Karlsruhe Institute of Technology

Tritium Laboratory Karlsruhe

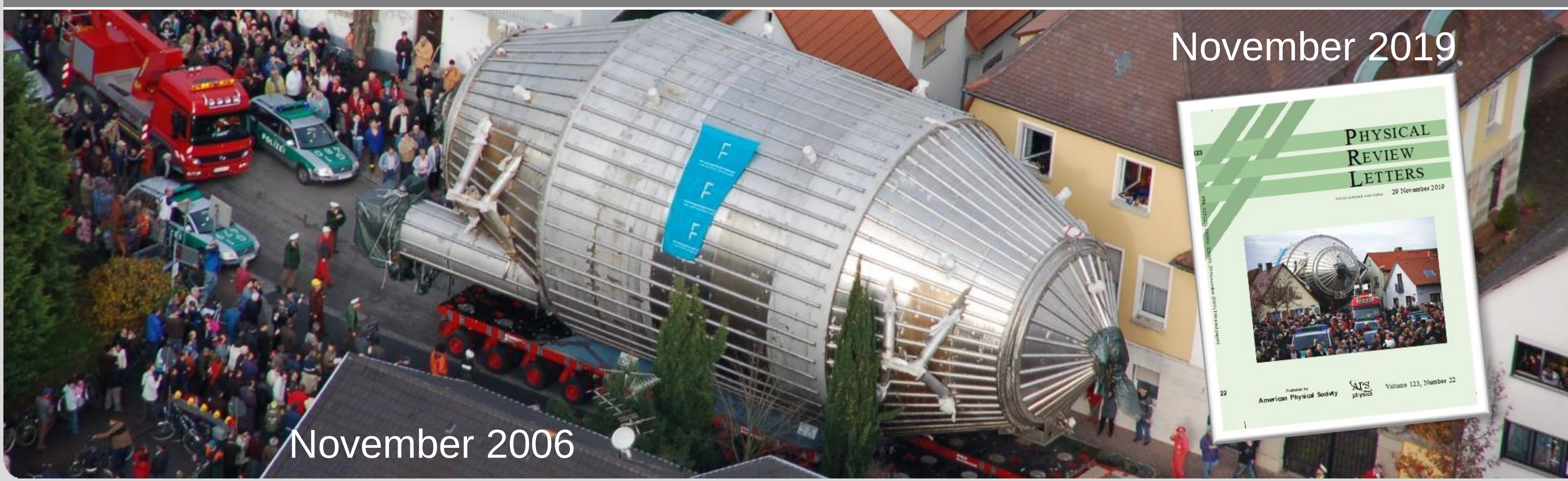
Pushing the Frontier in Measuring the Mass of the Lightest Lepton

Results from the Karlsruhe Tritium Neutrino Experiment

Magnus Schlösser for the KATRIN collaboration

9th International Conference on New Frontiers in Physics 2020

INSTITUTE FOR NUCLEAR PHYSICS, TRITIUM LABORATORY KARLSRUHE



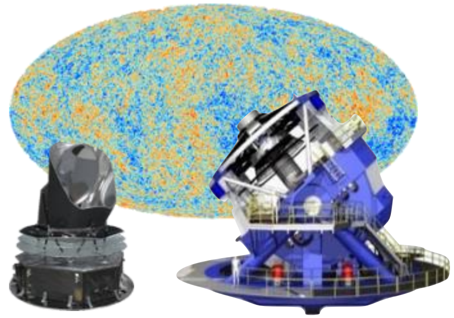
Short motivation

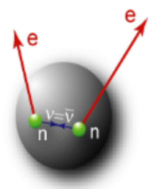
~300 neutrinos per cm^3

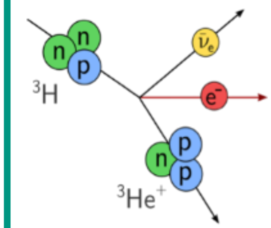
m_ν?

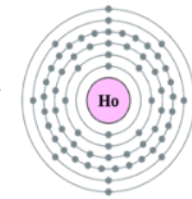
Hubble Ultra Deep field, NASA and the European Space Agency, http://hubblesite.org/newscenter/archive/releases/2004/07/image/a/warn/

Ways to access the neutrino mass





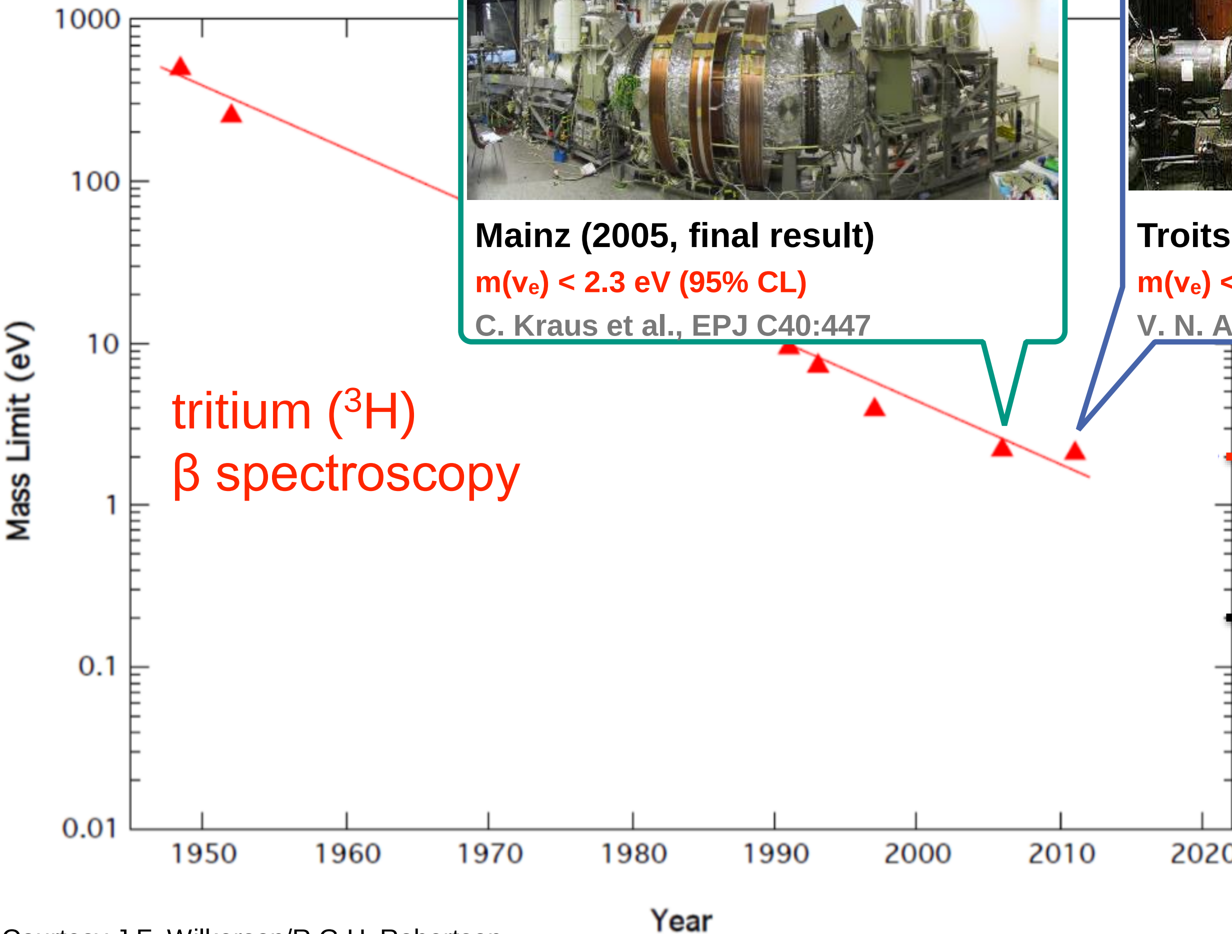




	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert^2$	$m_\beta^2 = \sum_i \lvert U_{ei} \rvert^2 m_i^2$
Present upper limit	0.12 – 1 eV	0.2 – 0.4 eV	2 eV
Model dependence	Multi-parameter cosmological model	- Majorana ν - contributions other than m(ν)? - nuclear matrix elements, g_A	**Direct,** only kinematics; no cancellations in incoherent sum

KATRIN → 200 meV

Moore's Law of direct neutrino mass searches



Mainz (2005, final result)
$m(\nu_e) < 2.3$ eV (95% CL)
C. Kraus et al., EPJ C40:447

Troitsk (2011, re-analysis)
$m(\nu_e) < 2.05$ eV (95% CL)
V. N. Aseev et al., PRD 84:112003

previous limits (2 eV)

ν ruled out as DM

upcoming (KATRIN: 200 meV)

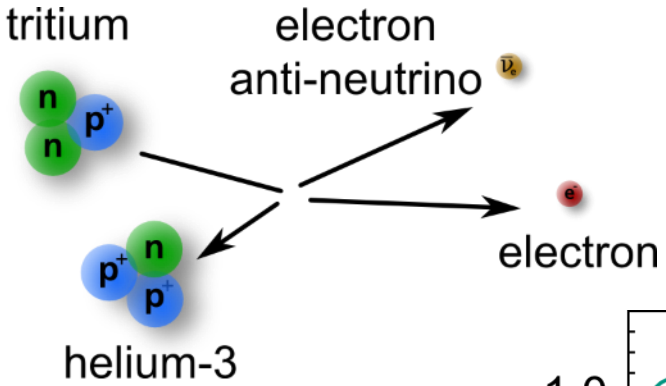
degeneracy scale

future approaches (40 meV)

