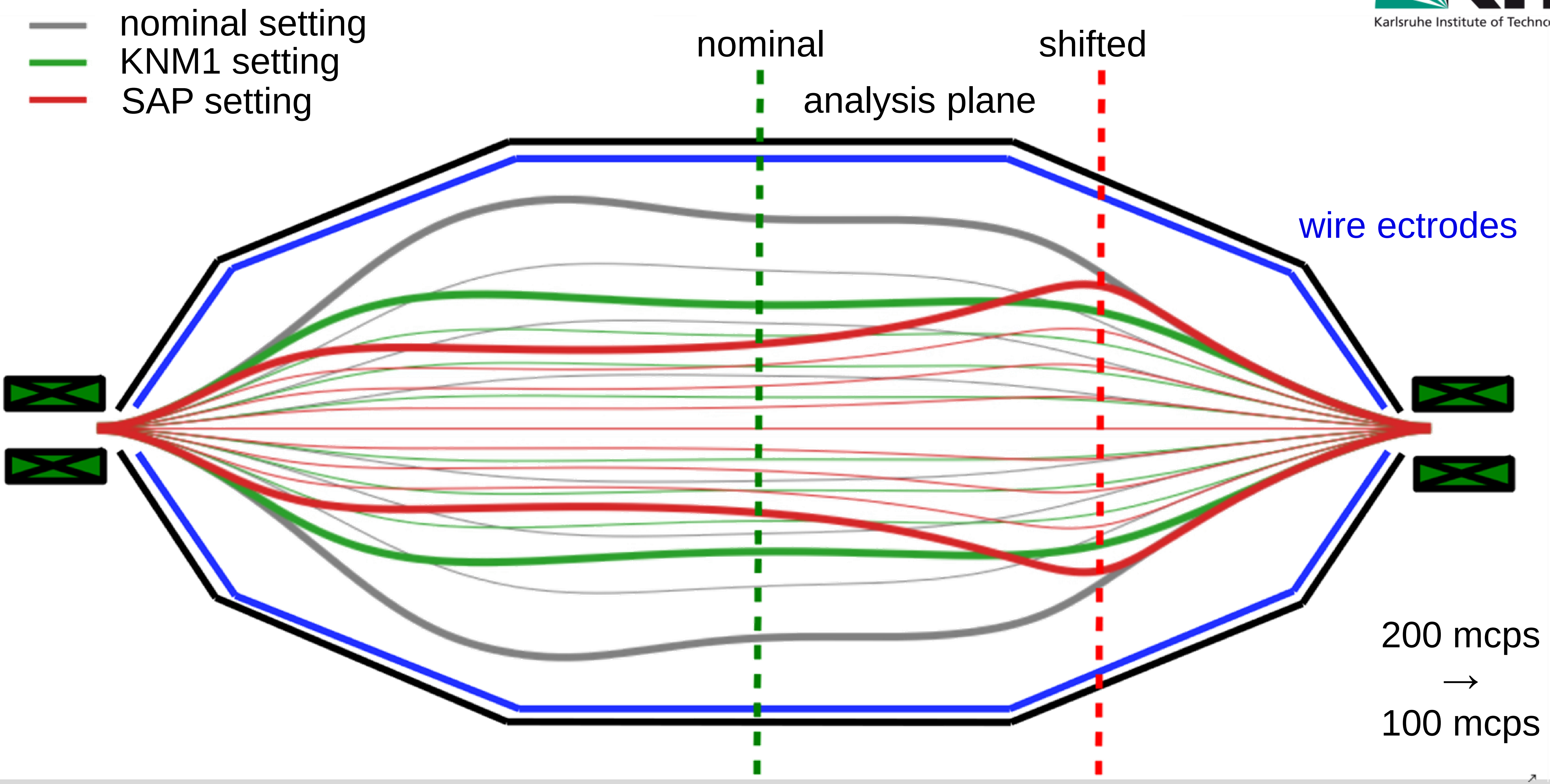
ADDITIONAL TRANSPARENCIES

Background sources



- Various processes contribute to the KATRIN background

Background mitigation: shifted analysis plane (SAP)



neutrino mass upper limit

calculation of confidence belts

- procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC): no empty confidence intervals for fluctuations into region $m^2(\nu_e) < 0$

