Searching for sterile neutrinos at the keV scale with the KATRIN experiment

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on behalf of the KATRIN collaboration

TAUP 2025, Xichang, 24-30 August 2025

β spectrum and neutrino mass

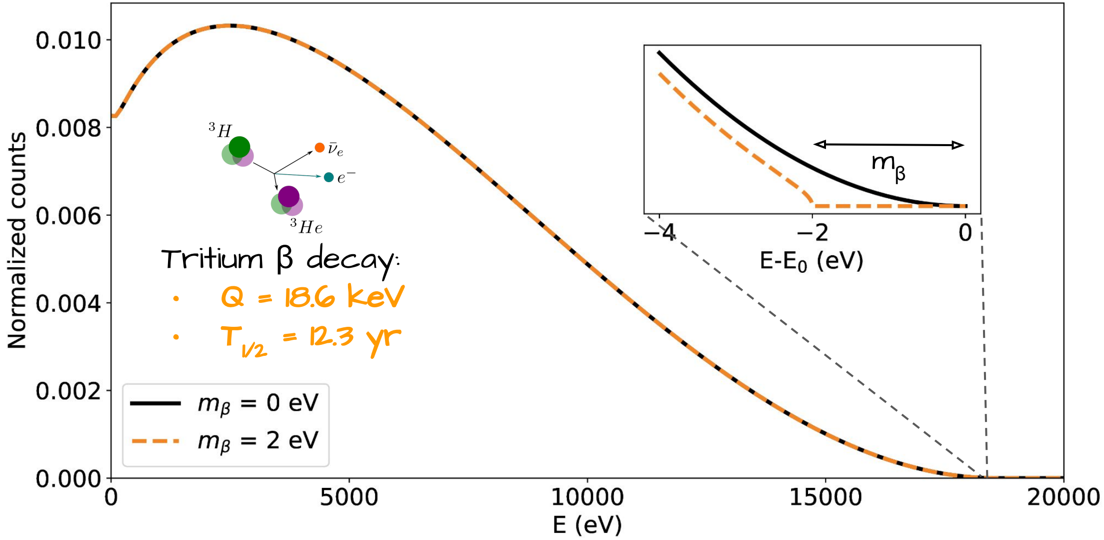
- Oscillations prove that at least two **neutrinos have mass**
- However, oscillations are not sensitive to the neutrino mass scale → need another observable

$$\frac{dN}{dE} \cong C \cdot F(E,Z) P_e (E_e + m_e c^2)(E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\beta^2}$$

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

Non-zero neutrino mass induces a distortion close to the β spectrum **endpoint**

→ see C. Wiesinger talk on 25/8



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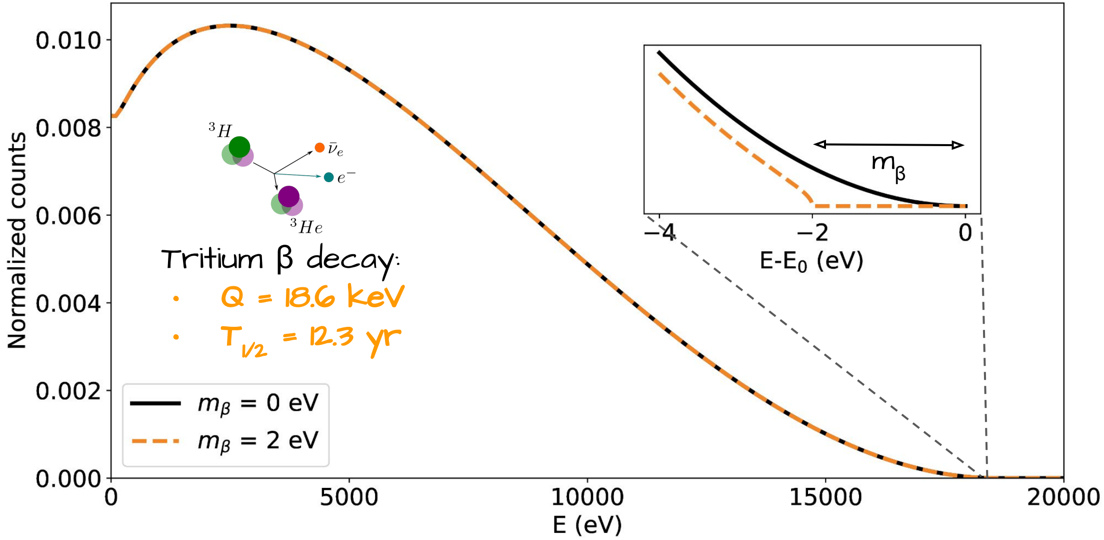


Requirements

- source with ultra-high activity and low Q
- excellent energy resolution (O(1 eV) @ endpoint)
- low background

KATRIN

Source

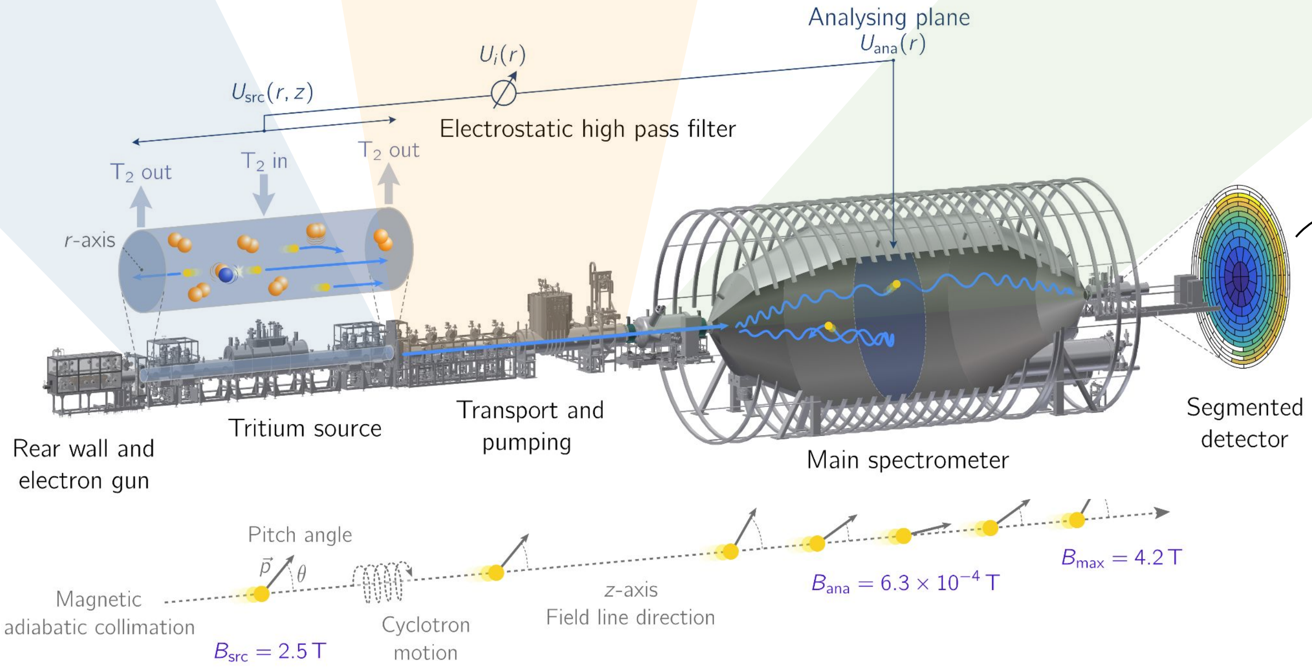
- molecular tritium in closed loop
- 10^{11} decays/s

