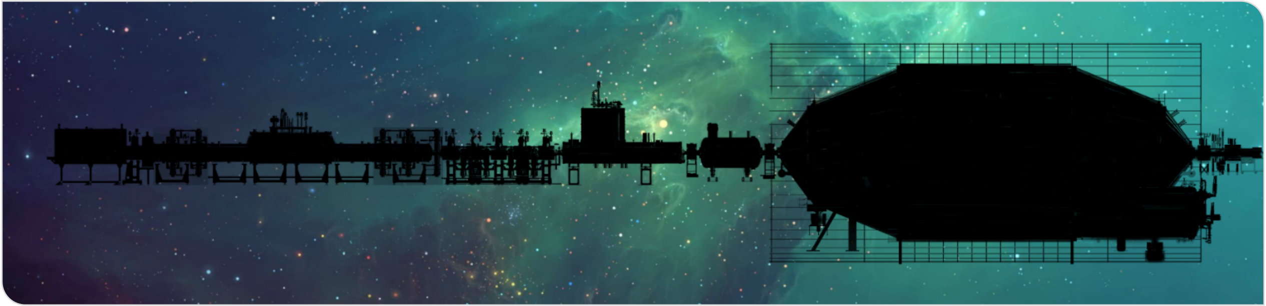
Karlsruhe Institute of Technology

Overview of KATRIN Results on the Neutrino Mass and New Physics Searches

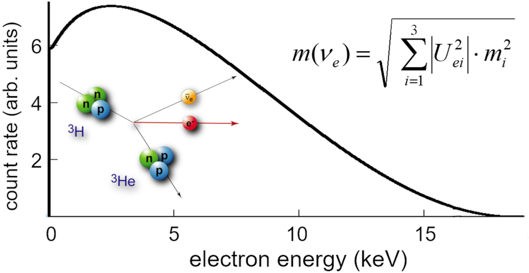
Caroline Fengler for the KATRIN Collaboration | November 7th, 2022

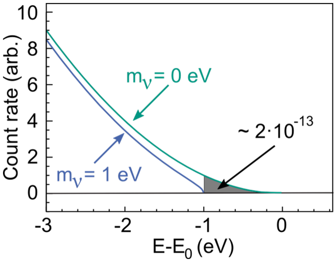


Tritium β-decay

Continuous β-spectrum described by Fermi's Golden Rule, measurement of effective mass $m(\nu_e)$ based on kinematic parameters & energy conservation

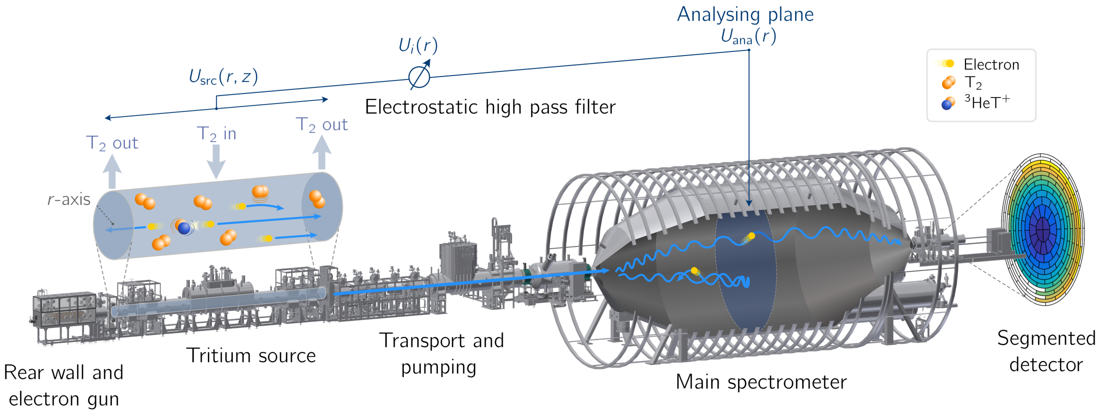
$$\frac{d\Gamma}{dE} = C\,p\,(E + m_e)\,(E_0 - E)\sum_i |U_{ei}^2|\,\sqrt{(E_0 - E)^2 - m_i^2}\,F(E,Z)\,\Theta(E_0 - E - m_i)$$



