Karlsruher Institut für Technologie

KATRIN beyond the neutrino mass measurement

KCETA Colloquium – April 27, 2023

Alexey Lokhov

Outline

- KATRIN neutrino mass measurement in a nutshell
- Beyond neutrino mass searches with KATRIN
  - Sterile neutrinos
  - Relic neutrinos
  - General neutrino interactions and light boson production
  - Lorentz invariance violation
- Summary and outlook

Three ways to assess the absolute neutrino mass scale

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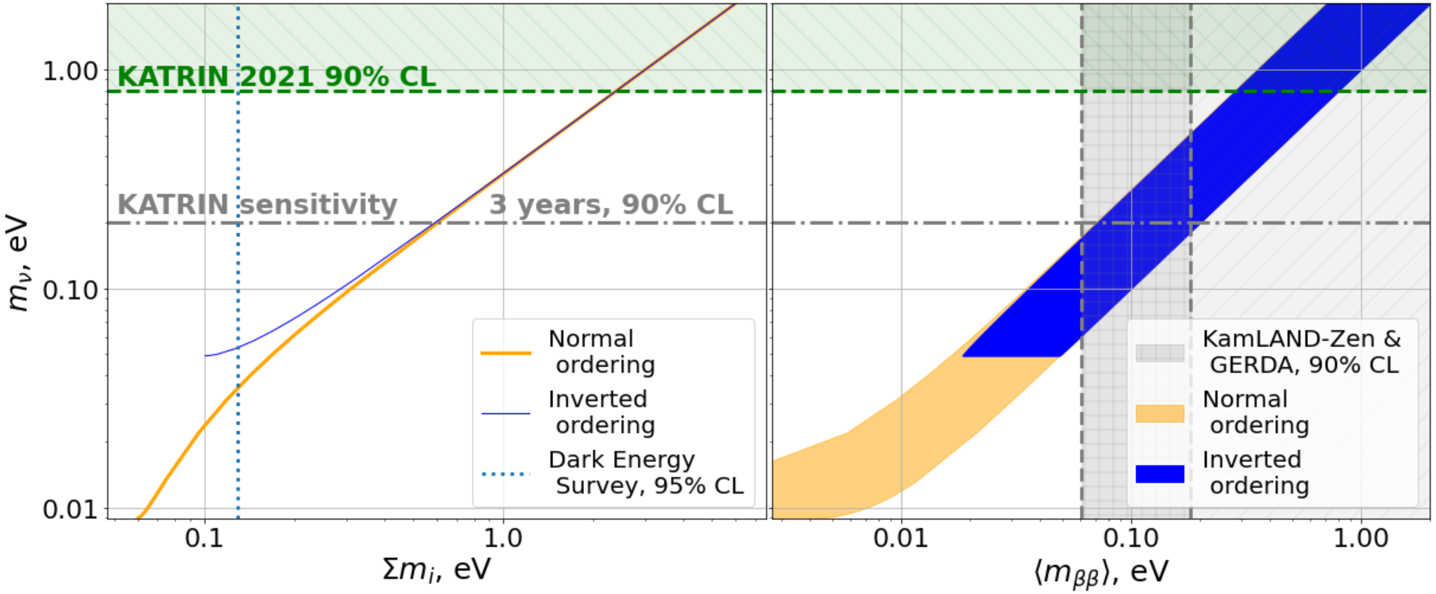
1) Cosmology

- very sensitive: era of precision cosmology
- compares power at different scales
- current sensitivity: **$\Sigma m(\nu_i) \approx$ 0.12 eV (Planck, DES)**



2) Search for 0νββ

- Sensitive to Majorana neutrinos, model-dependent, LNV
- Upper limits by CUORE, EXO-200, GERDA, KamLAND-Zen:

$m_{\beta\beta}$ < 0.1-0.4 eV

3) Direct neutrino mass determination

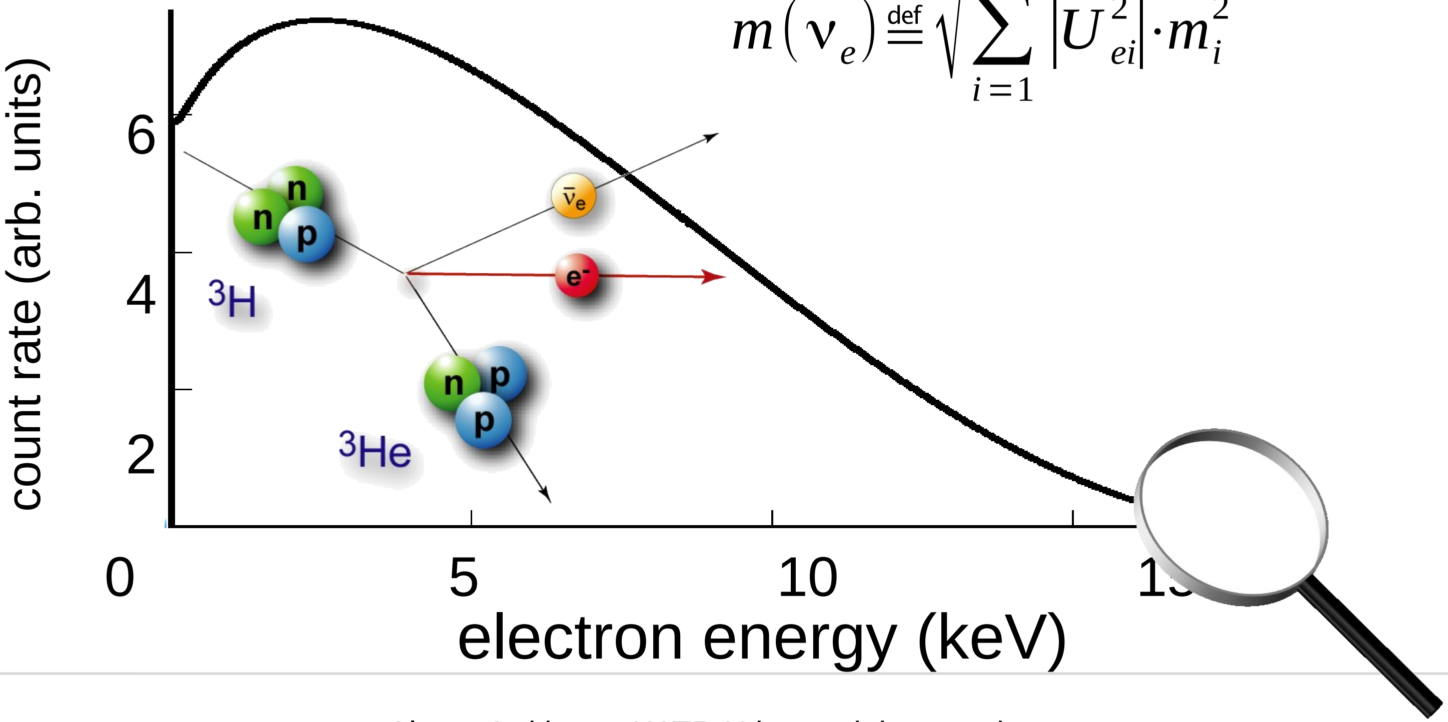
- No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4$ $\Rightarrow m^2(\nu)$
- Time-of-flight measurements (ν from supernova)
- Kinematics of weak decays / beta decays, e.g. T, ^{163}Ho

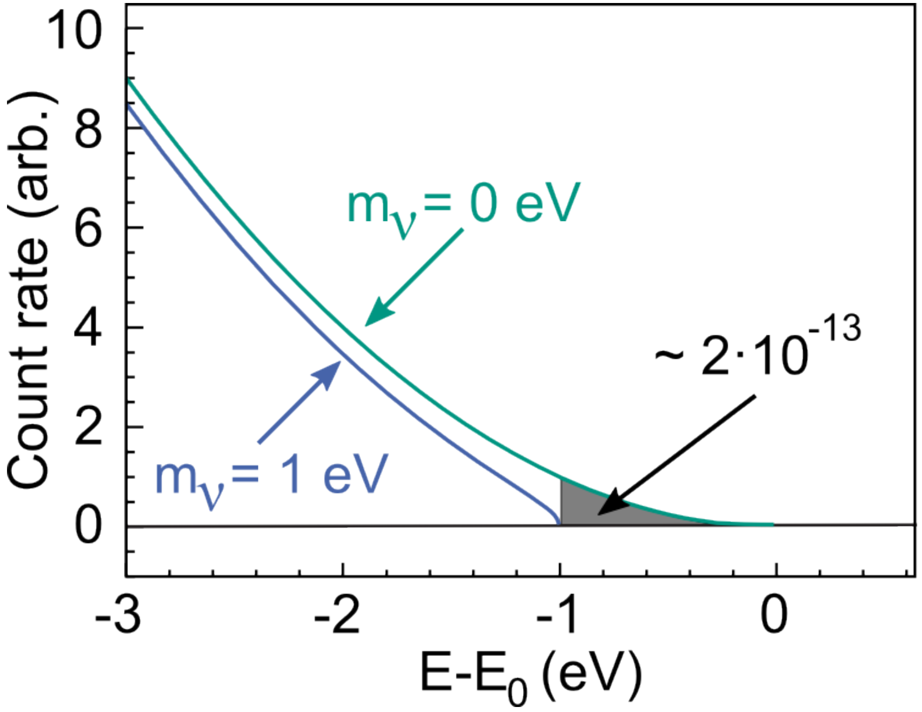
Tritium β-decay

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

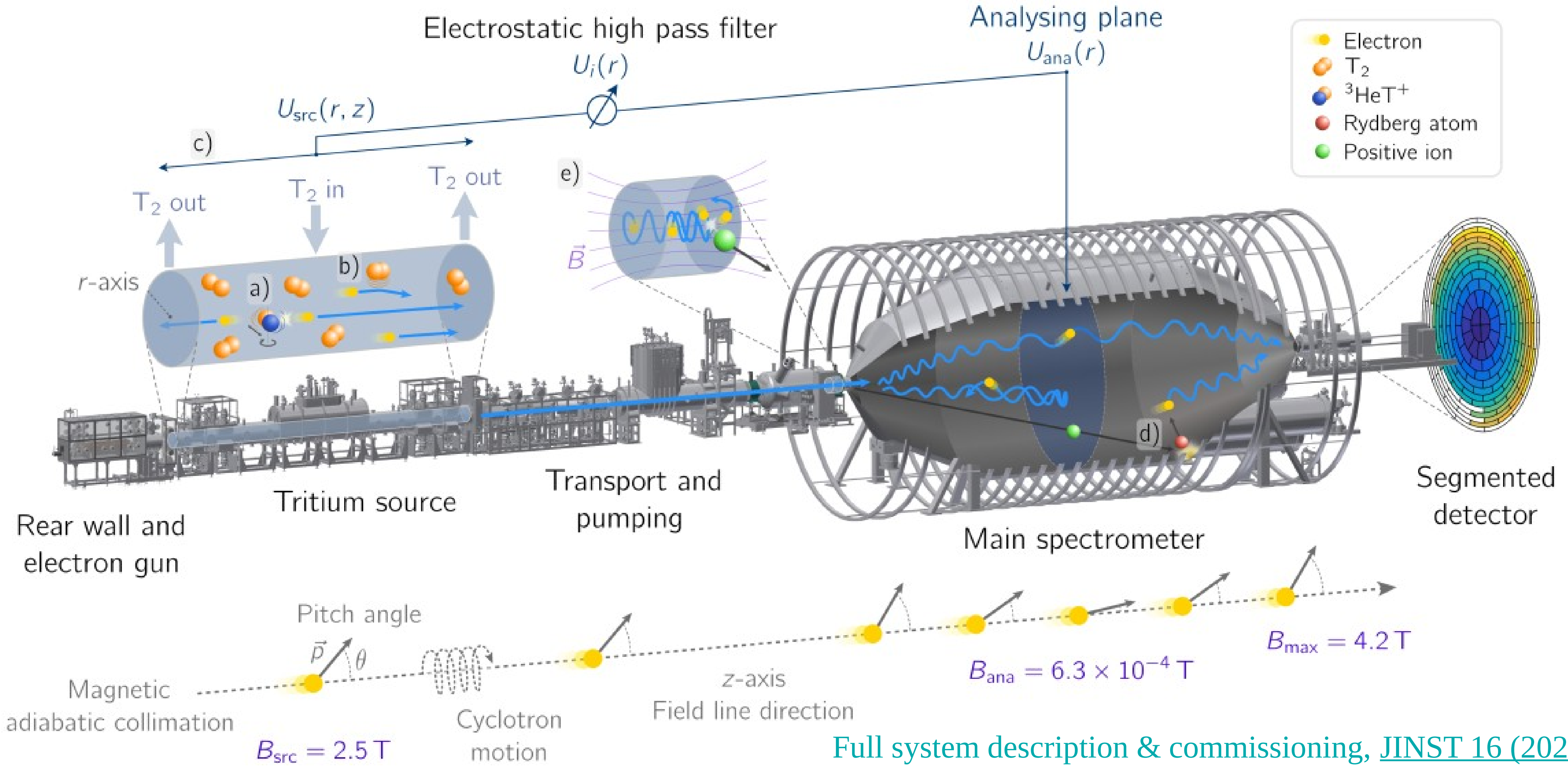
$$\frac{d\Gamma}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot \sqrt{(E_0 - E)^2 - m_{\nu_i}^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_{\nu_i})$$

$$m(\nu_e) \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$





KATRIN experiment



Full system description & commissioning, JINST 16 (2021) T08015

Beta-spectrum and neutrino mass

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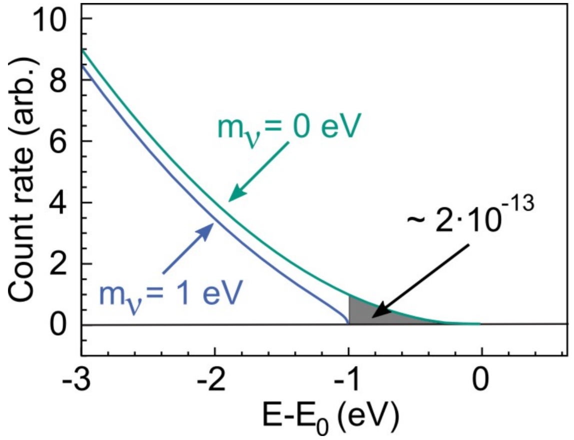
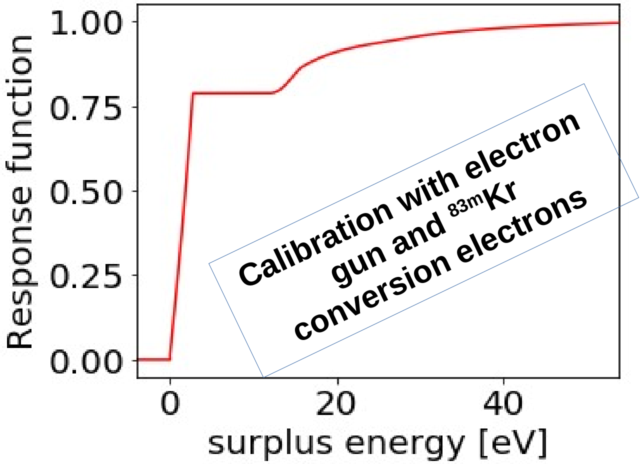
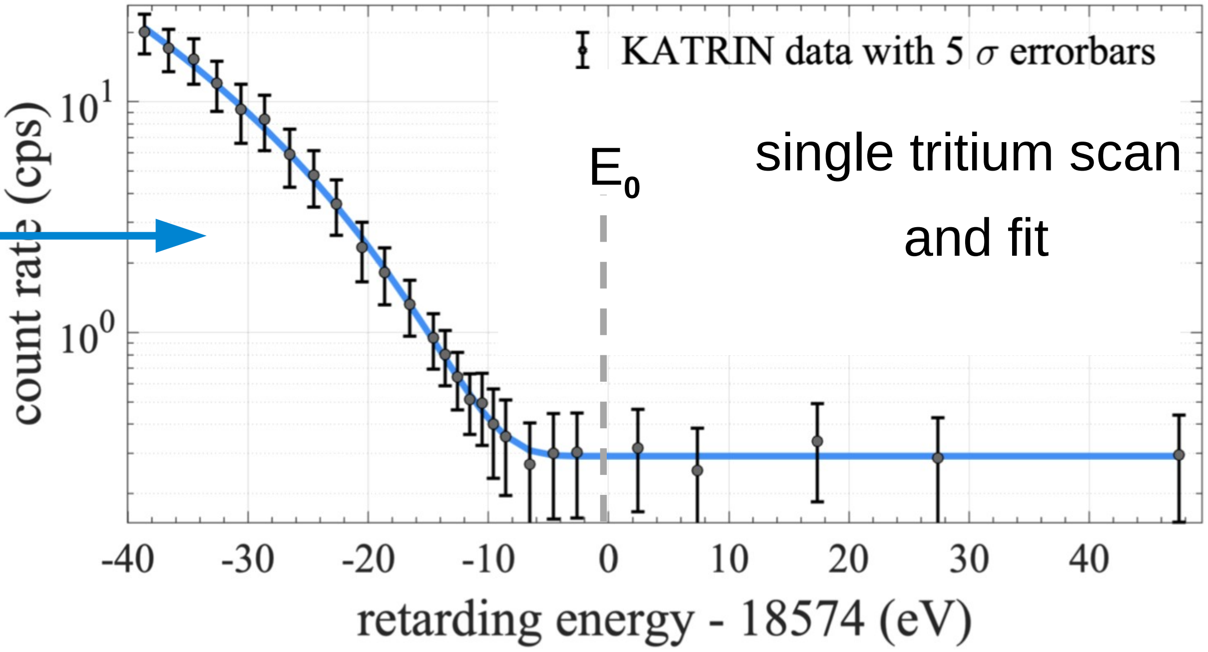
- **Beta spectrum: $R_\beta(E, m^2(\nu_e))$**



