Karlsruhe Institute of Technology

Recent neutrino mass results from the KATRIN experiment

33rd Rencontres de Blois

Stephanie Hickford | Tuesday 24th May 2022

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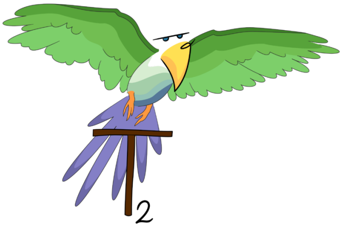
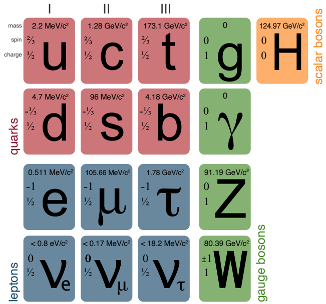


Massive neutrinos

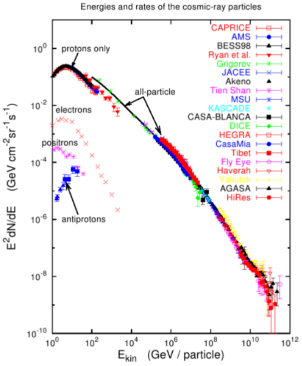


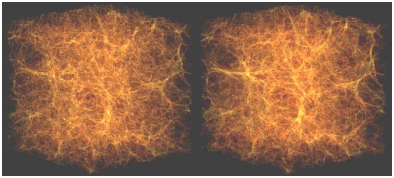
Standard Model

- Mass generation
- Weak interactions
- Oscillation
- Sterile
- LIV
- RH current

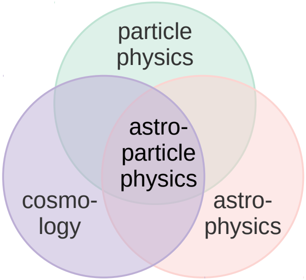
Understanding astro-physical processes

- Nuclear reactions in stars
- ν as probes for cosmic rays





$m_\nu = 0$ $\quad$ $m_\nu > 0$



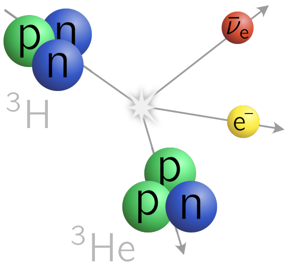
Massive neutrinos as "cosmic architects"

