Recent results from the KATRIN experiment

Sub-eV neutrino mass detection and light sterile neutrinos

IJCLab seminar – Sept. 15th, 2025

Chloé Goupy,
on behalf of the KATRIN collaboration

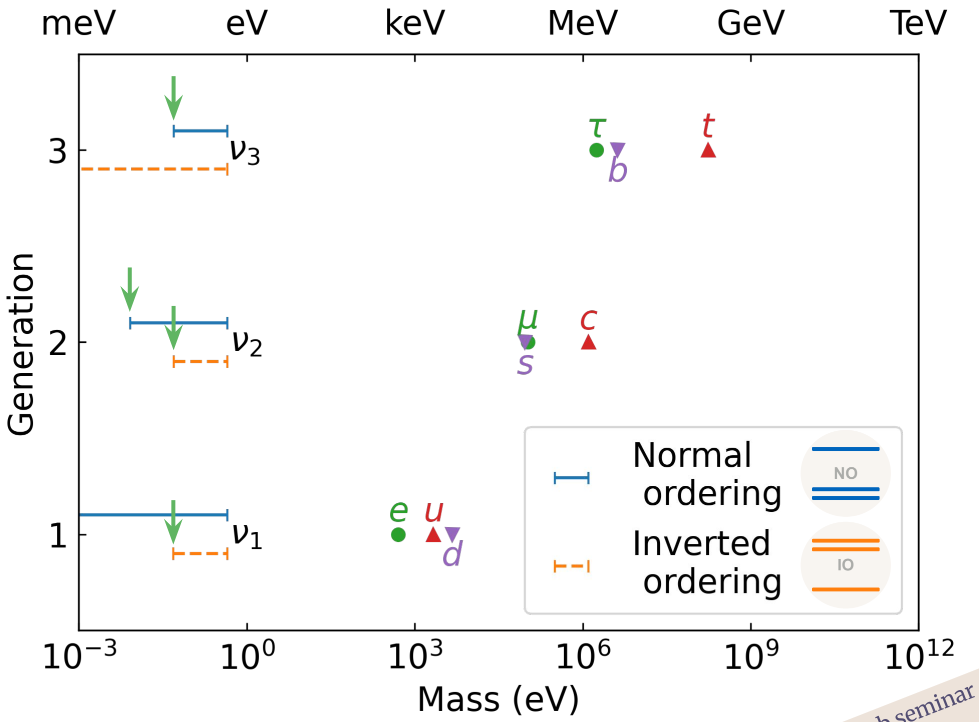
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

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 0νββ-decay (relies on Majorana nature)
  - via **β-decay** (*"direct" measurement*, this talk)

with data from PDG - Phys. Rev. D 110, 030001 (2024)
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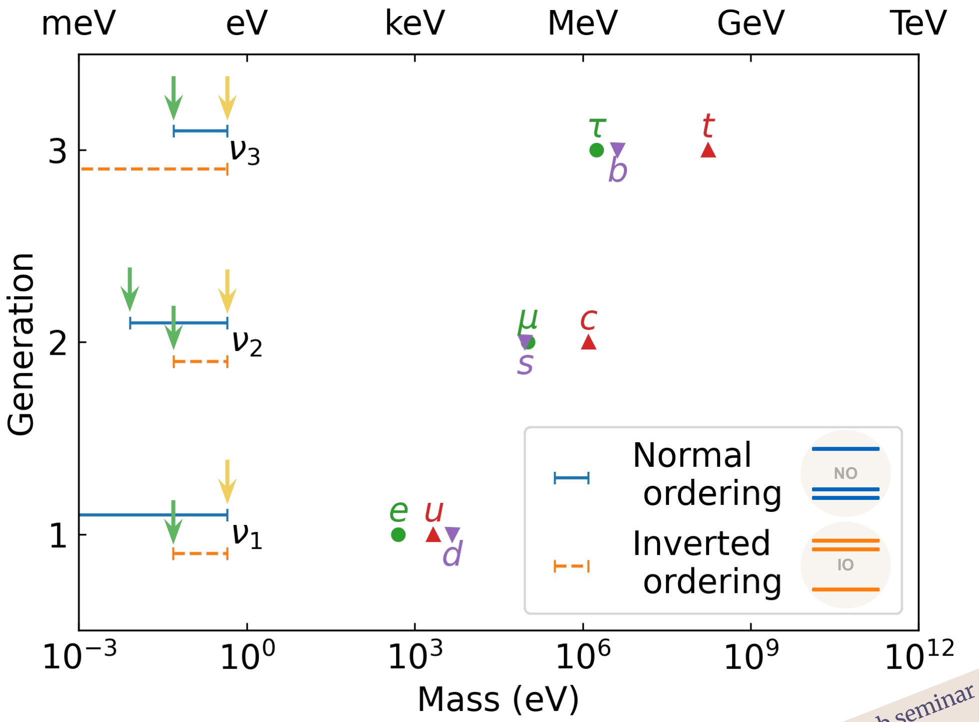


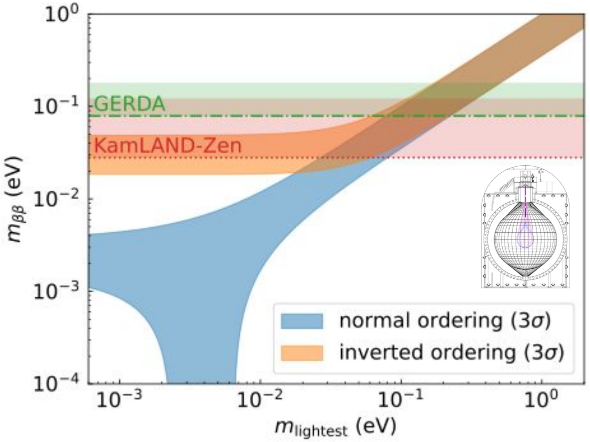
Neutrino mass observables

And complementarities

[NuFIT 5.3, nu-fit.org]
Courtesy of A. Schwemmer

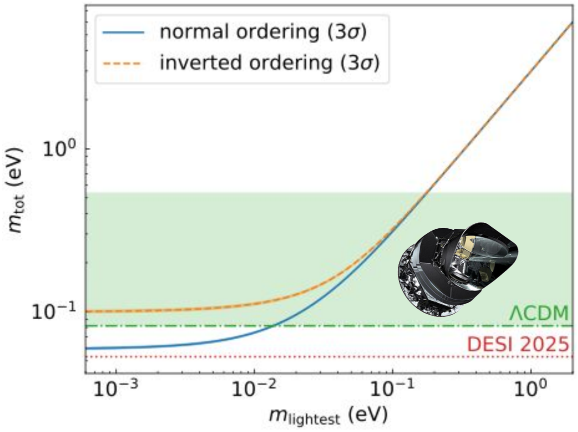
Neutrinoless ββ-decay

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



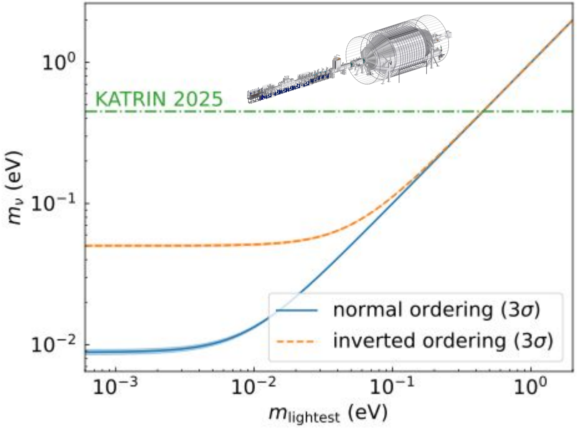
Cosmology

$$m_{\text{tot}} = \sum_i m_i$$



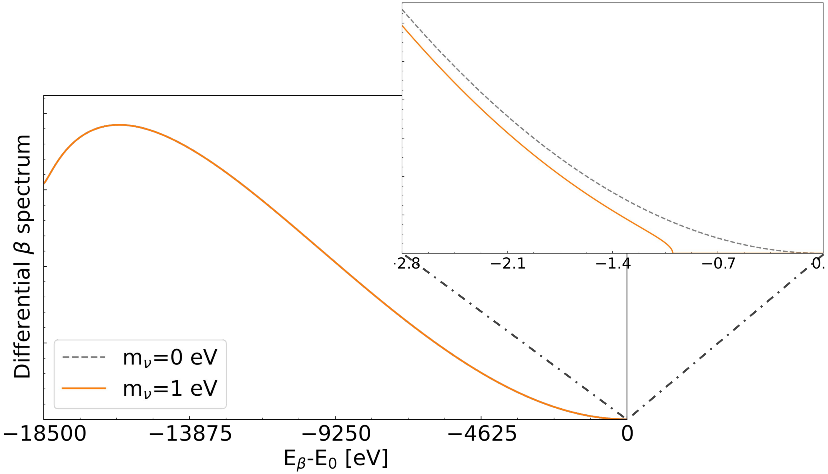
β-decay kinematics

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



Direct measurement of the neutrino mass

From β-decay kinematics



- β-decay with end point E_0: $n \rightarrow p^+ + e^- + \bar{\nu_e}$
- **Spectral distortion** near end point
  → **low background** (< 1 cps)
  → high **energy resolution** (~1eV)

Direct measurement of the neutrino mass

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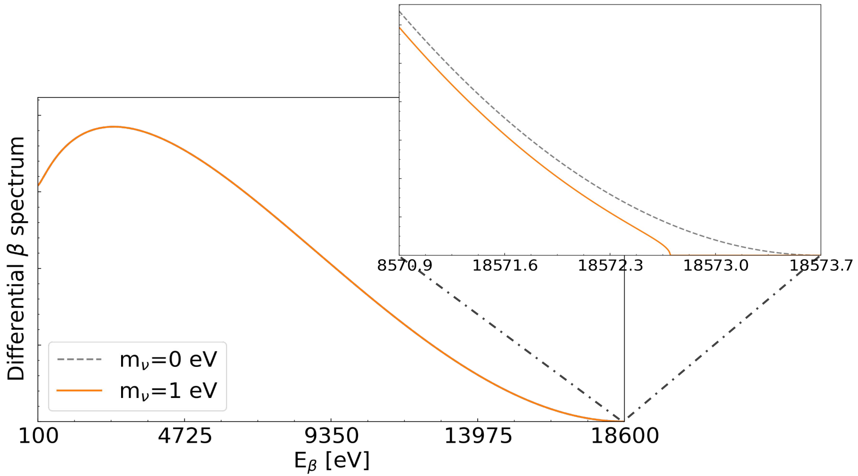
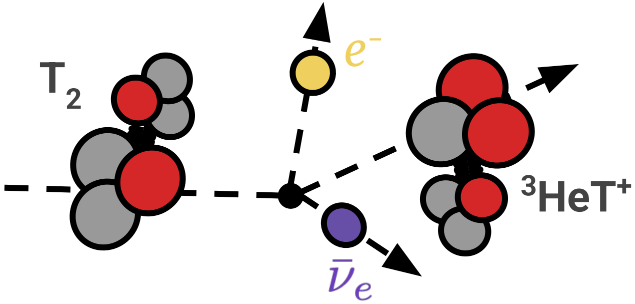




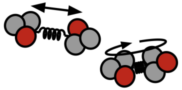
T_2 (molecular tritium) :

→ low end point E_0= 18.6 keV

→ half life τ = 12.3 years

But

→ molecular binding energies



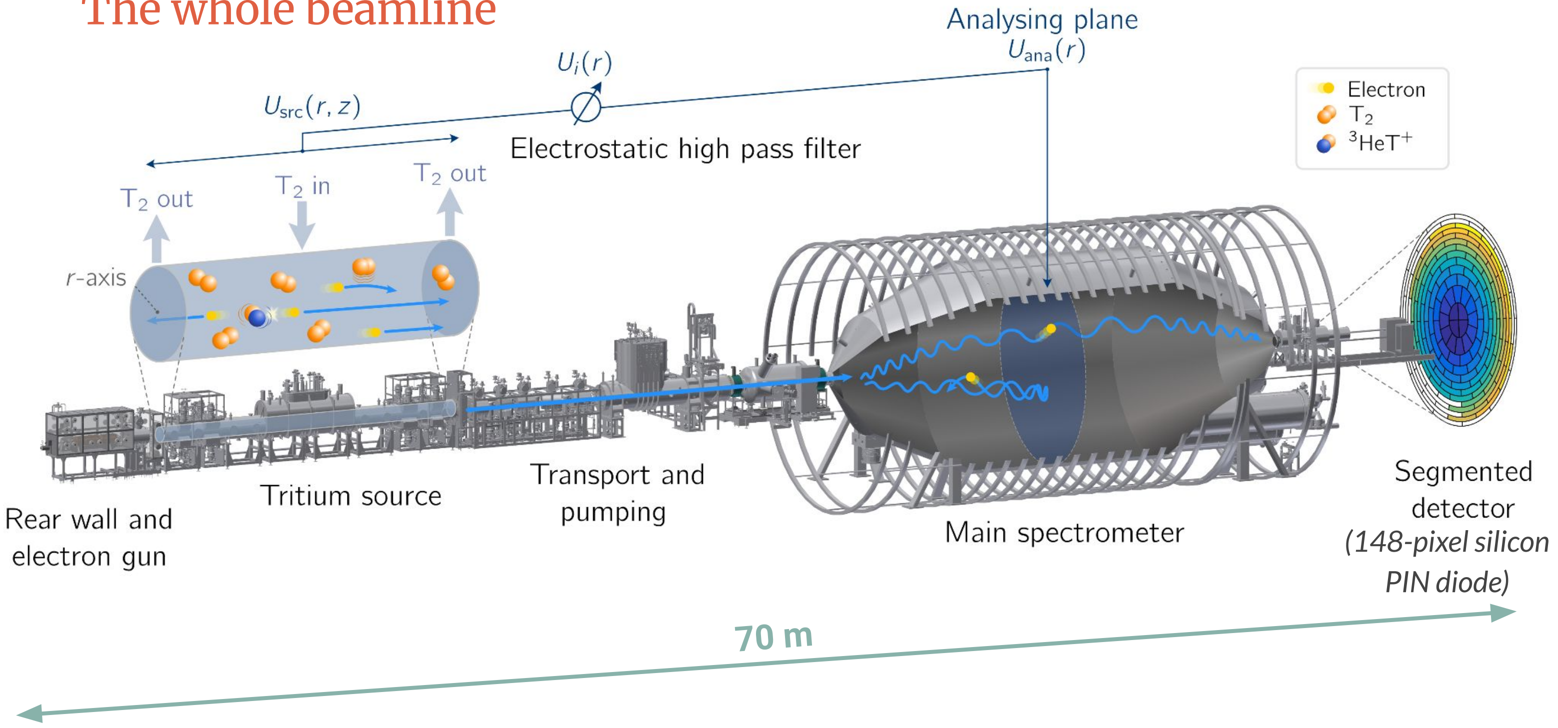
- (molecular) Tritium β-decay: $T_2 \rightarrow ^3HeT^+ + e^- + \bar{\nu}_e$
- **Spectral distortion** near end point
  → **low background** (< 1 cps)
  → high **energy resolution** (~1eV)

