Recent results from the KATRIN experiment

Sub-eV neutrino mass detection and eV-sterile neutrinos

Les rencontres de Moriond,
Electroweak Interactions & Unified Theories
March 15-22, 2026

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

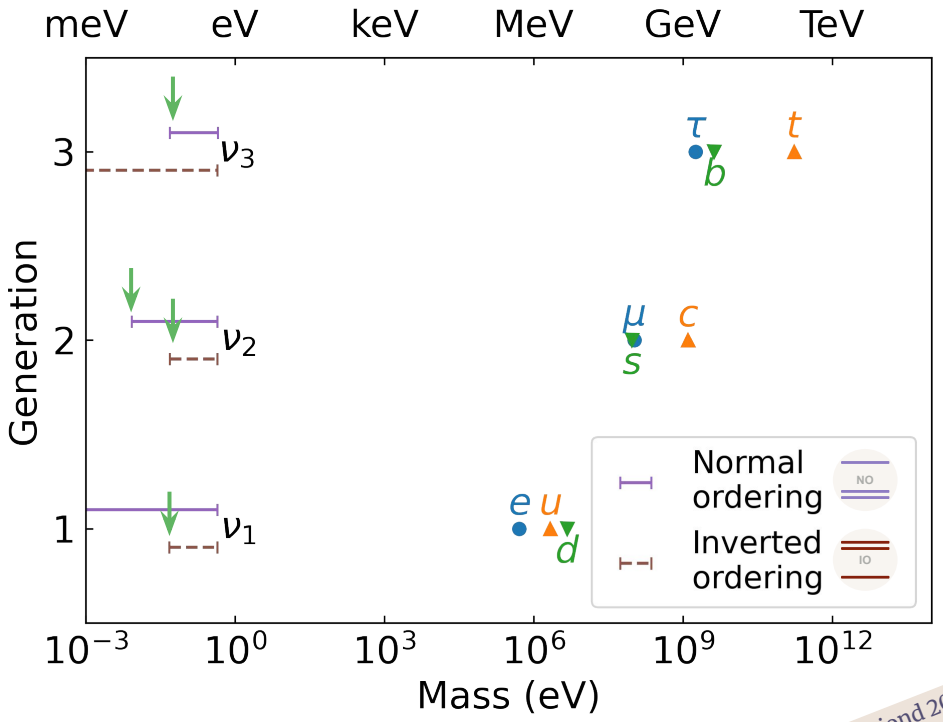
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

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

Motivations for direct mass measurement

- **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 0$\nu\beta\beta$-decay (relies on Majorana nature)
  - via **β-decay** (*direct measurement*, this talk)

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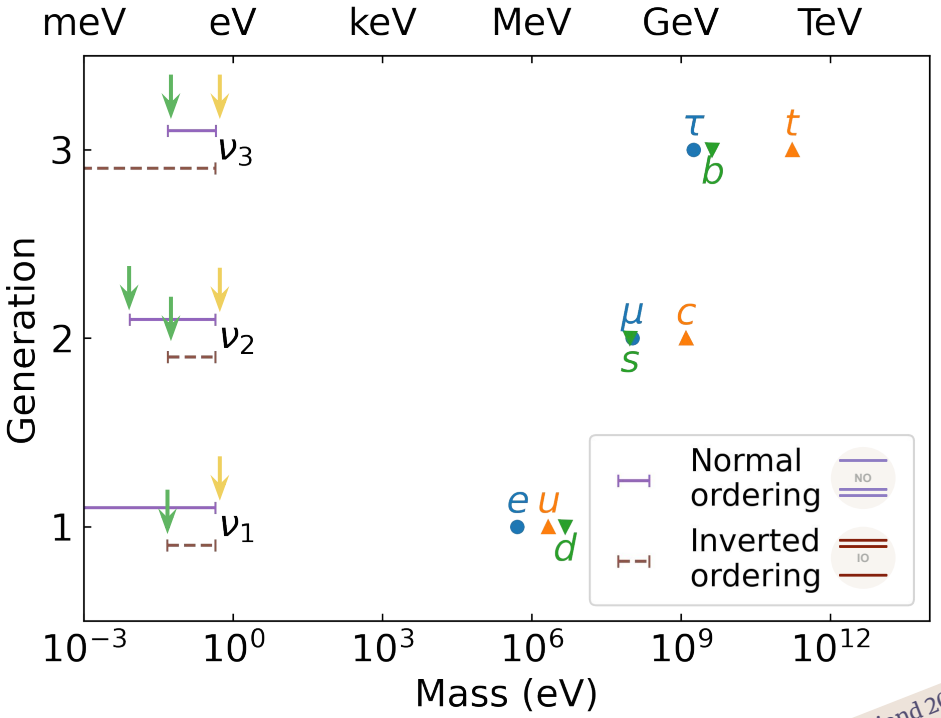
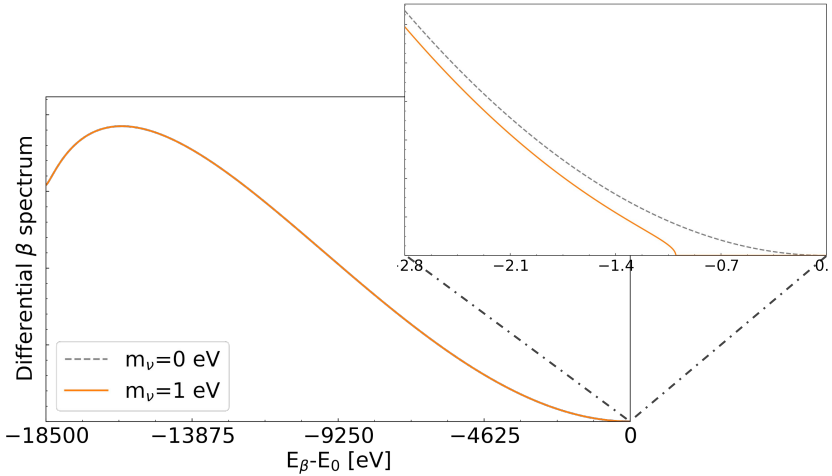


Direct measurement of the neutrino mass

From β-decay kinematics



- β-decay with end point E_0: $n \rightarrow p^+ + e^- + \bar{\nu}_e$
- 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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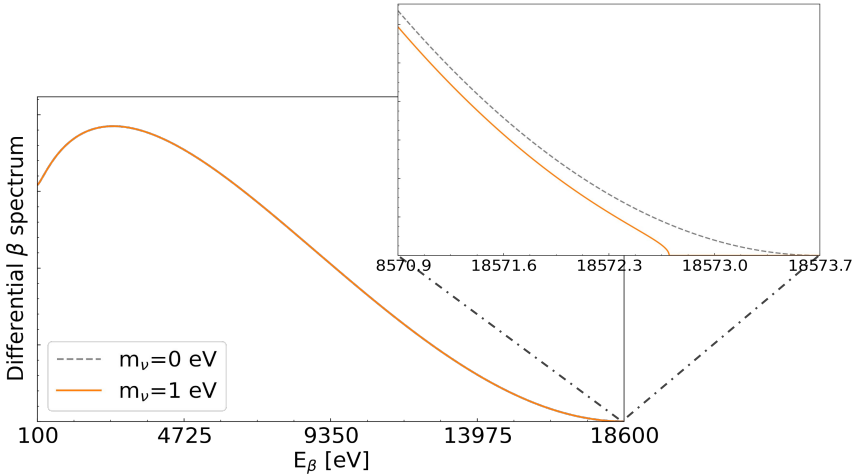
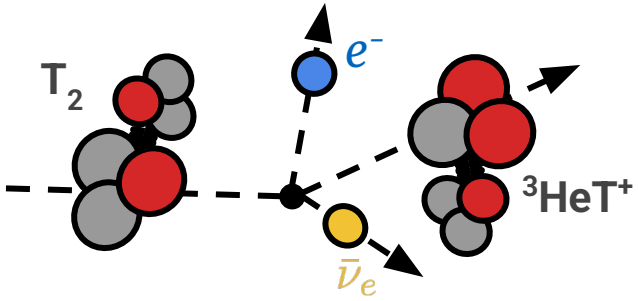




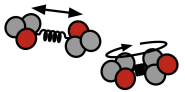
T_2 (molecular tritium) :

→ 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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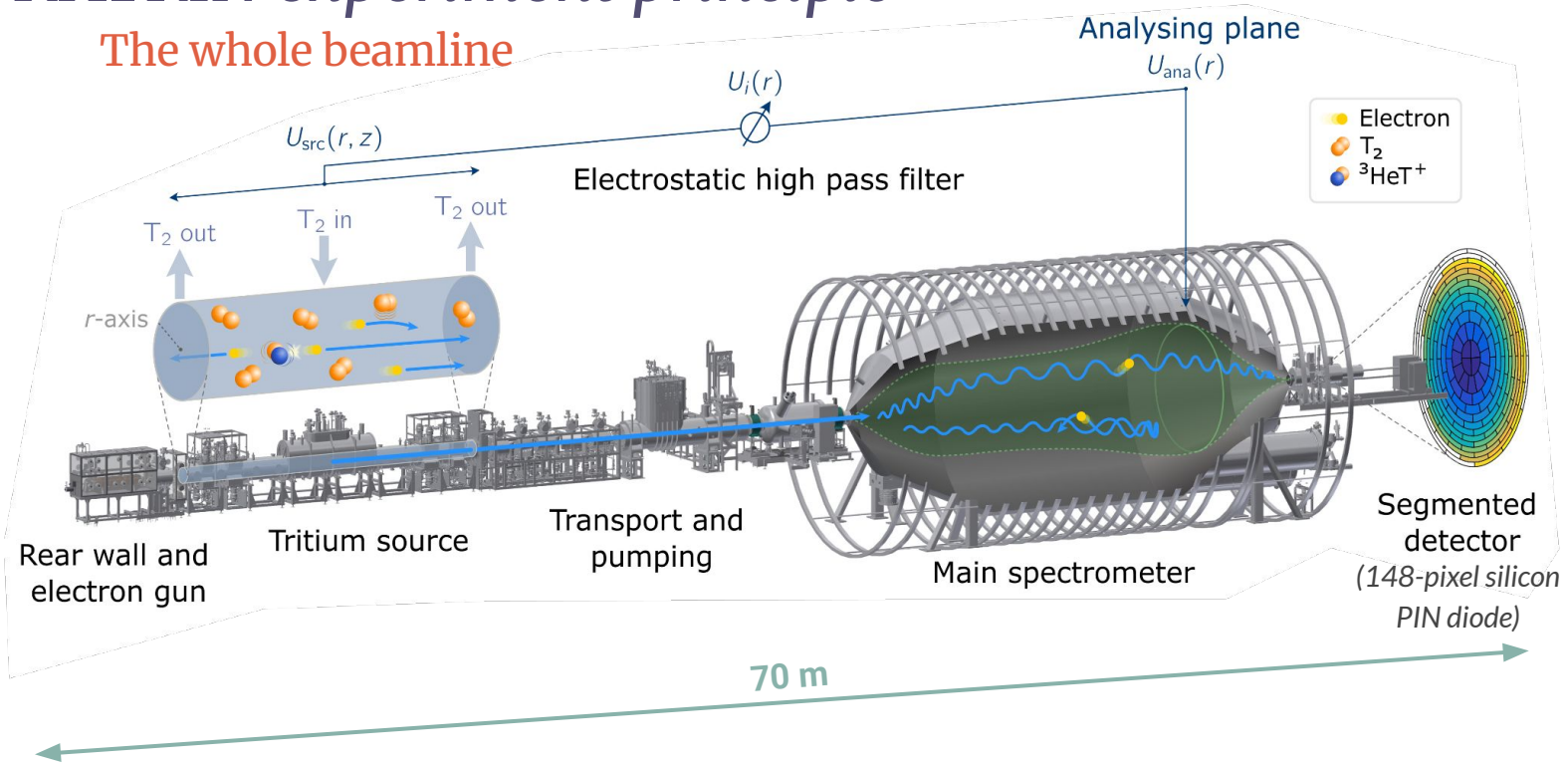
  → high **energy resolution** (~1eV)

