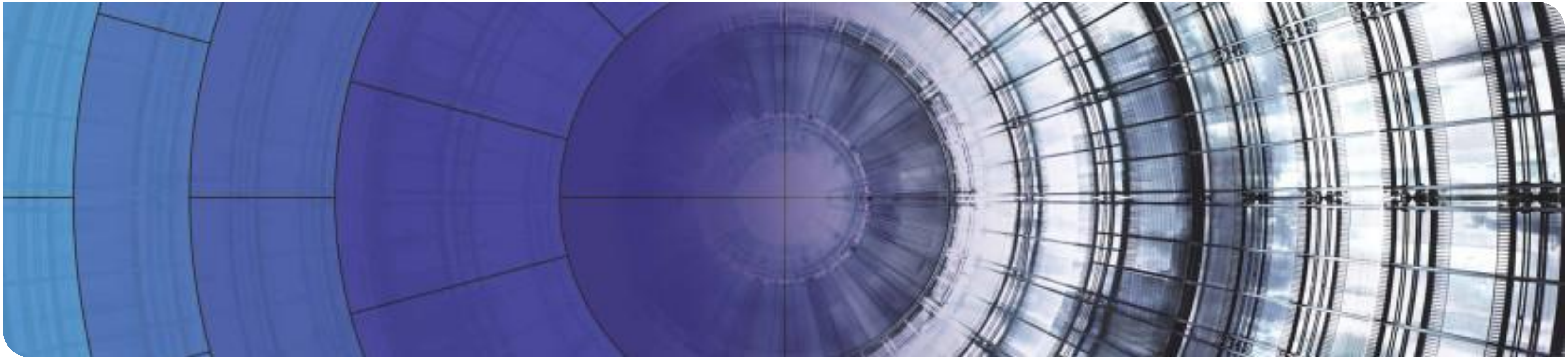
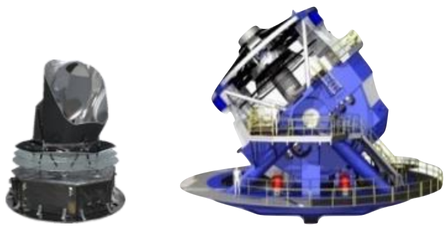
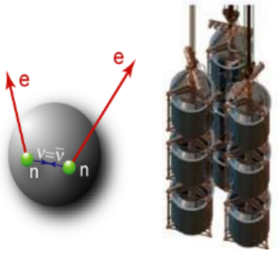
Probing the Neutrino Mass Scale with the KATRIN Experiment

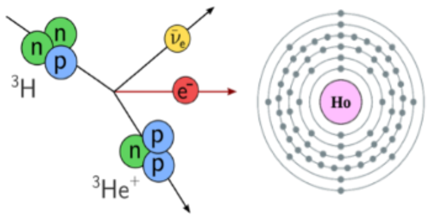
Alexander Marsteller for the KATRIN Collaboration



Access to the absolute neutrino mass scale







	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\lvert \sum_i U_{ei}^2 \, m_i \right\rvert^2$	$m_\beta^2 = \sum_i \lvert U_{ei} \rvert^2 \, m_i^2$
Present upper limit	0.072 eV*	0.18 eV*	0.8 eV
Model dependence	Multi-parameter cosmological model	- Majorana ν - nuclear matrix elements, g_A	**Direct,** only kinematics; no cancellations in incoherent sum

ADAME, A. G., et al. Desi Collaboration arXiv preprint arXiv:2404.03002, 2024.
M. Agostini et al., Phys. Rev. Lett. 125, 252502
S. Abe et al., Phys. Rev. Lett. 130, 051801
M. Aker et al., Nat. Phys. 18, 160–166 (2022)

Complementarity and need for direct mass measurements

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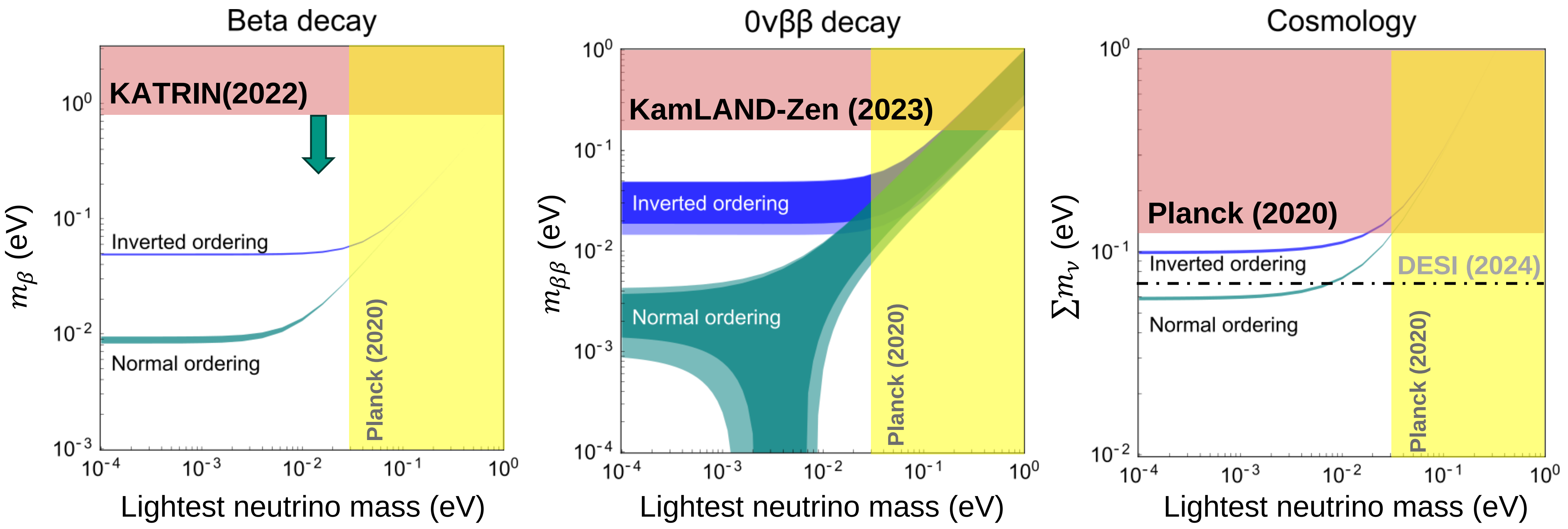
Standard neutrino picture: ***observations have to be found in colored regions***



NuFit, J. High Energ. Phys. 2020, 178 (2020).

Inspired by IUPAP neutrino panel white paper, www.iupapneutrinopanel.org

Tie-breaker needed to exclude exotic models in neutrino nature or cosmology

KATRIN, Nat. Phys. ***18*** *(2022) 160*

KamLAND-Zen, PRL **130,** 051801 (2023)

Planck, Astron. Astrophys. **641** (2020) A6
DESI, 2406.14554 (2024)

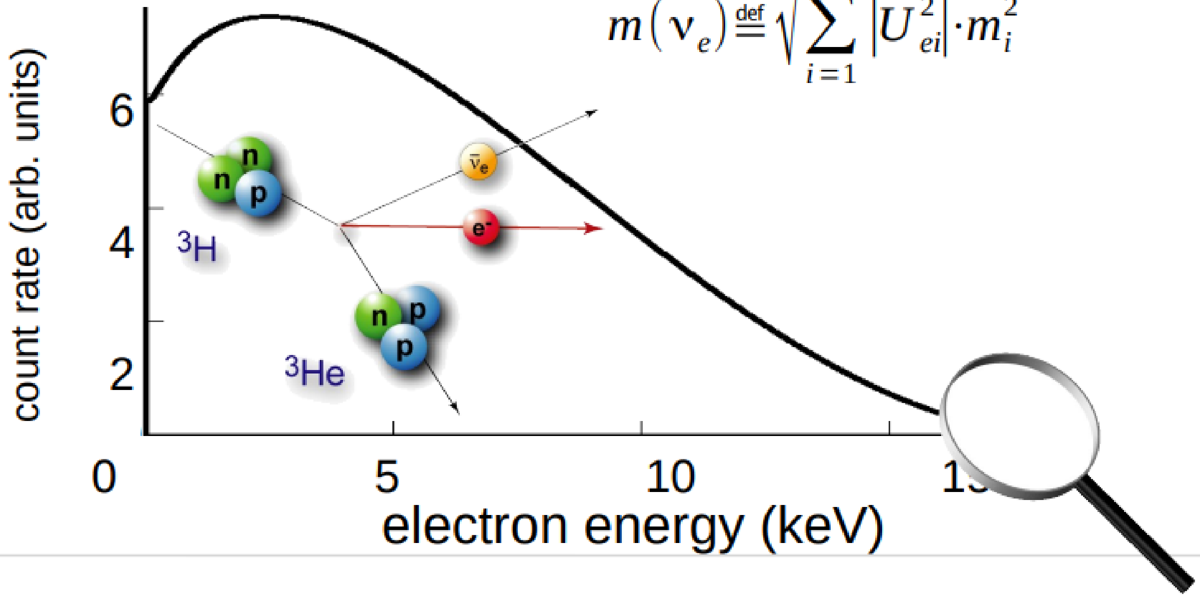
Tritium β-decay

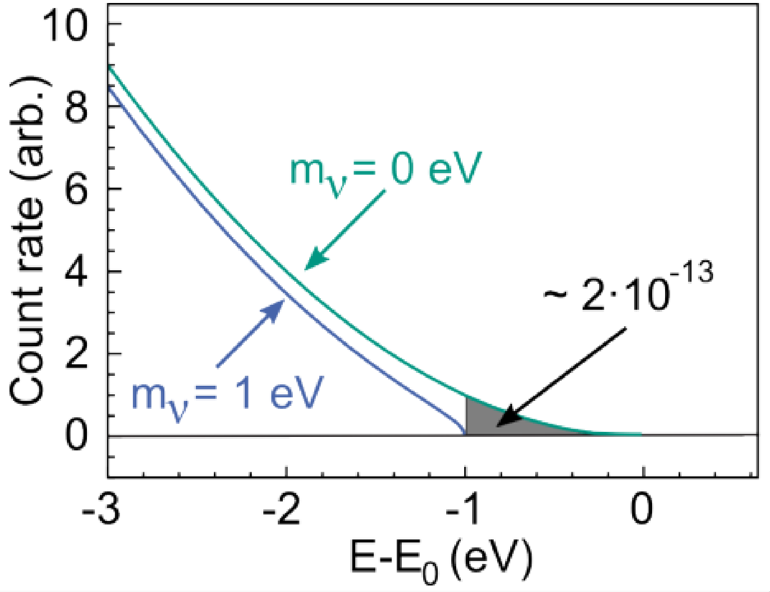
- Continuous β-decay spectrum described by Fermi‘s Golden Rule