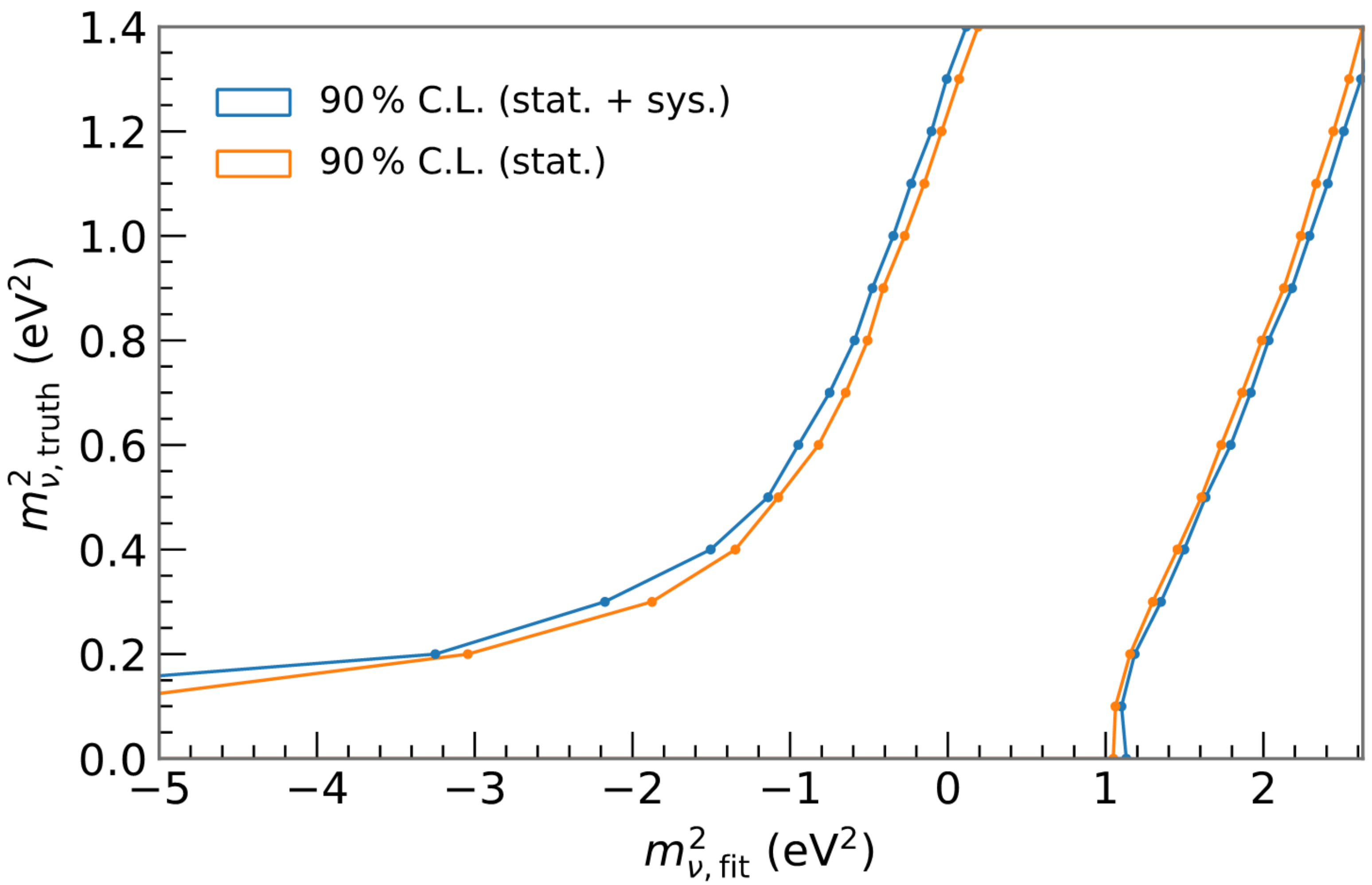
- **KATRIN upper limit on neutrino mass** (LT)

  m(ν) < 1.1 eV (90% CL)

- KATRIN upper limit on neutrino mass (FC)

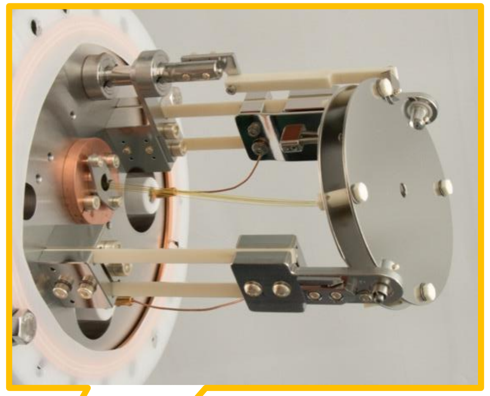
  m(ν) < 0.8 eV (90% CL)

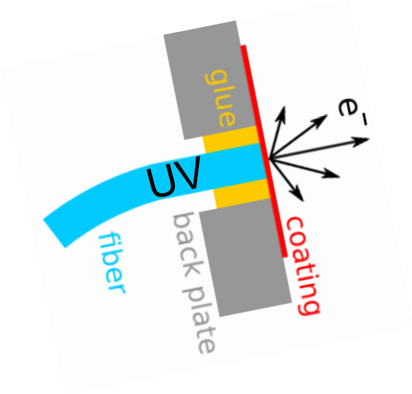
  < 0.9 eV (95% CL)

