KATRIN: First neutrino mass results, next steps and the future

Magnus Schlösser for the KATRIN collaboration

INFN seminar, 8 July 2020, Online

INSTITUTE FOR NUCLEAR PHYSICS, TRITIUM LABORATORY KARLSRUHE

Short motivation

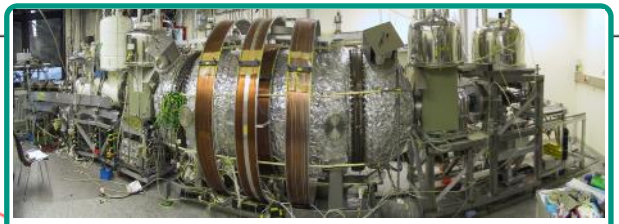
~300 neutrinos per cm^3

m_ν?

More motivation in previous talks

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

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

tritium (^{3}H)
β spectroscopy

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

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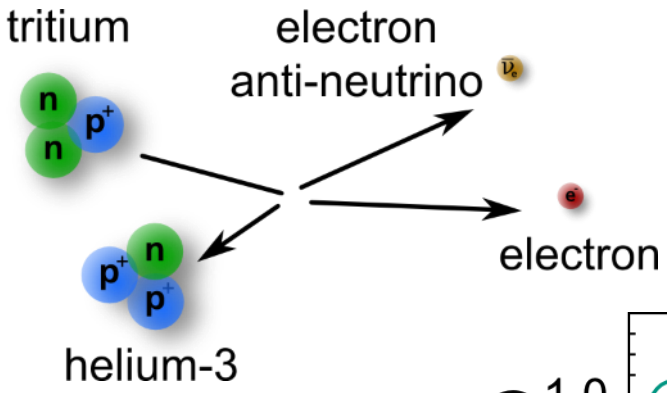
Tritium β-decay

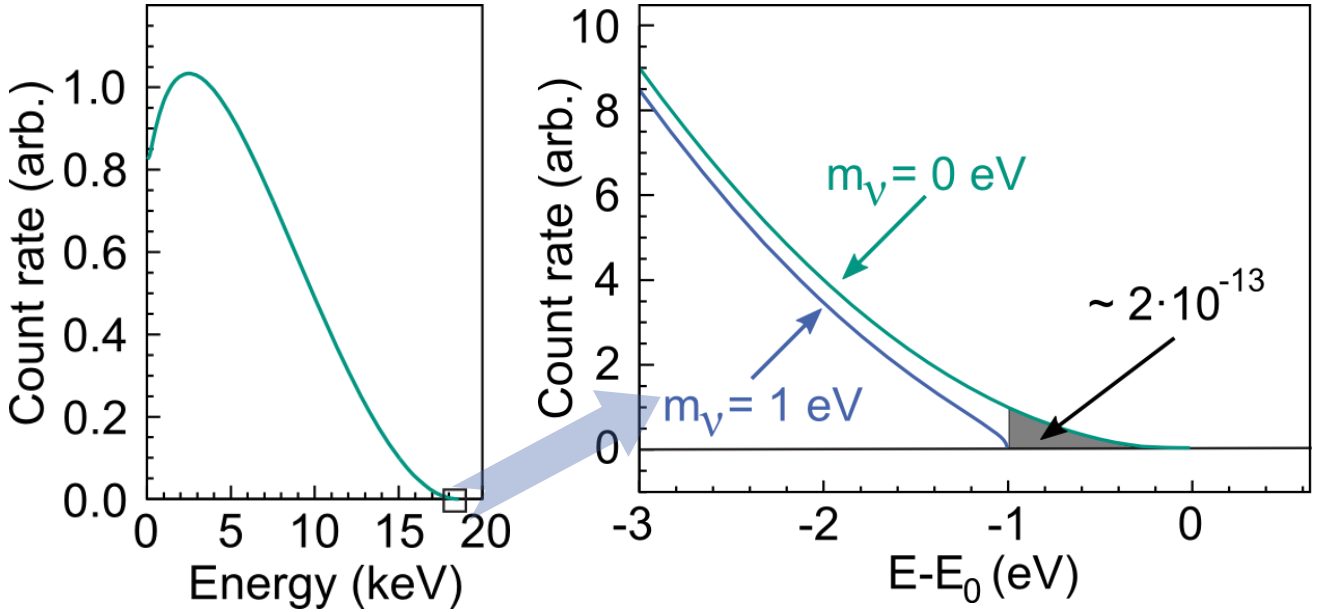


β -electron spectrum

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

E_0 = 18.6 keV

$T_{1/2}$ = 12.3 y



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

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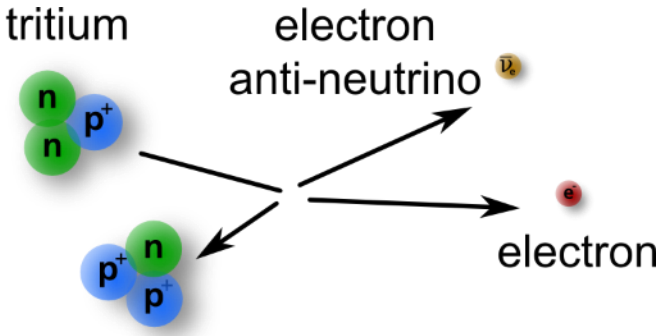
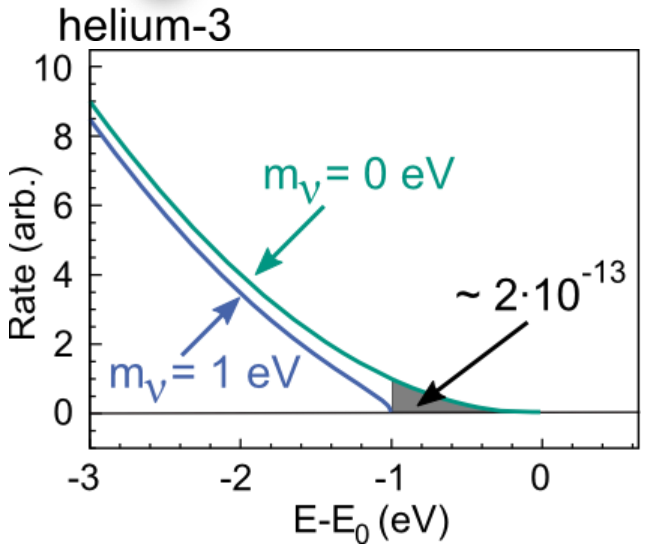
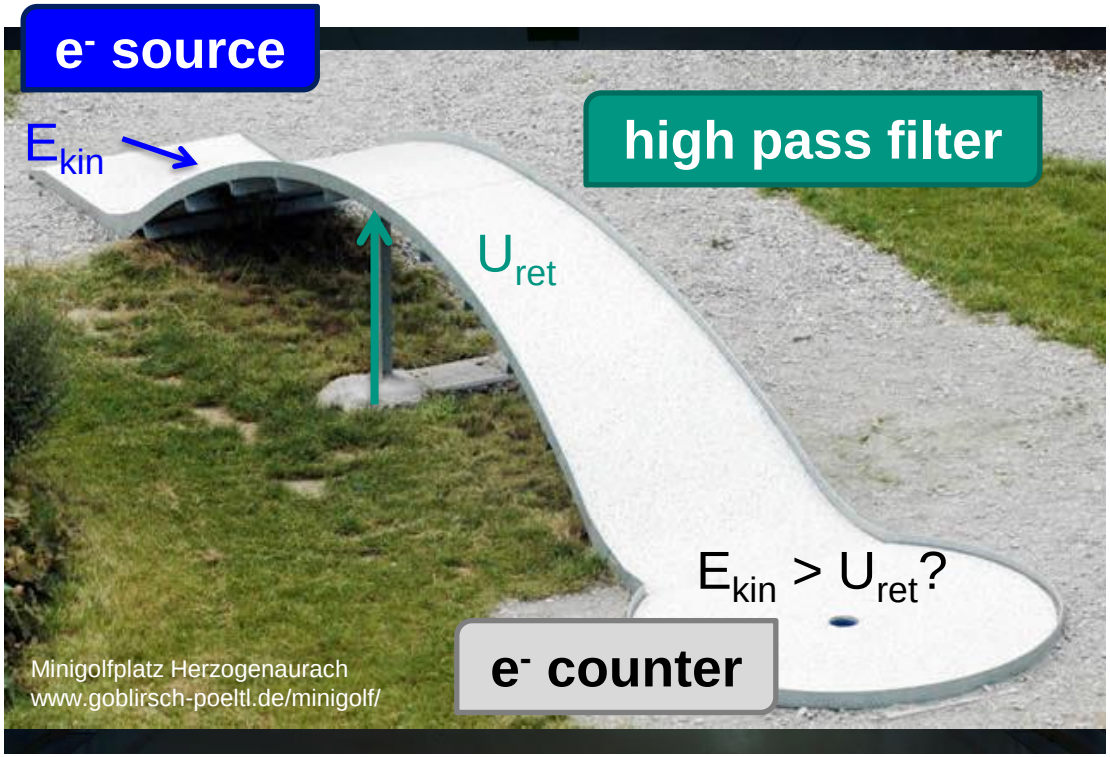
The Karlsruhe Tritium Neutrino Experiment







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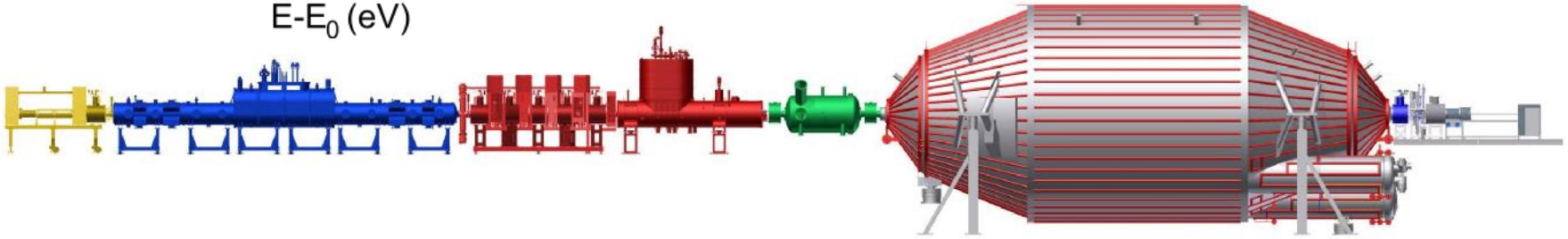

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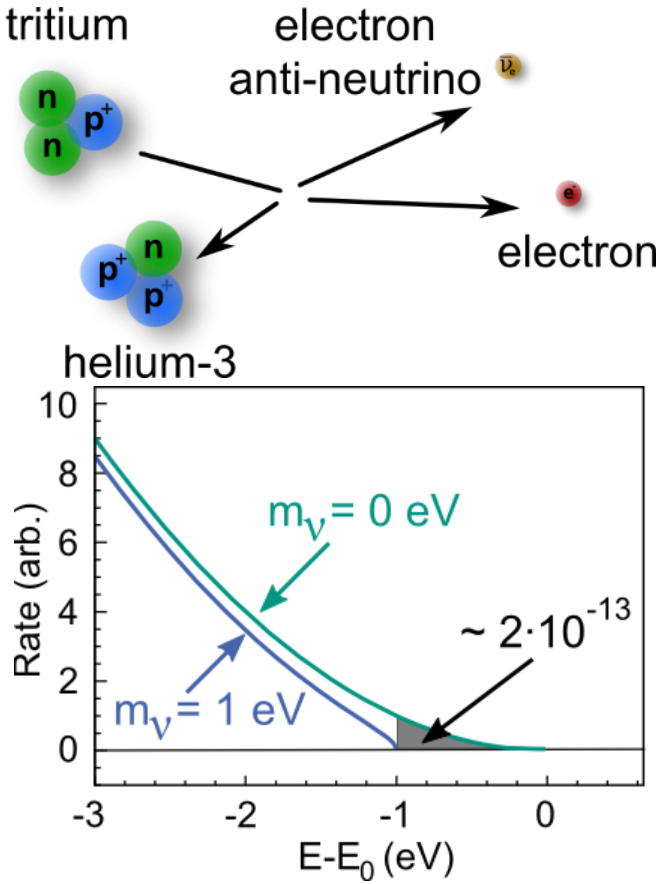
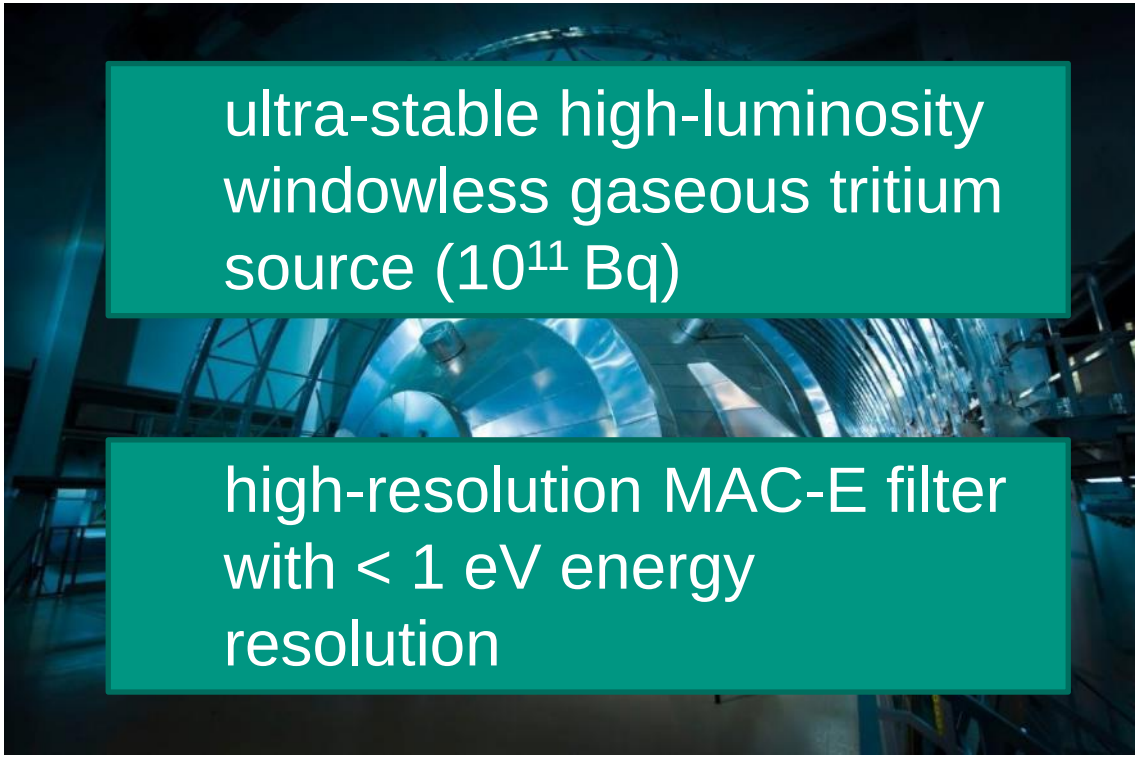
The Karlsruhe Tritium Neutrino Experiment





