Direct Neutrino Mass Measurement and beyond with the KATRIN Experiment

Alessandro Schwemmer for the KATRIN collaboration

Rencontres de Noirmoutier

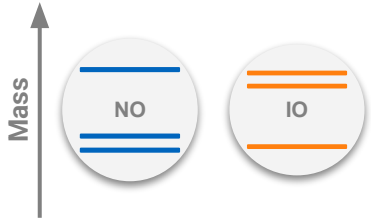
04/06/2026

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

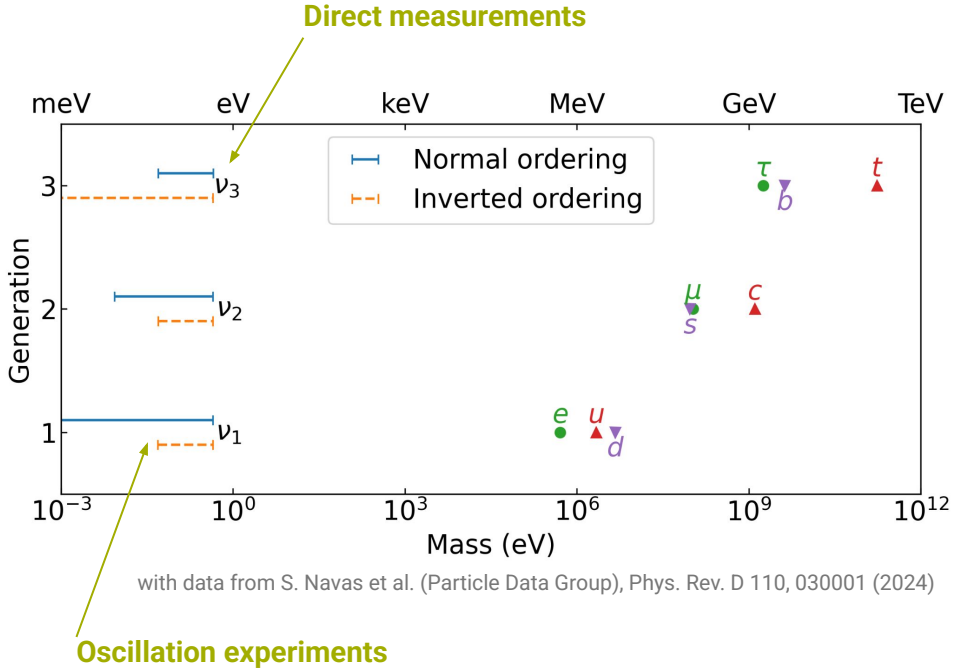
Direct Neutrino Mass Measurement…

Motivation

- **Nobel Prize** in Physics 2015
  "for the discovery of neutrino oscillations, which shows that neutrinos have mass" [1]
- **Absolute mass** and **mass ordering** remain unknown



- **Most abundant** matter particle in the universe



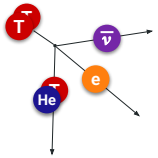
with data from S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

[1] The Nobel Prize in Physics 2015. NobelPrize.org. Nobel Prize Outreach 2026. Mon. 18 May 2026.

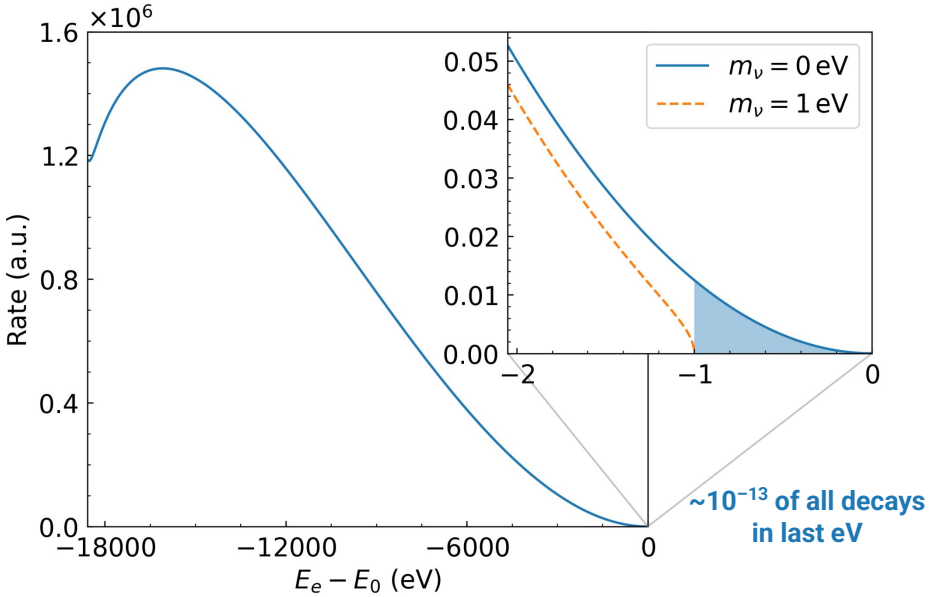
Direct measurement via β-decay

- **β^-– decay** (of molecular tritium)

