# Direct detection of ultralight dark matter with charged-lepton-flavor-violation

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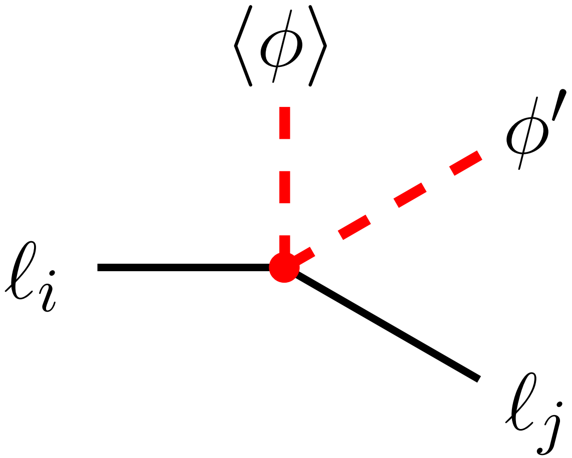
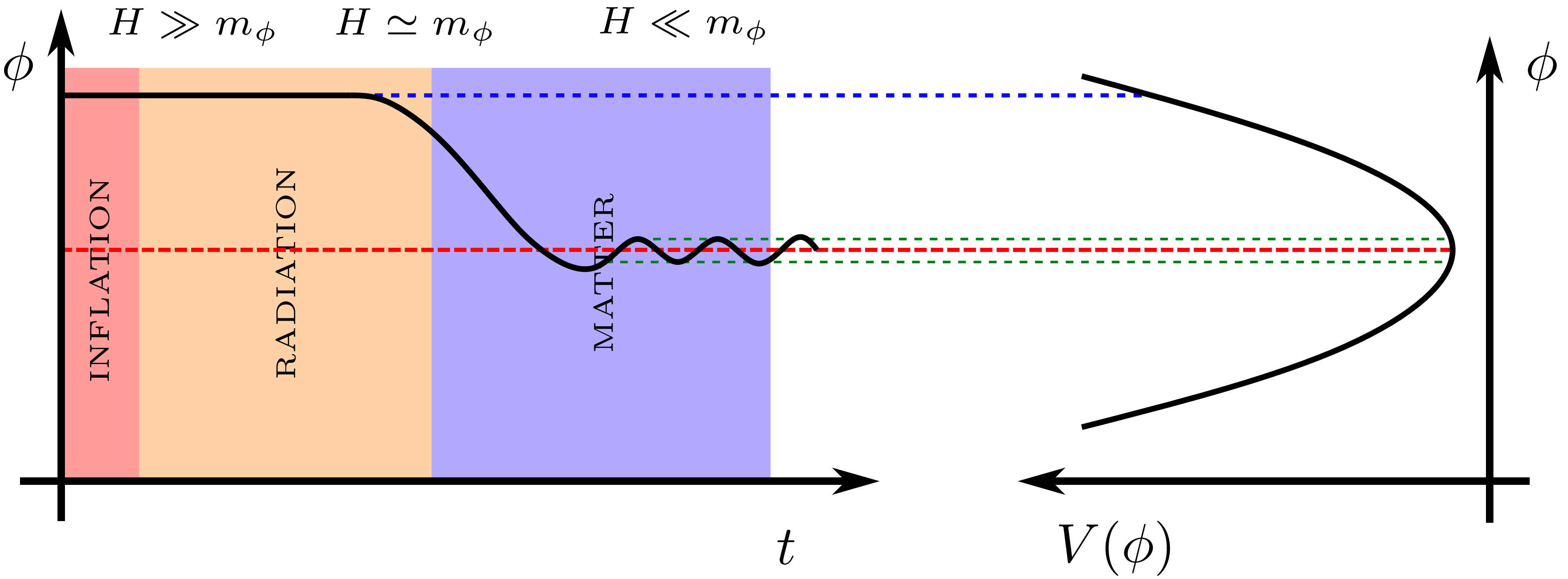



Based on 2503.07722 with Innes Bigaran, Patrick Fox, Yann Gouttenoire, Roni Harnik, Gordan Krnjaic, and Jure Zupan

# Standard lore - ULDM

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



# Standard lore - ULDM

At late times ultralight DM behaves as pressureless nonrelativistic matter. Because the de Broglie volume admits a huge occupation number

$$N \sim n\lambda_{\mathrm{dB}}^3 \sim \frac{\rho_{DM}}{m}\left(\frac{1}{mv}\right)^3$$

