# Neutrino Measurements at the KATRIN experiment

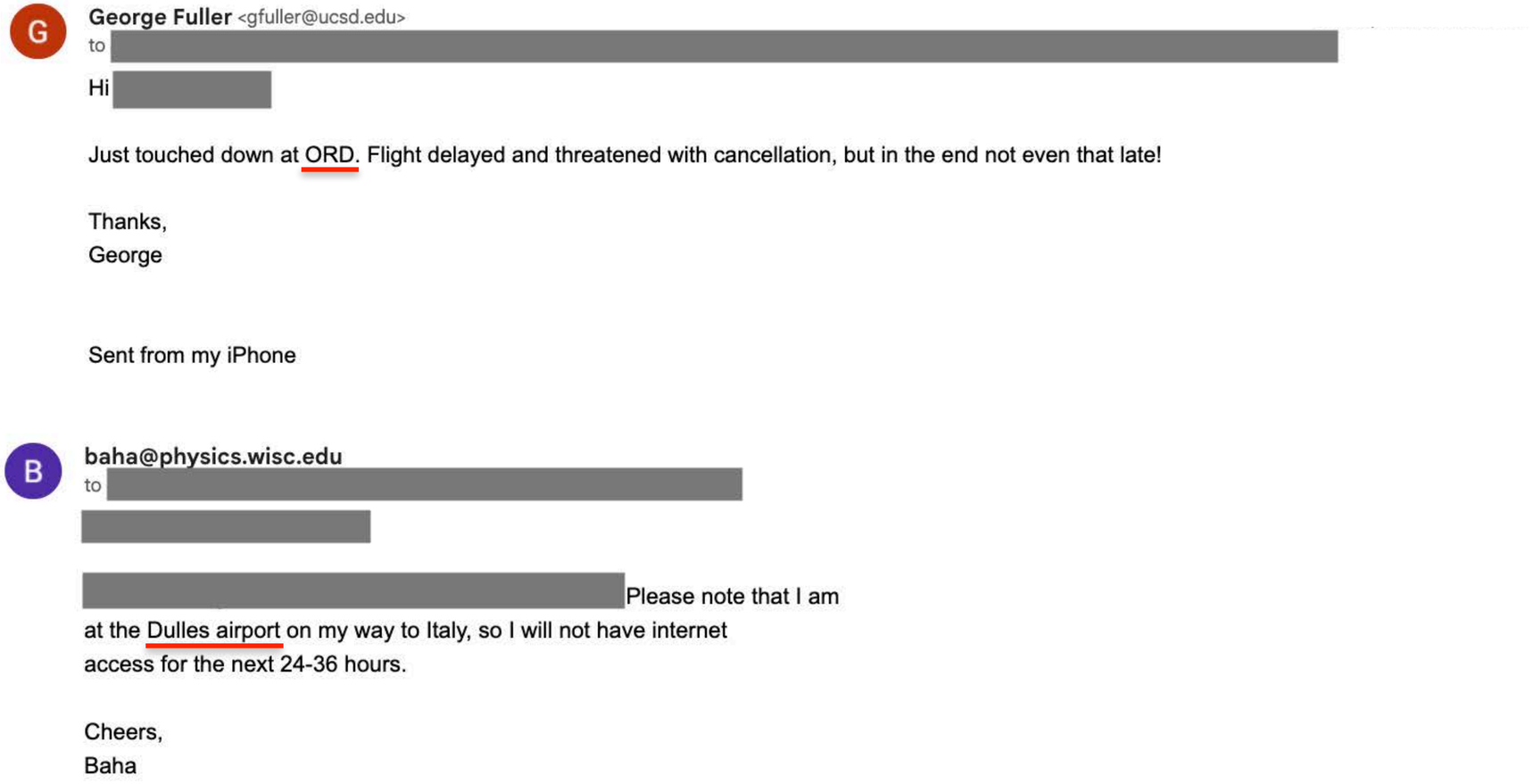
**Alan Poon**

**Nuclear Science Division**

**2025.01.17**

# What do I know about Baha and George?

1. They travel a lot
2. They like to send emails from airports



**George Fuller** <gfuller@ucsd.edu>
to [redacted]

Hi [redacted]

Just touched down at ORD. Flight delayed and threatened with cancellation, but in the end not even that late!

Thanks,
George

Sent from my iPhone

**baha@physics.wisc.edu**
to [redacted]

[redacted] Please note that I am at the Dulles airport on my way to Italy, so I will not have internet access for the next 24-36 hours.

Cheers,
Baha

# You decide…

Popular Latest Newsletters

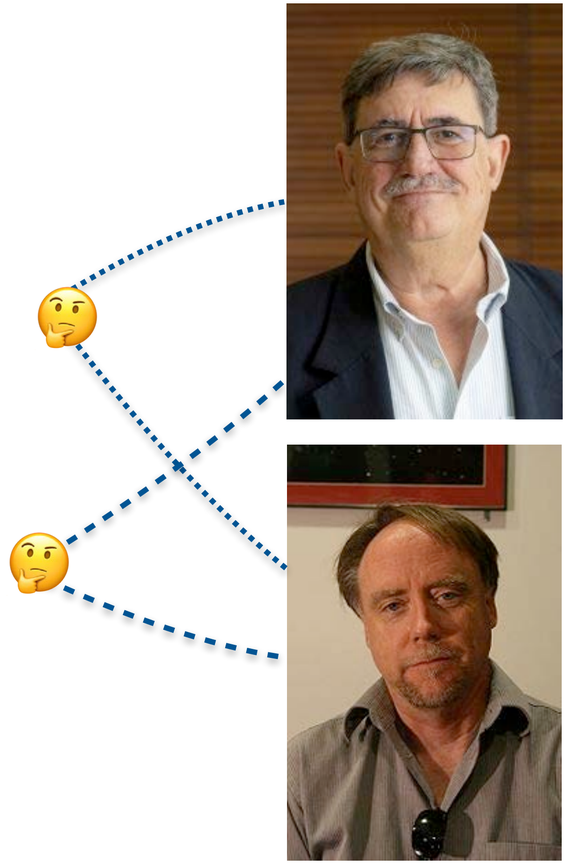
*The Atlantic* MAY 29, 2019

HEALTH

## There Are Two Types of Airport People

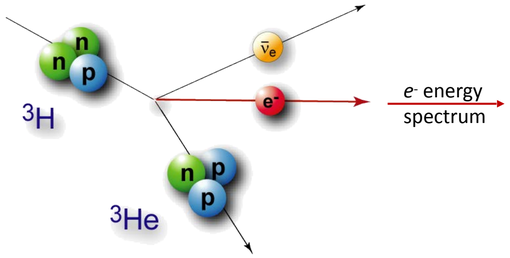
Compulsively early people: Why would anyone look at an experience as expensive and anxiety-inducing as flying and want to make it a little bit riskier?

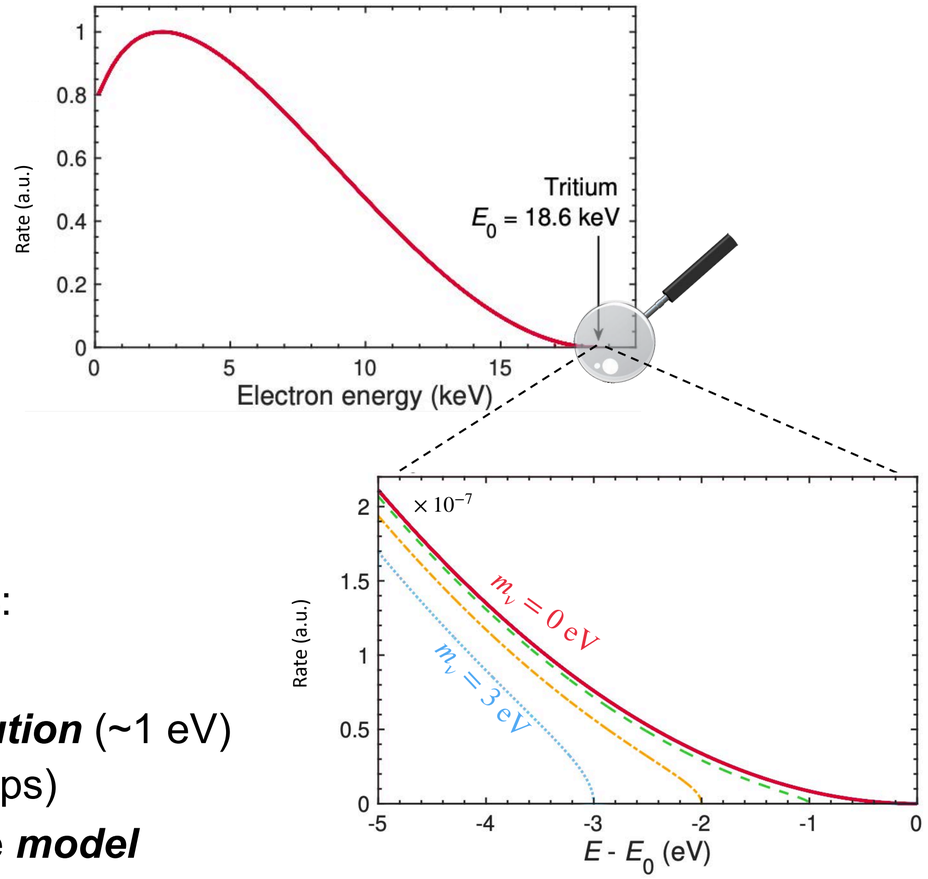
Chronically late people: Some chronically late people do, of course, intend to be on time. But a smaller group of frequent fliers heads into air travel with lateness as the goal, relishing the thrill of snatching victory from the jaws of defeat.



