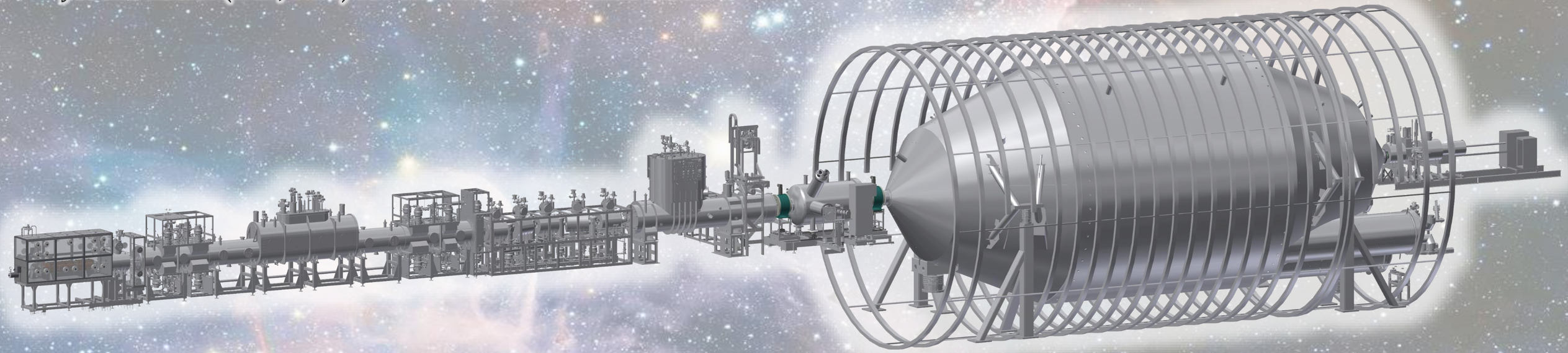
Probing the neutrino mass and beyond with the KATRIN experiment

Joscha Lauer (IAP, KIT) for the KATRIN Collaboration



October 9th, 2024 – BLV2024 Workshop

https://www.eso.org/public/germany/images/eso1208db/?lang (ESO/T. Preibisch, accessed Sept. 2024)

Kinematics of β-decay

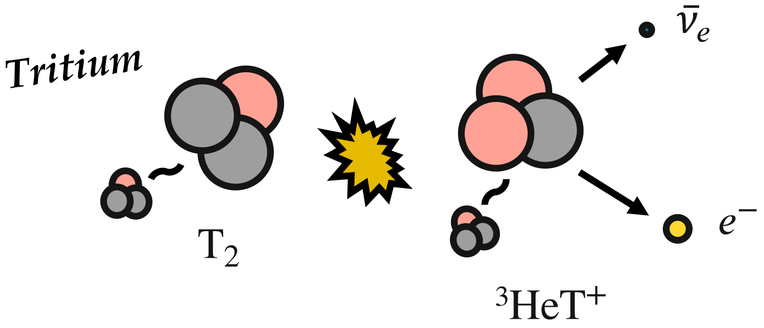
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E; E_0, m_\nu^2) = C\,(E + m_e)\,p_e\,(\boldsymbol{E_0 - E})\,\sqrt{(\boldsymbol{E_0 - E})^2 - \boldsymbol{m_\nu^2}}\,F(Z+1, E)$$

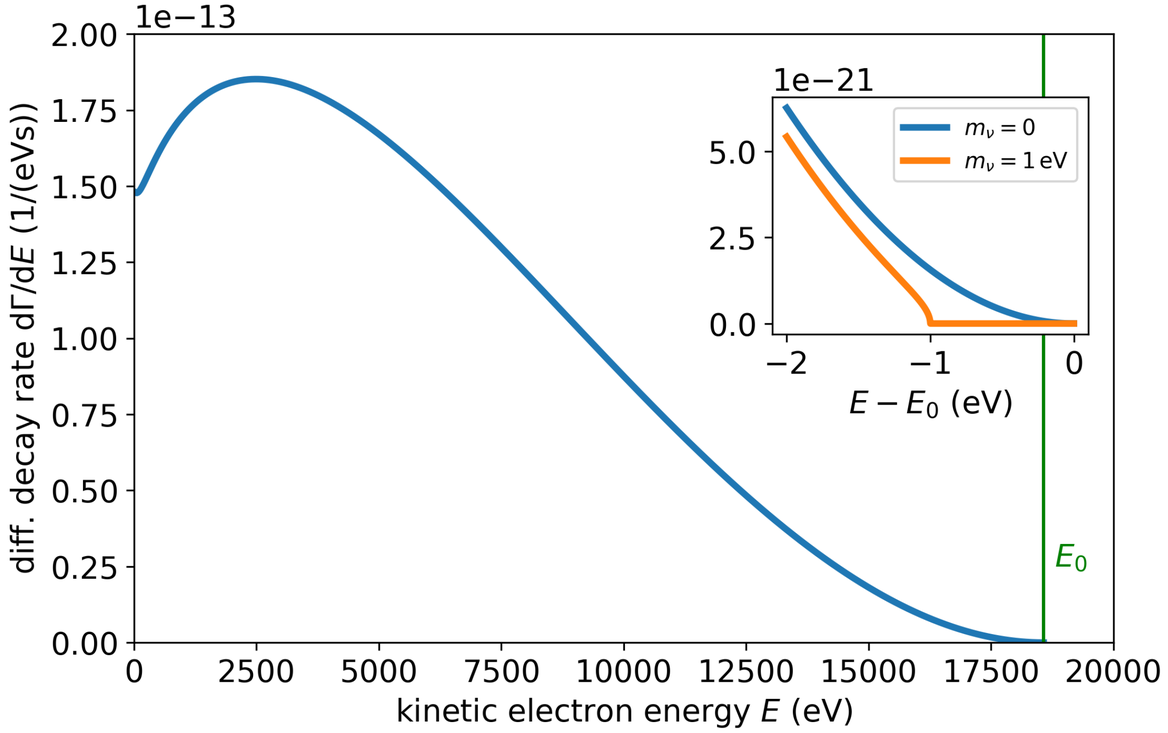
$E_0 \approx 18.6\ \mathrm{keV}$

- Phase space modification → direct neutrino mass determination:

