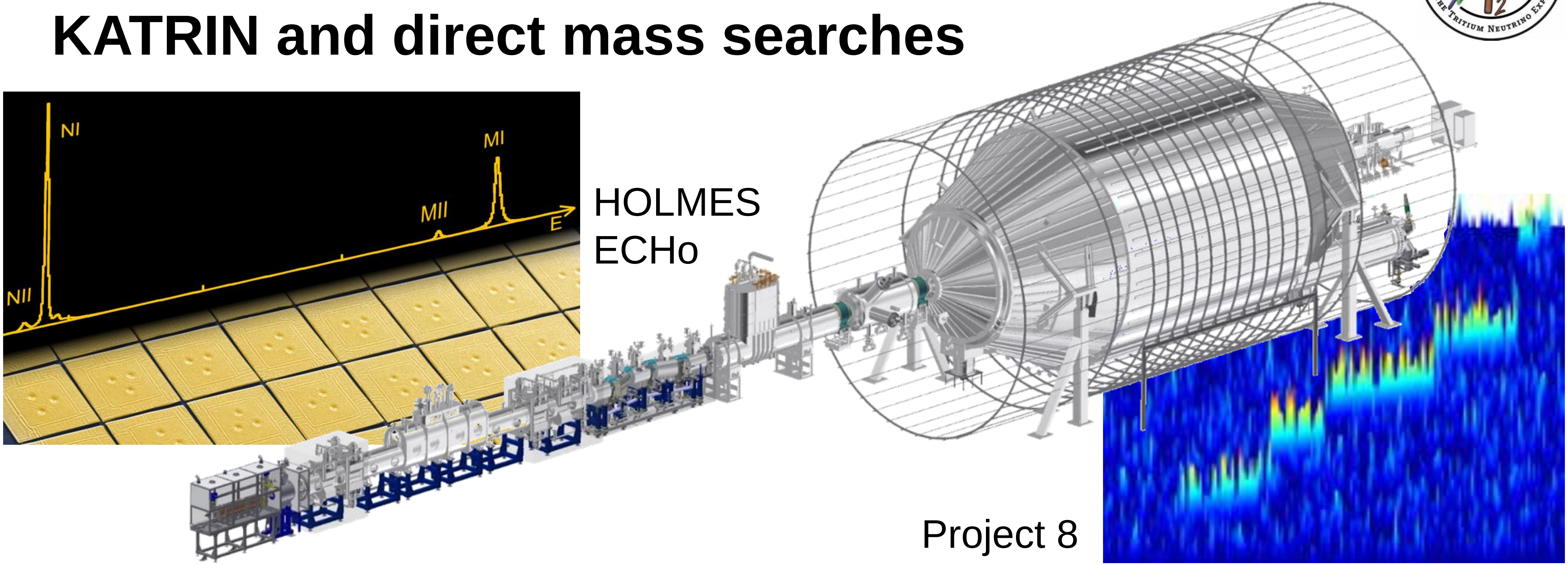
KATRIN and direct mass searches

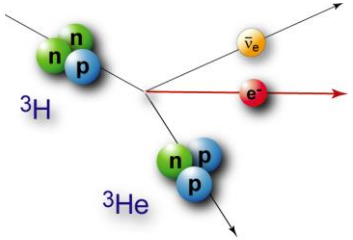


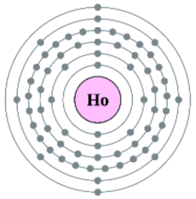
assessing the neutrino mass scale: an overview

three complementary approaches: laboratory-based & cosmology

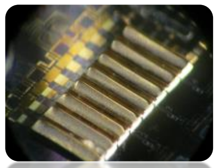
kinematics of weak decays

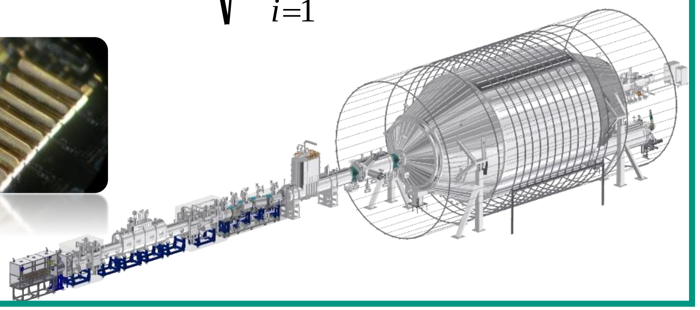
- ß-decay: ^{3}H, EC: ^{163}Ho
- **model-independent**





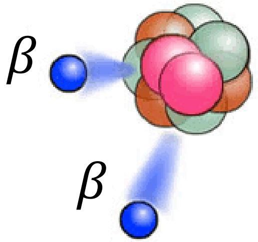
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}\right|^2 \cdot m_i^2}$$



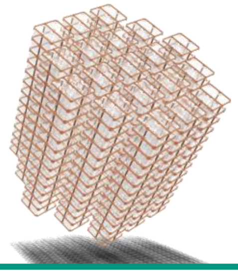


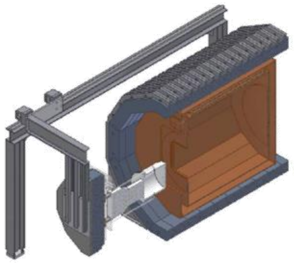
search for 0νßß-decay

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



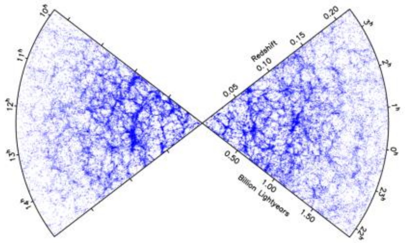
$$\langle m_{ßß} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$

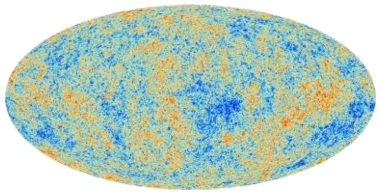




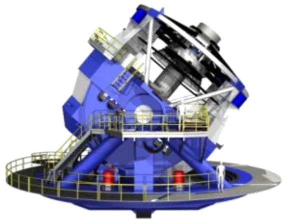
large-scale structures

- CMB, galaxy surveys,…
- **model-dependent** (H_0)





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



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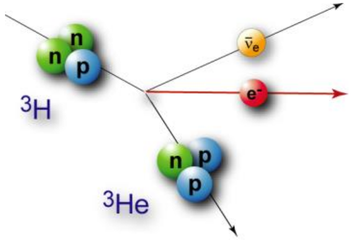
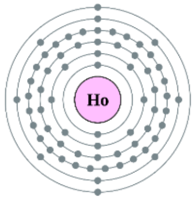
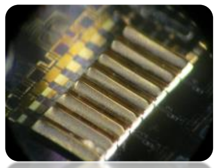
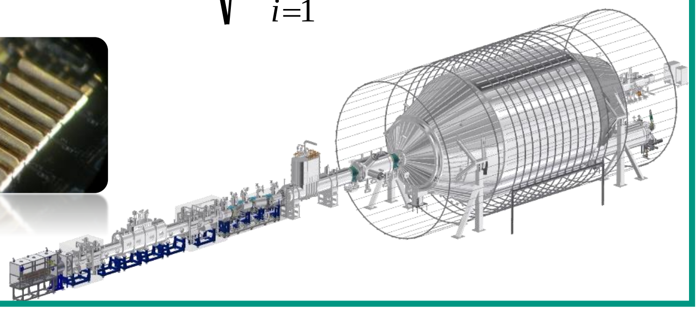




$$m(\nu_e)=\sqrt{\sum_{i=1}^{3}\left|U_{ei}\right|^2\cdot m_i^2}$$





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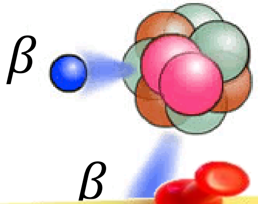
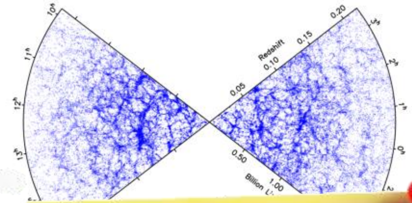


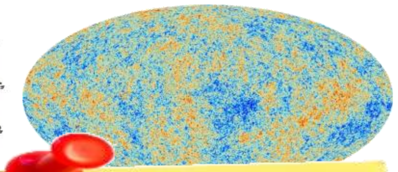
Andrea Giuliani

Majorana neutrinos and rare decays: Where are we going?

large-scale structures

- CMB, galaxy surveys,…
- **model-dependent** (H_0)





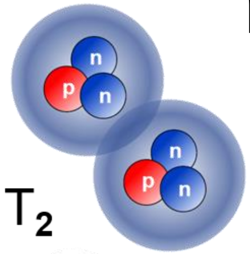
Massimiliano Lattanzi

Cosmology and Neutrino Properties

assessing the neutrino mass scale

- **model independent approaches: sources**

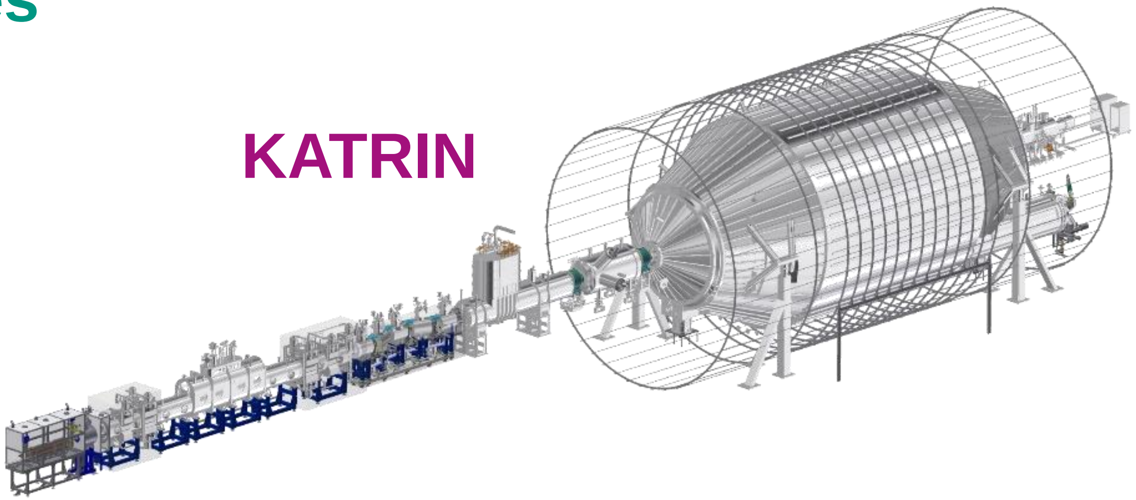
future:
combination of all source technologies required!



T_2

molecular tritium

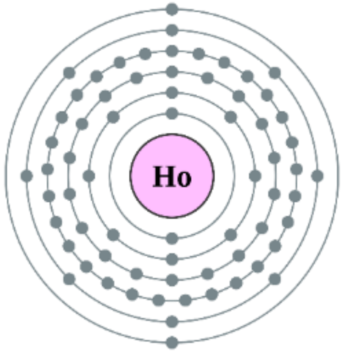
KATRIN



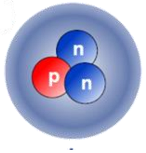
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}\right|^2 \cdot m_i^2}$$

incoherent sum

HOLMES
ECHo



Project8
Ptolemy



T

atomic tritium

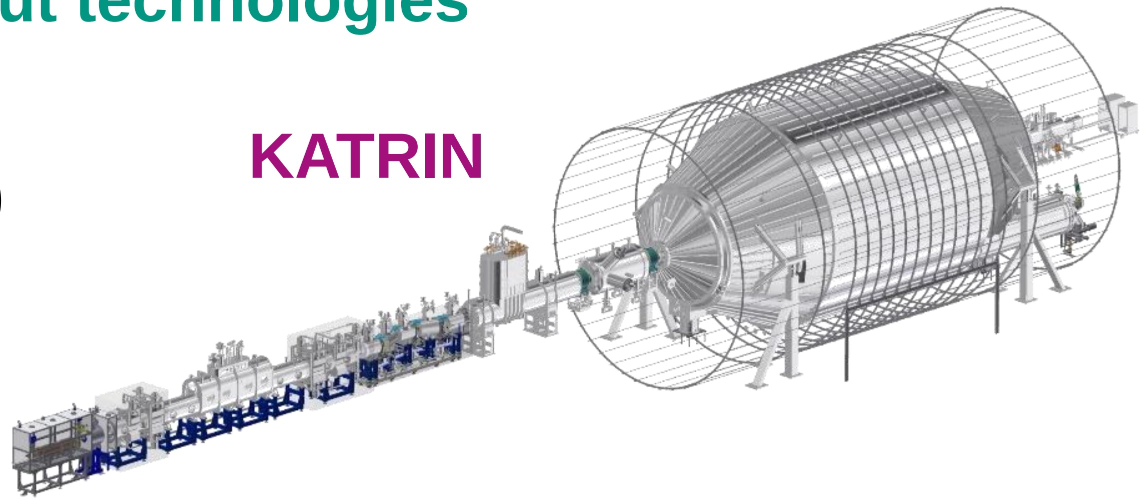
EC of Ho-163

assessing the neutrino mass scale

- model independent approaches: read-out technologies

electrostatic Filter (MAC-E)

KATRIN



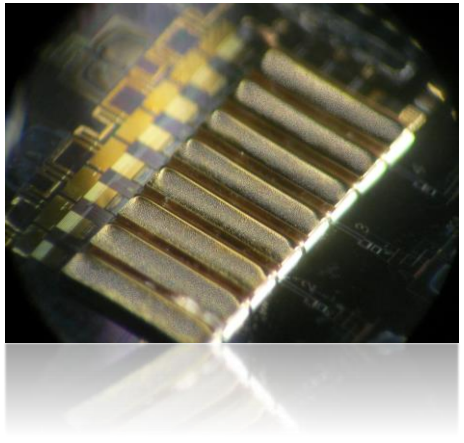
future:
combination of all read-out technologies required!

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

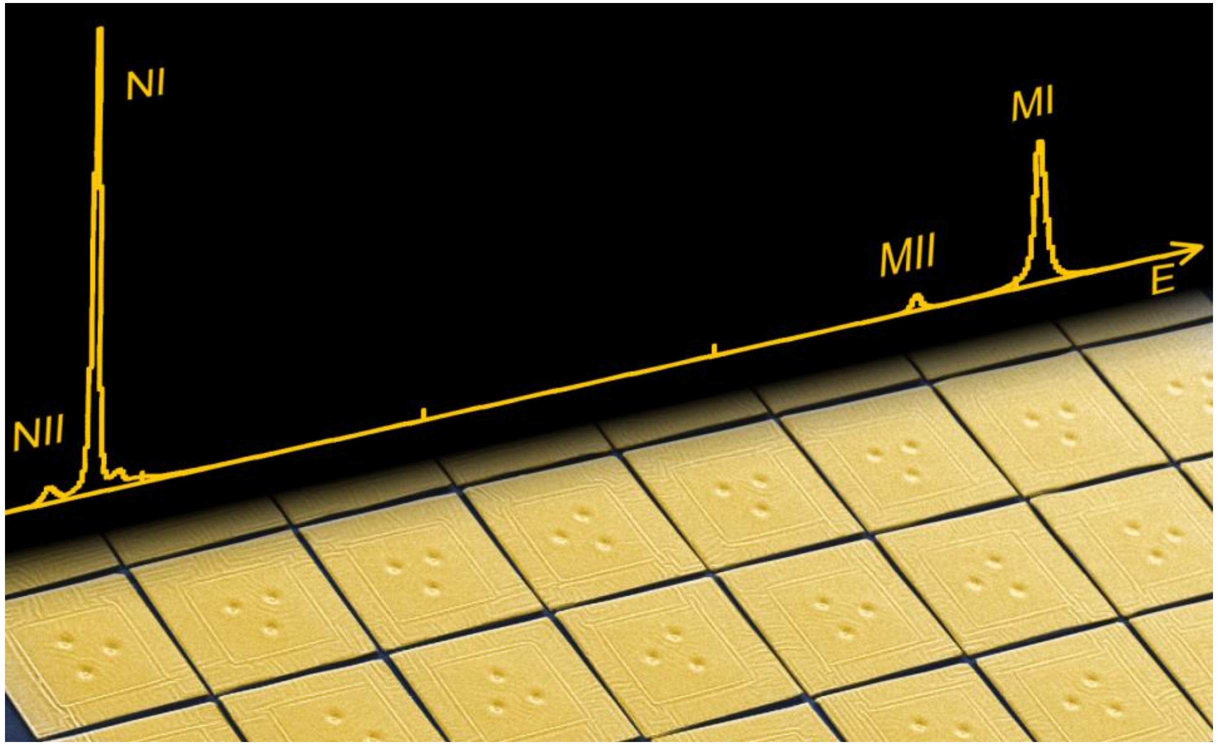
Project8

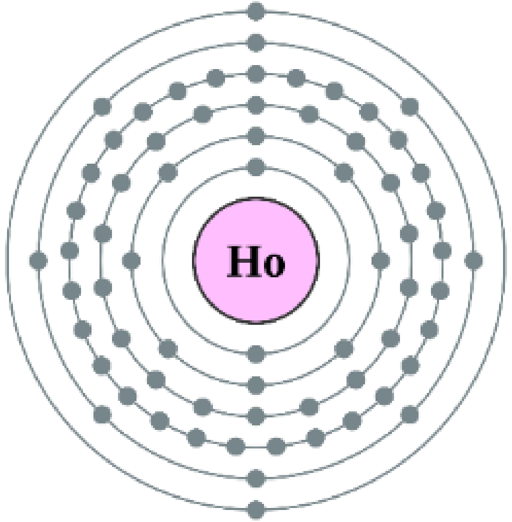
cyclotron radiation

HOLMES
ECHo
Ptolemy



phonons





HOLMES

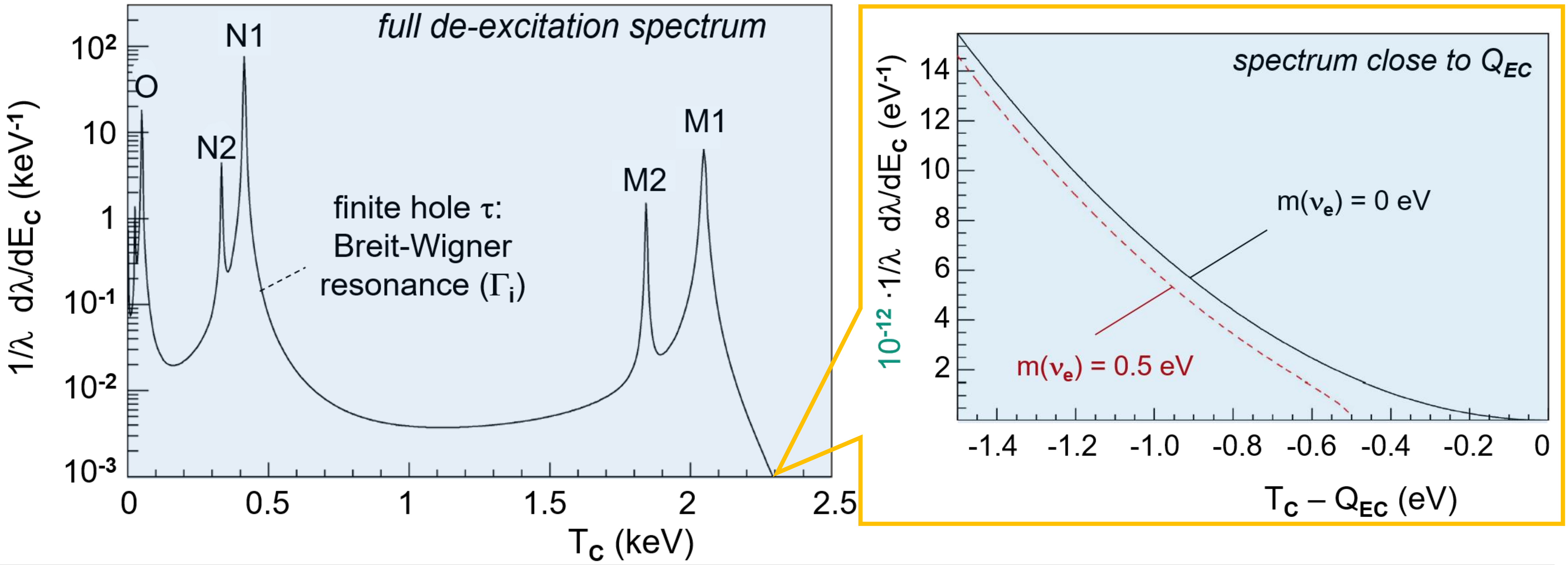
ECHo

EC ON HOLMIUM-163: ECHo, HOLMES

ν-mass from electron capture

- **EC-process of ^{163}Ho :** $^{163}Ho + e^- \rightarrow \nu_e + {}^{163}Dy^*$ (no K, L shell capture due to Q_{EC})

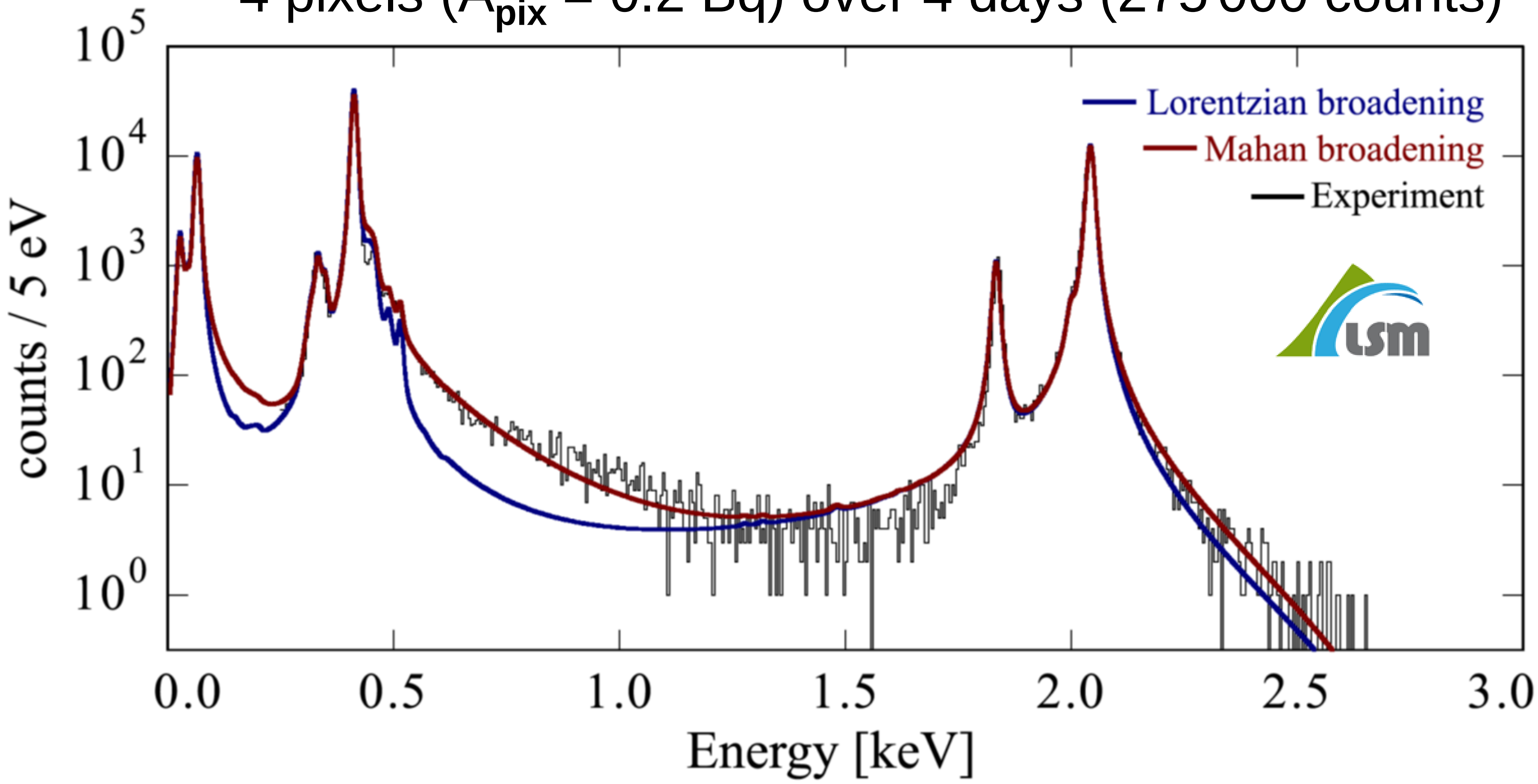
$$t_{1/2} = 4570\ a \qquad Q_{EC} = 2.8\ keV$$



ν-mass from EC: calorimetric approach

- **Quantum sensors (MMC, TES) to measure atomic de-excitation of ^{163}Dy***

  - 4 pixels (A_{pix} = 0.2 Bq) over 4 days (275 000 counts)



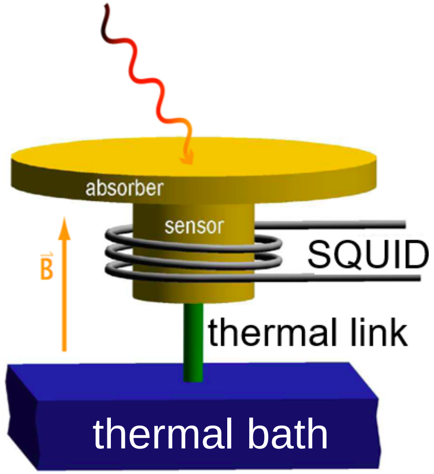
Q_{EC} = (2838 ± 14) eV

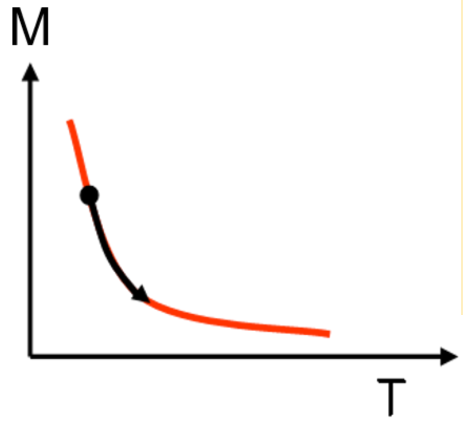
$m(\nu_e)$ < 150 eV (95% C.L.)

