Recent results from the KATRIN experiment

Sub-eV neutrino mass detection and eV-sterile neutrinos

Weak interactions and Neutrinos (WiN), June 2025
Brighton, Sussex

Chloé Goupy (MPIK),
on behalf of the KATRIN collaboration

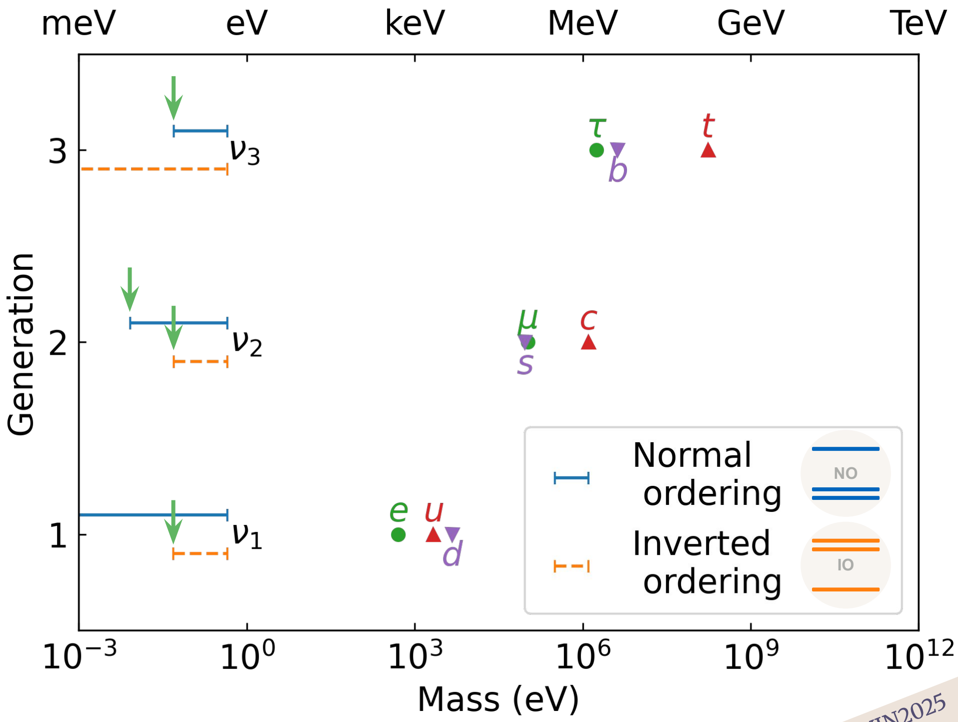
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

Neutrinos have a mass

Motivations for direct mass measurement

- **Neutrino oscillations** imply that neutrinos do have a **non zero mass**
  → **lower bounds** for the neutrino mass

with data from PDG - Phys. Rev. D 110, 030001 (2024)
Courtesy of A. Schwemmer



Neutrinos have a mass

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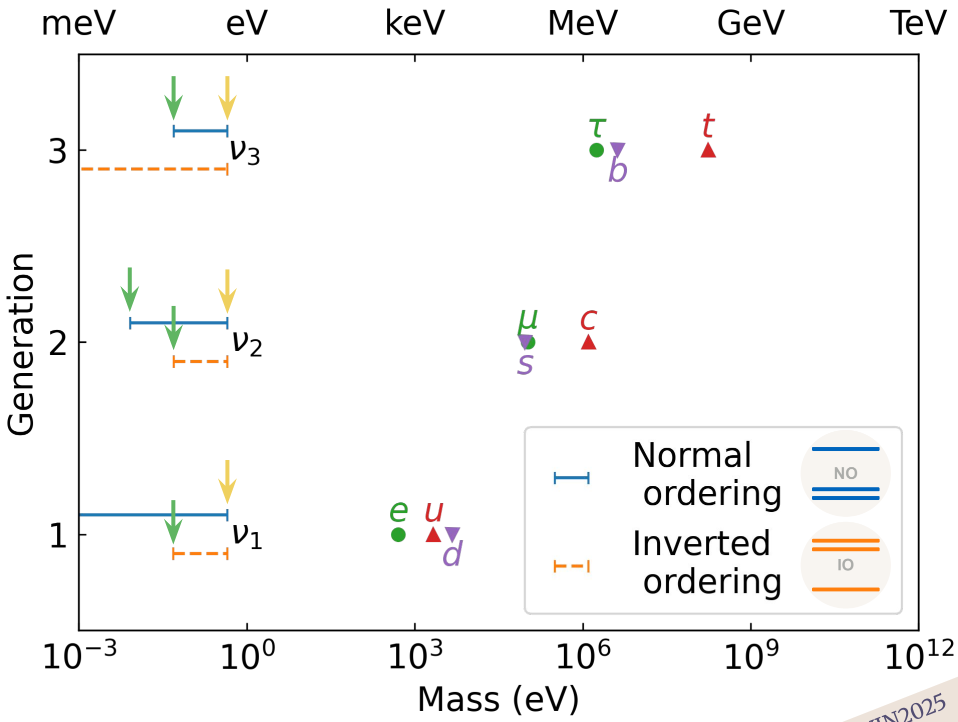
- **Neutrino oscillations** imply that neutrinos do have a **non zero mass**
  → lower bounds for the neutrino mass

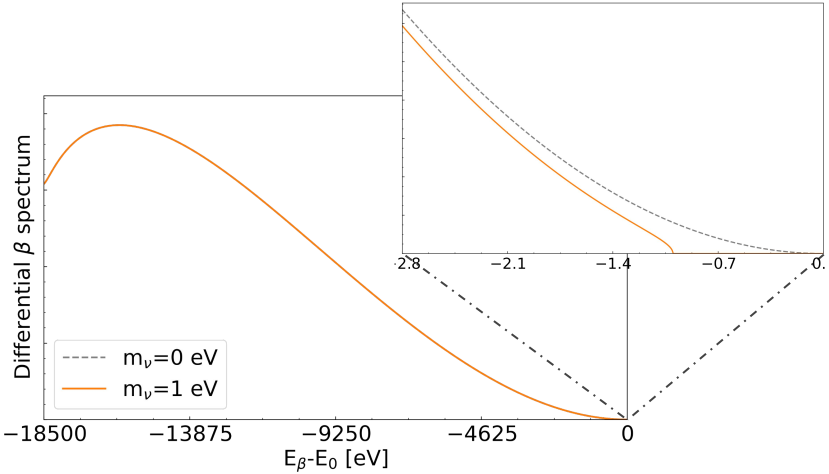
But

- What is the **absolute scale**? And the **mass ordering?**
  → upper limit from neutrino mass measurements
    - via cosmology (depends on model, e.g. ΛCDM)
    - via 0νββ-decay (relies on Majorana nature)
    - via **β-decay** (*direct measurement*, this talk)



Direct measurement of the neutrino mass

From β-decay kinematics



- β-decay with end point E_0: $n \to p^+ + e^- + \bar{\nu_e}$
- probe **effective electron anti-neutrino** mass $m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$
- **Spectral distortion** near end point
  → **low background** (< 1 cps)
  → high **energy resolution** (~1eV)

