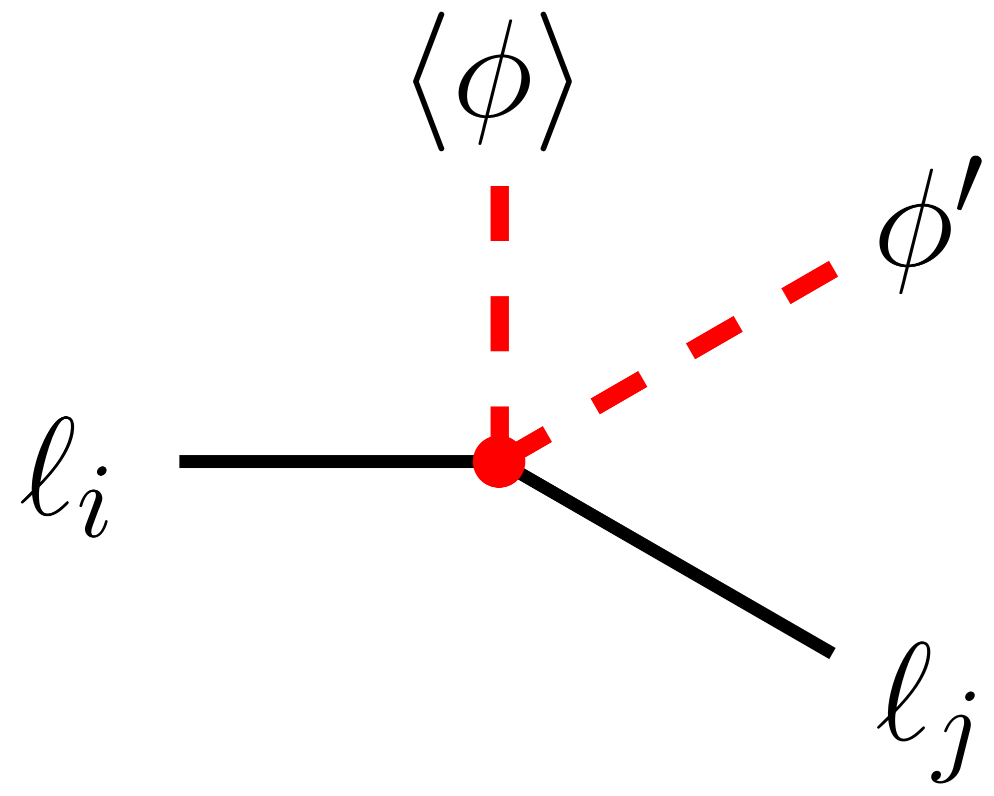


Detecting **Ultralight DM** via CLFV

Based on 2503.07722 w/ I. Bigaran, P. Fox, Y. Gouttenoire, R. Harnik, G. Krnjaic, and J. Zupan

CLFV 2026

June 19th, 2026

Tony Menzo, PhD

Joint postdoc @ the University of Alabama and Fermilab

The menu

1. Ultralight dark matter (**ULDM**)
   - Production, properties, UV perspectives
2. **CLFV + ULDM**
   - Model building constraints
   - Explicit realization
3. Experimental sensitivity (μ, τ)

Lore – ULDM

What is ultralight dark matter?

Wave dark matter.

(0003365)

- Spin-0, (pseudo)scalar, $(10^{-21} - 10^{-19})\,\text{eV} \lesssim m \lesssim \text{eV}$

Tremaine & Gunn (1979)

$$m_\psi \gtrsim \left(\frac{\rho_\phi}{\sigma_v^3}\right)^{1/4} \sim \text{keV}$$

Lyman-α (2007.12705, 2606.06969)

Dwarf heating (2203.05750, 2405.20374)

$$\mathcal{N} \sim \frac{\rho_\phi}{m_\phi^4 \sigma_v^3} \gg 1$$

- Described by a classical wave $\phi_c(\mathbf{x}, t) = \phi_0(\mathbf{x}) \cos(m_\phi t + \delta)$

where $\phi_0 = \sqrt{2\rho_\phi}/m_\phi, \quad \rho_\phi = 0.4\text{GeV/cm}^3 \simeq 10^{-42}\,\text{GeV}^4$

Lore — ULDM

What is ultralight dark matter?

- Spin

- Desc

where

Scales

Two halo #'s:

$$\rho_{\mathbf{DM}} \simeq 3 \times 10^{-6} \mathbf{eV}^4$$

$$\sigma_{\mathbf{v}} \simeq 10^{-3}$$

+ m_ϕ

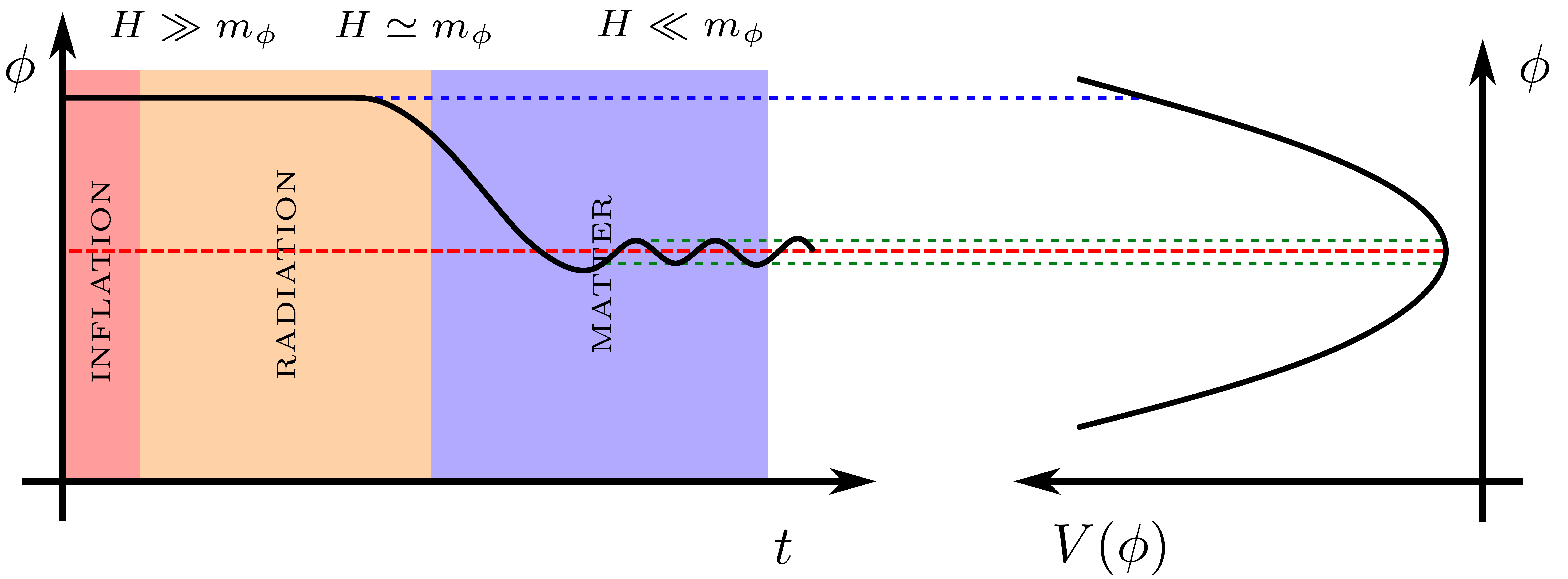
$$T_{\mathbf{osc}} = \frac{2\pi}{m_\phi} \approx 4\,\mathbf{s}\left(\frac{10^{-15}\,\mathbf{eV}}{m_\phi}\right)$$

$$\tau_{\mathbf{coh}} \sim \frac{1}{m_\phi \sigma_{\mathbf{v}}^2} \approx 1\,\mathbf{week}\left(\frac{10^{-15}\mathbf{eV}}{m_\phi}\right)$$

Lore – ULDM

Early universe production via misalignment

$$\int d^4x\sqrt{-g}\left(\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2\right) \to \ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + m_\phi^2\phi = 0$$



Lore — ULDM

Light scalars are unnatural, radiative corrections drag m_ϕ^2 up to the cutoff.

Easiest way to get ultralight field is starting with exact NGB (linear-sigma), and giving mass via

1. Anomalous coupling to a gauge group: $\Lambda^4 \cos(\phi/f), m \sim \Lambda^2/f$
2. Explicit spurion: $m^2 \sim m_q \Lambda$
3. Gravity: $\delta m^2 \sim f^{n-2}/M_{\text{Pl}}^{n-4}$

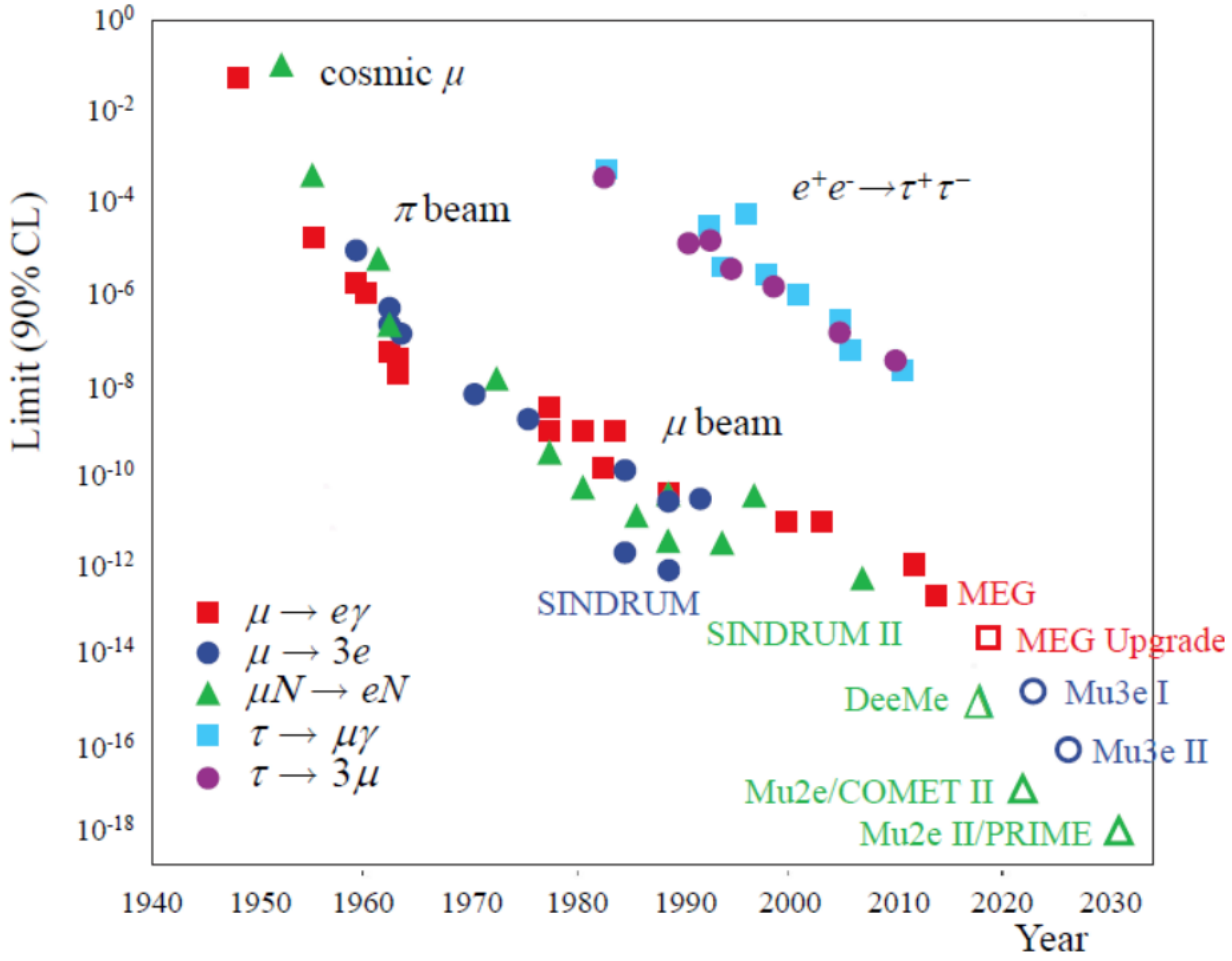
***Fine-tuning is the biggest model-building challenge**