ν-mass from EC: calorimetric approach

- **Quantum sensors (MMC, TES) to measure atomic de-excitation of ^{163}Dy***

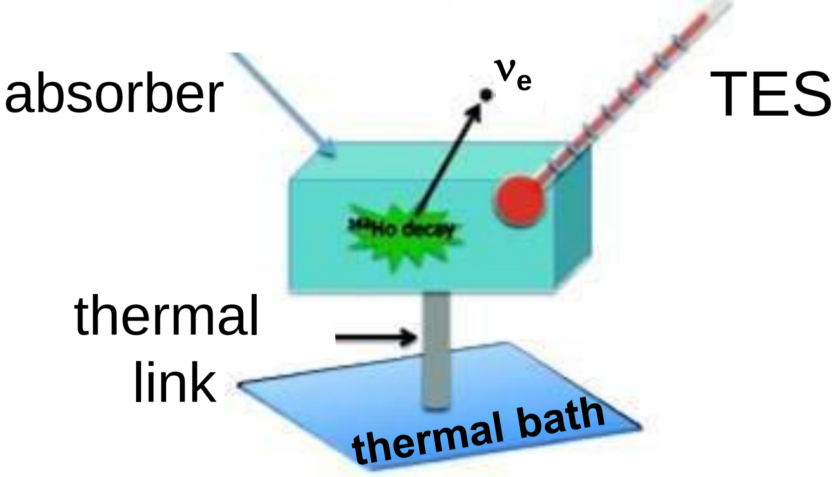
Metallic **M**agnetic **C**alorimeter





δT in absorber after EC-process

Transition **E**dge **S**ensor



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

⇨ change in temp. δT of TES thermistor

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

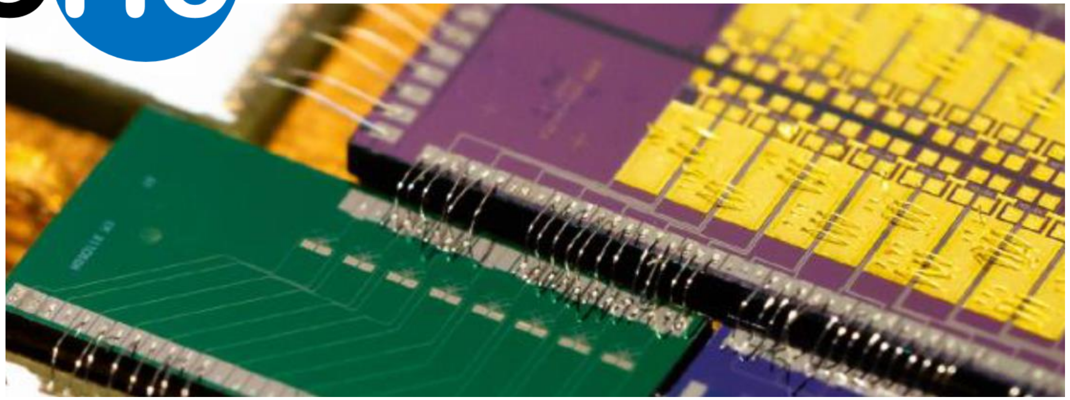
signal: $$\Delta T = \frac{\delta E}{V\cdot C_V}$$

ν-mass from EC: calorimetric approach

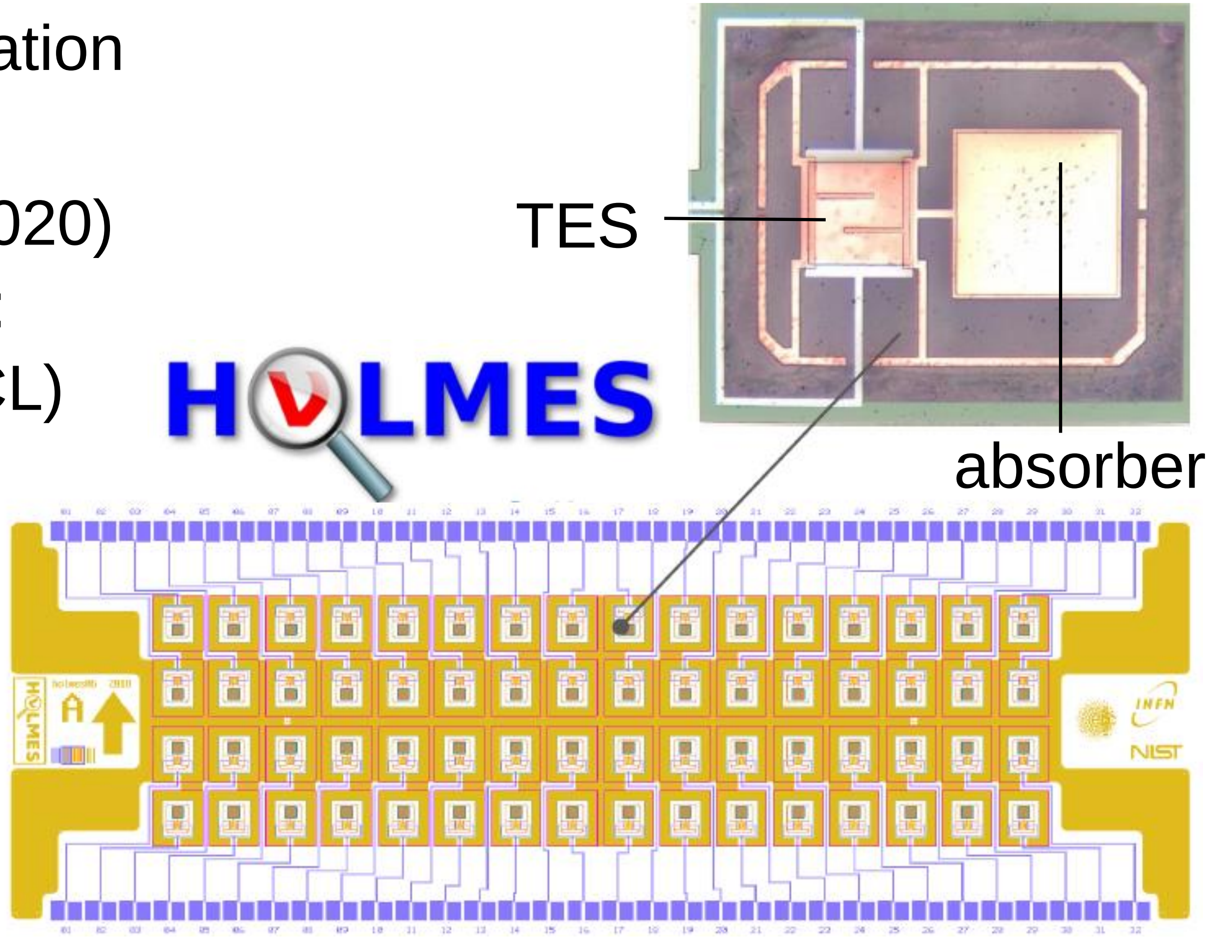
- **Quantum sensors: large arrays with read-out via muliplexing**

  - enclosing ^{163}Ho source via ion implantation
    Mainz university / Genoa university
  - 60 MMC pixels with ~ 1 Bq of ^{163}Ho (2020)
    $>10^8$ EC events, achievable sensitivity:
    $m(\nu_e) < 20$ eV (95% CL)

ECHo



HOLMES

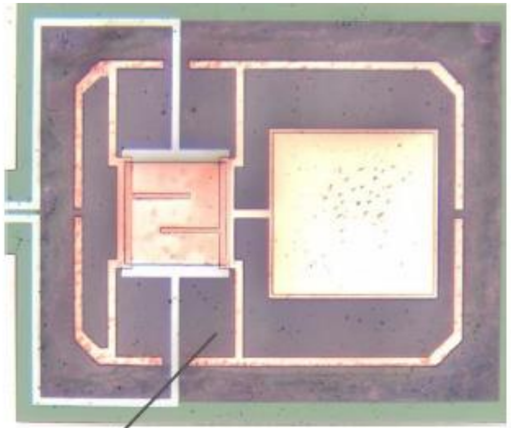


ν-mass from EC: calorimetric approach

Karlsruhe Institute of Technology

- **ongoing R&D: multiplexing & reliable operation of arrays ($10^3 \ldots 10^4$ pixels)**

  - ECHo & HOLMES:
    moving forward to reach sensitivity at eV-scale ☑
    ^{163}Ho source available in suitabale amounts / purity
  - theoretical description of ^{163}Ho shape & Q_{EC}:
    further work required



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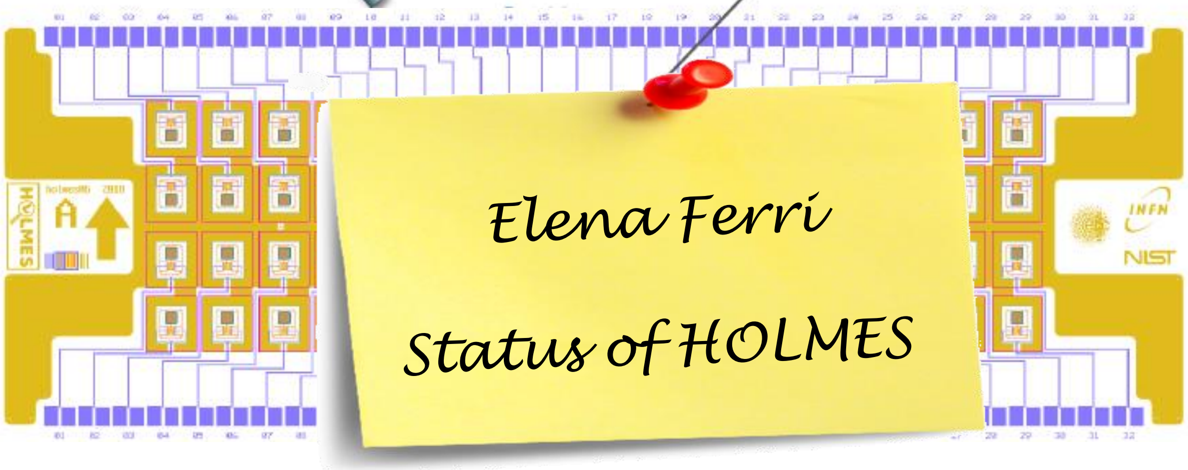
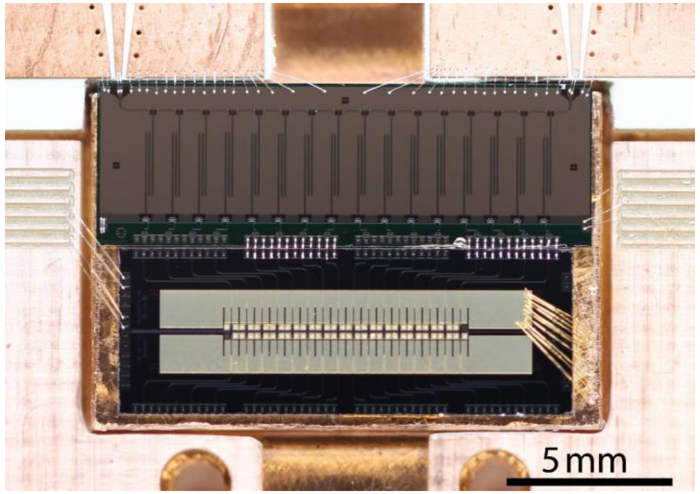
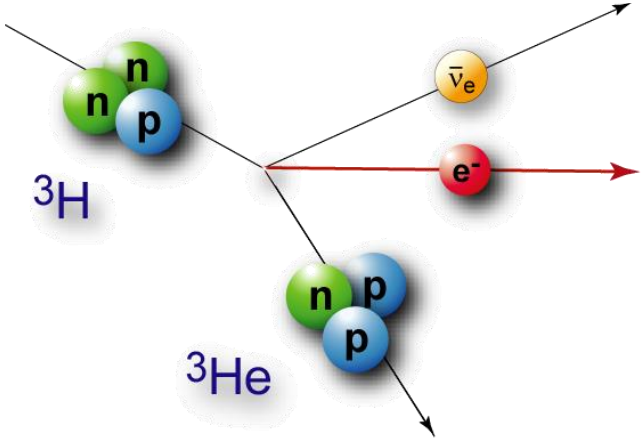


ECHo

-100 k:
12000 pixels
each 10 Bq
$m(\nu_e) < 2$eV





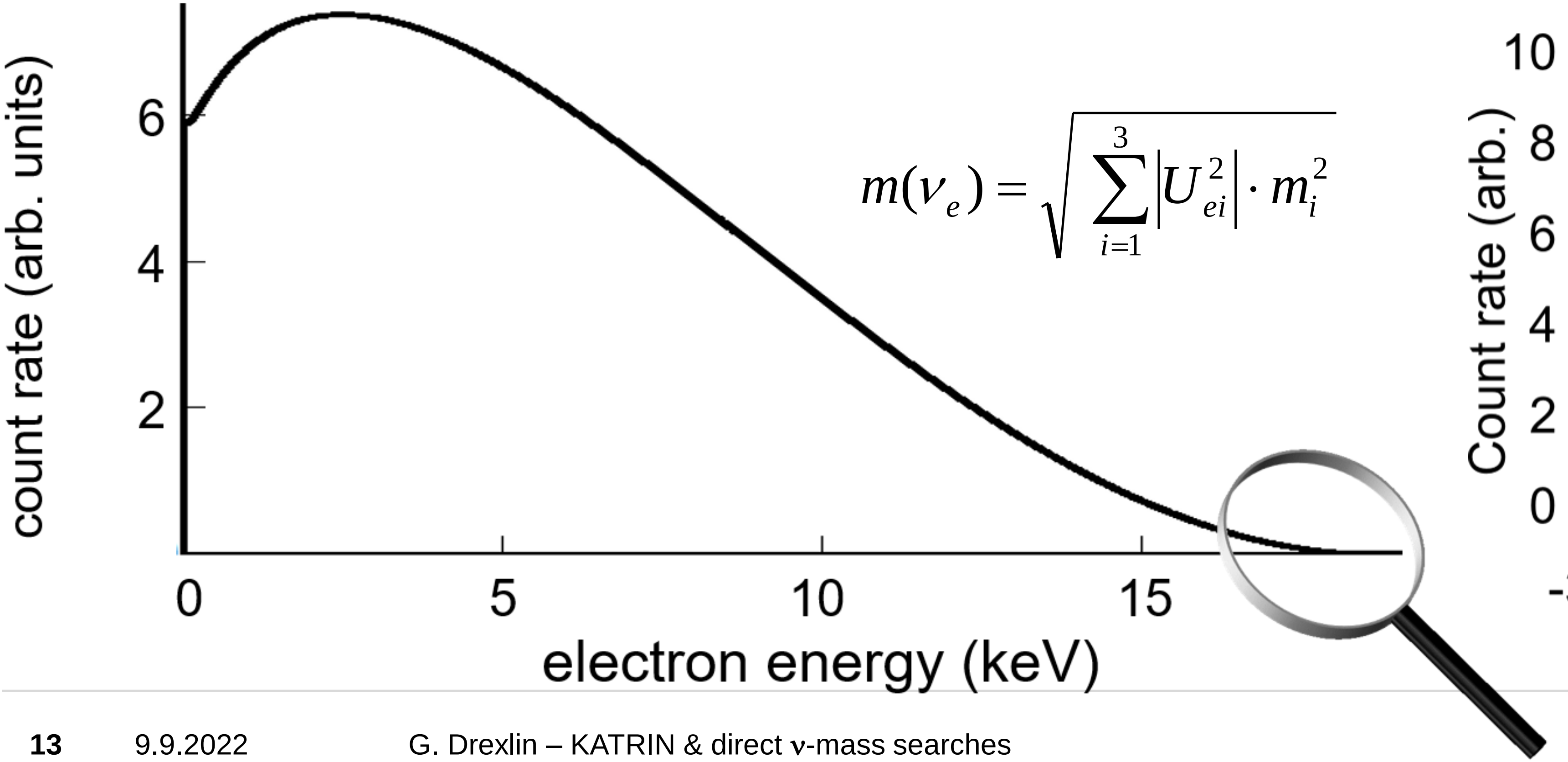
ß-DECAY OF TRITIUM: KATRIN, PROJECT 8

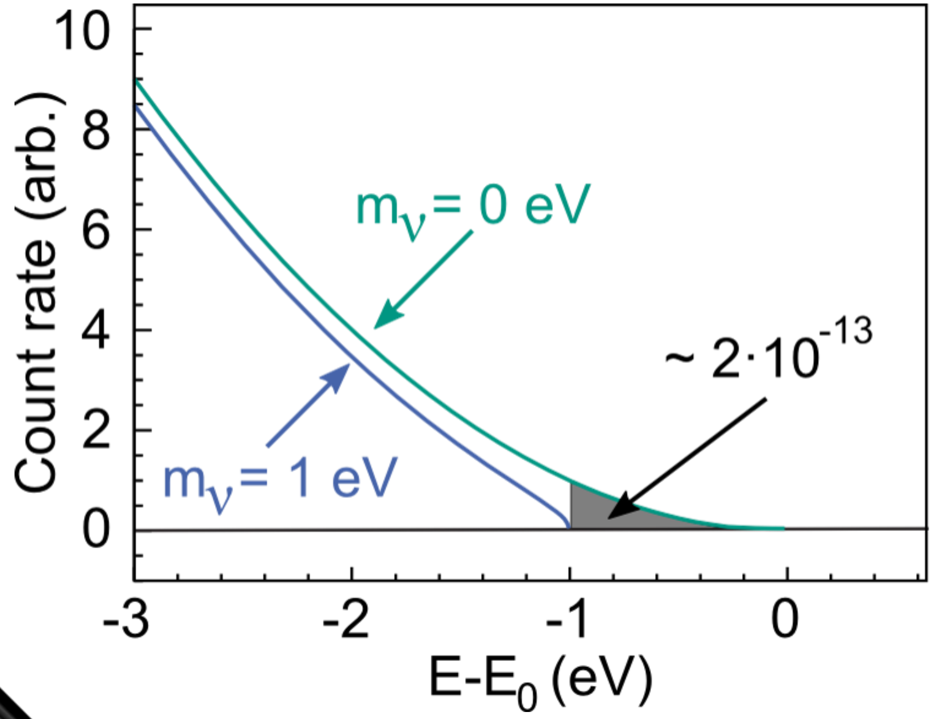
Tritium ß-decay: kinematics and ν-mass

- **Fermi´s Golden rule: kinematic parameters & energy conservation**

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

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





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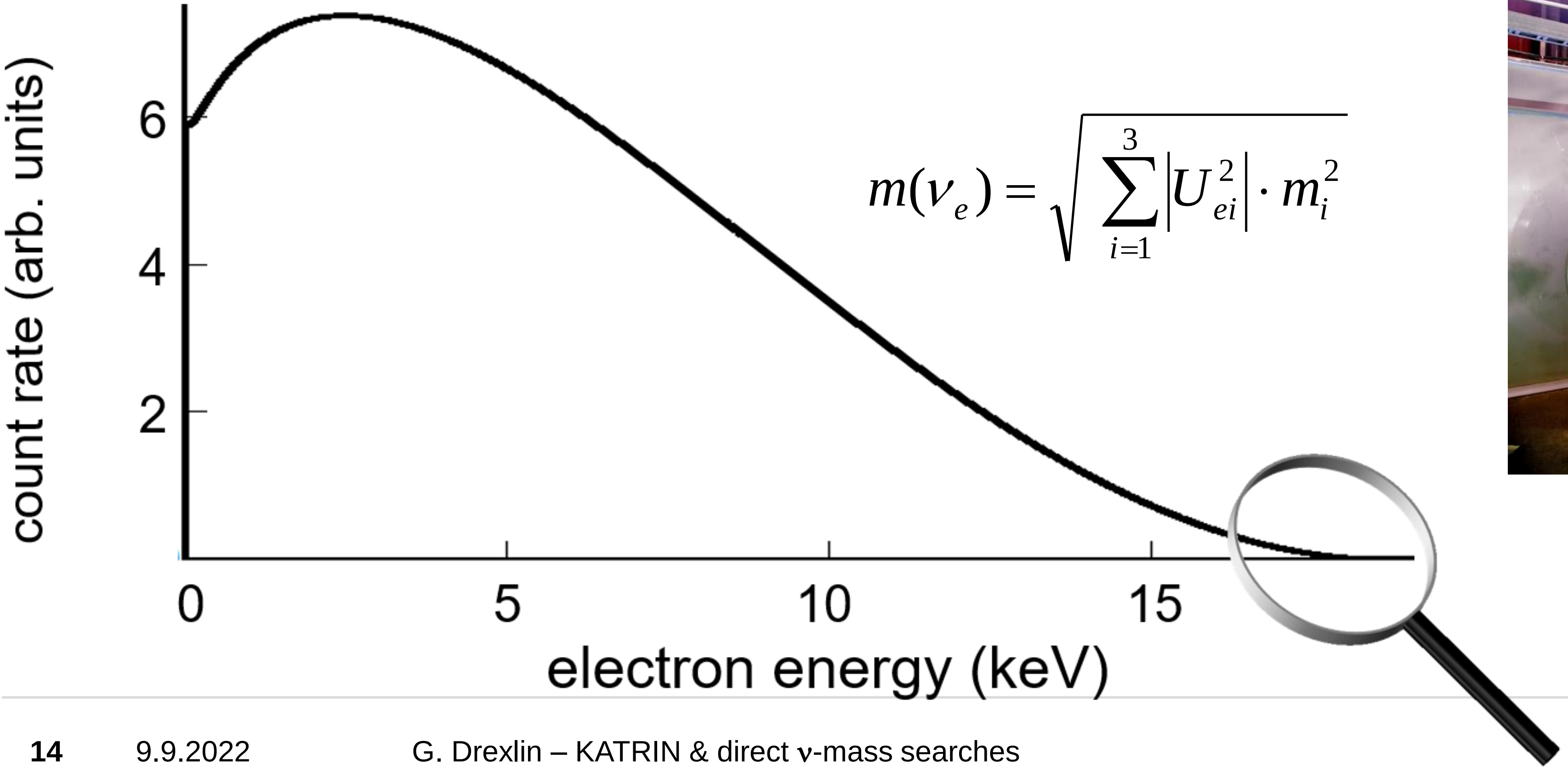


$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}^2| \cdot m_i^2}$$

Project 8: a new spectroscopic approach

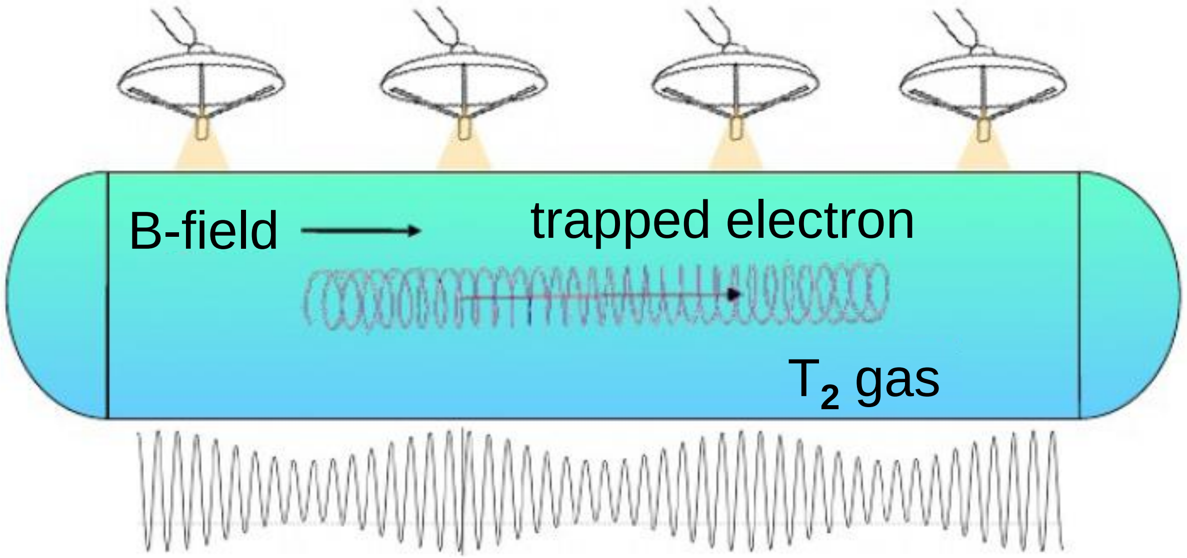
- **CRES: Cyclotron Radiation Emission Spectroscopy**
  - trapped electrons from tritium ß-decay in homogeneous, strong B-field
  - precise measurement of **frequency ω** yields electron kinetic energy $E_{e,kin}$

