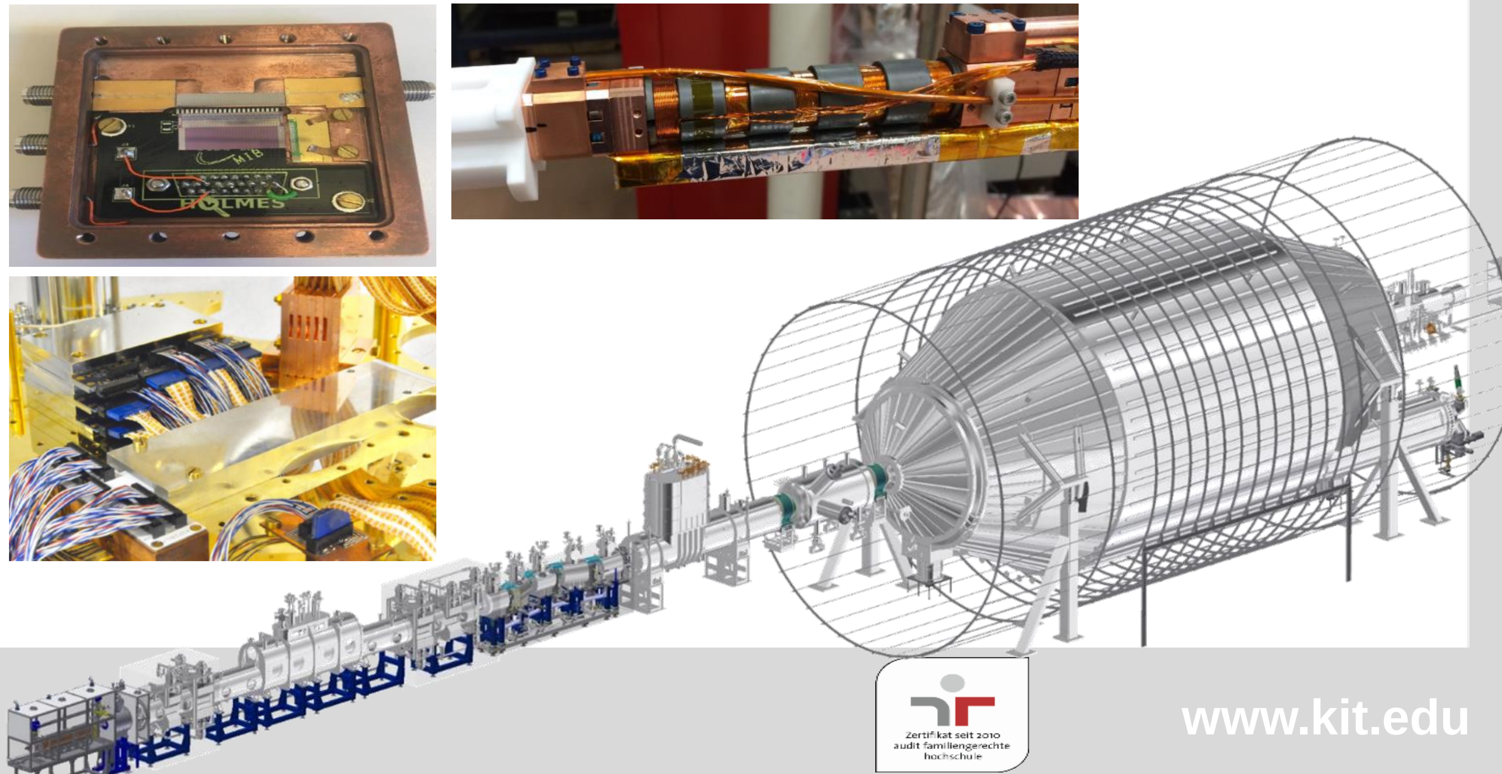
Direct neutrino mass measurement

16th International Conference on Topics
in Astroparticle Physics and Underground Physics (TAUP)
Toyama, September 9-13, 2019

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

- introduction
- electron capture on holmium
- beta-decay of tritium
- **first ν-mass result of KATRIN**
- keV-sterile neutrinos
- conclusion

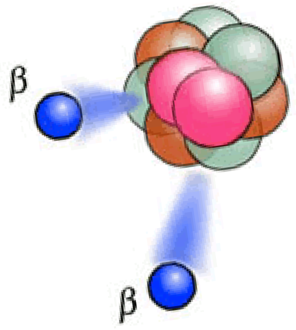


assessing neutrino masses: the three-fold way

0νßß-decay

- ßß-decay: ^{76}Ge, ^{130}Te, ^{136}Xe
- **model-dependent:** **Majorana-ν**

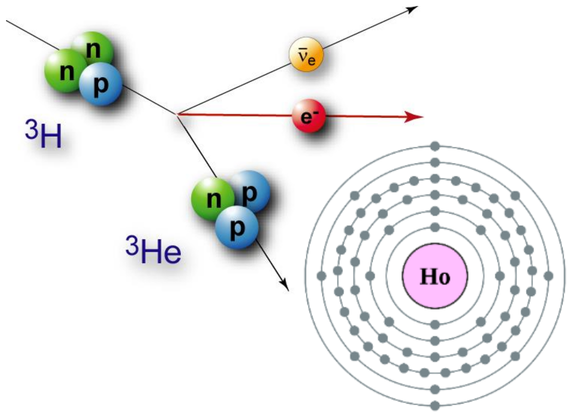
$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^{2} \cdot m_i\right|$$



kinematics weak decays

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

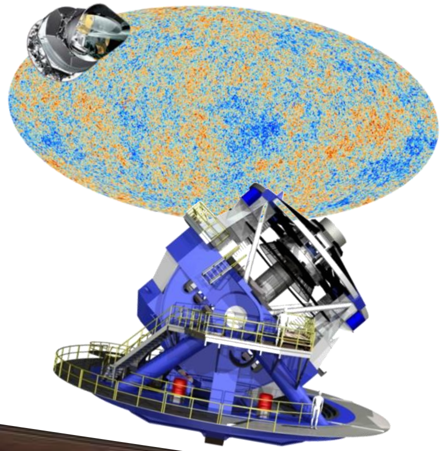
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}\right|^{2} \cdot m_i^{2}}$$



cosmology

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

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



Eligio
Lisi
Neutrino
Theory

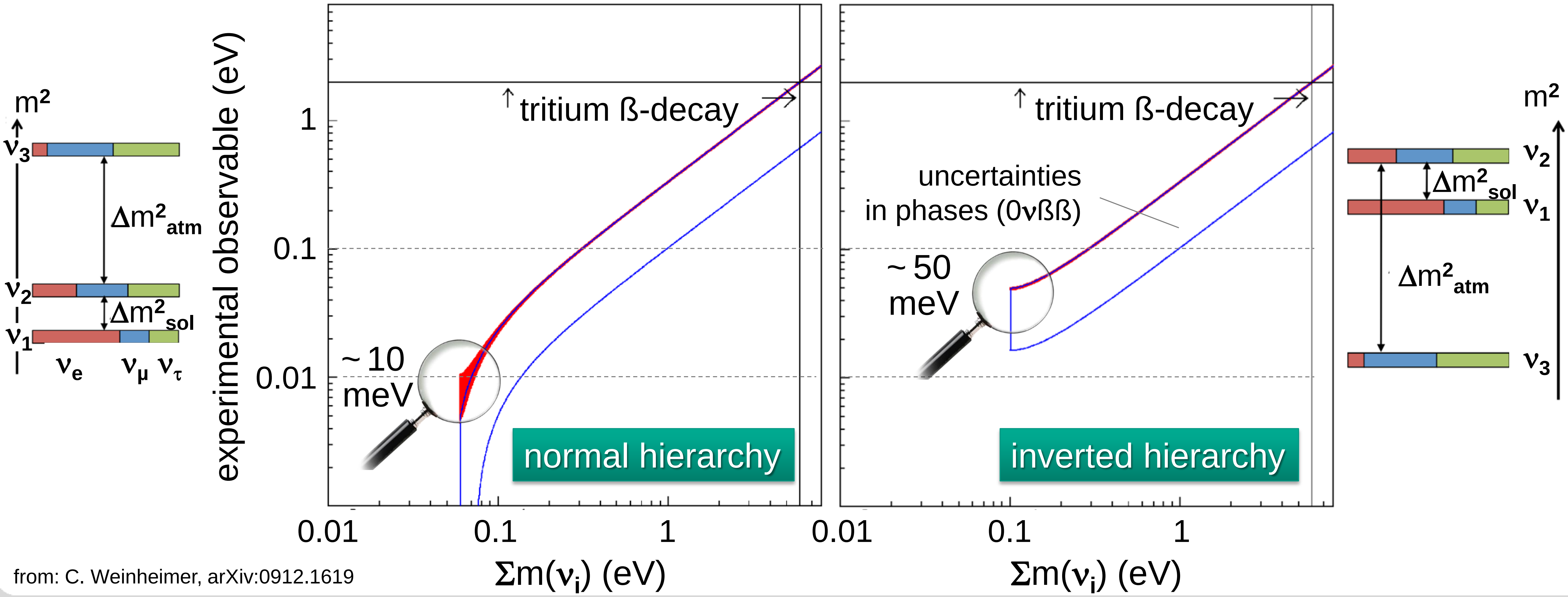
Fedor
Simkovic
0νßß
Theory

Yong-Hamb
Kim
0νßß
Experiment

Ofer
Lahav
Cosmology
Overview

ν-masses from kinematic studies – the challenge

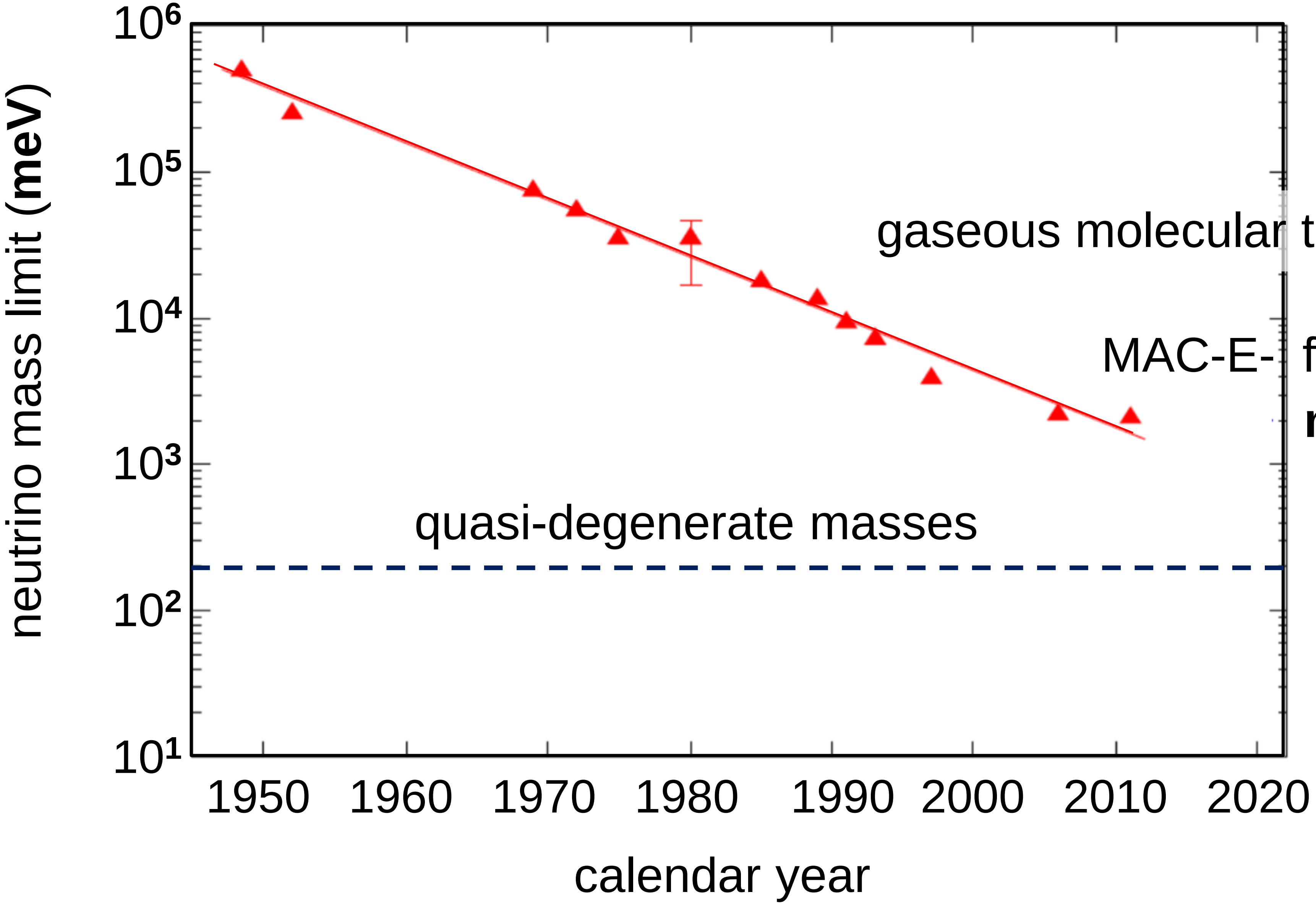
- **setting the stage:** experimental observables $m(\nu_e)$ in ß-decay & EC
  $m_{ßß}$ in 0νßß-searches (Majorana/CP-phases)



from: C. Weinheimer, arXiv:0912.1619

Moore´s law* of direct ν-mass sensitivities

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

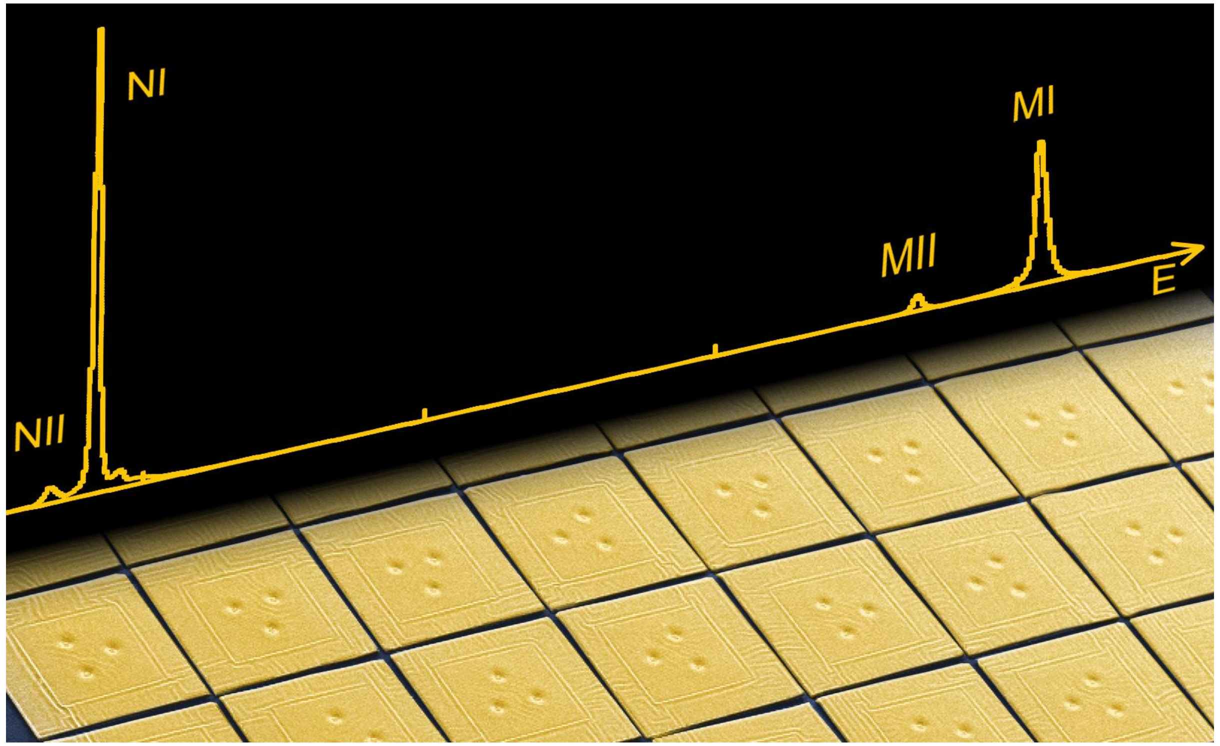


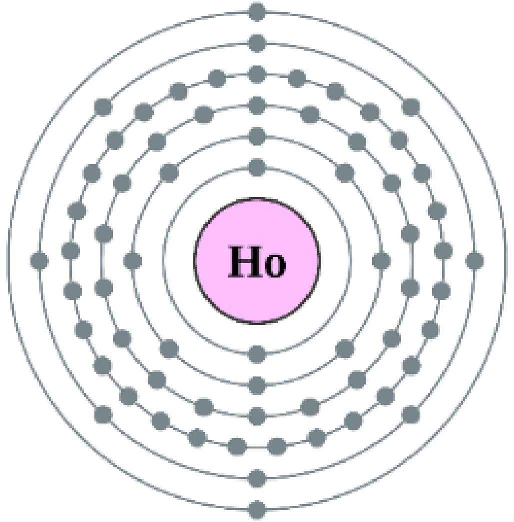
gaseous molecular tritium source: Los Alamos

MAC-E-filters: Mainz, Troitsk

$m(\nu_e)$ < 2 eV (95% CL)

*courtesy of JF Wilkerson





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

EC ON HOLMIUM-163: ECHo, HOLMES

L. Gastaldo
The Electron
Capture in Ho-163
Experiment
ECHO

Neutrino # 19

electron capture: Q-value

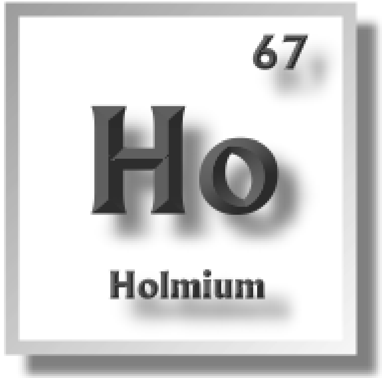
- **EC-process of ^{163}Ho :** $^{163}\text{Ho} + e^- \rightarrow \nu_e + {}^{163}\text{Dy}^*$ ($t_{1/2}$ = 4570 yr)

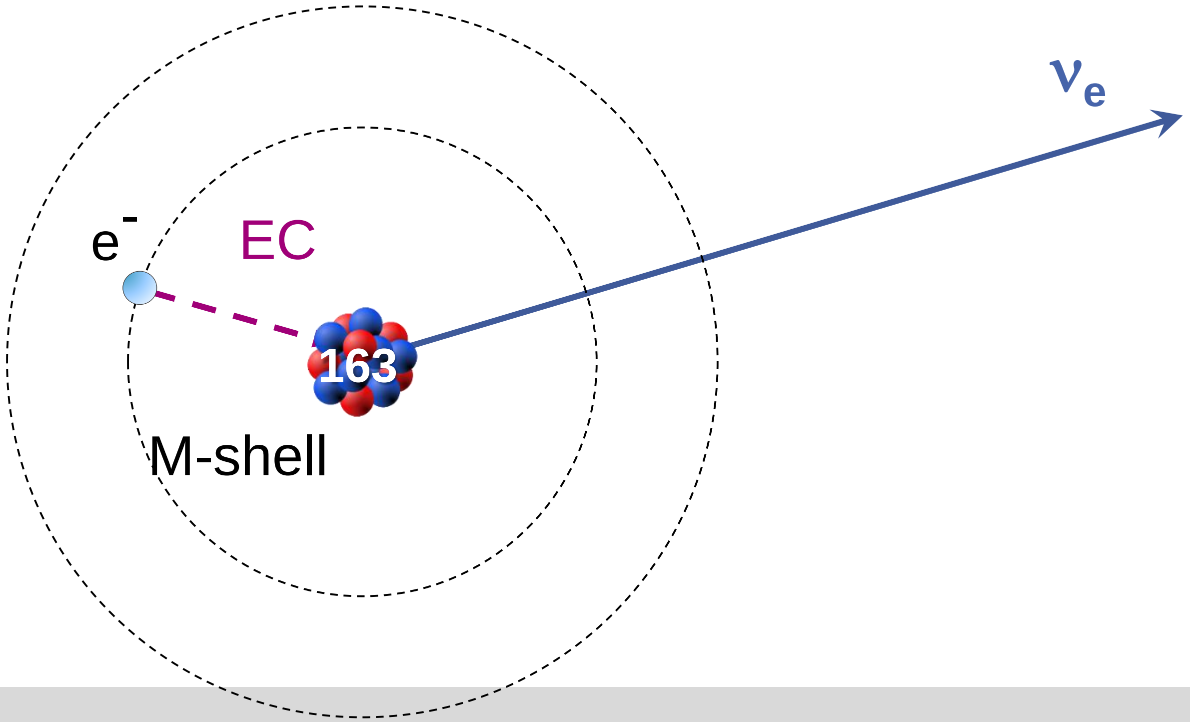
➊ – after EC: ν_e carries away energy & momentum

Q_{EC}: Penning trap mass spectroscopy
M(^{163}Ho) – M(^{163}Dy)
$Q_{EC} = (2\,833 \pm 30_{stat} \pm 15_{syst})$ eV

- agrees with MMC-value from Ho-spectrum
$Q_{EC} = (2\,858 \pm 10_{stat} \pm 50_{syst})$ eV

Q_{EC} ⇨ no EC from K, L shells possible



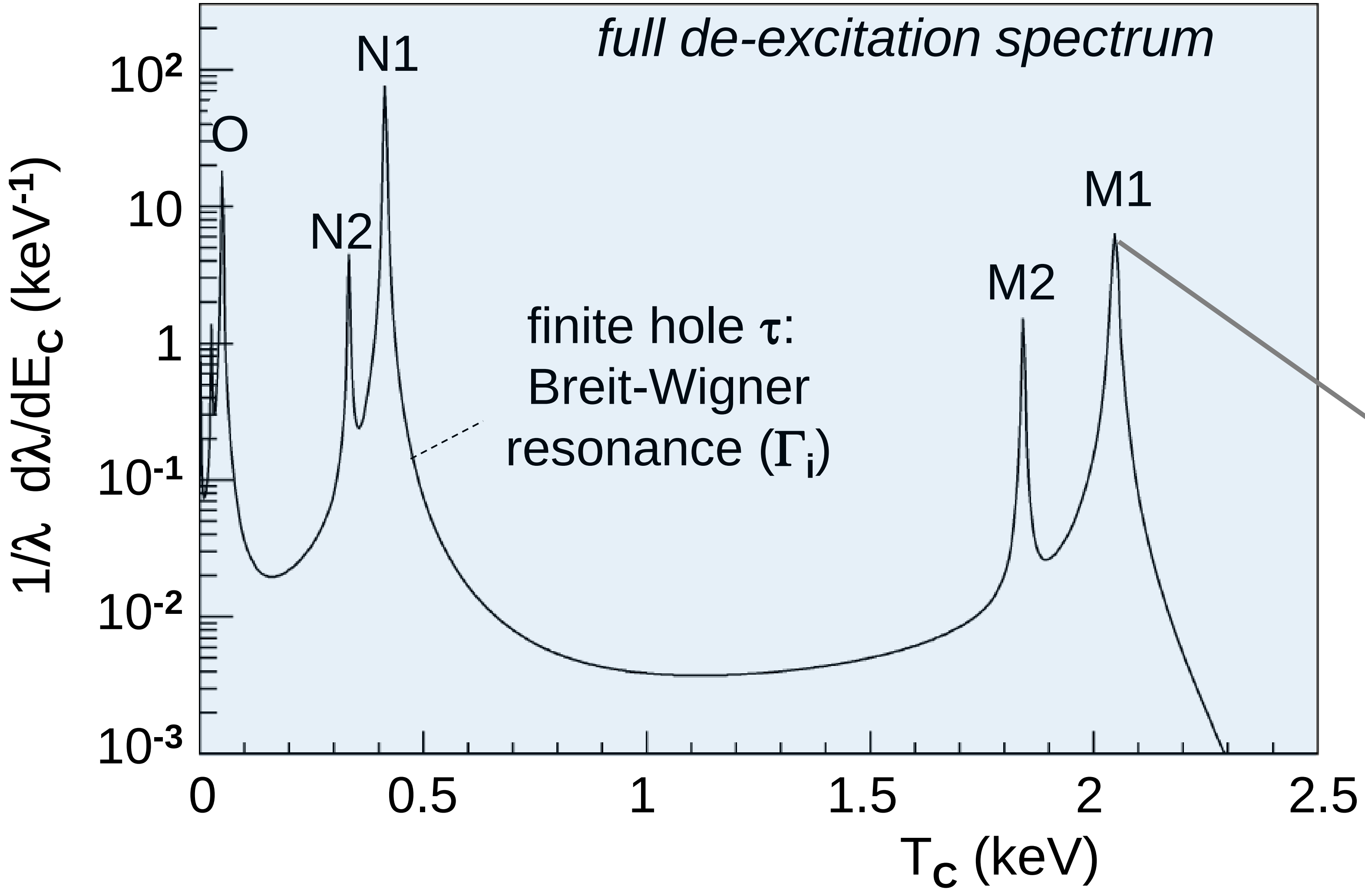


A. De Rújula, M. Lusignoli, Phys. Lett 118B (1982)

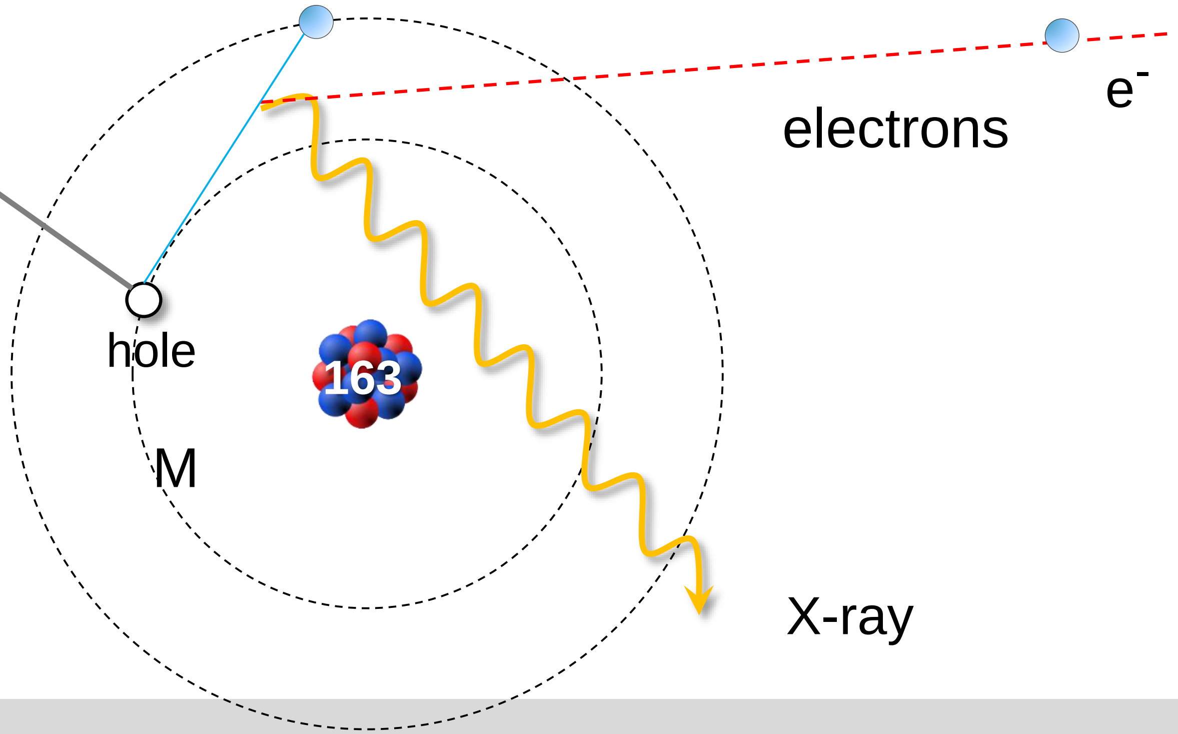
electron capture: de-excitation

- **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)

