Nelson-Barr ultralight dark matter

(non-QCD) Axion DM solving the strong CP problem

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Who cares ? & outline

(i) Different approach to CP violation (non-QCD axionic dark matter (DM))

(ii) It is testable & potentially correlates CKM oscillation \w signal @ clocks

- The strong CP & Nelson-Barr
- Phenomenology, flavor factories vs. nuclear clock
- Challenges
- An island or a continent ?

The strong CP problem

- 3 levels of formulating the strong CP problem: (for alternative view \w gravity see: Dvali (05, 22))

  $(i)\ \bar{\theta} = \theta - \arg\left[\det\left(Y_u Y_d\right)\right] \lesssim 10^{-10}$, is it a problem?

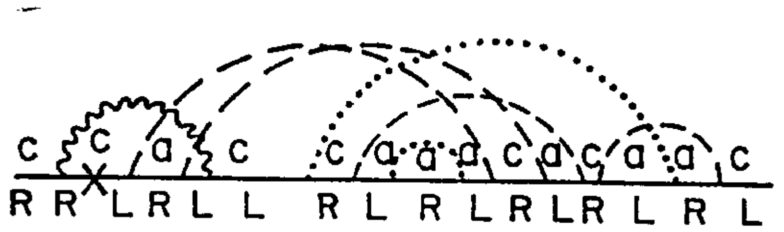
  (who knows?)

  $(ii)\ \bar{\theta} = \lesssim 10^{-10} \ll \theta_{\rm KM} = \arg\left\{ \det\left[Y_u Y_u^{\dagger}, Y_d Y_d^{\dagger}\right]\right\} = \mathcal{O}(1)$, is it a problem?

  (not if these are natural/protected and sequestered)

  $(iii)\ \bar{\theta} = \lesssim 10^{-10} \ll \theta_{\rm KM}$, but $\bar{\theta} = \bar{\theta}_{\rm bare} + \epsilon\, \theta_{\rm KM} \ln\left(\Lambda_{\rm UV}/M_W\right)$, is it a problem? Ex: Ellis & Gaillard (78))

  (ϵ appears in 7 loops and contains several other suppression factor)



- We should probably be be cautious [but should reach the $\mathcal{O}\left(10^{-16}\right)$ precision]

Solving the QCD problem ***not*** with QCD axion

- There's a class of models where CP is UV-sym' and at tree level we find:

$$\bar{\theta} = \theta - \arg\left[\det\left(Y_u Y_d\right)\right] = 0 \quad \& \quad \theta_{\rm KM} = \arg\left\{\det\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]\right\} = \mathcal{O}(1)$$

- This is realized if:

1. Yukawas are Hermitian (left-right models or wave function renorm')

Georgi; Mohapatra & Senjanovic (78); Hiller & Schmaltz (01); Harnik, GP, Schwartz & Shirman (04); Cheung, Fitzpatrick & Randall (08)

2. Structure/sym. => det(0), concretely, Nelson-Barr (NB) Nelson; Barr (84)

- We focus on NB, which are easy to control & of higher quality

Nelson-Barr ultralight DM (UDM)

$$\mathcal{L}_{\rm NB} = \mu\,\psi^c\,\psi + \left(g_i\,\Phi + \tilde{g}_i\,\Phi^*\right)u_i^c\,\psi + Y_u\,\tilde{H}\,Q\,u^c + Y_d\,H\,Q\,d^c$$

Bento, Branco & Parada (91)

- Assume approx' flavor sym' => $g_i \propto (1,0,0)$ & $\tilde{g}_i \propto (0,1,0)$ with $\Phi = \frac{f+\rho}{\sqrt{2}}\exp\left(\frac{ia}{f}\right)$; $\langle a\rangle \neq 0$

Dine, GP, Ratzinger, Savoray (24)

- Then a is a pseudo-Nambu-Goldstone-boson, with suppressed potential, but with $\langle a\rangle = 0$

- Furthermore, one can show that $\theta_{\rm KM} = \frac{a}{f}$

Involved the 1-2 generation

$$\left\{ m_u^{\rm eff} m_u^{\rm eff\dagger} \sim m_u \left[\mathbf{1}_3 + r\begin{pmatrix} 1 & e^{\frac{2ia}{f}} & 0 \\ e^{\frac{-2ia}{f}} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}\right] m_u^T \right\}$$

- Also, mixing angles develop quadratic dependence on a (but not masses)

Nelson-Barr ultralight-DM pheno

- In case another sector breaks the shift sym' (say Planck suppress or other) then the minimum of potential generically would lead to $\langle a \rangle \neq 0$ and spontaneous breaking of CP => $\bar{\theta} = 0 \quad \& \quad \theta_{\rm KM} = \mathcal{O}(1)$

