KATRIN's Latest Neutrino Mass Results & eV-Scale Sterile Neutrino Sensitivity

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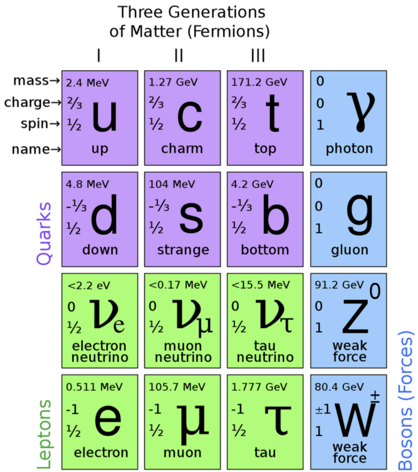
Institute for Astroparticle Physics |

Significance of ν Mass

> *"We have learned that neutrinos are not massless, and that they change flavor as they propagate through space"*
> — *Takaaki Kajita & Arthur McDonald 2015 Nobel Prize in Physics*

In Particle Physics:

- Nature of ν: Dirac or Majorana?
- ν masses are at least 500,000 times lighter than electrons, less than 0.8 eV. Why so small? Sea-saw mechanism: Type-I & Type-II, etc
- Possible connection to generation of matter-antimatter asymmetry Leptogenesis



Three Generations of Matter (Fermions)

mass→
charge→
spin→
name→

	I	II	III	Bosons (Forces)
Quarks	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
Leptons	<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
Leptons	0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

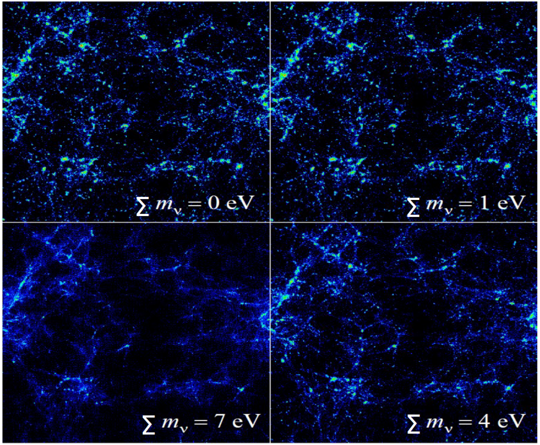
Source: PBS NOVA/Fermilab/Office of Science/US Dept of Energy

Significance of ν Mass

> *"The mass of the neutrino, though incredibly small, holds profound implications for the evolution of the universe."*
> — *Steven Weinberg, Nobel Laureate in Physics, 1979*

In Cosmology:

- Significant abundance of mass carrying νs can influence structure formation and the expansion of universe
- With finite masses, cosmological neutrinos become part of the total matter field and contribute to its smoothing

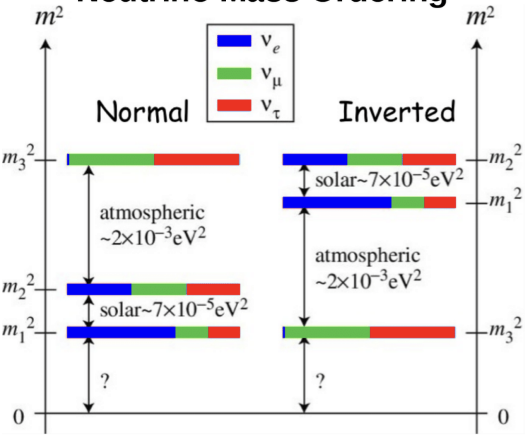


Chung-Pei Ma 1996

Status of Neutrino Puzzle

- Absolute mass scale: minimum m_ν
- What is the neutrino mass ordering, normal or inverted?
- Are neutrinos Majorana type particles, and if so, what new physics lies behind this fact?
- Is there leptonic CP violation?
- Are there more than 3 known flavors i.e. Sterile neutrinos?
- Can neutrinos explain the matter-antimatter asymmetry in the Universe?

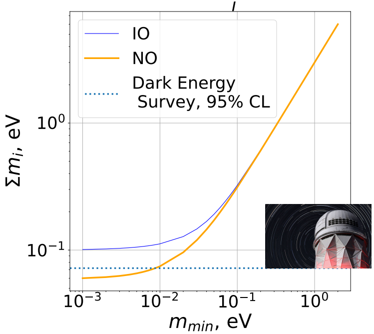
Neutrino Mass Ordering



Measurement of ν mass(es): complementary approaches

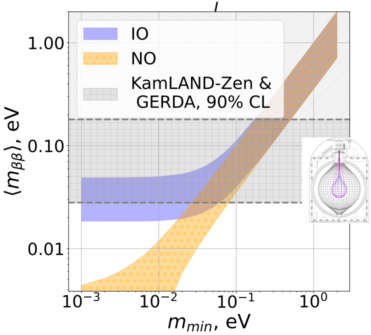
Cosmology

$$\Sigma m_i = \sum_i m_i$$



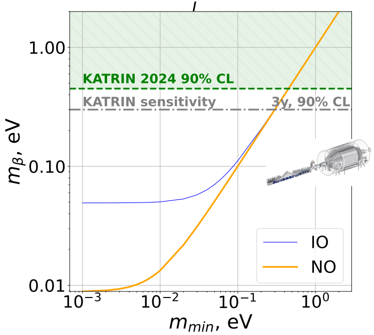
$0\nu\beta\beta$-decay

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



β-decay kinematics

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

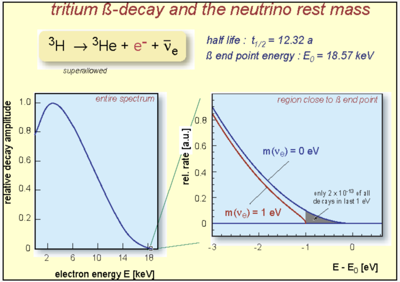


Direct kinematic ν mass measurement

- ✓ Model independent:
  - Independent of cosmological model and neutrino nature
  - ✓ Measurement of electron β spectrum:

$$\frac{d\Gamma}{dE} = C\,p\,(E + m_e)(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}\,F(Z+1, E)\Theta(E_0 - E - m_\nu)S(E)$$

