Direct Detection of Ultralight Dark Matter with Lepton Flavour Violation
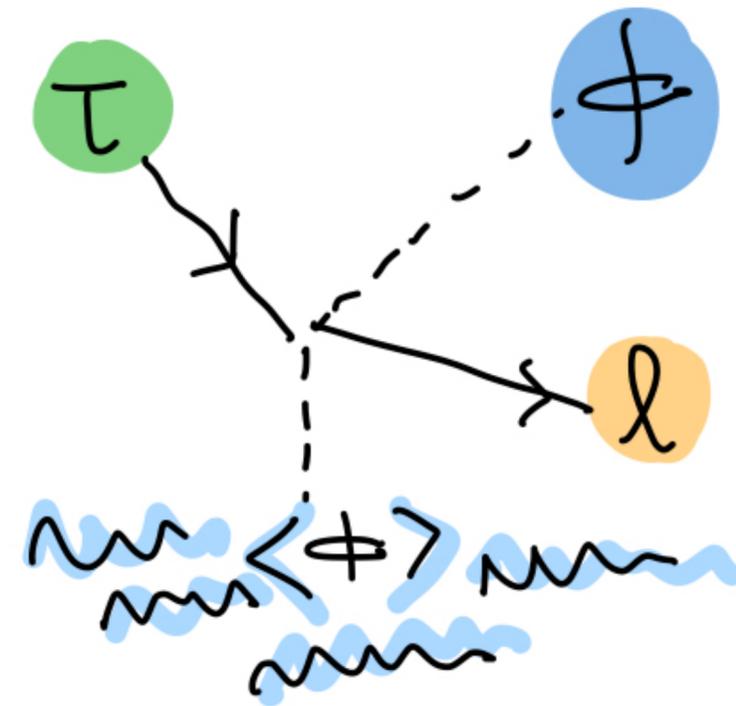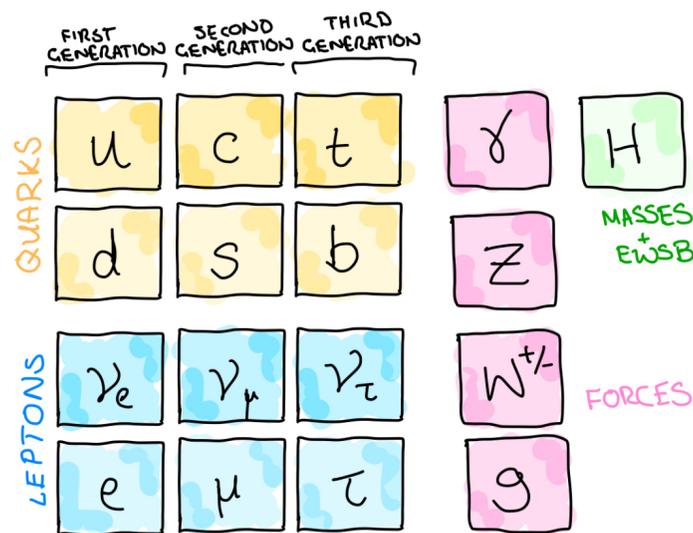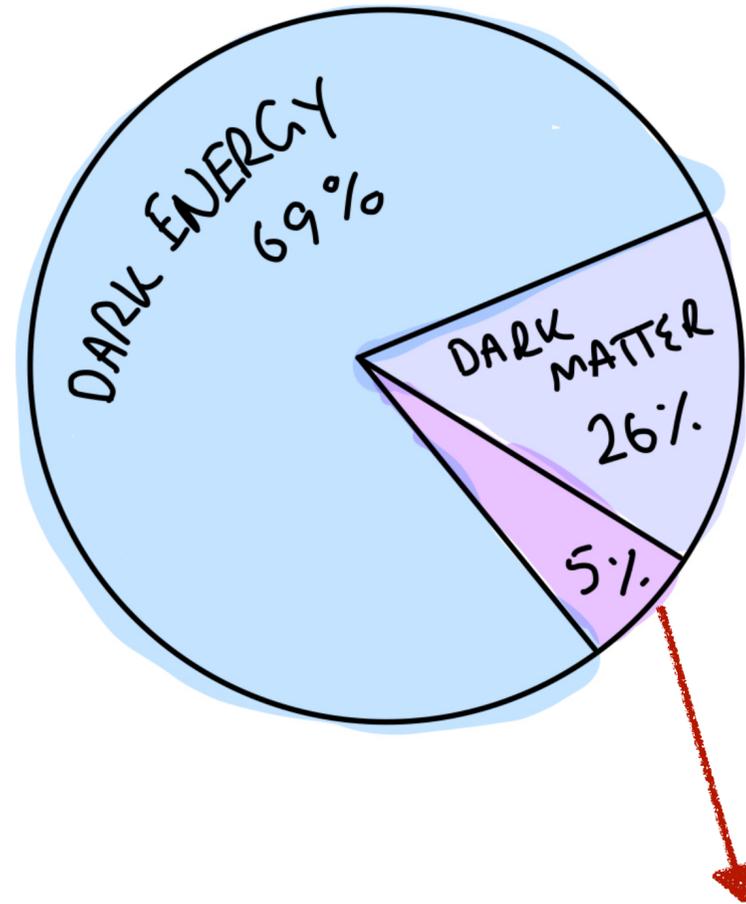
Dr Innes Bigaran (FNAL+Northwestern)

*Based on **IB,** Fox, Gouttenoire, Harnik, Krnjaic, Menzo, Zupan 2503.07722*
+ work in progress

