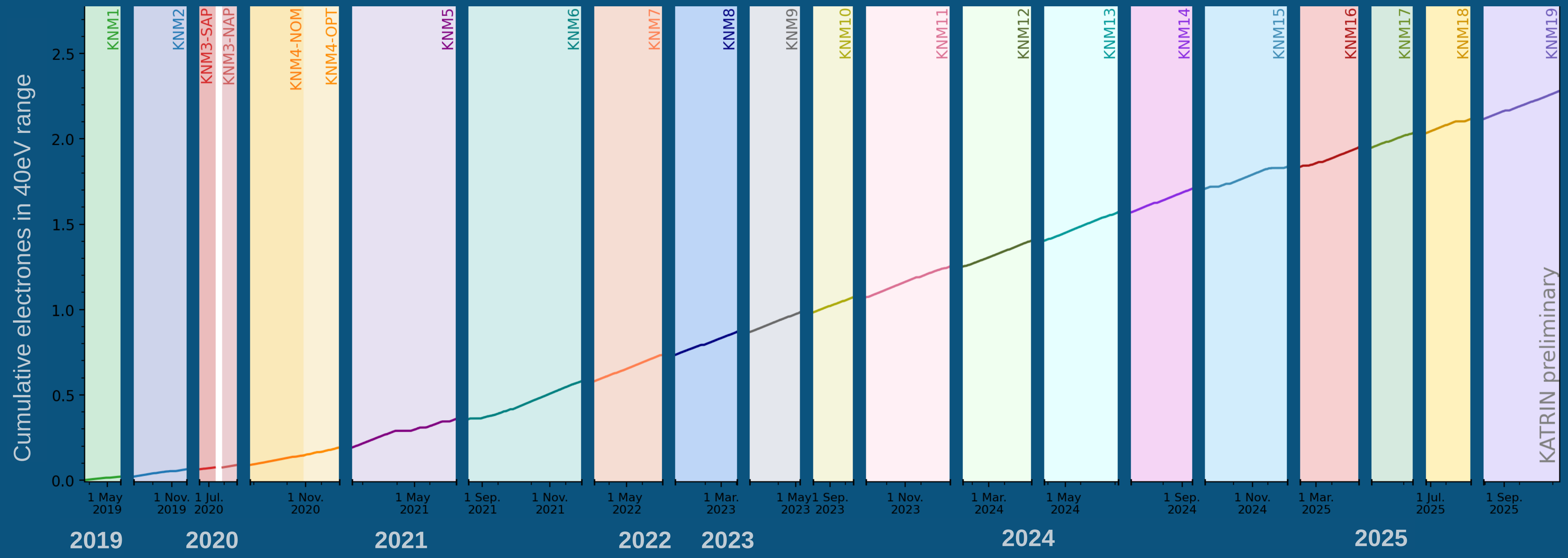


Towards the final analysis of the KATRIN data

Karo Erhardt

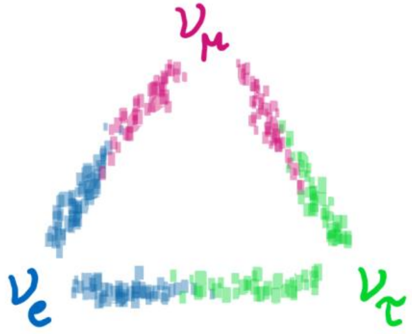
on behalf of the KATRIN collaboration, PASCOS 2026

Karlsruhe Institute of Technology

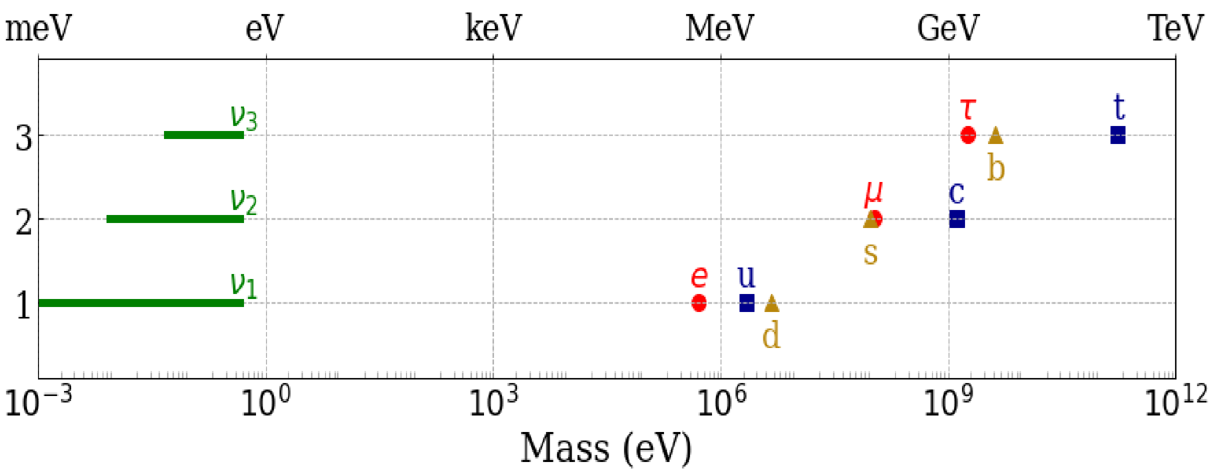
23.06.2026

Unveiling new physics with neutrino mass

- Neutrino flavor oscillations → neutrinos are not massless
  ⇒ absolute masses are not given
- The most abundant known massive particle in the universe
- Absolute neutrino mass helps to understand:
  - formation of cosmological structures
  - neutrino mass generation models, necessary extension of the SM



Absolute masses **x10⁶** smaller than $\boldsymbol{m_e}$!

