Determination of neutrino mass and search for sterile neutrino with the KATRIN experiment

Seminar, INFN Sezione Di Cagliari | May 22, 2024

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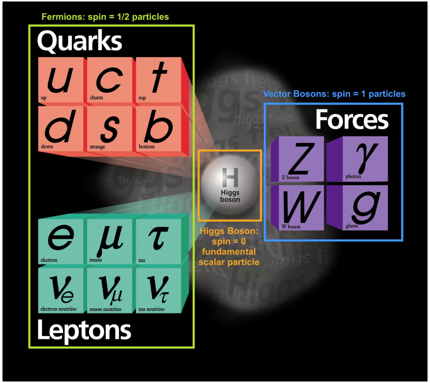
Institute for Astroparticle Physics |

The "Standard Model" & Neutrinos

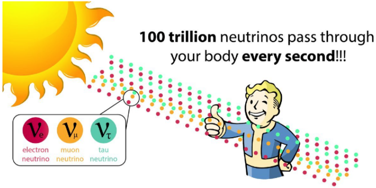
- The SM explains how the building blocks of matter interact via 4 fundamental forces
- Our quest to understand radioactivity took hundred years and culminated in the discovery of Higgs boson

- Neutrinos are fundamental particles that do not feel the strong force (no color) or electromagnetic force (no charge)
- Interact via weak force
- In SM: Neutrinos are massless, light-speed travelers and always left-handed (opposite for anti-neutrinos)

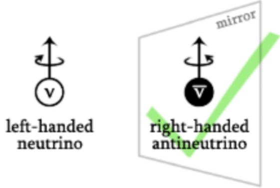


More about Neutrinos

- Remarkable penetrative ability: Require a light year ($\sim 10^{13}$ km) of lead to have a 50% chance of stopping.
- Abundant presence: Outnumber atoms in the universe, with relic neutrinos $\sim 3 \times 10^8$ per cubic meter
- Indications of importance: Their sheer abundance suggests significant roles in cosmology and particle physics
- Unique weak interactions: Only engage in left-handed weak interactions
- Could be Majorana or Dirac fermions

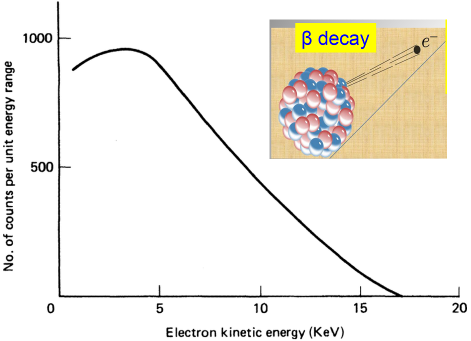


Neutrinos from the Sun



Neutrinos are known since 1930

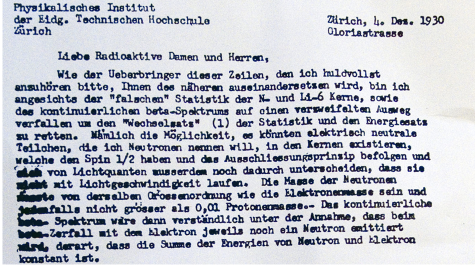
- For a two-body β-decay, the energy spectrum must be discrete. This is not the case! Energy-momentum not conserved in β decays?



β decay spectrum of ${}^3_1\text{H} \rightarrow {}^3_2\text{He} + e^-$ (*Source:* Lewis, G. M. (1970) Neutrinos, Wykeham, London, p. 30.)

Neutrinos are known since 1930

- For a two-body β-decay, the energy spectrum must be discrete. This is not the case! Energy-momentum not conserved in β decays?
- Pauli did not believe energy-momentum conservation was violated and proposed a desperate remedy: "Neutron: A new invisible neutral particle"
  - Neutron (later coined "Neutrino") could carry the missing energy and have angular momentum 1/2
  - Endpoint & shape of β spectrum depend on neutrino mass



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

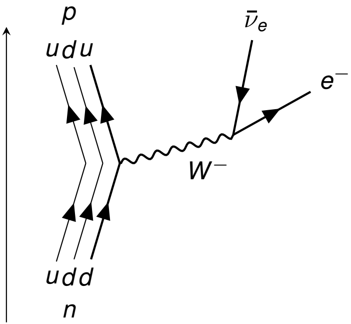
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Source: Pauli letter collection, letter to Lise Meitner 4 December 1930,
`https://cds.cern.ch/record/83282/export/hm?ln=en`

Neutrinos are known since 1930

- E. Fermi's Three-Body Decay Model: Inspired by Chadwick's experiments and Pauli's theory, Fermi proposed β-decay as a single-vertex three-body decay: $n \to p + e^- + \overline{\nu}_e$
- Successful theory of weak interactions
- From 1968 to 1998, evidence showed that neutrinos can oscillate among different types, implying mass. *History of neutrinos*
- Discovery of neutrino mass challenged fundamental assumptions in particle physics & cosmology

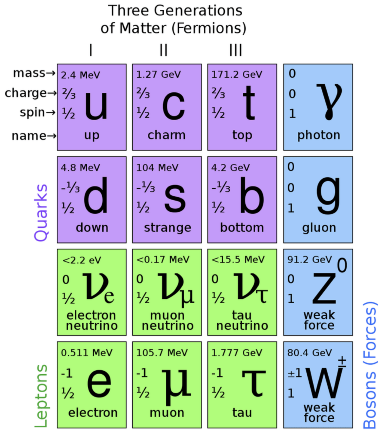
Weak interaction today:



Significance of ν mass

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. What is the reason of smaller mass? Sea-saw mechanism: Type-I & Type-II, etc
- Possible connection to generation of matter - antimatter asymmetry Leptogenesis



Three Generations of Matter (Fermions)

	I	II	III	
mass→ charge→ spin→ name→				
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