Relaxion: Graham, Kaplan & Rajendran (15)

NB-relaxion - Davidi, Gupta, GP, Redigolo, & Shalit (17)

- Now if we tip the NB-axion from it's minimum it'd behave as a new type of ultralight DM

Dine, GP, Ratzinger, Savoray (24)

New type of pheno: *time dependent CKM angles*

While the strong CP is always zero

NB-UDM signature & parameter space

- What is the size of the effect? $\delta a \sim \frac{\sqrt{\rho_{\rm DM}}}{m_{\rm NB}\, f}\cos(m_{\rm NB}t) \sim 10^{-4} \times \frac{10^{13}\,{\rm GeV}}{f} \times \frac{10^{-21}\,{\rm eV}}{m_{\rm NB}} \times \cos(m_{\rm NB}t)$

Dine, GP, Ratzinger, Savoray (24)

- How to search such signal?

(i) Luminosity frontier: oscillating CP violation + oscillating CKM angles:

$$\frac{\delta V_{us}}{V_{us}} \sim \delta a \Rightarrow \text{oscillating Kaon decay lifetime}$$

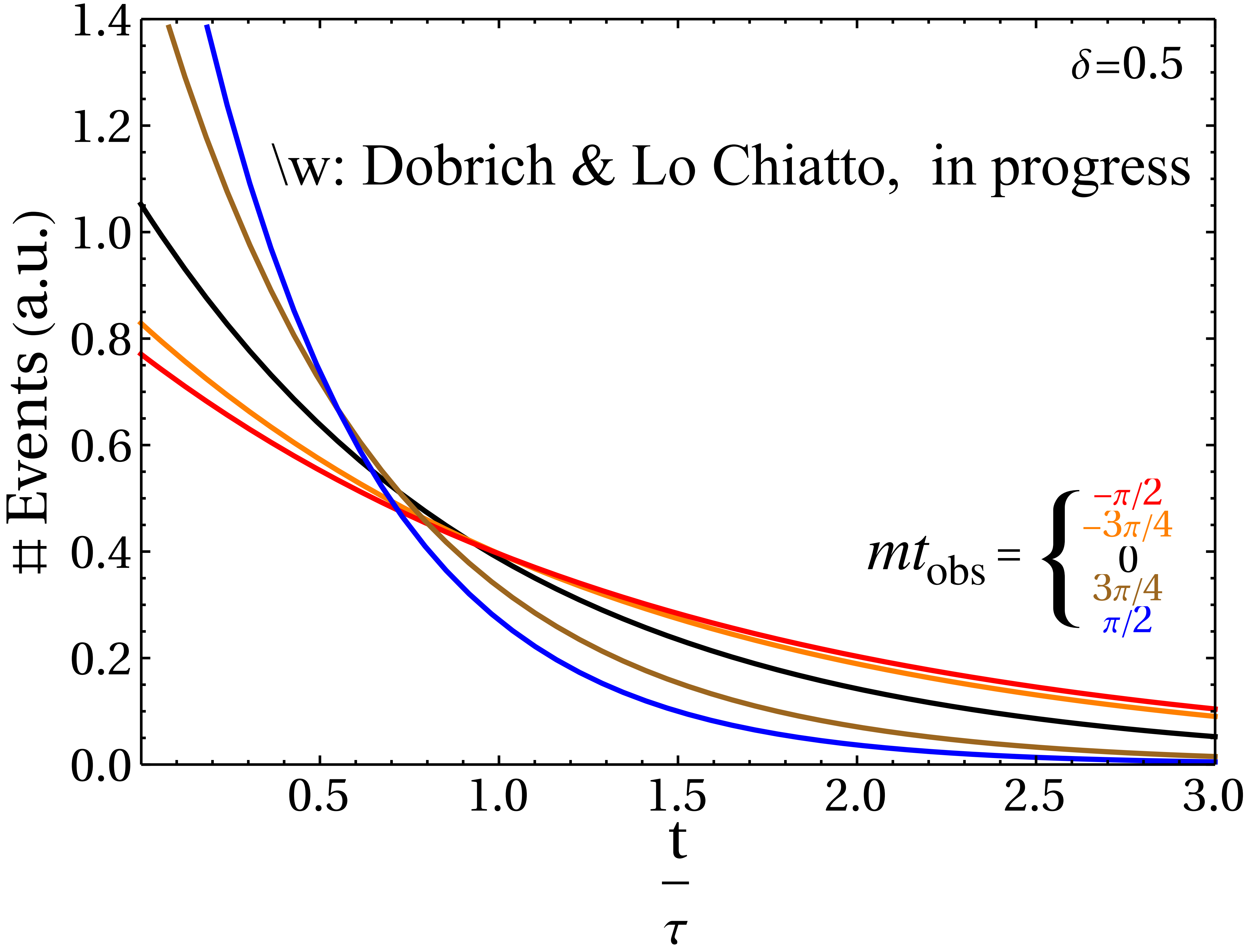
$$\frac{\delta \theta_{\rm KM}}{\theta_{\rm KM}} \sim \delta a \Rightarrow \text{oscillating CP violation}$$

