First direct neutrino-mass measurement with sub-eV sensitivity

Susanne Mertens
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Neutrino mass

Upper bound from direct measurements

Lower bound from oscillation experiments
Neutrino mass

**Cosmology**
potential: \( m_\nu = 10 - 50 \text{ meV} \)
\[
m_\nu = \sum_i m_i
\]

**Search for 0\(\nu\)\(\beta\)\(\beta\)**
potential: \( m_{\beta\beta} = 7 - 17 \text{ meV} \)
\[
m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|
\]

**Kinematics of \(\beta\)-decay**
potential: \( m_\beta = 50 - 200 \text{ meV} \)
\[
m_\beta^2 = \sum_i |U_{ei}|^2 \cdot m_i^2
\]
General Idea

- Non-zero neutrino mass distorts the spectrum close to the endpoint
  - Independent of cosmology
  - Independent of neutrino nature

- Observable: $m_V^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$
The challenge

Key requirements:

• Ultra-strong radioactive source
  • Tritium (12.3 years, $E_0 = 18.6$ keV)
  • Holmium (4500 years, $E_0 = 2.8$ keV)
• Excellent energy resolution (~ 1 eV)
• Low background (< 100 mcps)
Where do we stand?

- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment
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- KATRIN goal: Distinguish between degenerate and hierarchical scenario
Where do we stand?

- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment

- KATRIN goal: Distinguish between degenerate and hierarchical scenario

- Future: Resolve normal vs inverted neutrino mass ordering
Experimental efforts

Electrostatic filter (MAC-E)

Cyclotron Radiation

Phonons

frequency

region close to end point

only $2 \times 10^{-13}$ of all decays in last 1 eV

$m(v_\beta) = 0 \text{ eV}$

$m(v_\beta) = 1 \text{ eV}$

counting above threshold

heat

Susanne Mertens (MPP, TUM)
Experimental efforts

Electrostatic filter (MAC-E)

Project-8 (Tritium)

QTNM (Tritium)

Cyclotron Radiation

KATRIN (Tritium)

Ptolemy (Tritium)

Holmes (Holmium)

ECHo (Holmium)

Phonons
Karlsruhe Tritium Neutrino Experiment
KATRIN

- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Design sensitivity: 0.2 eV (90% CL) (1000 days of measurement time)
Overview

• How does KATRIN work?

• What are the latest results?

• What’s next?

• What else can we do with the data?
KATRIN Working Principle

**Windowless gaseous tritium source**
- molecular tritium in closed loop system
- $10^{11}$ decays/s

β-decay
KATRIN Working Principle

Transport section
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by $> 10^{14}$ + tritium ion removal

β-decay
KATRIN Working Principle

Spectrometer section
- Electrostatic filter
- Selects electrons above $U_{\text{ret}}$
KATRIN Working Principle

MAC-E Filter principle
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°
KATRIN Working Principle

**Focal plane detector**
- 148-pixel Si-PIN detector
- counting of electrons
KATRIN Working Principle

- **Forward Beam Monitor:** Activity monitoring @ 0.1%/min
- **Laser Raman System:** Gas composition monitoring @ 0.1%/min
- **High Voltage System:** HV monitoring @ ppm-level
- **Gaseous krypton source:** EM field calibration
- **Electron gun:** Determination of scattering parameters
- **Magnetic field sensor system**
Measurement strategy

- **Scan:** ~ 30 HV set points
- **Scanning time:** ~ 2 hours
- **Analysis interval:** $E_0 - 40 \text{ eV}, E_0 + 130 \text{ eV}$
- **Campaign:** several hundreds of scans
Data combination

Scan combination
• sum the counts at the same HV set point
• use average HV ($\sigma_{HV} < 34 \text{ mV}$)

Pixel combination
• sum the counts of ALL pixels or in a ring
• use average response function

Uniform \rightarrow 1 \text{ spectrum}

ring-wise \rightarrow 12 \text{ spectra}
Data analysis

• Fit of theoretical prediction: \( \Gamma(qU) \propto A \cdot \int_{qU}^{E_0} D(E; m^2_\nu, E_0) \cdot R(qU, E) \, dE + B \)

[Graphs showing rate (cps) vs. retarding energy (eV), rate per energy (a.u.) vs. energy (keV), and transmission vs. surplus energy (eV).]

