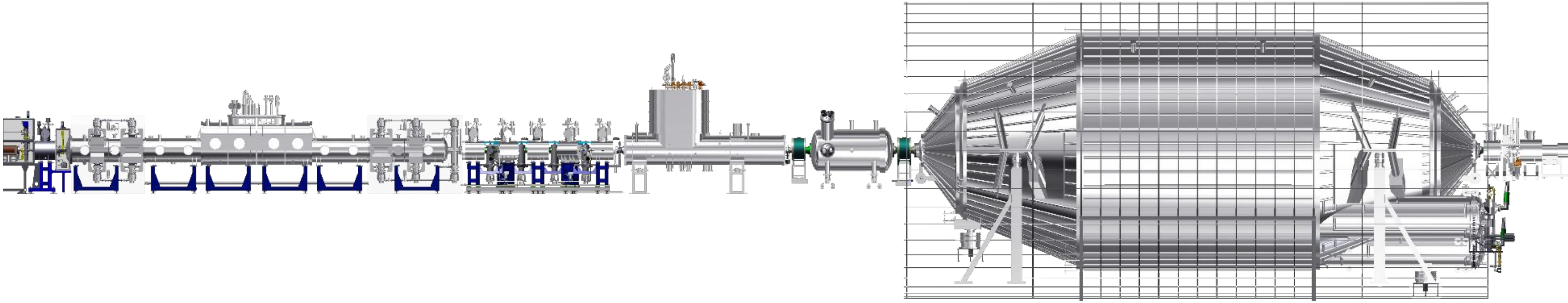
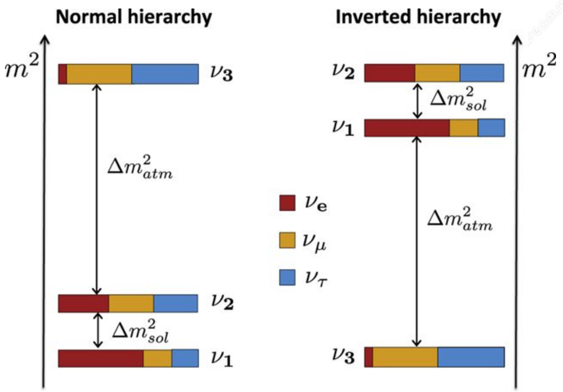
Direct neutrino mass measurement with KATRIN: Latest Results and Future Prospects

Khushbakht Habib (KIT) on behalf of the KATRIN Collaboration
CosPA/ACGRG 2026 - Christchurch
July 5^{th}-9^{th}, 2026

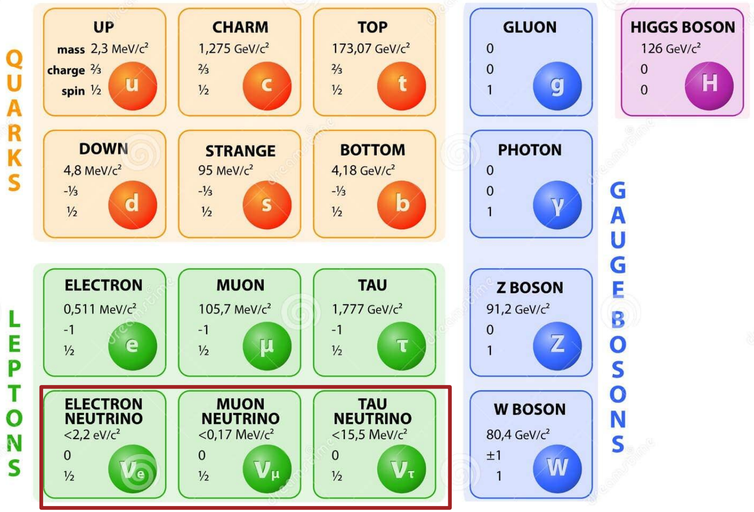


Neutrinos and their oscillations

- **Neutrino** $\longrightarrow$ fundamental, electrically neutral particle
- Originally predicted to be massless in SM
- **Neutrino oscillations** verify non-zero neutrino mass
  - mass eigenstates differ from flavour eigenstates
- **Oscillations** provide information on mass squared differences
  - $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- Still unknown: exact mechanism of mass generation, mass hierarchy, and **absolute mass scale**



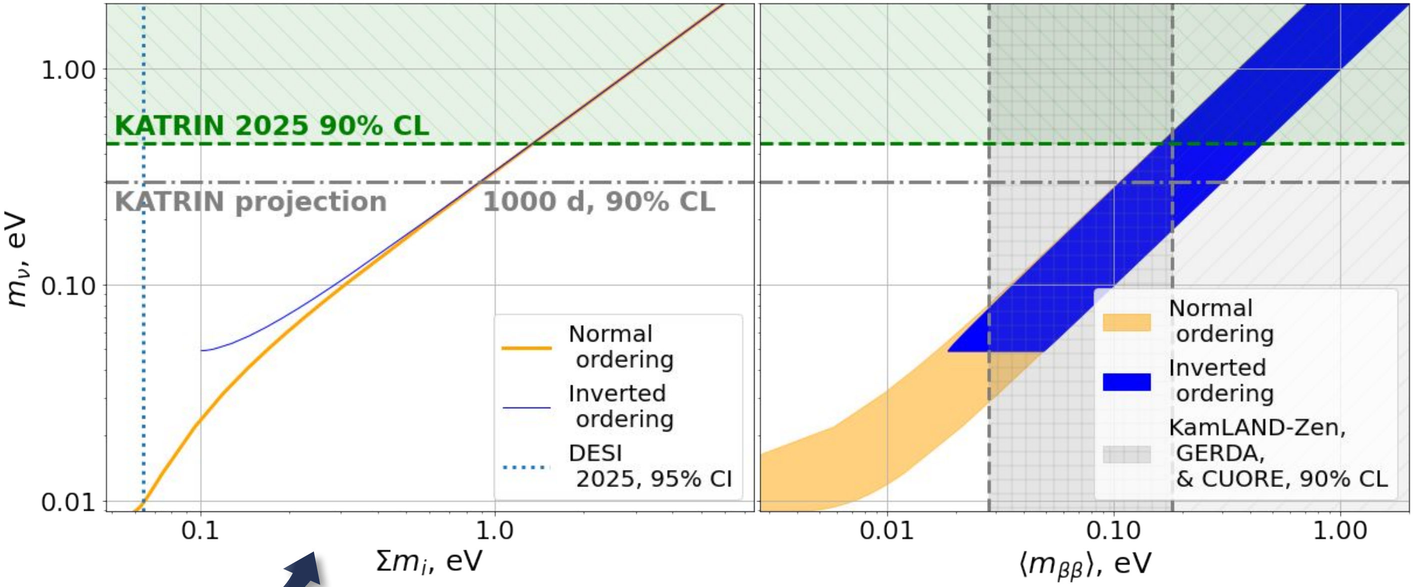
The Standard Model



Neutrino Mass observables

A.Lokhov, updated plot from Lokhov, Mertens, Parno, Schlösser, Valerius, Ann.Rev.Nucl.Part.Sci. 72 (2022) 259-282

