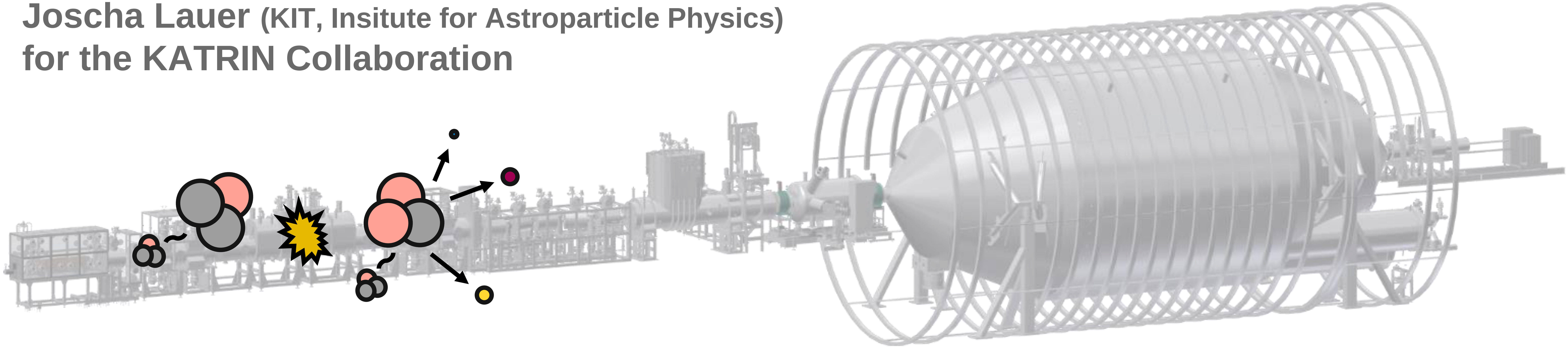
Probing new light particles in tritium β-decay with the KATRIN experiment

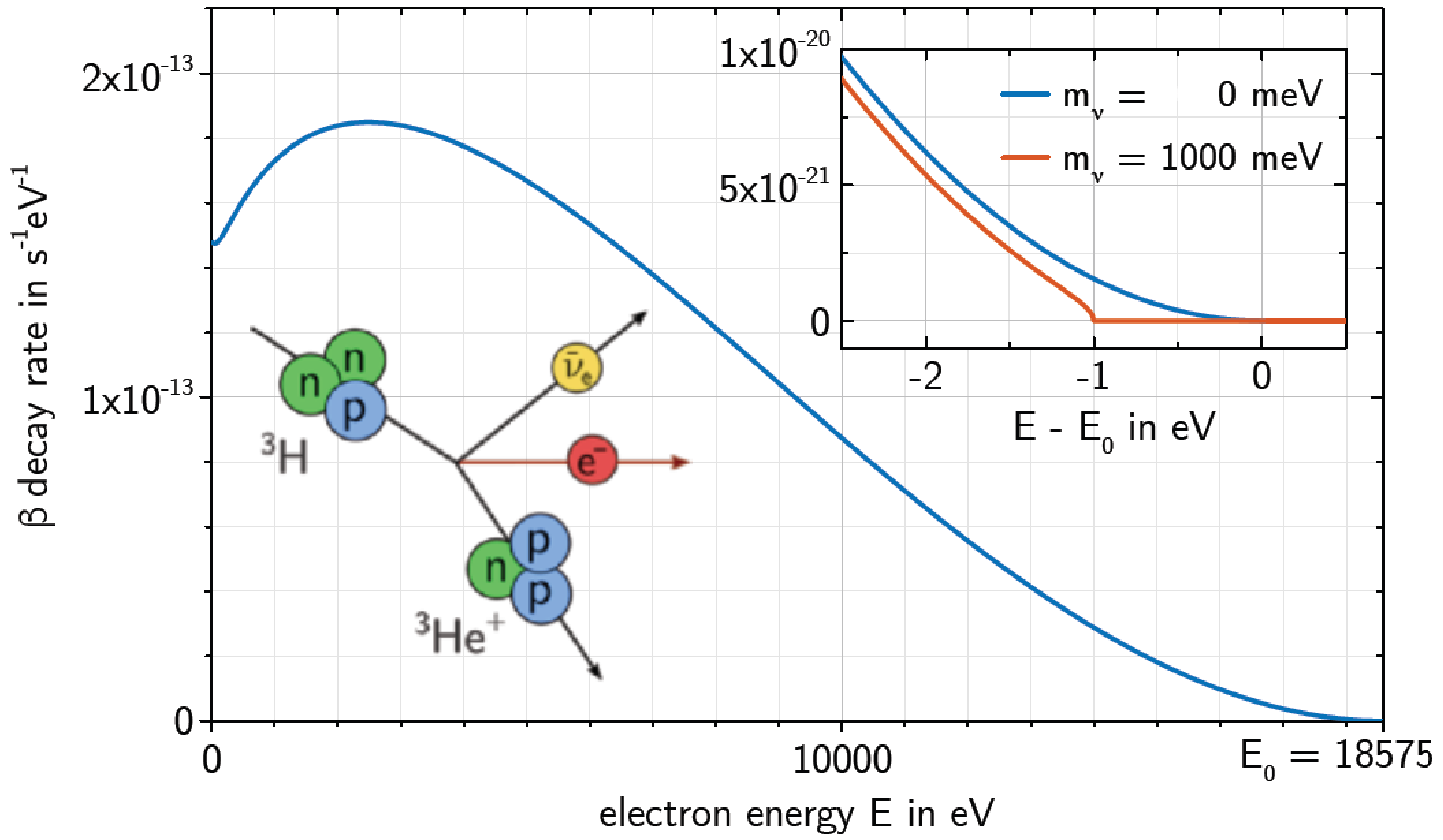
Joscha Lauer (KIT, Insitute for Astroparticle Physics)
for the KATRIN Collaboration

