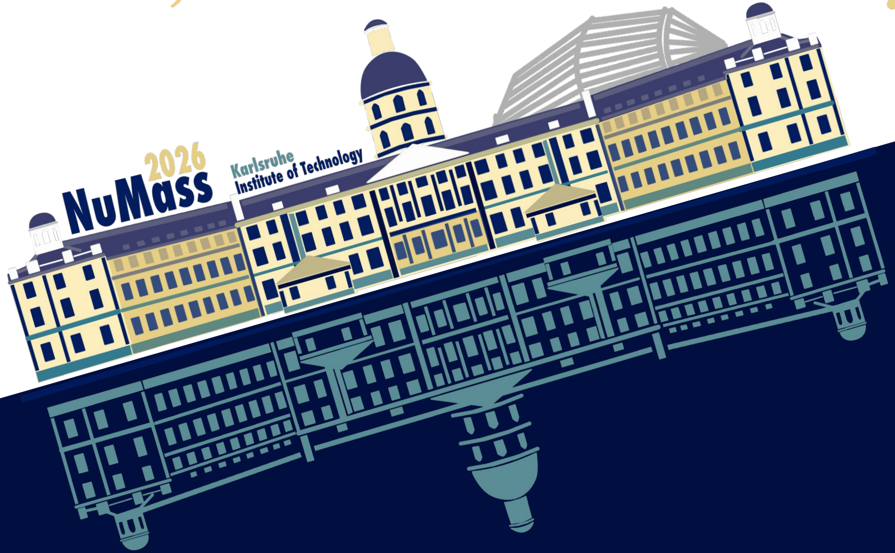
The KATRIN experiment

An overview *(as much as possible)*



Chloé Goupy,
on behalf of the KATRIN collaboration

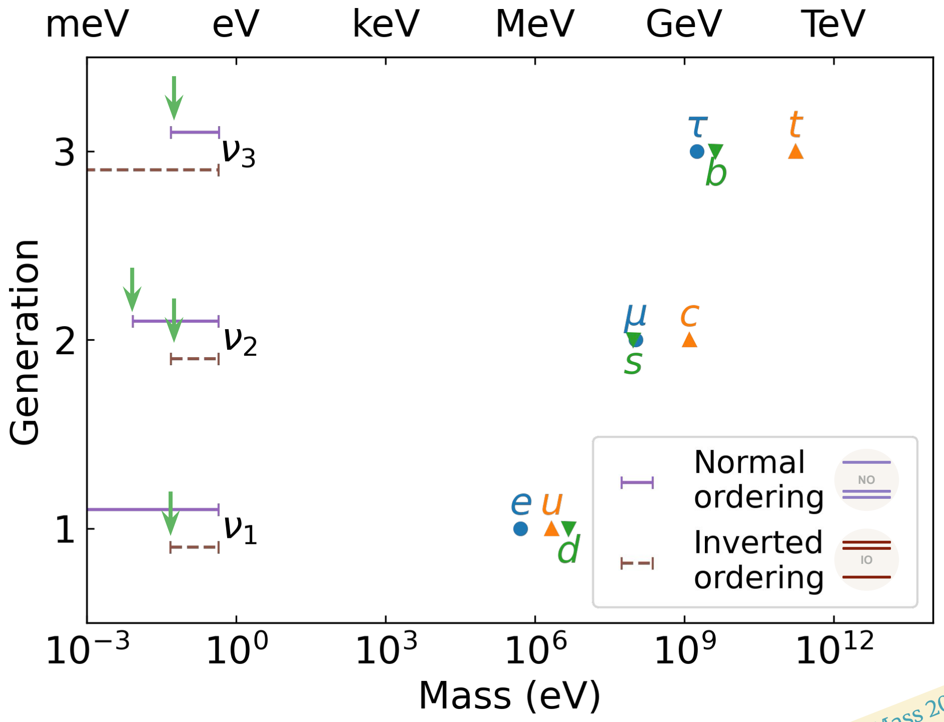
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

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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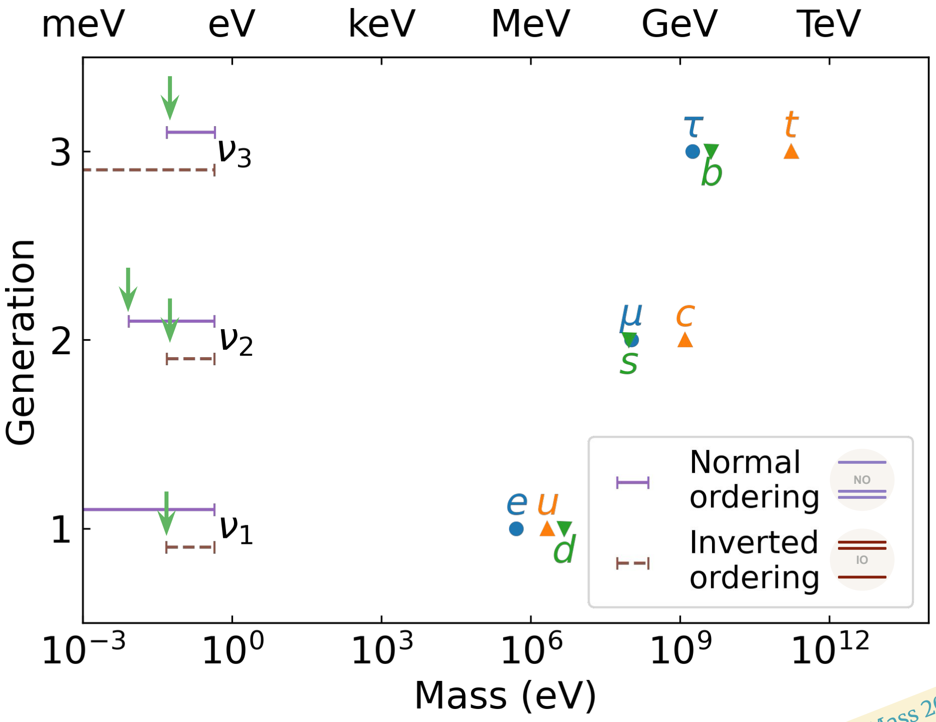


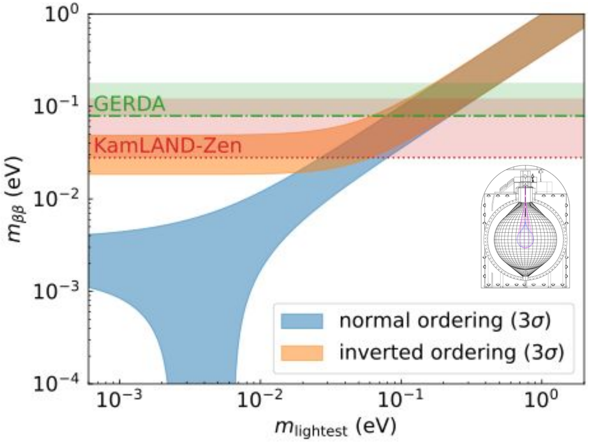
Neutrino mass observables

And complementarities

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

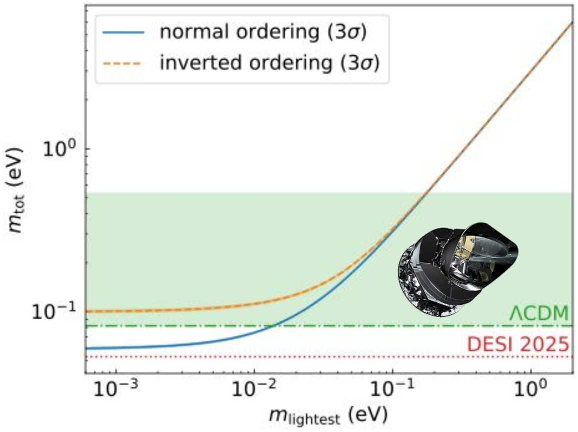
Neutrinoless ββ-decay

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



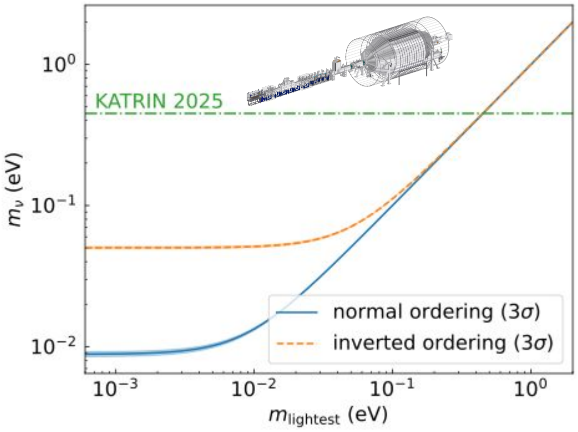
Cosmology

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



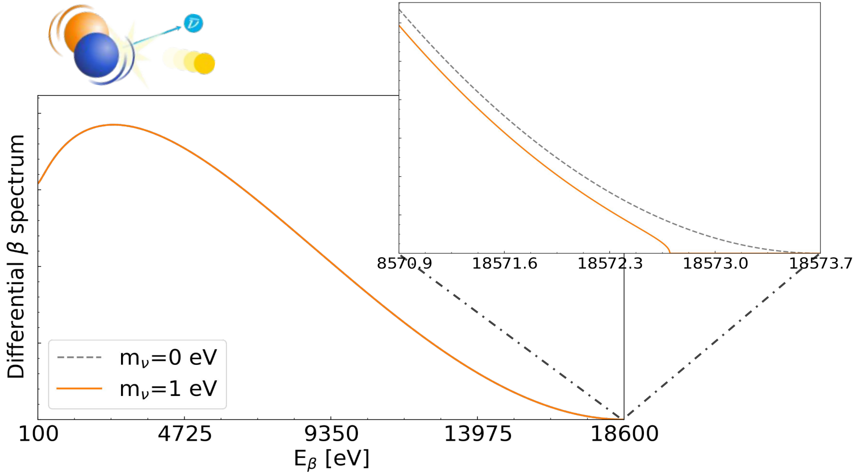
β-decay kinematics

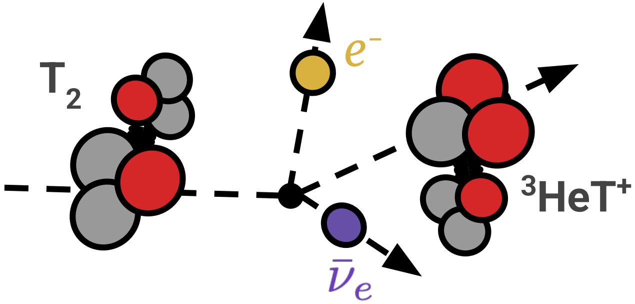
$$m_\nu = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$



Direct measurement of the neutrino mass

From β-decay kinematics





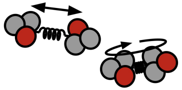
T_2 (molecular tritium) :

→ low end point E_0= 18.6 keV

→ half life τ = 12.3 years

But

→ molecular binding energies



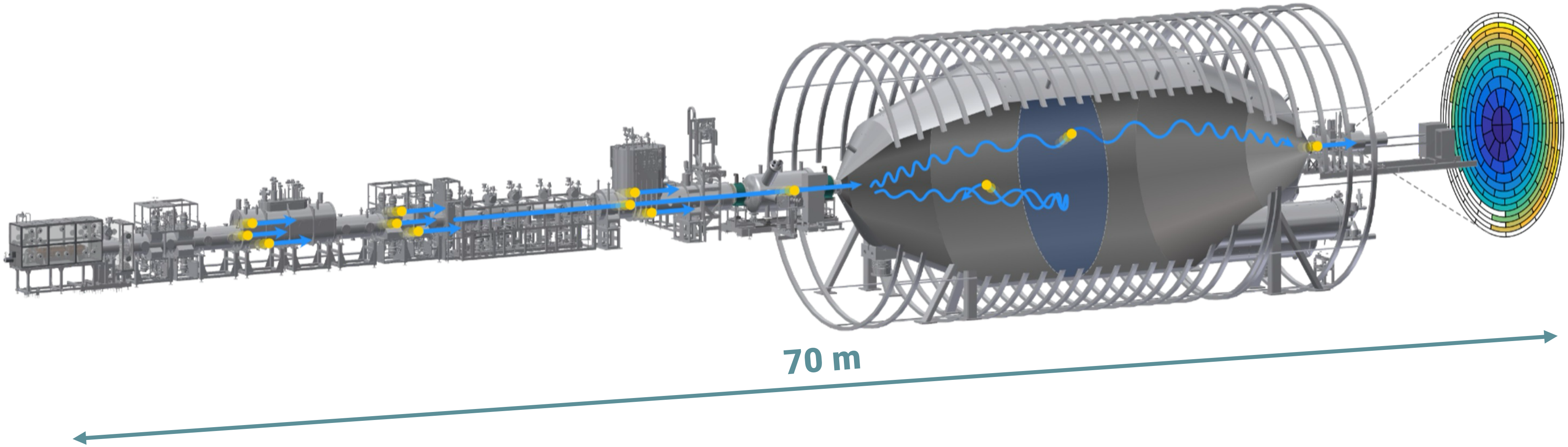
- (molecular) Tritium β-decay: $T_2 \rightarrow ^3HeT^+ + e^- + \bar{\nu}_e$
- **Spectral distortion** near end point
  → **low background** (< 1 cps)
  → high **energy resolution** (~1eV)

The Karlsruhe Tritium Neutrino (KATRIN) experiment

Arrival of the main spectrometer in Karlsruhe
November 2006

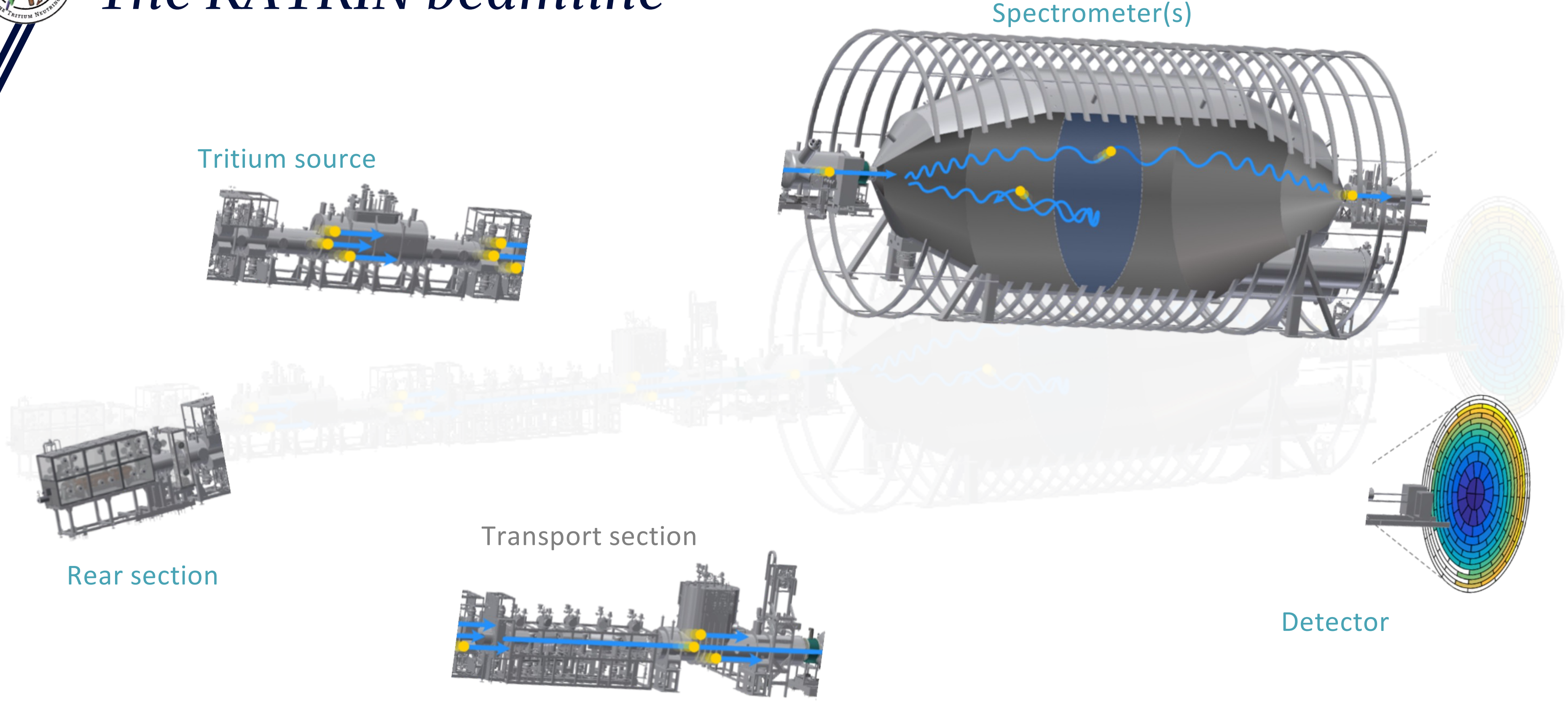
The KATRIN experiment principle

The KATRIN beamline

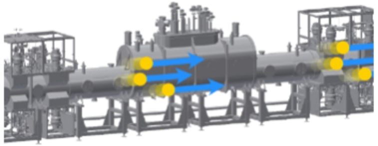


KATRIN collaboration, JINST 16 (2021) T08015

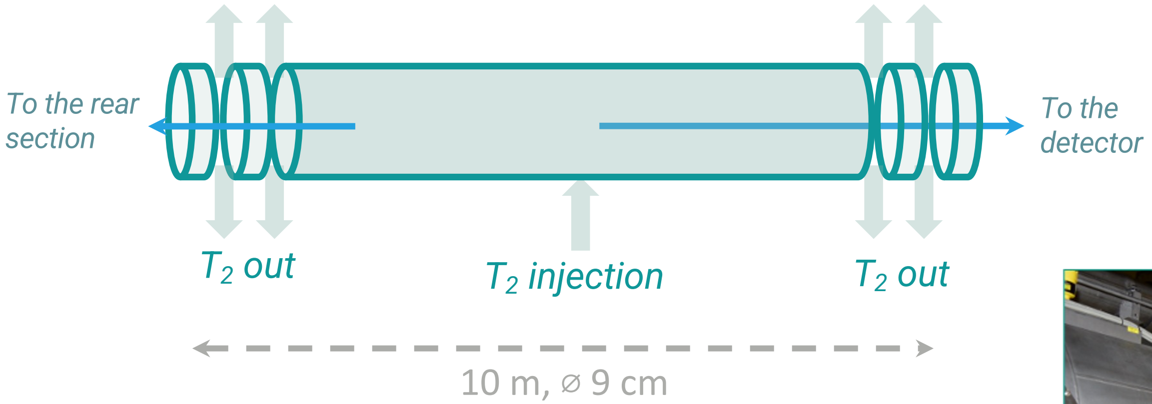
The KATRIN beamline



The KATRIN tritium source



Windowless Gaseous Tritium Source



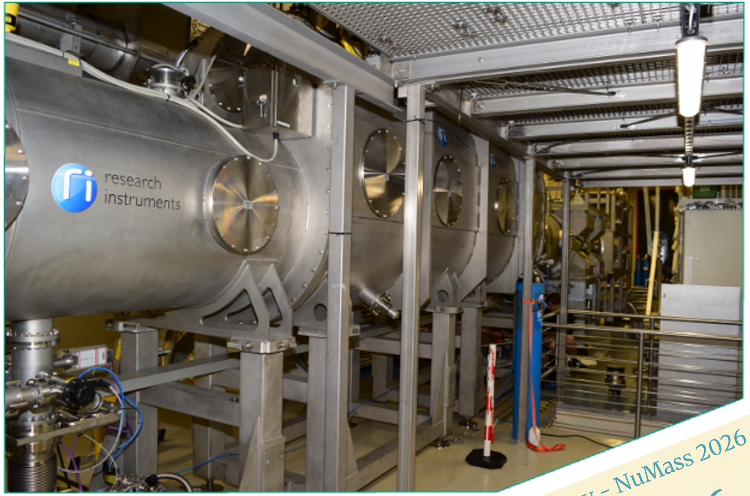
Search for neutrino mass - 8 decades of tritium source evolution
Beate Bornschein

