Exploring eV-Scale Sterile Neutrinos: Insights from the KATRIN Experiment

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β-decay spectrum

Direct model-independent way to determine the absolute scale of neutrino mass

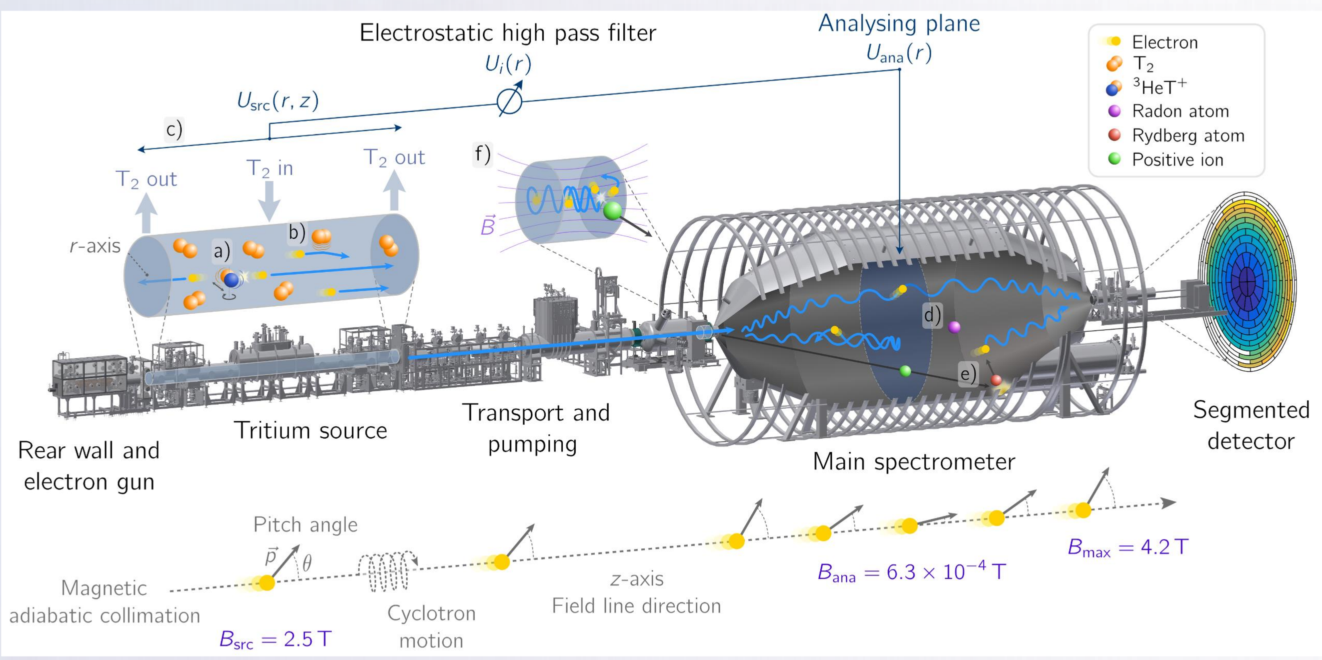
$$\frac{d\Gamma}{dE}(E,\mathrm{m}_\upsilon^2) = \frac{G_F^2\cos^2\theta_c}{2\pi^3}\cdot|\mathcal{M}_{\mathrm{nucl.}}|^2\cdot F(Z,E)\cdot(E+\mathrm{m_e})\cdot\sqrt{(E+\mathrm{m}_e)^2-\mathrm{m}_e^2}\cdot(E_0-E)\cdot\sqrt{(E_0-E)^2-\mathrm{m}_\upsilon^2}\cdot\Theta(E_0-E-\mathrm{m}_\upsilon)$$

Kinematic neutrino mass measurement with KATRIN

The **KA**rlsruhe **TRI**tium **N**eutrino experiment performs a high precision and direct kinematic measurement of the electron anti-neutrino mass with the target sensitivity better than $\mathbf{0.3\,eV/c^2}$ at 90% CL

$$^3_1\mathrm{H}\rightarrow {}^3_2\mathrm{He}^+ + e^- + \bar{\nu}_e$$

Result from first two science runs $m_\nu < 0.8\ \mathrm{eV/c^2}$ (90 % C.L.)