The Karlsruhe Tritium Neutrino (KATRIN) experiment

Arrival of the main spectrometer in Karlsruhe
November 2006

KATRIN experiment principle

The whole beamline

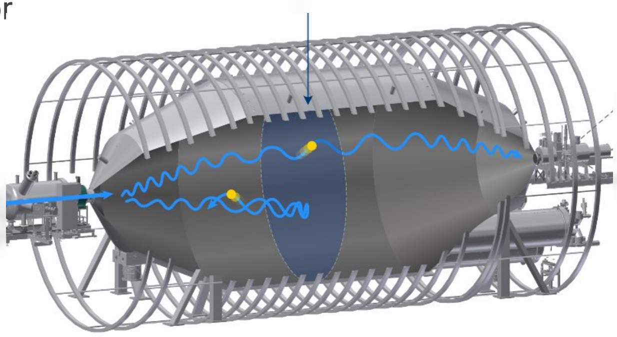


KATRIN collaboration, JINST 16 (2021) T08015

KATRIN experiment principle

The main spectrometer

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



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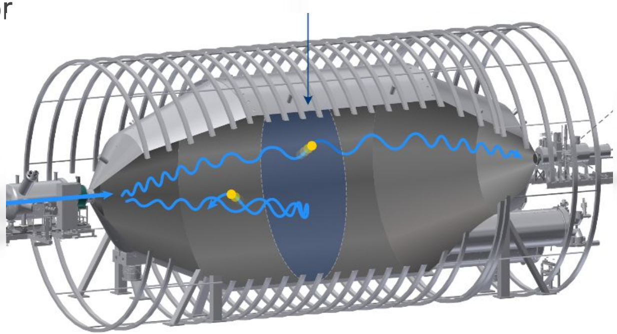
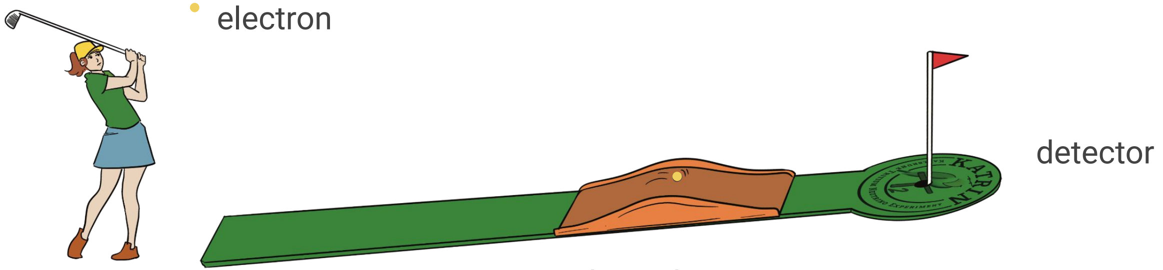


Electrostatic filter principle:
"the mini golf"



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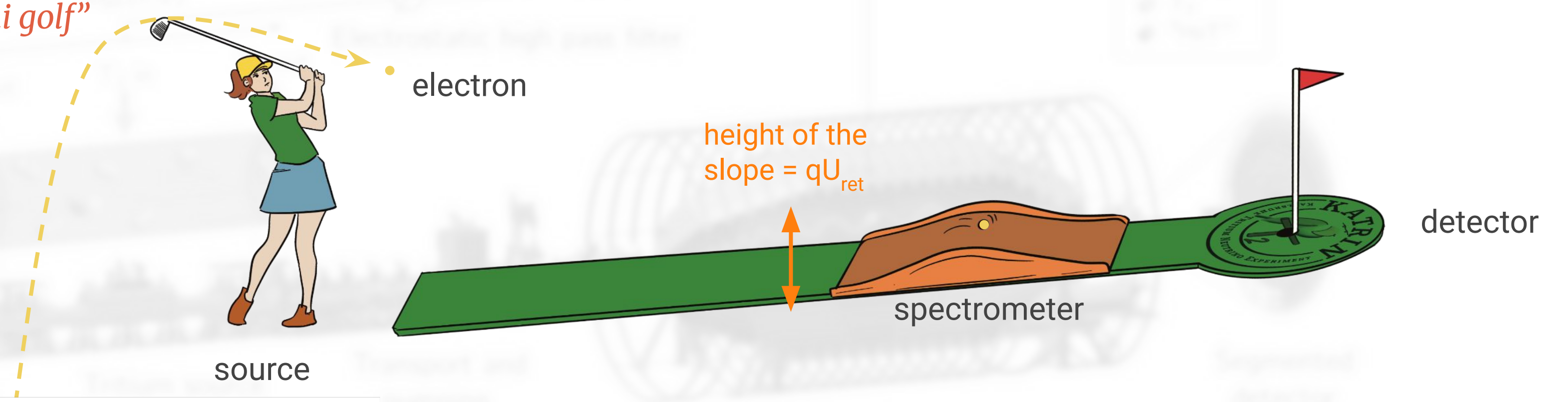

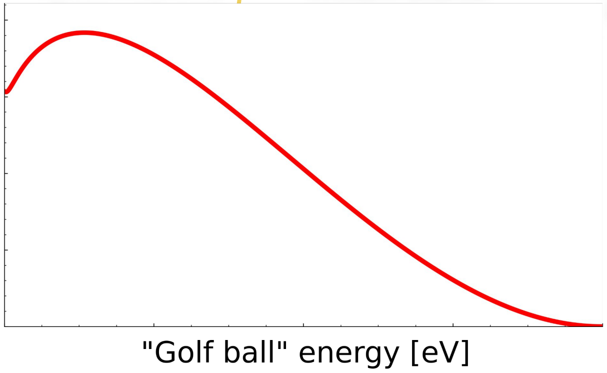

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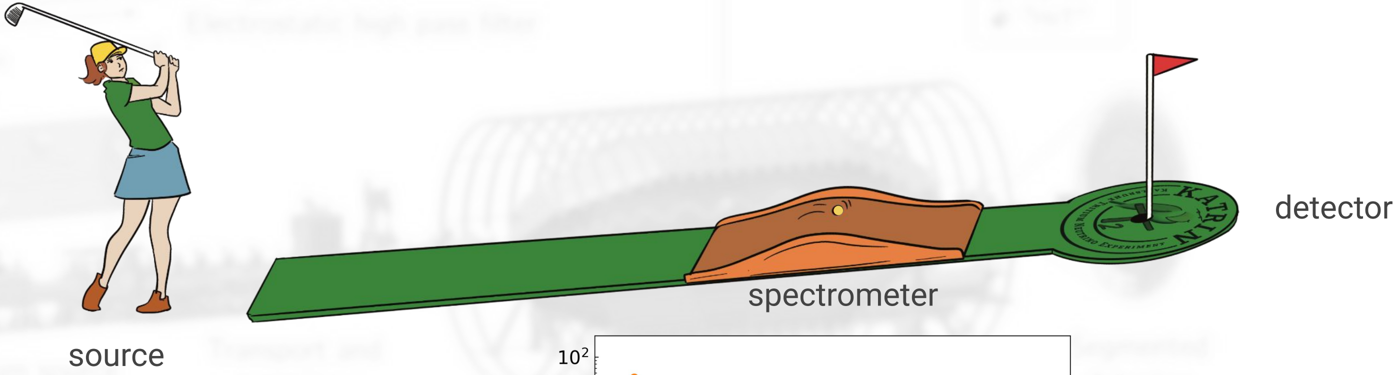

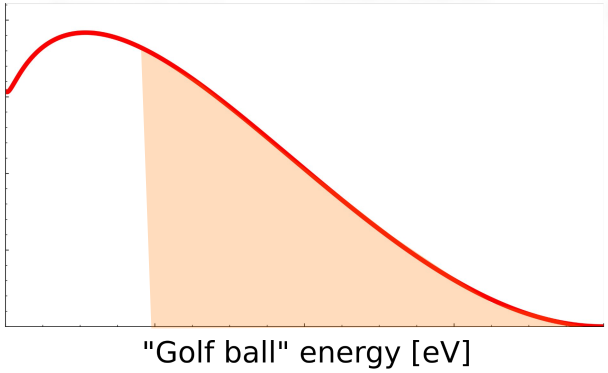

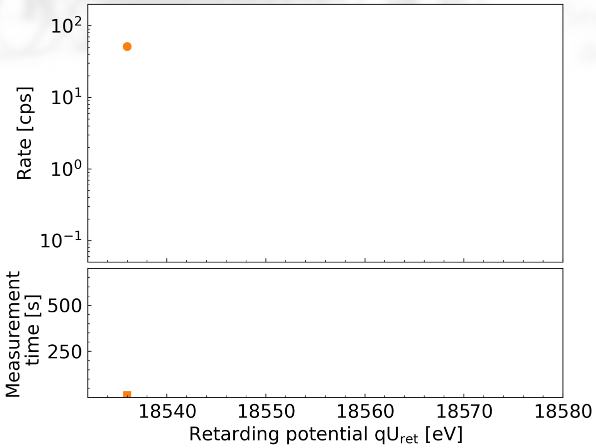

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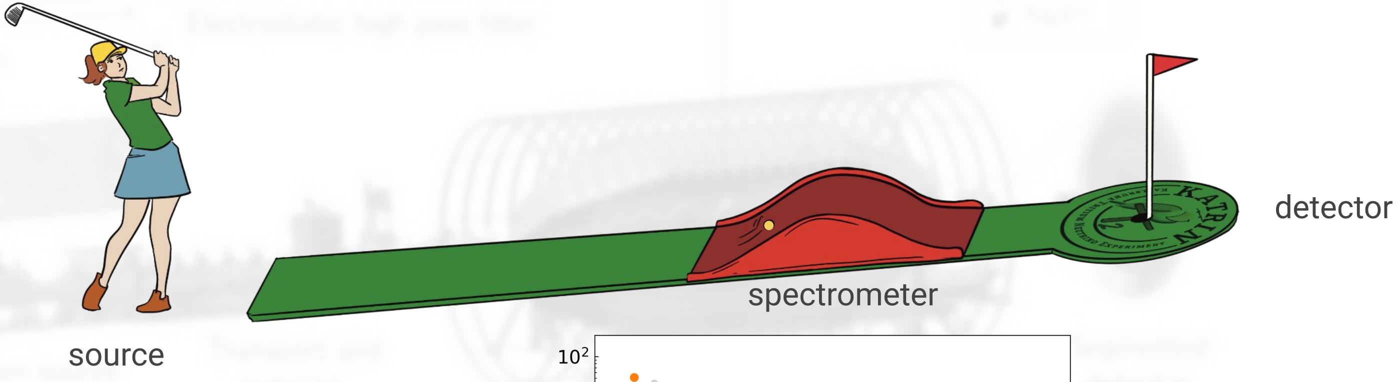

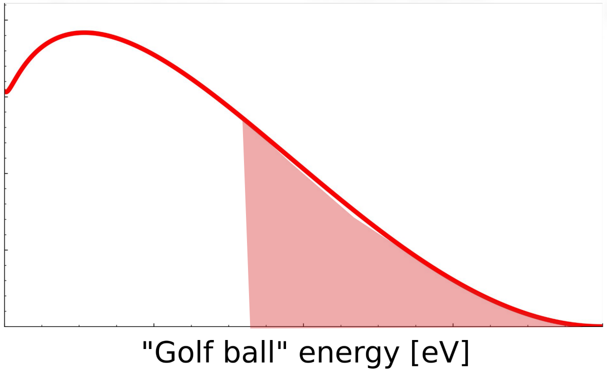

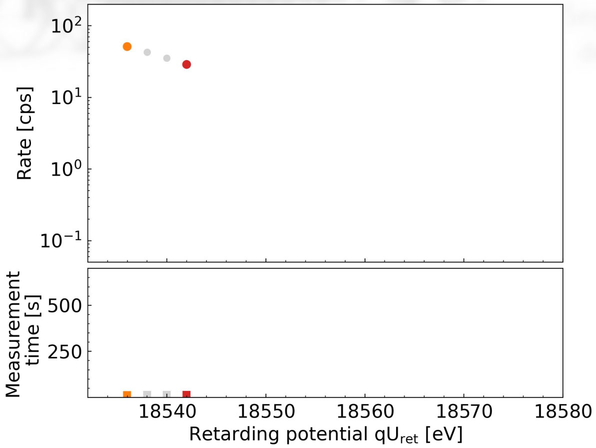

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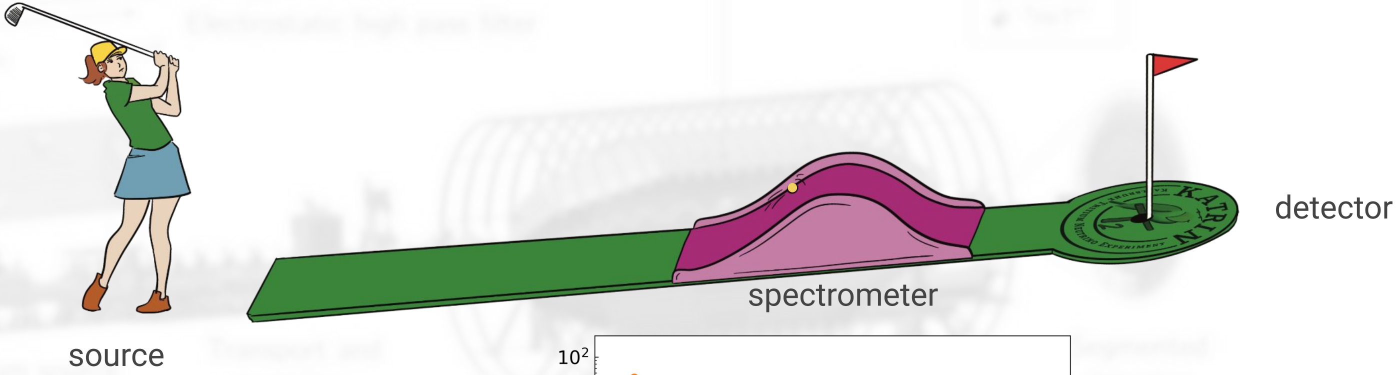

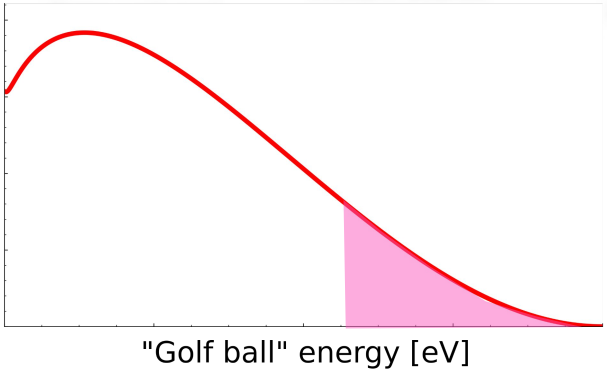

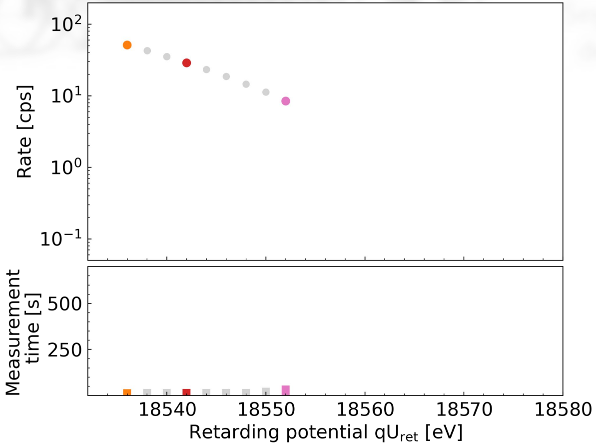

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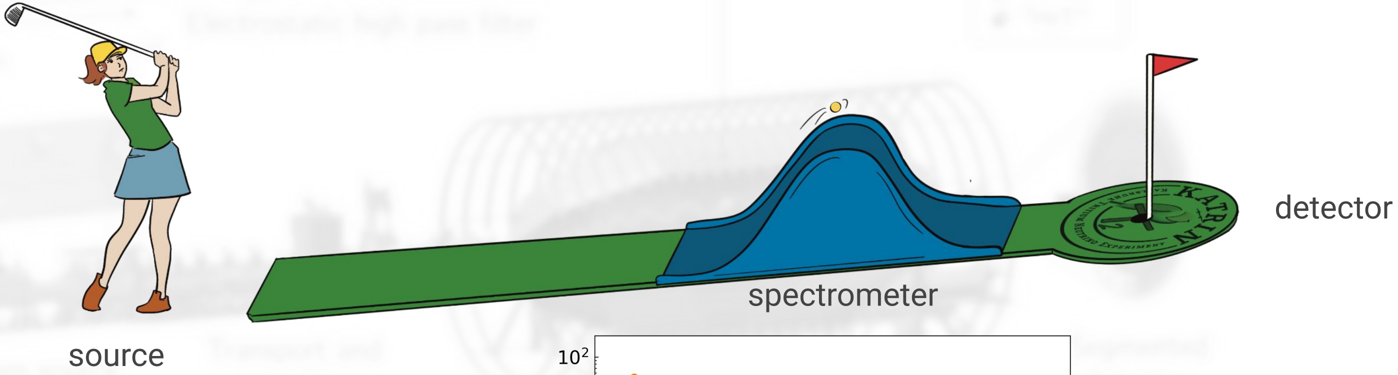

