Ultralight dark matter

(i) the dilatonic dark matter (DM) challenge — Hubisz, Ironi, GP & Rosenfeld (24)

(ii) Oscillation of constants at K/B-factories \w Nelson-Barr-DM

In progress \w: Dine, Nir, Ratzinger & Savoray

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Outline

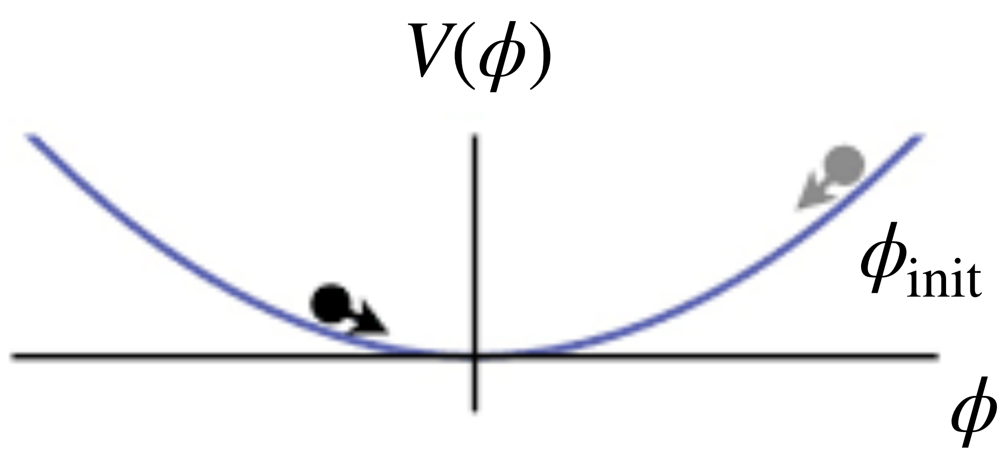
- Intro. (spin-0) ultralight dark-matter (UDM)
- A case against natural ultralight dilaton dark matter
- Nelson-Barr solution to strong CP & UDM
- Why Kaon/B-factory/LHCb becomes huge tabletop/quantum sensors
- Challenges of the model
- Summary

Spin-0 ultralight dark matter (UDM)

- Possibly simplest dark matter (DM) model is of misalignment ultralight DM, free massive spin-0:

$$\mathscr{L} \in m_\phi^2 \phi^2 \,,\; \rho_{\rm Eq}^{\rm DM} \sim {\rm eV}^4 \sim m_\phi^2 \phi_{\rm Eq}^2 = m_\phi^2 \phi_{\rm init}^2 ({\rm eV}/T_{\rm osc})^3 \qquad \left[T_{\rm os} \sim \sqrt{M_{\rm Pl} m_\phi}\right]$$

