Probing Neutrino Mass: Latest Results from the KATRIN Experiment

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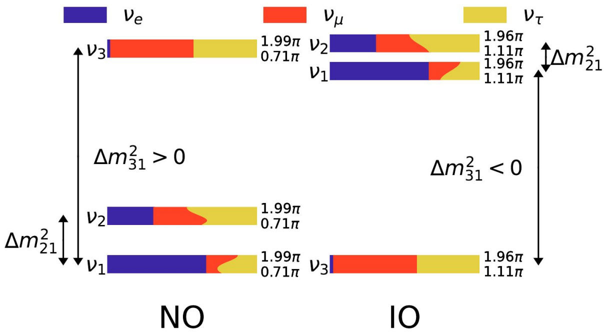
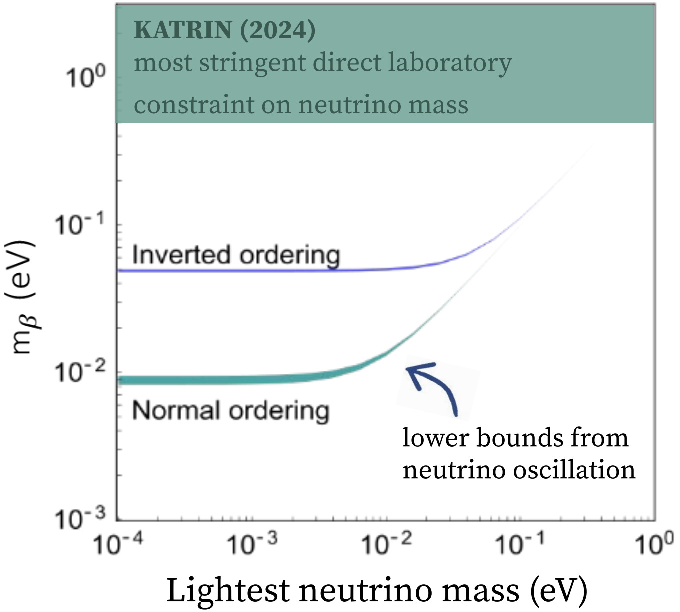
35th Rencontres de Blois on Particle Physics and Cosmology
Oct 20-25, 2024

Neutrinos and their oscillations

- **Neutrino** ⟶ fundamental, electrically neutral particle
- Originally predicted to be massless
- **Neutrino oscillations** verify non-zero neutrino mass
  - mass eigenstates differ from flavour eigenstates
- **Oscillations** provide information on mass squared differences
  - $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- Still unknown: exact mechanism of mass generation, mass hierarchy, and **absolute mass scale**

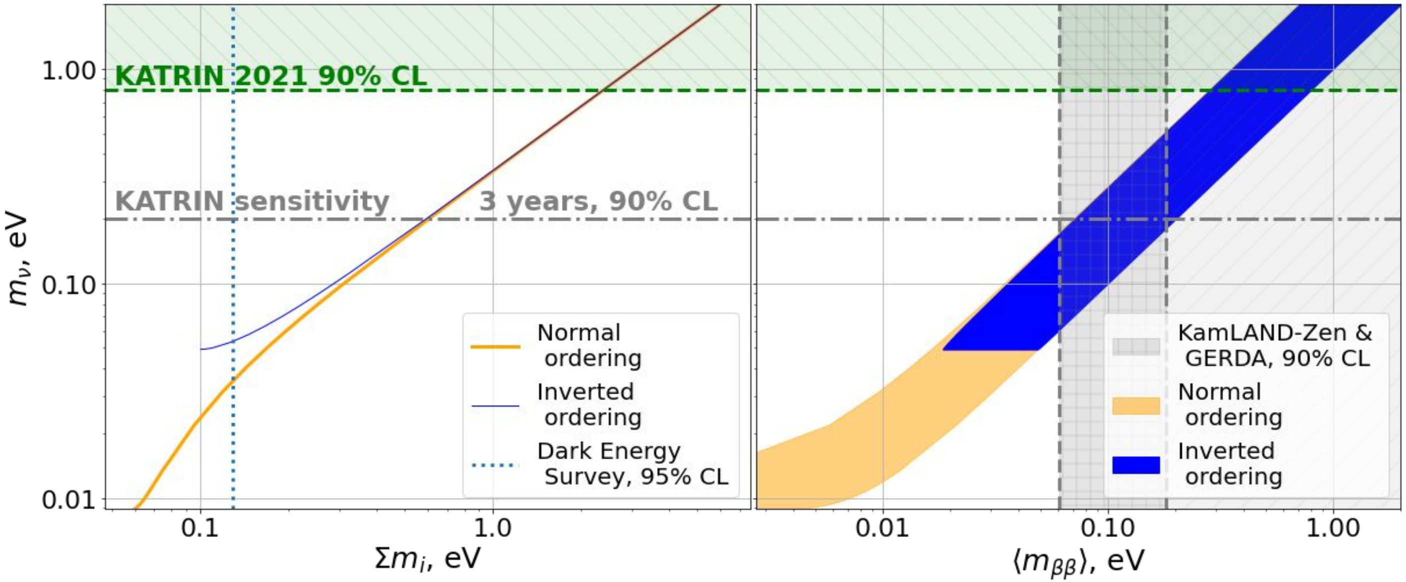




Neutrino Mass observables

Lokhov, Mertens, Parno, Schlösser, Valerius, Ann.Rev.Nucl.Part.Sci. 72 (2022) 259-282

Kinematic experiments



Cosmological observables

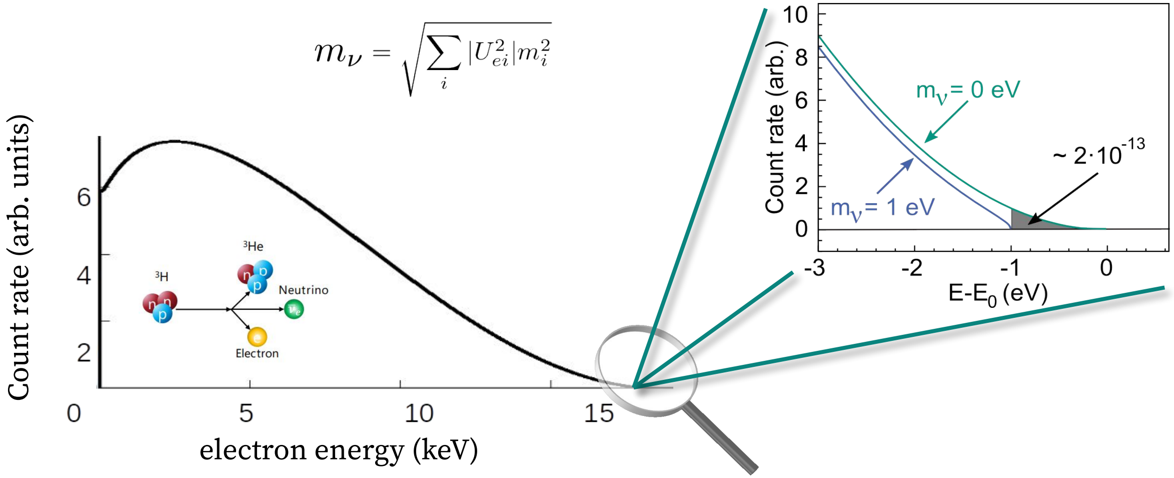
Neutrinoless ββ-decay, Majorana nature

Tritium β-Decay: A key to measure m_ν

- Decay scheme: $T_2 \rightarrow {}^3HeT^+ + e^- + \bar{\nu}_e + Q(T_2)$
- Effective neutrino mass determined through **kinematic parameters and energy conservation** principles

$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

$$m_\nu = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$



Why Tritium:

- Half-life: 12.3 yr
- Low endpoint energy: 18.57 keV
- Non-zero neutrino mass changes the shape of the spectrum near E_0
- Enables precise measurements of spectrum tail

