Latest Constraints on Sterile Neutrinos from the KATRIN Experiment

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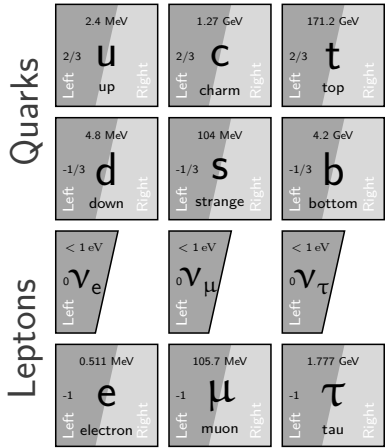
Neutrinos: Massless in the Standard Model

- 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



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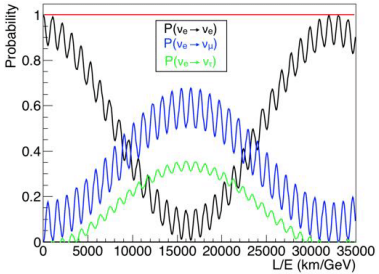

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e3} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

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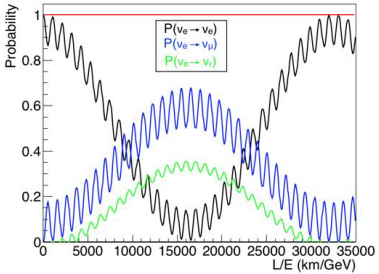

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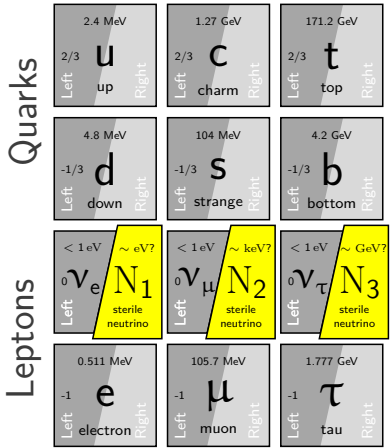
Extension via Sterile Neutrinos

- 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
- Motivation for ν_s (see talk by Manfred Lindner on Monday)
- This work focused on eV-scale search



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$3-4 σ); **tested independently via β-decay**

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

small, large

$$\Delta m_{21}^2 \ll \Delta m_{31}^2 \ll \Delta m_{41}^2,$$
$$|U_{e4}|^2,\ |U_{\mu 4}|^2,\ |U_{\tau 4}|^2 \ll 1, \quad |U_{s4}|^2 \simeq 1.$$

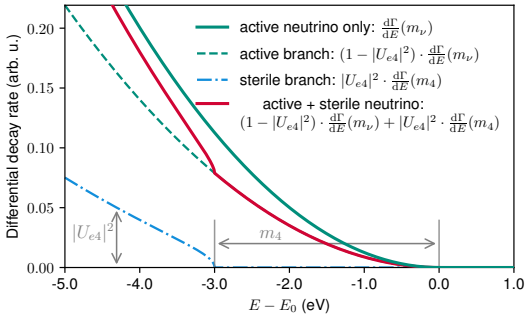
Signature in β-decay

- **Differential decay rate**:

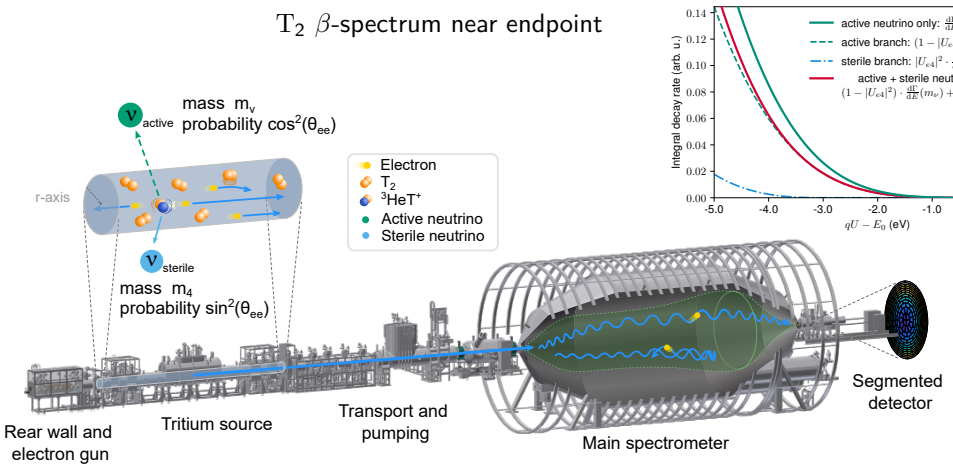
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E, m_\nu^2, m_4^2, |U_{e4}|^2)$$
$$= \underbrace{(1-|U_{e4}|^2)\cdot\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E, m_\nu^2)}_{\text{Active branch}} + \underbrace{|U_{e4}|^2\cdot\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E, m_4^2)}_{\text{Sterile branch}}$$

- 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

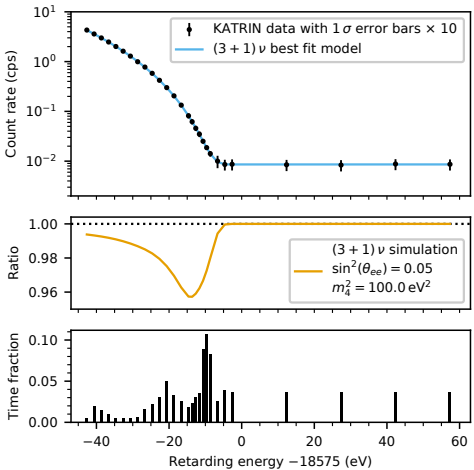


Spectrum Modeling

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

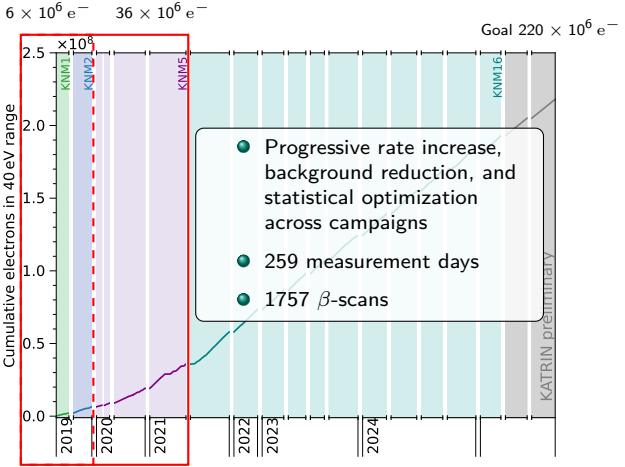
$$\dot{N}_{\mathrm{model}}(qU, \boldsymbol{\theta}) = A \cdot \int_{qU}^{E_0} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E, \boldsymbol{\theta}) \cdot R(E, qU)\, \mathrm{d}E + \dot{N}_{\mathrm{bg}}(qU)$$

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



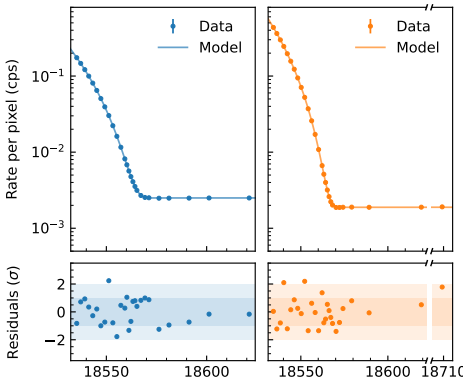
Data Collection Overview

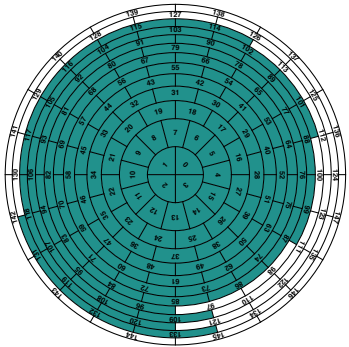
- **KNMx**: KATRIN mass-Measurement campaign
- **Scan time**: $\sim$ 3 hours per scan, $O(100)$ scans per campaign, **stacked data**
- **Scan points**: $\sim$ 30 high-voltage set points
- **Scan interval**: $E_0 - 40\,\mathrm{eV}$ to $E_0 + 135\,\mathrm{eV}$



