

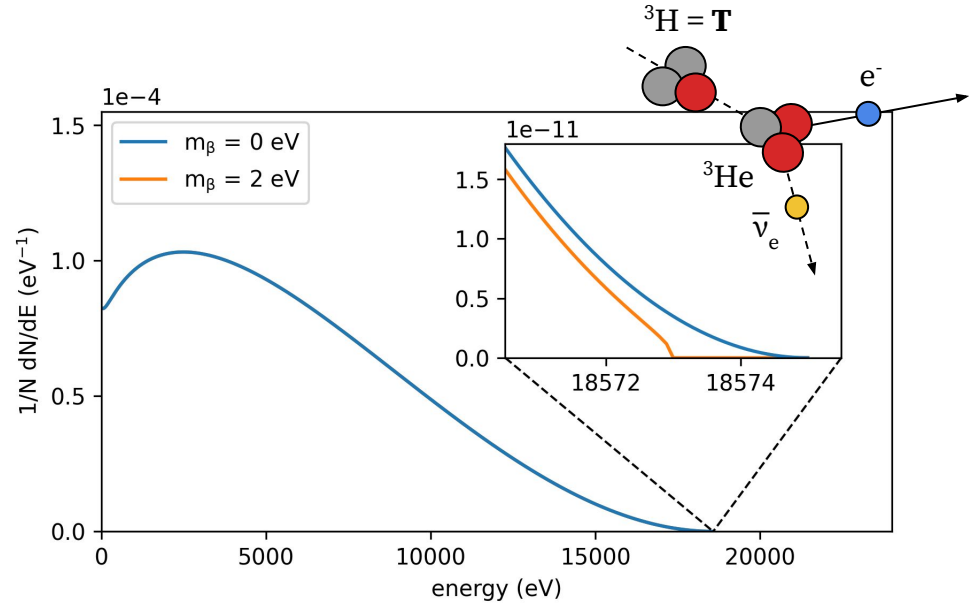
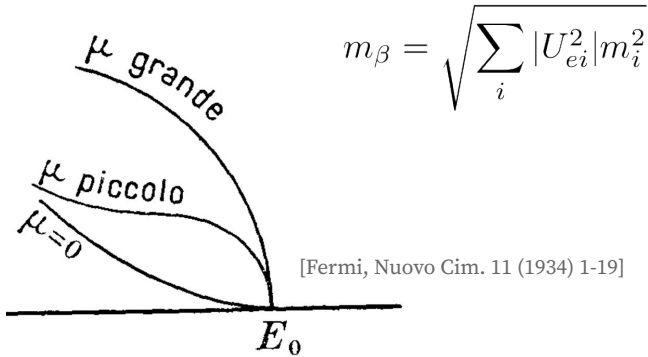
*Direct neutrino mass measurements
and sterile neutrino searches with KATRIN*

Christoph Wiesinger (MPIK) for the KATRIN collaboration, Neutrino, 23.06.2026



Beta decay kinematics

- **Direct measurement** of phase space modification, **squared neutrino mass**, maximum distortion at endpoint
- **Effective electron anti-neutrino mass**, weighted incoherent sum

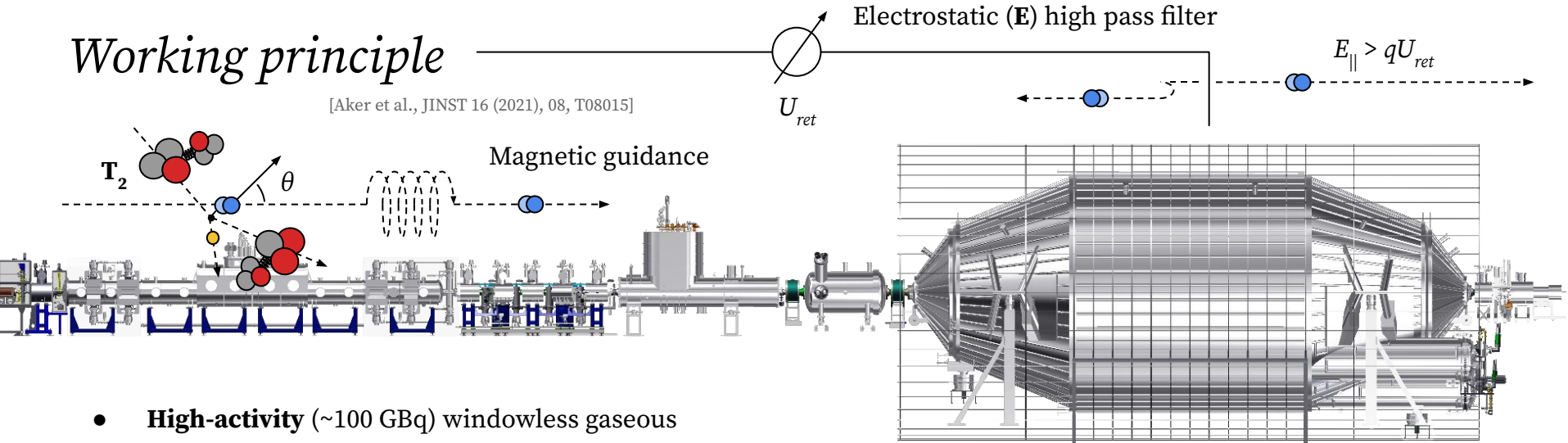


*Karlsruhe Tritium Neutrino
(KATRIN) experiment*

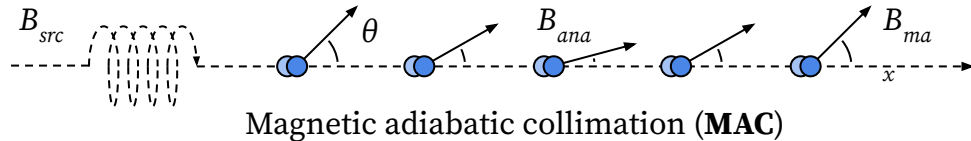


Working principle

[Aker et al., JINST 16 (2021), 08, T08015]



- **High-activity** (~ 100 GBq) windowless gaseous molecular tritium source, closed loop
- **High-resolution** (~ 1 eV) **large-acceptance** (0 - 51°) MAC-E spectrometer system
- **Electron counting** at focal plane detector, 148-pixel silicon PIN diode
- **Integral spectrum** scans, discrete retarding potential steps



