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

LULBI @ Weizmann Institute of Science
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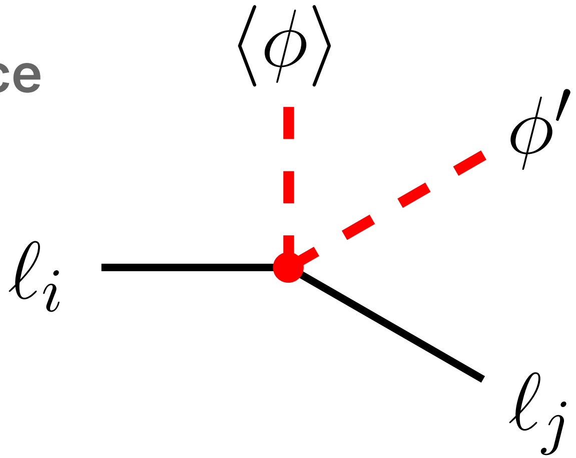
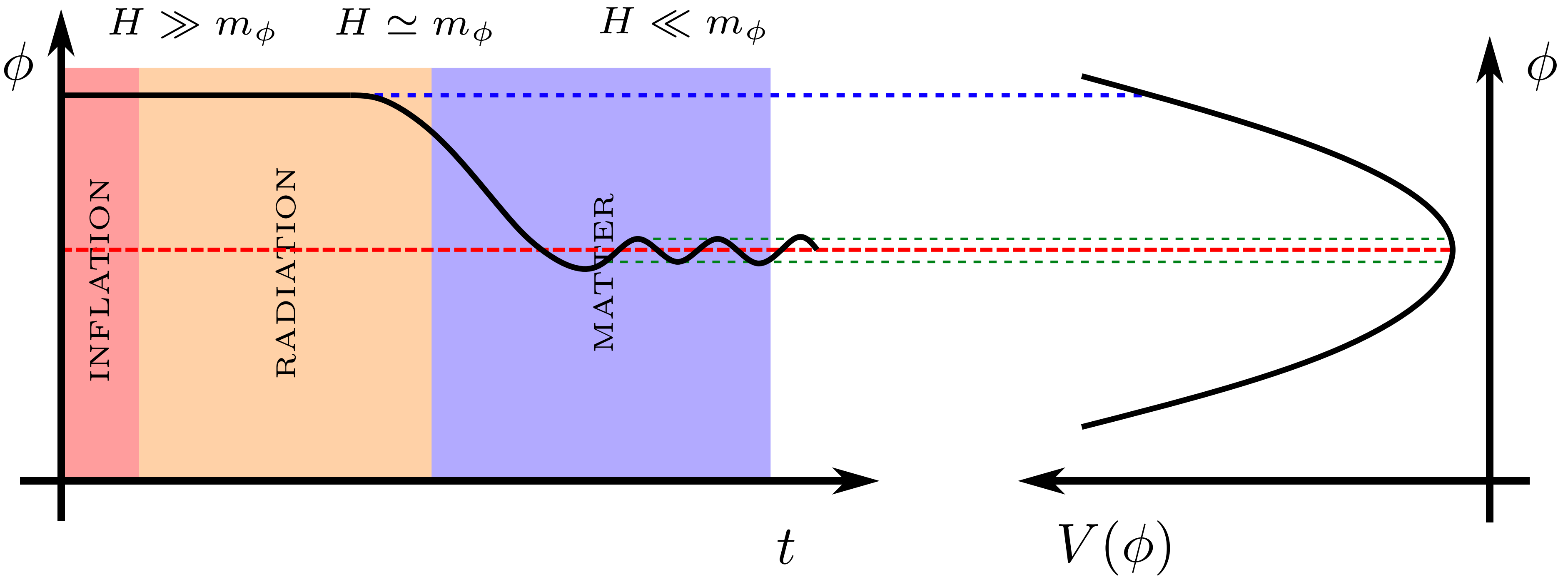


Based on 2503.07722 with Innes Bigaran, Patrick Fox, Yann Gouttenoire, Roni Harnik, Gordan Krnjaic, and Jure Zupan

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

For $m_\phi \lesssim \mathrm{eV}$ the de Broglie volume admits a huge occupation number

$$N \sim n\lambda_{\mathrm{dB}}^3 \sim \frac{\rho_\phi}{m_\phi}\left(\frac{1}{m_\phi v}\right)^3 \simeq 10^3 \left(\frac{1\ \mathrm{eV}}{m_\phi}\right)^4 \left(\frac{10^{-3}}{v}\right)^3 \left(\frac{\rho_\phi}{10^{-42}\ \mathrm{GeV}^4}\right)$$

ULDM can be accurately 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

For $m_\phi \lesssim \mathrm{eV}$ the de Broglie volume admits a huge occupation number

$N \sim n\lambda_{\mathrm{dB}}^3$ ... $\frac{\rho_\phi}{{}^{42}\ \mathrm{GeV}^4}\Big)$

Each mass has an associated "timescale"

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

ULDM ca... wave

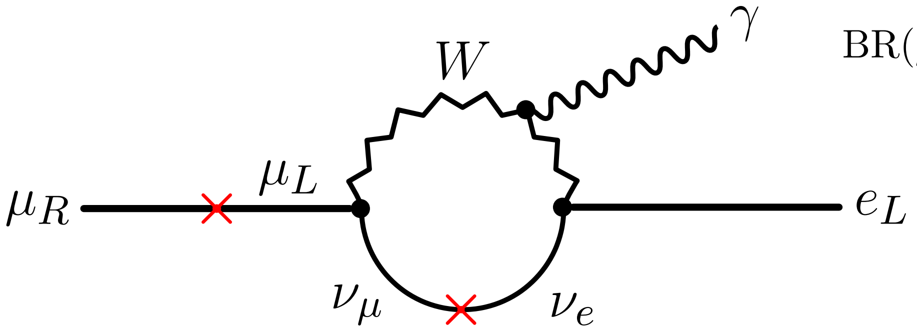
$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \qquad \rho_\phi = 0.4\,\mathrm{GeV/cm}^3 \simeq 10^{-42}\mathrm{GeV}^4$$

