CHALLENGING BSM SEARCHES WITH TAUS

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based on work with I. Bigaran, P. Fox, Y. Gouttenoire, R. Harnik, J. Kopp, G. Krnjaic, T.Menzo, 2412.nnnnn

2024 Belle II Physics Week, KEK, Aug 16 2024

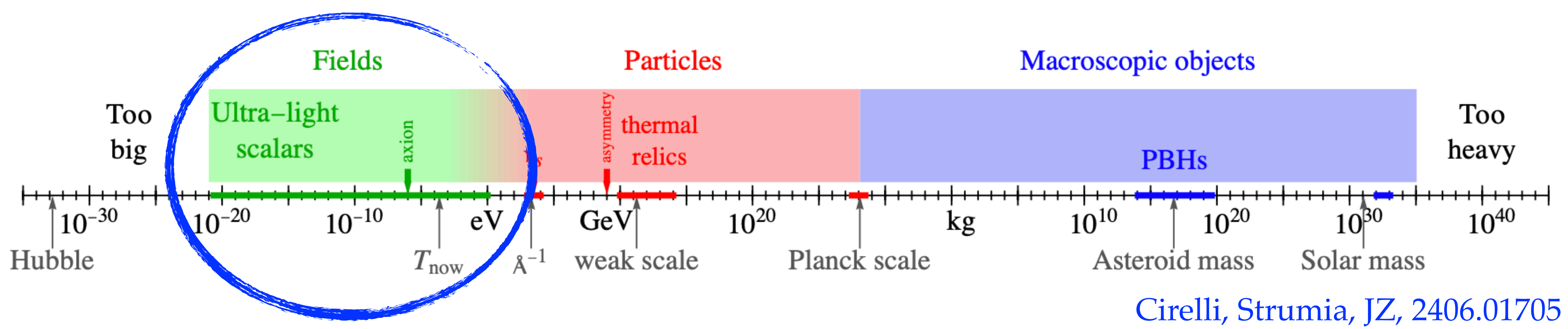
GOAL

see, e.g., review by Cirelli, Strumia, JZ, 2406.01705

- diagonal couplings to light DM $\bar{\psi}_i \psi_i \phi_{\rm DM}$
  $\Rightarrow$ time dependent signals
  - time-varying constants of nature, $\alpha_{\rm em}$
  - time-varying electron, proton, neutron masses
- any implications for flavor violating transitions?

GOAL

- yes! DM could be discovered in FCNCs
  - for instance, in $\tau \to \mu + \text{inv}$
  - here, interested in very light DM
    - time dependent $\tau \to \mu + \text{inv}$ rate



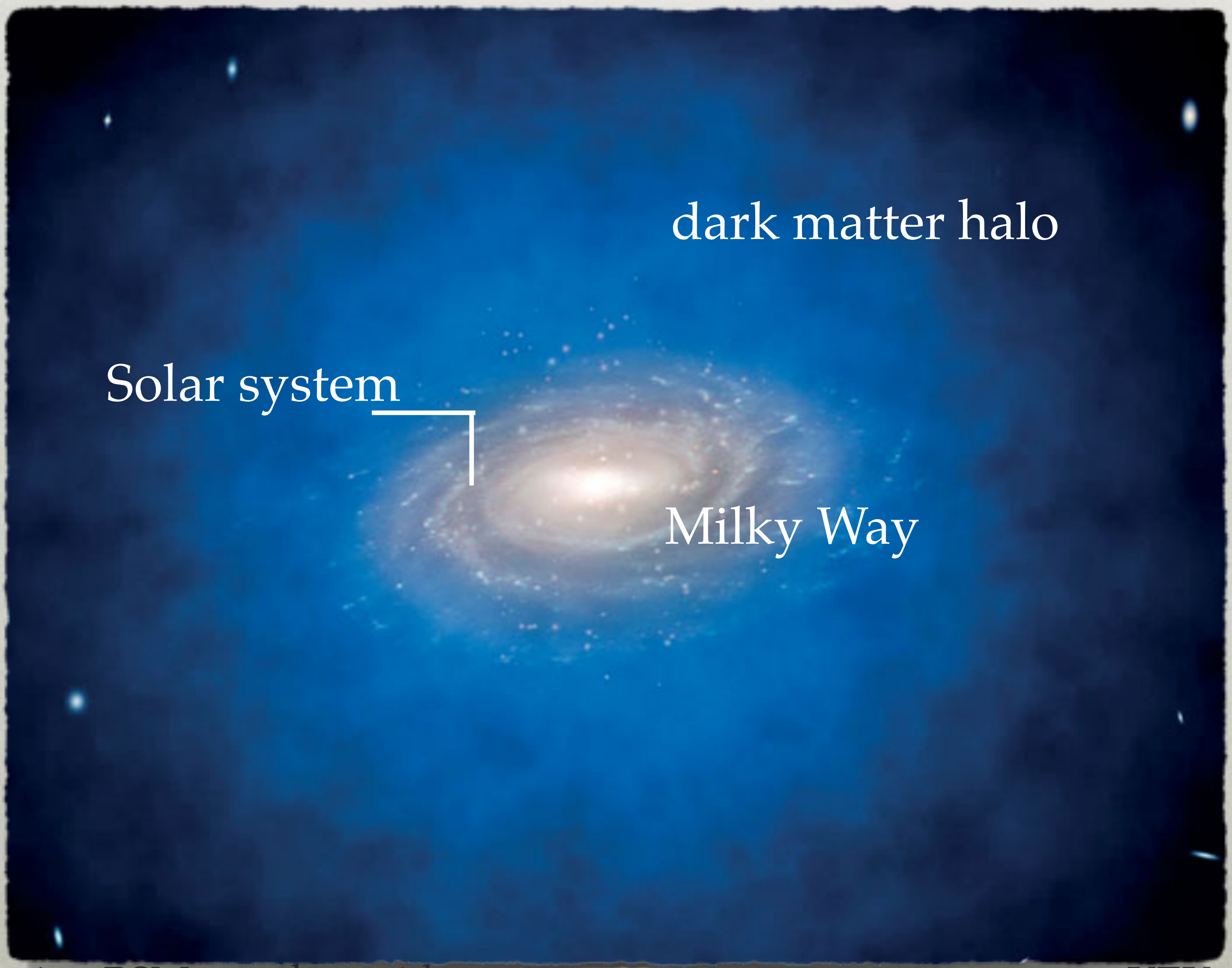
Cirelli, Strumia, JZ, 2406.01705

OUTLINE

- light DM and coherent background field oscillations
- light scalars
  - single axion-like particle
  - non-Abelian pNGBs
- time dependent FCNCs