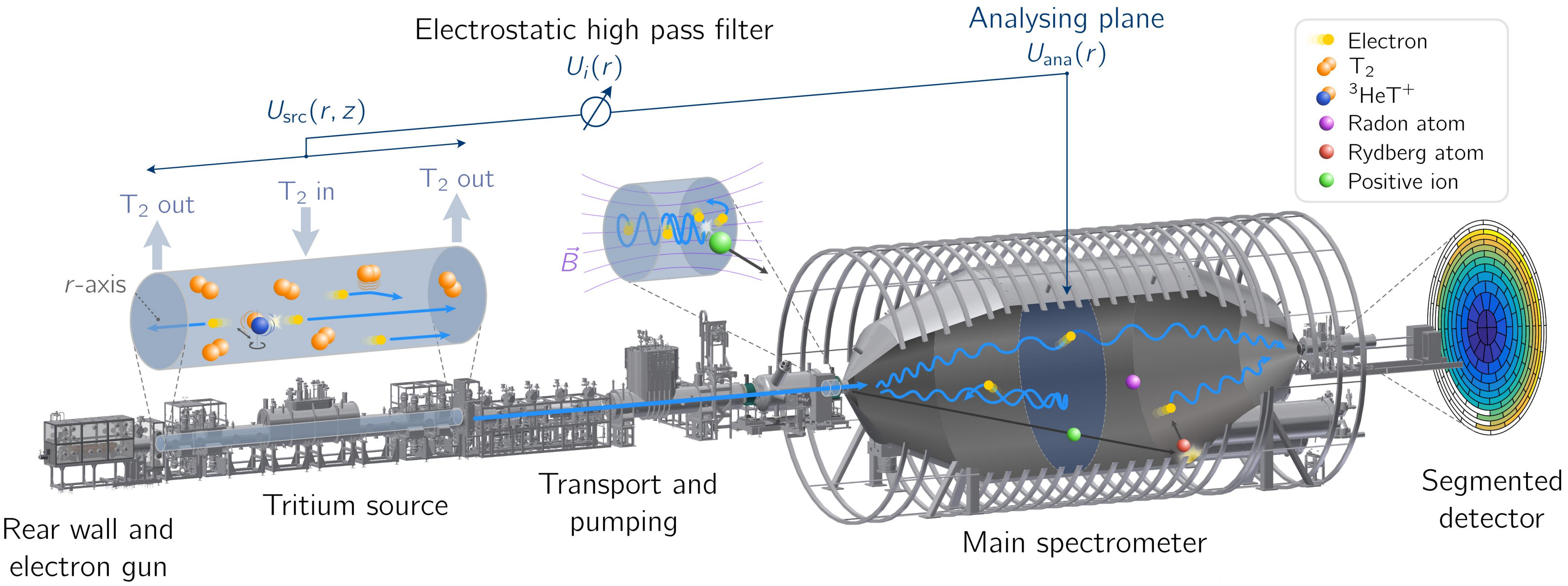


August 28th, 2025

The KATRIN experiment

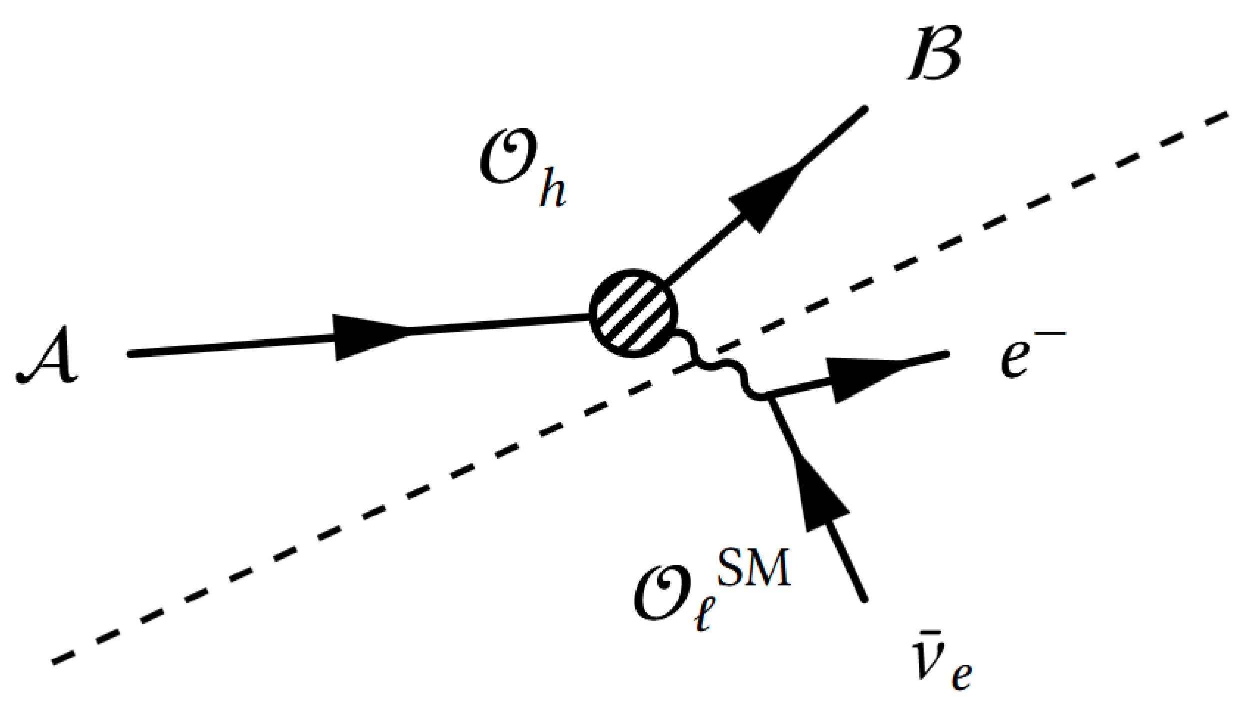
- Observable: effective electron antineutrino mass $m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$
- Kinematic approach: electron energy spectrum of **tritium β-decay**





Standard Model β-decay of tritium

$$\mathcal{A} \to \mathcal{B} + e^- + \bar{\nu}_e$$

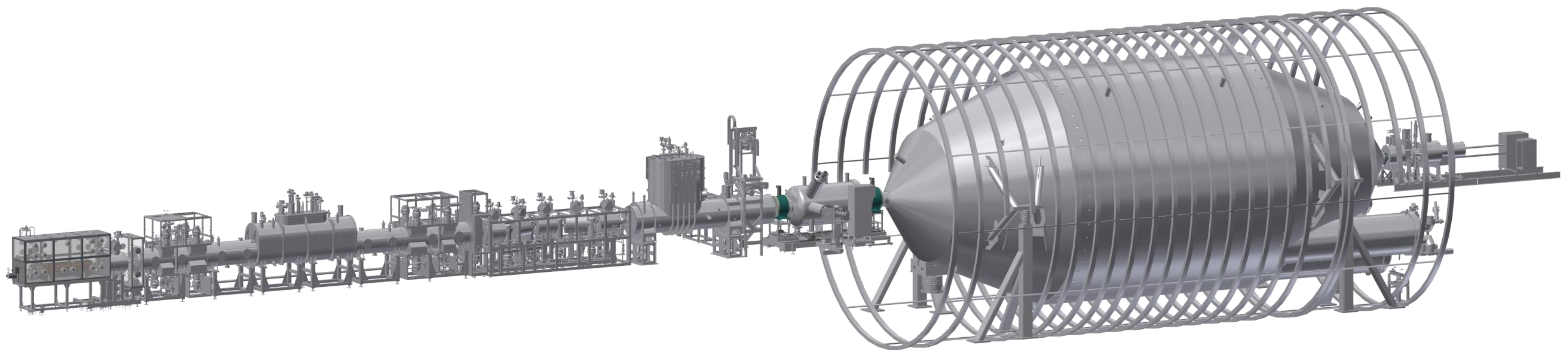


- Fermi's golden rule (decay rate): $\mathrm{d}\Gamma = \frac{(2\pi)^4}{2m_{\mathcal{A}}}\overline{|\mathcal{M}|^2}\,\mathrm{d}\Phi$

$$\mathcal{M} = -\frac{G_\mathrm{F}}{\sqrt{2}}(\bar{\mathcal{B}}\mathcal{O}_h\mathcal{A})(\bar{e}\mathcal{O}_\ell\nu)$$

- Differential spectrum $\frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E}\left(E, \boldsymbol{m_\nu^2}\right) = C \cdot (E + m_e) \cdot p_e \cdot E_\nu \cdot \sqrt{(E_0 - E)^2 - \boldsymbol{m_\nu^2}} \cdot \mathrm{Corr}(E)$

- Energy scale: tritium *Q*-value ~ $\boldsymbol{E_0 \approx}$ **18.6 keV** (kinematic limit)



→ Measurement of **integrated spectrum** beyond set retarding potential U_{ret}

Inferring the neutrino mass – spectrum fitting

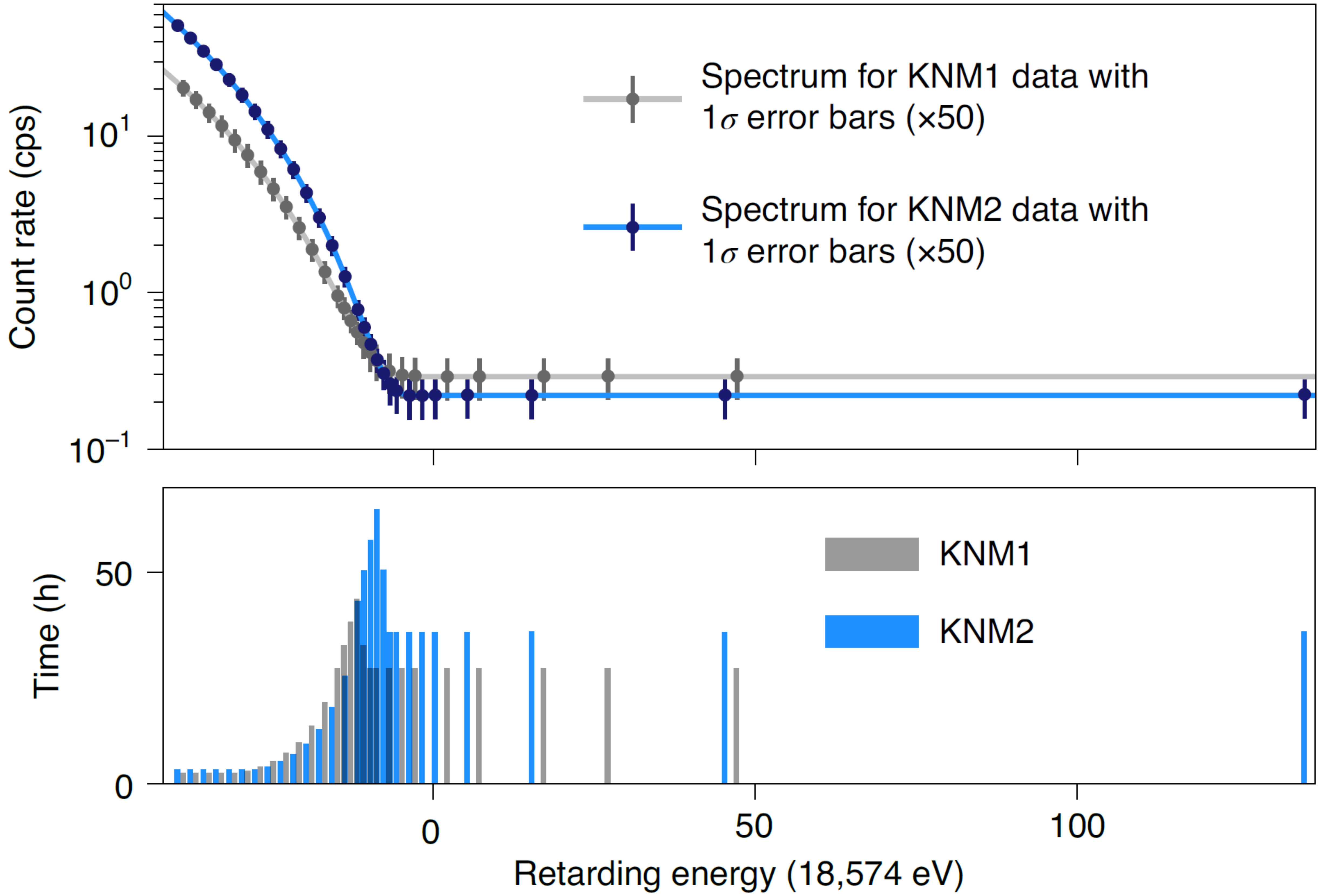
$$\mathcal{A} \rightarrow \mathcal{B} + e^{-} + \bar{\nu}_e$$

- ***C++***-based analysis framework *KaFit*
- $R(qU_{\text{ret}}) = A_{\text{Sig}} \int_{qU_{\text{ret}}}^{E_0} f(E - qU_{\text{ret}}) \frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E}(E, m_\nu^2)\, \mathrm{d}E + R_{\text{Bg}}$
- Four free fit parameters:
  - Neutrino mass m_ν^2
  - Endpoint E_0
  - Amplitude A_{Sig}
  - Background R_{Bg}
- Many free nuisance parameters (systematic effects)