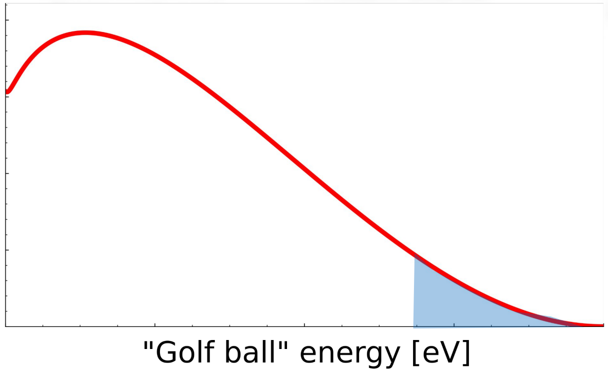

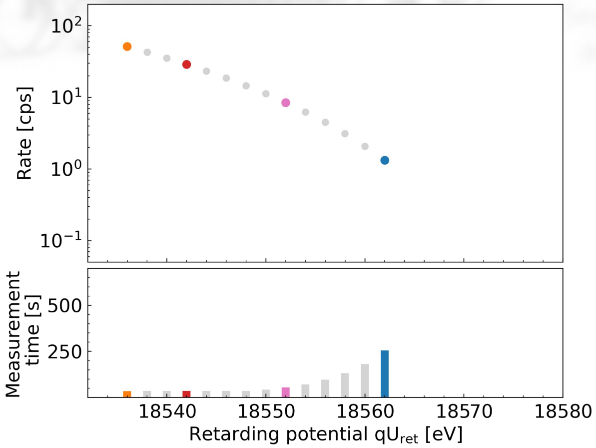

KATRIN experiment principle

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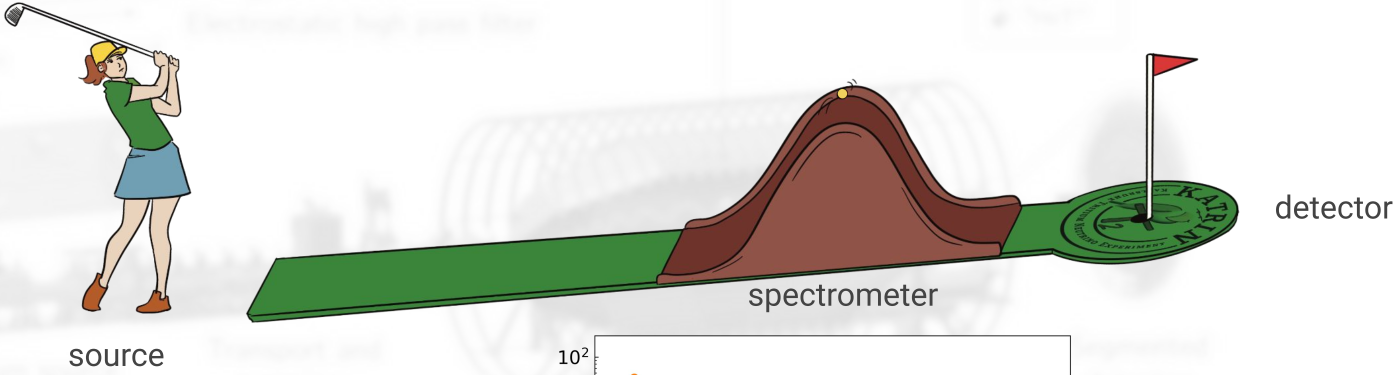

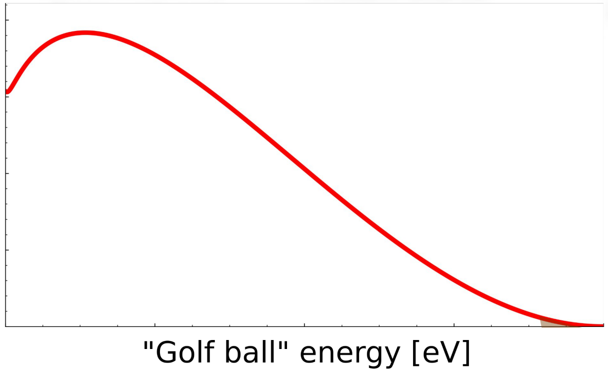

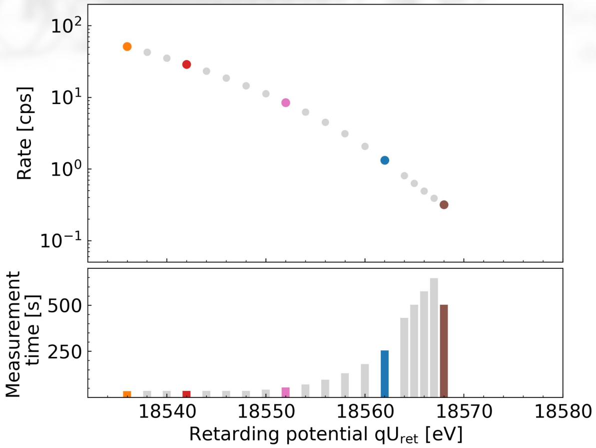

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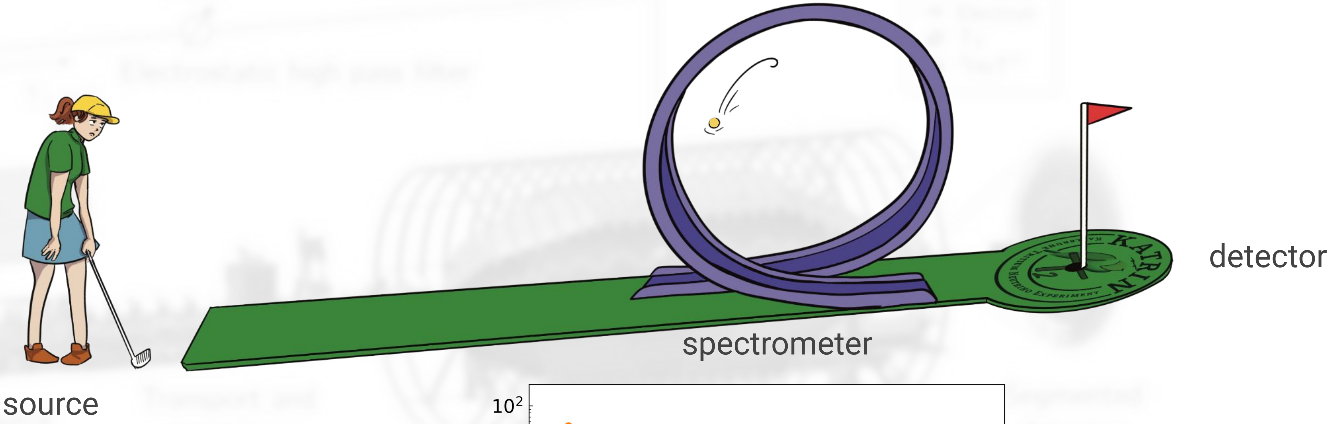

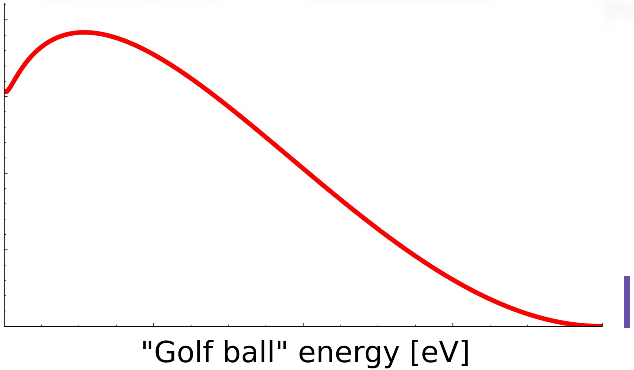

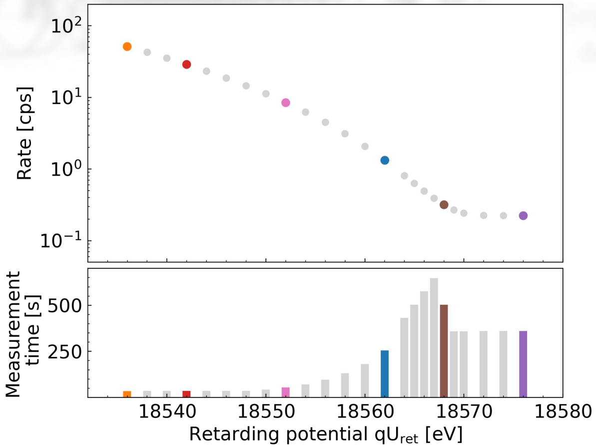

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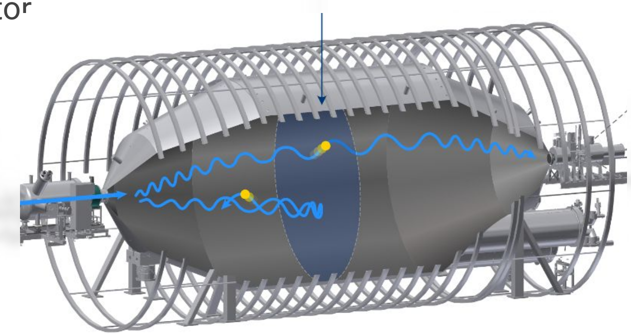
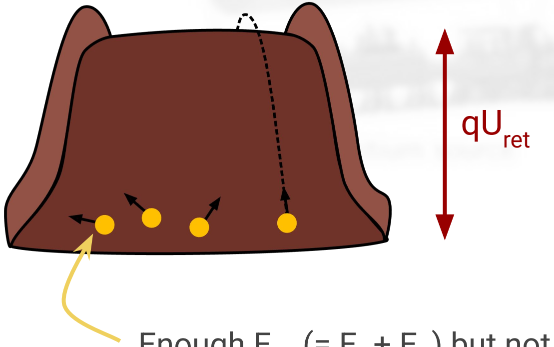


Magnetic adiabatic collimation principle:



Enough E_{tot} (= $E_{\perp}$ + $E_{//}$) but not enough $E_{//}$

⇒ transform $E_{\perp}$ into $E_{//}$

KATRIN experiment principle

The main spectrometer

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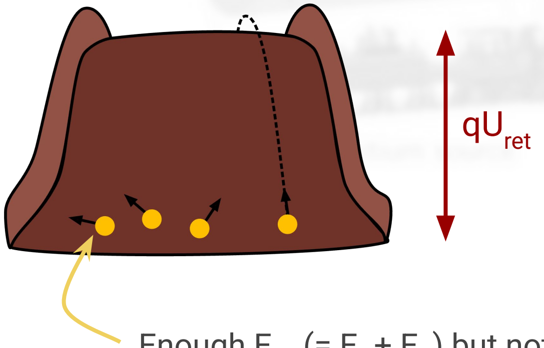

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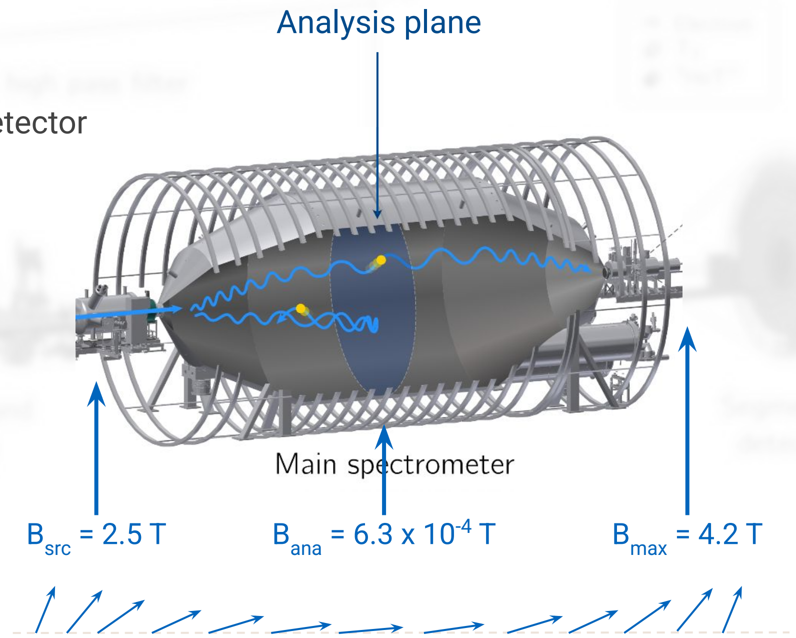

KATRIN experiment principle

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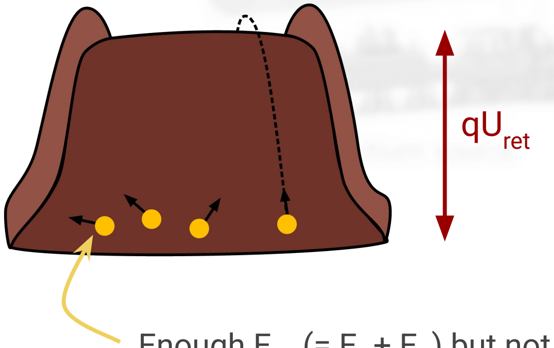

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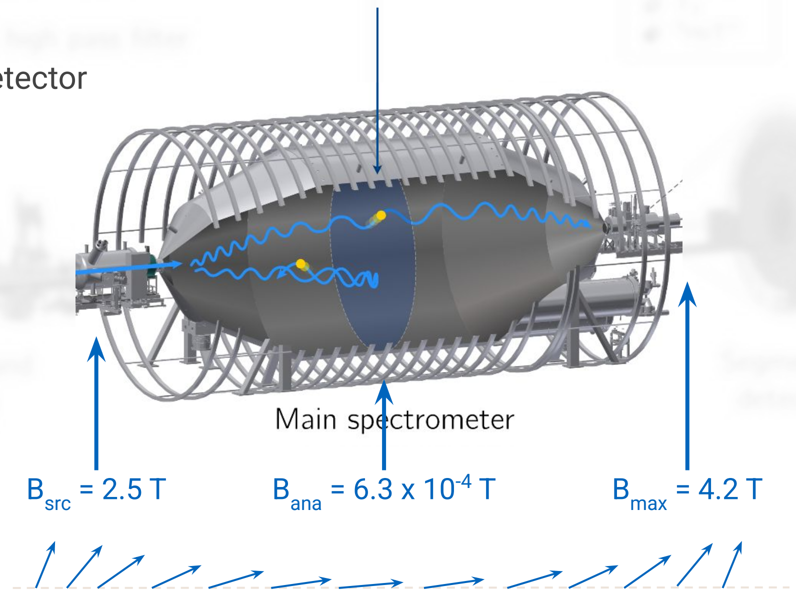