Transport

- magnetic guidance
- tritium removal

Spectrometer

- MAC-E filter
- O(1 eV) resolution
- background <0.1 cps



Rate vs spectrometer potential

m_β< 0.45 eV (90% C.L.)

KATRIN collab: Science (2025)

β spectrum and keV sterile neutrinos

- a fourth mass eigenstate in the keV scale would be a **candidate for Dark Matter**
- predicted by many BSM theories

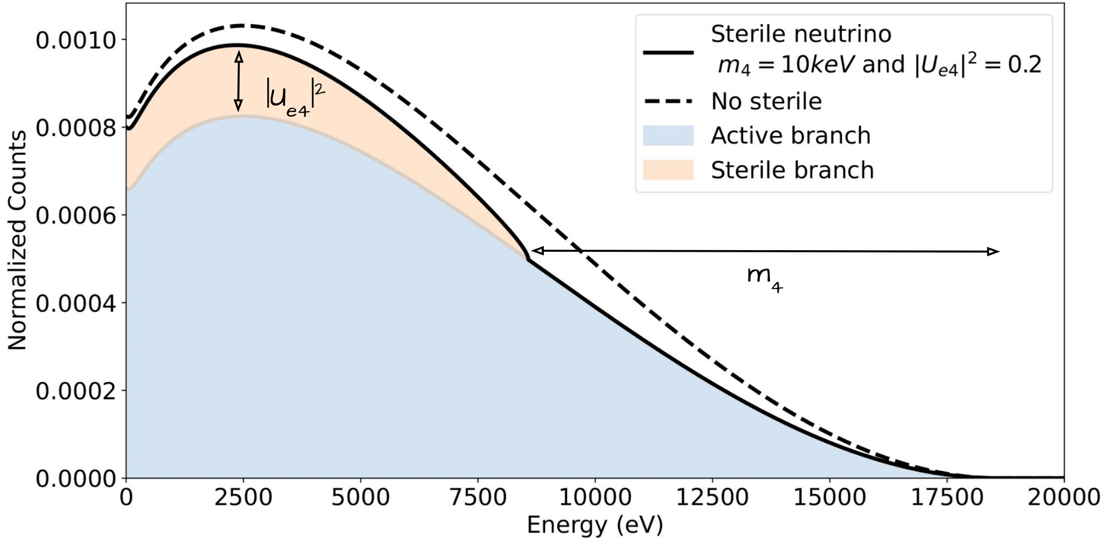
$$\frac{dN}{dE}_{tot} = (1-|U_{e4}|^2)\frac{dN}{dE}(m_\beta)+|U_{e4}|^2\,\frac{dN}{dE}(m_4)$$

mixing probability — sterile mass

⇒ The presence of a sterile neutrino creates an additional branch in the β decay

↓

global signature



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mixing probability (→ $|U_{e4}|^2$)

sterile mass (→ m_4)

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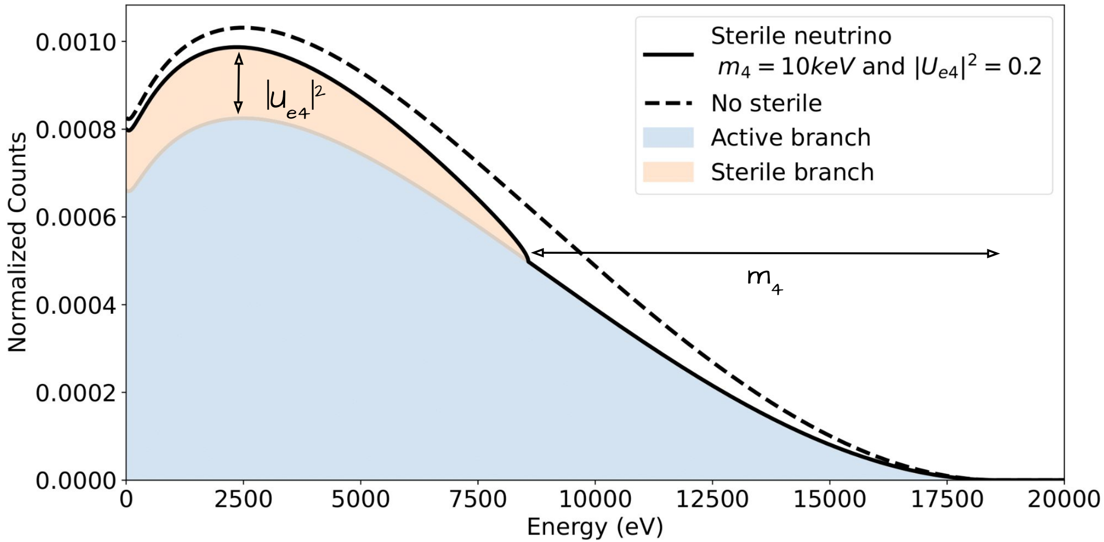
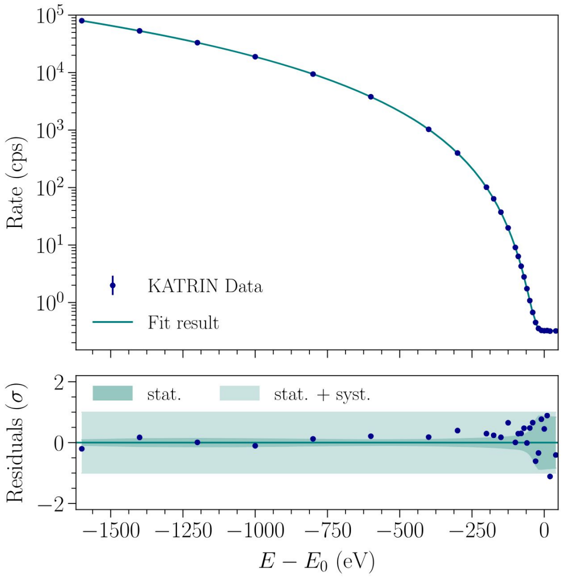