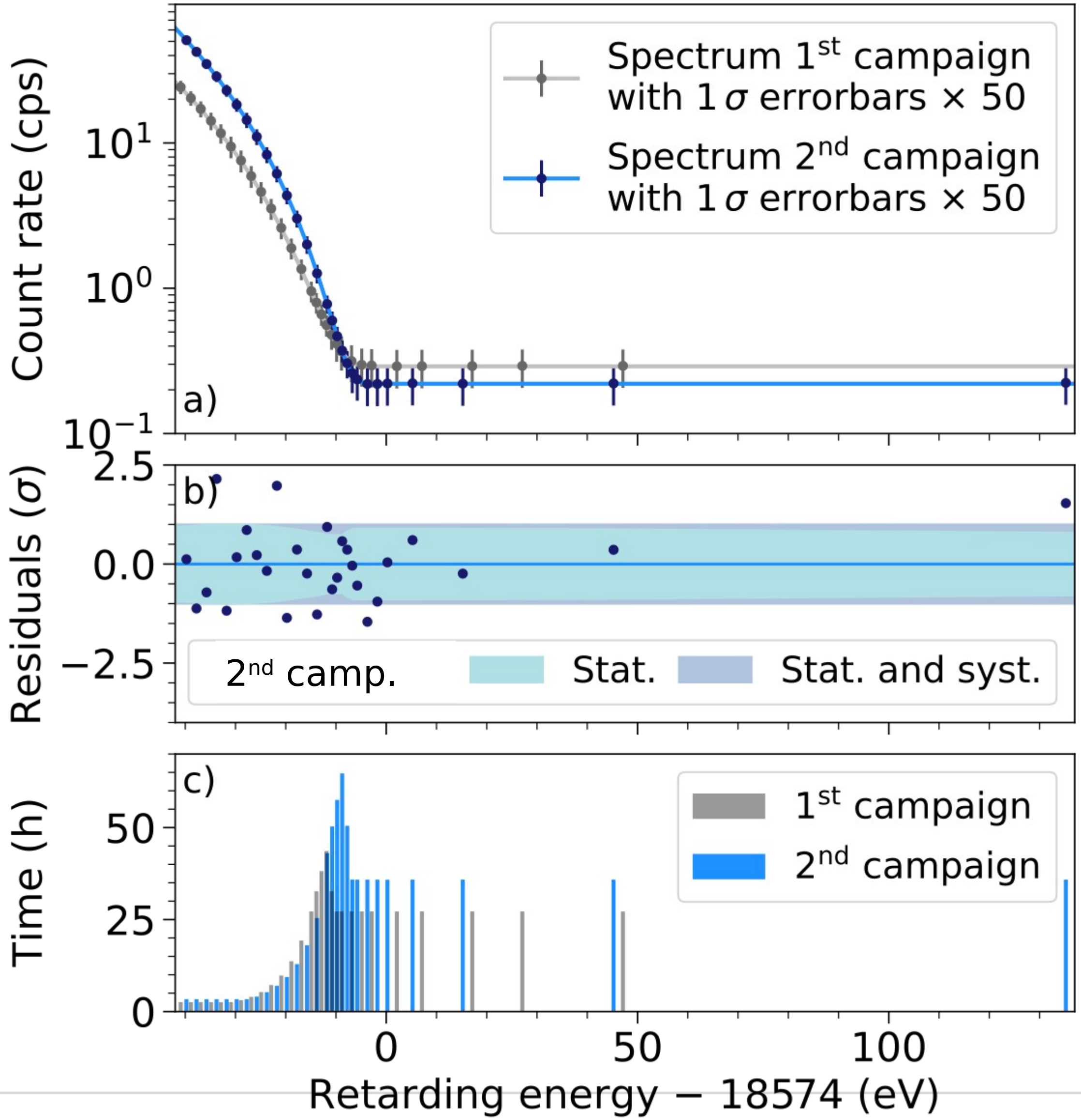
- **Experimental response: f(E-qU)**





$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_ß(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

Recent ν-mass results



First campaign (spring 2019):

✓ total statistics: 2 million events

✓ best fit: $m_\nu^2 = (-1.0^{+0.9}_{-1.1})$ eV² (stat. dom.)

✓ limit: $m_\nu < 1.1$ eV (90% CL)

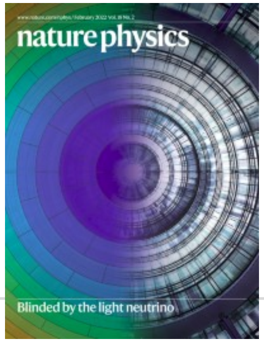
Second campaign (autumn 2019):

✓ total statistics: 4.3 million events

✓ best fit: $m_\nu^2 = (0.26^{+0.34}_{-0.34})$ eV² (stat. dom.)

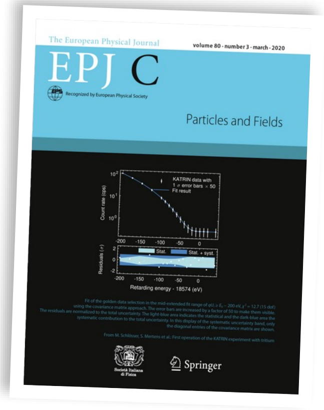
✓ limit: $m_\nu < 0.9$ eV (90% CL)

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



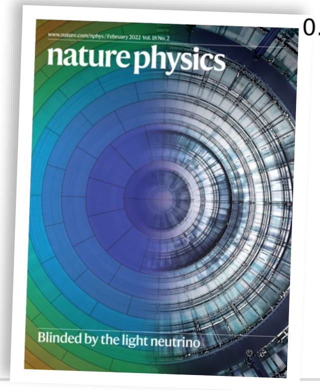
KATRIN Collab, Nature Phys. 18 (2022) 160

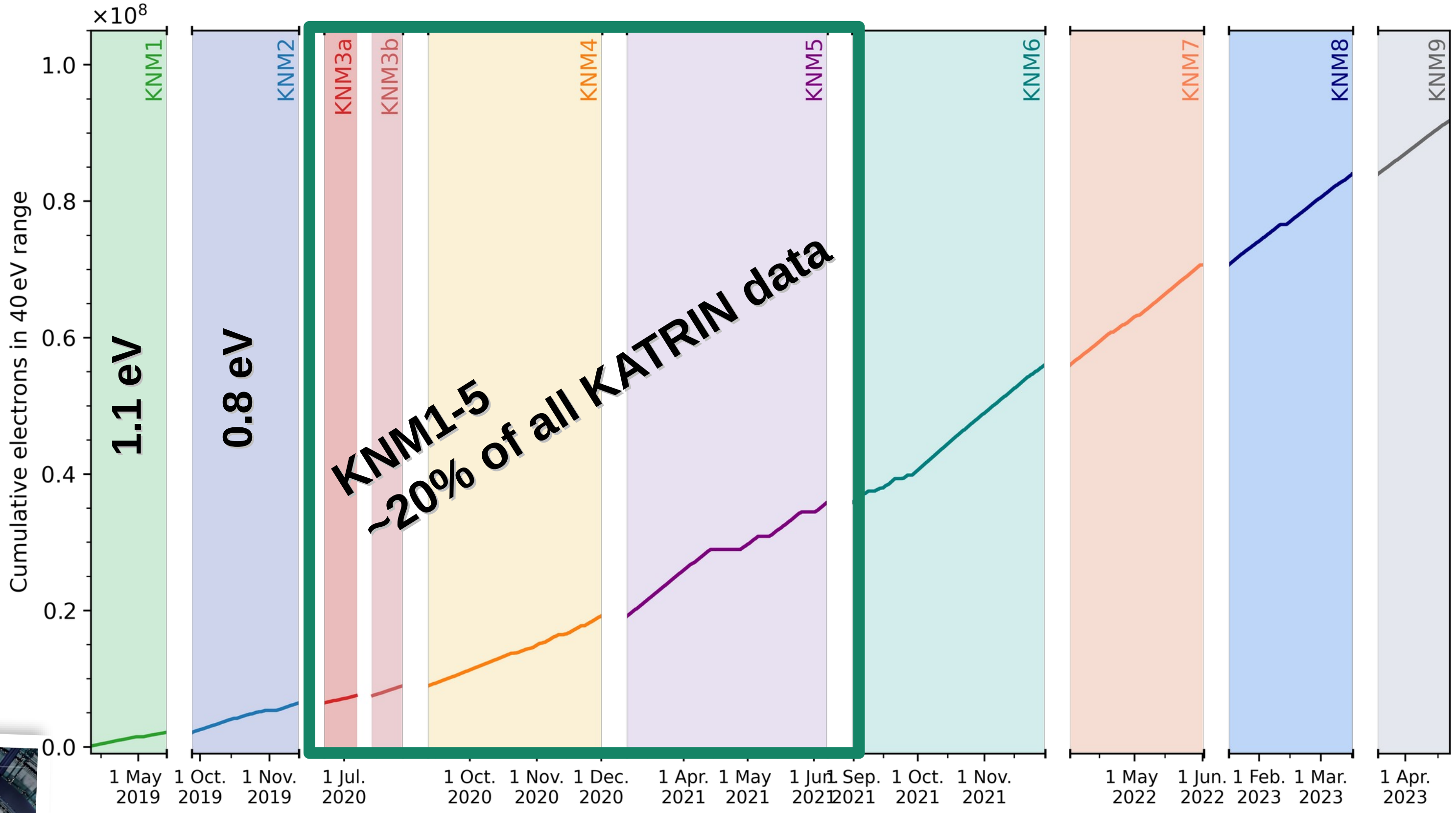
KATRIN Data taking



EPJ C 80, 264 (2020)

PRL 123 (2019) 221802
PRD 104 (2021) 012005





Analysis of 5 scientific runs → ongoing

Statistical sensitivity ~ 0.5 eV (90% CL)

Nature Phys. 18 (2022) 160

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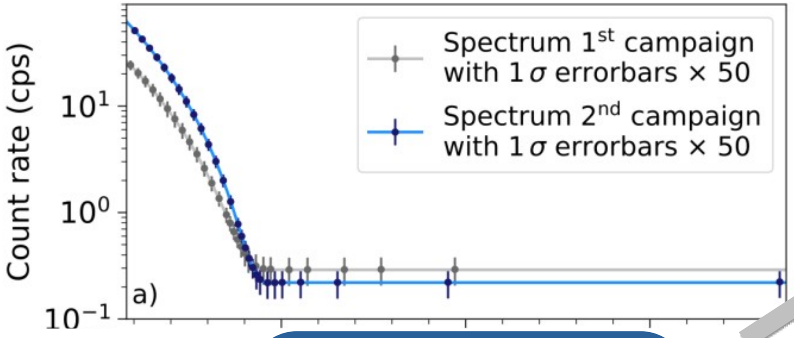
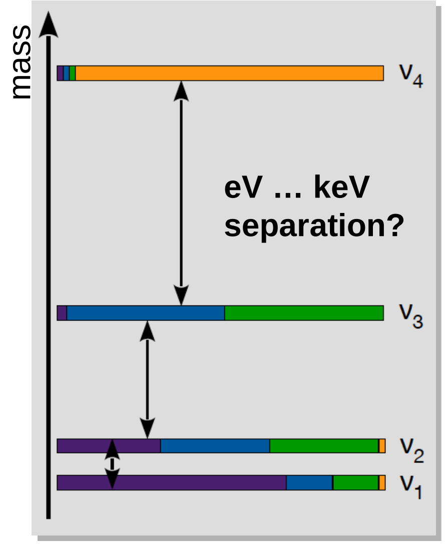
“Beyond neutrino mass” in KATRIN



β-spectrum of high statistics and precision

Is there a fourth (sterile) neutrino?