→ $\boldsymbol{m_\nu < 0.45}$ **eV (90% CL)**

KATRIN Collaboration (2025): Science 388, 180

KATRIN Collaboration (2022): Nature Physics 18, 160–166



Beyond the SM: emission of additional light particles

$$\mathcal{A} \to \mathcal{B} + e^- + \bar{\nu}_e + X$$

- Beyond SM (BSM) theories: new leptophilic particles (→ light boson *X*)

$$\mathrm{i}g\bar{\nu}_e\gamma^5\nu_e X,\ \ \mathrm{i}g\bar{e}\gamma^5 eX,\ \ \text{or}\ \ g\bar{\nu}_e\gamma^\mu\nu_e X_\mu,\ \ g\bar{e}\gamma^\mu eX_\mu,\ \ g\,j^\mu_{L_e}X_\mu$$

ref. *Arcadi et al.:*

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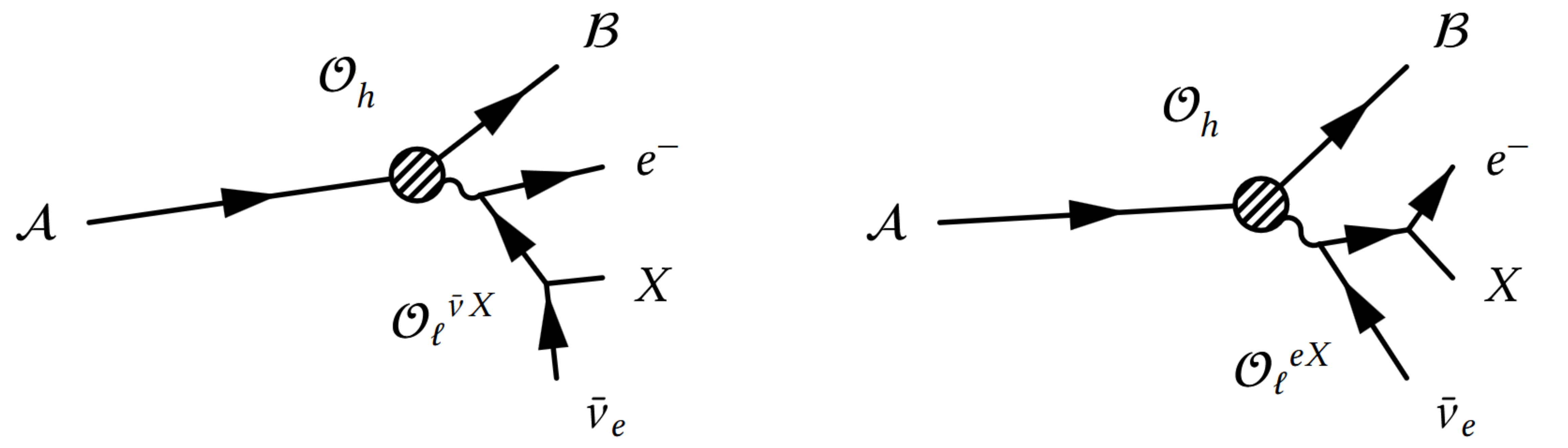


(a) boson X coupling to the neutrino $\bar{\nu}$ (b) boson X coupling to the electron e^-

→ Consequence: spectral modification due to emission of the additional real particle

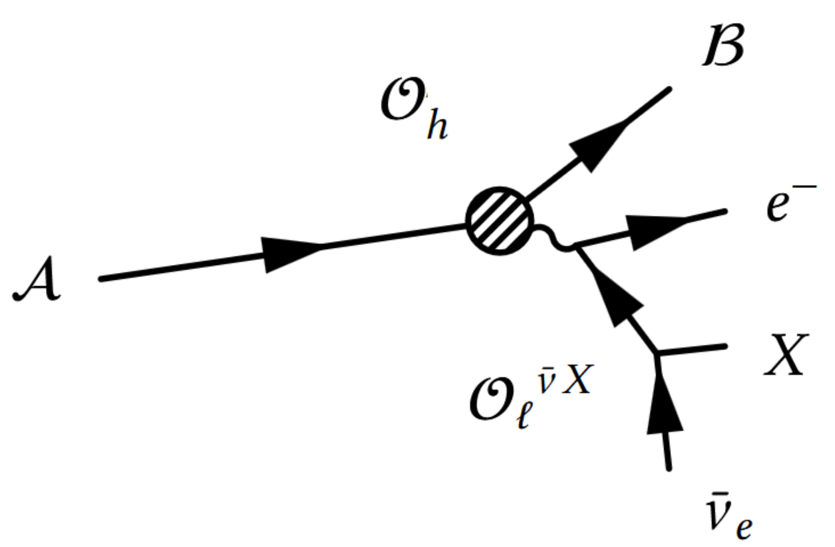
1. *dynamics*: special coupling structures, virtual intermediate leptons

2. *kinematics*: shifted endpoint, four-body final state

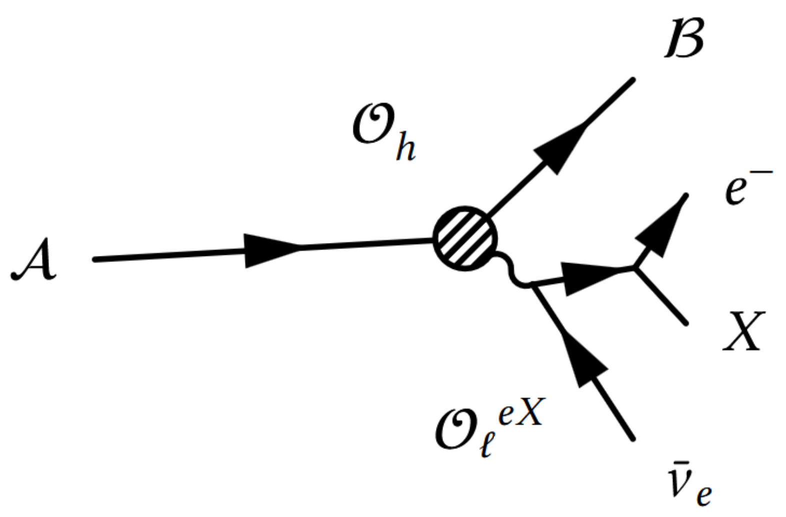
$$\mathrm{d}\Gamma = \frac{(2\pi)^4}{2m_{\mathcal{A}}}\overline{|\mathcal{M}|^2}\,\mathrm{d}\Phi$$

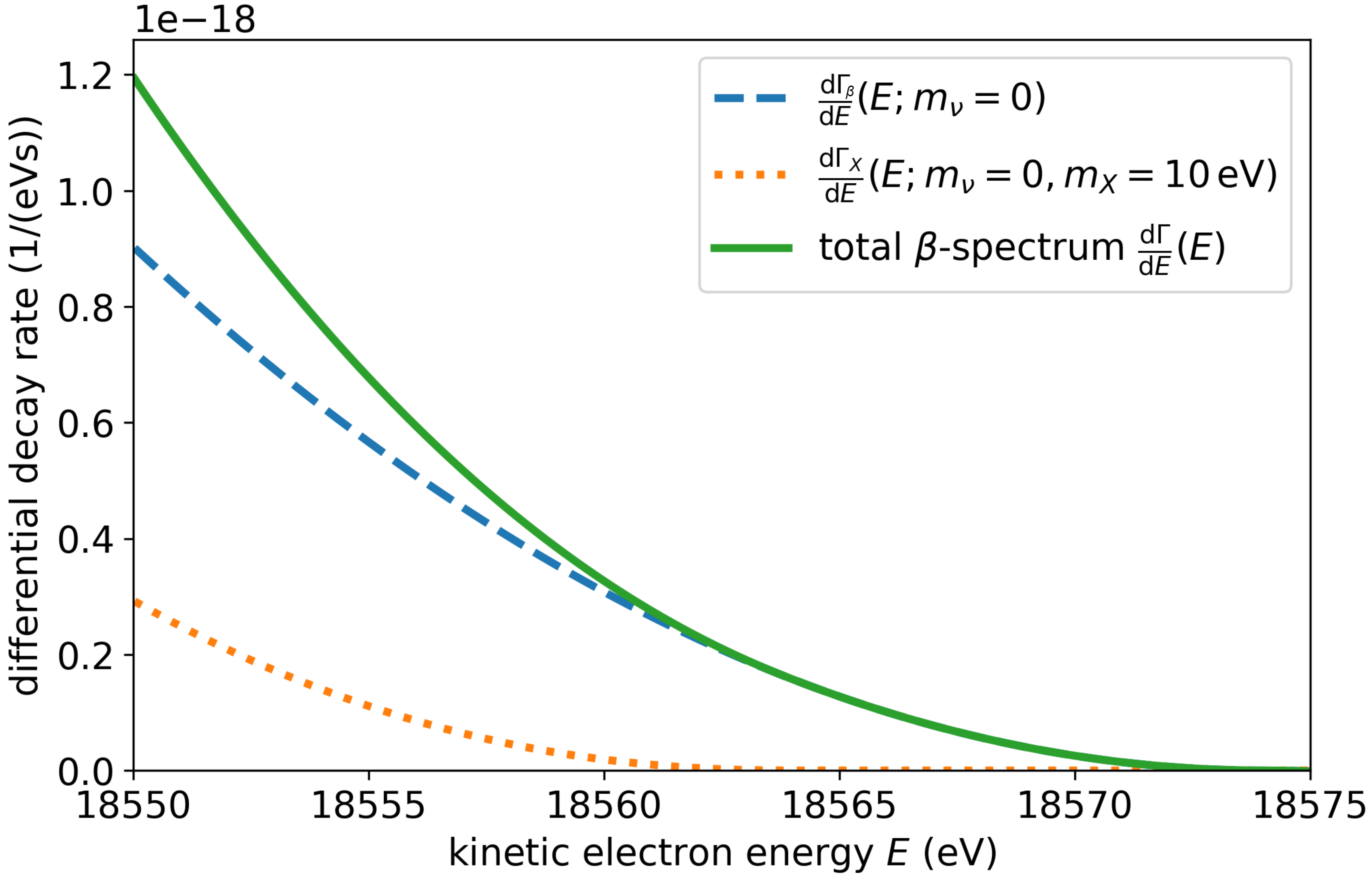
Spectral modifications with light bosons