minimal misalignment mechanism

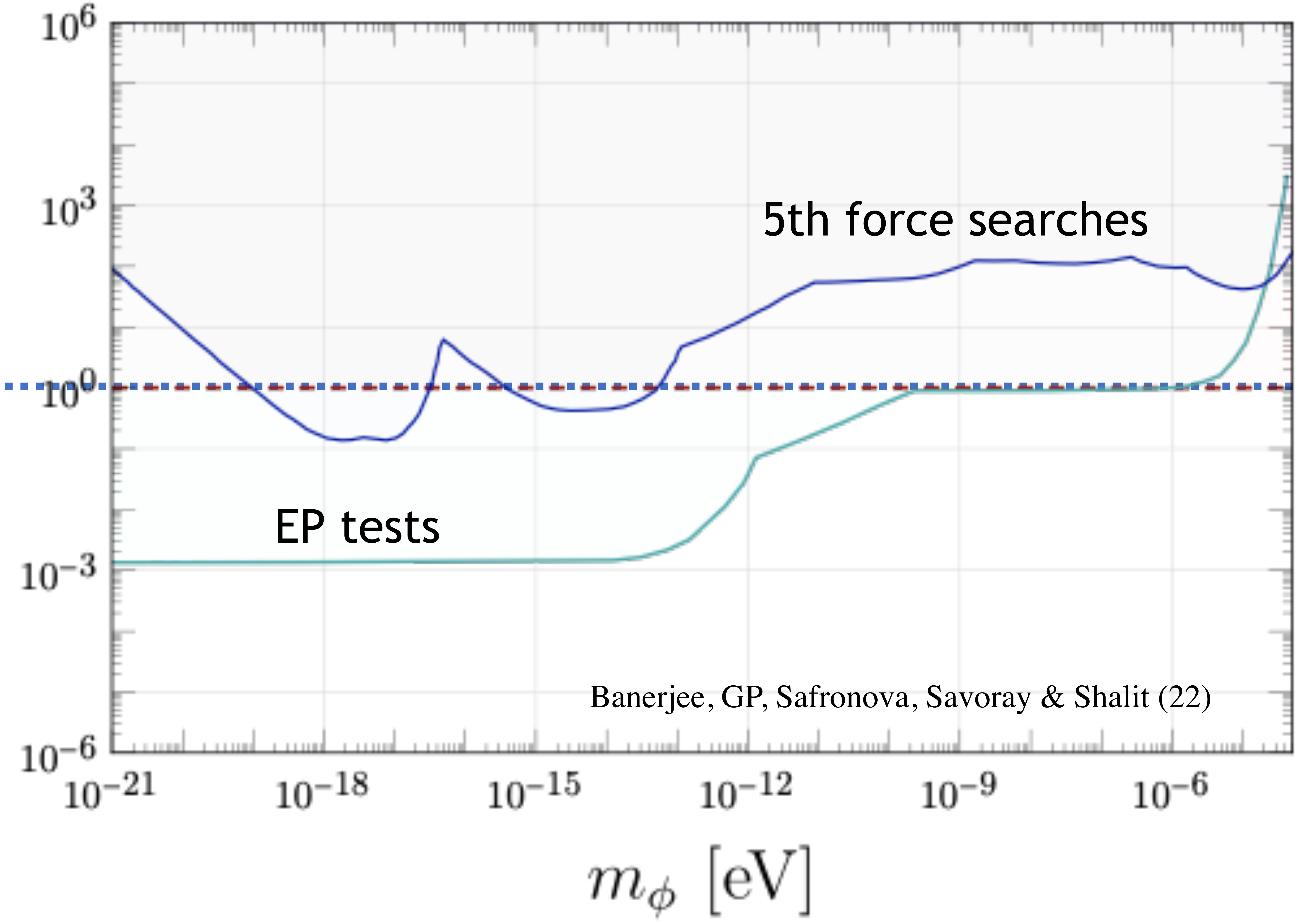


- Assuming ("best case") MeV reheating: $\phi_{\rm init} \equiv \theta f \left(f_{\rm min}\right) = \begin{cases} 10^{17}\,{\rm GeV} \left(\frac{10^{-27}\,{\rm eV}}{m_\phi}\right)^{\frac{1}{4}} & m_\phi \lesssim 10^{-15}\,{\rm eV} \\ 10^{15}\,{\rm GeV} \left(\frac{10^{-15}\,{\rm eV}}{m_\phi}\right) & m_\phi \gtrsim 10^{-15}\,{\rm eV} \end{cases}$

However, even Planck suppressed operators would exclude it

$$d_{m_e} \frac{m_e}{M_{\rm Pl}} \phi \, \bar{e} e \equiv g_e \phi \, \bar{e} e$$

$$d_{m_e} \sim 1 \text{ or } g_e \sim \frac{m_e}{M_{\rm Pl}}$$



EP: Planck suppressed operators are excluded for $m_\phi \lesssim 10^{-6}$ eV

5th force: operators are excluded for $10^{-19} \lesssim m_\phi \lesssim 10^{-13}$ eV

