Latest KATRIN Results on

ν Mass and Light Sterile ν's

NEW!

http://arxiv.org/abs/2503.18667

Moriond EW 2025, La Thuile, 25/03/2025

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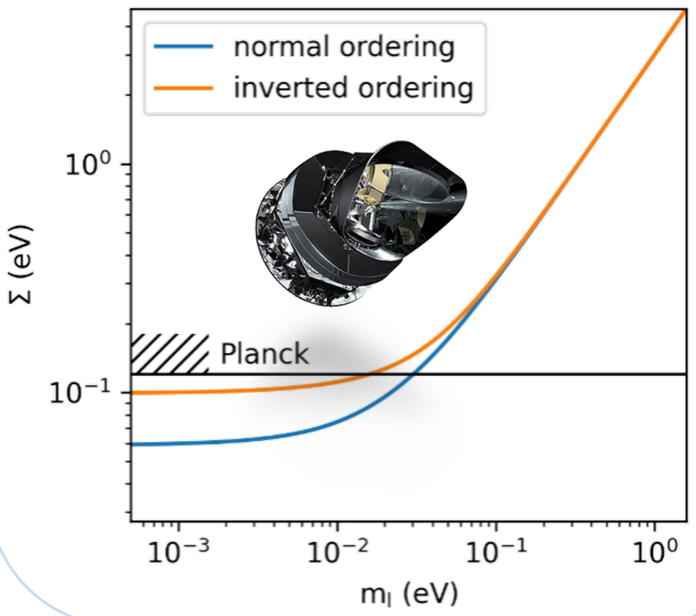
Neutrino mass(es)

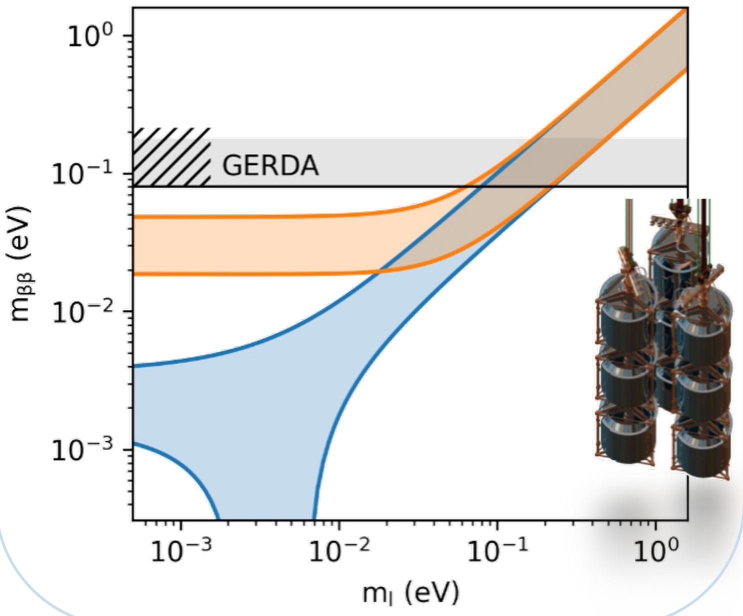
Cosmology

$$\Sigma = \sum_i m_i$$



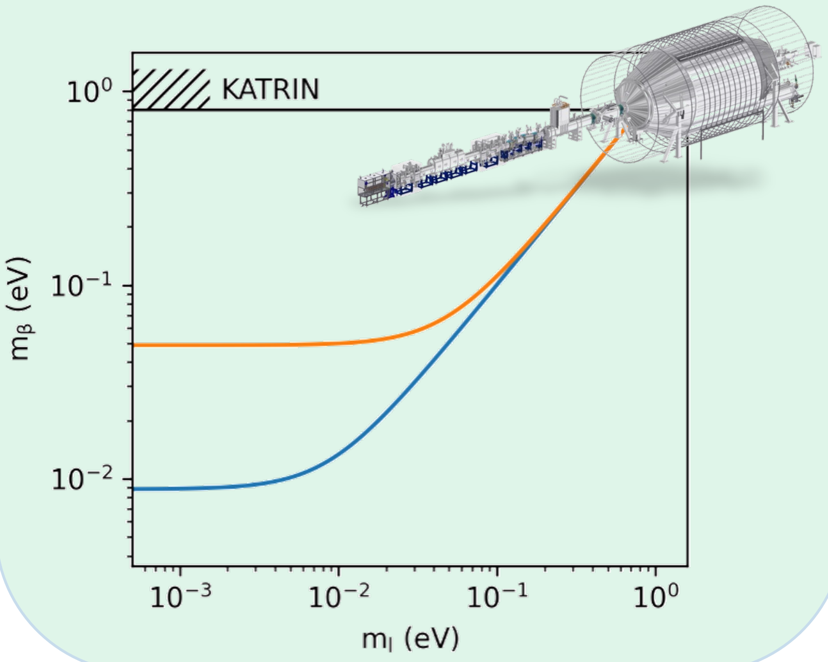
Neutrinoless ßß decay

$$m_{\beta\beta} = \sum_i U_{ei}{}^2 \cdot m_i$$

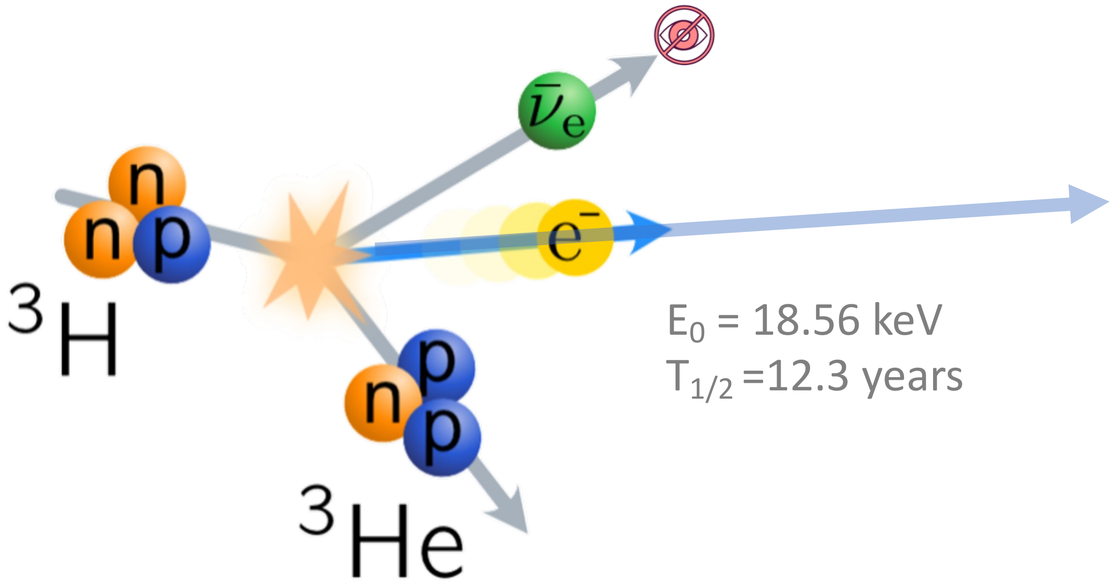


ß-decay kinematics

$$m^2_{\nu / \beta} = \sum_i |U_{ei}|^2 \cdot m_i^2$$



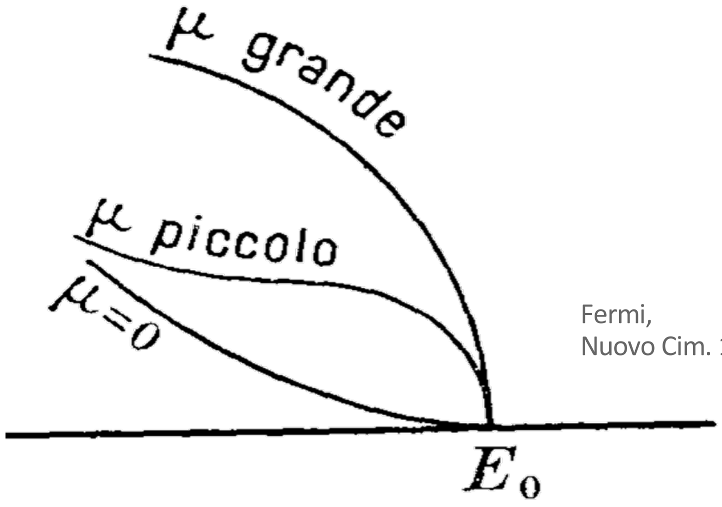
Kinematic neutrino mass measurement



E_0 = 18.56 keV
$T_{1/2}$ =12.3 years

✓ measurement of the electron β −spectrum

- independent of cosmology
- independent of neutrino nature



Fermi,
Nuovo Cim. 11 (1934) 1-19

✓ based on kinematics and energy conservation

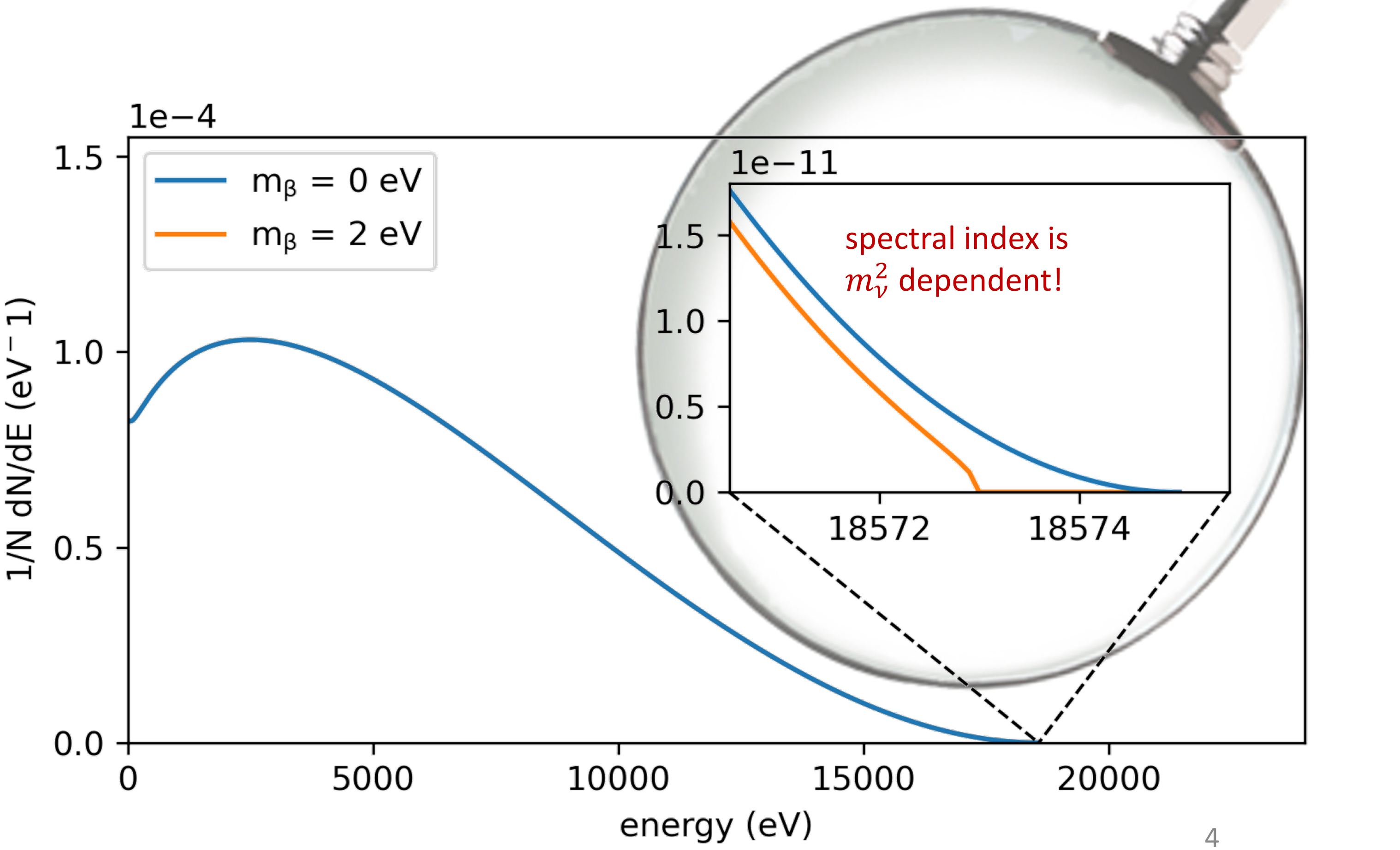
✓ m_ν^2 spectral distortion, maximal at endpoint energy E_0

✓ incoherent neutrino mass : $m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$

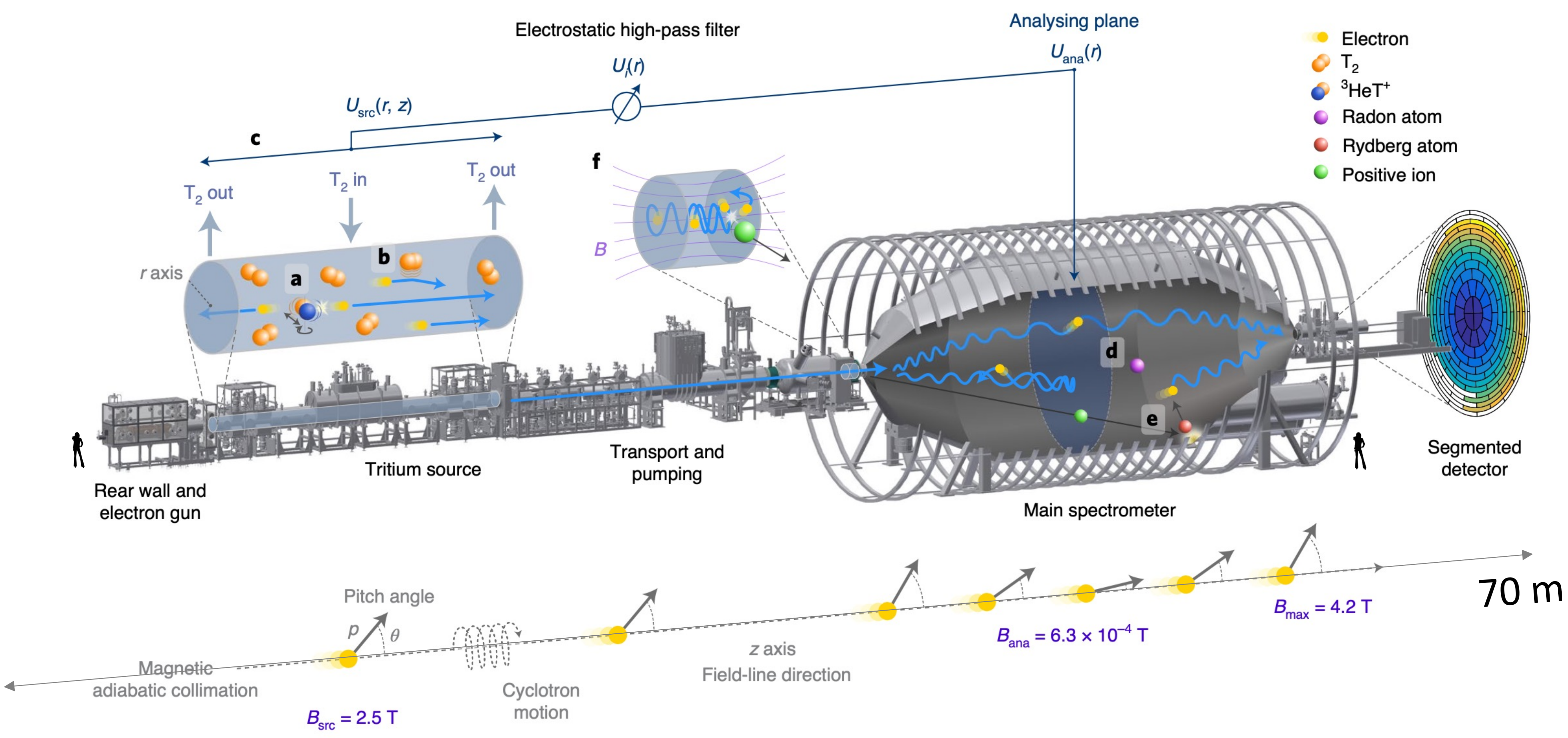
KATRIN experimental challenges

- ✓ strong tritium source: 10^{11} decays/s
- ✓ $\mathcal{O}$(0.1 cps) background
- ✓ $\mathcal{O}$(1 eV) resolution
- ✓ $\mathcal{O}$(0.1%) understanding of the spectrum shape
- ✓ $\mathcal{O}$(0.1%) hardware stability controlled over the years

10^{-8} of all decays in last 40 eV



Working principle



Measurement strategy

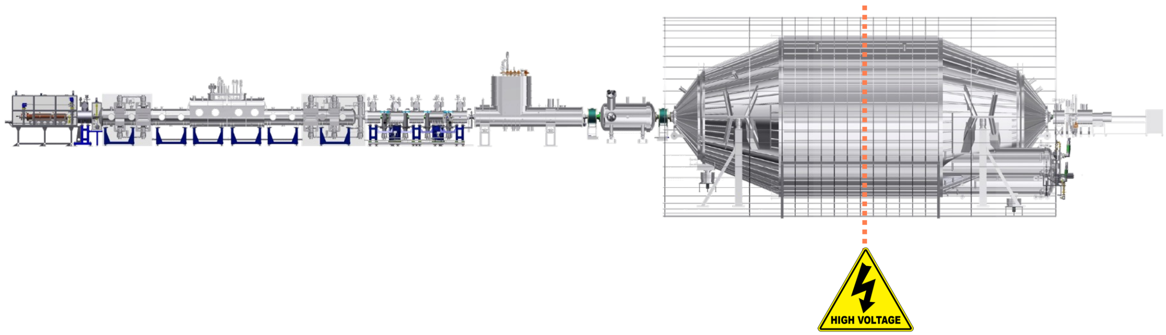
Integral spectral measurement !