Implying ULDM can be described as a classical wave

$$\phi_c(\mathbf{x},t) = \phi_0(\mathbf{x})\cos(m_\phi t + \delta)$$

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \qquad \rho_\phi = 0.4\,\mathrm{GeV/cm^3} \simeq 10^{-42}\mathrm{GeV}^4$$

# Standard lore - ULDM

At late times ultralight DM behaves as pressureless nonrelativistic matter. Because the de Brogile volume admits a huge o

**Each mass has an associated "timescale"**

$$\tau_\phi = \frac{2\pi}{m_\phi} \simeq 4\mathrm{s}\left(\frac{10^{-15}\mathrm{eV}}{m_\phi}\right)$$

Implying ave

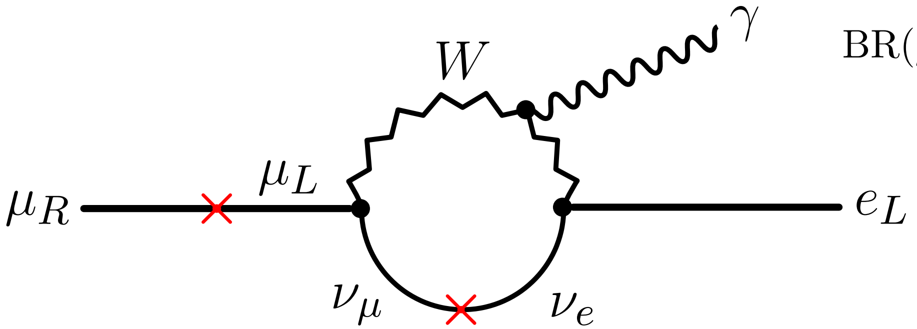
$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \qquad \rho_\phi = 0.4\,\mathrm{GeV/cm}^3 \simeq 10^{-42}\mathrm{GeV}^4$$

# Standard lore - CLFV

- The Standard Model (SM) has an accidental global flavor symmetry

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- Because $m_\nu \neq 0$ charged-lepton-flavor violation (CLFV) can occur at one-loop




$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{3\alpha}{32\pi M_W^4} |U_{\mu 3} U_{e3}^* \Delta m_{31}^2 + U_{\mu 2} U_{e2}^* \Delta m_{21}^2|^2 \simeq 10^{-54}$$

$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi} \left( \log \frac{m_\mu^2}{m_e^2} - 3 \right) \times \mathrm{BR}(\mu \to e\gamma)$$

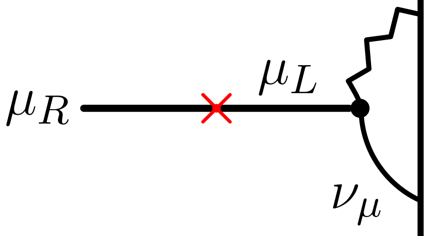
$$\mathrm{CR}(\mu \mathrm{N} \to e\mathrm{N}) \simeq \alpha \times \mathrm{BR}(\mu \to e\gamma)$$