$$\boldsymbol{m_\nu^2} = \sum_i |\boldsymbol{U_{ei}}|^2\,\boldsymbol{m_i^2}$$

effective electron antineutrino mass



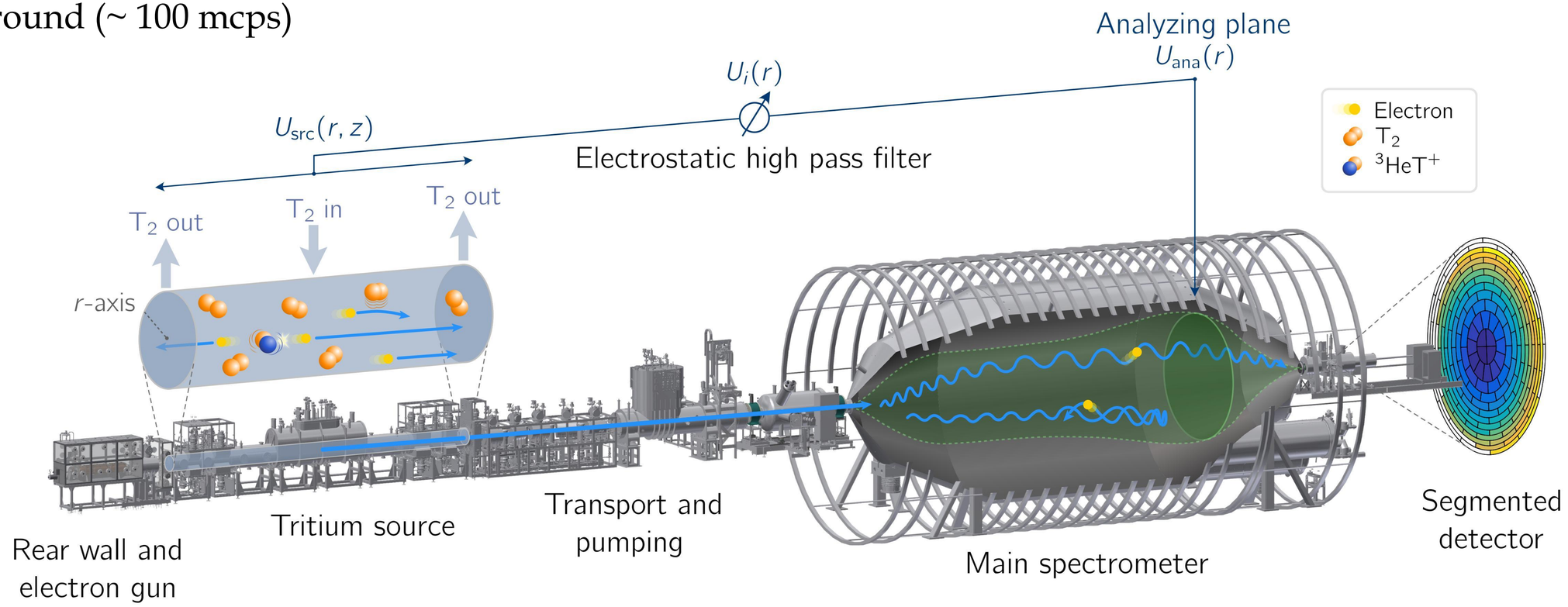



KATRIN
Karlsruhe Tritium Neutrino Experiment

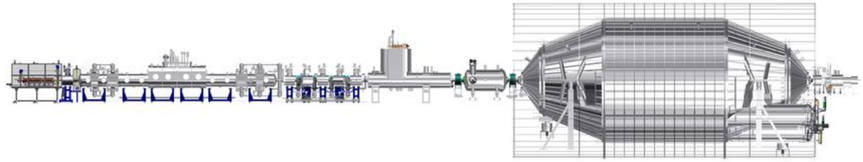
The KATRIN experiment

- High luminosity (~ 100 GBq) tritium source
- High resolution (~ 1 eV) spectrometer
- Low background (~ 100 mcps)

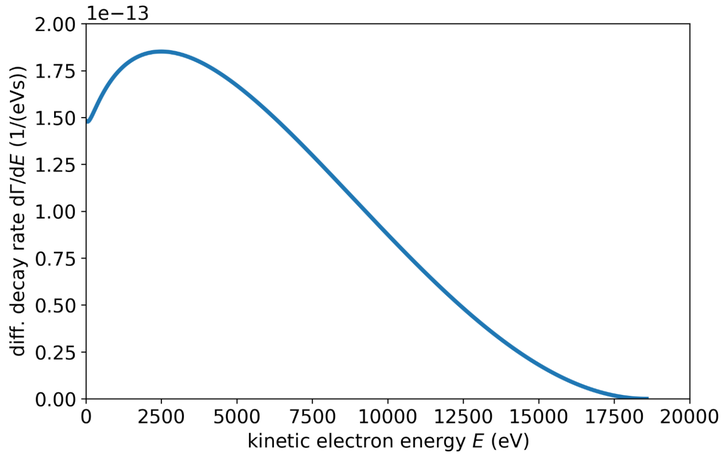
full description in
JINST 16 (2021) T08015



Data analysis



Differential spectrum



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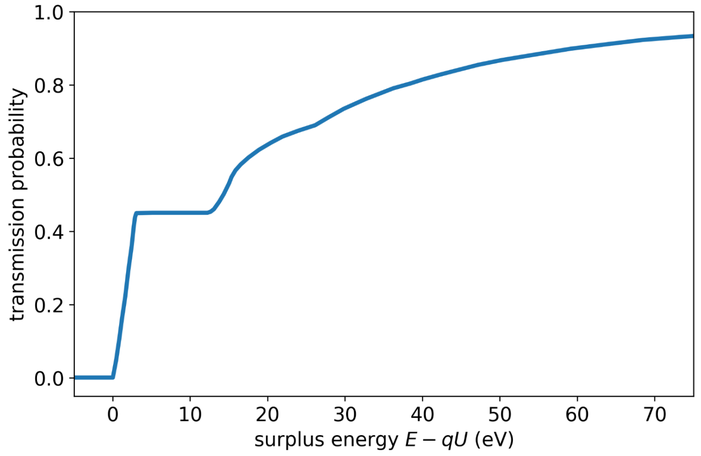
Experimental response



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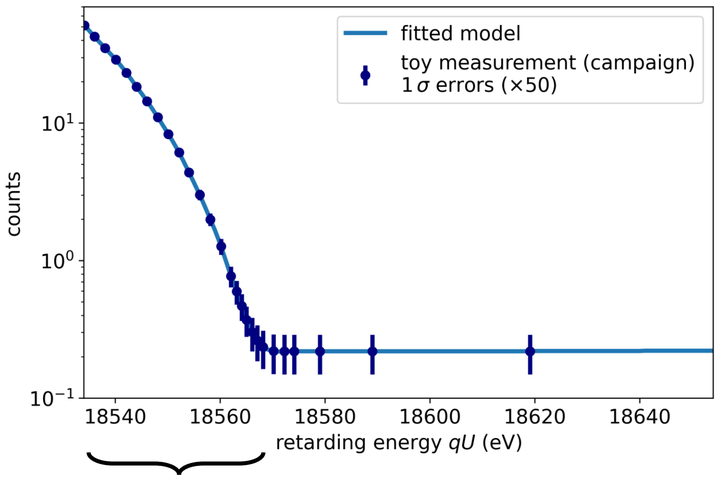
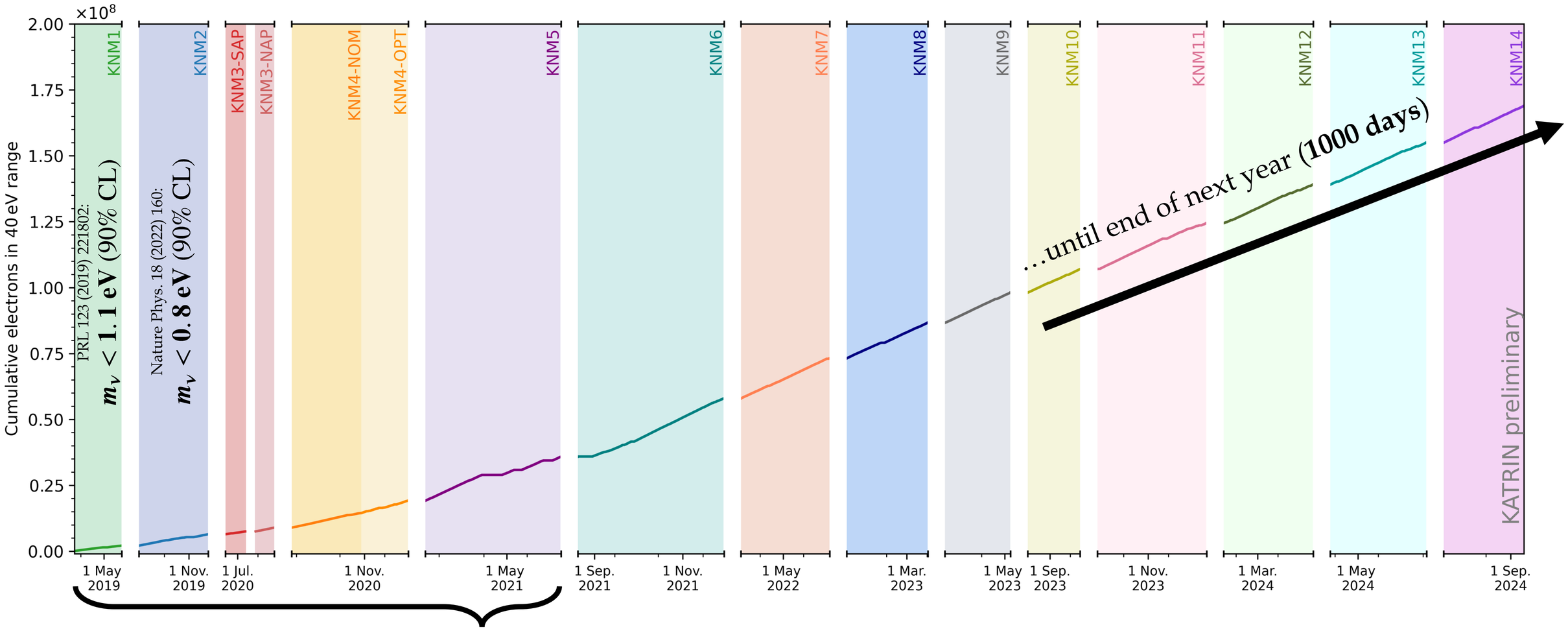
Measured rate