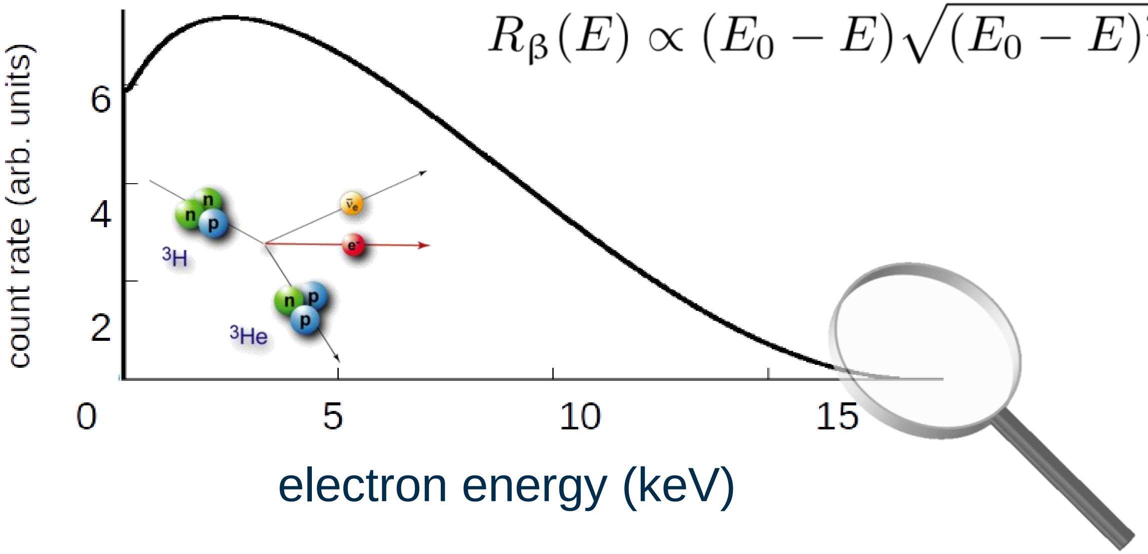


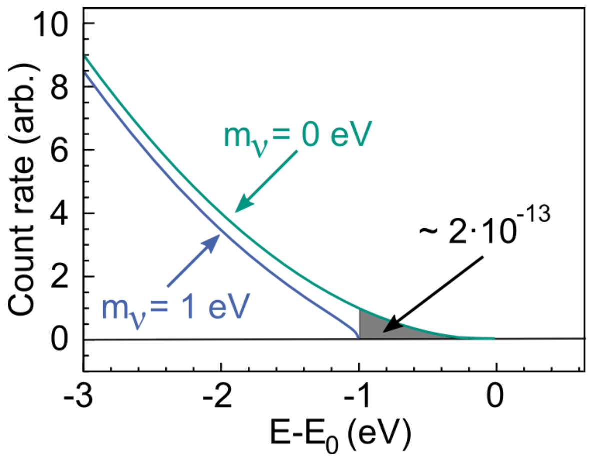
Direct kinematic measurement

- Observable: effective mass $\boldsymbol{m_\nu}$
- Tritium β-decay kinematics & energy conservation

$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$





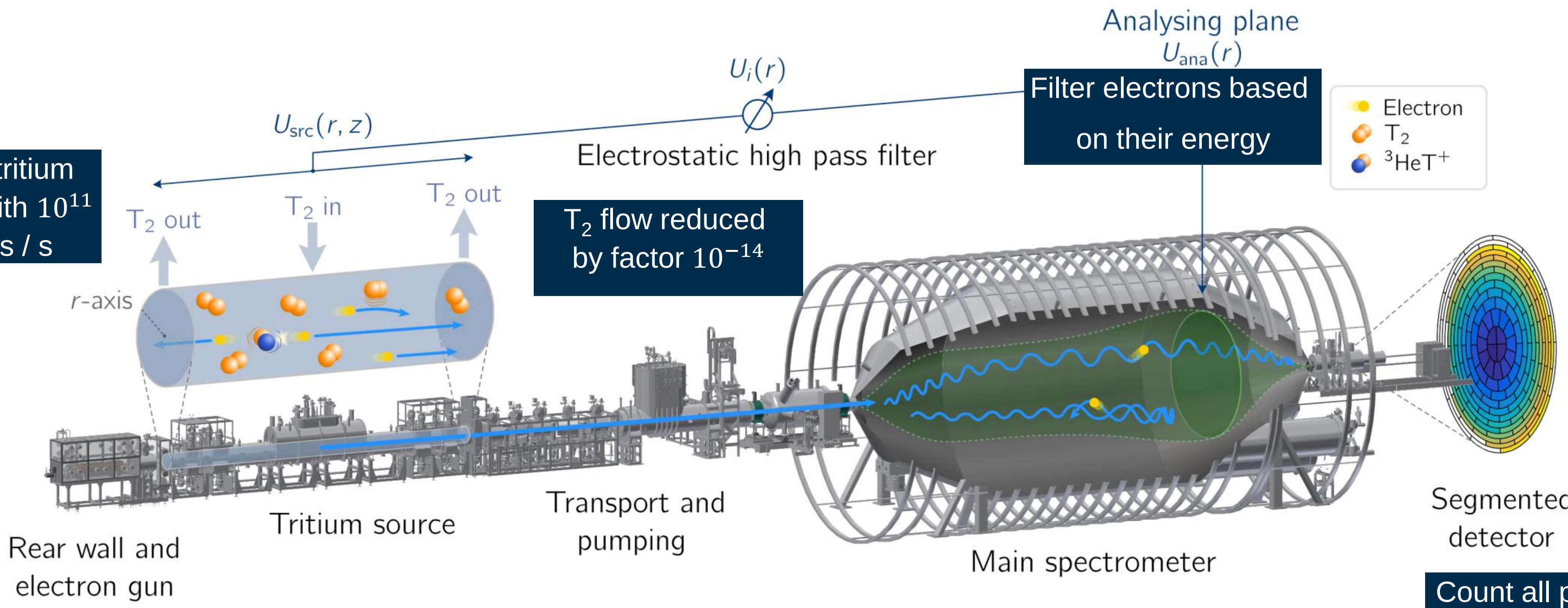
- Small rates → high activity source needed
- Small effect → high precision and low background needed

KATRIN measurement principle

Strong tritium source with 10^{11} decays / s

T_2 flow reduced by factor 10^{-14}

Filter electrons based on their energy



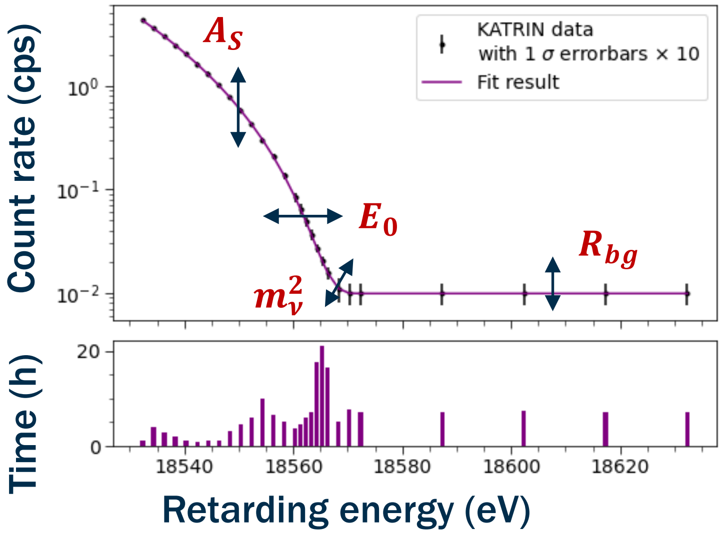
Count all passed electrons = integral measurement

