First Sub-eV Neutrino Mass Limit from the KATRIN Experiment

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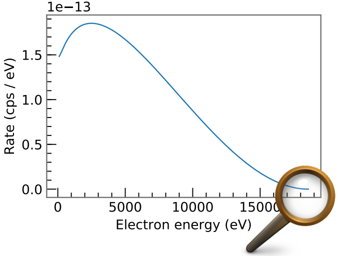
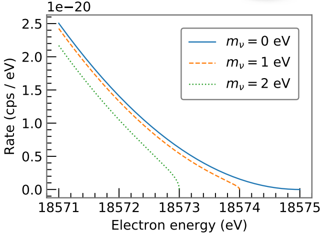
Direct neutrino mass measurement from β-decay

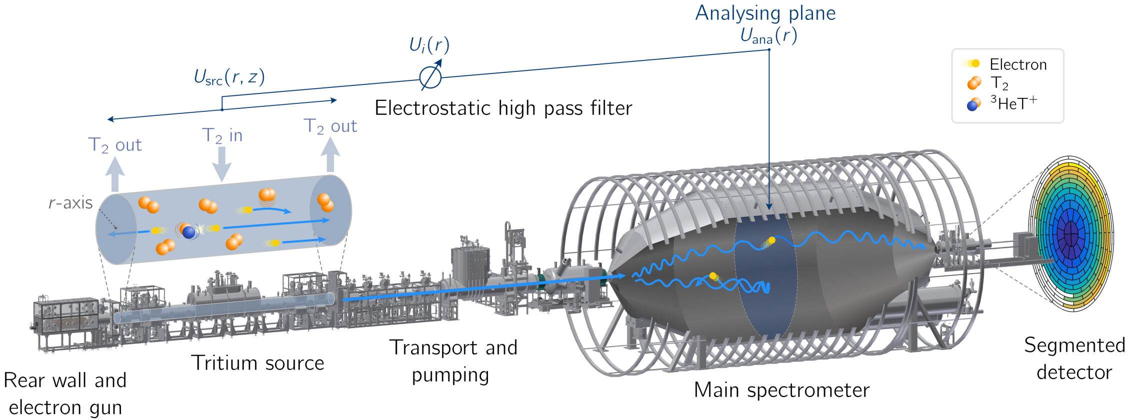
- β-decay: $X \to Y^+ + e^- + \bar{\nu}_e$
- Endpoint energy $E_0 = Q - E_{\text{rec}}$ split between e^- and $\bar{\nu}_e$
- Shape distortion of electron spectrum due to non-zero neutrino mass at highest energies
- Independent of cosmology and neutrino nature
- Experimental challenges:
  - Very small effect on the eV-scale
  - Low count rate in region of interest near the endpoint
- Current leading experiment: KATRIN
  $m_\nu = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 1.1\,\text{eV}\ (90\,\%\ \text{CL})$[1]





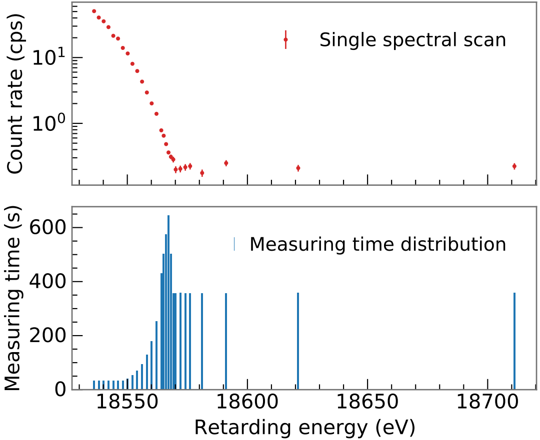
[1] M. Aker et al., Phys. Rev. Lett., Nov 2019

KATRIN experiment

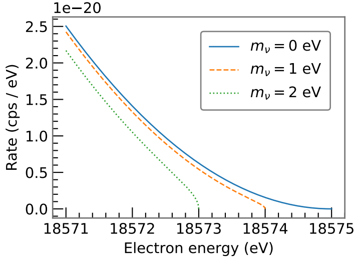


Measurement principle

- Main spectrometer acts as high-pass filter that rejects low-energy electrons
- Set different retarding energies in the main spectrometer
- Count all electrons that pass the filter
- Integral measurement of the tritium β-spectrum
- Repeat the ≈ 2 h long spectral scan hundreds of times