- $336\,\nu/\mathrm{cm}^3$ in the universe
- Cosmic relic neutrinos

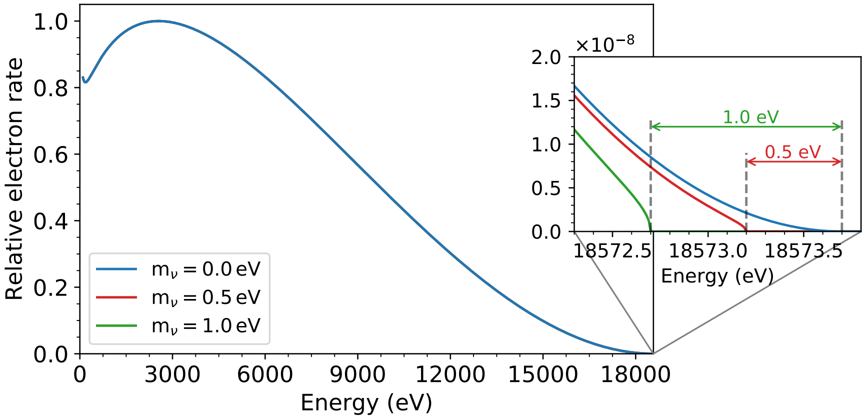
Tritium single β-decay

Decay of molecular tritium produces a β-electron spectrum

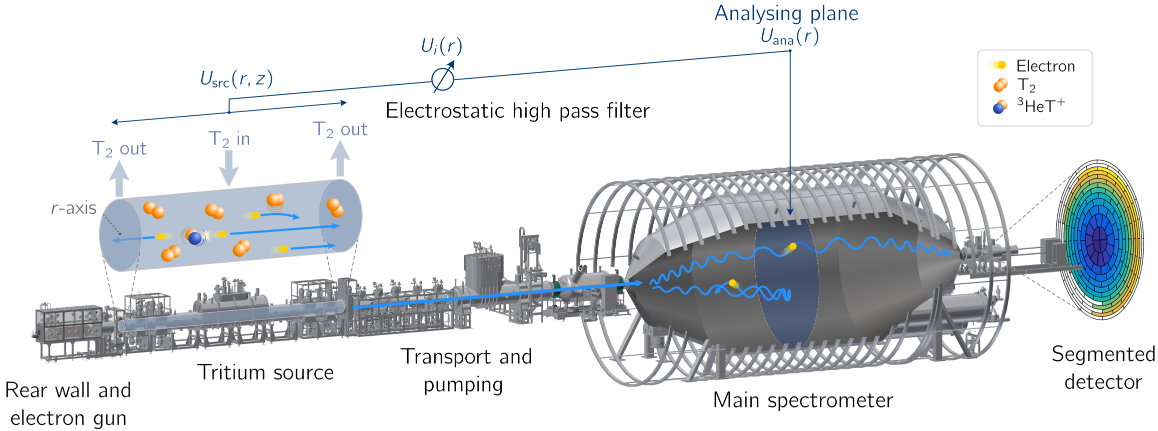
$\Longrightarrow$ m_ν^2 can be determined with a precise measurement of the spectral shape near the endpoint



$$T_2 \longrightarrow THe^+ + e^- + \bar{\nu}_e$$



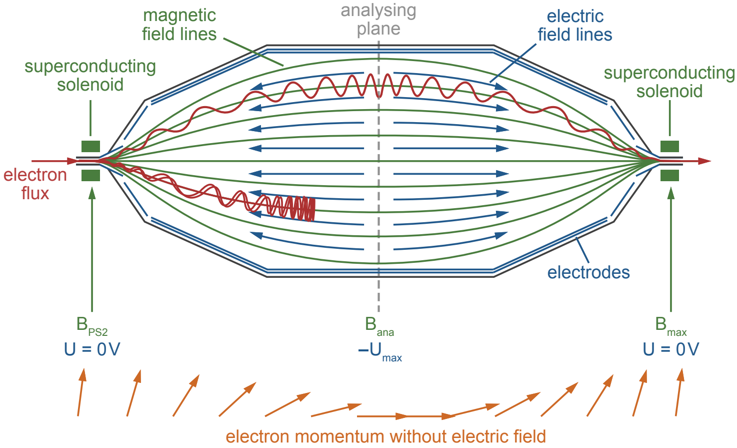
Beamline


Analysing plane
$U_{ana}(r)$
$U_i(r)$
$U_{src}(r, z)$
Electrostatic high pass filter
T_2 out
T_2 in
T_2 out
r-axis
Electron
T_2
$^3HeT^+$
Rear wall and electron gun
Tritium source
Transport and pumping
Main spectrometer
Segmented detector

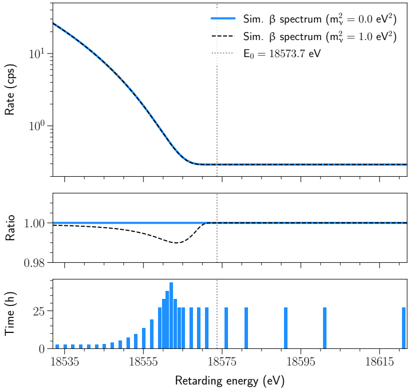
Integrated spectrum measurement

Magnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic filter (MAC-E filter)

Beamson et al. (1980), Lobashev, Spivak (1985), Picard et al. (1992)



Voltage set points are scanned through to obtain an *integrated spectrum*



The Measurement Time Distribution (MTD) optimised for best sensitivity

Spectra fitting

Data combination: Counts are summed, experimental parameters are averaged

Pixel combination

$\Longrightarrow$ Uniform

$\Longrightarrow$ Multi-patch

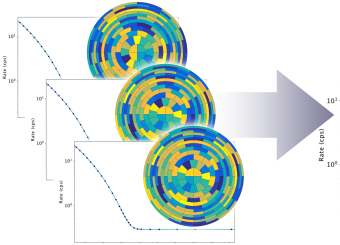
$\Longrightarrow$ Multi-pixel

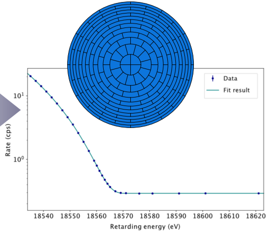
Run combination

$\Longrightarrow$ Stacked

$\Longrightarrow$ Multi-period

$\Longrightarrow$ Multi-run





Fit is performed with many contributing spectra

$\Longrightarrow$ One minimisation

$\Longrightarrow$ One combined likelihood, $\mathcal{L}$

$$-\log \mathcal{L} = \sum_i -\log \mathcal{L}_i \left(m_\nu^2, E_{0\,i}, \mathrm{Sig}_i, \mathrm{Bg}_i \right)$$

