Direct Neutrino Mass Measurements

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23rd International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

CBPF, Rio de Janeiro, Brazil

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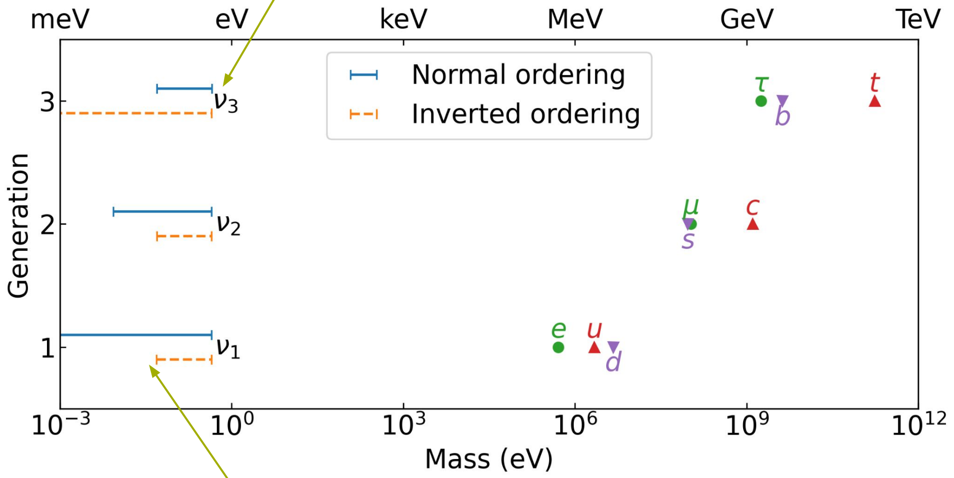
Motivation

- Neutrino oscillations imply **neutrinos have mass**

➔ **Insensitive** to **absolute mass scale**

➔ Neutrino **mass ordering** (hierarchy) not yet resolved

Direct measurements



with data from S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

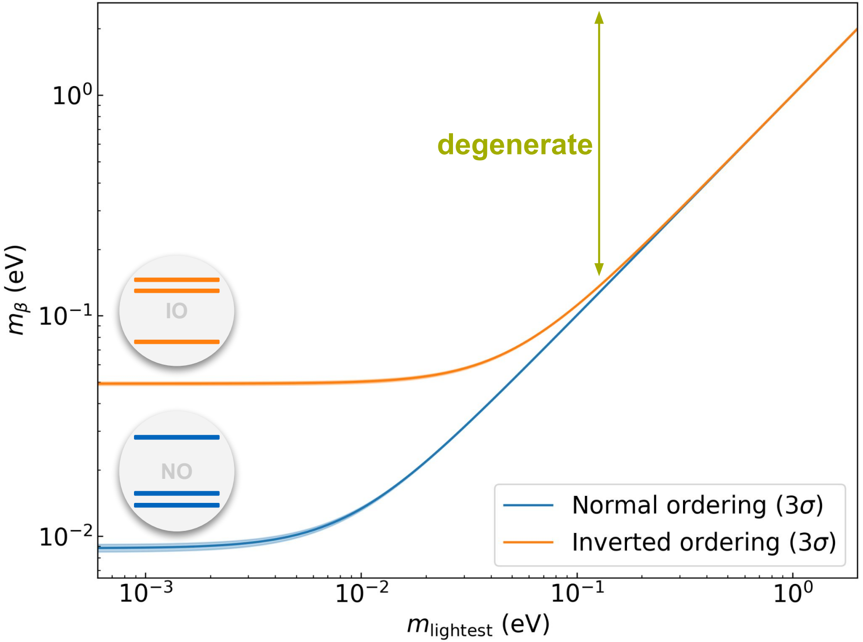
Oscillation experiments

Motivation

- **Direct measurements** rely only on **kinematics** of β-decay / electron capture (EC) decay

$$m_\beta^2 = \Sigma_i |U_{ei}^2| m_i^2$$

➔ **Independent** of neutrino nature



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MAC-E
for β-decay

m_β

CRES
for β-decay

Calorimetry
for EC-decay

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for β-decay

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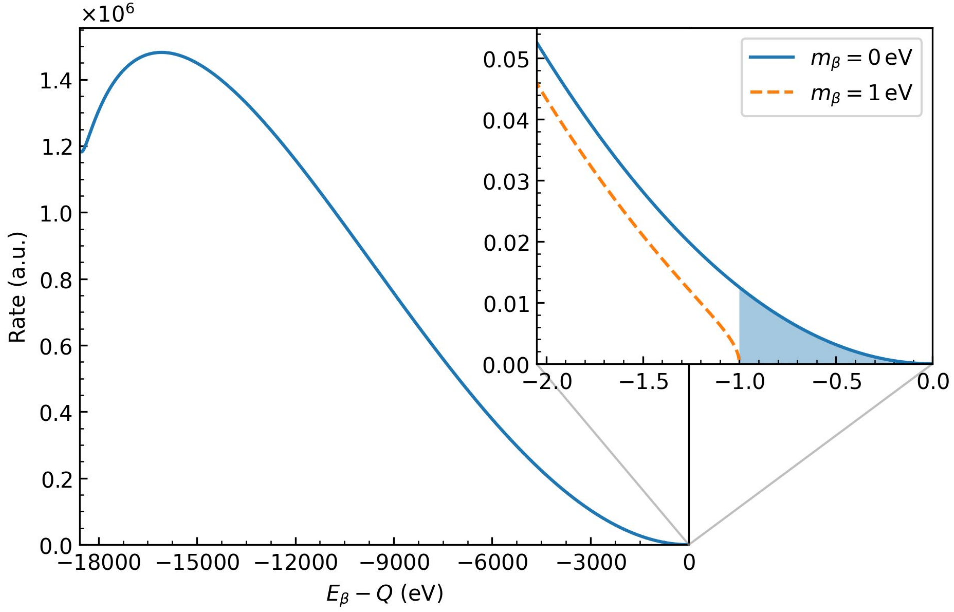
Calorimetry
for EC-decay

Tritium β-decay

- **β⁻– decay** (of molecular tritium)

$$T_2 \rightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$$

- Perform **electron spectroscopy**

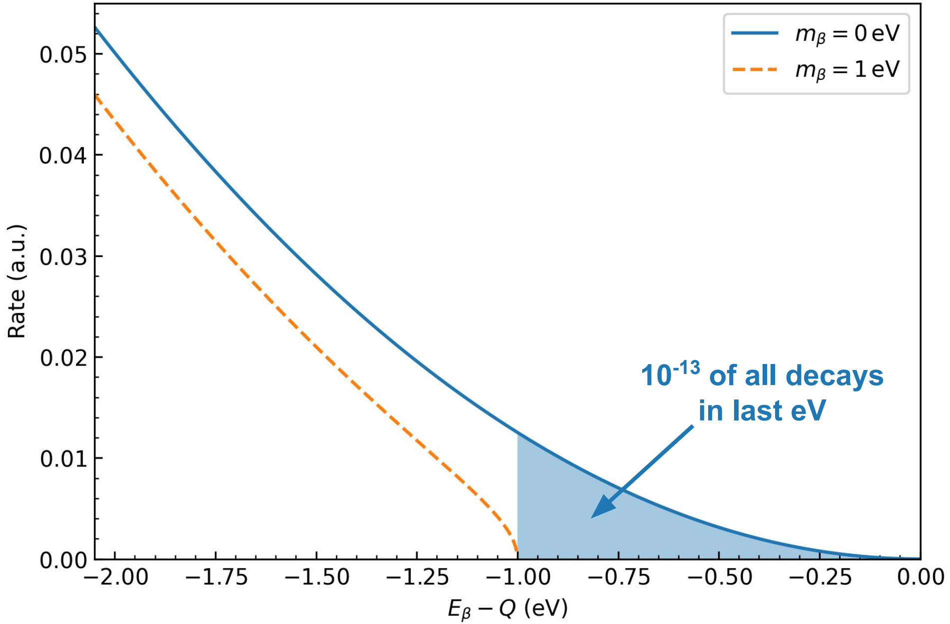


Tritium β-decay

- **β^-– decay** (of molecular tritium)

  $T_2 \rightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$

- Perform **electron spectroscopy**
- **Spectral distortion** near Q-value
  - ➔ **low background**
  - ➔ high **energy resolution** (~1eV)
- Tritium **half life** $\tau \approx 12.3$ years
- Tritium **Q** ≈ 18.6 keV