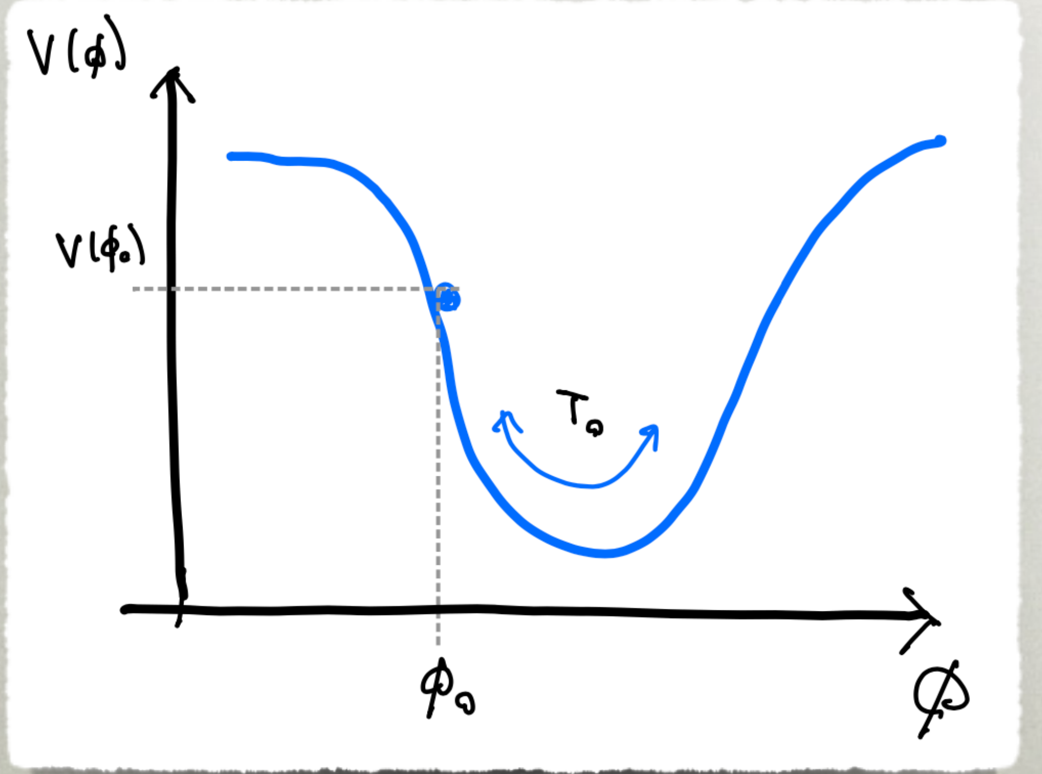
COHERENT OSCILLATIONS

- we are immersed in DM halo
  - non-relativistic DM particles $v \sim \mathcal{O}(10^{-3})$



COHERENT OSCILLATIONS

- local DM density $\rho_\phi = 0.4\,\mathrm{GeV/cm^3} \approx 3 \times 10^{-42}\,\mathrm{GeV}^4$
- bosonic DM of mass $m_\phi \lesssim 30\,\mathrm{eV}$
  - highly degenerate: many DM particles per de Broglie volume, $n_{\mathrm{DM}}(m_\phi v)^3 \gg 1$
  - well approximated by oscillating wave $\phi_{\mathrm{cl}}(t)$



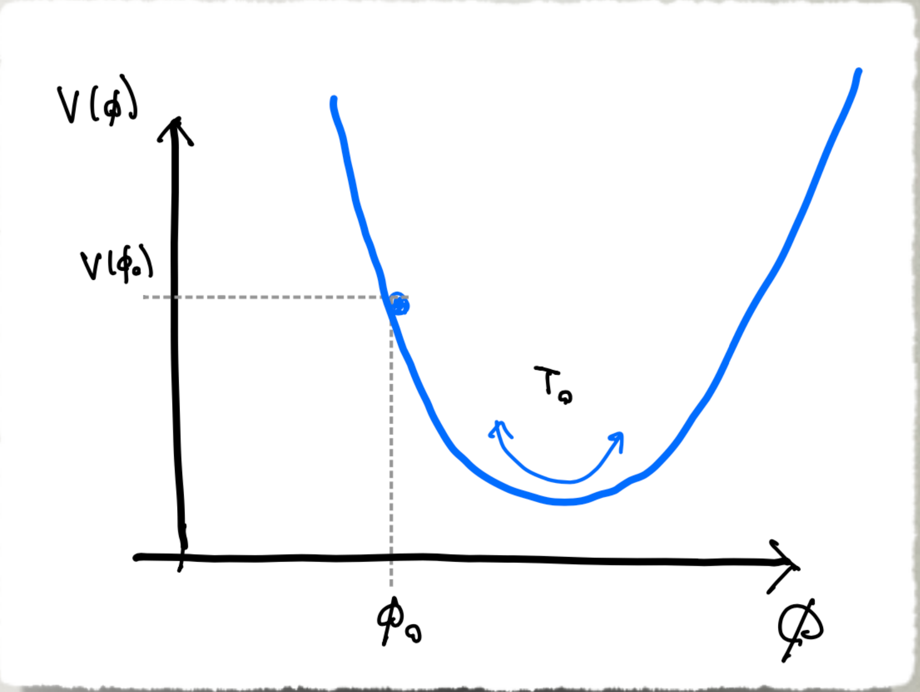
Amplitude:

$$\rho_\phi = V(\phi_0),$$

Oscillation period:

$$T_0 = 2\sqrt{2}\int_0^{\phi_0} \frac{d\phi}{\sqrt{V(\phi_0) - V(\phi)}}.$$

COHERENT OSCILLATIONS



- example: quadratic potential

$$V_{\rm quad}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 .$$

- harmonic oscillations

$$\phi_{\rm cl}(t) = \phi_0 \cos(m_\phi t + \delta) \quad , \quad \phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} ,$$

  - note: oscillation amplitude larger for lighter DM

$$\phi_0 \simeq 2.5\,{\rm TeV} \left(\frac{10^{-15}\,{\rm eV}}{m_\phi} \right),$$

  - oscillation frequency given by the DM mass $T_0 = 2\pi/m_\phi$

$$T_0 \simeq 4.1\,{\rm ns} \left(\frac{1\,\mu{\rm eV}}{m_\phi} \right) \simeq 4.1\,{\rm s} \left(\frac{10^{-15}\,{\rm eV}}{m_\phi} \right) \simeq 16\,{\rm month} \left(\frac{10^{-22}\,{\rm eV}}{m_\phi} \right).$$