$$\frac{\delta V_{ub}}{V_{ub}} \sim \delta a \Rightarrow \text{oscillating semi inclusive } b\text{->}u \text{ decay}$$

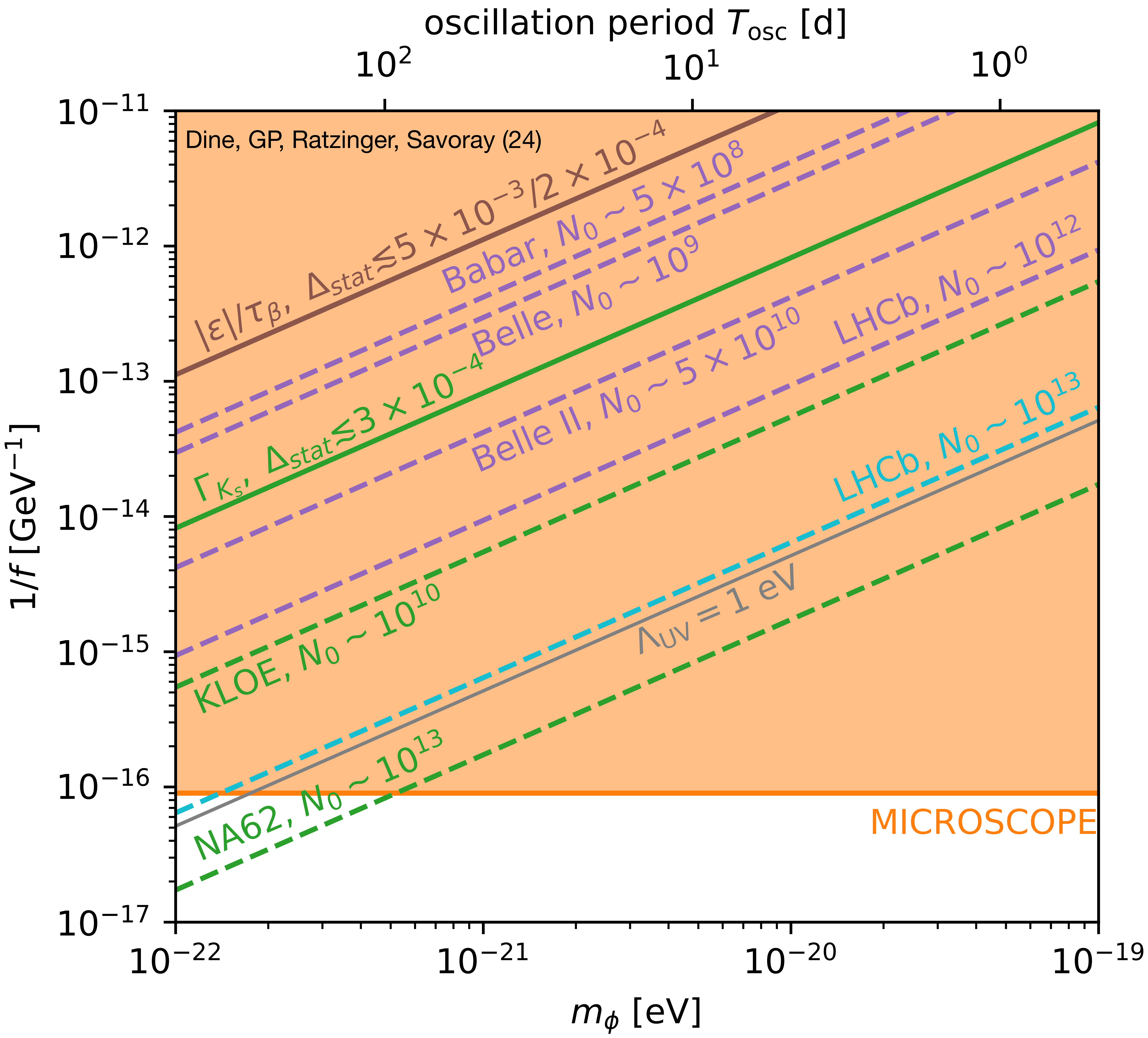
Example: time-dependent decay length

Assume that the decay time << oscillation period, $\tau^0 \ll 1/m$:

$$\tau \propto V_{\rm CKM}^2 \sim \left(V_{\rm CKM}^0\right)^2 \left(1 + \delta \cos m t_{\rm obs}\right) \quad \Longrightarrow \quad P \propto \exp\left(\frac{-t}{\tau^0(1+\delta\cos m t_{\rm obs})}\right)$$