- Simple structure allows accurate theoretical modelling

$$\frac{d\Gamma}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} |U_{ei}^2| \cdot \sqrt{(E_0 - E)^2 - m_{\nu_i}^2} \cdot F(E, Z) \cdot \theta(E_0 - E - m_{\nu_i}^2)$$

$$m(\nu_e) \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}^2| \cdot m_i^2}$$





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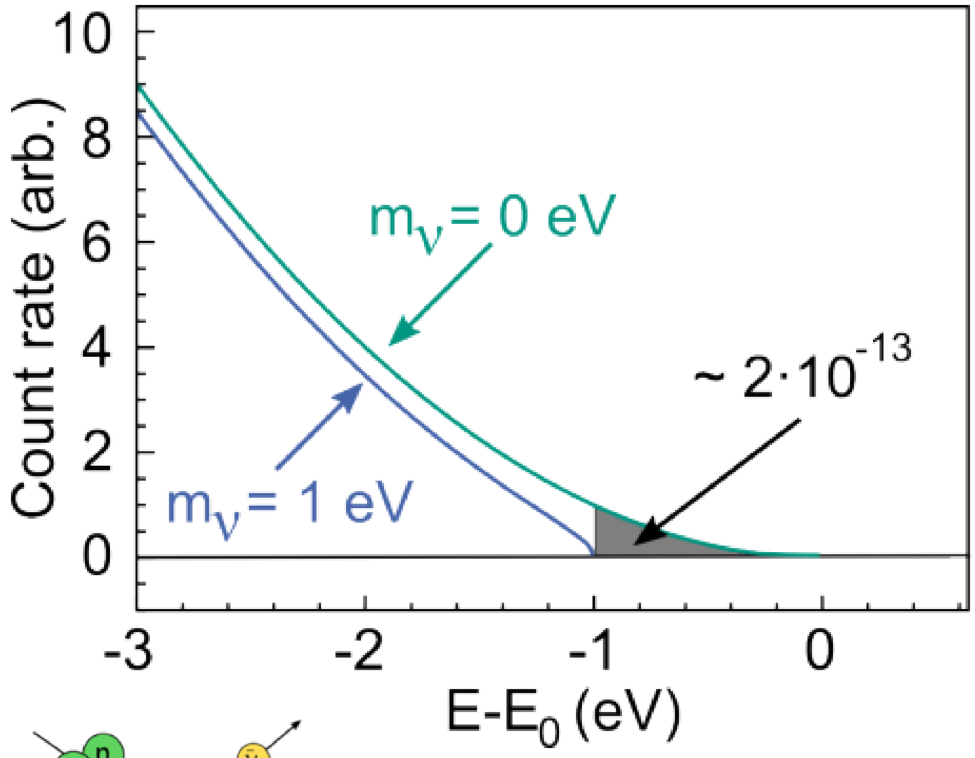
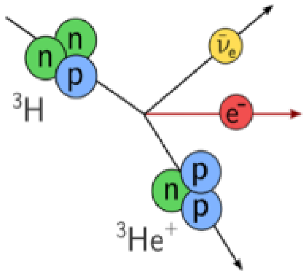
KATRIN requirements

- Low probability for decays to be in interesting energy region → small rate
  - Source with high luminosity
  - Low background
- Distortion is on the scale of the neutrino mass
  - Good energy resolution required
- Source not single atom in complete vacuum
  - Exact understanding of spectrum shape and all contributing effects





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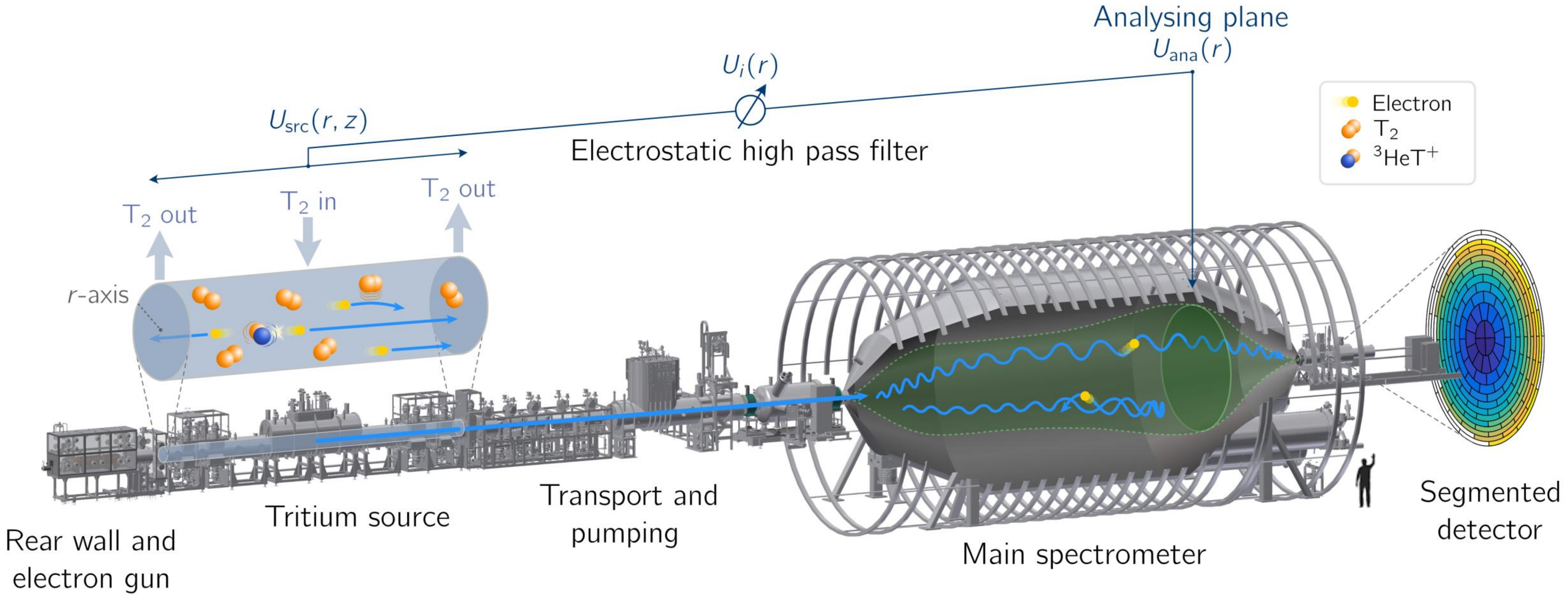
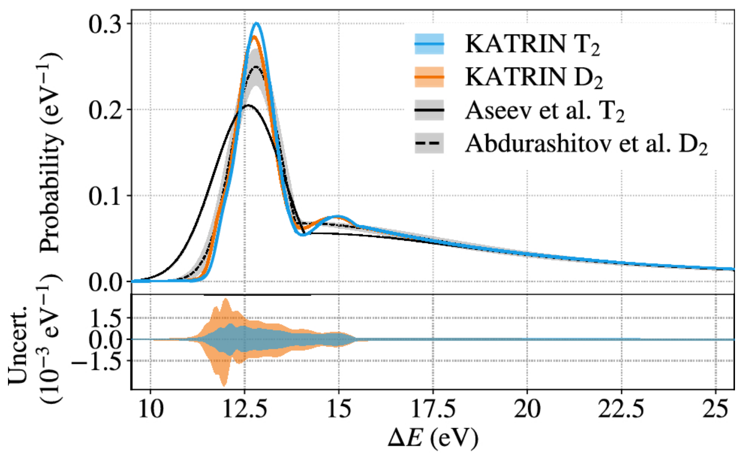
The KATRIN experiment

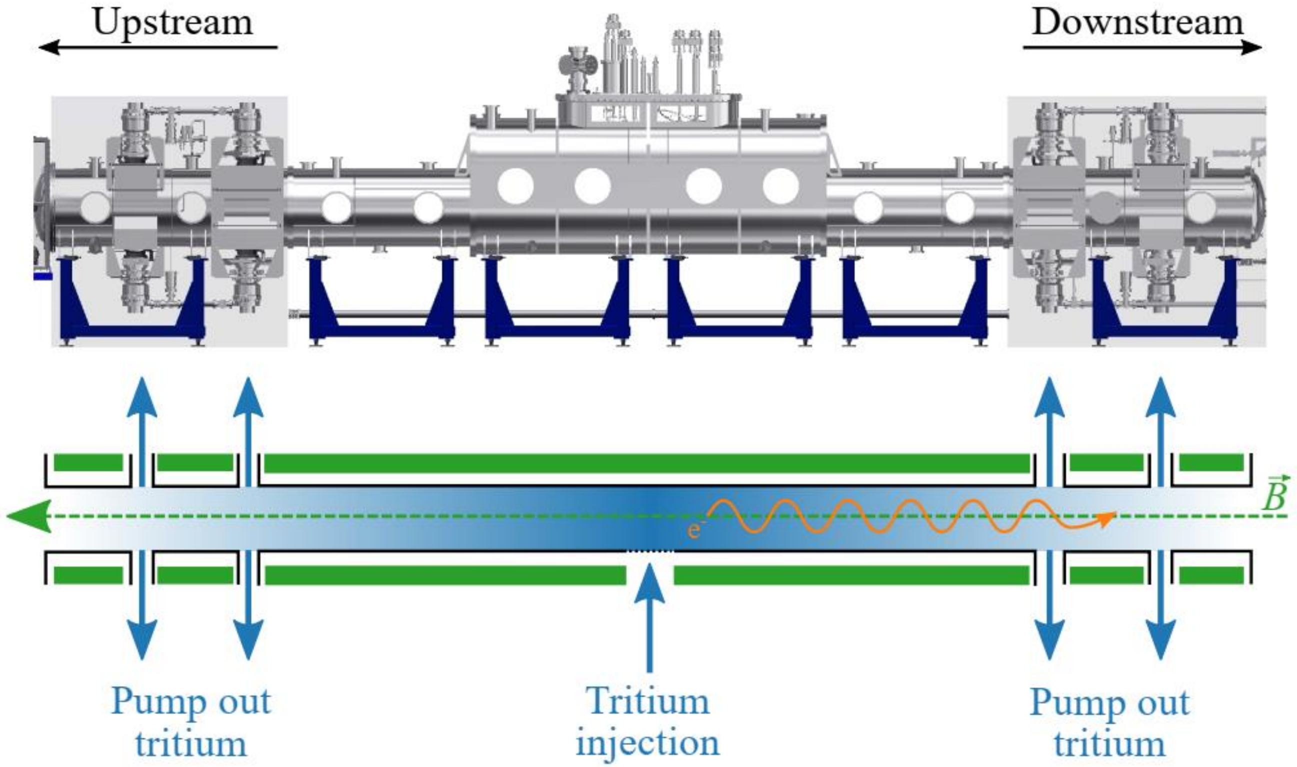


Tritium Source

- Stabilzed tritium gas column
  - Temperature (80 ± 0.01) K
  - Throughput $< 0.1\%$
- Magnetic guiding of decay electrons with nominal field strength of 2.5 T
- Activity of $\approx 10^{11}$ Bq
  - Optimum with regards to opacity

Aker, M. et al. Eur. Phys. J. C 81, 579 (2021).