40 eV

- Integral rate $A\left(\int_{qU}^{\infty}\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E;E_0,m_\nu^2)\,f_{\mathrm{exp}}(E-qU)\,\mathrm{d}E\right)+R_{\mathrm{Bg}}=R(qU)$
- Maximum likelihood fit with four free parameters (m_ν^2, E_0, A, R_{Bg})
- Experimental parameters → nuisance parameters

Collected statistics



Most recent result (36×10^6 electrons in analysis range)

Fit result and neutrino mass limit

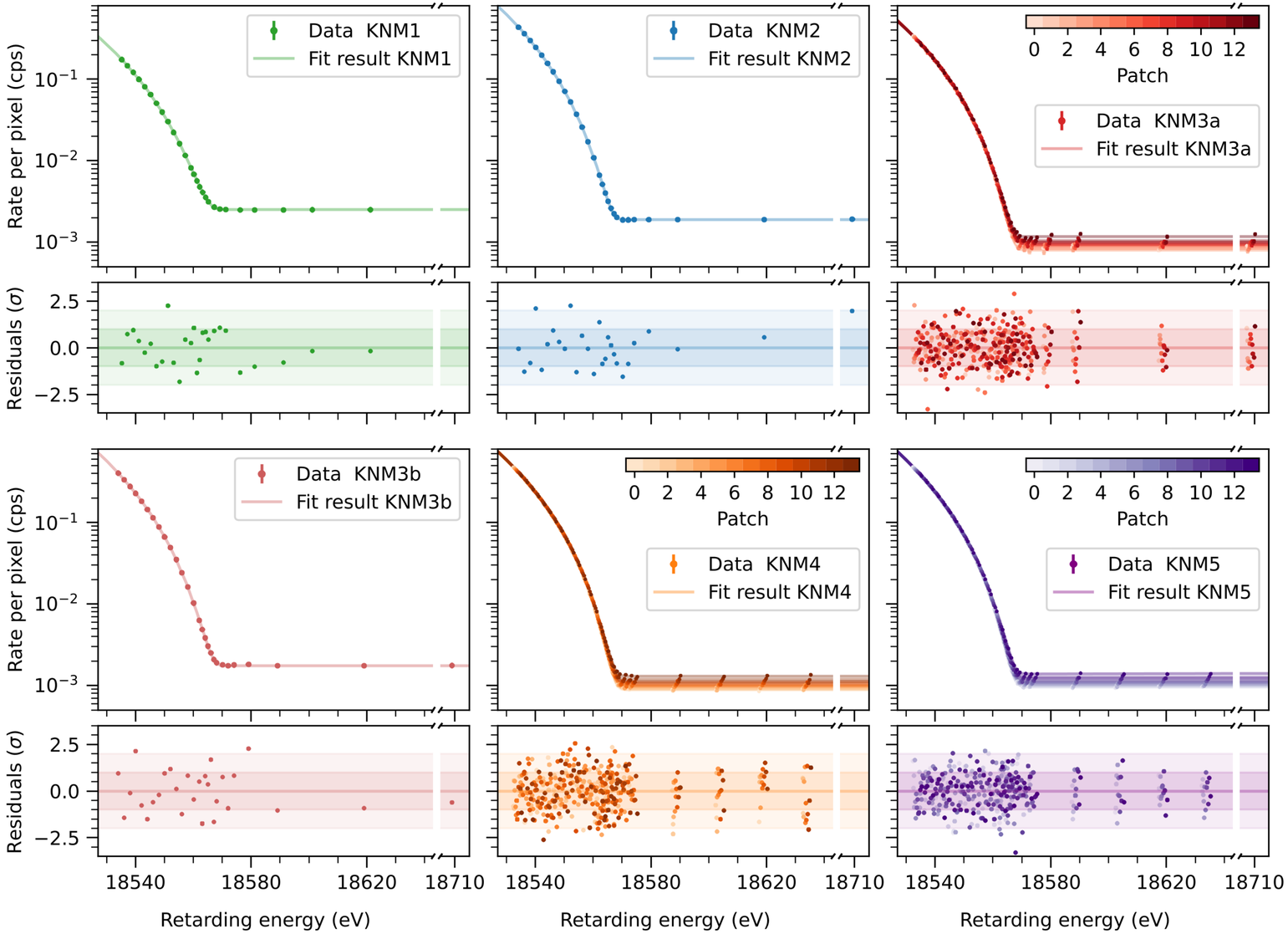
arXiv (2024) 2406.13516

- Best fit central value:
  $m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$ $(p = 0.84)$

  dominated by statistical uncertainty

- New upper limit:
  $m_\nu < 0.45\ \mathrm{eV}$ (90% CL)

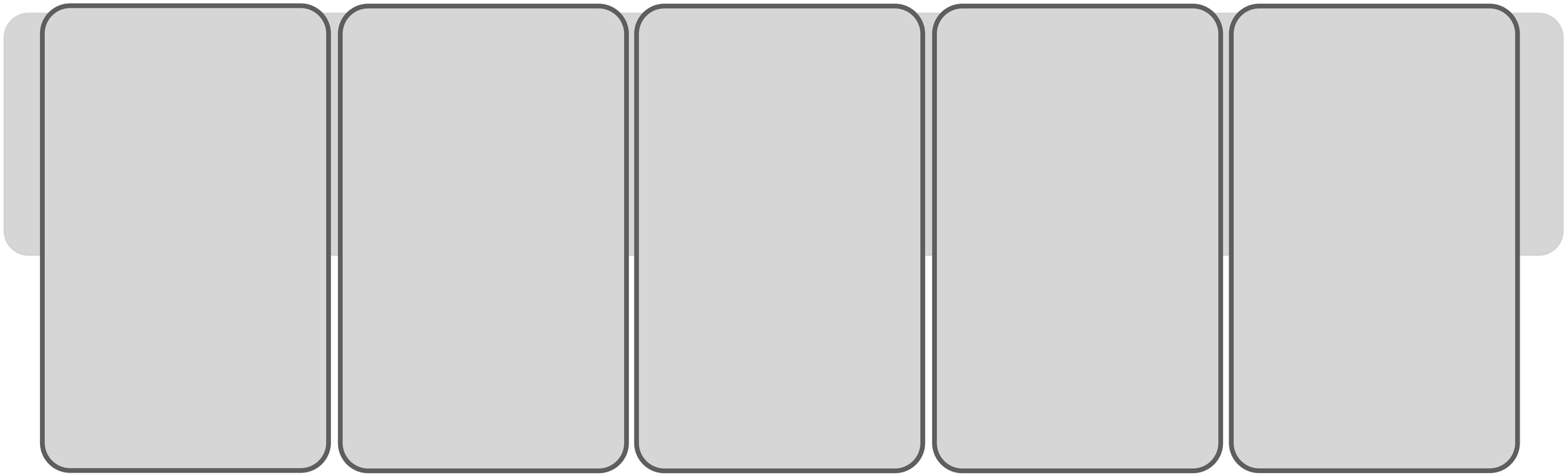
  ~ 20% of expected final dataset



Beyond the neutrino mass

$$\mathrm{d}\Gamma \propto \overline{|\mathcal{M}|^2}\ \mathrm{d}\Phi(E_i, \vec{p}_i) \rightarrow \text{other physics channels modify observed spectrum} \propto \int_{qU}^{\infty} \frac{\mathrm{d}\Gamma}{\mathrm{d}E_e}\,\mathrm{d}E_e$$

