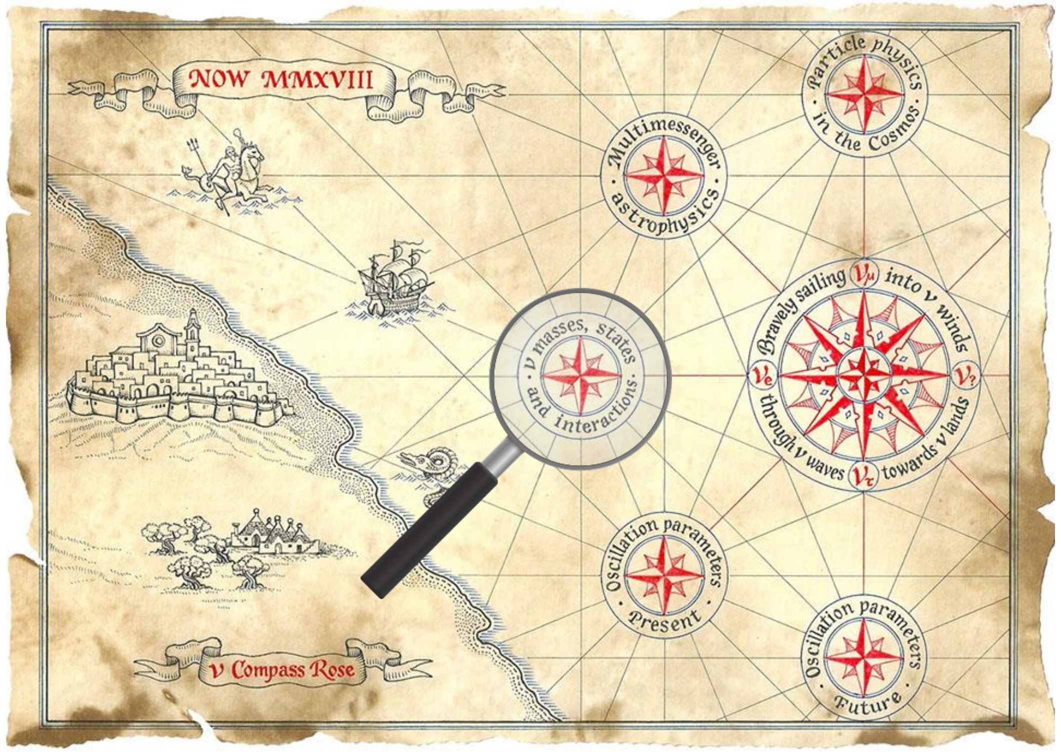
Karlsruher Institut für Technologie

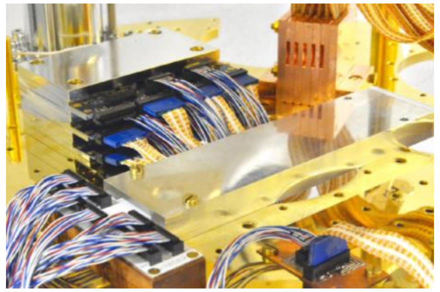


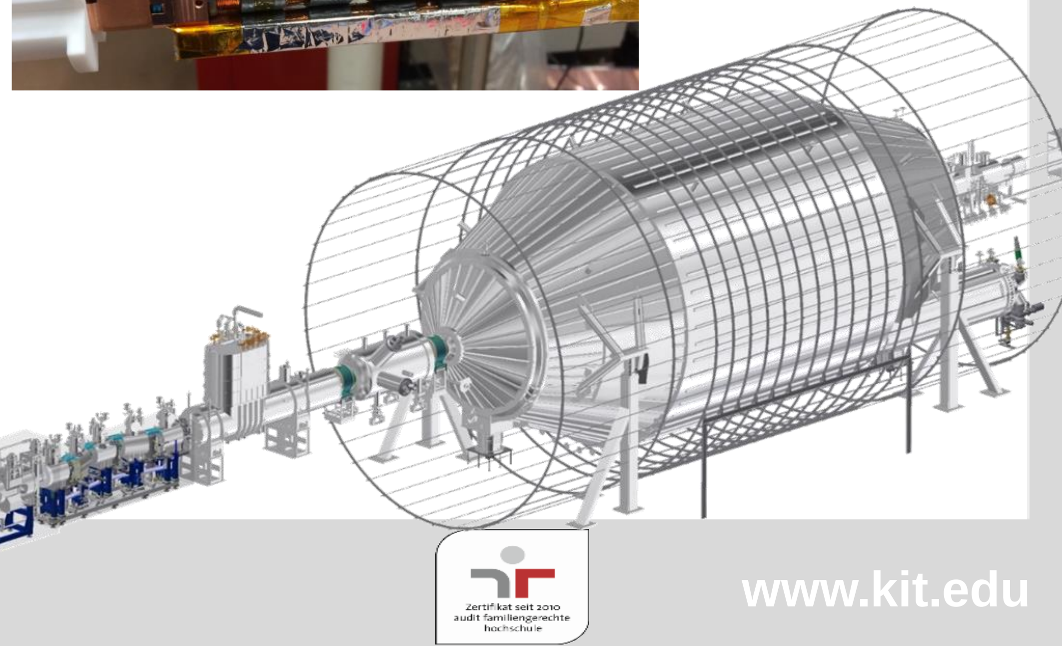
Direct neutrino mass searches

Neutrino Oscillation Workshop NOW 2018
Ostuni, September 9-16, 2018

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

- introduction
- spectroscopy in ß-decay + EC
- **EC of Ho-163**: ECHo & HOLMES
- **ß-decay of H-3**: Project 8 & KATRIN
- searching for keV-sterile neutrinos
- conclusion & outlook





assessing neutrino masses: the three-fold way

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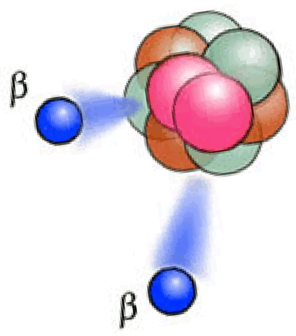
0νßß-decay

- ßß-decay: ^{76}Ge, ^{136}Xe, …
- **model-dependent:**
  Majorana-ν

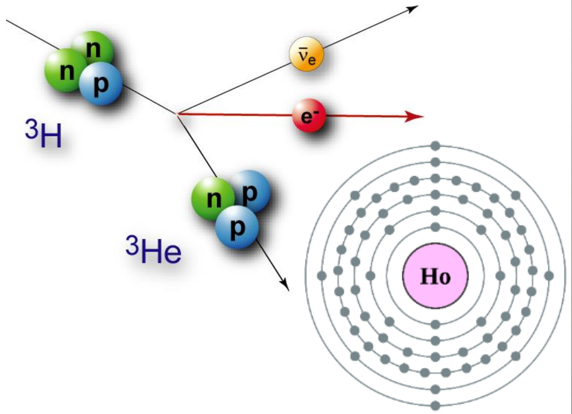
$$\langle m_{ßß} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$



kinematics weak decays

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

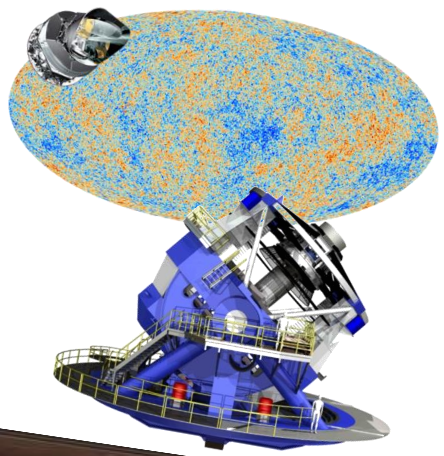
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$



cosmology

- LSS: CMB, GRS, lensing
- **model-dependent:**
  ΛCDM

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



Jose Valle
ν-masses and mixings

Manfred Lindner
new ν-states and interactions

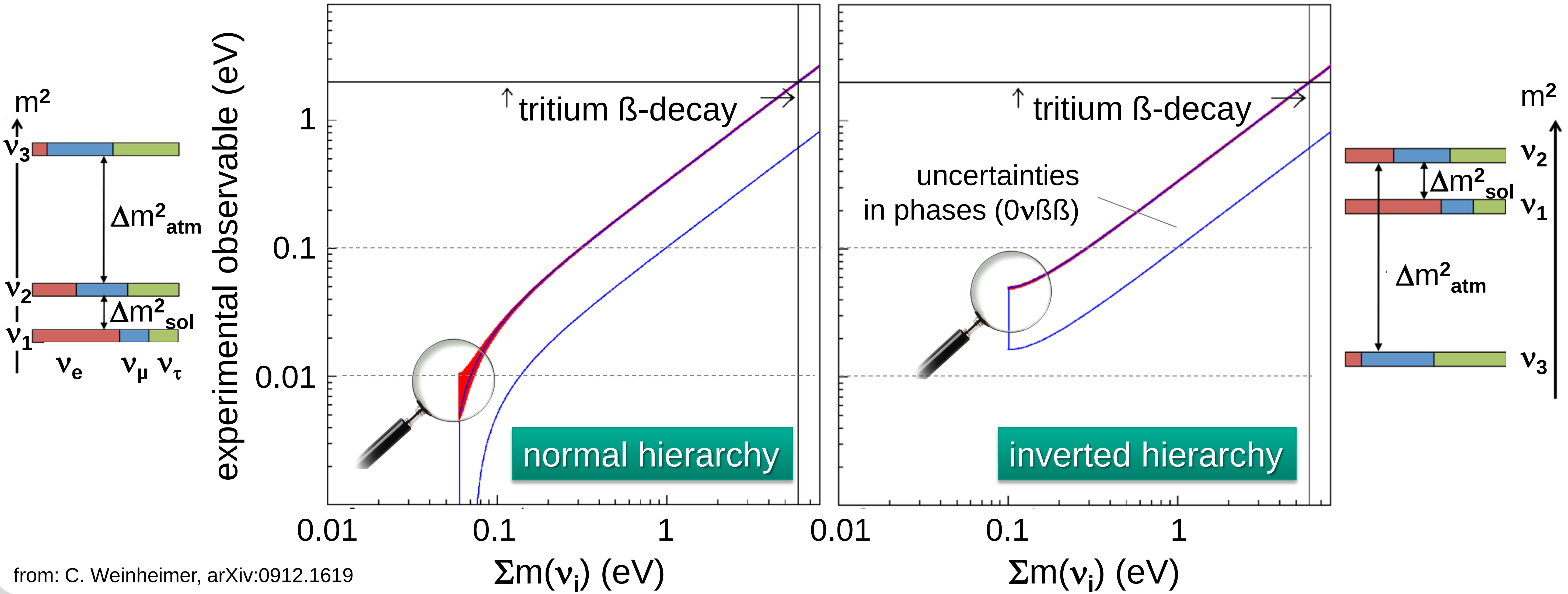
K.Gusev/ F. Simkovic
0νßß- exp./theor. challenges

Yvonne Wong
Neutrinos In Cosmology

ν

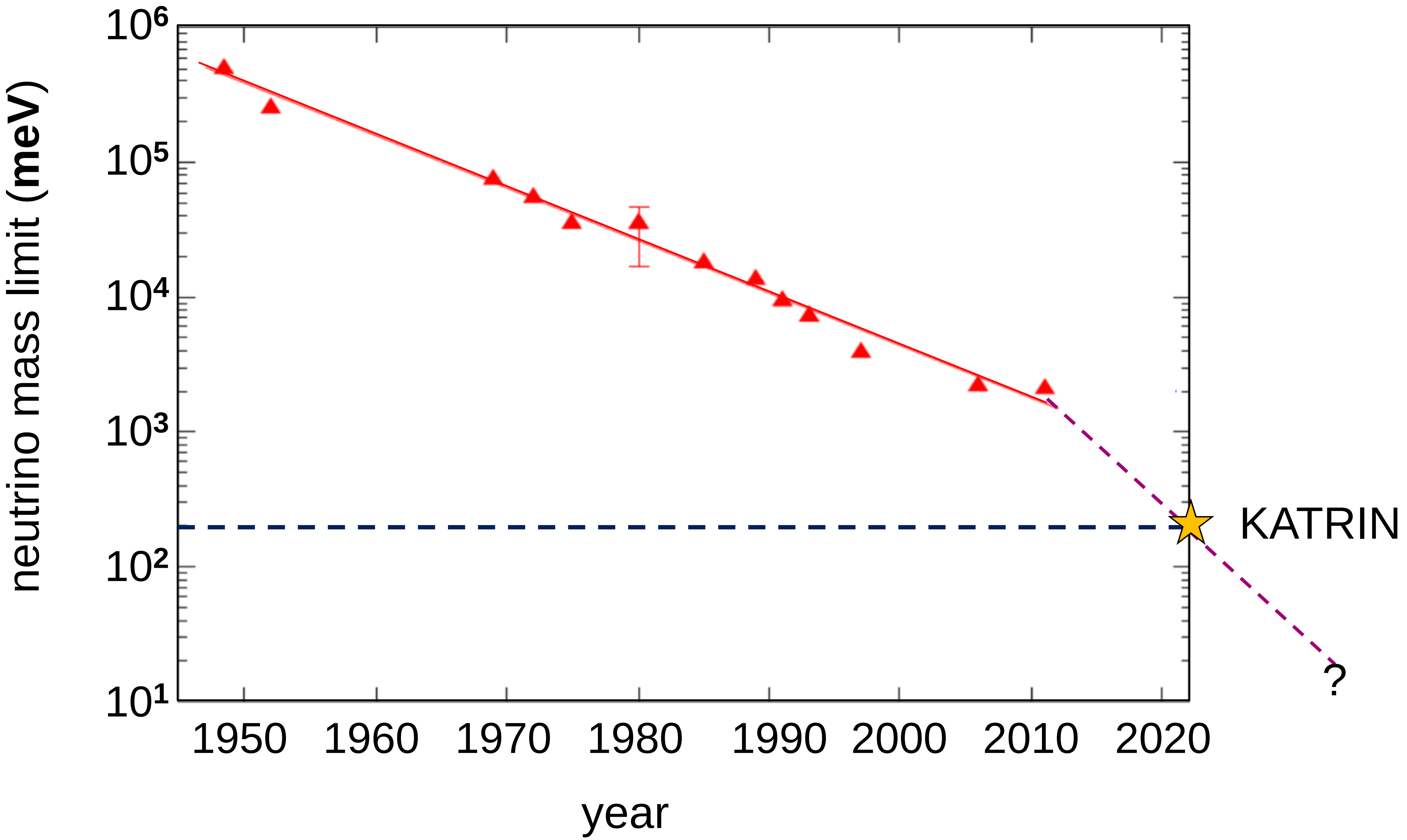
ν-masses from kinematic studies – the challenge

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

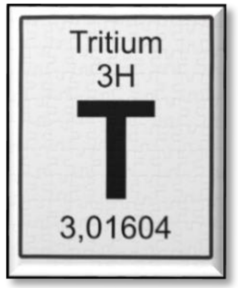


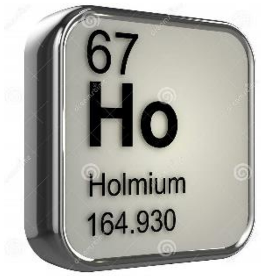
from: C. Weinheimer, arXiv:0912.1619

Moore´s law of direct ν-mass sensitivities



Complementarity: tritium ß-decay & EC of ^{163}Ho

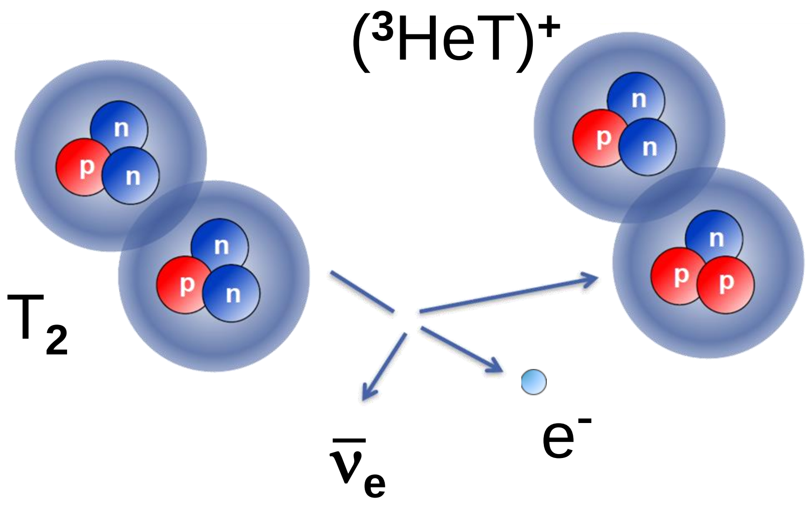




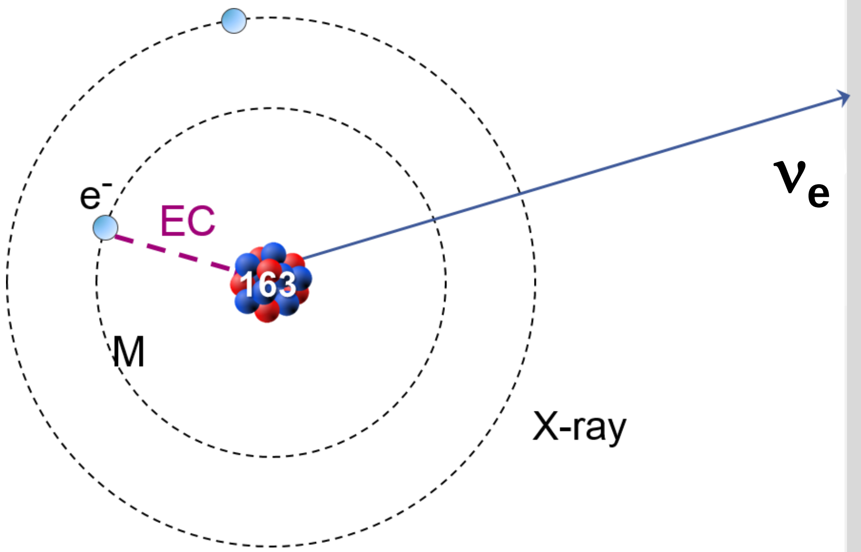
$(^3H)_2 \rightarrow (^3He\text{-}T)^+ + e^- + \bar{\nu}_e$

ß-source requirements
kinematics: short $t_{½}$ & low E_0
(super-) allowed transition
good understanding of final state
high isotopic purity & source stability
well-established procurement method

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



only two isotopes of choice:
tritium & holmium



Complementarity: tritium ß-decay & EC of ^{163}Ho

4 × 10^8 atoms for 1 Bq

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

molecular ☑
condensed ☑ (but charging)
atomic, gas (?)

ß-source requirements
kinematics: short $t_{½}$ & low E_0
(super-) allowed transition
good understanding of final state
high isotopic purity & source stability
well-established procurement method

only two isotopes of choice:
tritium & holmium

2 × 10^{11} atoms for 1 Bq

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

atomic, in solid state, embedded in (ordered) crystal

direct neutrino mass experiments – read-out

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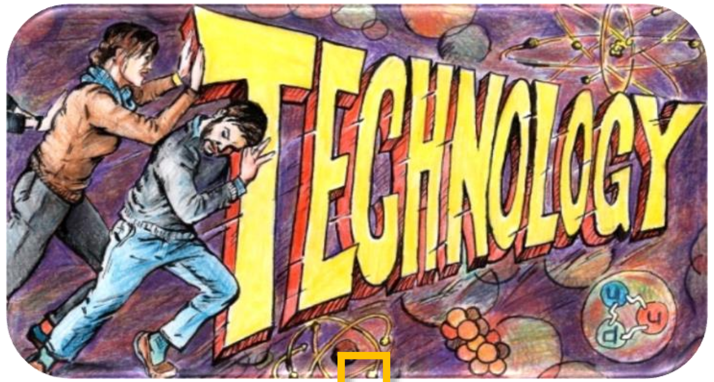
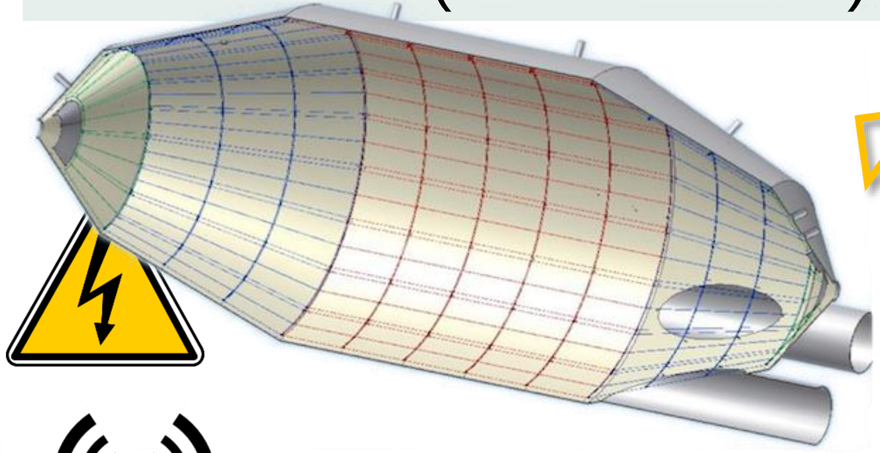


MAC-E filter

min. longitudinal ß-energy $E_{\parallel}$

ΔE = 0.9 eV (100% transm.)



electron energies

cyclotron radiation

max. transversal ß-energy $E_{\perp}$

ΔE = 2-3 eV (FWHM)

ß-detection requirements

Tritium 3H T 3,01604

cover large solid angle (~ 2π)

very low background rate at E_0

high energy resolution (~ eV)

short dead time, no pile up

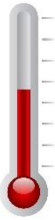
67 Ho Holmium 164.930

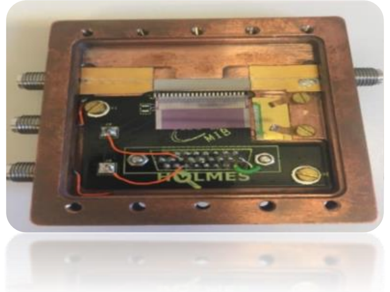
MAC-E filter:
highest energy resolution

thermal μ-calorimeter

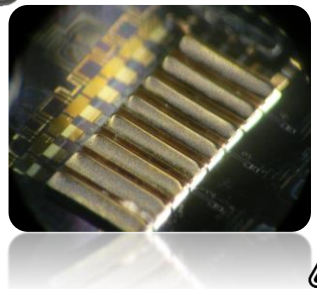
released decay-energy

ΔE ~ 5 eV (FWHM)





calorimeter: source ⬄ detector



metallic magnetic calorimeter

released decay-energy

ΔE = 2-5 eV (FWHM)

direct neutrino mass experiments – the projects

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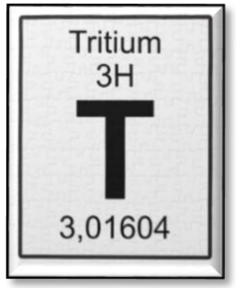
MAC-E filter
min. longitudinal ß-energy $E_{\parallel}$
ΔE = 0.9 eV (100% transm.)

thermal µ-calorimeter
released decay-energy
$\Delta E \sim$ 5 eV (FWHM)

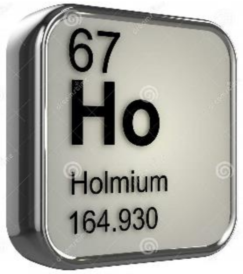


KATRIN
KARLSRUHE TRITIUM NEUTRINO EXPERIMENT

PROJECT 8

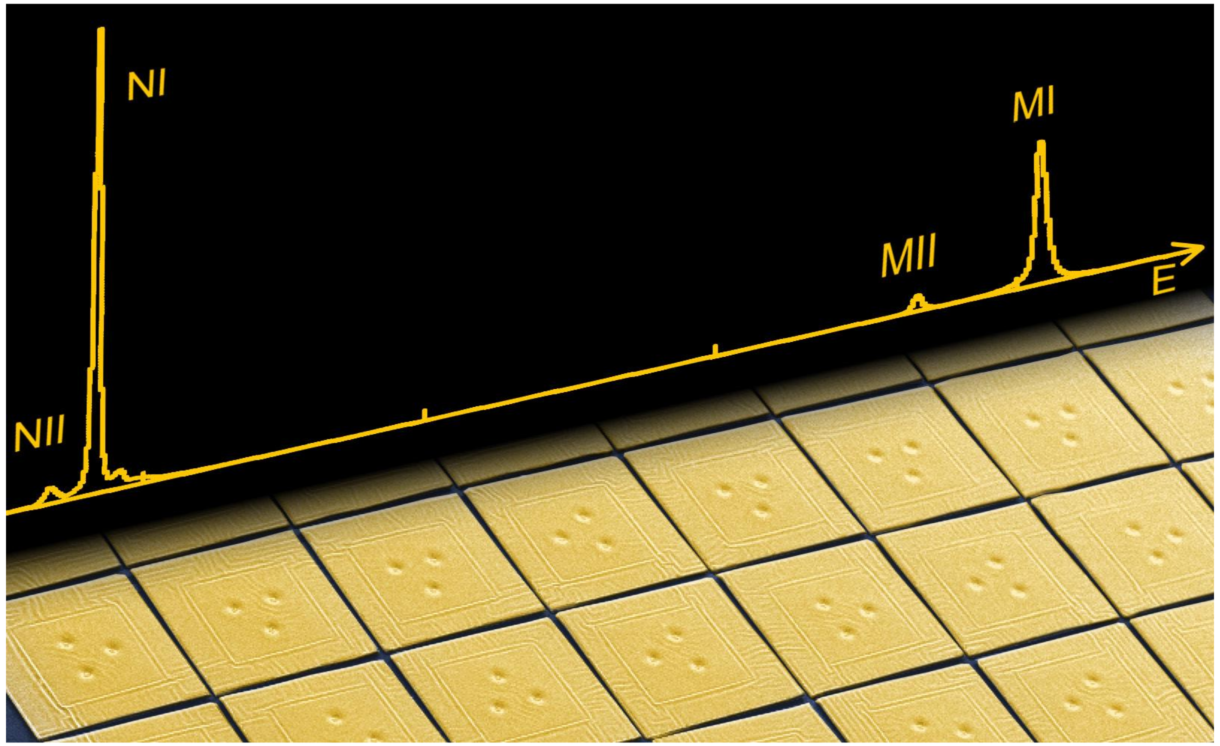
HOLMES

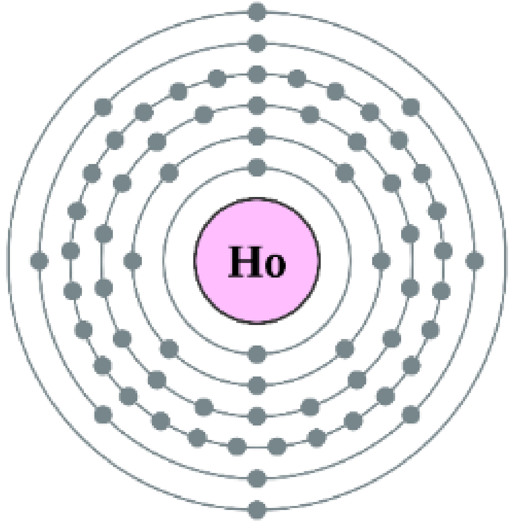
ECHo



cyclotron radiation
max. transversal ß-energy $E_{\perp}$
ΔE = 2-3 eV (FWHM)

metallic magnetic calorimeter
released decay-energy
ΔE = 2-5 eV (FWHM)





$m(\nu_e) < 225$ eV (1987)

EC ON HOLMIUM-163: ECHo, HOLMES

electron capture & ν-mass

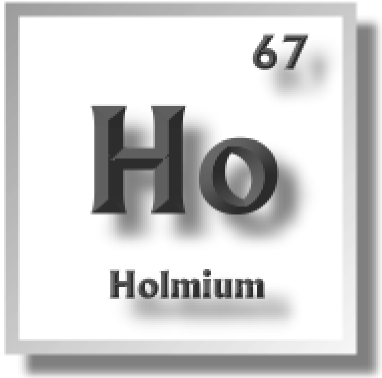
- **EC-process of ^{163}Ho :** $^{163}\mathrm{Ho} + e^- \rightarrow \nu_e + {}^{163}\mathrm{Dy}^*$ (only from $s_{1/2}$ or $p_{1/2}$ orbitals)