# Neutrino mass in $^3$H β-decay

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

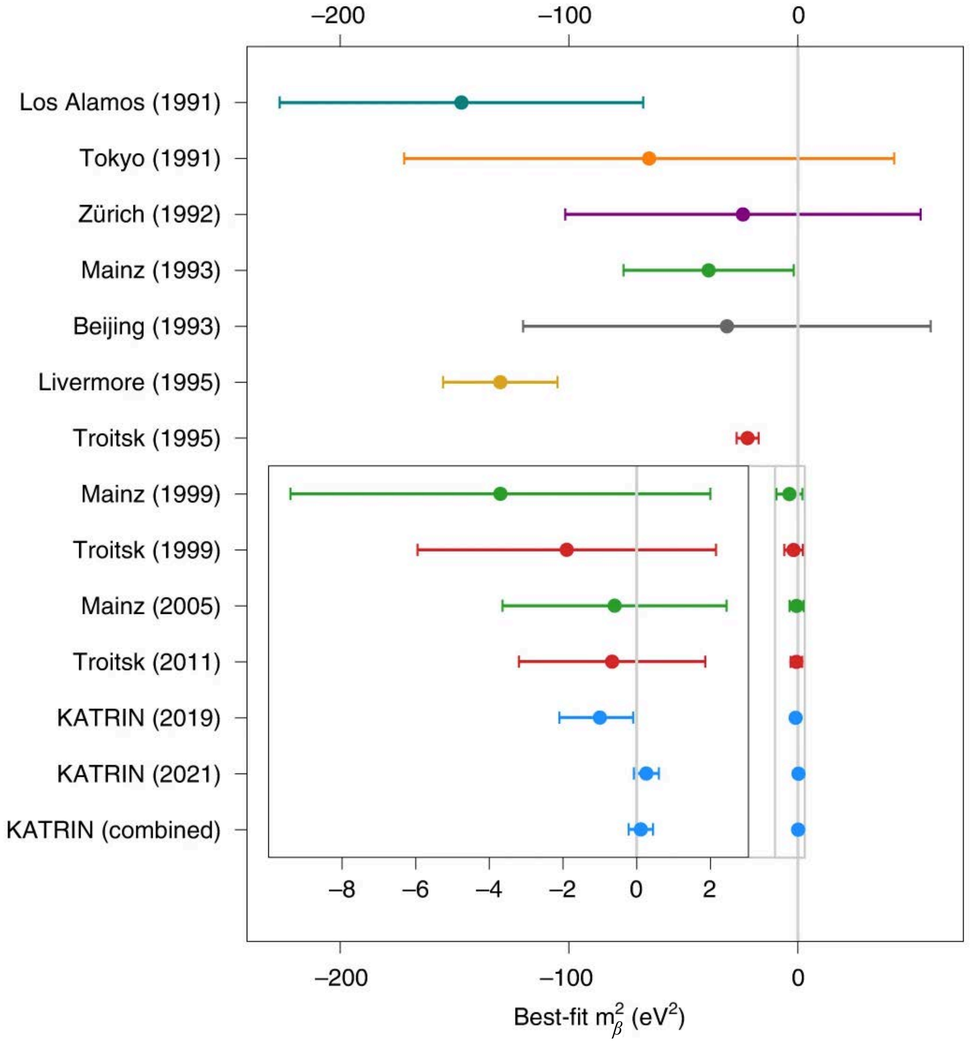



**Experimental challenges**:

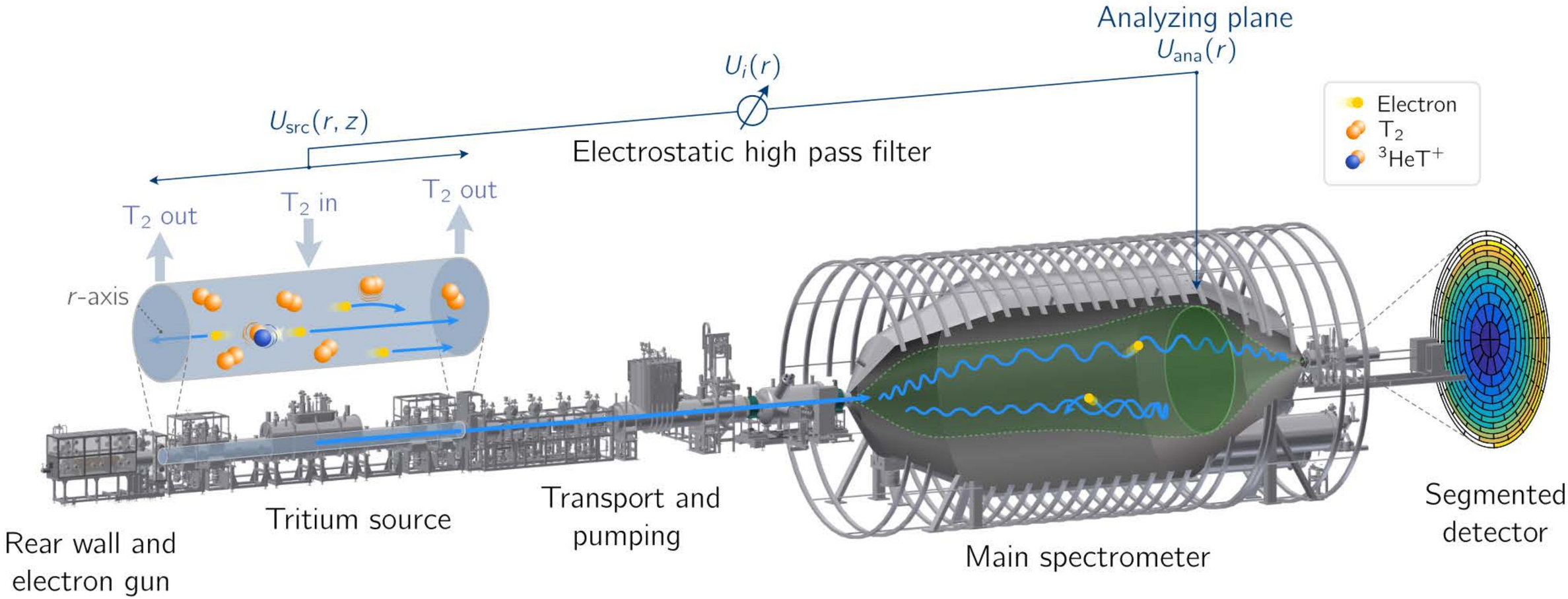
- High source ***activity***
- Excellent energy ***resolution*** (~1 eV)
- Low ***background*** (≪1 cps)
- Spectrum and response ***model***