Why a solid tritium source was not an option for KATRIN
Lutz Bornschein

2.5 T

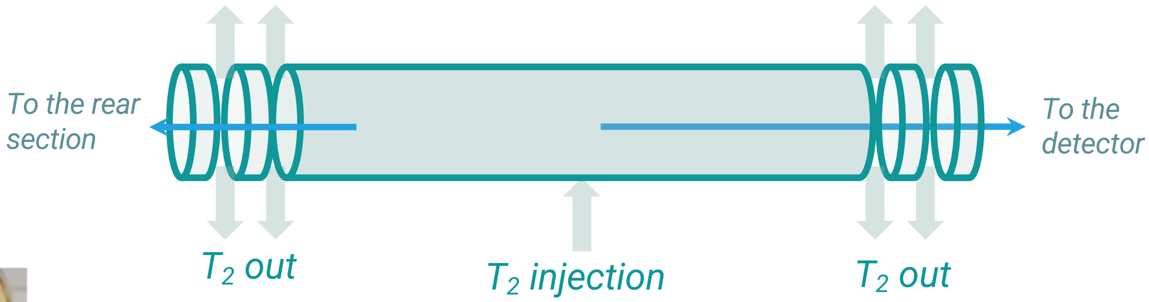
80 K

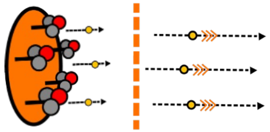
> 95% T_2, ~ 5×10^{17} T_2/cm^2



The two ends of KATRIN

Rear section



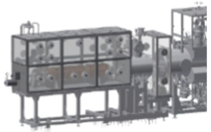


Rear wall: ⌀ 145 mm gold coated back wall of the source

⇒ provides a well-defined surface and starting potential of the electrons

Calibration systems (e.g. Electron gun)

The two ends of KATRIN



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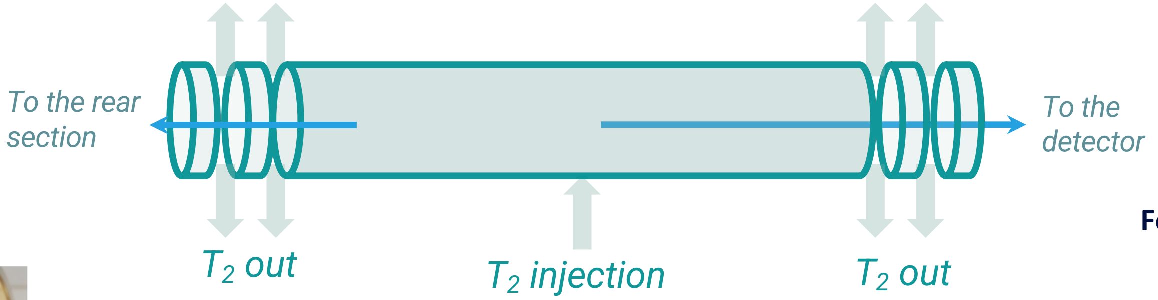
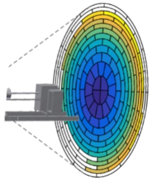
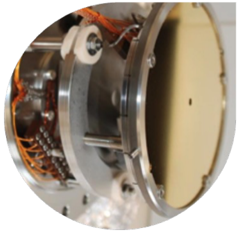
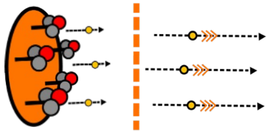




Focal plane detector





Segmented Si PIN diode

- ⌀ 90 mm
- 148 pixels

Active veto and shielding

Energy resolution: ~ 1keV

Topical session: Data analysis
→ Sanshiro Enomoto

Electron backscattering at the Focal Plane Detector (FPD) of KATRIN
Philipp Lingnau

Rear wall: ⌀ 145 mm gold coated back wall of the source

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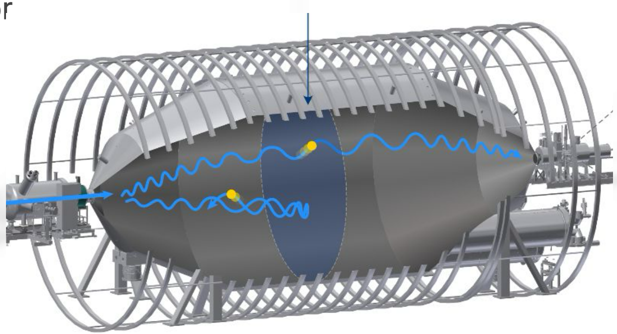
Calibration systems (e.g. Electron gun)

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


Main spectrometer

KATRIN collaboration, JINST 16 (2021) T08015

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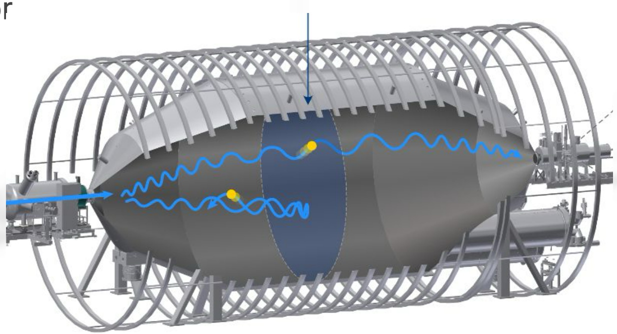
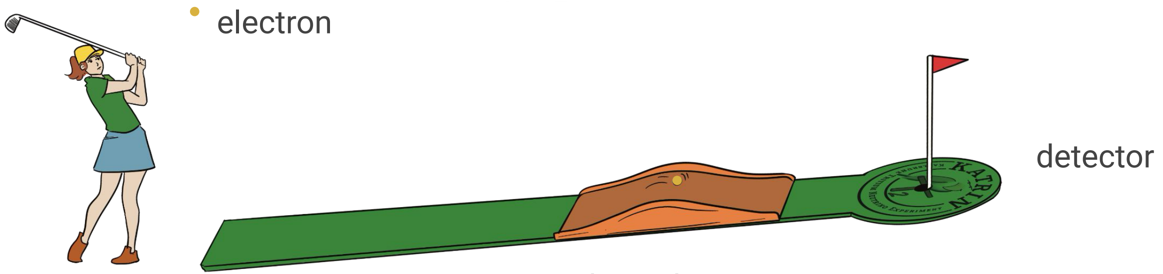


Electrostatic filter principle:
"the mini golf"



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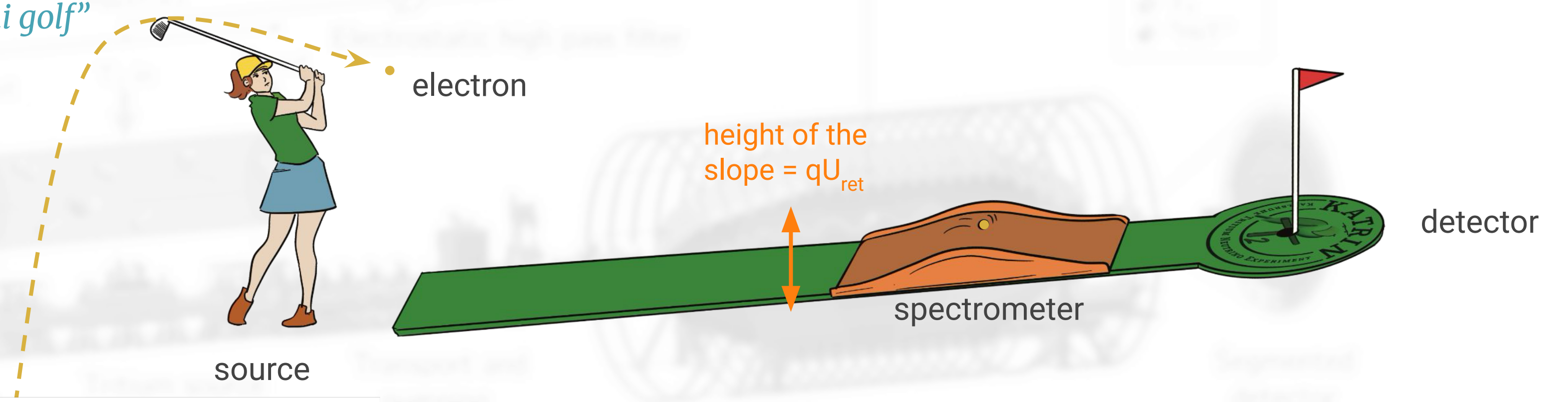

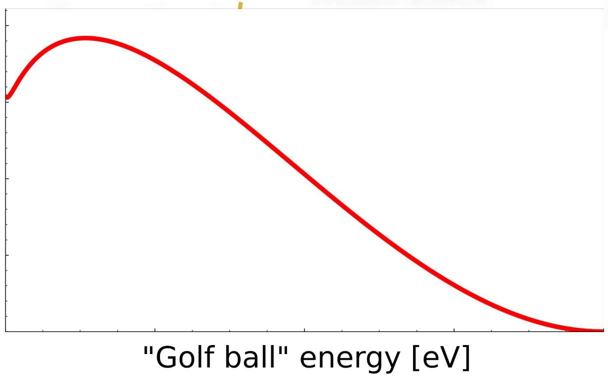

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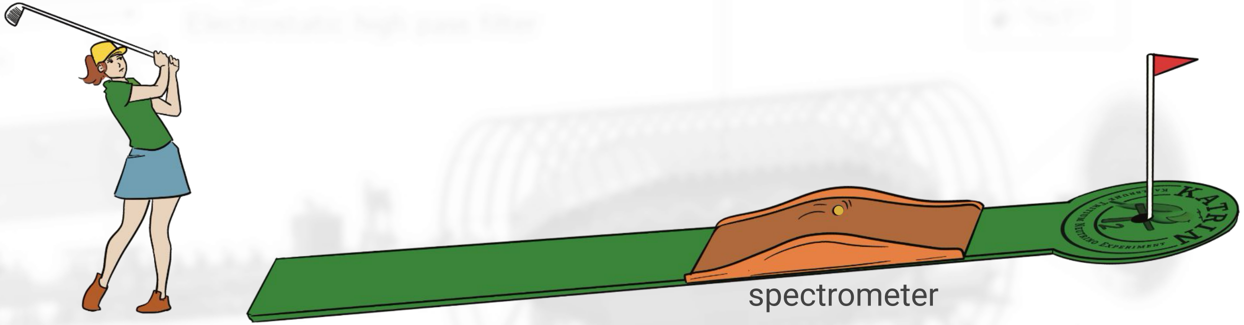

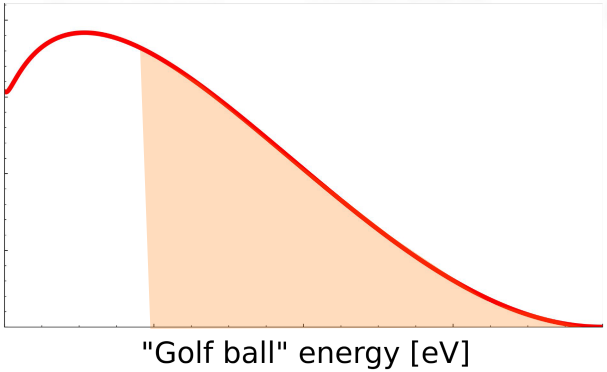

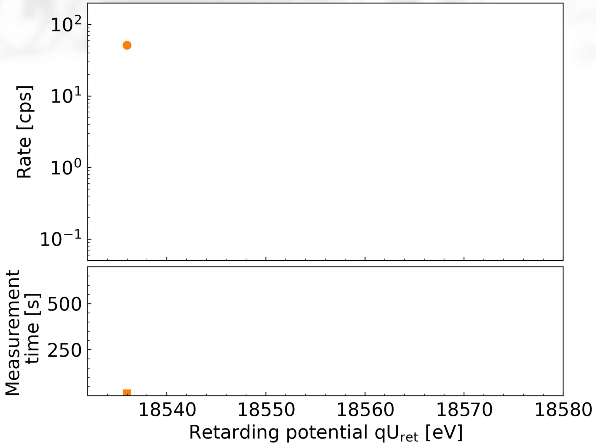

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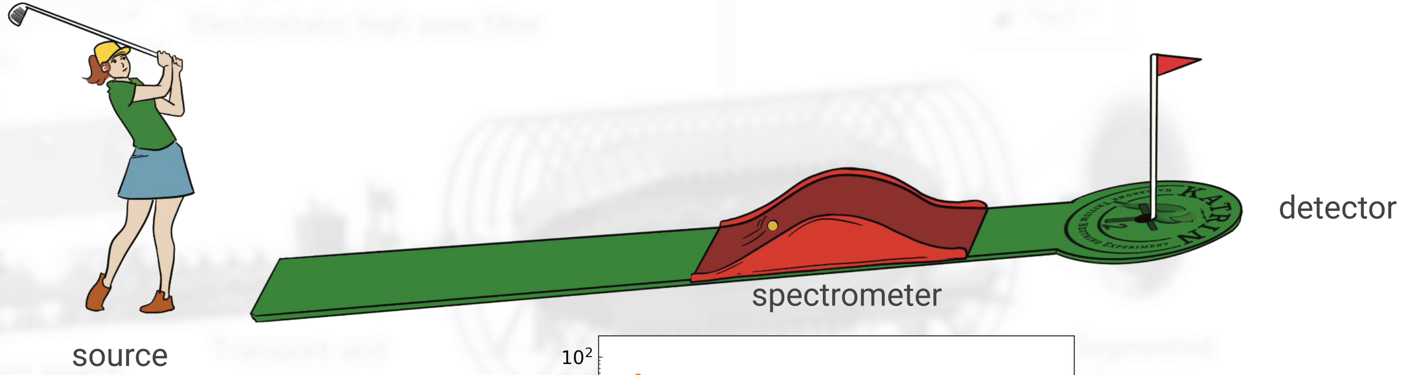

