

Proposal for Direct Detection of Ultralight Dark Matter via Charged Lepton Flavor Violation

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We propose a dark matter direct-detection strategy using charged particle decays at accelerator-based experiments. If ultralight ($m_\phi \ll \text{eV}$) dark matter has a misalignment abundance, its local field oscillates in time at a frequency set by its mass. If it also couples to flavor-changing neutral currents, rare exotic decays such as $\mu \rightarrow e\phi'$ and $\tau \rightarrow e(\mu)\phi'$ inherit this modulation. Focusing on such charged lepton flavor-violating decays, we show that sufficient event samples can enable detection of ultralight dark matter candidates at Mu3e, Belle-II, and FCC-ee.

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The existence of dark matter (DM) would provide smoking-gun evidence for physics beyond the Standard Model (SM), yet its particle nature remains unknown despite decades of dedicated experiments [1]. While these searches have traditionally focused on DM masses near the weak scale, in recent years, this global effort has broadened to cover a wide range of DM masses. Such strategies incorporate techniques from diverse disciplines, including accelerator [2], condensed matter [3,4], and atomic/molecular/optical physics [5], and their relative advantages depend greatly on the DM mass scale.

Based on the measured dark matter mass density and the Tremaine-Gunn bound [6], any self-consistent theory of “ultralight” DM *must* be both bosonic and wavelike with a present day classical field value [7]

$$\phi_c(t) = \phi_0 \cos(m_\phi t + \delta), \quad (1)$$

where m_ϕ is the DM mass, δ is an arbitrary phase. The amplitude satisfies

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \simeq 2.5 \text{ TeV} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right), \quad (2)$$

where $\rho_\phi = 0.4 \text{ GeV}/\text{cm}^3$ is the local dark matter mass density [8] and ϕ is said to be “misaligned” from its potential minimum [9–11]. This unique [12] description of ultralight DM offers a powerful first-principles starting point for *any* investigation into DM candidate masses in the range $10^{-21} \text{ eV} < m_\phi < 1 \text{ eV}$. Masses below 10^{-21} eV are excluded because the DM de-Broglie wavelength exceeds the scale of dwarf galaxies [13,14].

As the field in Eq. (1) modulates in time with frequency m_ϕ , interactions between ϕ and the SM fields can inherit the characteristic periodicity

$$\tau_\phi = \frac{2\pi}{m_\phi} \simeq 4 \text{ s} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right), \quad (3)$$

which may be appreciable on experimental timescales. While there is a large literature on DM-induced time variation in fundamental constants, particle masses, and nuclear spin-precession, these strategies assume flavor blind interactions between ϕ and SM fields (see Refs. [15–17] for reviews). Ultralight DM has been studied as a catalyst for time variation in the quark and lepton mixing matrices [18–24], in the CP phase of strong interactions [25–27], and of fundamental constants (see, e.g., [28]). However, to date, no study has explored its possible impact on flavor violating processes.

In this Letter, we introduce a novel DM search strategy based on flavor changing neutral current (FCNC)

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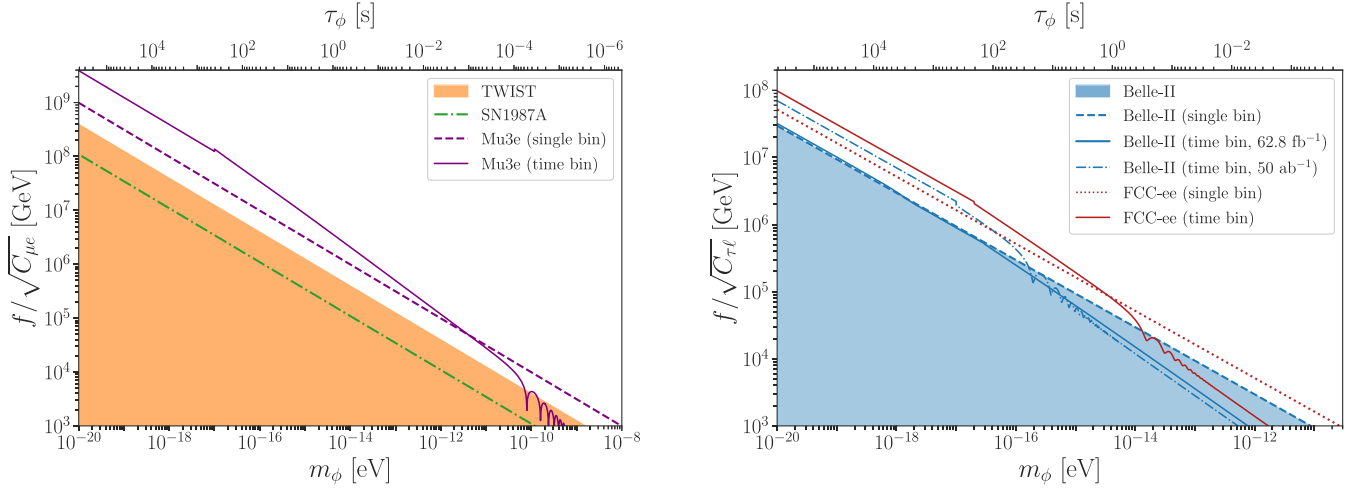


