Karlsruhe Institute of Technology

Sterile neutrino search with the KATRIN experiment

DISCRETE 2022 - Baden Baden

Leonard Köllenberger *for the KATRIN collaboration* | Wednesday 9th November 2022

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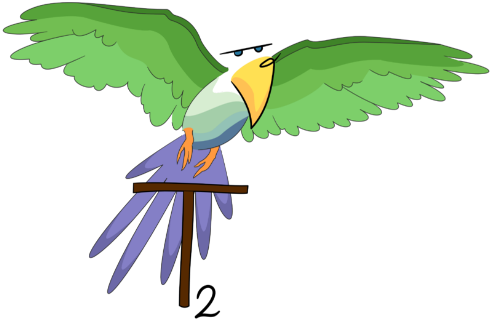


Motivation

- Neutrino oscillation $\rightarrow$ neutrinos are massive
- Mass generation $\rightarrow$ existence of sterile neutrinos? (Seesaw mechanism)

$\Longrightarrow$ Right-handed (sterile) neutrinos are a simple extension to the standard model (νMSM)

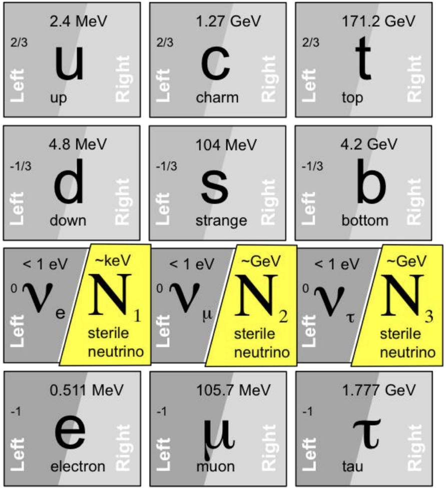
- Additional mass eigenstates of arbitrary mass

eV-sterile neutrino motivation:

- Resolve anomalies in short-baseline oscillation experiments

keV-sterile neutrino motivation:

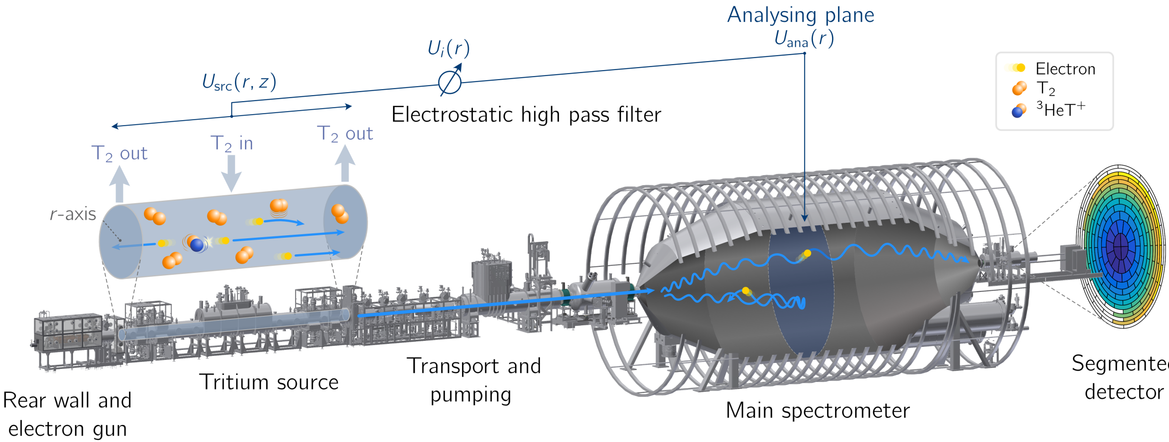
- Warm dark matter candidate



L. Canetti,et al. PRL 110 061801 (2013)

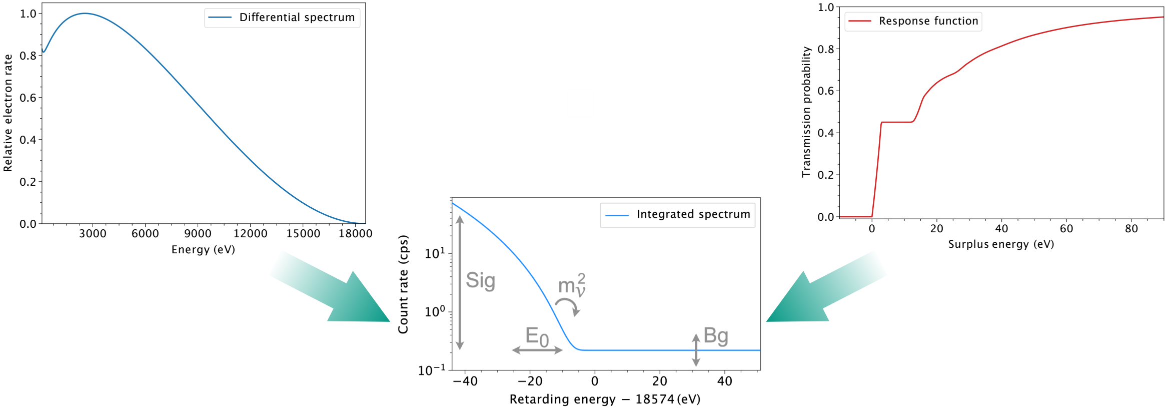
Experimental setup

Goal: Measurement of the effective electron anti-neutrino mass with 0.2 eV sensitivity at 90 % C.L.



Tritium model

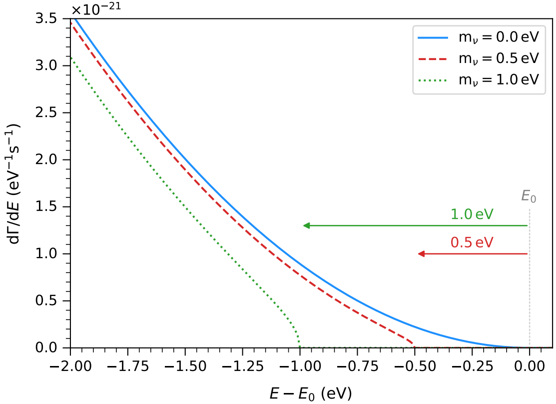
$$\dot{N}(qU) = \mathrm{Sig} \cdot N_{\mathrm{T}} \cdot \frac{\Omega}{4\pi} \cdot \int_{qU}^{E_0} \frac{\mathrm{d}\Gamma}{\mathrm{d}E} \cdot R(E, qU)\, \mathrm{d}E + \mathrm{Bg}$$



Tritium model – differential spectrum

Differential β-decay spectrum according to Fermi's golden rule:

$$\frac{d\Gamma}{dE} = C \cdot p \cdot F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_i |U_{ei}^2| \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot \Theta(E_0 - E - m_i)$$



In KATRIN – measurement of the effective neutrino mass:

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

m_i: Mass eigenstates

U_{ei}: Elements of the 3 × 3 PMNS matrix

Tritium model – 3+1ν framework

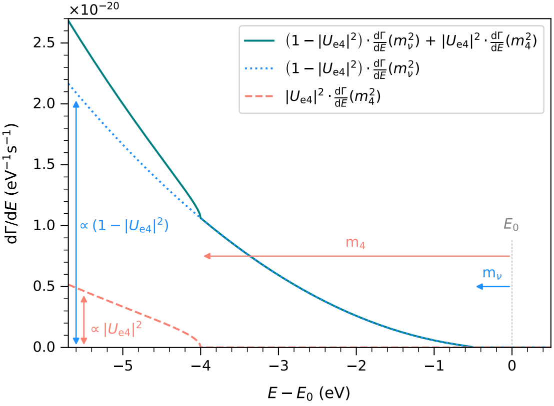
Motivation: Sterile neutrinos ($\geq$ 1 eV) could explain observations such as reactor and gallium anomalies

- Differential spectrum can be adapted to account for sterile neutrinos

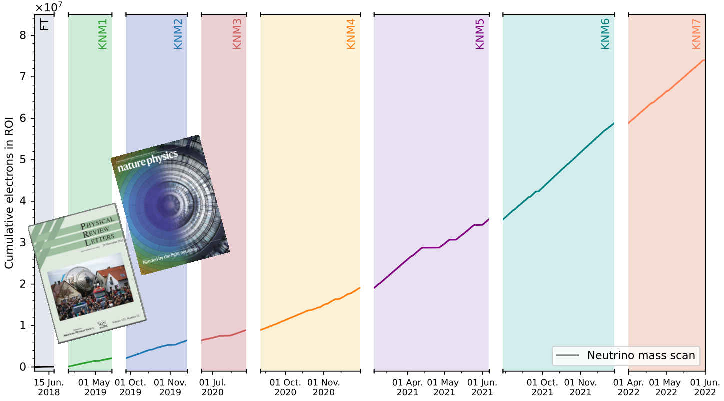
$\Longrightarrow$ Extend model of β-spectrum to 3+1ν framework

$$\frac{d\Gamma}{dE} = (1 - |U_{e4}|^2) \cdot \frac{d\Gamma}{dE}(m_\nu^2) + |U_{e4}|^2 \cdot \frac{d\Gamma}{dE}(m_4^2)$$

