Karlsruher Institut für Technologie

KATRIN experiment - recent results and future prospects

September 16-22, 2022 – Erice, Sicily

Alexey Lokhov for the KATRIN collaboration

Outline

- Neutrino mass measurements
- KATRIN experiment
- First neutrino mass results of KATRIN
- “Beyond neutrino mass” with KATRIN
- Summary and outlook

Three ways to assess the absolute neutrino mass scale

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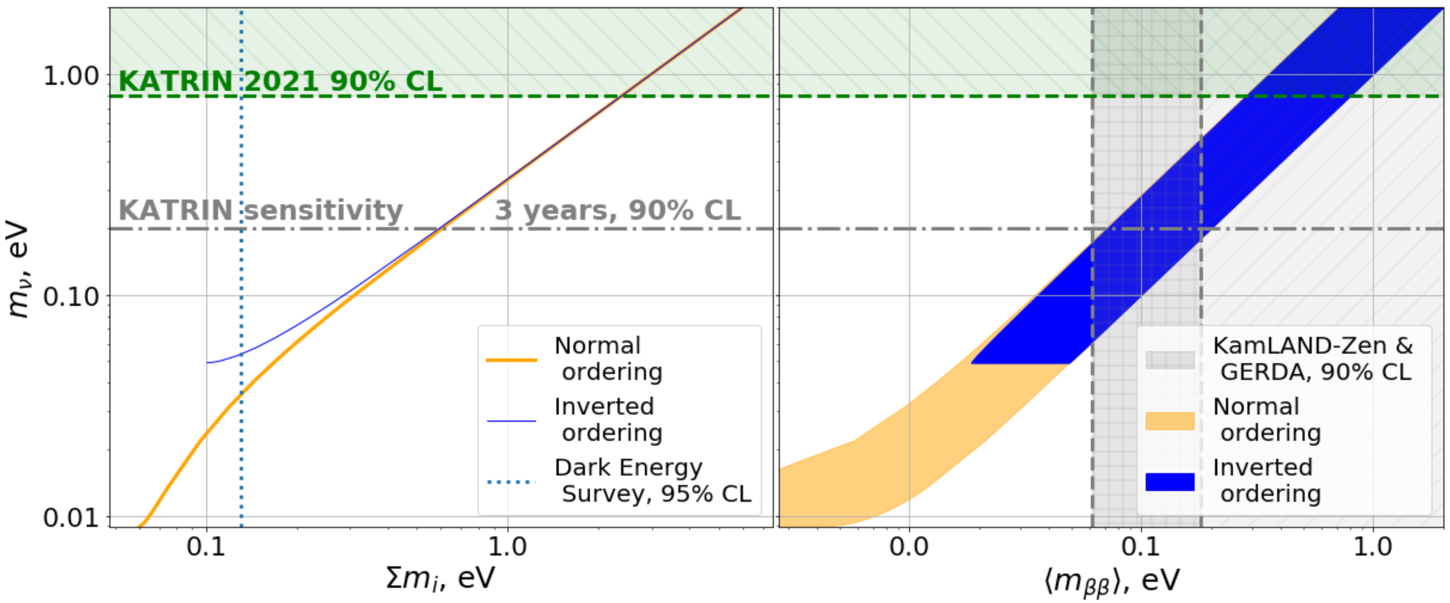
1) Cosmology

- 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:

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

3) Direct neutrino mass determination

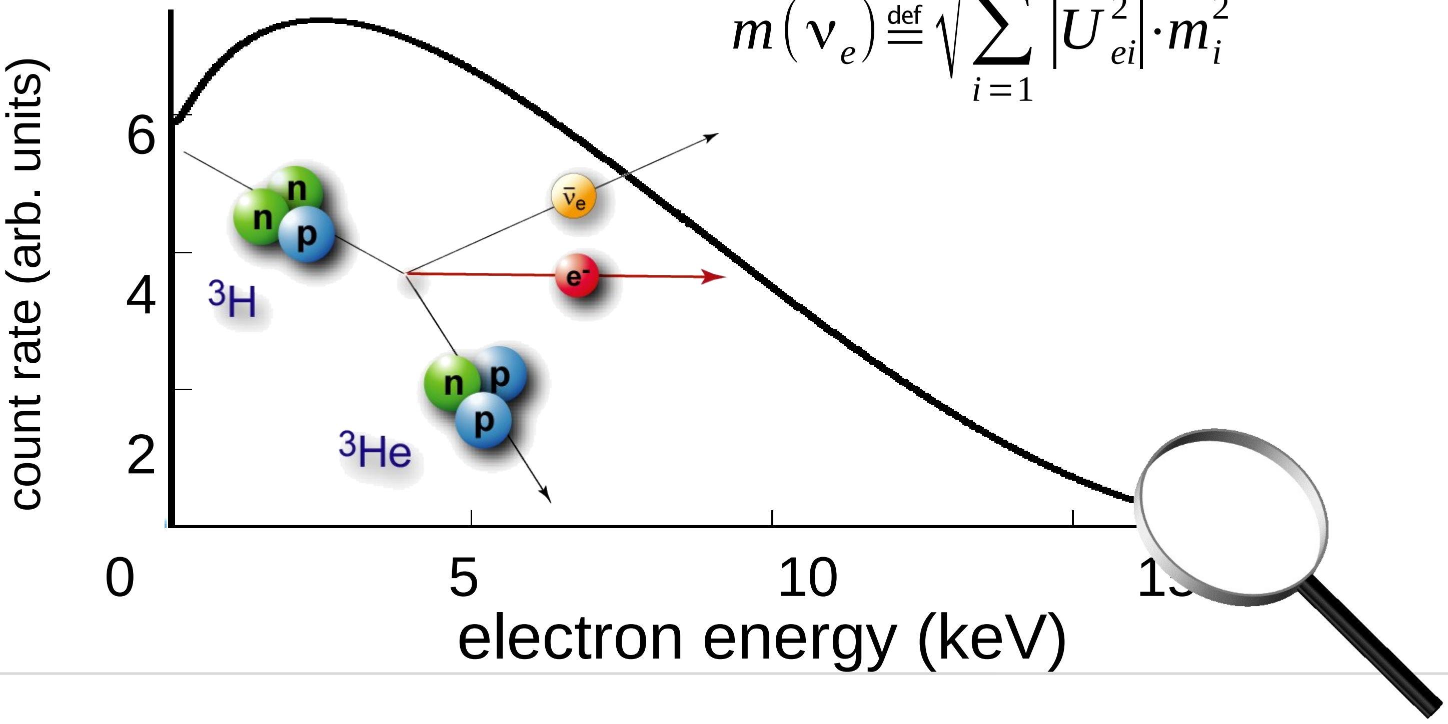
- No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$
- Time-of-flight measurements (ν from supernova)
- Kinematics of weak decays / beta decays, e.g. T, ^{163}Ho

