KATRIN experiment and its recent results

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Outline

- Introduction: massive neutrinos
- KATRIN experiment
- Recent results
- Near future plans
- Summary & Outlook

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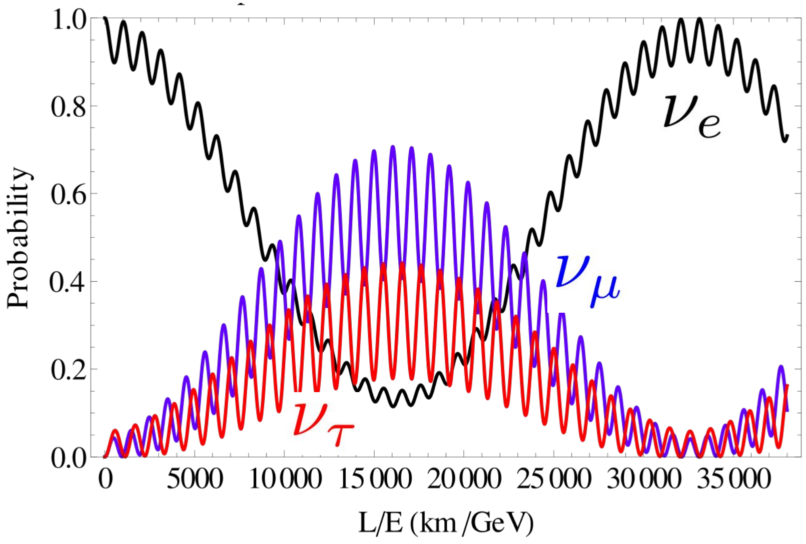
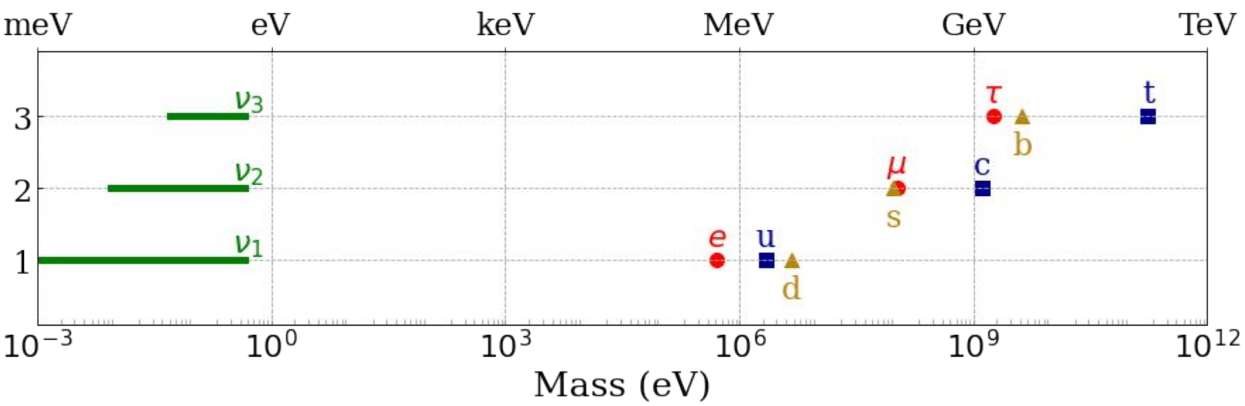
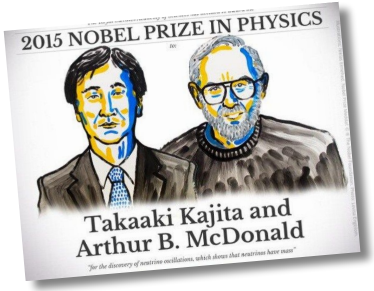
Massive neutrinos

- Neutrino oscillations →
  - 3 different massive ***ν*s**
- Most abundant **massive** particle in the universe
  - **Impacts** the cosmological evolution
- Absolute masses **unknown**
  - but **x10^6** smaller than m_e !

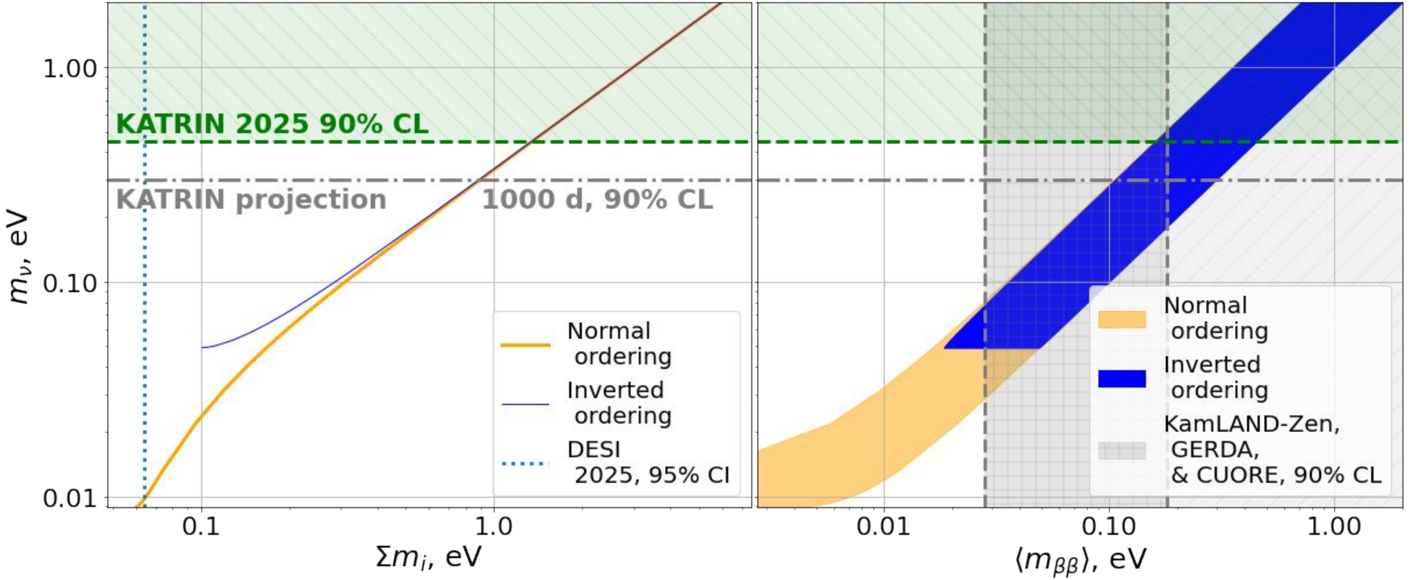






Neutrino mass observables

Direct neutrino mass determination



Assuming mixing angles θ and Δm^2 from oscillations

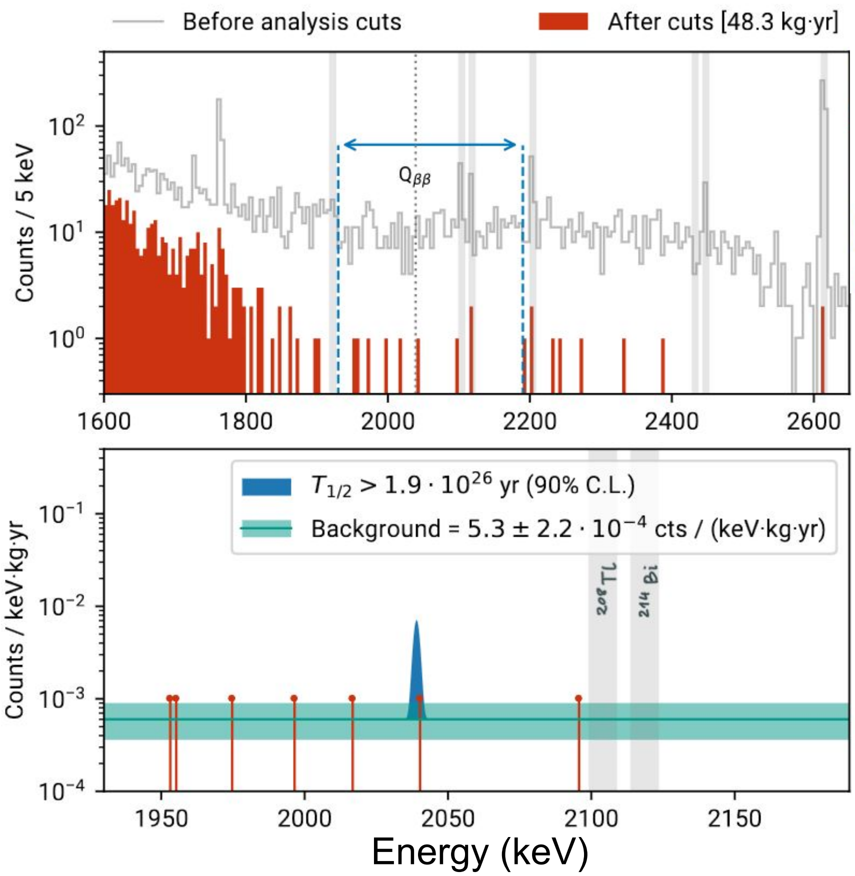
Cosmological observables

Neutrinoless double β-decay

Updated, based on Lokhov, Mertens, Parno, Schlösser, Valerius, Ann.Rev.Nucl.Part.Sci. 72 (2022) 259-282

$0\nu\beta\beta$ news

- Updated constraints on half-life from
  - **KamLAND-Zen 800** (complete data set)
    - ^{136}Xe: $T_{1/2} > 3.8\mathrm{x}10^{26}$ yr,
    - $m_{\beta\beta}$ < **28 - 122 meV** (90% CL)
  - **LEGEND-200** (first year)
    - ^{76}Ge: $T_{1/2} > 1.9\mathrm{x}10^{26}$ yr (90 CL)
    - $m_{\beta\beta}$ < **75 - 200 meV** (90% CL)
  - **CUORE**
    - ^{130}Te: $T_{1/2} > 3.8\mathrm{x}10^{25}$ yr,
    - $m_{\beta\beta}$ < **70 - 240 meV** (90% CL)



CUORE, **With or without ν? Hunting for the seed of the matter-antimatter asymmetry**, arXiv:2404.04453; LEGEND-200 arXiv:2505.10440; KamLAND-Zen, arXiv:2406.11438

Cosmological news

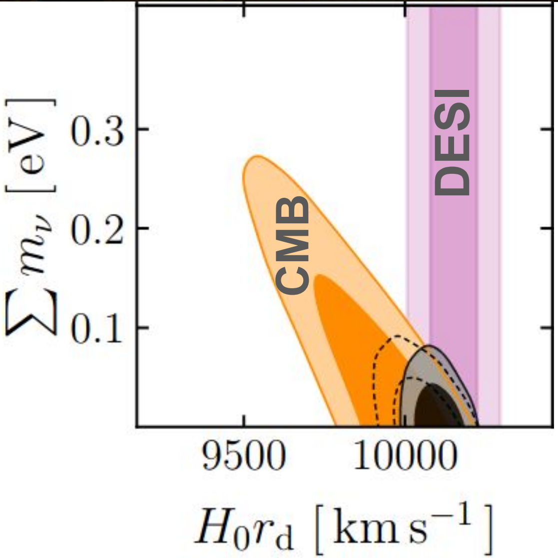
DR2 data from DESI (Dark Energy Spectroscopic Instrument)

- Galaxy survey
- Clustering of galaxies at z ~ 0.1-4.2
- Combined with CMB → sensitive to Σm_ν