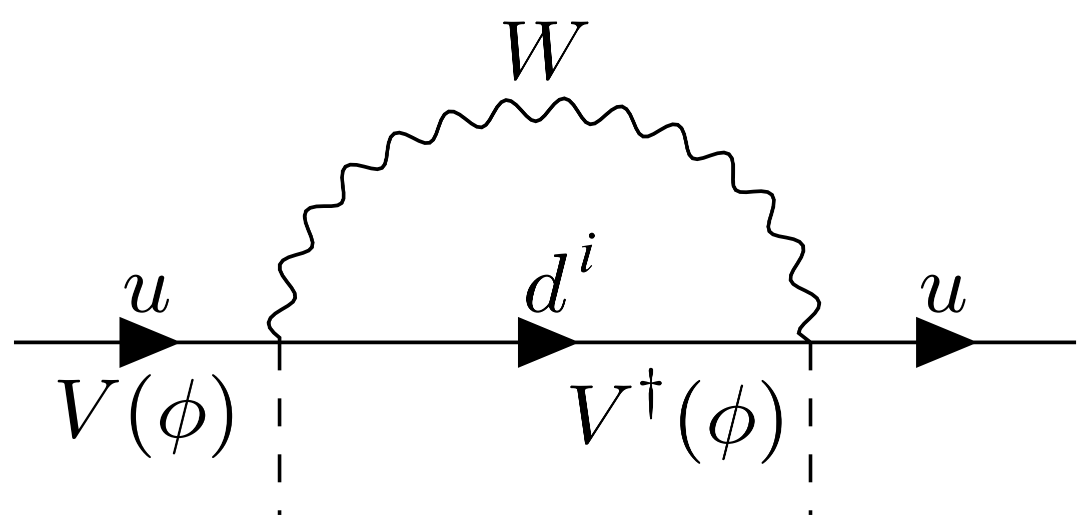
NB-UDM signature & parameter space



Correlation with the precision front

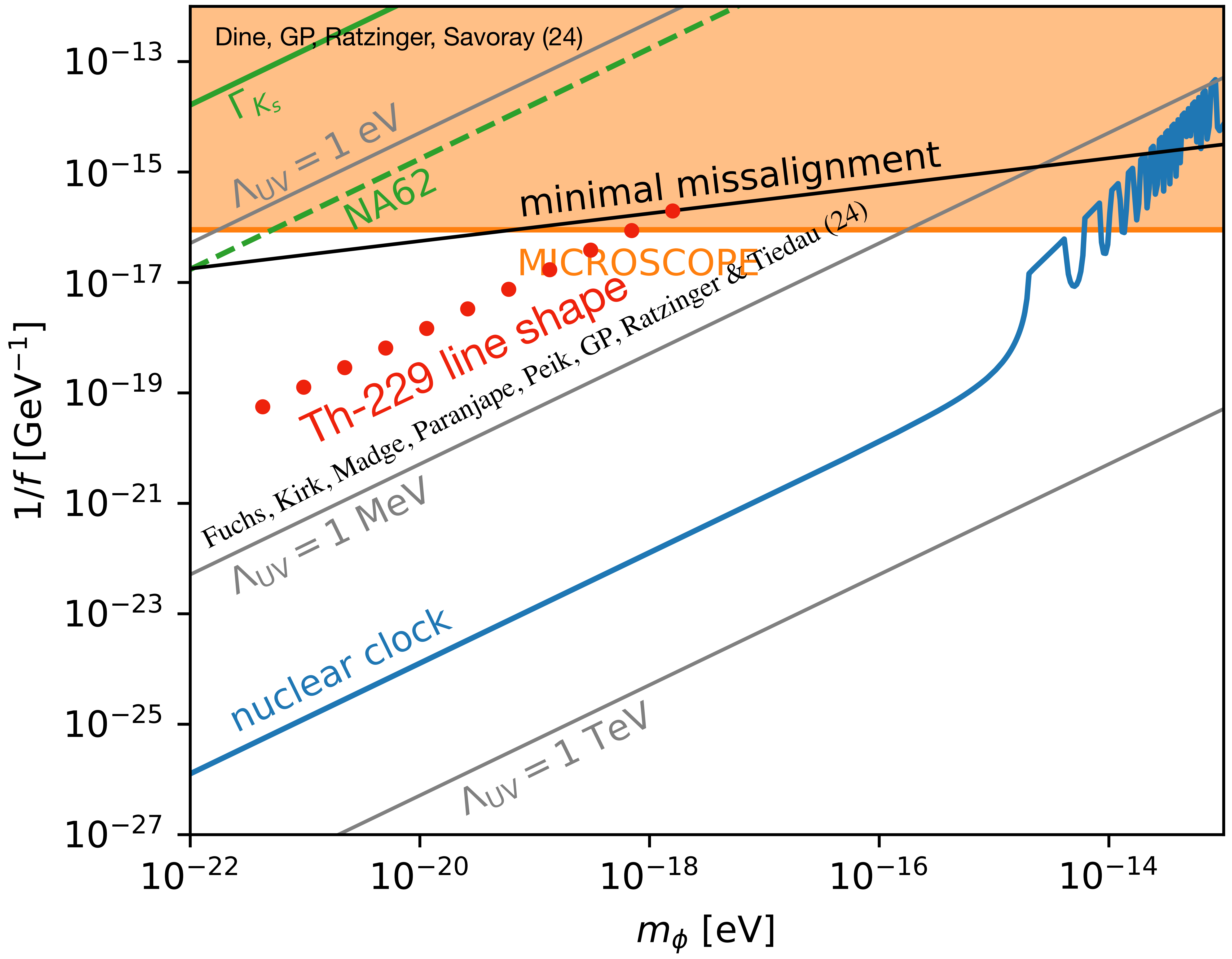
(i) Equivalence principle (EP) + (nuclear) clocks, at 1-loop scalar coupling to mass is induced:

$$\frac{\Delta m_u}{m_u} \approx \frac{3}{32\pi^2} y_s^2 |V_{us}^{\rm SM}|^2 \frac{a}{f}$$



- EP $\Rightarrow f \gtrsim 10^{16}\,\mathrm{GeV}$
- Nuclear clock (1:10^{24}) $\Rightarrow f \gtrsim 10^{19}\,\mathrm{GeV} \times \frac{\mathrm{m_{NB}}}{10^{-15}\,\mathrm{eV}}$

NB-UDM signature & parameter space nuclear clock reach



Successes and Challenges

- Minimal misalignment DM bound, can't be satisfied: $f \gtrsim 10^{15}\,\text{GeV}\left(\frac{10^{-19}\,\text{eV}}{m_\phi}\right)^{\frac{1}{4}}$, works nicely!

