Karlsruhe Institute of Technology

# Search for eV sterile neutrino with the KATRIN experiment

**ISAPP 24, Bad Liebenzell**

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Institute for Astroparticle Physics | September 26, 2024

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Sterile neutrino = SM neutral singlet fermion

- Existence could be revealed through effects of mass and mixing with active neutrinos (neutrino oscillations, $\beta$**- decay**, $0\nu\beta\beta$-decay)

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- *Theoretical motivation:*

DM exists $\implies$ uncharged particles under SM gauge group $\implies$ singlet fermions

- Singlet fermions naturally appear in the dark sector
- Members of dark sector could mix with active neutrinos via neutrino portal coupling
- Sterile neutrinos can live at any mass scale: GeV..., keV..., $\boxed{eV}$...

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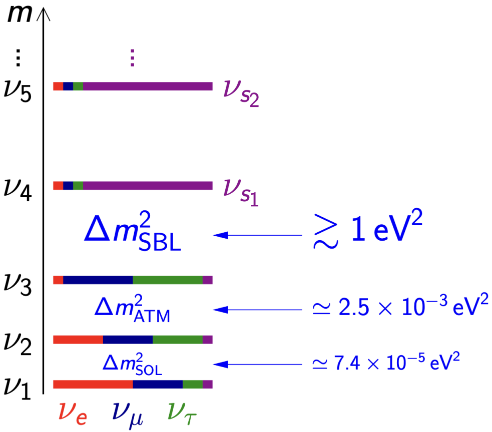
- *Experimental hints for eV scale* :
  - *Appearance* LSND ($3\sigma$) and MiniBooNE ($4.8\sigma$) excess observations
    Explained by ($\nu_\mu \rightarrow \nu_\mathrm{s} \rightarrow \nu_\mathrm{e}$)
  - *Disappearance* SAGE and GALLEX: Gallium anomaly ($2.9\sigma$ deficit)
    Explained by $\nu_e \rightarrow \nu_s$
  - The Gallium anomaly reaffirmed by BEST experiment

  Lecture by T.Lasserre

# Interpretation


- SBL anomalies could be explained by an additional neutrino flavor ($\nu_s$)
- There must be at least one additional mass squared difference,
  3$\nu$ + 1 framework $\Delta m^2_{SBL} \approx (1-2)\,\mathrm{eV}^2$
- Allowed by solar, atmospheric and long baseline experiments, achieved with $|U_{e4}|^2 \ll 1$



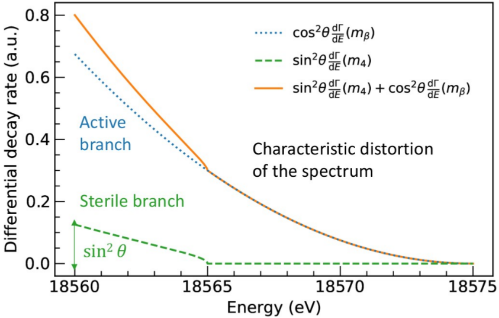
# Single $\beta$-decay

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

- **Differential decay rate**:

$$R_\beta(E, m_\nu^2, m_4^2, |U_{e4}|^2)$$
$$= \underbrace{(1-|U_{e4}|^2) \cdot R_\beta(E, m_\nu^2)}_{\text{Active branch}} + \underbrace{|U_{e4}|^2 \cdot R_\beta(E, m_4^2)}_{\text{Sterile branch}}$$
$$= \cos^2\theta \cdot R_\beta(E, m_\nu^2) + \sin^2\theta \cdot R_\beta(E, m_4^2)$$

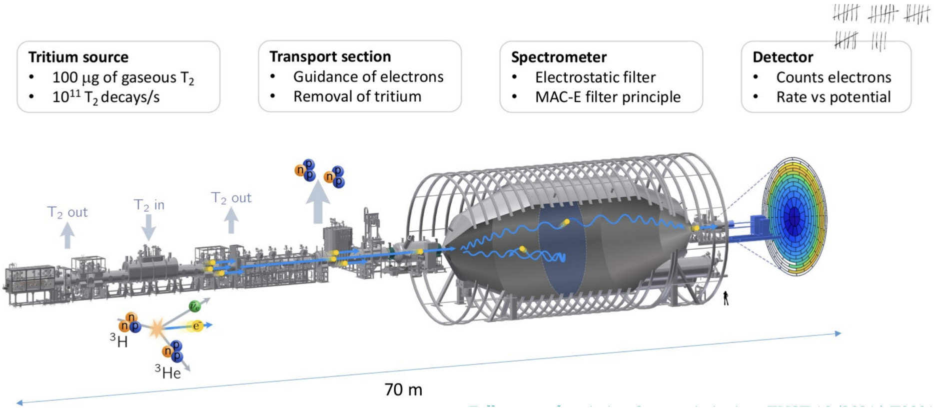
- Sterile neutrino branch leads to a kink at $E_0 - m_4$