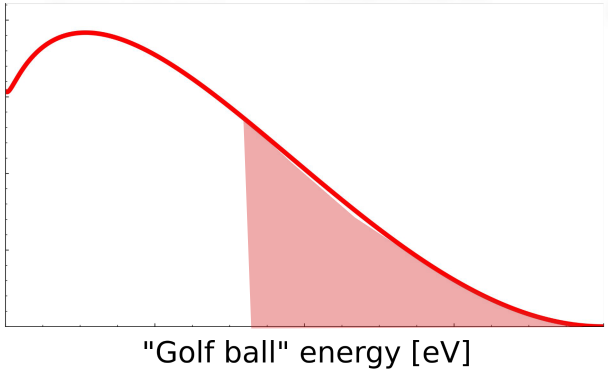

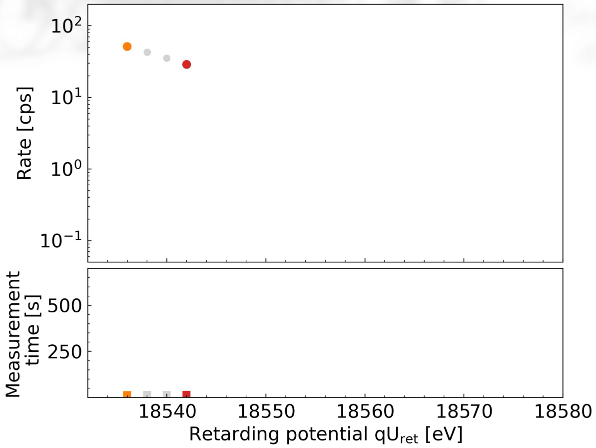

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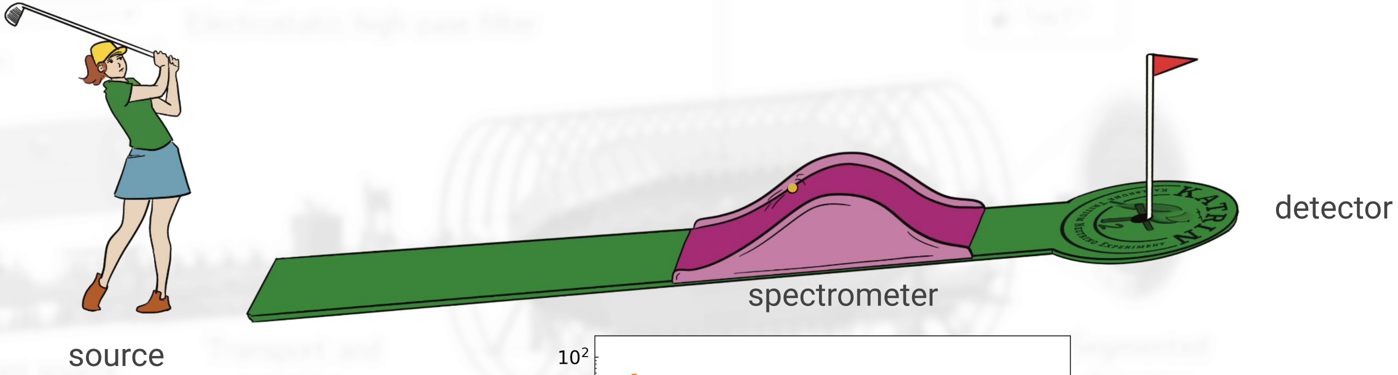

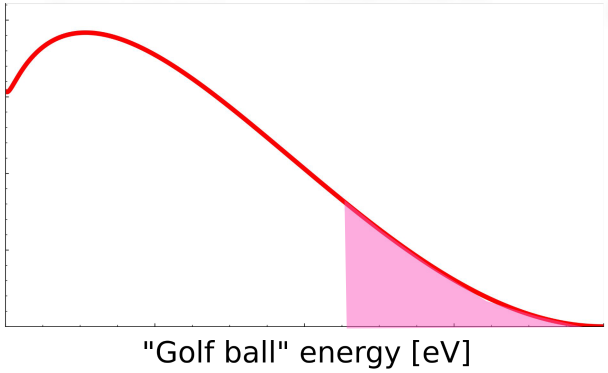

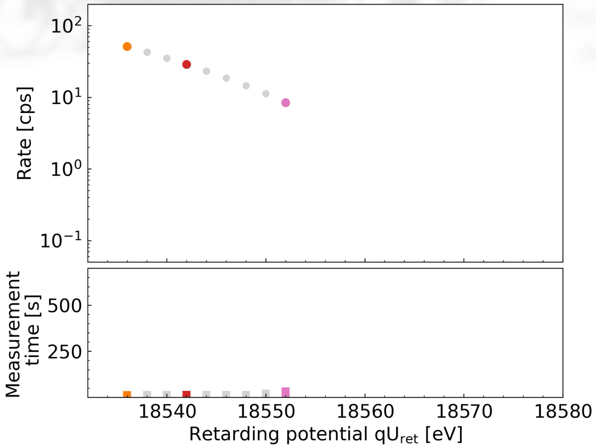

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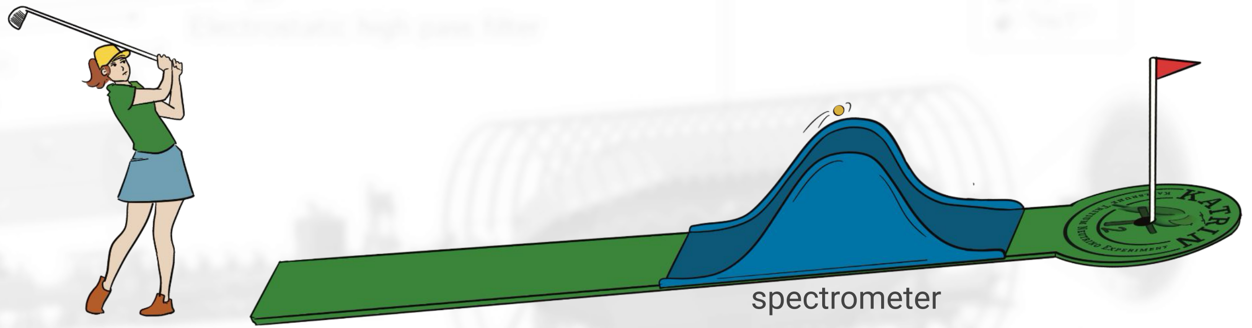

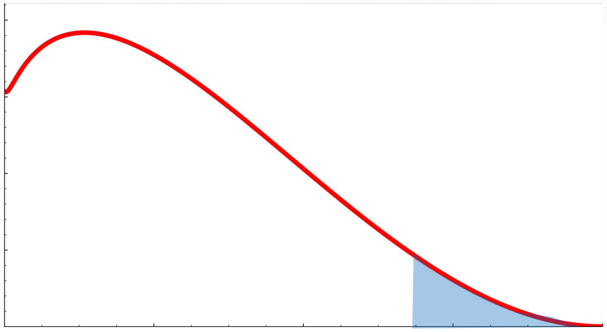

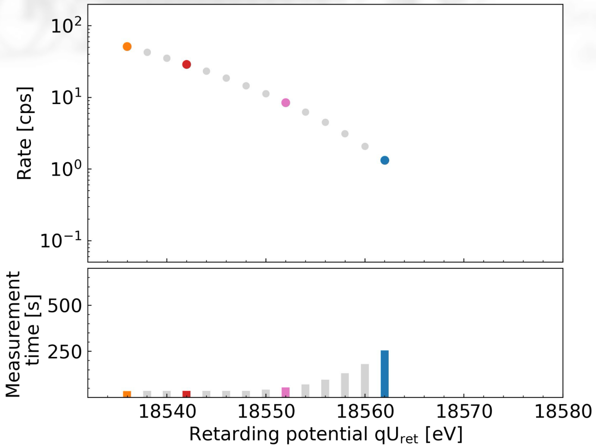

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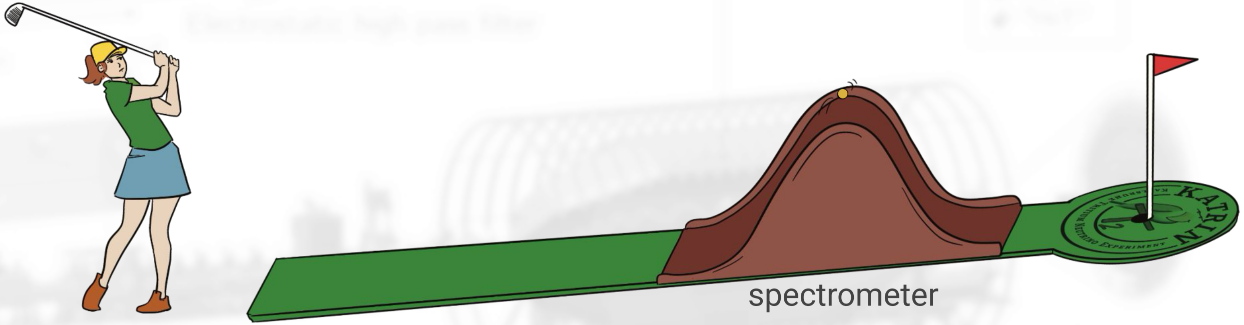

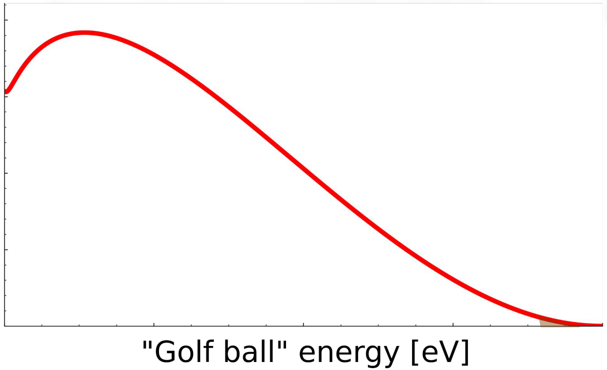

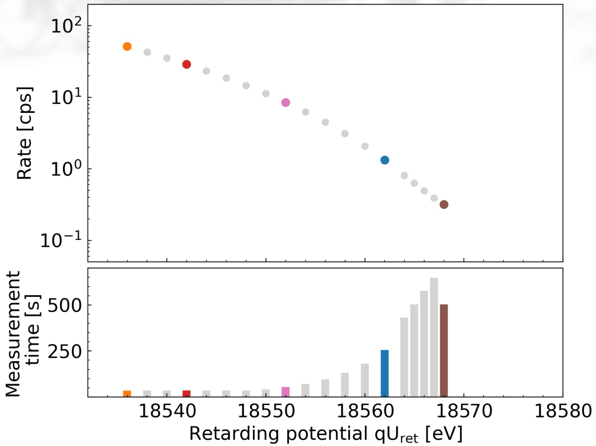

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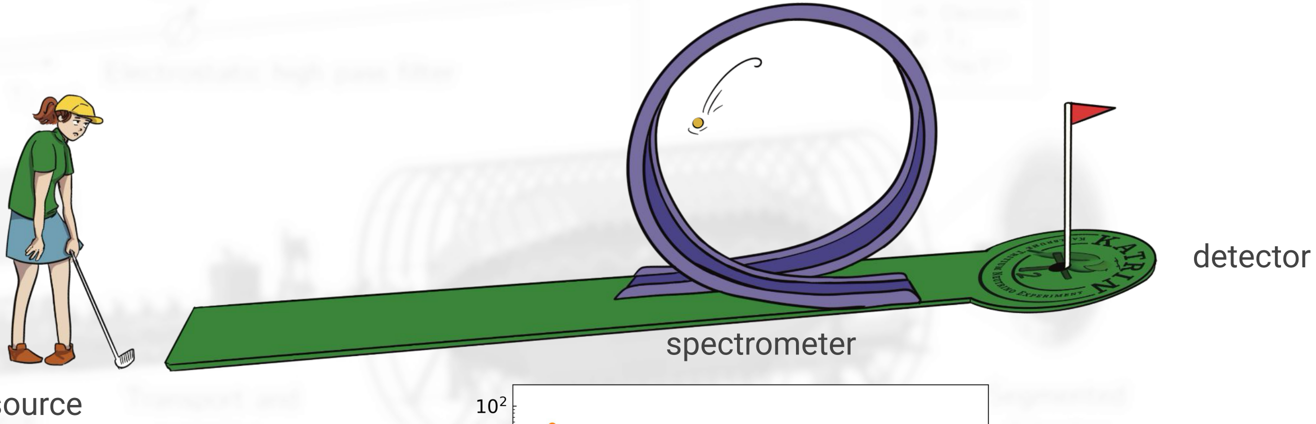

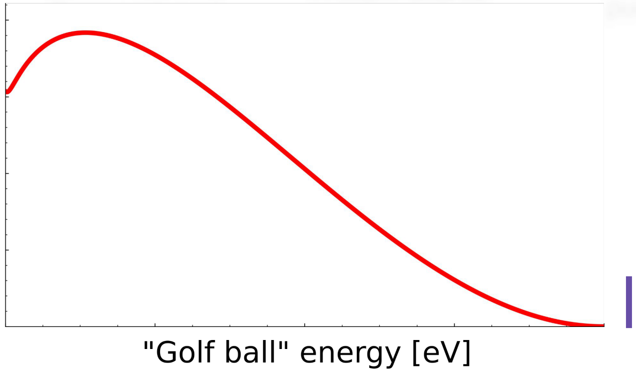

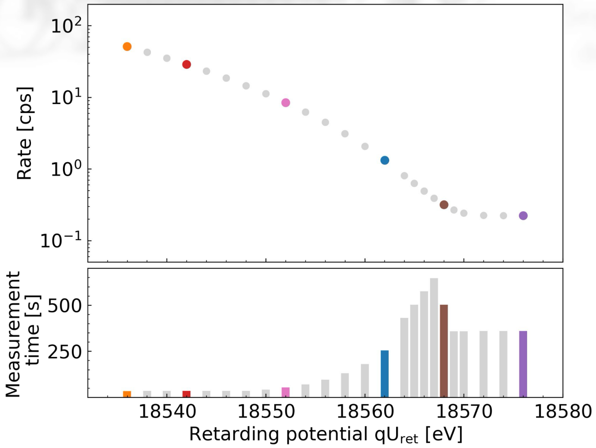

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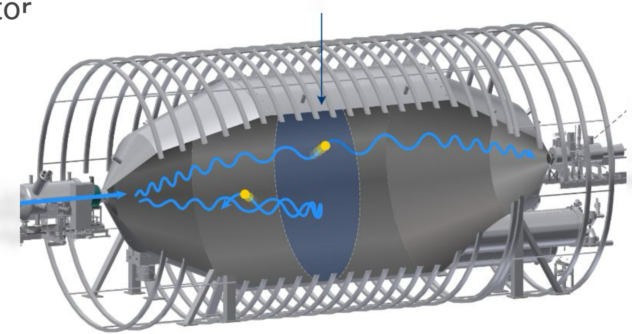
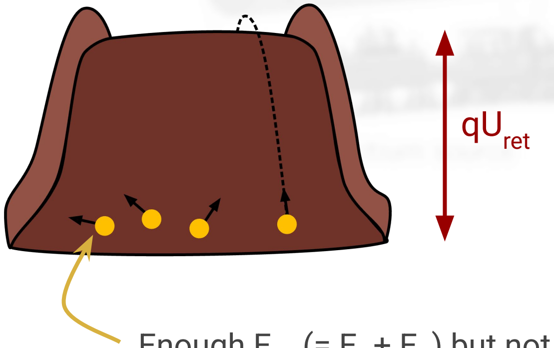


Magnetic adiabatic collimation principle:



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

⇒ **transform $E_{\perp}$ into $E_{//}$**

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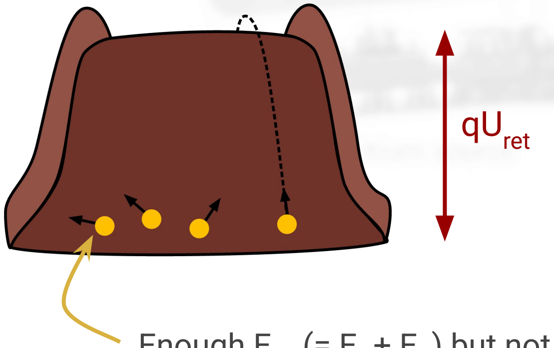

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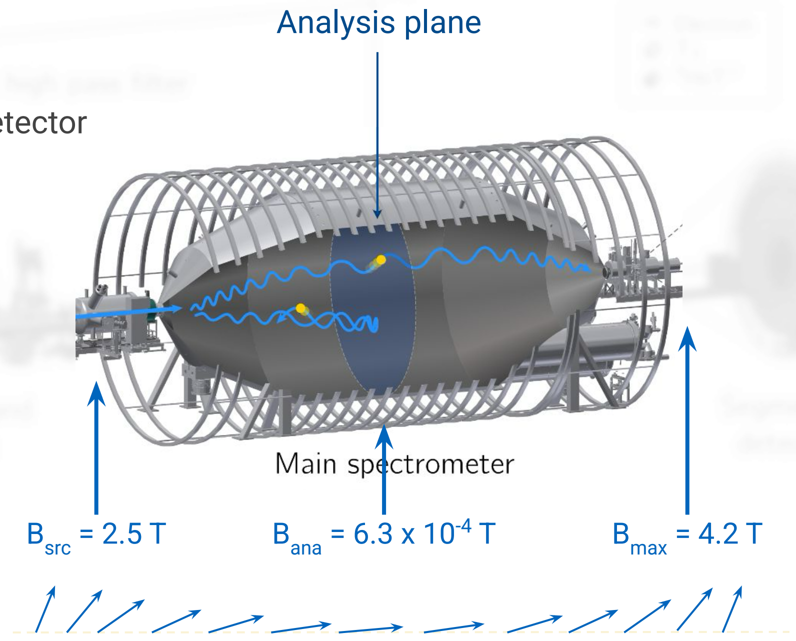

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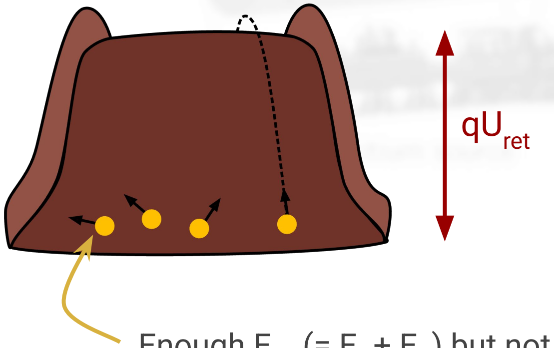