- excellent energy resolution: $\frac{\Delta E}{E} \sim \frac{B_{ana}}{B_{max}} \sim 10^{-4}$
- low background with ultra-high vacuum of 10^{-11} mbar

Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

KATRIN spectrum modeling

Measured β-spectrum	Convolution of theoretical spectrum with experimental response



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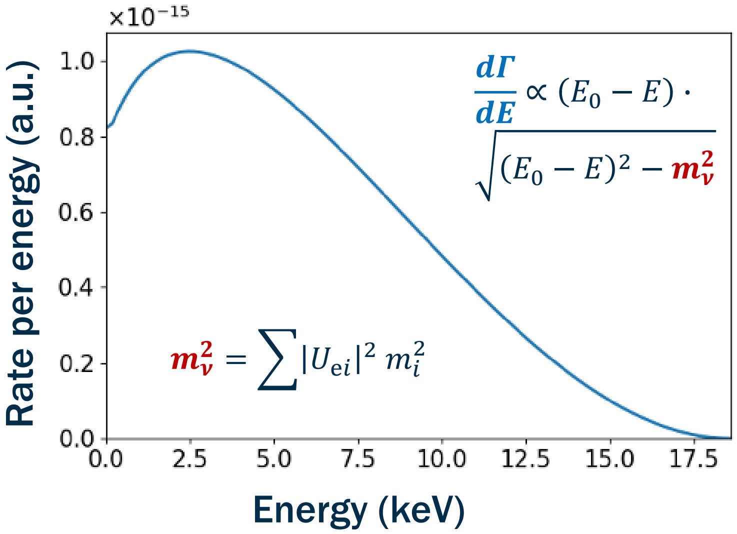

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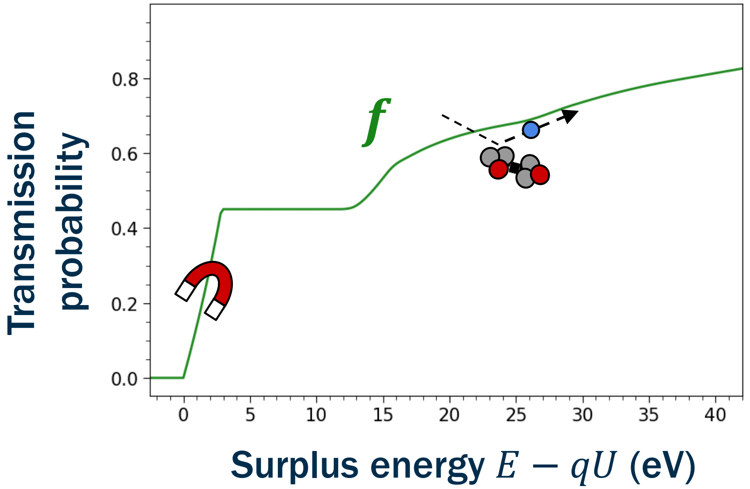


2 independent analysis frameworks

Kleesiek et al. EPJ C 79 (2019) 204; Karl et al., EPJ C 82 (2022) 439

Fermi theory with radiative corrections and molecular excitations

spectrometer transmission and energy losses in source

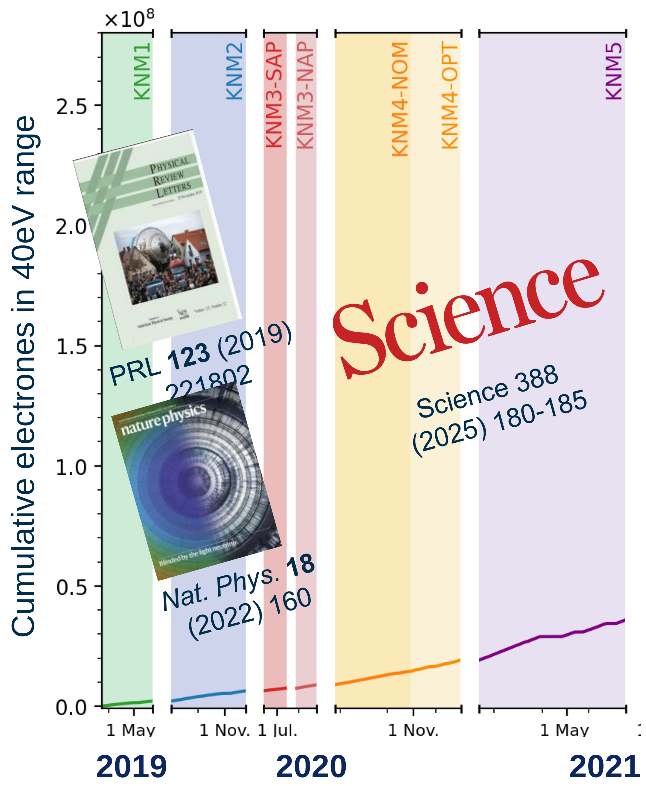
$$R(U) = A_s \cdot N_T \int_{qU}^{E_0} \frac{d\Gamma}{dE}(E, m_\nu^2) \cdot f(E,U)\mathrm{d}E + R_{bg}$$

4 free fit parameters: $A_S, E_0, m_\nu^2, R_{bg}$

KATRIN neutrino-mass results

Measurment campaign = hundreds of β-spectrum scans with similar measurment conditions combined for the analysis