hierarchy scale

Courtesy J.F. Wilkerson/R.G.H. Robertson

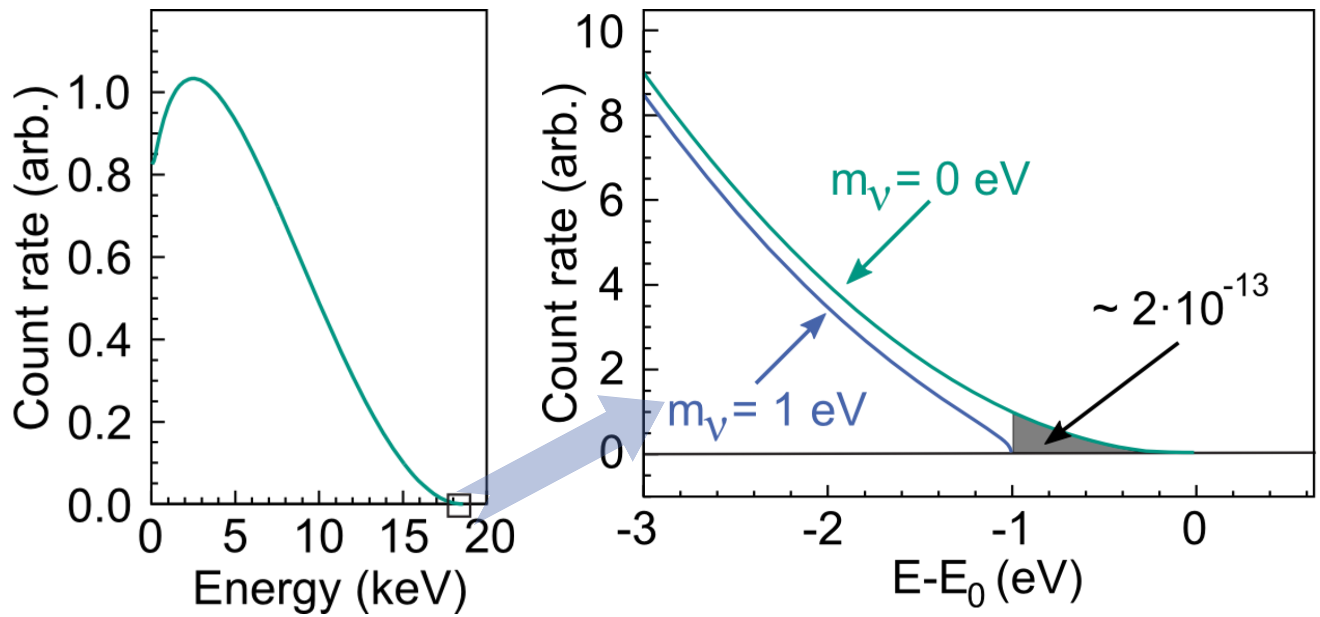
Tritium β-decay



E_0 = 18.6 keV
$T_{1/2}$ = 12.3 y

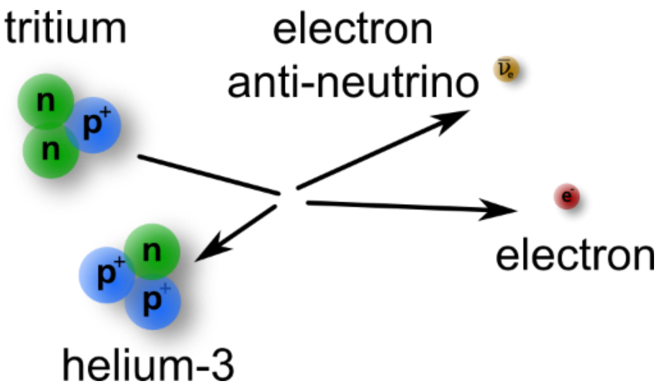
β -electron spectrum

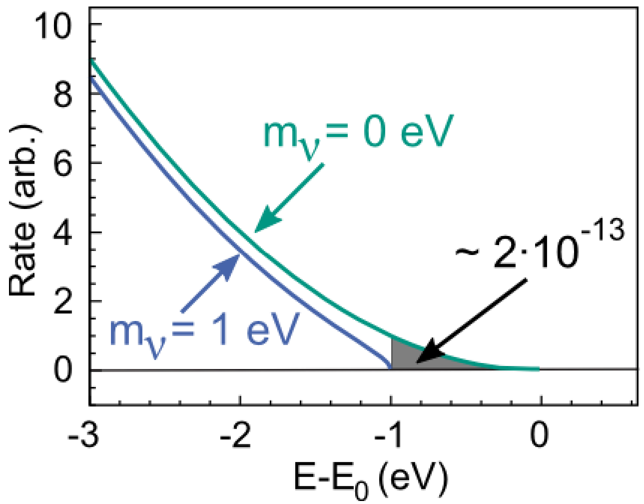
$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\bar{\nu}_i}^2 c^4}$$

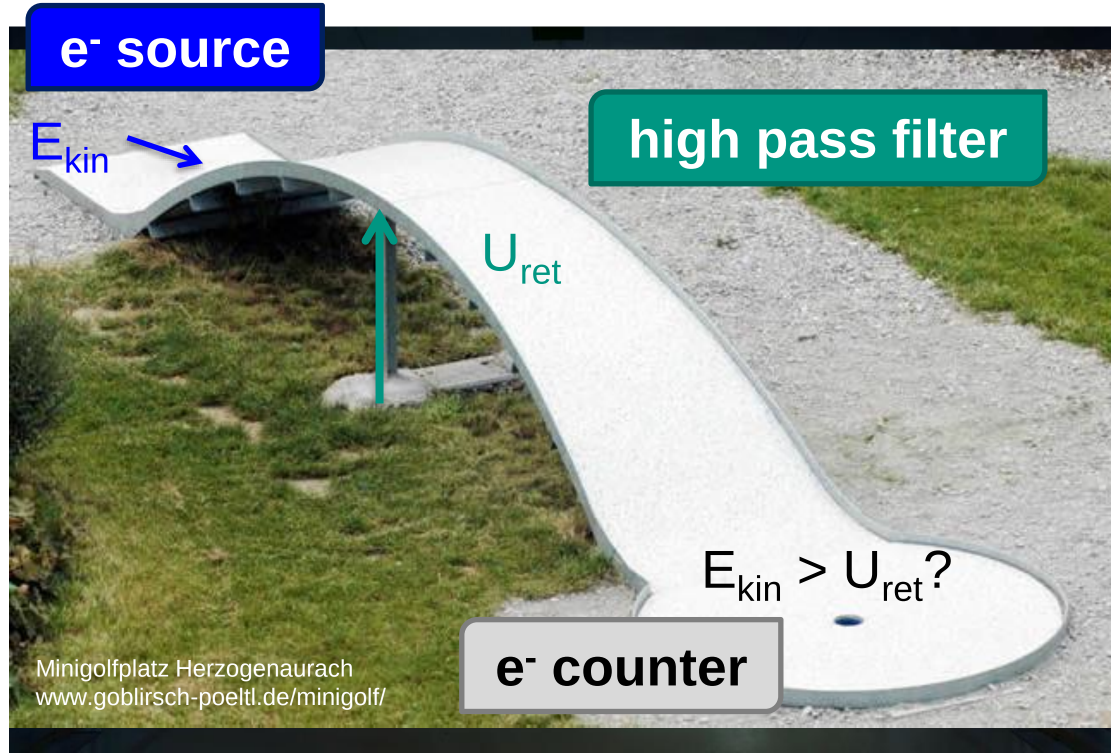


KATRIN's aim: Measurement of m_ν with a sensitivity of 200 meV/c²

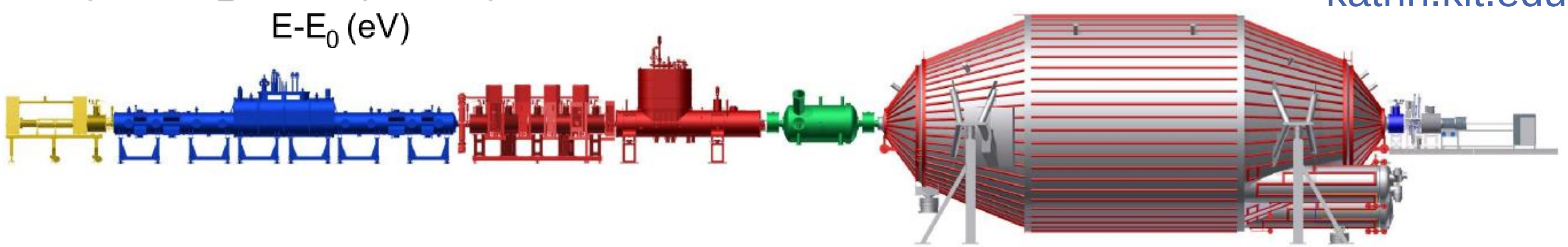
The Karlsruhe Tritium Neutrino Experiment