The Karlsruhe Tritium Neutrino (KATRIN) experiment

Arrival of the main spectrometer in Karlsruhe
November 2006

KATRIN experiment principle

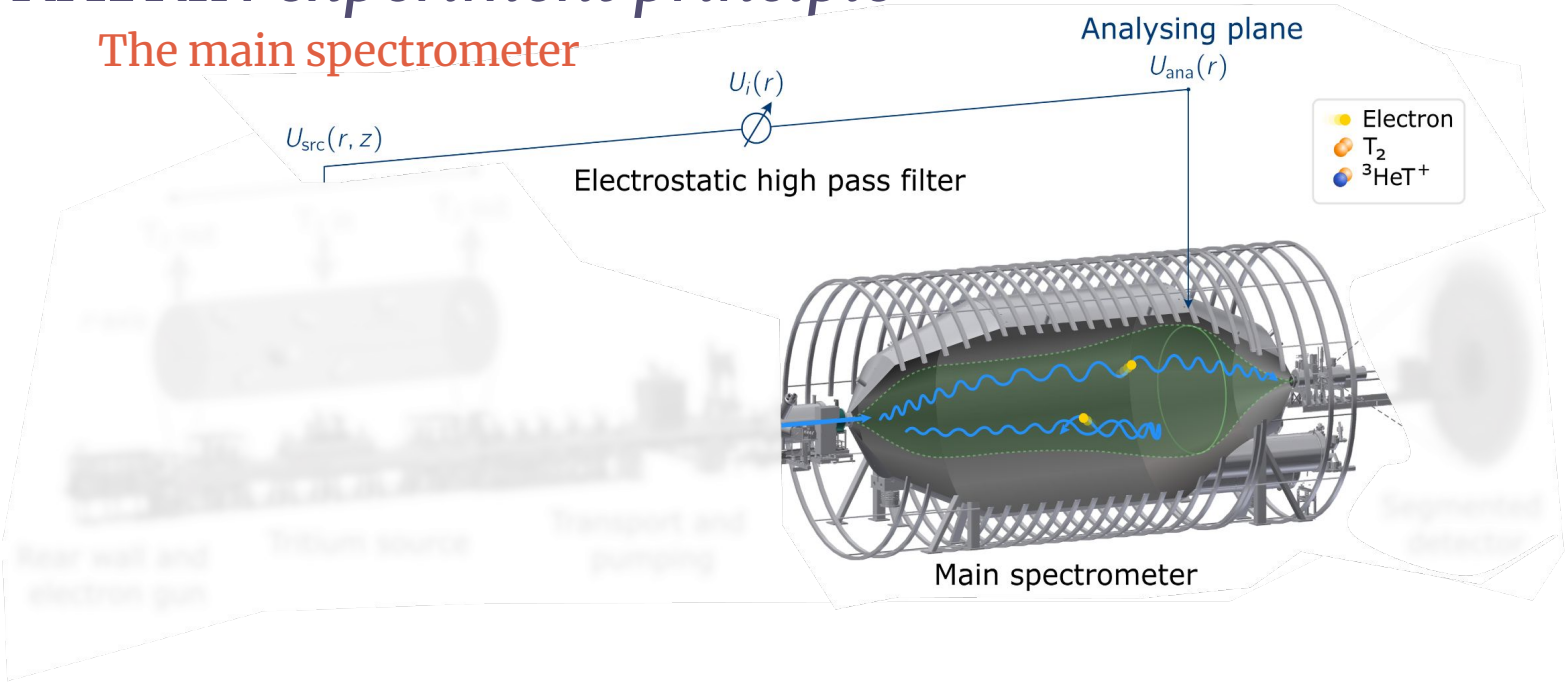
The whole beamline



KATRIN collaboration, JINST 16 (2021) T08015

KATRIN experiment principle

The main spectrometer



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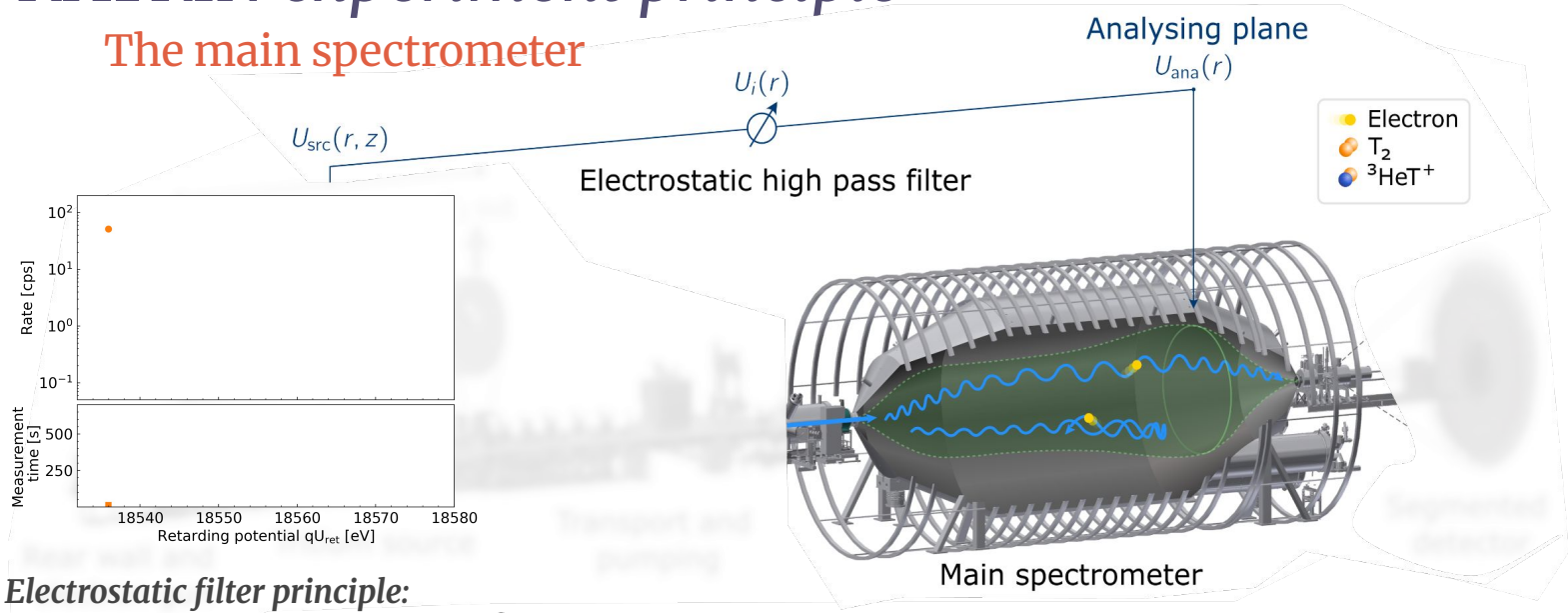
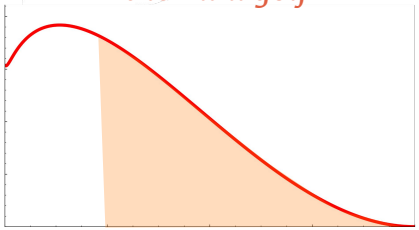
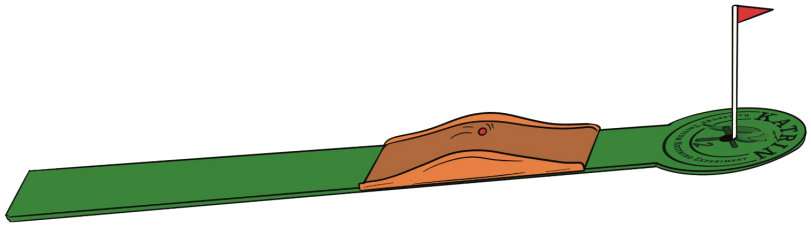


Electrostatic filter principle:

"the mini golf"





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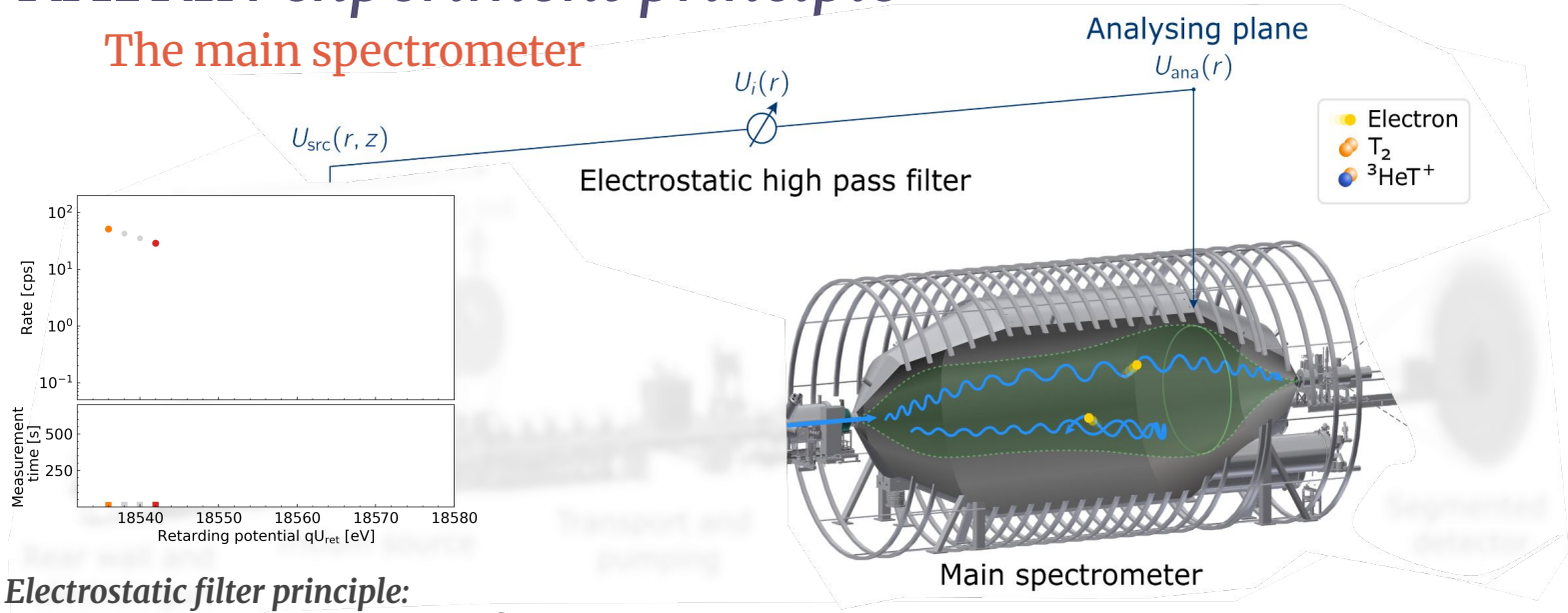

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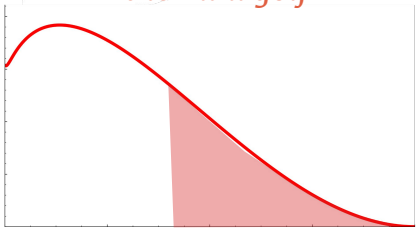

