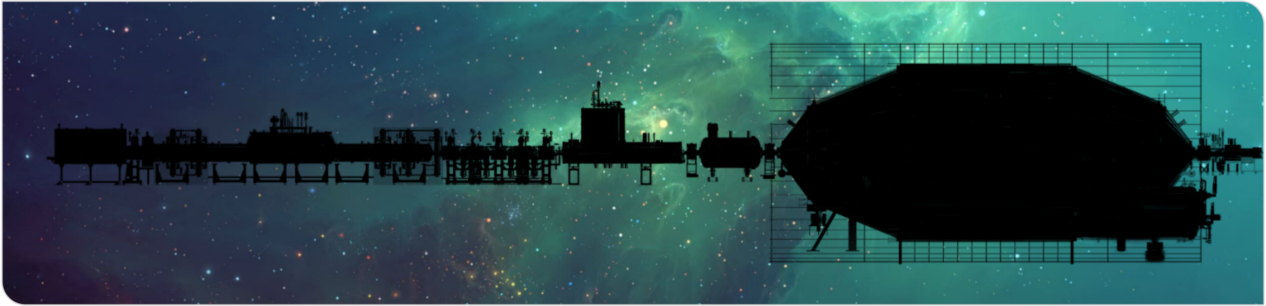
Probing Physics Beyond the Neutrino Mass at the KATRIN Experiment

42nd International Conference on High Energy Physics

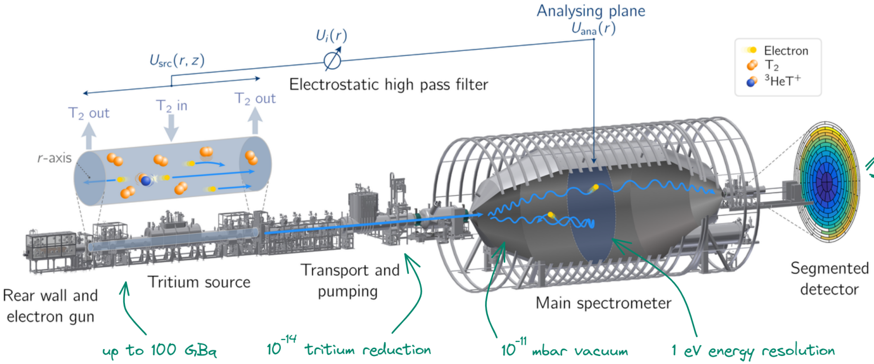
Caroline Fengler for the KATRIN Collaboration | July 20th, 2024

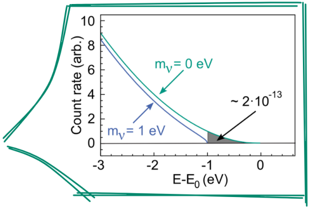


The KATRIN Experiment

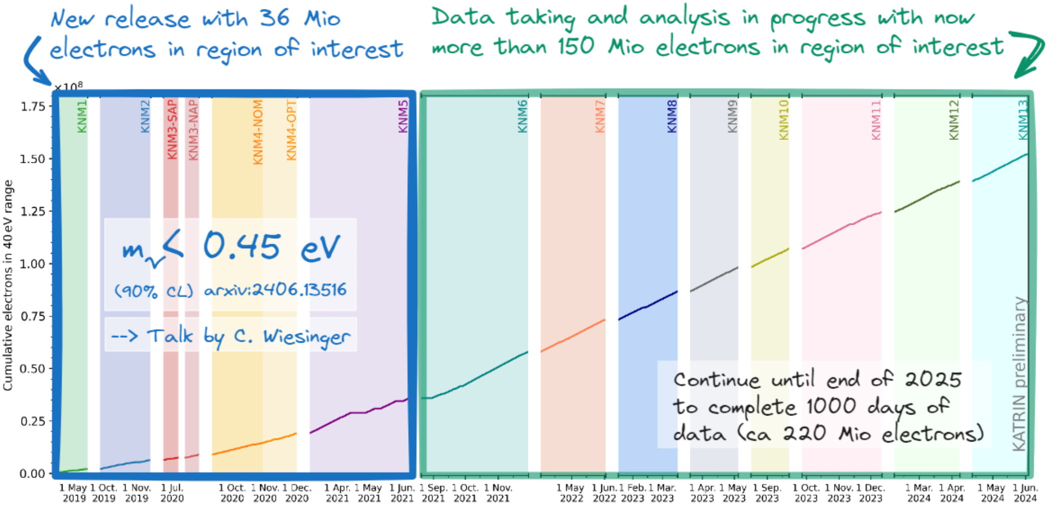
70 m long set-up: a gaseous tritium source & high resolution MAC-E filter