- Naive naturalness => currently only probing sub-MeV cutoff , $\Delta m_a \approx \frac{y_b |V_{ub}| m_u \Lambda_{\text{UV}}}{16\pi^2 f}$

- Is this model the only possibility to get CKM oscillation?

  We think that the answer is negative, working now on alternative realization

  (Hiller-Schmaltz (01), twisted-split fermions …)

- Rely on NB construction, \w Z_2 and a (non-anomalous) U(1)

  Two models: $Q^{U(1)}(\Phi, u_1, Q_1, d_1, u_2, Q_2, d_1) = (+1, +1, +1, +1, -1, -1, -1)$

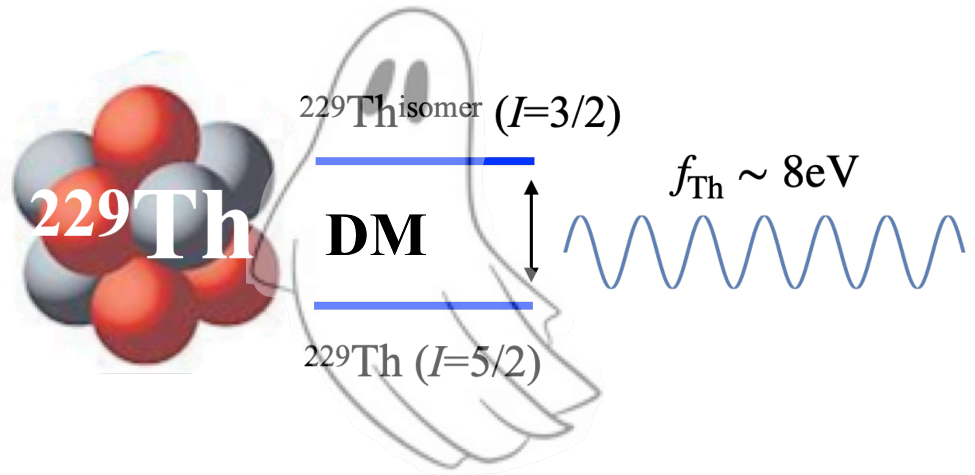
  $Q^{U(1)}(\eta, \Phi, \psi, \psi^c, \bar{u}_1) = +1, +1/2, -1/2, -1/2, +1$ (η additional flavon)