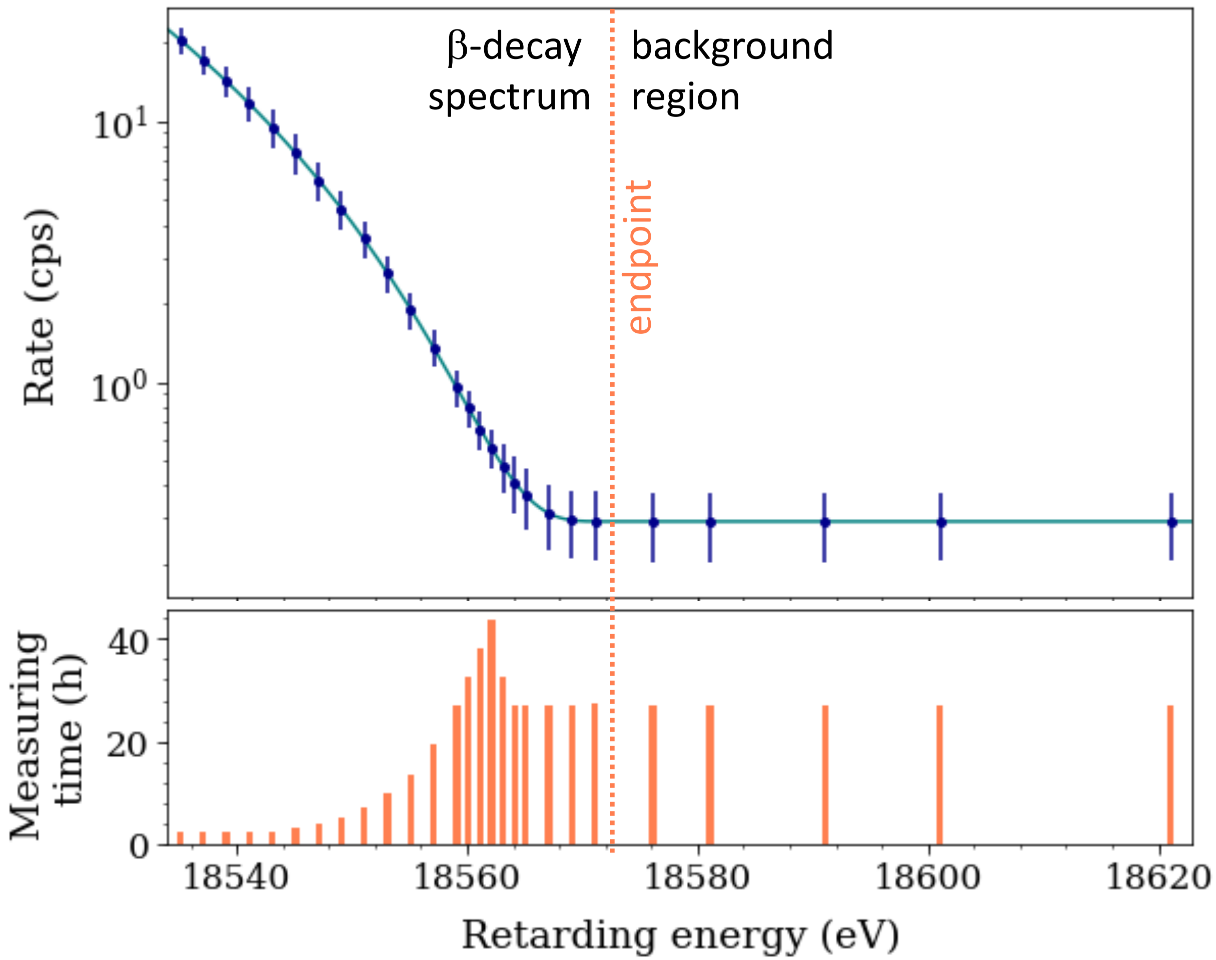
β-scans illustration:

✓ scan points: **~30 HV set points**

✓ scan interval: **E_0 – 40 eV , E_0 + 135 eV**

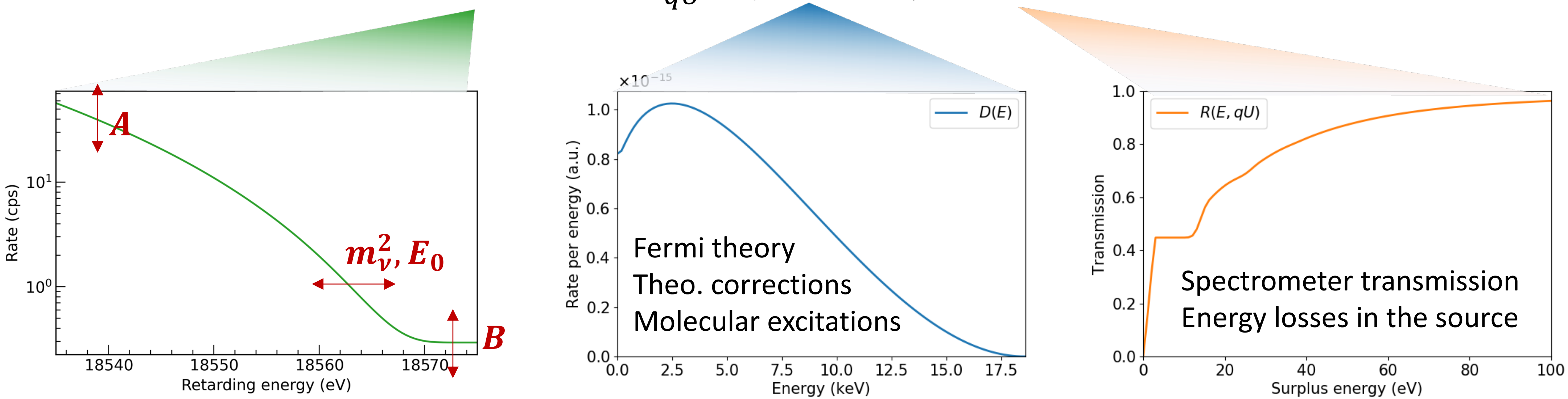
✓ scan time: **~2 hours**





Analysis strategy

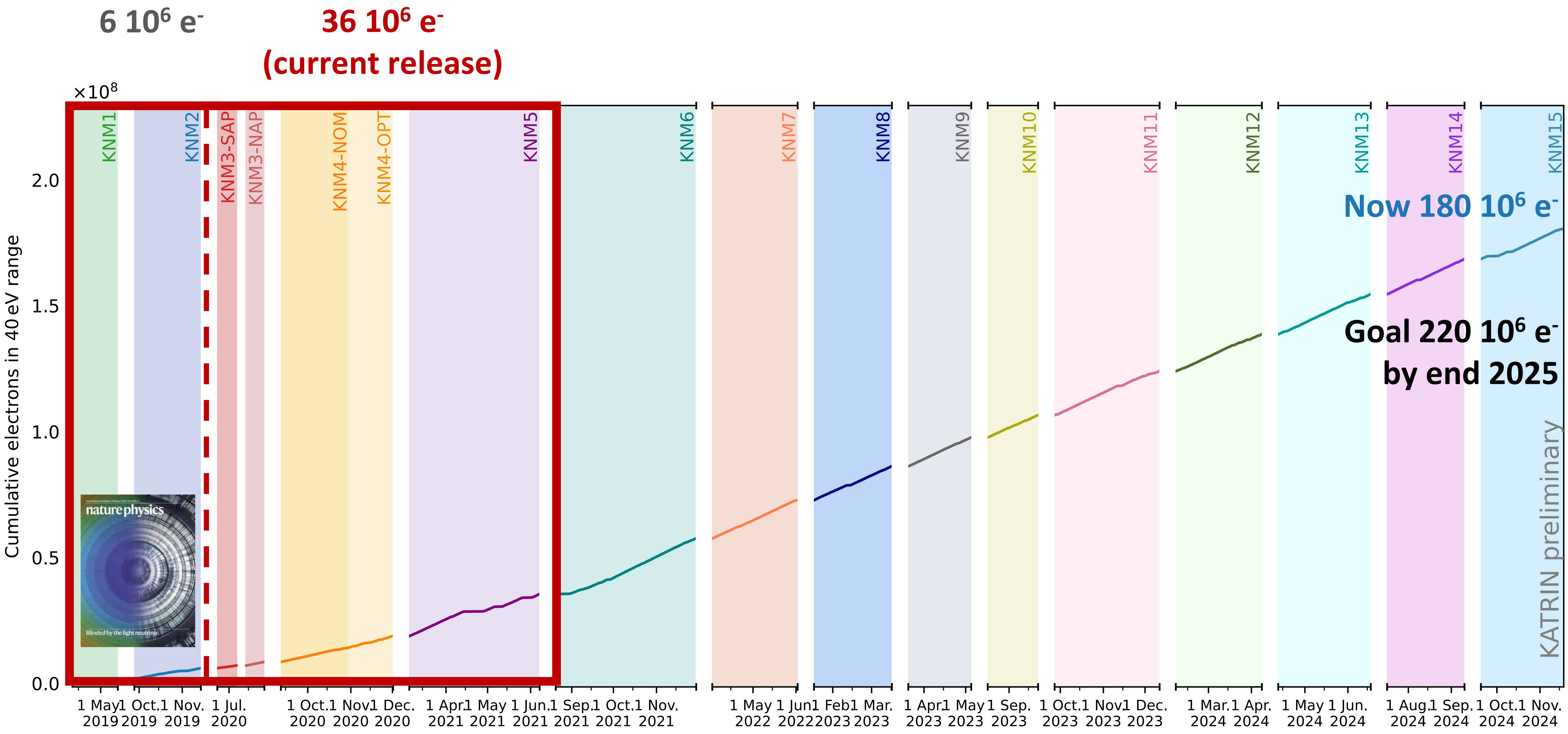
✓ fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$



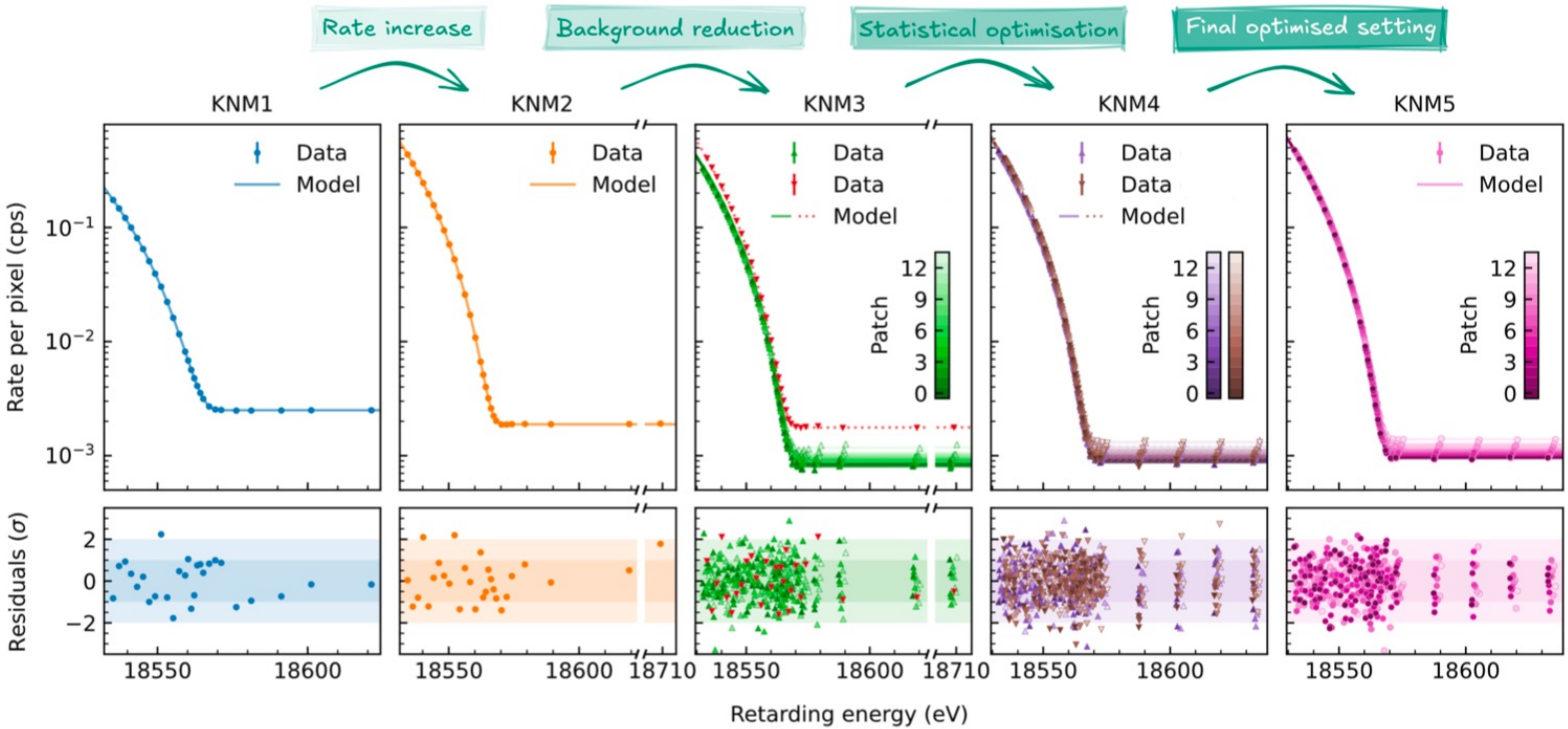
✓ neutrino mass fit parameters: $\boldsymbol{m_\nu^2}, \boldsymbol{E_0}, \boldsymbol{B}, \boldsymbol{A}$

✓ fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, …)

Data taking & new released dataset



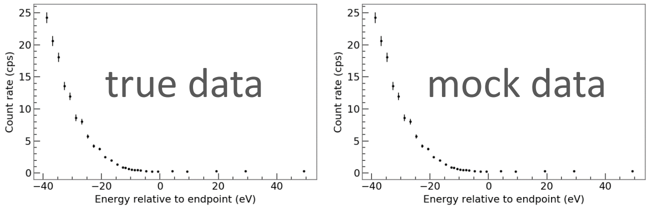
5 measurement campaigns & spectra

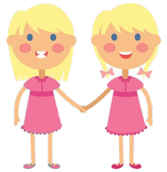


3-tiered blind analysis

Freeze analysis on MC-twin data

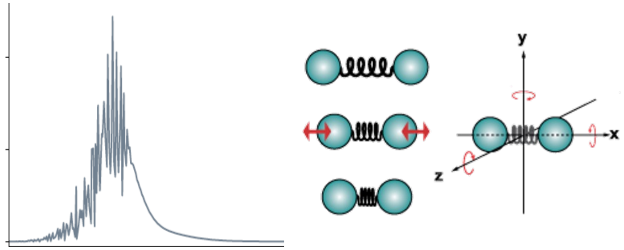
- mock data mimicking each scan





Blinded model

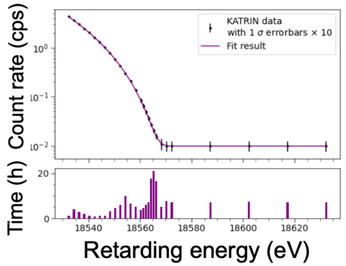
- modified molecular final state dist.