  ➊ – after EC: ν_e carries away energy & momentum

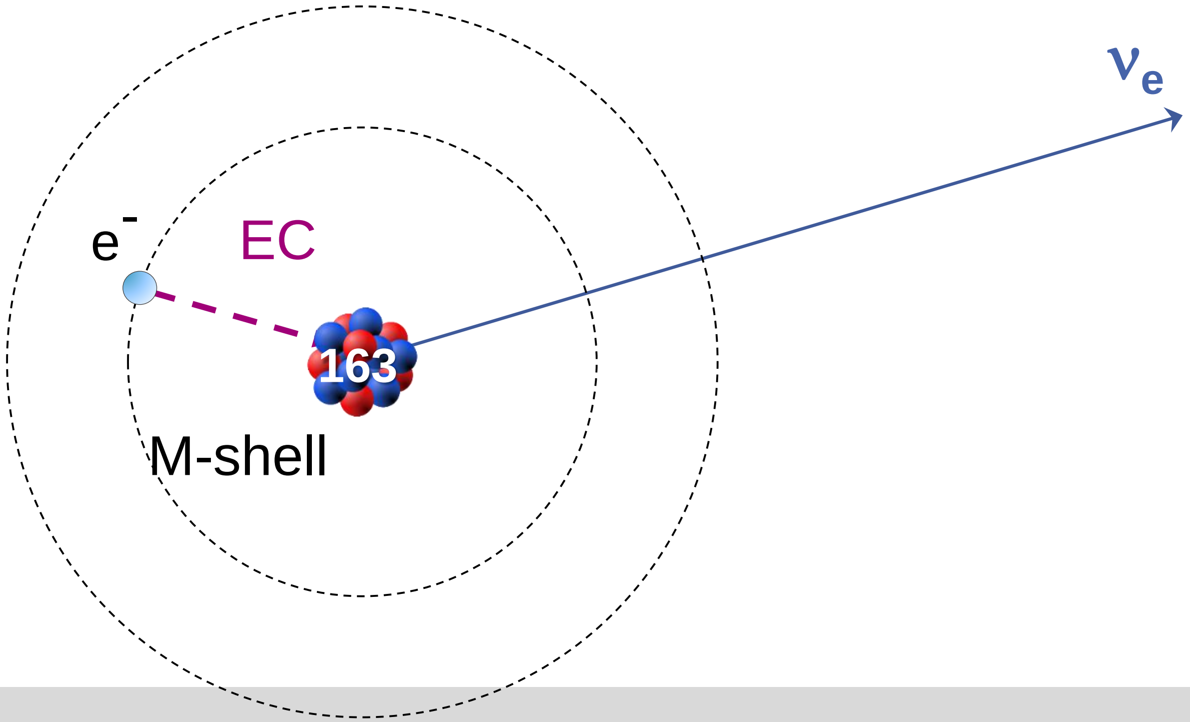
Q_{EC}: Q-value of EC-process
M(^{163}Ho) – M(^{163}Dy) = **2 833** (30)(15) **eV**

- measured by SHIPTRAP

- independently measured by MMCs
$Q_{EC} = (2\,843 \pm 9_{stat} - 60_{syst})$ eV



no capture from K, L shells possible due to small small mass difference Q_{EC}

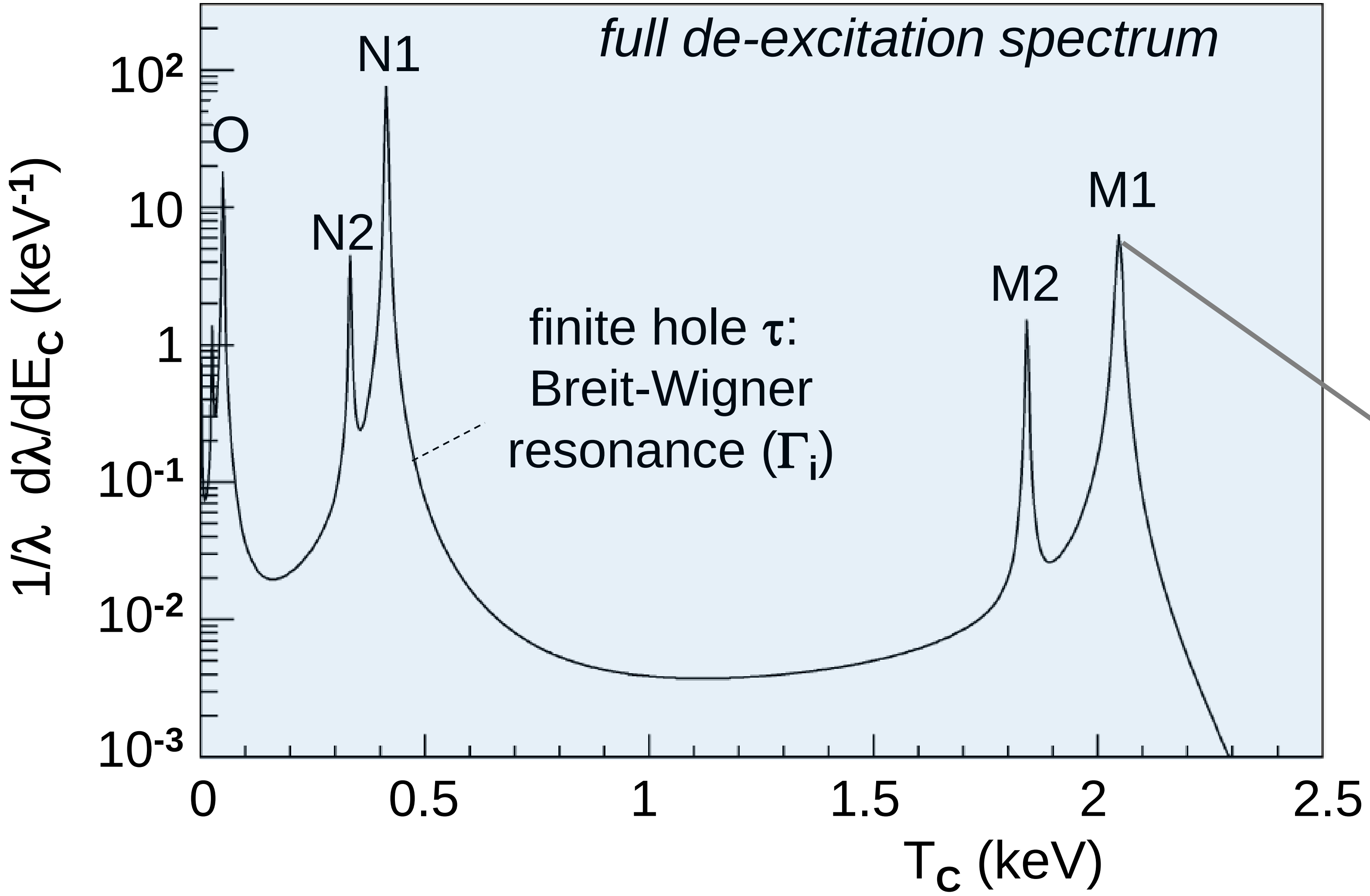


A. De Rújula, M. Lusignoli, Phys. Lett 118B (1982)

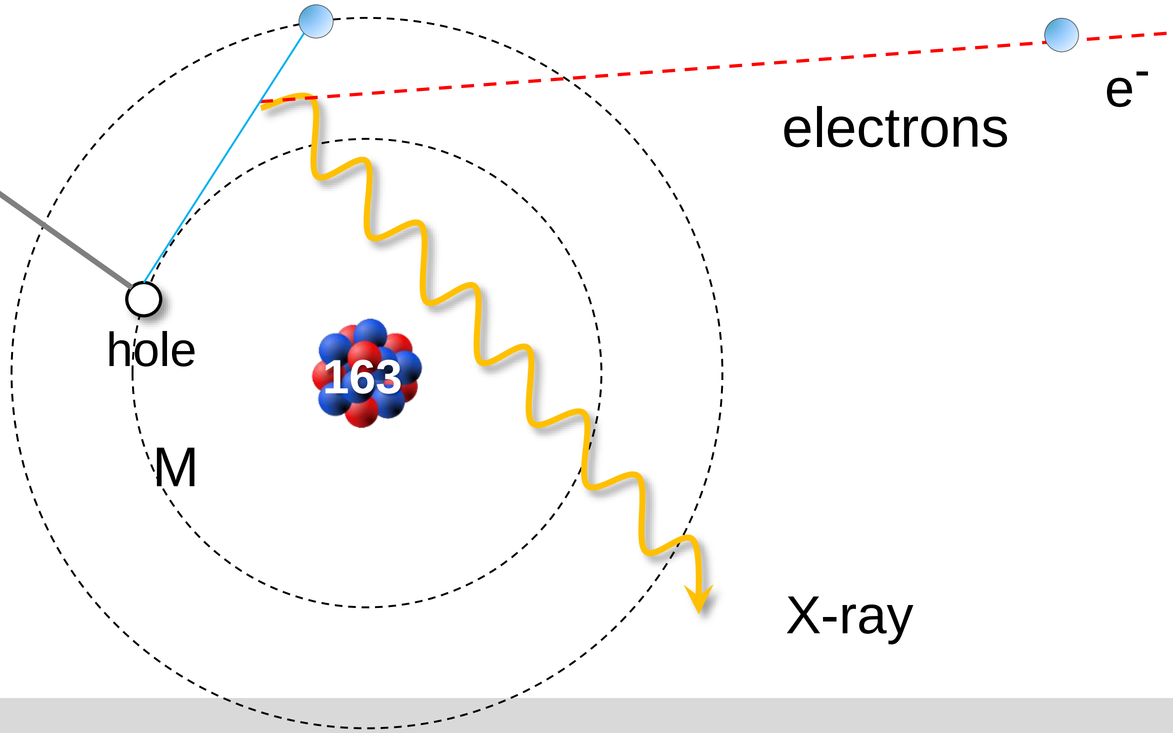
electron capture & ν-mass

- **EC-process of ^{163}Ho :** $^{163}Ho + e^- \rightarrow \nu_e + {}^{163}Dy^*$ (only from $s_{1/2}$ or $p_{1/2}$ orbitals)

❷ – atomic hole state de-excites to atomic g.s. ⇨ Auger & Koster-Kronig electrons, X-rays



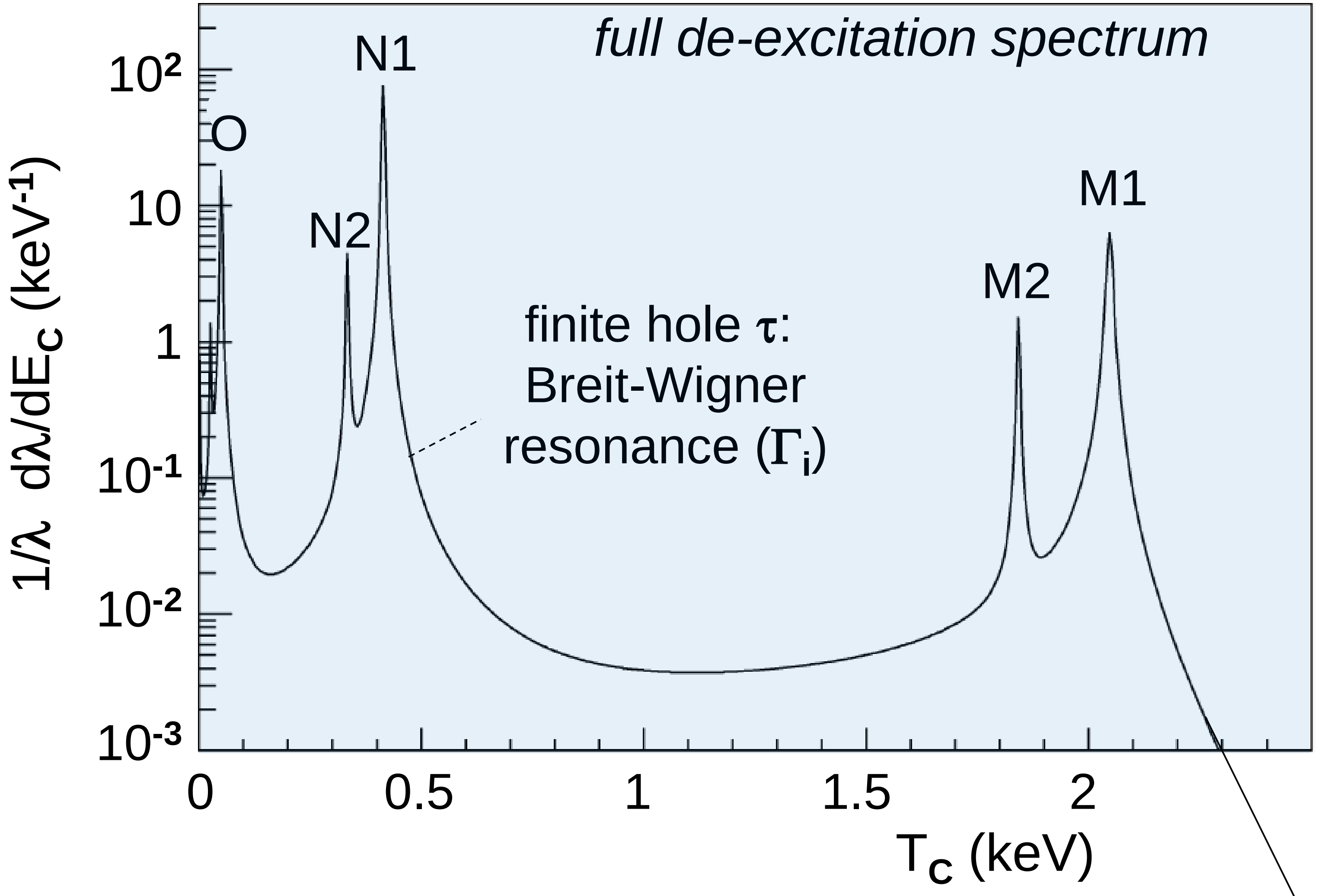
T_C: **calorimetric energy** from atomic de-excitations

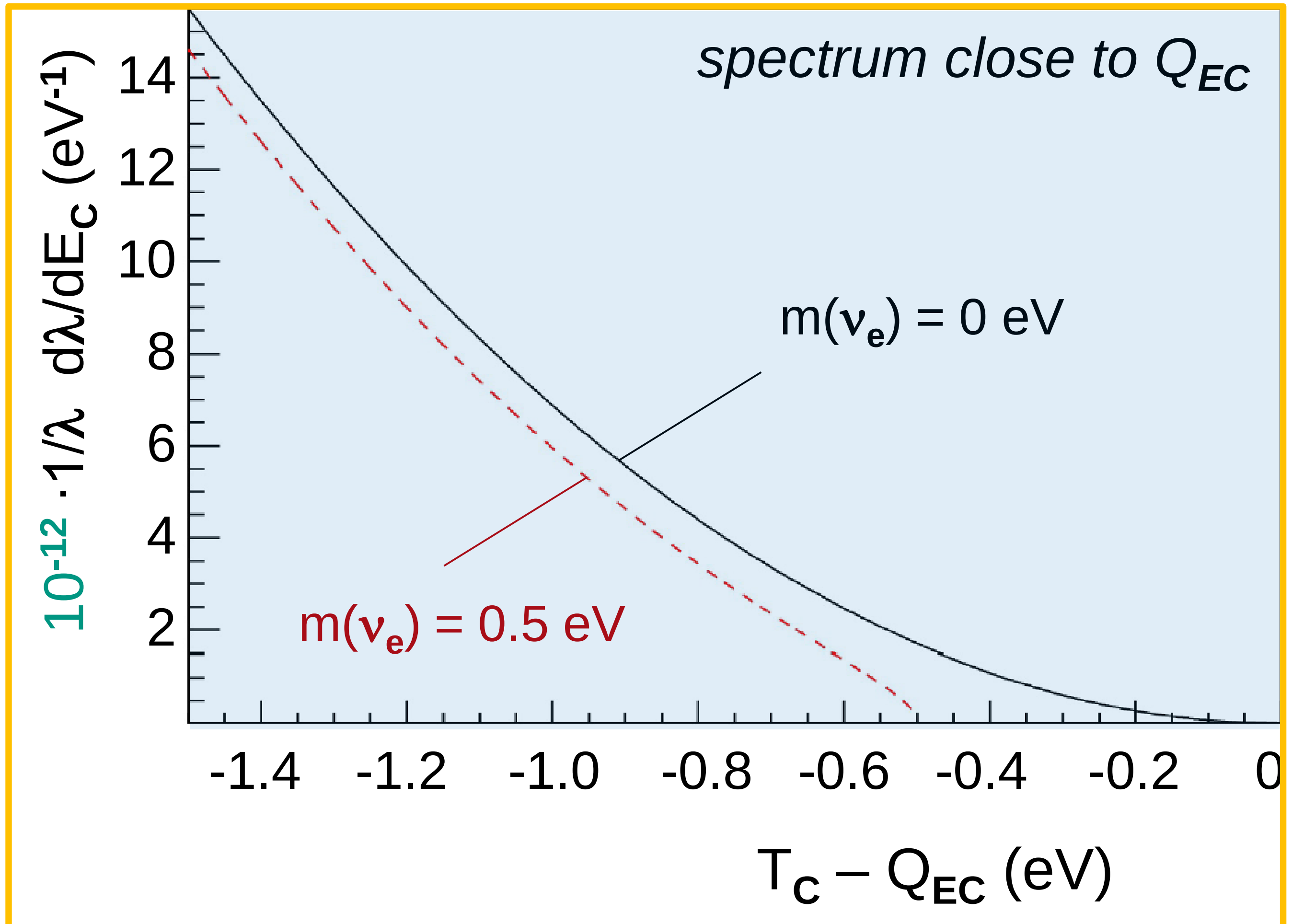


electron capture & ν-mass

- shape:

$$\frac{d\lambda_{EC}}{dT_C} \sim (Q_{EC}-T_C)\cdot\sqrt{(Q_{EC}-T_C)^2 - m^2(\nu_e)}\cdot\sum_i \underbrace{n_i \cdot C_i \cdot \beta_i^2 \cdot B_i \cdot \frac{\Gamma_i}{2\pi}\cdot\frac{1}{(T_C-E_i)^2+\Gamma_i^2/4}}_{M1,\,M2,\ldots}$$





calorimeters to measure ^{163}Dy* atomic de-excitation

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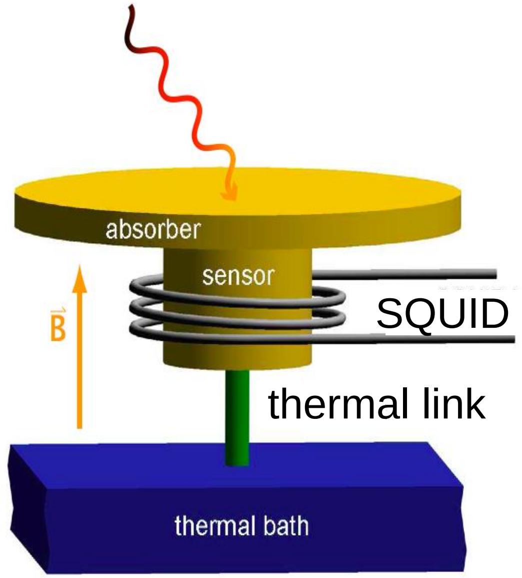
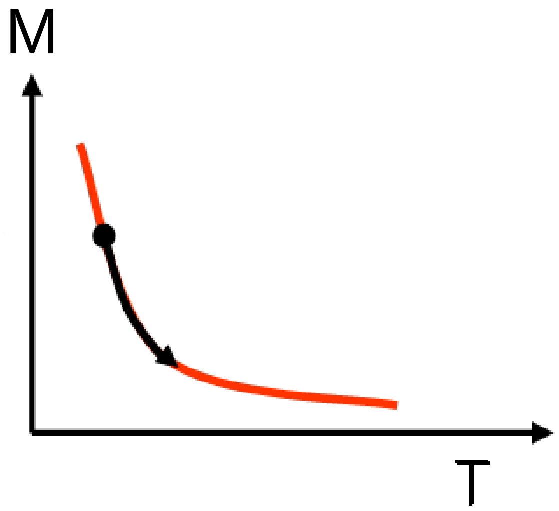
- **MMC**: **m**etallic **m**agnetic **c**alorimeters with paramagnetic sensor Au:Er



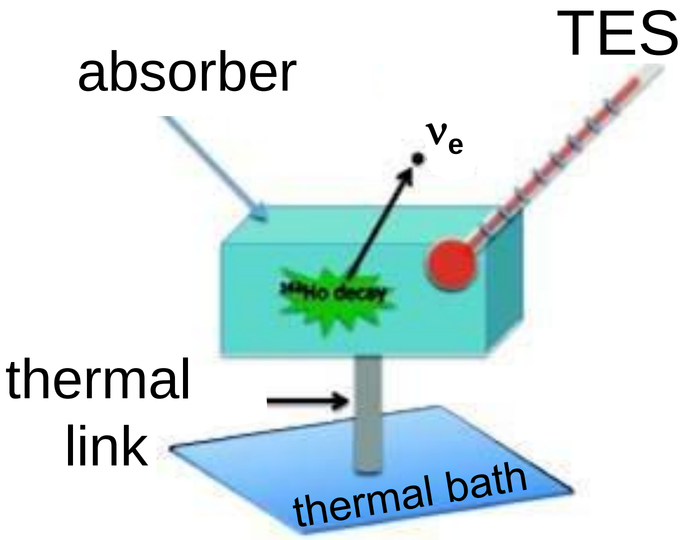


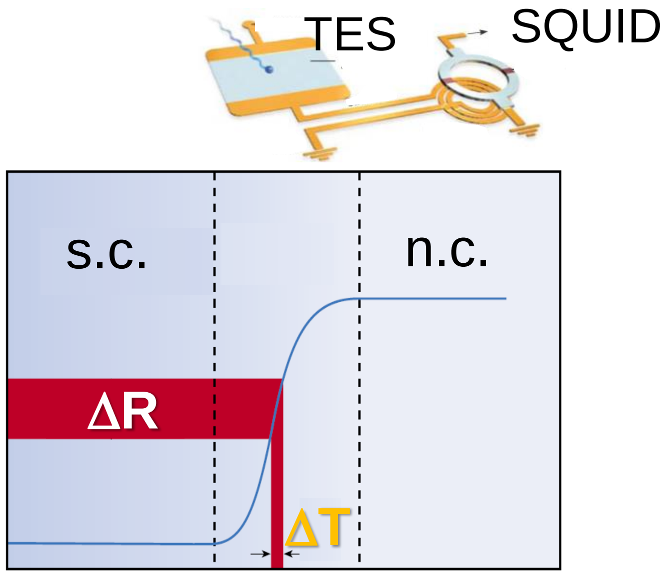
δT in absorber from EC-decay

⇨ change in **magnetism δM** of sensor

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 micro-calorimeters with **TES** read-out





δT in absorber from EC-decay

⇨ change in temperature δT of TES thermistor

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

^{163}Ho-experiments: overview

Karlsruhe Institute of Technology

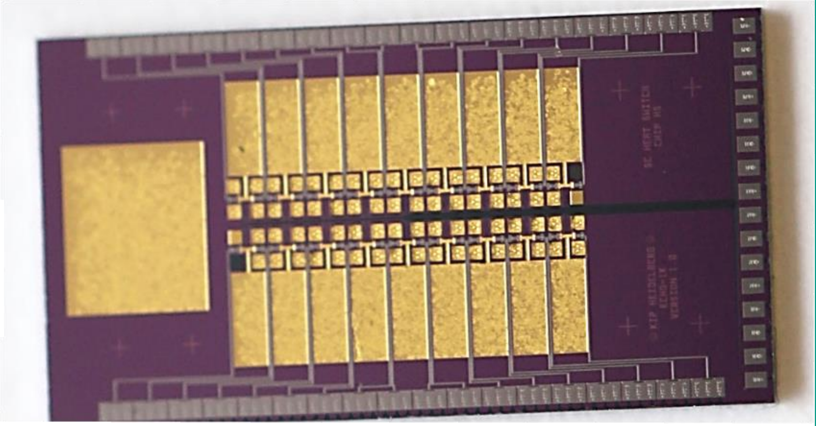
Common challenges to reach sub-eV sensitivity:

- source: production of high purity ^{163}Ho source: goal: A = 1 kBq → 10 MBq
- detector: high energy resolution & small pile-up rate: goals: $\Delta E \sim$ 2-3 eV, $f_{pu} \sim 10^{-6}$
- analysis/theory: description of spectral shape & features (shake-off satellites, 2 holes)

ECHo

- 14 institutions with ~ 50 scientists
- read-out technology: **MMC**
- main funding:

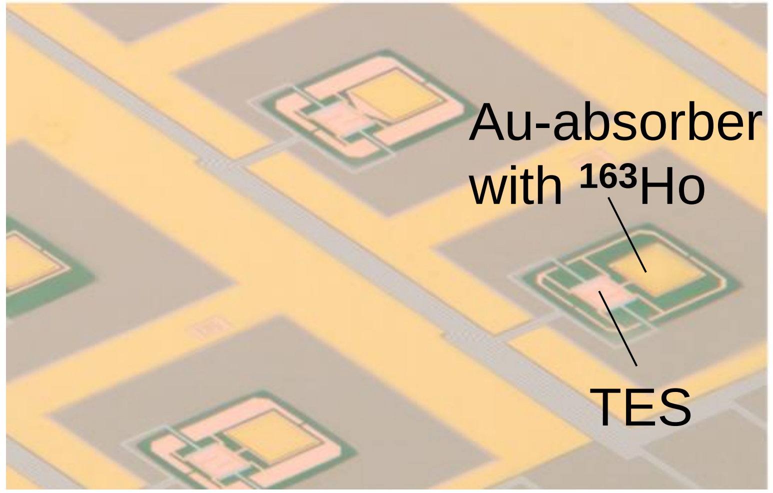
DFG Deutsche Forschungsgemeinschaft



HOLMES

- 6 institutions with ~ 40 scientists
- read-out technology: **TES**
- main funding:

erc European Research Council



EC on holmium – sensitivity

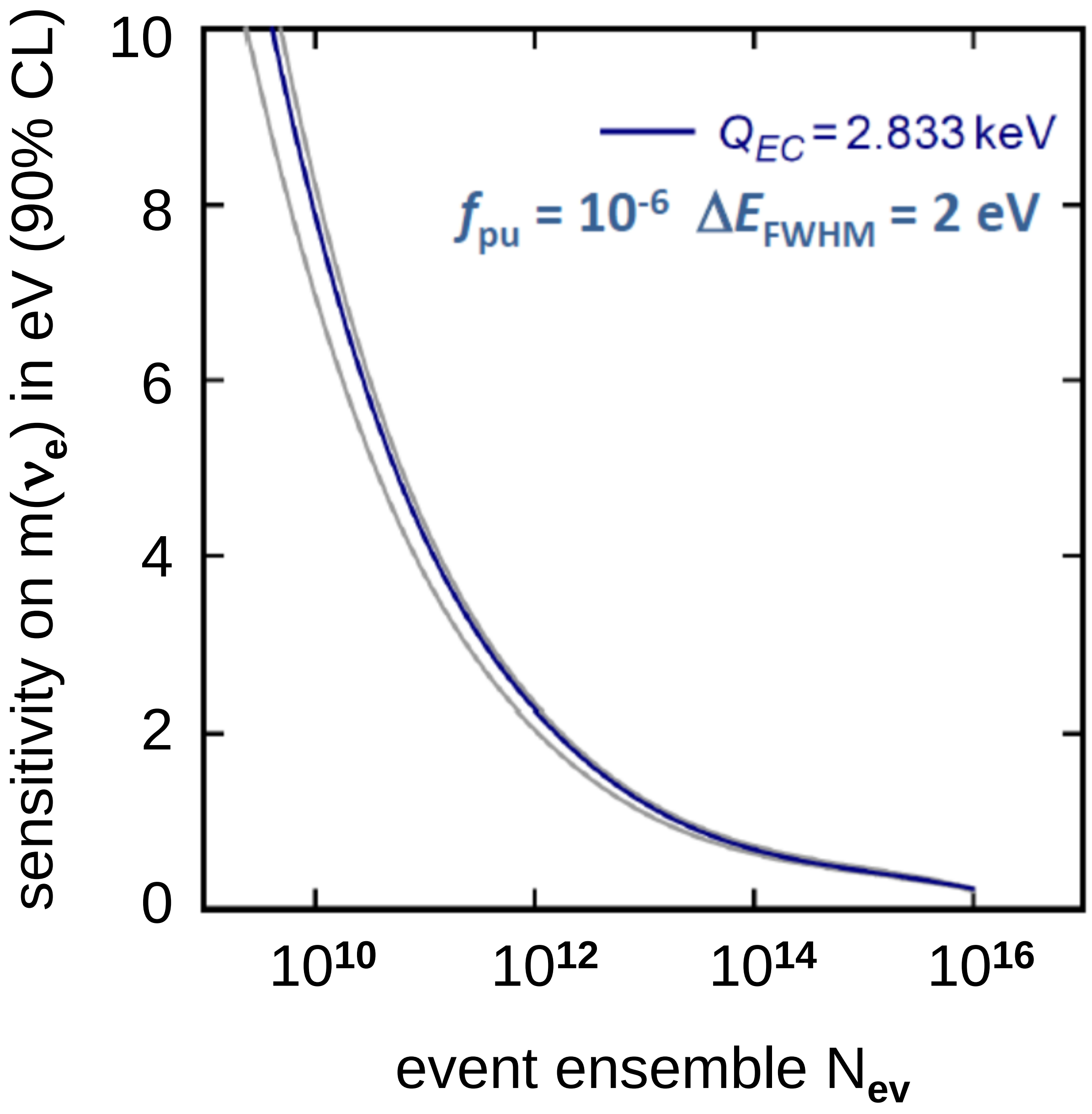
- requirements for **sub-eV sensitivity**

  - good statistics in endpoint region:
    $N_{ev} > 10^{14}$ → overall A ~ 1 MBq

  - limit unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)
    $f_{pu} < 10^{-6}$
    for $\tau_r < 1\ \mu s$ ⇨ limit pixel a ~ 10 Bq