Lore – CLFV

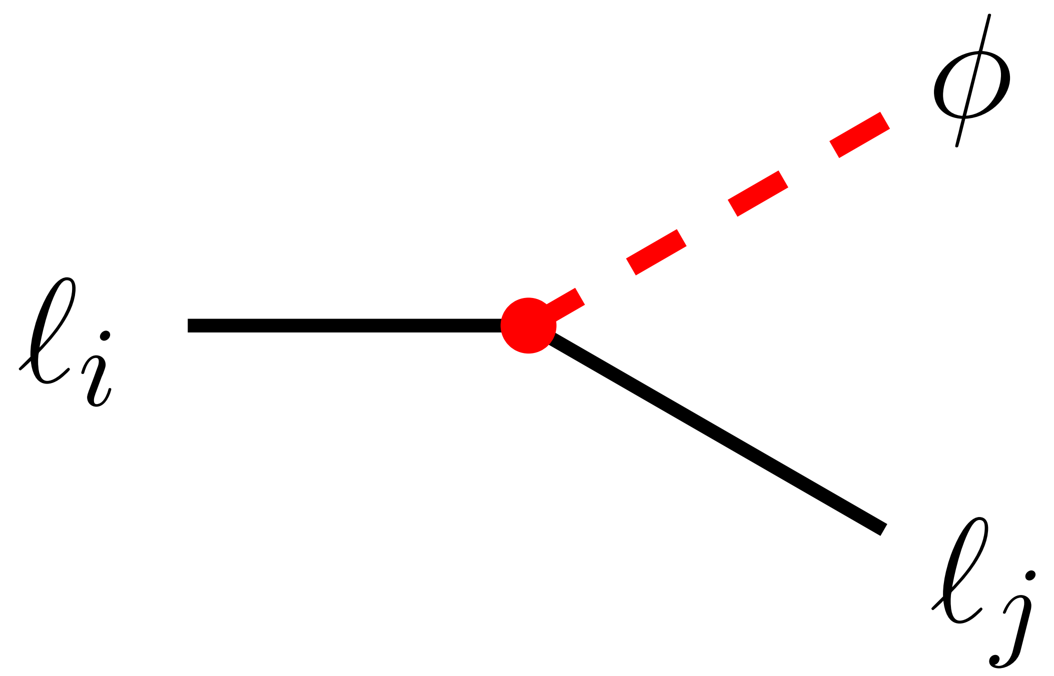
Observing CLFV = new physics

↓

Extensive experimental programs utilizing intense muon beams and e^+e^- colliders



CLFV + ULDM



Introducing CLFVing couplings to ϕ manifests as time-dependent modulations to leptonic rates.

$$\phi \to \phi_c(t) + \delta\phi \equiv \langle \phi \rangle(t) + \phi$$

Seeing a CLFV signal doesn't imply DM is the source, but detecting a ***time-dependent*** CLFV signal is a smoking gun for DM mediated CLFV.

CLFV + ULDM

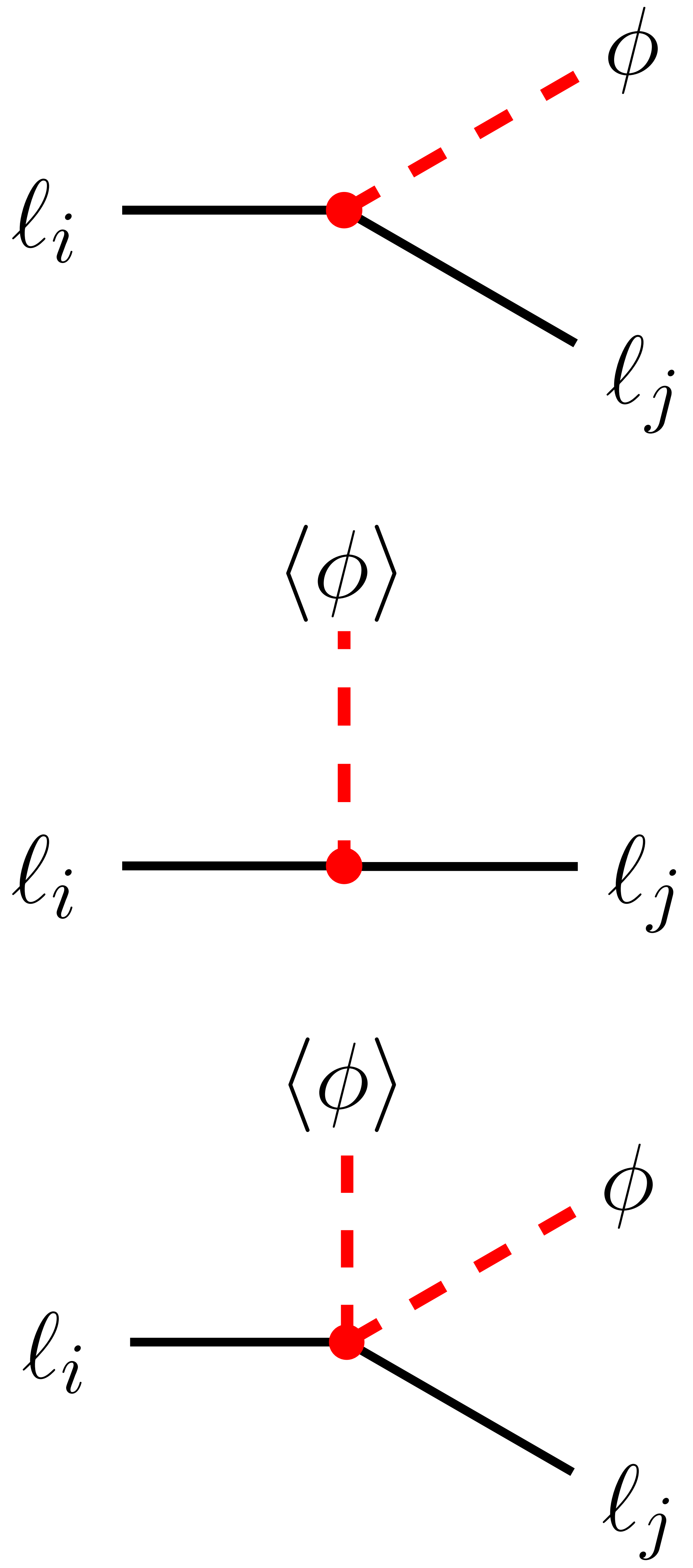
Two manifestations of time-dependence:

1. SM mass modulation

$$m_\ell(t) = m_\ell + y\phi_c(t)$$

2. Decay/scattering rates

Inherently higher-dimensional



CLFV + ULDM

Model building checklist:

1. Time-modulation

2. Fine-tuning

3. SM rate-modulation

CLFV + ULDM

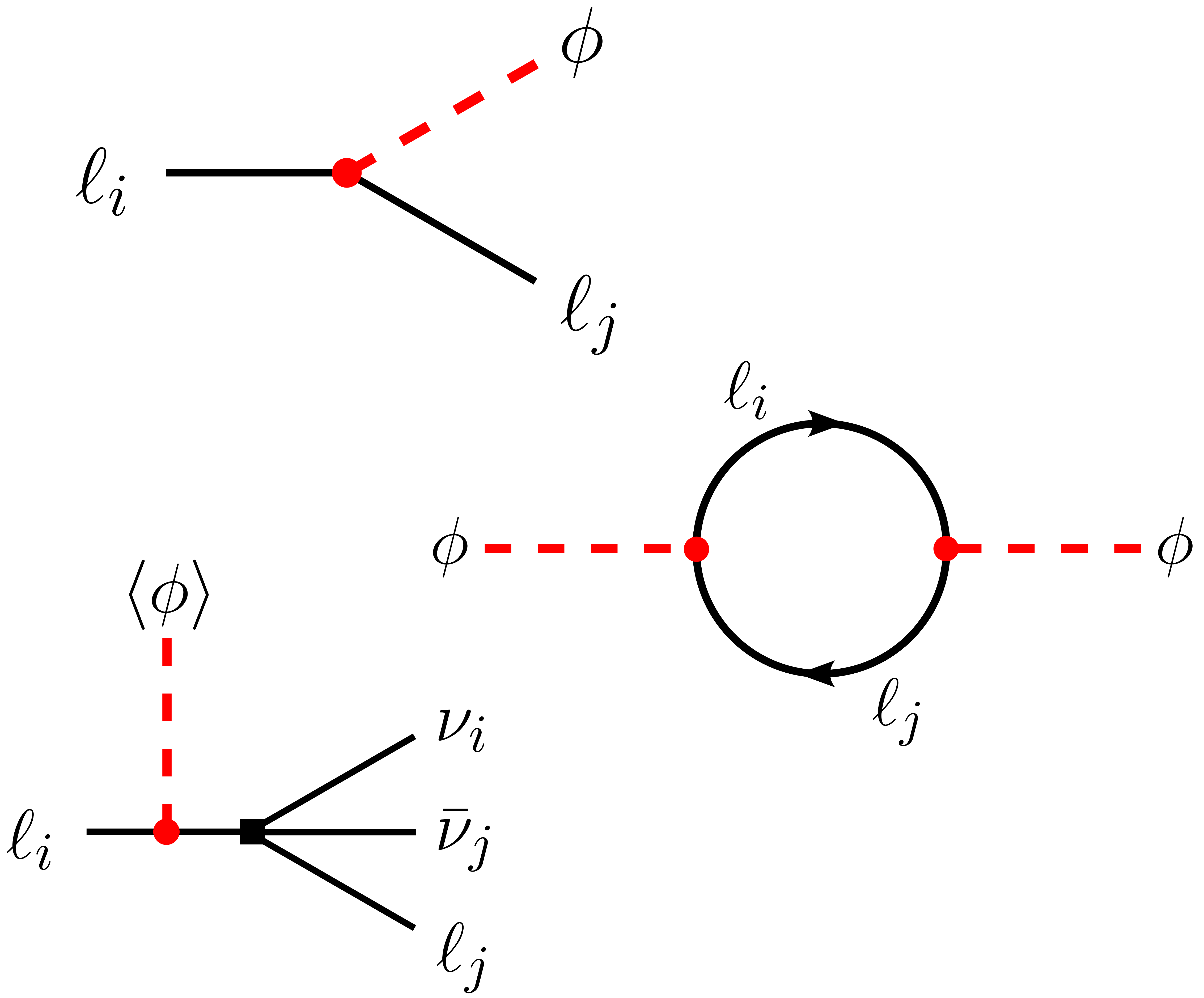
First guess: $\frac{C_{ij}}{\Lambda}\phi H \bar{L}_i \ell_j \to y_{ij}\phi \bar{\ell}_i \ell_j$

Model building checklist:

1. Time-modulation ✗
2. Fine-tuning ✓*
3. SM rate-modulation ✗

$|y_{\tau\ell}| \lesssim 10^{-7}$ **(Belle II)**

$|y_{\mu\ell}| \lesssim 10^{-10}$ **(TWIST)**



CLFV + ULDM

Second guess: $\frac{C_{ij}}{\Lambda}\partial_\mu\phi\,(\bar{\ell}_i\gamma^\mu\gamma^5\,\ell_j)$