Requirements

- source with high activity
- measure the entire spectrum → need a fast detector

keV sterile neutrinos in KATRIN

- **KATRIN searched for keV sterile neutrinos** in integral mode in the 0.01-1.6 keV mass range:
  - reduced isotopic abundance to handle higher rate
  - systematics dominated by source activity fluctuations



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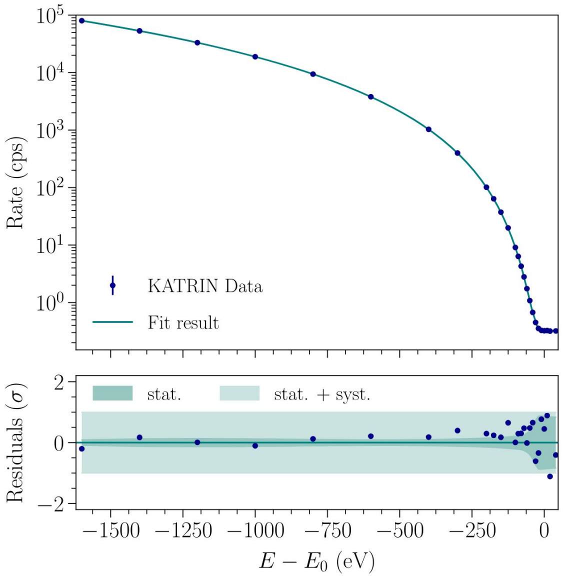
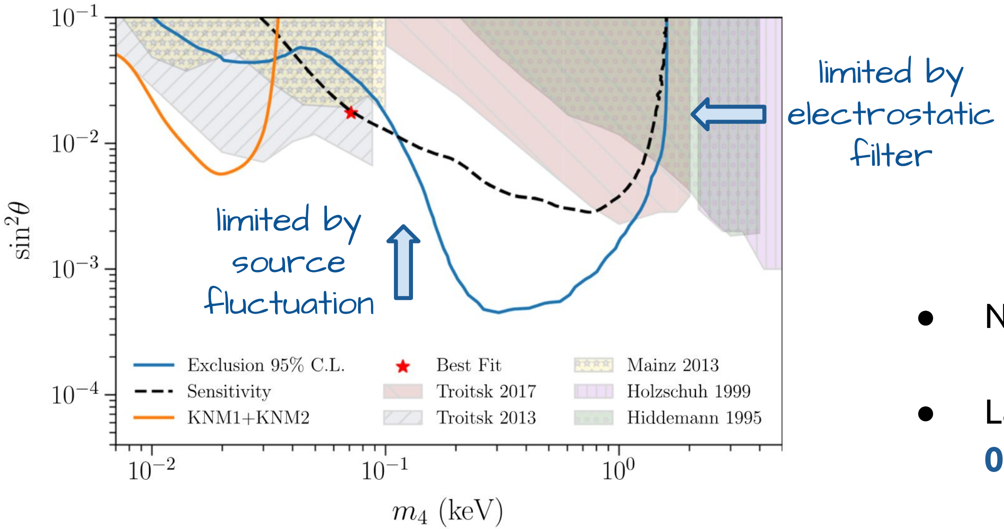




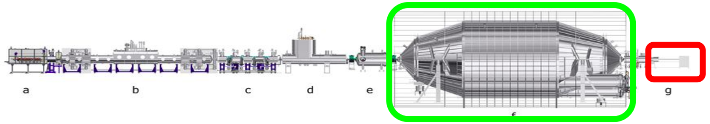
- No signal observed
- Laboratory **limit improved in the region 0.1-1 keV**

KATRIN collab: EPJC (2023)

How to search for smaller mixing?

Neutrino mass mode

- focus on the endpoint
- **integral measurement** with O(1 eV) energy resolution



- detector measures rate as a function of the spectrometer potential
- energy resolution given by the spectrometer

How to search for smaller mixing?

Neutrino mass mode

- focus on the endpoint
- **integral measurement** with O(1 eV) energy resolution

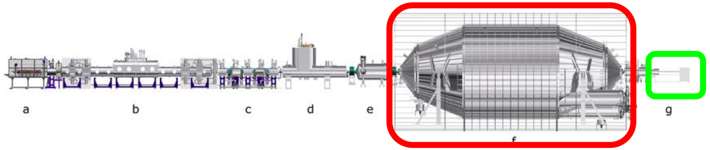
⇩

- detector measures rate as a function of the spectrometer potential
- energy resolution given by the spectrometer

keV sterile neutrino mode

- focus on the entire spectrum
- **differential measurement** with fast detector and O (100 eV) resolution