$$T_2 \rightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$$

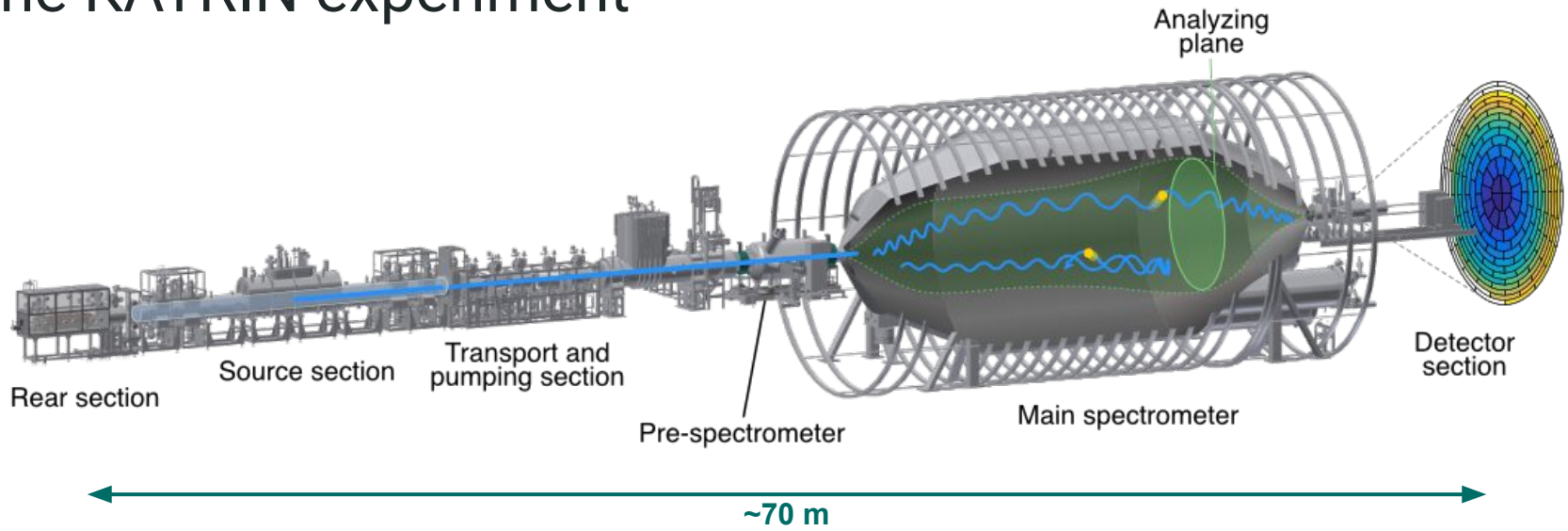


- **Electron** carries information about the **neutrino mass**
- Perform electrons spectroscopy with
  - **low background**, high activity
  - **excellent** energy **resolution**



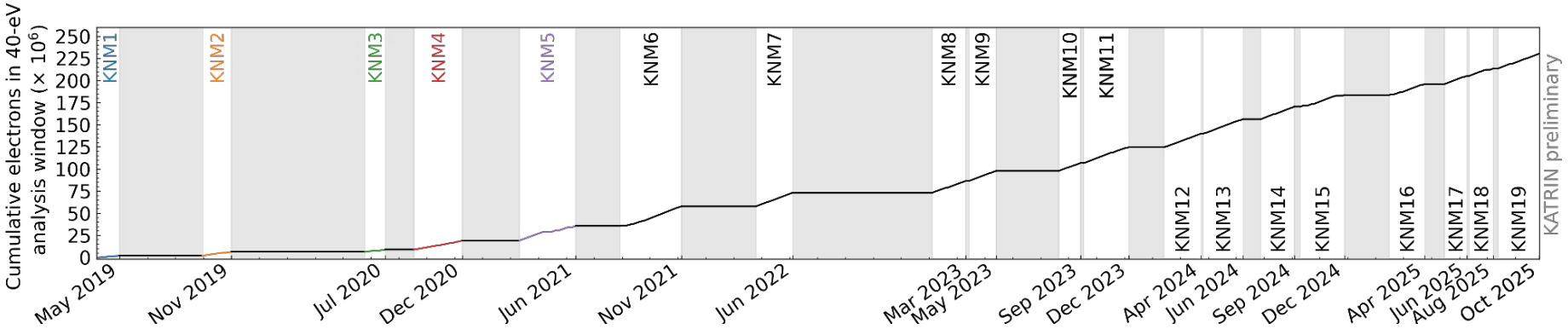
The KArlsruhe TRItium Neutrino (KATRIN) experiment

The KATRIN experiment



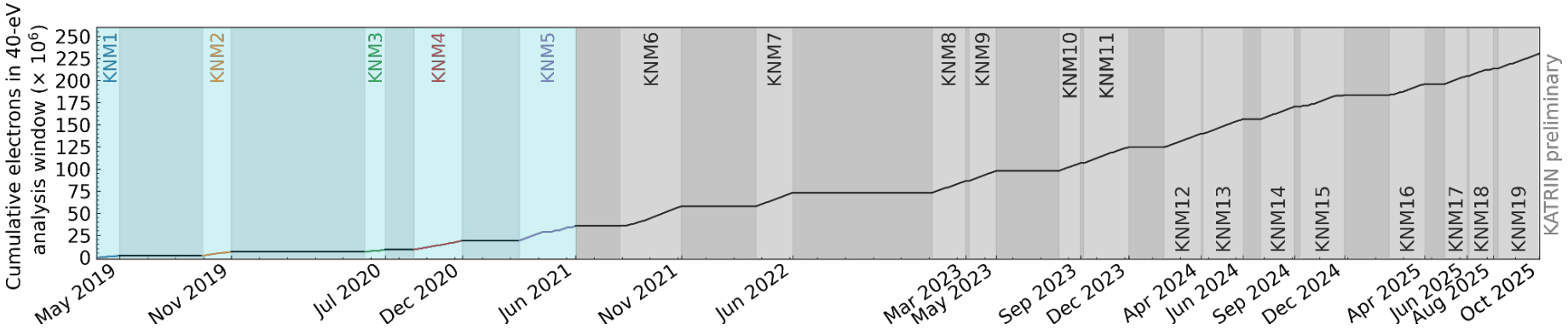
- **High activity** (10^{11} Bq) of β^- decays
- Integral measurement using a **high-pass filter** (MAC-E principle) setting a **retarding voltage**
- **Counting** of electrons (segmented detector)