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



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

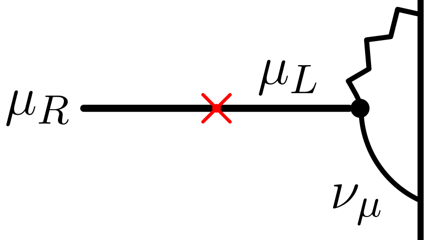
$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 3\right) \times \mathrm{BR}(\mu \to e\gamma)$$

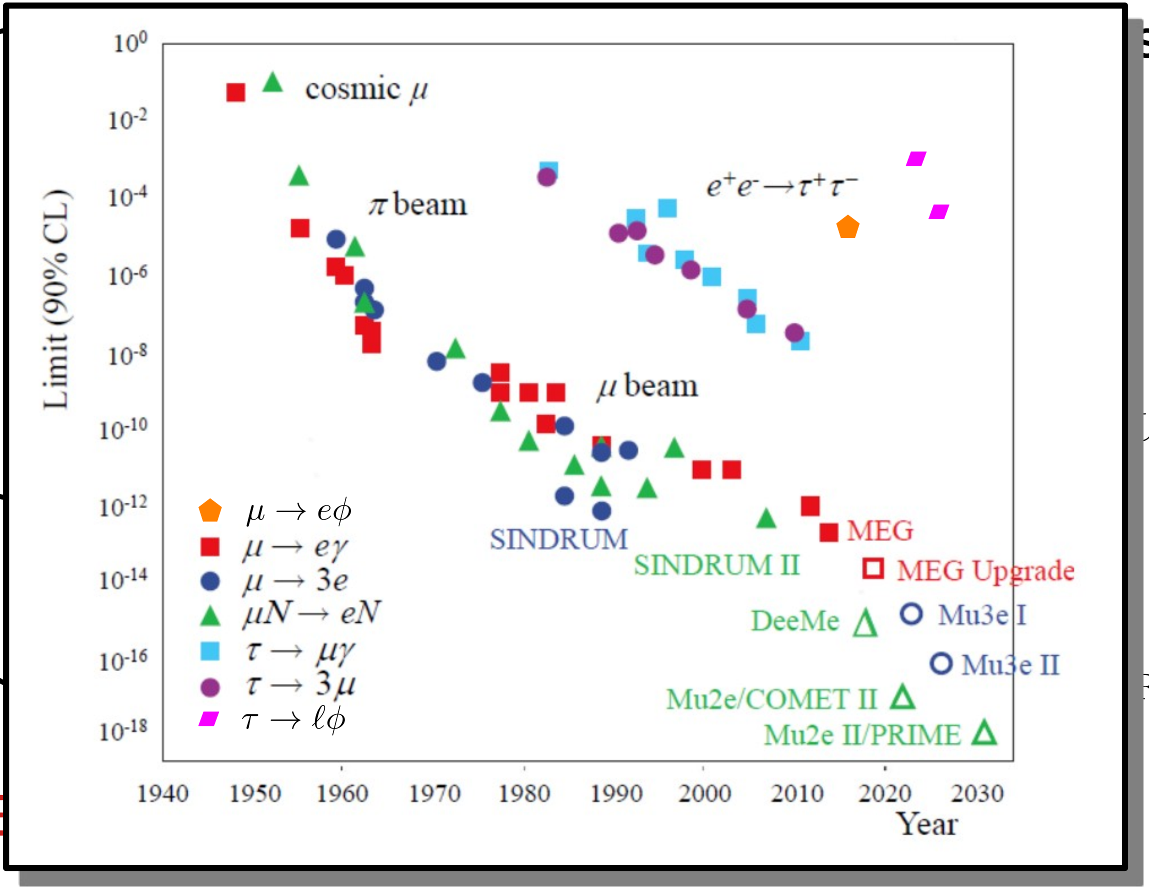
$$\mathrm{CR}(\mu \mathrm{N} \to e \mathrm{N}) \simeq \alpha \times \mathrm{BR}(\mu \to e\gamma)$$

Bottom line: Observing CLFV = new physics

Standard lore - CLFV

- The Standar symmetry
- Because mν n occur at one-loop





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

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

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

Why ULDM + CLFV?

CLFV experiments probe extremely high NP scales

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.

Minimal analysis can convert intensity frontier experiments into dark matter detectors

Outline

1) What operators are phenomenologically viable?
2) Explicit realization of operator structure
3) Experimental sensitivity and reach (Mu3e)

ULDM + CLFV

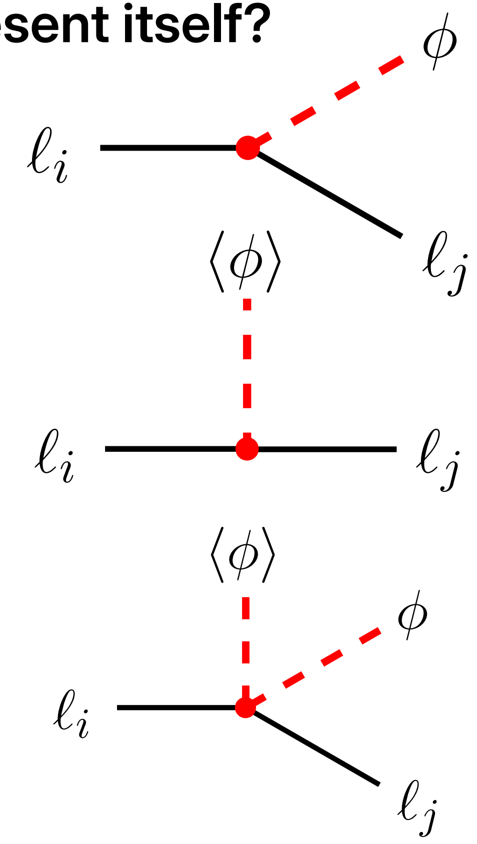
How and where does time-modulation present itself?