Direct measurement of the neutrino mass

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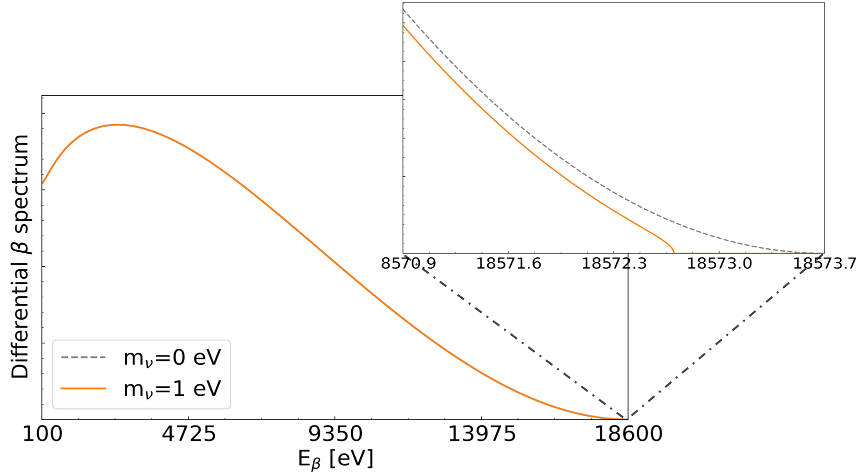
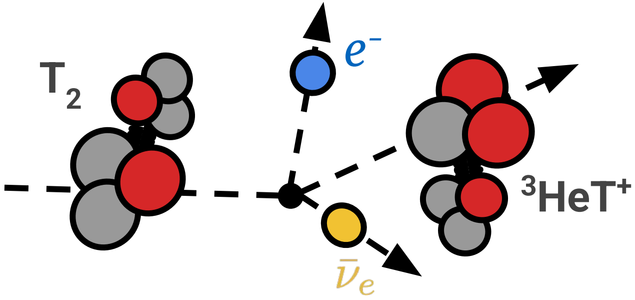




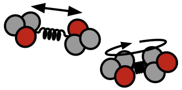
T_2 (molecular tritium) :

→ low end point E_0= 18.6 keV

→ half life τ = 12.3 years

But

→ molecular binding energies



- (molecular) Tritium β-decay: $T_2 \rightarrow ^3\mathrm{He}T^+ + e^- + \bar{\nu}_e$
- probe **effective electron anti-neutrino** mass $m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$
- **Spectral distortion** near end point
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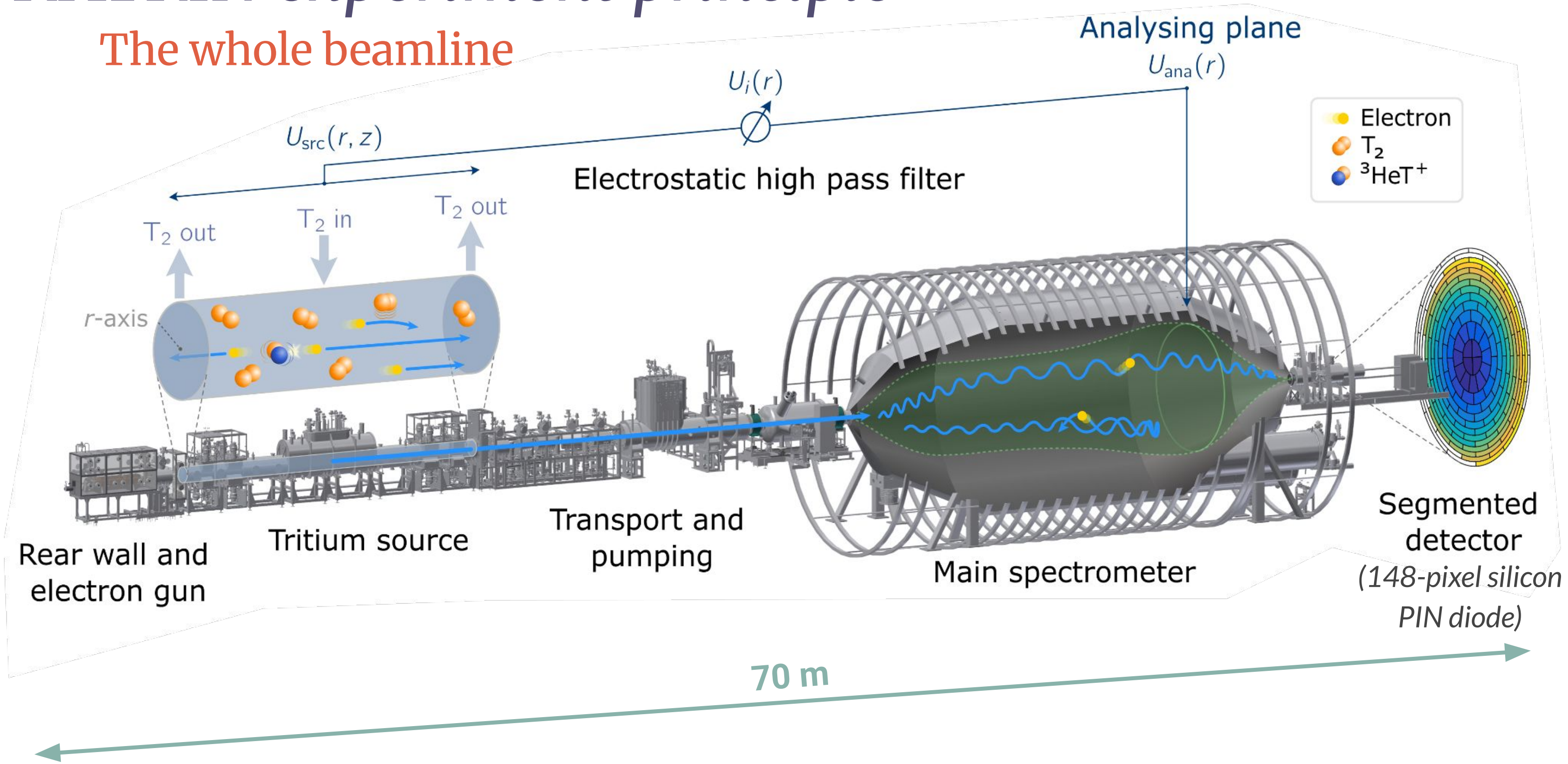
The Karlsruhe Tritium Neutrino (KATRIN) experiment