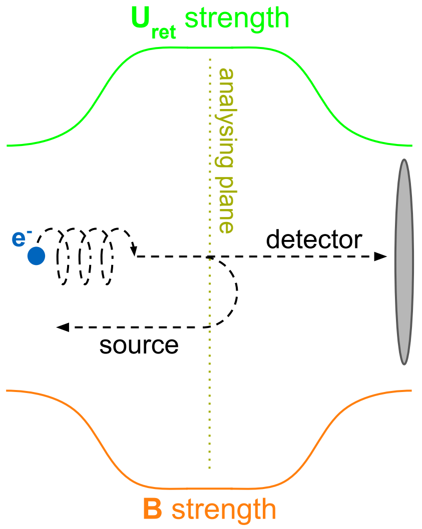


MAC-E filter

- **M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter

➔ **High-pass filter** for electrons

$$E_{||} > qU_{ret}$$



MAC-E filter

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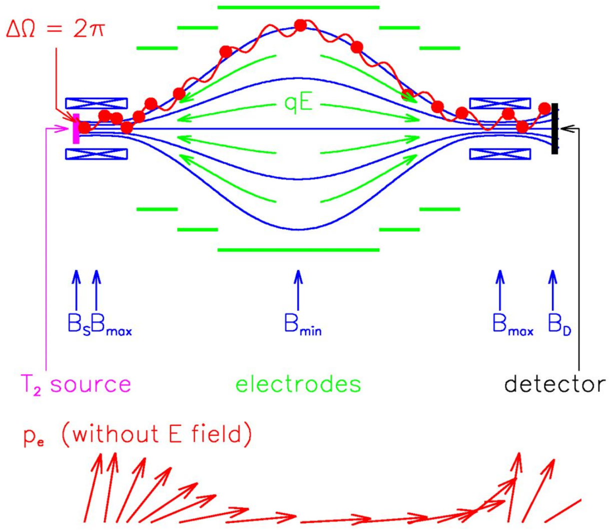
➔ **High-pass filter** for electrons

$$E_{||} > qU_{ret}$$

- High luminosity, **integral measurement**

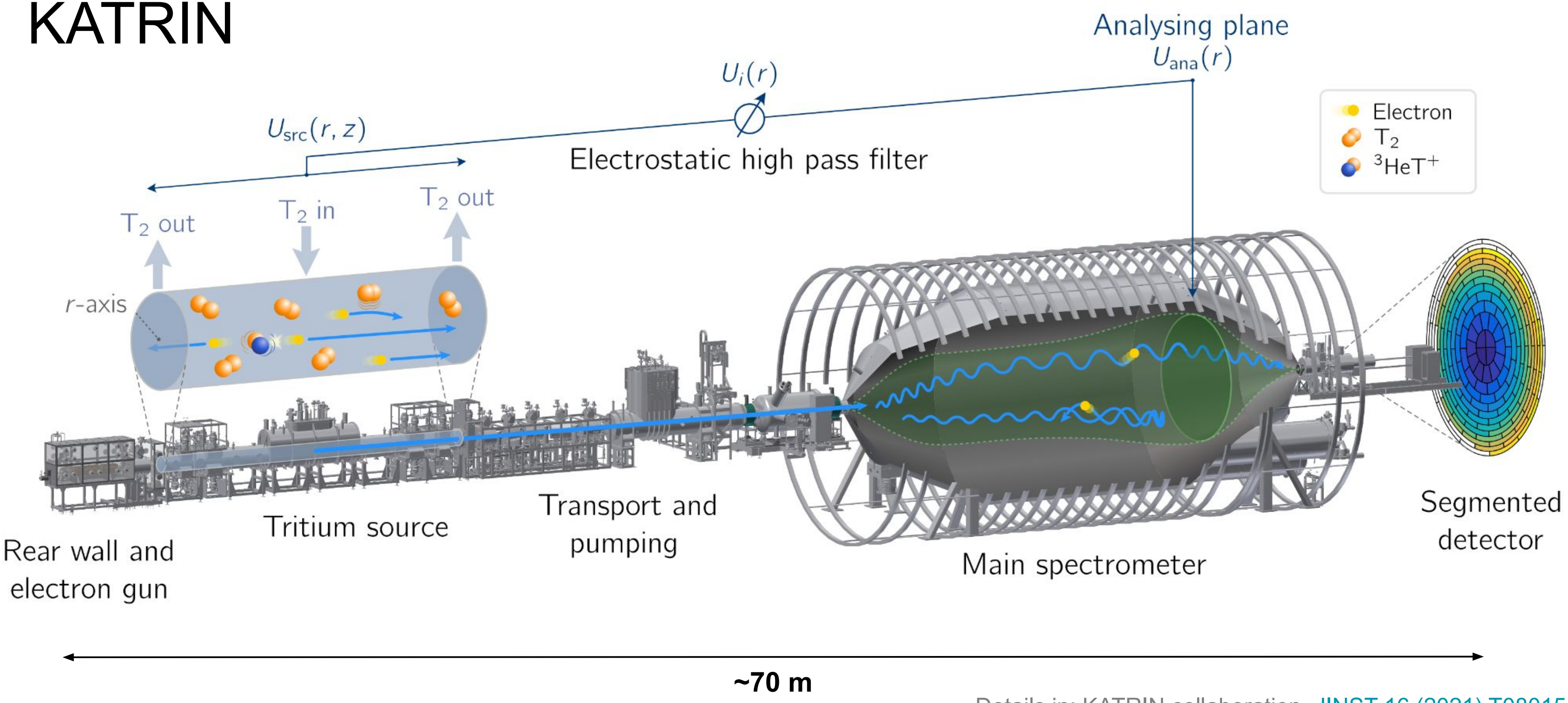


KATRIN collaboration

KATRIN

- Situated at Karlsruhe Institute of Technology
- International collaboration (~150 members)
- First science run in 2019

KATRIN

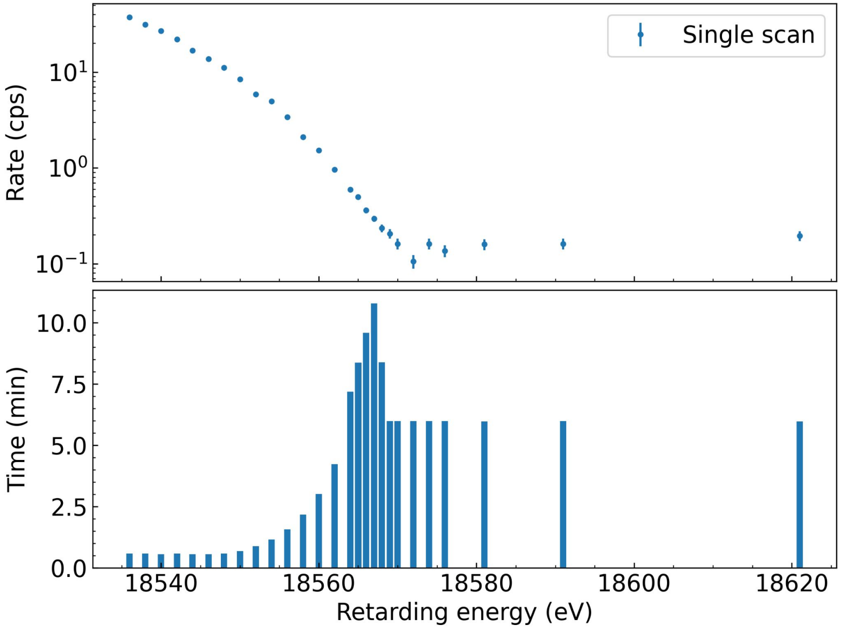


Details in: KATRIN collaboration, [JINST 16 (2021) T08015]

KATRIN measurement strategy

- **MAC-E filter**: Only electrons with $E_{||} > qU_{ret}$ reach the detector
  - ➔ Vary retarding energy to **scan spectrum**
  - ➔ Count events at the detector
  - ➔ **Integral spectrum** (2-3h in total)