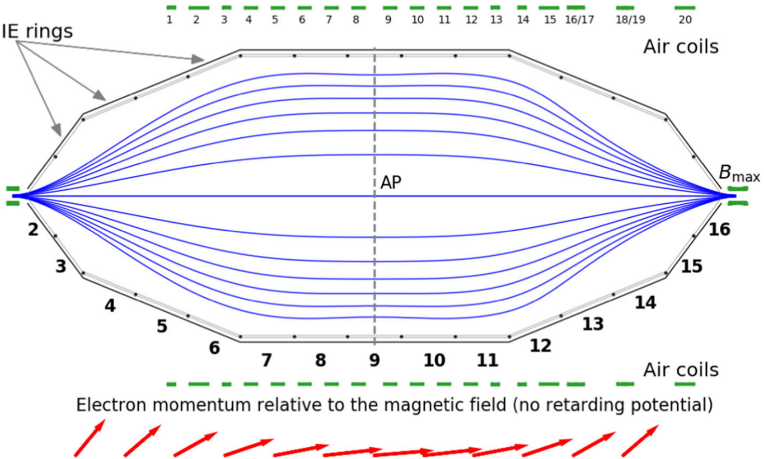


The KATRIN Experiment: Overview

70 m long set-up: a gaseous tritium source & high resolution MAC-E filter

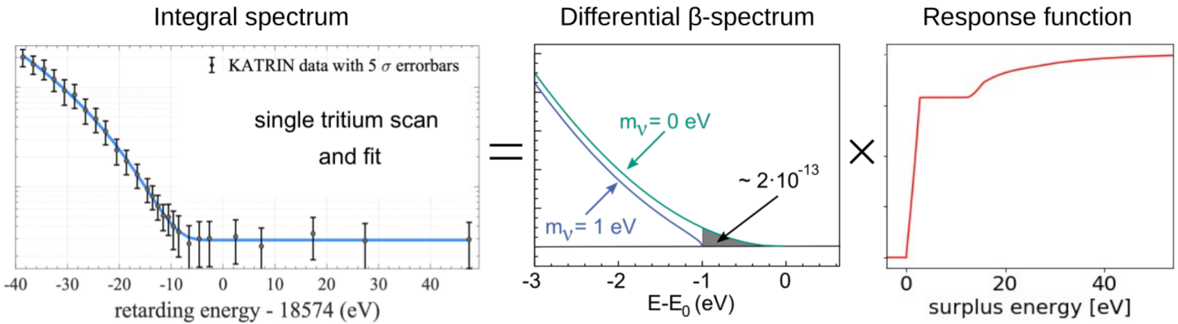


The KATRIN Experiment: MAC-E Filter



The Neutrino Mass

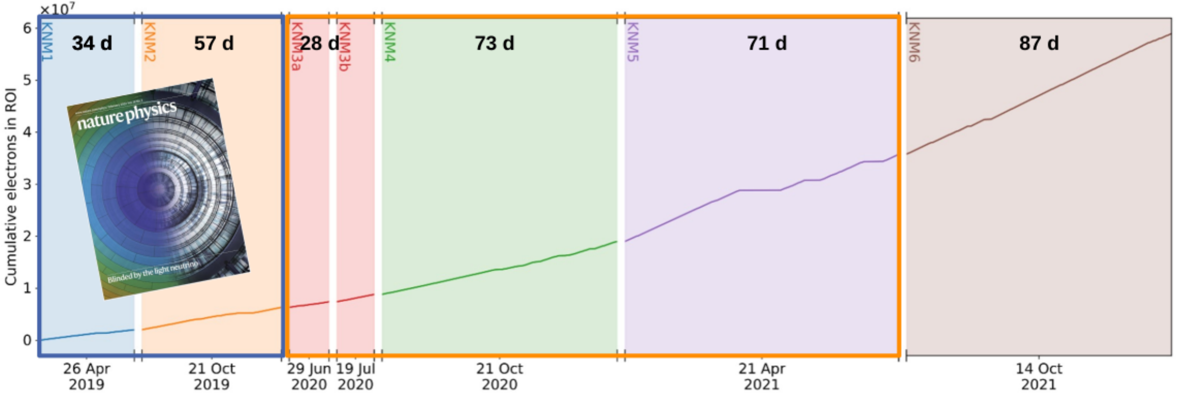
$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} \underbrace{R_\beta(e, m^2(\nu_e))}_{\text{Beta Spectrum}} \cdot \underbrace{f(E - qU)}_{\text{Response function}} \, dE + R_{bg}$$



New Results

2022: analyzed first 91 days
$\rightarrow m_\nu < 0.8\ eV$ (90% CL)
KATRIN Coll., 10.1038/s41567-021-01463-1

Now: Combining runs 1-5 (total 263 days)
for expected sensitivity $\sim 0.5\ eV$ + more data on disc