Arrival of the main spectrometer in Karlsruhe
November 2006

KATRIN experiment principle

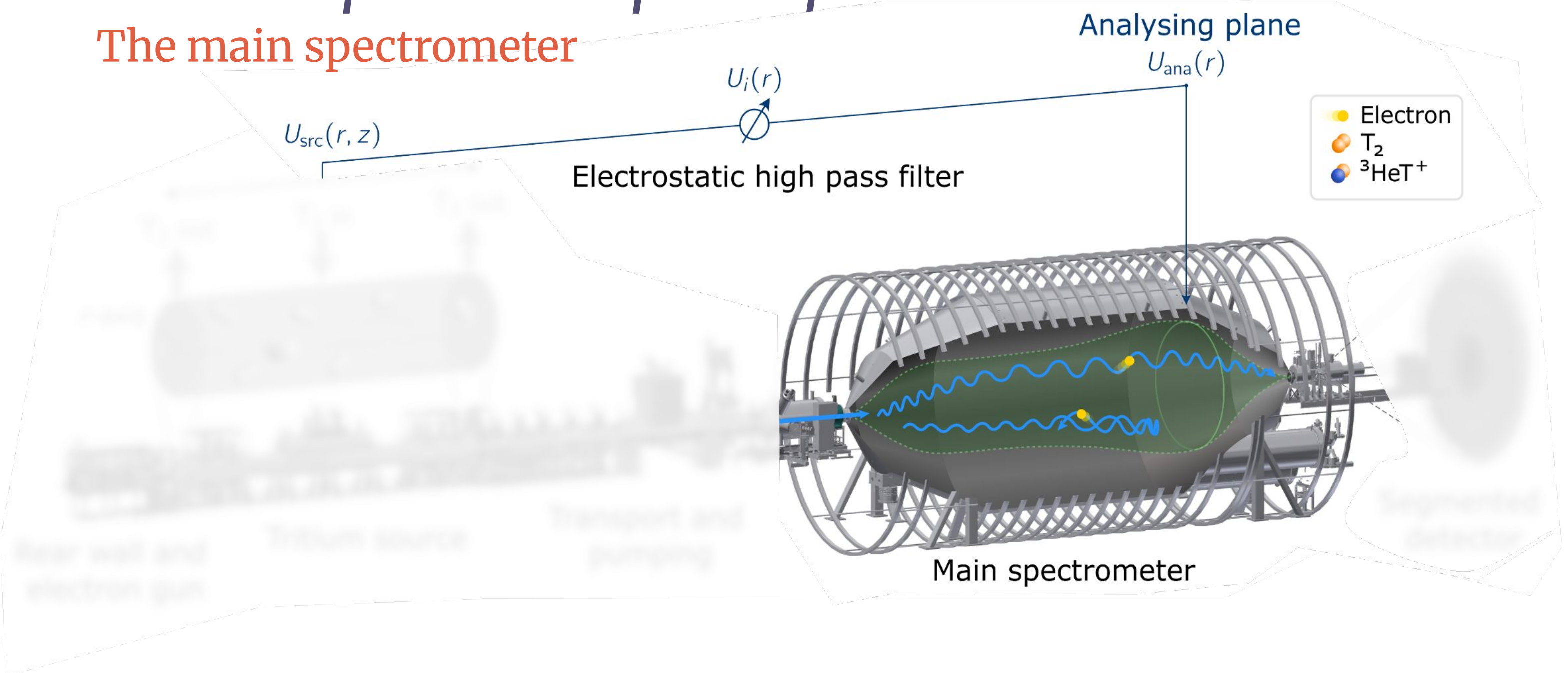
The whole beamline



KATRIN collaboration, JINST 16 (2021) T08015

KATRIN experiment principle

The main spectrometer



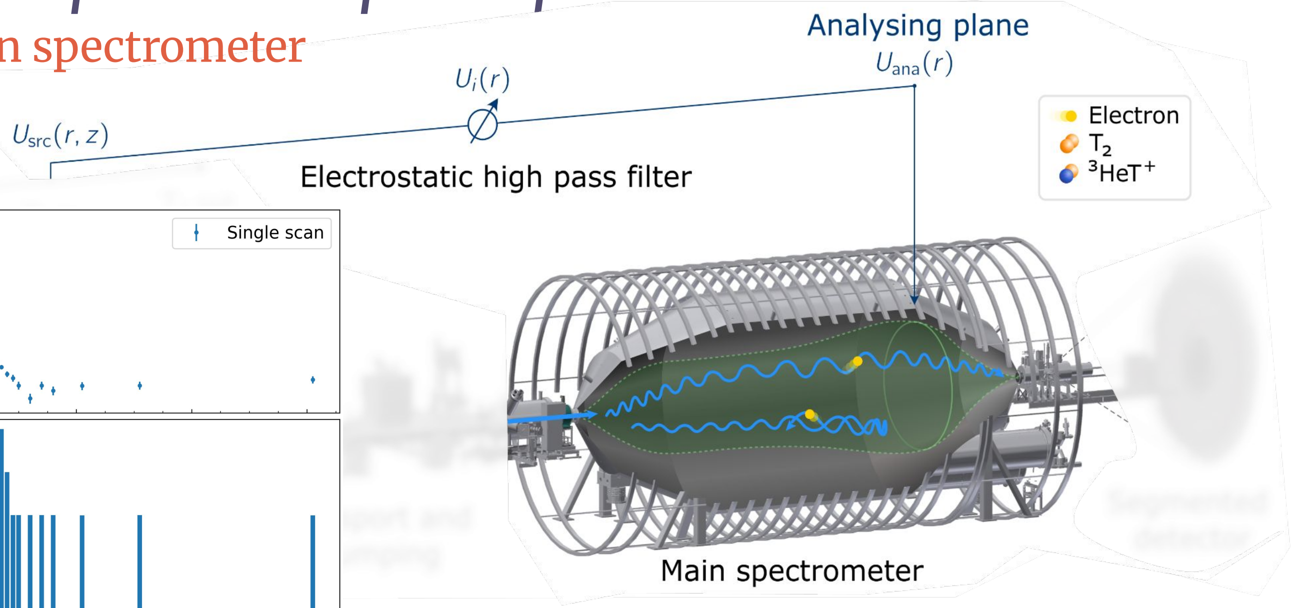
- **MAC-E (M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic filter**)**: Only electrons with $E_{||} > qU_{ret}$ reach the detector

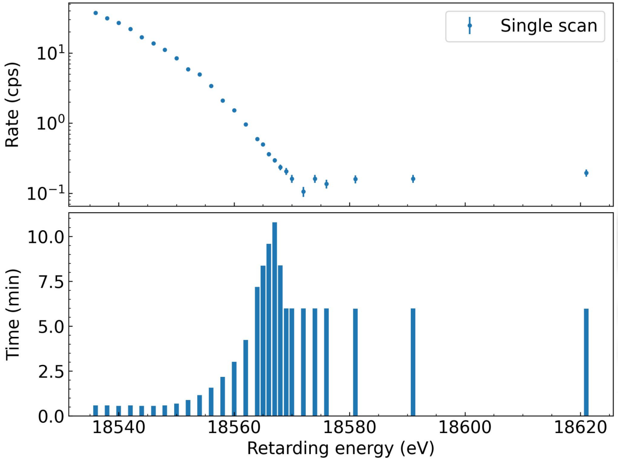
→ Vary retarding energy to **scan spectrum**
→ Count events at the detector
→ **Integral spectrum** (2-3h in total)
→ **Repeat** scanning procedure a few 100 times to obtain **one measurement campaign (KNM*)**

KATRIN collaboration, JINST 16 (2021) T08015

KATRIN experiment principle

The main spectrometer





- **MAC-E (Magnetic Adiabatic Collimation combined with an Electrostatic filter):** Only electrons with $E_{||} > qU_{ret}$ reach the detector