Nature Physics 18, 160-166 (2022)

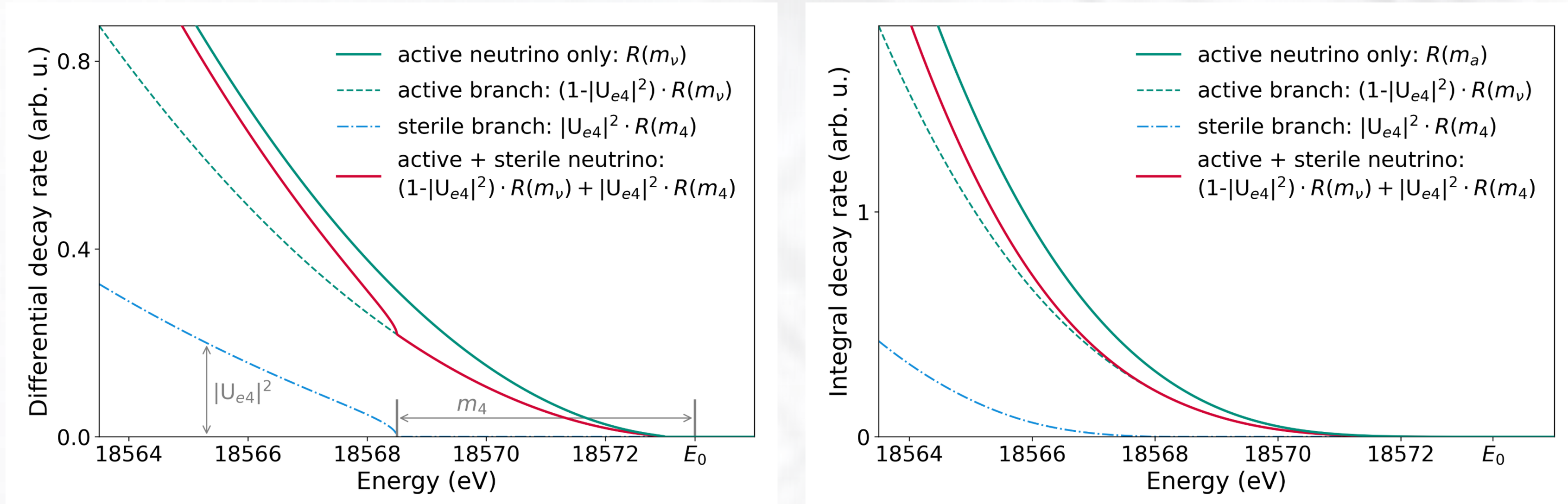
Phys. Rev. D 105, 072004 (2022)

Sterile neutrino in β-decay

- Fourth mass eigenstate m_4 can contribute to the spectrum via an extended PMNS matrix
- Sterile neutrino proposed as solution to anomalies in short baseline neutrino experiments which can be probed with β-decay

$$\frac{d\Gamma}{dE}(E,\mathrm{m}_\upsilon^2,\mathrm{m}_4^2,|U_{e4}|^2) = \underbrace{(1-|U_{e4}|^2)\frac{d\Gamma}{dE}(E,\mathrm{m}_\upsilon^2)}_{\text{3 active neutrinos}} + \underbrace{|U_{e4}|^2\frac{d\Gamma}{dE}(E,\mathrm{m}_4^2)}_{\text{1 sterile neutrino}}$$

$$\mathrm{m}_\upsilon = \sqrt{\sum_{k=1}^{3}|U_{ek}|^2\mathrm{m}_k^2} \xrightarrow{3+1\ model} \mathrm{m}_\upsilon = \sqrt{\sum_{k=1}^{3}\frac{|U_{ek}|^2}{1-|U_{e4}|^2}\mathrm{m}_k^2}$$