⇒ Tritium: $E_0$ **= 18.6 keV**, $T_{1/2}$ **= 12.3 yr**




*Nature Physics*, ***18***, *pages 160–166 (2022)*

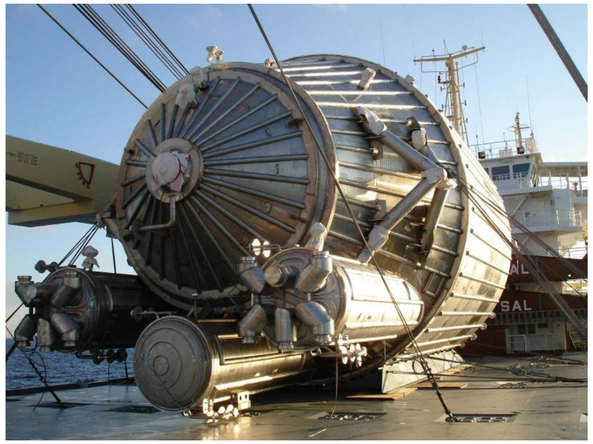
# The KATRIN experiment




**MAC-E-Filter** (**M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter)

**Full system description & commissioning: KATRIN, JINST 16 (2021) T08015**

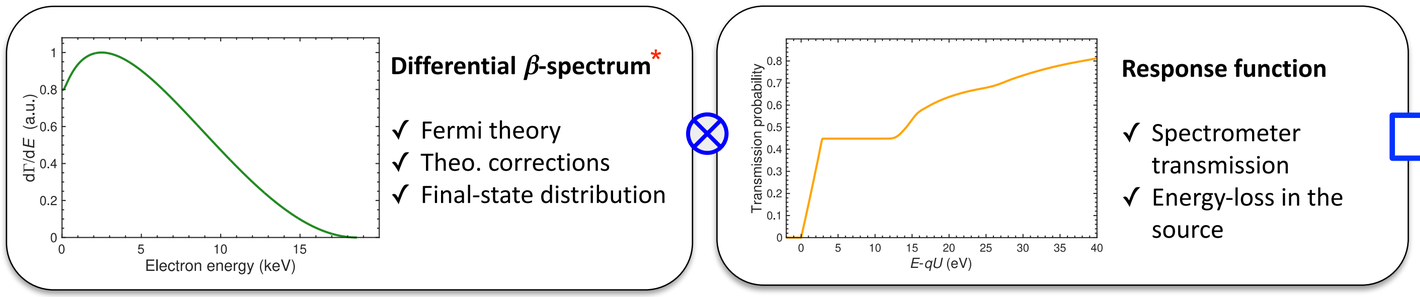
# KATRIN – An experimental tour-de-Europe

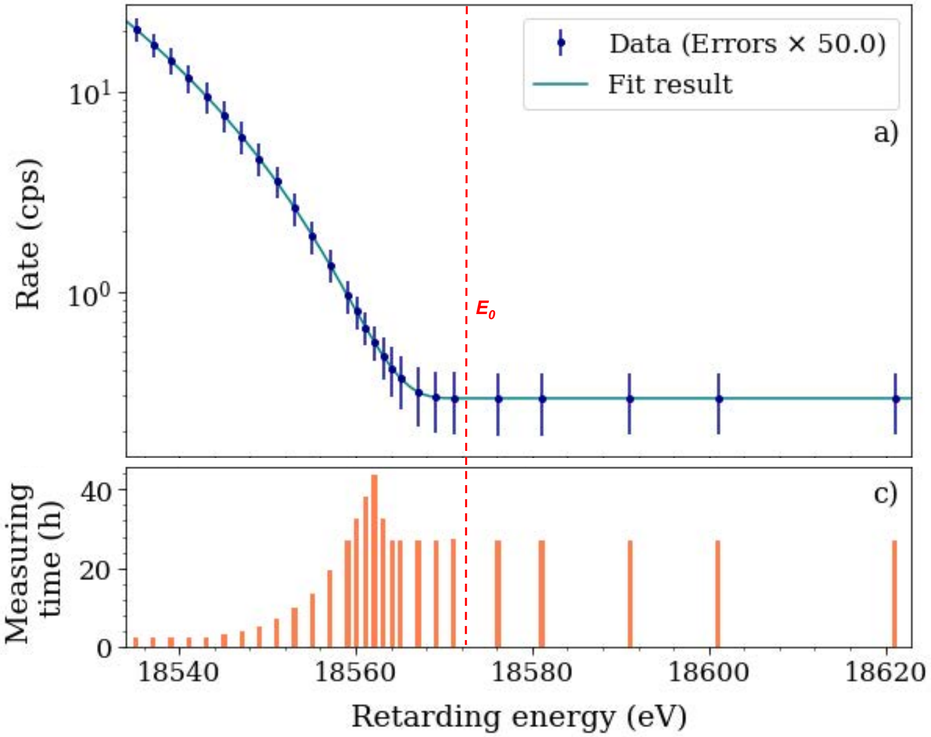




# Modeling the tritium spectrum

$R_\beta(E;m^2(\nu_e),E_0)$ $\quad\otimes\quad$ $f(E\text{-}qU)$



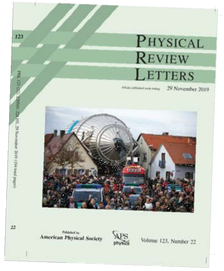

- **2-3 hour** scans, **O(100)** scans per campaign
- Each measurement campaign: **30,000 - 40,000** spectra
- **Stack** data points with the **same** measurement conditions
- Analysis window:

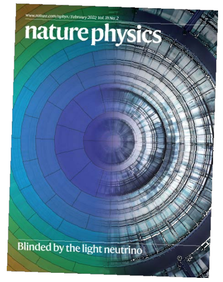
  **[$E_0$ - 40 eV, $E_0$ + 135 eV]**

$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E) dE + R_{\mathrm{bg}}$$

*Details in Kleesiek et al., Eur. Phys. J. C (2019) 79:204

# KATRIN data releases



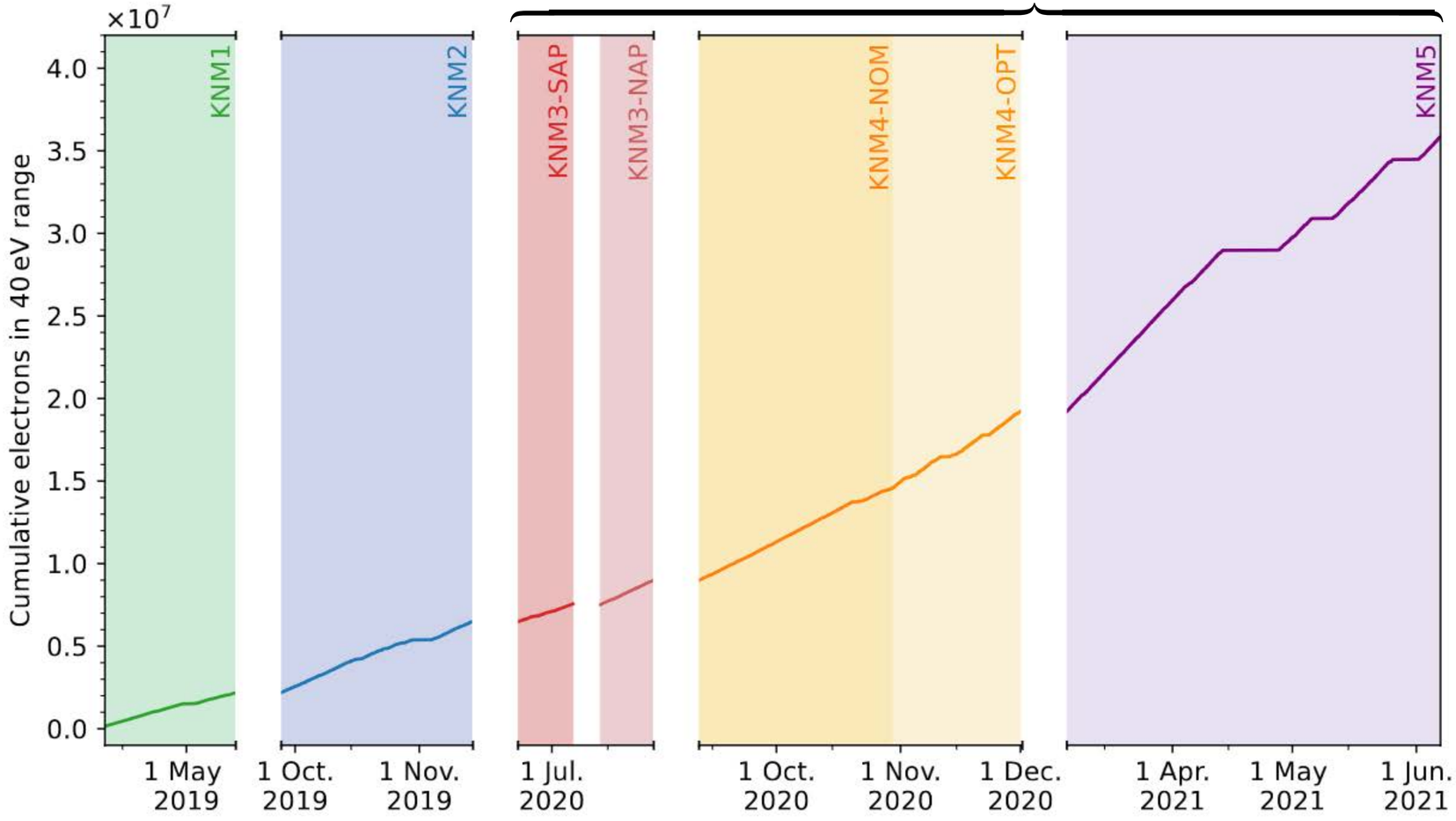




arXiv:2406.13516

**2019**: $m_\nu$ < 1.1 eV (90% CL)

**2022**: $m_\nu$ < 0.8 eV (90% CL)

- ~**6**M counts



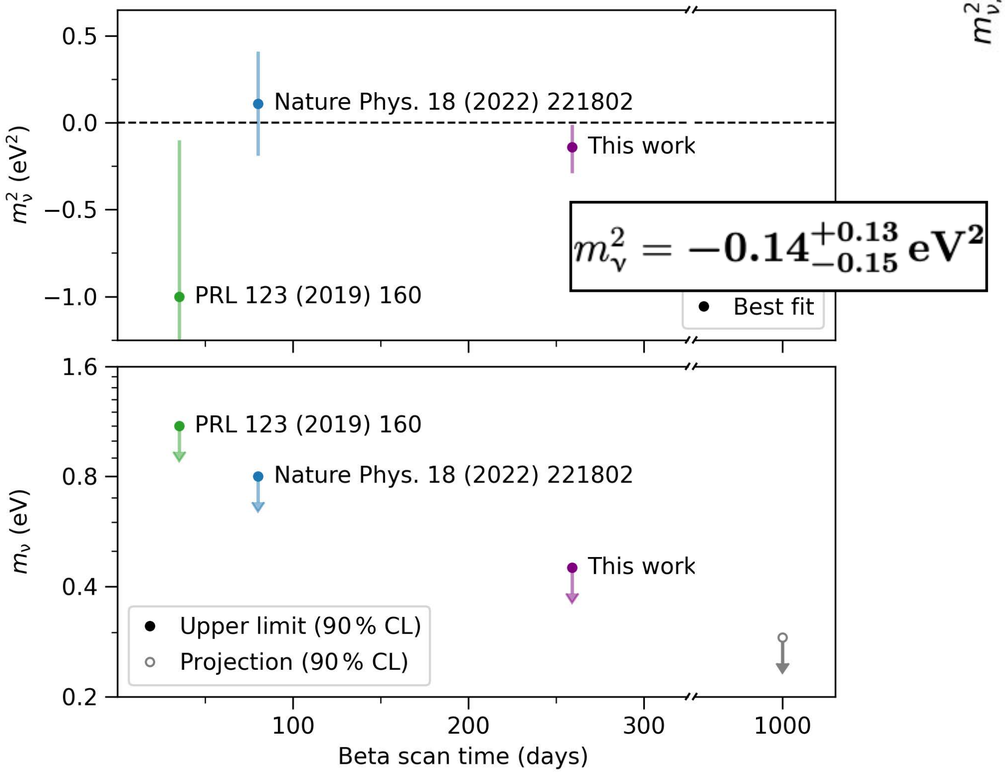

PRL 123 (2019) 221802
PRD 104 (2021) 012005

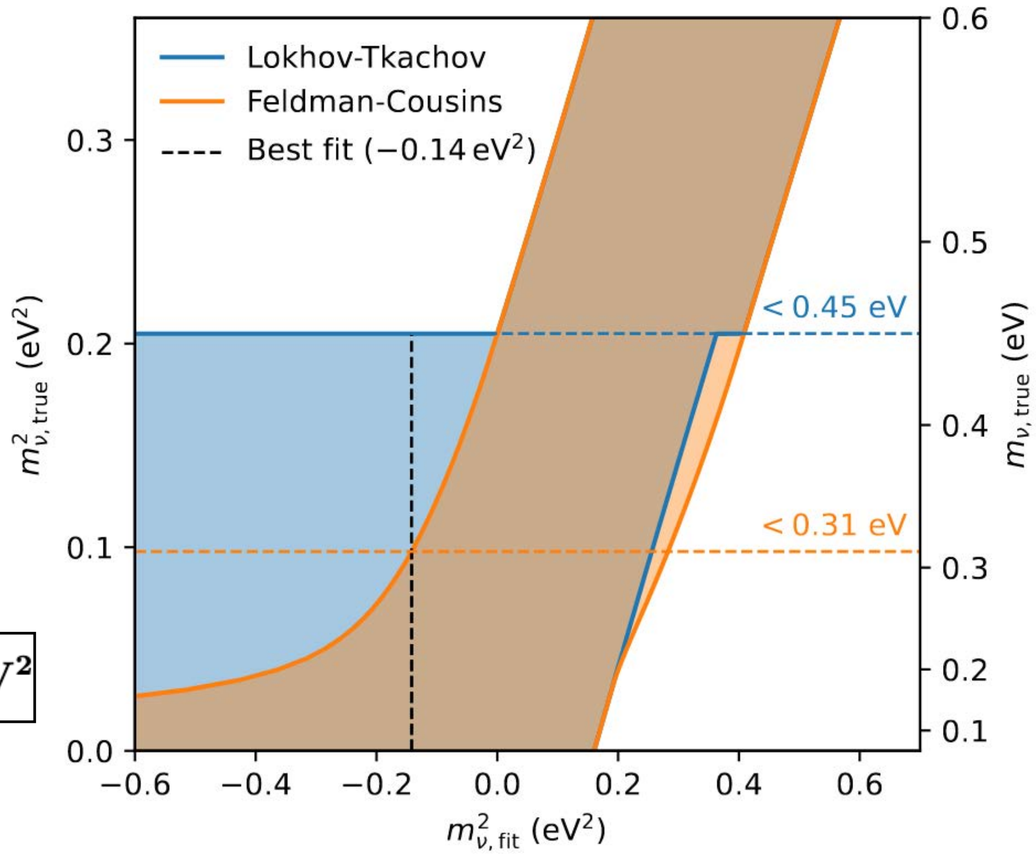
Nature Phys. 18 (2022) 160

# KATRIN data releases

**Neutrino 2024 (June 2024):**

- **259** measurement days
- **1757** $\beta$-scans (**~36M counts**)