Beyond the neutrino mass



Phys. Rev. D 105 (2022) 072004
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PoS EPS-HEP2023 (2024) 164

Phys. Rev. Lett. 129 (2022) 011806

PoS EPS-HEP2023 (2024) 0188

Phys. Rev. D 107 (2022) 082005

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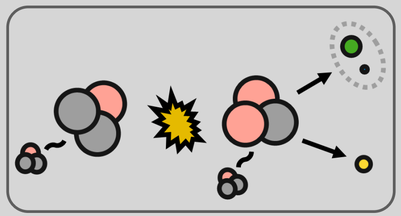

Sterile neutrinos

Kink search

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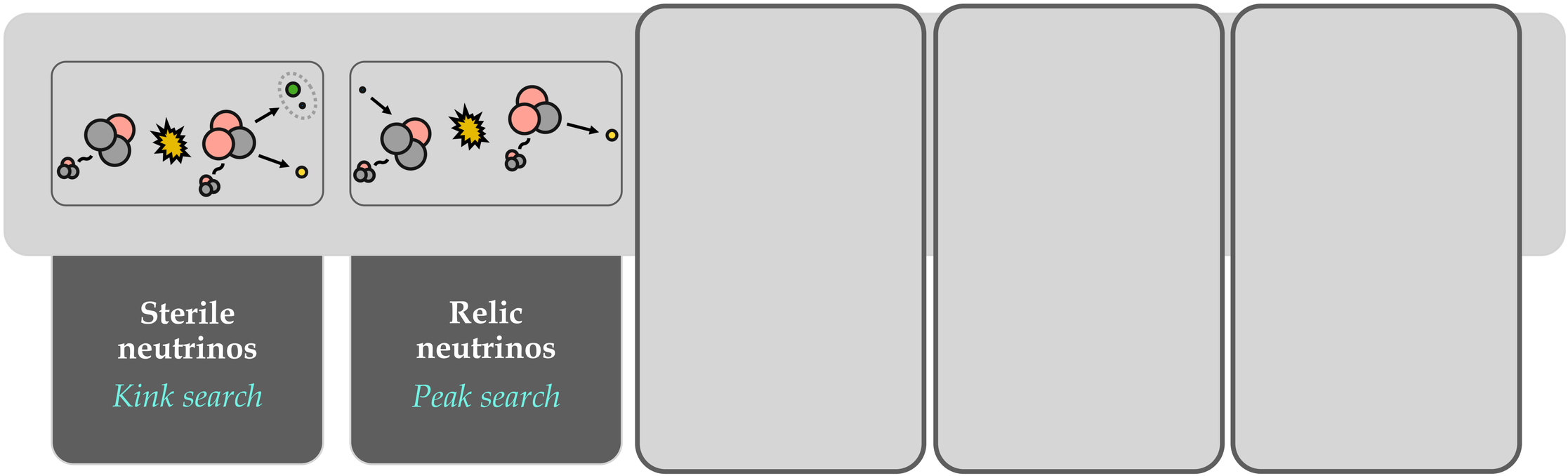

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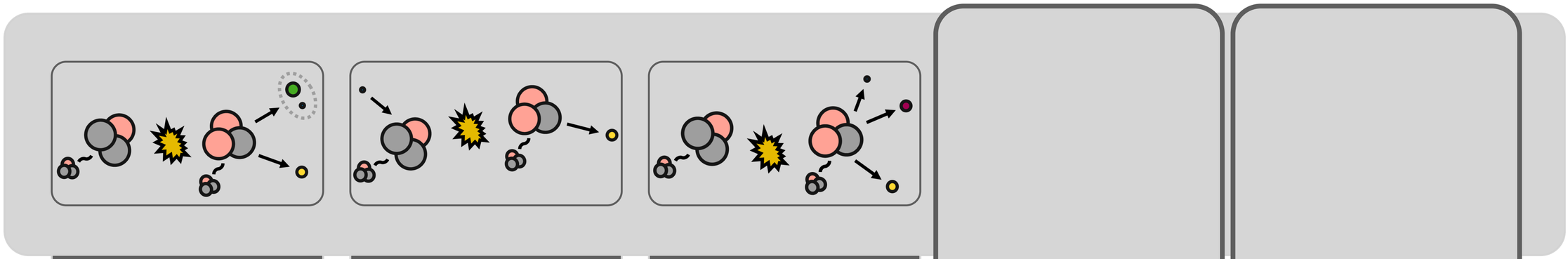

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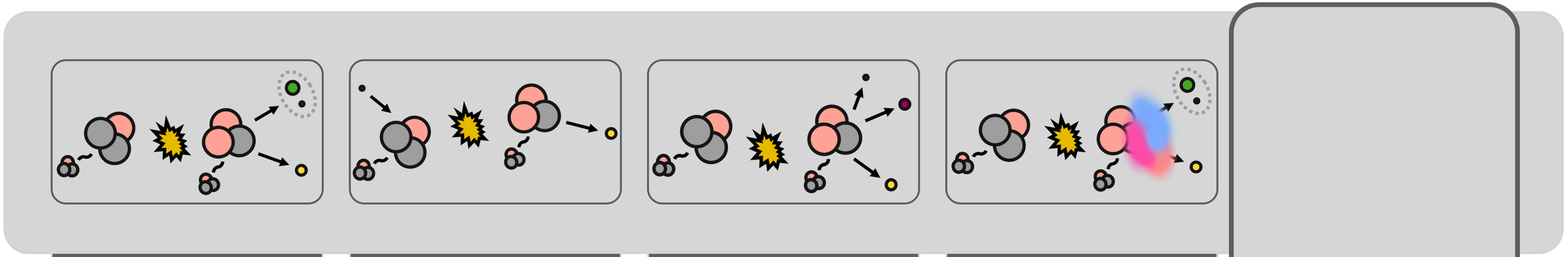

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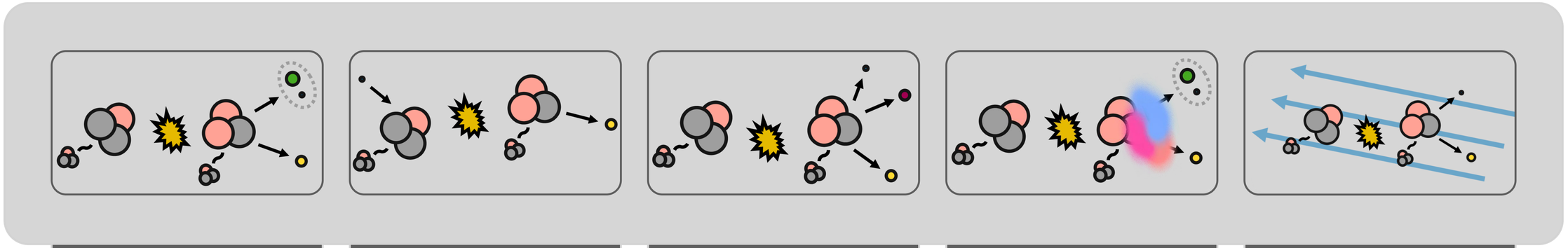