Status of the experiment



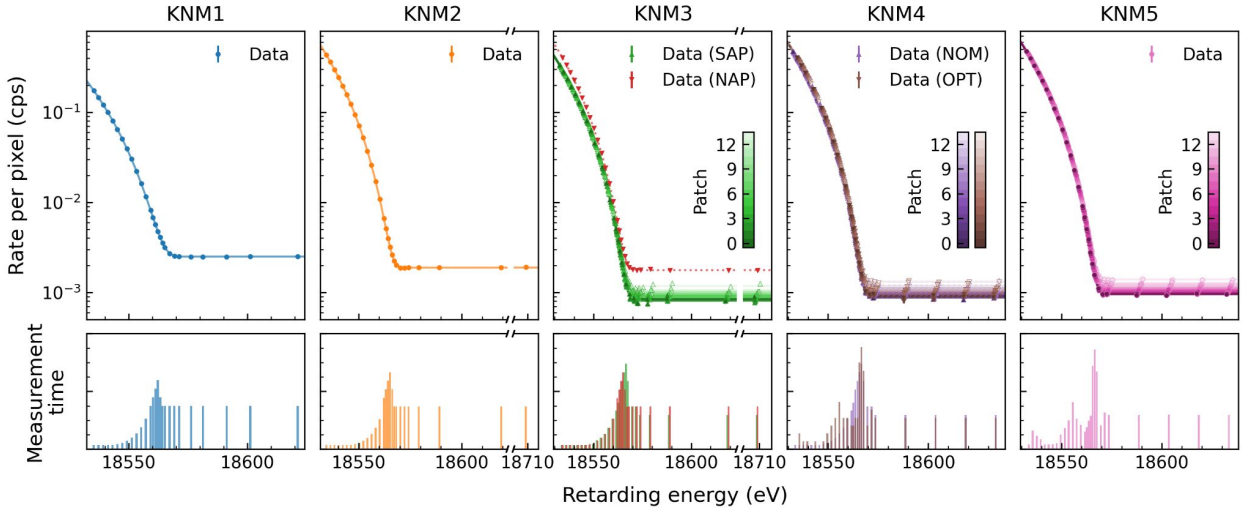
- **Data taking finished** in October 2025, **analysis ongoing** towards combined result of KNM1-19

Status of the experiment



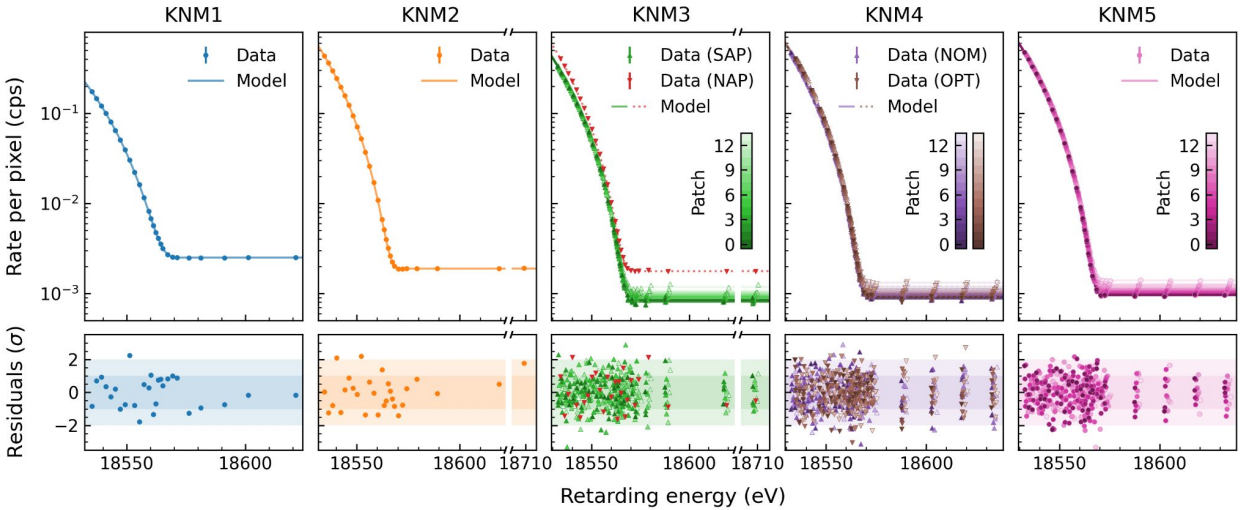
- **Data taking finished** in October 2025, **analysis ongoing** towards combined result of KNM1-19
- Analysis of **first five** measurement campaigns **KNM1-5 completed**

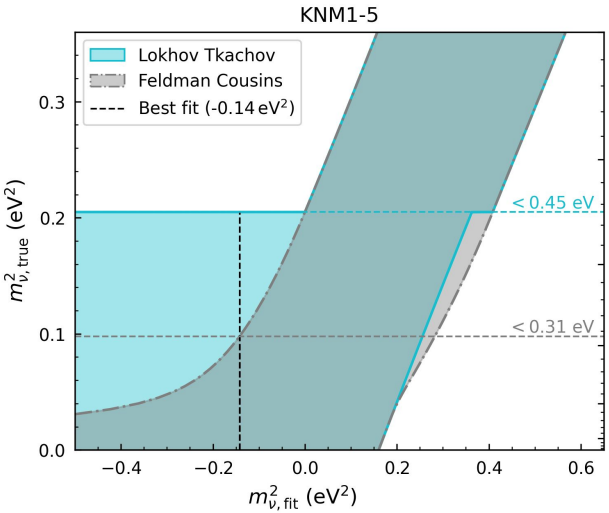
The first five measurement campaigns



- **259 days** of measurement, 59 integrated tritium spectra containing **1609 data points**
- **Unique experimental conditions** present in each spectrum

