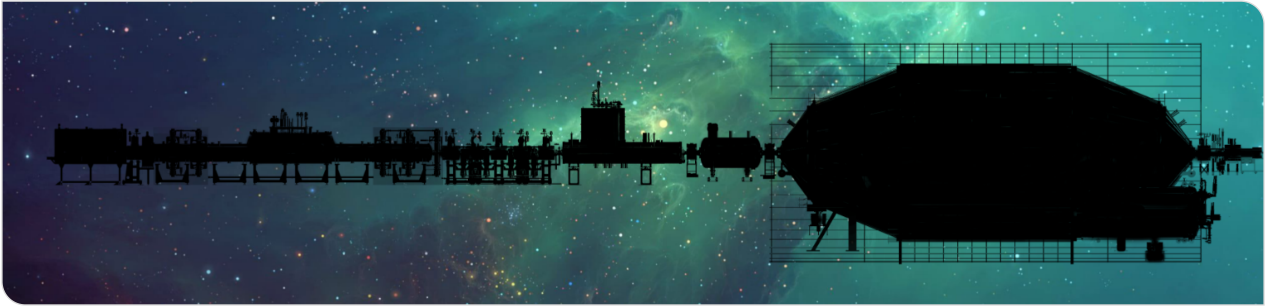
Looking beyond the Standard Model with KATRIN
– The neutrino mass and New Physics searches –

ICEPP Seminar

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



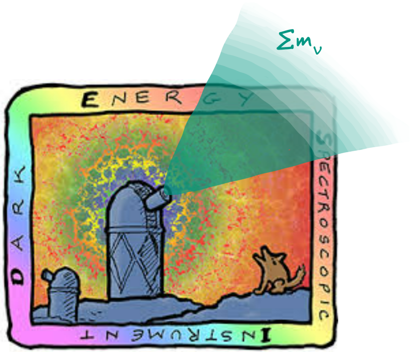
Mystery of the neutrino mass

New results from DESI suggest $\sum m_\nu < 72\,\text{meV}$, thereby approaching minimal $\sum m_\nu$ from oscillation experiments.

- Statistical fluctuations ?
- Model dependency ?
- New Physics in neutrino sector ?

$\Rightarrow$ Both $0\nu\beta\beta$ and cosmology strongly depend on the model assumptions.

$\Rightarrow$ Increased importance of direct lab searches, which can provide valuable input to cosmology.



Ways to assess the absolute neutrino mass scale

Karlsruhe Institute of Technology

Cosmology

- Expansion rate of the universe affected by neutrino mass
- Dependent on cosmological model
- **Observable:** direct sum of mass eigenstates $m_{tot} = \sum m(\nu_i)$
- **Upper limit:** $m_{\mathrm{tot}} < (0.072 - 0.145)\,\mathrm{eV}$ (95 % CL)

DESI Coll., arXiv:2404.03002

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:** $m_{\beta\beta} < (0.036 - 0.156)\,\mathrm{eV}$ (90 % CL)

KamLAND-Zen Coll., 10.1103/PhysRevLett.130.051801

Direct kinematic measurement

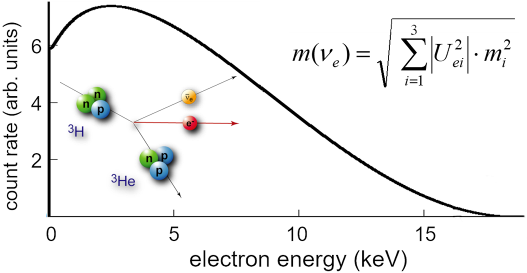
- Kinematics of weak decay
- No further assumptions needed, use energy-momentum-conservation.
- **Observable:** Effective electron antineutrino mass $m^2_{\bar{\nu}_e} = \sum_i |U^2_{ei}| m^2_i$
- **Upper limit:** $m_{\bar{\nu}_e} < 0.8\,\mathrm{eV}$ (90 % CL)

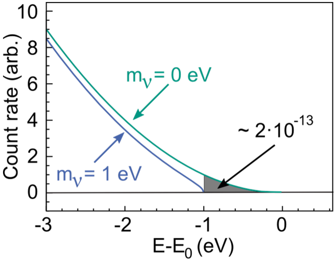
KATRIN Coll., 10.1038/s41567-021-01463-1

Direct neutrino mass measurement with 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