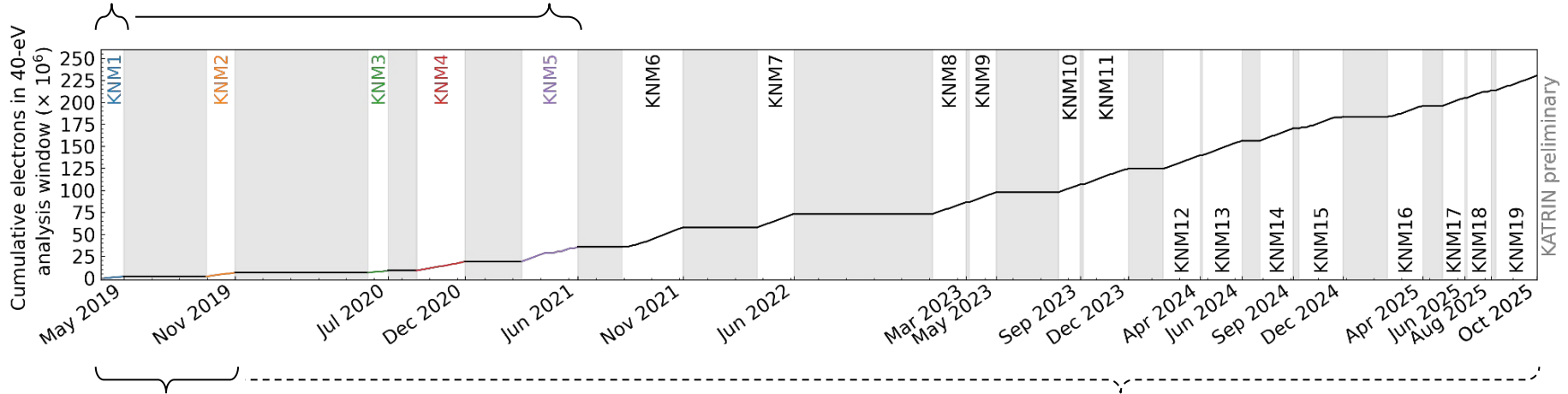
Data taking overview

First result, $m_\beta < 1.1$ eV (90% CL)

[Aker et al., PRL 123 (2019) 22, 221802]

Third result, 5 campaigns, 259 measurement days, 36 million electrons*

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



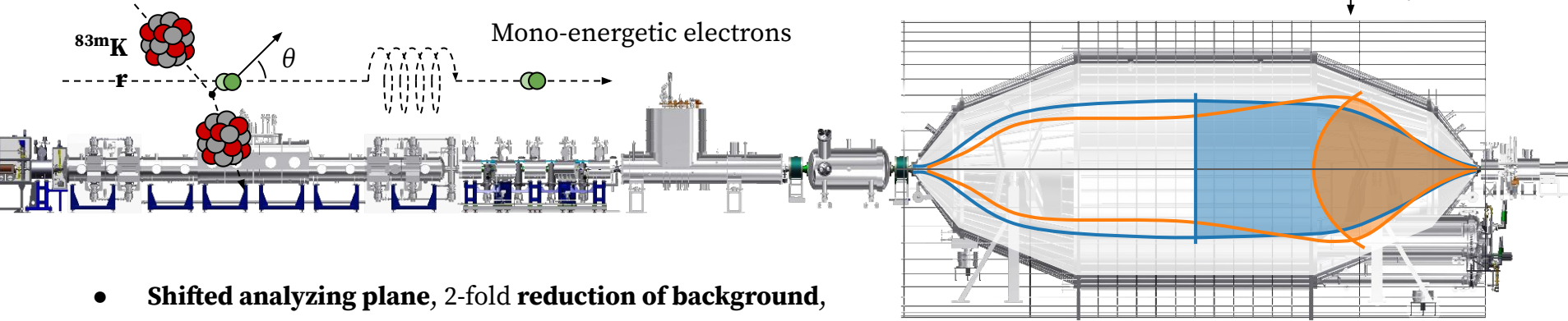
Second result, $m_\beta < 0.8$ eV (90% CL)

[Aker et al., Nature Phys. 18 (2022), 2, 160-166]

Final dataset, 1000 measurement days, 231 million electrons*

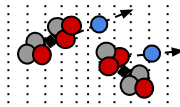
*40 eV below endpoint and above

(Selected) experimental improvements



- **Shifted analyzing plane, 2-fold reduction of background, inhomogeneous spectrometer fields**

[Lokhov et al., EPJ C 82 (2022)3, 258]



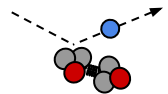
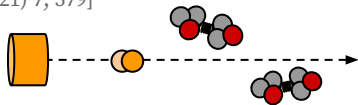
- **$^{83\text{m}}\text{Kr}$ co-circulation, determination of source potential and spectrometer fields**

[Altenmüller et al., J.Phys.G 47 (2020), 6, 065002]



- **Improved electron gun, mono-energetic angular-selective photoelectron source, probe scattering effects**

[Aker et al., EPJ C 81 (2021) 7, 579]

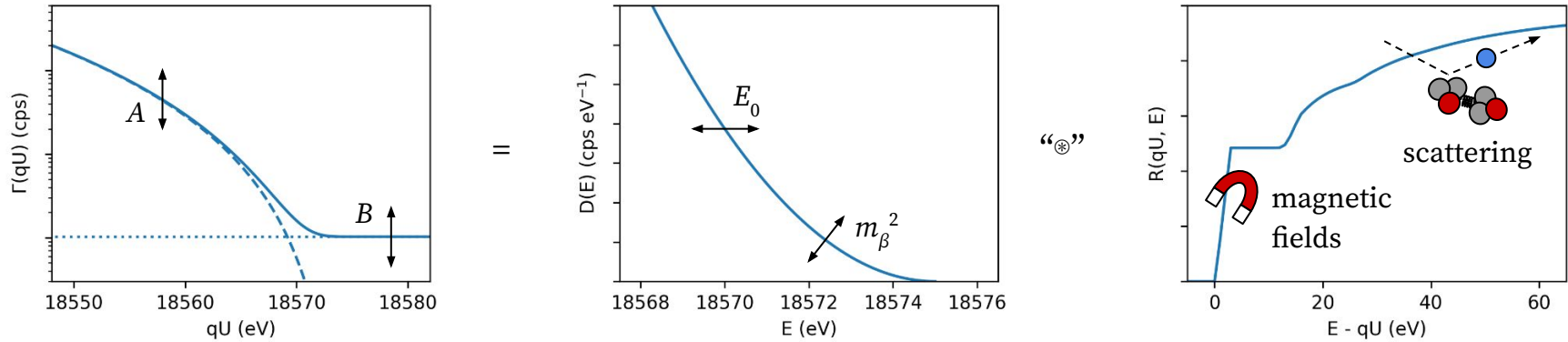


Poster 263, Florian Fränkle

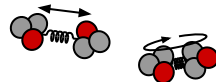
Analysis strategy

[Aker et al., PRD 104 (2021) 1, 012005]