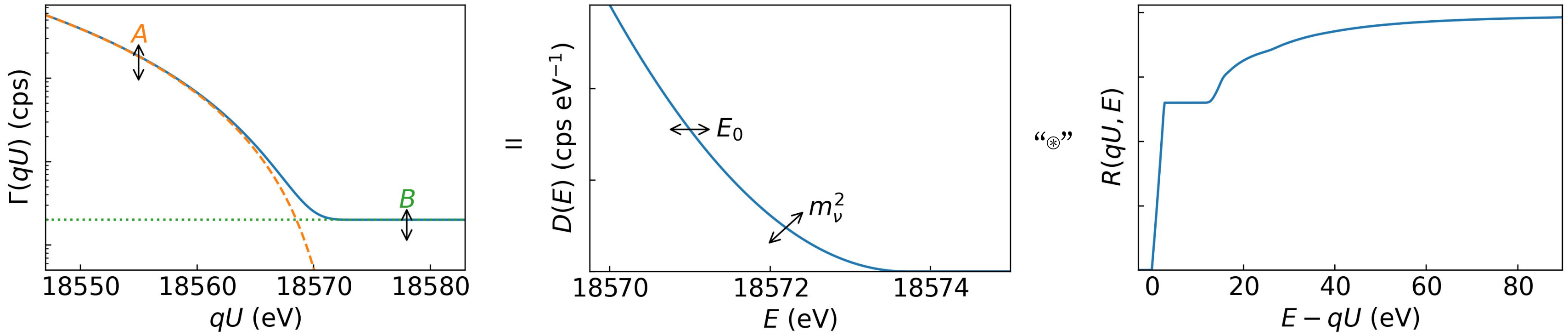
➔ **Repeat** scanning procedure a few 100 times to obtain **one measurement campaign**



KATRIN analysis strategy

- Maximum likelihood fit of **model:**

$$\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$$



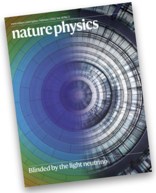
with free **amplitude** A, **squared neutrino mass** m_β^2, **endpoint** E_0 and **background** B

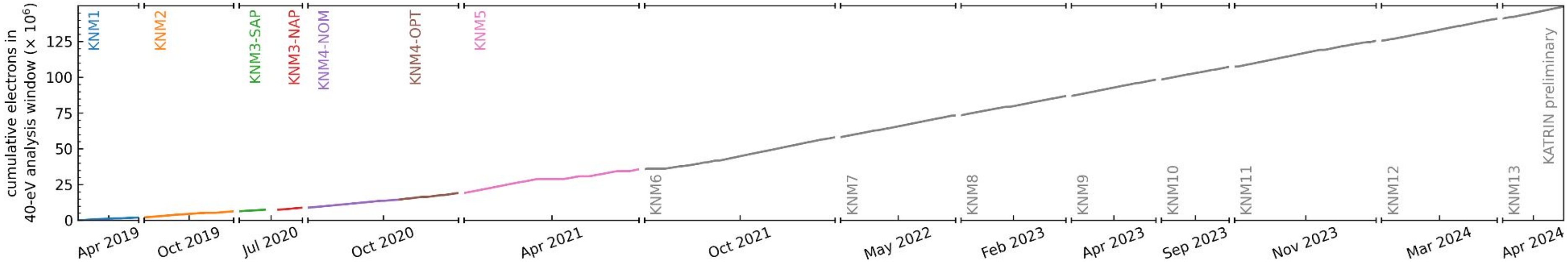
- **Theoretical** (Fermi theory, molecular excitations) and **experimental** inputs (calibration measurements)
- Two-step **blinding** procedure (simulated data, blinded model)

Current status

m_β < 0.8 eV (90% CL)

[Aker et al., Nature Phys. 18 (2022) 2, 160-166]





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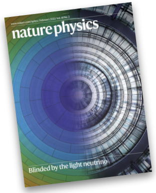

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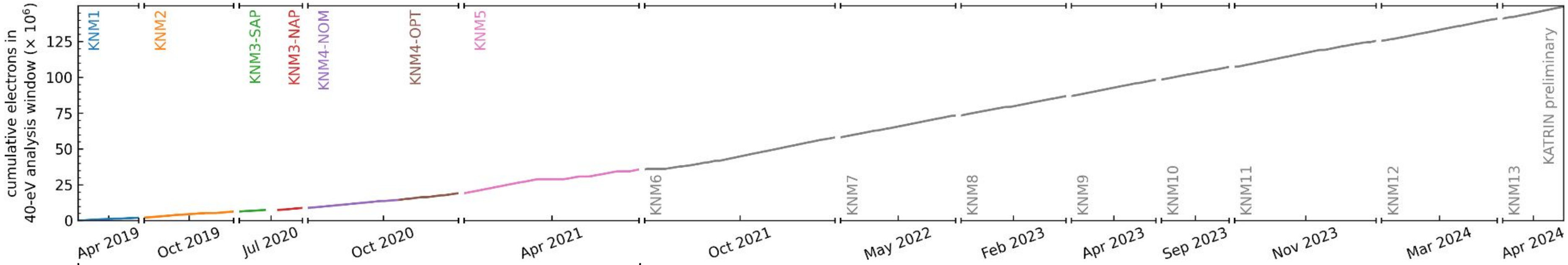
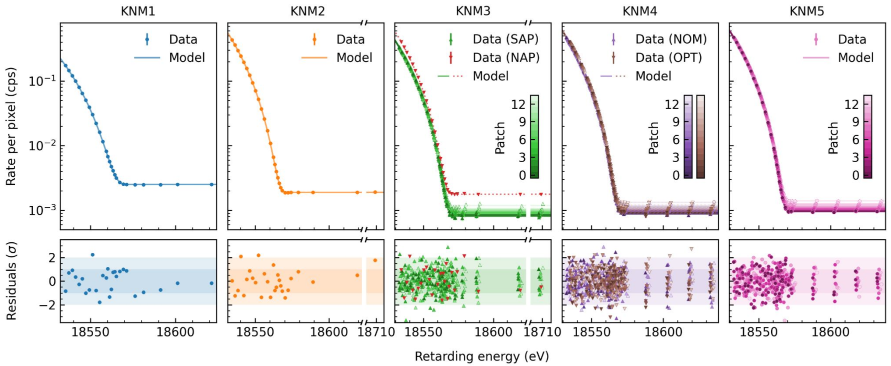


m_β < 0.45 eV (90% CL)

[Aker et al., arxiv: 2406.13516]

to be publishd soon



KATRIN latest results

- **259 days** of KATRIN data, ~**36 Mio** electrons
- **Best fit** consistent with zero

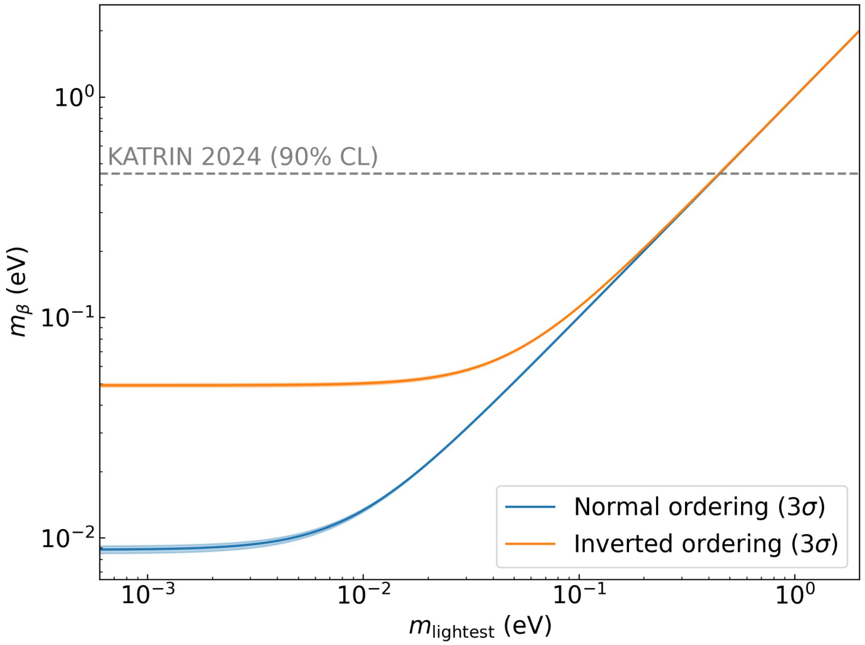
  $$\mathbf{m_\beta^2 = -0.14^{+0.13}_{-0.15}\ eV^2}$$