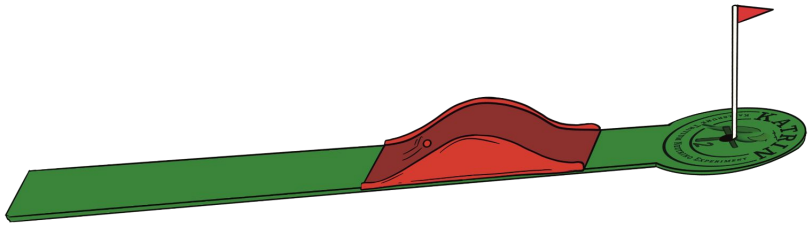

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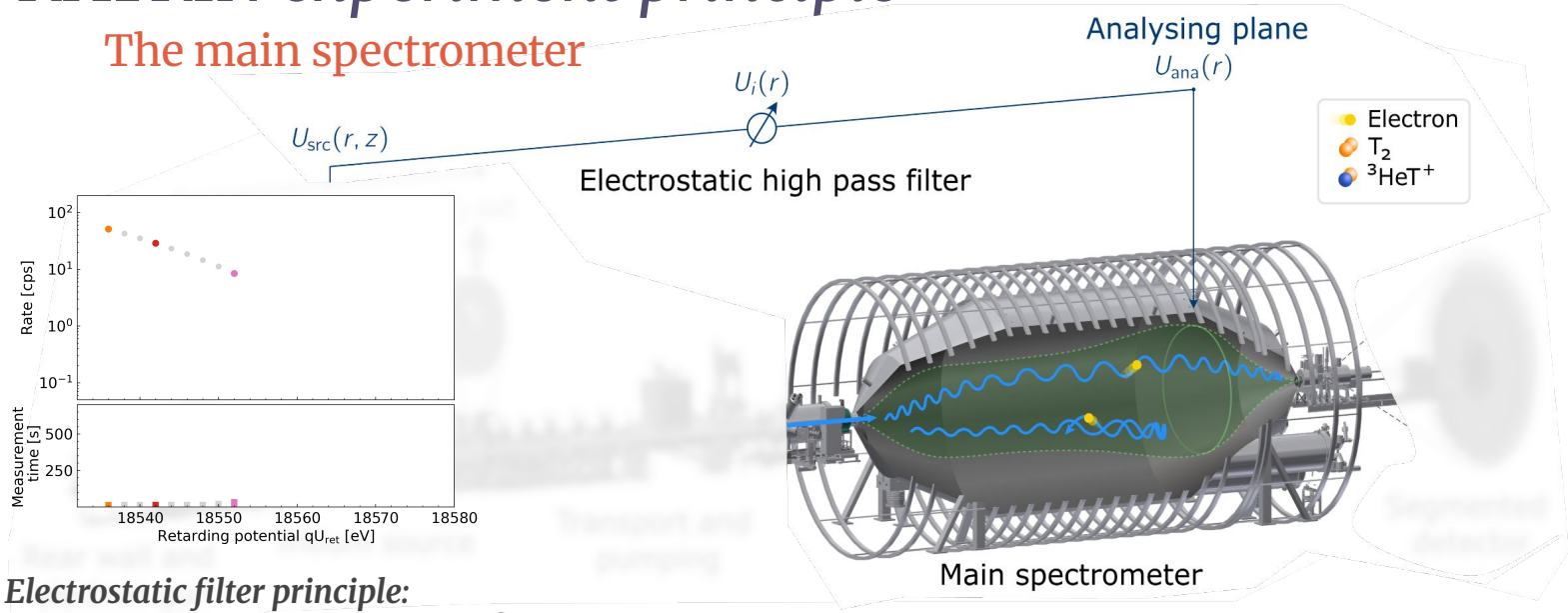

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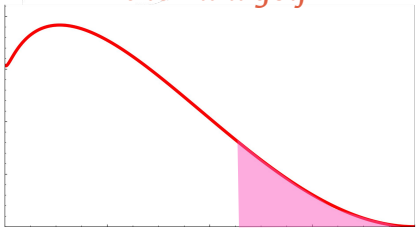

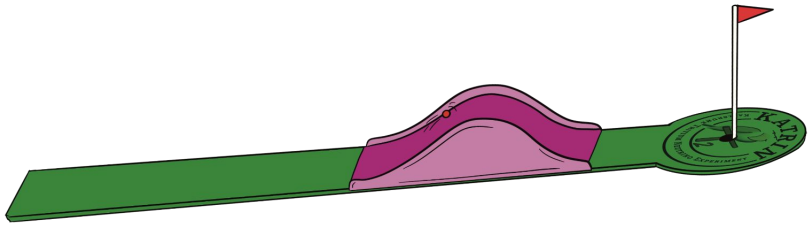

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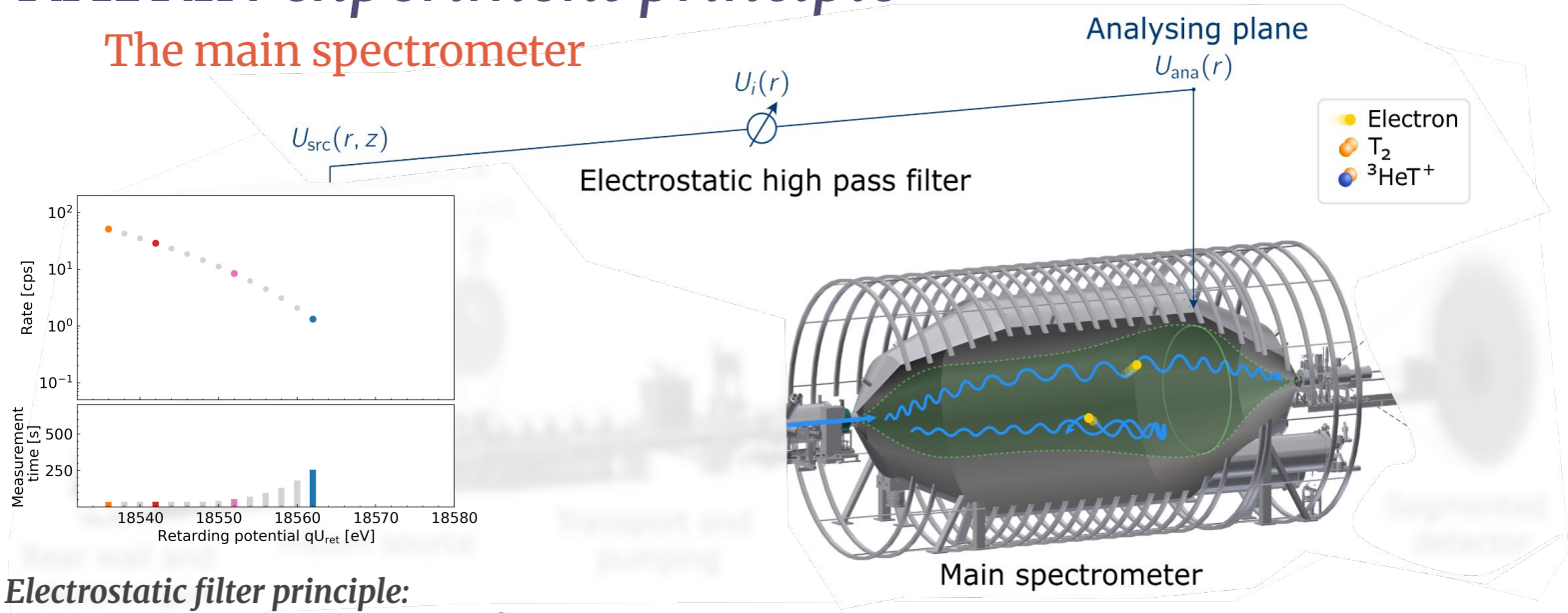

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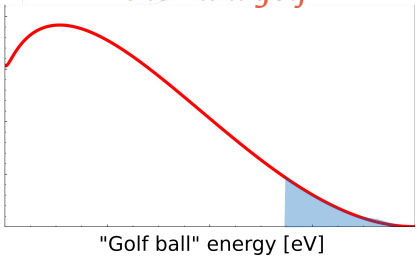

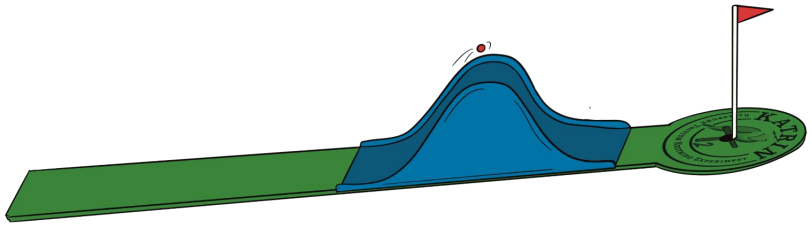

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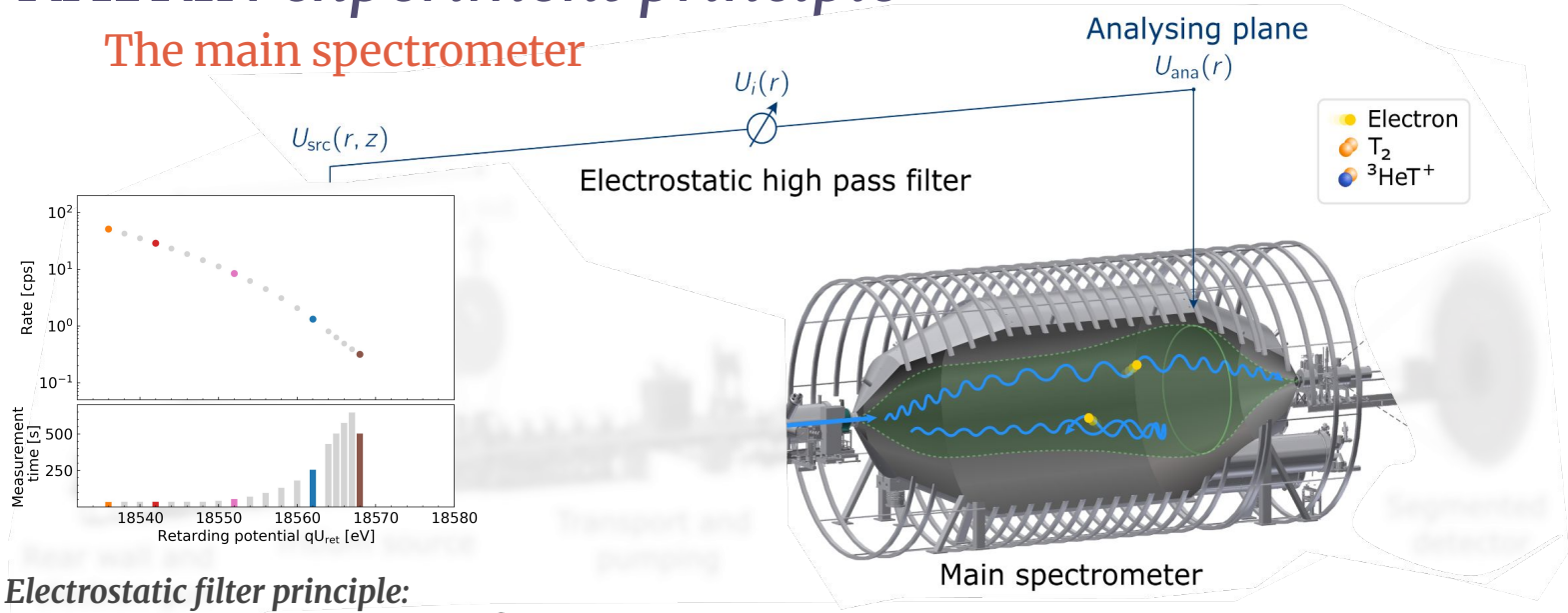