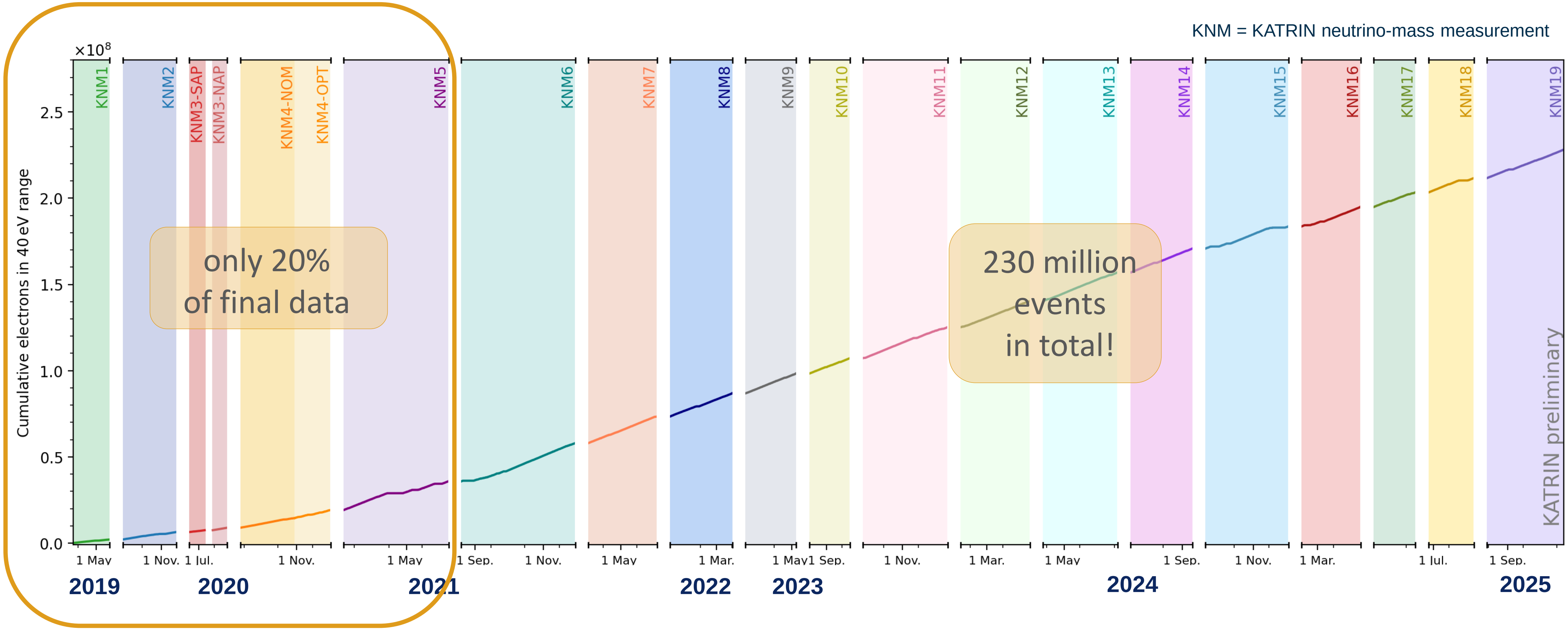
KNM = KATRIN neutrino-mass measurement



- KNM1: m_ν < 1.1 eV (90 % C.L.)
  PRL 123 (2019) 221802
- KNM1-2: m_ν < 0.8 eV (90 % C.L.)
  Nature Phys. 18 (2022) 160
- KNM1-5: m_ν < 0.45 eV (90 % C.L.)
  Science 388 (2025) 180-185

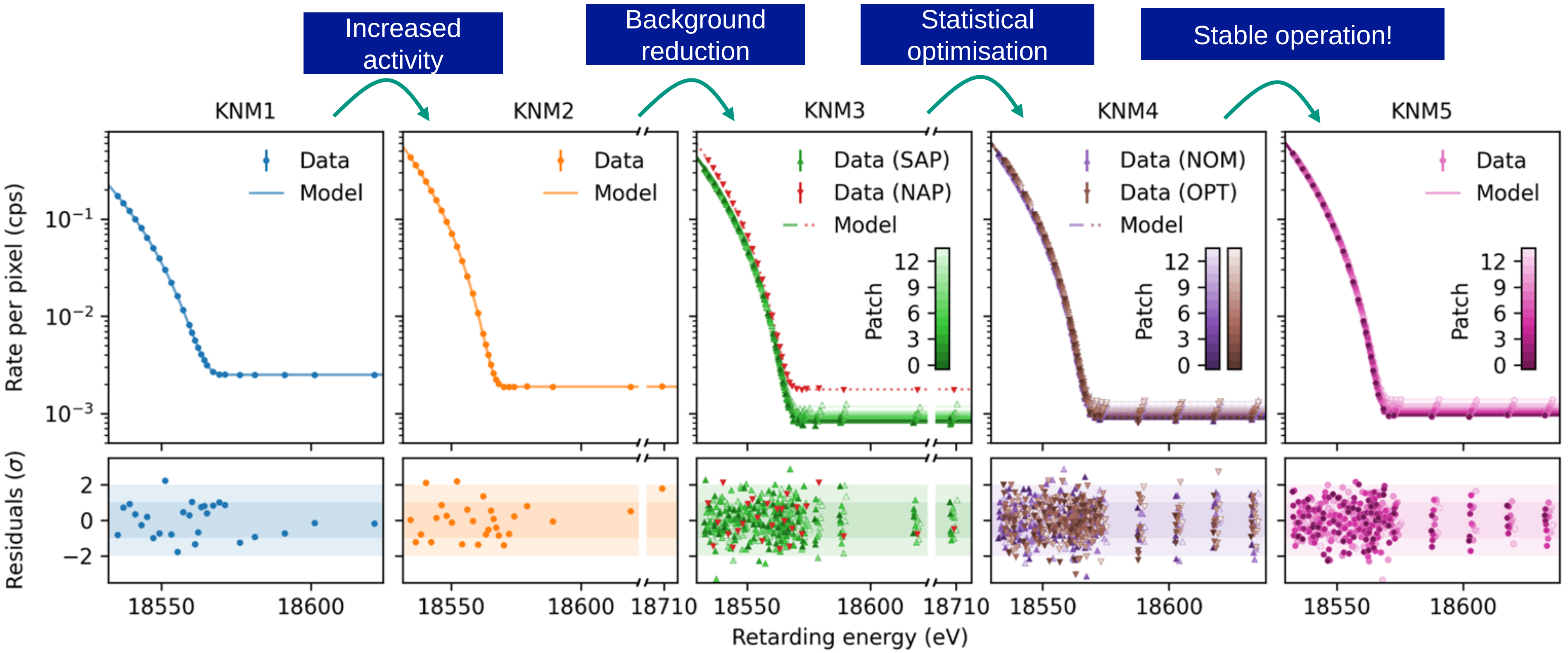
- 259 measurement days
- 36 million electrons in 40 eV analysis range

1000 measurement days of KATRIN



2019: m_ν < 1.1 eV (90% CL) **2022**: m_ν < 0.8 eV (90% CL) **2025**: m_ν < 0.45 eV (90 % C.L.)