KNM1-2 Analysis

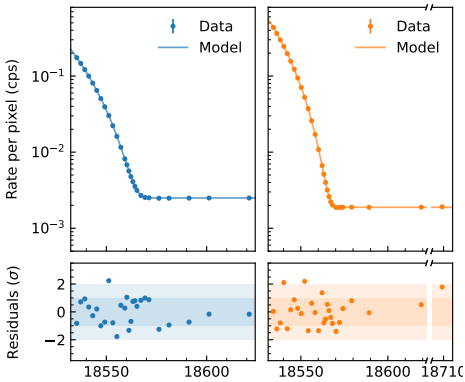
Data points: 27 28





KNM1-2 Analysis

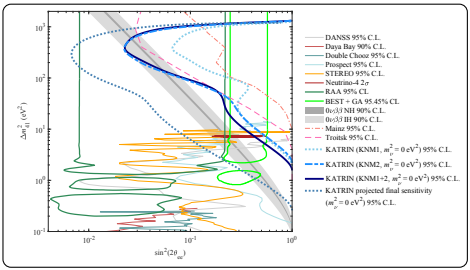
Data points: 27 (KNM1) 28 (KNM2)



Retarding energy (eV)

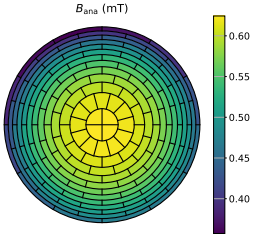
PHYSICAL REVIEW D **105,** 072004 (2022)

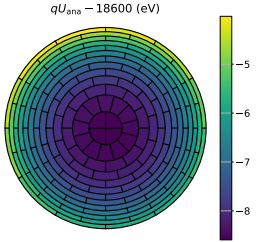
Improved eV-scale sterile-neutrino constraints from the second KATRIN measurement campaign

