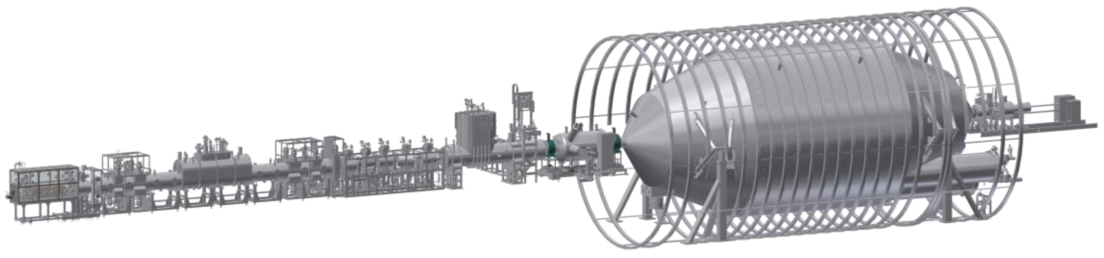
Direct neutrino mass measurement at KATRIN

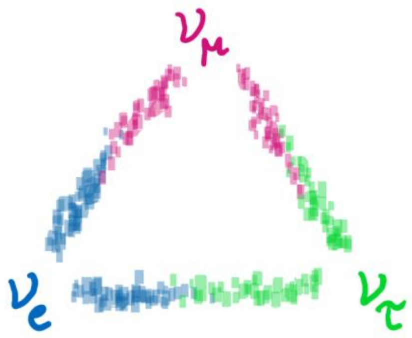


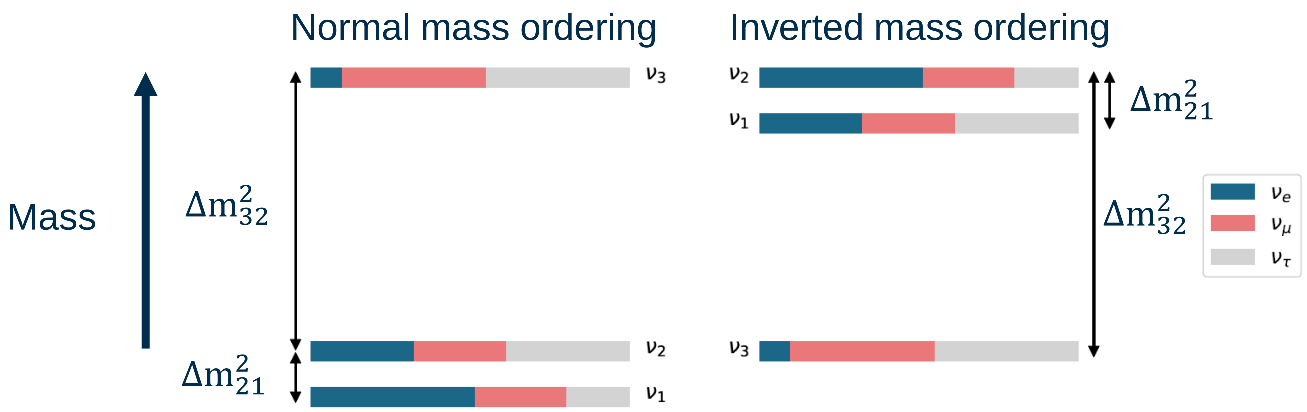
- Motivation for KATRIN
- Measurement principle
- Results

Jaroslav Štorek[1]
on behalf of the KATRIN collaboration
[1]Karlsruhe Institue of Technology

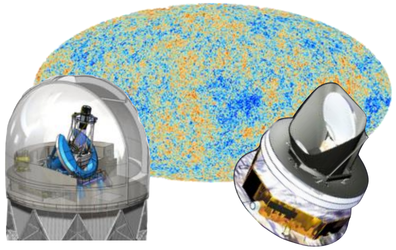
Unveiling new physics with neutrino mass

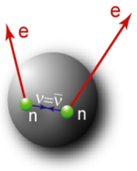
- Neutrino flavor oscillations → neutrinos are not massless
  ⇒ necessary extension of the SM
- The most abundant known massive particle in the universe
- Neutrino mass helps to understand:
  - Formation of cosmological structures
  - Neutrino mass generation models
  - Neutrino mass hierarchy – which neutrino is the lightest?