Result (for ΛCDM)

$$\Sigma m_\nu < 0.064 \text{ eV}$$

Excluding IO (Σm_ν > 0.10 eV) and almost excluding NO (Σm_ν > 0.06 eV) at 95% CL



DESI collab., arXiv:2503.14744

Cosmological news

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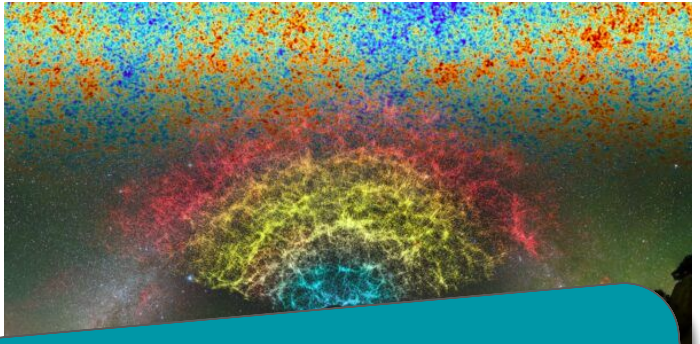
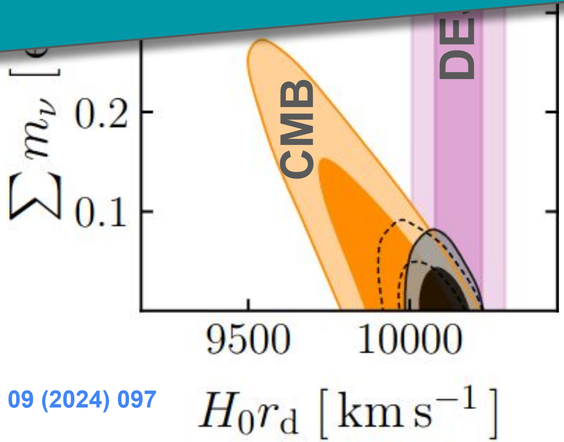


1. **Both 0νββ and cosmology depend strongly on the model assumptions**
2. **No νs in cosmology yet → increased importance of direct lab searches →input to cosmology**

$\Sigma m_\nu < 0.064$ eV

Excluding IO ($\Sigma m_\nu > 0.10$ eV) and almost excluding NO ($\Sigma m_\nu > 0.06$ eV) at 95% CL



No νs is Good News

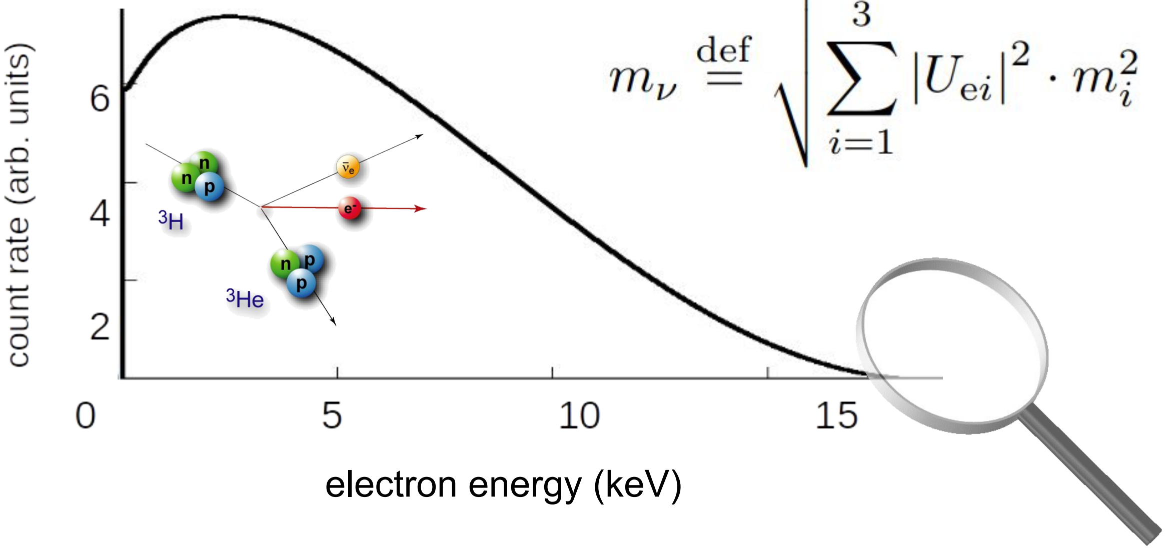
DESI collab., arXiv:2503.14744

N. Craig et al., JHEP 09 (2024) 097

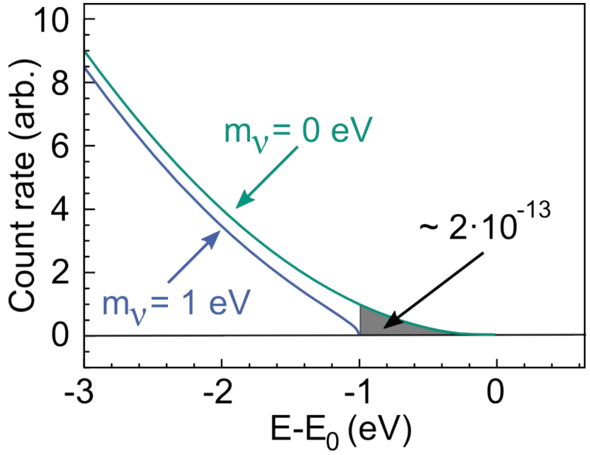
Neutrino mass in tritium β-decay

Measurement of effective mass $\boldsymbol{m_\nu}$ based on **kinematic parameters & energy conservation**

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



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



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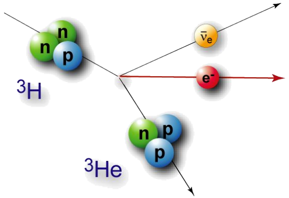
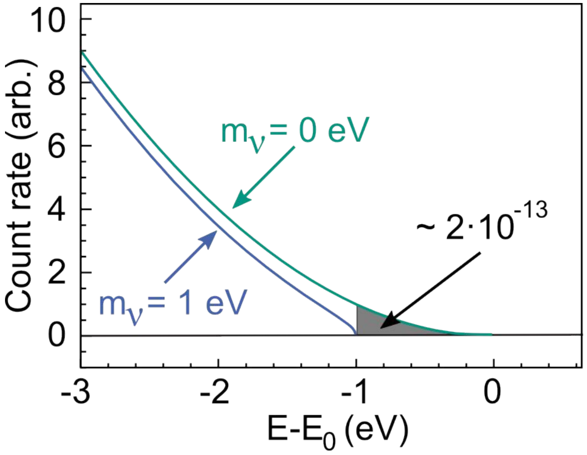
Experimental challenges:

- High source **activity**
- Excellent energy **resolution** (~1 eV)
- Low **background** (≪1 cps)
- Spectrum and response **model**

⇒ Tritium: $\boldsymbol{E_0}$ **= 18.6 keV**, $\boldsymbol{T_{1/2}}$ **= 12 yr**

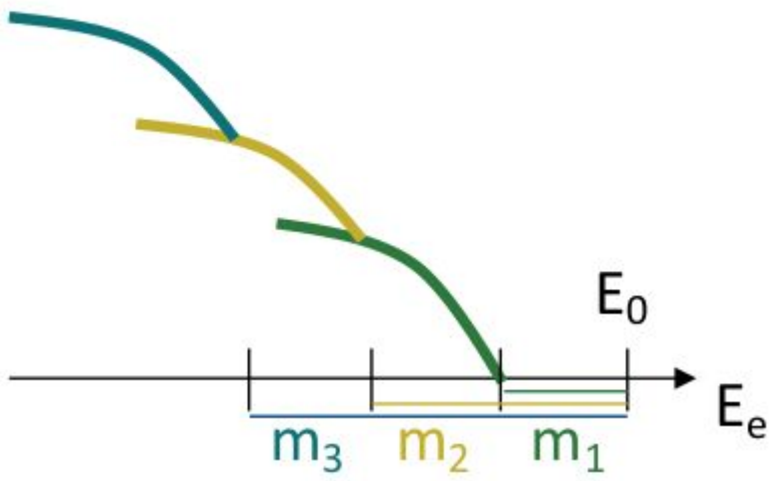




Effective neutrino mass parameter

$$\frac{d\Gamma}{dE}=\sum_i |U_{ei}|^2 C\cdot F(E,Z)\cdot(E+m_e)\cdot(E_0-E)\cdot\sqrt{(E+m_e)^2-m_e^2}\cdot\sqrt{(E_0-E)^2-m_i^2}$$

- Assume that we are measuring "far away" from ***E_0***



$$\sum_i |U_{ei}|^2\cdot(E_0-E)\cdot\sqrt{1-\frac{m_i^2}{(E_0-E)^2}}$$

$$\approx\sum_i |U_{ei}|^2\cdot(E_0-E)\cdot(1-\frac{1}{2}\cdot\frac{m_i^2}{(E_0-E)^2})$$

$$=(E_0-E)\cdot(1-\frac{1}{2}\cdot\frac{\sum_i |U_{ei}|^2\cdot m_i^2}{(E_0-E)^2})$$

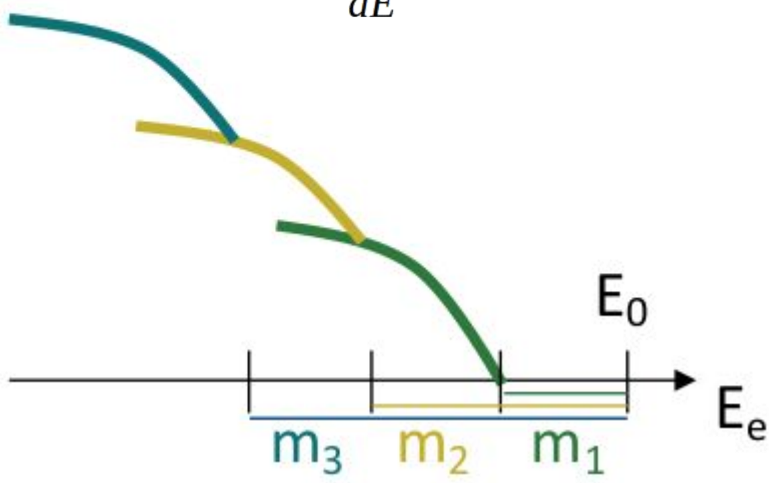
$$\approx\sqrt{(E_0-E)^2-\sum_i |U_{ei}|^2\cdot m_i^2}$$

Effective neutrino mass parameter

$$\frac{d\Gamma}{dE} = \sum_i |U_{ei}|^2 C \cdot F(E,Z) \cdot (E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E+m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_i^2}$$

- Assume that we are measuring “far away” from E_0

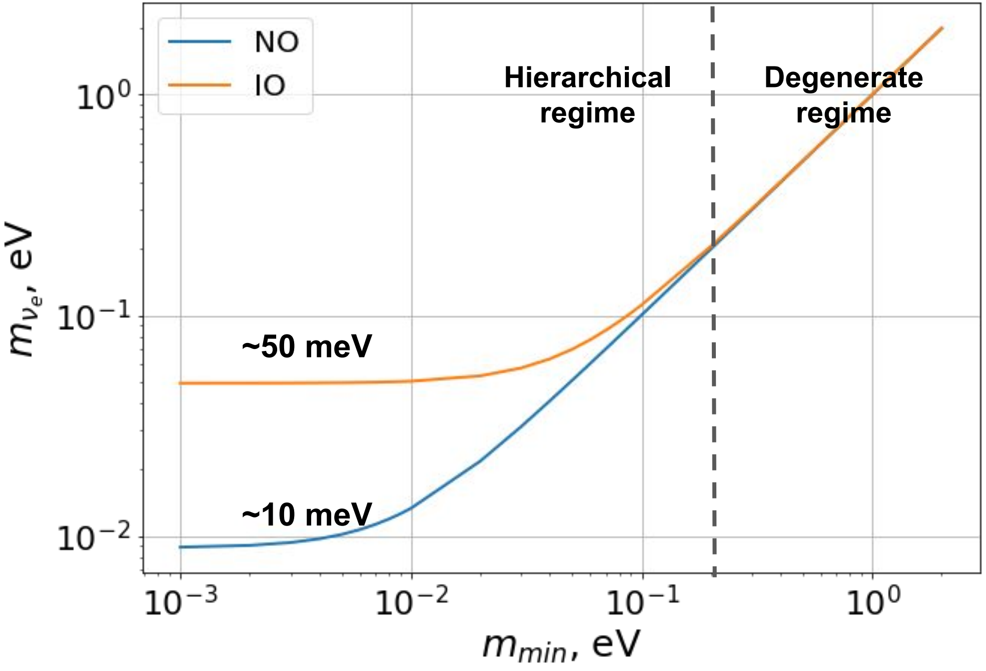
$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot (E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E+m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - \sum_i |U_{ei}|^2 \cdot m_i^2}$$