FIG. 1. Present and projected constraints on LFV couplings $f/\sqrt{C_{\mu e}}$ (left) and $f/\sqrt{C_{\tau \ell}}$ (right) for time-binned and single-bin analyses, as a function of the scalar mass, m_ϕ —see Eqs. (6) and (8). Left: Present constraint from TWIST [53,54] is shaded in yellow. The projected single-bin (dashed line) and time-binned (solid line) analysis reach from Mu3e [32,33] is shown in purple. The astrophysical bound on $f/\sqrt{C_{\mu e}}$ from SN1987A [38,55] is shown here as a dot-dashed green line—see main text for details. Right: The constraints on $f/\sqrt{C_{\tau \ell}}$ from present and projected Belle-II analyses [30] are shown here in blue: current 62.8 fb⁻¹ time-integrated constraint is shaded, single-bin constraint is a dashed line and projected time-binned constraint is a solid line; the 50 ab⁻¹ projected time-binned constraint is a dot-dashed line. The projected constraints from FCC-ee Tera-Z run [35] are shown in red: dotted line for single-bin analysis, and red solid line for time-binned analysis. The constraints on $C_{\tau \mu}$ and on $C_{\tau e}$ (denoted collectively here as $C_{\tau \ell}$) almost completely overlap on this logarithmic scale.

transitions induced by the presence of a misaligned field. We focus on charged lepton flavor violating (CLFV) decays, and find that certain classes of dark-visible interactions can viably induce timemodulation at levels that can be probed at existing and future experiments.

As numerical examples, we show projections for a possible reanalysis of existing Belle-II data [29,30], as well as the estimates for future Mu3e [31–33] and FCC-ee [34–36] sensitivities—these results are presented in Fig. 1. Similar analyses could be performed at other current and future CLFV experiments, including MEG-II [37–39], Mu2e [40–44], COMET [43,45,46], BES-III [47,48], Super Tau Charm Factory [49–51], and CEPC [52].

Time-dependent CLFV interactions—Arguably the simplest interactions of ϕ to the SM fermions arises from the dimension-5 Higgs interaction $\phi H \bar{L}_i \ell_j$. Once the Higgs acquires its vacuum expectation value this operator becomes $y_{ij} \phi \bar{\ell}_i \ell_j$ and leads to decays of the charged lepton to dark matter. However, this interaction does *not* lead to observable time-dependent CLFV transitions, due to several challenges that we outline below. (1) Time-independent limits: the off-diagonal interactions in the dimension-5 operators $\phi H \bar{L}_i \ell_j$ predict flavor changing processes, including the decays: $\tau \rightarrow \mu \phi$, $\tau \rightarrow e \phi$, and $\mu \rightarrow e \phi$, where the final state ϕ is invisible to experiments. For such linear ϕ couplings the decay rates are *independent* of the ϕ_c background at leading order and, therefore, do not inherit time modulation. Furthermore, conventional time-averaged searches for $\ell_i \rightarrow \ell_j +$ invisible decays yield stringent limits on the couplings [30,38,53,56]

$$|y_{\tau e}|, |y_{\tau \mu}| \lesssim 2 \times 10^{-7}, \quad |y_{\mu e}| \lesssim 10^{-10}, \quad (4)$$

which severely limit any CLFV time-dependent effects that could arise at higher orders, via additional y_{ij} insertions. (2) Mass-shift effects: in the case of the Higgs operator, $\phi H \bar{L}_i \ell_j$, setting ϕ to its background value ϕ_c yields corrections to the lepton mass matrix,

