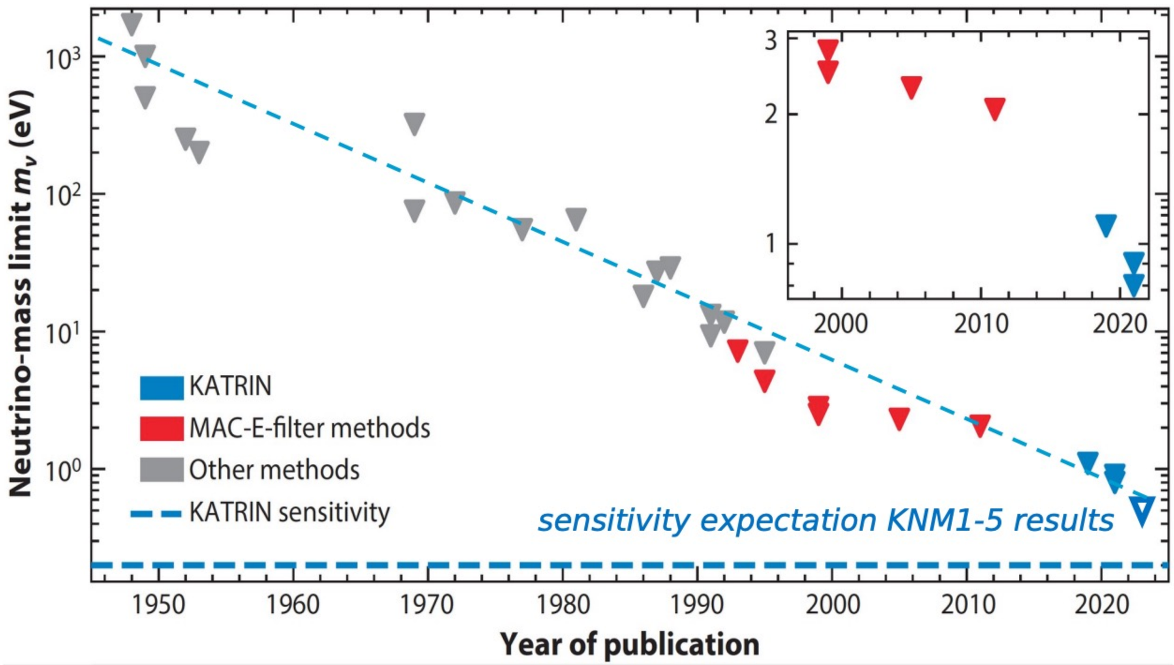
Direct Neutrino Mass Measurements at KATRIN and Beyond

Andrew Gavin, on behalf of the KATRIN Collaboration

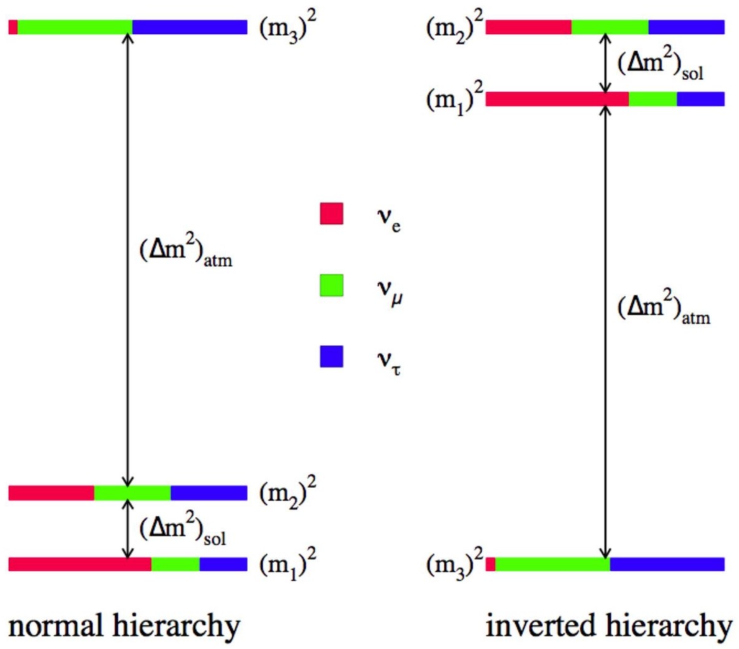
May 14th, 2023

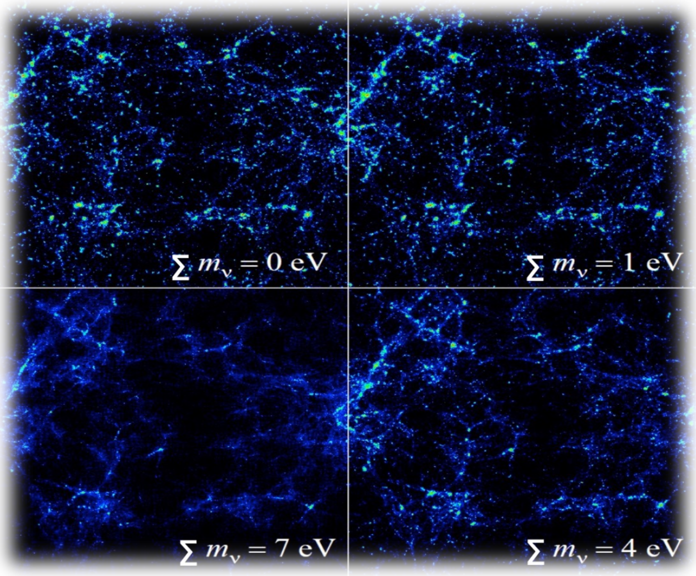


Neutrino Mass in Physics

What we know (incomplete)

- Difference in mass and flavor eigenstates cause neutrino oscillation
- Impact on structure formation
- Mixing angles and mass differences



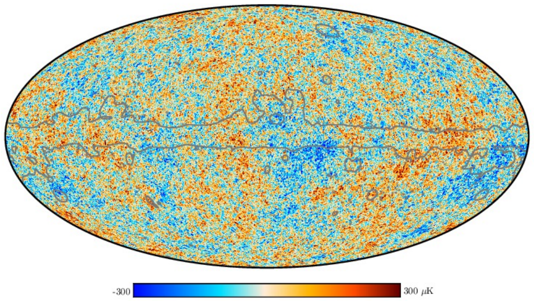


What we don't know (incomplete)

- Absolute mass scale
- Normal or inverted hierarchy
- Dirac or Majorana
- Right-handed neutrinos

Neutrino Mass Searches

Cosmology



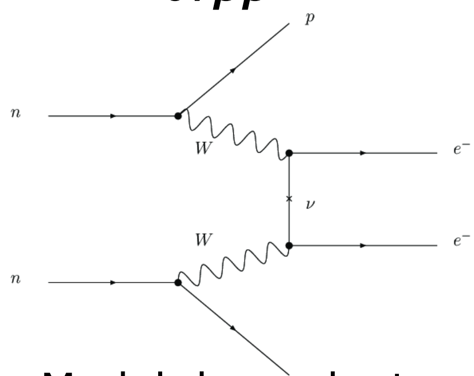
Model dependent
Analysis of CMB and structure formation

Planck

$\sum m_i$

$\sum m_i < 0.11$ eV

$0\nu\beta\beta$



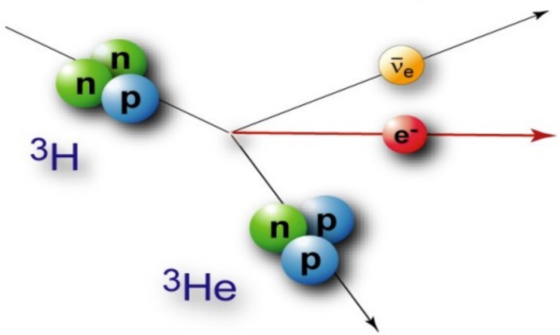
Model dependent

LEGEND, Majorana, KamLAND-Zen, etc.

$m_{\beta\beta} = \left|\sum U_{ei}^2 m_i\right|$

$m_{\beta\beta} < 0.036 - 0.156$ eV

β-decay kinematics



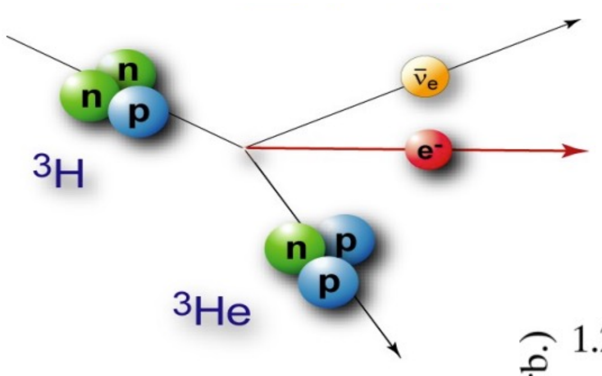
Model independent

KATRIN, Project 8, HOLMES, ECHo, etc.