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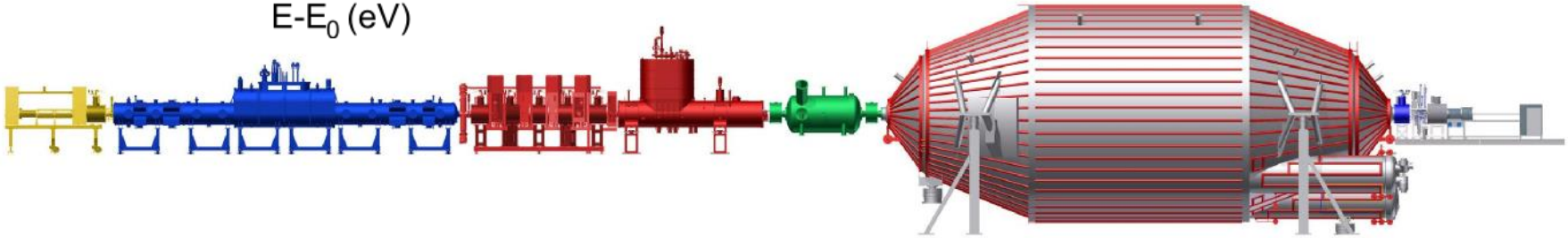

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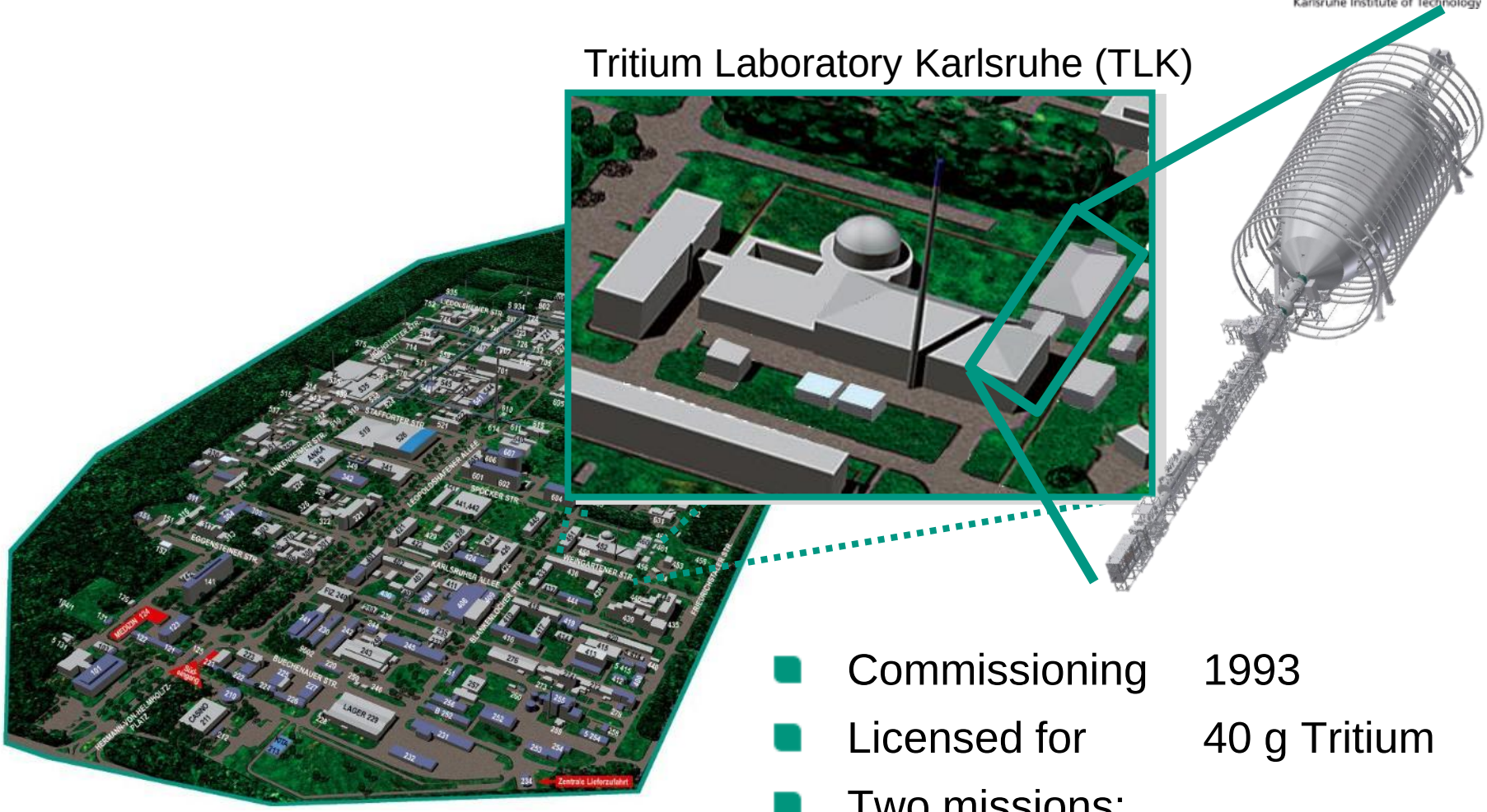
The Tritium Laboratory Karlsruhe



Karlsruhe Institute of Technology

Campus North

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

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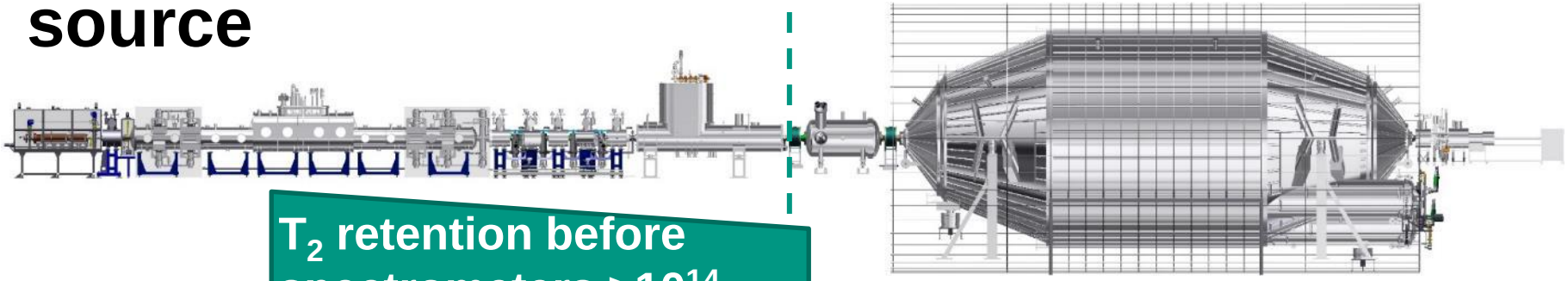
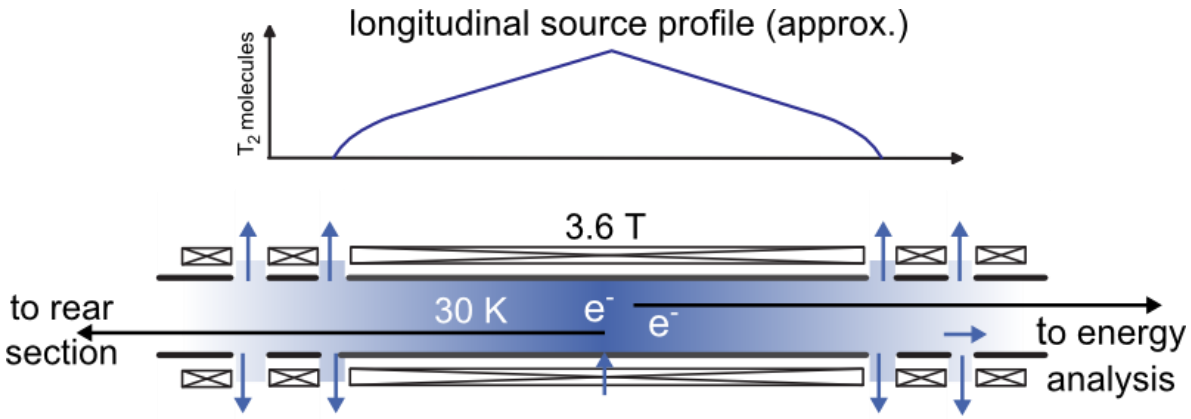
A high-luminosity, ultra-stable tritium source



T_2 retention before spectrometers >10^{14}



- 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

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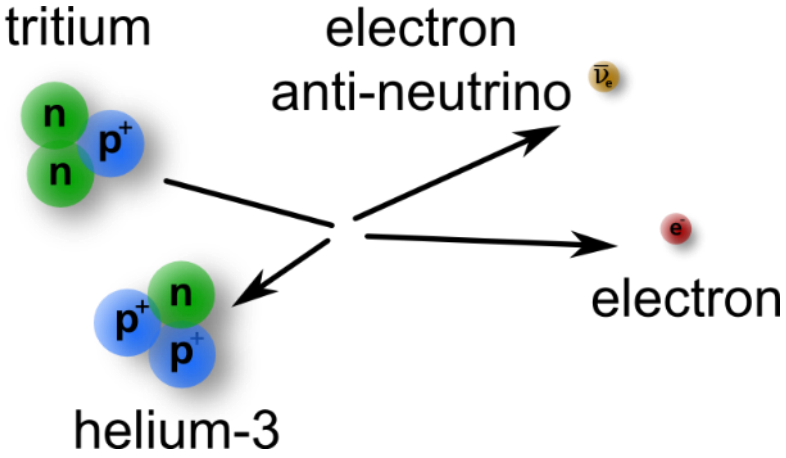
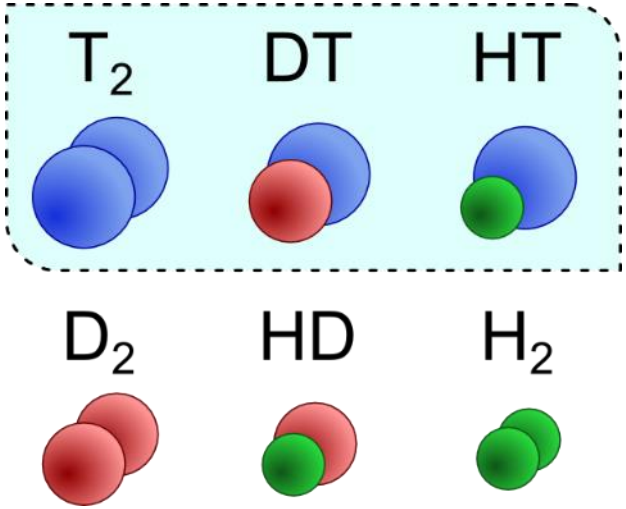
Molecular decay