- couplings $\bar\psi_i \psi_j \phi^n \to n \bar\psi_i \psi_j \phi_{\rm cl}^{n-1} \phi$ ⇒time dependent $\psi_j \to \psi_i \phi$ decays
  - $\Gamma(\psi_j \to \psi_i \phi) \propto \cos^{2(n-1)}(m_\phi t)$

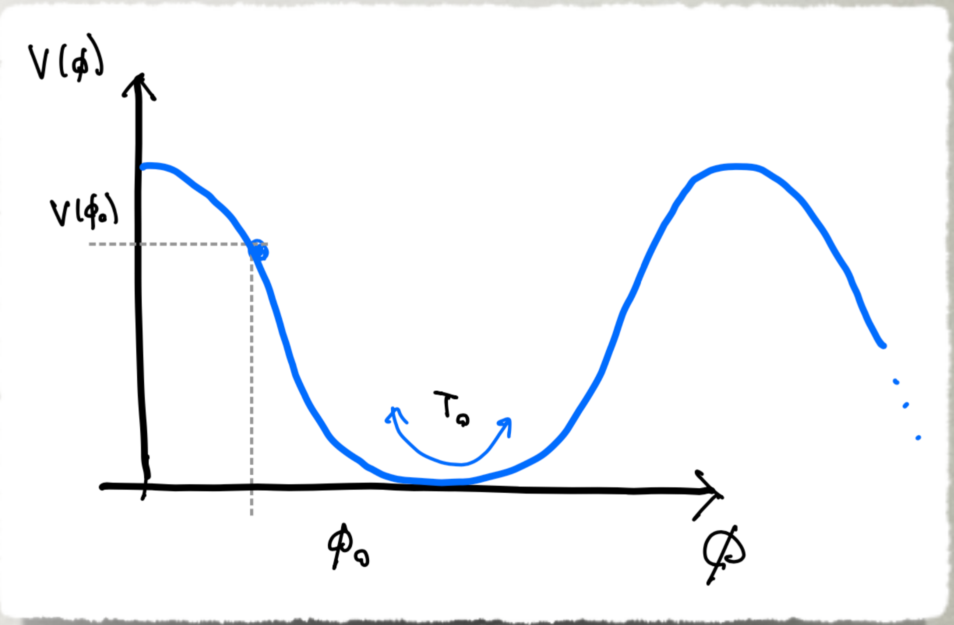
note: $\bar\psi_i \psi_j \phi \Rightarrow$ no time dependence
need at least $\bar\psi_i \psi_j \phi^2$

COHERENT OSCILLATIONS

- example: axion-like potential

$$V_{\text{ALP}}(\phi) = m_\phi^2 f^2 \left(1 - \cos\frac{\phi}{f}\right),$$

  - note: for fixed $f \Rightarrow$ max. DM density is $\rho_\phi^{\max} = m_\phi^2 f^2$



- anharmonic oscillations
  - oscillation period $$T_0 = \frac{2\pi}{m_\phi}\left(1 + \frac{1}{16}\phi_0^2 + \cdots\right)$$
  - amplitude of oscil. $$\phi_0 = f\cos^{-1}\left(1 - \frac{\rho_\phi}{m_\phi^2 f^2}\right).$$
- note: ϕ_0 at most $$\phi_0^{\max} = \frac{\pi}{2} f.$$

LIGHT SCALAR?

- why can ϕ be light?
  - if a pNGB of a global spontaneously broken symmetry
    - $\Rightarrow$ shift symmetry $\phi \to \phi + \delta$
    - $\Rightarrow$ mass m_ϕ protected
- three limits
  - a single axion-like particle
  - non-Abelian pNGBs
  - general light scalar

SINGLE ALP

- pNGB from spont. broken global U(1)
- the most general interaction at low energies starts at dim-5

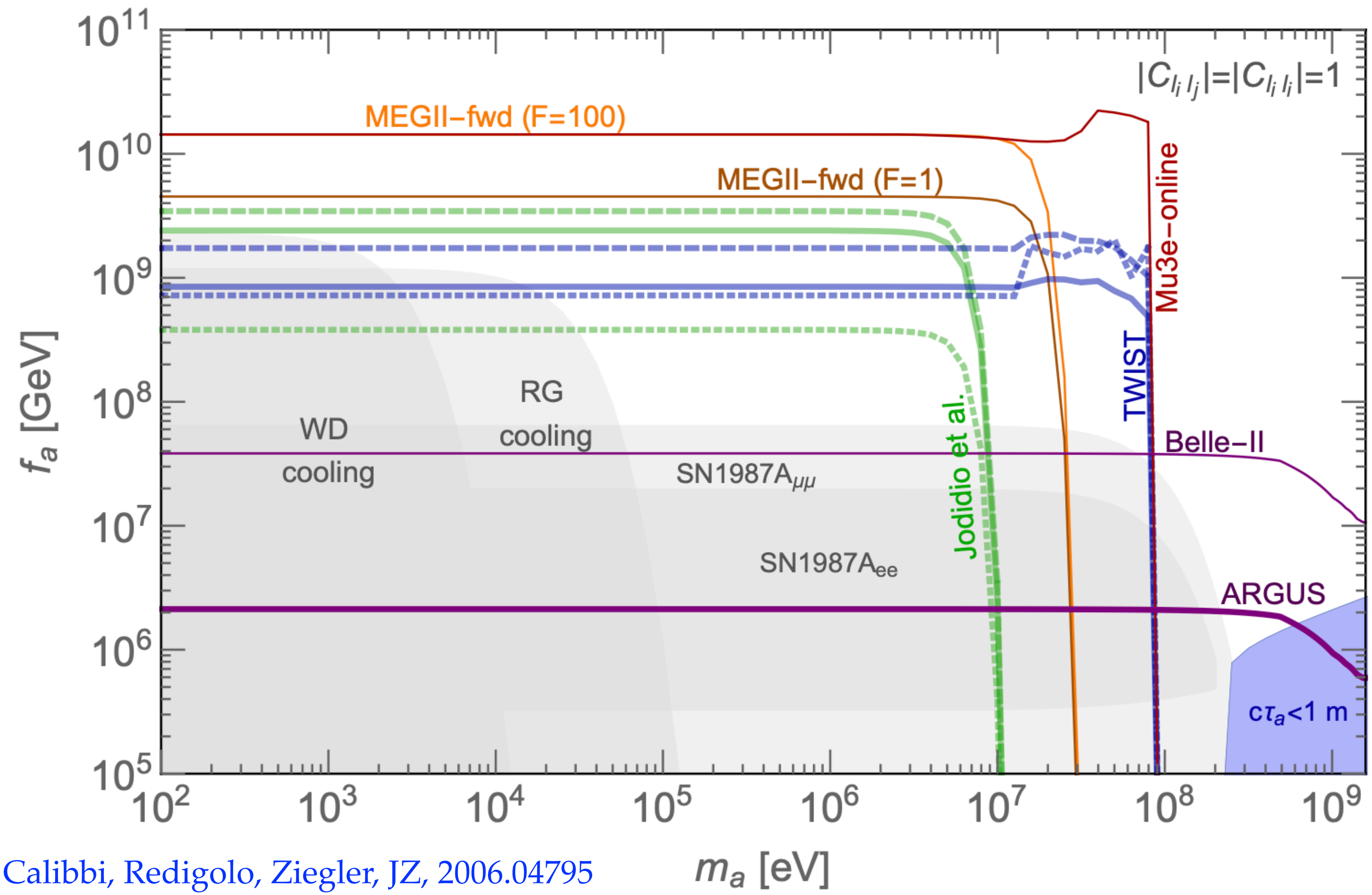
$$\mathcal{L}_{\rm int} = \frac{\partial_\mu \phi}{2f}\, \bar\psi_i \gamma^\mu (C^V_{\psi_i\psi_j} + C^A_{\psi_i\psi_j}\gamma_5)\psi_j + c_g \frac{\phi}{f}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde G^{a\mu\nu} + c_\gamma \frac{\phi}{f}\frac{\alpha_{\rm em}}{8\pi} F_{\mu\nu}\tilde F^{\mu\nu}$$