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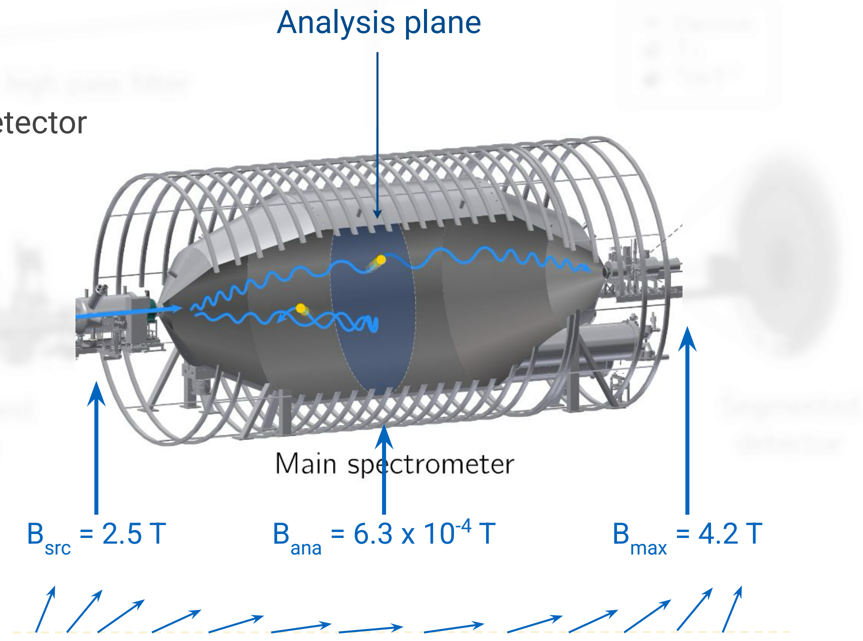

→ Energy resolution from the minimum $E_\perp$ at the analysis plane:

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

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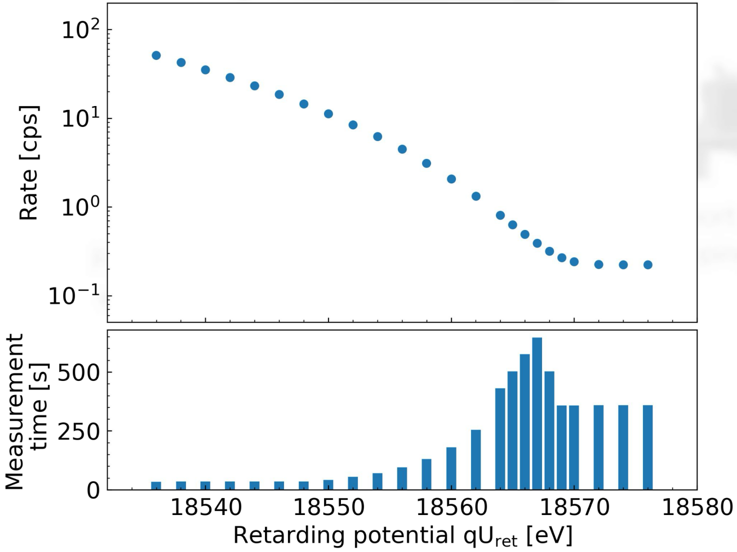
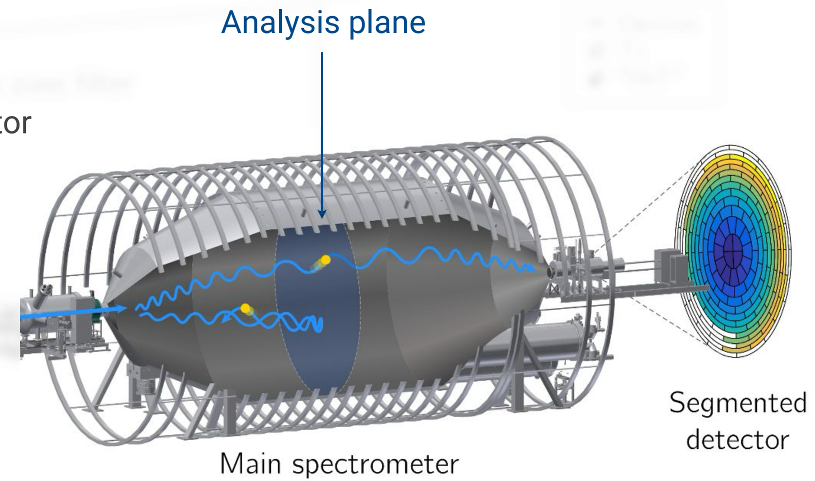




→ Vary retarding potential to **scan spectrum**
→ Count events at the detector
→ **Integral spectrum** (2-3h in total)
→ **Repeat** scanning procedure a few 100 times to obtain **one measurement campaign (KNM*)**

KATRIN collaboration, JINST 16 (2021) T08015

Data taking status

Latest results and future analyses

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

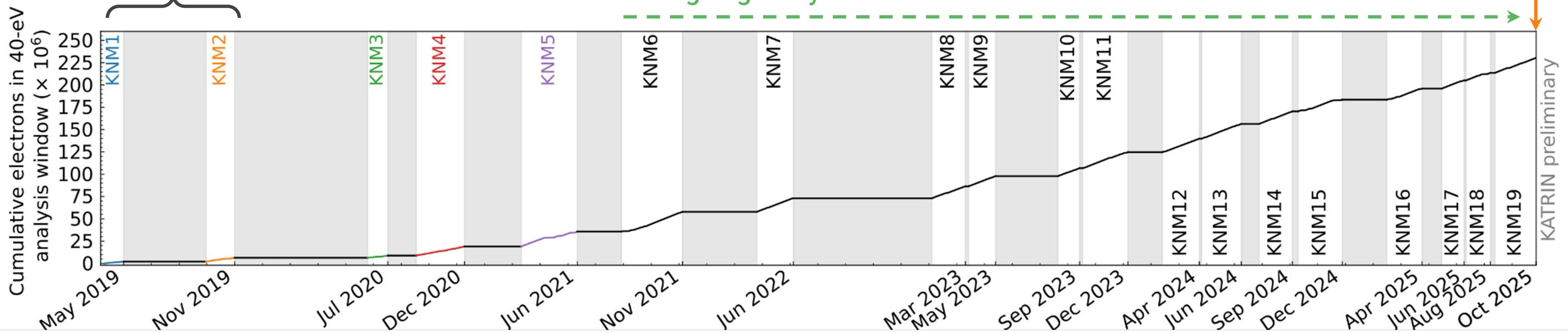
[M. Aker et al., Nature Phys. 18 (2022) 2, 160-166]

Analysis strategies for determining the neutrino mass with the final KATRIN data set
Jan Plößner, Karo Erhardt, Khushbakht Habib, and Svenja Heyns

On-going analysis

~ 240M electrons in the last 40 eV!

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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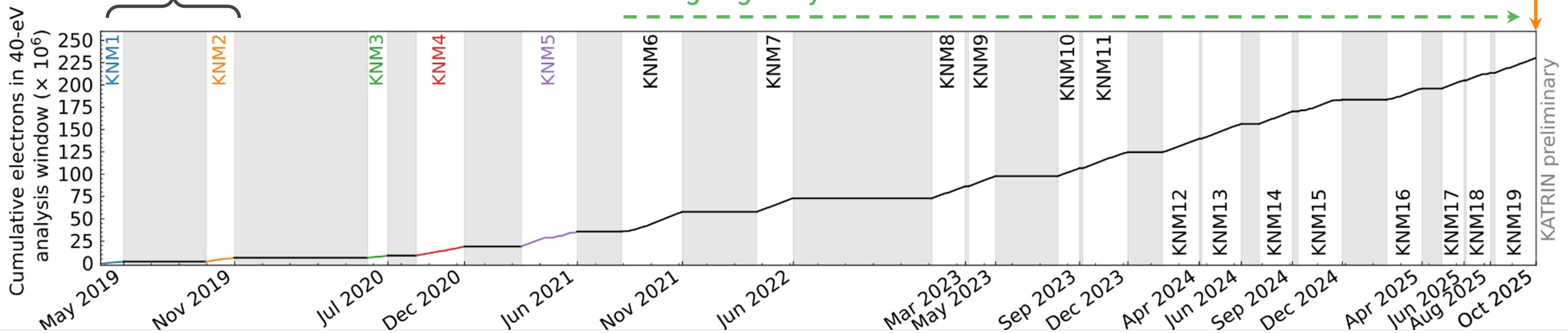

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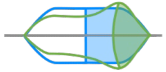
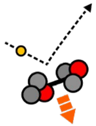


Shifted analysis plane:
→ reduce the background by a factor 2
[Lokhov et al., EPJ C 82 (2022)]

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)]

Neutrino mass analysis and latest result

Data taking status

Latest results and future analyses

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

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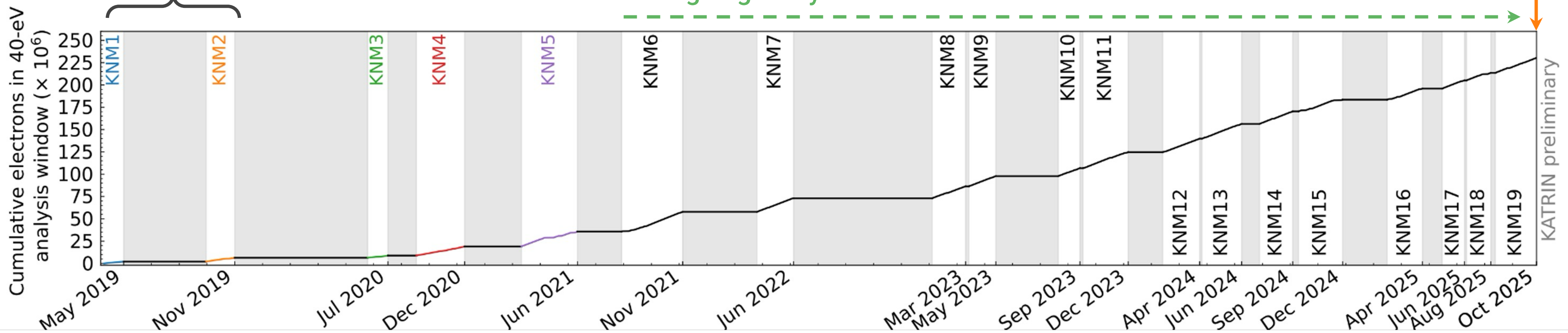
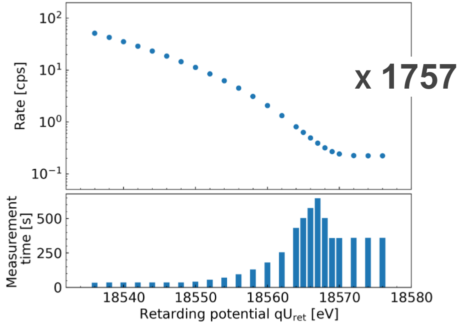


[KATRIN collaboration, *Science* 388,180-185(2025)]
[KATRIN collaboration, *Nature* volume 648, pages 70–75 (2025)]

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



Data taking status

Latest results and future analyses

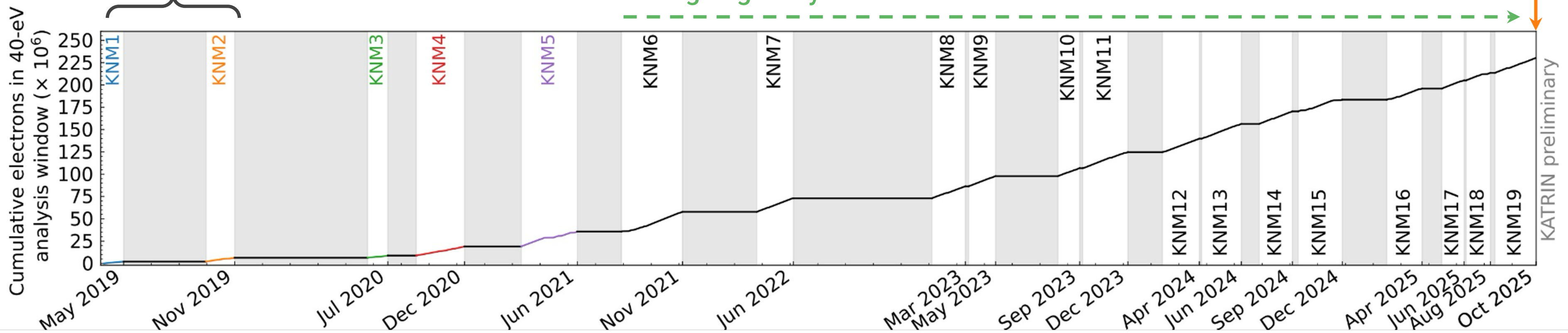
m_ν < 0.8 eV (90% CL)

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

On-going analysis

~ 240M electrons in the last 40 eV!

1000 days of neutrino mass data!



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

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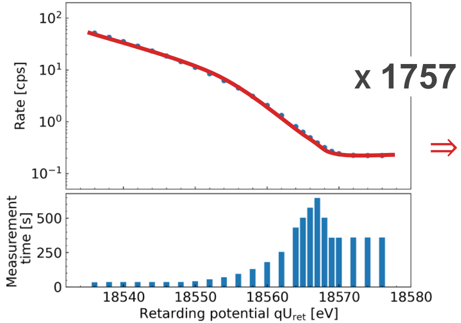


x 1757

⇒ **Model**

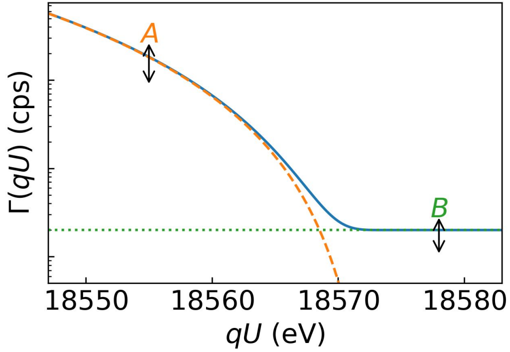
Spectrum modeling and input parameters

Integrated spectrum

Topical session: Data analysis
Khushbackht Habib and Sanshiro Enomoto

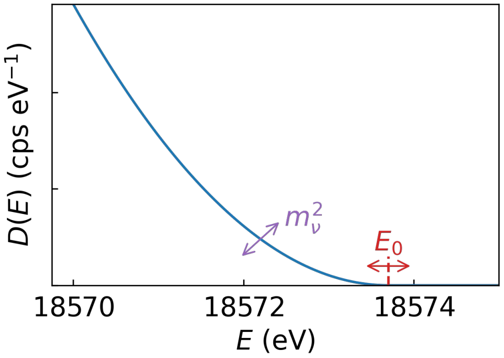
$$\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$$

integral spectrum measured at the detector



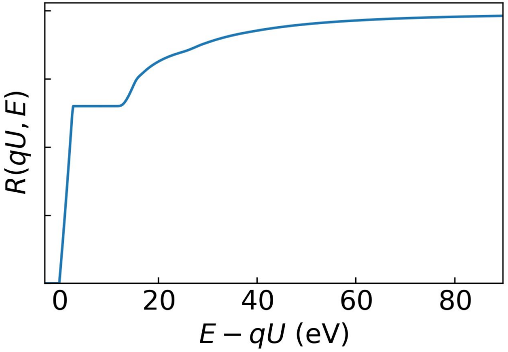
=

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

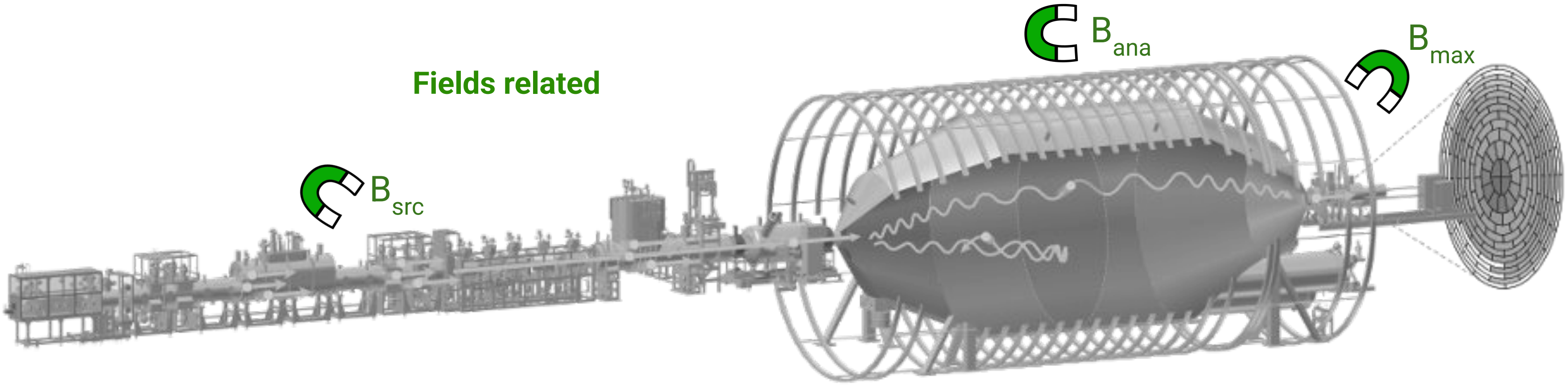
Spectrum modeling and input parameters

KATRIN systematics overview

Topical session: Background and Systematic
Sonja Schneidewind

Topical session: Calibration
Christoph Köhler and Rudolf Sack

Fields related



Spectrum modeling and input parameters

KATRIN systematics overview

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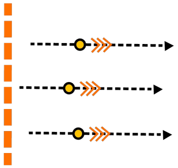
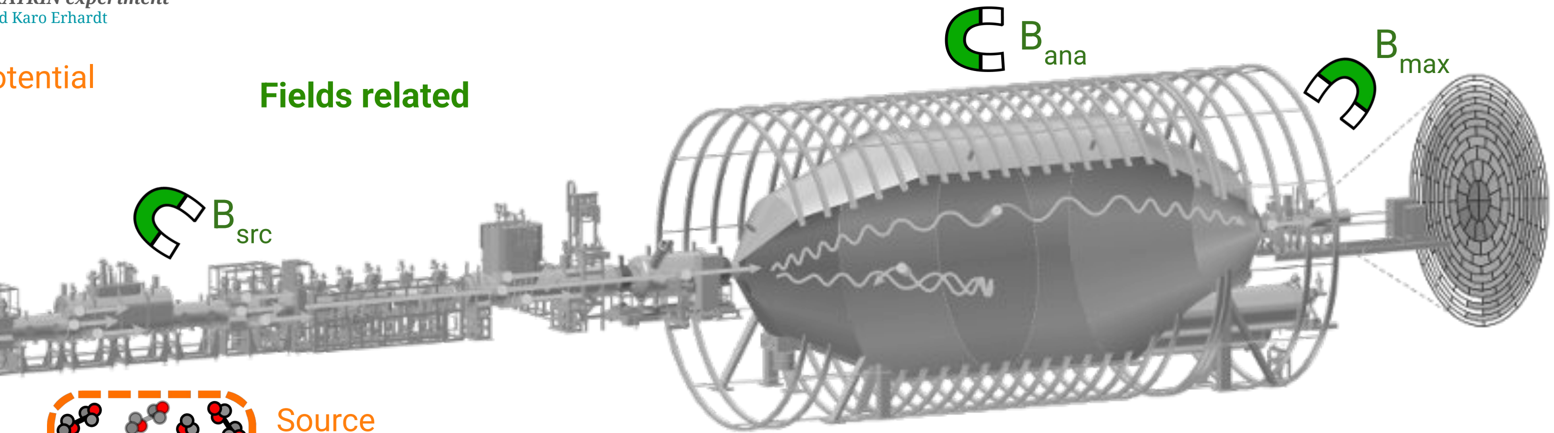
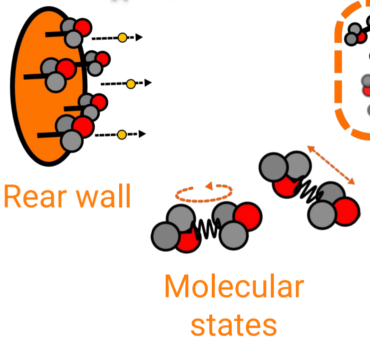
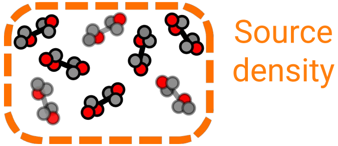
Measurement of the source electric potential the KATRIN experiment
Jaroslav Storek and Karo Erhardt