1 T

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

18.57 keV

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



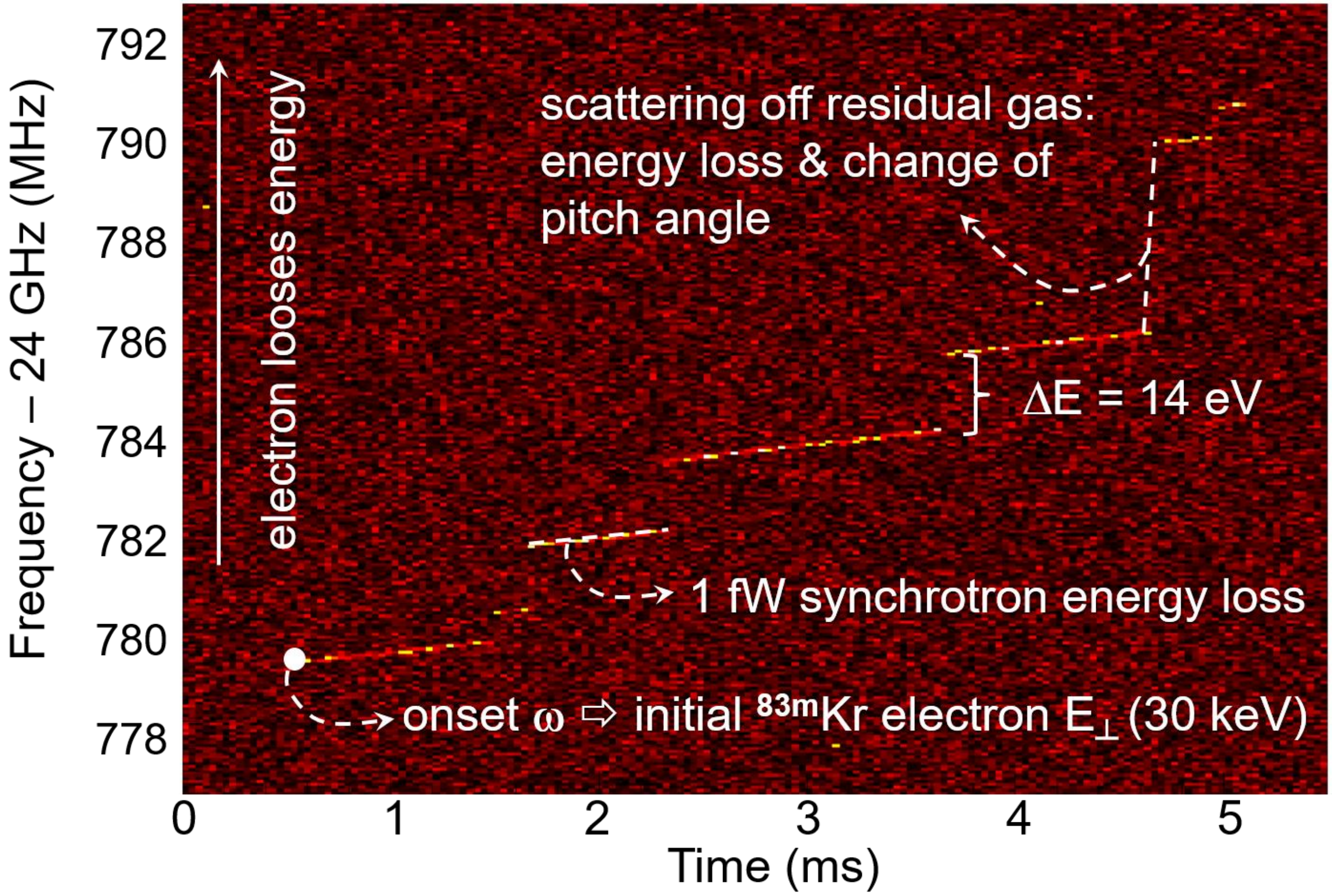
combined antenna signal

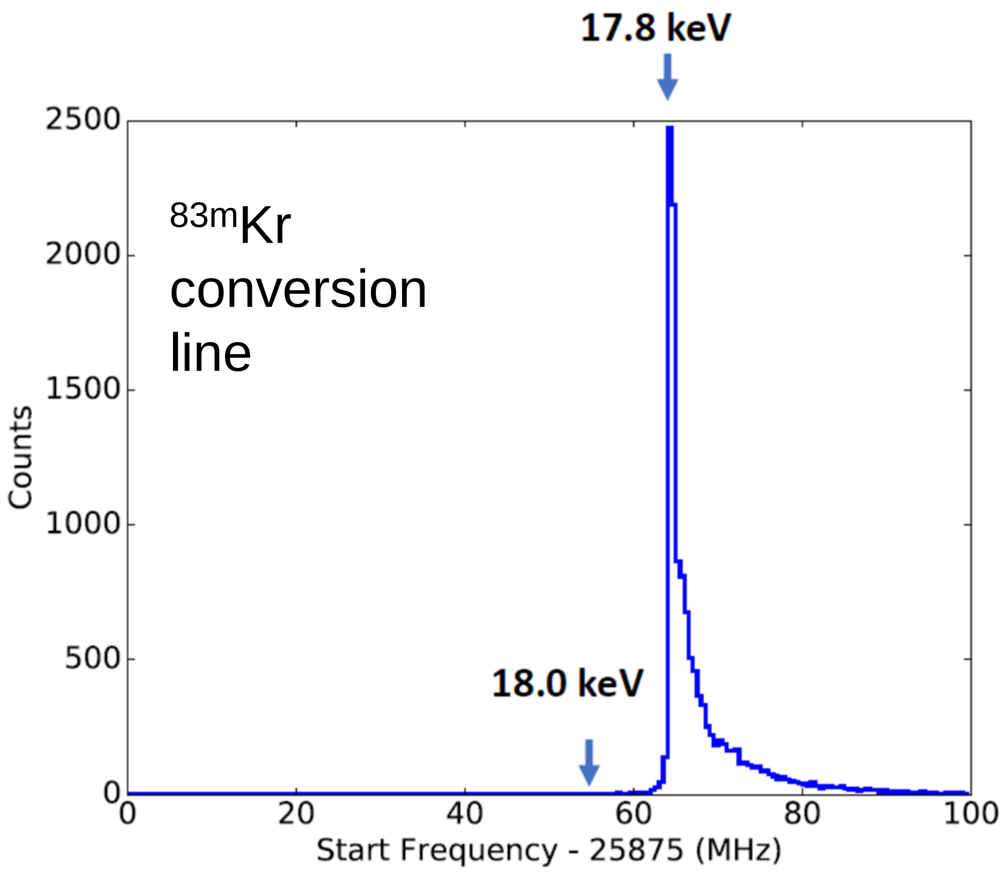
$\Delta\omega \sim 1 / t_s$
sampling time
$t_s \sim$ several µs
(magnetic bottle)

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

Project 8: proof-of-principle

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

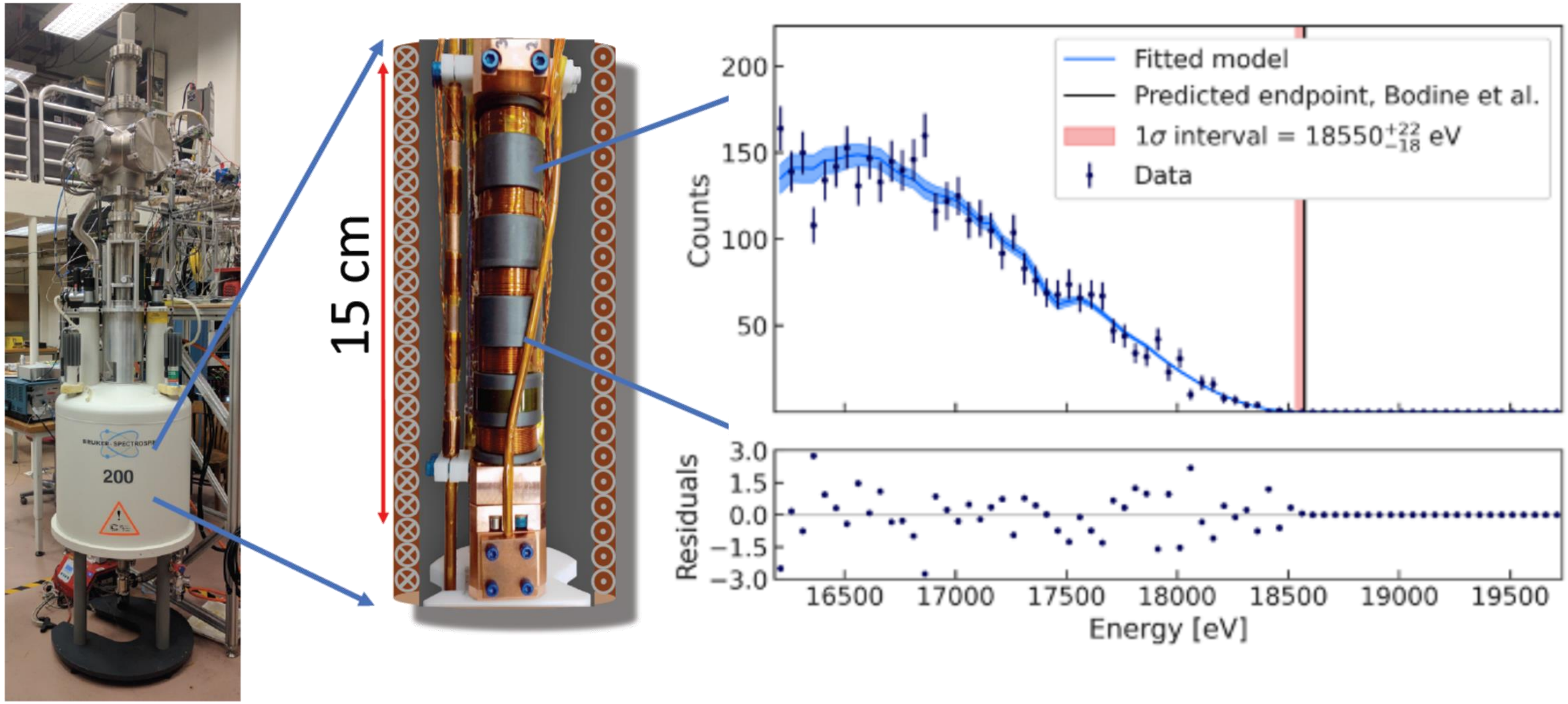




Project 8: a first spectrum & ν-mass limit

- **Phase-II result: 3 months of data taking – 3770 events observed**

  – a 1 mm³ volume yields the first CRES endpoint measurement: no bg-events!



- endpoint energy (frequentist):

$$E_0 = 18550^{+22}_{-18} \text{ eV}$$

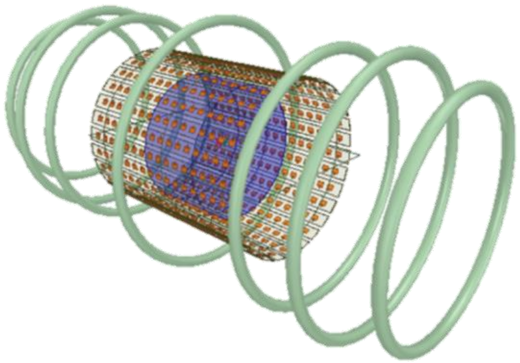
- mass limit (frequentist):

m(ν) < 178 eV (90% CL)

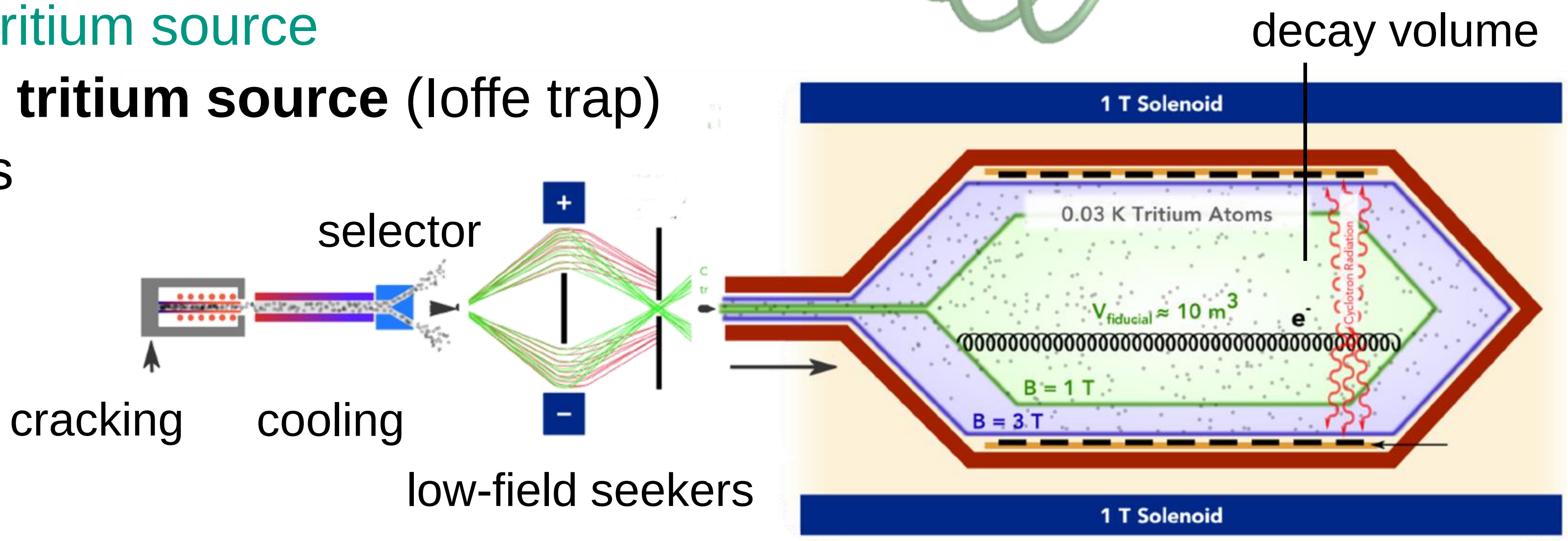
Project 8: near & long-term future

- **towards a large volume demonstrator & an atomic tritium source**

  – a large-volume demonstrator
  based on multi-antenna array
  tritium data „competitive with m(ν_e) ~ 2 eV“



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



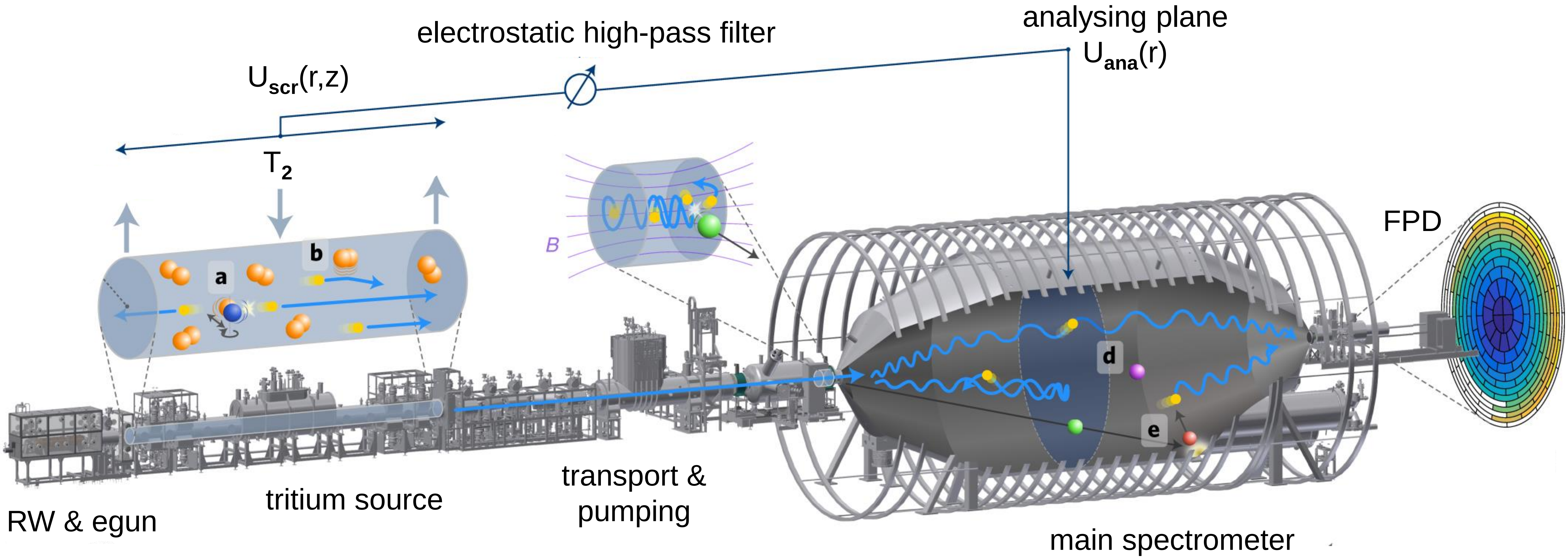
KATRIN Collaboration

- international team of ~ 150 members from 8 countries

Karlsruhe Institute of Technology
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
The Czech Academy of Sciences
POLITECNICO MILANO 1863
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
Massachusetts Institute of Technology
UNIVERSITY OF WASHINGTON
cea
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
UNIVERSIDAD COMPLUTENSE MADRID
CARNEGIE MELLON UNIVERSITY PITTSBURGH PENNSYLVANIA 1900
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG
Hochschule Fulda University of Applied Sciences
WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER
BERGISCHE UNIVERSITÄT WUPPERTAL
TECHNISCHE UNIVERSITÄT MÜNCHEN
HUMBOLDT-UNIVERSITÄT ZU BERLIN
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
BERKELEY LAB
universitätbonn

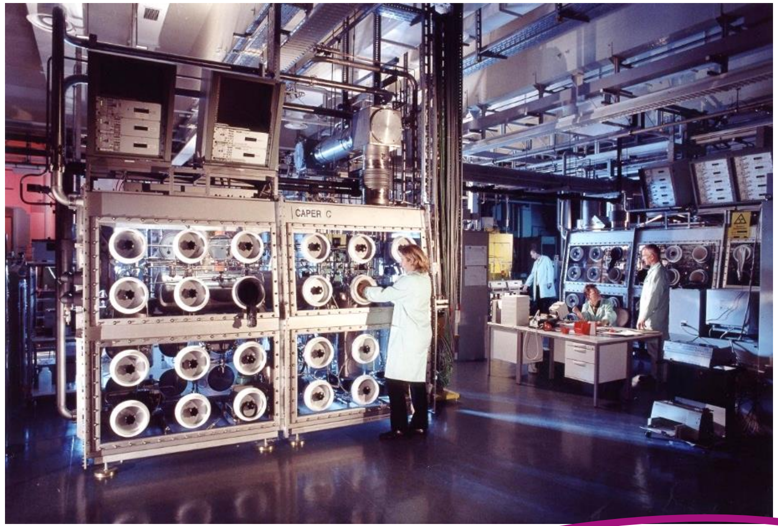
KATRIN experiment: overview

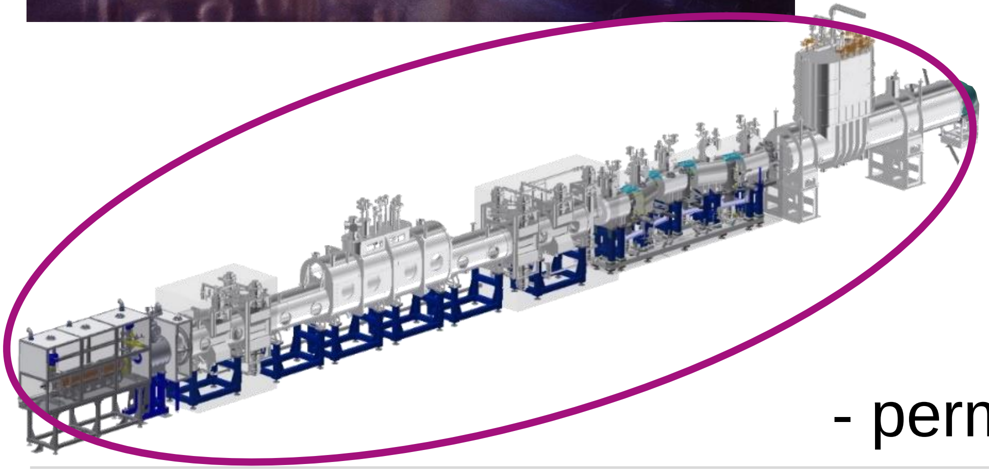
- a 70 m long set-up: a gaseous tritium source & high resolution MAC-E filter



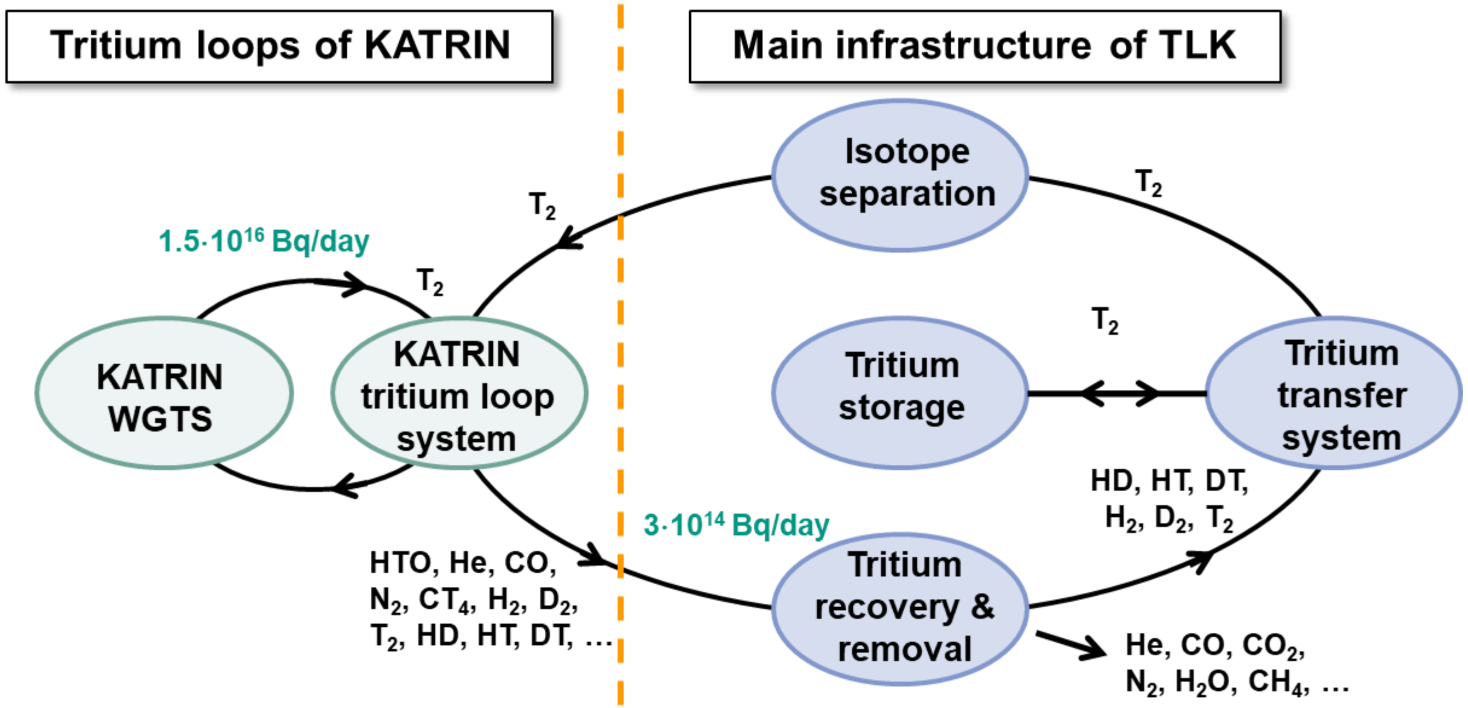
KATRIN experiment: tritium loops by TLK

- **a dedicated laboratory to handle large tritium inventory & throughputs**





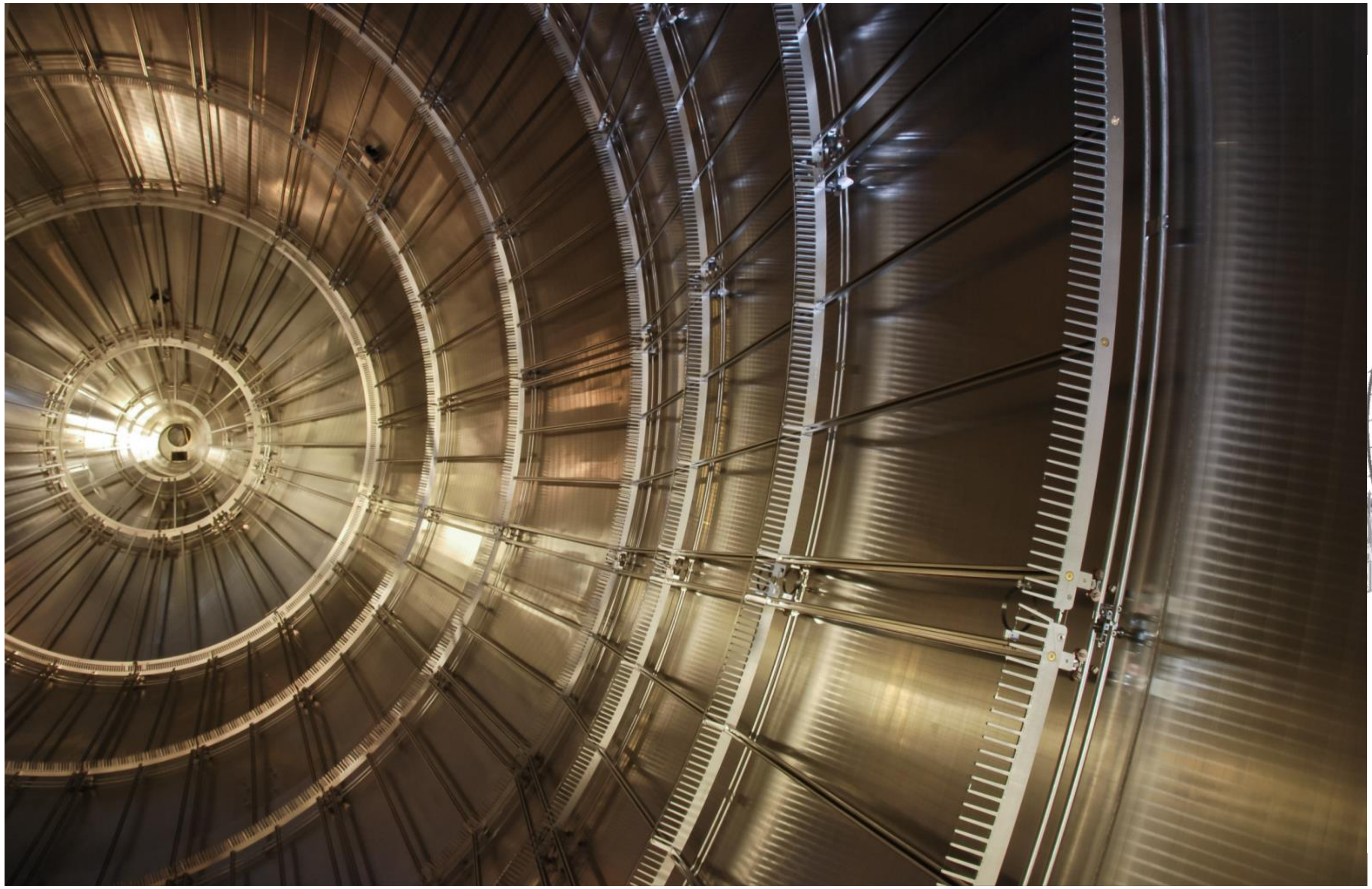
- license for **25 g gram** of T_2, **30 µg** in KATRIN source

