KATRIN beyond the neutrino mass and SM

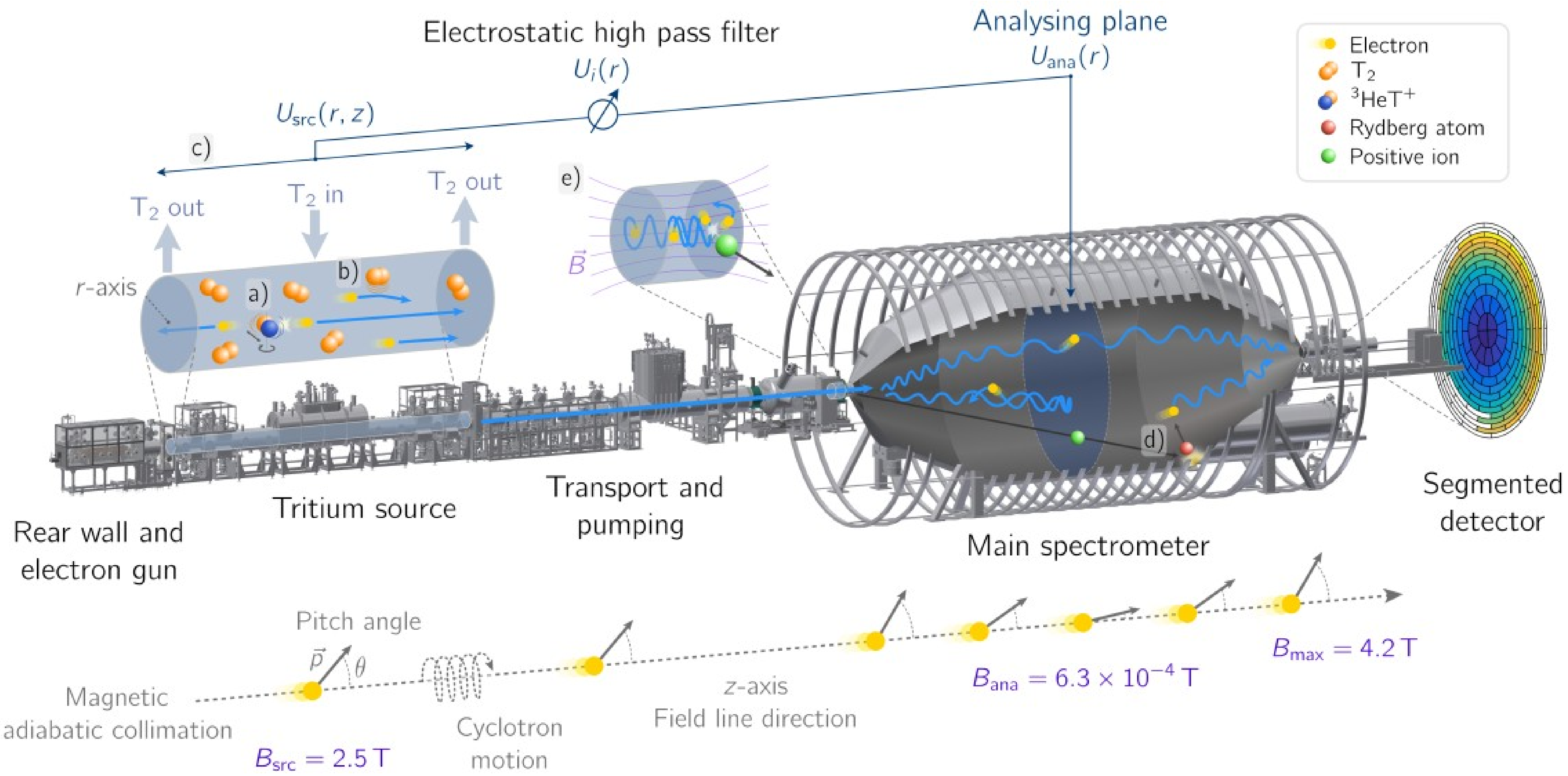
NuMass 2022 – Milano

Alexey Lokhov for the KATRIN collaboration

Outline

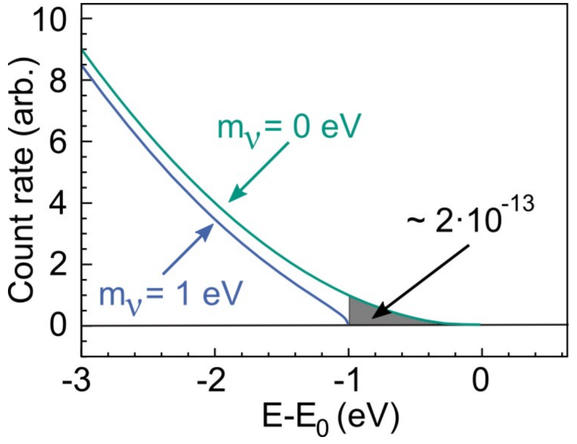
- KATRIN neutrino mass measurement in a nutshell
- BSM studies with KATRIN
  - Light sterile neutrinos
  - Relic neutrinos
  - New light bosons
  - General Neutrino Interactions and charged currents beyond the SM
  - Lorentz invariance violation
- Summary and outlook

KATRIN experiment

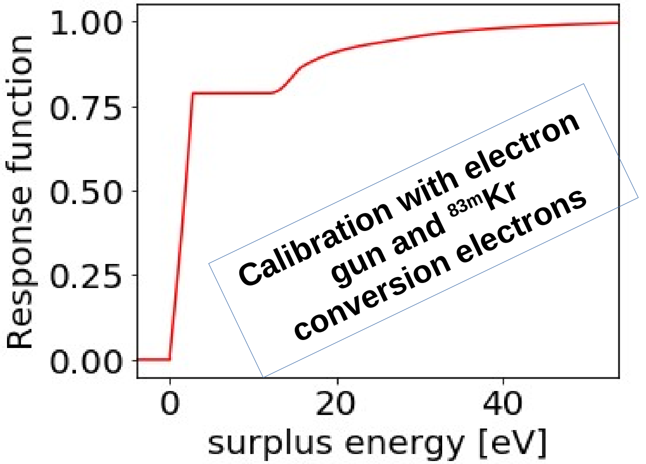


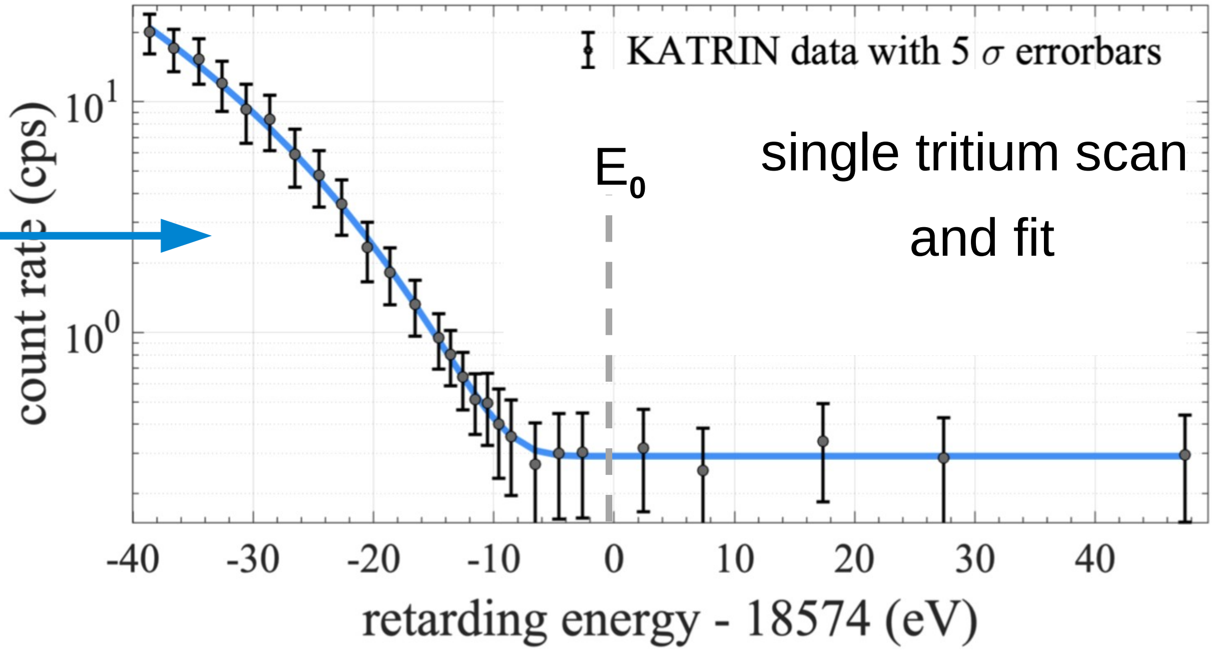
Beta-spectrum and neutrino mass

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



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

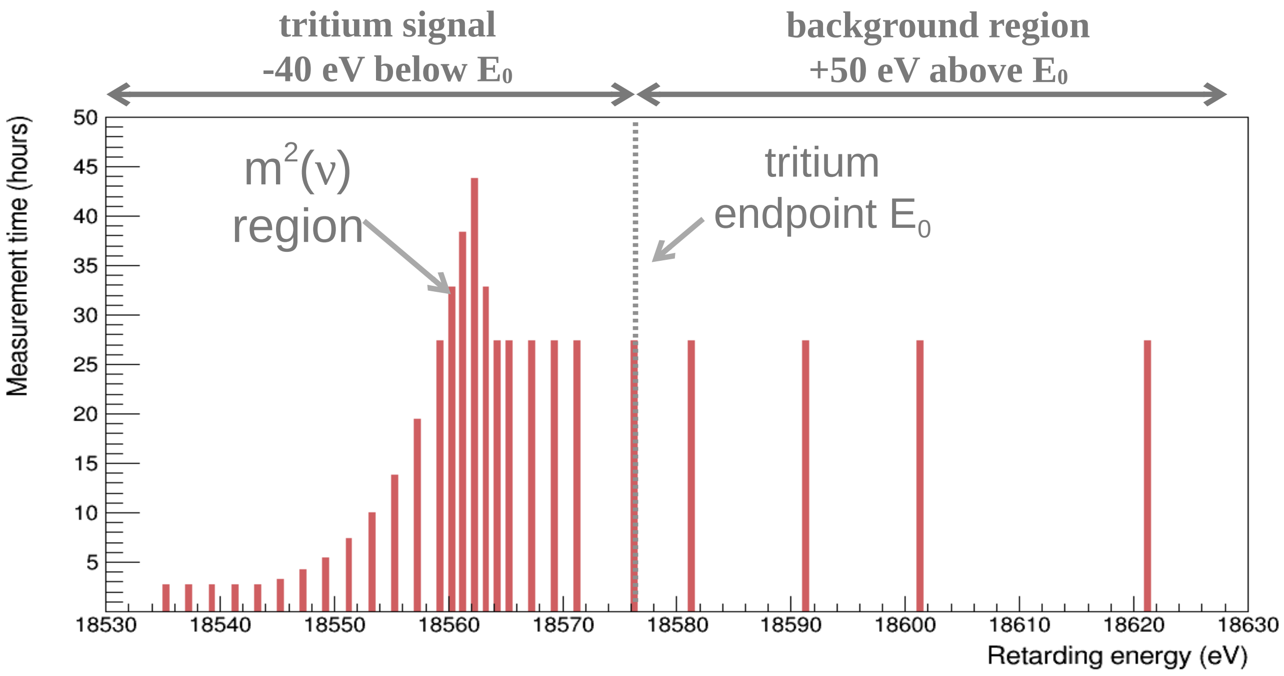




single tritium scan and fit

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

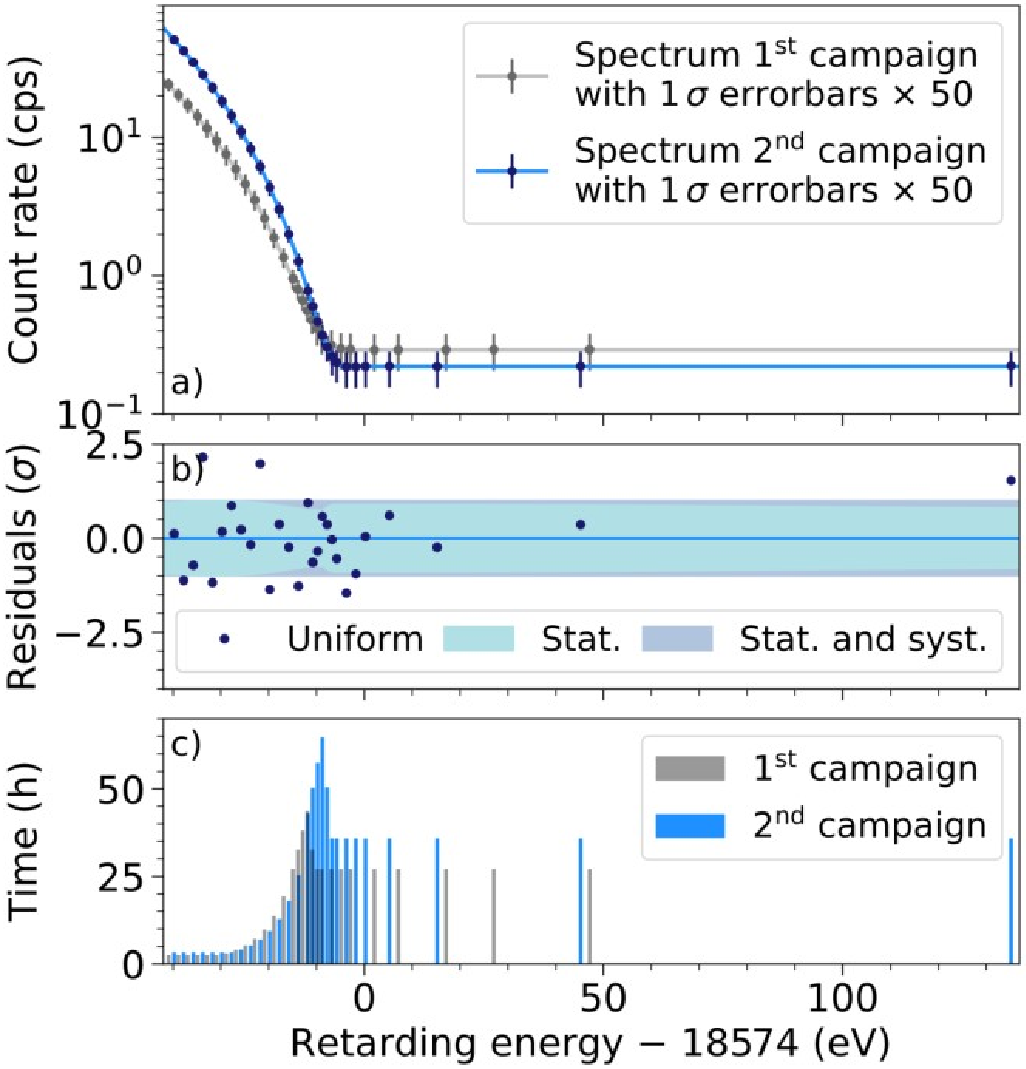
T_2 spectrum scanning



- Ca. 30 high-voltage steps in each scan
- Distribution optimized for $m^2(\nu)$ sensitivity
- Different regions for four fit parameters: **$m^2(\nu)$**, endpoint **E_0**, norm. **N**, background **B**
- Ca. 25% of time spent on background