- Maximum likelihood fit with analytical model $\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0) R(qU, E) dE + B$

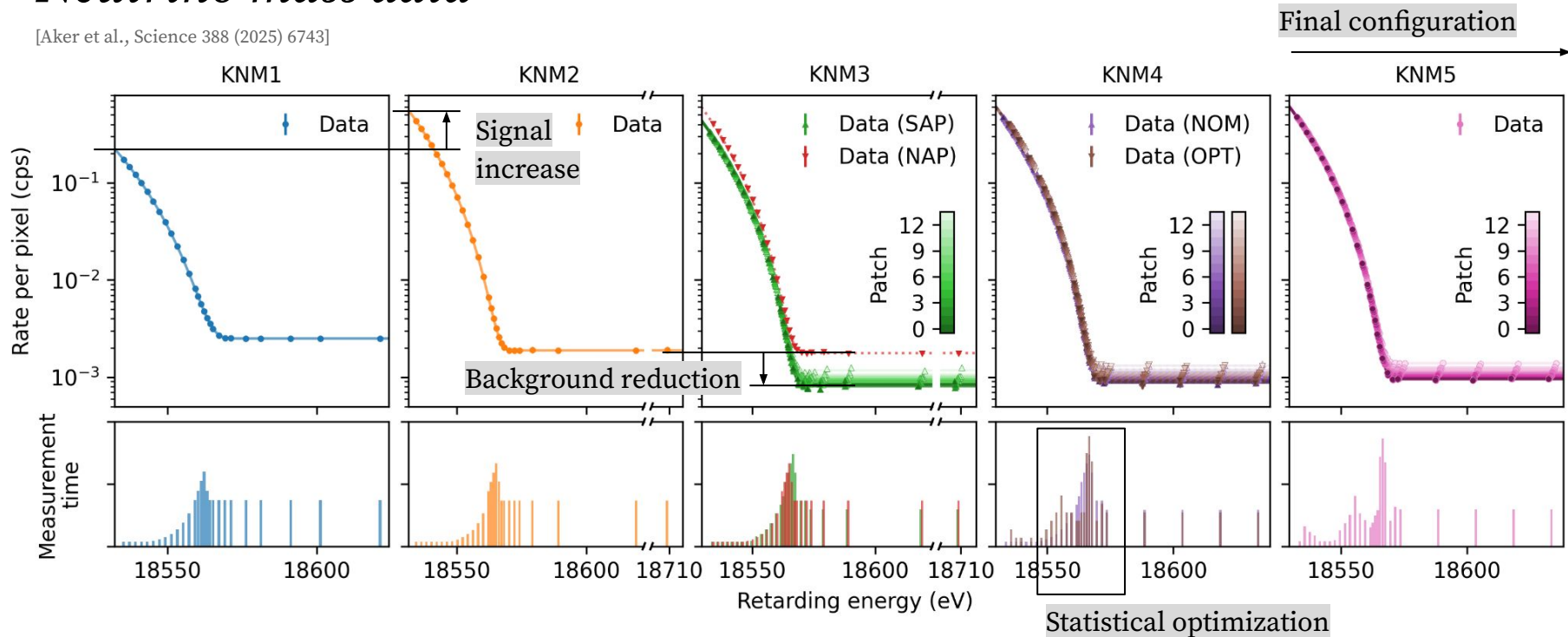


with free **squared neutrino mass** m_β^2 , **effective endpoint** E_0 , **amplitude** A and **background** B

- Calibration constraints as penalty terms, **2 analysis frameworks**, neural network surrogate [Karl et al., EPJ C 82 (2022) 5, 439]
- 2-stage blinding**, analysis of simulated data twins, blinded molecular final states 

Neutrino mass data

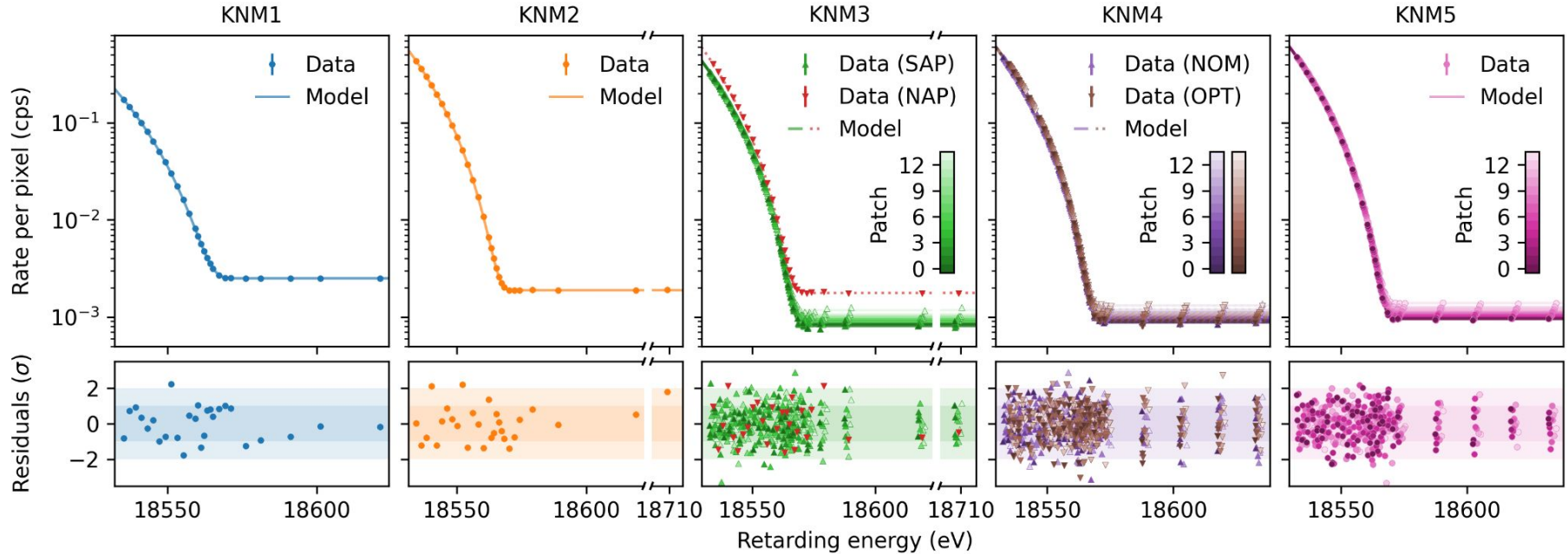
[Aker et al., Science 388 (2025) 6743]