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

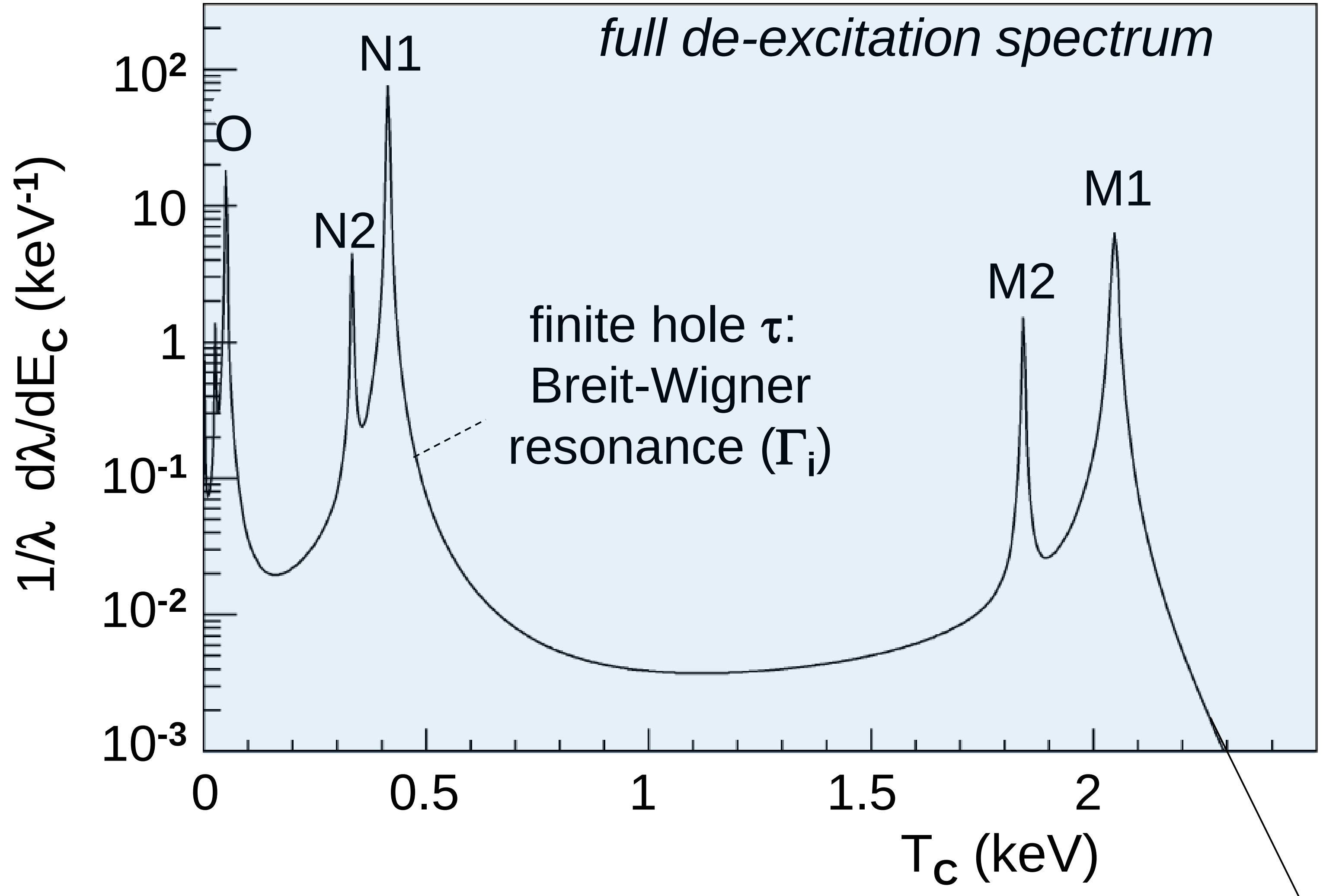


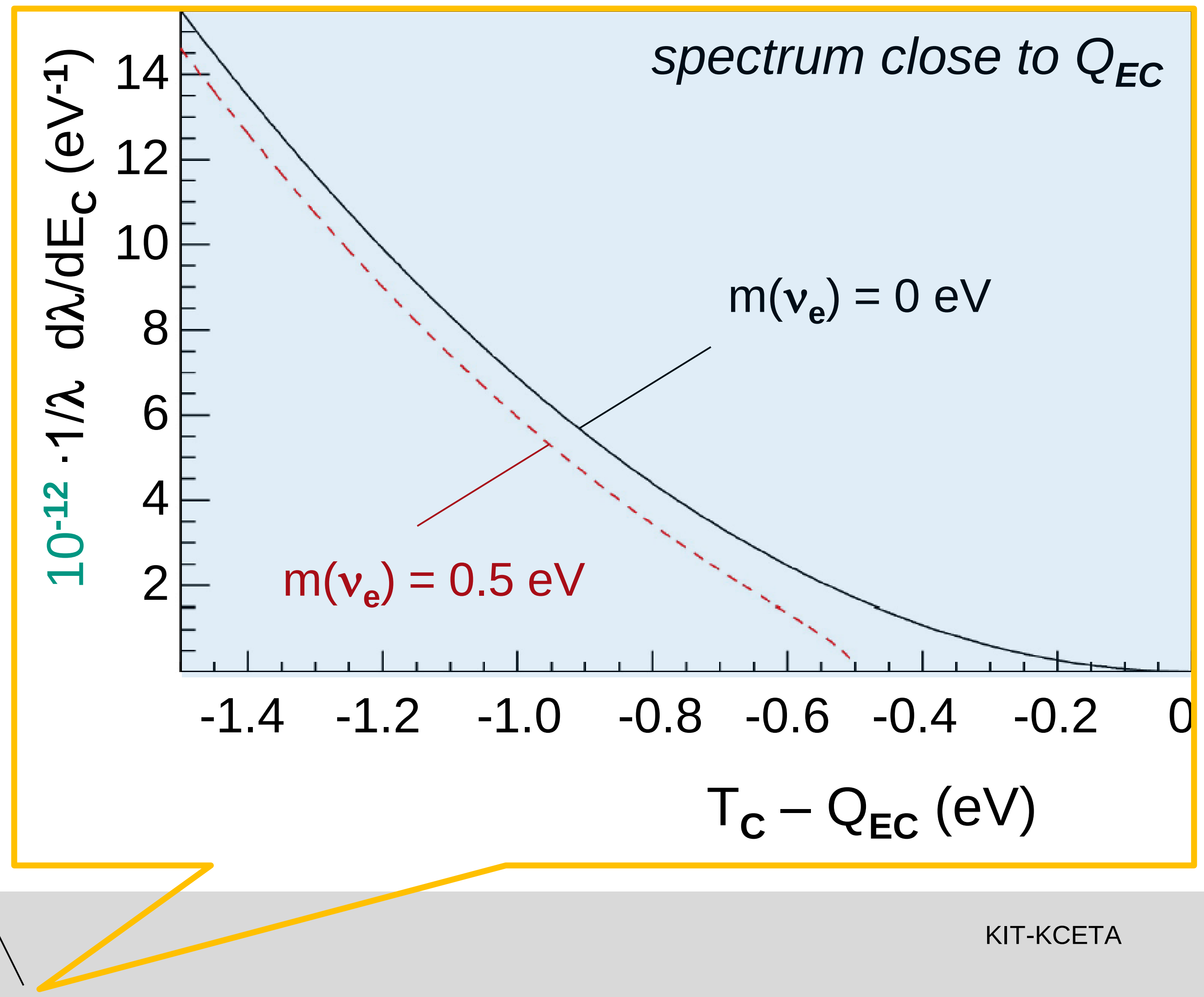
T_C: **calorimetric energy** from atomic de-excitations



electron capture: ν-mass

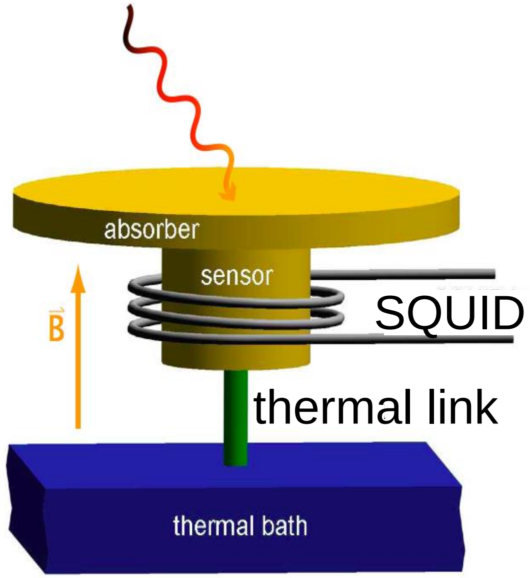
- shape: $$\frac{d\lambda_{EC}}{dT_C} \sim (Q_{EC}-T_C)\cdot\sqrt{(Q_{EC}-T_C)^2 - m^2(\nu_e)}\cdot\sum_i n_i \cdot \overbrace{C_i \cdot \beta_i^2 \cdot B_i \cdot \frac{\Gamma_i}{2\pi}\cdot\frac{1}{(T_C-E_i)^2+\Gamma_i^2/4}}^{\text{M1, M2,…}}$$

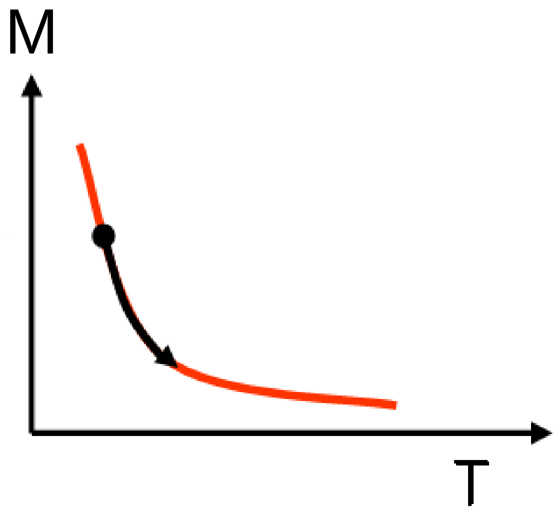




calorimeters to measure ^{163}Dy* atomic de-excitation

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



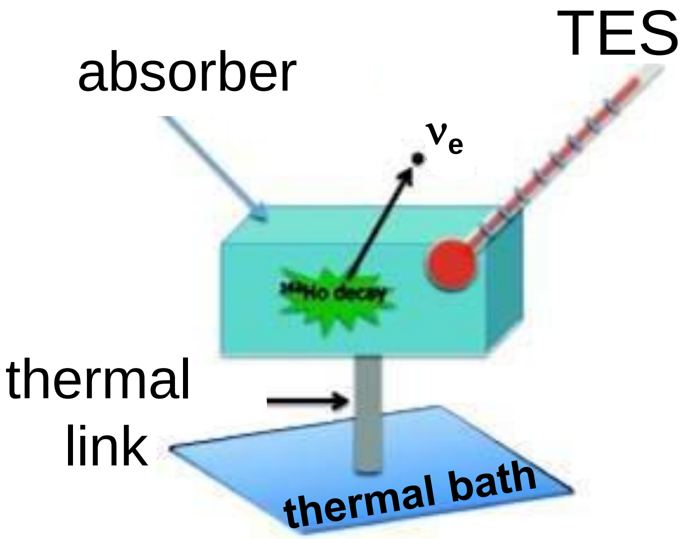


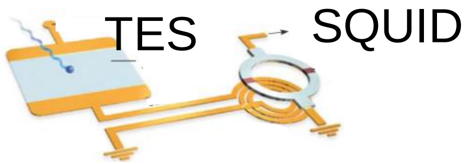
δT in absorber from EC-decay

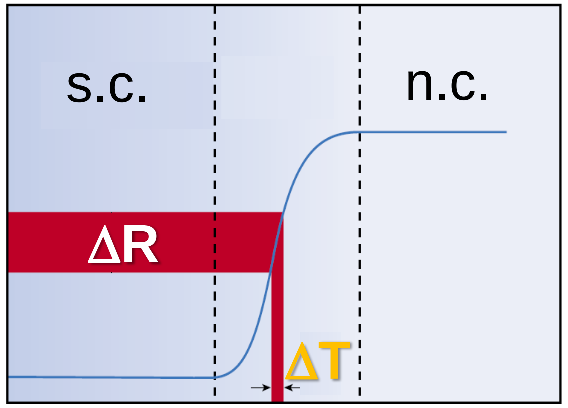
⇨ change in **magnetism δM** of param. sensor

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

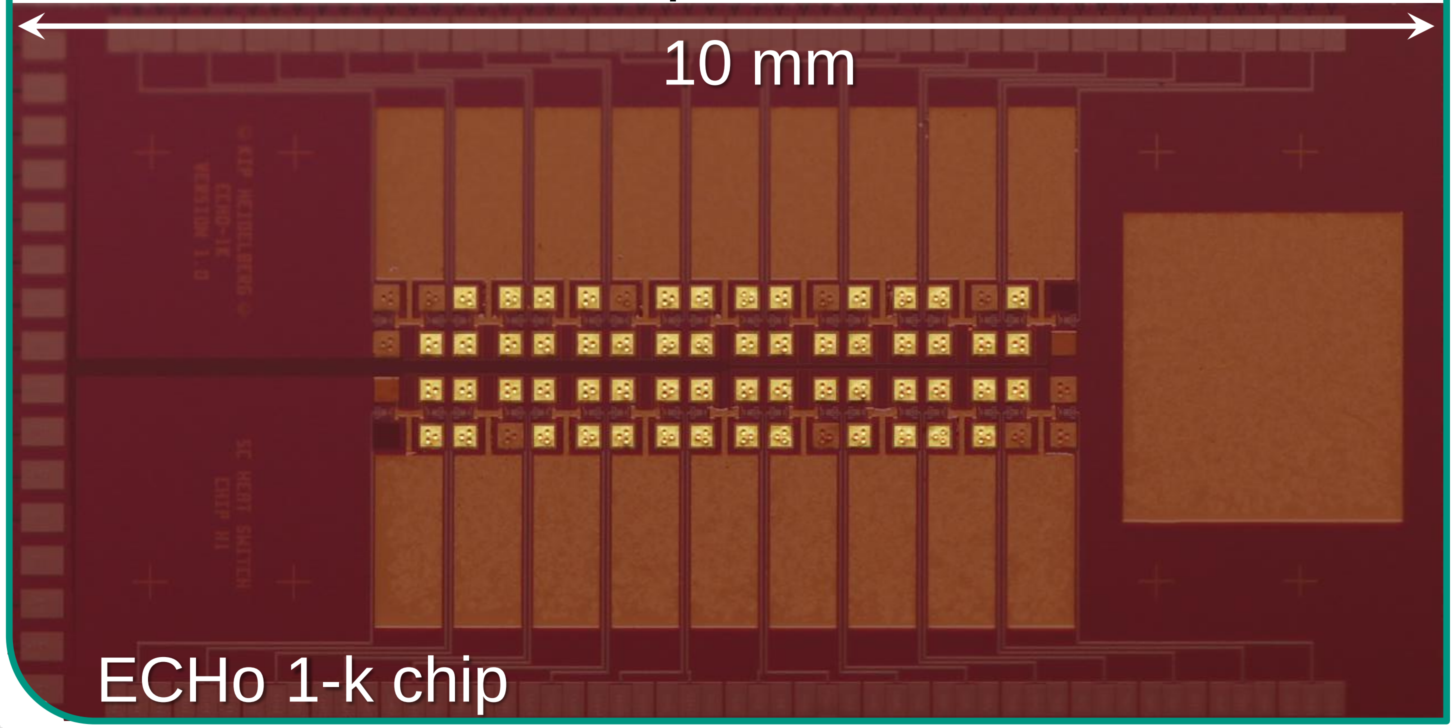
⇨ change in temperature δT of TES thermistor

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

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

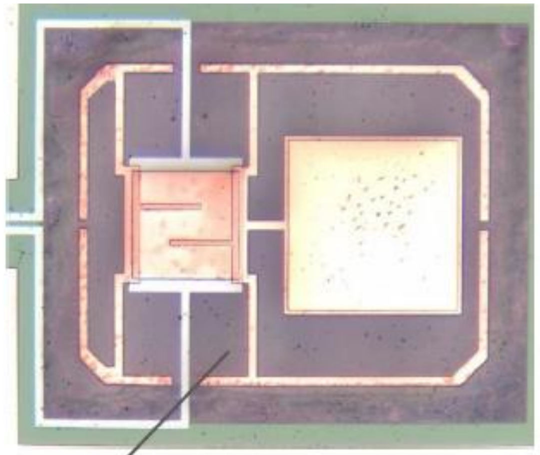
- **ECHo Collaboration**:
  8 institutions ~ 50 scientists

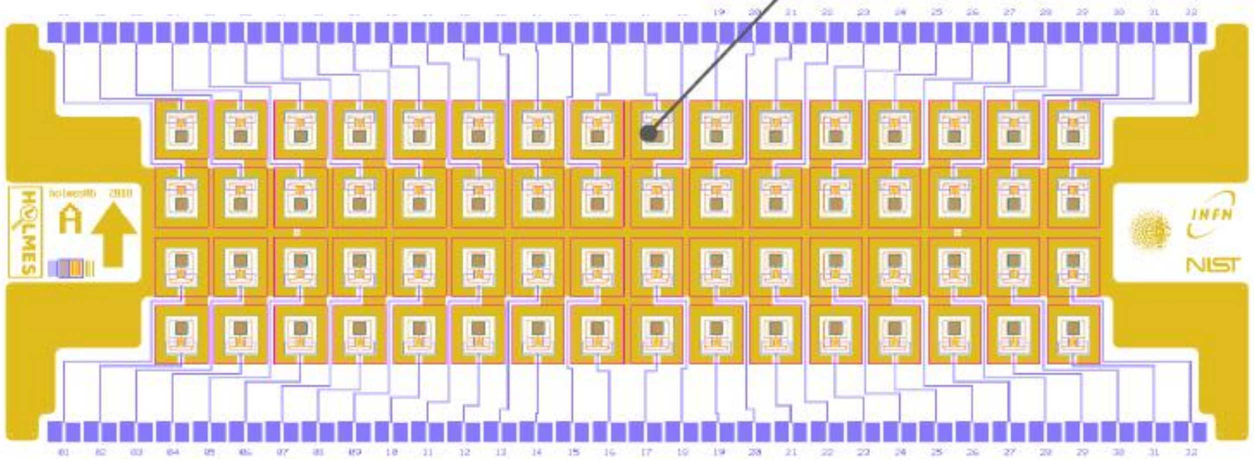
  - ECHo 1-k detector array (working horse)
    64 pixels implanted at RISIKO (Uni Mainz)
  - activity per pixel: A_{pix} ~ 1 Bq (**A_{tot} ~ 50 Bq**)



- **HOLMES Collaboration**:
  6 institutions ~ 40 scientists

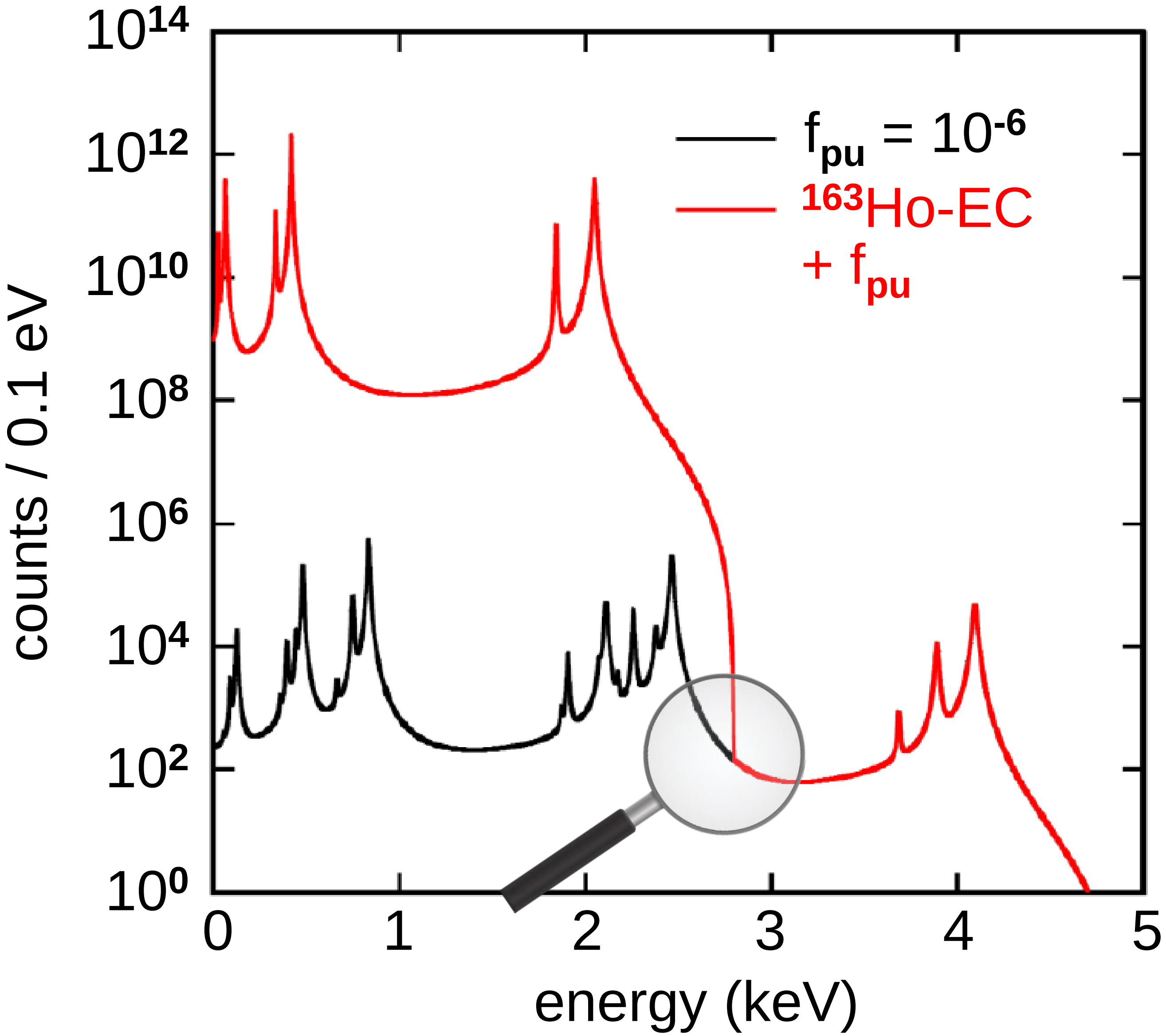
  - first pixels now being characterized:
    ΔE = 4.5 eV@ 2.6 keV
    Δt ~ 2.8 µs
  - ion implanter being being tested (Genova)





EC on holmium – challenges

- **challenges in reaching a sub-eV sensitivity**
  - good statistics in endpoint region:
    $N_{ev} > 10^{14}$ → overall $A \sim 1$ MBq
  - limit unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)
    $f_{pu} < 10^{-6}$
    for $\tau_r < 1\ \mu s$ ⇨ limit pixel $a \sim 10$ Bq
  - very good energy resolution at endpoint
    $\Delta E(\mathrm{FWHM}) < 3$ eV
  - detailed understanding of spectral features:
    2-hole excitations, line broadening
  - very low background level
    $R_{bg} < 10^{-5}$ events/eV/pixel/day

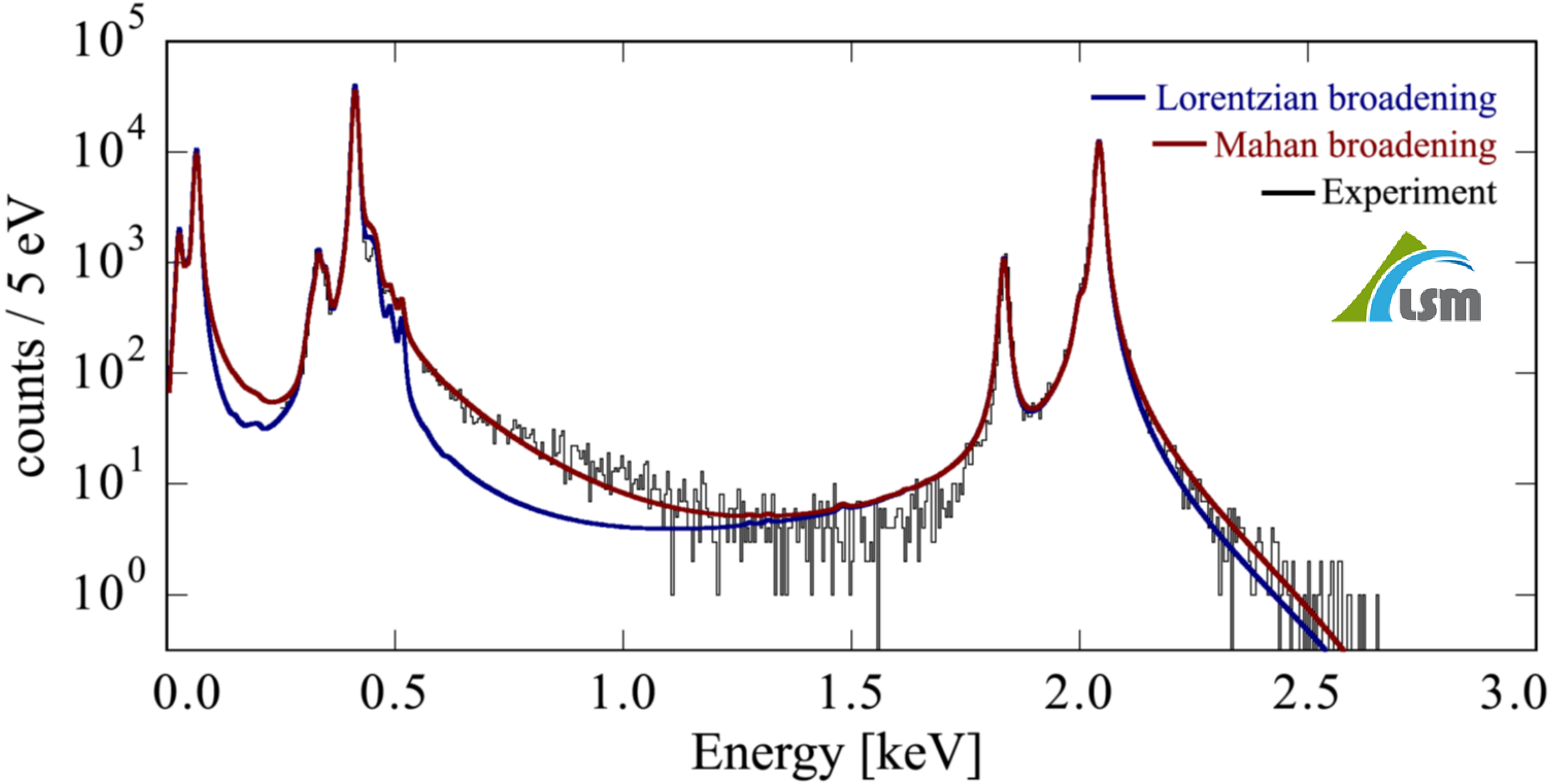


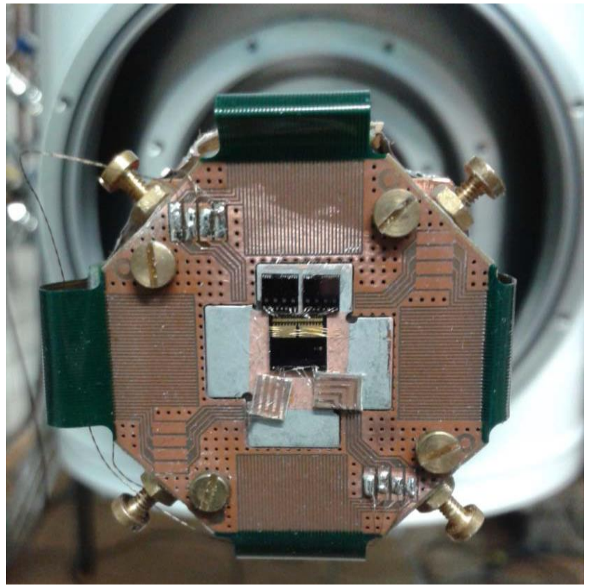
ECHo – final LSM result

- **final results from a first MMC-measurement phase at Modane (LSM)**

  - 4 pixels over 4 days (275 000 counts)

    $A_{pix} = 0.2$ Bq $\quad \Delta E_{FWHM} = 9.2$ eV





- profile log-likelihood ratio test:

$Q_{EC} = (2838 \pm 14)$ eV

$m(\nu_e) < 150$ eV (95% C.L.)

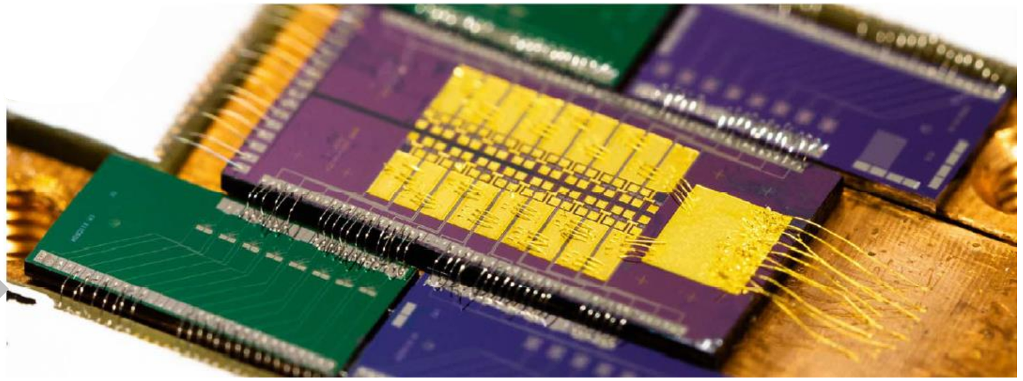
from ECHo-1k to ECHo-100k

Karlsruhe Institute of Technology

❶ **ECHo-1k**: 2015 - 2020

- demonstrate scalability of arrays ☑
- MMC: $\Delta E_{\mathbf{FWHM}} < 5$ eV
- total activitiy A ~ 100 Bq
- 1 y measurement phase:

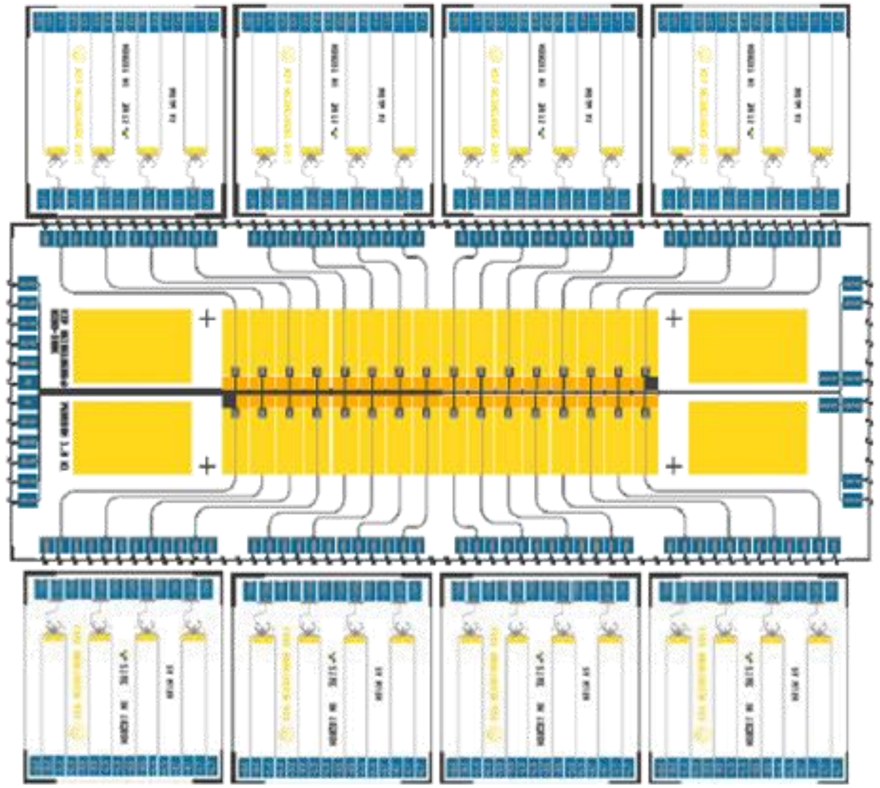
⇨ limit $m(\nu_e) < 10$ eV (90% CL)

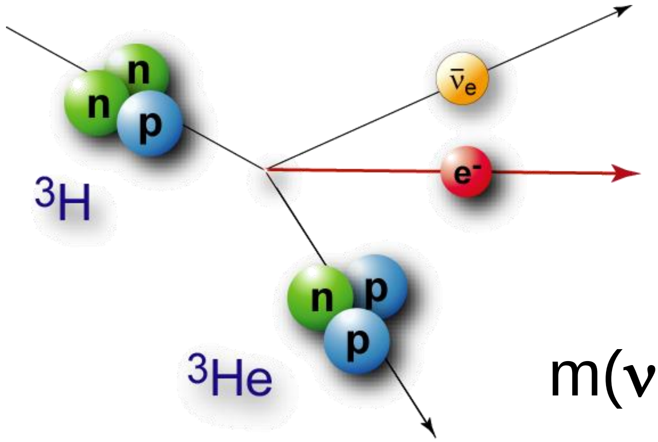


❷ **ECHo-100k**: 2020 ff

- ECHo-100k chip in fabrication
- 12000 pixels ($A_{\mathbf{pix}}$ ~ 10 Bq)
- microwave SQUID multiplexing
- 3 y measurement phase

⇨ limit $m(\nu_e) < 1.5$ eV (90% CL)