- ✓ Based on kinematics & energy conservation
- ✓ Incoherent sum of neutrino mass: $m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$
- ✓ Suitable isotopes:
  - **Tritium**
    - $E_0 = 18.6\,\text{keV},\ T_{1/2} = 12.3\,\text{y}$
    - $S(E) = 1$ (super-allowed)
  - **Alternative approach: Holmium (EC decay)**
    - $Q_{\text{EC}} \approx 2.5\,\text{keV},\ T_{1/2} = 4570\,\text{y}$



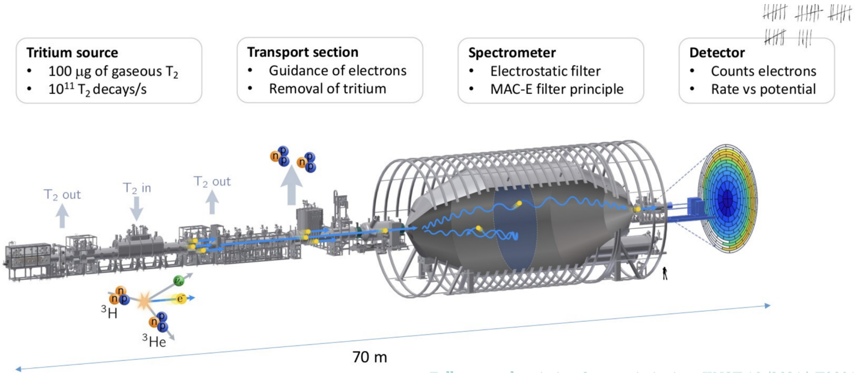
Source: `https://web.physics.utah.edu/~jui/5110/y2009m03d09/KATRIN.htm`

The KATRIN Experiment

- **Windowless Gaseous Molecular Tritium Source:**
  - High activity: $\sim$ 100 GBq

- **MAC-E Filter Technology:**
  - Excellent energy resolution: $\sim$ 1 eV
  - Large acceptance angle: 0°–51°

Sensitivity better than 0.3 eV (90% CL) after 1000 days of measurement time



Tritium source
- 100 μg of gaseous T_2
- 10^{11} T_2 decays/s

Transport section
- Guidance of electrons
- Removal of tritium

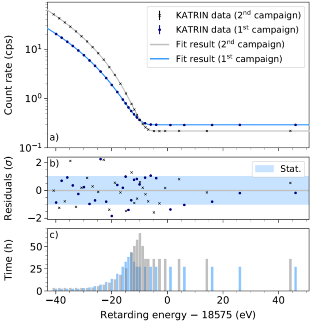
Spectrometer
- Electrostatic filter
- MAC-E filter principle

Detector
- Counts electrons
- Rate vs potential

ν mass analysis

Measurement strategy:

- **Scan points**: $\sim$ 30 HV set points
- **Scan time**: $\sim$ 3 hours per scan, $O(100)$ scans per campaign, **stacked data**
- **Scan interval**: $E_0 - 40\,\text{eV}$ to $E_0 + 135\,\text{eV}$



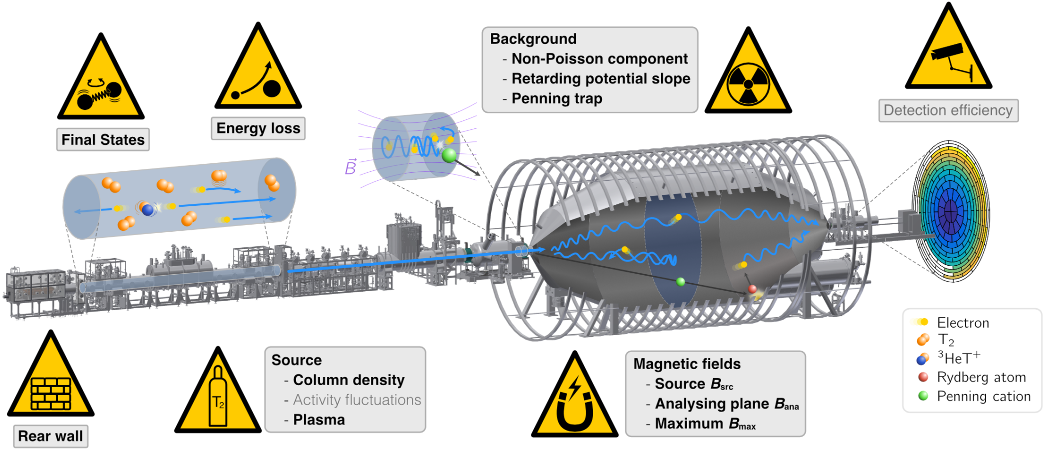
Nat. Phys. 18, 160–166 (2022)

- **Model** $N_{\text{model}}(qU, \Theta)$ is fitted to the measured integral spectrum $N_{\text{exp}}(qU)$:

$$N_{\text{model}}(qU, \Theta) = A \cdot \int_{qU}^{E_0} R_\beta(E,\, m_\nu^2,\, \Theta) \otimes f(E, qU)\, dE + B_g$$

- 4 model parameters:
  - A - Signal amplitude
  - E_0 - effective endpoint energy
  - m_ν^2 - effective mass of electron anti-neutrino
  - Bg - Background rate
- 3-tiered blind analysis
  - Freeze analysis on MC data
  - Blinded Model: Modified molecular final state distribution
  - Two different analysis teams: different strategies and codes