Two types of time-dependence:

- Manifestation in mass matrix

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

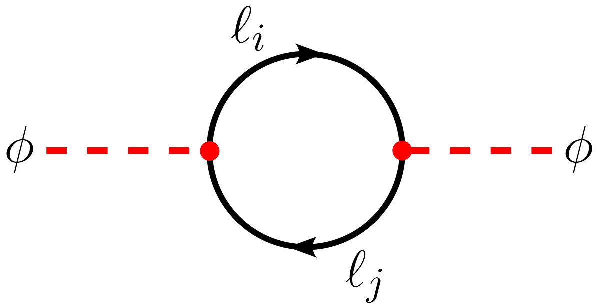
- Manifestation in decay/scattering rates
  - Inherently higher dimensional



Journey towards phenomenologically viable operator

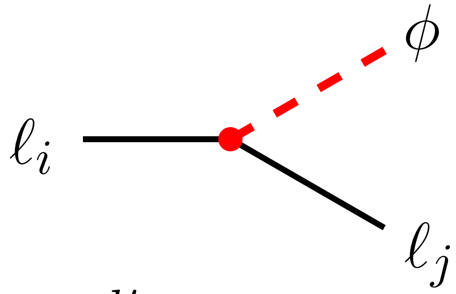
First guess: $\frac{C_{ij}}{\Lambda}\phi H \bar{L}_i \ell_j \to y_{ij}\phi\bar{\ell}_i\ell_j$

1. Fine-tuning

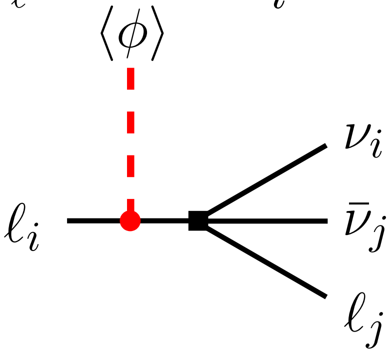


$\longrightarrow \delta m_\phi^2 \simeq \frac{\lambda^2}{4\pi^2} m_\ell^2$

2. No time-modulation



3. SM rate-modulation



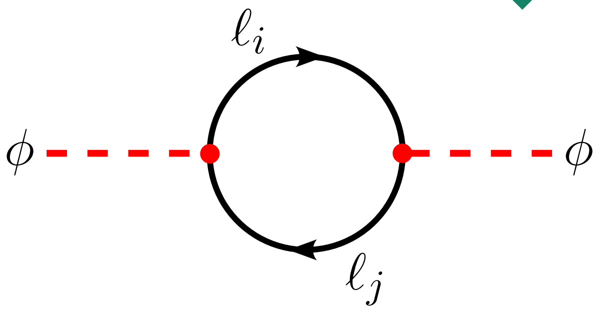
$|y_{\tau\ell}| \lesssim 10^{-7}$ (Belle II)

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

Journey towards phenomenologically viable operator

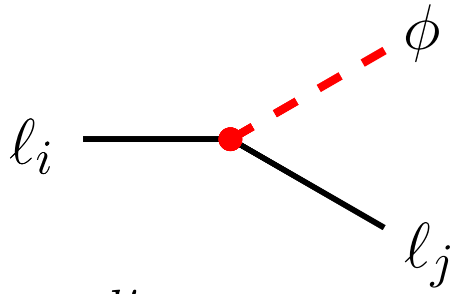
First guess: $\frac{C_{ij}}{\Lambda}\phi H \bar{L}_i \ell_j \rightarrow y_{ij}\phi\bar{\ell}_i\ell_j$

1. Fine-tuning "✓"

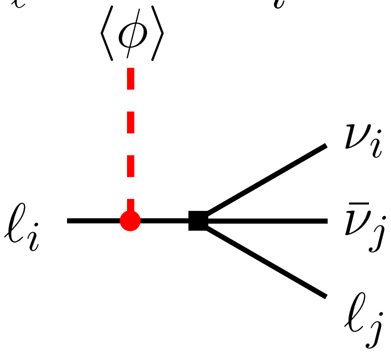


$\longrightarrow \delta m_\phi^2 \simeq \frac{\lambda^2}{4\pi^2} m_\ell^2$

2. No time-modulation X



3. SM rate-modulation X



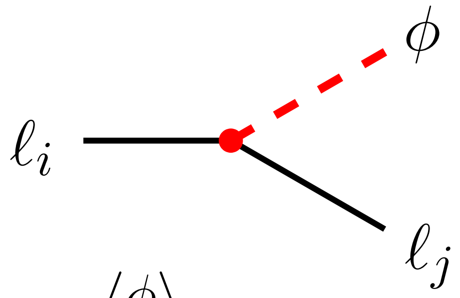
$|y_{\tau\ell}| \lesssim 10^{-7}$ (Belle II)

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

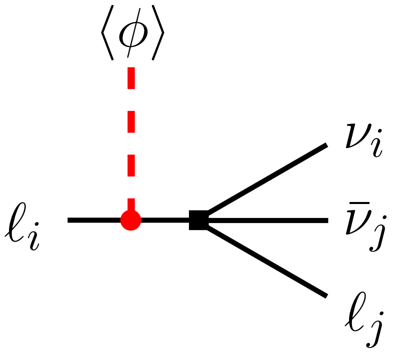
Journey towards phenomenologically viable operator