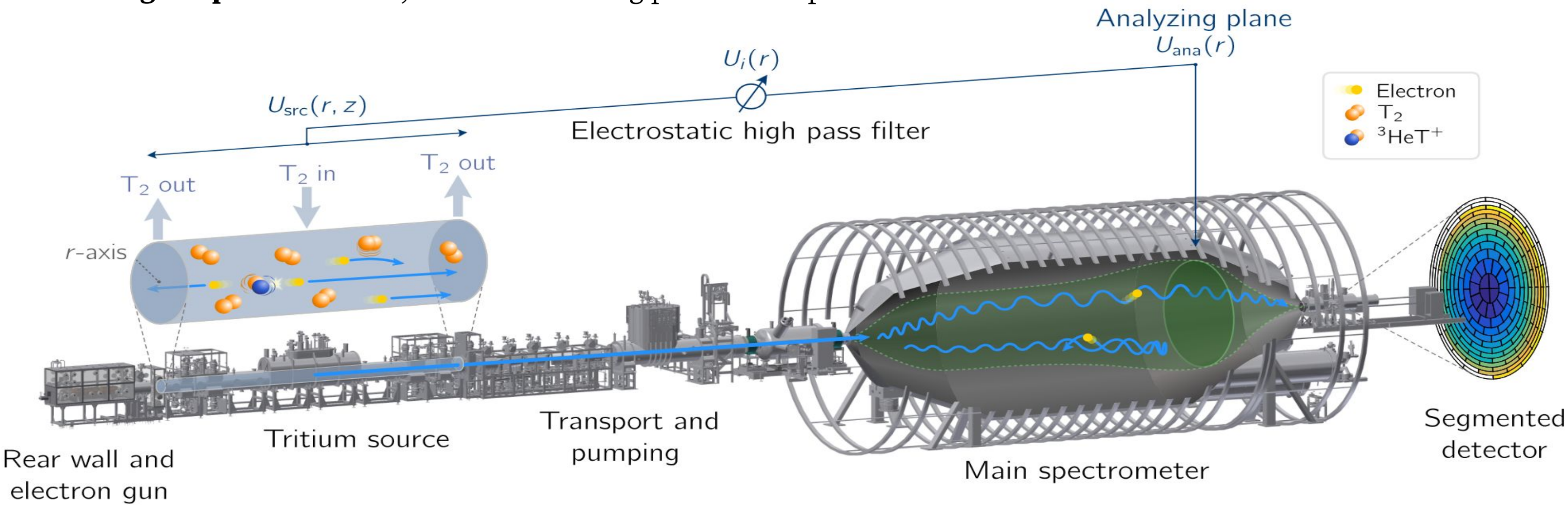
Collaboration: ~ 120 people @ 20 Institutions

KATRIN:
Karlsruhe
Tritium
Neutrino
Experiment

KATRIN Experimental setup

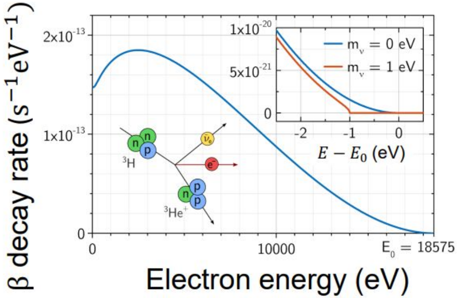
- **Tritium source:** high-activity (~100 GBq) windowless gaseous molecular source
- **Spectrometer:** high-resolution (~1 eV)
- **Segmented detector:** measures electron counts with a 148-pixel silicon PIN diode at the focal plane

➔ Conducts **integral spectrum** scans, discrete retarding potential steps



Full setup description: KATRIN, JINST 16 (2021) T08015

Modeling the tritium Spectrum



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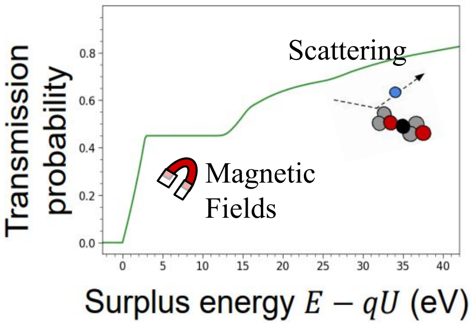

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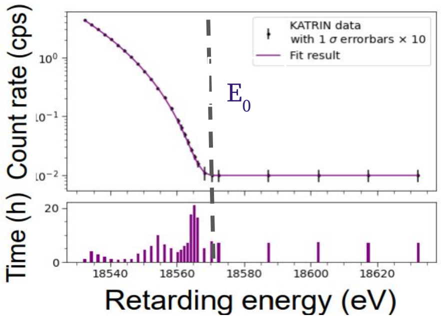


T_2 Beta spectrum R_β $(E;m^2(\nu_e),E_0)$

Response function: $f(E\text{-}qU)$

Determined by magnetic fields and scattering probabilities

Observed spectrum

- Maximum likelihood fit of analytical model

$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E) dE + R_{bg}$$

- with free parameters m_ν^2, E_0, A and R_{bg}
- Analysis window: **[E_0 - 40 eV, E_0 + 135 eV]**

Data Analysis

Approach

- **Two independent analysis teams** with different analysis frameworks
  - Highly optimized model evaluation
  - Neural network-assisted fast model predictions
    EPJC 82, 439 (2022)

- **A two-step blinding strategy:**
  - Fixing analysis procedure using MC-generated data
  - Using blinded model with unknown modifications of final states

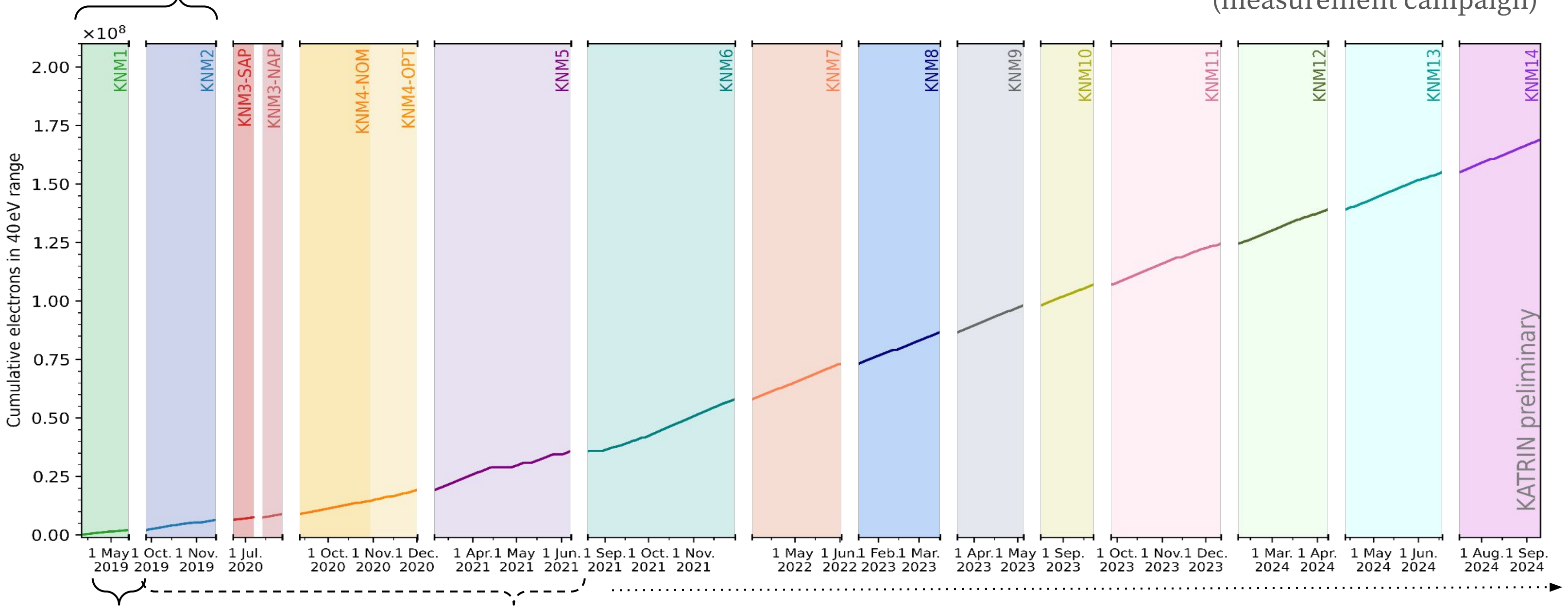
Challenges

- Handling of multiple campaigns maintaining high precision (over 1500 data points)
- Around **180** fitting parameters to manage
- **~ 150** correlated systematic parameters
- Computationally expensive model-calculations and fitting procedures

KATRIN data taking overview

Second result: $m_\nu < 0.8$ eV (90% CL)
[Aker et al., Nature Phys. 18 (2022)]

KNM = KATRIN Neutrino Mass (measurement campaign)