Sources of systematic uncertainties



Final States

Energy loss

Background
- **Non-Poisson component**
- **Retarding potential slope**
- **Penning trap**

Detection efficiency

Rear wall

Source
- **Column density**
- Activity fluctuations
- **Plasma**

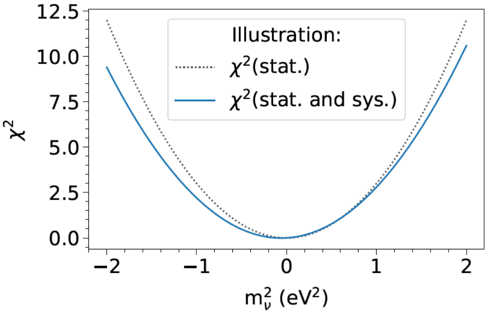
Magnetic fields
- **Source B_{src}**
- **Analysing plane B_{ana}**
- **Maximum B_{max}**

Source: L. Köllenberger

Systematic error propagation via Pull term approach

- Adding additional free parameters (θ_i)
- Constraining parameters with a penalty term
- Adding pull terms widens the χ^2 distribution:

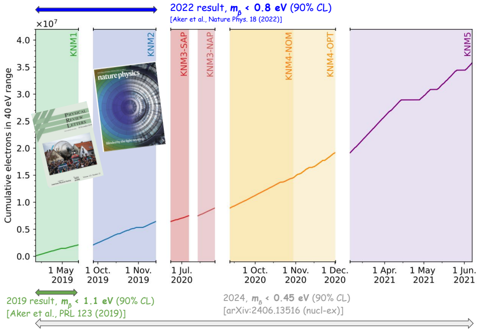
$$\chi^2\left(m^2, E_0, \mathrm{Sig}, \mathrm{Bg}, \theta_1, \ldots\right) + \frac{\left(\theta_1 - \hat{\theta}_1\right)^2}{\sigma_{\theta_1}^2} + \ldots$$



In the combined analysis of data across campaigns:

- Pull term as multivariate normal distribution
- Treatment of correlations between campaigns and segments
- High-cost model computations

Analysis Progress



2022 result, $m_\beta < 0.8$ eV (90% CL)
[Aker et al., Nature Phys. 18 (2022)]

2019 result, $m_\beta < 1.1$ eV (90% CL)
[Aker et al., PRL 123 (2019)]

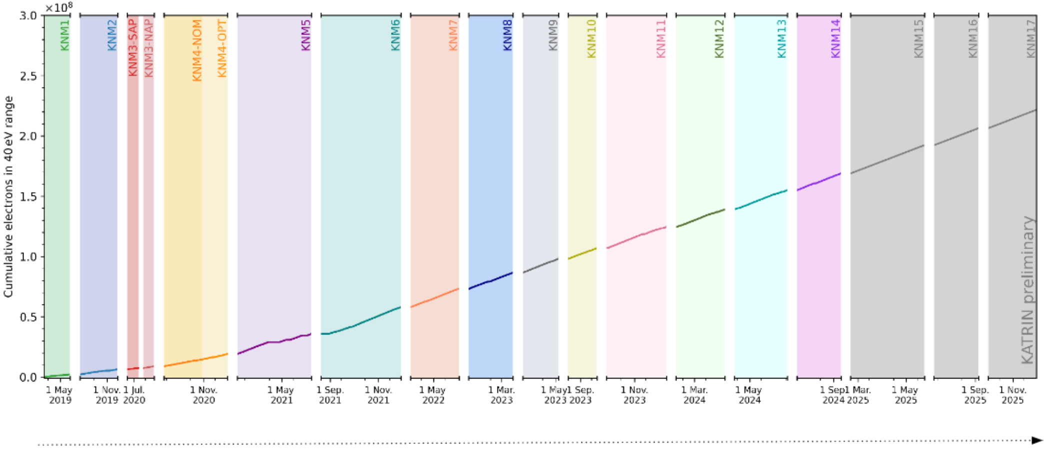
2024, $m_\beta < 0.45$ eV (90% CL)
[arXiv:2406.13516 (nucl-ex)]

Table: KATRIN Neutrino Mass Measurement Campaigns (KNM)

Campaign	Time (hrs)	Counts in ROI	Bg (mcps)
KNM1	522	1.48×10^6	370
KNM2	294	3.76×10^6	278
KNM3-SAP	220	9.77×10^5	137
KNM3-NAP	224	1.25×10^6	258
KNM-NOM	834	5.64×10^6	150
KNM4-OPT	431	4.58×10^6	150
KNM5	1232	1.60×10^7	160

- Suppression of background by factor 2: “Shifted Analyzing Plane” configuration *Eur. Phys. J. C (2022) 82:258)*
- Expected sensitivity < 0.5 eV

Data taking till 2025



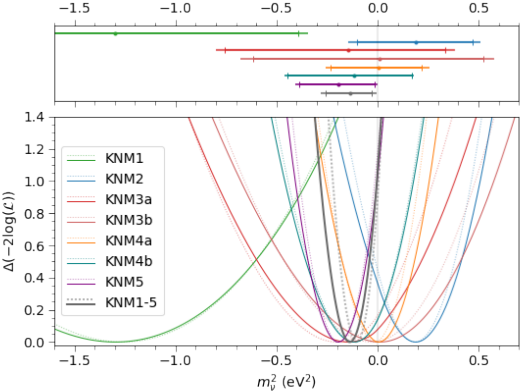
Latest results of ν mass

First five campaigns (KNM1-5) combined:

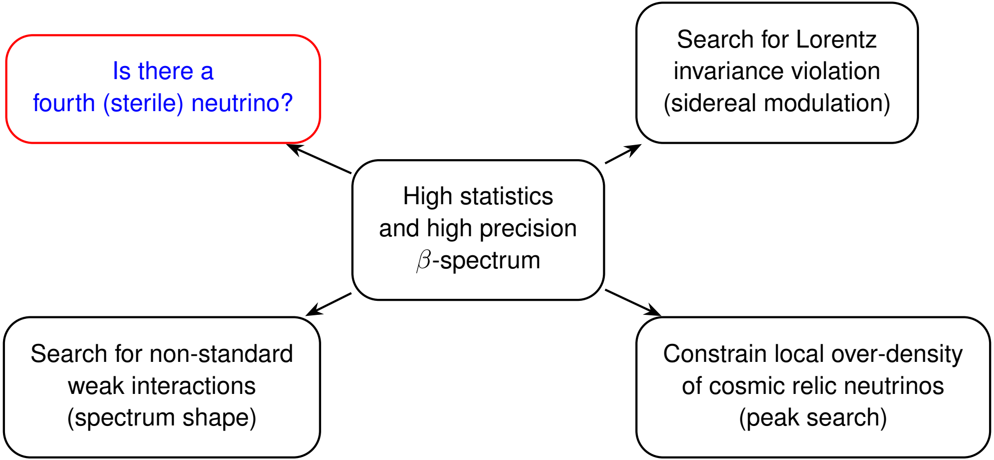
- A total of **59** spectra, **1609** data points
- Parameter correlations across datasets
- Post-unblinding a data-combination mistake was uncovered:
  - Resolved by splitting KNM4 into two data sets
  - Approximately 0.1 eV^2 impact on m_ν^2
- **Best fit :**$m_\nu^2 = -0.14^{+0.13}_{-0.15}$ **eV^2**
- Statistically dominated uncertainties

Combined result: Upper limit $m_\nu < 0.45$ eV (90% CL)

(arXiv:2406.13516v1 [nucl-ex])



KATRIN goals: Beyond Neutrino Mass



High statistics
and high precision
β-spectrum

Is there a
fourth (sterile) neutrino?

Search for Lorentz
invariance violation
(sidereal modulation)

Search for non-standard
weak interactions
(spectrum shape)

Constrain local over-density
of cosmic relic neutrinos
(peak search)

Non-standard or Sterile Neutrino

Sterile neutrino = SM neutral singlet fermion

- Existence could be revealed through effects of mass and mixing with active neutrinos (neutrino oscillations, β**- decay**, $0\nu\beta\beta$-decay)

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DM exists $\implies$ uncharged particles under SM gauge group $\implies$ singlet fermions

- Singlet fermions naturally appear in the dark sector
- Members of dark sector could mix with active neutrinos via neutrino portal coupling
- Sterile neutrinos can live at any mass scales: GeV, keV, $\boxed{eV}$

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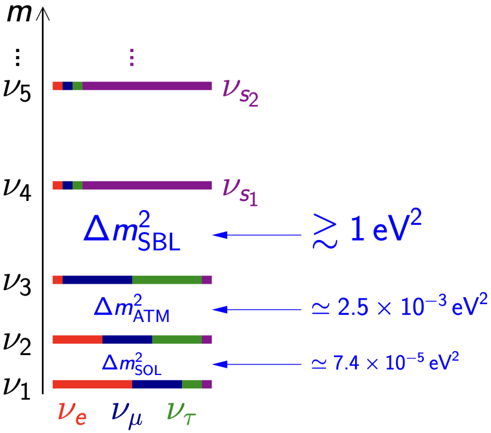
- *Experimental hints for eV scale* :
  - *Appearance* LSND (3σ) and MiniBooNE (4.8σ) excess observations
    Explained by ($\nu_\mu \to \nu_\mathrm{s} \to \nu_\mathrm{e}$)
  - *Disappearance* SAGE and GALLEX: Gallium anomaly (2.9σ deficit)
    Explained by $\nu_e \to \nu_s$
  - The Gallium anomaly reaffirmed by BEST experiment
    Phys. Rev. Lett. 128, 232501 (2022)

Interpretation

- SBL anomalies could be explained by an additional neutrino flavor (ν_s)
- There must be at least one additional mass squared difference,
  3ν + 1 framework $\Delta m^2_{SBL} \approx (1-2)\,\mathrm{eV}^2$
- Allowed by solar, atmospheric and long baseline experiments, achieved with $|U_{e4}|^2 \ll 1$



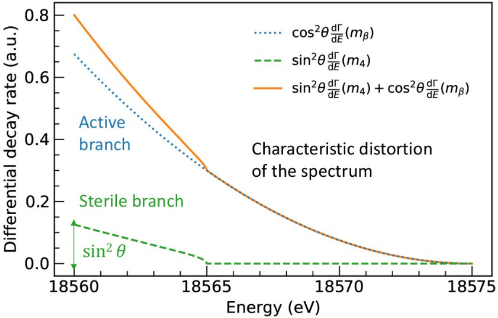
Sterile neutrino in β-decay

$$m_\nu^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2 \xrightarrow{3+1} \sum_{k=1}^{3} \frac{|U_{ek}|^2}{1-|U_{e4}|^2} m_k^2$$