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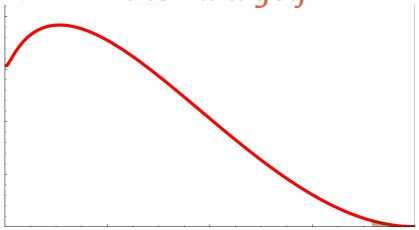

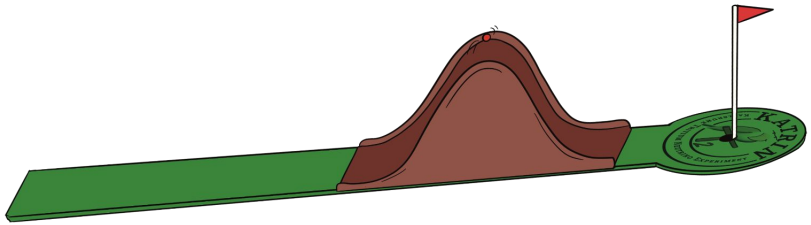

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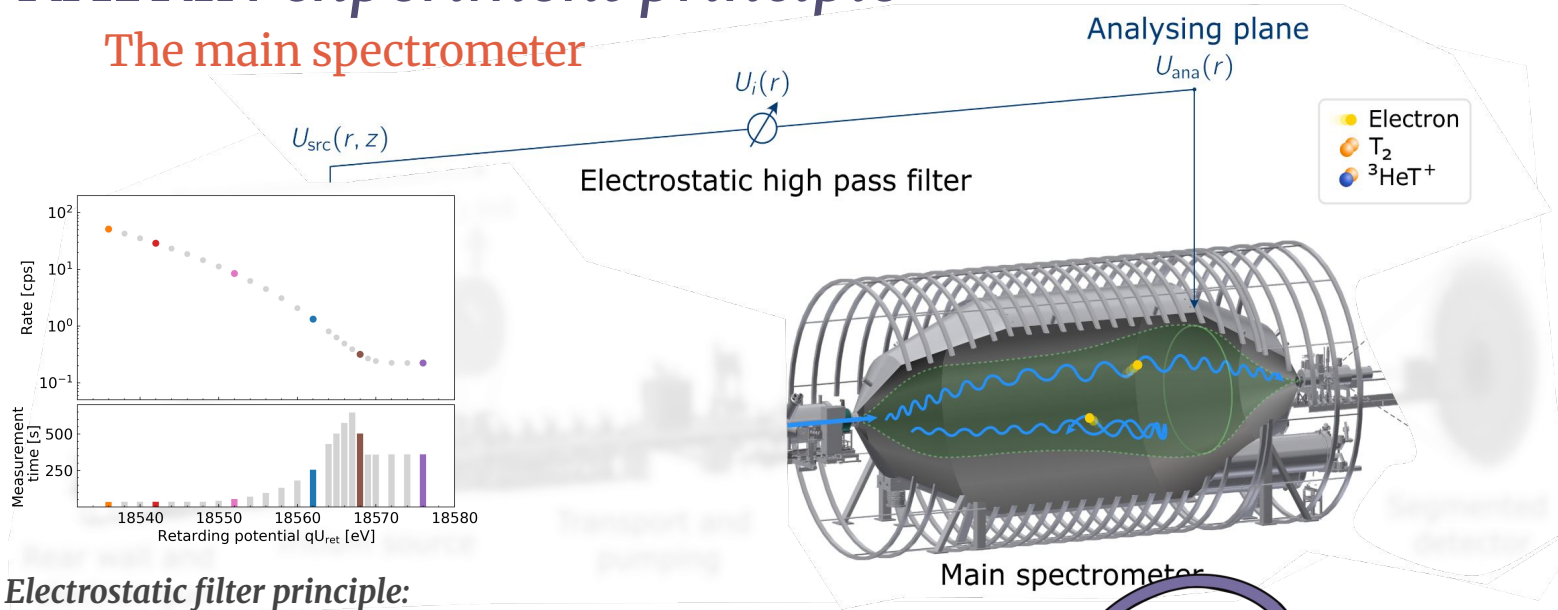

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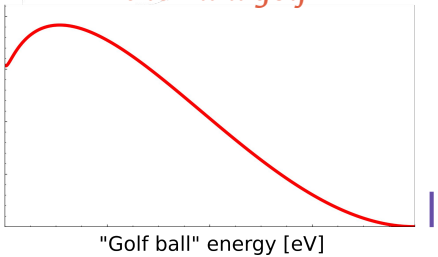

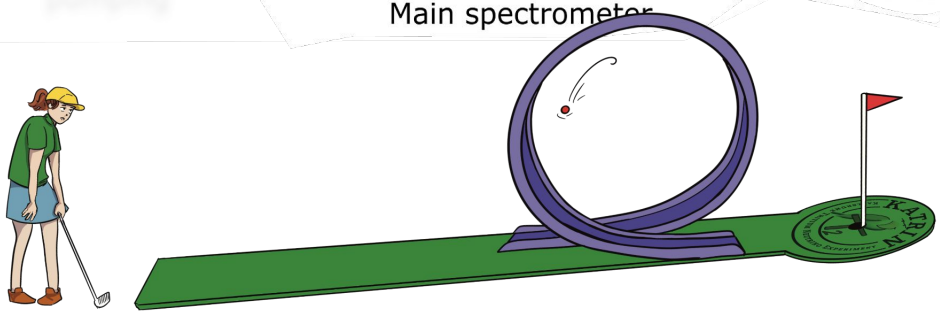

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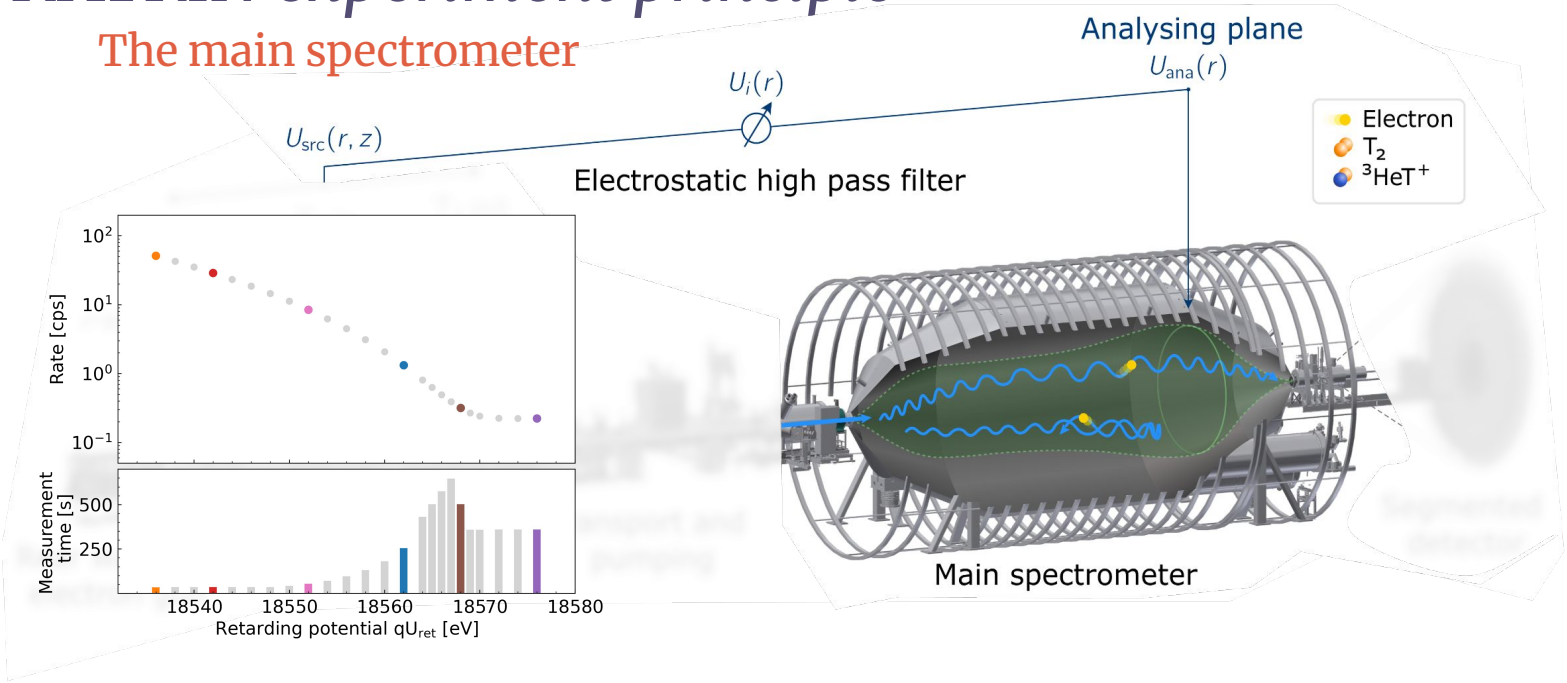


- **MAC-E (M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic filter**)**:
  Only electrons with $E_{||} > qU_{ret}$ reach the detector

→ 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

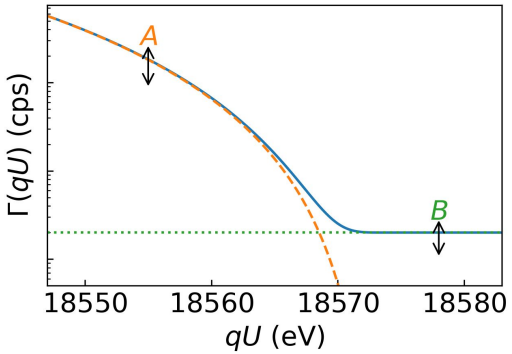
Analysis strategy

Principle

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

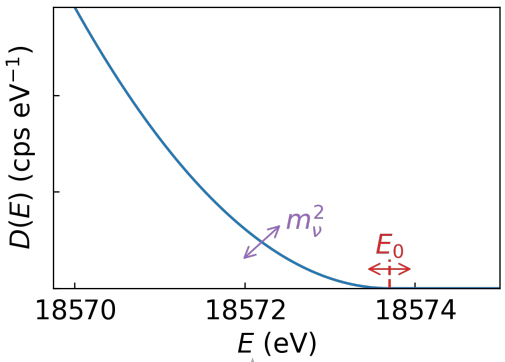
*with two-steps **blinding** procedure*

integral spectrum measured at the detector



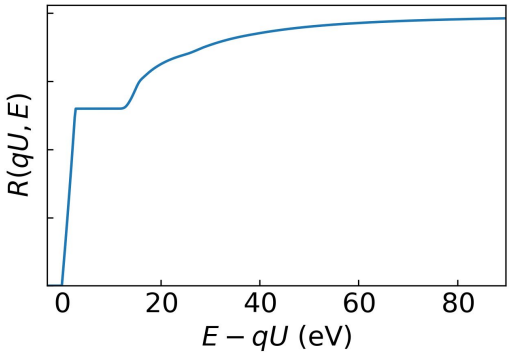
=

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)