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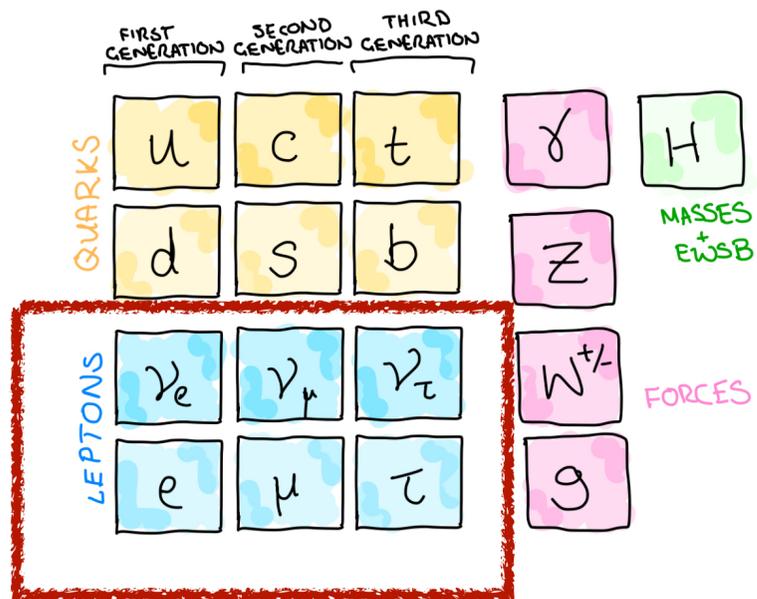# Symmetry + the Standard Model

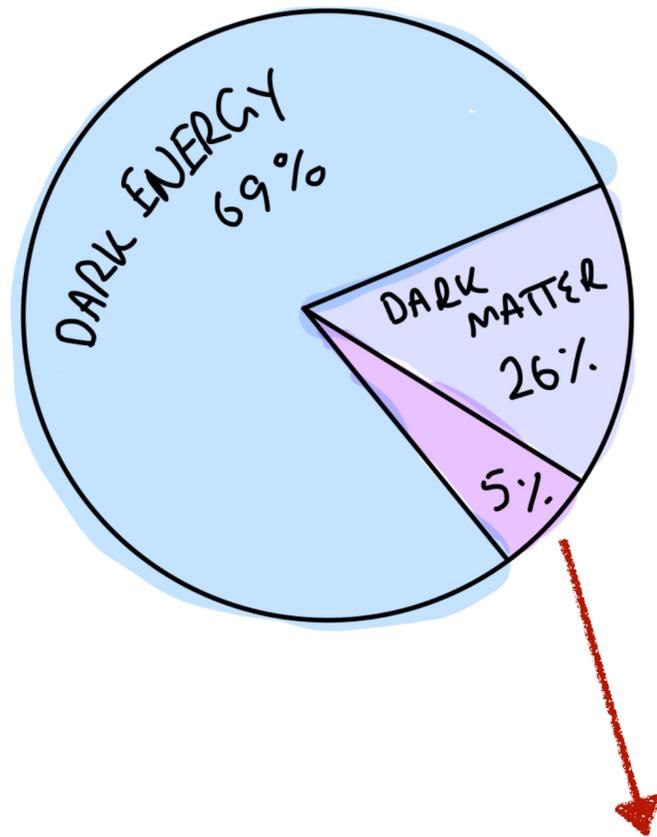- Visible matter only makes up ~5% of the energy density of the universe!

- We have an excellent (Standard) model which describes visible matter composition and interactions

$$SU(3) \otimes SU(2) \otimes U(1)$$

- Semi-empirical: requires at least 18 parameters from experimental measurements to prescribe the model - largest number of these from quark and lepton masses and mixing: the Flavour Sector

Lepton Flavour Violation (LFV)

- In the SM, neutrinos are *massless* particles and lepton flavour symmetry is conserved

$$\mathcal{G}_{\mathrm{L}} = U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$$

- Flavoured lepton number is conserved in SM interactions, thus also total lepton number

$$L = L_\mu + L_e + L_\tau$$
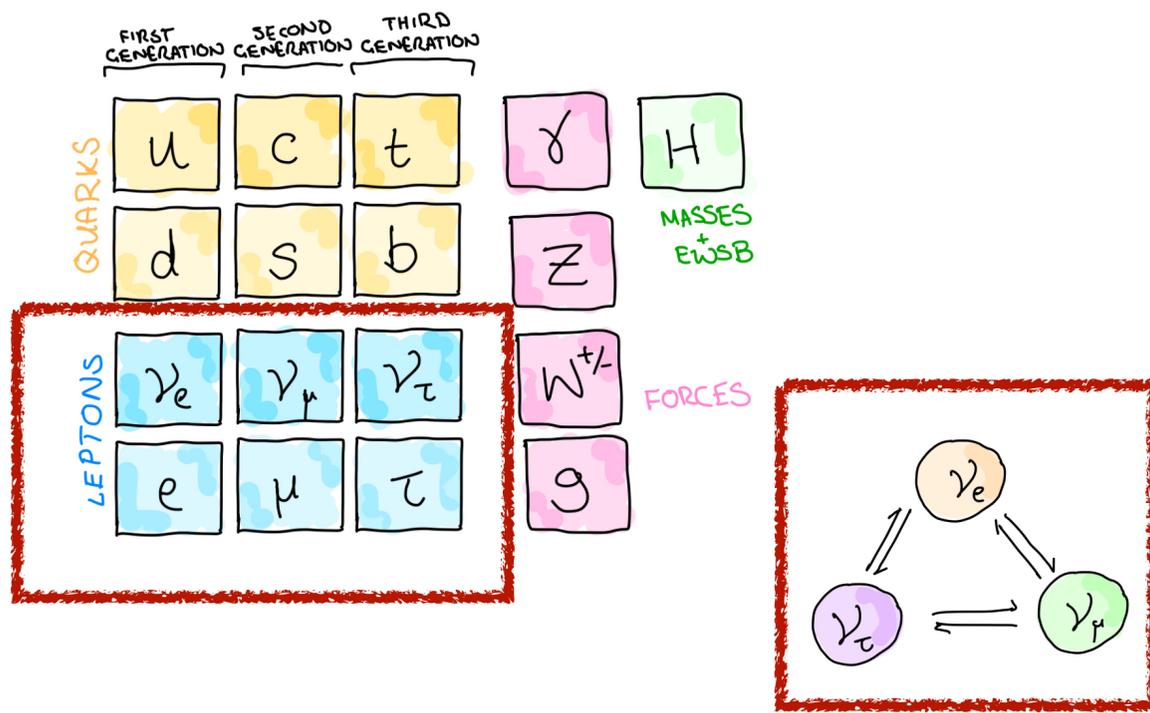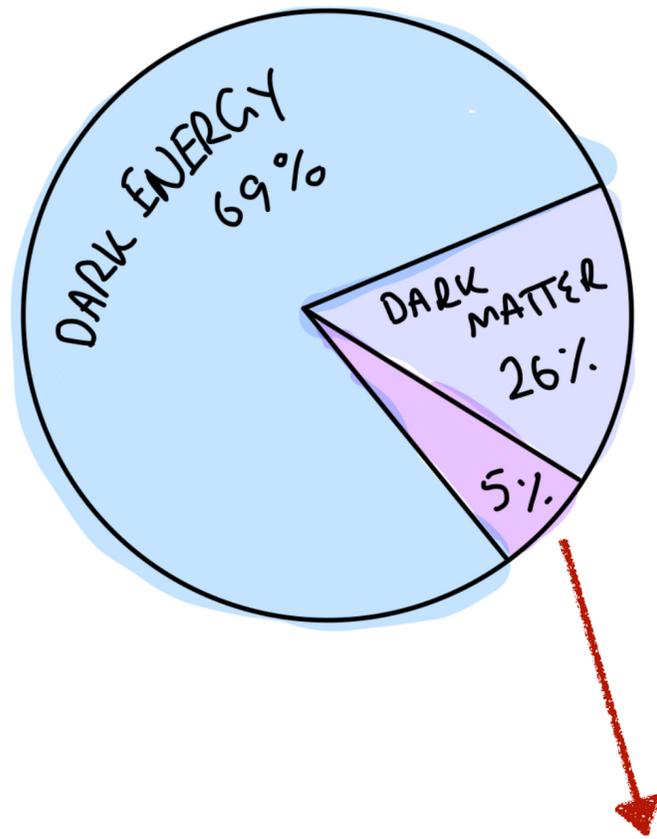
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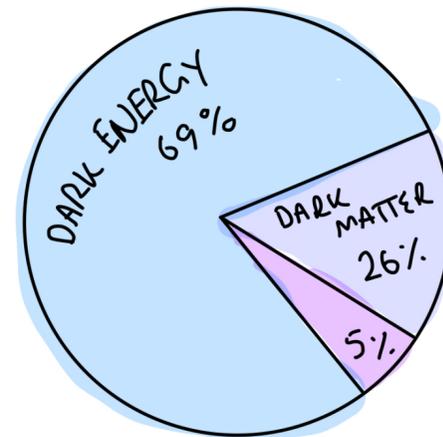- BUT neutrinos are not massless. We observe neutrino flavour oscillations. So any extended model which explains neutrino masses MUST have a source of LFV