Search for Lorentz Invariance Violations

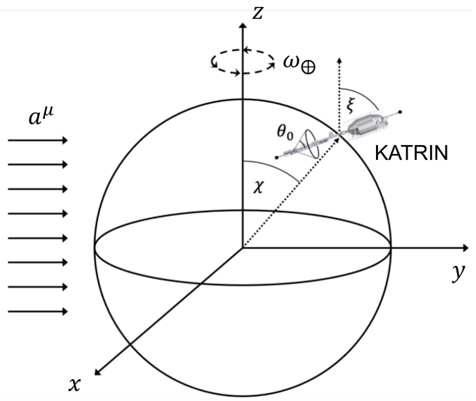
Karlsruhe Institute of Technology

- **Motivation:** BSM theories, e.g. String theory, loop quantum gravity and non-commutative QFT, suggest CPT and Lorentz invariance violation at high energies.
- **Standard Model Extension (SME):** Relativistic EFT, which contains all possible Lorentz-invariance violating operators for ν propagation.
- **Constraints:** Neutrino oscillation, time-of-flight experiments, experiments using interaction processes (KATRIN)

Search for Lorentz Invariance Violations

$$\mathcal{L}^{a}_{SME} = -\bar{\psi}_w\, a^\mu\, \gamma_\mu\, \psi_w \qquad w \in \{\mathrm{T, H, e, n}\}$$

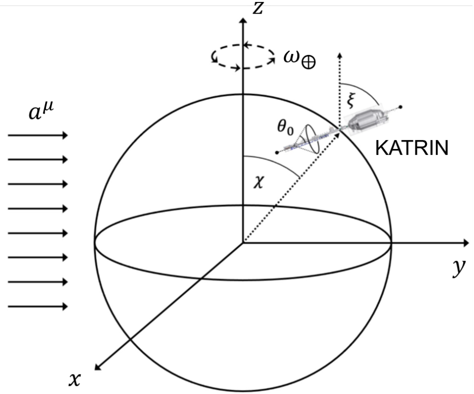
- Produces terms $\propto a^\mu\, p_\mu = a_0\, p_0 - a_i\, p_i$
  $\longrightarrow$ time-dependent & time-independent shift of E_0



Search for Lorentz Invariance Violations

$$\mathcal{L}^a_{SME} = -\bar{\psi}_w\, a^\mu\, \gamma_\mu\, \psi_w \qquad w \in \{\mathrm{T, H, e, n}\}$$

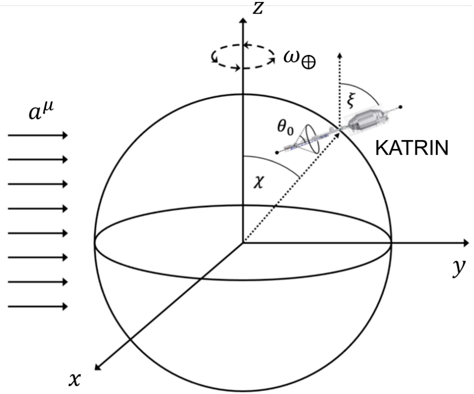
- Produces terms $\propto a^\mu\, p_\mu = a_0\, p_0 - a_i\, p_i$
  $\longrightarrow$ time-dependent & time-independent shift of E_0
- **Rotation of Earth:** relative direction of WGTS acceptance angle changes w.r.t Lorentz-violating vector a^μ
- **LIV-signature:** Endpoint energy E_0 oscillates with sidereal time (23 h 56 min 4 s)
  $\longrightarrow$ Sensitive to $|(a^{(3)}_{of})_{11}|$



Search for Lorentz Invariance Violations

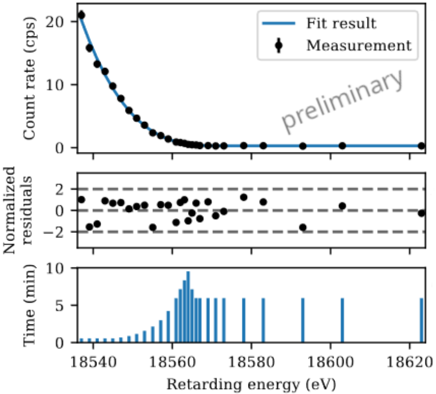
$$\mathcal{L}^{a}_{SME} = -\bar{\psi}_w \, a^\mu \, \gamma_\mu \, \psi_w \qquad w \in \{\mathrm{T, H, e, n}\}$$