  - very good energy resolution at endpoint
    $\Delta E(FWHM) < 3$ eV

  - very low background level
    $R_{bg} <$ 10-5 events/eV/pixel/day



Based on ν2018 transparency by L. Gastaldo

EC on holmium – source challenges

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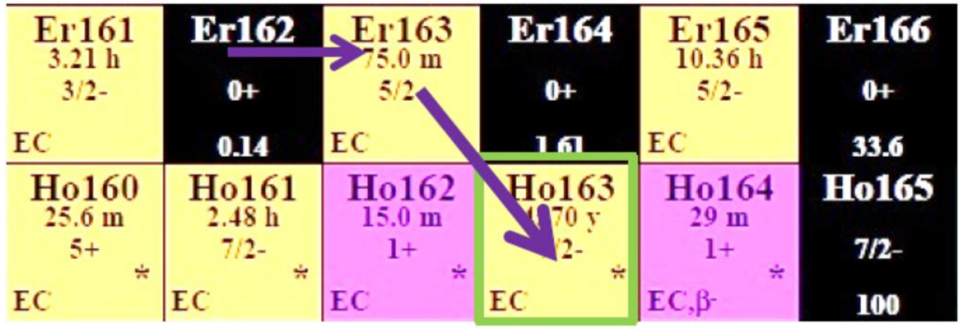
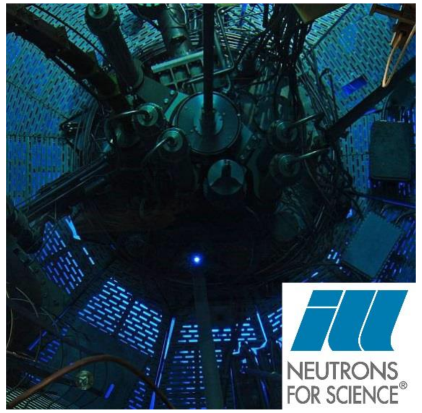
- **generating a large number of Ho-163 atoms (> 10^{17} atoms → > 1 MBq)**
  - pathway: n-irradiation of Er-162
  - chemical separation of radioactive contaminants

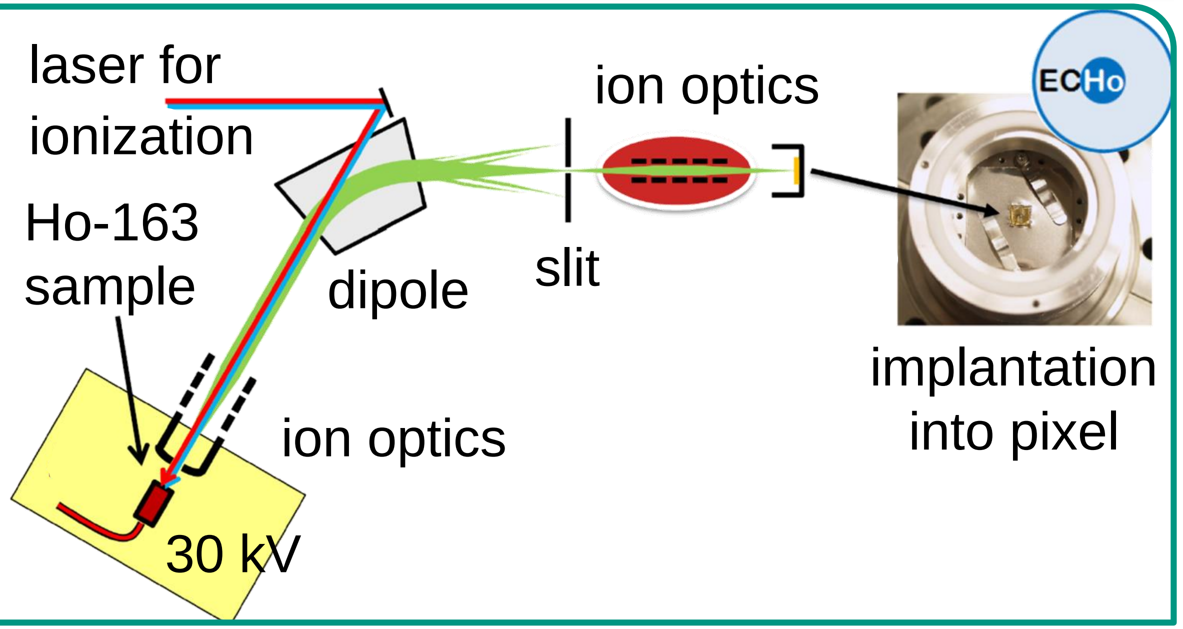




ECHo: 2×10^{18} atoms

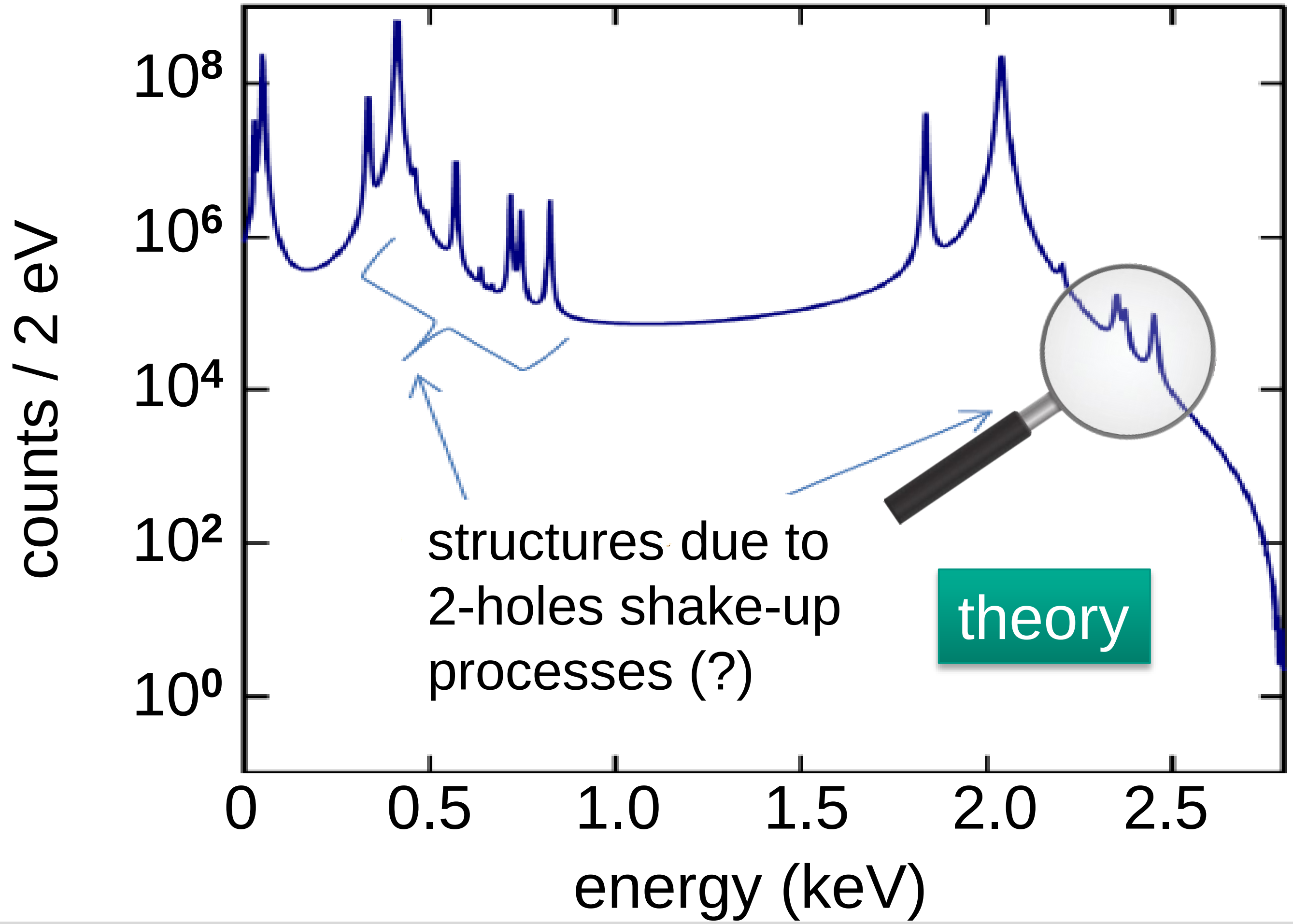
HOLMES: 2.7×10^{19} atoms

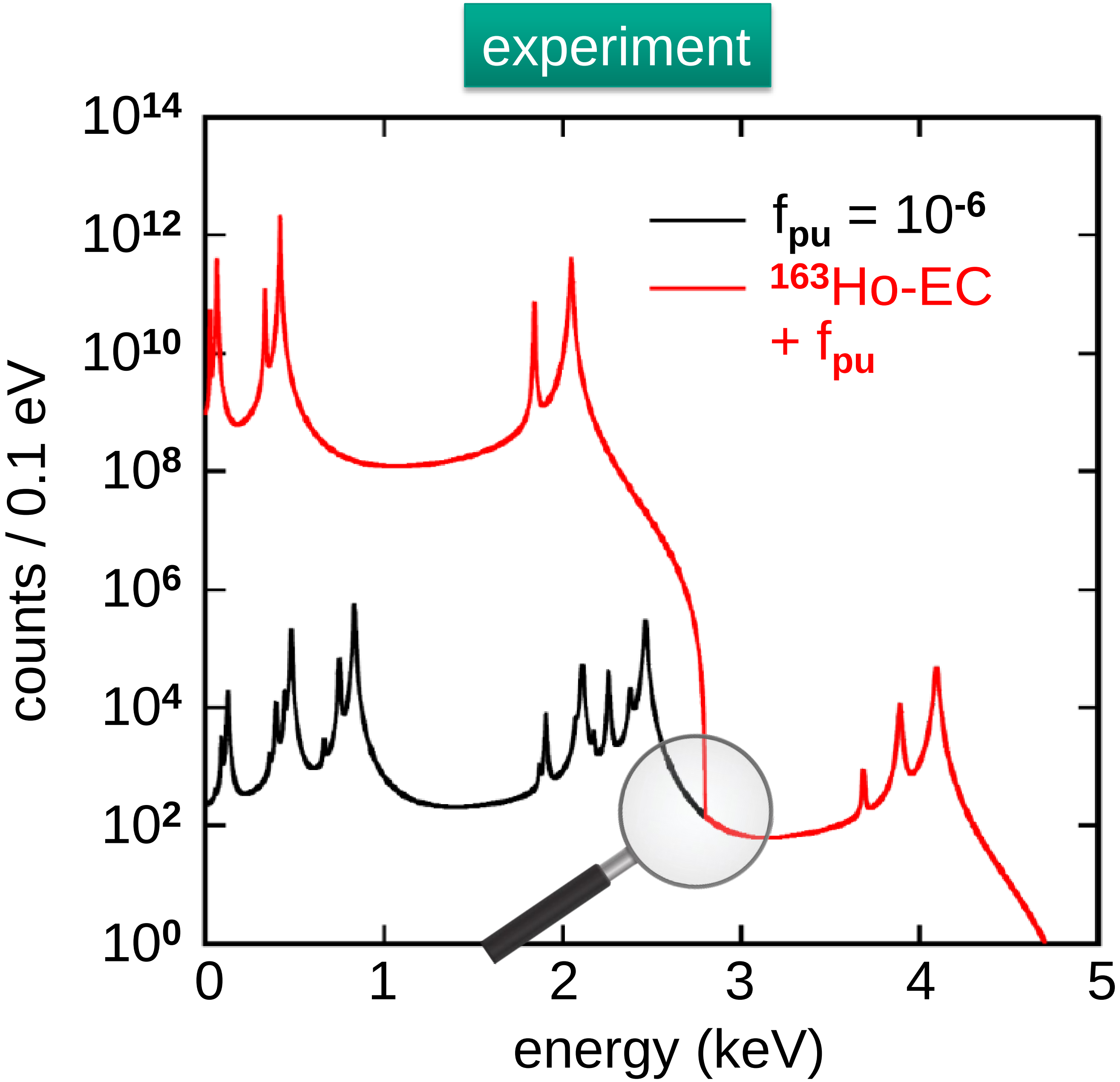
- **embedding of Ho-163 atoms into detectors**
  - resonant ionisation of chemically purified Ho-163 sample via laser
  - very good mass separation
  - ion implantation energy 30-50 kV
  - optimised beam focalisation onto pixel



EC on holmium – spectral challenges

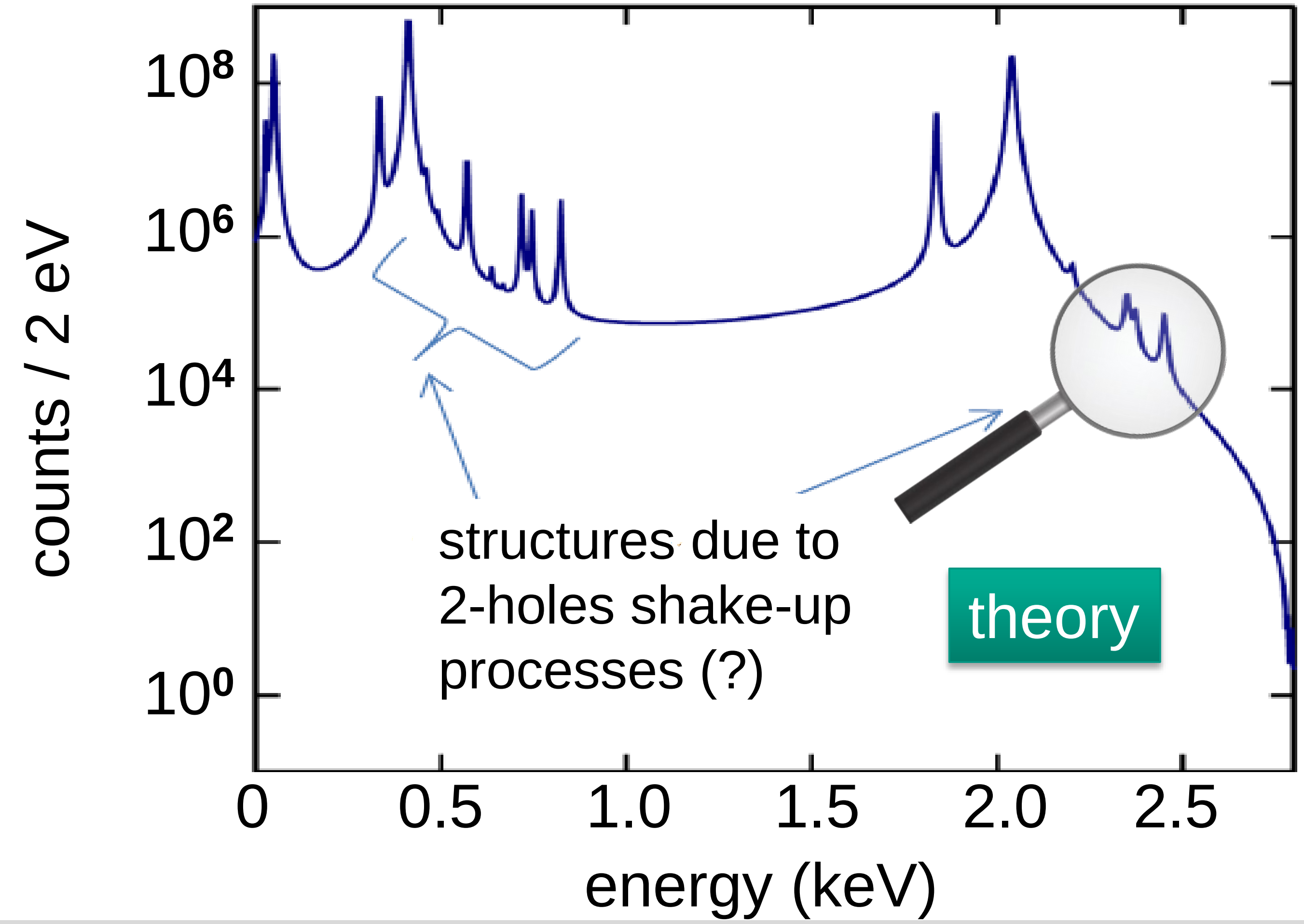
- challenges to be met for **sub-eV sensitivity**
  - limit pile-up to fraction $f_{pu} \sim 10^{-6}$
  - detailed understanding of 2-hole excitations



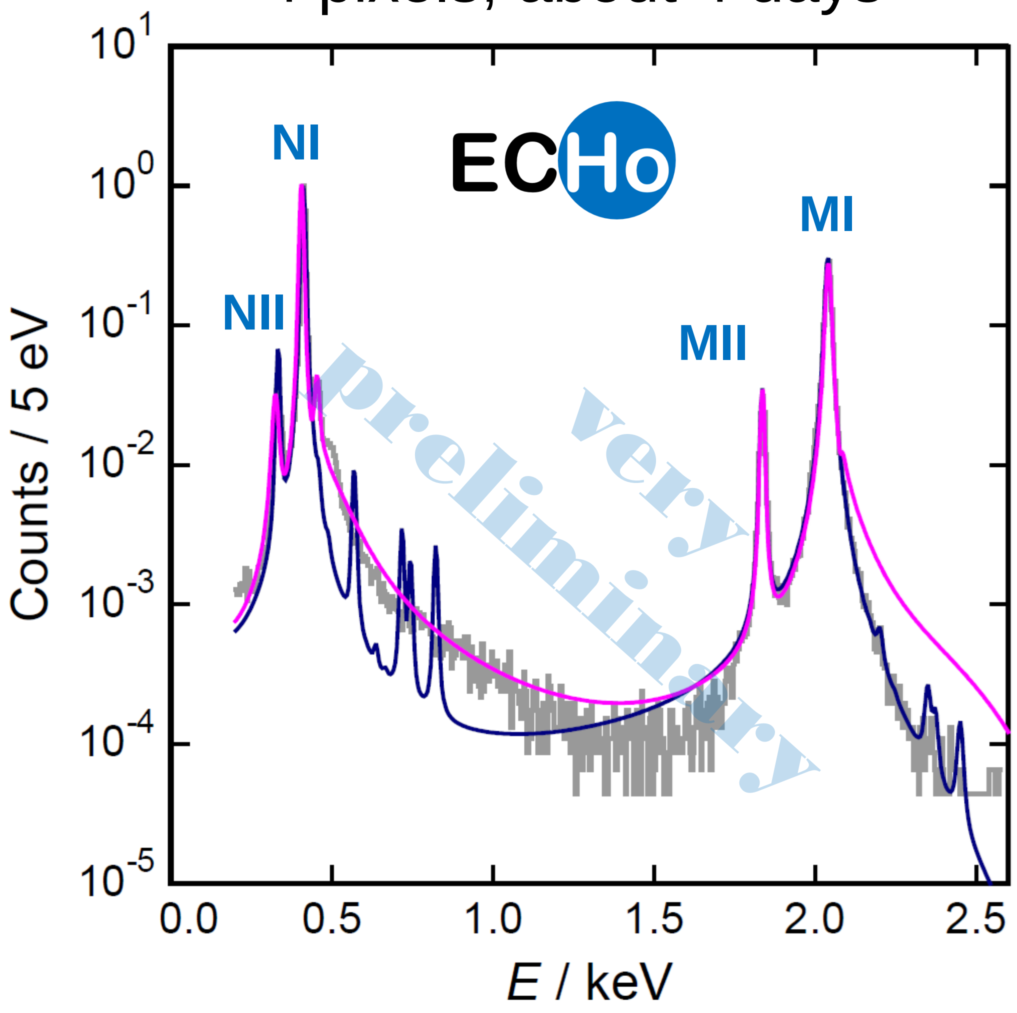


EC on holmium – spectral challenges & spectra

- ECHo data with limit on m(ν_e) to be released in the nearer future
  - more dedicated theory works on spectral shape



4 pixels, about 4 days



A. Faessler et al.
Phys. Rev. C **91**, 045505 (2015)

A. De Rujula et al.
arXiv:1601.04990v1

HOLMES – status mid-2018 & plans

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- **HOLMES source production and purification:**

  130 MBq available for tests and experiments

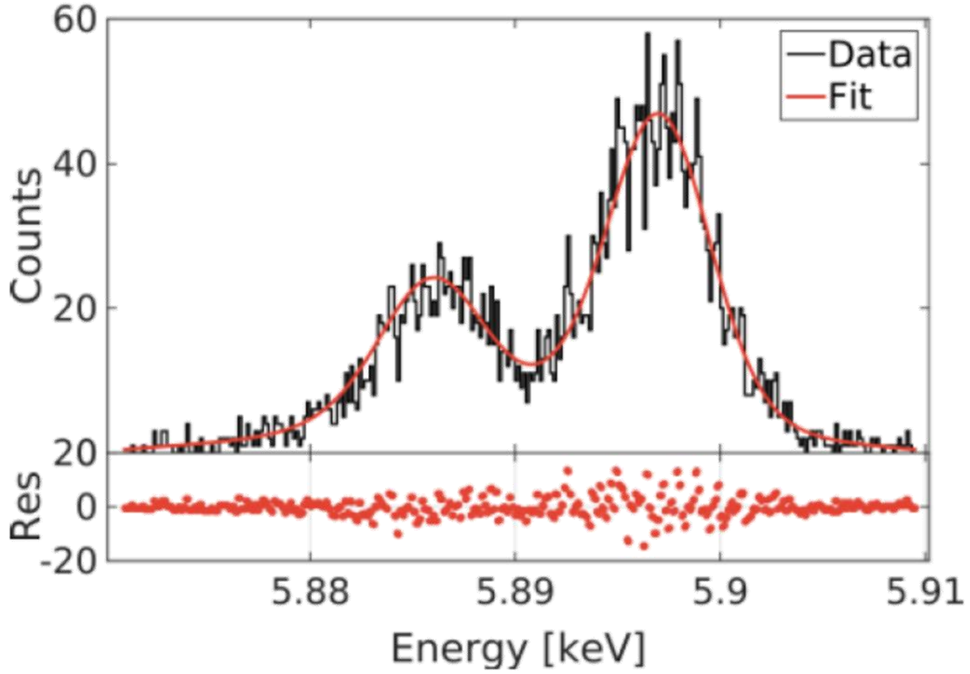
- **Detector arrays - characterization:**

  - very good single pixel performance
  - ΔE_{FWHM} = (4.9 ± 0.1) eV
  - operating microwave SQUID multiplexing
  - upcoming: loading of TES arrays with Ho-163

- **timeline**

  - proof-of-concept (2013-18), 64 channels, 1 month running
  - full scale (2019ff), 1000 channels, 3 years

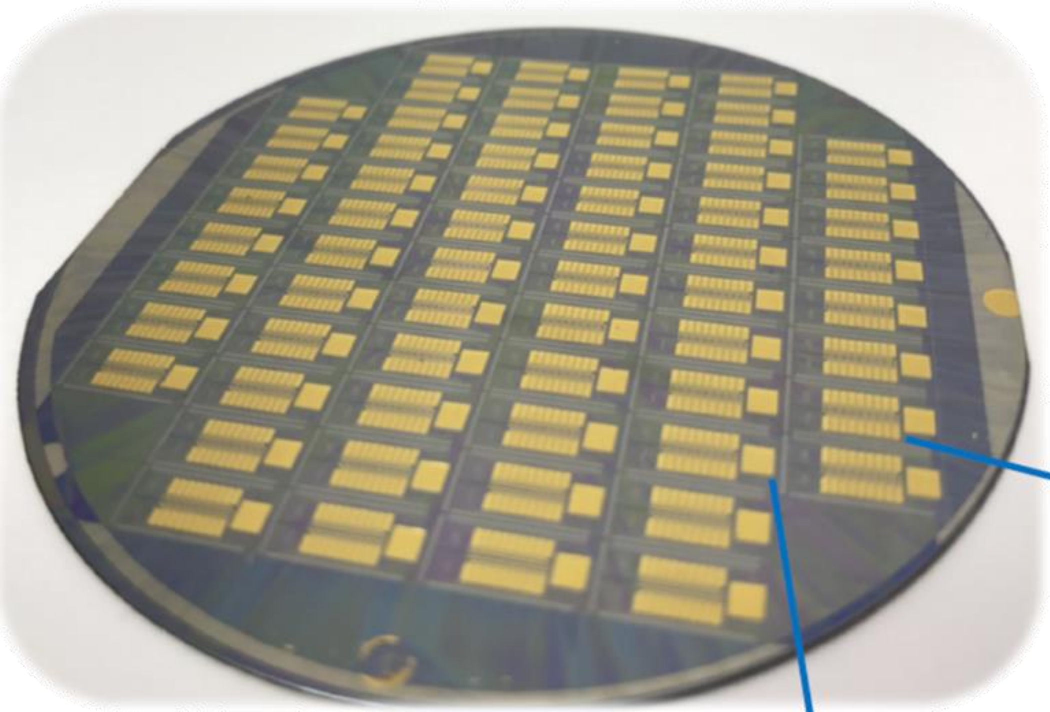
Based on ν2018 transparency by L. Gastaldo

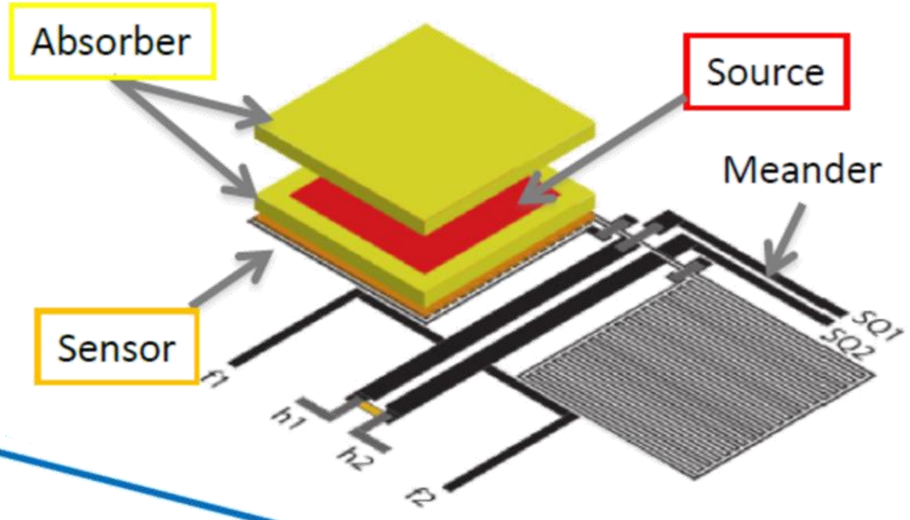


ECHo – actual status

- **ECHo-1k detector arrays**

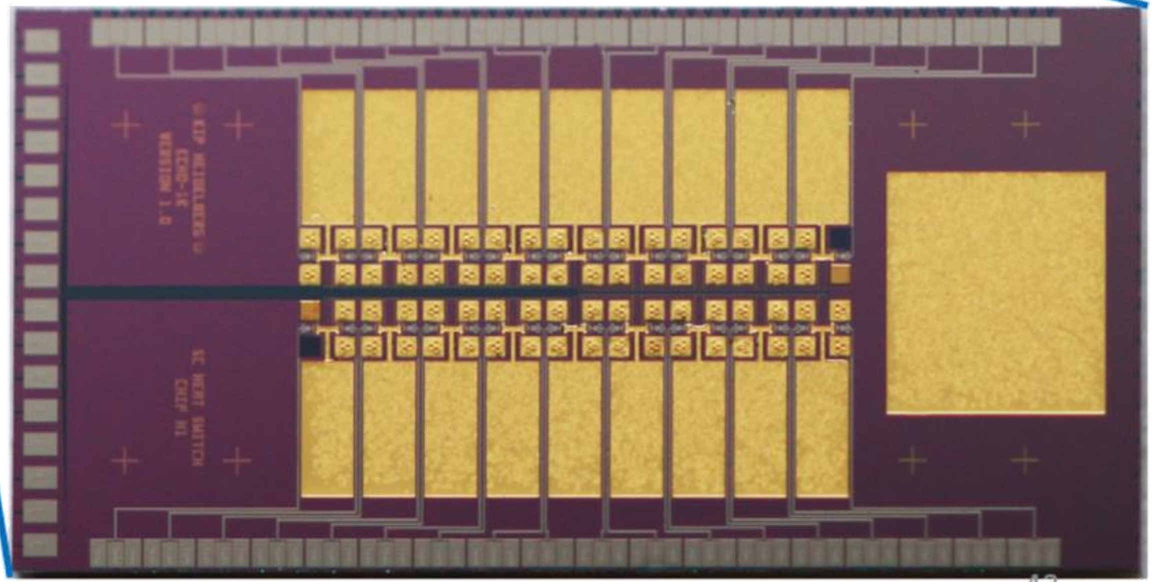
  3-inch wafer:
  64 pixels
  (loaded with ^{163}Ho)
  + 4 detectors for diagnostics





- **Design performance**

  ΔE(FWHM) ~ 5 eV
  τ_r ~ 90 ns : single channel
  τ_r ~ 300 ns : multiplexed
  read-out



S.Kempf *et al.*, *J. Low. Temp. Phys.* **176** (2014) 426

Based on ν2018 transparency by L. Gastaldo

ECHo – sensitivity & timeline

❶ ECHO-1k: 2015 - 2018

- demonstrate scalability of arrays ☑
- MMC: ΔE_{FWHM} < 5 eV, multiplexing total activitiy A ~ 100 Bq ☑
- achieve 10^{10} decays after 1 year:

⇨ sensitivity 10 eV (90%CL)

❷ ECHO-100k: 2019 - 2021

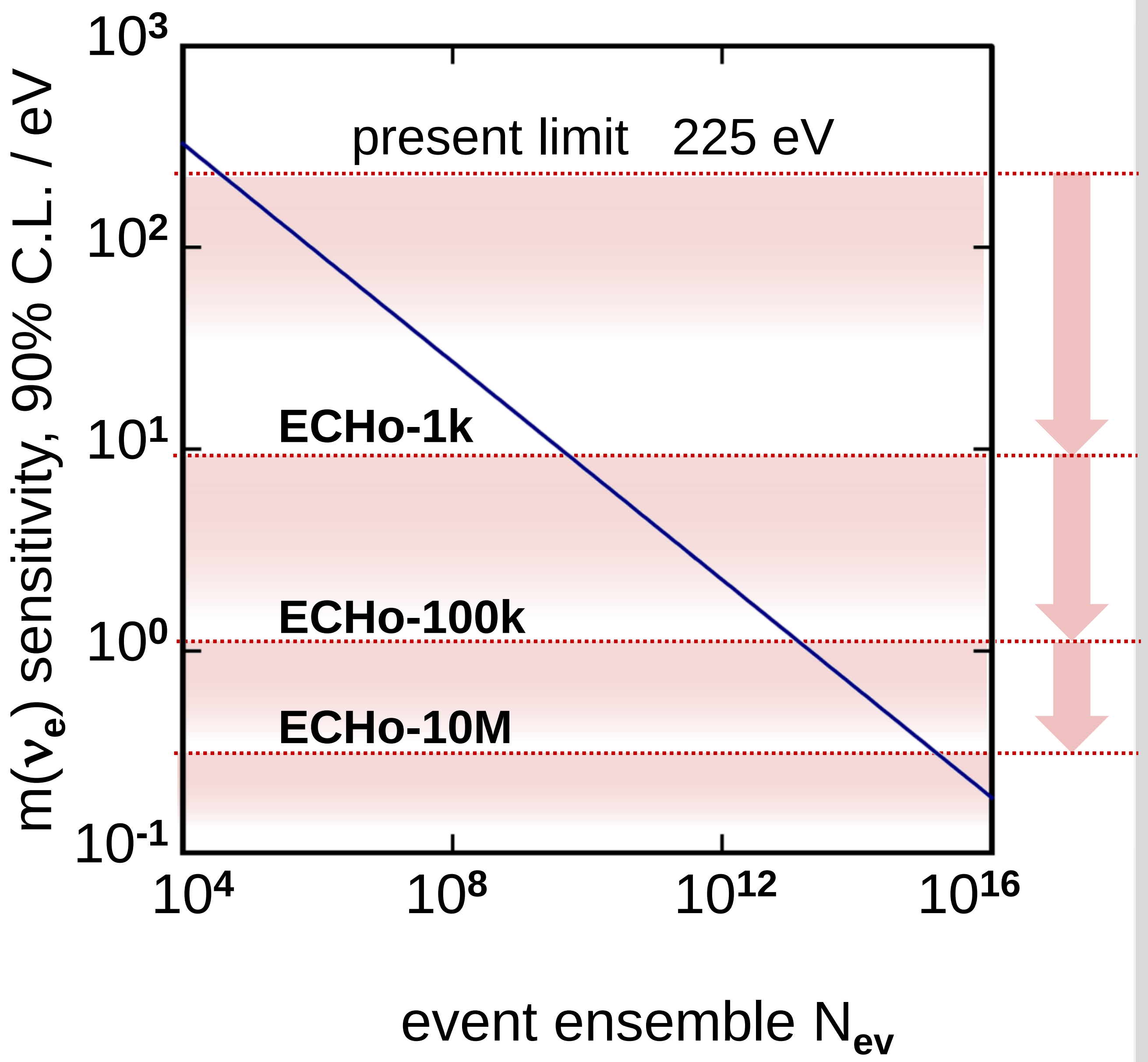
- 20 arrays × 500 pixels × 10 Bq A = 10^5 Bq (100 kBq)
- MMC: ΔE_{FWHM} < 3 eV

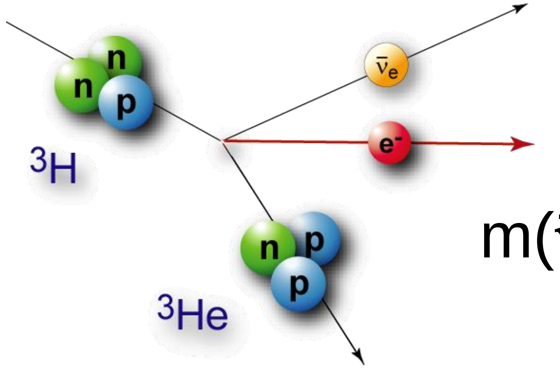
⇨ sensitivity 1 eV (90% CL)

❸ ECHO-10M: 2021-2027 (LSM?)