• Free parameters: \( m^2_\nu, E_0, B, A \)
• Fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, ...)

Susanne Mertens (MPP, TUM)
Systematic uncertainties

Source electric potential

Molecular Final States

- energy loss
- column density

Scattering

Activity fluctuations

- source
- spectrometer
- detector

Magnetic fields

Background:
- time correlation (radon, penning trap)
- retarding potential dependence

Detection efficiency

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Blinded analysis

Freeze analysis on MC-twin data
• MC-copy of each scan (with $m_v = 0$ eV)

![true data](image)
![MC copy](image)

Blinded model
• Modified molecular final state dist.

Independent analysis strategies
• Covariance matrix
• Monte Carlo propagation
• Pull term
MC propagation of uncertainties

- Fit performed $10^5$ times
- Each time the systematic parameter is varied according to its uncertainty
- Width of $m^2_\nu$ distribution reflects systematic uncertainty from this effect
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KATRIN Data Taking Overview
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This talk
2\textsuperscript{nd} ν-mass campaign

Cumulative electrons in ROI

# Improvements wrt 1\textsuperscript{st} campaign

<table>
<thead>
<tr>
<th></th>
<th>1\textsuperscript{st} campaign</th>
<th>2\textsuperscript{nd} campaign</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>PRL 123 (2019)</td>
<td>This talk</td>
</tr>
<tr>
<td><strong>Campaign date</strong></td>
<td>April-May 2019</td>
<td>Sept-Nov 2019</td>
</tr>
<tr>
<td><strong>Total scan time</strong></td>
<td>522 h (274 scans)</td>
<td>744 h (361 scans)</td>
</tr>
<tr>
<td><strong>Source activity</strong></td>
<td>25 GBq</td>
<td>nominal activity 98 GBq</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>290 mcps</td>
<td>reduction -25% 220 mcps</td>
</tr>
<tr>
<td><strong>Tritium purity</strong></td>
<td>97.6%</td>
<td>raised purity 98.7%</td>
</tr>
<tr>
<td><strong>Electrons in RoI</strong></td>
<td>2 Mio</td>
<td>stats doubled 4.3 Mio</td>
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New data release

- total statistics: 4 million events
- excellent goodness-of-fit: p-value = 0.8
- Uncertainties are statistics dominated
- Uniform and ring-wise fit lead to consistent results
\[ m_{\nu}^2 = (0.26^{+0.34}_{-0.34}) \text{eV}^2 \]

- compatible with zero

\[ E_0 = 18573.69 \pm 0.03 \text{ eV} \]
- Q-value: 18575.2 ± 0.5 eV
- good agreement with literature

\[ Q = 18575.72 \pm 0.07 \text{ eV} \]
New upper limit

- **Frequentist limit:** $m_\nu < 0.9$ eV (90% CL)
- **Bayesian:** $m_\nu < 0.85$ eV (90% CI)
- **Sensitivity:** $m_\nu < 0.7$ eV (90% CL)

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Lokhov & Tkachov, Phys. Part. Nucl. 46 (2015) 347
Historical context

- KATRIN (2021):
  
  *first direct neutrino-mass experiment to reach sub-eV sensitivity and limit*

- 1\textsuperscript{st} and 2\textsuperscript{nd} campaign combined result:
  
  \[ m_{\nu}^2 = (0.11^{+0.33}_{-0.33}) \text{eV}^2 \]

- 1\textsuperscript{st} and 2\textsuperscript{nd} campaign combined limit:
  
  \[ m_{\nu} < 0.8 \text{ eV} \text{ (90\% CL)} \]
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Uncertainty budget of 2\textsuperscript{nd} campaign

- Poisson statistics: 0.290
- Bg overdispersion: 0.111
- Bg penning trap: 0.074
- Plasma: 0.066
- Bg $qU$ dependence: 0.041
- Magnetic fields: 0.026
- Gas density: 0.013
- Molecular states: 0.012
- Rate fluctuations: 0.011
- Energy loss: 0.004

1\textsigma uncertainty on $m^2$ (eV\textsuperscript{2})
Uncertainty budget of 2nd campaign

- Measurements with intense krypton source
- Tritium scanning at the same temperature as krypton measurement (90K)