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

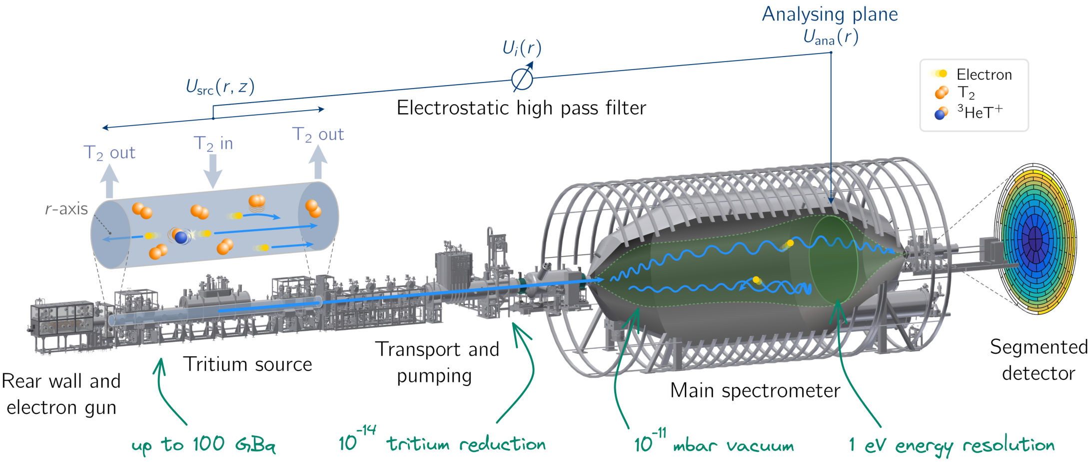




KArlsruhe
TRItium
Neutrino
Experiment

The KATRIN Experiment: Overview

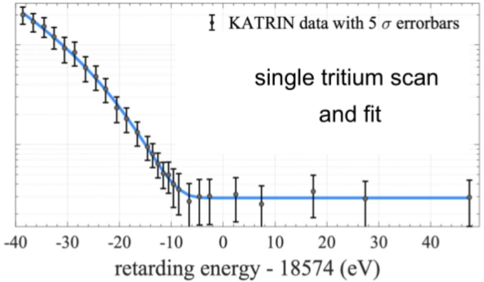
70 m long set-up: a gaseous tritium source & high resolution MAC-E filter



The Neutrino Mass: Spectrum Modelling

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

Integral spectrum



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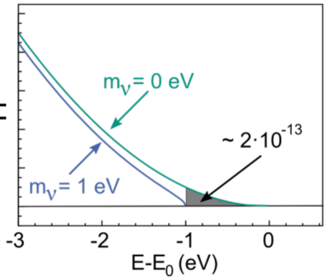
Differential β-spectrum



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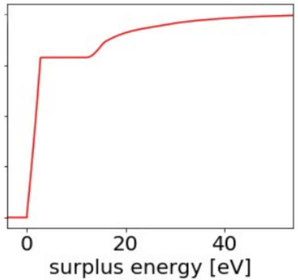
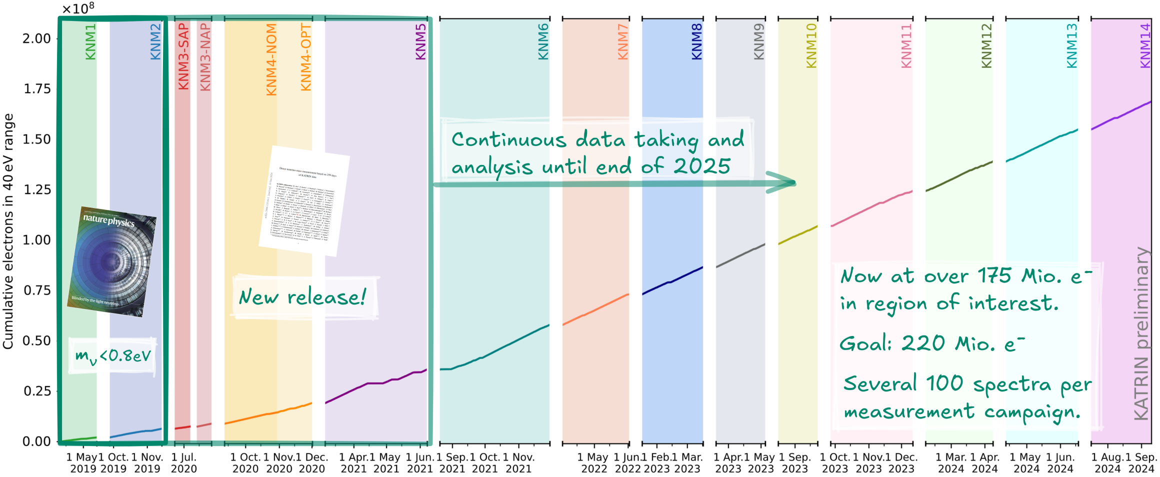
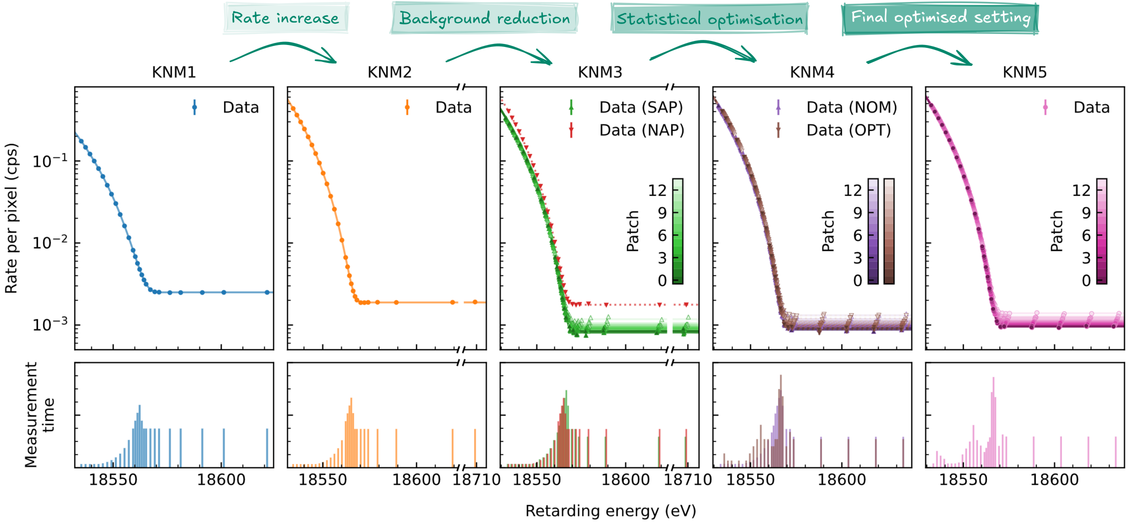
Response function