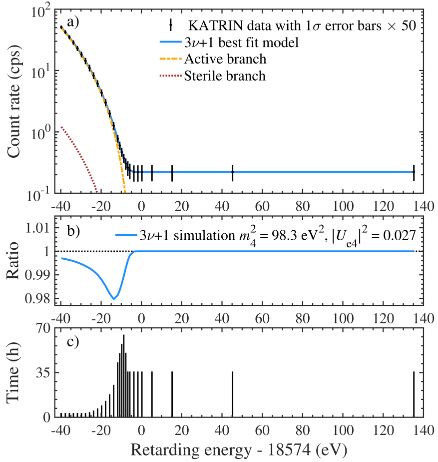
# KATRIN Experiment

- Kinematics-based neutrino mass experiment
  (expected sensitivity is better than 0.3 eV (90% CL) with 1000 days of measurement time)
- **Current result:** $m_\beta$**< 0.45 eV (90%) CL**, from 259 days of data only
  *e-Print: 2406.13516 [nucl-ex]*

Lecture by C.Weisinger



# Sterile Signal in $\beta$-decay Spectrum




- Measured integral spectrum $N_{\mathrm{exp}}(qU)$ is fitted to the **model** $N_{\mathrm{model}}(qU, \Theta)$:

$$N_{\mathrm{model}}(qU, \Theta) = A \cdot \int R_\beta(E, \Theta) \cdot f(E, qU) + Bg$$

- 6 model parameters:
  - A - Signal amplitude
  - $E_0$ - effective endpoint energy
  - $m^2$ - effective mass of electron anti-neutrino
  - Bg - Background rate
  - $m_4^2$ - sterile neutrino mass
  - $|U_{e4}|^2$ - sterile neutrino mixing

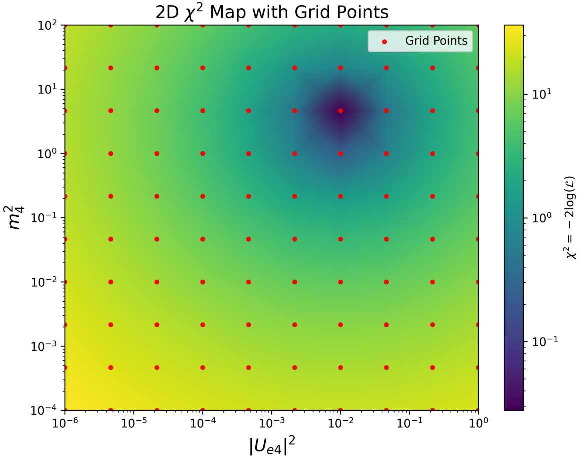
# Dataset and Bias-free Analysis

- **Data Combination Approach:**
  - Summed $\beta$-spectrum counts at identical set points.
  - Combined spectra from different detector pixels.
- **Modeling and Likelihood:**
  - Maximum-likelihood fit with Gaussian/Poisson likelihoods.
  - Minimize $\chi^2 = -2\log(\mathcal{L})$ with respect to nuisance parameters ($\Theta = (m_\nu^2, E_0, A, B, ..)$).
- **Systematic Uncertainties:**
  - Pull terms in likelihood for experimental parameters.
  - Calibration measurements for external estimates.

- **Unblinding Procedure**
  - Code validation on Monte Carlo twins.
  - Tritium spectrum, response model, systematics treatment and budget (pull term approach) same as active neutrino mass analysis.
  - **Two Independent Analysis Teams with Independent Codes:**
    - KaFit (exact model evaluation).
    - Netrium (uses neural nets for swift model interpolation).

# Analysis Method

- Extend $\beta$- spectrum model from 3 active to 3+1 (active + sterile) framework
- **Grid Scan:** 50 $\times$ 50 $\left[\log(|U_{e4}|^2), \log(m_4^2)\right]$ plane
- Contours are drawn at $\Delta\chi^2 = \chi^2 - \chi^2_{BF}$ = 5.99 (95% CL, 2 dof)
- Energy range: $[E_0 - 40, E_0 + 135]$ eV
- Sensitive to $m_4^2 \leq 1600$ eV$^2$ and $|U_{e4}|^2 \leq 0.5$
- Two complementing analyses
  - **Case-I - Fixed neutrino mass:** $m_\nu^2$**= 0** $(m_{1,2,3} \ll m_4)$
  - Case-II - Free neutrino mass: $m_\nu^2$ as nuisance parameter