→ Additional decay channdel $\mathrm{d}\Gamma_X$: $\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E_e} + \frac{\mathrm{d}\Gamma_X}{\mathrm{d}E_e} \geq \frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E_e}$



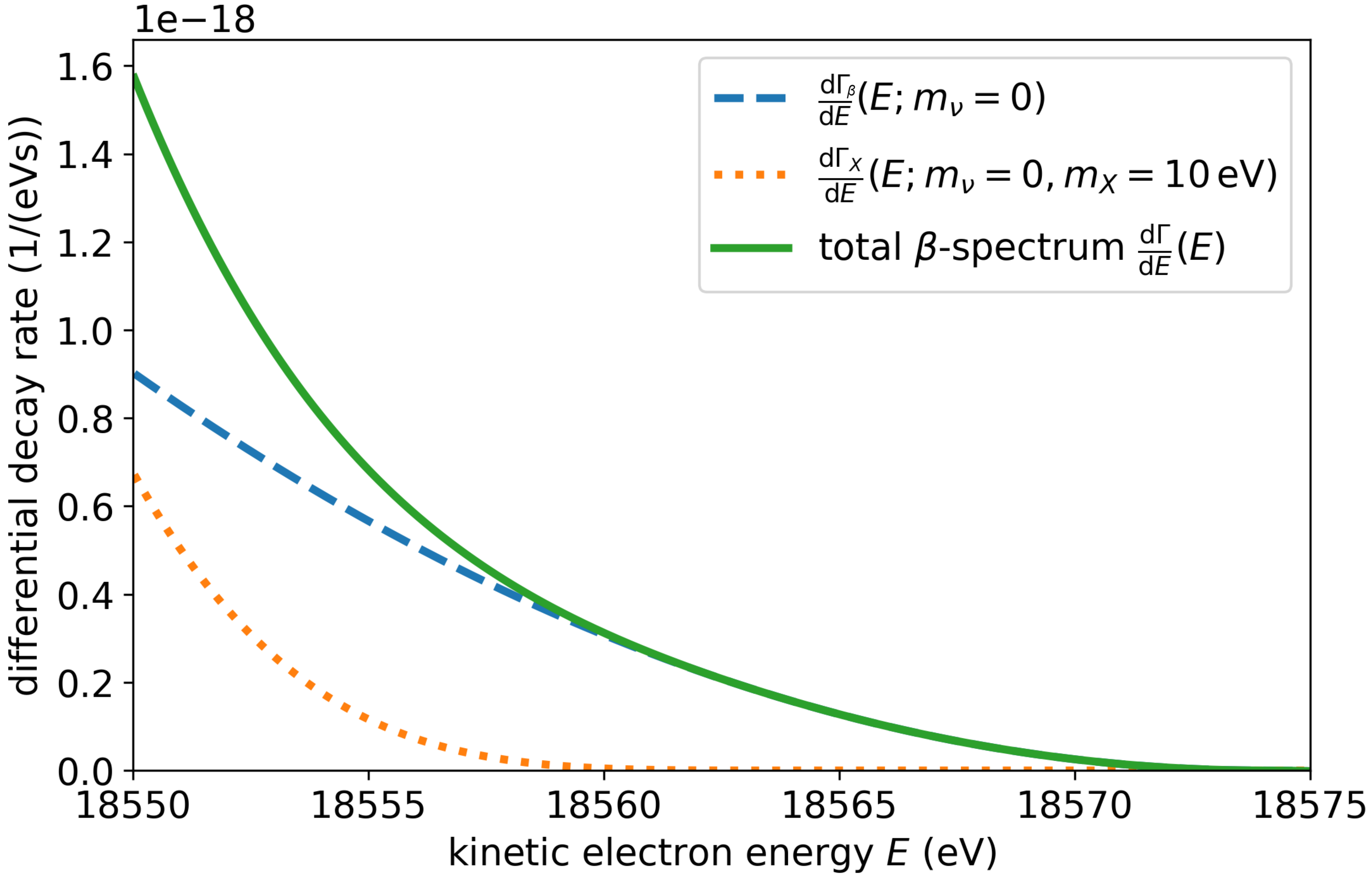
Example scenarios:
light **pseudoscalar** emission
$\mathcal{L} \supset \mathrm{i}g_X \bar\nu\gamma^5\nu X, \ \mathrm{i}g_X \bar e\gamma^5 eX$





tree-level process:
$\Gamma \propto g_X^2$

→ two parameters:
m_X and g_X



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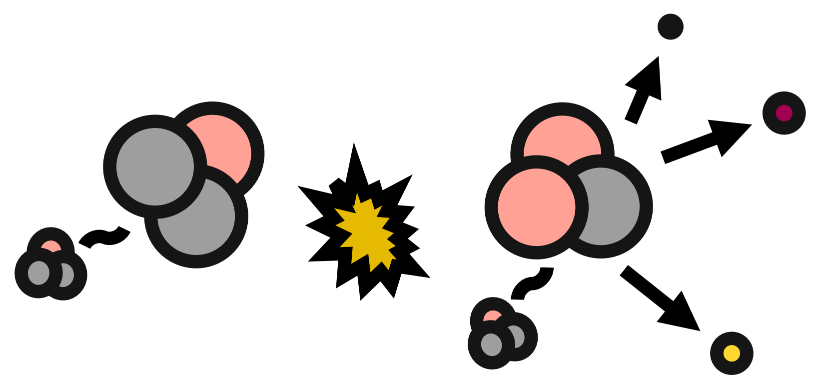
Search for light bosons with KATRIN



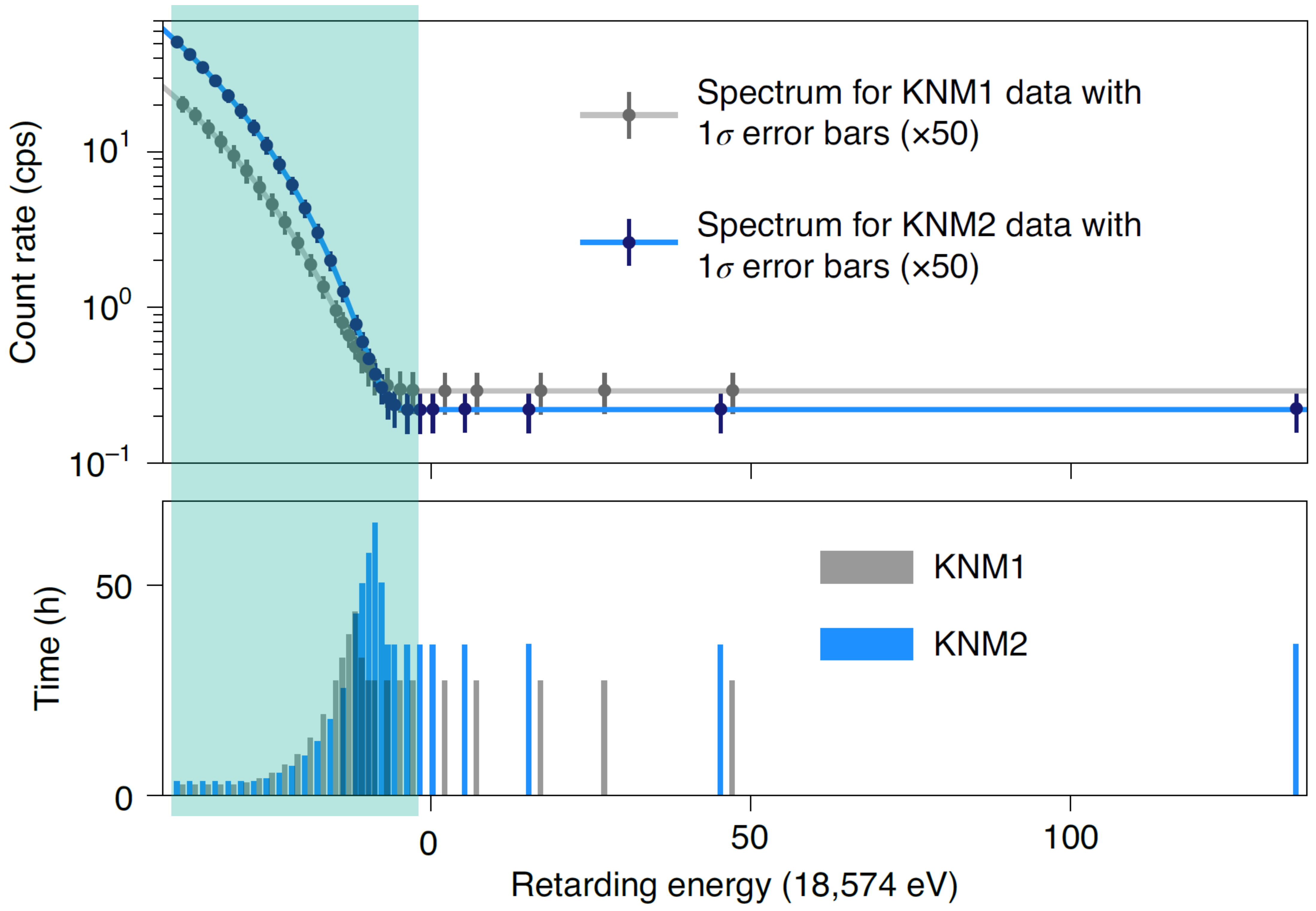
- Analysis procedure: **likelihood scan** over "new physics" parameter space ($\boldsymbol{m_X}$, $\boldsymbol{g_X}$)
- Model of emission spectrum required
- → Empirical parametrization in JHEP01(2019)206:

$$\frac{\mathrm{d}\Gamma_X}{\mathrm{d}E} = K\sqrt{\frac{E}{m_e}}\left(\frac{E_{\max}-E}{E_{\max}+m_e}\right)^n$$