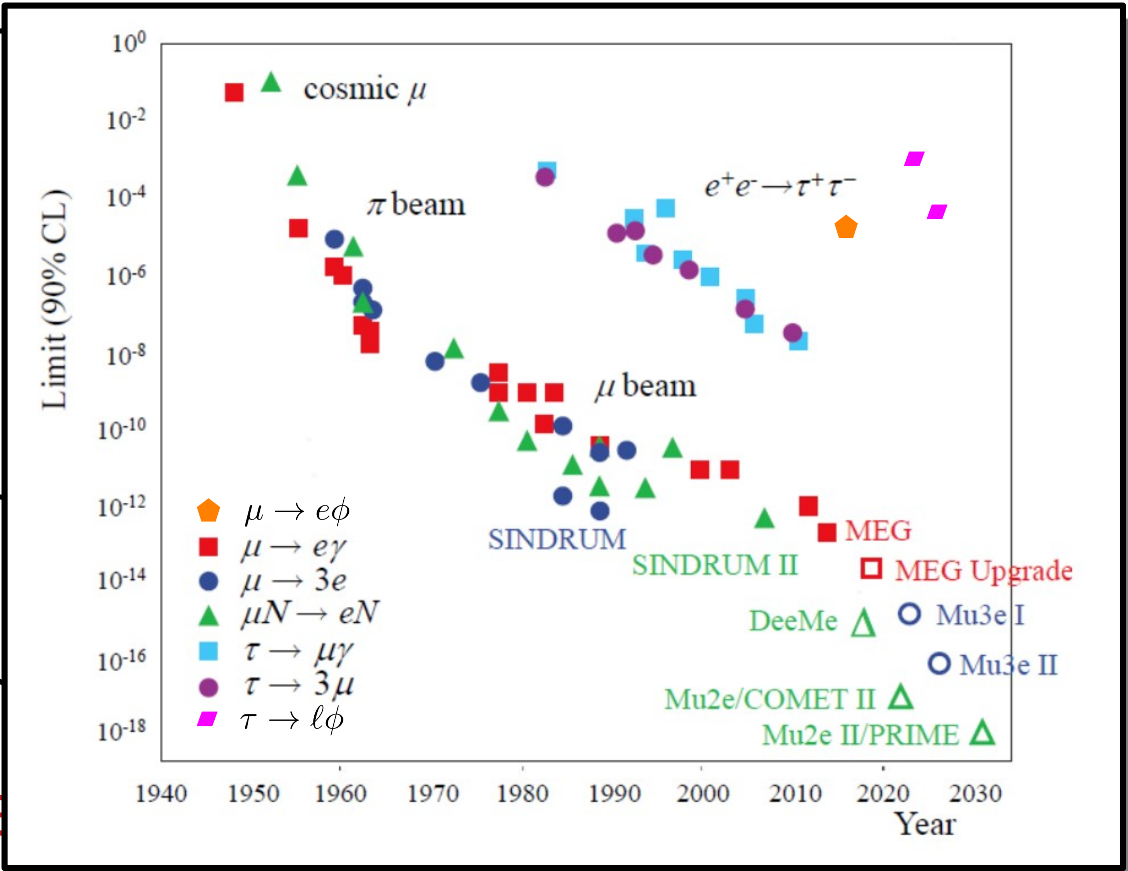
Bottom line: Observing CLFV = new physics

# Standard lore - CLFV

- The Standar … symmetry

- Because m$_\nu$ … n occur at one-loop




$\ldots U_{\mu 2} U^*_{e2} \Delta m^2_{21}|^2 \simeq 10^{-54}$

$\ldots 3\Big) \times \mathrm{BR}(\mu \to e\gamma)$

$\ldots \mathrm{R}(\mu \to e\gamma)$

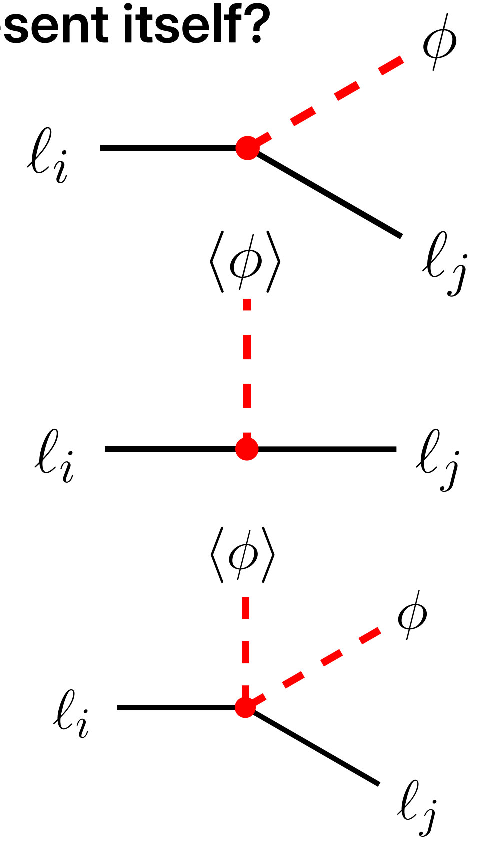
# ULDM + CLFV

Detecting a CLFV signal does not immediately imply DM is the source.

Detecting a *time-dependent* CLFV signal is a smoking gun signal of DM.

# ULDM + CLFV

How and where does time-modulation present itself?