arXiv:2406.13516

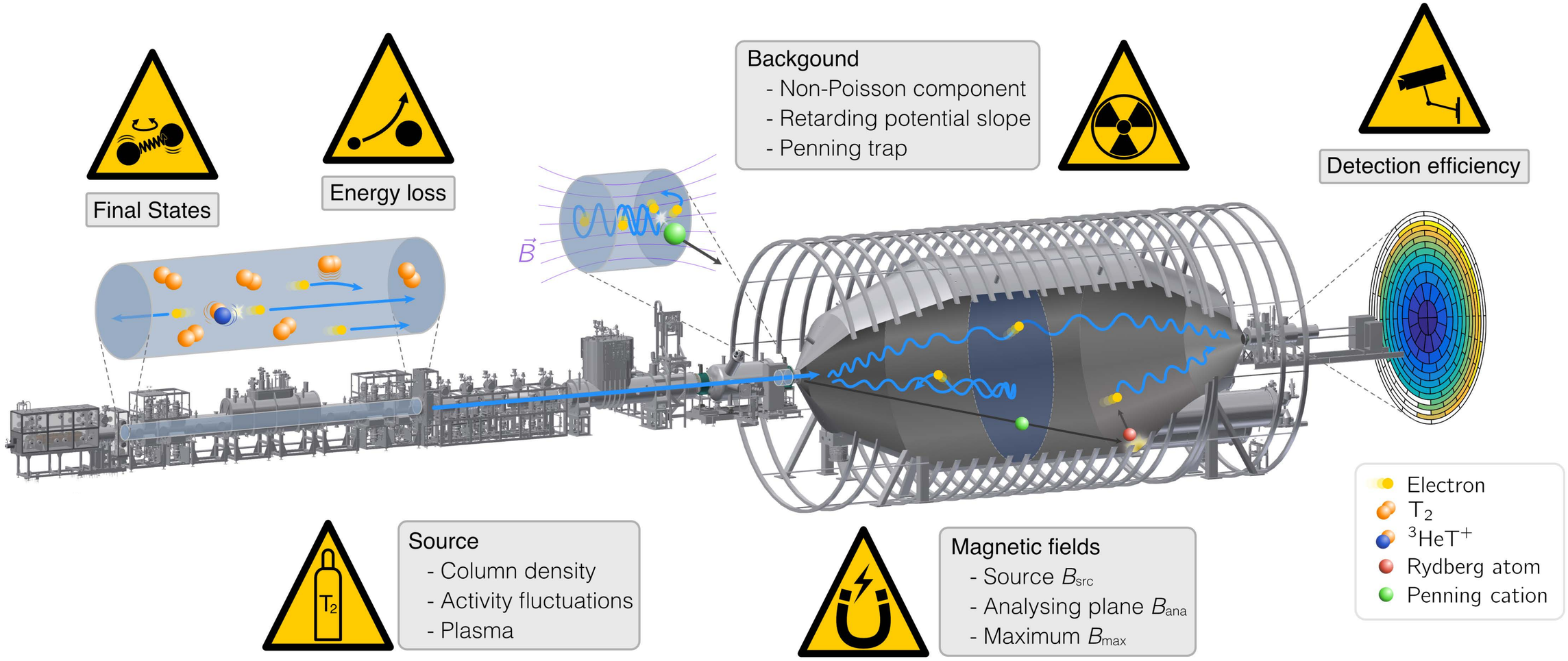
$$m_\nu < 0.45\,\mathrm{eV}\ (90\,\%\ \mathrm{CL})$$

**Lokhov-Tkachov** construction

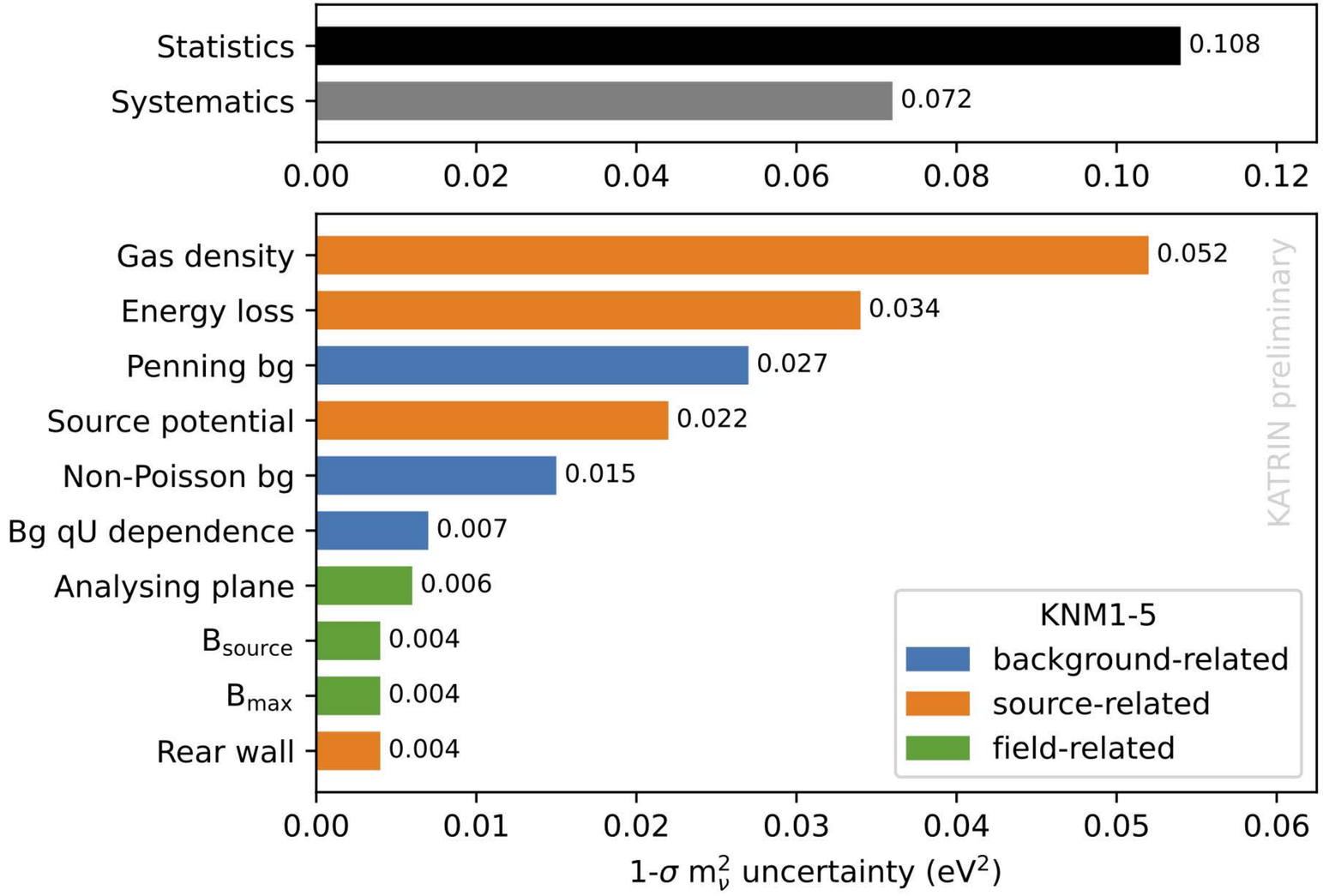
Ongoing data taking through 2025 →
Σ 1000 days

- target sensitivity below 0.3 eV

# Systematic effects overview



# Systematic uncertainties



# Limits of a MAC-E filter and molecular tritium

- The statistical sensitivity of a KATRIN-type experiment:

$$\delta m_\beta^2 \propto \frac{b^{\frac{1}{6}}}{r^{\frac{2}{3}} t^{\frac{1}{2}}}$$

$b$: background rate
$r$: radius of the spectrometer
$t$: measurement time

- The diameter of a spectrometer required to improve KATRIN's sensitivity by an order of magnitude would be unrealistically large.
- Spectral broadening induced by the final-state distribution (FSD) would become a significant limiting factor for future experiments.
- New experimental approach to detect the *cyclotron radiation* from *atomic* tritium decay. Goal: 40 meV

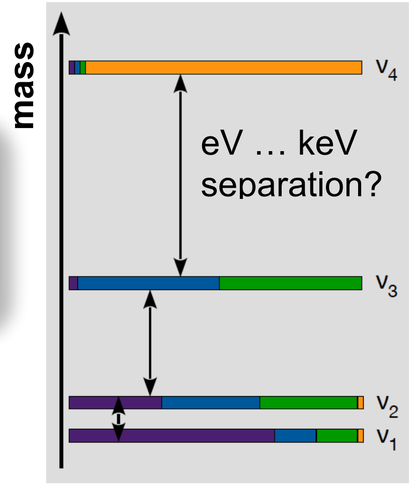
PROJECT 8

# KATRIN neutrino measurements (beyond $m\beta$)

**β-spectrum of high statistics and precision**

Is there a fourth (sterile) neutrino?
**(search for a kink)**

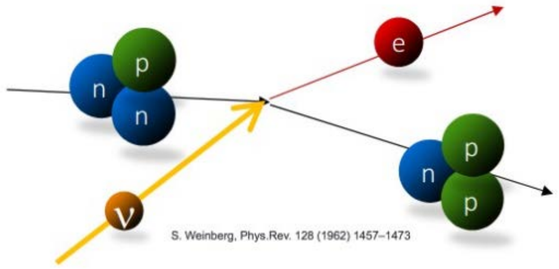
Phys.Rev.Lett. 126 (2021) 9, 091803
Phys.Rev.D 105 (2022) 7, 072004
EPJC 83 (2023) 763