→ parameters depending on interaction type, m_X, and g_X

- K and n from fit of semi-analytic results (with strict $m_\nu = 0$)

→ **This work:** Comparing ansatz above to investigation of very *detailed spectral shape* in the endpoint region (incl. m_ν)



→ current KATRIN analysis range: masses $\boldsymbol{m_X}$ **< 40 eV**

Spectrum calculation – *numerical integration*

$$\frac{\mathrm{d}\Gamma_X}{\mathrm{d}E_e} = \frac{1}{2^5(2\pi)^6 m_{\mathcal{A}}^2} \int_{M_{12-}^2}^{M_{12+}^2(E_e)} \int_{M_{34-}^2(E_e,M_{12}^2)}^{M_{34+}^2(E_e,M_{12}^2)} \int_{M_{134-}^2(M_{12}^2,M_{34}^2)}^{M_{134+}^2(M_{12}^2,M_{34}^2)} \int_{M_{14-}^2(E_e,M_{12}^2,M_{34}^2,M_{134}^2)}^{M_{14+}^2(E_e,M_{12}^2,M_{34}^2,M_{134}^2)} \frac{\overline{|\mathcal{M}|^2}}{\sqrt{-B}} \mathrm{d}M_{12}^2 \mathrm{d}M_{34}^2 \mathrm{d}M_{134}^2 \mathrm{d}M_{14}^2$$

$\bar{\nu} \to 1, \quad X \to 2, \quad e \to 3, \quad \mathcal{B} \to 4$

- No general exact analytic solution for the integral was found

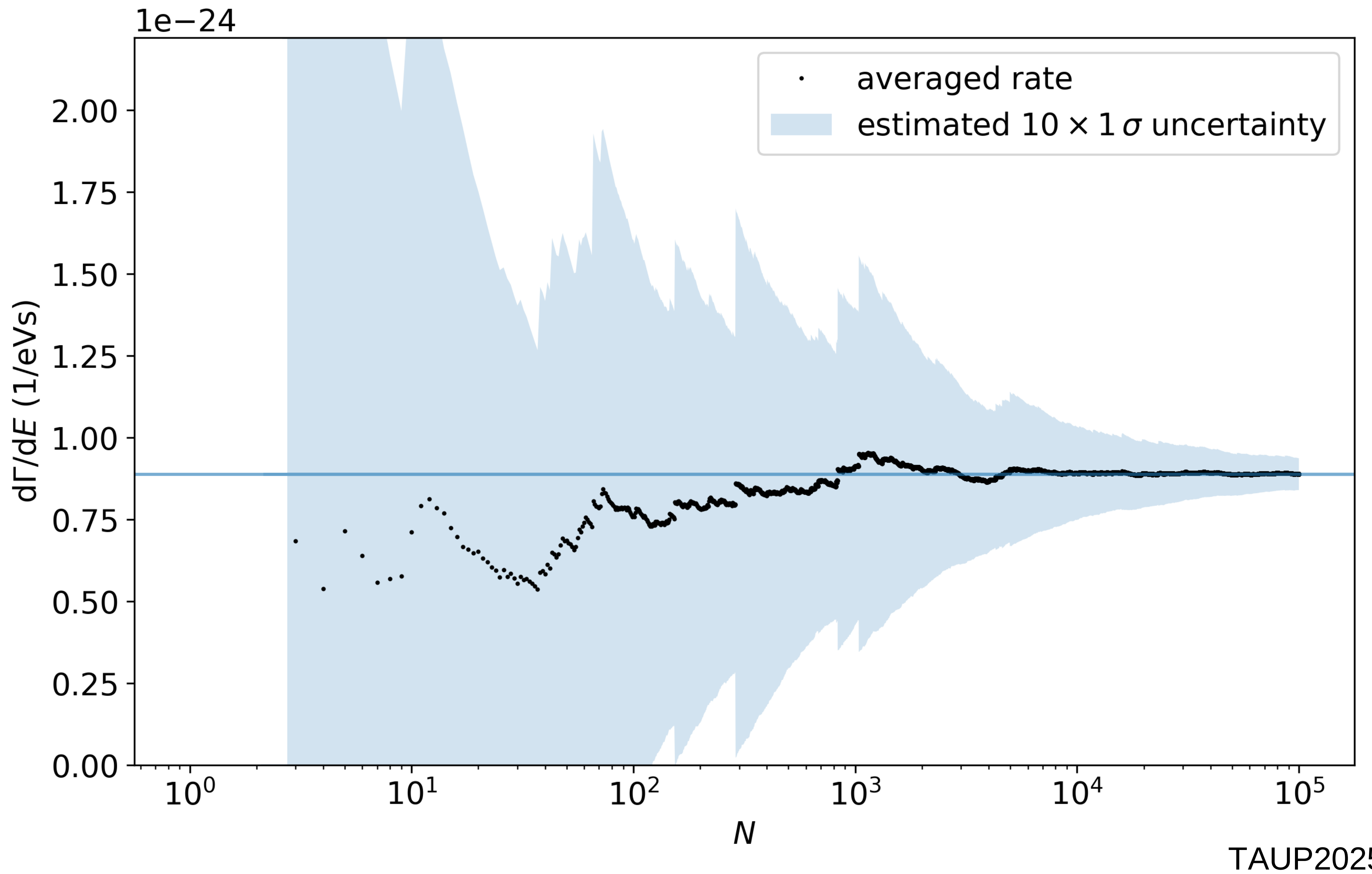
- Highest level of flexibility and modularity: **MC sampling** of entire phase space

  → statistically converging approximation of the integral (uncertainty $\propto 1/\sqrt{N}$)

- Numerical stability: **C++** framework with *GNU Multiple Precision Arithmetic Library* (**GMP**)

- Sampling stability: compensation of strong enhancements in the amplitude → **importance sampling**

Performance example



Refined parametrization

Example scenario:
electron-pseudoscalar coupling
$\mathcal{L} \supset \mathrm{i}g\bar{e}\gamma^5 eX \; (m_\nu = 0)$

- Numerical results are fitted with **new ansatz** of order *k:*

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \approx \exp\left(\sum_{j=0}^{k} \theta_j \ln^j(x)\right)$$

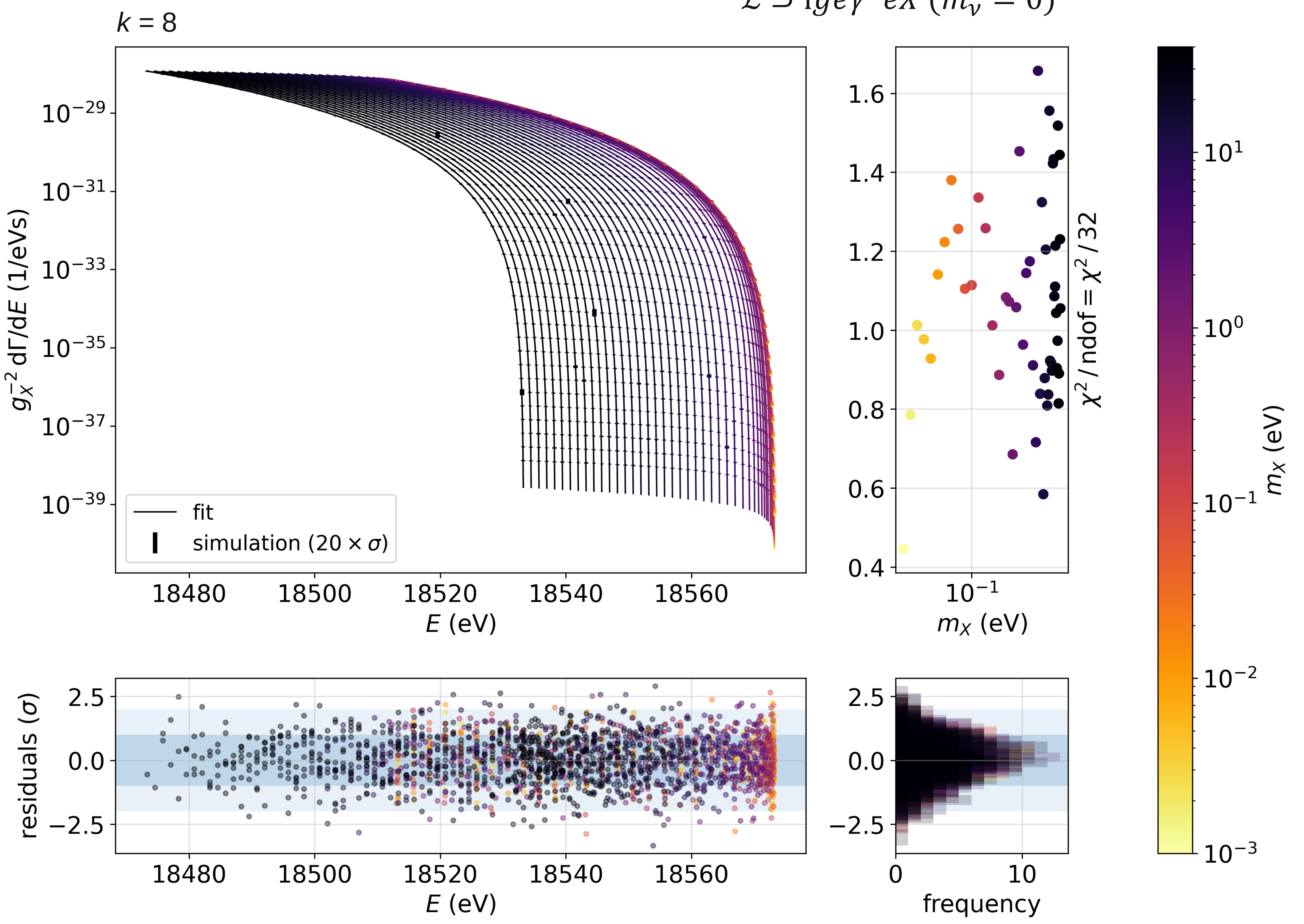
$$x = \frac{E_{\max} - E}{E_{\max}} \in [0, 1]$$