- Several **measurement campaigns** per year:
  each 2-3 months long, separated by calibration and maintenance breaks
- Several hundred **scans of the β-decay spectrum** in each campaign:
  each ~2.5 hours long, alternating in up/down direction

Beta-spectrum and neutrino mass

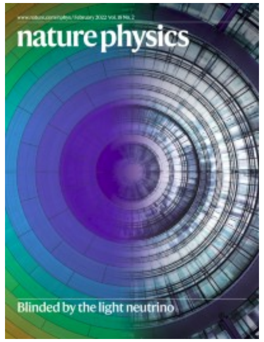


1st measurement campaign (spring 2019)

✔ total statistics: 2 million events

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

✔ upper limit: $m_\nu < 1.1$ eV (90% CL)



2nd measurement campaign (autumn 2019)

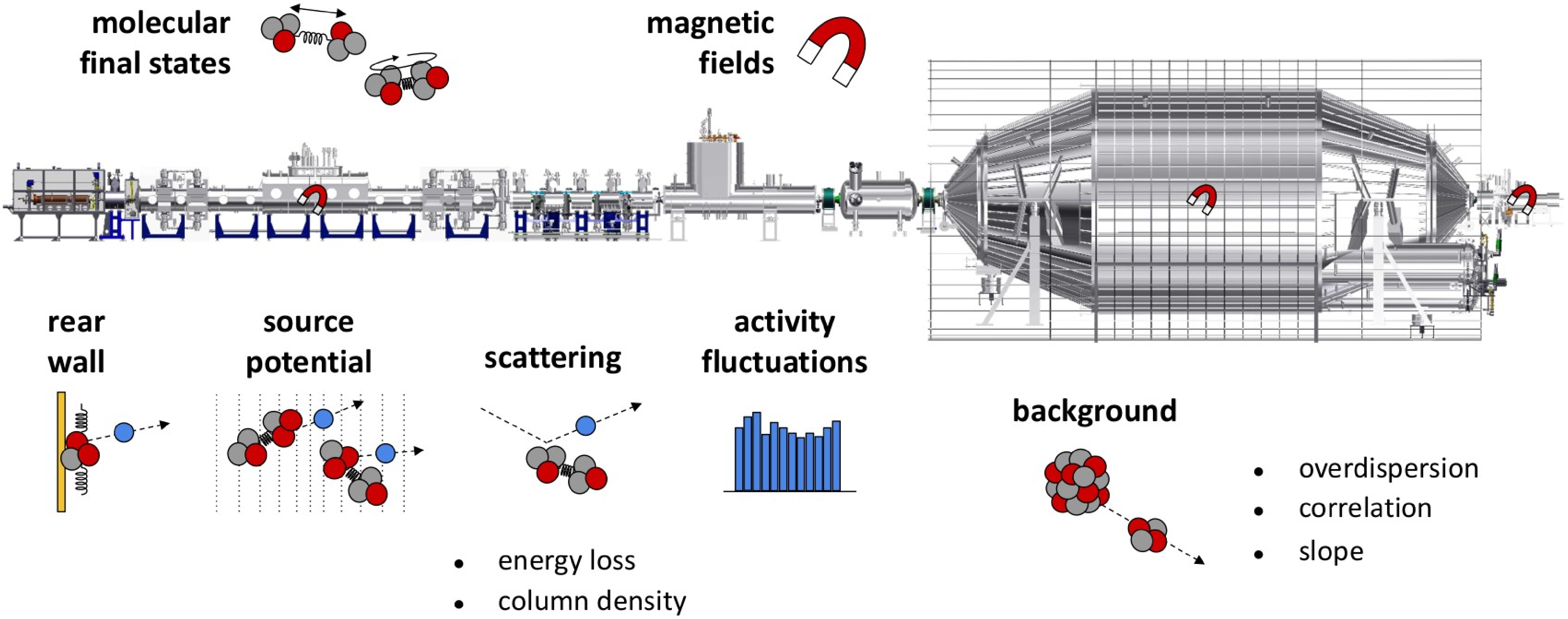
✔ total statistics: 2 million events

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

✔ upper limit: $m_\nu < 0.9$ eV (90% CL)

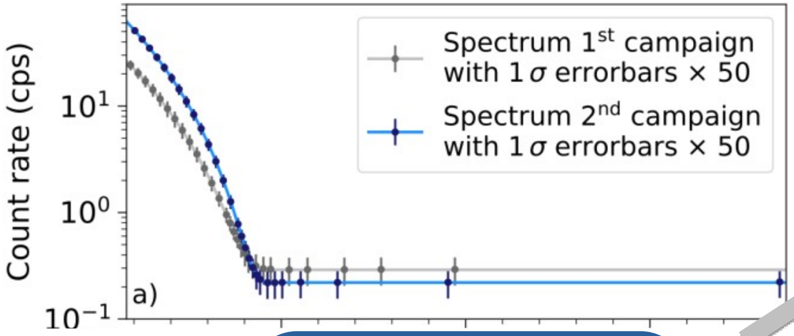
- **Combined result: $m_\nu < 0.8$ eV (90% CL)**

Main sources of systematics



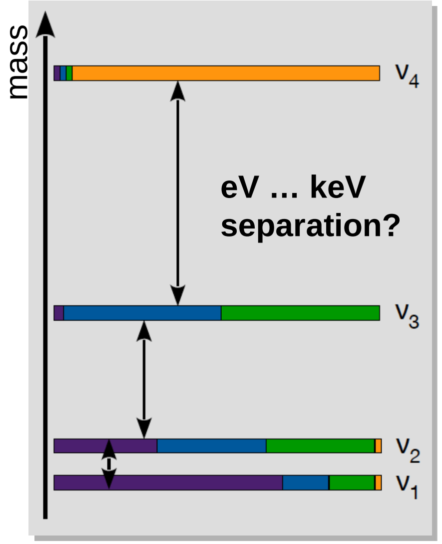
Karlsruher Institut für Technologie

“Beyond neutrino mass” in KATRIN



β-spectrum of high statistics and precision

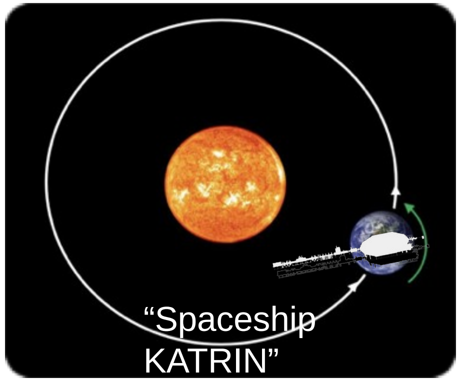
Is there a fourth (sterile) neutrino?



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

Search for exotic weak interactions (spectrum shape)

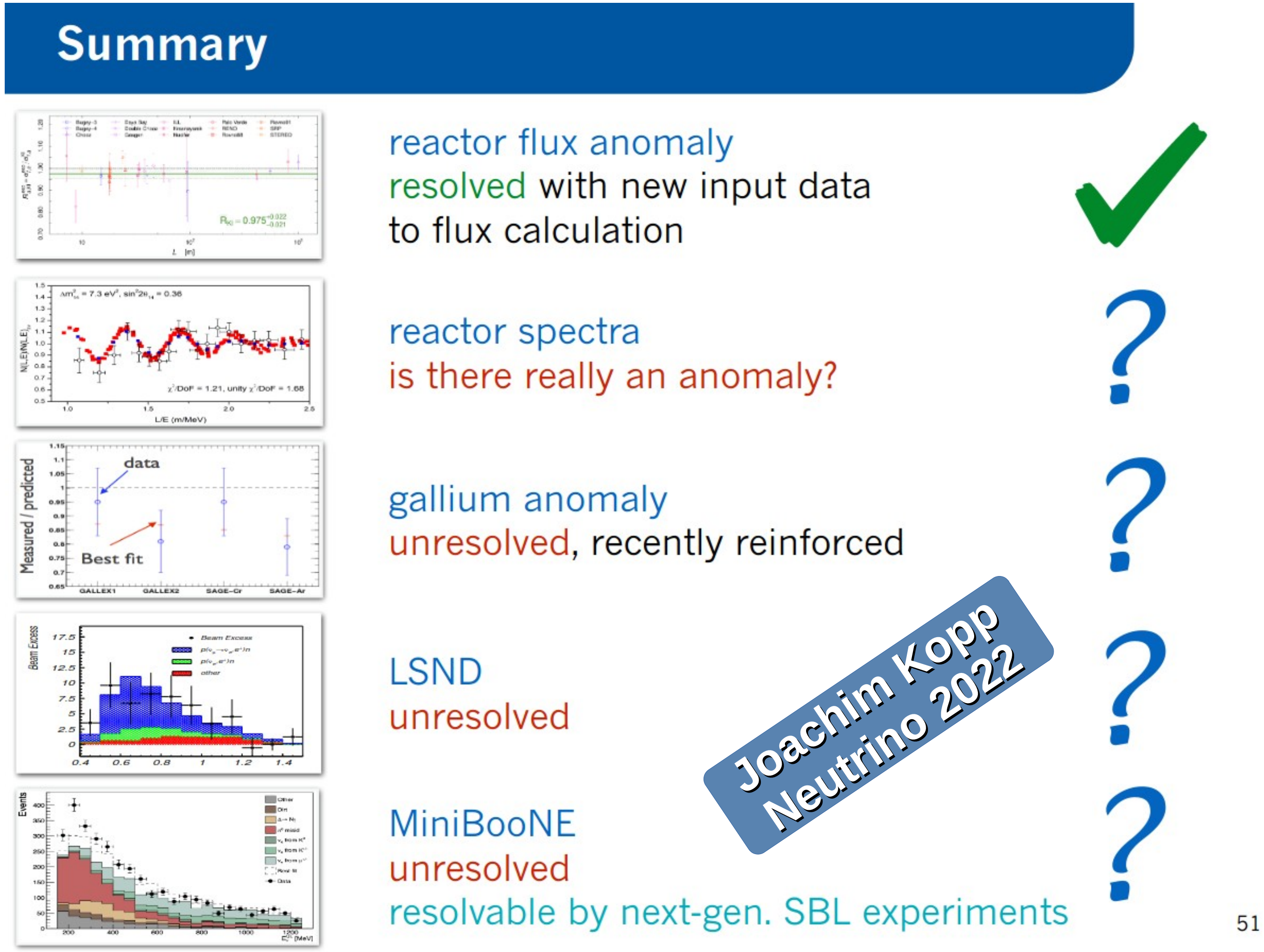
Search for Lorentz invariance violation (sidereal modulation)



Constrain local overdensity of cosmic relic neutrinos (peak search)

Light sterile neutrinos – Motivation

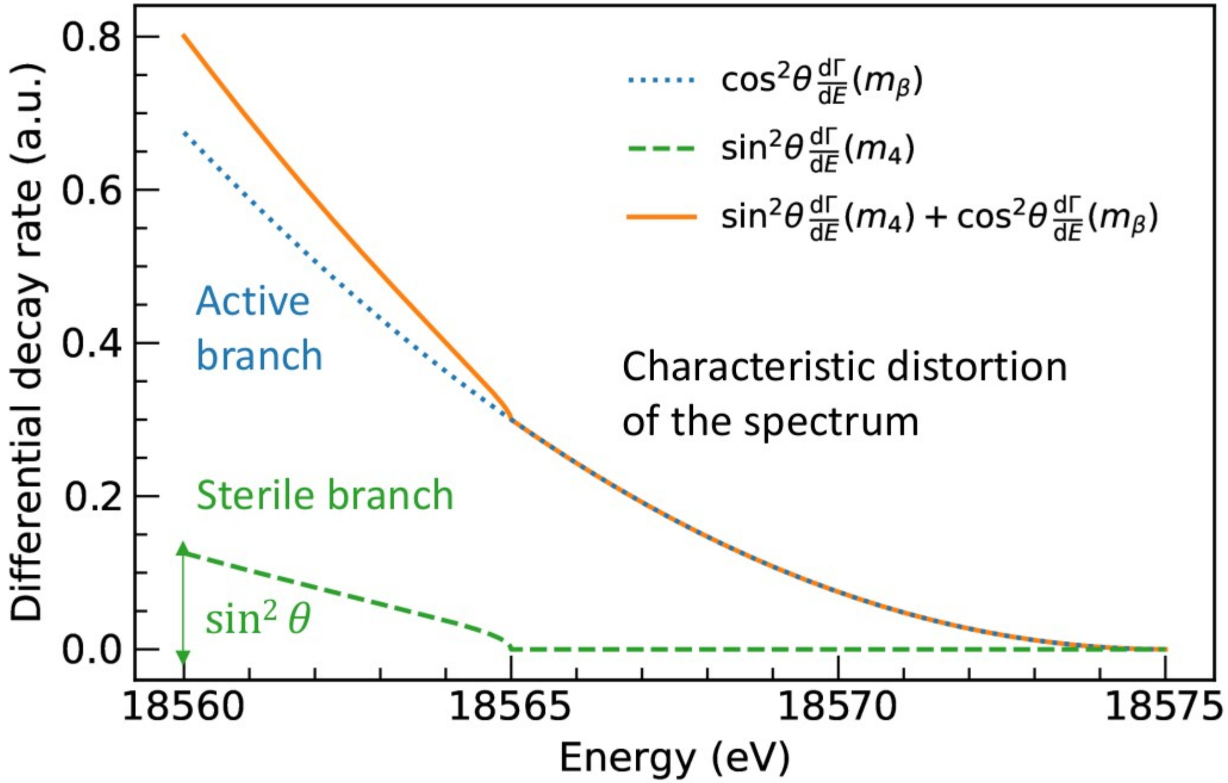
- Multiple anomalies in the oscillation data
- No universal explanation to all of them
- An oscillation-free measurement as an independent cross-check by KATRIN