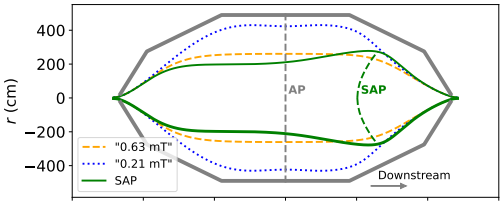


KNM1-5 Analysis

From KNM3 onward



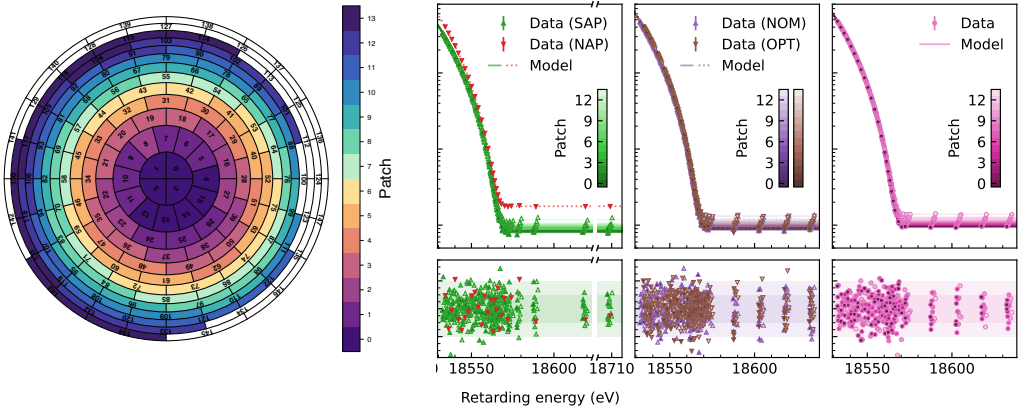




A. Lokhov et al., Eur. Phys. J. C 82, 258 (2022)
The KATRIN Collaboration, Eur. Phys. J. C 84, 1258 (2024)

KNM1-5 Analysis

Data points: $(14+1)\times 28$ | $14\times 28+14\times 25$ | 14×28



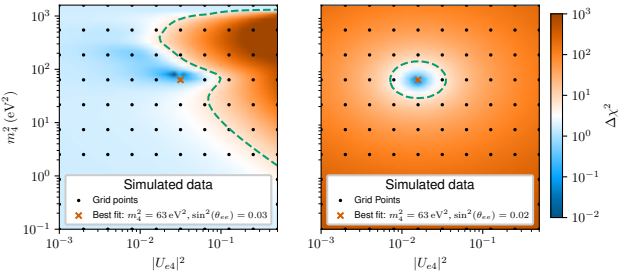
KNM1-5 Analysis Complexity

- 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

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



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

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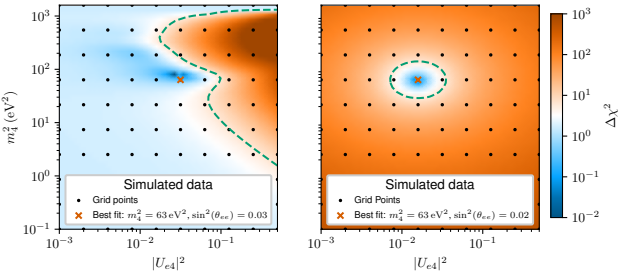

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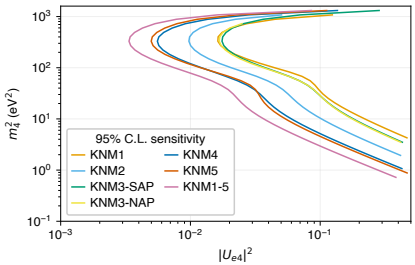
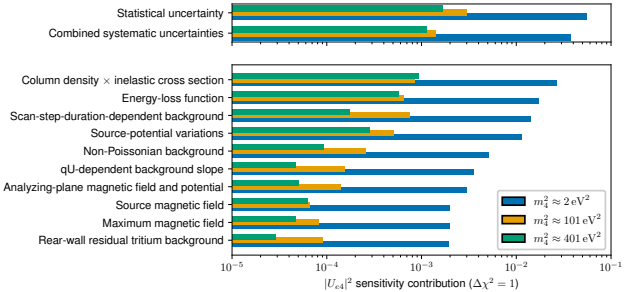
Sensitivity and Systematic Effects

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



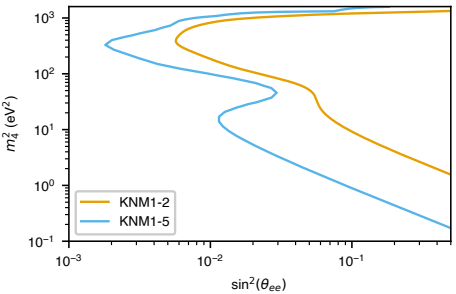
Sensitivity contribution of systematic uncertainties



Asimov dataset: expected data without fluctuations

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	$\lvert U_{e4}\rvert^2$	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