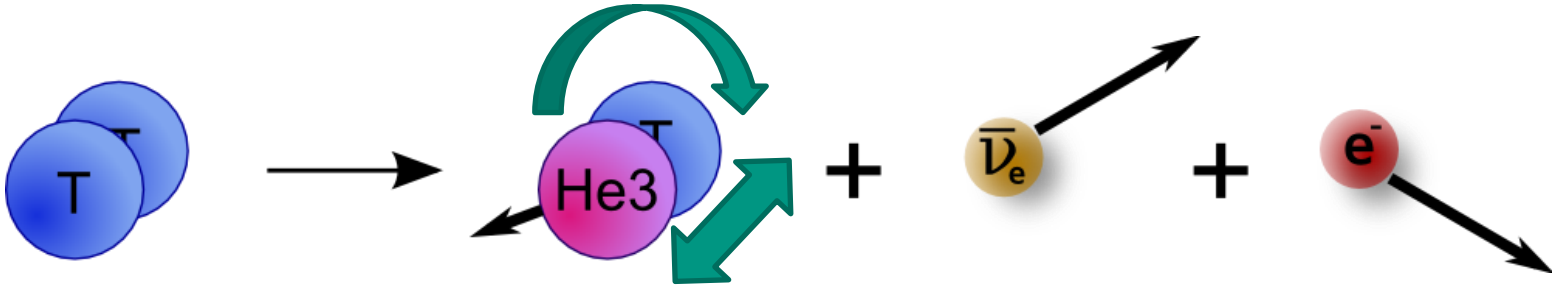
Atomic decay



Hydrogen isotopologues

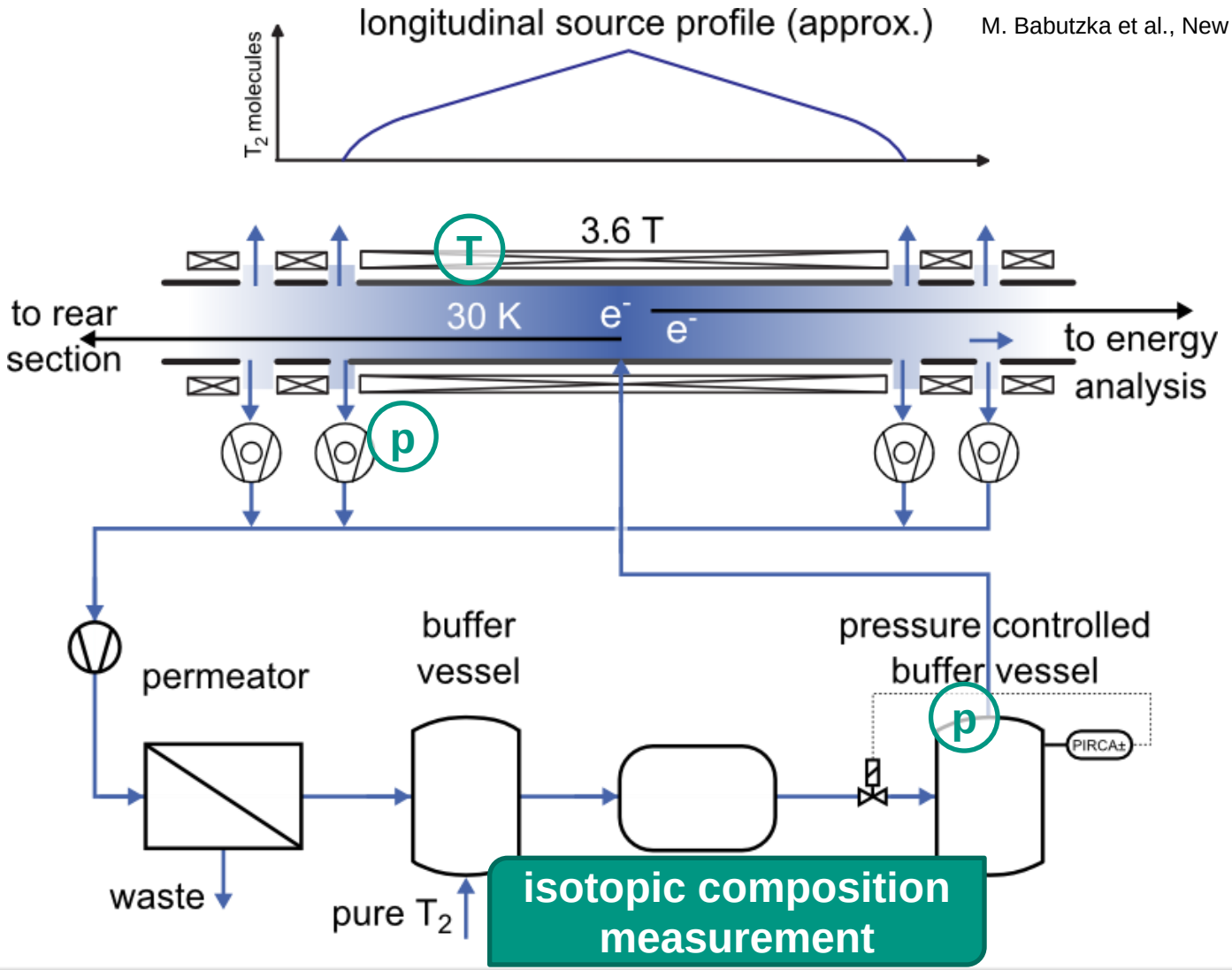


Decay from a molecule



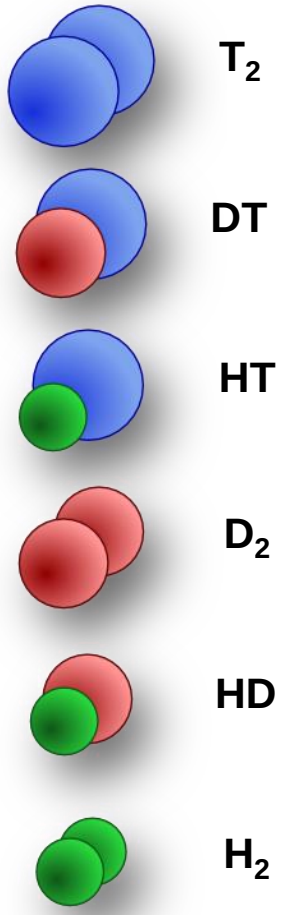
+ further inner excitations (rotation / vibration)

The stable tritium source



M. Babutzka et al., New J. Phys. **14** (2012) 103046

Hydrogen isotopologues



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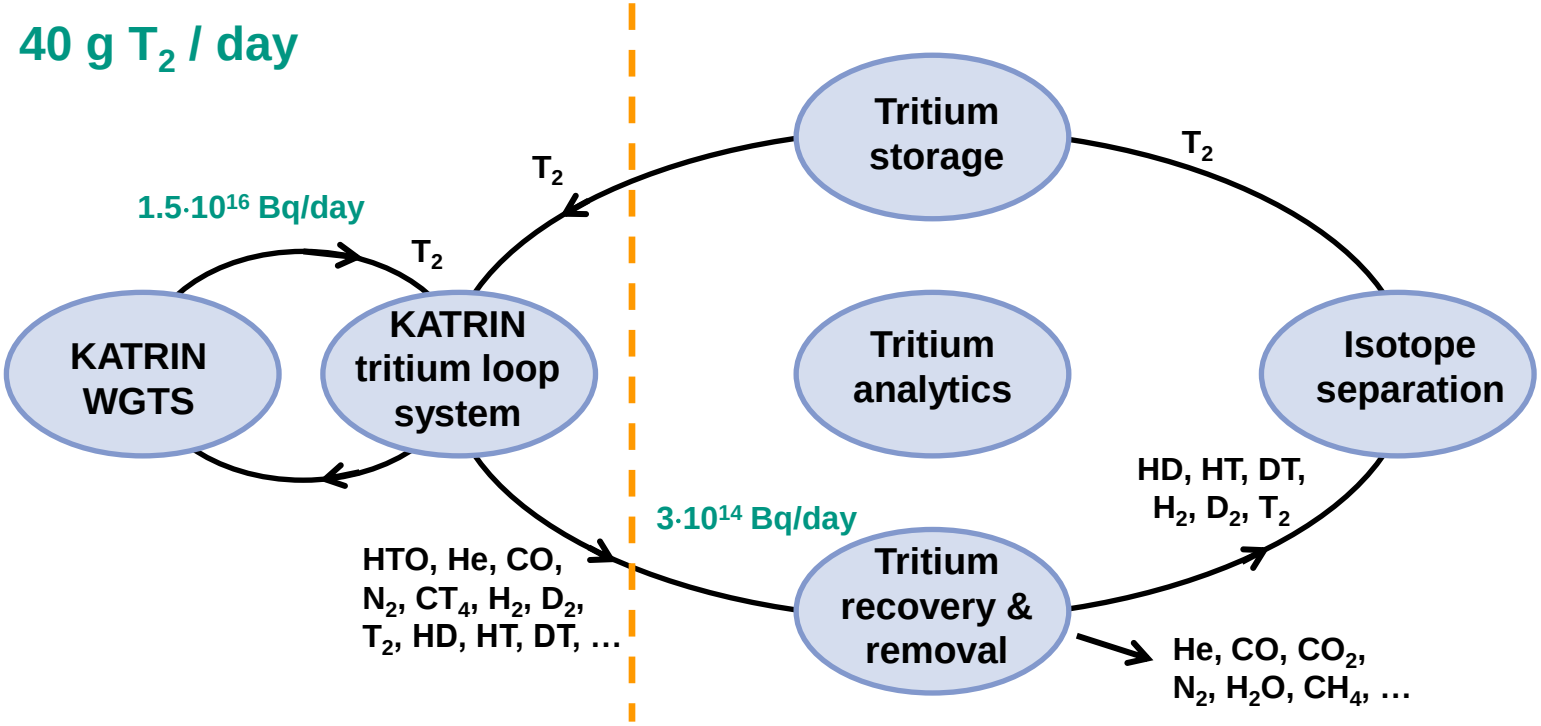
The closed tritium loop of KATRIN and the TLK

Tritium loops of KATRIN (STS) | **Main infrastructure of TLK**



Closed tritium processing needed to provide the high activity and isotopic tritium purity for KATRIN

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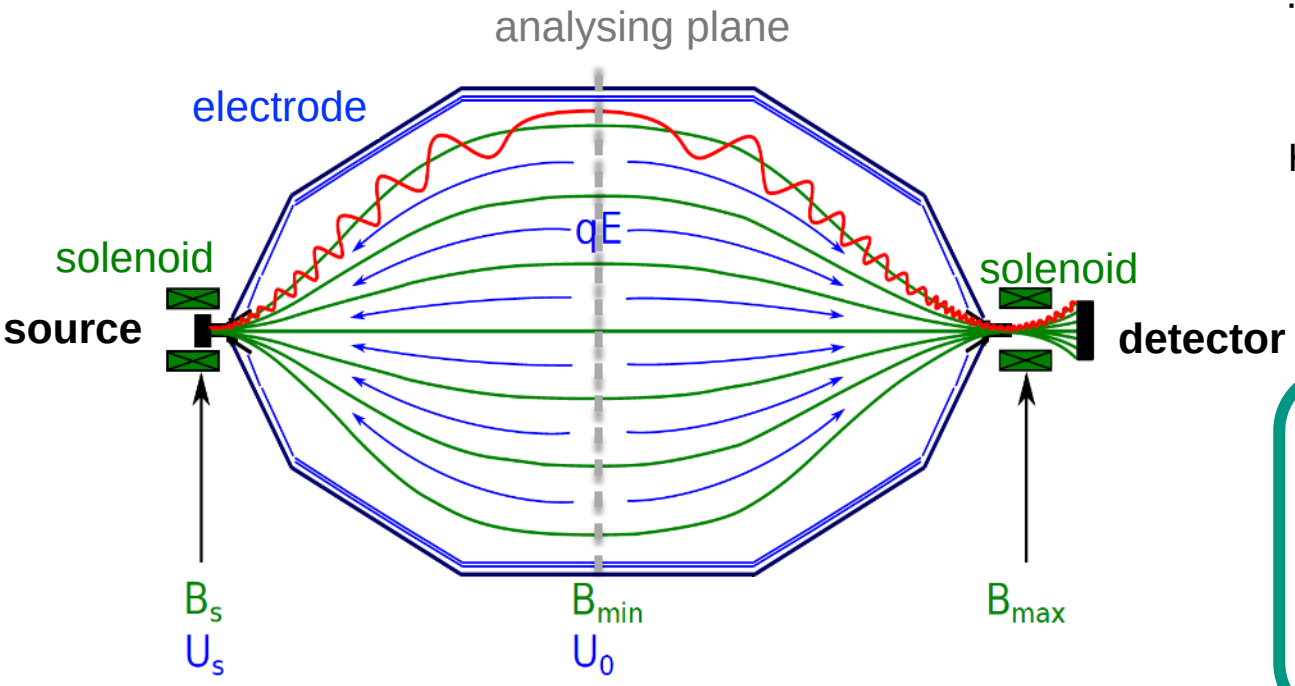
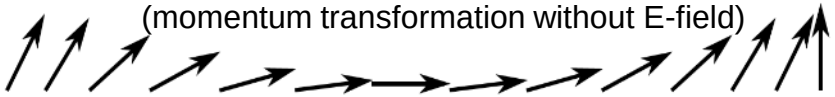
High-resolution spectrometer: MAC-E filter

Magnetic Adiabatic Collimation & Electrostatic Filter:

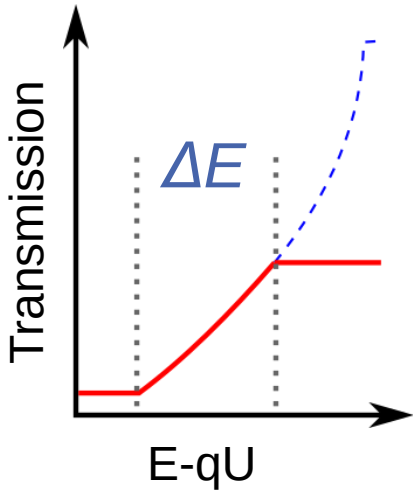
- integrating electrostatic filter ($E_{kin} > eU_0$)
- "clean" (analytic) response function



$\mu = E_\perp / B$



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)

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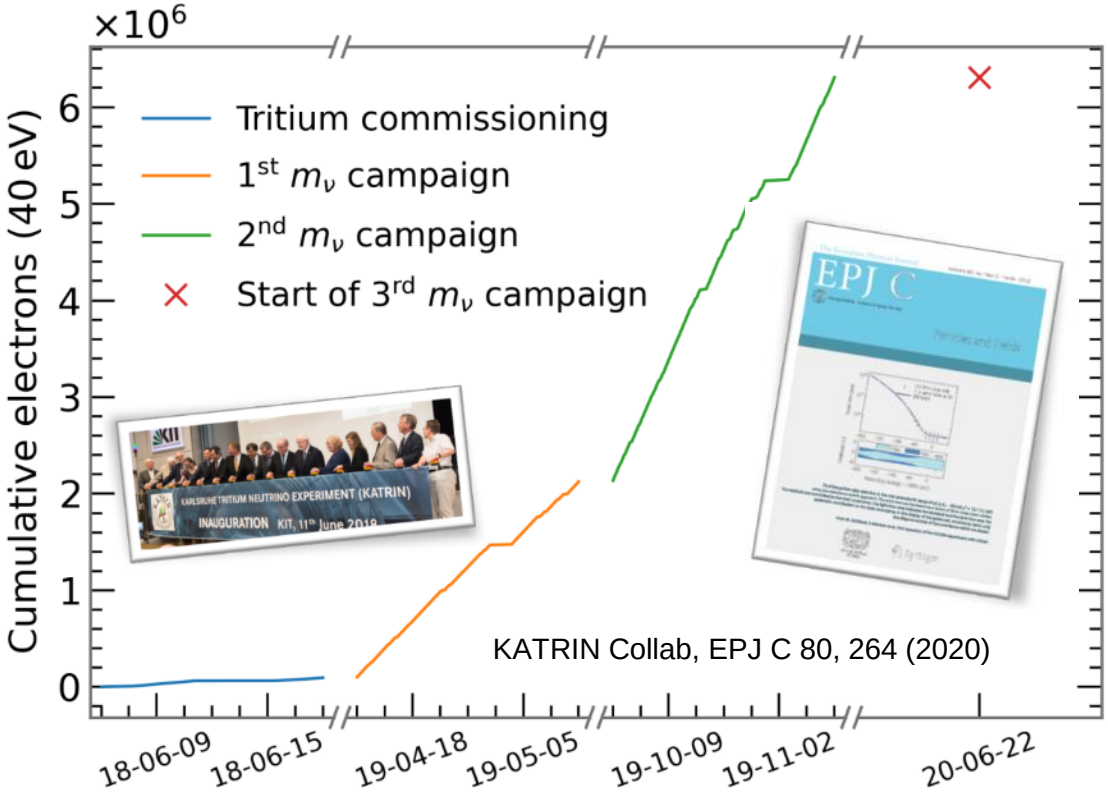
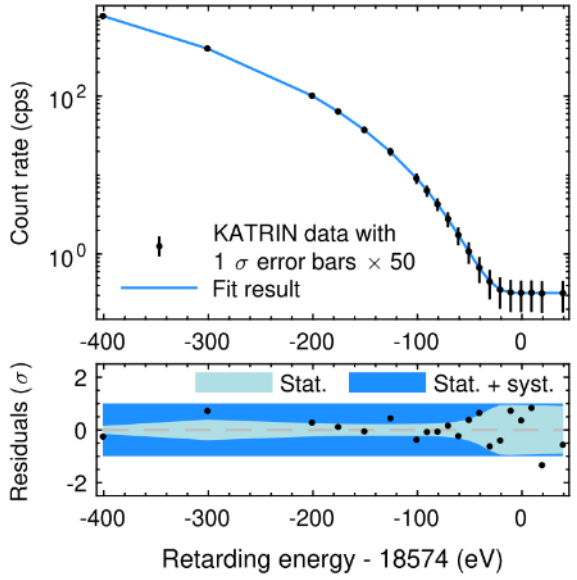
First tritium „engineering“ run with KATRIN 2018



- **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

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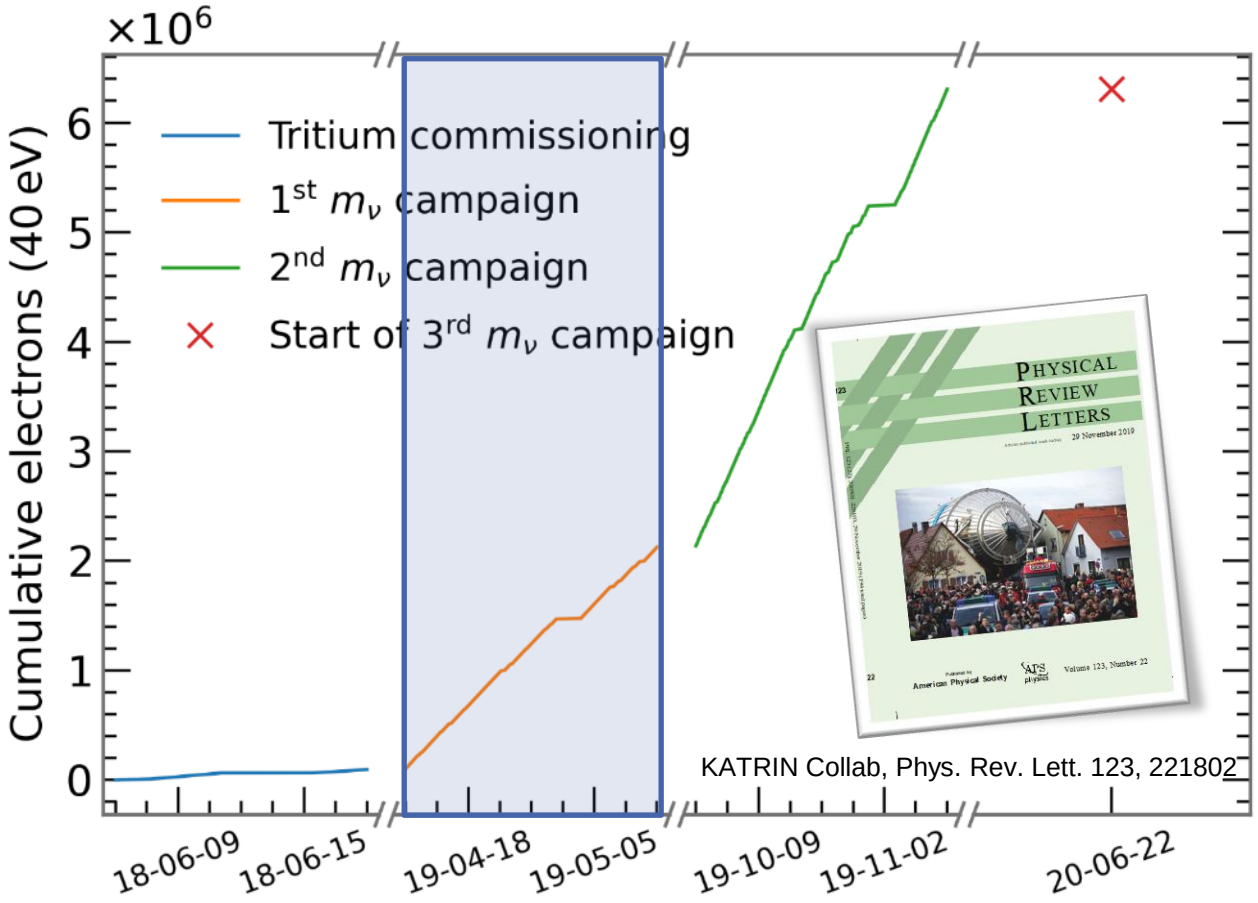
First neutrino mass campaign with KATRIN 2019



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

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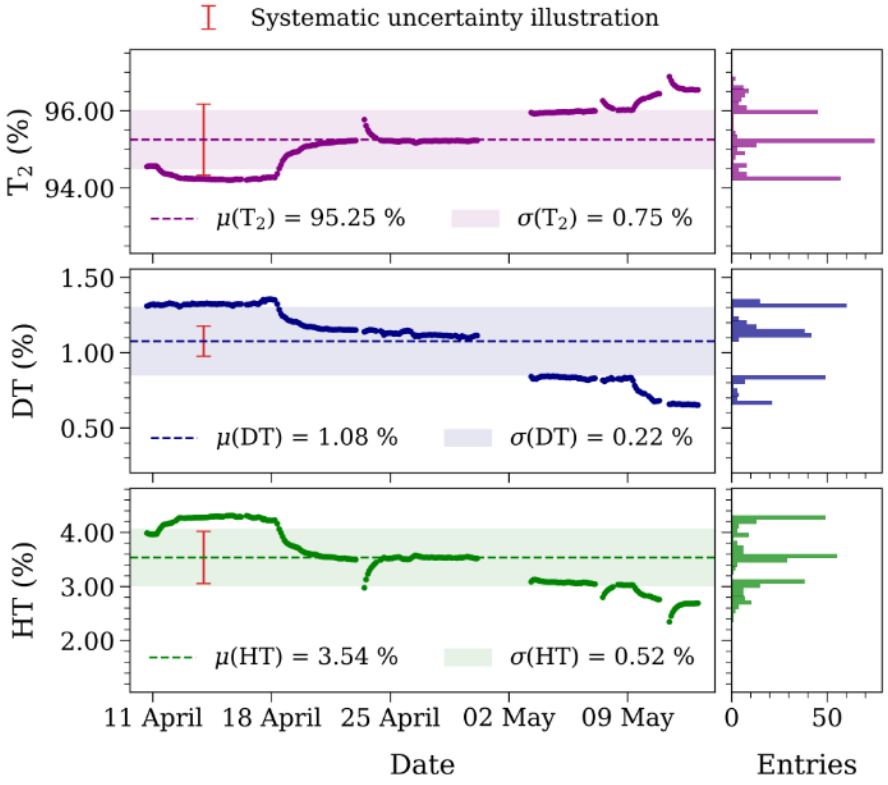
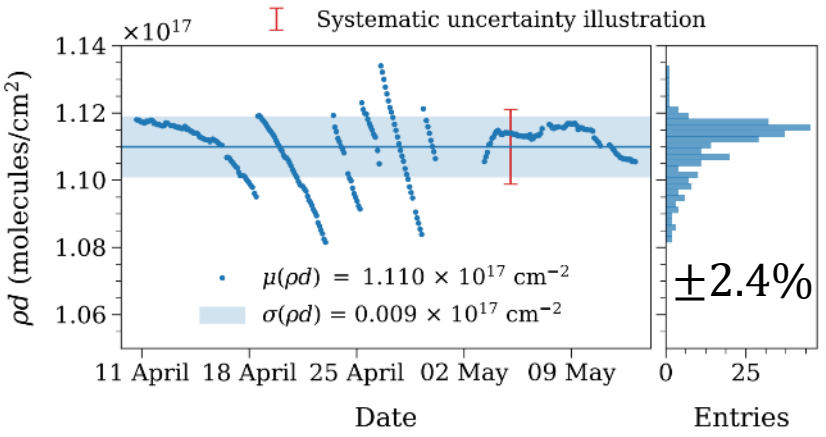
First KATRIN measurement campaign

- **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 source parameters

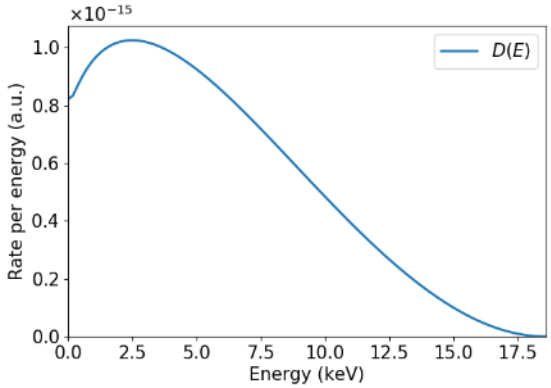


Very high tritium purity achieved

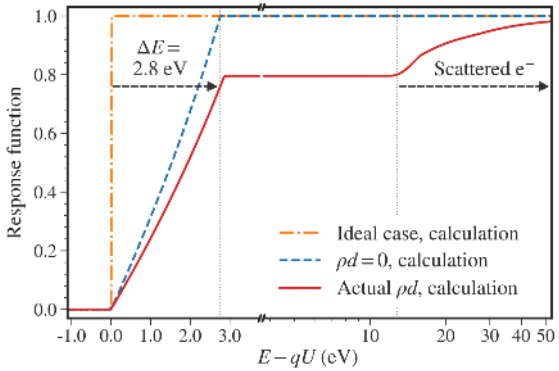


- **Reduced column density (22%)**
- **Radiochemical methane generation**
- **Throughput limited (initial burn-in effect)**

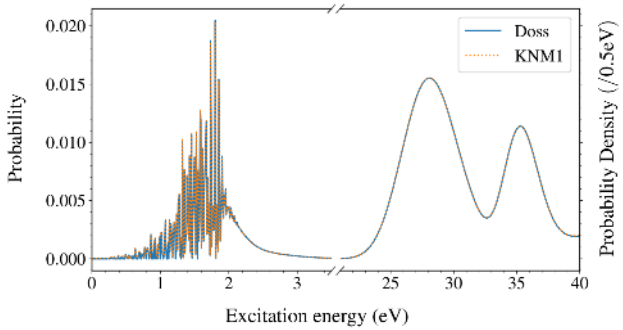
Ingredients for integral spectrum



Differential spectrum

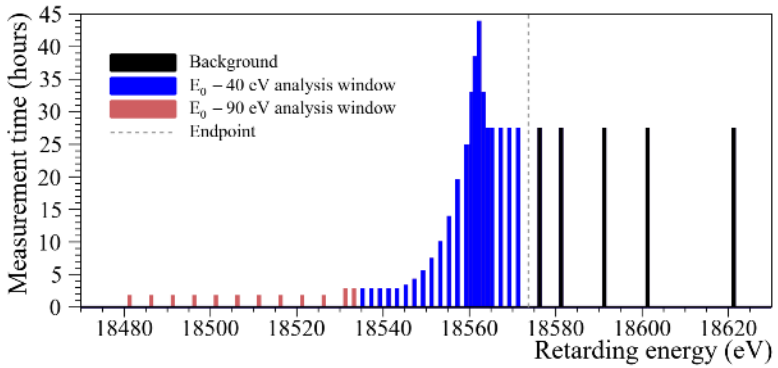


Experimental response (scattering, transmission, ..)