- First **5 campaigns**, 7 configurations, 59 spectra, **1609 data points**

Neutrino mass result

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



- Best-fit **compatible with zero** ($m_{\beta}^2 = -0.14^{+0.13}_{-0.15} \text{ eV}^2$), upper limit $m_{\beta} < 0.45 \text{ eV}$ (90% CL)

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

Sensitivity outlook

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

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

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

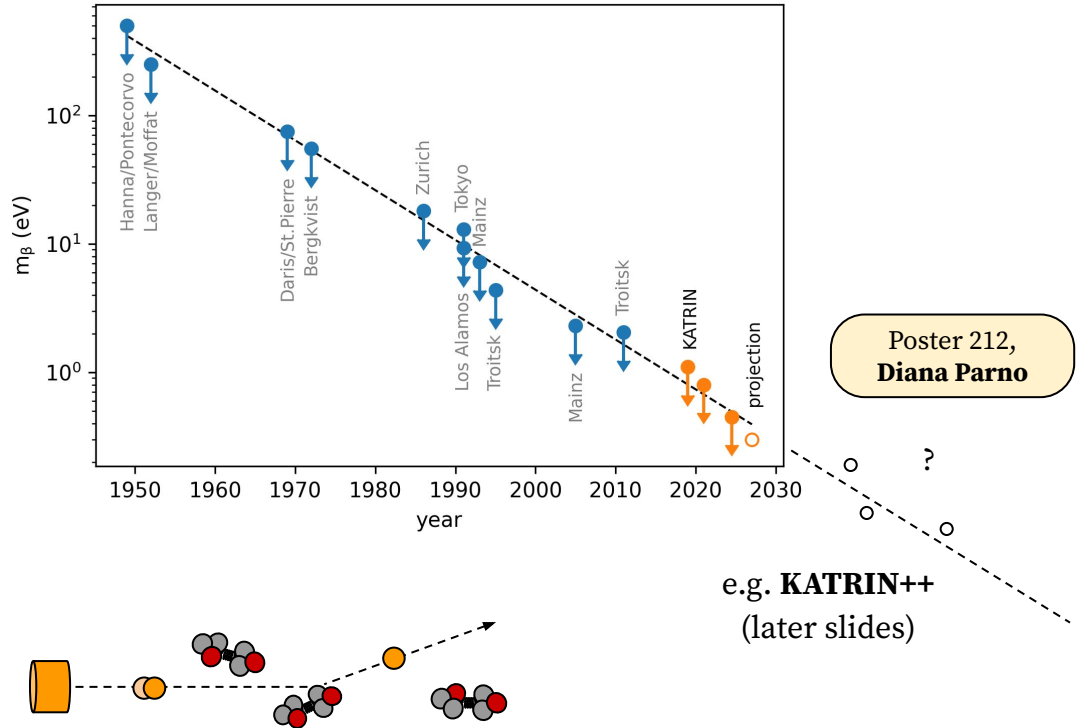
based on 259 measurement days
and 36 million electrons

- **Final dataset** with 1000 measurement days and 231 million electrons

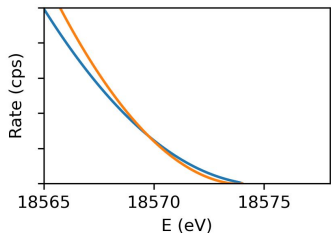
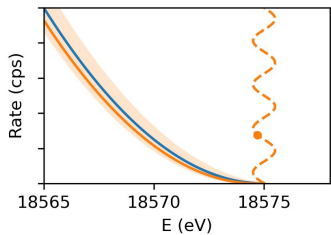
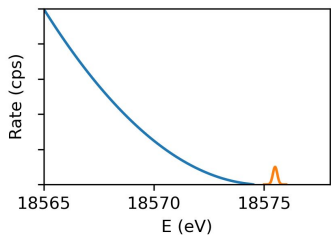
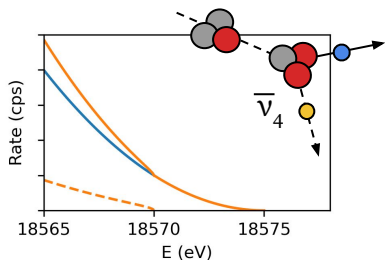
$$m_{\beta} < 0.28 \text{ eV}^* \text{ (90\% CL)}$$

* statistical sensitivity, no systematics

- Final **systematics budget in preparation**, scattering systematics under study, goal to reach below **0.30 eV**



Beyond neutrino mass studies

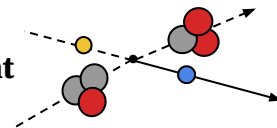


- **Sterile neutrinos**, eV-scale (next slide) to keV-scale (later slides), additional spectral component, **kink**, [Acharya et al., Nature 648 (2025) 8092, 70-75]
- **Extra dimensions**, multiple kinks [Antoniadis et al., JHEP 02 (2026) 015]

- **Relic neutrino** overdensity, **population above endpoint**

[Aker et.al, PRL 129 (2022) 1, 011806]

$$\eta < 1.1 \cdot 10^{11} \text{ (95\% CL)}$$



- **Lorentz invariance violation**, sidereal modulation

[Aker et. al, PRD 107 (2023) 8, 082005]

- **Ultra-light axions**, modulation

[Lee et al., PRR 2 (2020) 3, 033392]

- **General neutrino interactions**, shape distortion

[Aker et. al, PRL 134 (2025) 25, 251801]