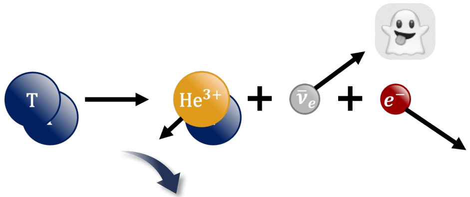
Kinematic experiments



Cosmological Observables

Neutrinoless double β-decay

Neutrino mass determination → $\boldsymbol{\beta}$-decay

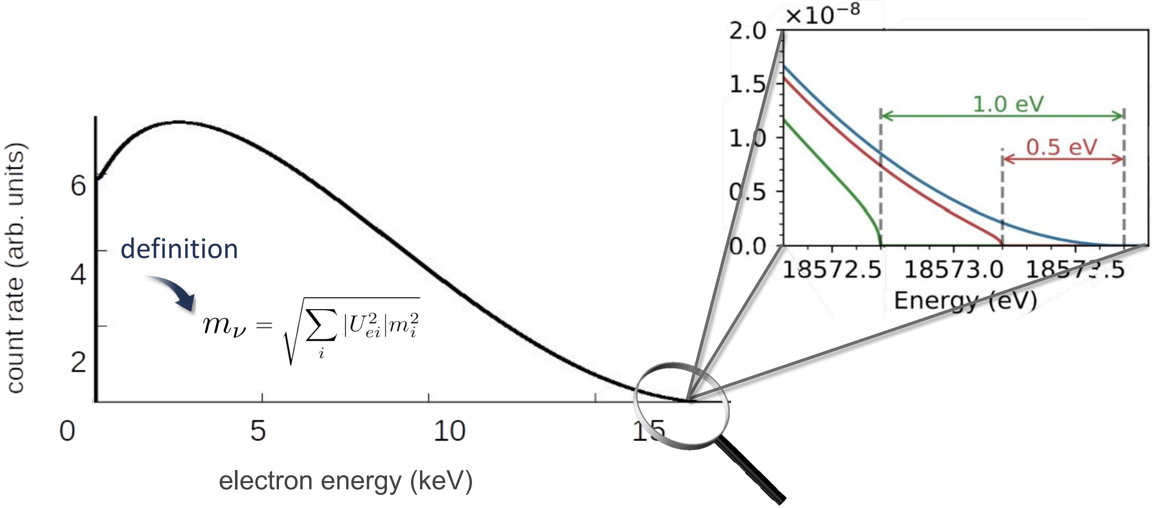


E_0 = 18.575 keV

How neutrino mass affects beta decay

- Electron spectrum depends on the neutrino mass
- Deviations most visible close to the endpoint ($E \approx E_0$)
- Measure K.E of β-decay electrons near E_0

$$\frac{dN}{dE} \propto (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \sum_i m_i^2 |U_{ei}|^2}$$



Why tritium as the source?

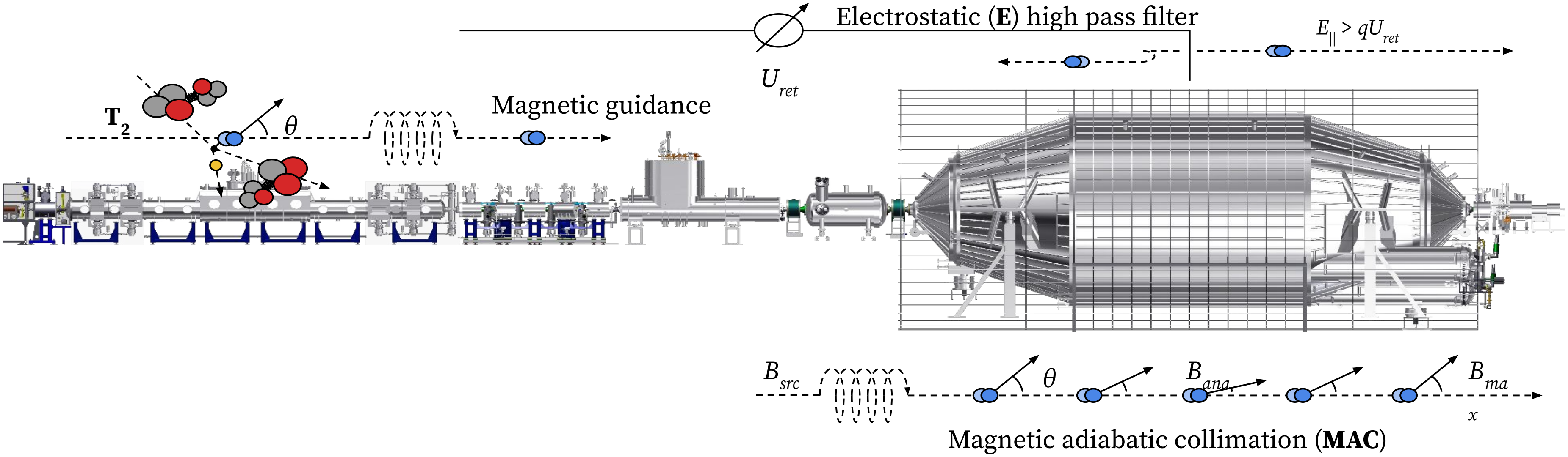
- Simple atomic/nuclear structure → easy to model
- Low endpoint energy: 18.6 keV
- Super-allowed transition
  → High decay rate ($T_{1/2}$ = 12.3 yr)

Collaboration: ~ 150 people @ 20 Institutions

KATRIN: Karlsruhe Tritium Neutrino Experiment

KATRIN Experimental setup

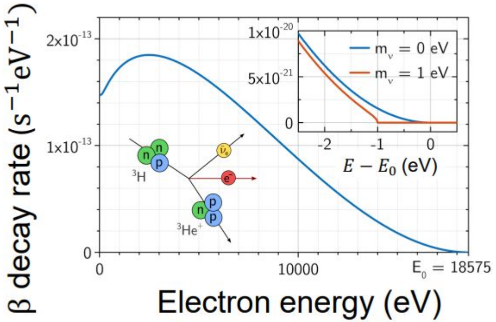
- **Tritium source:** high-activity (~100 GBq) windowless gaseous molecular source
- **Spectrometer:** high-resolution (~1 eV at 18.6 keV)
- **Segmented detector:** Electron counting at focal plane detector, 148-pixel silicon PIN diode
- **Integral spectrum** scans, discrete retarding potential steps



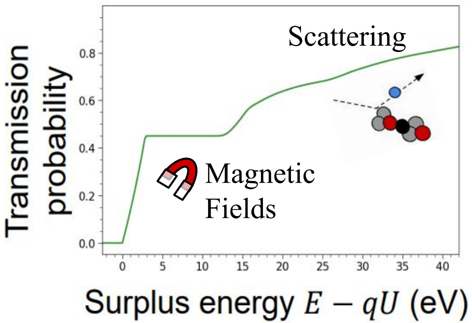
Full setup description: KATRIN, JINST 16 (2021) T08015

Image credit: C.Wiesinger

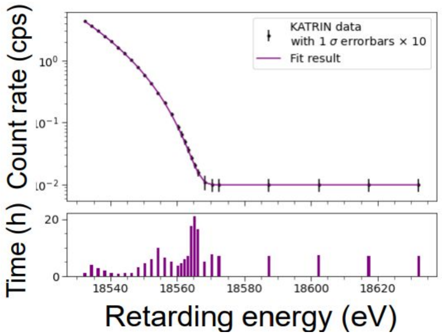
Modeling the tritium spectrum



$\otimes$



=



T_2 Beta spectrum $R_\beta\,(E;m^2(\nu_e))$

Response function: $f(E\text{-}qU)$

Determined by magnetic fields and scattering probabilities

Observed spectrum

$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

Four free fit parameters:

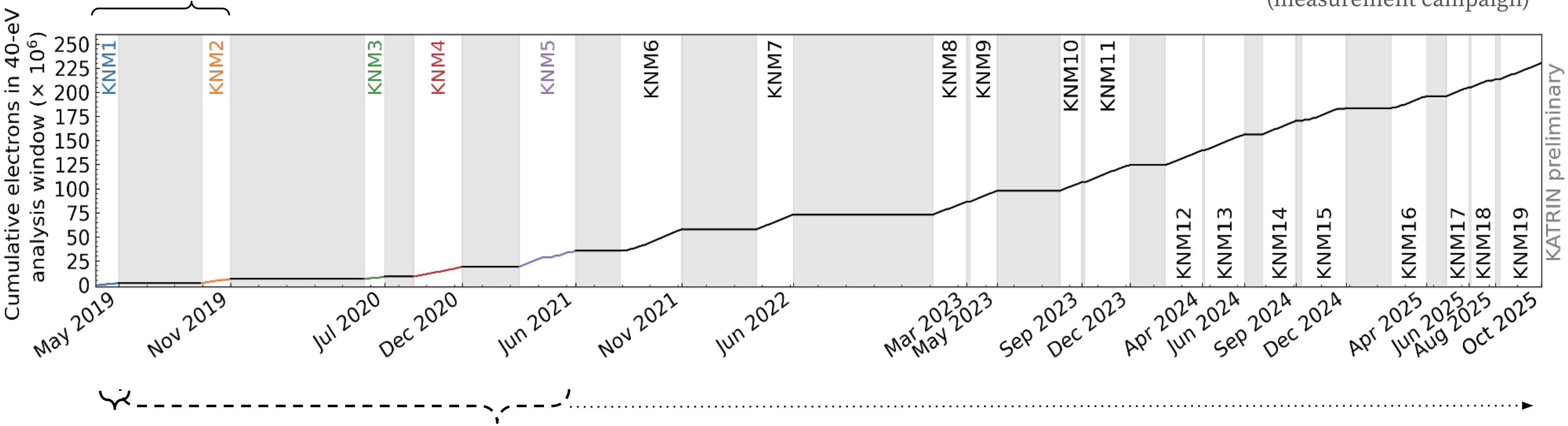
- Spectrum amp. A_s
- Spectrum Endpoint E_0
- Background rate R_{bg}
- Squared mass m^2_ν

$\sim 10^{-8}$ of all β-decays in scan region
~40 eV below endpoint

KATRIN data taking overview

Second result: $m_\nu < 0.8$ eV (90% CL)
[Aker et al., Nature Phys. 18 (2022)]

KNM = KATRIN Neutrino Mass (measurement campaign)

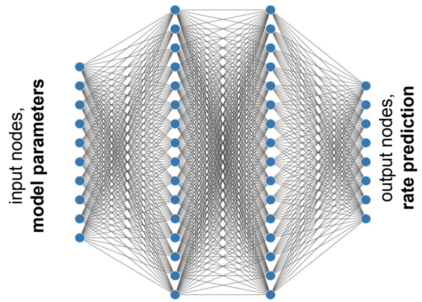


First result: $m_\nu < 1.1$ eV (90% CL)
[Aker et al., PRL 123 (2019)]

Third result: 5 campaigns, 1757 β-scans, **259 measurement days**
[Aker et al., Science 388 (2025) 6743]

Finished data-taking: **1000 measurement days, ~230 Million electrons (in 40 eV range)**

Data Analysis Challenges & Approaches



Challenges

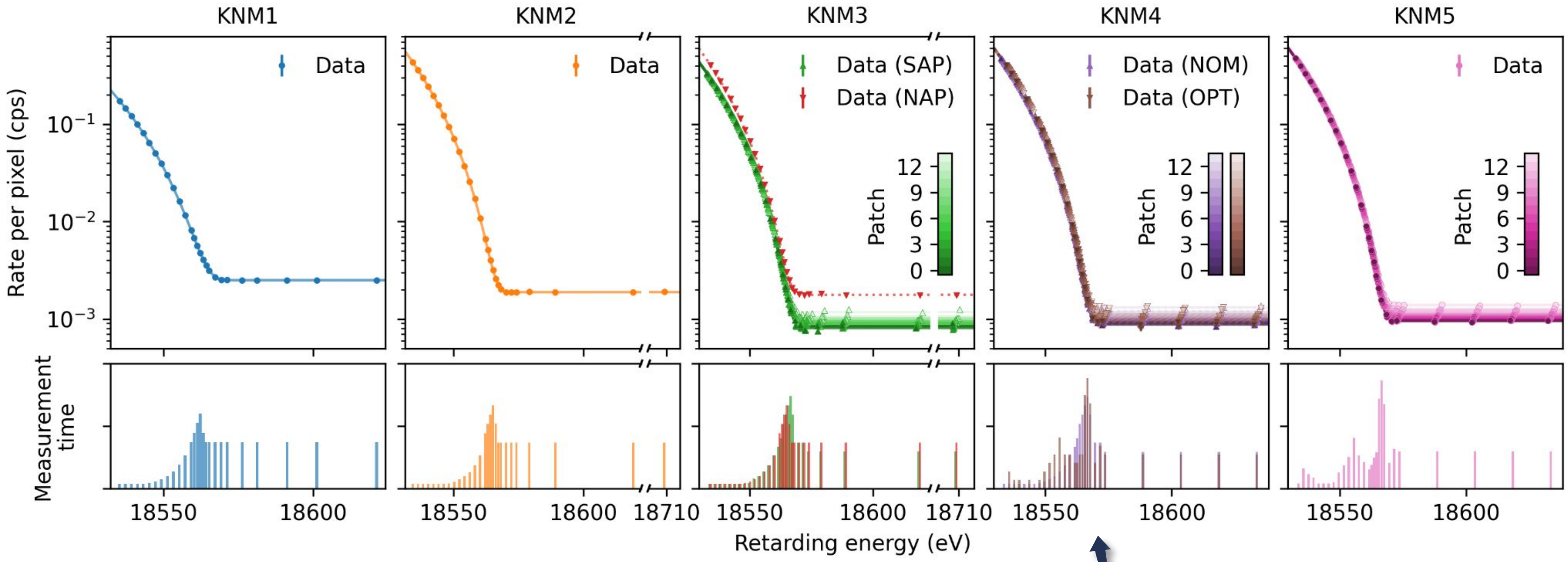
- **Large datasets:** multiple campaigns, >**1500** data points
- **Complex modeling:** ~ **180** fitting parameters
- **Strong correlations:~ 150** correlated systematic parameters
- **High computational cost:** expensive model evaluation and fitting procedures

Frameworks

- **Two independent analysis teams** with different analysis frameworks
  - Highly optimized model evaluation
    Kleesiek et al., *Eur. Phys. J. C* **79**, 204 (2019)
  - Neural network-assisted fast model predictions
    EPJC 82, 439 (2022)
- **A two-step blinding strategy:**
  - Fixing analysis procedure using MC-generated data
  - Using blinded model with undisclosed modifications of final states

Experimental Data: **Campaigns 1-5**

➔ 7 different configurations with 59 stacked spectra, 1609 data points

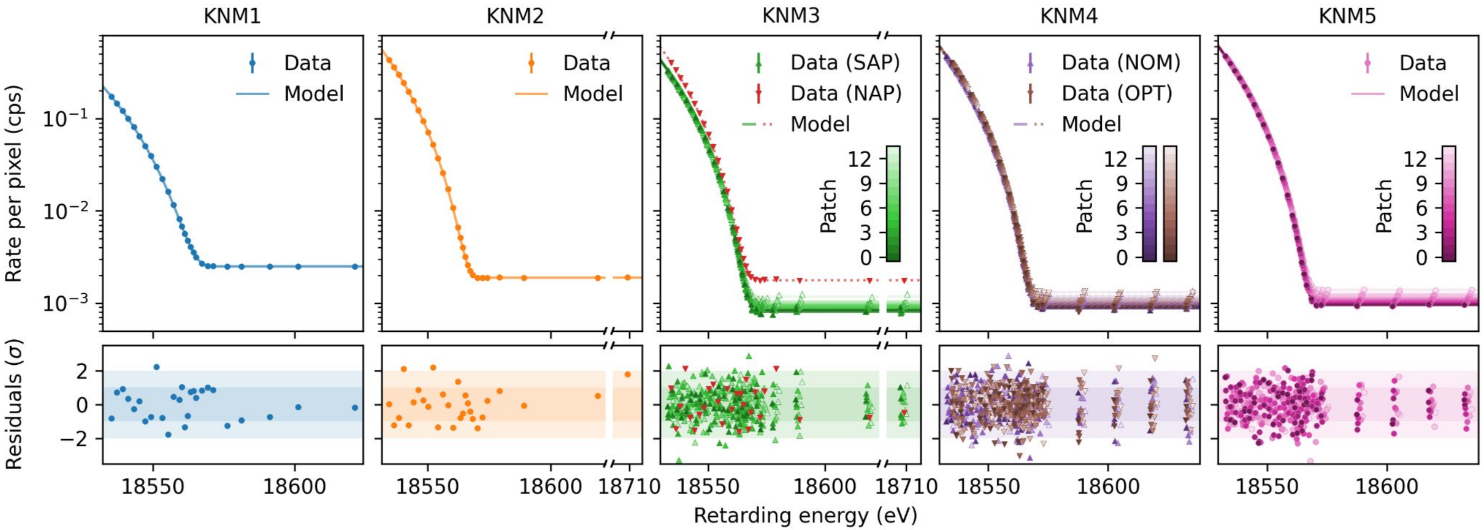


Background suppression

Optimised measurement time distribution
for higher sensitivity

Experimental Latest Results: **Campaigns 1-5**

Simultaneous **maximum likelihood fit** performed, using a common m_ν^2 parameter