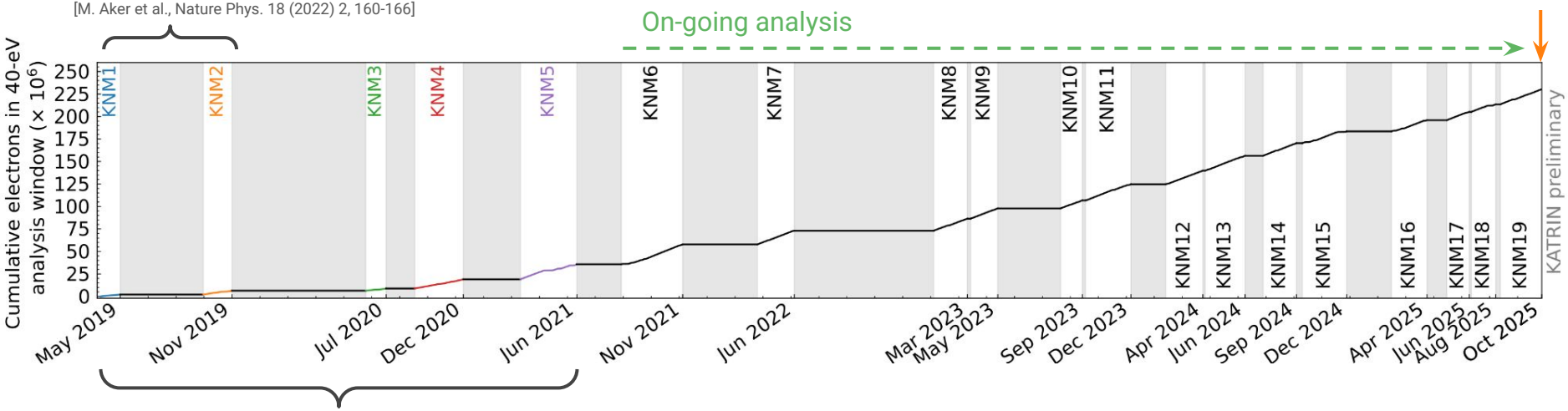
Data taking status

and experimental improvements

$m_\nu < 0.8$ eV (90% CL)

[M. Aker et al., Nature Phys. 18 (2022) 2, 160-166]

1000 days of neutrino mass data!



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

[KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]

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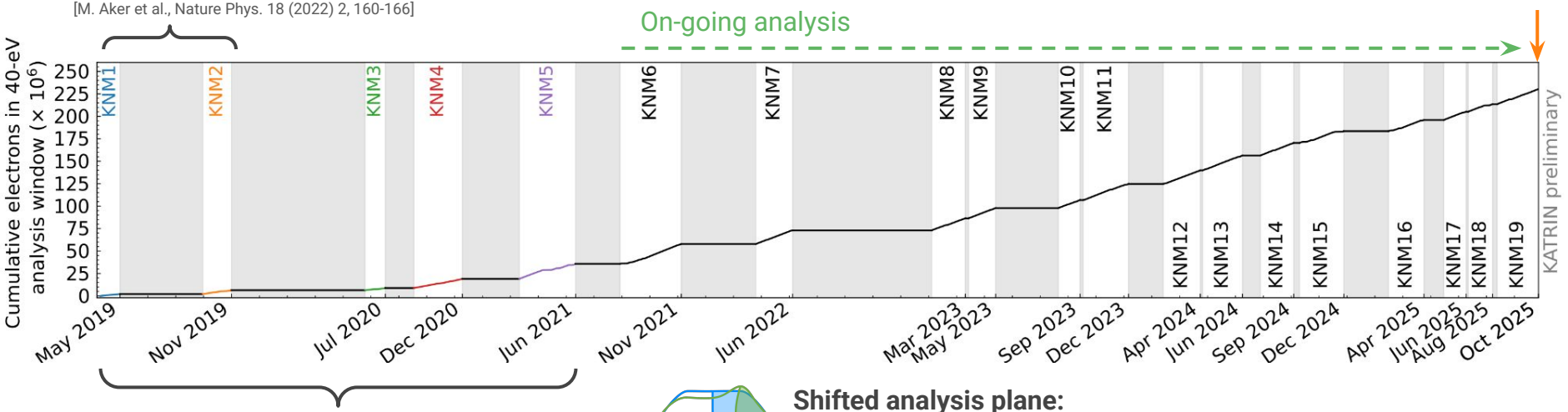
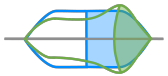


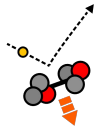
[KATRIN collaboration, *Science* 388,180-185(2025)]
[KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]

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



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

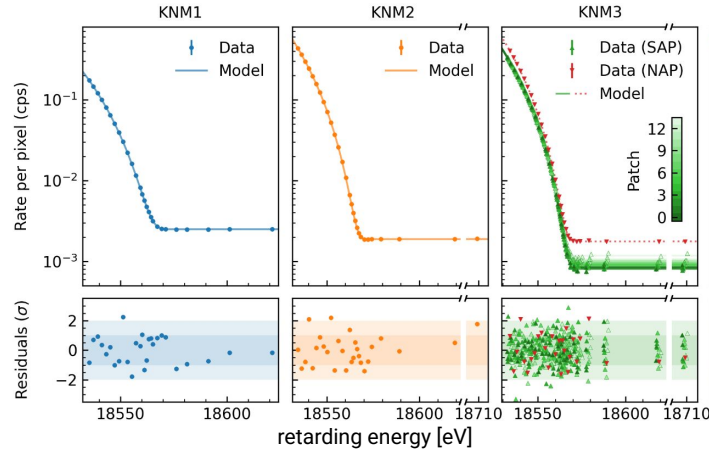
Precise calibration measurements:
→ with ^{83m}Kr circulation *(electric potential, field mapping…)*
[Lokhov et al., EPJ C 82 (2022)]

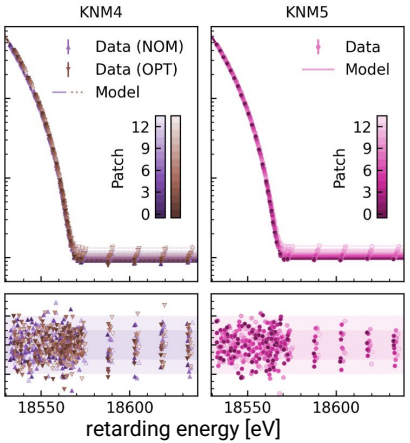


→ with an electron gun *(gas density, energy loss)*
[Aker et al., EPJ C 81 (2021)]

Fit results and systematic uncertainties

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





- **259 first measurement days:**
  - 1609 data points and 355 parameters
- ***KATRIN final*** *expected ~ 6705 data points and ~1400 parameters*

Fit results and systematic uncertainties

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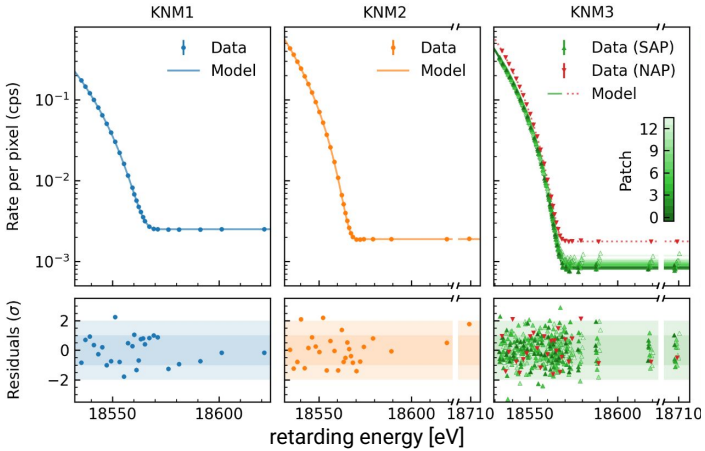
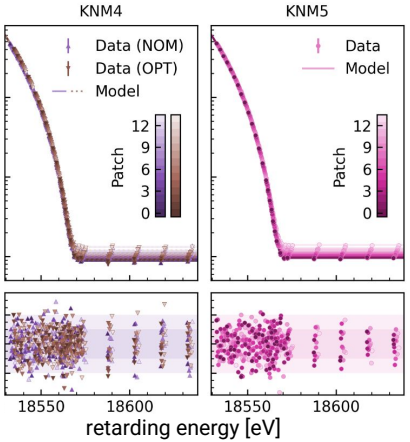
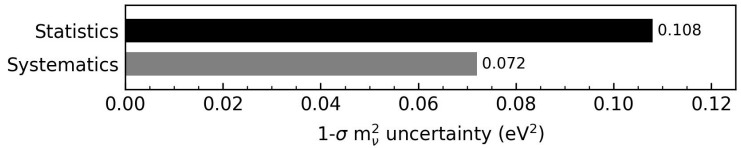


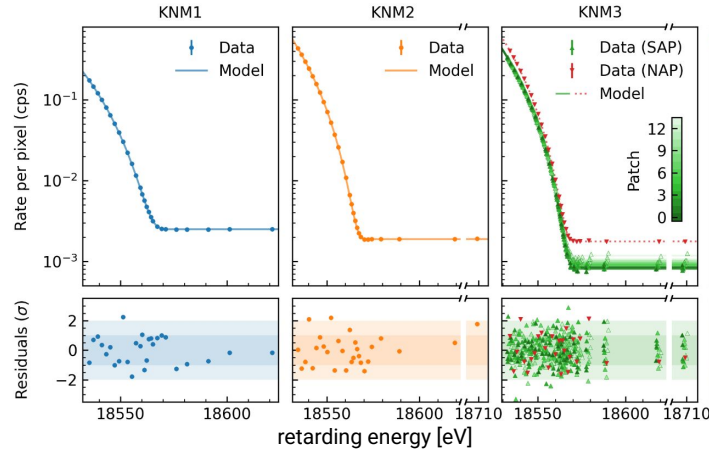


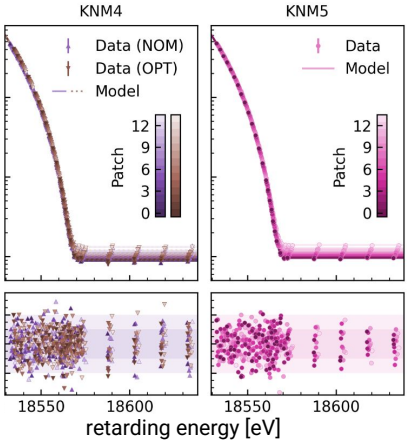


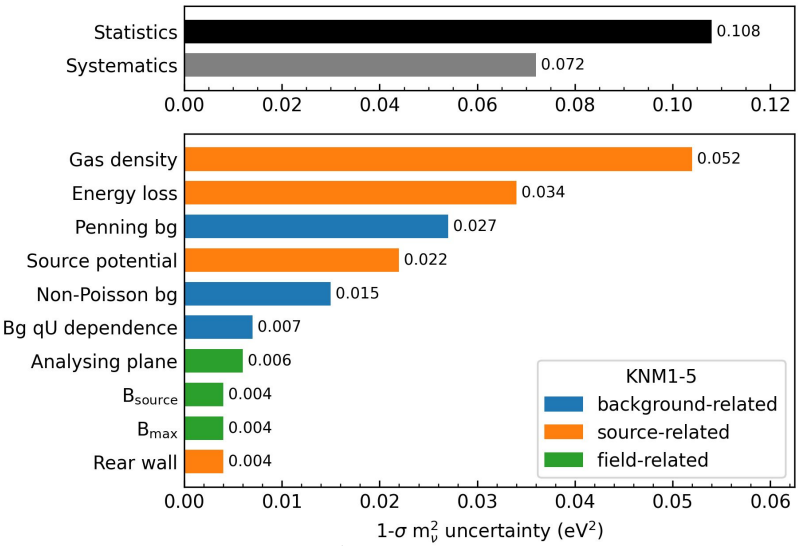
- **Two analysis frameworks:**
  - spectrum calculation (optimized calculation/neural network)
  [*M. Kleesiek, et al., Eur. Phys. J. C 79, 204 (2019)*] [Karl et al., EPJ C 82 (2022)]
  - fitting
- Best fit result (p-value: 0.84): $m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$
- **Statistics dominated**, systematics non-negligible