Latest neutrino mass result

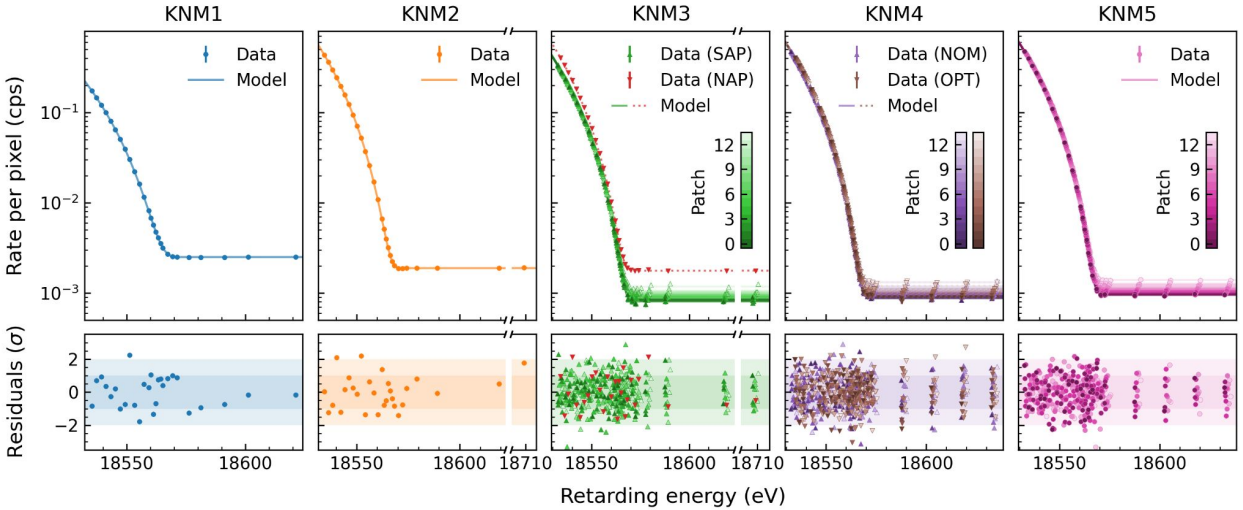


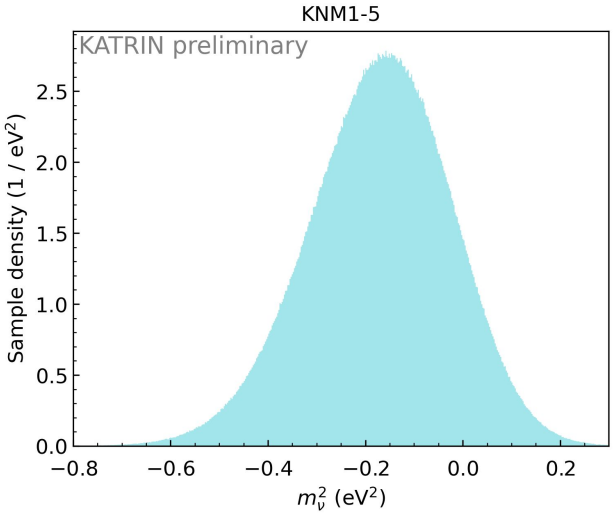


- **Simultaneous fit** of **355 parameters**, including 177 nuisance parameters and their correlations
- Excellent goodness-of-fit, **p-value of 84 %**

m_ν < 0.45 eV (90 % CL)
Science 388, 180-185 (2025)

Latest neutrino mass result



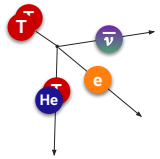


- **Full Bayesian** analysis **completed**, different **priors** considered
- **Consistent results** obtained, ***publication in preparation***

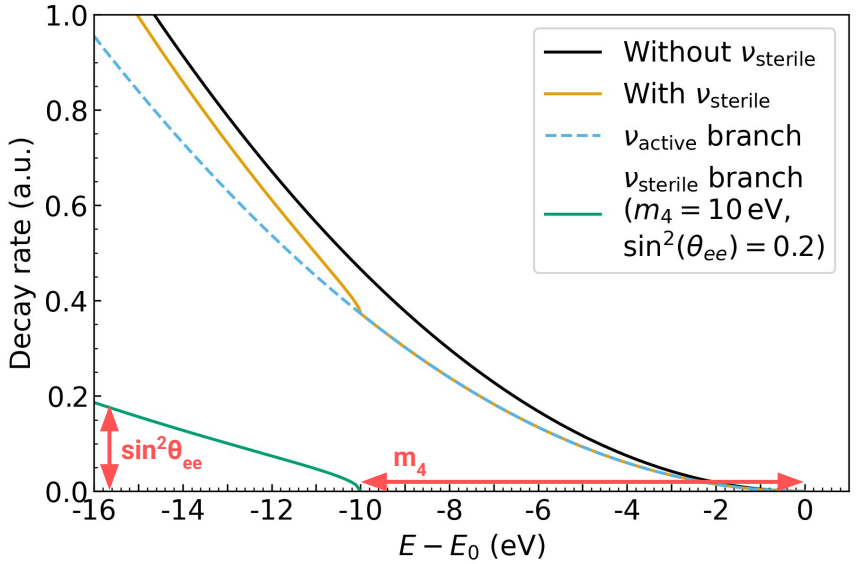
…and beyond

Light sterile neutrinos in KATRIN

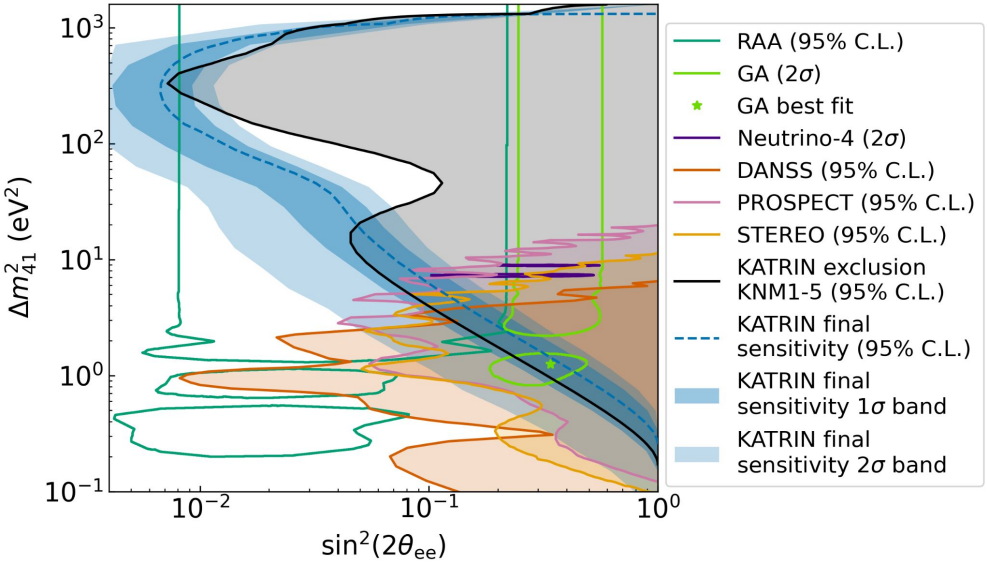
- Hypothetical **fourth neutrino** state, weakly interacting **only via mixing** (“*mainly sterile*”)



