

Latest Constraints on Sterile Neutrinos from the KATRIN Experiment

Shailaja Mohanty

s.mohanty@queensu.ca

Queen's University

Work performed while at Karlsruhe Institute of Technology

Testing the Standard Model in Charged-Weak Decays (INT Workshop)

January 12, 2026

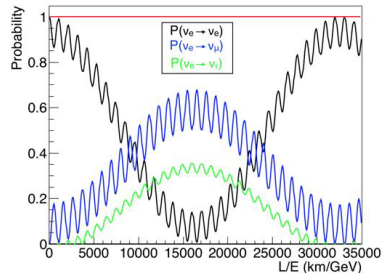
Neutrinos: Massless in the Standard Model

- Neutrinos are only "half of the particle" and were massless
- *Neutrino oscillation*: Quantum phenomenon in which a neutrino changes its flavor as it propagates
- Need for extension of the Standard Model to generate neutrino masses

Quarks	2.4 MeV 2/3 Left u Right up	1.27 GeV 2/3 Left c Right charm	171.2 GeV 2/3 Left t Right top
	4.8 MeV -1/3 Left d Right down	104 MeV -1/3 Left s Right strange	4.2 GeV -1/3 Left b Right bottom
	< 1 eV 0 Left ν_e Right	< 1 eV 0 Left ν_μ Right	< 1 eV 0 Left ν_τ Right
	0.511 MeV -1 Left e Right electron	105.7 MeV -1 Left μ Right muon	1.777 GeV -1 Left τ Right tau
Leptons			

Neutrinos: Massless in the Standard Model

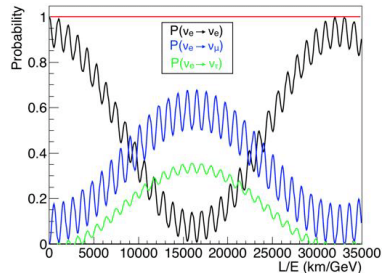
- Neutrinos are only "half of the particle" and were massless
- *Neutrino oscillation*: Quantum phenomenon in which a neutrino changes its flavor as it propagates
- Need for extension of the Standard Model to generate neutrino masses



$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{\mu 1}^* & U_{\tau 1}^* \\ U_{e2}^* & U_{\mu 2}^* & U_{\tau 2}^* \\ U_{e3}^* & U_{\mu 3}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Neutrinos: Massless in the Standard Model

- Neutrinos are only "half of the particle" and were massless
- *Neutrino oscillation*: Quantum phenomenon in which a neutrino changes its flavor as it propagates
- Need for extension of the Standard Model to generate neutrino masses



$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{\mu 1}^* & U_{\tau 1}^* \\ U_{e2}^* & U_{\mu 2}^* & U_{\tau 2}^* \\ U_{e3}^* & U_{\mu 3}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Extension via Sterile Neutrinos

- Sterile neutrino ν_s : SM gauge singlet fermion (no weak or EM interactions)
- Mass scope: ν_s can span masses from eV to GUT/Planck scales with small mixing angles
- This work focused on **eV-scale** search

Quarks	2.4 MeV $\frac{2}{3}$ u Left up Right	1.27 GeV $\frac{2}{3}$ c Left charm Right	171.2 GeV $\frac{2}{3}$ t Left top Right
	4.8 MeV $-\frac{1}{3}$ d Left down Right	104 MeV $-\frac{1}{3}$ s Left strange Right	4.2 GeV $-\frac{1}{3}$ b Left bottom Right
	< 1 eV 0 ν_e Left Right N_1 sterile neutrino	< 1 eV 0 ν_μ Left Right N_2 sterile neutrino	< 1 eV 0 ν_τ Left Right N_3 sterile neutrino
Leptons	0.511 MeV -1 e Left electron Right	105.7 MeV -1 μ Left muon Right	1.777 GeV -1 τ Left tau Right

Light Sterile Neutrinos: 3+1 Scheme

- Light sterile neutrino may participate in oscillations $\mapsto$ observable in short-baseline experiments
- Anomalies in GALLEX, SAGE, MiniBooNE, BEST, etc., could indicate its existence
- Appearance vs disappearance data tension ($\sim 3\text{-}4\ \sigma$); **tested independently via β -decay**

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{\mu 1}^* & U_{\tau 1}^* & U_{s1}^* \\ U_{e2}^* & U_{\mu 2}^* & U_{\tau 2}^* & U_{s2}^* \\ U_{e3}^* & U_{\mu 3}^* & U_{\tau 3}^* & U_{s3}^* \\ U_{e4}^* & U_{\mu 4}^* & U_{\tau 4}^* & U_{s4}^* \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix}$$

small, large

$$\Delta m_{21}^2 \ll \Delta m_{31}^2 \ll \Delta m_{41}^2,$$

$$|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2 \ll 1, \quad |U_{s4}|^2 \simeq 1.$$