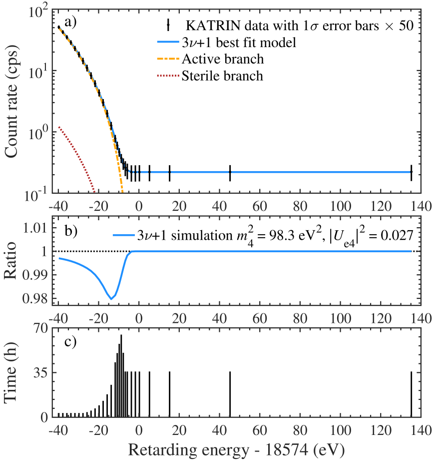
- **Differential decay rate**:

$$\begin{aligned} & R_\beta(E, m_\nu^2, m_4^2, |U_{e4}|^2) \\ & = \underbrace{(1-|U_{e4}|^2)\cdot R_\beta(E, m_\nu^2)}_{\text{Active branch}} + \underbrace{|U_{e4}|^2 \cdot R_\beta(E, m_4^2)}_{\text{Sterile branch}} \\ & = \cos^2\theta \cdot R_\beta(E, m_\nu^2) + \sin^2\theta \cdot R_\beta(E, m_4^2) \end{aligned}$$

- A kink at $E_0 - m_4$



Sterile Signal in β-decay Spectrum



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$$N_{\text{model}}(qU, \Theta) = A \cdot \int R_{\beta}(E, \Theta) \cdot f(E, qU) + Bg$$

- 6 model parameters:
  - A - Signal amplitude
  - E_0 - effective endpoint energy
  - m^2 - effective mass of electron anti-neutrino
  - Bg - Background rate
  - m_4^2 - sterile neutrino mass
  - $|U_{e4}|^2$ - sterile neutrino mixing

Analysis method for sterile neutrino search

- Extend Tritium β- spectrum model to 3+1 framework
- **Grid Scan:** 50×50 $\left[\log(|U_{e4}|^2), \log(m_4^2)\right]$ plane
- Contours are drawn at $\Delta\chi^2 = \chi^2 - \chi^2_{BF}$ = 5.99 (95% CL, 2 dof)
- Energy range: $[E_0 - 40, E_0 + 135]$ eV
- Sensitive to $m_4^2 \leq 1600$ eV^2 and $|U_{e4}|^2 \leq 0.5$
- Two complementing analyses
  - **Case-I - Fixed neutrino mass:** m_ν^2 **= 0** $(m_{1,2,3} \ll m_4)$
  - Case-II - Free neutrino mass: m_ν^2 as nuisance parameter

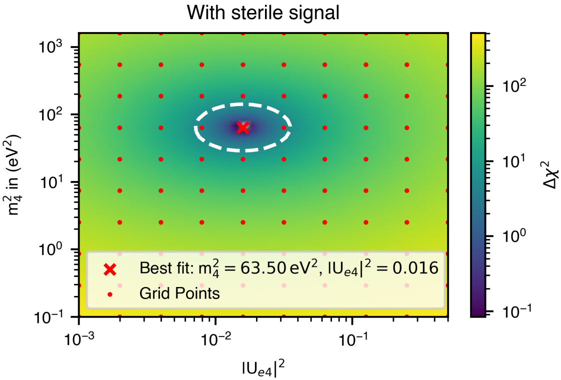
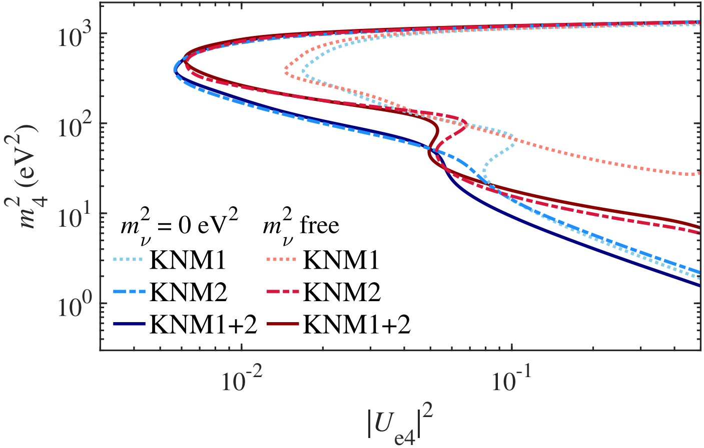


Figure: Simulated β-spectrum with sterile neutrino signal

Results from First Two Science Runs

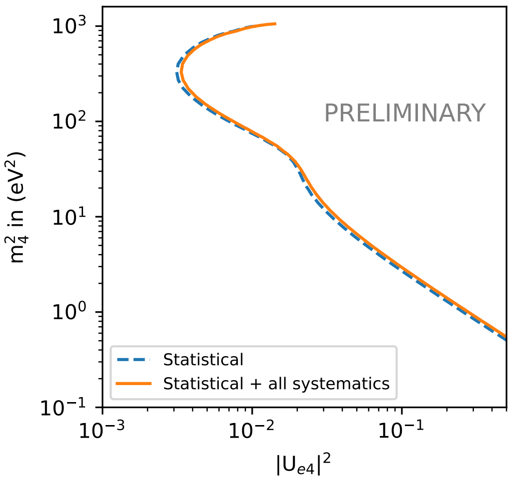
- 5.24×10^6 electrons for 40 eV below E_0, 1265 hours of data
  Best fit:
    - $m_4^2 = 59.9$ eV^2, $|U_{e4}|^2 = 0.011$, $m_\nu^2 = 0.0$ eV^2
    - $\Delta\chi^2_{null} = 0.66$
- Active neutrino mass set free
  Best fit:
    - $m_4^2 = 87.4$ eV^2, $|U_{e4}|^2 = 0.019$, $m_\nu^2 = 0.57$ eV^2
    - $\Delta\chi^2_{null} = 1.69$
- Signal-to-background ratio of up to 235
  Phys. Rev. D 105, (2022)