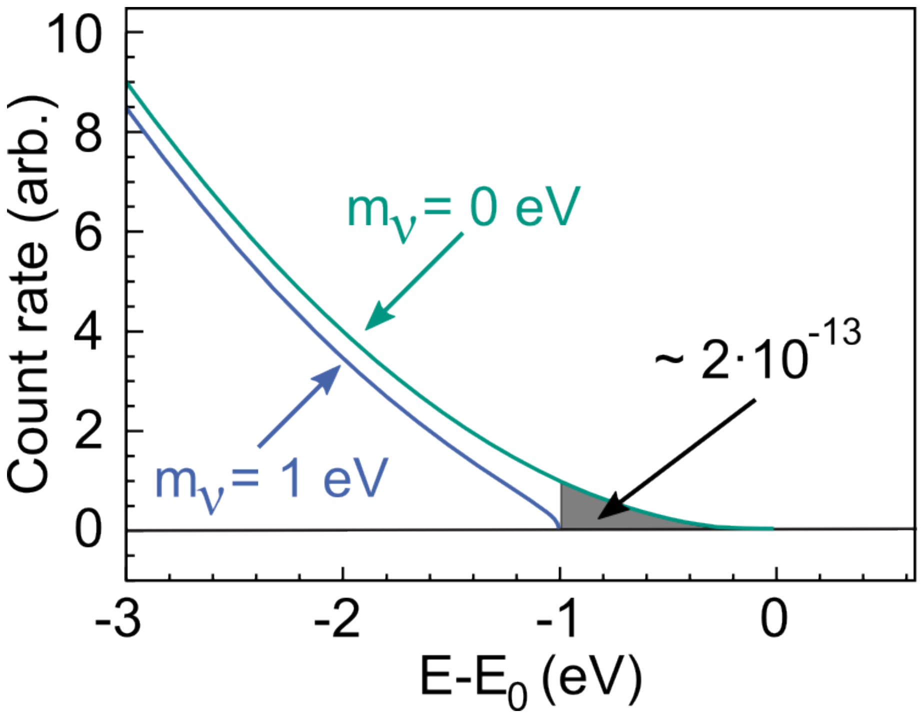
Tritium β-decay

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

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

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





Tritium β-decay

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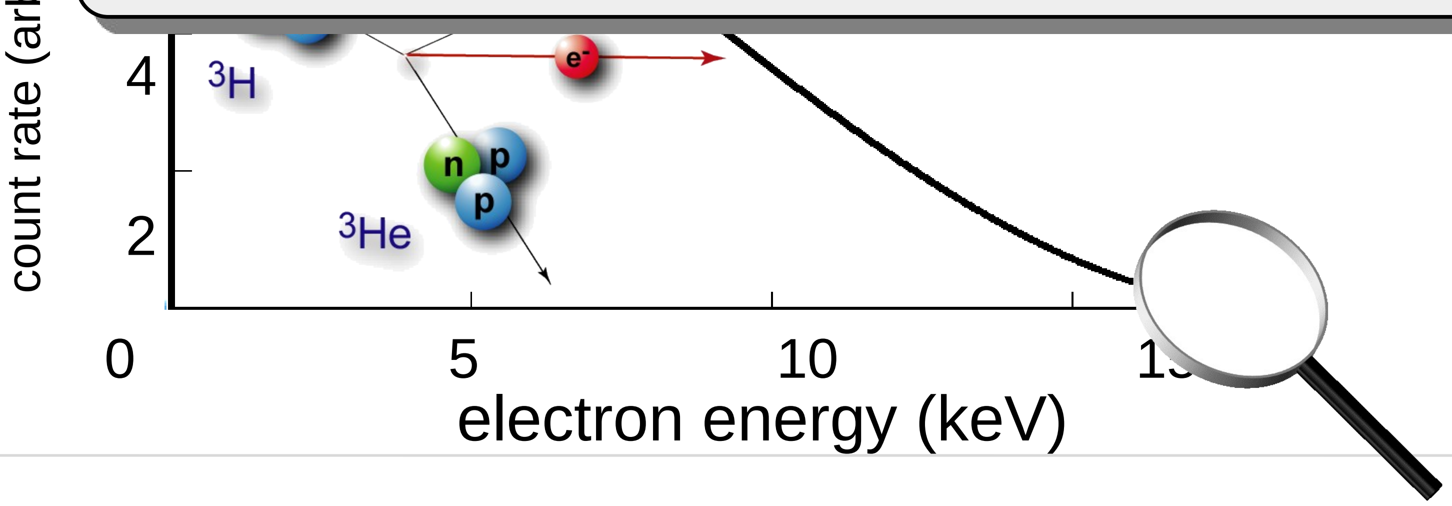
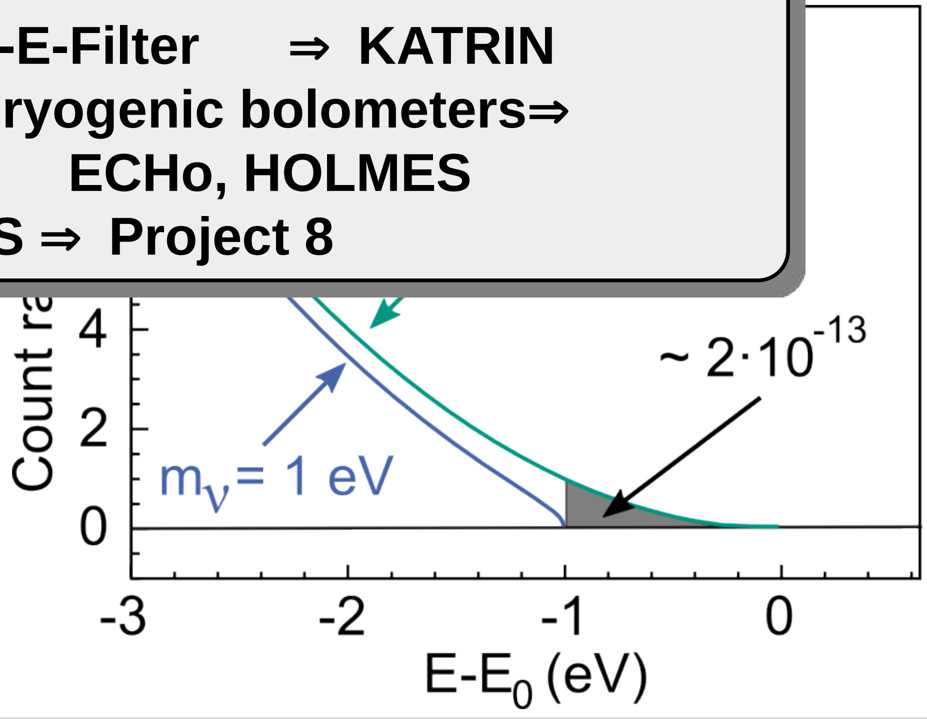
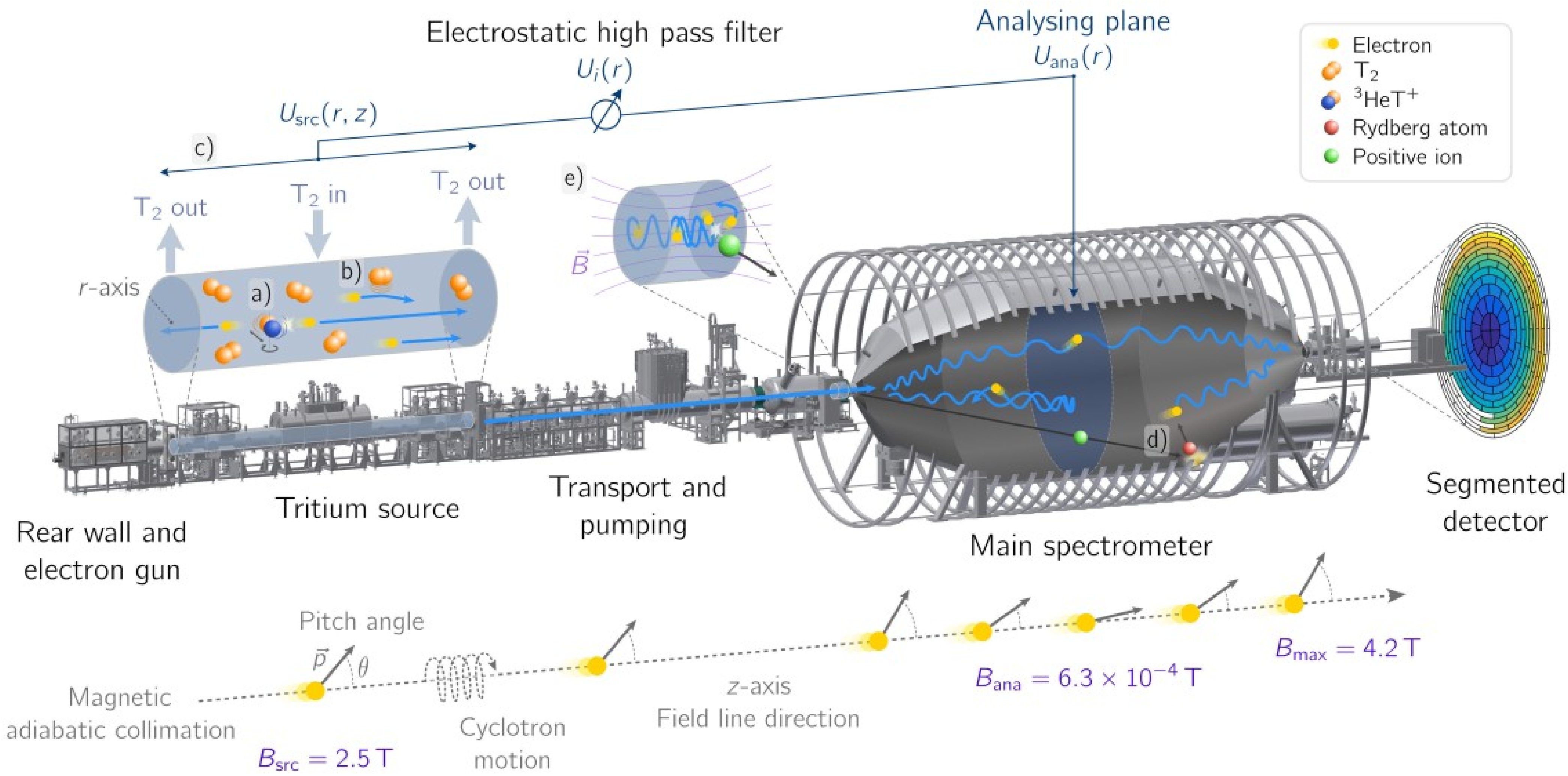
- **Need:**
  - **low endpoint energy** ⇒ **Tritium ^{3}H – 18.6 keV**
  - **short half-life (superallowed)** **– 12.3 yr**
  - **(^{163}Ho electron capture)**
  - **very high energy resolution &**
  - **very high luminosity &** ⇒ **MAC-E-Filter ⇒ KATRIN**
  - **cryogenic bolometers⇒ ECHo, HOLMES**
  - **very low background**
  - **CRES ⇒ Project 8**





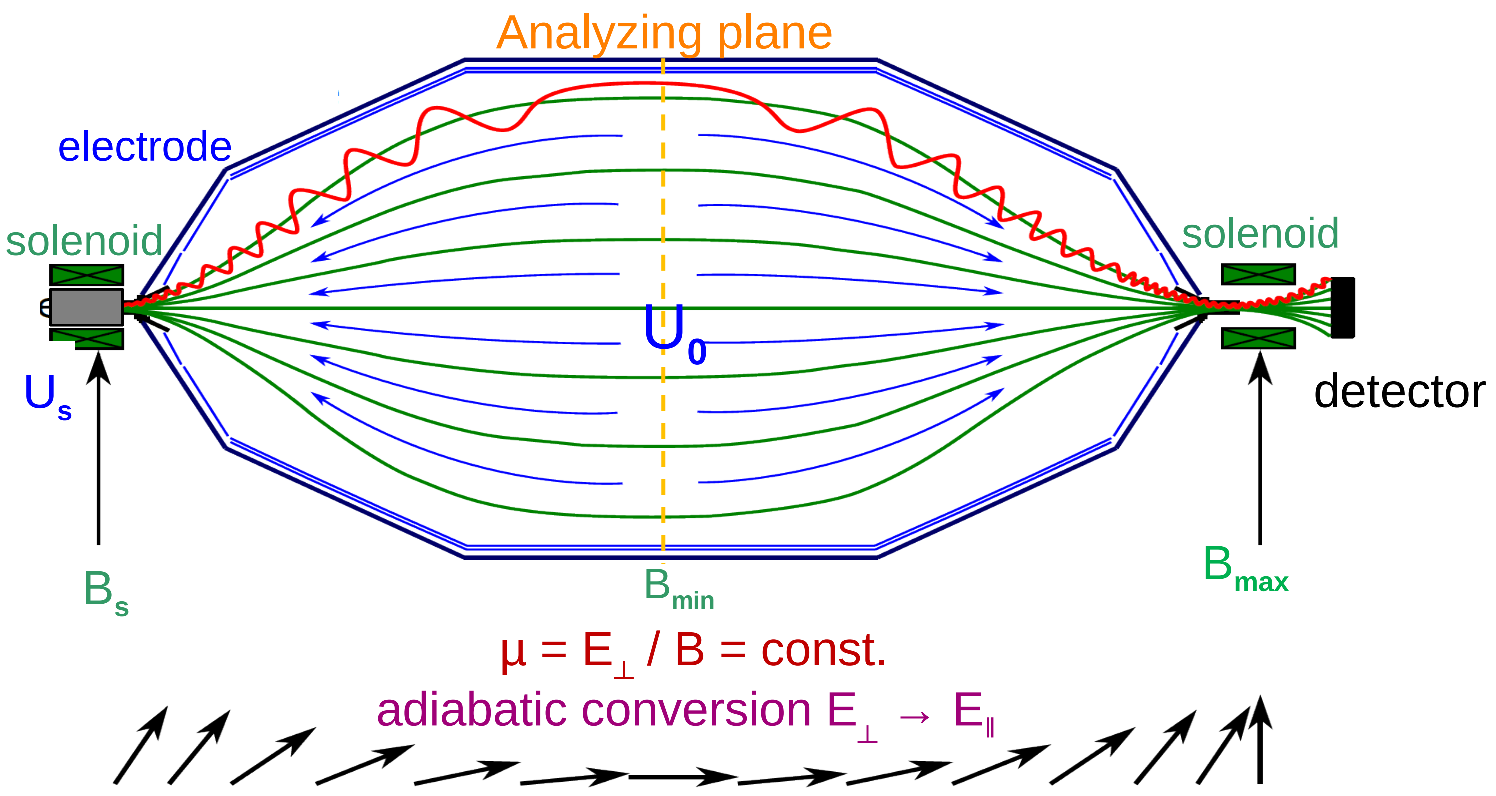
The KATRIN experiment at Karlsruhe Institute of Technology



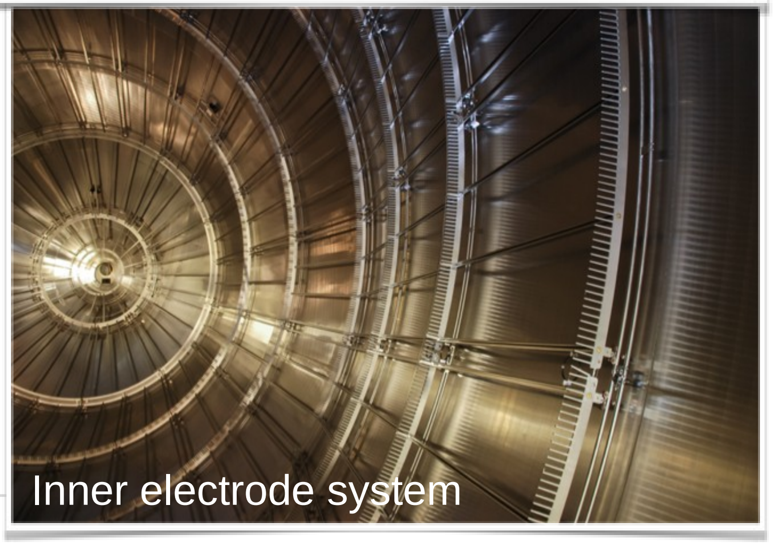
Full system description & commissioning, JINST 16 (2021) T08015

MAC-E-Filter: high-resolution β-spectroscopy

Magnetic Adiabatic Collimation & Electrostatic Filter:

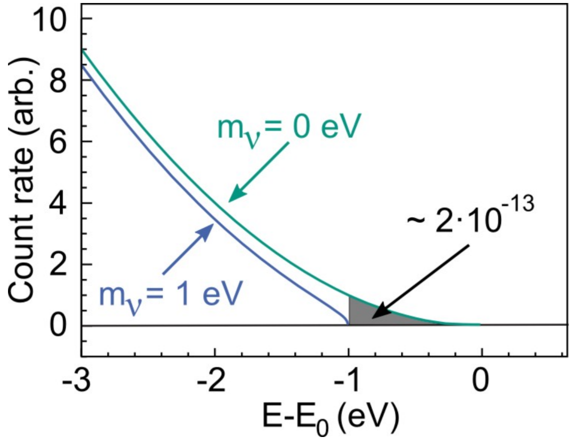


Momentum tranfsormation without the E-field

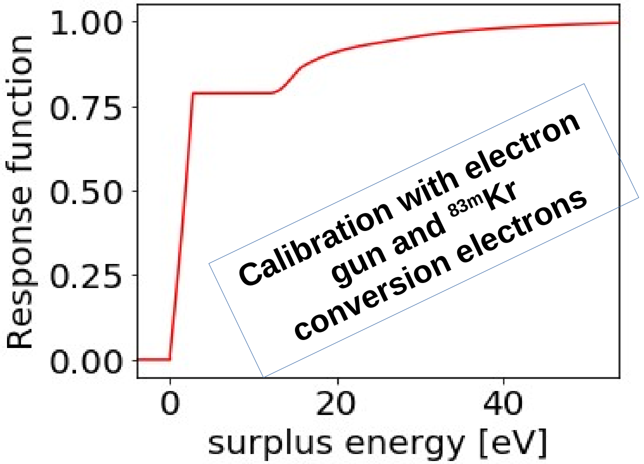


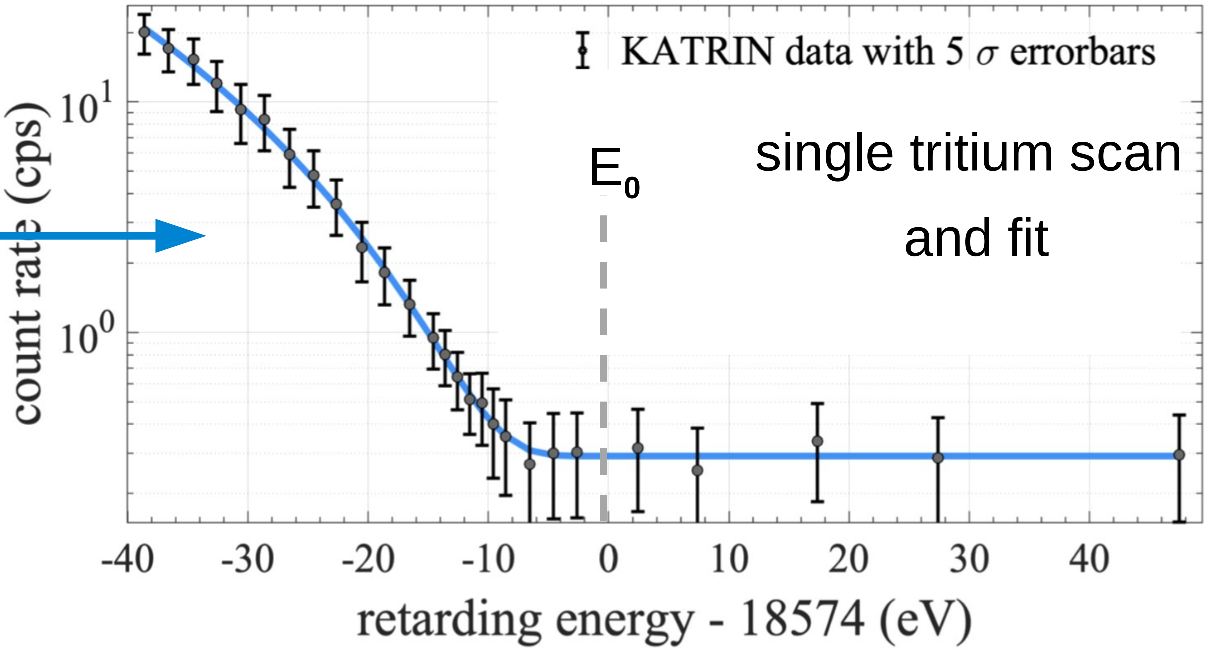
Beta-spectrum and neutrino mass

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



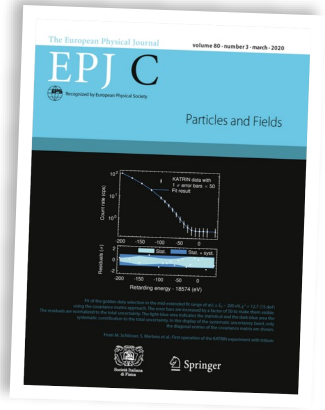
- **Experimental response: f(E-qU)**





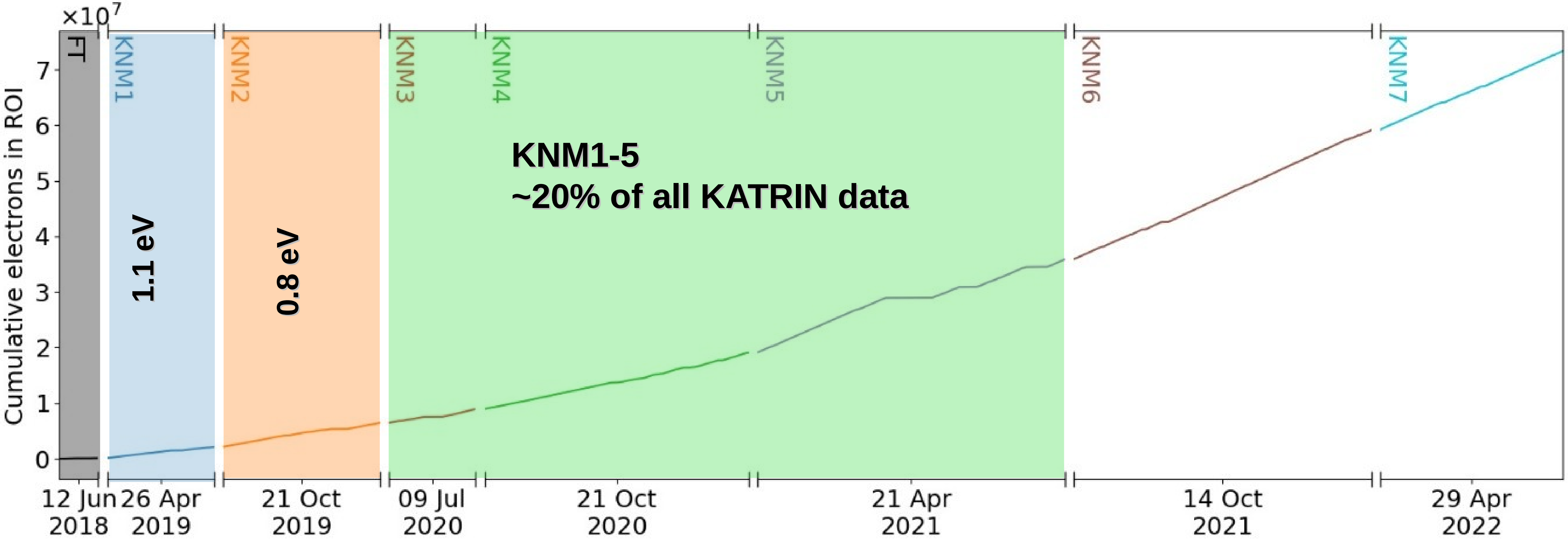
$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

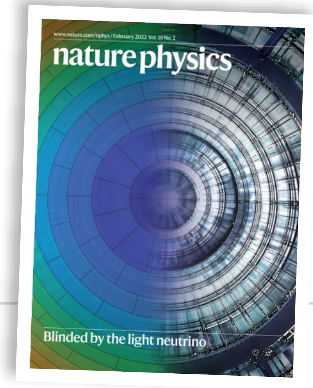
KATRIN Data taking



EPJ C 80, 264 (2020)

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





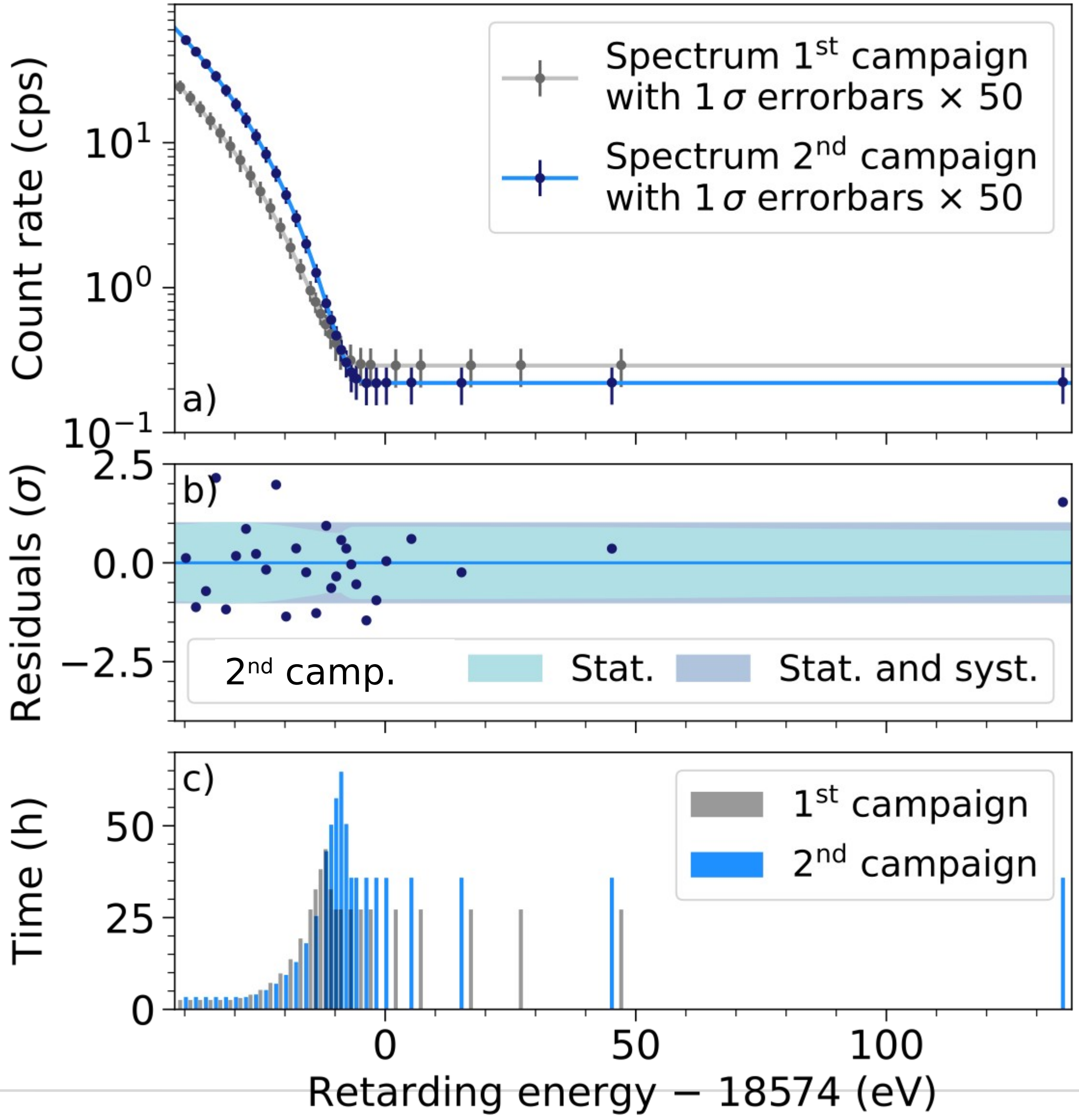
Analysis of 5 scientific runs → ongoing

Statistical sensitivity ~ 0.5 eV (90% CL)

See talk by A. Schwemmer Wed. 16:00

Nature Phys. 18 (2022) 160

Recent ν-mass results



First campaign (spring 2019):

- ✓ total statistics: 2 million events
- ✓ best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV² (stat. dom.)
- ✓ limit: $m_\nu < 1.1$ eV (90% CL)

Second campaign (autumn 2019):

- ✓ total statistics: 4.3 million events
- ✓ best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$ 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