→ Vary retarding energy to **scan spectrum**
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KATRIN collaboration, JINST 16 (2021) T08015

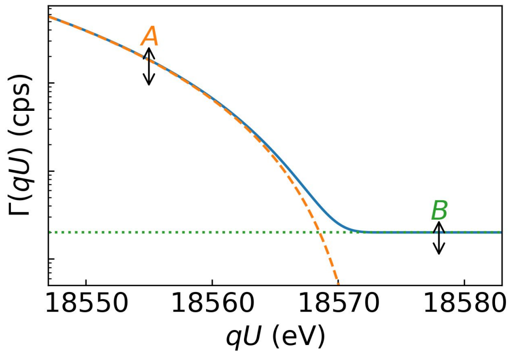
Analysis strategy

Principle

maximum likelihood fit of analytical model: $\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$

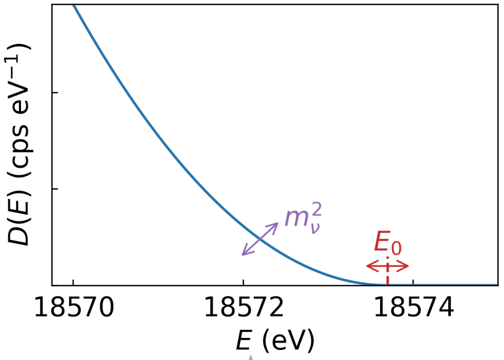
*with two-steps **blinding** procedure*

integral spectrum measured at the detector



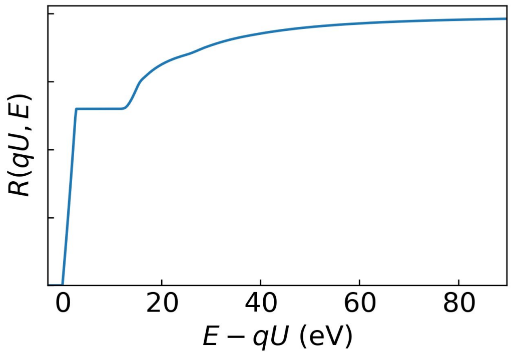
=

T_2 decay
→ differential spectrum



"⊛"

experimental response
(source, transport and spectrometer)



with free **amplitude *A***,
squared neutrino mass m_ν^2,
endpoint E_0,
background *B*

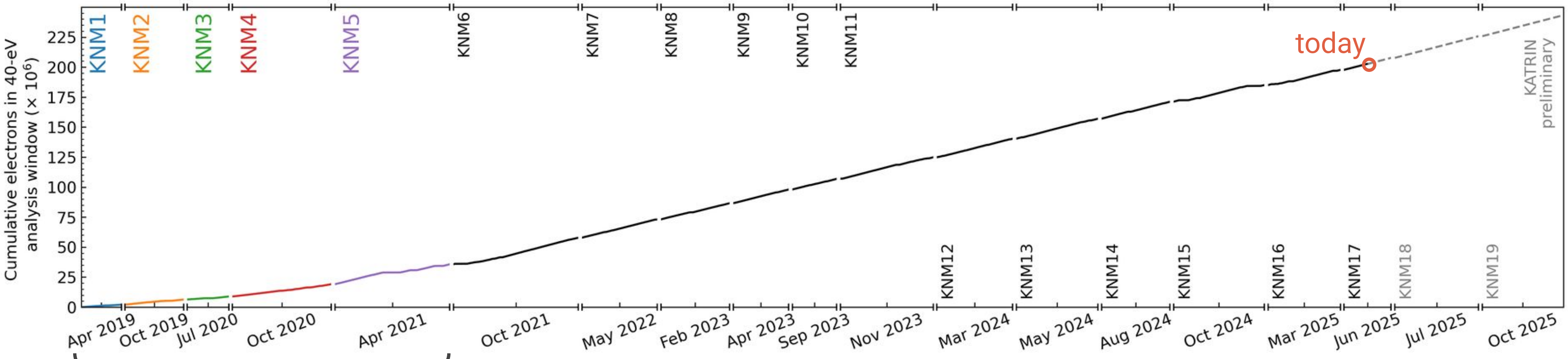
theoretical (Fermi theory, molecular excitations) and **experimental** inputs (calibration measurements)

Data taking status

and experimental improvements

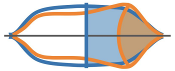
m_ν < 0.8 eV (90% CL)
[M. Aker et al., Nature Phys. 18 (2022) 2, 160-166]

On=going analysis

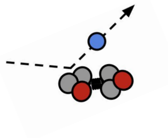


[KATRIN collaboration, *Science* 388,180-185(2025)]

- **259** measurement days
- **1757** β-scans
- ~**36 Mio** electrons
- experimental improvements



Shifted analysis plane:
→ reduce the background by a factor 2
[Lokhov et al., EPJ C 82 (2022)]

