The KATRIN Experiment: Past, Present, and Future

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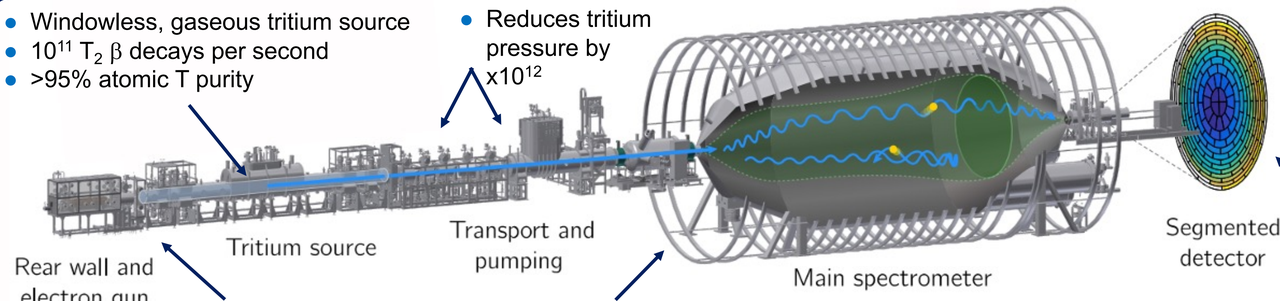
KATRIN [1] measures the neutrino-mass scale from the kinematics of T_2 β decay.

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

($|U_{ei}|^2$: Contribution of i^{th} neutrino-mass state to ν_e; m_i^2: i^{th} neutrino-mass value)

- Shape distortion near endpoint E_0 ~ 18.6 keV
- Model-independent laboratory measurement

- Windowless, gaseous tritium source
- 10^{11} T_2 β decays per second
- >95% atomic T purity
- Reduces tritium pressure by x10^{12}



- Calibration
- Tuning of plasma parameters
- Magnetic Adiabatic Collimation with Electrostatic (MAC-E) filter
- Integrating high-pass filter on β kinetic energy
- Scans threshold energy *qU* to measure β spectrum
- Si pin diode
- 148 pixels grouped into patches for analysis

! *Major systematic: Field Variations*

- Different β paths see different electromagnetic fields, yielding different transmission behavior

Map with electron gun and ^{83m}Kr gas, and group pixels for minimal variation within a patch [4].

! *Major systematic: Plasma Potential*

- Local potential variations in source plasma broaden the measured spectrum

Characterize by co-circulating ^{83m}Kr calibration gas with the T_2 source [2].

! *Major systematics: Column Density and Energy Loss*

- Column density controls overall β-decay rate plus β scattering rate
- Scattering changes both β energy and angular distributions

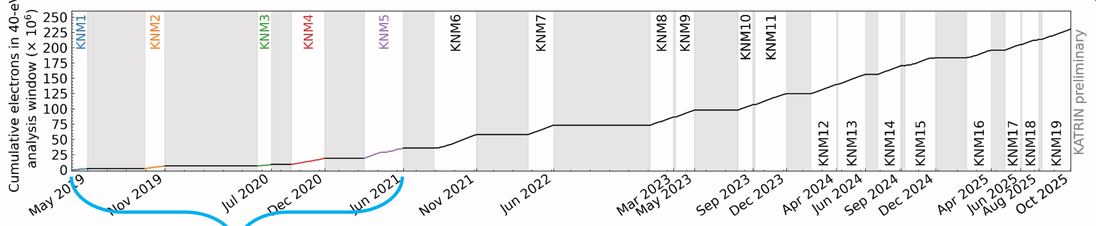
Use electron-gun measurements to monitor column density and to understand scattering interactions for low-energy βs on T_2 gas.

! *Primary background*

- Rydberg atoms sputter from spectrometer walls after radioactive decay
- Atoms ionize in volume, producing low-energy e^-

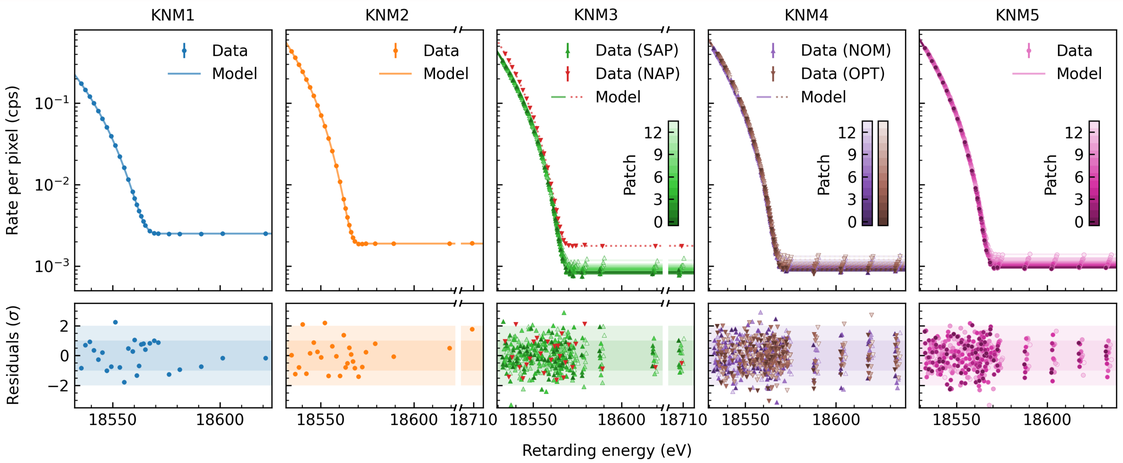
Reduce by magnetically squeezing imaged volume in "SAP" (shifted analyzing plane) mode [3].