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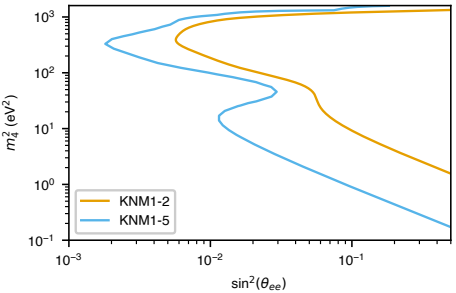
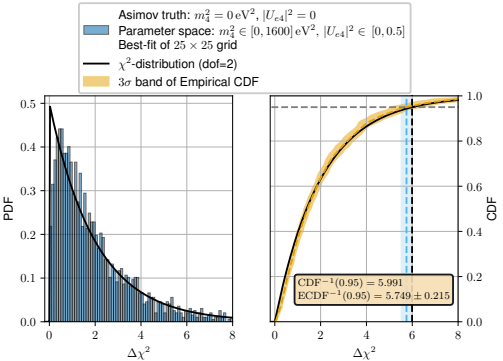
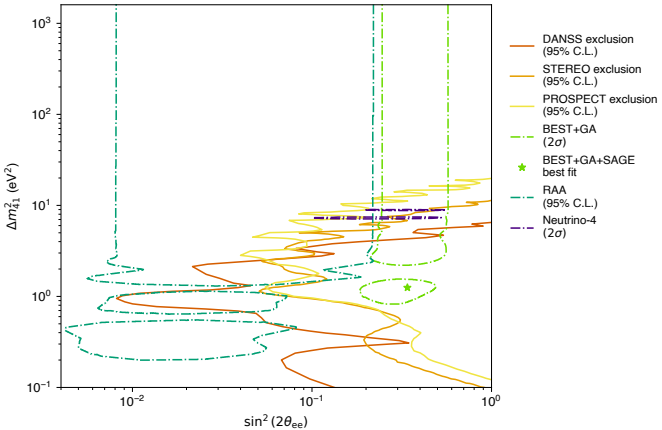


Verifying distribution of $\Delta\chi^2 = \chi^2_{\text{null}} - \chi^2_{\text{bf}}$



Comparison with Neutrino Oscillation Experiments

- $\Delta m^2_{41} \approx m^2_4 - m^2_\nu$, with $0 \leq m^2_\nu < m^2_4$
- $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$



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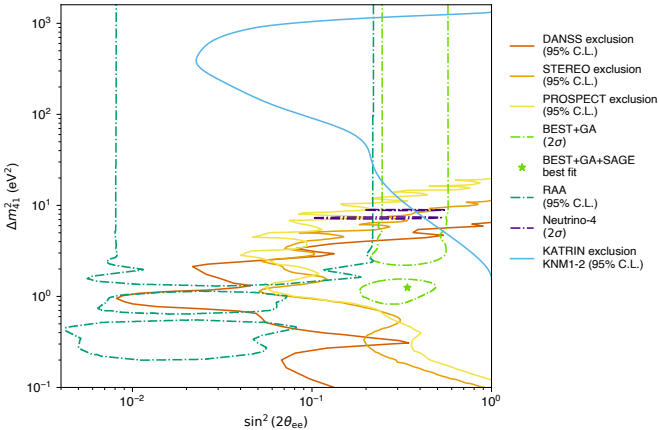

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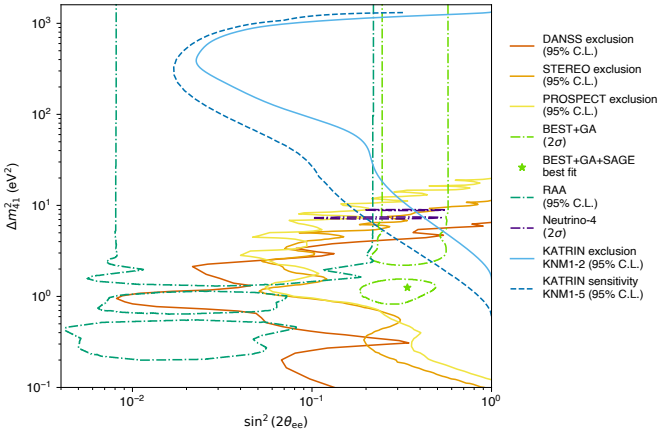