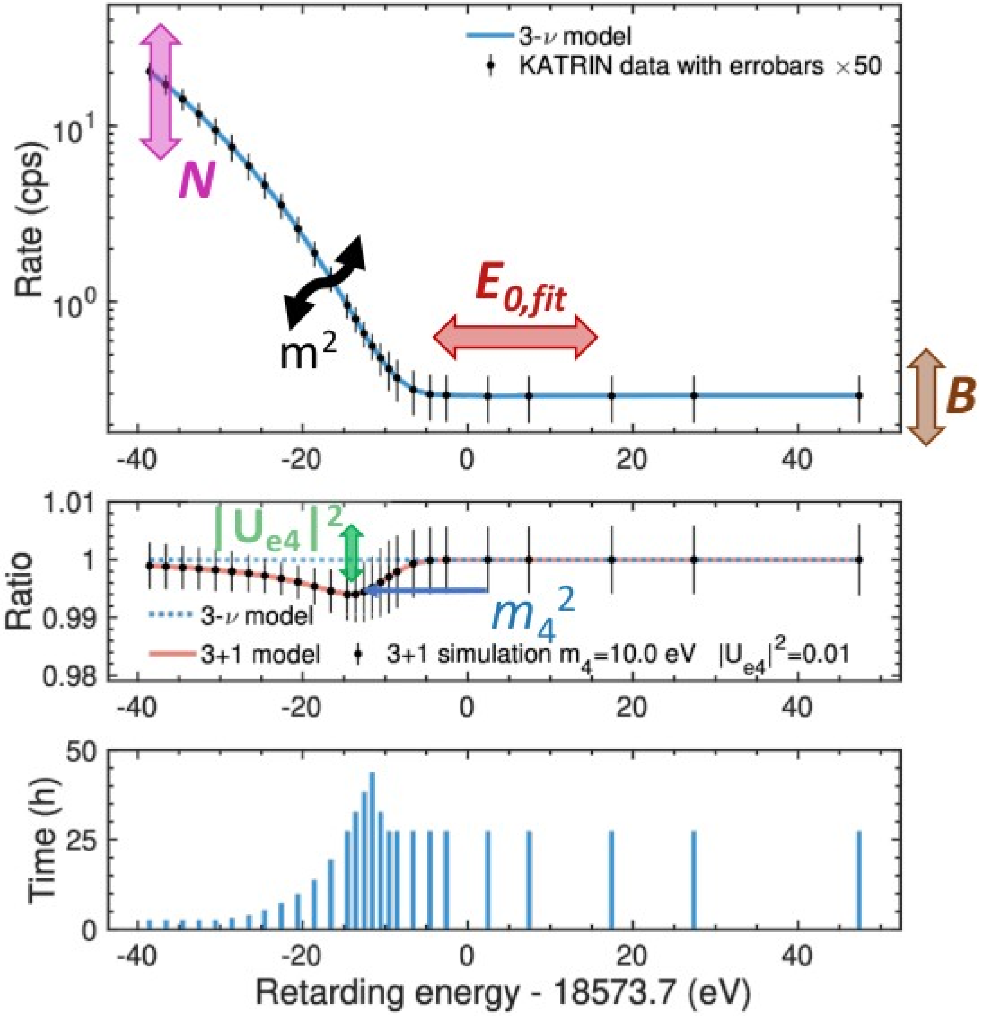
Sterile neutrinos signature in β-spectrum

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

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



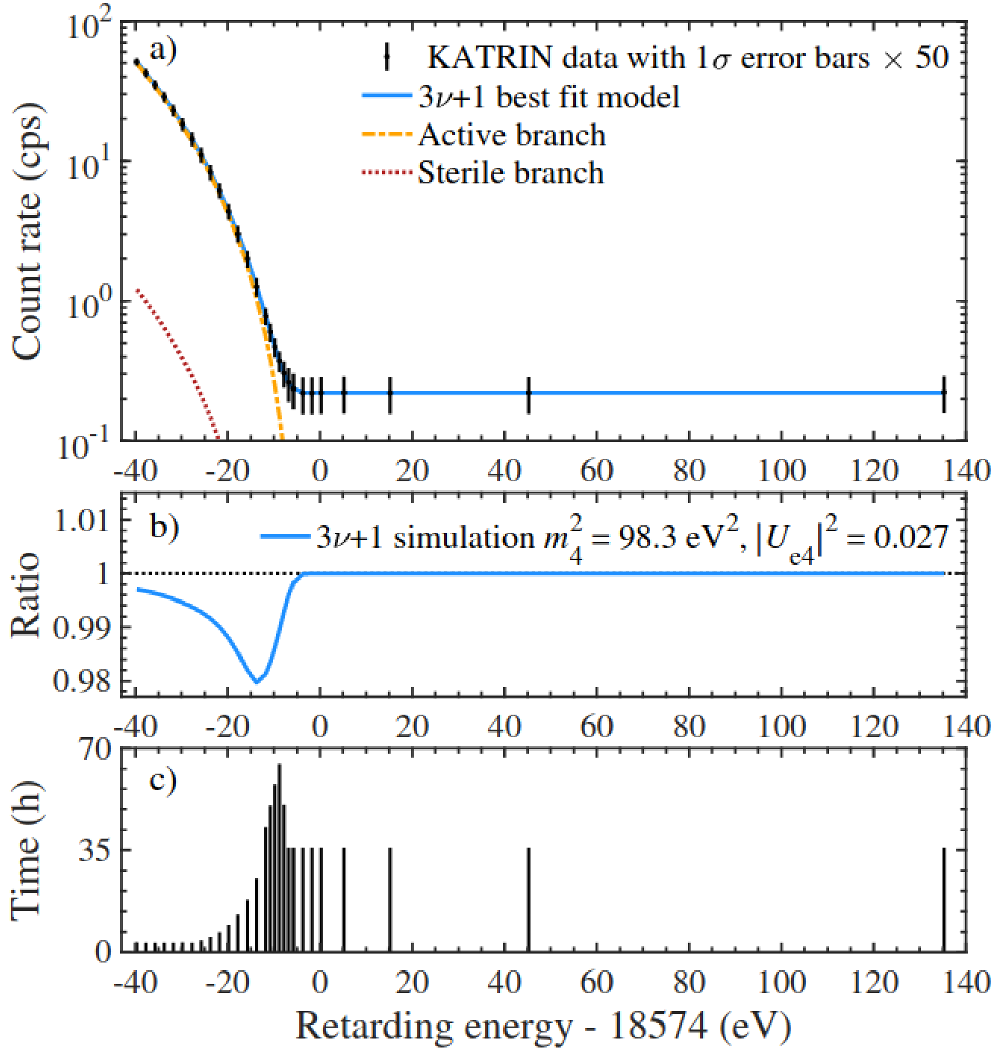
Sterile neutrinos signature in KATRIN



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 – 4th neutrino mass

Analysis of the 1st and 2nd science runs



3ν+1 model fitting

- Using χ^2 for parameter inference

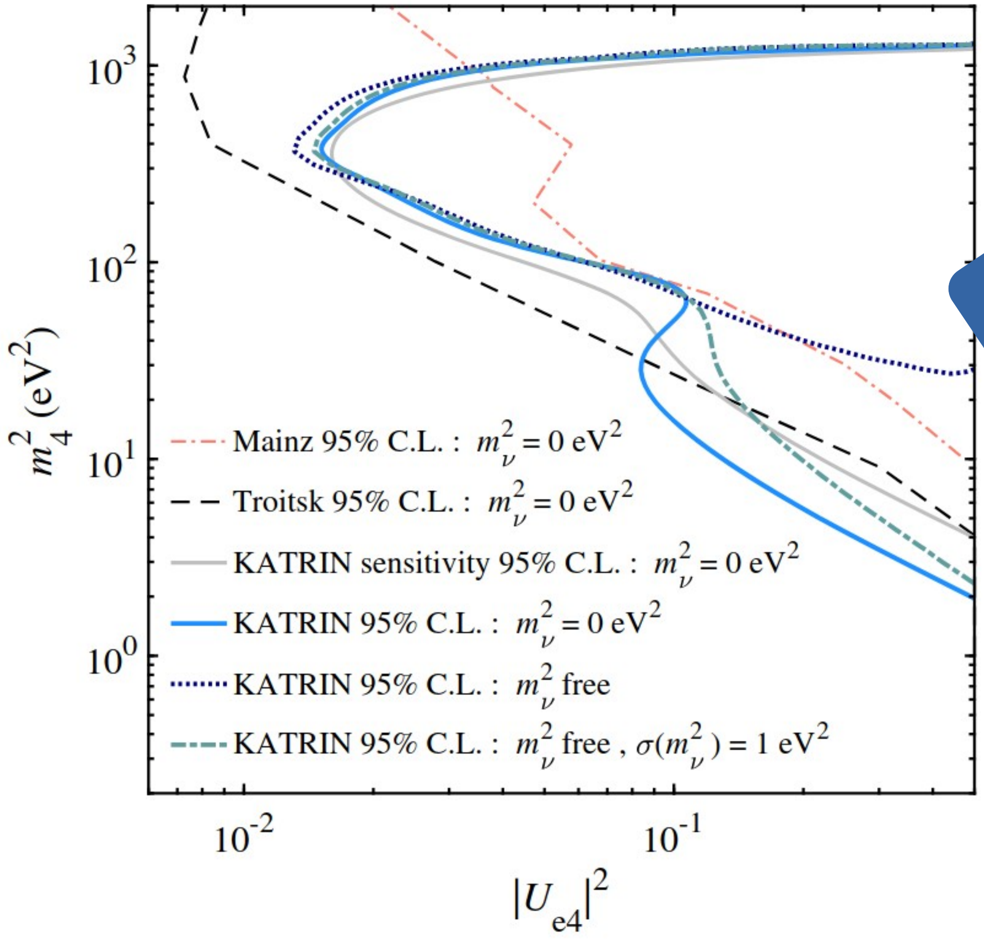
$$\chi^2(\vec{\xi}) = (\vec{R}_{\text{data}} - \vec{R}_{\text{model}}(\vec{\xi}))\ C^{-1}\ (\vec{R}_{\text{data}} - \vec{R}_{\text{model}}(\vec{\xi}))^{\top}$$

- Uncertainty inference via covariance matrix ***C***
- 50 x 50 logarithmically spaced grid
- $|U_{e4}|^2$ is constrained by < 0.5
  - otherwise active ↔ sterile
- 95% exclusion limit applying Wilks's theorem

$$\Delta\chi^2 = \chi^2 - \chi^2_{\text{min}} = 5.99$$

KATRIN Collab., PRD 105, 072004 (2022)

Results of the 1st science run



From only < 1% of KATRIN total statistics

Fixed $m_\nu^2 = 0$

$$m_4^2 = 77.5\,\mathrm{eV}^2, |U_{e4}^2| = 0.031$$
$$\Delta\chi^2_{null} = 1.43$$

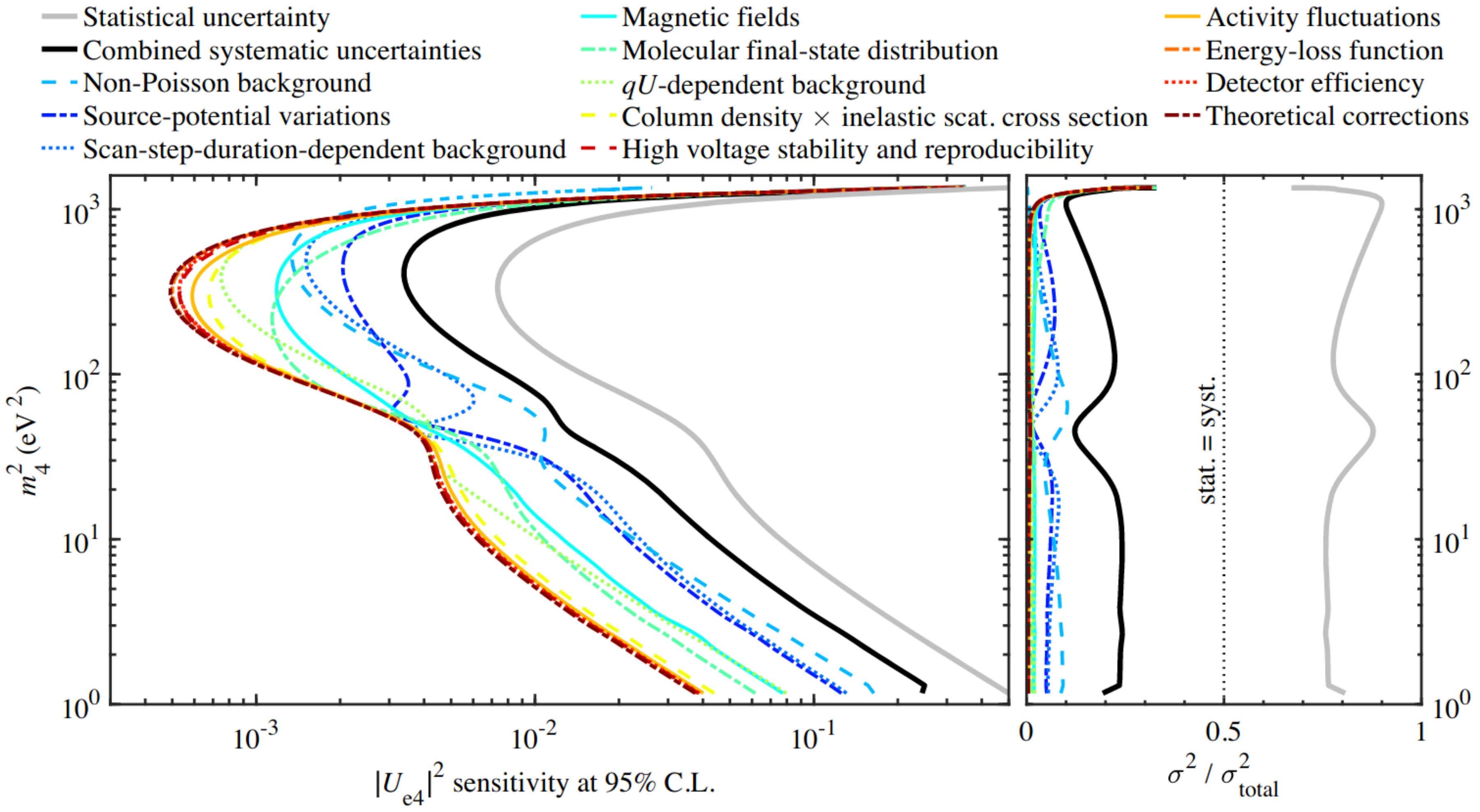
Free m_ν^2

$$m_4^2 = 21.8\,\mathrm{eV}^2, |U_{e4}^2| = 0.155$$
$$\Delta\chi^2_{null} = 1.30\,, m_\nu^2 = -5.3\,\mathrm{eV}^2$$

- ✓ Comparable to limits from Mainz and Troitsk

KATRIN Collab. PRL 126, 091803 (2021)

Sterile neutrino systematics (2nd campaign)