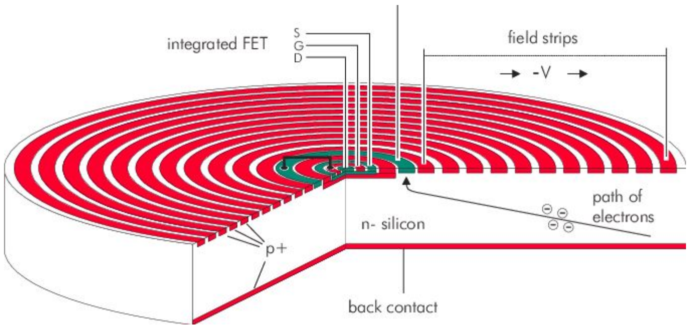
⇩

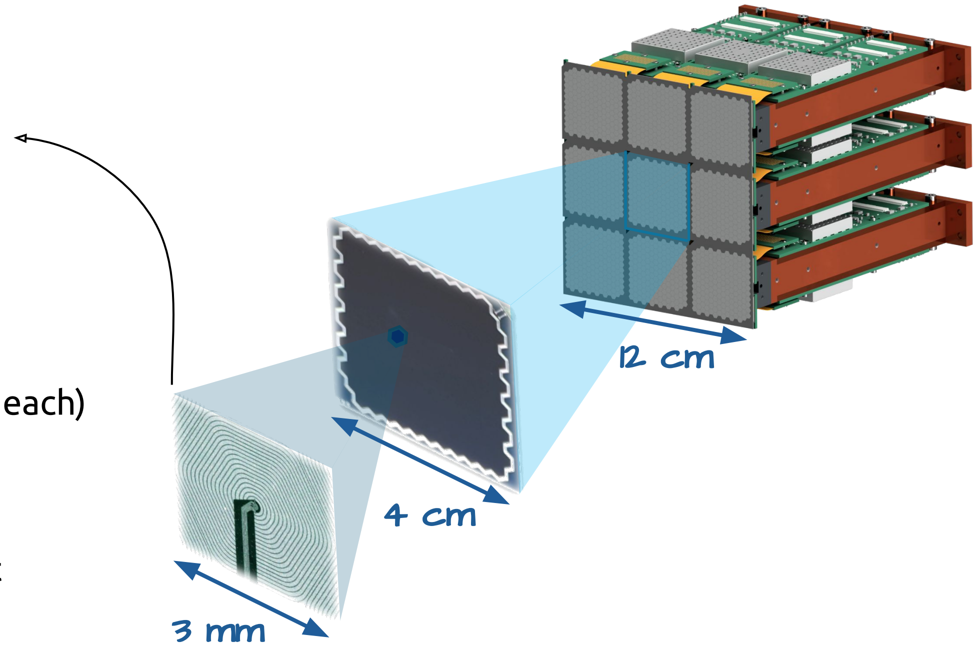


- detector measures the electron energy
- energy resolution given by the detector
- need of a fast detector to handle KATRIN's source activity

TRISTAN

- Silicon Drift Detector (**SDD**) technology
  - concentric rings to have radial drift towards a point-like anode → small capacitance





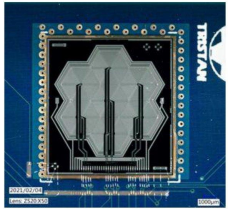
- TRISTAN is a matrix of >1000 SDDs
  → arranged in 9 multi-pixel modules (166 SDDs each)
  → to be installed in 2026

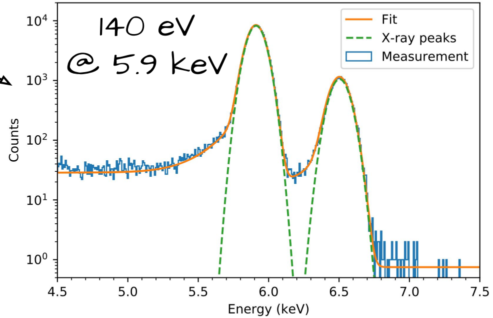
- each SDD is a hexagonal 3mm cell
  - energy resolution of ~300 eV @ endpoint
  - capability of handle ~10^5 cps

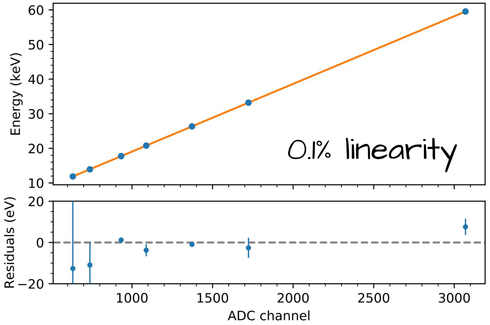
The TRISTAN project in a nutshell

Build a large SDD array and use it for β spectroscopy in the KATRIN beamline

2017: first prototypes







- SDD design optimization
- excellent spectroscopic properties demonstrated

Mertens et al: JPG (2020)

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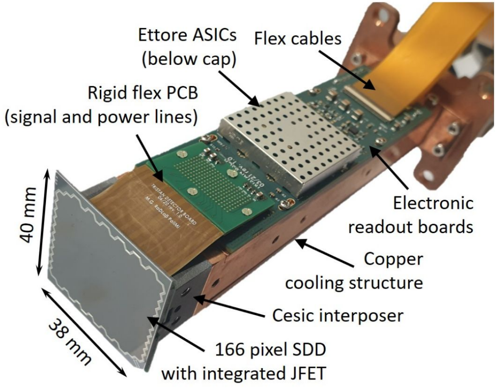
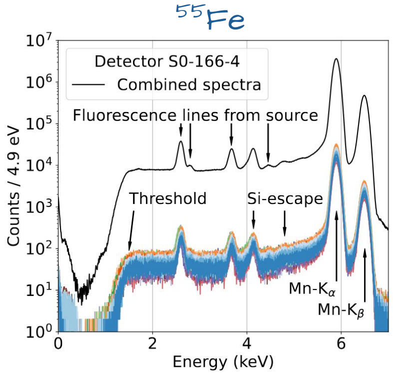
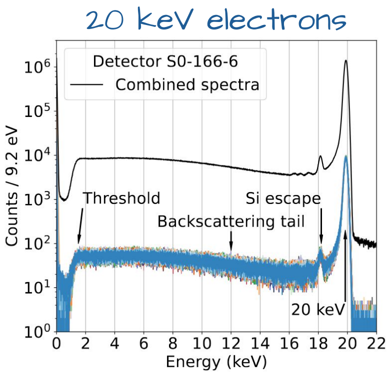
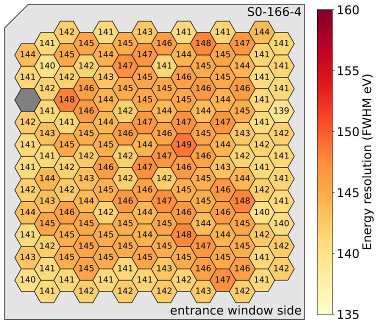
2021: assembly of a 3D TRISTAN module







Largest SDD array ever operated



- very good pixel yield and uniformity
- high-resolution spectroscopy of both X-rays and electrons

Siegmann et al: JPG (2024)