Progress of data-taking and analysis



Data of first five measurement campaigns



Systematic Effects: Overview

Precise modeling of FSD-related uncertainties
⟶ EPJ C 84 (2024) 494

Final States

Energy loss

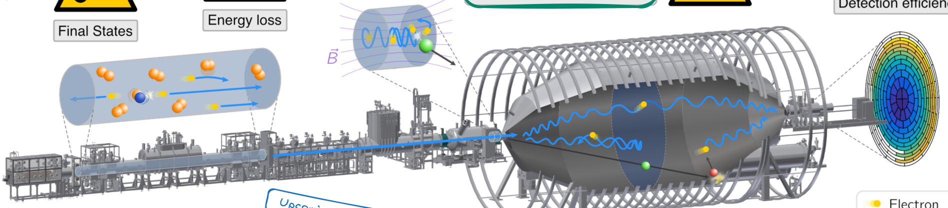
Background reduction by ~50% through fiducialisation: "shifted analysing plane"
⟶ arXiv:2408.07022

New publication!

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

Upcoming publication!

Detection efficiency



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

Rear wall

Significant reduction of RW activity
⟶ FST 80 (2024) 303-310

Upcoming publication!

Source
- Column density
- Activity fluctuations
- Plasma

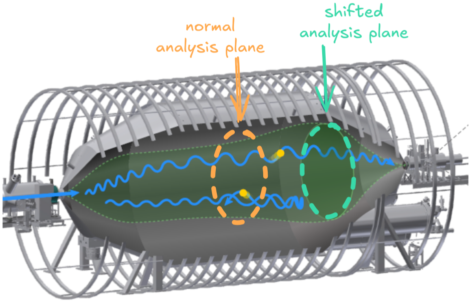
Improved source calibration with Kr-83m
⟶ JINST 17 (2022) P12010

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

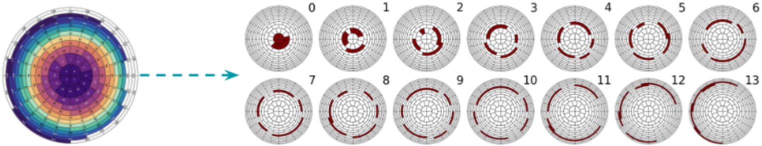
Experimental improvements: Background

Factor 2 lower background using "*shifted analysing plane*" configuration

- Smaller volume mapped onto detector
- Inhomogeneous EM-fields
  - 14 times more segmented data
  - Calibration of fields needed



Main spectrometer



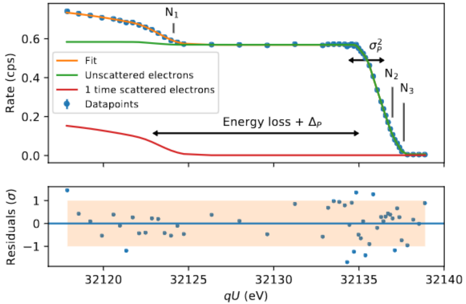
Experimental improvements: Source

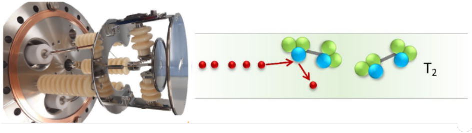
Precise calibration measurements with ^{83m}Kr co-circulation

- Probe of electric potential variation in the source
- Field mapping in the spectrometer
- Source temperature: 30 K to 80 K

With electron gun:

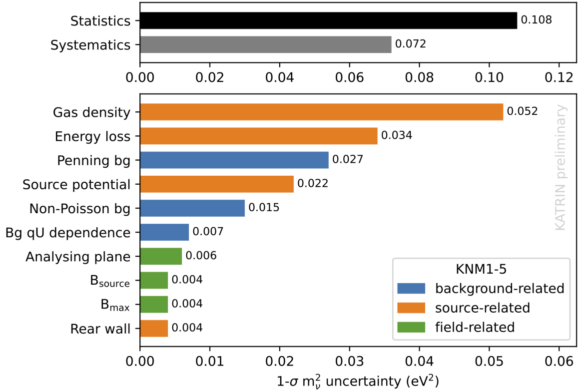
- Energy loss determination through scattering
- Tritium gas density