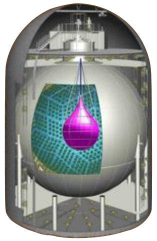


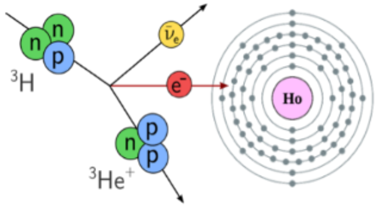


Ways to access the neutrino mass









	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

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

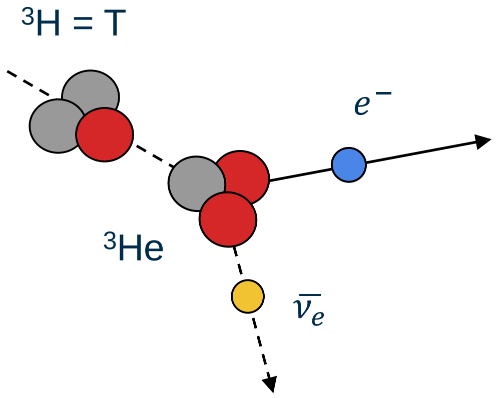
25

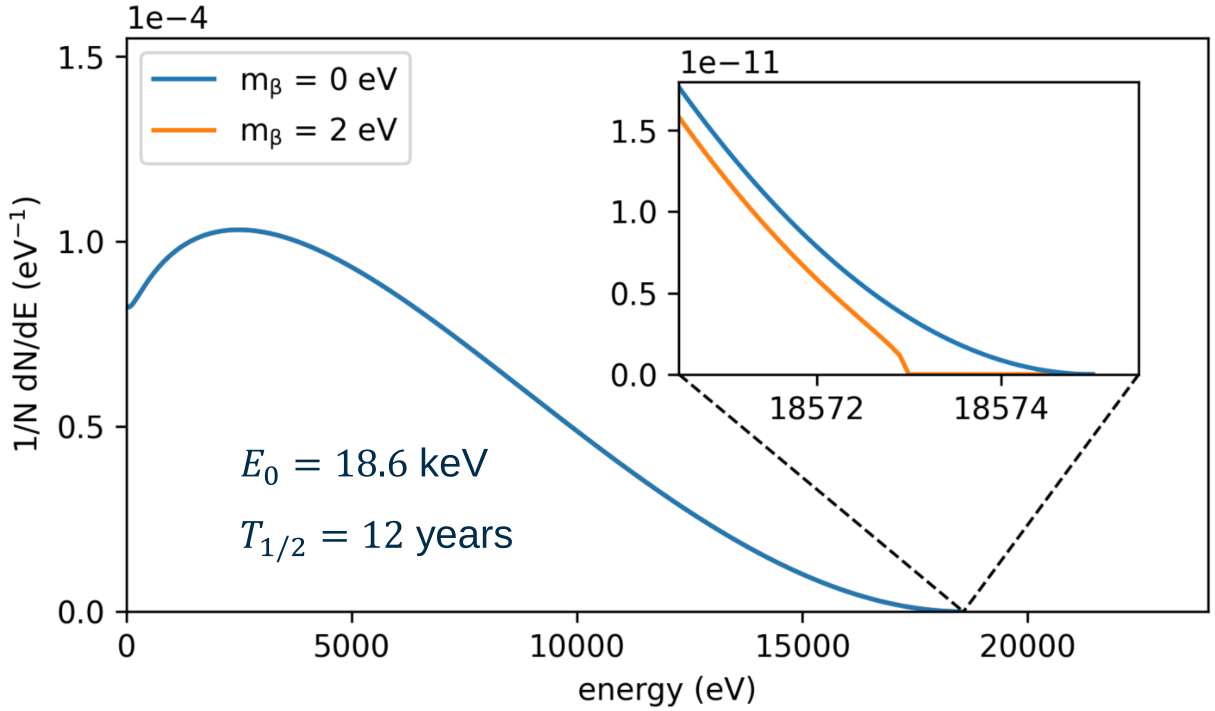
Tritium β-decay kinematics

High precision spectroscopy of β-electrons

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

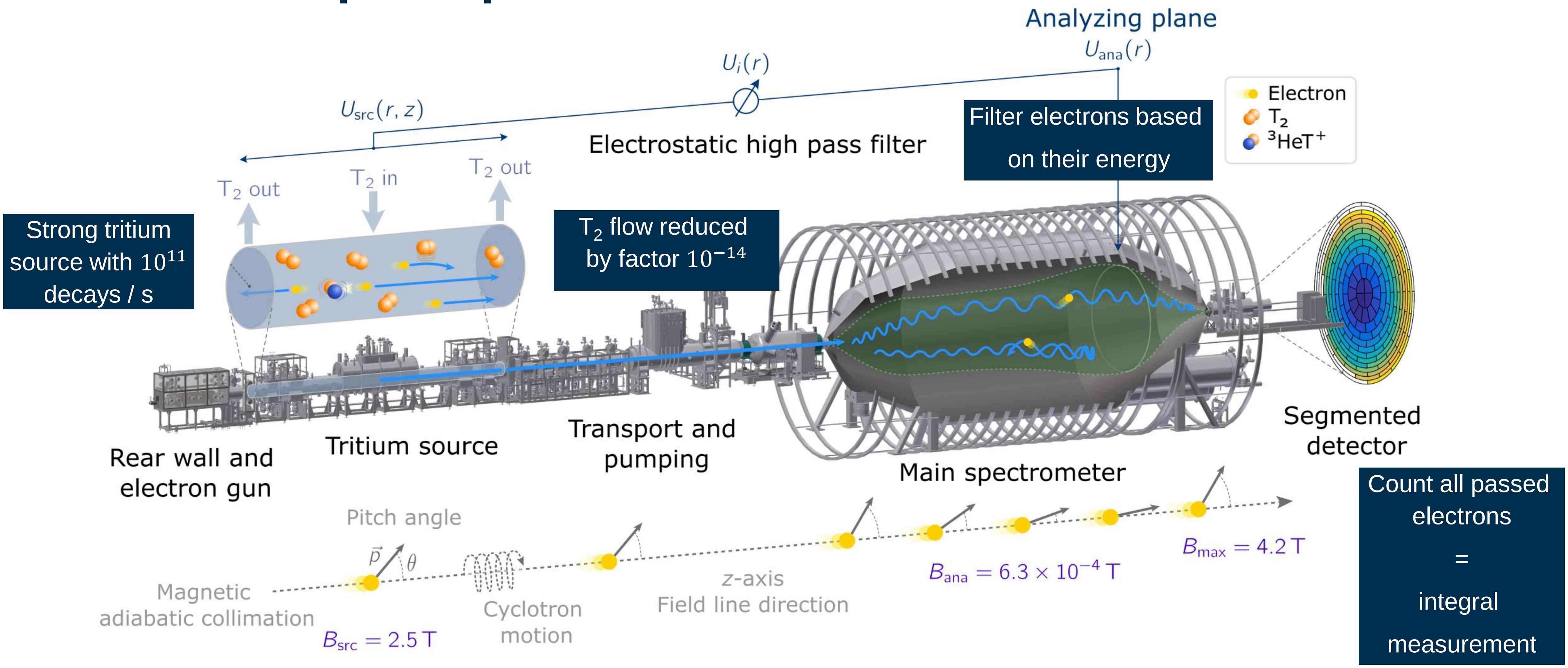
$$T_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e + Q(T_2)$$