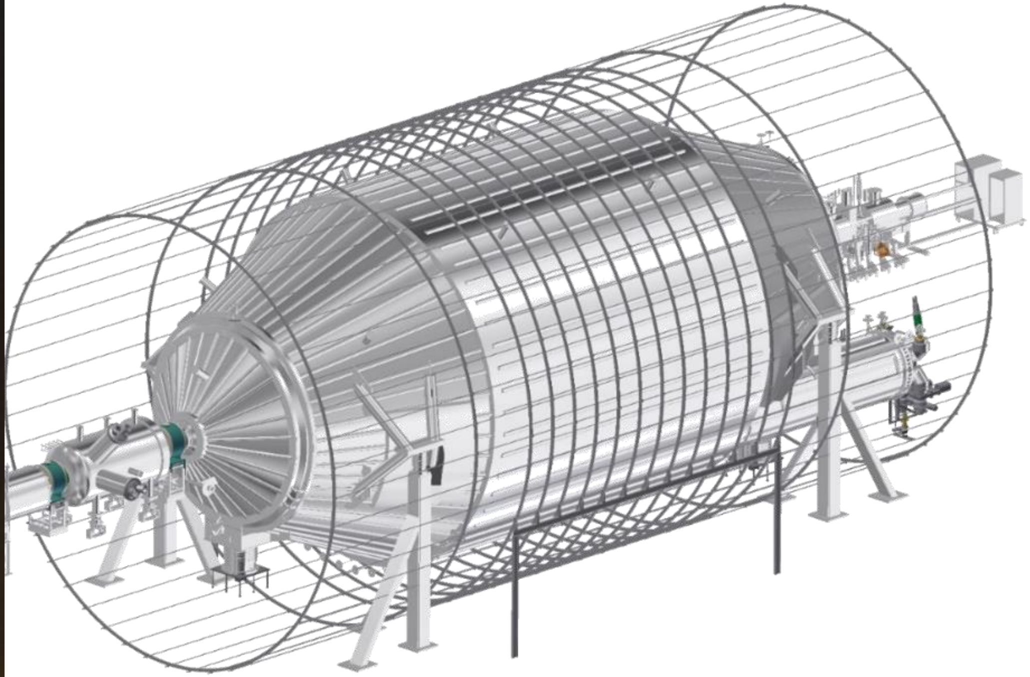


- permanent purification by TLK for large isotopic purity

a high resolution MAC-E filter

- challenges: ultra-high vacuum, HV stabilisation, background, and...

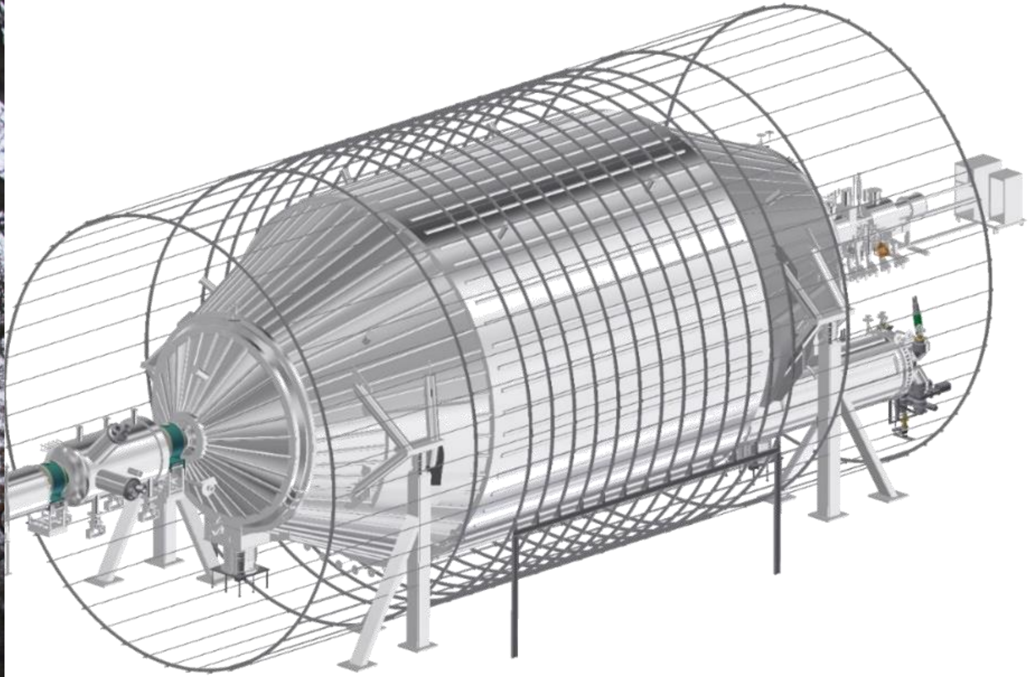




main spectrometer

a high resolution MAC-E filter

- **challenges: ultra-high vacuum, HV stabilisation, background, and transport**



main spectrometer

a high resolution MAC-E filter

- challenges: ultra-high vacuum, HV stabilisation, background, and transport

2006

main spectrometer transport

a high resolution MAC-E filter

Karlsruhe Institute of Technology

- challenges: ultra-high vacuum, HV stabilisation, background, and transport

Low Water Levels Disrupt European River Cruises

The New York Times

no KATRIN tour around Europe in 2022

a high resolution MAC-E filter & neutrino vessel

Karlsruhe Institute of Technology

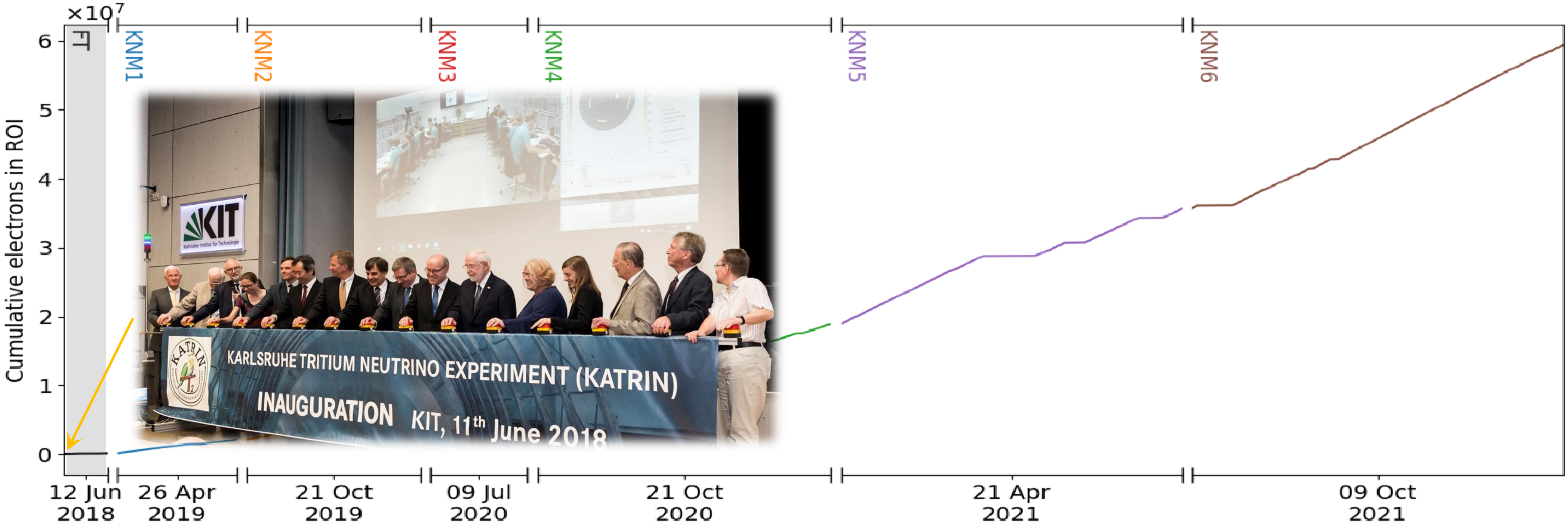
- future challenges: transport

Low Water Levels Disrupt European River Cruises

The New York Times

KATRIN data taking: 2018

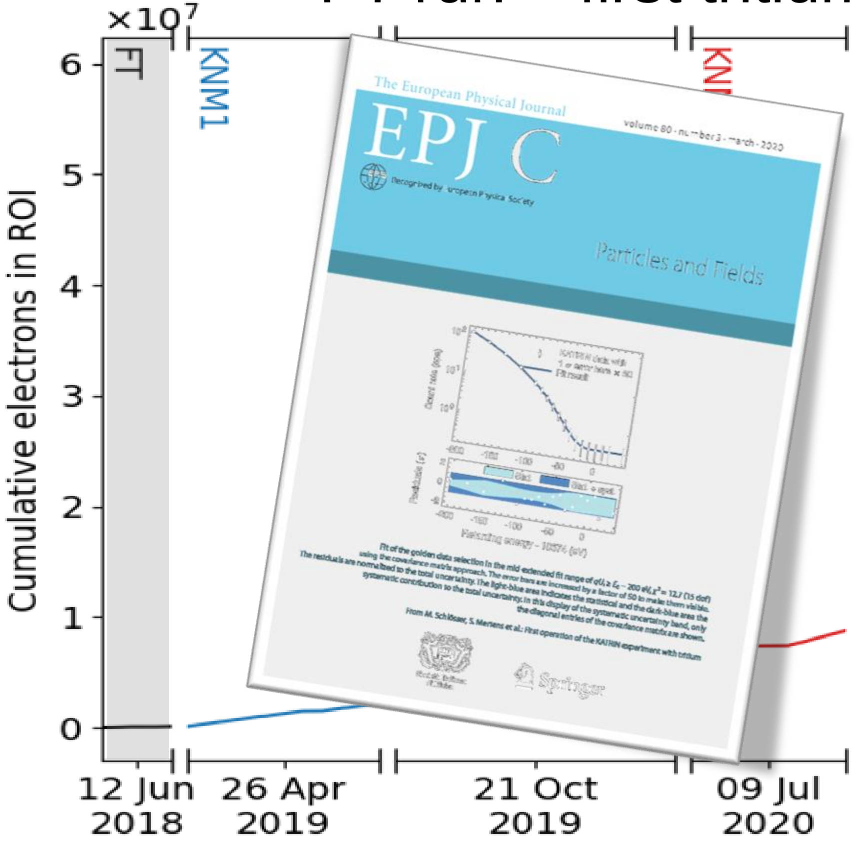
- Science runs from first day after inauguration on June 11, 2018

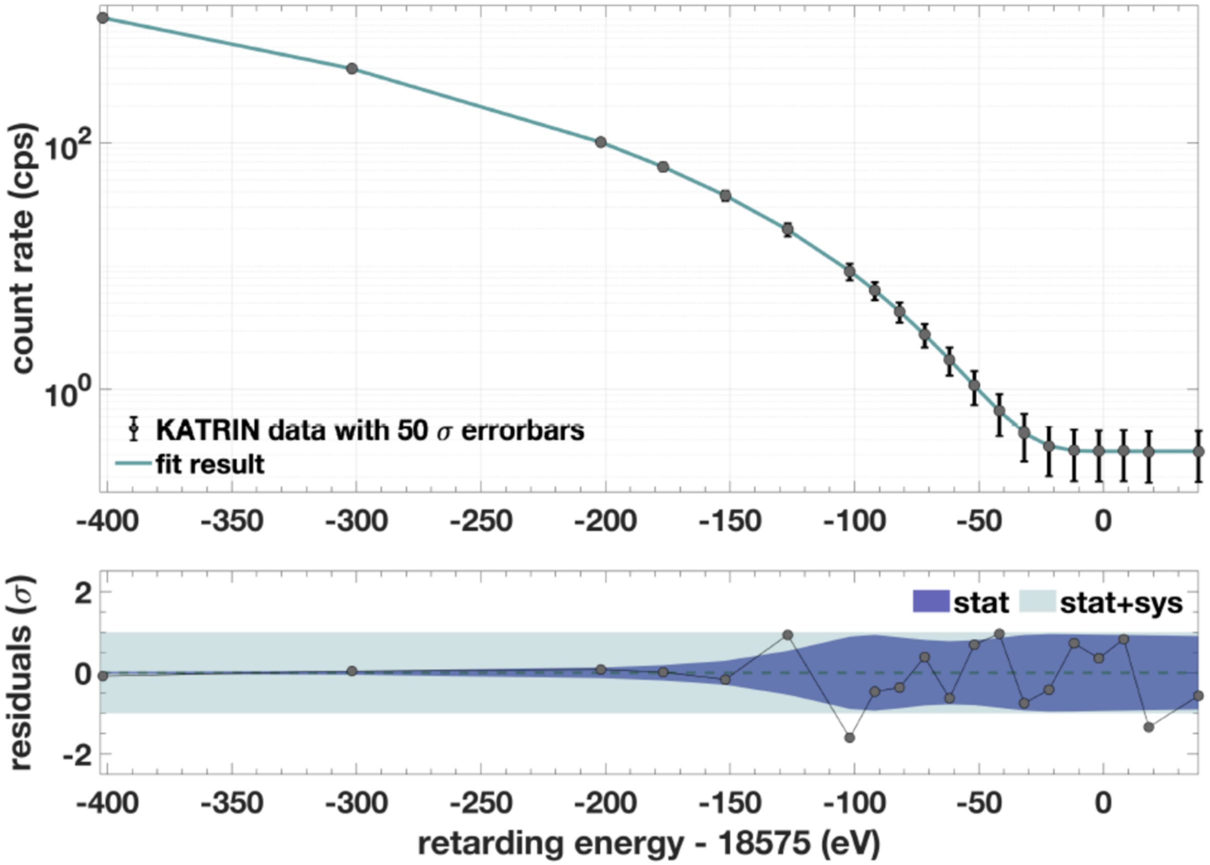


KATRIN data taking: 2018

- **Scientific results from first day after inauguration: searching for sterile ν´s**

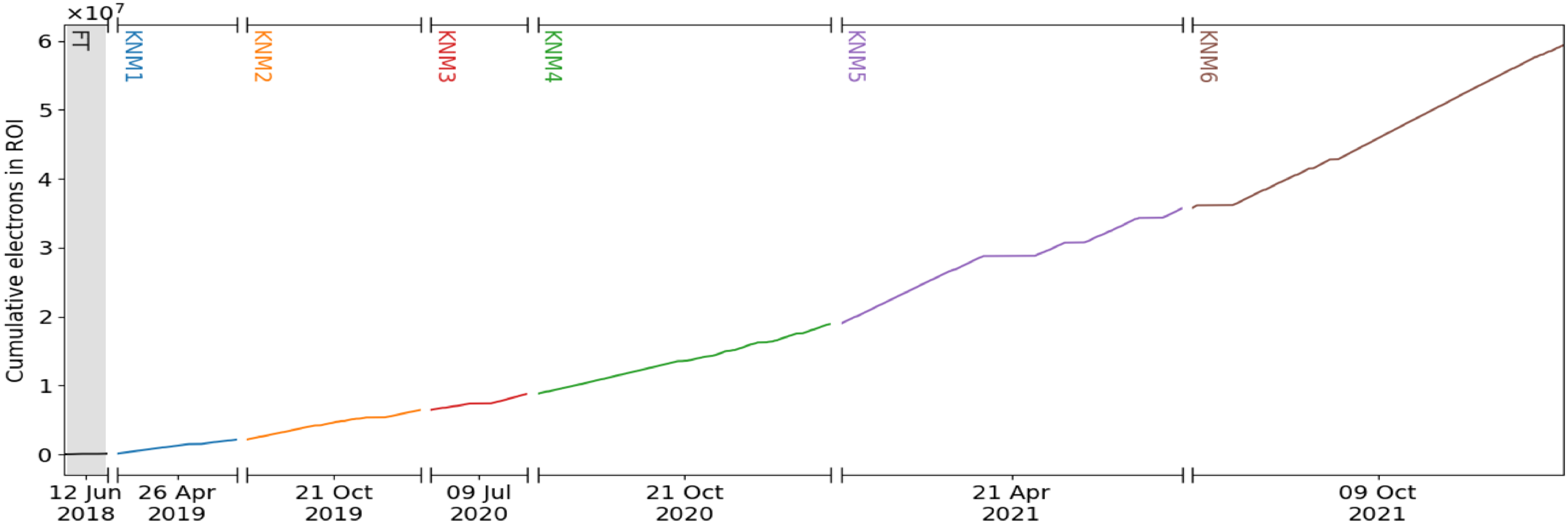
FT run = first tritium (0.5% of nominal column density)





KATRIN data taking: 2018ff…

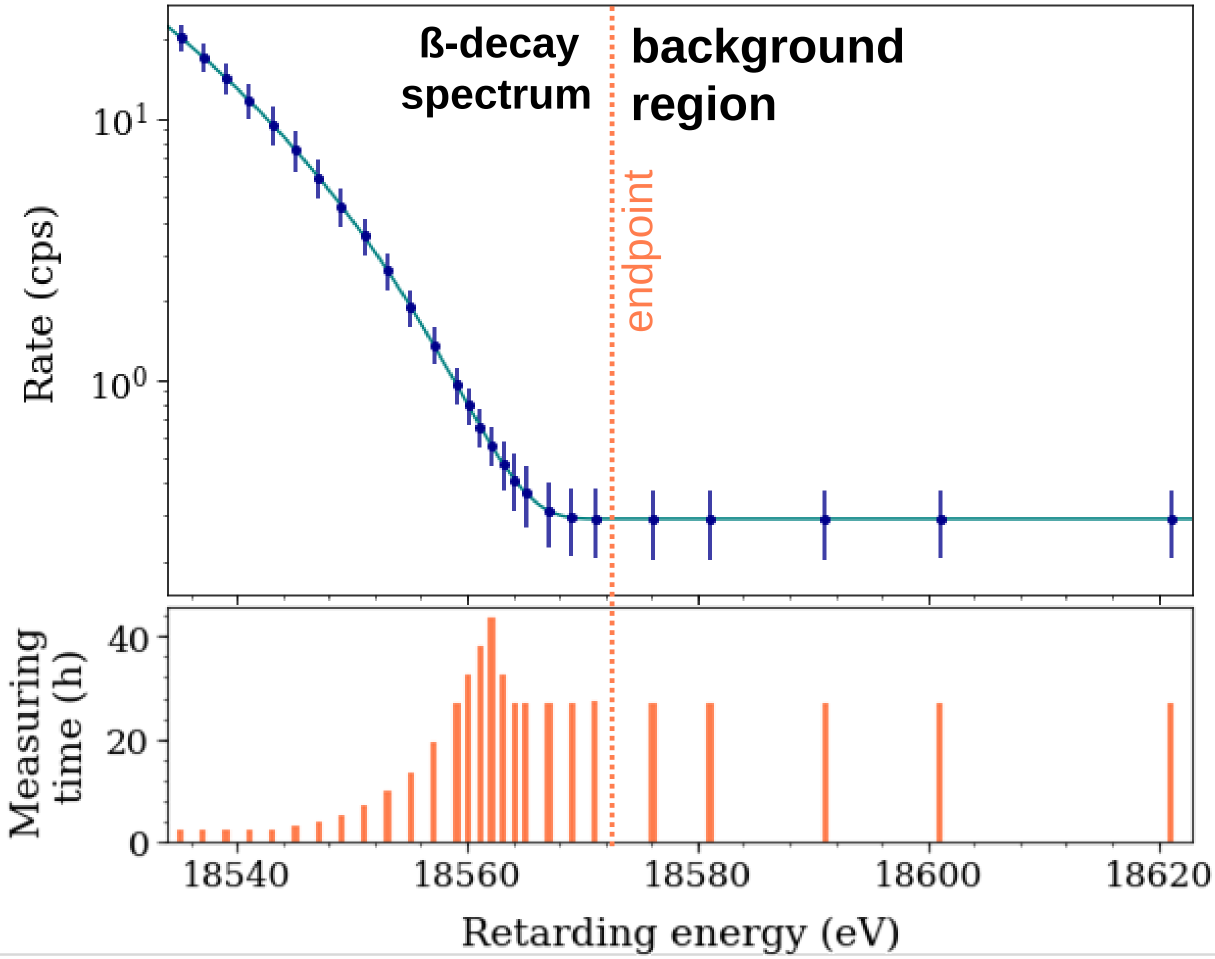
- **many more data taken in specific campaigns KNM1…KNM2…**



KATRIN – measurement principle & strategy

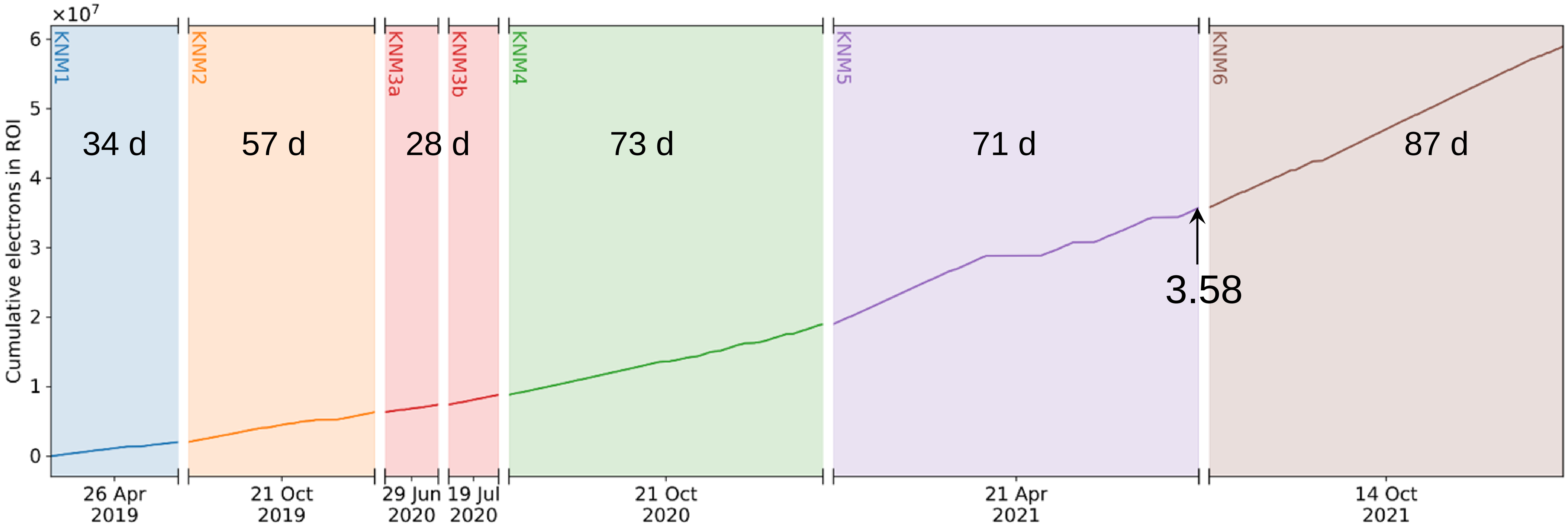
- **measurement: integrated rate above spectrometer retarding potential U_0**