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



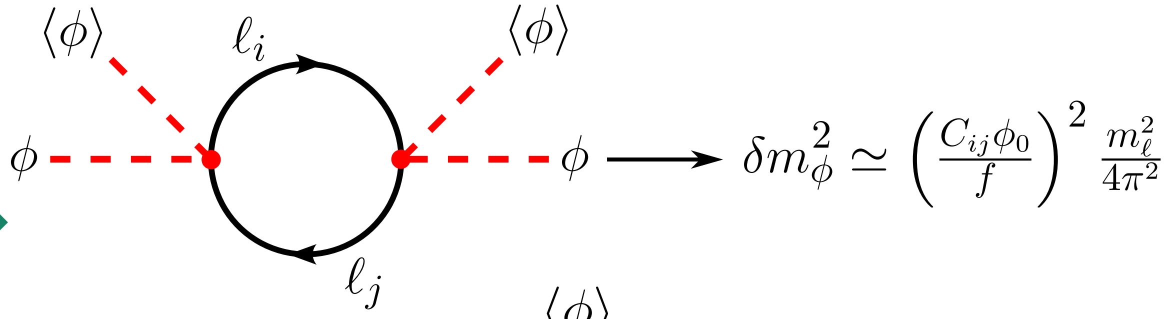
3. SM-modulation: X

Journey towards phenomenologically viable operator

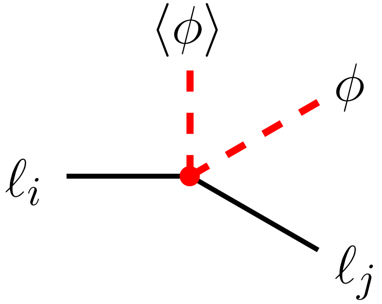
Third guess: $\frac{C_{ij}}{f}\phi^2(\bar{\ell}_i\ell_j)$

1. Fine-tuning: ✗

2. Time-modulation: ✓



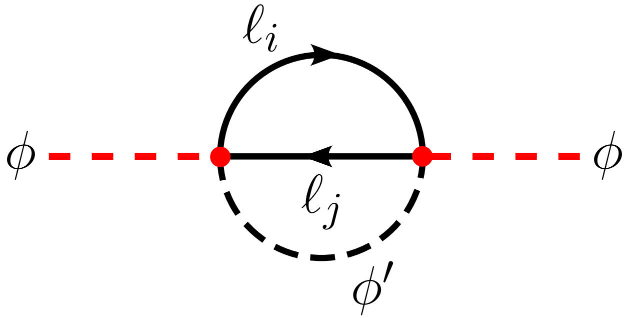
3. SM-modulation: ✓



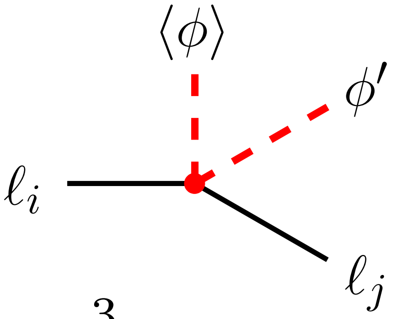
Journey towards phenomenologically viable operator

Fourth 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: ✓

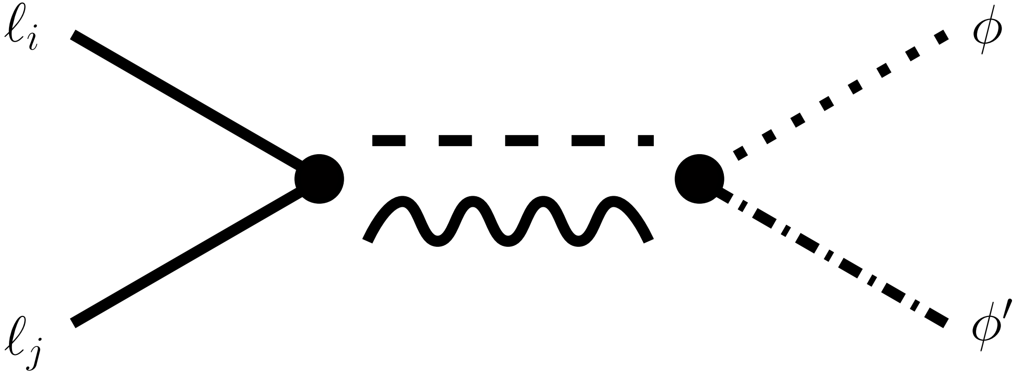


3. SM-modulation: ✓

$$\mathcal{B}(\ell_i \to \ell_j\phi) = \frac{C_{ij}^2\phi_0^2}{64\pi f^4}\frac{m_{\ell_i}^3}{\Gamma_{\ell_i}}\cos^2(m_\phi t + \delta)$$

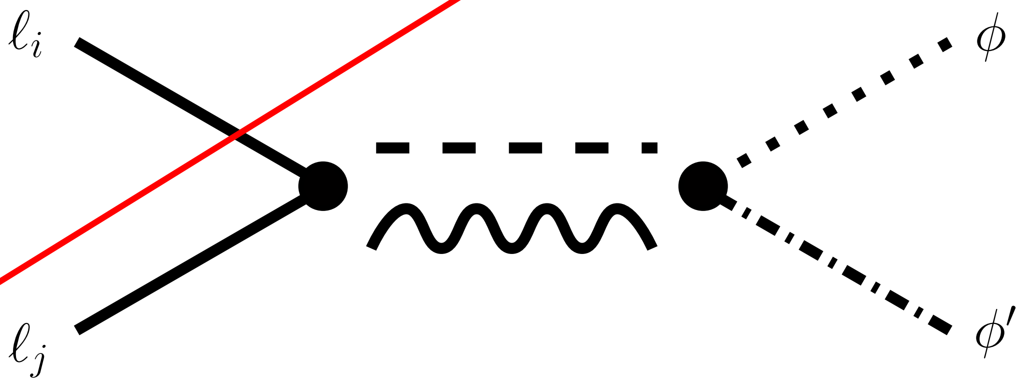
Explicit realization

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



Explicit realization

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



→ Non-abelian pseudo-NGB + portal

Explicit realization

- **Non-abelian pseudo-NGB + U(1)$_D$**

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

$$D_\mu \equiv \partial_\mu + i g_D A'_\mu [Q, U] \qquad U = \exp\left(i\sqrt{2}\Pi_D / f_D\right)$$