 Jaroslav Štorek, jaroslav.storek@kit.edu

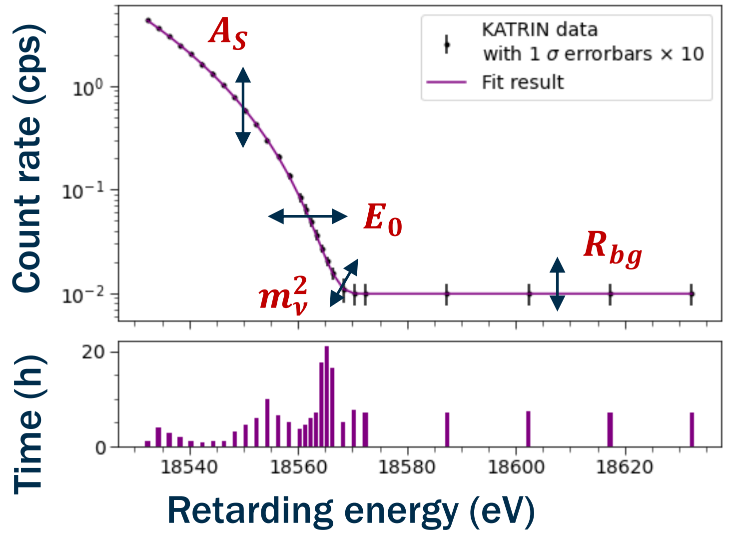
Measurement principle



- 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

Modeling

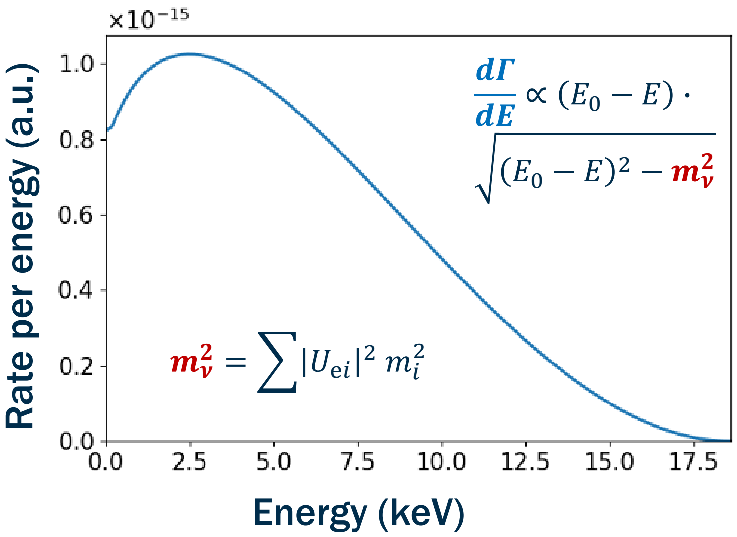
Measured individual β-spectrum



Duration of ~ 3 h per 40 voltage points

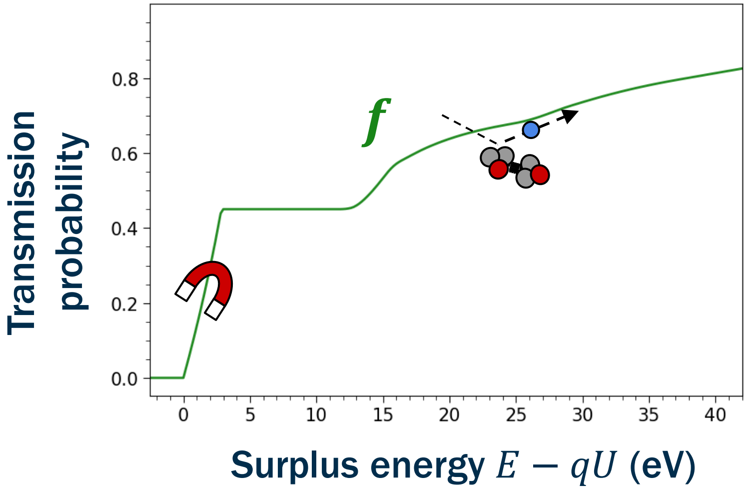
=

Convolution of **theoretical spectrum** with **experimental response**



Fermi theory with radiative corrections and molecular excitations

⊗



Spectrometer transmission and energy losses in source

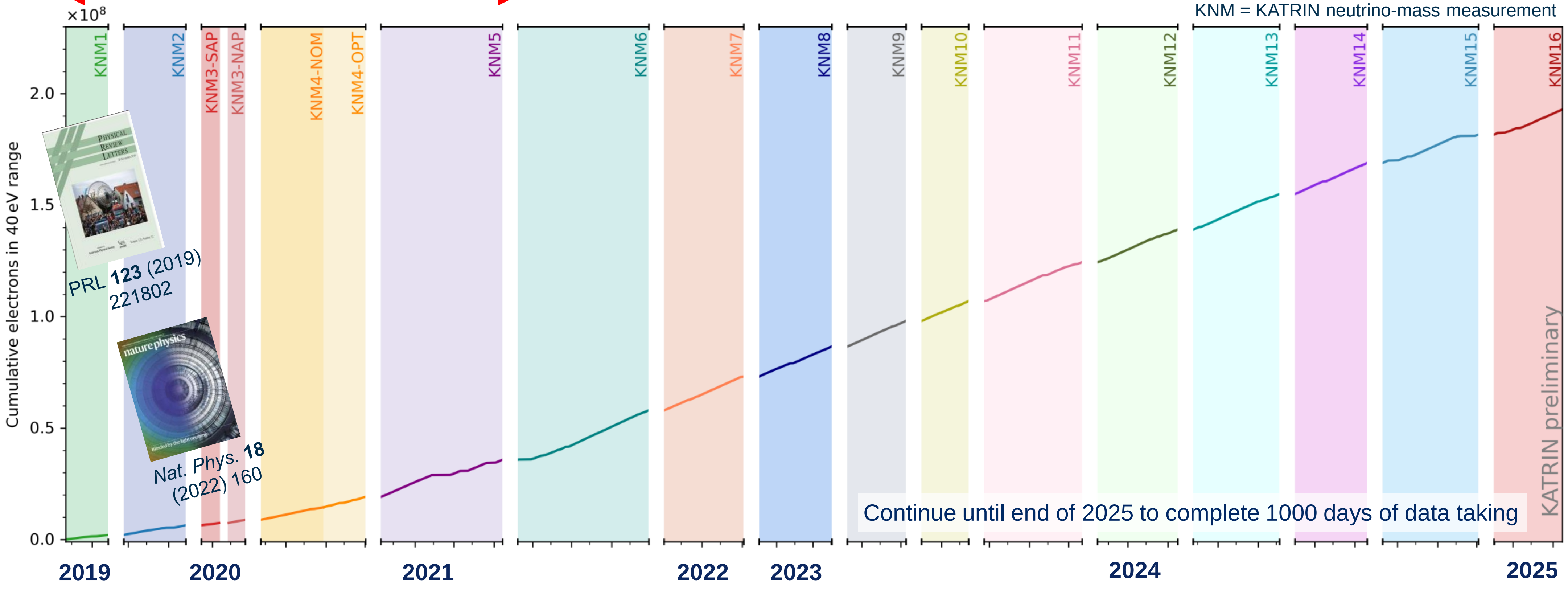
$$R(U) = A_s \cdot N_T \int_{qU}^{E_0} \frac{d\Gamma}{dE}(E, m_\nu^2) \cdot f(E,U)\mathrm{d}E + R_{bg}$$

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

KATRIN data taking

Stack data points with the same measurement conditions = hundreds of β-spectrum scans = campaign

Latest result

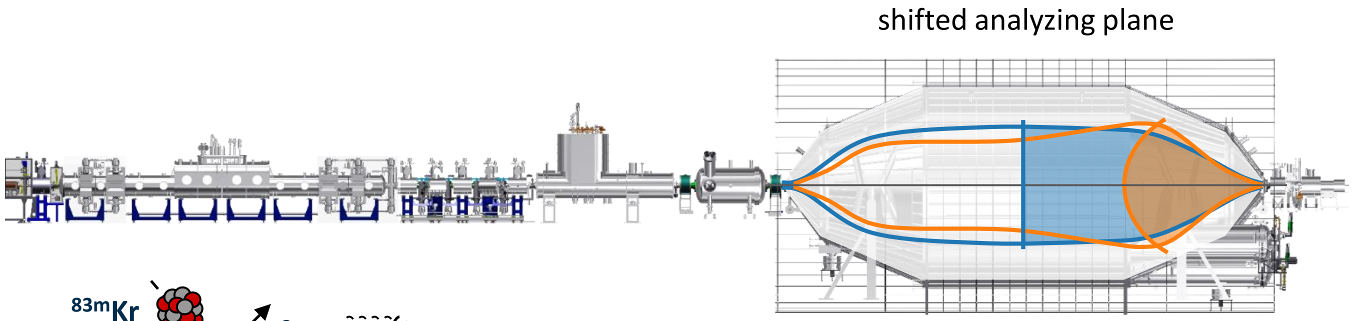


36 Mio. electrons

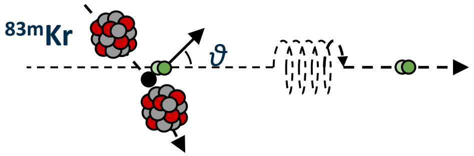
> 190 Mio. electrons

2019: m_ν < 1.1 eV (90% CL) **2022**: m_ν < 0.8 eV (90% CL)