Improving statistics and systematics

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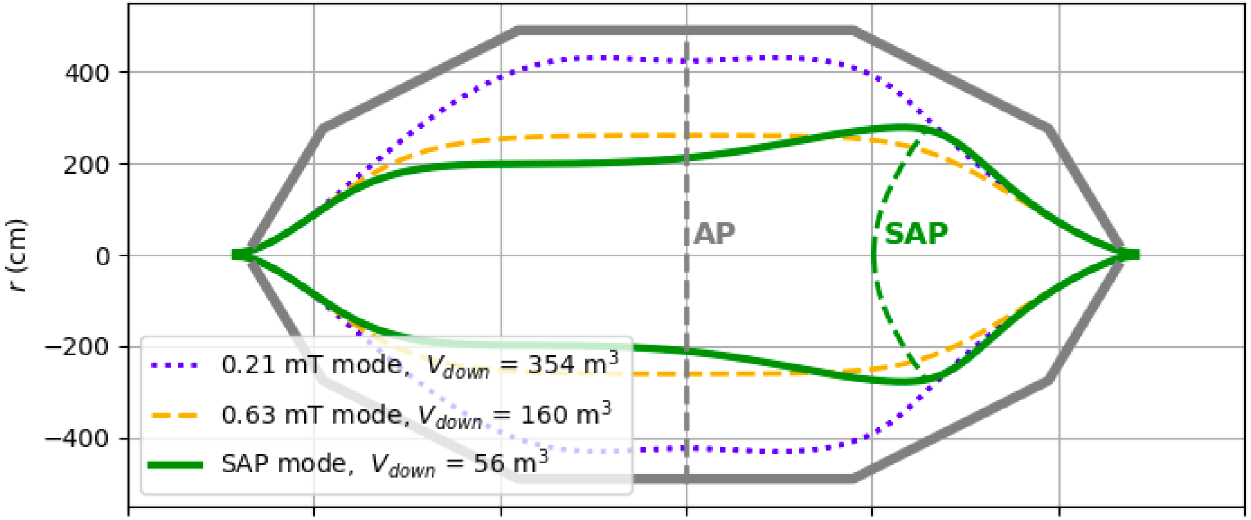
Background reduction



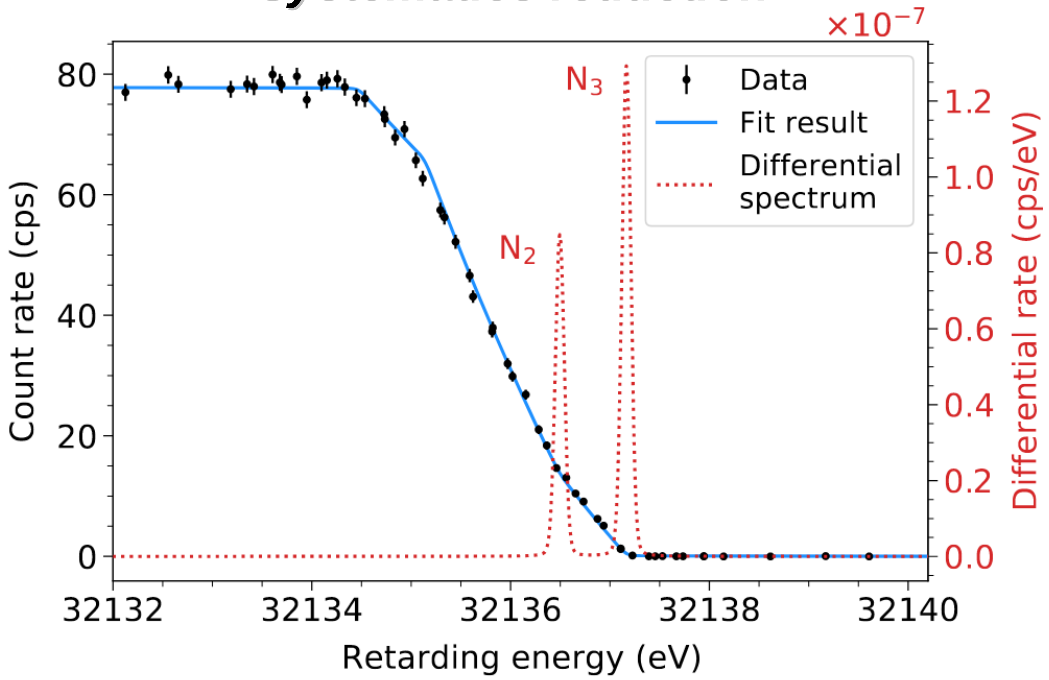
- Volume dependent background rate
- Reduce the volume of the flux

⇨ „shifted analyzing plane“ (SAP) ☑

– factor 2 signal/background improvement ☑

- Further reduction of background planned

Systematics reduction

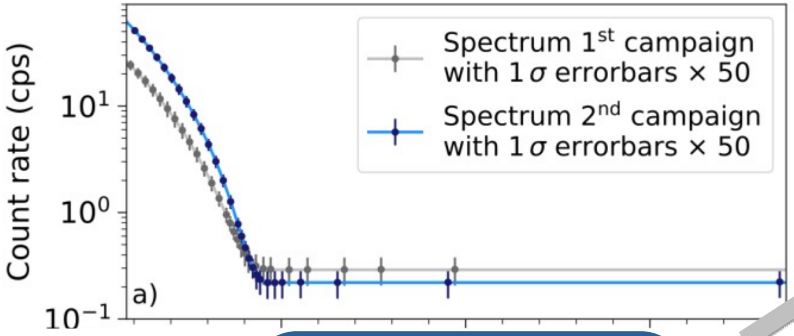


- Co-circulation of tritium and ^{83m}Kr at 80 K
- Estimating plasma conditions in the source

Implemented since 2020!

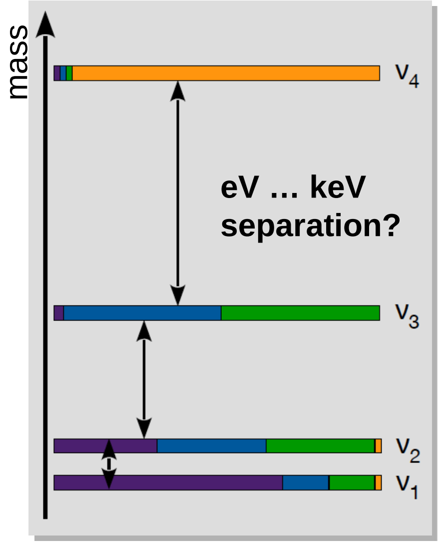
Eur.Phys.J.C 82 (2022) 3, 258

“Beyond neutrino mass” in KATRIN



β-spectrum of high statistics and precision

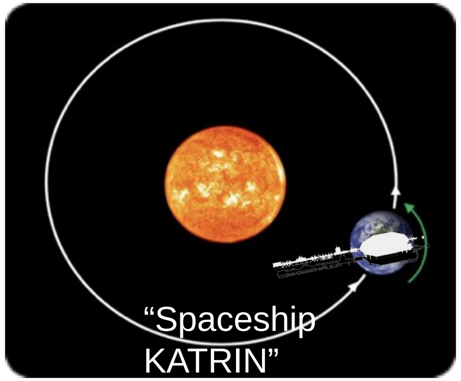
Is there a fourth (sterile) neutrino?



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)

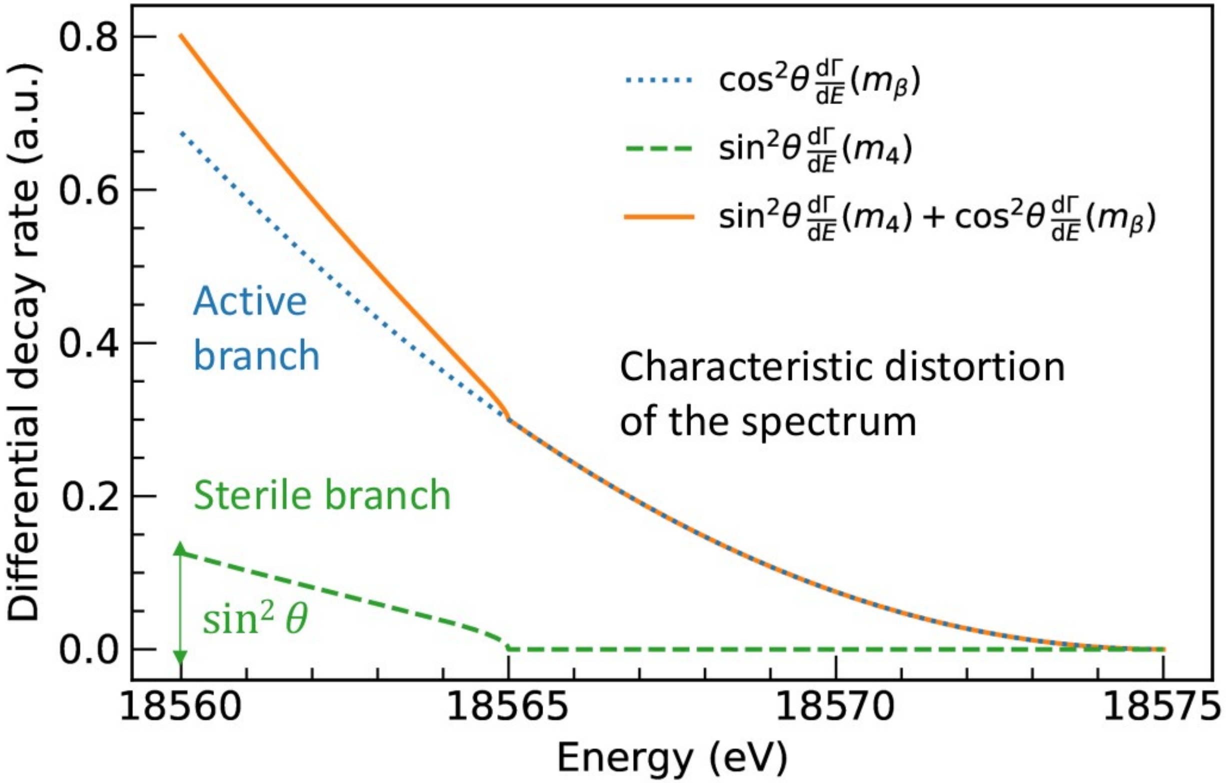
Light sterile neutrinos – Motivation

- Multiple anomalies in the oscillation data
  - reactor flux anomaly
  - reactor spectra
  - gallium anomaly
  - LSND, MiniBooNE
- No universal explanation to all of them
- An oscillation-free measurement as an independent cross-check by KATRIN

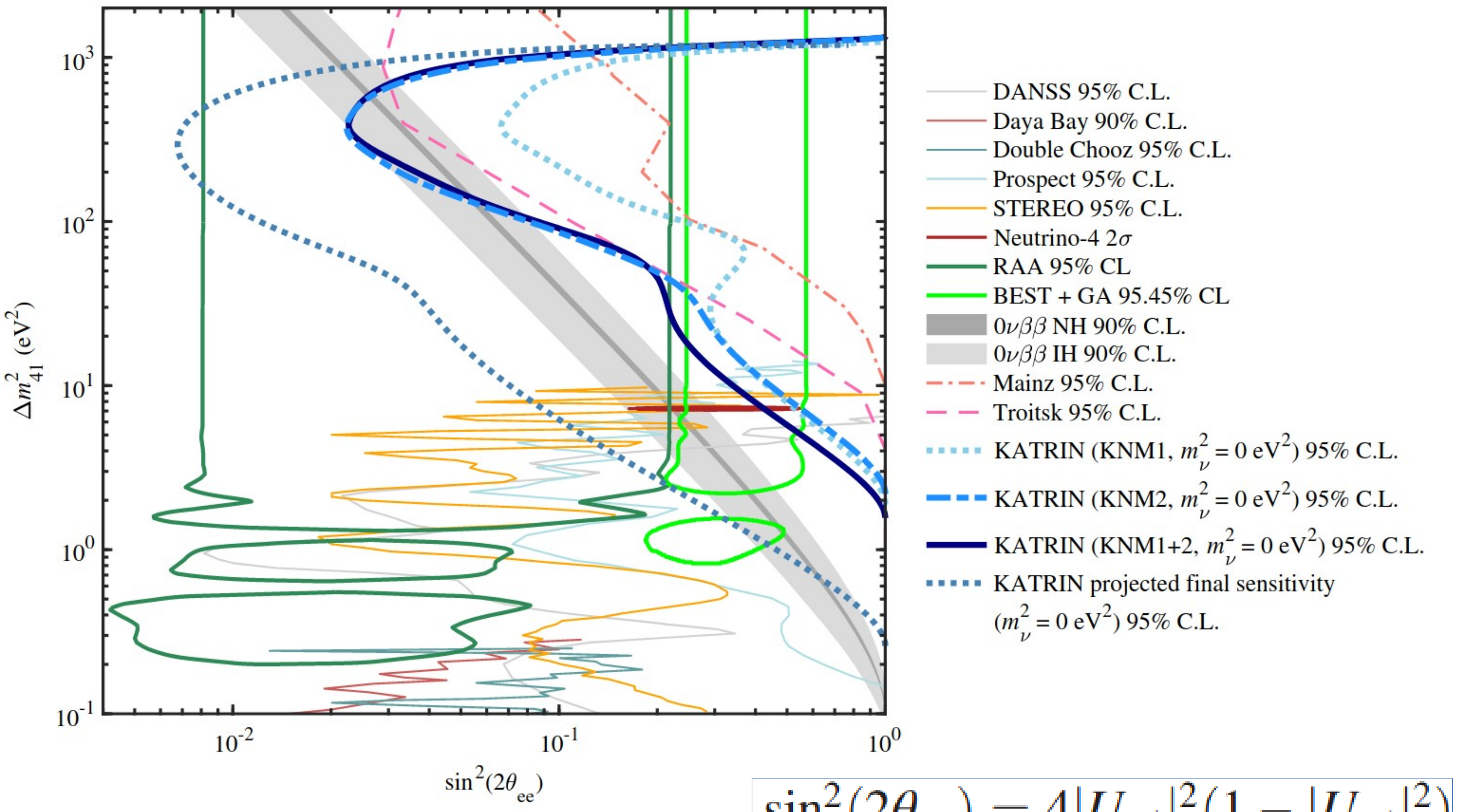
Sterile neutrinos signature in β-spectrum