## Two types of time-dependence:

- Manifestation in mass matrix

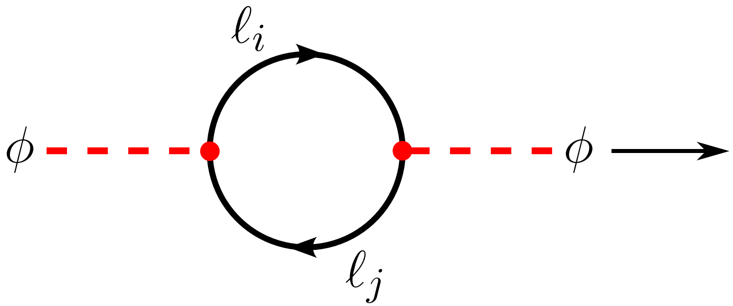
$$m_{ij} = \mathrm{diag}(m_e, m_\mu, m_\tau) + y_{ij}\phi_c$$

- Manifestation in decay/scattering rates
  - Inherently higher dimensional

# Operator palooza

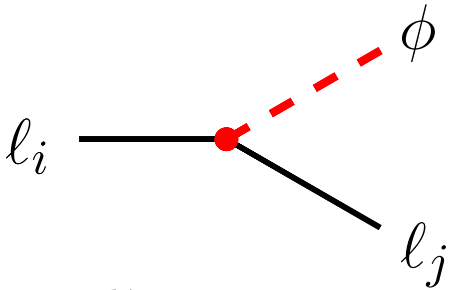
First guess: $\frac{C_{ij}}{\Lambda}\phi H \bar{L}_i \ell_j \rightarrow \lambda_{ij}\phi\bar{\ell}_i\ell_j$

**1. Fine-tuning**

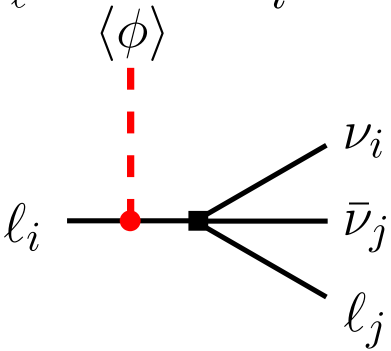



$\delta m_\phi^2 \simeq \frac{\lambda^2}{4\pi^2} m_\ell^2$

**2. No time-modulation**




**3. SM rate-modulation**



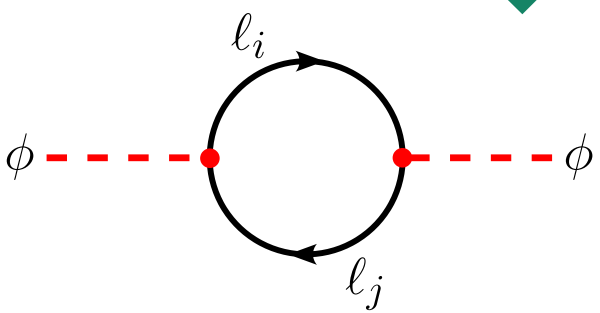

$|y_{\tau\ell}| \lesssim 10^{-7}$

$|y_{\mu e}| \lesssim 10^{-10}$

# Operator palooza

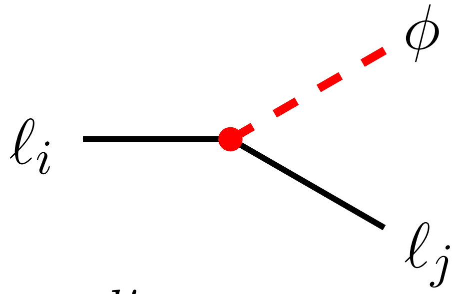
First guess: $$\frac{C_{ij}}{\Lambda}\phi H \bar{L}_i \ell_j \to \lambda_{ij}\phi\bar{\ell}_i\ell_j$$