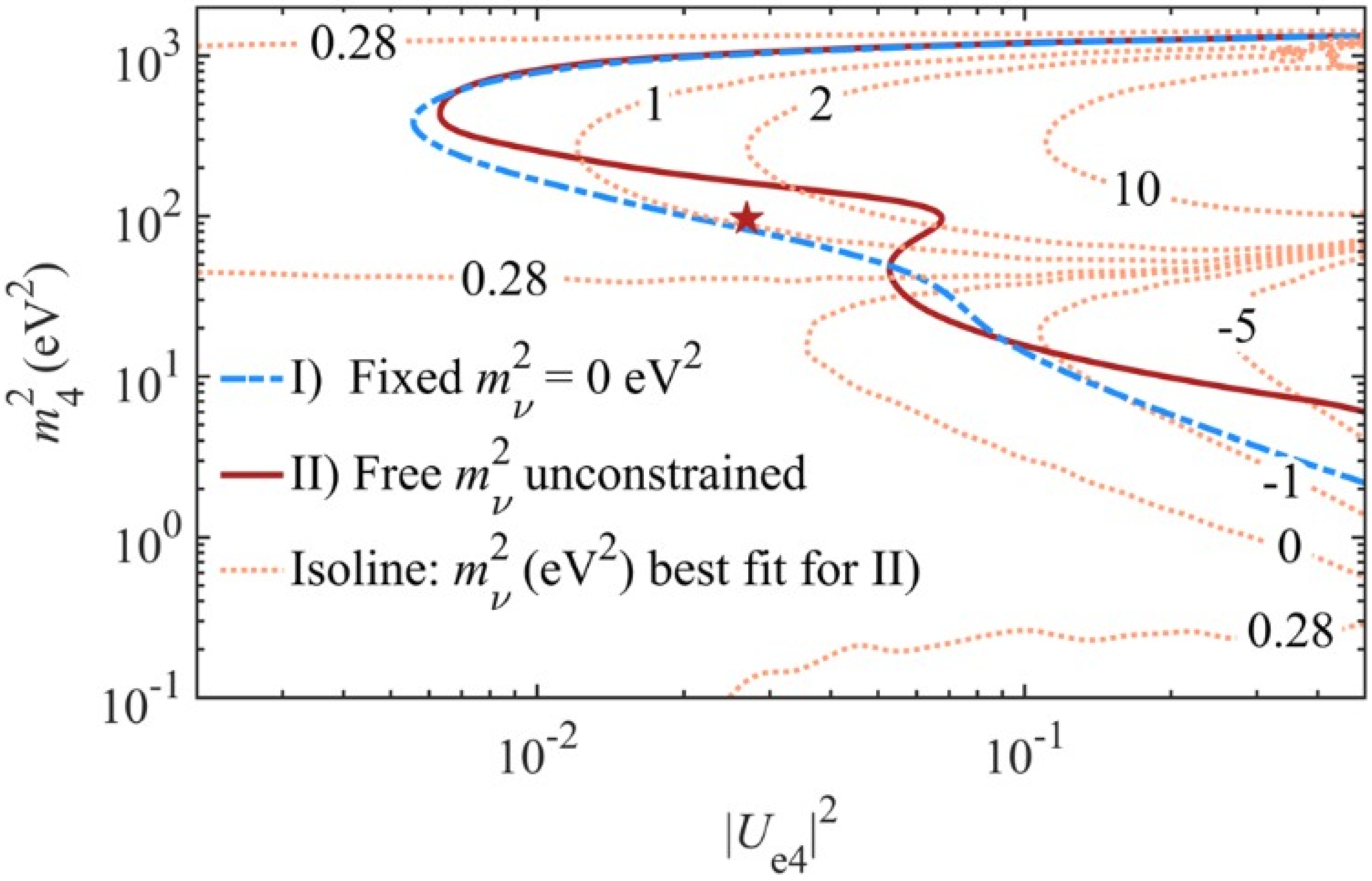
- Raster scan (fixed m_4^2)
- Estimate every systematic contribution to $|U_{e4}|^2$ uncertainty

$$\sigma_{syst} = \sqrt{\sigma^2_{total} - \sigma^2_{stat}}$$

- Statistics-dominated
  - Low m_4: background+source effects
  - High m_4: molecular final states

KATRIN Collab., PRD 105, 072004 (2022)

Interplay of m_ν^2 and m_4^2 (2nd campaign)



Fixed $m_\nu^2 = 0$

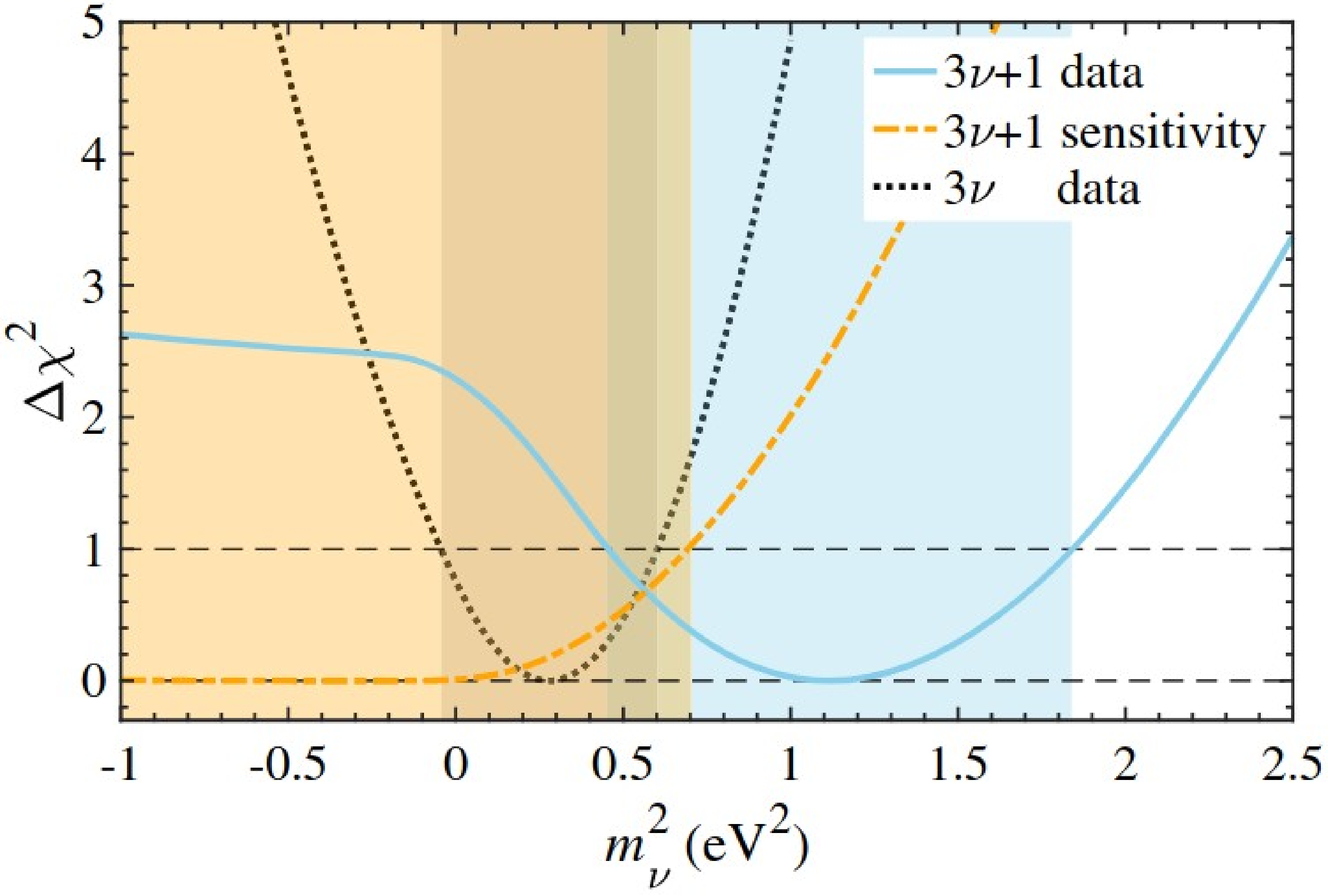
$$m_4^2 = 0.28\,\mathrm{eV}^2, |U_{e4}{}^2| = 1.0$$
$$\Delta\chi^2_{null} = 0.74$$

Free m_ν^2

$$m_4^2 = 98.3\,\mathrm{eV}^2, |U_{e4}{}^2| = 0.027$$
$$\Delta\chi^2_{null} = 2.49, m_\nu^2 = 1.1\,\mathrm{eV}^2$$

KATRIN Collab., PRD 105, 072004 (2022)

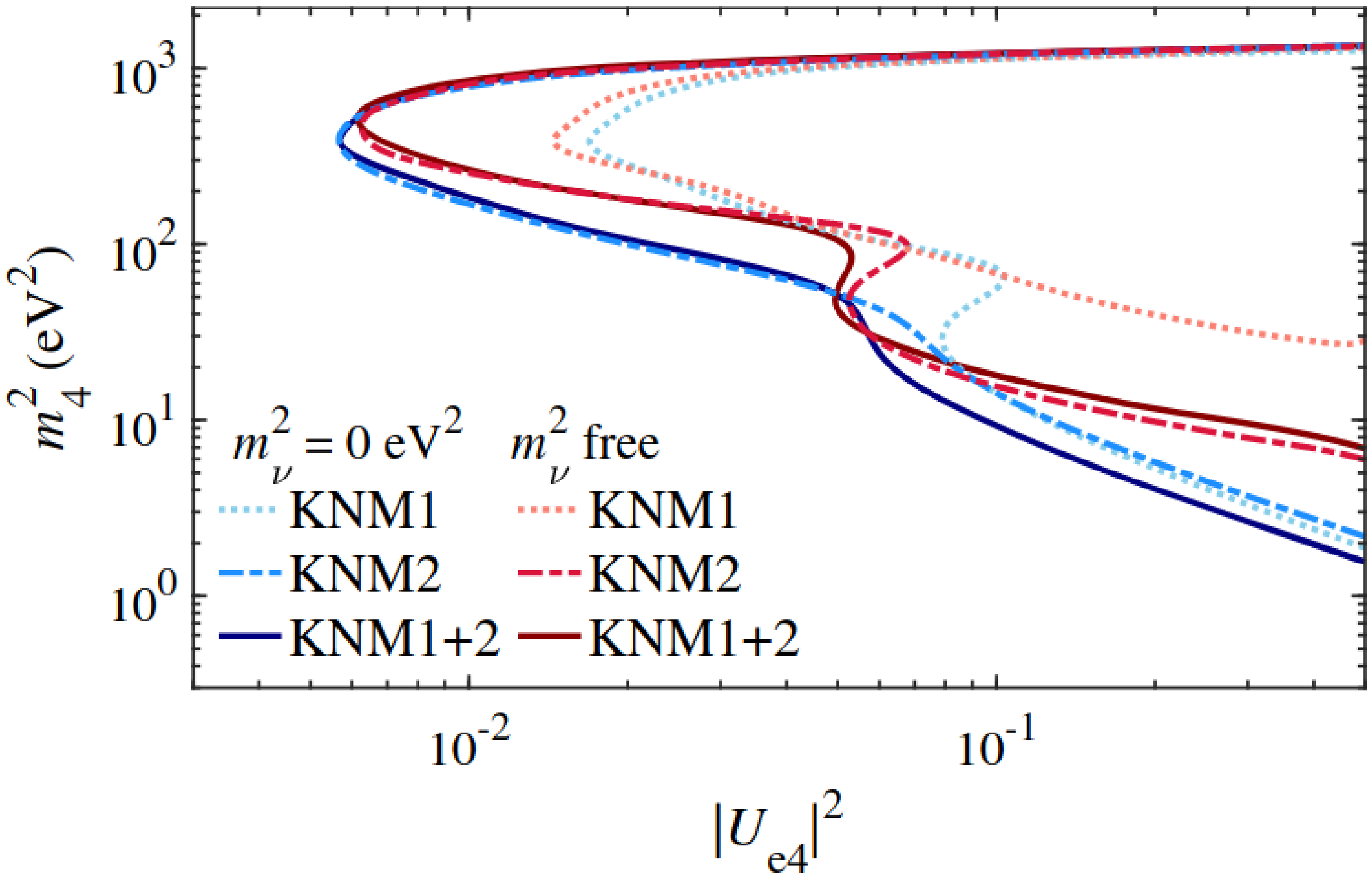
Interplay of m_ν^2 and m_4^2 (2nd campaign)



- Sizable correlation of $\boldsymbol{m_\nu^2}$ and $\boldsymbol{m_4^2}$
  - reduction in $\boldsymbol{m_\nu^2}$ sensitivity
- Strong correlation for $\boldsymbol{m_\nu^2 < 0}$ **eV²**
  - flat χ^2 profile → loss of sensitivity
  - restored by external constraints
- $\boldsymbol{m_\nu^2 > 0}$ **eV²** → x2 uncertainty on m_ν^2
- Fully restore sensitivity using
  - $|U_{e4}|^2 < 10^{-4}$

KATRIN Collab., PRD 105, 072004 (2022)

Combination of 1st and 2nd campaigns



Fixed $\boldsymbol{m_\nu^2 = 0}$

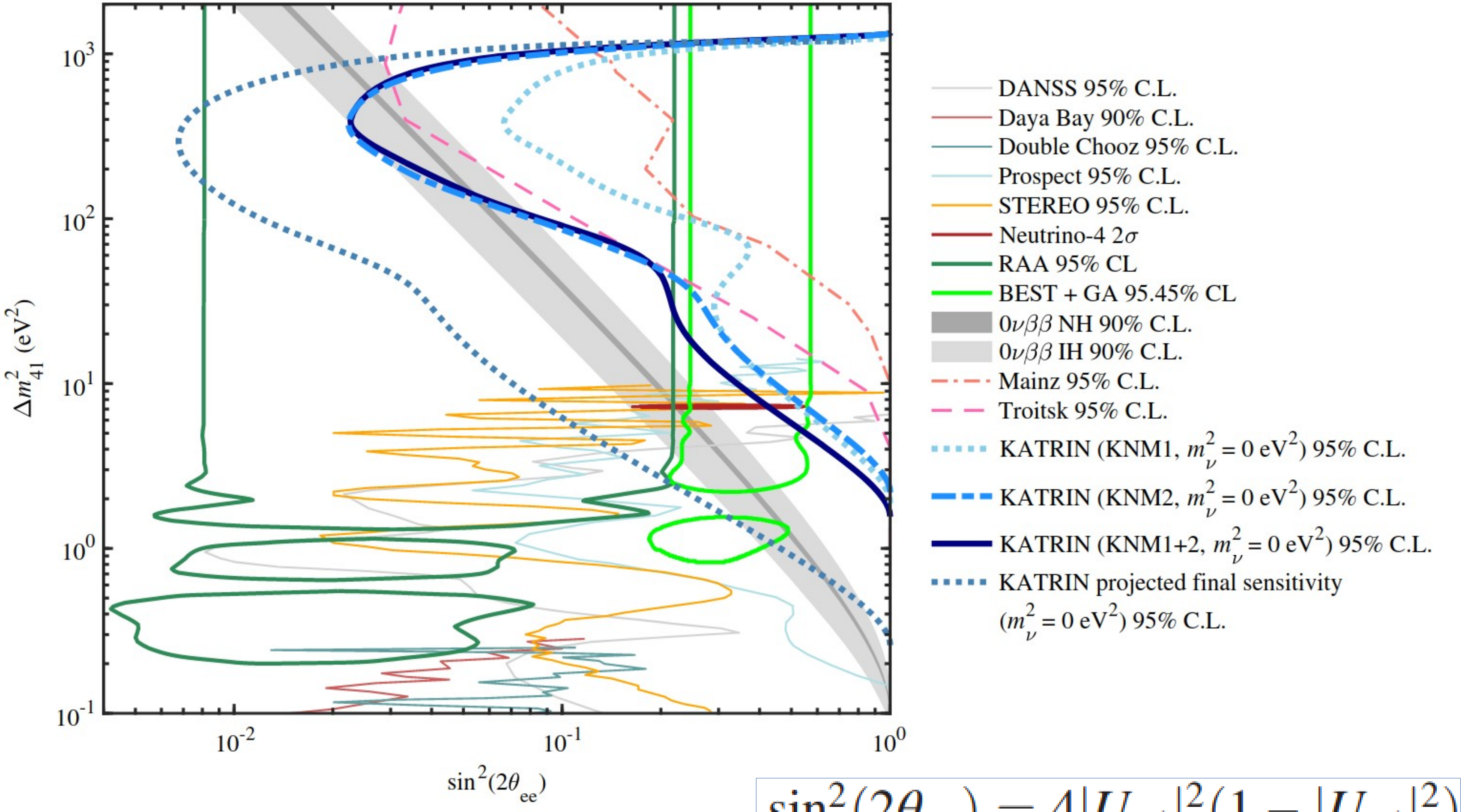
$$m_4^2 = 59.9\,\mathrm{eV}^2, |U_{e4}^2| = 0.011$$
$$\Delta\chi^2_{null} = 0.66$$