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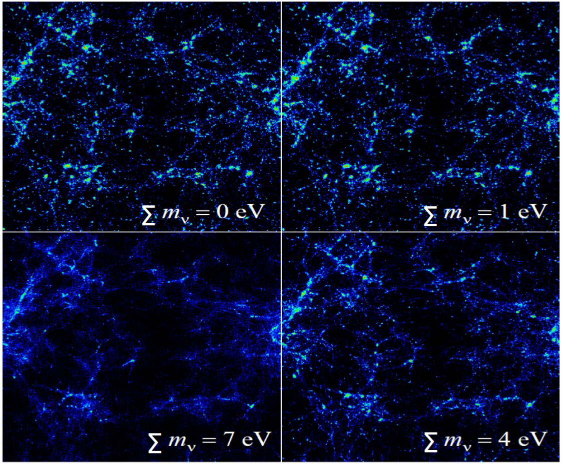
In cosmology:

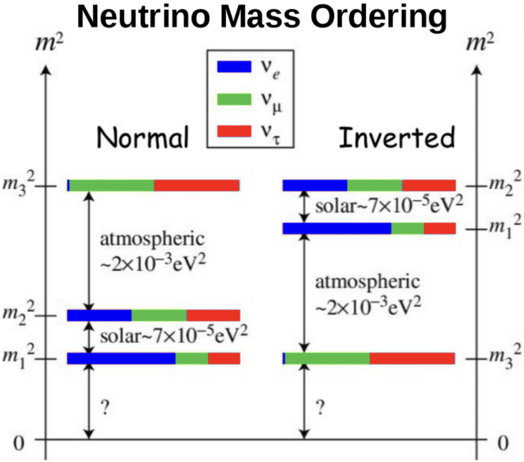
- Significant abundance of mass carrying νs can influence structure formation
- With finite masses, cosmological neutrinos become part of the total matter field and contribute to its smoothing



simulation Chung-Pei Ma 1996

Open questions

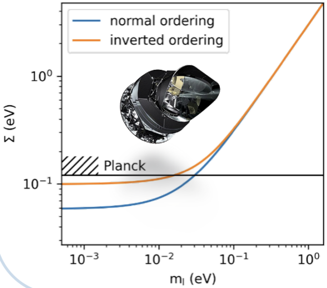
- Absolute mass scale: minimum m_ν
- What is the neutrino mass ordering, normal or inverted?
- Are neutrinos Majorana type particles, and if so, what new physics lies behind this fact?
- Is there leptonic CP violation?
- Are there more than 3 known flavors i.e. Sterile neutrinos?
- Can neutrinos explain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



Measurement of ν mass(es): complementary approaches

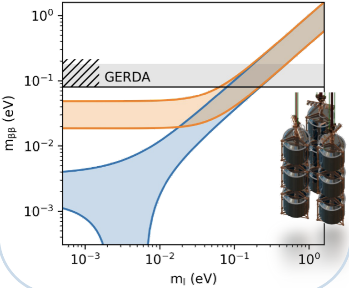
Cosmology

$$\Sigma = \sum_i m_i^2$$



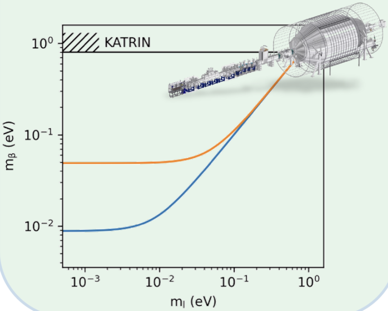
Neutrinoless ßß decay

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



ß-decay kinematics

$$m^2_{\nu/\beta} = \sum_i |U_{ei}|^2 \cdot m_i^2$$



Direct kinematic ν mass measurement

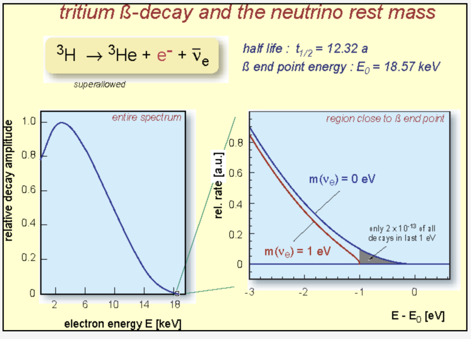
- ✓ Measurement of electron β spectrum:

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

- ✓ 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)
  - **Rhenium**
    - $E_0 = 2.47\,\text{keV},\ T_{1/2} = 43.2\,\text{Gy}$
  - **Alternative approach: Holmium (EC decay)**
    - $Q_{EC} \approx 2.5\,\text{keV},\ T_{1/2} = 4570\,\text{y}$

Model independent:

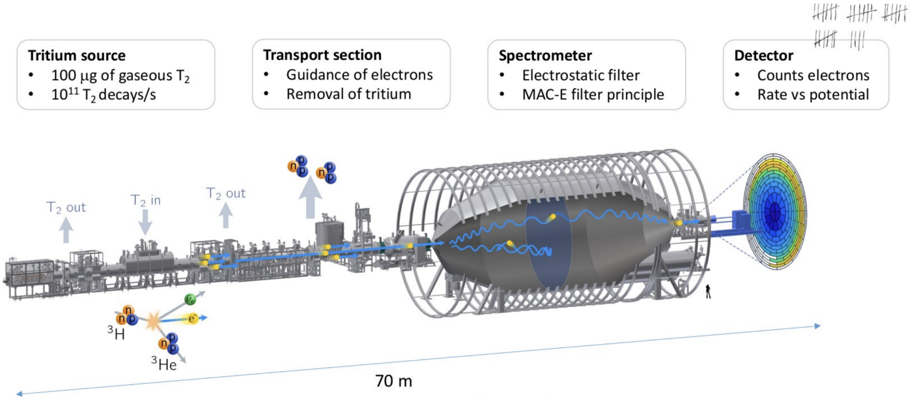
- Independent of cosmological model and neutrino nature



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

The KATRIN experiment in a nutshell

- Kinematics-based neutrino mass experiment
  (with sensitivity better than 0.3 eV (90% CL) after 1000 days of measurement time)
- Current result: $m_\beta < 0.8$ eV (90%) CL, *(Nature Phys. 18 (2022) 2, 160-166)*