$m_\nu^2 = \sum \left|U_{ei}^2\right| m_i^2$

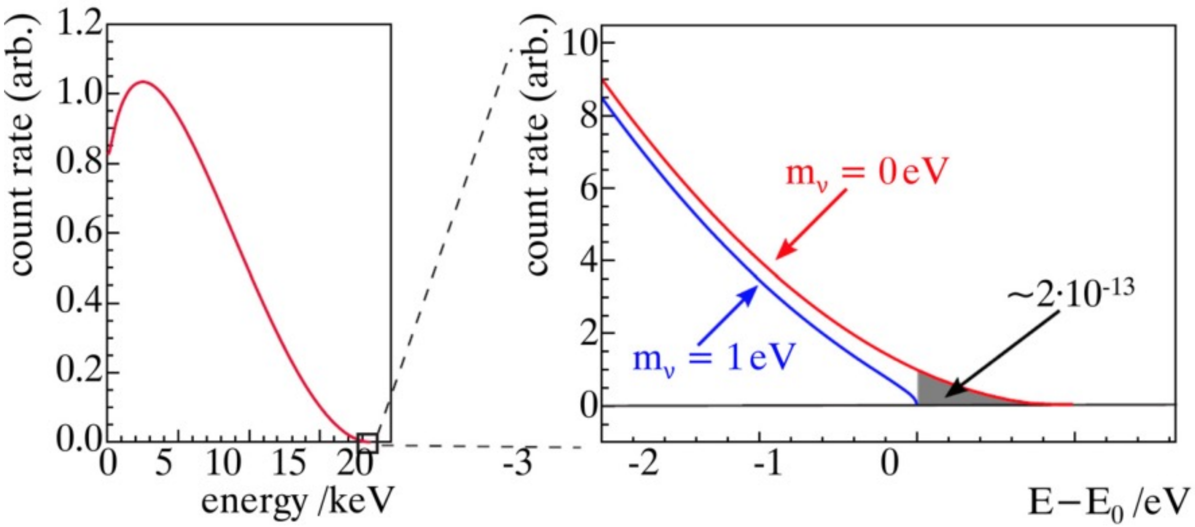
$m_\nu < 0.8$ eV

Kinematic Searches



- Neutrino mass impacts the allowed energies of β-decay electrons
- Experimental signal is an endpoint shape distortion

Why tritium?
- Super-allowed decay
- 18.6 keV Q-value
- 12.3 year half-life



- Experimental challenge is to perform a high statistics measurement around the endpoint with excellent energy resolution

KATRIN Collaboration

leaving

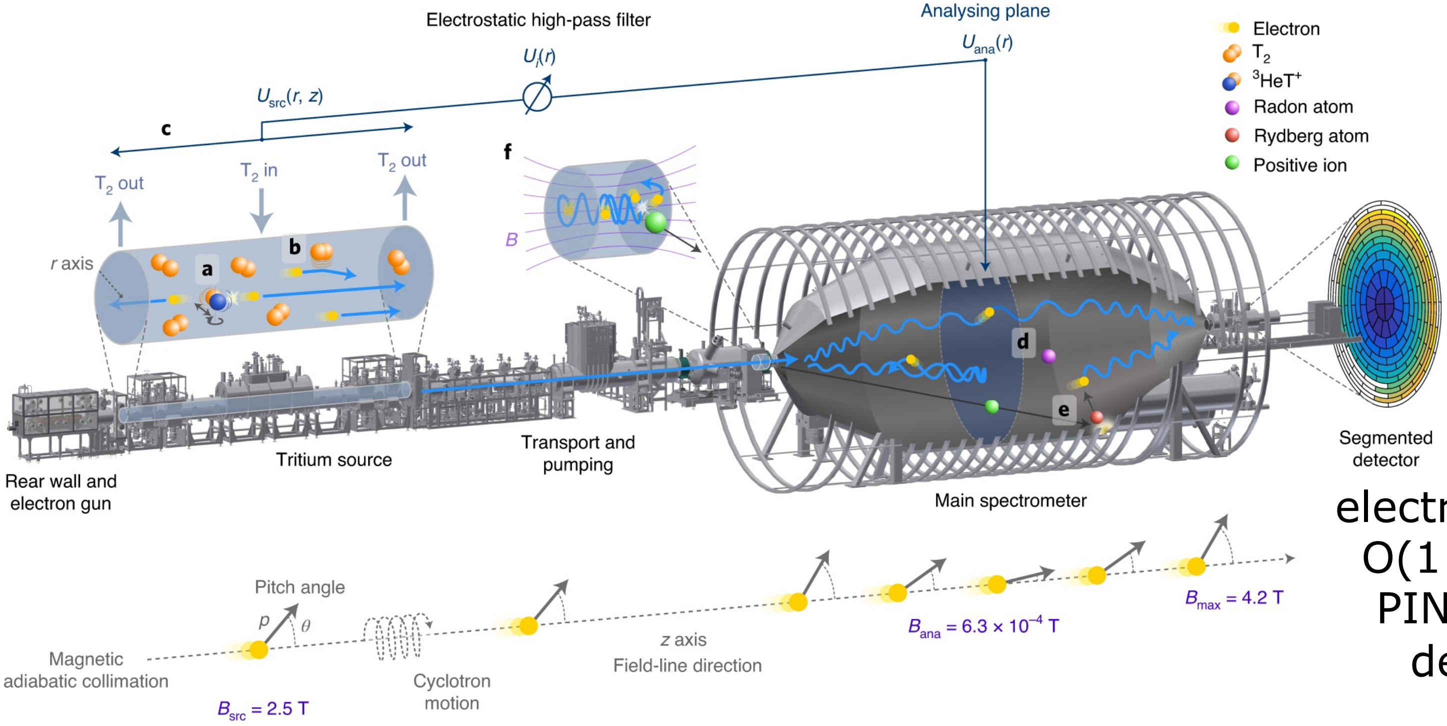
currently not active

KATRIN Operating Principle

Windowless Gaseous Tritium Source provides of $1.7 \cdot 10^{11}$ β-decay electrons per second

Adiabatic collimation and application of an electrostatic potential filter electrons

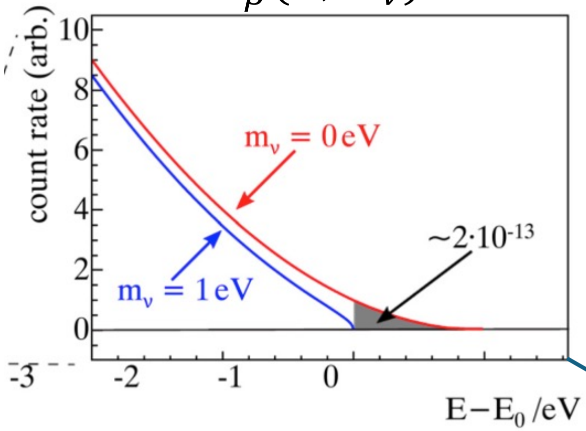
$$\Delta E/E = B_{ana}/B_{max}$$



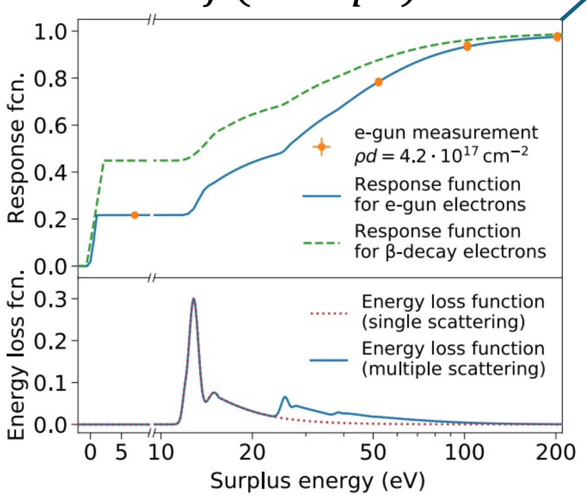
Count electrons at O(1 Hz) at PIN-diode detector