- **Additional** decay **branch** would lead to “kink” in the spectrum
- Precise **spectral analysis** allows to probe sterile neutrino **mass** m_4 and **mixing** $\sin^2\theta_{ee}$



Light sterile neutrinos in KATRIN



➔ Latest result largely **excludes gallium anomaly** and **challenges Neutrino-4 claim**

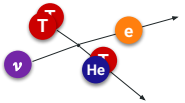
Nature 648, 70-75 (2025)

Cosmic neutrino background in KATRIN

- The universe is **filled with relic neutrinos** originating from the **big bang**
- **Extreme scenarios** might lead to huge overdensity η

  $n = \eta \times \langle n_0 \rangle$
- Probe **relic neutrino capture** (**RνC**) in KATRIN via

  $\nu_e + T_2 \rightarrow {}^3HeT^+ + e^-$



- **First searches** in KNM1-2 using a **simplified model**

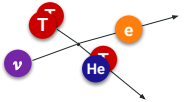
  PRL 129, 011806 (2022)

Cosmic neutrino background in KATRIN

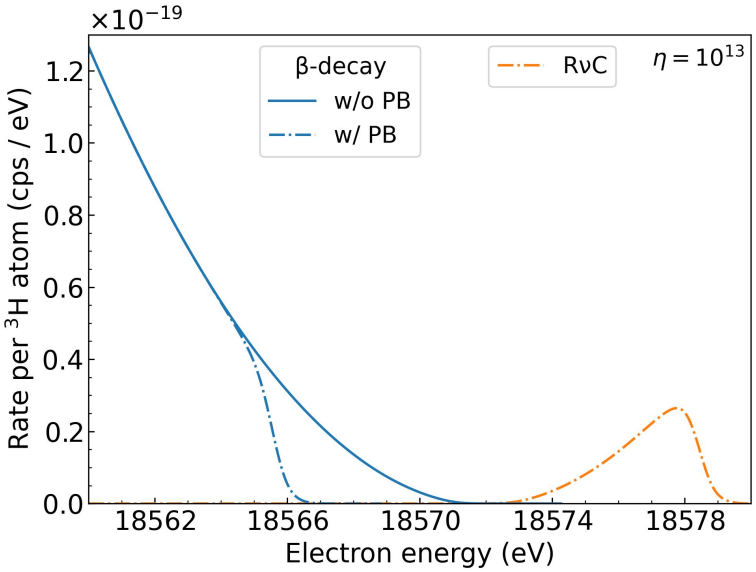
- The universe is **filled with relic neutrinos** originating from the **big bang**
- **Extreme scenarios** might lead to huge overdensity η

  $n = \eta \times \langle n_0 \rangle$
- Probe **relic neutrino capture** (**RνC**) in KATRIN via

  $\nu_e + T_2 \rightarrow {}^3HeT^+ + e^-$



- **Revised model** to account for
  - **Fermi gas** description of relic neutrinos
  - **Pauli blocking** (PB) affecting the β-decay spectrum



exaggerated overdensity

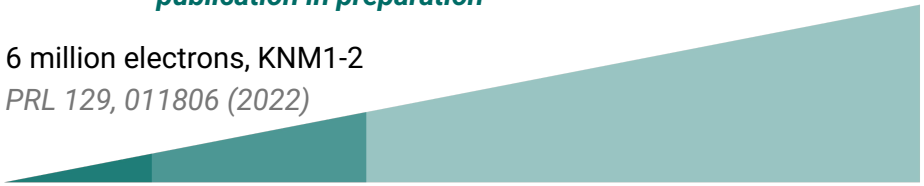
Cosmic neutrino background in KATRIN

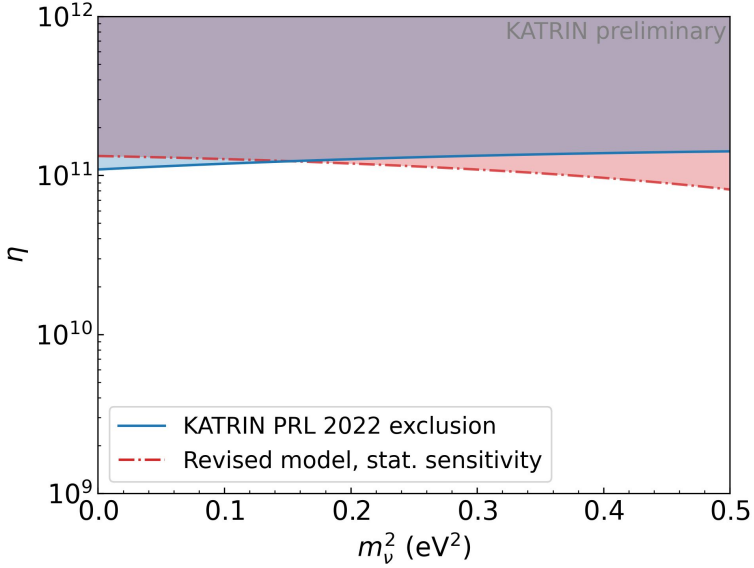
- **Validation** of **simplified model** applied to KNM1-2
- **Extend dataset** towards KNM1-5, **six-fold** increase of statistics

230 million electrons, KNM1-19
Final KATRIN

36 million electrons, KNM1-5
publication in preparation

6 million electrons, KNM1-2
PRL 129, 011806 (2022)





KNM1-2 contours at 99 % C.L.