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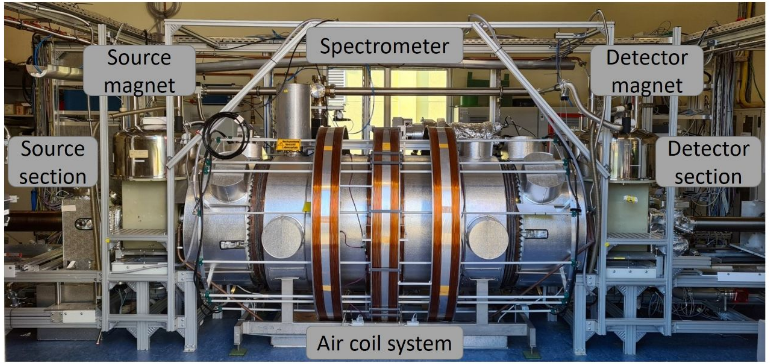
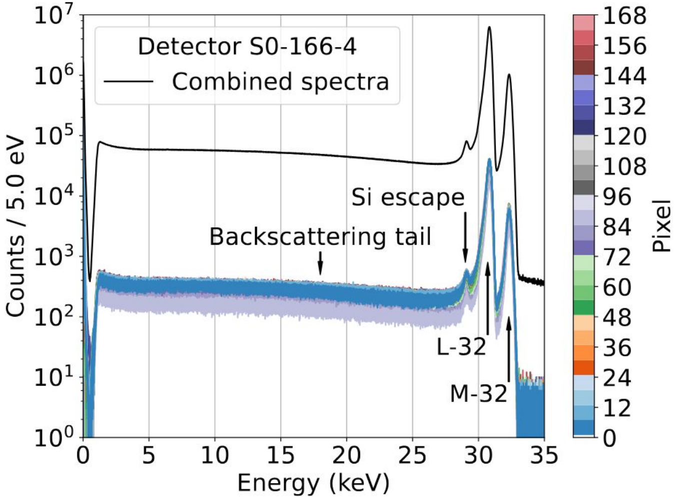
2022: first operation in KATRIN-like environment



KATRIN monitor spectrometer (ex Mainz)

L-32 and M-32 lines of ^{83m}Kr



- O(T) magnetic fields and O(kV) electric potential
- successful test in a realistic environment!

Siegmann et al: JPG (2024)

The TRISTAN project in a nutshell

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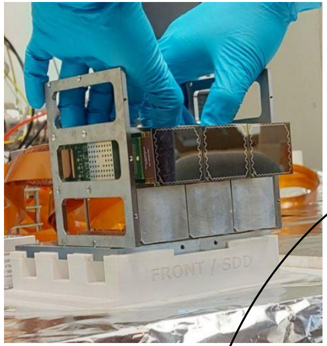
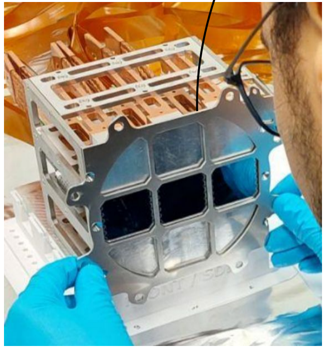
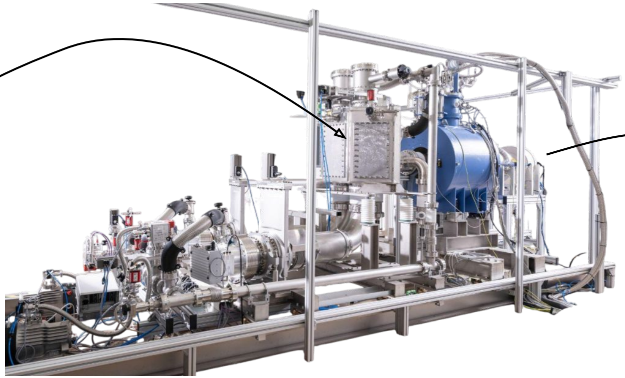
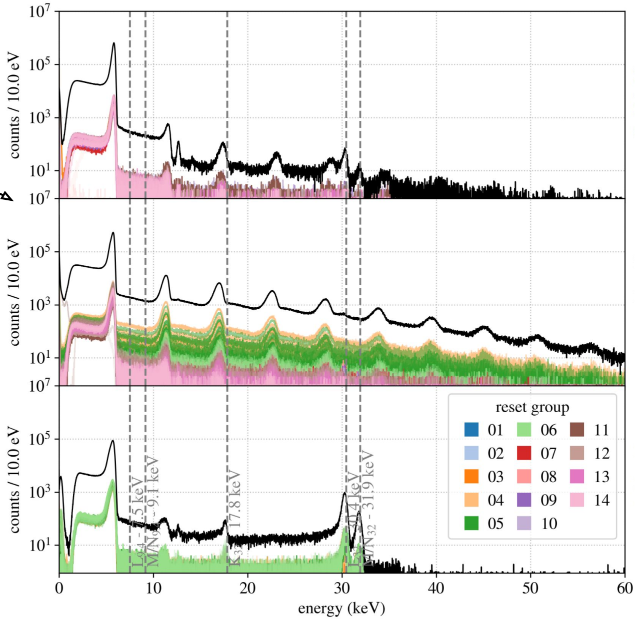
2024: operation at KATRIN detector replica







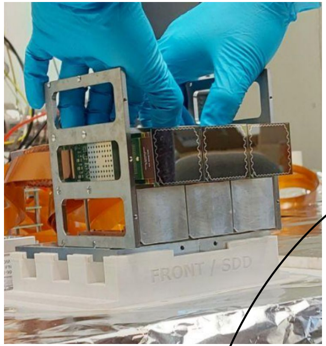


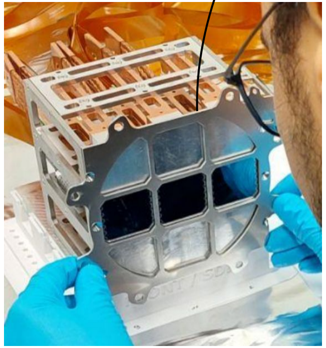
- 3 TRISTAN modules assembled with the final design
- e-gun electrons on all the pixels!