Continuous β-spectrum: measurement of effective mass $m(\nu_e)$ based on kinematic parameters & energy conservation





Neutrino Mass Results

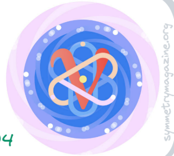


Beyond the Neutrino Mass - New physics searches

"Kink" search

for eV-scale sterile ν close to the endpoint

--> PRL 126 (2021) 091803
& PRD 105 (2022) 072004



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--> EPJ C 83 (2023) 763

Line search

for capture of local cosmic relic ν

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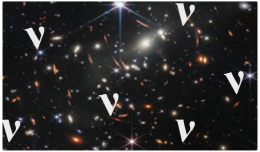

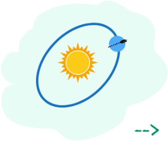

Search for Lorentz violation through sidereal modulation

--> PRD 107 (2023) 082005

Search for shape distortions through exotic weak interactions

--> eg JHEP 01 (2019) 206

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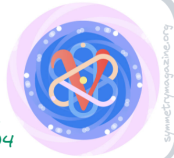

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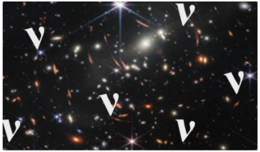

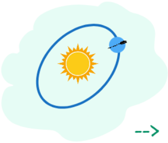

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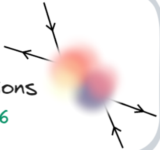
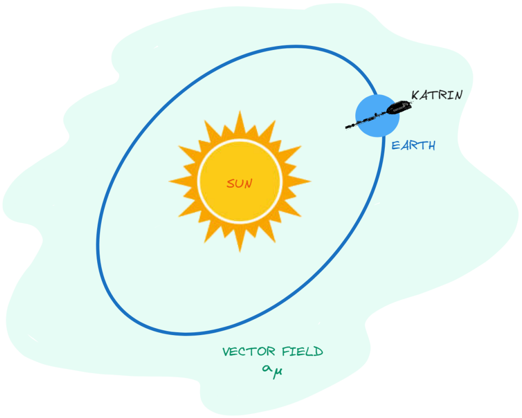


Search for Lorentz Invariance Violations

- **Motivation:** BSM theories (String theory, loop quantum gravity and non-commutative QFT) suggest CPT and Lorentz invariance violation at high energies.
- **Constraints:** Neutrino oscillation, time-of-flight experiments, experiments using interaction processes (KATRIN)

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

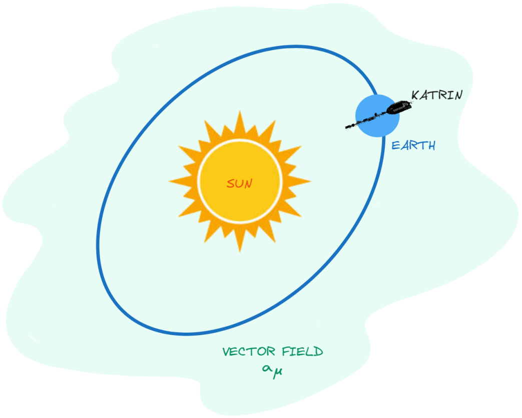
- Produces terms $\propto a^\mu \, p_\mu = a_0 \, p_0 - a_i \, p_i$
  $\longrightarrow$ time-dependent & time-independent shift of E_0