Conclusion

Direct Neutrino Mass Measurement…

- **First five** measurement campaigns (KNM1-5) **analyzed**, world-leading direct **upper limit**

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

- Full **Bayesian analysis** completed, *publication in preparation*

…and beyond

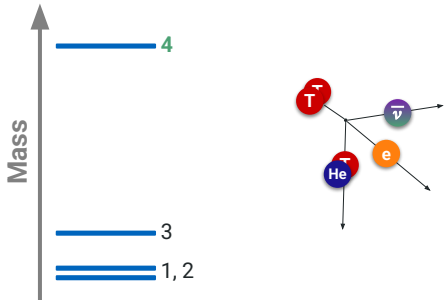
- Search for light sterile neutrinos largely **excluded gallium anomaly** and **challenged Neutrino-4 claim**
- Extended dataset for probing **relic neutrino capture** with **revised model**, *publication in preparation*

Thank you for your attention!

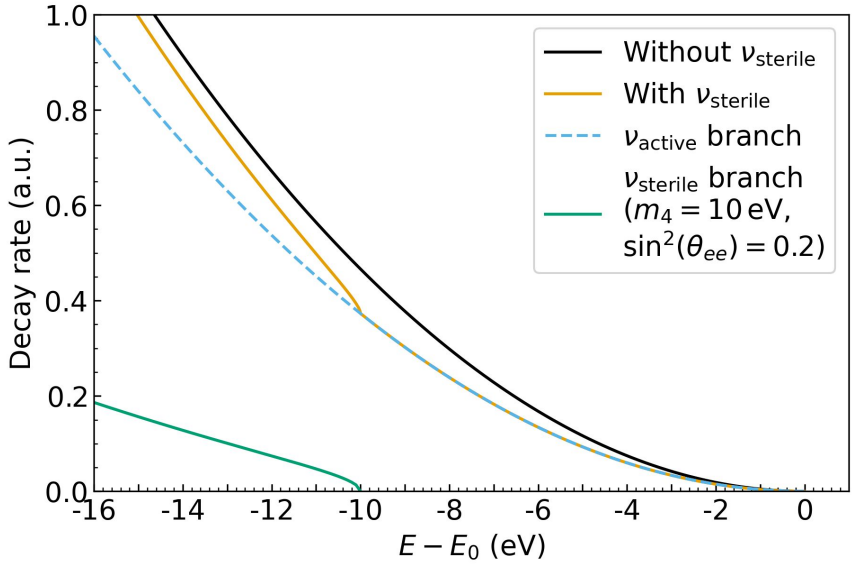
Backup

Light sterile neutrinos in KATRIN

- Hypothetical **fourth neutrino** state,
  weakly interacting **only via mixing** (“*sterile*”)



- **Additional** decay **branch** would lead to “kink” in the spectrum
- Precise **spectral analysis** allows to probe sterile **mass** m_4 and **mixing** $\sin^2\theta_{ee}$



Neutrino sources (extreme scenarios)

- **CνB** predicted to have a **number density** of

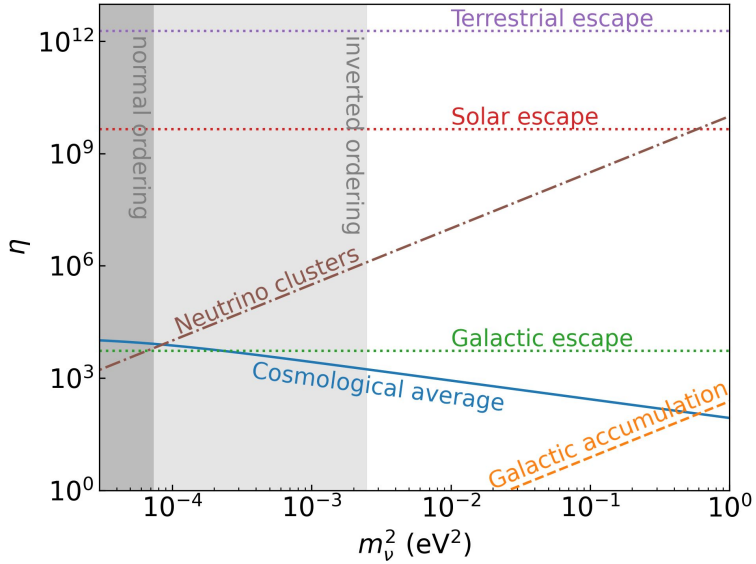
  $\langle n_0 \rangle = 56\ \mathrm{cm}^{-3}$ per neutrino flavor

➔ **Most abundant** matter particle

- **Extreme scenarios** might lead to huge (local) overdensities η

  $n = \eta \times \langle n_0 \rangle$

- Might be **within reach** utilizing relic neutrino capture (**RνC**) on β-decaying isotops (tritium)



based on *Bondarenko et al. JCAP 10 (2023) 026*

Cosmic neutrino background in KATRIN

- **Extreme scenarios** might lead to huge overdensity η

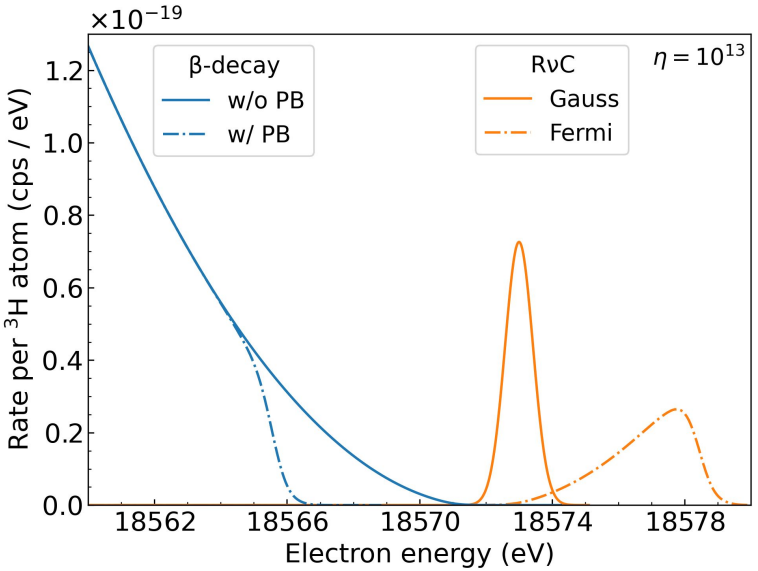
  $n = \eta \times \langle n_0 \rangle$

- Probe **relic neutrino capture** (**RνC**) in KATRIN via

  $\nu_e + T_2 \rightarrow {}^3HeT^+ + e^-$

  PRL 129, 011806 (2022)