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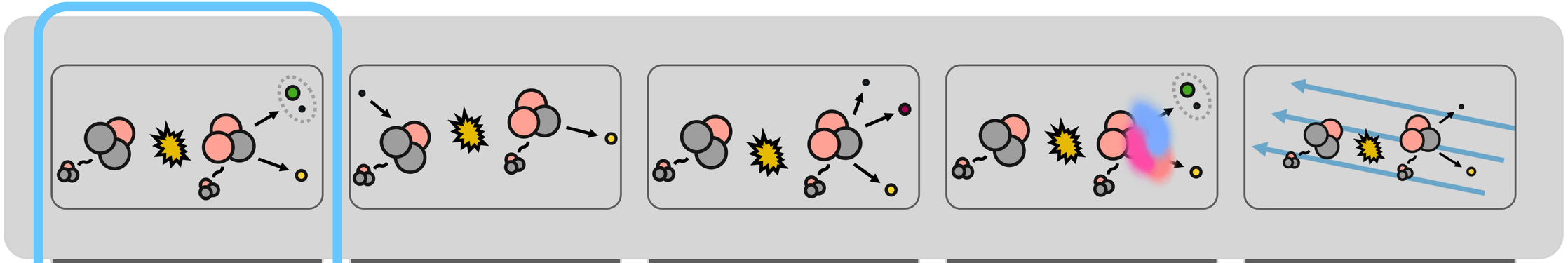

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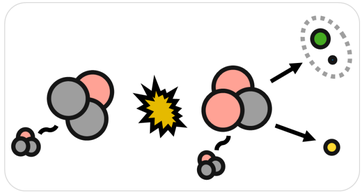
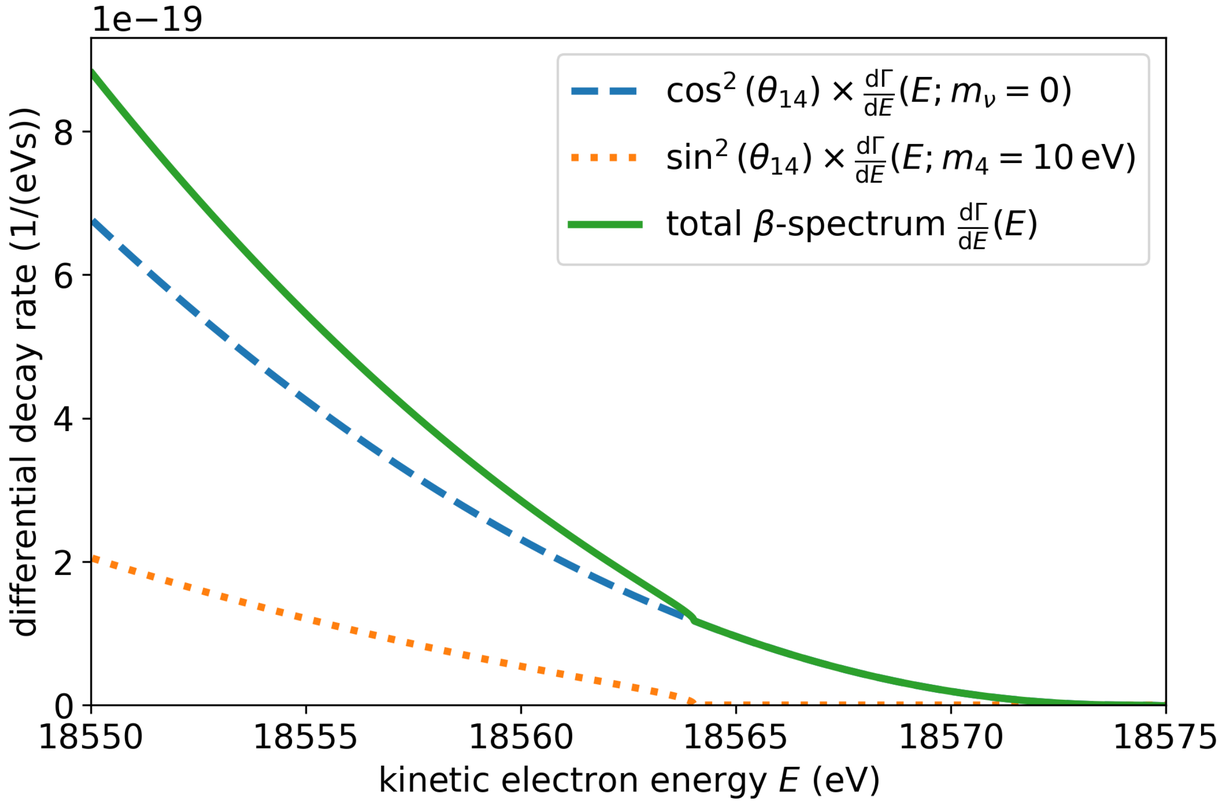


- Gallium and reactor anomaly
  → additional heavier neutrino state
- Kinetic mixing with active neutrinos
  → **kink** below the enpoint
- Parameters: mass splitting $\boldsymbol{\Delta m^2_{41}}$ and mixing $\boldsymbol{|U_{e4}|^2} = \sin^2(\theta_{14})$