$$m_{ij}(t) = \text{diag}(m_e, m_\mu, m_\tau) + y_{ij} \phi_c(t), \quad (5)$$

where the additional mass terms induce time dependence in SM decays. For example, the branching ratio $\mathcal{B}(\mu \rightarrow e \nu \bar{\nu})$ acquires time modulation with an amplitude $\propto \mathcal{O}(y_{\mu\mu}, y_{\mu e}^2)$, due to the modified muon mass. Furthermore, these terms can also induce time-dependent exotic FCNC decays, such as $\mu \rightarrow e \gamma$ or $\tau \rightarrow e \gamma$. However, the branching fractions for these processes are suppressed by both y_{ij}^2 and by ϕ_c . [57] Thus, after taking into account the constraints from Eq. (4), all time-varying CLFV signals are unobservably small. Similarly, a dimension-5 axion portal operator of the form $\partial_\mu \phi \bar{\ell}_i \gamma^\mu \gamma_5 \ell_j$ leads to time-independent dark matter decays of charged leptons.

For the charged lepton decays to be time dependent the operator must involve two insertions of dark sector fields, with at least one of these insertions being the ultralight dark matter. If both of the insertions are the dark matter, operators of the form $\phi^2 \bar{\ell}_i \ell_j$ then the decays can become time dependent as the decay amplitude is proportional to ϕ_c . However, this raises the problem that loop corrections

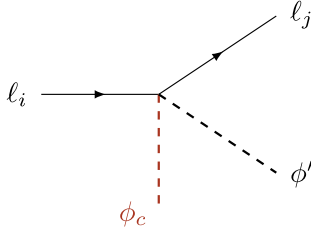


FIG. 2. Model contribution to $\ell_i \rightarrow \ell_j \phi'$, where the interaction with the background classical field (ϕ_c) is denoted in red.

to m_ϕ depend explicitly on the local DM density, ϕ_c , leading to *position dependent* fine-tuning. This problem does not exist if there are two separate fields only one of which has a classical field value.

As a concrete example we will consider interactions of the form

$$\mathcal{L}_{\text{int}} \supset \frac{i\phi(\partial_\mu \phi')}{2f^2} \bar{\ell}_i \gamma^\mu (C_{ij}^V + C_{ij}^A \gamma_5) \ell_j + \text{H.c.}, \quad (6)$$

where ϕ is DM and ϕ' is another ultralight dark sector field, $C_{ij}^{V,A}$ are Hermitian matrices in flavor space and the i, j indices run over all charged fermion species, and f is the effective energy scale associated with the generation of this operator. In Supplemental Material we show that the interaction in Eq. (6) can be the leading DM-SM interaction if ϕ and ϕ' are pseudo-Nambu-Goldstone bosons of a spontaneously broken non-Abelian global symmetry, and how f relates to the physics that generates this operator. In Supplemental Material [58] we also give further examples of such quadratic interactions with the dark sector.

Since the interaction in Eq. (6) contains two light field insertions, expanding ϕ around its background value, ϕ_c , results in time-dependent FCNC decays at leading order. To make this time modulation manifest, we integrate by parts and replace the ϕ field with ϕ_c to obtain

$$\mathcal{L}_{\text{int}} \supset \frac{\phi_c}{2f^2} \bar{\ell}_i \left[C_{ij}^V (m_{\ell_i} - m_{\ell_j}) + C_{ij}^A (m_{\ell_i} + m_{\ell_j}) \gamma_5 \right] \ell_j, \quad (7)$$

where m_{ℓ_i} is the mass of ℓ_i . The branching fraction for $\ell_i \rightarrow \ell_j \phi'$ decays is now explicitly calculated from the diagram in Fig. 2 and is time dependent,

$$\mathcal{B}(\ell_i \rightarrow \ell_j \phi') = \frac{C_{ij}^2 \phi_0^2 m_{\ell_i}^3}{64\pi f^4 \Gamma_{\ell_i}} \cos^2(m_\phi t + \delta), \quad (8)$$

where $C_{ij}^2 \equiv |C_{ij}^V|^2 + |C_{ij}^A|^2$, Γ_{ℓ_i} is the total width of lepton ℓ_i , ϕ_0 is the field amplitude from Eq. (2), and we have approximated all final state particles as massless except for the appearance of m_ϕ in the cosine. Note that, as part of the dark sector, ϕ' will be invisible on accelerator length scales.