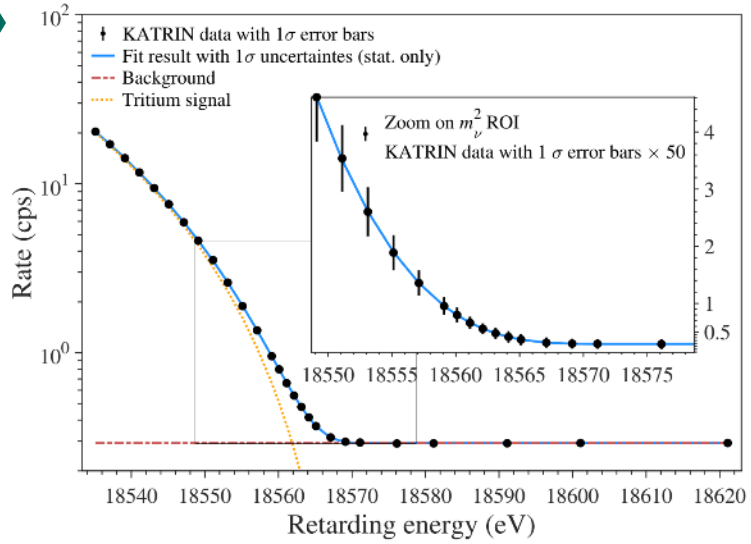


Molecular final state distribution

Measurement time distribution



Integrated spectrum



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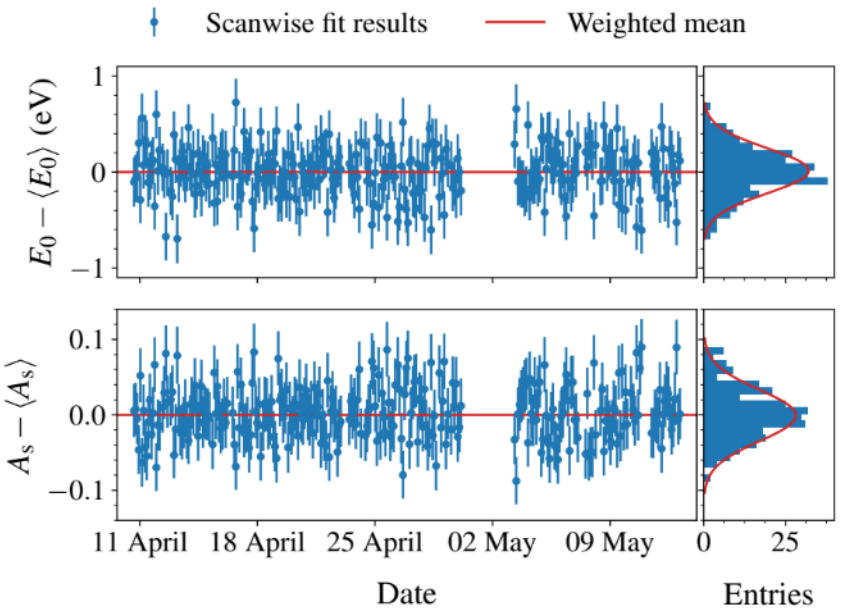
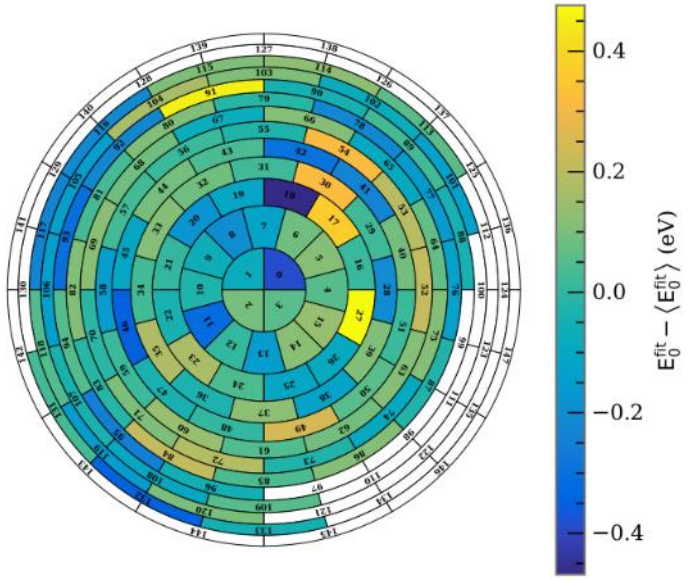
Generation of final spectrum

No temporal effects in single scan fits



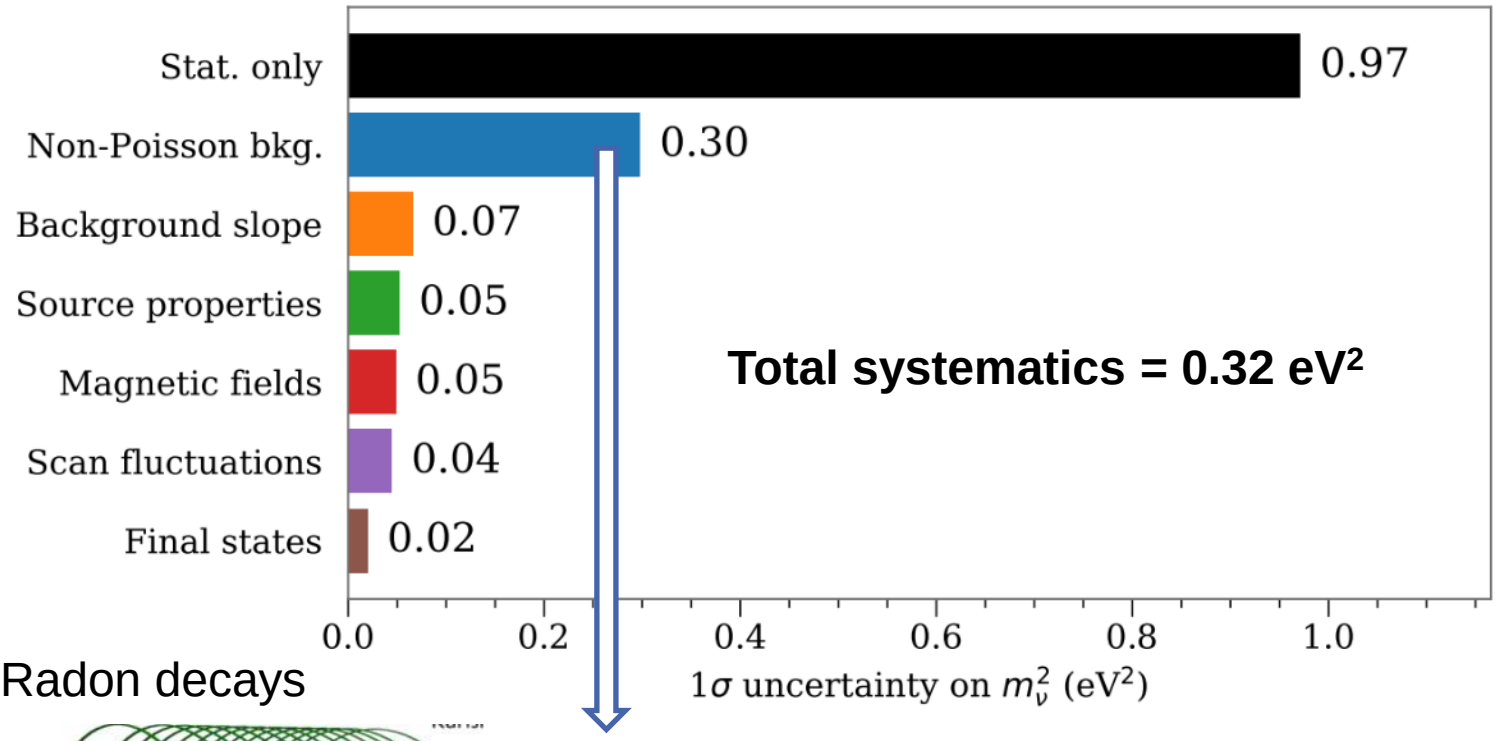
No spatial effects in single pixel fits



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

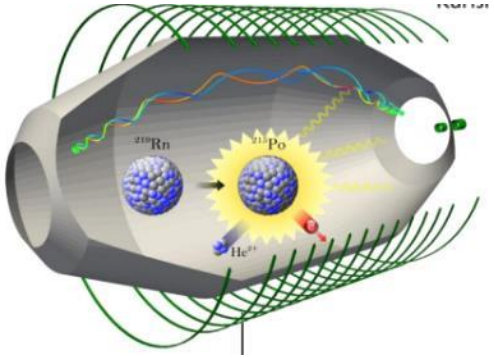
Additional systematics by „simplification“ (≪ statistical uncertainty in this run!)

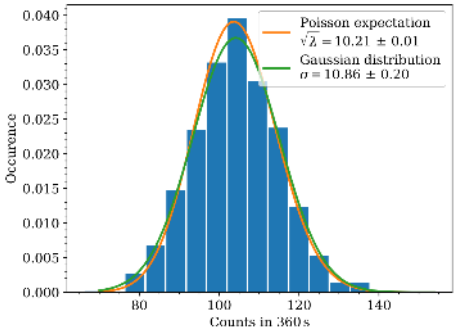
Uncertainty breakdown



Total systematics = 0.32 eV²

Radon decays





Dominated by statistics
(5 effective days of measurements)

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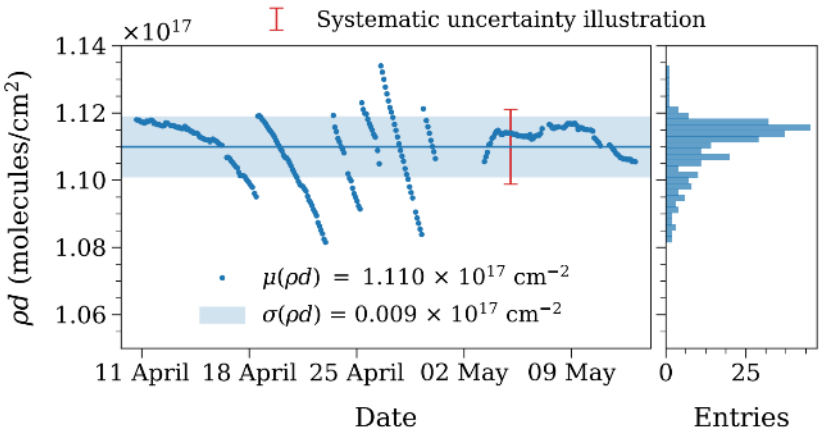
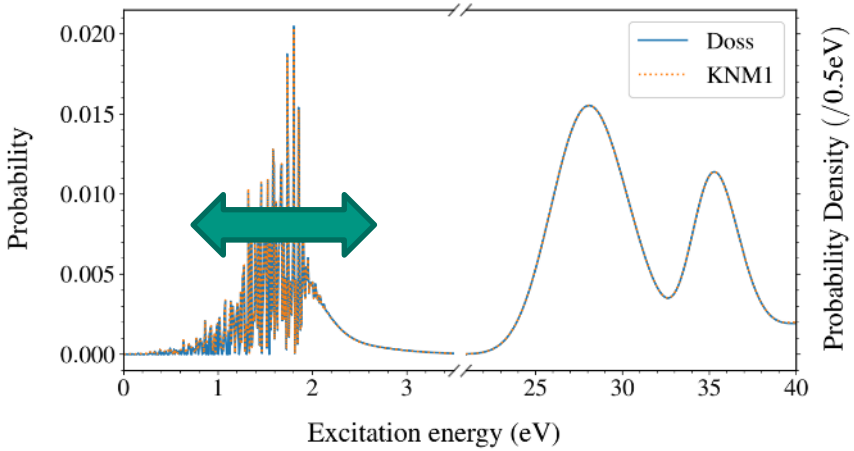
Analysis strategy