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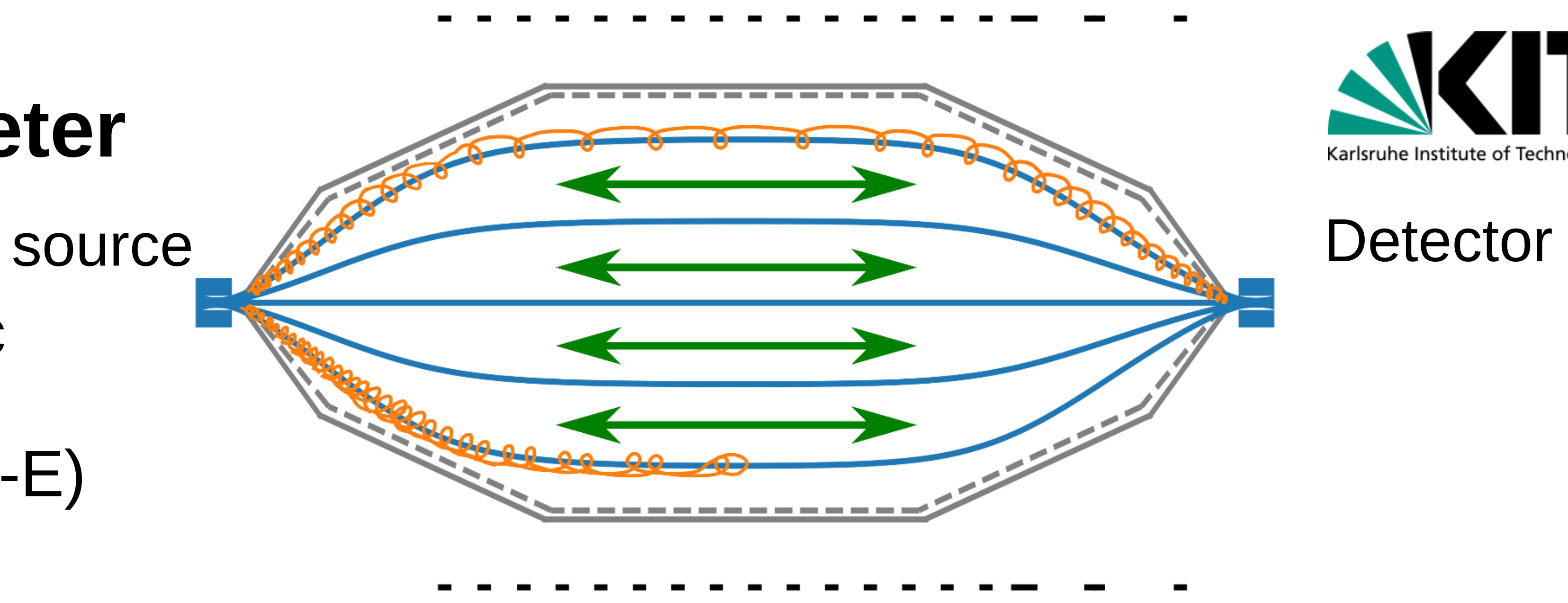
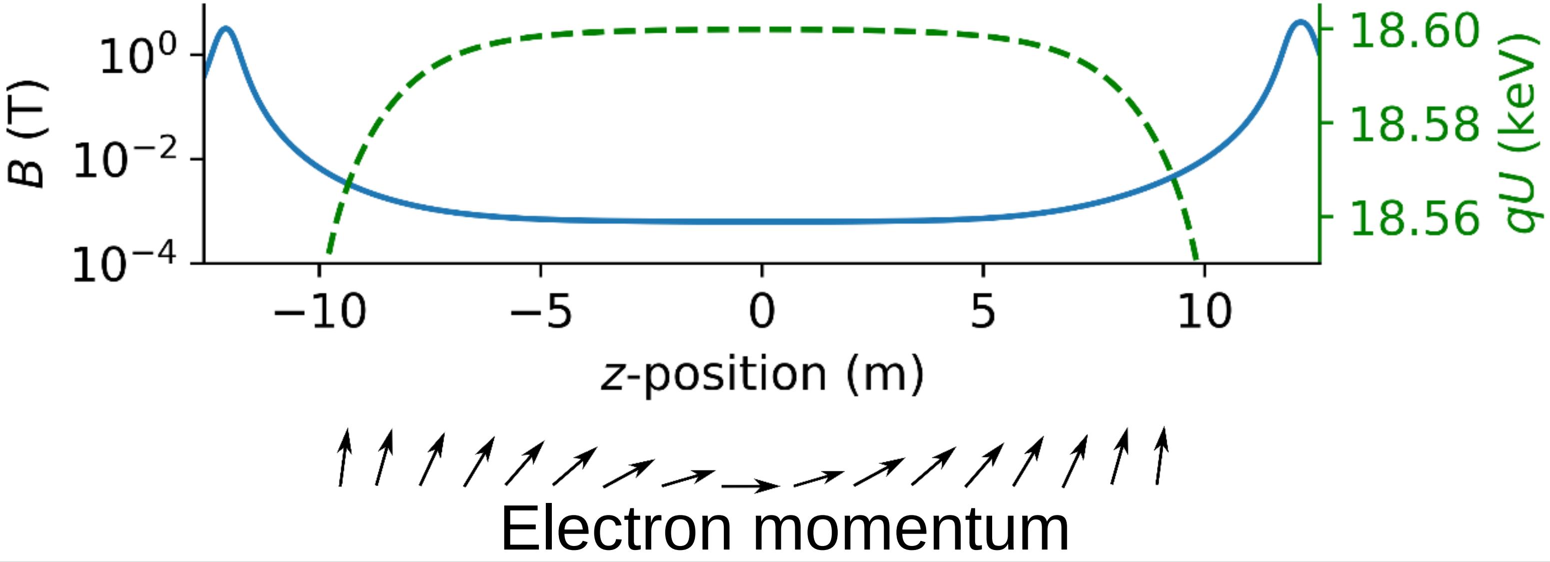
Main Spectrometer

- Magnetic Adiabatic Collimation with Electrostatic (MAC-E) filter
- Energy resolution proportional to magnetic field ratio
- Large acceptance angle





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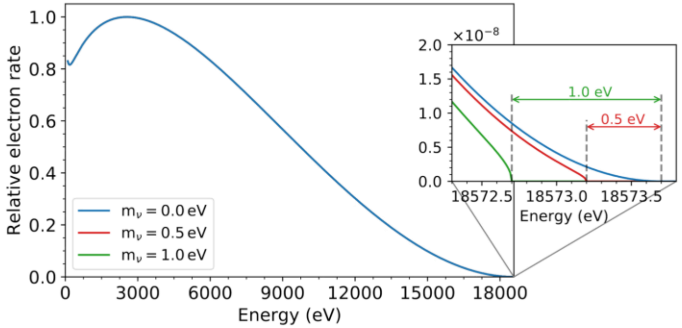
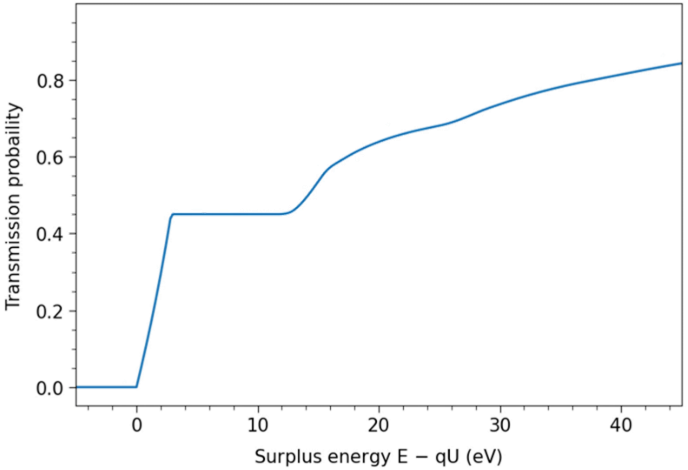
The Experimental Spectrum

- Differential β-spectrum



- Response function



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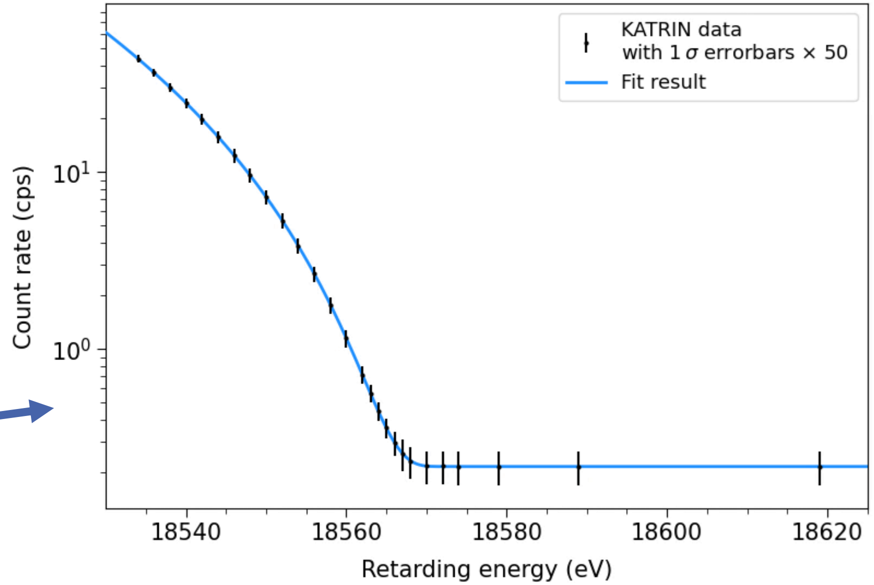