- Parameters K and $n(x)$ are extracted:

$$K\left(\frac{E_{\max} - E}{E_{\max}}\right)^{\overbrace{\sum_{j=0}^{k-1} \theta_{j+1} \ln^j(x)}^{n(E)}}$$

→ Computations performed on the *bwForCluster NEMO* (Freiburg, GER)

→ Precise analytic model in the sensitive region

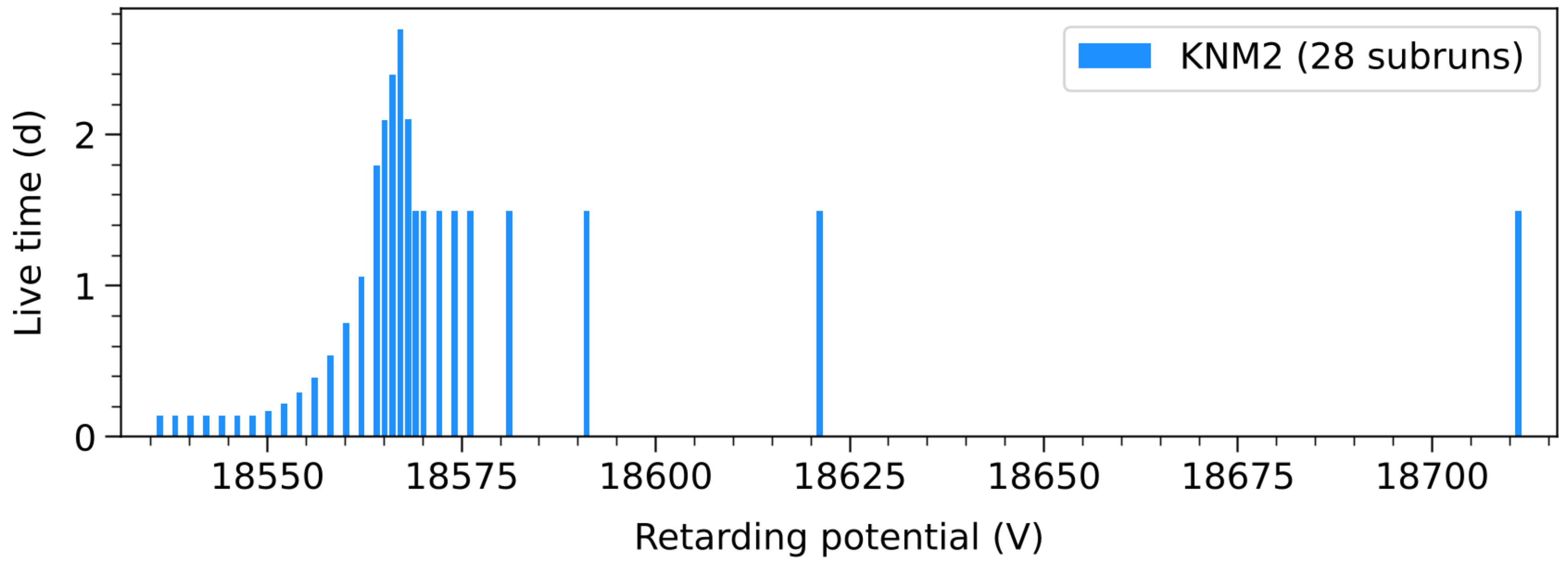


Analysis procedure

Dataset

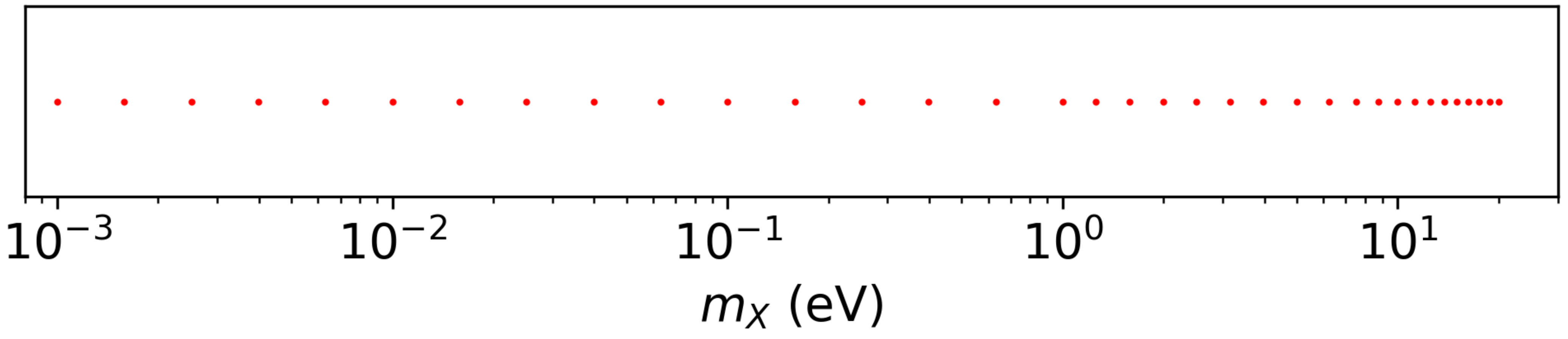
- Based on second KATRIN science run (*KNM2*, 2019):
  - 4×10^6 collected electrons in ROI
  - ROI: $[E_0 - 40\ \text{eV},\ E_0 + 130\ \text{eV}]$
- **This work:** using MC Asimov twin dataset of KNM2:
  - Experimental settings adapted
  - $m_\nu^2 = 0$, $g_X = 0$ (no signatures)

S. Hickford (2023)



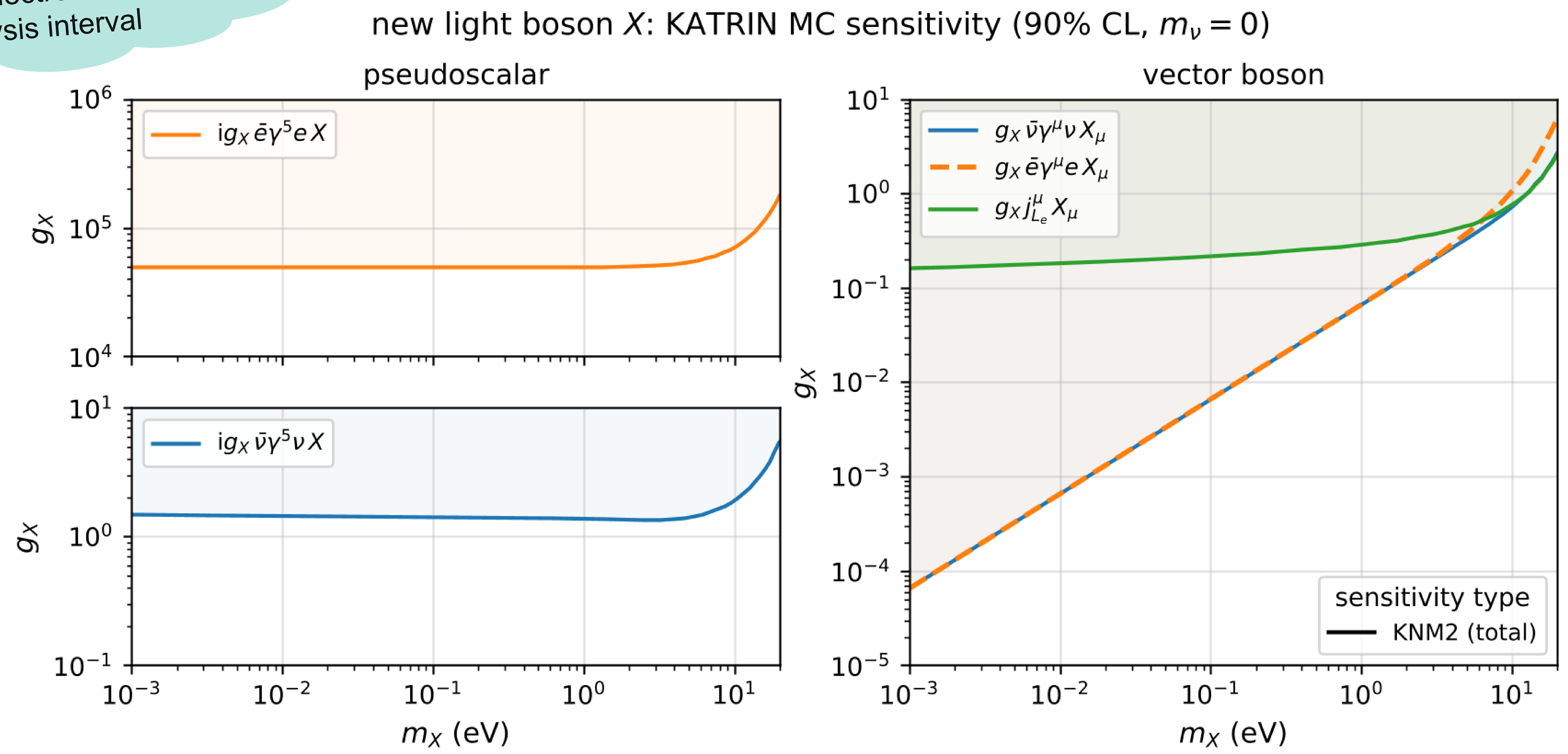
Analysis (grid scan)