36M electrons analyzed in first five campaigns (259 days, 2019-2021).



$$m_\beta^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$$
$$\rightarrow m_\beta < 0.45\ \mathrm{eV}\ (90\%\ \mathrm{C.L.})$$

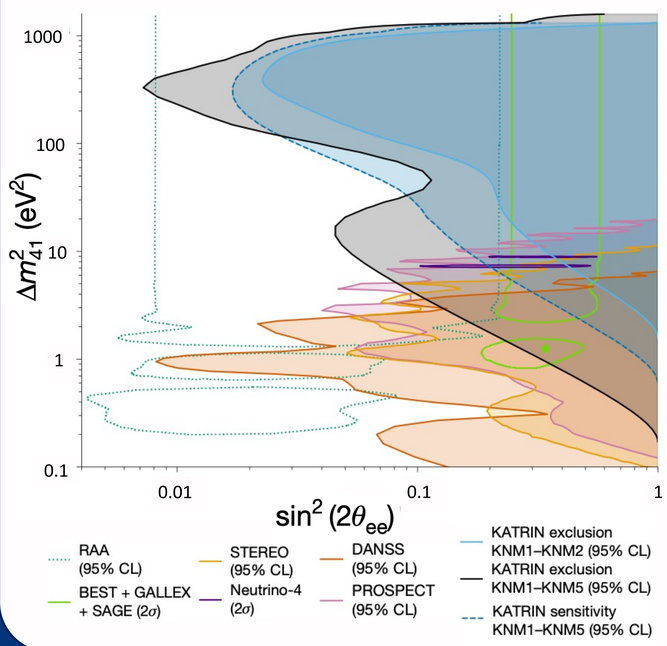
- Operating conditions optimized for backgrounds, calibrations.
- Blinded fit of model spectrum to measured data [5]
  - Operational parameters allowed to vary across campaigns
  - Physics parameters fit in common across all data sets



- The final data set (ended Fall 2025) has 230M electrons in the 40-eV analysis window below E_0.
- KATRIN is currently taking systematics data before reconfiguring the beamline.

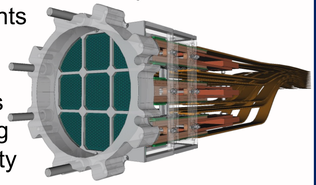
The KATRIN spectrum is sensitive to sterile neutrinos.

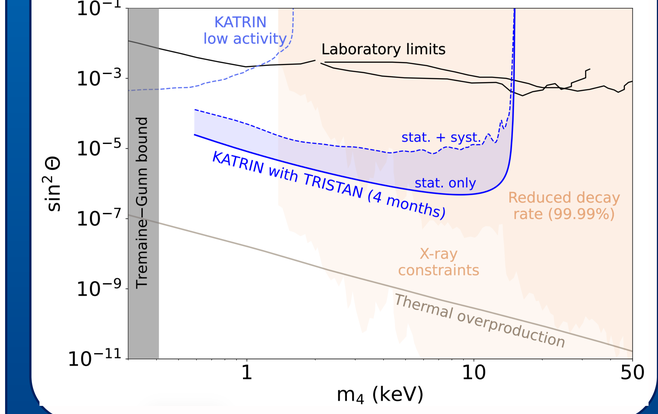
- Heavy sterile neutrinos alter the β-decay phase space, causing a characteristic spectral kink.
- The first 259 days of data rule out much of the parameter space for the gallium anomaly, plus the Neutrino-4 claim [6].



KATRIN's next phase (2027-2028) will explore deeper in the T_2 β spectrum.

- Low energies give access to beyond-Standard-Model effects (like sterile neutrinos) at larger mass scales [7].
- Enormous increases in rate require major changes:
  - New TRISTAN silicon drift-detector system
  - Differential measurements
  - Re-optimized electro-magnetic fields
  - New beamline materials to reduce backscattering
  - Reduced source intensity





KATRIN++ will develop new technologies for direct neutrino-mass measurements.

- Use unique KATRIN facilities as R&D testbed, e.g.
  - Atomic tritium beams
  - Cryogenic sensors for electron detection [8]

[1] KATRIN, JINST **16** T08015 (2021)
[2] KATRIN, Eur. Phys. J. C **85**, 757 (2025)
[3] Lokhov *et al.*, Eur. Phys. J. C **82**, 258 (2022)
[4] KATRIN, Eur. Phys. J. C **84**, 1258 (2024)
[5] KATRIN, Science **388**, 180 (2025)
[6] KATRIN, Nature **648**, 70 (2025)
[7] KATRIN, arxiv:2603.23256
[8] Kovač *et al.*, NIM A **1080**, 170662 (2025)

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