$$\Pi_D = \begin{pmatrix} \frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & \pi_D^+ & K_D^+ \\ \pi_D^- & -\frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & K_D^0 \\ K_D^- & \bar{K}_D^0 & -\sqrt{\frac{2}{3}}\eta_{D8} \end{pmatrix}$$

Explicit realization

- **Non-abelian pseudo-NGB + U(1)$_D$**

$$\mathcal{L}_D \supset \frac{f_{\mathrm{UV}}^2}{8}\left(D_\mu U D^\mu U^\dagger\right) + \frac{f_{\mathrm{UV}}^2}{8}\left(\chi^\dagger U + U^\dagger \chi\right) + \cdots$$

Explicit realization

- Non-abelian pseudo-NGB + U(1)$_D$

$$U \to e^{i\alpha} U$$

$$\mathcal{L}_D \supset \frac{f_{\rm UV}^2}{8}\left(D_\mu U D^\mu U^\dagger\right) + \frac{f_{\rm UV}^2}{8}\left(\chi^\dagger U + U^\dagger \chi\right) + \cdots$$

Explicit realization

- **Non-abelian pseudo-NGB + U(1)$_D$**

$$\mathcal{L}_D \supset \frac{f_{\rm UV}^2}{8}\left(D_\mu U D^\mu U^\dagger\right) + \frac{f_{\rm UV}^2}{8}\left(\chi^\dagger U + U^\dagger \chi\right) + \cdots$$

$$\mathrm{Q} \to q_U \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & q_U \\ 0 & q_U & 0 \end{pmatrix}$$

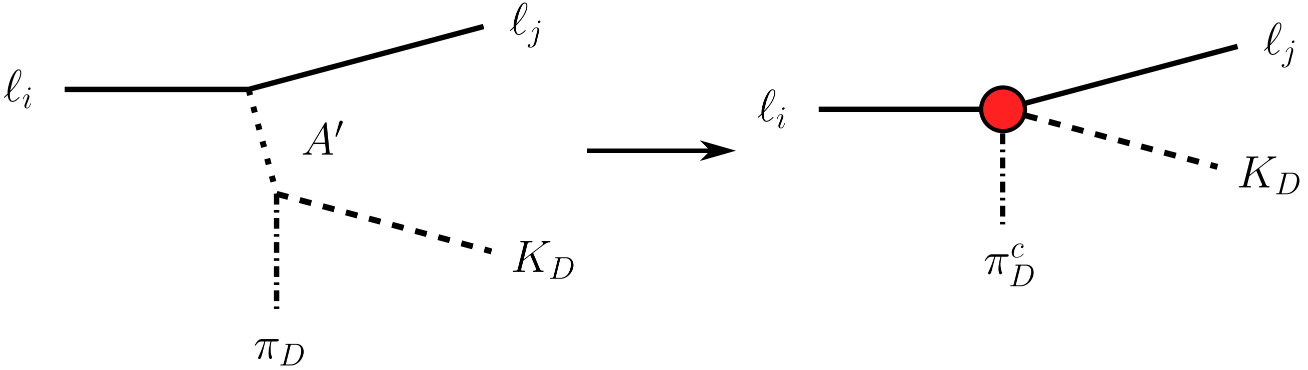
$$\supset -g' q_U A'_\mu \left(\pi_D^+ i\partial^\mu K_D^- - K_D^- i\partial^\mu \pi_D^+ + \text{h.c.}\right) + \cdots$$

Explicit realization

- Non-abelian pseudo-NGB + $U(1)_D$

$$\supset -g' q_U A'_\mu \left(\pi_D^+ i\partial^\mu K_D^- - K_D^- i\partial^\mu \pi_D^+ + \text{h.c.}\right) + \cdots$$

Charge the SM under $U(1)_D$: $$-\mathcal{L}_{\text{portal}} = i g' c_{ij} \ell_i \gamma^\mu A'_\mu \ell_j + \text{h.c.}$$