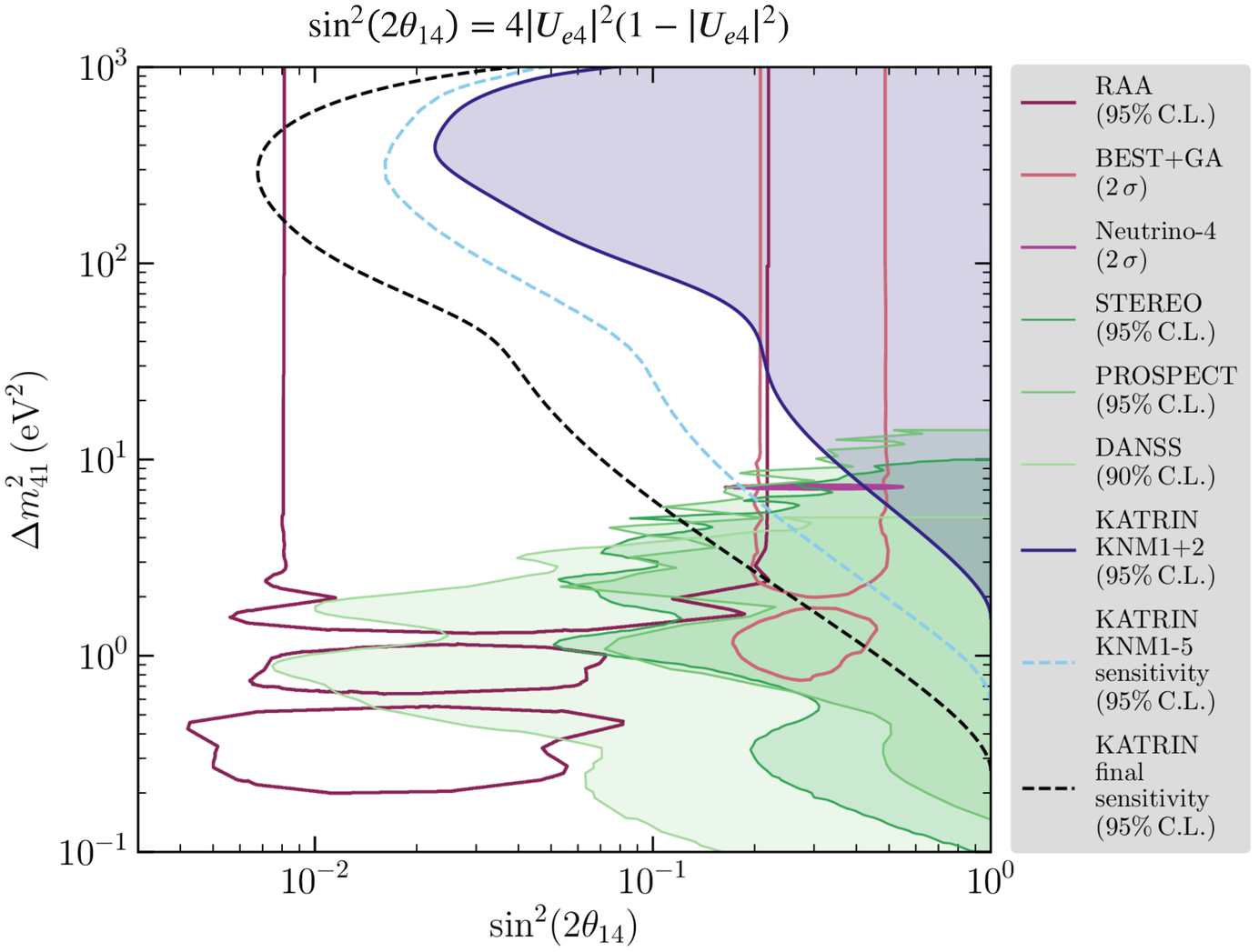
*this talk: **e**V-scale*



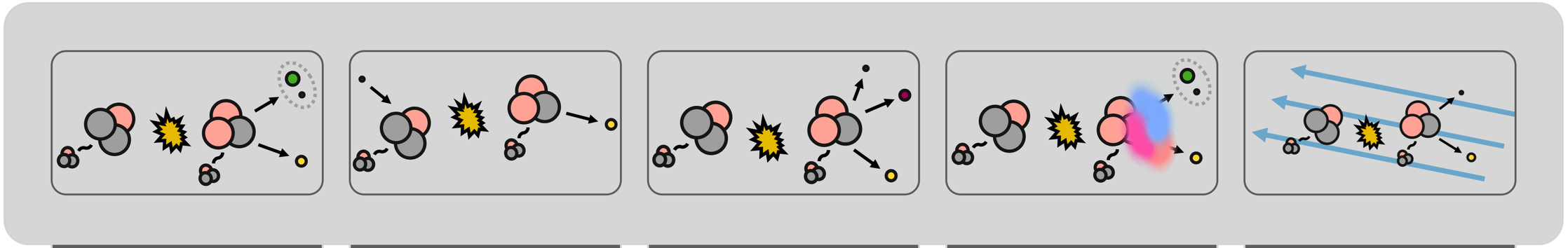
Sterile neutrinos

Phys. Rev. D 105 (2022) 072004

- Data of first two KATRIN campaigns: no significant **eV**-scale signature observed
- Regions of large Δm^2_{41} from reactor (RAA) and gallium anomaly (GA) excluded
- Projection for campaigns 1–5: probe Neutrino-4 claim and further RAA+GA space
- → 2026: focus on **keV**-scale in new operation mode, using TRISTAN detector in setup



Beyond the neutrino mass



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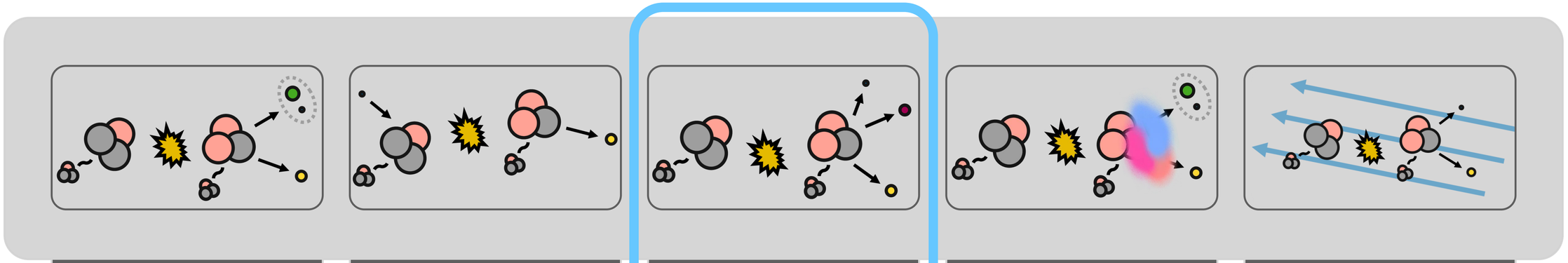

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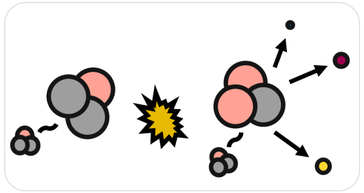
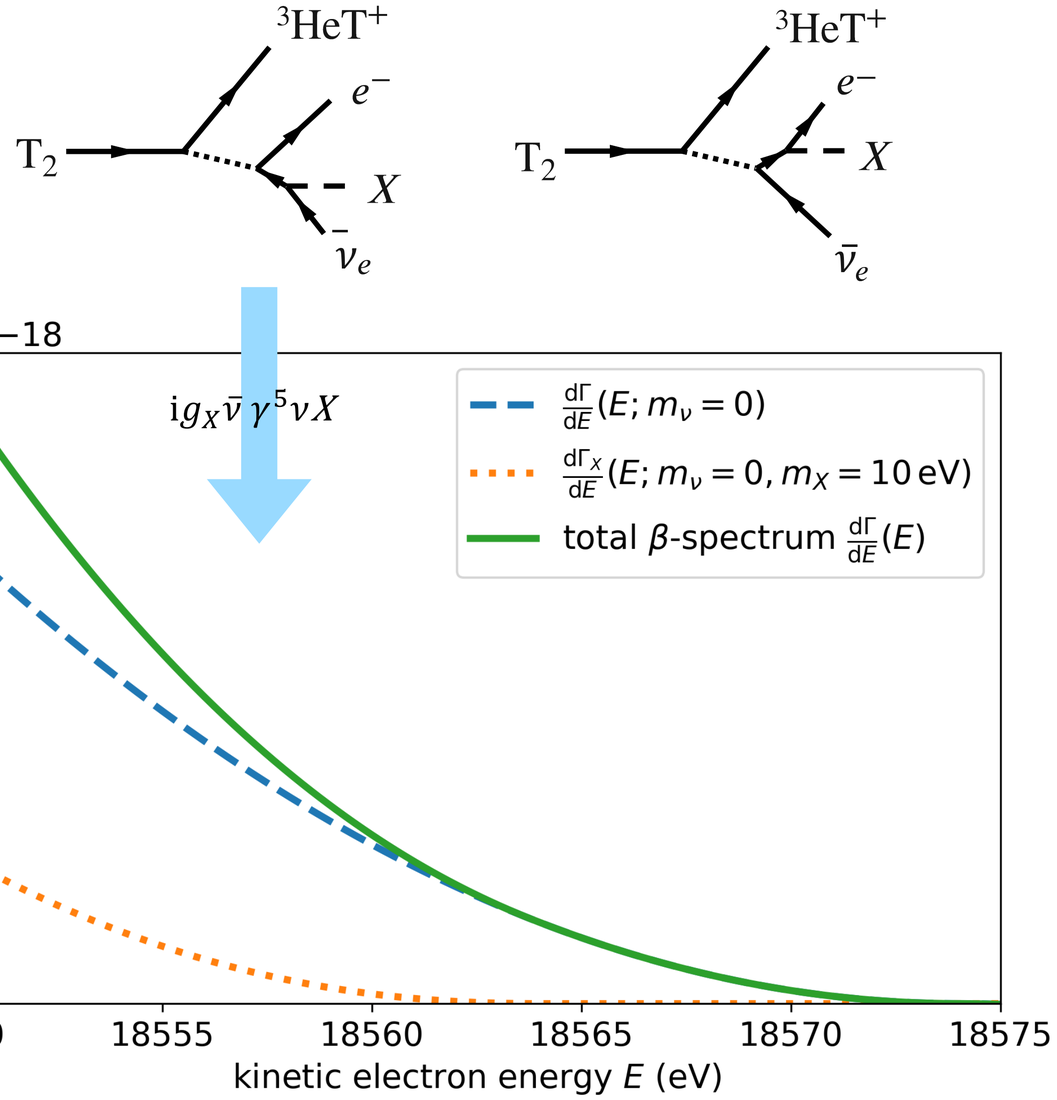


- Additional BSM bosons coupling to leptons
  → real emission in β-decay
- Emission branch $\frac{d\Gamma_X}{dE}$: modified spectral **shape** and **shifted** endpoint $\boldsymbol{E_0}$
- Parameters: boson mass $\boldsymbol{m_X}$ and coupling $\boldsymbol{g_X}$