$m(\nu_e) < 2$ eV

ß-DECAY OF TRITIUM: PROJECT8, KATRIN

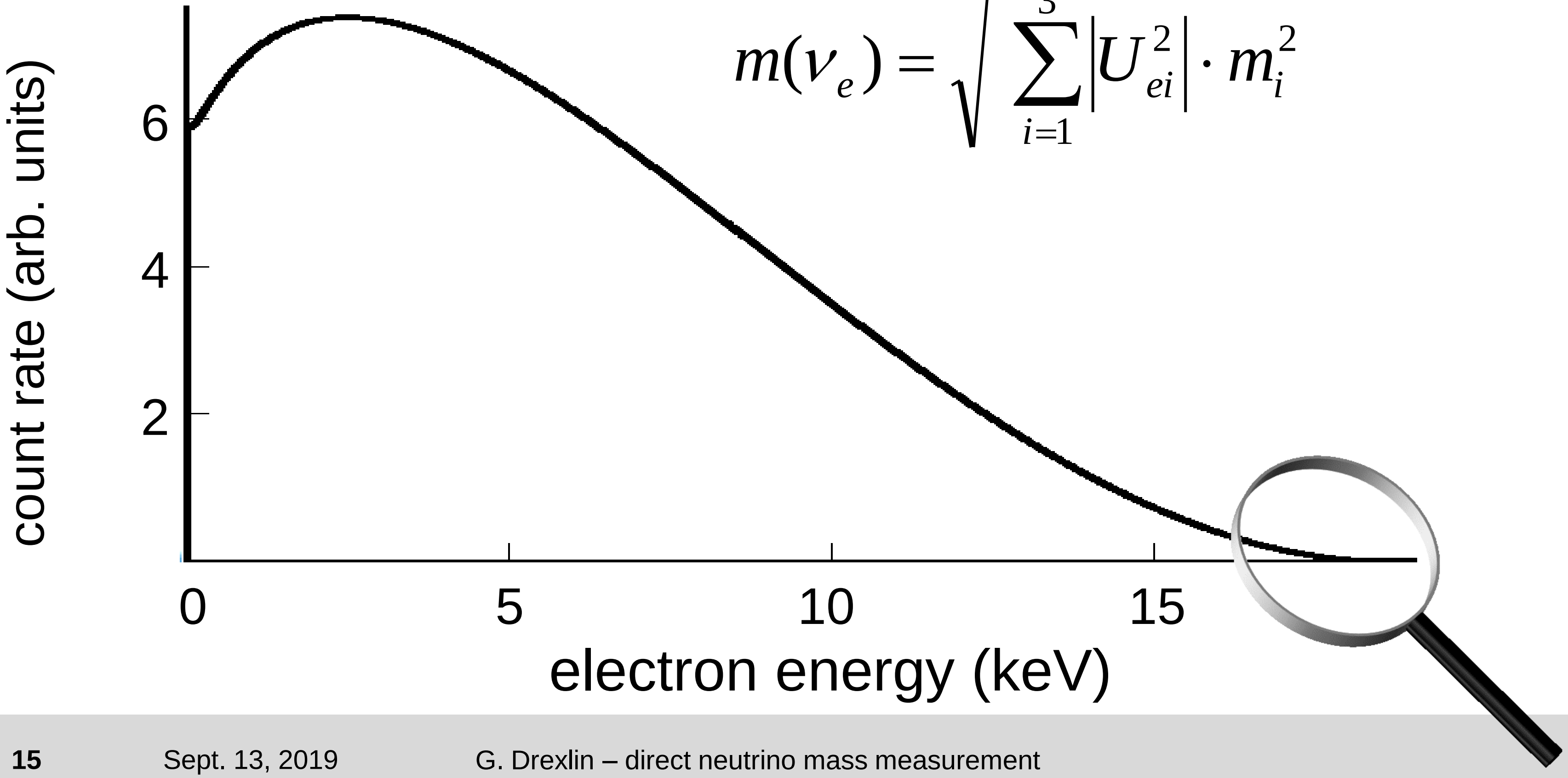
M. Tanabashi et al. (PDG), PRD 98 (2018) 030001

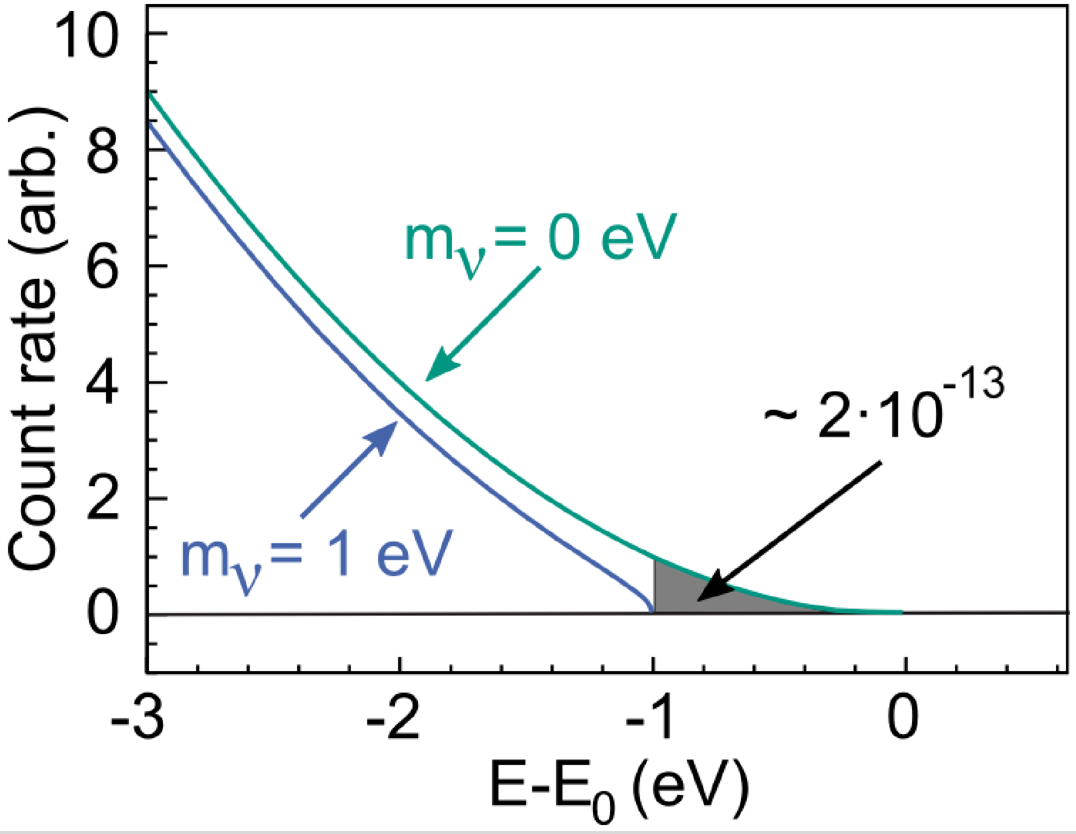
tritium ß-decay: kinematics

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

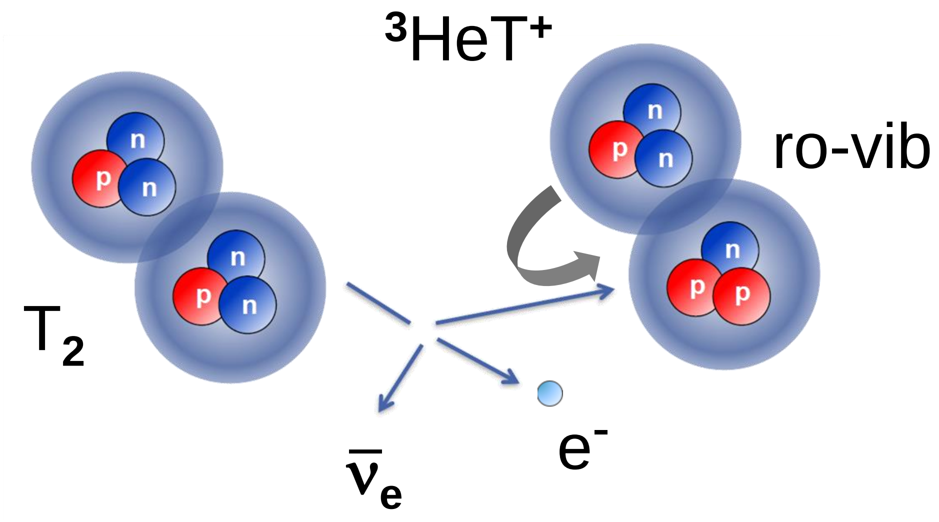
$$\boxed{\frac{d\Gamma_i}{dE} = C\cdot p\cdot(E+m_e)\cdot(E_0-E)\cdot\sqrt{(E_0-E)^2\ \boxed{-m_i^2}}\cdot F(E,Z)\cdot\theta(E_0-E-m_i)}$$

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

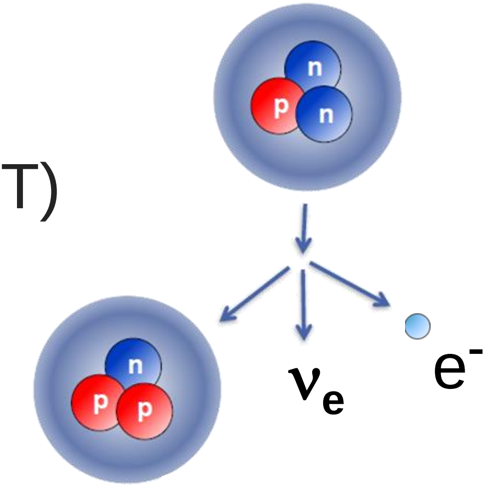




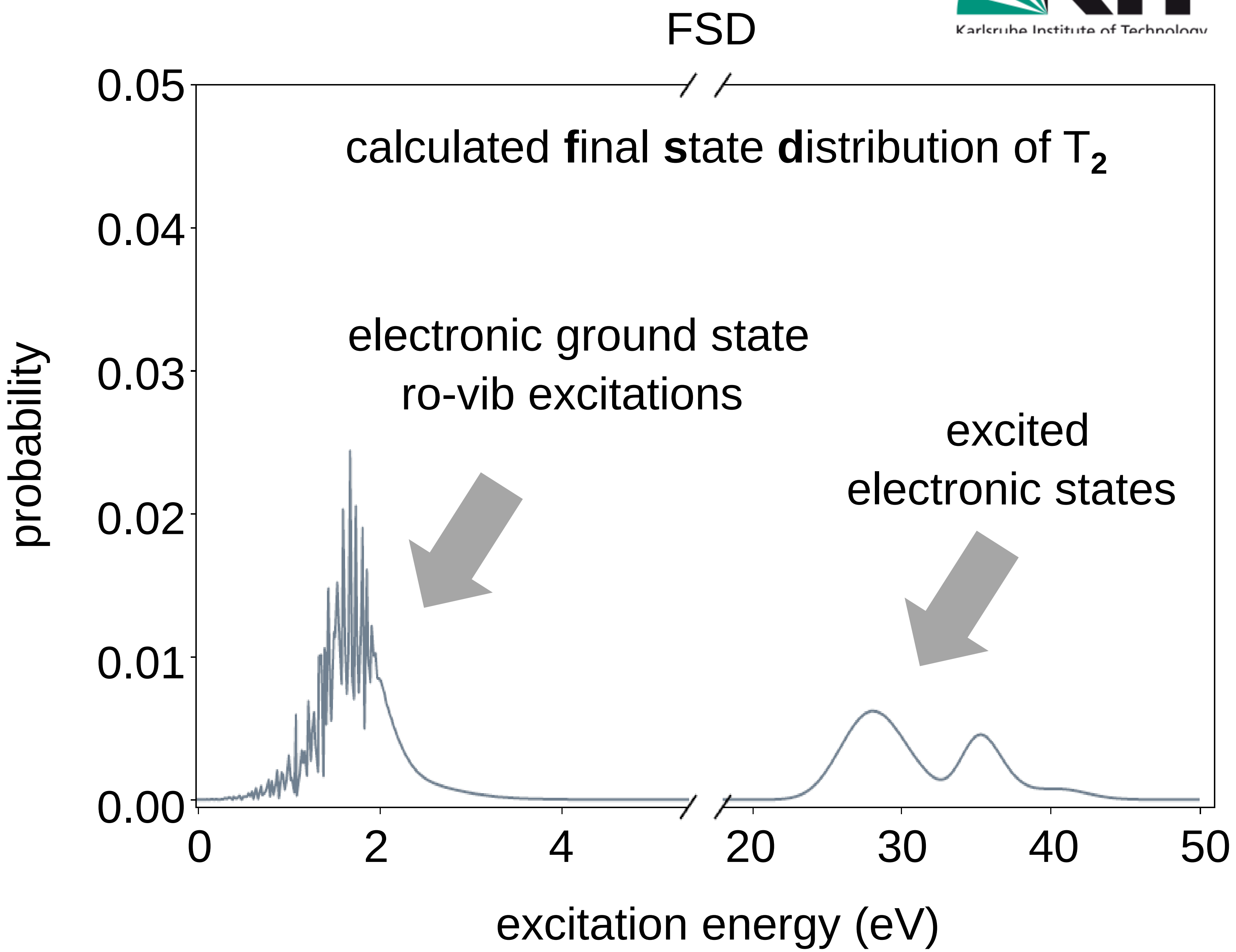
ß-spectroscopy: molecular & atomic tritium



molecular source (T_2) –
sensitivity limit ~ 100 meV



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

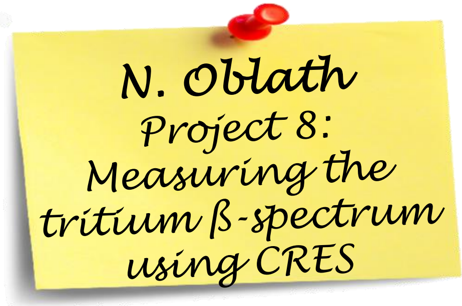


Project 8 – a novel spectroscopic approach

- **Cyclotron Radiation Emission Spectroscopy (CRES)**
  - CRES of *trapped* electrons from tritium ß-decay in homogeneous strong magnetic field B

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

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



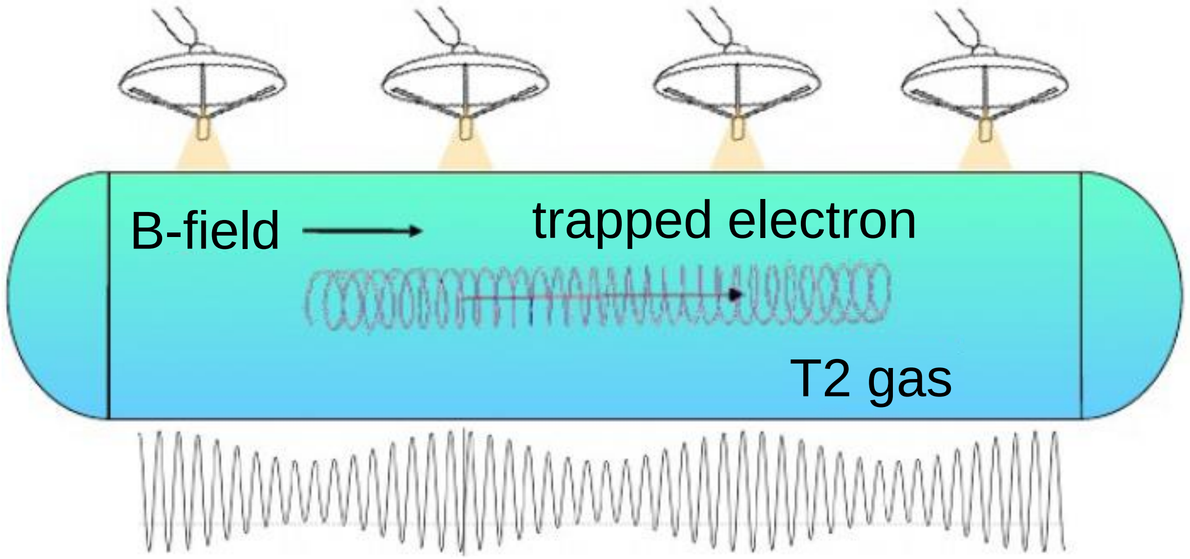
N. Oblath
Project 8:
Measuring the
tritium ß-spectrum
using CRES

Neutrino # 19

B = 1 T

$E_{e,kin}$ = 18.57 keV

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



combined antenna signal

$\Delta\omega \sim 1 / t_s$

sampling time

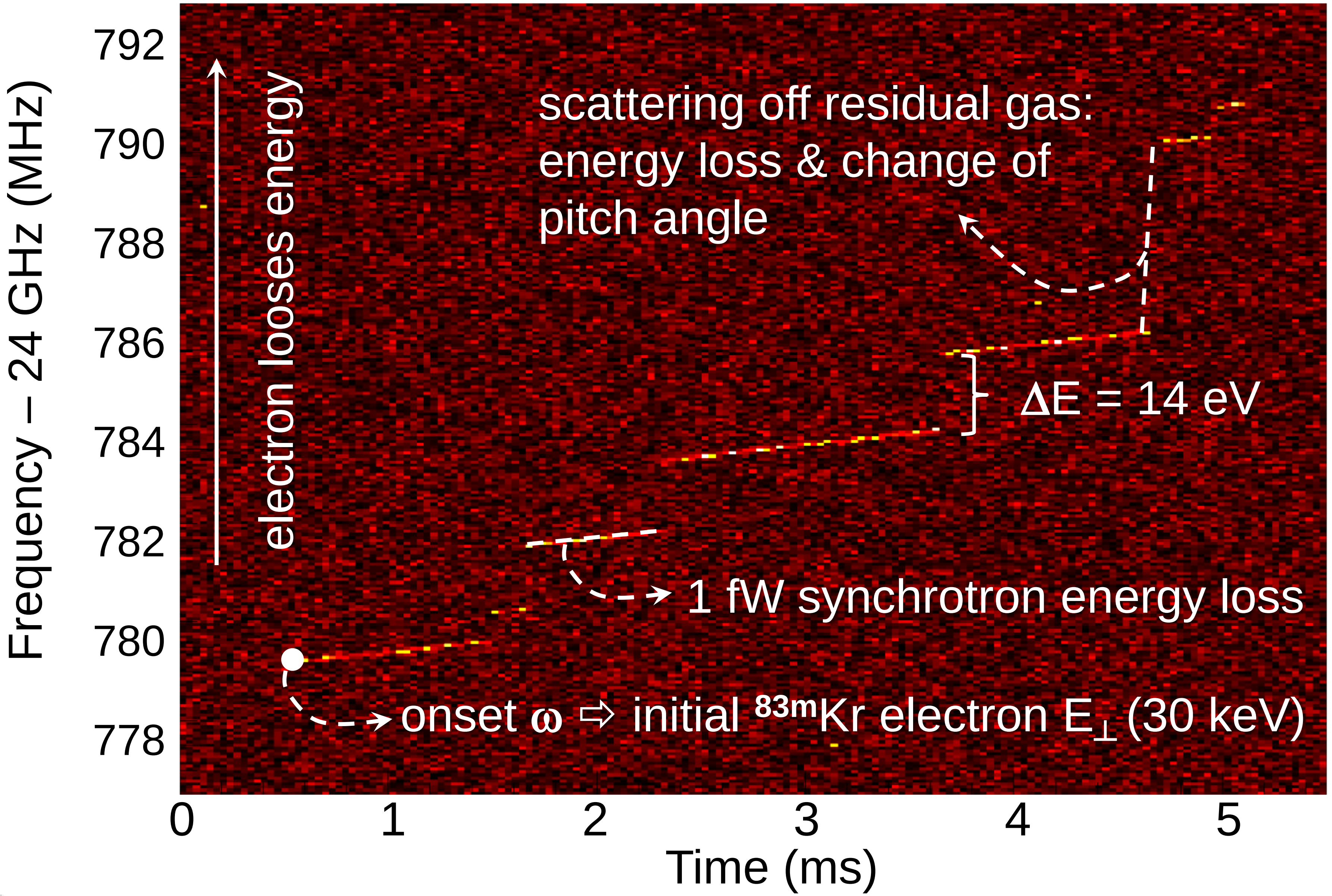
$t_s \sim$ several µs

(magnetic bottle)

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**



electron looses energy

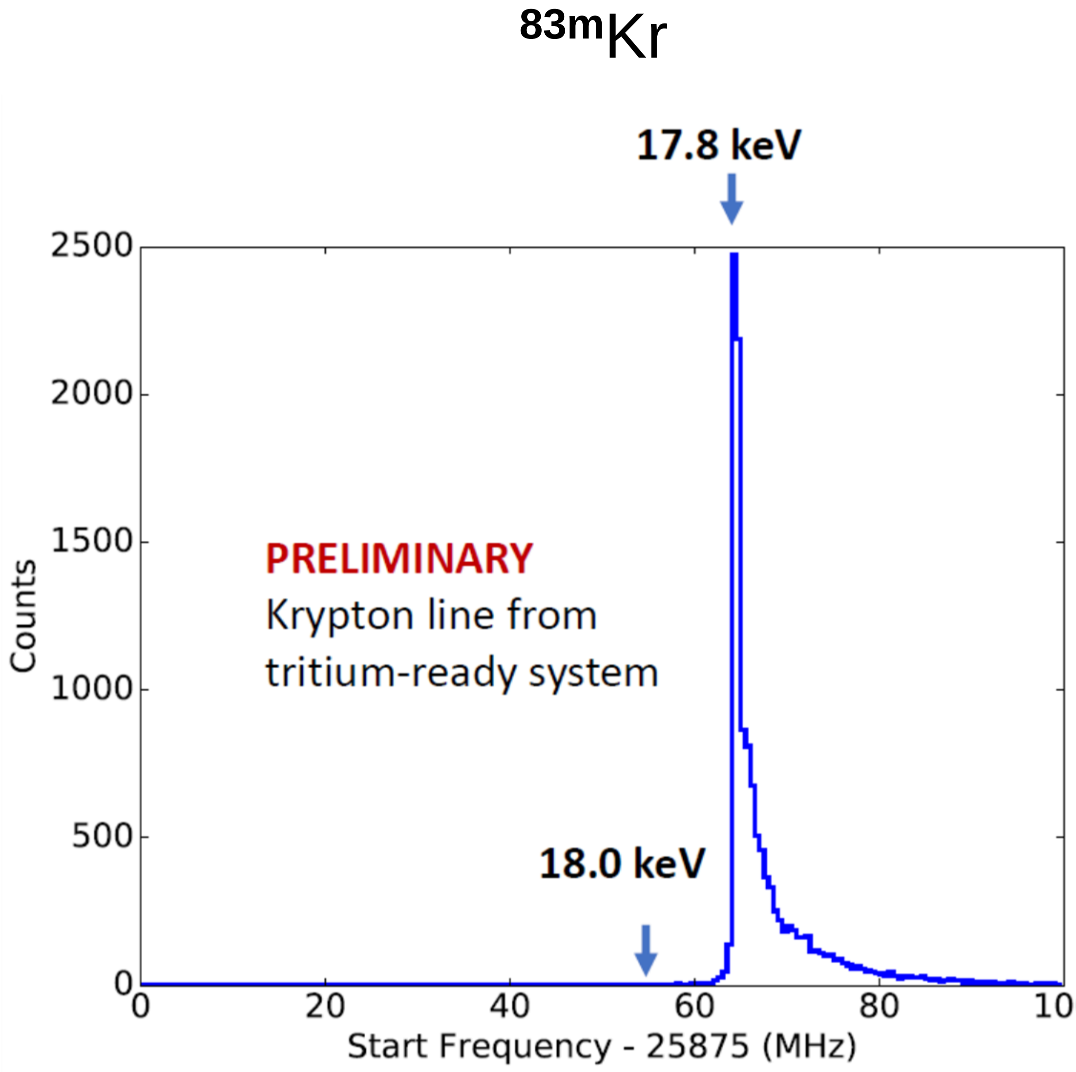
scattering off residual gas: energy loss & change of pitch angle

ΔE = 14 eV

1 fW synchrotron energy loss

onset ω ⇨ initial ^{83m}Kr electron $E_\perp$ (30 keV)

^{83m}Kr



17.8 keV

18.0 keV

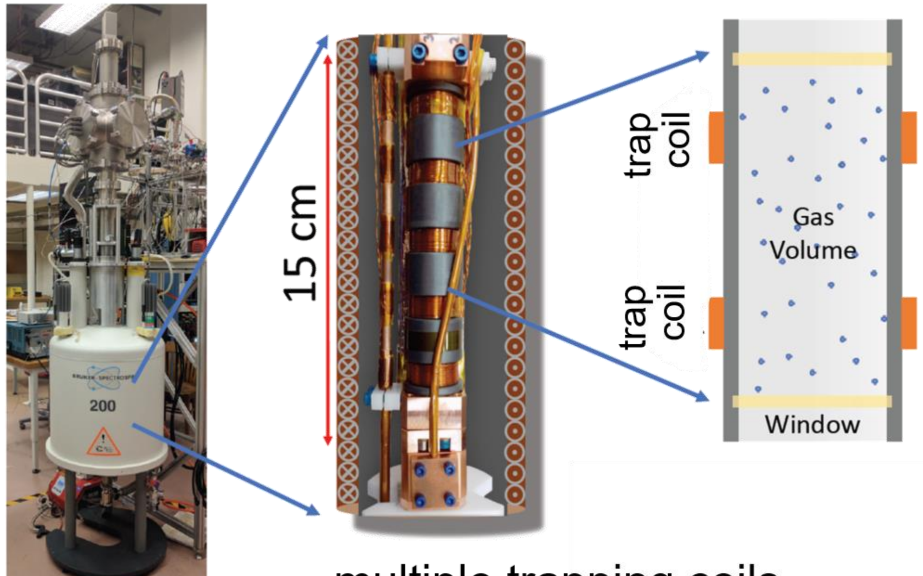
PRELIMINARY
Krypton line from tritium-ready system

Project 8 – a staged approach

❶ Phase – I: 2010-2016 – proof-of-principle

test measurements with ^{83m}Kr

CRES observed for first time



multiple trapping coils

❷ Phase – II: 2015-2019 - tritium

CRES demonstrator

first tritium data 2018

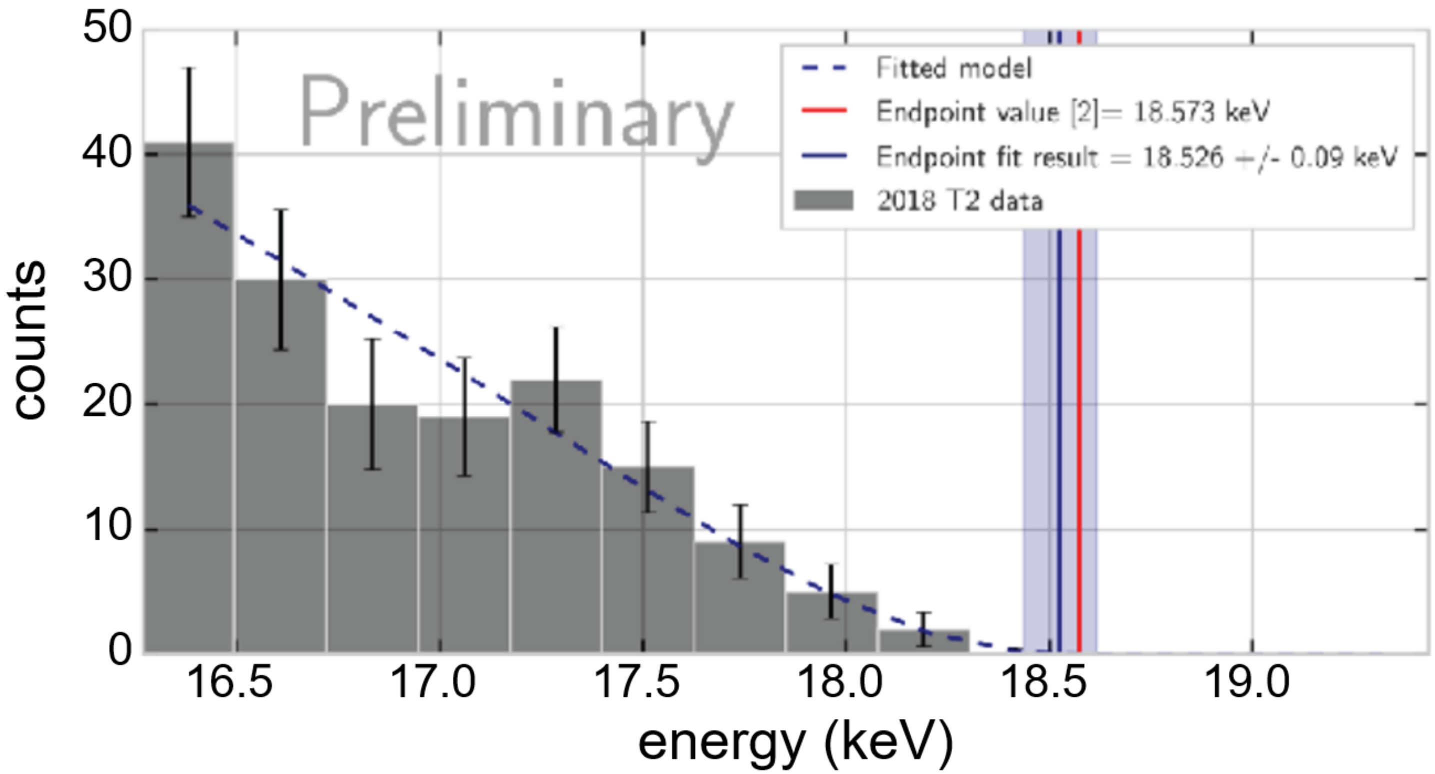
several days of runs

fitted ß-decay endpoint:

$E_0 = (18.526 \pm 0.09)$ keV

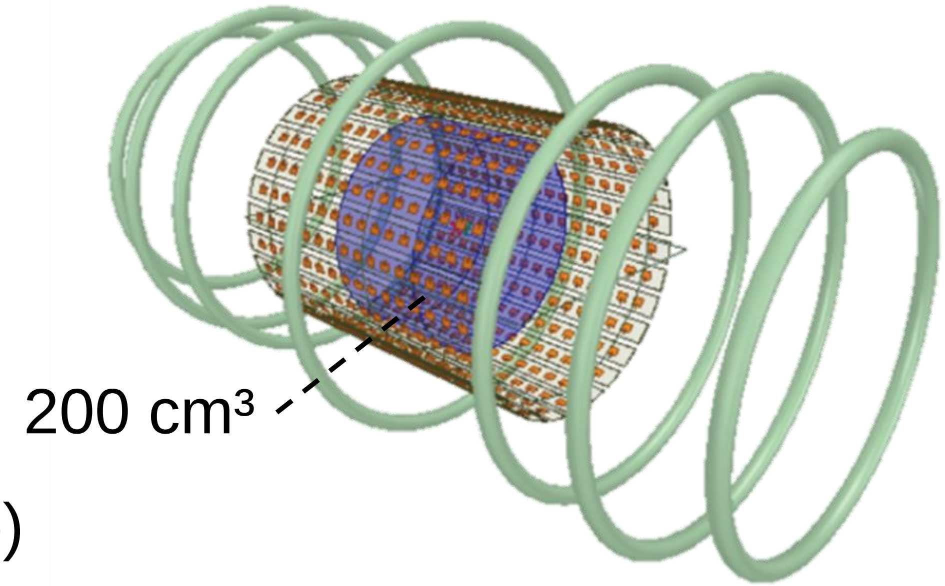
new 2019 campaign to

begin soon (100 d)