- Produces terms $\propto a^\mu p_\mu = a_0 p_0 - a_i p_i$
  $\longrightarrow$ time-dependent & time-independent shift of E_0
- **Rotation of Earth:** relative direction of WGTS acceptance angle changes w.r.t Lorentz-violating vector a^μ
- **LIV-signature:** Endpoint energy E_0 oscillates with sidereal time (23 h 56 min 4 s)
  $\longrightarrow$ Sensitive to $|(a^{(3)}_{of})_{11}|$
- **LIV-signature:** Global shift of endpoint energy E_0
  $\longrightarrow$ Sensitive to $|(a^{(3)}_{of})_{00}|$ and $|(a^{(3)}_{of})_{10}|$



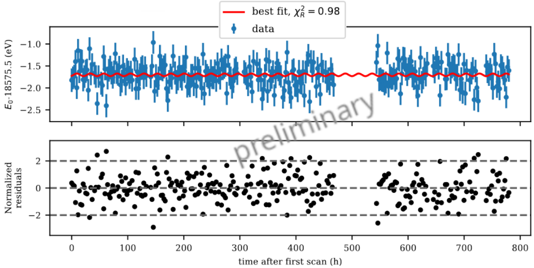
Lorentz Invariance Violation in KATRIN

- Fit each scan of β-spectrum with 2 h binning



- Estimate amplitude of E_0 oscillation
- Convert into estimation of LIV parameters

$$A = \sqrt{\frac{3}{2\pi}} |(a^{(3)}_{of})_{11}| \sqrt{B^2 \cos^2 \chi \cos^2 \xi + (\beta_{rot} - B \sin \xi)^2}$$



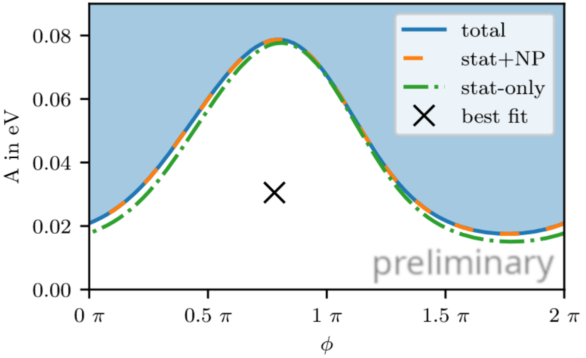
Results from first campaign

$$A = \sqrt{\frac{3}{2\pi}}\left|\left(a_{of}^{(3)}\right)_{11}\right|\sqrt{B^2\cos^2\chi\cos^2\xi + (\beta_{rot} - B\sin\xi)^2}$$

Preliminary results:

KATRIN Coll., arXiv 2207.06326, submitted to Phys. Rev. D

- No significant oscillation of E_0 observed
  First upper limit:
  $\left|\left(a_{of}^{(3)}\right)_{11}\right| < 3.7 \times 10^{-6}\ GeV$ (90 % CL)
- No significant shift of E_0 observed
  Improved upper limits:
  $\left|\left(a_{of}^{(3)}\right)_{00}\right| < 3.0 \times 10^{-8}\ GeV$ (90 % CL)
  $\left|\left(a_{of}^{(3)}\right)_{10}\right| < 6.4 \times 10^{-4}\ GeV$ (90 % CL)

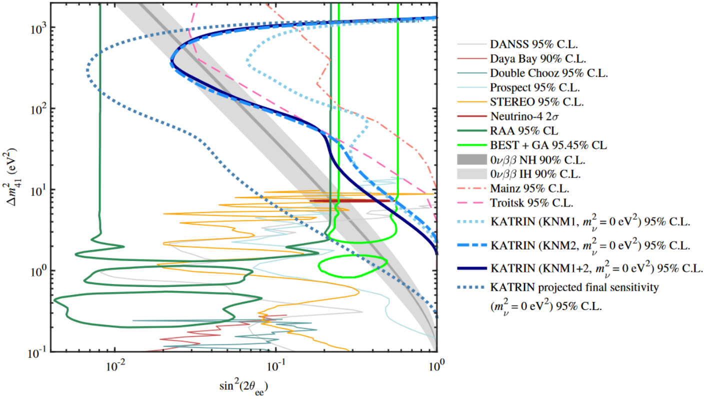


Light Sterile Neutrinos → Talk by L. Köllenberger

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

- **Motivation:** Multiple anomalies in the oscillation data, could be explained by $\geq 1\ eV$ sterile neutrino
- **Analysis:** Add sterile β-spectrum to active neutrino β-spectrum
- **Results:**

  KATRIN Coll., Phys. Rev. D, 10.1103/PhysRevD.105.072004
  - No significant sterile neutrino signal observed in first two measurement campaigns
  - Excluded large Δm^2_{41} solutions of reactor and gallium anomalies