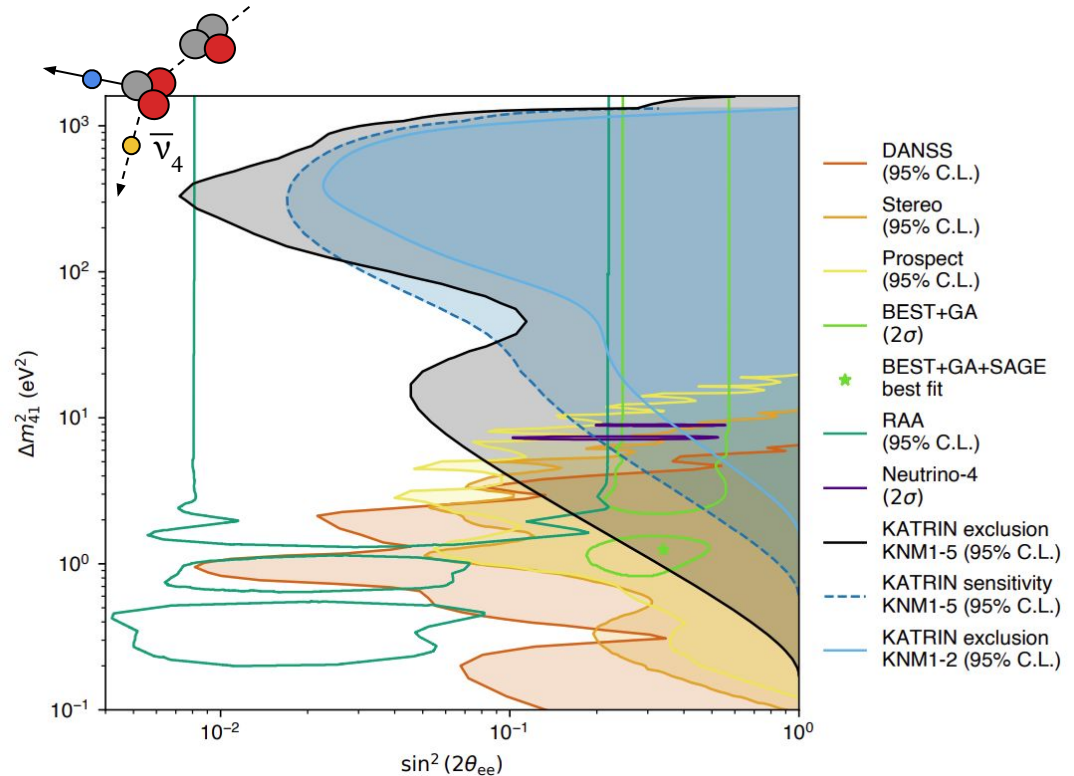
- **Light Bosons**, additional spectral component, shape distortion

[Lauer, PoS ICHEP2024 (2025) 326]

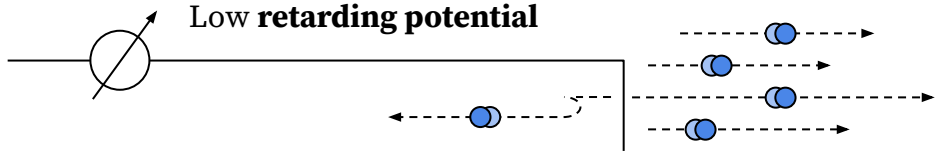
Sterile neutrino result

[Acharya et al., Nature 648 (2025) 8092, 70-75]

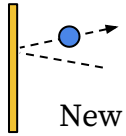
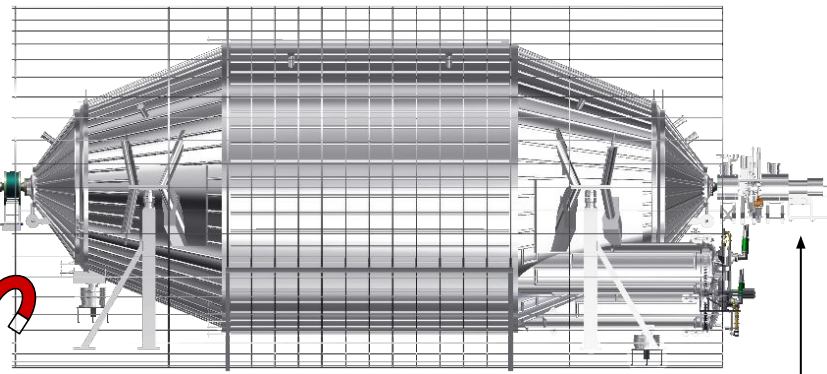
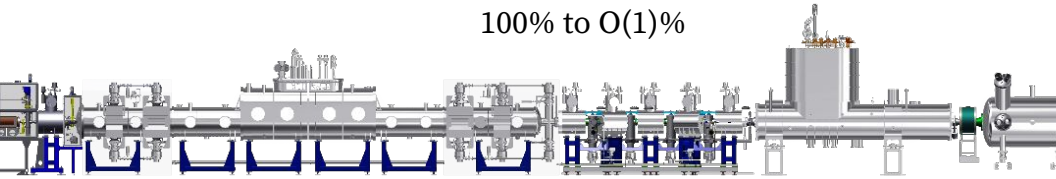
- **eV-scale sterile neutrinos**, motivated by anomalies, fourth mass eigenstate
- **3+1 model**, grid search analysis, based on 259 measurement days dataset
- No sterile-neutrino signal observed
 - Excludes substantial part of **Gallium anomaly**
 - Challenges Neutrino-4 claim
- **Complementary** to short-baseline oscillation experiments



Towards higher sterile masses



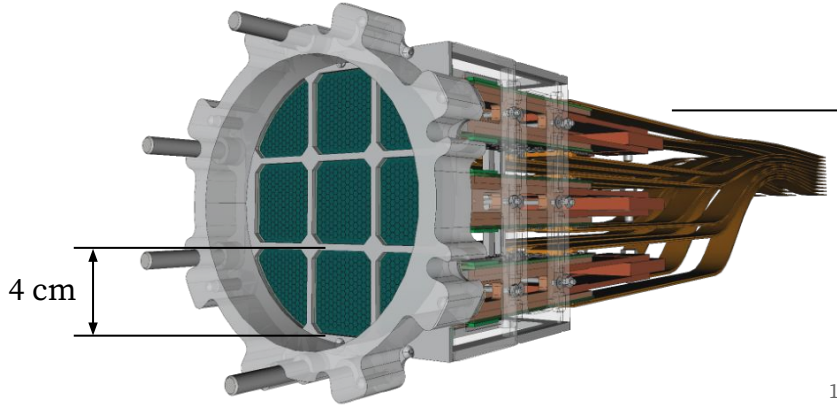
Reduced **source activity**,  
100% to O(1)%



New **rear wall**, Au to Be,
reduced back scattering

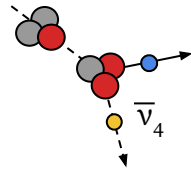
Optimized **electromagnetic fields**,
ensure adiabaticity

- **Beamline upgrade** for deep spectrum scans
[Mertens et al., J.Phys.G 46 (2019) 6, 065203]
- **TRISTAN detector, silicon drift detector (SDD) array** for high-rate (10^8 cps) beta spectroscopy, **9 x 166 pixels**
[Siegmann et al., J.Phys.G 51 (2024) 8, 085202]



Sensitivity to keV-scale sterile neutrinos

[Acharya et al., arXiv:2603.23256]