Signature in β -decay

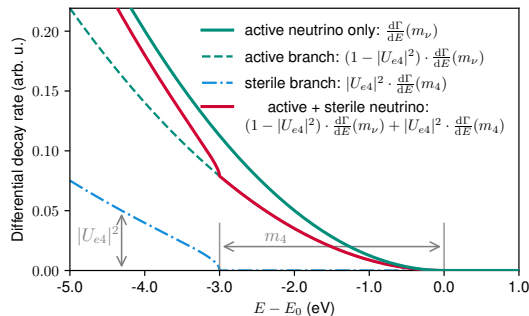
• Differential decay rate:

$$\frac{d\Gamma}{dE}(E, m_\nu^2, m_4^2, |U_{e4}|^2)$$

$$= \underbrace{(1 - |U_{e4}|^2) \cdot \frac{d\Gamma}{dE}(E, m_\nu^2)}_{\text{Active branch}} + \underbrace{|U_{e4}|^2 \cdot \frac{d\Gamma}{dE}(E, m_4^2)}_{\text{Sterile branch}}$$

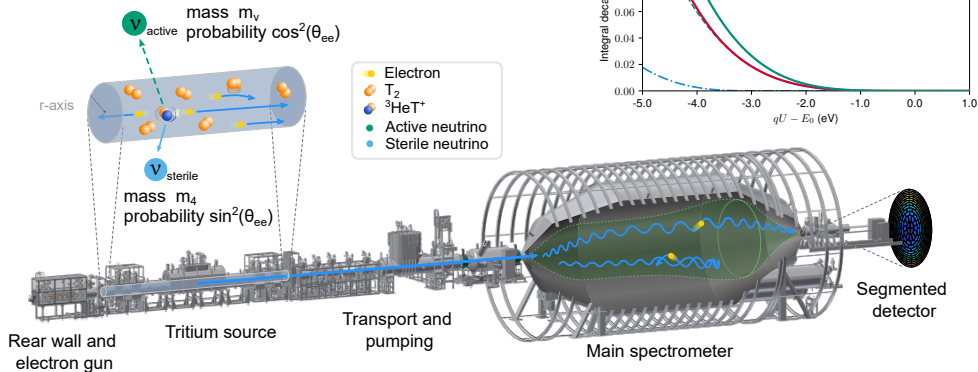
- Sterile neutrino branch leads to a kink at $E_0 - m_4$

$$m_\nu^2 = \sum_{k=1}^3 |U_{ek}|^2 m_k^2 \xrightarrow{3+1} \sum_{k=1}^3 \frac{|U_{ek}|^2}{1 - |U_{e4}|^2} m_k^2$$



KATRIN setup

70 m beamline: ultra-pure gaseous T_2 source
+ high-resolution electron spectrometer
for T_2 β -spectrum measurements near the endpoint



KATRIN Physics Goals

Direct neutrino mass measurement

- Combined Best fit: $m_\nu^2 = -0.14_{-0.15}^{+0.13} \text{ eV}^2$
- New upper limit: $m_\nu < 0.45 \text{ eV}$ (90% C.L.)
KATRIN Coll., Science 388 (2025) 180

Physics Beyond Neutrino Mass

- **eV-scale sterile neutrinos**
- Lorentz Invariance Violation (LIV)
- Relic neutrinos
- Light extra bosons
- General neutrino interactions

Selected KATRIN Coll. Results:

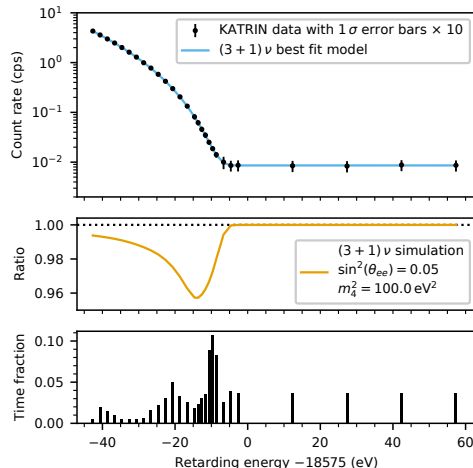
- Nature **648** (2025) 70
- Phys. Rev. D **107** (2023) 082005
- Phys. Rev. Lett. **129** (2022) 011806
- PoS ICHEP2024 (2024) 326
- Phys. Rev. Lett. **134** (2025) 251801

Spectrum Modeling

- **Model:** The measured rate $\dot{N}_{\text{exp}}(qU)$ is modeled as

$$\dot{N}_{\text{model}}(qU, \theta) = A \cdot \int_{qU}^{E_0} \frac{d\Gamma}{dE}(E, \theta) \cdot R(E, qU) dE + \dot{N}_{\text{bg}}(qU)$$