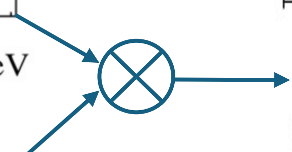
KATRIN Spectrum Modelling

$R_\beta(E, m_\nu^2)$

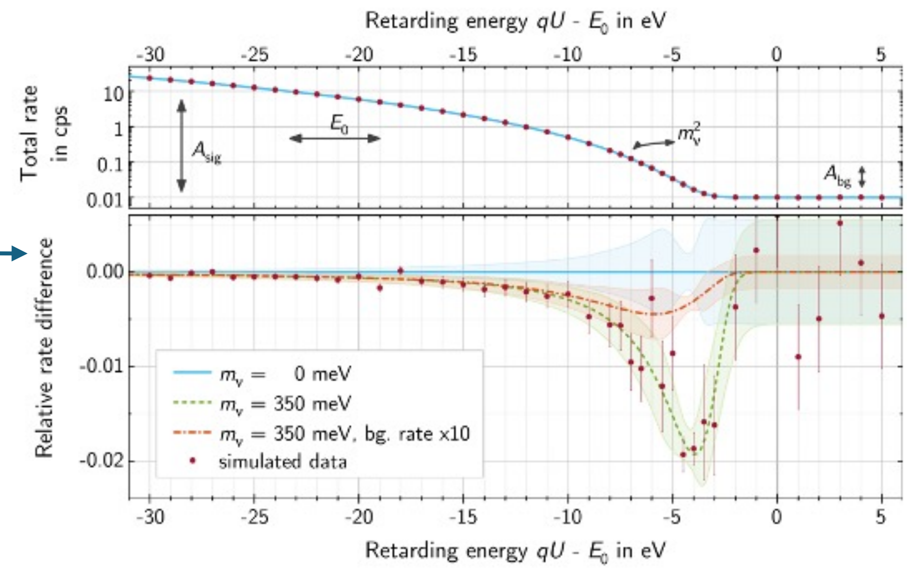


$f(E - qU)$





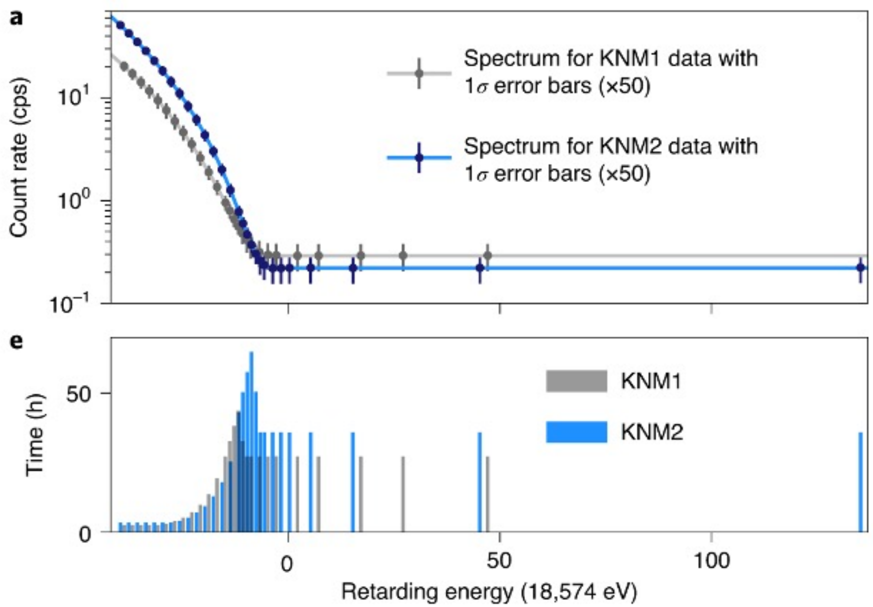
$$R(qU) = \boldsymbol{A_{sig}} \cdot N_T \int_{qU}^{\boldsymbol{E_0}} R_\beta(E, \boldsymbol{m_\nu^2}) \cdot f(E - qU)dE + \boldsymbol{A_{bg}}$$



- Fit four parameters
  - Amplitude, endpoint, neutrino mass, and background

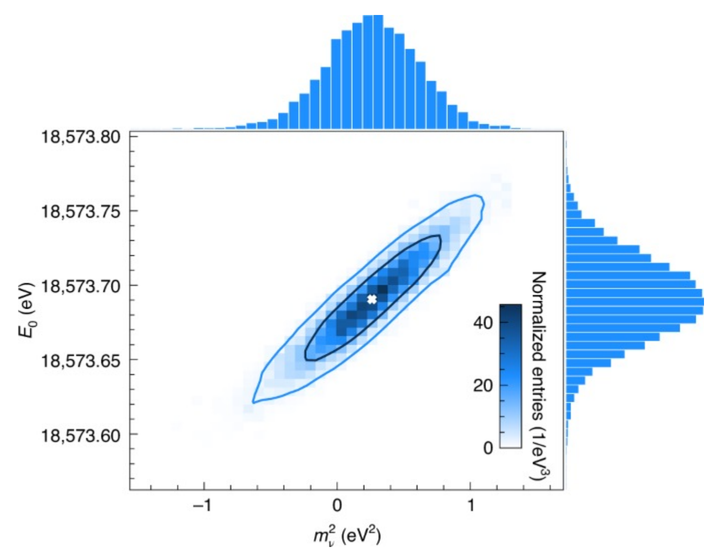
Phys. Rev. D **104**, 012005

KNM1-2 Neutrino Mass Limits

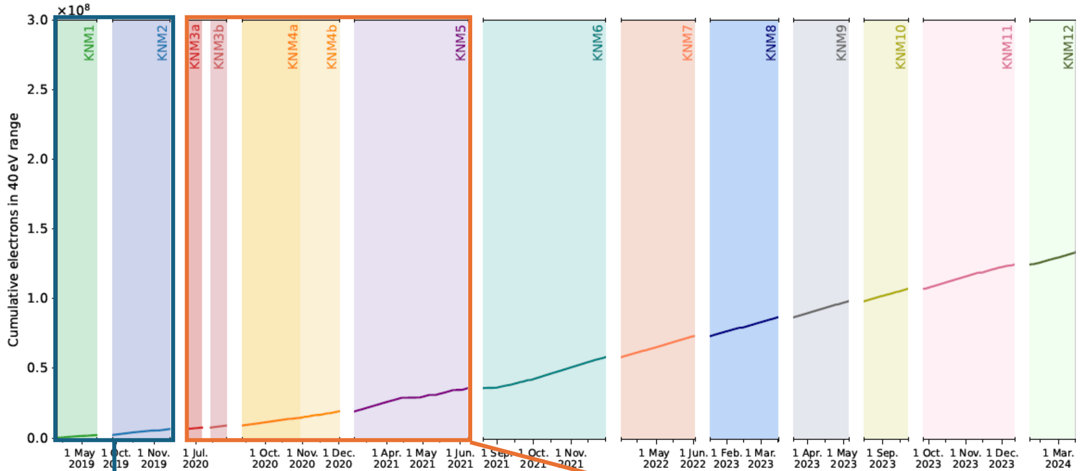


- Improvement in statistics and systematics between the two runs
- Result is still statistics dominated

- KNM1
  - $m_\nu < 1.1$ eV (90% CL)
- KNM2
  - $m_\nu < 0.9$ eV (90% CL)
- Combined
  - $m_\nu < 0.8$ eV (90% CL)



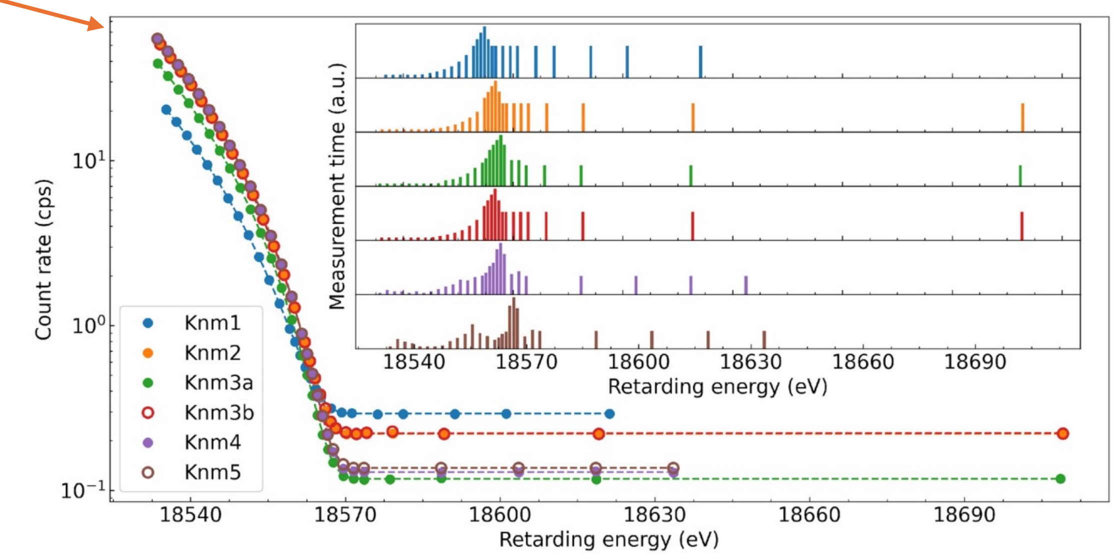
Data Taking and Next Results



Upcoming publication of first 5 data sets with a projected statistical sensitivity of $m_\nu < 0.5$ eV (90% CL)