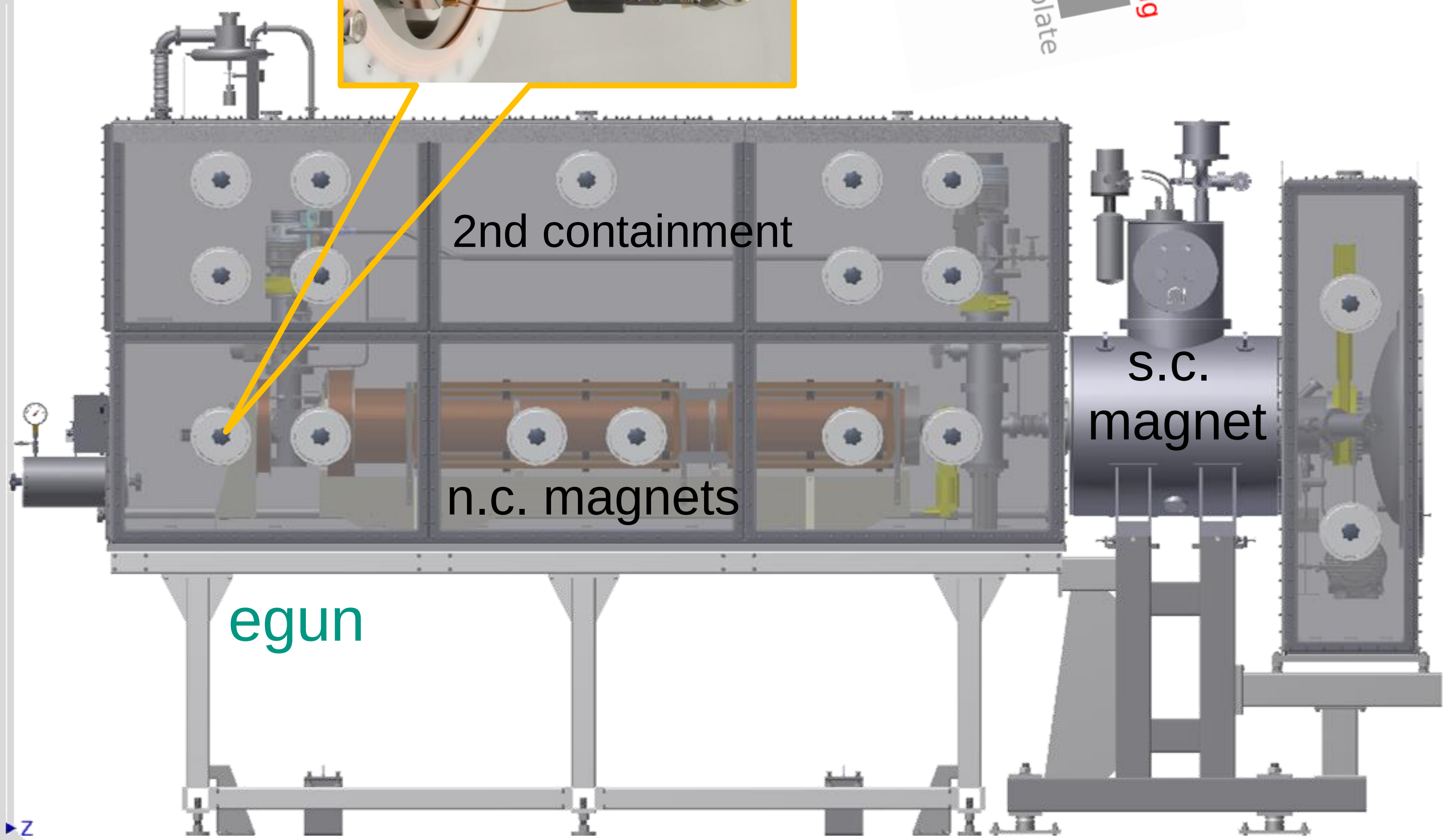


electron gun to measure electron energy losses

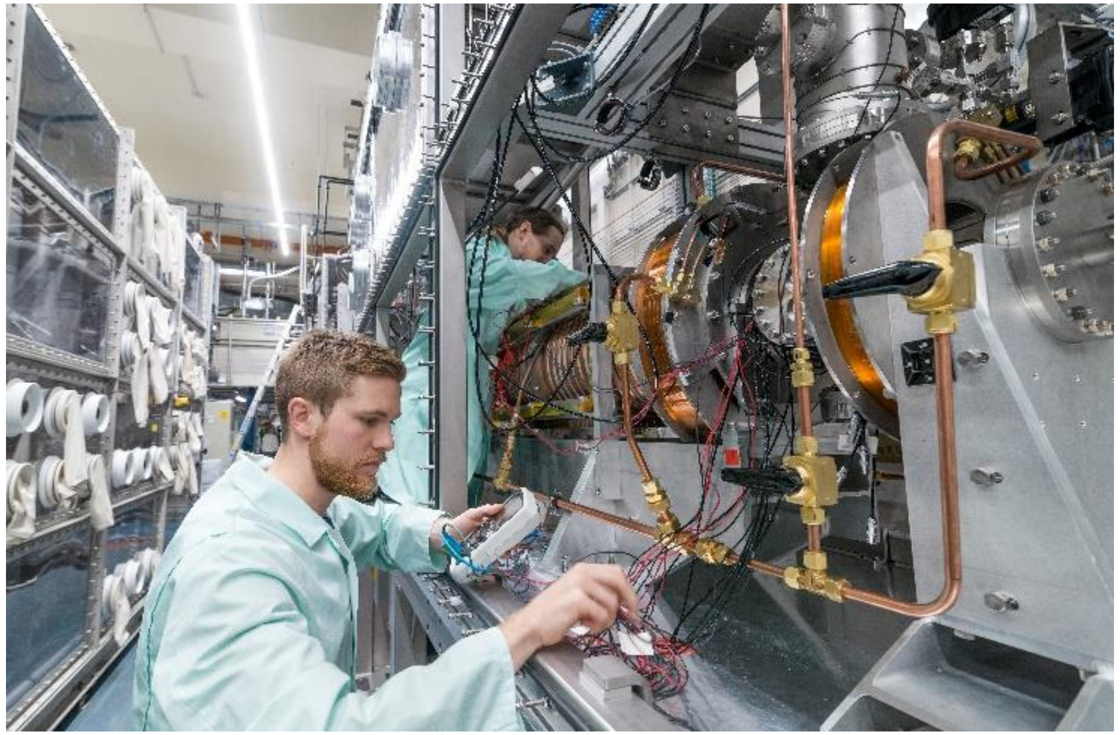
- **Angular selective precison egun:** determine nelastic energy losses in source & ρd





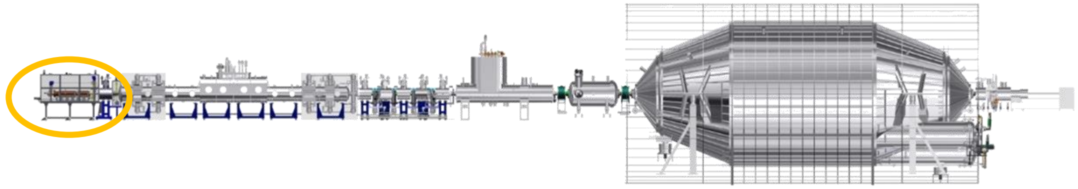


- well-defined pitch angle Δθ
- narrow energy spread ΔE
- excellent stability at high rates