**1. Fine-tuning** "✓"

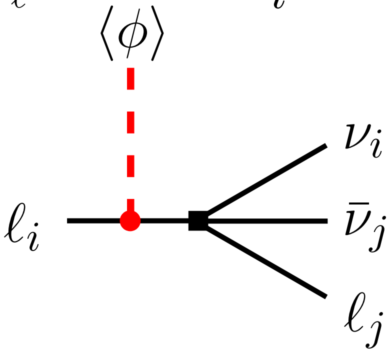



$$\longrightarrow \delta m_\phi^2 \simeq \frac{\lambda^2}{4\pi^2} m_\ell^2$$

**2. No time-modulation** X




**3. SM rate-modulation** X




$$|y_{\tau\ell}| \lesssim 10^{-7}$$

$$|y_{\mu e}| \lesssim 10^{-10}$$

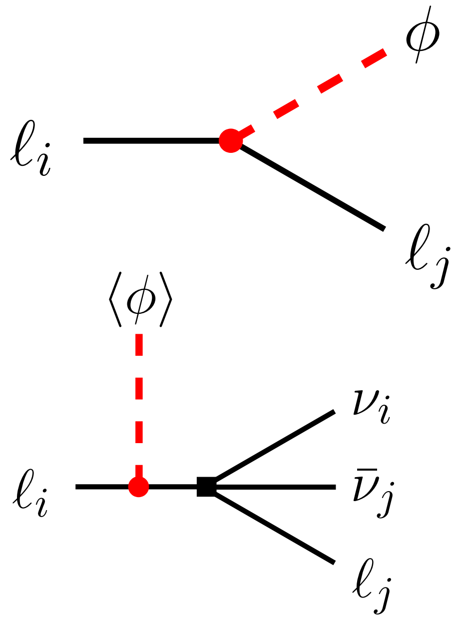
# Operator palooza

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

1. Fine-tuning: "✓"

2. Time-modulation: X

3. SM-modulation: X



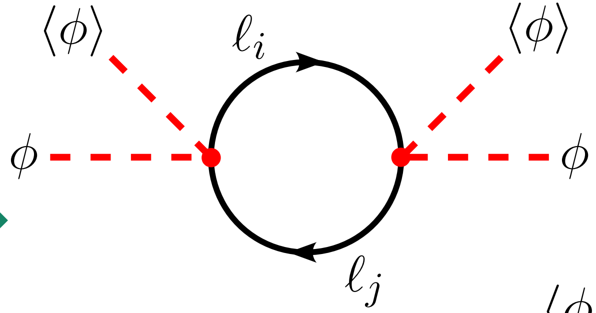
# Operator palooza

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

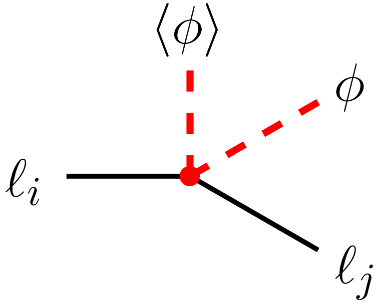
1. Fine-tuning: X

2. Time-modulation: ✓

3. SM-modulation: ✓




$$\longrightarrow \delta m_\phi^2 \simeq \left(\frac{C_{ij}\phi_0}{f}\right)^2 \frac{m_\ell^2}{4\pi^2}$$

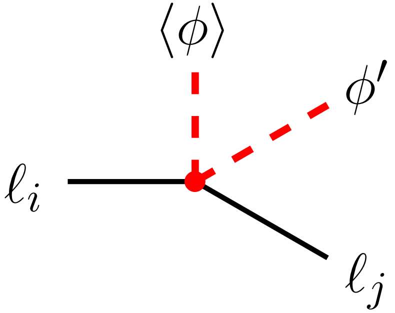


# Operator palooza

Third guess: $\frac{C_{ij}}{f}\phi\phi'(\bar{\ell}_i\ell_j)$ or $\frac{C_{ij}}{f^2}\phi\partial_\mu\phi'(\bar{\ell}_i\gamma^\mu\ell_j)$