Published:

- Neutrino mass results
- eV and keV scale sterile neutrino search
- Lorentz-invariance violation
- Constraints on cosmic relic neutrinos



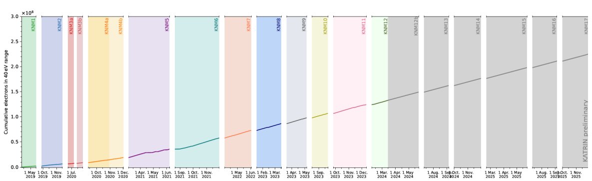
Future KATRIN Operation

2019-2025
Integral neutrino mass measurement

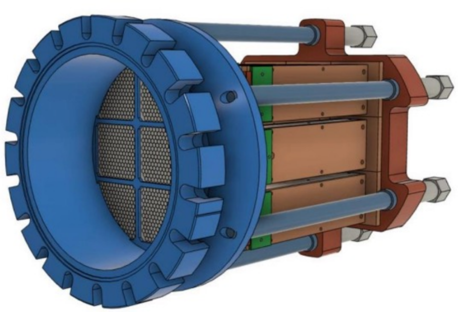
2026-2027
keV sterile ν search using TRISTAN detector

2028+
R&D for next generation KATRIN++

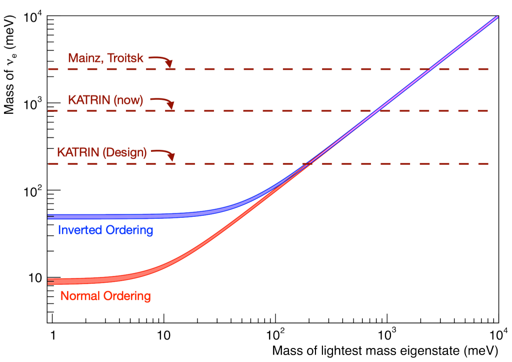
Accumulation of 1000 days of measurement time to reach final sensitivity of $m_\nu < 0.3$ eV



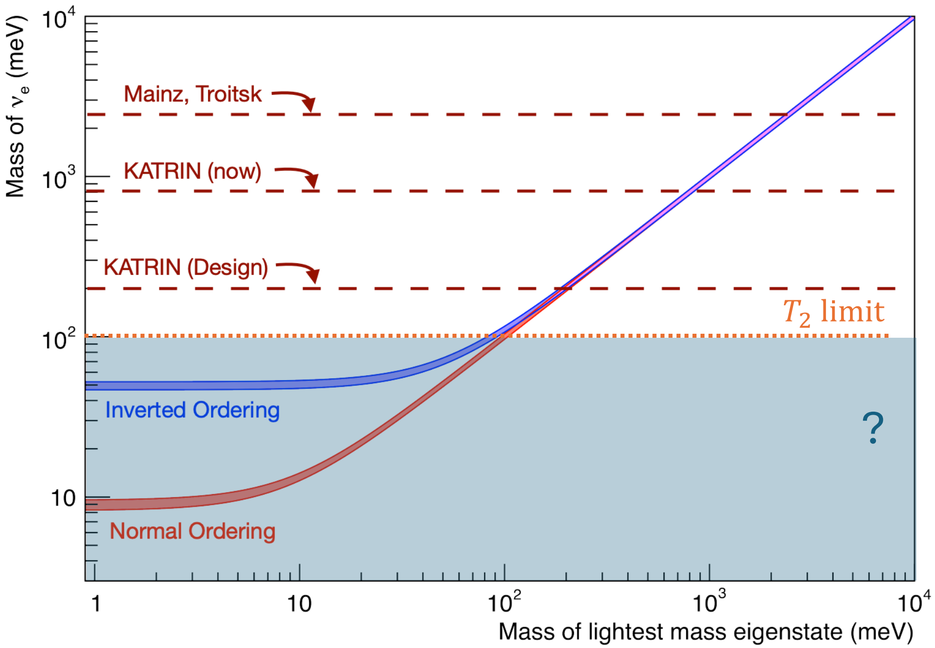
Detector upgrade to measure complete tritium spectrum with silicon drift detector



Tackling challenges to push past the current KATRIN limitations



Improving Kinematic Measurements

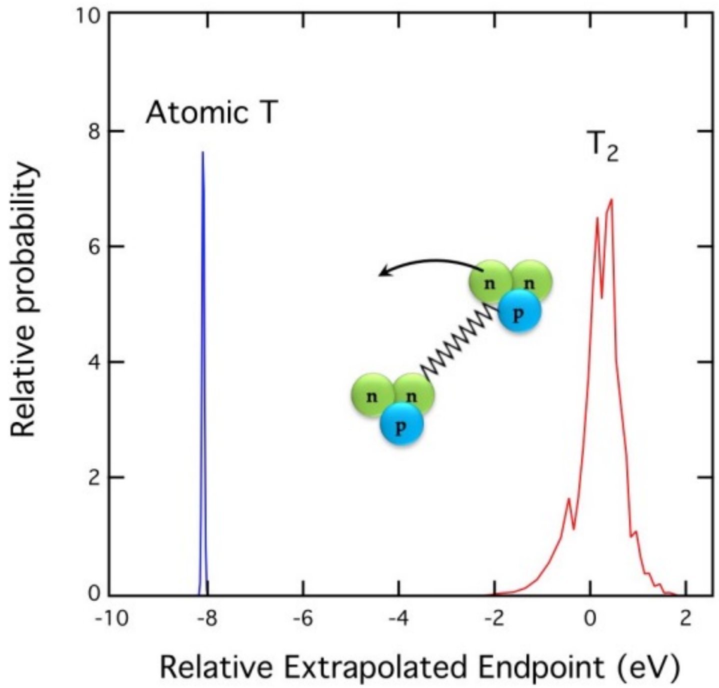


Limiting factors for KATRIN

- Molecular tritium systematics
- Energy resolution scaling
- Integral measurement

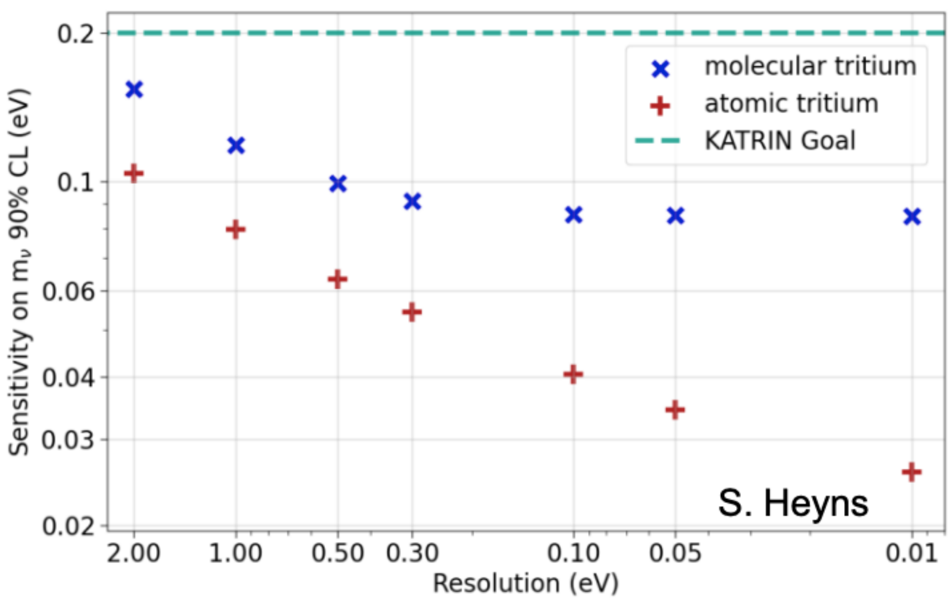
How can we increase sensitivity to investigate inverted vs. normal ordering?
Differential measurement using an atomic tritium source

Atomic Tritium Source



Near Gaussian broadening of endpoint caused by molecular final-state energies of daughter $^3HeT^+$