- 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 – complimentarity



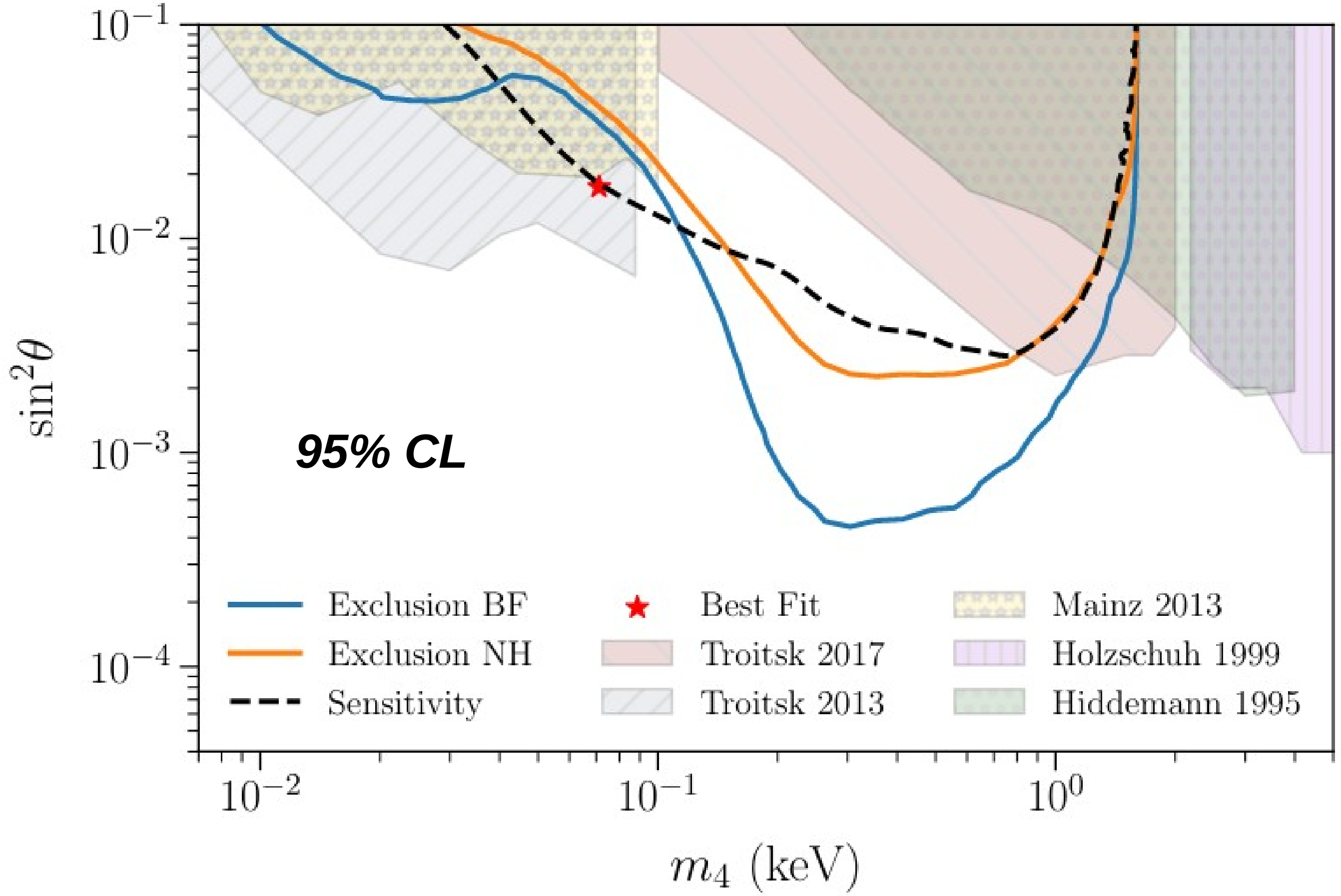
$$\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

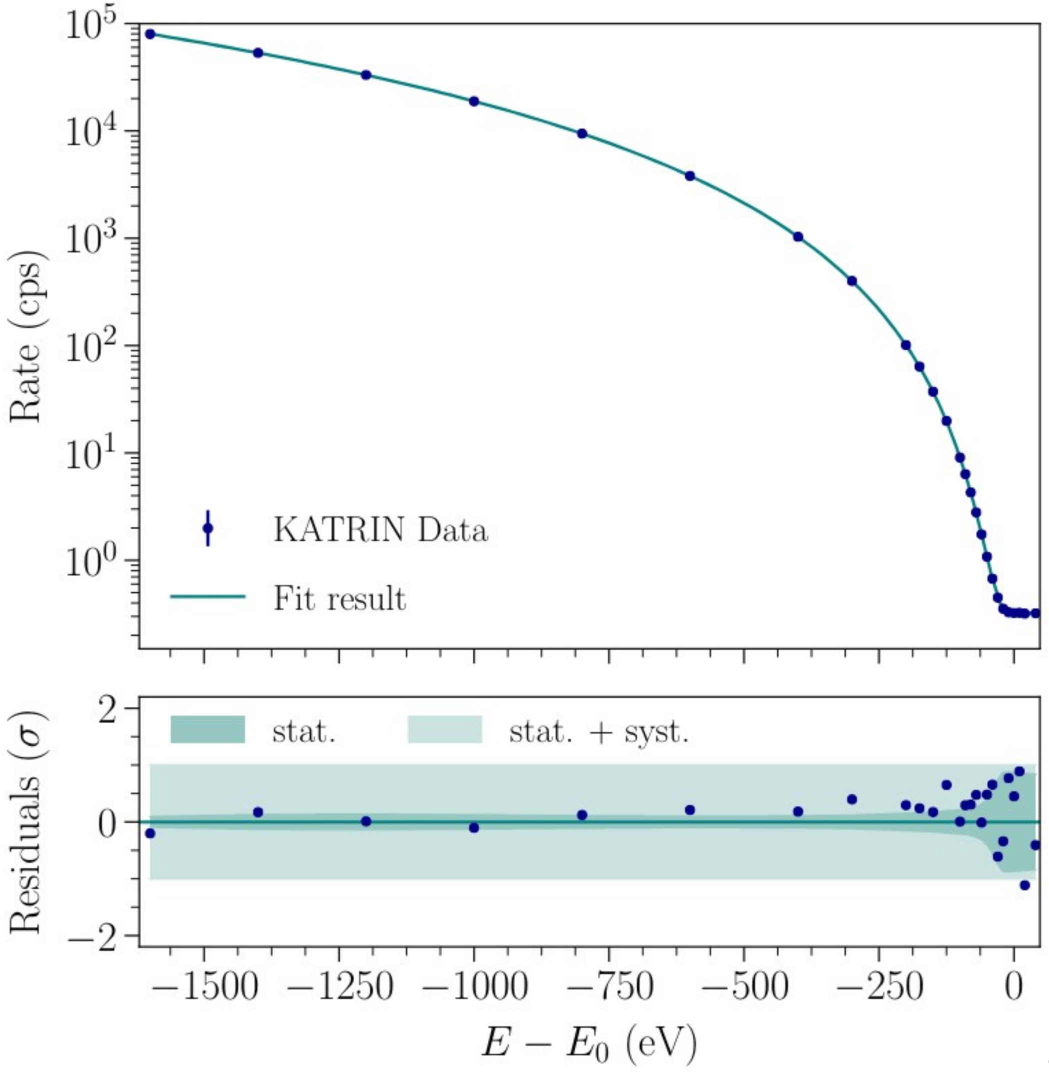
- looking at the short baseline anomalies from a different perspective
- Signal-to-background up to 250
- More stringent limits than Troitsk and Mainz
- approaching the BEST allowed regions with **Δm^2 > 10 eV^2**
- complementary probe to oscillation-based experiments

KATRIN Collab., PRD 105, 072004 (2022)