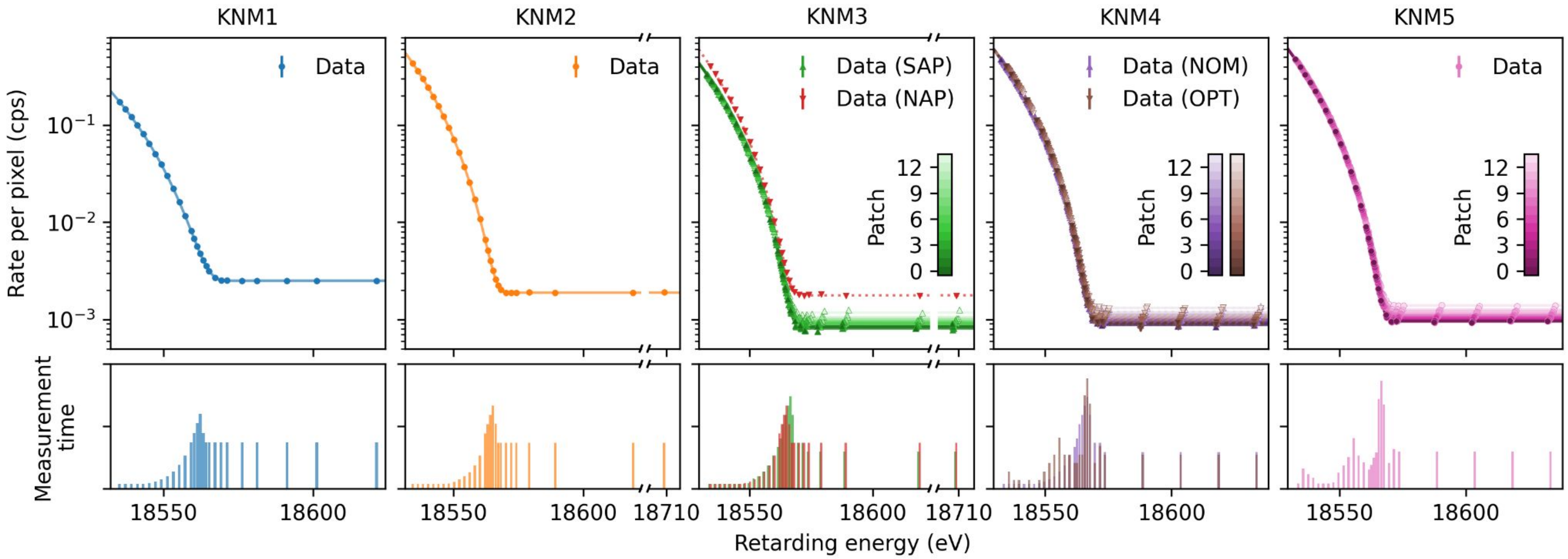
First result: $m_\nu < 1.1$ eV (90% CL)
[Aker et al., PRL 123 (2019)]

Third result: 5 campaigns, 1757 β-scans, **259 measurement days**

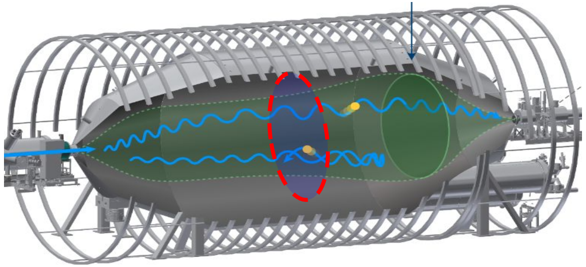
continue until end-2025, **1000 measurement days**

Experimental Data: Campaigns 1-5

- 7 different configurations
- 59 stacked spectra
- 1609 data points
- ~ 36 Mio counts in total
- parameter correlations across datasets
- fourth campaign split post unblinding, impact ~0.1 eV^2



Experimental Improvements in new data



- **Shifted analyzing plane** configuration
    - Achieved two-fold **reduction in background**

      [A.Lokhov et al., Eur. Phys. J. C 82, 258 (2022)]

- **^{83m}Kr co-circulation** mode
    - Used to determine both **source potential** and **spectrometer fields**

      [A. Marsteller et al 2022 JINST 17 P12010]

- Improved electron gun
    - Mono-energetic angular-selective photoelectron source
    - Better calibration of the **scattering effects**

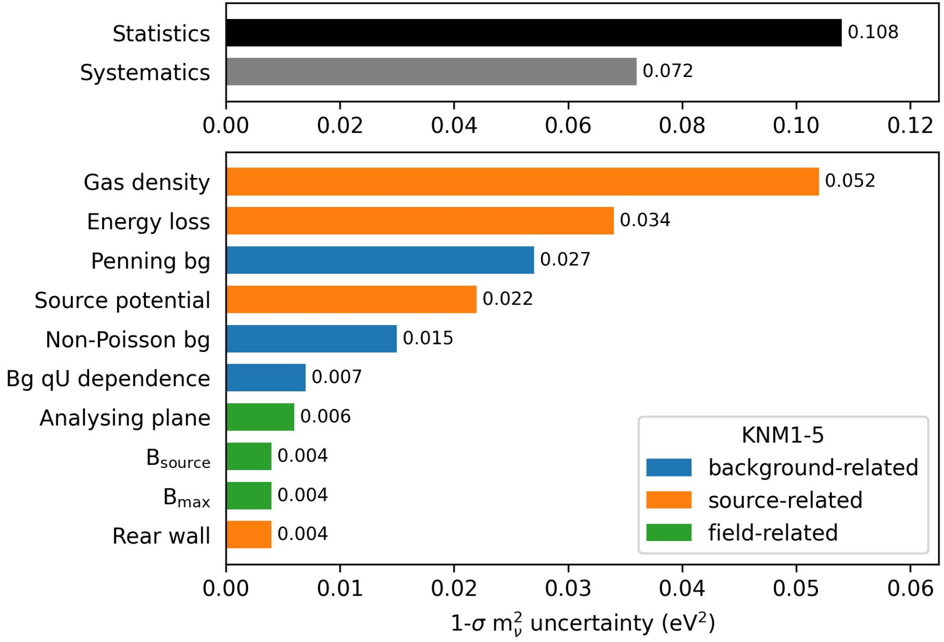
Systematic Uncertainty Breakdown: For measurement campaigns 1-5

- **6-fold increase in statistics**, 2-fold reduction of background

- **Improved** control over source-related effects

➔ **Statistical uncertainty dominates**, improved calibration precision in recent campaigns

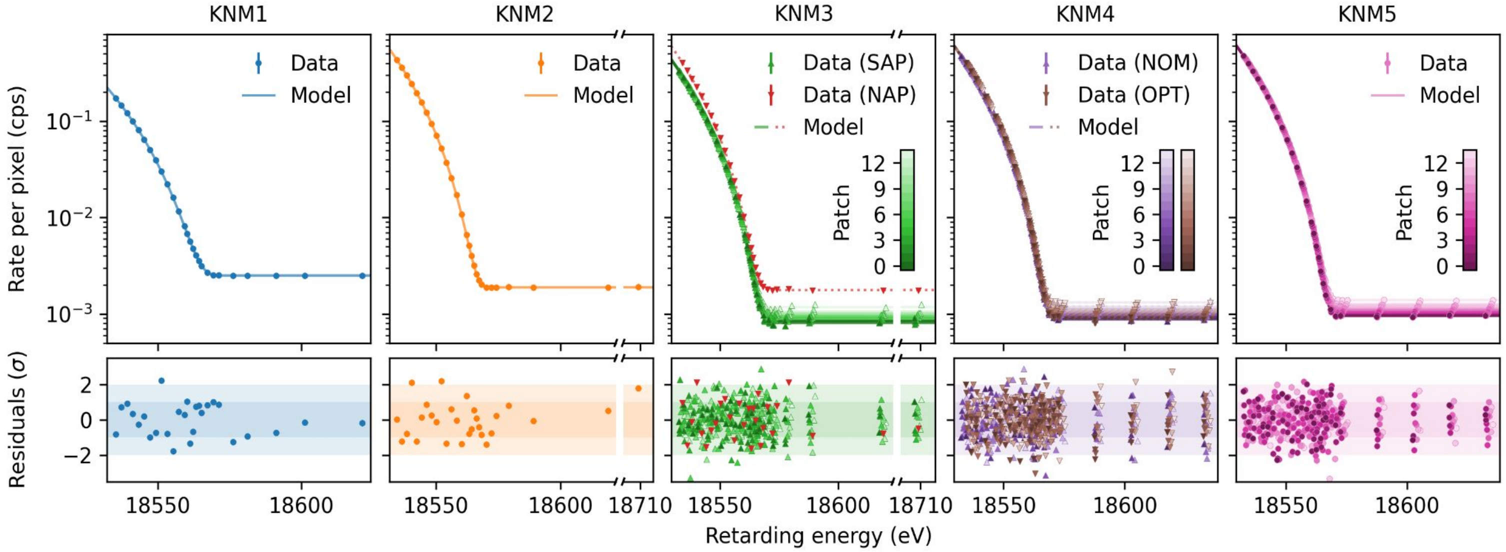
Further improvement for campaigns beyond KNM5