Model



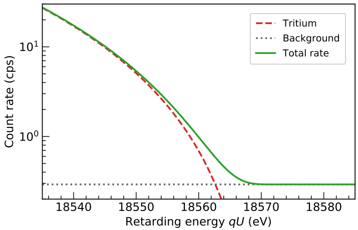
Differential β-spectrum

- Fermi theory of β-decay
- Final states of $(\mathrm{HeT})^+$
- Neutrino mass

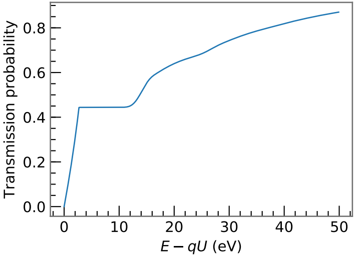
→ Model of measured data ←

$$R(qU) \propto \int_{qU}^{\infty} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E) \cdot R(qU, E)\, \mathrm{d}E + B$$

↓



Integrated β-spectrum + bg

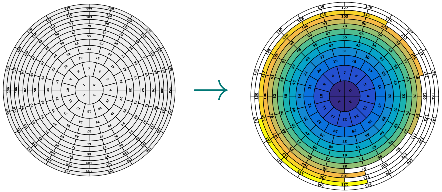


Experimental response

- MAC-E filter transmission
- Energy loss by scattering

Data combination and likelihood

- Scan combination: counts and times added, retarding potentials averaged
- Pixel combination: grouped into rings to account for radial potential effects
- Free parameters
  - 1 Neutrino mass squared m_ν^2
  - 12 ringwise endpoints $E_{0,\text{ring}}$
  - 12 ringwise background rates B_{ring}
  - 12 ringwise signal amplitudes A_{ring}

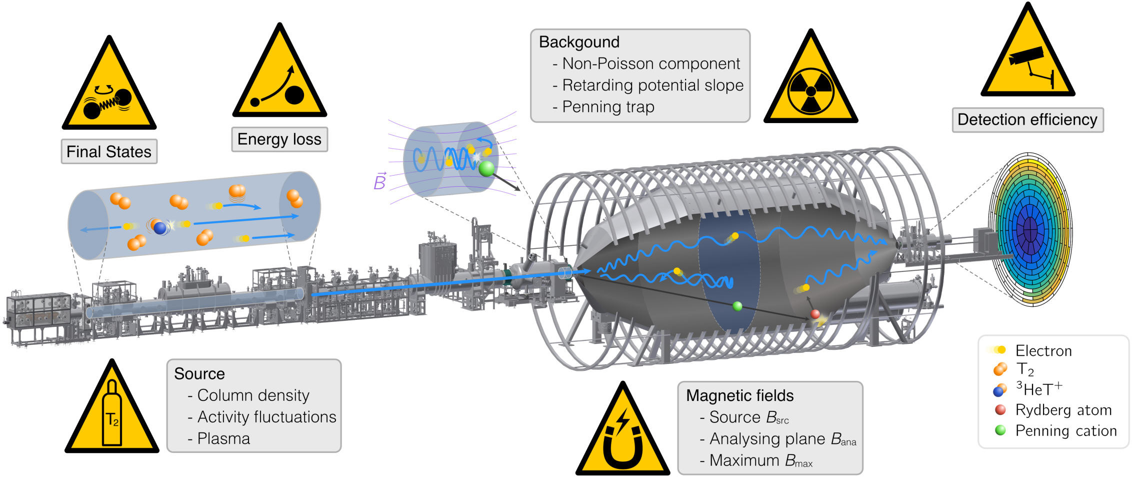


$$R_{\text{ring}}(qU) = A_{\text{ring}} \cdot \int_{qU}^{E_{0,\text{ring}}} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E; m_\nu^2, E_{0,\text{ring}}) \cdot R(qU, E)\, \mathrm{d}E + B_{\text{ring}}$$

$$\chi^2_{\text{ring}} = (R_{\text{data}}(qU) - R_{\text{ring}}(qU)) \cdot V^{-1} \cdot (R_{\text{data}}(qU) - R_{\text{ring}}(qU))^T$$ with the total covariance matrix V

$$\chi^2_{\text{total}} = \sum_{\text{ring}} \chi^2_{\text{ring}}$$

Systematics overview

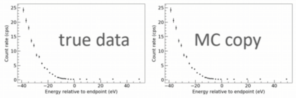


Analysis strategy

Blinding

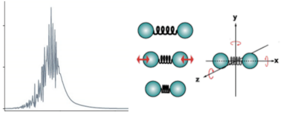
Freeze analysis on MC-twin data

- MC-copy of each scan (with $m_\nu = 0$ eV)



Blinded model

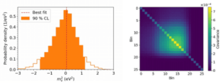
- Modified molecular final state dist.