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Beyond the SM lepton flavour *is* violated.

DM ($\subset$ BSM) interactions may also source LFV.

Ultralight Dark Matter

- Many exciting models for Dark Matter! spanning orders of magnitude in possible masses.

- If DM is *ultralight* ($m \ll 1\text{eV}$), then it must be a boson

  Tremain, Gunn 1979

- And it may be modeled as a wavelike. Our local DM field is modeled as a classical wave, misaligned from its potential minimum

Dark matter mass

$$\phi_{classical}(t) = \phi_0 \cos(m_\phi t + \delta)$$

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

- Oscillating with a period inversely proportional to the DM mass

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Ultralight LFV DM

Calibbi *et al* on LFV ALPs 2006.04795

+ other avenues of exciting work on expanding these searches!

- Simple case: consider an ultralight scalar.

- Now imagine this particle couples to SM fermions, irrespective of flavour

$$\mathcal{L} \supset \frac{\phi}{\Lambda} \bar{f}_i f_j$$

- Strong constraints from decays to missing energy searches, e.g. $\mu \to e\phi$, including energy loss in stellar environments

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What about the DM background?
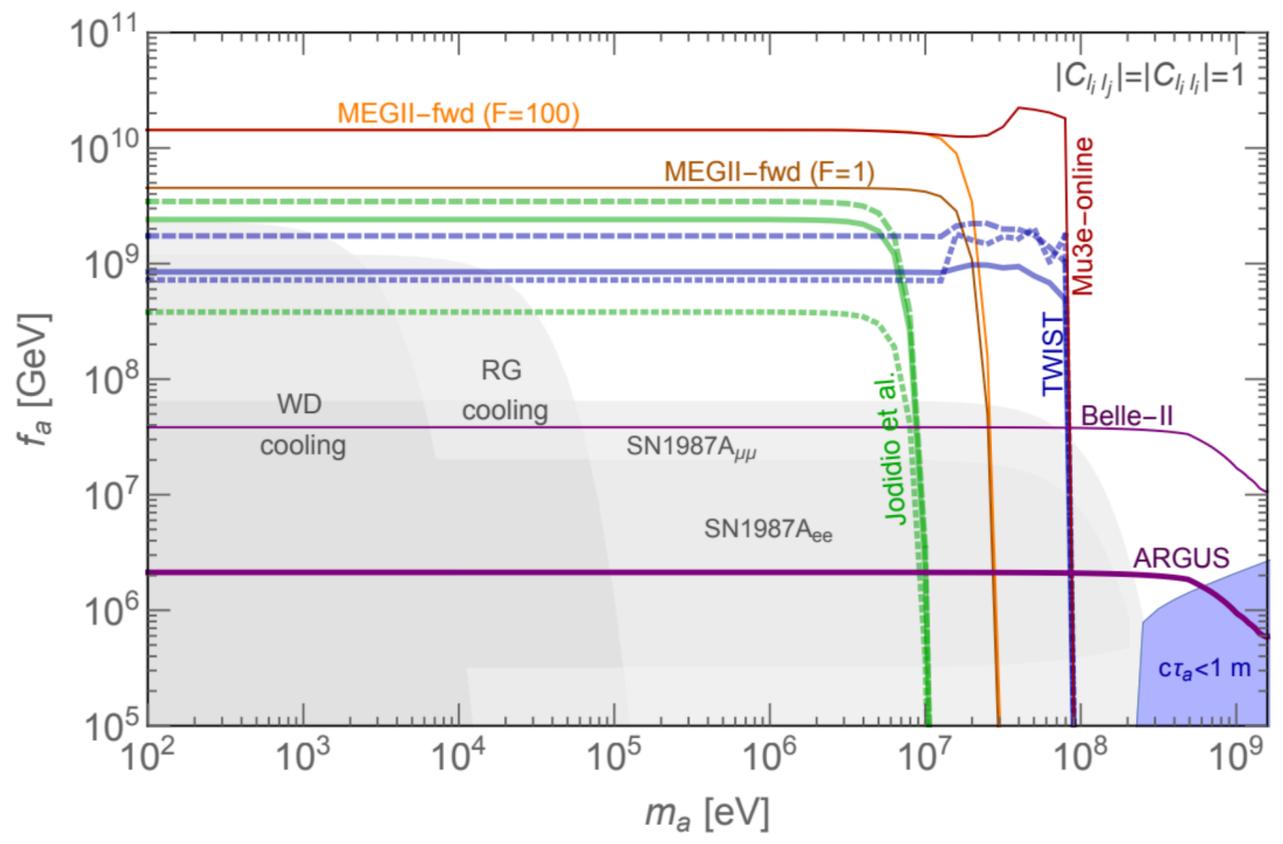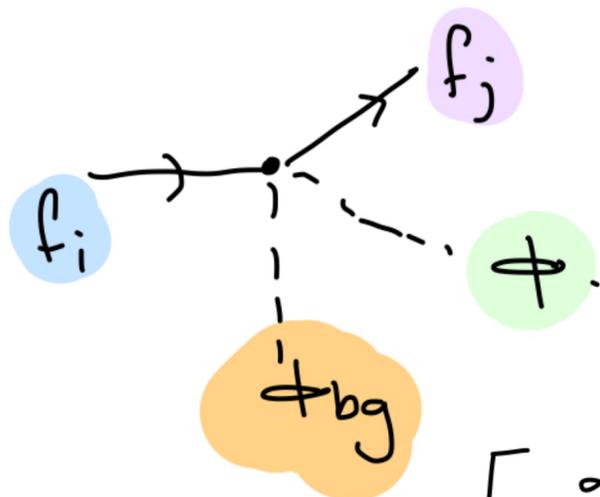
$$\mathcal{L} \supset \frac{\phi}{\Lambda^2} \bar{f_i} f_j \phi_{bg}$$