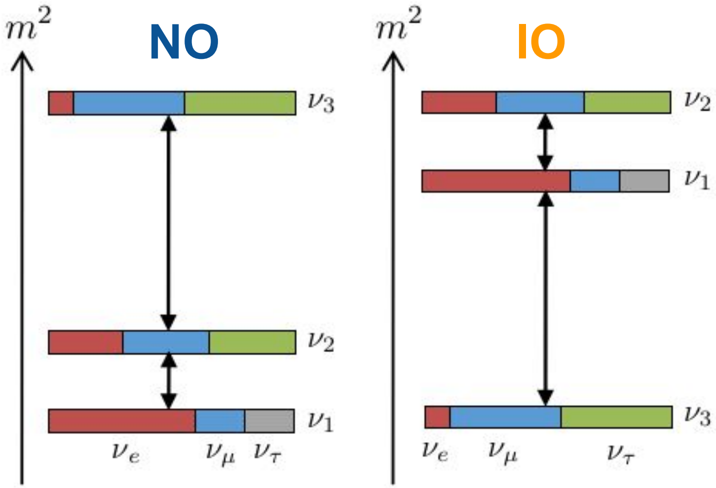
$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

- Incoherent sum of neutrino masses
- Effective squared mass of electron antineutrino

Effective neutrino mass



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



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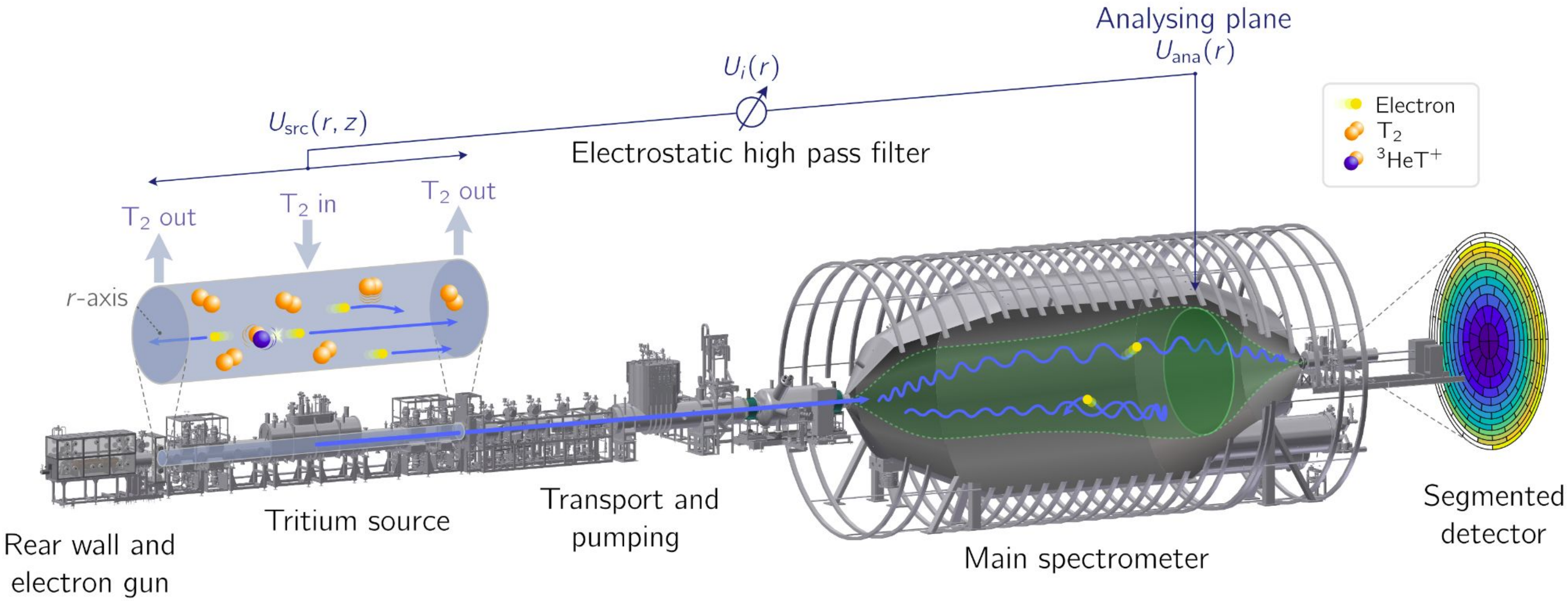
KATRIN:

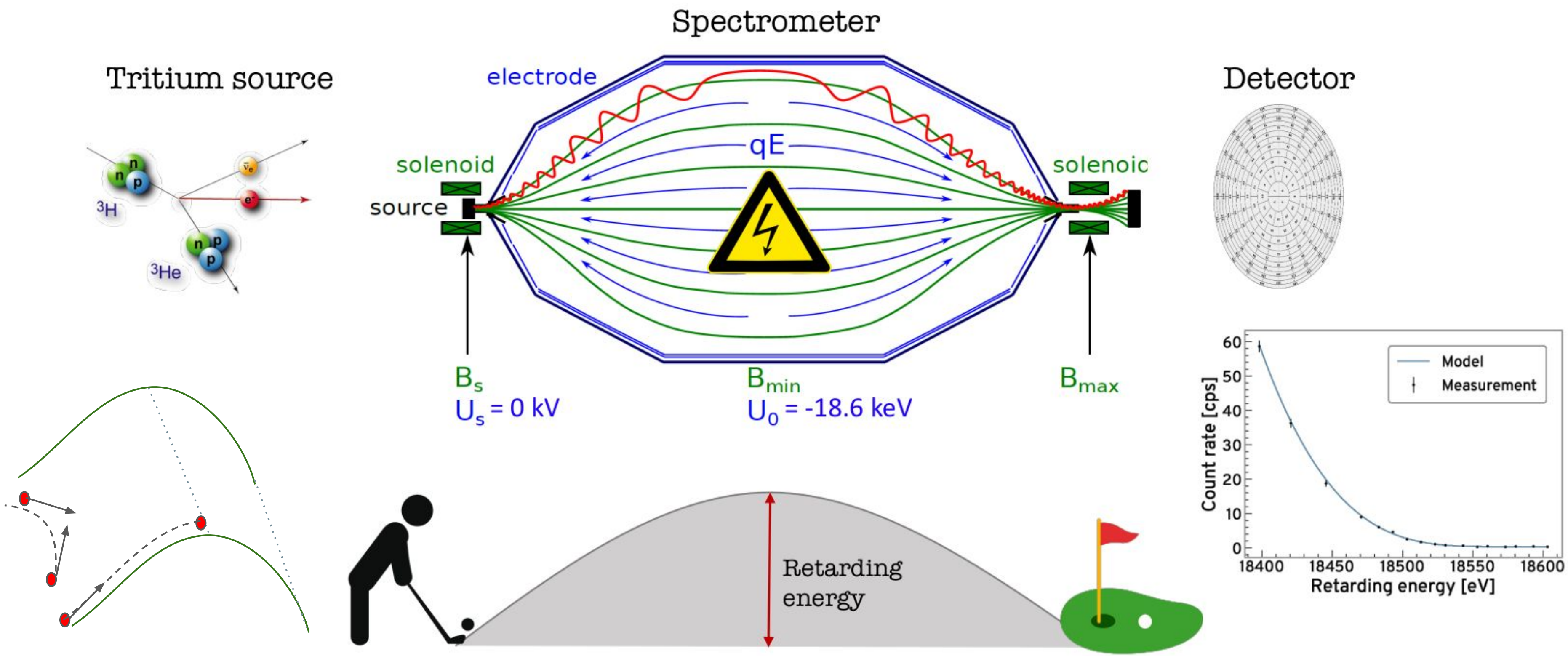
Karlsruhe
Tritium
Neutrino
Experiment

The KATRIN experiment

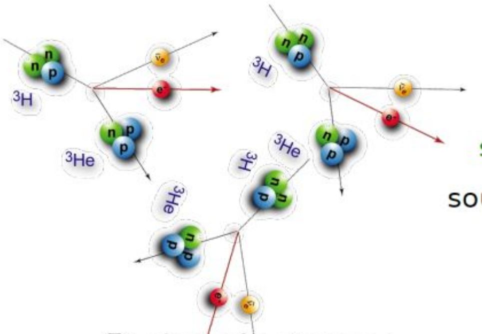


Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

Spectrometer: MAC-E-Filter



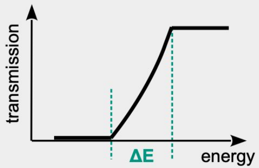
Spectrometer: MAC-E-Filter



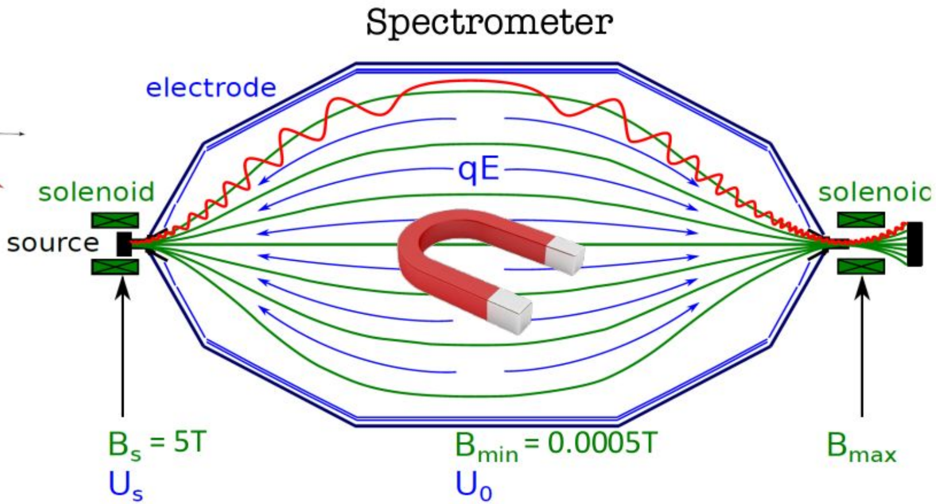
Isotropic source

$$E_{kin} = E_L + E_T$$

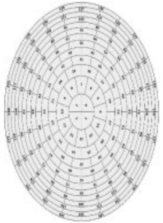
Sharp high-pass filter:



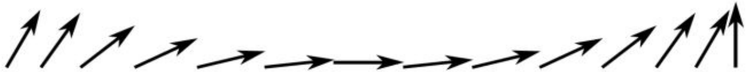
Steps of filter potential
→ integrated β spectrum



Detector



- ✓ Large angle acceptance
- ✓ eV-scale E-resolution



$$E_T^{center} = E_T^{start} \cdot \frac{B^{center}}{B^{start}} \quad \rightarrow \quad E_T^{center,max} = E \cdot \frac{B^{center}}{B^{start}} \approx 2 \text{ eV}$$

Spectrometer from inside and outside

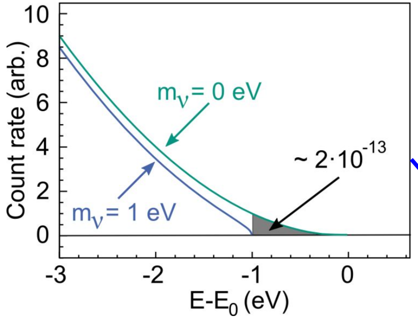
Inner electrode system
Ultra high vacuum