Fit results

- Simultaneous maximum likelihood fit performed, using a common m_ν^2 parameter
- **p-value** of 0.84
- Best fit value of m_ν^2:

$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$$



Neutrino-mass limit: For campaigns 1-5

- New world-leading direct upper limit on the neutrino mass:

  $m_\nu < 0.45$ **eV** (90% *CL*)

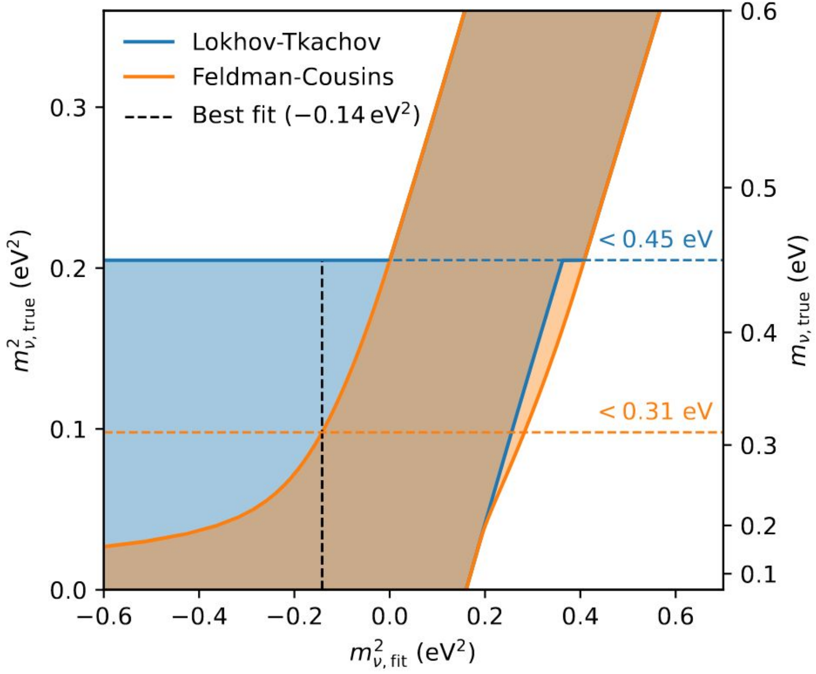
  based on **Lokhov-Tkachov** confidence interval construction (ensures upper limit is not reduced by negative m_ν^2 values)

  [Lokhov, Tkachov, Phys.Part.Nucl. 46 (2015)]

- **Feldman-Cousins limit:**

  $m_\nu < 0.31$ eV (90% *CL*), benefits from negative best-fit

- Latest results after 259 days of data taking: available at https://arxiv.org/abs/2406.13516



Beyond Neutrino mass physics with KATRIN

Search for a sterile neutrino

KATRIN sterile neutrino analysis

Phys.Rev.Lett. 126 (2021) 9, 091803
Phys.Rev.D 105 (2022) 7, 072004

Kink search: Close to the end-point of β-spectrum

Relic Neutrinos

KATRIN Relic neutrino analysis

Phys. Rev. Lett. 129 (2022) 1, 011806

Peak search: Probe for local overdensity of relic neutrinos

New light bosons

Theoretical basics & study

JHEP 01 (2019) 206

Shape distortion: Additional BSM bosons coupling to leptons →real emission in β-decay

General Neutrino interactions (GNIs)

GNIs search with KATRIN Experiment

arXiv:2410.13895

Shape distortion: Search for spectrum distortions due to exotic electro-weak interactions

Lorentz invariance violation

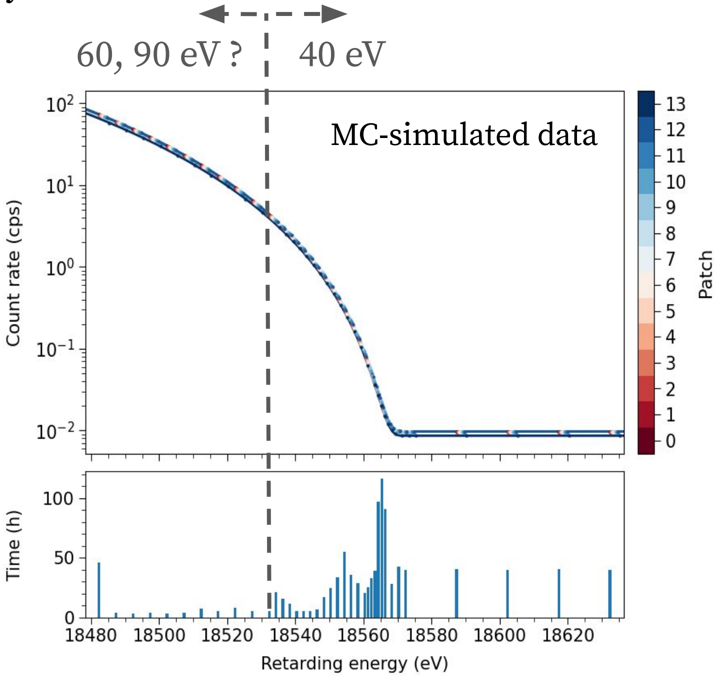
KATRIN first data search for Lorentz-violation

Phys.Rev.D 107 (2023) 8, 082005

Temporal variation: Search for Lorentz-violation by spectrum's sidereal modulation

Analysis Outlook: Extended Range Study

- We record data in a wider energy window below the endpoint E_0 (60 eV and 90 eV ranges)
- Use only 40 eV range for the analysis
- Idea: to go for higher ranges below E_0 to increase statistical power, but have to ensure good control over (energy-dependent) systematics



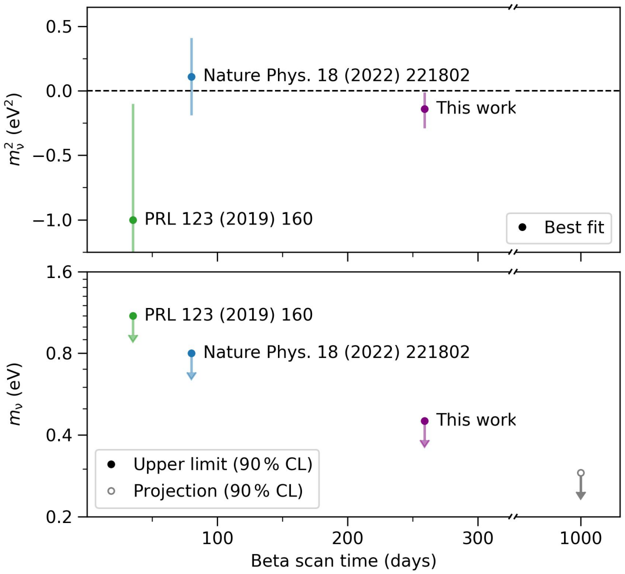
Conclusion and Outlook

- New **world-best** direct neutrino mass upper limit

  $\boldsymbol{m_\nu} < \mathbf{0.45\ eV}$ (90% *CL*)

- **KATRIN data taking continues** until end-2025
  - Aiming for 1,000 measurement days
  - Target sensitivity: below 0.3 eV
- **BSM physics searches**: sterile neutrinos, relic neutrinos and more ..
- **TRISTAN** detector upgrade in 2026
  - Focused on detecting keV-scale sterile neutrinos

    [Mertens et al., J.Phys.G 46 (2019)]
- **KATRIN++** (beyond 2027)
  - development of **differential** detection and **atomic** tritium technologies