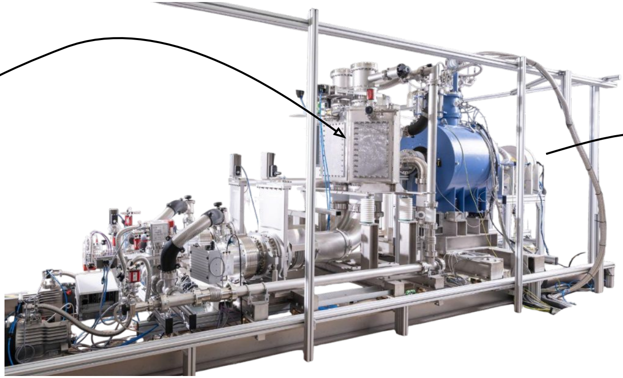
The TRISTAN project in a nutshell

Build a large SDD array and use it for β spectroscopy in the KATRIN beamline

2026: installation in KATRIN beamline







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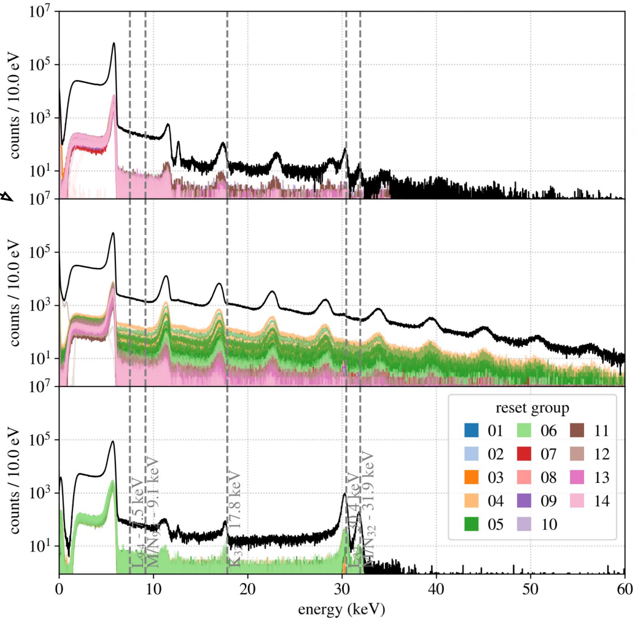
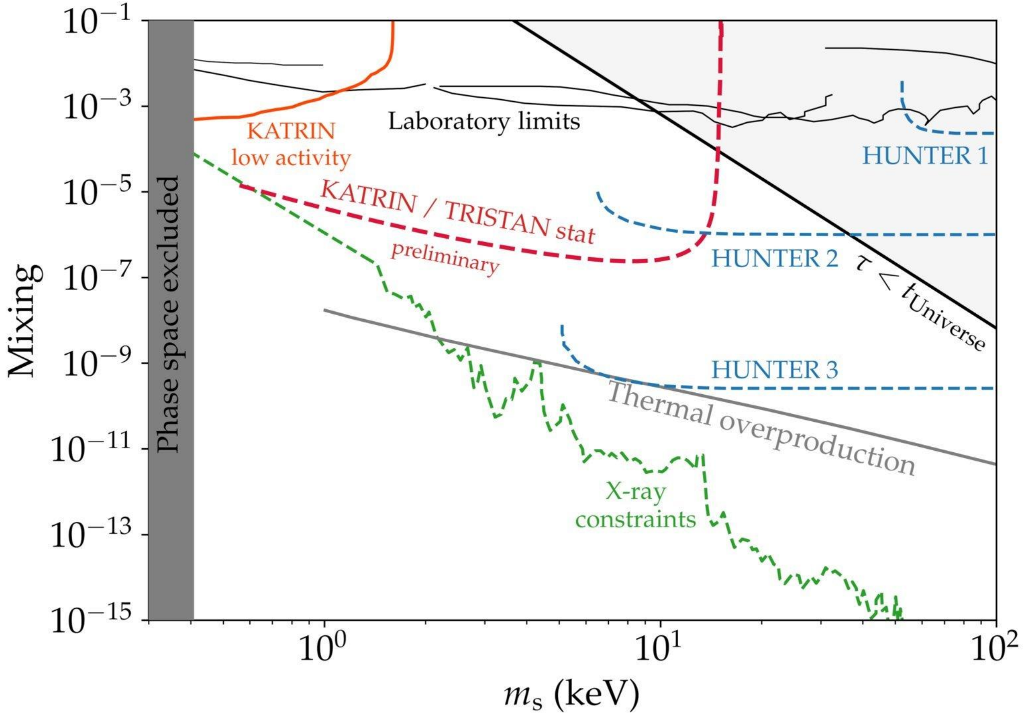


Sensitivity in differential mode



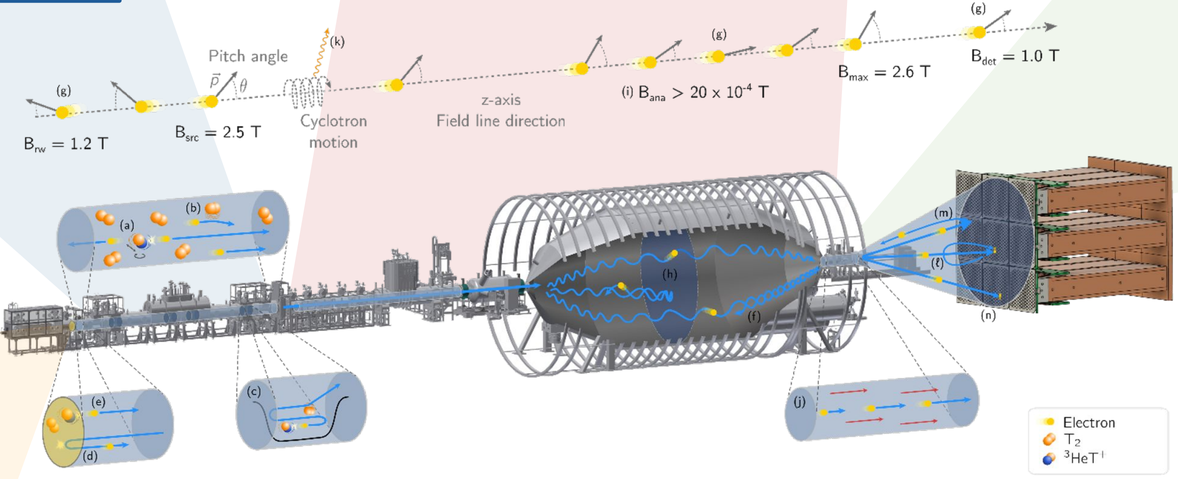
- with 1 year measurement KATRIN has the statistical potential to drastically improved the existing limits
- sensitivity: $|U_{e4}|^2 < 10^{-6}$
- complementarity with other experimental techniques