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

[Aker et al., Science 388 (2025) 6743]

Upper limit: $m_\nu < 0.45\,\mathrm{eV}\ (90\%\ \mathrm{C.L.})$

based on **Lokhov-Tkachov** confidence interval construction

[Lokhov, Tkachov, Phys.Part.Nucl. 46 (2015)]

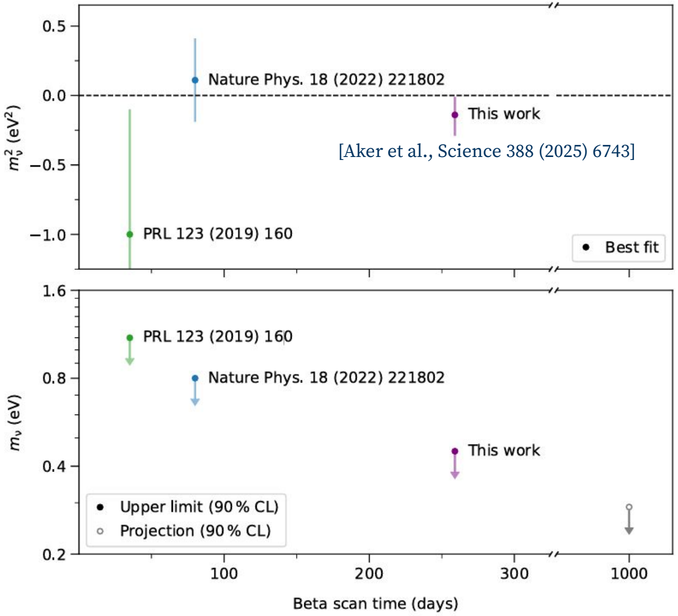
Sensitivity outlook: Campaigns 1-19

Latest KATRIN result

World-best direct neutrino mass upper limit

$\boldsymbol{m_\nu} < \mathbf{0.45\ eV}$ (90% *CL*)

based on 259 measurement days & 36 million electrons



Final KATRIN Dataset

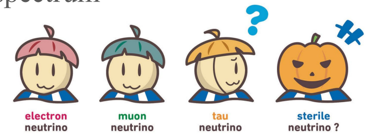
Target sensitivity: $\boldsymbol{m_\nu} < \mathbf{0.3\ eV}$ (90% *CL*)

based on 1000 days of data-taking & ~230 million electrons (in 40 eV range)

Beyond Neutrino mass physics with KATRIN

Phys.Rev.Lett. 126 (2021) 9, 091803
Phys.Rev.D 105 (2022) 7, 072004

Search for light **eV-sterile neutrinos** close to the end-point of β-spectrum



Kink search

Phys. Rev. Lett. 129 (2022) 1, 011806

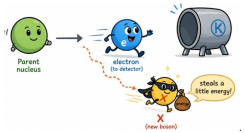
Probe for local overdensity of **relic neutrinos**

Peak search

JHEP 01 (2019) 206

New light bosons

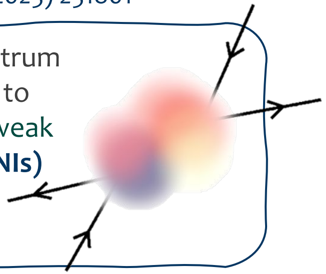
Additional BSM bosons coupling to leptons →real emission in β-decay



Shape distortion

PRL 134 (2025) 251801

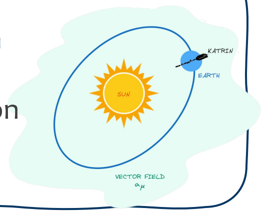
Search for spectrum distortions due to exotic electro-weak interactions **(GNIs)**



Shape distortion

Phys.Rev.D 107 (2023) 8, 082005

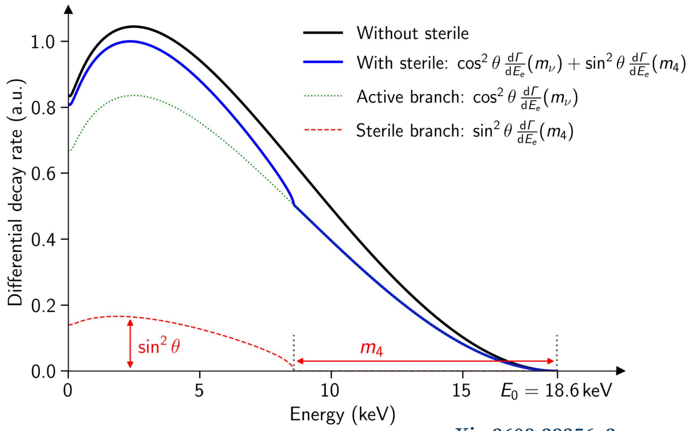
Search for **Lorentz-violation** by spectrum‘s annual modulation



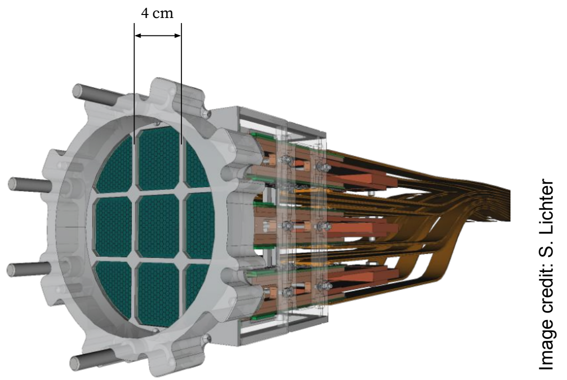
Temporal variation

Coming up: Beamline upgrade with new detector system $\rightarrow$ TRISTAN

- Search for keV sterile neutrinos
  - Novel detector for differential, **high-rate $\boldsymbol{\beta}$ spectroscopy**
- 1494-pixel **Silicon drift detector** (SDD) array
  - 9 modules (166 pixels each)
  - Designed for **10^8 cps**
- **Target sensitivity** to mixing of 10^{-6}
  - Ongoing systematics and modeling studies
- Installation in the KATRIN beamline: 2026



arXiv:2603.23256v2



9 Module SDD (166 pixels each)

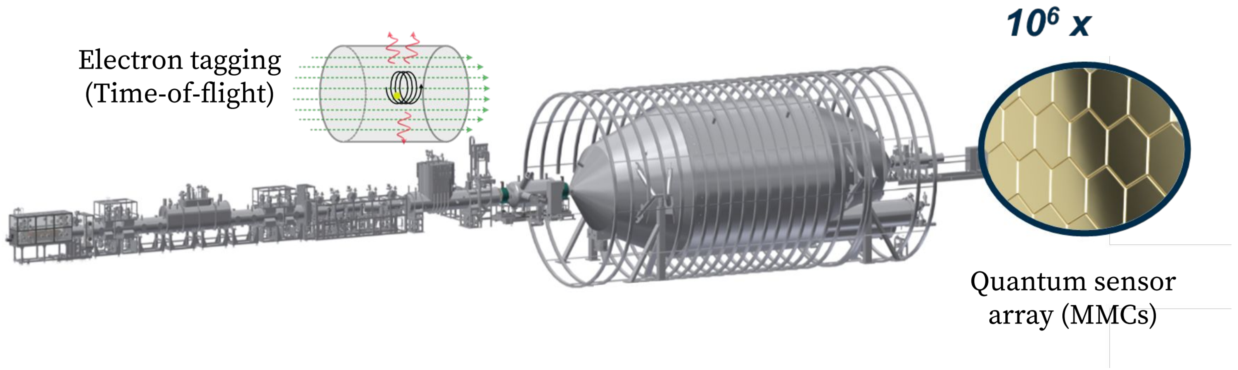
Next-generation program: KATRIN++

- Identify and develop **key technologies** for next generation direct neutrino mass measurement with tritium:

  KATRIN++

➢ **Differential β-spectroscopy** (FWHM < 1eV)
  - From **integral** $\rightarrow$ **differential** measurement
  - Allows to probe sub-100 meV region of m_ν
  - Lower background

➢ **Atomic** tritium source
  - Avoid **molecular final-state broadening**
  - Avoid limiting T_2 systematics



Conclusions and Outlook

- Absolute neutrino mass scale is an open question in **particle physics, astrophysics and cosmology**

- **KATRIN:** the **leading model-independent** laboratory probe of the absolute neutrino mass

- **World-best** direct neutrino mass upper limit
  m_ν **< 0.45 eV** (90% *CL*)

$\rightarrow$ Neutrinos are **lighter than one millionth of the electron mass**

- **Final KATRIN dataset (**under analysis)
  Target sensitivity: m_ν < 0.3 eV (90% CL)

- **TRISTAN,** Search for keV-scale sterile neutrinos

- **KATRIN++,** R&D for the next-generation experiment

KATRIN Collaboration

Thanks for your attention

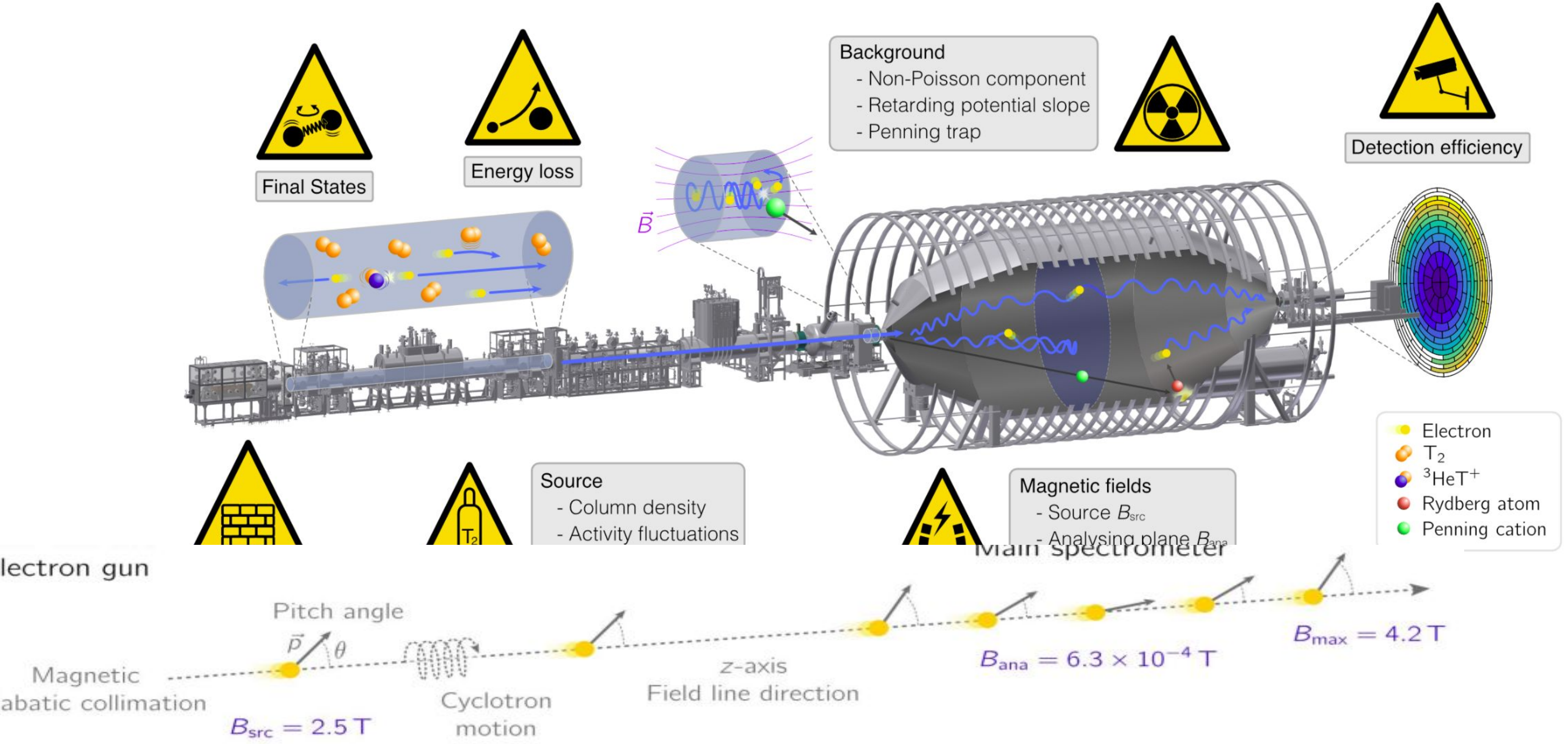
50th KATRIN collaboration meeting, Heidelberg 2026

Karlsruher Institut für Technologie
BERKELEY LAB
Nuclear Physics Institute
BERGISCHE UNIVERSITÄT WUPPERTAL
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
Max-Planck-Institut für Physik
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
Carnegie Mellon University
Universität Münster
UAM Universidad Autónoma de Madrid
UNIVERSITÄT BONN
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
INFN
POLITECNICO MILANO 1863
Chula Chulalongkorn University
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
Bundesministerium für Bildung und Forschung
DFG
MAX PLANCK GESELLSCHAFT
MINISTRY OF EDUCATION, YOUTH AND SPORTS