- New **world-leading** upper limit

  $$\mathbf{m_\beta < 0.45\ eV}\ \text{(90\% CL)}$$

- Dominated by **statistical uncertainty**

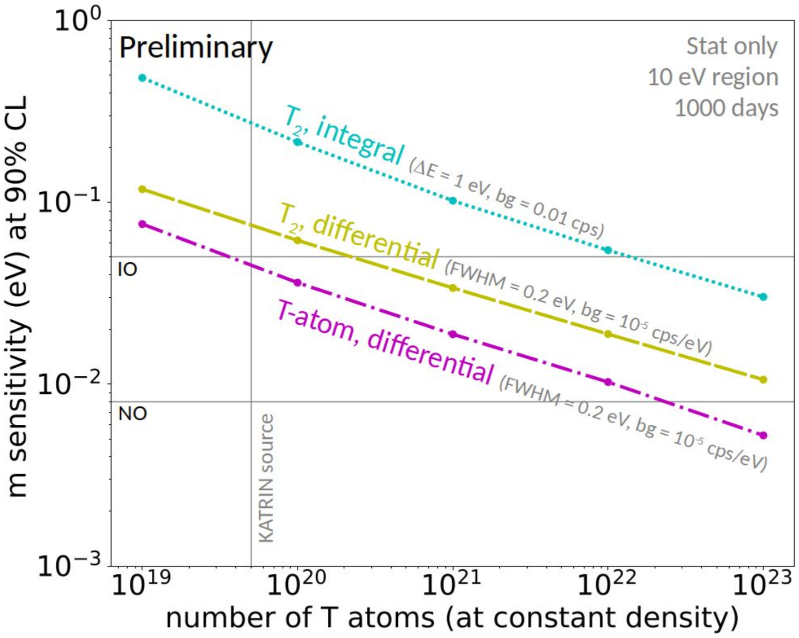
➔ **Measuring** continues, goal: **1000 days** of KATRIN data



with data from S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Beyond KATRIN

- **Leverage** existing **infrastructure**
- First **R&D projects** already launched
  - **New detector concepts**, e.g. micro-calorimeters
    - ➔ differential measurement
  - **Atomic source**
    - ➔ avoid limiting systematics of T_2



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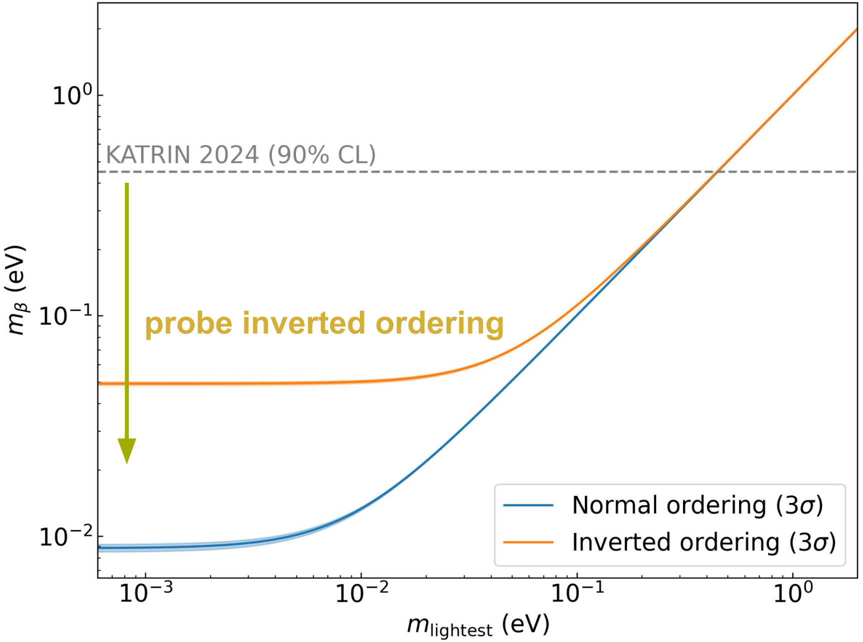
➔ Probe **inverted ordering** regime



MAC-E
for β-decay

m_β

CRES
for β-decay

Calorimetry
for EC-decay

Cyclotron Radiation Emission Spectroscopy (CRES)

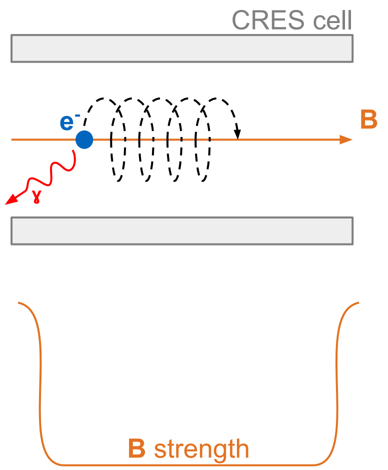
- Measurement of **cyclotron frequency** from **trapped electrons**

$$f_c = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

Esfahani et al., PRL 131, 102502 (2023)

- **Background free, differential** measurement

- **eV-scale** energy resolution



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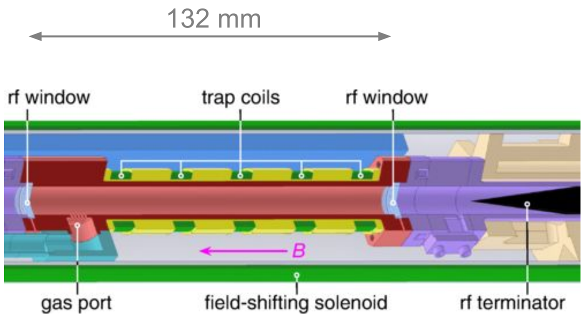
- **Background free, differential** measurement
- **eV-scale** energy resolution

➔ Very **homogenous B-field** needed

➔ Detection of **low-power radiation** (few fW at 1 T)

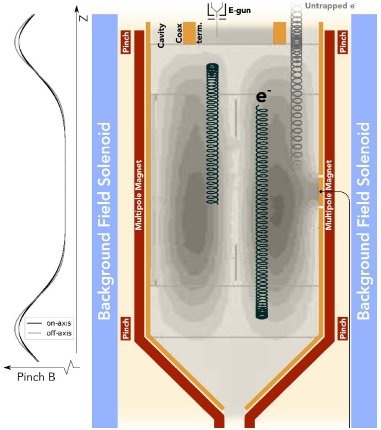


Project 8 CRES cell,
adapted from Esfahani et al., PRL 131, 102502 (2023)

Experiments

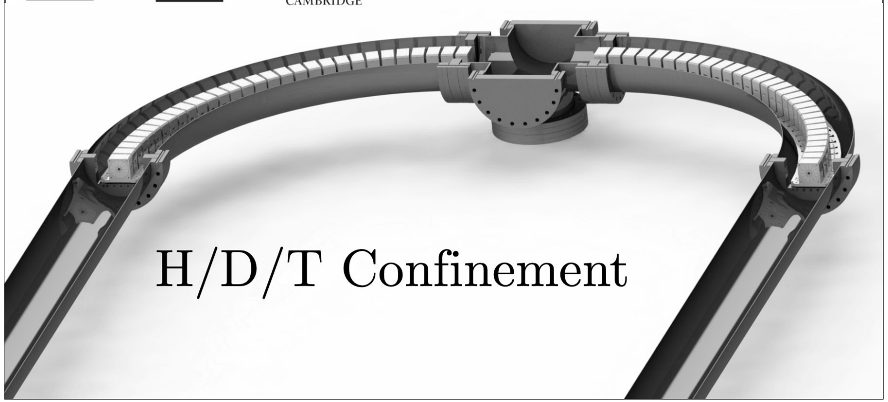
Project-8

- Cavity CRES + cold atomic tritium trap



QTNM

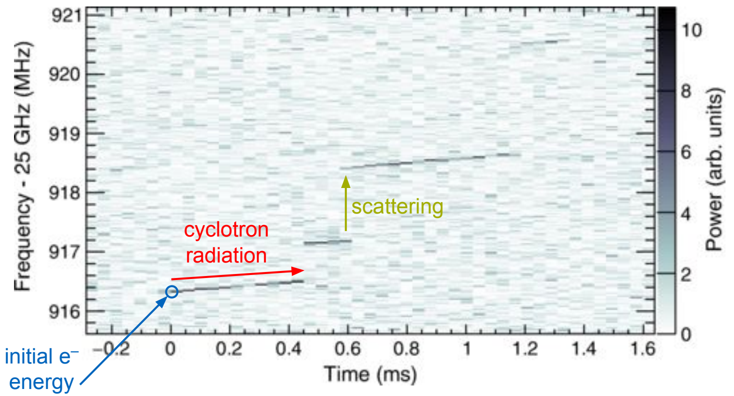
- Storage ring confinement
- New effort, conceptual stage



Project 8

➔ **First CRES event** detected from a **T_2 β-decay electron**

Esfahani et al., PRL 131, 102502 (2023)



Project 8

- ➔ **First CRES event** detected from a **T_2 β-decay electron**
- ➔ **No background** above Tritium endpoint observed