- **Analysis on Monte Carlo data**
  - Generated from actual sensor data
  - Neutrino mass = 0 eV
  - Freezing before unblinding

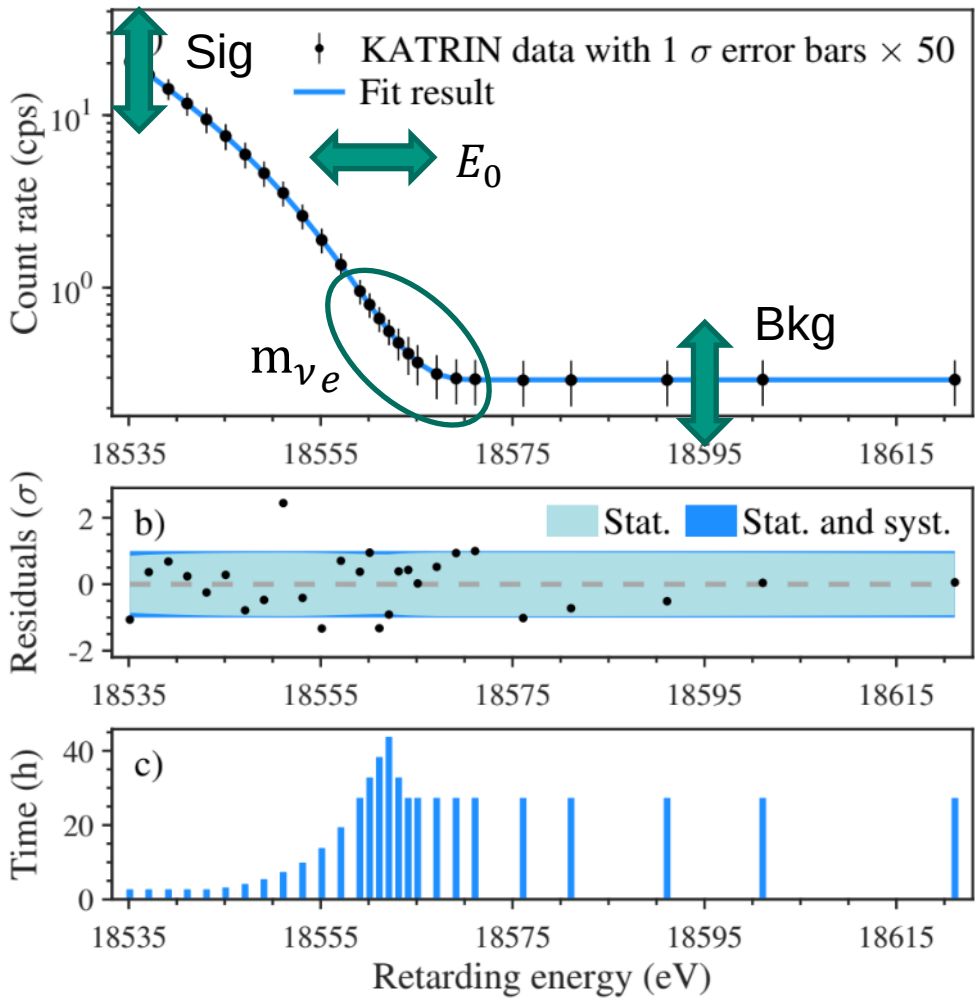


- **Model blinding**
  - Add unknown scaling to final-state distribution calculation → would result in shifted neutrino mass



- **Independent fitting strategy and teams**
  - Systematics via 1) Covariance matrix and 2) MC propagation

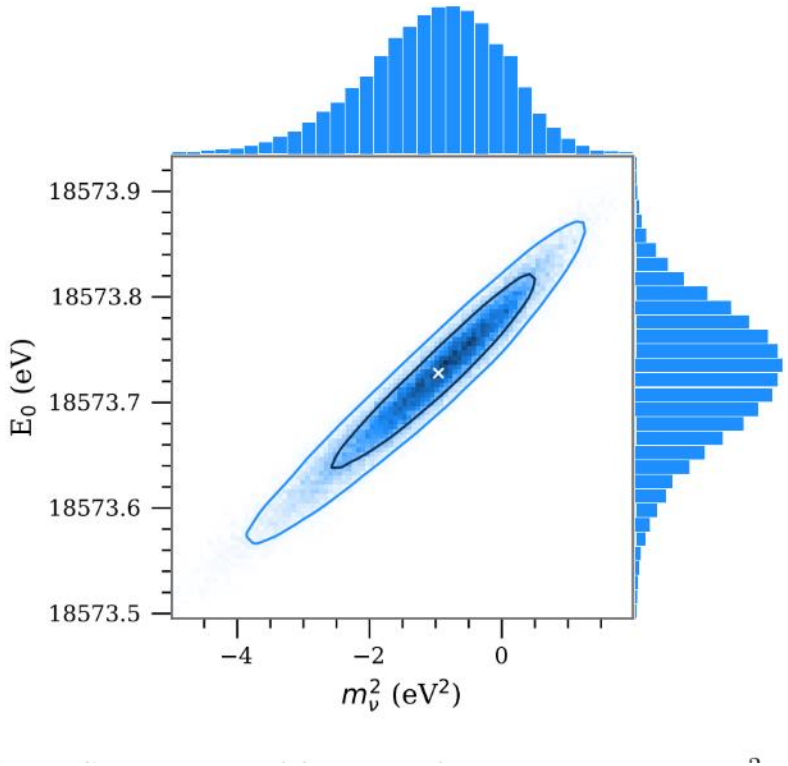
Final spectral fit



- **Number of eventa in ROI:**
  - $\mathbf{2 \cdot 10^6}$
- **4 parameter fit**
  Bkg, Sig, E_0, $m_{\nu e}$
- 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**

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

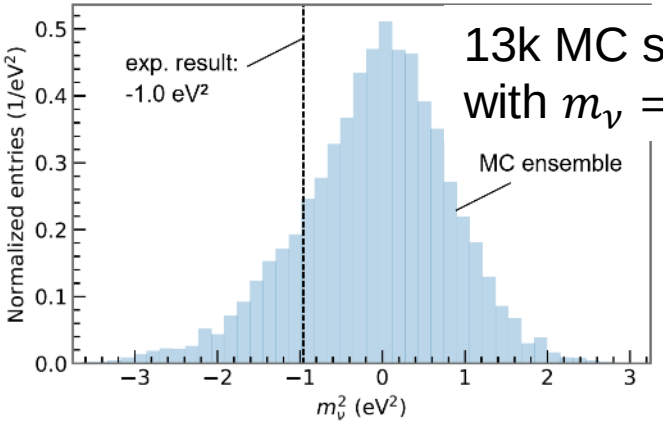
Phys. Rev. Lett. 114, 013003 (2015)

agreement

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

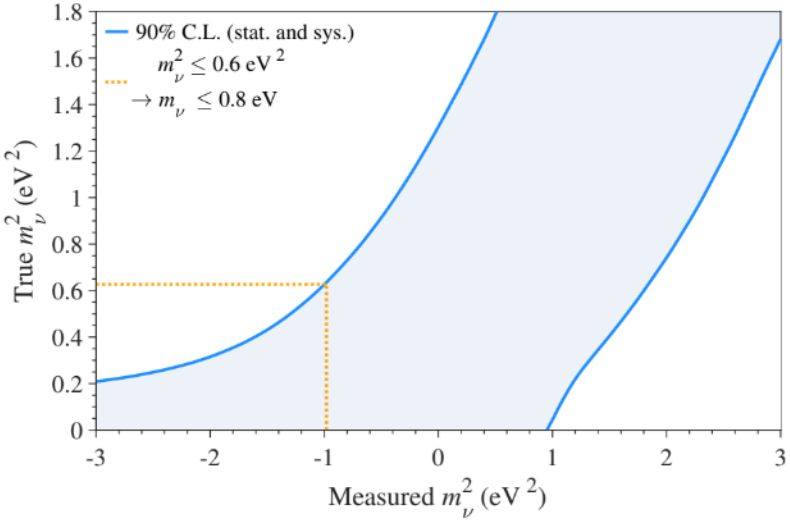
Understanding of final result

- **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)

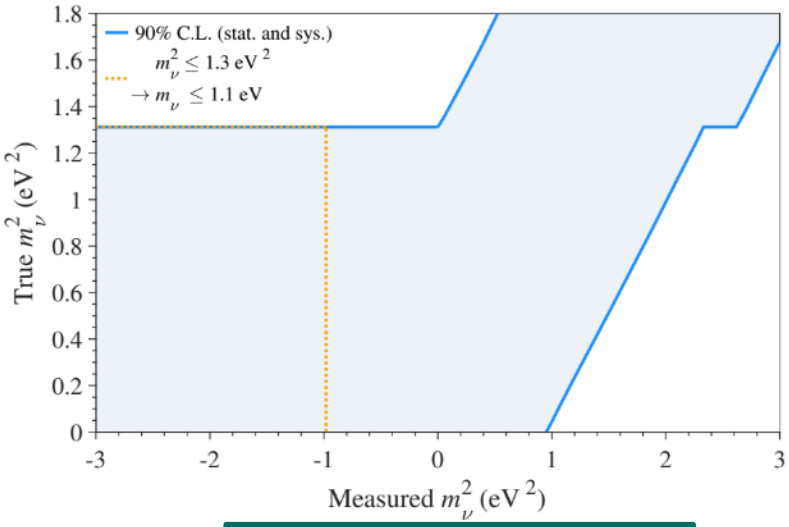


13k MC samples with $m_\nu = 0$ eV

Best fit: 1σ fluctuation to negative



Feldman-Cousins



Lokhov-Tkachov

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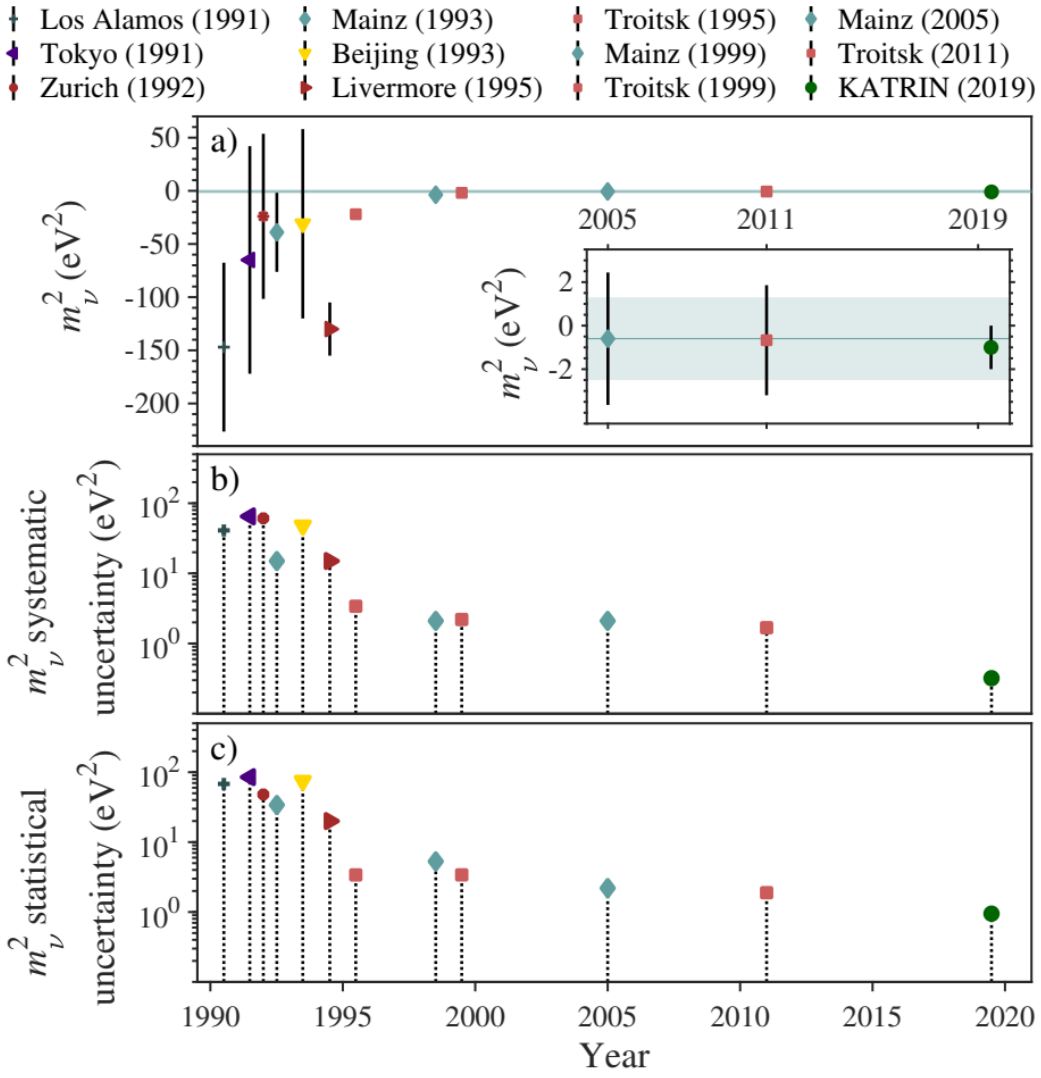
Neutrino mass measurements