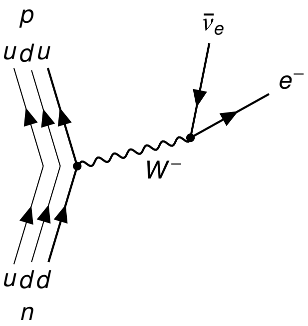


General Neutrino Interactions

- Add **novel interactions** which contribute to the weak interaction in β-decay.
- **Theory of General Neutrino Interactions (GNI)** uses Effective Field Theory, adds all possible interactions with neutrinos to the Standard Model. Based on close to no presumptions.

$$\mathcal{L}_{SMEFT}(\phi_{SM}) = \mathcal{L}_{SM}(\phi_{SM}) + \sum_{n\geq 5}\sum_{i} \frac{1}{\Lambda^{n-4}} C_i^{(n)} \mathcal{O}_i^{(n)}(\phi_{SM})$$

- GNI cause modifications to the β-spectrum
  → **Energy-dependent contributions to the rate** in KATRIN.

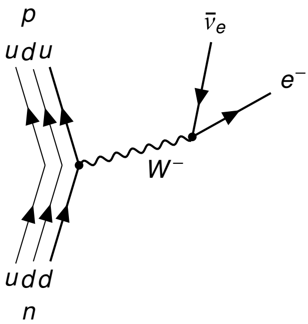


Bischer and Rodejohann, Nucl. Phys. B, 10.1016/j.nuclphysb.2019.114746

GNI Lagrangian for 4-Fermion-interaction

$$\mathcal{L}_{GNI}^{CC} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,ud} \right)^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha \mathcal{O}_j \nu_\beta\right) \left(\bar{u}_\gamma \mathcal{O}'_j d_\delta\right) + h.c.$$

- G_F : Fermi constant
- $V_{\gamma\delta}$: CKM matrix
- $\overset{(\sim)}{\epsilon}_{j,ud}$: Flavour space tensor describing **strength of interaction** type j with respect to SM Fermi interaction
  - $\epsilon_{L/R}$: Coupling for **left-/right-handed vector**-like interactions
  - ϵ_S: Coupling for **scalar** interactions
  - ϵ_P: Coupling for **pseudo-scalar** interactions
  - ϵ_T: Coupling for **tensor**-like interactions



GNI @ KATRIN

$$\frac{d\Gamma}{dE} = \frac{G_F^2\, V_{ud}^2}{2\pi^3} \sqrt{(E+m_e)^2 - m_e^2}(E+m_e)(E_0-E)$$

$$\times \left\{ \sum_{k=\beta,\, N} \sqrt{(E_0-E)^2 - m_k^2} \cdot \xi_k \left[1 + \boldsymbol{b_k} \frac{m_e}{E+m_e} - \boldsymbol{b'_k} \frac{m_k}{E_0-E} - \boldsymbol{c_k} \frac{m_e m_k}{(E+m_e)(E_0-E)} \right] \Theta(E_0 - m_k - E) \right\}$$

- Total differential decay rate for active neutrino and sterile neutrino
- Dimensionless coefficients ξ_k, b_k, b'_k and c_k defined in terms of factors ϵ, $\hat{\epsilon}$, U_{e4} and nuclear form factors g_V, g_S, g_T and g_A.
- Recover SM for $\xi_N = b_k = b'_k = c_k = 0$

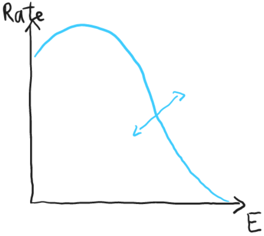
Bischer and Rodejohann, Nucl. Phys. B, 10.1016/j.nuclphysb.2019.114746

GNI @ KATRIN

$$\frac{d\Gamma}{dE} = \frac{G_F^2\, V_{ud}^2}{2\pi^3}\sqrt{(E+m_e)^2 - m_e^2}\,(E+m_e)(E_0-E)$$

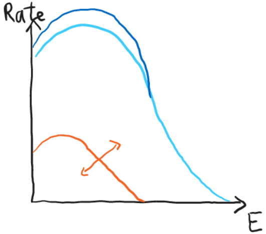
$$\times \left\{ \sum_{k=\beta,\, N} \sqrt{(E_0-E)^2 - m_k^2} \cdot \xi_k \left[1 + b_k \frac{m_e}{E+m_e} - \boldsymbol{b'_k} \frac{m_k}{E_0-E} - c_k \frac{m_e m_k}{(E+m_e)(E_0-E)} \right] \Theta(E_0 - m_k - E) \right\}$$