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

Transport section
- Guidance of electrons
- Removal of tritium

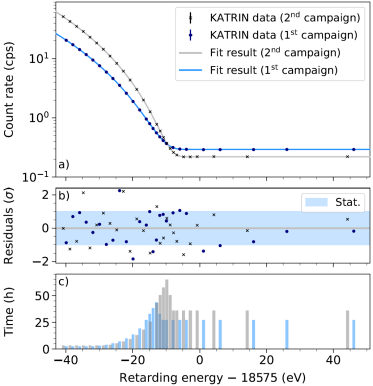
Spectrometer
- Electrostatic filter
- MAC-E filter principle

Detector
- Counts electrons
- Rate vs potential

ν mass analysis

Measurement strategy:

- **Scan points**: $\sim$ 30 HV set points
- **Scan interval**: $E_0 - 40\,\text{eV}$ to $E_0 + 135\,\text{eV}$
- **Scan time**: $\sim$ 3 hours



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

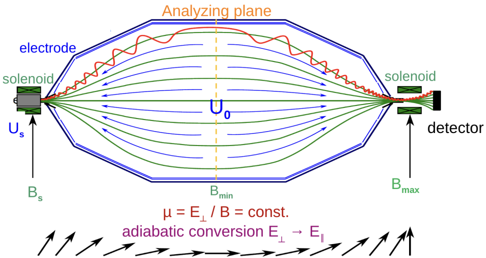
$$N_{\text{model}}(qU, \Theta) = A \cdot \int R_{\beta}(E, \Theta) \cdot f(E, qU) + Bg$$

- 4 model parameters:
  - A - Signal amplitude
  - E_0 - effective endpoint energy
  - m^2_{ν} - 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

MAC-E Filter: High resolution β-spectroscopy

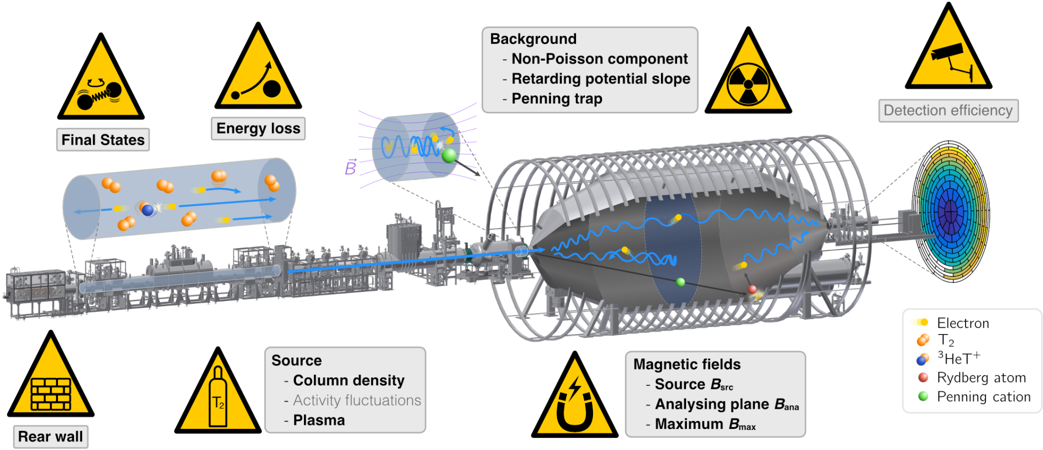
- **Adiabatic transport**: $\mu = \frac{E_\perp}{B} = \text{const.}$
- **Magnetic field reduction**: B drops by $2 \cdot 10^4$ from solenoid to analyzing plane: $E_\perp \rightarrow E_{||}$
- **Retardation potential**: Only electrons with $E_{||} > eU_0$ can pass the retardation potential
- **Energy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

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



Momentum tranfsormation without the E-field

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}**

- Electron
- T_2
- ${}^3HeT^+$
- Rydberg atom
- Penning cation

Source: L. Köllenberger

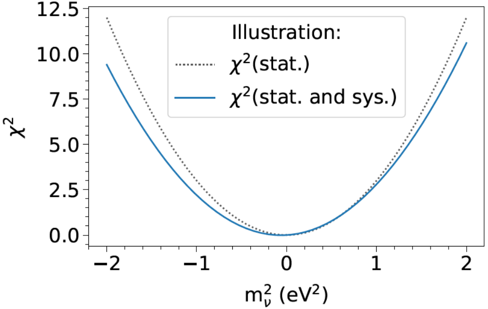
Systematic error propagation via Pull term approach

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

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

In the combined analysis of data across campaigns:

- Pull term as multivariate normal distribution
- Treatment of correlations between campaigns and segments
- $\sim$ 300 fit parameters and $\sim$ 100 correlations



Published ν mass results

First campaign (spring 2019):

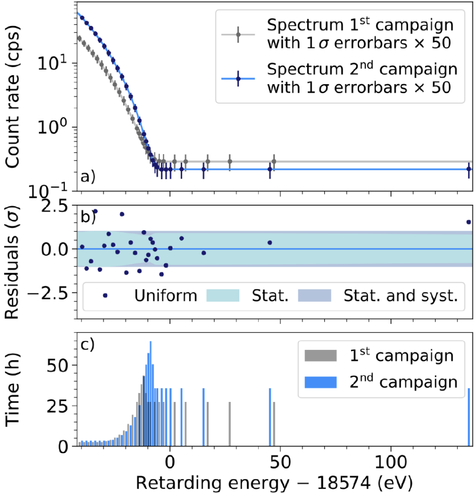
- Total statistics: 2 million events
- Best fit: $m_\nu^2 = -1.0^{+0.9}_{-1.1}$ eV^2 (stat. dom.)
- Limit: $m_\nu < 1.1$ eV (90% CL)

Second campaign (autumn 2019):