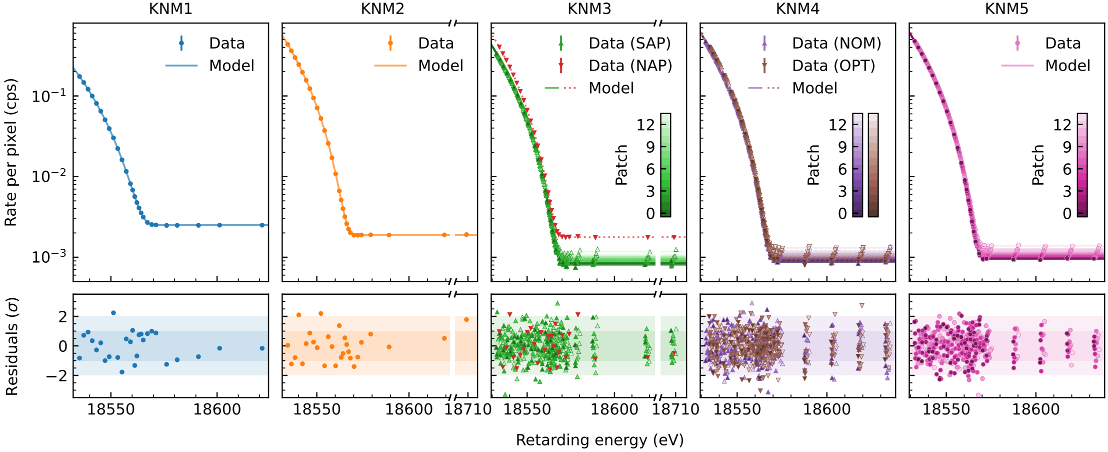
Systematic uncertainties

- Sensitivity dominated by statistical uncertainties
- Significant reduction of background-related systematics
- Better control over source scattering
- Reduction of molecular final-states uncertainties by theoretical reassessment



Fit result

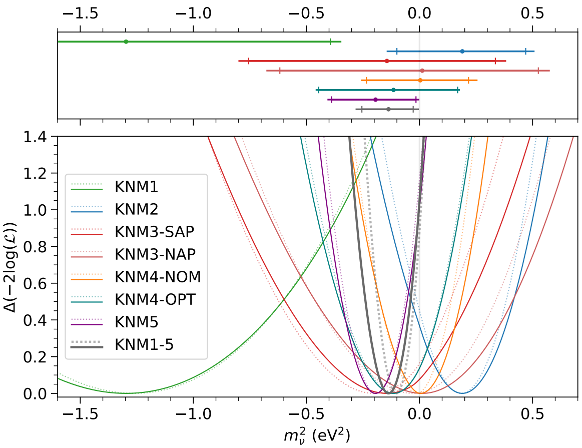
⇒ Two independent analysis teams with their own analysis framework & using double-layer blinding scheme



Neutrino Mass Results

- Simultaneous maximum likelihood fit with common m_ν^2 parameter.
- Excellent goodness-of-fit: p-value=0.84
- Best-fit value: $m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$

  → Negative m_ν^2 estimates allowed by the spectrum model to accommodate statistical fluctuations.



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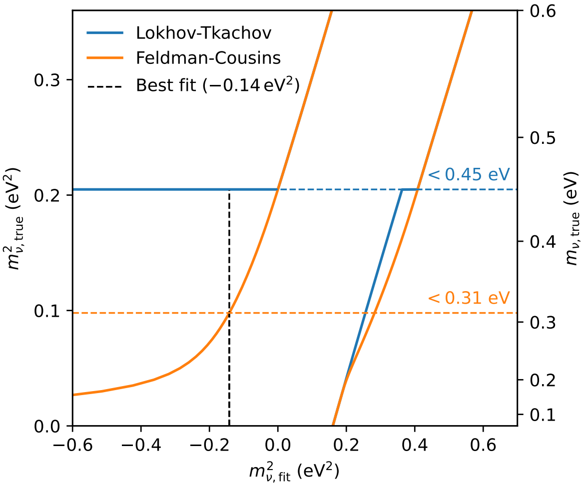
- Best-fit value: $m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$

  $\rightarrow$ Negative m_ν^2 estimates allowed by the spectrum model to accommodate statistical fluctuations.
- KATRIN's new upper limit:

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



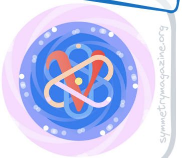
Beyond the Neutrino Mass - New physics searches

Upcoming publication!

"Kink" search

for eV-scale sterile ν close to the endpoint

→ PRL 126 (2021) 091803 & PRD 105 (2022) 072004



"Kink" search

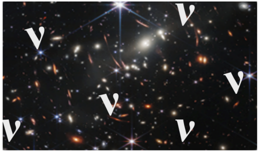
for keV-scale sterile ν far from the endpoint

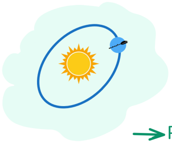
→ EPJ C 83 (2023) 763

Line search

for capture of local cosmic relic ν

→ PRL 129 (2022) 011806





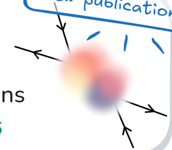
Search for Lorentz violation through sidereal modulation

→ PRD 107 (2023) 082005

New publication!

Search for shape distortions through exotic weak interactions

→ eg JHEP 01 (2019) 206



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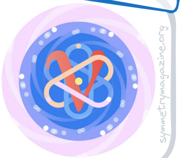

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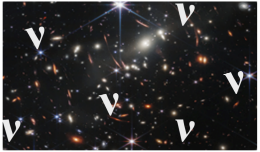

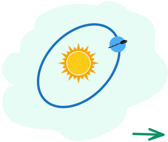

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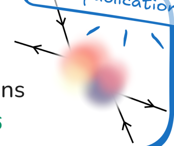


Theory of General Neutrino Interactions (GNI)

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

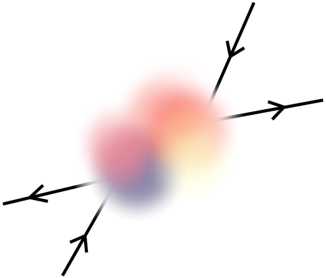
$$\mathcal{L}_{GNI}^{NC} = -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \overset{(\sim)}{\epsilon}_{j,f} \, (\bar{\nu}\, \mathcal{O}_j\, \nu)\, (\bar{f}\, \mathcal{O}'_j\, f)$$

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

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

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

→ Enables broad search for New Physics through precision measurements.