- if m_ϕ due to explicit breaking of shift symmetry also higher order terms

$$\mathcal{L}_{\rm int} \supset \sum_n \frac{m_\phi}{f}\left[\left(\frac{\phi}{f}\right)^n \bar\psi_i (C^{S(n)}_{\psi_i\psi_j} + C^{P(n)}_{\psi_i\psi_j}\gamma_5)\psi_j + c_g^{(n)}\left(\frac{\phi}{f}\right)^n \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde G^{a\mu\nu} + c_\gamma^{(n)}\left(\frac{\phi}{f}\right)^n \frac{\alpha_{\rm em}}{8\pi} F_{\mu\nu}\tilde F^{\mu\nu} + \cdots\right]$$

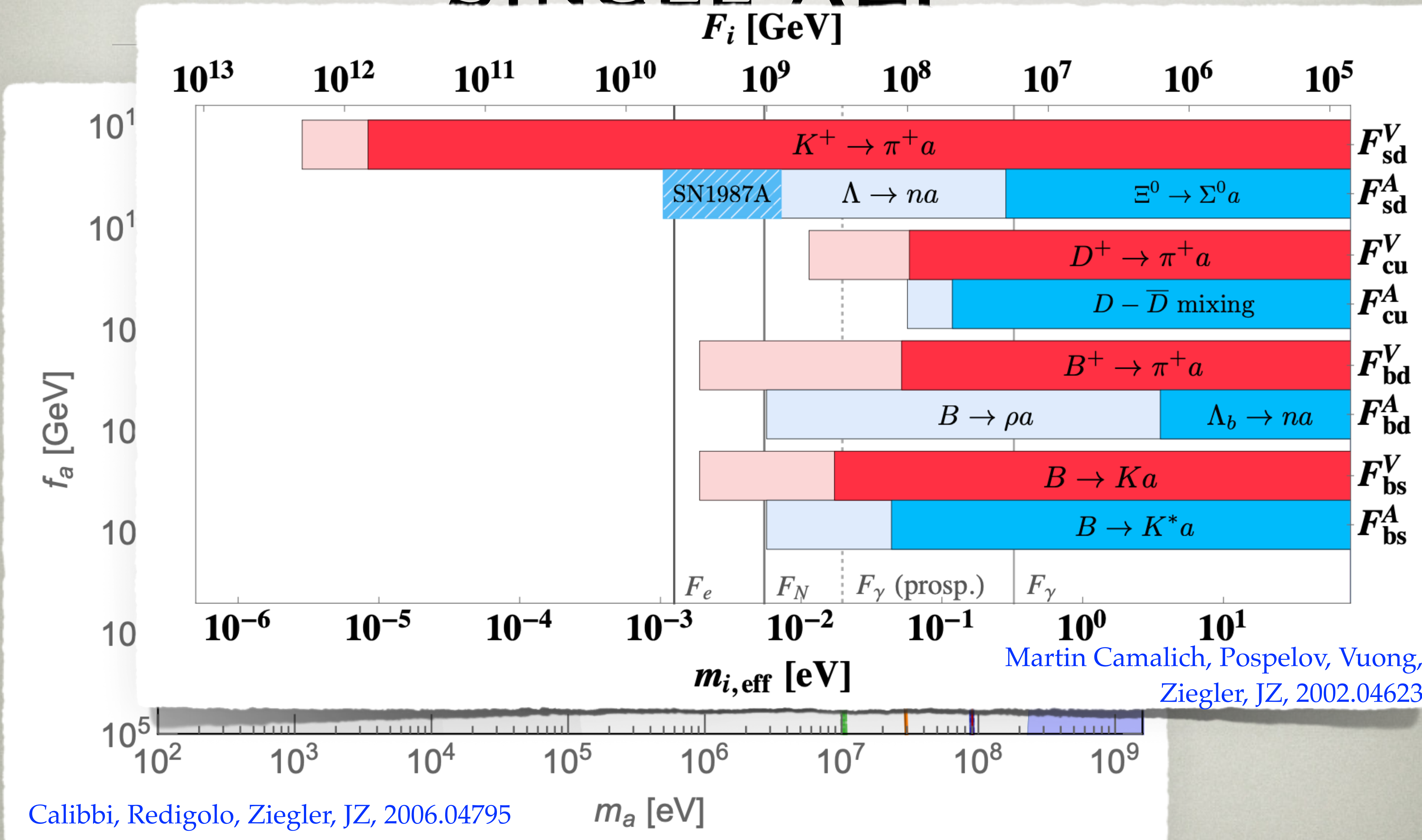
- for these to be comparable to dim-5 terms requires $\phi_0 \gg f$
  - $\Leftarrow$ hard to arrange in any realistic model
  - $\Rightarrow$time dependence of $\psi_i \to \psi_j\phi$ decays highly suppressed

SINGLE ALP



Calibbi, Redigolo, Ziegler, JZ, 2006.04795

single ALP



Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

non-Abelian pNGB

- consider $G \to H$ breaking
- where pNGBs in G/H coset $U(\phi)$ have non-linear interactions
  - low energy interaction start as

$$\mathcal{L}_{\rm int} \supset {\rm Tr}\left(U^\dagger i\partial_\mu U\right)\bar\psi_i\gamma^\mu(\tilde C^V_{\psi_i\psi_j}+\tilde C^A_{\psi_i\psi_j}\gamma_5)\psi_j + {\rm h.c.}$$

