Latest Results from the KATRIN Experiment

N3AS Seminar

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Outline

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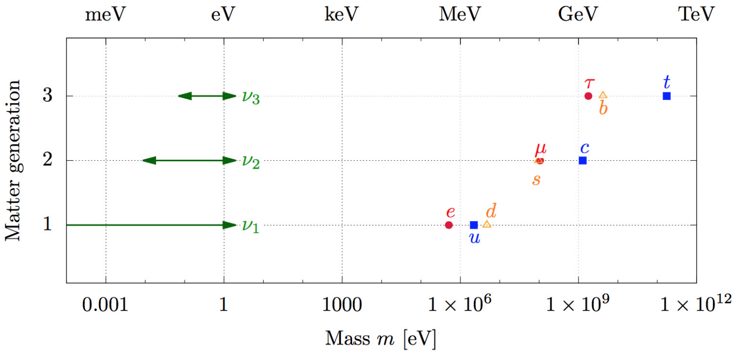
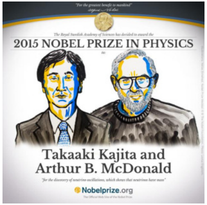
Unknown absolute mass scale





- Neutrino oscillations prove that at least two neutrino mass eigenstates are non-zero
- Absolute neutrino mass still unknown
- Interesting for cosmology and origin of particle mass

Measurement techniques

Cosmology

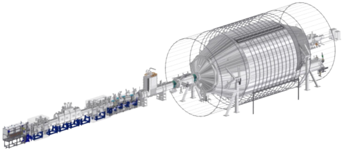
- ▶ Observable: m_Σ
- + Very sensitive
- + Independent of neutrino nature
- - Depends on cosmological model

Search for 0νββ

- ▶ Observable: $m_{\beta\beta}$
- + Very sensitive
- + Independent of cosmological model
- - Depends on neutrino nature

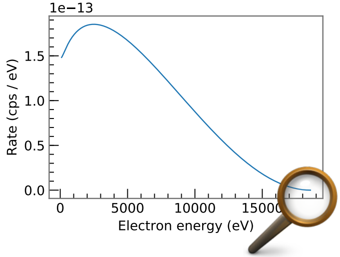
Kinematics of β-decay

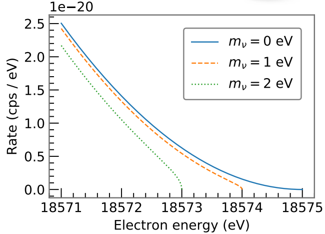
- ▶ Observable: m_β
- + Independent of cosmological model
- + Independent of neutrino nature
- - Less sensitive



Neutrino mass measurement from β-decay

- β-decay: $X \rightarrow Y^{+} + e^{-} + \bar{\nu}_e$
- 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
- Experimental challenges:
  - Very small effect on the eV-scale
  - Low count rate in region of interest near the endpoint
- Current leading experiment: KATRIN
  $m_\beta = m_\nu = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 0.8\,\text{eV}\ (90\,\%\ \text{CL})$[1]