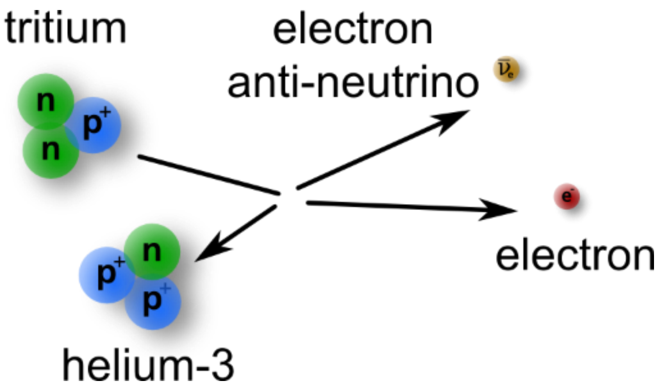


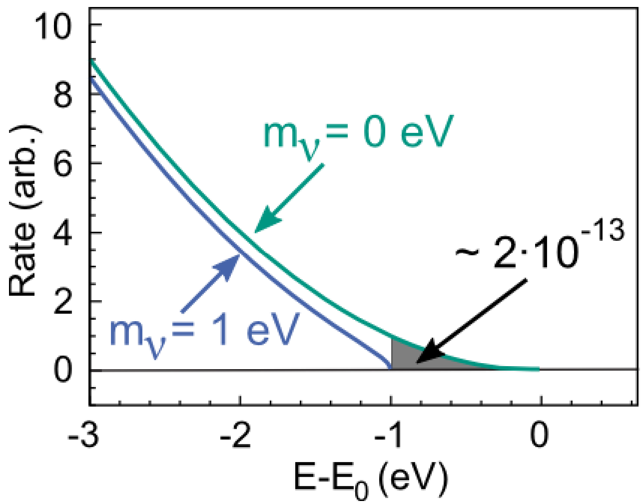
katrin.kit.edu

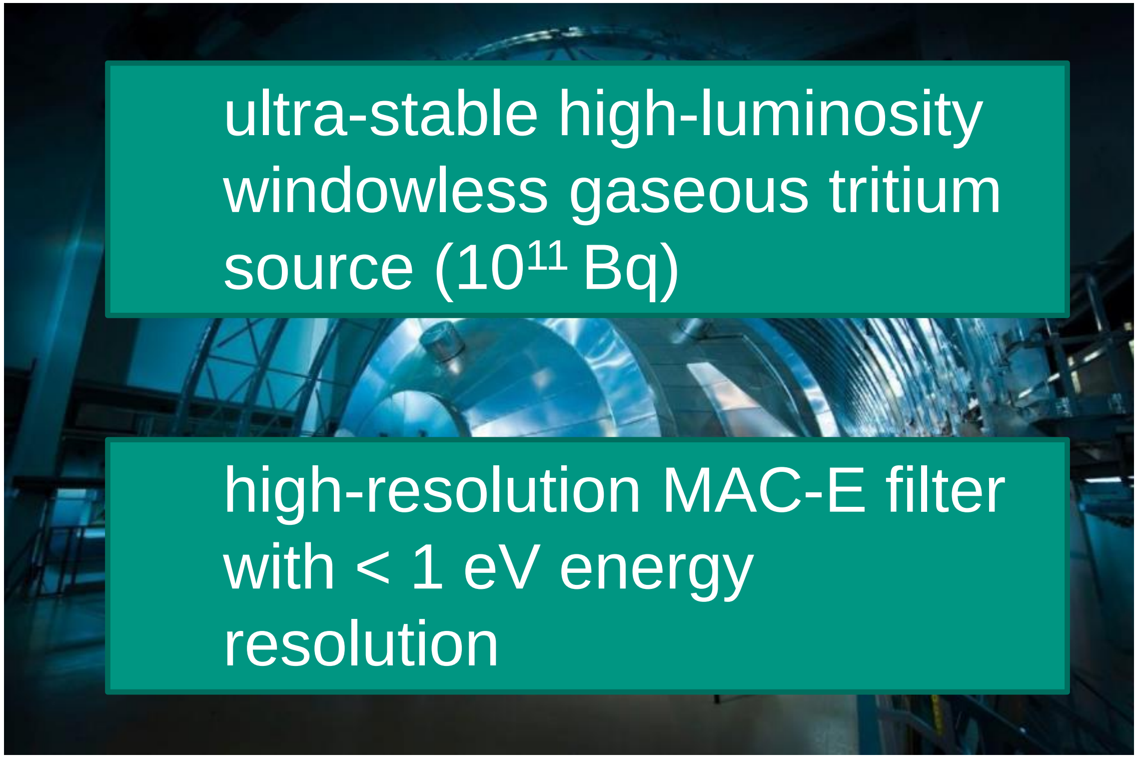


Tritium Laboratory Karlsruhe

The Karlsruhe Tritium Neutrino Experiment



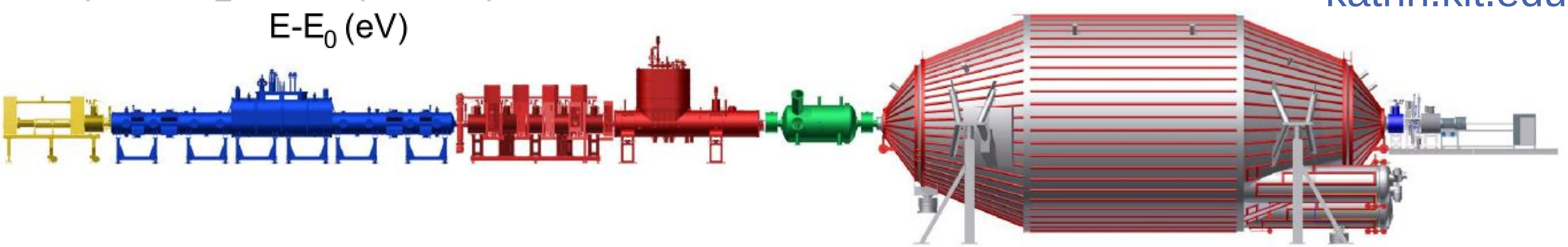




ultra-stable high-luminosity windowless gaseous tritium source (10^{11} Bq)

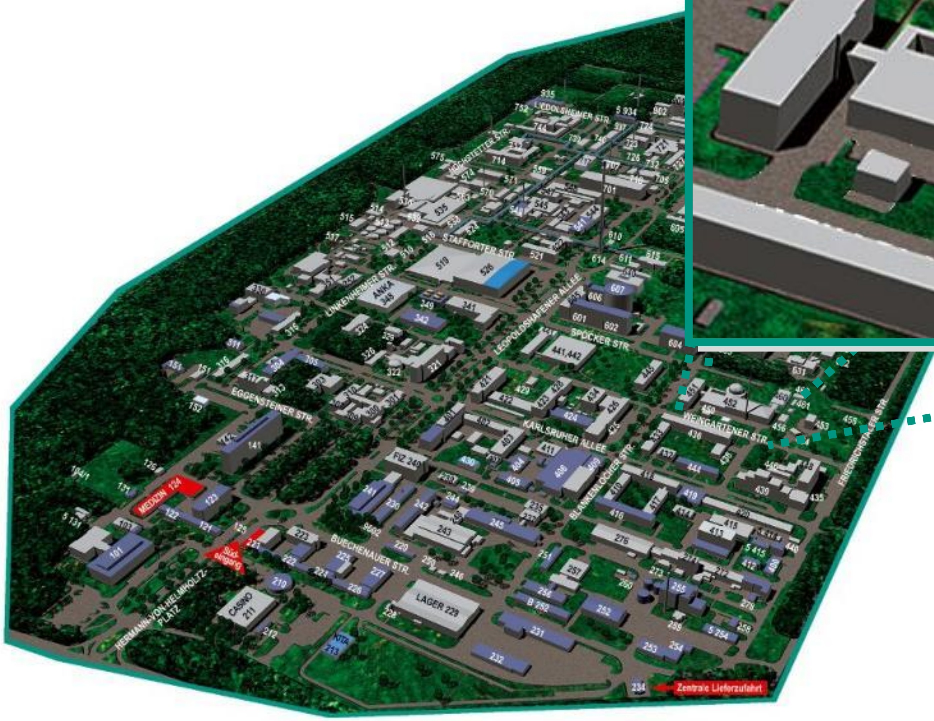
high-resolution MAC-E filter with < 1 eV energy resolution

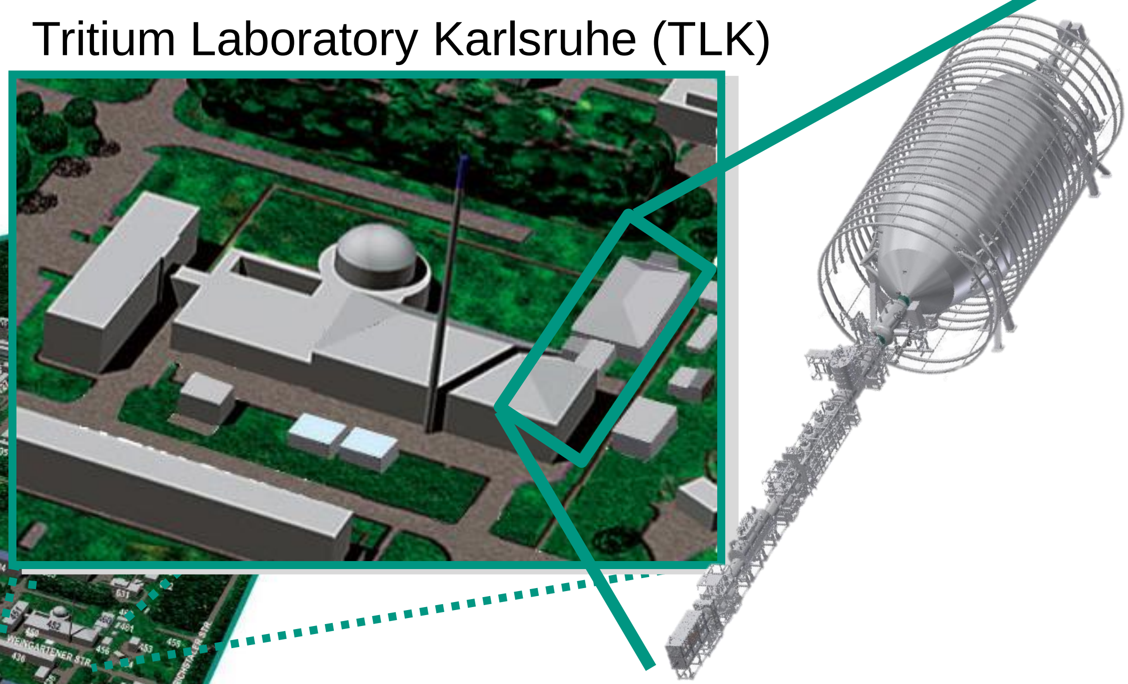
katrin.kit.edu



The Tritium Laboratory Karlsruhe

Tritium Laboratory Karlsruhe (TLK)





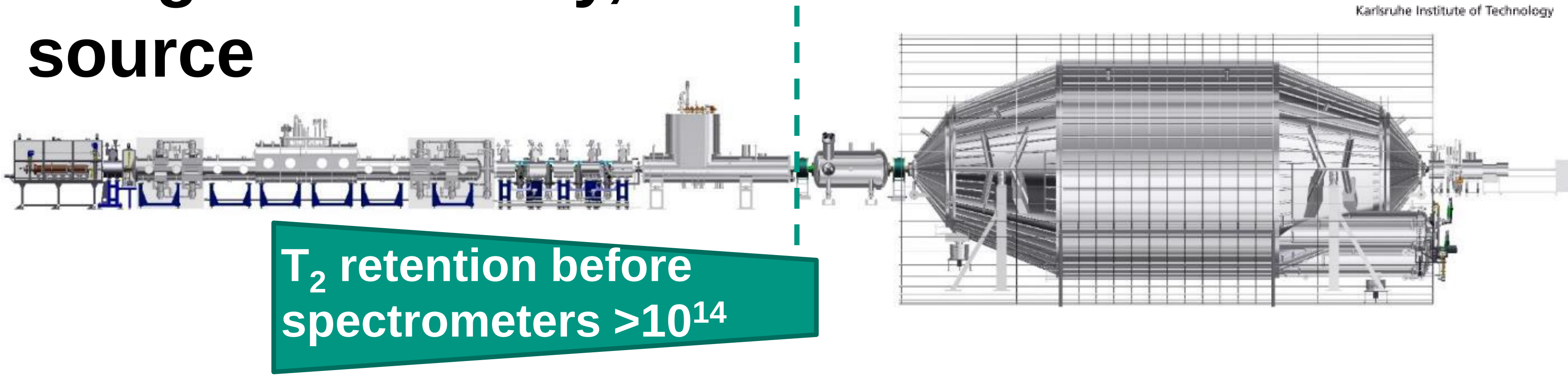
Karlsruhe Institute of Technology

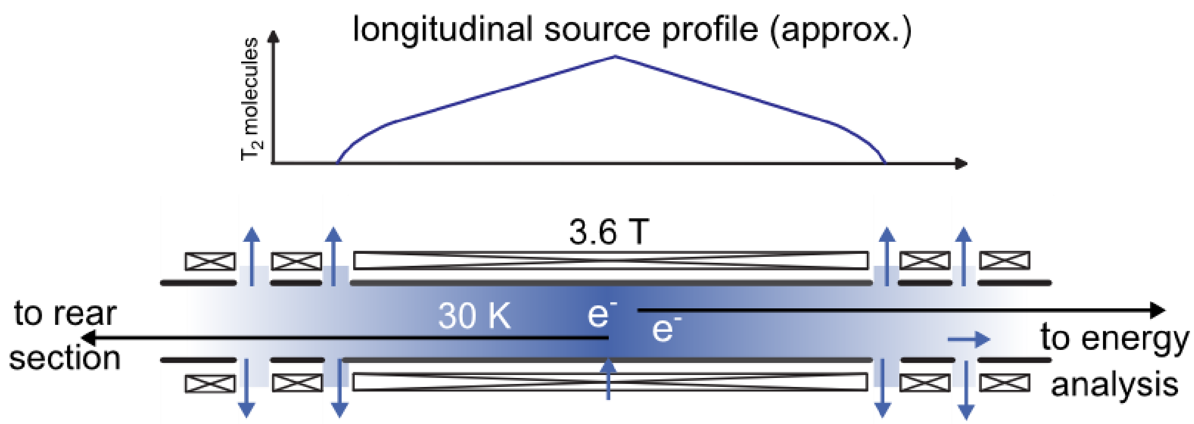
Campus North

- Commissioning 1993
- Licensed for 40 g Tritium
- Two missions:
  - Fuel cycle for fusion reactors
  - KATRIN Experiment