  - if no U(1) factors, interactions start at $\mathcal{O}(\phi^2)$

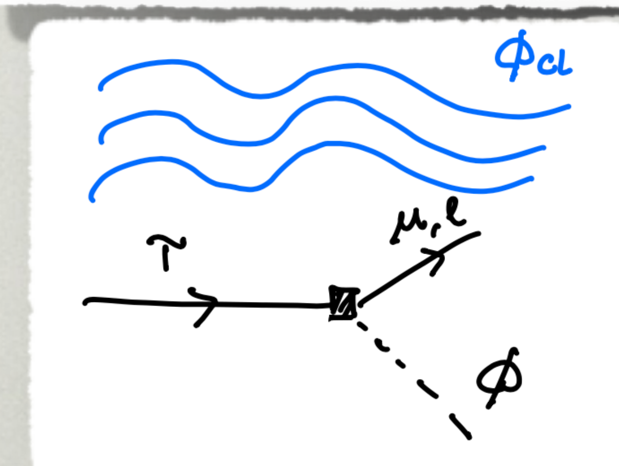
$$\mathcal{L}_{\rm int} \supset \sum_a \frac{\phi_a}{f}\frac{i\partial_\mu\phi_a}{f}\bar\psi_i\gamma^\mu(C^V_{\psi_i\psi_j}+C^A_{\psi_i\psi_j}\gamma_5)\psi_j + {\rm h.c.},$$

example from QCD+QED: $\pi^+\partial_\mu\pi^- J^\mu_{\rm em}$

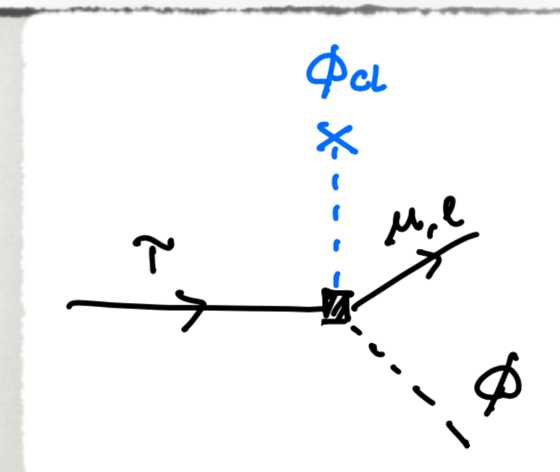
non-Abelian pNGB

- in the light DM background

$$\mathcal{L}_{\rm int} \supset \sum_a \frac{\phi_a}{f}\frac{i\partial_\mu \phi_a}{f}\bar\psi_i\gamma^\mu(C^V_{\psi_i\psi_j}+C^A_{\psi_i\psi_j}\gamma_5)\psi_j + \text{h.c.},$$



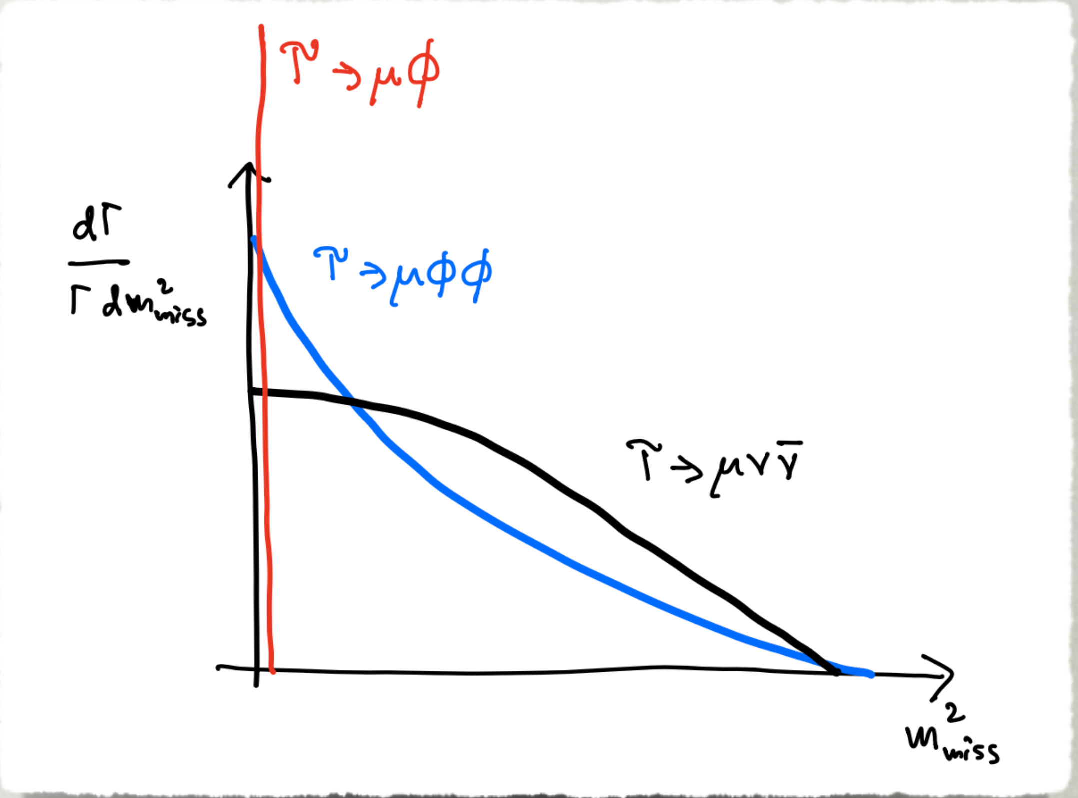
$\Downarrow$



$$\mathcal{L}_{\rm int} \supset \frac{\phi_{a,\rm cl}}{f}\frac{i\partial_\mu \phi_a}{2f}\bar\psi_i\gamma^\mu(C^V_{\psi_i\psi_j}+C^A_{\psi_i\psi_j}\gamma_5)\psi_j + \text{h.c.}$$