$p < 10^{-11}$ mbar in 1240 m^3 volume, surface ~650 m^2

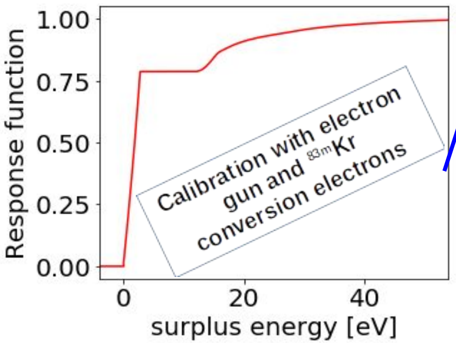
Air coil system

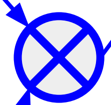
Modelling the tritium spectrum

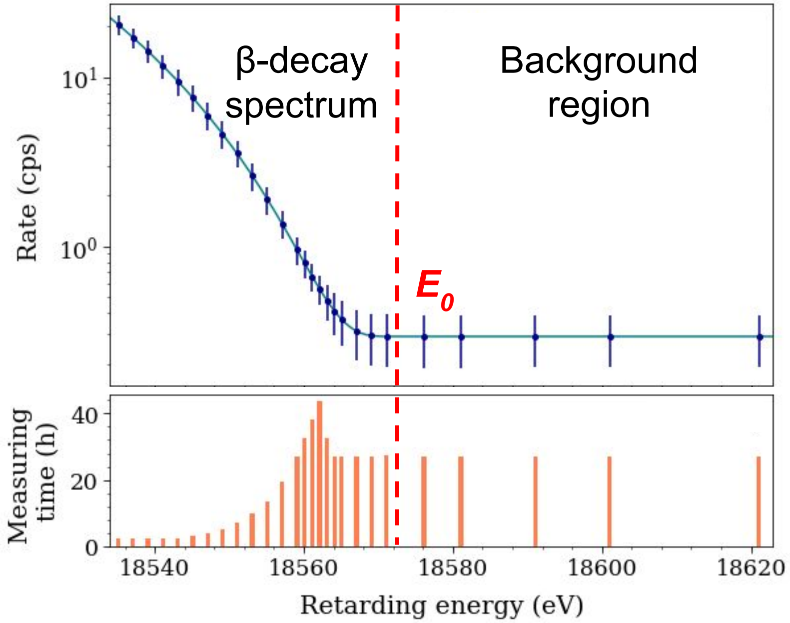
- Beta spectrum: $\boldsymbol{R_\beta(E;m^2(\nu_e),E_0)}$



- Experimental response: ***f*(*E-qU*)**





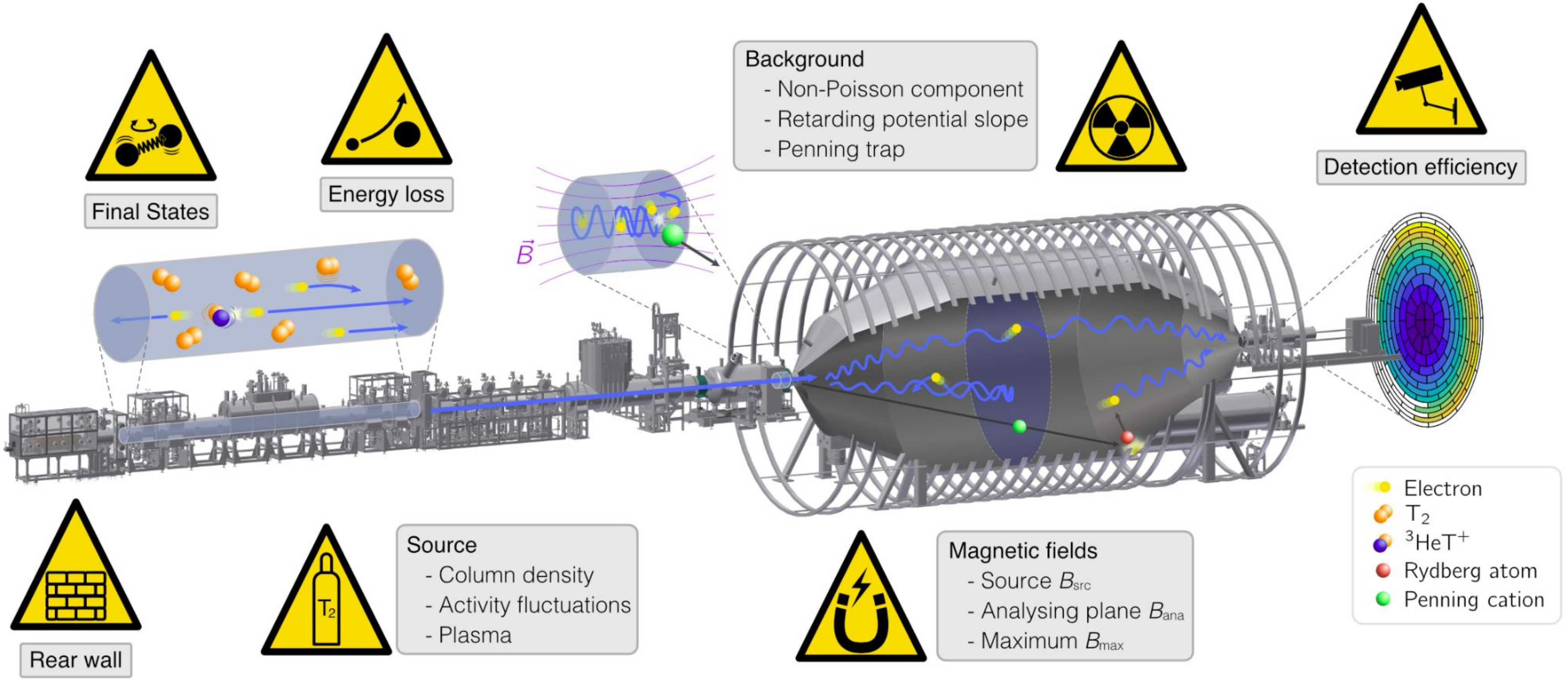


$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E)dE + R_{bg}$$

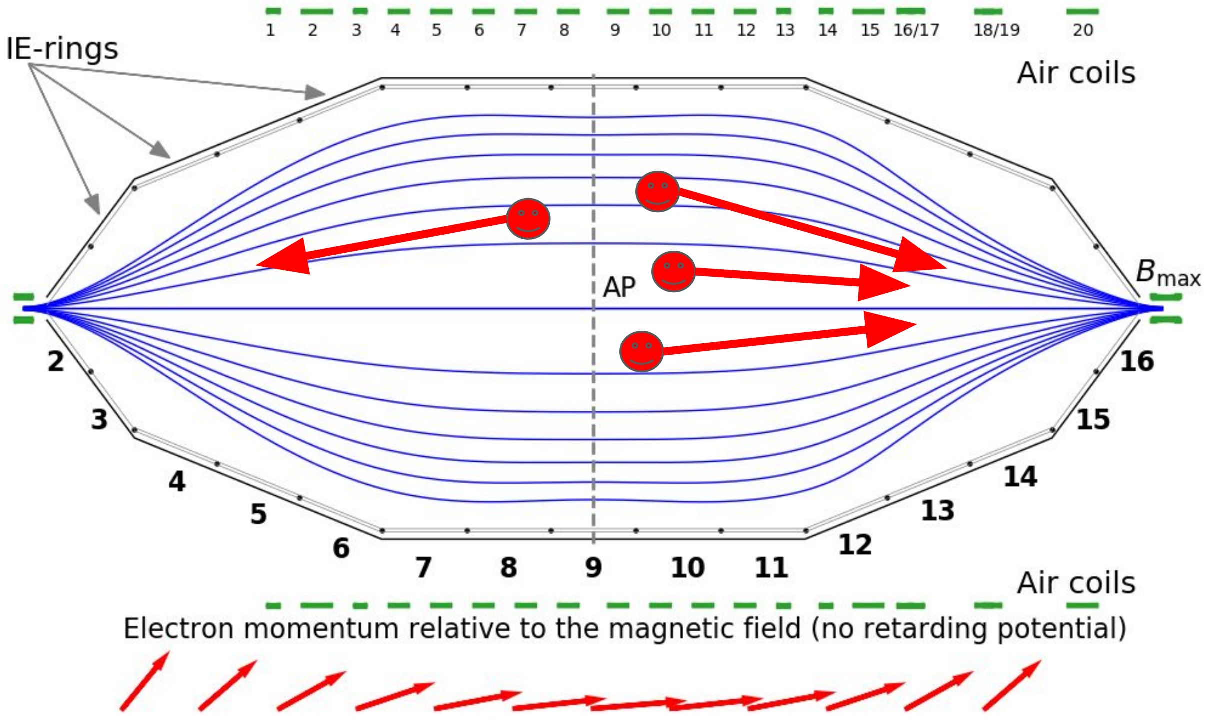
- **2-3 hour** scans, **O(100)** scans per campaign
- **Stack** data points with the **same** measurement conditions
- Analysis window: **[E_0 - 40 eV, E_0 + 135 eV]**

Systematic effects

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



MAC-E-filter and background



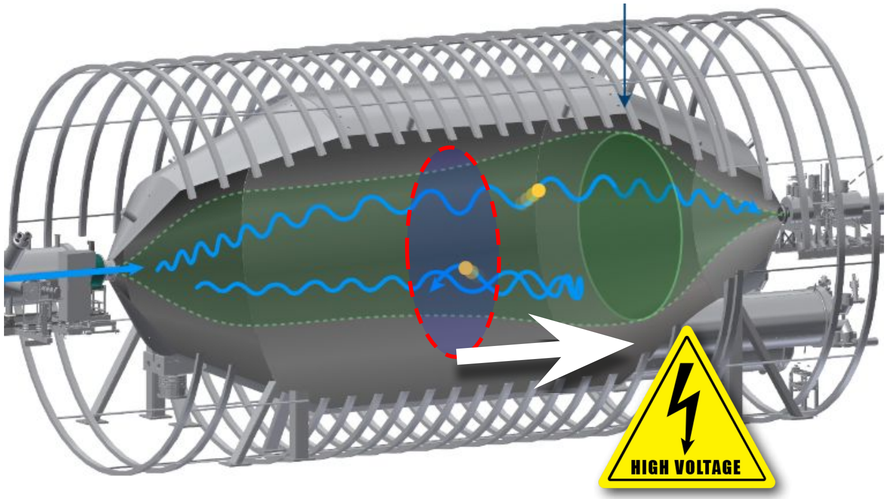
- Low energy **e⁻** accelerated to detector
  - Signal and background
- **e⁻** trapped in the magnetic bottle (or local Penning traps)
  - produce secondaries in scattering

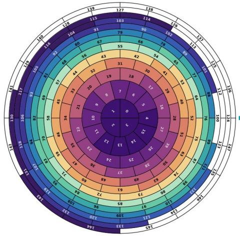
Analyzing plane (AP) ≈ positions of highest potential

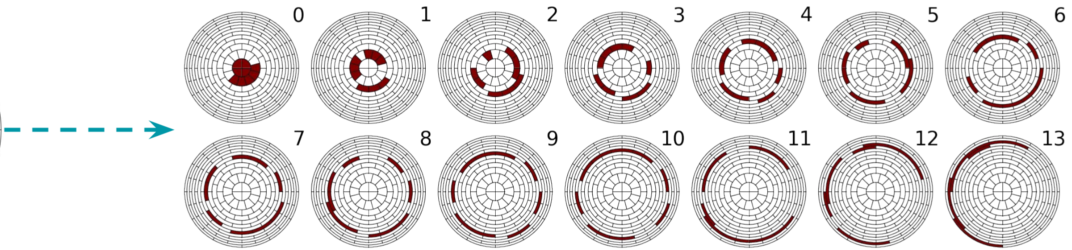
Background reduction

Factor 2 lower **background** using "*shifted analyzing plane*" configuration

- Smaller volume mapped onto detector
- Inhomogeneous EM-fields
  - More segmented data **x 14**
  - **Calibration** of fields needed