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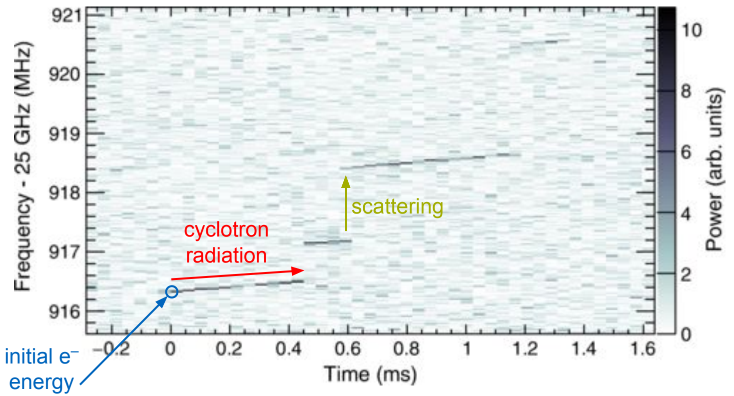

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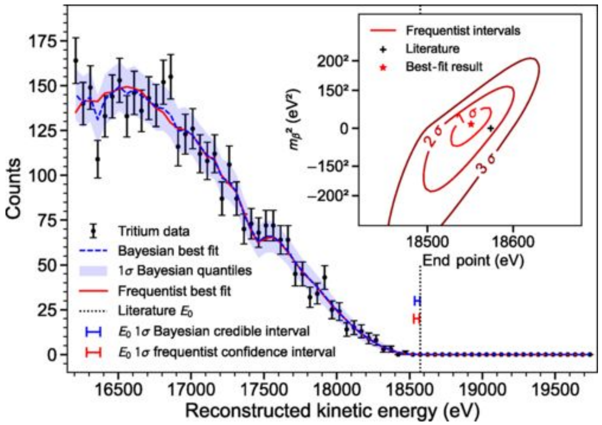

- ➔ First **frequency-based** upper limit: **m_β< 155 eV** (90 % CL)

Esfahani et al., PRL 131, 102502 (2023)

- ➔ Development of a **large-volume CRES** and an **atomic Tritium source**

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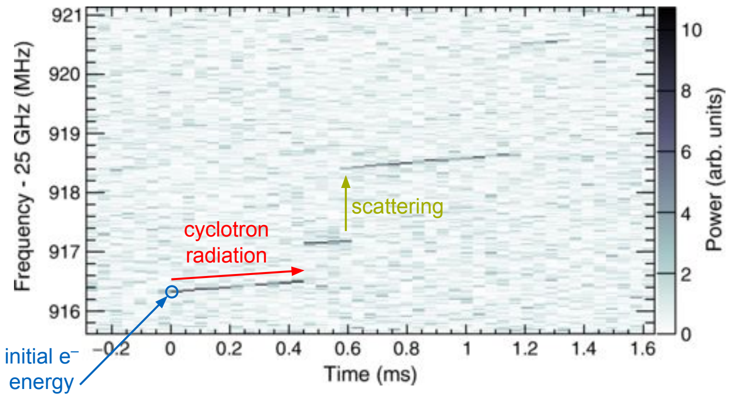
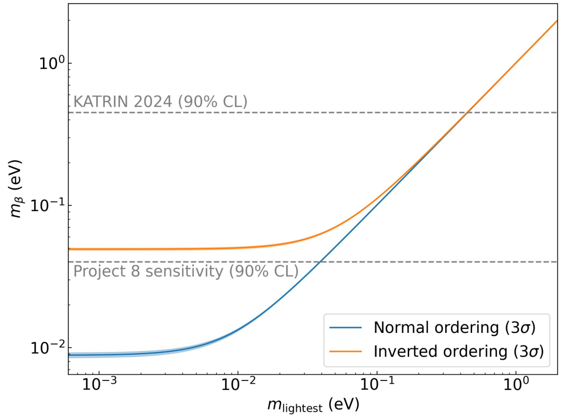




➔ First **frequency-based** upper limit:
m_β< 155 eV (90 % CL)

Esfahani et al., PRL 131, 102502 (2023)

➔ Development of a **large-volume CRES** and an **atomic Tritium source**

➔ **Goal:** Probe down towards **40 meV**

MAC-E

for β-decay

m_β

CRES

for β-decay

Calorimetry

for EC-decay

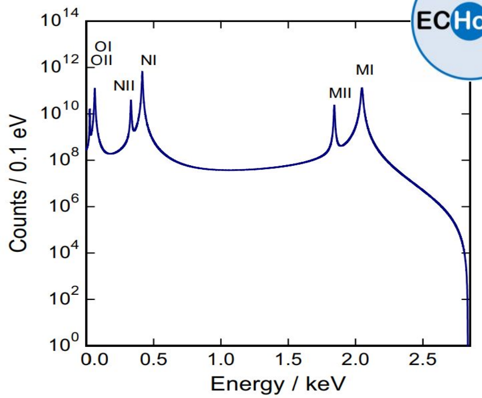
Holmium EC decay

- **Electron capture** (EC) decay (of ^{163}Ho):

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

  $^{163}\mathrm{Dy}^* \rightarrow {}^{163}\mathrm{Dy} + E_c$

- De-excitation leads to **electron cascade**



Gastaldo et al., EPJ Spec. Top. 226, 1623–1694 (2017).

Holmium EC decay

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

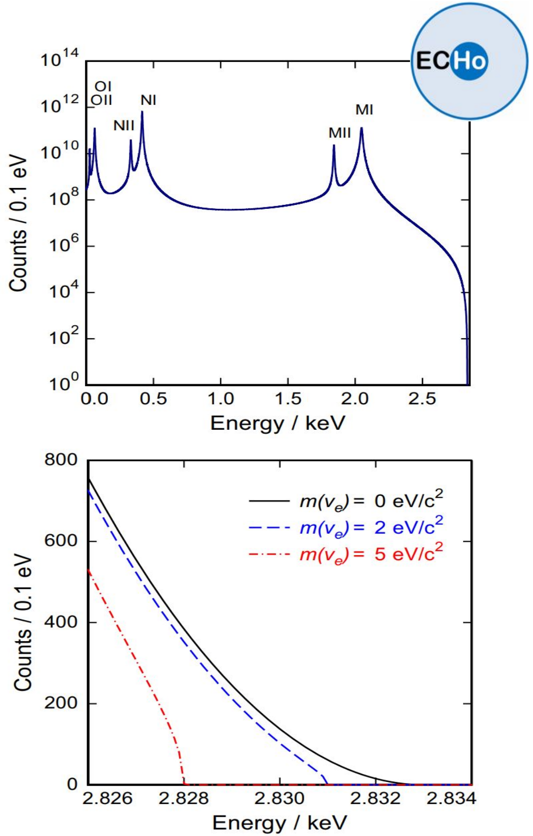
  $^{163}\mathrm{Dy}^* \rightarrow {}^{163}\mathrm{Dy} + E_c$

- De-excitation leads to **electron cascade**

➔ **Spectral distortion** near Q-value

- **Half life** $\tau \approx$ 4570 years

- $\mathbf{Q_{EC}} \approx$ 2.8 keV



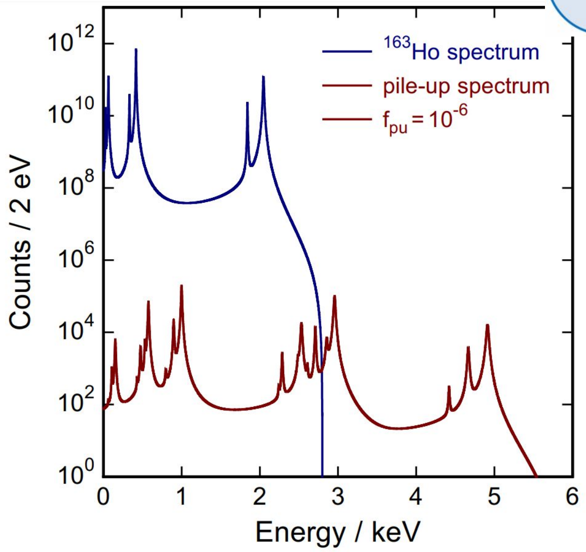
Gastaldo et al., EPJ Spec. Top. 226, 1623–1694 (2017).