B_{src} = 2.5 T B_{ana} = 6.3 x 10^{-4} T B_{max} = 4.2 T

→ Energy resolution from the minimum $E_{\perp}$ at the analysis plane:

$$\Delta E \simeq E \cdot \frac{B_{\rm ana}}{B_{\rm max}} = 2.8\,{\rm eV}\ (@18.6\,{\rm keV})$$

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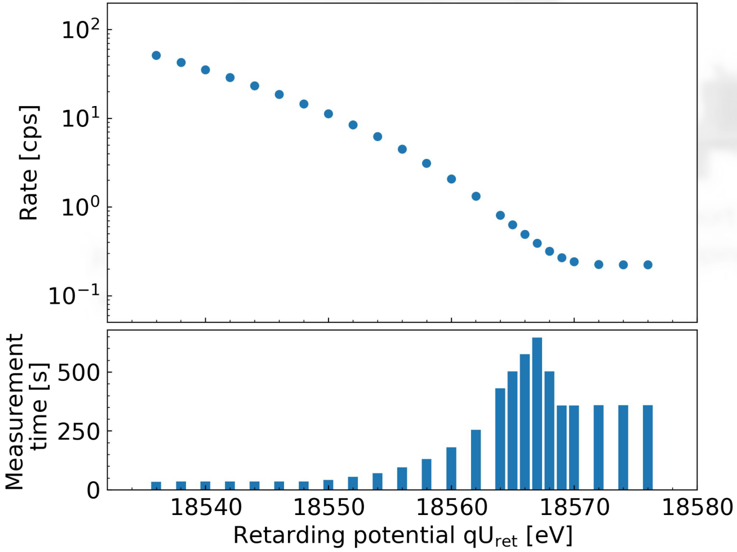
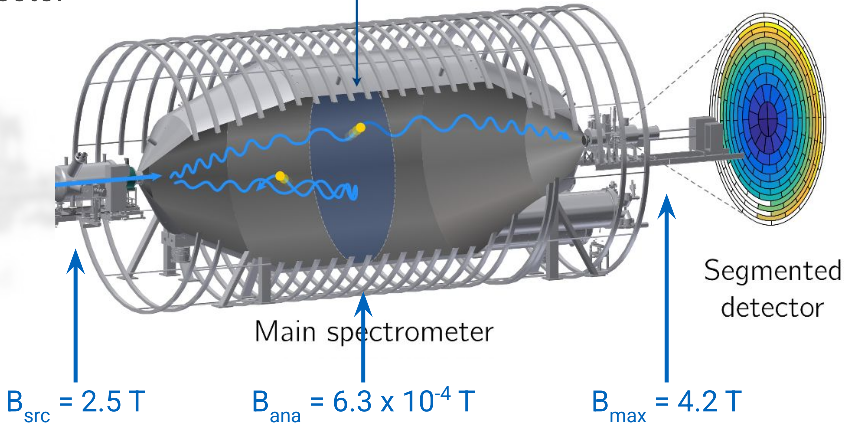


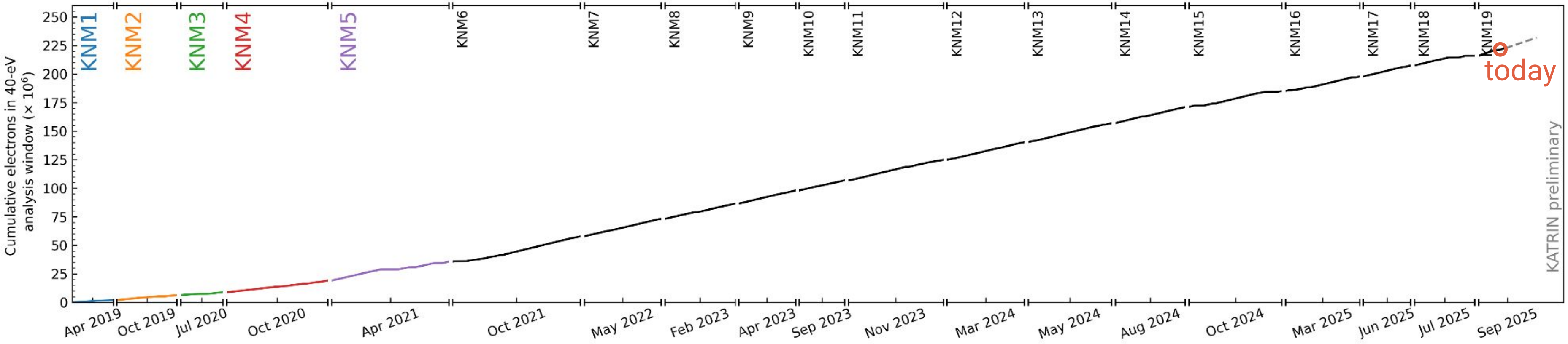


→ Vary retarding potential to **scan spectrum**
→ Count events at the detector
→ **Integral spectrum** (2-3h in total)
→ **Repeat** scanning procedure a few 100 times to obtain **one measurement campaign (KNM*)**

KATRIN collaboration, JINST 16 (2021) T08015

Data taking status

Analyzed and on-going



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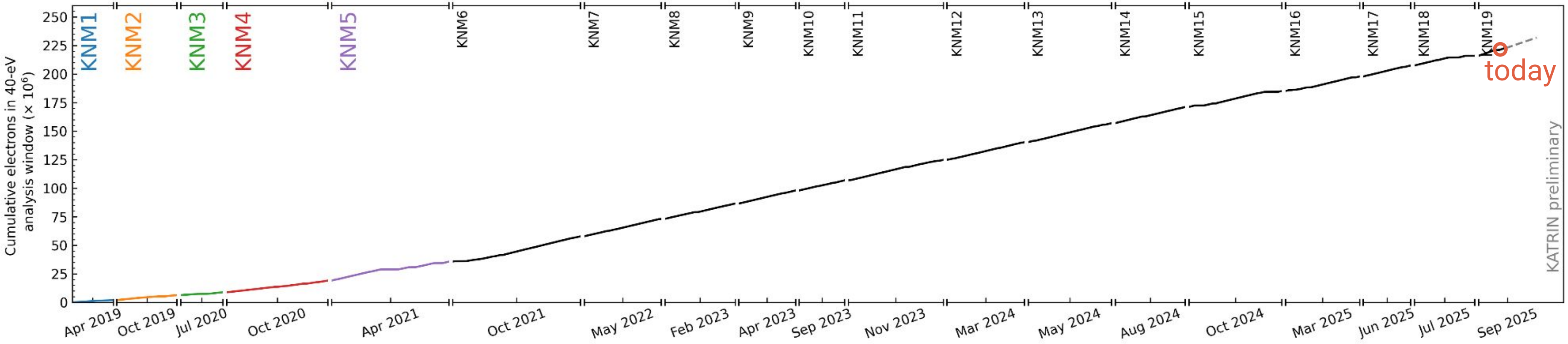
m_ν < 0.8 eV (90% CL)

[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

Data analysis principle and systematics sources

Data taking status

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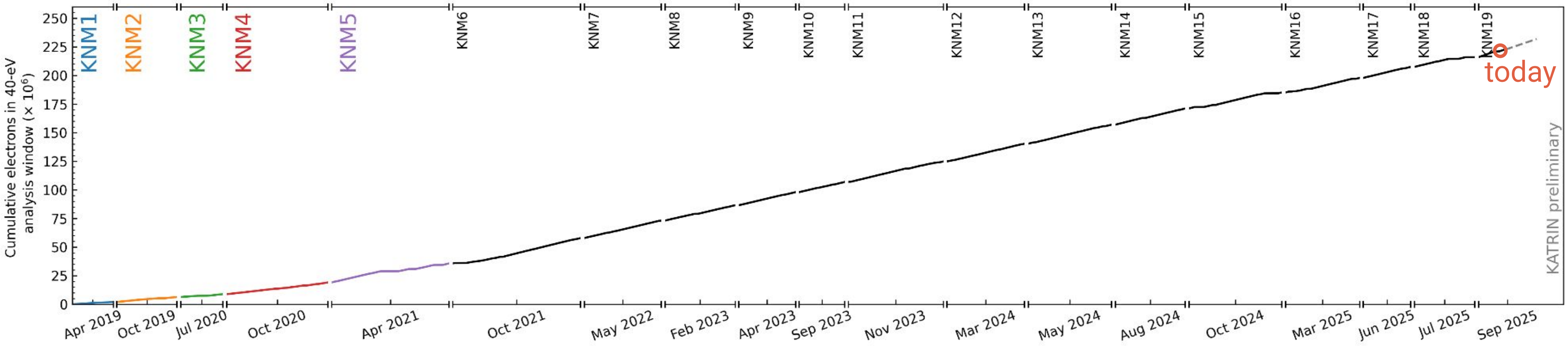

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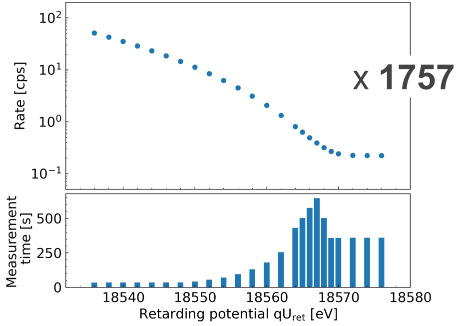

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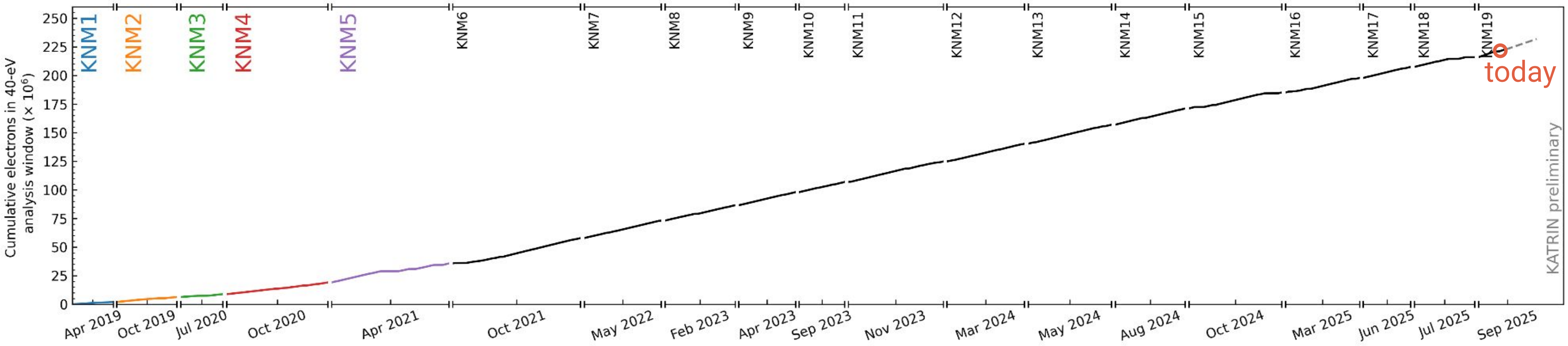

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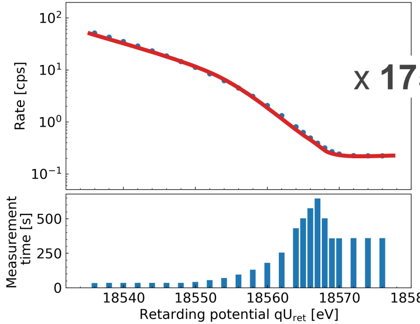


x **1757**

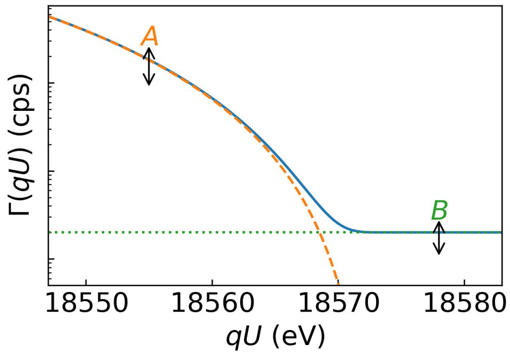
⇒ Model

Spectrum modeling and input parameters

Integrated spectrum

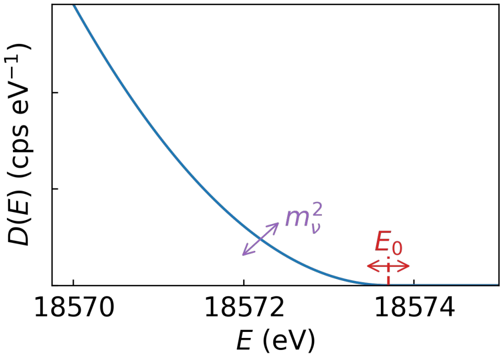
$$\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$$

integral spectrum measured at the detector



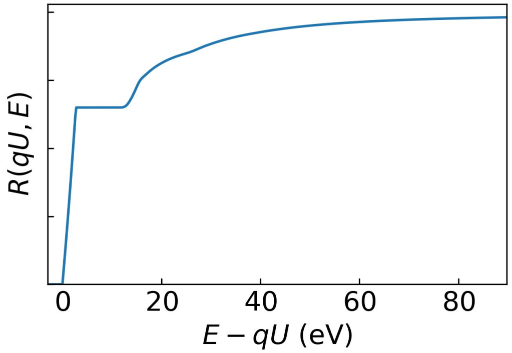
=

T_2 decay
→ differential spectrum



"⊛"

experimental response
(source, transport and spectrometer)



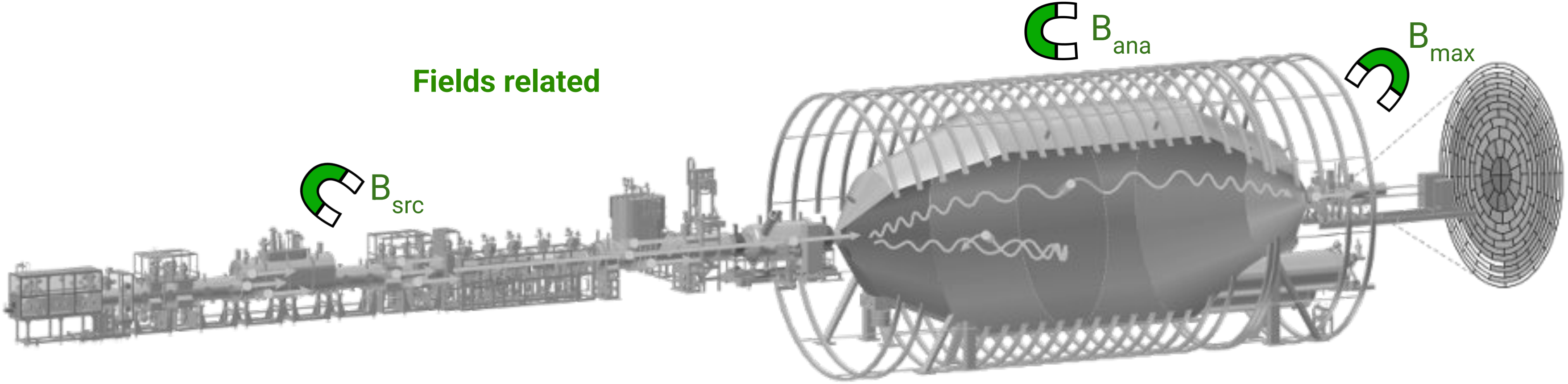
with free **amplitude** A,
squared neutrino mass m_ν^2,
endpoint E_0,
background B