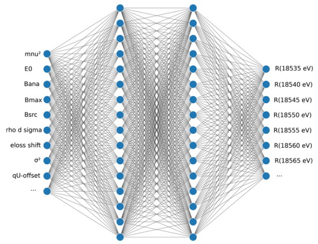


m_ν^2

Two independent analysis teams

- different strategies and codes





Systematic effects

Background reduction by ~50% through fiducialisation: "shifted analysing plane"
→ Eur.Phys.J.C 84 (2024) 12, 1258

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

Final States

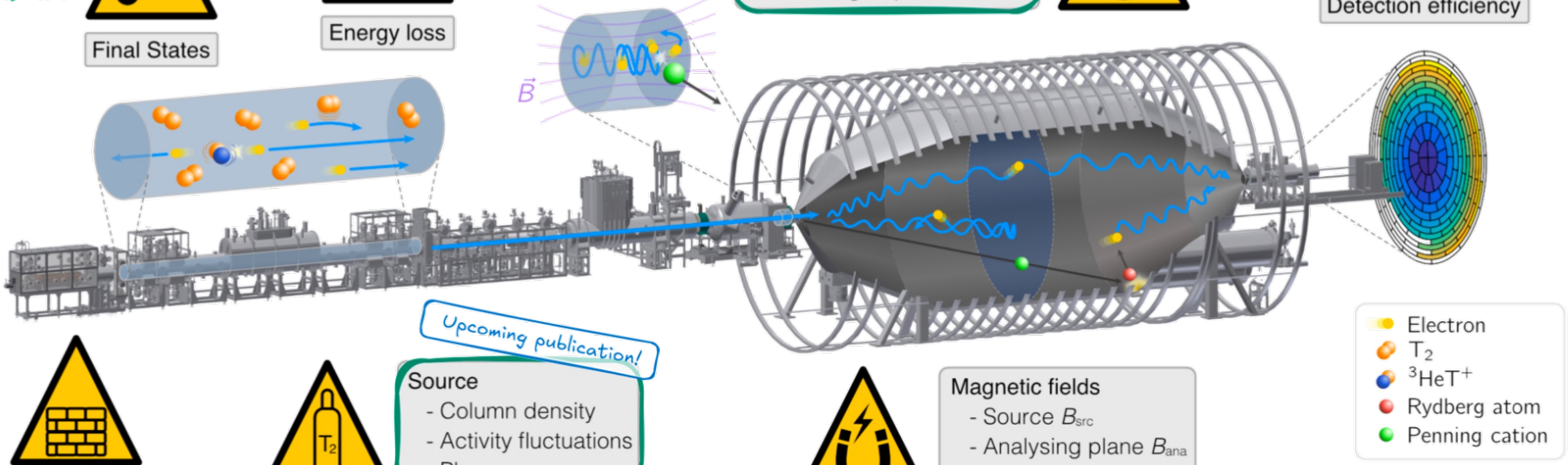
Energy loss

New publication!

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

Upcoming publication!

Detection efficiency



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
→ https://arxiv.org/abs/2503.13221

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

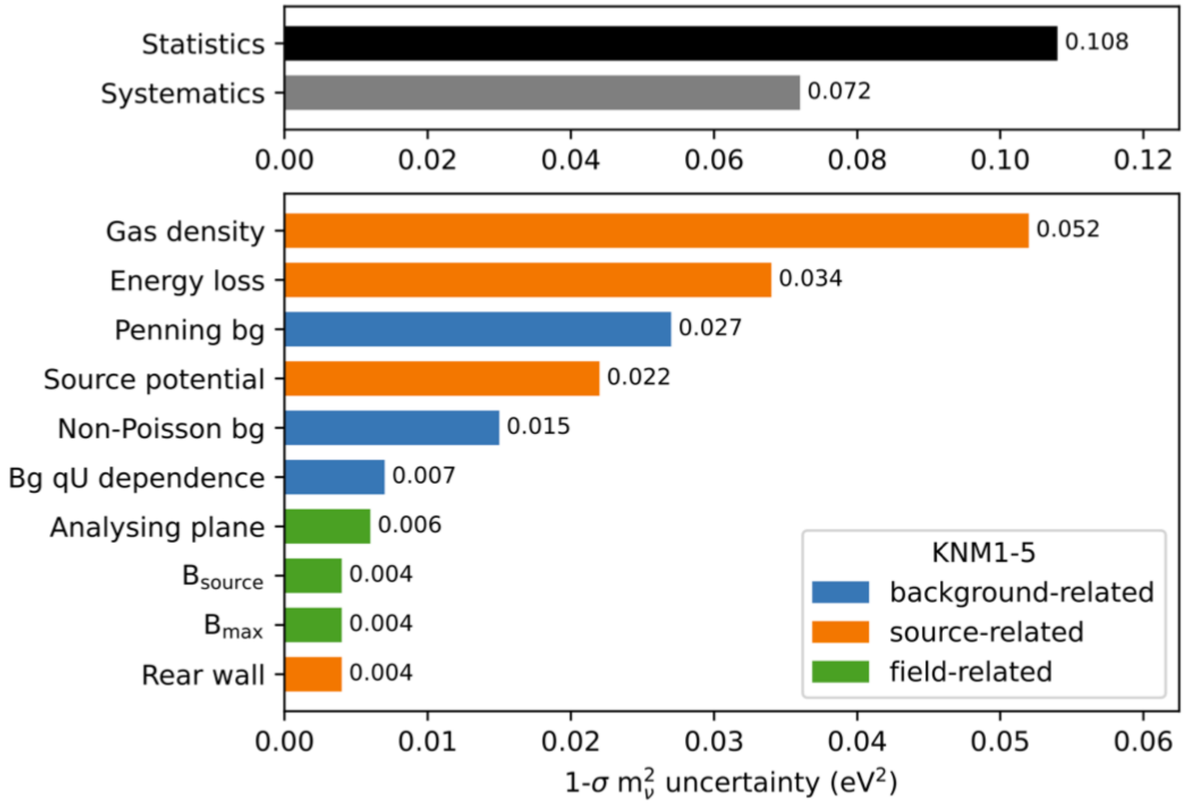
Systematic uncertainties

✓ **sensitivity dominated by statistical uncertainties**

✓ reduction of background-related systematics

✓ improved control over source scattering

✓ reduction of molecular final-states uncertainties by refined theoretical reassessment



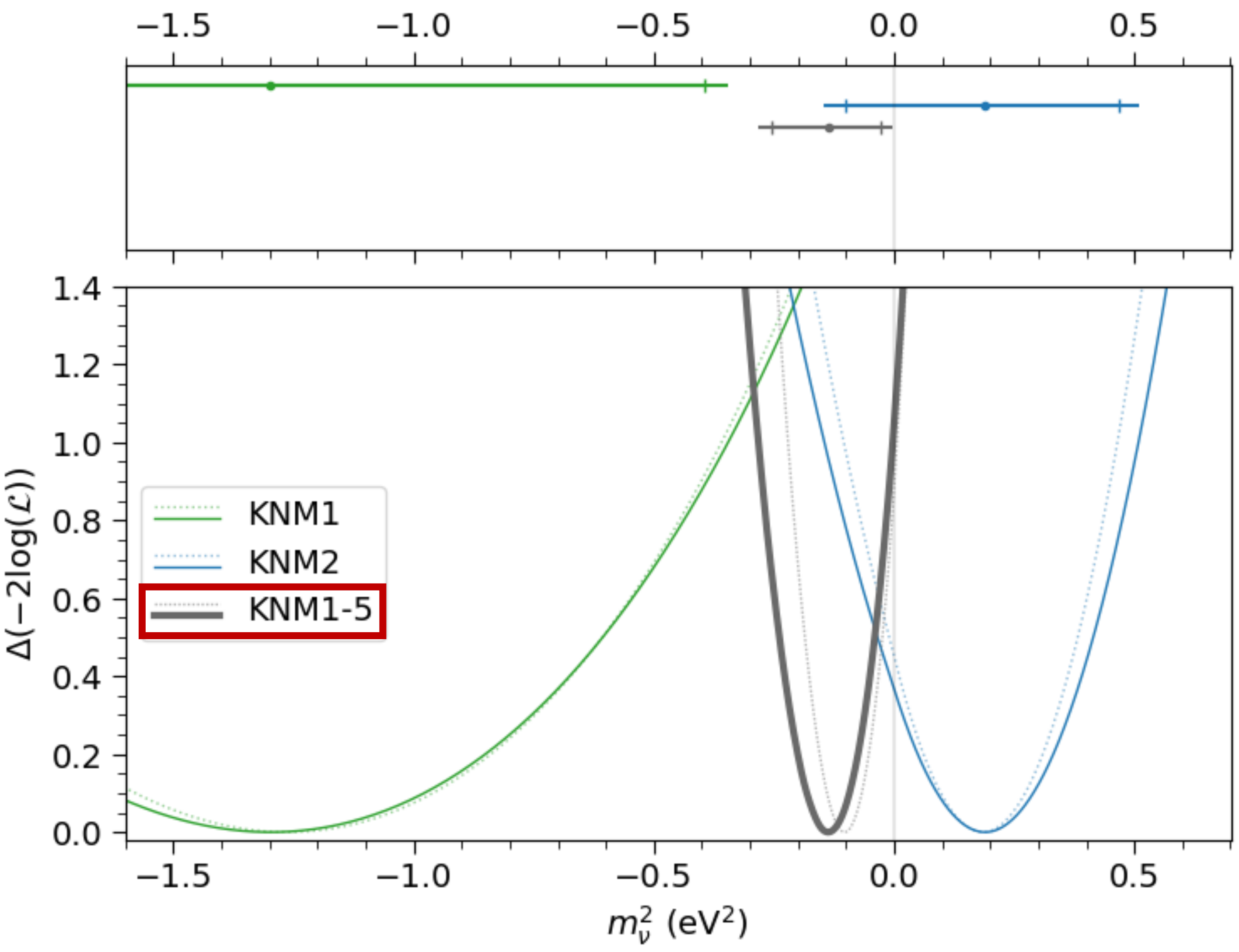
Latest neutrino mass results: best fit

https://arxiv.org/abs/2406.13516

- ✓ simultaneous maximum likelihood fit with common m_ν^2 parameter
- ✓ excellent goodness-of-fit: p-value=0.84
- ✓ best-fit value:

$$m_\nu^2 = -0.14^{+0.14}_{-0.15}\ \mathrm{eV}^2$$

- ✓ negative m_ν^2 estimates reflect statistical fluct allowed by the spectrum model



Latest neutrino mass results: upper limit

- ✓ best-fit value:

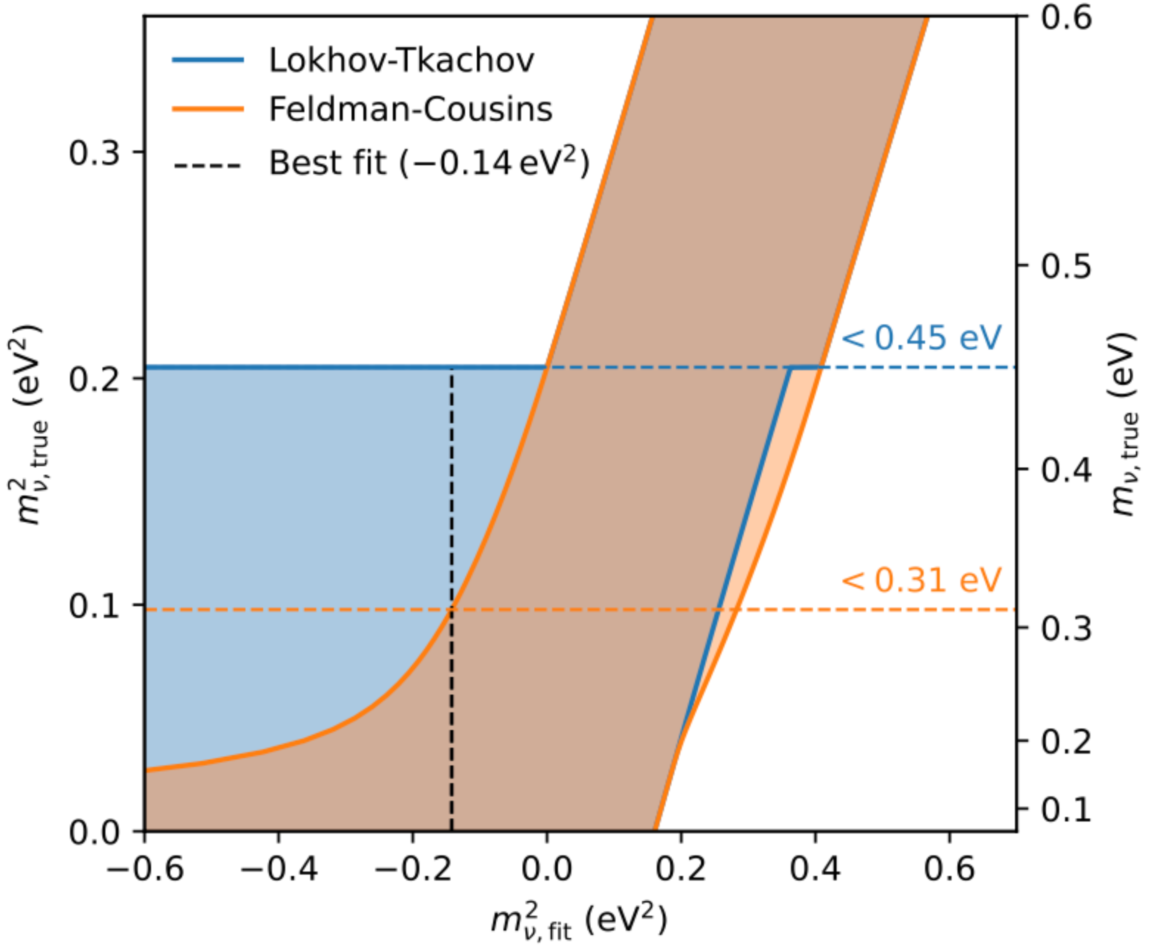
$$m_\nu^2 = -0.14^{+0.14}_{-0.15}\ \mathrm{eV}^2$$