Search for Lorentz Invariance Violations

Time-dependent & time-independent shift of E_0:

- **Rotation of Earth:** relative direction of KATRIN acceptance angle changes w.r.t Lorentz-violating vector a^{μ}
- **LIV-signature:** Measured endpoint energy E_0 oscillates with sidereal time (23 h 56 min 4 s)
  $\rightarrow$ Sensitive to $|(a_{of}^{(3)})_{11}|$
- **LIV-signature:** Global shift of measured endpoint energy E_0
  $\rightarrow$ Sensitive to $|(a_{of}^{(3)})_{00}|$ and $|(a_{of}^{(3)})_{10}|$



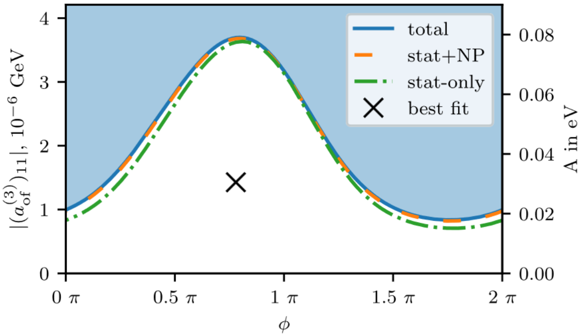
Results from first campaign

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

Results:

KATRIN Coll., PRD **107** (2023) 082005

- 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)



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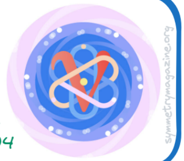

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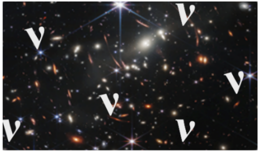

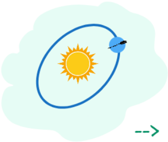

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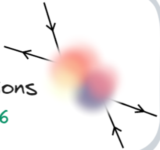
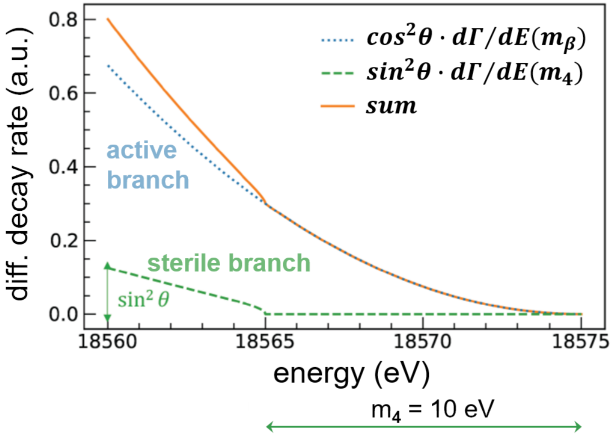


Light Sterile Neutrinos

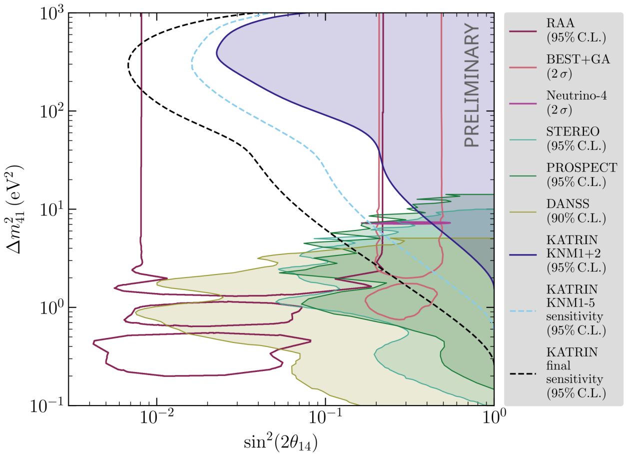
- **Motivation:** Multiple anomalies in the oscillation data, could be explained by ≥ 1 eV sterile neutrino
- **Analysis:** Add sterile β-spectrum with sterile mass m_4 and active-to-sterile mixing $\sin^2\theta$ to active neutrino β-spectrum



Light Sterile Neutrinos

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

- **Results of campaigns 1+2:**
  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
- **Projection for campaigns 1-5:**
  - Significant improvement in sensitivity
  - Able to test last part of the Gallium Anomaly (GA) not excluded by short baseline oscillation experiments, and Neutrino-4 result.