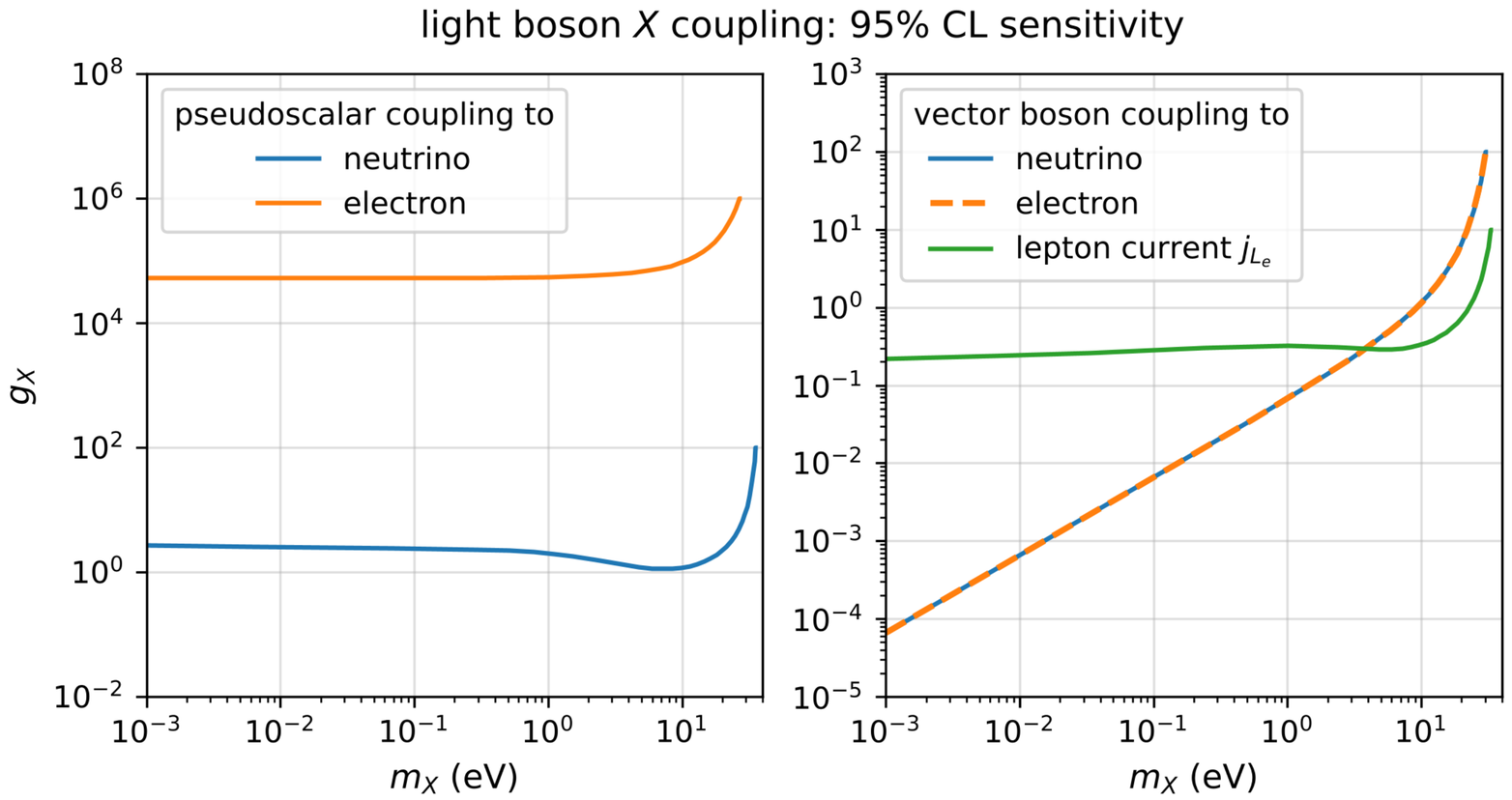
theoretical basics & study:
JHEP 01 (2019) 206

light vectors and pseudoscalars



New light bosons

- Sensitivity of second KATRIN campaign ($m_X \leq 40$ eV): statistics dominated
- Improvement from extension to larger dataset expected
- Probing physics at low energy scale $E_0 < 20$ keV



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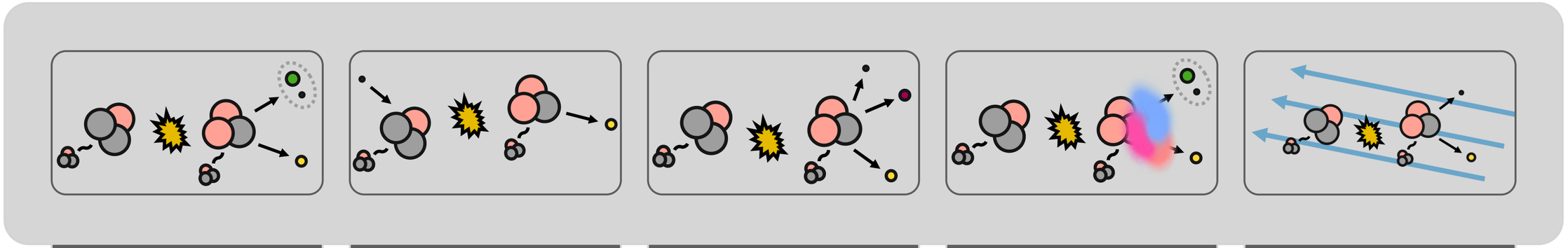

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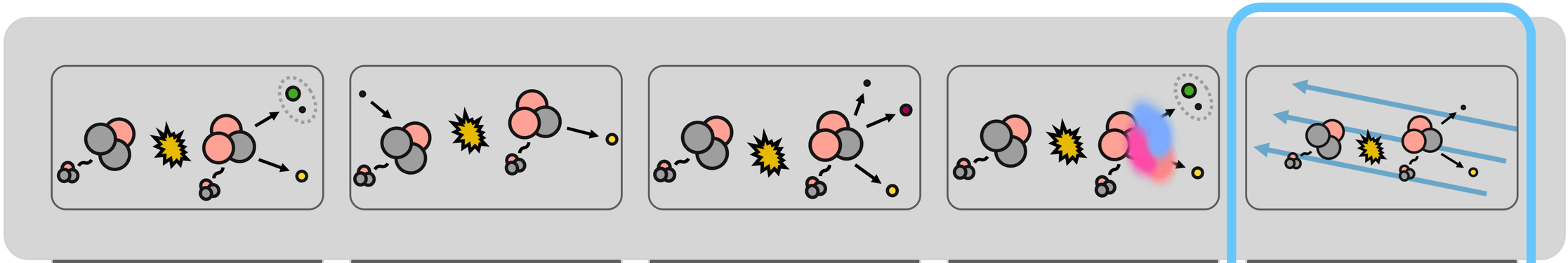