$$\Gamma \propto \frac{\phi_{bg}^2}{\Lambda^4} m_{f_i}^3$$

$$\sim \frac{\phi_0^2 \cos^2(m_\phi t)}{\Lambda^4} m_{f_i}^3$$

Observables:

- Mixing matrices modified by DM bg, see e.g. Berlin 1608.01307, Brdar ++1705.09455.

- Fundamental constants

- **Not yet considered LFV!**

- Consider a different phenomenology: a contribution to the decay to invisibles due to the presence of a DM background

- The decay rate picks up dependence on the DM density, but also picks up a modulation relative to the DM mass. Smoking gun: a modulating LFV signal!

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

- Relevant experimental time-scales!

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But wait…doesn't my mass blow up?

$$\mathcal{L} \supset \frac{\phi}{\Lambda^2} \bar{f_i} f_j \phi_{bg}$$

- Note that if the "invisible" field and the background DM field are the same, then the DM obtains a position-dependent mass correction
- Fine-tuning is… aesthetically unappealing. But fine-tuning with a dependence on the background DM density is very bad!

- This problem does not exist if we have two separate fields, only one of which has a classical background value.
- Regular old fine tuning then becomes a constraint, but an accomplishable hurdle

[e.g. pions in the SM, coupling to charged leptons.]

- Consider a theory invariant under a group G, broken to a subgroup H. G/H coset, $U(\phi) = \exp(i\phi_a T_a)$ consists of several scalar pNGBs with nonlinear interactions

$$\mathcal{L}_{\text{int}} \supset \text{Tr}\left(QU^\dagger i\partial_\mu U\right)\bar{\ell}_i\gamma^\mu(\tilde{C}^V_{\ell_i\ell_j} + \tilde{C}^A_{\ell_i\ell_j}\gamma_5)\ell_j + \text{h.c.}$$
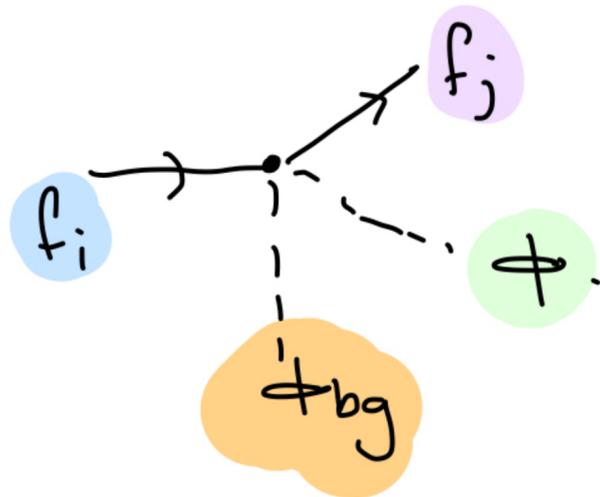
under G transformations, $U(\phi) \to V_L^\dagger U(\phi)V_R$

- Q is a spurion of $G \to H$ symmetry breaking. This interaction remains invariant under the shift symmetry, $U \to e^{-i\alpha}U$, where $\alpha = \alpha_a T_a$ (protects scalar masses!)
- Exponentiating, where f is the scale of symmetry breaking

Note $\phi_1 \neq \phi_2$, so need multiple fields!

$$\mathcal{L}_{\text{int}} \supset \left(\frac{\phi_1}{f}\frac{i\partial_\mu\phi_2}{2f} - \frac{\phi_2}{f}\frac{i\partial_\mu\phi_1}{2f}\right)\bar{\ell}_i\gamma^\mu(C^V_{\ell_i\ell_j} + C^A_{\ell_i\ell_j}\gamma_5)\ell_j + \text{h.c.}$$