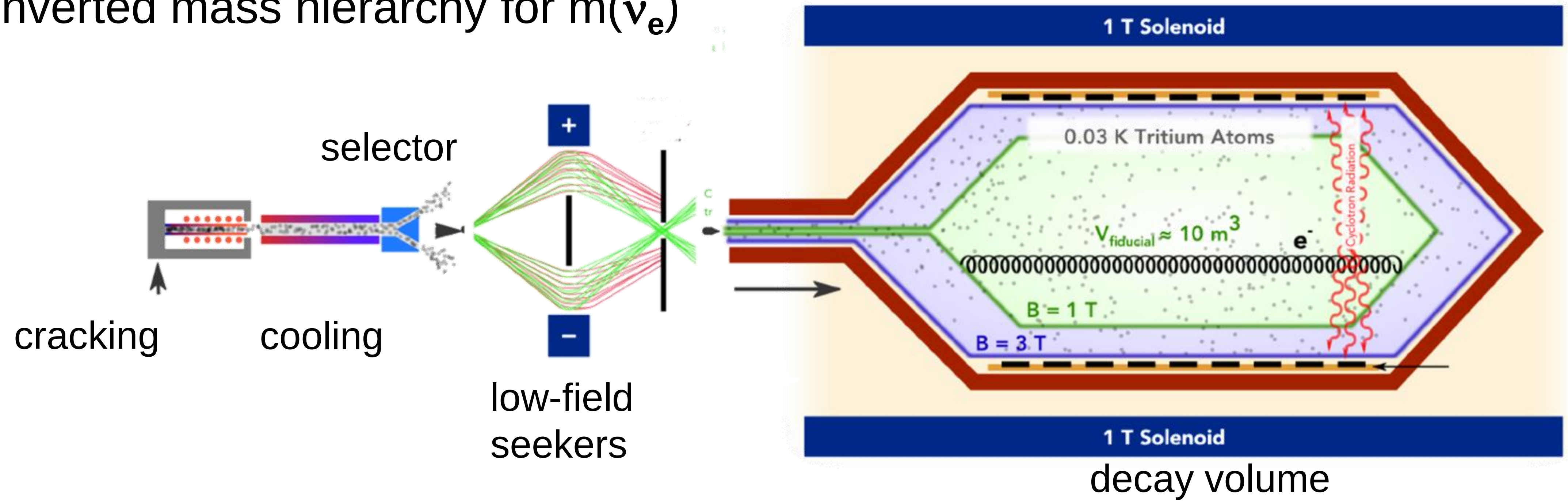


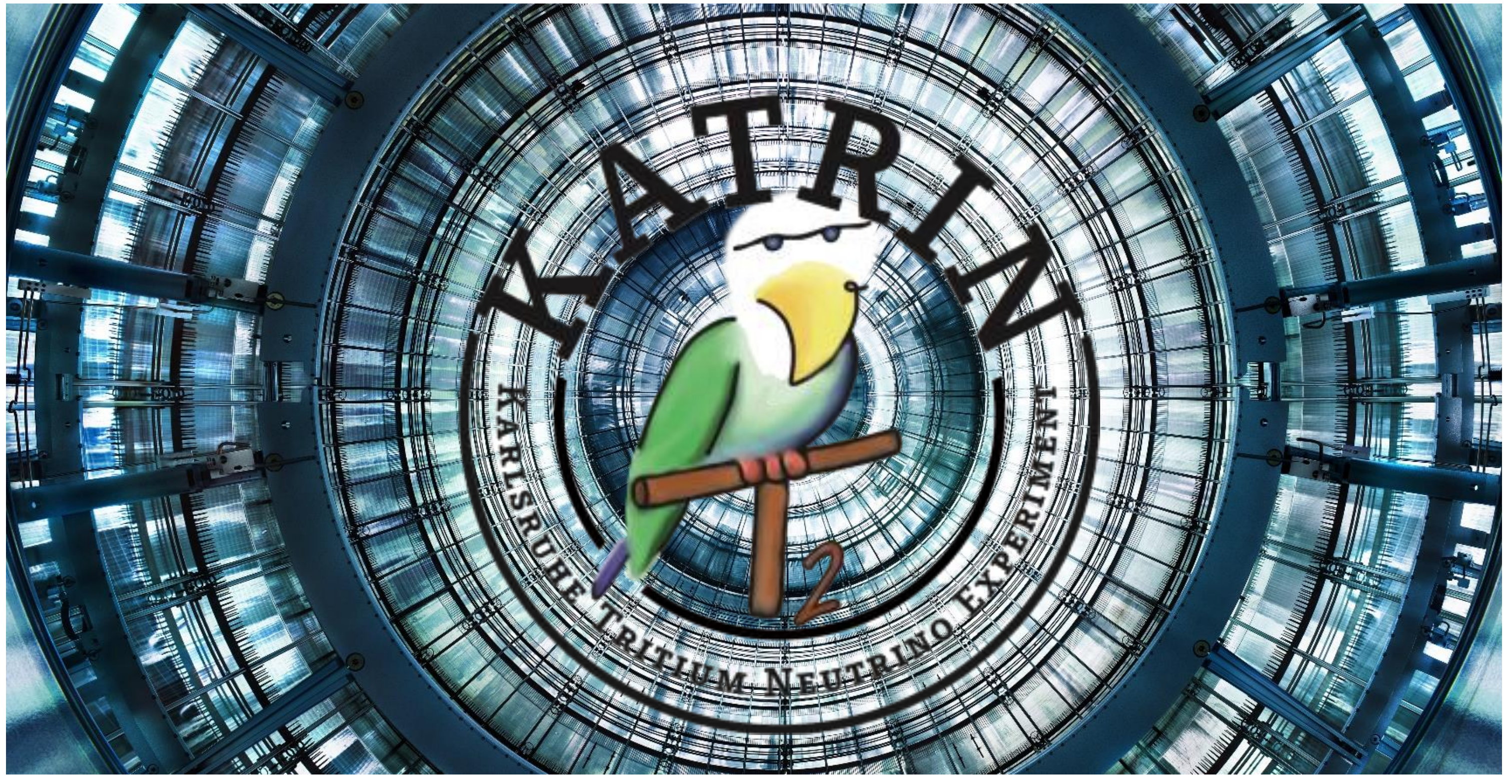
Project 8 – the future

❸ Phase – III: … – a large volume demonstrator
based on multi-antenna array in MRI
tritium spectrum for m(ν_e) ~ 2 eV



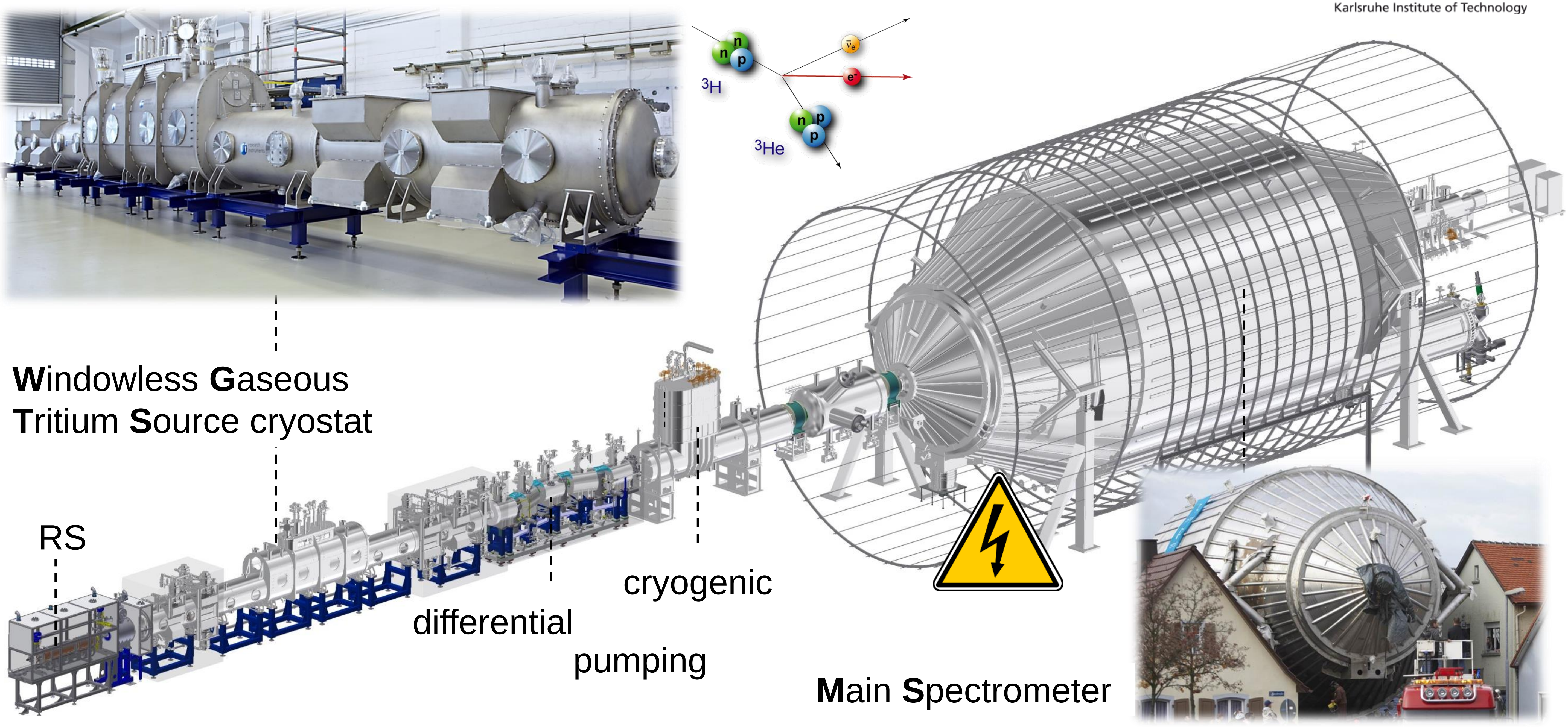
❹ Phase – IV: … – towards an atomic tritium source
R&D for an **atomic tritium source** (Ioffe trap)
goal: inverted mass hierarchy for m(ν_e)





KATRIN

KATRIN overview: 70 m long beamline



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

RS

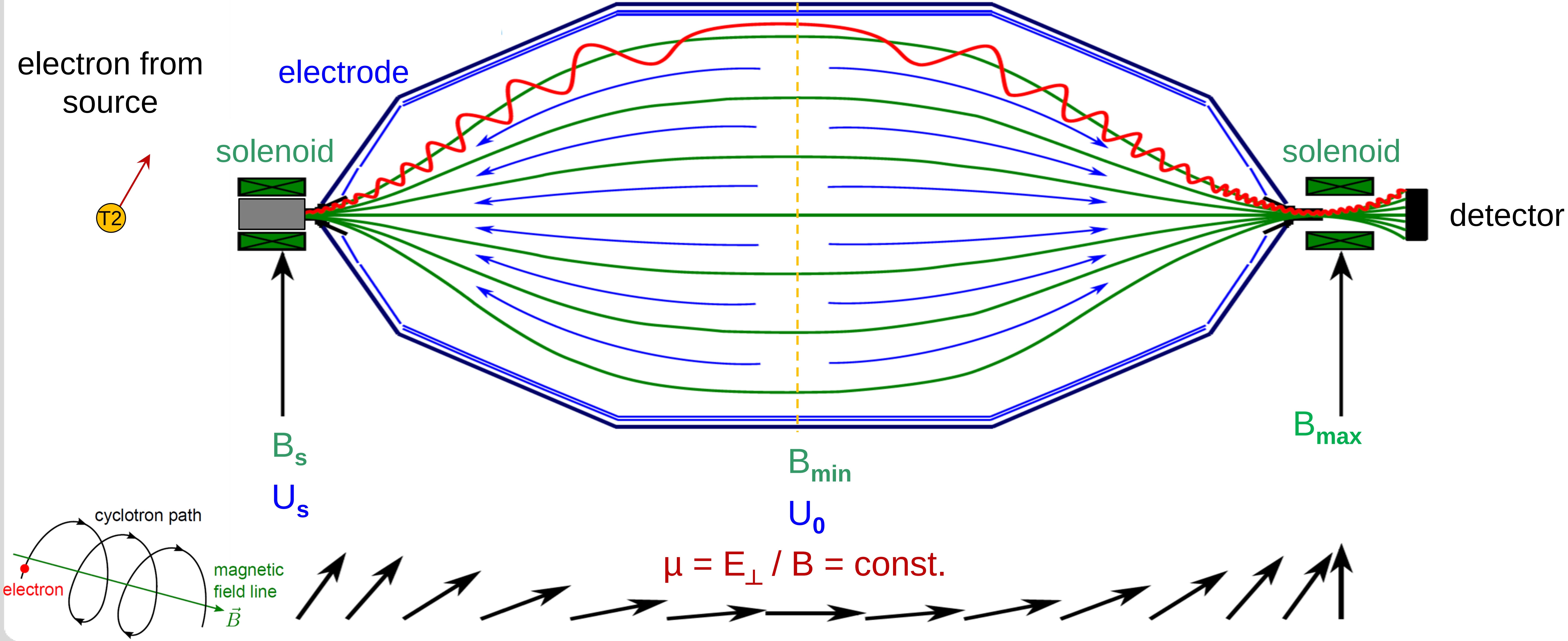
differential
pumping

cryogenic

Main **S**pectrometer

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

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

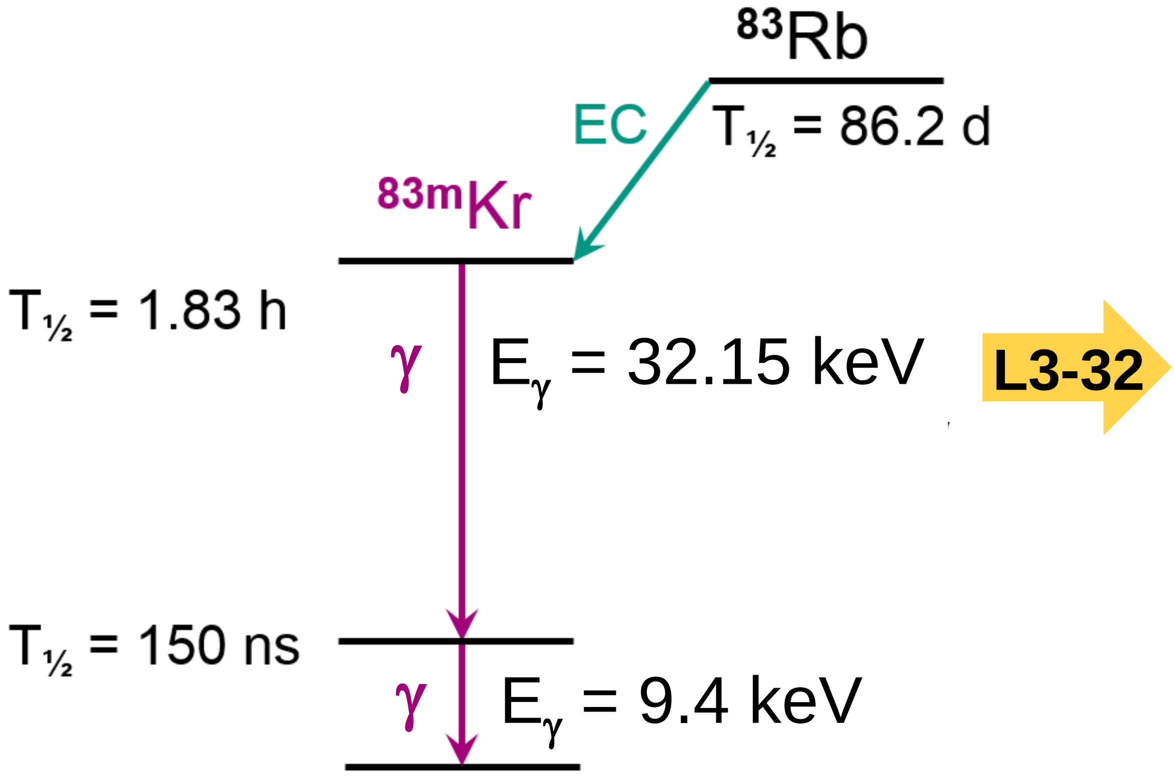


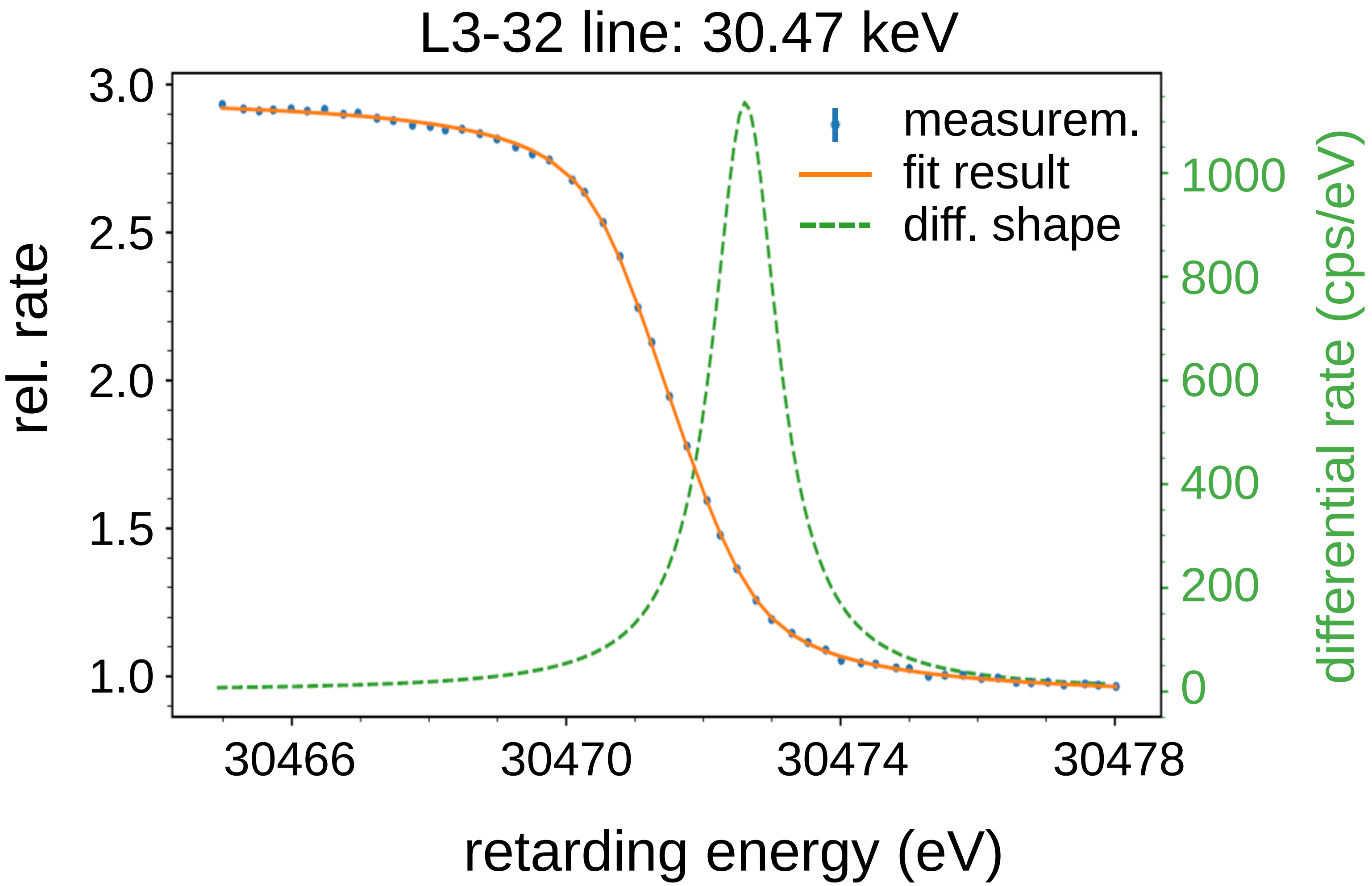
$\mu = E_\perp / B = \text{const.}$

response to quasi-monoenergic electrons

- **MAC-E filter characteristics well understood (also used to study plasma)**

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

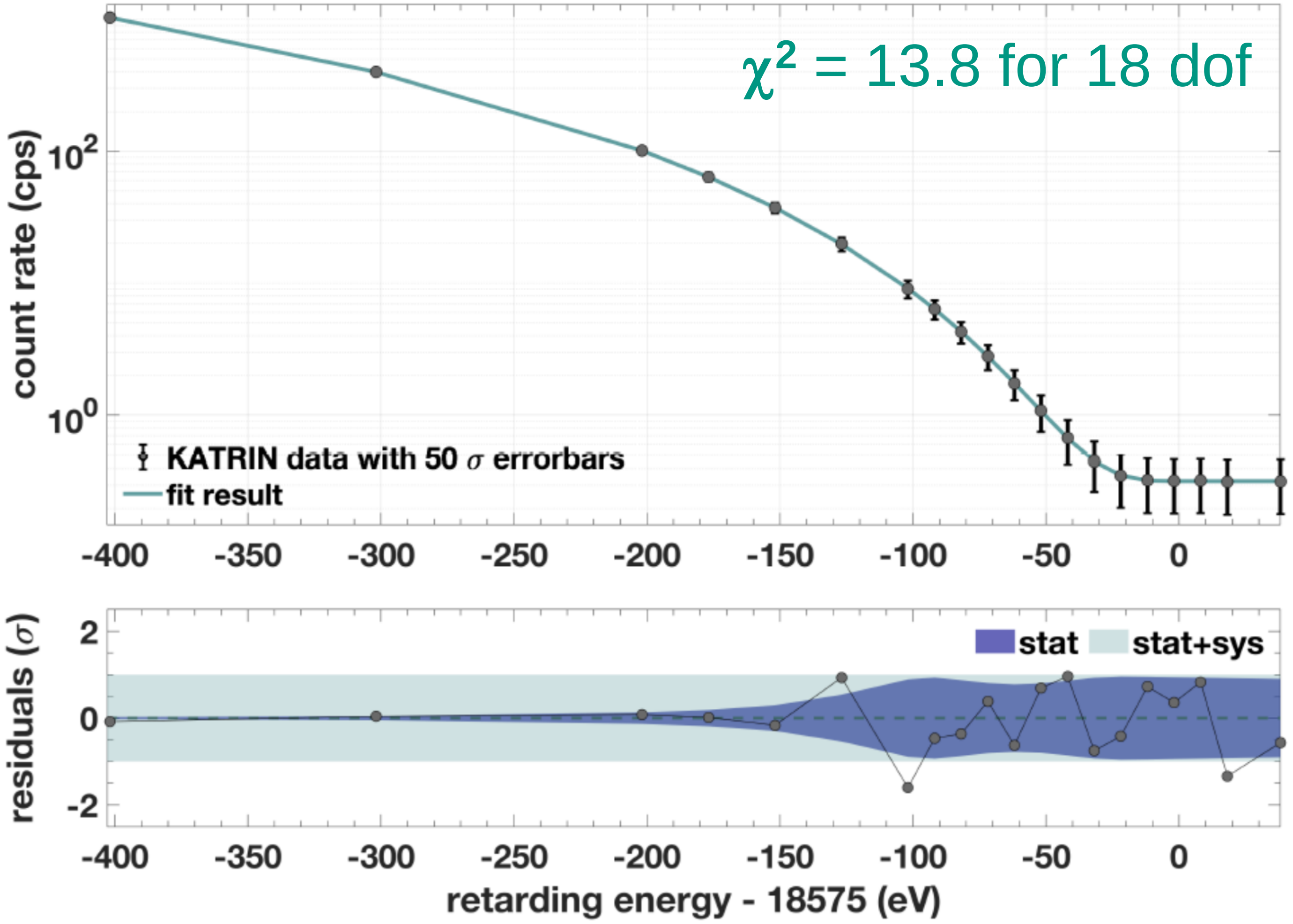




„First Tritium“ FT (2-week engineering run in mid-2018)

- 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


χ^2 = 13.8 for 18 dof

KATRIN Collab., “First operation of the KATRIN experiment with tritium”, to be subm. to 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 ($\varepsilon_T = 97.5\,\%$)	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**

T. Lasserre
First
KATRIN
Tritium Data

Neutrino # 19

M. Slezak
Analysis strategies
& treatment of
systematic effects
in KATRIN

Neutrino # 19

KATRIN neutrino mass campaign #1

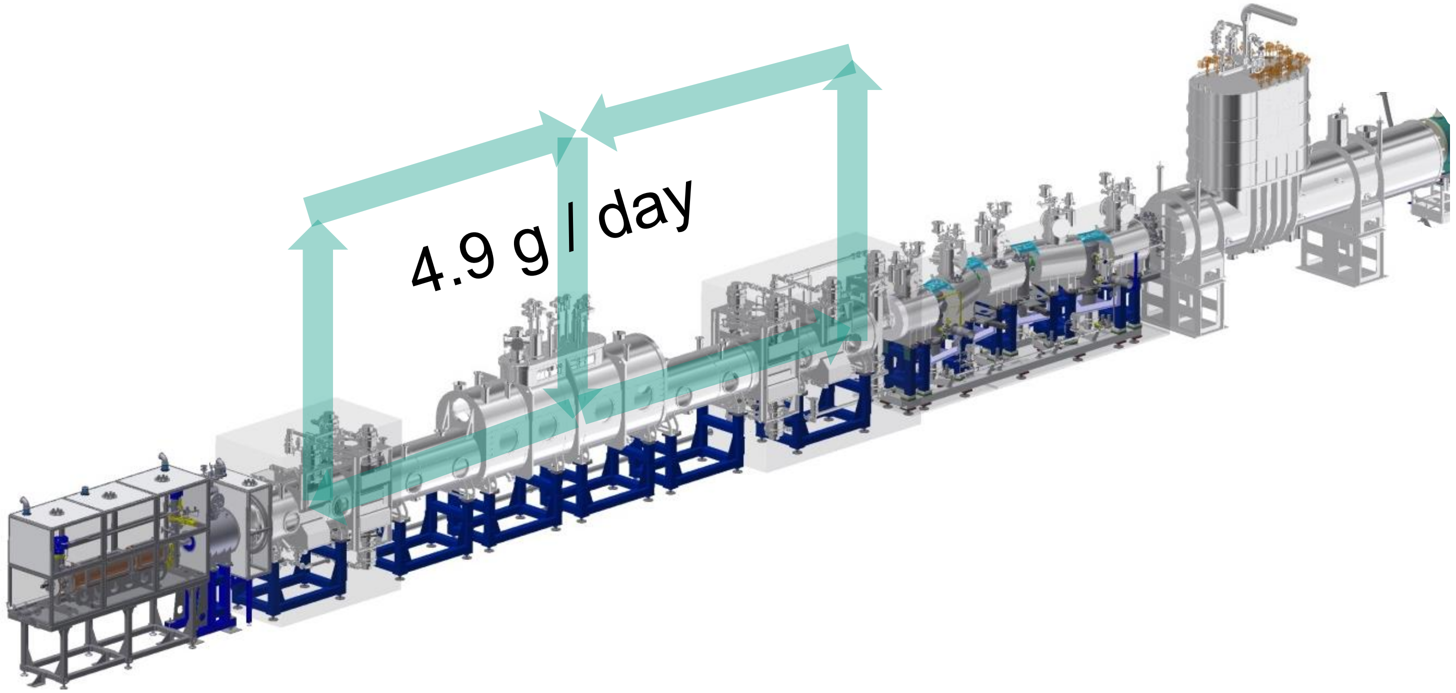
- **first ever large-scale throughput of high-purity tritium in closed loops**

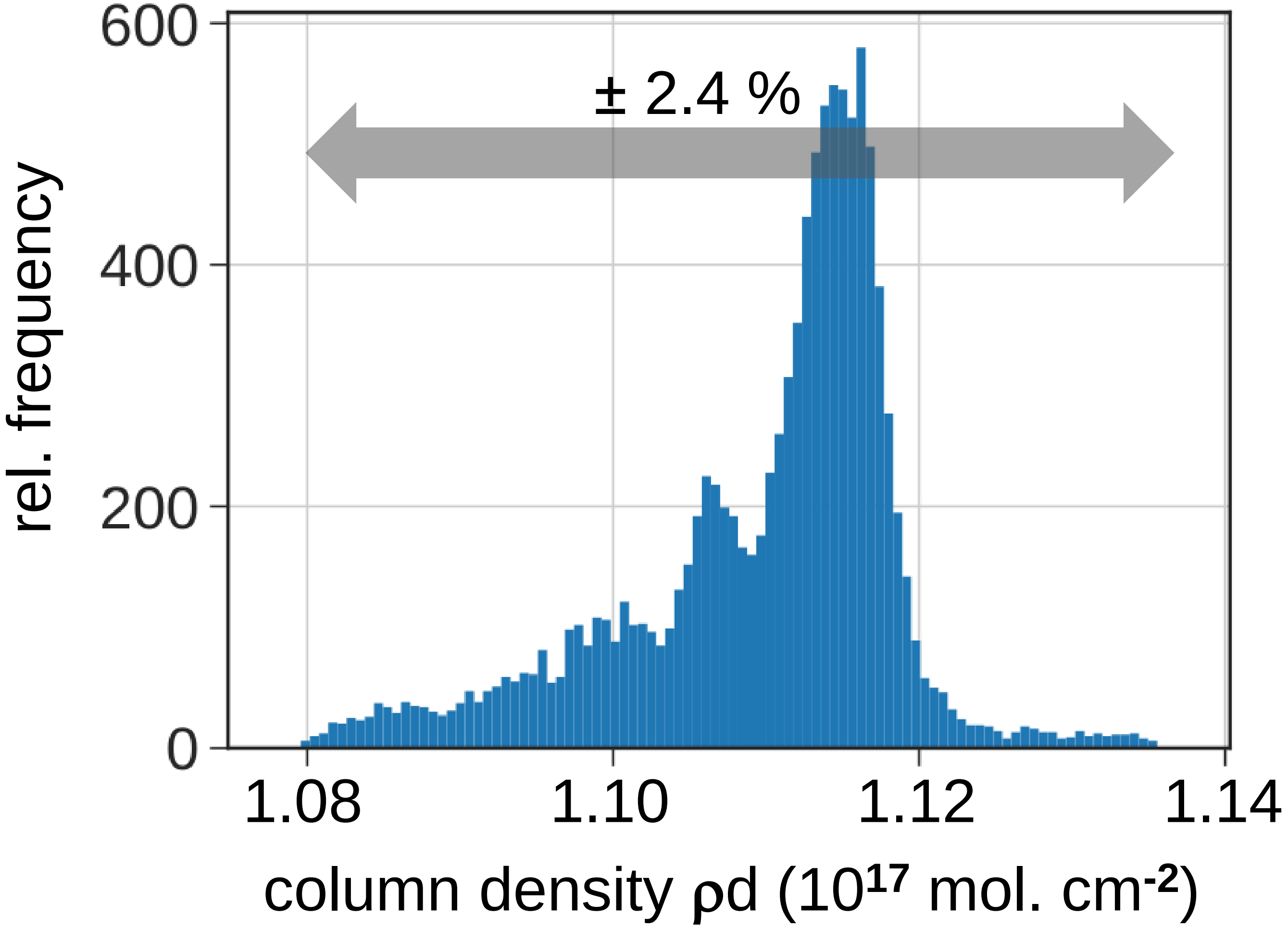
  - 22% of nominal source activity (column density)

    ⇨ 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 %)