The modeling challenge

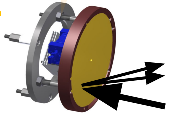
Source:
- scattering
- magnetic traps

Transport & filter:
- Motion in EM fields
- transmission condition

Detector response:
- Entrance window
- Backscattering and reflections
- Energy resolution
- Charge-sharing
- DAQ



Rear Wall:
- scattering on the surface
- residual tritium activity



- measurement will be systematics dominated!
- very different set of systematics wrt integral neutrino mass measurements

The modeling strategy

- **MC simulations** of the experimental response of the various parts of the beamline
- analytical modelization where possible
- **validation of the models** with experimental data taken both in lab and in the beamline

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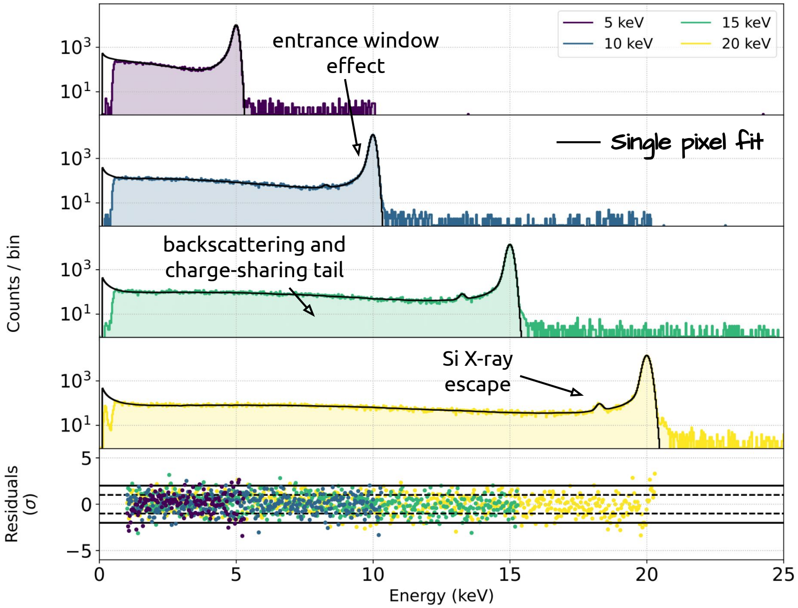
Example for detector response

- **laboratory measurement**: e-gun electrons at different energies homogeneously illuminating all the pixels of a TRISTAN module
- **model**: GEANT4 to simulate interactions in Silicon + analytical models for entrance window, energy resolution and charge-sharing effects



Summary and Outlook

- **keV-scale sterile neutrinos and other BSM physics can be searched with high precision in β spectra**

  → following talks by J. Lauer and S. Mohanty

- KATRIN already placed the most stringent limit in the region 0.1-1 keV

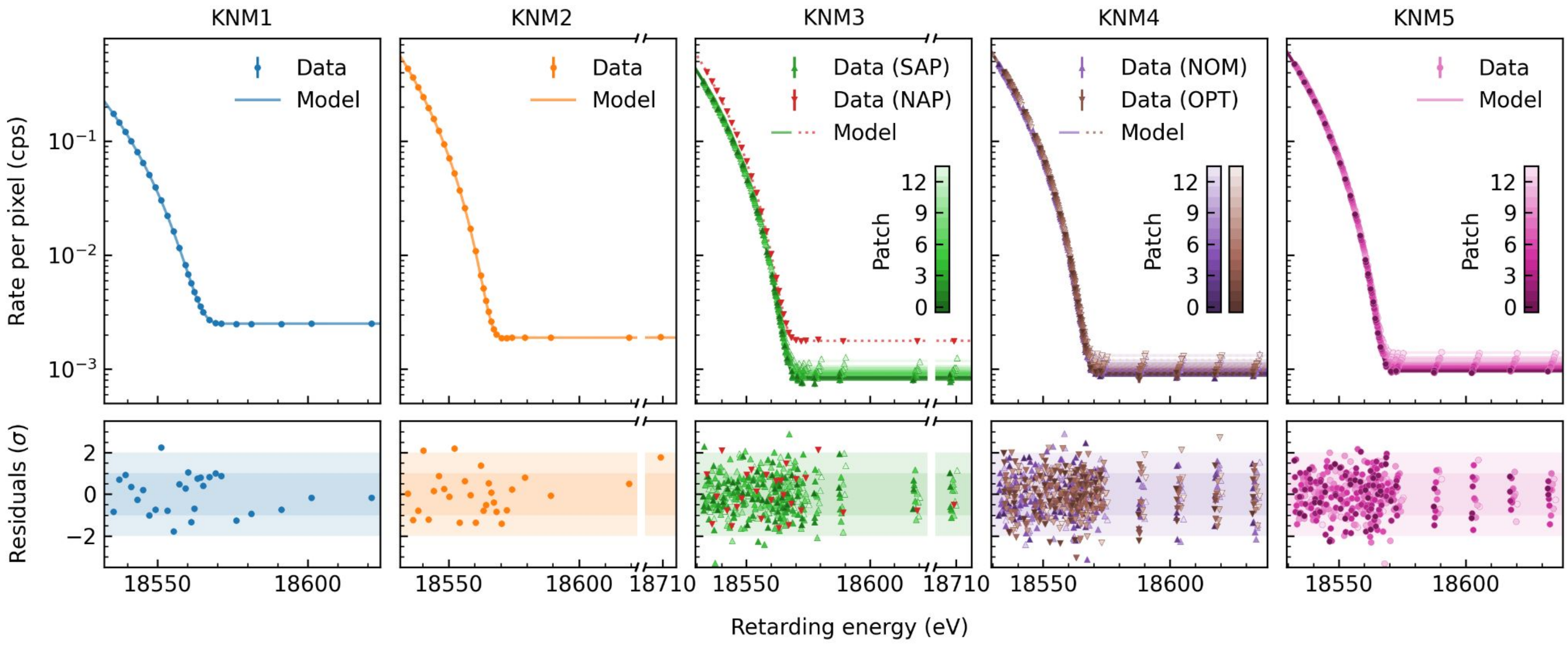
- KATRIN, due to its source strength, offers a unique environment to search for keV-scale sterile neutrinos with mixing down to 10^{-6}

- The TRISTAN detector is being developed and tests in KATRIN-like environment are ongoing, showing its capability in performing high-rate electron spectroscopy, efforts in modeling the measured spectrum are ongoing as well

- **TRISTAN will be installed in the beamline in 2026**, starting a new phase of the KATRIN experiment, stay tuned!