Sensitivity Results From Five Science Runs

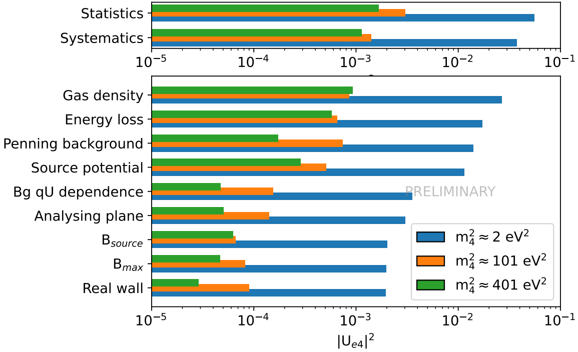
- **Case-I**: $m_\nu^2 = 0\ \mathrm{eV}^2$
- 40 eV fit range, $|U_{e4}|^2 \in [0, 0.5]$
- Stat. only + all systematics 95% CL
- Gain in overall sensitivity with increased statistics
  S. Mohanty, PoS EPS- HEP2023 (2024)

Sensitivity contours at 95% C.L. (2 dof)



Impact of Systematics

- Calculating 68% CL uncertainty on $|U_{e4}|^2$: $\sigma_{syst} = \sqrt{\sigma^2_{Stat+Syst} - \sigma^2_{Stat}}$
- Statistically dominated uncertainties
- Largest systematic contribution: Penning Bg (low m_4^2), Column Density (high m_4^2)

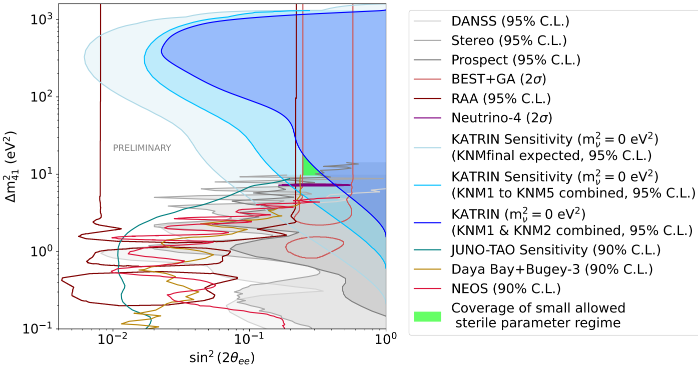


Sensitivity comparison to other experimental results

- Translation of parameters:

$$\sin^2(2\theta) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

- Large Δm^2_{41} solutions of RAA and BEST+GA anomalies excluded
- Current KATRIN data extends exclusion bounds from SBL oscillation experiments for $\Delta m^2_{41} \geq 10$ eV^2
- Probing large parameter space for light sterile neutrino anomalies
- Expected KNM1-5 sensitivity yields improved constraints in the sterile parameter space



Summary

- KATRIN's high-precision tritium spectrum measurement sets stringent neutrino mass limits.
- **Established the world-best direct neutrino mass limit: $m_\beta < 0.45\,$eV (90% CL)**
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- Results of sterile neutrino search first two science runs (KNM1 + KNM2):
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  - Improved exclusion limits compared to other experiments.

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  - **No significant sterile neutrino signal found in KNM1 + KNM2.**
  - Improved exclusion limits compared to other experiments.
- Sterile neutrino sensitivity projection for five science runs (KNM1...5):
  - KATRIN can extend the coverage of BEST and reactor experiments.
  - Sensitivity dominated by statistical uncertainties

Outlook

- KATRIN has the capability to study several physics topics beyond neutrino mass: relic neutrinos, lorentz invariance violation, non-standard interactions..
- **Data-taking until 2025 with a target senstivity below 0.3 eV**
- Stay tuned for upcoming eV sterile neutrino release!


John Wilkerson, UNC/TUNL (he/him)
R. G. Hamish Robertson
Joseph Formaggio
KATRIN
Diana Parno
Anton Huber (IAP)
Andrew Gavin
Korbinian Urban
Heiko Bouquet
Kevin Gauda
Enrico Ellinger
Robin Größle
marco roellig
Joachim Wolf

Thank You

Backups

Experimental hints

- *Appearance* LSND (3σ) and MiniBooNE (4.8σ) excess observations. Explained by ($\nu_\mu \rightarrow \nu_\mathrm{s} \rightarrow \nu_\mathrm{e}$)
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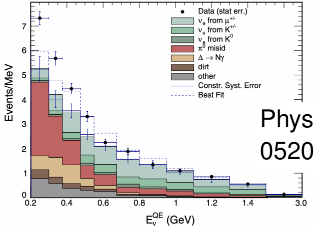
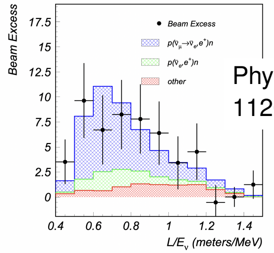
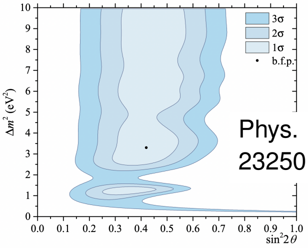


Phys. Rev. D 103, 052002 (2021)

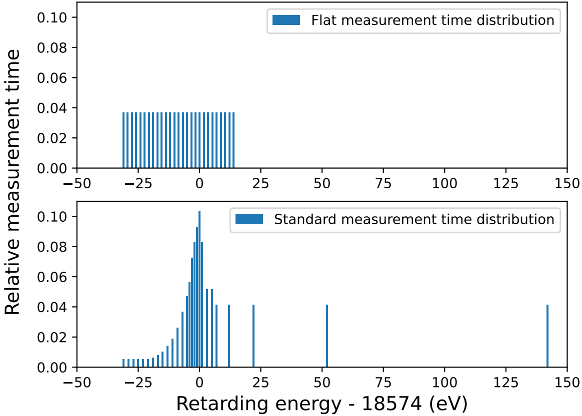


Phys. Rev. D, Vol. 64, 112007 (2001)