Holmium EC decay

- **Precise modelling** of spectrum necessary
- Limit **unresolved pile-up**

➔ High number of **individual pixels**

➔ **Fast read-out** system

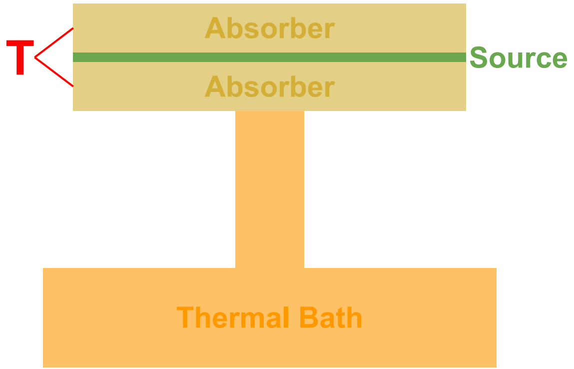


Gastaldo et al., EPJ Spec. Top. 226, 1623–1694 (2017).

Calorimetry

- **Source implantation** in detector material
- Measurement of **temperature** change: **calorimetric measurement**
- Performed using **low-temperature micro-calorimetry**

➔ **Low background**, **differential** measurement

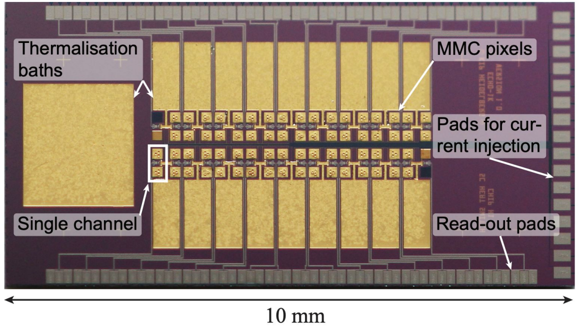


Experiments

ECHo

- Metallic magnetic calorimeters (MMC)

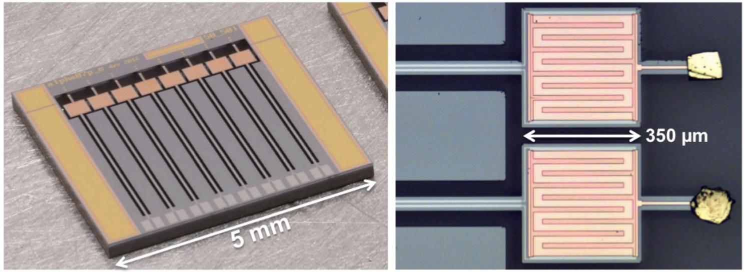
L. Gastaldo et al., Eur. Phys. J. Spec. Top. 226 (2017)



Holmes

- Transition edge sensors (TES)

Hays-Wehle et al., *J Low Temp Phys* **184**, 492-497 (2016)

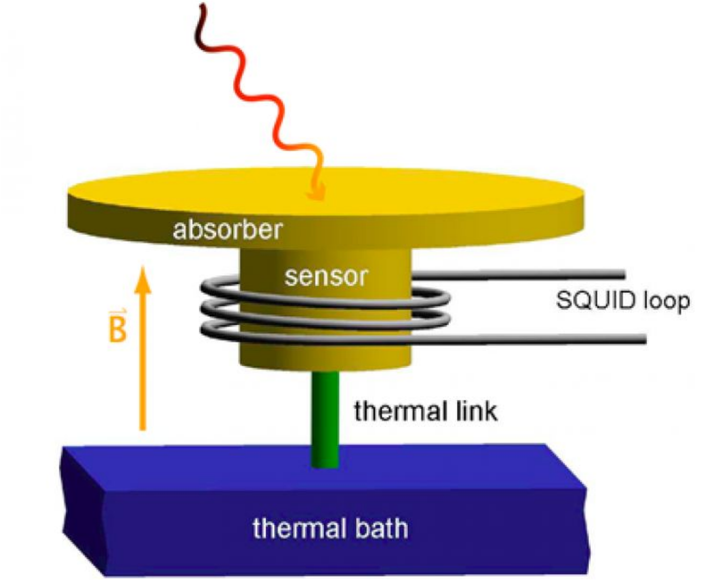


ECHo

- Use of **metallic magnetic calorimeters** (MMCs)

➔ Measure change of **magnetization** due to **temperature increase**

- Enables **high energy resolution**



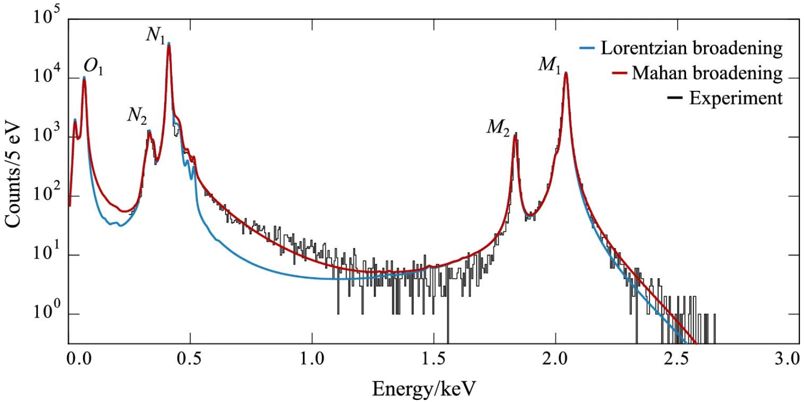
ECHo Collaboration

ECHo

- Use of **metallic magnetic calorimeters** (MMCs)

➔ Measure change of **magnetization** due to **temperature increase**

- Enables **high energy resolution**



Velte et al., [EPJ C 79, 1026 (2019)]

ECHo

- ECHo prototype (2019): **m_β< 150 eV** (95 % CL)

  Velte et al., [EPJ C 79, 1026 (2019)]

- ECHo-1k (2024): **m_β< 19 eV** (90 % CL)

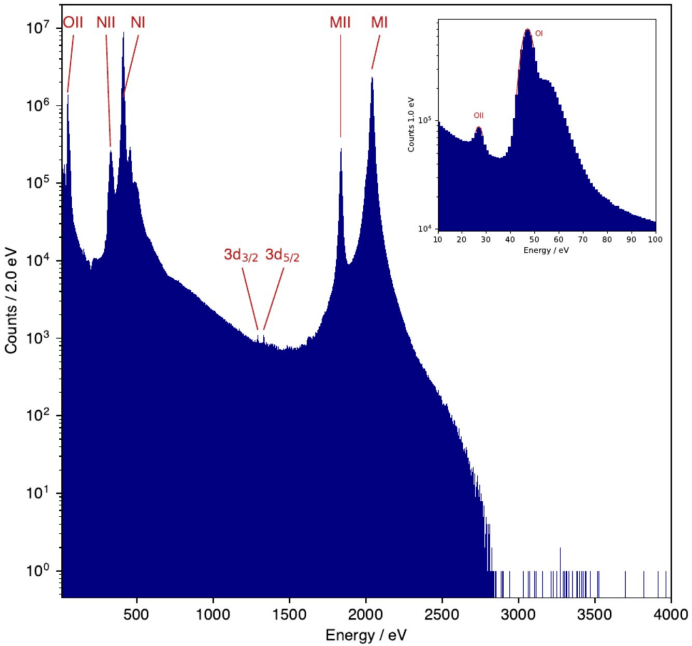
  Talk by Nucciotti at [Neutrino 2024]

  - **~1 Bq / pixel**
  - **$\Delta E_{FWHM} \approx$ 10 eV**

- Echo-100k: Sensitivity of **1.5 eV** (90 % CL)

  Increase **number of pixels** and **activity**

- Target sensitivity: **low sub-eV** level

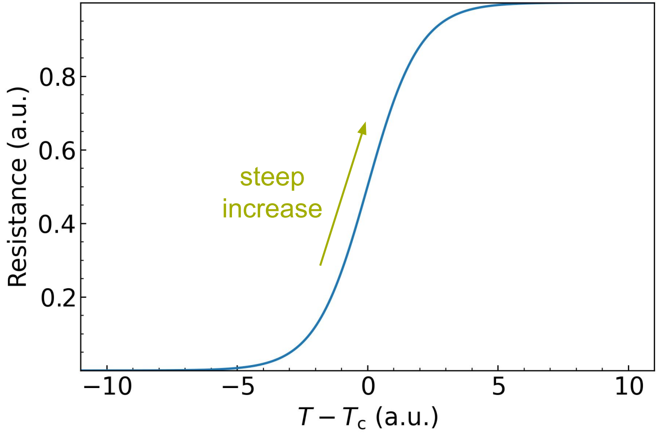


Talk by Nucciotti at [Neutrino 2024]