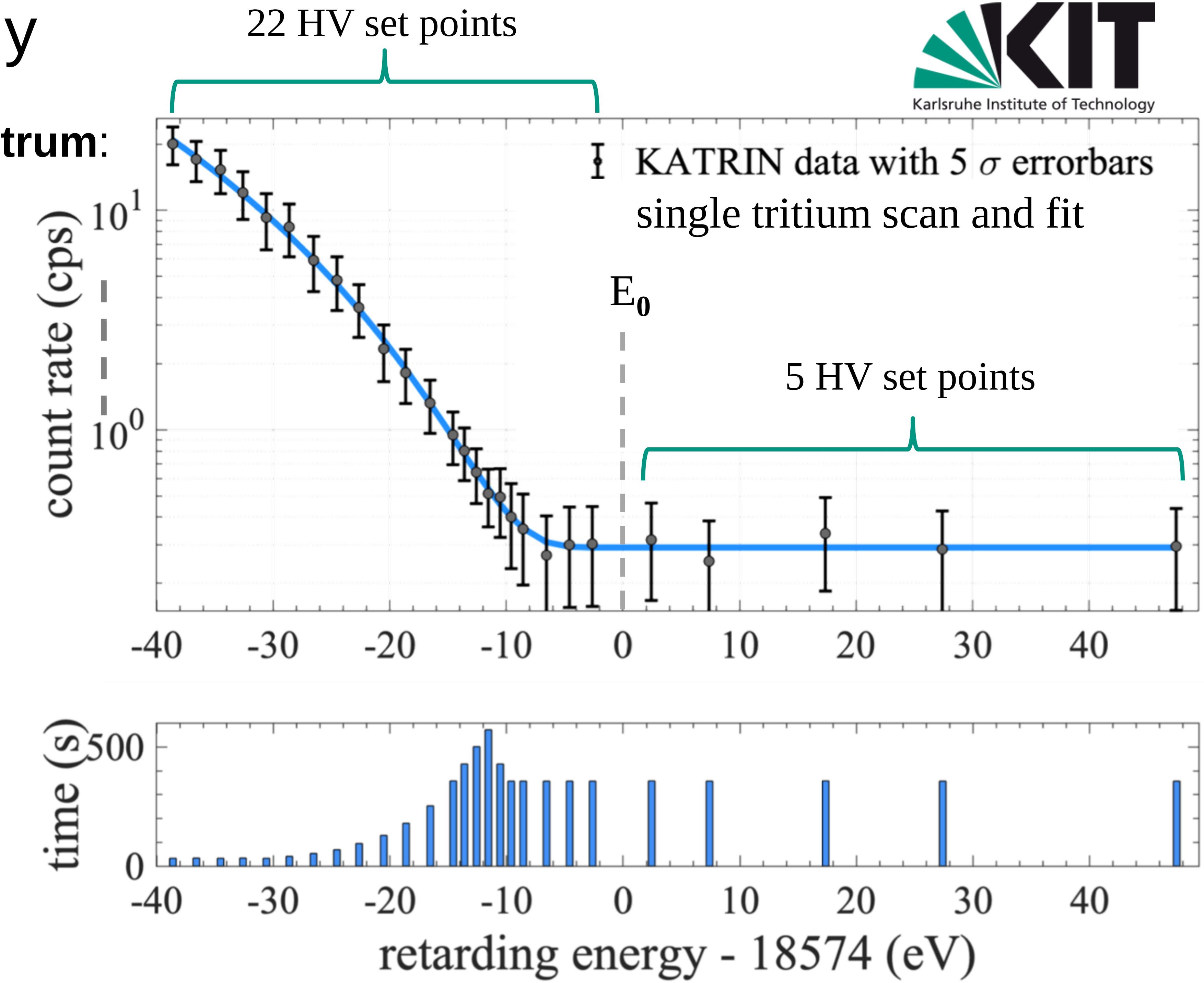


tritium scanning – strategy

- **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]

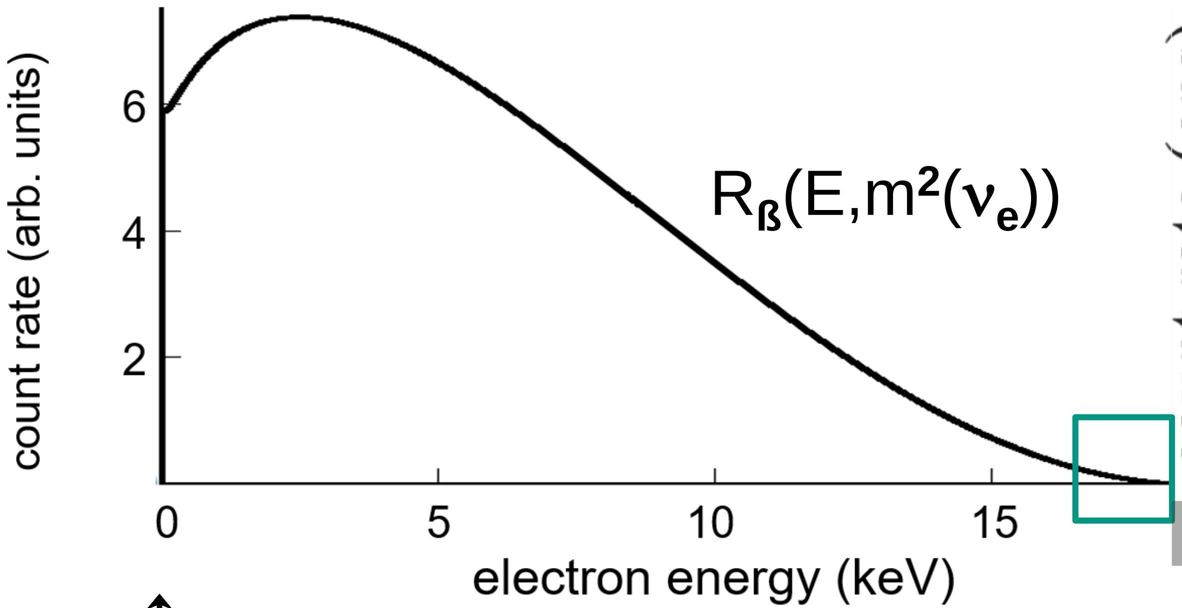
FSD bg-slope

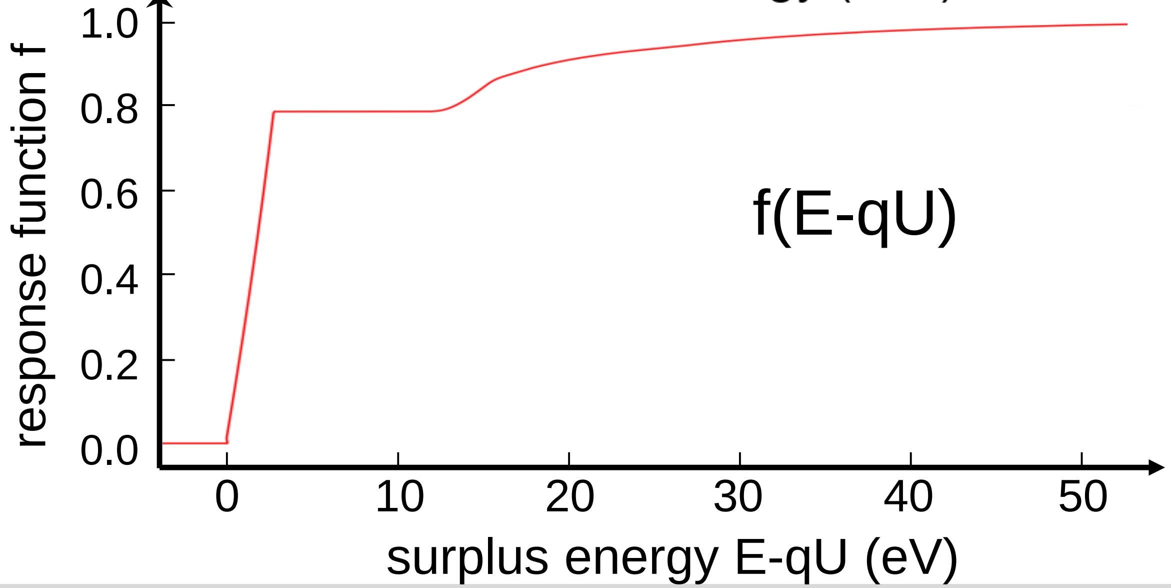
- **MTD maximises ν-mass sensitivity**
  - focus on region close to E_0

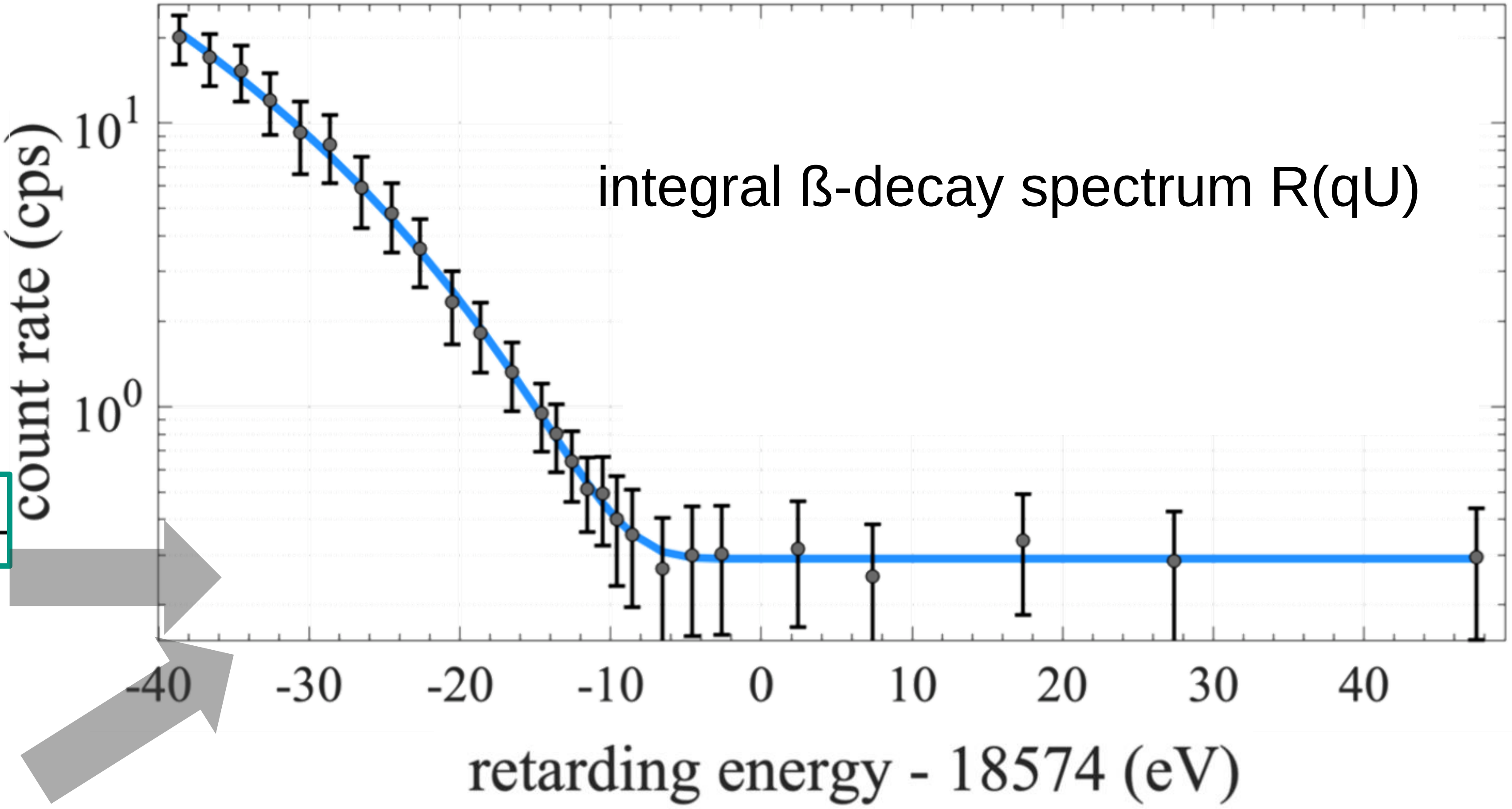


modelling of experimental data

- **ß-spectrum ⊗ response function**





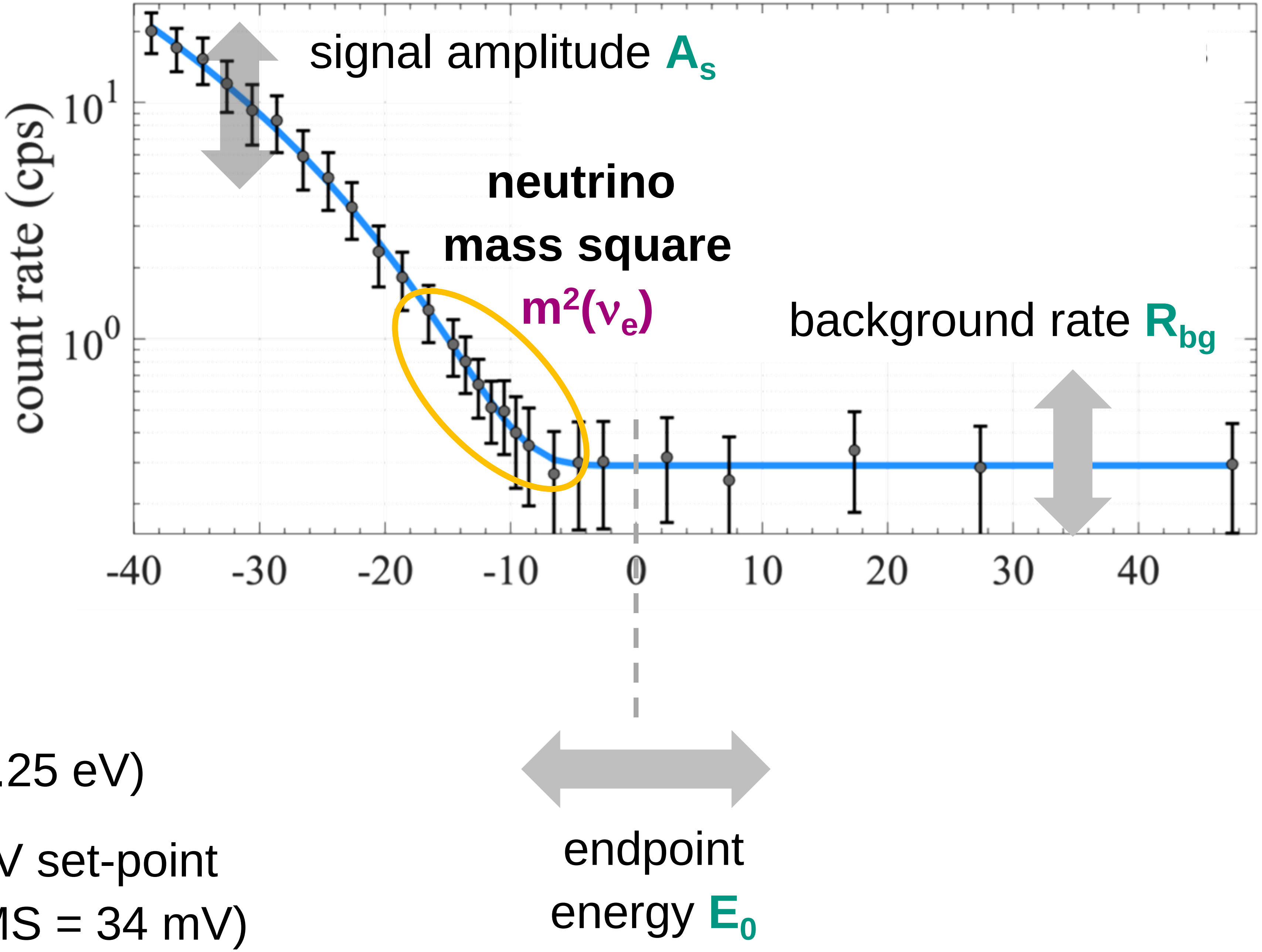


$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_{\text{ß}}(E, m^2(\nu_e)) \cdot f(E-qU)\,dE + R_{bg}$$

tritium scanning – fitting of spectrum

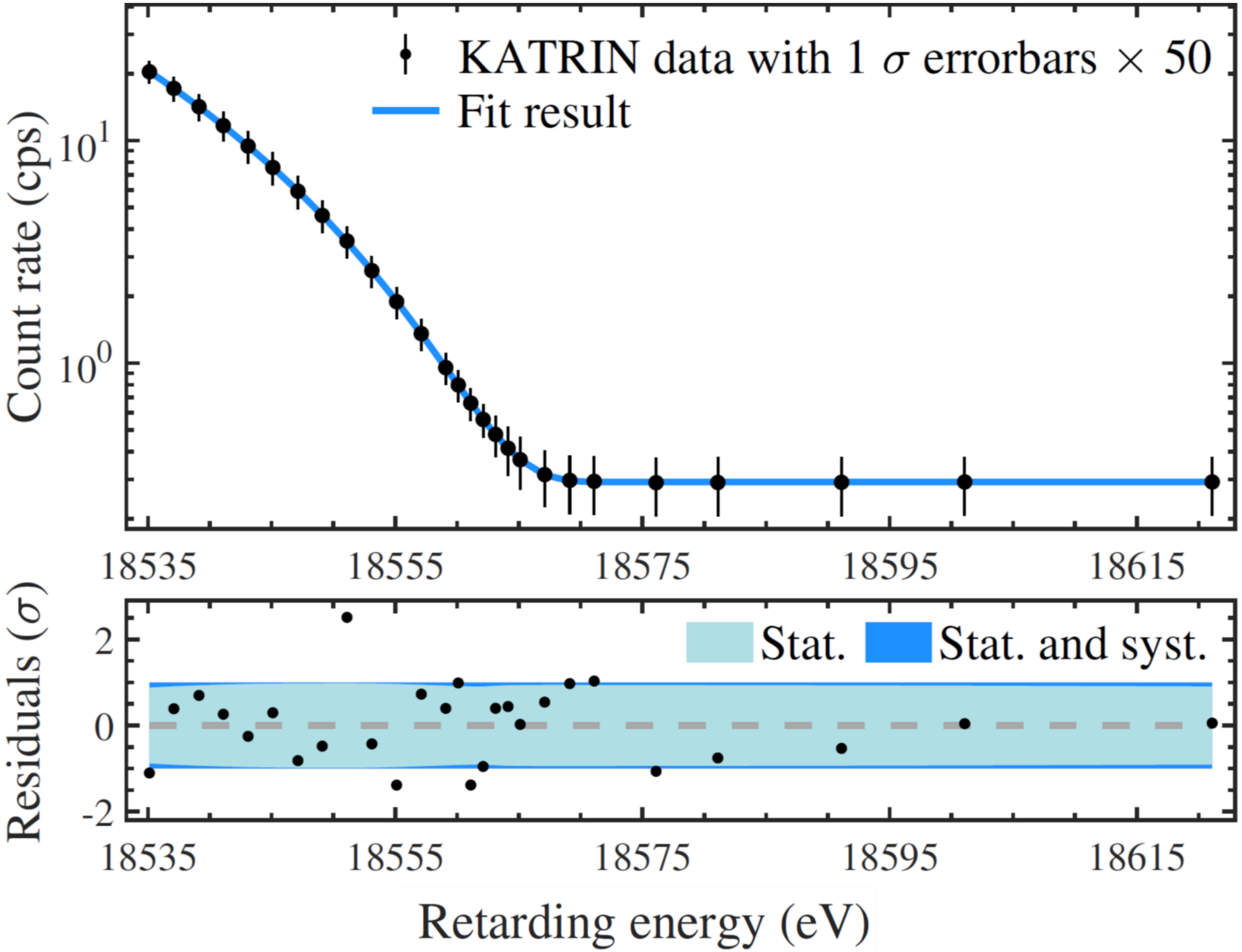
- **fit of integrated experimental energy spectrum** to theoretical model with **4 free parameters**
  - leave parameters A_s and E_0 unconstrained ´**shape-only**´ fit
- **merged data set**
  - combine all 274 scans: excellent stability of all fitted ß-decay endpoints E_0 (σ = 0.25 eV)

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



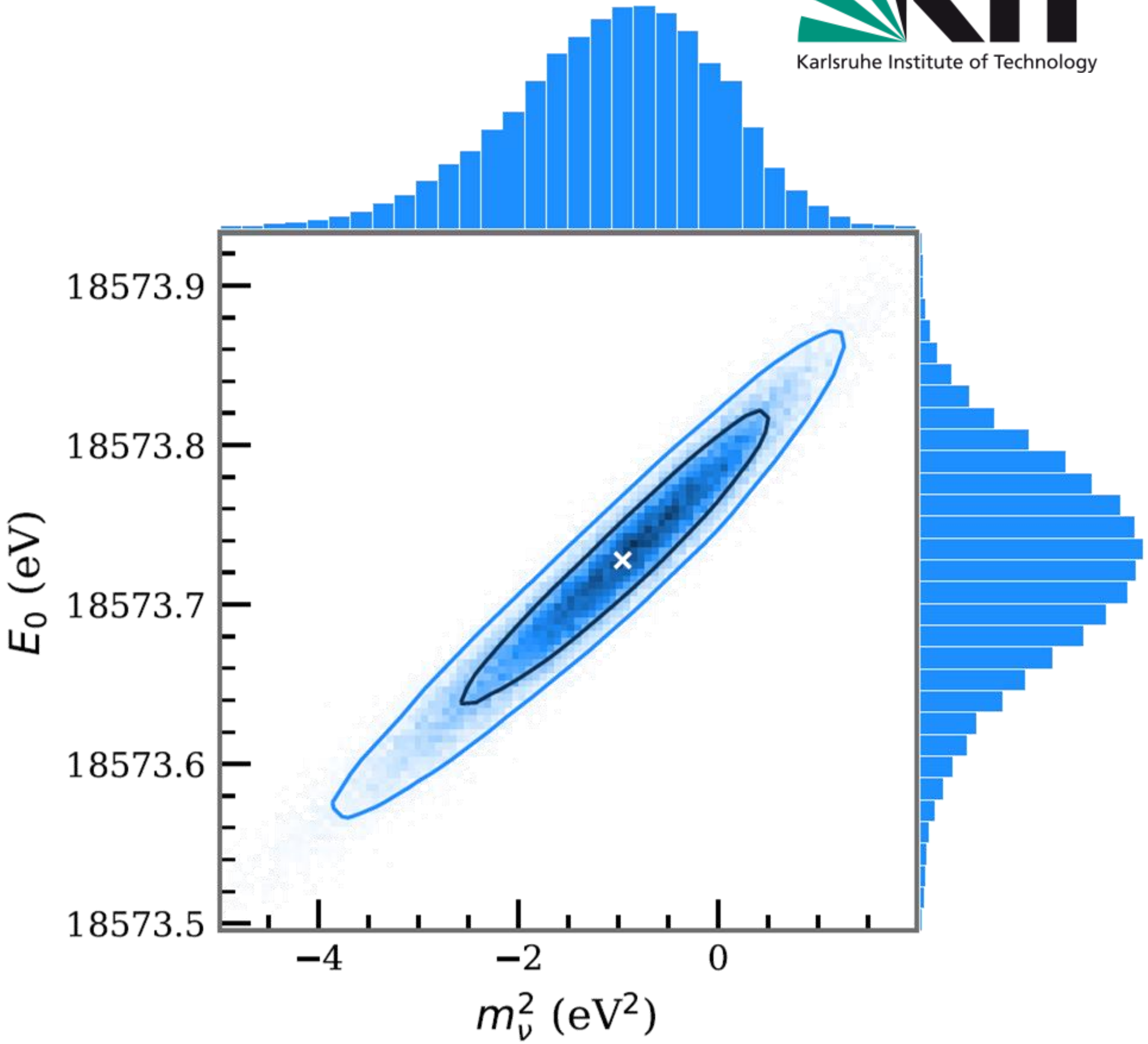
Integral tritium ß-decay spectrum

- **High-statistics ß-spectrum**
  - 2 million events in
    in 90-eV-wide interval
    (522 h of scanning)
  - excellent goodness-of-fit
    χ^2 = 21.4 for 23 d.o.f.
    (p-value = 0.56)
- **bias-free analysis**
  - blinding of FSD
  - full analysis chain first on
    MC data sets
  - 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**

$$\boxed{m^2(\nu_e) = \left(-1.0\,{}^{+\,0.9}_{-\,1.1}\right)\,\mathrm{eV}^2\ (90\%\ \mathrm{CL})}$$

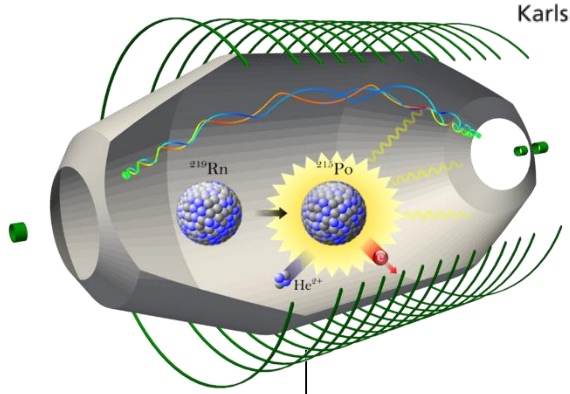
$E_0 = (18573.7 \pm 0.1)$ eV ⇨ Q-value : (18575.2 ± 0.5) eV Q-value [$\Delta M(^3H,^3He)$]: (18575.72 ± 0.07) eV

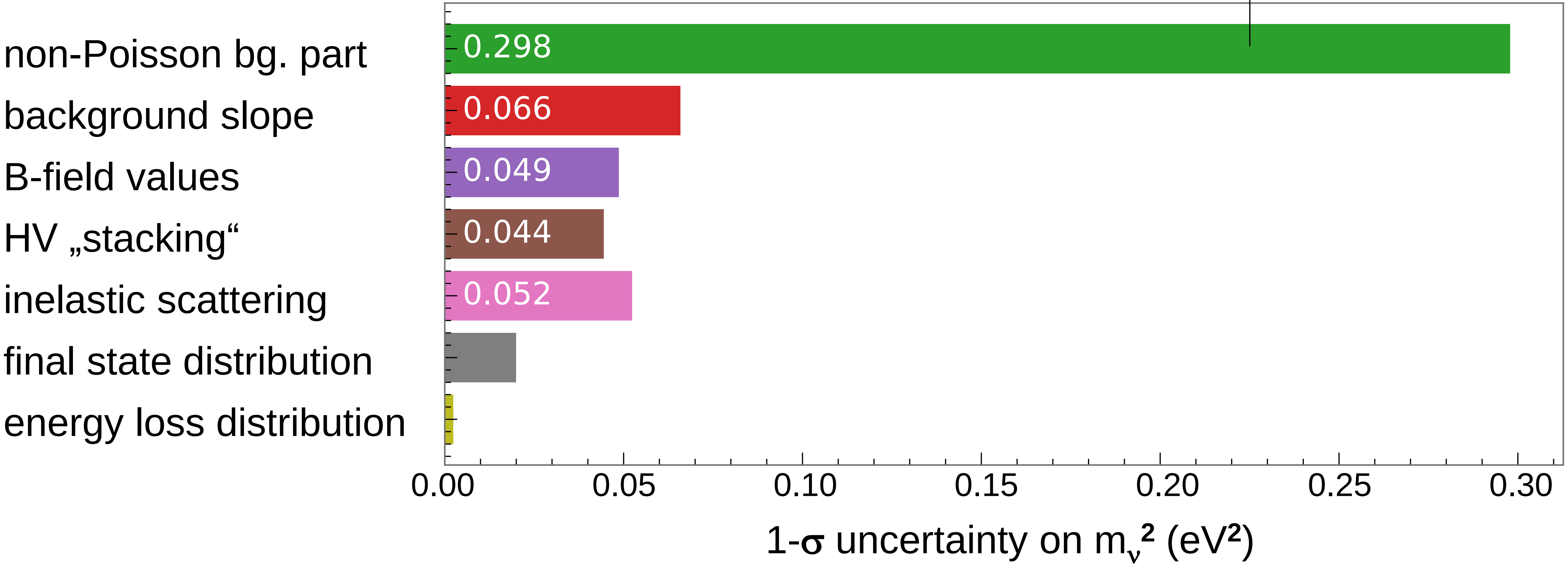
systematics breakdown

- **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



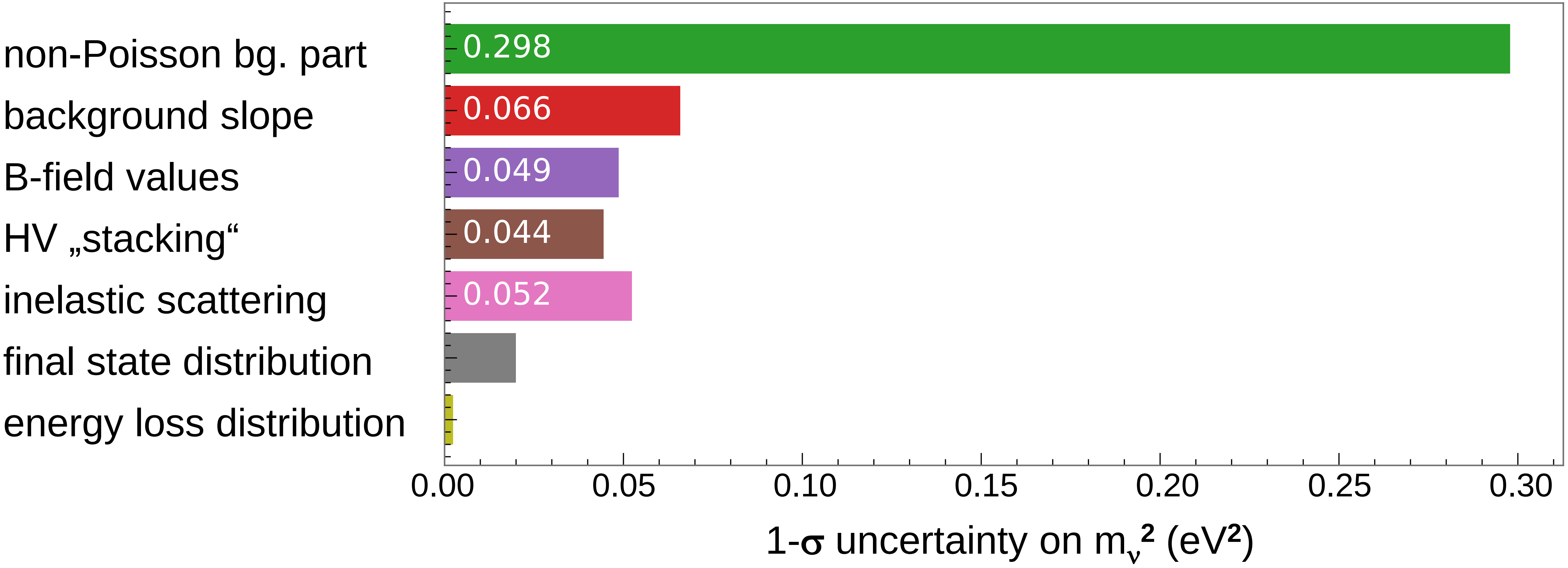


systematics breakdown

- **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

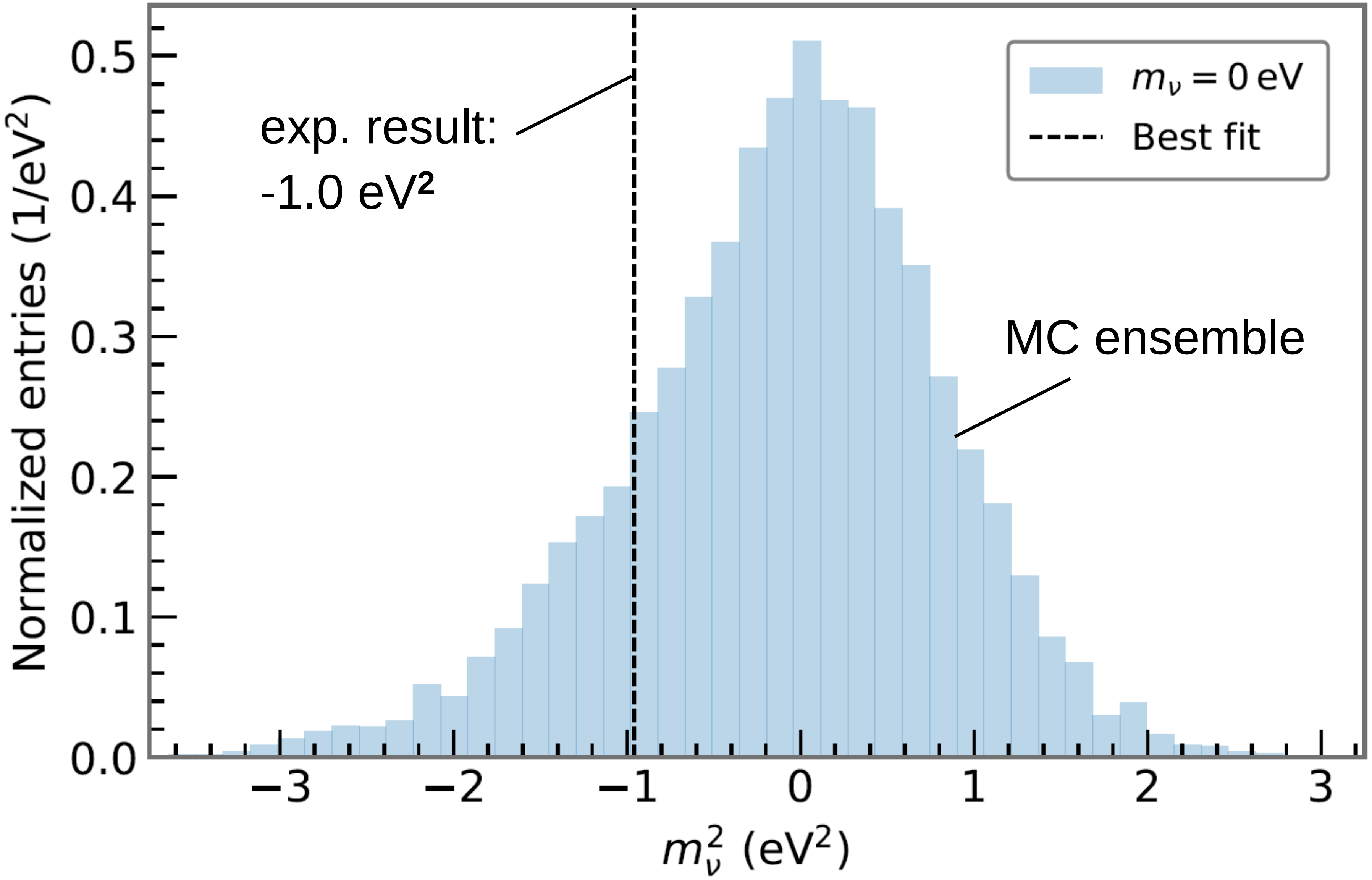
improves on Mainz/Troitsk by **factor 2** (statistical), **factor 6** (systematic)