Challenge: Combination of datasets of KNM1-5



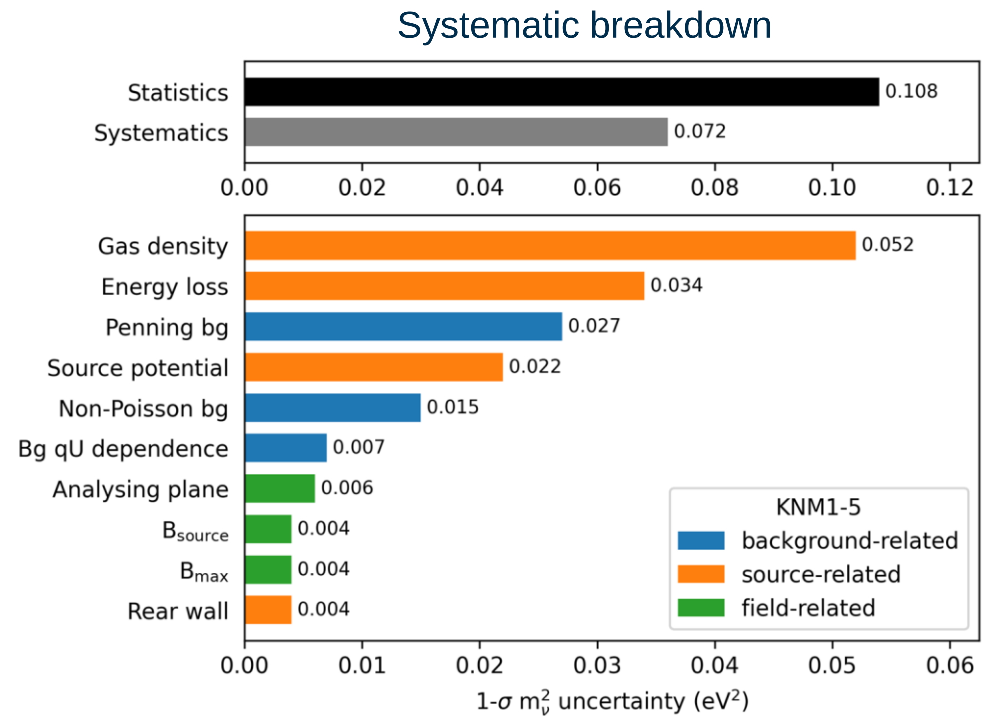
- **7** different configurations with their own parameters each
- one common neutrino mass
- 350 parameters in the model
- same configuration after KNM5

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

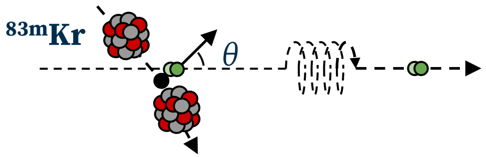
Combined best fit value

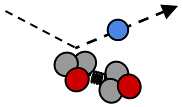
~1400 parameters in the final analysis

Challenge: Systematic uncertainties in KNM1-5



- systematic effects need to be
  - Recognized and measured
  - Mitigated or precisely described
- **factor 2** lower background by fiducialization
  Lokhov *et al.*, EPJ C **82** (2022) 258
  KATRIN Coll., EPJ C **84** (2024) 12
- precision **calibration tools**:
  probe source plasma potential by new co-circulation mode of krypton-83m with tritium
  KATRIN Coll., arXiv:2503.13221
  probe scattering effects by electron gun
  KATRIN Coll., EPJ C **81** (2021) 579



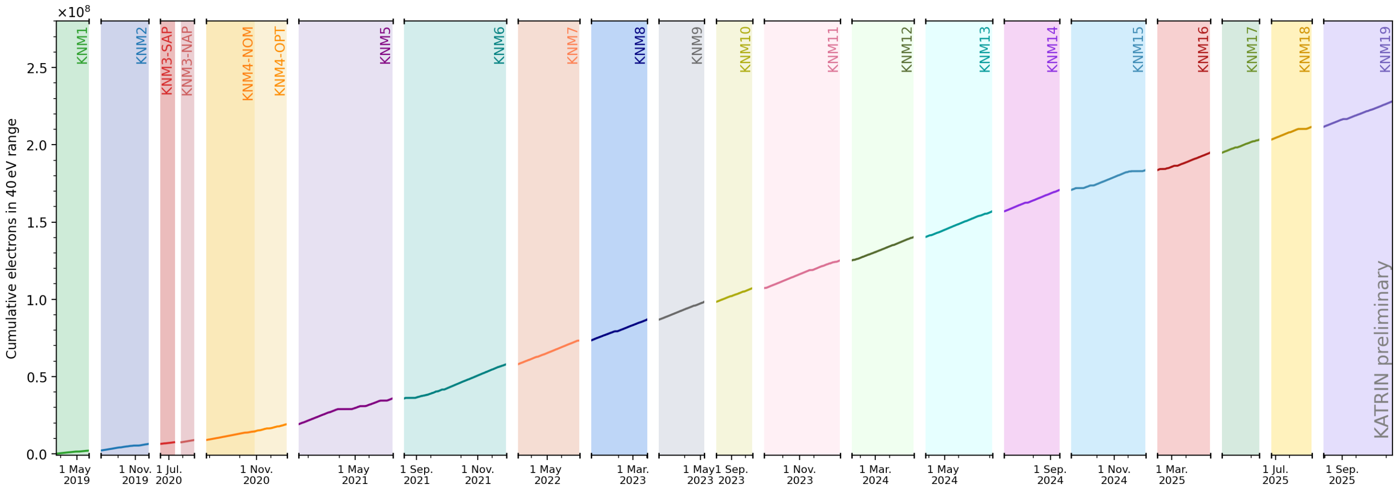


five times more statistics in the final dataset

Towards the final neutrino mass analysis I

- Final dataset is ready
- Projected sensitivity of $m_\nu < 0.3$ eV

- Optimization of analysis procedure
  - 1400 parameters
  - configuration unchanged since KNM5
  - studies on combination of KNMs
  - lightweight analysis