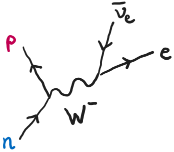


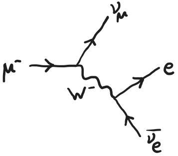
Bischer and Rodejohann, Nucl. Phys. B, 10.1016/j.nuclphysb.2019.114746

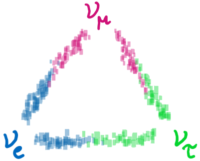
Search for General Neutrino Interactions

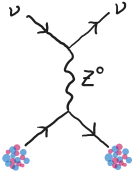
- **Possible interaction channels**:
  - Neutrino oscillation
  - LFV in μ- and τ-decays
  - Neutrino scatterings, e.g. CEνNS
  - π-decay
  - β-decay

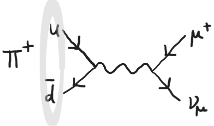
- Different interaction channels are sensitive to different combinations of ϵ_i in GNI Lagrangian.





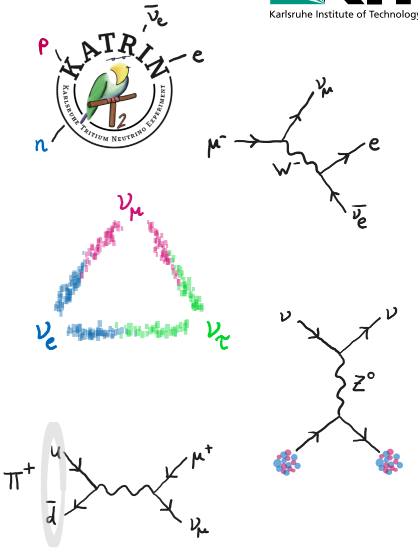






Search for General Neutrino Interactions

- **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.
- GNI cause modifications to the β-spectrum.
  $\rightarrow$ **Energy-dependent contributions to the rate** in KATRIN
  $\rightarrow$ First investigations on data!



GNI Signature in β-Decay

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

- 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 $\xi_N = b'_k = 0$.

GNI Signature in β-Decay

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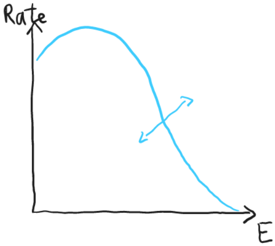
Only light active neutrinos

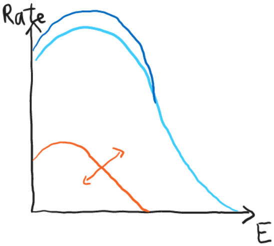
ξ_β & b'_β



With additional heavier neutrinos

ξ_β & ξ_N

ξ_β, ξ_N & b'_N



GNI Signature in β-Decay

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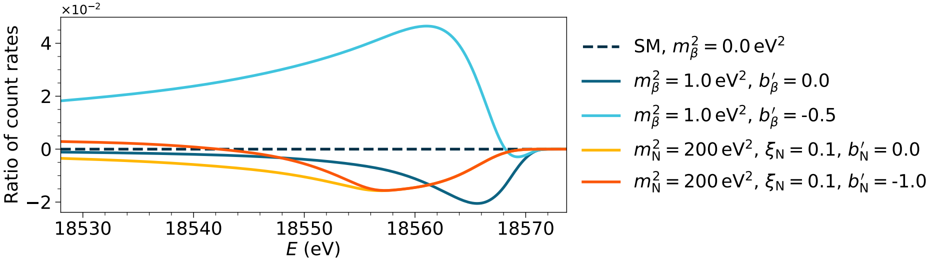
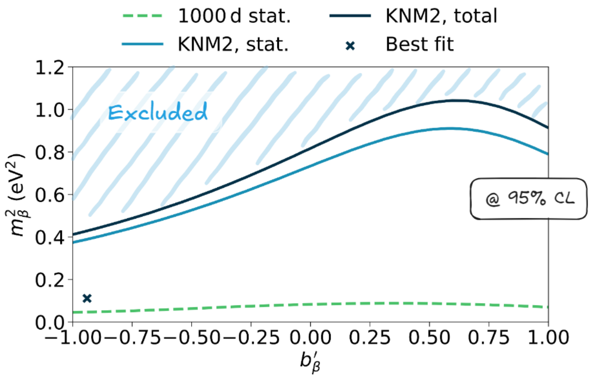


Sensitivity of GNI for light active neutrinos

- Able to search for GNI with KATRIN.
- No significant signal found in the KNM2 data set.
- Region with high m_β^2 excluded.
- Only slight effect of GNI on neutrino mass observable due to correlations between m_β^2 and b'_β, and the smallness of the neutrino mass.
- Combination of external constraints suggests $|b'| < 0.26$ (95 % CL).