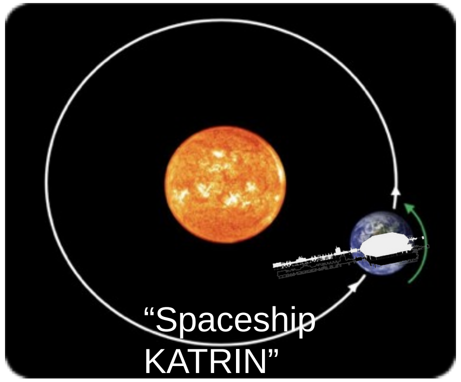


Neutrino mixing: “Kink” in regular β-spectrum tail (eV scale) or deep β-spectrum (keV scale)

Constrain local overdensity of cosmic relic neutrinos

Search for exotic interactions (spectrum shape)

Search for Lorentz invariance violation (sidereal modulation)



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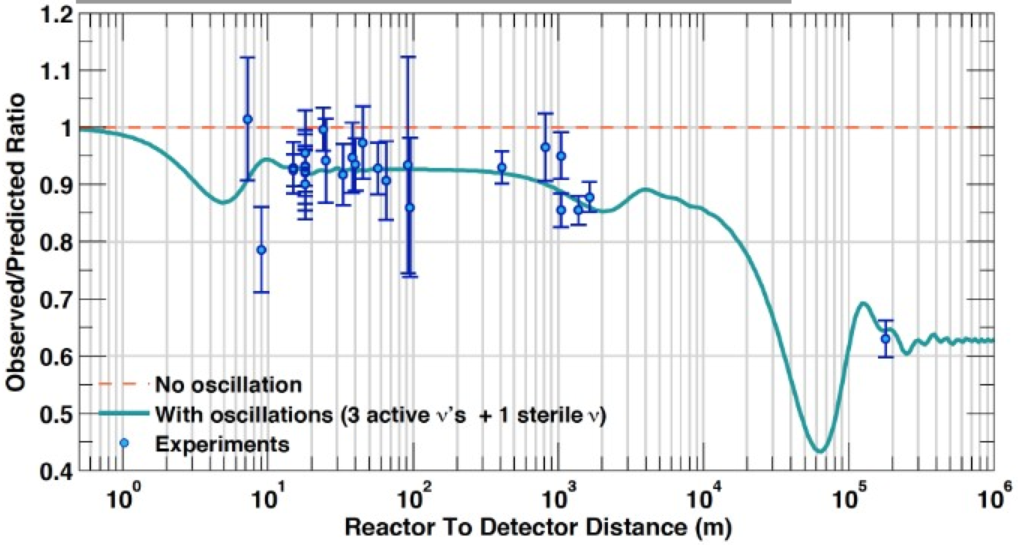
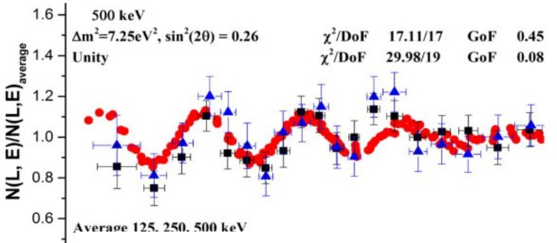
Light sterile neutrinos – Motivation

- Multiple (longstanding) anomalies in the oscillation data
- No universal explanation to all of them
- An oscillation-free measurement as an independent cross-check by KATRIN

Reactor antineutrino anomaly

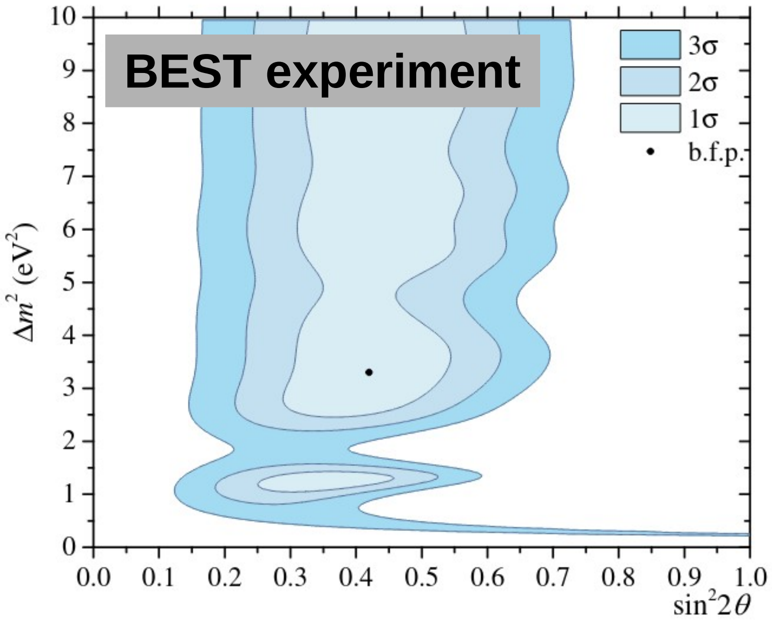


Neutrino-4 experiment



JETP Lett. 112 (2020) 4, 199-212

BEST experiment

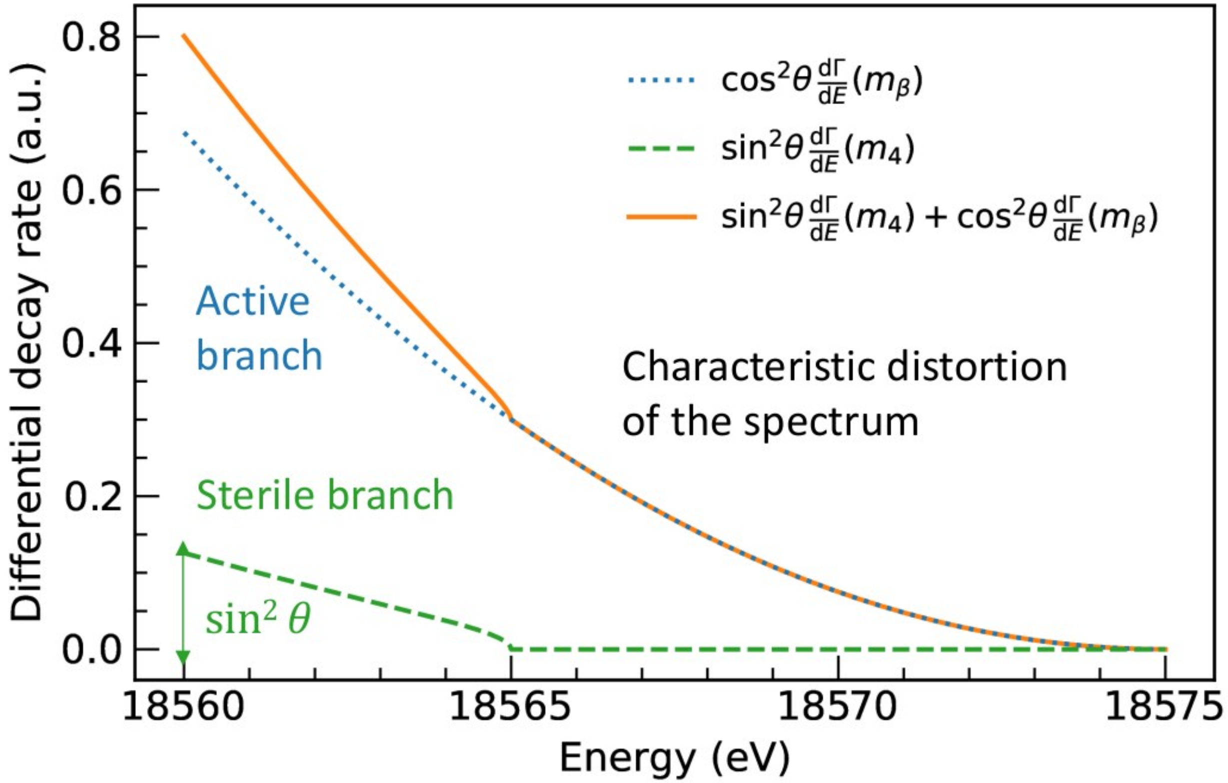


Phys.Rev.Lett. 128 (2022) 23, 232501

Sterile neutrinos signature in β-spectrum

- 3+1 sterile neutrino model
- Same data-set as for the neutrino mass
- Grid search in m_4, $|U_{e4}|^2$ plane

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



Sterile neutrinos signature in KATRIN

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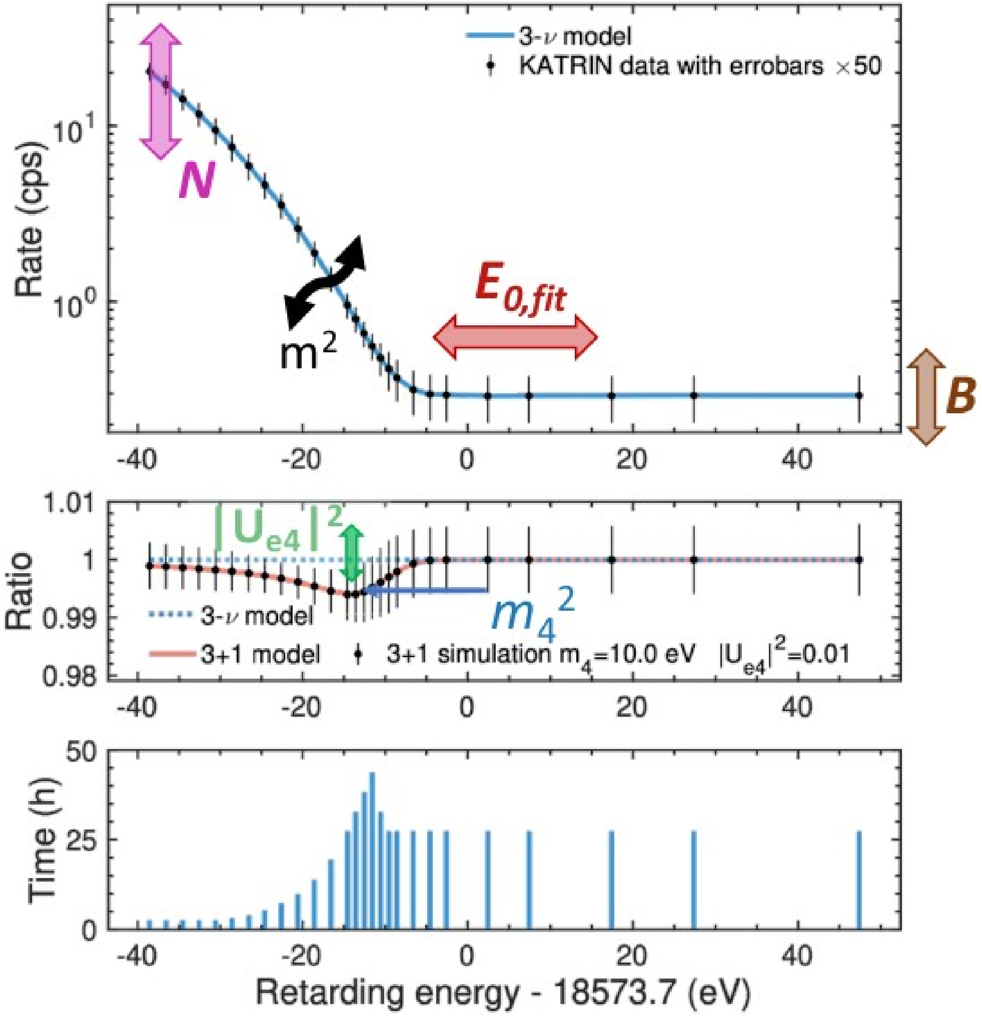
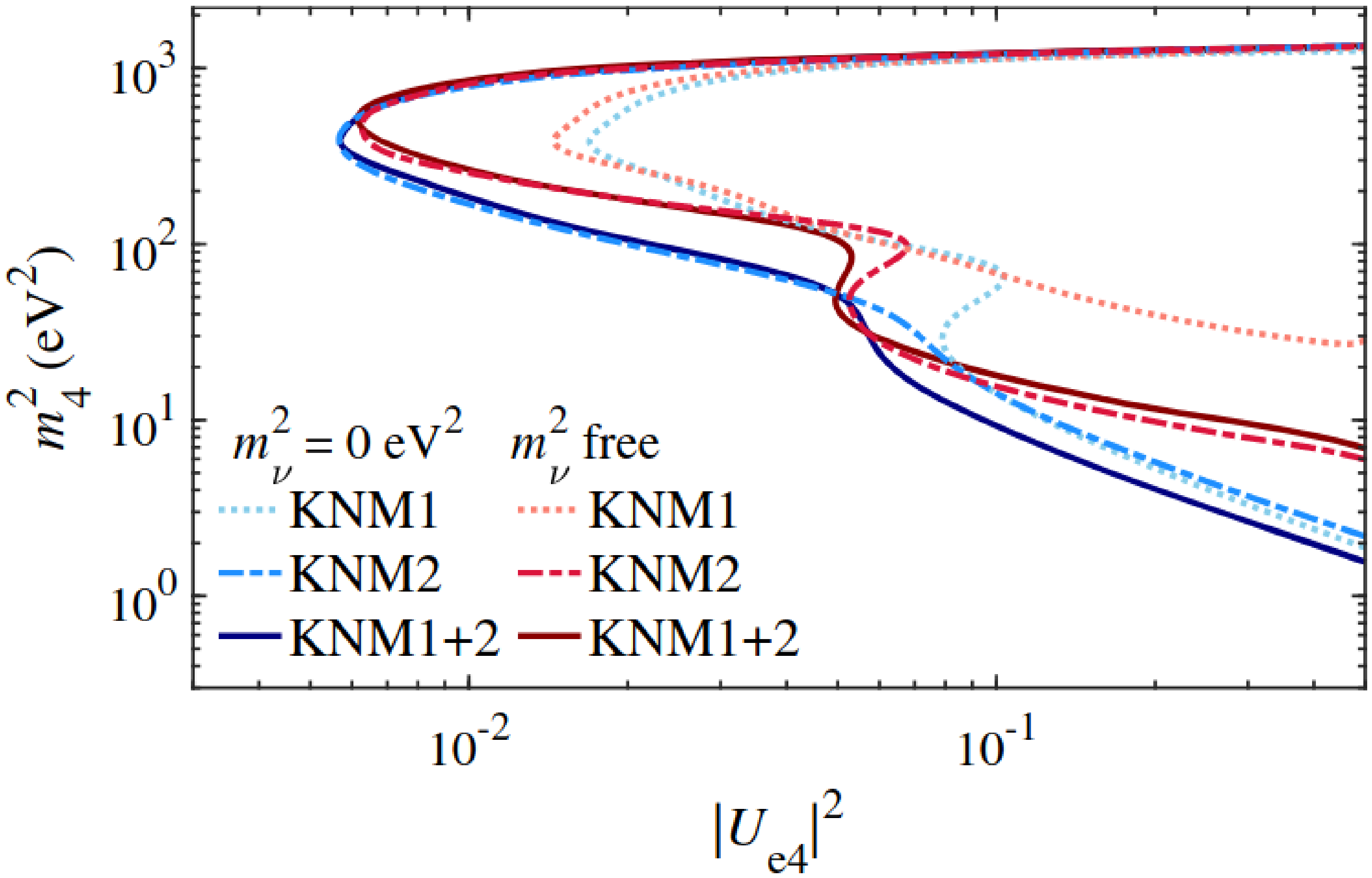


6 Fit parameters:

- N – amplitude of the signal
- E_0 – effective endpoint energy
- m^2 – effective mass of the electron antineutrino
- B – background rate
- $|U_{e4}|^2$ – 4th neutrino mixing
- m_4^2 – 4th neutrino mass