Tritium Laboratory Karlsruhe

A high-luminosity, ultra-stable tritium source



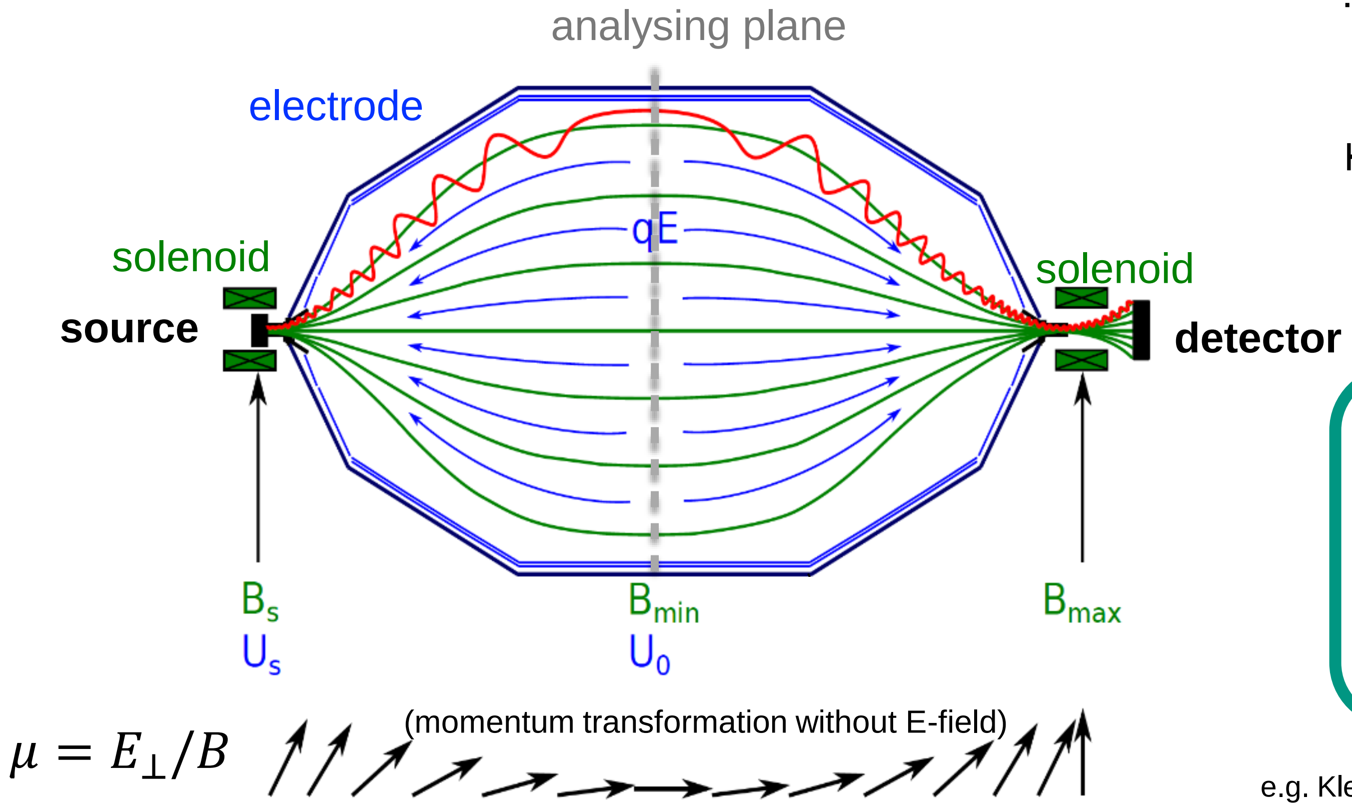


- T_2 purity > 95%
- Source activity 10^{11} Bq
- Source profile stable to 10^{-3} level
- T_2 throughput ~ 40 g/day
- Operation 24/7, 60 days/run
- Necessary inventory >15 g

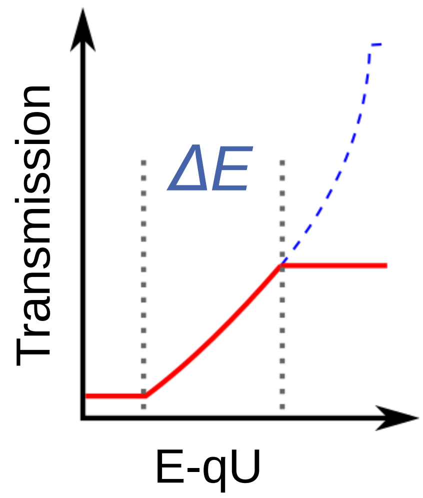
High-resolution spectrometer: MAC-E filter

Magnetic Adiabatic Collimation & Electrostatic Filter:

- integrating electrostatic filter ($E_{kin} > eU_0$)
- "clean" (analytic) response function



Sharp high pass filter:



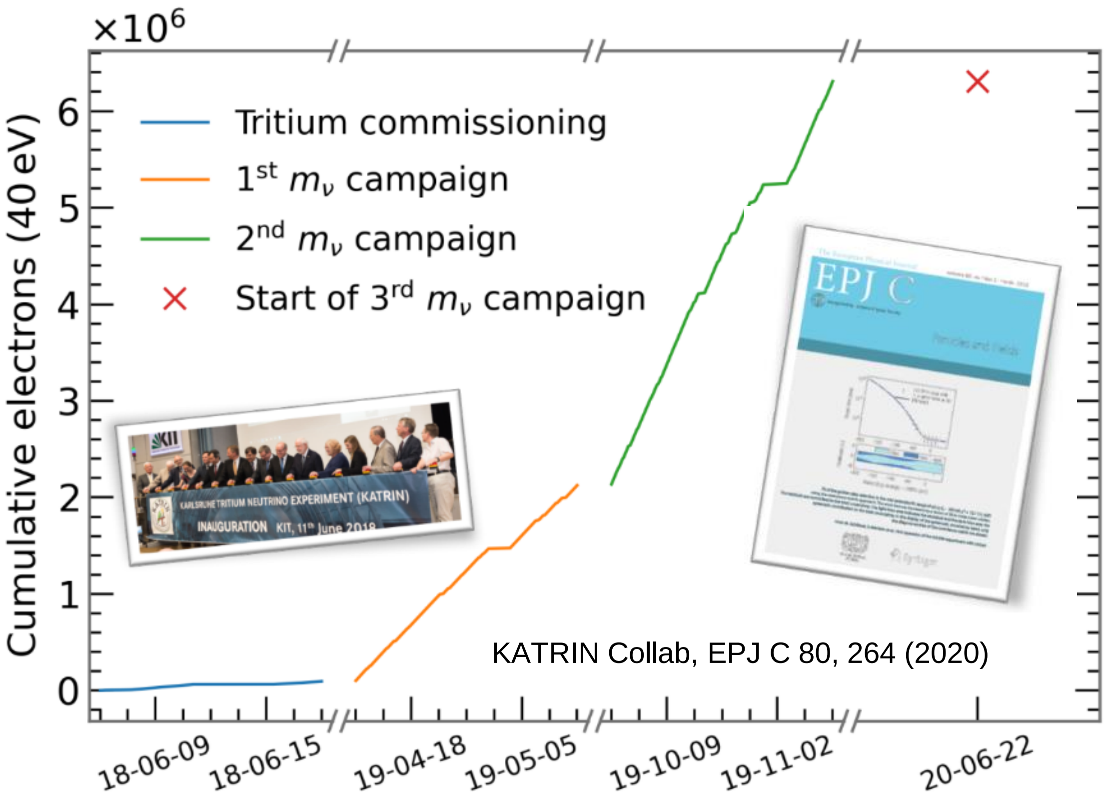
$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

→ **ΔE < 1 eV** at 18.6 keV

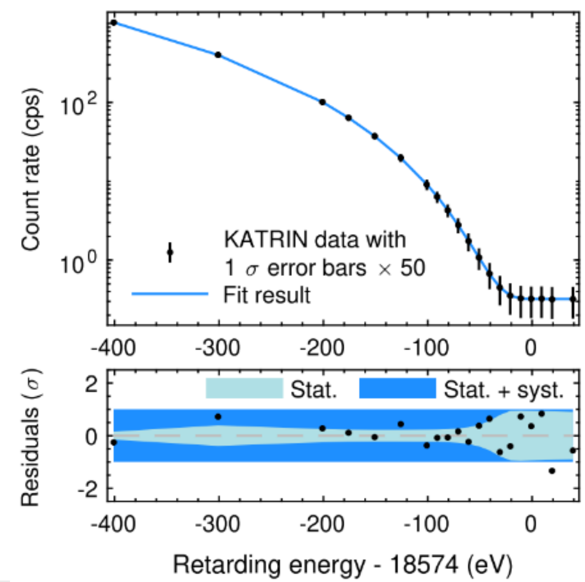
e.g. Kleesiek et al., EPJ. C 79, 204 (2019)