Observing periodic signals—New physics transitions $\ell_i \rightarrow \ell_j \phi'$ have an irreducible SM background from the tree-level W -boson mediated decays, $\ell_i \rightarrow \ell_j \nu_i \bar{\nu}_j$. Because of three-body kinematics, this background mimics the signal $\ell_i \rightarrow \ell_j \phi'$ only when the invariant mass of the two neutrinos is close to zero, within experimental resolution (the ϕ' mass is assumed to be far below the invisible mass resolution in these experiments). Time-dependent signals offer a valuable handle to distinguish signal from background, particularly because the background events do not exhibit periodic modulation. Observing a time modulation in $\ell_i \rightarrow \ell_j \phi'$ decays would constitute compelling evidence for DM or another misaligned field with nontrivial cosmological abundance. [92]. There is a non-time-dependent decay of $\ell_i \rightarrow \ell_j \phi \phi'$ which is hard to separate from background since the energy of the final state lepton closely mimics the SM decay.

There are many possible analysis techniques to determine the statistical sensitivity to the sinusoidal signals in Eq. (8) in the presence of substantial SM backgrounds. We follow a simplified approach, using the binned χ^2 when possible and the unbinned Rayleigh periodogram elsewhere [93]. Furthermore, we assume continuous data collection over total observation time T . For the χ^2 analysis, the data are divided into $n_{\text{bin}} = T/\Delta t$ equal-sized bins, each of duration Δt , which are longer than or equal to the experimental resolution. Using Eq. (8), the predicted event rate is

$$\dot{N}_{\text{pred}}(t) = \frac{N_{\text{tot}}}{T} [\mathcal{B}_{\text{bg}} f_{\text{bg}} + 2\mathcal{B}_{\text{sig}} f_{\text{sig}} \cos^2(m_\phi t + \delta)], \quad (9)$$

where N_{tot} is the total number of ℓ_i decays, $\mathcal{B}_{\text{bg(sig)}}$ and $f_{\text{bg(sig)}}$ are the background (signal) branching fractions and experimental efficiencies, respectively. Local DM with velocity $v \sim 10^{-3}$ sets a characteristic coherence time

$$\tau_{\text{coh}} \sim \frac{1}{m_\phi v^2} \simeq 7 \times 10^5 \text{ s} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right) \left(\frac{10^{-3}}{v} \right)^2, \quad (10)$$

during which the classical DM field maintains the same phase δ . For $T > \tau_{\text{coh}}$, an experiment can experience two or more coherent “patches” with different phases. Further details about decoherence in our analysis may be found in Supplemental Material [58]. In Eq. (9), the *time-averaged* branching ratio for the signal channel satisfies

$$\mathcal{B}_{\text{sig}} \equiv \langle \mathcal{B}(\ell_i \rightarrow \ell_j \phi') \rangle = \frac{C_{ij}^2 \phi_0^2 m_{\ell_i}^3}{128\pi f^4 \Gamma_{\ell_i}}, \quad (11)$$

where we have used Eq. (8). The number of background events, assumed to be nonmodulating and dominant over the signal, is given by

$$N_{\text{bg}} = N_{\text{tot}} \mathcal{B}_{\text{bg}} f_{\text{bg}}, \quad \mathcal{B}_{\text{bg}} f_{\text{bg}} \gg \mathcal{B}_{\text{sig}} f_{\text{sig}}. \quad (12)$$

The number of events per time bin is obtained from integrating $\dot{N}_{\text{pred}}(t)$ over each bin interval Δt . Using