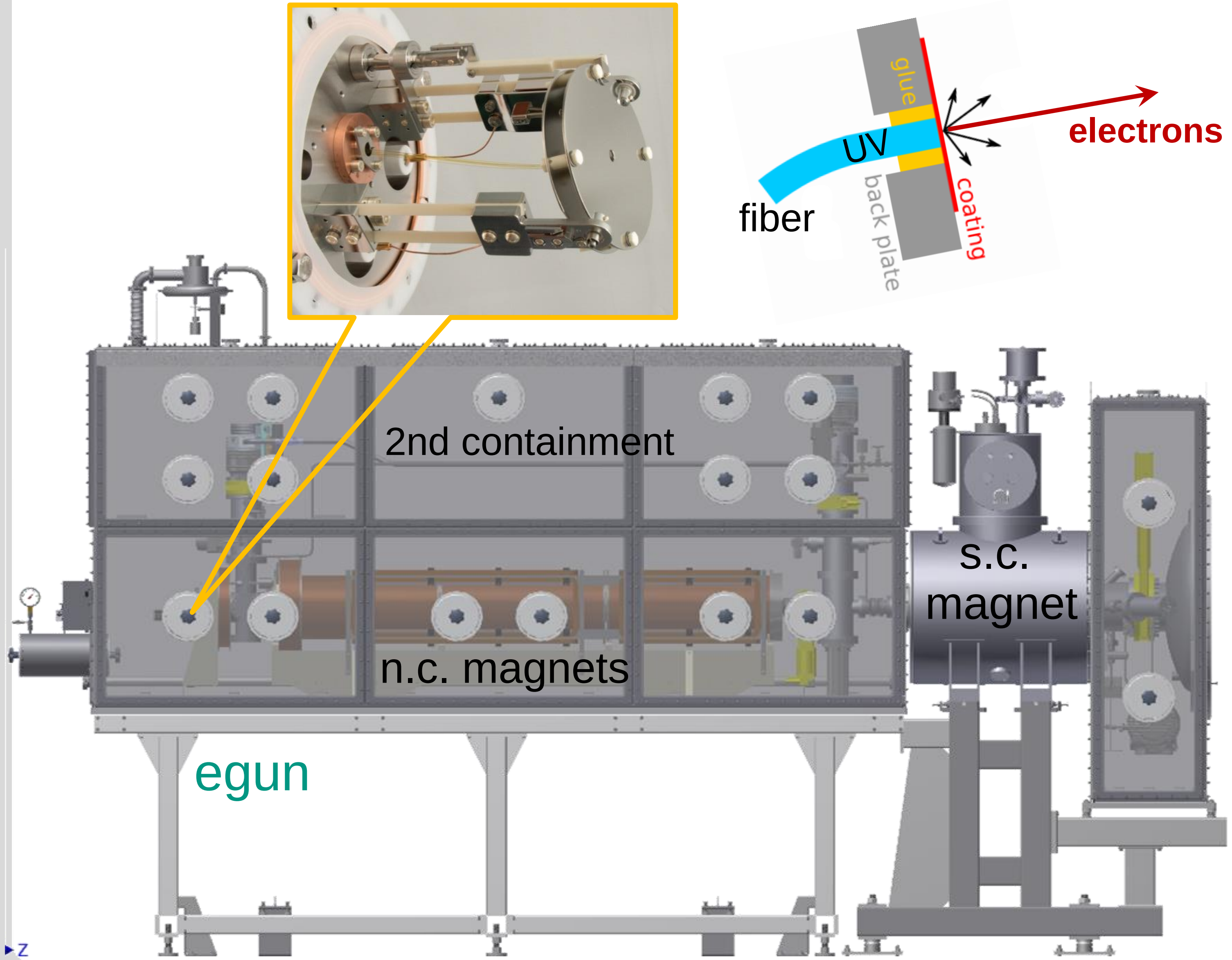


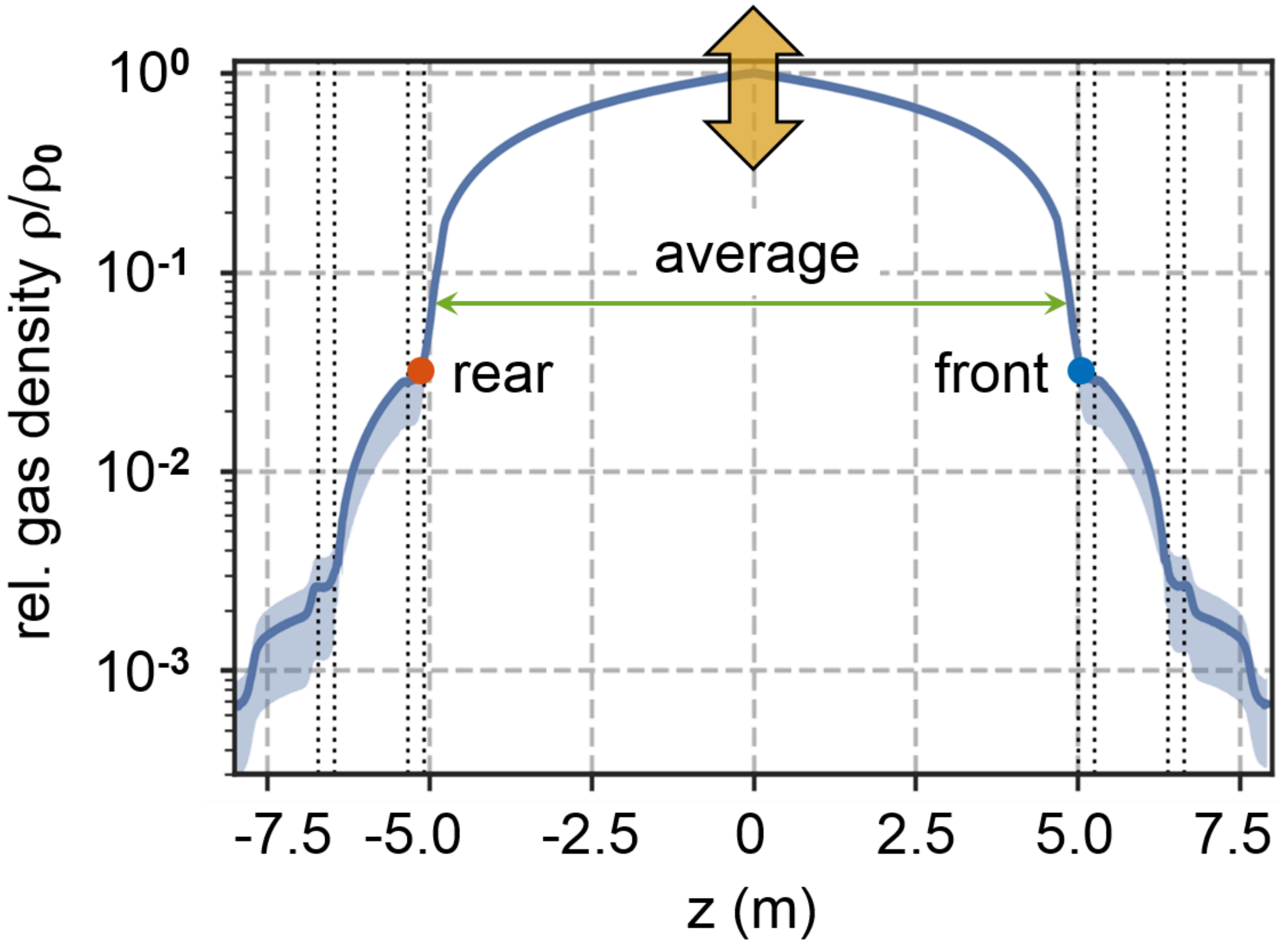
egun during commissioning phase