- 35×40 fixed grid points in $\boldsymbol{m_X}$-$\boldsymbol{g_X}$-plane
  → 1400 fits
- Fixed $m_\nu^2 = 0$
- Free E_0, A_{Sig}, R_{Bg}
- Systematic (nuisance) parameters free, with pull terms
- 90% CL contour at $\chi^2_{\text{crit}} = \chi^2_{\text{BF}} + \Delta\chi^2$ with $\Delta\chi^2 = 4.61$ for 2 DOF



Sensitivity of the 2nd KATRIN science run

4×10^6 electrons in the analysis interval



Breakdown of systematics

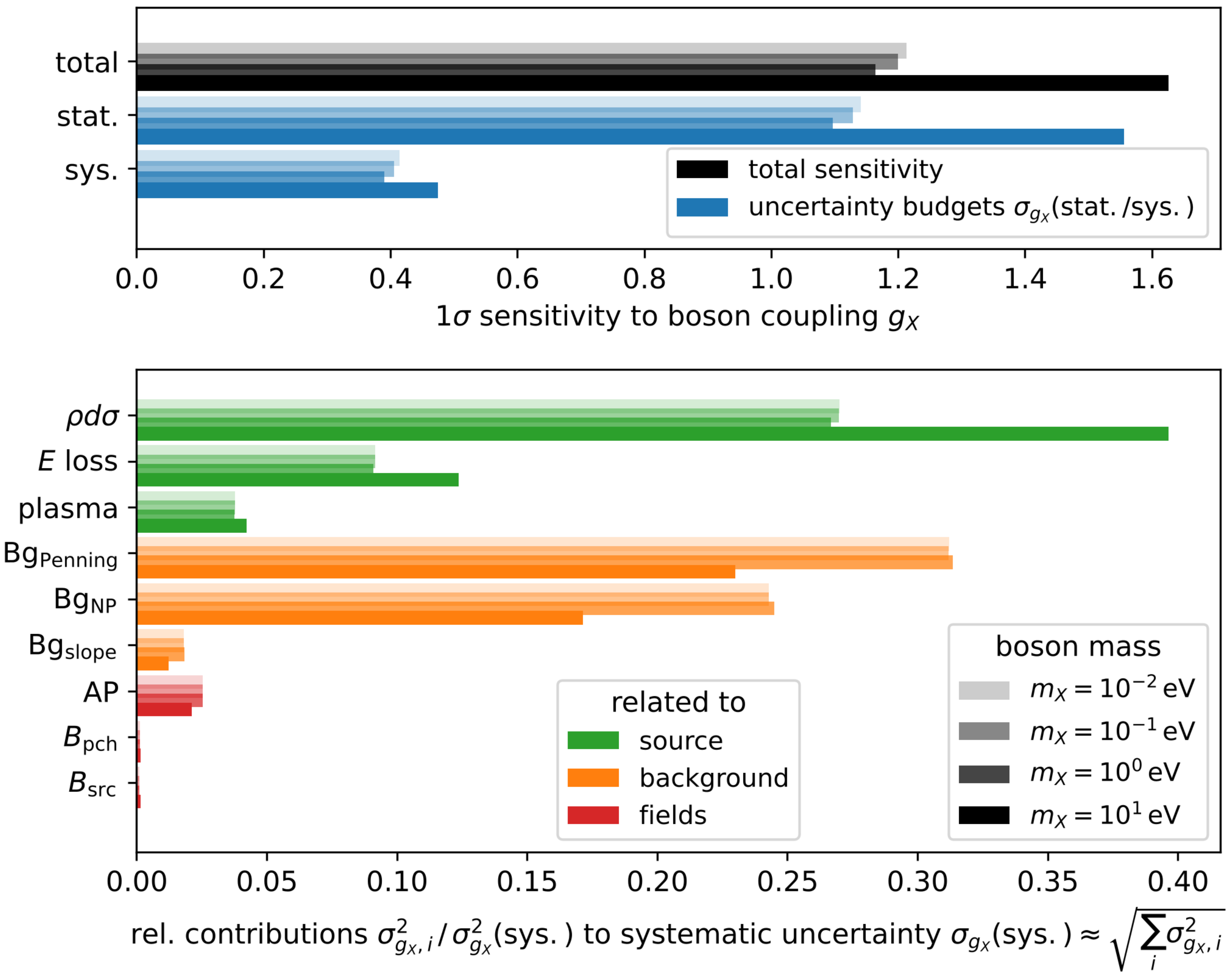
KNM2 MC data

- **Uncertainty budget** of systematic effect i: $\sigma_i = \sqrt{\sigma^2_{\mathrm{stat}+i} - \sigma^2_{\mathrm{stat}}}$

→ analysis with all relevant systematic contributions (i) **individually**

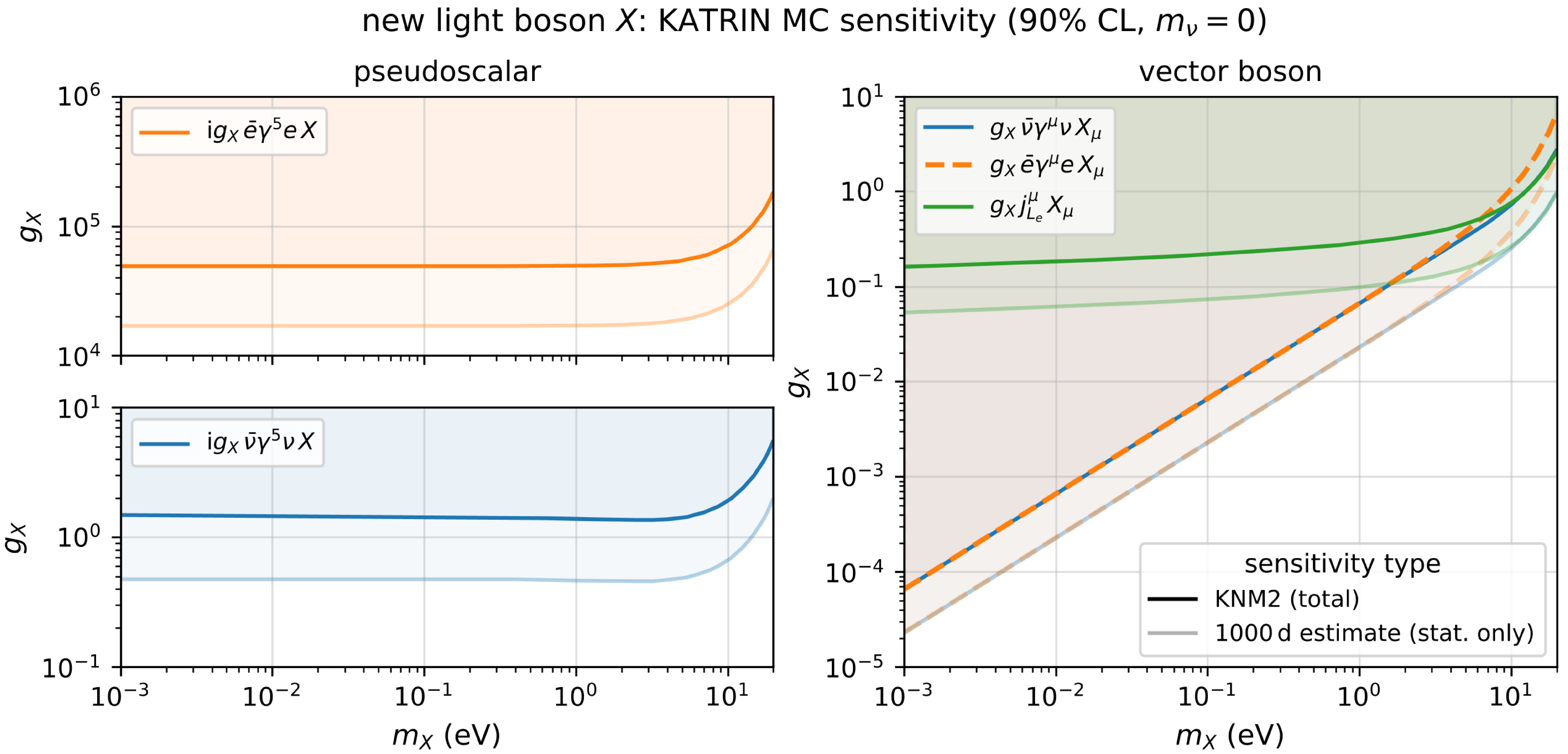
- *Relative* contributions reveal ordering for different masses m_X