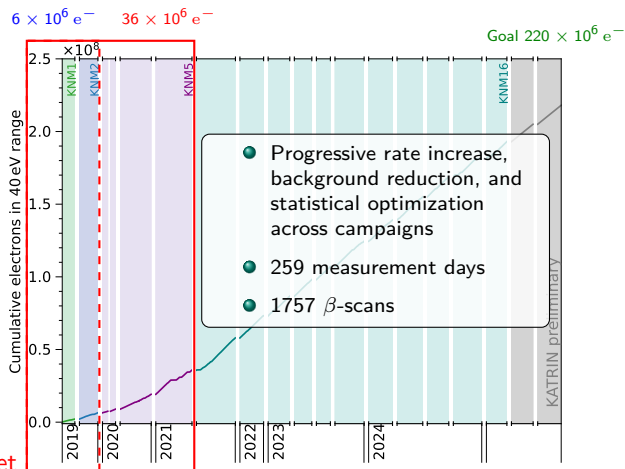
Parameter	Description
A	Signal amplitude
E_0	Effective endpoint energy
m_ν^2	Effective electron neutrino mass
$\dot{N}_{\text{bg}}$	Background rate
m_4^2	Sterile neutrino mass
$ U_{e4} ^2$	Sterile neutrino mixing



Data Collection Overview

- **KNMx**: KATRIN mass-Measurement campaign
- **Scan time**: ~ 3 hours per scan, $O(100)$ scans per campaign, **stacked data**
- **Scan points**: ~ 30 high-voltage set points
- **Scan interval**: $E_0 - 40$ eV to $E_0 + 135$ eV

20% of total data set

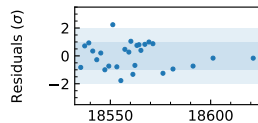
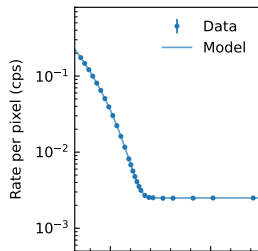


KNM1-2 Analysis

Data points:

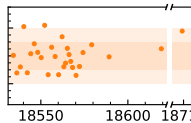
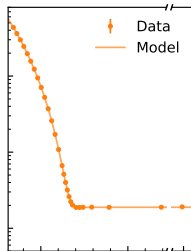
27

KNM1

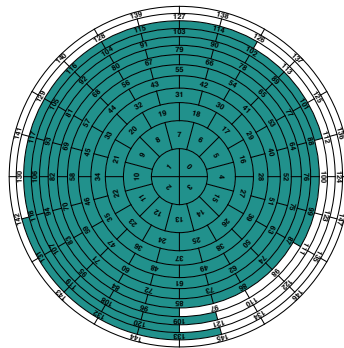


28

KNM2



Retarding energy (eV)

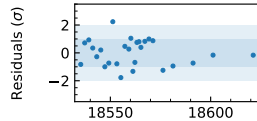
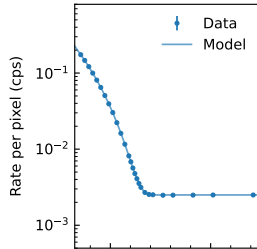


KNM1-2 Analysis

Data points:

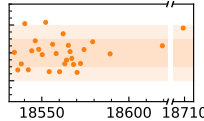
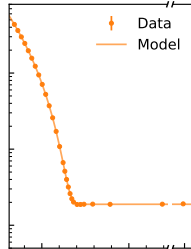
27

KNM1



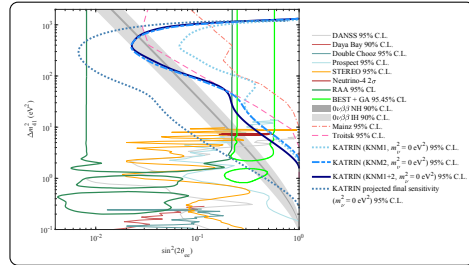
28

KNM2



PHYSICAL REVIEW D **105**, 072004 (2022)

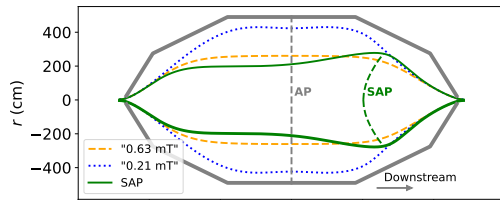
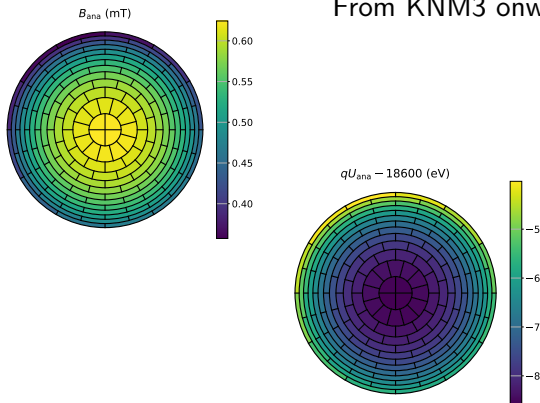
Improved eV-scale sterile-neutrino constraints from the second KATRIN measurement campaign