Status of spin-0 UDM, generalized quality problem

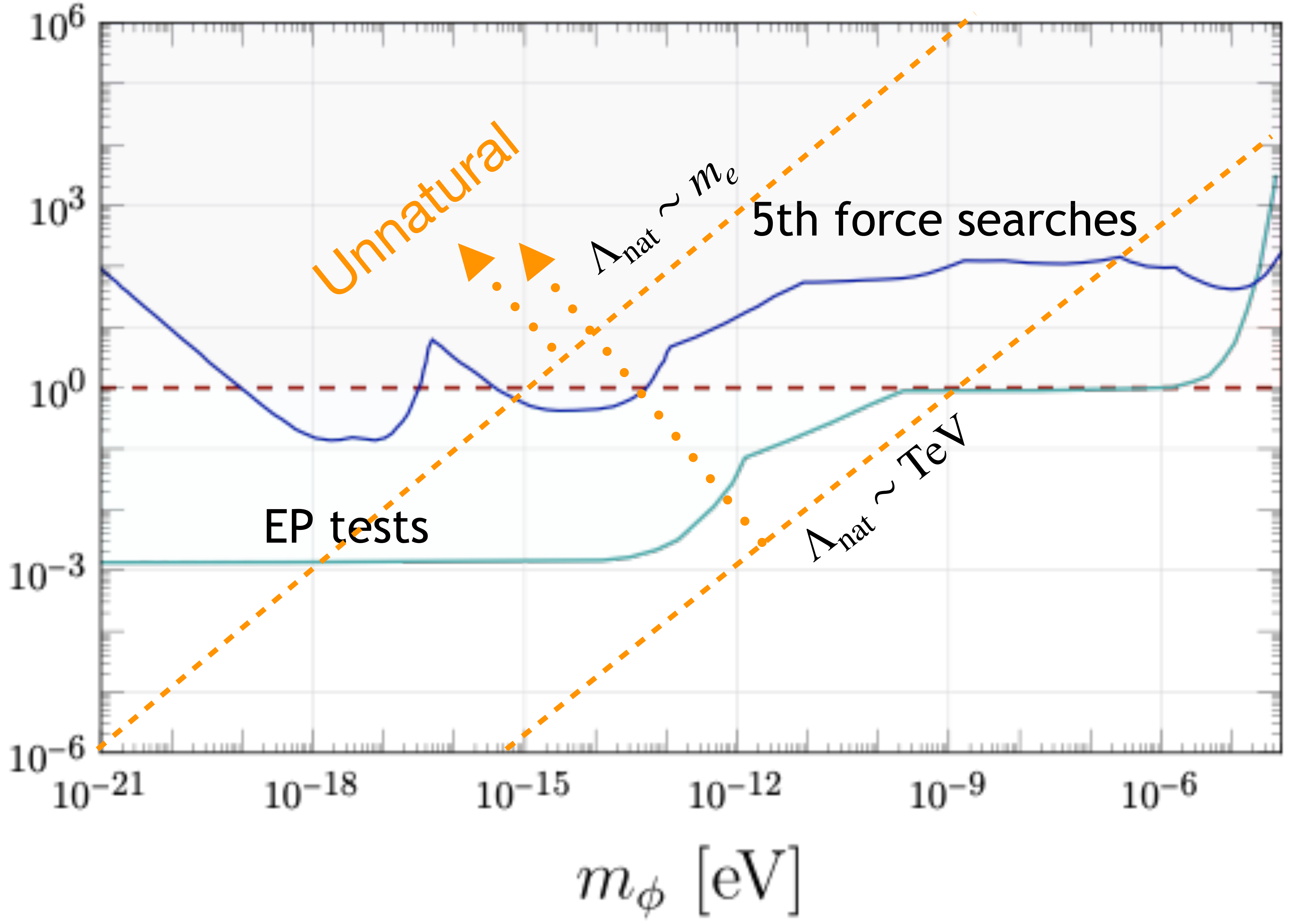
- It seems that genially linearly-coupled models are in troubles, however:
- If coupling is quadratic or more than situation is better -

$\frac{d_e^{(2)}}{8M_{\rm Pl}^2}\phi^2 F^{\mu\nu}F_{\mu\nu}$	$d_e^{(2)} \lesssim 10^{11}$ [67]	EP test: MICROSCOPE
$\frac{\left\lvert d_{m_e}^{(2)}\right\rvert}{2M_{\rm Pl}^2}\phi^2 m_e\psi_e\psi_e^c$	$\left\lvert d_{m_e}^{(2)}\right\rvert \lesssim 10^{12}$ [67]	EP test: MICROSCOPE
$\frac{d_g^{(2)}\beta_g}{4M_{\rm Pl}^2\, g}\phi^2 G^{\mu\nu}G_{\mu\nu}$	$d_g^{(2)} \lesssim 10^{11}$ [67]	EP test: MICROSCOPE.
$\frac{\left\lvert d_{m_N}^{(2)}\right\rvert}{2M_{\rm Pl}^2}\phi^2 m_N\psi_N\psi_N^c$	$\left\lvert d_{m_N}^{(2)}\right\rvert \lesssim 10^{11}$ [67]	EP test: MICROSCOPE

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

Naturalness

$$d_{m_e} \lesssim 4\pi m_\phi M_{\rm Pl}/m_e\Lambda_{\rm nat} \approx \frac{m_\phi}{10^{-15}\,{\rm eV}}\frac{\rm m_e}{\Lambda_{\rm nat}}$$



Linear coupling seems to also be seriously challenged by naturalness

What could solve these issues? (*i*) the axion way

- Axion solution: assume shift symmetry + axion being parity odd =>

  Leads to quadratic coupling that are:

  either suppressed by m_a^2/f^2 (generic axion) Banerjee, GP, Safronova, Savoray & Shalit (22)

  or in the case of the QCD-axion only suppressed by $\partial \ln m_\pi/\partial\theta \sim m_{u,d}/\Lambda_{\rm QCD}$

  Kim & GP (22)

(In passing: this is exciting as it implies that we can look for the QCD axion via scalar probes, and not spin-based, which are 10^{12} more sensitive;
it also leads to new type of "stochastic" signal, Kim, Lenoci, GP Ratzinger (23))

What could solve these issues? (*ii*) the scalar way

- Dilaton solution: assume (approx) spontaneously broken CFT symmetry
- Not trivial: sym' breaking scale, f, is a moduli requires stabilization via explicit breaking of the CFT (unlike axion)
- Generically it implies that the dilaton mass is not suppressed $m_\phi \sim f$
- Disastrous ultralight-DM (UDM) pheno as many states around $E \lesssim 4\pi\, m_\phi$
- Is there a way out?