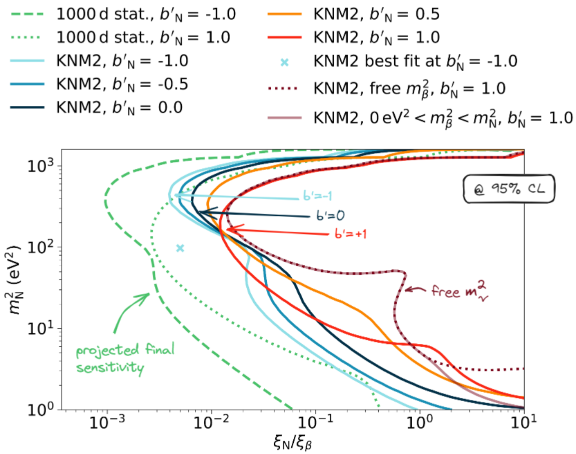
Limited sensitivity to general neutrino interactions acting on light neutrino mass states!

Sensitivity of GNI for additional heavier neutrinos

- Able to search for GNI with KATRIN.
- No significant signal found in the KNM2 data set.
- Region with high m_N^2 and ξ_N excluded.
- Signal structure of b'_N reflected in contour shapes.
- Explored change in contour shape when allowing $m_\nu^2 \neq 0$.
- Sensitivity is dominated by statistics.

$\Rightarrow$ Further significant improvements expected for final data set.

Additional heavier neutrino mass state gives sensitivity to general neutrino interactions!

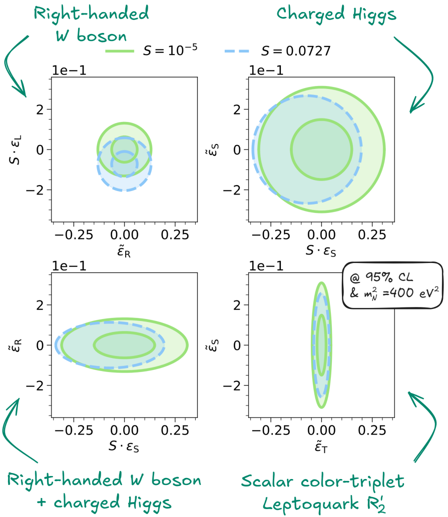


Sensitivity to $\tilde{\epsilon}$ couplings

- Able to probe more specific scenarios, such as single types of interactions, right-handed W bosons, Leptoquarks and charged Higgs.
- Obtained competitive bounds on individual $\tilde{\epsilon}$ from β-decay:
  $|\tilde{\epsilon}_L| < 0.063 - 0.131$ & $|\tilde{\epsilon}_T| < 0.022 - 0.046$ at 95 % CL
- Constraints from high-energy investigations about one order of magnitude more sensitive.

⟹ Further improvement in sensitivity of factor 3 expected for final data set.

Leading constraints from β-decay expected for extended data set!



Summary & Outlook

New KATRIN release improves direct neutrino-mass bound by a factor of 2: (arXiv:2406.13516)

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

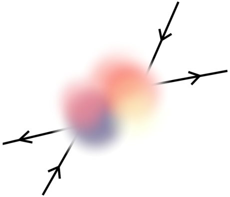
New BSM search at KATRIN sets competitive constraints on GNI couplings from β-decay and allows to probe more specific physics scenarios. (arXiv:2410.13895)

Ongoing data taking and analysis until 2025 will significantly increase sensitivities:

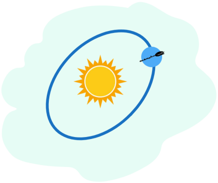
- Neutrino mass target sensitivity below 0.3 eV
- Leading constraints on GNI from β-decay

Light sterile ν

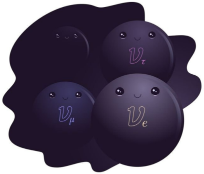
GNI



LIV



keV sterile ν

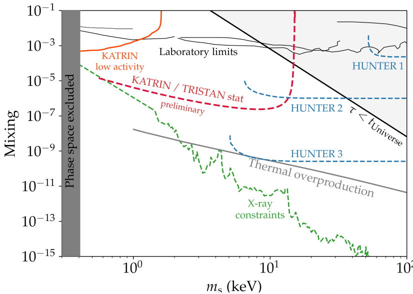


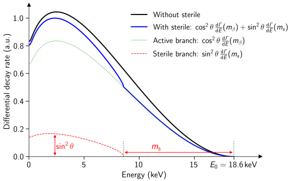
Relic Neutrinos, ...

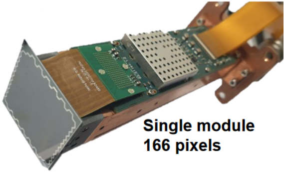
Future Perspectives: TRISTAN@KATRIN

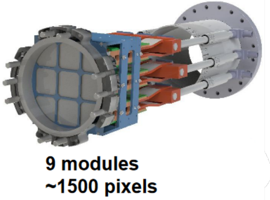
2026-2027: keV sterile neutrino search with TRISTAN@KATRIN

- Search for keV sterile neutrinos with novel SDD array for high rates
- Ongoing preparations for hardware upgrades.
- Analysis getting ready for data.
- Target sensitivity to mixing of 10^{-6}.
- Other BSM studies such as GNI can also profit from new measurement setup.





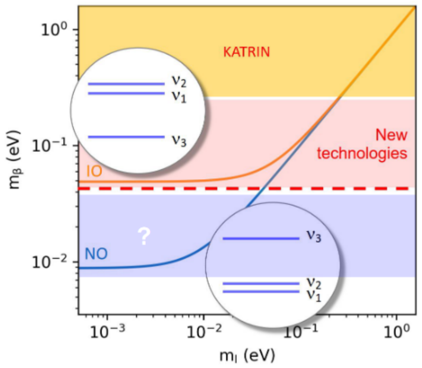




Future Perspectives: KATRIN++

2027+: R&D towards ultimate neutrino mass determination

- Differential methods, atomic tritium, background reduction
- Use KATRIN infrastructure to develop scalable technology for next generation neutrino mass experiments



Thank you for your attention!