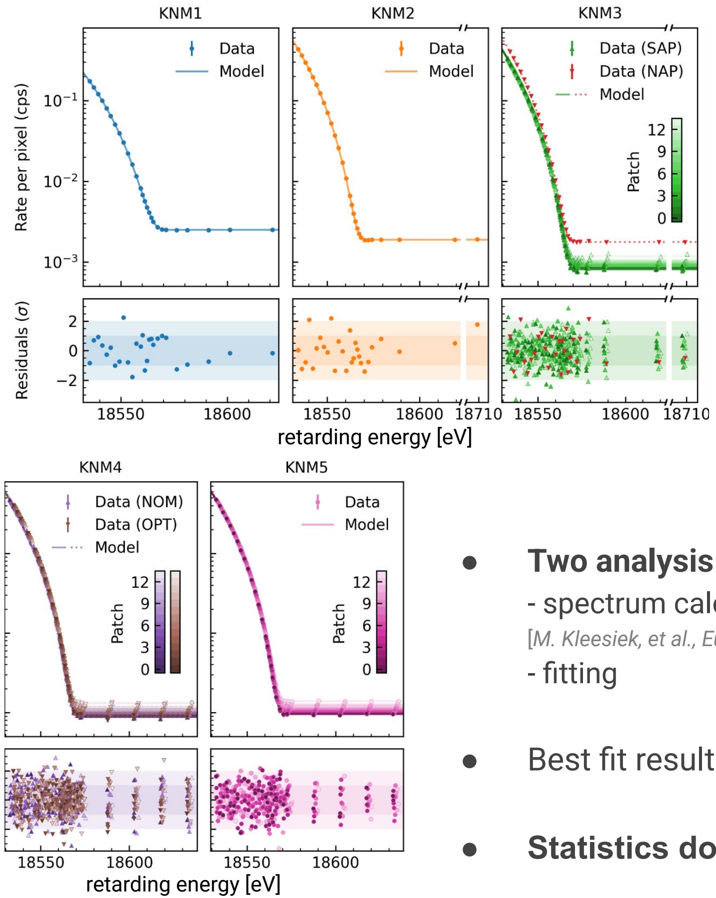


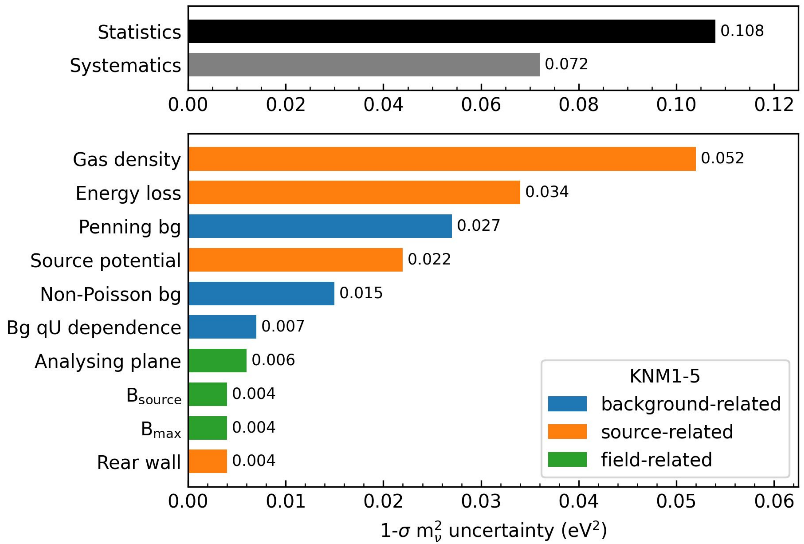
Precise calibration measurements:
→ with ^{83m}Kr circulation *(electric potential, field mapping…)*
[Lokhov et al., EPJ C 82 (2022)]

→ with an electron gun *(gas density, energy loss)*
[Aker et al., EPJ C 81 (2021)]

Fit results and systematic uncertainties

[KATRIN collaboration, *Science 388,180-185(2025)*]





- **Two analysis frameworks:**
  - spectrum calculation (optimized calculation/neural network)
  [M. Kleesiek, et al., Eur. Phys. J. C 79, 204 (2019)] [Karl et al., EPJ C 82 (2022)]
  - fitting

- Best fit result (p-value: 0.84): $m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$

- **Statistics dominated**, systematics non-negligible

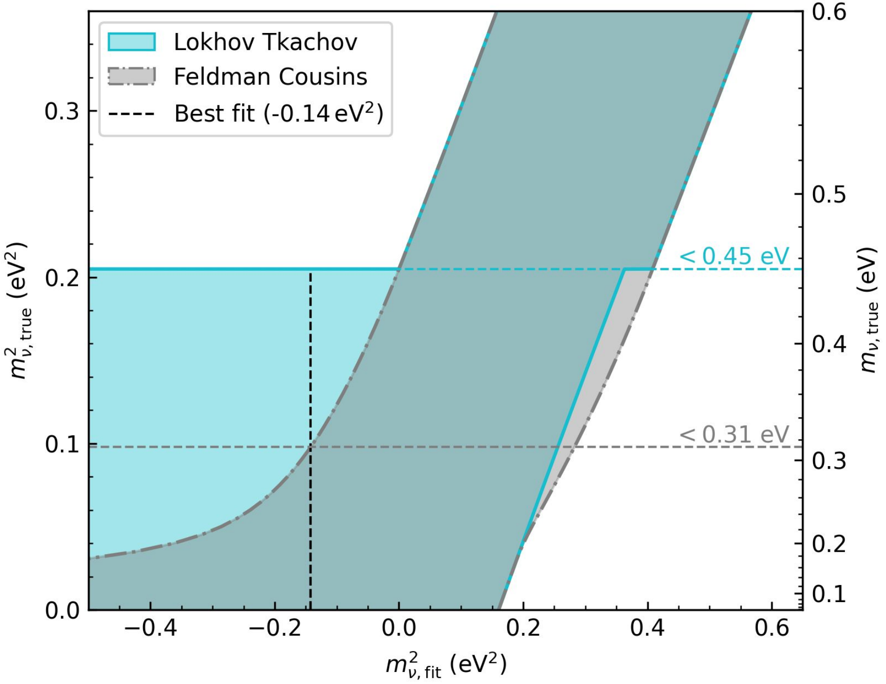
Neutrino mass limit

[KATRIN collaboration, *Science* 388,180-185(2025)]

- **KATRIN's new upper limit:**
  m_ν < 0.45 eV (90% CL)
  using **Lokhov-Tkachov** construction
  [Lokhov, Tkachov, Phys. Part. Nucl. 46 (2015) 3, 347-365)]

- Feldman-Cousins limit:
  m_ν < 0.31 eV (90% CL)
  [Feldman, Cousins, Phys. Rev. D 57 (1998) 3873-3889]

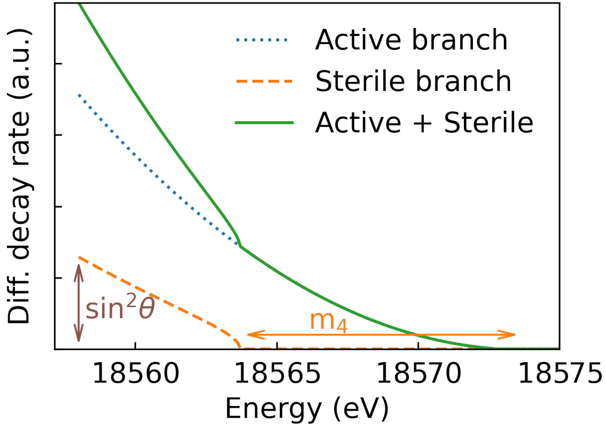
- **Bayesian analysis** in preparation



Beyond the neutrino mass
probing light sterile neutrinos

[H. Acharya et al., arXiv:2503.18667v1 (2025)]
Submitted, to be published soon

- KATRIN can probe **eV-sterile neutrinos signature** near the tritium end point
- Analysis of KNM1-5 (259 days of measurement)
- 2 additional parameters:
  → **m_4:** 4^{th} neutrino mass
  → **$\sin(\theta)$:** 4^{th} neutrino mixing



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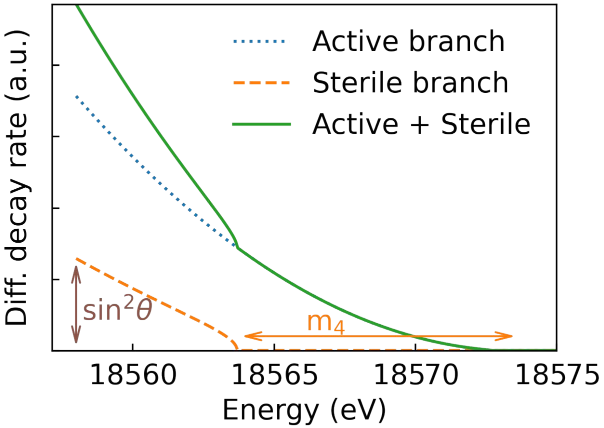