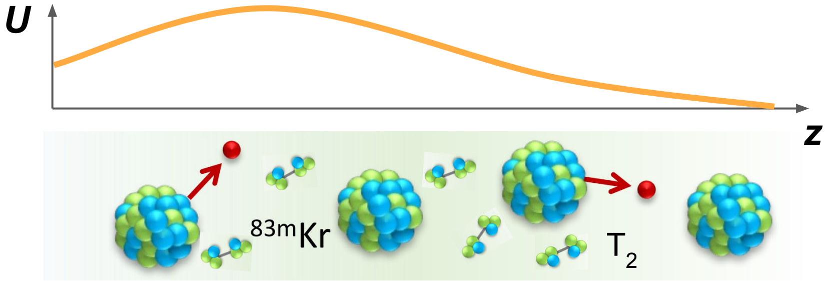


A. Lokhov et al., Eur.Phys.J.C 82 (2022) 3, 258; KATRIN Collab., Eur.Phys.J.C 84 (2024) 12, 1258

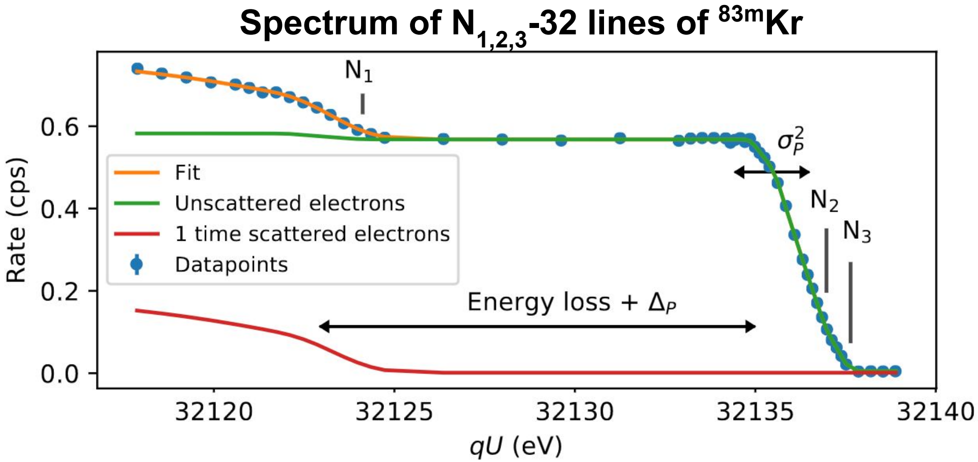
Precise calibration: source potential

Precise calibration measurements with ^{83m}**Kr** co-circulation:

- Probe of electric potential variation in the source
  - Cold magnetized plasma
- Source temperature: 30K→80K
- Also: field mapping in the spectrometer



KATRIN tritium source

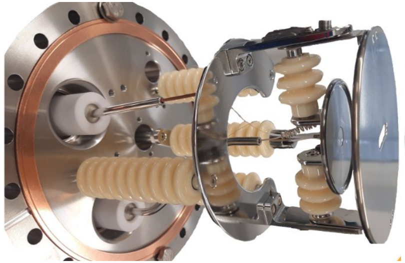


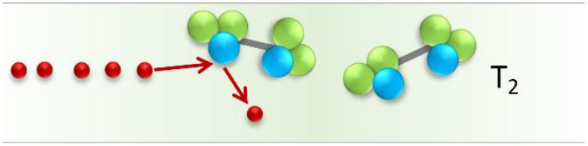
A. Marsteller et al., JINST 17, P12010 (2022); KATRIN Collab., 2503.13221

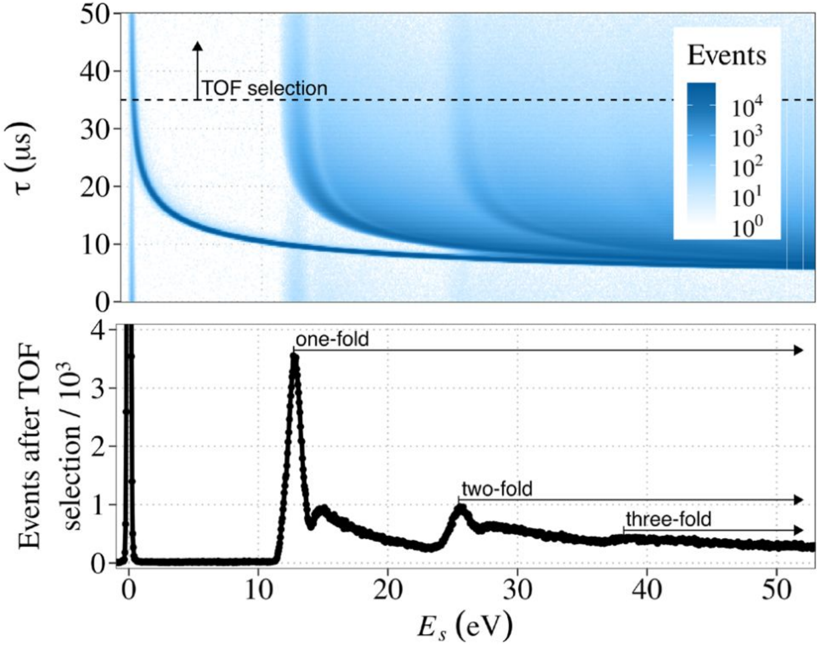
Precise calibration: energy loss

Precise calibration measurements with the **electron gun**:

- Energy loss through scattering
    - Time-of-flight method
- Tritium gas density







KATRIN collab, Eur. Phys. J. C 81, 579 (2021)

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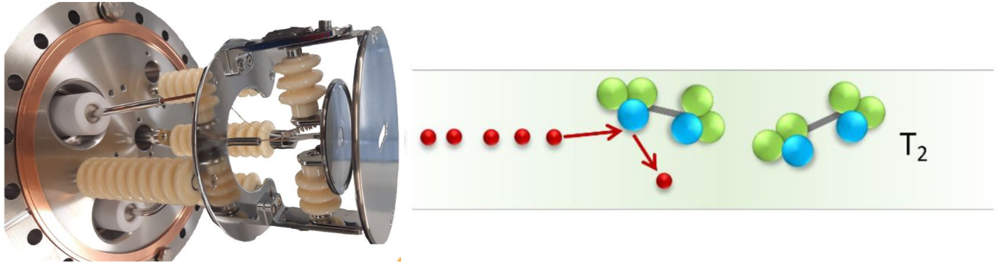
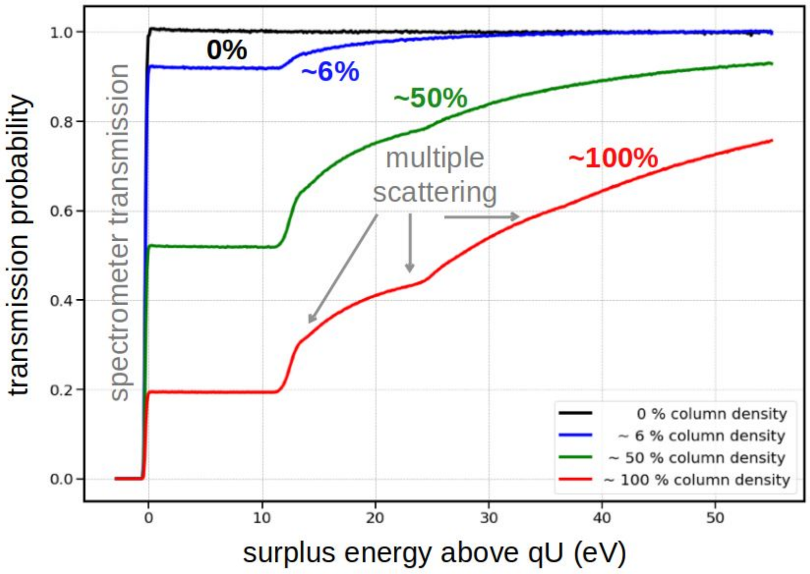


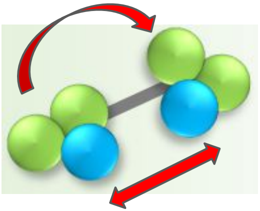


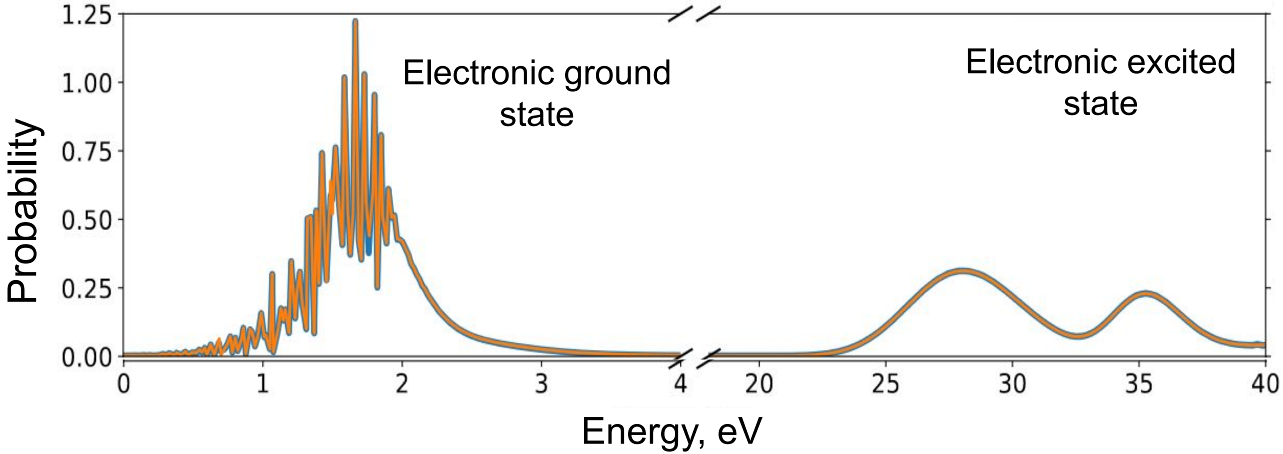
KATRIN collab, Eur. Phys. J. C 81, 579 (2021)

Theoretical improvements

Final states distribution of THe^+

- *Ab initio* calculations by A.Saenz et al.
- Negligible uncertainty





Saenz, Jonsell, Froelich, Phys. Rev. Lett. 84, 242 (2000)

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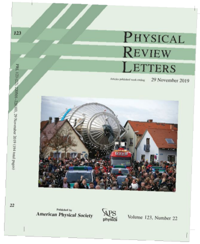
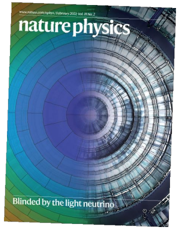
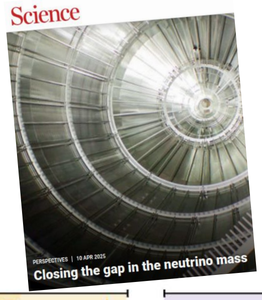
KATRIN data releases







2019: m_ν < 1.1 eV (90% CL)