  - **calendar year**:
    several measurement campaigns (KNMx), typically 4-5
  - **campaign**:
    several (up to 8) weeks
    hundreds of ß-scans (up-down mode)
  - **ß-scan**:
    typical scan time: 2 h
    30 HV set points with specific holding time & U_0 distribution
    interval [E_0 - 40 eV, E_0 + 130 eV]



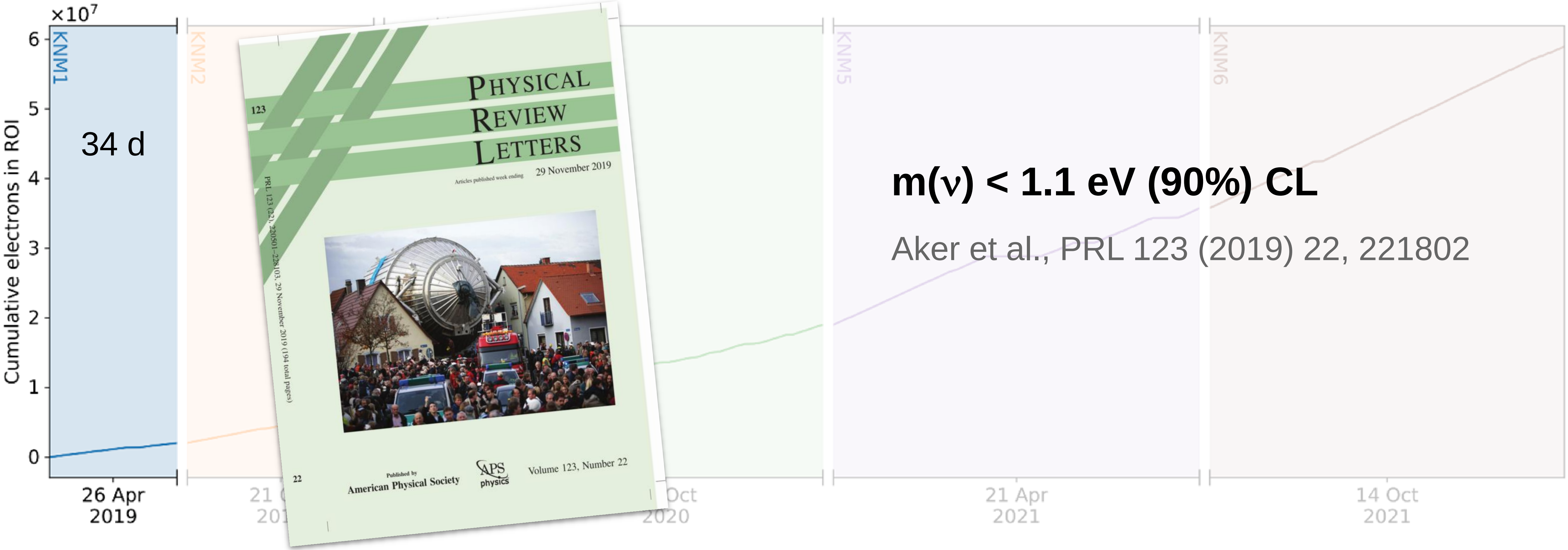
KATRIN data taking: overview 2019 – 2021

- number of electrons in ROI of detector: the first 6 campaigns



KATRIN data taking: first campaign KNM1

- **2019: initial 34 days of ß-scanning (spring)**

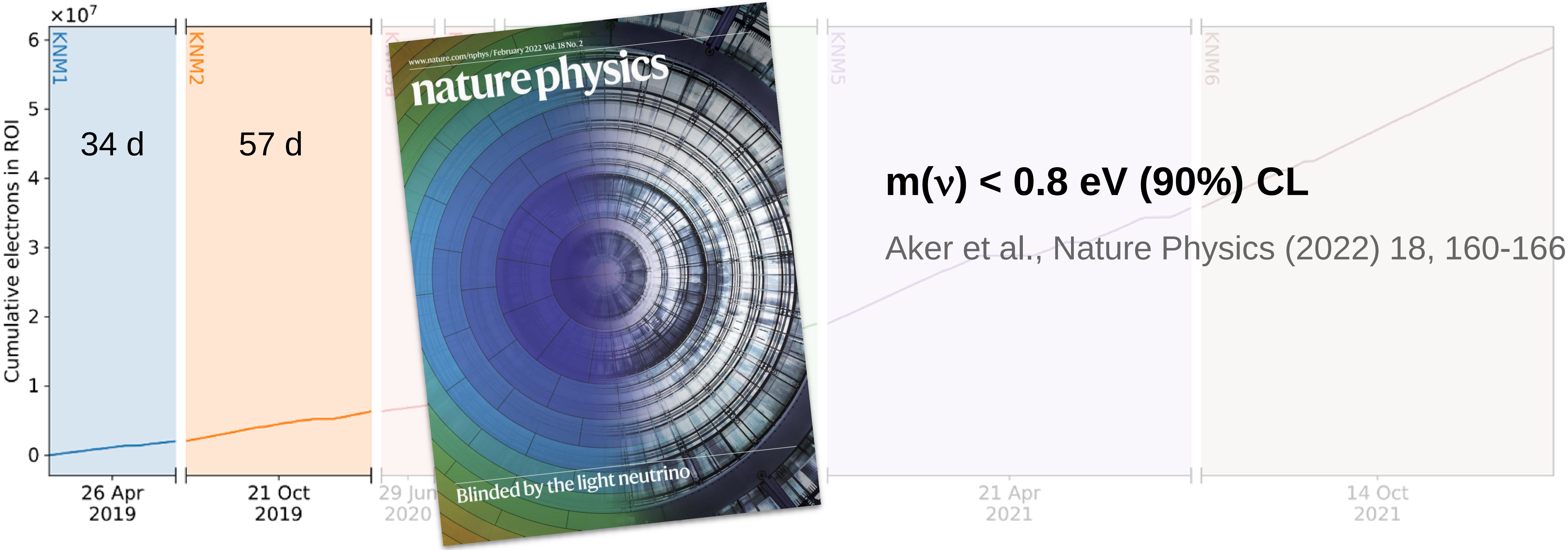


m(ν) < 1.1 eV (90%) CL

Aker et al., PRL 123 (2019) 22, 221802

KATRIN data taking: first 2 campaigns KNM1+2

- 2019: initial **91 days** of ß-scanning (spring & autumn)

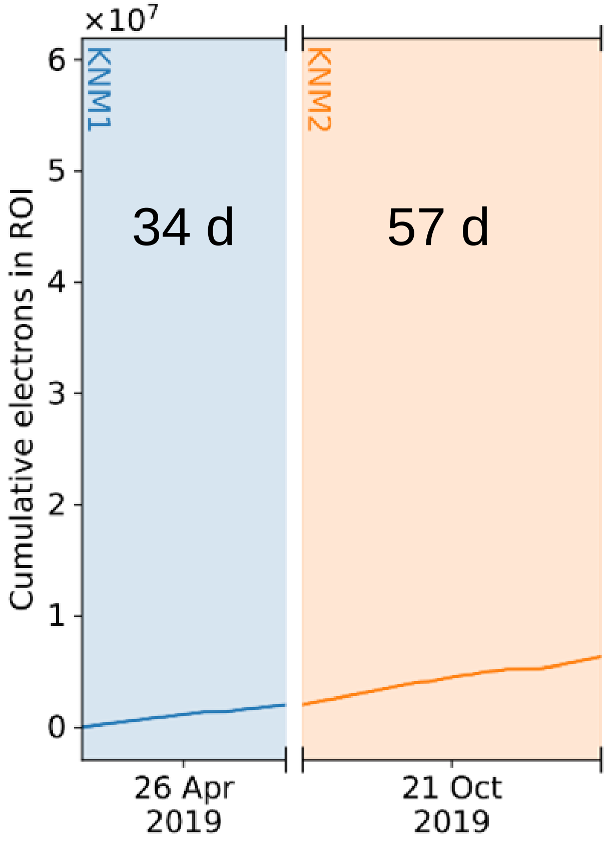


m(ν) < 0.8 eV (90%) CL

Aker et al., Nature Physics (2022) 18, 160-166

KATRIN data taking: first 2 campaigns KNM1+2

- **2019 improvements – better S/B ratio**

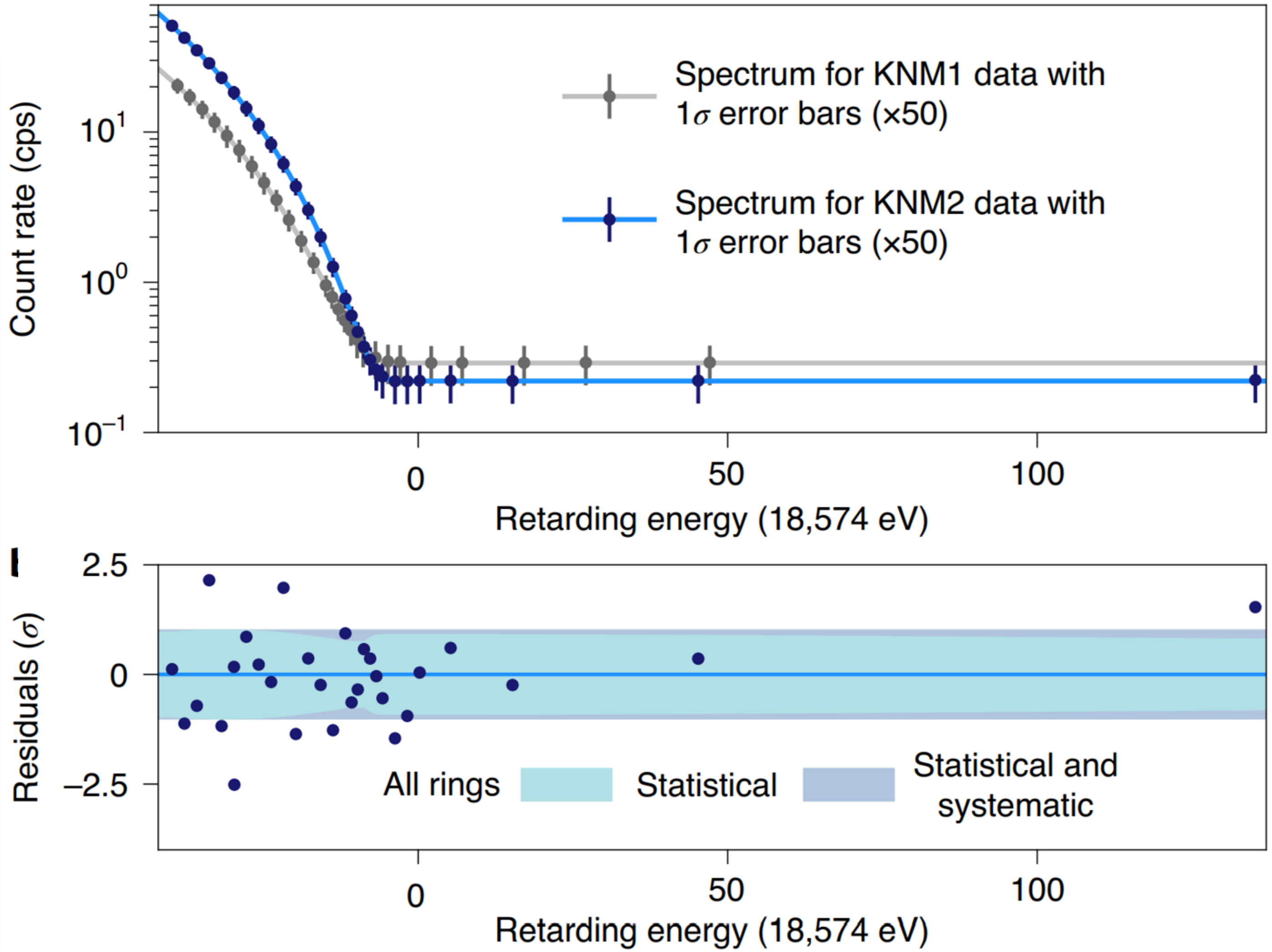


	1st campaign	2nd campaign
time	spring 2019	autumn 2019
golden scans	274	361
measuring time	21.7 d	27.1 d
gas density	22.2 % →	84.5 %
background rate	292 mcps	220 mcps
total e^- in ROI	2.0 million →	4.3 million

KNM1 vs. KNM2: improved S/B ratio

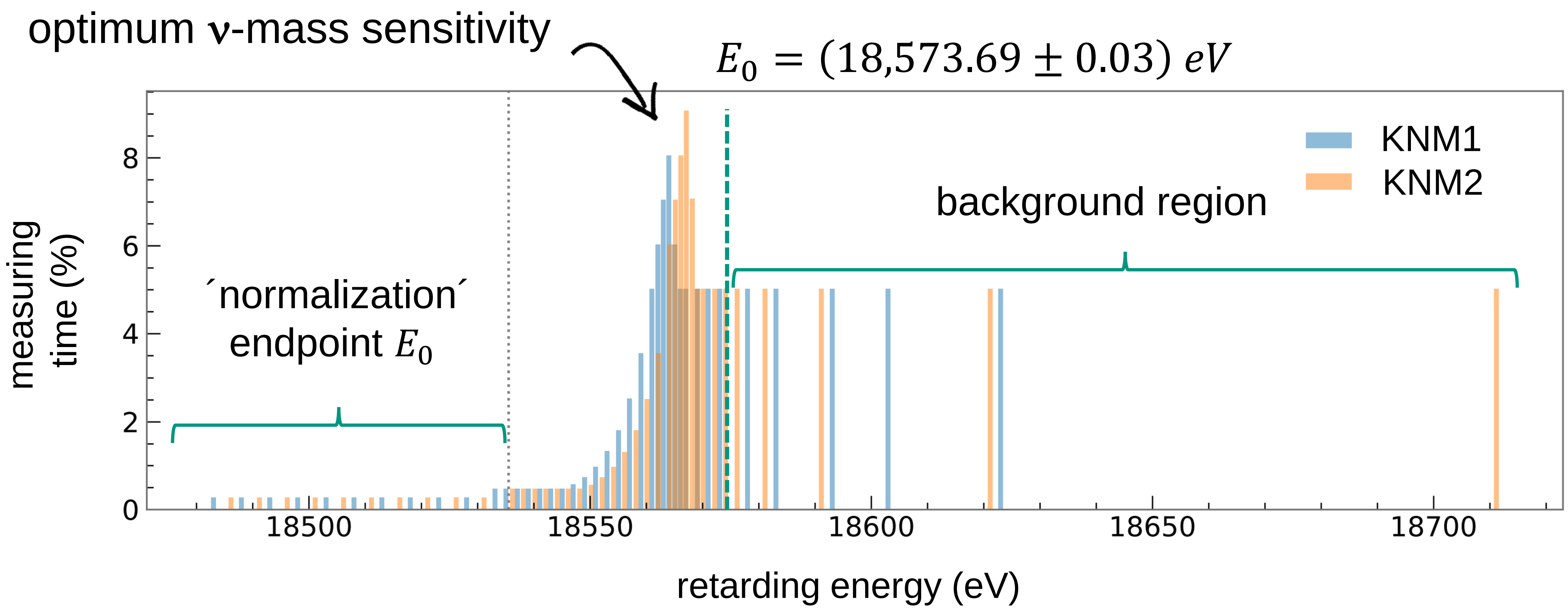
- **analysis in 40 eV wide energy below E_0 (+ bg)**

  - increased signal strength
  - reduced background level
  - better overall statistics (error bars × 50)
  - comparison of data points to best-fit model
  - ring-wise (FPD) analysis



KNM1 & KNM2: scan procedures

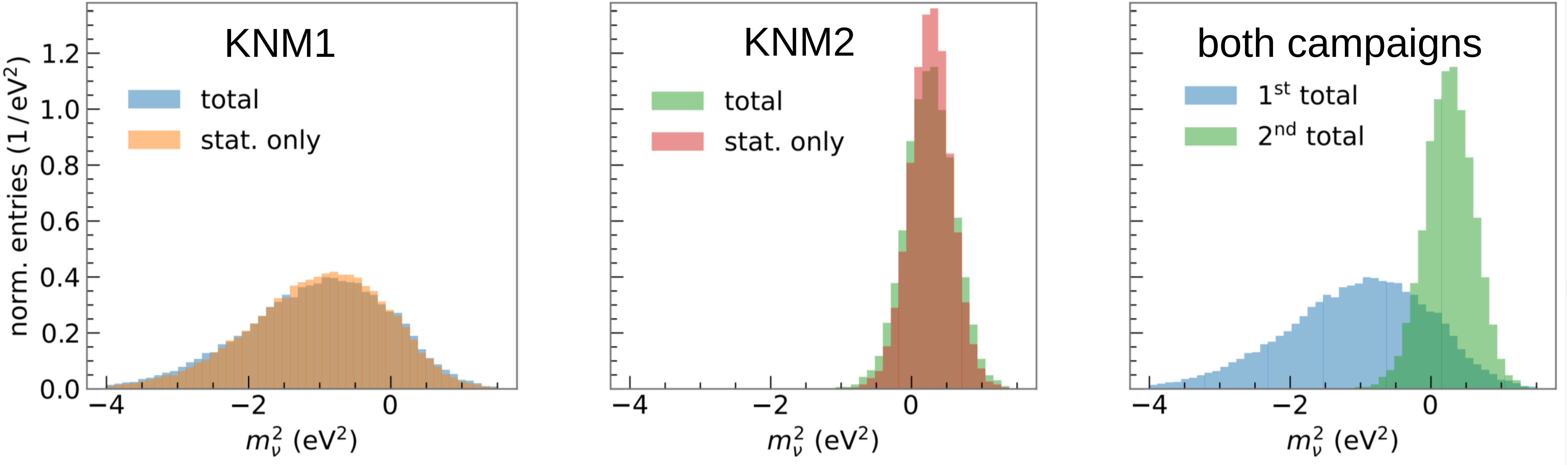
- **KNM1 and KNM2 – different scan strategies due to different S/B ratio**



KNM1 & KNM2: ν-mass results

- **Results of individual campaigns: dominated by statistics!**

  - no indication for non-zero neutrino mass



KATRIN – 2022 result

- **distribution of fitted m_ν^2 and E_0 values**

  - best-fit value for ν-mass-parameter:

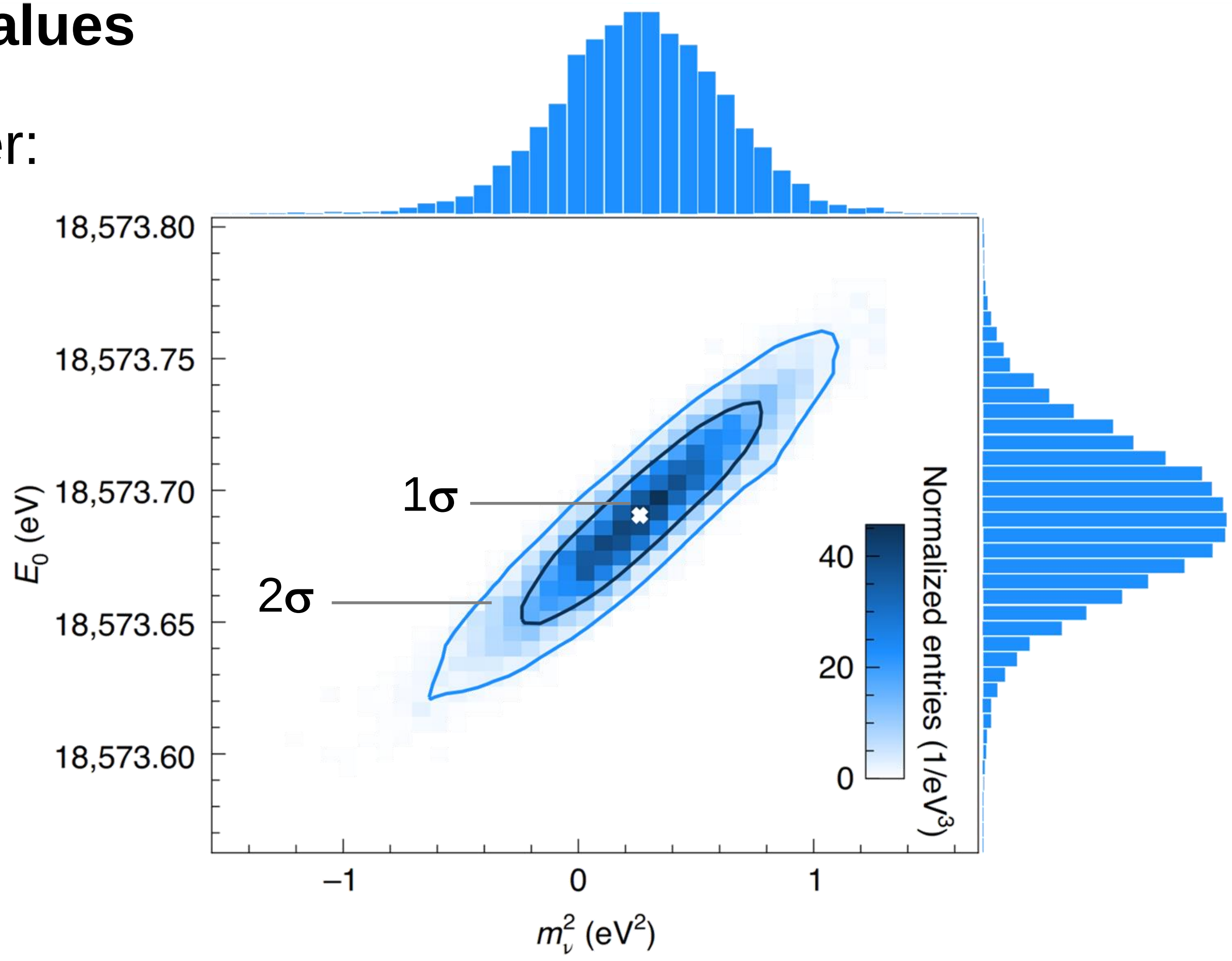
$$m_\nu^2 = (0.26 \pm 0.34)\ eV^2$$

$$E_0 = (18{,}573.69 \pm 0.03)\ eV$$

combined result KNM1 & KNM2:

$$m(\nu) < 0.8\ eV\ (90\%)C.L.$$

  - only 7% of expected final data-set



KATRIN – 2022 result and earlier values

- **distribution of fitted m_ν^2 and E_0 values**

  - best-fit value for ν-mass-parameter:

$$m_\nu^2 = (0.26 \pm 0.34)\ eV^2$$

$$E_0 = (18{,}573.69 \pm 0.03)\ eV$$

combined result KNM1 & KNM2:

$$m(\nu) < 0.8\ eV\ (90\%)\ C.L.$$

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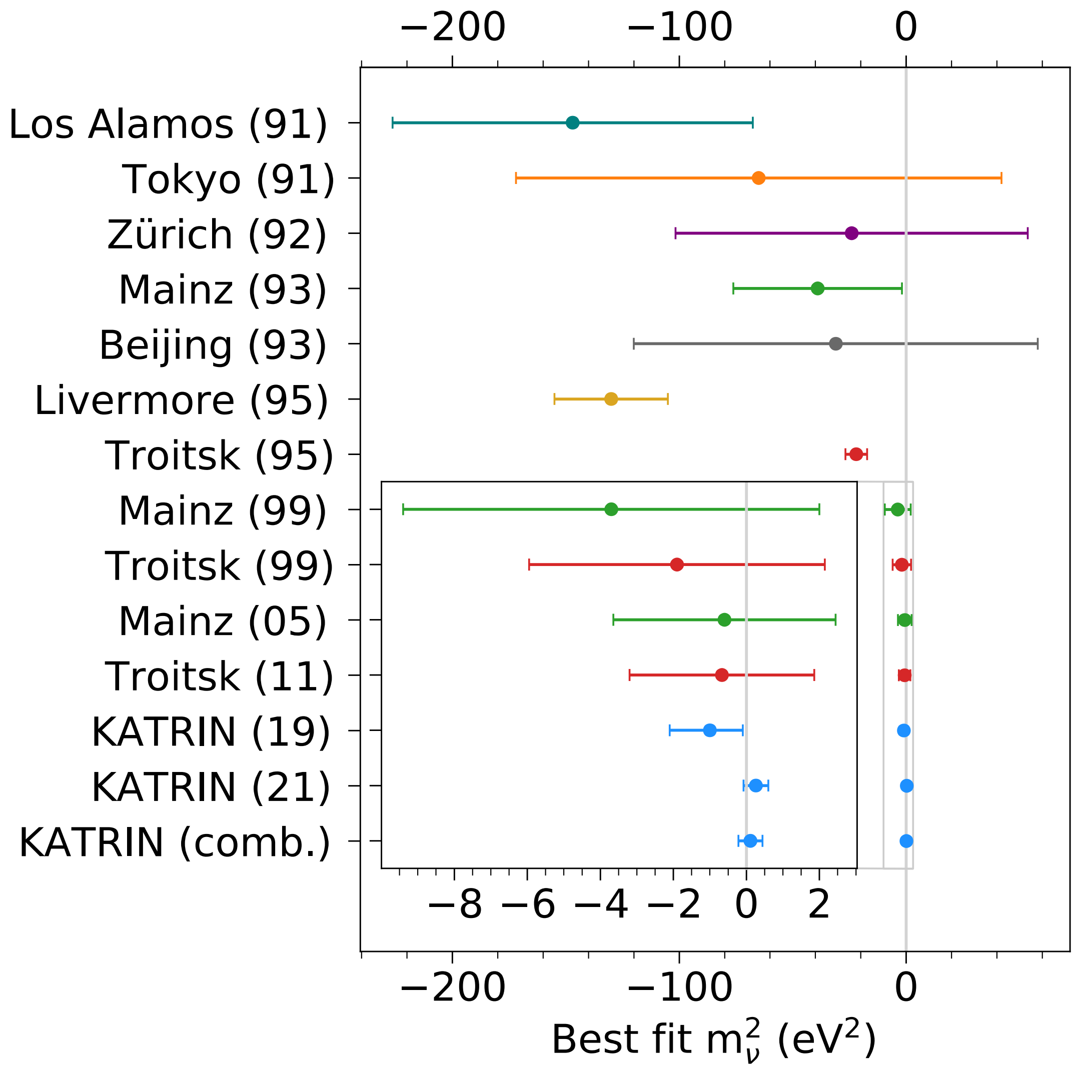
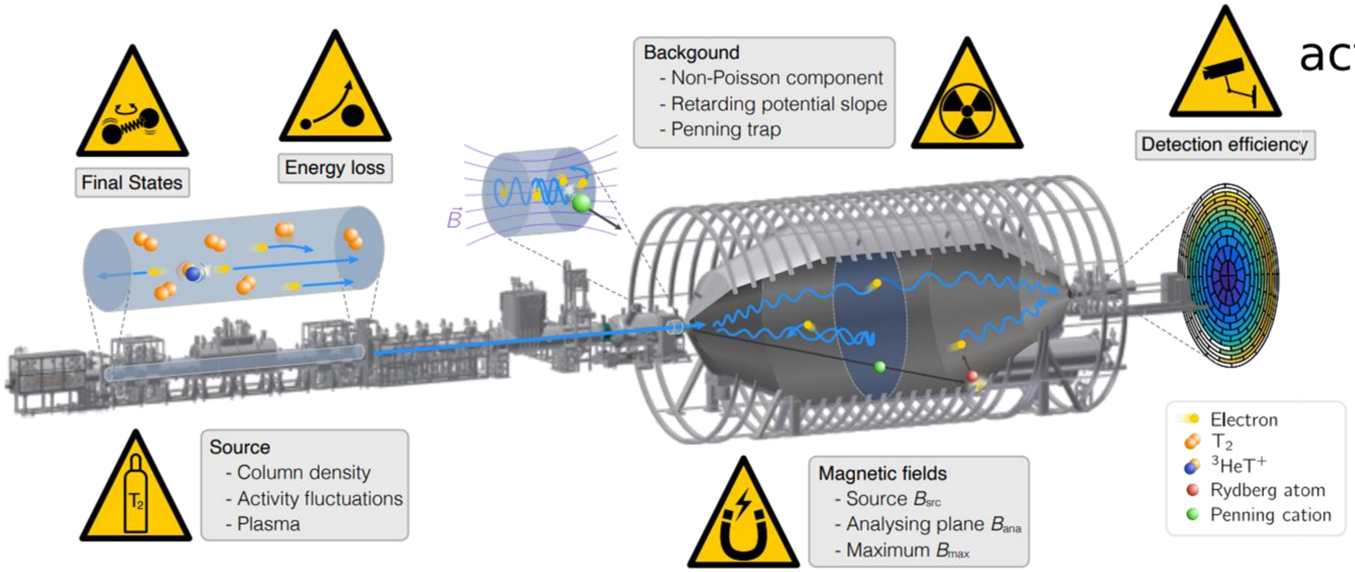
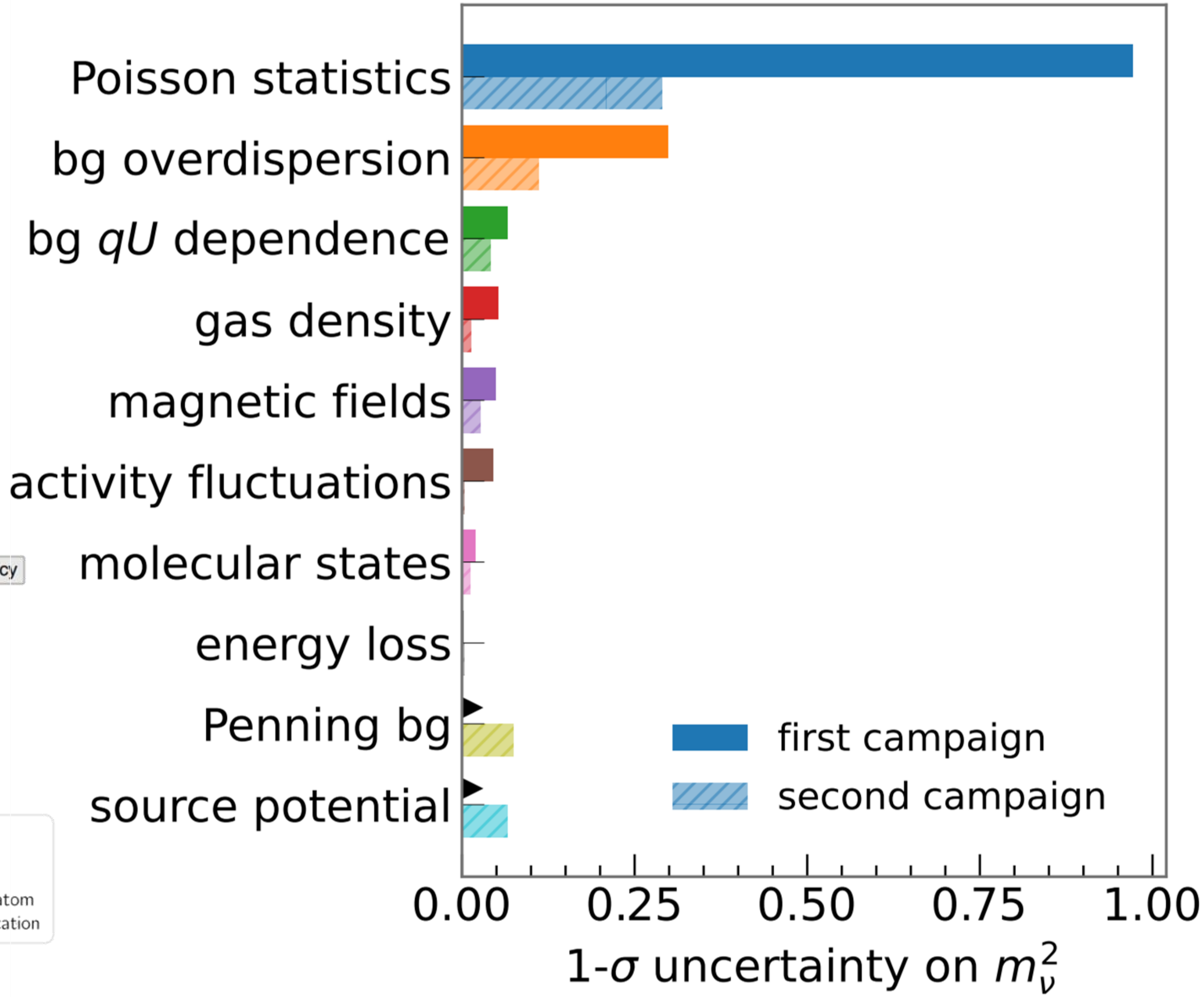


KATRIN – uncertainty breakdown

- **dominated by statistical uncertainty**

  - systematics: dominated by background & source potential





KATRIN – searches for BSM physics

Karlsruhe Institute of Technology

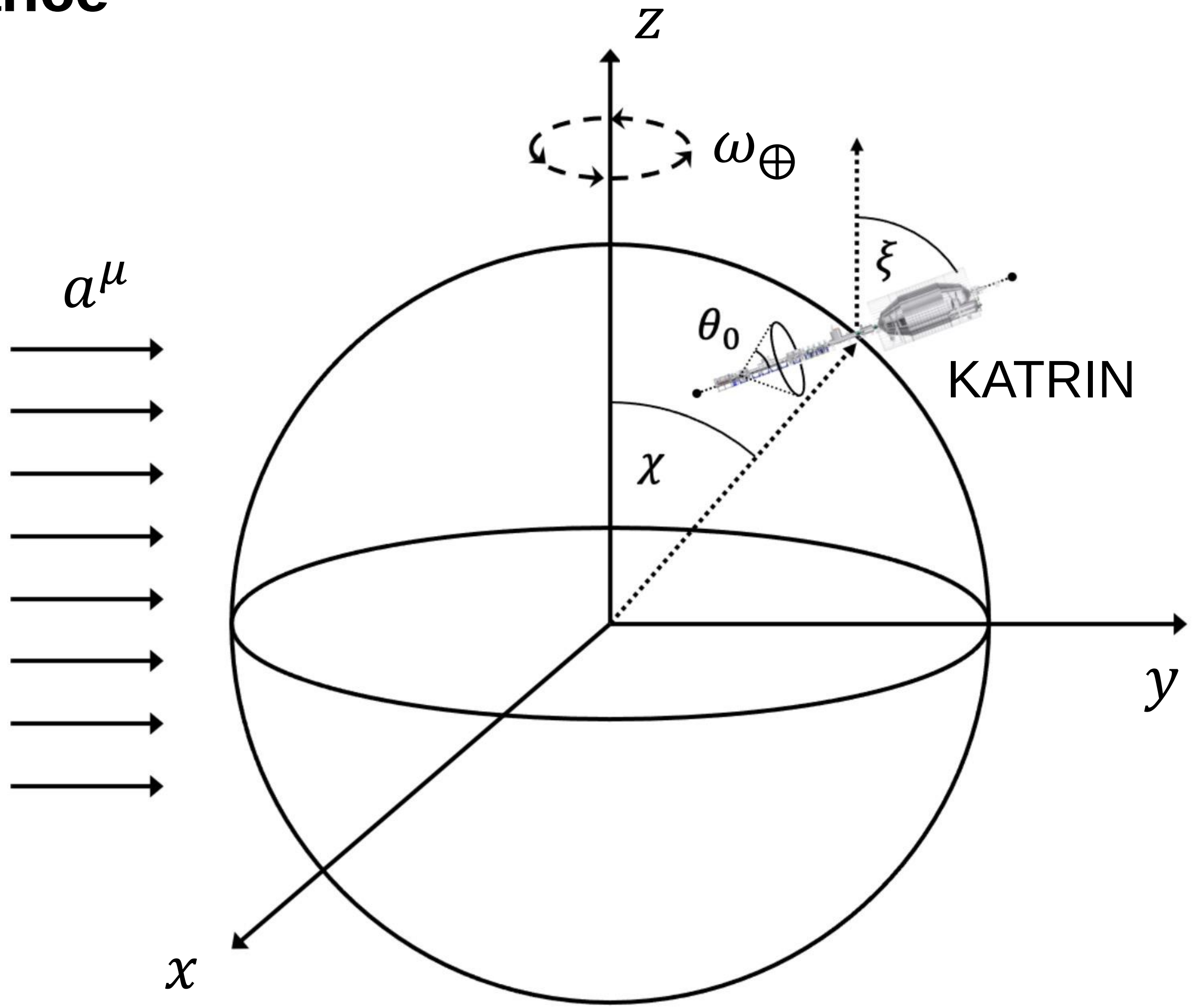
Search for violation of Lorentz invariance

- rotation of Earth: relative direction of WGTS acceptance angle changes w.r.t Lorentz-violating vector a^μ

- **LV-signature**: endpoint energy E_0 oscillates with sidereal time (23 h 56 min 4s)
  ⇨ aribitrary amplitude / phase

- sensitive to LV-parameter

$$\left|\left(a_{of}^{(3)}\right)_{11}\right|$$



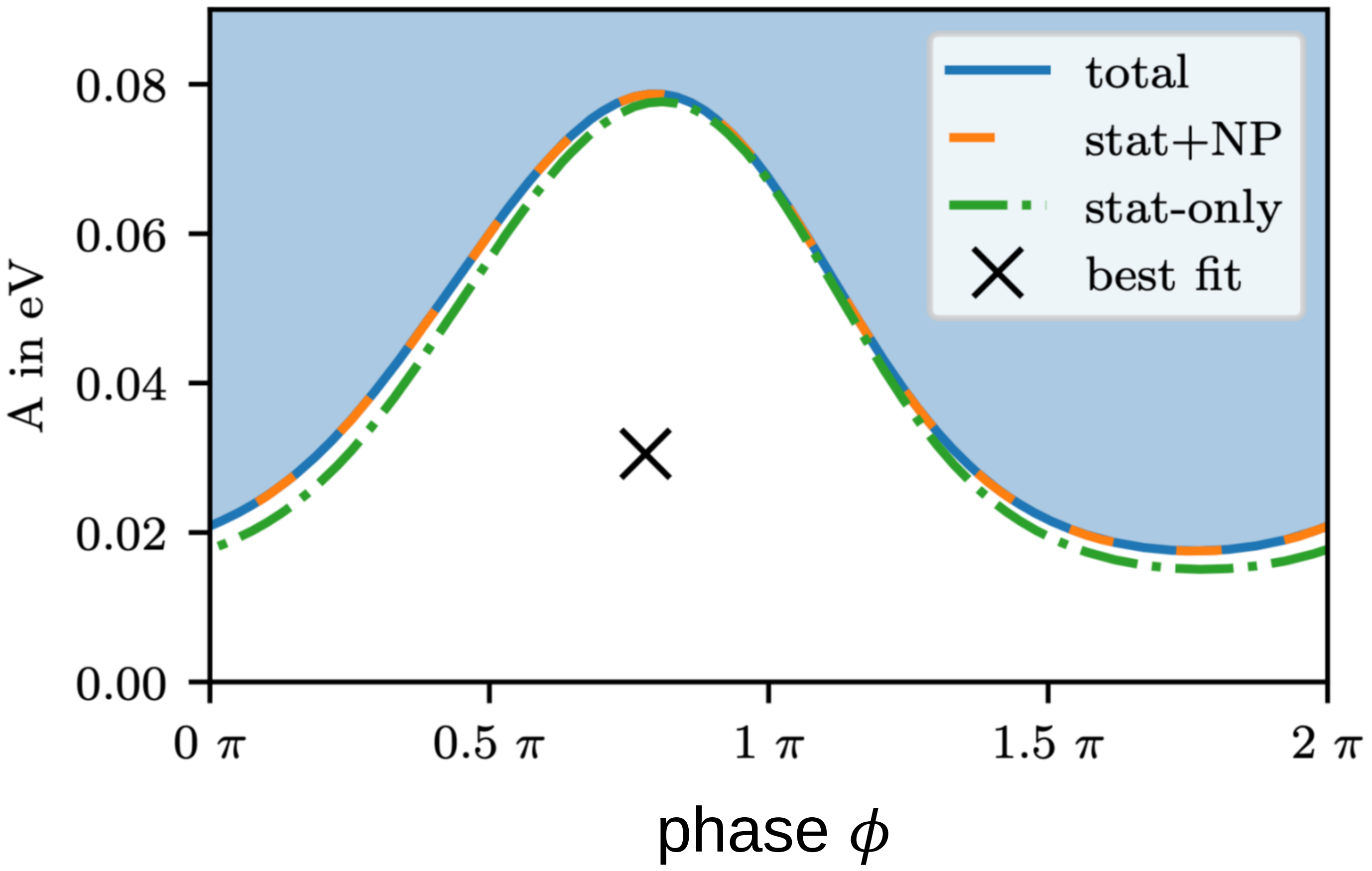
KATRIN – searches for BSM physics

- **analysis of data from first campaign (KNM1) – fit of endpoints E_0**

- use 2 h binning for fit of E_0
- no significant oscillation of E_0 observed
- conversion following https://arxiv.org/pdf/2112.13803.pdf

$$\left|\left(a_{of}^{(3)}\right)_{11}\right| < 3.7 \cdot 10^{-6}\, GeV\, (90\% CL)$$

- for more details see https://arxiv.org/abs/2207.06326



KATIRN – searches for BSM physics

Karlsruhe Institute of Technology

- **Search for local relic neutrino overdensities via** $\nu_e + {}^3H \rightarrow {}^3He^+ + e^-$

- capture on ß-unstable nuclei: no threshold

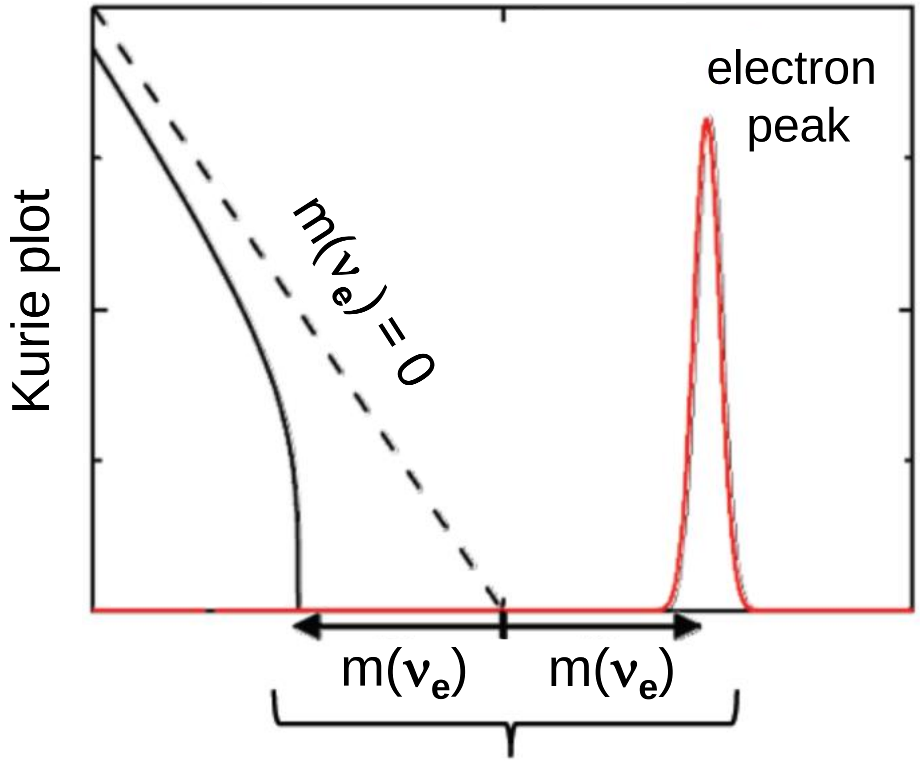
- differential spectrum: peak above E_0

- consider effects:
    - integral scan, finite energy resolution
    - molecular smearing, source potential

- 100 g of tritium: 10 CνB captures/year
  but: only few 10 µg in KATRIN source!

- constrain local CνB overdensities

ideal differential spectrum



excellent ΔE required

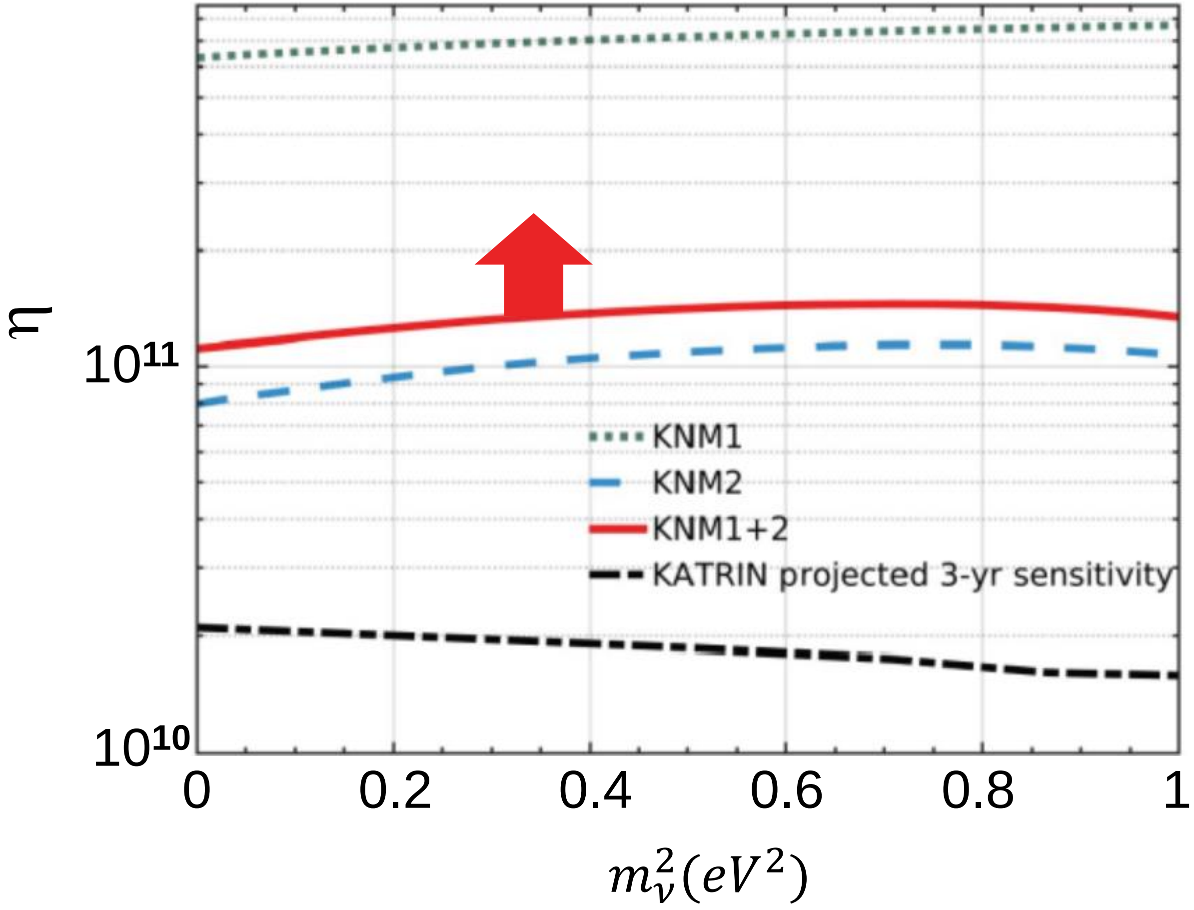
KATRIN – searches for BSM physics

- **Search for local relic neutrino overdensities via $\nu_e + {}^3H \rightarrow {}^3He^+ + e^-$**

  - no CνB signal in first two campaigns

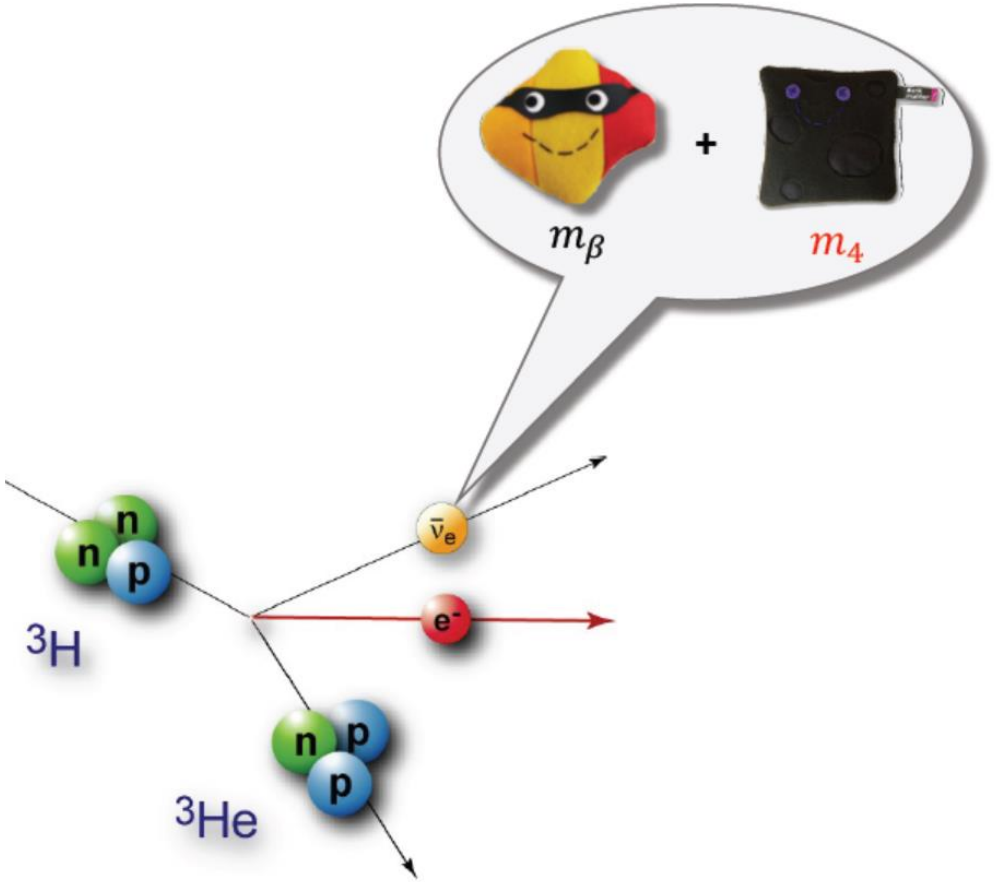
  - improved (factor ~ 10^2) constraints on local CνB overdensity η

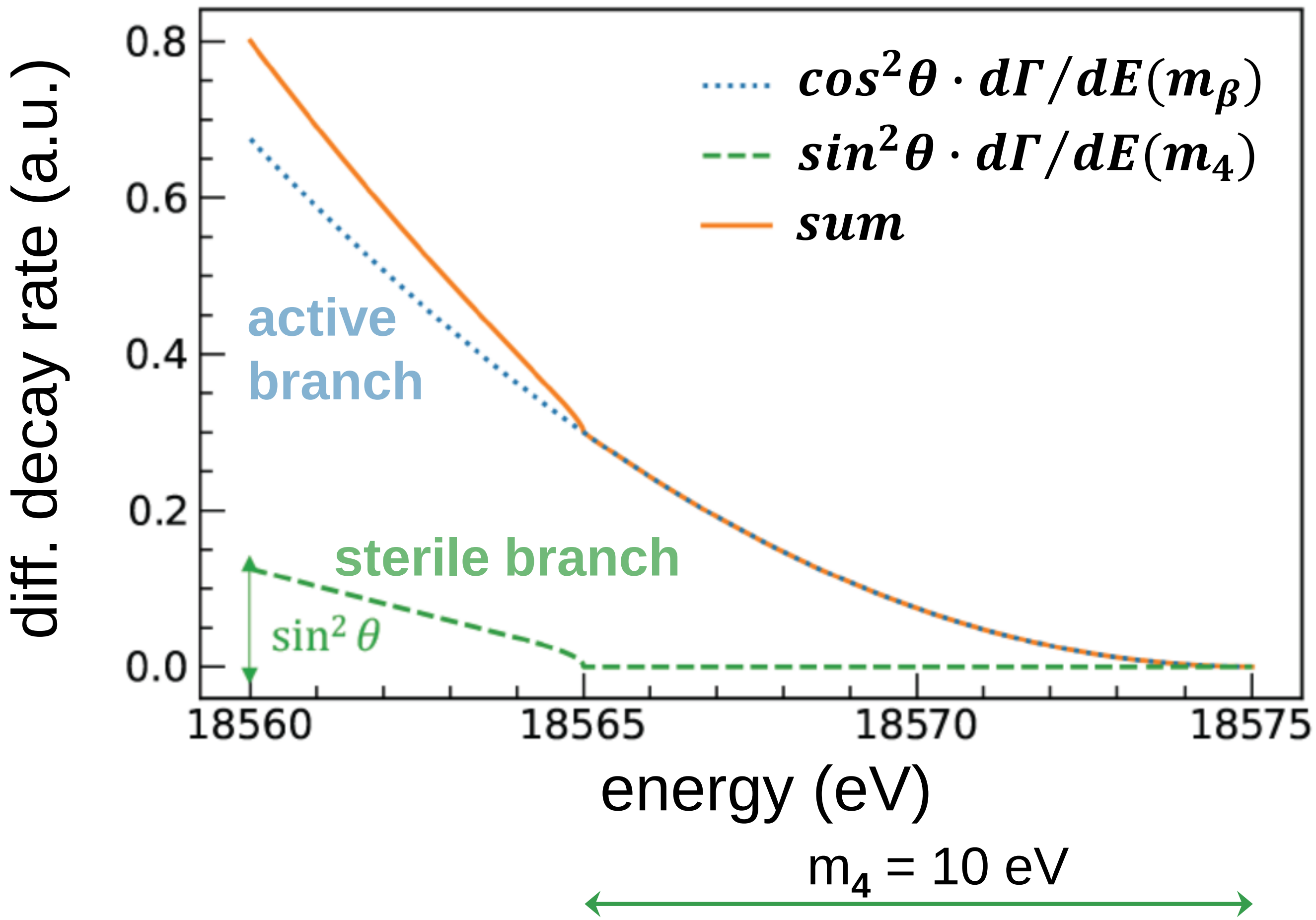
  - KATRIN++
    R&D twoards novel source & read-out technologies



search for light eV-sterile neutrinos: principle

- signature: a characteristic ´kink´ in the energy spectrum of electrons





search for light eV-sterile neutrinos: no evidence!