Tritium Laboratory Karlsruhe

First tritium „engineering“ run with KATRIN 2018



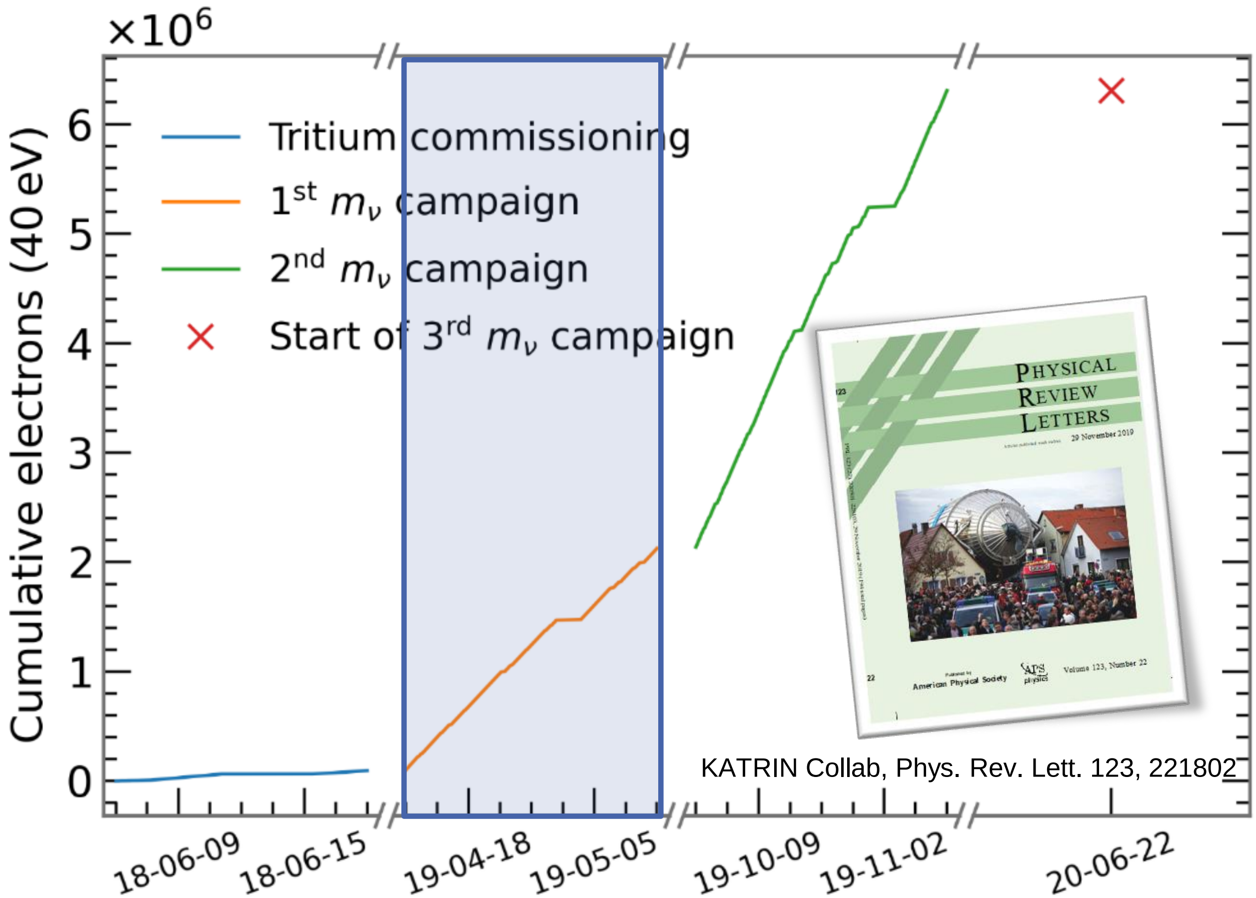
- 2 week run at full column density
- Reduced activity and tritium purity: 1% DT, 99% D_2



Successful operation of source and spectrometer sections at 10^{-3} stability

Tritium Laboratory Karlsruhe

First neutrino mass campaign with KATRIN 2019



KATRIN Collab, Phys. Rev. Lett. 123, 221802

Tritium Laboratory Karlsruhe

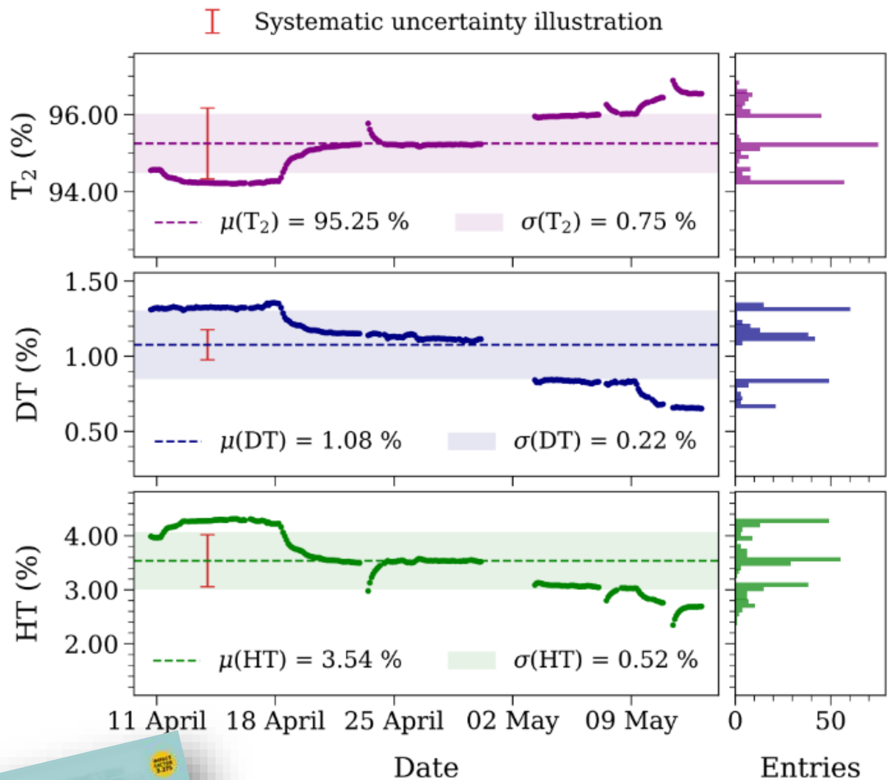
First KATRIN measurement campaign

- **4-week long campaign with high-purity tritium**
- April 10 – May, 13 2019
- 274 spectra (each 2 h)
- 521.7 h for analysis interval $[\mathrm{E}_0 - 40\ \mathrm{eV}, \mathrm{E}_0 + 50\ \mathrm{eV}]$
- Source activity $2.45\ 10^{10}$ Bq
- Tritium purity ($\epsilon_T = 97.5\ \%$)
- Tritium throughput 4.9 g / day

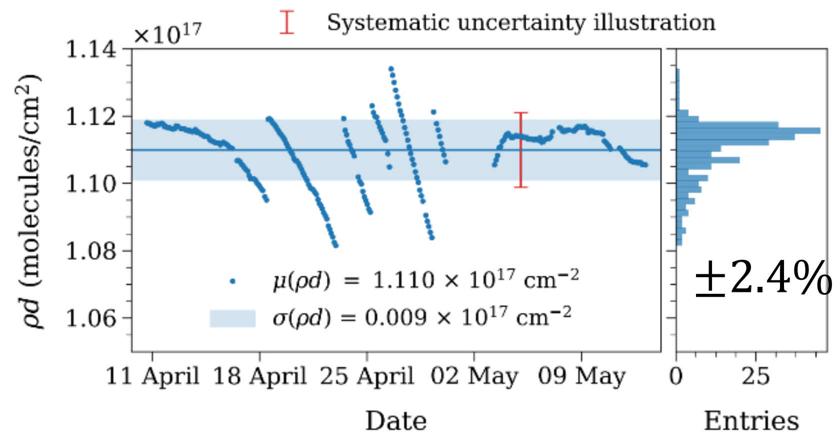
Tritium Laboratory Karlsruhe

Tritium source parameters

Composition via Raman spectroscopy



Column density

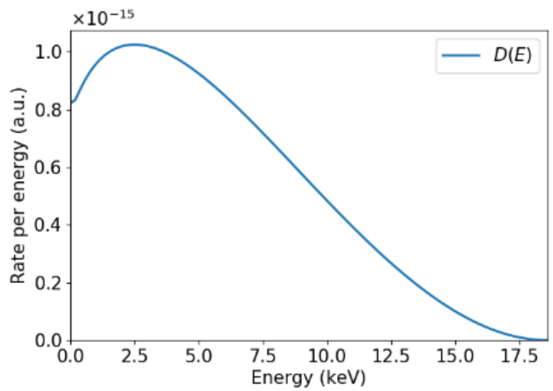


- **Reduced column density (22%)**
- **Radiochemical methane generation**
- **Throughput limited (initial burn-in effect)**

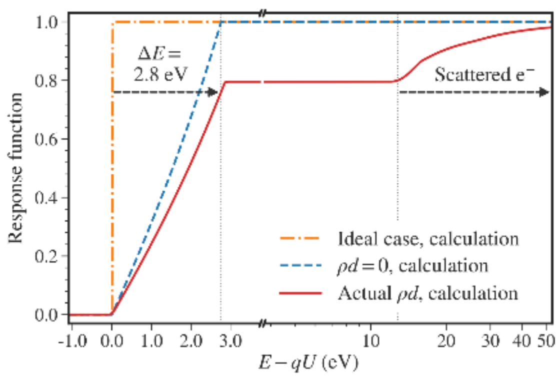
Very high tritium purity achieved

KATRIN Collab, Sensors 2020, 20(17), 4827

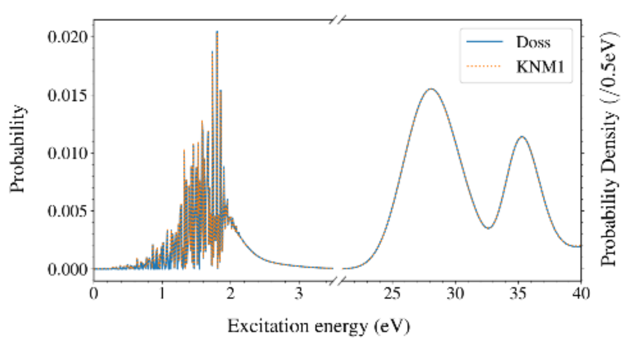
Ingredients for integral spectrum



Differential spectrum

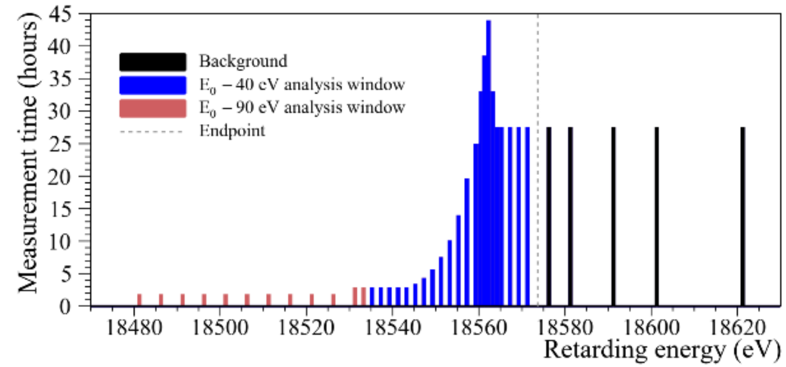


Experimental response (scattering, transmission, ..)