Egun measurements



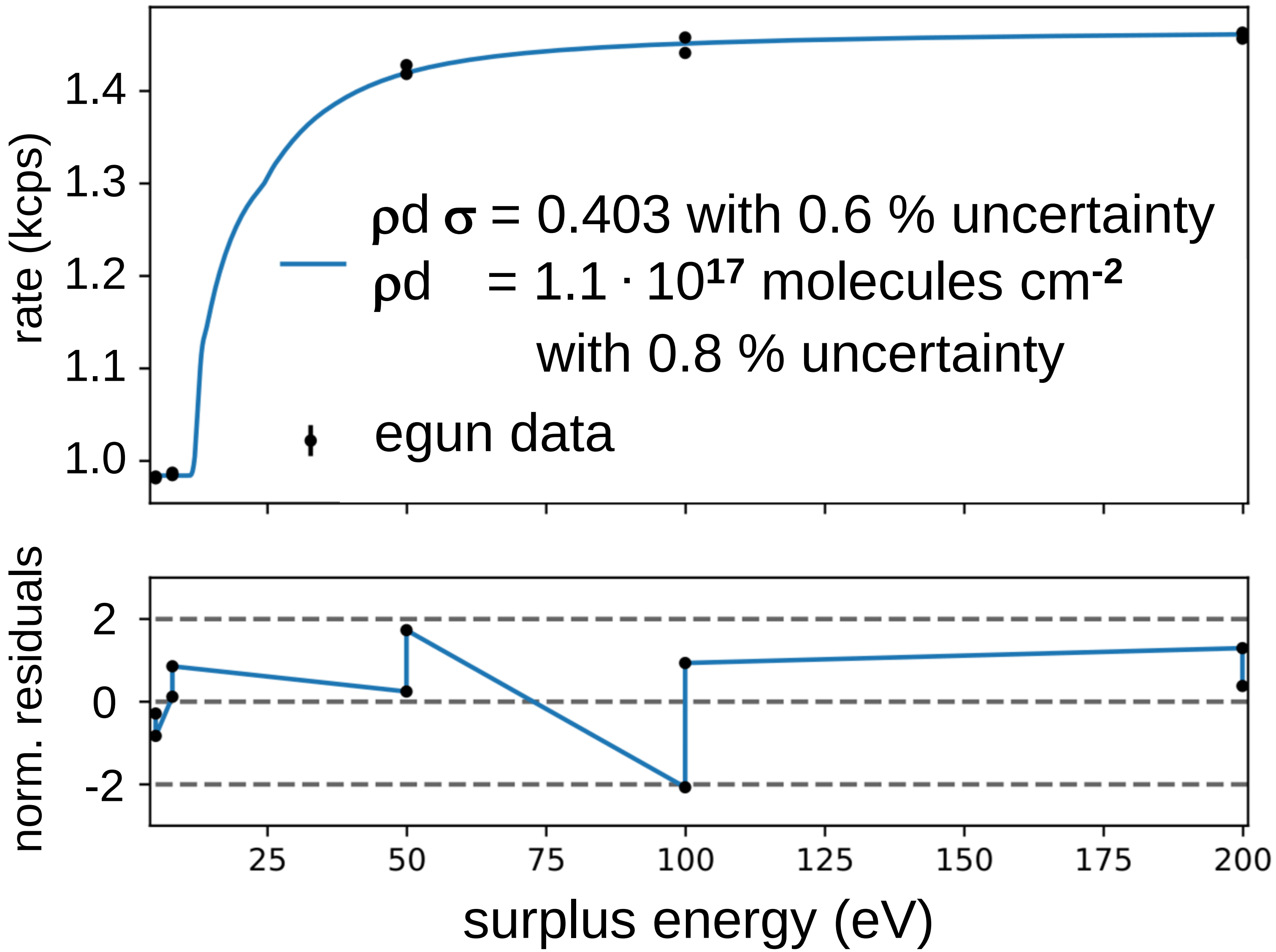
- **Angular selective precison electron gun:** column density ρd