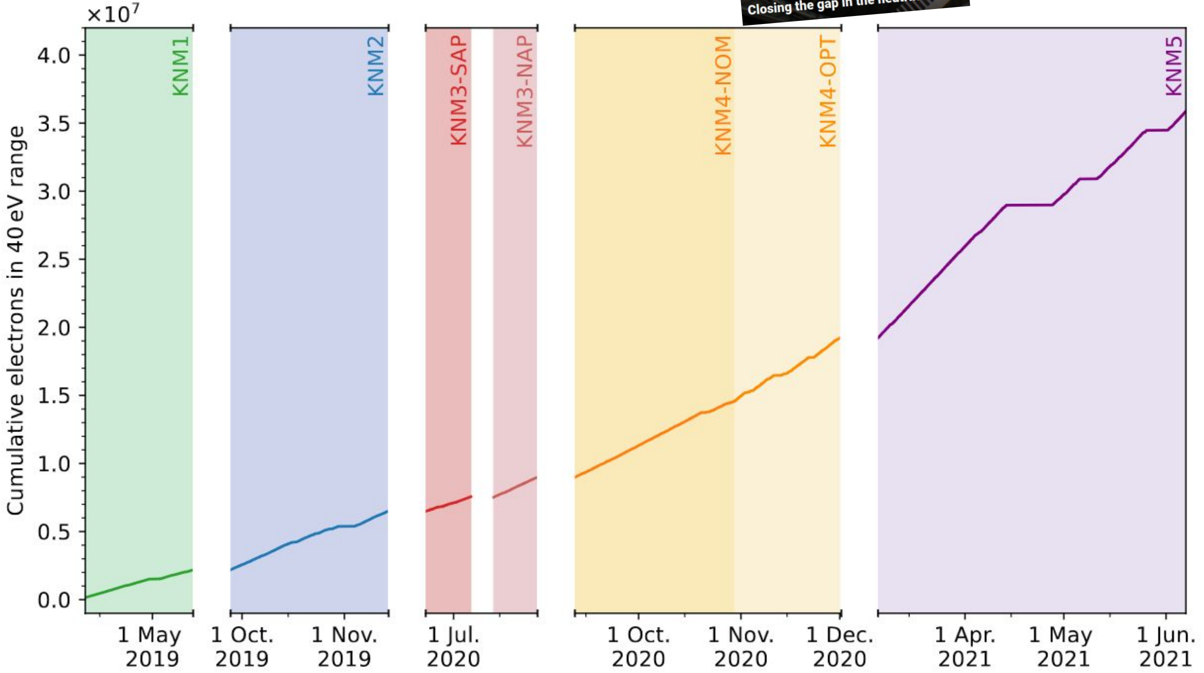
2022: m_ν < 0.8 eV (90% CL)

- **~6** Mio counts

2024:

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

Expected sensitivity < 0.5 eV



PRL 123 (2019) 221802
PRD 104 (2021) 012005

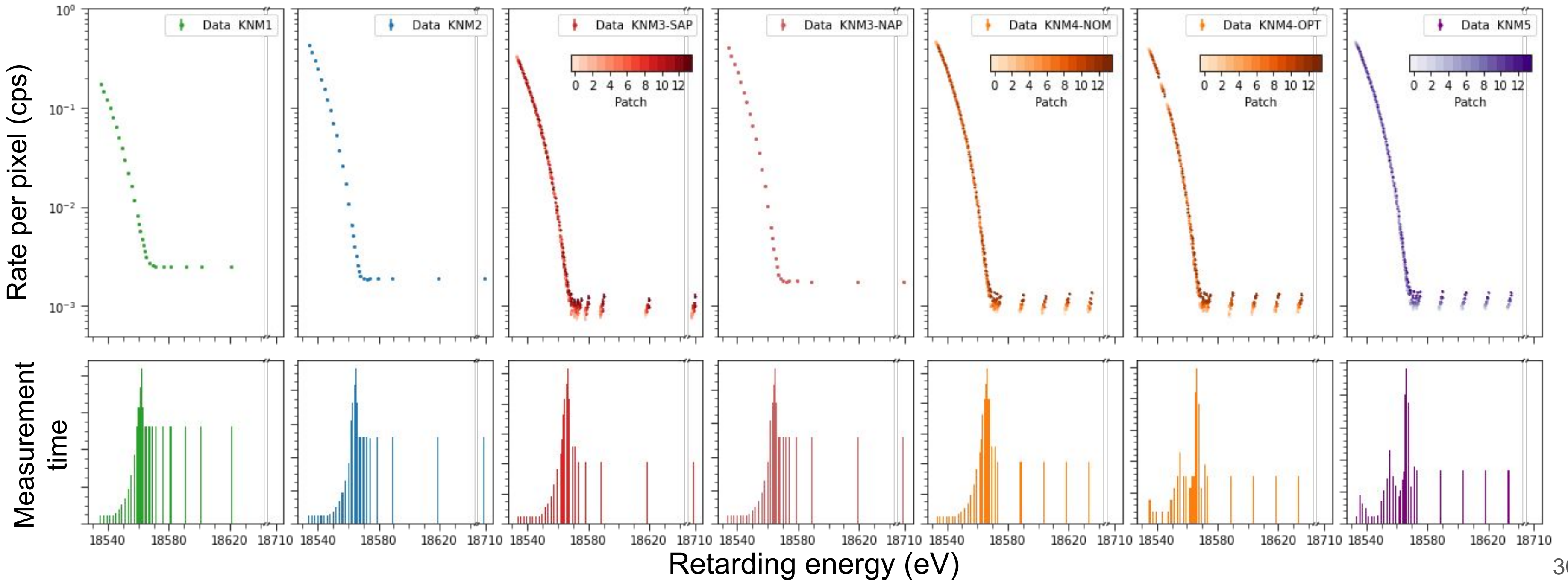
Nature Phys. 18 (2022) 160

Science 388 (2025) 6743

Data

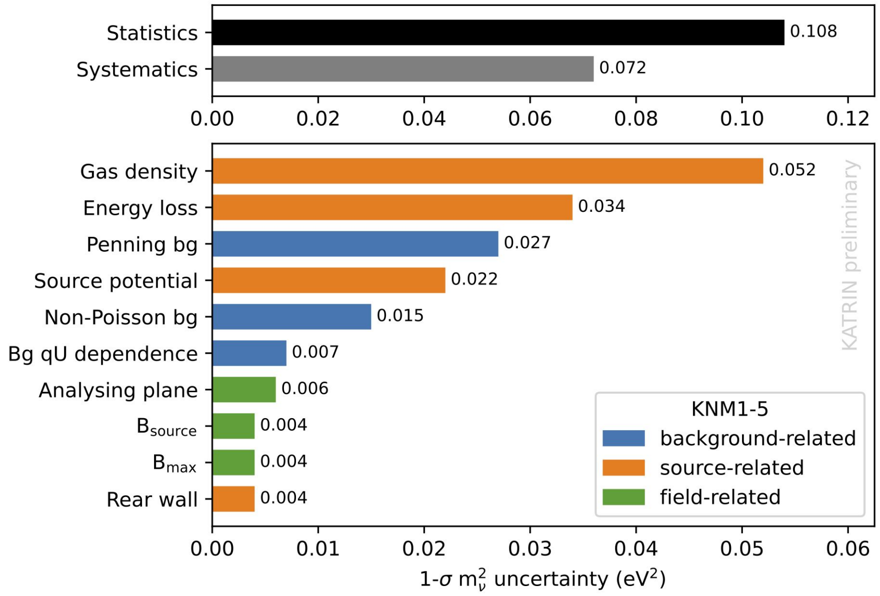
36 Mio counts in total

59 stacked spectra with
27 + **28** + **14 x 28** + **28** + **14 x 28** + **14 x 25** + **14 x 28** =
1609 data points



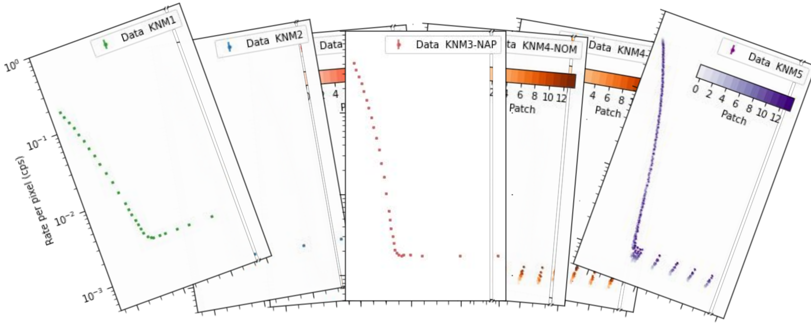
Systematic uncertainties

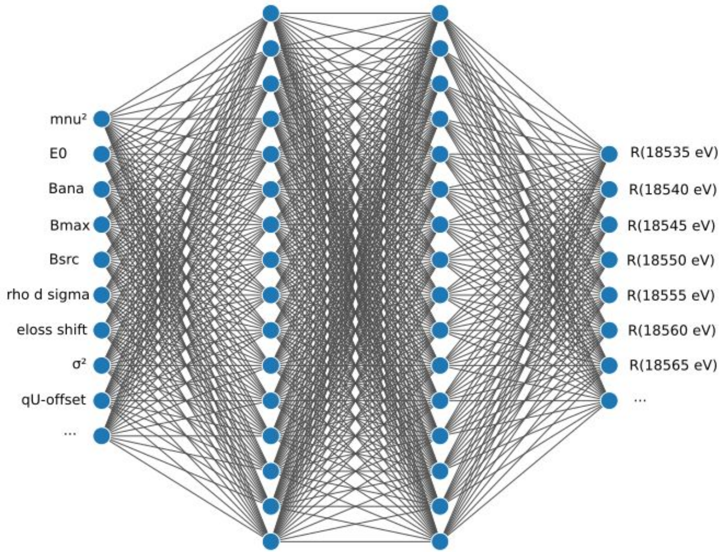
- **Statistical** uncertainties dominate
- Significant reduction of the **background**-related systematics
- Better control over source **scattering**
  - Increased conservative uncertainties in this release
  - Reduced uncertainties in current data
- **Reduction** of the molecular **final-states** uncertainties
  - Reassessment of theoretical uncertainty estimation: **S. Schneidewind et al., Eur. Phys. J. C 84, 494 (2024)**

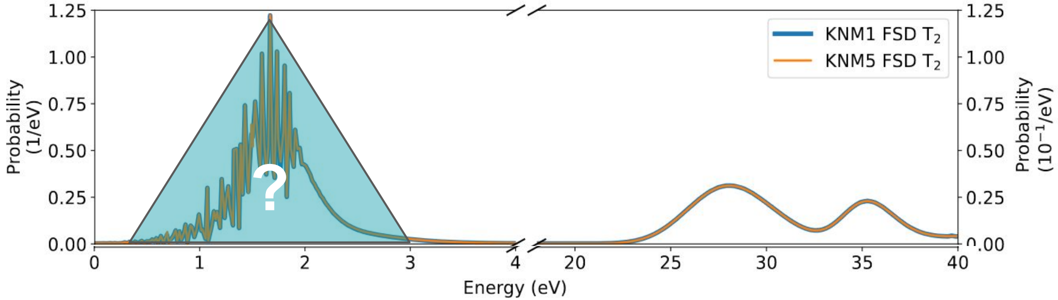


Analysis challenges

- Highly segmented data (**1609** data points)
- Computationally **expensive** model evaluations
- **144** correlated systematic parameters
- **Two** independent analysis teams and frameworks
  - optimized model evaluation
  - fast model prediction with a neural network
- Double-layer **blinding** scheme
  - fixing analysis procedure on MC data
  - using model blinding, unknown modification of final states