# Results from First Two Science Runs

- $5.24 \times 10^6$ electrons for 40 eV below $E_0$, 1265 hours of data
  **Best fit:**
  - $m_4^2$ = 59.9 eV$^2$, $|U_{e4}|^2$ = 0.011, $m_\nu^2$ = 0.0 eV$^2$
  - $\Delta\chi^2_{null}$ = 0.66
- Active neutrino mass set free
  **Best fit:**
  - $m_4^2$ = 87.4 eV$^2$, $|U_{e4}|^2$ = 0.019, $m_\nu^2$ = 0.57 eV$^2$
  - $\Delta\chi^2_{null}$ = 1.69
- Signal-to-background ratio of up to 235

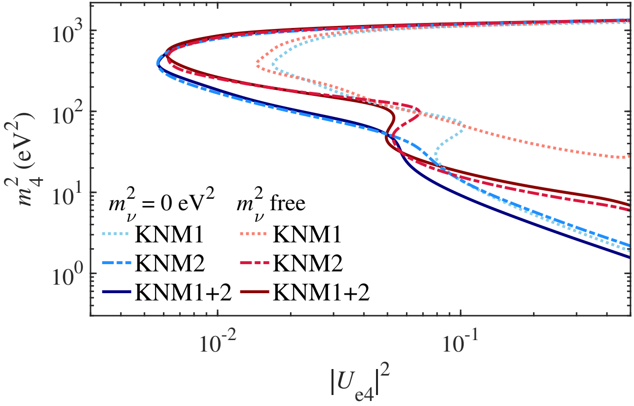
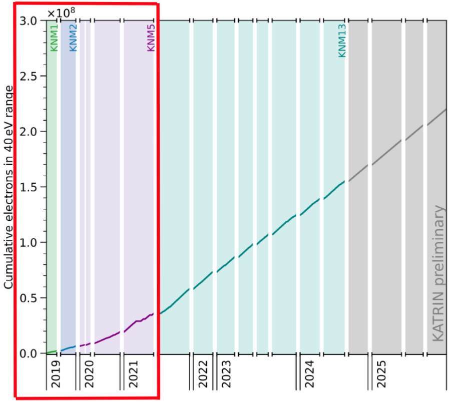



Figure: *Phys. Rev. D 105 (7 2022)*

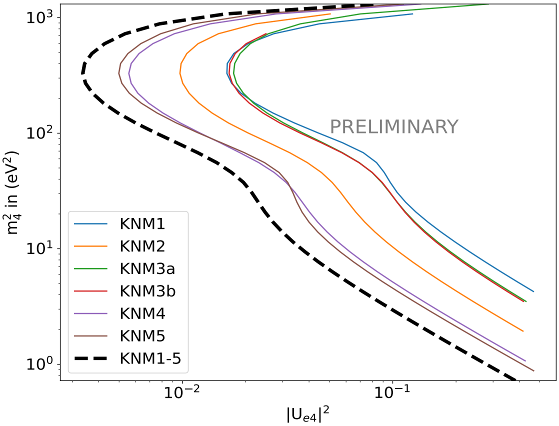
# Data Collection Status

- KNM1 to KNM5: 20 % of expected KATRIN data
- Significant experimental development: Shifted Analyzing Plane (SAP) background reduction method
  *Lokhov et al., EPJ C 82 (2022) 3, 258*



# Sensitivity Projection From Five Science Runs

- **Case-I**: $m_\nu^2 = 0$ eV$^2$
- 40 eV fit range, $|U_{e4}|^2 \in [0, 0.5]$
- Stat. only + all systematics 95% CL
- Gain in overall sensitivity with increased statistics
  *S. Mohanty, PoS EPS- HEP2023 (2024)*




| Campaign | KNM1 | KNM2 | KNM3a | KNM3b | KNM4 | KNM5 | KNM1-5 |
|---|---|---|---|---|---|---|---|
| No. of signal electrons ($\times 10^6$) | 2.0 | 4.3 | 1.1 | 1.4 | 10.2 | 16.8 | 35.8 |

# 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 $m_4^2$)

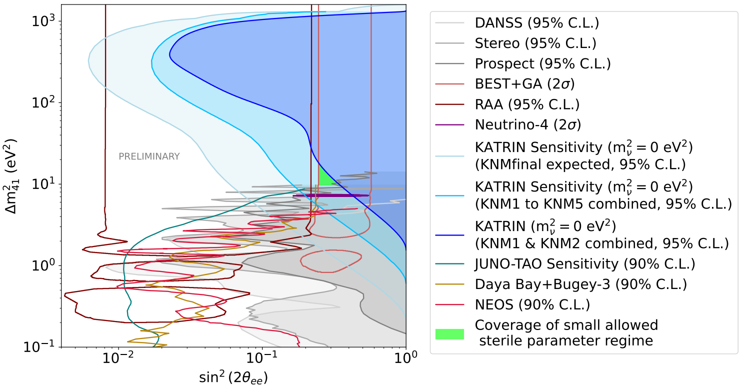
# Comparison to Other Experimental Results