KATRIN Collaboration

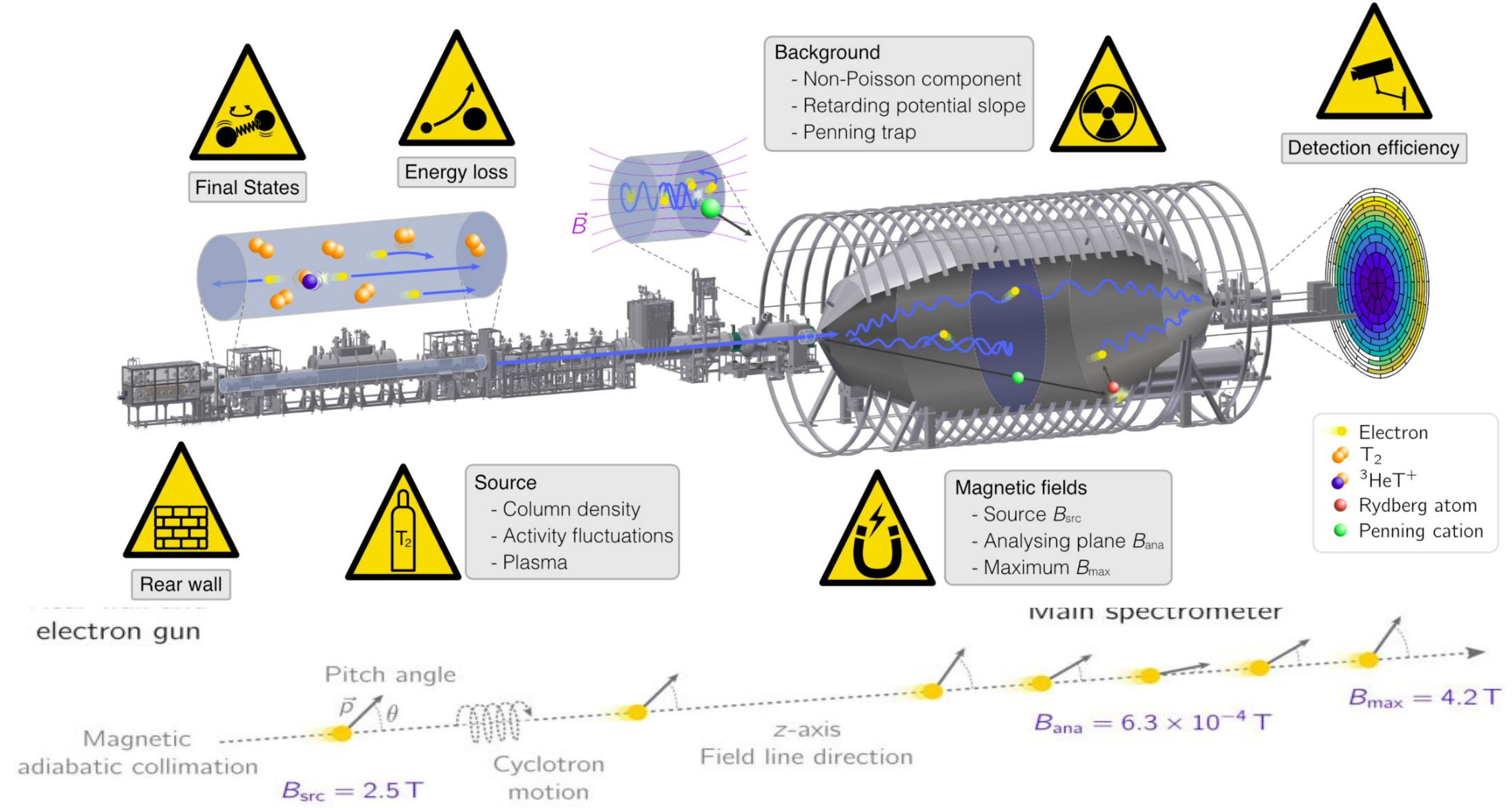
Thanks for your attention

Collaboration meeting in October 2024, Karlsruhe

Back up

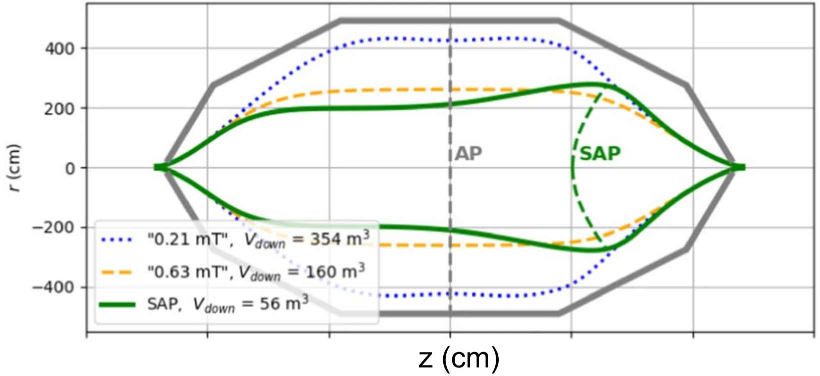
Systematic effects

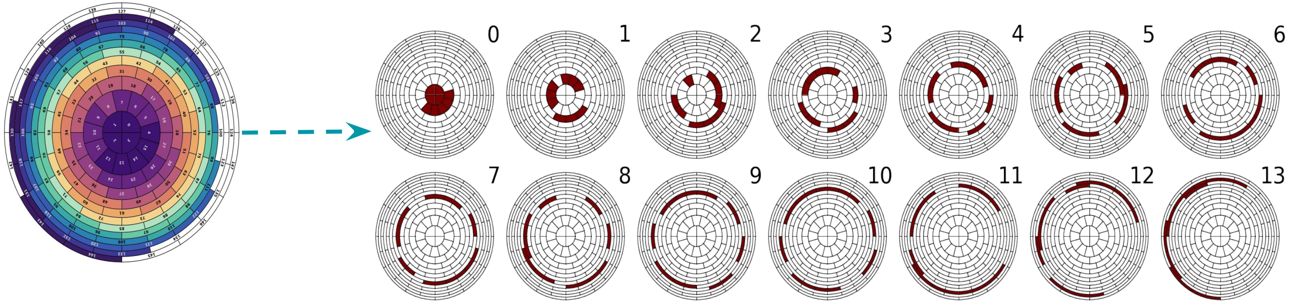
$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E)\,dE + R_{\mathrm{bg}}$$