KATRIN search for keV sterile neutrinos

- **Using data of the first comissioning run with 0.5% tritium (2018)**

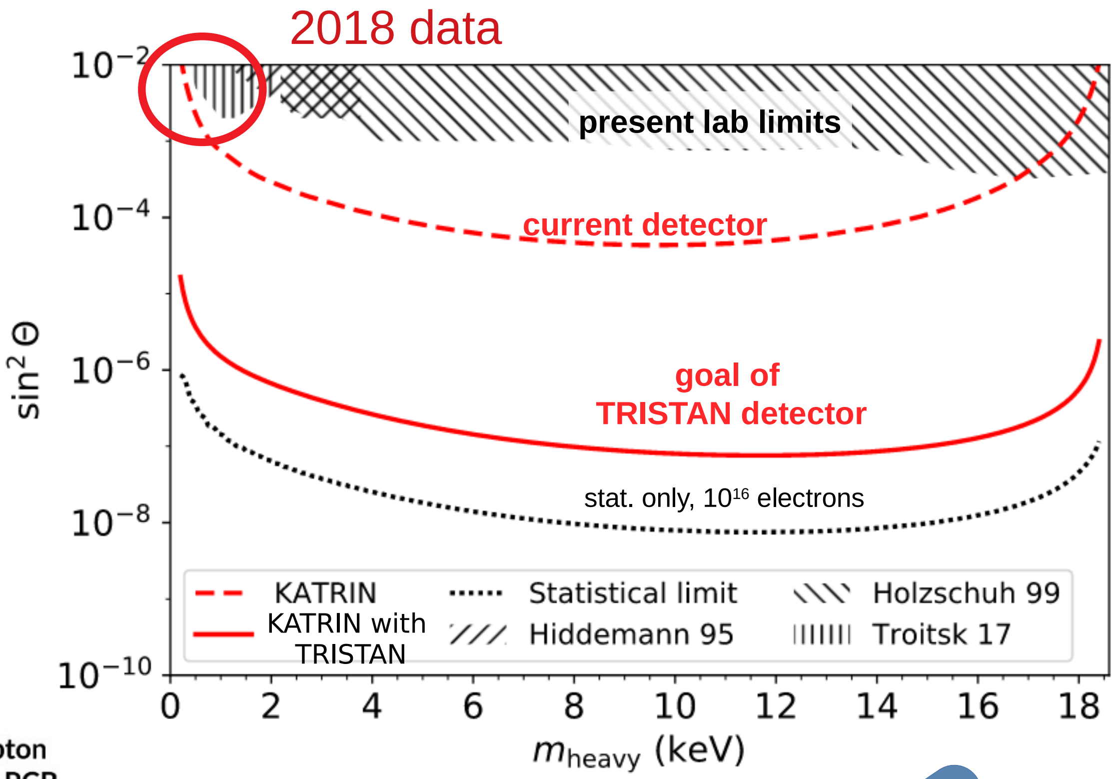


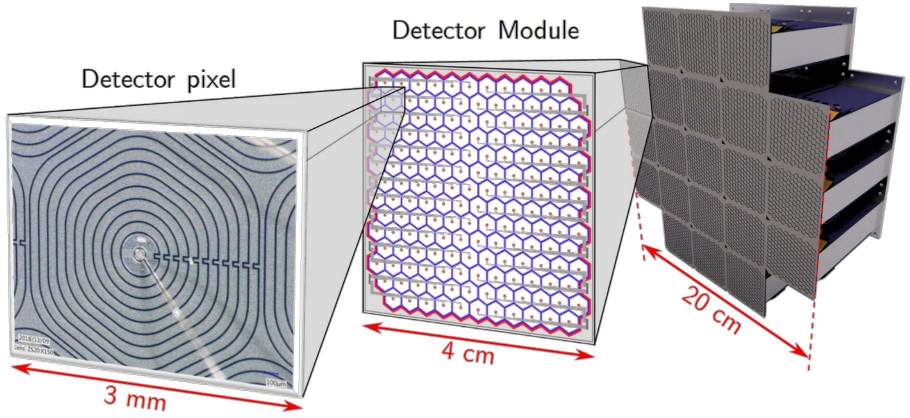


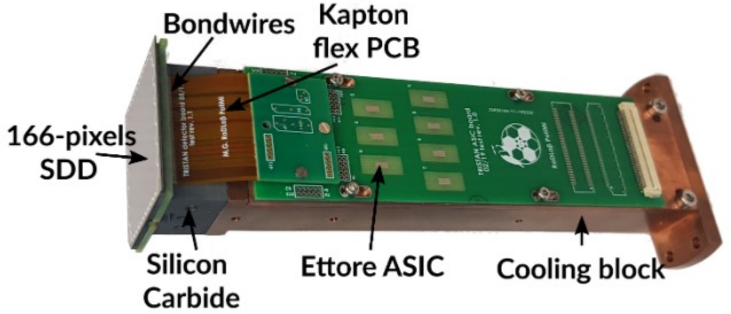
KATRIN Collab., arXiv:2207.06337

KATRIN search for keV sterile neutrinos

- **TRISTAN project in KATRIN:**
  - novel multi-pixel Silicon Drift Detector array
  - large count rates
  - excellent energy resolution
  - Prototypes installed as monitoring devices @ KATRIN
  - Target sensitivity: $\sin^2\theta < 10^{-6}$

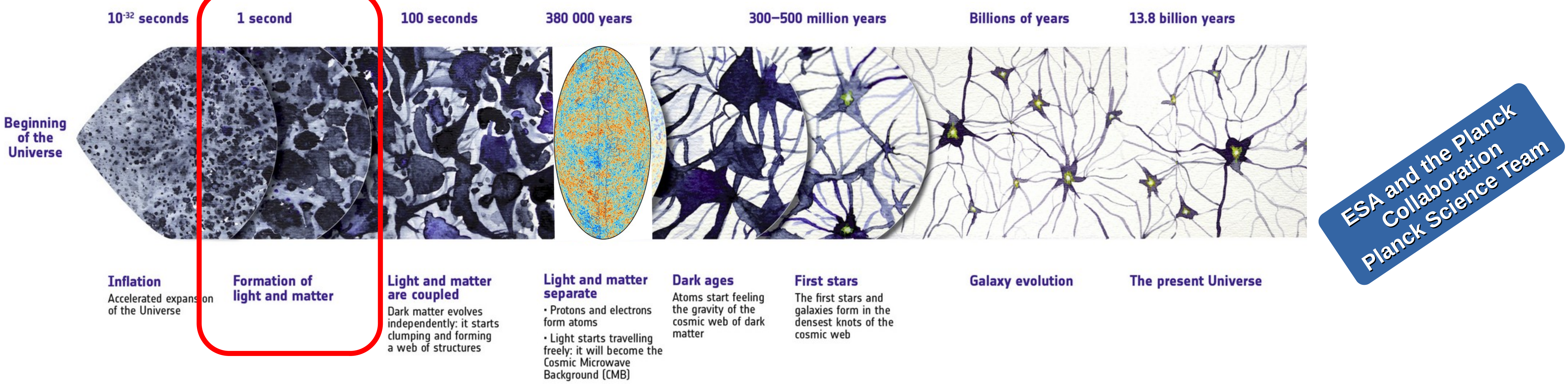






See talk by D. Siegmann on Saturday

Cosmic neutrino background

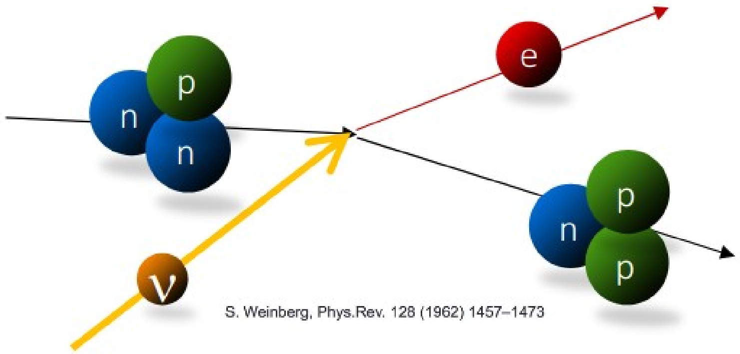


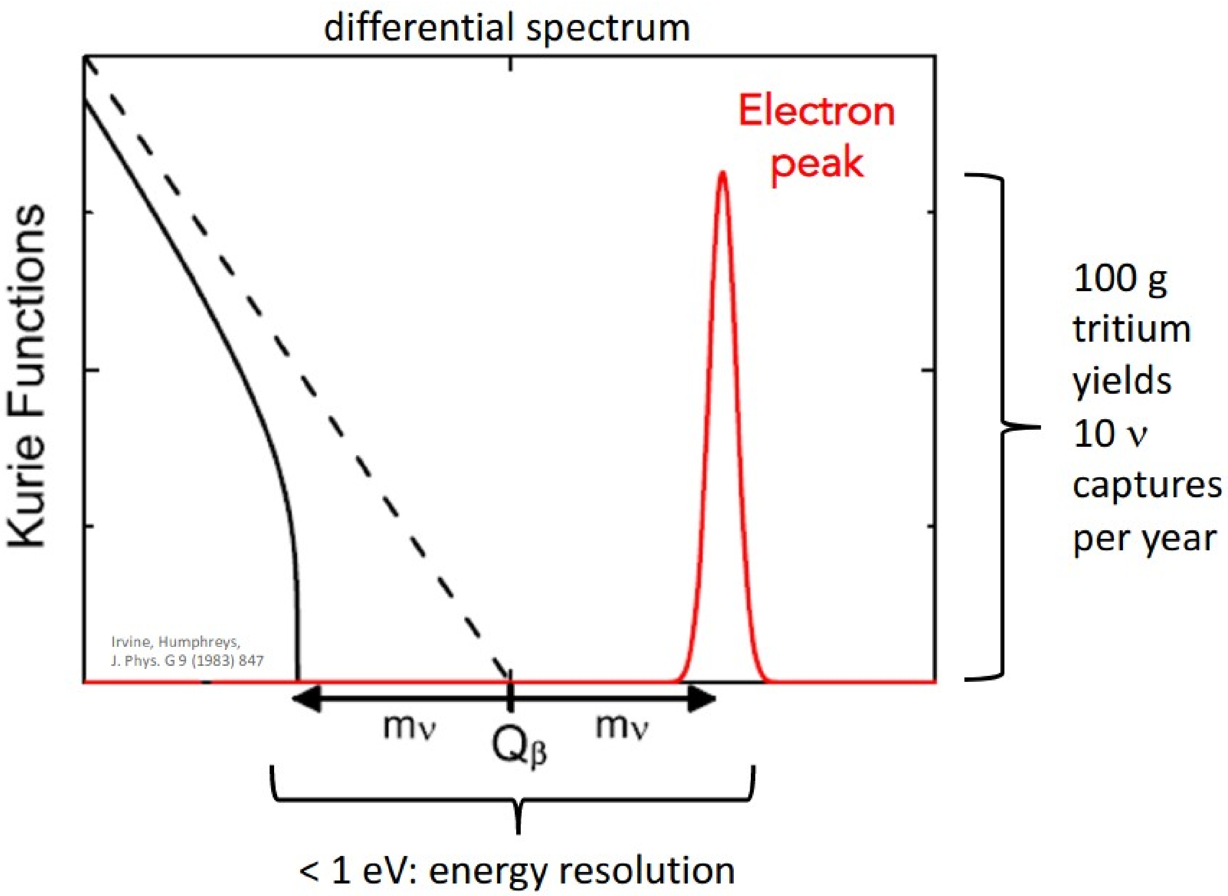
- ~340 relic neutrinos of all species /cm^3 in the Universe (56 /cm^3 per species)
- Decoupled the first second (1 MeV) after Big Bang
- Predicted overdensity $\eta \approx (1.2..20)$
- upper limits from previous kinematic neutrino mass measurements: 10^{13}

Relic neutrinos search with KATRIN

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

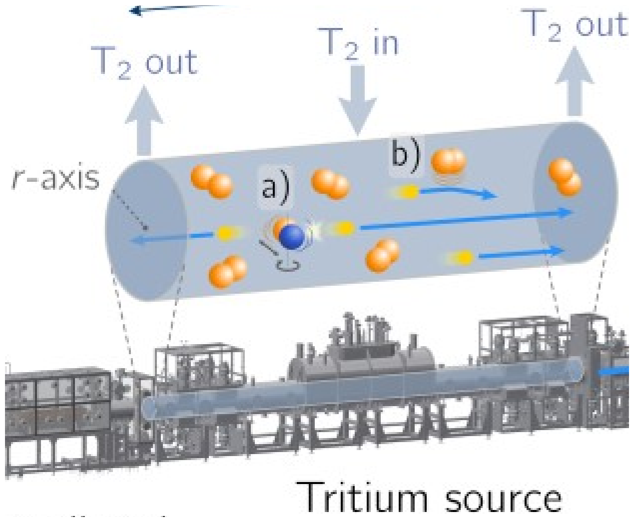
$$^{3}\text{H} + \nu_e \longrightarrow \ ^{3}\text{He}^{+} + e$$

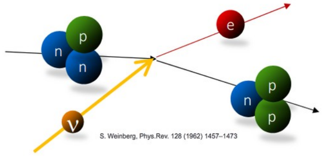




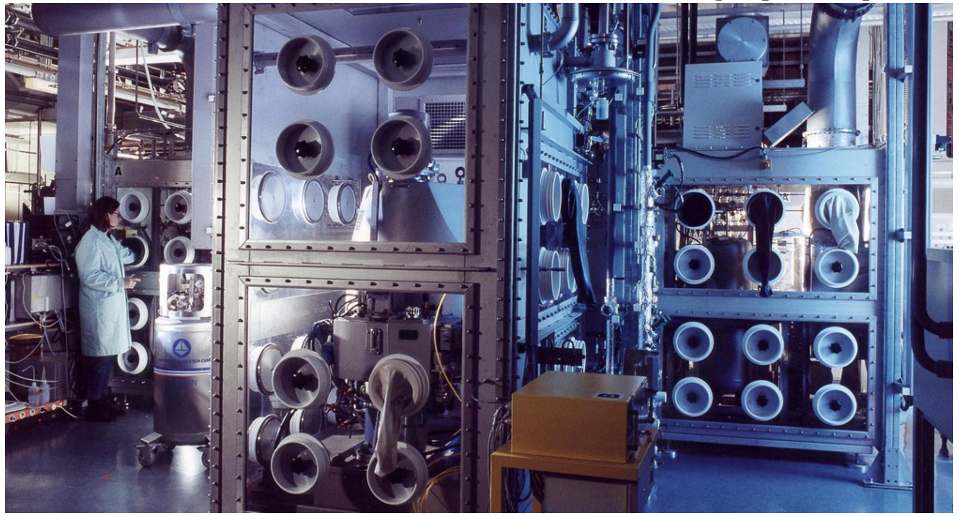
KATRIN Collab., Phys.Rev.Lett. 129 (2022) 011806