ξ_β & b'_β



ξ_β & ξ_N

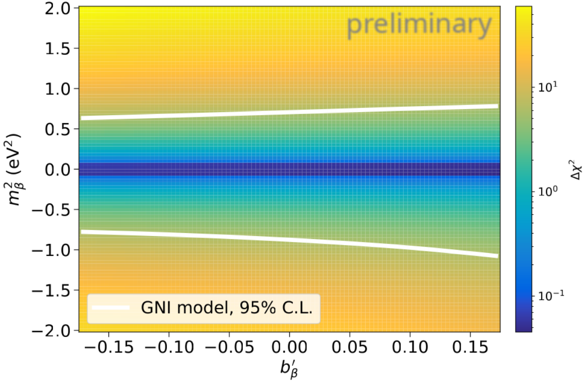
ξ_β, ξ_N & b'_N



Sensitivity of GNI on β-spectrum

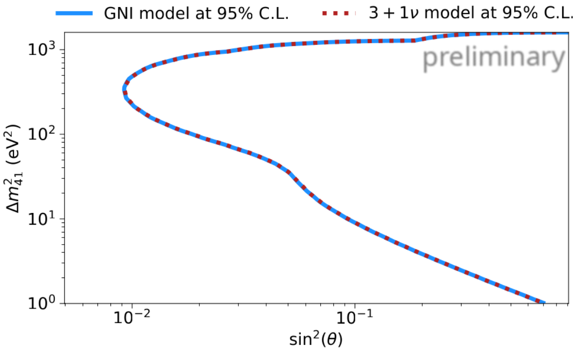
- b'_β has slight effect on neutrino mass sensitivity.
- $\xi_\beta\, b'_\beta$ depends on ϵ_S and ϵ_T
  $\longrightarrow$ derive sensitivity on scalar- and tensor-like interactions

Preliminary Study on first year MC



Sensitivity of GNI on sterile spectrum

Preliminary Study on first year MC

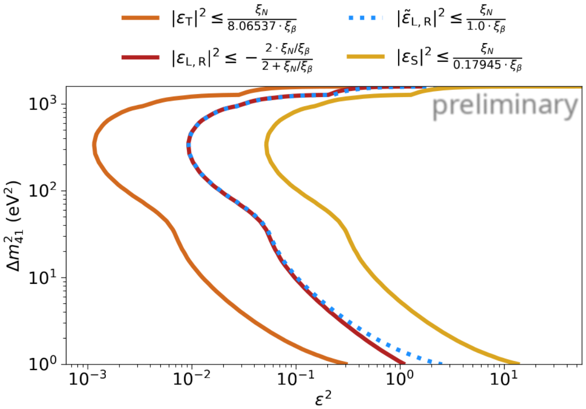


- Able to probe sterile parameter space with GNI model using $\xi_N = \tan^2\theta \cdot (g_A^2 + 3g_V^2)$.
- Cross-check between GNI and 3 + 1 ν model $\longrightarrow$ shows good agreement

Sensitivity of GNI on sterile spectrum

Preliminary Study on first year MC at 95 % CL

- Draw conclusions from sensitivity on $\frac{\xi_N}{\xi_\beta}$ to sensitivity on ϵ-parameters.
- Most sensitive to ϵ_T at $\mathcal{O}(10^{-2})$
- Constraints for similar parameters from other experiments (LHC, neutron decay) at $\mathcal{O}(10^{-3})$



10.1016/j.ppnp.2018.08.002, 10.1002/andp.201300072

KATRIN Highlights from 2022

- Improved upper limit on neutrino mass for first two measurement campaigns
  KATRIN Coll., Nature Physics, 10.1038/s41567-021-01463-1
- First upper limit on Lorentz invariance violating parameter
  KATRIN Coll., arXiv 2207.06326, submitted to Phys. Rev. D
- Improved sensitivity on local relic neutrino background
  KATRIN Coll., Physical Review Letters, 10.1103/PhysRevLett.129.011806
- Light sterile neutrino search excludes large Δm^2_{41} solutions of reactor and gallium anomalies
  KATRIN Coll., Physical Review D, 10.1103/PhysRevD.105.072004
- New exclusion limit on the sterile-to-active mixing amplitude for keV sterile neutrinos
  KATRIN Coll., arXiv 2207.06337, submitted to EPJC
- Ongoing investigations for general neutrino interactions in KATRIN data
- KATRIN is continuously taking and analysing data for goal sensitivity of 0.2 eV - stay tuned!