Retarding energy (eV)

KNM1-5 Analysis

From KNM3 onward



A. Lokhov et al., Eur. Phys. J. C 82, 258 (2022)

The KATRIN Collaboration, Eur. Phys. J. C 84, 1258 (2024)

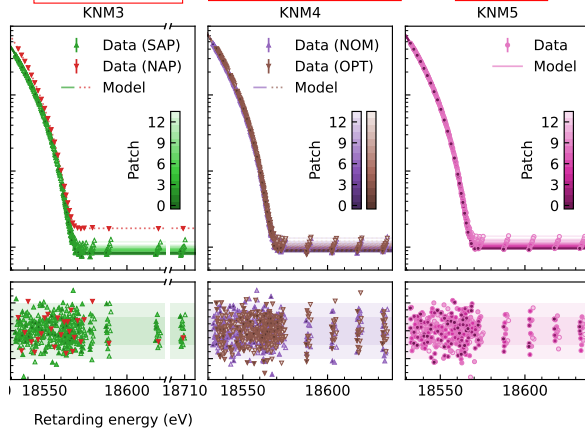
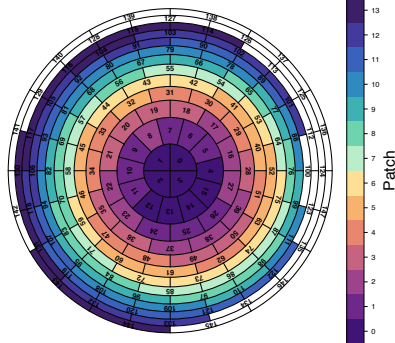
KNM1-5 Analysis

Data points:

$$(14 + 1) \times 28$$

$$14 \times 28 + 14 \times 25$$

$$14 \times 28$$



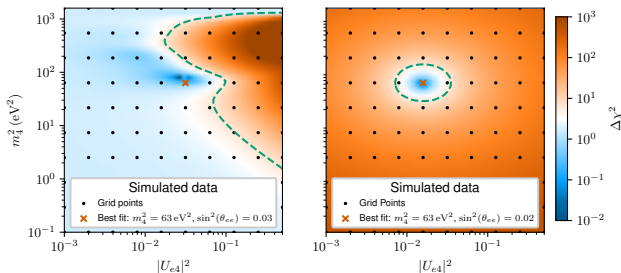
KNM1-5 Analysis Complexity

- Highly segmented data (14 patches)
 - **7** different configurations
 - **59** spectra
 - **1609** data points
- **144** correlated systematic parameters
- Computationally **expensive** model

Data set	No. of data points	stat.-only			total		
		Fit param.	Constr.	dof	Fit param.	Constr.	dof
KNM1	27	5	0	22	24	19	22
KNM2	28	5	0	23	24	19	23
KNM3-SAP	392	44	0	348	106	62	348
KNM3-NAP	28	5	0	23	27	22	23
KNM4-NOM	392	44	0	348	106	62	348
KNM4-OPT	350	44	0	306	105	61	306
KNM5	392	44	0	348	105	61	348
KNM1-5	1609	180	0	1429	340	160	1429

Analysis Method for Sterile Neutrino Search

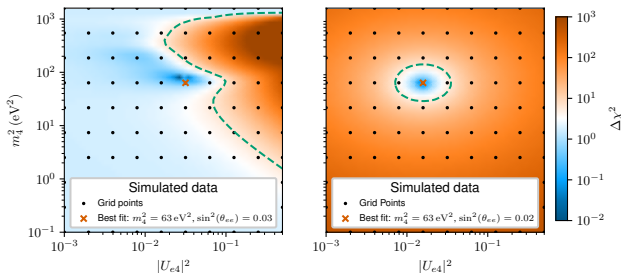
- $\chi^2 \left(\dot{\mathbf{N}}_{\text{exp}}, \dot{\mathbf{N}}_{\text{model}}(\theta) \right) = -2 \log \mathcal{L} \left(\dot{\mathbf{N}}_{\text{exp}}, \dot{\mathbf{N}}_{\text{model}}(\theta) \right)$
- **Grid Scan:** χ^2 minimized on 50×50 grid with $m_4^2 \in [0.1, 1600] \text{ eV}^2$ and $|U_{e4}|^2 \in [0.001, 0.5]$; $m_4^2 = 0 \text{ eV}^2$ & $|U_{e4}|^2 = 0$ (null-hypothesis)



- Primary analysis: $m_\nu^2 = 0$ ($m_{1,2,3} \ll m_4$)
- $\Delta\chi^2 = \chi_{\text{null}}^2 - \chi_{\text{global min}}^2$
- 95% significance level
 $\leftrightarrow \Delta\chi^2 = 5.99$, per Wilks theorem (2 degrees of freedom)