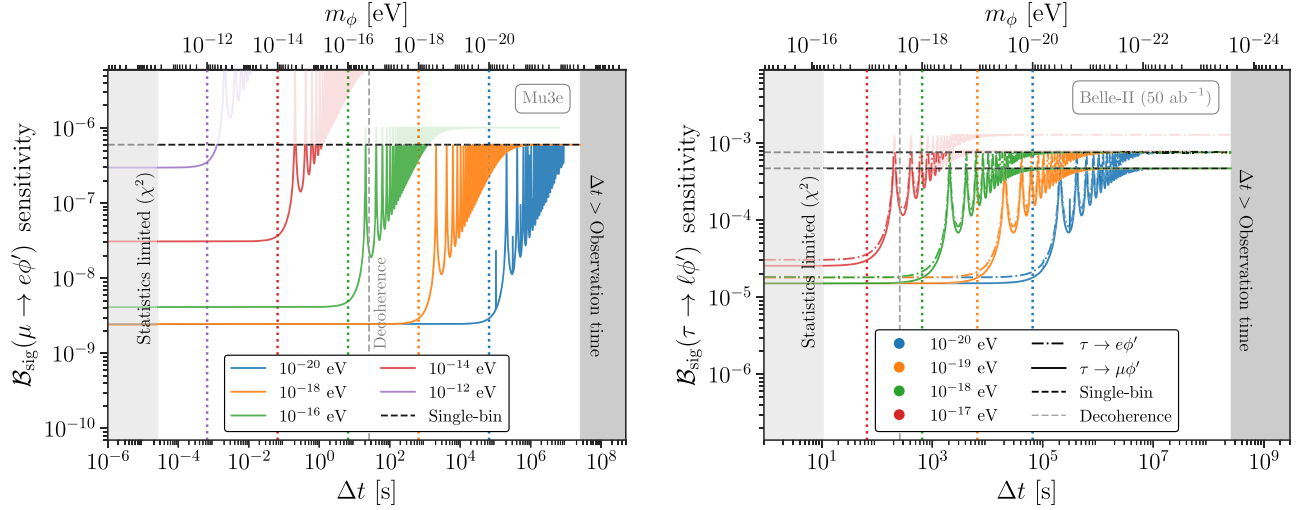


FIG. 3. The 90% confidence upper limit on the signal branching $\mathcal{B}_{\text{sig}}$ obtained from a time-dependent analysis, as a function of bin size Δt (solid, dashed-dotted lines) for different ϕ masses at Mu3e (left) and Belle II using the full projected integrated luminosity (right), using the same assumptions as in Fig. 1. The dotted vertical lines denote approximately when the oscillatory signal for each mass is resolved, $\Delta t \sim m_\phi^{-1}$. The horizontal dashed black line denotes the upper limit for a time-independent, single-bin, analysis.

Asimov datasets [94] we construct a χ^2 test statistic, which depends on the quadratic sum of statistical and systematic errors in each bin, which, respectively, satisfy

$$\sigma_{\text{stat}} = \sqrt{N_{\text{bg}}/n_{\text{bin}}}, \quad \sigma_{\text{sys}} = \alpha N_{\text{bg}}/n_{\text{bin}}, \quad (13)$$

where α is the relative systematic uncertainty. The χ^2 test statistic can then be translated to the expected bounds on $f/\sqrt{C_{ij}}$ from Eq. (8) using time-dependent $\ell_i \rightarrow \ell_j \phi'$ searches. As shown in Supplemental Material [58], in the “fine-binned” (fb) limit where $m_\phi \Delta t \ll 1$, $m_\phi T \gg 1$, the time-dependent test statistic χ_{fb}^2 can be written

$$\chi_{\text{fb}}^2 = \frac{3}{2} \left[1 + \frac{n_{\text{bin}}}{3} \left(\frac{\sigma_{\text{sys}}}{\sigma_{\text{stat}}} \right)^2 \right] \chi_{\text{const}}^2, \quad (14)$$

where χ_{const}^2 is the usual time-independent test statistic. Thus, in the fine-binned limit, the sensitivity to a time-dependent signal is significantly enhanced if systematic uncertainties dominate over statistical ones. The time dependence of the signal allows the background rate to be measured *in situ*, in the low signal rate bins, thus removing the associated uncertainty. In fact, in the systematics-dominated regime, Eq. (14) reduces to [58]

$$\chi_{\text{fb}}^2 = \frac{(\mathcal{B}_{\text{sig}} f_{\text{sig}} N_{\text{tot}})^2}{2 n_{\text{bin}} \sigma_{\text{stat}}^2}, \quad (15)$$

which shows complete independence from systematic uncertainties. Thus, with an appropriate analysis, it is possible to measure a time-dependent signal even in the presence of large systematic uncertainties, as long as all the systematics are time independent.

The expected sensitivity generally depends on the choice of time-bin width Δt (equivalently, the number of bins

n_{bin}), as shown in Fig. 3. The time-independent limit corresponds to $n_{\text{bin}} = 1$ (horizontal dashed line in Fig. 3). Sensitivity gradually decreases as Δt increases: small Δt corresponds to a regime fully resolving oscillations, whereas large Δt approaches a less sensitive, time-integrated analysis dominated by systematics.