Combination of 1st and 2nd campaigns



Fixed $m_\nu^2 = 0$

$$m_4^2 = 59.9\,\mathrm{eV}^2, |U_{e4}^2| = 0.011$$

$$\Delta\chi^2_{null} = 0.66$$

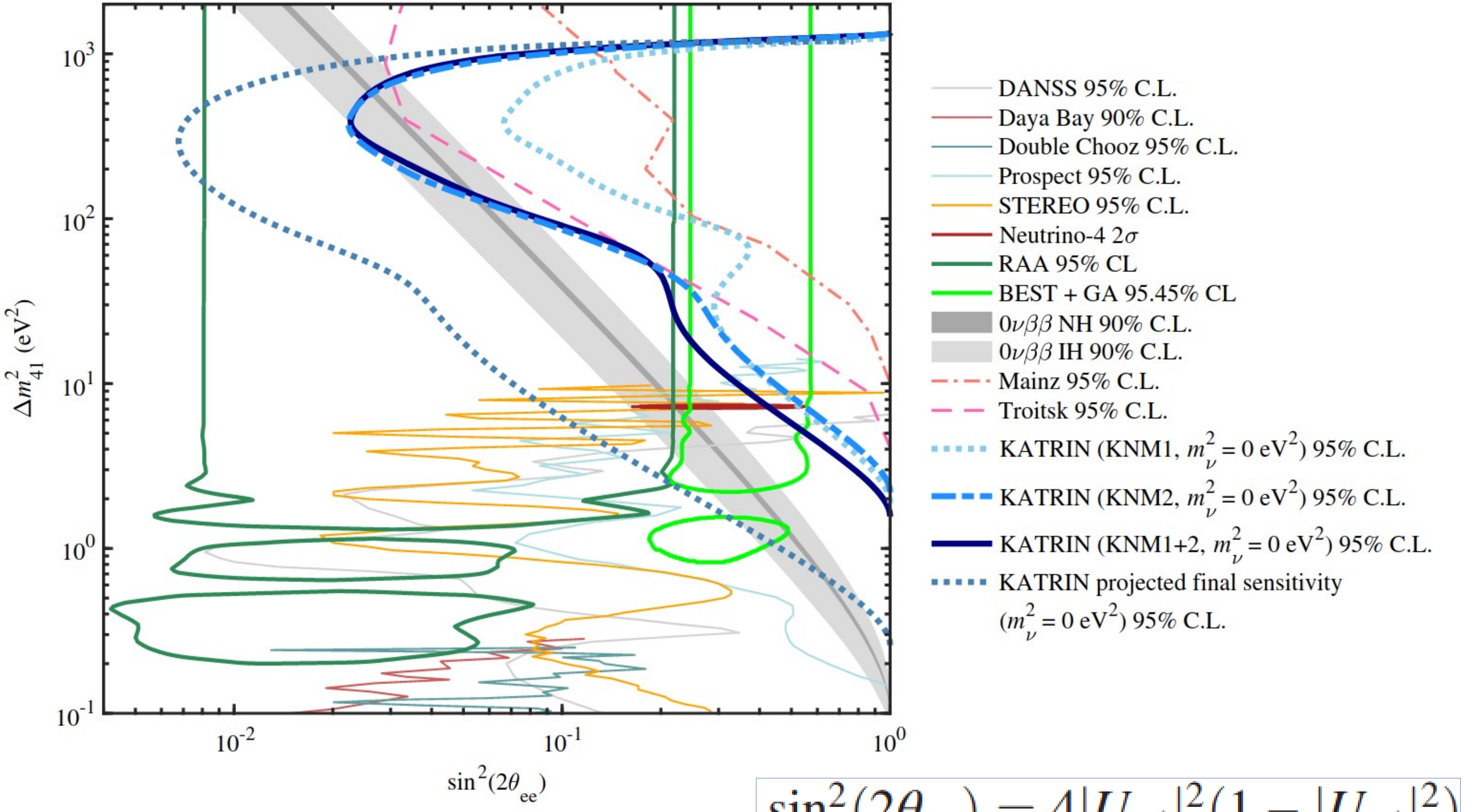
Free m_ν^2

$$m_4^2 = 87.4\,\mathrm{eV}^2, |U_{e4}^2| = 0.019$$

$$\Delta\chi^2_{null} = 1.69, m_\nu^2 = 0.57\,\mathrm{eV}^2$$

KATRIN Collab., PRD 105, 072004 (2022)

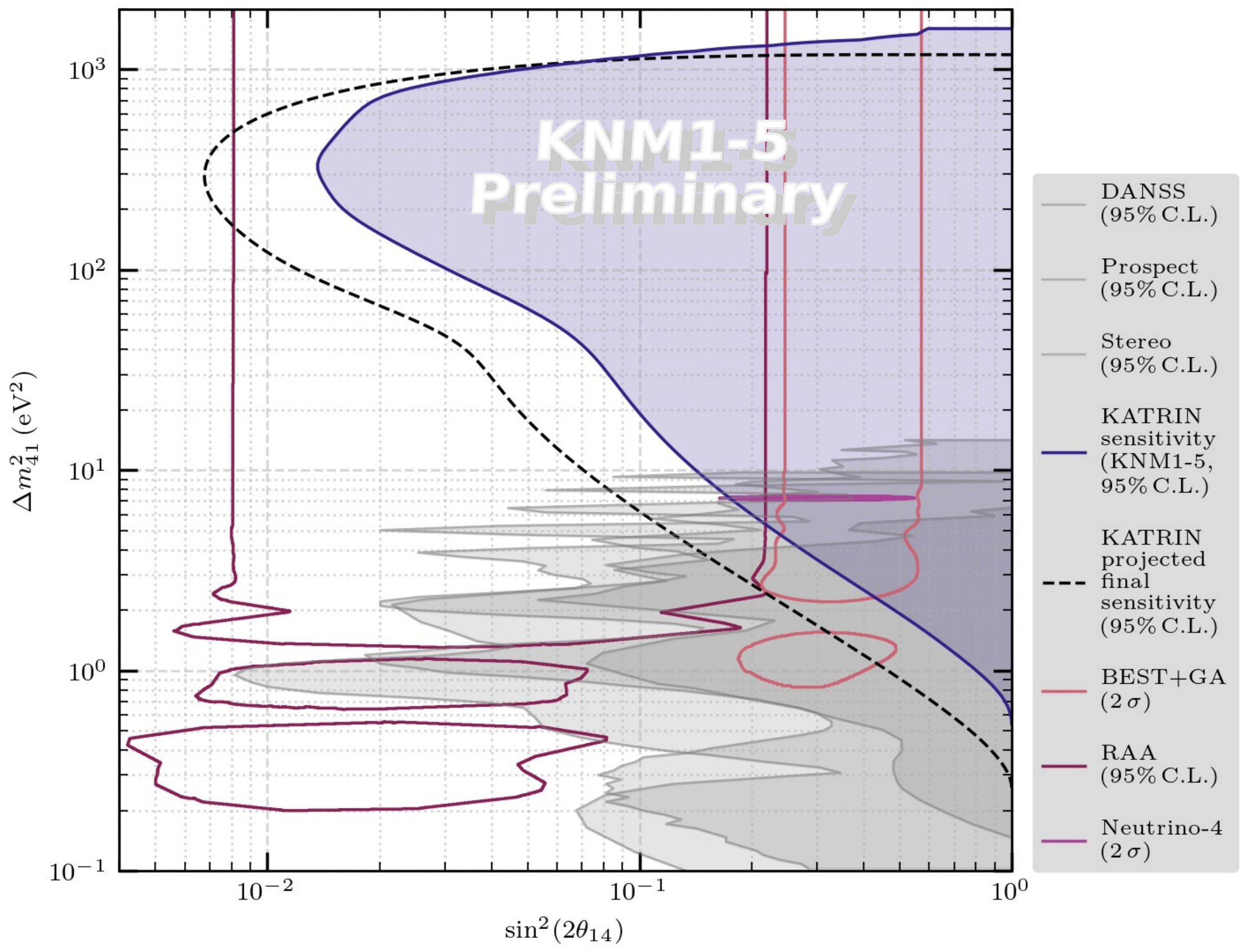
Sterile neutrinos – complimentarity



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

- looking at the short baseline anomalies from a different perspective
- Signal-to-background up to 250
- More stringent limits than Troitsk and Mainz
- approaching the BEST allowed regions with **$\Delta m^2 \gtrsim$ 10 eV^2**
- complementary probe to oscillation-based experiments

Sterile neutrinos – prospects



With first 5 datasets

- Probing large portion of the RAA, BEST and Neutrino-4

With full dataset

- Sensitive to interesting parameter range
- comparable sensitivities to neutrinoless double β-decay

keV sterile neutrinos

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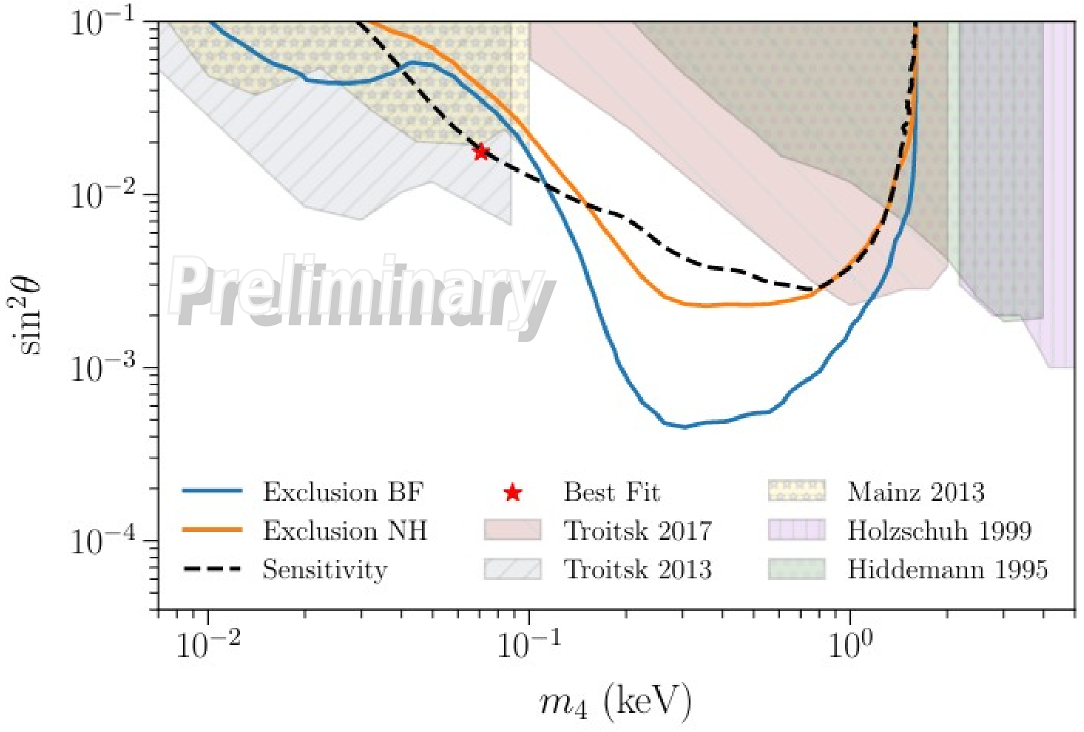
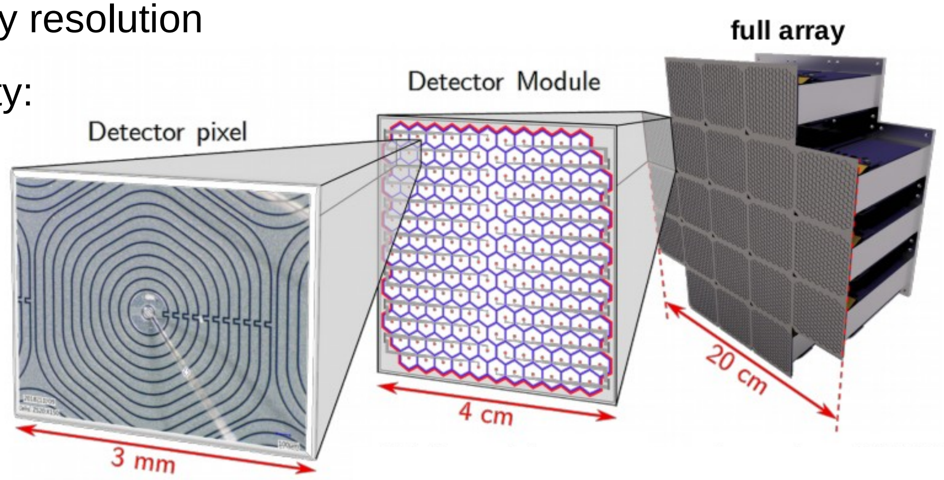


- Probing neutrinos with keV masses
  - using the first (technical) measurement phase
- TRISTAN project in KATRIN:
  - novel multi-pixel Silicon Drift Detector array
  - large count rates
  - excellent energy resolution
  - Target sensitivity:

    $\sin^2\theta$ <10^{-6}



KATRIN Collab., arXiv:2207.06337

S. Mertens et al., J.Phys.G 46 (2019) 6, 065203; T. Brunst et al.,JINST 14 (2019) 11, P11013, T. Houdy et al.,J. Phys.:C.Ser. 1468 (2020) 012177

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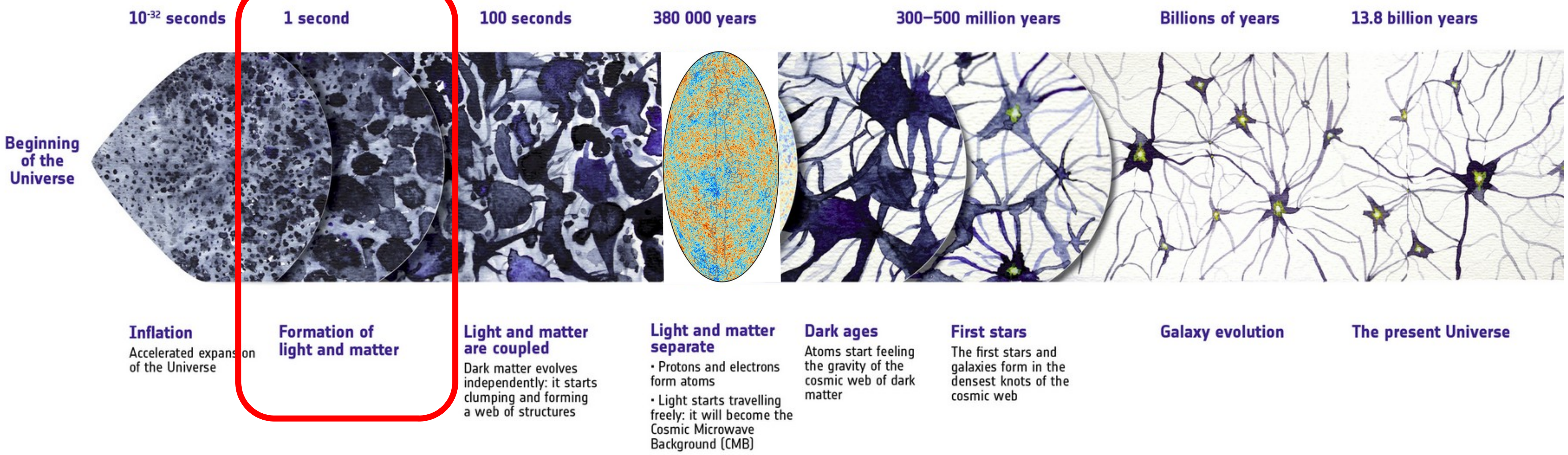
Cosmic neutrino background: Motivation



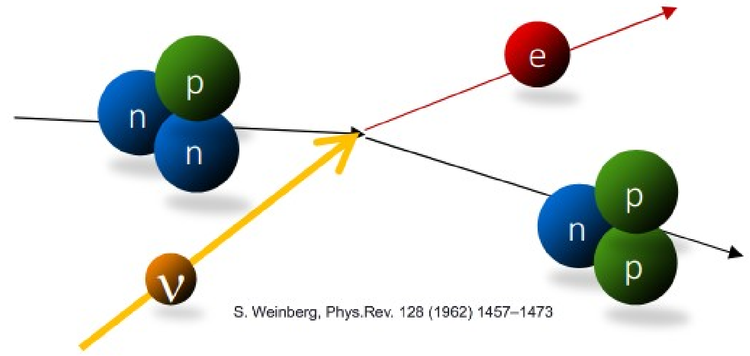
ESA and the Planck Collaboration
Planck Science Team