Relic neutrinos search with KATRIN





Karlsruhe Tritium Laboratory (TLK)



up to 40 g of tritium

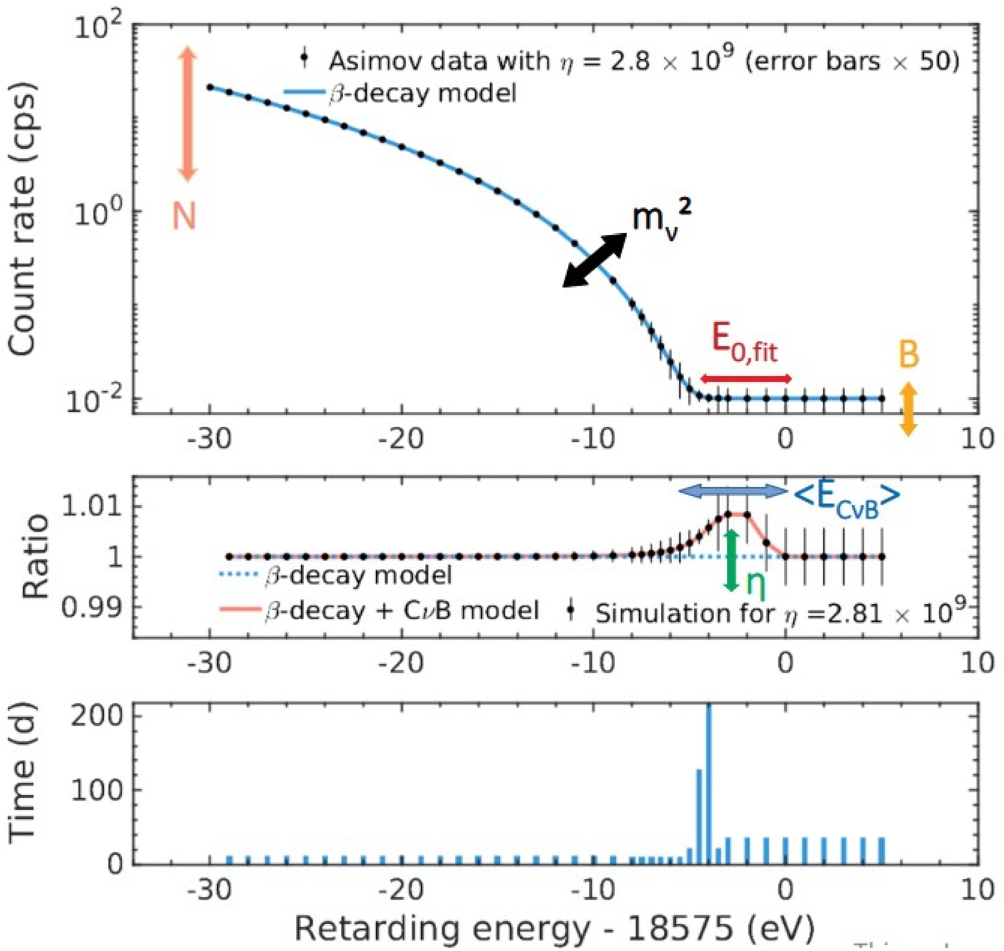
30 µg of T_2 in the source
10^{-6} captures per year

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

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

KATRIN Collab., Phys.Rev.Lett. 129 (2022) 011806

Model for the relic neutrinos in KATRIN



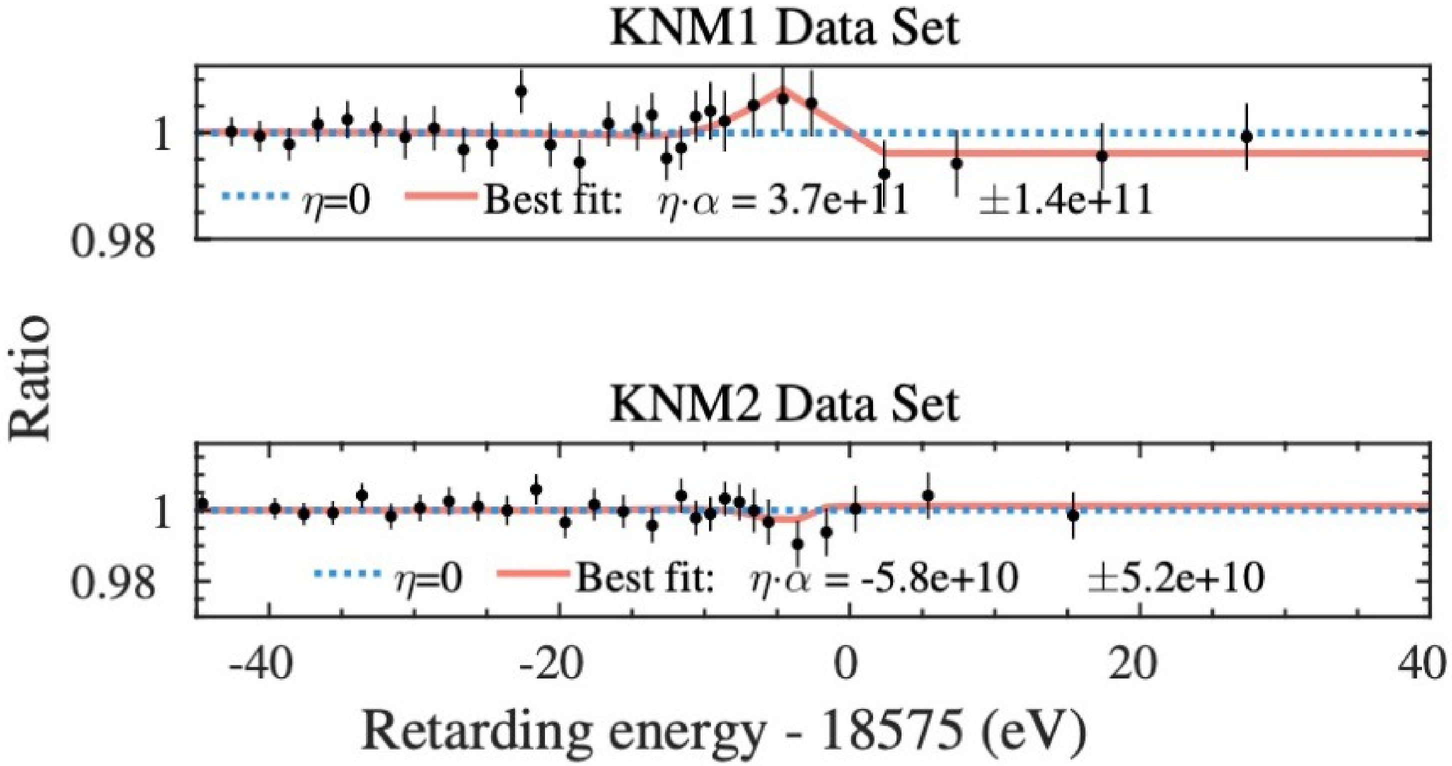
Fit parameters:

- 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

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

KATRIN Collab., Phys.Rev.Lett. 129 (2022) 011806

Relic neutrinos in the first science runs

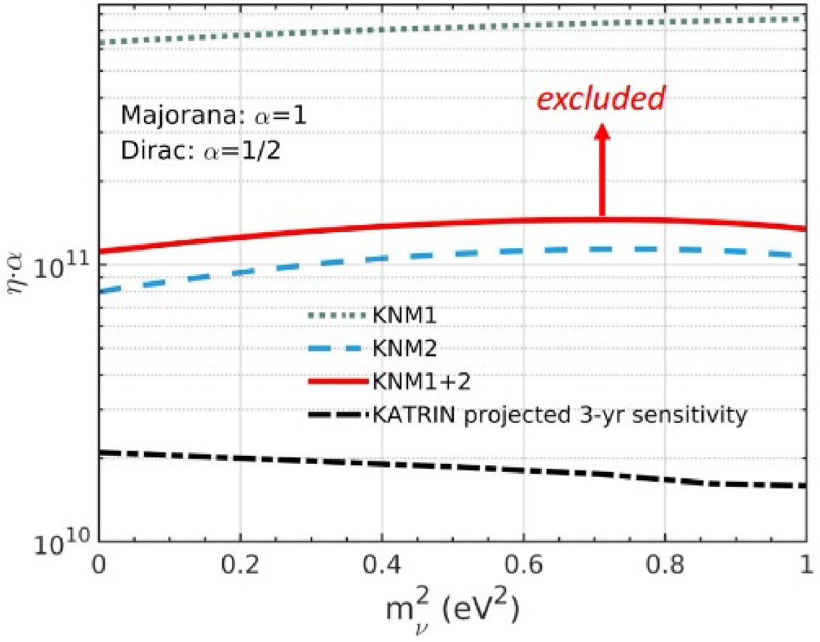


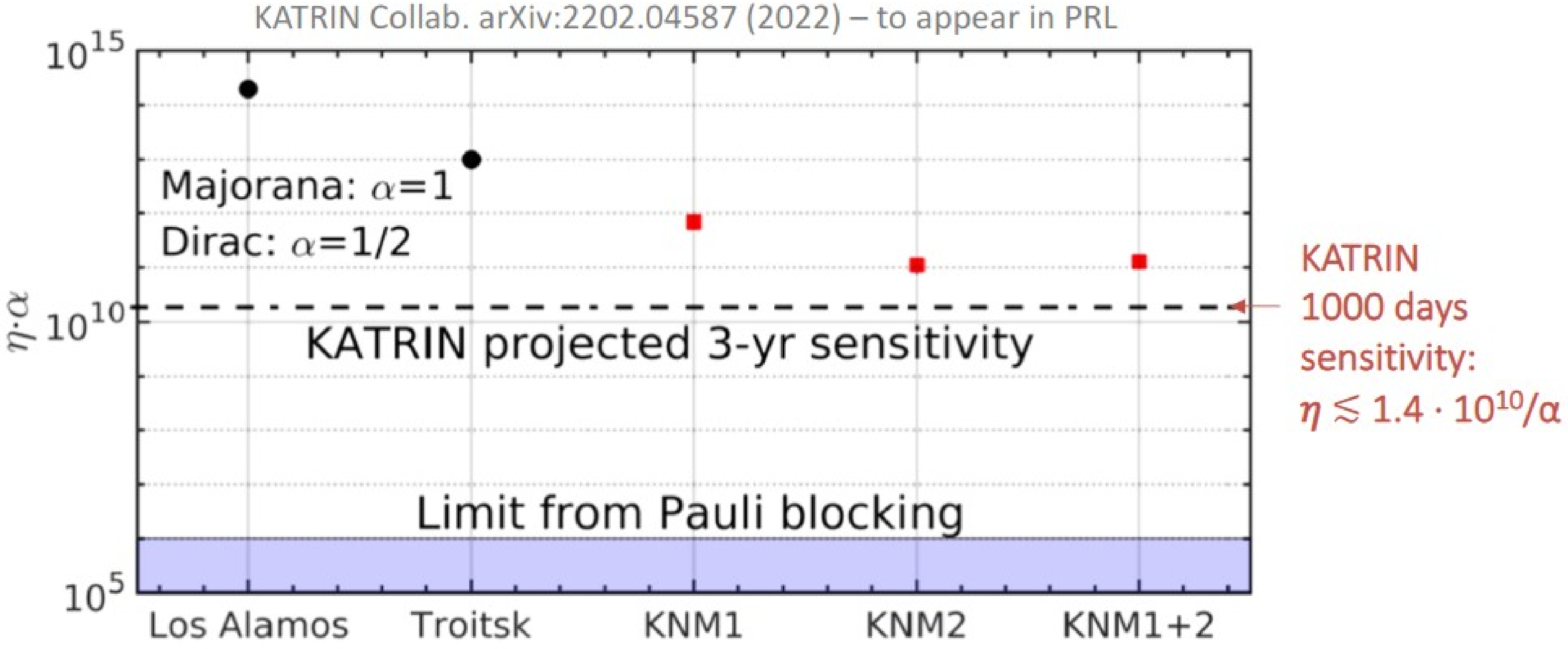
- 1st campaign (2019)
  - 522 hours
  - 3.4 µg for capture on tritium
- 2nd campaign (2019)
  - 744 hours
  - 13.0 µg for capture on tritium
- no evidence for relic neutrino overdensity
  - upper limits