Search for Lorentz invariance violation
**(sidereal modulation)**

Phys.Rev.D 107 (2023) 8, 082005

Constrain local density of cosmic relic neutrinos
**(peak search)**




Phys. Rev. Lett. 129 (2022) 1, 011806

Search for exotic interactions
**(spectrum shape)**

arXiv:2410.13895

# Sterile Neutrinos

Eur. Phys. J. C (2023) 83:763
https://doi.org/10.1140/epjc/s10052-023-11818-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

## Search for keV-scale sterile neutrinos with the first KATRIN data

Dark Population Transfer Mechanism for Sterile Neutrino Dark Matter #1

George M. Fuller (UC, San Diego), Lukáš Gráf (UC, San Diego and UC, Berkeley), Amol V. Patwardhan (SLAC and Minnesota U.), Jacob Spisak (UC, San Diego and Heidelberg, Max Planck Inst.) (Feb 21, 2024)

Published in: *Phys.Rev.Lett.* 133 (2024) 18, 181002 • e-Print: 2402.13878 [hep-ph]

pdf DOI cite claim reference search 4 citations

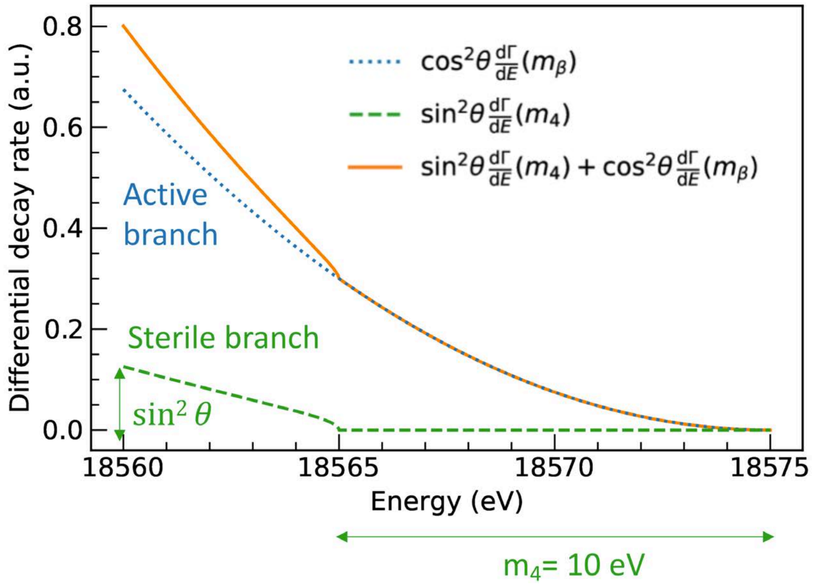
Probing self-interacting sterile neutrino dark matter with the diffuse supernova neutrino background #2

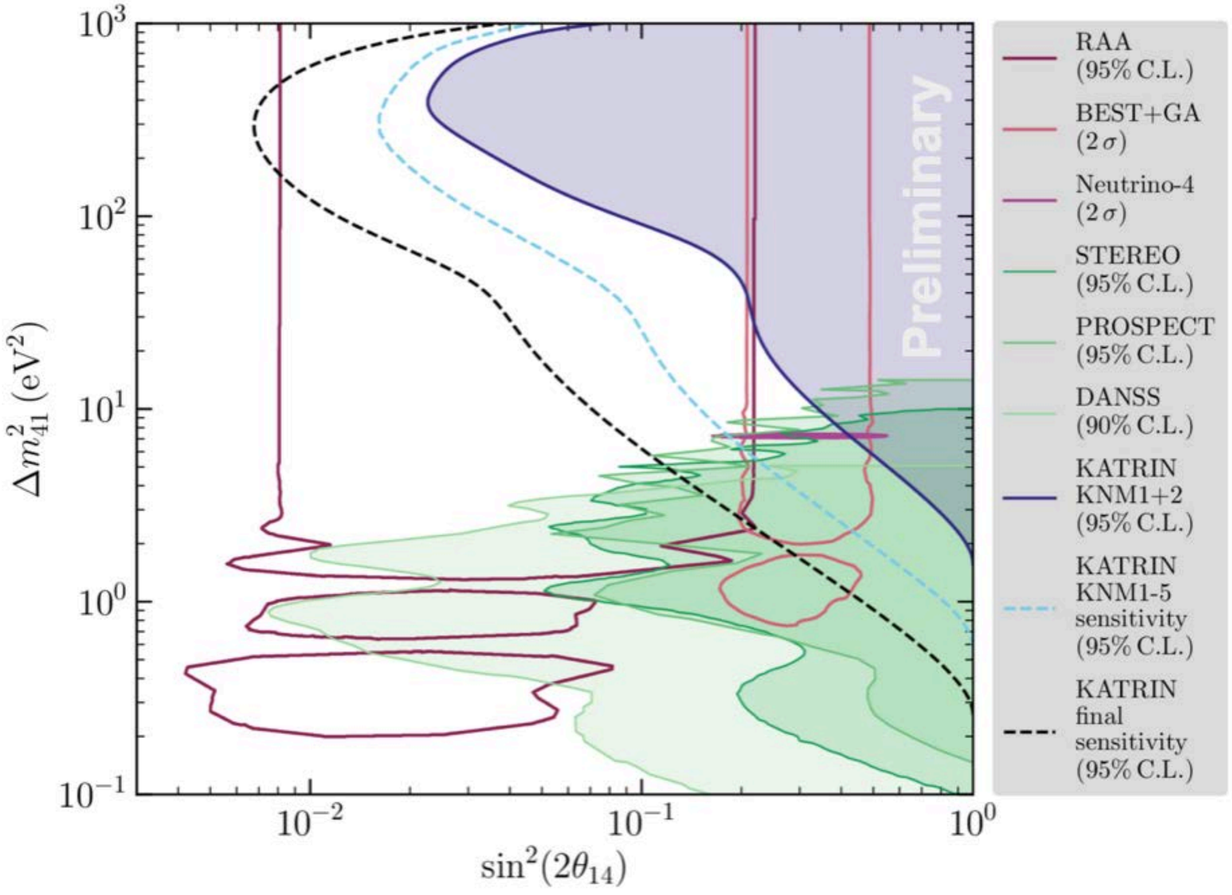
A. Baha Balantekin (Wisconsin U., Madison), George M. Fuller (UC, San Diego), Anupam Ray (UC, Berkeley and Minnesota U.), Anna M. Suliga (Wisconsin U., Madison and UC, San Diego and UC, Berkeley) (Oct 10, 2023)

Published in: *Phys.Rev.D* 108 (2023) 12, 123011 • e-Print: 2310.07145 [hep-ph]

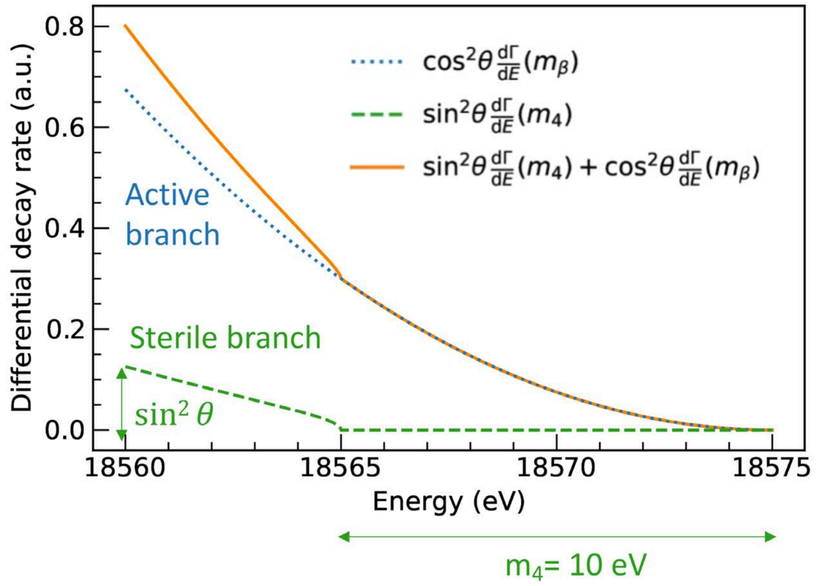
pdf DOI cite claim reference search 12 citations