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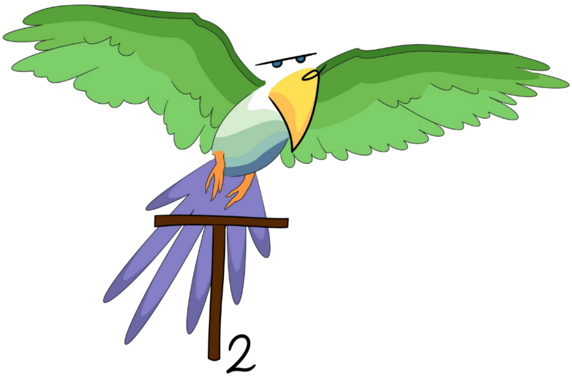
Backup



General Neutrino Interactions

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	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(1+\gamma^5)$	$\sigma^{\mu\nu}(1+\gamma^5)$

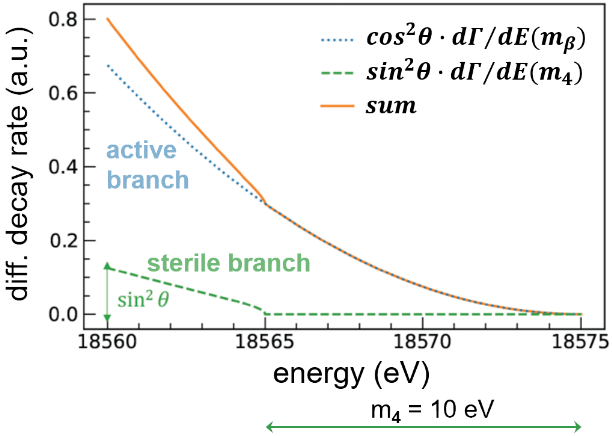
$$\mathcal{L}^{CC}_{GNI} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,ud}\right)^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha \mathcal{O}_j \nu_\beta\right) \left(\bar{u}_\gamma \mathcal{O}'_j d_\delta\right) + h.c.$$

- $\epsilon_{L/R}$: 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

eV-scale sterile neutrinos

Light Sterile Neutrinos

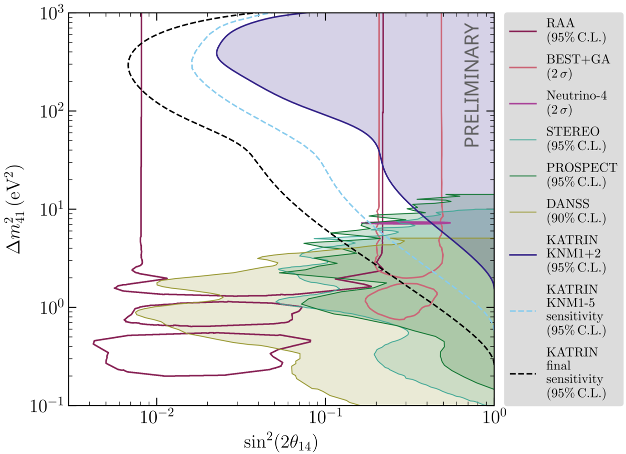
- **Motivation:** Multiple anomalies in the oscillation data, could be explained by $\geq 1\,\text{eV}$ sterile neutrino
- **Analysis:** Add sterile β-spectrum with sterile mass m_4 and active-to-sterile mixing $\sin^2\theta$ to active neutrino β-spectrum



Light Sterile Neutrinos

- **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.

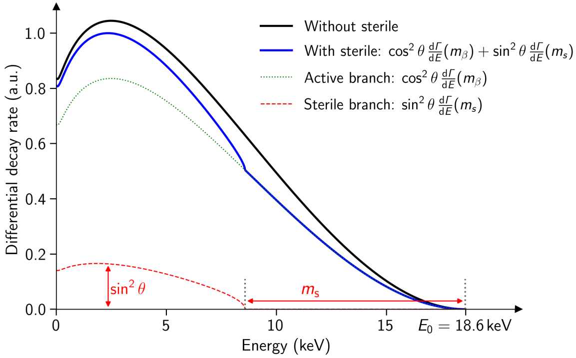
$$\sin^2 2\theta = 4\,|U_{e4}|^2\,(1 - |U_{e4}|^2)$$



keV-scale sterile neutrinos

keV-Sterile Neutrinos

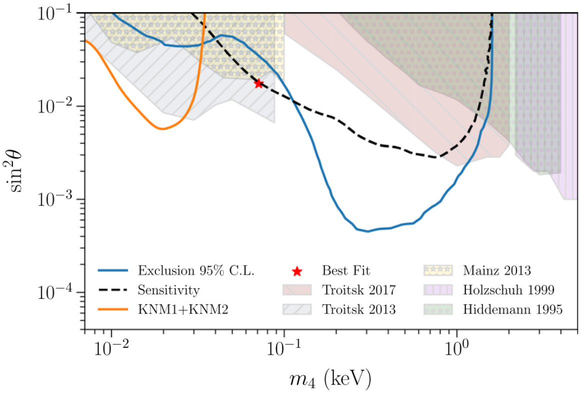
- **Motivation:** Candidate for (warm) dark matter. Indirect and cosmological surveys set strong, but model-dependent constraints on the sterile mixing of $\sin^2\theta < 10^{-6} - 10^{-10}$ at sterile masses of (1-50) keV. Laboratory bounds much weaker.
- **Signature:** Kink-like structure due to overlay of active and sterile β-spectrum branches, encodes information on additional mass state m_4 and active-to-sterile mixing $\sin^2\theta$.
- **Analysis:** Data obtained in a commissioning phase in 2018 with only 0.5 % nominal activity allowing extension of sterile mass search from 40 eV up to 1.6 keV.