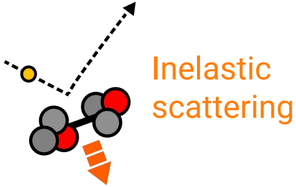






Source related

Measurement of the Tritium Column Density at the KATRIN Experiment
Christoph Köhler and Neven Kovac



Extended range measurement of the KATRIN energy loss function up to 200 eV
Justus Beisenkötter

Simulation of source scattering systematic for KATRIN
Chloé Goupy and Xaver Stribl

Spectrum modeling and input parameters

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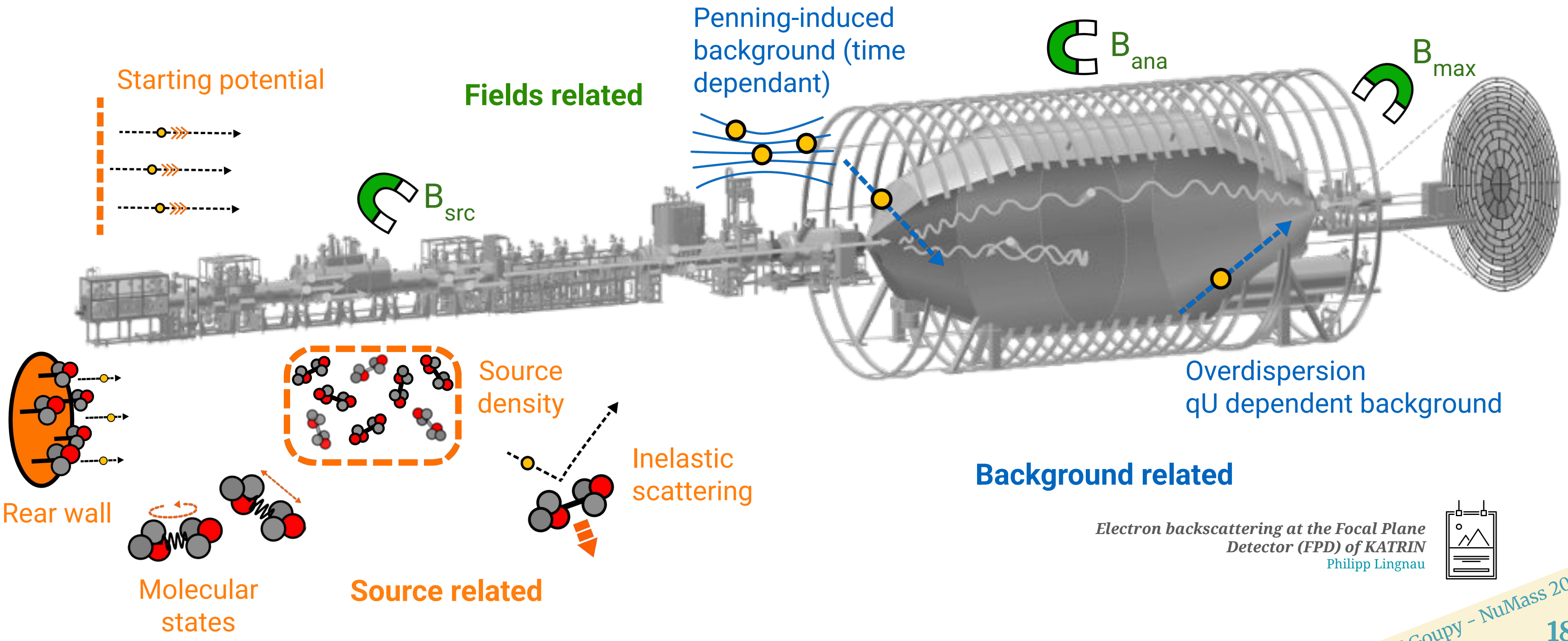


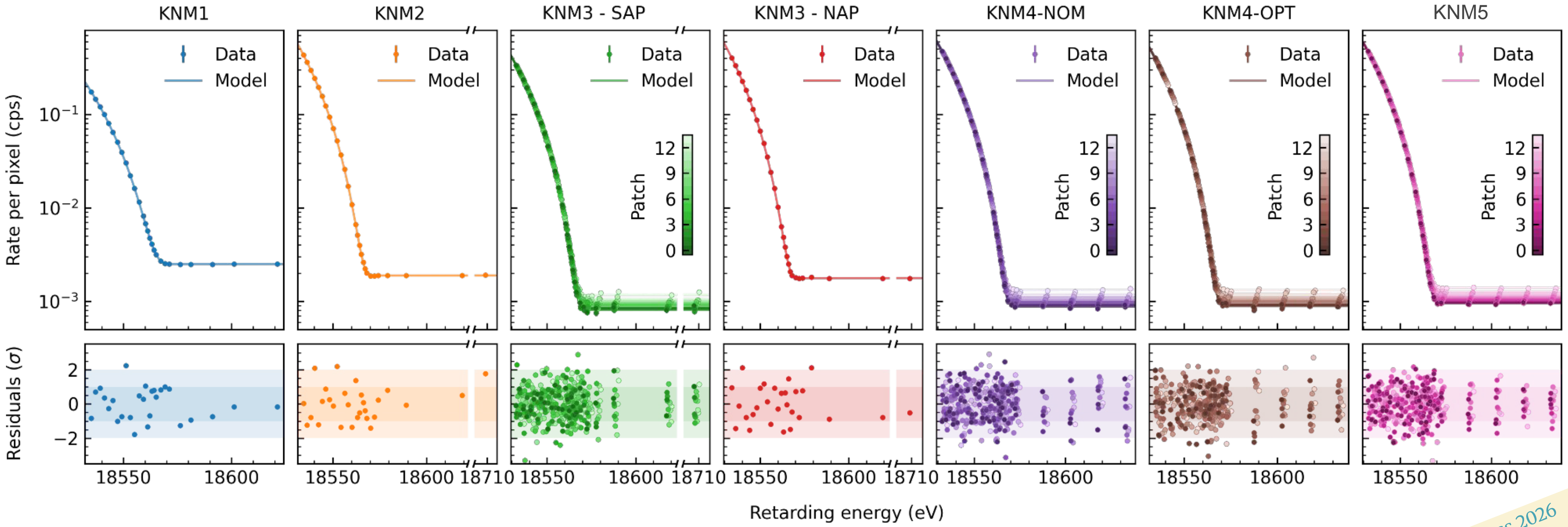
Electron backscattering at the Focal Plane Detector (FPD) of KATRIN
Philipp Lingnau

Neutrino mass result, KNM1 to 5

Topical session: Data analysis
Khushbackht Habib and Sanshiro Enomoto

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 free and constrained parameters)

Neutrino mass result, KNM1 to 5

Topical session: Data analysis
Khushbackht Habib and Sanshiro Enomoto

- **Two steps blinding procedure and 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): $m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$

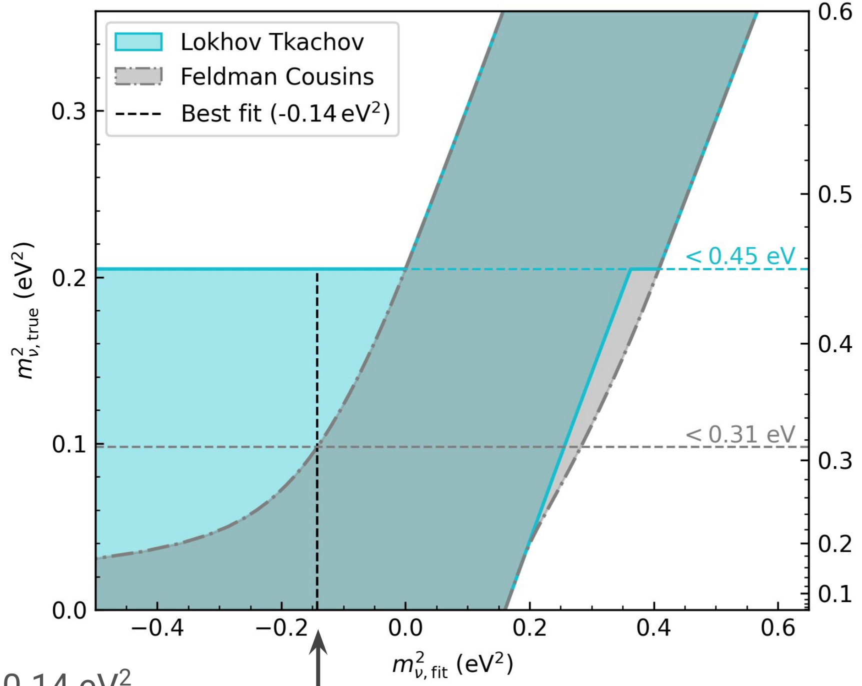
- **Statistics dominated**, systematics non-negligible

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

Neutrino mass limit

Topical session: Data analysis
Khushbackht Habib and Sanshiro Enomoto

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



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

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

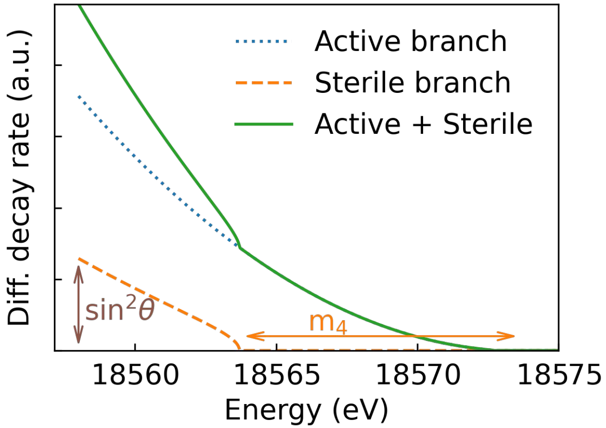
KATRIN beyond the neutrino mass

Probing Light Sterile neutrinos

Sterile-neutrino search based on 259 days of KATRIN data
Christoph Köhler and Xaver Stribl

[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:** 4^{th} neutrino mass
  → **$\sin(\theta)$:** 4^{th} neutrino mixing



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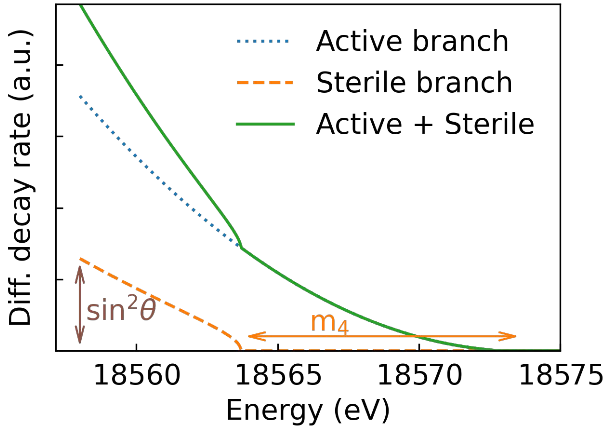
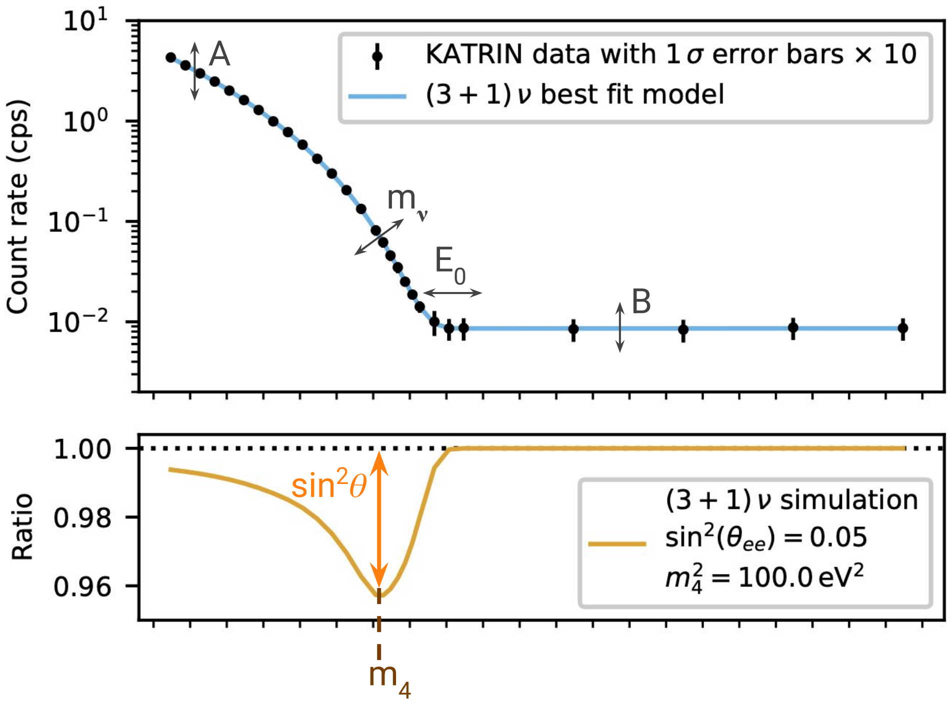




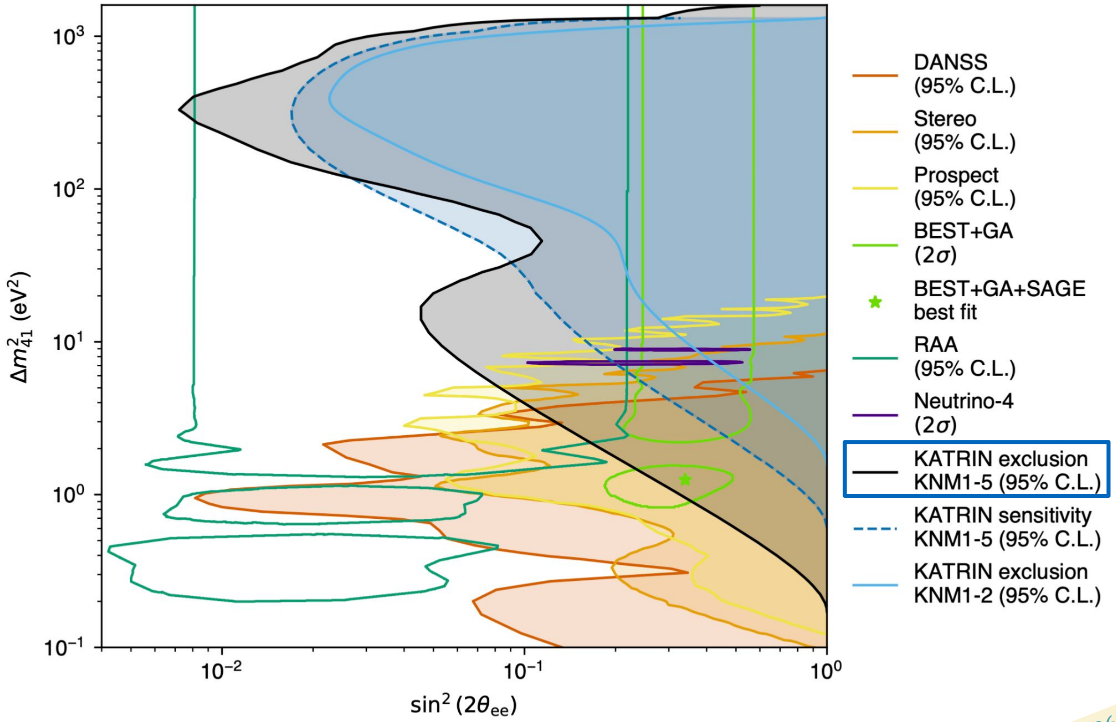
Probing Light Sterile neutrinos

Sterile-neutrino search based on 259 days of KATRIN data
Christoph Köhler and Xaver Stribl