- ✓ new upper limit:

$$\mathrm{m}_\nu < 0.45\ \mathrm{eV}\ (90\%\ \mathrm{CL})$$

Lokhov-Tkachov ~ sensitivity

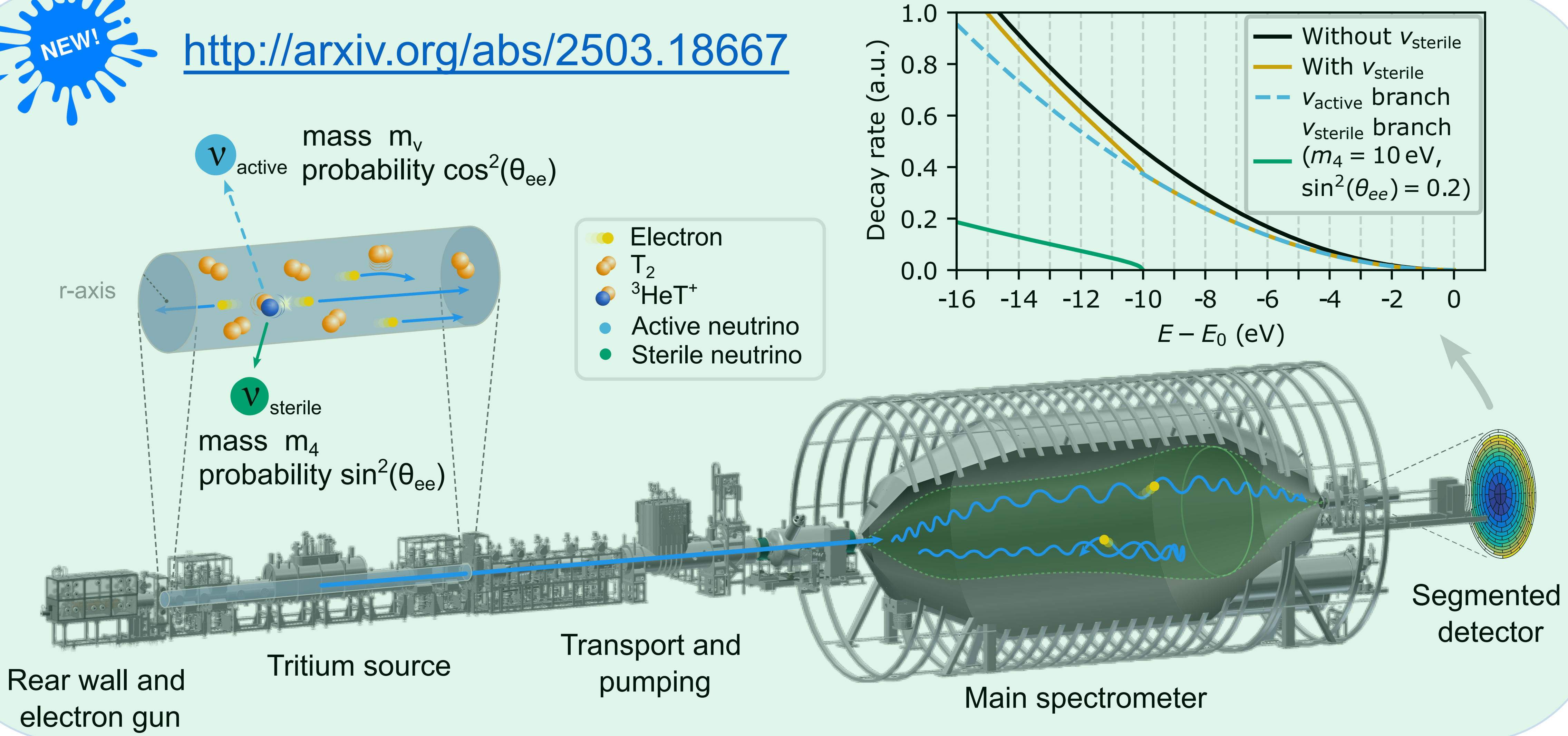
https://arxiv.org/abs/2406.13516



Light-sterile neutrino search (eV-scale)

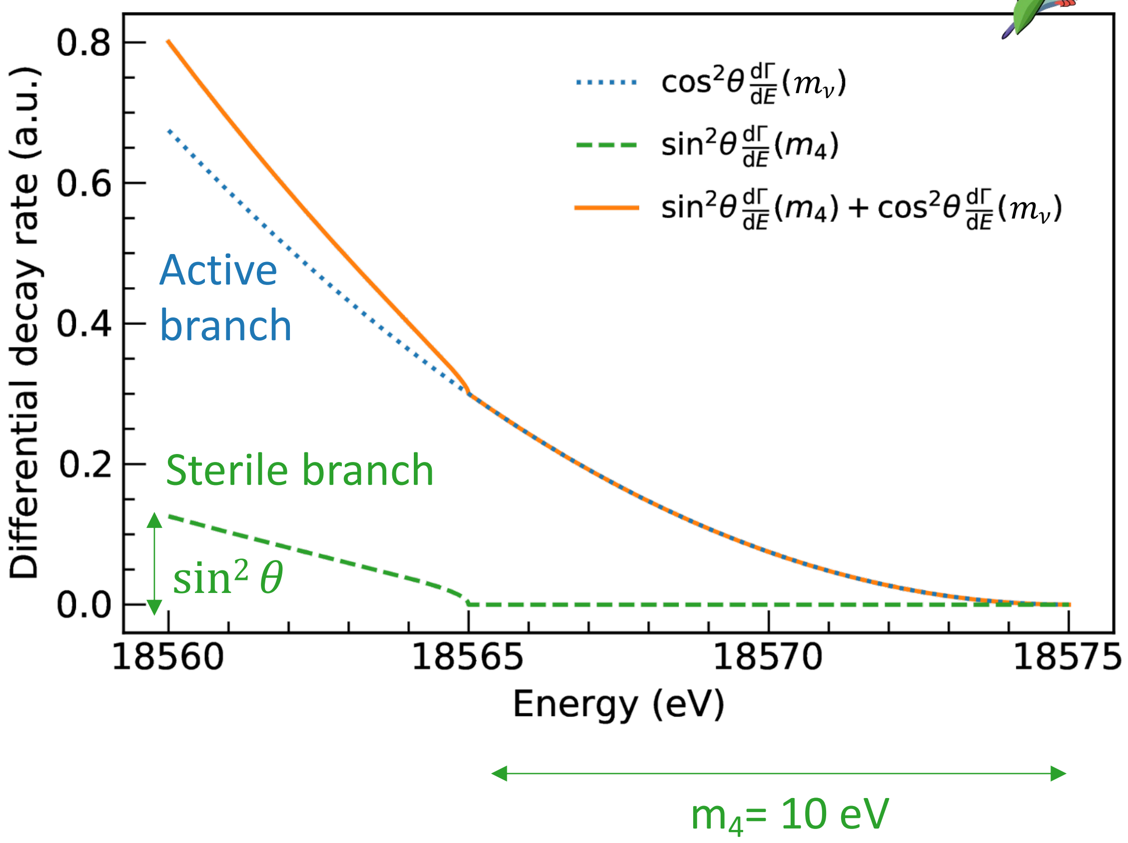
NEW!

http://arxiv.org/abs/2503.18667



Generic eV-sterile neutrino signal

Expected signature in KATRIN



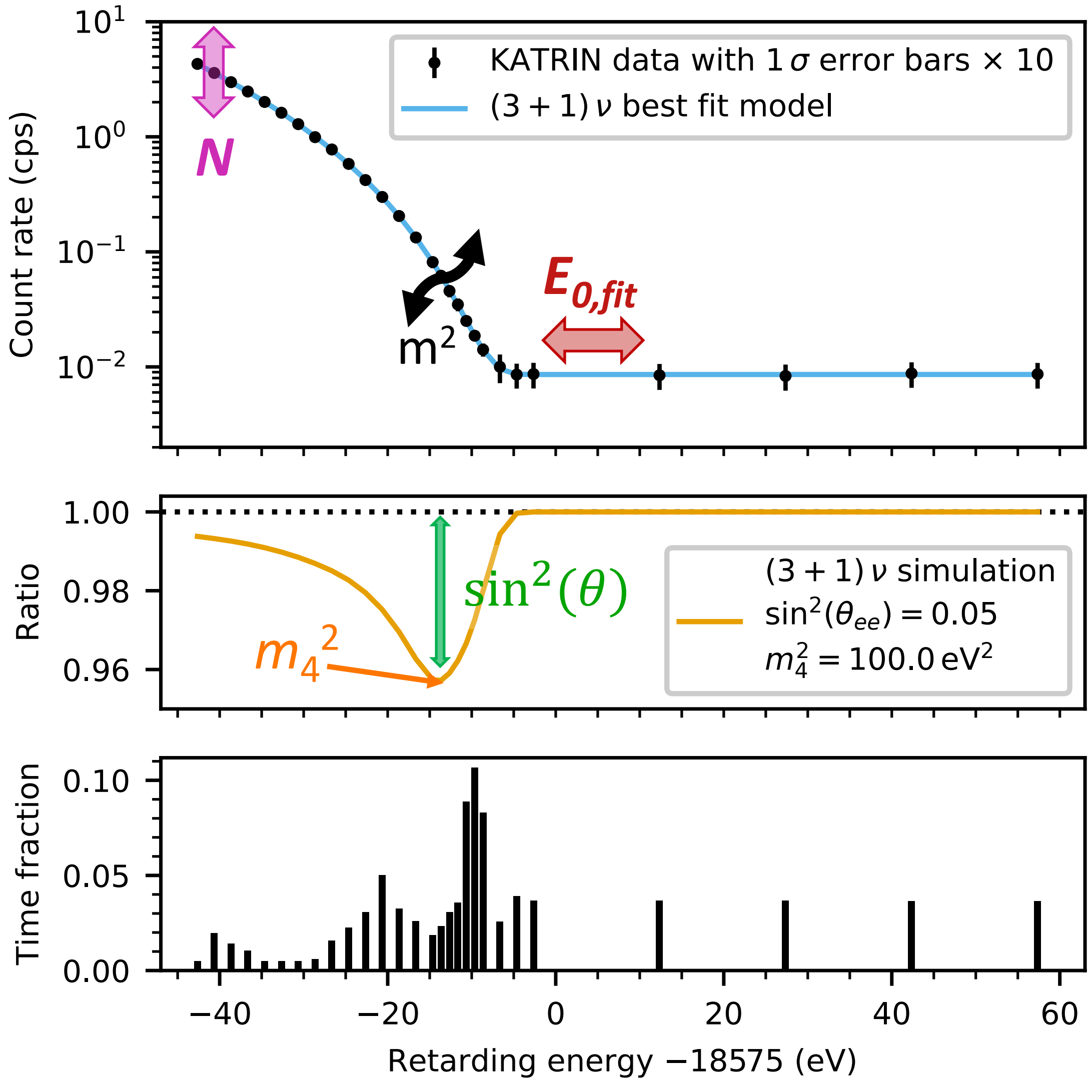
$$\frac{d\Gamma}{dE} = \underbrace{\left(1 - \sin^2(\theta)\right) \frac{d\Gamma}{dE}(m_\nu^2)}_{\text{light neutrino}} + \underbrace{\sin^2(\theta) \frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$

Fit Parameters:

m_ν^2 neutrino mass (fixed/free/constrained)
$E_{0,fit}$ endpoint
N signal normalization
B background rate

${m_4}^2$ 4th neutrino mass
$\sin^2(\theta)$ 4th neutrino mixing

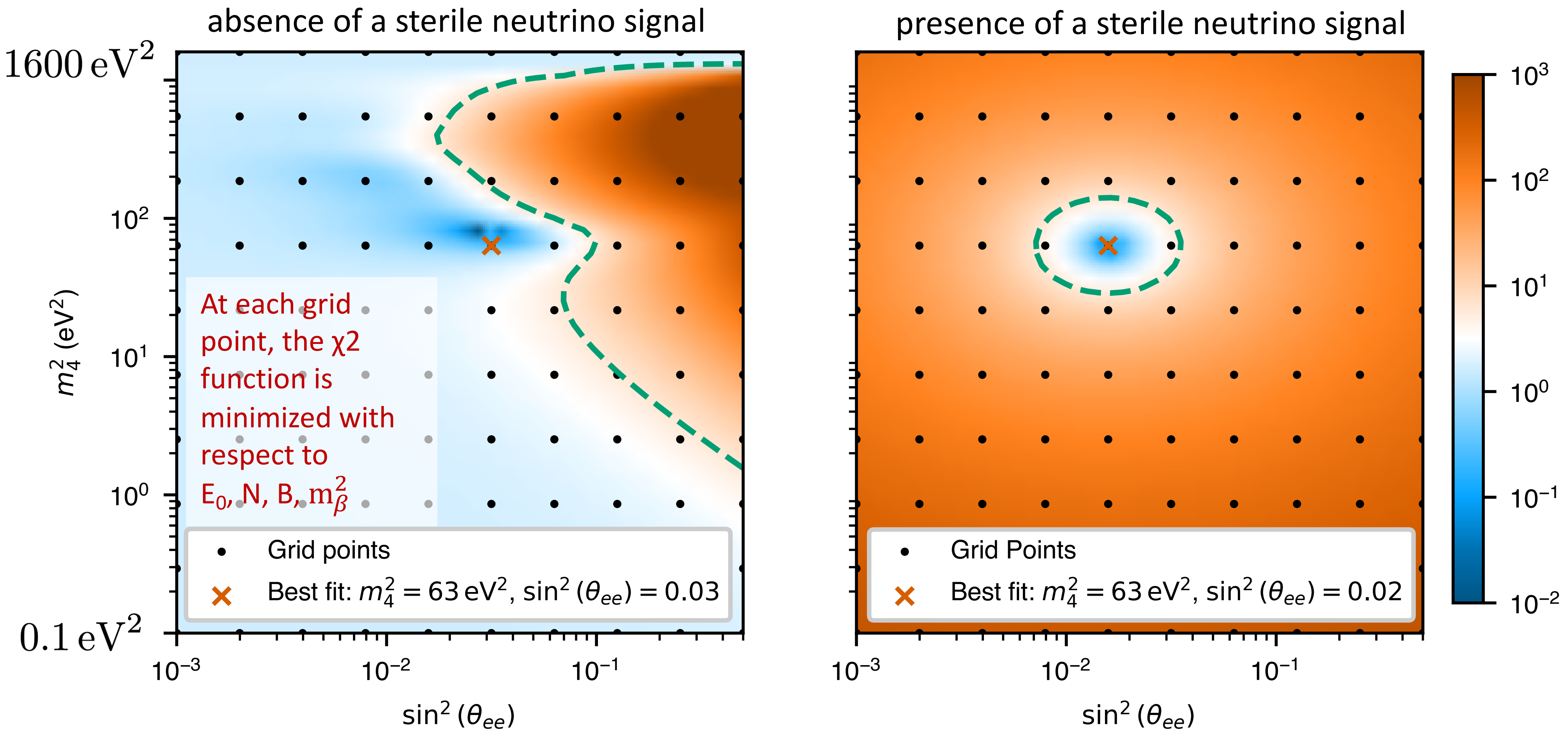
Expected eV-neutrino signal in KATRIN



- ✓ tritium Spectrum Endpoint – *Actual data*
  - ✓ ROI: -40 eV below endpoint
  - ✓ ROI: +60 eV above endpoint (background)
- ✓ 3 active + 1 sterile neutrino – *Simulation*
  - ✓ Mass = 10 eV - Mixing = 5%
- ✓ Measurement Time Distribution (MTD)