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

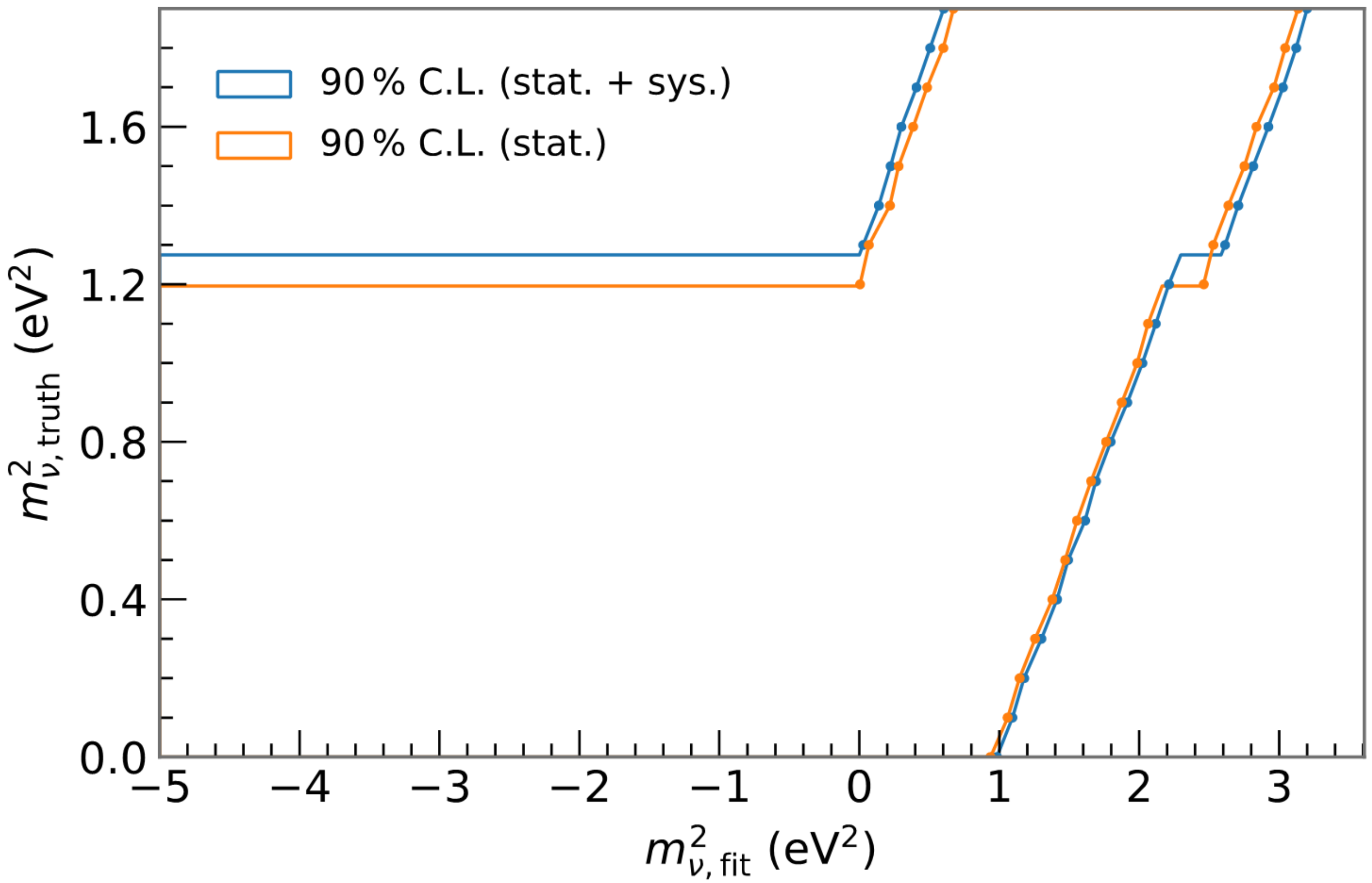
- **confidence belts:** procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC)

- 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

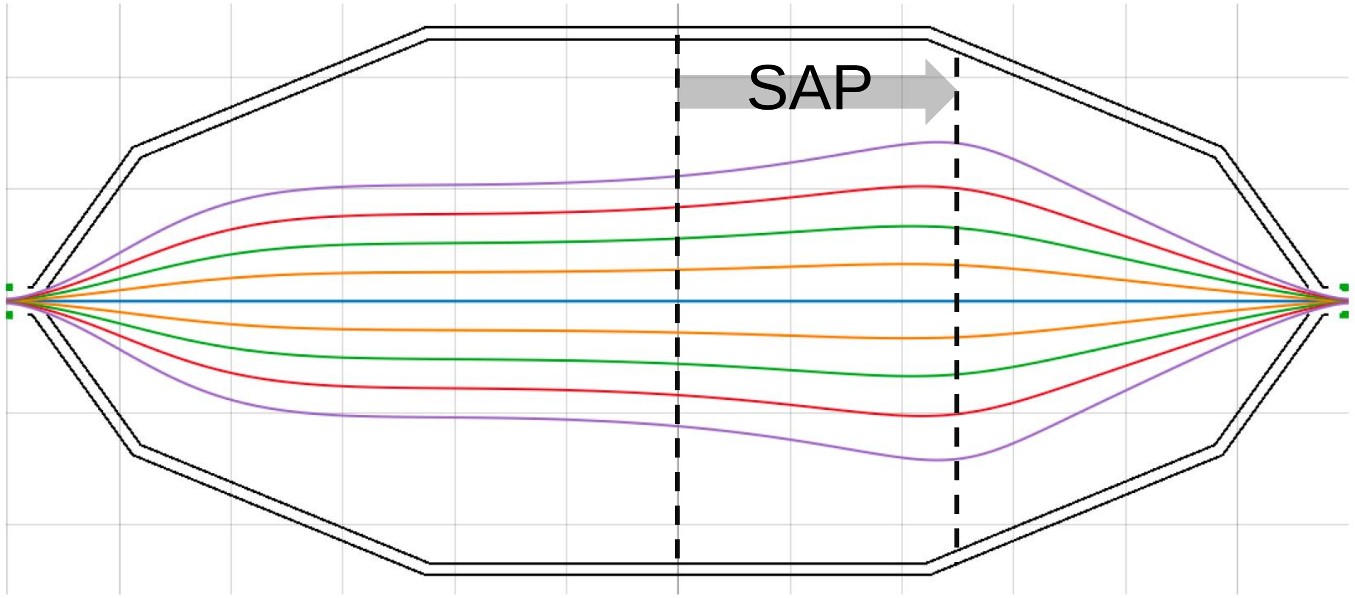
M. Aker et al. (KATRIN Collab.), *An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN*, to be subm. to PRL today

KATRIN – future plans

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

  - further reduction of background
  from decays of Radon & Rydberg atoms
  ⇨ spectrometer bake-out successful ☑
  ⇨ upgraded aircoil system ☑
  „shifted analysis plane“ (SAP)
  bg-studies & tritium scans soon

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



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

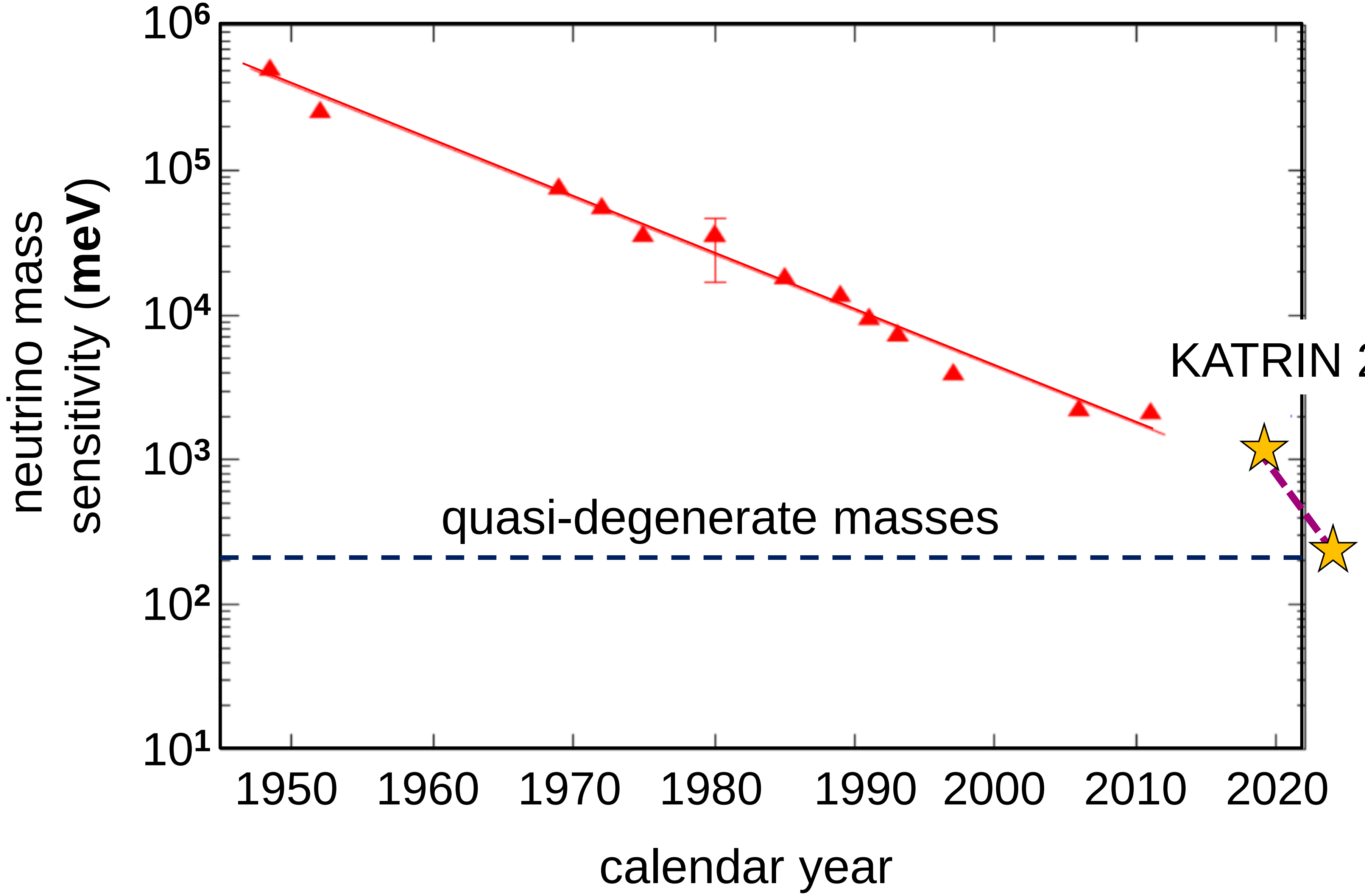
- **1000 days of measurements** at
nominal ρd ($5 \cdot 10^{17}$ molecules cm^{-2})
3 tritium campaigns (65 days each)
per calendar year

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**



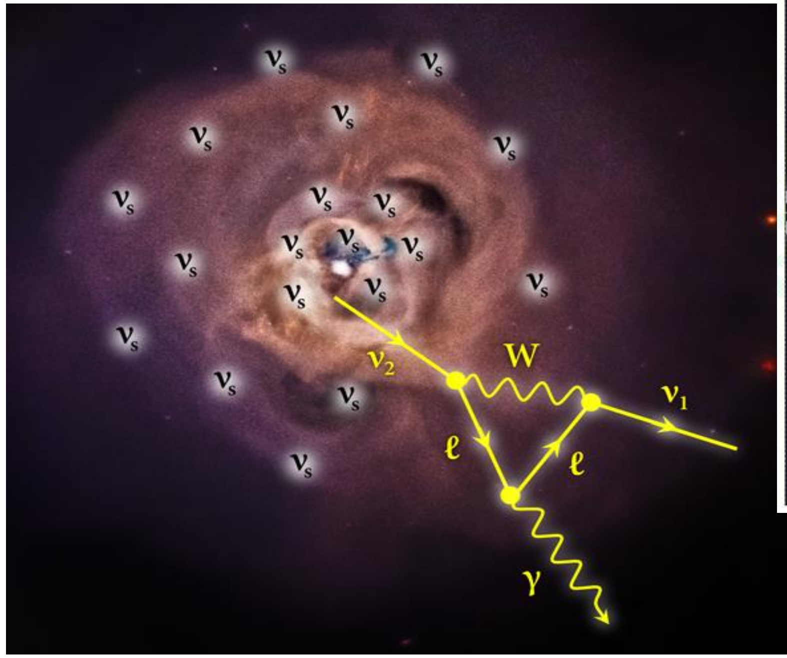
KATRIN 2019

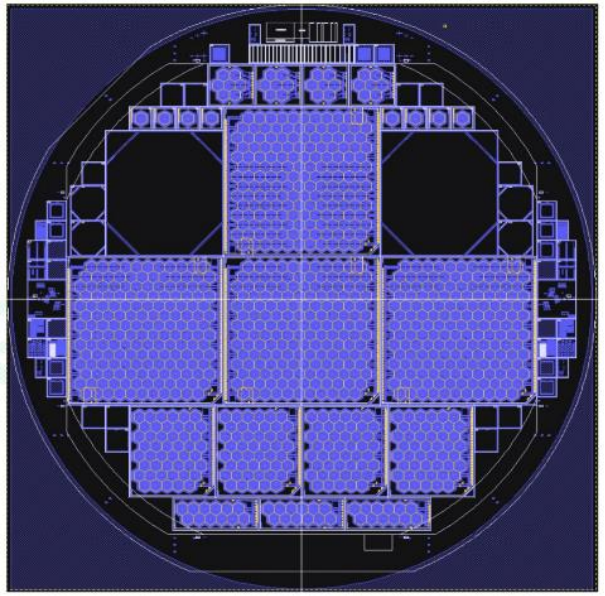
$m(\nu_e)$ < 1.1 eV (90% CL)

KATRIN 2024:

$m(\nu_e)$ < 0.2 eV (90% CL)

or = 0.35 eV (5 σ)





T. Houdy

The TRISTAN Project

Neutrino # 22

T. Brunst

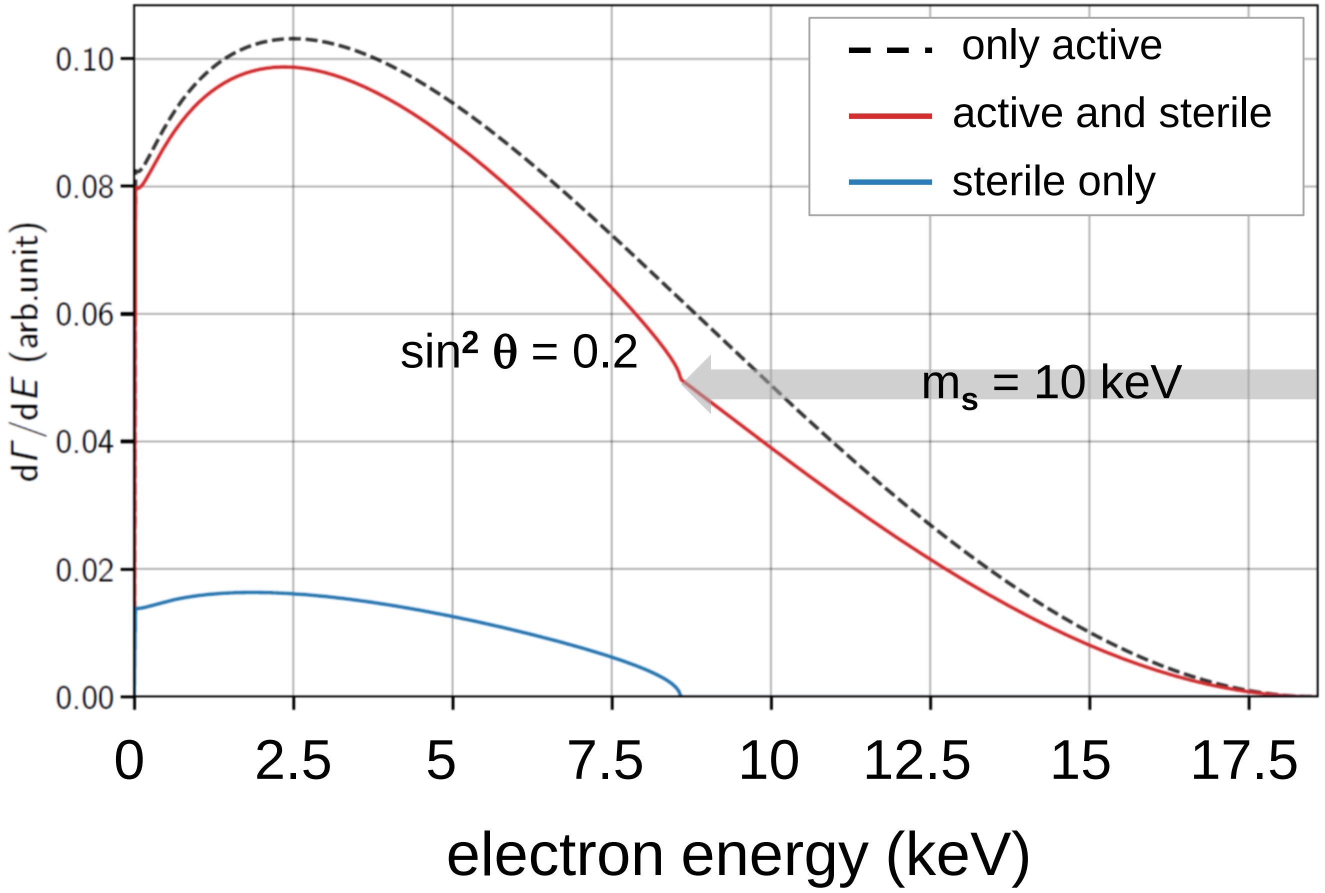
TRISTAN measurements at Troitsk nu-mass experiment

Neutrino # 22

SEARCH FOR KEV STERILE NEUTRINOS

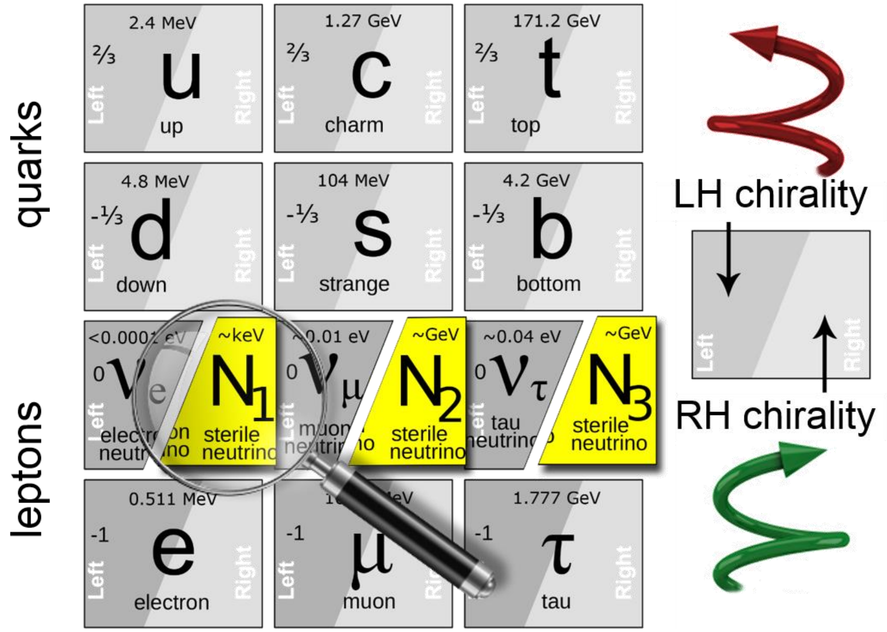
Tritium ß-decay and dark fermions

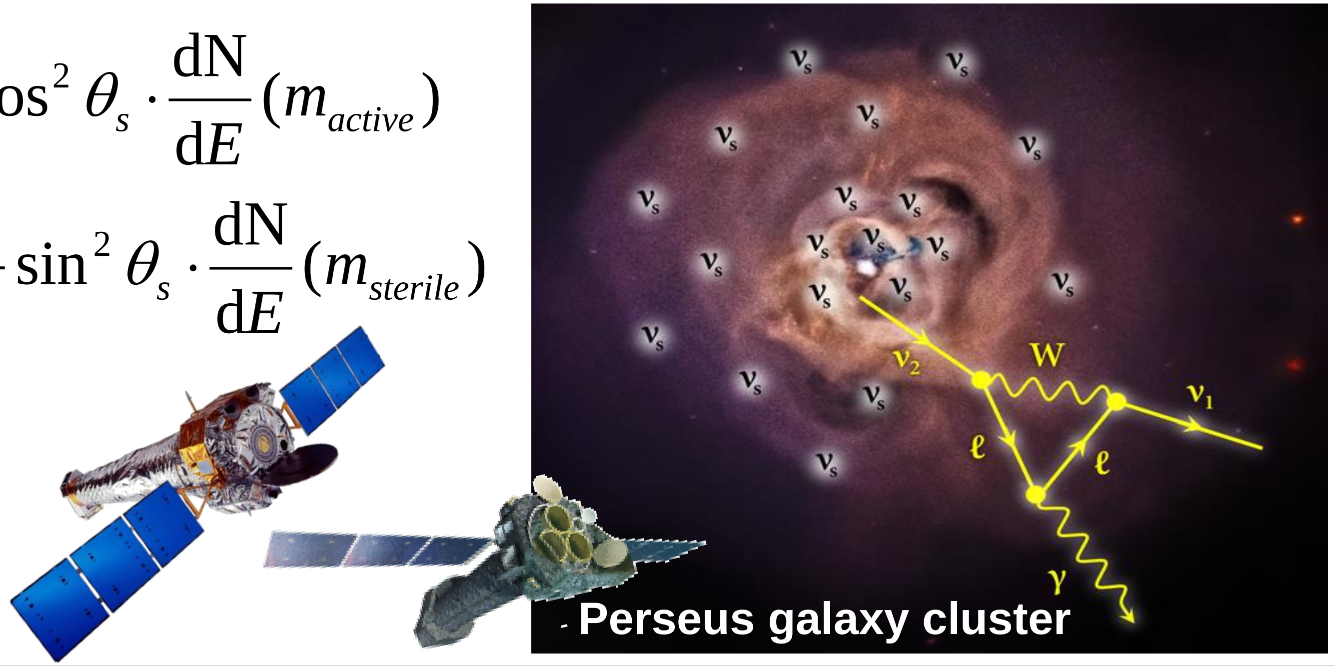
- **BSM particles (sterile neutrinos, light fermionic DM)** in keV-mass scale would produce a **´kink´ in the ß-spectrum**
  - - cover entire phase space (masses up to 18 keV)
  - - cover tiny couplings (~10^{-7}) ⇨ left-right coulings (Rodejohann)



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

νMSM

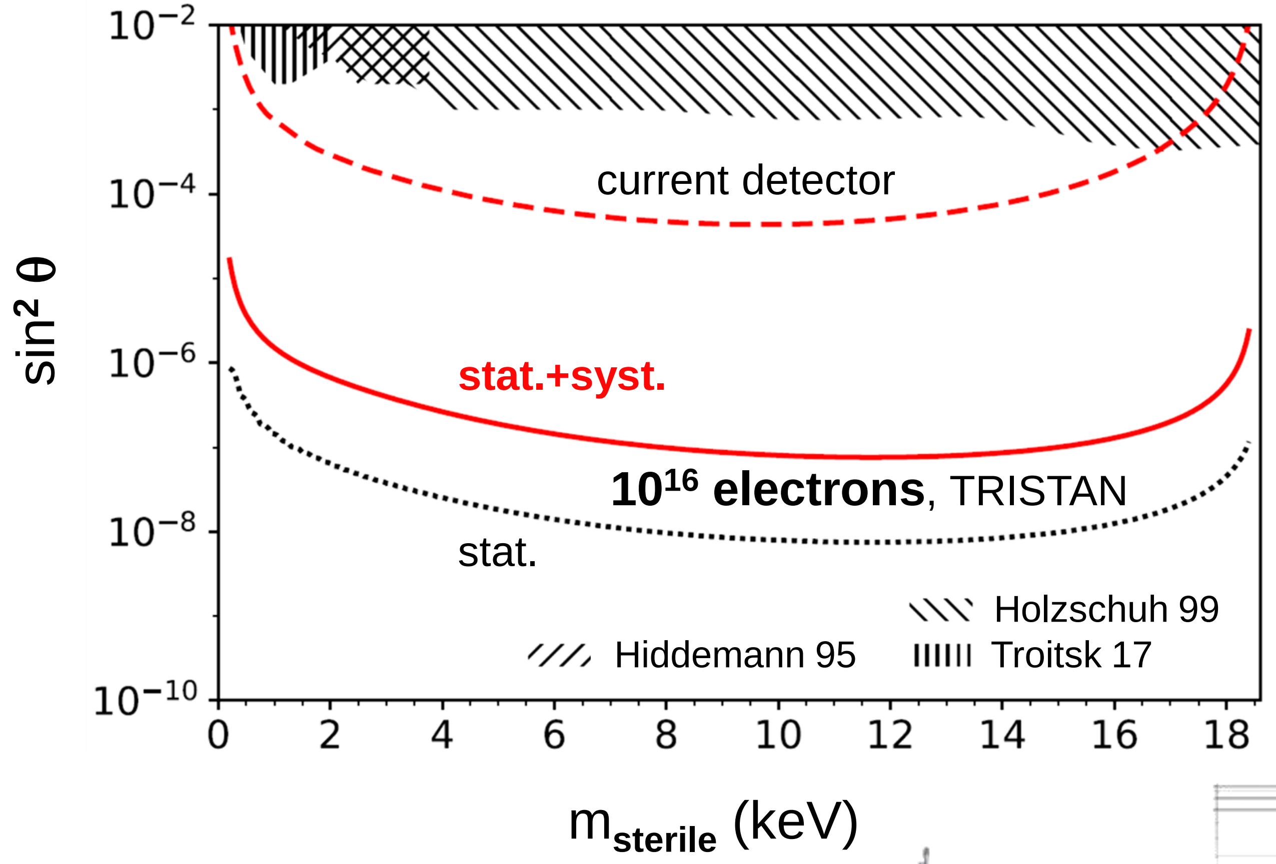


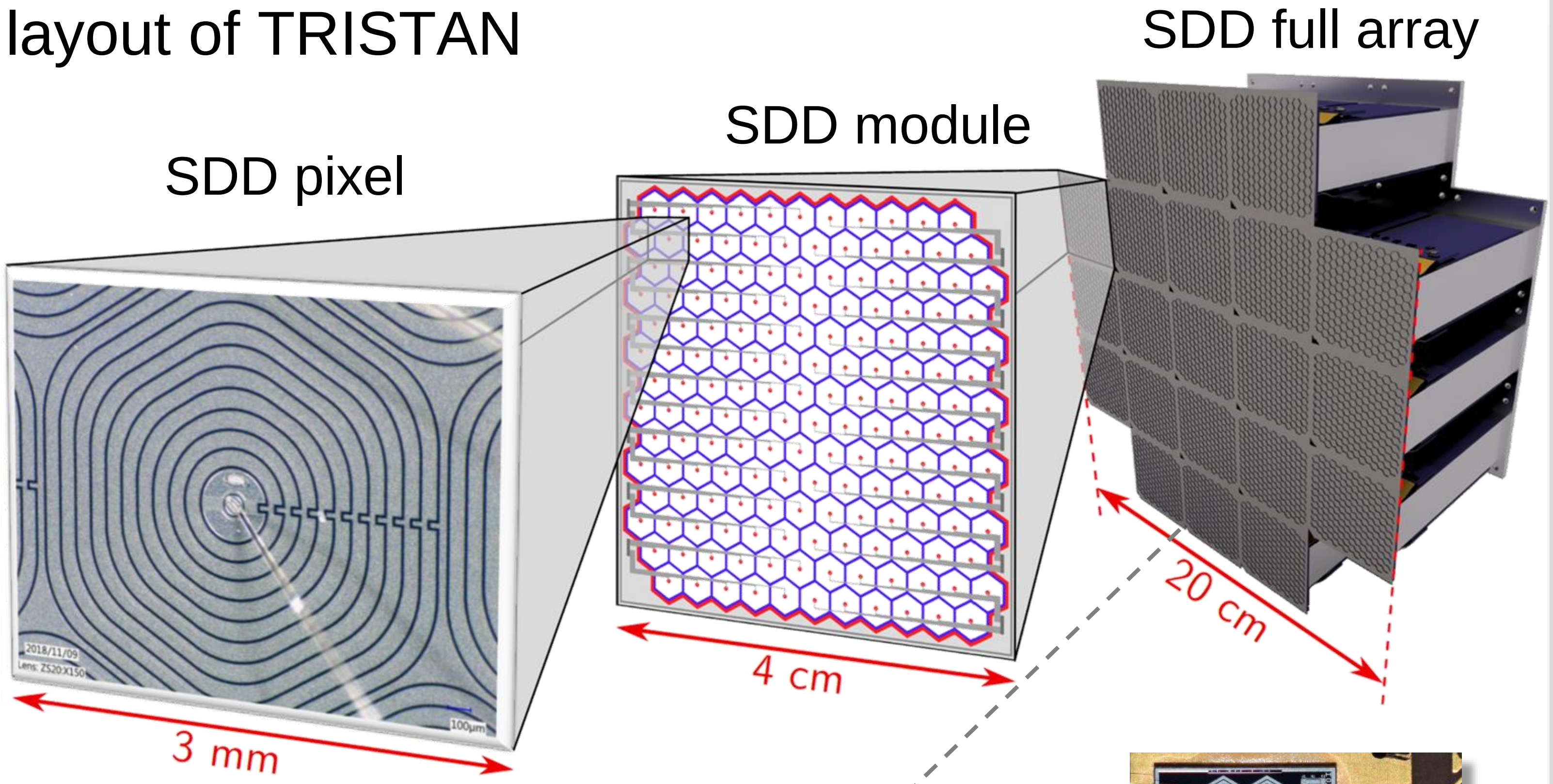


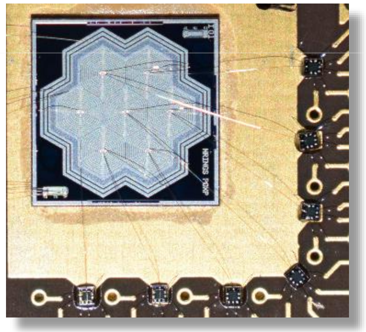
Perseus galaxy cluster

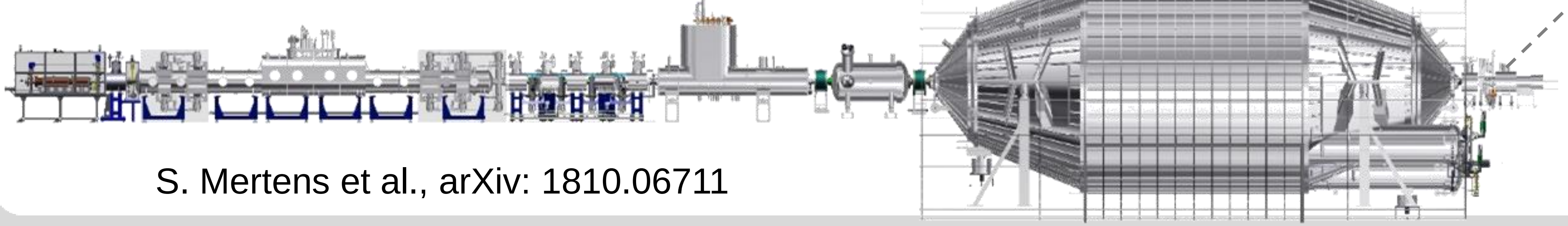
Science reach of KATRIN with new detector array

- estimated **KATRIN sensitivity** and SDD layout of TRISTAN









S. Mertens et al., arXiv: 1810.06711

TRitium **I**nvestigation on **ST**erile
(**A**) **N**eutirnos

Conclusion

- **major experimental progress of direct kinematic methods** since NEUTRINO 2018!