Take more data!
Uncertainty budget of 2\textsuperscript{nd} campaign

- Poisson statistics: 0.290
- Bg overdispersion: 0.111
- Bg penning trap: 0.074
- Plasma: 0.066
- Bg \(qU\) dependence: 0.041
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Related to background

1\sigma uncertainty on \(m_\nu^2\) (eV\(^2\))
KATRIN backgrounds
KATRIN backgrounds

- $^{219}$Rn-induced background
- $^{210}$Pb-induced background

Electrons created in the volume of the large spectrometer
KATRIN background mitigation

- LN cooled baffle + shifted analyzing plane
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004

- Background reduction by factor of 2.3 to about 130 mcps (original design: 10 mcps)

- Further R&D ongoing
Outlook

- Operation in optimized configuration
- 3rd, 4th, 5th campaign completed
- With upcoming 1000 days of measurement time tackle $m_\nu < 0.2 - 0.3$ eV
Overview

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New Physics with KATRIN

- Search for eV-keV sterile neutrinos (*kink search*)
- Constrain local overdensity of cosmic relic neutrinos (*peak search*)
- Neutrino mass (*endpoint shape*)
- Search for Lorentz invariance violation (*sidereal modulation*)
- Search for exotic weak interactions (*spectrum shape*)
Sterile neutrinos

- Additional neutrino mass eigenstates or arbitrary scale
- Interaction via their mixing with active states
Sterile neutrinos

**Heavy sterile neutrinos (> GeV)**
- Lightness of neutrinos
  + Matter/Anti-matter asymmetry

**Light sterile neutrinos (~1 eV)**
- Short-baseline neutrino oscillation anomalies

**KeV-scale sterile neutrinos (~ 1 - 50 keV)**
- Dark matter candidate
  - Accessible in beta-decays
Sterile neutrinos

**Light sterile neutrinos**

- Active branch
- Sterile branch

\[ m_4 = 10 \text{ eV} \]
\[ \sin^2 \theta \]

Accessible in current data sets

**keV-scale sterile neutrinos**

- Active branch
- Sterile branch

\[ m_4 = 10 \text{ keV} \]
\[ \sin^2 \theta \]

Measurement of full range requires new detector system
eV-scale sterile neutrino search

- Search performed on data set of **first** and **second** neutrino mass campaign
- 3+1 sterile neutrino model
- Grid search in $m_4$, $|U_{e4}|^2$ plane

\[
\frac{dN}{dE} = (1 - |U_{e4}|^2) \frac{dN}{dE}(m_\beta^2) + |U_{e4}|^2 \frac{dN}{dE}(m_4^2)
\]

- Signal to Background $= 70$
eV-scale sterile neutrino search (1st campaign)

High $\Delta m_{41}$ region:

- Improve exclusion with respect to DANSS, PROSPECT, STEREO
- Exclude parameter space of Reactor Anomaly (RAA)

Low $\Delta m_{41}$ region:

- Improve MAINZ and TROITSK limit
- The NEUTRINO-4 hint at the edge of exclusion limit
- Test part of BEST result with future data
keV-scale sterile neutrinos

- Idea: make use of the luminous KATRIN source to explore full beta spectrum to search for BSM physics
  - Develop a novel detector system

Signal rate of up to $10^{10}$ electrons/s

Tritium source: $10^{11}$ decays/s
TRISTAN detector

- Silicon drift detector (SDD) technology
  - Capability of handling high rates (> $10^8$ cps)
  - Excellent energy resolution (300 eV @ 20 keV)

- Challenge
  - Control of systematics at the ppm-level
  - Operation of 3500 pixel focal plane array

- Status
  - Excellent performance of prototypes
    M. Gugiatti et al, NIM-A 979 (2020)
    P. King et al, JINST 16 T07007 (2021)
  - Operation of 166-pixel module
    (largest SDD module ever operated) – thanks to Polimi and Bicocca
Conclusion

- First sub-eV neutrino mass limit from a direct experiment
- Various improvements of systematics and background in place
- Sensitivity close to 0.2 eV (90% CL) targeted within next years
- High precision KATRIN data available for interesting new physics searches
- Upgrade of KATRIN beamline with SDD array will allow to extend the measurement interval
Thank you for your attention

Susanne Mertens
Technical University Munich & Max Planck Institute for Physics

Thanks to
To my group
The KATRIN collaboration
Thierry Lasserre
And many others...