- Effective measurement time
  5 days

  Full KATRIN measurement time
  1000 days

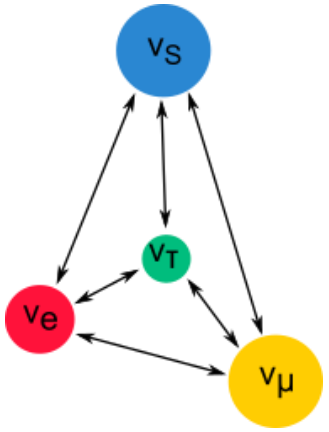
Improve systematics:
factor 6

Improve statistics:
factor 2

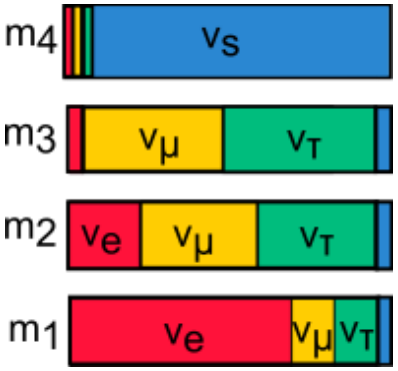


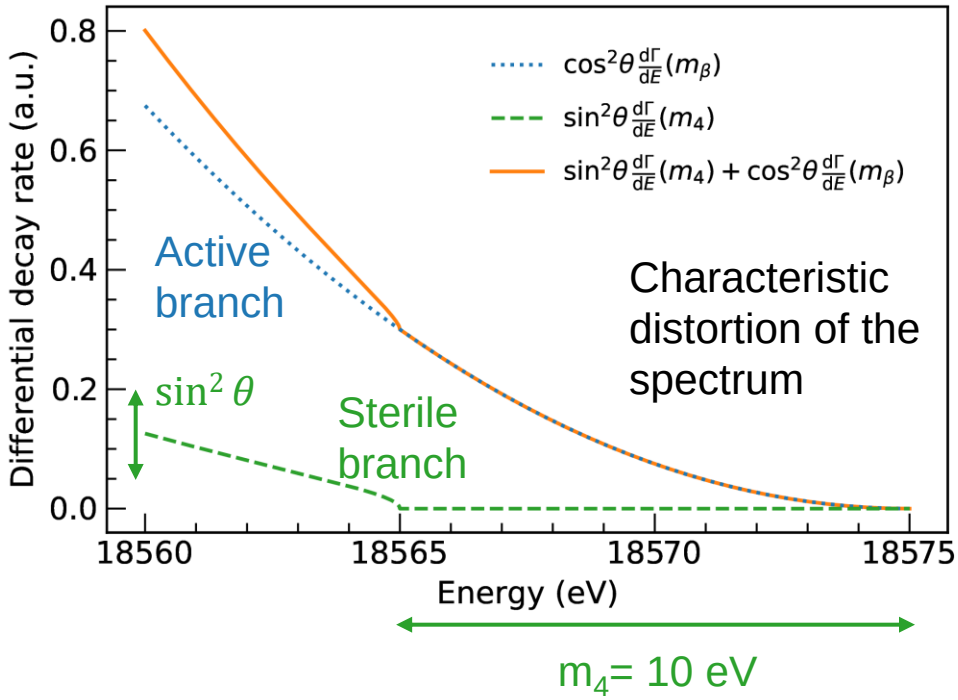
Search for eV sterile neutrinos

- Minimal extension of SM



- Mixing of active and sterile ν

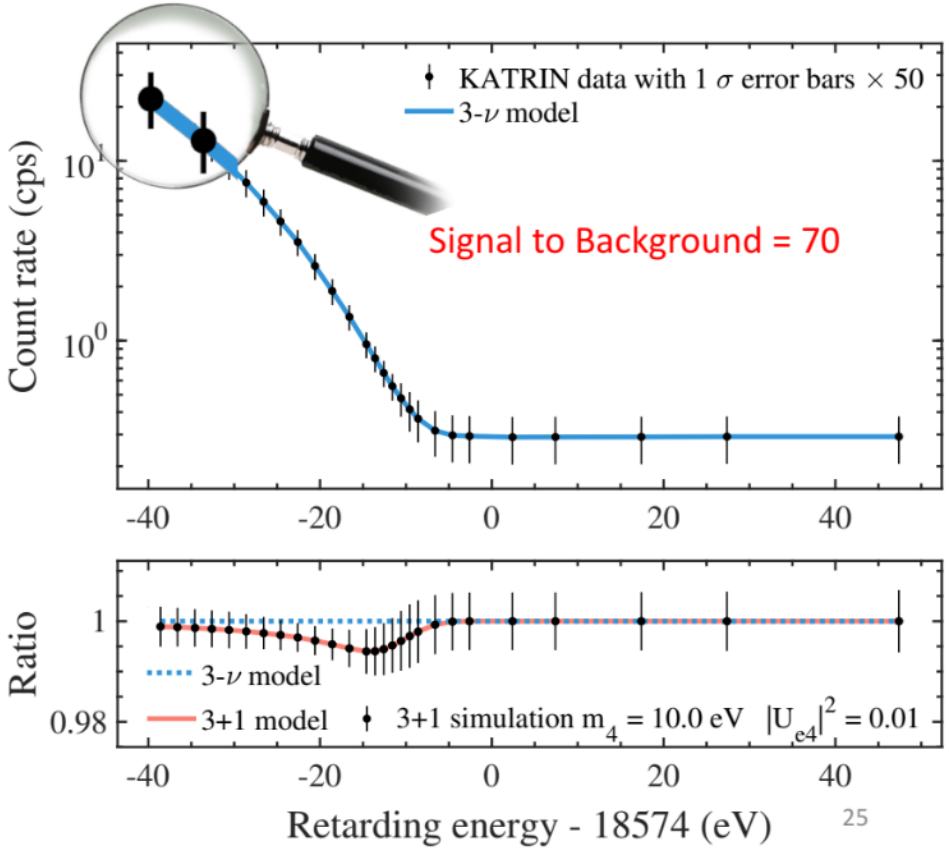




Can we see such a signature in the beta spectrum?

Approach for eV sterile search

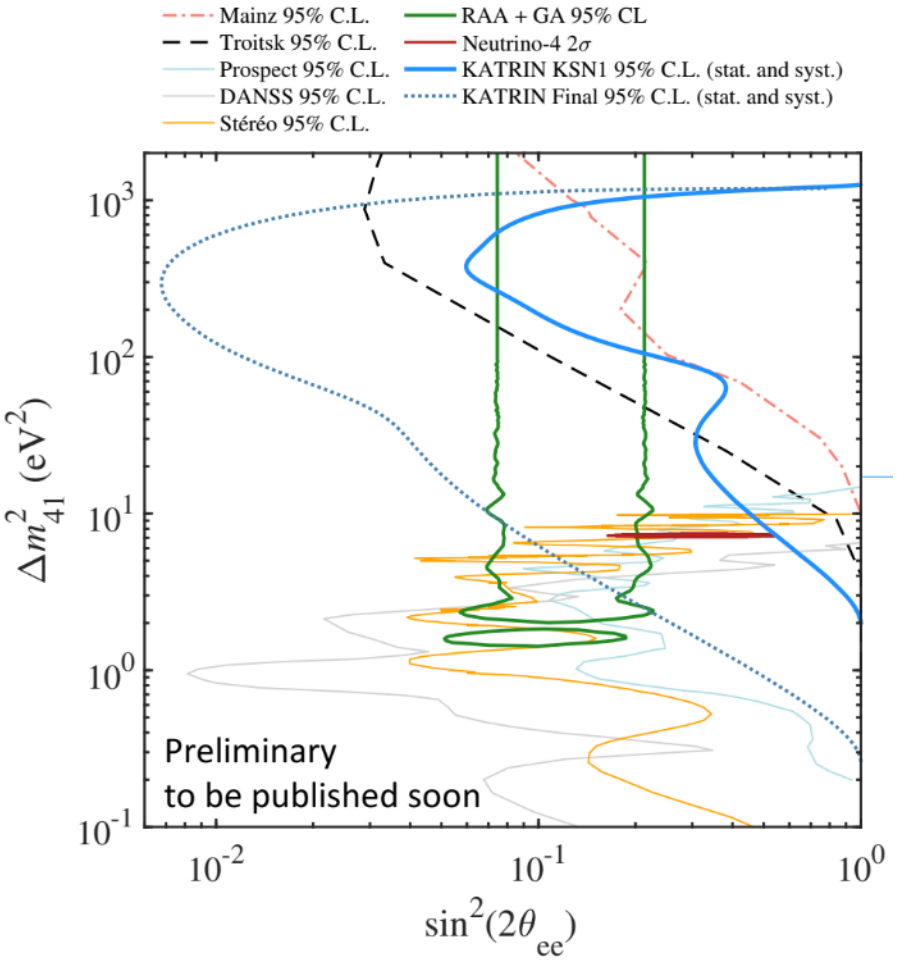
- Same data as for neutrino mass measurement range: $[\mathrm{E}_0 - 40\ \mathrm{eV}, \mathrm{E}_0 + 50\ \mathrm{eV}]$
- Same systematics inputs
- Model: 3 active + 1 sterile neutrino
- Grid search: m_4 (mass) and $|U_{e4}|^2$(mixing)



25

- Lowest effective mass for active neutrino 0.009 eV (in normal ordering)

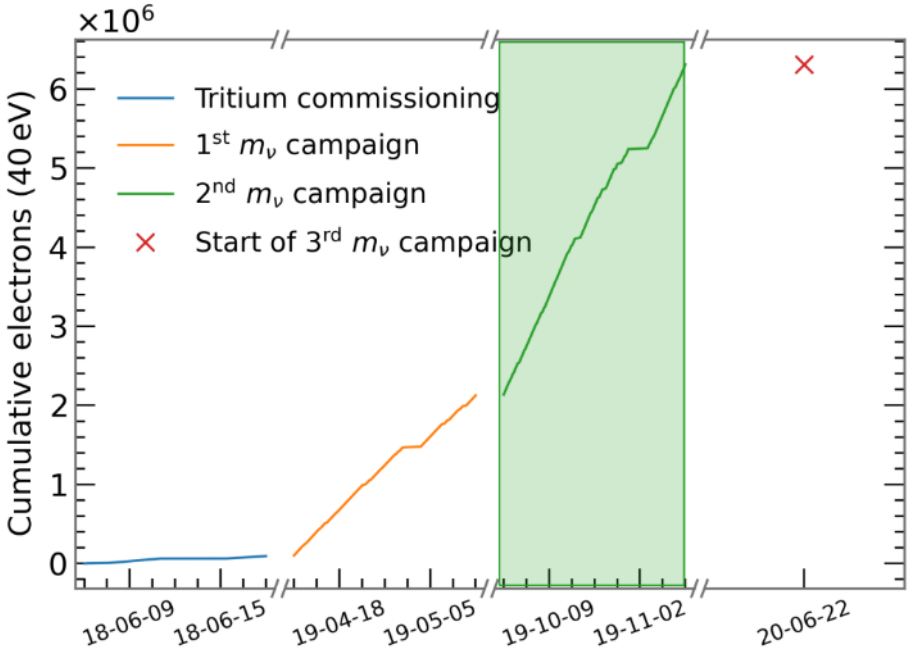
First KATRIN results for sterile neutrinos



- Demonstrated sterile neutrino search complementary to oscillation measurements
- Better sensitivity than Mainz and Troitsk for low masses
- We are approaching to the Neutrino-4 results

Large fractions of the *reactor anti-neutrino anomaly* (RAA) will be covered in future KATRIN campaigns