Analysis Method for Sterile Neutrino Search

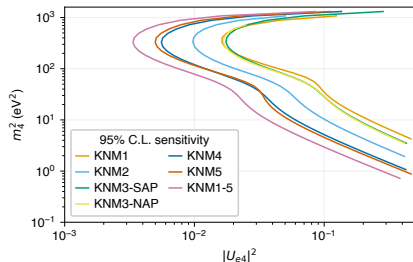
- $\chi^2 \left(\dot{\mathbf{N}}_{\text{exp}}, \dot{\mathbf{N}}_{\text{model}}(\theta) \right) = -2 \log \mathcal{L} \left(\dot{\mathbf{N}}_{\text{exp}}, \dot{\mathbf{N}}_{\text{model}}(\theta) \right)$
- **Grid Scan:** χ^2 minimized on 50×50 grid with $m_4^2 \in [0.1, 1600] \text{ eV}^2$ and $|U_{e4}|^2 \in [0.001, 0.5]$; $m_4^2 = 0 \text{ eV}^2$ & $|U_{e4}|^2 = 0$ (null-hypothesis)



- Primary analysis: $m_\nu^2 = 0$ ($m_{1,2,3} \ll m_4$)
- $\Delta\chi^2 = \chi_{\text{null}}^2 - \chi_{\text{global min}}^2$
- 95% significance level
 $\Leftrightarrow \Delta\chi^2 = 5.99$, per Wilks theorem (2 degrees of freedom)

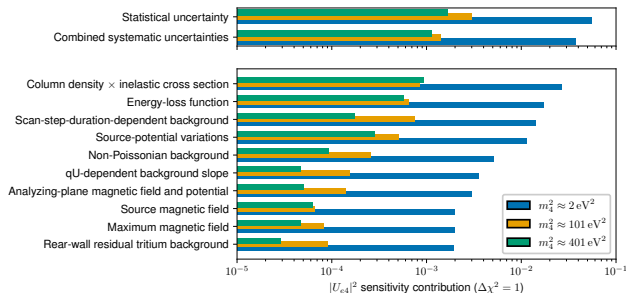
Sensitivity and Systematic Effects

$$m_\nu^2 = 0 \text{ eV}^2, m_4^2 = 0 \text{ eV}^2 \text{ \& } |U_{e4}|^2 = 0$$



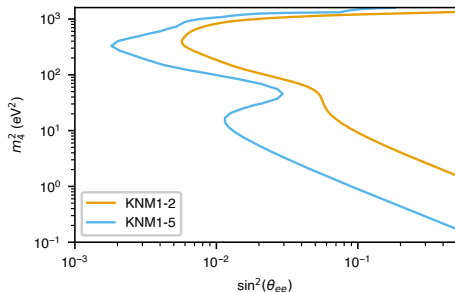
Asimov dataset: expected data without fluctuations

Sensitivity contribution of systematic uncertainties



Exclusion Limits from First Five Science Runs

- Previous (KNM1-2): 6×10^6 electrons
- New (KNM1-5): 36×10^6 electrons



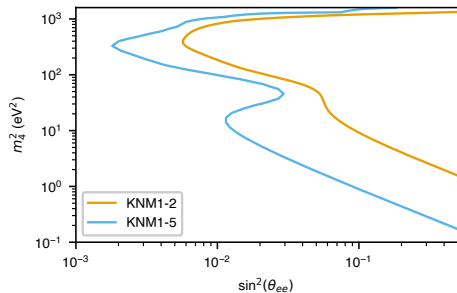
Dataset	m_4^2	$ U_{e4} ^2$	χ^2/dof	p	$\Delta\chi^2$	Sig.%
KNM1	82.63	0.027	22.1/22	0.46	1.40	50.36 %
KNM2	0.33	0.500	27.7/23	0.23	0.34	15.77 %
KNM3-SAP	25.26	0.058	309.5/348	0.93	1.75	58.30 %
KNM3-NAP	725.98	0.005	31.1/23	0.12	0.18	8.56 %
KNM4-NOM	45.68	0.024	360.2/348	0.31	2.58	72.48 %
KNM4-OPT	884.56	0.013	309.5/306	0.43	1.69	57.12 %
KNM5	82.63	0.006	309.3/348	0.93	0.88	35.75 %
KNM1-5	55.66	0.011	1374.7/1430	0.85	4.00	86.50 %

$$\text{Sig.\%} = \text{CDF}_{F(\Delta\chi^2)}(\Delta\chi^2) \times 100\%$$

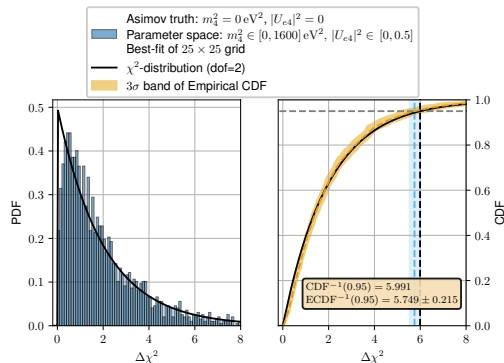
$F(\Delta\chi^2)$: Chi-squared distribution with two degrees of freedom