Fit results and systematic uncertainties

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







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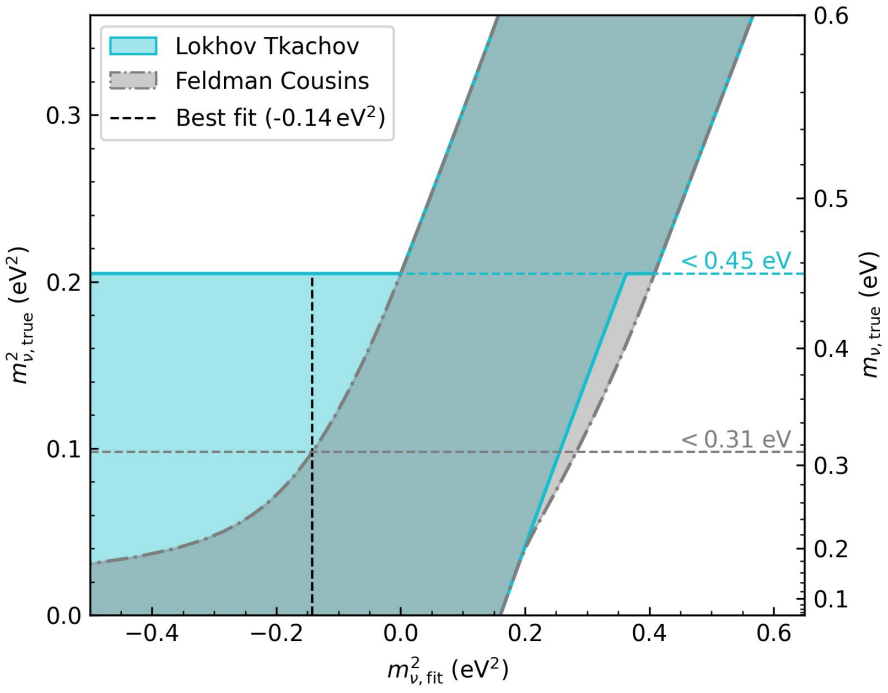
Neutrino mass limit

[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**
  publication in preparation

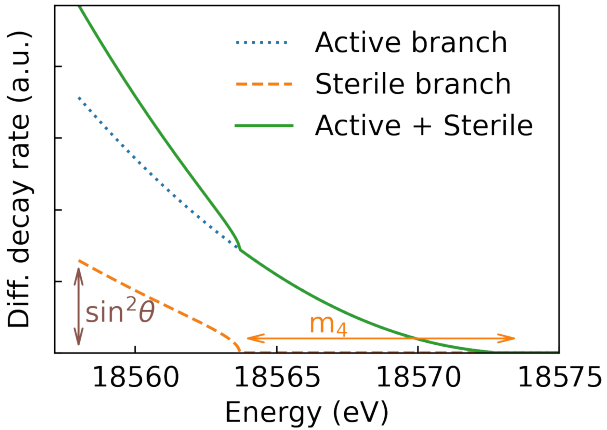


Beyond the neutrino mass

probing light sterile neutrinos

[The KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]

- 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:** 4th neutrino mass
  → **sin(θ):** 4th neutrino mixing



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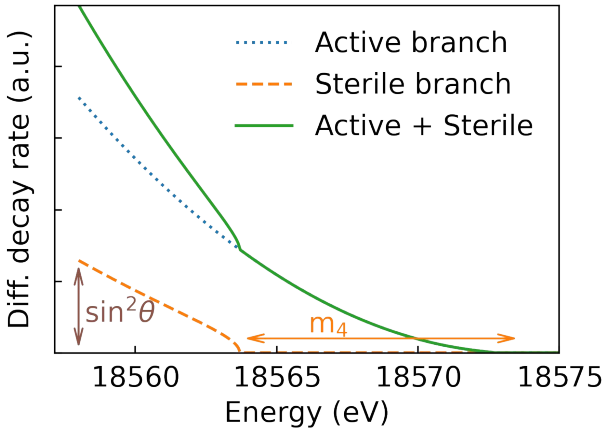
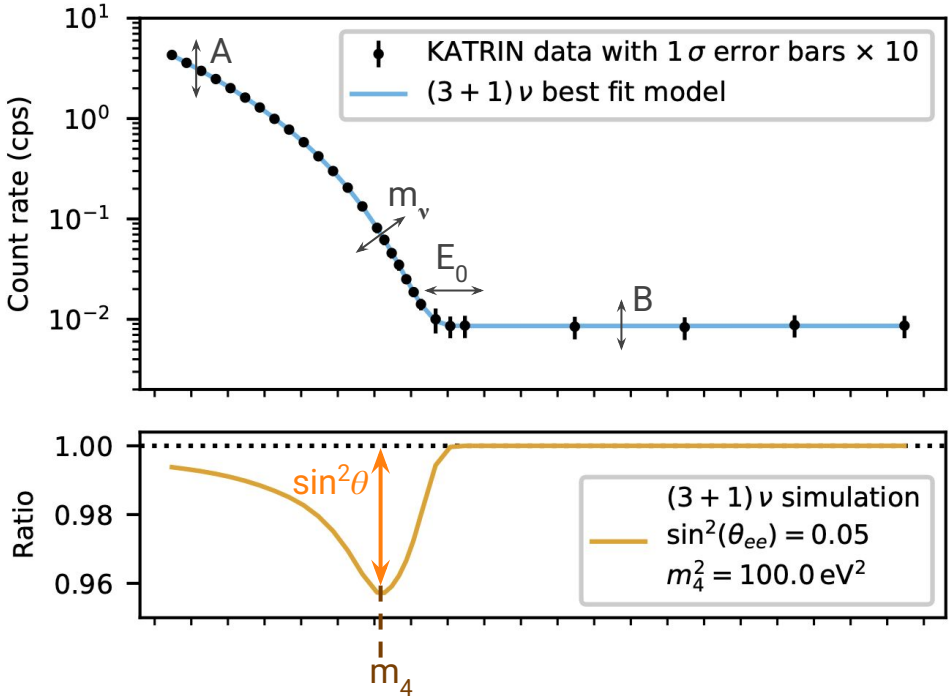




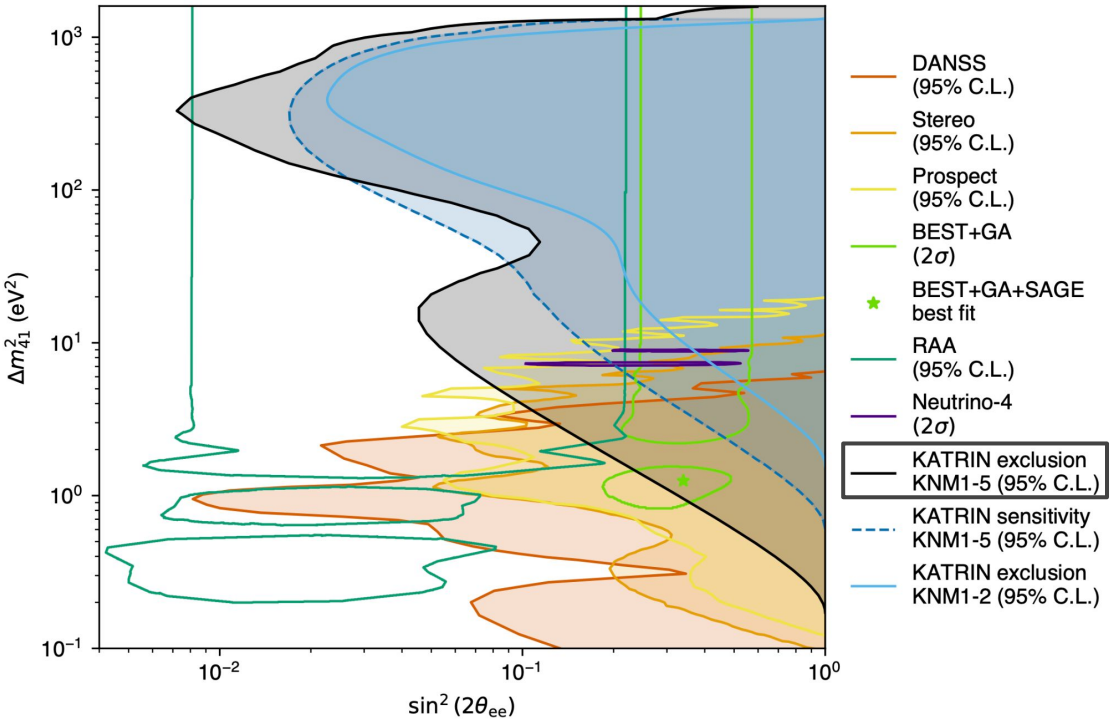
Beyond the neutrino mass

probing light sterile neutrinos

[The KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]

- 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 concluded at the **end of 2025**
  → towards 0.3 eV sensitivity

- **Beyond neutrino mass analysis**
  → new eV sterile neutrino rejection limits
  [The KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]

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

Conclusions and outlook

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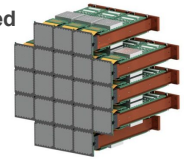
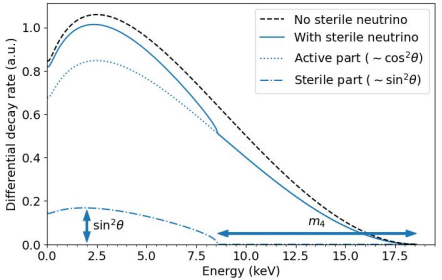
  *[M. Aker et al., Phys. Rev. D **107**, 082005 (2023)]*

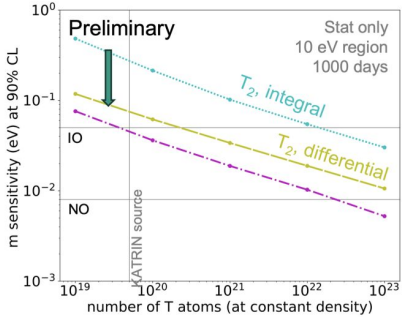
Outlook beyond KATRIN

- 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]
  Sensitivity publication to be released in a few days





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



Recent results from the KATRIN experiment

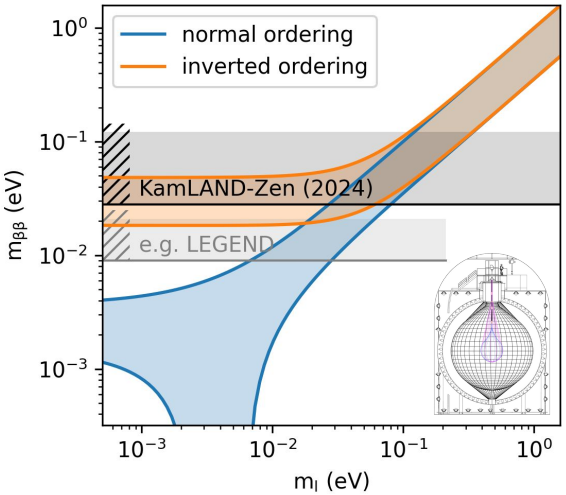
Sub-eV neutrino mass detection and eV-sterile neutrinos

Thank you for your attention !