The χ^2 approach requires at least ~ 10 events per time bin, which places a lower bound on the bin size Δt . To resolve shorter period oscillations, but above the experimental time resolution, we utilize the unbinned approach of the Rayleigh periodogram [23]. Further details on the procedure can be found in Supplemental Material [58]. In Fig. 1, we summarize the expected sensitivity to $\mathcal{B}(\ell_i \rightarrow \ell_j \phi')$ as a function of m_ϕ for representative numerical examples detailed below.

Numerical examples—As representative examples we consider a possible search for time-dependent $\mu \rightarrow e \phi'$ decays at Mu3e, and for $\tau \rightarrow \ell \phi'$ decays at Belle II and at FCC-ee. More details regarding the chosen numerical values for each example can be found in Supplemental Material [58].

For Mu3e, we assume $T = 300$ days of continuous data collection, yielding $N_{\text{tot}} \sim 3 \times 10^{15}$ muon decays. The endpoint region for $m_\phi \simeq 0$ includes $N_{\text{bg}} \sim 10^{13}$ background events from $\mu \rightarrow e \nu \bar{\nu}$, corresponding to a background fraction $f_{\text{bg}} \sim 3 \times 10^{-3}$ [32,33]. For these large data samples, the $\mu \rightarrow e \phi'$ search will be dominated by systematics, which we conservatively assume are set by theoretical uncertainties, implying a 90% CL upper bound of $\mathcal{B}(\mu \rightarrow e \phi') < 6 \times 10^{-7}$ (Fig. 12 of Ref. [59]), and thus a relative systematic uncertainty of $\alpha \sim 10^{-4}$. Given the dataset above, the time-dependent search for $\mu \rightarrow e \phi'$ can result in a sensitivity to the $\mu \rightarrow e \phi'$ branching ratio well below the systematic uncertainty for $m_\phi \lesssim 10^{-10}$ eV (solid purple line in Fig. 1 left).

Estimating the Belle-II sensitivity to time-dependent $\tau \rightarrow \ell \phi'$ decays is complicated by the fact that the state-of-the-art time-integrated search for these decays relies on the combined fit to the shape of $\tau \rightarrow \ell \nu \bar{\nu}$ background and the $\tau \rightarrow \ell \phi'$ signal in the pseudo-rest-frame of the tau [30]. Since, in this frame, the spectrum of lepton energies in SM $\tau \rightarrow \ell \nu \bar{\nu}$ decays is similar to the spectrum from $\tau \rightarrow \ell \phi'$, we approximate the sensitivity using a simplified counting experiment. For the existing Belle-II analysis [30], using data corresponding to an integrated luminosity of 62.8 fb^{-1} , we consider only the $\tau \rightarrow \ell \nu \bar{\nu}$ events with lepton energies in the range that contains 90% of the signal leptons from $\tau \rightarrow \ell \phi'$ decays. Taking experimental efficiencies into account gives $f_{\text{sig}}^{e[\mu]} \sim 1.8[2.4] \times 10^{-2}$ and $f_{\text{bg}}^{e[\mu]} \sim 1.1[1.4] \times 10^{-2}$. Using this, the background process branching $\mathcal{B}_{\text{bg}}^{e[\mu]} \sim 0.178[0.174]$, the 90% CL upper limits set by the analysis $B(\tau \rightarrow e[\mu] \phi') < 7.6[4.7] \times 10^{-4}$ [30], and assuming that the search is systematic limited, gives the relative systematic uncertainty of $\alpha_{e[\mu]} \sim 2.7[1.9] \times 10^{-2}$. For simplicity, we also assume that the $N_{\text{tot}} \sim 10^8$ taus were collected uniformly within $T = 300$ days. Using this relatively small data sample, the time-dependent search resolves oscillations only for ϕ masses below $m_\phi \lesssim 10^{-17} \text{ eV}$ (blue solid line in Fig. 1 right). With the full 50 ab^{-1} integrated luminosity, Belle-II will have $N_{\text{tot}} \sim 10^{11}$, which should significantly improve the reach in $f^2/C_{\tau\ell}$ and sensitivity to larger ϕ masses. Assuming continuous data collection over $T = 3 \times 10^3$ days with unchanged f_{bg} , f_{sig} , and α , yields the blue dashed-dotted line in Fig. 1 (right).