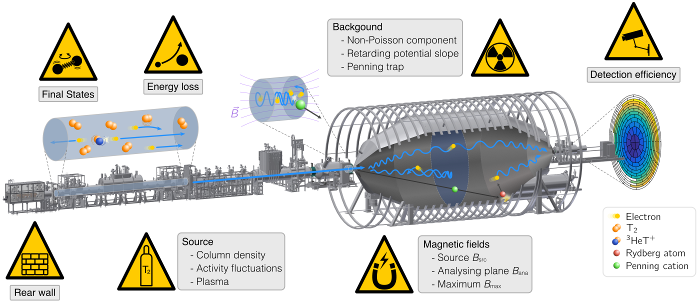
Many parameters

$\Longrightarrow$ One common neutrino mass, m_ν^2

$\Longrightarrow$ Multiple E_0, Sig, and Bg

$\Longrightarrow$ Systematic parameters either common or multiple

Systematics



Treatment of systematics

$\Longrightarrow$ Pull term

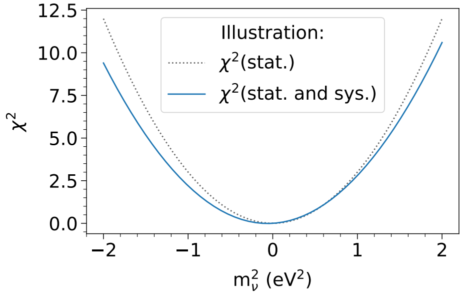
$\Longrightarrow$ Covariance matrix

$\Longrightarrow$ Monte Carlo propagation

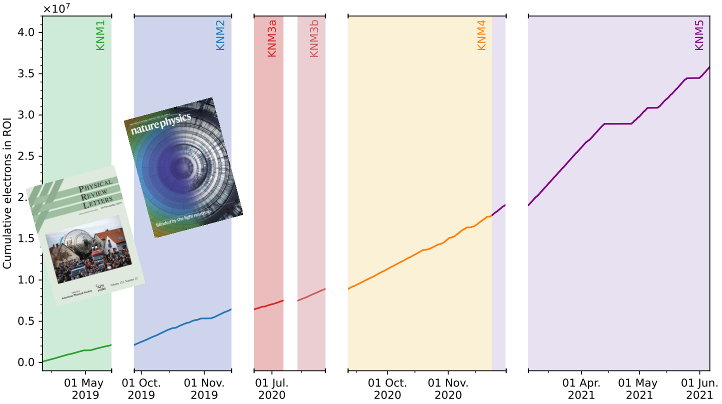
$\Longrightarrow$ Markov Chain Monte Carlo (MCMC)

Adding pull terms widens the χ^2 distribution

$$\chi^2\left(m_\nu^2, E_0, \mathrm{Sig}, \mathrm{Bg}, \theta_1, \ldots\right) + \frac{\left(\theta_1 - \hat{\theta}_1\right)^2}{\sigma_{\theta_1}^2} + \ldots$$



Measurement campaigns



KATRIN **N**eutrino mass **M**easurements

	Time (hrs)	$\rho d\sigma$ **(m^{-2})**	**Bg (mcps)**
KNM1	522	1.11×10^{21}	370
KNM2	294	4.23×10^{21}	278
KNM3a	220	2.08×10^{21}	137
KNM3b	224	3.75×10^{21}	258
KNM4	1267	3.77×10^{21}	150
KNM5	1232	3.78×10^{21}	160

- Published results: KNM1 and KNM2
- Current analysis: KNM1 – KNM5
- Data-taking: KNM6, KNM7, ...