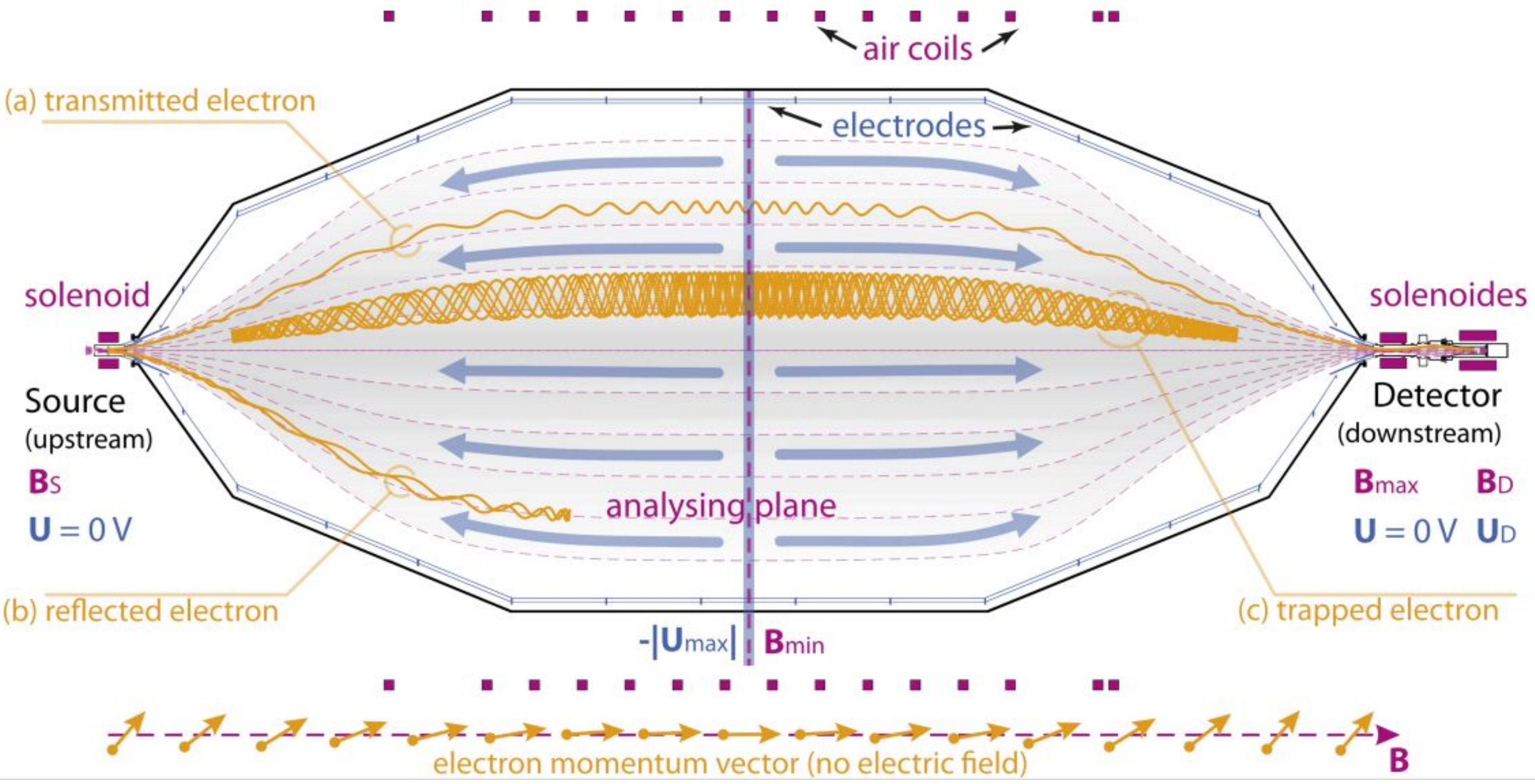
Experimental Improvements in new data

- **Shifted analyzing plane** configuration
  - Achieved two-fold **reduction in background**
  - Inhomogeneous spectrometer fields
    - Increased segmentation of data **by factor of 14**



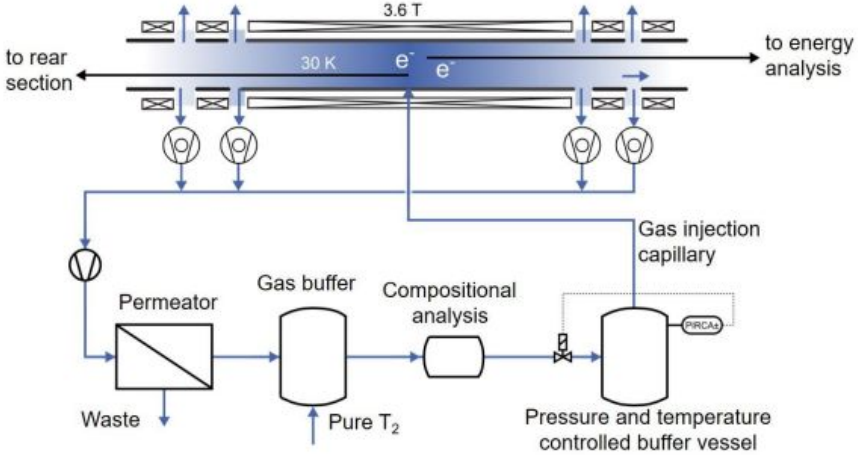


The MAC-E filter principle



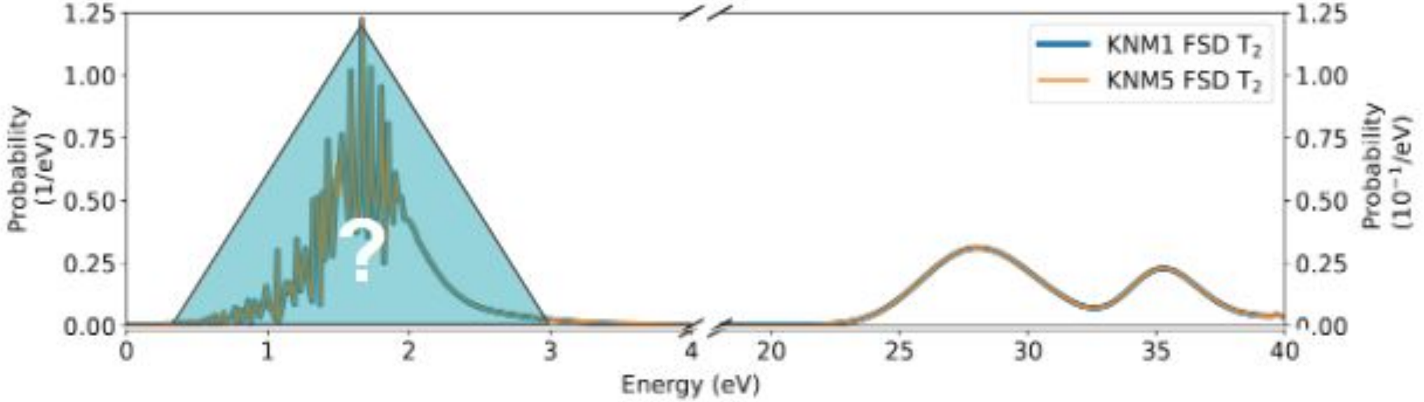
Tritium source

- 10m long Windowless Gaseous Tritium Source (WGTS)
- Stable amount of tritium (σ ~ 0.1%/h)
- Gas composition with high tritium purity (>95%)
- Activity ~100 GBq
- Stable cryostat temperature (mK scale)



Model Blinding:

- Unknown broadening of molecular final state distribution
- unknown shift of m^2



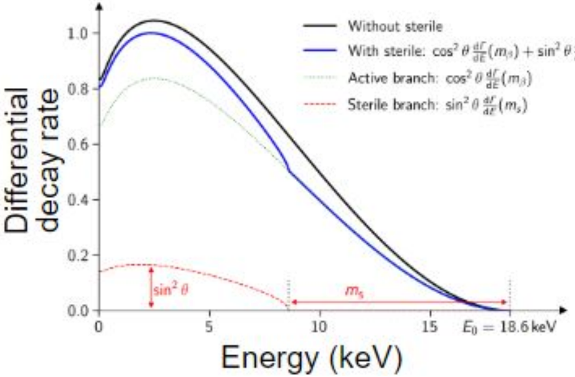
The theoretical β-decay spectrum is calculated with Fermi's golden rule

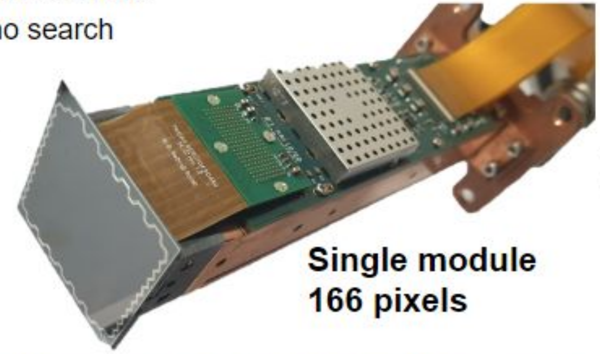
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{\mathrm{C}} = \frac{G_{\mathrm{F}}^2\,|V_{\mathrm{ud}}|^2}{2\pi^3}\,(g_{\mathrm{V}}^2 + 3g_{\mathrm{A}}^2)\,F_{\mathrm{rel}}(Z,E) \cdot p\,(E + m_{\mathrm{e}}) \cdot S\,L\,C\,I \cdot \sum_f G\,R\,Q \cdot P_f\,\epsilon_f\,\sqrt{\epsilon_f^2 - m_\nu^2}\,\Theta(\epsilon_f - m_\nu)$$

$$-2\log\mathcal{L}_{\mathrm{combined}} = \sum_{\mathrm{KNM1,2,3-NAP}}\sum_i \frac{\left(R_{\mathrm{calc}}(qU_i) - R_{\mathrm{data}}(qU_i)\right)^2}{\sigma_{R,i}^2} + \sum_{\mathrm{KNM3-SAP,4,5}}\sum_{i,k} 2\left(R_{\mathrm{calc},k}(qU_i)\cdot t_i - N_{i,k} + N_{i,k}\cdot\ln\frac{N_{i,k}}{R_{\mathrm{calc},k}(qU_i)\cdot t_i}\right)$$