Key optimizations since previous release

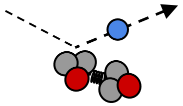


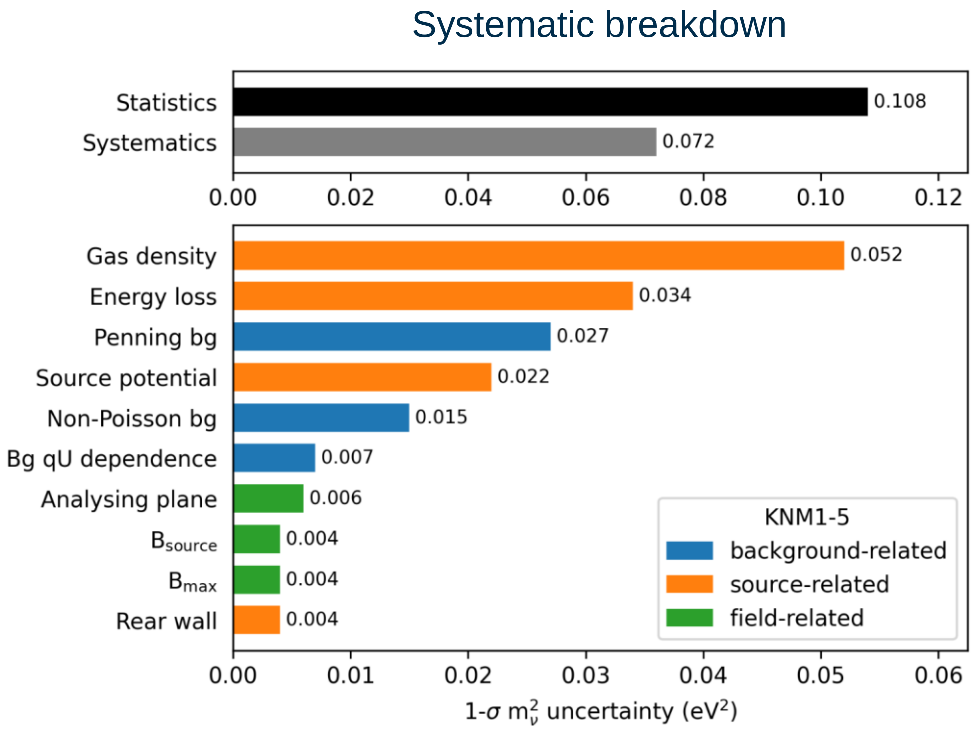
- ✓ **Factor 2** lower background by fiducialization
  Lokhov *et al.*, EPJ C **82** (2022) 258
  KATRIN Coll., EPJ C **84** (2024) 12



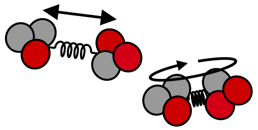
- ✓ **Optimized** scan-time distribution

- ✓ 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

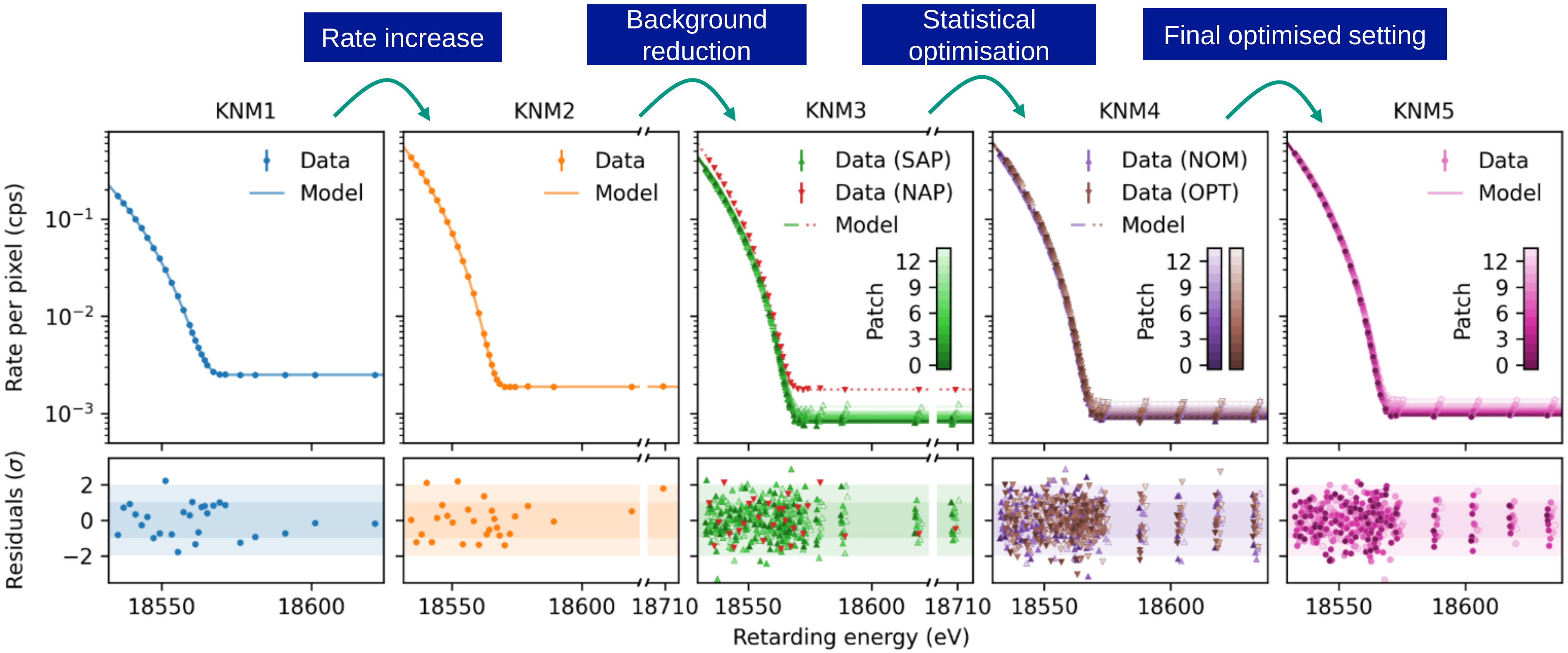




- ✓ Reduced **molecular final-states** uncertainty by dedicated assay using ab-initio calculations
  Schneidewind *et al.*, EPJ C **84** (2024) 494



Results of KNM1-5 science runs

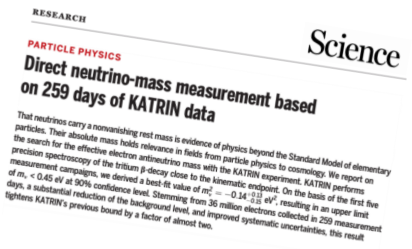


- **7** different configurations, **59** spectra, **1609** data points, parameter correlations across datasets
- 2 independent analysis frameworks
  Kleesiek et al. EPJ C 79 (2019) 204; Karl et al., EPJ C 82 (2022) 439

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

Combined best fit value

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 $m_\nu^2 = -0.14^{+0.13}_{-0.15}$ eV^2, resulting in an upper limit of $m_\nu < 0.45$ 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.

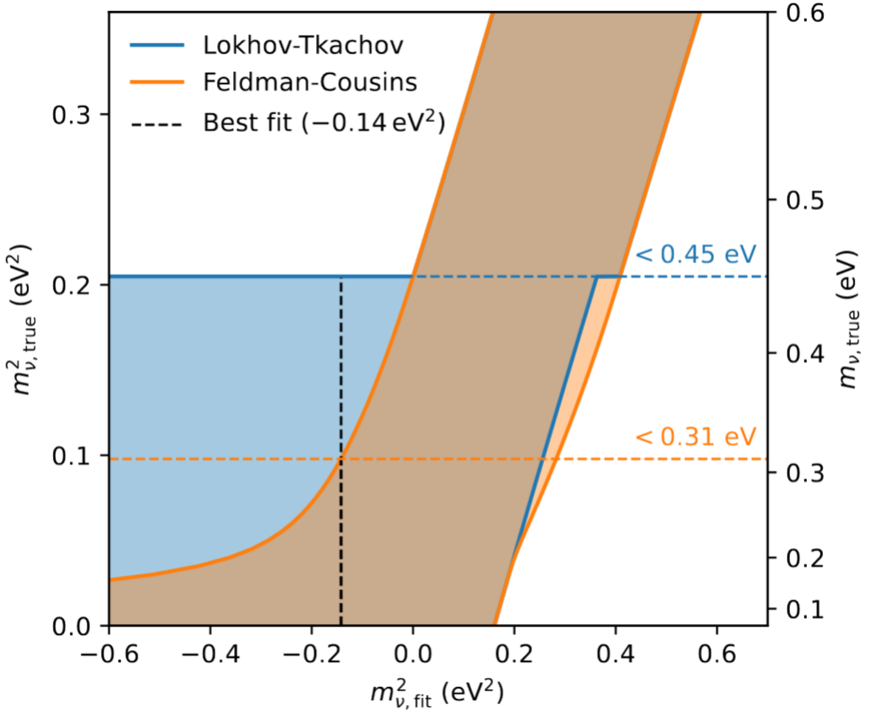
- **New world-best** direct neutrino mass constraint