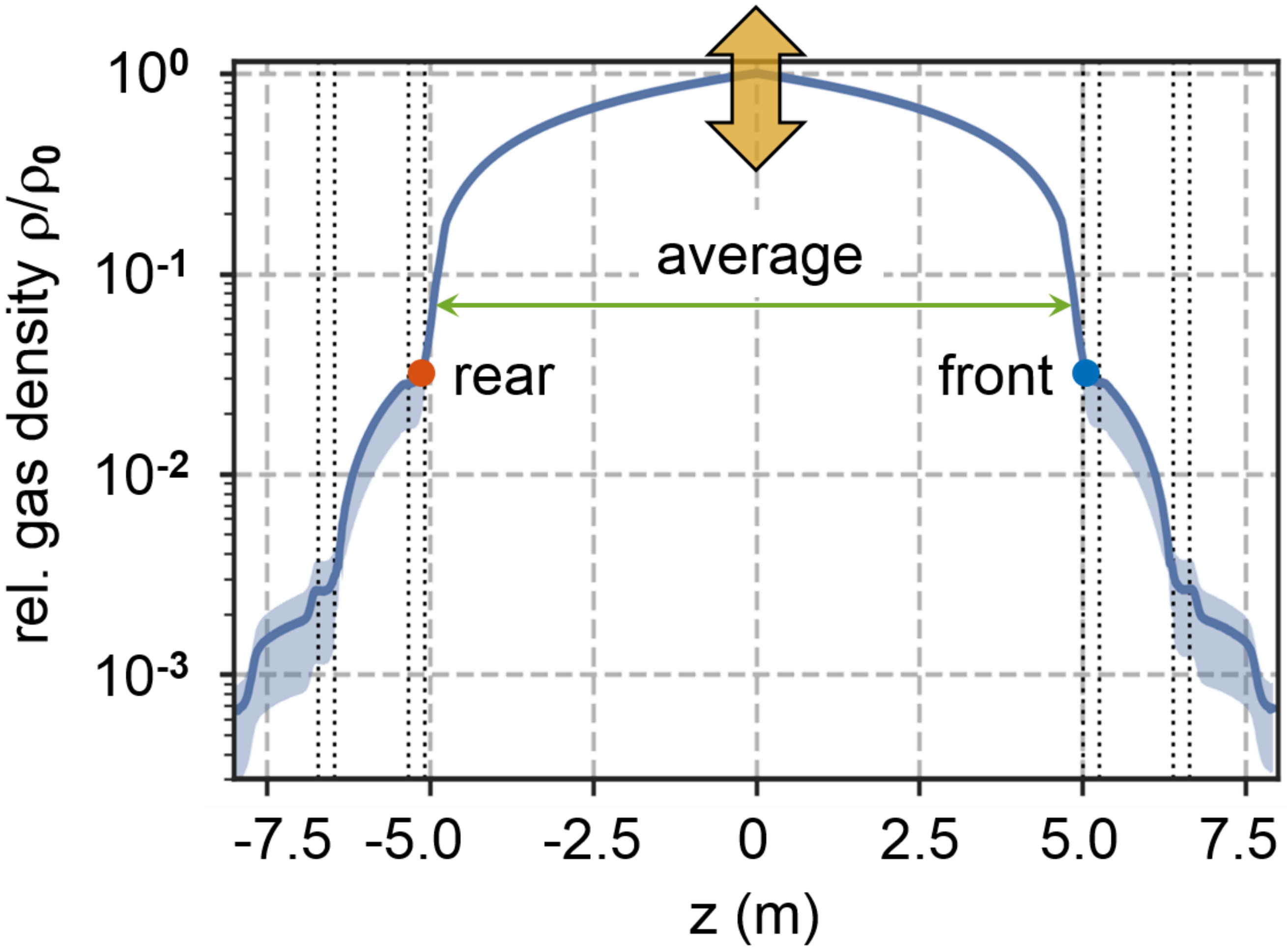




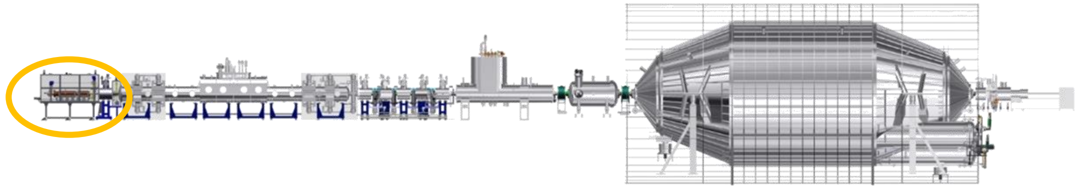
systematics due to column density

- **column density ρd** – in situ measurement of transmission function with egun