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

Spectrum modeling and input parameters

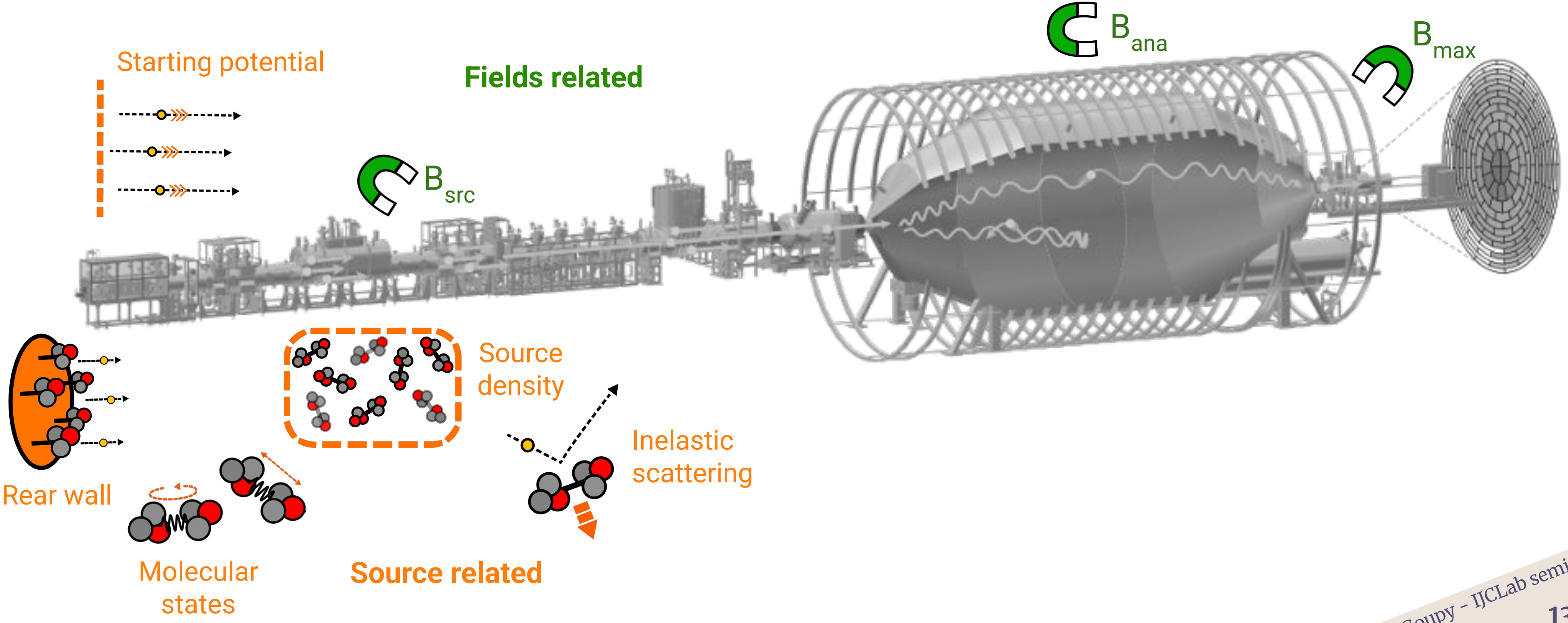
KATRIN systematics overview

Fields related



Spectrum modeling and input parameters

KATRIN systematics overview



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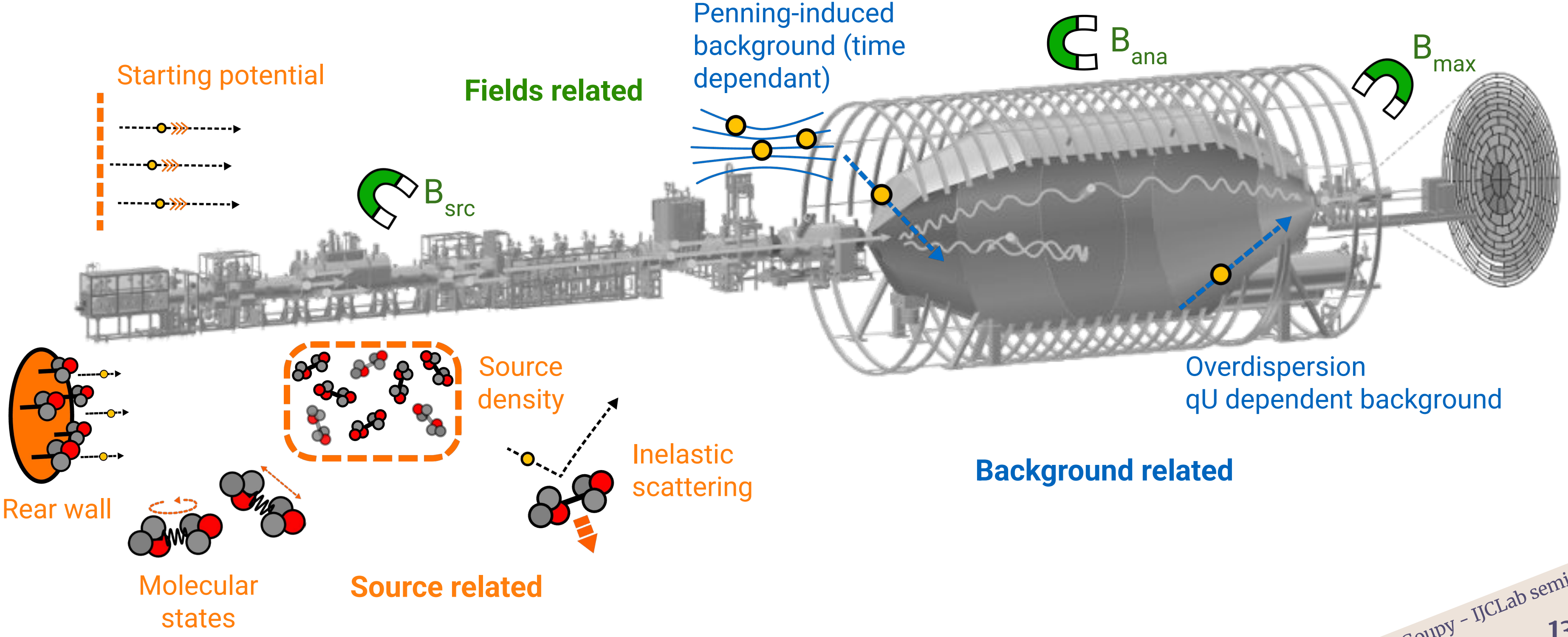
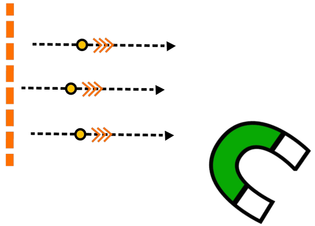


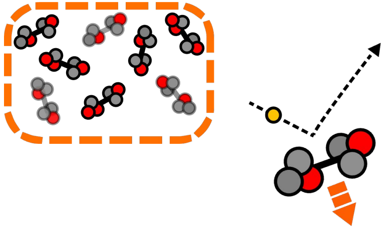
Spectrum modeling and input parameters

Systematics breakdown principle

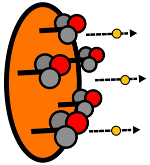
Model inputs characterized by external measurements



Kr lines measurements



Electron gun calibration measurements

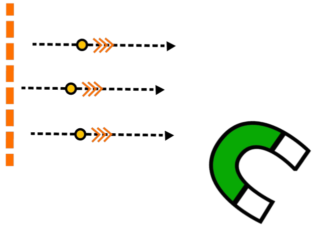


External measurement with empty source

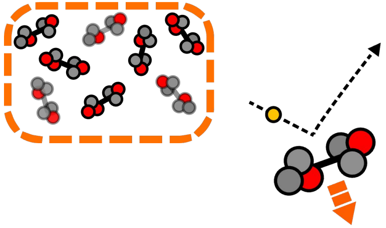
Spectrum modeling and input parameters

Systematics breakdown principle

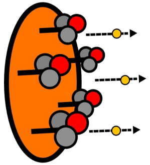
Model inputs characterized by external measurements



Kr lines measurements

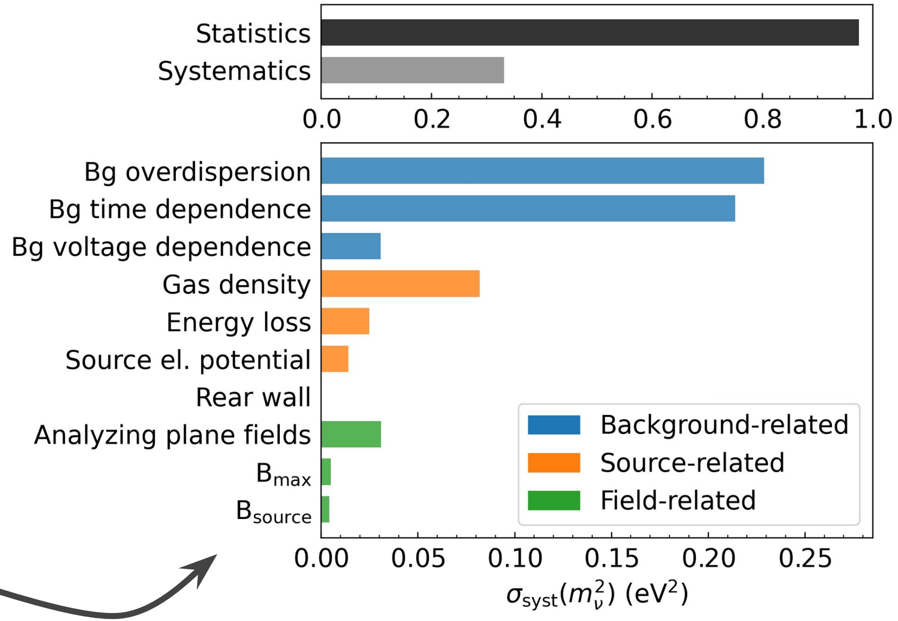


Electron gun calibration measurements



External measurement with empty source

Example of uncertainty breakdown for KNM1



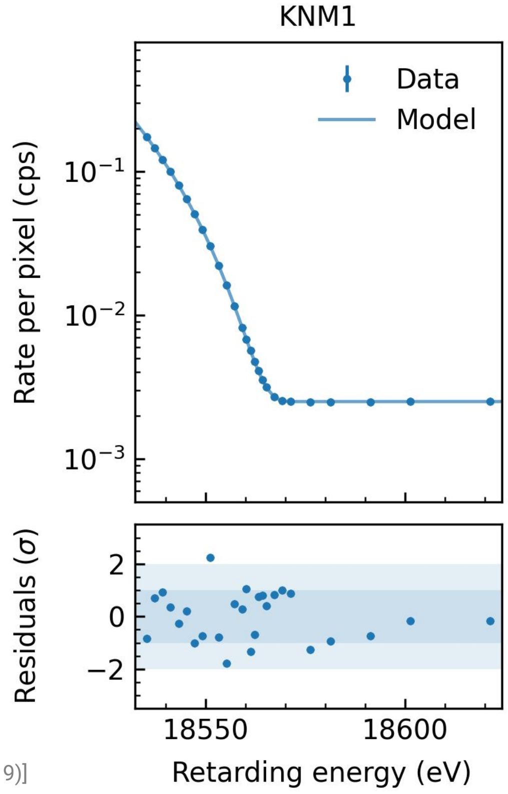
Uncertainties impact the neutrino mass

Experimental improvements from KNM1 to KNM5

KNM1 to KNM2

From demonstrator to increased statistics

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



m_ν **< 1.1 eV** (90% CL)

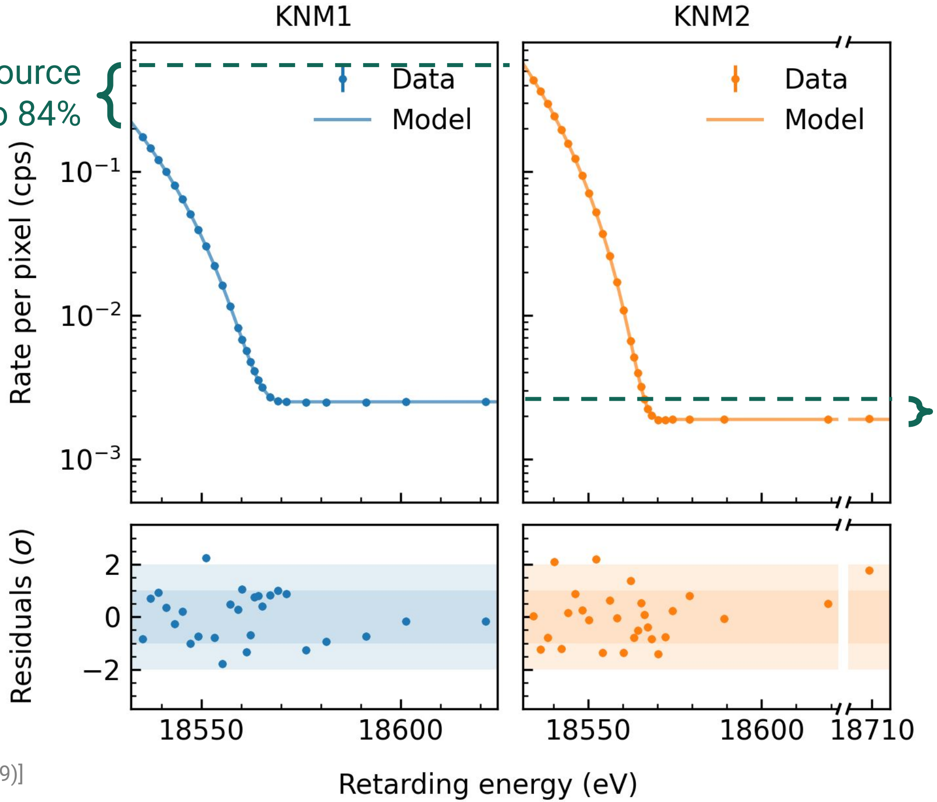
[M. Aker et al., Phys. Rev. Lett. 123, 221802 (2019)]

KNM1 to KNM2

From demonstrator to increased statistics

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

Increase of the source density from 22% to 84%



Improved vacuum: background reduced

m_ν **< 1.1 eV** (90% CL)

[M. Aker et al., Phys. Rev. Lett. 123, 221802 (2019)]

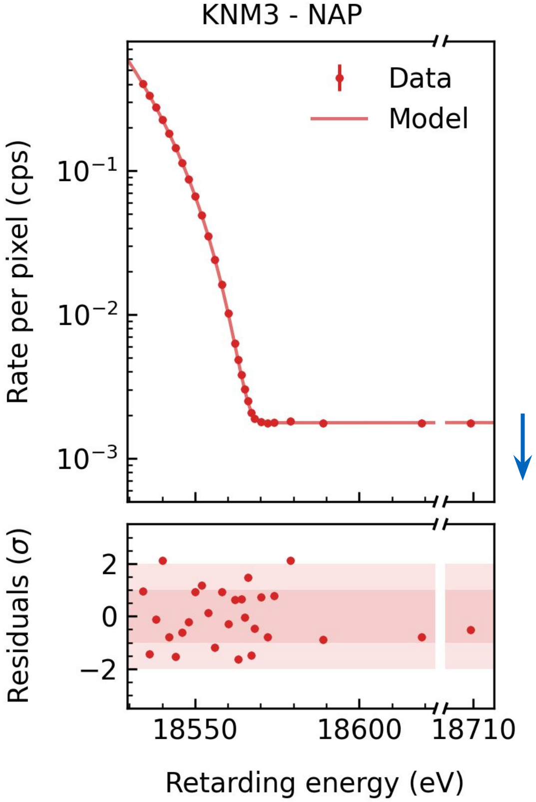
m_ν **< 0.8 eV** (90% CL)

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

KNM3

Shifted analysis plane

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

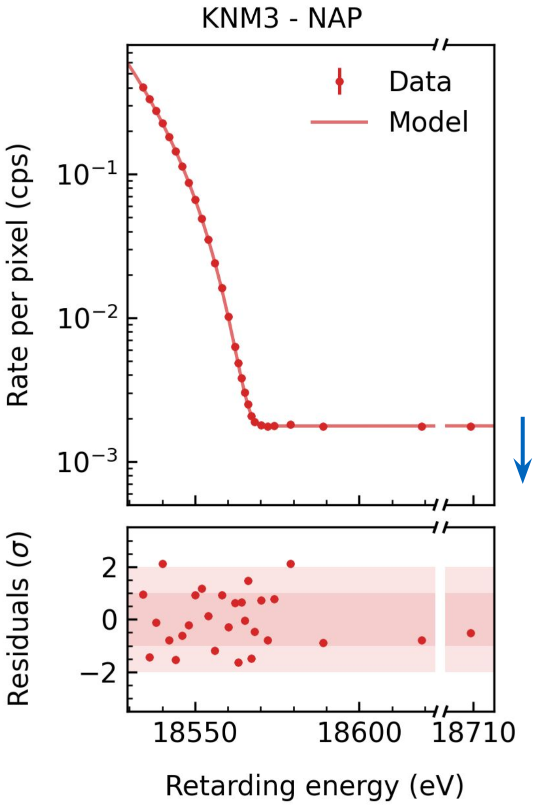


Can we reduce the flat background ?