Comparison with Neutrino Oscillation Experiments

Latest release: arXiv:2503.18667

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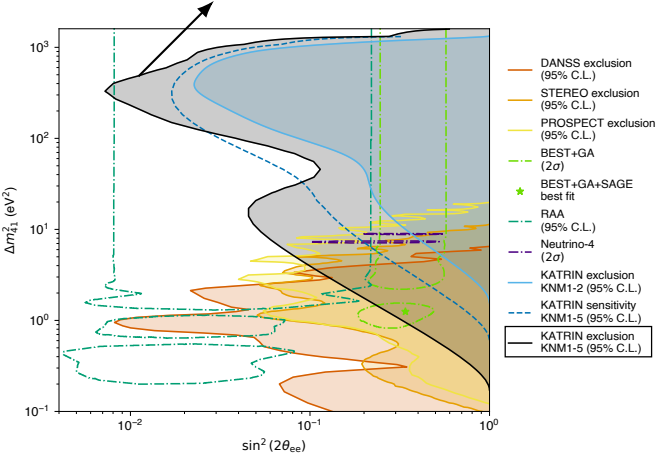
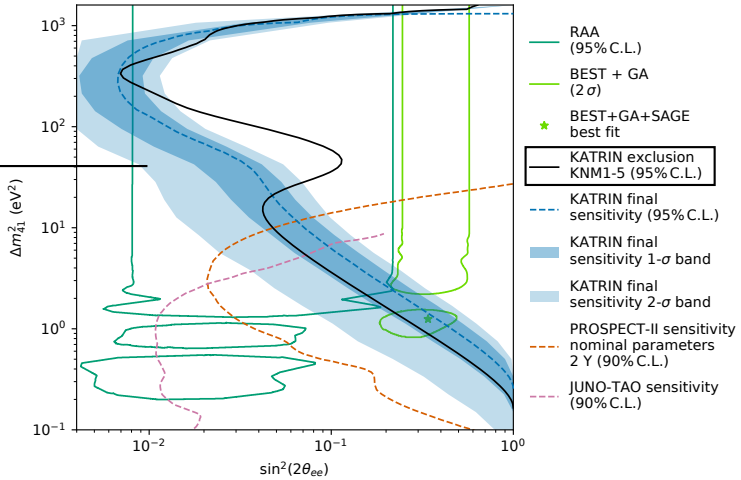
- $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$
- Tests most of Gallium anomaly region and excludes Neutrino-4 claimed discovery
- Complementary to SBL reactor searches (PROSPECT, STEREO, DANSS); KATRIN has significant sensitivity for $\Delta m^2_4 > 6\,\mathrm{eV}^2$

Talk on DANSS by Igor Alekseev



KATRIN Final Sensitivity Forecast

KATRIN
1000 days
Forecast
Band



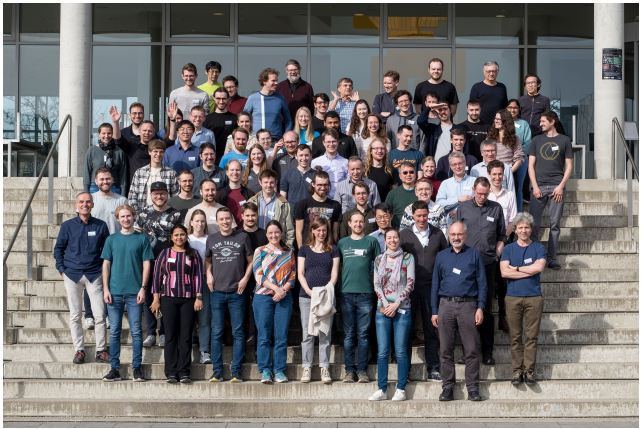
Summary and Outlook

- KATRIN probes short baseline anomalies via β-spectrum shape
- **No significant sterile neutrino signal found**
- Exclusion limits complementary to neutrino disappearance searches
- Analysis of complete KATRIN dataset
- Analysis with extended analysis range beyond $E_0 - 40\,\mathrm{eV}$

2025: Latest Sterile Neutrino Results
arXiv:2503.18667

2026–2027: keV-Sterile Neutrino
TRISTAN detector upgrade

Thank You!