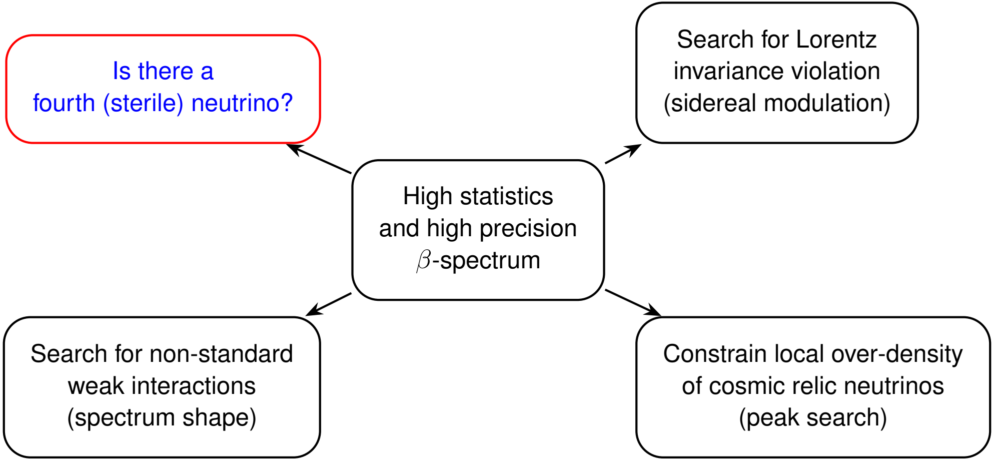
- Total statistics: 4.3 million events
- Best fit: $m_\nu^2 = 0.26^{+0.34}_{-0.34}$ eV^2 (stat. dom.)
- Limit: $m_\nu < 0.9$ eV (90% CL)

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

(Nature Phys. 18 (2022) 2, 160-166)



KATRIN goals: Beyond Neutrino Mass



Is there a
fourth (sterile) neutrino?

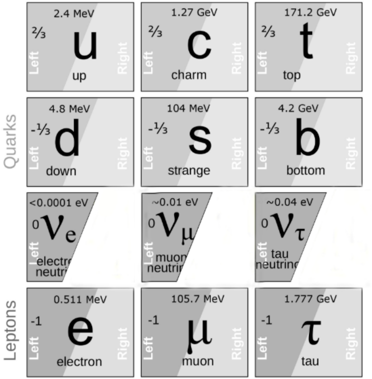
Search for Lorentz
invariance violation
(sidereal modulation)

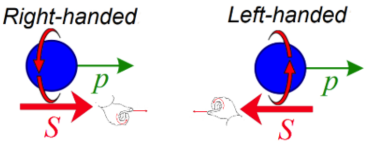
High statistics
and high precision
β-spectrum

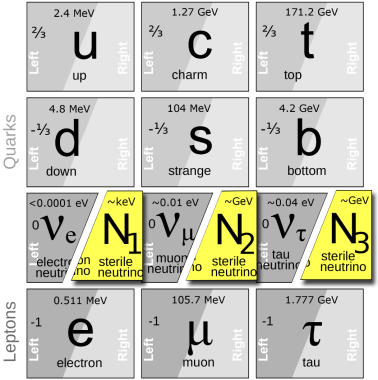
Search for non-standard
weak interactions
(spectrum shape)

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

Neutrinos are only "half of the particle"







Source: Based on nuMSM model by Boyarsky et al.

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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- *Theoretical motivation:*

DM exists $\Longrightarrow$ uncharged particles under SM gauge group $\Longrightarrow$ 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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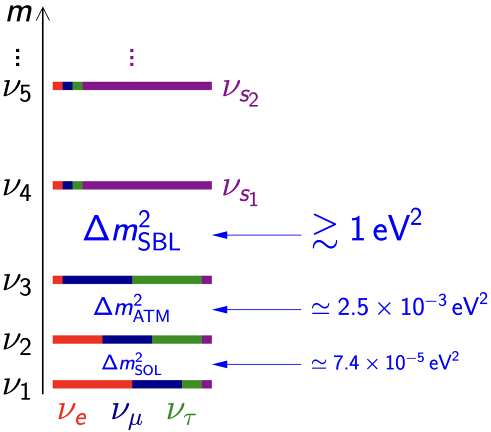
- *Experimental hints for eV scale* :
  - *Appearance* LSND (3σ) and MiniBooNE (4.8σ) excess observations
    Explained by ($\nu_\mu \to \nu_\mathrm{s} \to \nu_\mathrm{e}$)
  - *Disappearance* SAGE and GALLEX: Gallium anomaly (2.9σ deficit)
    Explained by $\nu_e \to \nu_s$
  - The Gallium anomaly reaffirmed 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 $|U_{e4}|^2 \ll 1$



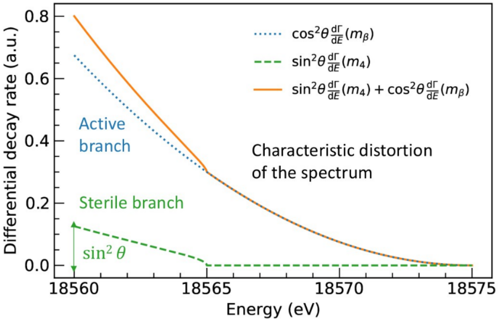
Sterile neutrino in β-decay

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

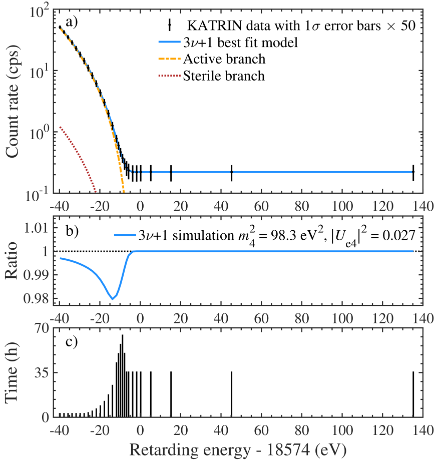
- **Differential decay rate**:

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

- A kink at $E_0 - m_4$



Sterile Signal in β-decay Spectrum



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

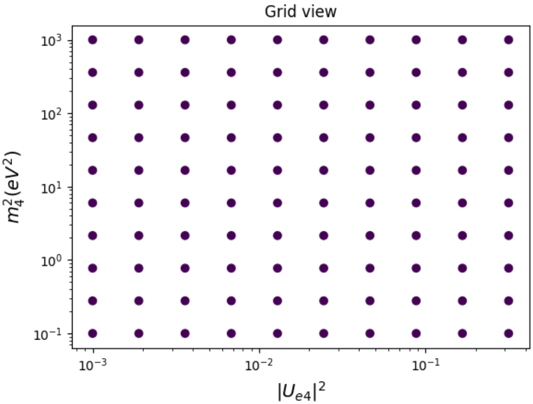
- 6 model parameters:
  - A - Signal amplitude
  - E_0 - effective endpoint energy
  - m^2 - effective mass of electron anti-neutrino
  - Bg - Background rate
  - m_4^2 - sterile neutrino mass
  - $|U_{e4}|^2$ - sterile neutrino mixing

Dataset and Analysis Strategy

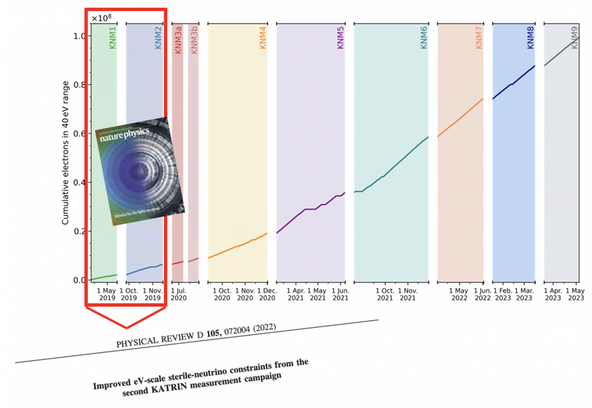
- Data selection and combination, active neutrino model configuration are the same as for the active neutrino mass analysis.
- Unblinding procedure *Phys. Rev. D 105, (2022)*
  - Code validation on Monte Carlo twins
  - Tritium spectrum, model, systematics treatment and budget (pull term approach) same as active neutrino mass analysis
  - **Two independent analysis teams with independent codes**:
    - KaFit (exact model evaluation)
    - Netrium (use neural nets for swift model interpolation)

Analysis method for sterile neutrino search

- Extend Tritium β- spectrum model to 3+1 framework
- **Grid Scan:** $50 \times 50 \left[\log(|U_{e4}|^2), \log(m_4^2)\right]$ 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:** $m_\nu^2 = \mathbf{0}$ $(m_{1,2,3} \ll m_4)$
  - Case-II - Free neutrino mass: m_ν^2 as nuisance parameter



Data collection status



PHYSICAL REVIEW D **105,** 072004 (2022)

Improved eV-scale sterile-neutrino constraints from the second KATRIN measurement campaign

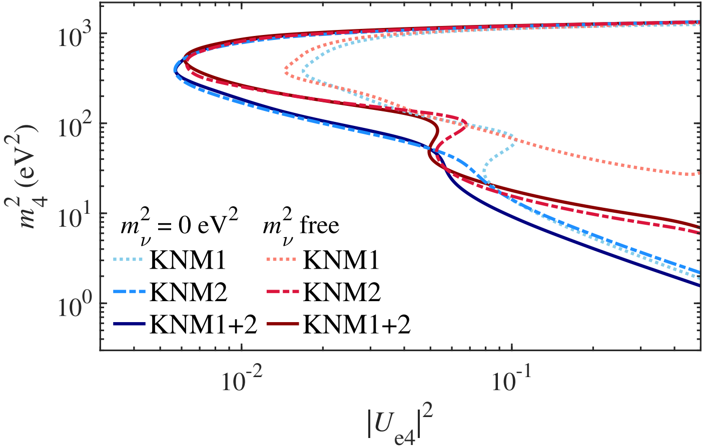
Table: KATRIN Neutrino Mass Measurement Campaigns (KNM)

Campaign	Time (hrs)	$\rho d\sigma$ (m^{-2})	Bg (mcps)
KNM1	522	1.11×10^{21}	370
KNM2	294	4.23×10^{21}	278
KNM3a	220	2.08×10^{21}	137
KNM3b	224	3.75×10^{21}	258
KNM4	1267	3.77×10^{21}	150
KNM5	1232	3.78×10^{21}	160

- KNM1, KNM2 , KNM3b operated in Nominal Analyzing Plane (NAP) mode

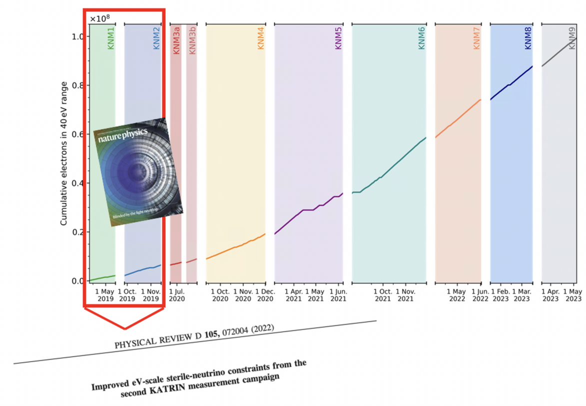
Results from First Two Science Runs

- 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



Data collection status

- Significant experimental development: Shifted Analyzing Plane (SAP) background reduction method
  Lokhov et al., EPJ C 82 (2022) 3, 258