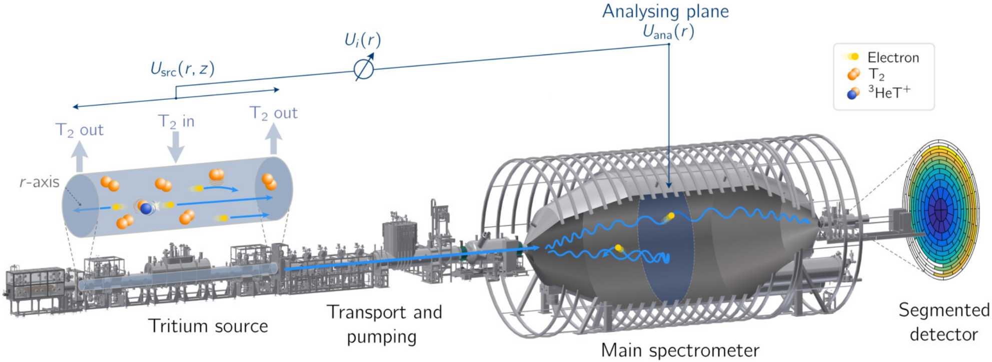


[1] M. Aker et al., arXiv:2105.08533, in print

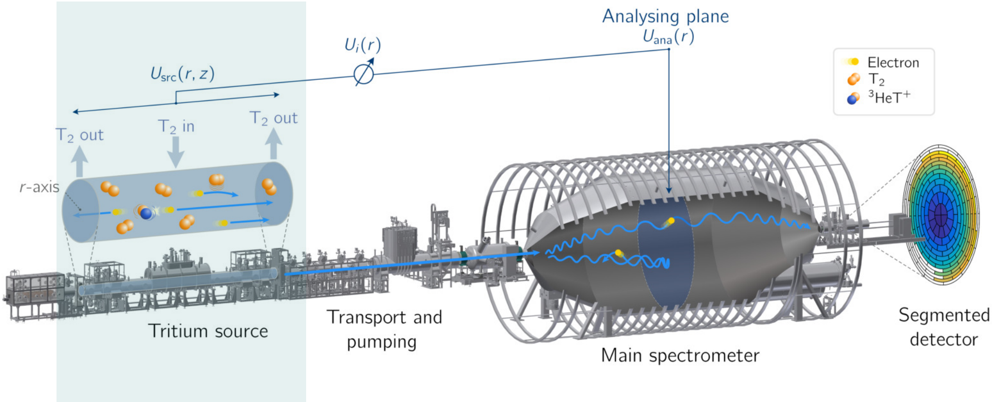
Outline

KATRIN experiment

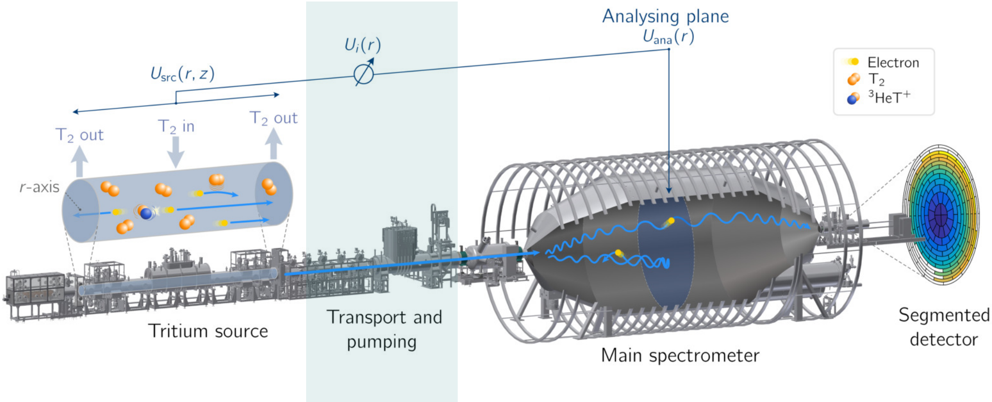
- Experimental site: Karlsruhe Institute of Technology (KIT)
- International collaboration (≈ 150 members) with participation of LBNL
- Design sensitivity: $200\,\mathrm{meV}$ after 1000 days



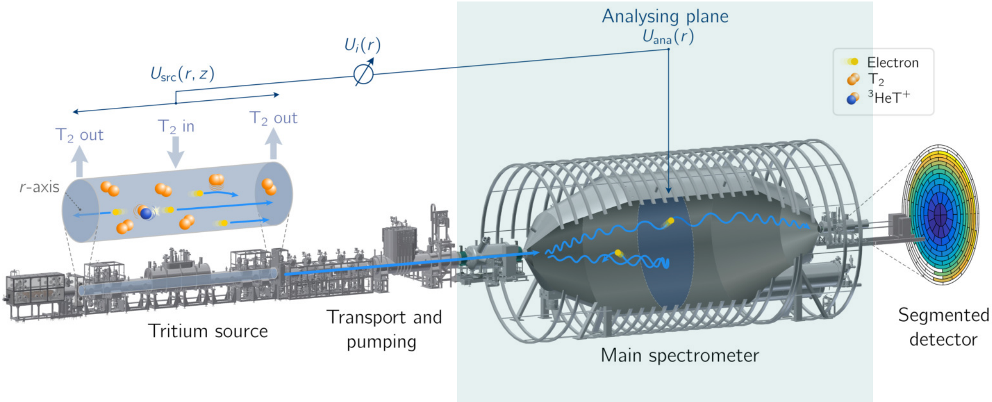
- 70 m long beamline of KATRIN



- windowless gaseous tritium source
- molecular tritium in closed loop system
- 1×10^{11} decays per second

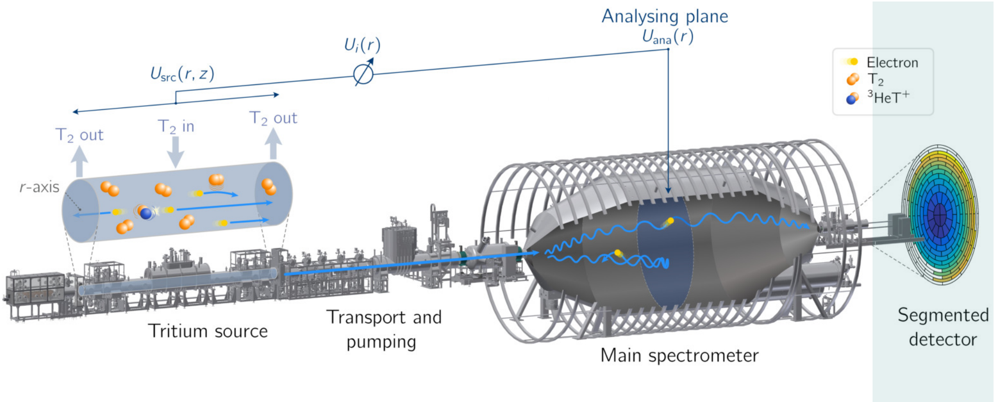


- transport section
- magnetic guidance of the electrons
- removal of tritium gas and ions