- 5 cryostats with 10^6 pixels (10 Mbq)
- ΔE (FWHM) < 3 eV

⇨ sensitivity 0.3 eV (90% CL)





$m(\bar{\nu}_e) < 2$ eV (2001)

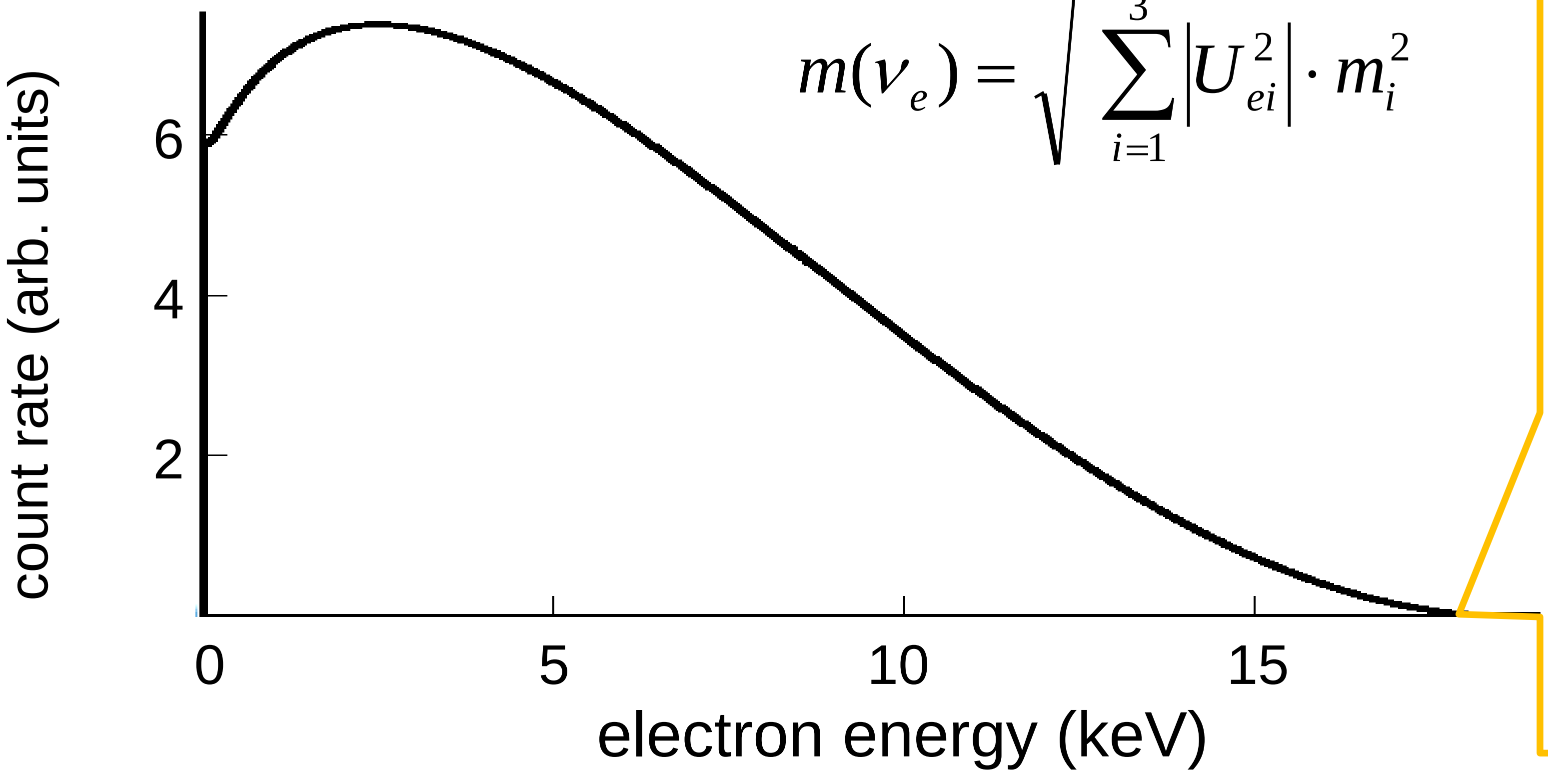
ß-DECAY OF TRITIUM: PROJECT8, KATRIN

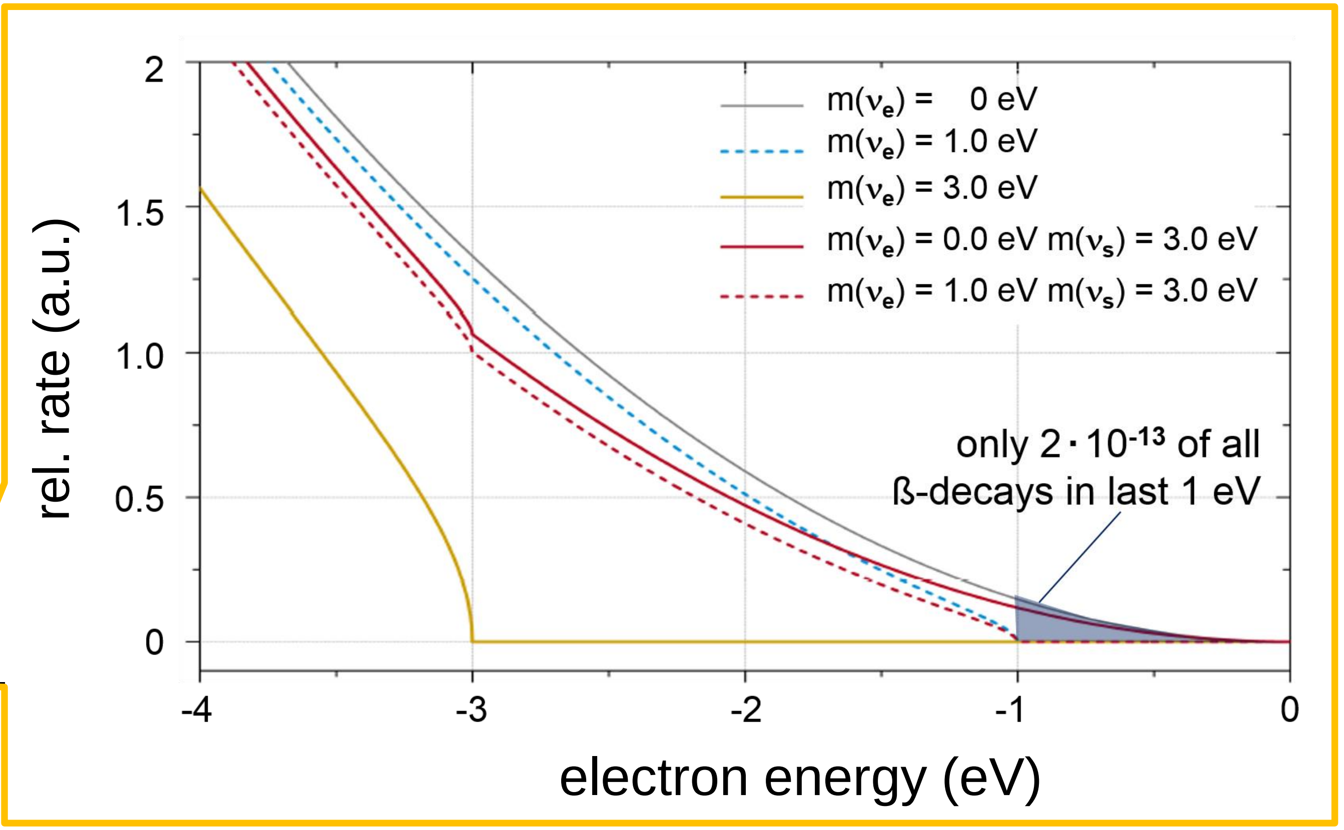
tritium ß-decay: kinematics

- continuous ß-spectrum described by Fermi´s Golden Rule, measurement of effective mass $m(\nu_e)$ based on **kinematic parameters & energy conservation**

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

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

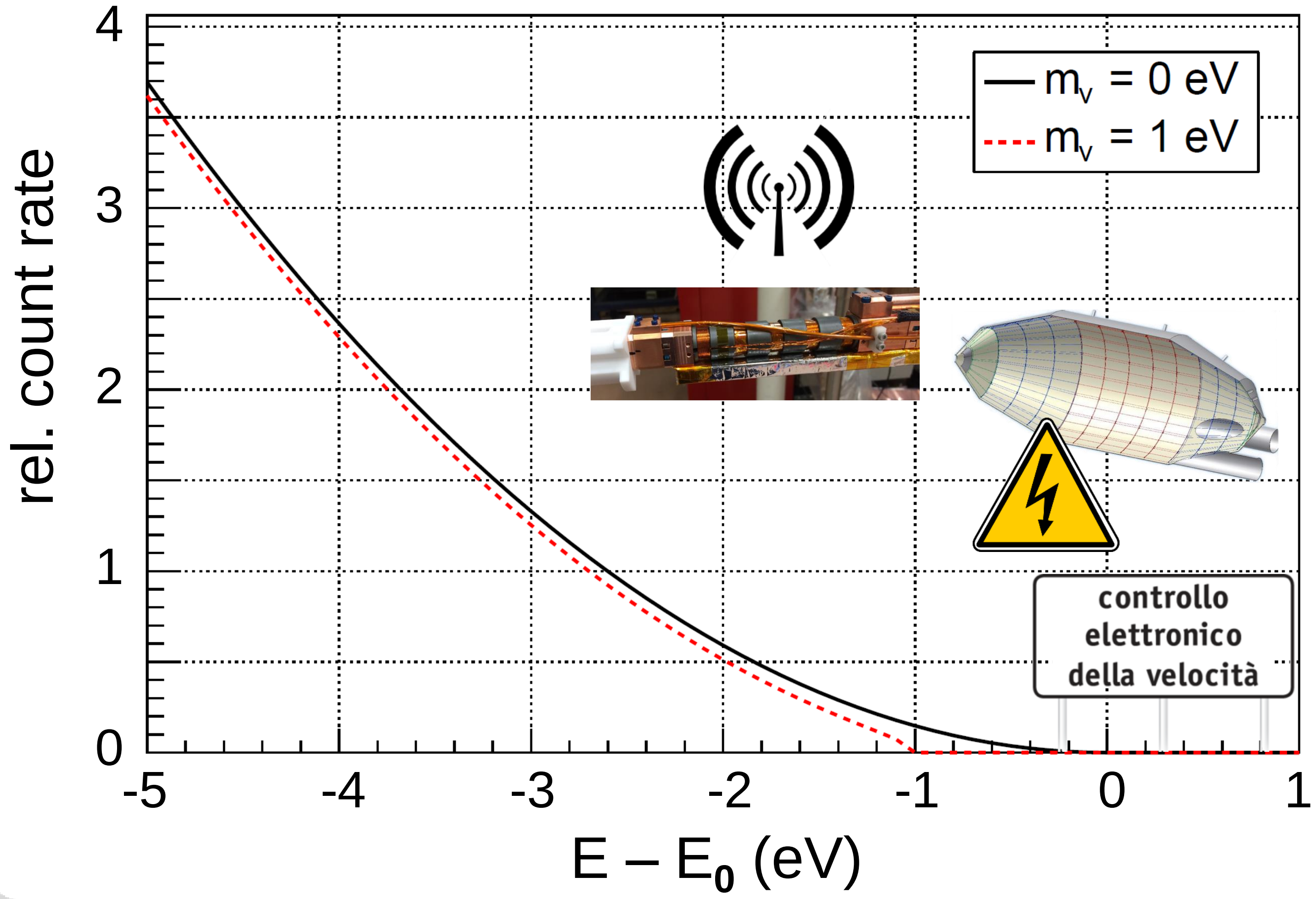




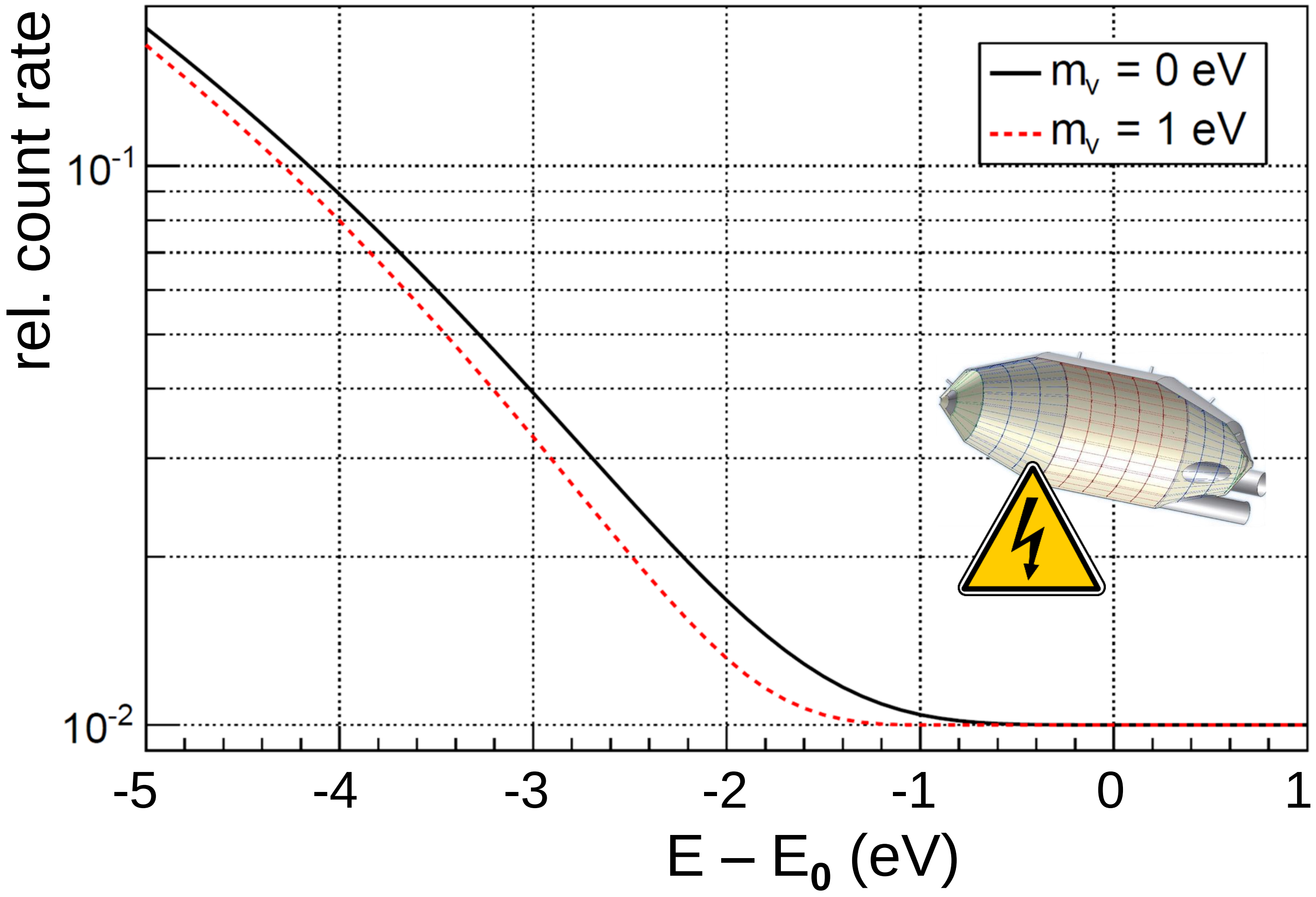
ß-spectroscopy: integrating & differential

- **ß-spectroscopy of tritium**: integral scan (MAC-E-filter)
  differential read-out (CRES, MAC-E-ToF)

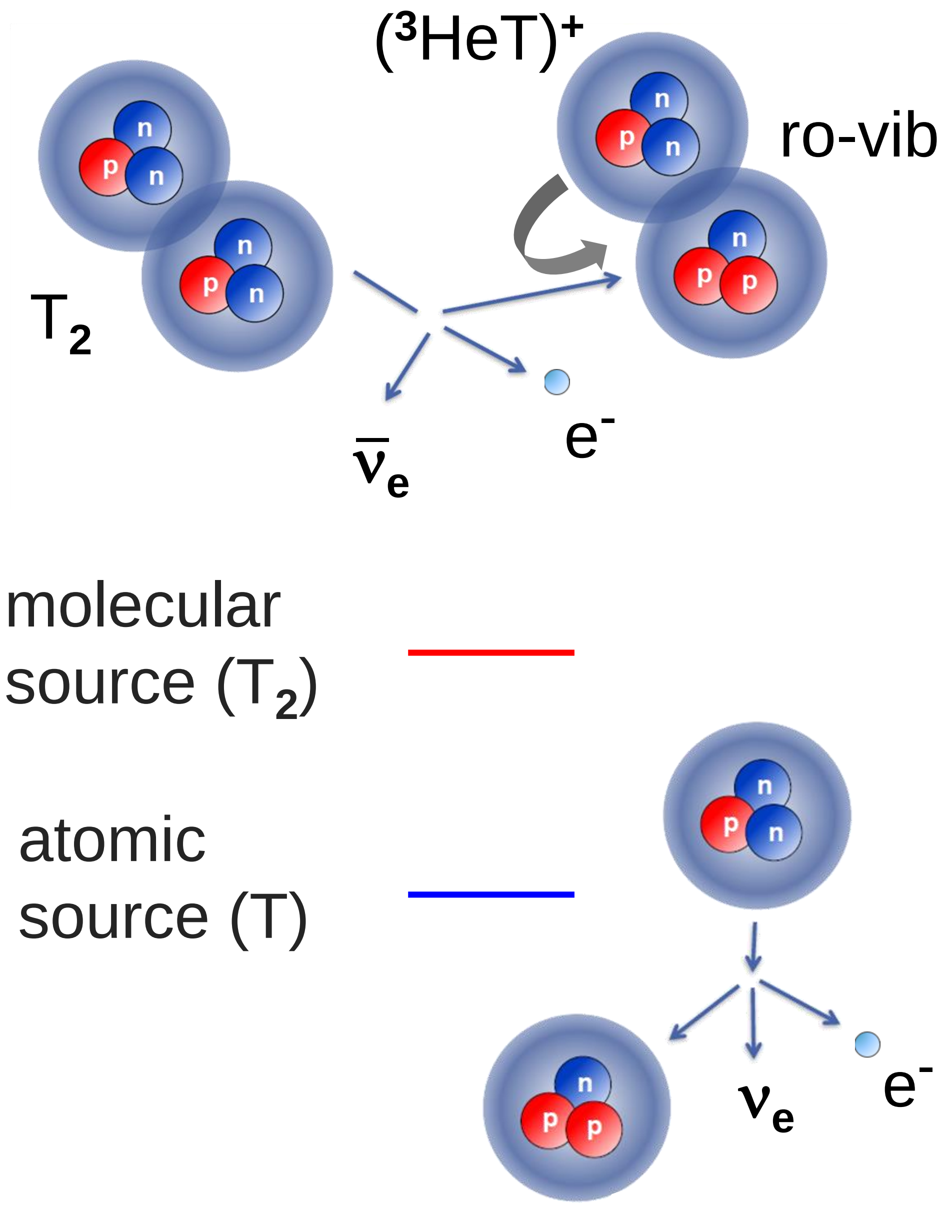
differential tritium ß-spectrum

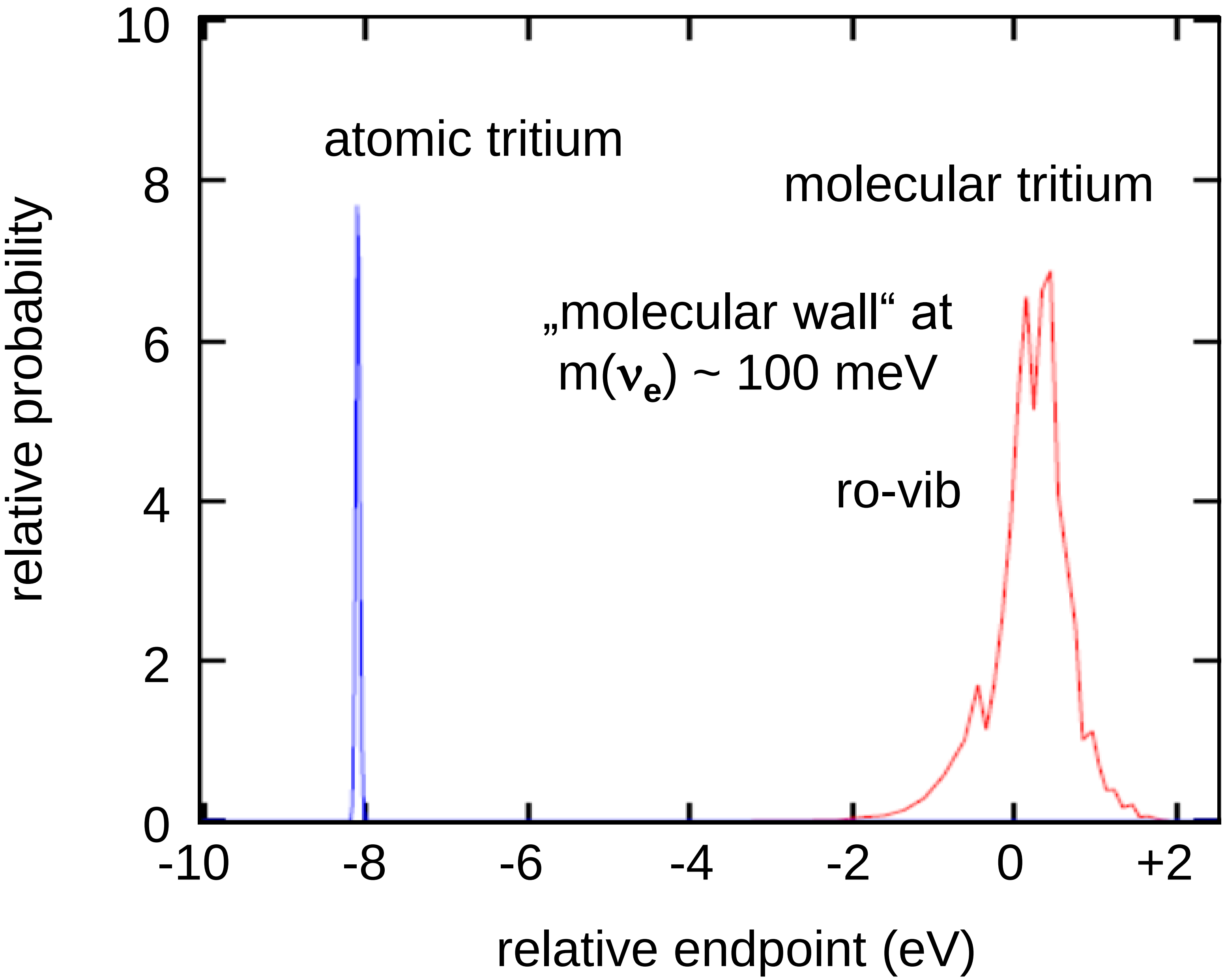


integrated tritium ß-spectrum

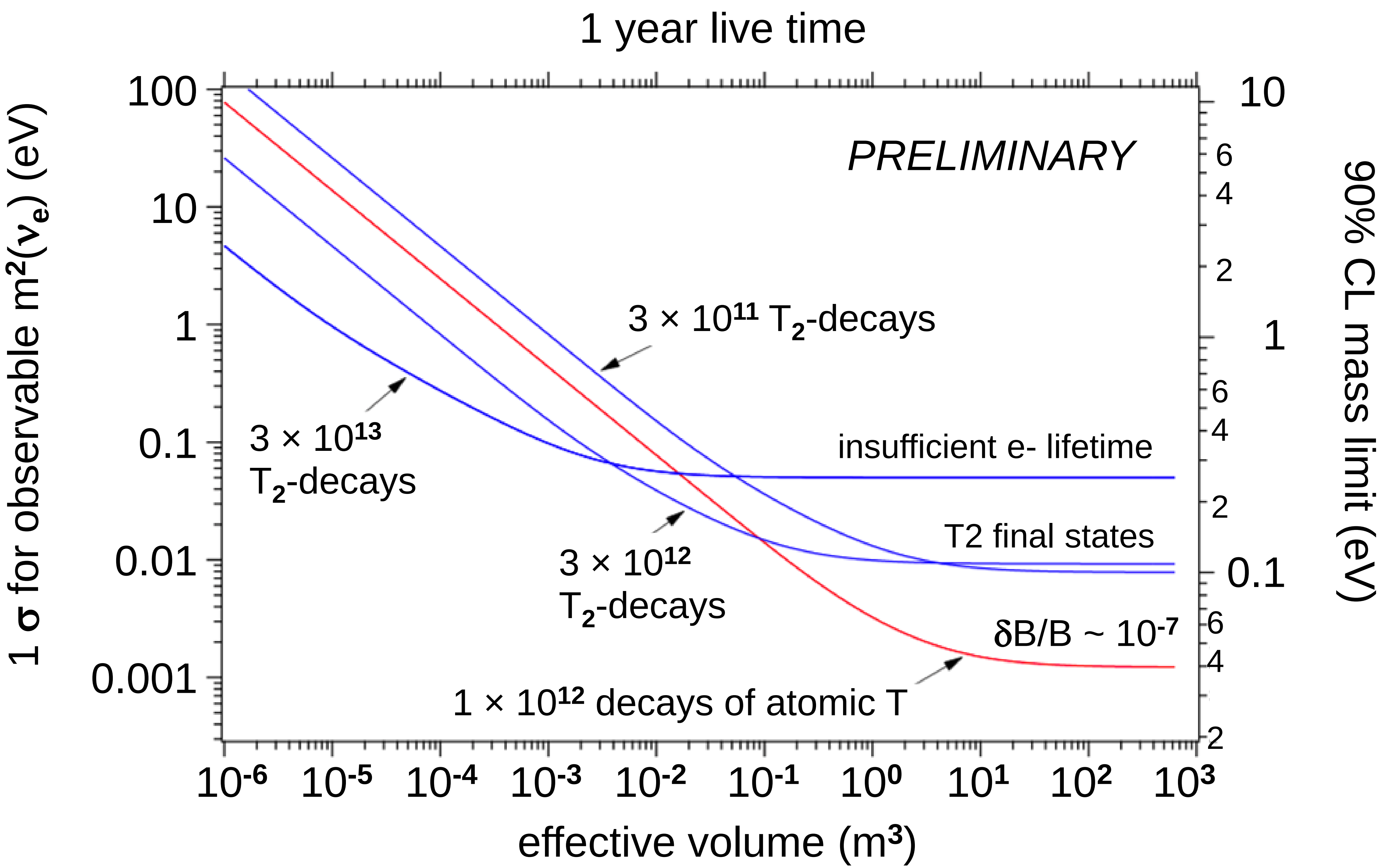


ß-spectroscopy: molecular & atomic tritium





estimated sensitivities (statistics only)