Free $\boldsymbol{m_\nu^2}$

$$m_4^2 = 87.4\,\mathrm{eV}^2, |U_{e4}^2| = 0.019$$
$$\Delta\chi^2_{null} = 1.69, m_\nu^2 = 0.57\,\mathrm{eV}^2$$

KATRIN Collab., PRD 105, 072004 (2022)

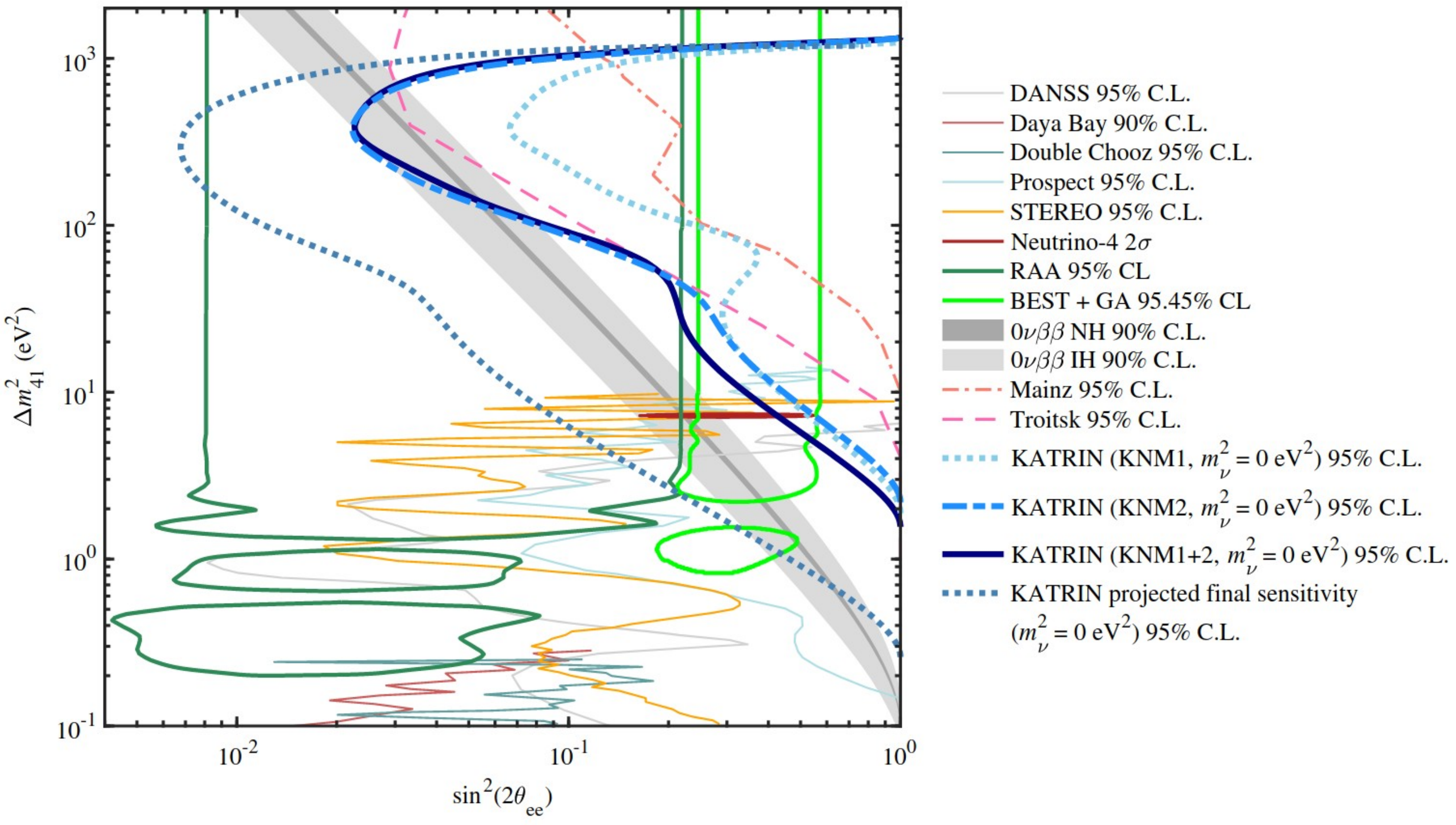
Sterile neutrinos – complimentarity



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

- 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 **Δm² > 10 eV²**
- complementary probe to oscillation-based experiments

Sterile neutrinos – prospects

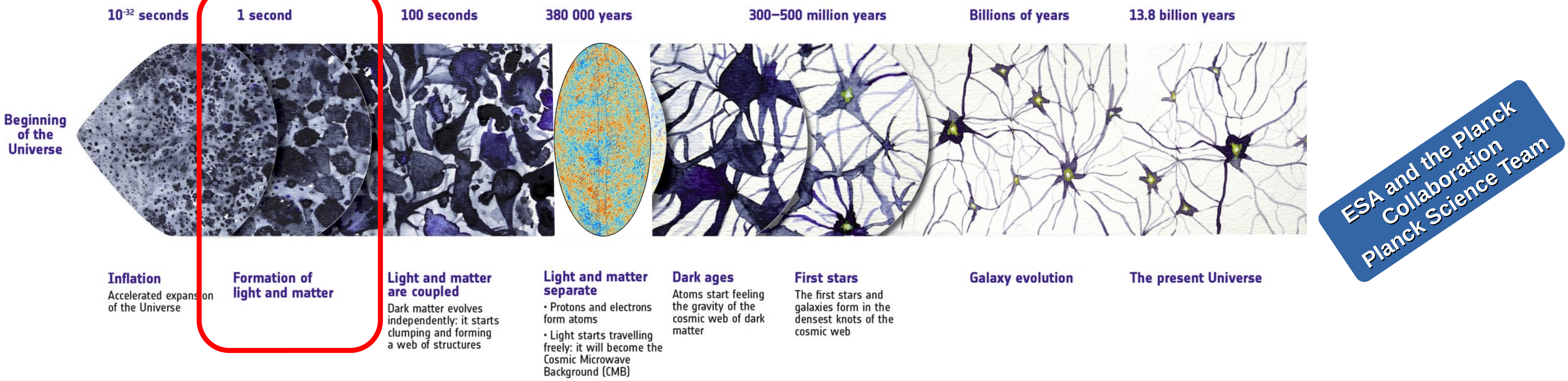


With final dataset

- Probing large portion of the RAA, BEST and Neutrino-4
- comparable sensitivities to neutrinoless double β-decay

KATRIN Collab., PRD 105, 072004 (2022)

Cosmic neutrino background: Motivation

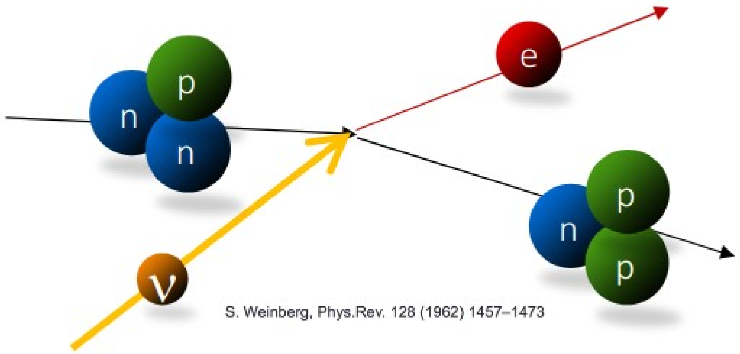


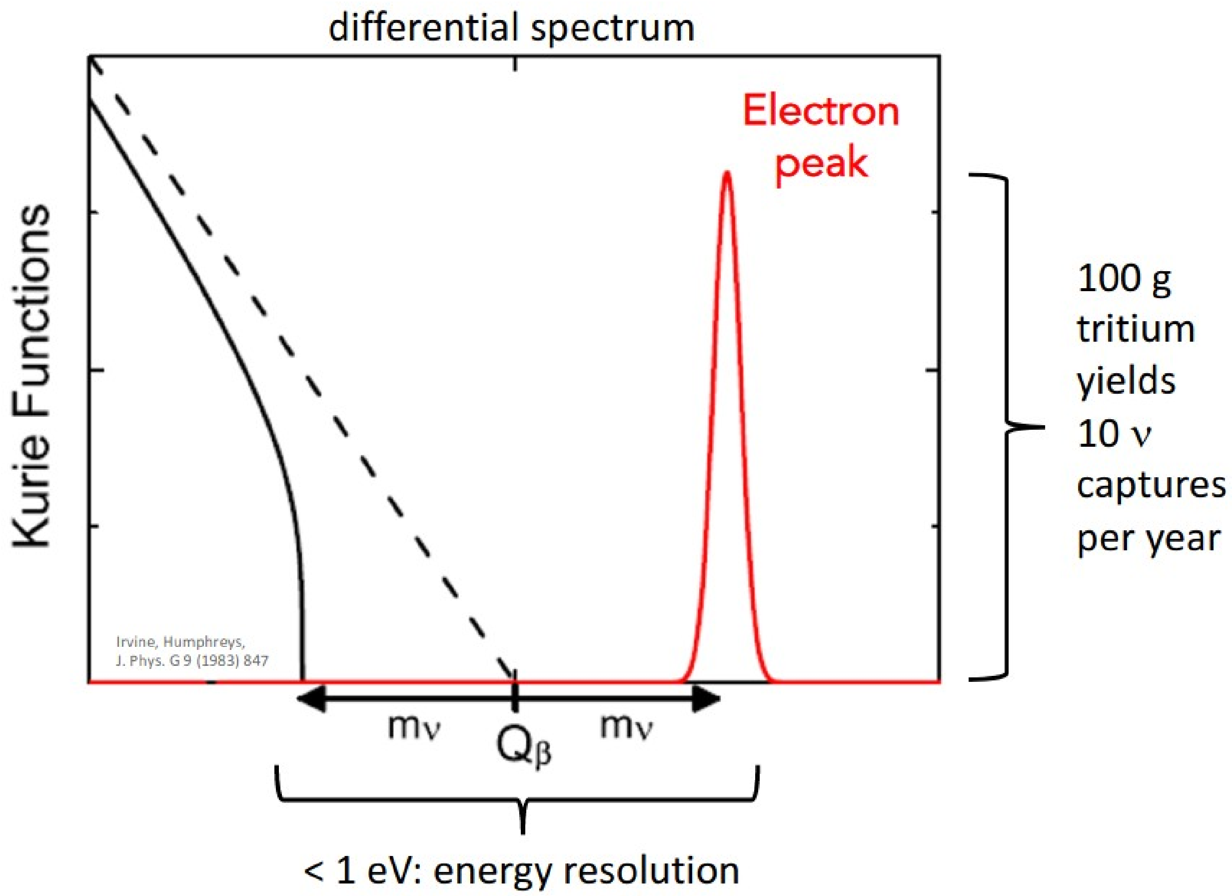
- ~340 relic neutrinos of all species /cm^3 in the Universe (56 /cm^3 per species)
- Decoupled the first second (1 MeV) after Big Bang
- Predicted overdensity $\eta \approx (1.2..20)$
- upper limits from previous kinematic neutrino mass measurements: 10^{13}

Relic neutrinos search with KATRIN

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

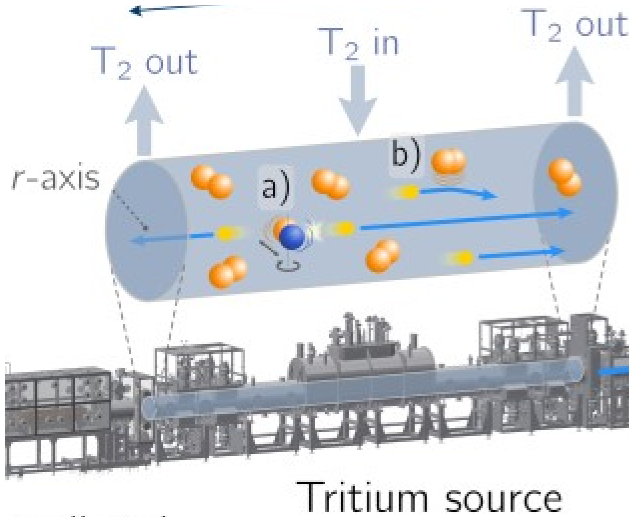
$$^3\mathrm{H} + \nu_e \longrightarrow {}^3\mathrm{He}^+ + e$$

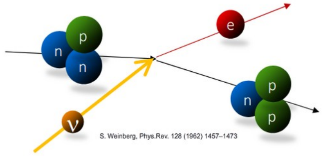




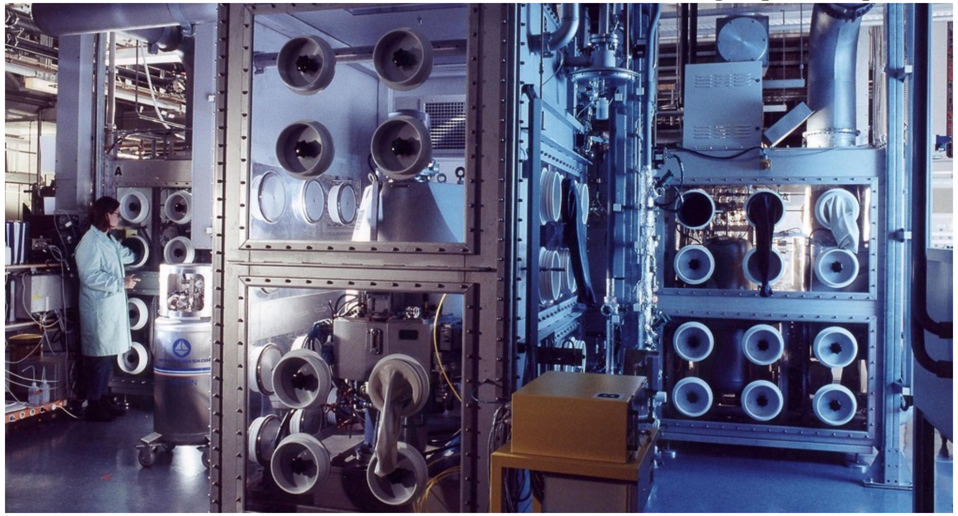
KATRIN Collab., arXiv:2202.04587, accepted to PRL