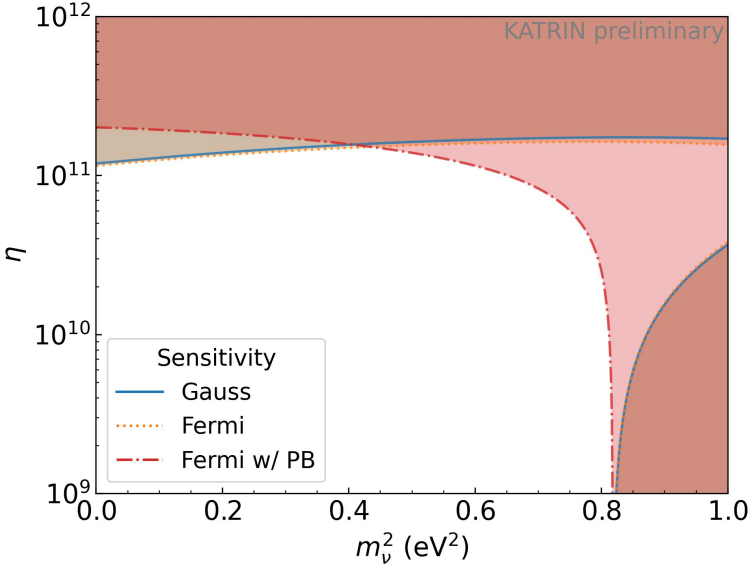
- **Revised model** to account for
  - **Fermi gas** description of relic neutrinos
  - **Pauli blocking** (PB) affecting the β-decay spectrum



exaggerated overdensity

Cosmic neutrino background in KATRIN

- Detailed **sensitivity studies** based on simulations representing **KNM1-2**
- **Good agreement** of **RνC** by Gauss and Fermi model for $\eta \lesssim 10^{11}$
- Significant impact of **Pauli blocking** on the **contour shape** (integral measurement)
- Analysis of **KNM1-5 completed**, *publication in preparation*

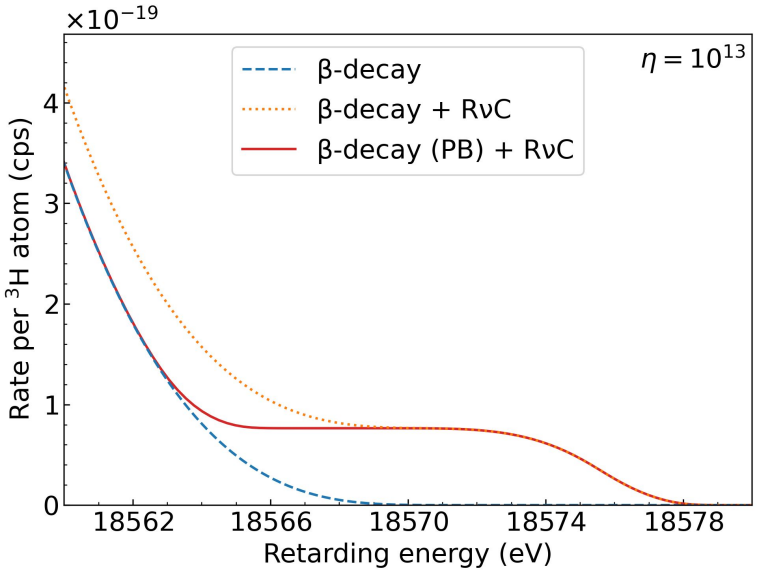


Sensitivities based on KNM1-2, 99 % C.L.