Project 8 – a novel spectroscopic approach

Karlsruhe Institute of Technology

Cyclotron Radiation Emission Spectroscopy (CRES)

- CRES of ***trapped*** electrons from tritium ß-decay in homogeneous strong magnetic field B

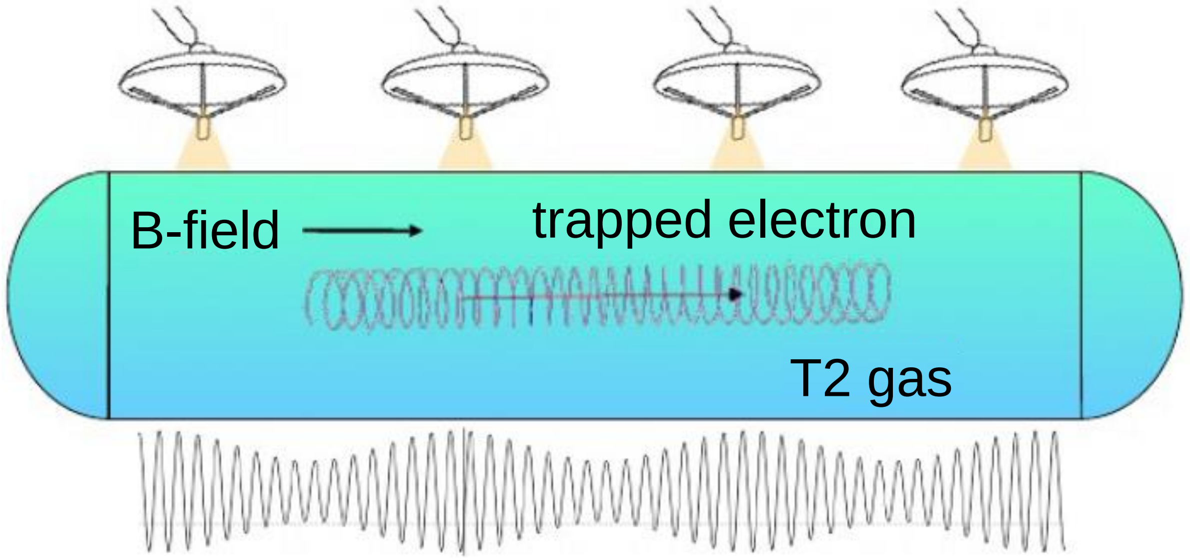
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{e \cdot B}{m_e + E_{e,kin}}$$

⇨ **precise measurement of ω yields electron kinetic energy $E_{e,kin}$**

$E_{e,kin}$ = 18.575 keV

B = 1 T

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



combined antenna signal

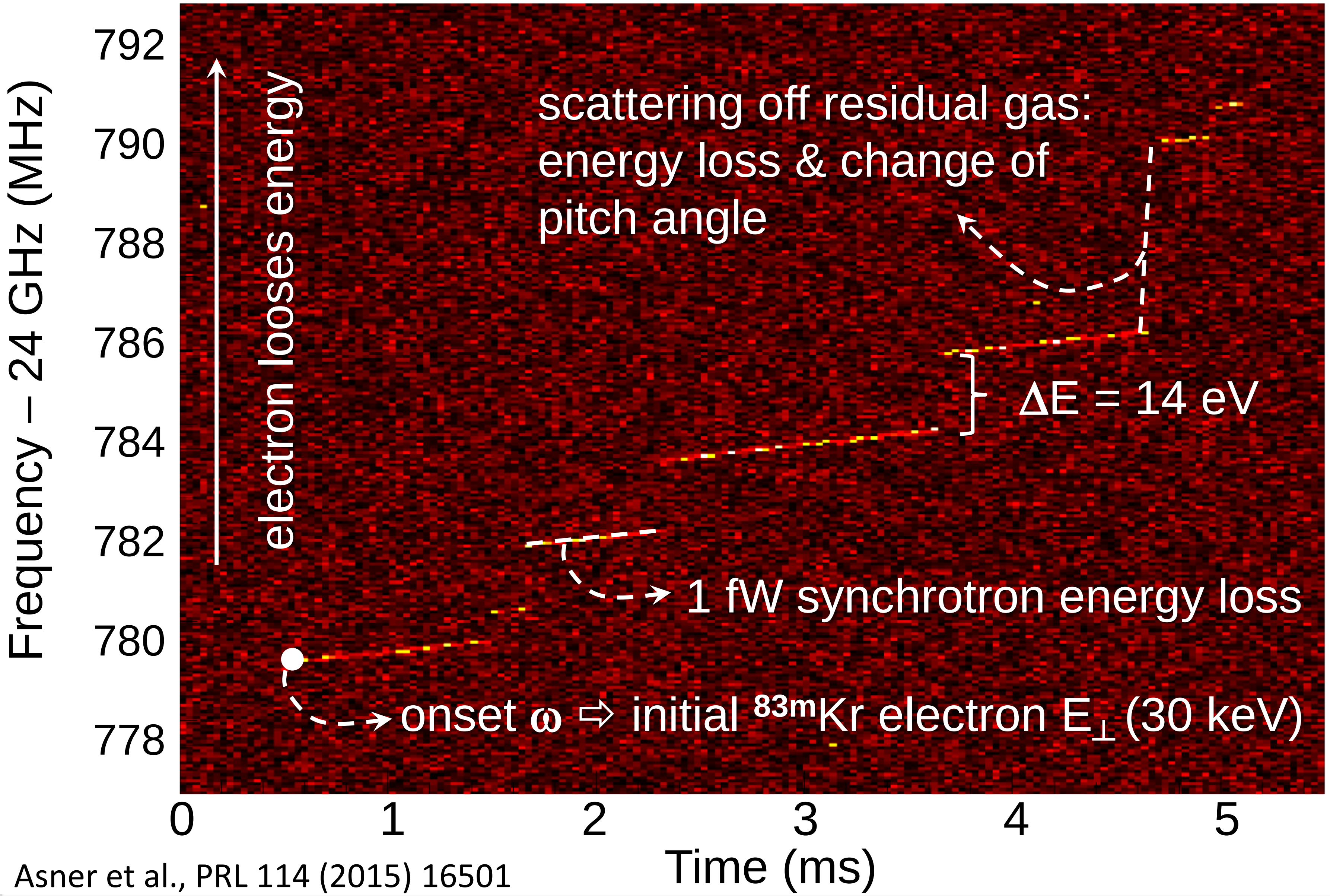
$\Delta\omega \sim 1/t_s$
sampling time
t_s ~ several µs
(magnetic bottle)

ΔE = 1 eV

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

Project 8 – single electron history

first detection of cyclotron radiation from a single keV electron



Asner et al., PRL 114 (2015) 16501

25
20
15
10
5

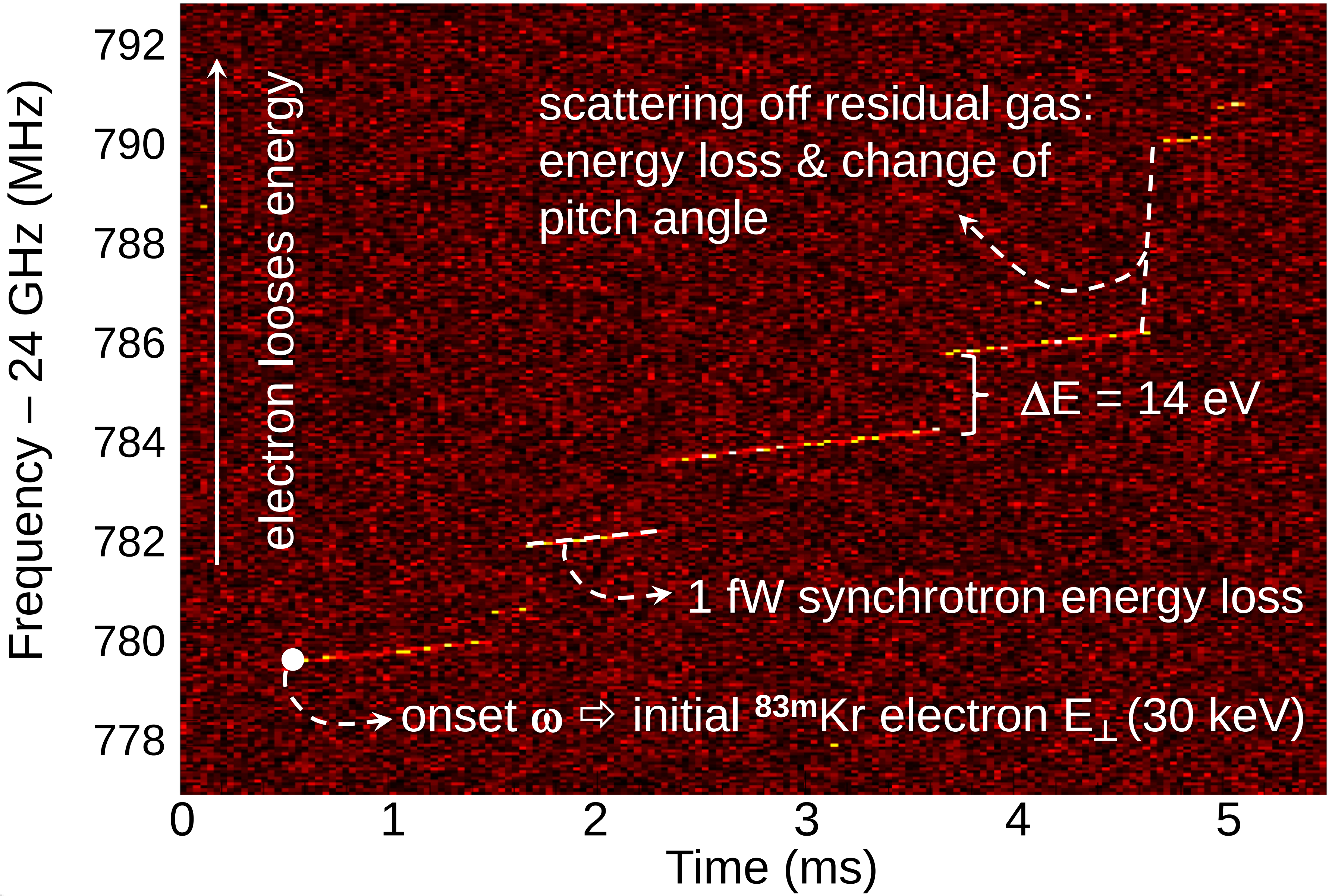
UW Seattle, Yale, MIT, LLNL, Pacific NW, Harvard-Smithonian, UCSB

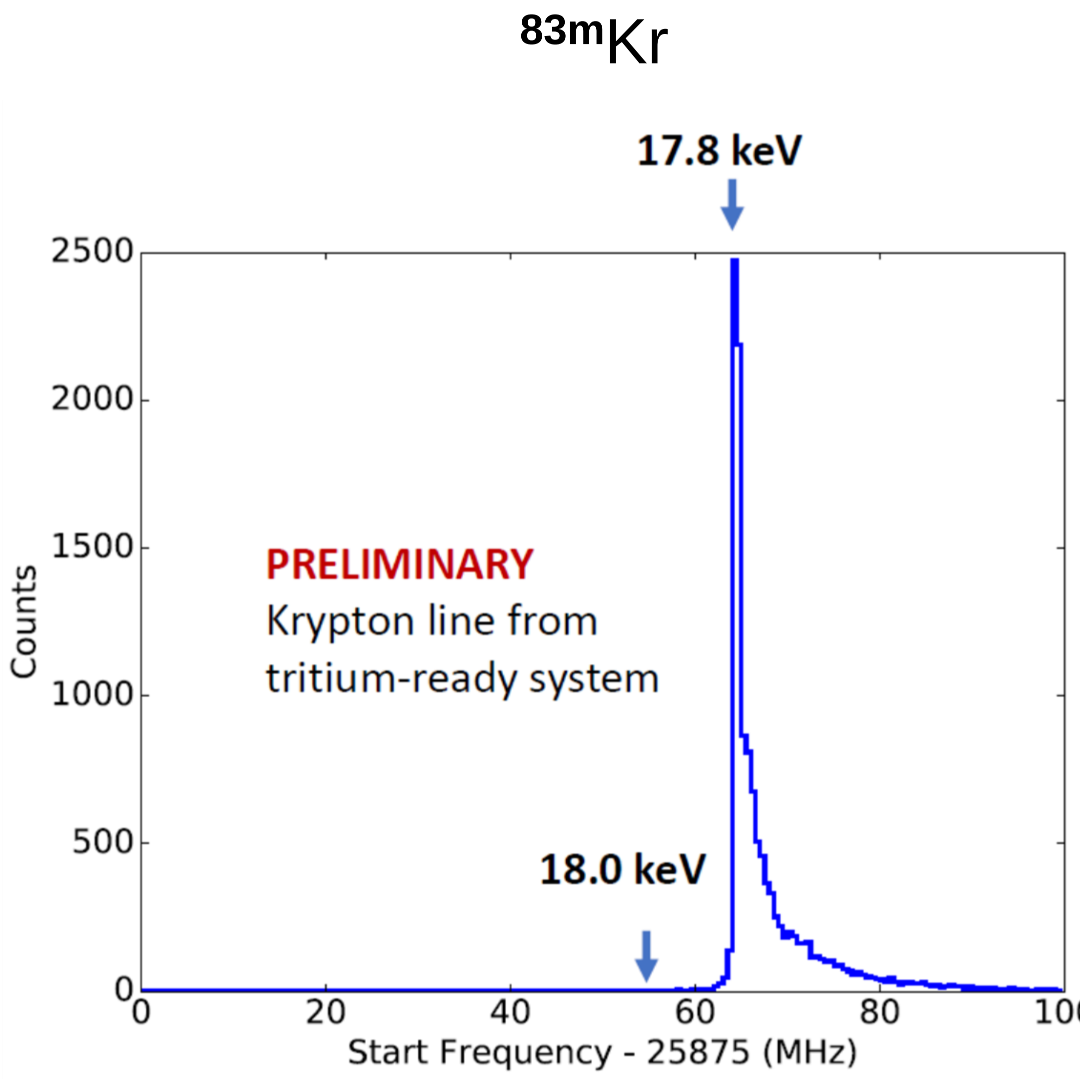
German partners:
U Mainz
(plus support by KIT)

Phase-I cryostat

Project 8 – single electron history

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





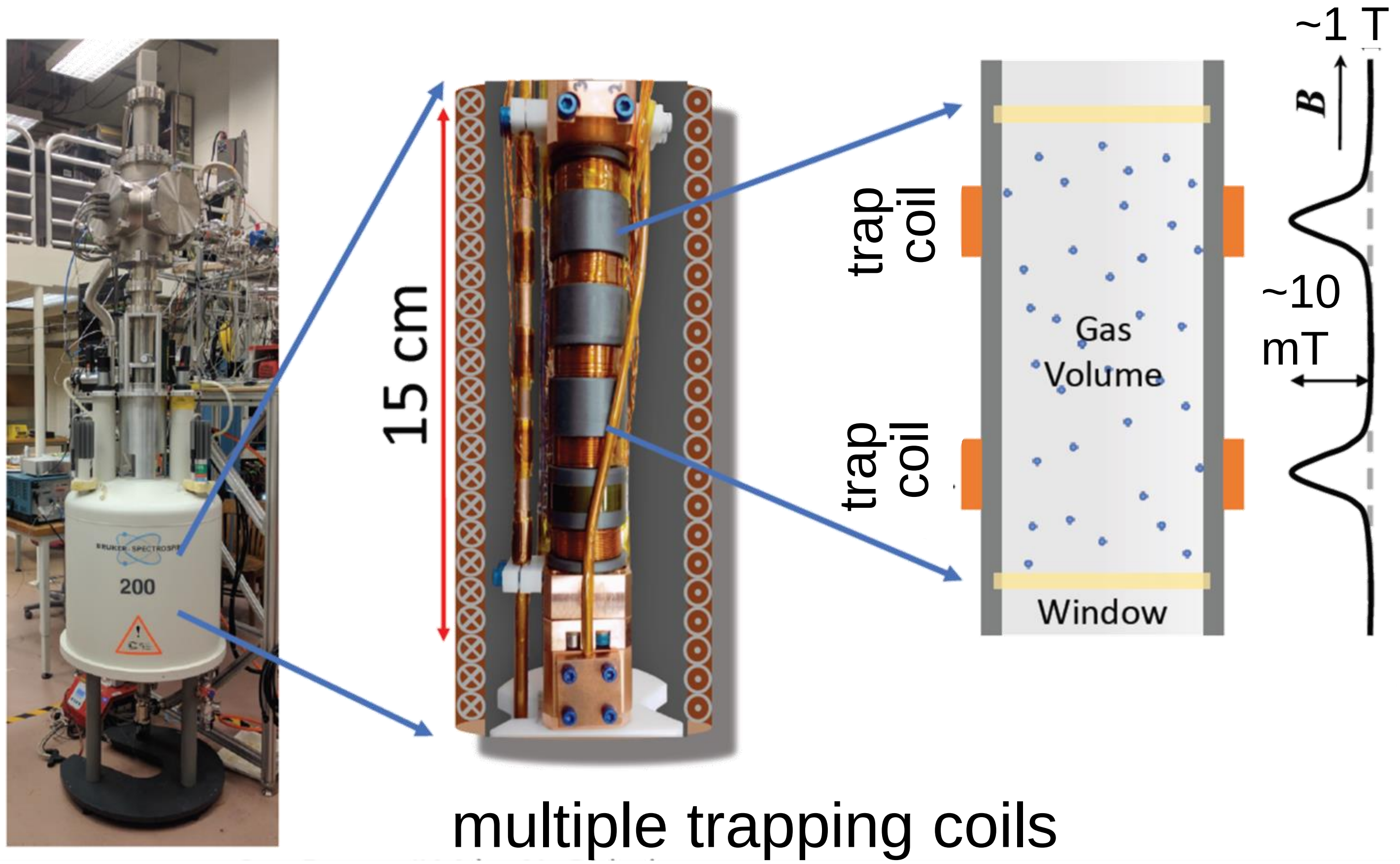
Project 8 – a staged approach

❶ Phase – I: 2010-2016 – proof-of-principle
test measurements with ^{83m}Kr
CRES observed for first time

❷ Phase – II: 2015-2018 - tritium demonstrator
improved read-out
circular waveguide
runs with ^{83m}Kr
first tritium (T2) data
(second half 2018)
record continuous ß-spectrum
m(ν_e) ~ 10.. 100 eV

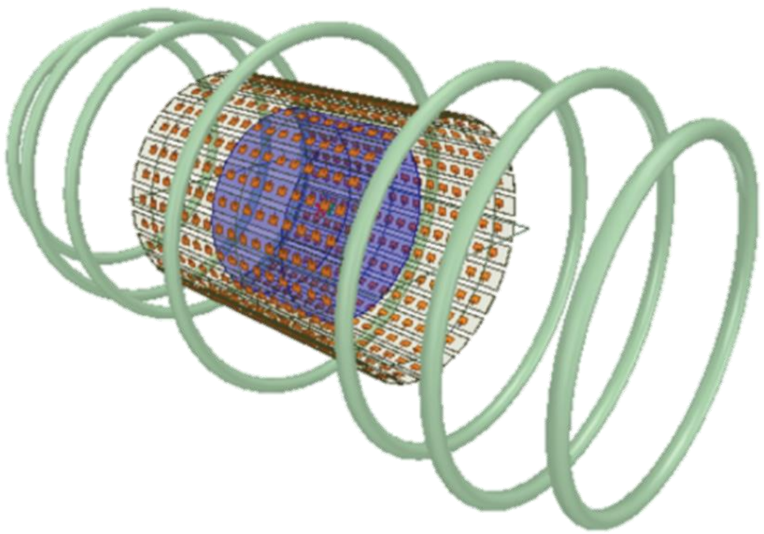
Phase - II

T2 and Kr-83
co-magnetometry



multiple trapping coils

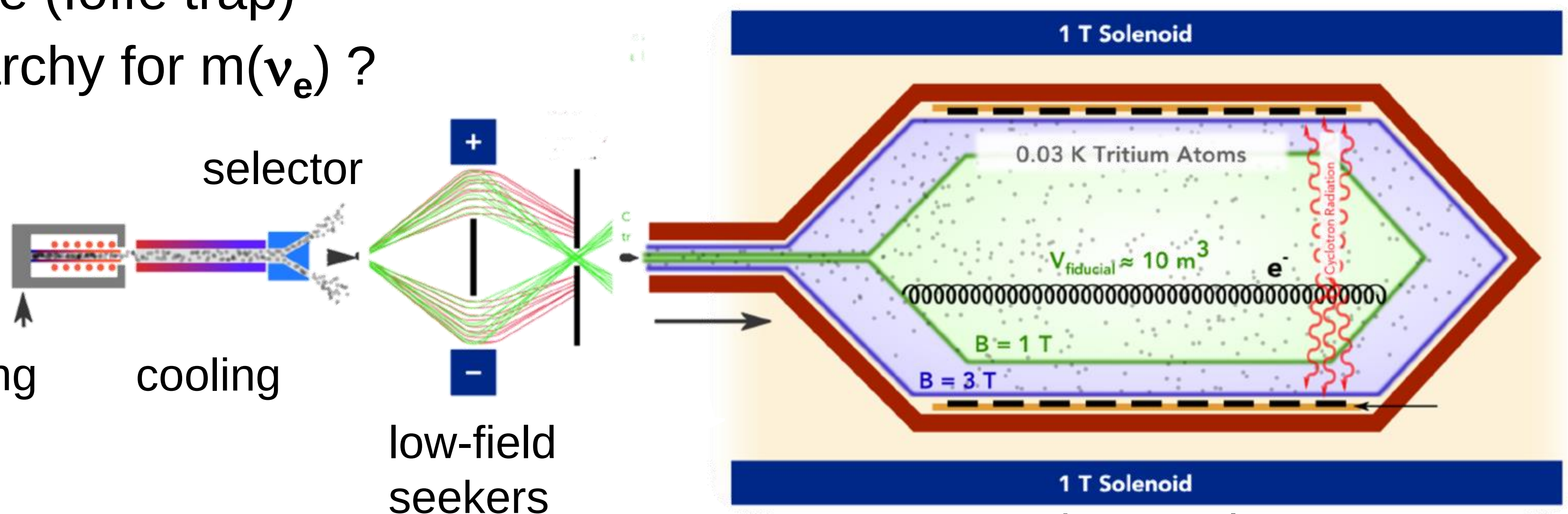
Project 8 – a staged approach



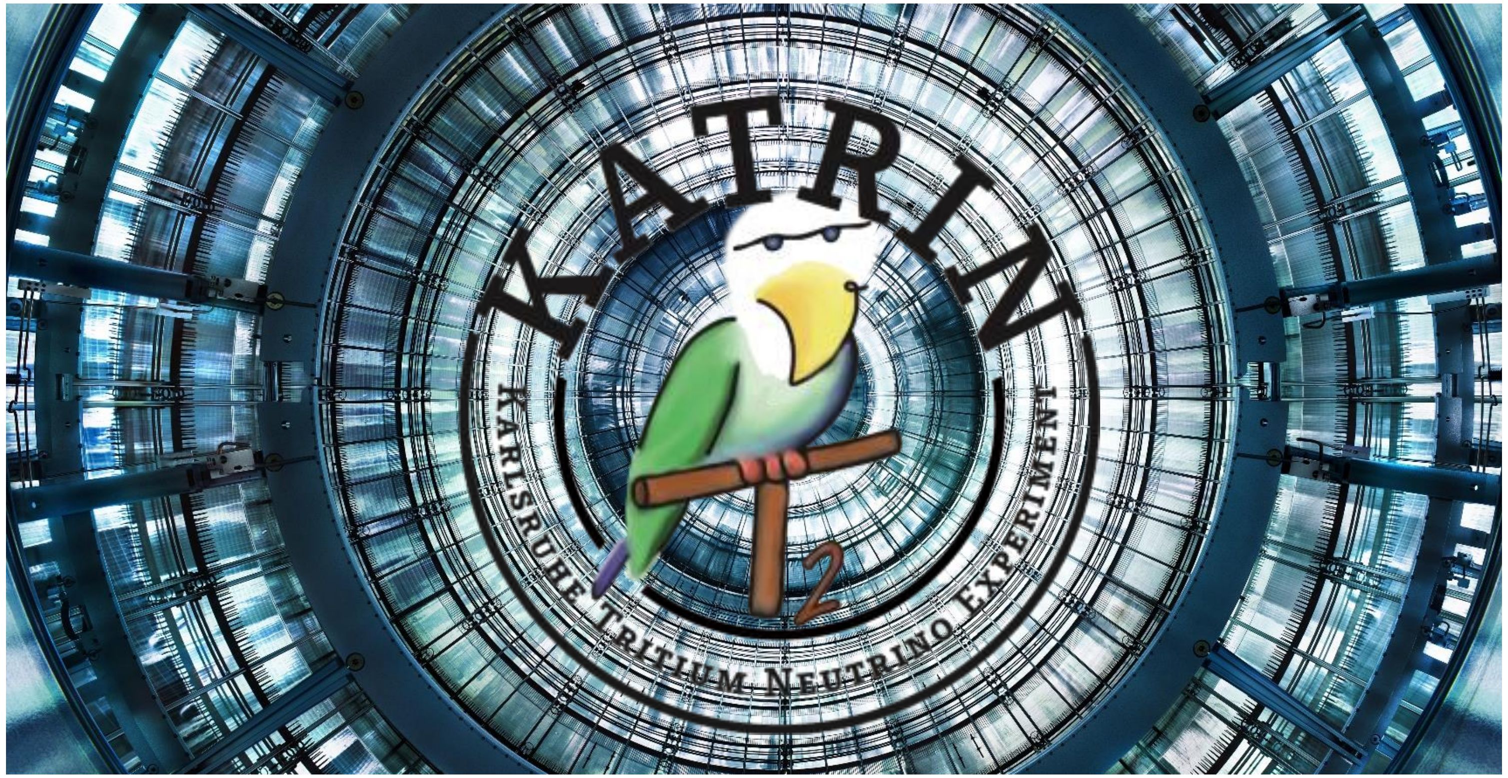
❸ Phase – III: 2019-2020ff – large volume demonstrator
conceptual design for multi-antenna array
tritium data competitive with m(ν_e) ~ 2 eV

❹ Phase – IV: … - towards an atomic tritium source
conceptual design for very large set-up
atomic tritium source (Ioffe trap)
inverted mass hierarchy for m(ν_e) ?