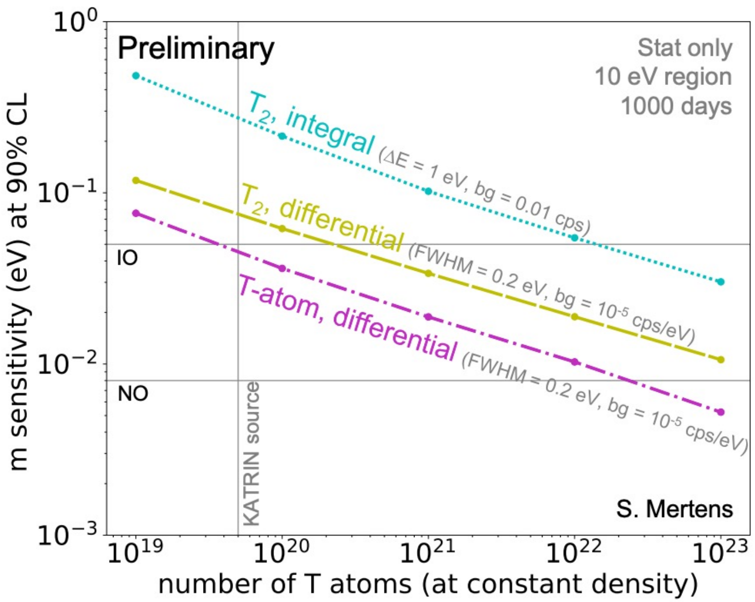
Systematic uncertainty limits neutrino mass sensitivity to ≈ 0.1 eV



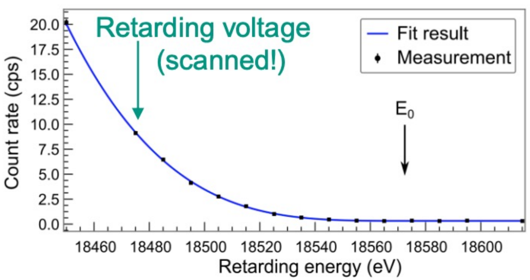
Development of atomic tritium source is essential for next generation neutrino mass experiments

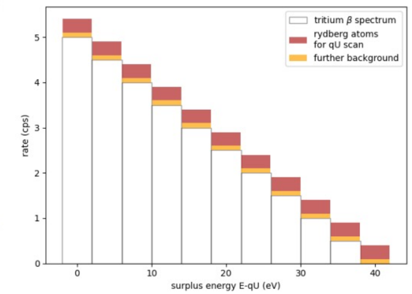
Phys. Rev. Lett. **84**, 242

Differential Measurements

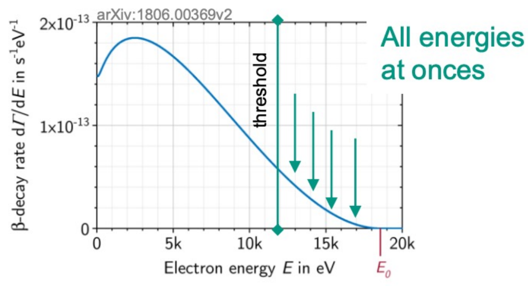


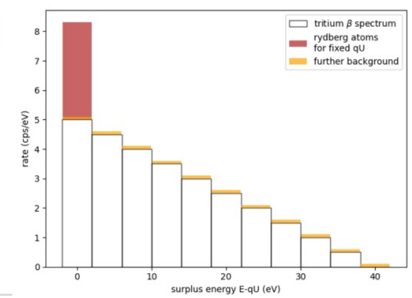
Increase in statistics by removing need to scan through retarding voltages



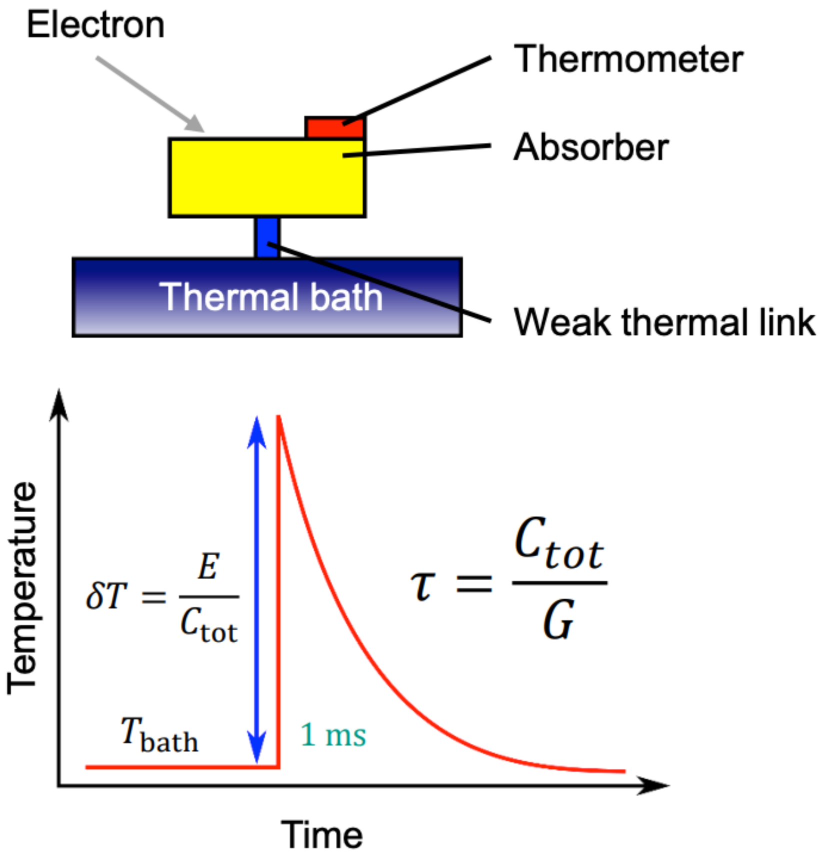


Background reduction from removal of retarding potential dependent background





Quantum Sensors



Ultra low noise particle detectors working at cryogenic temperatures

Provide measurement with high quantum efficiency, linear response, and no dead layer effects

MMCs have O(1 eV) FWHM response for X-rays in energy range of interest

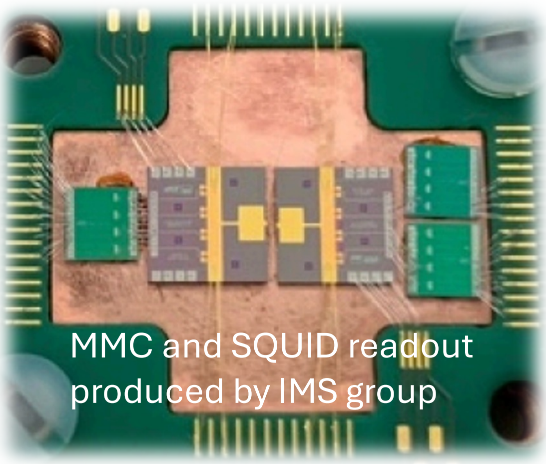
Response to external electrons is to be investigated

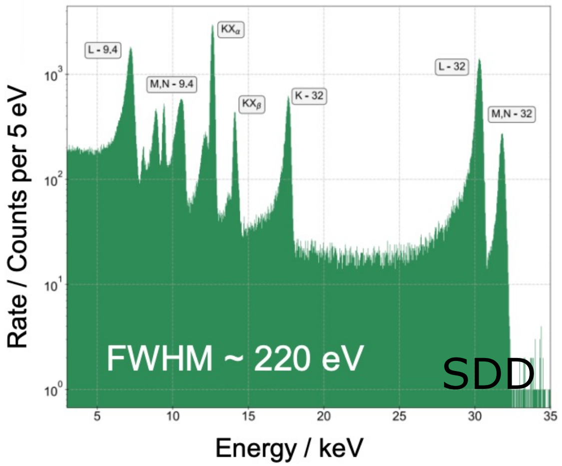
ELECTRON Project

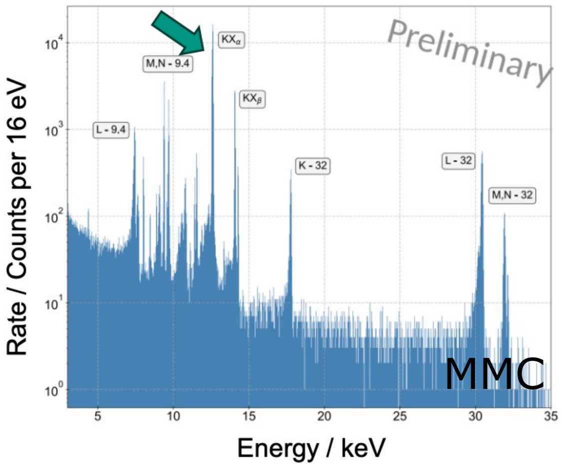
Investigation in the group of Sebastian Kempf at KIT-IMS

Goals:

I. Test whether MMC detectors can be used to measure external electrons
II. Study the detector-electron interplay and investigate potential systematic effects
III. First ever measurement of the differential tritium spectrum with a cryogenic micro-calorimeter