- spectrometer section
- electrostatic filter removes electrons with energies below U_i

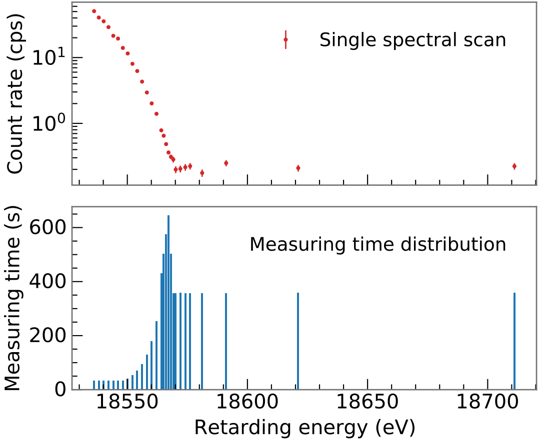
⇒ integral measurement, energy resolution defined by the filter properties



- focal plane detector
- 148 pixel Si-PIN detector
- simple counting of electrons, energy resolution not important

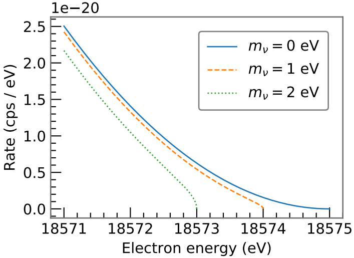
Measurement principle

- 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 $\approx 2\,\mathrm{h}$ long spectral scan hundreds of times



Outline

Model



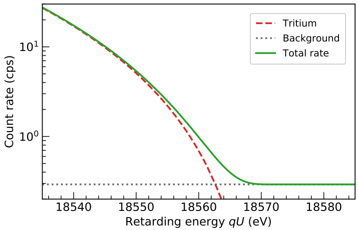
Differential β-spectrum

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

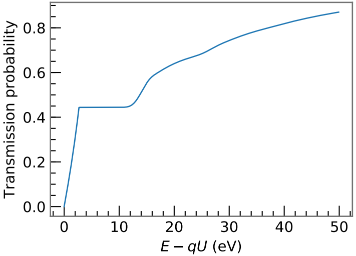
→ Model of measured data ←

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

↓



Integrated β-spectrum + bg

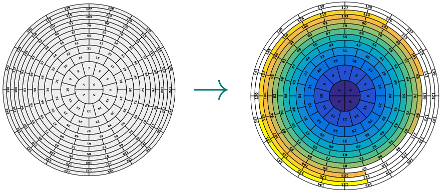


Experimental response

- 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}

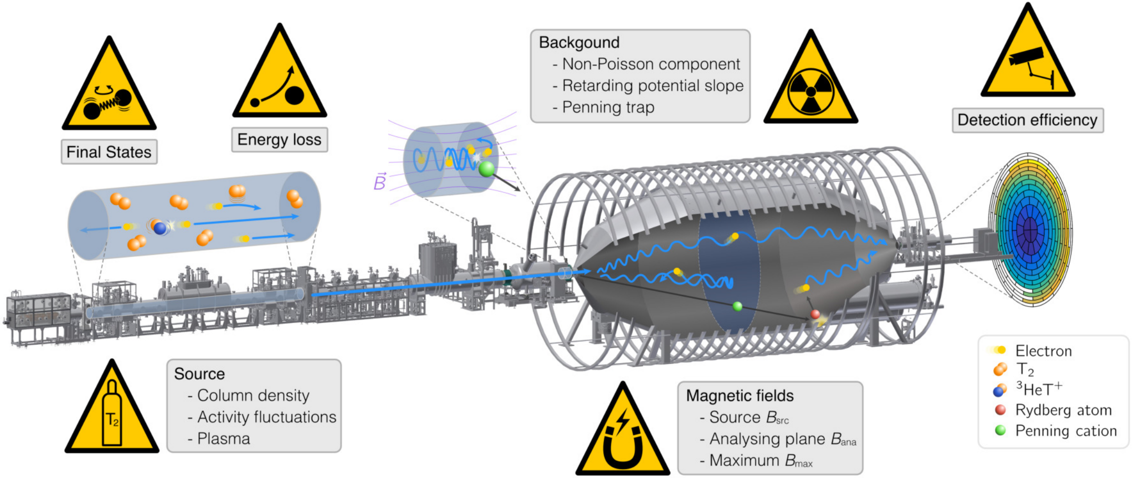


$$R_{\text{ring}}(qU) = A_{\text{ring}} \cdot \int_{qU}^{E_{0,\text{ring}}} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E; m_\nu^2, E_{0,\text{ring}}) \cdot R(qU, E)\,\mathrm{d}E + B_{\text{ring}}$$

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

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

Systematics overview

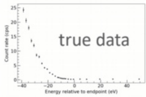


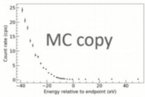
Analysis strategy

Blinding

Freeze analysis on MC-twin data

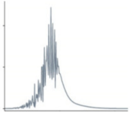
- MC-copy of each scan (with $m_\nu = 0$ eV)

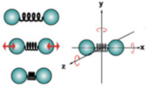




Blinded model

- Modified molecular final state dist.