Beyond the Neutrino Mass - New physics searches

Karlsruhe Institute of Technology

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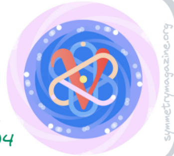

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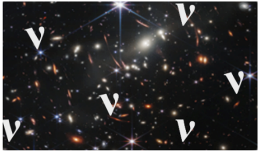

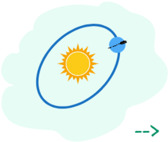

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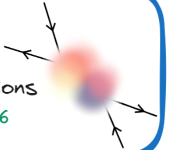


Theory of General Neutrino Interactions (GNI)

- Generalisation of neutrino Non-Standard Interactions (NSI)
- Considers scalar, pseudoscalar, vector, axial vector or tensor interactions of neutrinos with fermions:

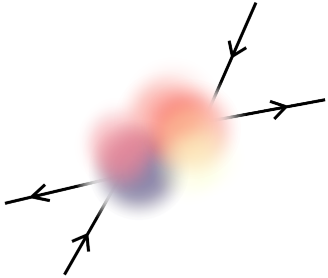
$$\mathcal{L}_{GNI}^{NC} = -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \overset{(\sim)}{\epsilon}_{j,f} \, (\bar{\nu} \mathcal{O}_j \, \nu) \, (\bar{f} \mathcal{O}_j' \, f)$$

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

- Assume that GNI arise from heavy New Physics $\longrightarrow$ Map low energy GNI operators onto dim 6 SM(N)EFT terms.

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

$\longrightarrow$ Enables broad search for New Physics through precision measurements.



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

GNI @ KATRIN

$$\frac{d\Gamma_{\text{GNI}}}{dE} = \frac{d\Gamma_{\text{SM}}}{dE} \sum_{k=\beta,\, N} \sqrt{(E_0 - E)^2 - m_k^2} \cdot \xi_k \left[1 - b'_k \frac{m_k}{E_0 - E}\right] \Theta(E_0 - m_k - E)$$

- Total differential decay rate for light active neutrinos and additional heavier neutrinos
- Dimensionless coefficients ξ_k and b'_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 $\xi_N = b'_k = 0$.

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

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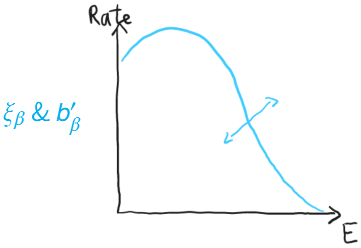
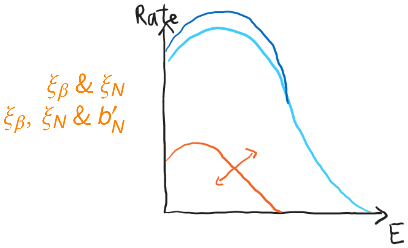
Only light active neutrinos

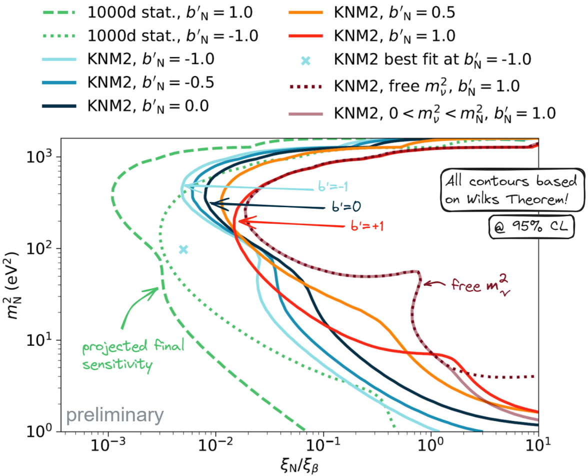


With additional heavier neutrinos



Sensitivity of GNI for additional heavier neutrinos

- Able to search for GNI with KATRIN.
- No significant signal found in the KNM2 data set.
- Studied change in contour shape when allowing $m_\nu^2 \neq 0$.
- Sensitivity is dominated by statistics.
  → Further significant improvements expected for final data set.
- Able to probe more specific scenarios, such as single types of interactions, right-handed W bosons, Leptoquarks and charged Higgs.