Relic neutrinos search with KATRIN





Karlsruhe Tritium Laboratory (TLK)



up to 40 g of tritium

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

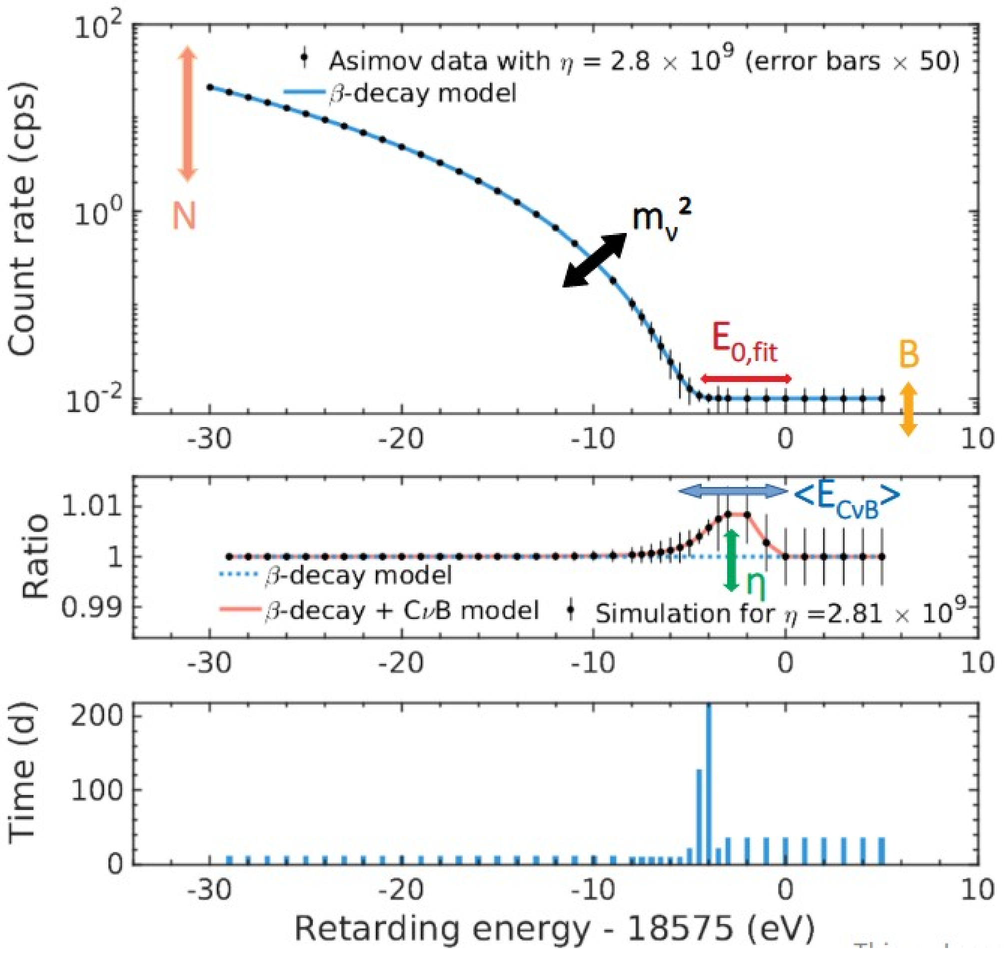
KATRIN has the sensitivity to probe large clustering of cosmic neutrinos around the solar system

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

KATRIN Collab., arXiv:2202.04587, accepted to PRL

Model for the relic neutrinos in KATRIN

Karlsruher Institut für Technologie



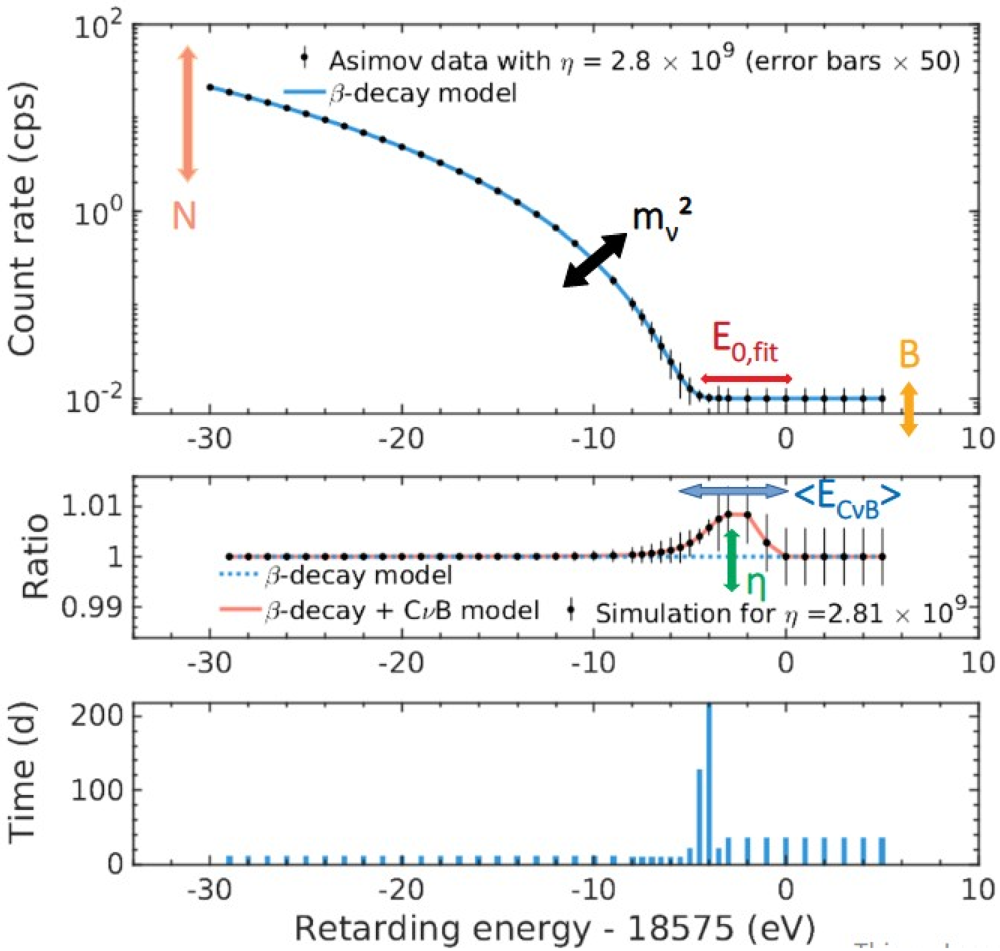
Fit parameters:

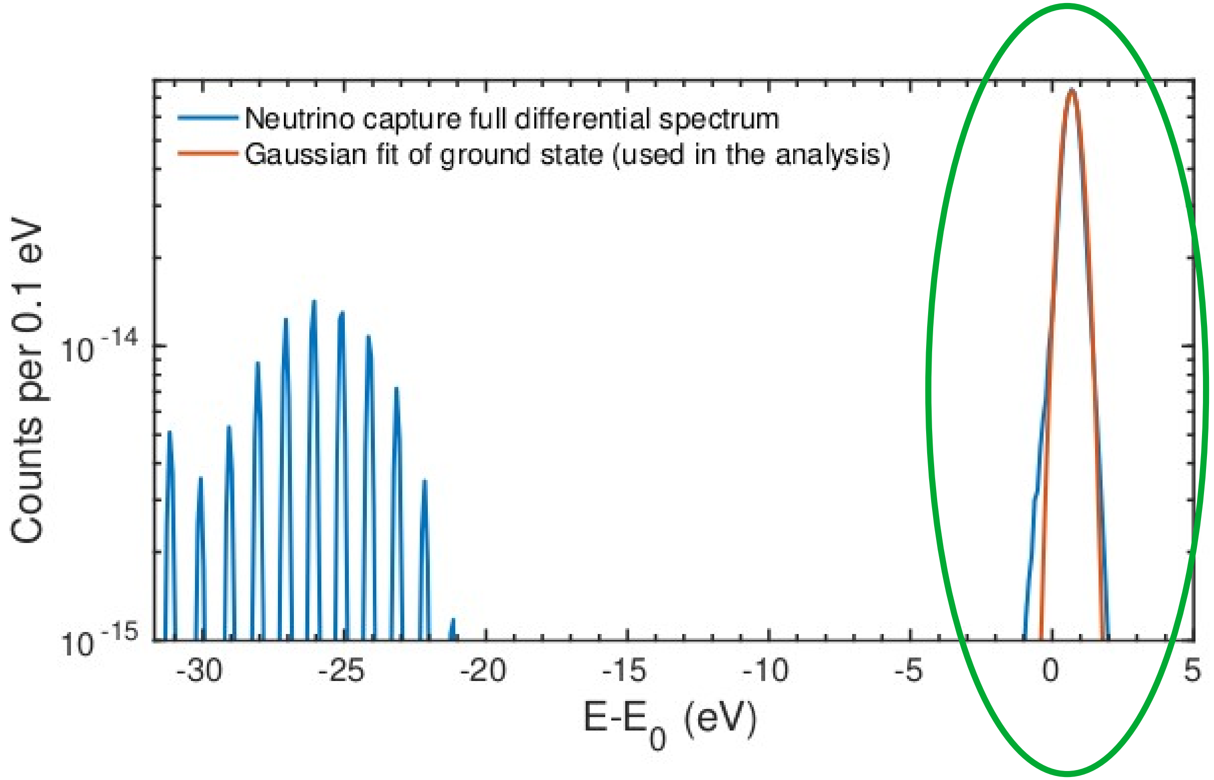
- N – amplitude of the signal
- E_0 – effective endpoint energy
- m_2 – effective mass of the electron antineutrino
- B – background rate
- η – local overdensity
- meV energy is neglected

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

KATRIN Collab., arXiv:2202.04587, accepted to PRL

Model for the relic neutrinos in KATRIN

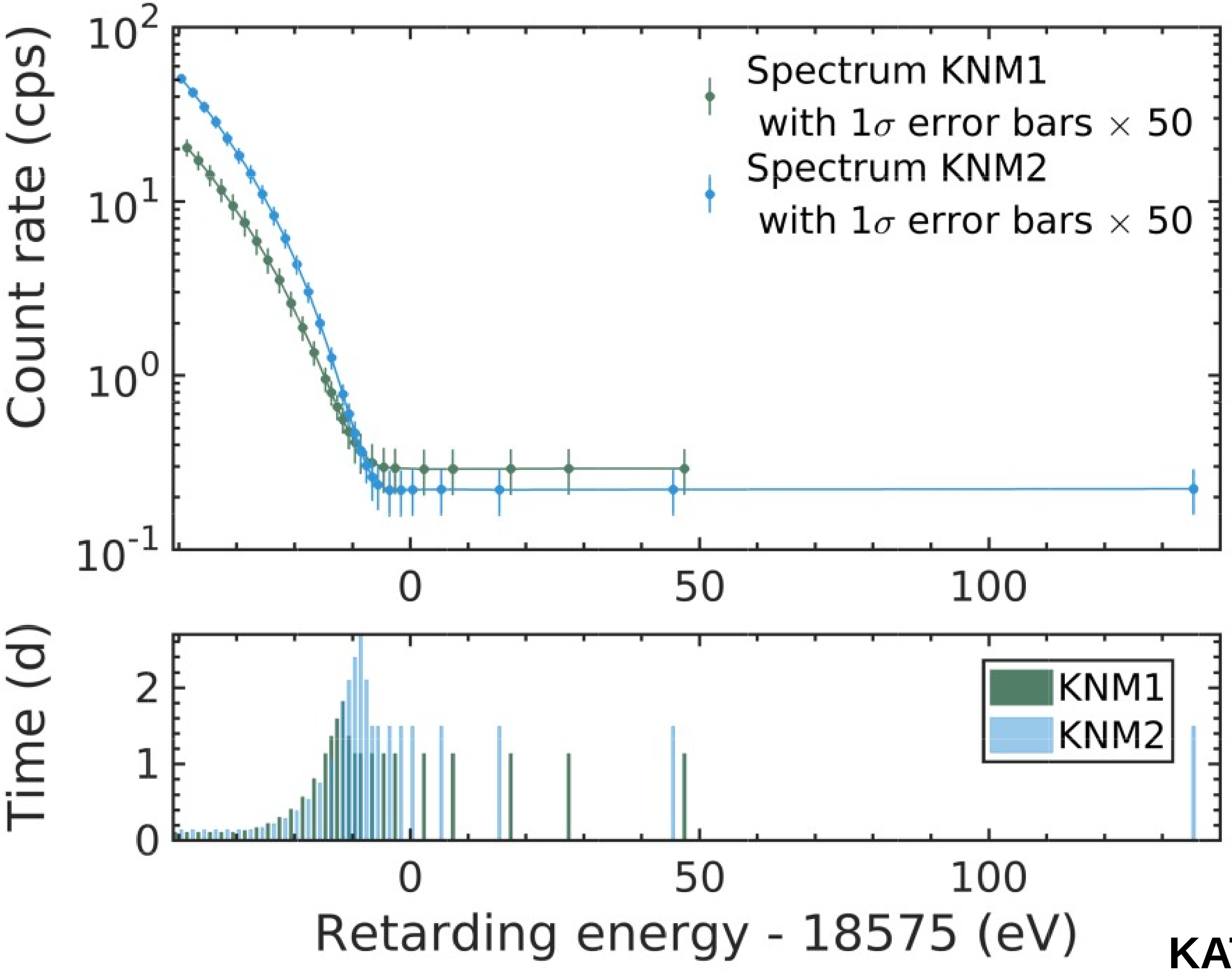




$$R_{\rm diff}(E) = R_\beta(E) + R_{\rm C\nu B}(E)$$

KATRIN Collab., arXiv:2202.04587, accepted to PRL

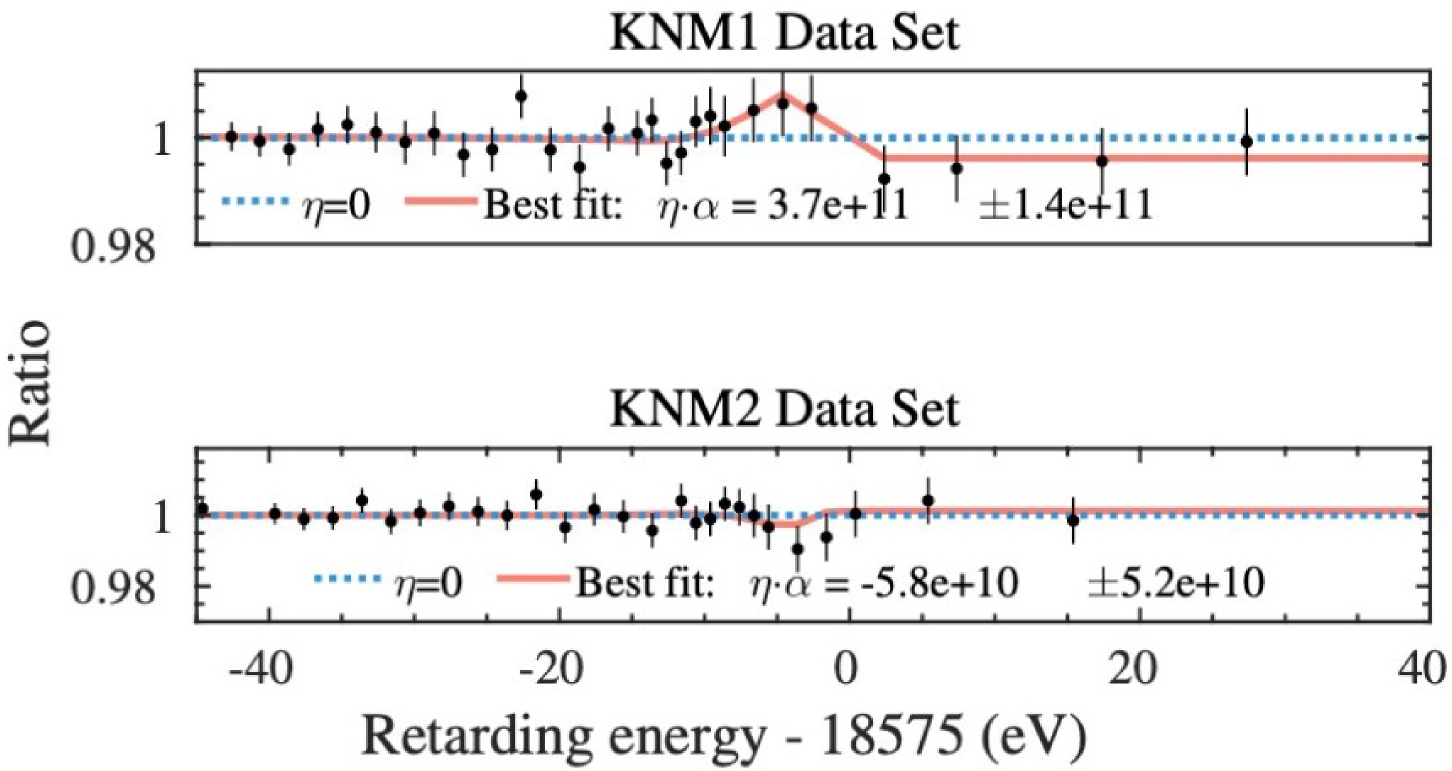
Relic neutrinos in the first science runs