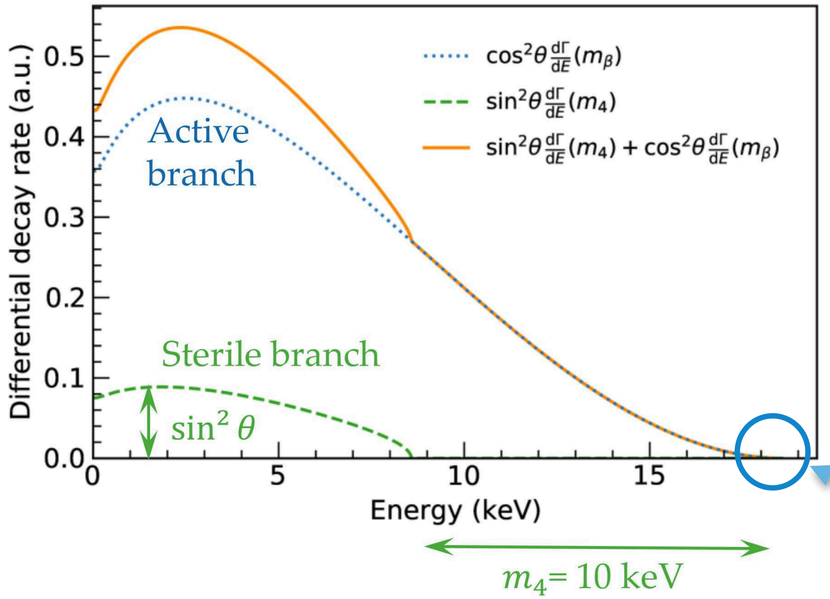
# Sterile Neutrinos

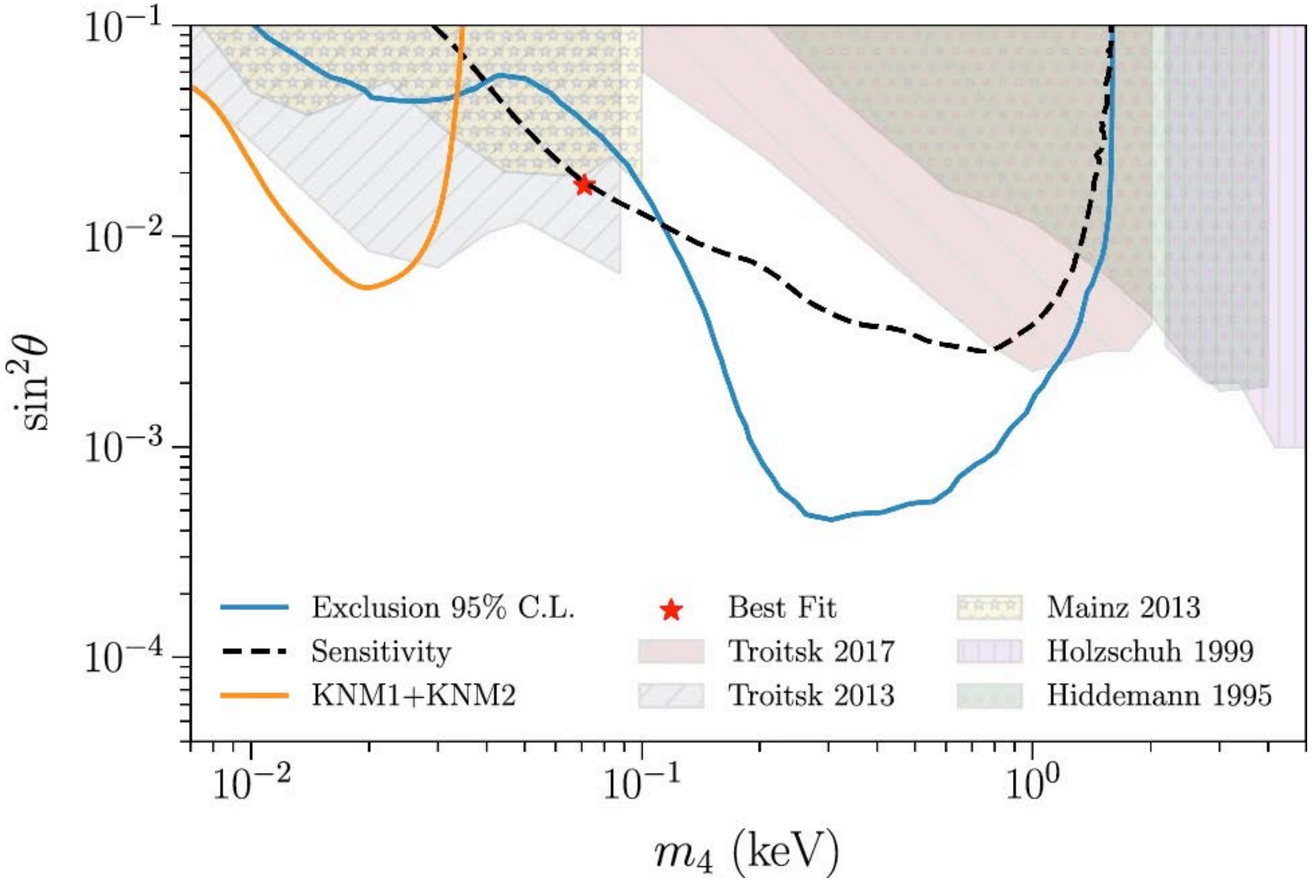


# Sterile Neutrinos



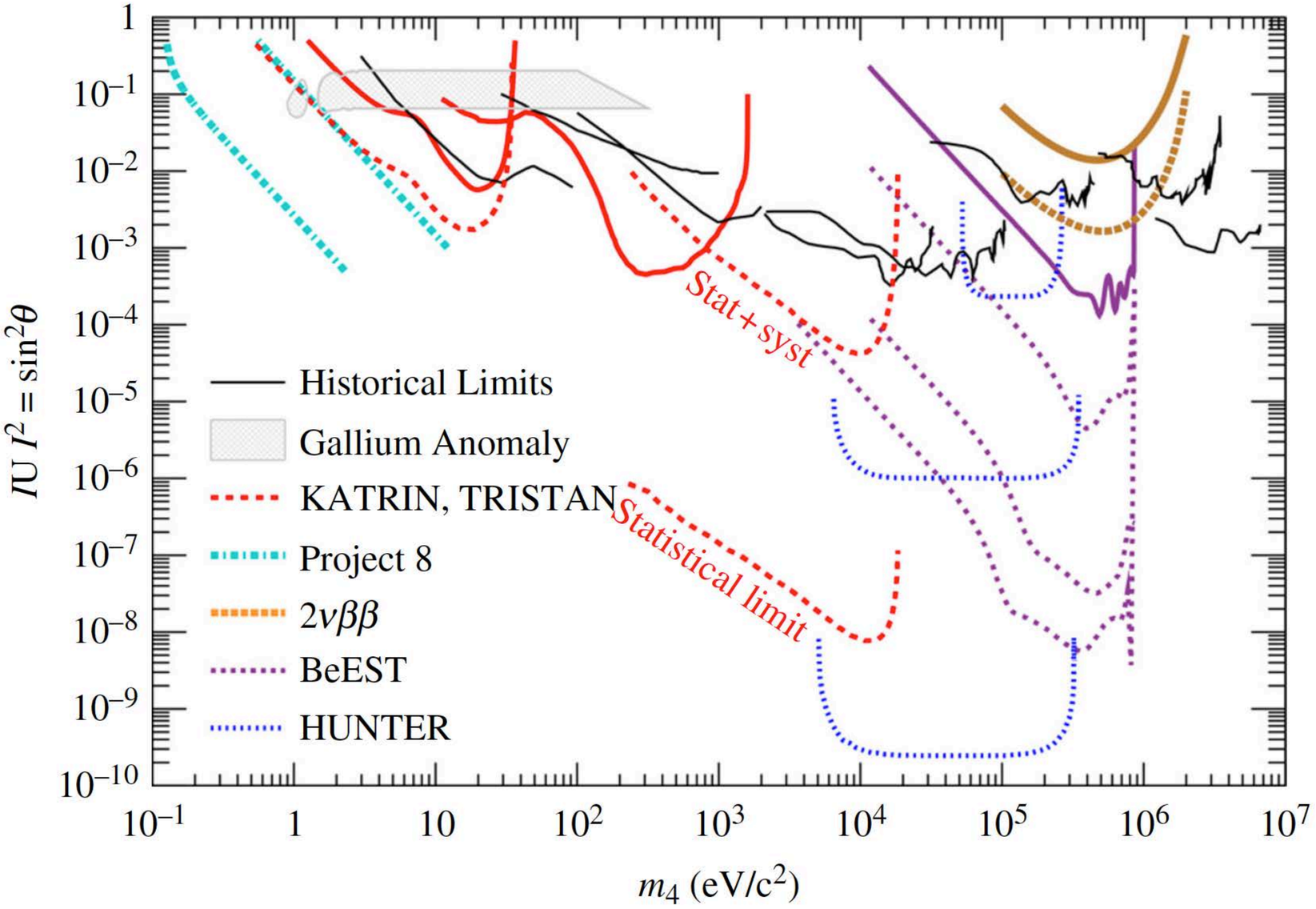




EPJC 83 (2023) 763

12 days commissioning campaign in 2018
Reduced isotopic abundance of 0.5%
Integral spectrum: 0.01 -1.6 keV mass