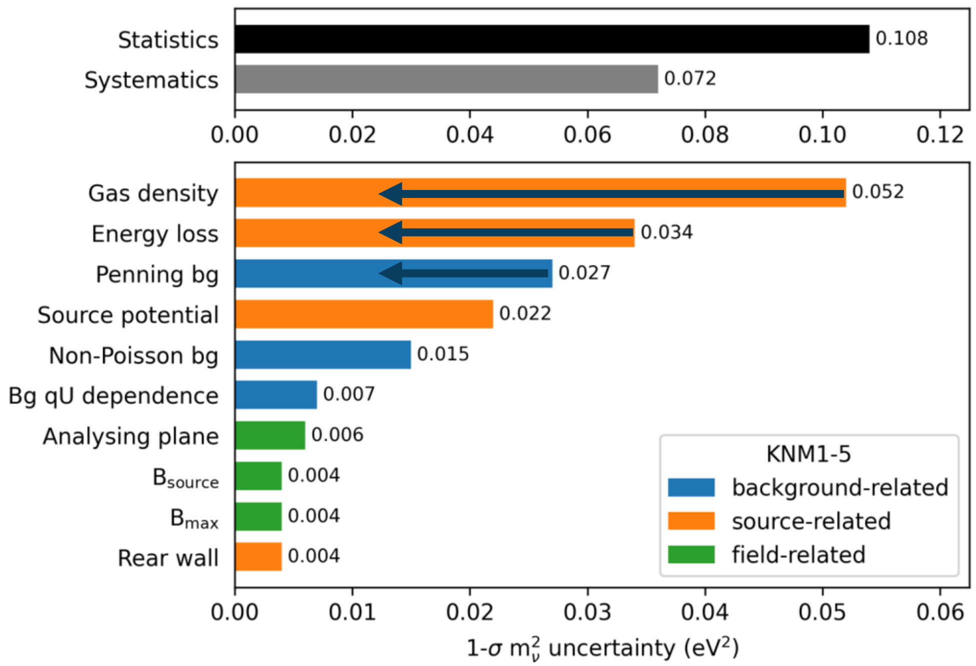


Towards the final neutrino mass analysis II

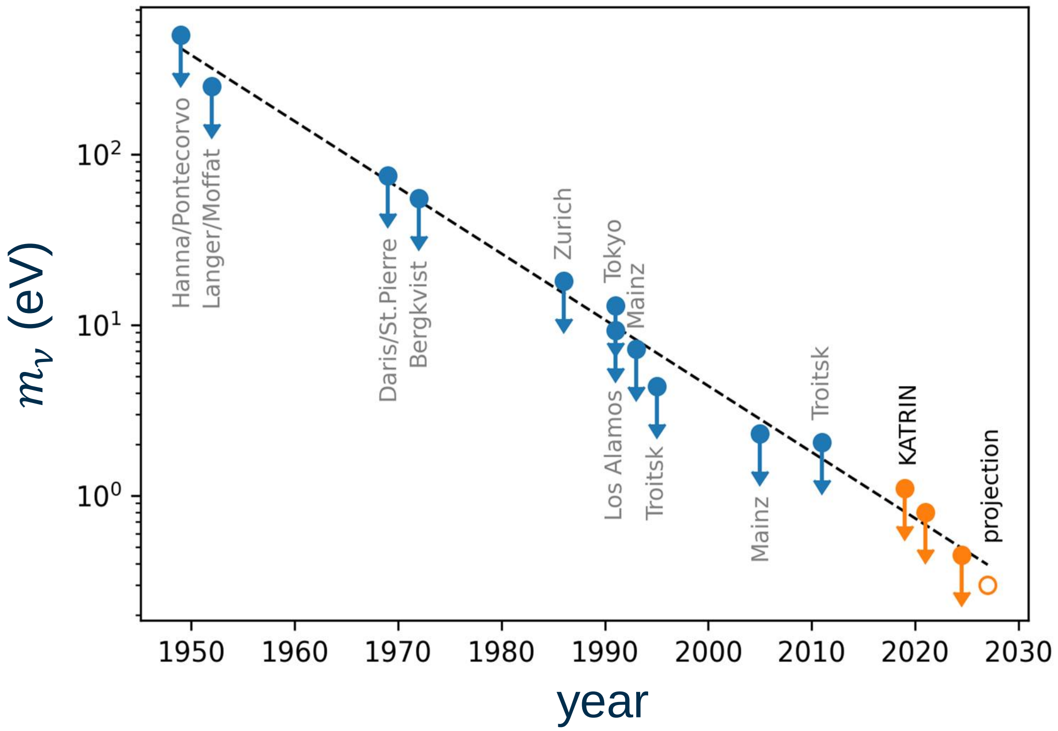
- Final dataset is ready
- Projected sensitivity of $m_{\nu} < 0.3$ eV

- Optimization of analysis procedure
  - 1400 parameters
  - configuration unchanged since KNM5
  - studies on combination of KNMs
  - lightweight analysis

- Full characterisation of systematic uncertainty
  - dedicated systematic campaigns: KNM20 and KNM21
  - soon finished
  - finalization of inputs



Summary



- Current world-best **direct neutrino mass limit** by KATRIN

$$m_\nu < 0.45\ \text{eV (90\% CL)}$$

  - combined analysis of first 5 science runs
  - data taking completed with 1000 days
  - final projected sensitivity of < 0.3 eV
- Optimization of analysis procedure
  - reduction of data and model granularity
- Full characterisation of systematic uncertainty
  - systematic measurements and analysis ongoing

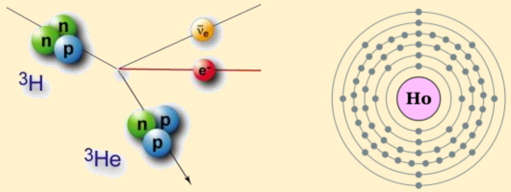
Goal: Lightweight, fast analysis of the final dataset with precise understanding of all systematic effects. ⟶ Stay tuned!