Conclusions

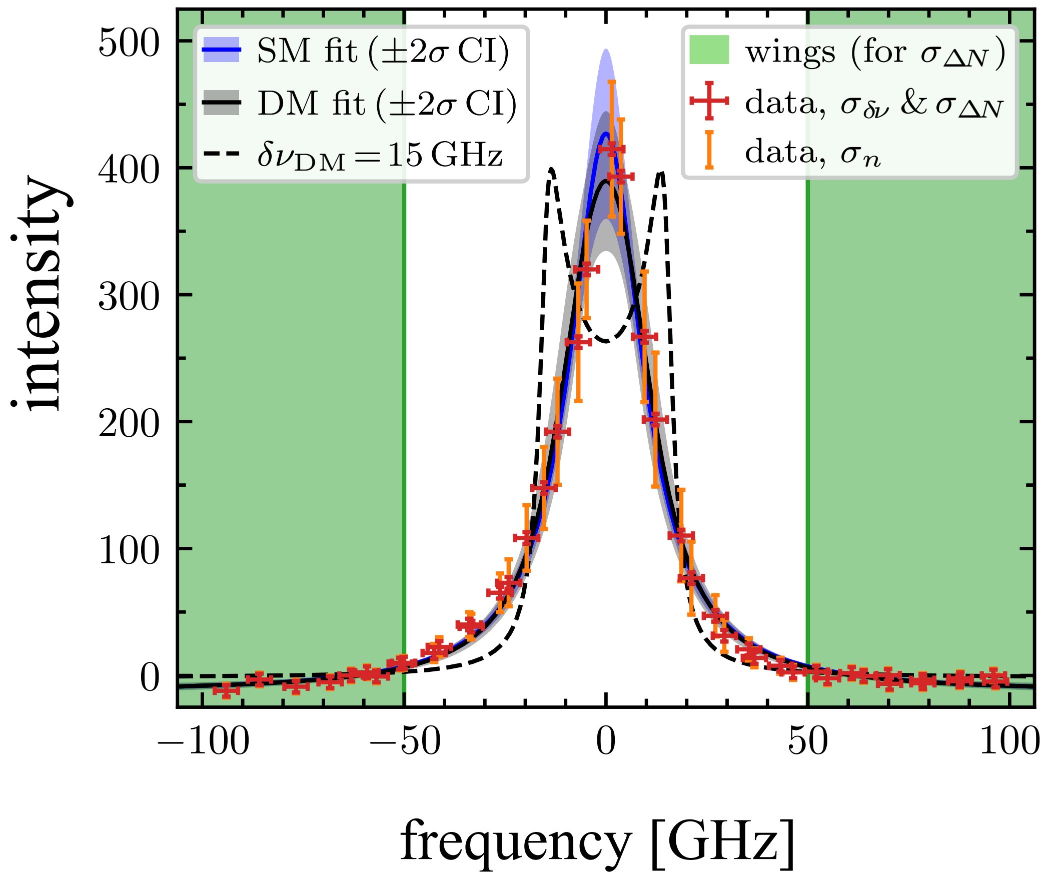
- Nelson-Barr models account for the smallness of the strong CP phase & the fact the KM phase is order one, which requires spontaneous CP violation
- Spontaneous breaking may lead to the presence of a light axion-like field
- If this field consist of ultralight dark matter it'd lead to new type of pheno', with time-dependent CKM angles
- Might be probed by the K/B-factories & (nuclear)-clocks/^{229}Th line-shape
- Is it a unique model or just a 1st example of a broad class?