Exclusion Limits from First Five Science Runs

- **Previous (KNM1-2):** 6×10^6 electrons
- **New (KNM1-5):** 36×10^6 electrons

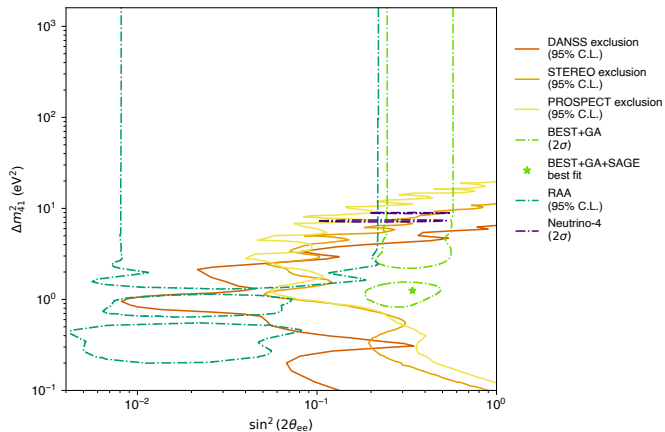


Verifying distribution of $\Delta\chi^2 = \chi_{\text{null}}^2 - \chi_{\text{bf}}^2$



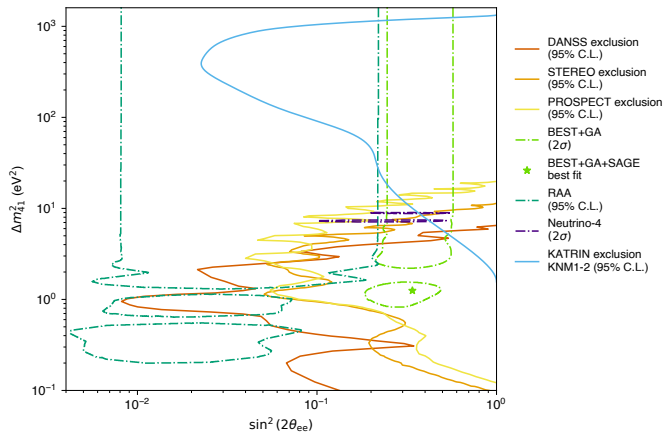
Comparison with Neutrino Oscillation Experiments

- $\Delta m_{41}^2 \approx m_4^2 - m_\nu^2$, with
 $0 \leq m_\nu^2 < m_4^2$
- $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$



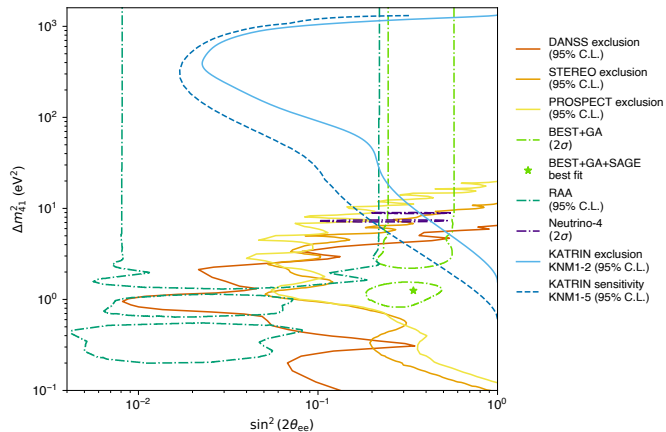
Comparison with Neutrino Oscillation Experiments

- $\Delta m_{41}^2 \approx m_4^2 - m_\nu^2$, with
 $0 \leq m_\nu^2 < m_4^2$
- $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$



Comparison with Neutrino Oscillation Experiments

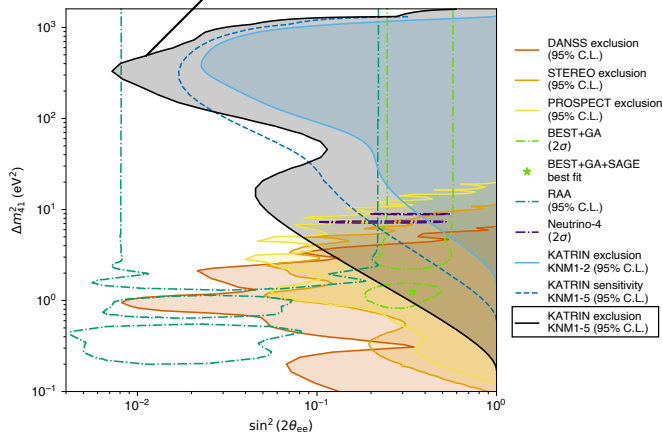
- $\Delta m_{41}^2 \approx m_4^2 - m_\nu^2$, with
 $0 \leq m_\nu^2 < m_4^2$
- $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$