1. Fine-tuning: "✓"

2. Time-modulation: ✓



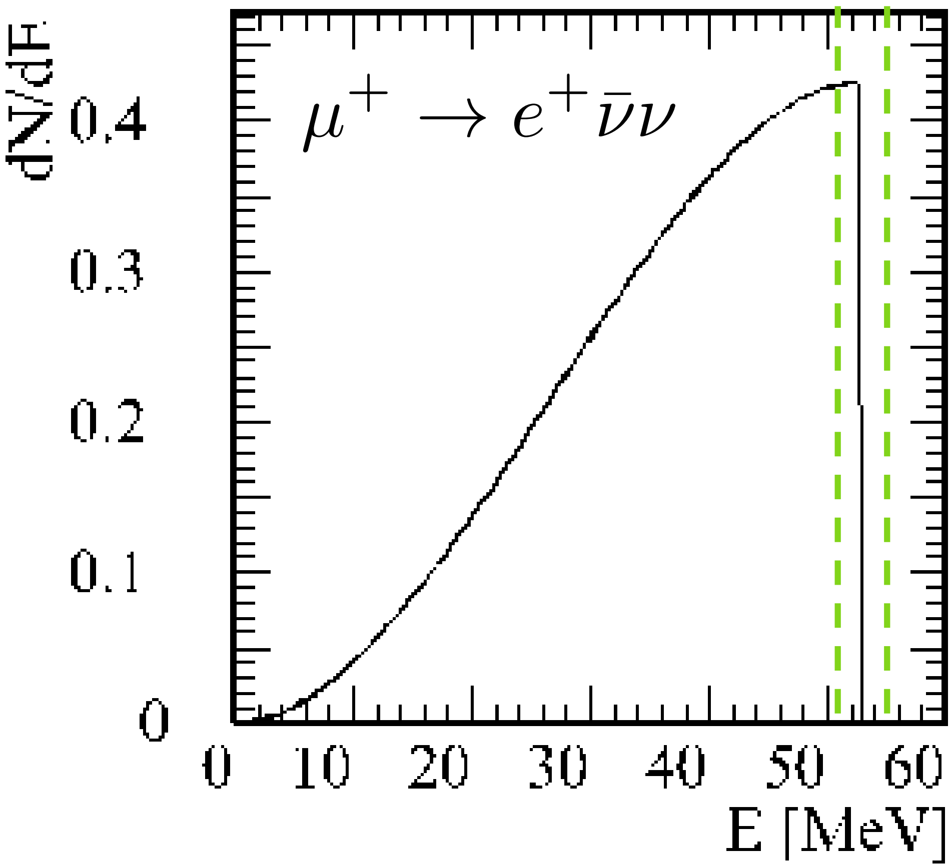

3. SM-modulation: ✓ $\mathcal{B}(\ell_i \to \ell_j\phi) = \frac{C_{ij}^2\phi_0^2}{64\pi f^2}\frac{m_{\ell_i}}{\Gamma_{\ell_i}}\cos^2(m_\phi t + \delta)$

# Sensitivity

Consider, for example, Mu3e.

- Will run for T~300 days
- ~$10^{15}$ muon decays
- ~$10^{13}$ of which will lie in the final kinematic bin
- ~$10^{8}$ muon decays/s

Michel spectrum



# Sensitivity

- Sensitivity can essentially be determined by:

$$m_\phi, \quad T, \quad N_{\rm total}$$

- Statistical uncertainty + systematic uncertainty maximally correlated across all time bins

$$\sigma_{\rm stat} = \sqrt{N_{\rm bg}/n_{\rm bin}} \ , \quad \sigma_{\rm sys} = \alpha N_{\rm bg}/n_{\rm bin}$$

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

# Sensitivity

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

$$S_k = 2\mathcal{B}_{\rm sig} f_{\rm sig} \frac{N_{\rm tot}}{T} \int_{(k-1)\Delta t}^{k\Delta t} dt \cos^2(m_\phi t + \delta)$$

$$= \mathcal{B}_{\rm sig} f_{\rm sig} \frac{N_{\rm tot}}{T} \left[ \Delta t + \frac{\sin(2k m_\phi \Delta t + 2\delta) - \sin(2(k-1) m_\phi \Delta t + 2\delta)}{2 m_\phi} \right]$$