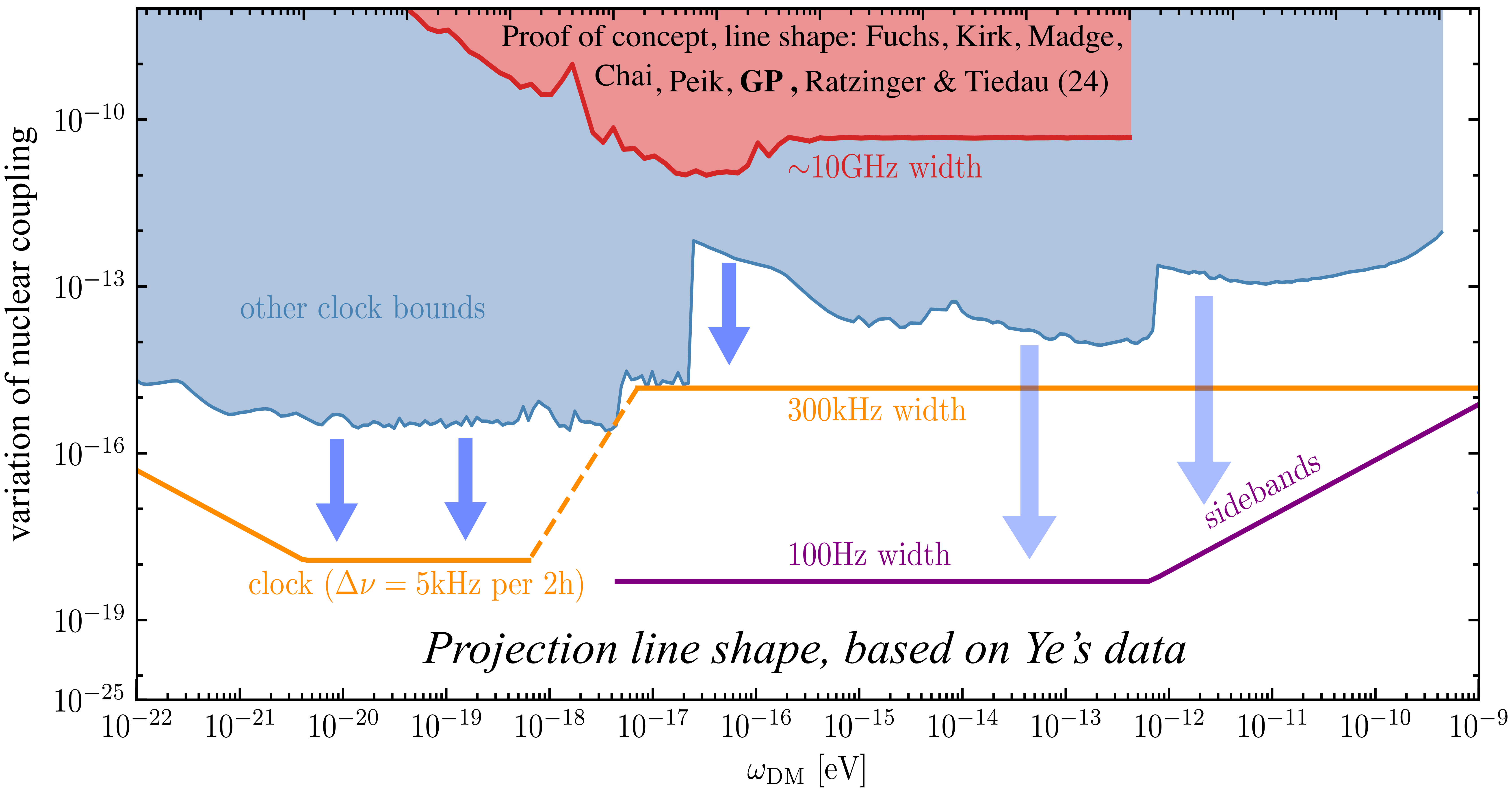
Backups

Line shape analysis - no need to wait for nuclear clocks



The presence of DM modifies the shape of light coming out of the isomeric excitation of Th-229





Progression of effective DM sensitivity via Th-229:

$1:10^{10}$ (2020) => $1:10^{13}$ (2022) => $1:10^{16}$ (2024)

Current line shape, projection

$1:10^{23}$ => $1:10^{25}$

Nelson-Barr (crash course, just flashing for followups)

- $\mathscr{L}_{\rm NB} = \mu\,\psi^c\,\psi + \left(g_i\,\Phi + \tilde{g}_i\,\Phi^*\right) u_i^c\,\psi + Y_u\,\tilde{H}\,Q\,u^c + Y_d\,H\,Q\,d^c \quad \left(\text{with}\ \ \psi, \psi^c, \Phi \subset Z_2 - \text{odd}\right)$

Bento, Branco & Parada (91)

- Assume that theory is real + only $\Phi = \dfrac{f+\rho}{\sqrt{2}} \exp\left(\dfrac{ia}{f}\right)$; $\langle a \rangle \neq 0$ breaks CP, then:

1. $\mathscr{M}_d = \begin{pmatrix} \mu & B_i \\ 0 & m_d \end{pmatrix}$; $m_d \equiv Y_d v$; $B_i \equiv (g_i\Phi + \tilde{g}_i\Phi^*)$ => $\det\left[\mathscr{M}_d\right] \in$ Real

2. At low energy ($v \ll \mu, B_i$), effective m_d satisfies $m_u^{\rm eff} m_u^{\rm eff\dagger} = m_u \left(\mathbf{1}_3 + \dfrac{B_i^* B_j}{\mu^2 + B_f B_f^\dagger}\right) m_u^\dagger$,

   which if g_i isn't parallel to $\tilde{g}_i$, and $\mu \lesssim B_i$ lead to $\theta_{\rm KM} = \mathcal{O}(1)$

Ultralight scalar => simplest dark matter (DM) model

- A sub-eV misaligned homogeneous scalar field => viable DM model
- Its amplitude oscillates with frequency equal to its mass, $w \sim \text{Hz} \times \frac{m_\phi}{10^{-15}\,\text{eV}}$
- However, this field has no coupling to us (apart from gravitational), how can we search for it?
- A minimal plausible assumption is that it'd couple to us suppressed by some very high scale (Planck suppressed?), which are extremely weak, for instance:

scalar coupling effecting energy levels

pseudo-scalar axial coupling magnetic/spin-observables

$$\mathscr{L}_{\text{Pl}} \in d_g \frac{\alpha_s}{\pi} \frac{\phi}{M_{\text{Pl}}} GG + \frac{a}{32\pi^2 f} G\tilde{G} \implies d_g \frac{m_n}{M_{\text{Pl}}} \phi\, \bar{n} n + \frac{m_n}{f} a\, \bar{n}\gamma_5 n$$

Planck suppression for ultralight spin 0 field

- Let's consider some dimension 5 operators, and ask if current sensitivity reach the Planck scale (assumed linear coupling and that gravity respects parity):

Graham, Kaplan, Rajendran;
Stadnik & Flambaum;
Arvanitaki Huang & Van Tilburg (15)

$$\boxed{m_\phi = 10^{-18}\ \mathrm{eV}} \quad (1/\mathrm{hour})$$

operator	current bound	type of experiment
$\frac{d_e^{(1)}}{4\,M_{\rm Pl}}\phi\,F^{\mu\nu}F_{\mu\nu}$	$d_e^{(1)} \lesssim 10^{-4}$ [58]	DDM oscillations
$\frac{\tilde{d}_e^{(1)}}{M_{\rm Pl}}\phi\,F^{\mu\nu}\tilde{F}_{\mu\nu}$	$\tilde{d}_e^{(1)} \lesssim 2\times 10^{6}$ [68]	Astrophysics
$\frac{\lvert d_{m_e}^{(1)}\rvert}{M_{\rm Pl}}\phi\,m_e\psi_e\psi_e^c$	$\lvert d_{m_e}^{(1)}\rvert \lesssim 2\times 10^{-3}$ [58]	DDM Oscillations
$i\frac{\lvert \tilde{d}_{m_e}^{(1)}\rvert}{M_{\rm Pl}}\phi\,m_e\psi_e\psi_e^c$	$\lvert \tilde{d}_{m_e}^{(1)}\rvert \lesssim 7\times 10^{8}$ [63]	Astrophysics
$\frac{d_g^{(1)}\beta(g)}{2M_{\rm Pl}\,g}\phi\,G^{\mu\nu}G_{\mu\nu}$	$d_g^{(1)} \lesssim 6\times 10^{-6}$ [67]	EP test: MICROSCOPE
$\frac{\tilde{d}_g^{(1)}}{M_{\rm Pl}}\phi\,G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\tilde{d}_g^{(1)} \lesssim 4$ [69]	Oscillating neutron EDM
$\frac{\lvert d_{m_N}^{(1)}\rvert}{M_{\rm Pl}}\phi\,m_N\psi_N\psi_N^c$	$\lvert d_{m_N}^{(1)}\rvert \lesssim 2\times 10^{-6}$ [67]	EP test: MICROSCOPE
$i\frac{\lvert \tilde{d}_{m_N}^{(1)}\rvert}{M_{\rm Pl}}\phi\,m_N\psi_N\psi_N^c$	$\lvert \tilde{d}_{m_N}^{(1)}\rvert \lesssim 4$ [69]	Oscillating neutron EDM

DDM = direct dark matter searches

For updated compilation see: Banerjee, Perez, Safronova, Savoray & Shalit (22)