Sterile branch at $E < E_0 - m_4$, kink-like spectral distortion

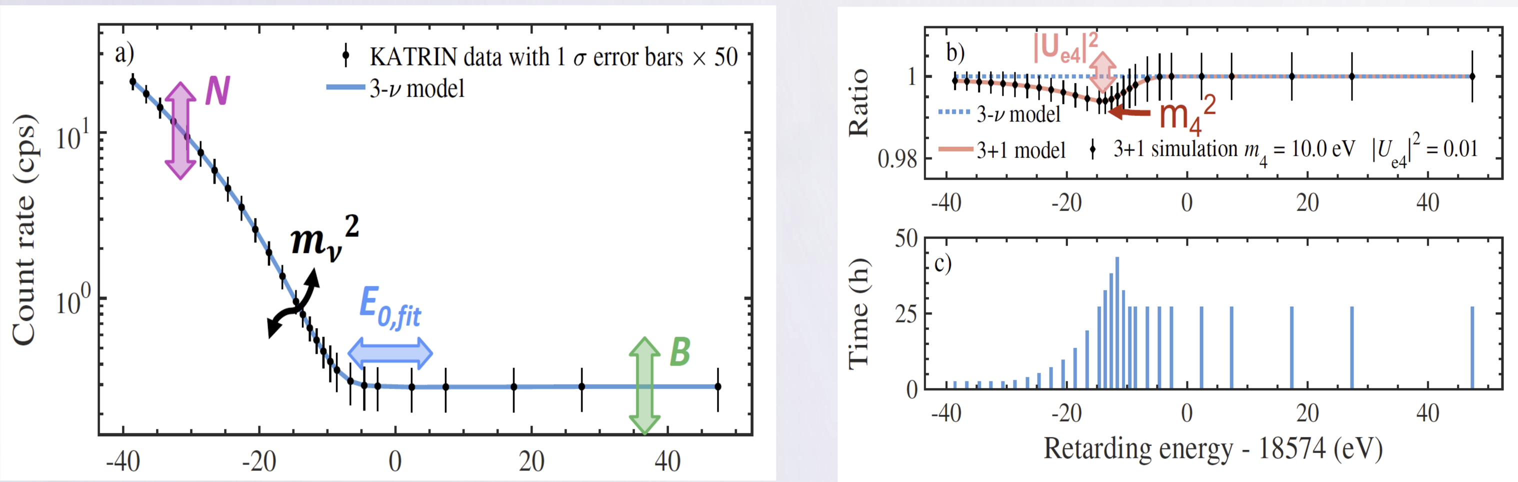
Model

- The expected electron rate can be calculated as

$$\dot{N}^{\mathrm{model}}(qU,\boldsymbol{\Theta}) = A\cdot\int_{qU}^{\infty}\frac{d\Gamma}{dE}(E,\boldsymbol{\Theta})\cdot R(E,qU)dE + B$$

- Rate converted to counts through multiplication with associated measurement time t