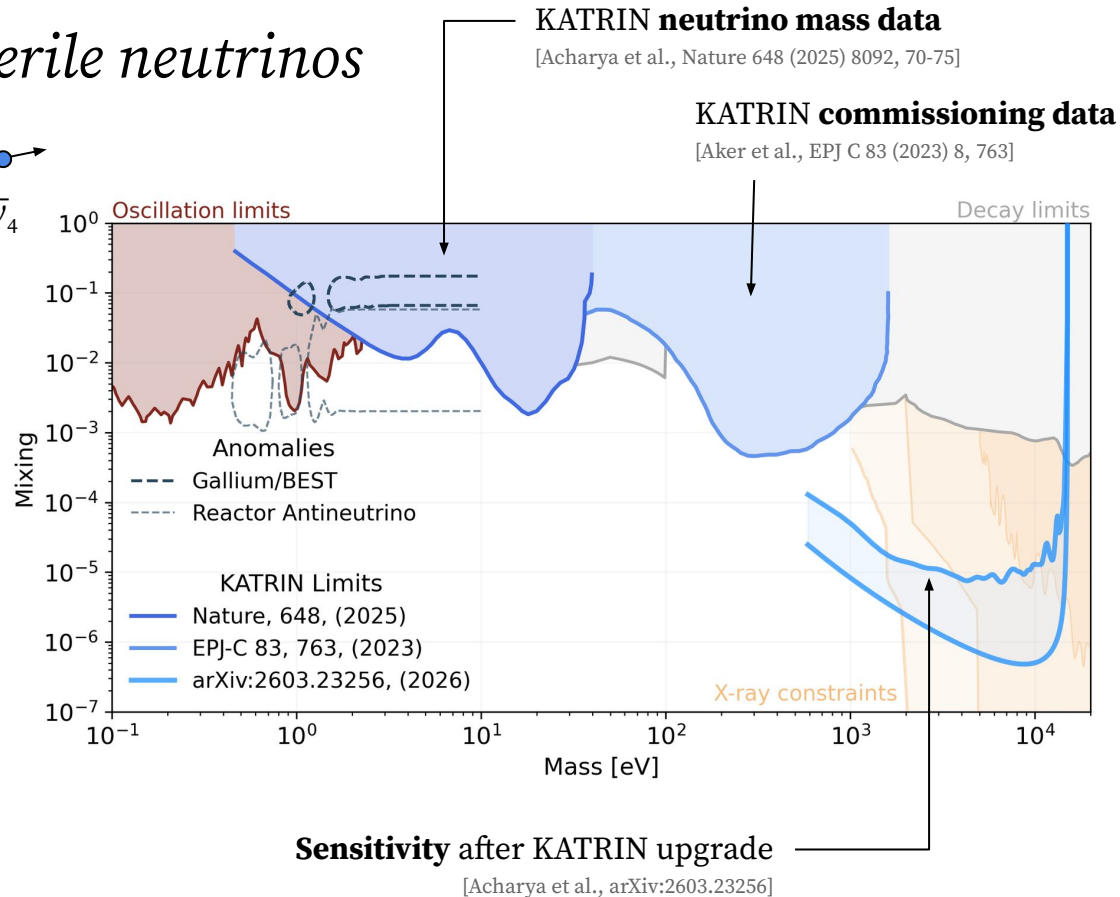


- High statistical sensitivity

$$|U_{e4}| < 10^{-6} \text{ (95\% CL)} \\ \text{for } m_4 = (4-13) \text{ keV}$$

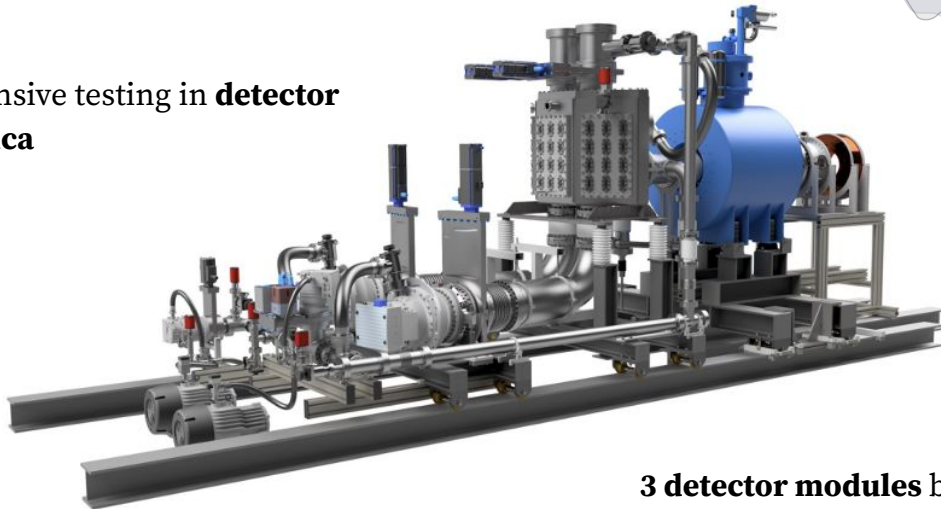
after 4 months of measurement

- **Systematic uncertainties** reduce sensitivity by factor 10-50
- **Extensive calibrations** and characterization measurements
- New **full beamline simulation**

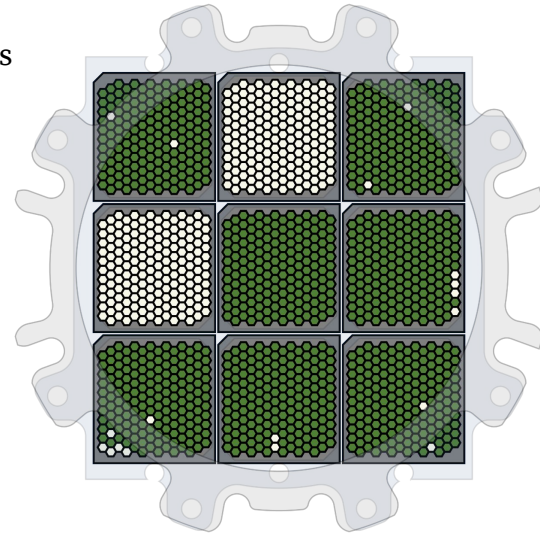


Status

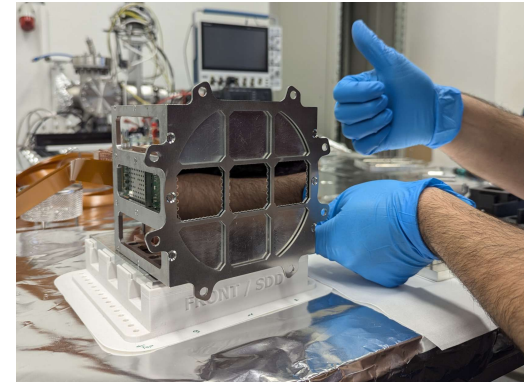
- **7 detector modules** approved for beamline integration, **260-330 eV (FWHM)** for 20 keV electrons
- **Installation after systematics measurements** for neutrino mass program
- Extensive testing in **detector replica**