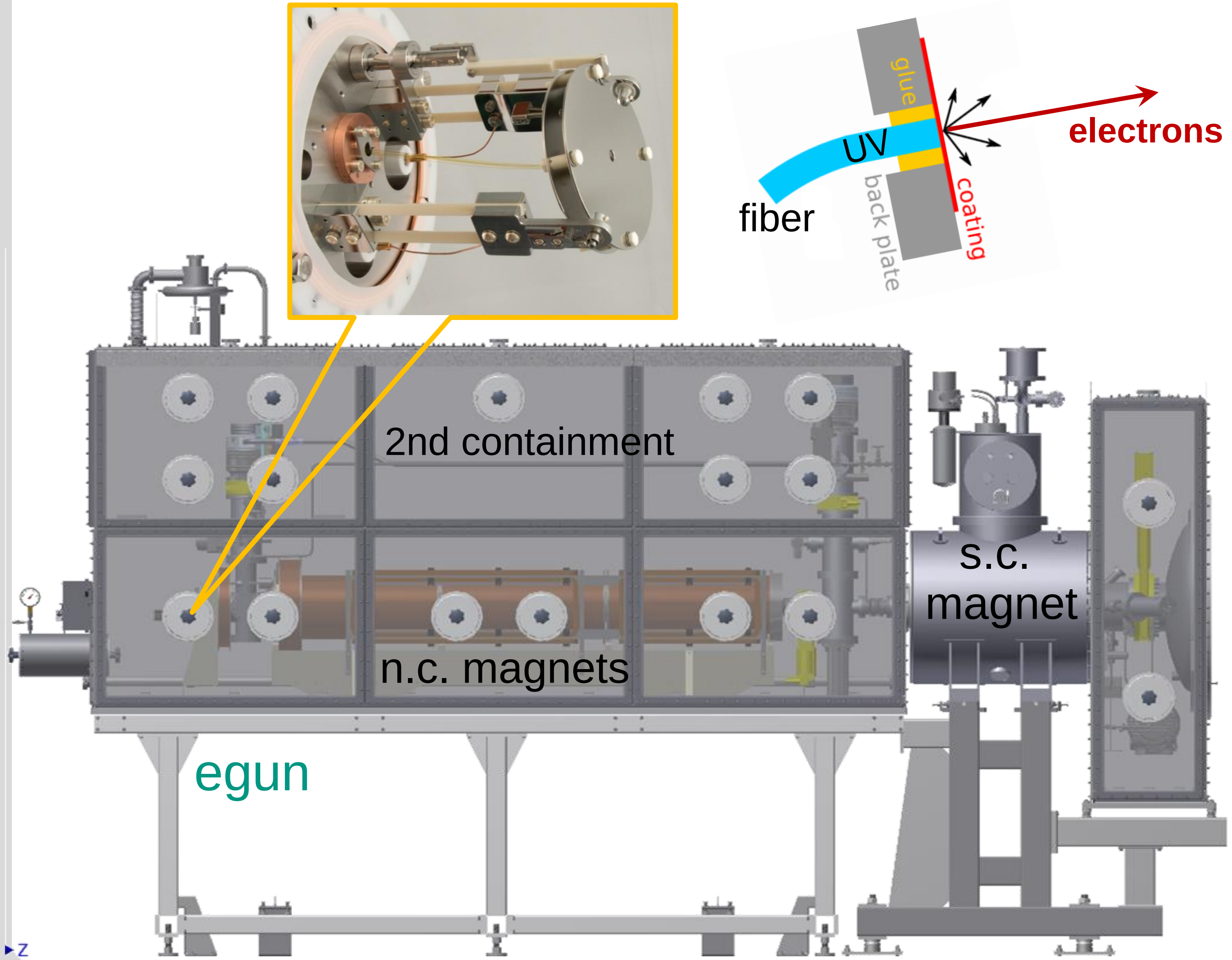


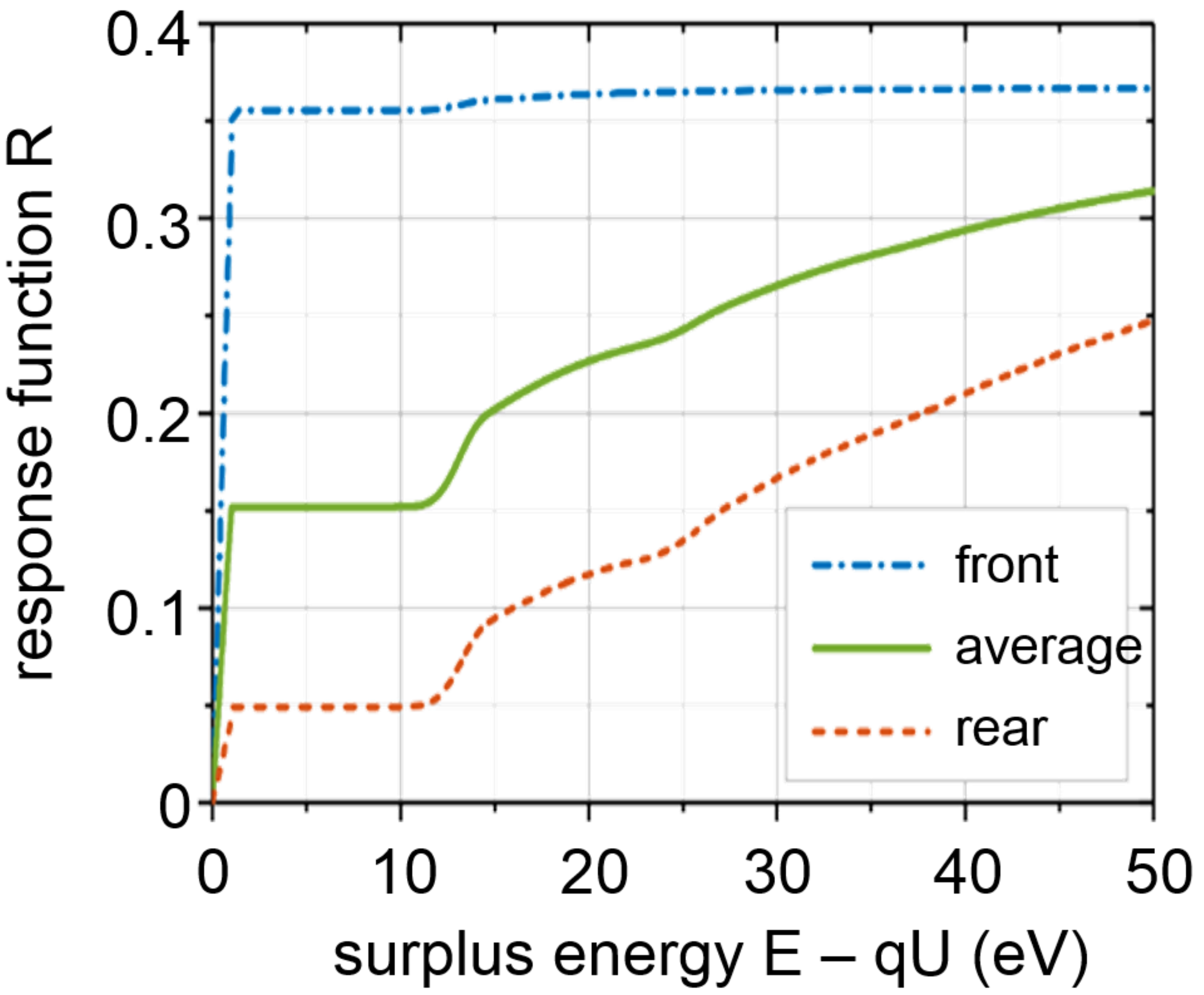


Egun measurements

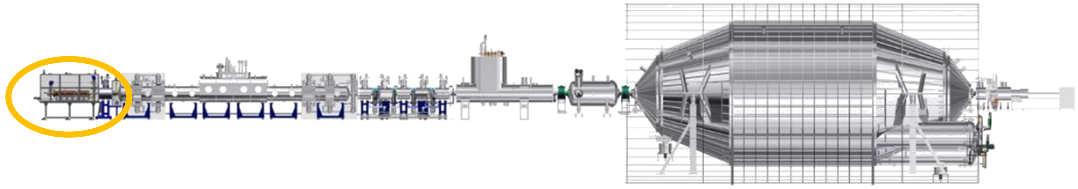


- **Angular selective precison electron gun:** column density ρd & energy losses in source