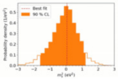


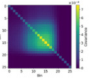


m_ν^2

Independent analysis strategies

- Covariance matrix
- Monte Carlo propagation
- Pull term

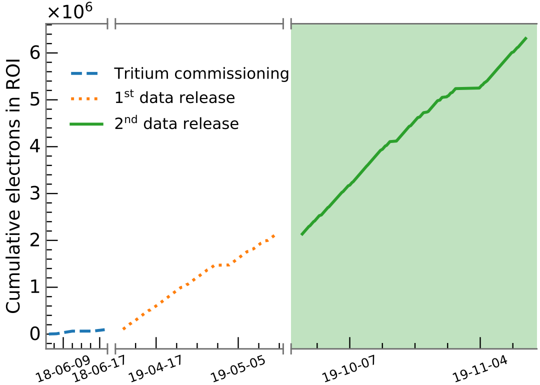




Outline

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: $220\,\mathrm{mcps}$
- Source activity: $84\,\%$ of nominal
- Sensitivity: $m_\nu < 0.7\,\mathrm{eV}$ ($90\,\%$ CL)

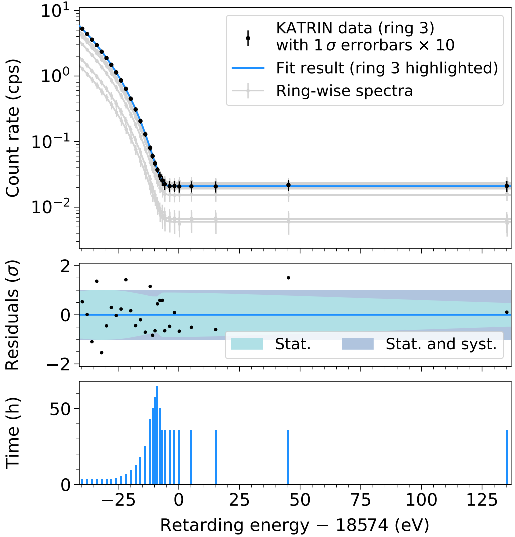


Data fit

- 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

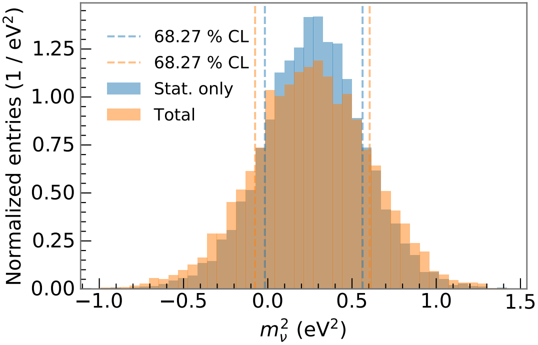
$\Rightarrow$ p-value: 0.8

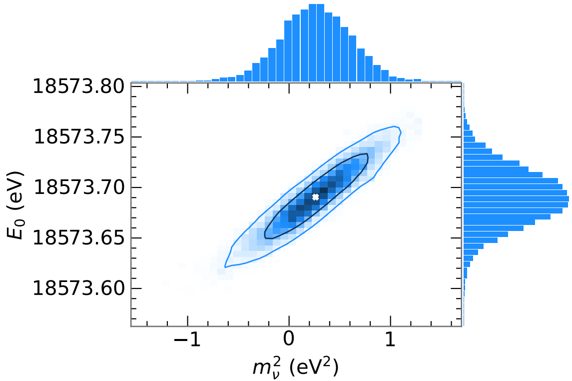
- Good agreement of model with data



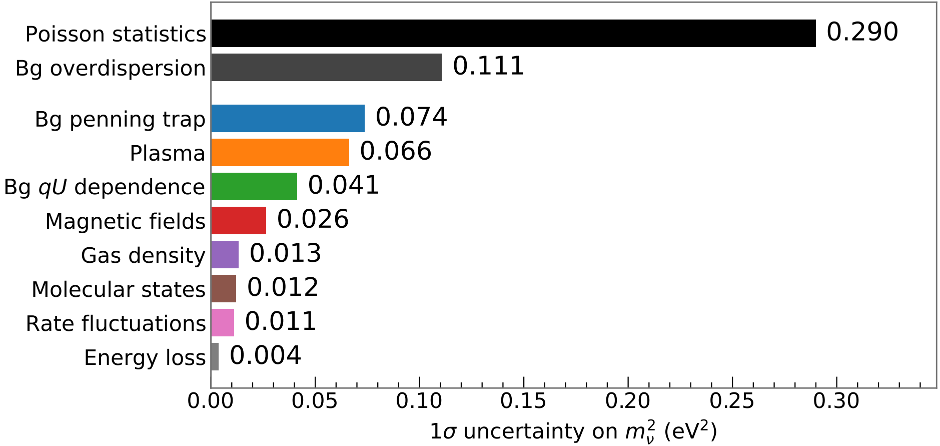
Neutrino mass squared distribution

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





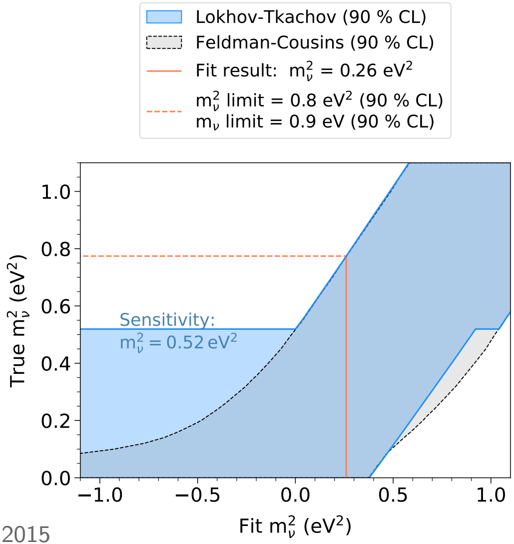
Uncertainty breakdown



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**



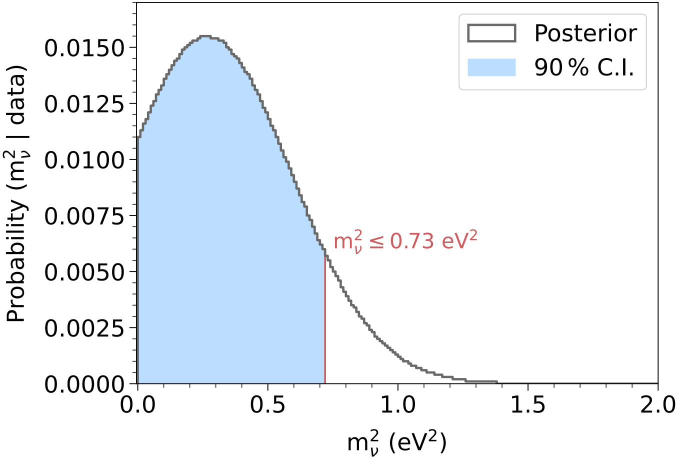