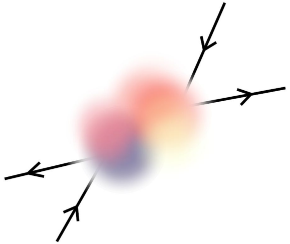
- KATRIN can probe **eV-sterile neutrinos signature** near the tritium end point

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

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

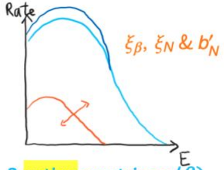


Other Beyond the Neutrino Mass Analyses



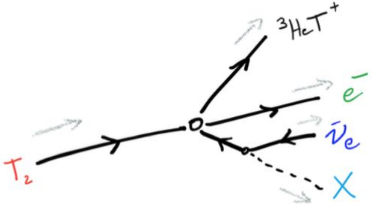
General neutrino interactions

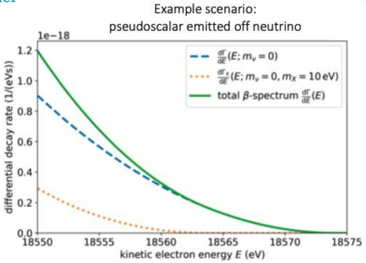
[The KATRIN collaboration, Physical Review Letters 134, 251801 (2025)]



Search for new light bosons

Probing new light bosons with the KATRIN experiment
Joschua Lauer

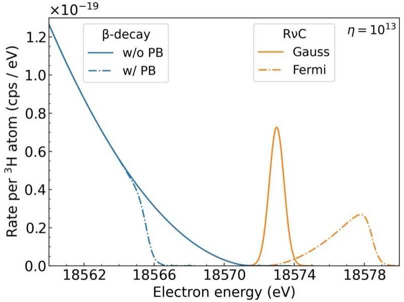




Probing relic neutrino background

[Aker et al., Phys. Rev. Lett. 129, 01180 (2022)]

Search for Local Relic Neutrino Overdensities with the KATRIN experiment
Alessandro Schwemmer



Extra dimensions, Lorentz invariance violation, Ultralight Axion Oscillations…

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

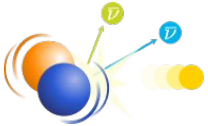
Just after KATRIN neutrino mass…

Comes TRISTAN

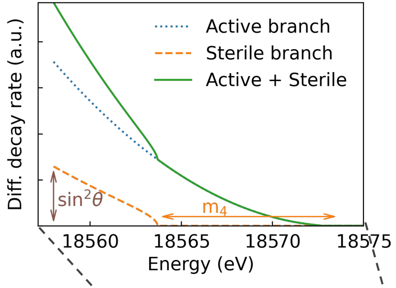
Sterile neutrinos at KATRIN

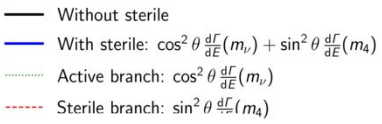
[Siegmann et al., J. Phys. G: Nucl. Part. Phys. 51 085202 (2024)]
[S. Mertens *et al.*, JCAP02(2015)020]

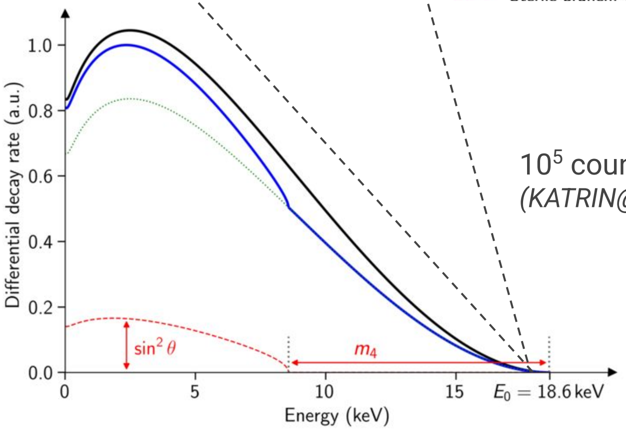
But heavier!



Search for keV sterile neutrino with the TRISTAN detector at KATRIN
Anthony Onillon







10^5 counts per seconds/pixel
(KATRIN@40 eV ~ 0.6 cps)

Sterile neutrinos at KATRIN

[Siegmann et al., J. Phys. G: Nucl. Part. Phys. 51 085202 (2024)]
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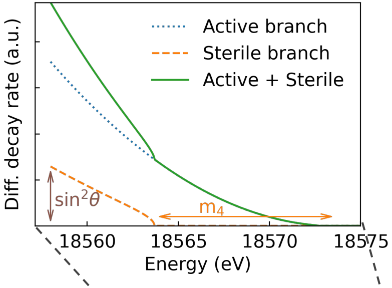
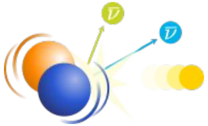
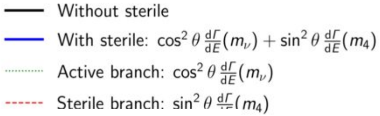
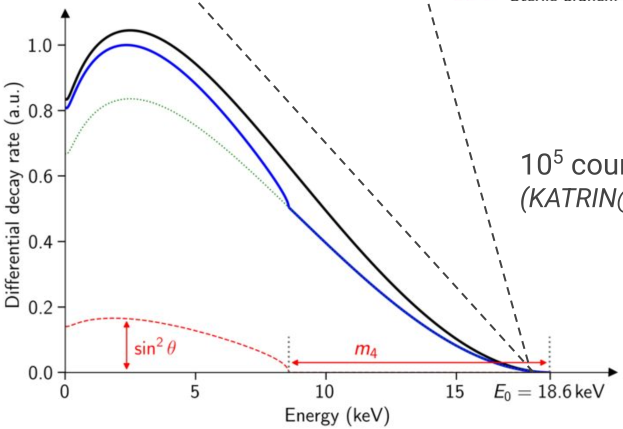
But heavier!









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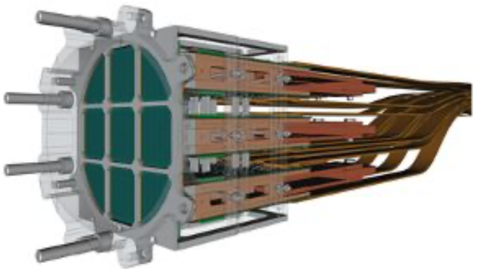
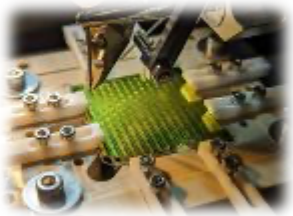
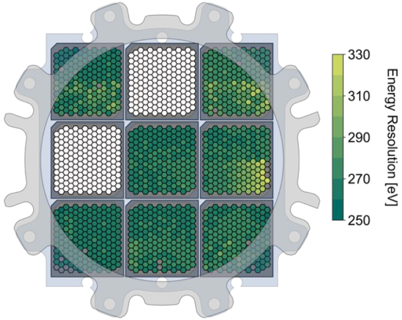
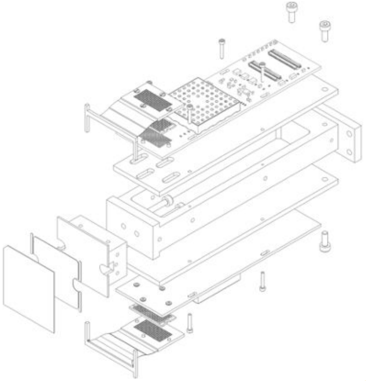
Search for keV sterile neutrino with the TRISTAN detector at KATRIN
Anthony Onillon

The TRISTAN detector





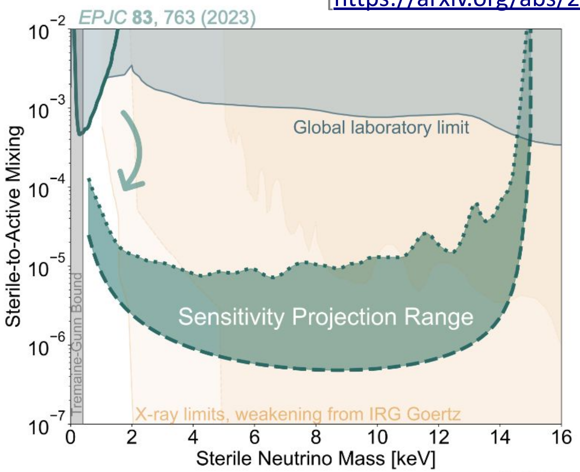




Magnetic-field compatibility and longterm-stability of TRISTAN detectors for the KATRIN keV sterile neutrino search
Fiona Braun and Simon Gentner

TRISTAN sensitivities and analysis challenges

[https://arxiv.org/abs/2603.23256]



Search for keV sterile neutrino with the TRISTAN detector at KATRIN
Anthony Onillon

4-months measurement:

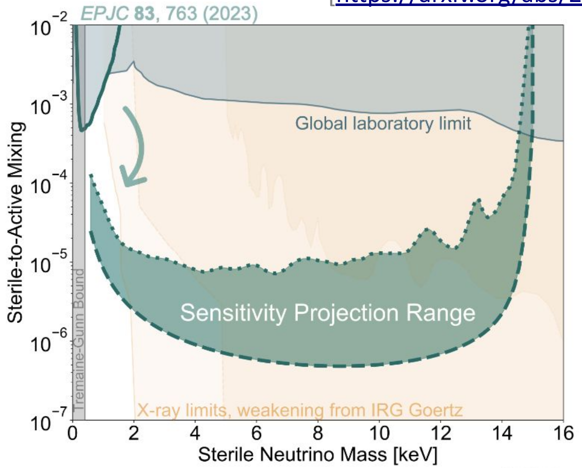
4×10^{14} electrons !

Search of part per million signature

⇒ **Precise, accurate and fast analysis strategy**

TRISTAN sensitivities and analysis challenges

[https://arxiv.org/abs/2603.23256]



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4 x 10^{14} electrons !

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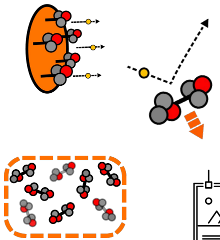


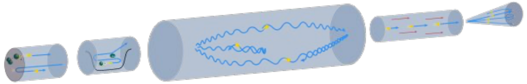
Strong control of systematics uncertainties

Measurement of the Electron Backscattering on the KATRIN Rear Wall
Justus Beisenkötter, Neven Kovac and Rudolf Sack

Qualification measurements towards a new KATRIN Rear Wall
Kerstin Trost

Precision modeling dealing with extremely large statistics

Detailed Monte Carlo



KAMELEON: a montecarlo and analytical approach to simulating electrons in the KATRIN beamline
Giugliio Galliardi and Tom Geigle

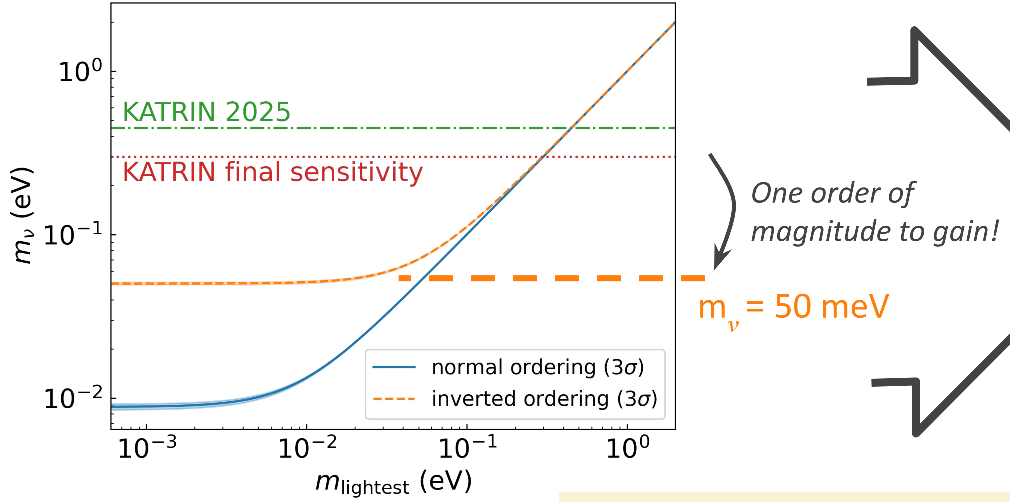
Machine learning driven response modelling

Search for keV-Scale Sterile Neutrinos with TRISTAN at KATRIN Using Neural Simulation-Based Inference
Luca Fallböhmer

About next-generation direct neutrino-mass experiments

R&D Using KATRIN and TLK infrastructure

After TRISTAN, can KATRIN be used for new generation R&D?

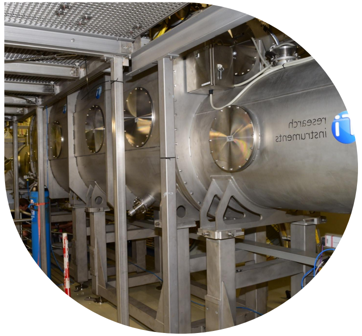


Next generation of direct neutrino mass experiments:

- Electron capture on Holmium
- **Atomic Tritium sources**
- **Differential spectrum measurement**

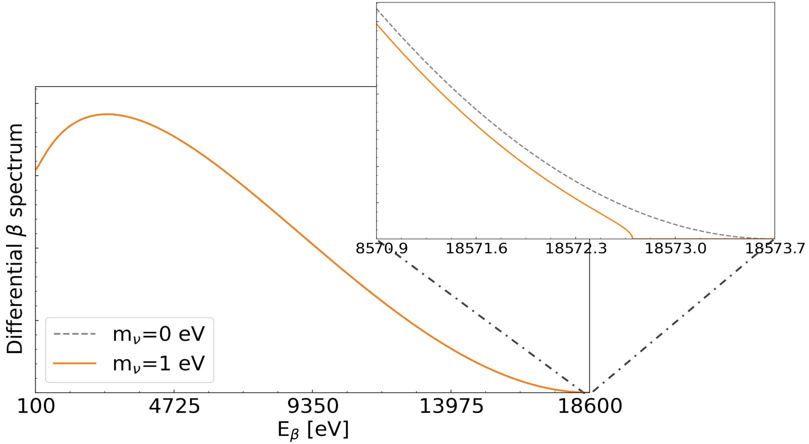
KATRIN++ mission:

→ Next generation neutrino mass experiment
→ Identify and develop scalable technology
→ Use KATRIN/TLK infrastructure for R&D phase



Improve the sensitivity: 2-key parameters

1- Differential measurement

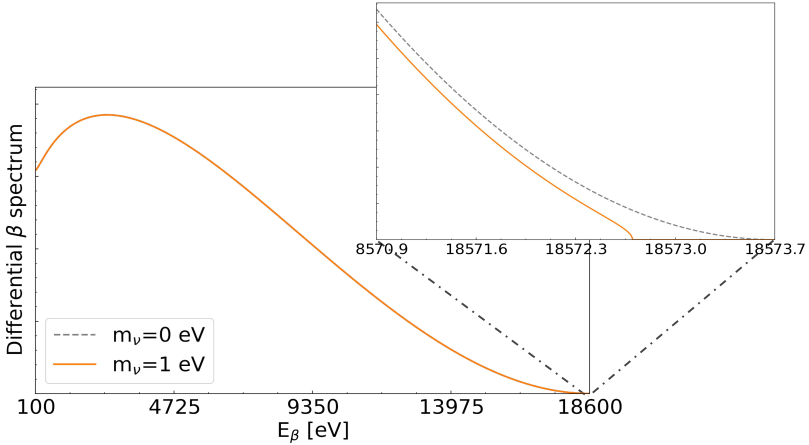


- ❖ Full use of data taking time
  - ➢ **gain of statistics**
- ❖ Need of sub-eV resolution
  - ➢ **To reach ≲ 50 meV sensitivities**

Improve the sensitivity: 2-key parameters

Sensitivities beyond KATRIN: first steps towards a next-generation neutrino mass experiment
Chloé Goupy, Svenja Heyns and Neven Kovac

1- Differential measurement



- Full use of data taking time
  - ➢ **gain of statistics**
- Need of sub-eV resolution
  - ➢ **To reach ≲ 50 meV sensitivities**

Not enough if we don't use atomic tritium

Improve the sensitivity: 2-key parameters

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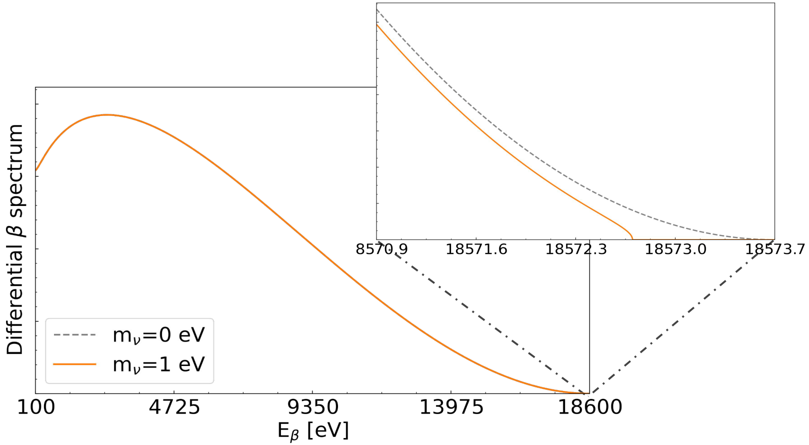
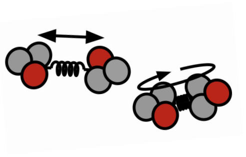
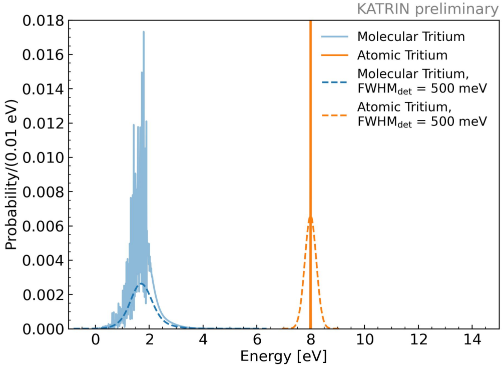