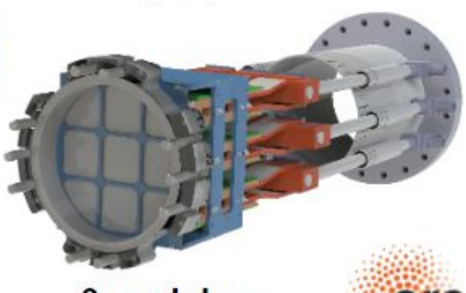
TRISTAN @ KATRIN

- Search for keV sterile neutrinos
  - Novel SDD array for high rates
- Target sensitivity to mixing of **10^{-6}**
  - Ongoing systematic and modeling studies
- Timeline
  - 2024 – Assembling a full detector replica
  - 2026 – Installation in the KATRIN beamline
  - 2026-2027 – keV sterile neutrino search





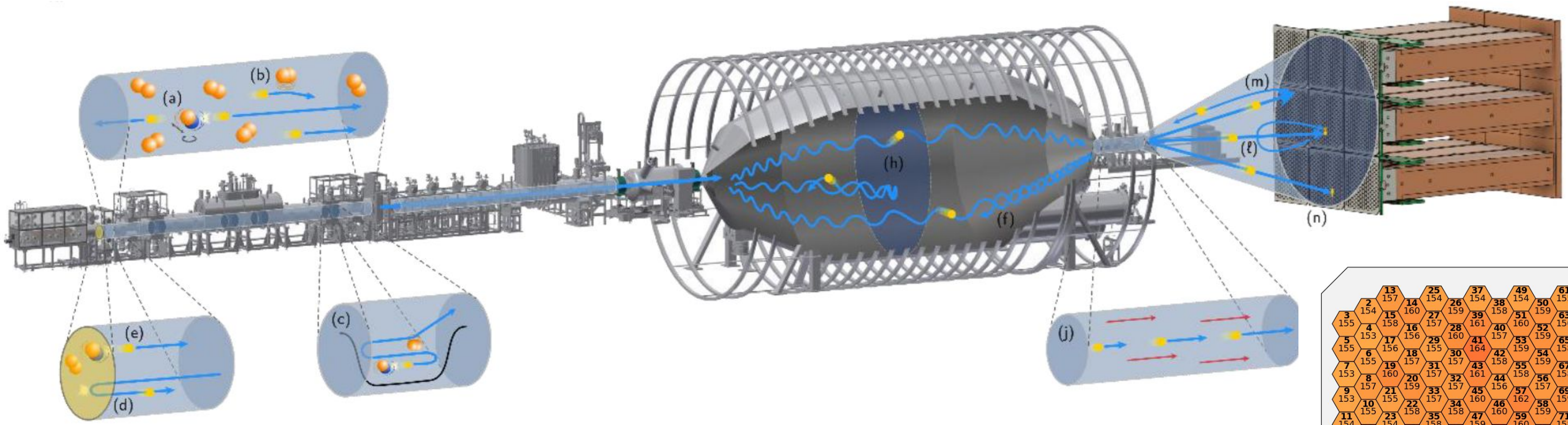
Single module
166 pixels

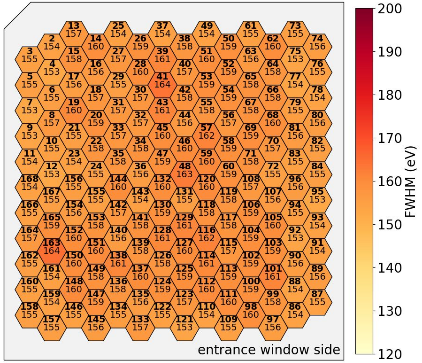


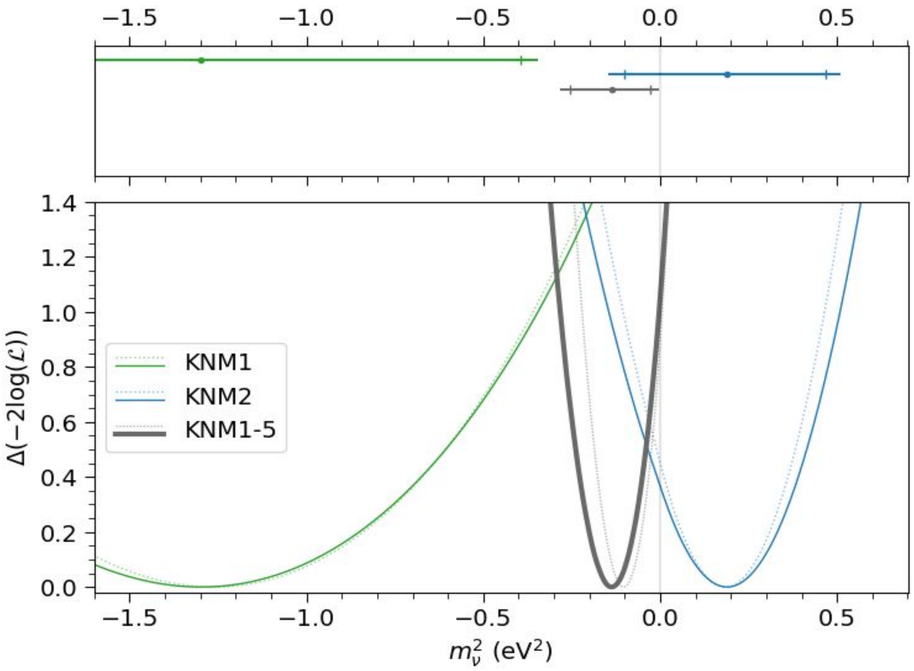
9 modules
~1500 pixels

S. Mertens et al., J. Phys. G46 (2019); S. Mertens et al., J. Phys. G48 (2020); D.Siegmann et al., J. Phys. G (2024)

TRISTAN detector in KATRIN setup

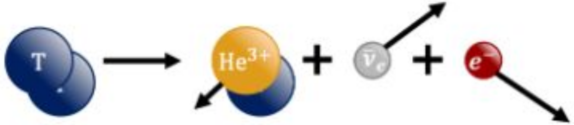


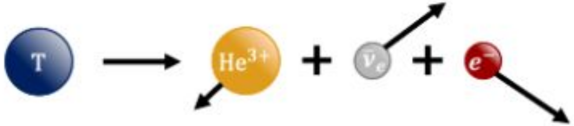




Q-value: (18 575.0 ± 0.3) eV

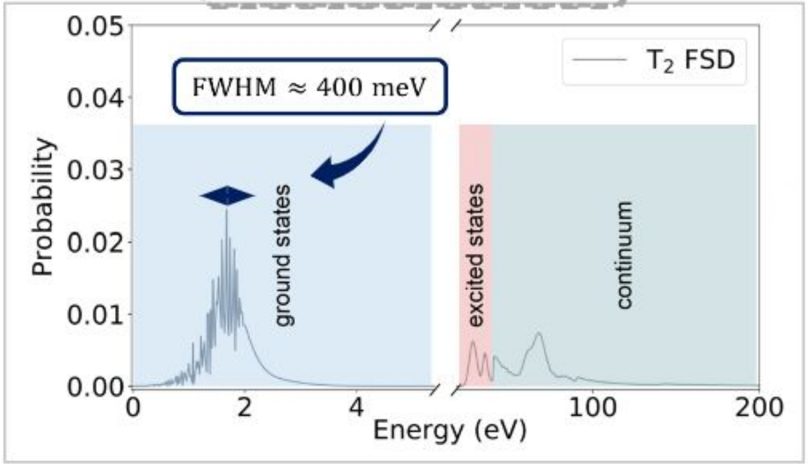
Final State Distributions





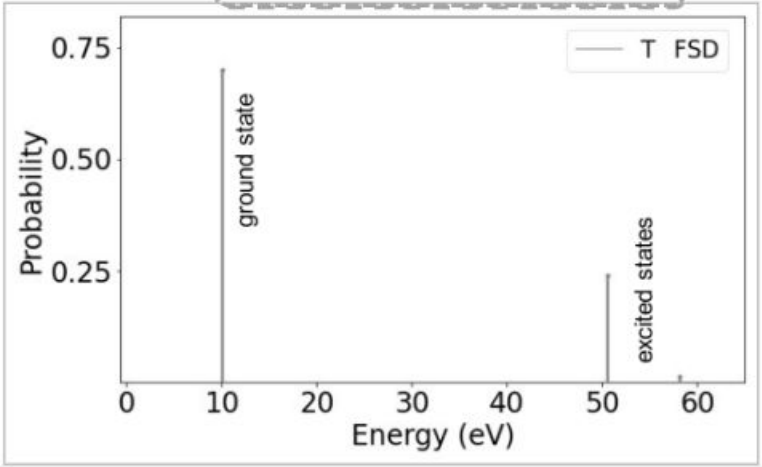