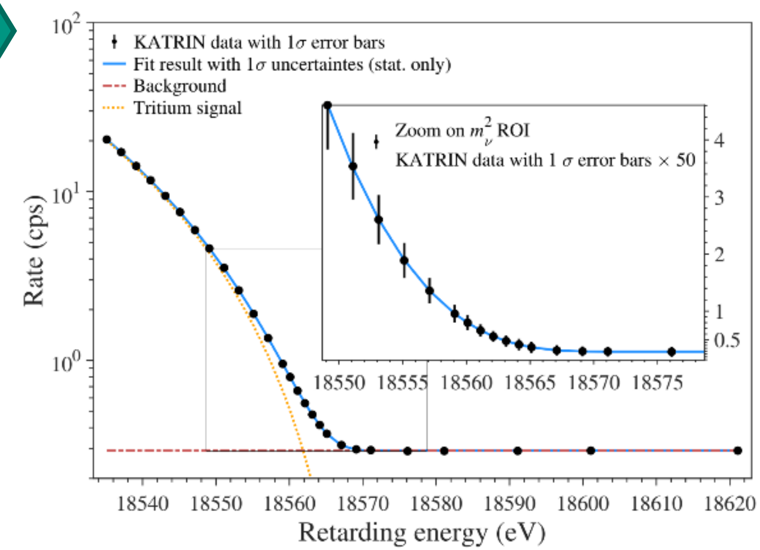


Molecular final state distribution

Measurement time distribution

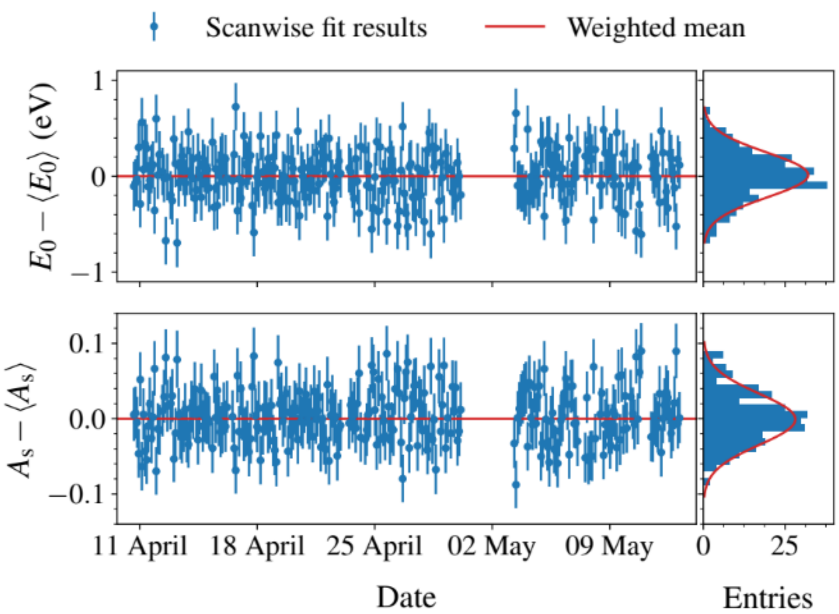


Integrated spectrum

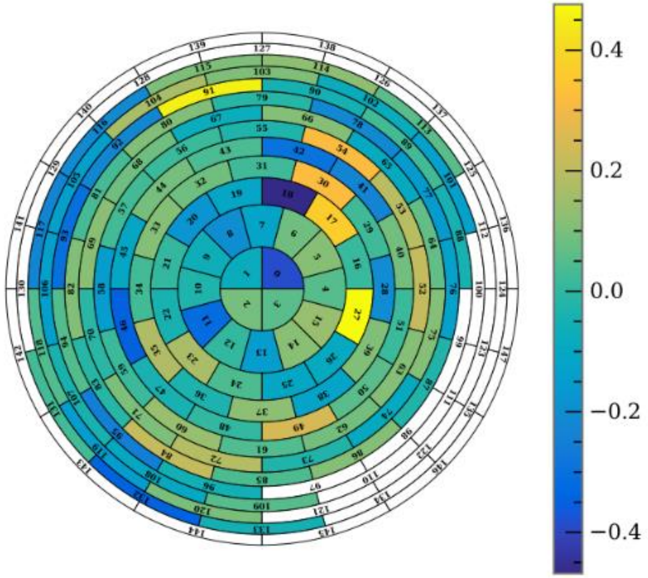


Generation of final spectrum

No temporal effects in single scan fits



No spatial effects in single pixel fits

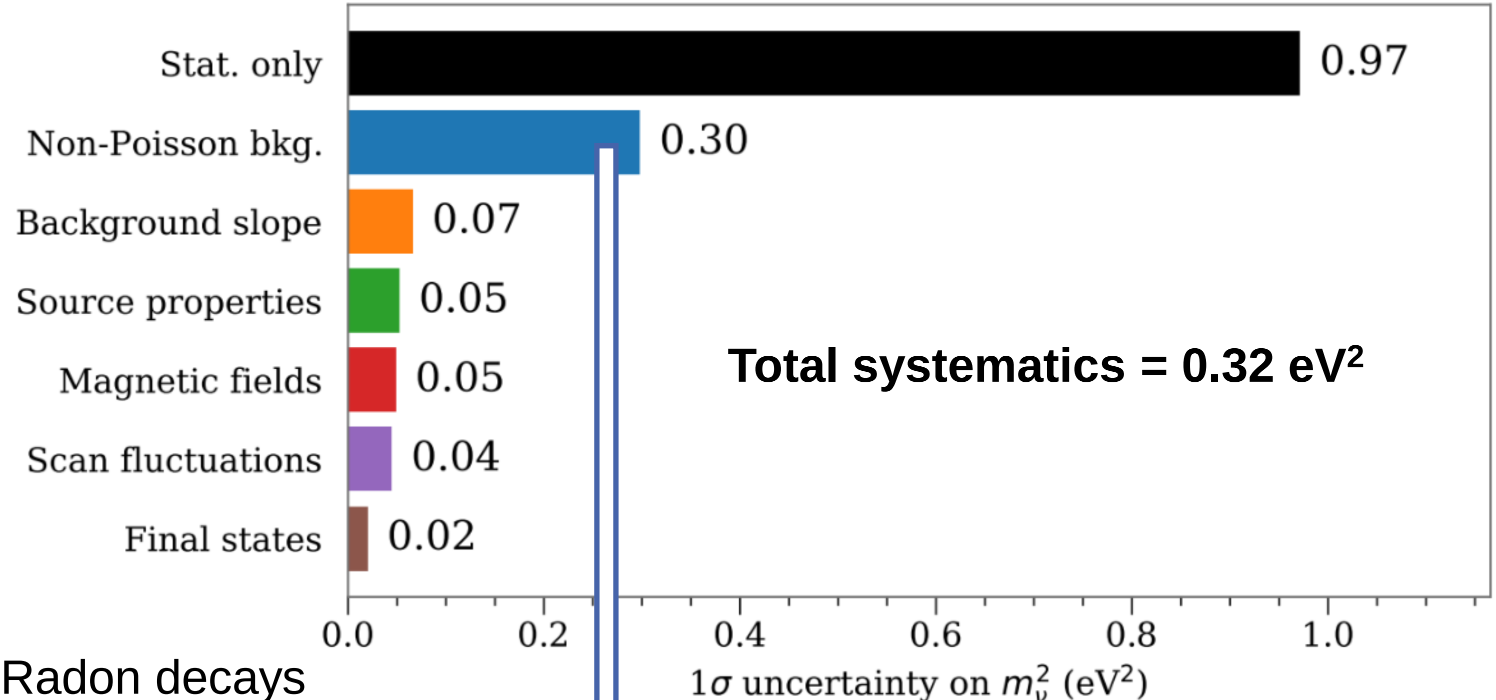


- **Strategy for first neutrino mass analysis**
  - Add up all runs (average slow control parameters, excellent HV stability!)
  - Add up all pixel (average transmission function)

Additional systematics by „simplification“ (≪ statistical uncertainty in this run!)

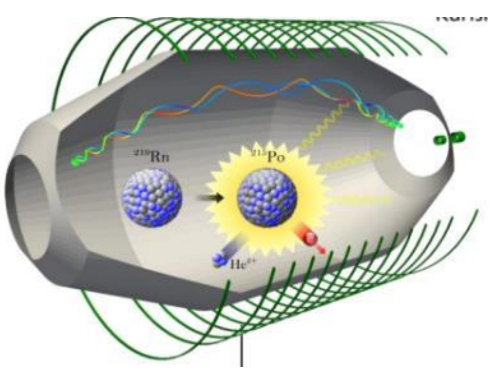
Tritium Laboratory Karlsruhe

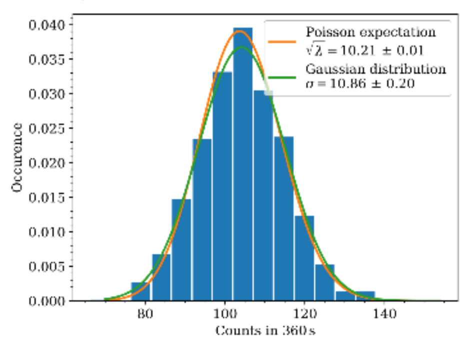
Uncertainty breakdown



Total systematics = 0.32 eV^2

Radon decays

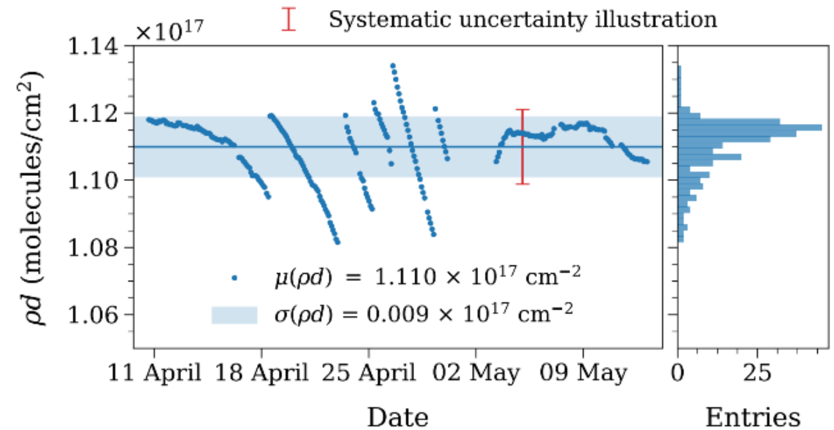


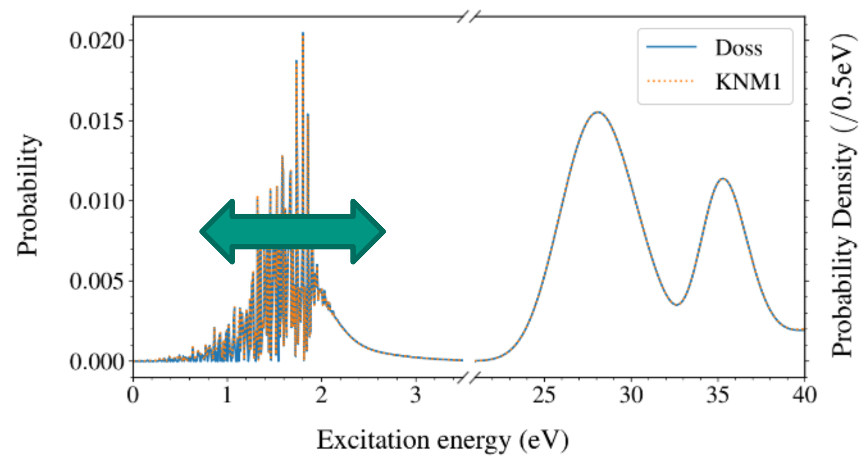


Dominated by statistics
(5 effective days of measurements)