Model building checklist:

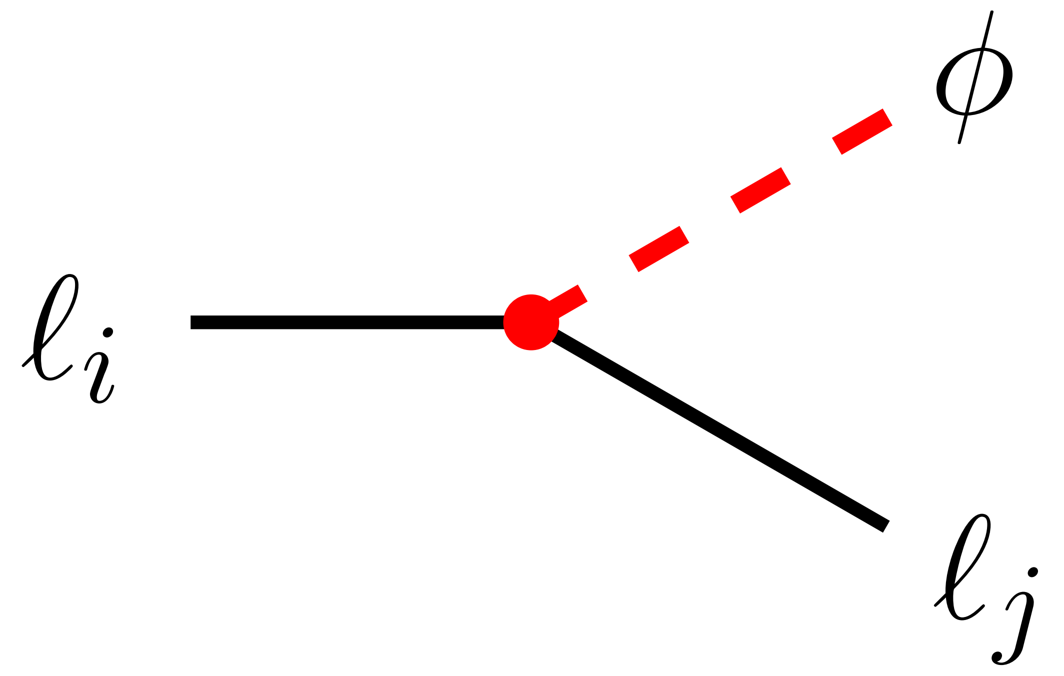
1. Time-modulation ✗

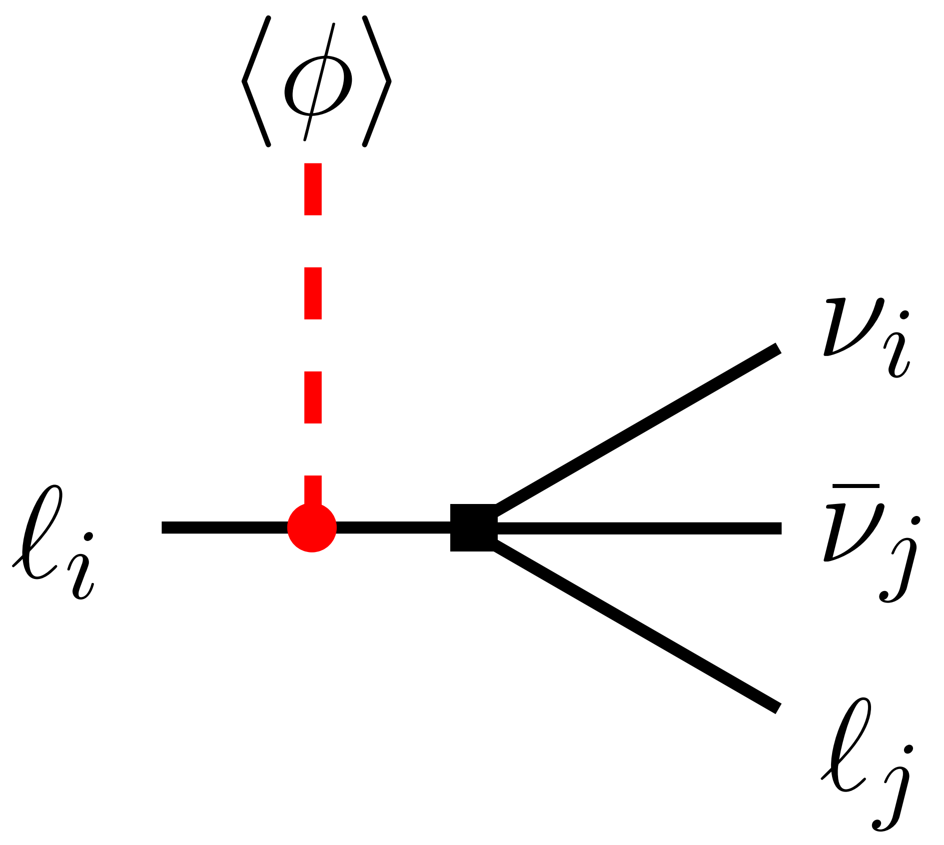
2. Fine-tuning ✓

3. SM rate-modulation ✗

$|y_{\tau\ell}| \lesssim 10^{-7}$ **(Belle II)**

$|y_{\mu\ell}| \lesssim 10^{-10}$ **(TWIST)**



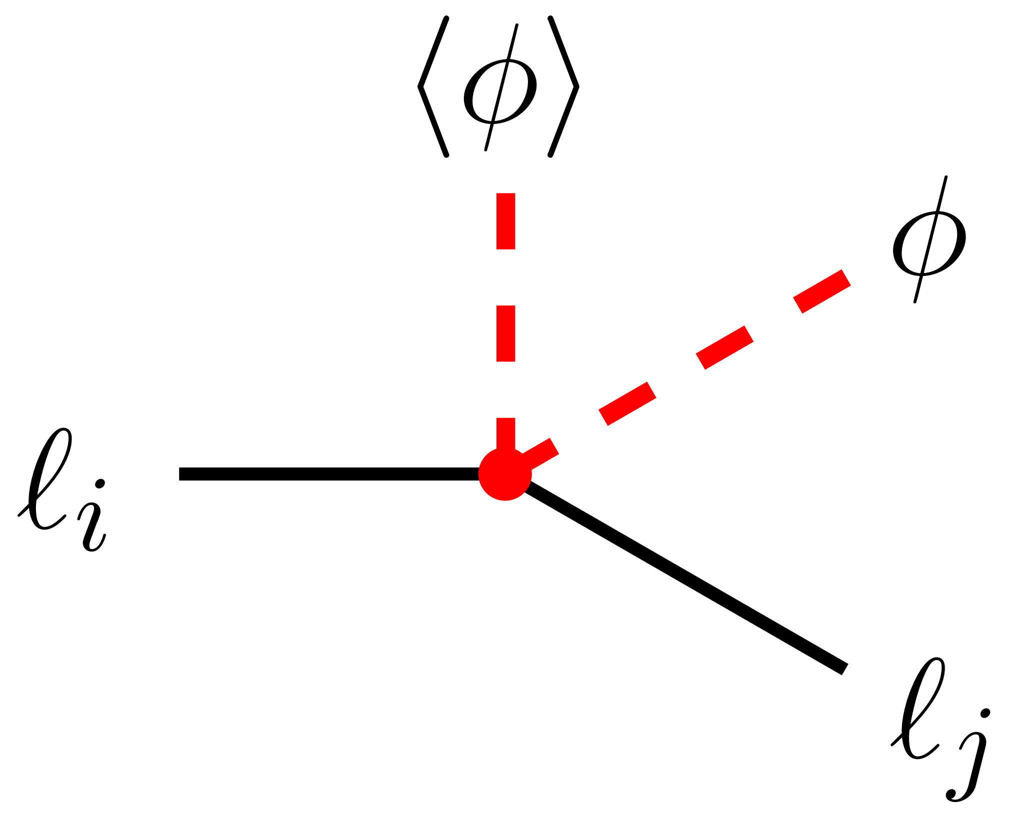


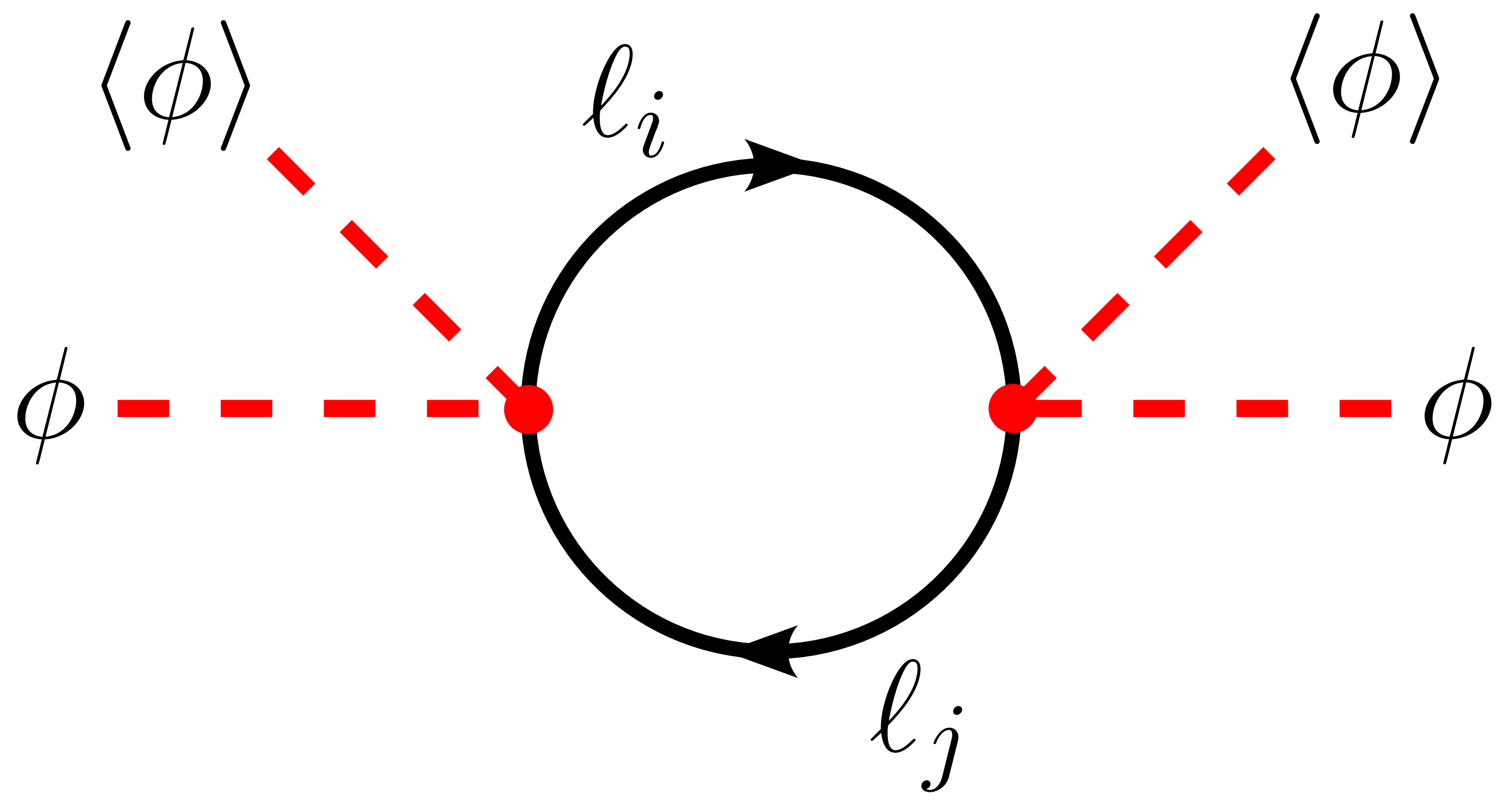
CLFV + ULDM

Third guess: $\frac{C_{ij}}{\Lambda}\phi^2(\bar{\ell}_i \ell_j)$

Model building checklist:

1. Time-modulation ✓
2. Fine-tuning ✗
3. SM rate-modulation ✓





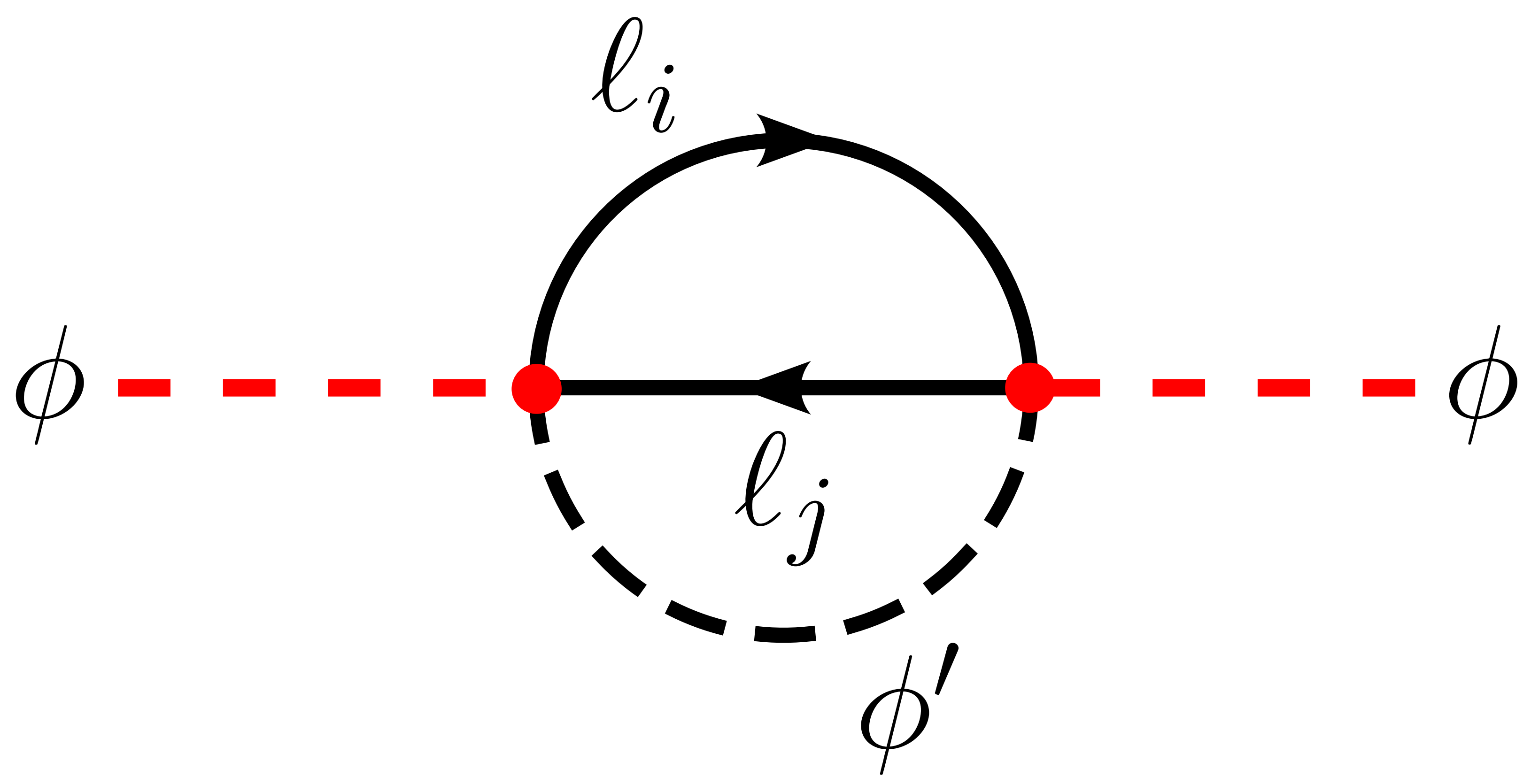
CLFV + ULDM

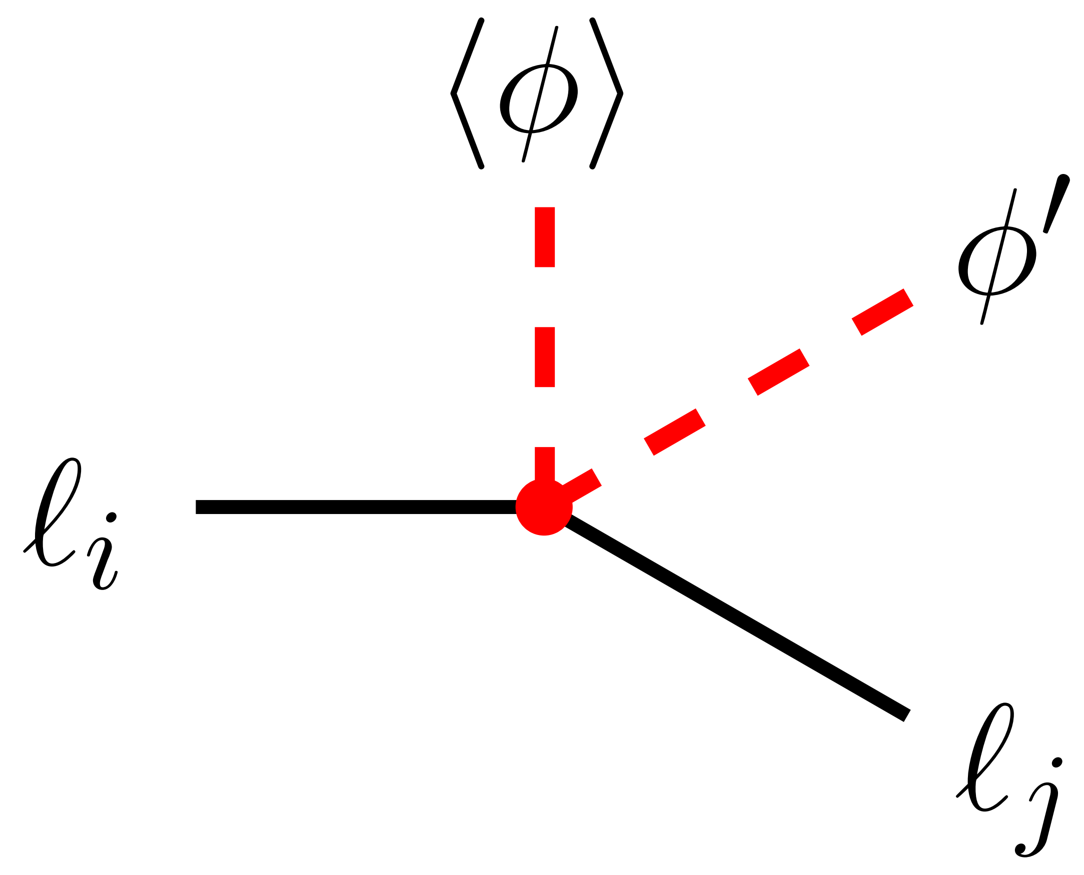
Fourth guess:

Model building checklist:

$$\frac{C_{ij}}{\Lambda}\phi\phi'(\bar{\ell}_i \ell_j) \quad \textbf{or} \quad \frac{C_{ij}}{\Lambda^2}\phi\partial_\mu\phi'(\bar{\ell}_i\gamma^\mu \ell_j)$$

1. Time-modulation ✓
2. Fine-tuning ✓
3. SM rate-modulation ✓

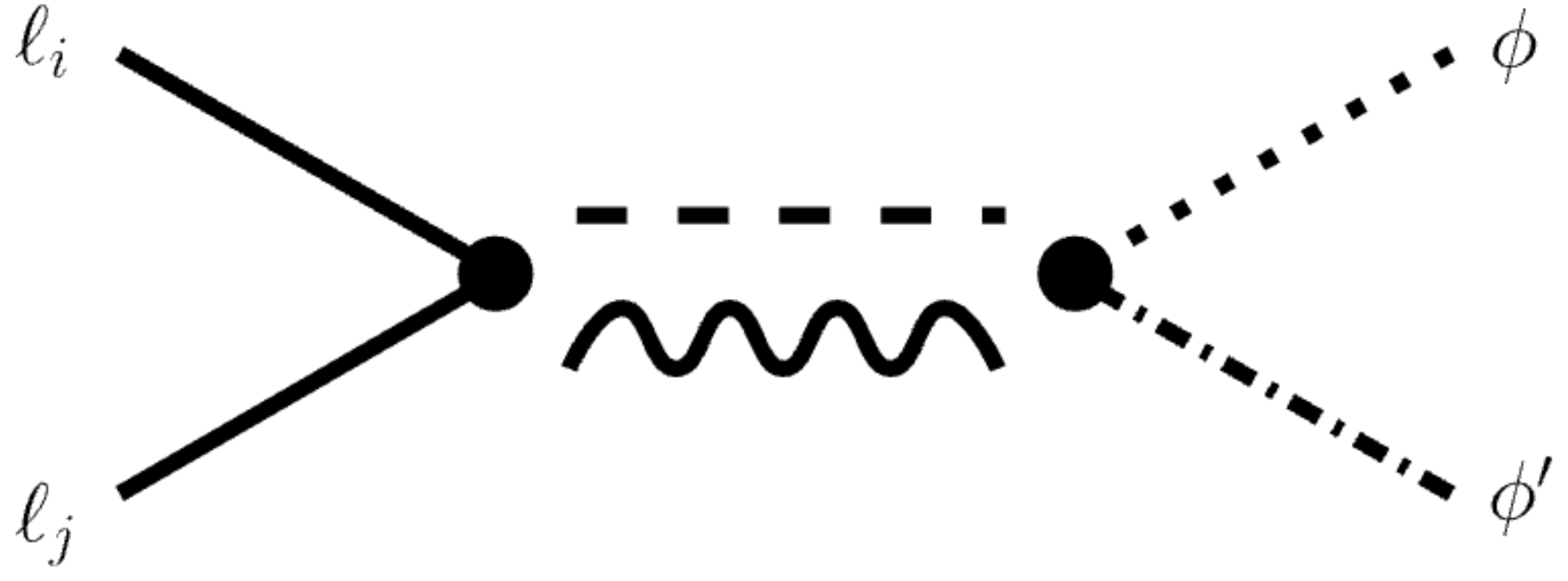




$$\mathscr{B}(\ell_i \to \ell_j \phi') = \frac{C_{ij}^2\,\phi_0^2}{64\pi\,\Lambda^4}\frac{m_{\ell_i}^3}{\Gamma_{\ell_i}}\cos^2(m_\phi t + \delta)$$

CLFV + ULDM

Explicit realization: $\frac{C_{ij}}{\Lambda^2}\phi\partial_\mu\phi'(\bar{\ell}_i\gamma^\mu\ell_j)$