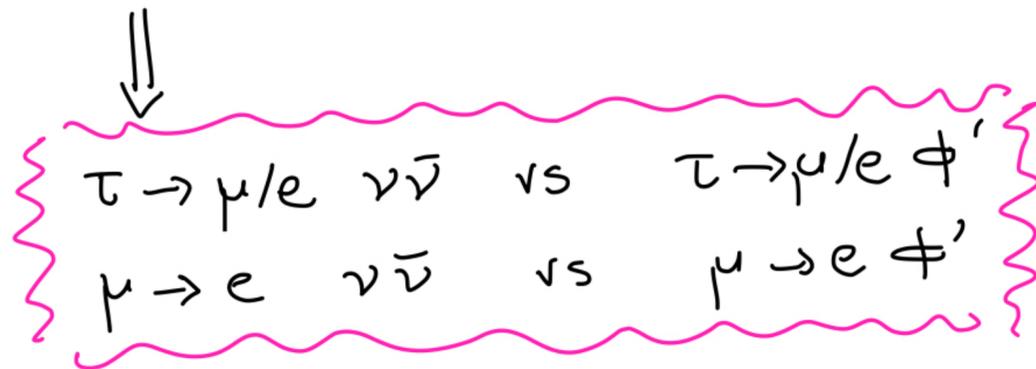$\mathcal{L} \supset \frac{\phi}{\Lambda^2}\bar{f}_i\, f_j\, \phi_{bg}$

[Sorry I can't find my ipad to do equation drawings for this slide, :( ]

Observables: time-dependent LFV

$$\mathcal{L} \supset \frac{i\,\Phi\,(\partial_r \Phi')\,\overline{l}_i\, \partial^r l_j}{2f^2}$$

dark matter

scalar final state.

$$\left(\begin{array}{l} \text{e.g.} \quad \Phi, \Phi' \text{ pnGB of} \\ \text{non-Abelian global symmetry.} \\ \text{a lá pions in SM.} \end{array} \right)$$

$$\Downarrow$$

$$\tau \to \mu/e \;\; \nu\bar{\nu} \quad \text{vs} \quad \tau \to \mu/e\, \Phi'$$
$$\mu \to e \;\; \nu\bar{\nu} \quad \text{vs} \quad \mu \to e\, \Phi'$$

- With a particular (effective) model in mind, we can then re-examine the existing searches for decays to invisible final states *[TBC: Cosmology and other effects. Work in progress]*

- We now predict a modulating signal over a temporally flat SM background.

- IDEA: If the data for a traditional LFV search is now time-binned we now have the opportunity to not just constrain the presence of the decay, but also the presence of modulation.

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$$Br(\mu \to e \, \phi) \propto \frac{\phi_0^2}{f^4} \frac{m_\tau^3}{\Gamma_\mu} \cos^2(m_\phi t)$$

Possible to measure period and amplitude:
disentangle mass and energy-scale!

$$Br(\mu \to e\, \phi) \propto \frac{\phi_0^2}{f^4} \frac{m_\tau^3}{\Gamma_\mu} \cos^2(m\phi t)$$
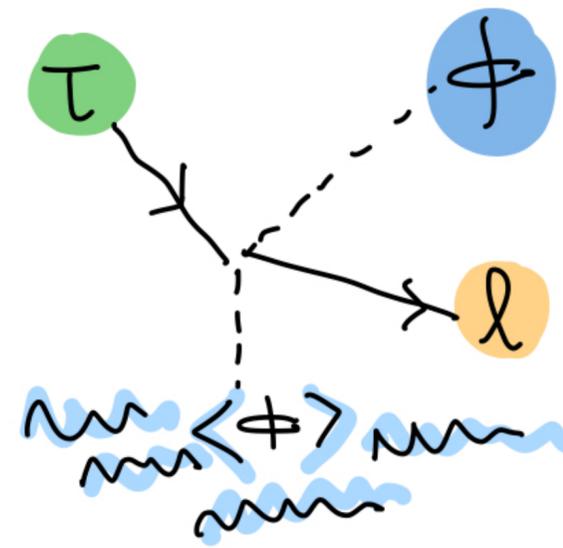
Possible to measure period and amplitude: disentangle mass and energy-scale!

…a post champagne achievement!

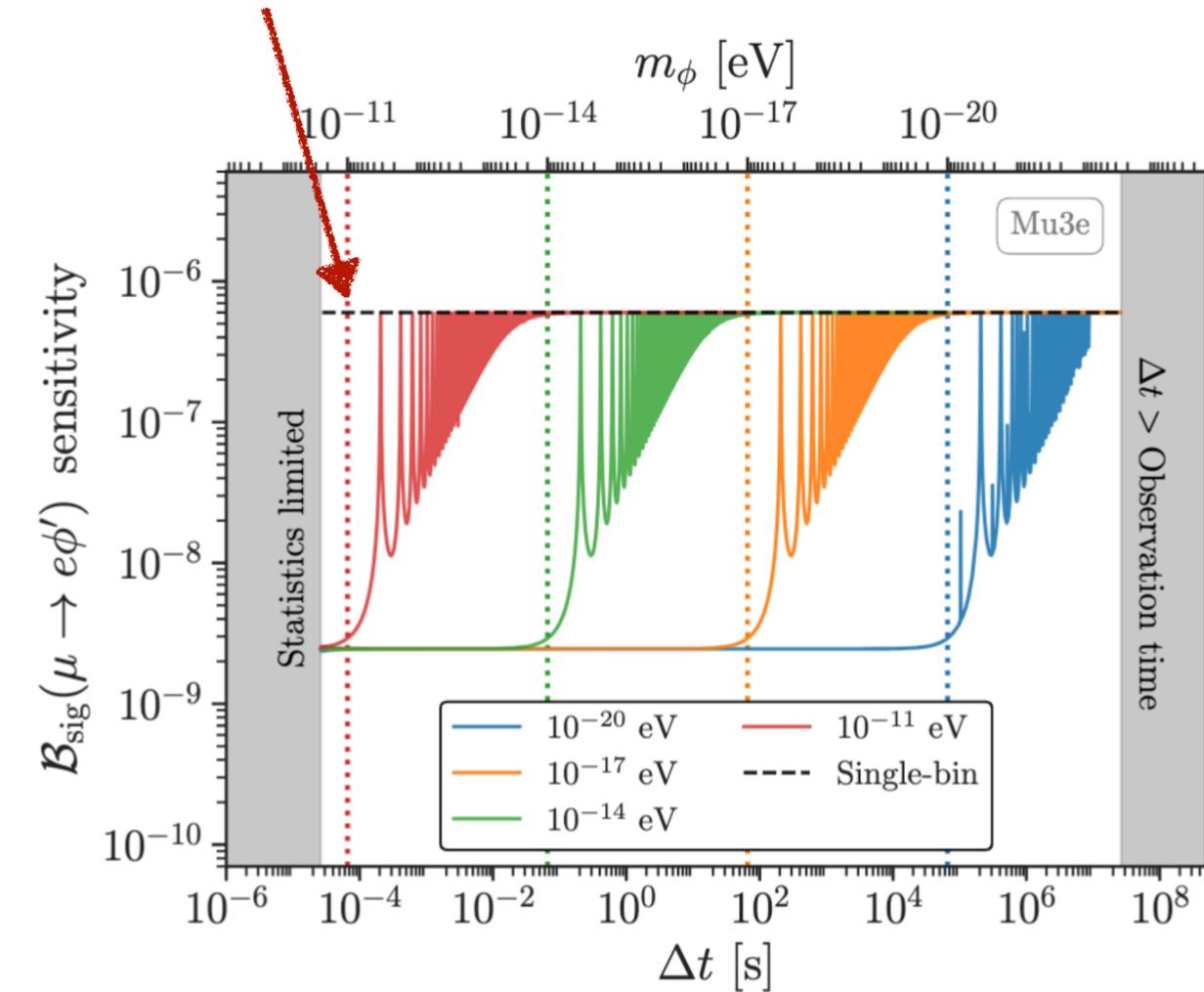# What can we do with LFV to invisible searches **before** we observe LFV in charged leptons?