- ❖ Full use of data taking time
  - ➢ **gain of statistics**
- ❖ Need of sub-eV resolution
  - ➢ **To reach ≲ 50 meV sensitivities**

2- Atomic Tritium

- ❖ Get rid of the intrinsic broadening of the molecular tritium final state (~ 1 eV FWHM)
  - ➢ **gain in resolution**





- ❖ Larger ground state probability (*Molecular ~ 0.57* vs *Atomic ~ 0.7*)
- ❖ *for gaseous sources:* smaller scattering probability for atomic tritium
  - ➢ **gain of statistics**

"KATRIN++": investigations of these two keys

1- Differential measurement

Time-of-flight by electron tagging

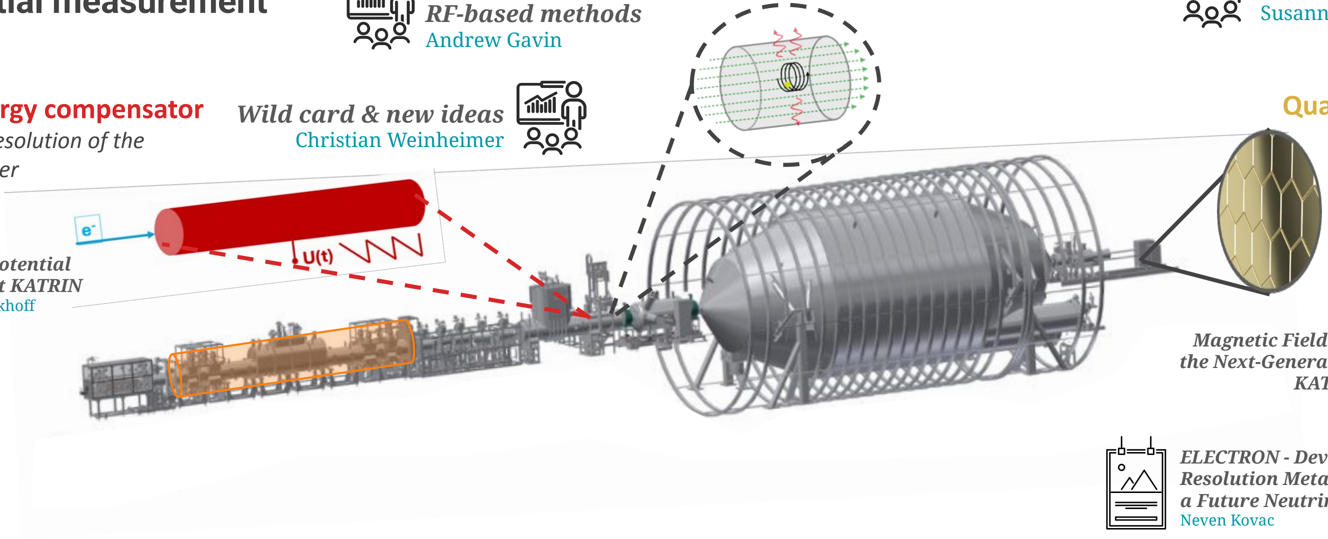
RF-based methods
Andrew Gavin

Strategy and synergies
Susanne Mertens

Transverse energy compensator
Improves energy resolution of the MAC-E spectrometer

Wild card & new ideas
Christian Weinheimer

Quantum sensor array
Via MMCs or TES



Test setup for a potential electron tagger at KATRIN
Patrick Alexander Unkhoff

Magnetic Field Simulations for the Next-Generation MMC-Based KATRIN Experiment
Carlotta Buchner

ELECTRON - Development of High Resolution Metallic Microcalorimeters for a Future Neutrino Mass Experiment
Neven Kovac

"KATRIN++": investigations of these two keys

1- Differential measurement

Time-of-flight by electron tagging

RF-based methods
Andrew Gavin

Strategy and synergies
Susanne Mertens

Transverse energy compensator
Improves energy resolution of the MAC-E spectrometer

Wild card & new ideas
Christian Weinheimer

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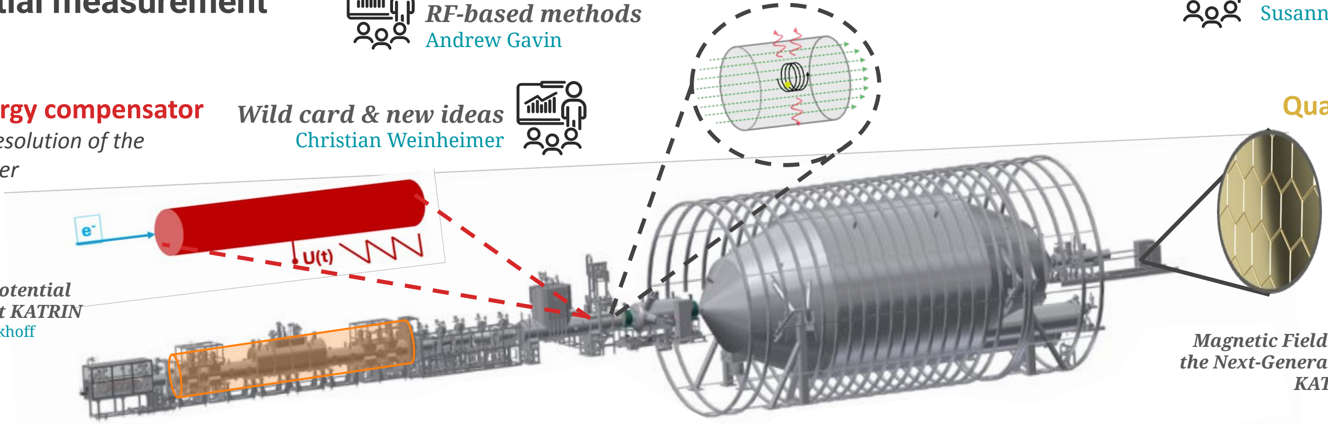

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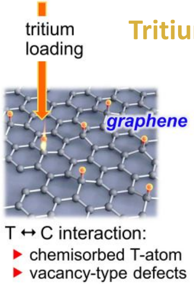
2- Atomic Tritium

Magnetically-trapped cold tritium atoms

Topical session: Atomic Tritium
Caroline Rodenbeck and Marco Röllig



Tritium atoms bound to graphene

Topical session: Tritiated graphene
Genrich Zeller

A graphene-based atomic hydrogen sensor
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Characterization of a Mass Spectrometer for Atomic Tritium Source Studies
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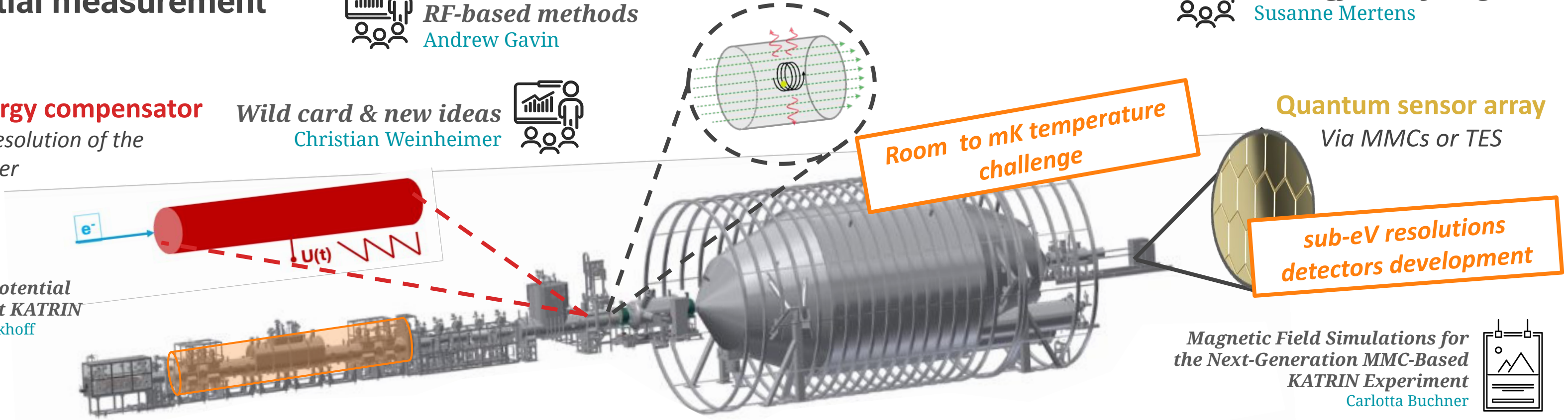

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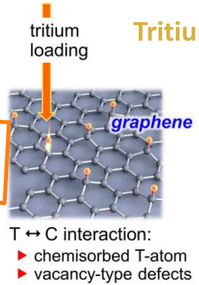
Magnetically-trapped cold tritium atoms

Production and trapping of atomic Tritium



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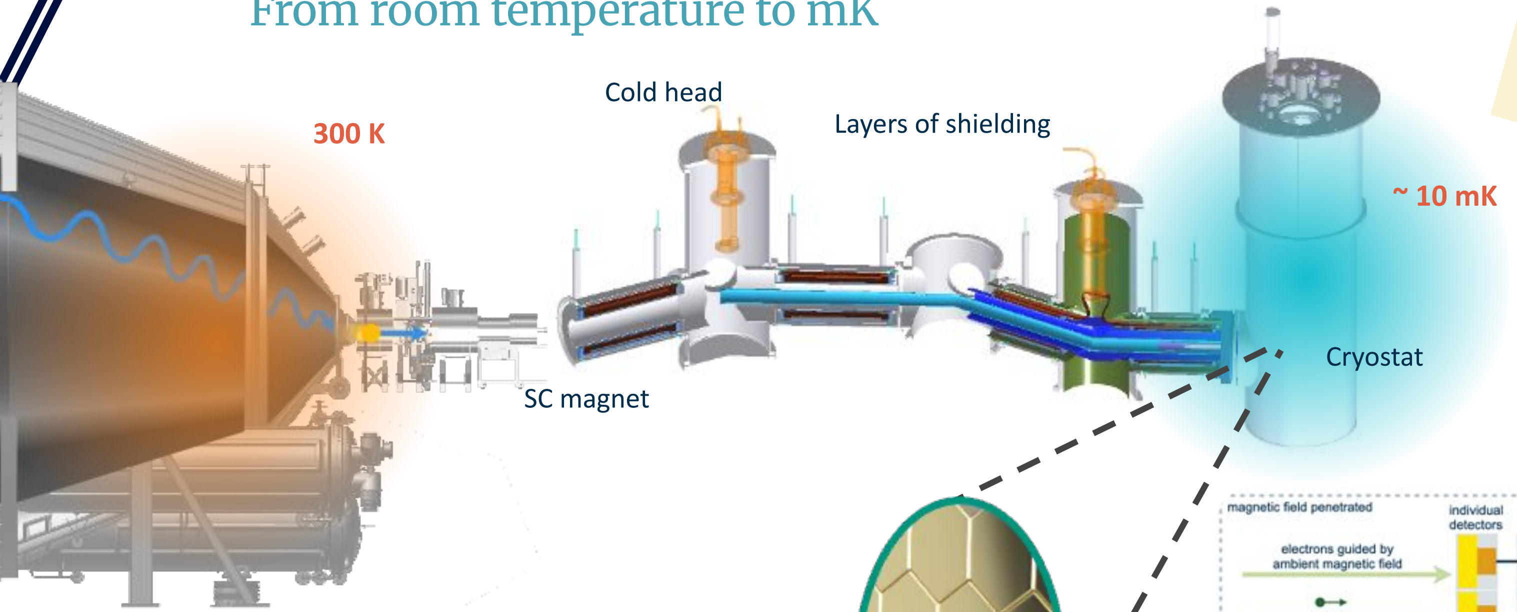
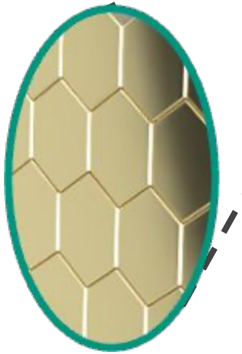
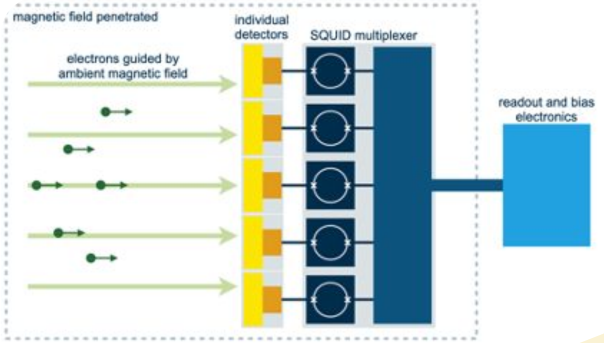
Challenges of tomorrow are addressed today

From room temperature to mK

Quantum sensor demonstrator at KATRIN beamline







Sub-eV resolution detectors

Development, production, and deployment of Superconducting QuantumSensor array (QSA)

QSA = Pixel-Detectors + SQUID Multiplexer + Microwave Readout

Quantum sensors
Sebastian Kempf

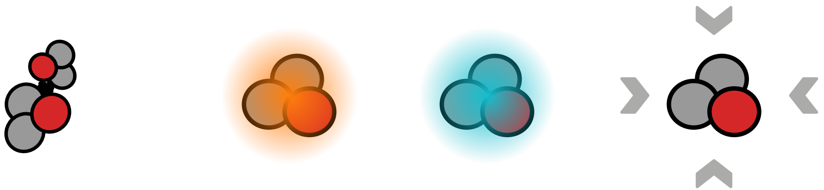
Challenges of tomorrow are addressed today

Atomic Tritium source

Topical session: Atomic Tritium
Caroline Rodenbeck and Marco Röllig

Pathfinder at TLK

Now	2025-2028	> 2028

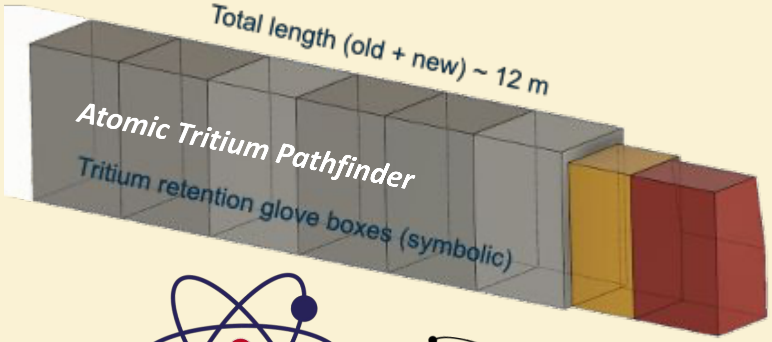


Molecular tritium | *Hot atomic tritium* | *Cold atomic tritium* | *Trapped atomic tritium*

TLK – Tritium Laboratory Karlsruhe · PROJECT 8 · UNIVERSITY OF TURKU · QTNM – Quantum Technologies for Neutrino Mass

Karlsruhe Atomic Tritium Development Platform (KAT-DP)

→ *extension of source@TLK / Tritium retention system*



KAMATE · TLK – Tritium Laboratory Karlsruhe · QTNM – Quantum Technologies for Neutrino Mass · PROJECT 8

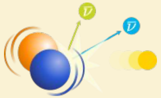
Take-home message

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

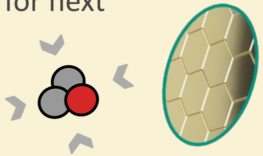
- Data taking ongoing until **end of 2025**
  ⟶ towards 0.3 eV sensitivity

- **Beyond neutrino mass analysis**
  ⟶ new eV sterile neutrino rejection limits
  ⟶ *GNI, Light boson, Relic neutrino, Lorentz invariance violation…*
  *[Aker et al., Phys. Rev. Lett. **129**, 01180 (2022)]*
  *[M. Aker et al., Phys. Rev. D **107**, 082005 (2023)]*

- 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



The KATRIN experiment

An overview *(as much as possible)*

Thank you for your attention !