- Observed integral spectrum

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

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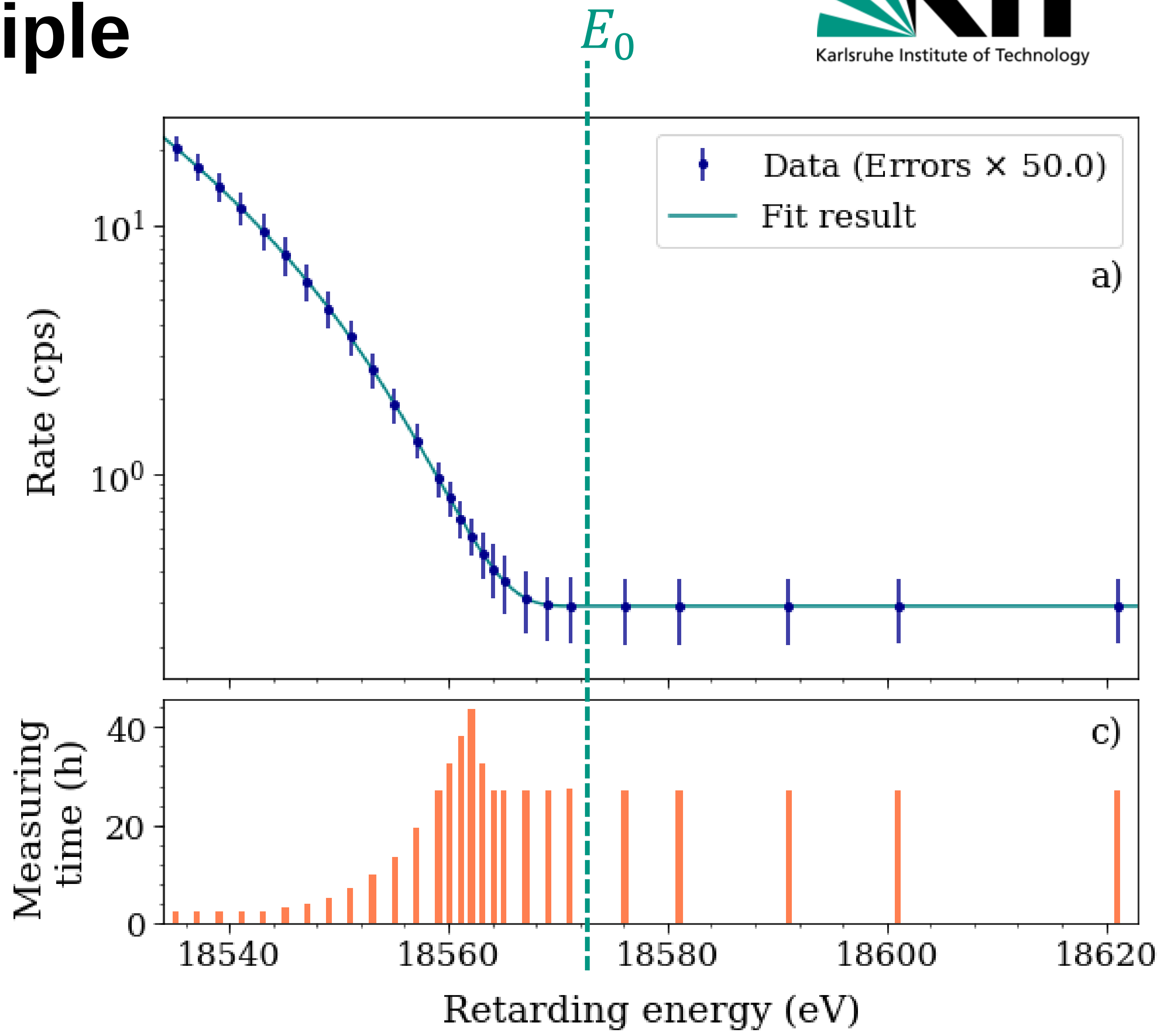
KATRIN measurement principle

- Scan through spectrum integrated by highpass MAC-E filter:
  - ~30 steps with varying duration
  - From $[E_0 - 300\ \text{eV}, E_0 + 135\ \text{eV}]$
  - ~3 h measurement time per scan
  - O(500) scans per year



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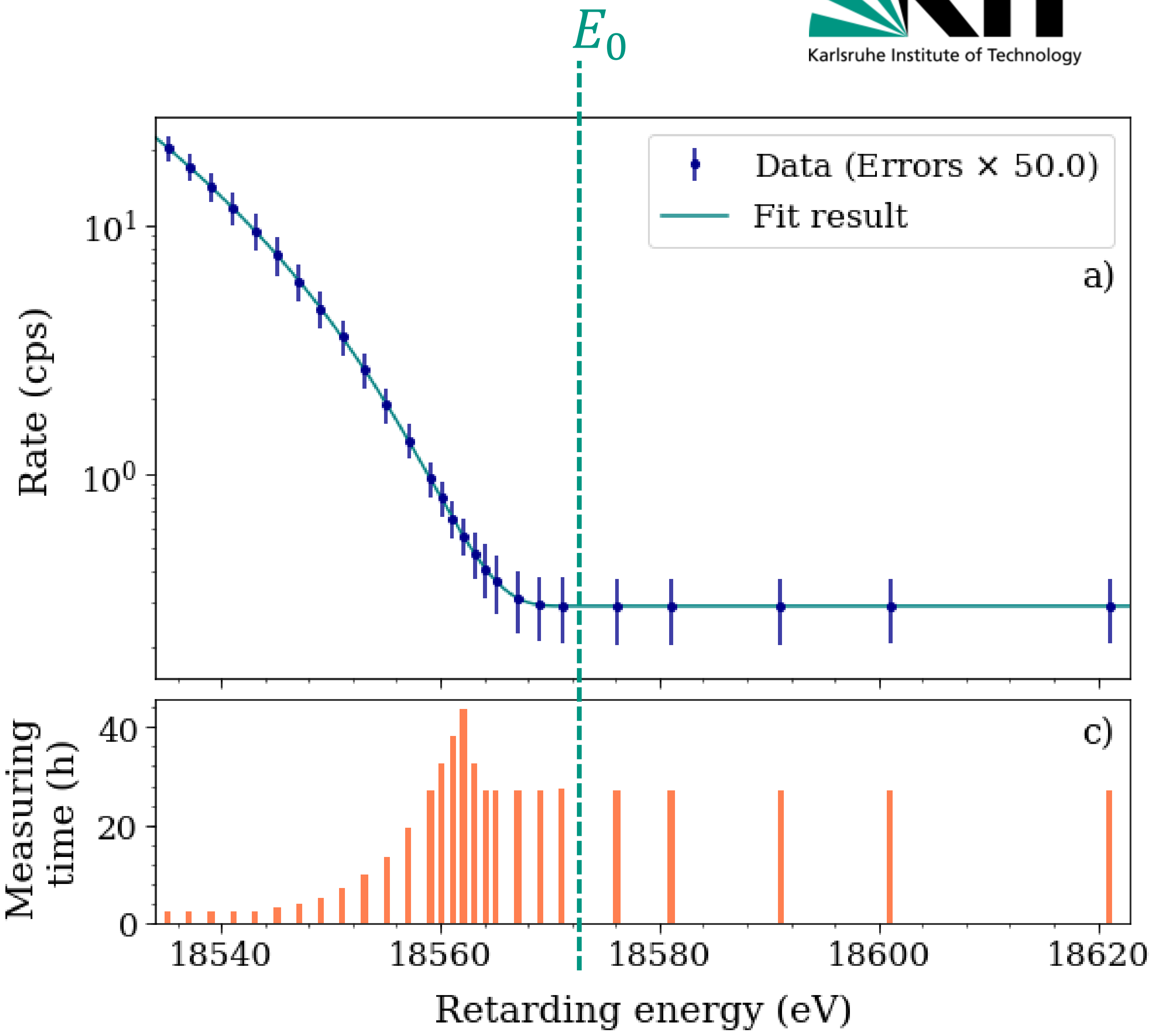
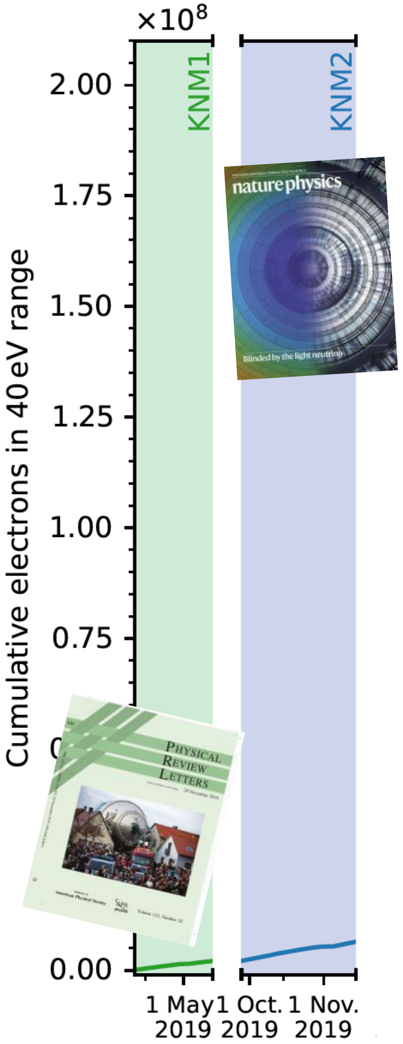
KATRIN Analysis Strategy