**Three interesting limits:**

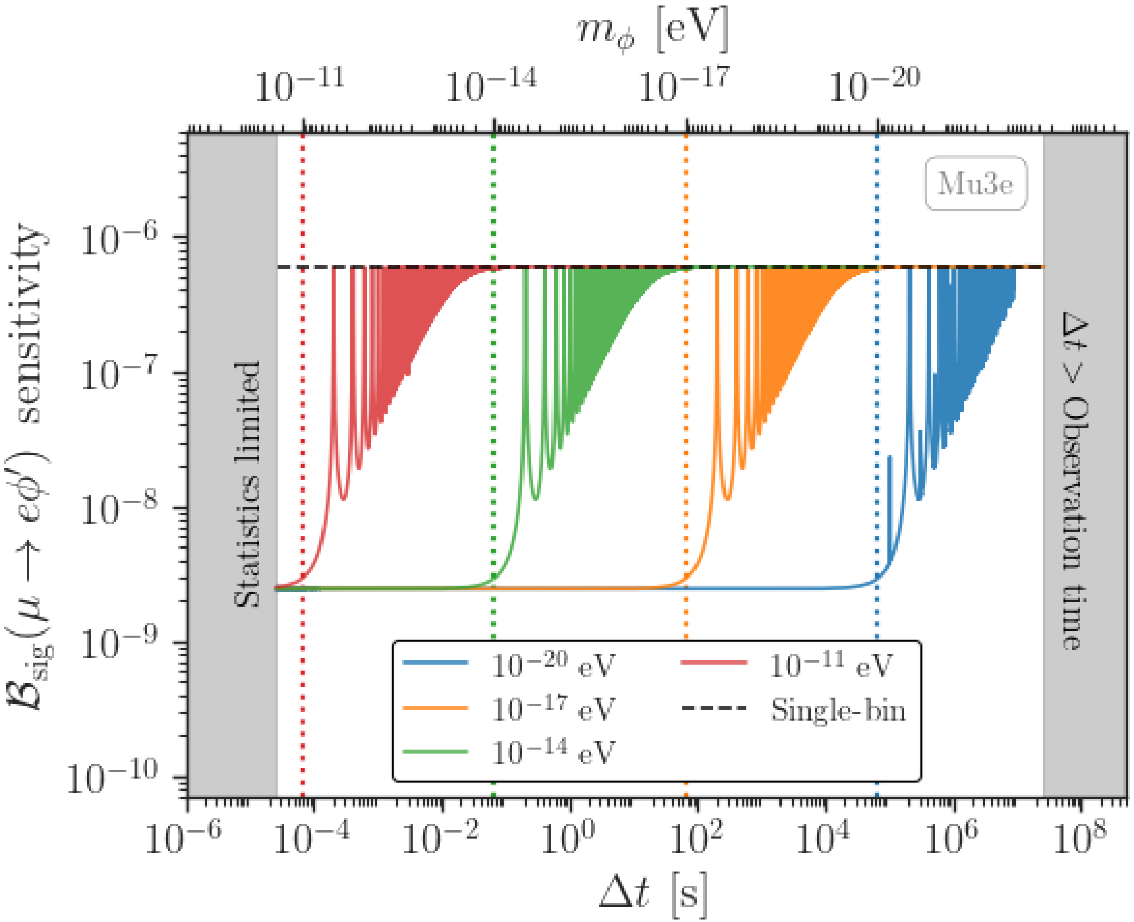
1. **Signal does not oscillate over the duration of the experiment**
2. **Signal oscillates but time bins cannot resolve the oscillations**
3. **Signal oscillates and time bins resolve the oscillations**

**Systematics dominate** (limits 1–2)

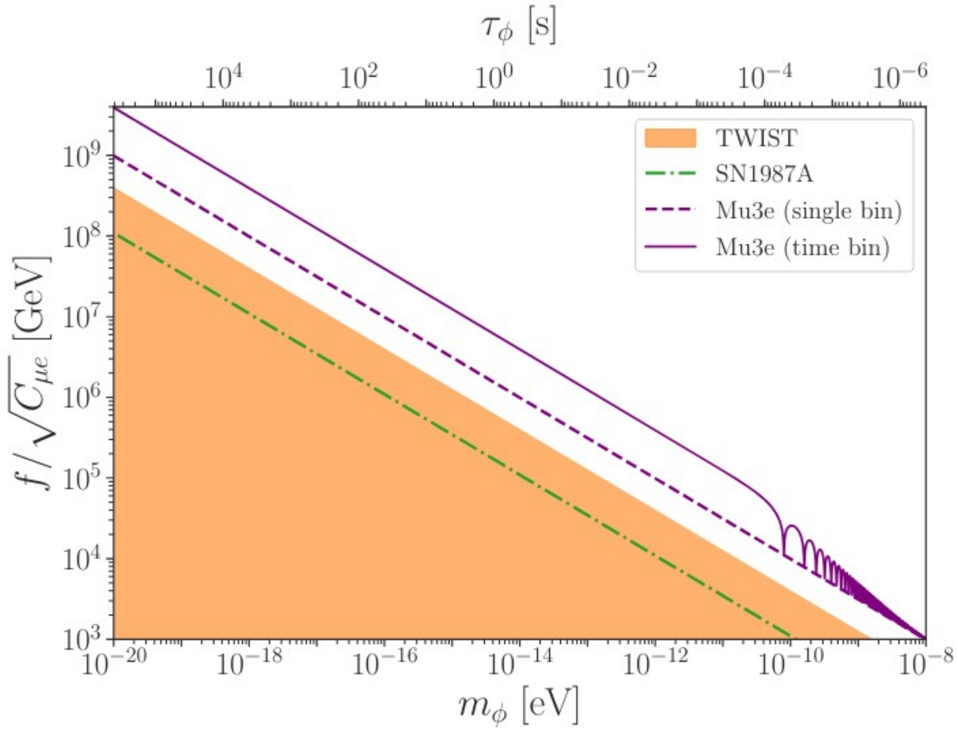
**Statistics dominate** (limit 3)