$$N^{\mathrm{model}}(qU) = \dot{N}^{\mathrm{model}}(qU)\cdot t(qU)$$

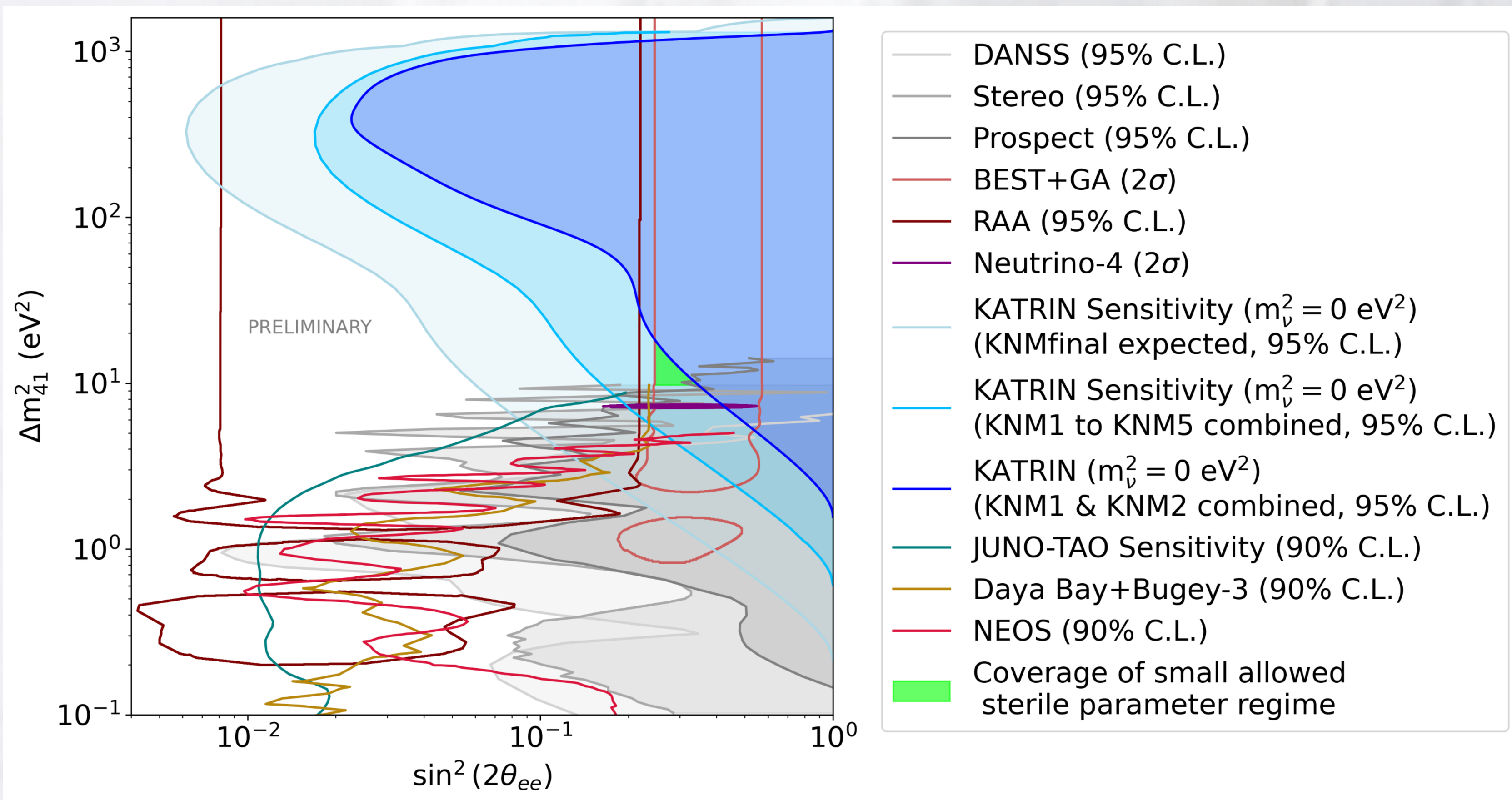


Simulated sterile neutrino signal in KATRIN (Phys. Rev. Lett. 126, 091803, 2021)