What can we do with LFV to invisible searches **before** we observe LFV in charged leptons?

…different types of searches?! Oscillating signal over large SM (Michel spectrum) bg!

Improvement from time-binning

Time-independent constraint

- Assume: background dominates signal, and has no time modulation

- Construct χ^2 test statistic, assuming a fixed relative systematic uncertainty, translates to bounds on signal BR
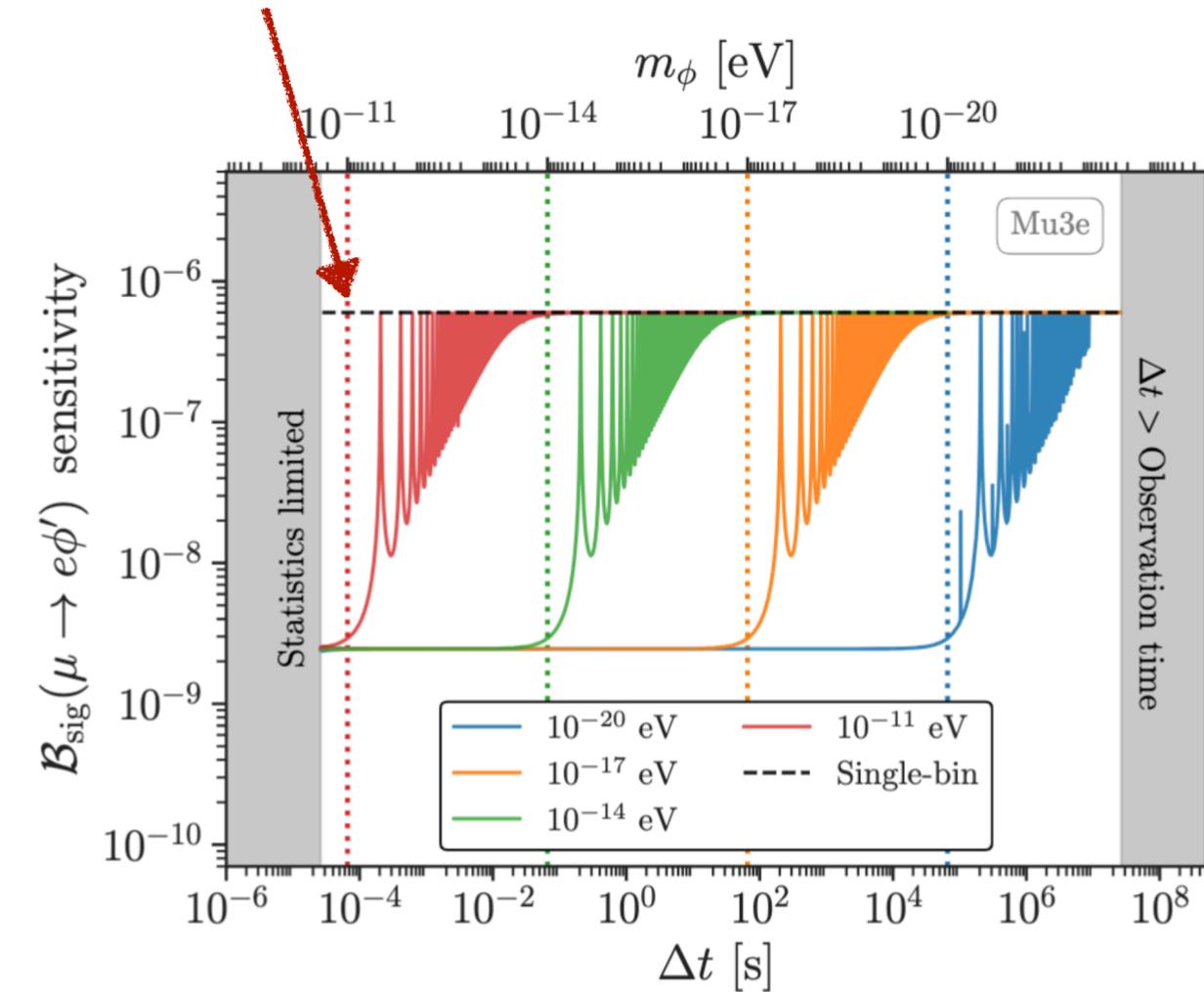
$$\sigma_{\text{stat}} = \sqrt{N_{\text{bg}}/n_{\text{bin}}} \qquad \sigma_{\text{sys}} = \alpha N_{\text{bg}}/n_{\text{bin}}$$