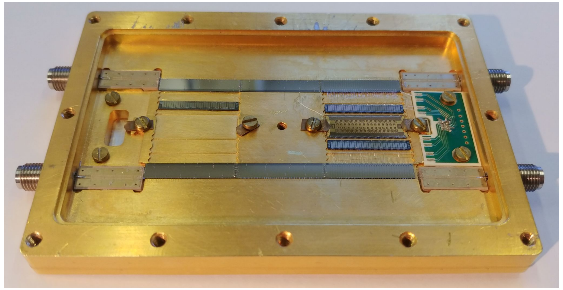
HOLMES

- Use of **transition edge sensors** (TES)

➔ Measure change of **resistance** due to **temperature increase**



- ~50 active detectors
- **~0.3 Bq / pixel**
- **$\Delta E_{FWHM} \approx 7$ eV**



see talk by Nucciotti at [Neutrino 2024]

HOLMES

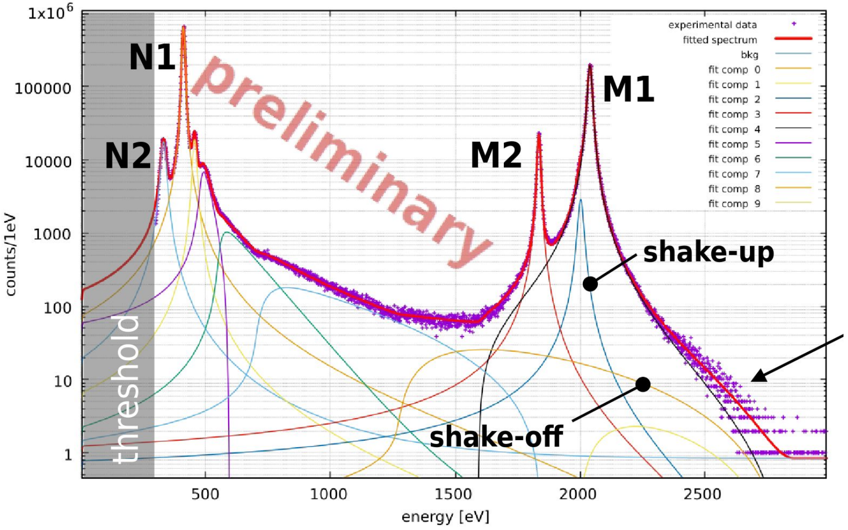
- Use of **transition edge sensors** (TES)

➔ Measure change of **resistance** due to **temperature increase**

- First preliminary result: $\mathbf{m_\beta < 28\ eV}$ (90 % CL)

  Talk by Nucciotti at [Neutrino 2024]

- Target sensitivity: low **sub-eV** level

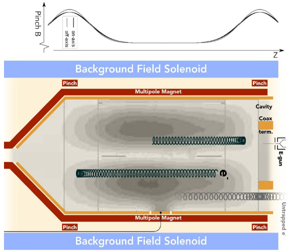


Talk by Nucciotti at [Neutrino 2024]

Conclusion

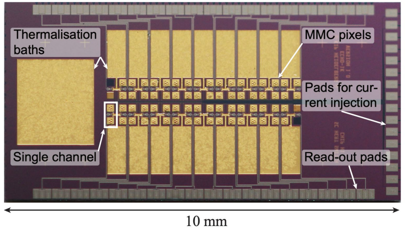
KATRIN

- New **leading upper limit** from **KATRIN**: **m_β< 0.45 eV**
- **Continue** measuring, target **sensitivity m_β< 0.2 eV**
- **R&D** phase started for **atomic source** and **micro-calorimeters**



Project 8

- First **frequency-based** upper limit from **Project 8: m_β< 155 eV**
- Development of **large-volume CRES** and **atomic source**



ECHo and HOLMES

- New / updated results: **m_β< 19 eV** (ECHo) and **m_β< 28 eV** (HOLMES)

➔ Increase **number of detectors** and **activity**

Thank you for your attention!

and thanks to the KATRIN collaboration
Project-8 collaboration
ECHo collaboration
Holmes collaboration
QTNM collaboration

KATRIN Collaboration meeting, October 2024

Karlsruher Institut für Technologie · BERKELEY LAB · Nuclear Physics Institute · Bergische Universität Wuppertal · Universität Heidelberg Zukunft seit 1386 · Max-Planck-Institut für Physik · The University of North Carolina at Chapel Hill · University of Washington · Johannes Gutenberg Universität Mainz · Carnegie Mellon University · Universität Münster · UAM Universidad Autónoma de Madrid · Universität Bonn · Università degli Studi di Milano Bicocca · INFN · Politecnico Milano 1863 · Chula Chulalongkorn University

Backup

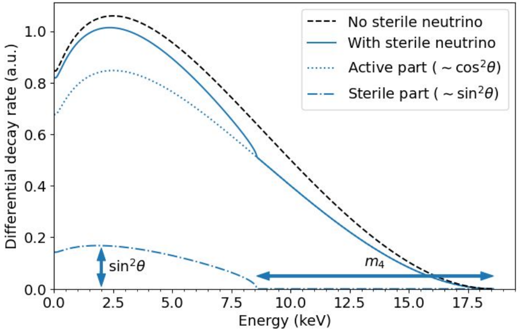
KATRIN timeline

end of 2025 | **end of 2027**

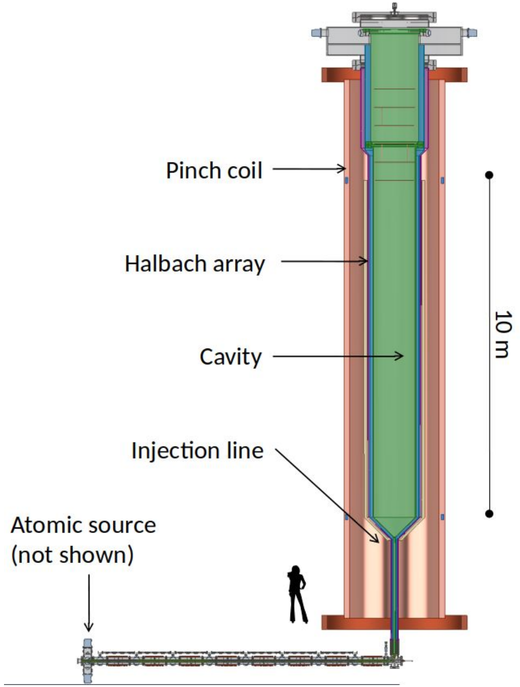
neutrino mass | keV-sterile neutrino search with TRISTAN | beyond KATRIN

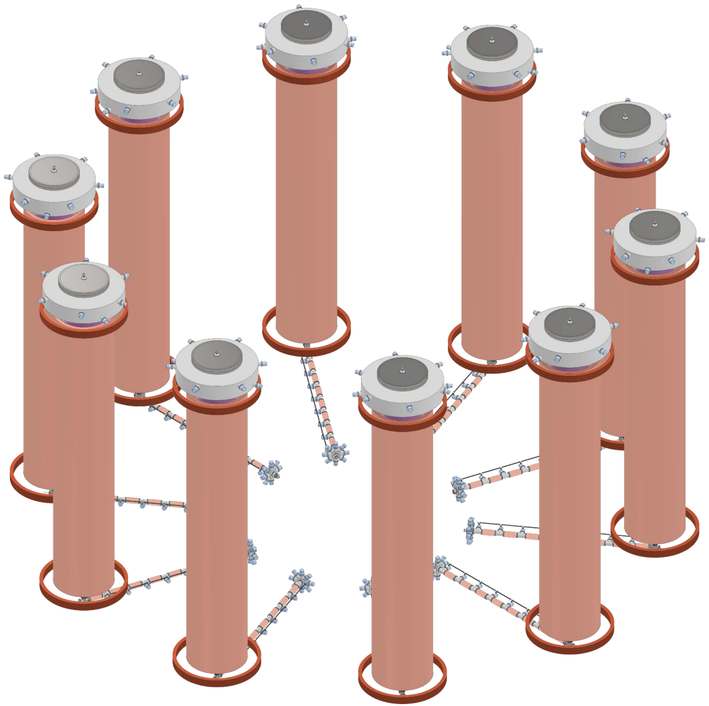
- Measurement of **full tritium spectrum**
- Installation of ~1000-pixel **silicon drift detectors**

  Carminati et al., [NIM A 1049 (2023) 168046](NIM A 1049 (2023) 168046)