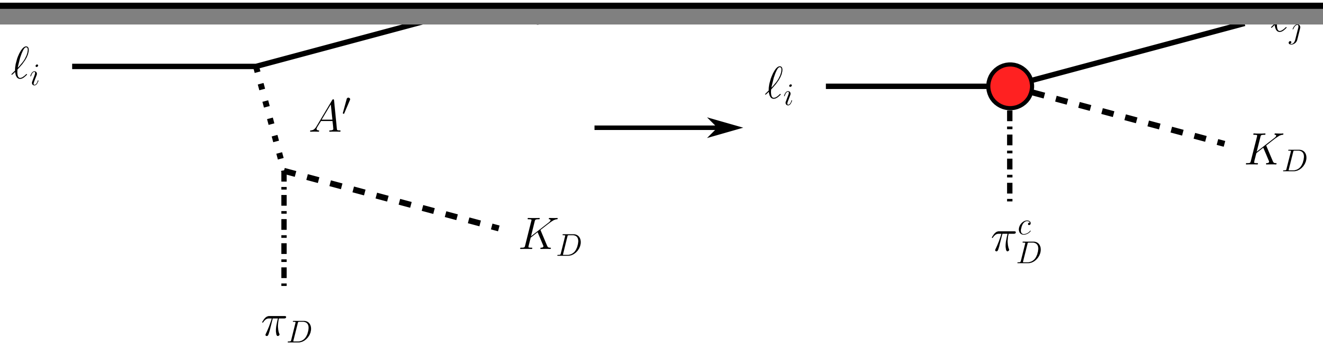
Explicit realization

- Non-abelian pseudo-NGB + U(1)$_D$

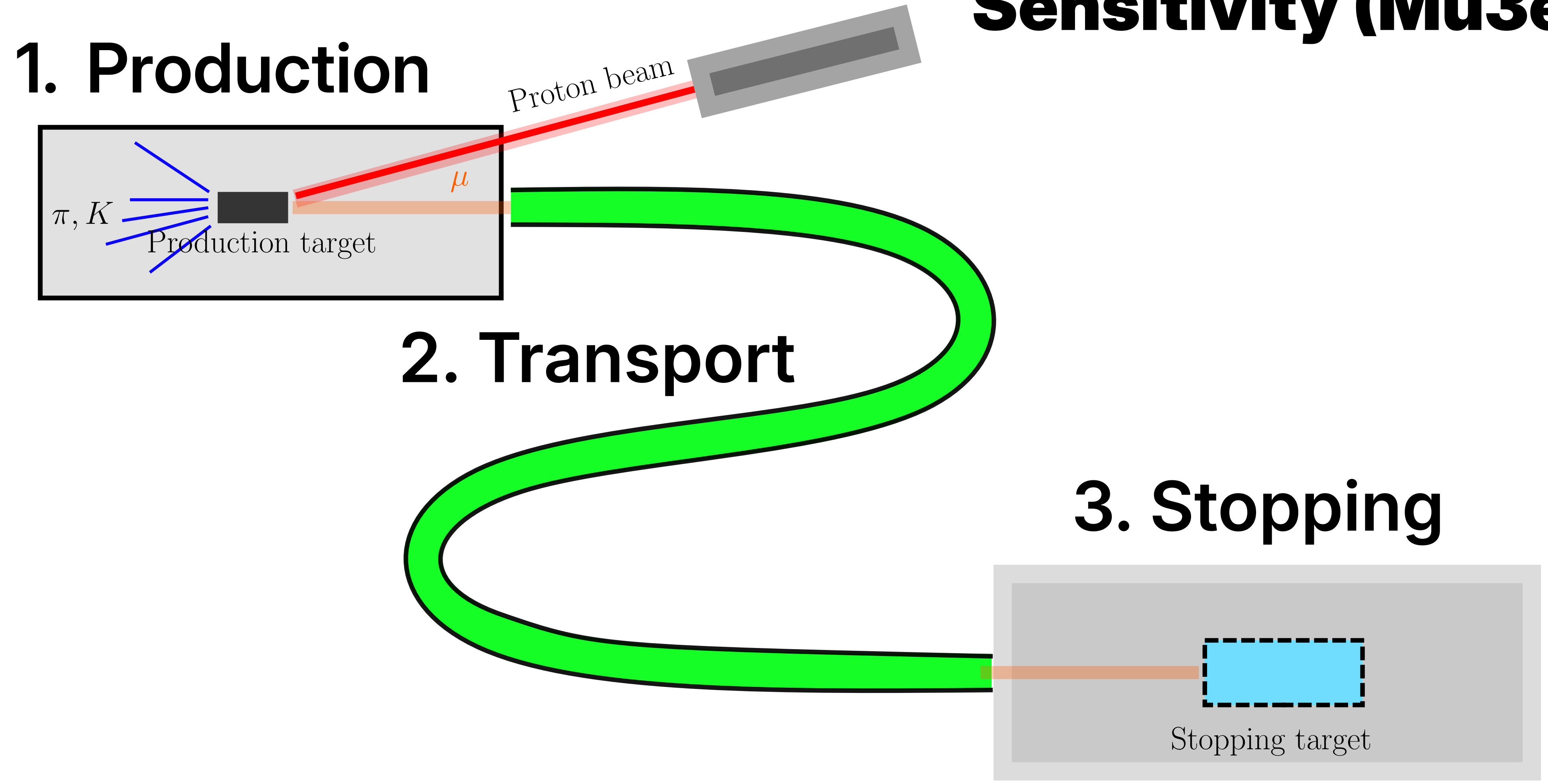
$$\supset -g' q_U A'_\mu \left(\pi_D^+ i\partial^\mu K_D^- - K_D^- i\partial^\mu \pi_D^+ + \text{h.c.}\right) + \cdots$$

$$\supset \frac{c_{ij} q_U g'^2}{m_{A'}^2} \left(\bar{\psi}_i \gamma^\mu \psi_j\right)\left(\pi_D^+ \partial_\mu K_D^-\right) + \cdots$$

Charge t ... + h.c.



Sensitivity (Mu3e)