- ($\leftarrow$) Sensitivity to average BR, reach as a function of the bin size Δt (lower x) for different scalar mass models

$$\text{Br} \, (\mu \rightarrow e\, \phi) \propto \frac{\phi_0^2}{f^4} \frac{m_r^3}{\Gamma_\mu} \cos^2(m_\phi t)$$

Improvement from time-binning

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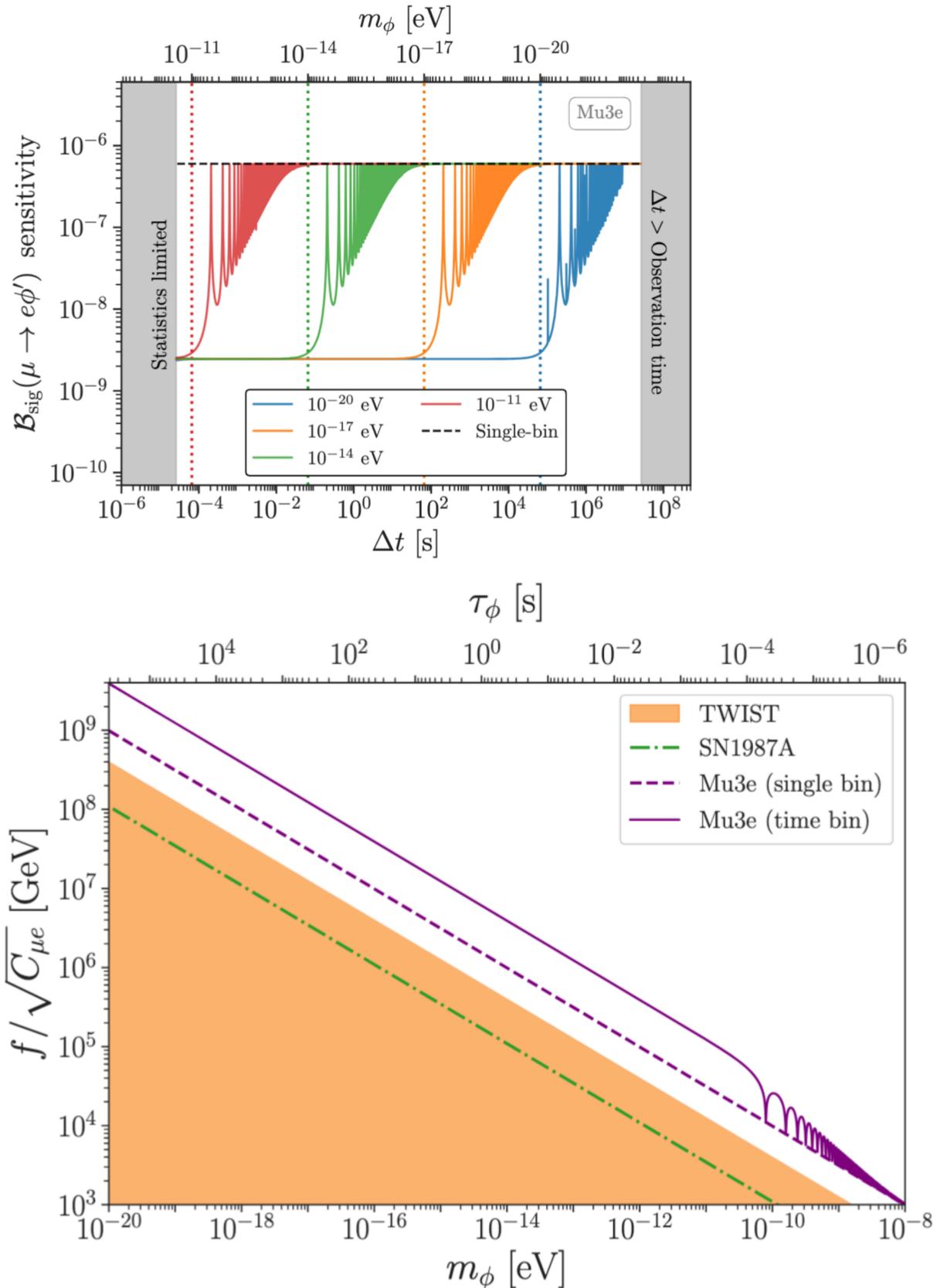- Once the bin size reaches the **characteristic length defined by the DM mass**: maximum improvement in sensitivity

$$m_\phi \Delta t \ll 1, \quad m_\phi T \gg 1$$

"Fine-binned and many oscillations in obs time"

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

Max improvement if sys dominates of statistic!

- **Background rate measured in situ in low signal rate bins, reducing associated uncertainties**

$$Br \, (\mu \to e \, \phi) \propto \frac{\phi_o^2}{f^4} \frac{m_r^3}{\Gamma_\mu} \cos^2(m_\phi t)$$