Ways to assess the absolute neutrino mass scale

Cosmology

- Formation of large scale cosmic density structures
- Dependent on cosmological model
- **Observable:** direct sum of mass eigenstates $m_{tot} = \sum m(\nu_i)$
- **Upper limit:** $m_{tot} < 0.72$ - $0.12\,\text{eV}$ (95 % CL)
  Planck Coll., 10.1051/0004-6361/201833910

Search for $0\nu\beta\beta$

- Sensitive to Majorana neutrinos, model dependent
- $T^{0\nu}_{1/2} \sim \frac{1}{m^2_{\beta\beta}}$
- **Observable:** Effective Majorana neutrino mass $m_{\beta\beta} = |\sum_i U^2_{ei} m_i|$
- **Upper limits:** $m_{\beta\beta} < 0.1 - 0.4\,\text{eV}$ (90 % CL)
  GERDA Coll., 10.1103/PhysRevLett.125.252502
  CUORE Coll., 10.1103/PhysRevLett.124.122501

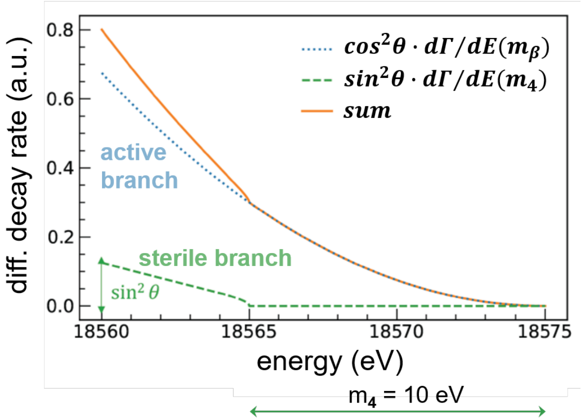
Direct kinematic measurement

- Kinematics of weak decay
- No further assumptions needed, use energy-momentum-conservation.
- **Observable:** Effective electron antineutrino mass $m^2_{\bar{\nu}_e} = \sum_i |U^2_{ei}| m^2_i$
- **Upper limit:** $m_{\bar{\nu}_e} < 0.8\,\text{eV}$ (90 % CL)
  KATRIN Coll., 10.1038/s41567-021-01463-1

Light Sterile Neutrinos

- Independent cross-check with KATRIN as an oscillation-free experiment
- **Analysis:** 3+1 sterile neutrino model on KATRIN data

$$\frac{d\Gamma}{dE} = \underbrace{(1 - |U_{e4}|^2)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{active neutrino}} + \underbrace{|U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)}_{\text{sterile neutrino}}$$



Flavour Space Tensor

j	ϵ_j	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ϵ_L	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
2	$\tilde{\epsilon}_L$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
3	ϵ_R	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
4	$\tilde{\epsilon}_R$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
5	ϵ_S	$(1-\gamma^5)$	1
6	$\tilde{\epsilon}_S$	$(1+\gamma^5)$	1
7	$-\epsilon_P$	$(1-\gamma^5)$	γ^5
8	$-\tilde{\epsilon}_P$	$(1+\gamma^5)$	γ^5
9	ϵ_T	$\sigma_{\mu\nu}(1-\gamma^5)$	$\sigma^{\mu\nu}(1-\gamma^5)$
10	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(1+\gamma^5)$	$\sigma^{\mu\nu}(1+\gamma^5)$

$$\mathcal{L}^{CC}_{GNI} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,ud}\right)^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha \mathcal{O}_j \nu_\beta\right) \left(\bar{u}_\gamma \mathcal{O}'_j d_\delta\right) + h.c.$$

- $\epsilon_{L/R}$: Coupling for left-/right-handed vector-like interactions
- ϵ_S: Coupling for scalar interactions
- ϵ_P: Coupling for pseudo-scalar interactions
- ϵ_T: Coupling for tensor-like interactions

GNI - ϵ and ϵ^2

Karlsruhe Institute of Technology

- For different ϵ-parameters we get slightly different transformations
- $q \geq C \cdot |\epsilon|^2$ with
  - $C = \frac{1}{1 - \frac{1}{2}|\epsilon|^2}$ for ϵ_L^N or ϵ_R^N
  - $C = 1$ for $\widetilde{\epsilon_L^N}$ or $\widetilde{\epsilon_R^N}$
  - $C = \frac{g_S^2}{g_V^2 + 3g_A^2} \approx 0.17945$ for ϵ_S^N or $\widetilde{\epsilon_S^N}$
  - $C = \frac{48 g_T^2}{g_V^2 + 3g_A^2} \approx 8.06537$ for ϵ_T^N or $\widetilde{\epsilon_T^N}$
- See results on the next slides!