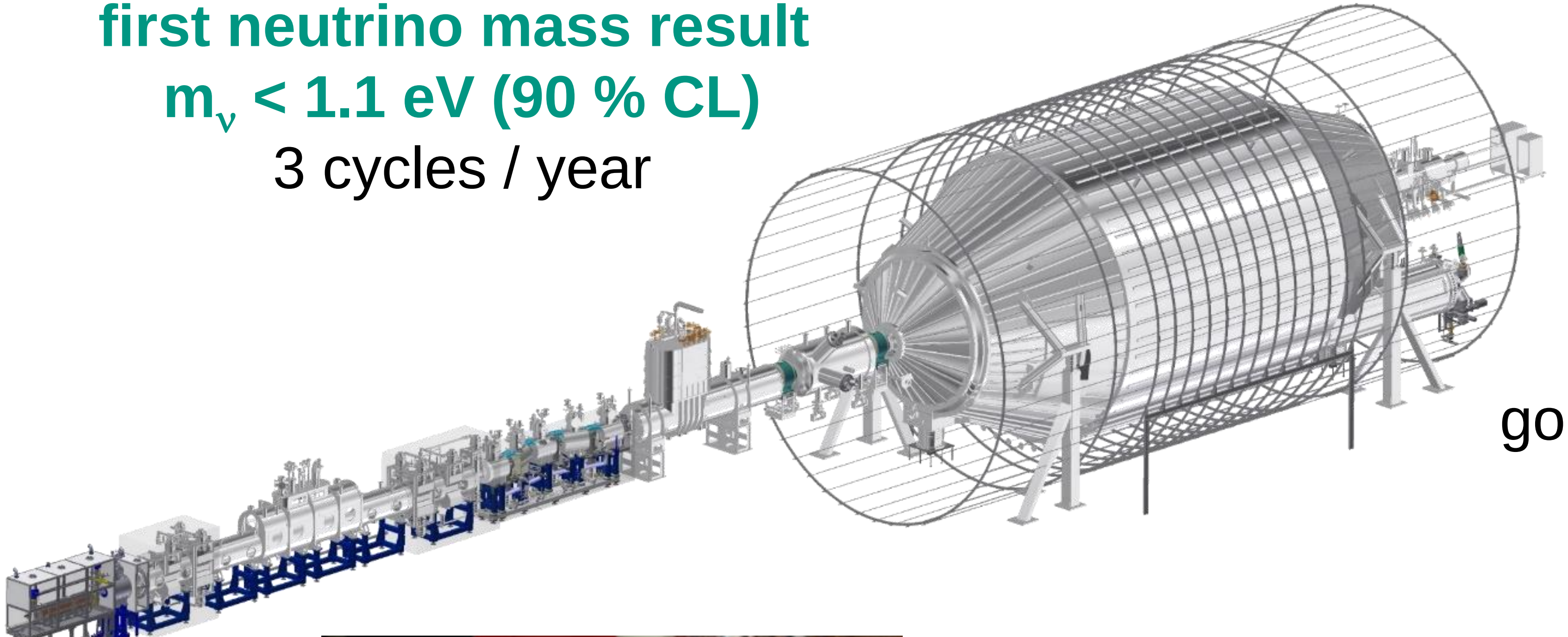
NEUTRINO 2018
4–9 June
Heidelberg

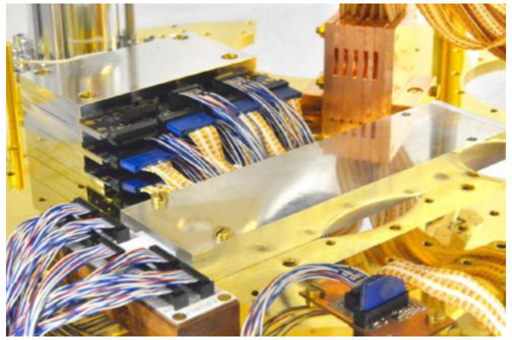
KATRIN:

first neutrino mass result

$m_\nu < 1.1$ eV (90 % CL)

3 cycles / year





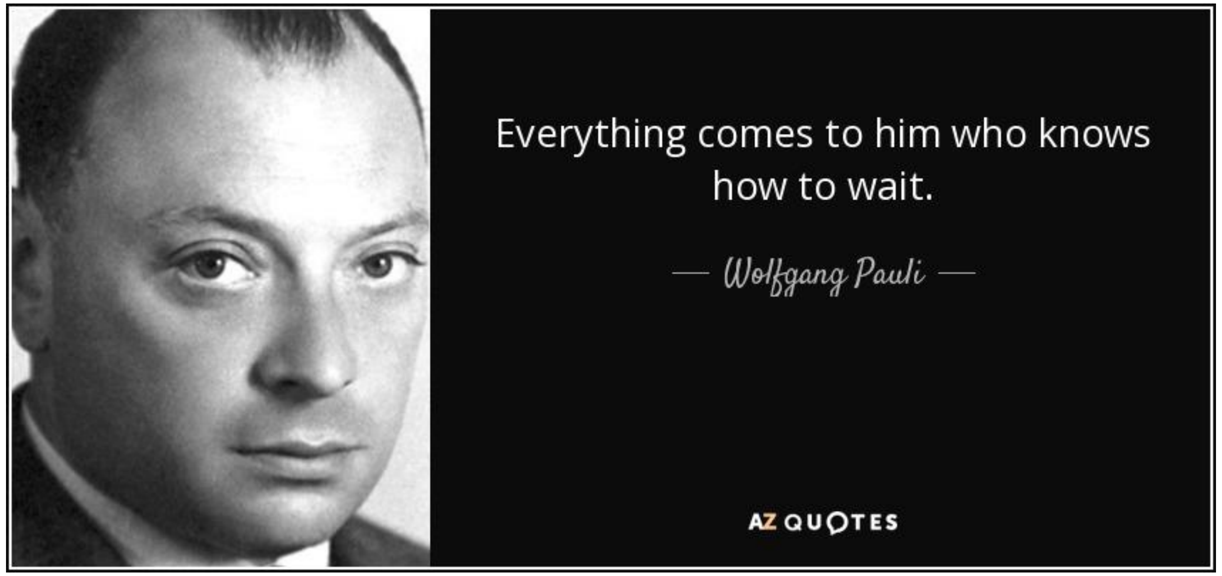
ECHo:

goal: $m(\nu_e) < 20$ eV in 2020

TAUP 2019 TOYAMA

P8: first tritium CRES spectrum

HOLMES: significant R&D progress



Everything comes to him who knows how to wait.

— Wolfgang Pauli —

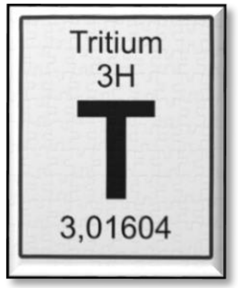
THANK YOU!

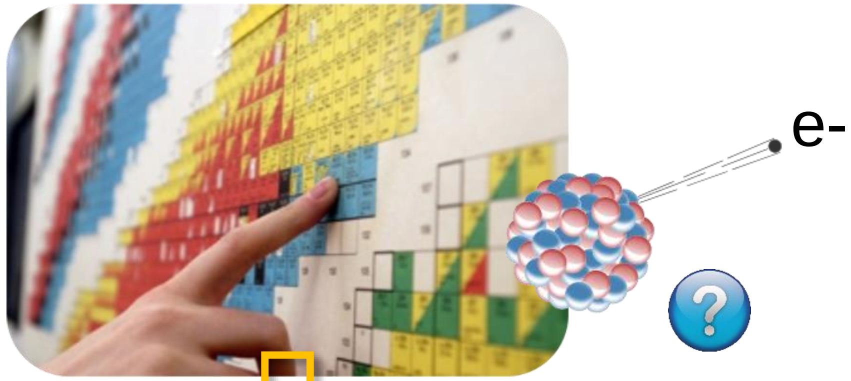
this talk is dedicated to V.M. Lobashev & E.W. Otten

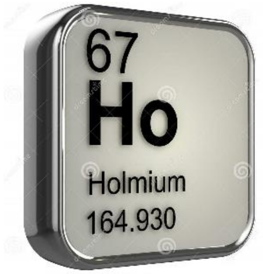
thank you to L. Gastaldo, J. Formaggio, N. Oblath, A. Nucciotti

ADDITIONAL TRANSPARENCIES

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



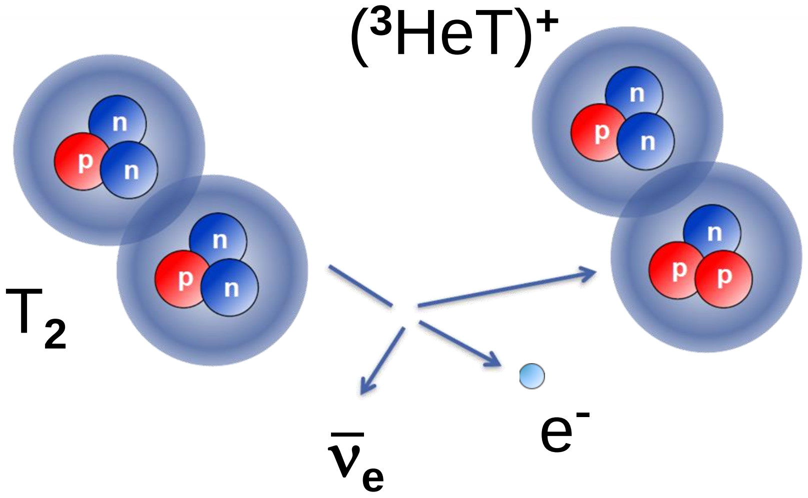


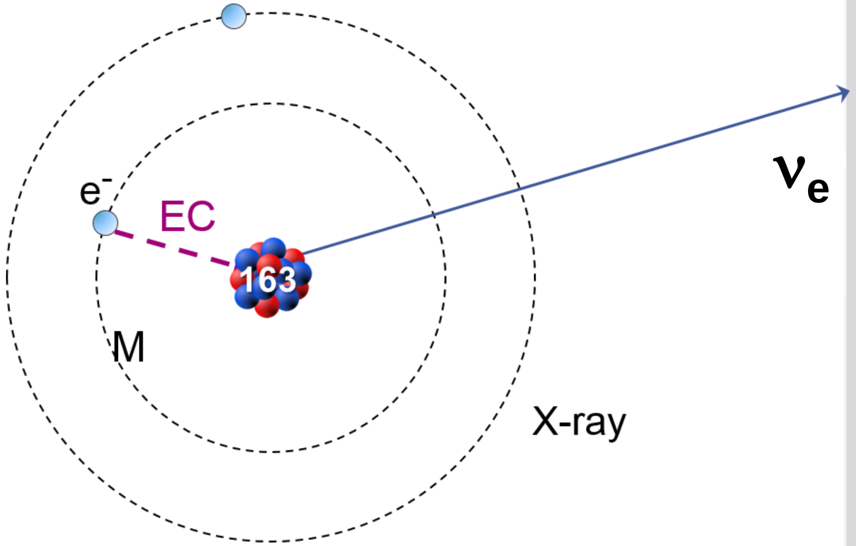


$(^3H)_2 \rightarrow {}^3HeT^+ + e^- + \bar{\nu}_e$

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

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

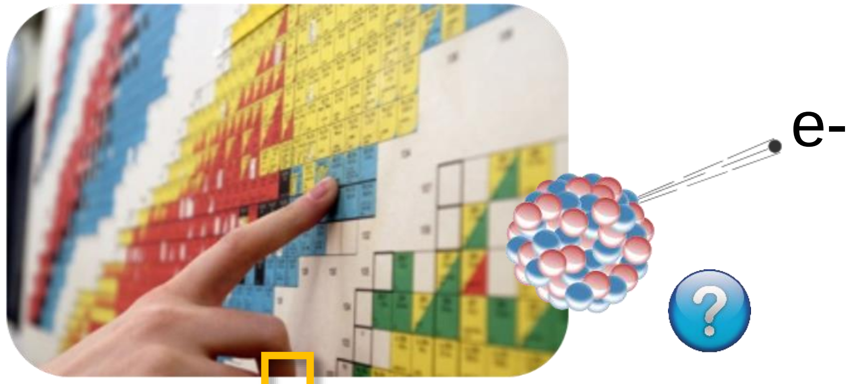




only two isotopes of choice:
tritium & holmium

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

4×10^8 atoms
for 1 Bq



2×10^{11} atoms
for 1 Bq

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

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

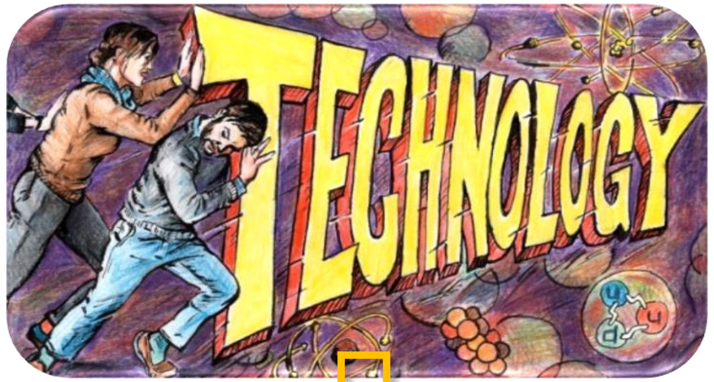
molecular ☑
atomic (R&D)

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

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

only two isotopes of choice:
tritium & holmium

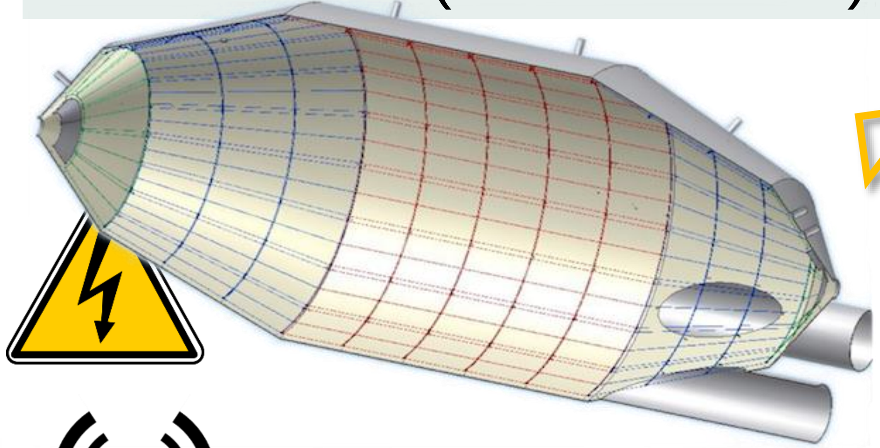
direct neutrino mass experiments – read-out



MAC-E filter

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

$\Delta E = 0.9$ eV (100% transm.)



electron energies

cyclotron radiation

max. transversal ß-energy $E_{\perp}$

$\Delta E = 2\text{-}3$ 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

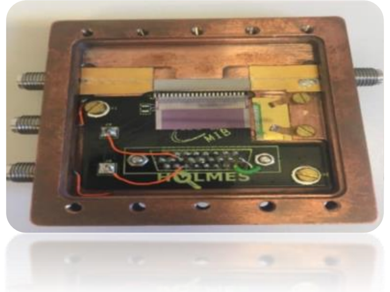
67 Ho Holmium 164.930

MAC-E filter:
highest energy resolution

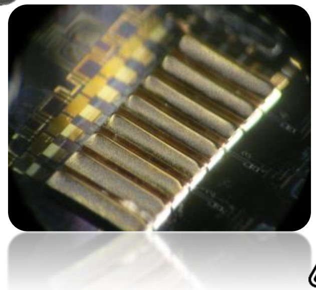
thermal μ-calorimeter

released decay-energy

$\Delta E \sim 5$ eV (FWHM)



**calorimeter:
source ⇔
detector**



metallic magnetic calorimeter

released decay-energy

$\Delta E = 2\text{-}5$ eV (FWHM)

direct neutrino mass experiments – the projects

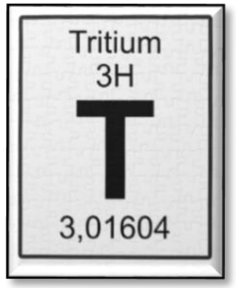
Karlsruhe Institute of Technology

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

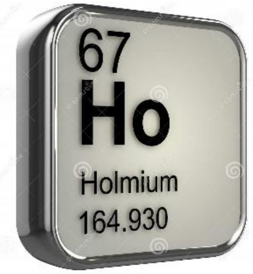
thermal µ-calorimeter
released decay-energy
$\Delta E \sim 5$ eV (FWHM)

KATRIN

KARLSRUHE TRITIUM NEUTRINO EXPERIMENT



HOLMES



PROJECT 8

ECHo

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

PTOLEMY:
R&D efforts
to combine
techniques

metallic magnetic calorimeter
released decay-energy
$\Delta E = 2\text{-}5$ eV (FWHM)

HOLMES – status & plans

- **HOLMES source production and purification:**

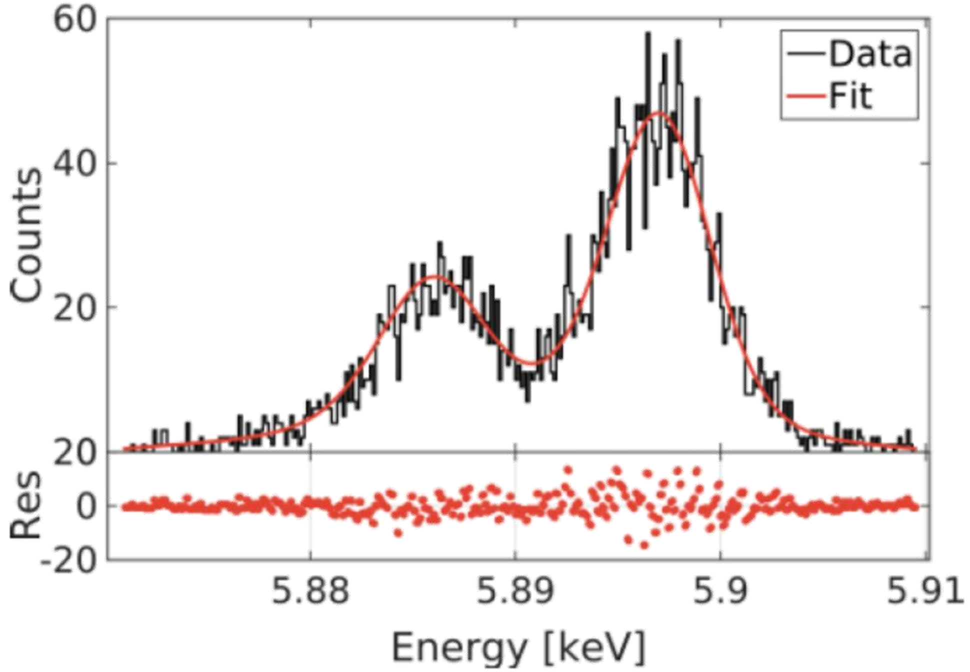
  130 MBq available for tests and experiments

- **Detector arrays - characterization:**

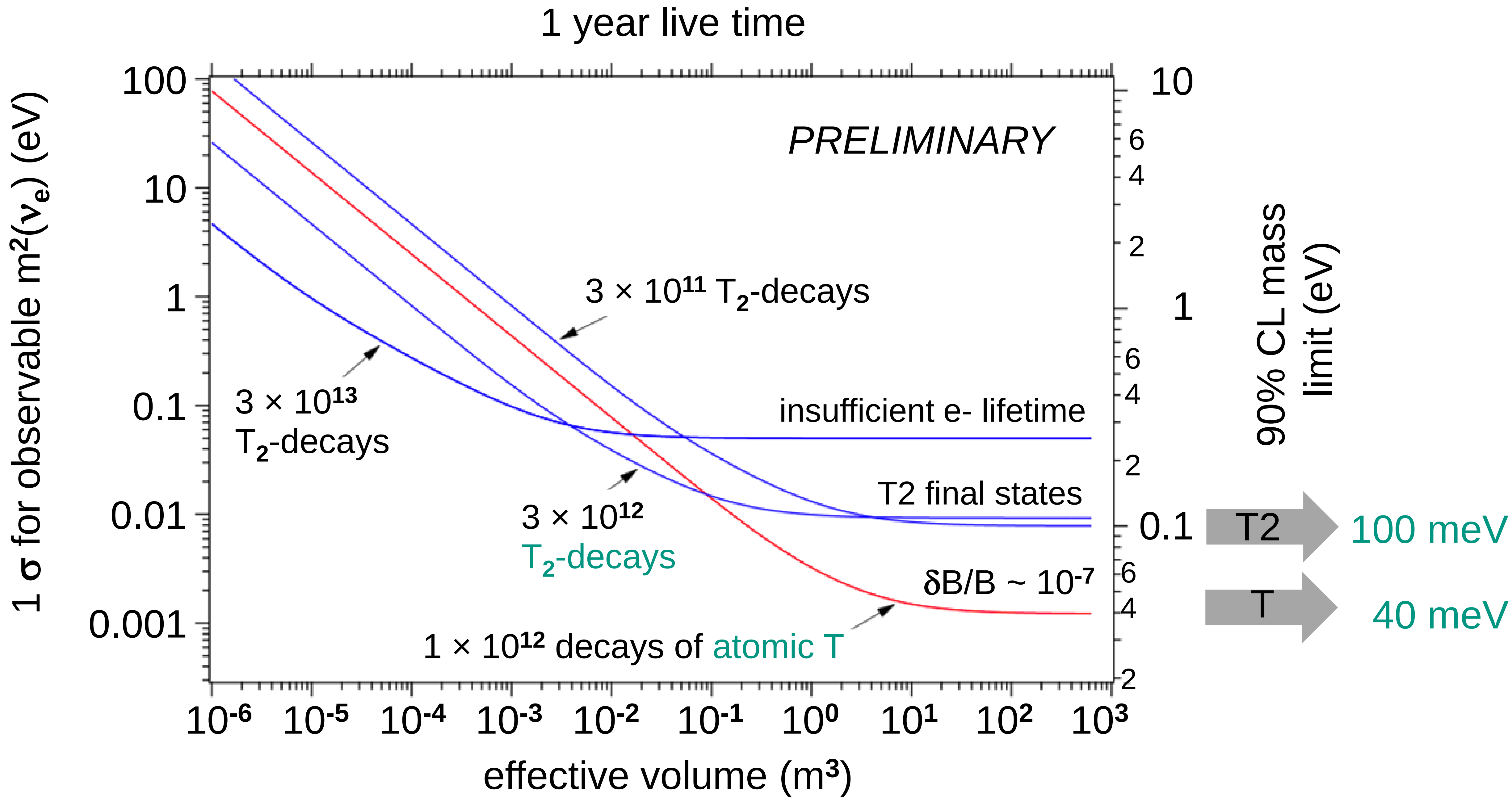
  - very good single pixel performance
  - $\Delta E_{\mathbf{FWHM}} = (4.9 \pm 0.1)$ eV
  - operating microwave SQUID multiplexing
  - upcoming: loading of TES arrays with Ho-163

- **timeline**

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



estimated sensitivities (statistics only)

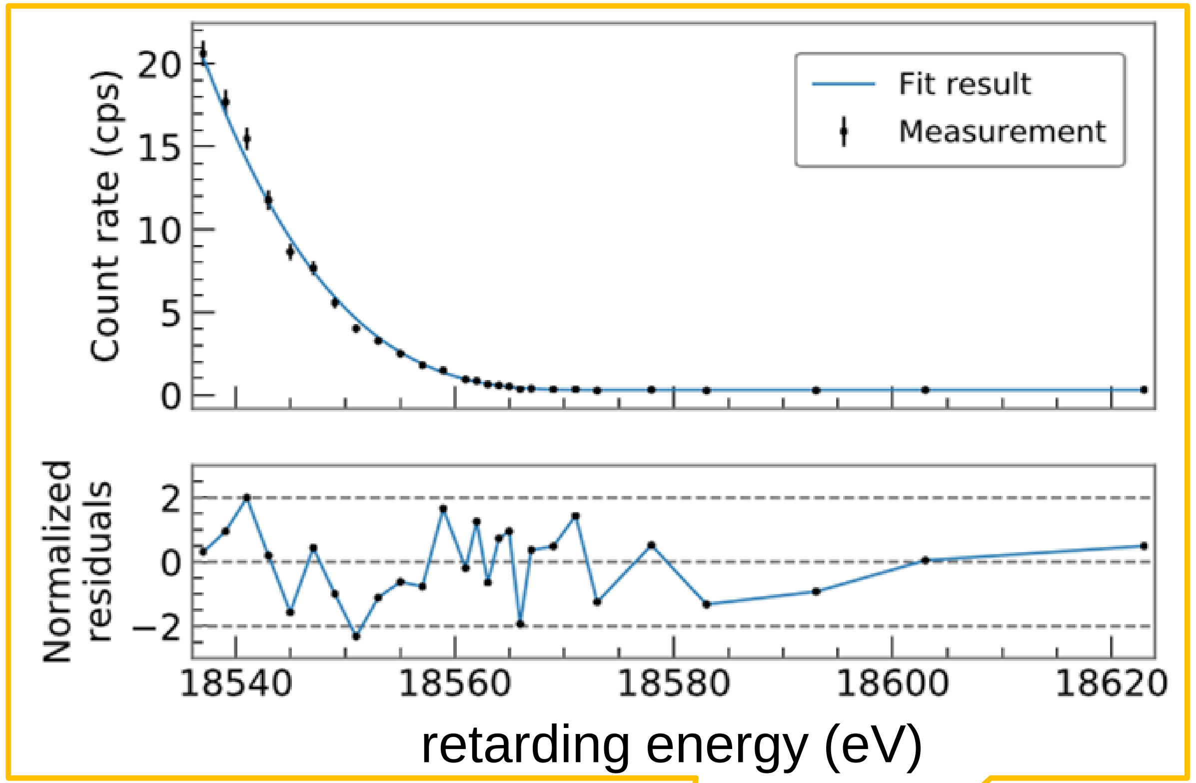


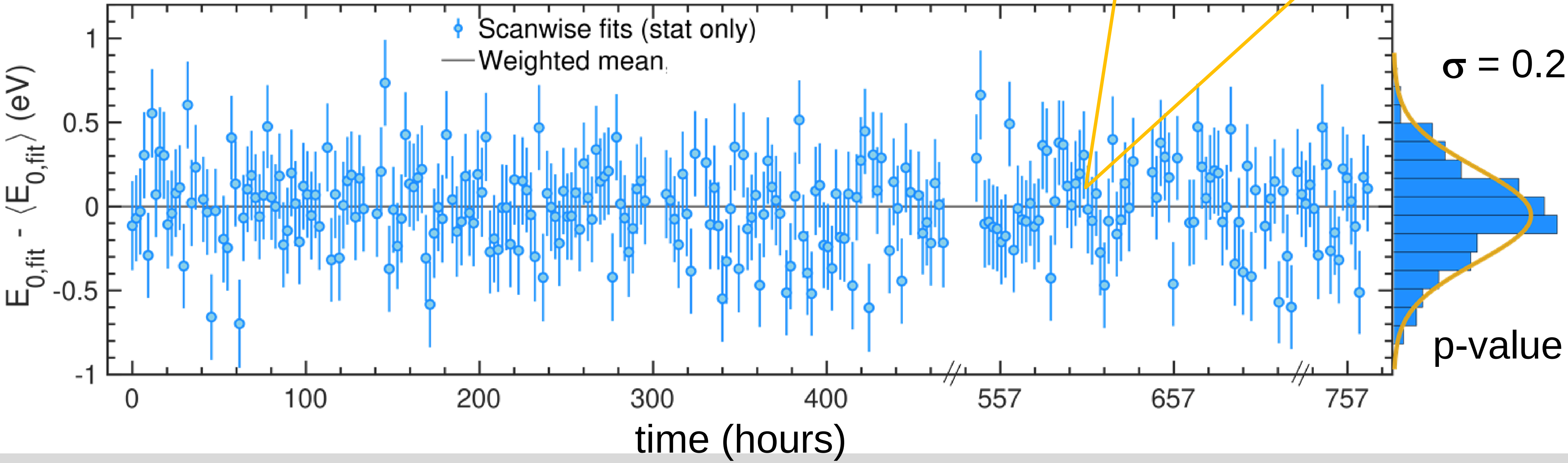
adopted from P8 Collab.