Full release of GNI analysis will follow soon.
Stay tuned!

Summary & Outlook

Karlsruhe Institute of Technology

New publication in preparation, able to test critical parts of the parameter space

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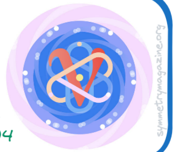

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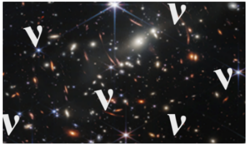
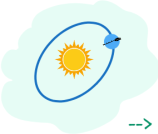


Analysis constrained new parameter and improved others



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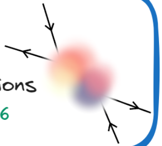
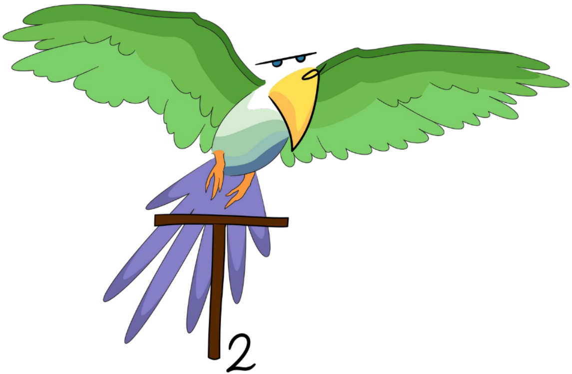


Glimpse at first results with KATRIN, full analysis in publication process

Thank you for your attention!



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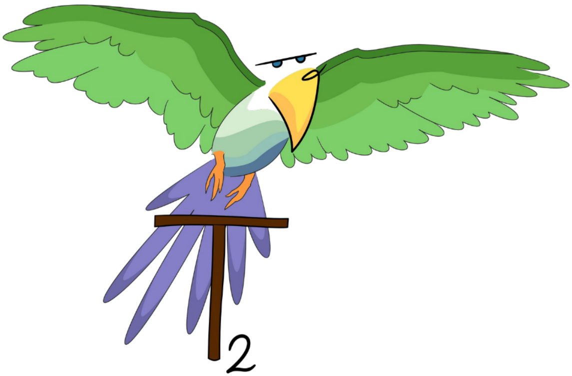
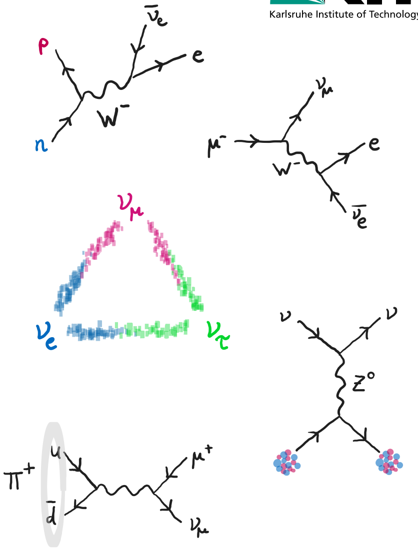
Backup



Search for General Neutrino Interactions

- **Possible interaction channels**:
  - Neutrino oscillation
  - LFV in μ- and τ-decays
  - Neutrino scatterings, e.g. CEνNS
  - π-decay
  - β-decay

- Different interaction channels are sensitive to different combinations of ϵ_i in GNI Lagrangian.



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

Effect of GNI parameters on β-spectrum

- Effect of neutrino mass and GNI on the tritium β-spectrum.
- b'_N enhances/diminishes kink-like structure due to additional heavier mass state contribution to the spectrum.