KNM3

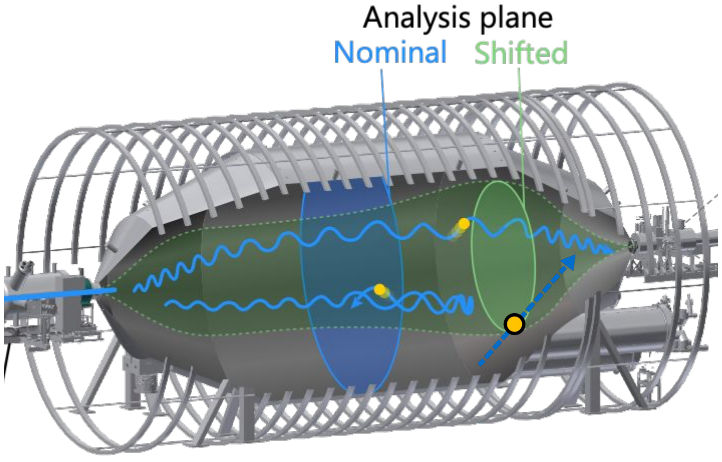
Shifted analysis plane

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

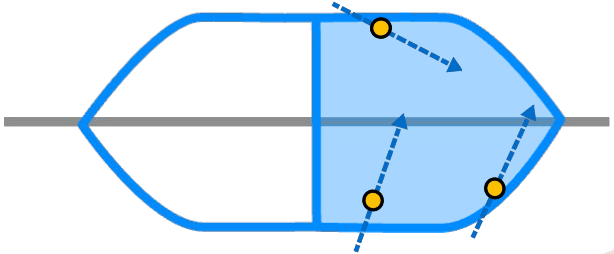


Can we reduce the flat background ?

What is its origin?

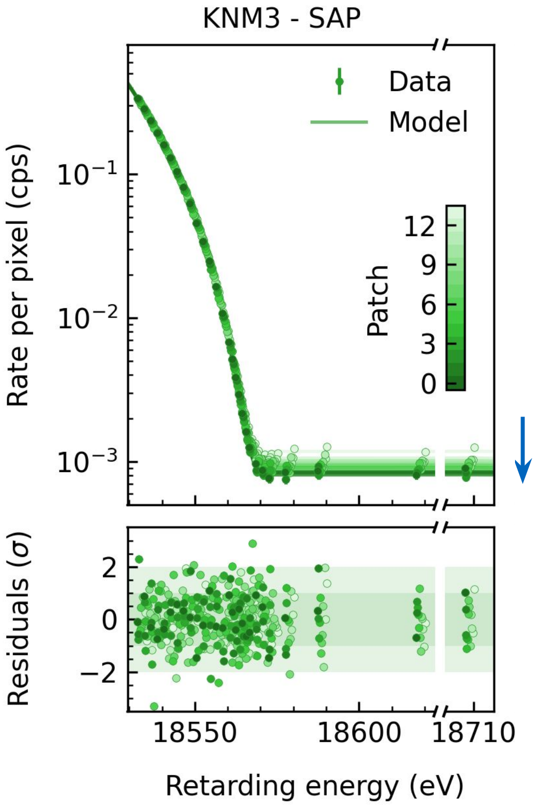


Nominal analysis plane (NAP)



KNM3

Shifted analysis plane

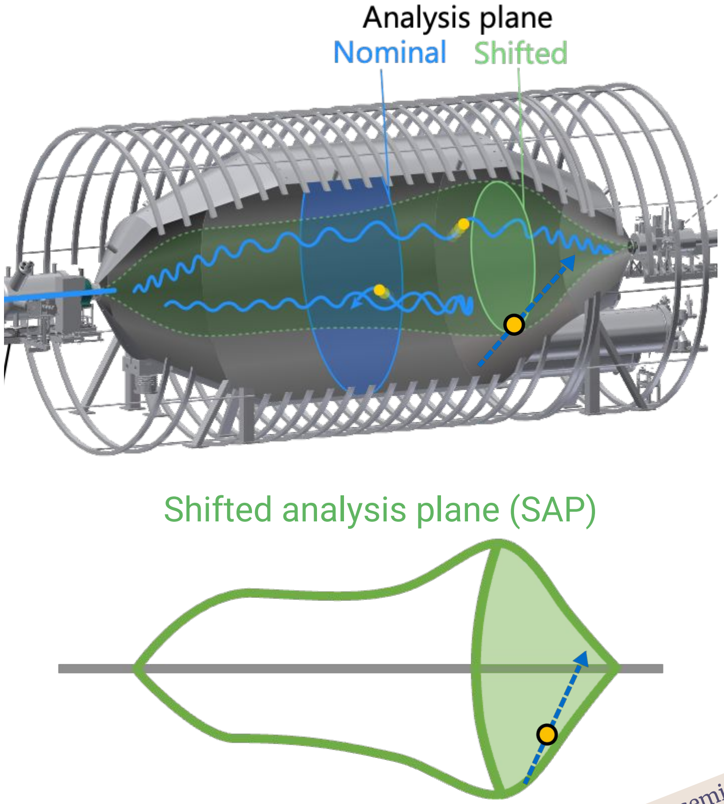


Can we reduce the flat background ?

Yes!

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

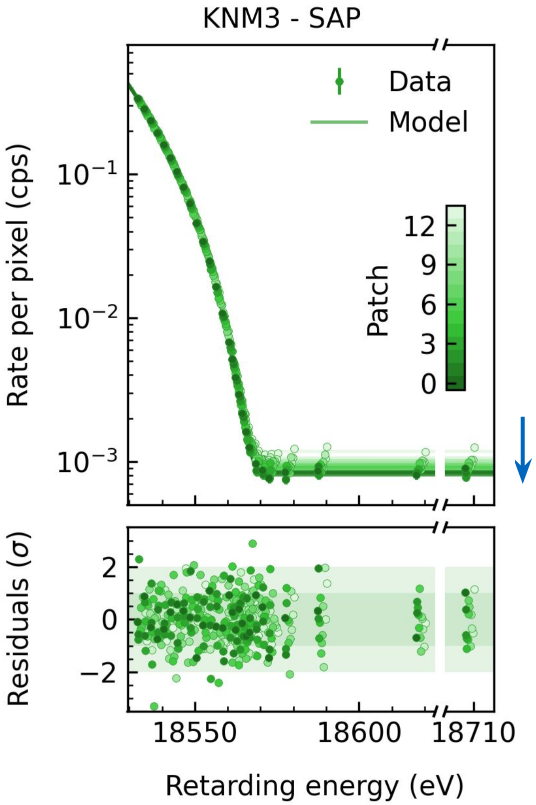
[Lokhov et al., EPJ C 82 (2022)]



KNM3

Shifted analysis plane

[KATRIN collaboration, *Science* 388,180-185(2025)]
[Lokhov et al., EPJ C 82 (2022)]



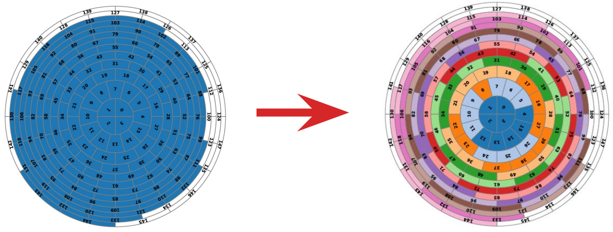
↓ Can we reduce the flat background ?

Yes!

but…

⇒ field inhomogeneities (B_{ana}) seen by the detector pixels

→ requires a thinner segmentation of the detector: 14 patches



→ larger uncertainties in simulated B_{ana}

⇒ measurement with ^{83m}Kr co-circulation in the source

[Altenmüller et al., J.Phys.G 47 (2020)]

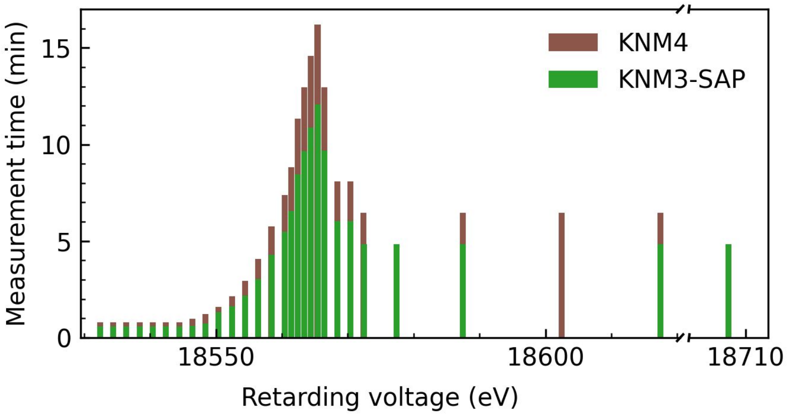
KNM4

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

Measurement times and penning background

Stable operation over hours in KNM3:

→ **increase the measurement time** of each scan to lose less time in the high voltage stabilization



KNM4

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

Measurement times and penning background

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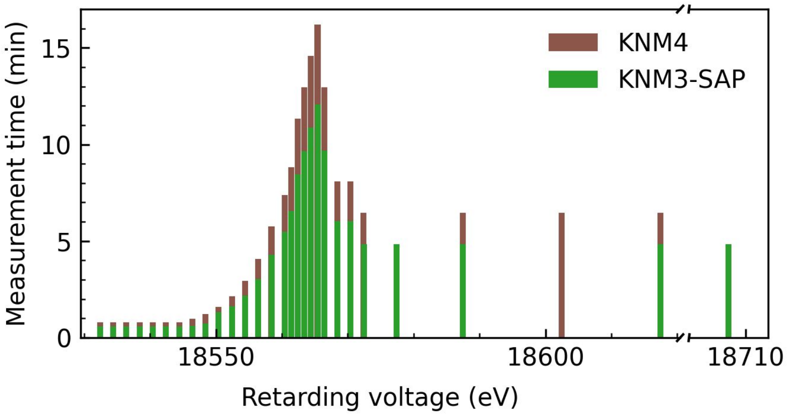
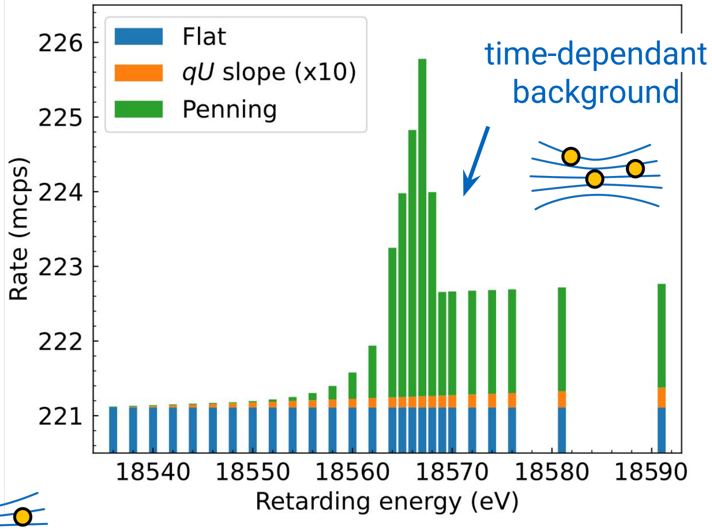
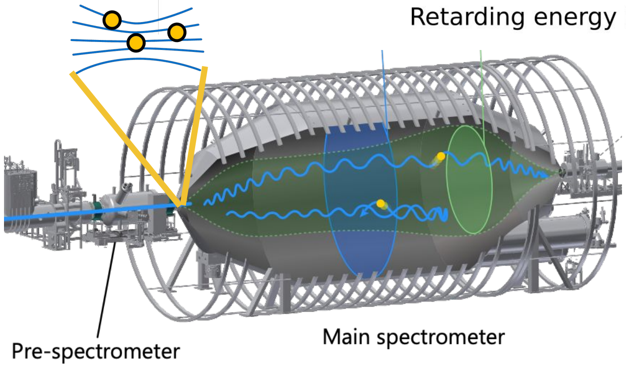


but...





KNM4

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

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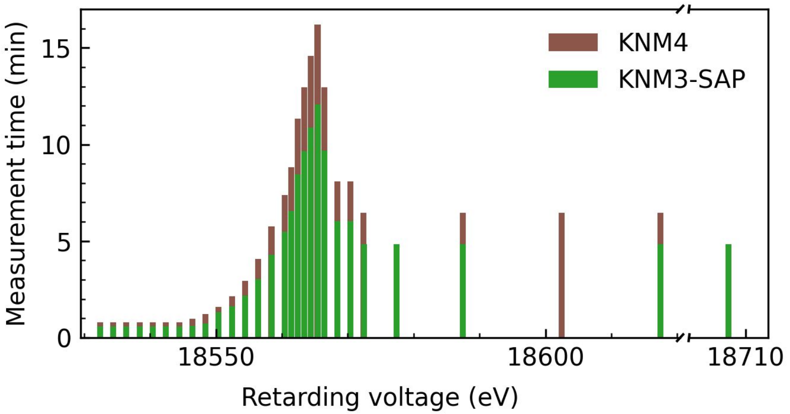
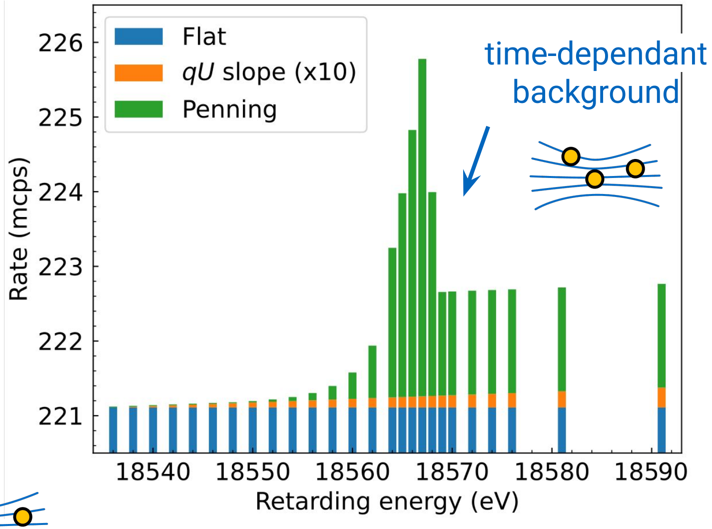
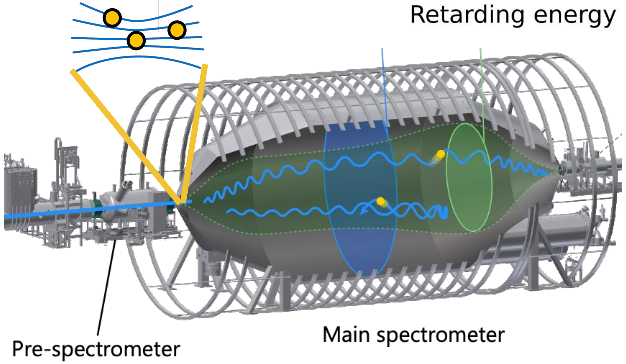


but...