- Translation of parameters:

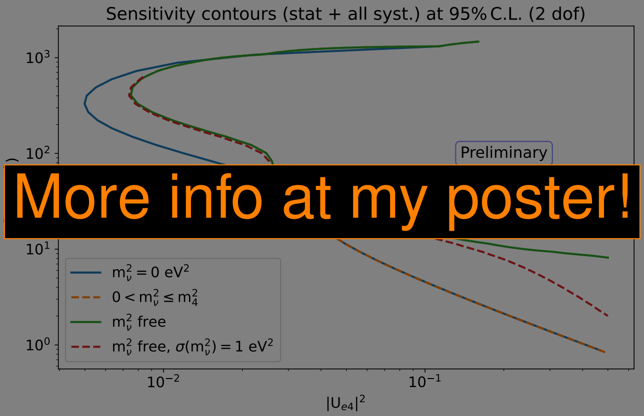
$$\sin^2(2\theta) = 4|U_{e4}|^2(1-|U_{e4}|^2)$$

- Large $\Delta m^2_{41}$ solutions of RAA and BEST+GA anomalies excluded
- Current KATRIN data extends exclusion bounds from SBL oscillation experiments for $\Delta m^2_{41} \geq 10$ eV$^2$
- Probing large parameter space for light sterile neutrino anomalies

Analysis has been applied to the real data and results to be released soon!



# Impact of active neutrino on sterile neutrino search




**More info at my poster!**

# Summary

- New physics beyond the SM can include sterile neutrinos at all mass scales
- KATRIN uniquely addresses SBL anomalies via spectral shape analysis
- Results from first two science runs (KNM1 + KNM2):
  - No significant sterile-neutrino signal observed
  - Improved exclusion limits w.r.t. complementary experiments

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  - Sensitivity dominated by statistical uncertainties

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Outlook:

- Analysis on data for first five science runs ongoing
- Stay tuned for upcoming release!

Karlsruher Institut für Technologie


# *Thank You*

# Backups

# Experimental hints

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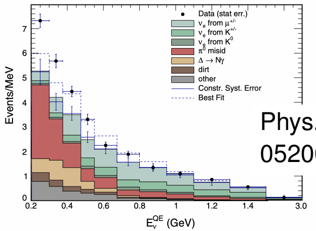
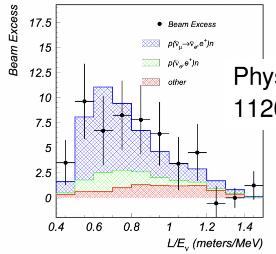
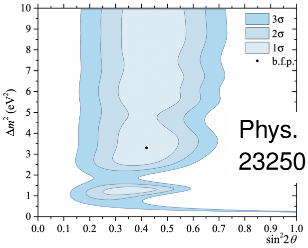



Phys. Rev. D 103, 052002 (2021)



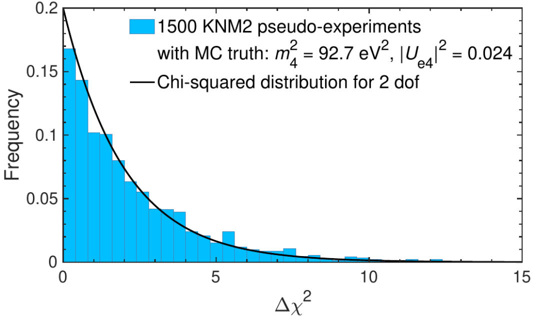

Phys. Rev. D, Vol. 64, 112007 (2001)




Phys. Rev. Lett. 128, 232501 (2022)

# Testing applicability of Wilks' Theorem

- Generate $\mathcal{O}(10^3)$ twins with statistical fluctuations for particular choice of MC truth
- Perform fitting for sterile parameter values on a grid and for MC truth for each sample ($m_\nu^2 = 0$)
- Evaluate $\Delta\chi^2 = \chi^2_{\text{MC truth}} - \chi^2_{\text{best fit}}$ for each sample
- Compare distribution of $\Delta\chi^2$ values to $\chi^2$-distribution with 2 dof




(c) KNM2, MC truth: $m_4^2 = 92.7\,\text{eV}^2$ and $|U_{e4}|^2 = 0.024$