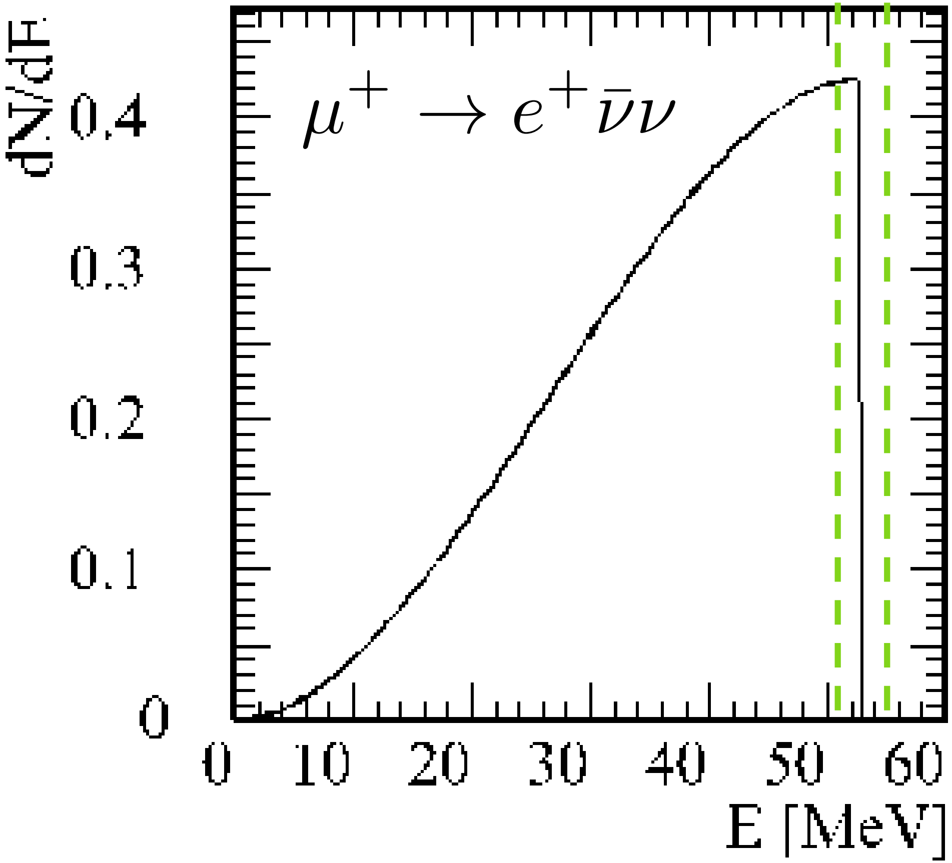


Sensitivity (Mu3e)

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

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

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

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**

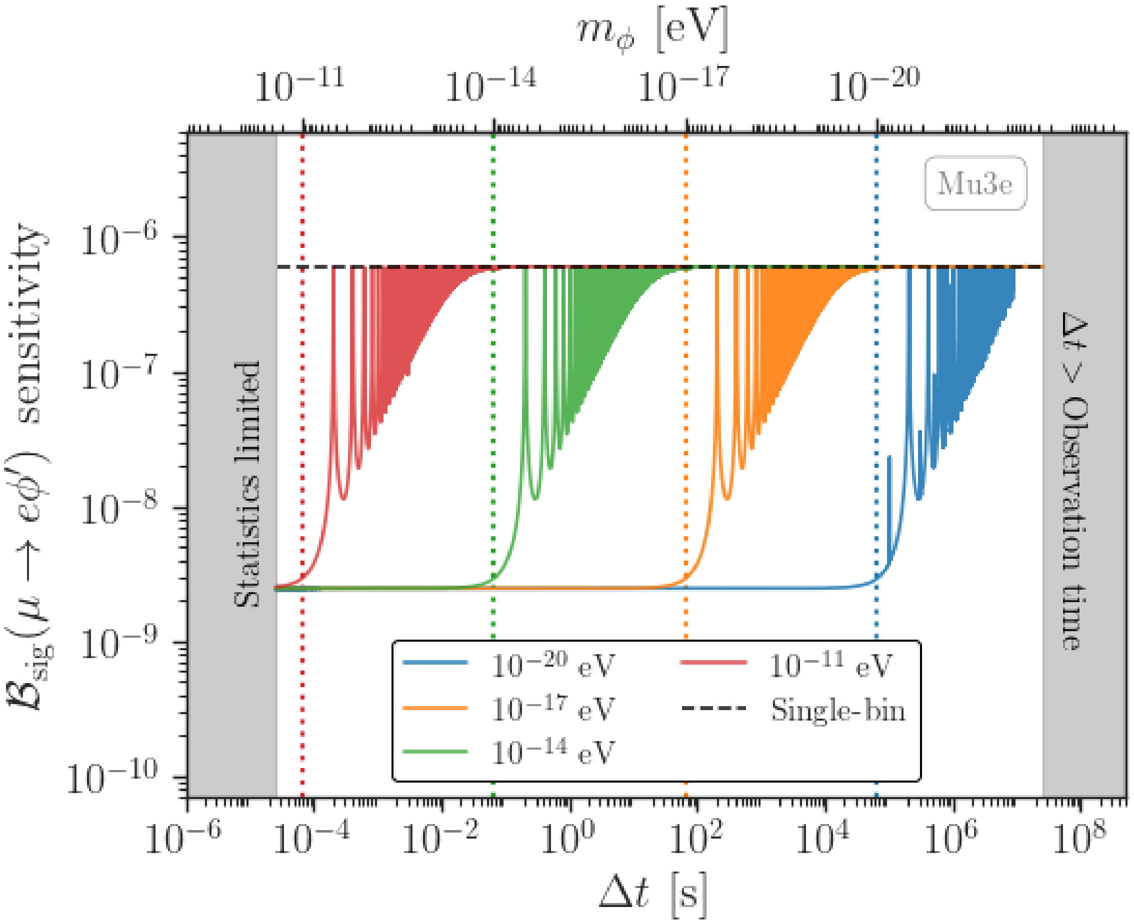
Systematics dominate (limits 1, 2)

Statistics dominate (limit 3)