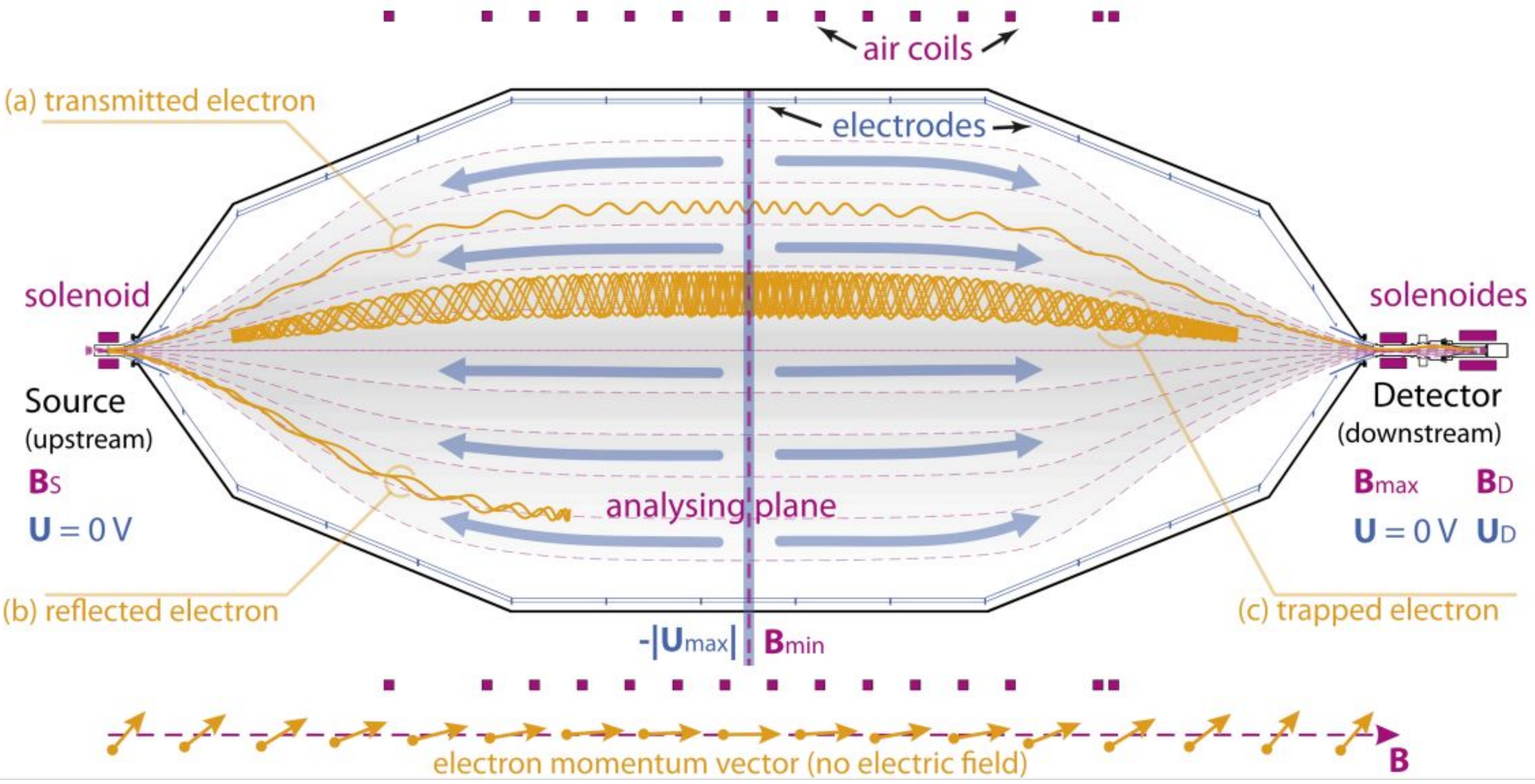
Backup

Systematic effects

$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E)\,dE + R_{bg}$$



The MAC-E filter principle

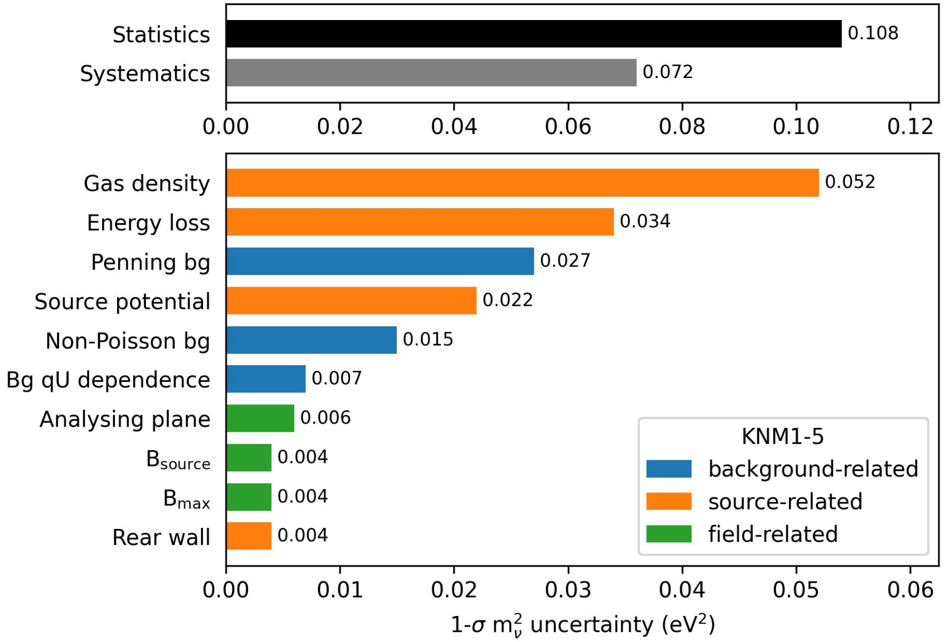


Systematic Uncertainty Breakdown: For measurement campaigns 1-5

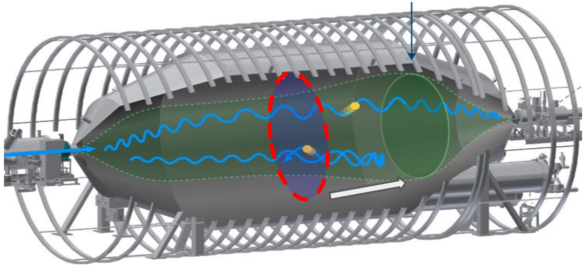
- **6-fold increase in statistics**, 2-fold reduction of background
- **Improved** control over source-related effects

➔ **Statistical uncertainty dominates**, improved calibration precision in recent campaigns

Further improvement for campaigns beyond KNM5



Experimental Improvements in new data



- **Shifted analyzing plane** configuration
  - Achieved two-fold **reduction in background**

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

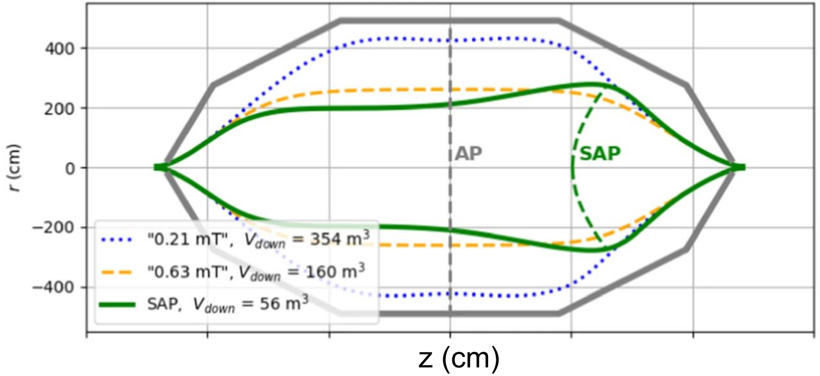
- ^{83m}**Kr co-circulation** mode
  - Used to determine both **source potential** and **spectrometer fields**

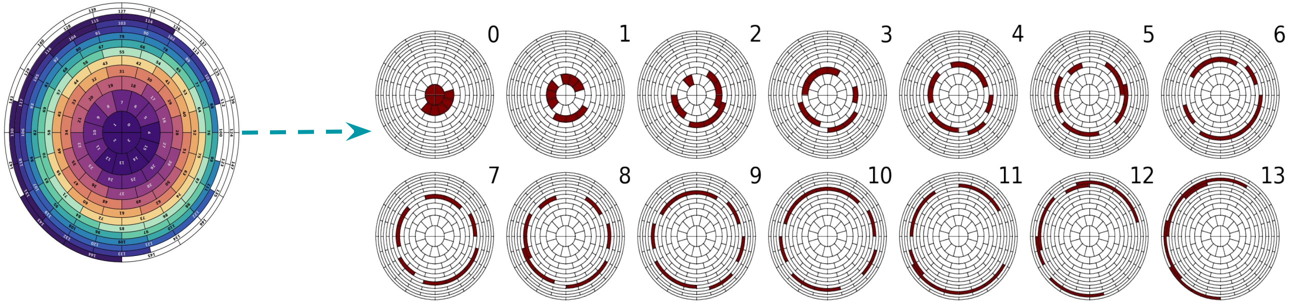
    [A. Marsteller et al 2022 JINST 17 P12010]

- Improved electron gun
  - Mono-energetic angular-selective photoelectron source
  - Better calibration of the **scattering effects**

Experimental Improvements in new data

- **Shifted analyzing plane** configuration
  - Achieved two-fold **reduction in background**
  - Inhomogeneous spectrometer fields
    - Increased segmentation of data **by factor of 14**





Neutrino-mass limit: For campaigns 1-5

- New world-leading direct upper limit on the neutrino mass:

  m_ν < 0.45 eV (90% *CL*)