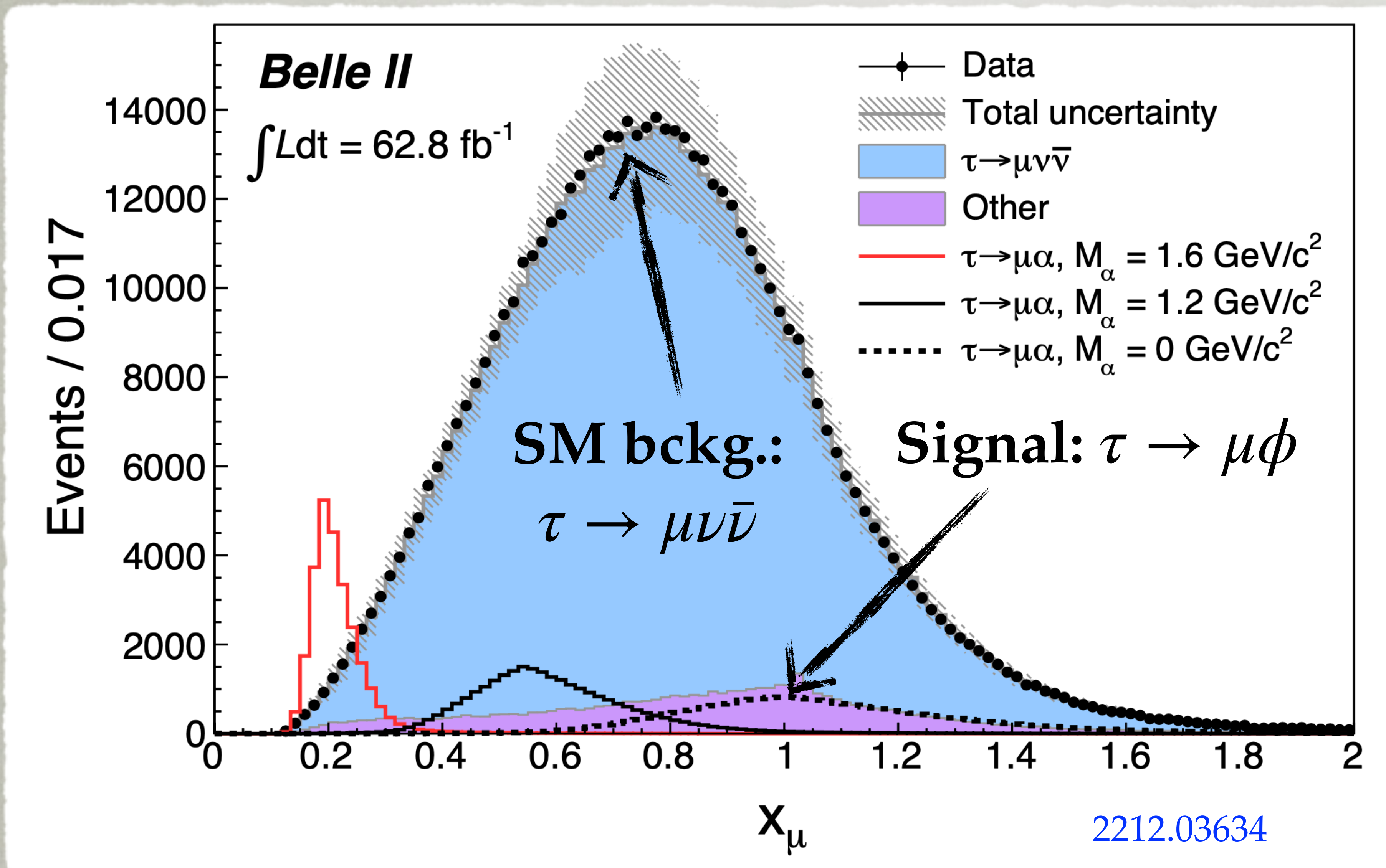
- induces time dependent FCNCs
- example: $Br(\tau \to \mu\phi) \propto \cos^2(m_\phi t)$

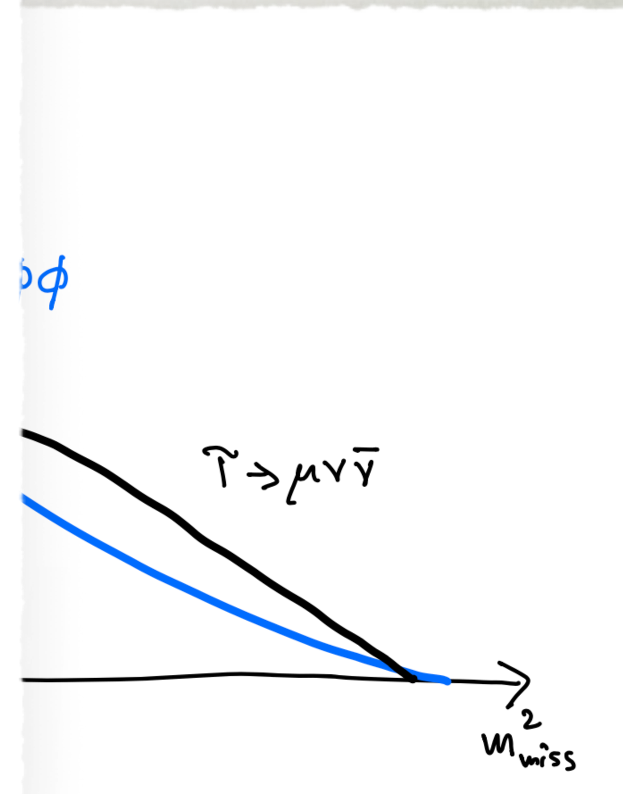
TIME DEPENDENT $\tau \to \mu\phi$



- interaction: $\phi\partial_\alpha\phi\bar{\tau}\gamma^\alpha\mu$
  - induces $\tau \to \mu\phi\phi$
    - three body decay, large background from $\tau \to \mu\nu\bar{\nu}$
    - very poor bound on f
  - DM background induces time dependent $\tau \to \mu\phi$
    - two body decay: mono-energetic μ in tau rest- frame
- tau decays additional complication
  - $e^+e^- \to \tau^+\tau^-$, at least one neutrino on tag side
  - not possible to reconstruct tau rest frame $\Rightarrow$ use pseudo rest-frame
  - time dependence of the signal helps
- same for $\tau \to e\phi$