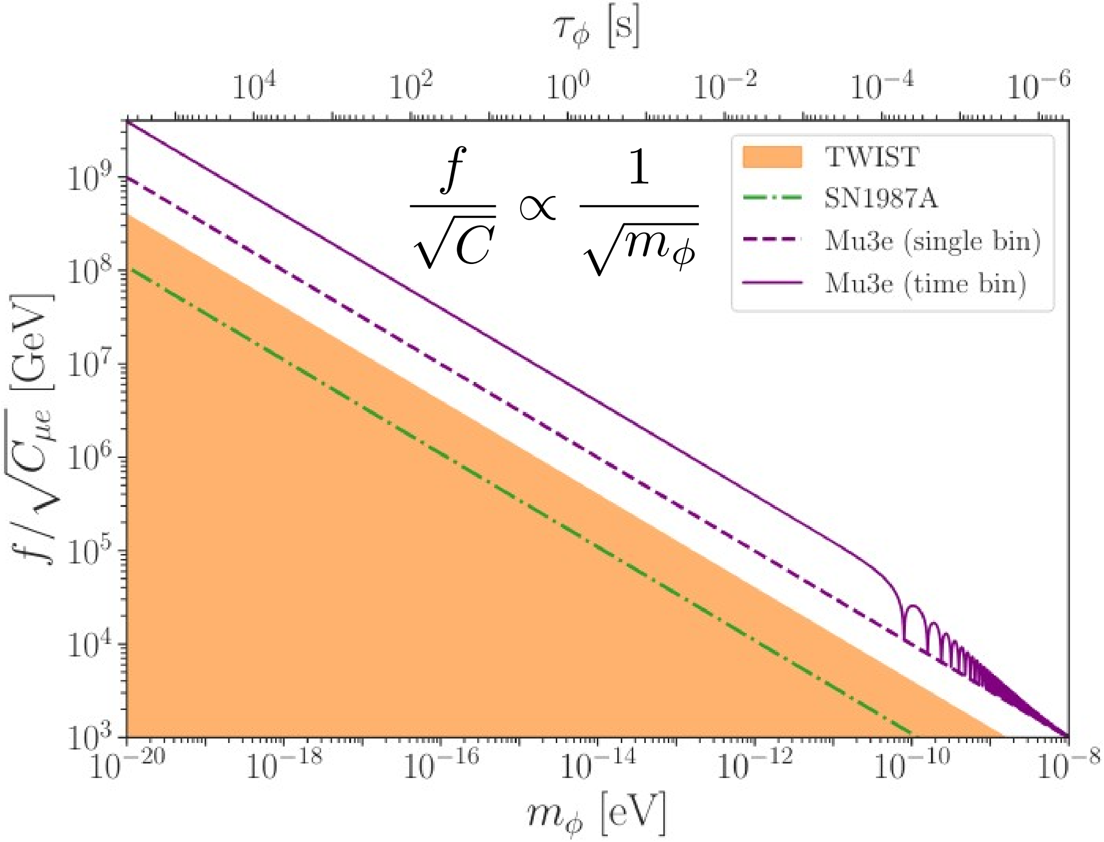
Sensitivity

Assumptions:
1) Asimov dataset
2) Continuous running
3) Time-independent systematics

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



Reach


τ_ϕ [s]
10^4 10^2 10^0 10^{-2} 10^{-4} 10^{-6}
$\frac{f}{\sqrt{C}} \propto \frac{1}{\sqrt{m_\phi}}$
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_ϕ [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
- Cosmology of UV realizations (Maleknejad, McDonough 2205.12983)

Conclusions

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What's next:

- Quark sector
- Cosmology of UV realizations (Maleknejad, McDonough 2205.12983)

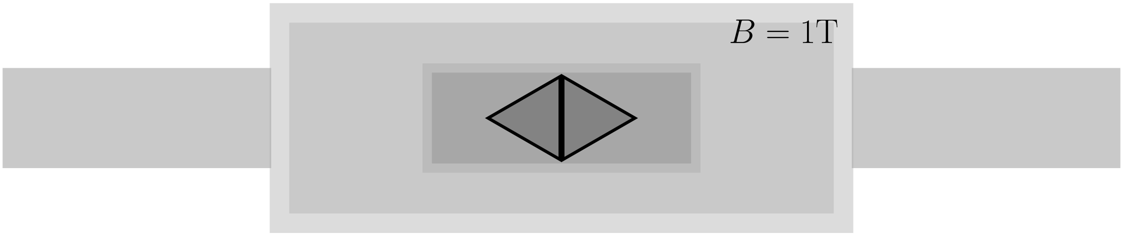
Thank you :)

Back-up

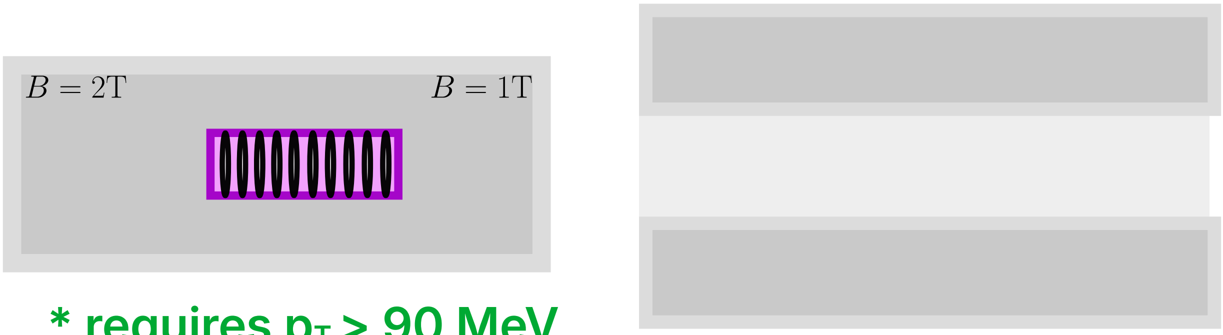
4. Detection (phenomenology is influenced by detector)

Mu3e (μ^+)

* requires $p_T > 10$ MeV



Mu2e (μ^-)



* requires $p_T > 90$ MeV

Michel spectrum errors at Mu3e

NNLO, NNLL 2211.01040