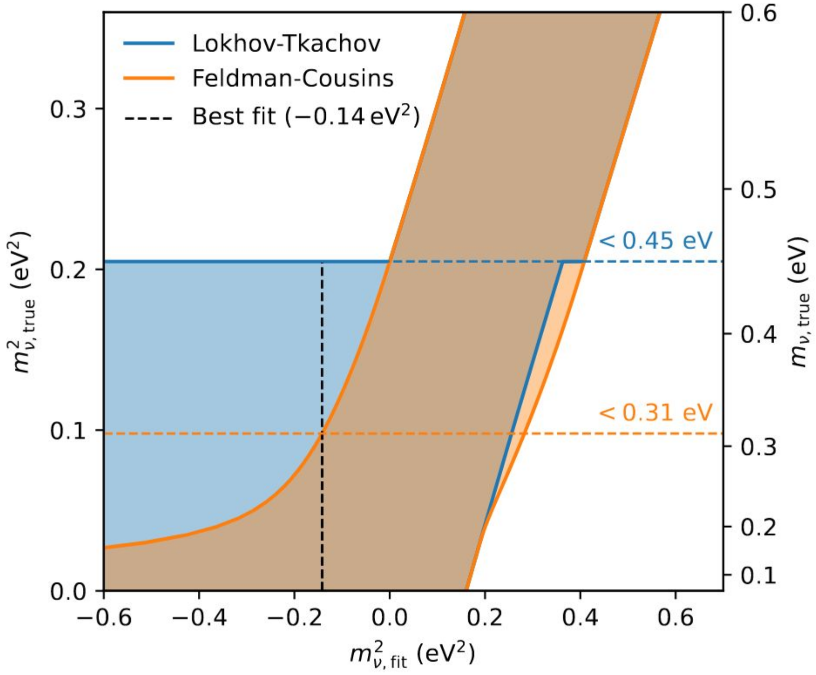
  based on **Lokhov-Tkachov** confidence interval construction (ensures upper limit is not reduced by negative m_ν^2 values)

  [Lokhov, Tkachov, Phys.Part.Nucl. 46 (2015)]

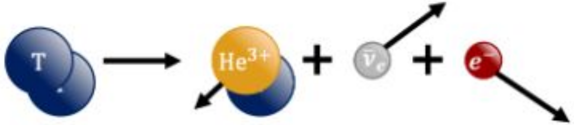
- **Feldman-Cousins limit:**

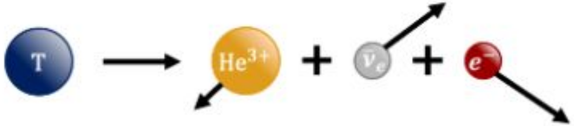
  m_ν < 0.31 eV (90% *CL*), benefits from negative best-fit

- Latest results after 259 days of data taking: available at https://arxiv.org/abs/2406.13516