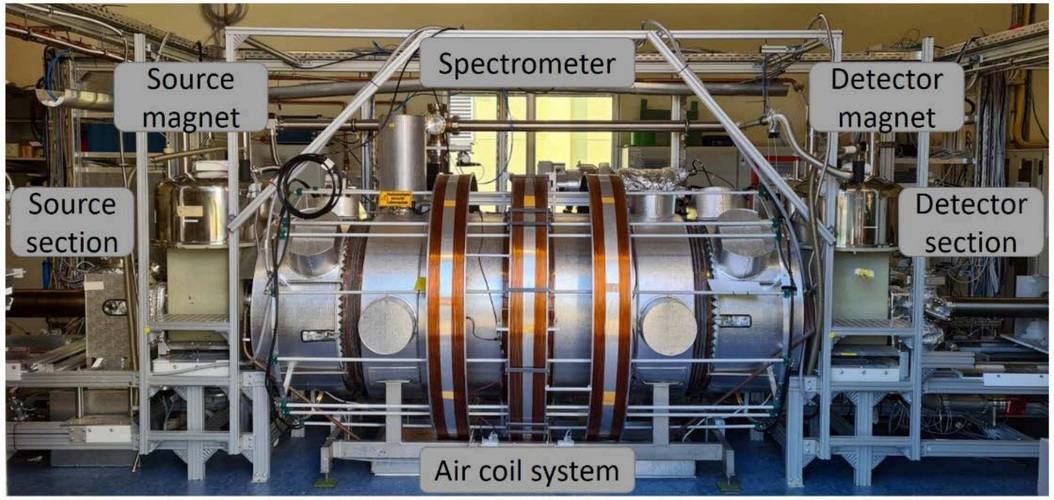
# Sterile neutrinos (β-decay experiments)



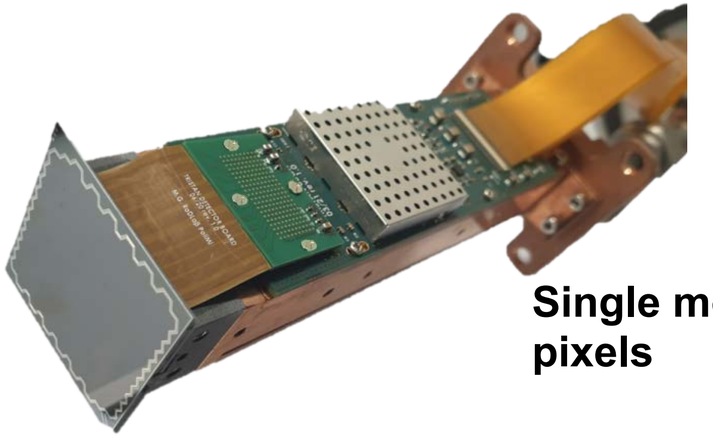



Parno, AP, Singh, *Phil. Trans. R. Soc. A* **382:** 20230122

# TRISTAN @ KATRIN




**First measurement at MOnitor Spectrometer (MOS)**

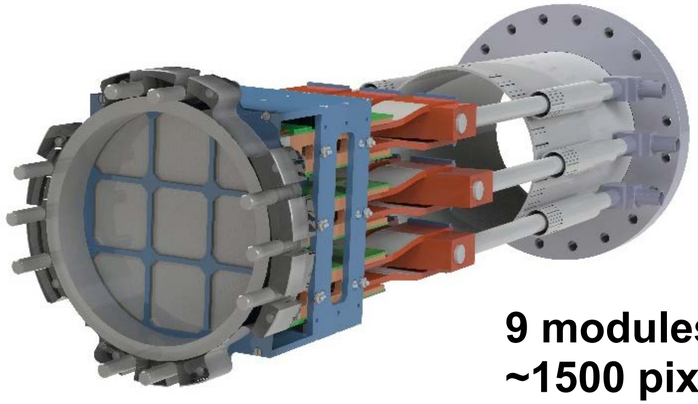


**Single module 166 pixels**

S. Mertens et al., J. Phys. G46 (2019); S. Mertens et al., J. Phys. G48 (2020); D.Siegmann et al., J. Phys. G (2024)

## After the neutrino mass campaign ends at the end of 2025:

- Search for keV sterile neutrinos
  - Novel SDD array for high rates
- Target sensitivity to mixing of $10^{-6}$
- Timeline
  - 2024 – Assembling a full detector replica
  - 2026 – Installation in the KATRIN beamline
  - 2026-2027 – keV sterile neutrino search



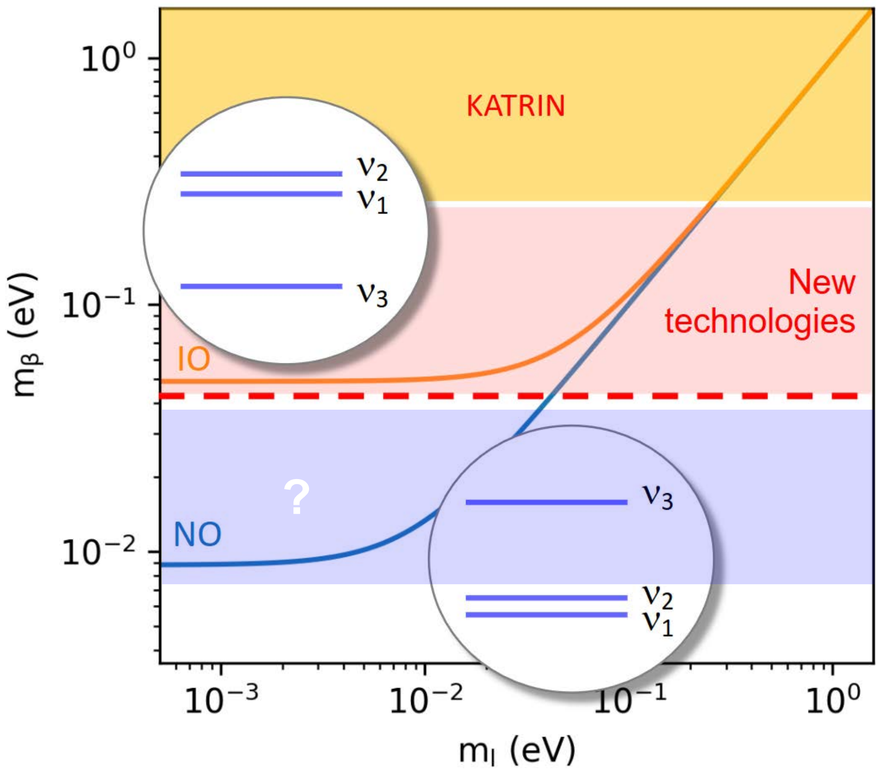
**9 modules ~1500 pixels**

# KATRIN Outlook

**2026-2027**: keV sterile neutrino search with **TRISTAN@KATRIN**

- Preparations for hardware upgrades, analysis is getting ready for the data

**2027+: R&D** towards the ultimate neutrino mass determination




- Differential methods, atomic tritium, background reduction
- **KATRIN++** mission:
  - Identify and develop scalable technology for the next neutrino mass experiments
  - Use **KATRIN infrastructure** for R&D phase (~7 years)

# Baha Fest


*soundazed.com*

# George Fest


*georgeharrison.com*

# Baha-George Fest (BG Fest in Berkeley)

# Congratulations, George and Baha!

## We appreciate your contributions to the scientific community


U.S. DEPARTMENT OF ENERGY

UNIVERSITY OF CALIFORNIA