$\rightarrow \mu\phi$





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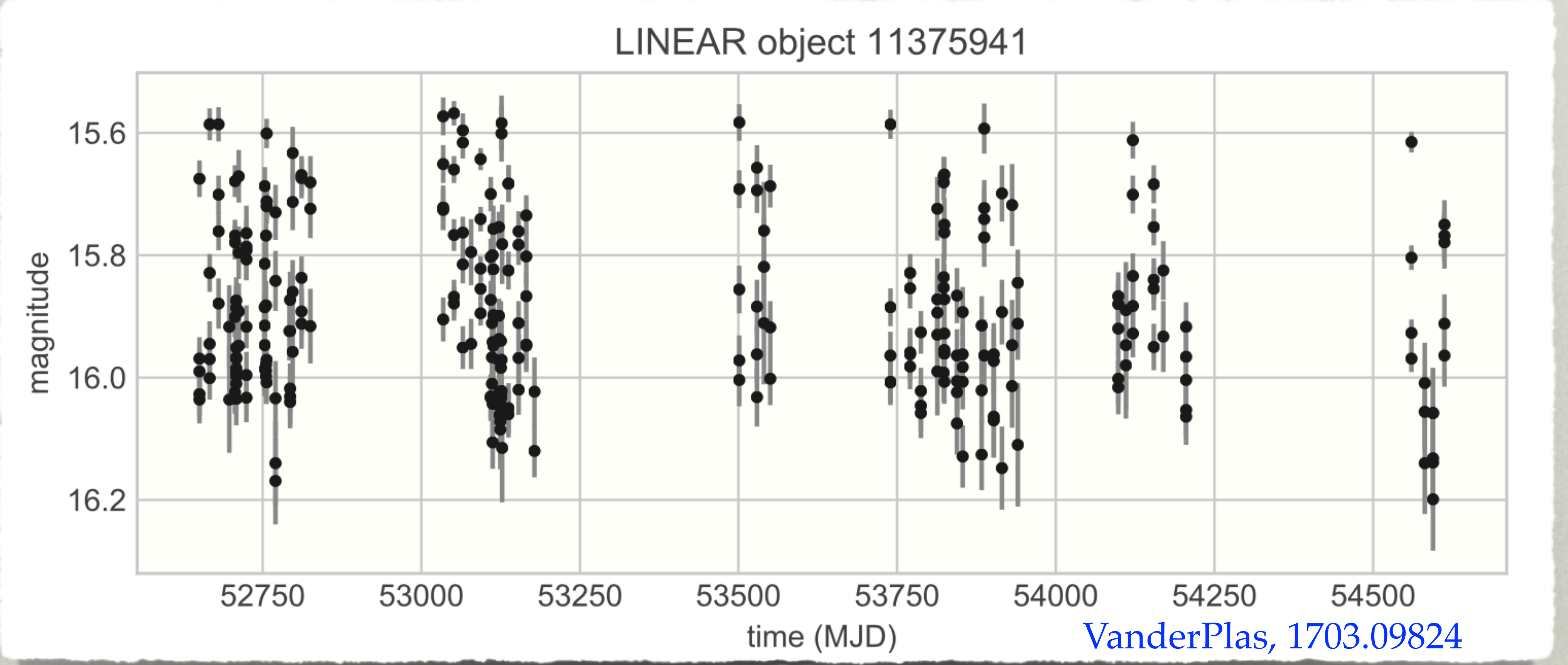
HOW TO SEARCH FOR PERIODIC SIGNALS

w/ Ilten et al, work in progress

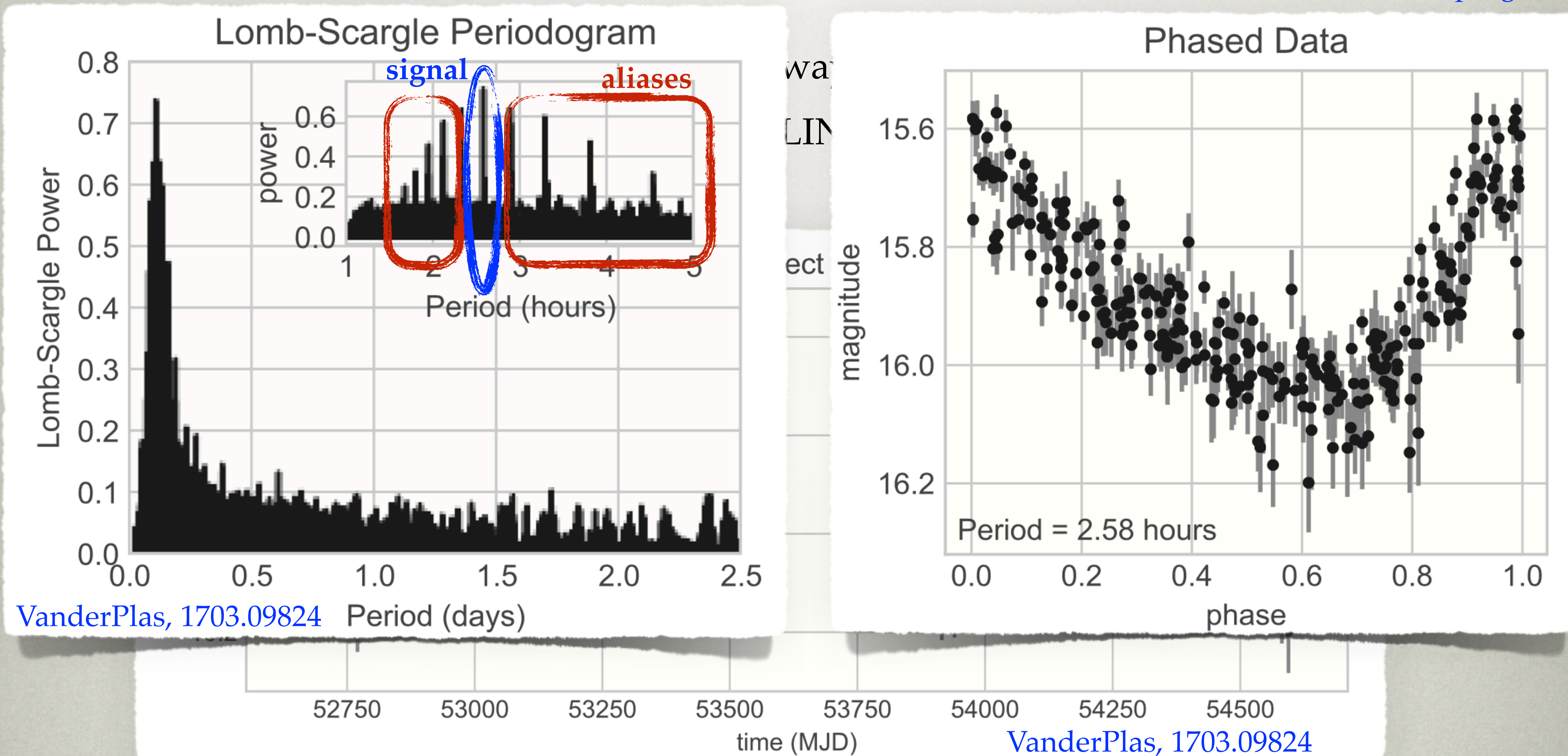
- Lomb-Scargle periodogram an efficient way of searching for periodic signals
  - example: observed light curve from LINEAR object ID 11375941