selector

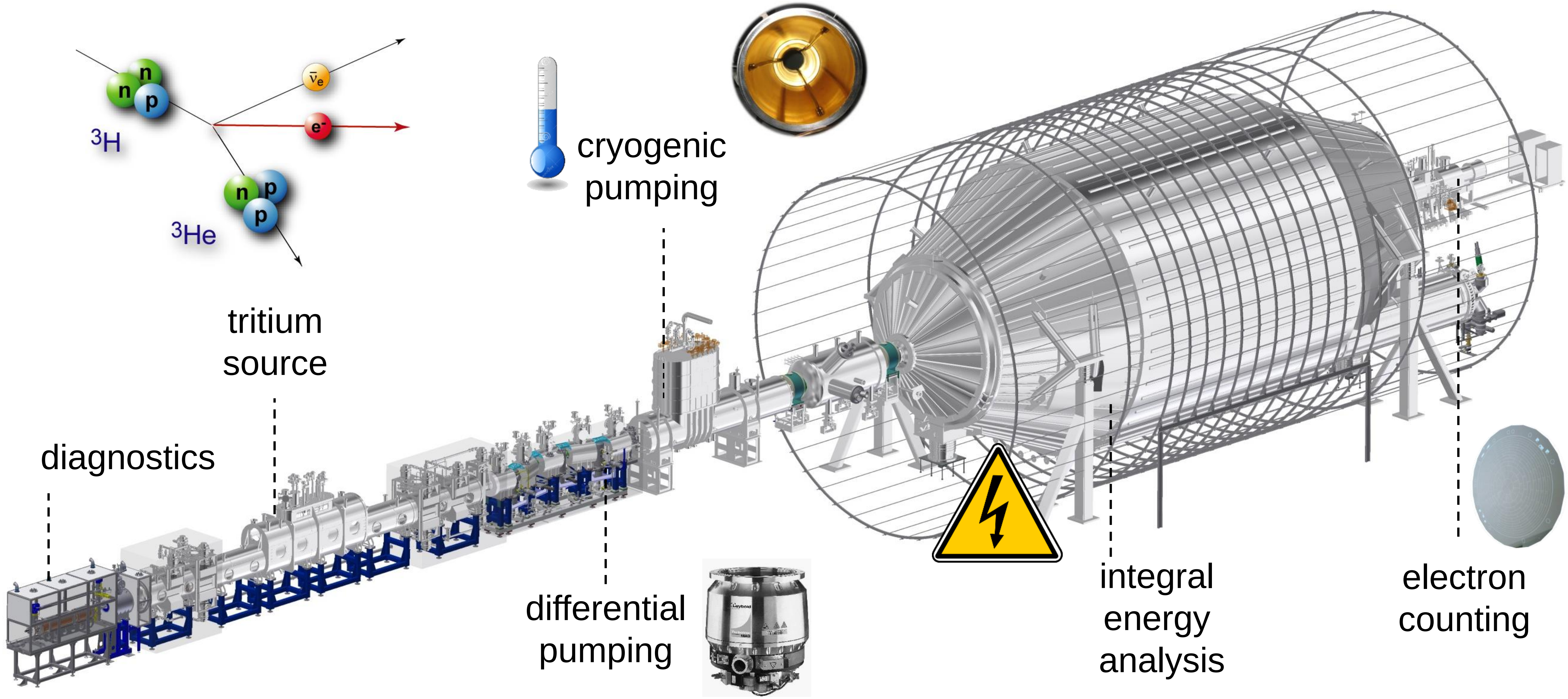


cracking cooling low-field seekers decay volume

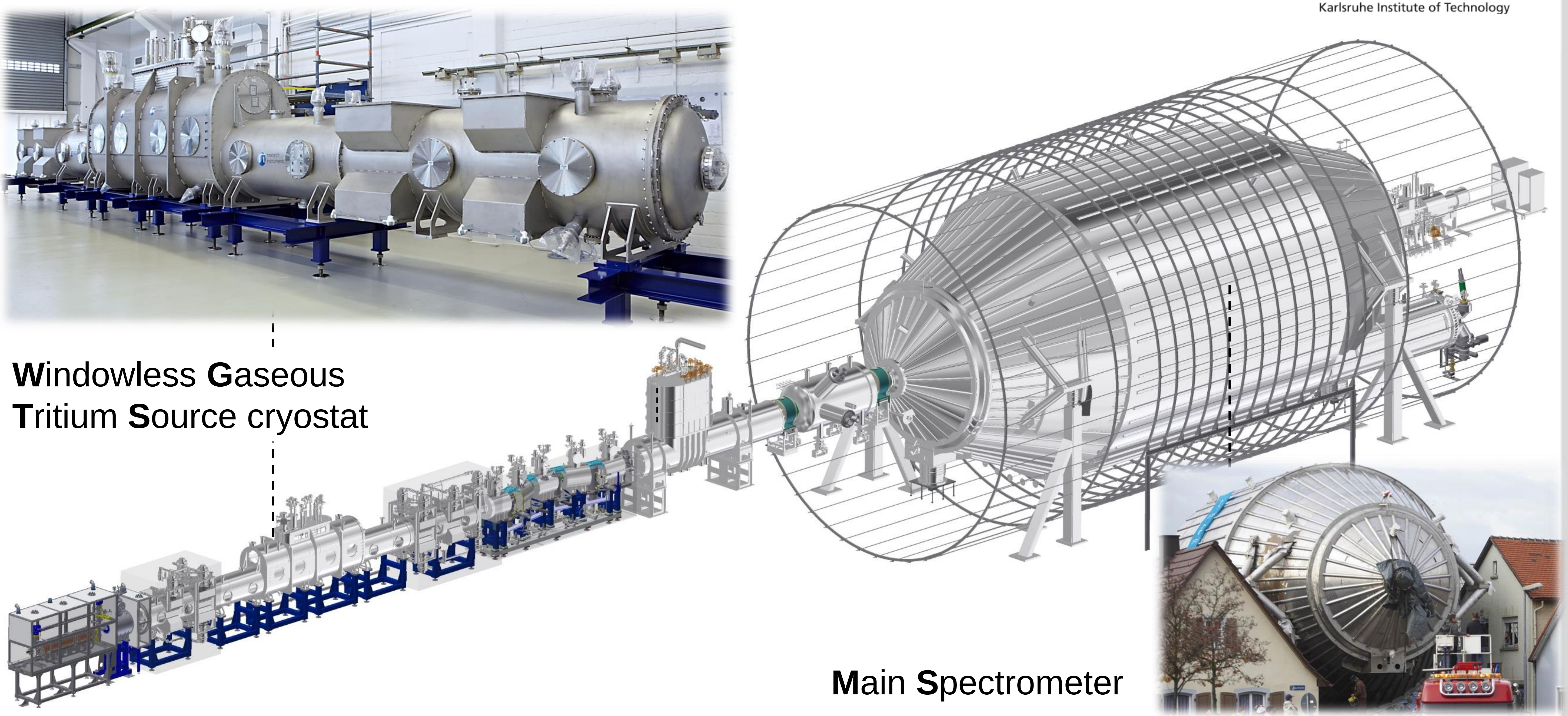


KATRIN

KATRIN overview: 70 m long beamline



KATRIN overview: 70 m long beamline

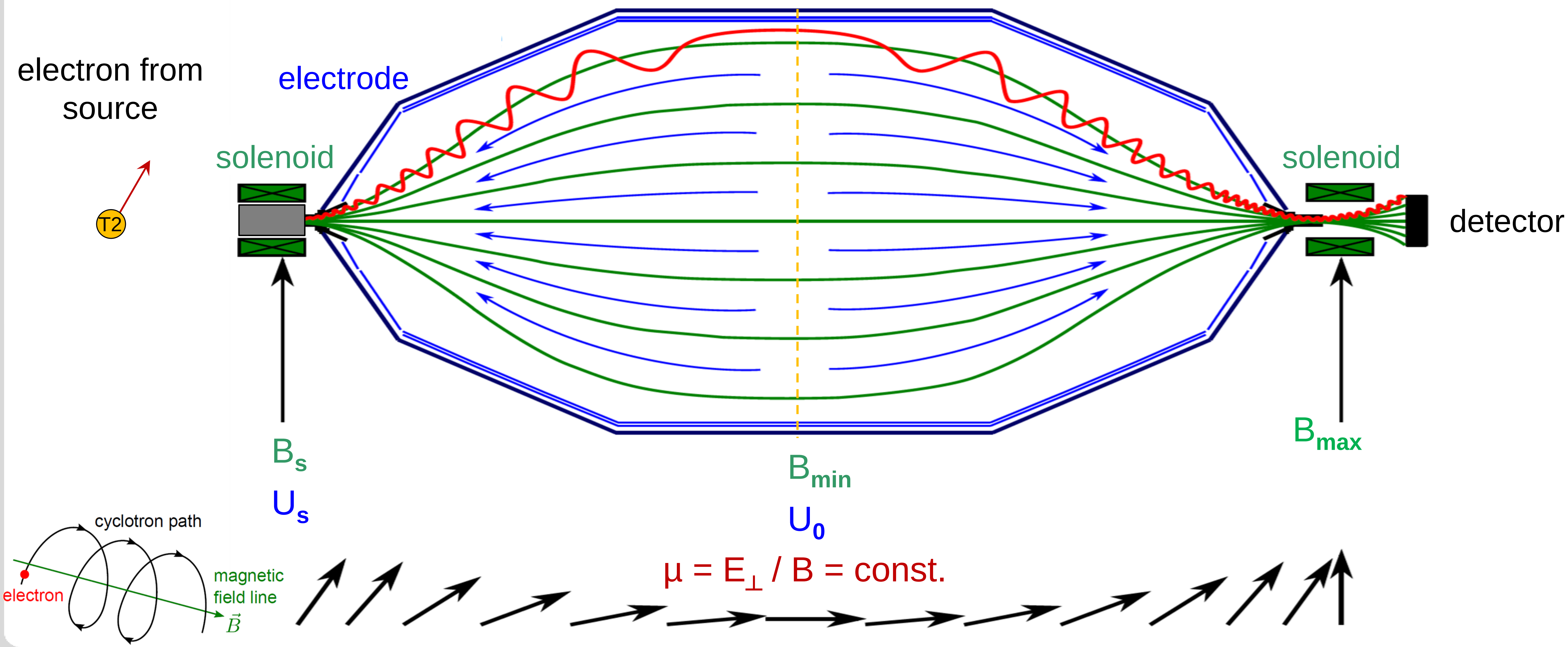


Windowless **G**aseous
Tritium **S**ource cryostat

Main **S**pectrometer

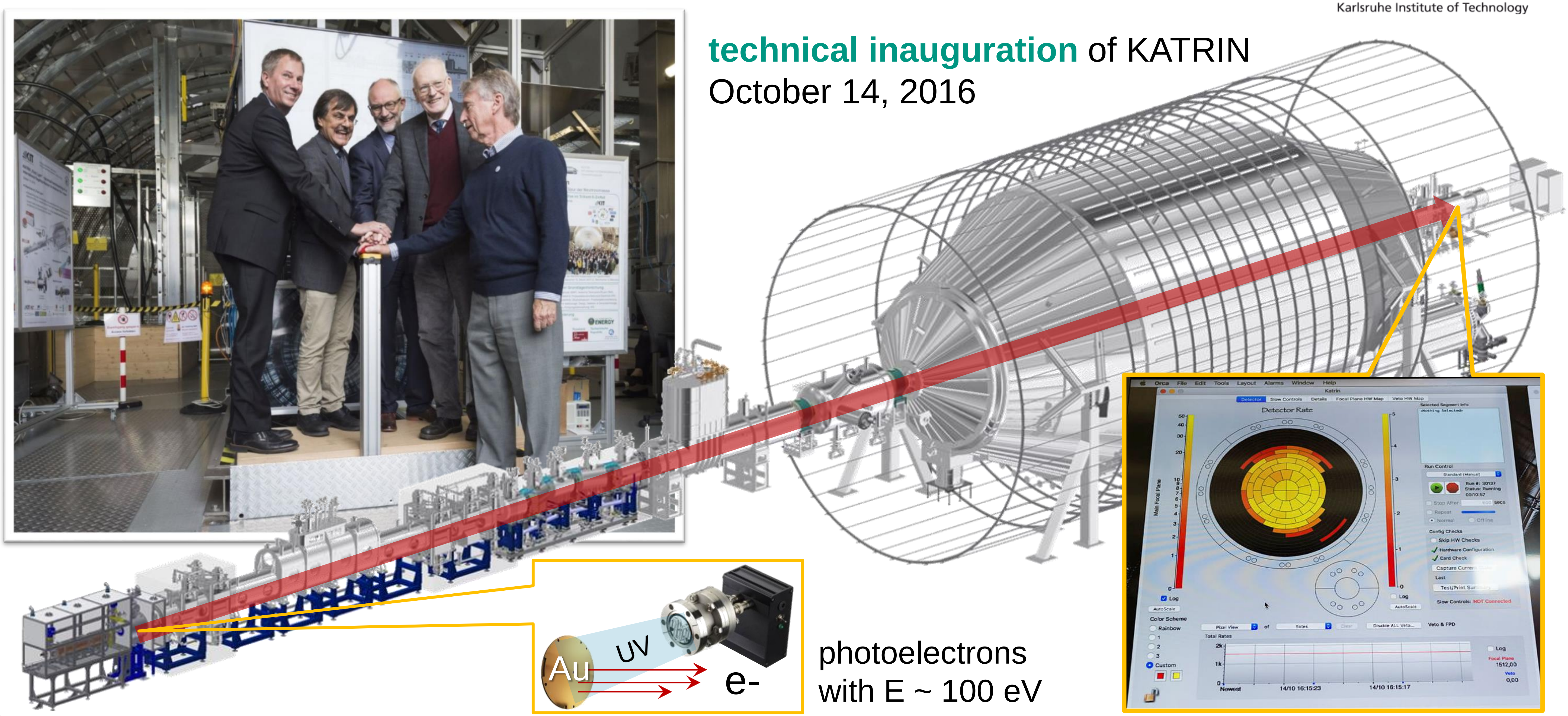
MAC-E principle: high-resolution tritium ß-spectroscopy

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



Project milestones – first light (after NOW 2016)

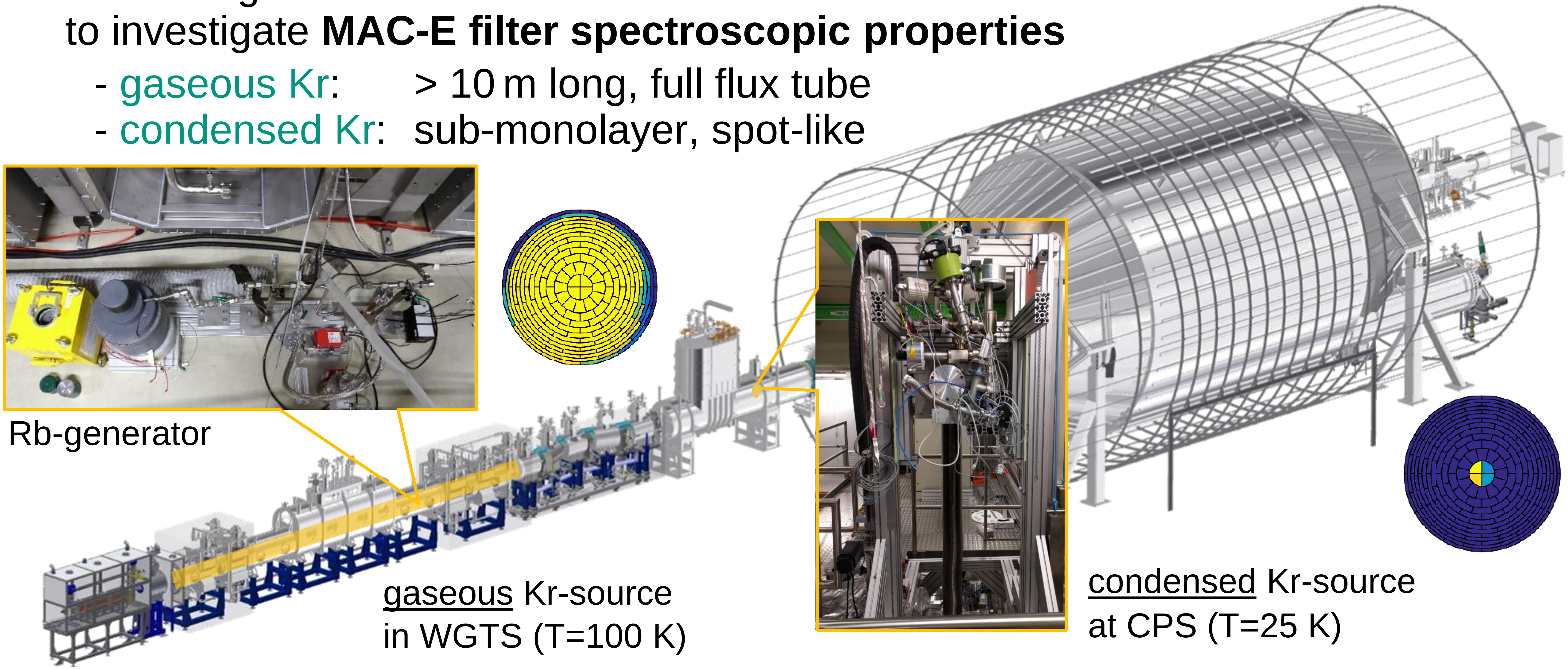
technical inauguration of KATRIN
October 14, 2016



photoelectrons
with E ~ 100 eV

science runs 2017: krypton campaign

- monoenergetic conversion electrons from ^{83m}Kr sources to investigate **MAC-E filter spectroscopic properties**
  - gaseous Kr: > 10 m long, full flux tube
  - condensed Kr: sub-monolayer, spot-like



Rb-generator

gaseous Kr-source
in WGTS (T=100 K)

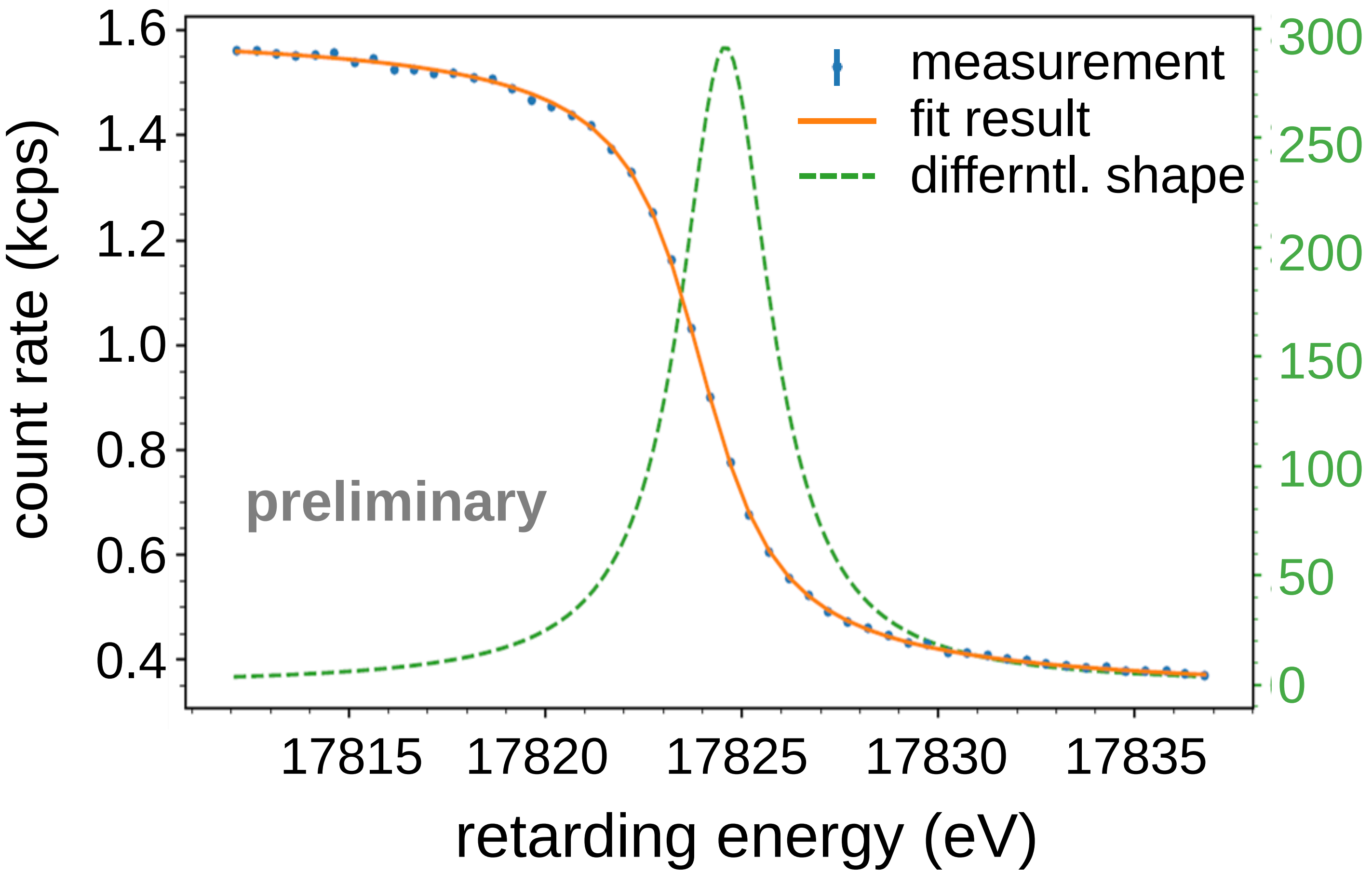
condensed Kr-source
at CPS (T=25 K)

Krypton measurements – GKrS results

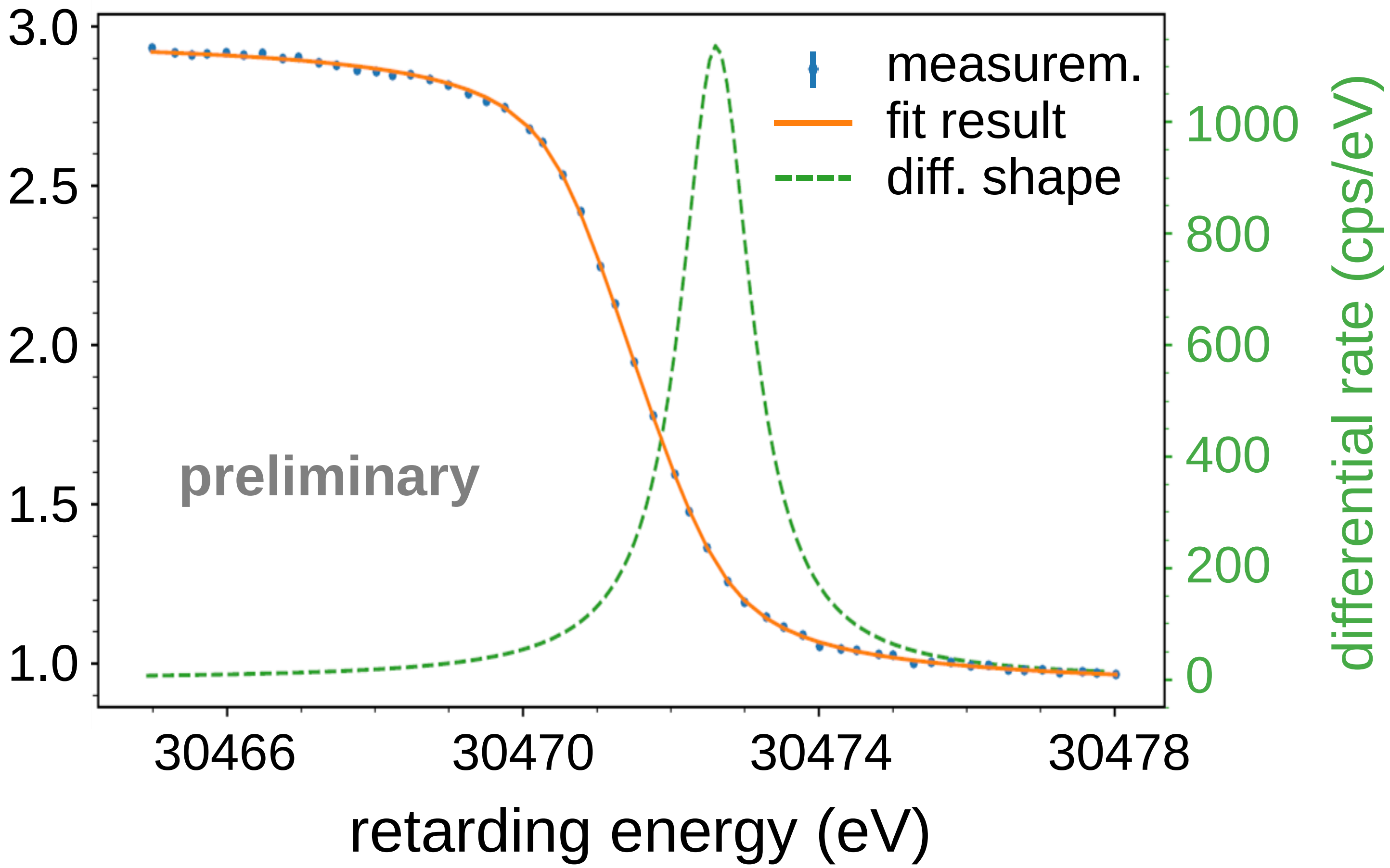
- **excellent filter characteristics** of main spectrometer
  - no large source tube potential systematics
  - new method for HV calibration

$$\Rightarrow \quad \frac{\Delta E}{E} \cong \frac{B_{min}}{B_{max}} \quad (1.15\ \text{eV @ } 17.82\ \text{keV})$$

K-32 line: 17.82 keV

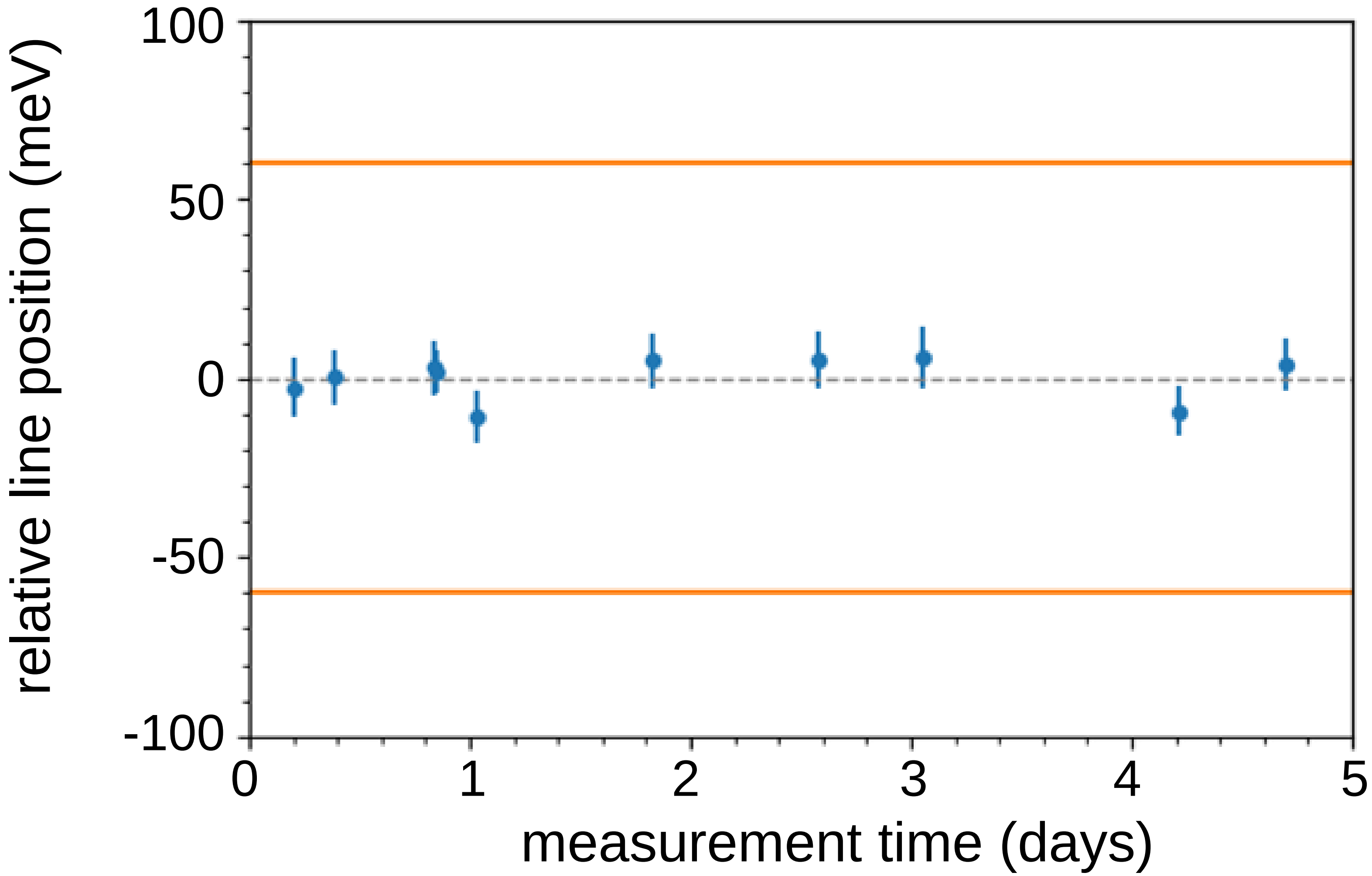


L3-32 line: 30.47 keV



Krypton measurements – line stability test

- **stability of mono-energetic conversion electrons** from Kr-83m:
  - repeated scans of L3-32 line over a week
    ⇨excellent stability of KATRIN energy scale over many days (later: 8 weeks)