Neutrino mass observables

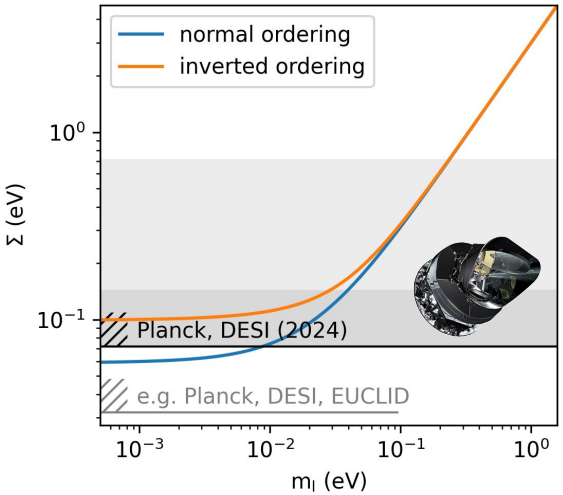
Neutrinoless ββ-decay

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



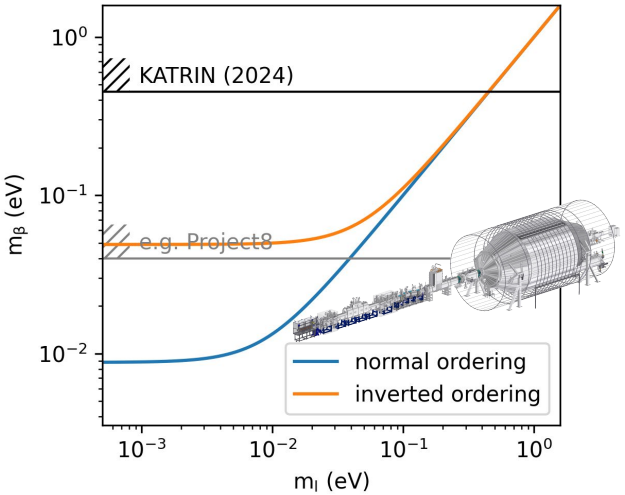
Cosmology

$$\Sigma = \sum_i m_i$$



β-decay kinematics

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



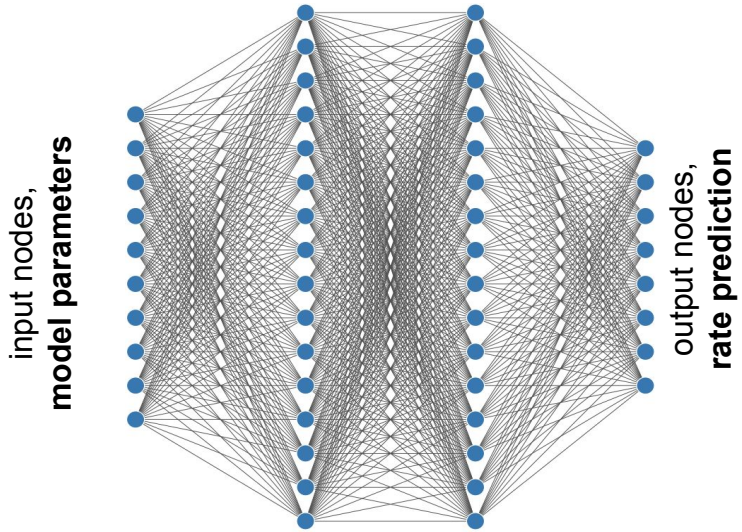
Courtesy C. Wiesinger/ A. Schwemmer

[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

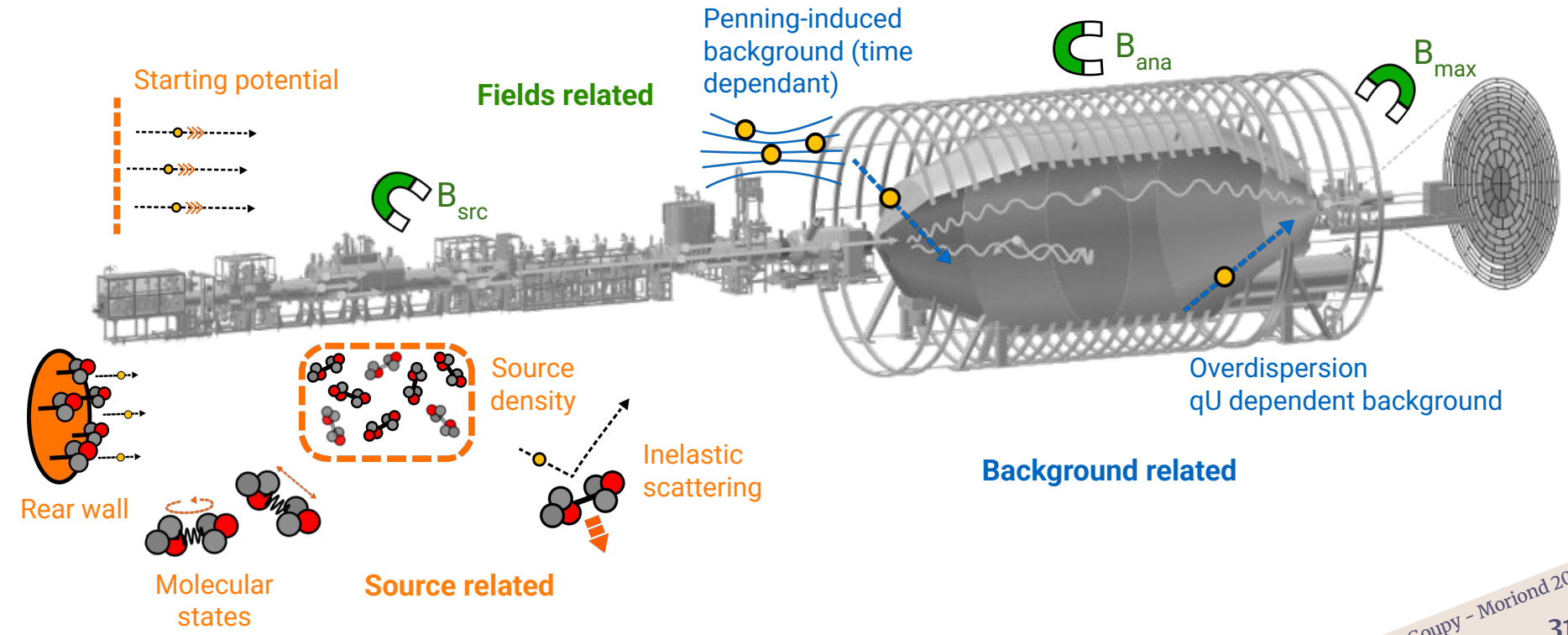
- Two independent analysis teams and frameworks
  - optimized model evaluation
  - fast model prediction with a neural network



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

Spectrum modeling and input parameters

KATRIN systematics overview



Experimental improvements: summary

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

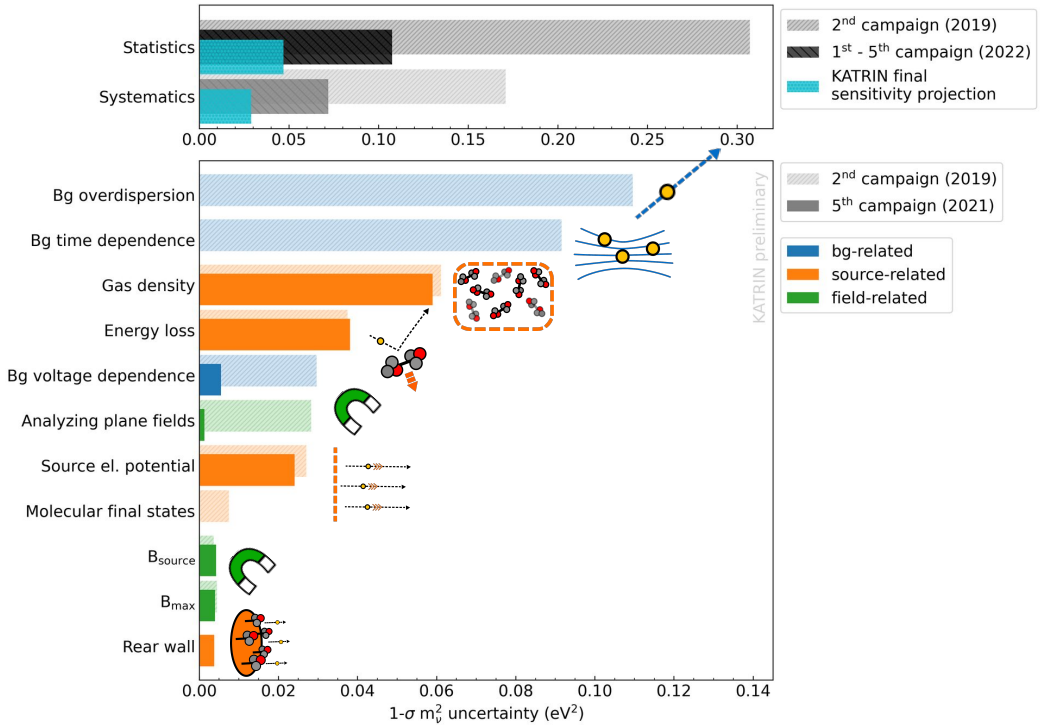
Lokhov et al., Eur. Phys. J. C 82, 258 (2022)