Individual campaign results

First measurement campaign

Fit strategy: Stacked uniform fit

$\Longrightarrow$ One spectrum with 27 data points

$\Longrightarrow$ Four free fit parameters (m_ν^2, E_0, Sig, Bg)

Statistics dominated fit result

$$m_\nu^2 = -1.0 \pm 1.0\,\text{eV}^2$$

Factor of ~ 2 improvement on previous m_ν limit

$$m_\nu < 1.1\,\text{eV}\ (90\,\%\ \text{CL})$$

Phys. Rev. Lett. **123** (2019) 221802

Second measurement campaign

Fit strategy: Stacked multi-ring fit

$\Longrightarrow$ 12 spectra with $12 \times 28 = 336$ data points

$\Longrightarrow$ 37 free fit parameters (m_ν^2, $12 \cdot E_0$, 12·Sig, 12·Bg)

Statistics dominated fit result

$$m_\nu^2 = 0.26 \pm 0.34\,\text{eV}^2$$

New sub-eV neutrino mass limit

$$m_\nu < 0.9\,\text{eV}\ (90\,\%\ \text{CL})$$

Nat. Phys. **18**, 160–166 (2022)

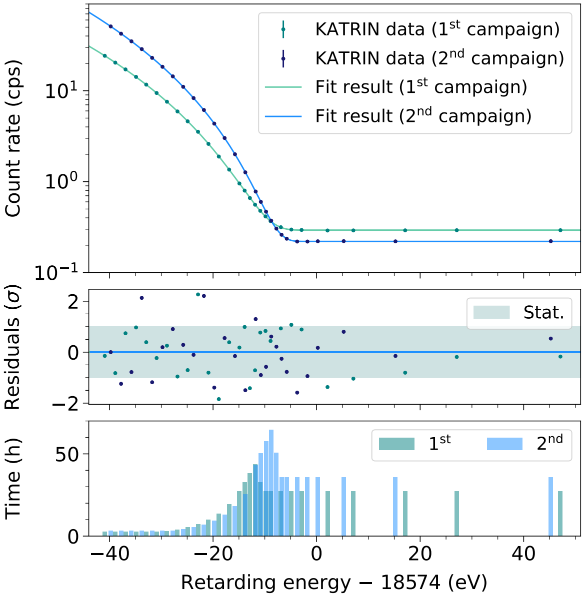
Combined campaign results

Fit strategy: Multi-period uniform fit

⟹ Data is stacked *within* the measurement phases

⟹ Two spectra with $27+28=55$ data points

⟹ 7 free fit parameters (m_ν^2, 2·E_0, 2·Sig, 2·Bg)



Statistics dominated fit result

$$m_\nu^2 = 0.08 \pm 0.32\,\mathrm{eV}^2$$

Sub-eV upper limit on the neutrino mass

$$m_\nu < 0.75\,\mathrm{eV}\ (90\,\%\ \mathrm{CL})$$

Nat. Phys. **18**, 160–166 (2022)
Supplementary material

(Further) BSM analyses

- **eV-sterile neutrinos**

  Constrain parameter space of eV-steriles from spectrum shape

  $\Longrightarrow$ First measurement campaign: Phys. Rev. Lett. **126** (2021) 2011.05087

  $\Longrightarrow$ First and second measurement campaigns: Phys. Rev. D **105** 072004

- **keV-sterile neutrinos**

  Constrain parameter space of keV-steriles with dedicated measurements over larger energy range

- **Cosmic relic neutrinos**

  Constrain local overdensity of relic neutrinos from peak search

  $\Longrightarrow$ First and second measurement campaigns: arXiv: 2202.04587

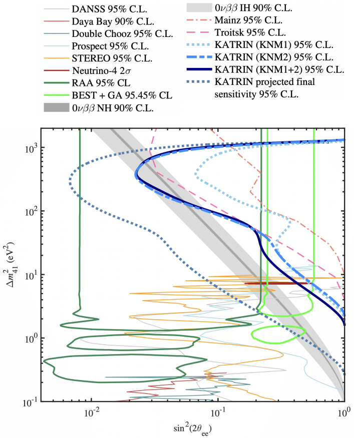
- **Lorentz invariance violation**

  Constrain LIV from sidereal modulation of tritium endpoint

  $\Longrightarrow$ First measurement campaign: In preparation

- **Right-handed currents**

  Constrain exotic weak interactions from spectrum shape



Exclusion curve (mass vs. mixing angle parameter space) for eV-sterile neutrinos

Summary

Leading upper limit on the neutrino mass from direct single β-decay measurements

⟹ KATRIN combined analysis of KNM1 and KNM2 measurement campaigns

$m_\nu < 0.75\,\mathrm{eV}$ (90 % CL)

Nat. Phys. **18**, 160–166 (2022)

Towards improved sensitivity

⟹ KATRIN combined analysis of KNM1 to KNM5 measurement campaigns is ongoing

⟹ Expected sensitivity $<0.5\,\mathrm{eV}$