- **KSN1 & KSN2: statistics dominated, combined best fit (1.2 σ) no evidence**

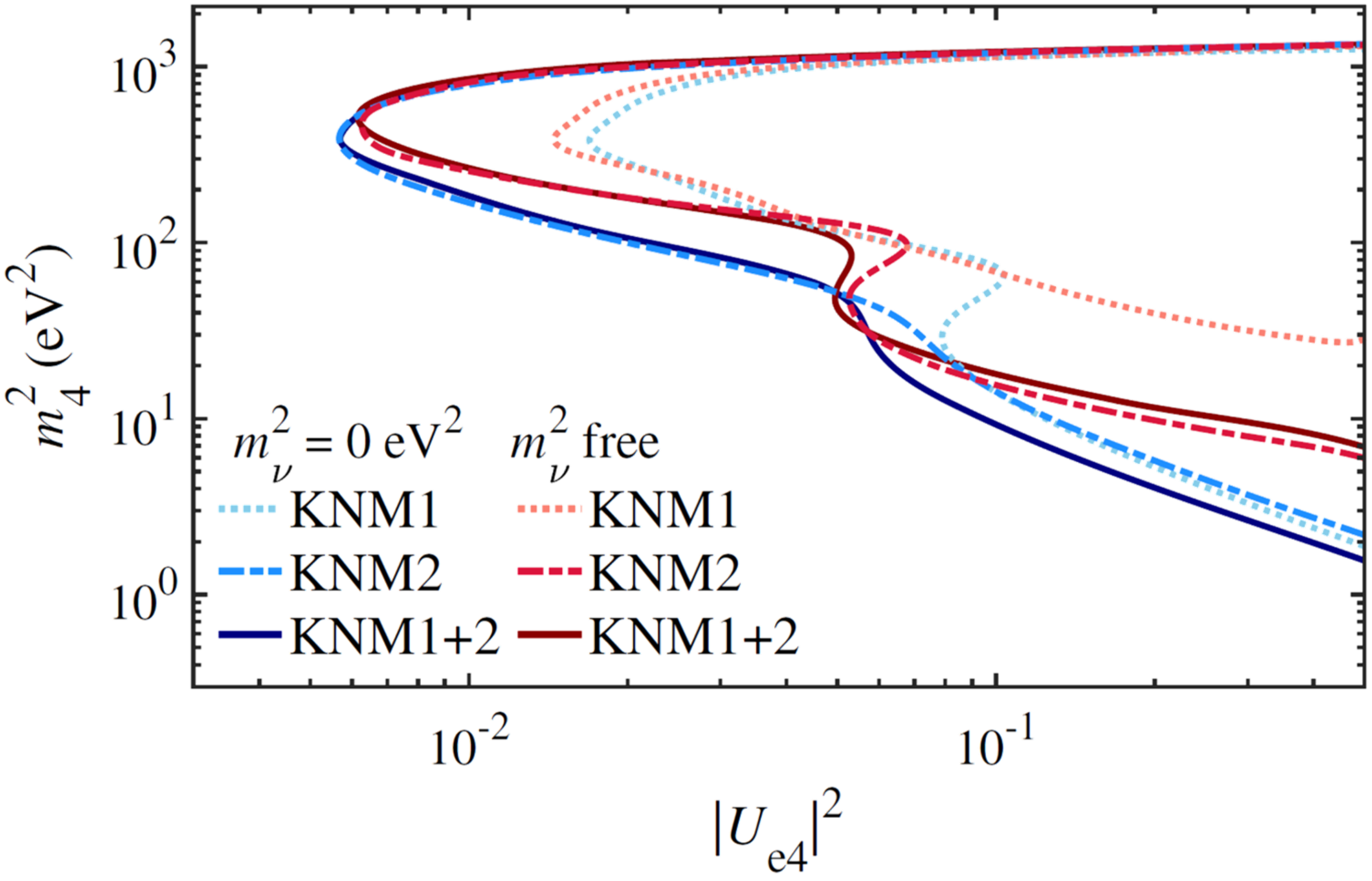
- scenario I

$$m_{1,2,3} \ll m_4 \ (m_\nu^2 = 0 \text{ eV}^2)$$

- scenario II

m_ν^2 unconstrained
nuisance parameter

best fits yield no significant improvments (0.8 σ, 1.4 σ) over no-sterile hypothesis



search for sterile neutrinos: future prospects

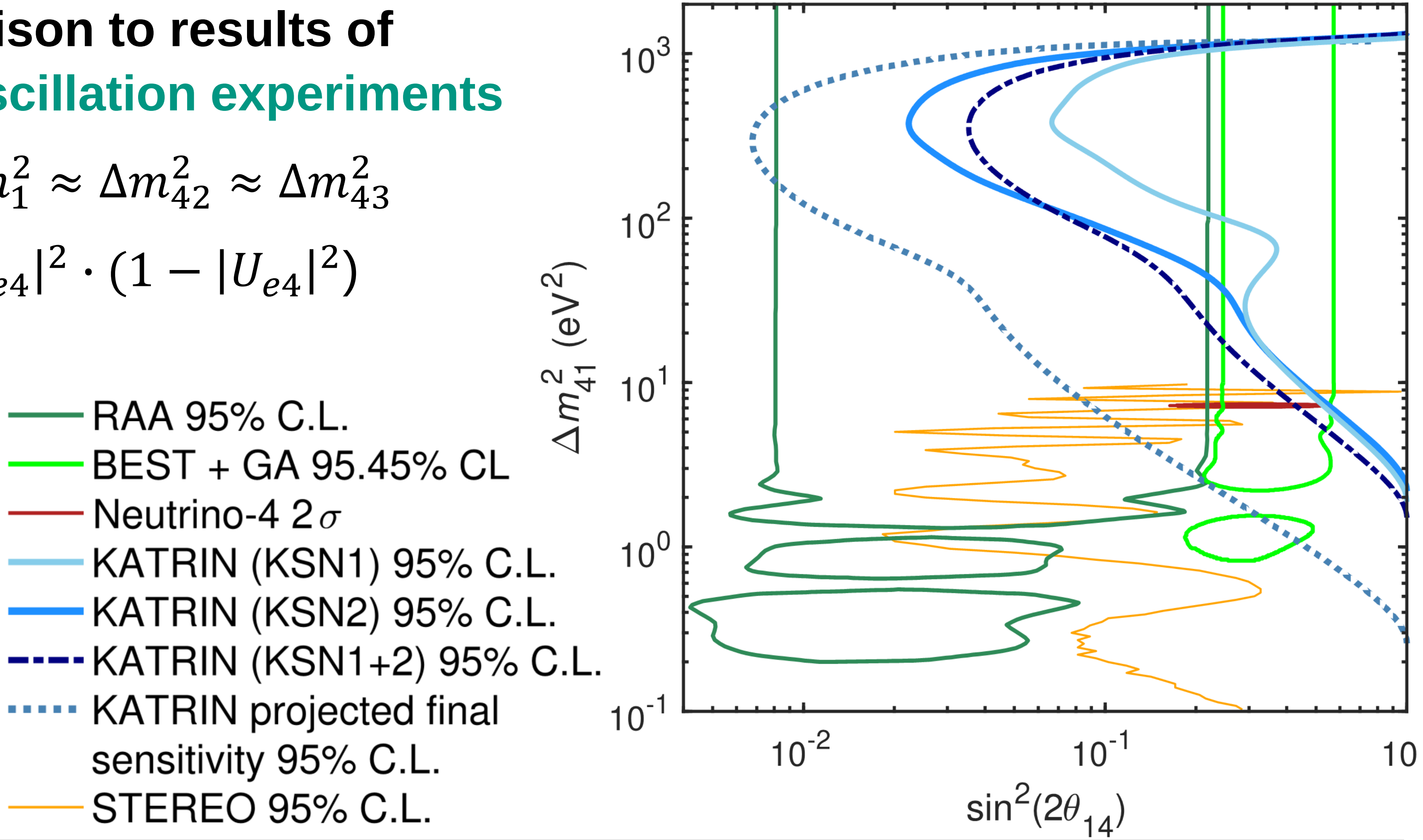
- **KATRIN - comparison to results of disappearance oscillation experiments**
  - $\Delta m^2_{41} = m^2_4 - m^2_1 \approx \Delta m^2_{42} \approx \Delta m^2_{43}$
  - $sin^2 2\theta = 4 \cdot |U_{e4}|^2 \cdot (1 - |U_{e4}|^2)$

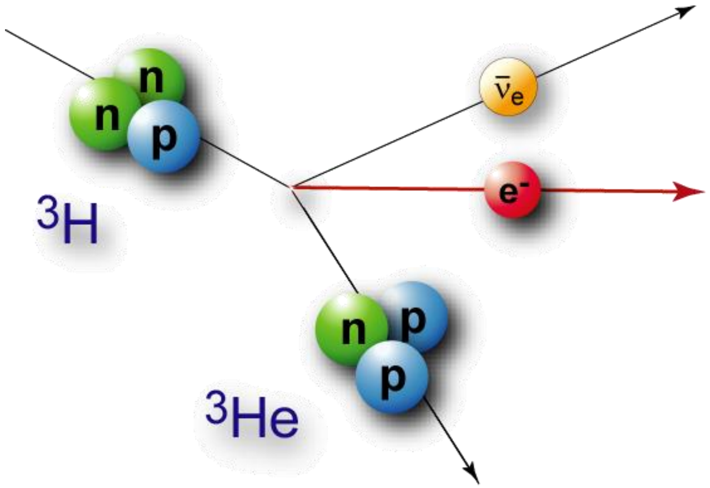
KATRIN:

m_β and m_4

$\Delta m^2_{41} \cong m^2_4 - m^2_\beta$

$sin^2 2\theta = 4 \cdot sin^2\theta \cdot (1 - sin^2\theta)$

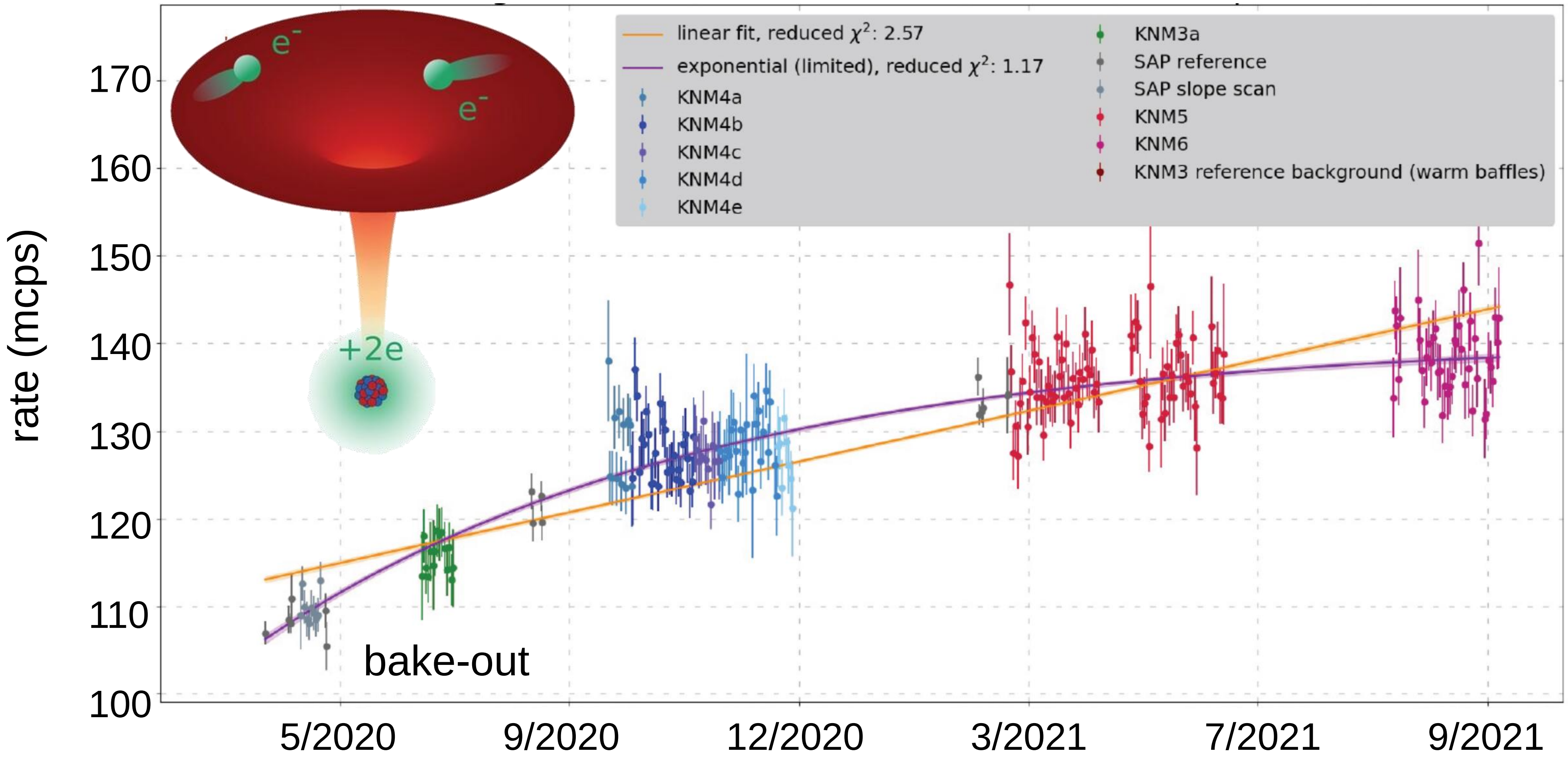




KATRIN: FUTURE

KATRIN: improving ν-mass sensitivity

- **goal: further reduction of current bg-rate (~140 mcps) by factor ~ 10**



neutral H, O atoms sputtered off walls:

- Rydberg states
- 2 e- states
  ⇨ autoionization

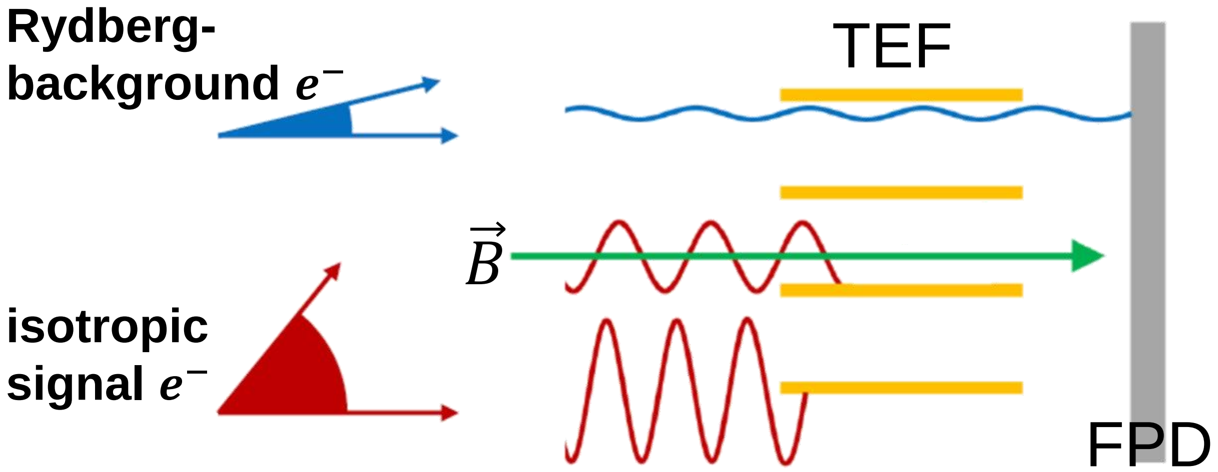
bg-electrons in sub-eV range!

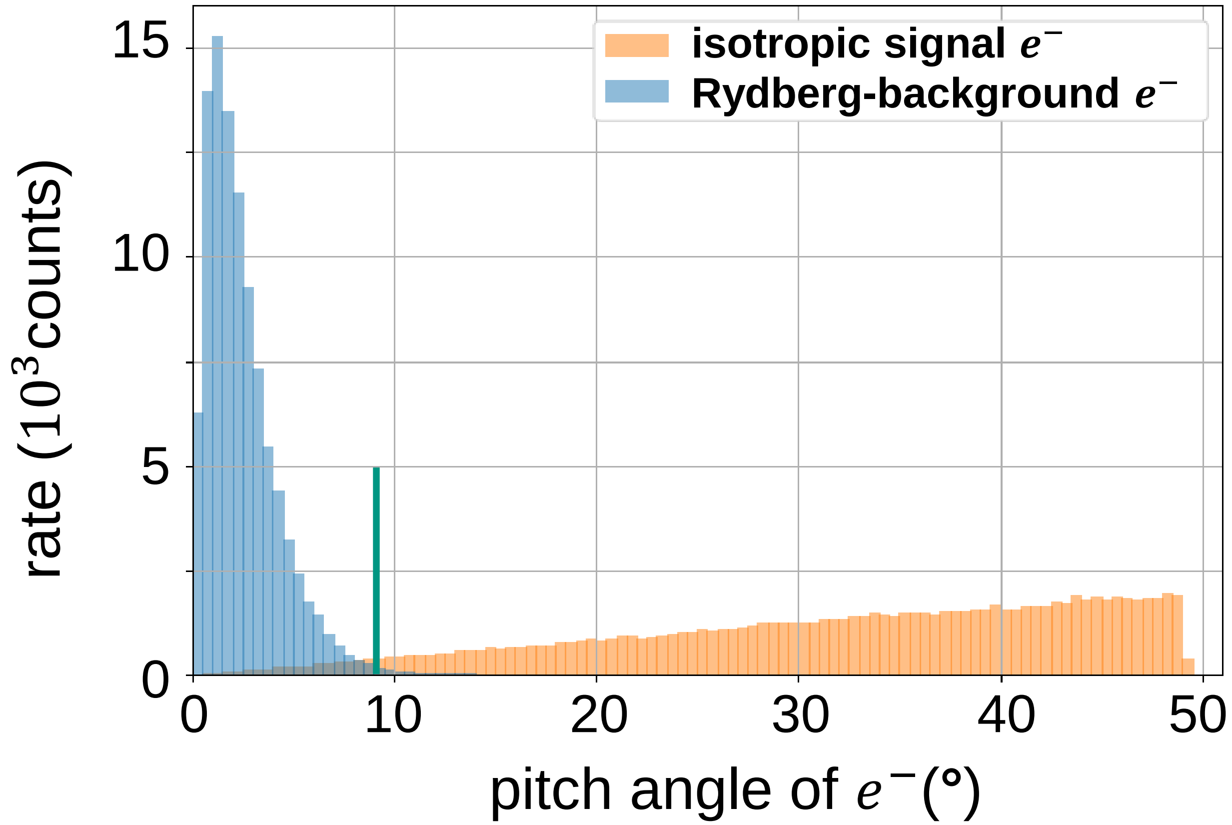
Signal/background discrimination via TEF

- **Transversal Energy Filter (TEF) to exploit different pitch angles**

- forward peaked background vs. isotropic ß-decay signal

- requires **micro-structured unit**
  to be deployed before FPD
  (⇨ filter cyclotron radius)



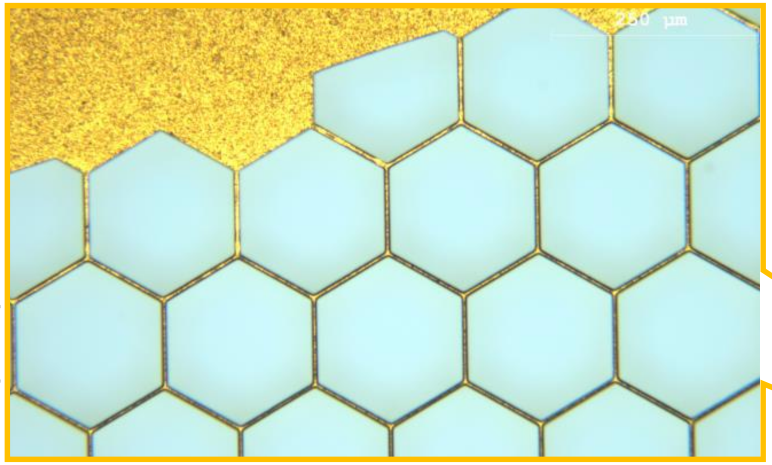


Background: study via passive TEF (pTEF)

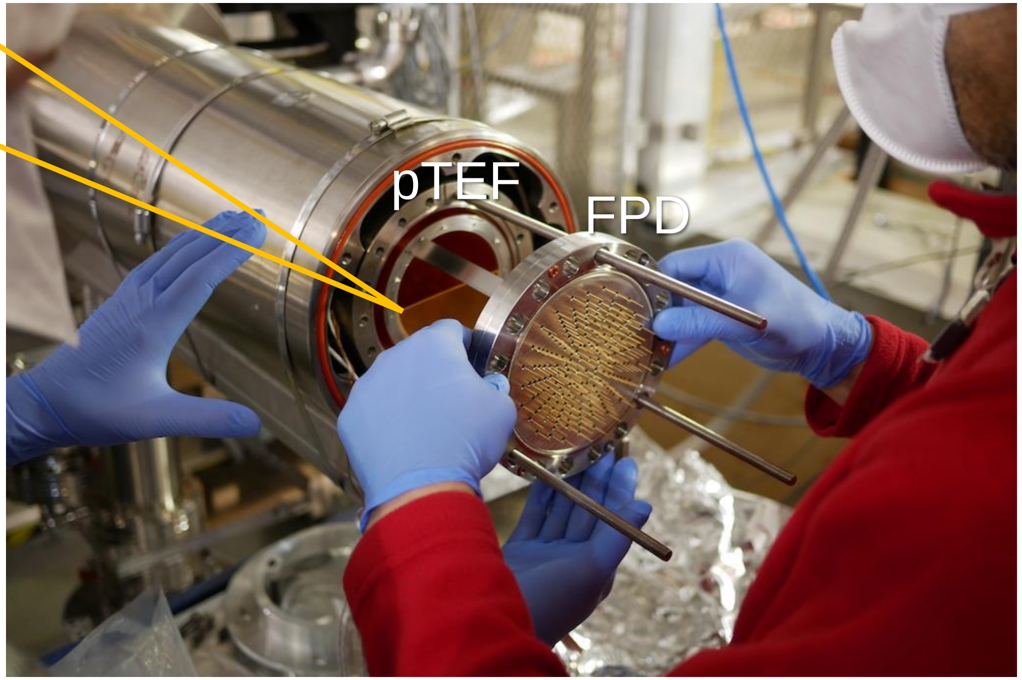
■ Step 1: validity of background model (Rydberg & autoionizing states)