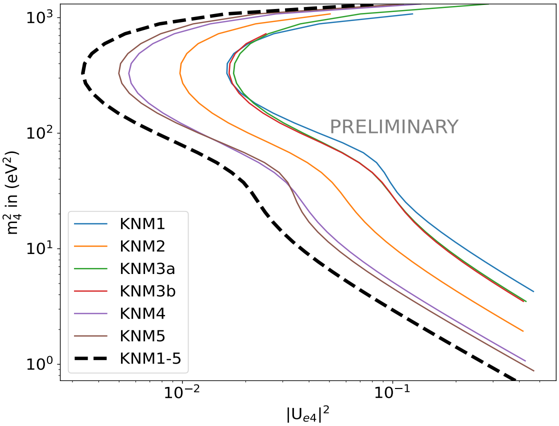


PHYSICAL REVIEW D **105**, 072004 (2022)

Improved eV-scale sterile-neutrino constraints from the second KATRIN measurement campaign

Sensitivity Results From Five Science Runs

- **Case-I**: $m_\nu^2 = 0$ 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)



Campaign	KNM1	KNM2	KNM3a	KNM3b	KNM4	KNM5	KNM1-5
No. of signal electrons ($\times 10^6$)	2.0	4.3	1.1	1.4	10.2	16.8	35.8

Impact of Systematics

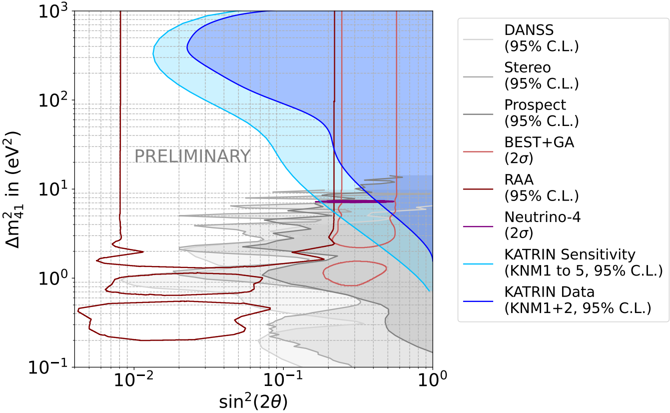
- Calculating 68% CL uncertainty on $|U_{e4}|^2$: $\sigma_{syst} = \sqrt{\sigma^2_{Stat+Syst} - \sigma^2_{Stat}}$
- Statistically dominated uncertainties
- Largest systematic contribution: Penning Bg (low m_4^2), Column Density (high m_4^2)

Sensitivity comparison to other experimental results

- Translation of parameters:

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

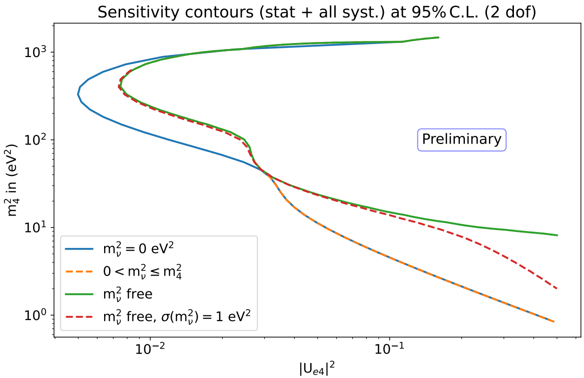
- Large Δm^2_{41} solutions of RAA and BEST+GA anomalies excluded
- Current KATRIN data extends exclusion bounds from SBL oscillation experiments for $\Delta m^2_{41} \geq 10\ \mathrm{eV}^2$
- Probing large parameter space for light sterile neutrino anomalies
- Expected KNM1-5 sensitivity yields improved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



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 $\mathbf{0 \pm 1}$ 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



Summary

- High precision measurement of Tritium spectrum near the endpoint with KATRIN
- New physics beyond the SM can include sterile neutrinos at all mass scales
- KATRIN uniquely addresses SBL anomalies via spectral shape analysis

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    - Published groundbreaking sub-eV neutrino mass limit: $m_\nu < 0.8$ eV
    - No significant sterile-neutrino signal was observed, and improved exclusion limits were achieved compared to complementary experiments

Summary

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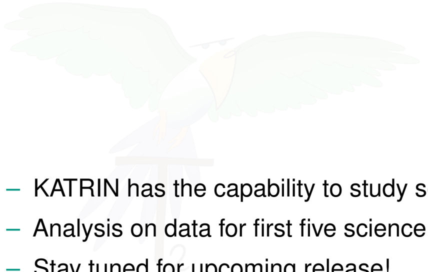
  - Published groundbreaking sub-eV neutrino mass limit: $m_\nu < 0.8$ eV
  - No significant sterile-neutrino signal was observed, and improved exclusion limits were achieved compared to complementary experiments
- Sterile neutrino sensitivity projection for five science runs (KNM1...5):
  - Sensitivity dominated by statistical uncertainties
  - Reasonable option for optimized sensitivity $m_4^2 > m_\nu^2 \geq 0$

Outlook



- KATRIN has the capability to study several physics topics beyond neutrino mass
- Analysis on data for first five science runs ongoing
- Stay tuned for upcoming release!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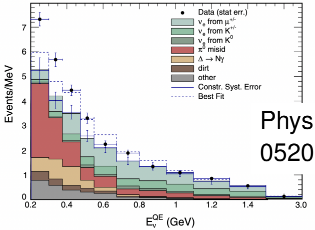
R. G. Hamish Robertson
Joseph Formaggio
KATRIN
Karlsruhe Tritium Neutrino Experiment
T_2
Diana Parno
Anton Huber (IAP)
Andrew Gavin
Korbinian Urban
Heiko Bouquet
Kevin Gauda
Enrico Ellinger
Robin Größle
marco roellig
Joachim Wolf