sensitivity breakdown for coupling of pseudoscalar to neutrino

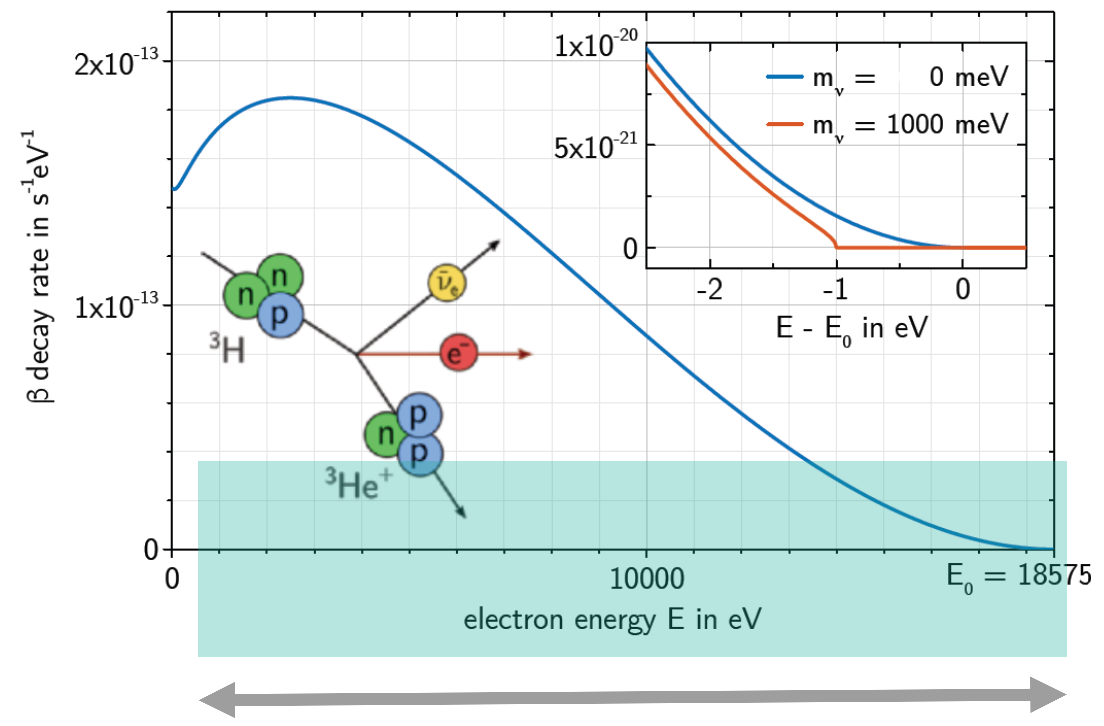


Future: final light boson sensitivity of KATRIN

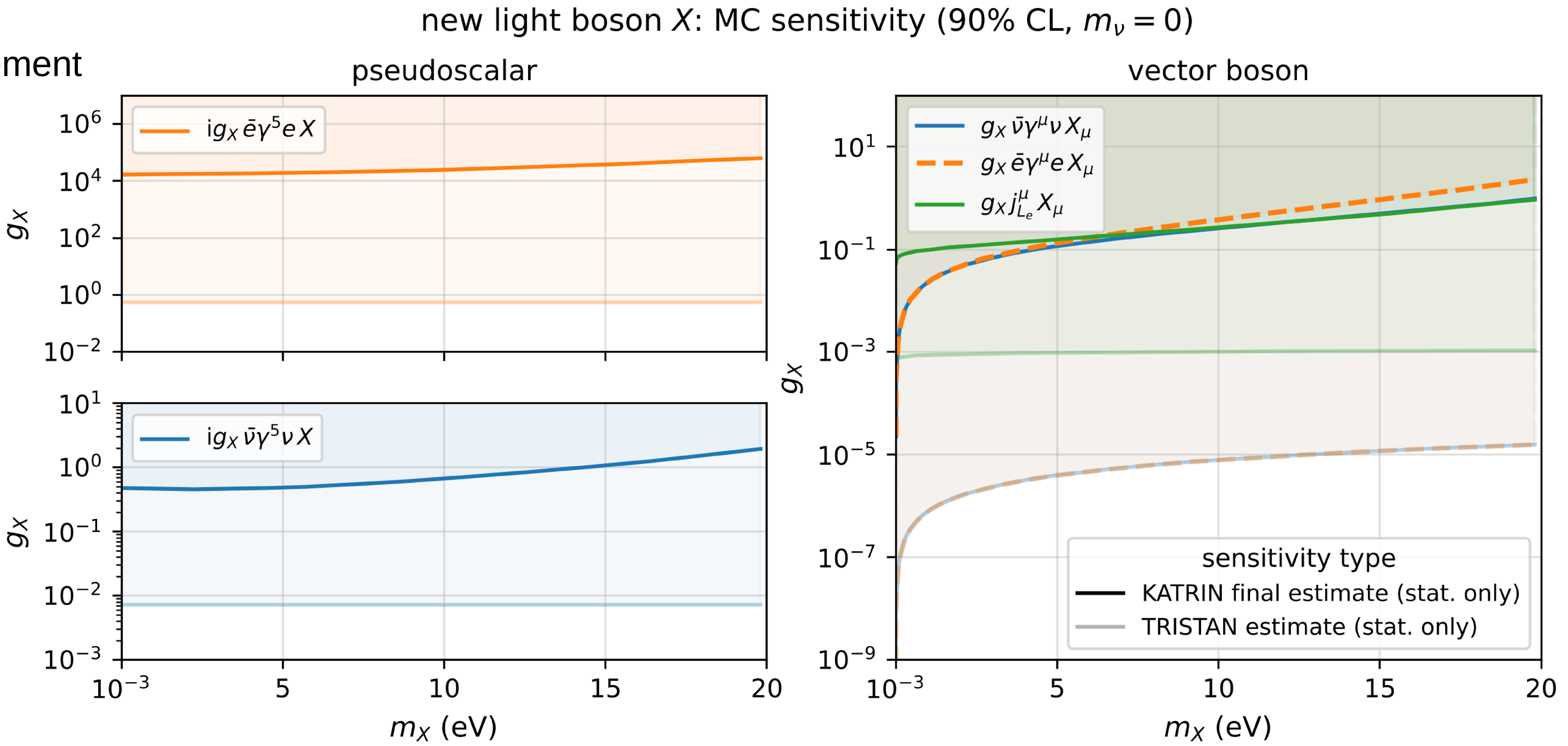
- Data taking with KATRIN continues until end of 2025
- Expected final dataset: improvement of factor ~40 in statistics (1000 days in total)



Future: TRISTAN upgrade



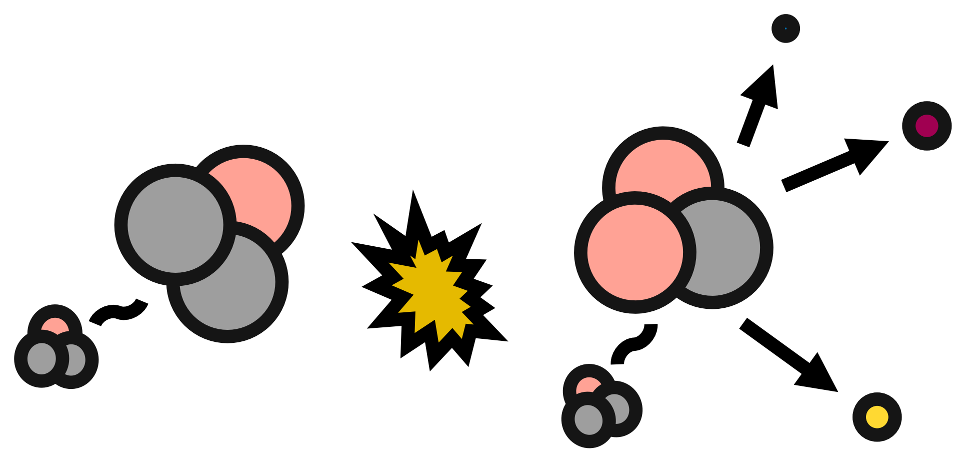
- Detector upgrade in 2026 → search for keV sterile neutrinos
- Measurement of full tritium β-spectrum
- Differential measurement



Summary & outlook

This work:

- Highly **adaptable and modular framework** for boson emission spectrum computation
- Detailed description of the spectral branch in the **endpoint region of β-decay** (incl. boson and neutrino mass)
- Refined **sensitivity** of tritium-based **direct probe** to new light particles at low energy scale
- Impact of the individual **systematic effects** of KATRIN
- **Improved sensitivity** (stat.) with further data of **KATRIN and TRISTAN** upgrade



Outlook:

- Analysis of a **subset of our data** (second science run) w.r.t. light boson signature is currently **in preparation**
- Potential for significant **future improvement** with upcoming data and upgrades