- Blinding procedure involving multiple steps
  - Establish analysis strategy on Asimov twins
  - First analysis of the data using model blinding
- Two independent analysis methods
  - KaFit (fast direct model evaluation)
  - Netrium (neural network)

EPJ C **82**, 439 (2022)



Overview of data taking



Previous neutrino mass results

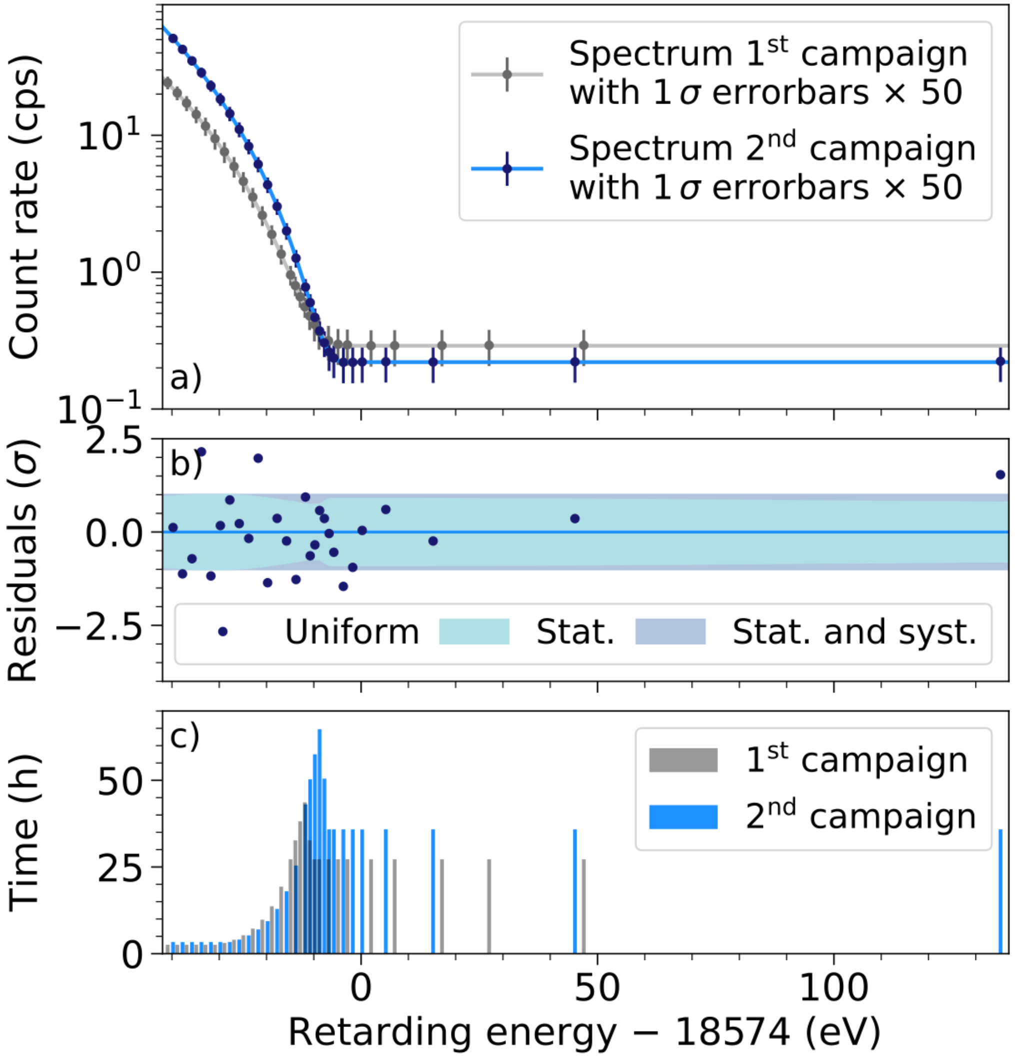
- First measurement campaign (KNM1)
  - Best fit: $m_\nu^2 = (-1.0^{+0.9}_{-1.1})\ \mathrm{eV}^2$
  - Upper limit: $m_\nu < 1.1\ eV\ (90\%\ C.L.)$

M. Aker et al., Phys. Rev. Lett. **123**, 221802 (2019)

- Second measurement campaign (KNM2)
  - Best fit: $m_\nu^2 = (0.26^{+0.34}_{-0.34})\ eV\ (90\%\ C.L.)$
  - Upper limit: $m_\nu < 0.9\ eV\ (90\%\ C.L.)$

- Combined result: $m_\nu < 0.8\ eV\ (90\%\ C.L.)$

M. Aker et al., *Nat. Phys.* **18**, 160–166 (2022)



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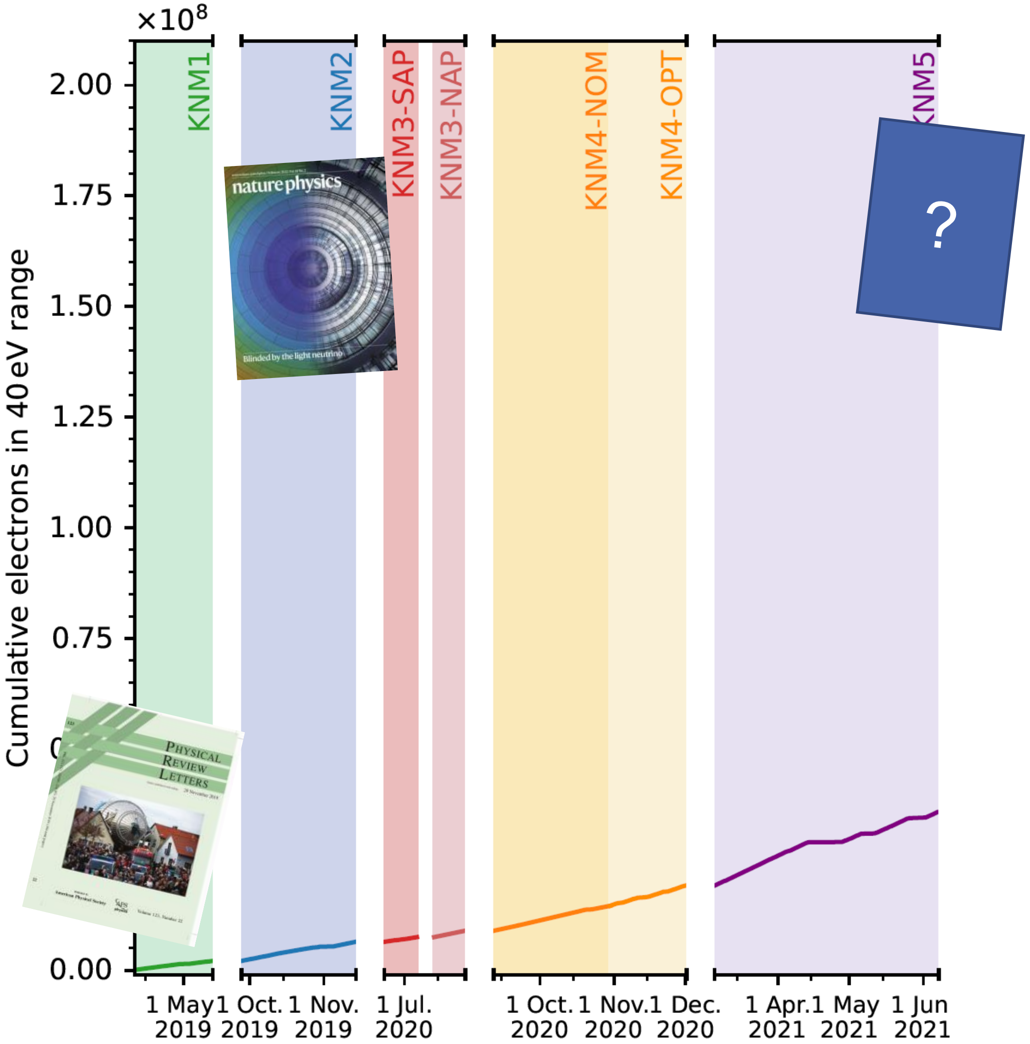
Newest analysis release



- KNM1: $m_\nu < 1.1\ eV\ (90\%\ C.L.)$
  M. Aker et al., Phys. Rev. Lett. **123**, 221802 (2019)
- KNM1-2: $m_\nu < 0.8\ eV\ (90\%\ C.L.)$
  M. Aker et al., *Nat. Phys.* **18**, 160–166 (2022)
- KNM1-5 Key Points:
  - 259 measurement days
  - 36 million electrons in 40 eV analysis window (6 times KNM1-2)
    $[E_0 - 40\ \text{eV}, E_0 + 135\ \text{eV}]$
  - Rigorous reevaluation of systematics
  - Expected sensitivity
    $m_\nu < 0.5\ eV\ (90\%\ C.L.)$

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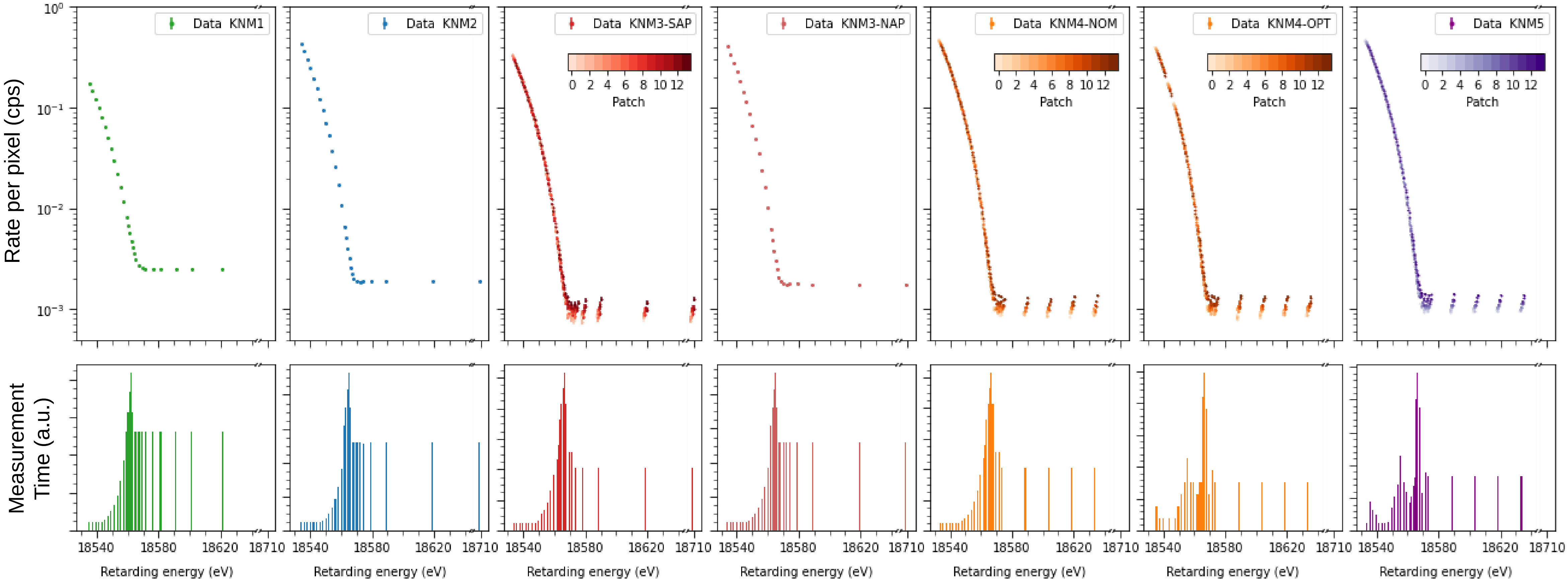
Spectra KNM1-5