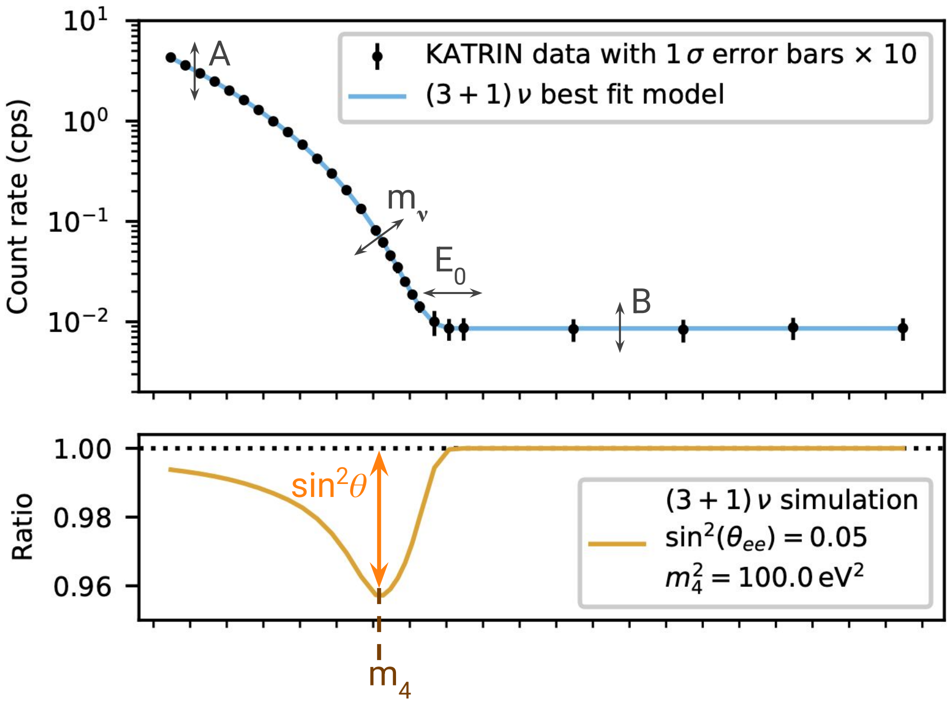

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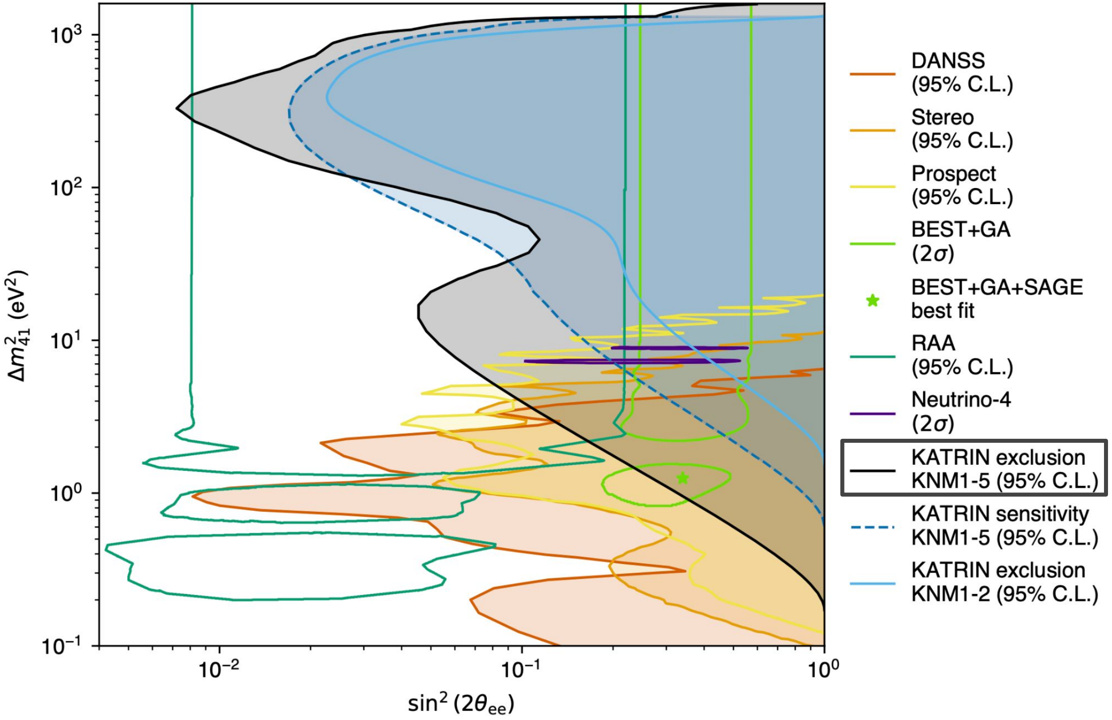
- KATRIN can probe **eV-sterile neutrinos signature** near the tritium end point
- New exclusion limit:
  → almost excludes the whole Gallium anomaly allowed region
  → excludes Neutrino-4
  → synergy with short baseline reactor experiments:
  - Prospect
  - Stereo
  - DANSS



Conclusions and outlook

Take away messages

- KATRIN direct neutrino mass bound:
  m_ν < 0.45 eV (90% CL)
  [KATRIN collaboration, *Science* 388,180-185(2025)]

- Data taking ongoing until **end of 2025**
  → towards 0.3 eV sensitivity

- **Beyond neutrino mass analysis**
  → new eV sterile neutrino rejection limits
  Preprint available [H. Acharya et al., arXiv:2503.18667v1 (2025)], *submitted for publication*

  → *Relic neutrino, Lorentz invariance violation…*
  *[Aker et al., Phys. Rev. Lett. **129**, 01180 (2022)]*
  *[M. Aker et al., Phys. Rev. D **107**, 082005 (2023)]*

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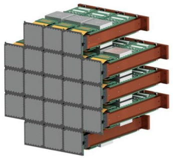
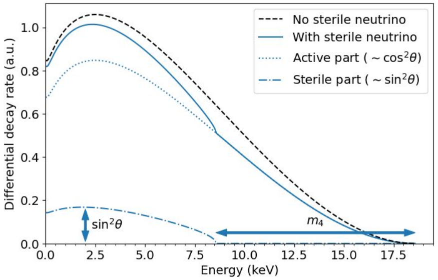
  *[M. Aker et al., Phys. Rev. D **107**, 082005 (2023)]*

Outlook beyond KATRIN

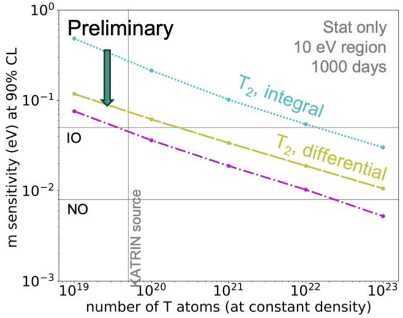
- 2026-2027: **search for keV sterile neutrino** with TRISTAN detector
  [Siegmann et al., J. Phys. G: Nucl. Part. Phys. 51 085202 (2024)]
  [S. Mertens *et al.*, JCAP02(2015)020]





- 2027 onwards (KATRIN++): **Research and Development** for next neutrino mass experiments
  → Differential methods
  → Atomic tritium

Tuesday's talk by A. Marsteller
Research activities for a next generation neutrino mass measurement: KATRIN++



Recent results from the KATRIN experiment

Sub-eV neutrino mass detection and eV-sterile neutrinos

Thank you for your attention !