Thank You

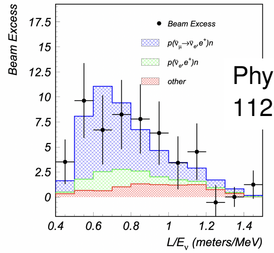
Backups

Experimental hints

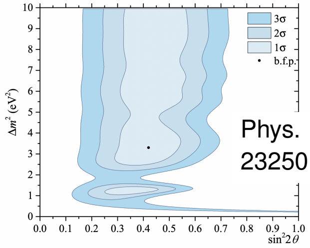
- *Appearance* LSND (3σ) and MiniBooNE (4.8σ) excess observations. Explained by $(\nu_\mu \rightarrow \nu_\mathrm{s} \rightarrow \nu_\mathrm{e})$
- *Disappearance* SAGE and GALLEX: Gallium anomaly (2.9σ deficit).
  Explained by $\nu_e \rightarrow \nu_s$
- The Gallium anomaly reaffirmed by BEST experiment



Phys. Rev. D 103, 052002 (2021)

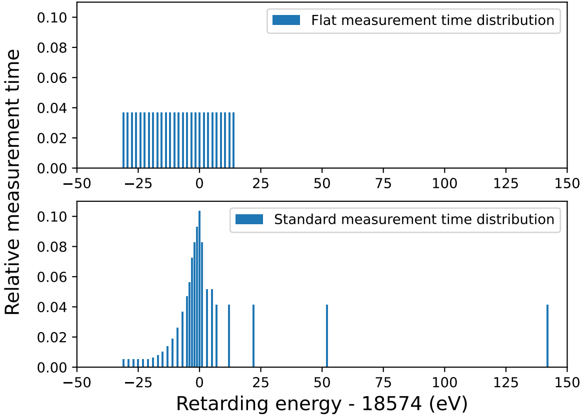


Phys. Rev. D, Vol. 64, 112007 (2001)

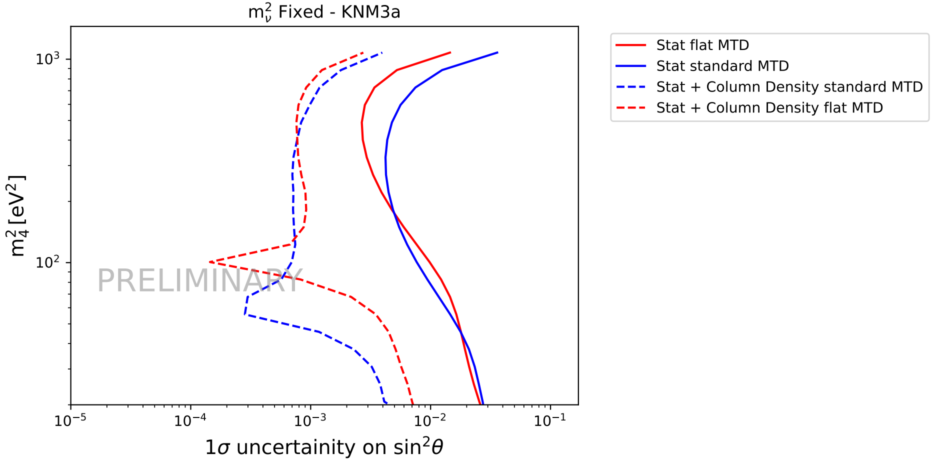


Phys. Rev. Lett. 128, 232501 (2022)

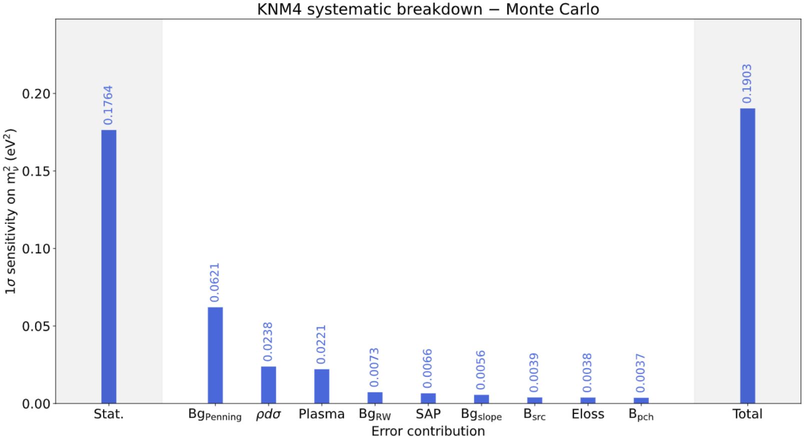
Measurement time distribution - Standard vs Flat



Raster scan on different measured time distributions



Monte Carlo breakdown



Active neutrino correlation with sterile neutrino

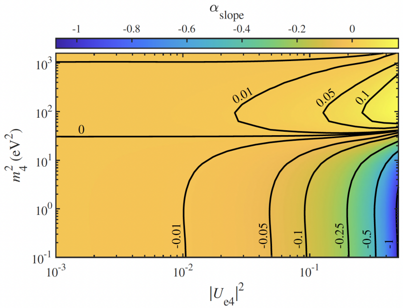
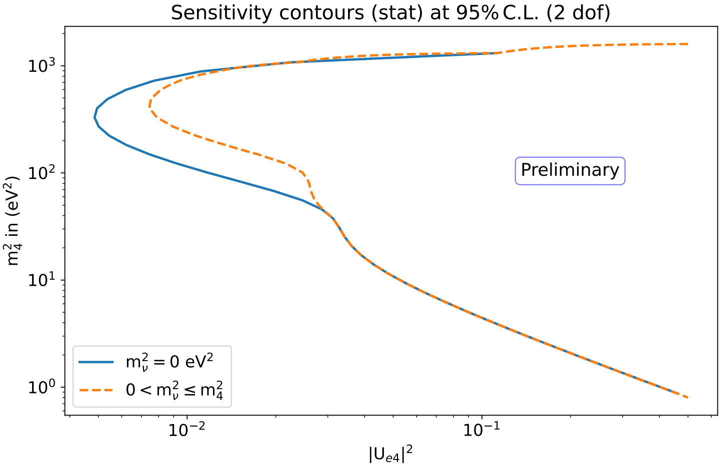