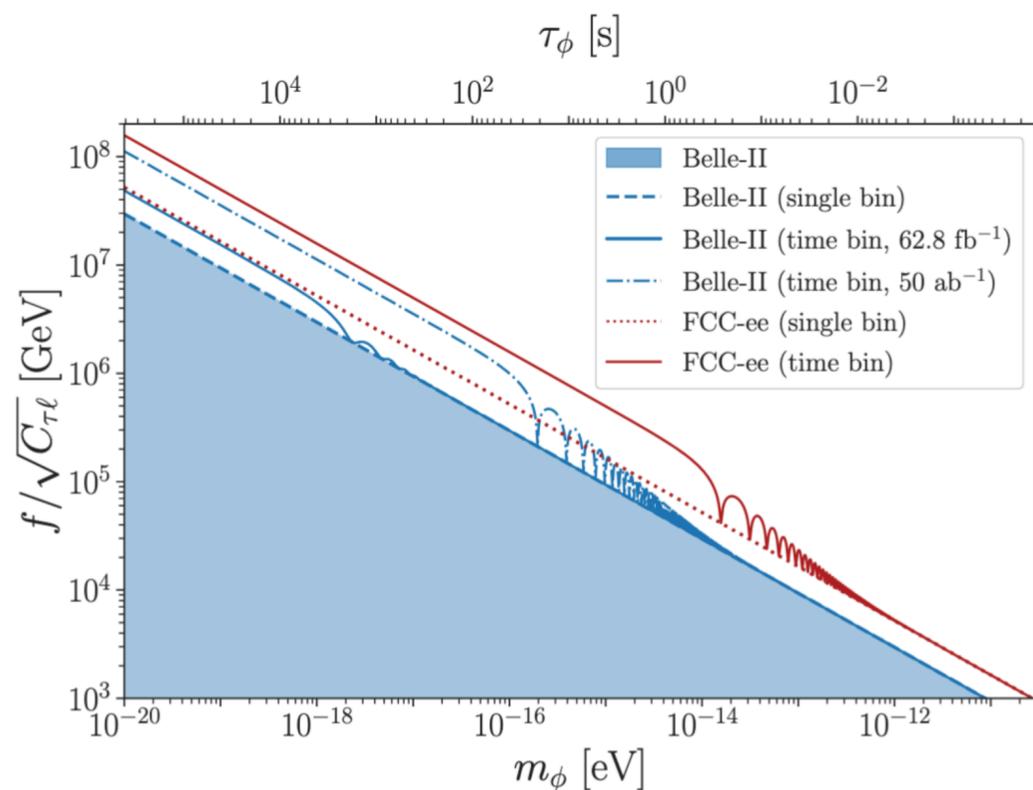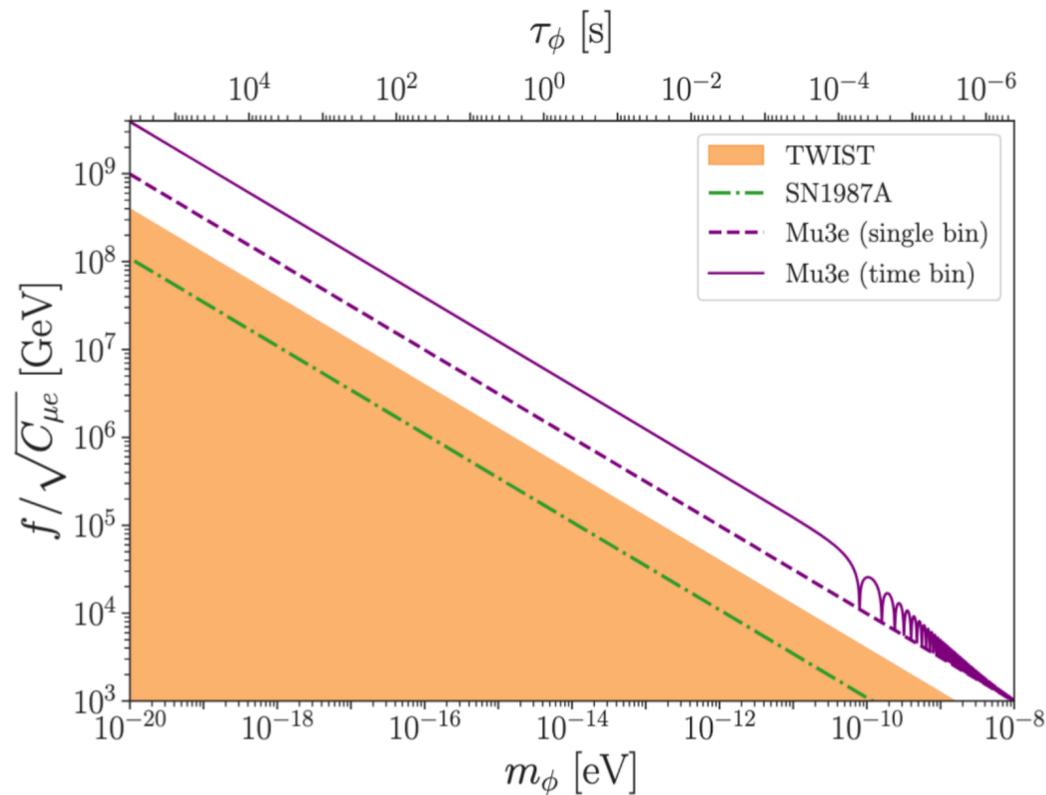Innes Bigaran, Lepton Photon 2025, August 26 2025

Time-binning sensitivity

$$Br\,(\mu \to e\,\phi) \propto \frac{\phi_0^2}{f^4}\,\frac{m_\mu^3}{\Gamma_\mu}\,\cos^2(m_\phi t)$$
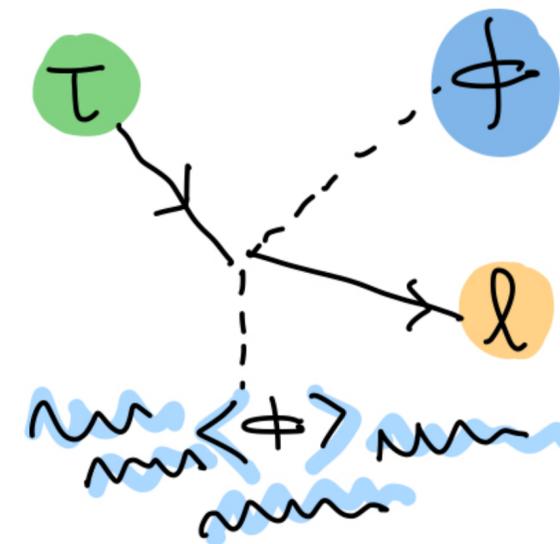
- Results in multiple orders of magnitude improvement in time-average BR reach

- Translating this to an effective symmetry-breaking scale for our pNGB~ order of magnitude improvement in reach

Adding time-binning to data collection: significantly improve the reach of existing experimental searches!

Conclusions

- Dark Matter could very well violate lepton flavour: well motivated!

- If DM is ultralight, bosonic and wavelike: modulation inversely proportional to the DM mass inherited by seeded decay rates: novel phenomenology!

- So long as systematics are time-independent and signal modulates, adding appropriate time-binning to LFV decays to invisible particles permits leading constraints on ultralight LFV dark matter

IB, Fox, Gouttenoire, Harnik, Krnjaic, Menzo, Zupan 2503.07722

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