- Kink-like signature of sterile neutrinos at m_4



Measurement campaigns – overview



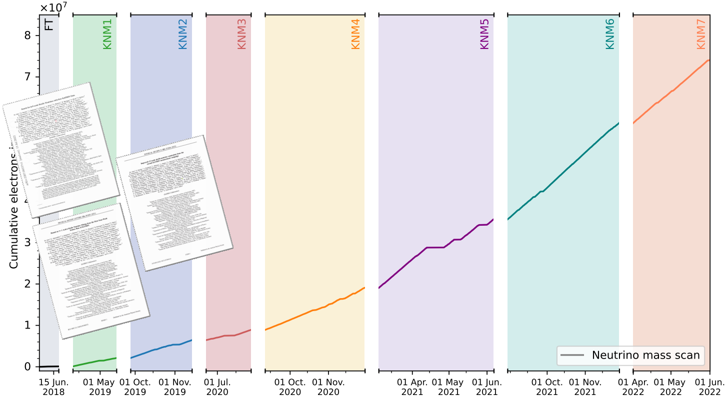
- Seven **K**ATRIN **N**eutrino mass **M**easurements to date
- Published neutrino mass results: KNM1 and KNM2

  KNM1: $\Rightarrow m_\nu \leq 1.1\,\text{eV}$
  Phys. Rev. Lett. 123, 22180 (2019)

  KNM1 & KNM2: $\Rightarrow m_\nu \leq 0.8\,\text{eV}$
  Nat. Phys. 18, 160–166 (2022)

- Currently analysing: KNM1 – KNM5
- More data: KNM6, KNM7, ...

Search for eV and keV scale sterile neutrinos



- Using the same data sets we also search for sterile neutrinos
- Published sterile neutrino results:

  First tritium:
  arXiv, 2207.06337v1 (2022)

  KNM1:
  Phys. Rev. Lett. 126, 091803 (2021)

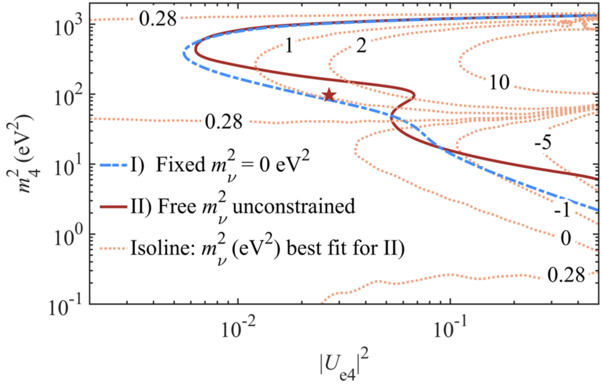
  KNM1 & KNM2:
  Phys. Rev. D 105, 072004 (2022)

- Currently analysing: KNM1 – KNM5

eV-scale sterile neutrinos

[Phys. Rev. D 105, 072004 (2022)]

- Analysis of KATRIN data with 3+1ν model
- Grid scan over $|U_{e4}|^2$ and m_4^2
  $\Longrightarrow$ Exclusion contour: $\Delta\chi^2 = 5.99$ (95 % C.L.)
- Sterile neutrino analysis up to $m_4^2 \leq 1600\,\text{eV}^2$
- Evaluation using two analysis strategies
  - $m_\nu^2 = 0.0\,\text{eV}^2$
  - $m_\nu^2 = \text{free}$
- For KNM2, best fits at:
  $m_\nu^2 = 0.0\,\text{eV}^2$: $|U_{e4}|^2 = 1.0;\ m_4^2 = 0.28\,\text{eV}^2$
  $m_\nu^2 = $ free: $|U_{e4}|^2 = 0.027;\ m_4^2 = 98.3\,\text{eV}^2;\ m_\nu^2 = 1.1\,\text{eV}^2$



$\Longrightarrow$ **No significant sterile neutrino signal was observed in KNM1 and KNM2**