$$
\begin{aligned}
\xi_\beta &= g_V^2 \left(|\hat{\epsilon}_L + \epsilon_R|^2 + |\tilde{\epsilon}_L + \tilde{\epsilon}_R|^2\right) + g_S^2 \left(|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2\right) \\
&\quad + 3g_A^2 \left(|\hat{\epsilon}_L - \epsilon_R|^2 + |\tilde{\epsilon}_L - \tilde{\epsilon}_R|^2\right) + 48 g_T^2 \left(|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2\right), \\
\xi_\beta b_\beta &= g_V g_S \, 2\mathrm{Re}\left[(\hat{\epsilon}_L + \epsilon_R)\epsilon_S + (\tilde{\epsilon}_L + \tilde{\epsilon}_R)(\tilde{\epsilon}_S)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(\hat{\epsilon}_L - \epsilon_R)(\epsilon_T)^* - (\tilde{\epsilon}_L - \tilde{\epsilon}_R)(\tilde{\epsilon}_T)^*\right], \\
\xi_\beta b'_\beta &= g_V g_S \, 2\mathrm{Re}\left[(\hat{\epsilon}_L + \epsilon_R)\tilde{\epsilon}_S + \epsilon_S(\tilde{\epsilon}_L + \tilde{\epsilon}_R)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(\hat{\epsilon}_L - \epsilon_R)(\tilde{\epsilon}_T)^* - (\tilde{\epsilon}_L - \tilde{\epsilon}_R)(\epsilon_T)^*\right], \\
\xi_\beta c_\beta &= 2\mathrm{Re}\left[g_V^2 (\hat{\epsilon}_L + \epsilon_R)(\tilde{\epsilon}_L + \tilde{\epsilon}_R) + g_S^2 \epsilon_S (\tilde{\epsilon}_S)^*\right] \\
&\quad + 2\mathrm{Re}\left[-3 g_A^2 (\hat{\epsilon}_L - \epsilon_R)(\tilde{\epsilon}_L - \tilde{\epsilon}_R)^* + 48 g_T^2 \epsilon_T (\tilde{\epsilon}_T)^*\right].
\end{aligned}
$$

$$
\begin{aligned}
\xi_N &= g_V^2 \left(|U_{e4} + \epsilon_L + \epsilon_R|^2 + |\tilde{\epsilon}_L + \tilde{\epsilon}_R|^2\right) + g_S^2 \left(|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2\right) \\
&\quad + 3g_A^2 \left(|U_{e4} + \epsilon_L - \epsilon_R|^2 + |\tilde{\epsilon}_L - \tilde{\epsilon}_R|^2\right) + 48 g_T^2 \left(|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2\right), \\
\xi_N b_N &= g_V g_S \, 2\mathrm{Re}\left[(U_{e4} + \epsilon_L + \epsilon_R)(\epsilon_S)^* + (\tilde{\epsilon}_L + \tilde{\epsilon}_R)(\tilde{\epsilon}_S)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(U_{e4} + \epsilon_L - \epsilon_R)(\epsilon_T)^* - (\tilde{\epsilon}_L - \tilde{\epsilon}_R)(\tilde{\epsilon}_T)^*\right], \\
\xi_N b'_N &= g_V g_S \, 2\mathrm{Re}\left[(U_{e4} + \epsilon_L + \epsilon_R)(\tilde{\epsilon}_S)^* + \epsilon_S(\tilde{\epsilon}_L + \tilde{\epsilon}_R)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(U_{e4} + \epsilon_L - \epsilon_R)(\tilde{\epsilon}_T)^* - (\tilde{\epsilon}_L - \tilde{\epsilon}_R)(\epsilon_T)^*\right], \\
\xi_N c_N &= 2\mathrm{Re}\left[g_V^2 (U_{e4} + \epsilon_L + \epsilon_R)(\tilde{\epsilon}_L + \tilde{\epsilon}_R)^* + g_S^2 \epsilon_S (\tilde{\epsilon}_S)^*\right] \\
&\quad + 2\mathrm{Re}\left[-3 g_A^2 (U_{e4} + \epsilon_L - \epsilon_R)(\tilde{\epsilon}_L - \tilde{\epsilon}_R)^* + 48 g_T^2 \epsilon_T (\tilde{\epsilon}_T)^*\right].
\end{aligned}
$$

Effect of GNI parameters on β-spectrum

- Effect of GNI on sterile neutrino spectrum
- b'_N enhances/diminishes kink-like structure of sterile neutrino spectrum