[2] A. V. Lokhov and F. V. Tkachov, Phys. Part. Nucl., May 2015

Bayesian analysis

Analysis by Björn Lehnert and
Ann-Kathrin Schütz at LBNL

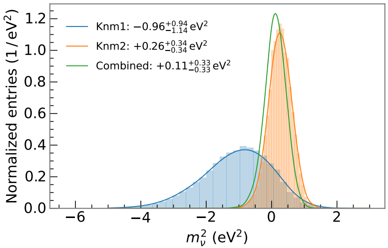
- Bayesian sampling with flat positive prior in m_ν^2
- Systematics treated with priors as well as an approach based on Monte Carlo sampling
- Limit by integrating the posterior distribution up to $90\,\%$
- Result: $m_\nu^2 < 0.73\,\text{eV}^2$

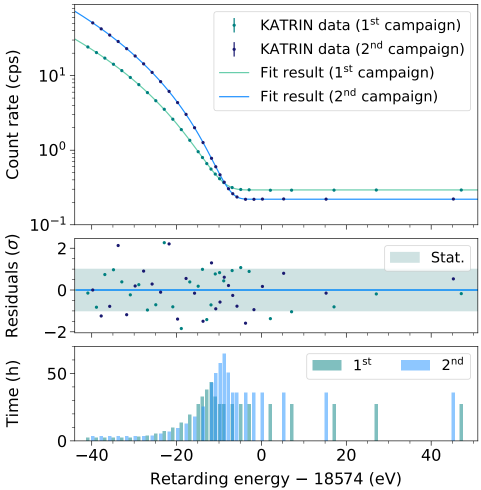
$\Rightarrow$ $m_\nu < 0.85\,\text{eV}$



Combination with first neutrino mass campaign

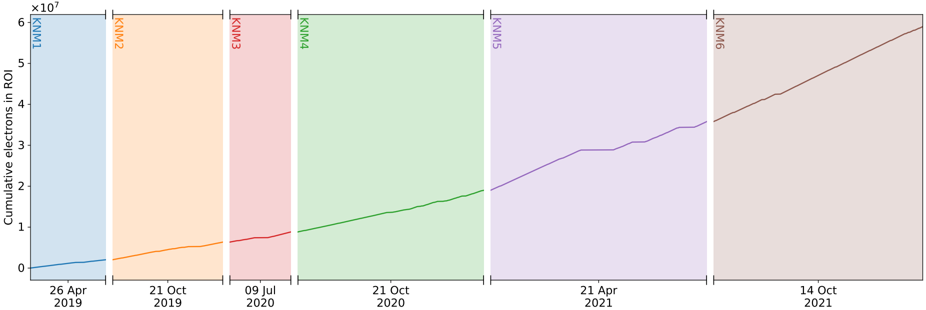
- Different strategies pursued:
  1. Combined fit with shared neutrino mass
  2. Multiply distributions from MC propagation
  3. Bayesian analysis: use posterior of first campaign as prior for second campaign
- Frequentist: $m_\nu < 0.8\,\text{eV}$ ($90\,\%$ CL)
- Bayesian: $m_\nu < 0.7\,\text{eV}$ ($90\,\%$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