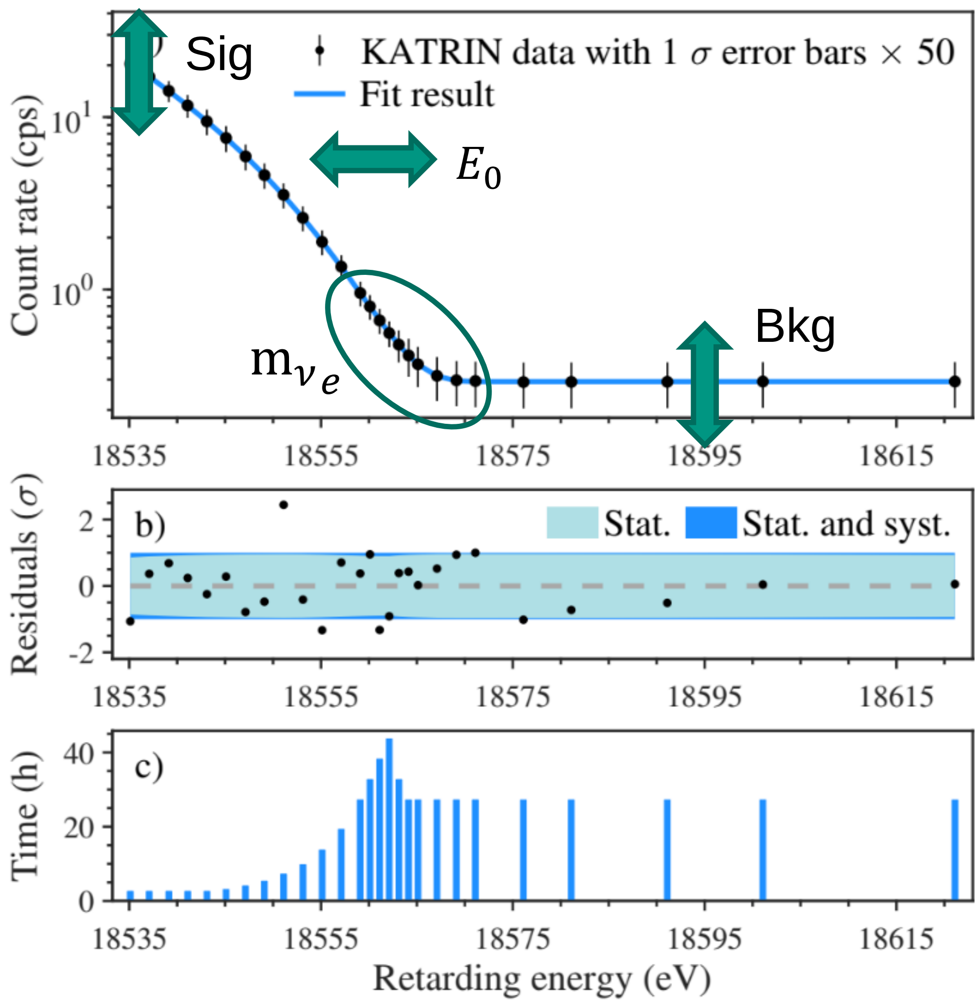
Analysis strategy

- **Analysis on Monte Carlo data**
  - Generated from actual sensor data
  - Neutrino mass = 0 eV
  - Freezing before unblinding
- **Model blinding**
  - Add unknown scaling to final-state distribution calculation → would result in shifted neutrino mass
- **Independent fitting strategy and teams**
  - Systematics via 1) Covariance matrix and 2) MC propagation





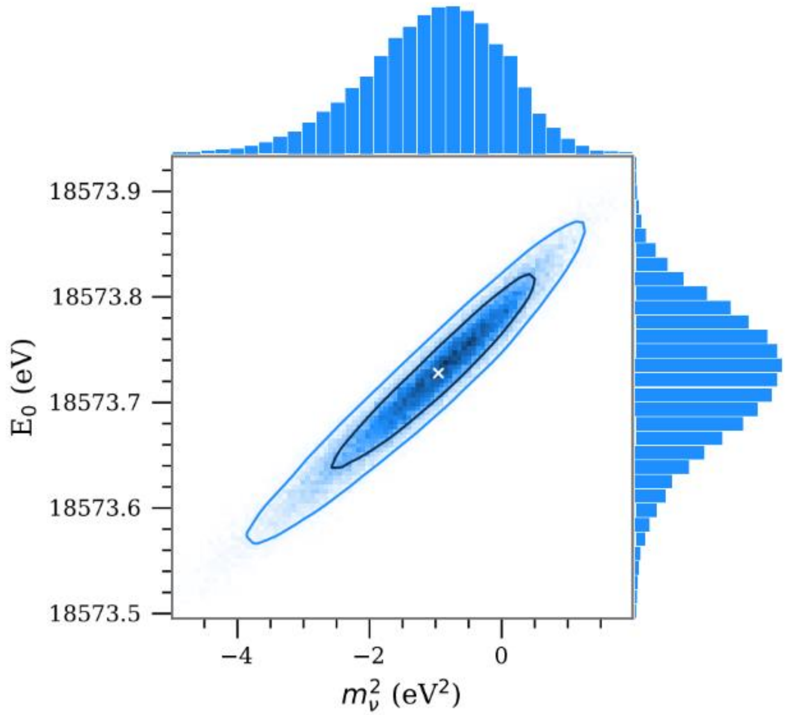
Final spectral fit



- **Number of eventa in ROI:**
  - $\mathbf{2 \cdot 10^6}$
- **4 parameter fit**
  Bkg, Sig, E_0, m_{ν_e}
- p-value = 0.56

excellent goodness-of-fit

Final fit results



- **Independent analysis methods**
  systematics propagation and parameter fit

- **Neutrino mass**

$$m^2(\nu_e) = (-1.0^{+0.9}_{-1.1})\ \mathrm{eV}^2$$
$$(90\%\ \mathrm{C.L.})$$

- **Endpoint**

$$E_0 = 18573.7 \pm 0.1\ \mathrm{eV}$$

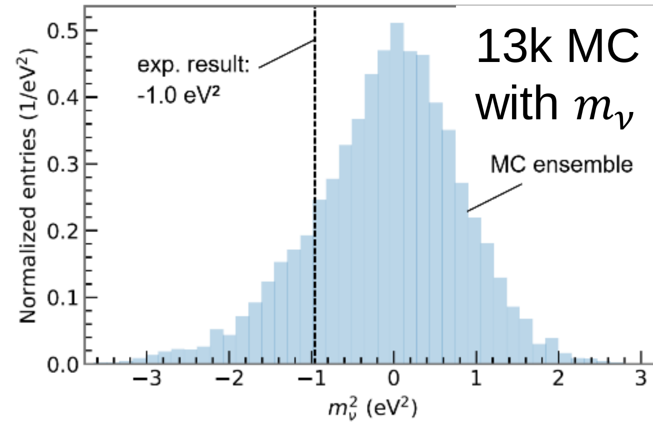
Phys. Rev. Lett. 114, 013003 (2015)

agreement

Q-value $(\Delta M(\mathrm{T},\ {}^3\mathrm{He}) = (18575.2 \pm 0.5)\ \mathrm{eV}$ ⟺ Q-value (KATRIN) $(18575.72 \pm 0.07)\ \mathrm{eV}$

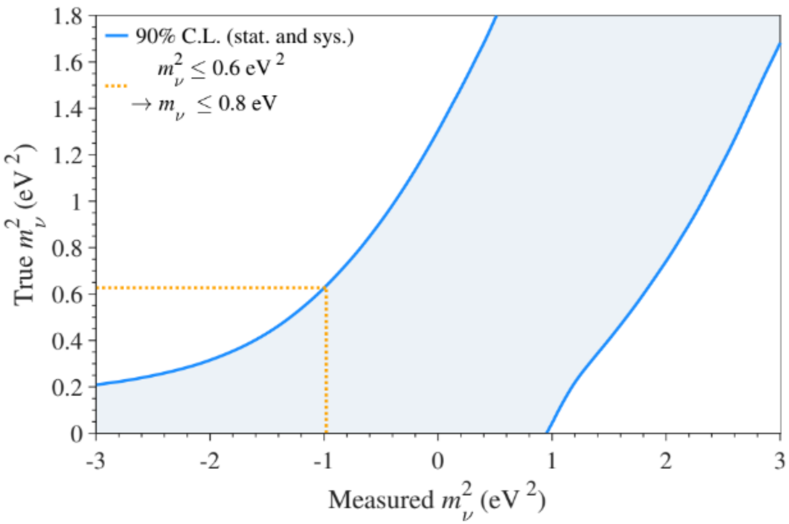
Understanding of final result

- **Confidence belts**
  - **Lokhov-Tkachov**
    $m_\nu < 1.1$ eV (90% CL)
  - **Feldman-Cousins**
    $m_\nu < 0.8$ eV (90% CL)
  - **Bayesian Confidence Interval (m_ν^2, flat)**
    $m_\nu < 0.9$ eV (90% CL)