Thanks for your attention!

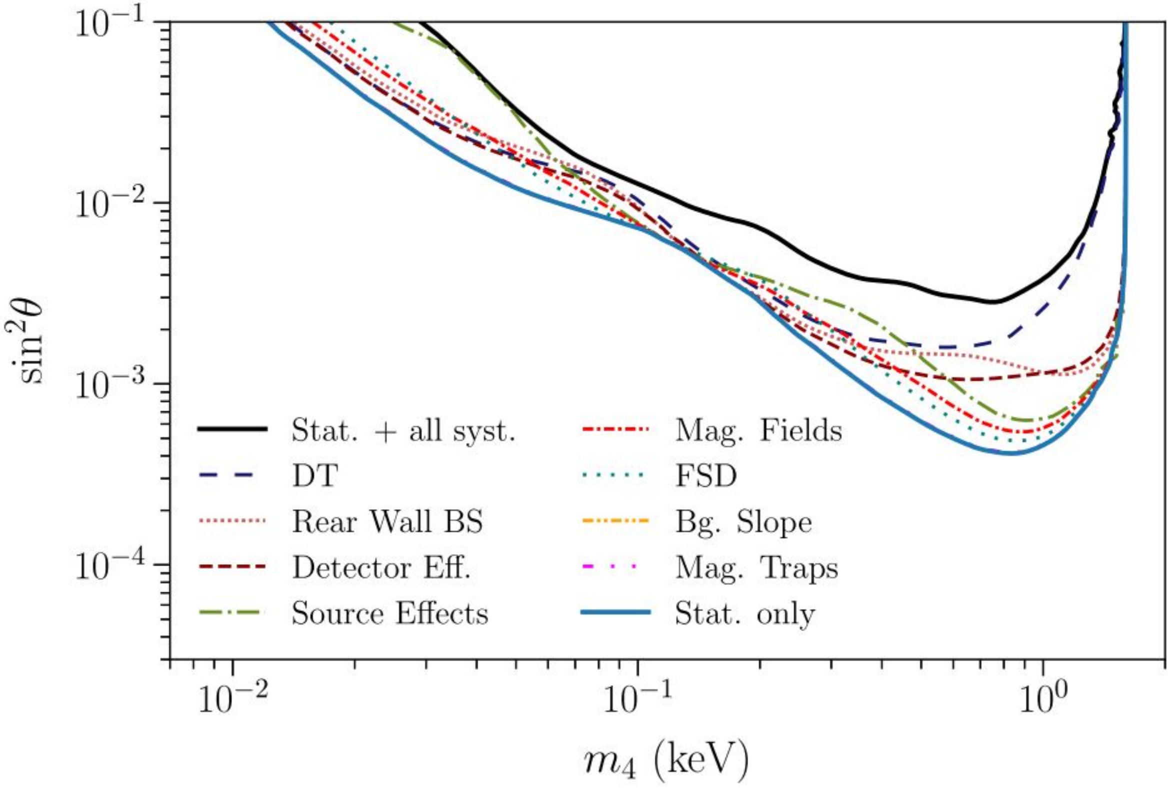
KATRIN neutrino mass result



Combined analysis of the first 5 campaigns → **m_β< 0.45 eV (90% C.L.)**

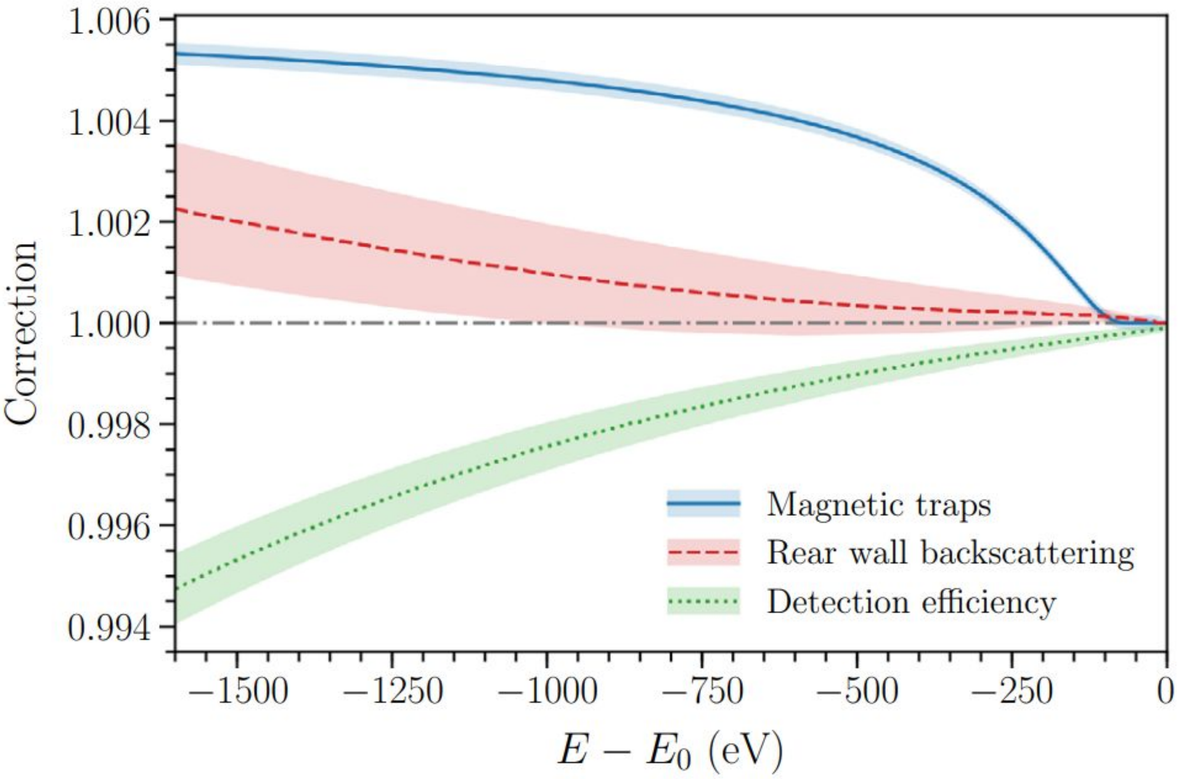
KATRIN collab: Science (2025)

Systematics breakdown



KATRIN collab: EPJC (2023)

Spectrum corrections



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