Project 8

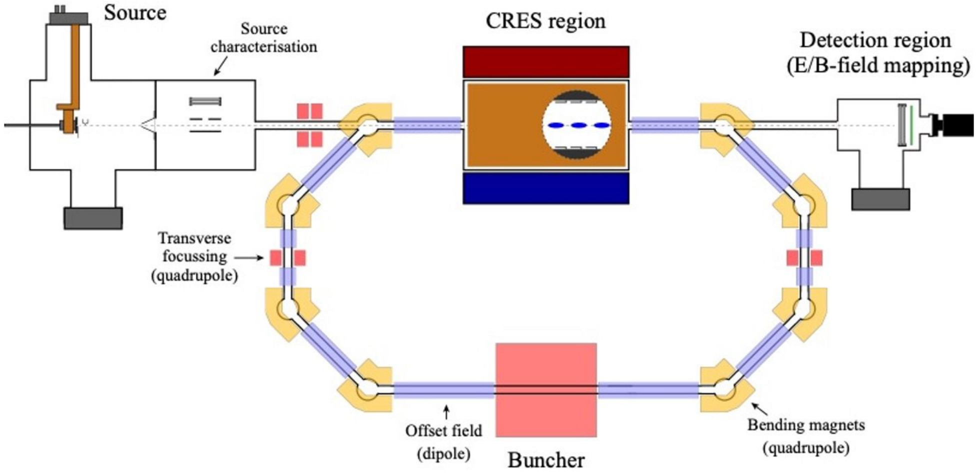

Pinch coil
Halbach array
Cavity
Injection line
Atomic source
(not shown)
10 m



Quantum Technologies for Neutrino Mass

- **Confine H/D/T** atoms with **storage ring**

➔ β-decay in **CRES region**, detection of cyclotron radiation using **quantum amplifiers**



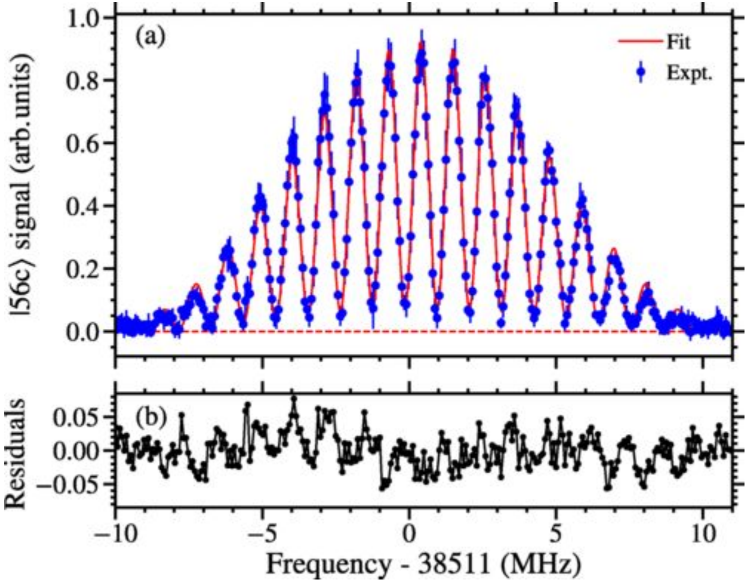
QTNM collaboration

Quantum Technologies for Neutrino Mass

- **Confine H/D/T** atoms with **storage ring**

➔ β-decay in **CRES region**, detection of cyclotron radiation using **quantum amplifiers**

- **Rydberg Magnetometry** (**<1μT** level sensitivity, **<1mm** spatial resolution)



Zou et al., Phys. Rev. A 107, 062820 (2023)

PTOLEMY

- Detection of **cosmic neutrino background** CνB

  $T_2 + \nu_e \rightarrow {}^3HeT^+ + e^-$

  via **neutrino capture on β-decaying** nuclei (NCB)

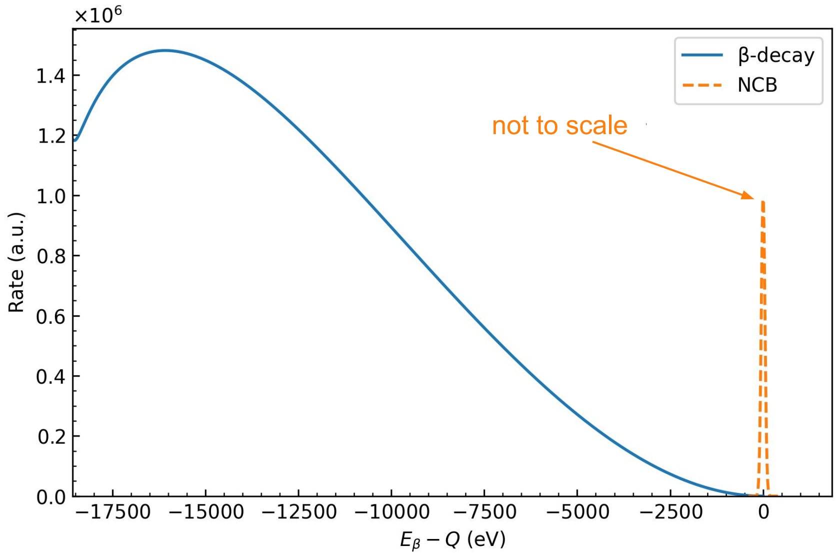
  Iwasaki et al., arxiv:2404.00817

➔ Investigate **neutrino properties** (e.g. mass ordering)

- Combination of **various technologies**

➔ Sensitivity to **m_β< 10 meV**

  Betti et al., JCAP07 (2019) 047



Neutrino Mass Observables

Neutrinoless ββ-decay

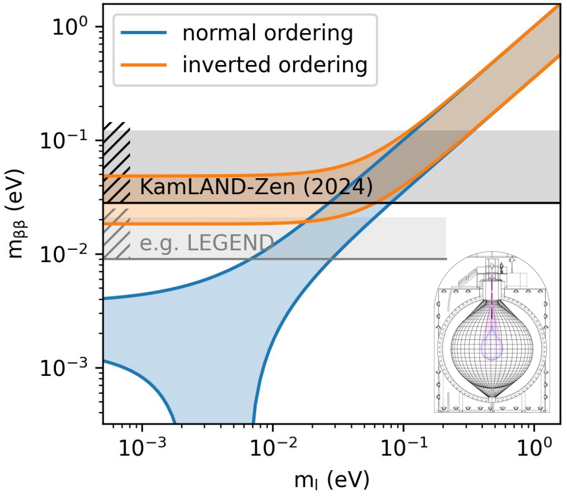
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

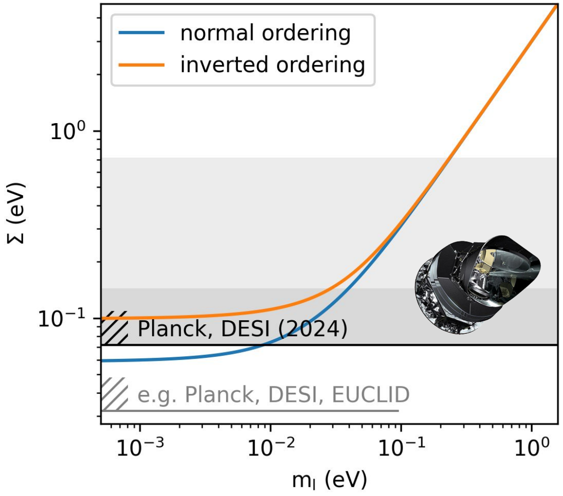
Cosmology

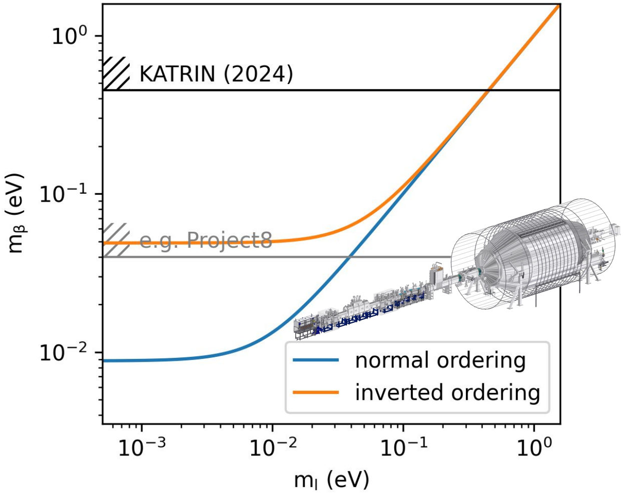
$$\Sigma = \sum_i m_i$$

β-decay kinematics

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$







Courtesy C. Wiesinger

[NuFIT 5.3, nu-fit.org]