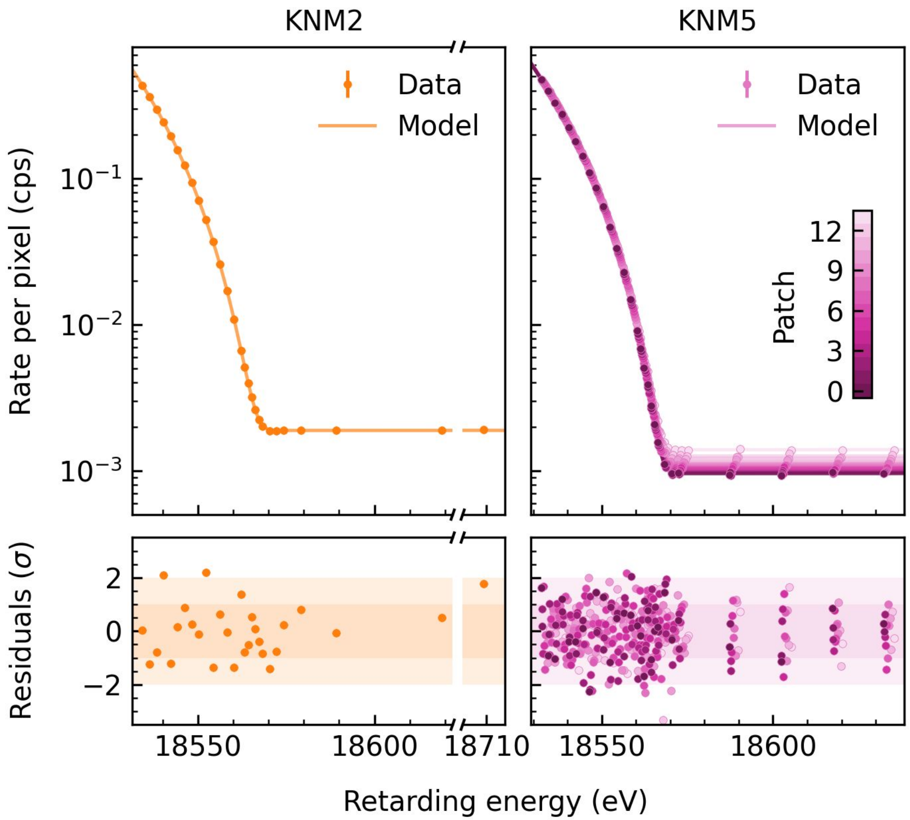
⇒ Solution:

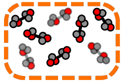
switch-off the pre-spectrometer
→ Tested in **KNM4**, applied in **KNM5**

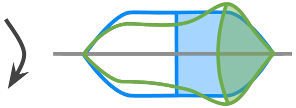
KNM5

Paving the way

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



- final source density value (77%) 
- final measurement time distribution
- High activity ^{83m}Kr source
  → improved magnetic fields calibration 

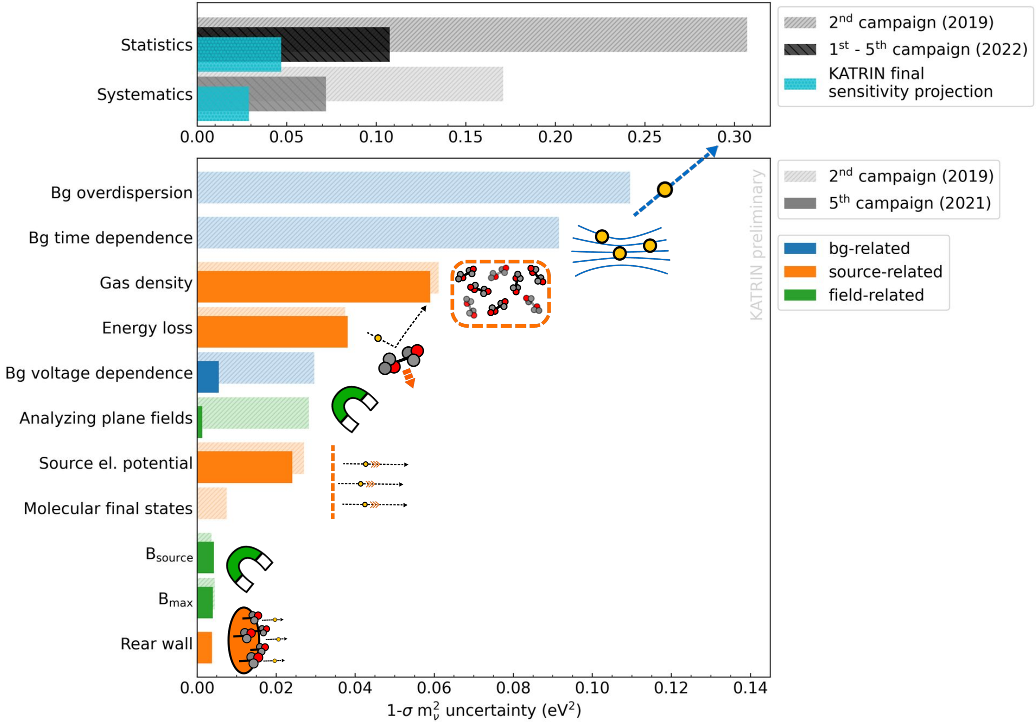


Experimental improvements: summary

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



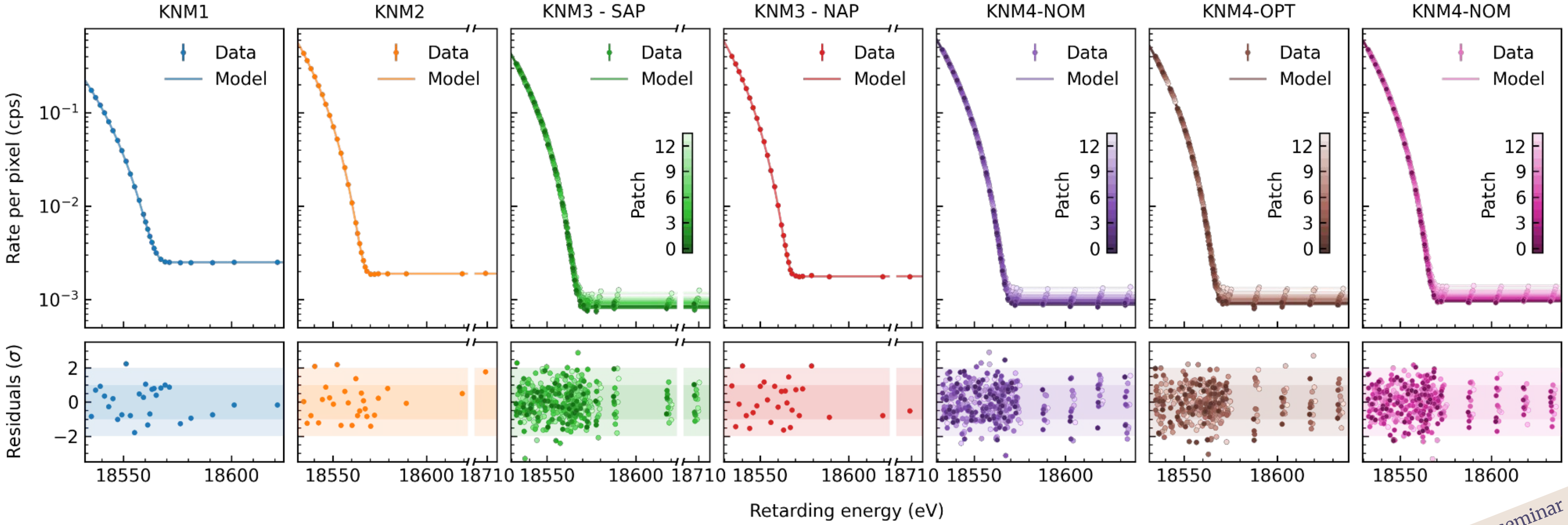
Combined analysis results

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

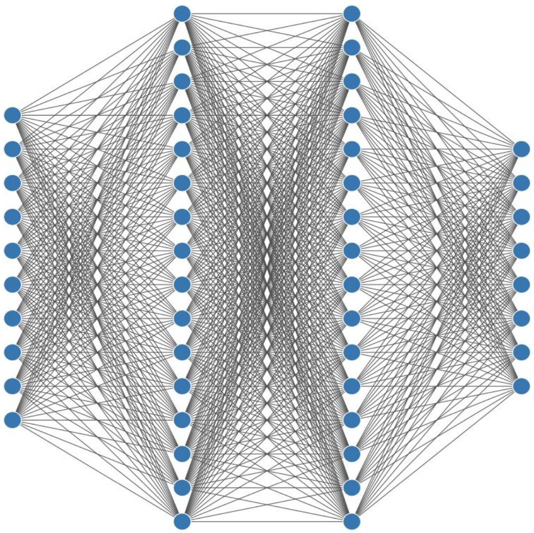
- **Maximum likelihood fit of analytical model**

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

→ 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)]

input nodes, **model parameters**



output nodes, **rate prediction**

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

Sampling/training

Fitting

Analysis challenges and methods

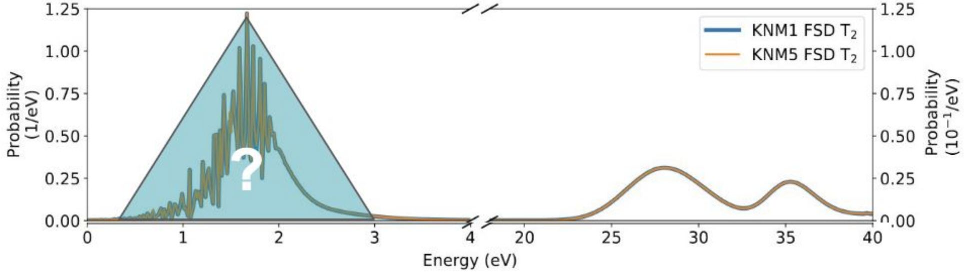
2-steps blinding procedure

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

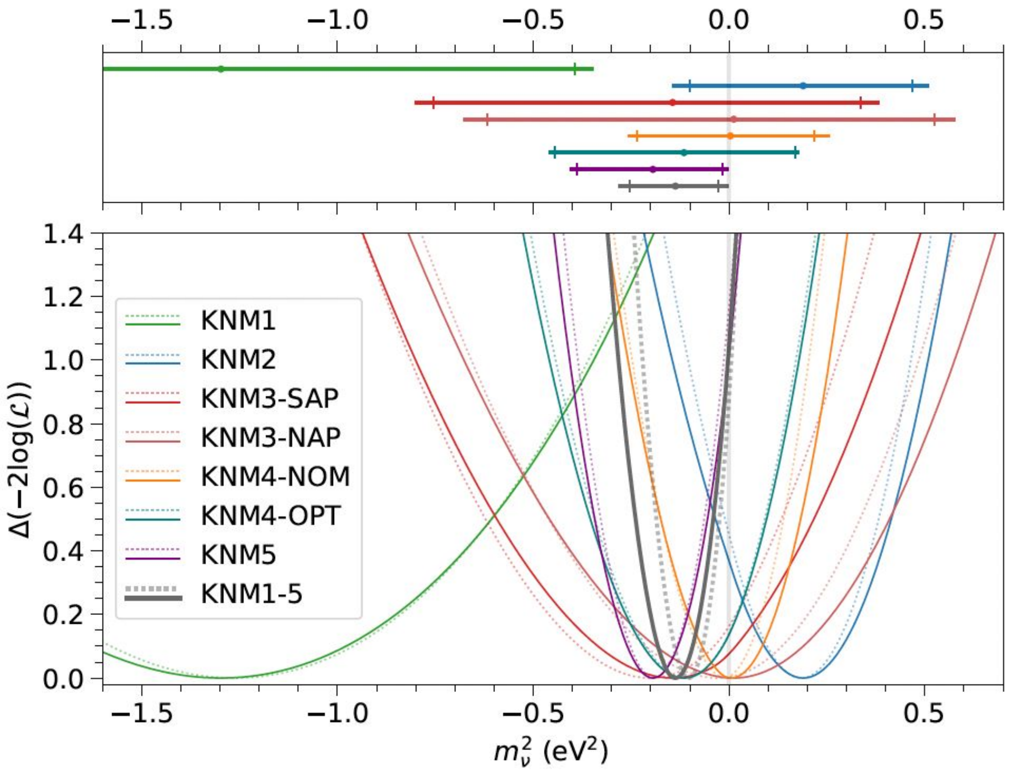


3- Analysis of the data with final model and final inputs

Neutrino mass analysis result

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

Likelihood profiles



Best fit result (p-value: 0.84):

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

- - - : statistics only

— : statistics and systematics

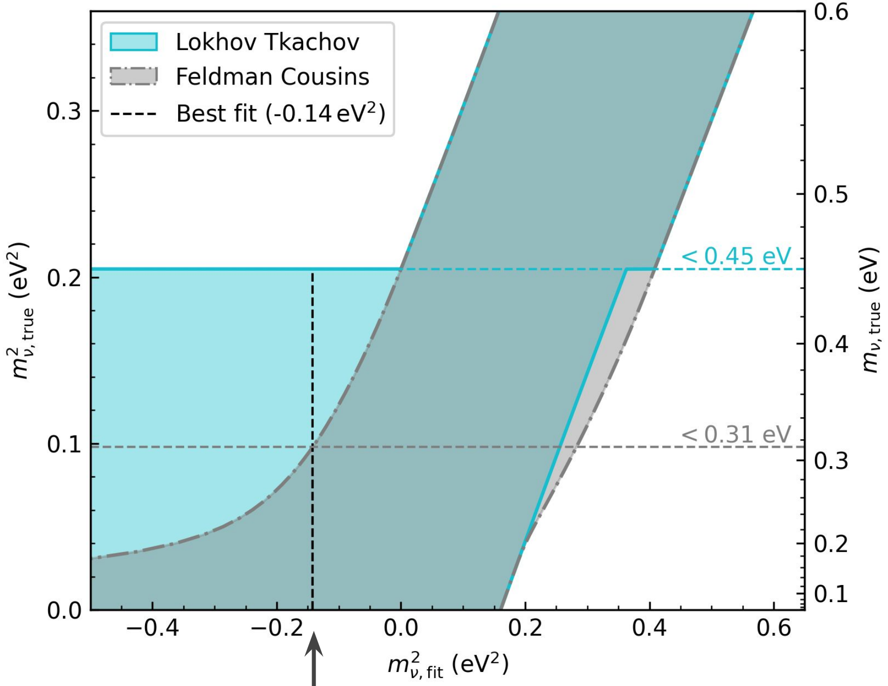
Neutrino mass limit

[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



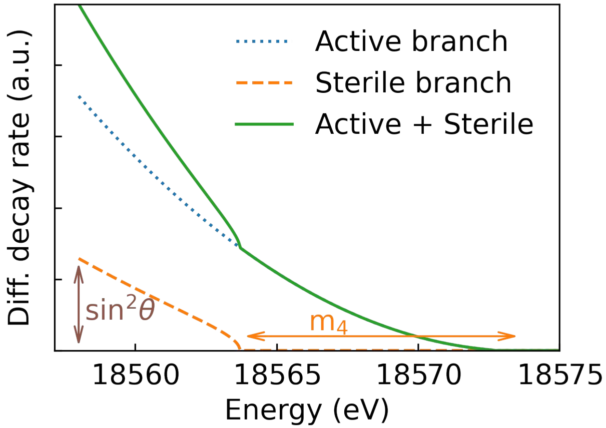
Square neutrino mass best fit:
$m_\nu^2 = -0.14\ eV^2$