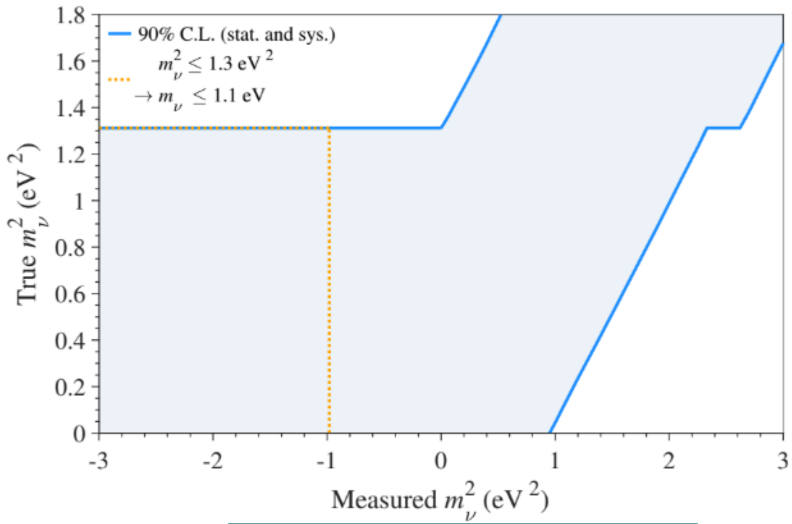


13k MC samples with $m_\nu = 0$ eV

Best fit: 1σ fluctuation to negative



Feldman-Cousins



Lokhov-Tkachov

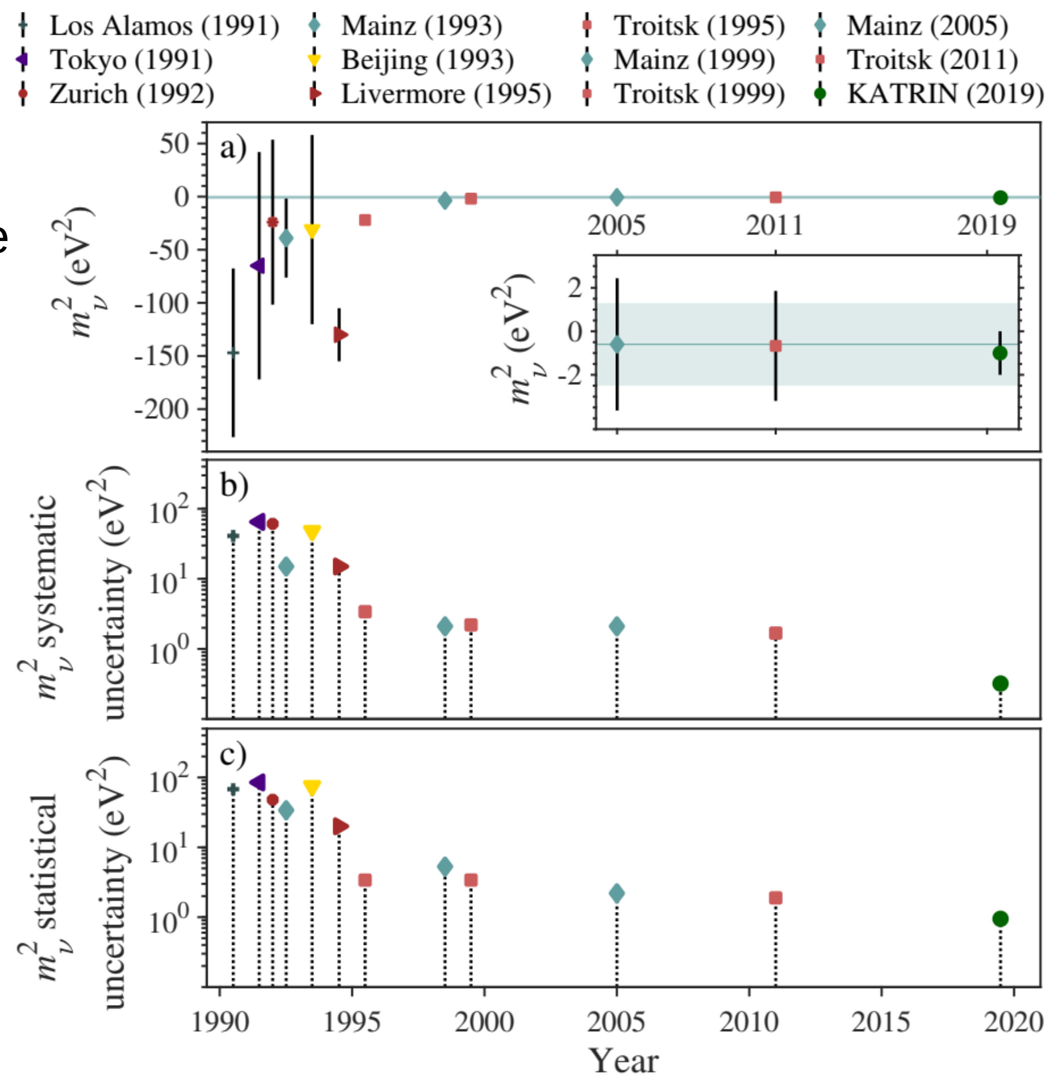
Neutrino mass measurements

- Effective measurement time
  5 days

  Full KATRIN measurement time
  1000 days

Improve systematics:
factor 6

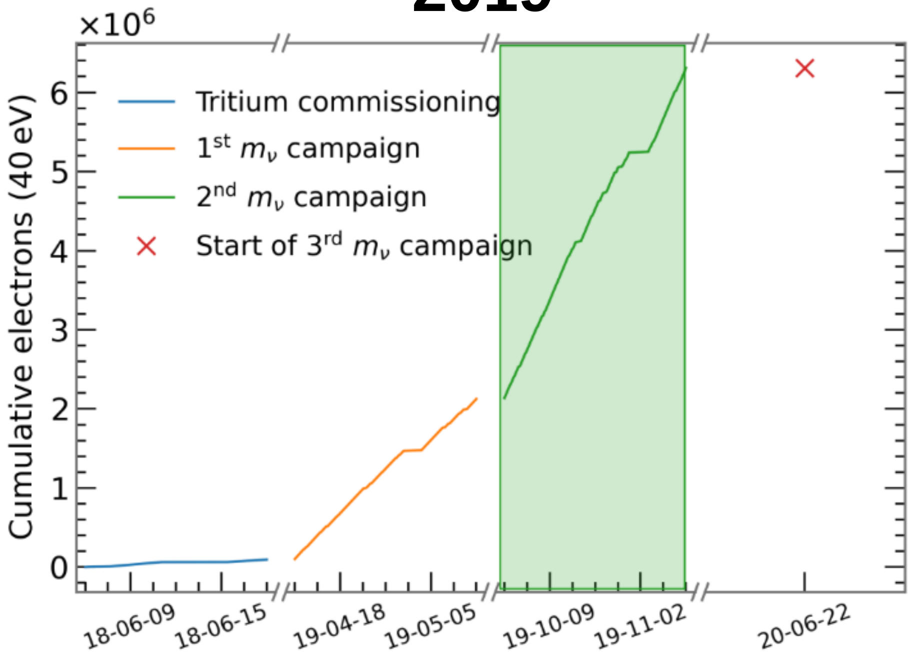
Improve statistics:
factor 2



Tritium Laboratory Karlsruhe

Next neutrino mass campaigns

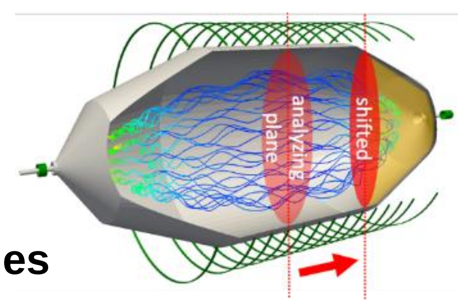
2019



• Measurement time:	31 days
• **Gas density:**	**84%**
• Isotopic purity:	97.5% tritium
• **Source activity:**	**$9.8 \cdot 10^{10}$ Bq**
• Total statistics:	$4 \cdot 10^6$ e's

Unblinding soon in the next weeks

- **2020**
  - **Spring/Summer: Third neutrino mass run**
    - **Study of source plasma systematics**
    - **Implementation of background reduction techniques**



  - **Fall/Winter: Fourth neutrino mass run**

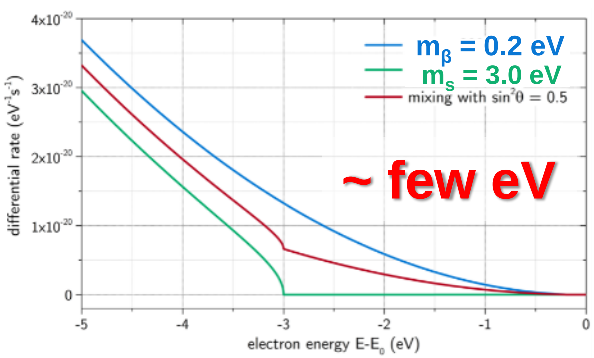
Starting this week

A view to the future

2019 – 2023…
Neutrino mass measurement

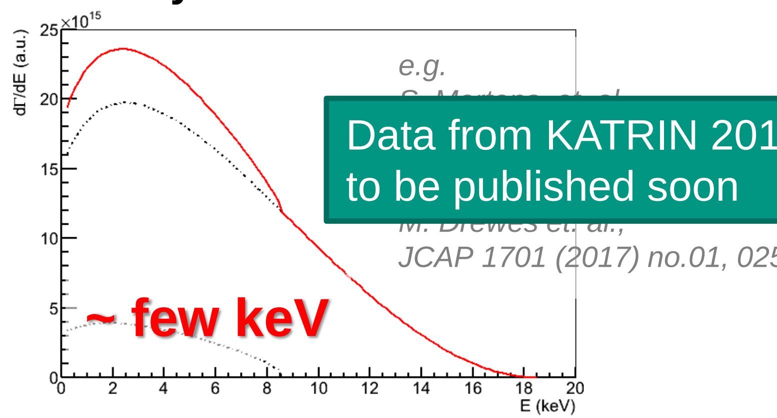
R&D: new techniques (e.g. ToF spectroscopy, atomic sources, …)

BSM searches (eV sterile, Lorentz-Violation, …)



No extra data taking required!

Heavy sterile neutrino search



Data from KATRIN 2018 to be published soon

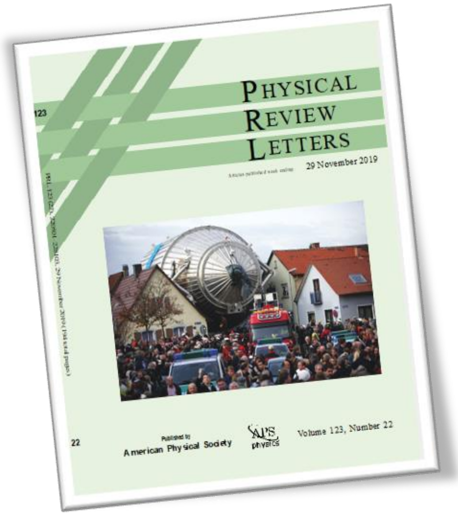
KATRIN with new TRISTAN detector

Tritium Laboratory Karlsruhe

Summary & Conclusion

- **KATRIN achieved world-best direct neutrino mass limit**

m_ν < 1.1 eV (90% CL)



KATRIN Collab, Phys. Rev. Lett. 123, 221802

- **KATRIN is in operation for next „1000 days“**

m_ν < 200 meV (90%CL) & search for “new physics”

- ***First data on eV and keV sterile neutrinos will be published soon***

The KATRIN collaboration

Funding and support from: **Helmholtz Association** (HGF), **Ministry for Education and Research BMBF** (05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), **Helmholtz Alliance for Astroparticle Physics** (HAP), and **Helmholtz Young Investigator Group** (VH-NG-1055) in Germany; **Ministry of Education, Youth and Sport** (CANAM-LM2011019), cooperation with the **JINR Dubna** (3+3 grants) 2017–2019 in the Czech Republic; and the **Department of Energy** through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, and DE-SC0011091 in the US.