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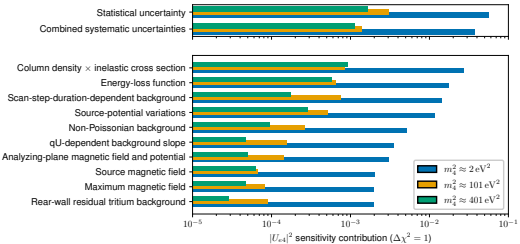
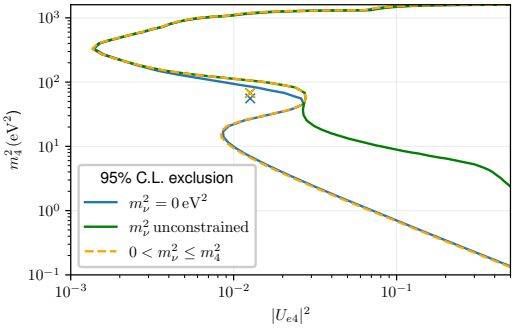
Backups

Impact of Systematics

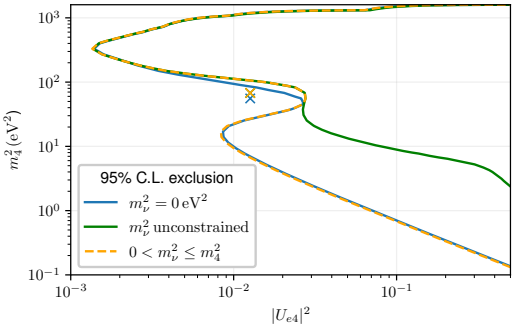
- Calculating 68% CL uncertainty on $|U_{e4}|^2$: $\sigma_{syst} = \sqrt{\sigma^2_{Stat+Syst} - \sigma^2_{Stat}}$
- Statistically dominated uncertainties
- Largest systematic contribution: Penning Bg (low m_4^2), Column Density (high m_4^2)

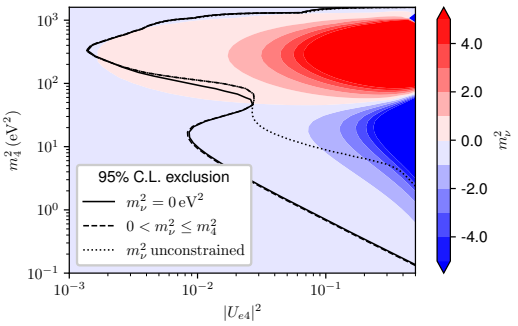


Active Neutrino Mass Treatments

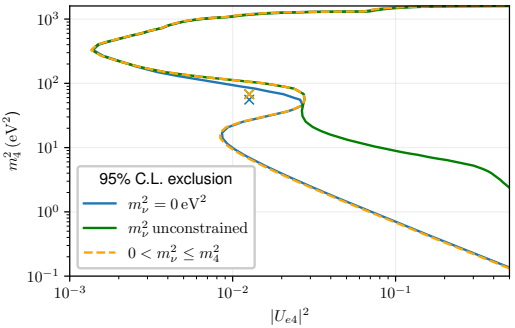


Active Neutrino Mass Treatments

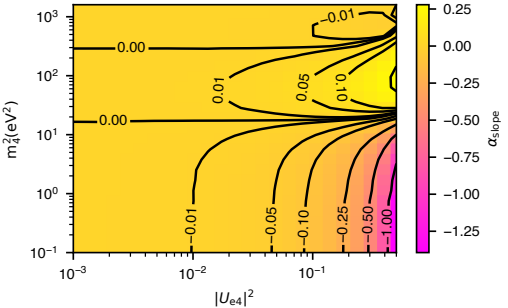




Active Neutrino Mass Treatments



$$m_\nu^2 = \alpha_{\mathrm{slope}} \cdot m_4^2 + \mathrm{const.}$$



Exclusion Bounds Compared to Sensitivity

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