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

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

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

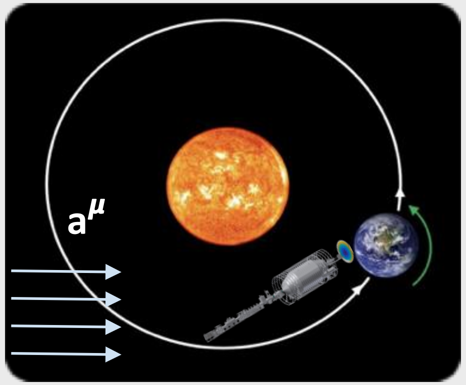
→ arXiv:2503.18667 (2025)

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

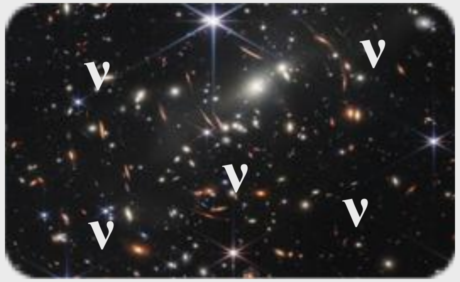
- General neutrino interactions

→ PRL **134** (2025) 251801

- New light bosons

Line search for capture of local cosmic relic ν

→ PRL **129** (2022) 011806



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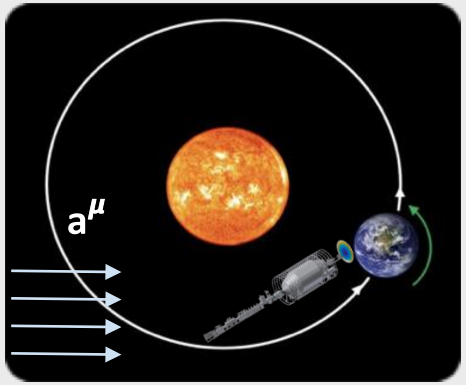

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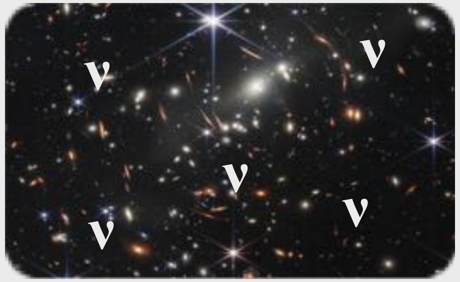
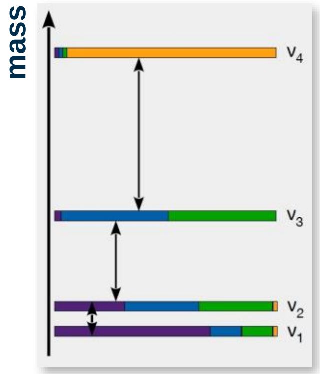


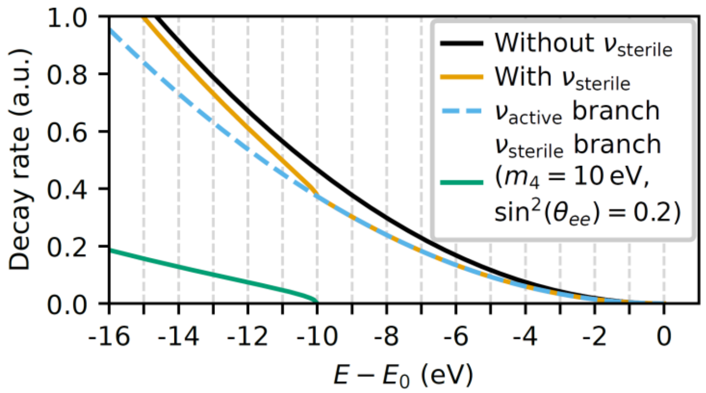
eV-scale sterile neutrino search

KATRIN Coll, arXiv:2503.18667

NEW!

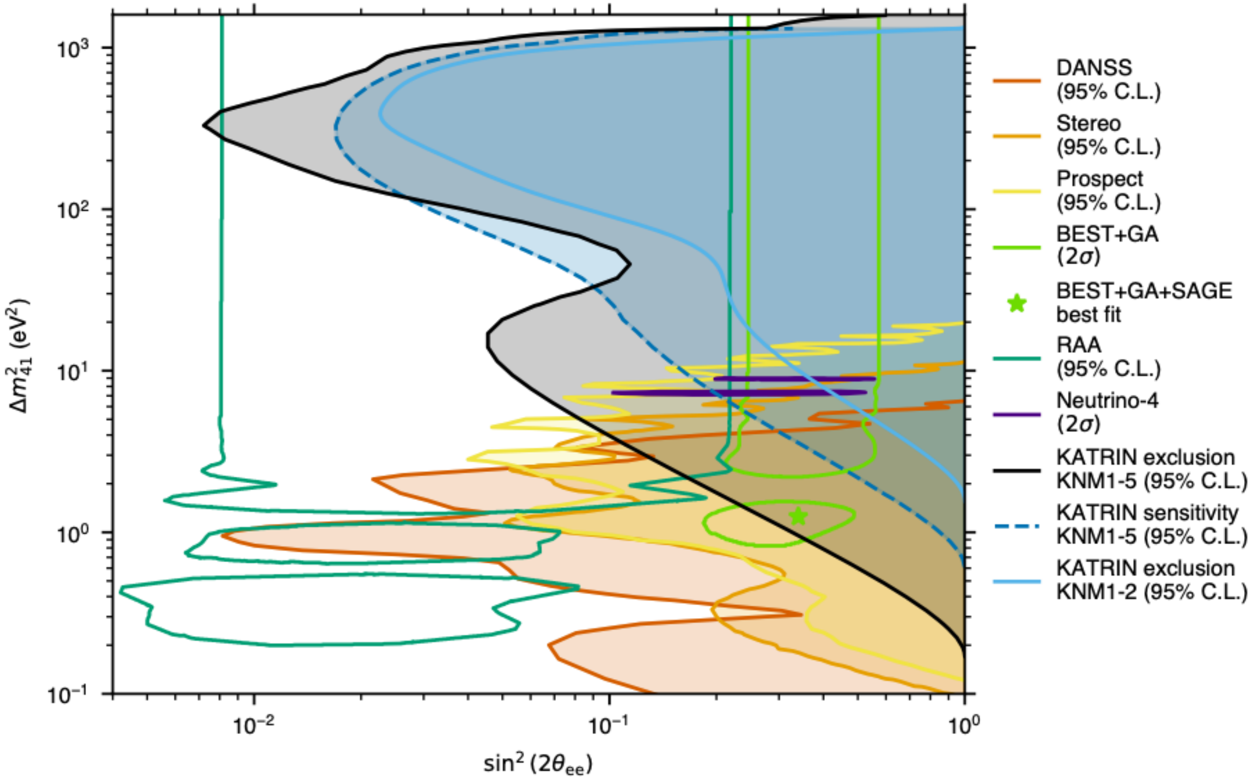
- Fourth neutrino mass eigenstate that does not interact weakly





$$\frac{d\Gamma}{dE} = (1 - |U_{e4}|^2)\frac{d\Gamma}{dE}(m_\beta^2) + |U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)$$

active   sterile



- Motivated by short-baseline oscillation anomalies, direct comparison with

$$\Delta m^2_{41} \approx m_4^2 - m_\beta^2$$

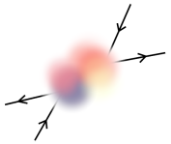
$$\sin^2(2\theta_{\text{ee}}) = 4|U_{\text{e4}}|^2\left(1 - |U_{\text{e4}}|^2\right)$$