m_ν^2

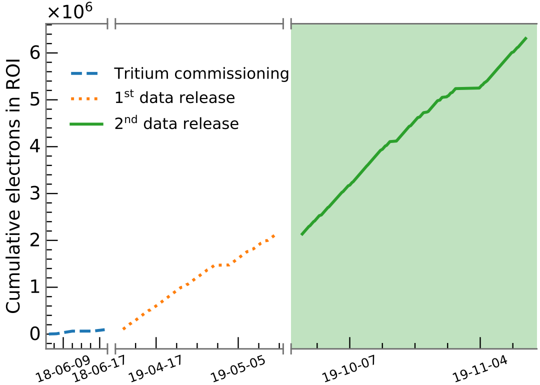
Independent analysis strategies

- Covariance matrix
- Monte Carlo propagation
- Pull term



Our second neutrino mass campaign

- Runtime: 2019-09-27 to 2019-11-14
- Scan time: 31 days
  split in 361 scans
- Electrons in ROI: 4.3 million
- Background: 220 mcps
- Source activity: 84 % of nominal
- Sensitivity: $m_\nu < 0.7\,\text{eV}$ (90 % CL)



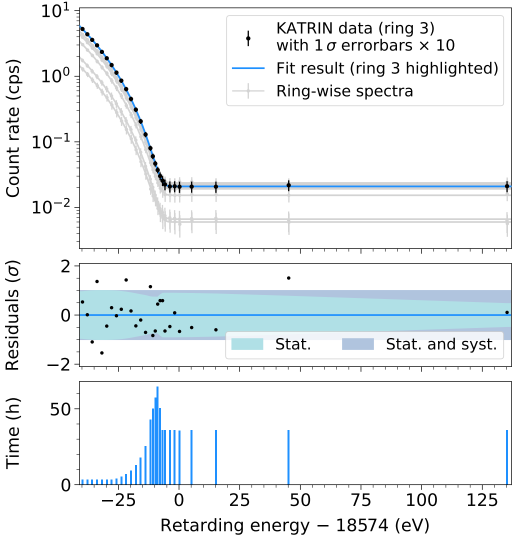
Data fit

- Multi-ring fit with 3 ringwise parameters, 1 shared neutrino mass squared, 37 free parameters
- Reduced χ^2: 0.9 at 299 degrees of freedom

$\Rightarrow$ p-value: 0.8

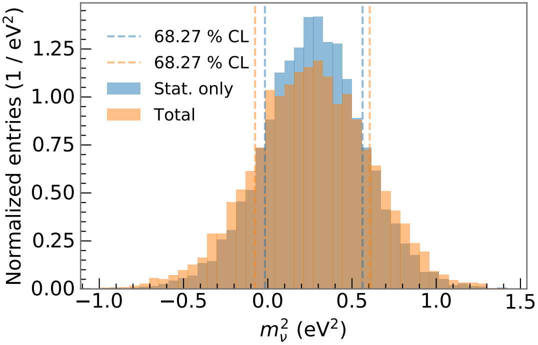
- Number of pixels in each ring vary due to alignment

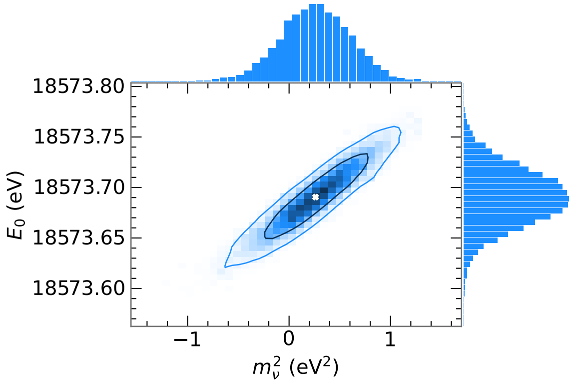
$\Rightarrow$ Different count rates in each ring