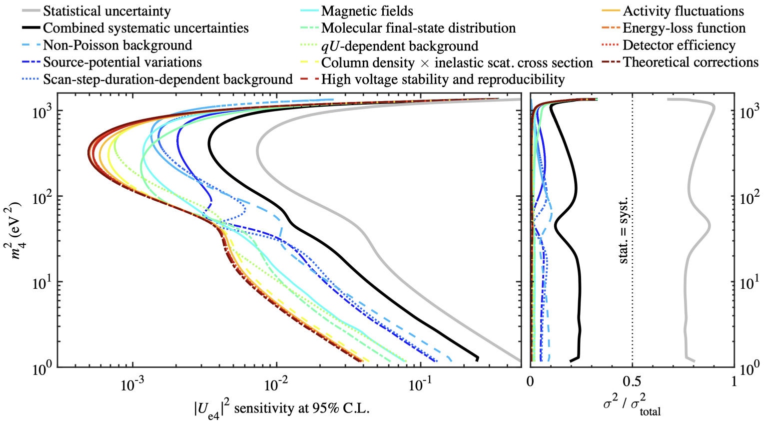
eV-scale sterile neutrinos – impact of systematics

[Phys. Rev. D 105, 072004 (2022)]

- Treatment of systematics via covariance matrices, based on Monte Carlo spectra
- Include covariance matrix in the χ^2-minimisation
- Investigation of individual systematics

$$\sigma_{\text{sys}}(|U_{e4}|^2) = \sqrt{\sigma^2_{\text{stat+sys}} - \sigma^2_{\text{stat}}}$$

$\Longrightarrow$ **Results are statistics dominated for all m_4^2**



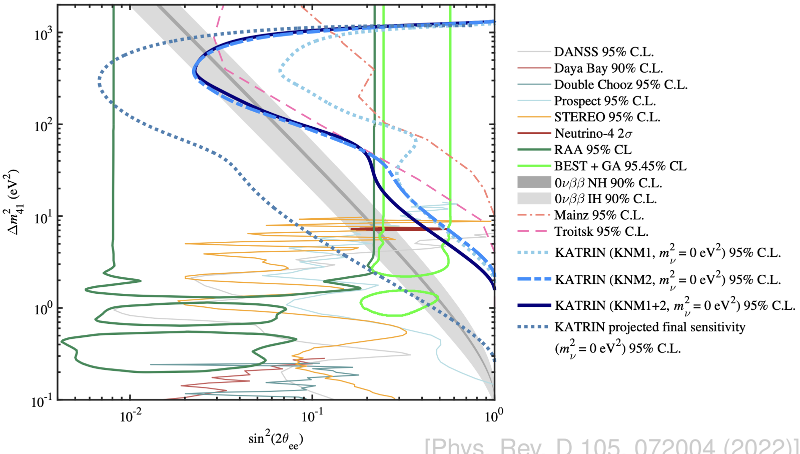
eV-scale sterile neutrinos – comparison to other exeriments

– For comparison with oscillation experiments:

$$\Delta m^2_{41} = m^2_4$$
$$\sin^2(2\theta) = 4|U_{e4}|^2 \cdot \left(1 - |U_{e4}|^2\right)$$

$\Longrightarrow$ **KATRIN already excludes large Δm^2_{41} range of the reactor and gallium anomalies**

$\Longrightarrow$ Improved range with full data set



[Phys. Rev. D 105, 072004 (2022)]

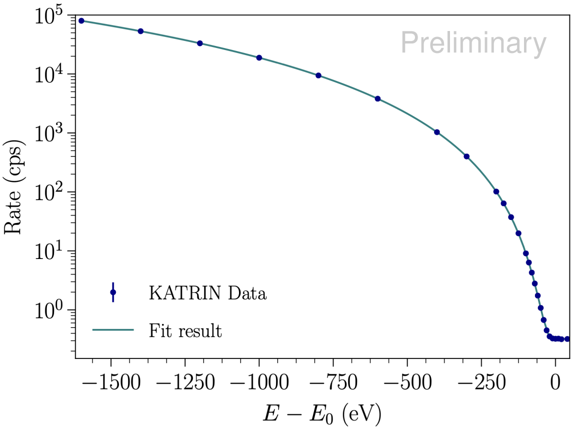
keV-scale sterile neutrinos – analysis

Motivation: keV-scale sterile neutrinos are viable candidates for warm dark matter

– Comissioned during **first tritium** operation with DT and at low column density

⟹ Performed scans deep into the spectrum (1.6 keV below the endpoint)

[arXiv, 2207.06337v1, submitted to EPJC]



keV-scale sterile neutrinos – analysis

Motivation: keV-scale sterile neutrinos are viable candidates for warm dark matter