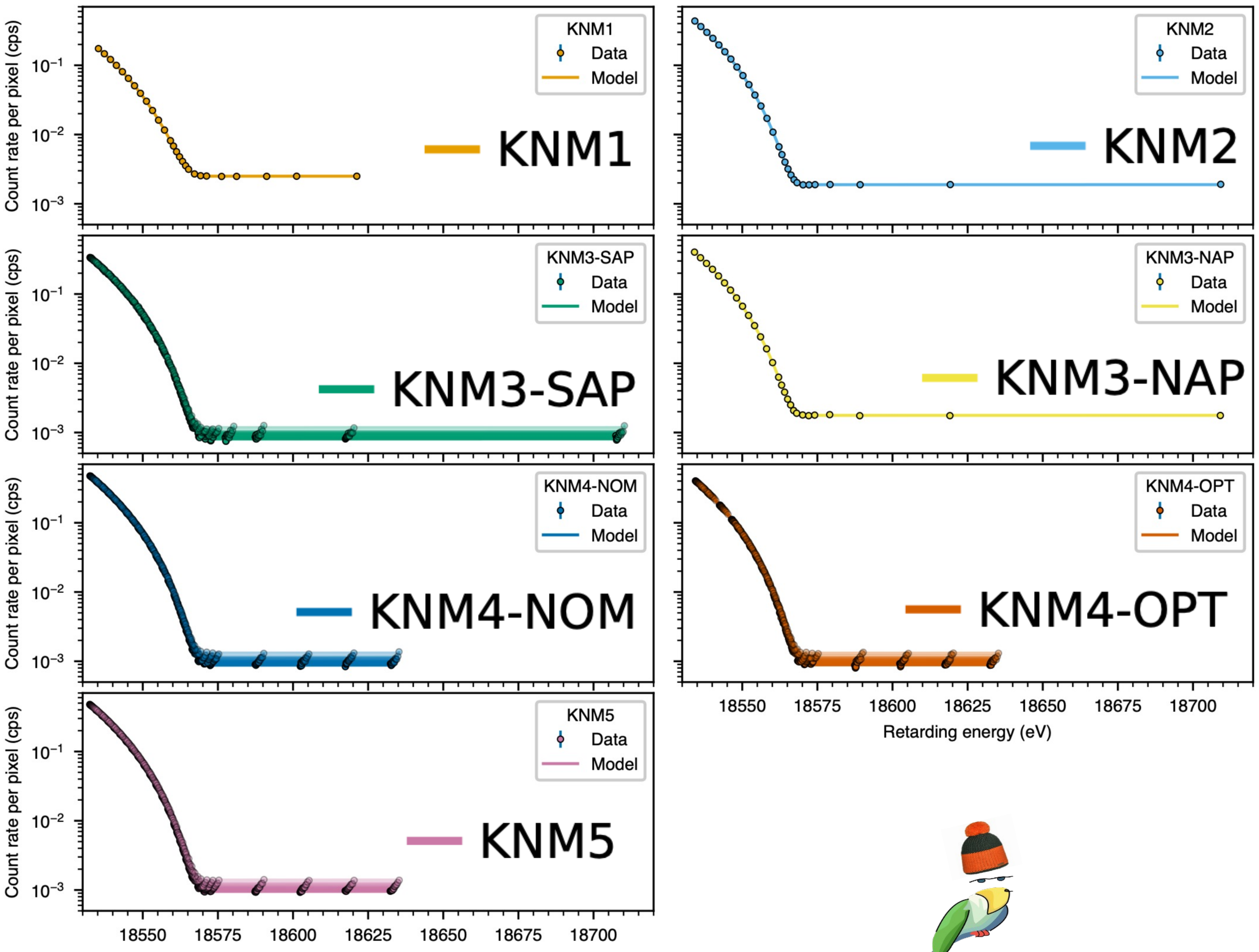
Grid-search analysis method (simulation)

we use 95% C.L. – $\Delta\chi^2 = \chi^2 - \chi^2_{global\ min} = 5.99$ (2 dof – Wilks' theorem applicable)



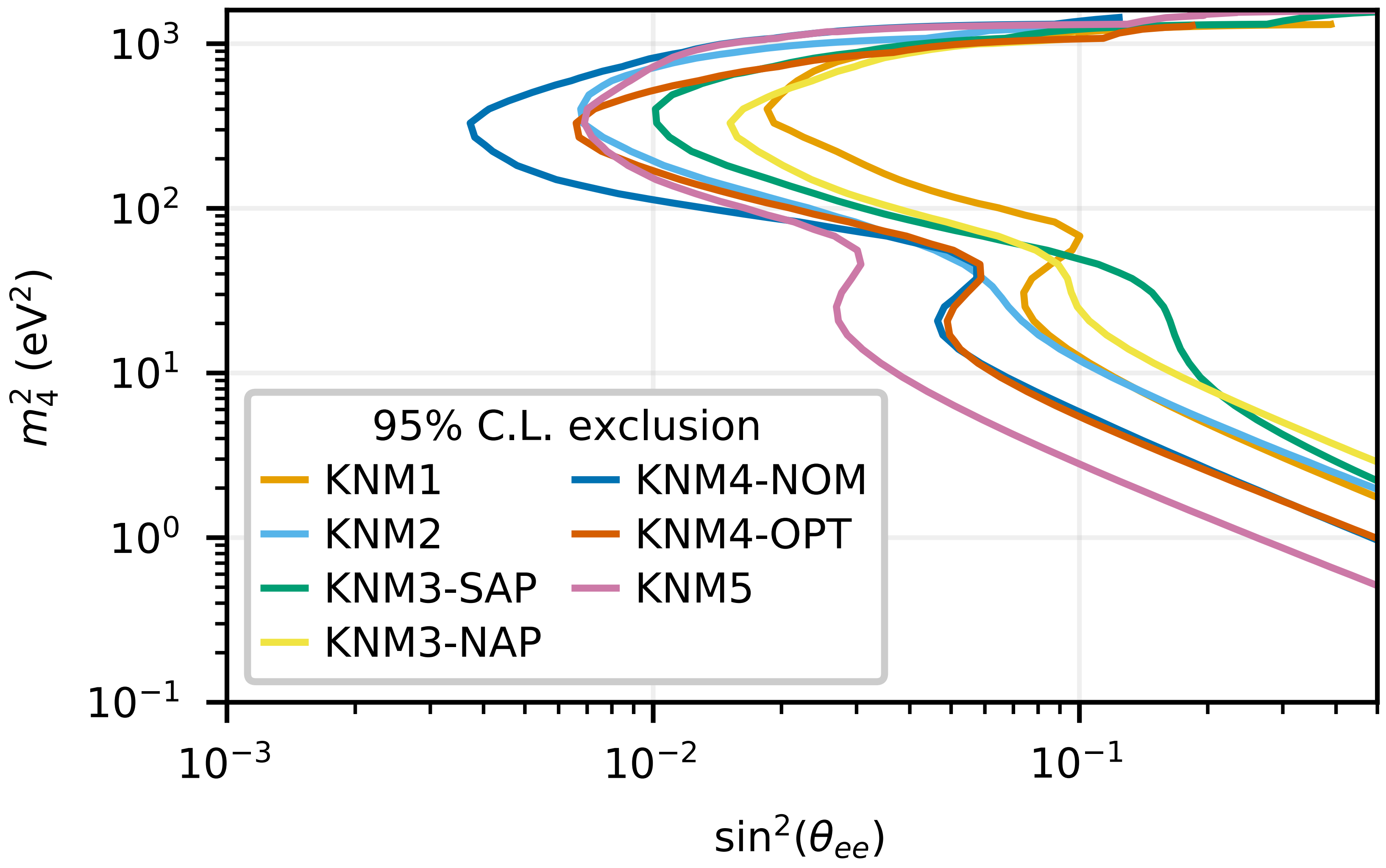
Data set – blinding scheme

- ✓ same dataset as for the m_ν analysis
  - ✓ 2019 – 2021 – 36 million electrons
  - ✓ ROI: E_0-40 to E_0+135 eV
- ✓ blinding scheme
  - ✓ analysis on simulations before analysis of data
  - ✓ two teams cross-checked results
  - 5 campaigns analyzed separately first
    - ✓ one issue found in KNM4
  - ✓ final step: combined fit of KNM1-5



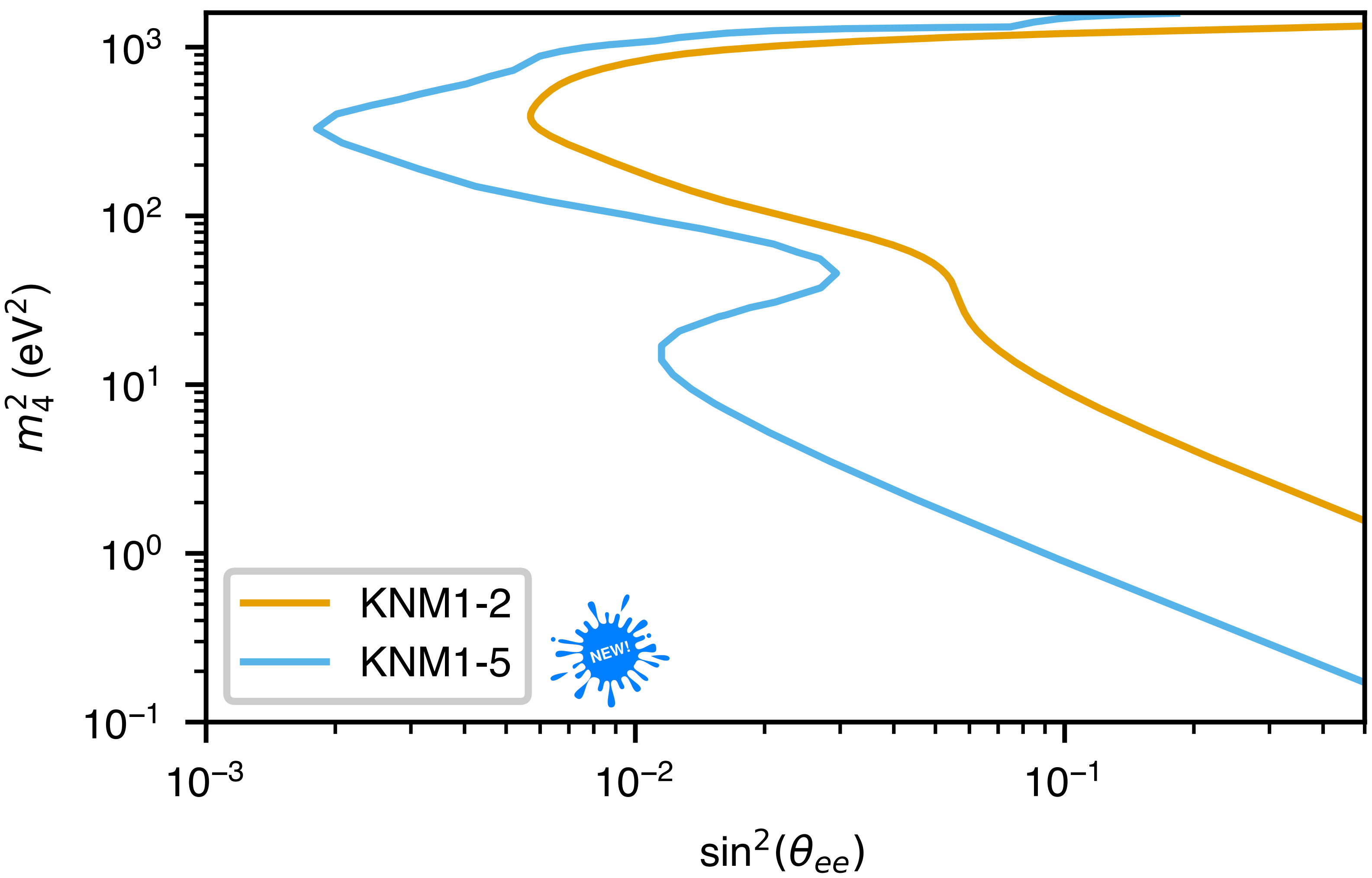
Results on individual campaigns (data)

no evidence for sterile neutrinos in any campaign



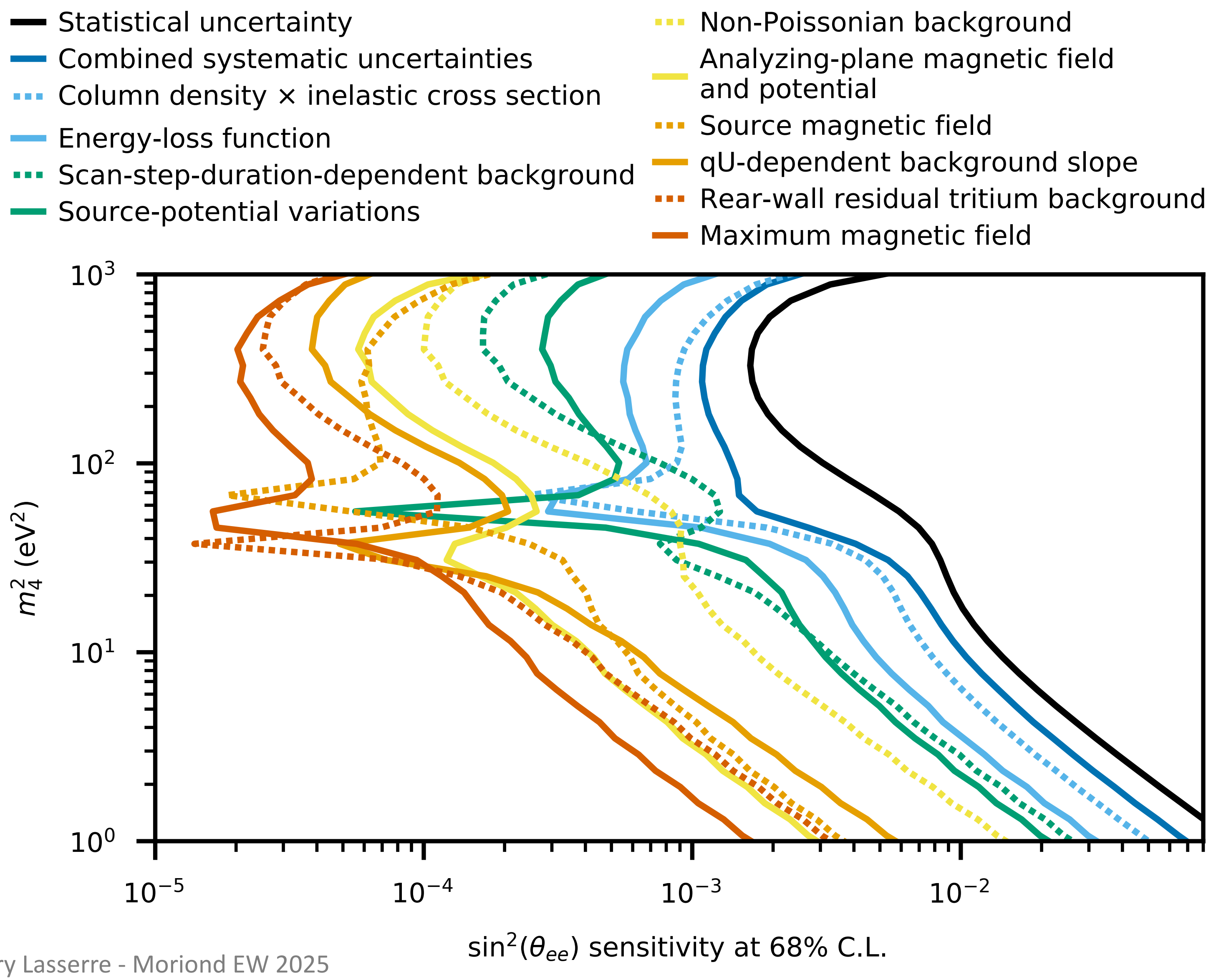
KNM1	2 millions e$^-$
KNM2	4 millions e$^-$
KNM3-SAP	3 millions e$^-$
KNM3-NAP	
KNM4-NOM	11 millions e$^-$
KNM4-OPT	
KNM5	17 millions e$^-$