Cosmic neutrino background in KATRIN

- **Kinematic symmetry** resulting in rate **cancellation**

➔ **Integral** measurement leads to **compensation** of **signal**



exaggerated overdensity

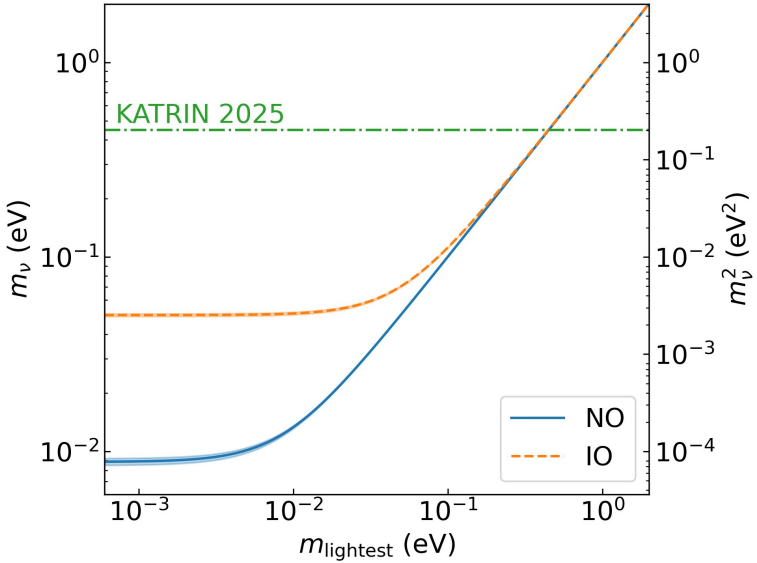
Direct measurement via β-decay

- Current **world-leading direct limit**

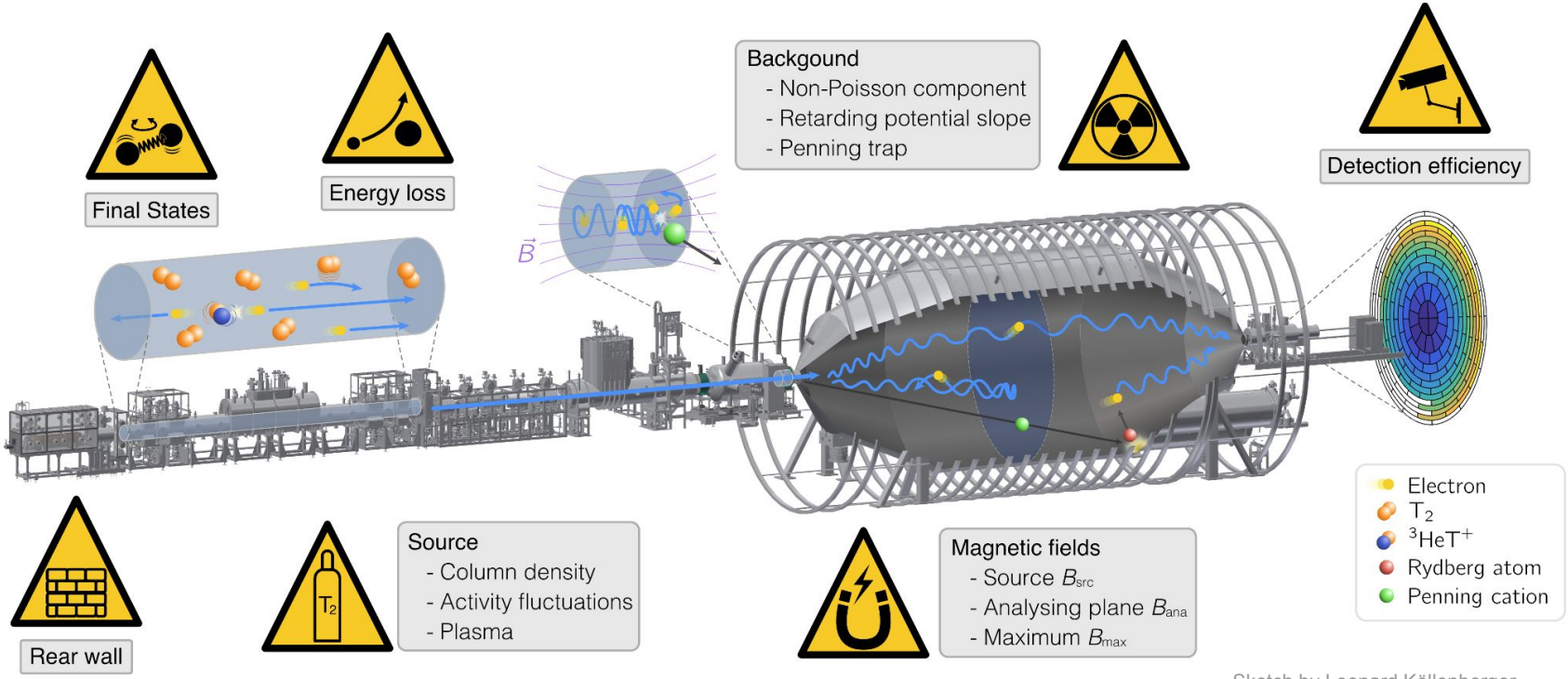
  m_ν < 0.45 eV (90 % CL)

  Science 388, 180-185 (2025)

- **Final sensitivity** estimated to be **0.3 eV** (90 % CL)
- **R&D** ongoing to probe normal ordering (NO) using
  - an **atomic tritium** source
  - a **differential measurement**

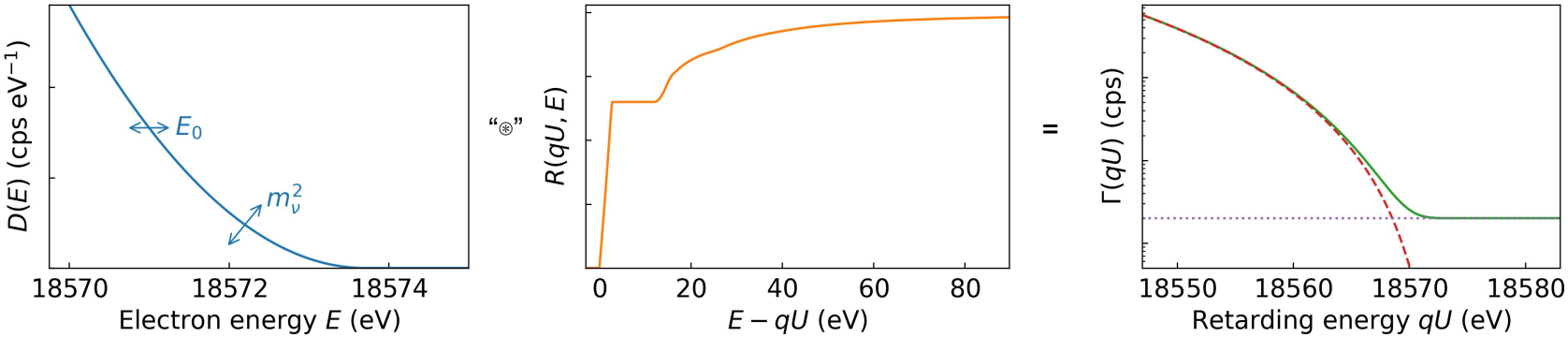


Systematic uncertainties



Sketch by Leonard Köllenberger

Model description



Differential spectrum

- Built on **Fermi theory**
- Includes description of **molecular excitations**

Experimental response function

- Describes **transmission** properties and **scattering**
- Depends on **experimental inputs**

Rate model

- Combines **background** and **signal** model
- Relies on several **numerical integrations**

Neural network approach

Neural network (NN) based calculation of the **integrated** spectrum

*Karl et al. Eur. Phys. J. C **82**, 439 (2022)*

- Stringent **accuracy** requirements of the model prediction **fulfilled within training range**
- Model constrained to **discrete** retarding energies