Backup

Neutrino Mass observables

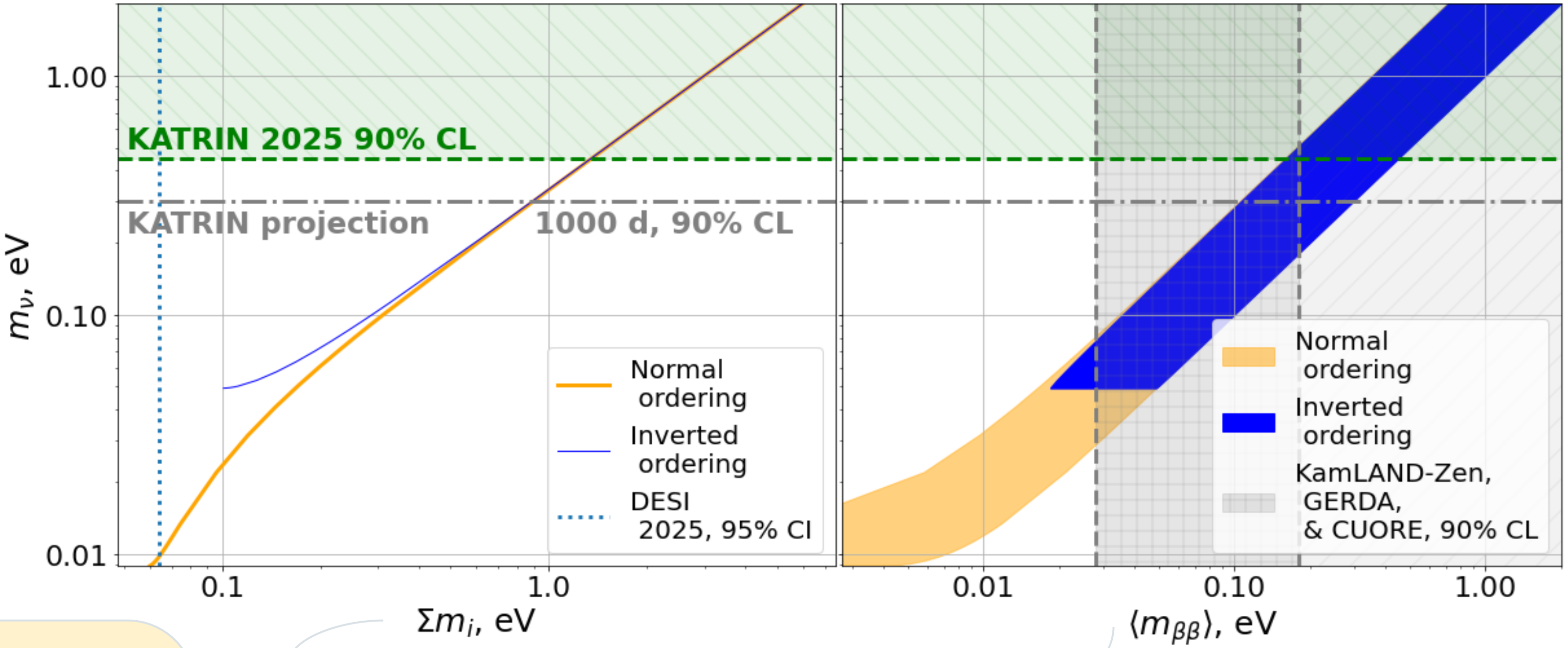
Updated, based on Ann.Rev.Nucl.Part.Sci. 72 (2022) 259-282

Direct kinematic measurements



Beta-decay and electron capture

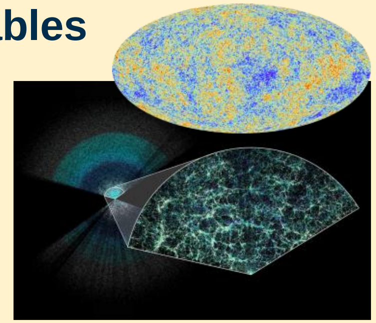
$$m_\nu^2 = \sum |U_{ei}|^2 \cdot m_i^2$$



Cosmological observables

$$M = \sum m_i$$

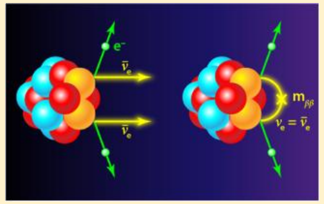
Interpretation within ΛCDM model



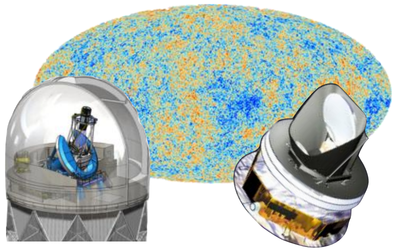
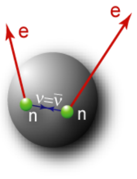
Neutrinoless double β-decay

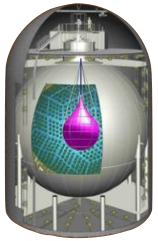
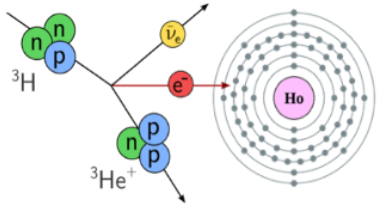
$$m_{\beta\beta} = \sum U_{ei}^2 \cdot m_i$$

Assumes Majorana nature of neutrinos



Neutrino Mass observables

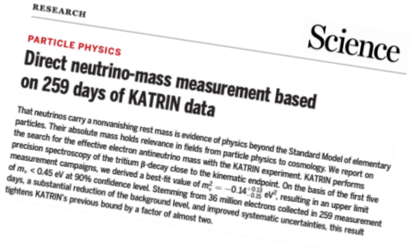



	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$	$m_\nu^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Present upper limit	0.12[1] eV (0.064[2] eV)	0.036 – 0.156[3] eV	0.45[4] eV
Model dependence	Multi-parameter cosmological model	- Majorana ν - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

(1) Planck Coll., A&A **641** (2020) A6
(2) DESI Coll.,arXiv:2503.14738
(3) KamLAND-Zen Coll., PRL **130** (2023) 051801
(4) KARTIN Coll., Science **388** (2025) 180

Confidence interval


RESEARCH

Science

PARTICLE PHYSICS

Direct neutrino-mass measurement based on 259 days of KATRIN data

That neutrinos carry a nonvanishing rest mass is evidence of physics beyond the Standard Model of elementary particles. Their absolute mass holds relevance in fields from particle physics to cosmology. We report on the search for the effective electron antineutrino mass with the KATRIN experiment. KATRIN performs precision spectroscopy of the tritium β-decay close to the kinematic endpoint. On the basis of the first five measurement campaigns, we derived a best-fit value of $m_\nu^2 = -0.14^{+0.13}_{-0.15}$ eV², resulting in an upper limit of m_ν < 0.45 eV at 90% confidence level. Stemming from 36 million electrons collected in 259 measurement days, a substantial reduction of the background level, and improved systematic uncertainties, this result tightens KATRIN's previous bound by a factor of almost two.

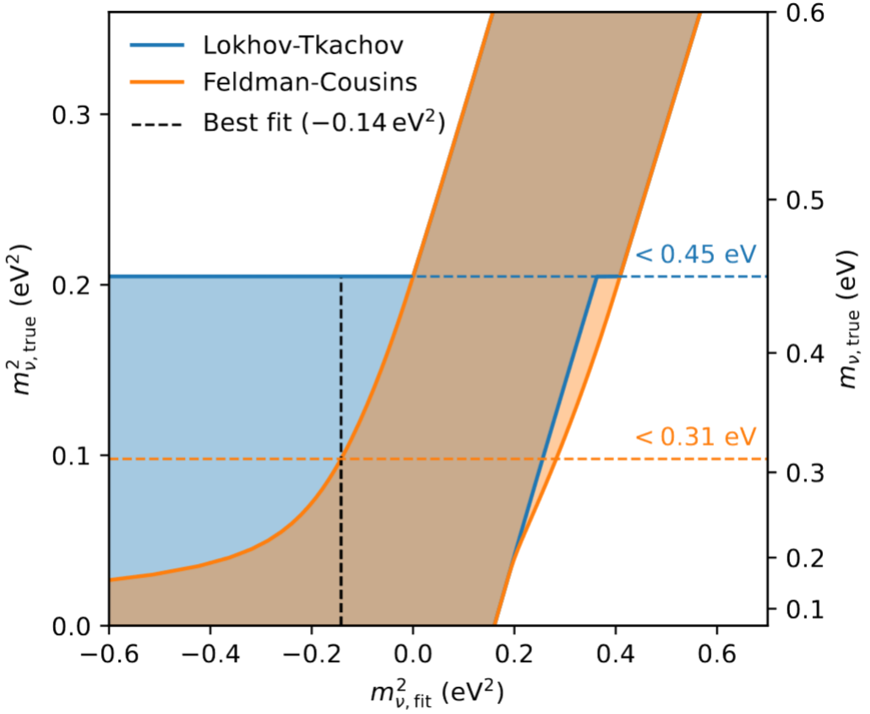
- **New world-best** direct neutrino mass constraint