Comparison with Neutrino Oscillation Experiments

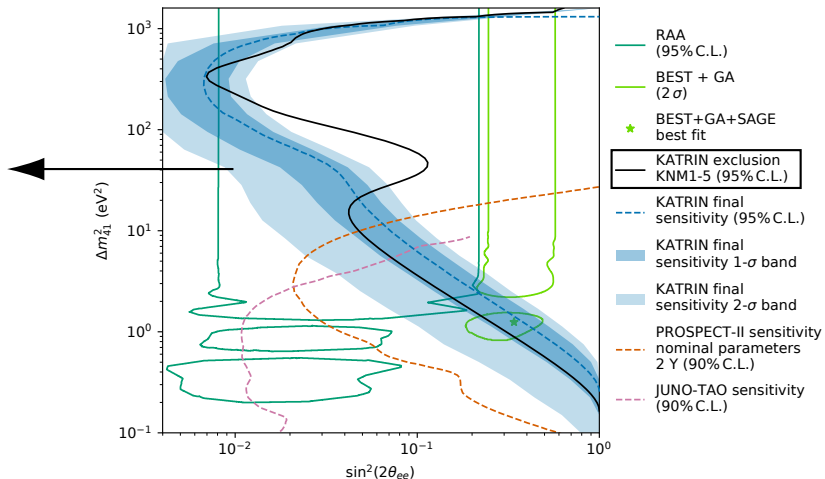
Latest result: Nature 648, 70-75 (2025)

- $\Delta m_{41}^2 \approx m_4^2 - m_\nu^2$, with $0 \leq m_\nu^2 < m_4^2$
- $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$
- Tests most of Gallium anomaly region and excludes Neutrino-4 claimed discovery
- Complementary to SBL reactor searches (PROSPECT, STEREO, DANSS); KATRIN has significant sensitivity for $\Delta m_{41}^2 > 6 \text{ eV}^2$



KATRIN Final Sensitivity Forecast

KATRIN
1000 days
Forecast
Band



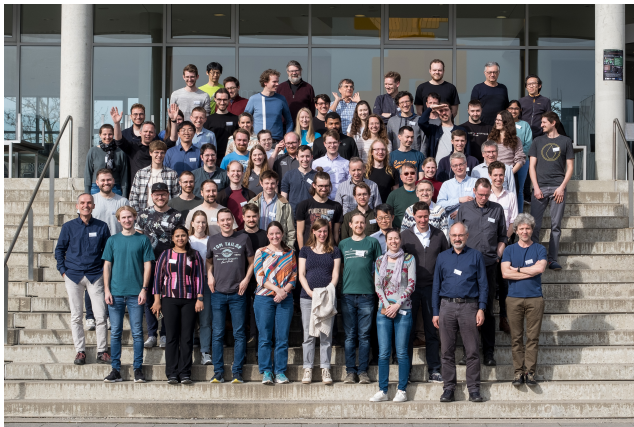
Summary and Outlook

- KATRIN probes short baseline anomalies via β -spectrum shape
- **No significant sterile neutrino signal found**
- Exclusion limits complementary to neutrino disappearance searches
- **Oct 2025:** Completed 1000 days of data collection
- Analysis of full dataset of ~ 230 mio. events ongoing

2025: Latest Sterile Neutrino Results
Nature 648, 70-75 (2025)

2026–2027: keV-Sterile Neutrino
TRISTAN detector upgrade to cover full tritium β -spectrum

Thank You!



We acknowledge the support of Helmholtz Association (HGF), Ministry for Education and Research BMBF (05A23PMA, 05A23PX2, 05A23VK2, and 05A23WO6), the doctoral school KSETA at KIT, Helmholtz Initiative and Networking Fund (grant agreement W2/W3-118), Max Planck Research Group (MaxPlanck@TUM), and Deutsche Forschungsgemeinschaft DFG (GRK 2149 and SFB-1258 and under Germany's Excellence Strategy EXC 2094 – 390783311) in Germany; Ministry of Education, Youth and Sport (CANAM-LM2015056, LTT19005) in the Czech Republic; Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation (grant B37G660014) in Thailand; and the Department of Energy through Awards DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-SC0011091 and DE-SC0019304 and the Federal Prime Agreement DE-AC02-05CH11231 in the United States. This project has received funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme (grant agreement No. 852845).

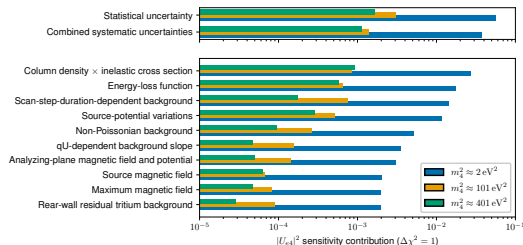
We thank the computing cluster support at the Institute for Astroparticle Physics at Karlsruhe Institute of Technology, Max Planck Computing and Data Facility (MPCDF), and the National Energy Research Scientific Computing Center (NERSC) at Lawrence Berkeley National Laboratory.