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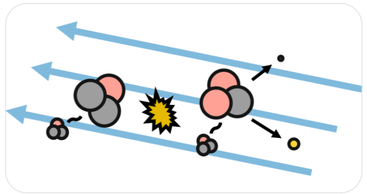
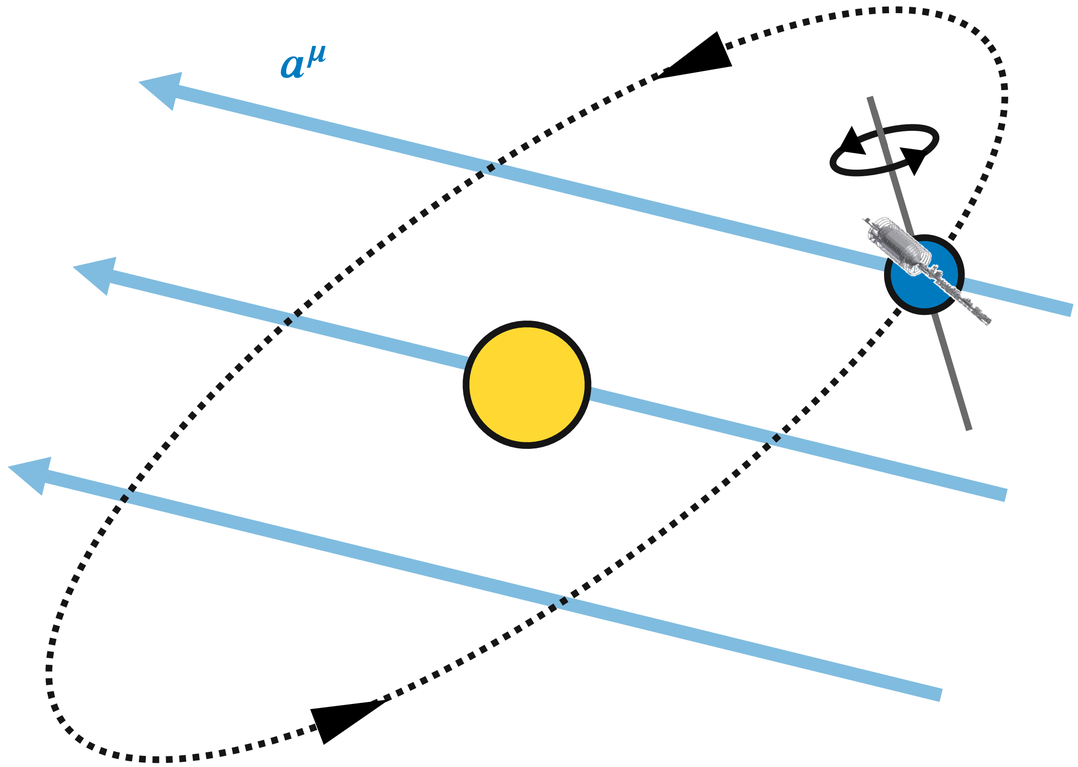
Lorentz invariance violation (LIV)



- SM extensions: LIV and CPT violation
- Contribution $\mathscr{L} \supset -\bar{\psi}\, a^{\mu} \gamma_{\mu}\, \psi$ for each fermion: Lorentz-violating field $\boldsymbol{a^{\mu}}$
- β-decay: **shift** of spectral endpoint $\boldsymbol{E_0}$

time-dependent & -independent

- Parameters: coefficients $\left(\boldsymbol{a}_{\mathbf{of}}^{(\mathbf{3})}\right)_{\boldsymbol{jm}}$ and (for $j = m = 1$) phase $\boldsymbol{\phi}$



Lorentz invariance violation (LIV)

Phys. Rev. D 107 (2022) 082005

- Data of first KATRIN campaign: no significant LIV observed in the endpoint E_0

- **First constraint** for $\left(a_{\mathrm{of}}^{(3)}\right)_{11}$:

sidereal oscillation

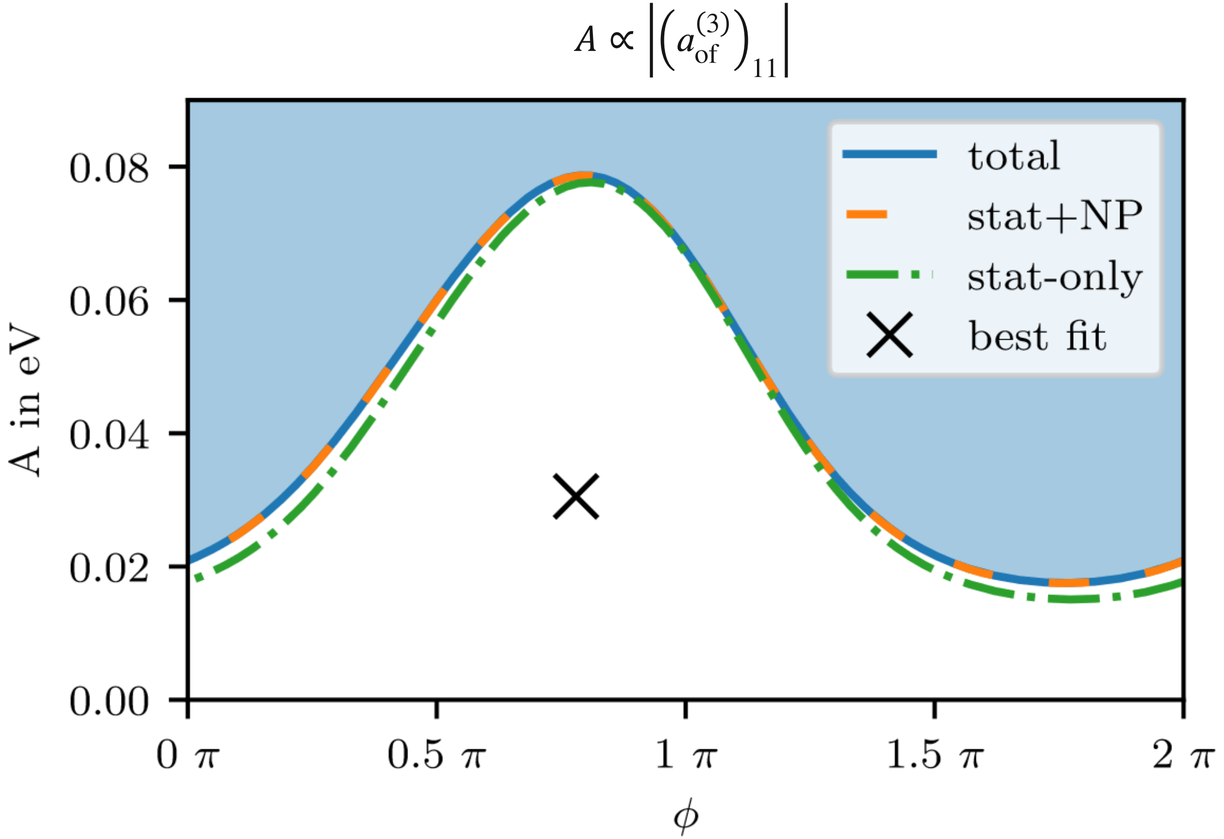
$$\left|\left(a_{\mathrm{of}}^{(3)}\right)_{11}\right| < 3.7 \times 10^{-6}\ \mathrm{GeV}\ (90\%\ \mathrm{CL})$$

- Other LIV parameters (improved bounds):

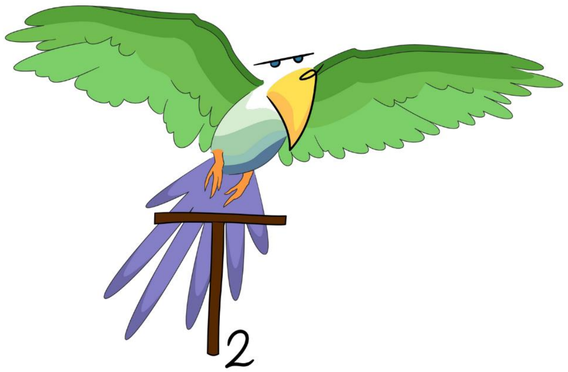
$$\left|\left(a_{\mathrm{of}}^{(3)}\right)_{00}\right| < 3.0 \times 10^{-8}\ \mathrm{GeV}\ (90\%\ \mathrm{CL})$$

$$\left|\left(a_{\mathrm{of}}^{(3)}\right)_{01}\right| < 6.4 \times 10^{-4}\ \mathrm{GeV}\ (90\%\ \mathrm{CL})$$

time-independent



Summary & outlook



- New world-leading direct limit on neutrino mass: $m_\nu < 0.45$ eV (90% CL)
- Rich program **beyond the neutrino mass**

  → KATRIN probes parameter space of many physics cases:

Sterile neutrinos	Relic neutrinos	New light bosons	General neutrino interactions	Lorentz invariance violation
Kink search	*Peak search*	*Shape distortion*	*Shape distortion*	*Temporal variation*

- Data-taking continues through 2024 and 2025: ~ 220×10^6 electrons in 40 eV range expected
- Afterwards: modified experimental setup → probe β-spectrum deep (**keV**) below the endpoint E_0 for access to much **broader range of new physics**

Thank you!