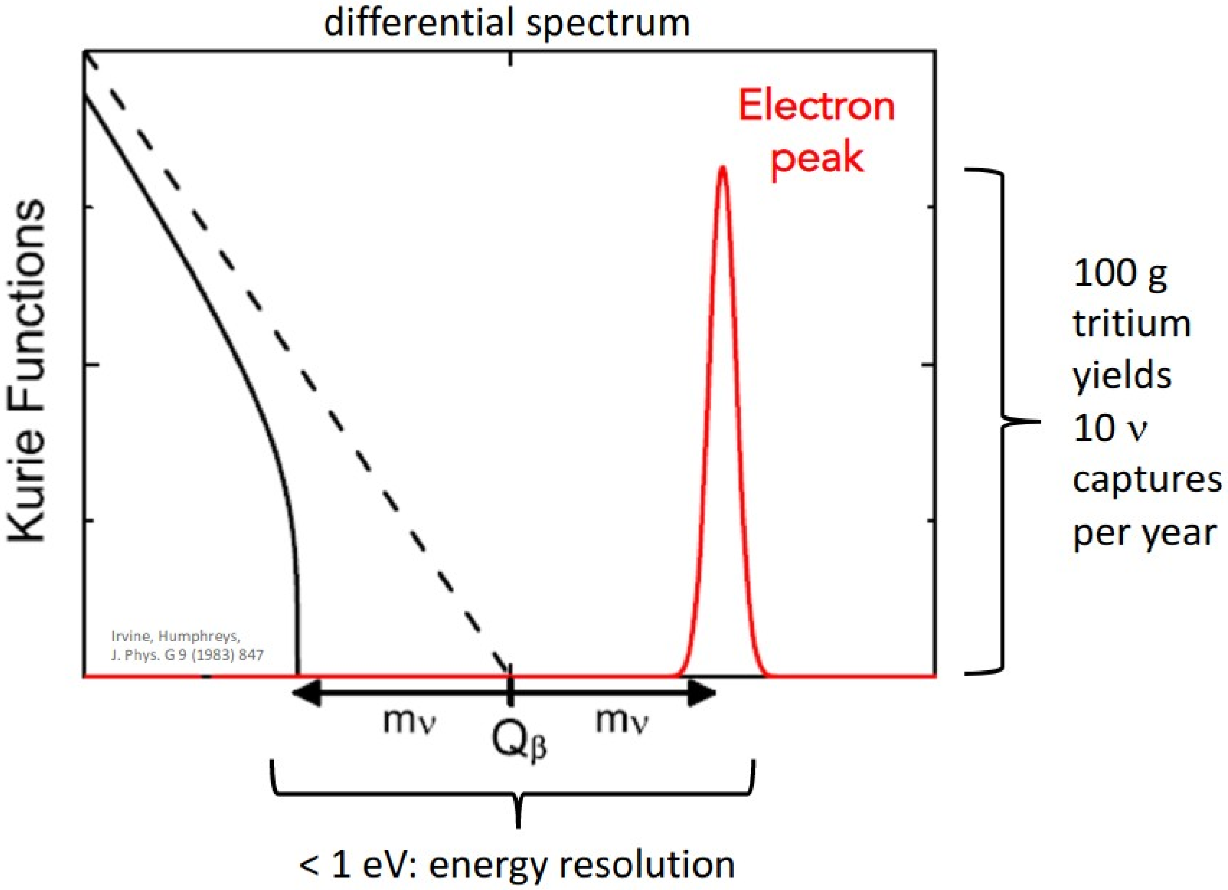
- ~340 relic neutrinos of all species /cm^3 in the Universe (56 /cm^3 per species)
- Decoupled the first second (1 MeV) after Big Bang
- Predicted overdensity $\eta \approx (1.2..20)$
- Upper limits from previous kinematic neutrino mass measurements: 10^{13}

Relic neutrinos search with KATRIN

- relic neutrinos with meV energies
- neutrino capture on tritium (no energy threshold)
- Peak above the endpoint

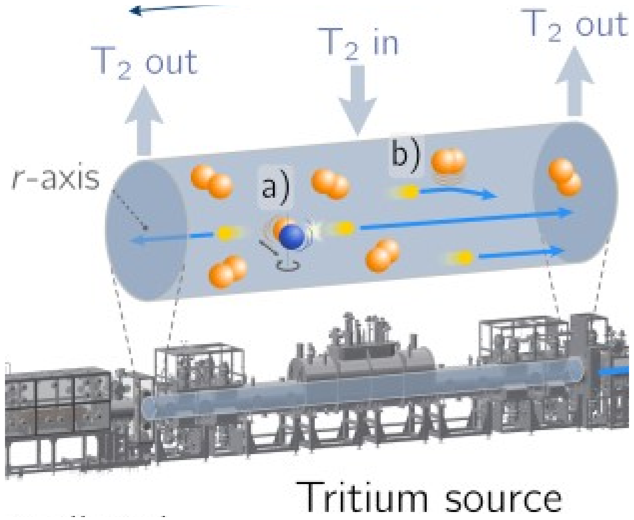
$$^{3}\mathrm{H} + \nu_e \longrightarrow {}^{3}\mathrm{He}^{+} + e$$

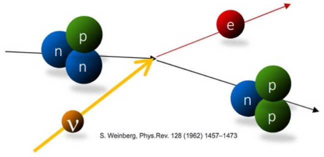




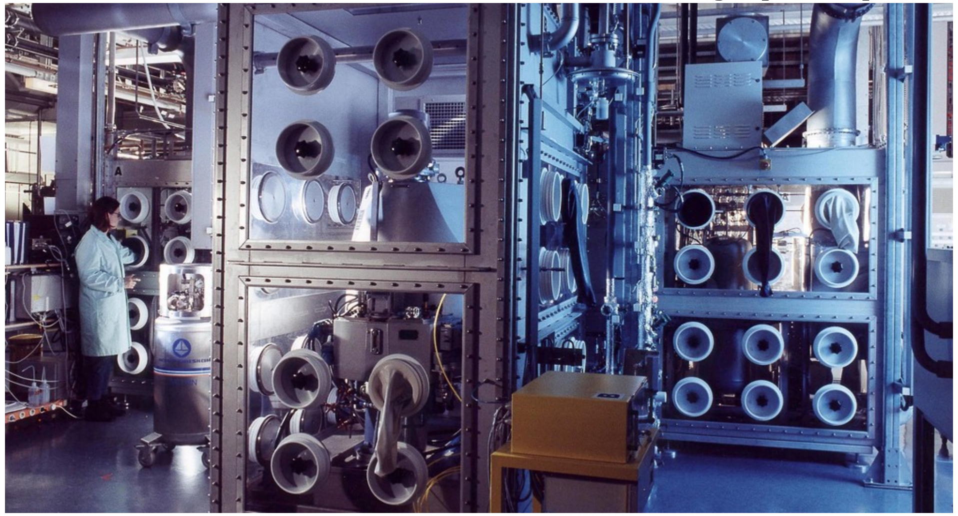
KATRIN Collab., PRL 129 (2022) 1, 011806

Relic neutrinos search with KATRIN





Karlsruhe Tritium Laboratory (TLK)



up to 40 g of tritium

tens of μg of T_2 in the source
10^{-6} captures per year

KATRIN has the sensitivity to probe large clustering of cosmic neutrinos around the solar system

$$\eta = n_\nu / \langle n_\nu \rangle$$

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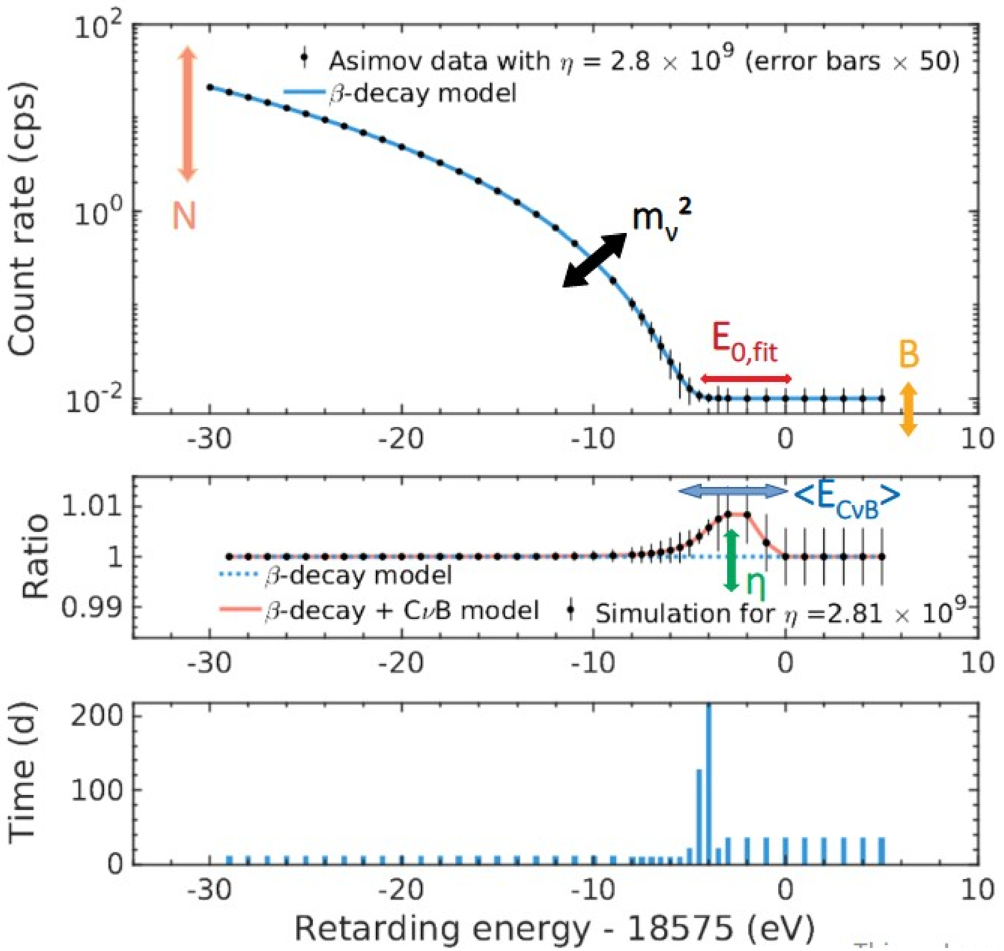
Model for the relic neutrinos in KATRIN



Fit parameters:

- N – amplitude of the signal
- E_0 – effective endpoint energy
- m^2 – effective mass of the electron antineutrino
- B – background rate
- η – local overdensity
- meV energy is neglected

$$R_{\text{diff}}(E) = R_{\beta}(E) + R_{\text{C}\nu\text{B}}(E)$$

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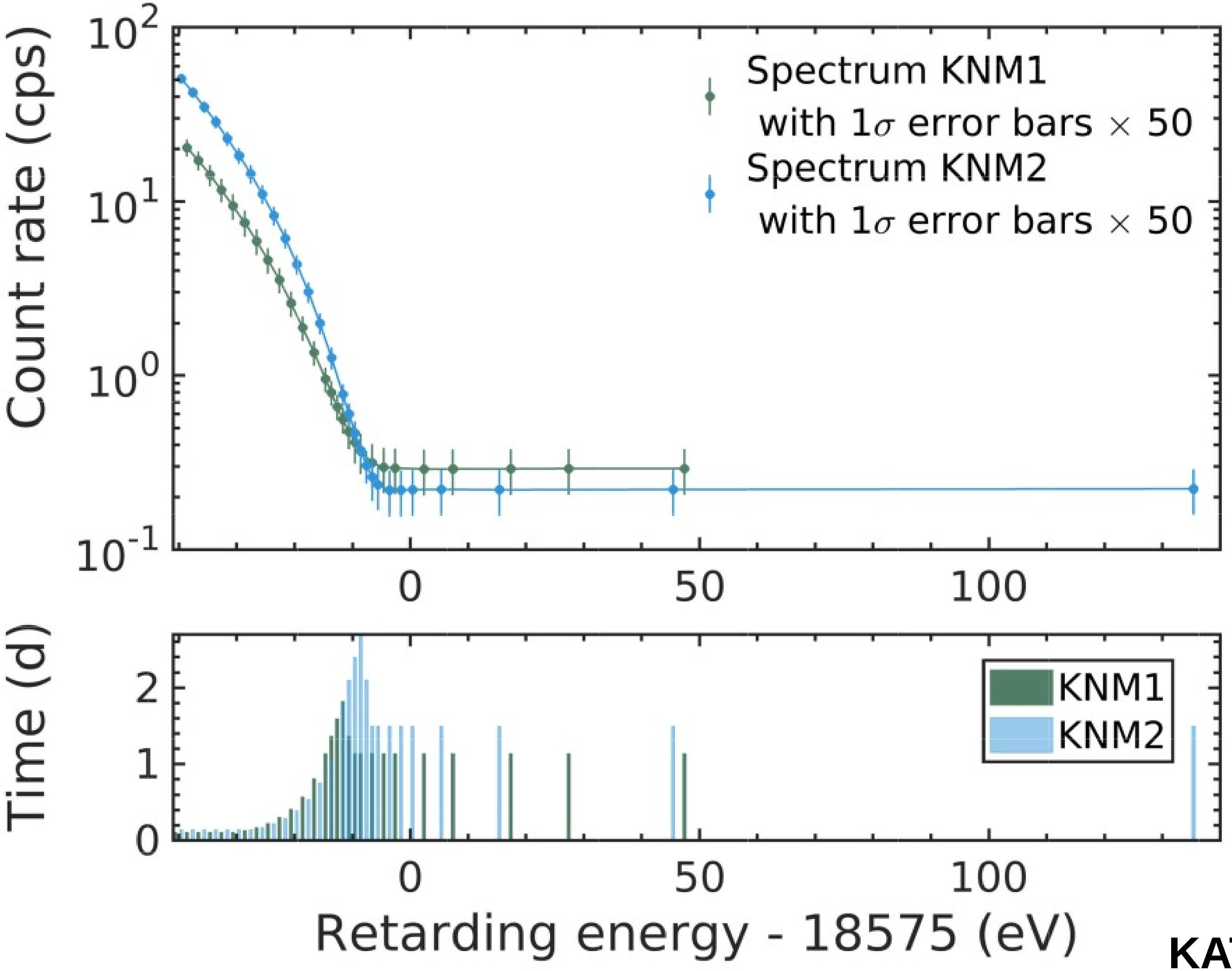
Relic neutrinos in the first science runs



- 1st campaign (2019)
  - 522 hours
  - 3.4 µg for capture on tritium
- 2nd campaign (2019)
  - 744 hours
  - 13.0 µg for capture on tritium