Finally, we also consider $\tau \rightarrow \ell \phi'$ searches at FCC-ee. While running in Tera-Z mode the proposed FCC-ee experiment will produce approximately $N_{\text{tot}} = 3.4 \times 10^{11}$ taus over $T = 740$ days of running [35]. Using a relative systematic uncertainty of $\alpha \sim 2.6 \times 10^{-4}$, $f_{\text{bg}} \sim 8.1 \times 10^{-2}$, and $f_{\text{sig}} \sim 0.12$ we obtain the projected sensitivities shown as the red solid line in Fig. 1 (right), resolving oscillations up to $m_\phi \lesssim 10^{-13} \text{ eV}$.

Astrophysical and laboratory constraints—Light particles with CFLV interactions can modify energy transport in supernovae and conflict with the observed properties of SN1987A in the Large Magellanic Cloud (LMC) [38]. Previous bounds on such particles assumed environment-independent couplings, but our interaction from Eq. (7) depends on ϕ_c and thus requires knowledge of the DM density in the LMC. At the SN1987A location ($\sim 1 \text{ kpc}$ from the LMC center [95]), the DM density is estimated to be [96]

$$\rho_\phi^{\text{LMC}} \in [0.4, 8] \text{ GeV/cm}^3, \quad (16)$$

and in Fig. 1 (left) we use the lower end of this range to place conservative limits on the quantity $f/\sqrt{C_{\mu\mu}}$, following the same procedure as outlined in Ref. [97].

It is instructive to compare CLFV constraints to those on flavor-diagonal couplings. As diagonal scalar couplings vanish in our model at leading order, see Eq. (7), we consider constraints on an ultralight pseudoscalar DM and define $C_{\mu e}|_{\text{Mu3e}}$ as the maximum Mu3e sensitivity in Fig. 1, reflecting a time-binned analysis with fine binning. The strongest constraints on the diagonal electron couplings are from Red Giant cooling [98]

$$C_{ee} \left(\frac{\text{GeV}}{f} \right)^2 \lesssim 2 \times 10^2 \left(\frac{m_\phi}{\text{eV}} \right), \quad (17)$$

while for the diagonal muon coupling, the strongest constraints come from SN1987A cooling, where [99,100]

$$C_{\mu\mu} \left(\frac{\text{GeV}}{f} \right)^2 \lesssim 8 \times 10^4 \left(\frac{m_\phi}{\text{eV}} \right), \quad (18)$$

which yields the relations

$$C_{ee} \lesssim 30 C_{\mu e}|_{\text{Mu3e}}, \quad C_{\mu\mu} \lesssim 10^4 C_{\mu e}|_{\text{Mu3e}}. \quad (19)$$

Without fine-tuned cancellations, rotating into the charged-lepton mass basis generally produces

$$C_{\mu e} \lesssim \sqrt{C_{ee} C_{\mu\mu}} \lesssim 5 \times 10^2 C_{\mu e}|_{\text{Mu3e}} \quad (20)$$

where we have combined Eqs. (17)–(19) in the last expression. This indicates that Mu3e searches can probe new and *natural* DM parameter space without special hierarchies between diagonal and off-diagonal couplings. Given the much weaker bounds on $C_{\tau\tau}$, the Belle-II searches we describe above also do not face any such fine-tuning considerations, especially for $\tau \rightarrow \mu \phi'$ decays.

Conclusions—In this Letter we demonstrated that FCNC decays may offer a new window into ultralight DM candidates. Crucially, the presence of FCNC couplings to charged SM leptons can induce time modulation with DM mass frequency in $\tau \rightarrow \ell \phi'$ and $\mu \rightarrow e \phi'$ decays, where ϕ' is a light dark sector scalar. Since observing time dependence in these decays would be smoking-gun evidence of DM, we find that rare lepton decay experiments can also serve as potential dark matter direct detection experiments without any instrumental modifications. Furthermore, such time-oscillating signals can improve the experimental reach compared to time-independent searches, if the latter are dominated by systematic uncertainties, see Fig. 1.

While our analysis focused on flavor violation in charged lepton decays, the same approach directly extends both to other observables in the lepton sector (such as $\mu \rightarrow e$ conversion in the field of a nucleus), as well as to flavor violation in the quark sector. We leave a more detailed analysis of these phenomena for future work.

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Data availability—There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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