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

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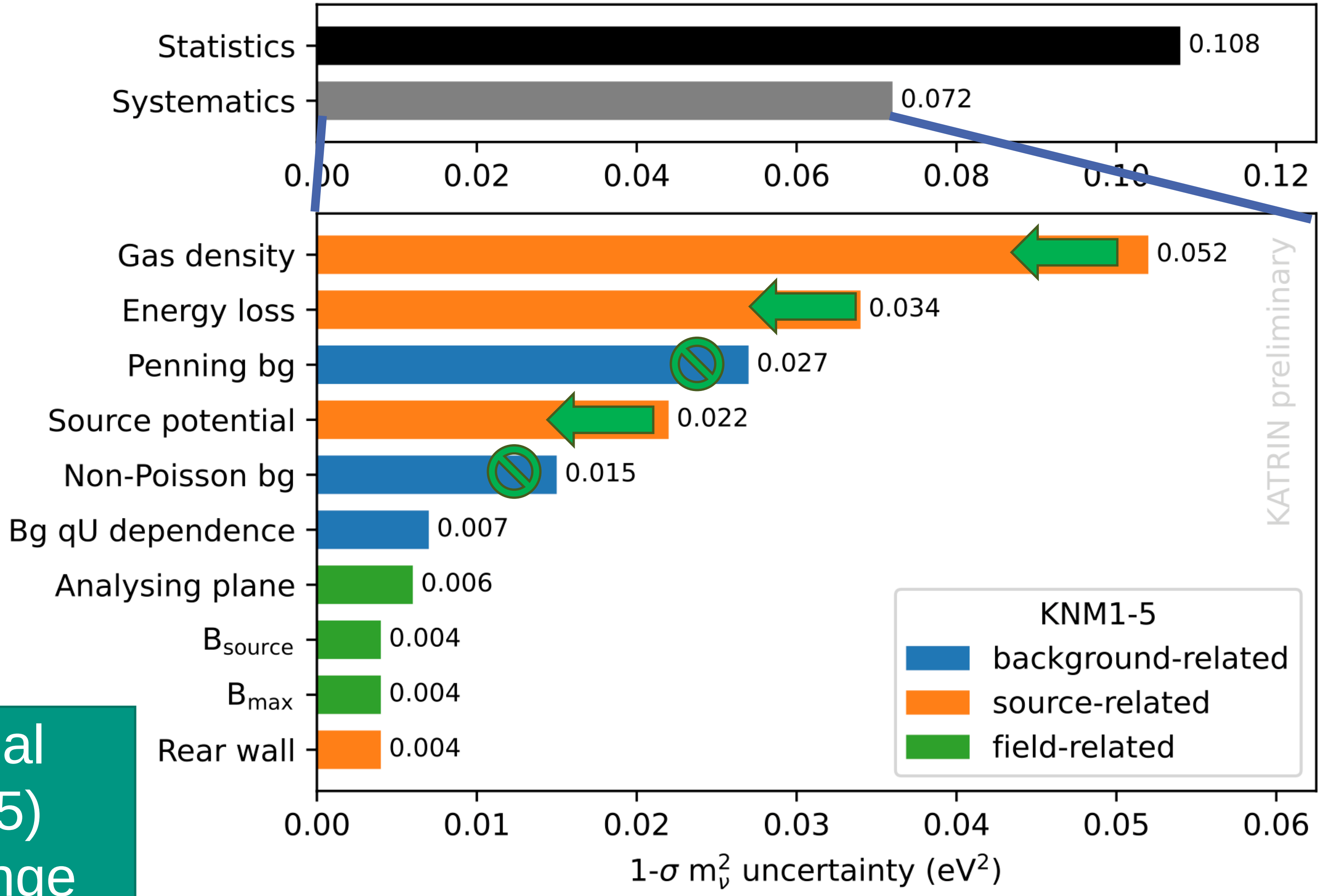
Uncertainty breakdown

- Uncertainty dominated by statistical uncertainty
- Thorough reevaluation of systematic uncertainties
- Efforts to minimize systematic uncertainties continue

Individual systematics in final KATRIN analysis (post 2025) expected to be <0.01 eV² range



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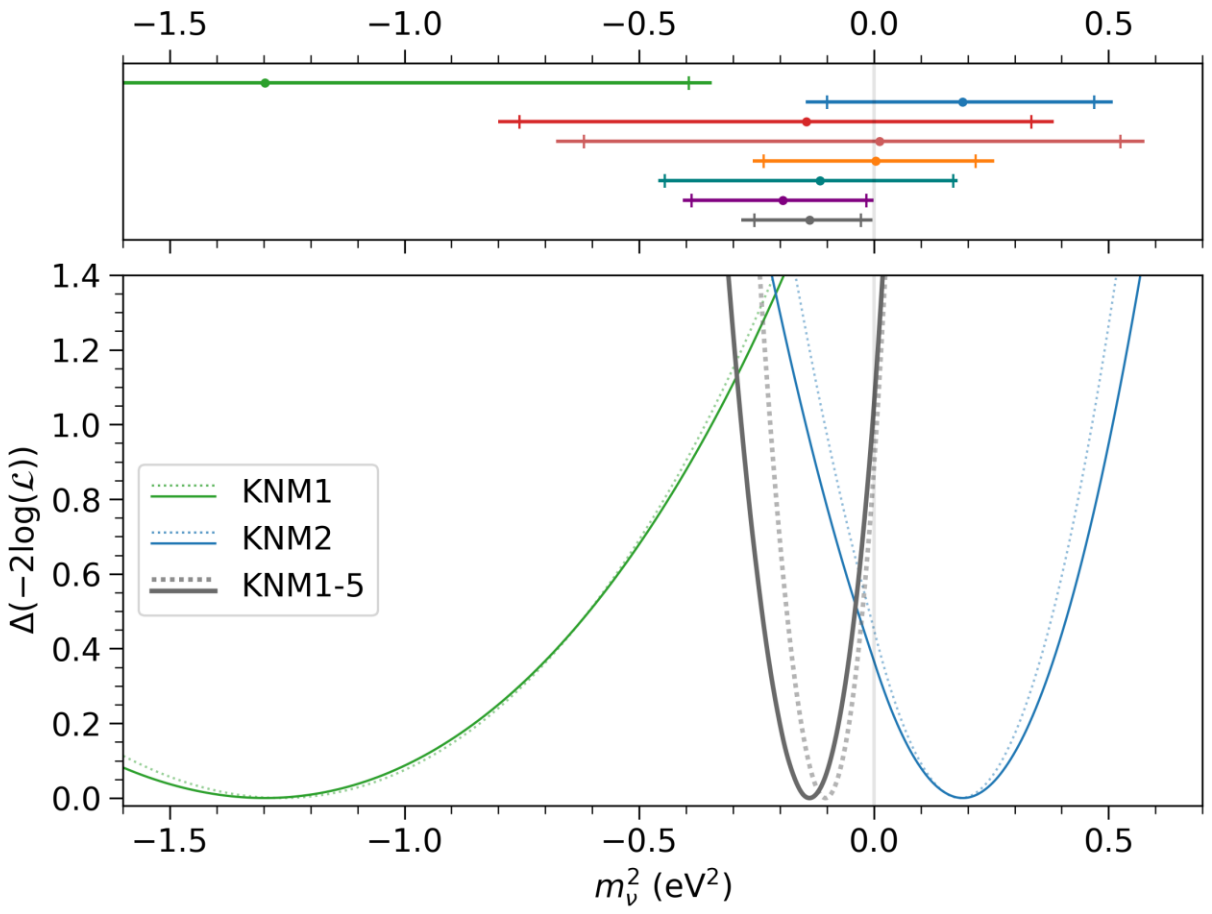
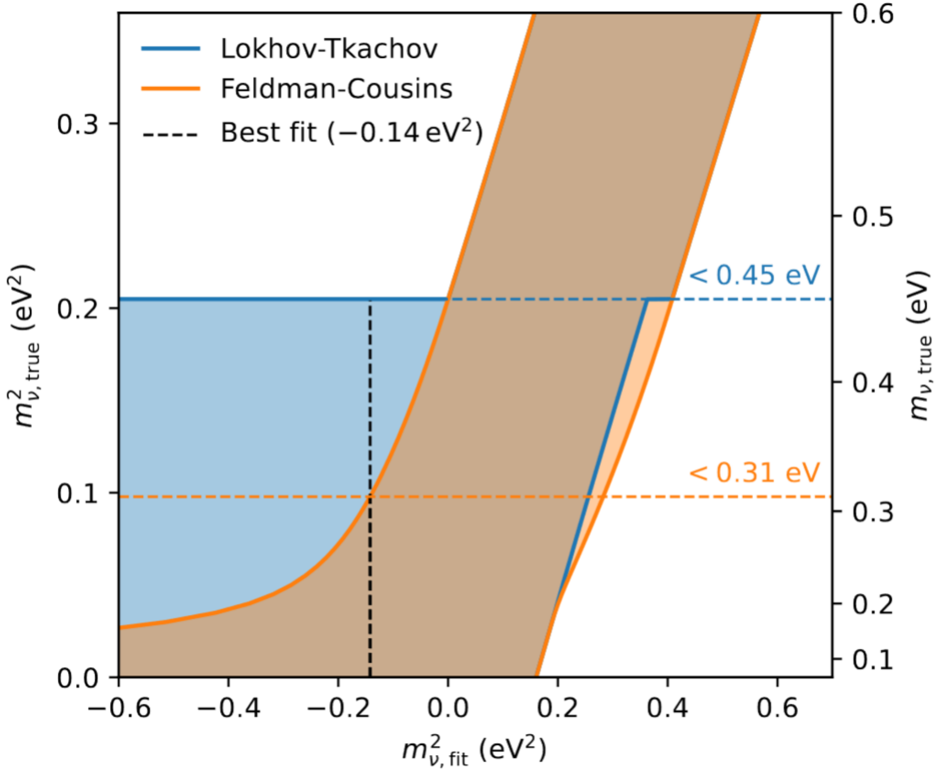
New best fit