KATRIN Collab., Phys.Rev.Lett. 129 (2022) 011806

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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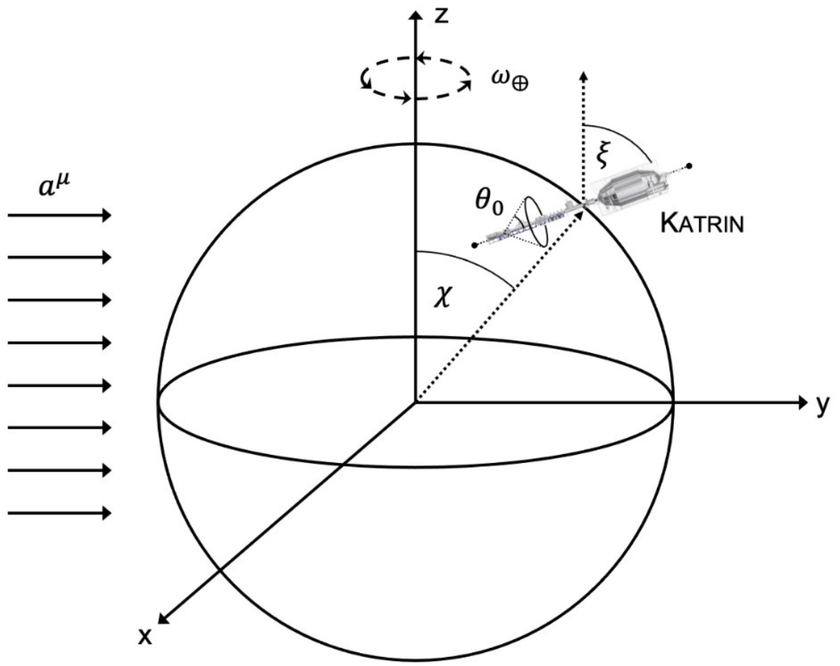
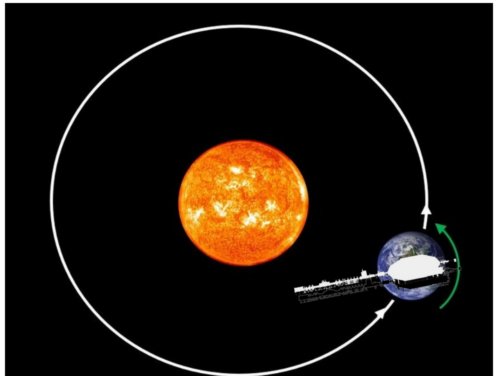
Lorentz invariance violation

- 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)




"Spaceship KATRIN"

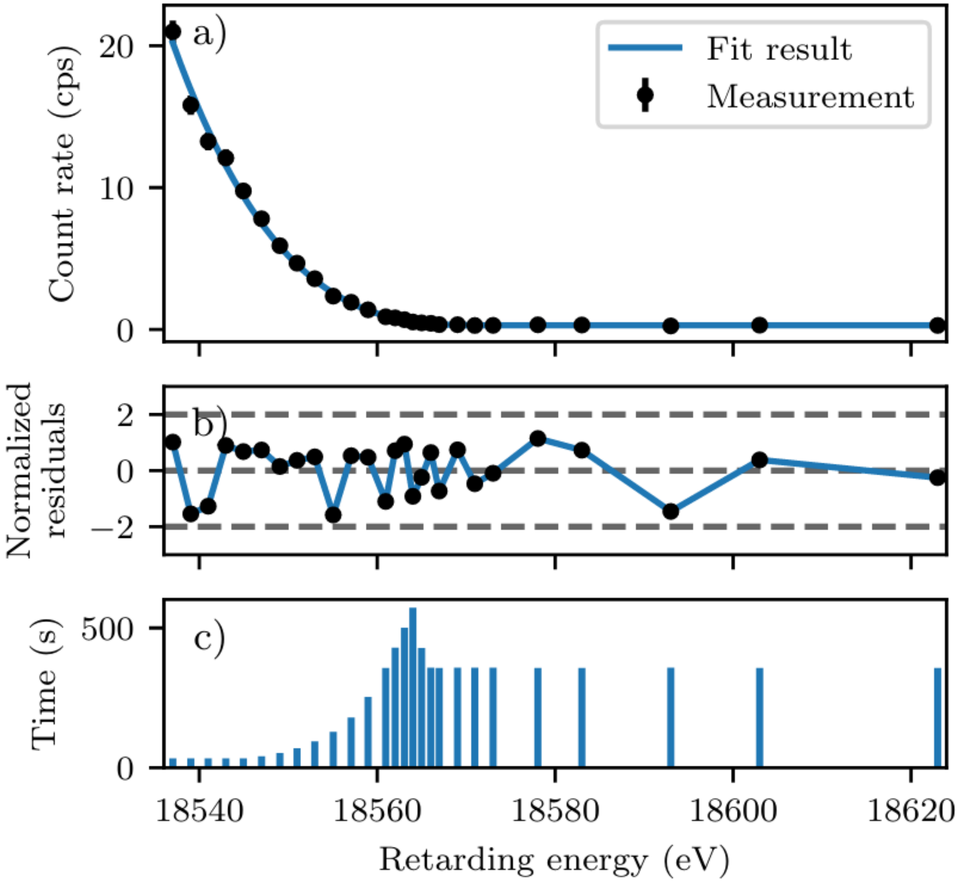
Possible impact on β-spectrum:

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

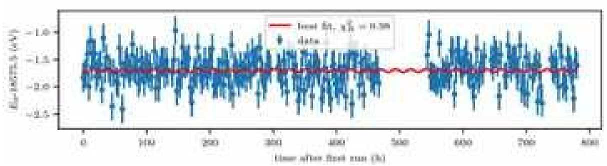
KATRIN Collab., arXiv:2207.06326

Lorentz invariance violation in KATRIN

Fit each scan of β-spectrum



Estimate amplitude of E_0 oscillation



Convert into estimation of LIV parameters

KATRIN Collab., arXiv:2207.06326

Lorentz invariance violation in KATRIN

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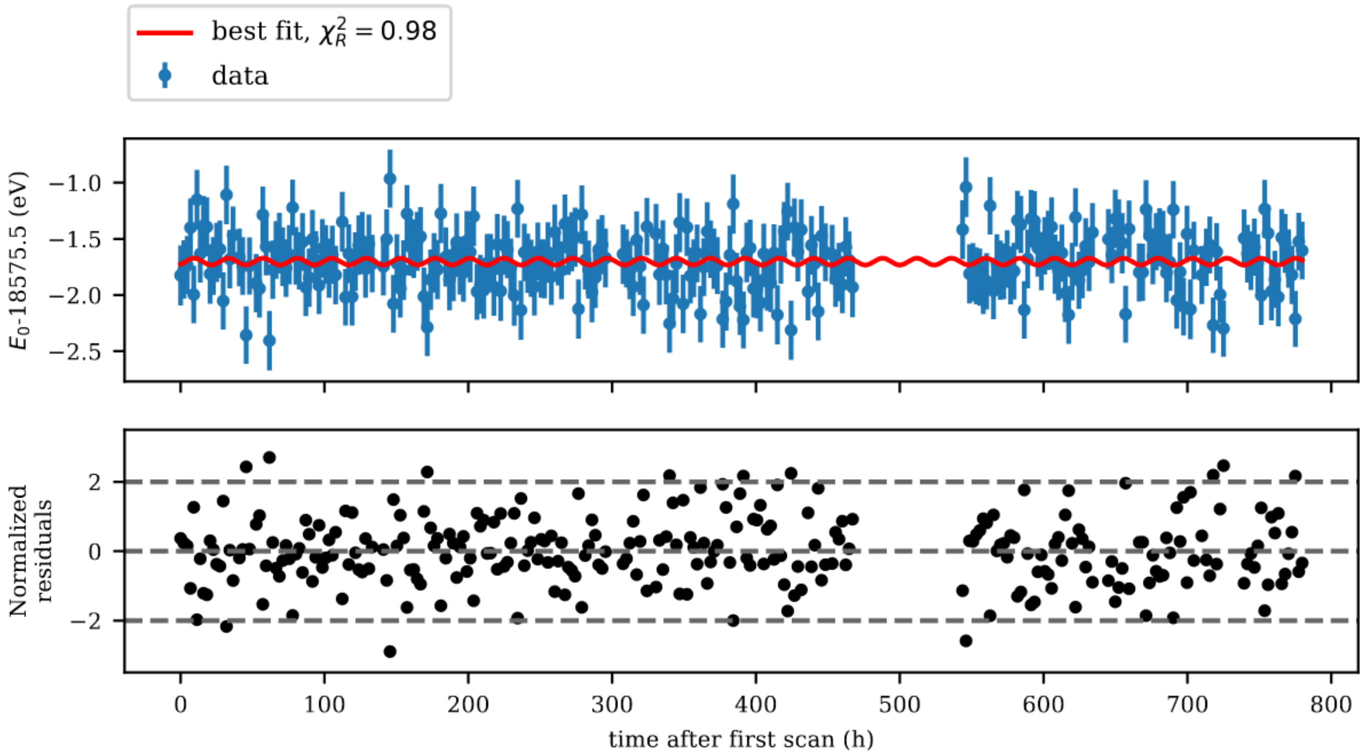
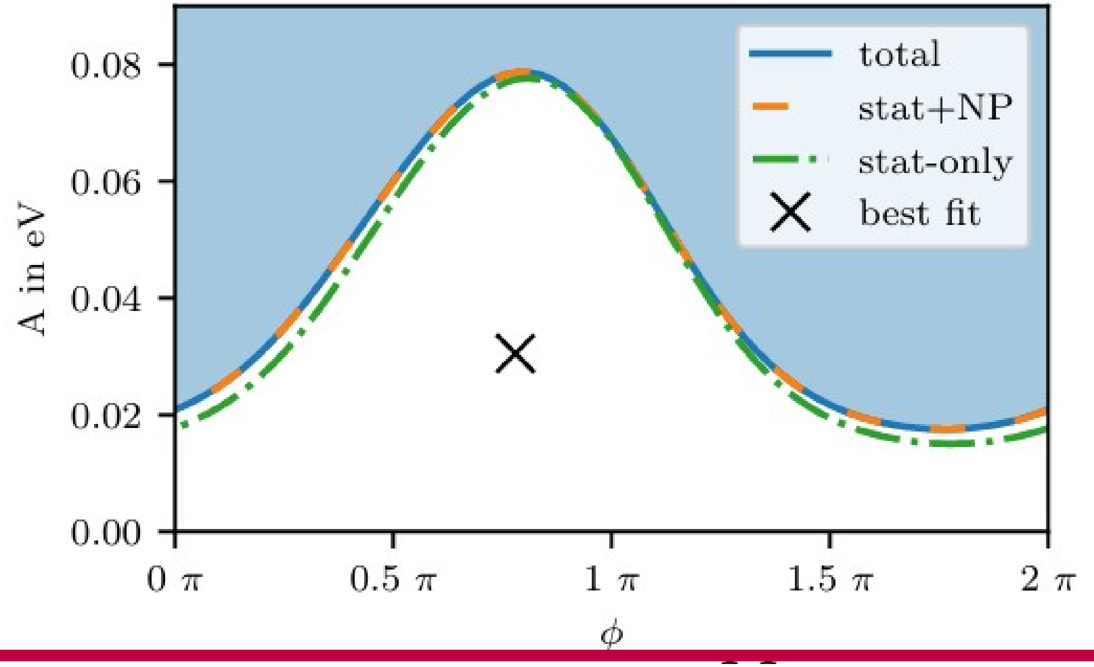
Estimate amplitude of E_0 oscillation

Convert into estimation of LIV parameters





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

$$\left|(a_{\text{of}}^{(3)})_{00}\right| < 3.0 \cdot 10^{-8}\ \text{GeV}$$

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

KATRIN Collab., arXiv:2207.06326

Conclusion & Outlook

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- **Recent results and improvements**
  - First sub-eV result from KATRIN: ***m_ν < 0.8 eV (90 % CL) with the full 2019 dataset***
  - Optimized configuration of EM-fields → background reduction
  - Optimized source operation mode → reduction of source systematics
- **KATRIN is continuosly taking data**
  - 200 days/year, target sensitivity: ***m_ν < 0.2-0.3 eV (90 % CL), measurement or upper limit?***
  - Further improvement of background by "active transverse energy filter" (aTEF), reduction of systematics
- **Physics programme beyond ν mass**
  - First searches for eV- and keV- scale sterile neutrinos, relic neutrinos as well as the LIV
  - keV sterile neutrino searches with a novel silicon drift detector (SDD) to start in ~2025

Thank you for your attention!

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