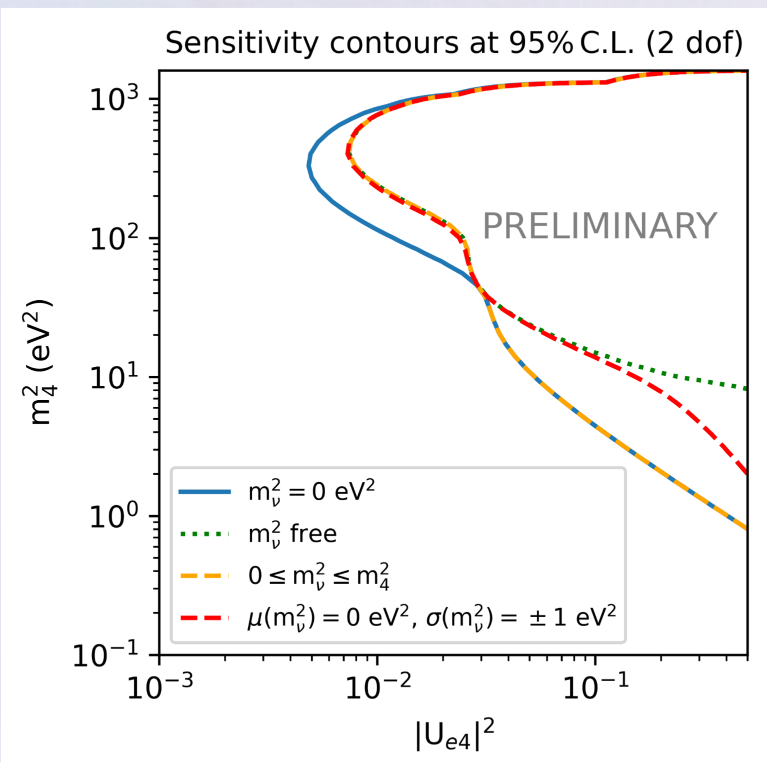
Analysis Method

- Study performed on simulated data sets of first five science runs (35.8×10^6 electrons)
- Full analysis chain developed and tested on *Monte Carlo twins*
- Grid scan over $[\mathrm{m}_4^2,\ \sin^2\theta\ (|U_{e4}|^2)]$ 2-D logarithmic plane [50 × 50]
- Sensitivity contour drawn at 95% CL ($\Delta\chi^2_{critical} = 5.99$) for 2 dof
- Analysis case **(I)** $\mathbf{m_\upsilon^2 = 0\ eV^2}$ (II) m_υ^2 fitting parameter

Comparison of KATRIN Bounds with Oscillation-based Sterile Neutrino Searches



$$\sin^2(2\theta_{ee}) = 4\sin^2\theta(1-\sin^2\theta)$$

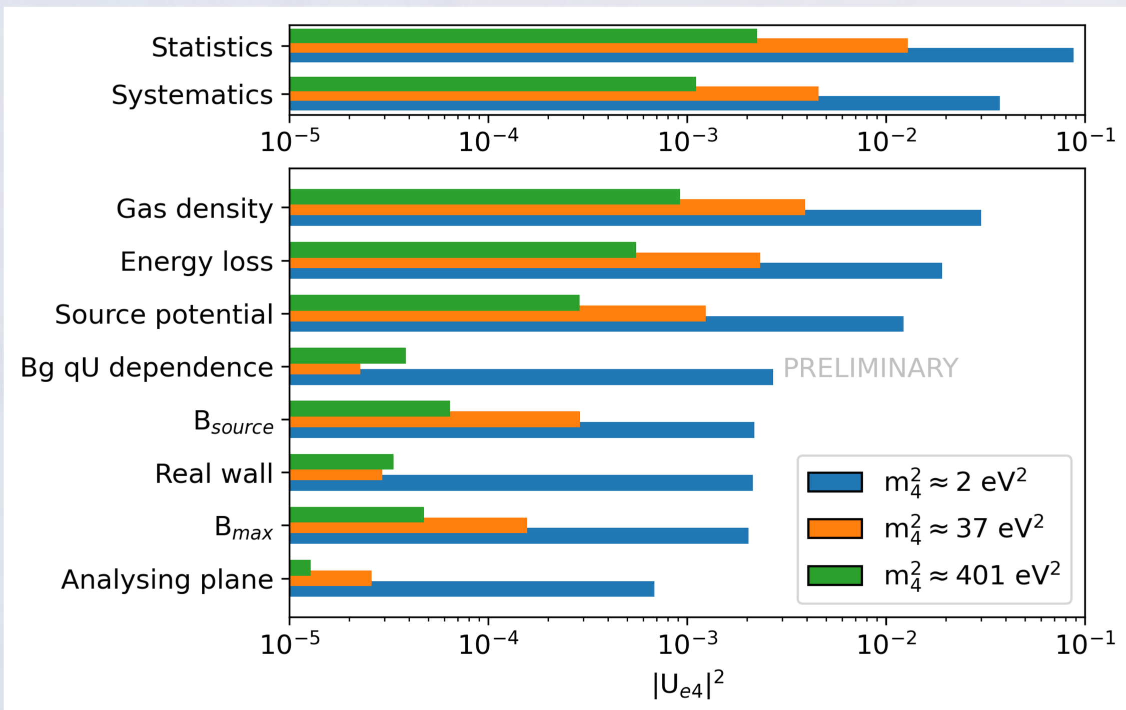


Impact of active neutrino mass

- Active neutrino mass also a fitting parameter
- Three different types of constraints on the active neutrino mass
- Limiting the active neutrino mass to be positive and less than the sterile neutrino mass yields best sensitivity

Impact of systematics

- Sensitivity is statistically dominated for all m_4^2
- Impact of systematics differs as function of the sterile neutrino mass



Conclusion

- Probing a large parameter space of interest for light sterile neutrino anomalies
- Consideration of various options for treating the active neutrino mass
- Evaluation of the optimized sensitivity condition: $\mathrm{m}_4^2 \geq \mathrm{m}_\upsilon^2 \geq 0$

Outlook

- Analysis of data from first five science runs ongoing
- New release expected this fall

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