- Best fit: $m_\nu^2 = \left(-0.14^{+0.13}_{-0.15}\right)\,\mathrm{eV}^2$
- Compatible with 0 within ~1σ
- Parallel analysis with two different codes in good agreement
- Negative mass values allowed to obtain continuous likelihood in case of statistical fluctuations

Limit Setting



- Upper limit by Lokhov-Tkachov construction:

$$m_\nu < 0.45\; eV\; (90\%\; C.L.)$$

  - Returns sensitivity for negative m_ν^2 best fits
  - Statistical underfluctuations do not produce stricter limit
  - More conservative approach than Feldman-Cousins

- Upper limit by Feldman-Cousins construction:

$$m_\nu < 0.31\; eV\; (90\%\; C.L.)$$

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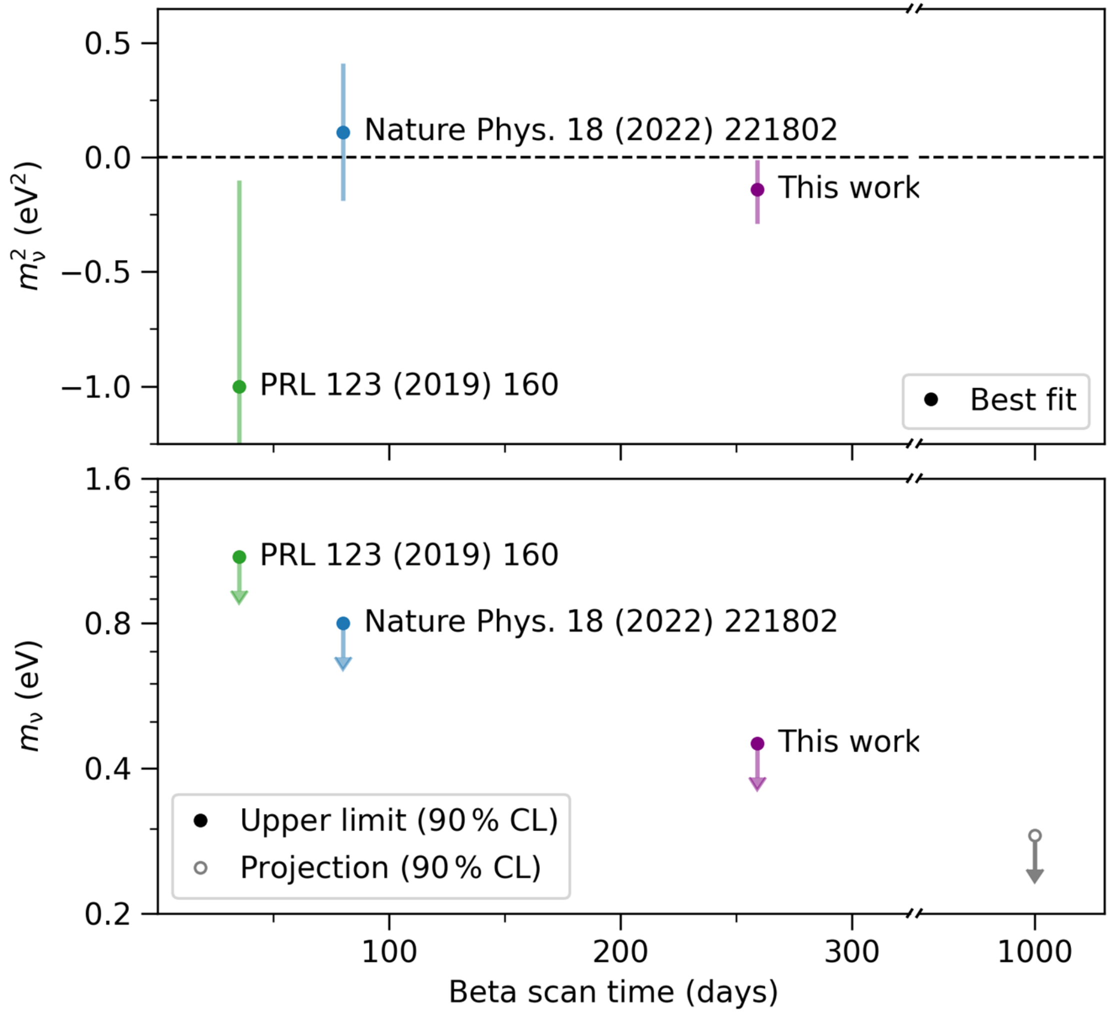
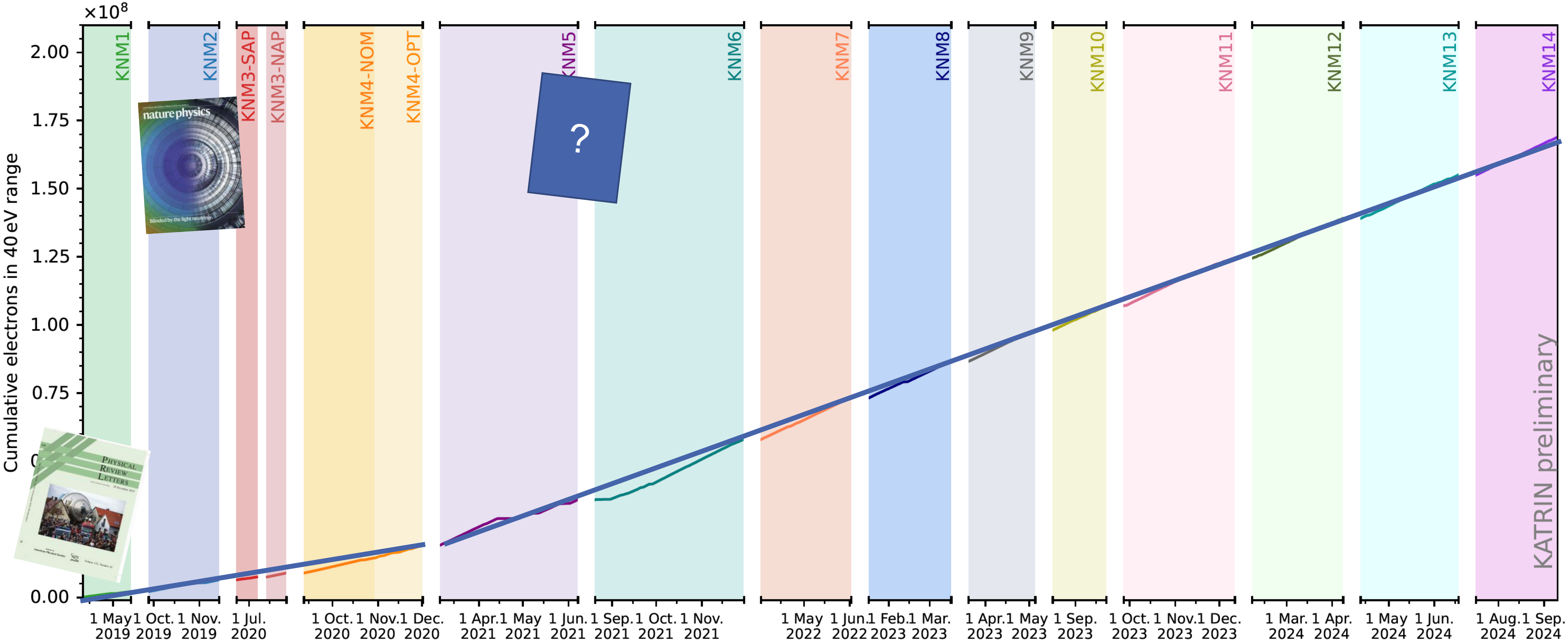
Newest best fit and upper limit



- Best fit: $m_\nu^2 = \left(-0.14^{+0.13}_{-0.15}\right)\ \mathrm{eV}^2$
- Upper limit: $m_\nu < 0.45\ eV\ (90\%\ C.L.)$
  https://arxiv.org/abs/2406.13516
- Factor 6 times the statistics
- Rigorous reevaluation of systematics