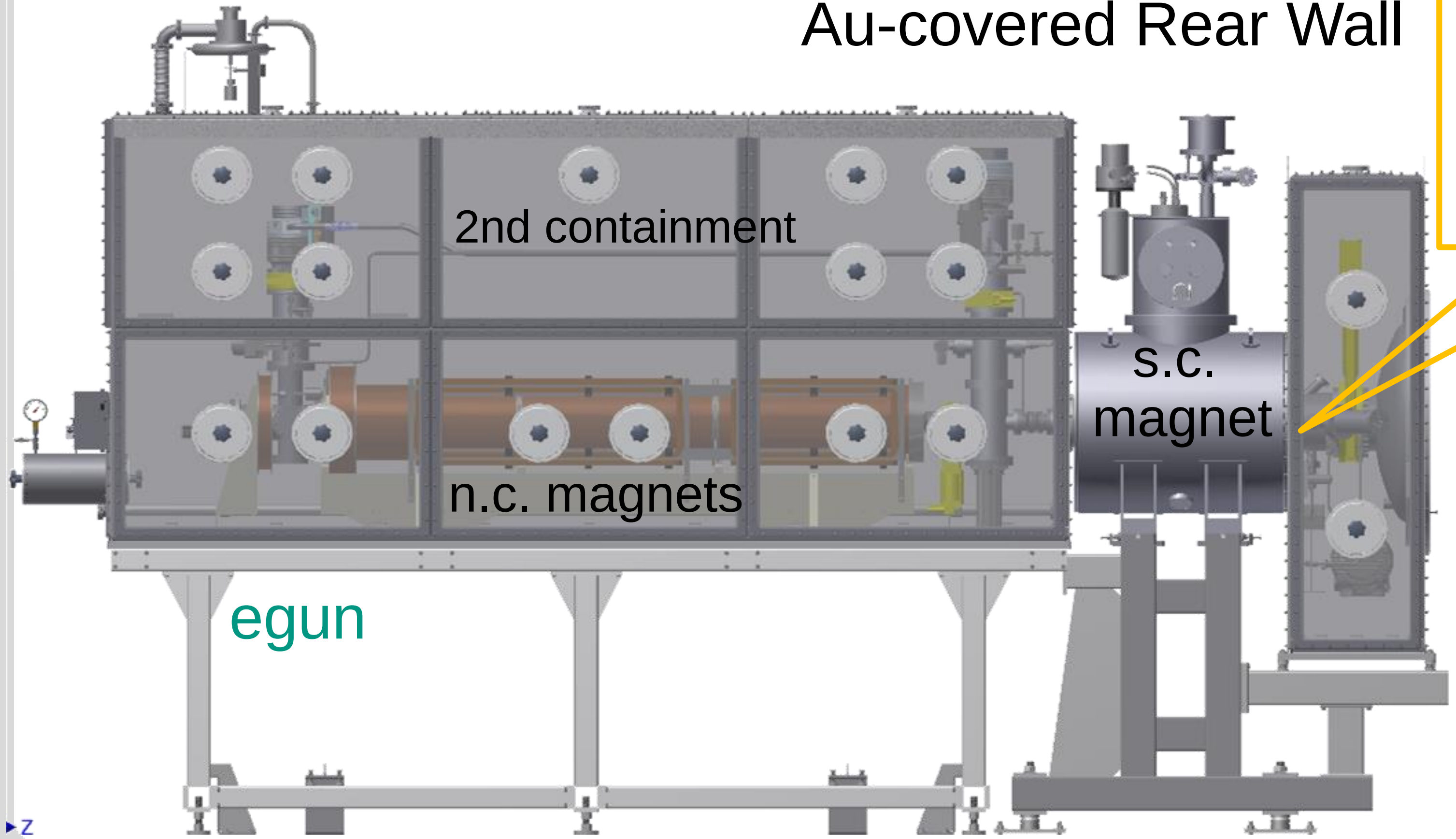




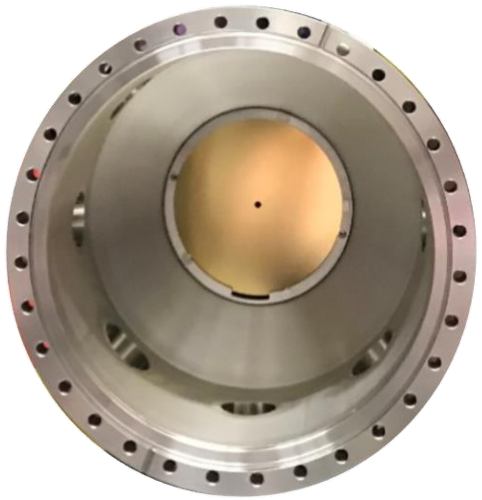
Rear Section-II: Rear Wall



- **Rear Wall:** definition of **source potential** & injection of UV-generated low-energy photo-electrons for **quasi-neutrality of WGTS plasma**, monitoring of T_2 ß-activity via **BIXS** (**B**eta-**I**nduced **X**-Ray **S**pectroscopy)



Au-covered Rear Wall



VUV-illumination source CERMAX