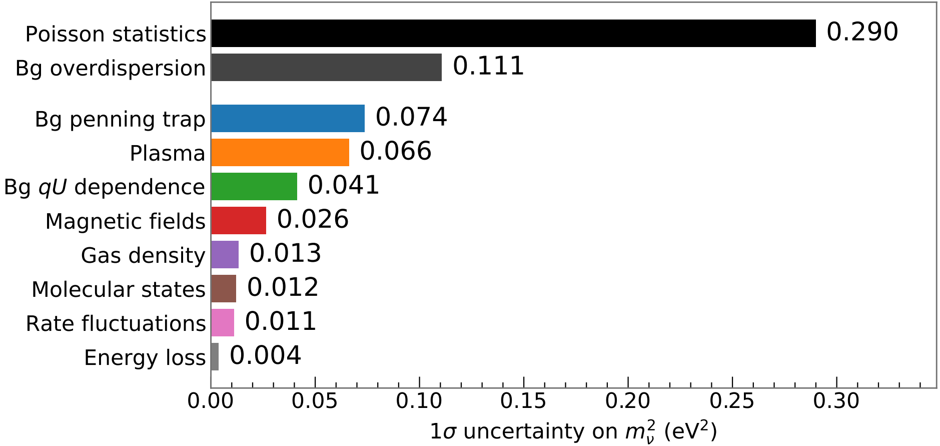
Neutrino mass squared distribution

Stat. only	$m_\nu^2 = 0.27 \pm 0.29\,\text{eV}^2$	$E_0 = 18\,573.69 \pm 0.02\,\text{eV}$
Stat. + syst	$m_\nu^2 = 0.26 \pm 0.34\,\text{eV}^2$	$E_0 = 18\,573.69 \pm 0.03\,\text{eV}$





Uncertainty breakdown

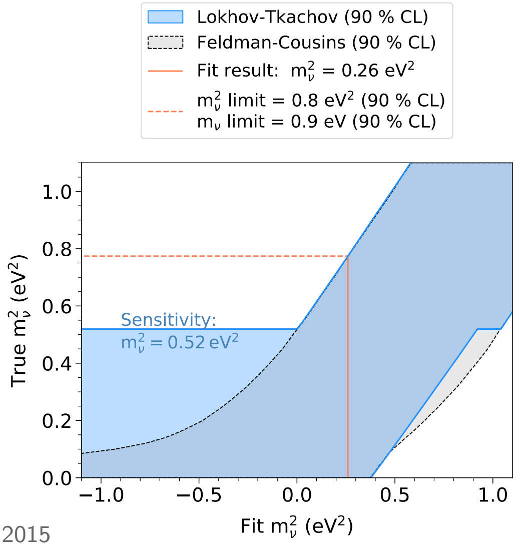


Design requirement for KATRIN final: $\sigma_{\text{total}} = 0.024\,\text{eV}^2$, $\sigma_{\text{stat}} = \sigma_{\text{syst}} = 0.017\,\text{eV}^2$,

Frequentist limit

- Insert best-fit into belt using method of Lokhov and Tkachov[2] (90 % CL)
- Coincides with method of Feldman and Cousins for upper limits with $m^2_{\nu,\text{fit}} \geq 0$
- Sensitivity: $m_\nu < 0.7\,\text{eV}$ (90 % CL)
- Limit: $m_\nu < 0.9\,\text{eV}$ (90 % CL)

⇒ **First sub-electronvolt direct neutrino mass measurement and sensitivity**

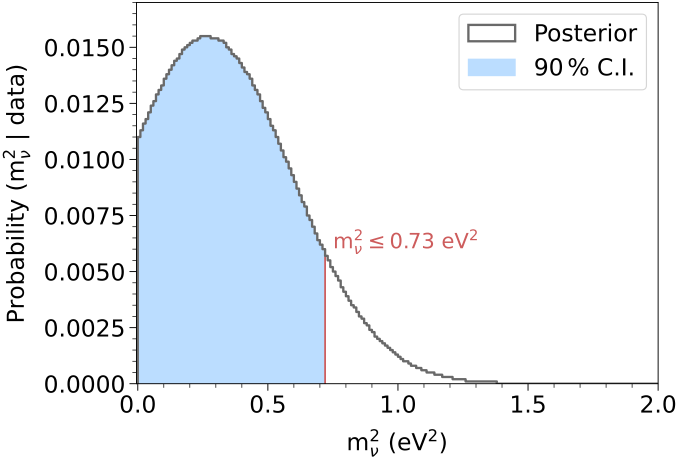


[2] A. V. Lokhov and F. V. Tkachov, Phys. Part. Nucl., May 2015

Bayesian analysis

- Bayesian sampling with flat positive prior in m_ν^2
- Systematics treated with priors as well as an approach based on Monte Carlo sampling
- Limit by integrating the posterior distribution up to 90 %
- Result: $m_\nu^2 < 0.73\,\text{eV}^2$