  $$m_\nu < 0.45 \text{ eV (90\% CL)}$$

  using Lokhov-Tkachov construction
  Lokhov & Tkachov, Phys. Part. Nucl. **46** (2015) 347

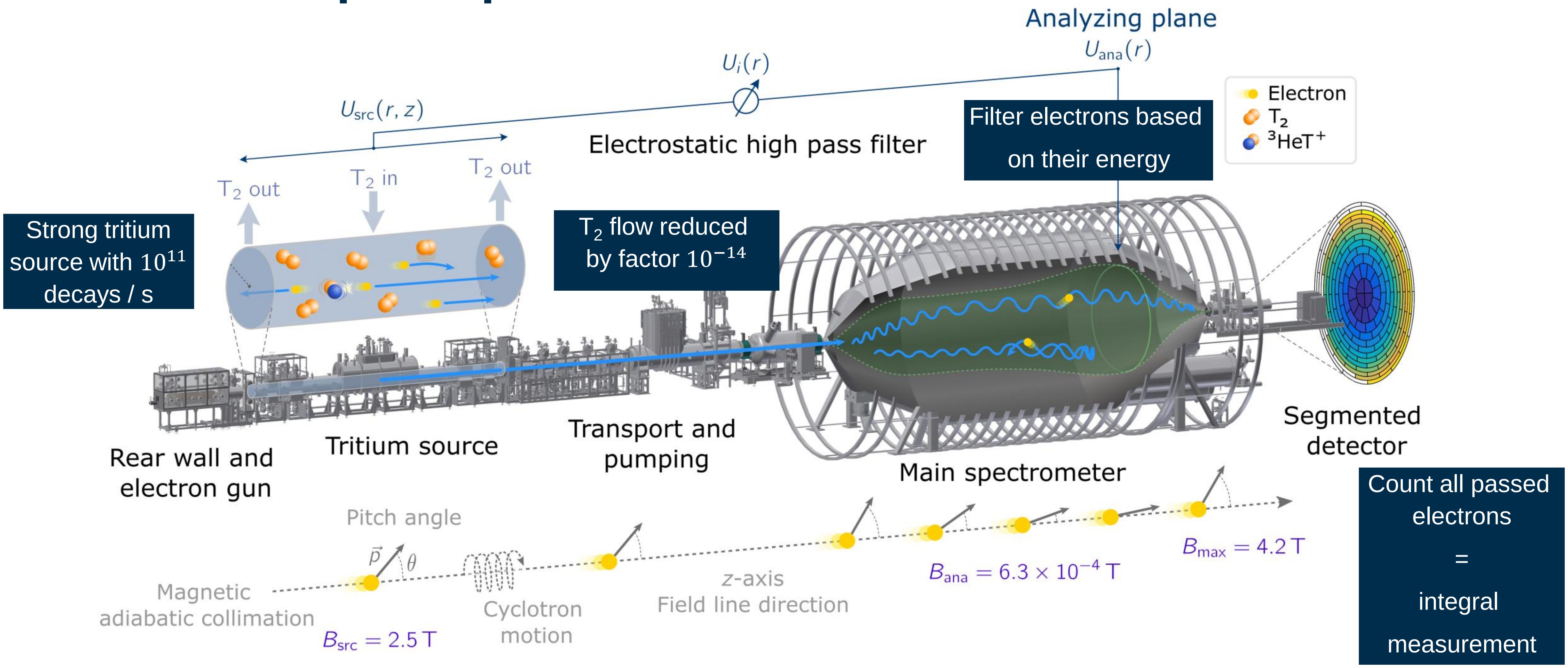
- Upper limit from Feldman-Cousins construction $m_\nu < 0.31$ eV (90% CL) benefits from negative best-fit
  Feldman & Cousins, Phys. Rev. D **57** (1998) 3873

- Bayesian analysis results in preparation



KATRIN Coll., Science 388 (2025) 180

Measurement principle



- Excellent energy resolution: $\frac{\Delta E}{E} \sim \frac{B_{ana}}{B_{max}} \sim 10^{-4}$
- Low background with ultra-high vacuum of 10^{-11} mbar

Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

KATRIN: International collaboration

Karlsruhe Tritium Neutrino Experiment

- Located in Karlsruhe because of the Tritum Laboratory Karlsruhe at KIT Campus Nord
- ~ 20 institutes from Germany, US, Italy, Czechia, Thailand, Spain, France
- ~ 150 people

Physics beyond the neutrino mass

β-spectroscopy at high precision & high stability

“Kink” search for fourth (sterile) neutrino

eV mass scale

→ PRL **126** (2021) 091803 & PRD **105** (2022) 072004

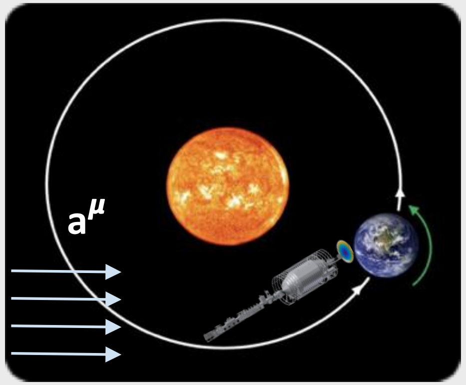
→ arXiv:2503.18667 (2025)

keV mass scale

→ EPJ C **83** (2023) 763

Search for Lorentz violation through **sidereal modulation**

→ PRD **107** (2023) 082005



Search for **shape distortion** through exotic weak interactions

- General neutrino interactions

→ PRL **134** (2025) 251801

- New light bosons

Line search for capture of local cosmic relic ν

→ PRL **129** (2022) 011806