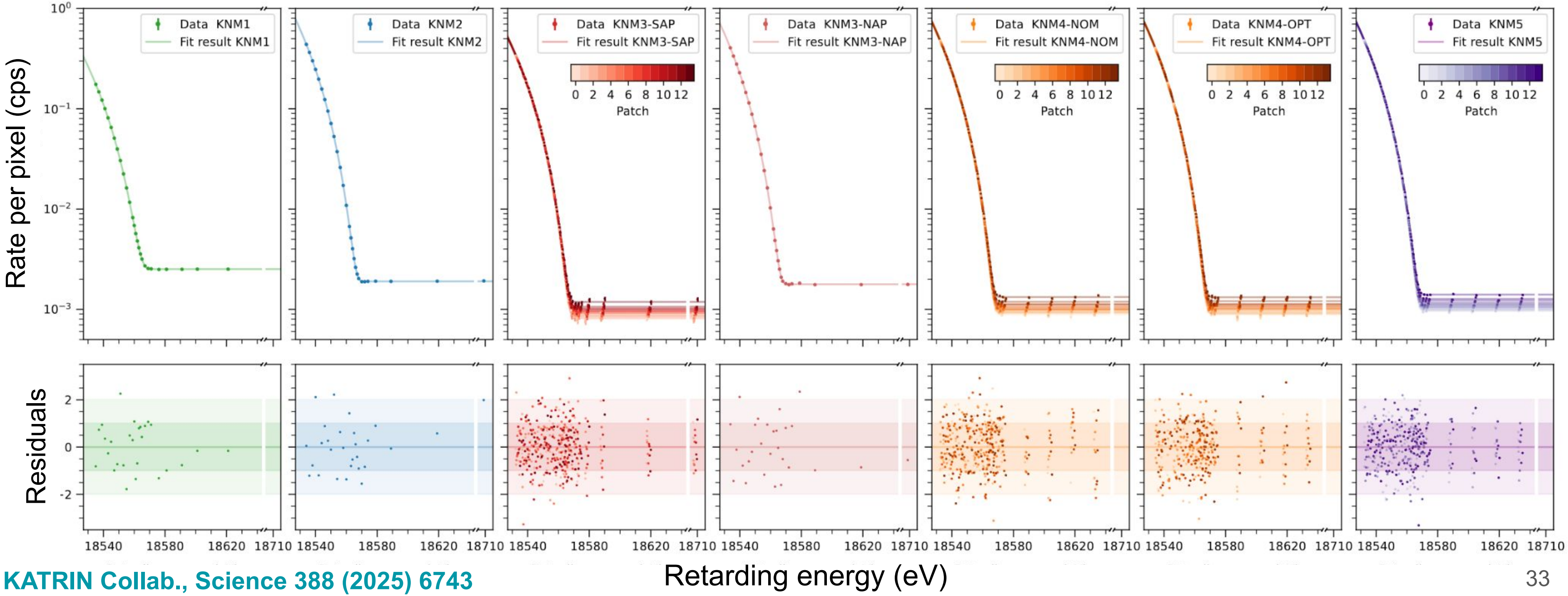




C. Karl, P. Eller, S. Mertens, Eur. Phys. J. C 82, 439 (2022)

Fit result

- Simultaneous maximum likelihood **fit** with common $\boldsymbol{m_\nu^2}$ parameter
- Excellent goodness-of-fit: **p-value=0.84**



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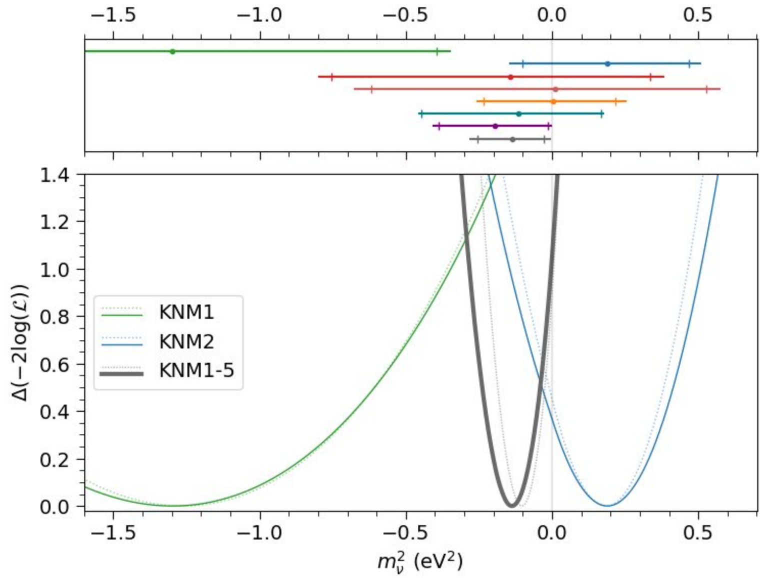
Fit result

- Best-fit value

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

- Negative m^2 estimates allowed by the spectrum model to accommodate statistical fluctuations

- Post-unblinding a data-combination mistake was uncovered →
  - Resolved by splitting **KNM4** into **two** data sets
  - ~ 0.1 eV^2 impact on m^2



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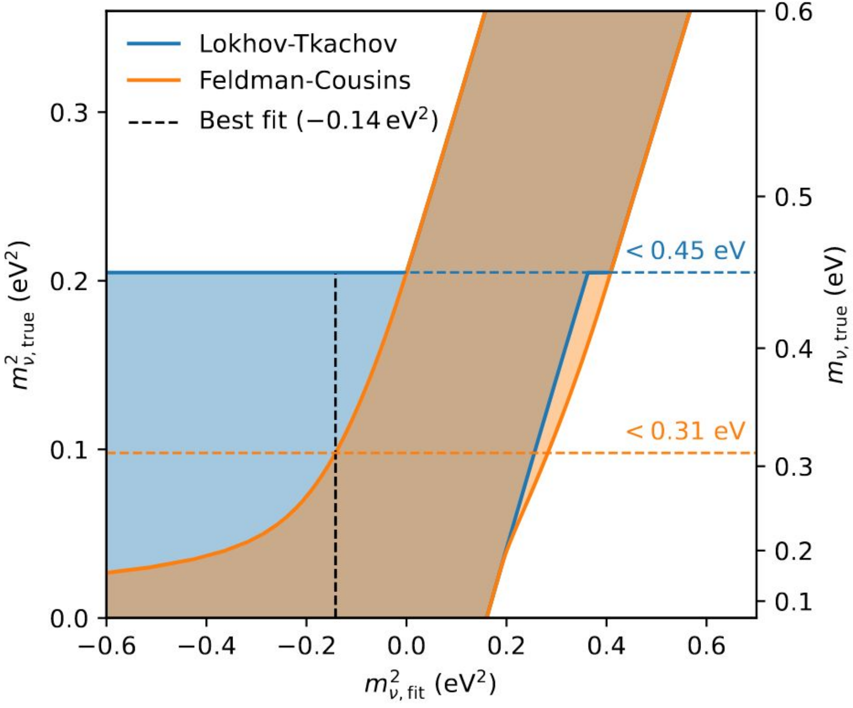
Confidence interval

- KATRIN's **new** upper limit

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

  using **Lokhov-Tkachov** construction
- Feldman-Cousins limit:
  - $\boldsymbol{m_\nu}$ < 0.31 eV at 90 % CL
  - Shrinking upper limit for negative $\boldsymbol{m_\nu^2}$
- Bayesian analysis in preparation



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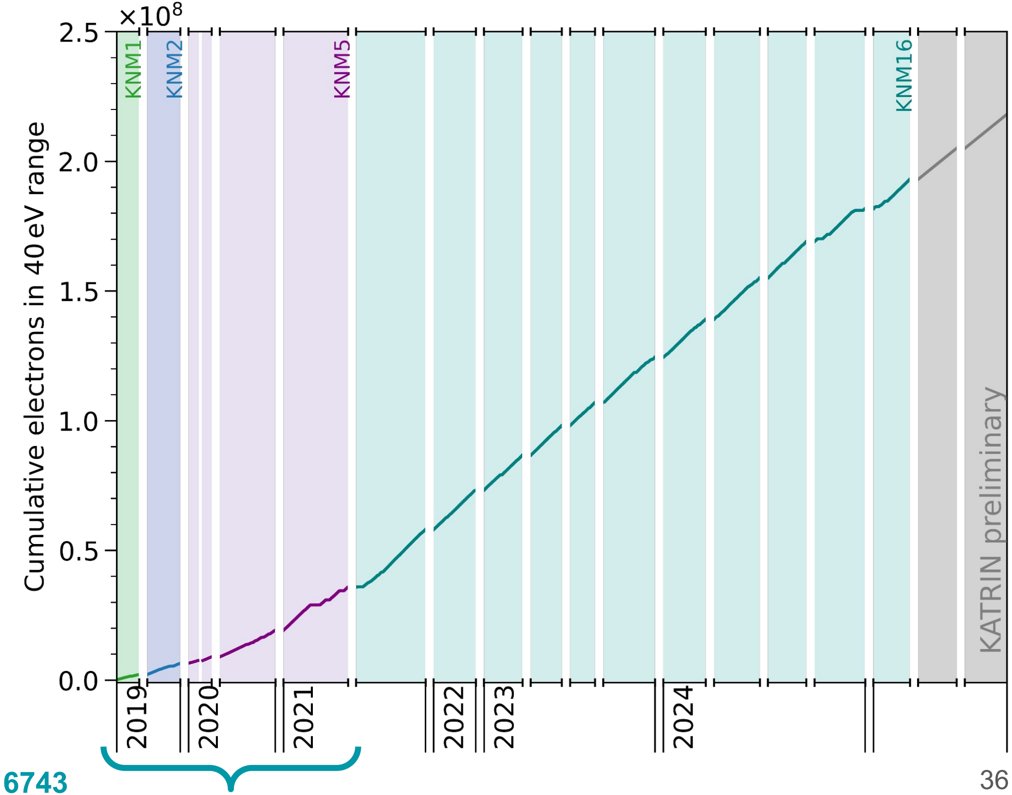
Lokhov, Tkachov, Phys. Part. Nucl. 46 (2015) 3, 347-365
Feldman, Cousins, Phys. Rev. D 57 (1998) 3873-3889

KATRIN data taking continues

- Measurement campaign **#18** ongoing
- **~ 200 Mio** counts recorded – **x5** of this release!
- Another 2 campaigns in 2025 to reach **1000** days + calibration measurements



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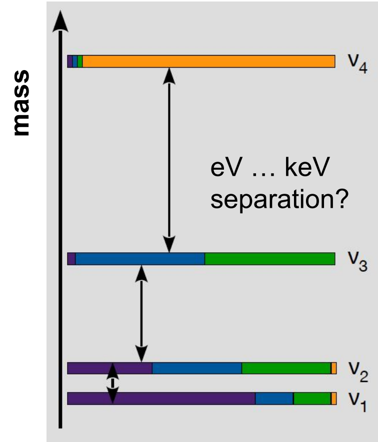
KATRIN “beyond neutrino mass”

β-spectrum of high statistics and precision

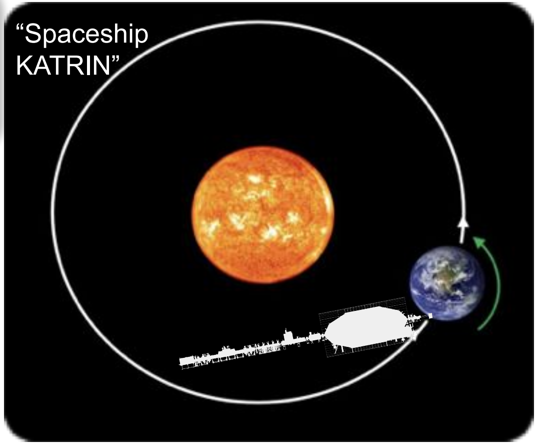
Is there a fourth (sterile) neutrino?
(search for a kink)

Phys.Rev.Lett. 126 (2021) 9, 091803
Phys.Rev.D 105 (2022) 7, 072004
arXiv:2503.18667

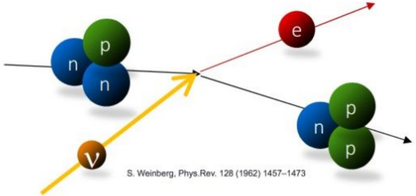


Search for Lorentz invariance violation
(sidereal modulation)

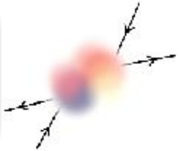
Phys.Rev.D 107 (2023) 8, 082005



Constrain local density of cosmic relic neutrinos
(peak search)



Search for exotic interactions
(spectrum shape)