Working pixels



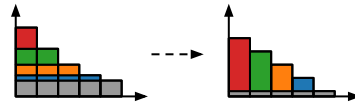
3 detector modules before operation in detector replica



Back to neutrino mass

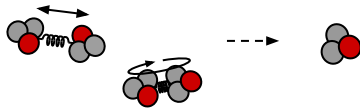
- Identify and develop **scalable technologies** for future direct neutrino mass measurement with tritium, **KATRIN++**

+ **Differential spectroscopy**

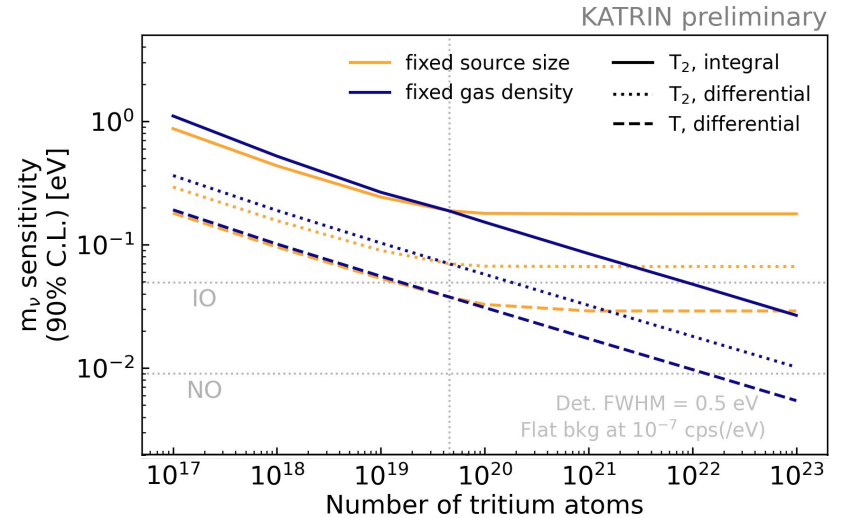


- **Efficient** use of each electron
- Lower background

+ **Atomic tritium**



- Avoid **molecular broadening**
- Avoid limiting T_2 systematics

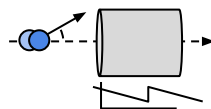
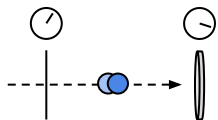


Status

[Input to EPPSU 2026]

+ KATRIN as R&D facility for **differential beta spectroscopy**

- **Time-of-flight** with spectrometer as delay line, **electron tagging**, cyclotron radiation, image current or 2d membrane with superconducting nanowire



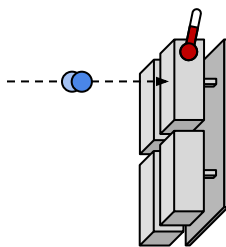
Enhanced resolution with **transverse energy compensator**

[Weinheimer, Patent PCT/EP2025/075997]

- **Cryogenic micro-calorimeters** with sub-eV resolution

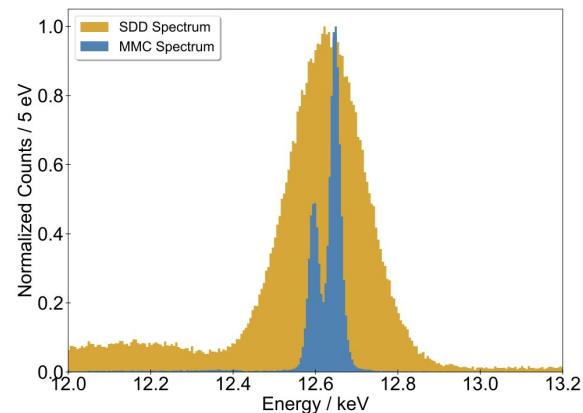
Electron spectroscopy with **metallic magnetic calorimeters (MMCs)**

[Kovač et al., NIM A 1080 (2025) 170662]



+ **Tritium Laboratory Karlsruhe** as R&D facility for **atomic tritium technology**

- Large-scale **generation and cooling** of atomic tritium



K_α lines of ^{83m}Kr

Conclusions

- World-best **direct neutrino mass constraint** based on 259 measurement days

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

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

- Final **1000 day dataset on disk**, analysis ongoing, aiming for data release in 2027
- **Sterile neutrino result** challenges anomalies, complementary to short baseline experiments
[Acharya et al., Nature 648 (2025) 8092, 70-75]
- **keV-sterile neutrino search** in preparation, **beamline upgrade**, TRISTAN detector
[Acharya et al., arXiv:2603.23256]
- **KATRIN++**, technology development towards future direct neutrino mass experiment

Collaboration

- **~150 members**
- **~20 institutions** from 7 countries

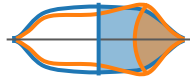
50th KATRIN collaboration meeting
in Heidelberg (April 2026)



Backup

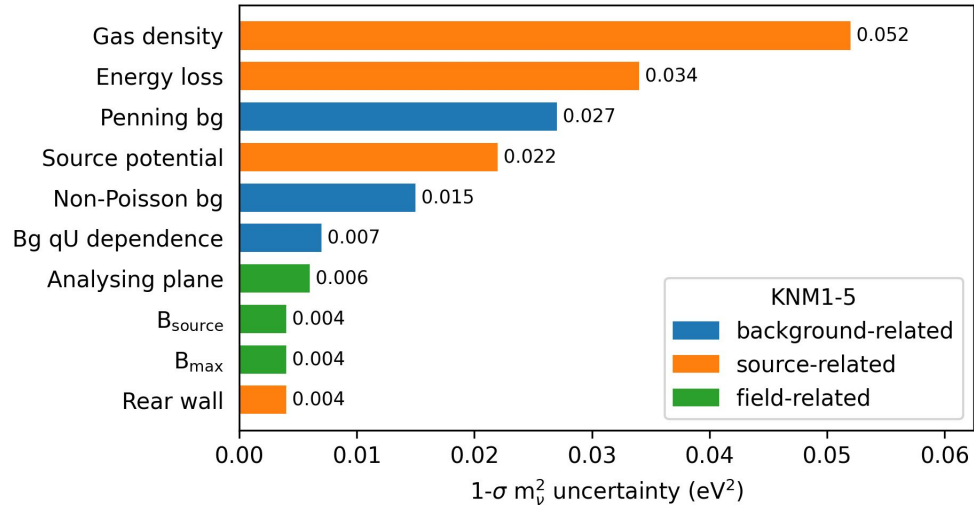
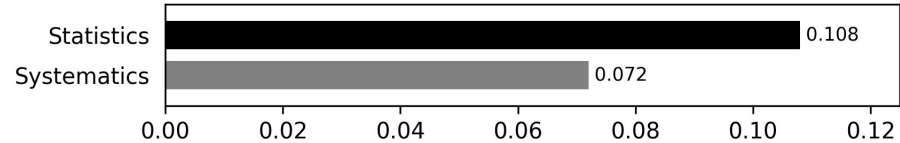
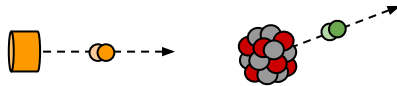
Uncertainties