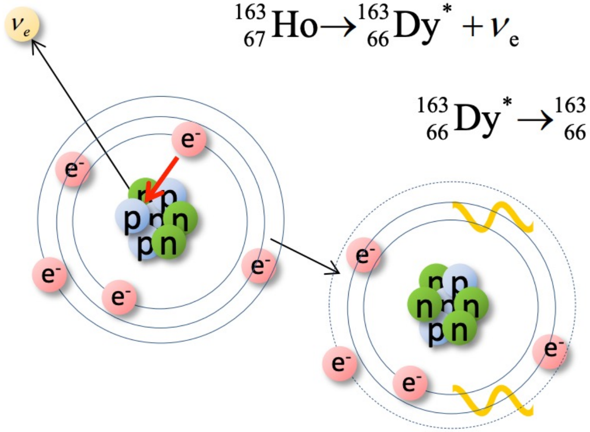
Krypton-83m measurement with ≈ 25 eV FWHM for external electrons

Courtesy of Neven Kovac

Holmium Electron Capture

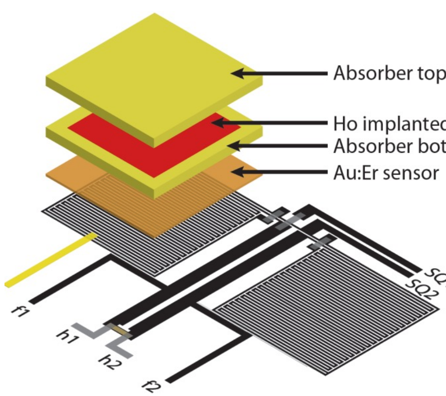
$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

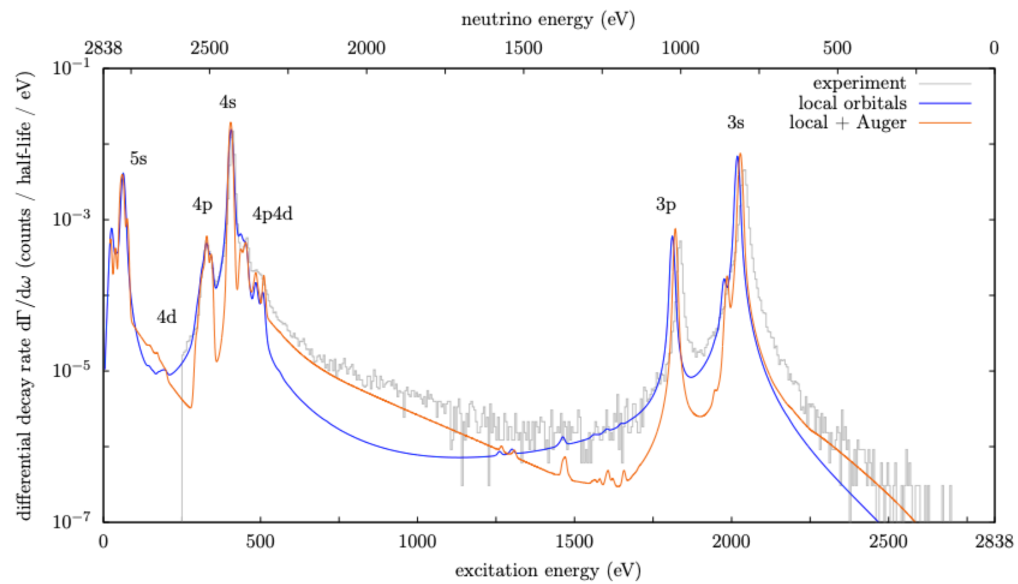


Neutrino mass signature also visible in excitation energy of decay product of holmium

Holmium is implanted within the absorber material and full spectrum is measured c



Impl
150



[arXiv:1206.5647](https://arxiv.org/abs/1206.5647) [arXiv:1807.09269](https://arxiv.org/abs/1807.09269)

New J. Phys. **22** 093018

ECHo and HOLMES

ECHo and HOLMES collaborations use MMC and TES based arrays with 1.58 eV and 4.22 eV FWHMs, respectively

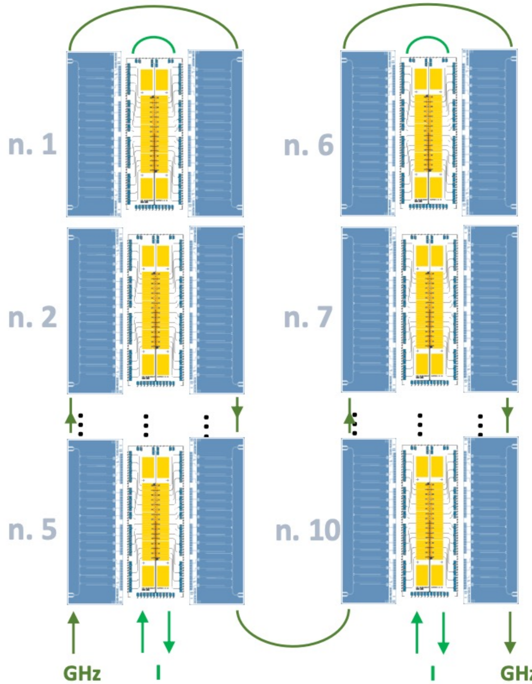
Large detector arrays are necessary due to unavoidable pileup effects, limiting the activity per pixel to O(10 Bq)

ECHo-1k
- 1 Bq/pixel with ≈ 60 MMCs
- Goal to place $m_\nu < 20$ eV (90% CL) limit

ECHo-100k
- 10 Bq/pixel with ≈ 12000 MMCs
- Wafer production and implantation demonstrated

HOLMES
- 64 pixel arrays with O(10 Bq) total

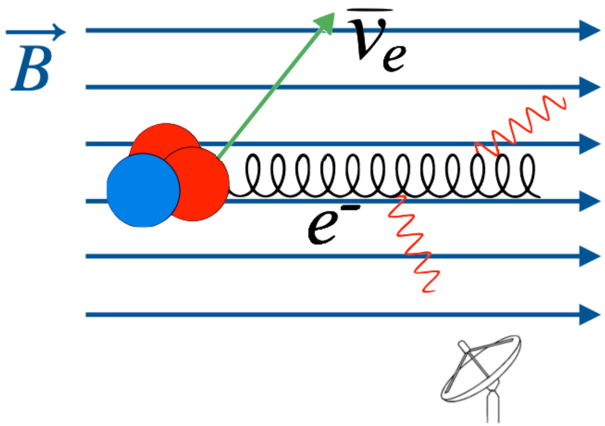
ECHo-100k



DFG Deutsche Forschungsgemeinschaft

New J. Phys. **22** 093018 EPJ-ST 226 8 (2017) 1623 arXiv:1206.5647 arXiv:1807.09269

Cyclotron Radiation Emission Spectroscopy



$$2\pi f = \frac{eB}{m_e + E/c^2}$$

$f_0 \approx 28$ GHz T^{-1}

1 fW of radiated power in 1 T field

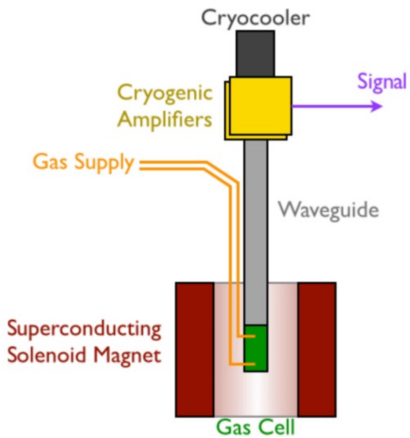
Energy resolution is determined by precision of frequency measurement

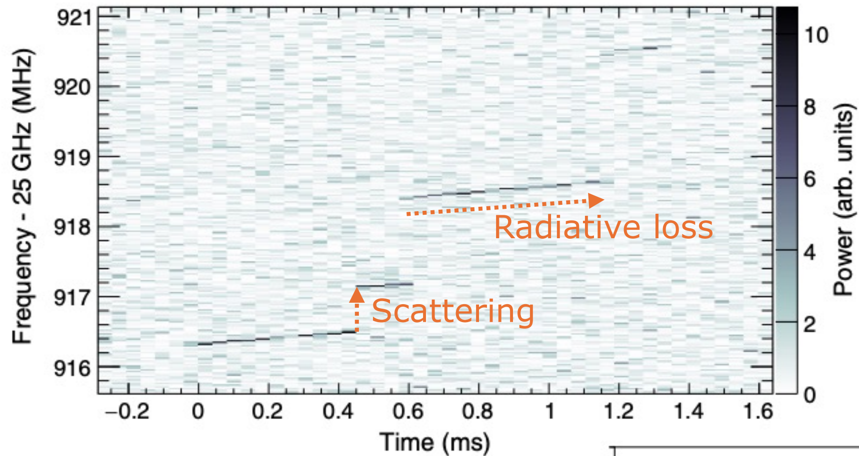
$$\Delta E/m_e = \Delta f/f$$

Long measurement time needed for good energy resolution and thermal noise suppression

arXiv:2203.07349 Phys. Rev. D 80, 051301 (2009)