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





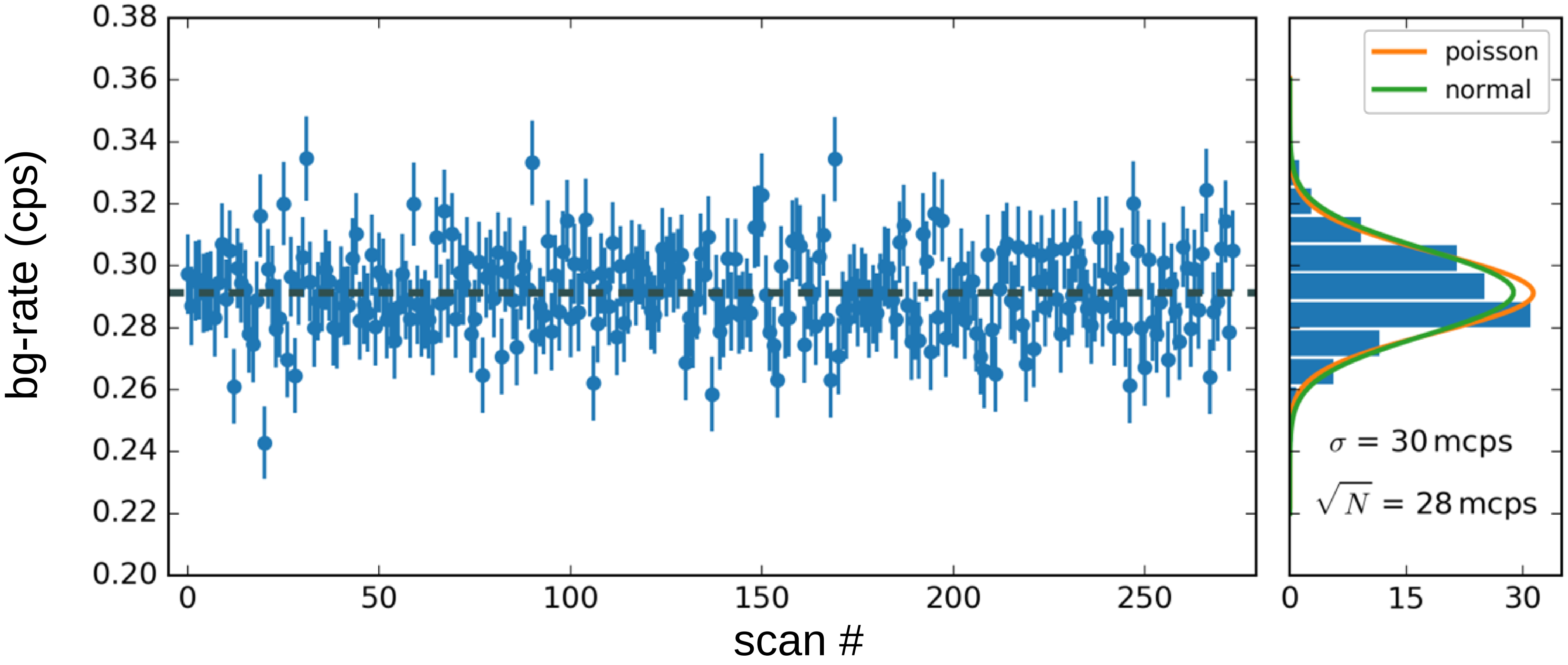
σ = 0.254 eV

p-value = 0.51

systematics: background

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

  - ~50%: ionisation of Rydberg states due to BBR ⇨ purely Poisson component
  - ~50%: α-decays of ^{219}Rn atoms from NEG pump ⇨ with small non-Poisson part



neutrino mass upper limit

- **calculation of confidence belts**

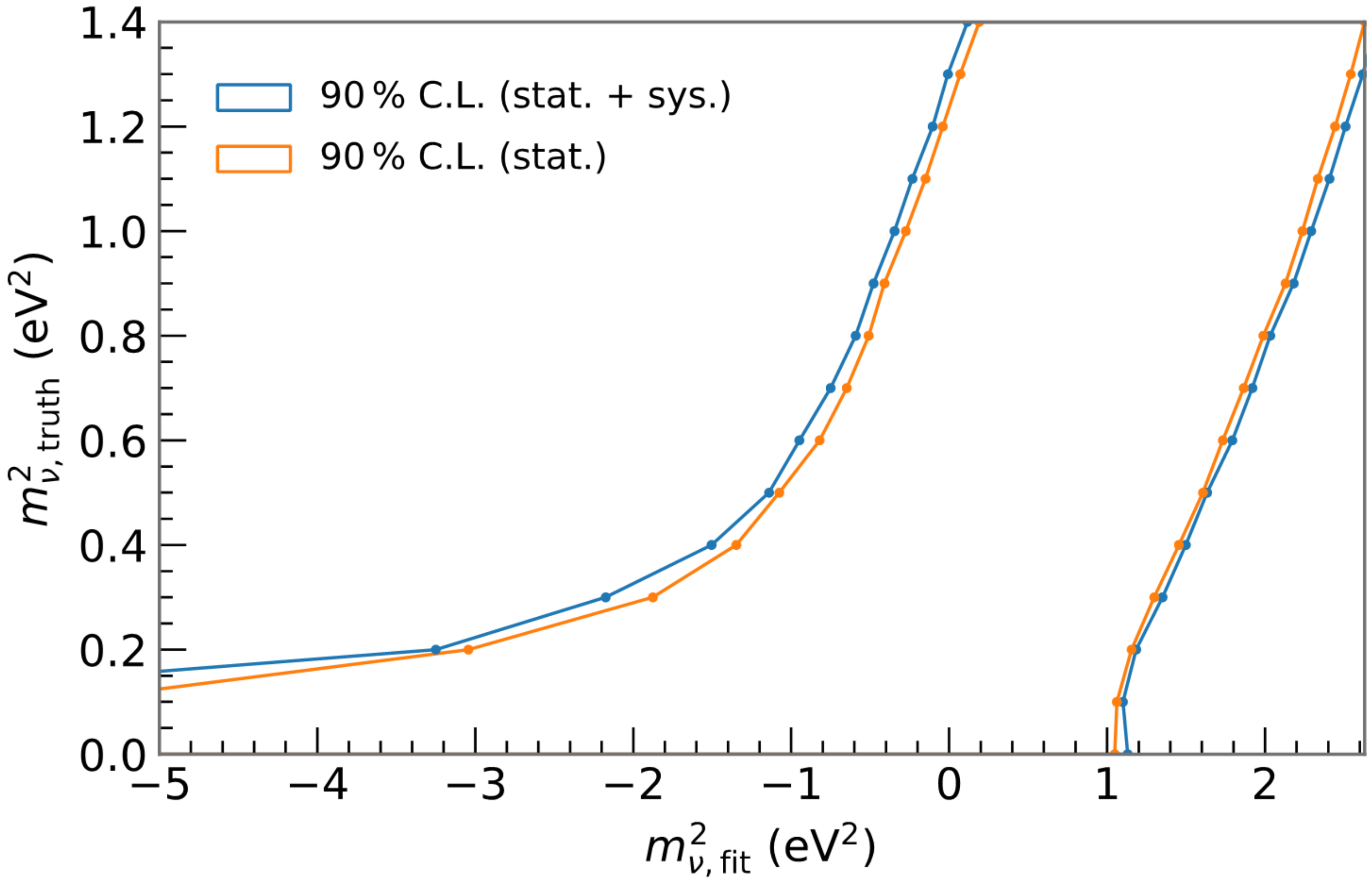
  - procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC): no empty confidence intervals for fluctuations into region $m^2(\nu_e) < 0$

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

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

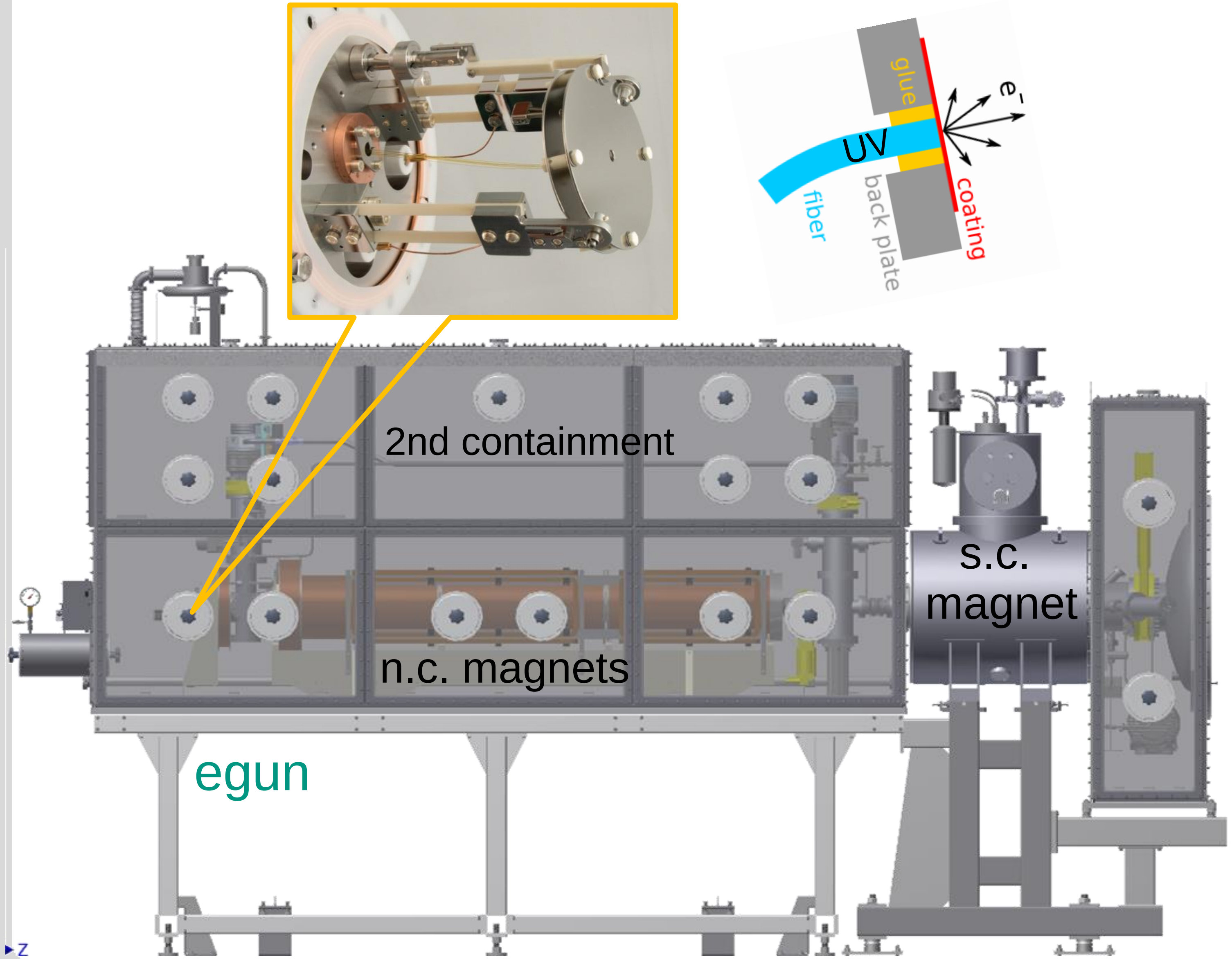
  - KATRIN upper limit on neutrino mass (FC)

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

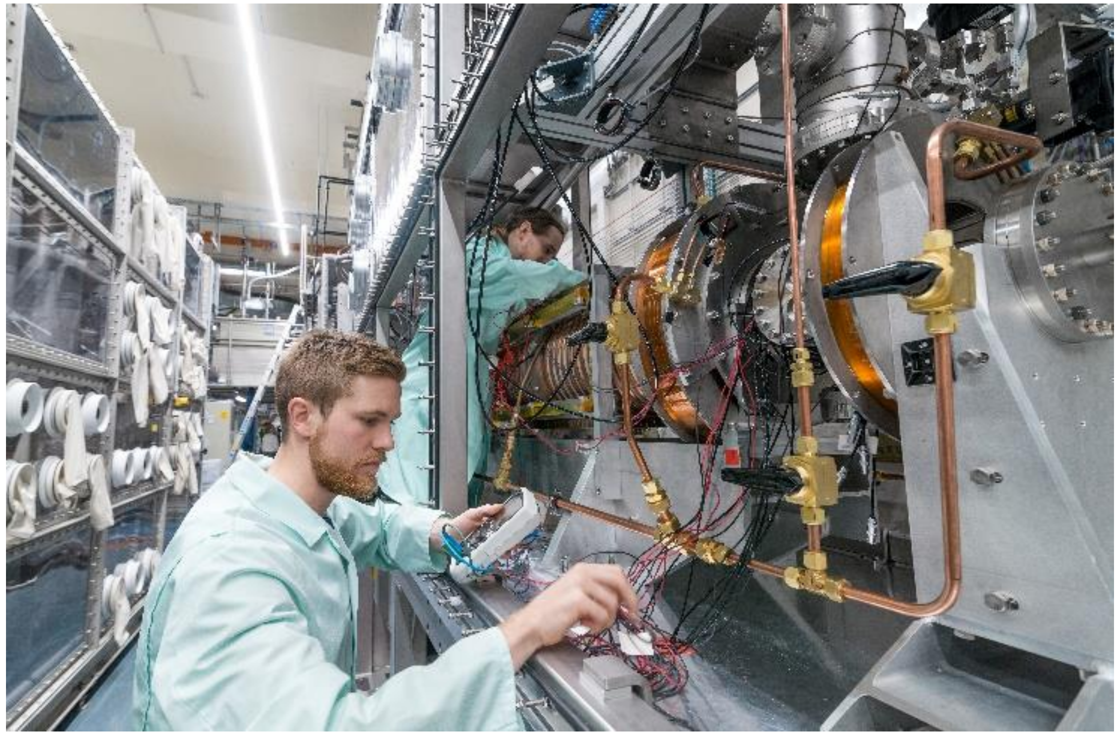


electron gun to measure electron energy losses

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



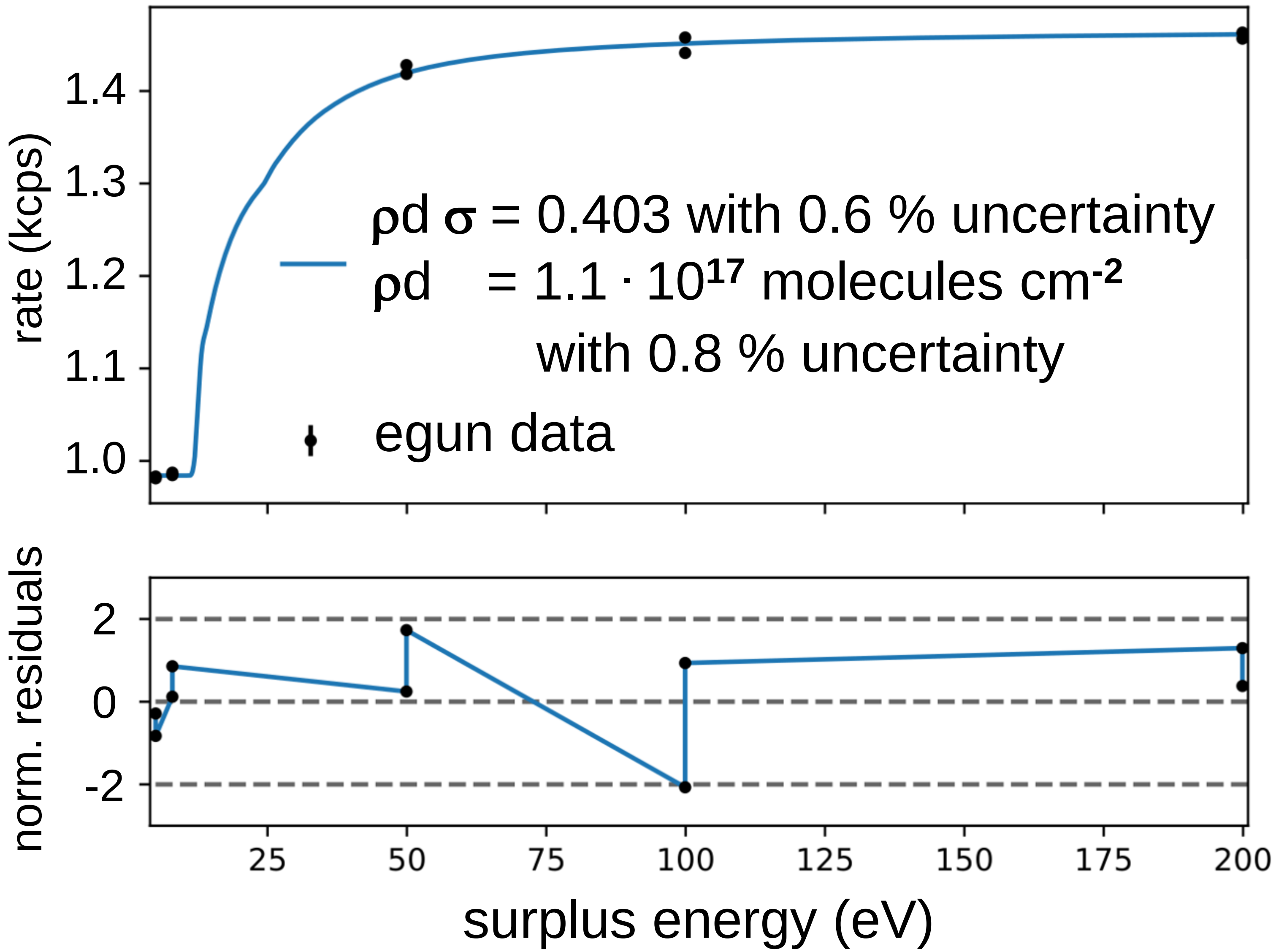
- well-defined pitch angle $\Delta\theta$
- narrow energy spread ΔE
- excellent stability at high rates

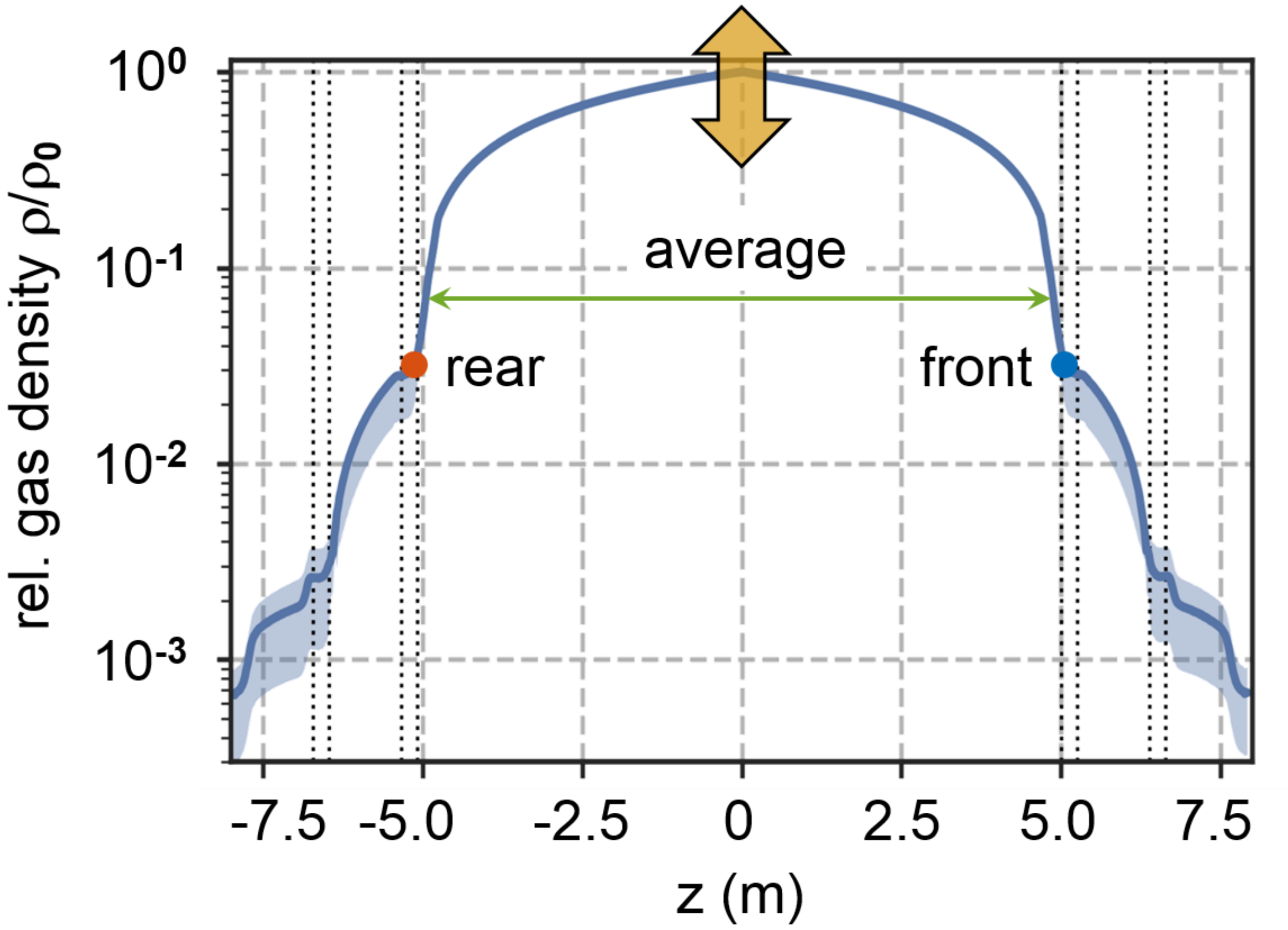


egun during commissioning phase

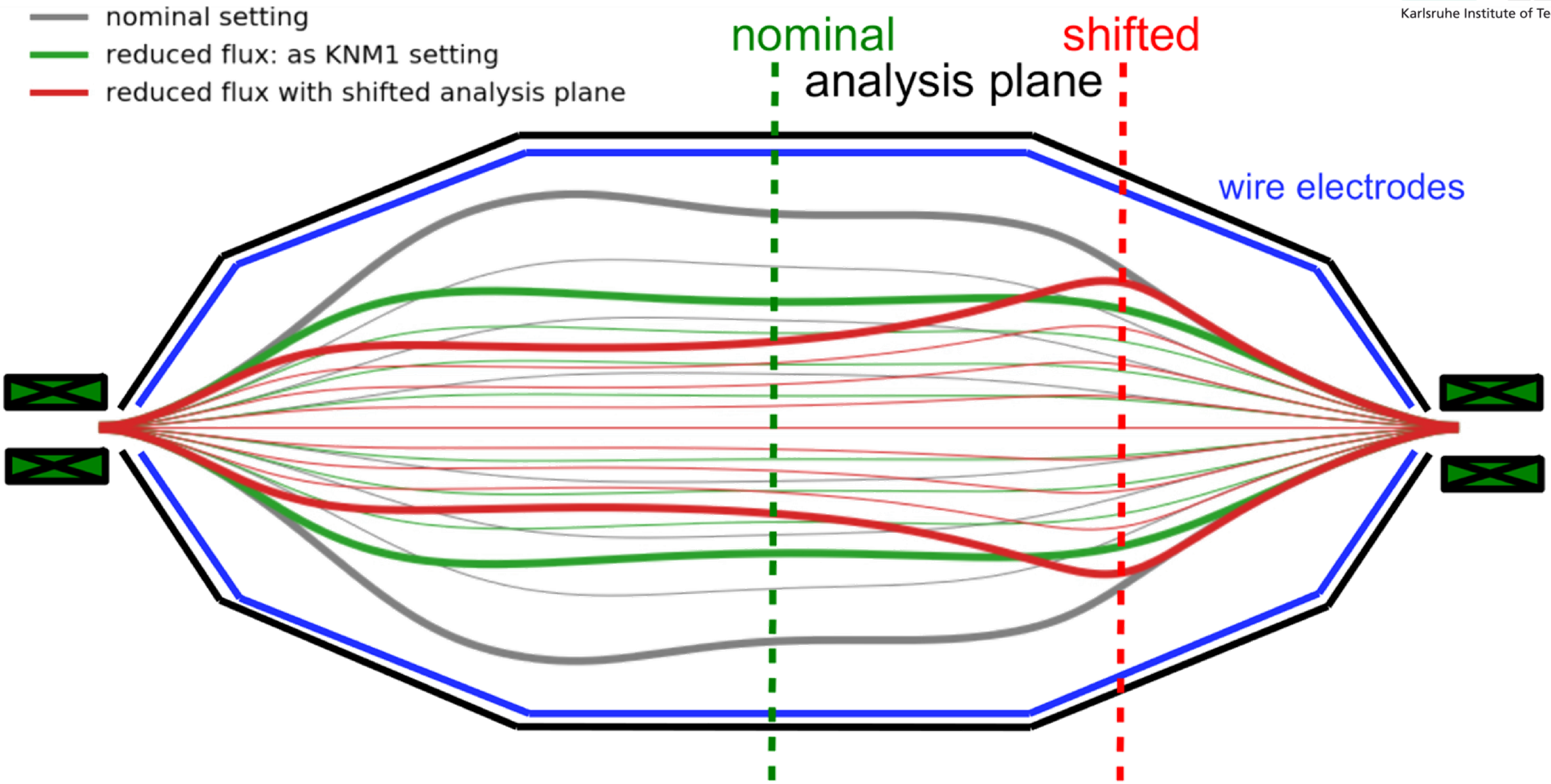
systematics due to column density

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





Concept of shifted analysis plane



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 ($f_{pu} \sim a \cdot \tau_r$)

    $f_{pu} < 10^{-6}$

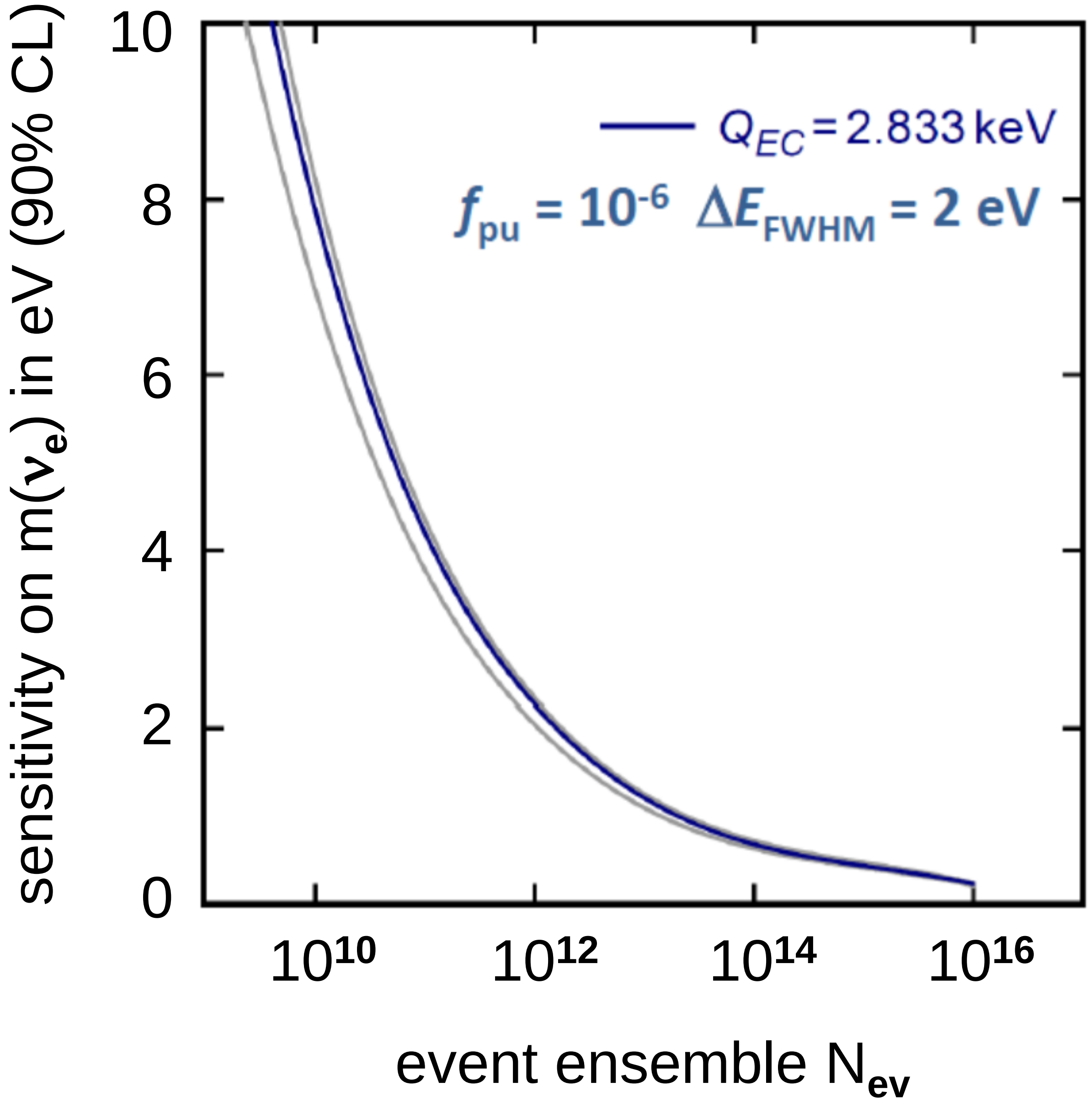
    for $\tau_r < 1\ \mu s$ ⇨ limit pixel a ~ 10 Bq

  - 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