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

KATRIN Collab., arXiv:2202.04587, accepted to PRL

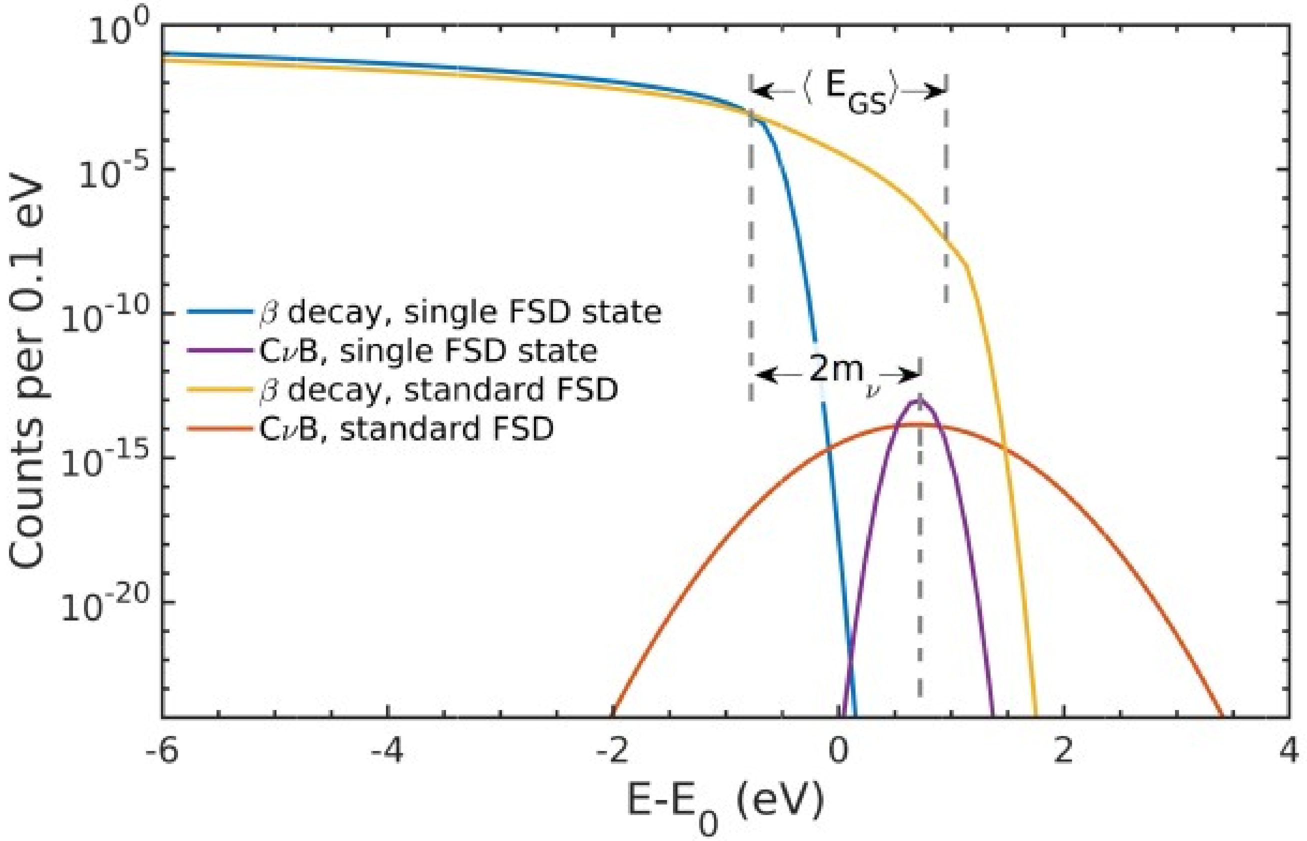
Relic neutrinos in the first science runs



- 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

KATRIN Collab., arXiv:2202.04587, accepted to PRL

Relic neutrinos: challenges

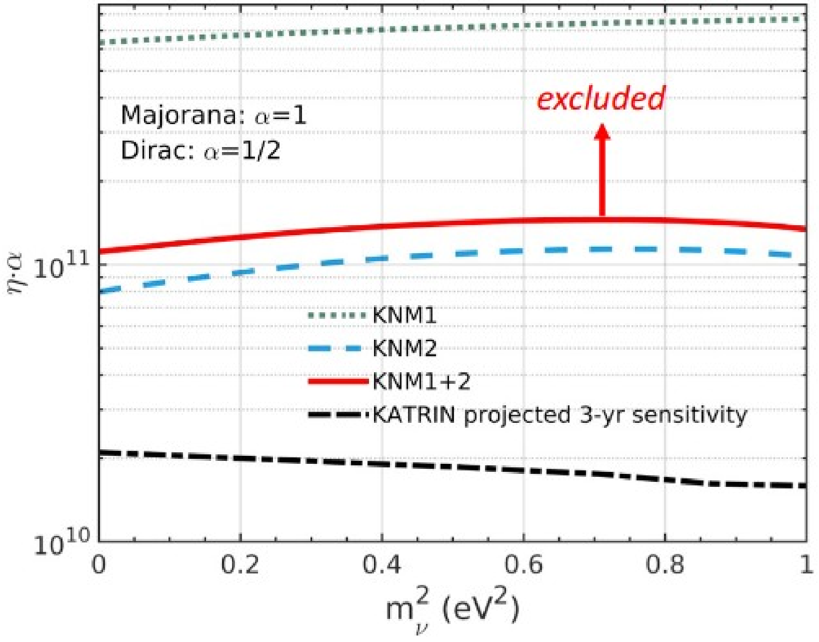


- Background rate
  - order of magnitude higher
- β-spectrum creates irreducible background
  - $m_\nu < \langle E_{GS} \rangle /2 = 0.85$ eV
  - increase of the target mass does not increase the CνB sensitivity

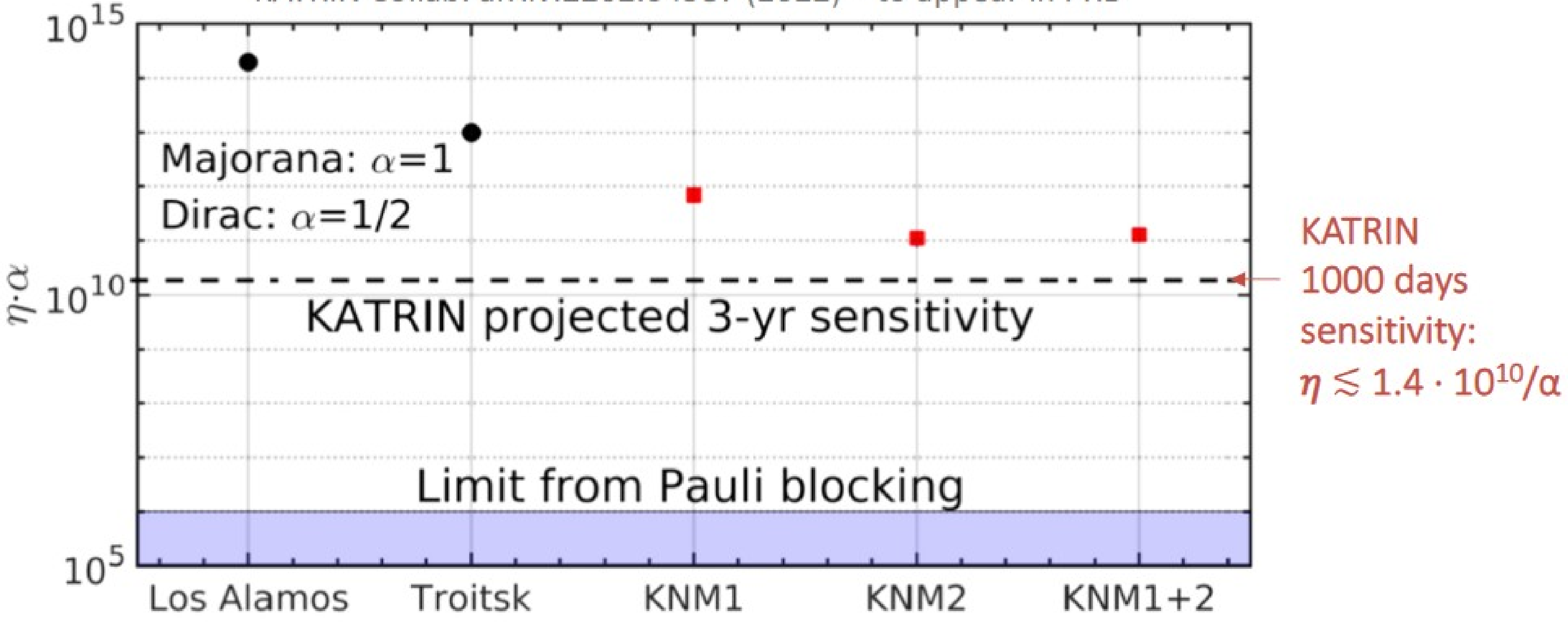
KATRIN Collab., arXiv:2202.04587, accepted to PRL

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



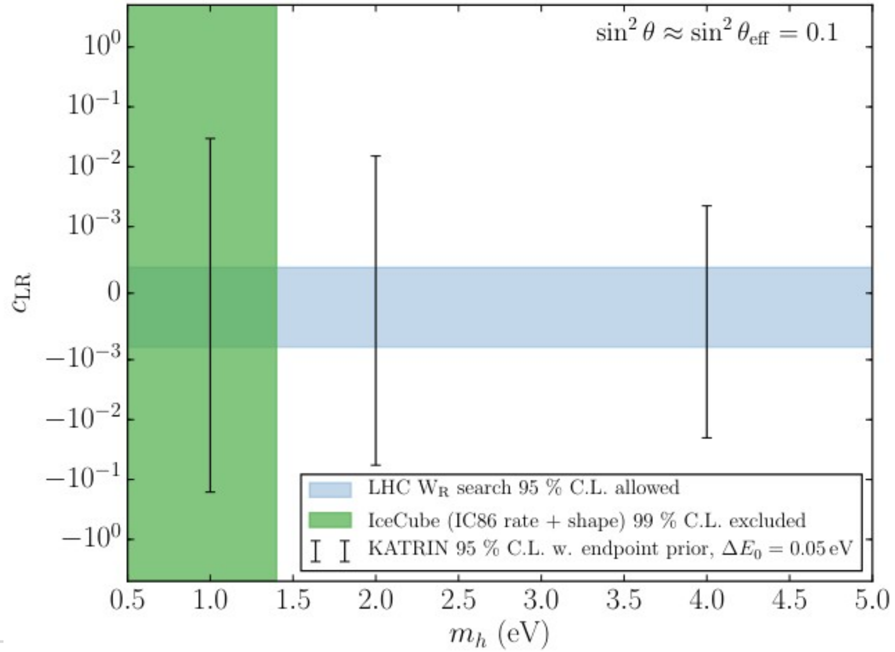
KATRIN Collab. arXiv:2202.04587 (2022) – to appear in PRL



GNI and BSM charged currents

- Generalized neutrino interactions
  - new neutrino interactions of scalar, pseudoscalar, vector, axial vector and tensor type
  - energy-dependent distortions of the measured β-decay spectrum
  - E_0 is a free parameter → better knowledge of the absolute energy scale is required

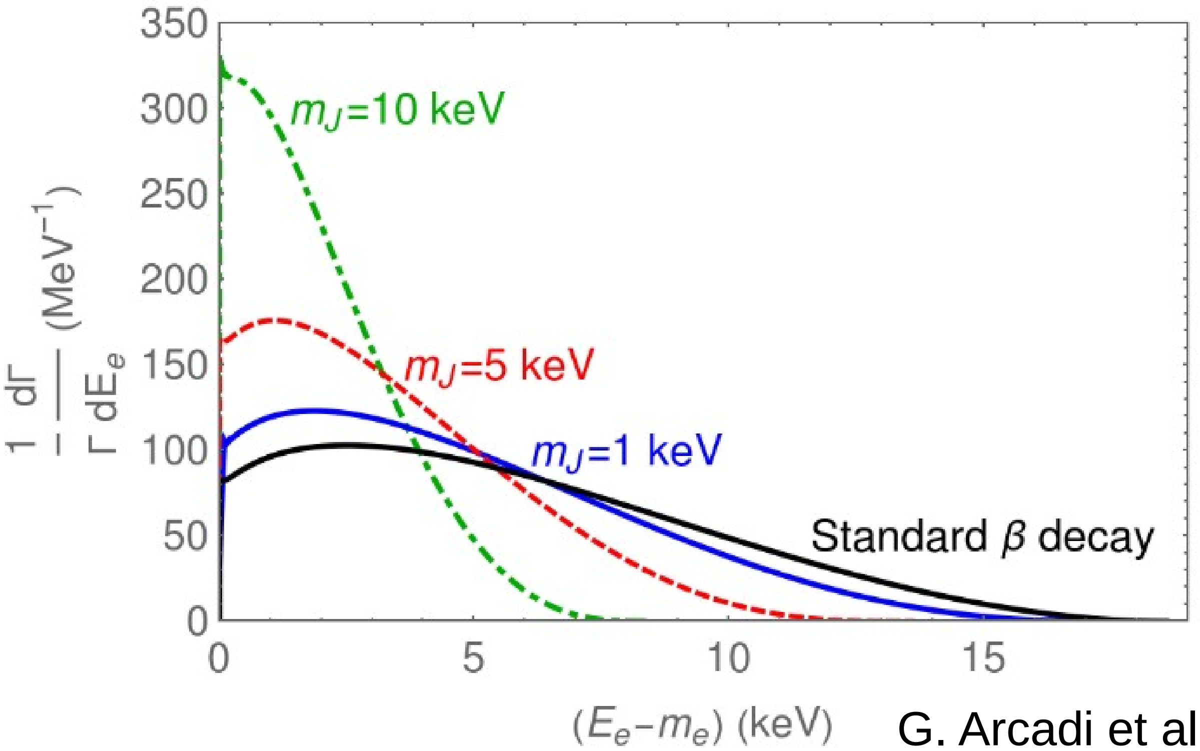
    → see talk by Caroline Rodenbeck later today
- Right-handed currents combined with sterile neutrinos
  - sensitivity to the left-right interference term
  - precise knowledge of E_0 required