Neutrino mass observables

Neutrinoless ββ-decay

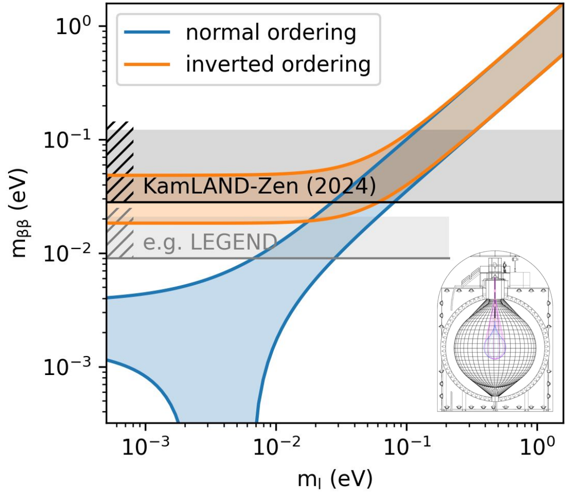
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

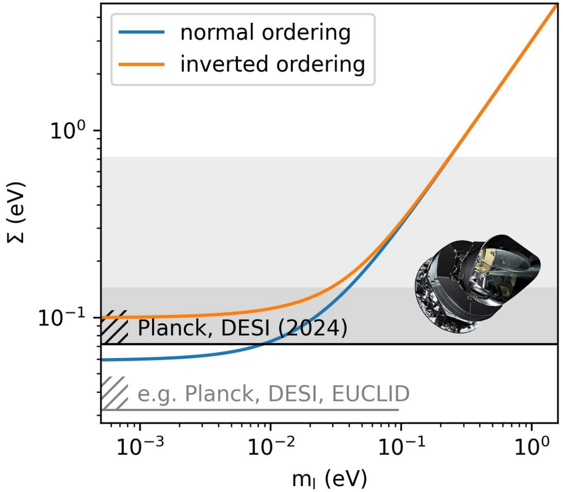
Cosmology

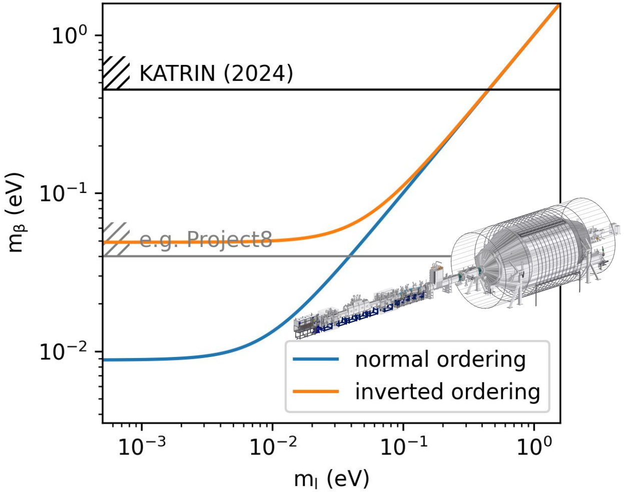
$$\Sigma = \sum_i m_i$$

β-decay kinematics

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







Courtesy C. Wiesinger/ A. Schwemmer

[NuFIT 5.3, nu-fit.org]

Analysis challenges
and how to handle them

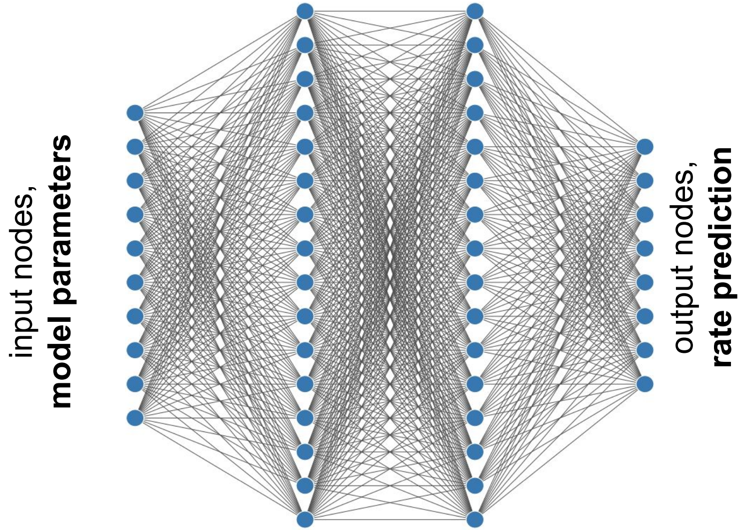
- **Highly segmented** data (1609 data points)
  high granularity and dimensionality

- **complex model**, differential spectrum integrated over response
  → **Computationally expensive** model evaluations

- 144 correlated systematic parameters

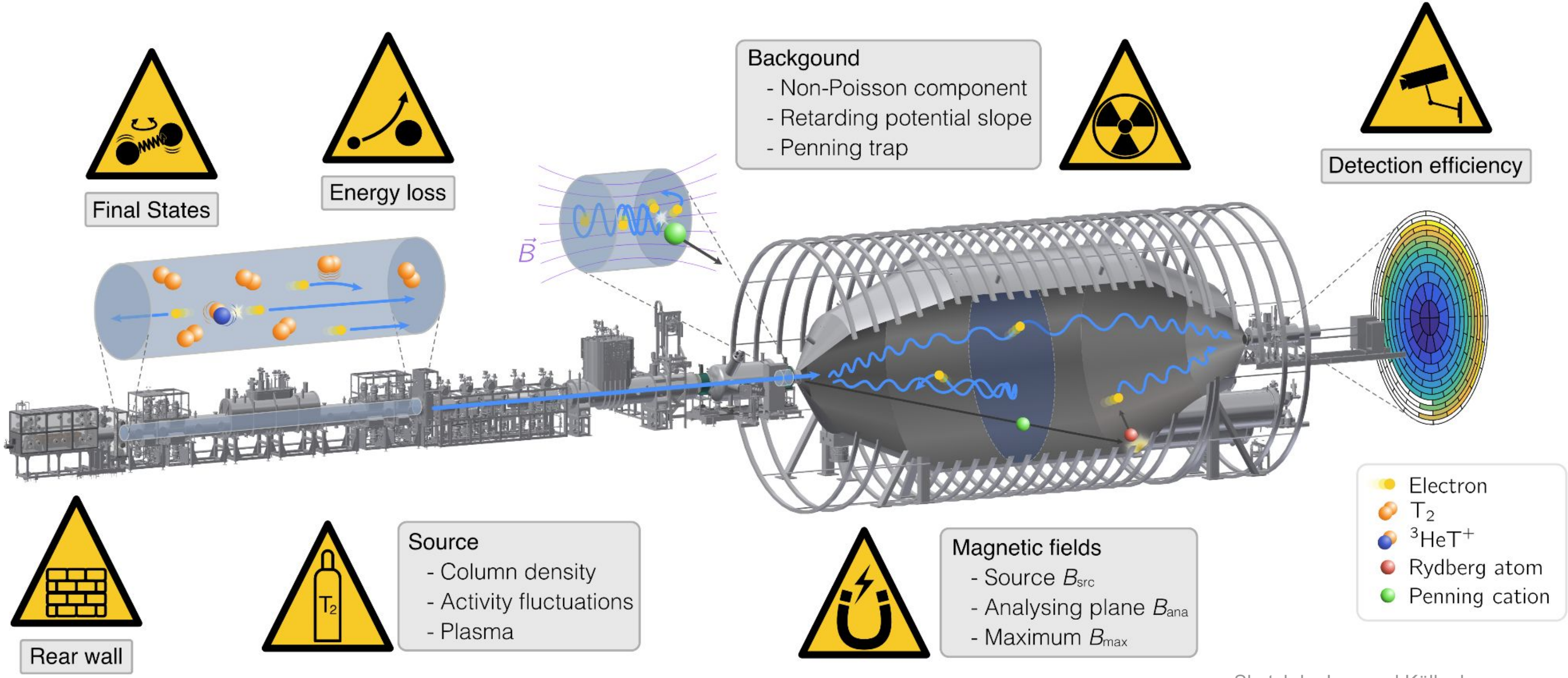
- Double-layer blinding scheme
  - fixing analysis procedure on MC data
  - using model blinding, unknown modification of final states