Project 8 Phase I & II

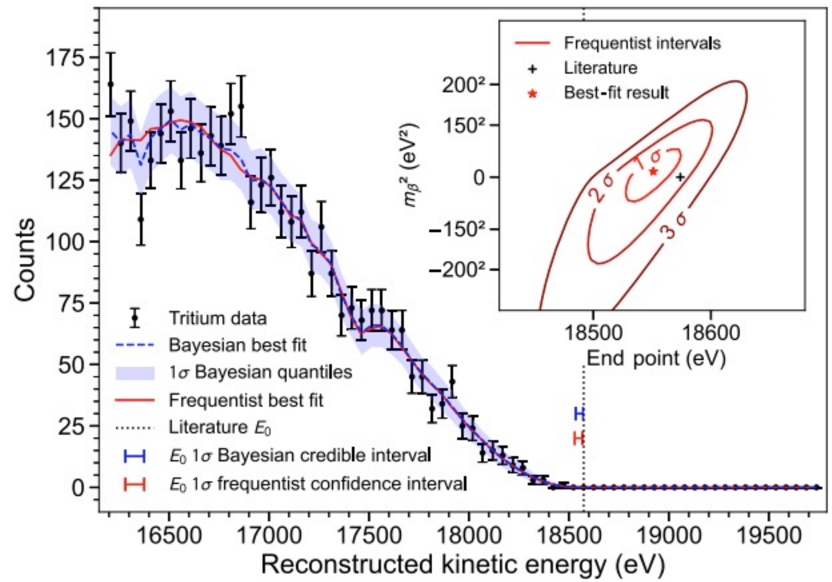




Electrons are trapped in an ≈ 1 T field and radiation is readout in a circular waveguide

Energy resolution of 1.66 ± 0.19 eV in a 1 cm^3 detection volume

$$m_\nu < 155 \text{ eV (90\% CL)}$$

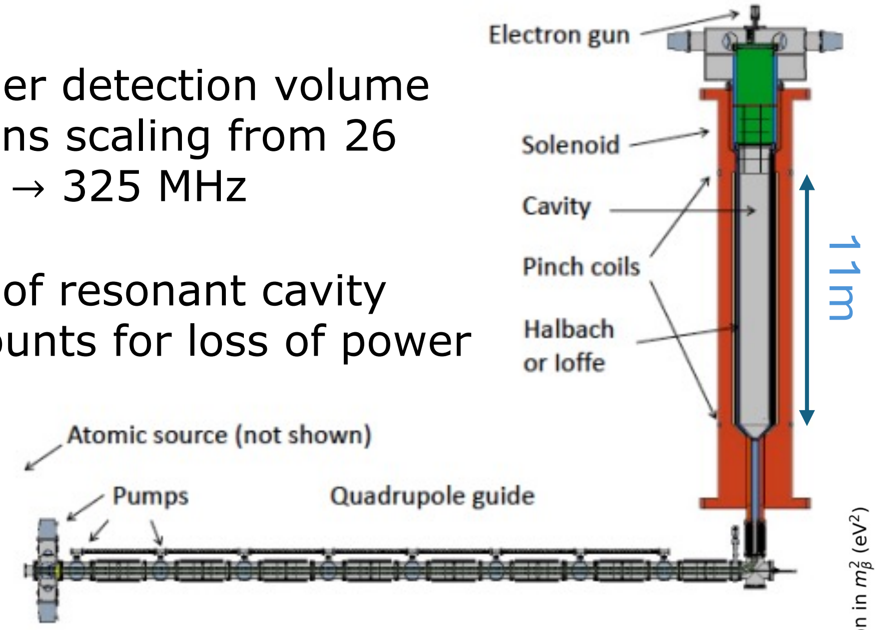


Phys. Rev. Lett. **131**, 102502

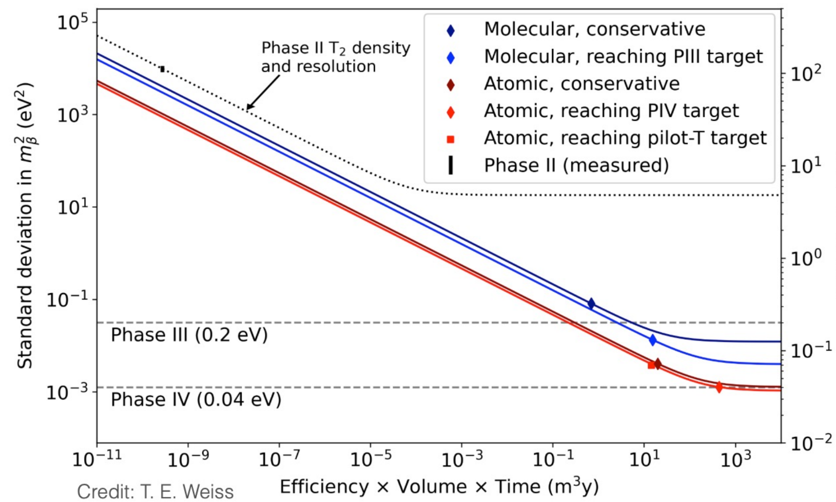
Project 8 Phase III & IV

Larger detection volume means scaling from 26 GHz → 325 MHz

Use of resonant cavity accounts for loss of power



Magneto-gravitationally trapped tritium



Sensitivity Goals

Phase III (11 m^3 volume, 1 year)

Molecular: $m_\nu < 0.2$ eV (90% CL)

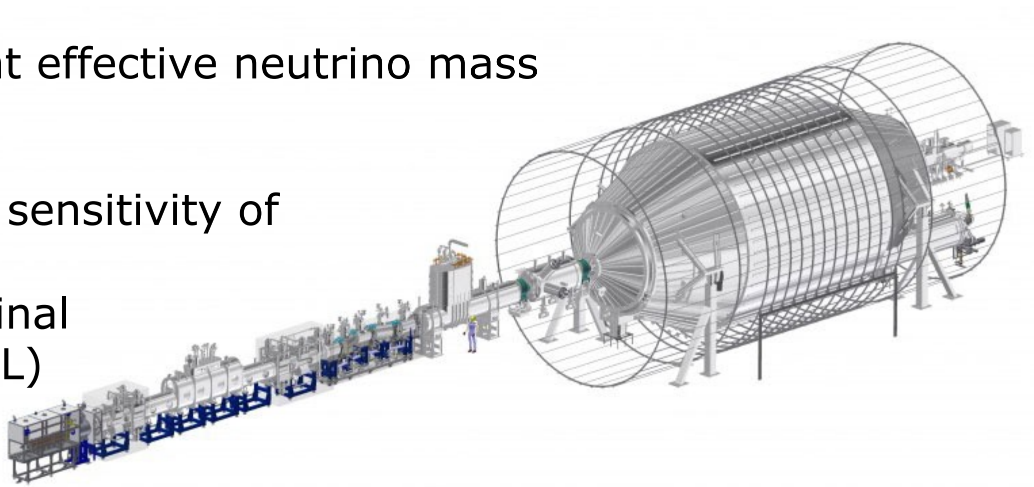
Atomic: $m_\nu < 0.1$ eV (90% CL)

arXiv:2311.16415

Conclusion and Outlook

KATRIN places the most stringent effective neutrino mass limit of $m_\nu < 0.8$ eV (90% CL)

Upcoming results with projected sensitivity of $m_\nu < 0.5$ eV (90% CL)
Continued data taking to reach final projection of $m_\nu < 0.3$ eV (90% CL)



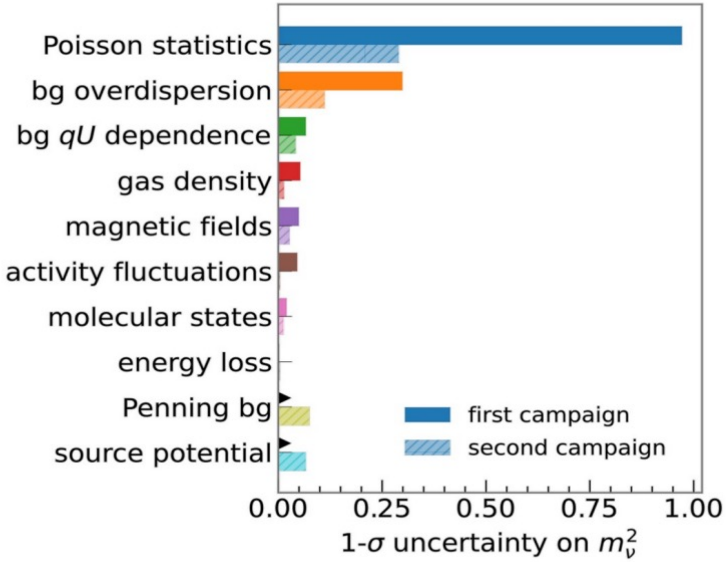
Active R&D for atomic tritium source and high-resolution differential detectors needed to push limit further