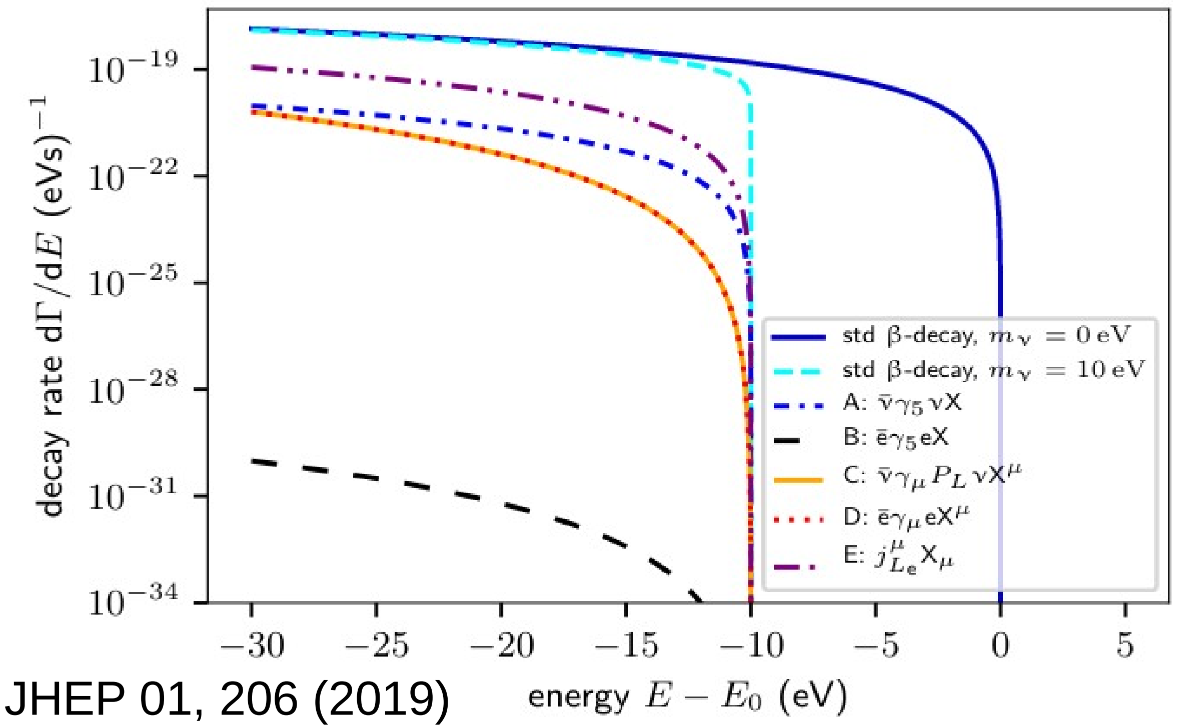


N. M. N. Steinbrink et al.,JCAP 06, 015 (2017)

New light bosons: Motivation

- 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'

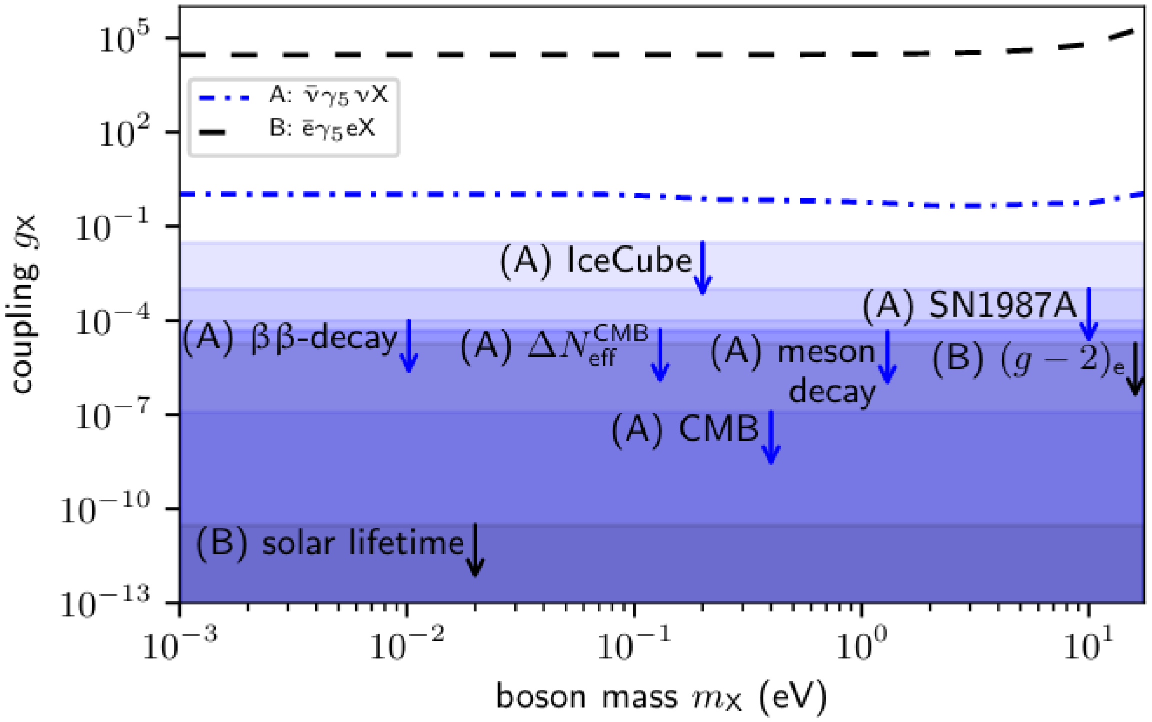


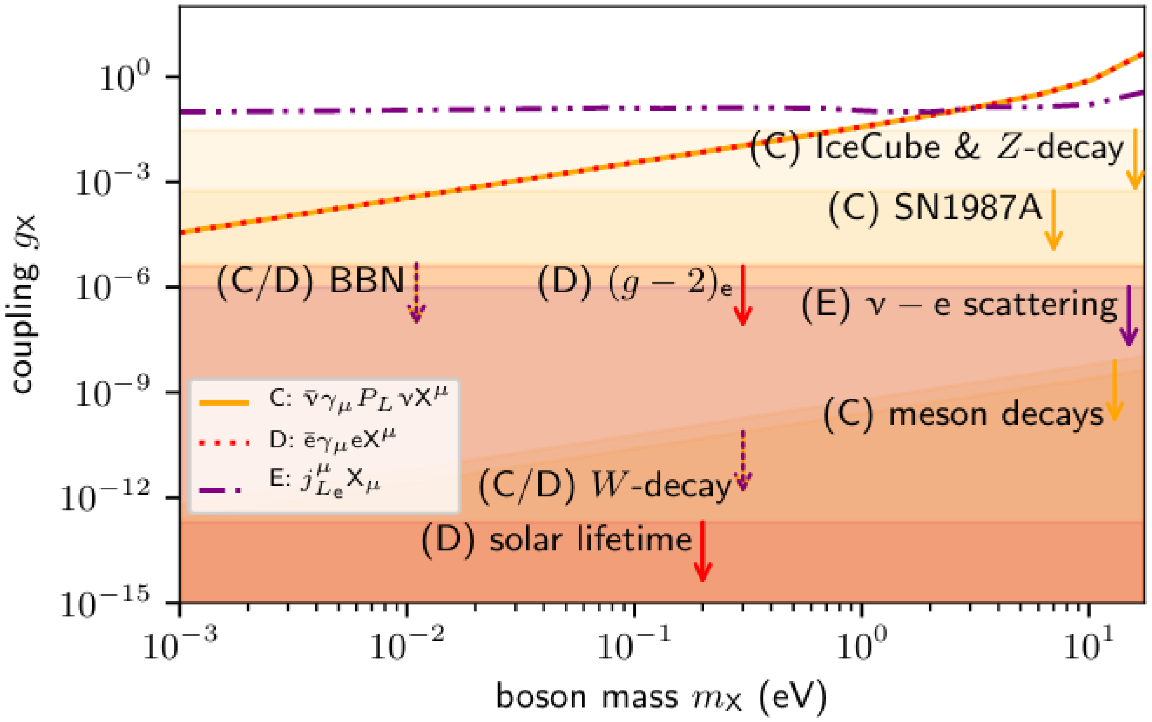


G. Arcadi et al. JHEP 01, 206 (2019)

New light bosons: Sensitivity

- Searching for new physics in the low-energy range
  - a pseudoscalar coupling to neutrino, to electron, and a Z′ coupling to neutrino, electron and both



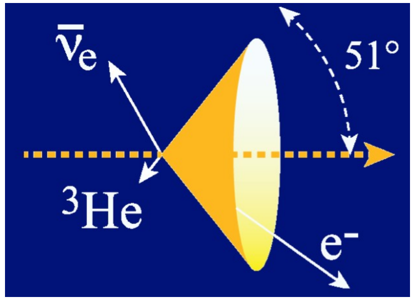


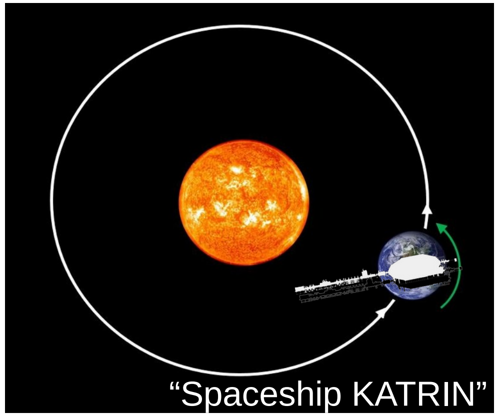
G. Arcadi et al. JHEP 01, 206 (2019)

Lorentz invariance violation

- Lorentz invariance violation (LIV) can be probed by KATRIN (oscillation-free parameters accessible only in kinematics / endpoint experiments)
- “Standard Model Extension” (SME) based on effective field theory + background fields: Anisotropic effects could be observable at KATRIN (“intrinsic direction” via acceptance cone)

illustrations by R. Lehnert





➜ See, e.g.: Colladay & Kostelecký 1998;
Díaz, Kostelecký & Lehnert 1305.4636

Possible impact on β-spectrum:

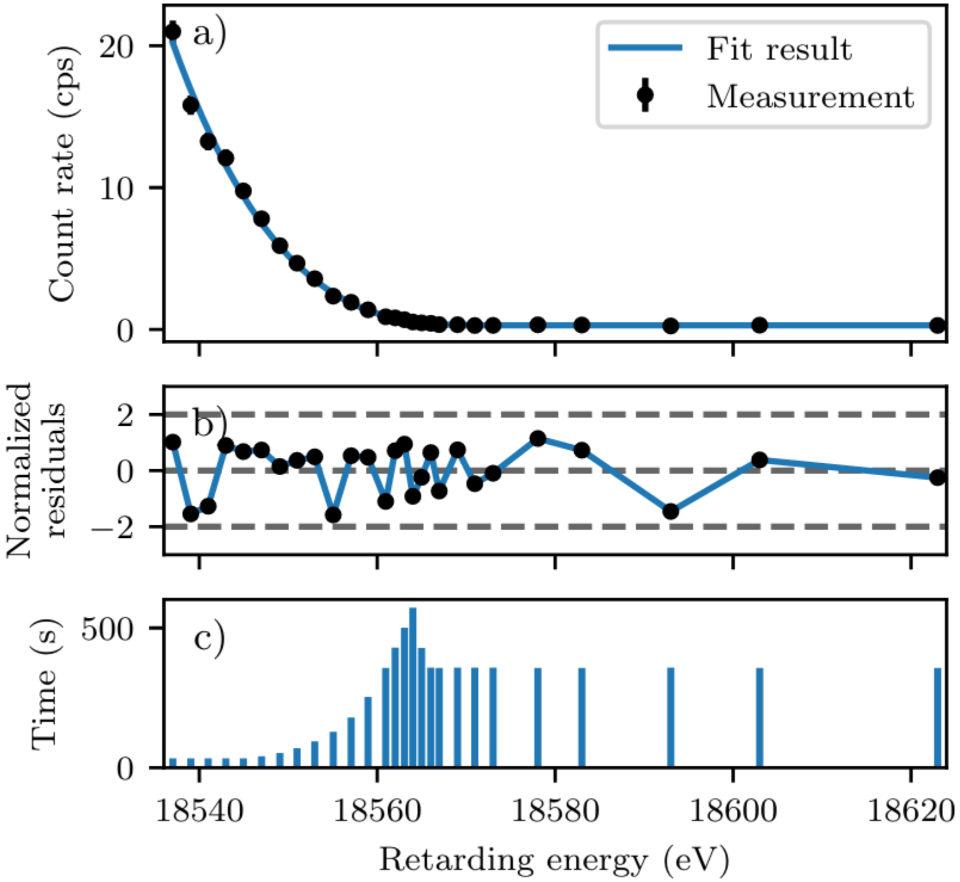
- Global shift of endpoint E_0
- Sidereal oscillation of E_0: search in repeated spectrum scans (typ. scan sequence ~2 hrs)

Modulation search: Need careful examination of potential systematic effects

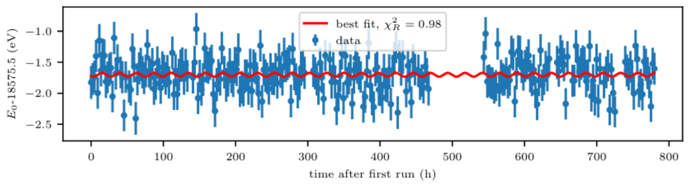
Other speculative influences, e.g. space weather or orbital distance impact on decay constants …?

Lorentz invariance violation in KATRIN

Fit each scan of β-spectrum



Estimate amplitude of E_0 oscillation



Convert into estimation of LIV parameters

Publication in preparation – stay tuned!

Conclusion & Outlook

- High precision measurement of tritium endpoint with KATRIN
- 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 signatures near E_0 – light bosons and
- 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!