- Two independent analysis teams and frameworks
  - optimized model evaluation
  - fast model prediction with a neural network



→ **Simultaneous fit** with common m_ν^2 in **O(min)**

Systematic uncertainties



Sketch by Leonard Köllenberger

Experimental improvements

KNM2 ⇒ KNM5

- **Statistics dominated**, systematics non-negligible

➔ Still statistics dominated, **significant improvements** of systematics

- **Background**-related systematics dominate

➔ Successful **mitigation**: New measurement mode (SAP), removal of Penning trap

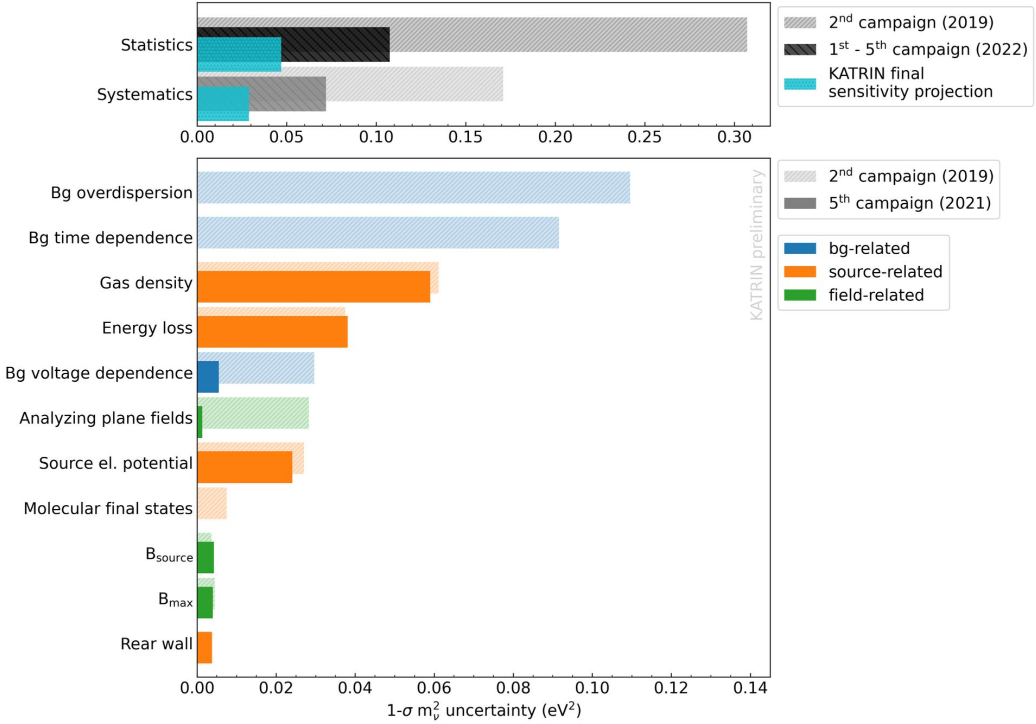
Lokhov et al., Eur. Phys. J. C 82, 258 (2022)

- Significant contribution from **analysing plane fields**

➔ **High-statistic ^{83m}Kr** calibration campaign

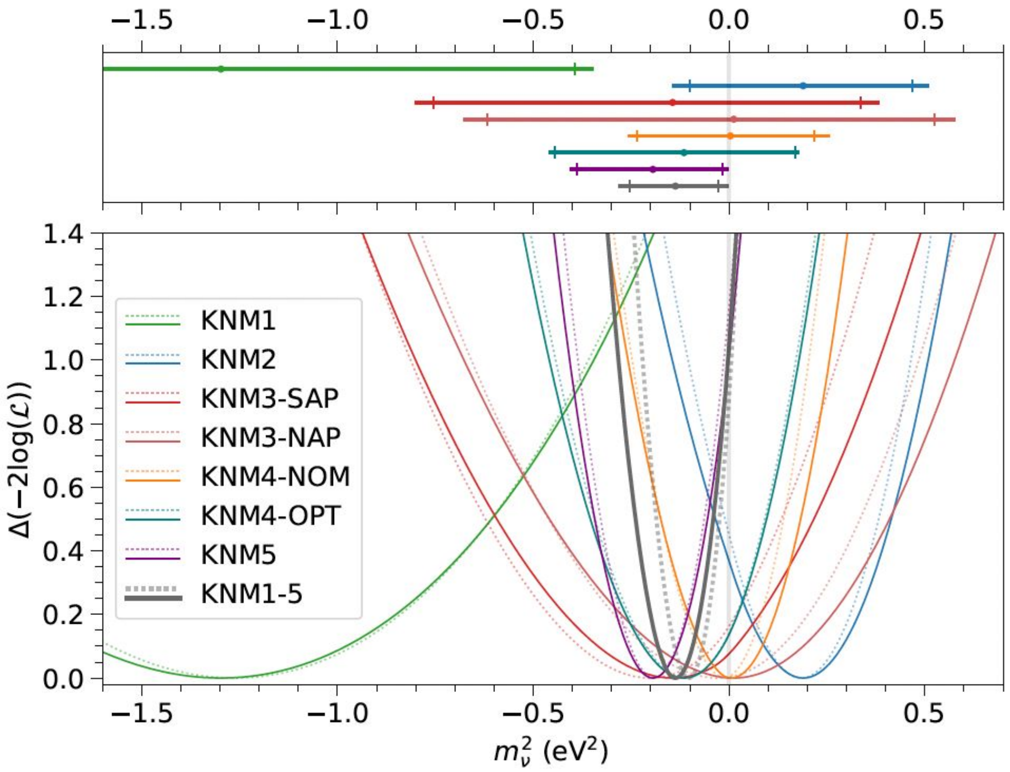
K. Altenmüller et al., J.Phys.G 47 6, 065002 (2020)

Courtesy of A. Schwemmer



KNM1–5 analysis

Likelihood profiles



- - - : statistics only

— : statistics and systematics