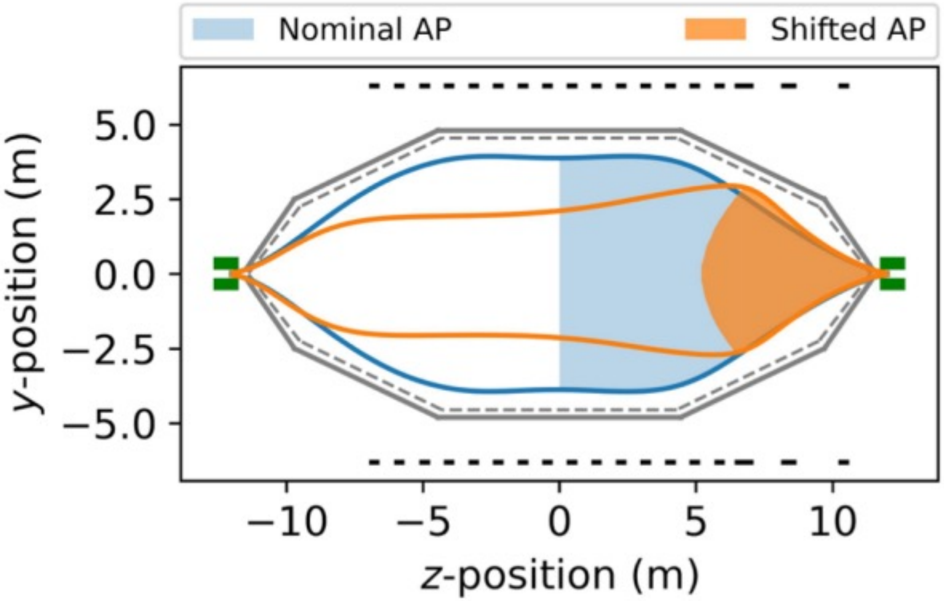
First science results are coming out from CRES and quantum readout based neutrino mass measurements

Funded by:
Czech Republic:
currently not active

Backup Slides

Systematic Improvements

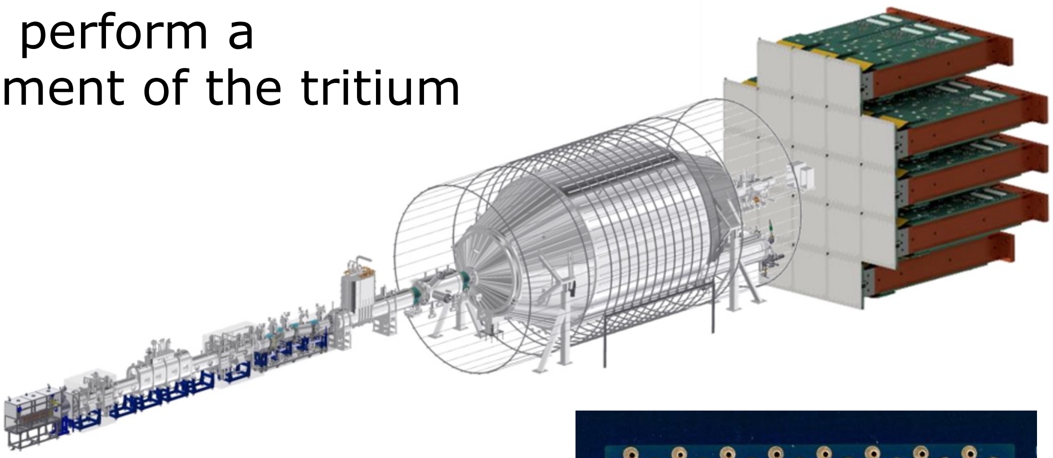


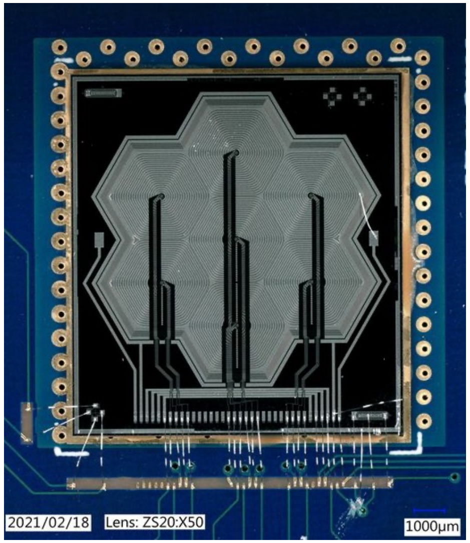


- Background reduction from shifted analysis plane and removal of Penning trap
- Plasma systematic reduction from measurement with new krypton source

TRISTAN Detector Upgrade

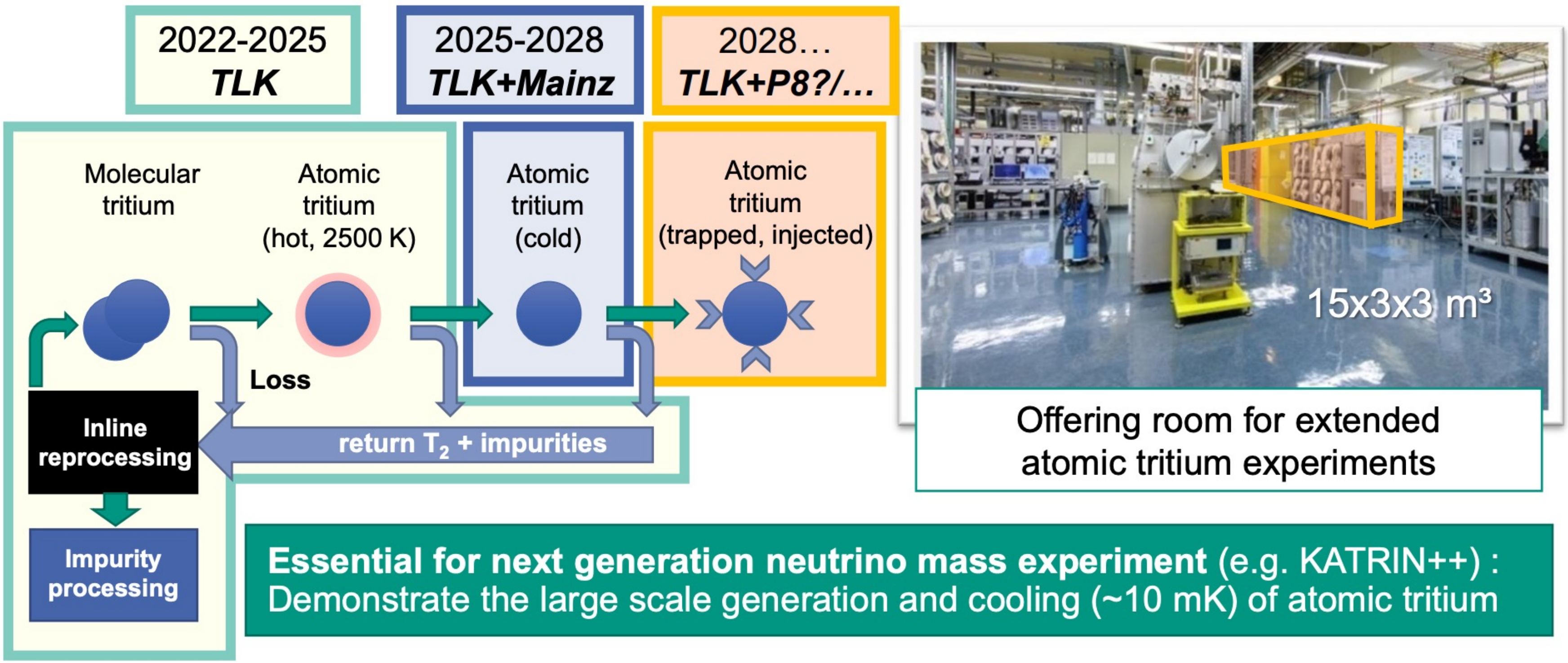
- Detector upgrade to perform a differential measurement of the tritium β-decay spectrum





- Key detector requirements:
  - 300 eV FWHM at 20 keV (ENC ~ 20)
  - 10^8 counts per second
  - $\mathcal{O}$(mm) pixel diameter
  - Deadlayer minimization ($\mathcal{O}(10 - 100$ nm))

TLK Atomic Tritium Processing



Essential for next generation neutrino mass experiment (e.g. KATRIN++) :
Demonstrate the large scale generation and cooling (~10 mK) of atomic tritium

From M. Schlösser