Improvement over KATRIN previous results



- ✓ combined fit with common sterile neutrino parameters
  - ✓ m_4^2
  - ✓ $\sin^2(\theta_{ee})$
- ✓ no evidence for light sterile neutrino
- ✓ previous result: KNM 1+2
  - ✓ 6 million electrons
- ✓ new result: KNM 1+2+3+4+5
  - ✓ 36 million electrons (x6)

Systematic uncertainties: m_4^2 raster scan



✓ $\sigma_{syst}(m_4^2) = \sqrt{\sigma^2_{stat+syst} - \sigma^2_{stat}}$

✓ statistics dominated for all m_4^2

✓ dominant syst. effects

- ✓ column density
- ✓ energy loss function
- ✓ source plasma potential

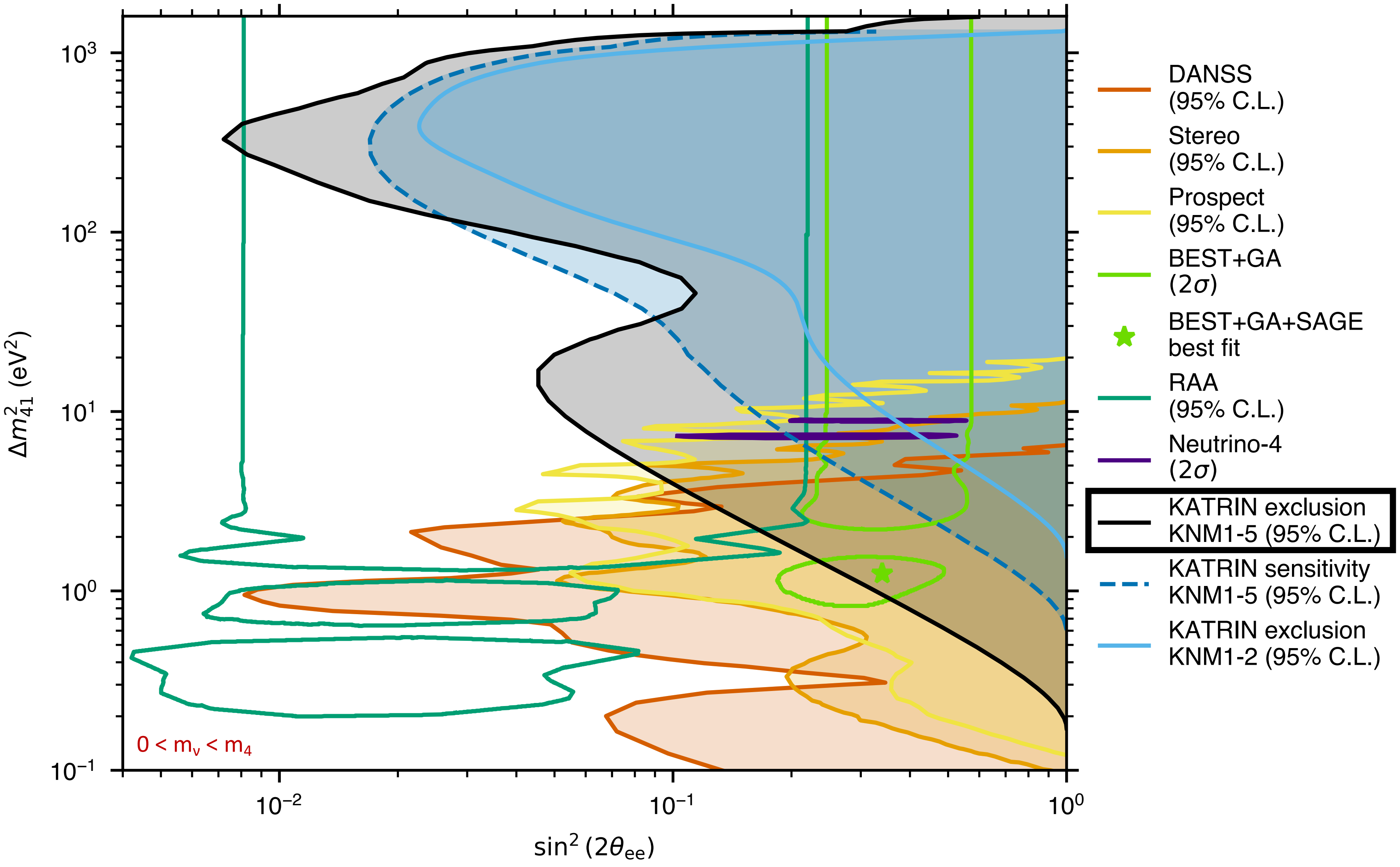
KATRIN in the light of ν-oscillation experiments

- ✓ **new exclusion limit** NEW!
  http://arxiv.org/abs/2503.18667

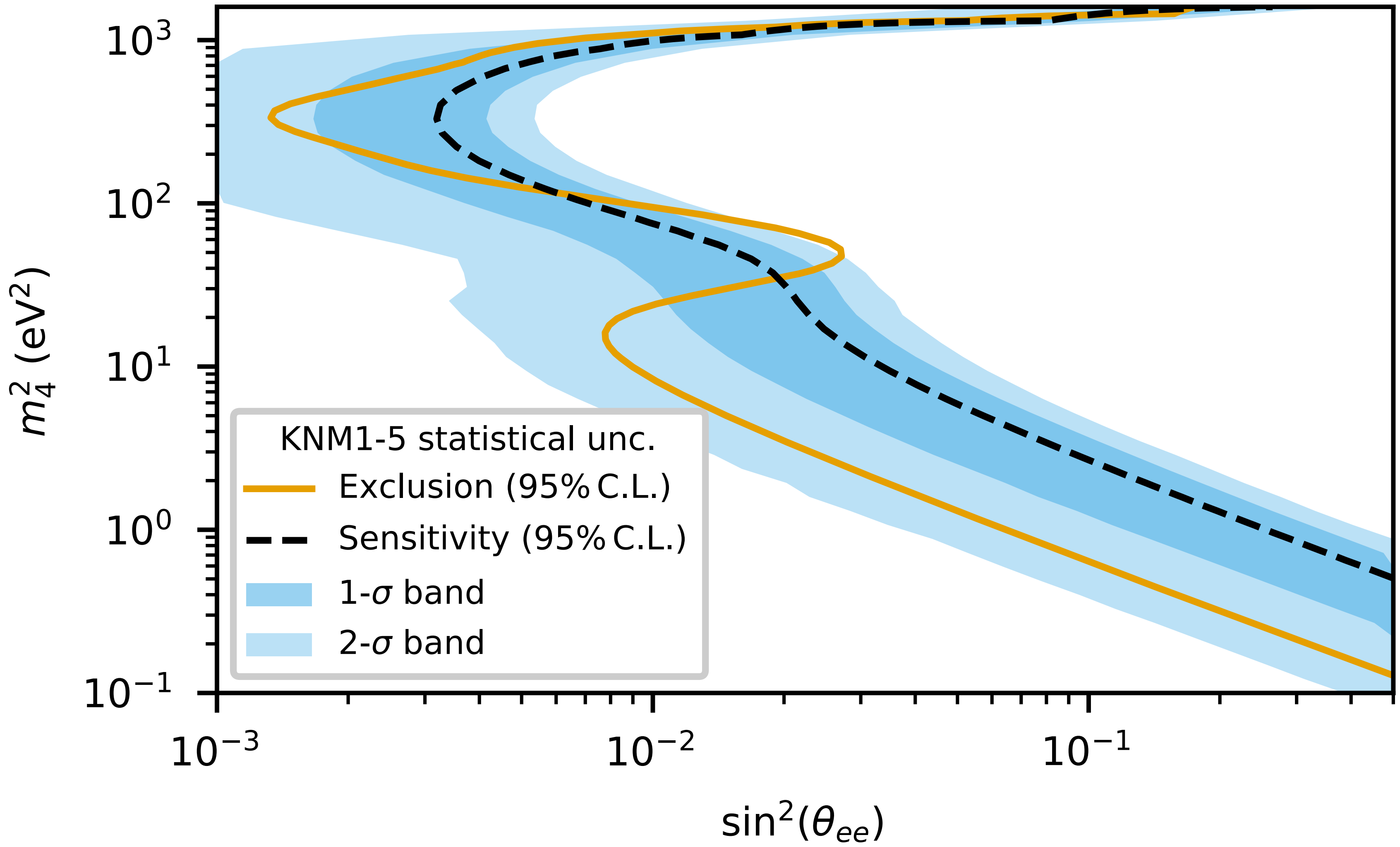
- ✓ almost exclude the whole Gallium Anomaly allowed region

- ✓ exclude Neutrino-4

- ✓ synergy with Short Baseline Reactor Experiments
  - Prospect
    Stereo
    DANSS …
  - KATRIN provides superior sensitivity for $\Delta m_4^2 > 5eV^2$



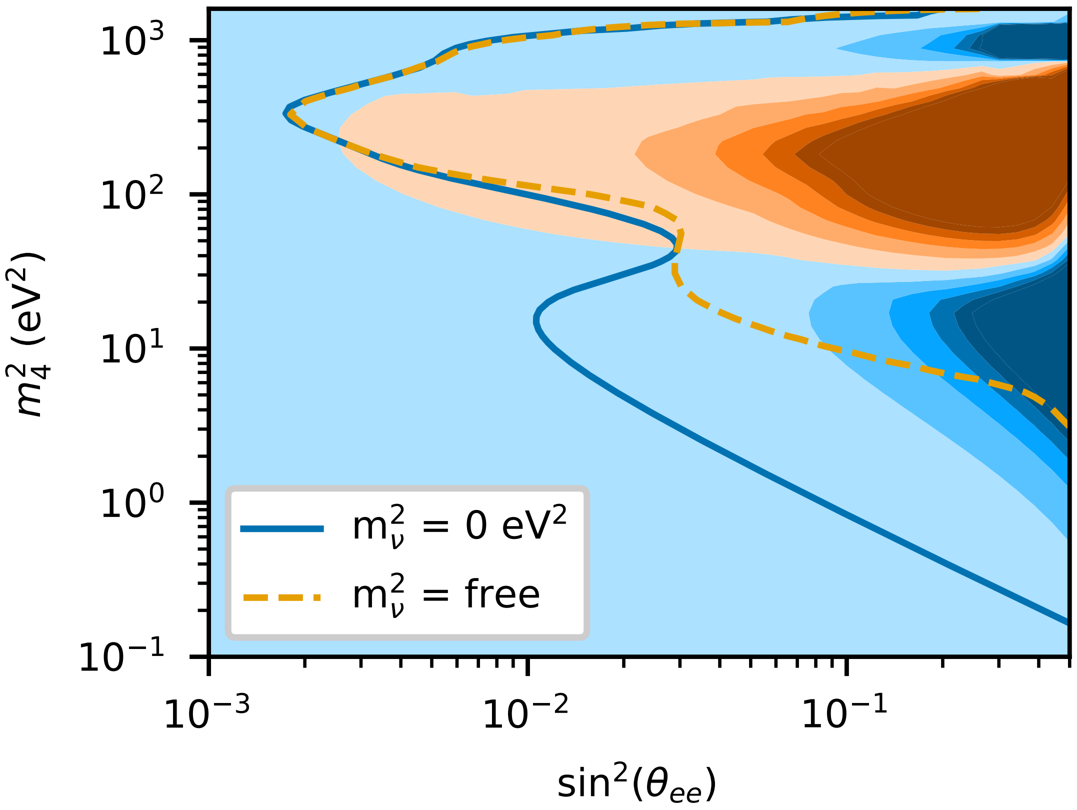
New exclusion compared to sensitivity



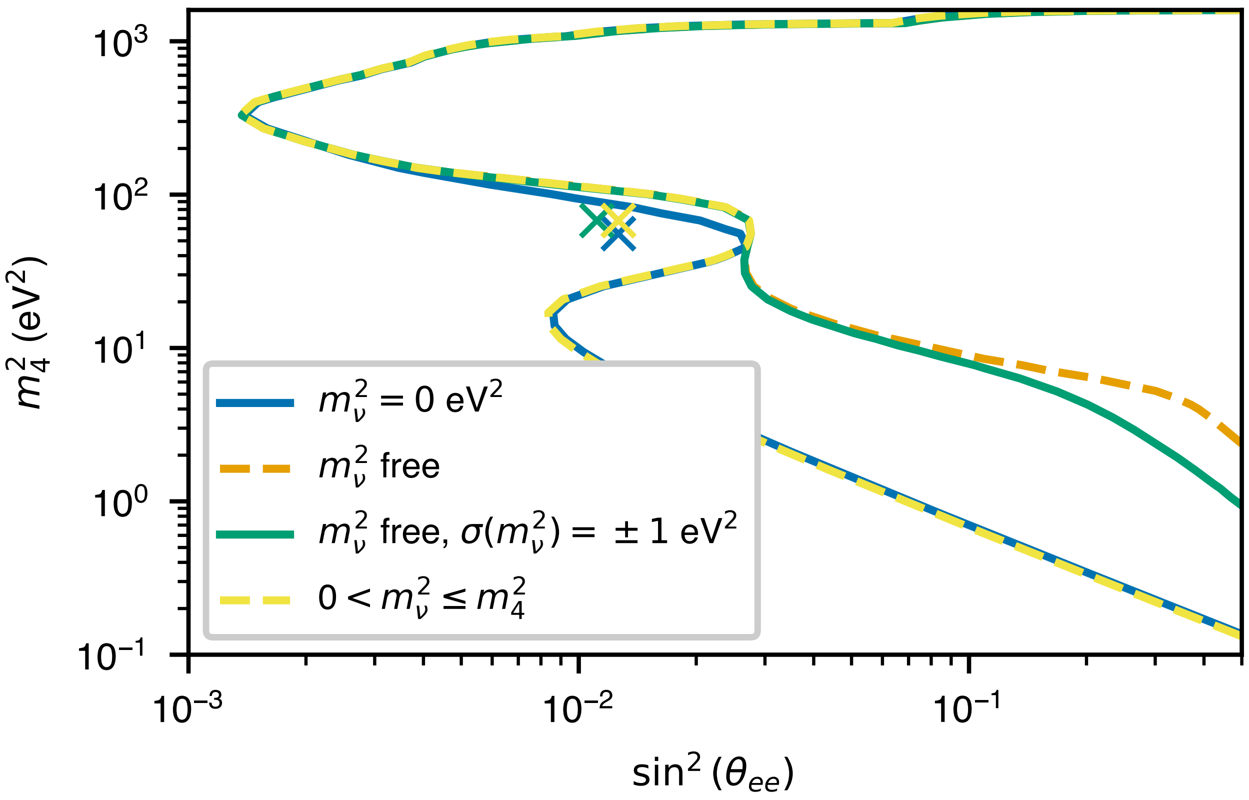
- ✓ sensitivity contour (simulation) intersects exclusion contour (data)
  - ✓ $m_4^2 < 30$ eV², exclusion extends beyond sensitivity
  - ✓ $m_4^2 > 30$ eV², exclusion oscillates around sensitivity
- ✓ 1σ and 2σ statistical sensitivity bands reconstructed from simulations
- ✓ New exclusion contour aligns with expected statistical fluctuations within 95% C.L.