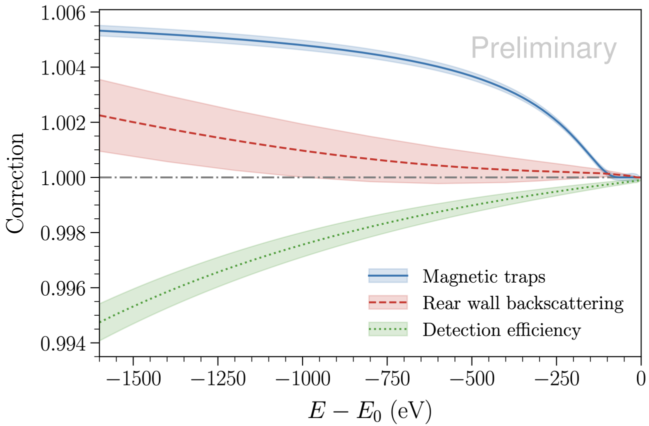
– Comissioned during **first tritium** operation with DT and at low column density

⟹ Performed scans deep into the spectrum (1.6 keV below the endpoint)

– Additional effects play a more significant role:

  – β-decays in magnetic traps
  – Backscattering from the rear wall
  – Energy dependent detection efficiency

[arXiv, 2207.06337v1, submitted to EPJC]



keV-scale sterile neutrinos – results

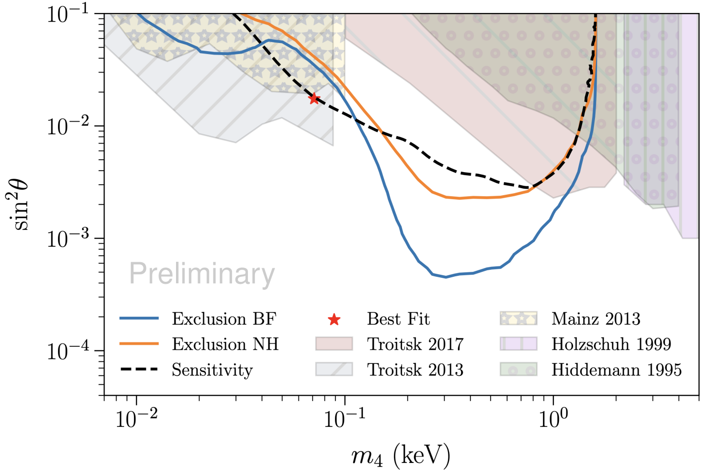
– Search for sterile neutrinos with mass up to 1.6 keV

⟹ **No significant sterile neutrino signal was observed**

⟹ **Improved previous laboratory-based bounds in the range 0.1 keV $\leq m_4 \leq$ 1.0 keV**

– **Outlook:** Dedicated deep spectrum scans with detector upgrade TRISTAN (2025+)

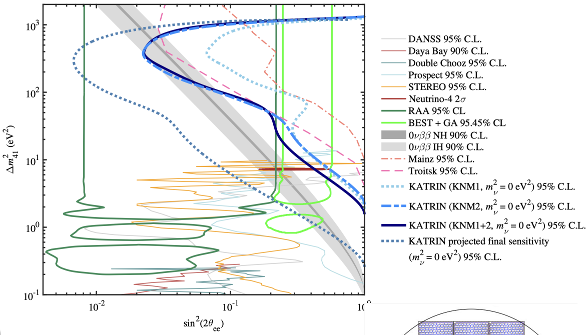
[arXiv, 2207.06337v1, submitted to EPJC]



Summary

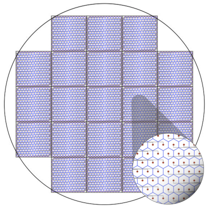
eV-scale sterile neutrinos:
Phys. Rev. Lett. 126, 091803 (2021) and Phys. Rev. D 105, 072004 (2022)

- Publication of KATRIN exclusion contours based on first and second campaigns
- Improved 3+1ν constraints from KATRIN excludes large Δm^2_{41} range of gallium and reactor anomalies



keV-scale sterile neutrinos: arXiv, 2207.06337v1 (2022)

- Improved previous laboratory-based bounds
- Major milestone for the keV-scale sterile-neutrino program of KATRIN



$\Longrightarrow$ **New eV-sterile neutrino bounds with KATRIN published**
$\Longrightarrow$ **Analysis of additional data is ongoing**
$\Longrightarrow$ **KATRIN is getting ready for keV-sterile neutrinos (TRISTAN upgrade)**