Beyond the neutrino mass

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(θ):** 4^{th} neutrino mixing



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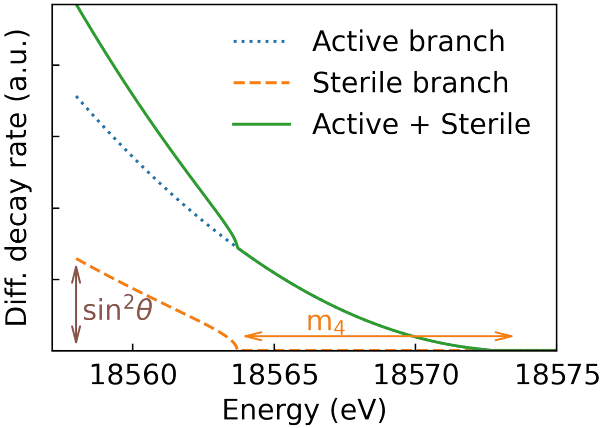

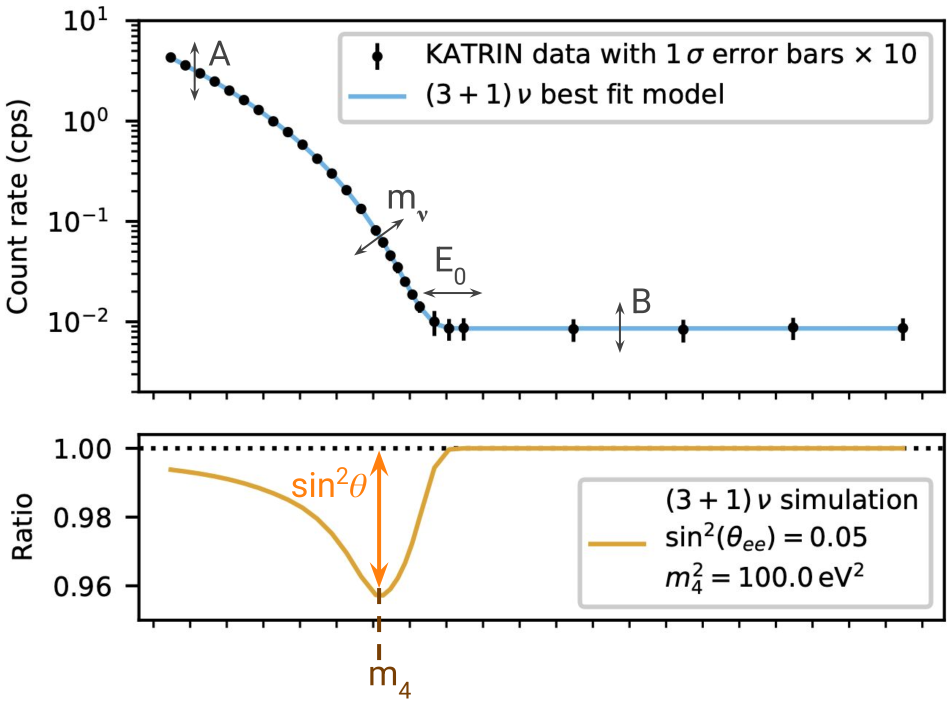

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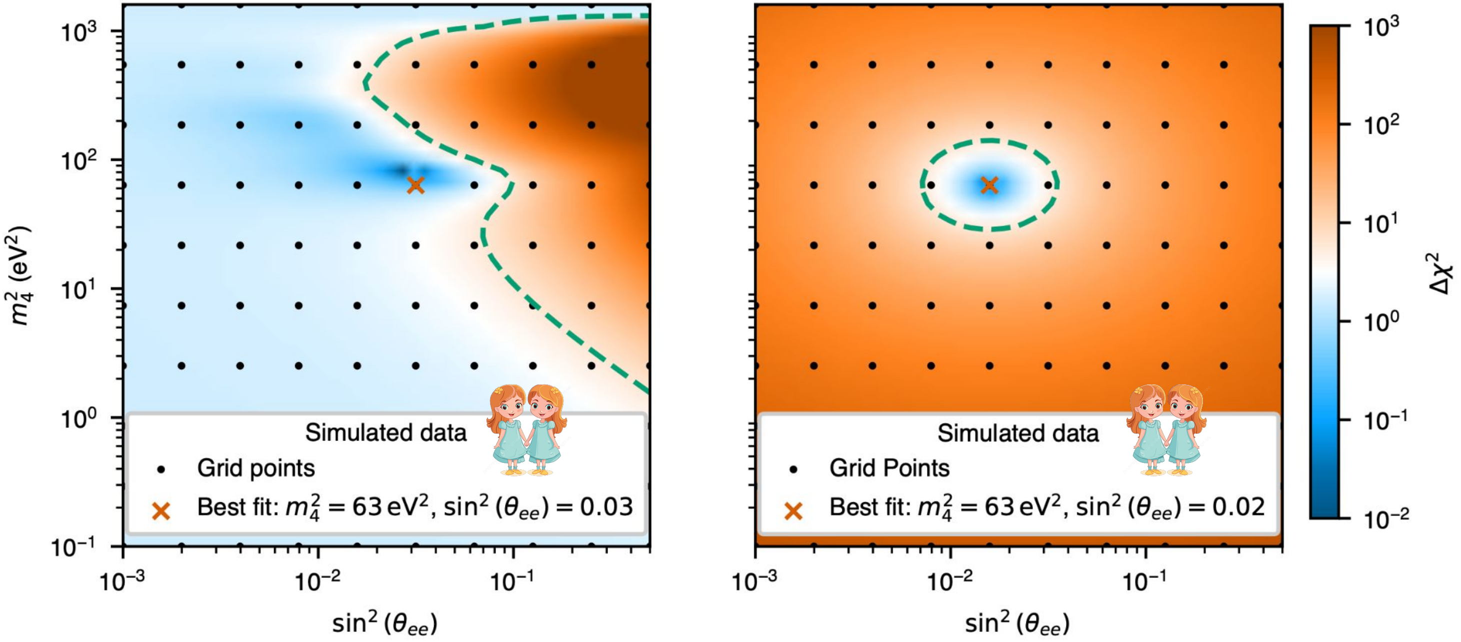
- *Method:* Grid scan of the parameters to construct exclusion contour/closed contour



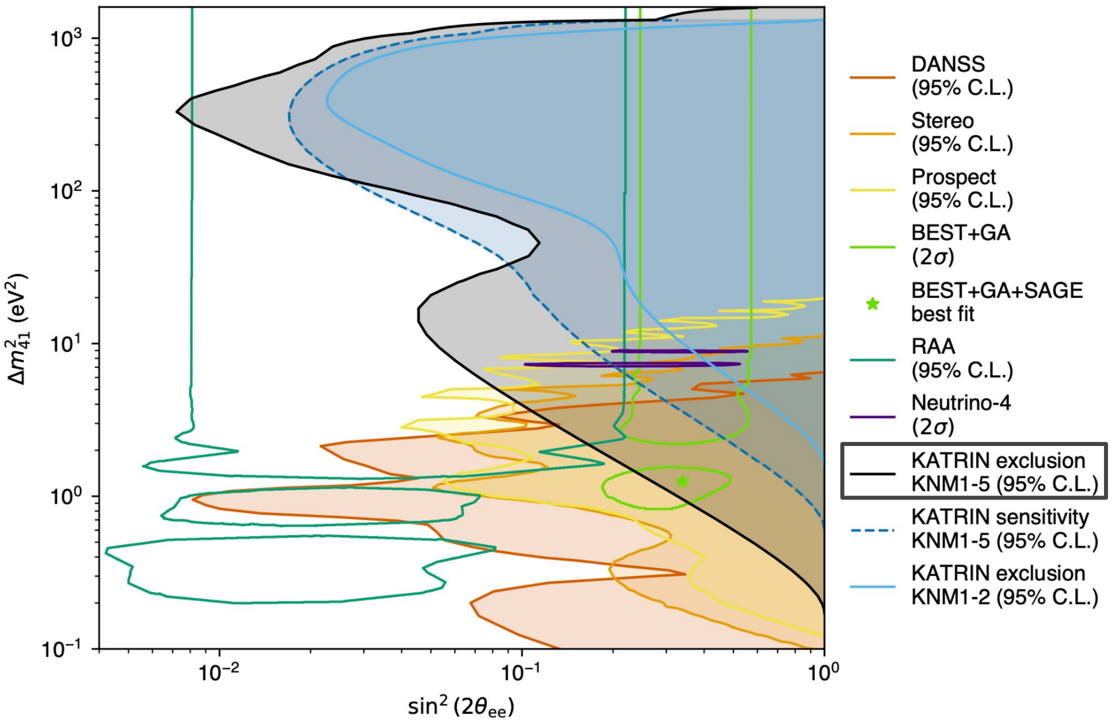
Beyond the neutrino mass

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

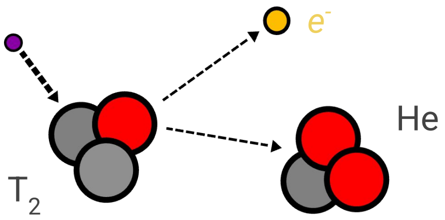
- New exclusion limit:
  → almost excludes the whole Gallium anomaly allowed region
  → excludes Neutrino-4
  → synergy with short baseline reactor experiments:
  - Prospect
  - Stereo
  - DANSS



Beyond the neutrino mass

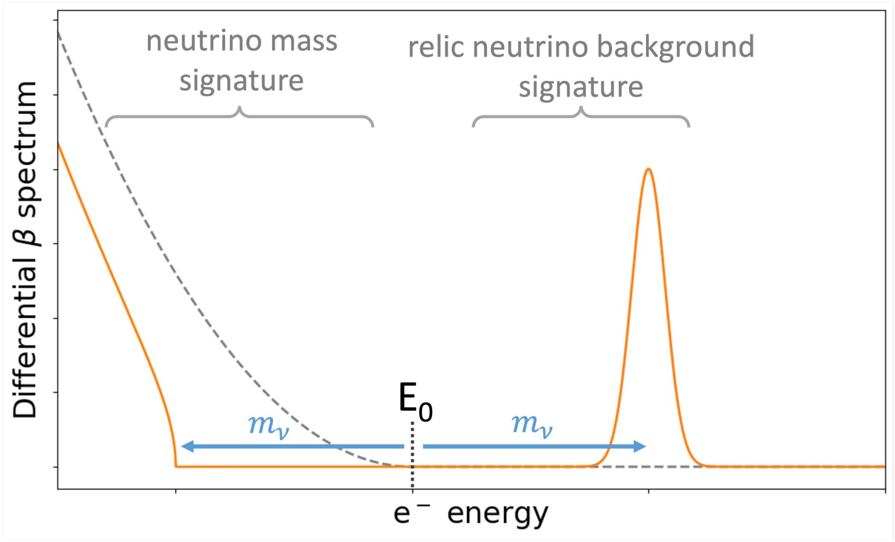
Cosmic relic neutrinos

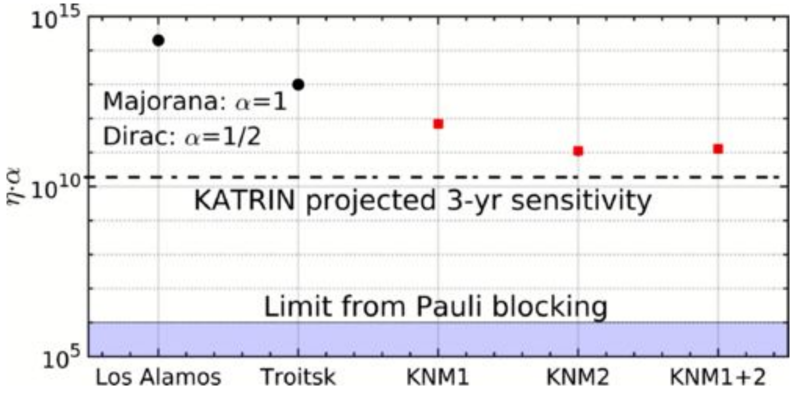
Big bang relic neutrinos
(1s after the Big Bang)



but…

KATRIN only sensitive to large overdensities η





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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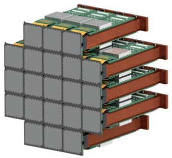
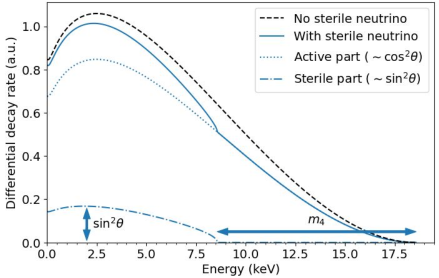
  *[Aker et al., Phys. Rev. Lett. **129**, 01180 (2022)]*
  *[M. Aker et al., Phys. Rev. D **107**, 082005 (2023)]*

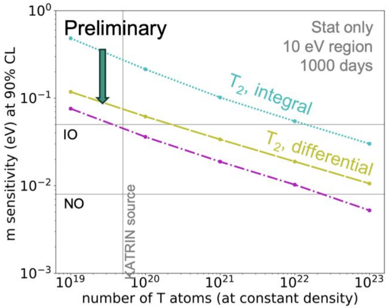
Outlook beyond KATRIN

- 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



Recent results from the KATRIN experiment

Sub-eV neutrino mass detection and eV-sterile neutrinos

Thank you for your attention !

KNM4

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

Measurement times and penning background

⇒ **Solution(s):**

1- Empty the penning trap regularly (every 100 s)

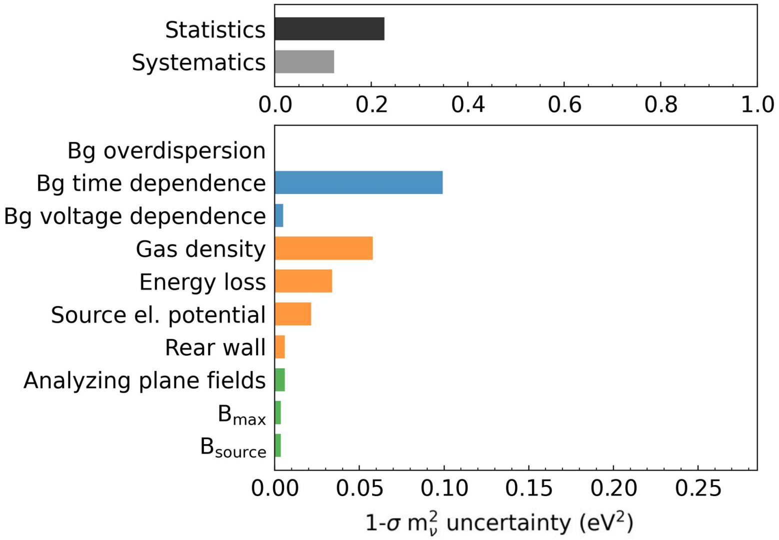
→ ***KNM4 "optimized"***

more difficult data taking, and data combination

2- Switch off the pre-spectrometer

→ Tested in **KNM4**, applied in *KNM5*

KNM4 - Nominal



KNM4 - Optimized