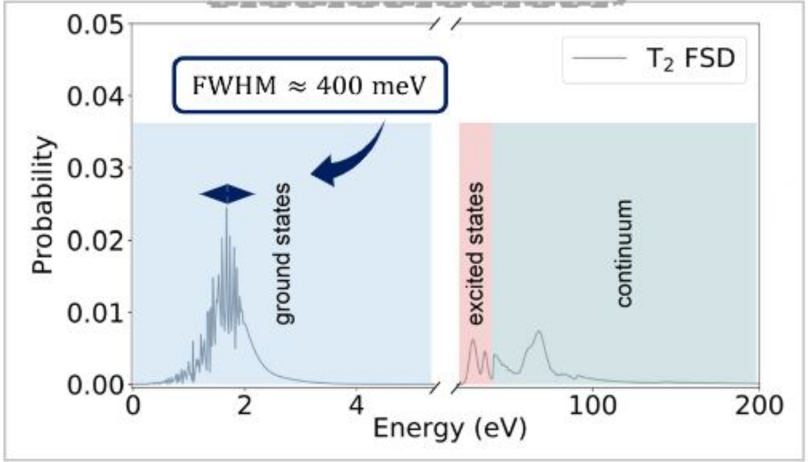
Final State Distributions





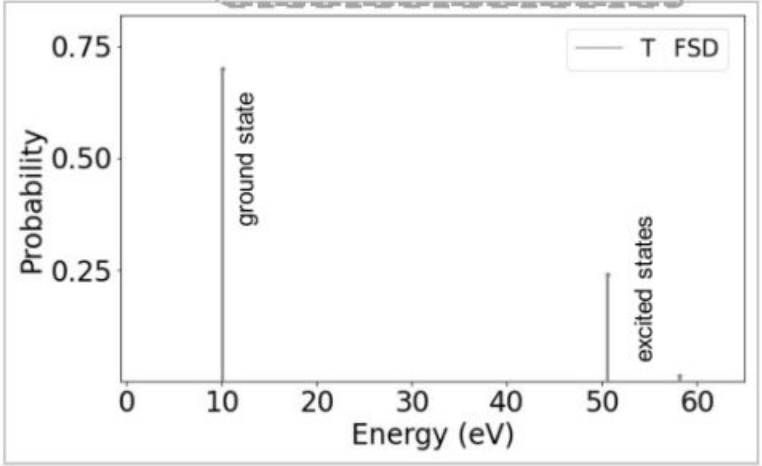
Molecular Tritium

KATRIN operating @ 80 K

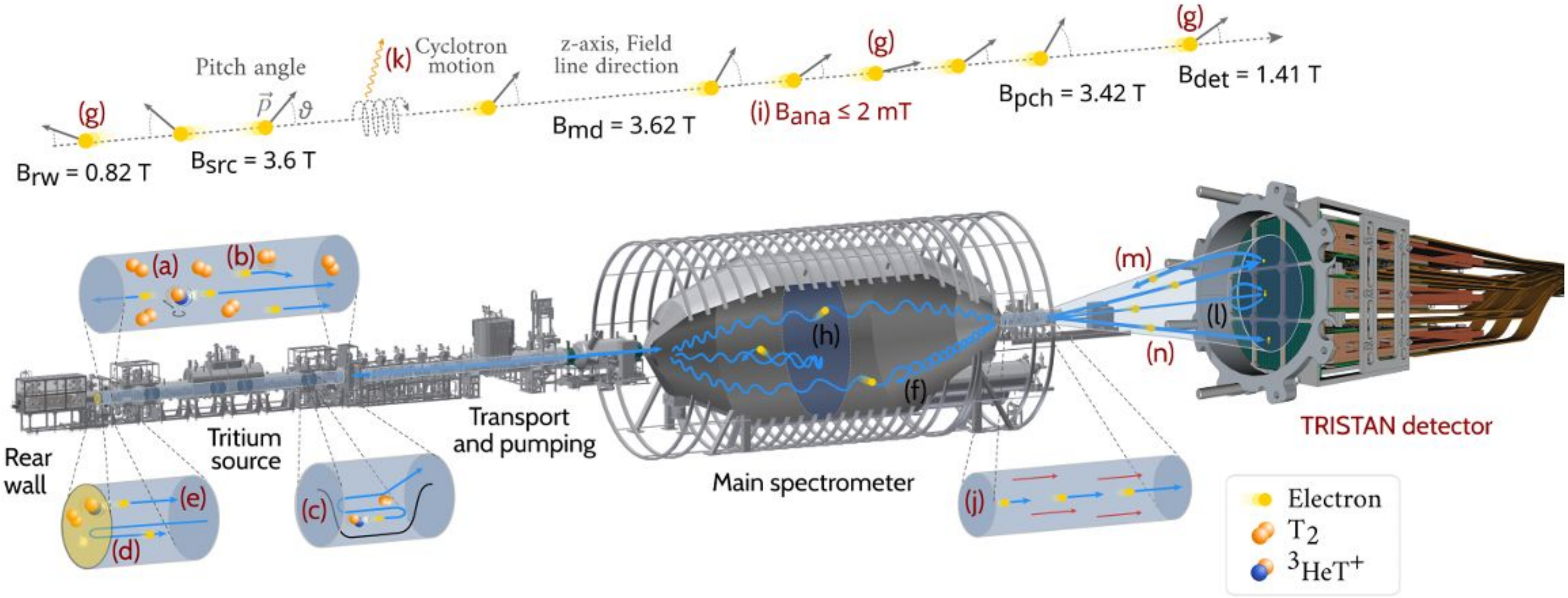


Atomic Tritium

Simulated cold source @ 5 K

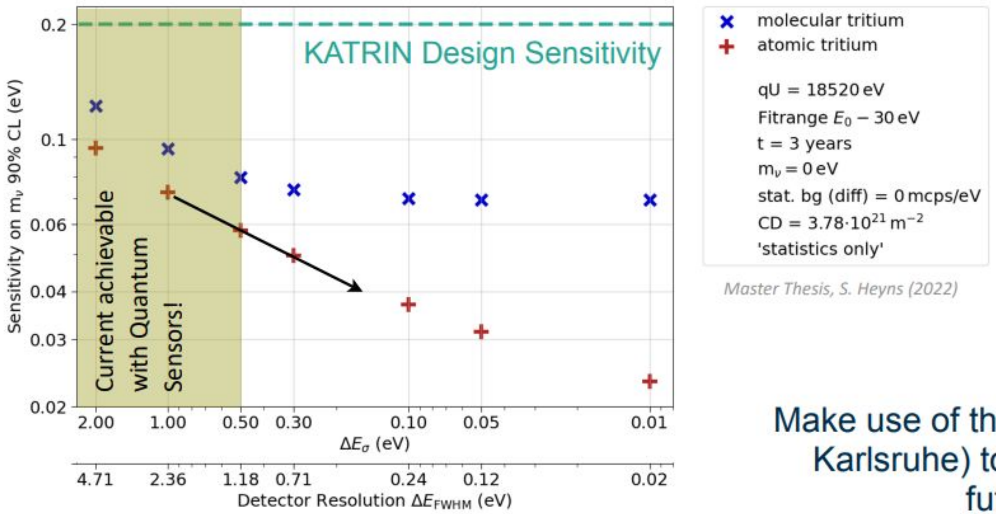


TRISTAN detector in KATRIN beamline



Going Beyond KATRIN

- Going beyond KATRIN final sensitivity requires paradigm shift in measurement approach



Master Thesis, S. Heyns (2022)

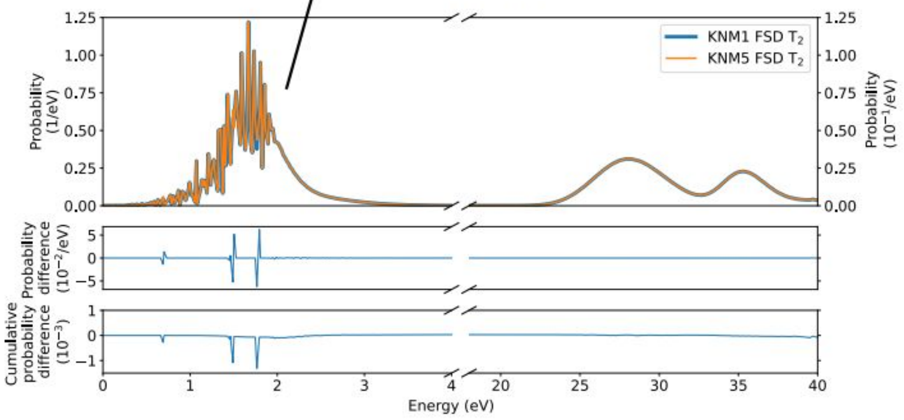
- Two directions forward:
  - Differential measurement mode:
    - → Significant increase in statistics
    - → Reduction of backgrounds
    - → Increase in energy resolution
  - Change from molecular tritium source to an atomic one:
    - → Eliminate effects due to molecular final states

Make use of the existing KATRIN & TLK (Tritium Laboratory Karlsruhe) to develop new and scalable technology for future neutrino mass experiments!

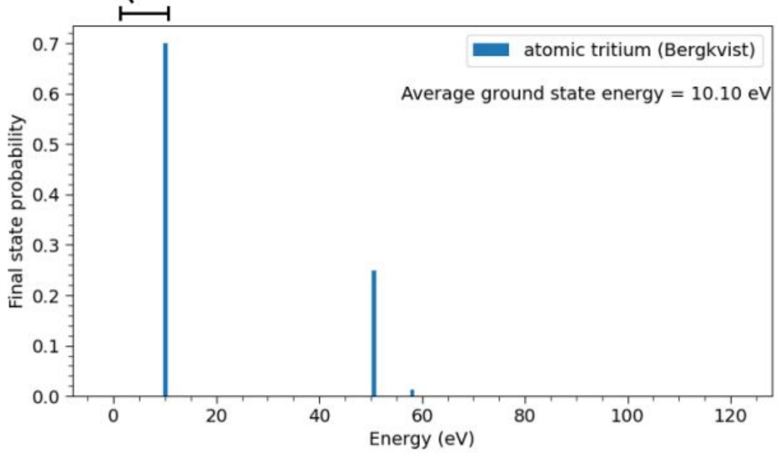
Atomic Tritium Source

- Molecular tritium source
  - 57% of decays in to electronic ground state
  - Intrinsic broadening of the end point on the level of 1 eV

The KATRIN Collaboration, Science 388,180-185(2025)



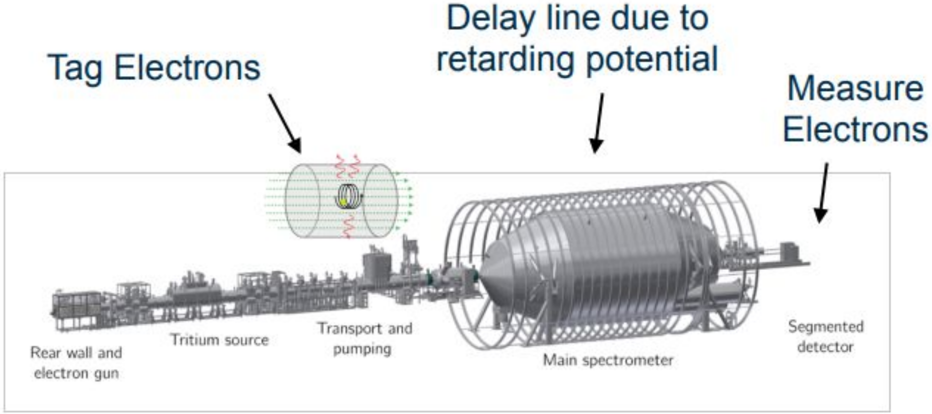
- Atomic tritium source
  - 70% decays in to electronic ground state
  - ~ 8 eV shift of the end point



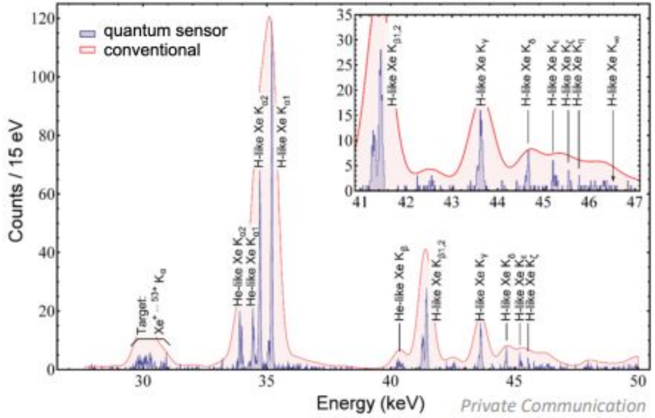
Differential Detection Method

- Time-of-Flight (ToF) Measurements
  - Tag electrons as they pass through the beam line
  - Combine this information with arrival time at the detector to reconstruct differential spectrum
  - 1000 Hz single electron tagger with high Signal-to-Noise ration required!

- Quantum Sensors - Metallic Microcalorimeters (MMCs)
  - Orders of magnitude better energy resolution compared to conventional detectors
  - Close to 100% quantum efficiency
  - Near-linear detector response over broad energy range
  - No surface dead layer



high-resolution X-ray spectroscopy



KIT