- **6-fold increase in statistics**, 2-fold reduction of background



- **3-fold reduction of systematic uncertainties**, source effects leading

- **Statistical uncertainty dominates**, improved calibration precision in later campaigns



Neutrino mass limit

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

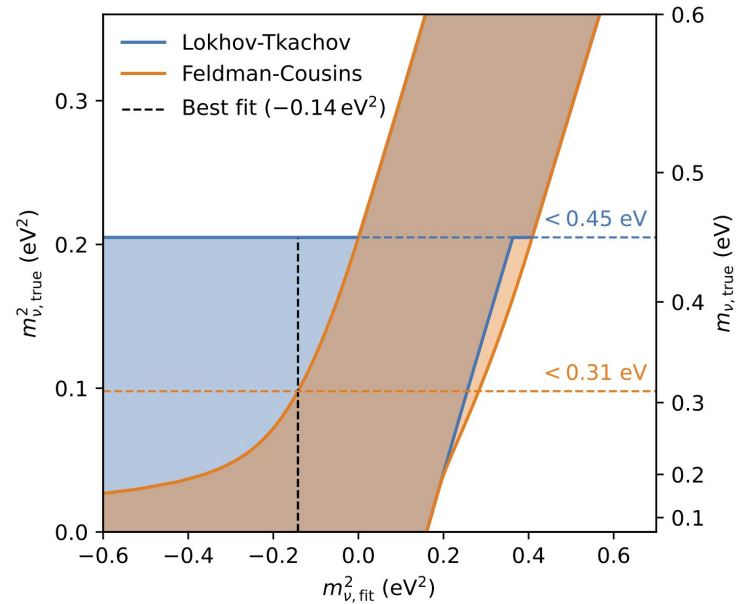
- World-best **direct neutrino mass constraint**

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

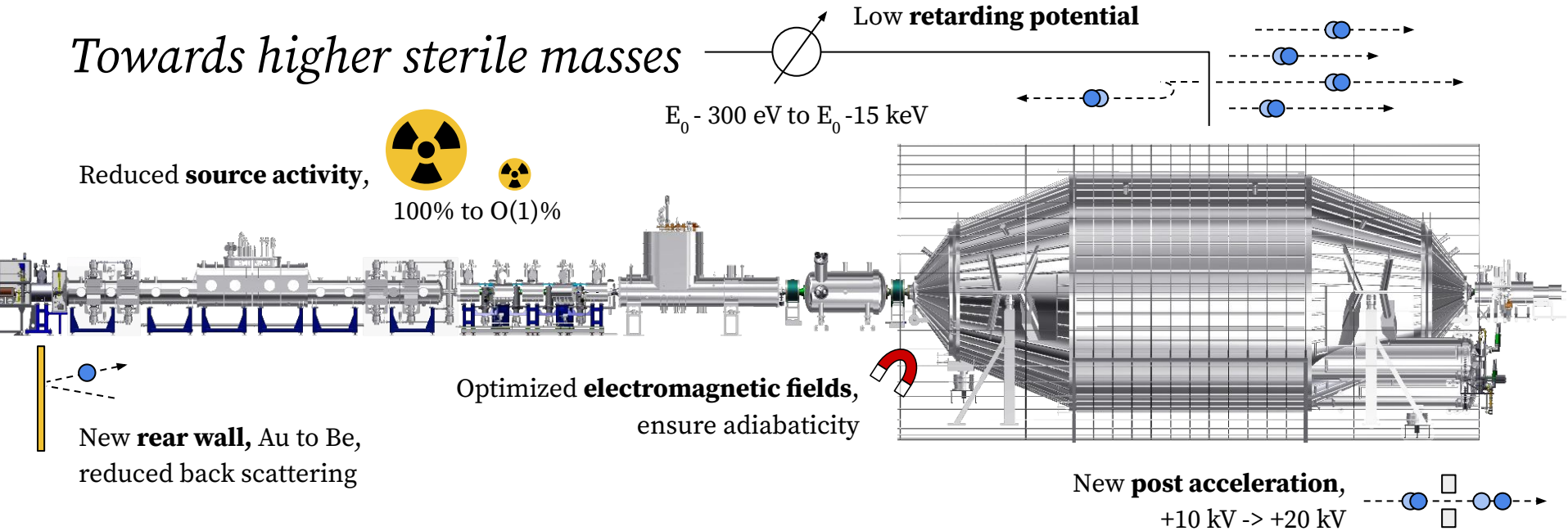
using **Likhov-Tkachov** confidence interval construction

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

- Feldman-Cousins construction, $m_\beta < 0.31 \text{ eV (90\% CL)}$, benefits from negative best-fit



Towards higher sterile masses



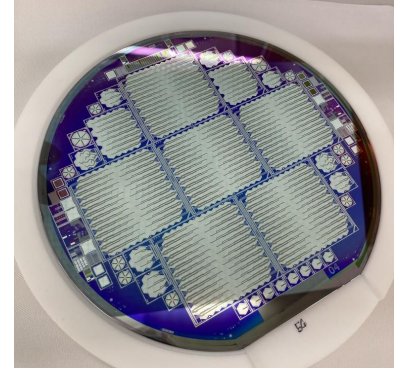
- **KATRIN neutrino mass measurement limited to endpoint region**
(but competitive search with commissioning data up to 1 keV)
[Aker et al., EPJ C 83 (2023) 8, 763]
- **Beamline upgrade for deep spectrum scans, keV-scale sterile neutrino search**
[Mertens et al., J.Phys.G 46 (2019) 6, 065203]

TRISTAN detector (next slide)
and **high-performance DAQ**

[Gavin et al., arXiv:2602.04976]

TRISTAN detector

SDD wafer at Max Planck
semiconductor laboratory



- Novel detector for **high-rate high-resolution beta spectroscopy**
- **Silicon drift detector** (SDD) array, small anode capacitance, good energy resolution
- 3x3 tower of detector modules with 166 pixels each, **1494 pixels**, optimized for **10^8 cps**
- Extensive characterization, e.g. in KATRIN monitor spectrometer

[Siegmann et al., J.Phys.G 51 (2024) 8, 085202]