- Challenging the Neutrino-4 result
- KATRIN bound dominates for $\Delta m^2_{41} > 5$ eV^2

Exotic weak interactions from spectrum shape distortion

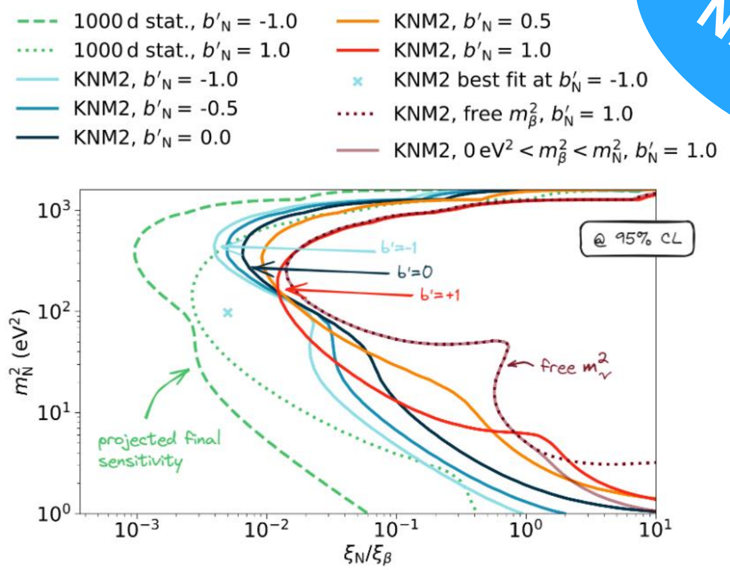
NEW!

General neutrino interactions



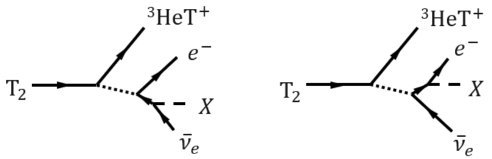
KATRIN Coll, PRL (2025) 251801

- Effective field theory of weak interactions
- New interactions considered (S, P, V, AV, T couplings)
- Modification of the effective decay rate: $\frac{d\Gamma_{\mathrm{GNI}}}{dE} = \frac{d\Gamma_{\mathrm{SM}}}{dE} \sum_{k=\beta,N} \xi_k \left[1 - b'_k \frac{m_k}{E_0 - E}\right]$
- Competitive coupling limits to the high-energy investigations

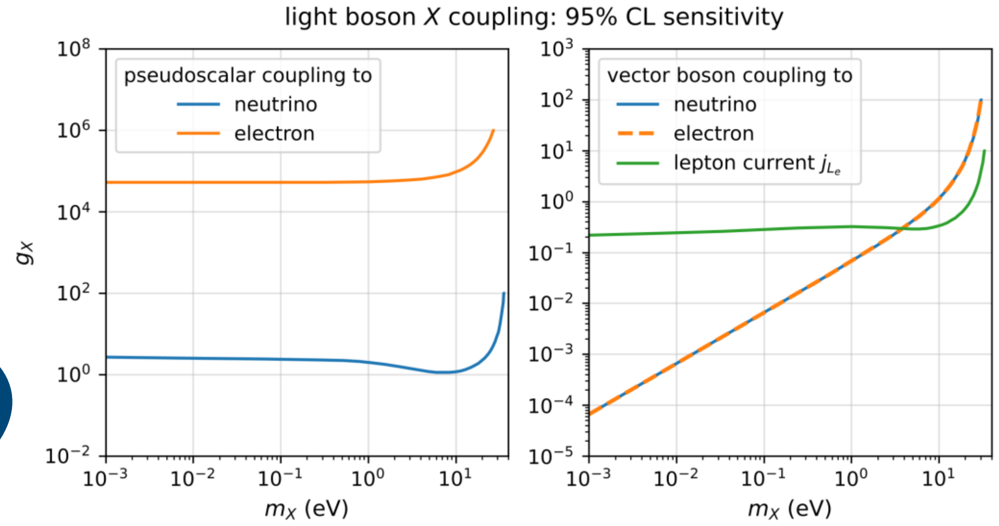


Light boson searches

- Consider additional new light bosons coupling to leptons
- Contribution to the decay rate: $\frac{d\Gamma}{dE} = \frac{d\Gamma_{\mathrm{SM}}}{dE} + \frac{d\Gamma_{\mathrm{X}}}{dE}$
- New parameters: boson mass m_X and coupling g_X
- Probe new physics at low energy scale of < 20 keV
- Complementary search for new light bosons



New results soon

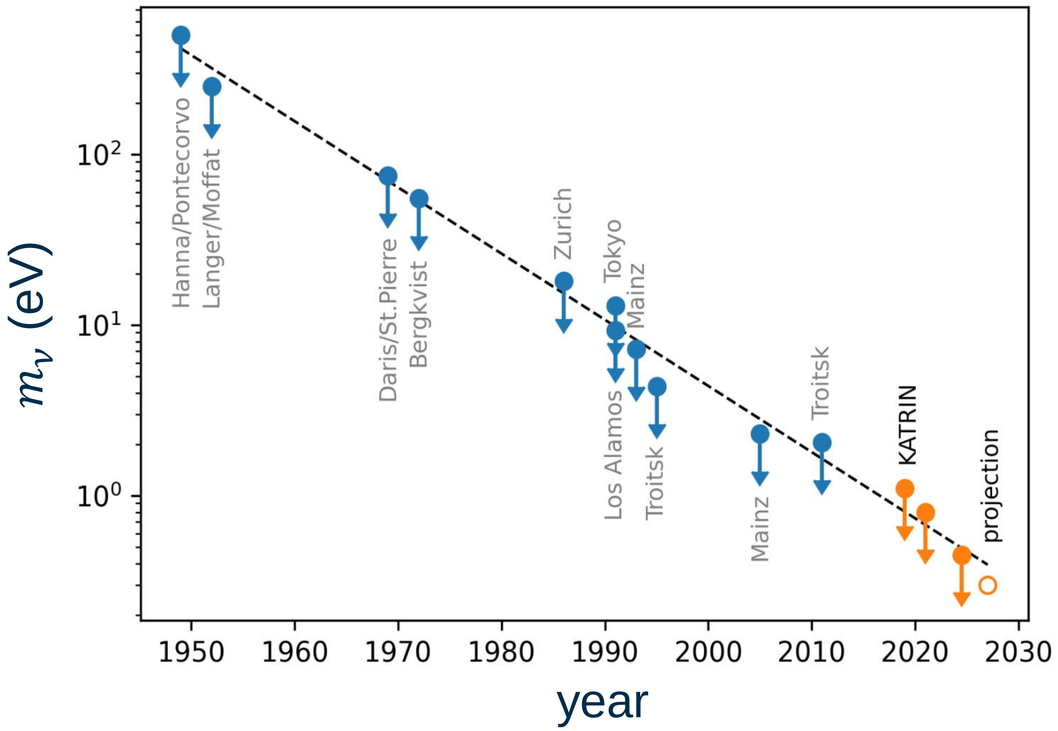


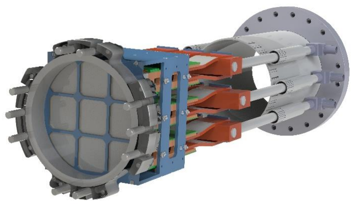
Summary

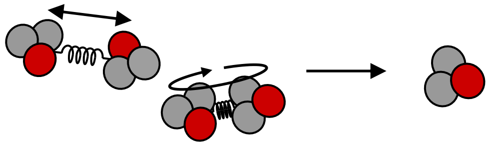
- Current world-best **direct neutrino mass limit** by KATRIN