Analysis with free neutrino mass

combined KNM1-5 – stat+syst



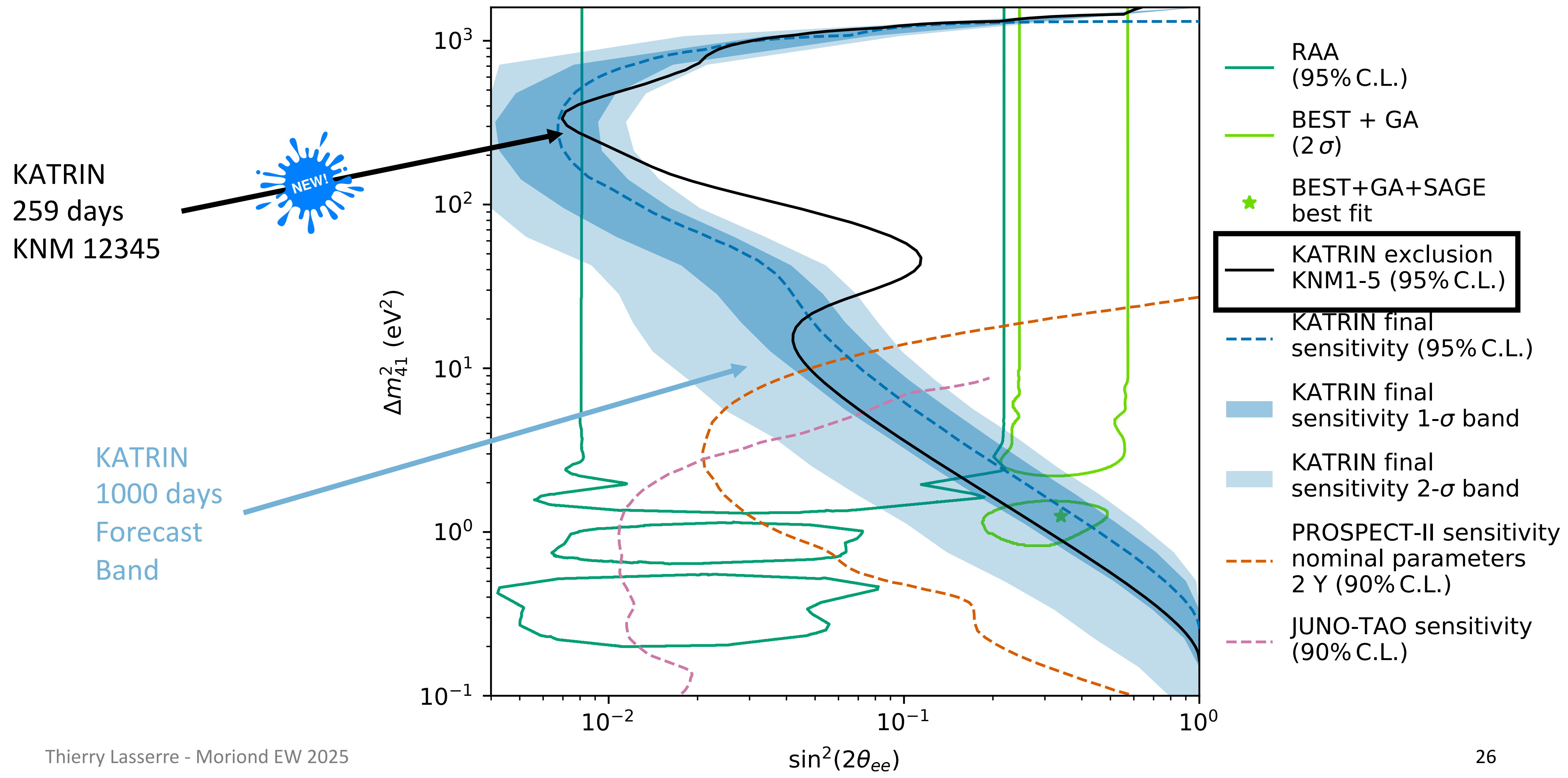
combined KNM1-5 – stat – 4 scenarios



free active neutrino mass (m_ν) analysis leads to a m_ν – m_4 degeneracy → sensitivity loss at $m_4^2 < 30$ eV^2

Full sensitivity at low m_4 is recovered for $0 < m_\nu < m_4$

KATRIN 1000 days sensitivity forecast

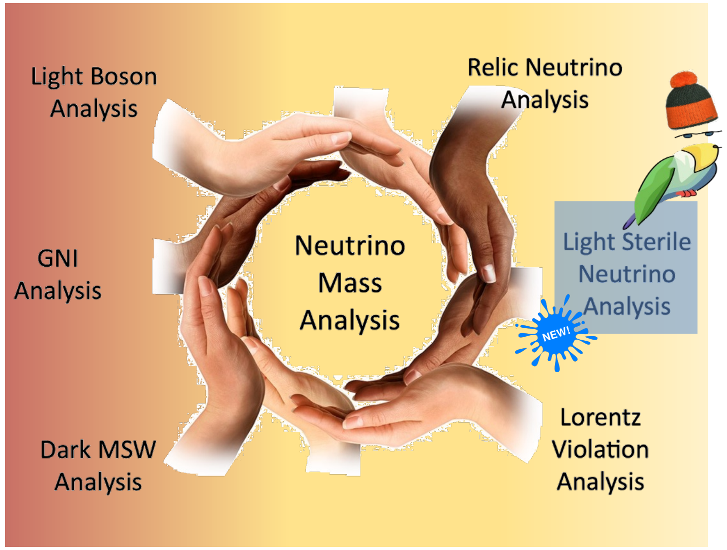


Summary and outlook

2025: neutrino mass

https://arxiv.org/abs/2406.13516

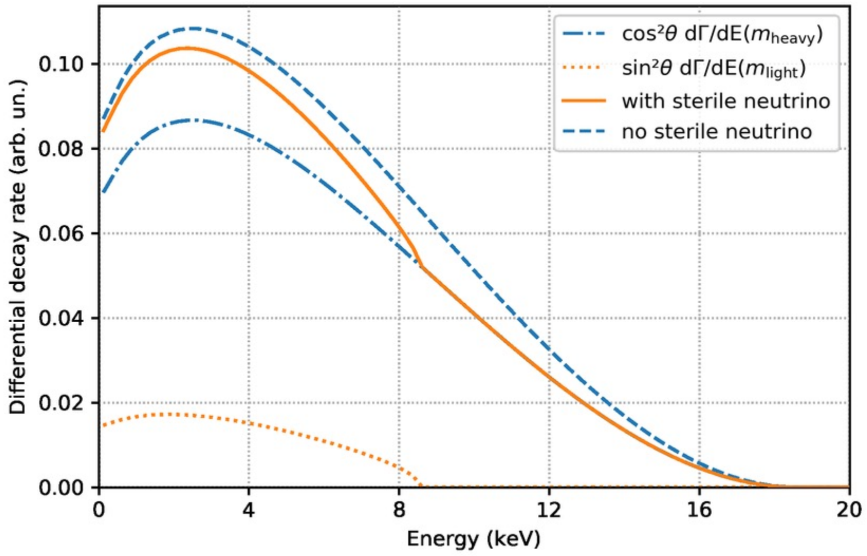
+



NEW! http://arxiv.org/abs/2503.18667

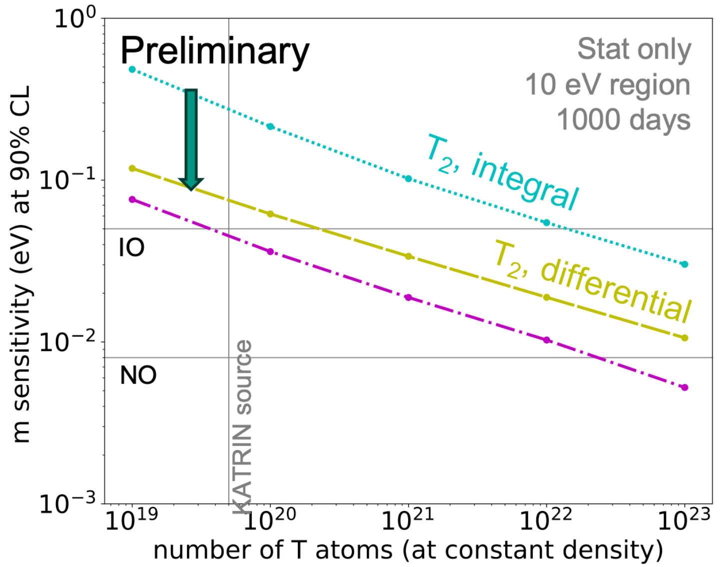
2026- 2027: keV-sterile neutrino

- TRISTAN detector
- Measurement of the entire T-spectrum



KATRIN ++ R&D

- Differential measurement
- Atomic T source



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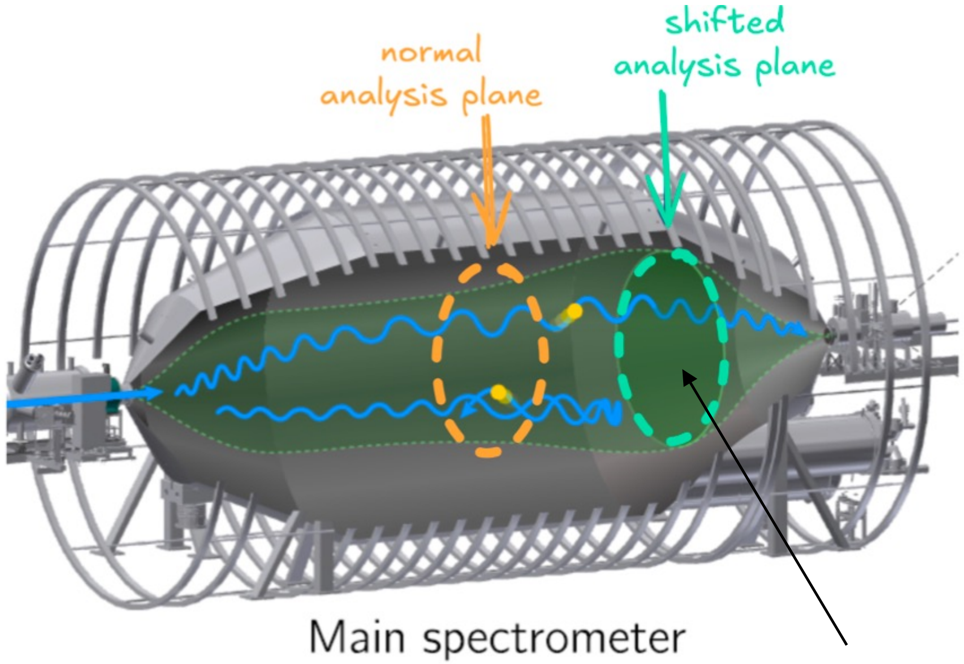
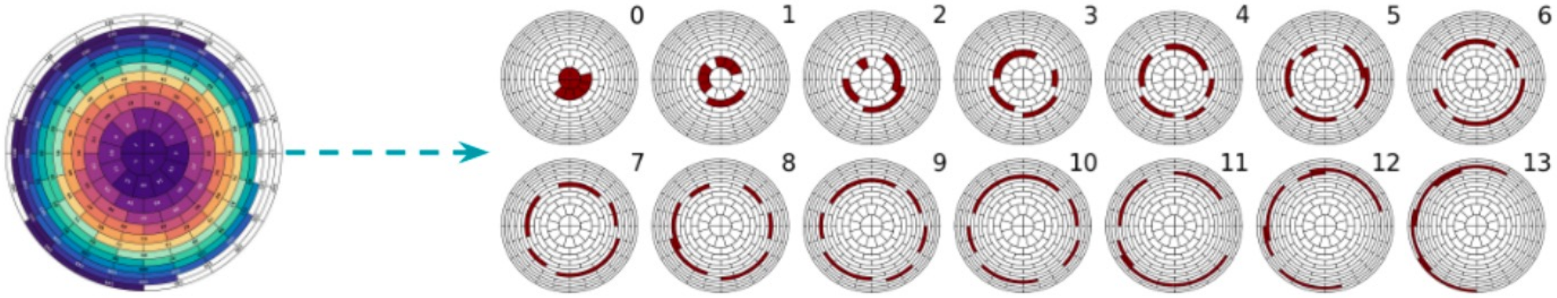
Thank you!

KATRIN
KARLSRUHE TRITIUM NEUTRINO EXPERIMENT
0.8eV
C. Goupy

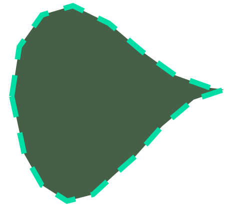
Experimental improvements: background

- ✓ factor 2 lower background using "shifted analysing plane" configuration
  - ✓ smaller volume mapped onto detector
  - ✓ inhomogeneous EM-fields
    - ✓ In-situ calibration of fields
    - ✓ 14 times more segmented data





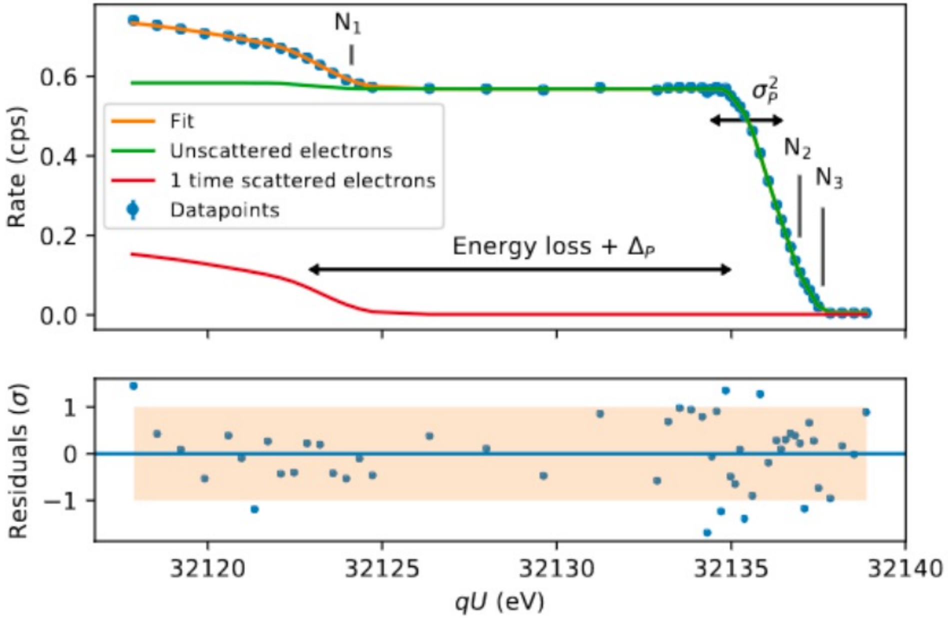
Background scales with



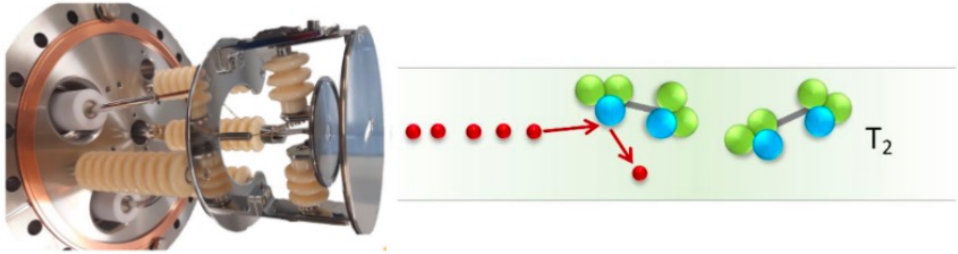
Experimental improvements: source

- ✓ precise calibration measurements with ^{83m}Kr co-circulation
  - ✓ source temperature: 30 K to 80 K
  - ✓ probe of electric potential variation in the source
  - ✓ high-resolution spectroscopy of conversion-e