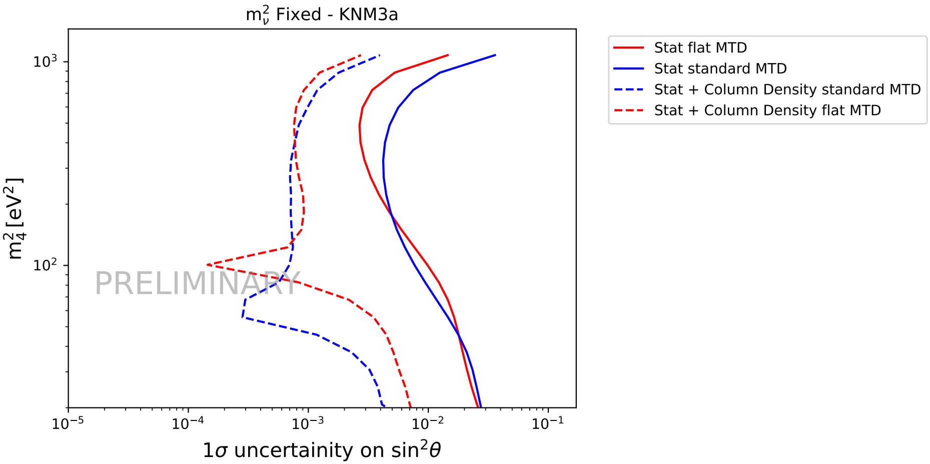


Phys. Rev. Lett. 128, 232501 (2022)

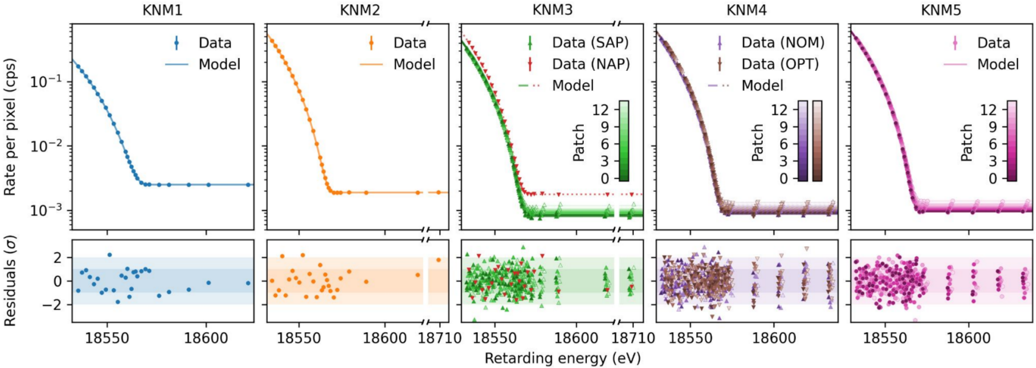
Measurement time distribution - Standard vs Flat



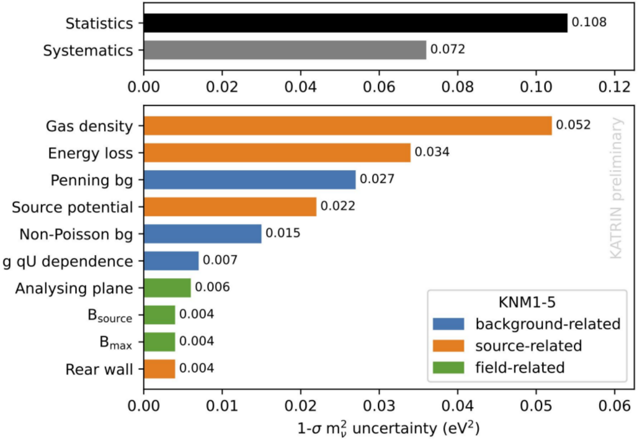
Raster scan on different measured time distributions



KNM1-KNM5 Analysis Results



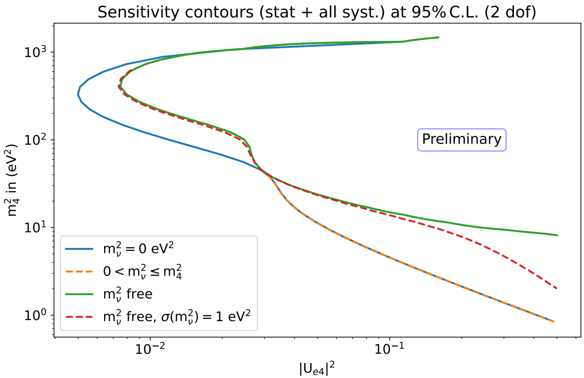
Impact of systematic uncertainties on m_ν^2



Impact of active neutrino on sterile neutrino search

Possible treatments for m_ν^2: Extension of Case-II

- Free m_ν^2
  Correlation between m_4^2 and m_ν^2.
- Pull term using **0**$\pm$**1** eV^2
  Intermediate sensitivity between two extremes (fixed and free)
- $m_4^2 > m_\nu^2 \geq 0$: Limit m_ν^2 by mass of right-handed neutrino
  Reasonable option of optimizing sensitivity in addition to free m_ν^2 case