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

  - Based on first 5 science runs
  - Data taking continues until the end of 2025
  - Final sensitivity of < 0.3 eV
- **Rich** physics **program** beyond the neutrino mass
- **Future** plans:
  - Detector upgrade for **keV sterile neutrino** search: TRISTAN (2026-27)
    Mertens *et al., J. Phys. G* 46 (2019) 065203
  - **next-generation** ν-mass experiment (R&D phase)
    - Differential detection and atomic tritium technologies







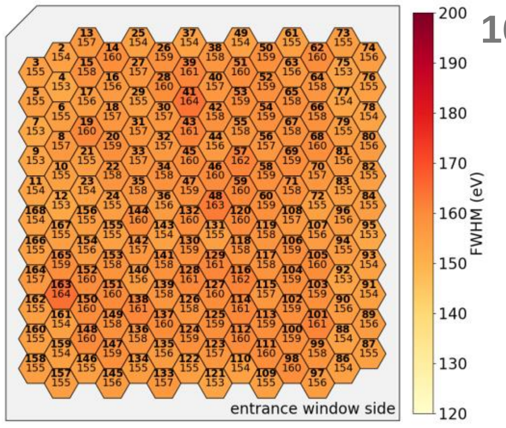
Backup

TRISTAN project

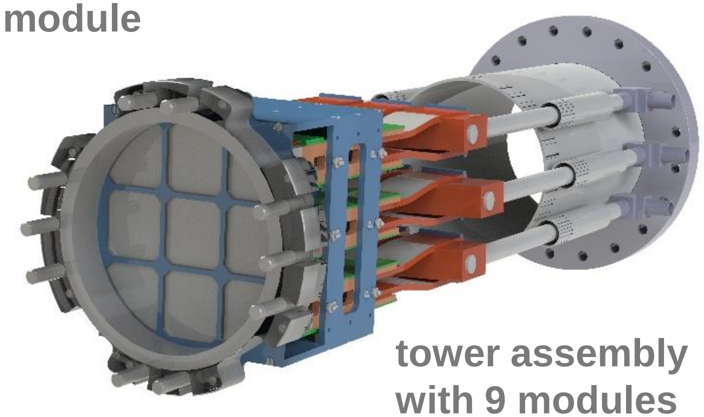
Aim: Measure the full tritium spectrum to search for keV steriles at ~10^{-6} admixture

Challenges: Energy range x 400, electron rate x 10^6, high energy resolution, control of systematics

Technology: Silicon Drift Detector (SDD) array with > 1000 pixels



166-pix module



tower assembly with 9 modules

replica beamline for system characterization

- ✓ Capacity to handle high rates (> 10^8 cps)
- ✓ Excellent energy resolution (160 eV @ 5.9 keV)

Timeline: Implement in KATRIN beamline for measurements during 2026-2027

Mertens *et al.*, J. Phys. G**46** (2019) & G**48** (2021); Gugiatti *et al.*, NIM A**979** (2020) & NIM A**1025** (2022),
Biassoni *et al.*, EPJ Plus **136** (2021) 125, Siegmann *et al.*, J. Phys. G**51** (2024) 8, 085202, Spreng *et al.*, JINST **19** (2024) P12009

KATRIN as R&D facility for differential detector

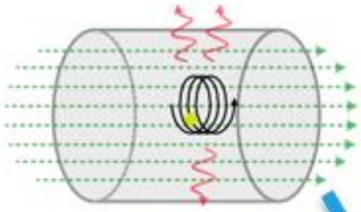
Karlsruhe Institute of Technology

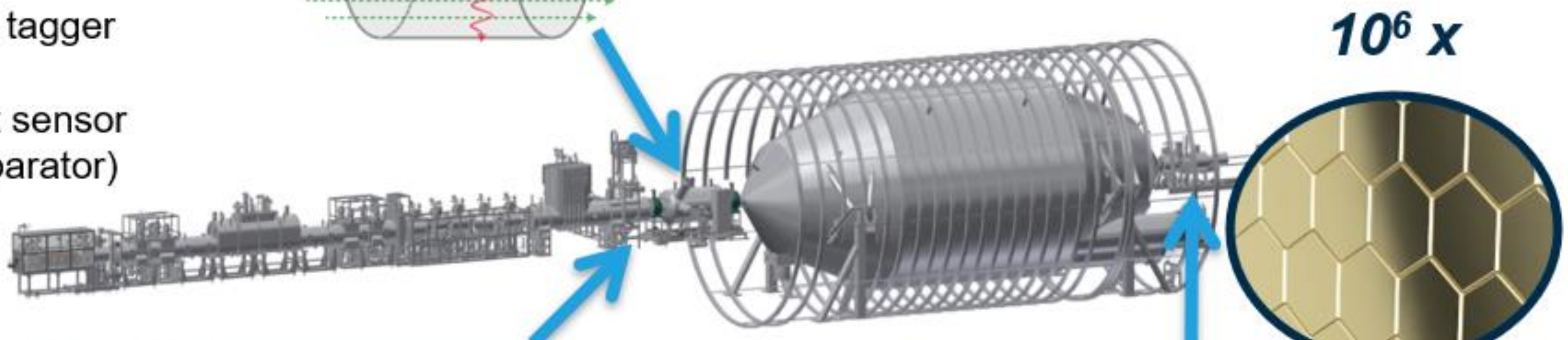
Goal: Sub-eV resolution for **differential** energy measurement.
Added benefit: Immune to MAC-E filter backgrounds!

Several promising technology options

Option 1b
Time-of-flight via electron tagging

- 1000 Hz single-electron tagger with high SNR
- CRES, or image current sensor (cryogenic current comparator)