Neutrino mass observables

Neutrinoless ββ-decay

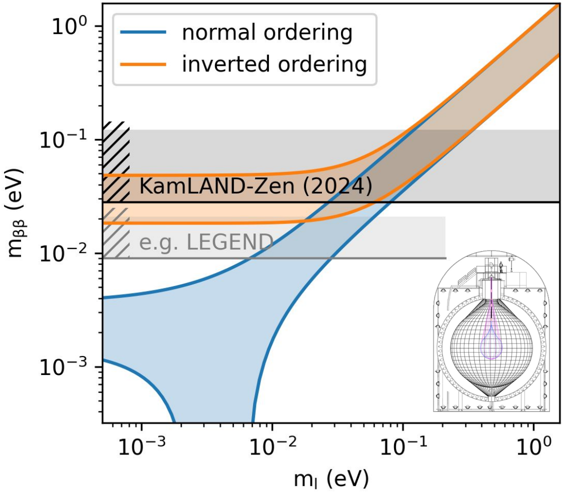
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

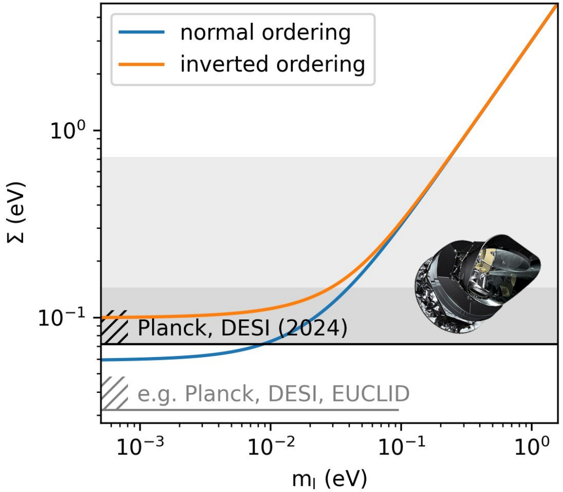
Cosmology

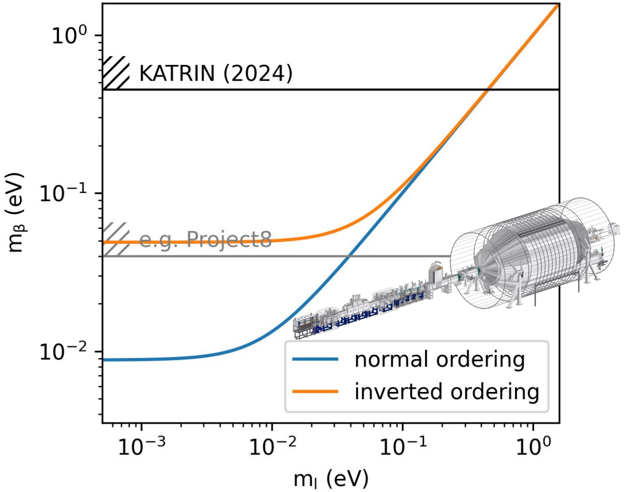
$$\Sigma = \sum_i m_i$$

β-decay kinematics

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





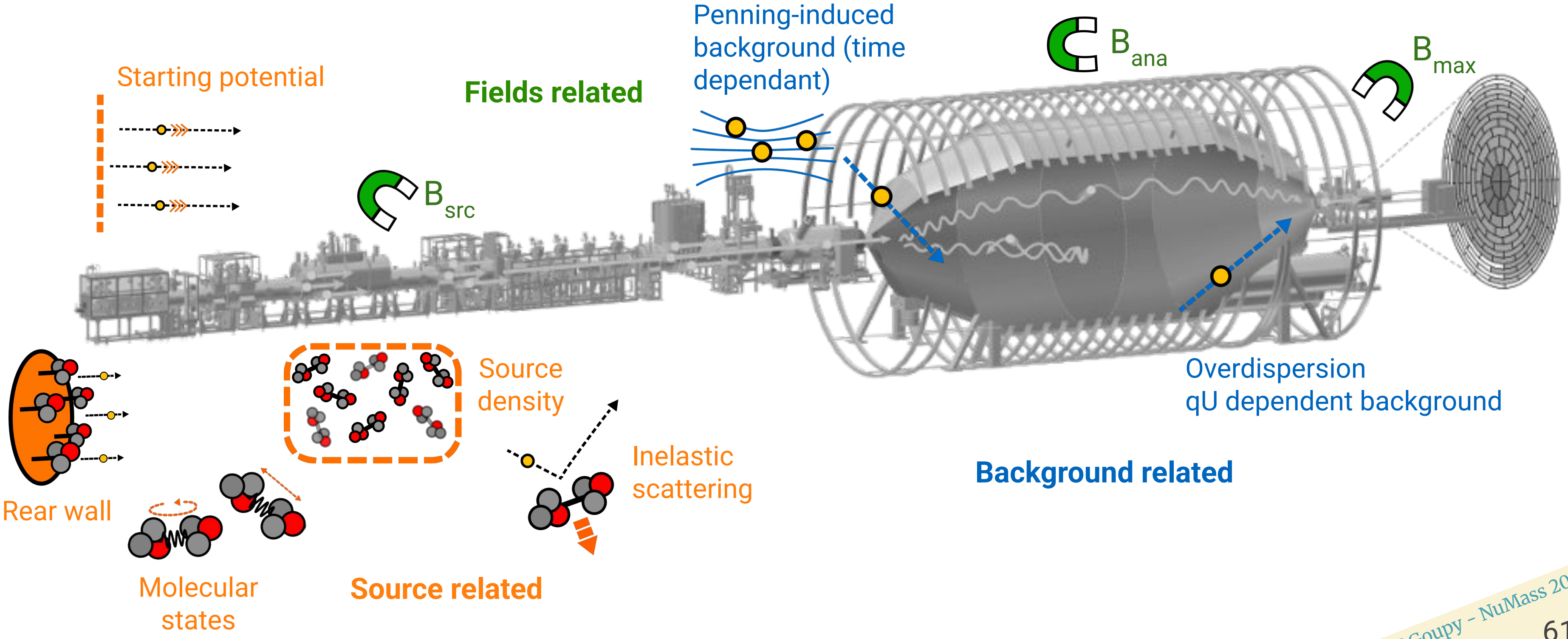


Courtesy C. Wiesinger/ A. Schwemmer

[NuFIT 5.3, nu-fit.org]

Spectrum modeling and input parameters

KATRIN systematics overview



Experimental improvements: summary

KNM2 ⇒ KNM5

Courtesy of A. Schwemmer

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

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

- **Background**-related systematics dominate

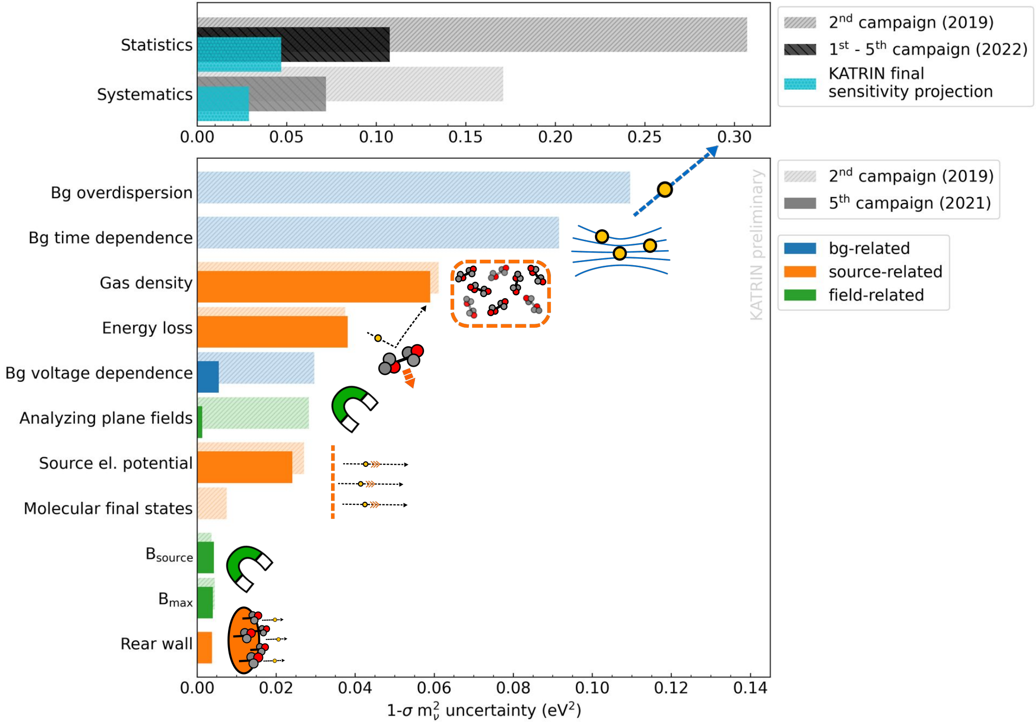
➔ Successful **mitigation**: New measurement mode (SAP), removal of Penning trap

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)



Analysis challenges and methods

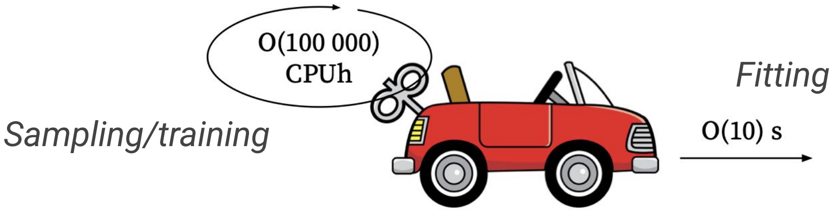
Neural network surrogate

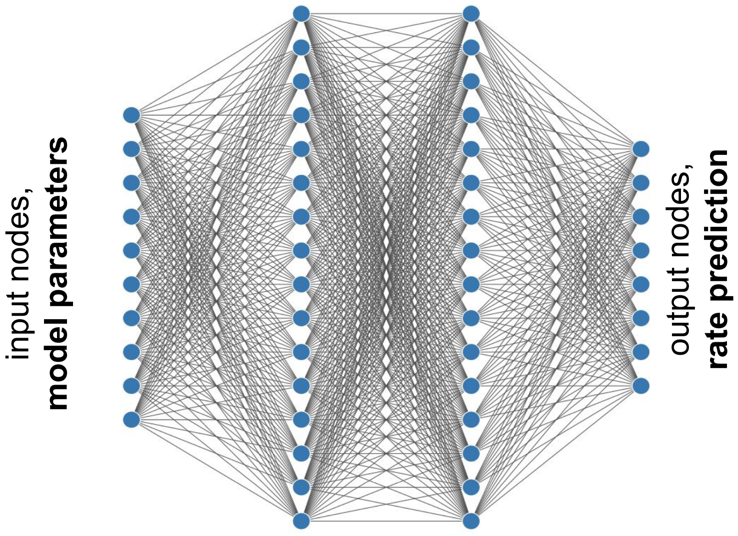
- **Maximum likelihood fit of analytical model**

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

→ 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

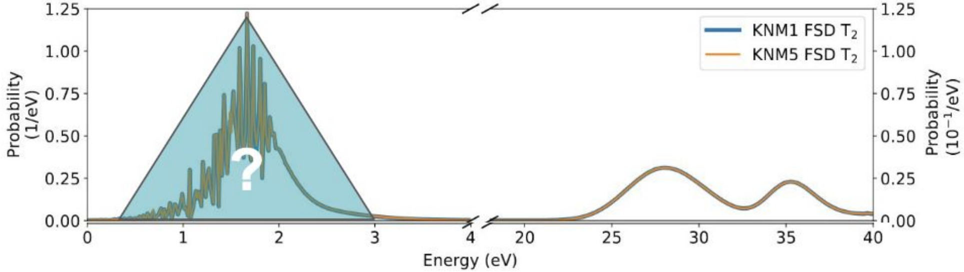
2-steps blinding procedure

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

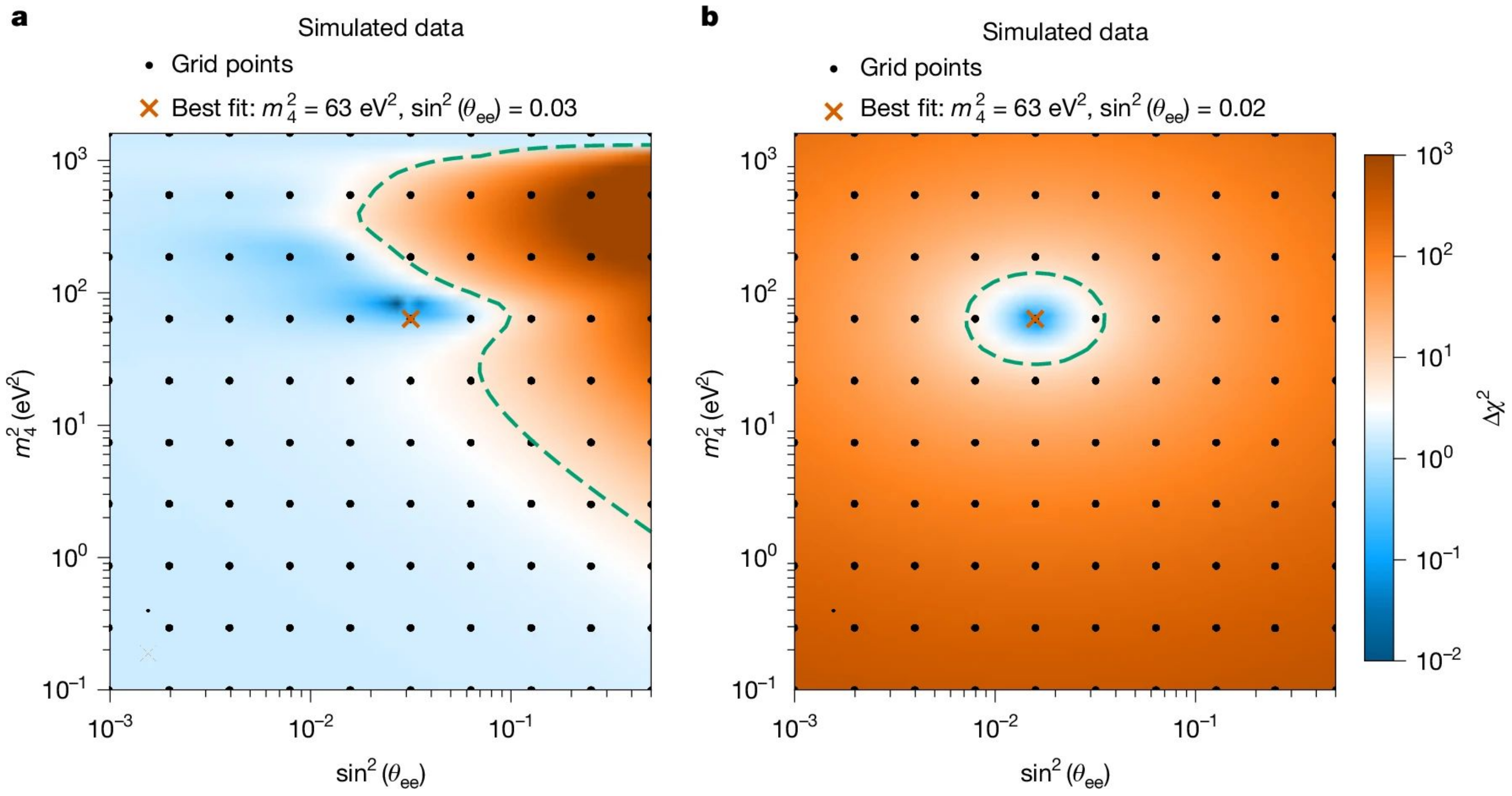


3- Analysis of the data with final model and final inputs

Light sterile neutrinos

Grid scan

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



Simulation of no sterile signature

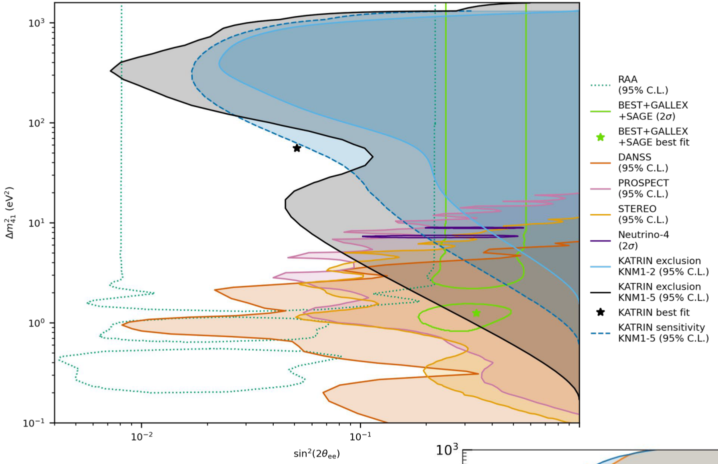
Simulation of a sterile signature

Light sterile neutrinos

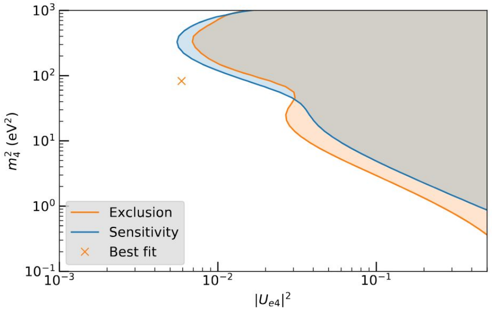
Contour shape

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

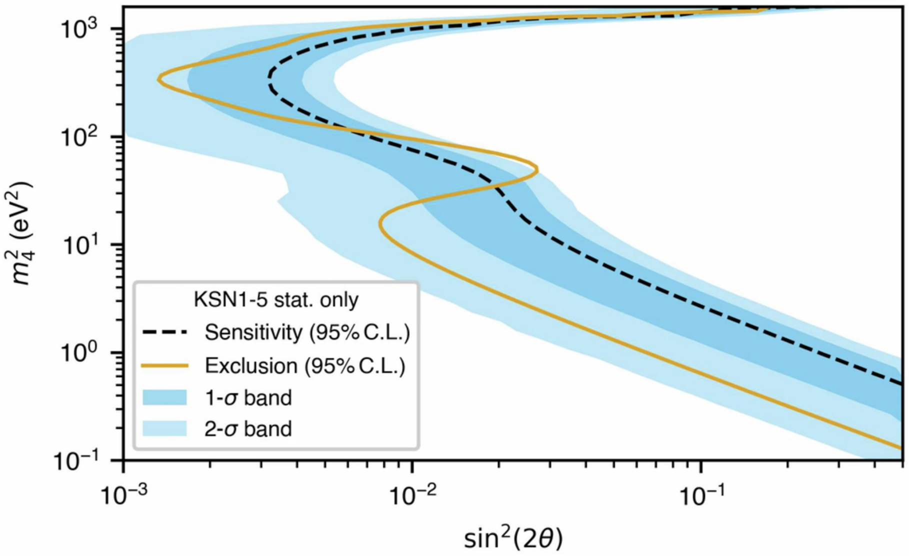
Best fit position



KNM5 only →



Result agrees with statistical fluctuations



Light sterile neutrinos

Systematic uncertainty impact

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