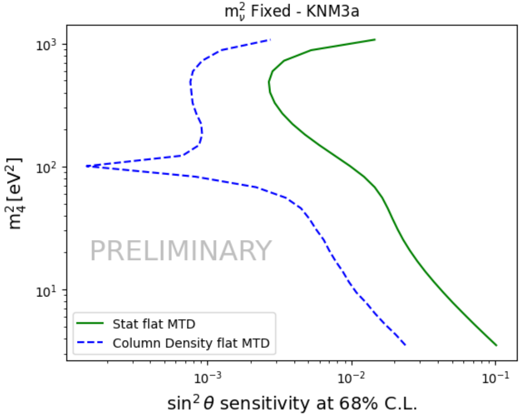
FIG. 4. The correlation between active and sterile neutrino mass is approximately a linear slope $m_\nu^2 = \alpha_{\text{slope}} \cdot m_4^2 + \text{const}$ for various values of m_4^2 and $|U_{e4}|^2$ by analyzing simulated spectra. The gradient indicates the magnitude of α_{slope}. For small mixing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

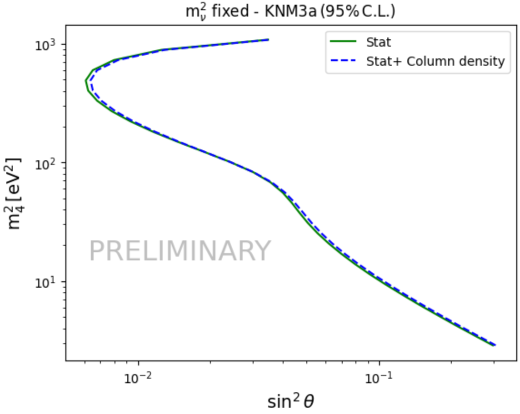
$m_\nu^2 = 0$ **vs** $m_4^2 > m_\nu^2 \geq 0$



Impact of Measured Time Distribution

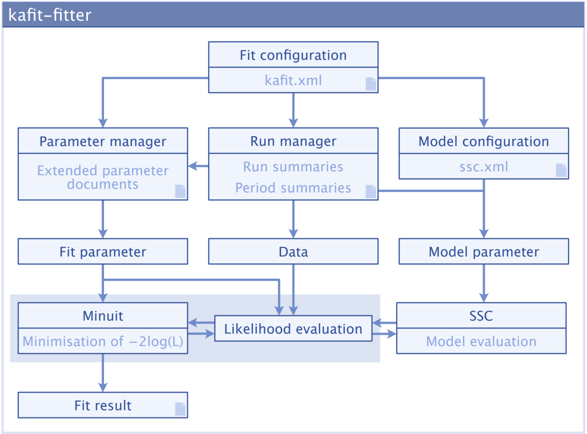
- Objective: To investigate spikes in the raster contours.


m_ν^2 Fixed - KNM3a


m_ν^2 fixed - KNM3a (95% C.L.)

Schematic overview of KaFit

- C++ based fitting framework used to analyse measured KATRIN data and simulated data
- Applicable for Frequentist (based on MINUIT class of ROOT) and Bayesian analysis
- Minimisation is performed with MINUIT by minimising the -2log(L)



kafit–fitter

Fit configuration
kafit.xml

Parameter manager
Extended parameter documents

Run manager
Run summaries
Period summaries

Model configuration
ssc.xml

Fit parameter

Data

Model parameter

Minuit
Minimisation of −2log(L)

Likelihood evaluation

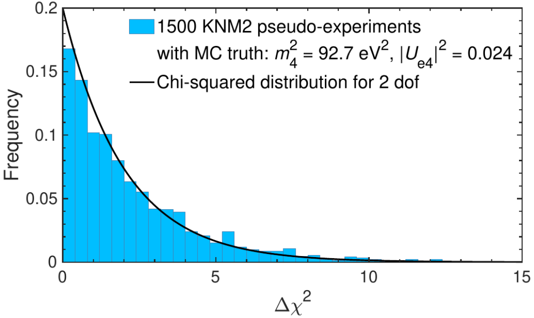
SSC
Model evaluation

Fit result

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



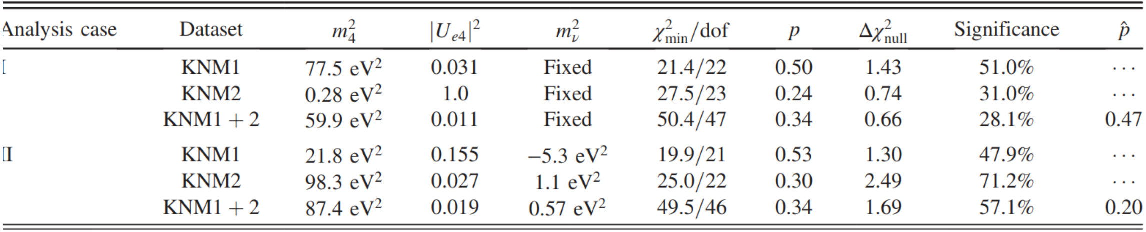
(c) KNM2, MC truth: $m_4^2 = 92.7\,\text{eV}^2$ and $|U_{e4}|^2 = 0.024$

Figure: Taken from H.9 of Schlüter, L. (2022). Neutrino-Mass Analysis with sub-eV Sensitivity and Search for Light Sterile Neutrinos with the KATRIN Experiment. PhD Thesis, TU München, Garching bei München.

Brief history

- Late 19th Century: Discovery of radioactivity
- 1914: Chadwick observes continuous electron spectrum in β-decay, challenging assumptions of monoenergetic emissions
- 1930: Bohr suggests questioning conservation of energy and momentum in light of continuous β-decay spectrum.
- 1930: Pauli proposes neutrino as a solution to the continuous spectrum problem in β decay, maintaining energy conservation
- 1934: Fermi develops theory of β-decay , introducing the term "neutrino" and incorporating it into decay processes.
- Fermi's theory remains valid for low-energy β emitters like tritium, influencing modern understanding and experimental approaches.

Sterile neutrino result



Analysis case	Dataset	m_4^2	$\|U_{e4}\|^2$	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