Active neutrino correlation with sterile neutrino

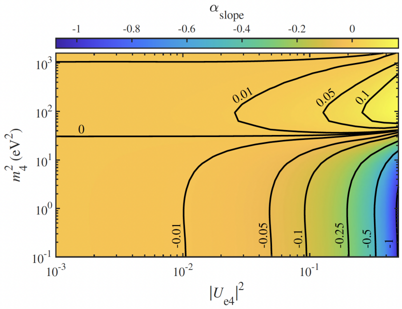
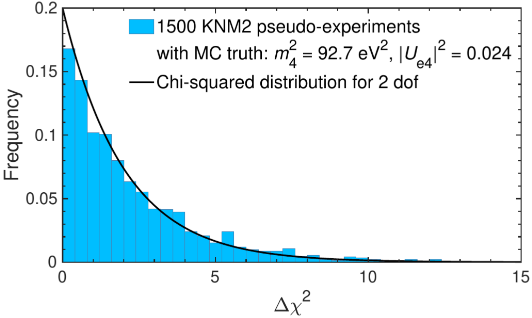


FIG. 4. The correlation between active and sterile neutrino mass is approximately a linear slope $m_\nu^2 = \alpha_{\rm slope} \cdot m_4^2 + {\rm const}$ for various values of m_4^2 and $|U_{e4}|^2$ by analyzing simulated spectra. The gradient indicates the magnitude of $\alpha_{\rm slope}$. For small mixing $|U_{e4}|^2 < 0.01$, we observe small slope values $|\alpha_{\rm slope}| < 0.01$. For larger mixing, we find a strong negative correlation for small $m_4^2 \lesssim 30$ eV^2 and a weaker positive correlation for larger m_4^2.

Testing applicability of Wilks' Theorem

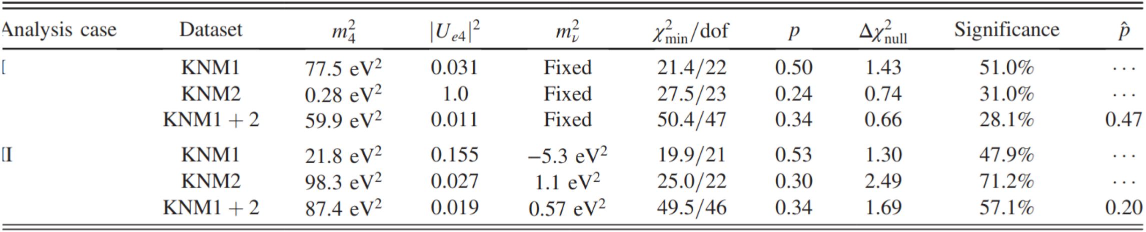
Previously done

- Generate $\mathcal{O}(10^3)$ twins with statistical fluctuations for particular choice of MC truth
- Perform fitting for sterile parameter values on a grid and for MC truth for each sample ($m_\nu^2 = 0$)
- Evaluate $\Delta\chi^2 = \chi^2_{\text{MC truth}} - \chi^2_{\text{best fit}}$ for each sample
- Compare distribution of $\Delta\chi^2$ values to χ^2-distribution with 2 dof



(c) KNM2, MC truth: $m_4^2 = 92.7\,\text{eV}^2$ and $|U_{e4}|^2 = 0.024$

Sterile neutrino result

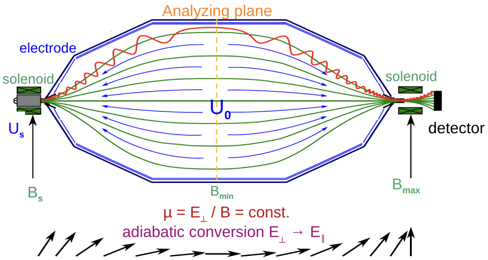


Analysis case	Dataset	m_4^2	$\lvert U_{e4}\rvert^2$	m_ν^2	$\chi^2_{\text{min}}/\text{dof}$	p	$\Delta\chi^2_{\text{null}}$	Significance	$\hat{p}$
I	KNM1	77.5 eV^2	0.031	Fixed	21.4/22	0.50	1.43	51.0%	...
	KNM2	0.28 eV^2	1.0	Fixed	27.5/23	0.24	0.74	31.0%	...
	KNM1 + 2	59.9 eV^2	0.011	Fixed	50.4/47	0.34	0.66	28.1%	0.47
II	KNM1	21.8 eV^2	0.155	−5.3 eV^2	19.9/21	0.53	1.30	47.9%	...
	KNM2	98.3 eV^2	0.027	1.1 eV^2	25.0/22	0.30	2.49	71.2%	...
	KNM1 + 2	87.4 eV^2	0.019	0.57 eV^2	49.5/46	0.34	1.69	57.1%	0.20

MAC-E Filter: High resolution β-spectroscopy

- **Adiabatic transport**: $\mu = \frac{E_\perp}{B} = \text{const.}$
- **Magnetic field reduction**: B drops by $2 \cdot 10^4$ from solenoid to analyzing plane: $E_\perp \to E_{||}$
- **Retardation potential**: Only electrons with $E_{||} > eU_0$ can pass the retardation potential
- **Energy resolution**: $\Delta E = E_{\perp,\text{max,start}} \cdot \frac{B_\text{min}}{B_\text{max}} < 1$ eV

Magnetic **A**diabatic **C**ollimation **& E**lectrostatic **Filter:**



Momentum tranfsormation without the E-field

Published ν mass results

First campaign (spring 2019):

- Total statistics: 2 million events
- Best fit: $m_\nu^2 = -1.0^{+0.9}_{-1.1}\,\mathrm{eV}^2$ (stat. dom.)
- Limit: $m_\nu < 1.1\,\mathrm{eV}$ (90% CL)

Second campaign (autumn 2019):

- Total statistics: 4.3 million events
- Best fit: $m_\nu^2 = 0.26^{+0.34}_{-0.34}\,\mathrm{eV}^2$ (stat. dom.)
- Limit: $m_\nu < 0.9\,\mathrm{eV}$ (90% CL)

Combined result: Upper limit $m_\nu < 0.8\,\mathrm{eV}$ (90% CL)

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