Improvement of direct neutrino mass bound by factor 2

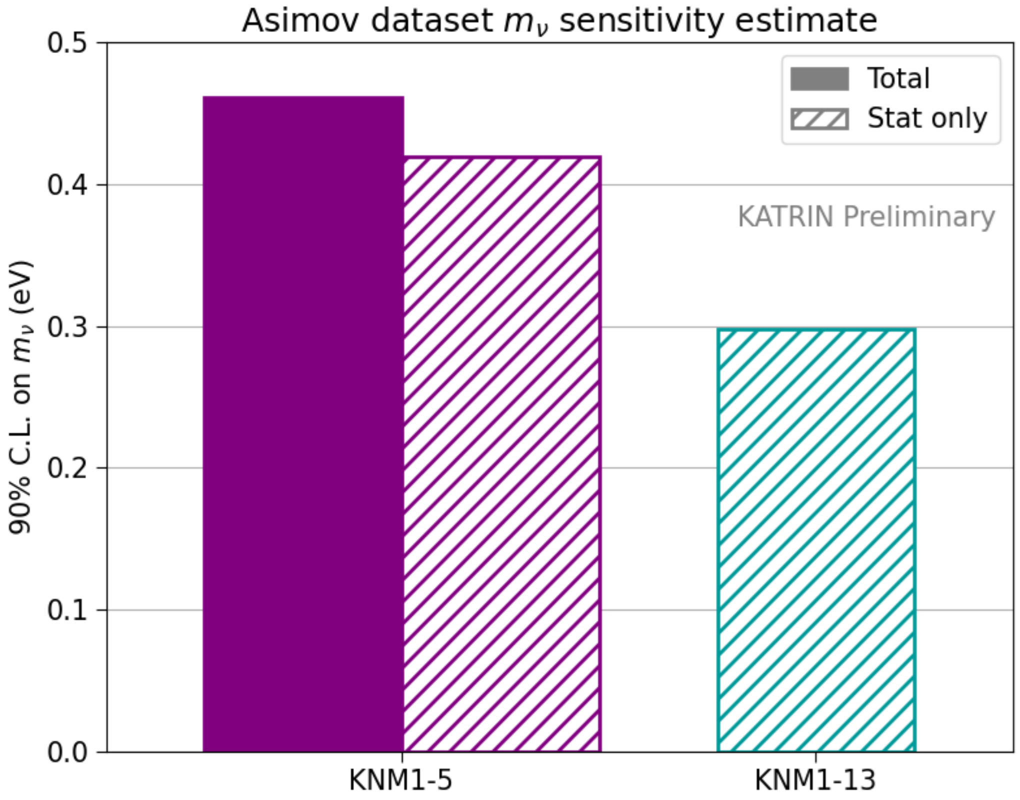
Overview of data taking



Statistical uncertainty outlook

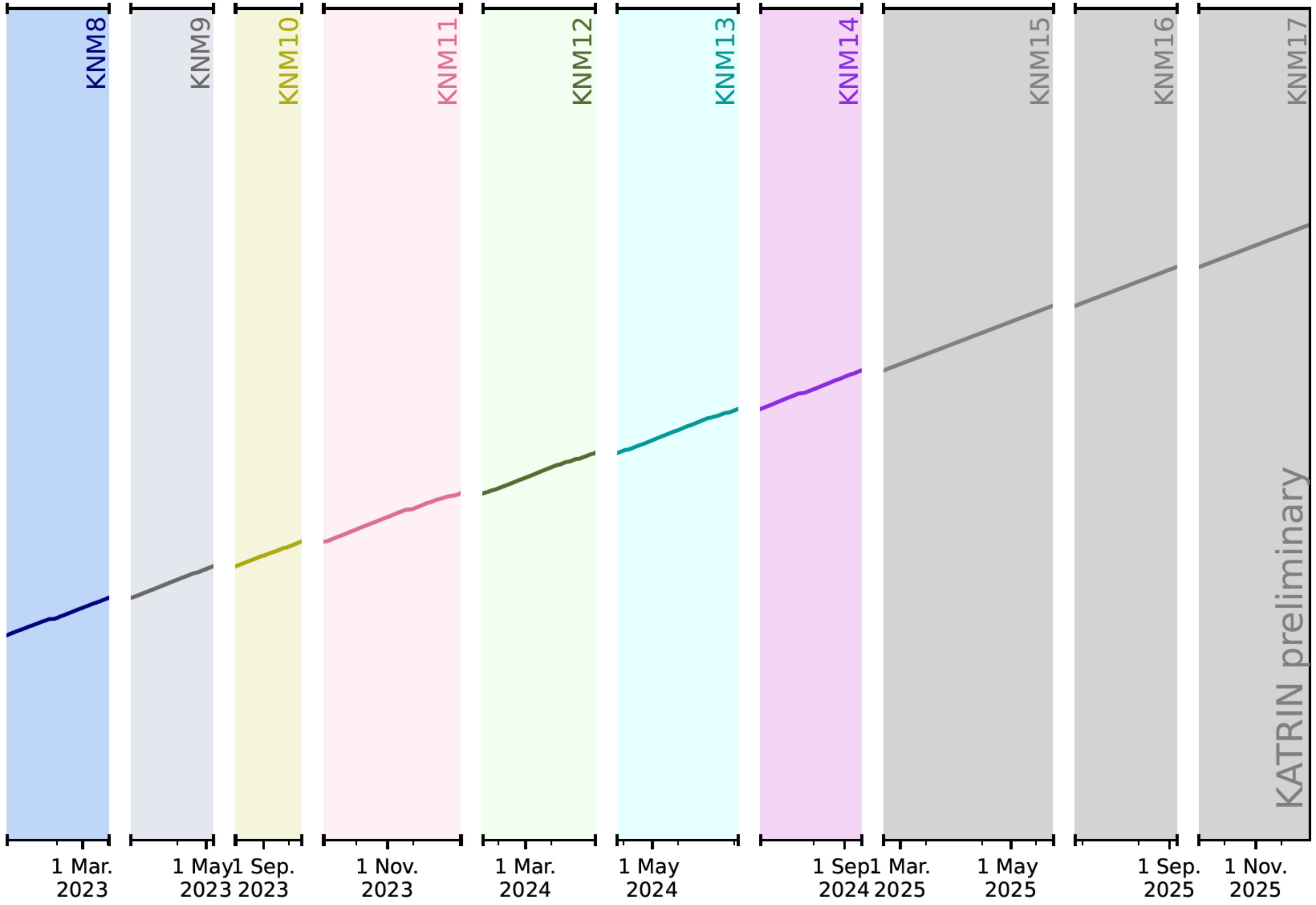
- Collected data until summer 2024 improves statistical sensitivity to 0.3 eV

- Computational challenge grows
  - 6313 data points and 682 free fit parameters (KATRIN Final)
  - Additional analysis steps on Asimov data



Future projection of data taking

- >75% of entire KATRIN statistics on tape
- KATRIN projected to conclude neutrino mass data taking **end of 2025**
- KATRIN final sensitivity after 1000 measurement days expected to be below 0.3 eV



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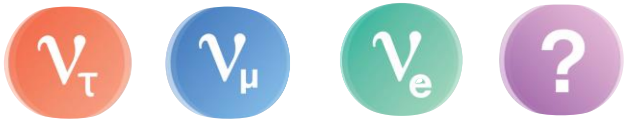
Thank you for your attention

Physics beyond the neutrino mass

β-spectroscopy at high precision & high stability

Upcoming publication!

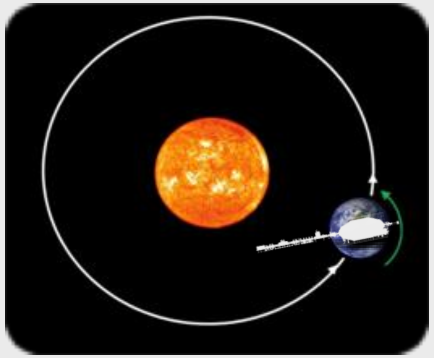
“Kink” search
for eV-scale sterile ν close to endpoint
→ PRL **126** (2021) 091803
& PRD **105** (2022) 072004



“Kink” search
for keV-scale sterile ν far from endpoint
→ EPJ C **83** (2023) 763

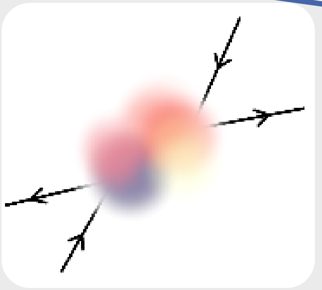
Line search for capture of local cosmic relic ν
→ PRL **129** (2022) 011806

Search for Lorentz violation through **sidereal modulation**
→ PRD **107** (2023) 082005



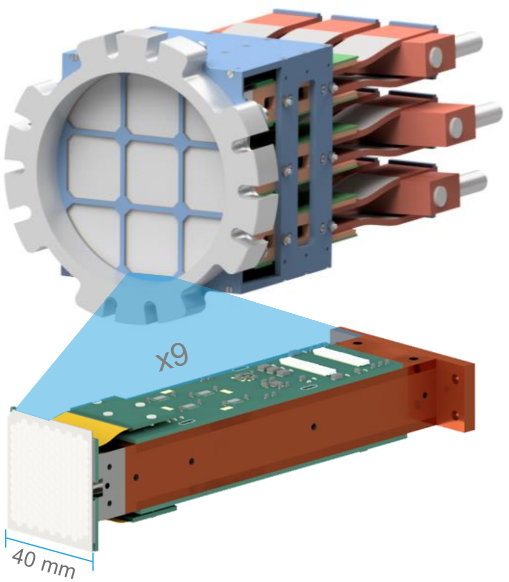
Upcoming publication!

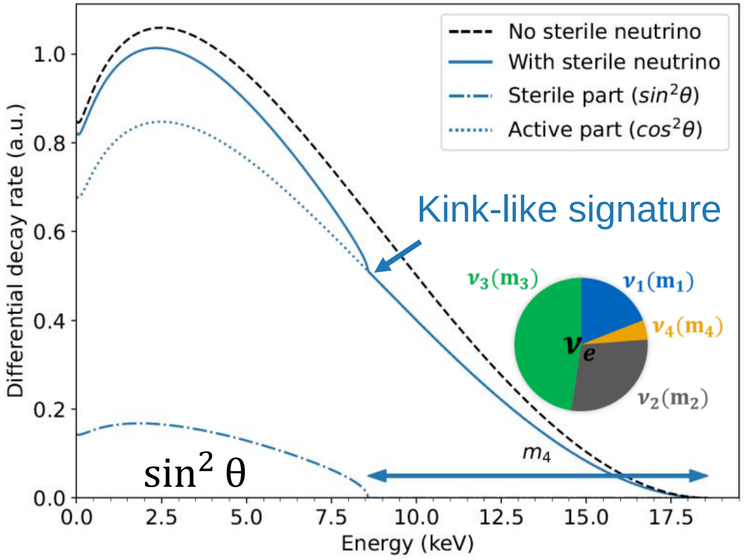
Search for **shape distortion** through exotic weak interactions
→ e.g. JHEP **01** (2019) 206



KATRIN beyond KATRIN

- TRISTAN
  (TRItium Sterile Anti-Neutrino)
  - keV-scale sterile Neutrinos
  - Coming 2026





- KATRIN++
  - Next generation m_ν experiment
    - Atomic tritium source
    - Differential detectors
  - R&D Phase