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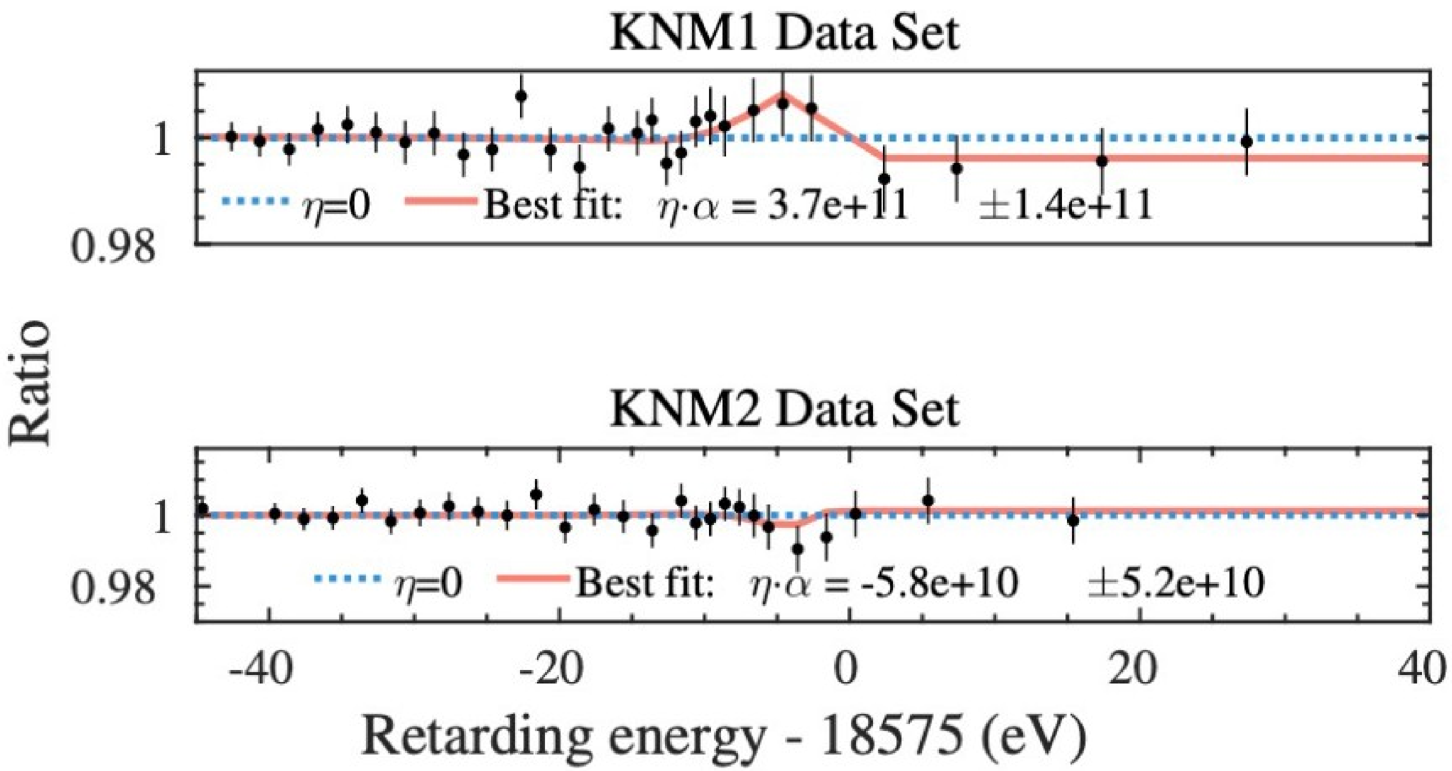
Relic neutrinos in the first science runs



- 1st campaign (2019)
  - 522 hours
  - 3.4 µg for capture on tritium
- 2nd campaign (2019)
  - 744 hours
  - 13.0 µg for capture on tritium
- no evidence for relic neutrino overdensity
  - upper limits

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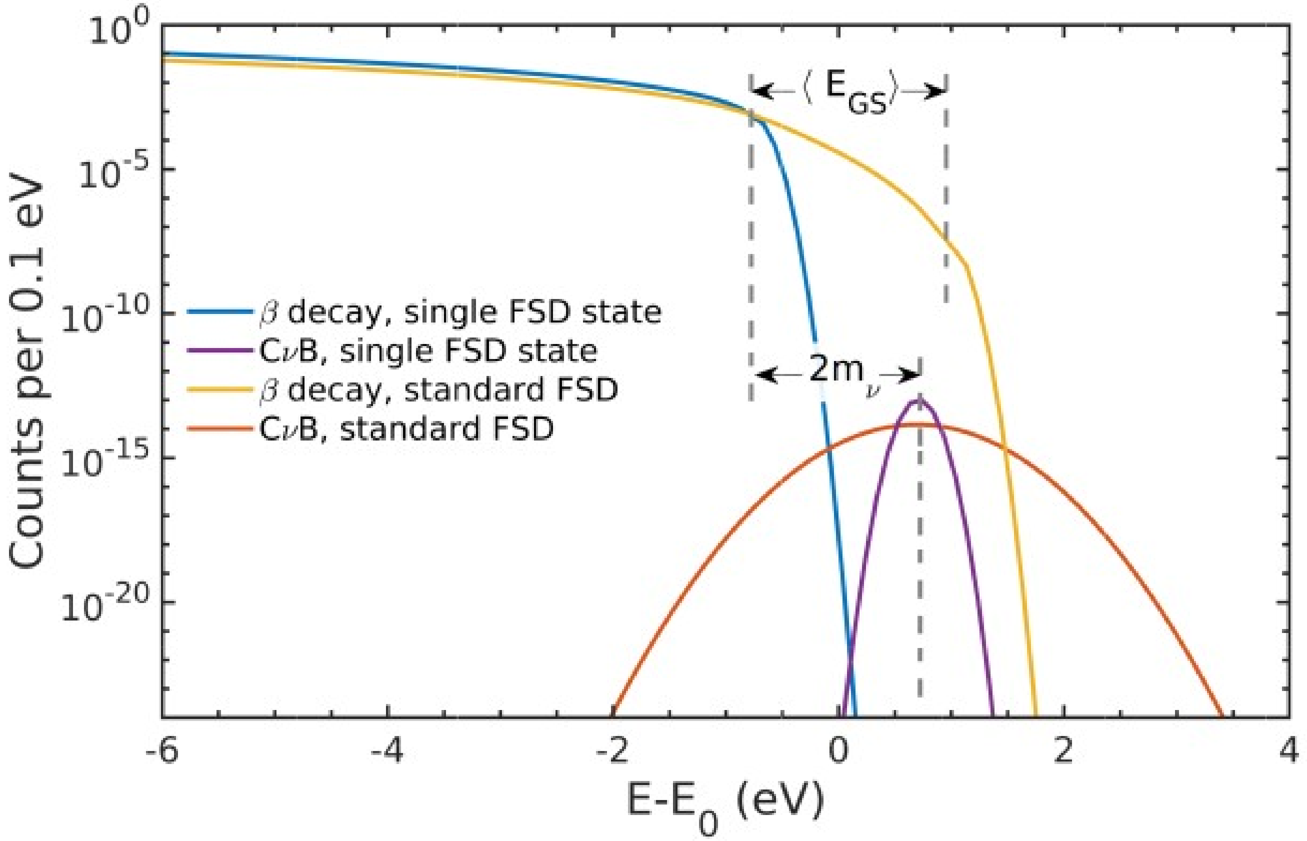
Relic neutrinos: challenges



- Background rate
  - order of magnitude higher
- T_2 β-spectrum creates irreducible background
  - $m_\nu < \langle E_{GS} \rangle/2 = 0.85$ eV
  - increase of the target mass does not increase the CνB sensitivity

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Relic neutrinos: results and prospects

- search for large overdensity η of relic neutrinos near the Earth
- $\eta < 1.1 \cdot 10^{11}/\alpha$ at 95% C.L. – the search is statistically limited
- improved by 2 orders of magnitude compared to previous laboratory limits

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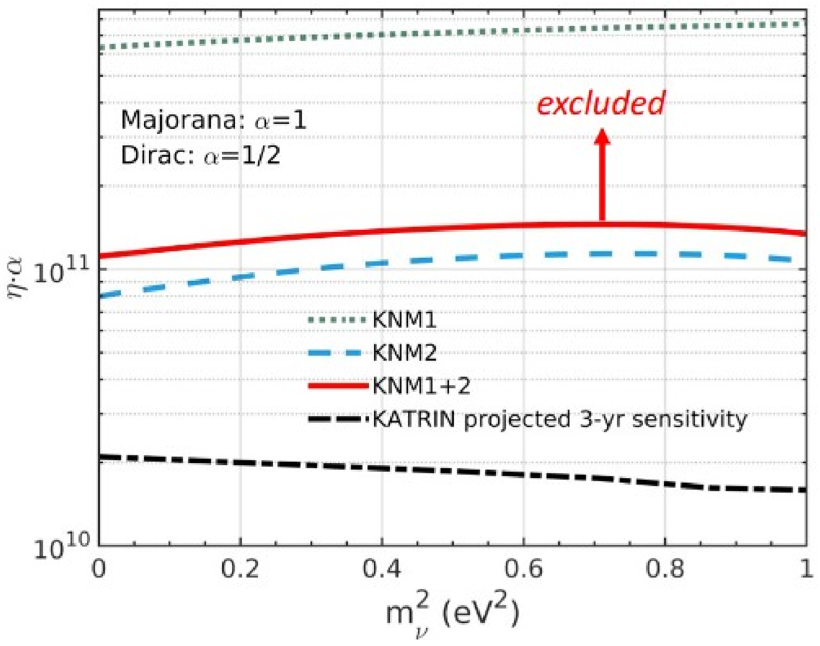

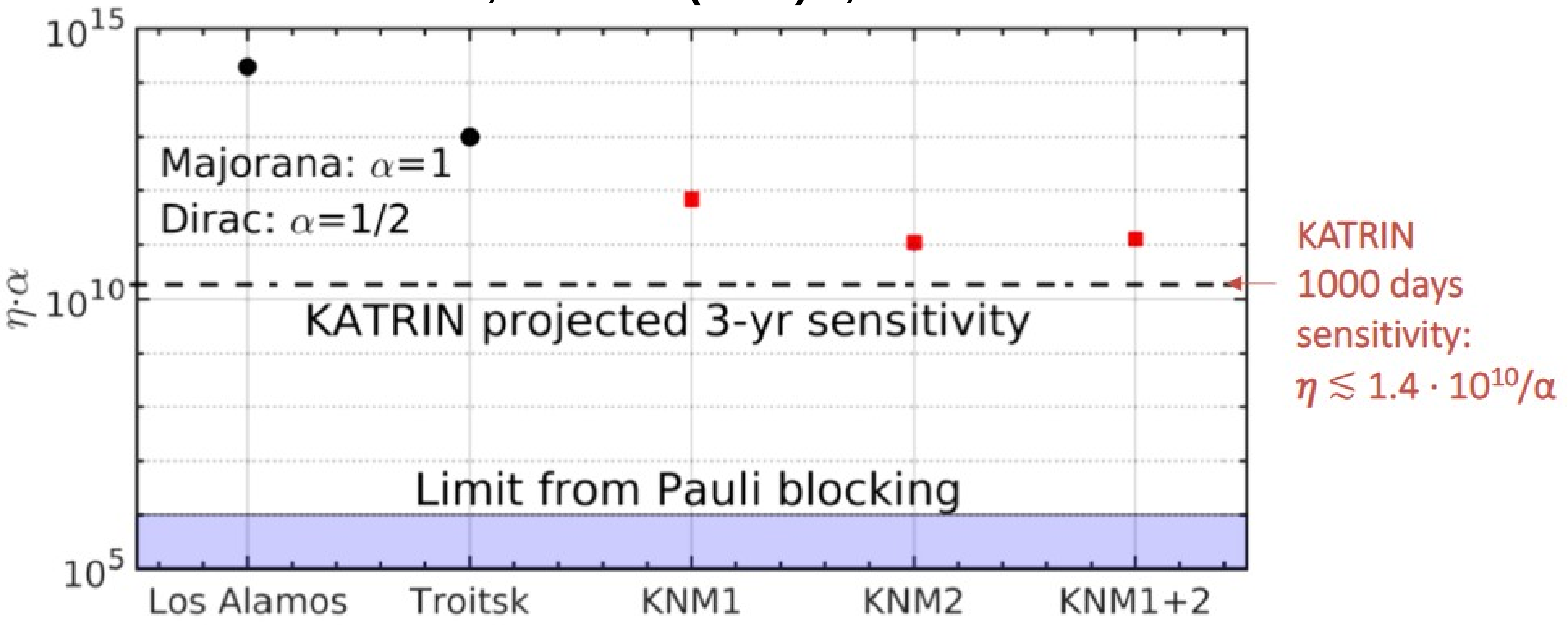

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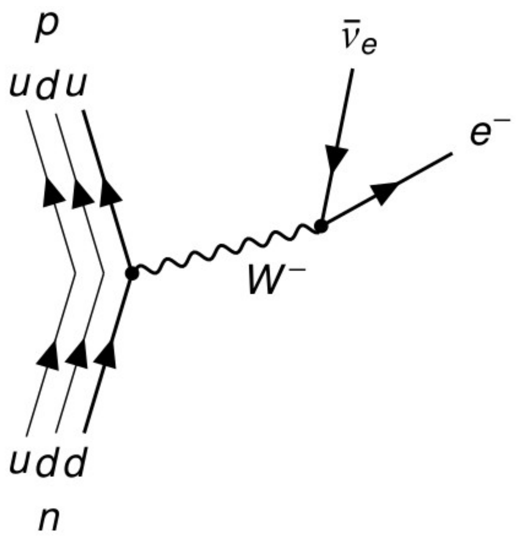
General Neutrino Interactions

- Additional interactions which contribute to the weak interaction in the β-decay
- SM Effective Field Theory with additional right-handed neutrinos
  - Truncated at the order ***n* = 6**



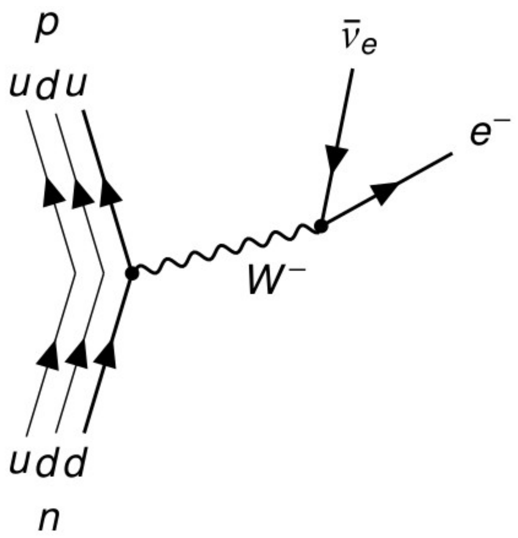
$$\mathcal{L}_{SMEFT}(\phi_{SM}) = \mathcal{L}_{SM}(\phi_{SM}) + \sum_{n\geq 5} \sum_{i} \frac{1}{\Lambda^{n-4}} C_i^{(n)} O_i^{(n)}(\phi_{SM})$$

- GNI could modify the β-spectrum
  - Energy-dependent contributions to the rate could be studied with KATRIN