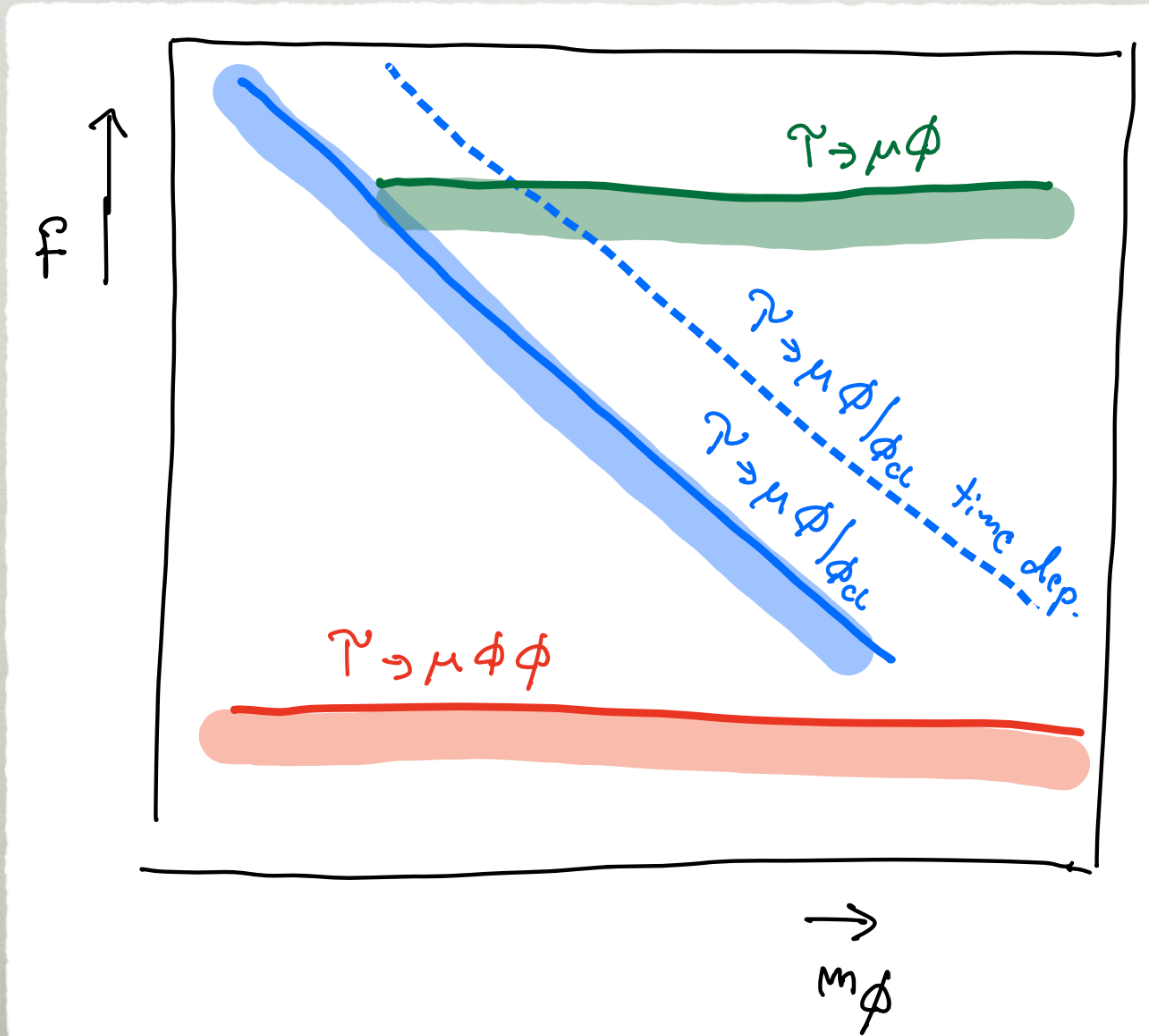
VanderPlas, 1703.09824

HOW TO SEARCH FOR PERIODIC SIGNALS

w/ Ilten et al, work in progress



TIME DEPENDENT $\tau \to \mu\phi$



TIME DEPENDENT SIGNALS

- any $\psi_i \to \psi_j \phi$ FCNC process now time dependent
  - $\mu \to e\phi$
  - $s \to d\phi$: $K^+ \to \pi^+\phi$, $K_{S,L} \to \pi^0\phi$, $K^+ \to \pi^+\pi^0\phi$, $\Lambda \to n\phi$,...
  - $c \to u\phi$: $D \to \pi\phi, \rho\phi$, $D_s \to K^{(*)}\phi$, $\Lambda_c \to p\phi$,...
  - $b \to s\phi$:$B \to K^{(*)}\phi$, $\Lambda_b \to \Lambda\phi$, ...
  - $b \to d\phi$:$B \to \pi\phi$, $B \to \phi\phi$, $\Lambda \to n\phi$
- the coherence of the signal is $m_\phi / m_\phi v^2 \sim v^{-2} \sim 10^6$ oscillations
  - for month-scale oscillations only need time-stamps with precision of seconds
- in principle also contributions to FCNCs without missing energy
  - meson mixing, hadronic and leptonic meson decays

CONCLUSIONS

- we are immersed in DM background
- if DM light ⇒ coherently oscillating field
  - can be searched for through time dependent FCNC transitions
  - example: $\tau \to \mu\phi$ (+many more)

BACKUP SLIDES

Lomb-Scargle periodogram

- data with time-stamps, $y(t_i)$, $i = 1,\ldots,N$
- Lomb-Scargle power for frequency $f = \omega/2\pi$

$$P(f) = \frac{1}{2\sigma^2}\left(\frac{\left[\sum_{i=1}^N W_i\,(y(t_i)-\bar{y})\,\cos\,\omega(t_i-\tau)\right]^2}{\sum_{i=1}^N W_i\,\cos^2\,\omega(t_i-\tau)} + \frac{\left[\sum_{i=1}^N W_i\,(y(t_i)-\bar{y})\,\sin\,\omega(t_i-\tau)\right]^2}{\sum_{i=1}^N W_i\,\sin^2\,\omega(t_i-\tau)}\right)$$

  - $\bar{y}$ is weighted average, σ weighted variance of data
  - weights W_i are $W_i = \frac{1/\sigma_i^2}{\langle 1/\sigma_i^2\rangle}$
  - phase factor τ $\tan(2\omega\tau) = \frac{\sum_{i=1}^N W_i\,\sin\,2\omega t_i}{\sum_{i=1}^N W_i\,\cos\,2\omega t_i}$