- 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

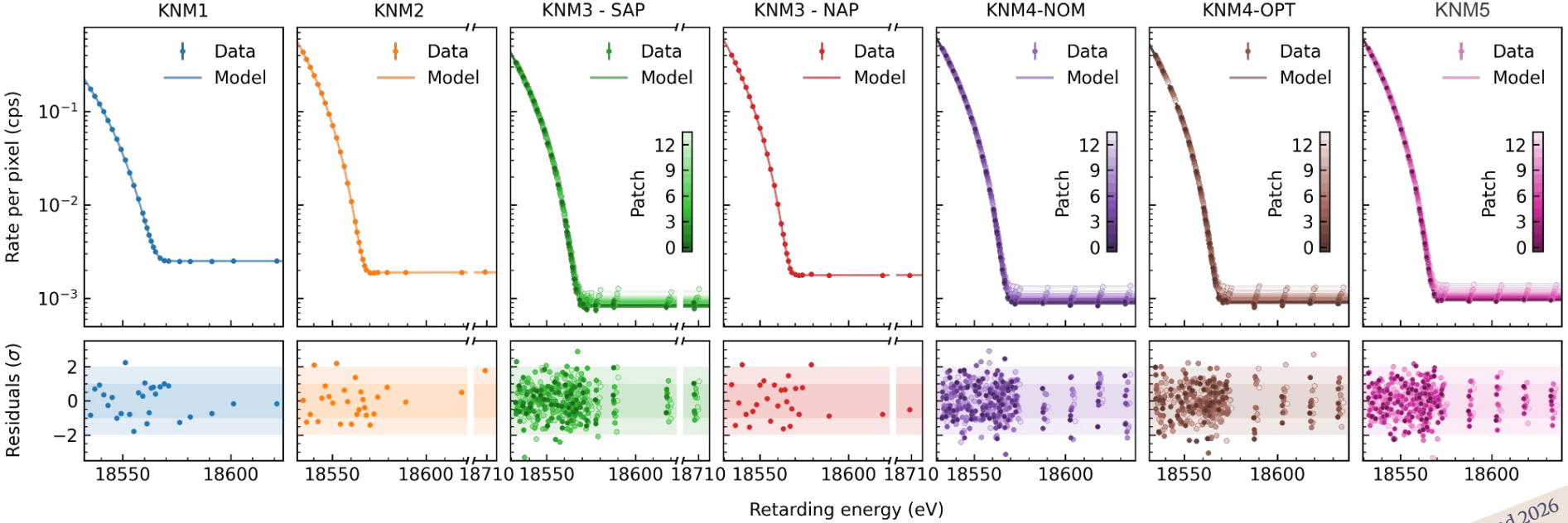


Analysis challenges

59 stacked spectra with

27 + 28 + 14 x 28 + 28 + 14 x 28 + 14 x 25 + 14 x 28

= 1609 data points



and 144 correlated systematic parameters

Analysis challenges and methods

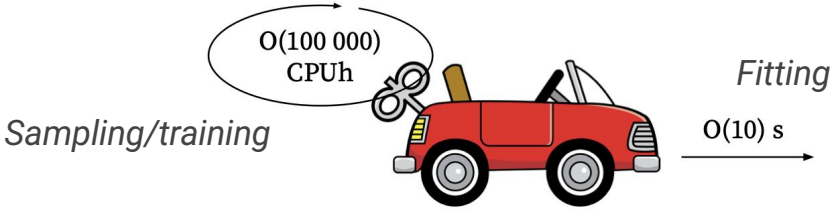
Neural network surrogate

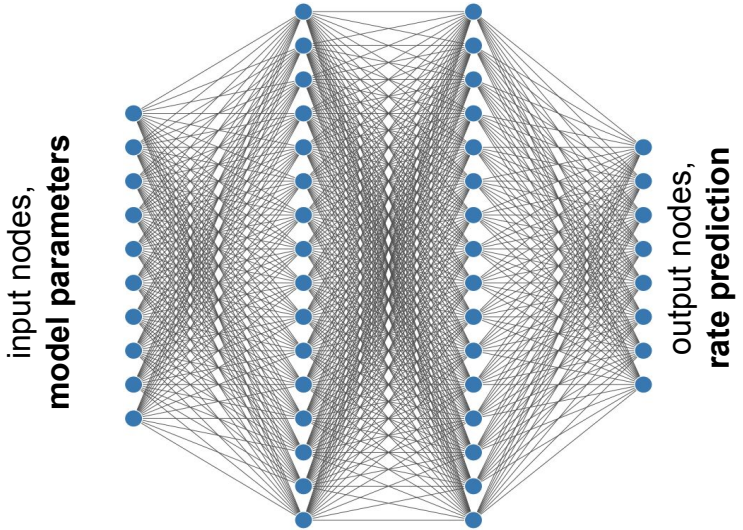
- **Maximum likelihood fit of analytical model**

$$\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$$

→ High granularity, numerous parameters:
computationally expensive model evaluations

- Two independent analysis teams and frameworks
  - optimized model evaluation
  - fast model prediction with a neural network
    [Karl et al., EPJ C 82 (2022)]





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

Analysis challenges and methods

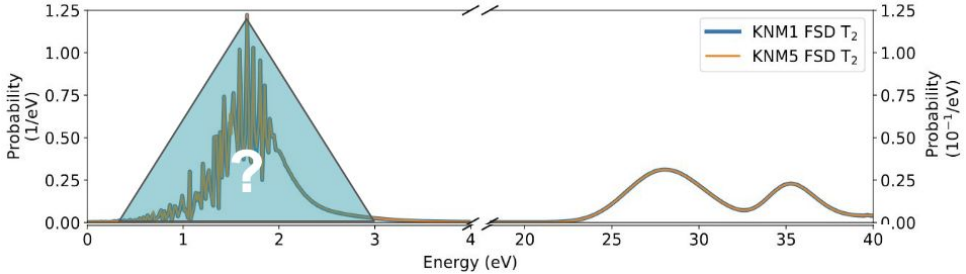
2-steps blinding procedure

1- Analysis of simulations (Asimov twins)

→ data-like twins
→ only study effects included in simulations
→ can point input mistakes/training mistakes
i.e. hide the data

2- Analysis of data with blind-model

→ Unknowingly modified final state distribution ⇒ unknown bias of the neutrino mass result
I.e. hide the result

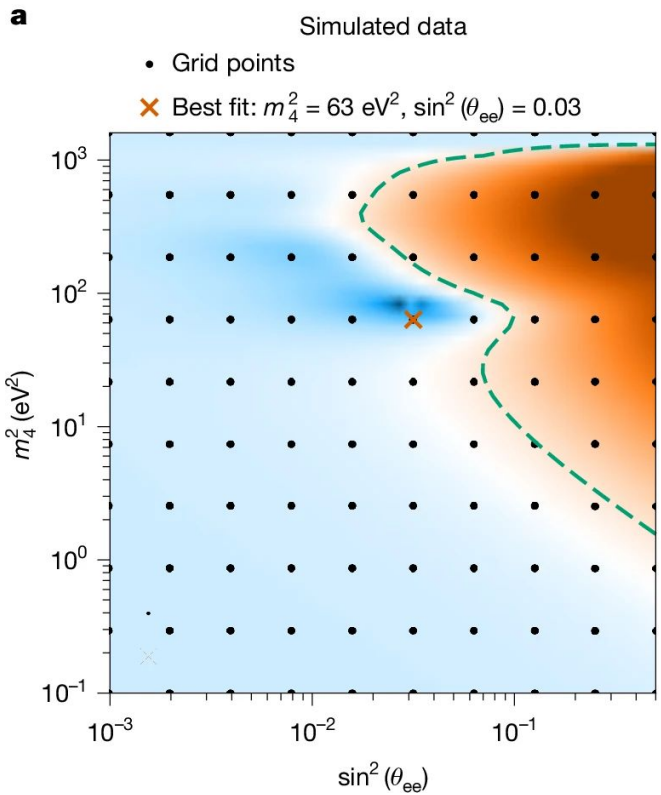


3- Analysis of the data with final model and final inputs

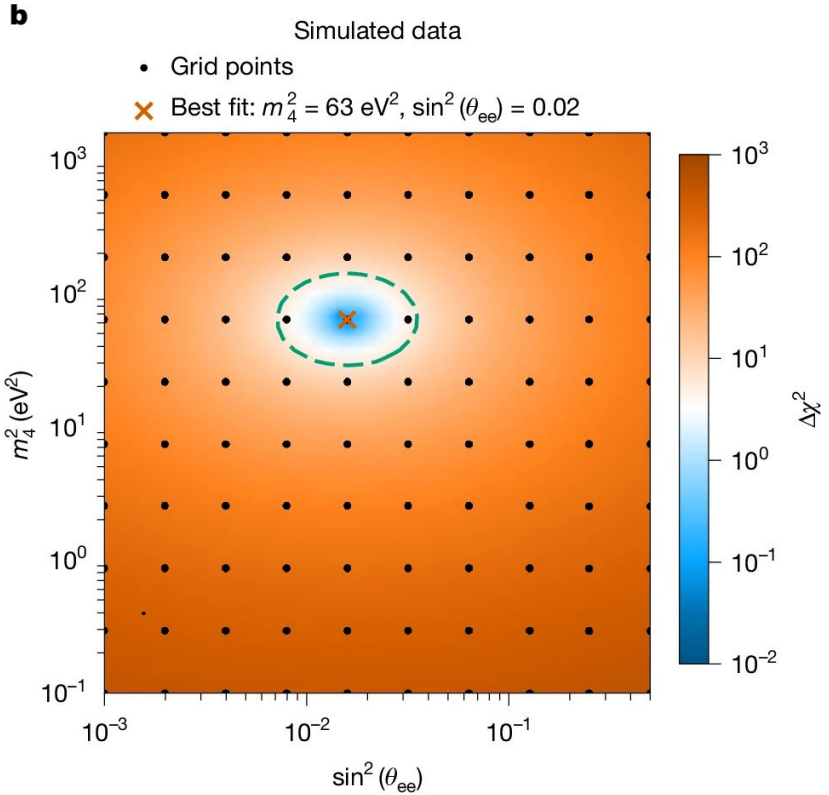
Light sterile neutrinos

Grid scan

[The KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]



Simulation of no sterile signature



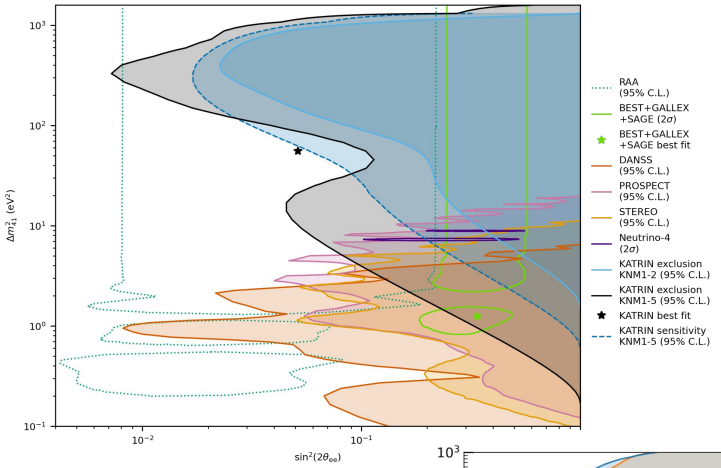
Simulation of a sterile signature

Light sterile neutrinos

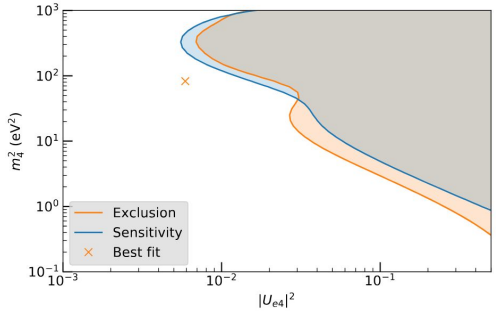
Contour shape

[The KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]

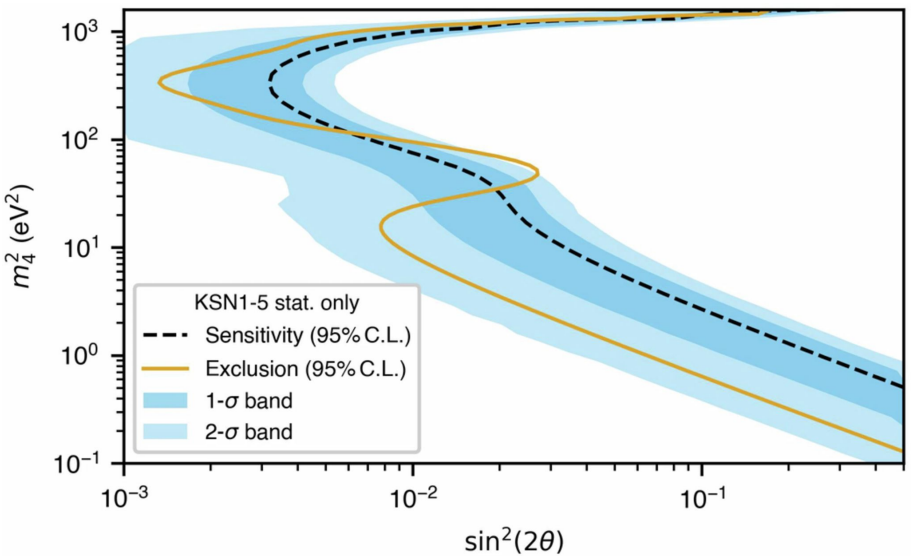
Best fit position



KNM5 only →



Result agrees with statistical fluctuations



Light sterile neutrinos

Systematic uncertainty impact

[The KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]