GNI Lagrangian for 4-fermion-interaction

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

- 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



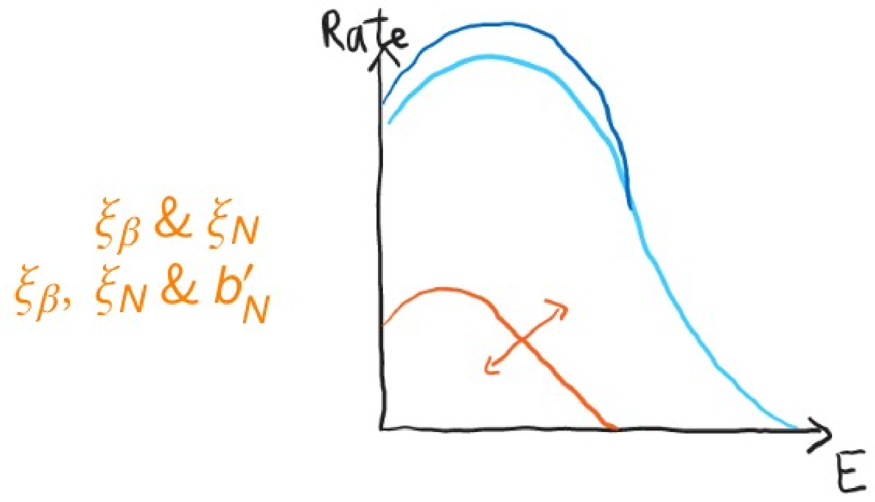
GNI in the tritium β-spectrum

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

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

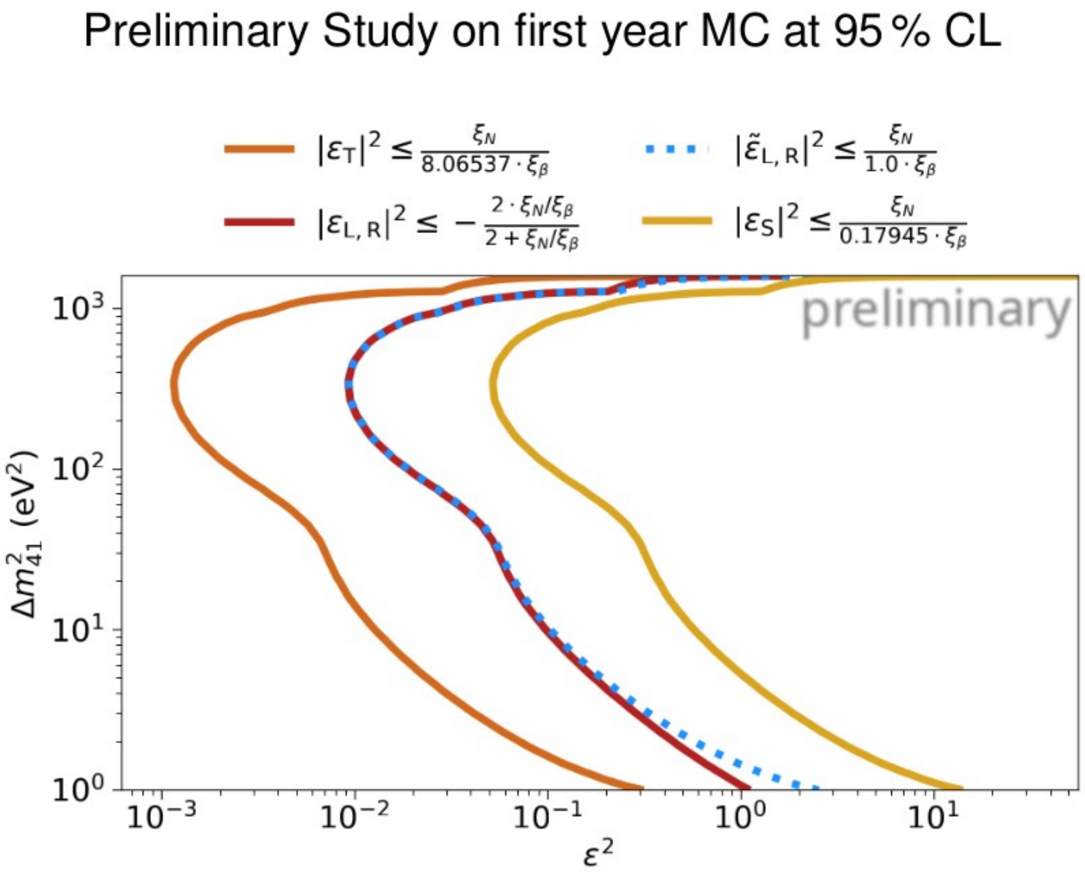
- Total decay rate for active and sterile neutrino
- ξ_k, b_k, b'_k, c_k are defined in terms of $\boldsymbol{\epsilon}$, $\boldsymbol{U_{e4}}$ and $\boldsymbol{g_V, g_S, g_T, g_A}$

  The SM case: $\xi_N = b_k = b'_k = c_k = 0$



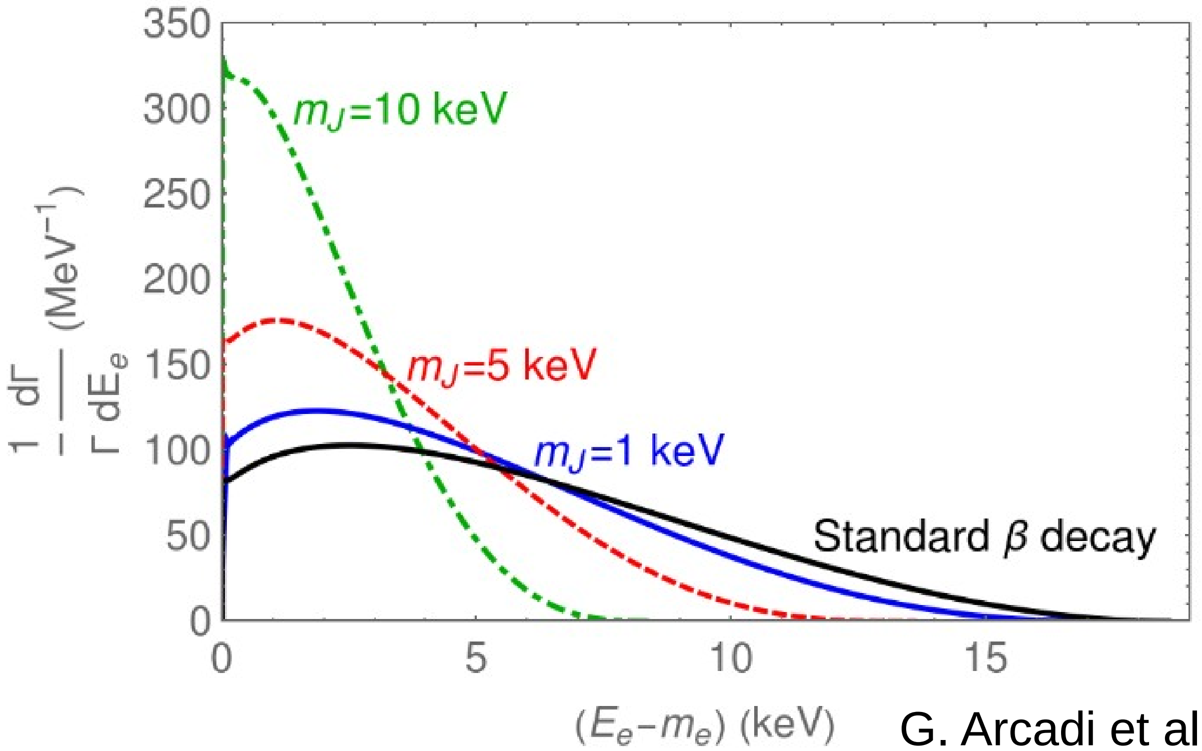
Sensitivity to GNI with the sterile branch

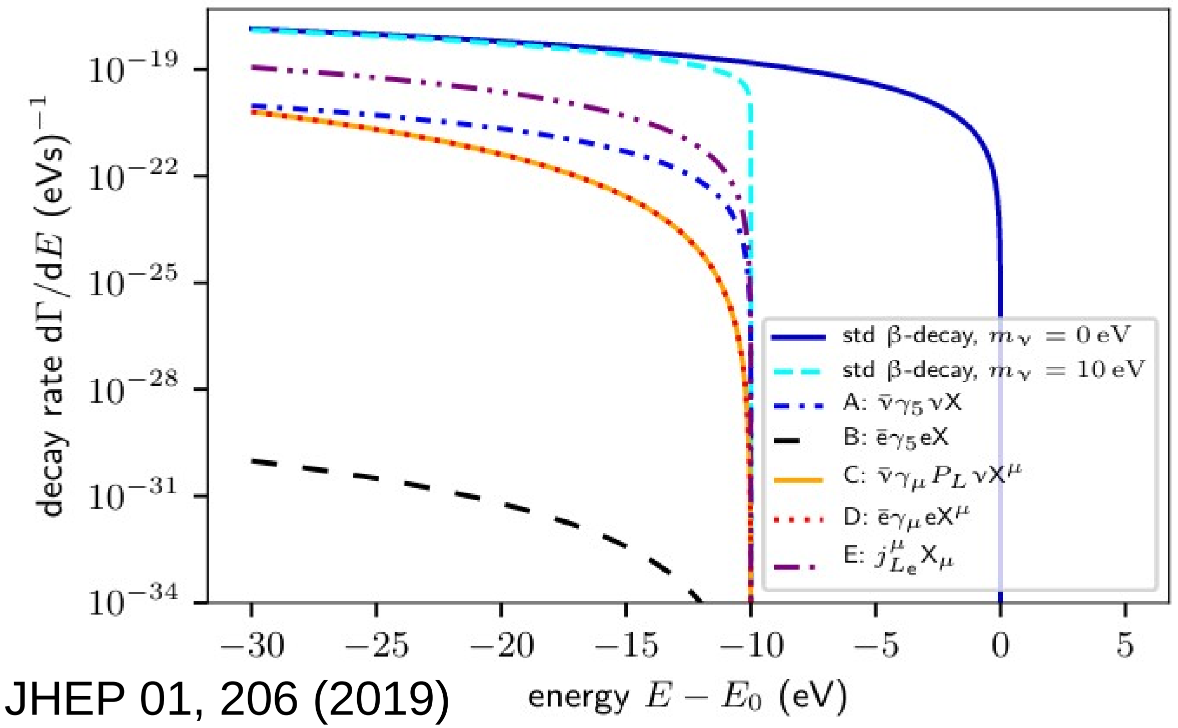
- Converting mixing $\frac{\xi_N}{\xi_\beta}$ into sensitivity to ϵ
- Strongest constraints on ϵ_T
- Other constraints:
  - neutrino oscillations
  - ν-e and ν-N scattering
  - charged lepton flavor violation



New light bosons

- Searching for new physics in the low-energy range
  - Light scalar or vector bosons can be emitted if their mass < Q_T
  - axions and axion-like particles, Majoron models, Z′

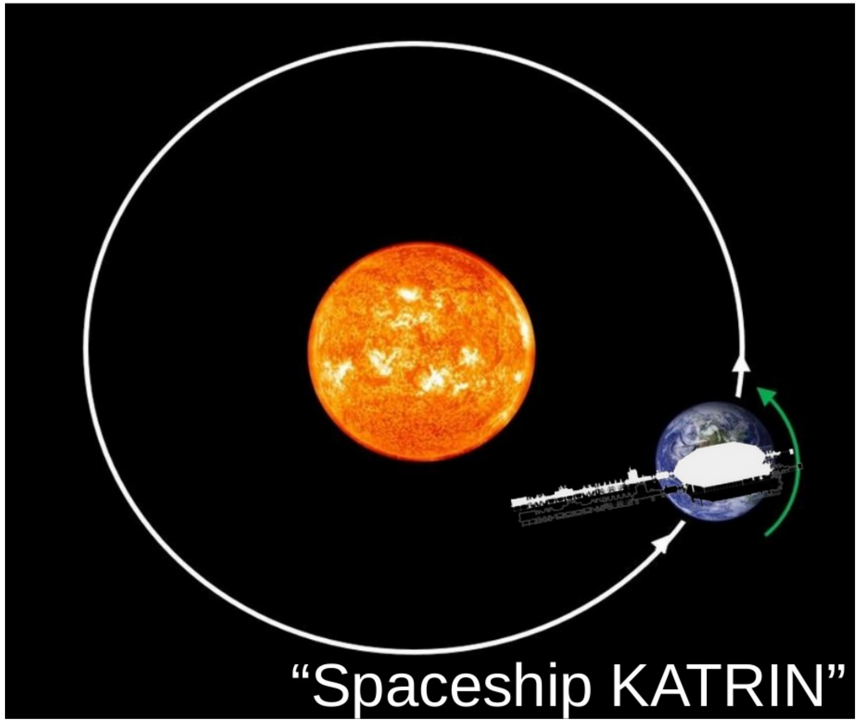




G. Arcadi et al. JHEP 01, 206 (2019)

Outline

- KATRIN neutrino mass measurement in a nutshell
- Beyond neutrino mass searches with KATRIN
  - Sterile neutrinos
  - Relic neutrinos
  - General neutrino interactions and light boson production
  - **Lorentz invariance violation**
- Summary and outlook



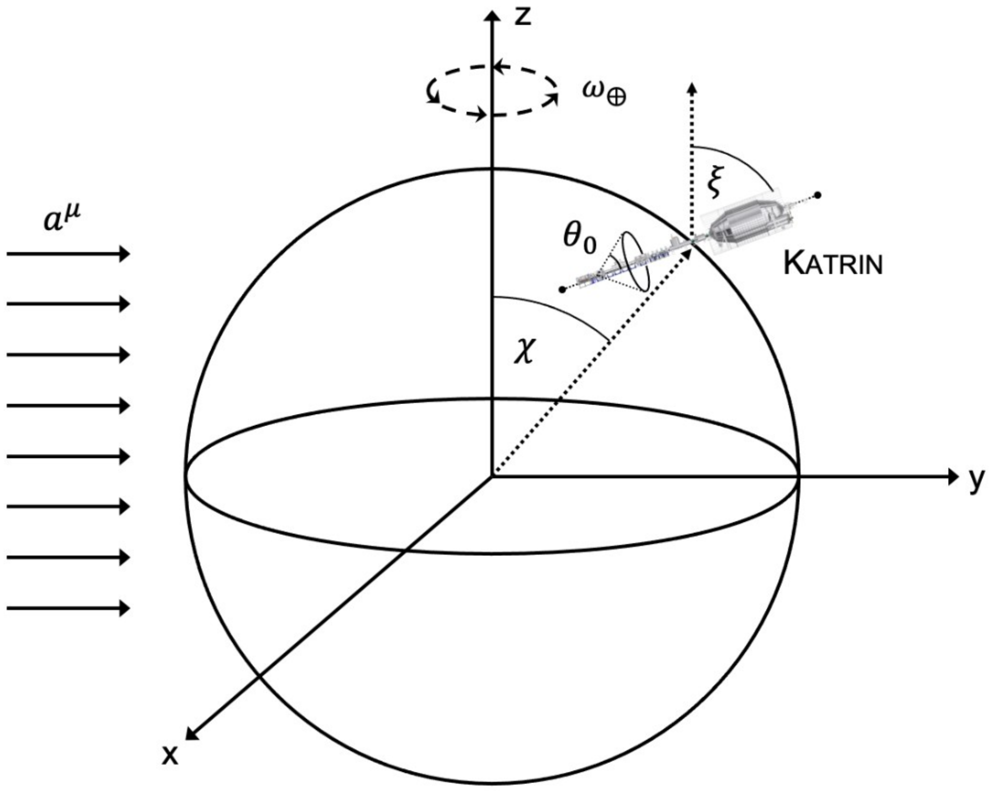
Search for Lorentz Invariance Violation

- Standard Model Extention: relativistic EFT with all possible LIV operators for neutrino propagation

$$L^{a}_{SME} = -\bar{\psi}_w a^\mu \gamma_\mu \psi_w$$

- for all particles in the β-decay
- terms $\propto \bar{a}^\mu p_\mu = a^0 p_0 - \vec{a} \cdot \vec{p}$