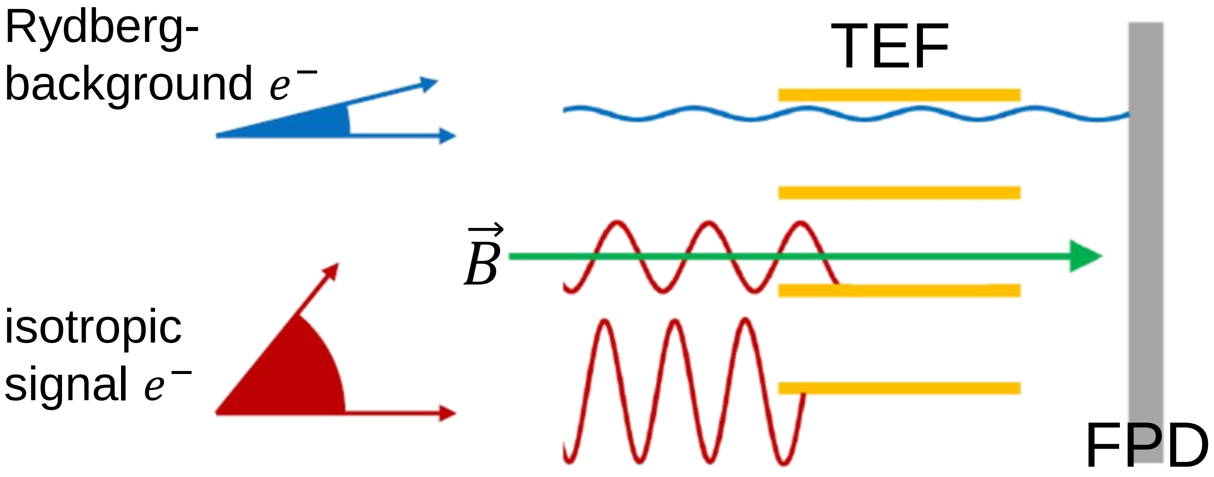
- pTEF located at centre of $\boldsymbol{B_{Det}}$

100 µm



- temporarily installed to study spectrometer background (⇨ energy scale of $\boldsymbol{e^-}$)

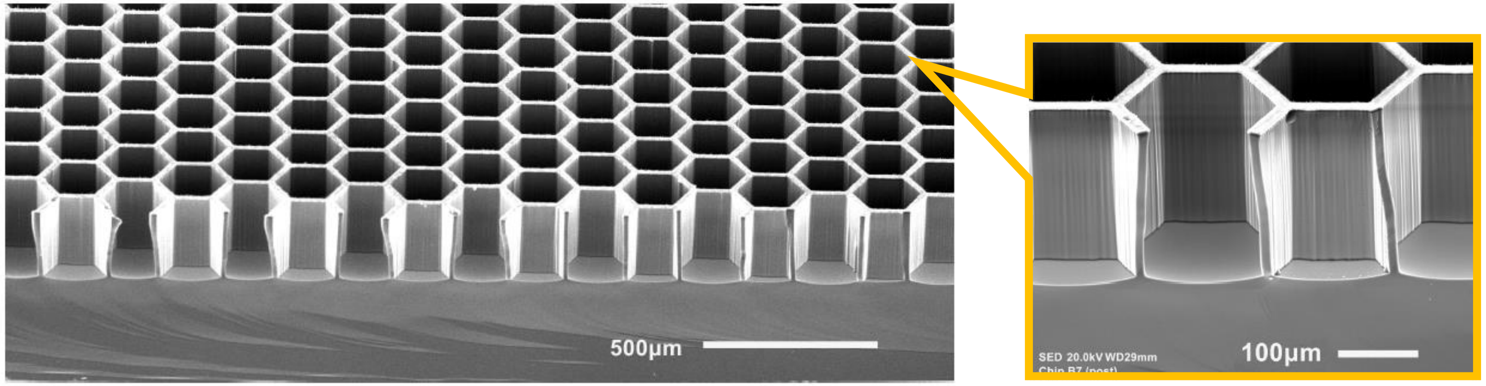




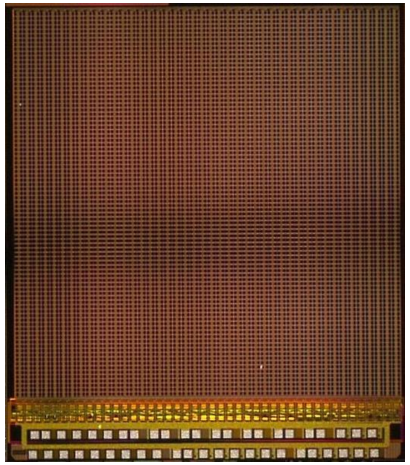
Background: suppression via active TEF (aTEF)

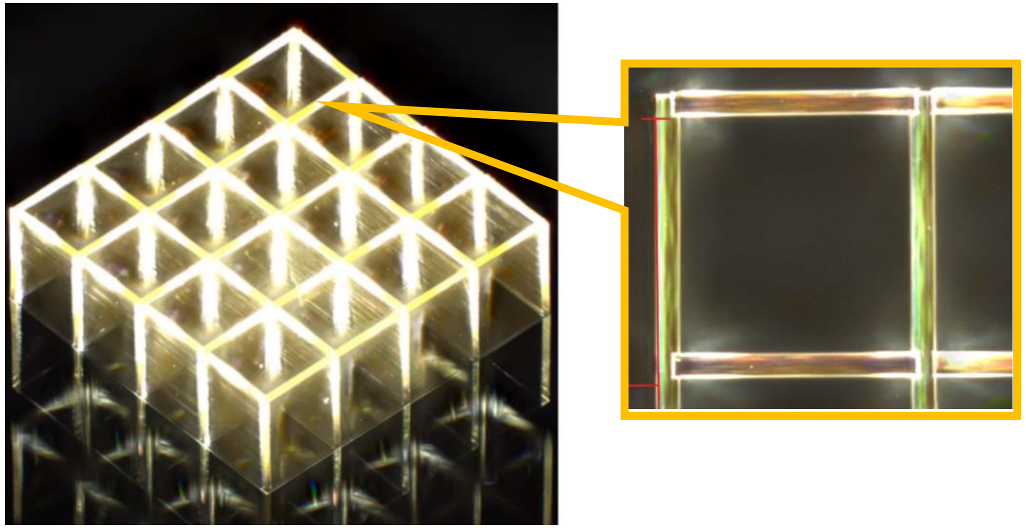
- **Step 2: microstructured detectors to suppress background**

  - University Münster:
    silicon-semiconductor –
    deep-teching process
    ⇨ **Si-aTEF**



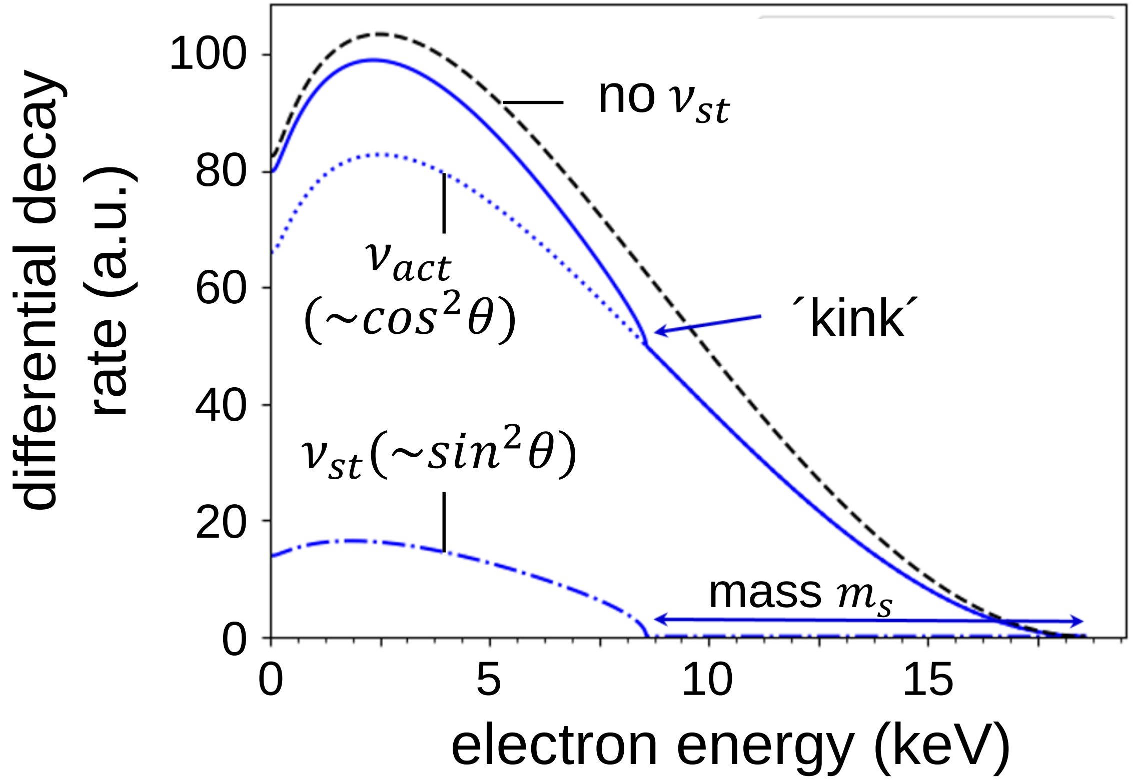
  - KIT / University of Heidelberg:
    3D-printed scintillator
    with SPAD-readout
    ⇨ **scint-aTEF**


Si-PMT



KATRIN future: search for keV-steriles

- **extending the measuring interval to the entire 18.6 keV phase space of T_2**
  - scans with high rates (up to 10^8 cps)

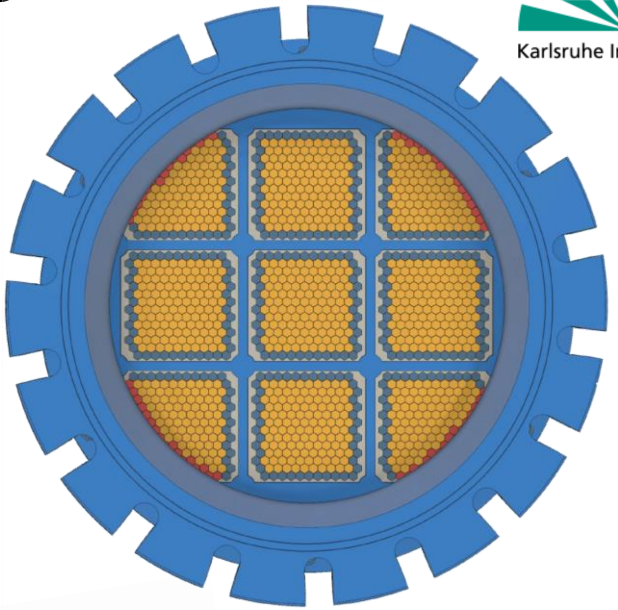


KATRIN future: search for keV-steriles

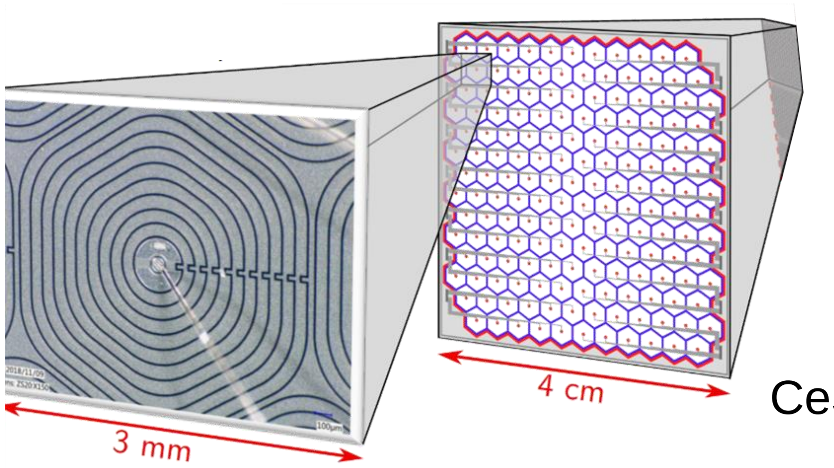
- **Silicon Drift Detectors: from a single pixel to a large monolithic SDD-array**

  - excellent energy resolution

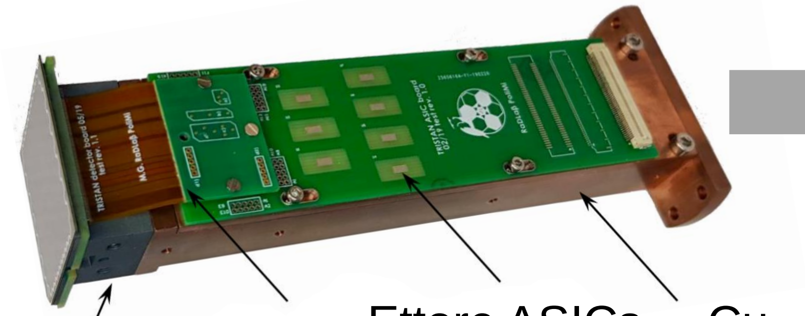
  - fast signals, able to handle huge rate of ß-decay electrons



TRISTAN array



166 SDD pixels

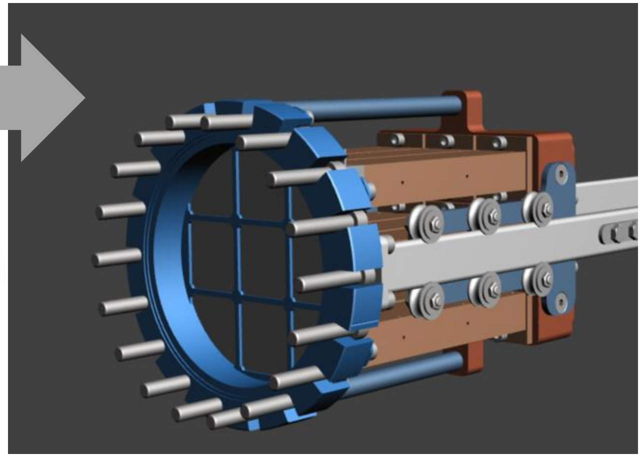


CeSiC thermal link

PCB

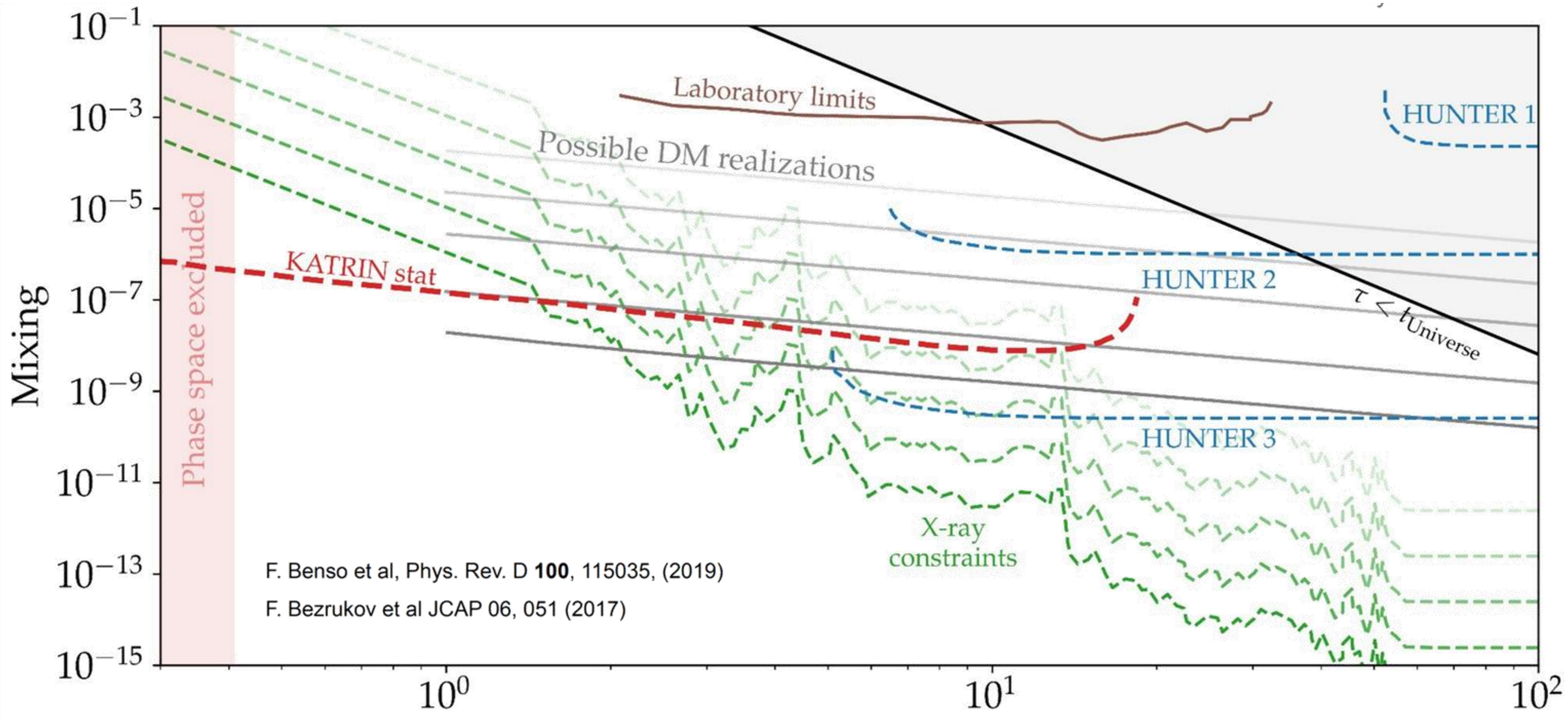
Ettore ASICs

Cu cooling



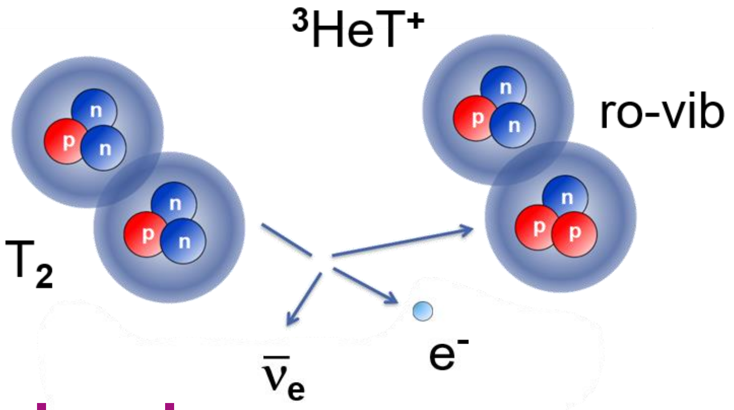
KATRIN sensitivity & other bounds

- KATRIN will advance experimental sensitivity by many orders

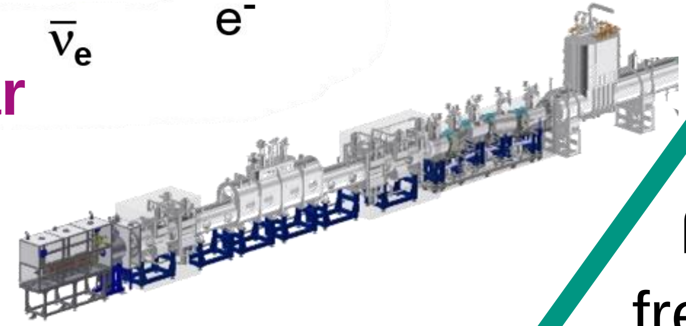


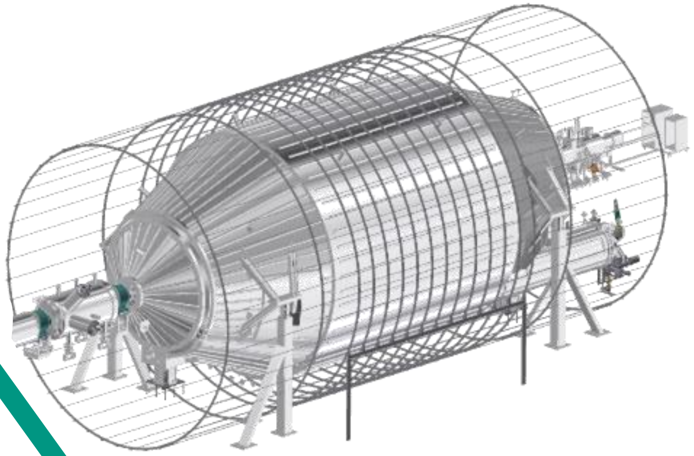
long-term future: from KATRIN to KATRIN++

- **R&D on novel source & read-out technologies**



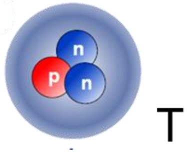
molecular tritium





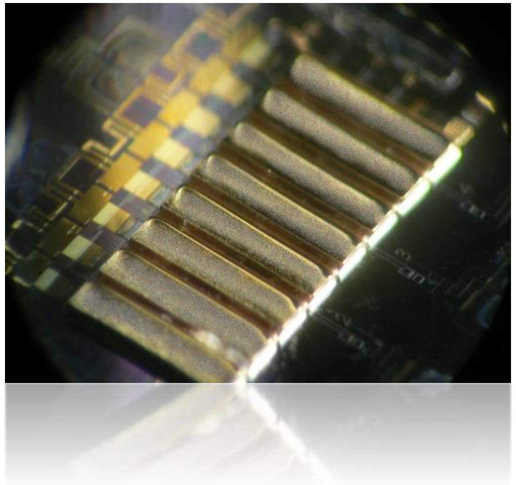
electrostatic Filter (MAC-E)

hi-res
differential
ß-spectroscopy
free of background
using atomic tritium beam



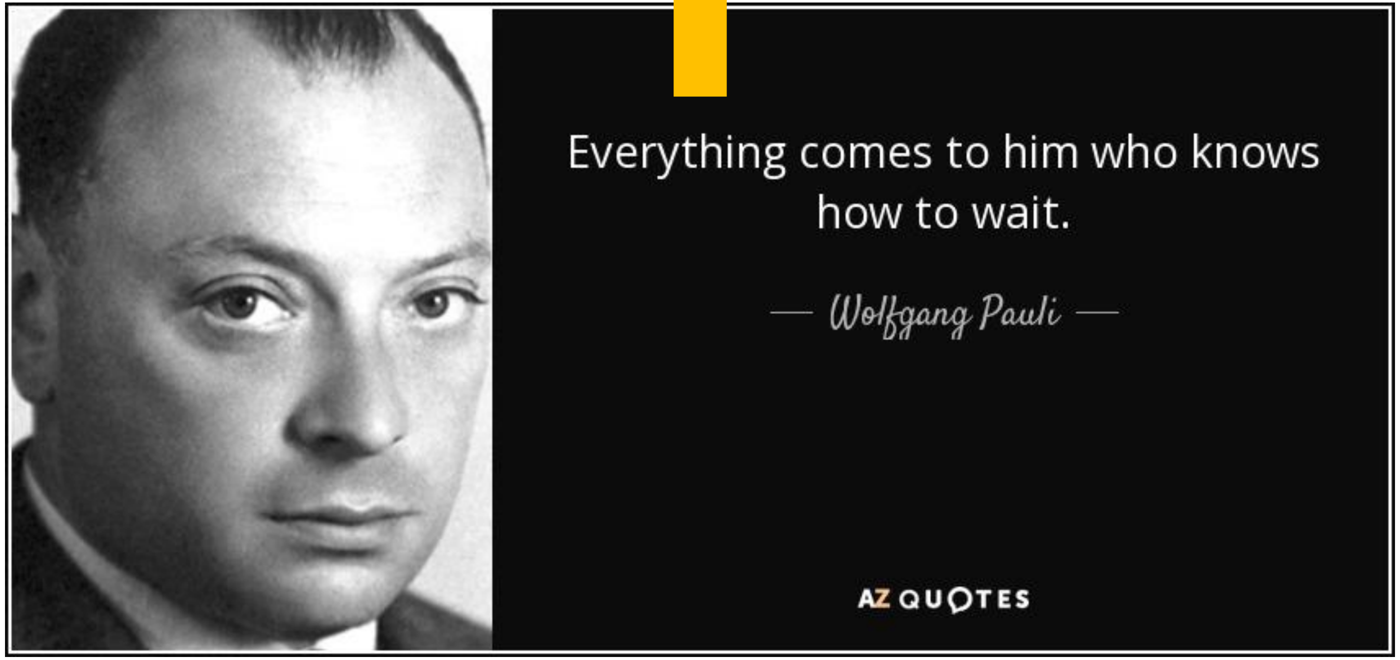
atomic tritium

quantum sensors



Direct neutrino mass searches – conclusion

ν-mass scale, BSM physics, eV/keV-steriles, relic ν´s,…



THANK YOU!