keV-Sterile Neutrinos

Karlsruhe Institute of Technology

- **Results of commissioning phase:**
  10.1140/EPJC/S10052-023-11818-Y
  - No significant sterile neutrino signal observed in data set
  - Already coverage of new parameter space down to $\sin^2\theta < 5 \times 10^{-4}$ at $m_4 = 300\,\text{eV}$ (95 % CL) with first data set.
- **Future outlook:**
  - Dedicated detector upgrade to scan up to 18 keV into the β-spectrum with 1 % of nominal activity (10^9 Bq).
  - Sensitivity goal in mixing of 10^{-6}
  - Installation and measurement phase scheduled for 2026-2027



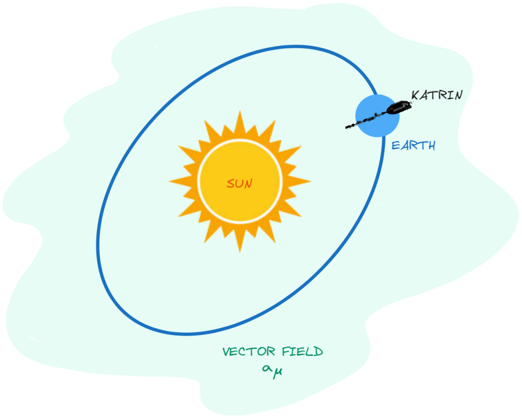
Lorentz Invariance Violations

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)

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

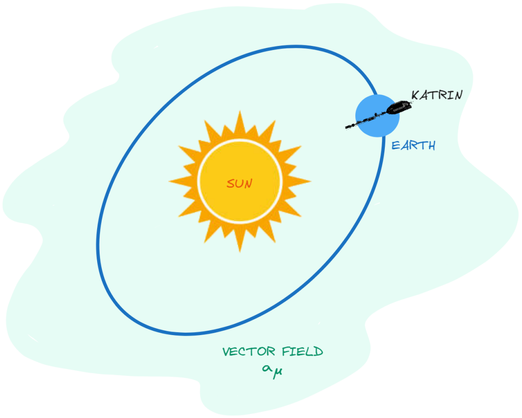
- Produces terms $\propto a^{\mu} \, p_{\mu} = a_0 \, p_0 - a_i \, p_i$
  $\longrightarrow$ time-dependent & time-independent shift of E_0



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 $|(a_{of}^{(3)})_{10}|$



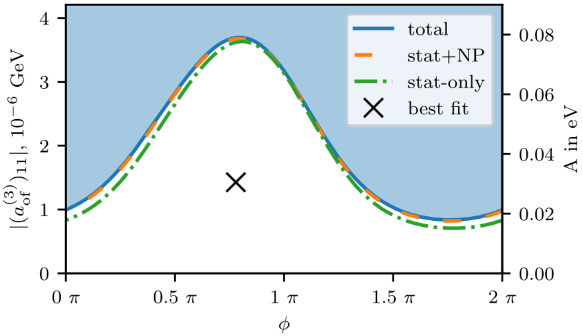
Results from first campaign

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)

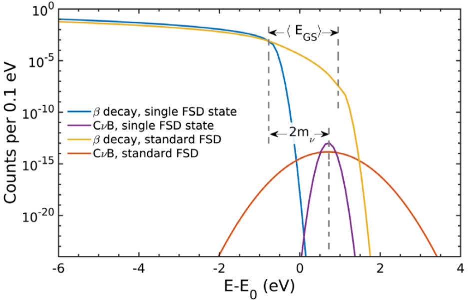
$$A = \sqrt{\frac{3}{2\pi}} \left|(a_{of}^{(3)})_{11}\right| \sqrt{B^2 \cos^2\chi \cos^2\xi + (\beta_{rot} - B\sin\xi)^2}$$



Local cosmic relic neutrinos

Local cosmic relic neutrino overdensity

- **Motivation:**
  - Production of cosmic neutrinos before freeze-out in the early universe.
  - Well established but not experimentally confirmed yet.
  - Possible clustering around galaxies with overdensity ratio η.
  - Would yield direct information about the early history of the Universe.



- **Signature:** Peak above Endpoint from neutrino capture on tritium:

$$\nu_e + N_Z^A \longrightarrow N_{Z+1}^A + e^-$$

- **Analysis:** Data of first two measurement campaign from 2019, taking $m_\nu > 0$.

Local cosmic relic neutrino overdensity

Results of KNM1+2:

10.1103/PhysRevLett.129.011806

- No significant relic neutrino signal found in data set.
- Leading constraint with $\eta < 1.3 \times 10^{11}/\alpha$ (99 % CL)
- Compared to cosmological model expectation for density ratio of 1.2 - 20 (standard model)/10^{13} (exotic models) still mayor experimental improvements necessary.