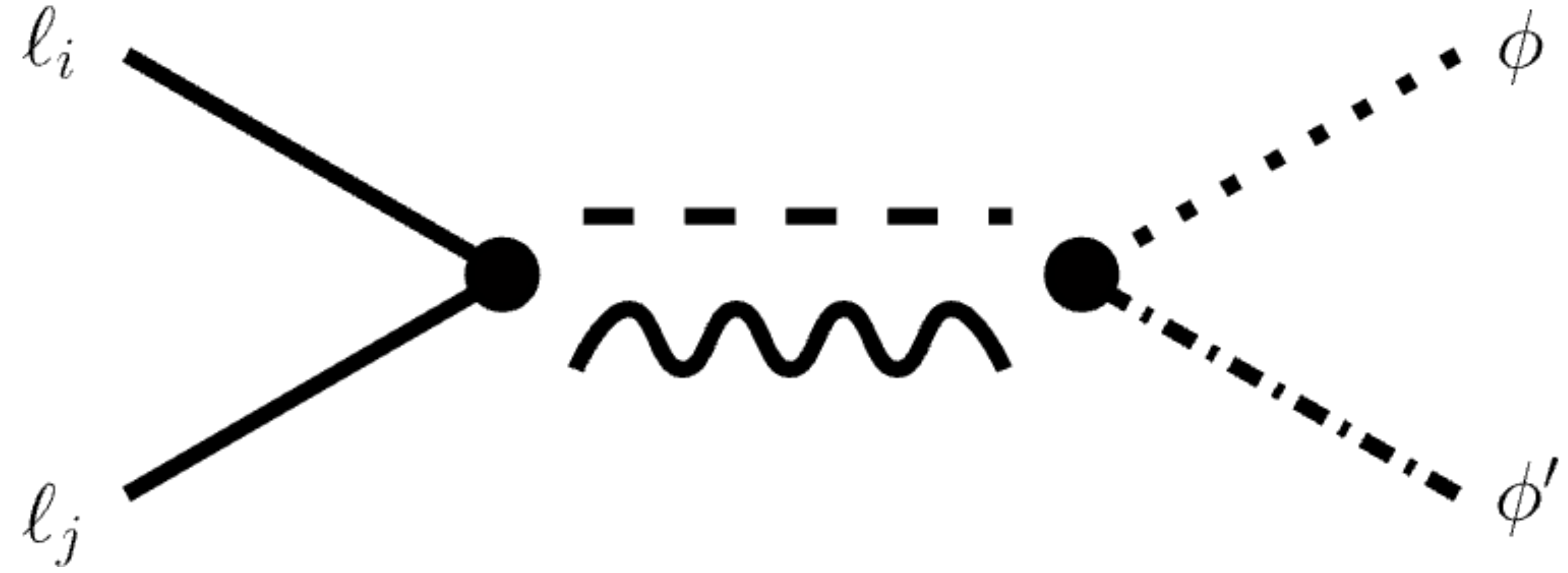
Non-abelian pseudo Nambu-Goldstone boson + gauged $U(1)_D$

CLFV + ULDM

Explicit realization: $\frac{C_{ij}}{\Lambda^2}\phi\partial_\mu\phi'(\bar{\ell}_i\gamma^\mu\ell_j)$

$$SU(3)_R \times SU(3)_L \times U(1)_D \to SU(3)_V \times U(1)_D$$

$$D_\mu \equiv \partial_\mu - igA_\mu[Q, U], \quad U \equiv \exp(i\Pi/f)$$



Experimental sensitivity

One ingredient for all intensity frontier experiments to become dark matter detectors:

Clock!

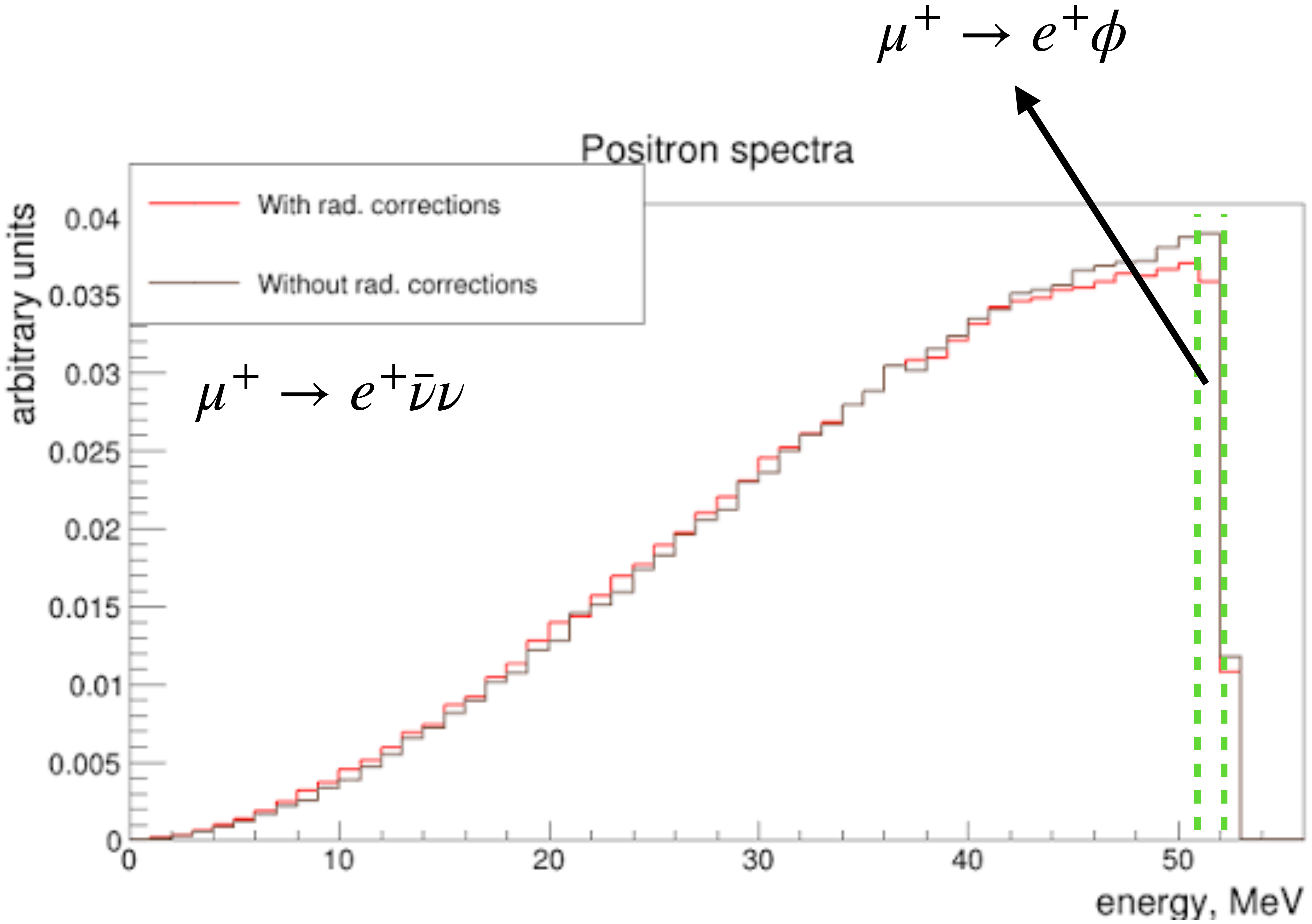
Time-dependent analyses also convert systematics limited searches to statistics limited with the reach in the rate improving by

$$\sigma_{\mathbf{sys}}/\sigma_{\mathbf{stat}} = \alpha\sqrt{N_{\mathbf{bkg}}}.$$

Experimental sensitivity (μ)

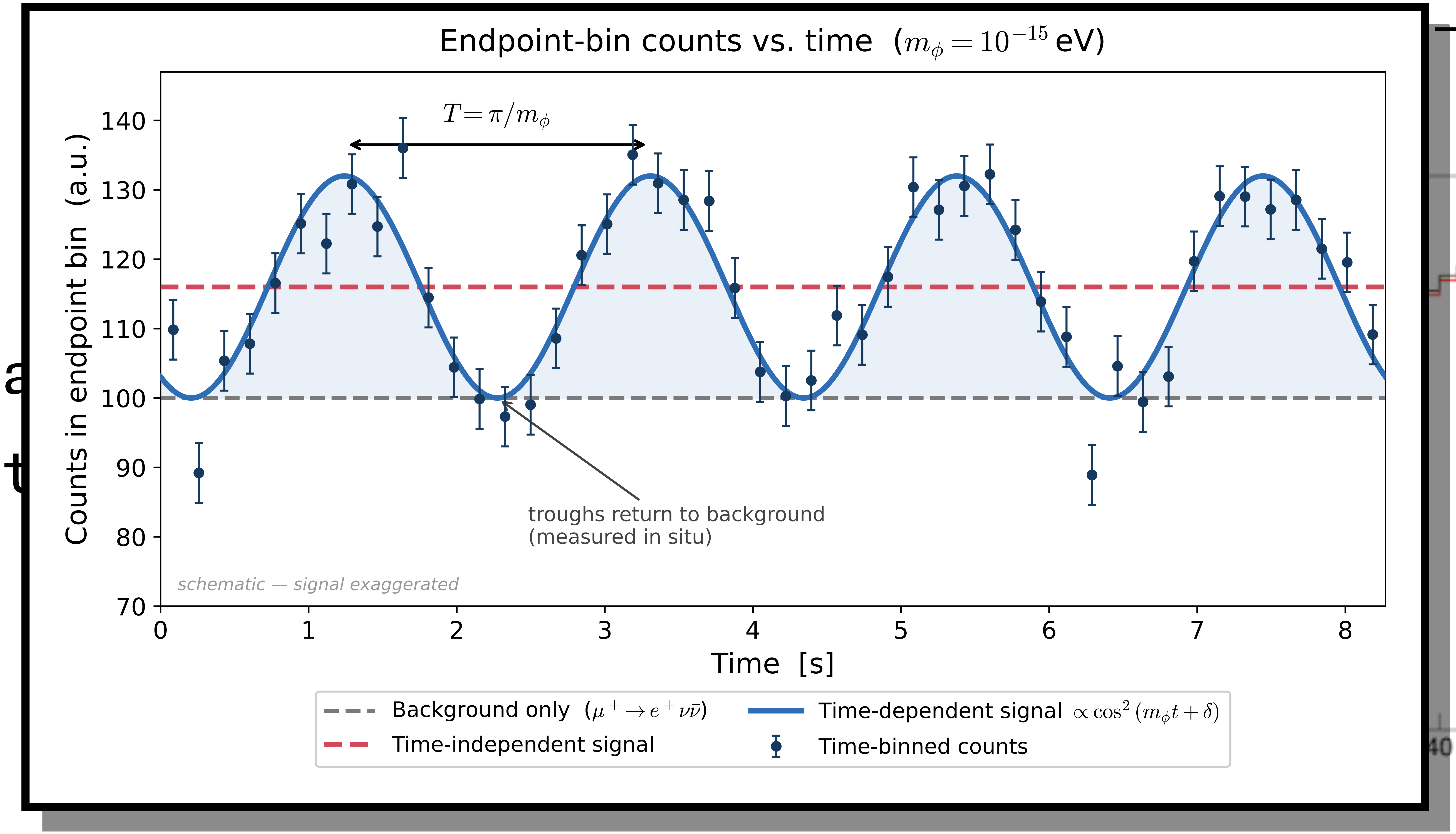
Mu3e:

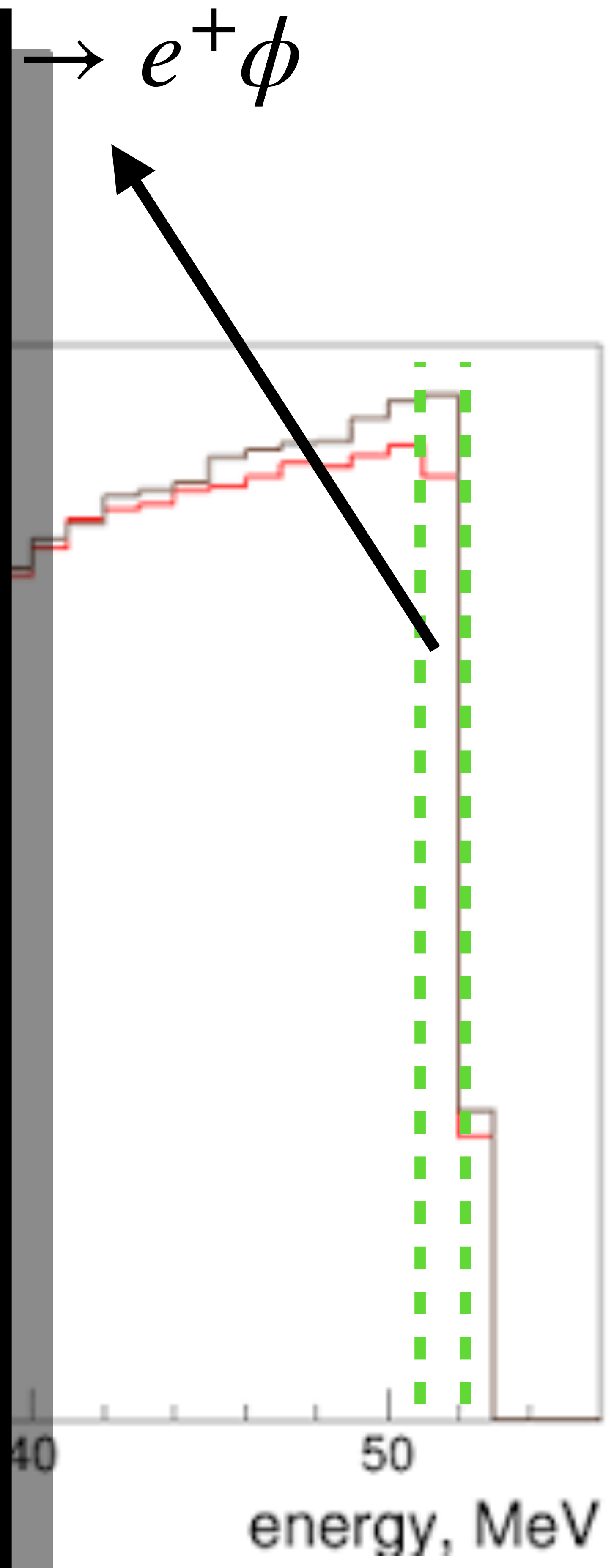
- 300 day run time
- 10^{15} total μ decays
- 10^{13} in the last bin



Experimental sensitivity (μ)

Mu3e:





- 300 day
- 10^{15} tota
- 10^{13} in t

Experimental sensitivity (μ)

We considered two test-statistics:

1. χ^2

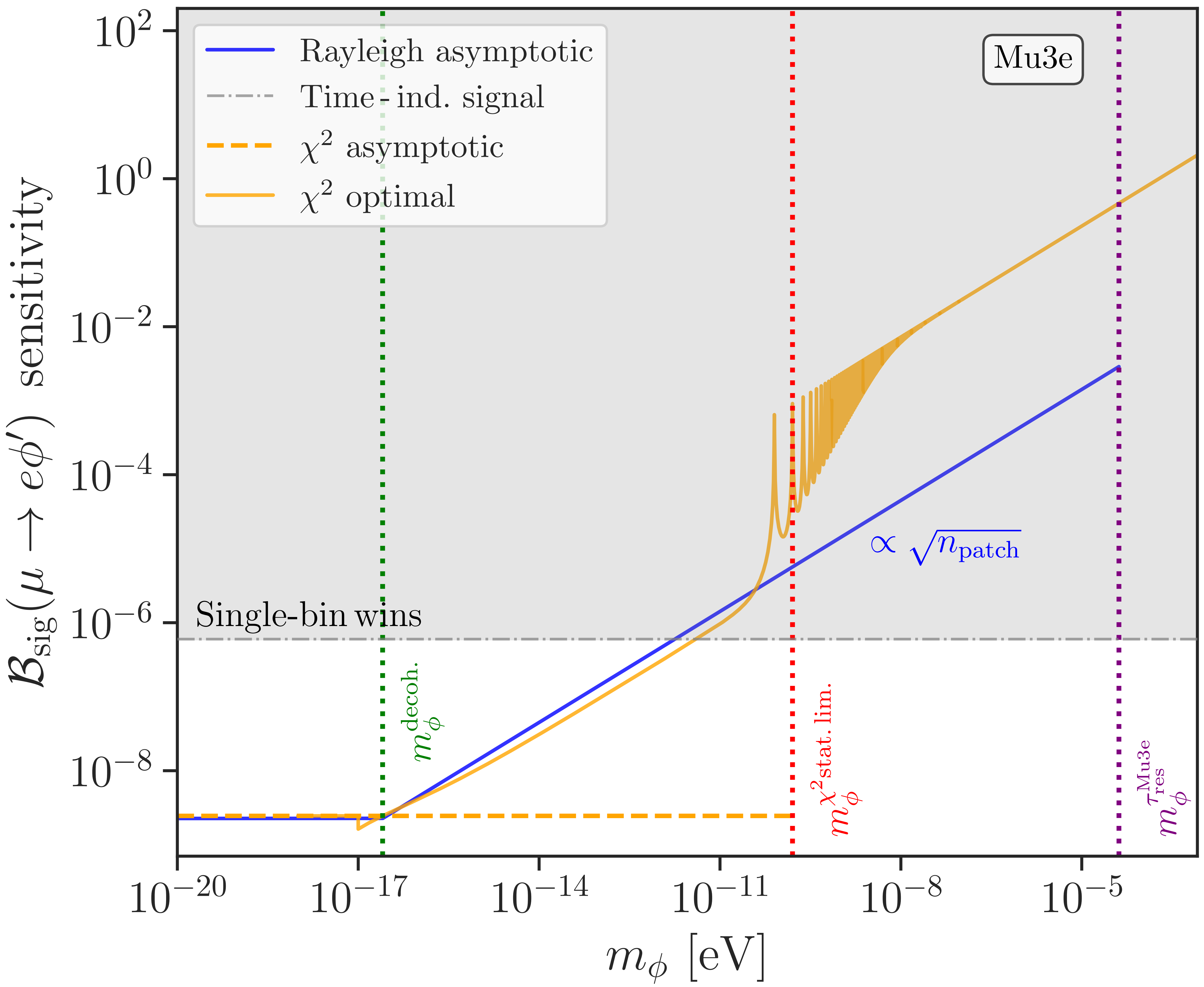
$$\chi^2 = \sum_{k,p=1}^{n_{\text{bin}}} S_k C_{kp}^{-1} S_p = \frac{1}{N_{\text{bg},1}} \sum_{k=1}^{n_{\text{bin}}} S_k^2 - \frac{\alpha^2}{1 + \alpha^2 n_{\text{bin}} N_{\text{bg},1}} \left(\sum_{k=1}^{n_{\text{bin}}} S_k \right)^2$$

2. Rayleigh power spectrum ***Not limited by bin statistics**

$$z\left(f\right) = \frac{2}{N_e} \left(\left[\sum_{n=1}^{N_e} \cos\left(2\pi f t_n\right) \right]^2 + \left[\sum_{n=1}^{N_e} \sin\left(2\pi f t_n\right) \right]^2 \right)$$

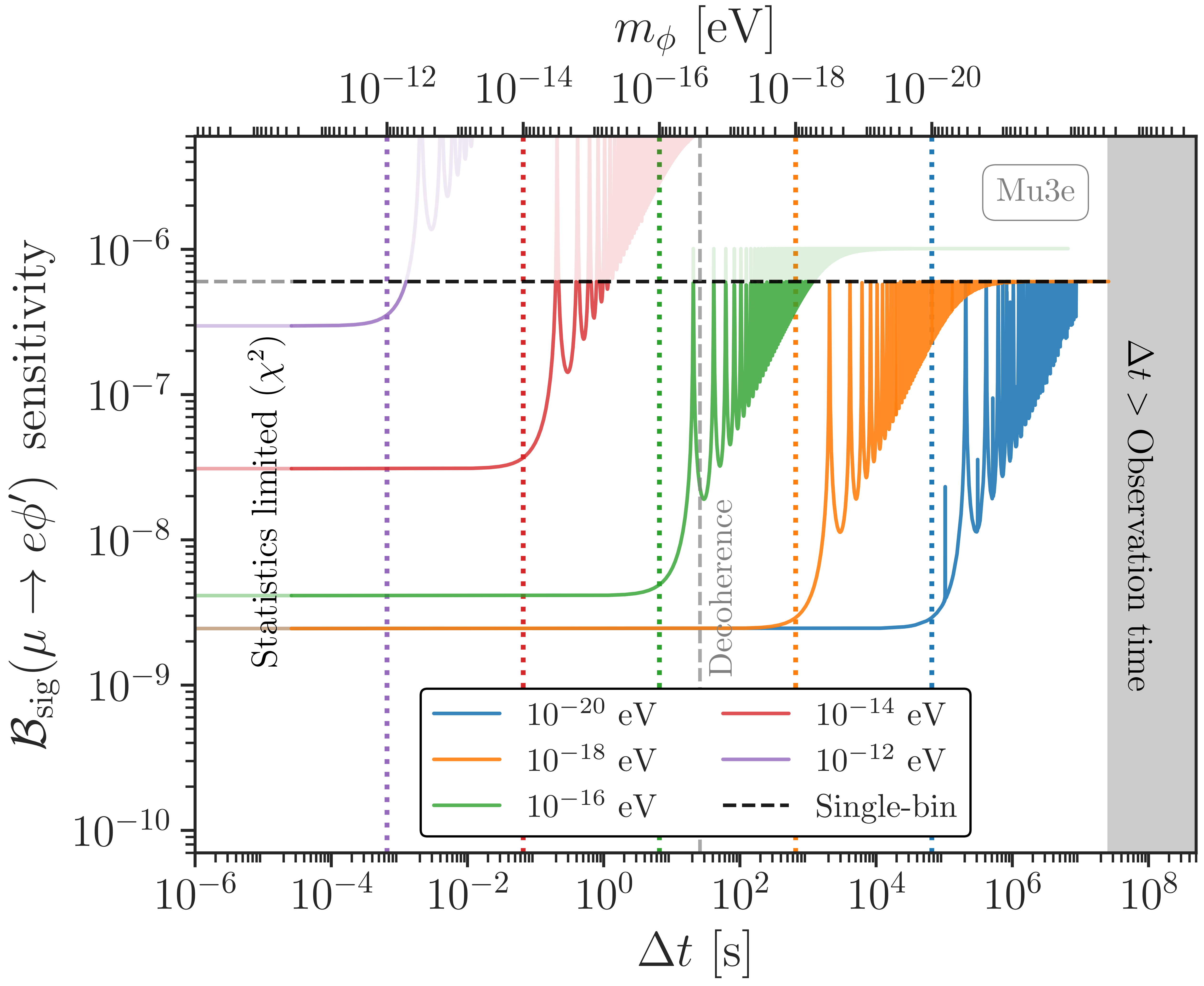
Experimental sensitivity (μ)