Outline

Outlook: further neutrino mass campaigns



- Roughly nine times more electrons in ROI
- Reduced background and systematic uncertainties
- Expected sensitivity below $0.5\,$eV ($90\,\%$ CL)
- Unblinding procedure started at the end of last year
- Further measurement campaigns planned for 2022

Outlook: challenge of combined analysis

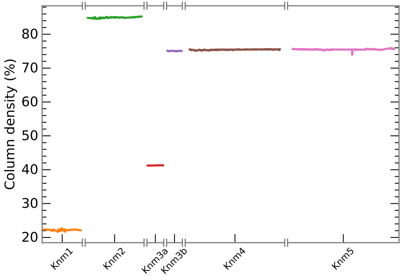
- Model calculation numerically expensive
- Slow control parameters such as gas density differ between measurement campaigns

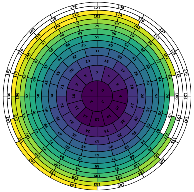
$\rightarrow$ Data segmentation over time

- Field settings differ over radius

$\rightarrow$ Data segmentation over detector patches

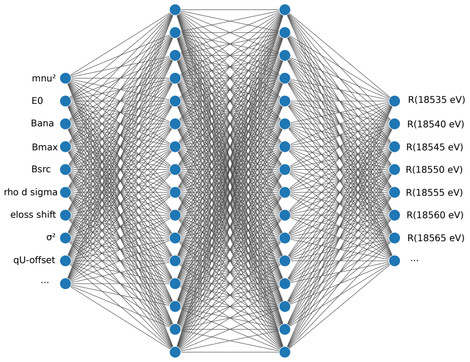
$\Rightarrow$ More than 1000 free parameters in final fit, computationally not feasible with current (slow) model





Outlook: improved performance using a NN

- Need faster model to analyse final dataset
- Our idea: train a neural network to learn the full integrated spectrum depending on a few parameters
- Induced bias $< 1 \times 10^{-3}\,\mathrm{eV}^2$
- Improved performance by several orders of magnitude
- Successful proof-of-concept for Monte Carlo data similar to final KATRIN dataset



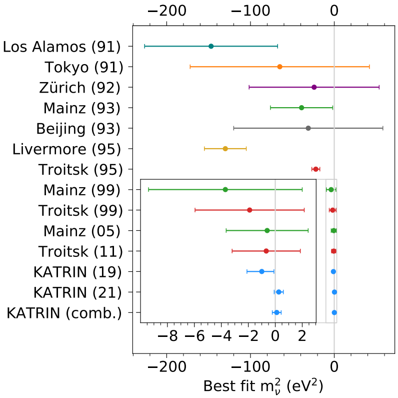
C. Karl et al., arXiv:2201.04523

Outline

Wrapping up

- 2^{nd} KATRIN neutrino mass campaign analysed
- Sensitivity: $m_\nu < 0.7\,$eV $(90\,\%$ CL)
- Best fit: $m_\nu^2 = 0.26 \pm 0.34\,\text{eV}^2$
- Limit: $m_\nu < 0.9\,$eV $(90\,\%$ CL)
- Limit combined with first campaign:
  $m_\nu < 0.8\,$eV $(90\,\%$ CL)

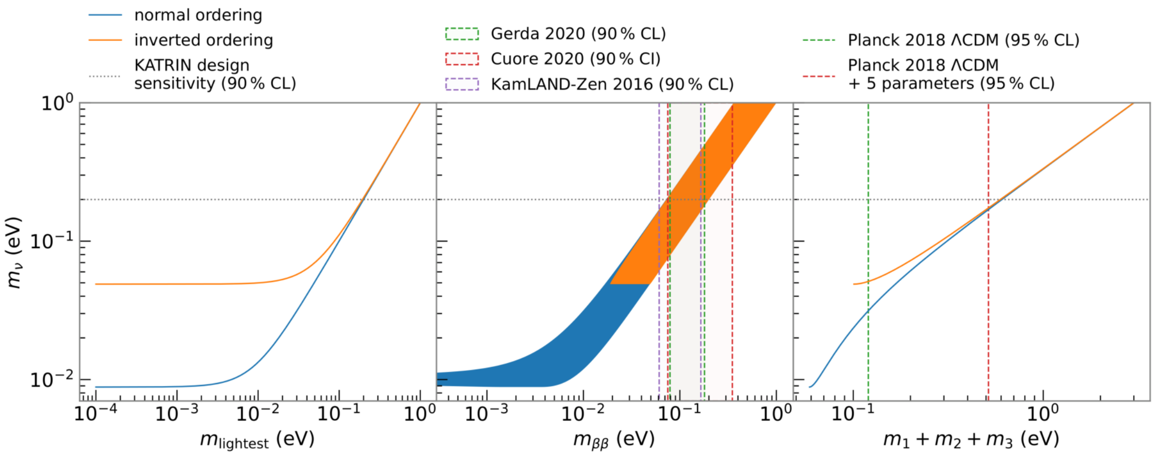
- Publication in print (arXiv:2105.08533)
- Still only about $\frac{1}{50}^{\text{th}}$ of the final statistics to be collected in the coming years, stay tuned! :)