Phys.Rev.Lett. 134 (2025) 25, 251801

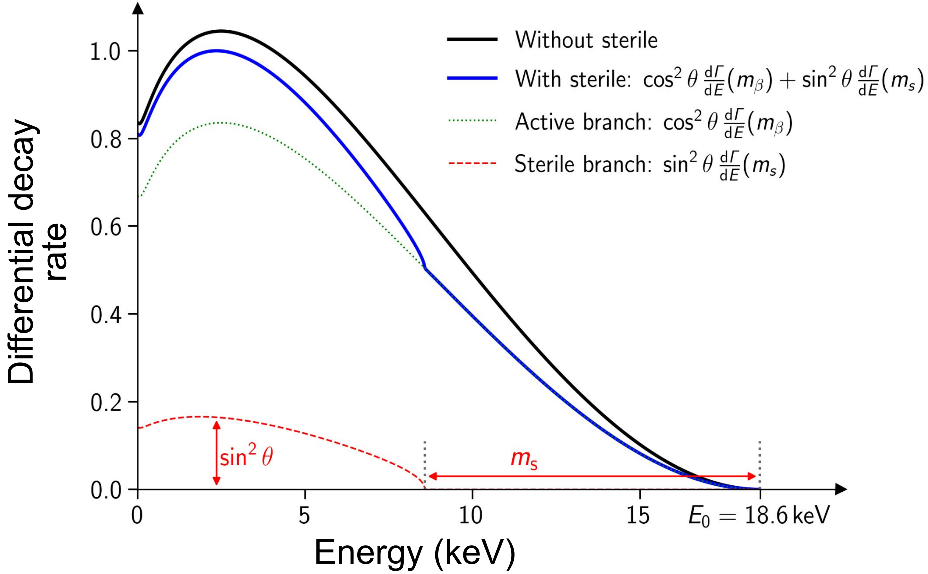
Phys. Rev. Lett. 129 (2022) 1, 011806

Outline

- Introduction: massive neutrinos
- KATRIN experiment
- Recent results
- **Near future plans**
- Summary & Outlook

keV sterile neutrinos search with TRISTAN @ KATRIN

- Search for keV sterile neutrinos
  - Novel SDD array for high rates
- Target sensitivity to mixing of **10^{-6}**
  - Ongoing systematic and modeling studies
- Timeline
  - 2026 – Installation in the KATRIN beamline
  - 2026-2027 – keV sterile neutrino search



TRISTAN @ KATRIN

- Search for keV sterile neutrinos
  - Novel SDD array for high rates
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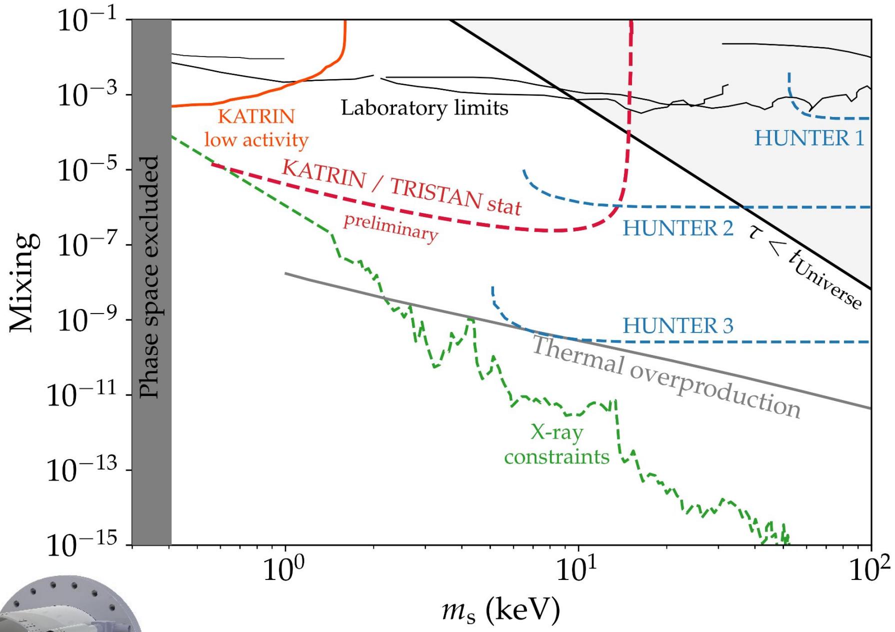
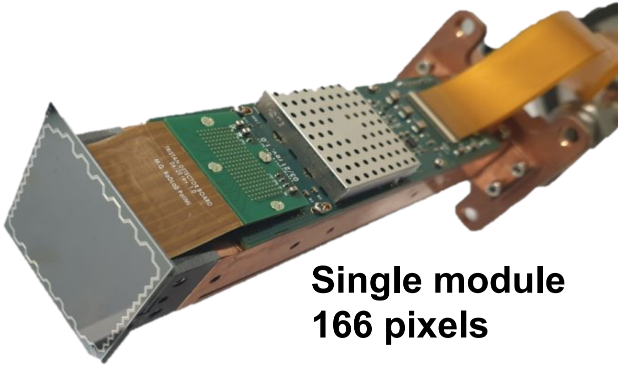
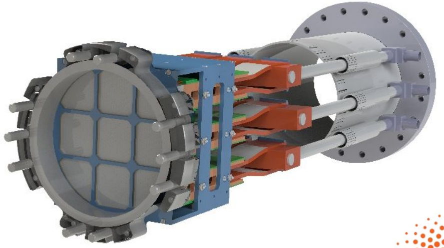




Single module
166 pixels



9 modules
~1500 pixels

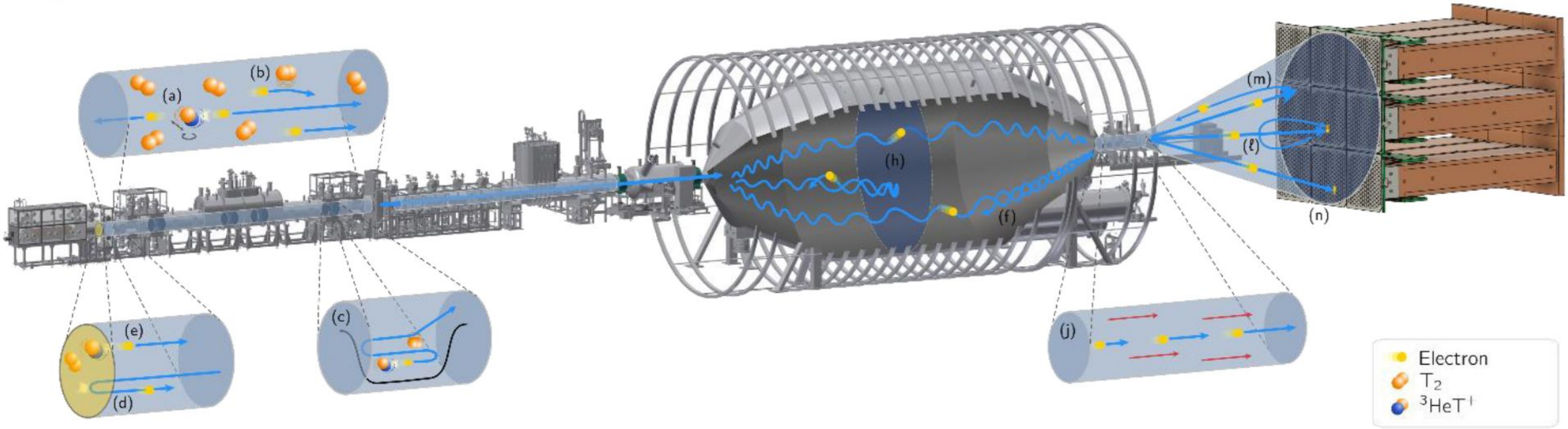
erc

MAX PLANCK SEMICONDUCTOR LABORATORY

XG LAB BRUKER NANO ANALYTICS

S. Mertens et al., J. Phys. G46 (2019); S. Mertens et al., J. Phys. G48 (2020); D.Siegmann et al., J. Phys. G (2024)

TRISTAN @ KATRIN



- Multiple new experimental effects to consider
  - Backscattering of electrons at the rear wall and detector
  - Non-adiabatic motion of electrons
  - …

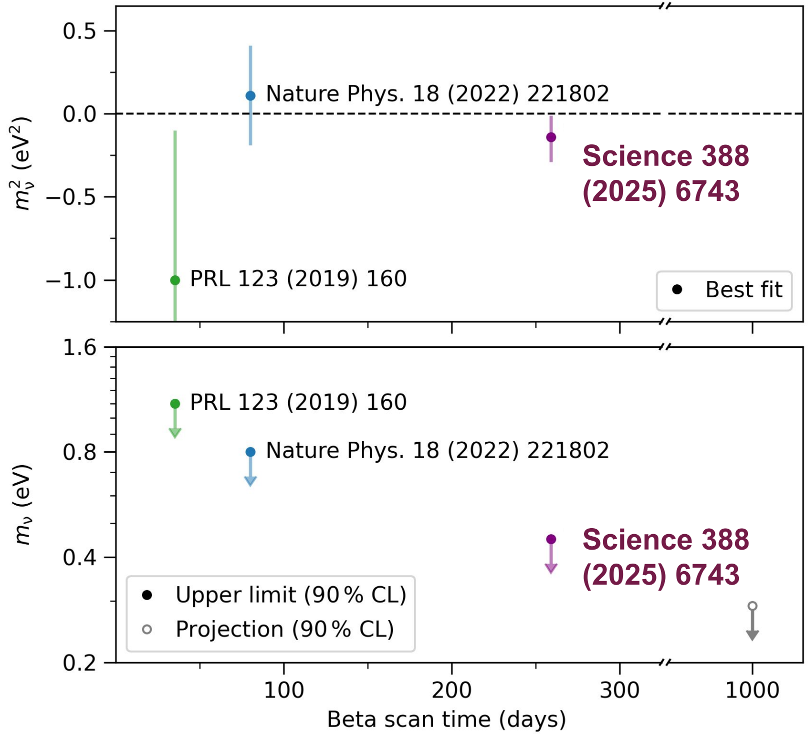
Conclusion and Outlook

KATRIN leads the field with the world-best direct neutrino-mass upper limit:

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

Towards the full dataset of KATRIN

- >85 % of total anticipated data recorded, analysis in preparation
- Several BSM physics searches: eV-sterile, exotic interactions, light bosons, relic ν… ⇒ stay tuned!
- **Ongoing data taking** through **2025 → Σ 1000 days**
- target sensitivity below 0.3 eV



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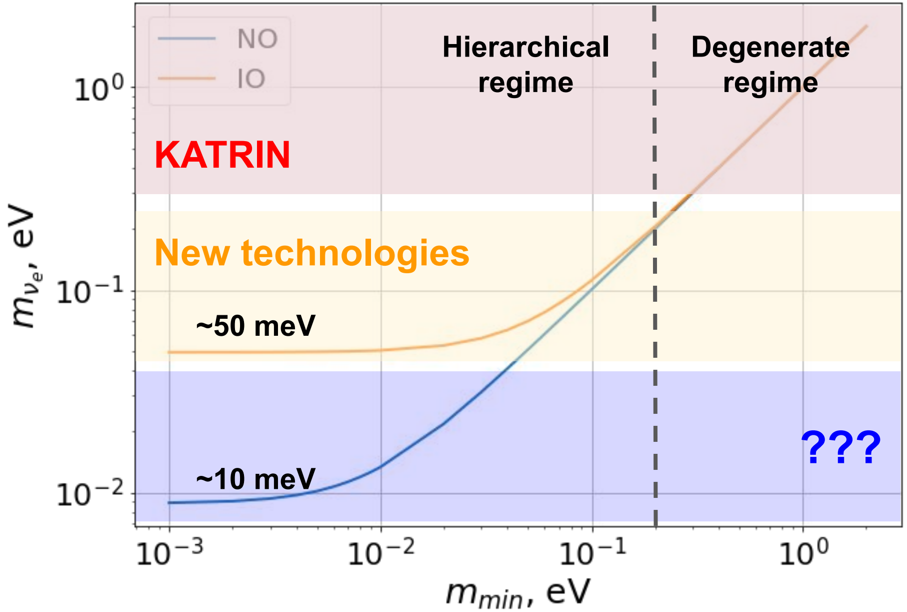
Future perspectives

2026-2027: keV sterile neutrino search with **TRISTAN@KATRIN**

- Preparations for hardware upgrades, analysis is getting ready for the data

2027+: R&D towards the ultimate neutrino mass determination



KATRIN collaboration

Collaboration meeting, March 2025, Münster

KIT Karlsruher Institut für Technologie
MIT
BERKELEY LAB
Humboldt-Universität zu Berlin
Nuclear Physics Institute
cea
TUM
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

Bundesministerium für Bildung und Forschung
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DFG
MAX PLANCK GESELLSCHAFT
U.S. DEPARTMENT OF ENERGY
Office of Science
Czech Republic: MŠMT MINISTRY OF EDUCATION, YOUTH AND SPORTS
erc
INFN