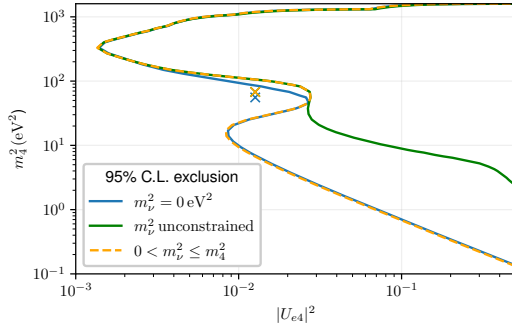
Backups

Impact of Systematics

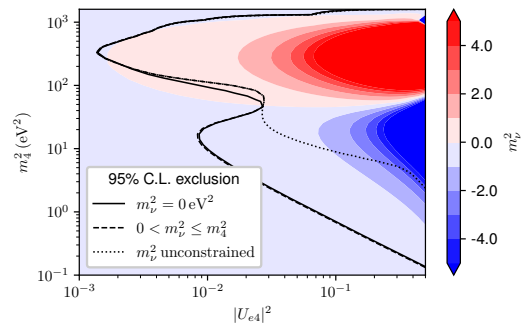
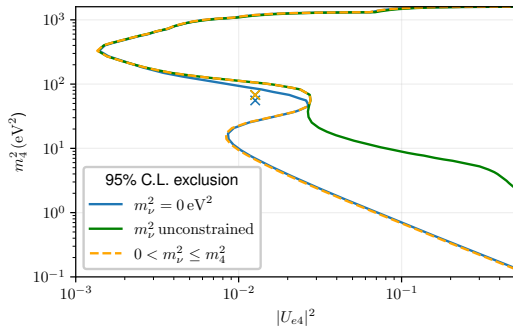
- Calculating 68% CL uncertainty on $|U_{e4}|^2$: $\sigma_{syst} = \sqrt{\sigma_{Stat+Syst}^2 - \sigma_{Stat}^2}$
- Statistically dominated uncertainties
- Largest systematic contribution: Penning Bg (low m_4^2), Column Density (high m_4^2)



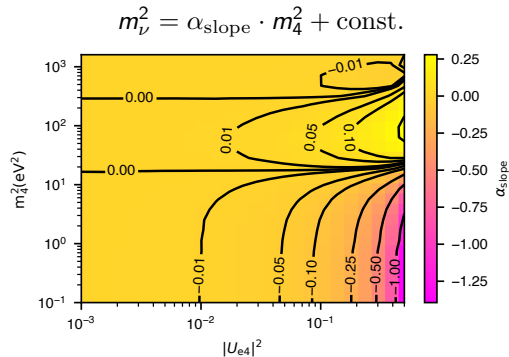
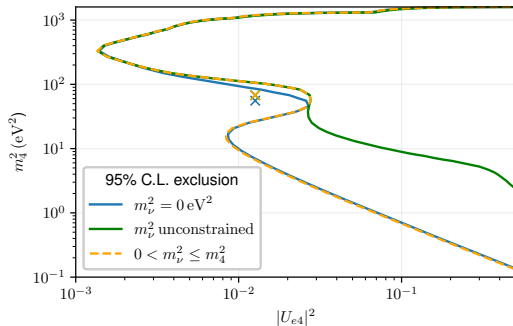
Active Neutrino Mass Treatments



Active Neutrino Mass Treatments

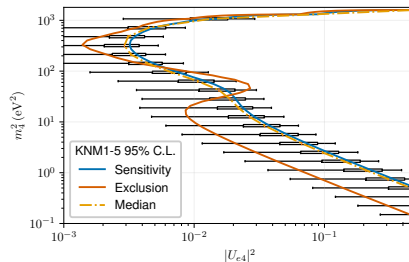


Active Neutrino Mass Treatments



Exclusion Bounds Compared to Sensitivity

- Sensitivity (simulation) and exclusion (data) contours overlap
- $m_4^2 < 30 \text{ eV}^2$: exclusion stronger than sensitivity
- $m_4^2 > 30 \text{ eV}^2$: exclusion fluctuates around sensitivity
- Exclusion contour remains within the 95% intervals expected from statistical fluctuations



Systematic error propagation via Pull term approach

- Adding additional free parameters (θ_i)
- Constraining parameters with a penalty term
- Adding pull terms widens the χ^2 distribution:

$$\chi^2(m^2, E_0, \text{Sig}, \text{Bg}, \theta_1, \dots) + \frac{(\theta_1 - \hat{\theta}_1)^2}{\sigma_{\theta_1}^2} + \dots$$

In the combined analysis of data across campaigns:

- Pull term as multivariate normal distribution
- Treatment of correlations between campaigns and segments
- High-cost model computations