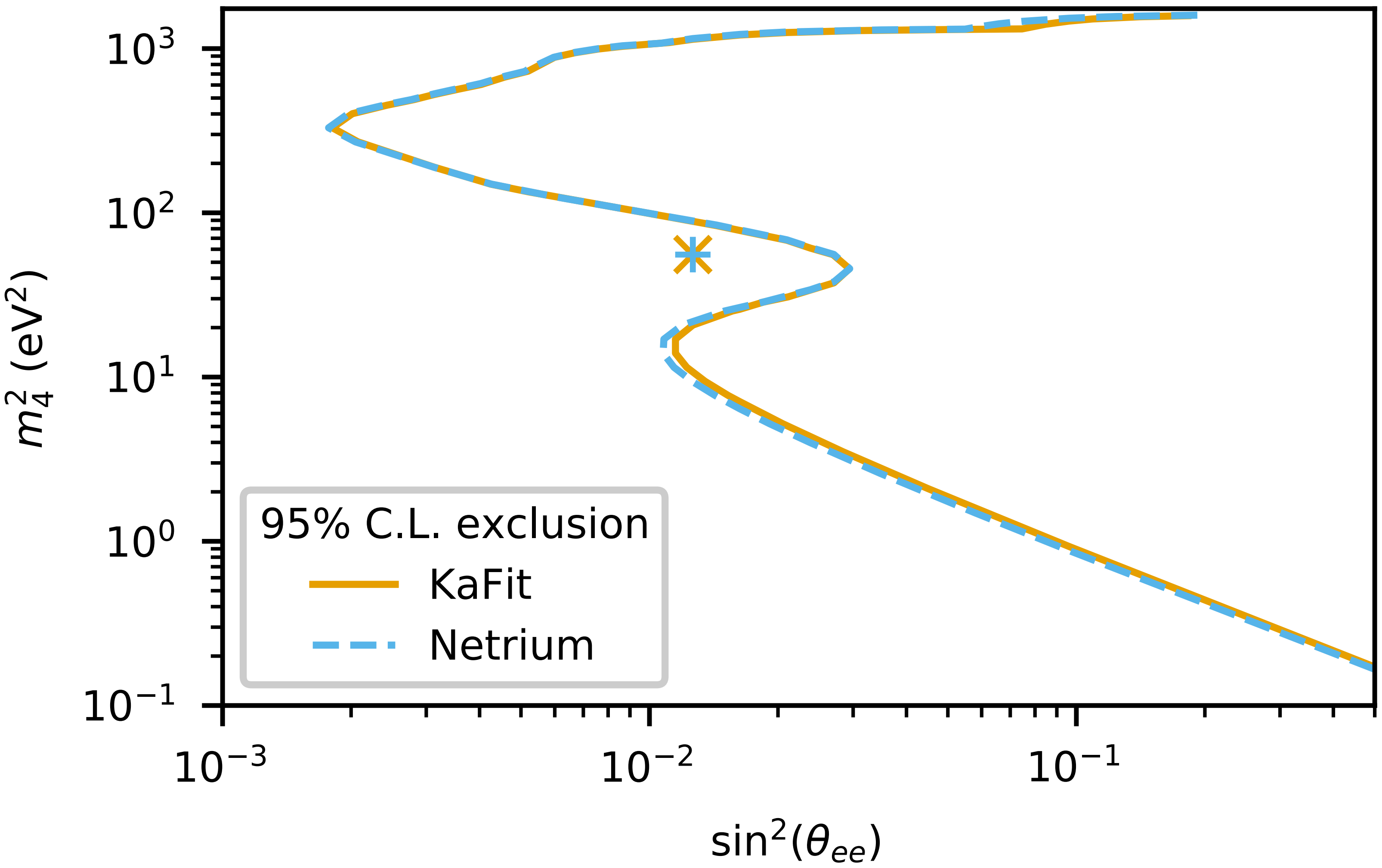
    https://arxiv.org/abs/2503.13221



- ✓ Electron gun measurements:
  - ✓ energy loss determination through scattering
  - ✓ monitoring of tritium gas density

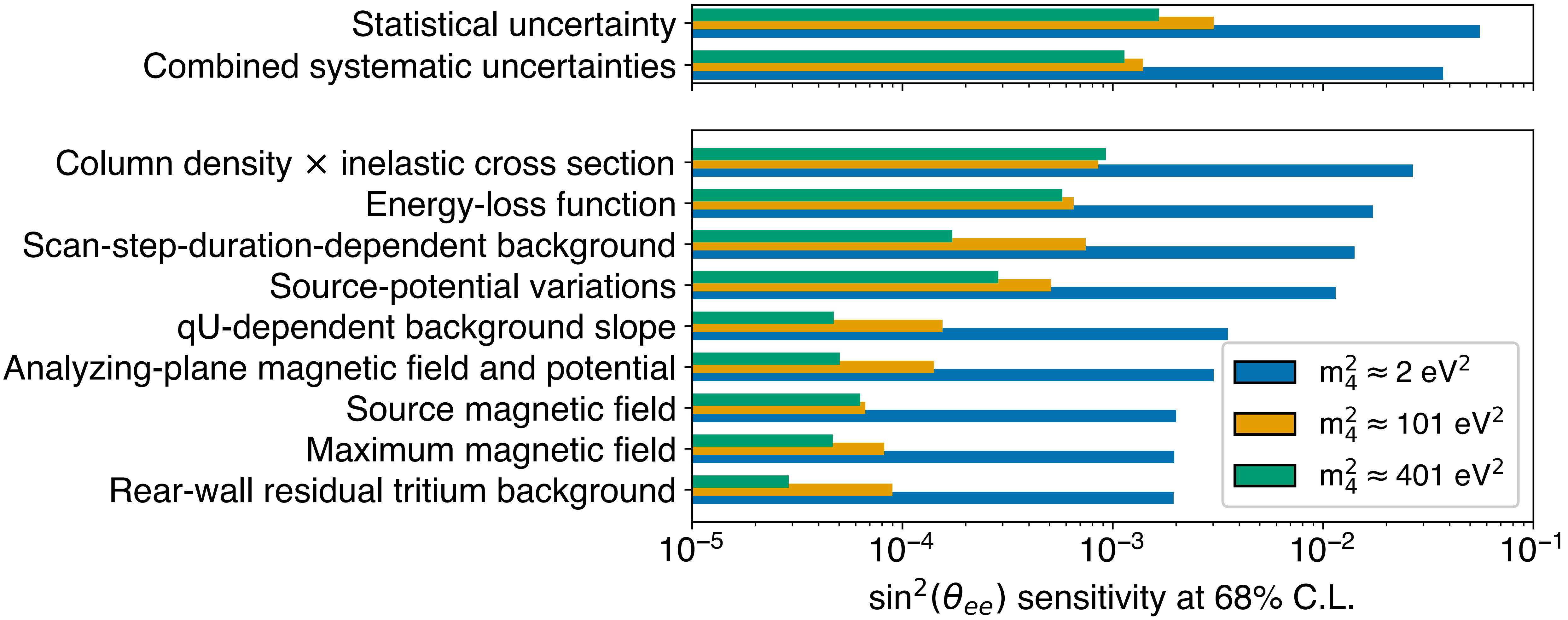


Combined results – KNM 1 2 3 4 5

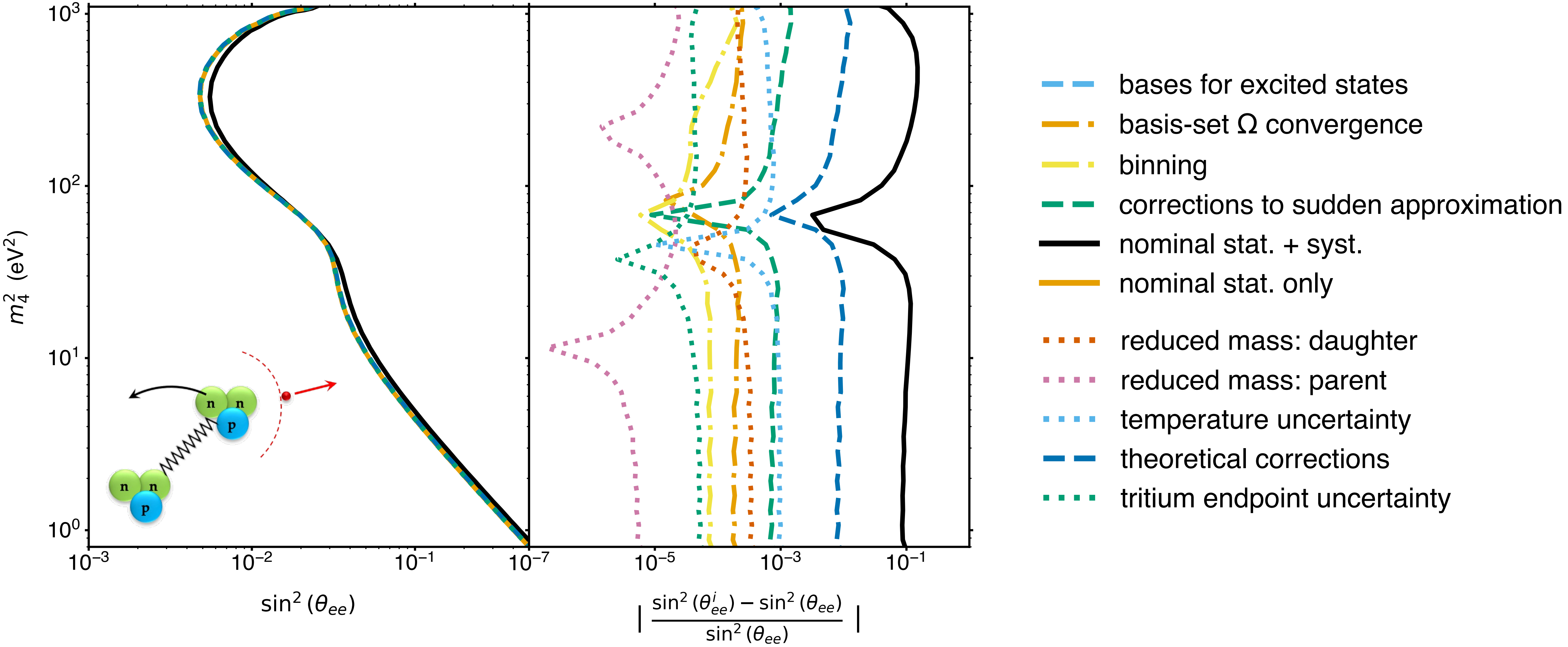


- ✓ combination of 7 dataset
  - ✓ time-wise
    - ✓ ppm-level HV reproducibility
    - ✓ 68,237 scans
  - ✓ detector-wise
    - ✓ NAP: all pixels stacked
    - ✓ SAP: 14 patches of 9 pixels
- ✓ two analysis chains
  - ✓ KaFit
    - ✓ smart caching
  - ✓ Netrium
    - ✓ neural net

Light sterile neutrino search
Systematics summary for 3 m_4^2 values

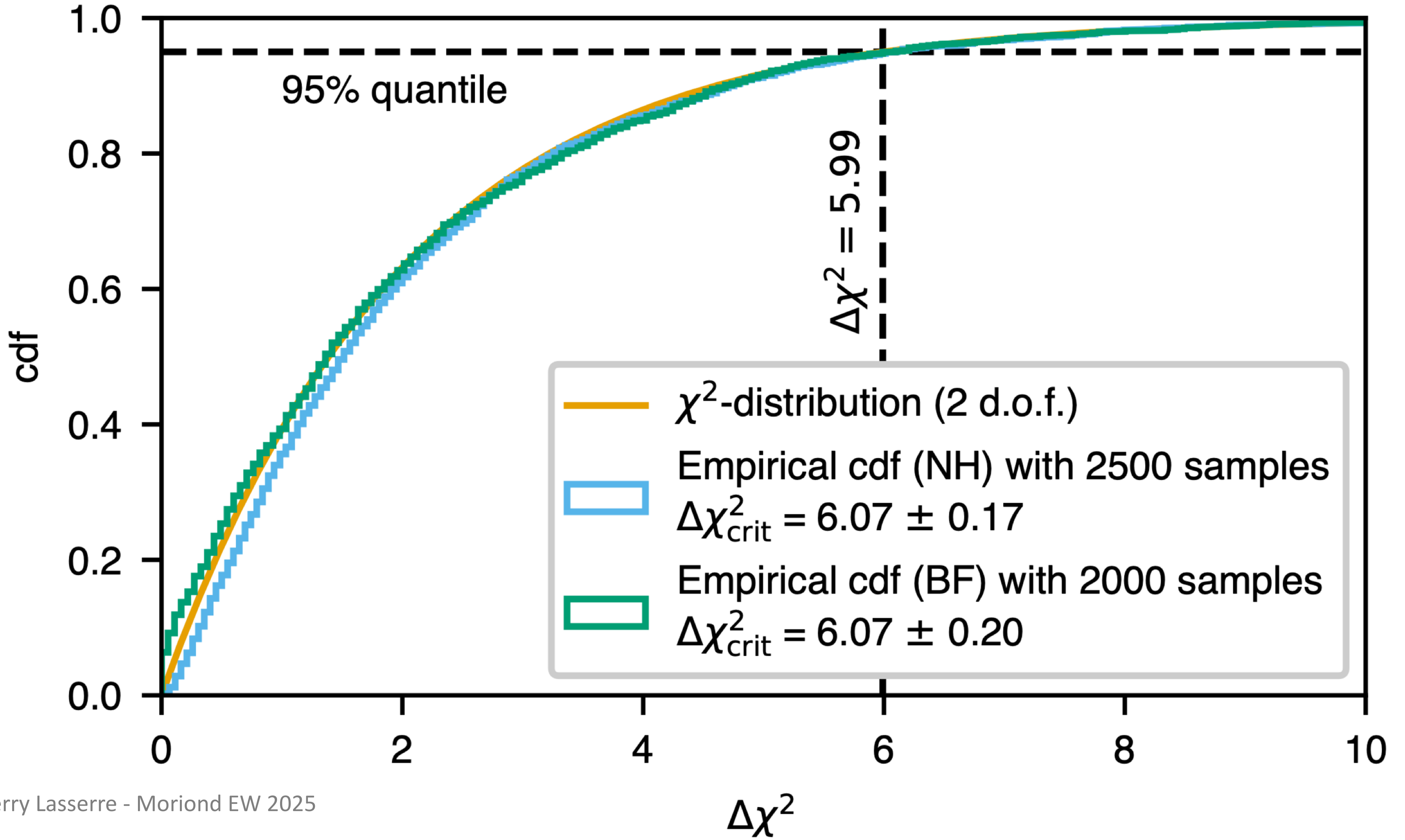


New systematic treatment: FSD



Verification of the contour's coverage

Wilks' theorem applicability is validated by comparing the $\Delta\chi^2$ distribution to Monte Carlo simulations.



Synergy with oscillation experiments

- ✓ Oscillation Electron Disappearance Experiments
  - ✓ $\Delta m_{41}^2 = m_4^2 - m_1^2 \approx \Delta m_{42}^2 \approx \Delta m_{43}^2$
  - ✓ $\sin^2 2\Theta = 4|U_{e4}|^2(1-|U_{e4}|^2)$
- ✓ KATRIN
  - ✓ m_ν and m_4
  - ✓ $\sin^2\Theta = |U_{e4}|^2$
- ✓ Conversion KATRIN -to- Oscillation
  - ✓ $\Delta m_{41}^2 \simeq m_4^2 - m_\beta^2$
  - ✓ $\sin^2 2\Theta = 4\sin^2\Theta(1-\sin^2\Theta)$
- ✓ Here, $0 < m_\nu < m_4$