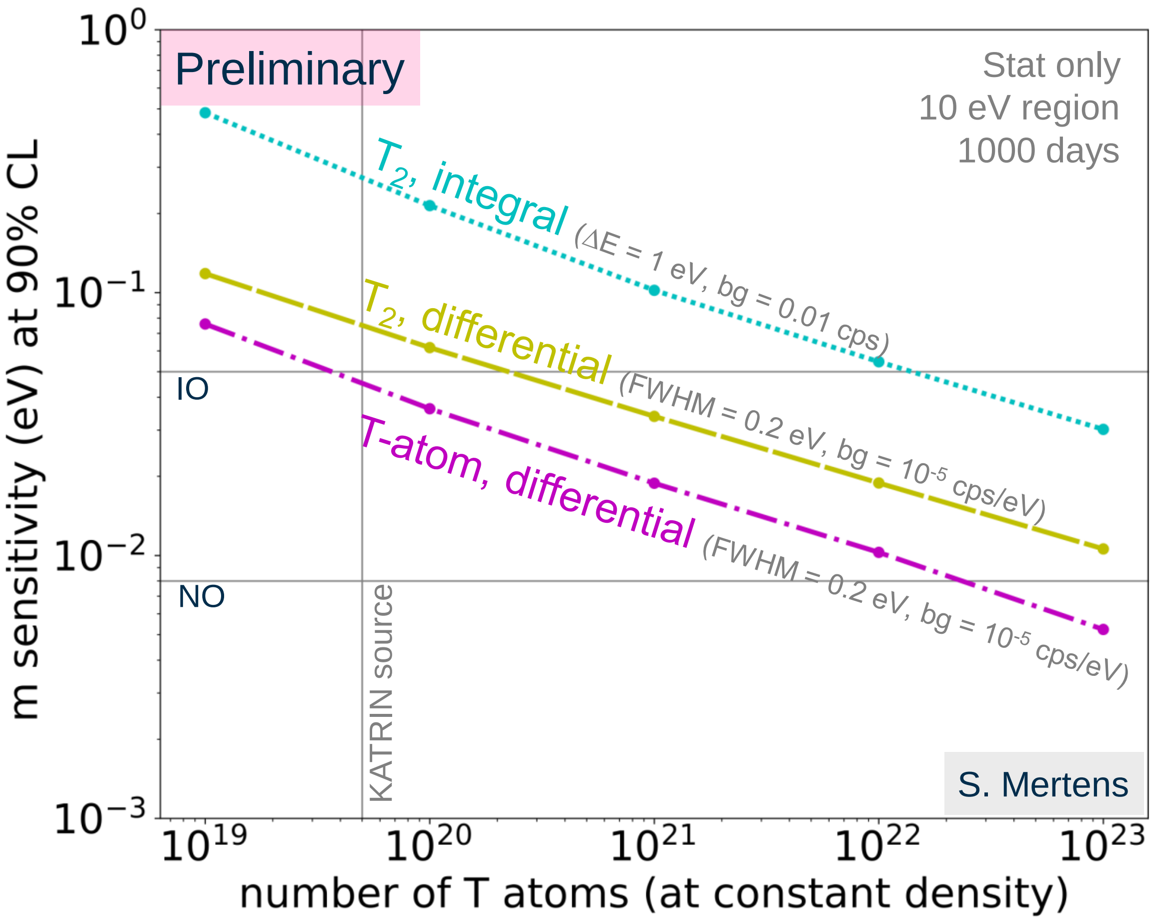
Option 1a
Transverse Energy Compensator (idea: C. Weinheimer / U Münster)

- Angle-dependent acceleration of e^- in ramped drift tube
- Demonstrated to improve MAC-E resolution by factor ~10

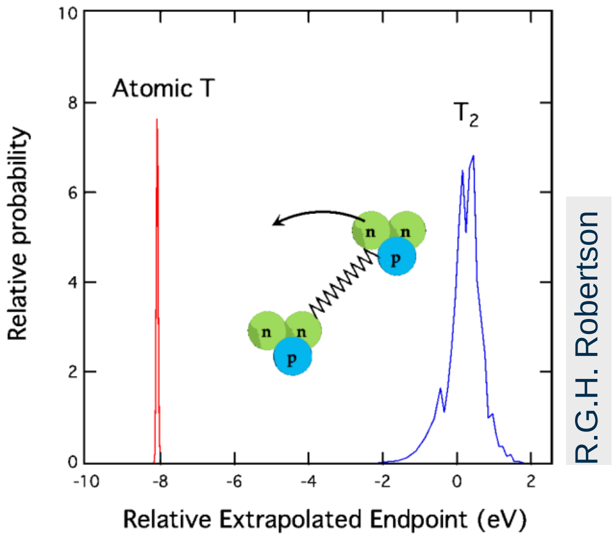
Option 2
Quantum sensors (MMC, TES)

- Operation in magnetic field (~20-50 mT)
- Coupling of mK cryo-platform with RT spectrometer

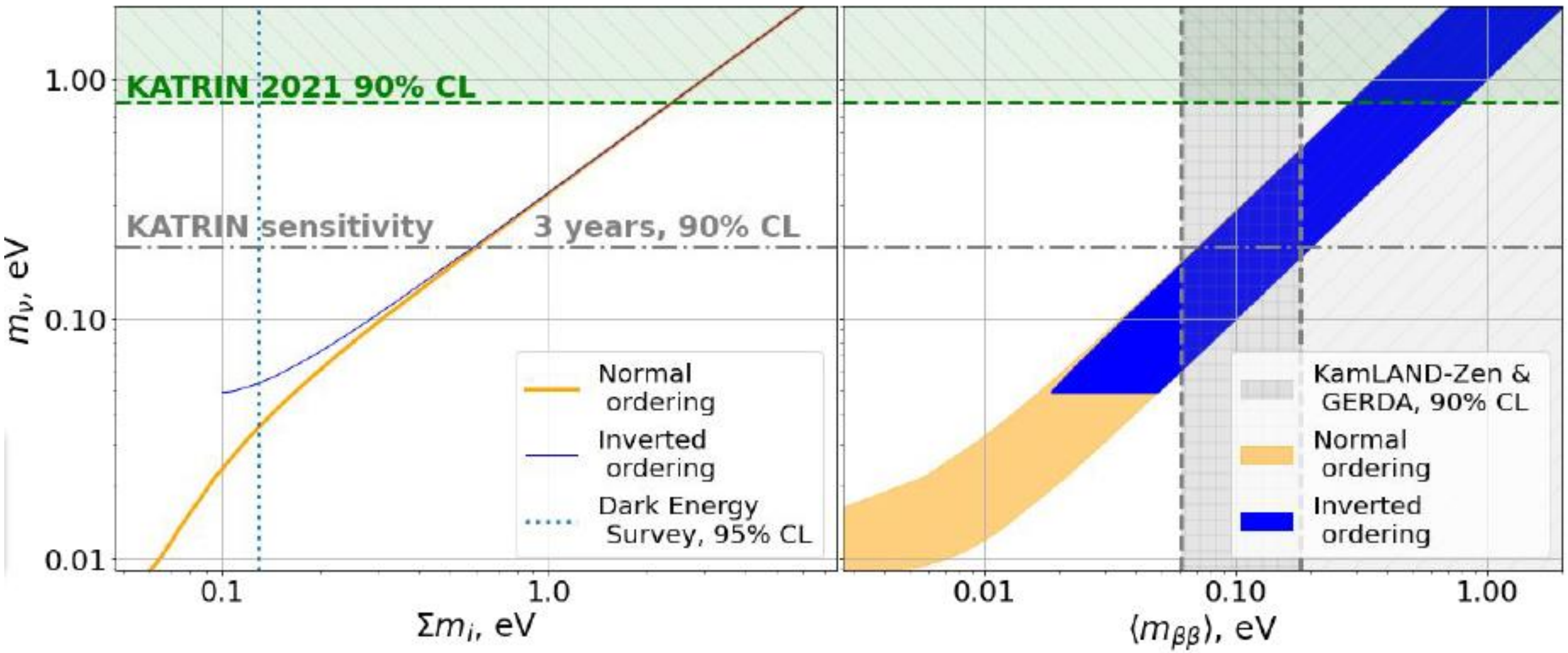
Sensitivity beyond KATRIN



- **KATRIN now:**
  Integral, ΔE = 2.7 eV, bg = 0.1 cps
  More tritium would help, but ultimately need:
- **Differential* measurement (FWHM < 1 eV)**
  ***) meaning: non-integrating spectroscopy**
  - ✓ Better use of statistics
  - ✓ Intrinsically low background
- **Atomic tritium**
  - ✓ Avoid broadening (~ 1 eV)
  - ✓ Avoid limiting systematics of T_2



Backup



Cosmological observables **Neutrinoless double β-decay**