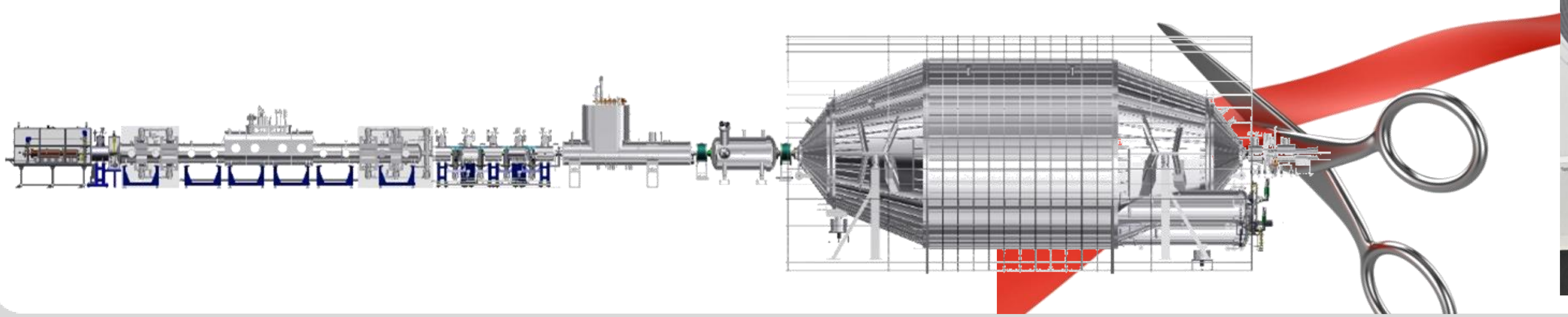


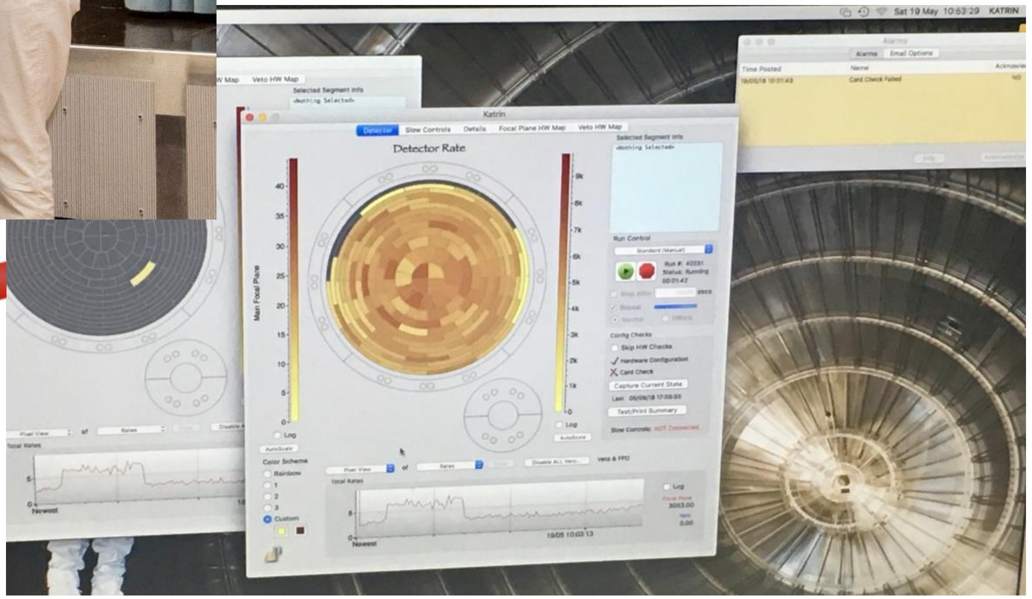
stability goal: ± 60 mV

GKrS, preliminary

Project milestones – inauguration (before NOW 2018)

- **official KATRIN inauguration** : **June 11, 2018**
  successful start of long-term tritium data taking

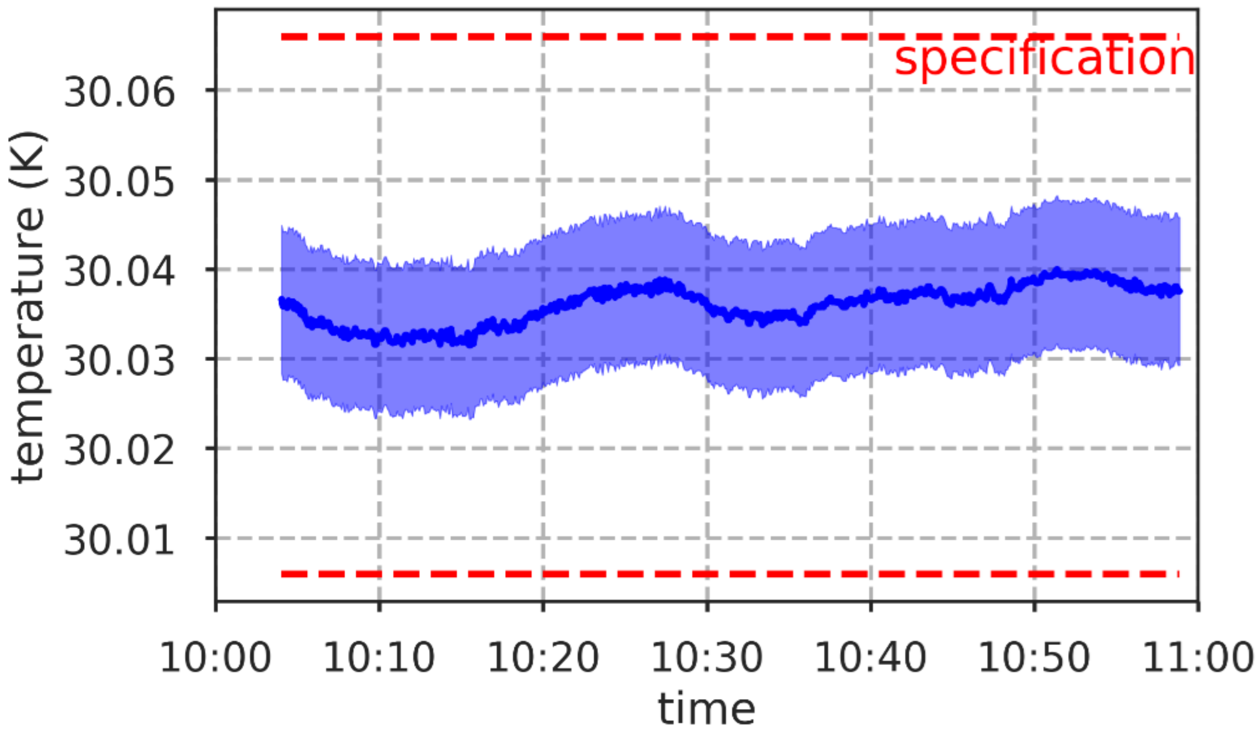




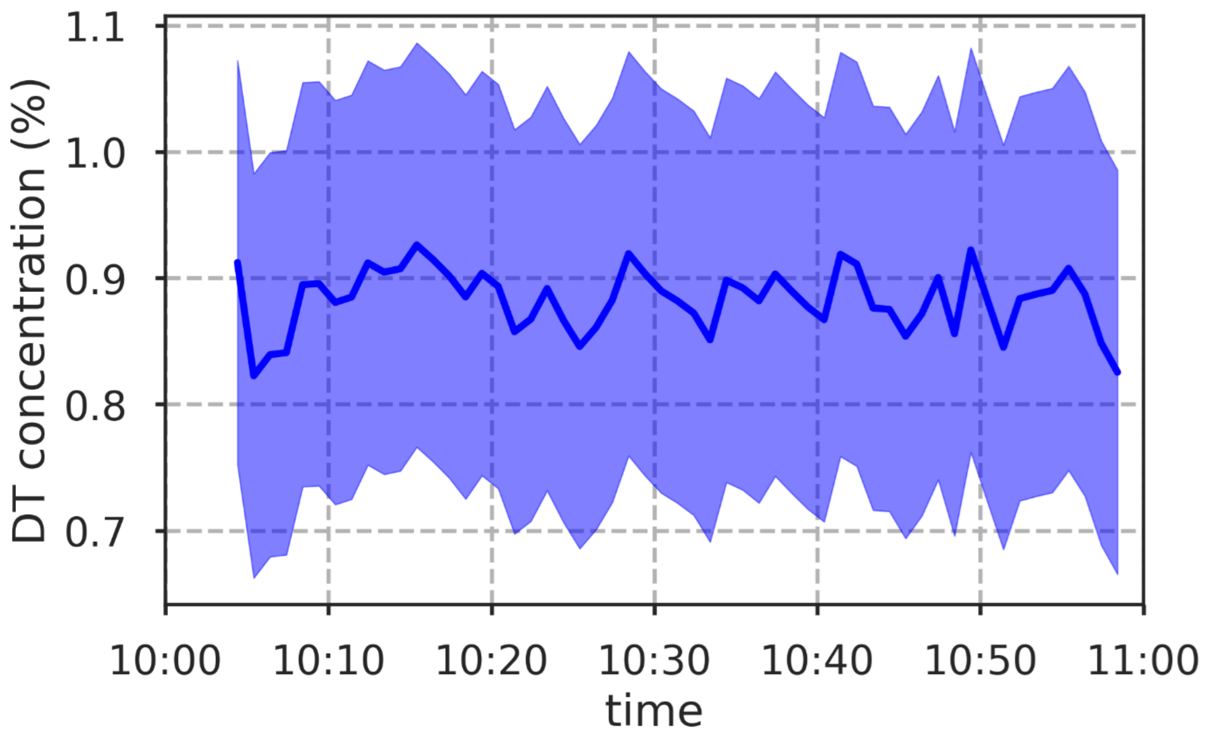
first tritium campaign (engineering run)

- method: **inject known gas mix** from prepared cylinders
  - **low tritium concentration**: ~1% DT and ~99% D_2
  - verify functionality of all system components
  - operate close to nominal column density ρd (~80%), need determination of ρd via egun (systematics)

stability of source temperature



stability of source composition

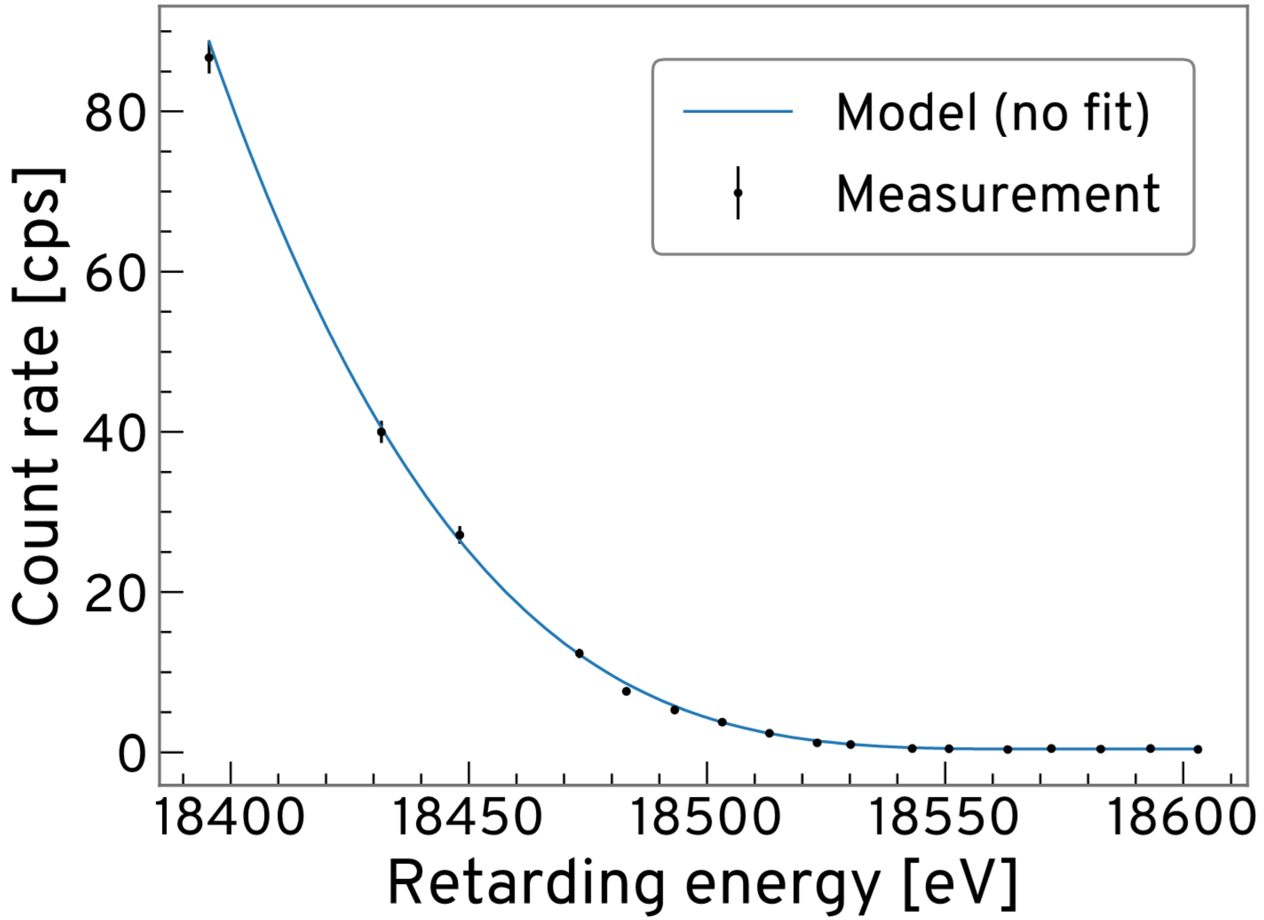


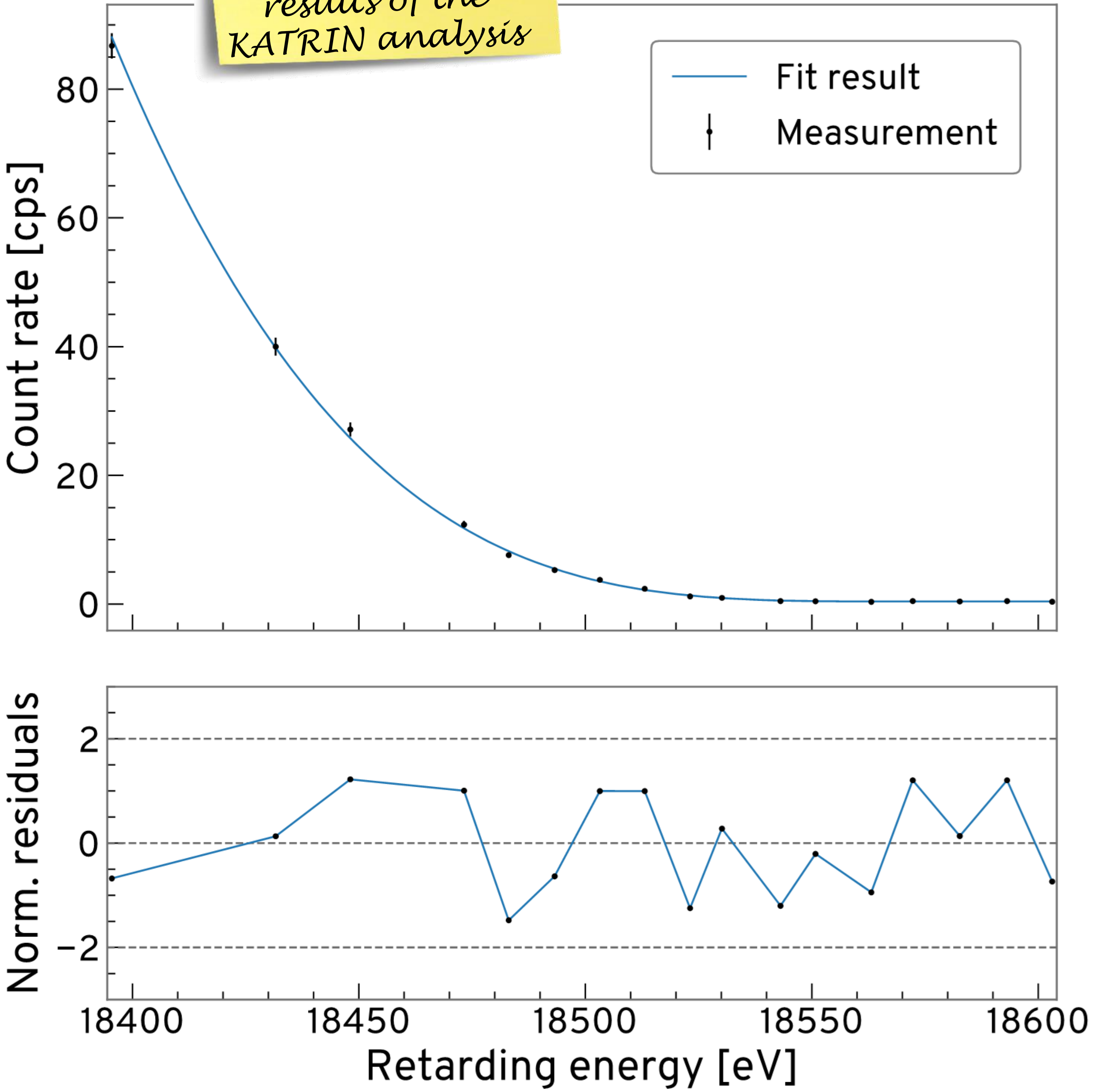
first tritium campaign (engineering run)

Valerian Sibille
first tritium
results of the
KATRIN analysis

Karlsruhe Institute of Technology

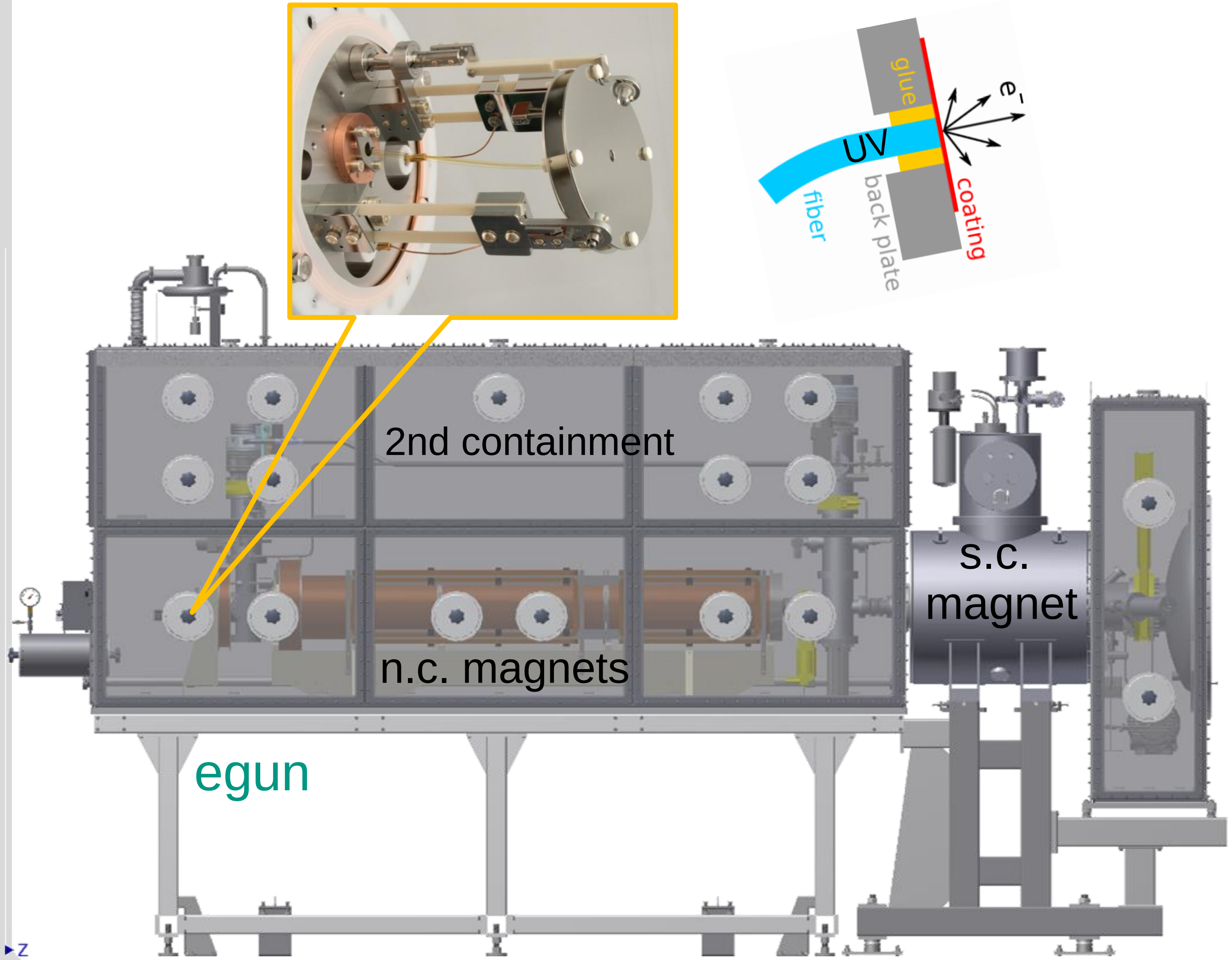
- analysis of first tritium scan (200 eV):
  - **model** gives very good understanding of both rate and shape (even up to 2 keV!!)
  - **fit results** agree with expectations



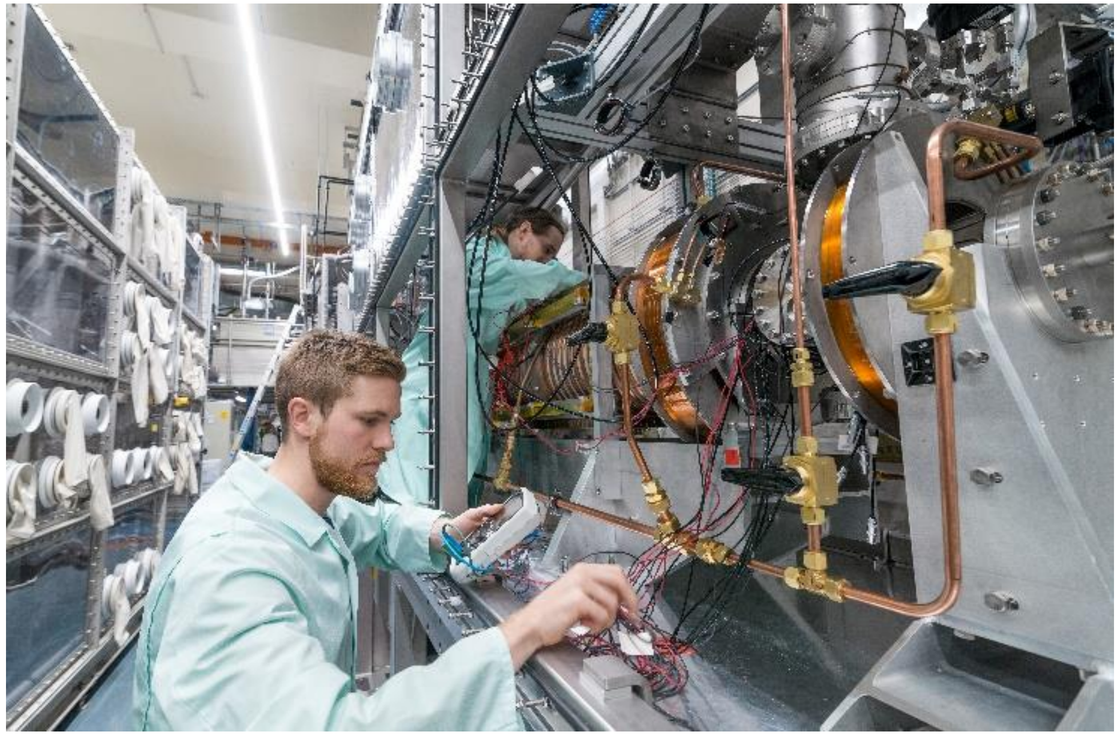


preparing egun measurements for systematics

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



- well-defined pitch angle $\Delta\theta$
- narrow energy spread ΔE
- excellent stability at high rates

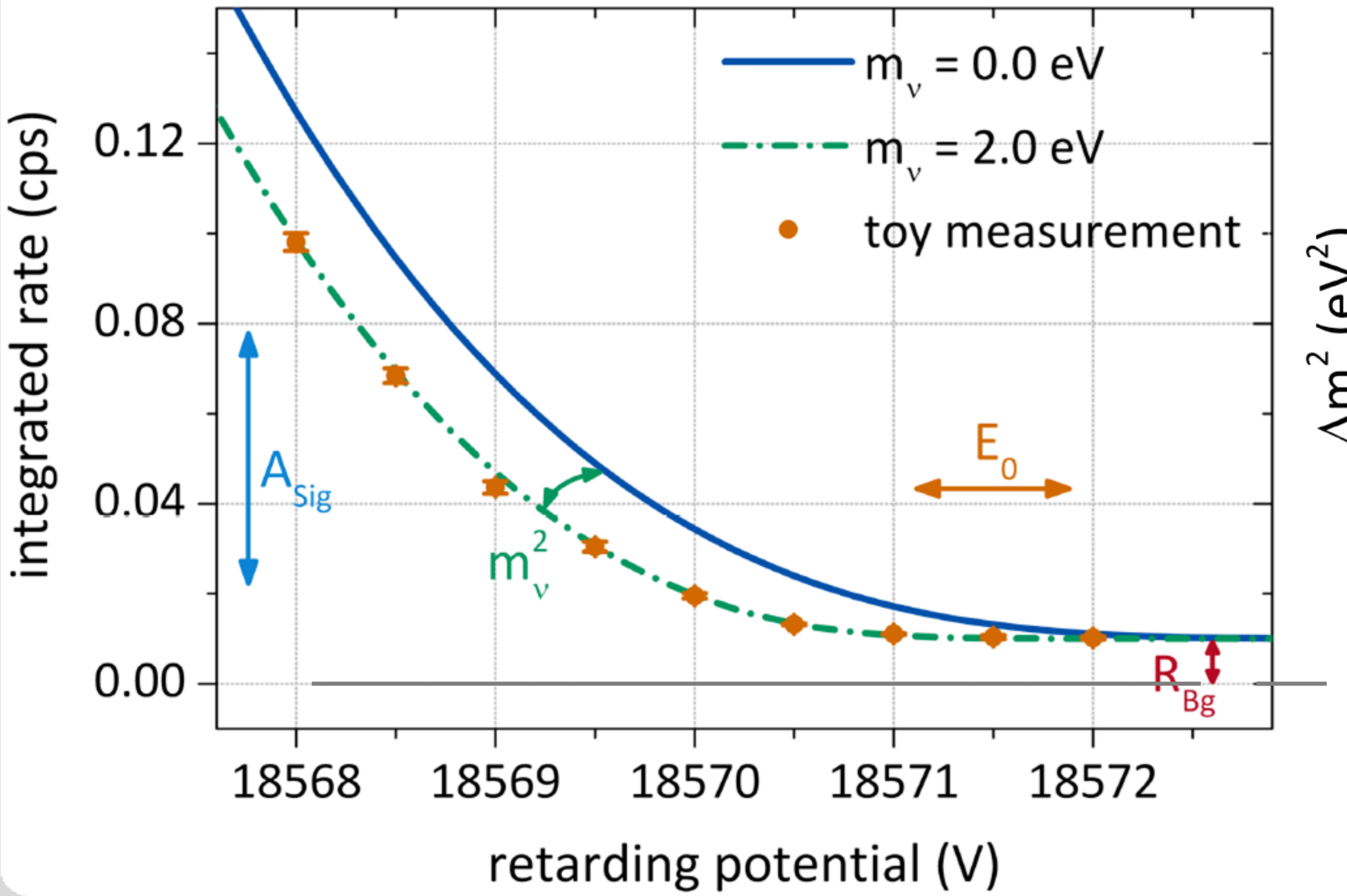


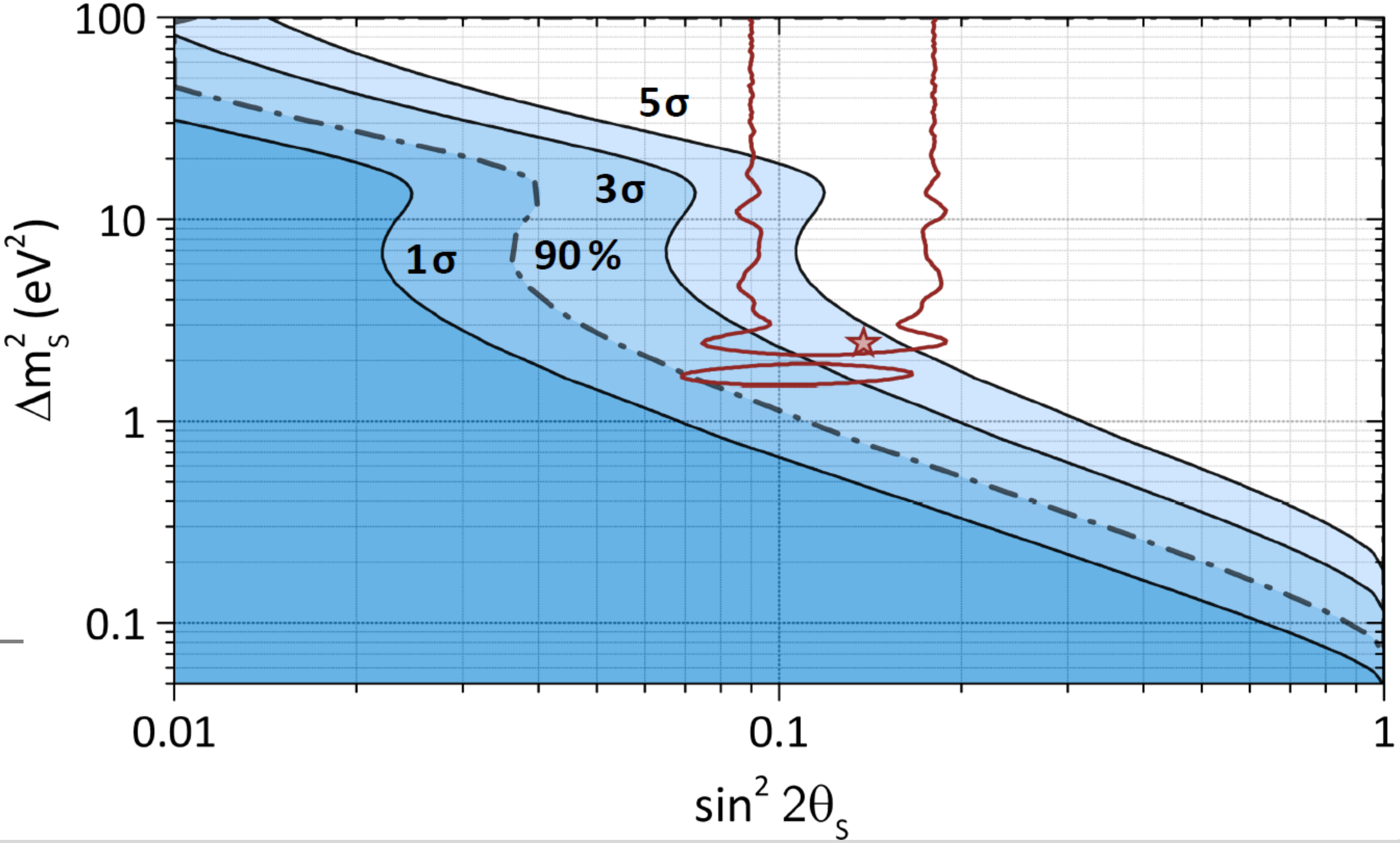
egun commissioning works 2018

KATIRIN physics programme

■ physics channels:

- 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 violations, exotic currents, BSM physics …

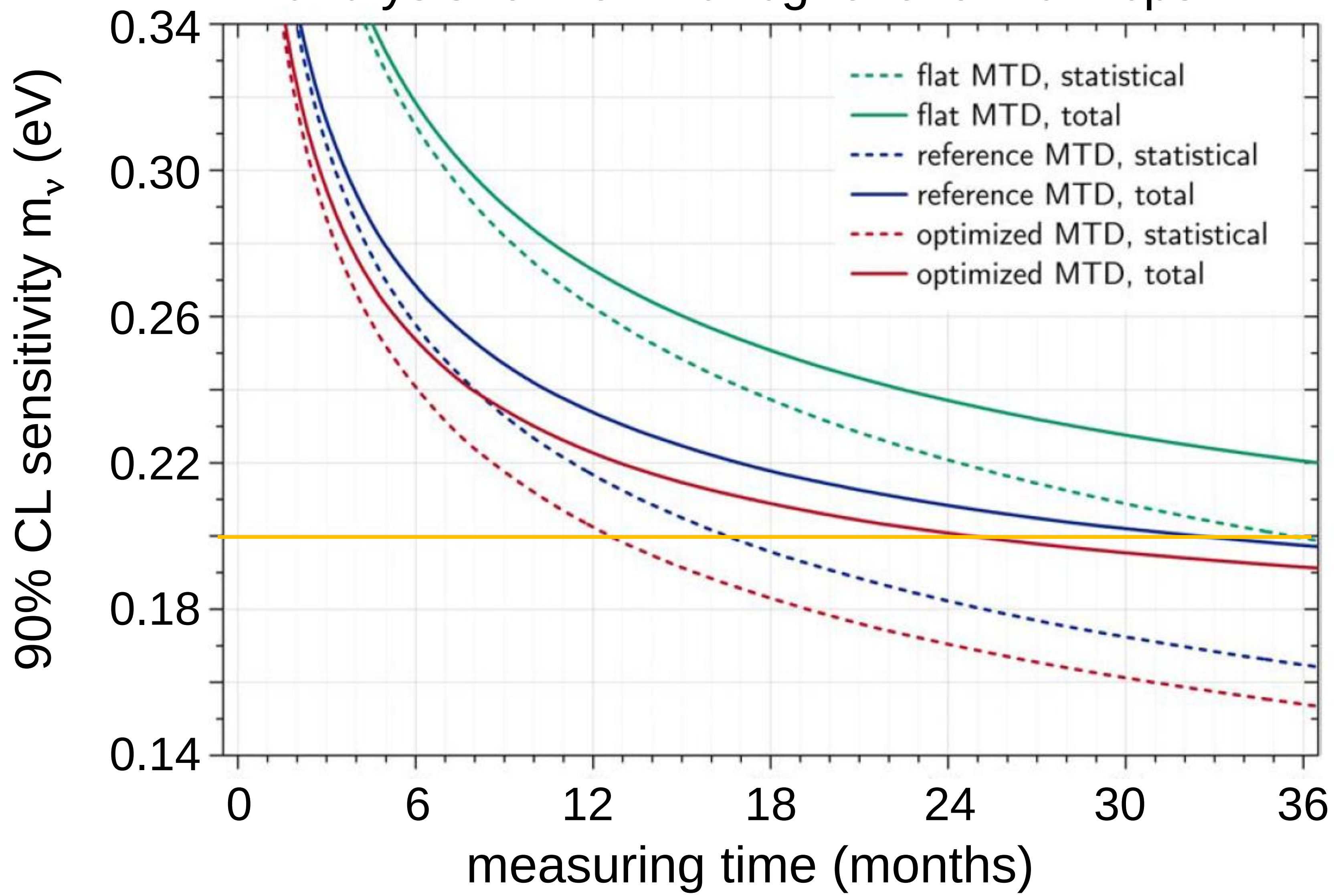




KATRIN - reference ν-mass sensitivity & beyond

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

analysis for nominal bg-level of 10 mcps



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

0.35 eV (5σ)

- 2019ff detailed study of systematics: MTD, plasma & molecular effects,...

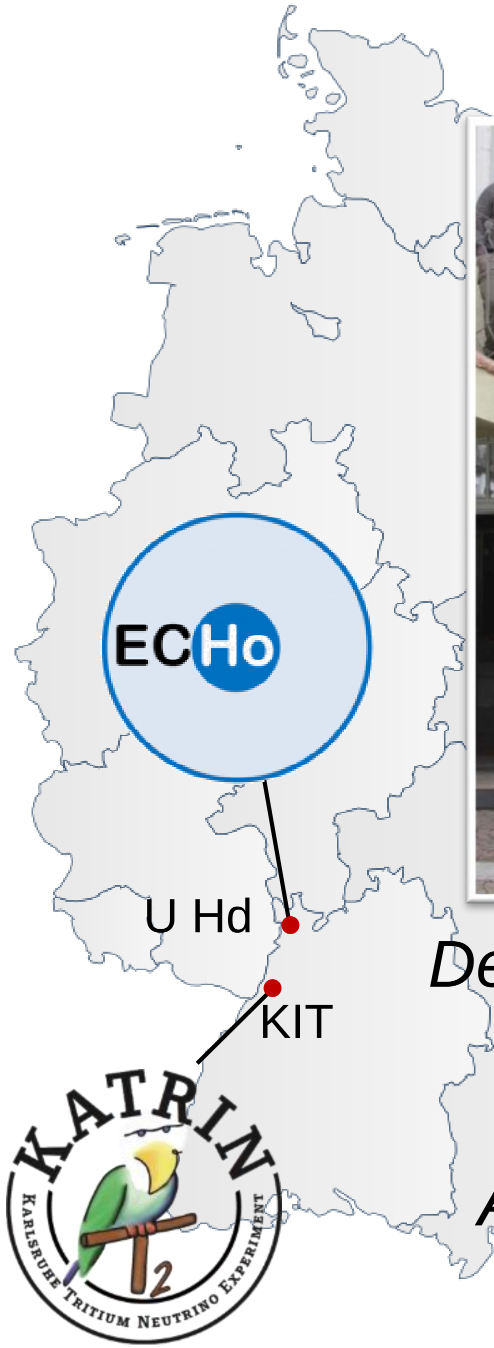
- **Differential tritium scan (2023ff)**
  - push for **$m(\nu_e)$ ~ 0.1 eV** and below
  - ToF-technique using combination of spectrometers (PS-MS)
  - hi-res bolometer with fixed HV at MS (bg-free scans)

A neutrino mass network

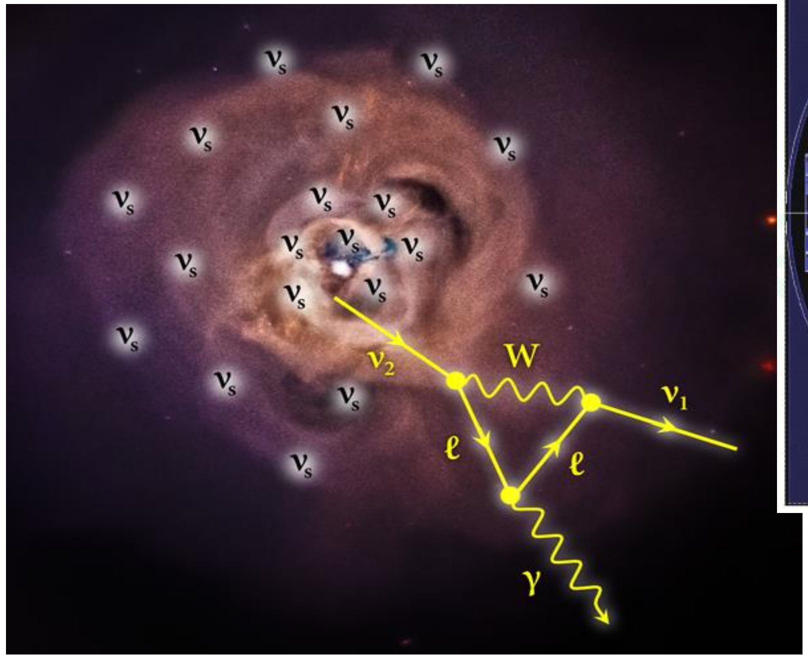
- March 2017: **MoU signed at KIT** on
  „absolute neutrino mass scale from nuclear ß-decay and electron capture“

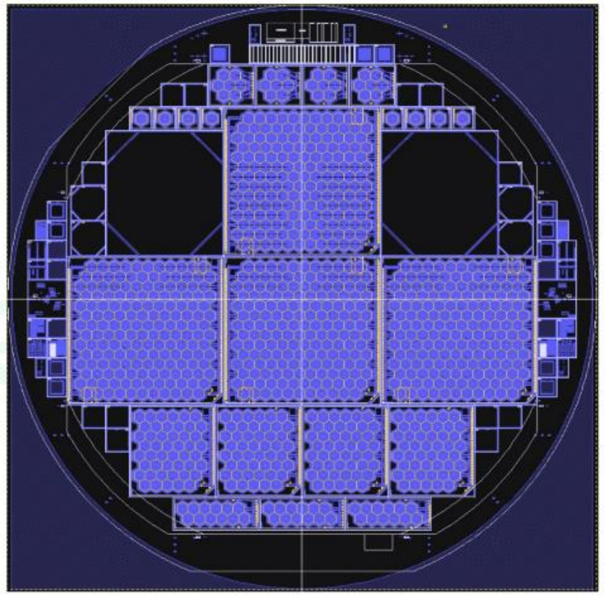
L. Gastaldo & K. Valerius (spokespersons)

- **Preparation of a Community „White Paper“**
  on „direct neutrino mass experiments“



Determination of the absolute (anti)neutrino mass, ECT workshop series, April 2016, March 2018,…*

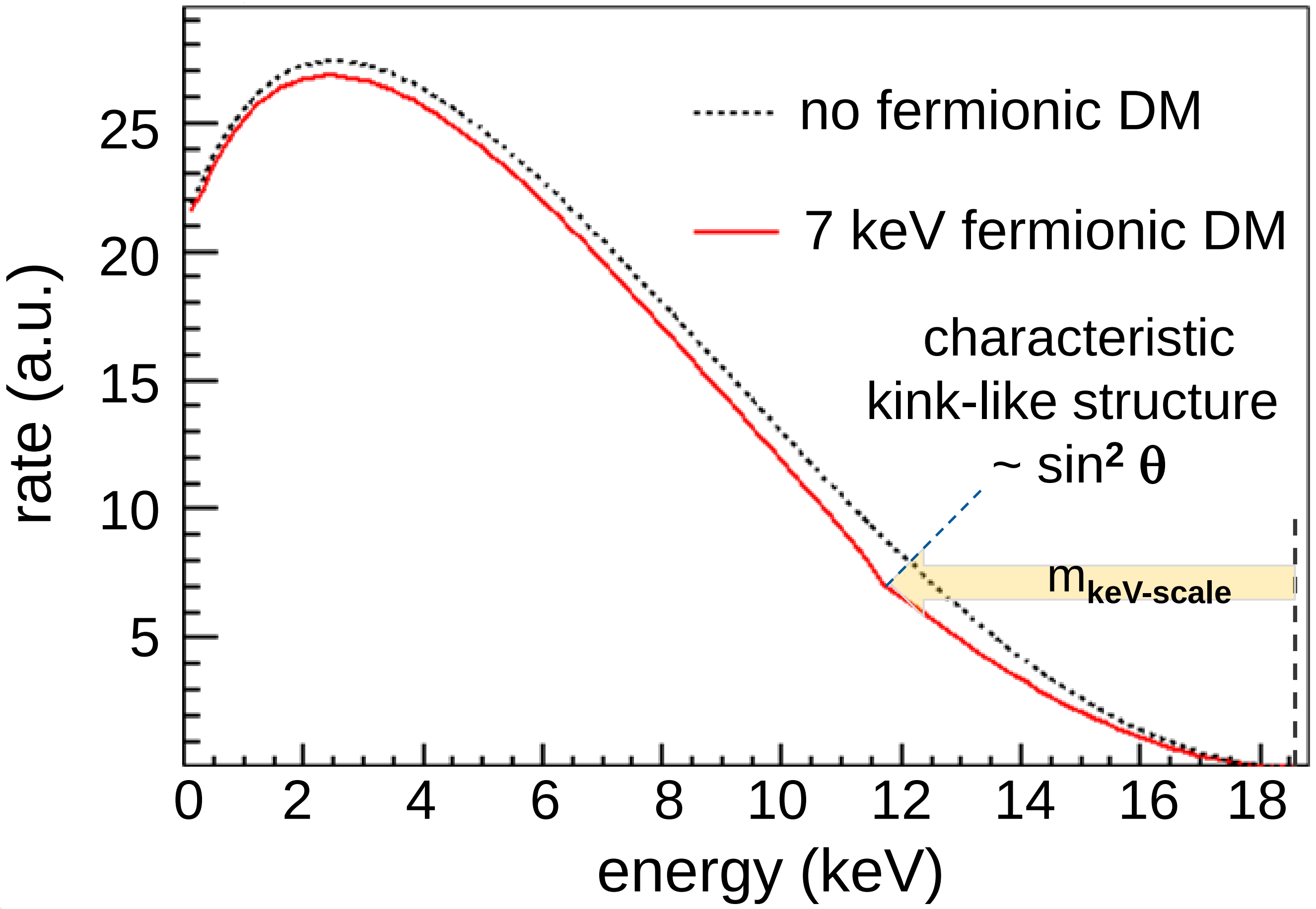




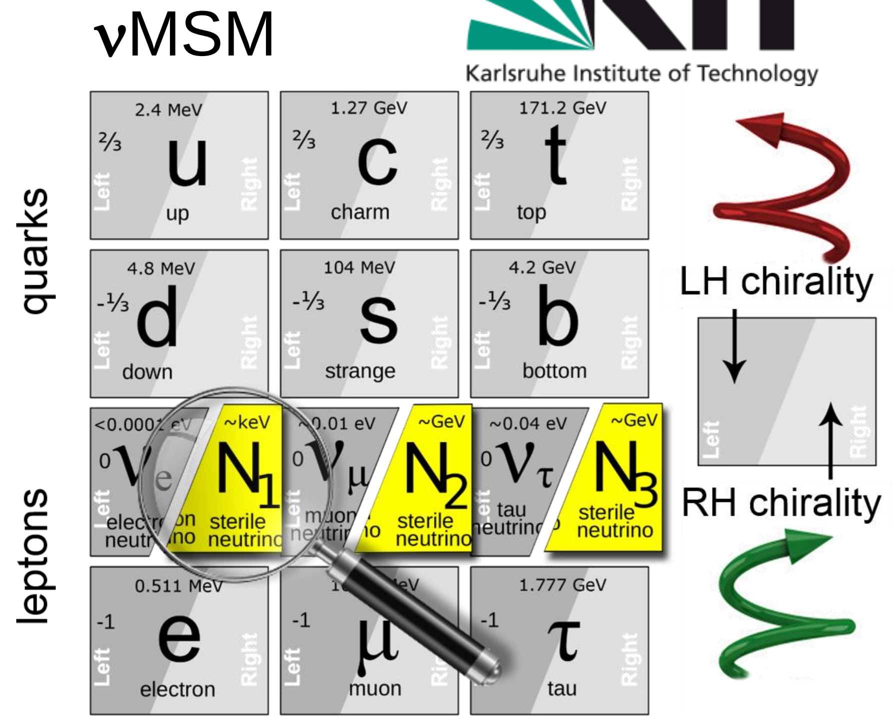
SEARCHING FOR KEV STERILE NEUTRINOS

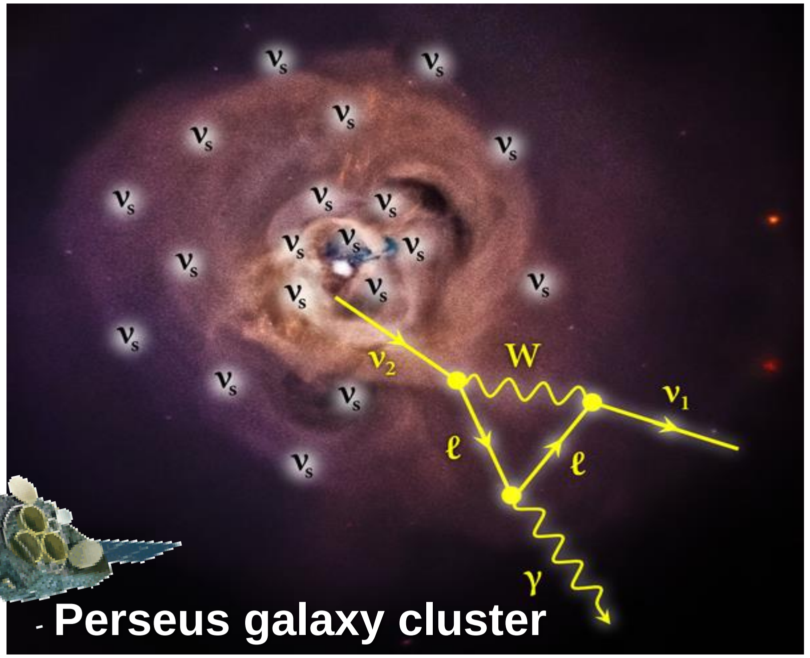
Tritium ß-decay and dark fermions

- **BSM particles (sterile neutrinos, light fermionic DM)** in keV-mass scale will 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)



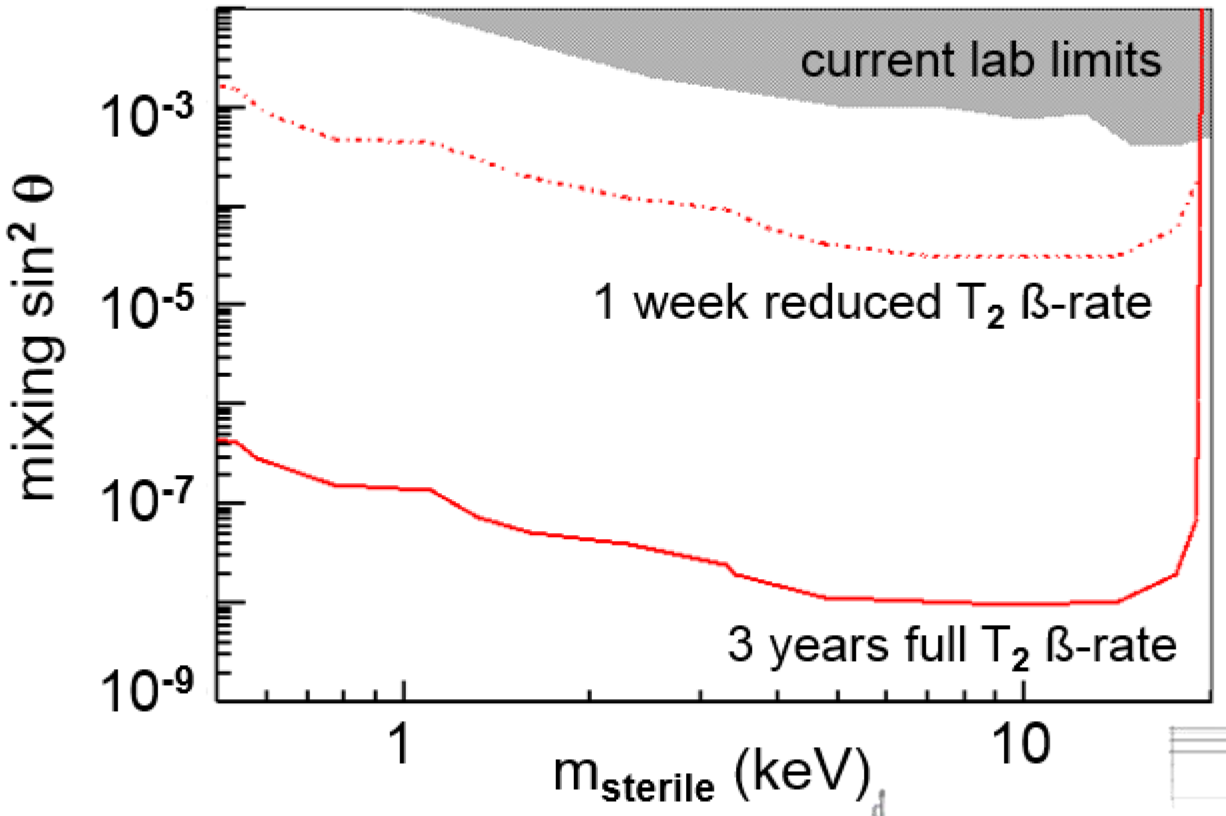
$$\frac{dN}{dE} = \cos^2\theta_s \cdot \frac{dN}{dE}(m_{active}) + \sin^2\theta_s \cdot \frac{dN}{dE}(m_{sterile})$$

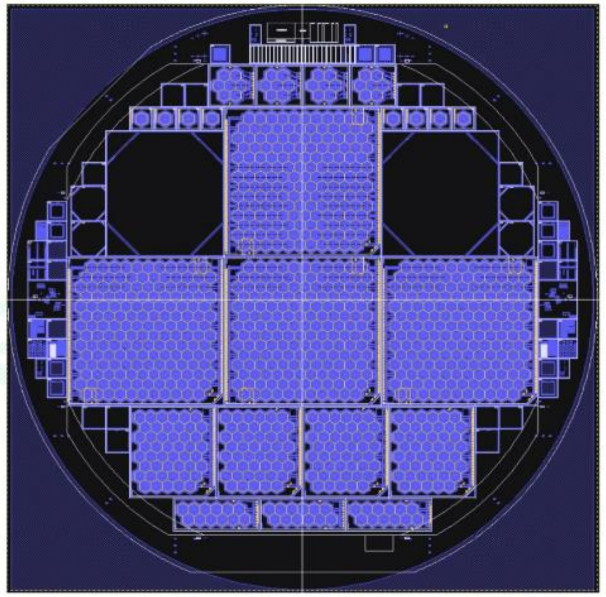


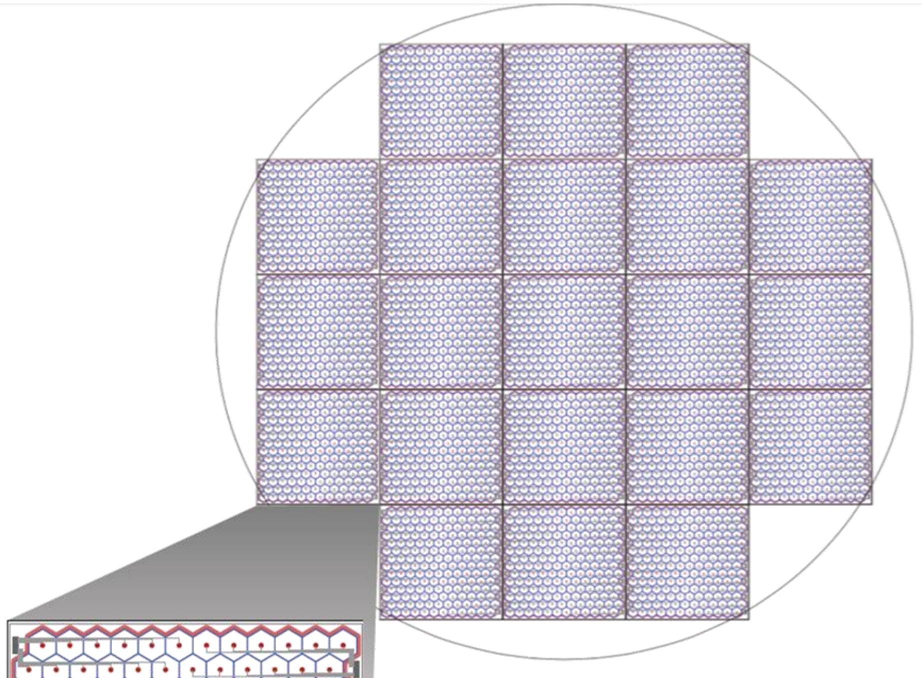


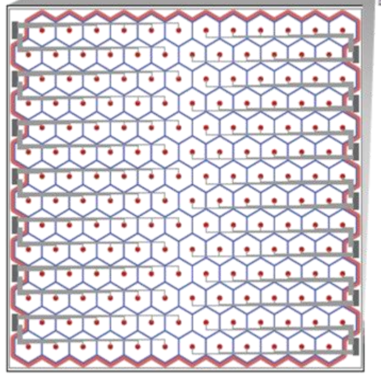
Science reach of KATRIN with TRISTAN detector

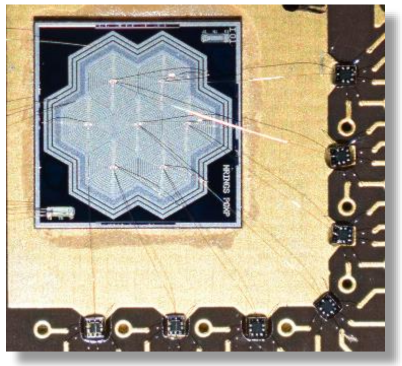
- **TRISTAN** – a large array of SDD-pixels with ΔE ~ 200 eV to search for tiny kink in ß-spectrum: expected sensitivity ~10^{-7}

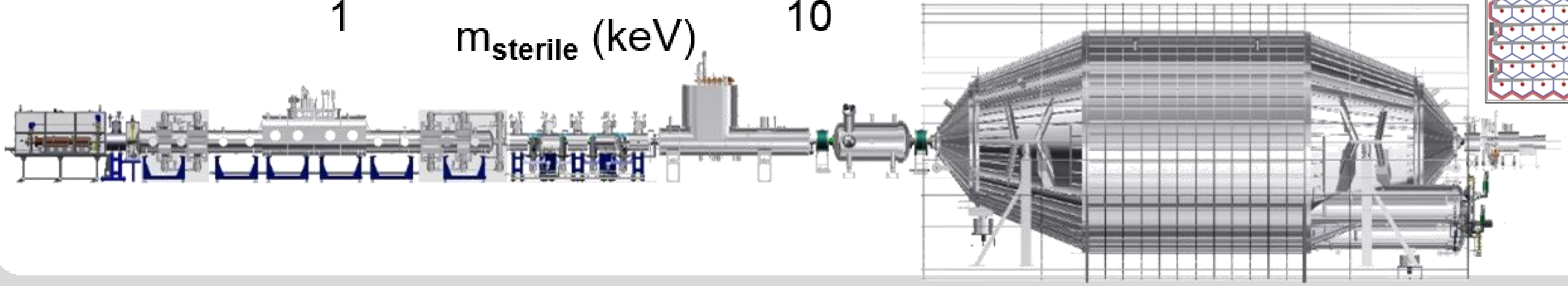










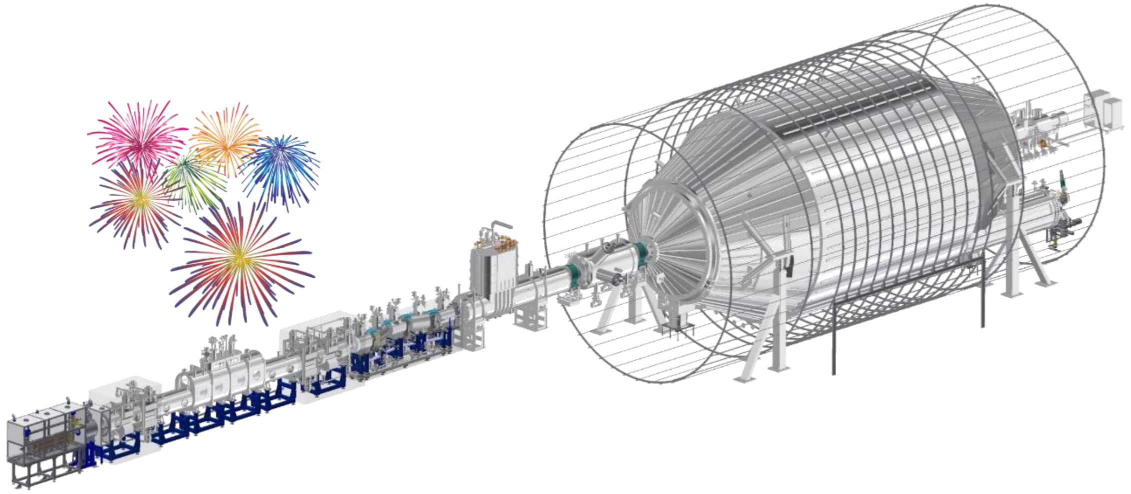


TRISTAN prototype

Conclusion

- **major experimental progress** over last 2 years since NOW 2016!

KATRIN:
first tritium ß-spectra
very promising



ECHo:
first limit on m(ν_e)
imminent

Eligo Lisi at Neutrino 2018:
Let the ν-fireworks begin!

P8: first tritium ß-spectra imminent **HOLMES:** excellent R&D progress