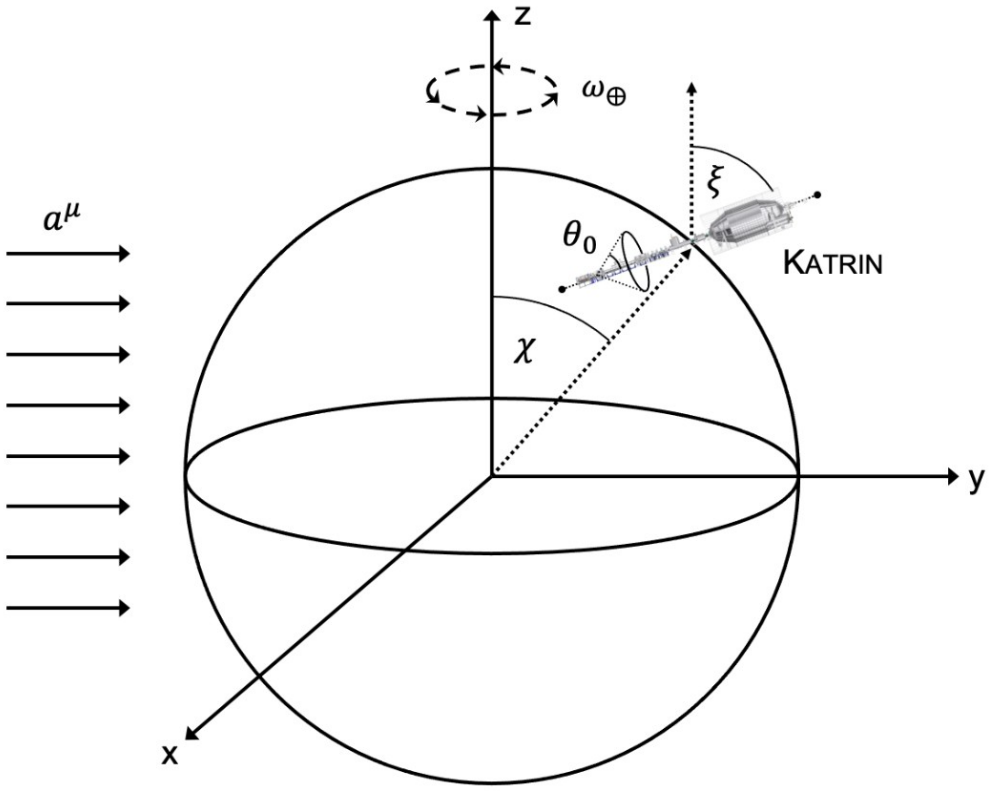
→ 1 sideral-day modulation of $\boldsymbol{E_0}$ and absolute shift of $\boldsymbol{E_0}$



KATRIN Collab. arxiv:2207.06326, accepted to PRD

Search for Lorentz Invariance Violation

- Time-dependent
  - Rotation of the Earth: change of intrinsic KATRIN direction w.r.t. $\mathbf{a^\mu}$
  - $\boldsymbol{E_0}$ oscillates with *23 h 56 min* period
  - $\left|(a_{\text{of}}^{(3)})_{11}\right|$
- Time-independent
  - Measurements of $\boldsymbol{E_0}$ at Mainz and KATRIN
  - $\left|(a_{\text{of}}^{(3)})_{00}\right|$ and $\left|(a_{\text{of}}^{(3)})_{10}\right|$



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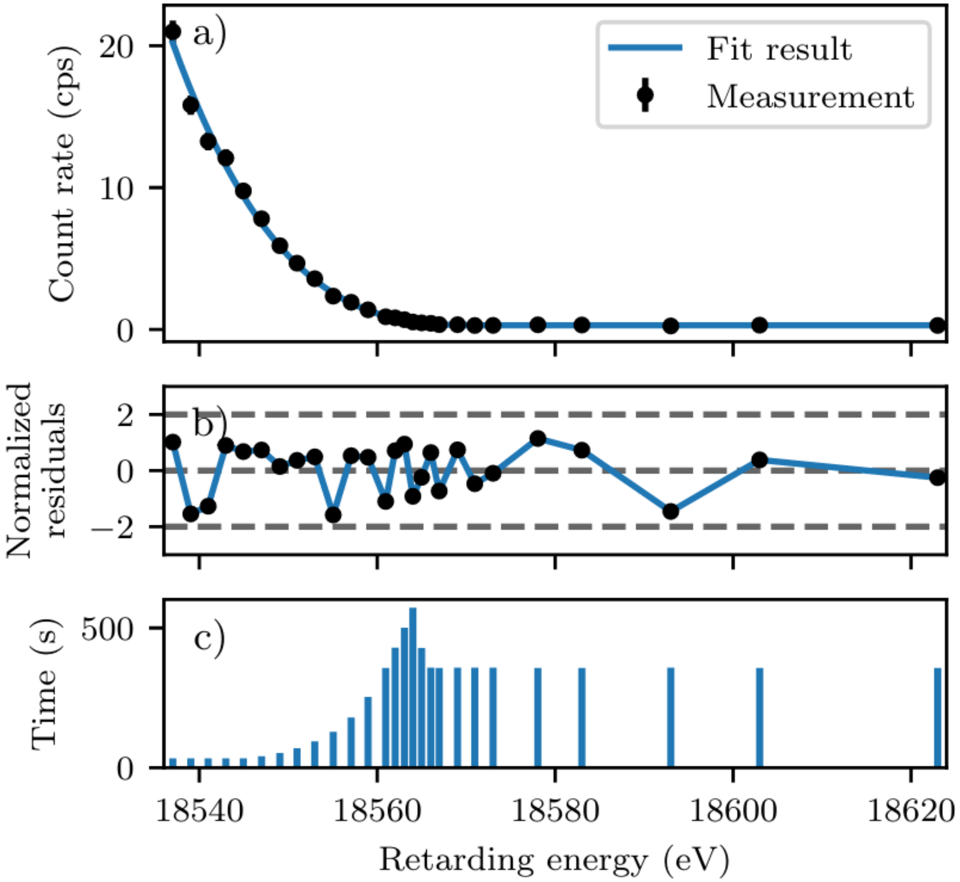
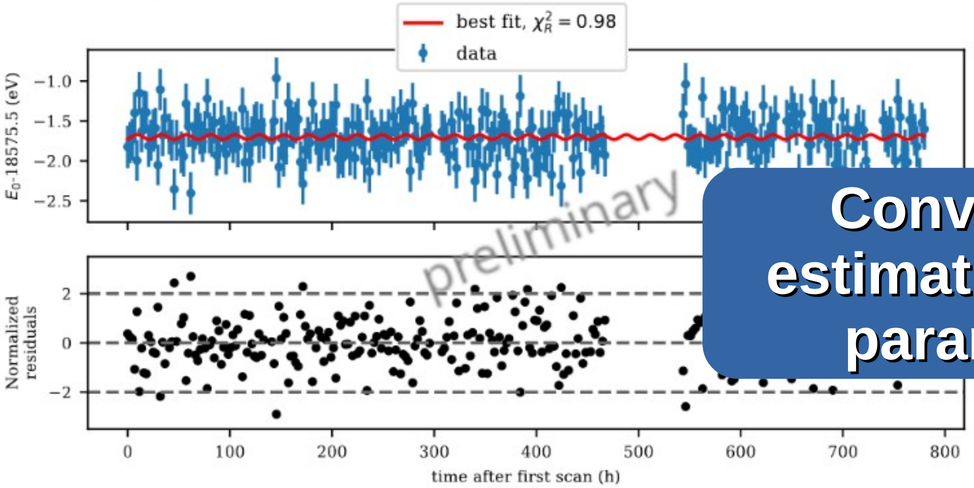
Lorentz invariance violation in KATRIN

Karlsruher Institut für Technologie

Fit each 2h scan of β-spectrum



Estimate amplitude of E_0 oscillation



Convert into estimation of LIV parameters

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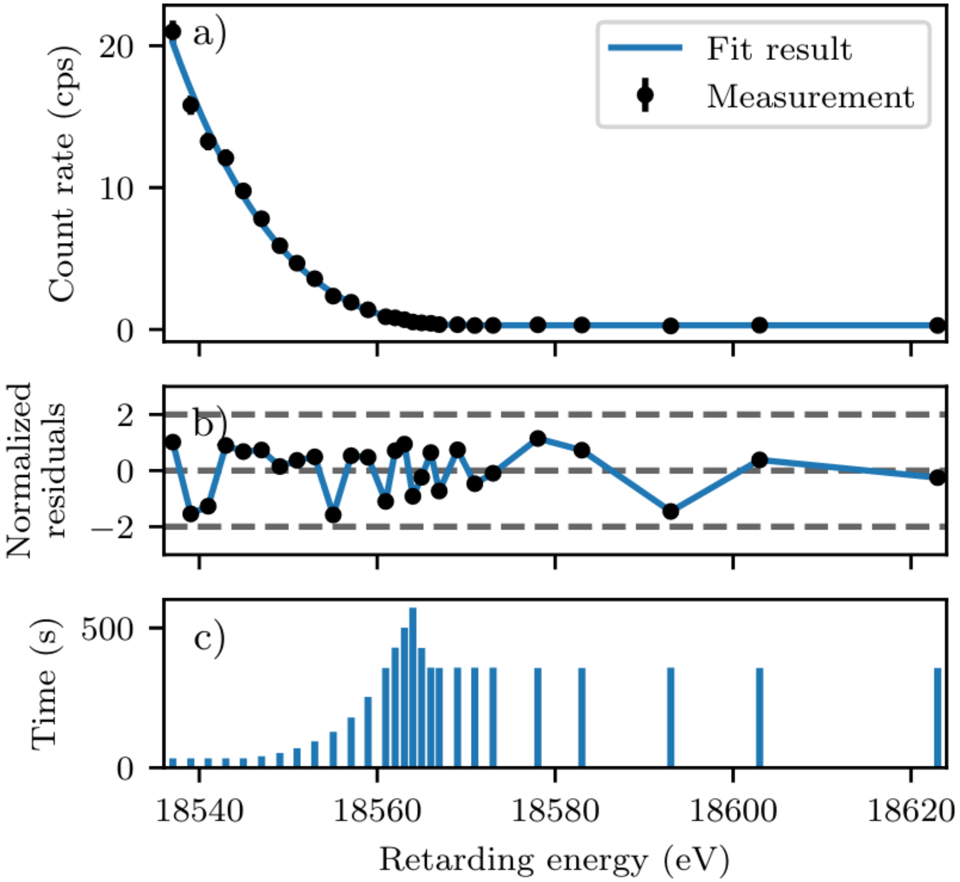
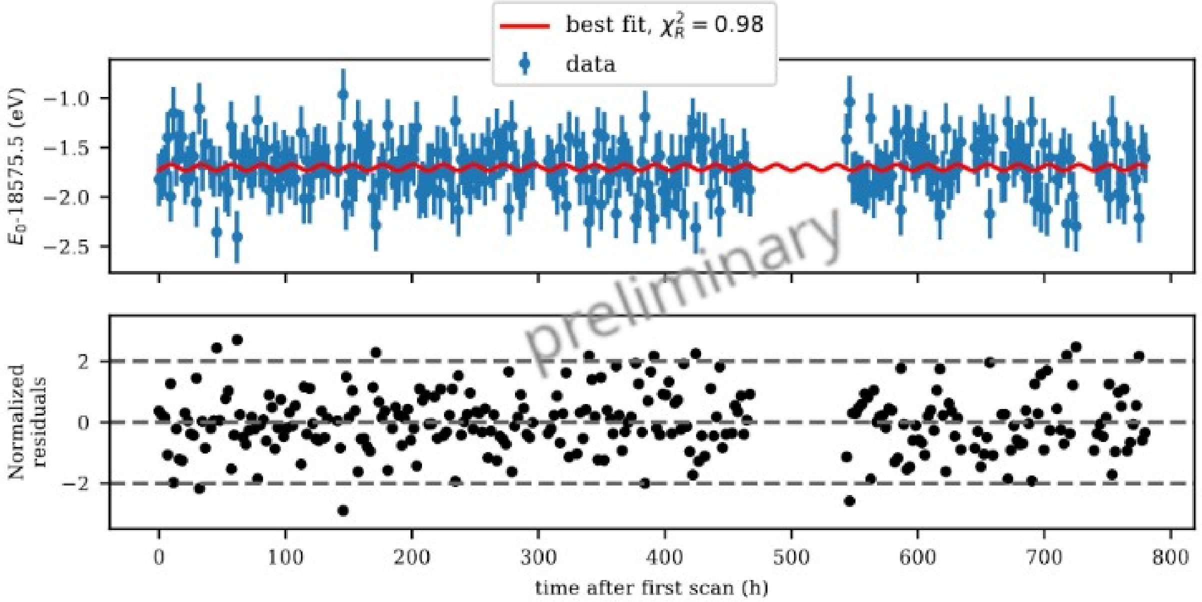
Lorentz invariance violation in KATRIN

Fit each 2h scan of β-spectrum

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





$$E_0^{\mathrm{fit}}(t_e) = D + A\cos(\omega t_e - \phi)$$

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Lorentz invariance violation in KATRIN

- No significant oscillation of E_0 observed

First upper limit:

$$\left|\left(a_{of}^{(3)}\right)_{11}\right| < 3.7 \times 10^{-6}\ GeV\ (90\,\%\ CL)$$

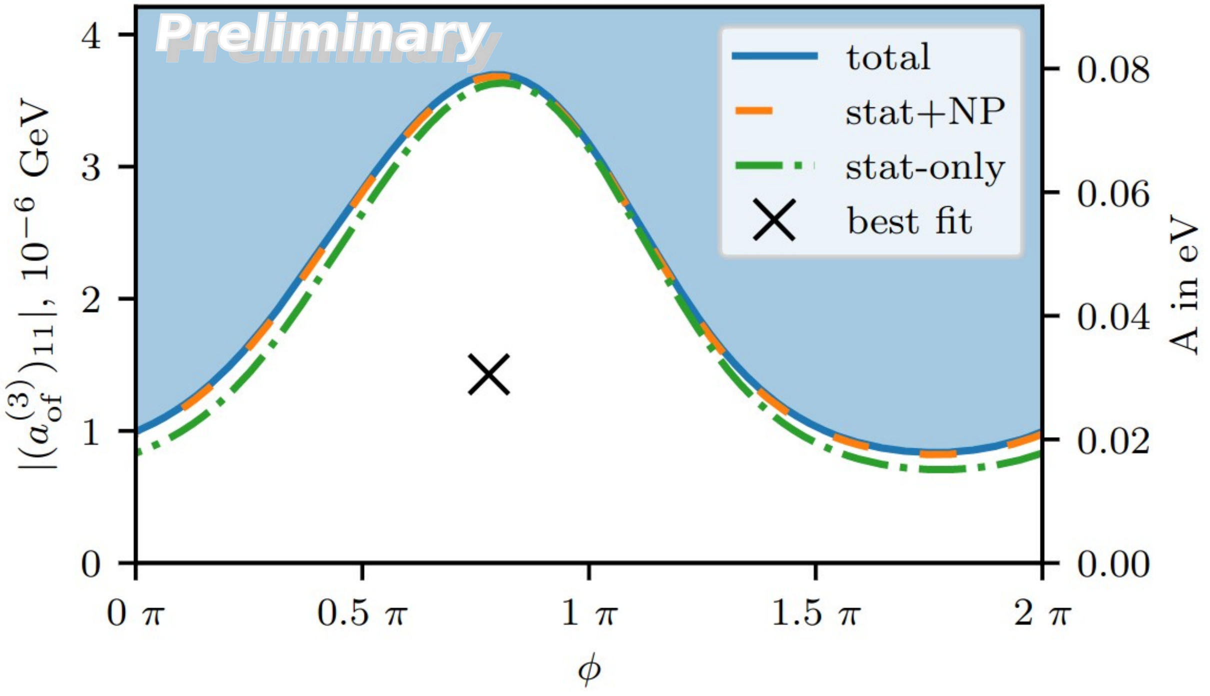
- No significant shift of E_0 observed

Improved upper limits:

$$\left|\left(a_{of}^{(3)}\right)_{00}\right| < 3.0 \times 10^{-8}\ GeV\ (90\,\%\ CL)$$

$$\left|\left(a_{of}^{(3)}\right)_{10}\right| < 6.4 \times 10^{-4}\ GeV\ (90\,\%\ CL)$$

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



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Summary & Outlook

- First results on the eV-scale sterile neutrinos
  - complementary to oscillation data
  - competitive sensitivity in relevant parameter regions
- Cosmic neutrino overdensity
  - improved limits from the first science runs
- New physics searches near E_0: GNI and light bosons
- Lorentz invariance violation
  - KATRIN is probing parameters inaccessible to oscillation experiments
- New data-sets with higher statistics and lower background!

Thank you for your attention!