Signal sensitivity
vs
m_ϕ



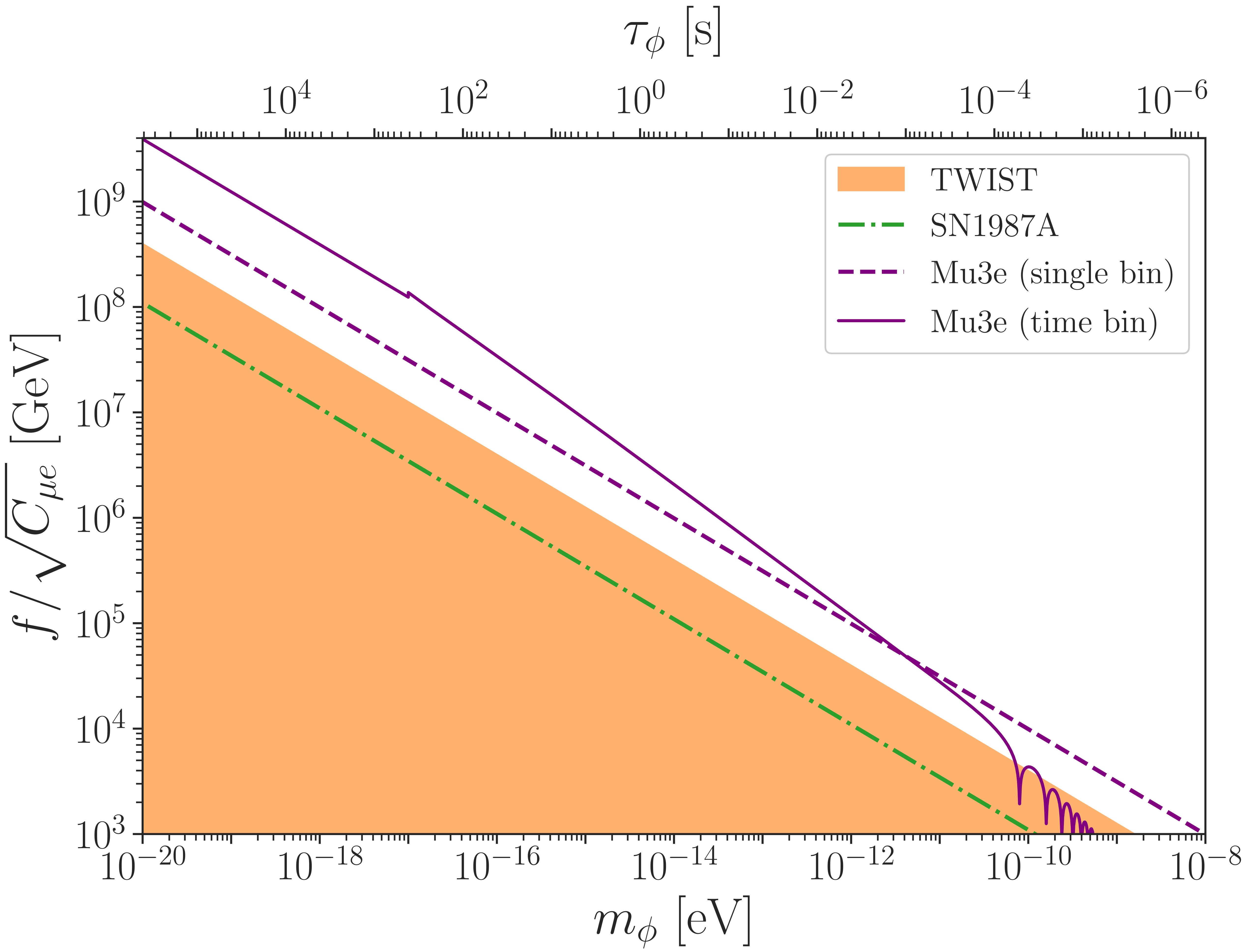
Experimental sensitivity (μ)

Signal sensitivity vs time resolution



Experimental sensitivity (μ)

Reach assuming oscillation is fully resolved

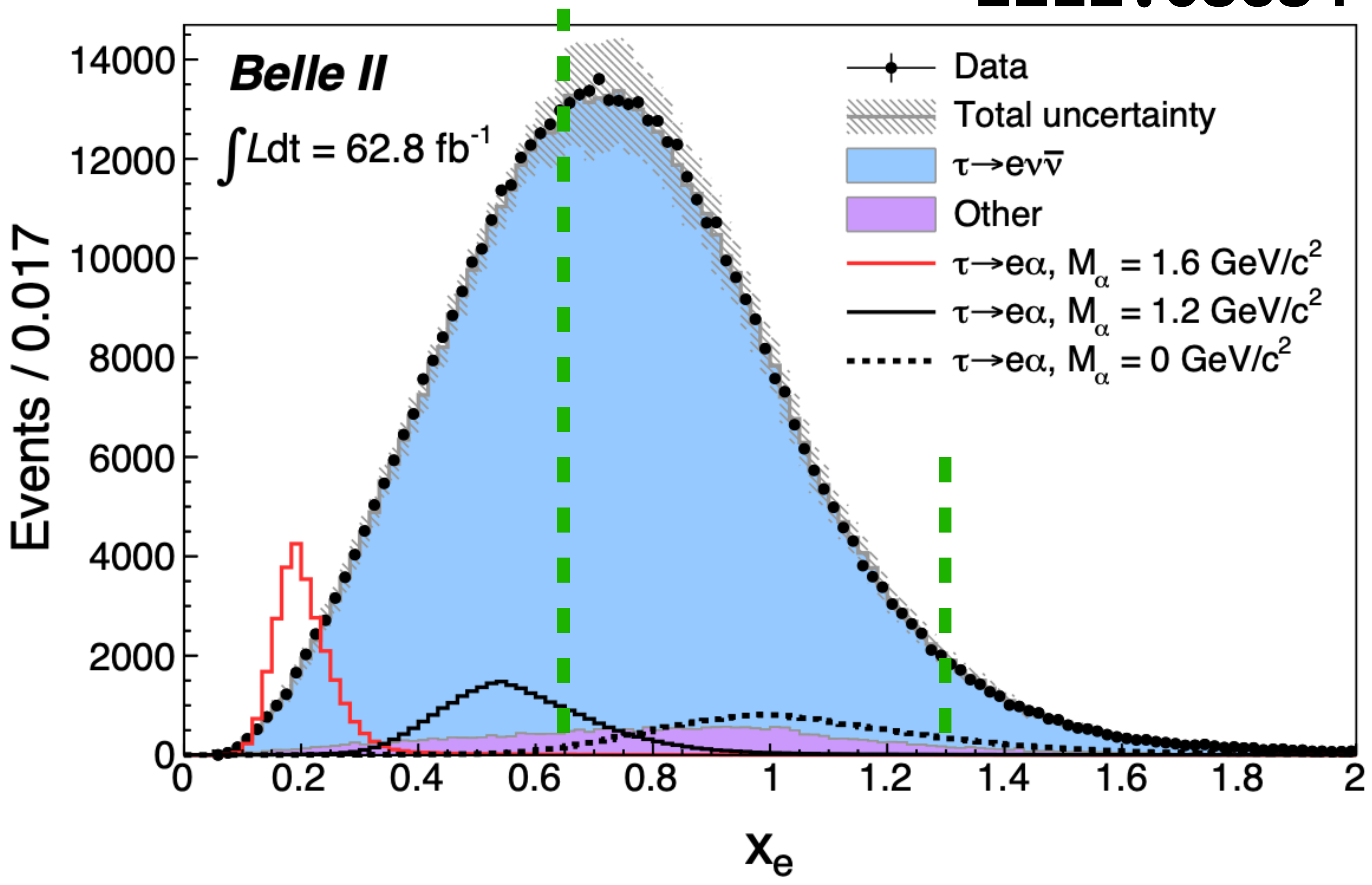


Experimental sensitivity (τ)

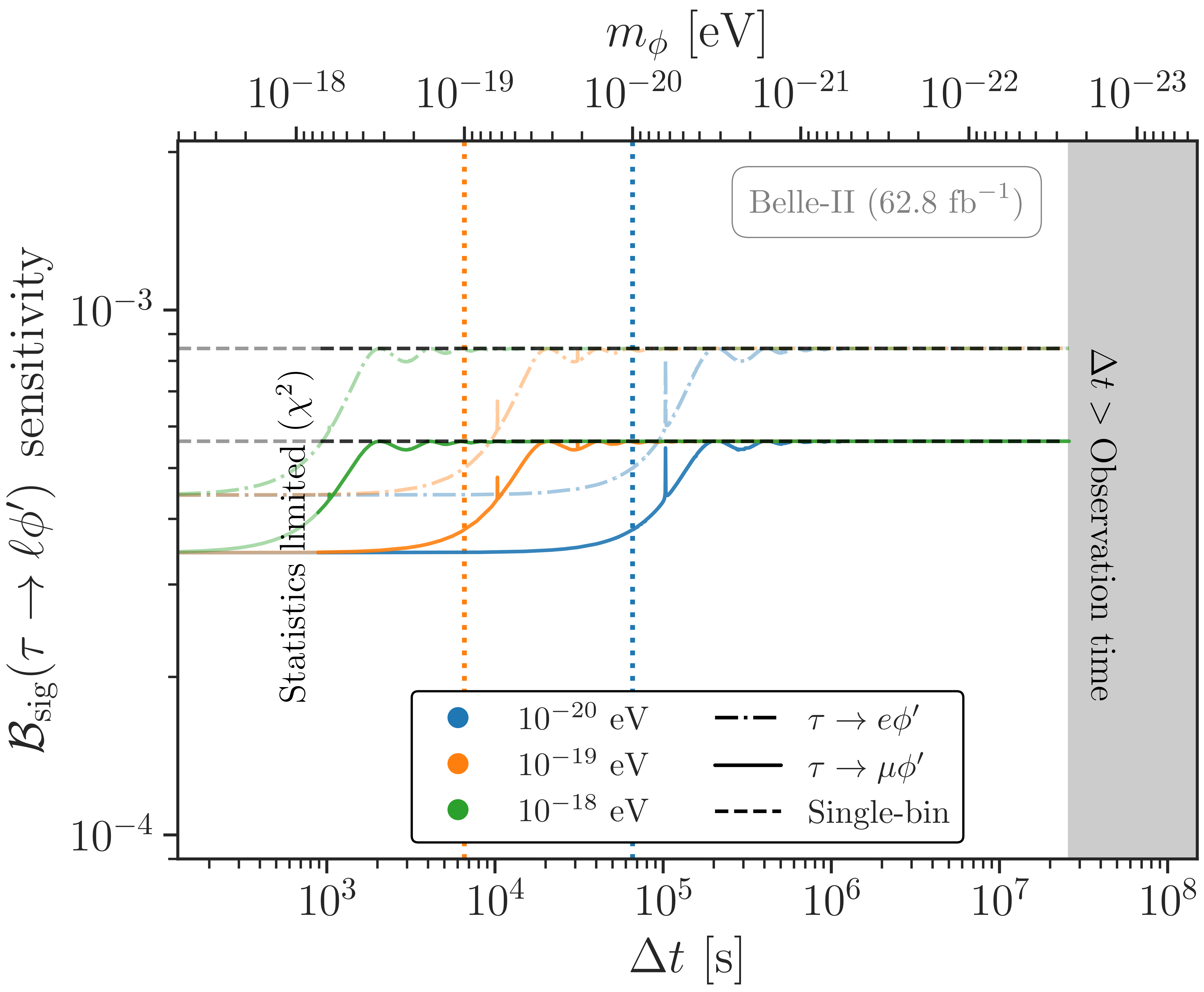
Belle II:

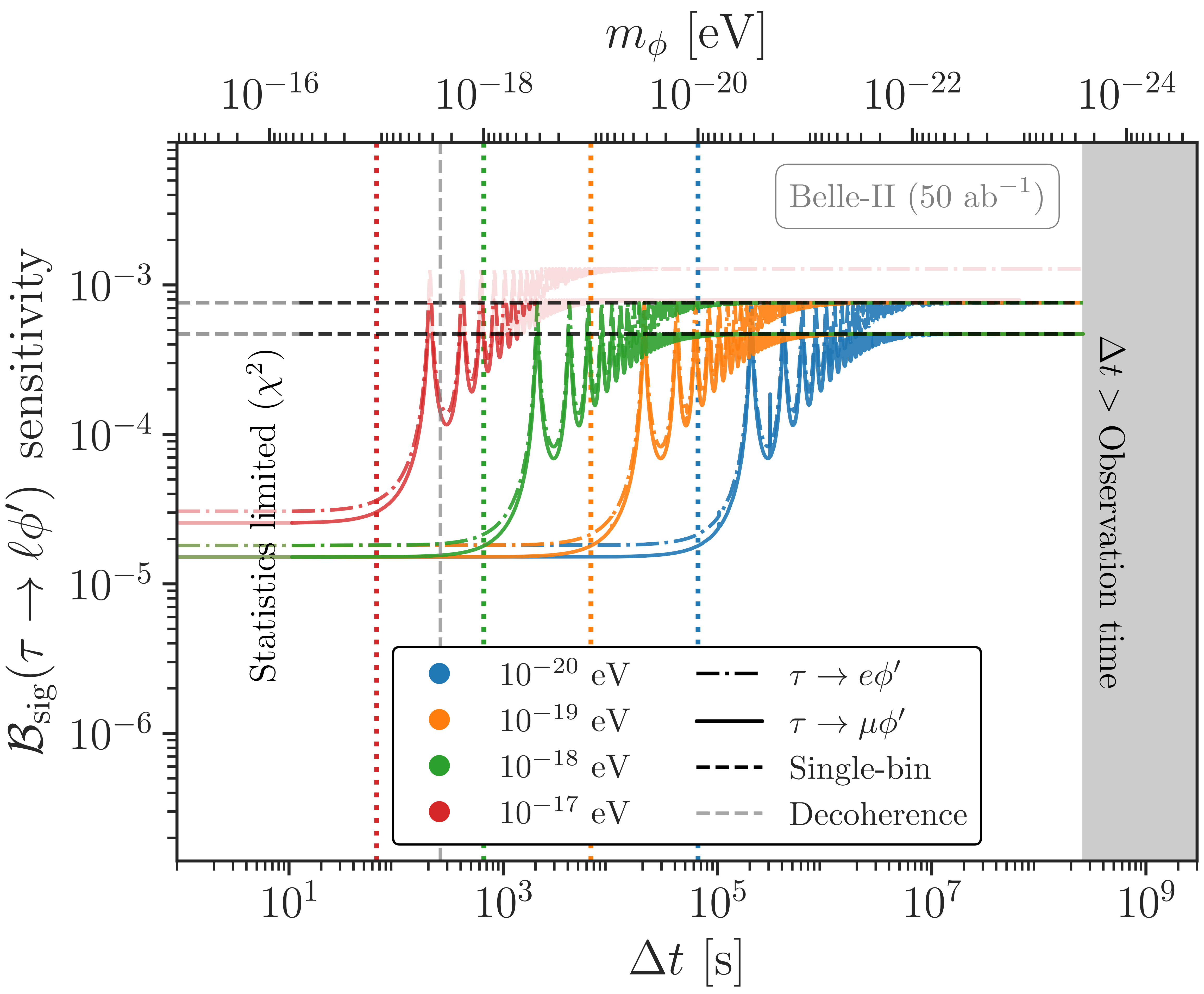
- 300 day run time
- 10^8 total τ pairs
- Analysis required three charged hadrons on tag side, on charged lepton on signal side

2212.03634



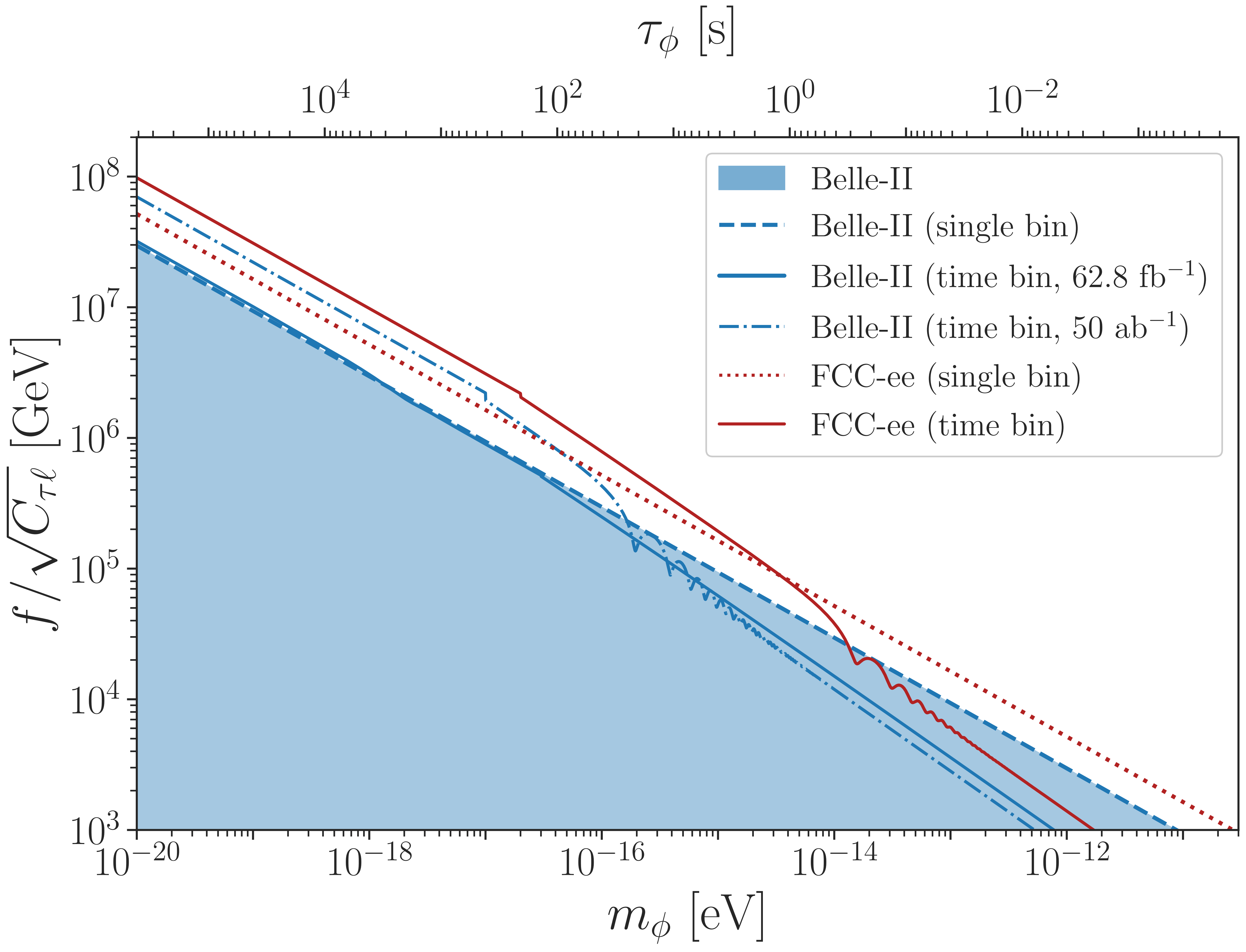
Experimental sensitivity (τ)





Experimental sensitivity (τ)

Reach assuming oscillation is fully resolved



Conclusions

- Detecting a time-dependent CLFV signal is a smoking gun for DM.
- Intensity frontier experiments can become dark matter experiments via precise timing.
- Time-dependent analyses can overcome systematics dominated measurements.

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Thank you :)

Back-ups

Michel spectrum errors at Mu3e

NNLO, NNLL

2211.01040

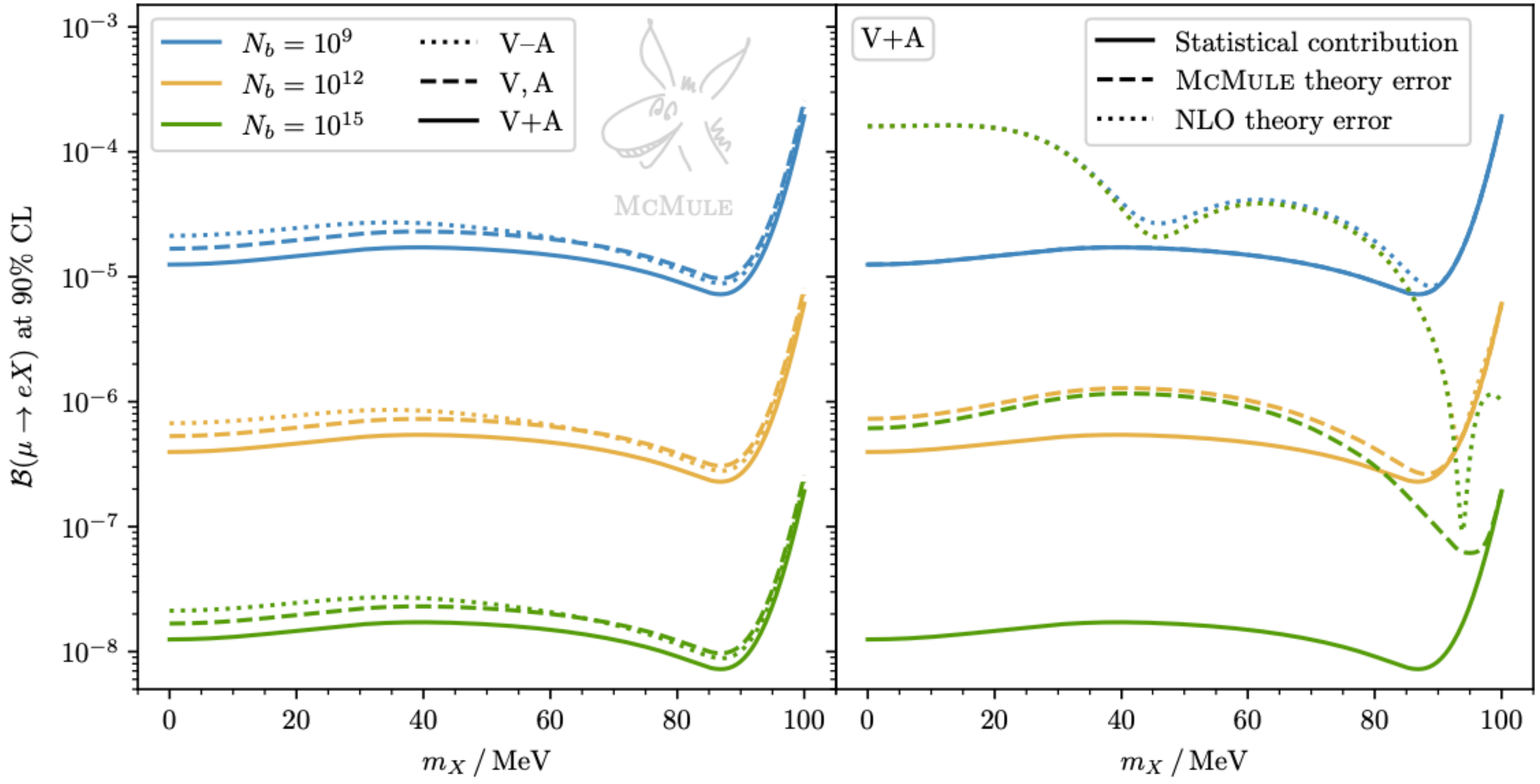

Figure 12: Sensitivity on the branching ratio for $\mu \to eX$ in our Mu3e scenario. The left panel includes the statistical error only, while the right panel shows the effect of taking into account the theory error for a $V+A$ coupling. The combined limit with the best theory error (dashed lines) is compared to the limit from the statistical contribution only (solid lines) and a NLO background prediction (dotted lines). For $N_b = 10^9$ the solid and dashed lines nearly coincide.