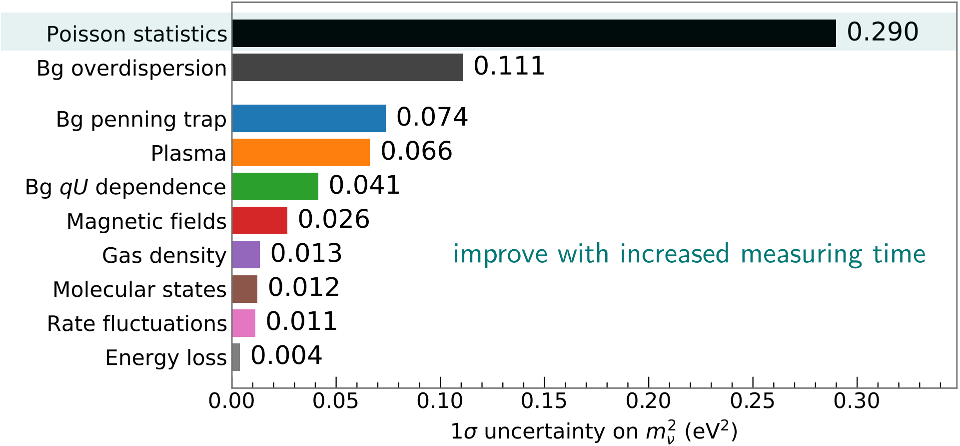
Thanks to everyone involved! Thank you for your attention!

Backup

Backup: comparison of measurement techniques

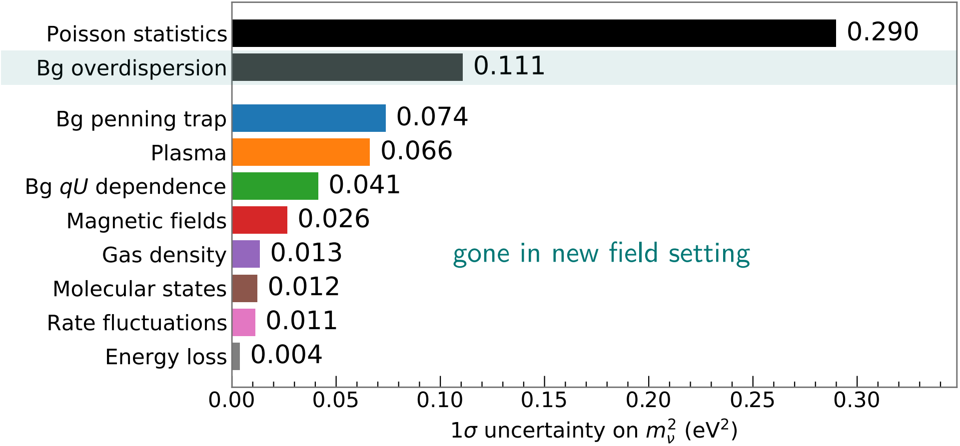


Backup: improving our uncertainty budget



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

Backup: improving our uncertainty budget



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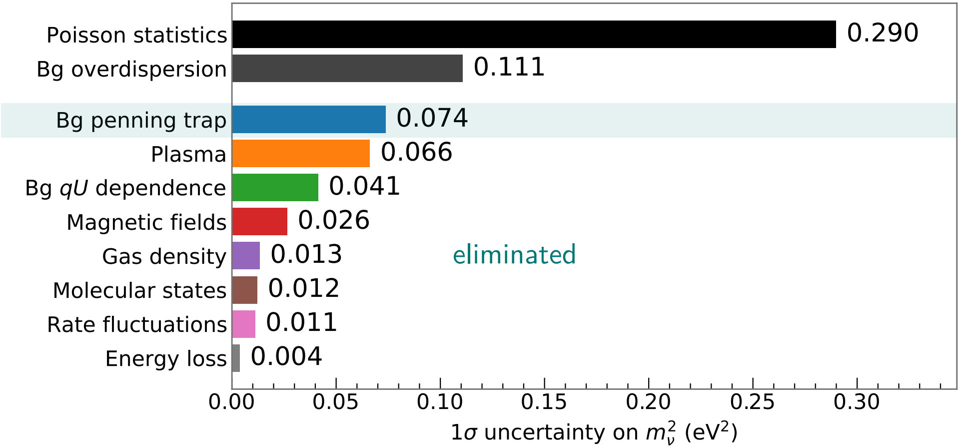