Molecular Tritium

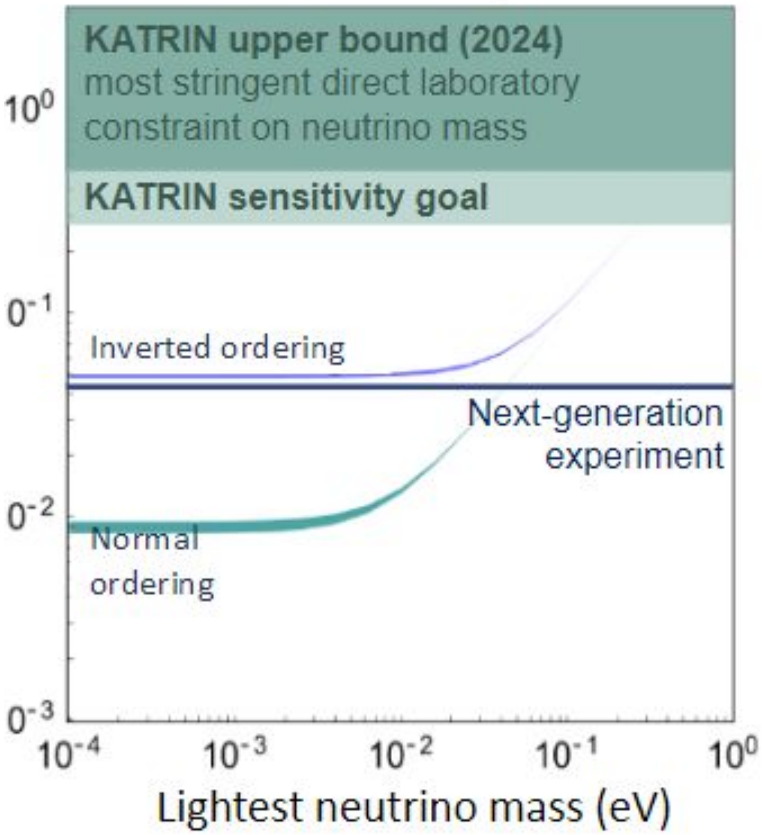
KATRIN operating @ 80 K



Atomic Tritium

Simulated cold source @ 5 K




KATRIN upper bound (2024)
most stringent direct laboratory constraint on neutrino mass
KATRIN sensitivity goal
Inverted ordering
Next-generation experiment
Normal ordering
10^0
0^-1
0^-2
0^-3
10^-4
10^-3
10^-2
10^-1
10^0
Lightest neutrino mass (eV)

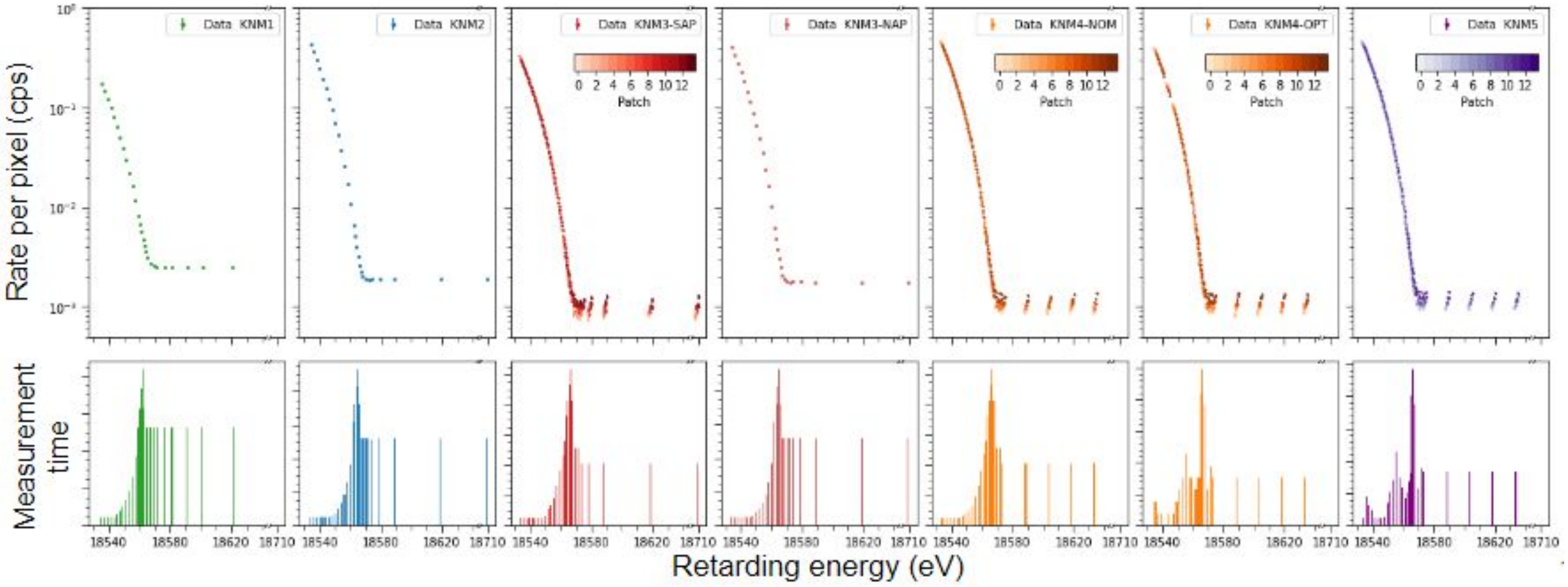
Data

36 Mio counts in total

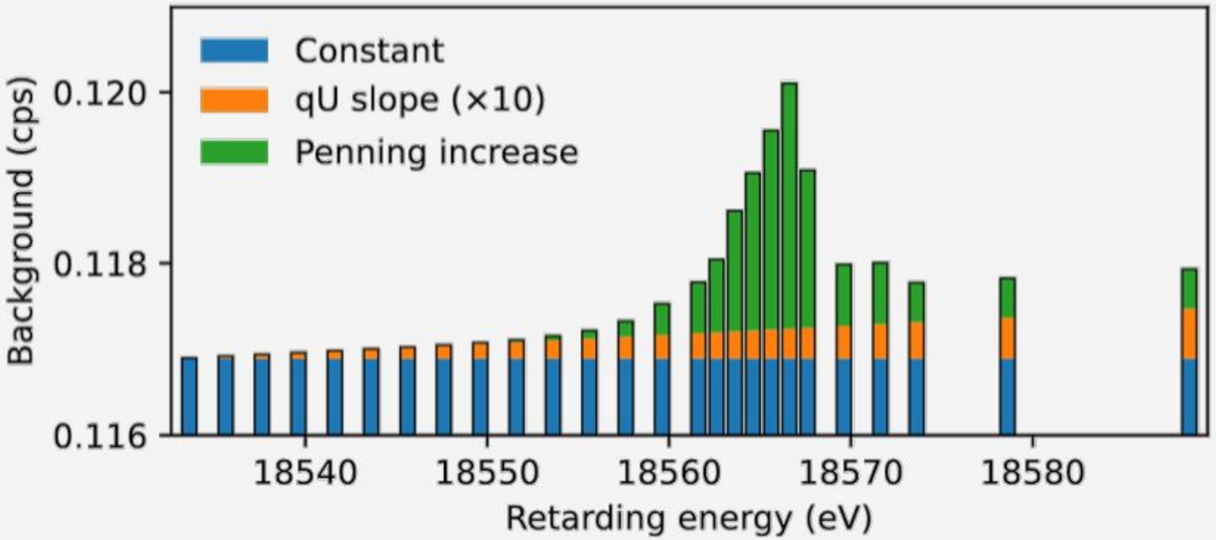
59 stacked spectra with

27 + **28** + **14 x 28** + **28** + **14 x 28** + **14 x 25** + **14 x 28** =

1609 data points



Backgrounds



KNM4 Data Combination

- Split KNM4 into KNM4-NOM and KNM4-OPT
- nominal and optimized time distribution
- Sourcepotentialdriftof60mV during KNM4 wasnottaken into account
- Modification causes shift of $m^2$by - 0.1 eV^2
- Additional analysis steps before unblinding in the future