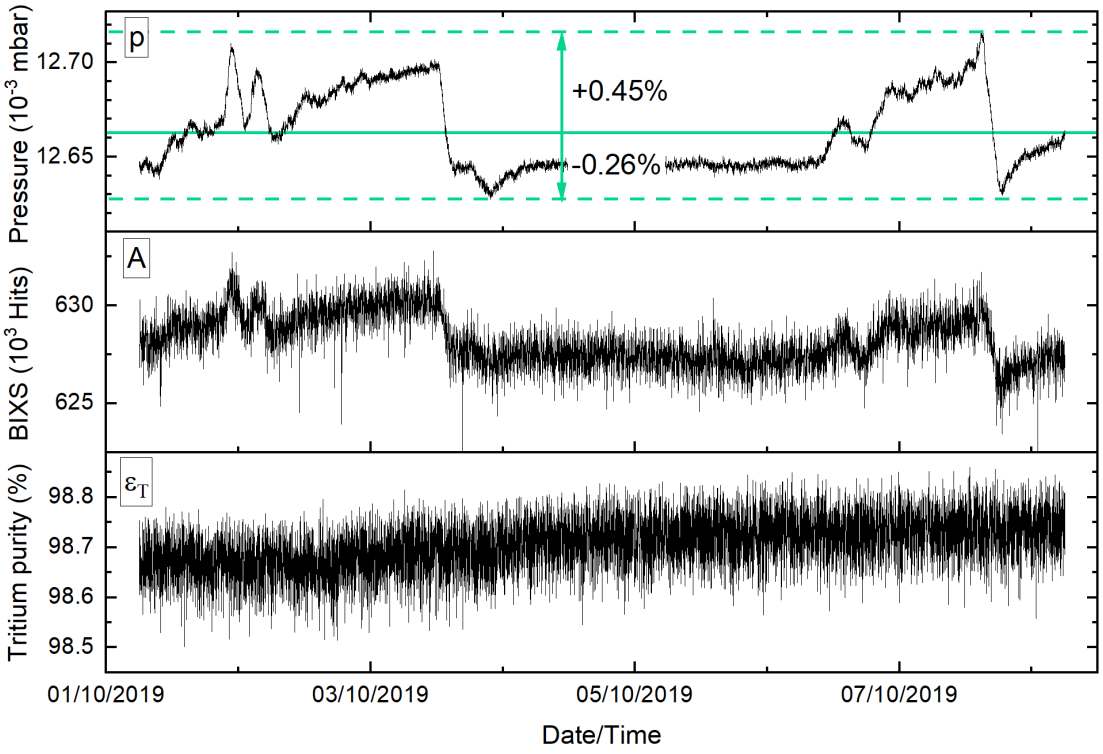
2nd neutrino mass campaign



- 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

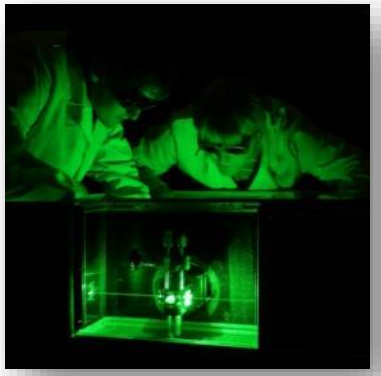
Source operation during 2nd neutrino mass run



Tritium purity *(in selected data)*
Required > 95%, Achieved ≈ 99%

Methane problem solved!

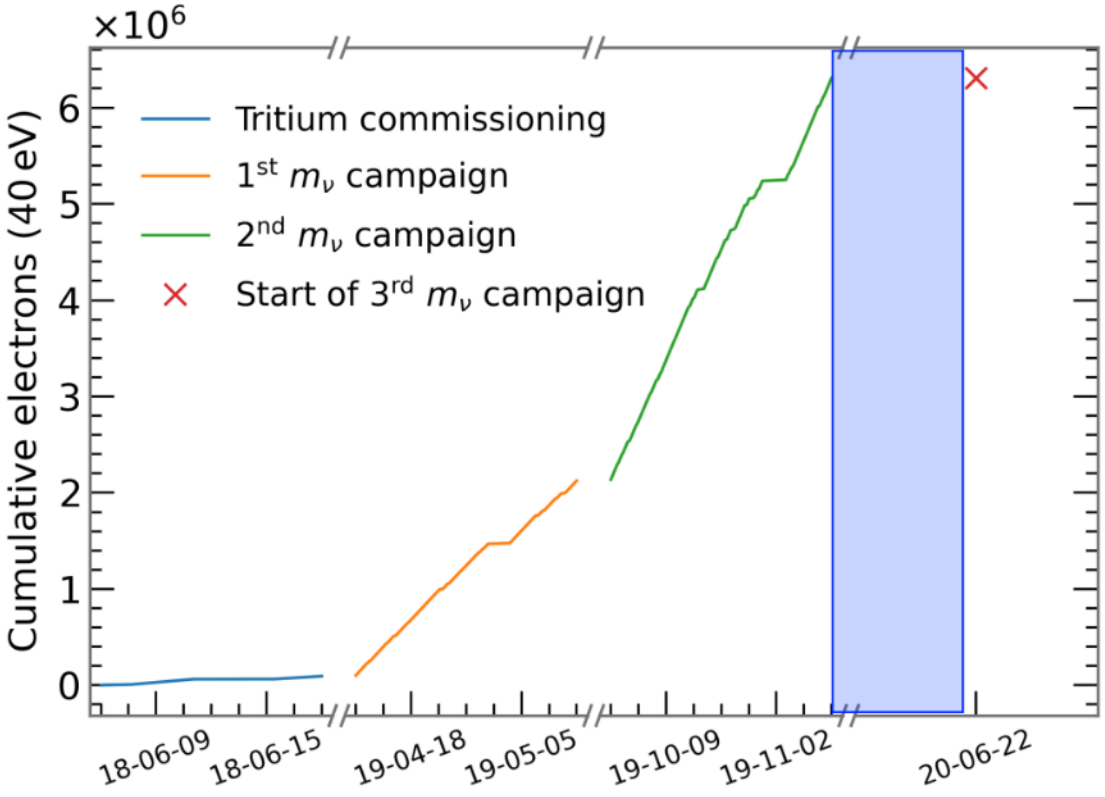
Remaining structure correlated to small temperature fluctuations

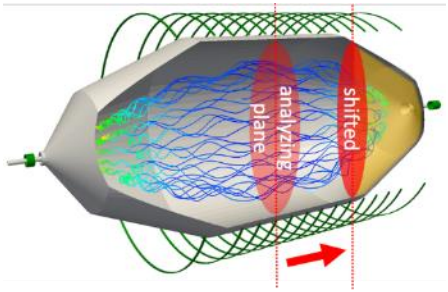


24/7 inline
Raman spectroscopy

Tritium Laboratory Karlsruhe

Operations in 2020





Reduction of background by factor 2 is possible

- Some delay in Spring by COVID-19
- Since May **Calibration campaign**
  - **Plasma studies**
  - **Background reduction via B-field optimiation**
- Since 22nd June **3rd neutrino mass measurement**

A view to the future

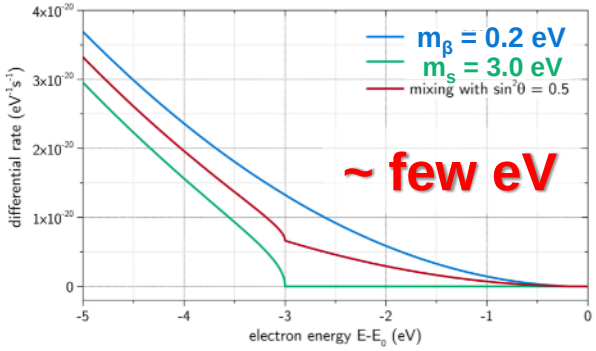
2019 – 2023…
Neutrino mass measurement

„1000 days“

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

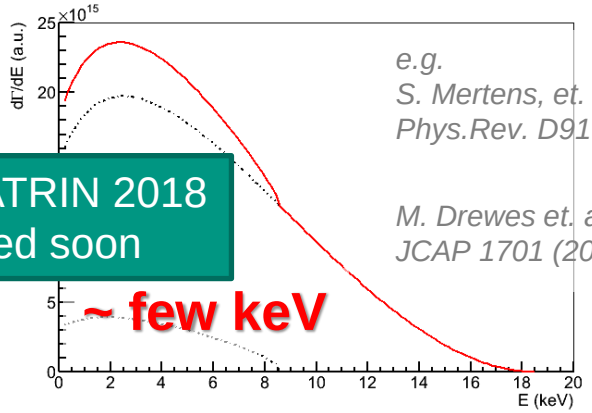
m_ν

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



No extra data taking required!

Heavy sterile neutrino search



Data from KATRIN 2018
to be published soon

e.g.
S. Mertens, et. al.
Phys.Rev. D91 (2015) 4, 042005

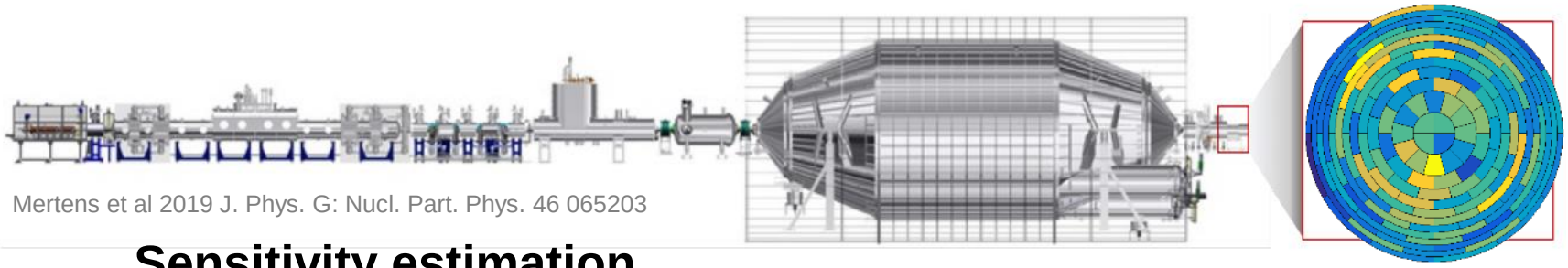
M. Drewes et. al.,
JCAP 1701 (2017) no.01, 025

KATRIN with new TRISTAN detector

Tritium Laboratory Karlsruhe

keV sterile searches at KATRIN

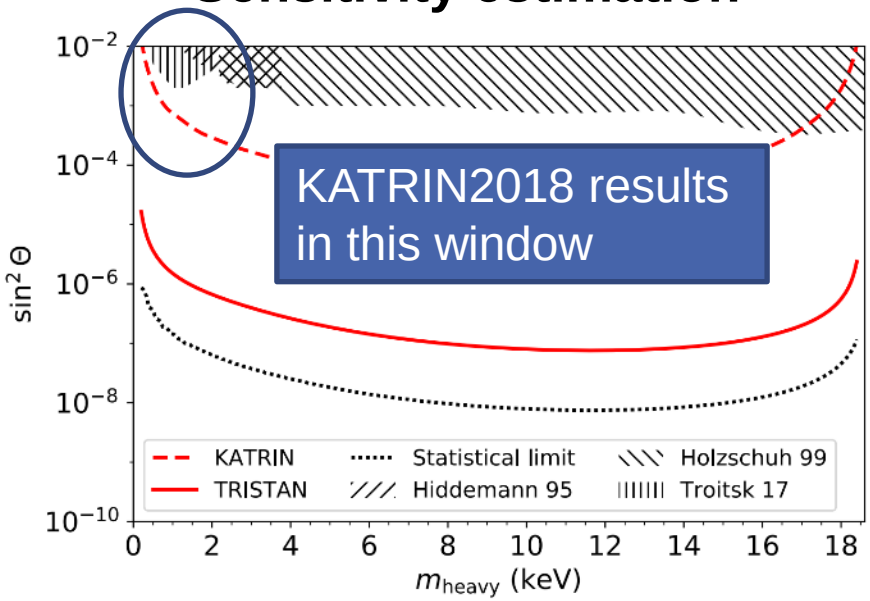
KATRIN beamline with novel SDD „TRISTAN“ detector



Mertens et al 2019 J. Phys. G: Nucl. Part. Phys. 46 065203

KATRIN (148 pixel)

Sensitivity estimation



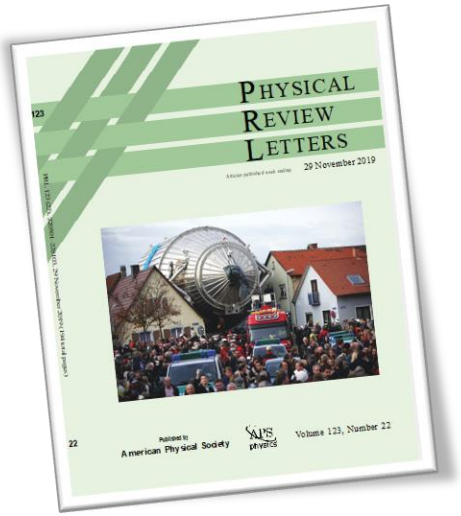
- **Baseline**
  - **Activity ~10^8 Bq**
  - **Max rate per pixel 100 kcps**
  - **3500 pixel**
  - **Energy resolution 300 eV @ 20 keV**
  - **Low energy threshold: 1 keV**

3y (10^{16} decays) and ppm systematics
➔ 10^{-6} sensitivity on sterile neutrino

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

Karlsruhe Institute of Technology

BERGISCHE UNIVERSITÄT WUPPERTAL

BERKELEY LAB

UNIVERSITÄT BONN

Carnegie Mellon University

CASE WESTERN RESERVE UNIVERSITY

cea

Hochschule Fulda
University of Applied Sciences

HUMBOLDT-UNIVERSITÄT ZU BERLIN

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Max-Planck-Institut für Physik

Nuclear Physics Institute of the CAS
public research institution

TECHNISCHE UNIVERSITÄT MÜNCHEN

UNIVERSITÄT MAINZ

Karlsruhe Institute of Technology

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

UNIVERSITY of WASHINGTON

WWU MÜNSTER

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