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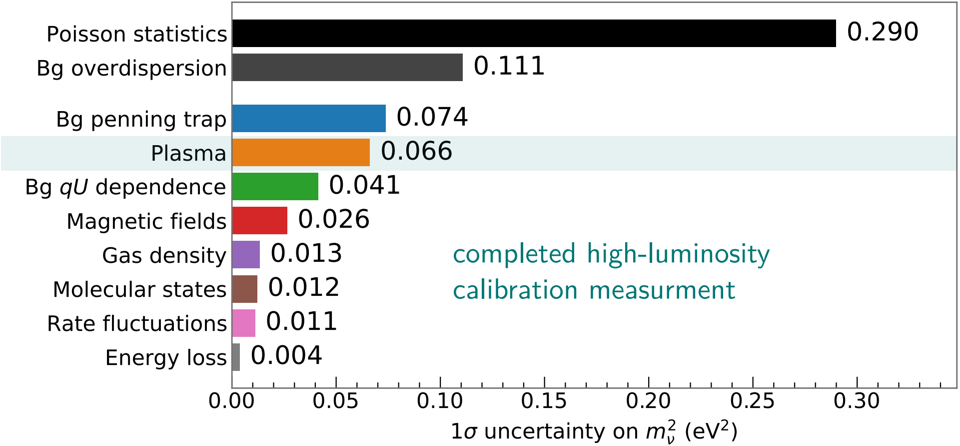

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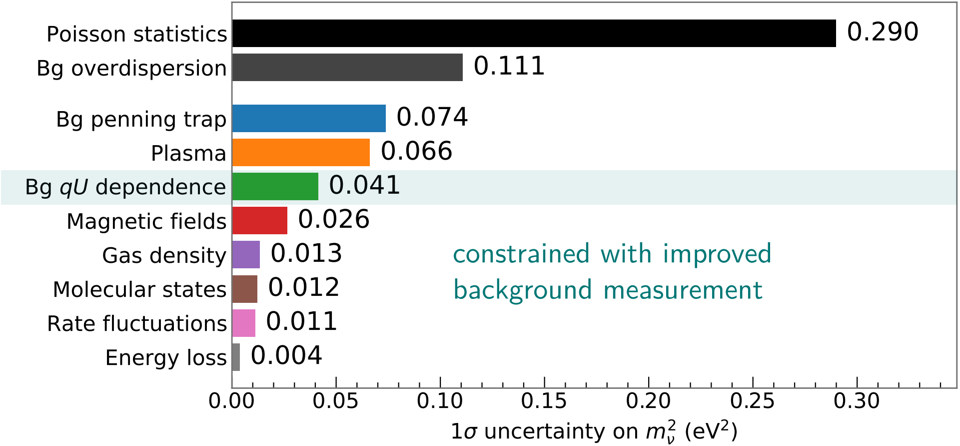

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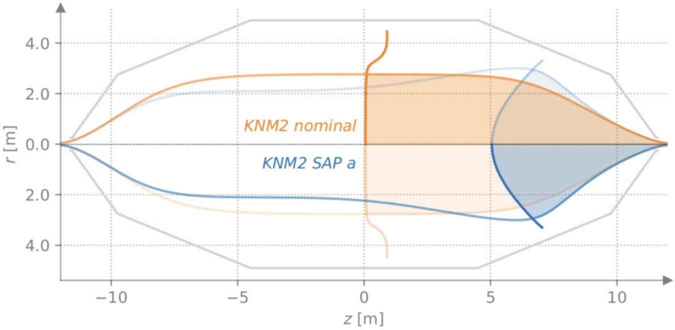
Backup: bg reduction via shifted analysing plane

- Main background proportional to flux-tube volume in the main spectrometer
- Origin: radioactive decay of Pb^{210} in the spectrometer walls
- Idea: reduce flux-tube volume by shifting the "analysing plane"

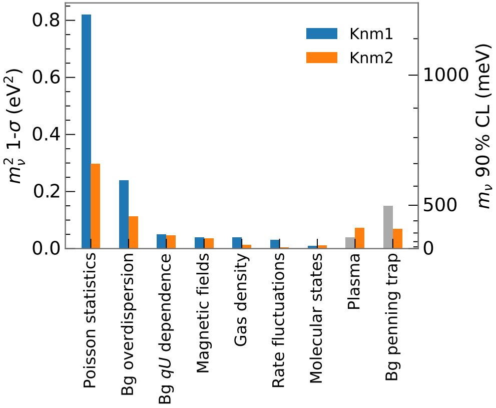
⇒ Reduce background by factor of two, but fields radially inhomogeneous



Backup: comparing the first two campaigns

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