# Sensitivity

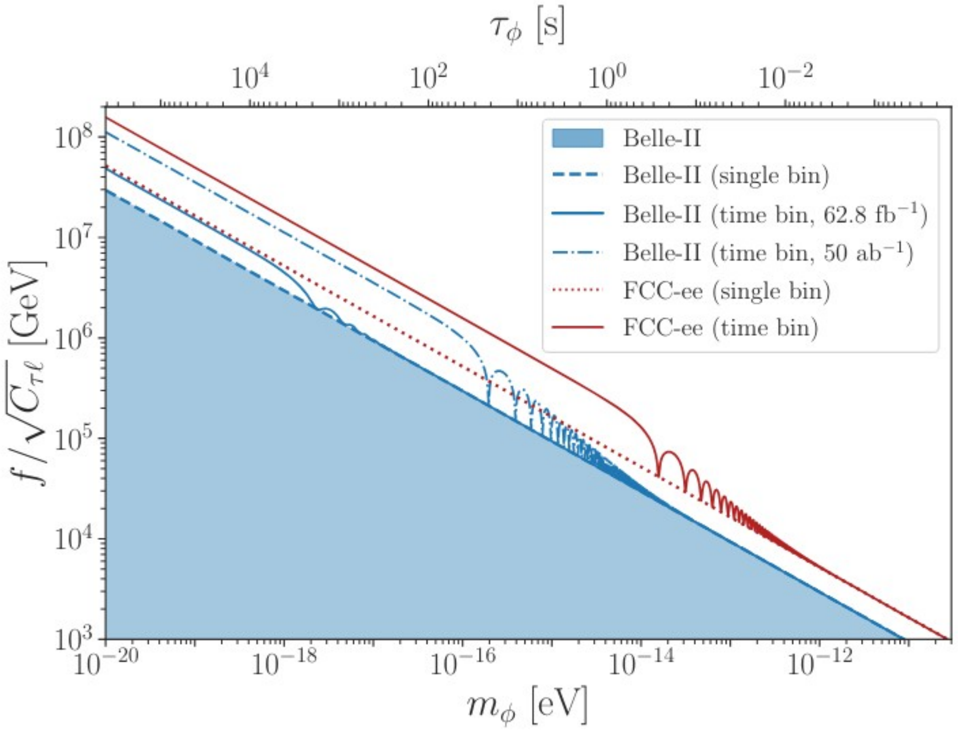
- **Notably, the sensitivity to ULDM mass is limited by statistics, not experimental time resolution**



# Reach



$\tau_\phi$ [s]
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
TWIST
SN1987A
Mu3e (single bin)
Mu3e (time bin)
$f/\sqrt{C_{\mu e}}$ [GeV]
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$10^9$
$10^{-20}$
$10^{-18}$
$10^{-16}$
$10^{-14}$
$10^{-12}$
$10^{-10}$
$10^{-8}$
$m_\phi$ [eV]

$\tau_\phi$ [s]
$10^4$
$10^2$
$10^0$
$10^{-2}$
Belle-II
Belle-II (single bin)
Belle-II (time bin, 62.8 fb$^{-1}$)
Belle-II (time bin, 50 ab$^{-1}$)
FCC-ee (single bin)
FCC-ee (time bin)
$f/\sqrt{C_{\tau\ell}}$ [GeV]
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$10^{-20}$
$10^{-18}$
$10^{-16}$
$10^{-14}$
$10^{-12}$
$m_\phi$ [eV]

# Conclusions

- Detecting a time-dependent CLFV signal is a smoking gun for dark matter. In this way, intensity frontier experiments can function also as dark matter detectors.
- Time-dependent analyses can overcome systematics dominated measurements.

What's next:

- Quark sector
- Natural UV completion?
- Cosmology of UV realizations

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- Time-dependent analyses can overcome systematics dominated measurements.

What’s next:

- Quark sector
- Natural UV completion?
- Cosmology of UV realizations

Thank you :)

# Back-up

# Michel spectrum errors at Mu3e

NNLO, NNLL 2211.01040