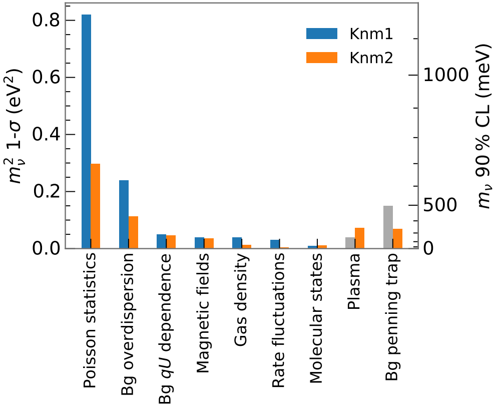
$\Rightarrow$ $m_\nu < 0.85\,\text{eV}$



Comparison with first neutrino mass campaign

quantity	Knm1	Knm2	improved
best fit (eV^2)	-0.96	0.26	–
Poisson uncert. (eV^2)	0.97	0.29	factor 3.3
other uncert. (eV^2)	0.31	0.16	factor 1.9
total uncert. (eV^2)	1.04	0.34	factor 3.2
90 % CL sensitivity (eV)	1.1	0.7	factor 1.5
90 % CL limit (eV)	1.1	0.9	factor 1.2

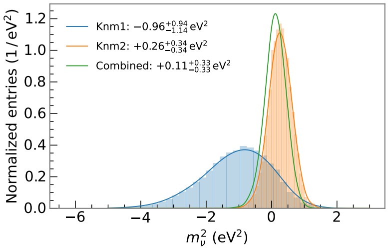
- Significantly more statistics collected
- Improvement of all “known” systematics
- New systematic effects identified, counter-measurements in progress

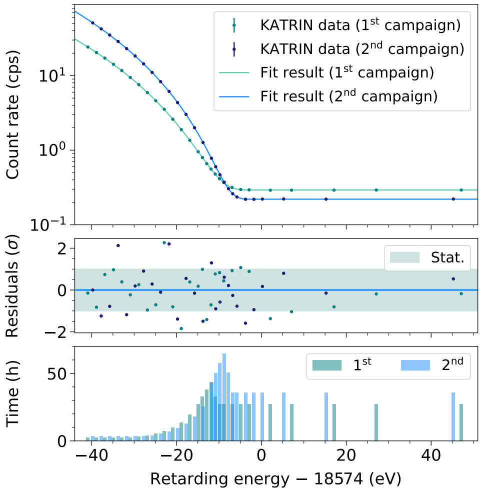


Comparison of sensitivity

Combination with first neutrino mass campaign

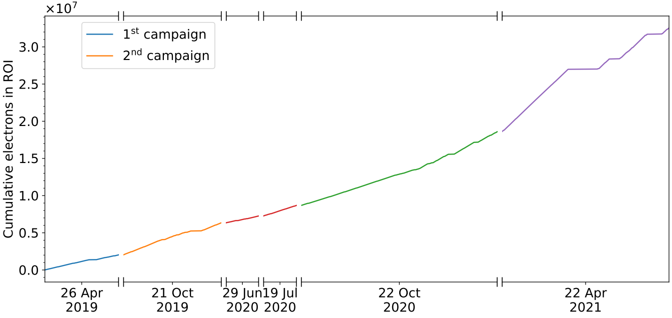
- Different strategies pursued:
  1. Combined fit with shared neutrino mass
  2. Multiply distributions from MC propagation
  3. Bayesian analysis: use posterior of first campaign as prior for second campaign
- Frequentist: $m_\nu < 0.8\,\text{eV}$ (90 % CL)
- Bayesian: $m_\nu < 0.7\,\text{eV}$ (90 % CI)





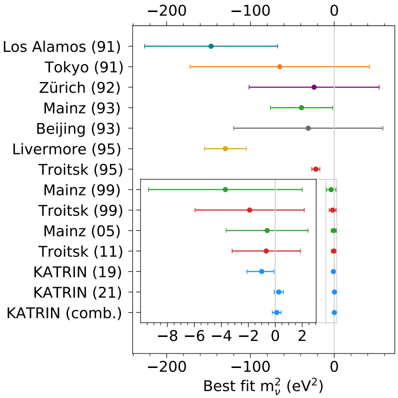
Outlook: next neutrino mass campaigns

- Have data from three more campaigns
- Roughly 5 times more statistics
- Unblinding procedure planned for the end of this year
- Two more measurement phases planned this year



Wrapping up

- 2^{nd} KATRIN neutrino mass campaign analysed
- Sensitivity: $m_\nu < 0.7\,\text{eV}$ (90 % CL)
- Best fit: $m_\nu^2 = 0.26 \pm 0.34\,\text{eV}^2$
- Limit: $m_\nu < 0.9\,\text{eV}$ (90 % CL)
- Limit combined with first campaign: $m_\nu < 0.8\,\text{eV}$ (90 % CL)
- Publication upcoming (arXiv:2105.08533)
- Still only about $\frac{1}{50}^{\text{th}}$ of the final statistics to be collected in the coming years, stay tuned! :)



Thanks to everyone involved! Thank you for your attention!