A case against natural ultralight dilaton DM

Hubisz, Ironi, GP & Rosenfeld (24)

Dilaton mass: minimal dilatonic formalism

- The effective dilaton potential is given by: $V(\chi) = \lambda(\chi)\chi^4$
- The min' condition: $\lambda_*(\chi_*) = -\beta_*/4\,, \quad \beta \equiv d\lambda/d\log\chi$ & $\chi_* \equiv f$
- Dilaton mass: $m_\phi^2 = \left[\left(d\log\beta/d\log\chi\right)_* + 4\right]\beta_* f^2$
- Note that usually the beta function isn't small at the stabilization, thus the dilaton (ex.: σ in QCD) isn't light (relative to f)
- Inherent tension to achieve $m_\phi \ll f$:

Small mass => small β_* . However, the min' cond.: small β_* => small quartic

An ultralight dilaton => *conspiracy:* both β and λ be tiny at the scale f .

Naturally light dilaton

- A way out, have tiny $\beta = \epsilon g(\chi)$, with $\epsilon \ll 1$, and many decades of RGE
- Generically, λ slowly runs over large range of scales, and eventually becomes

  small, triggering the breaking of conformal symmetry when $\beta = -4\lambda$

Contino, Pomarol, Rattazzi, (Planck10); Coradeschi, et al. (13)

- Leads to exponential large UV scale $\Lambda_{\rm UV} \sim f \exp\left[\left|\frac{\lambda(\Lambda_{\rm UV})}{\epsilon}\right|\right]$

For the case with potentially small initial quartic see: Csáki et al. (2023); Agashe et al. (20)

Parametric scaling, dilaton mass vs. volume size

Polynomially light dilaton mass requires exponential large volume/UV scale:

$$\Lambda_{\rm UV} \sim f \exp\left[\left|\frac{\lambda(\Lambda_{\rm UV})}{\epsilon}\right|\right]$$

$$m_\phi^2 \sim \epsilon f^2$$

$$\epsilon = \frac{m_\phi^2}{f^2} \gtrsim 0.01 \times \lambda(\Lambda_{\rm UV}) \left(\ln\left(\frac{\Lambda_{\rm UV}}{m_\phi}\right)\right)^{-1}$$

for $\Lambda_{\rm UV} = M_{\rm Pl}$ & $m_\phi \sim \mathrm{eV}$

Implication for UDM from misalignment

$$\rho_{\rm Eq}^{\rm DM} \sim {\rm eV}^4 \sim = m_\phi^2 \phi_{\rm init}^2 ({\rm eV}/T_{\rm osc})^3 \gtrsim m_\phi^2 f^2 ({\rm eV}/T_{\rm osc})^3 = m_\phi^2 \times \frac{m_\phi^2}{\epsilon} ({\rm eV}/T_{\rm osc})^3$$

$$\epsilon \lesssim 10^{-8} \left(\frac{m_\phi}{\rm eV}\right)^4 \left(\frac{1{\rm keV}}{T_{\rm osc}}\right)^3$$

TENSION!

UDM misalignment $\epsilon \lesssim 10^{-8}\left(\frac{m_\phi}{\text{eV}}\right)^4\left(\frac{1\text{keV}}{T_{\text{osc}}}\right)^3$

Natural light dilaton $\epsilon = \gtrsim 0.01 \times \lambda(\Lambda_{\text{UV}})\left[\ln\left(\frac{\Lambda_{\text{UV}}}{m_\phi}\right)\right]^{-1}$

Nelson-Barr UDM

In progress \w: Dine, Nir, Ratzinger & Savoray

The strong CP problem

- 3 levels of formulating the strong CP problem:

(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?

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

- Should we be cautious [at least till we reach $\mathcal{O}\left(10^{-16}\right)$ 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 (crash course)

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

- 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 $\theta_{\rm KM} = \mathcal{O}(1)$

Nelson-Barr axion-like pheno for the CP breaking

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

- Assume approx' flavor sym' such that $g_i \propto (1,0,0) \quad \& \quad \tilde{g}_i \propto (0,1,0)$
- Then a is a pseudo-Nambu-Goldstone-boson, with suppressed potential, but with $\langle a \rangle = 0$
- Furthermore, one can show that $\theta_{\rm KM} = \dfrac{a}{f}$

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 UDM, implications

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 => $\bar{\theta} = 0$ & $\theta_{\rm KM} = \mathcal{O}(1)$

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

↓

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

- How to search such signal?

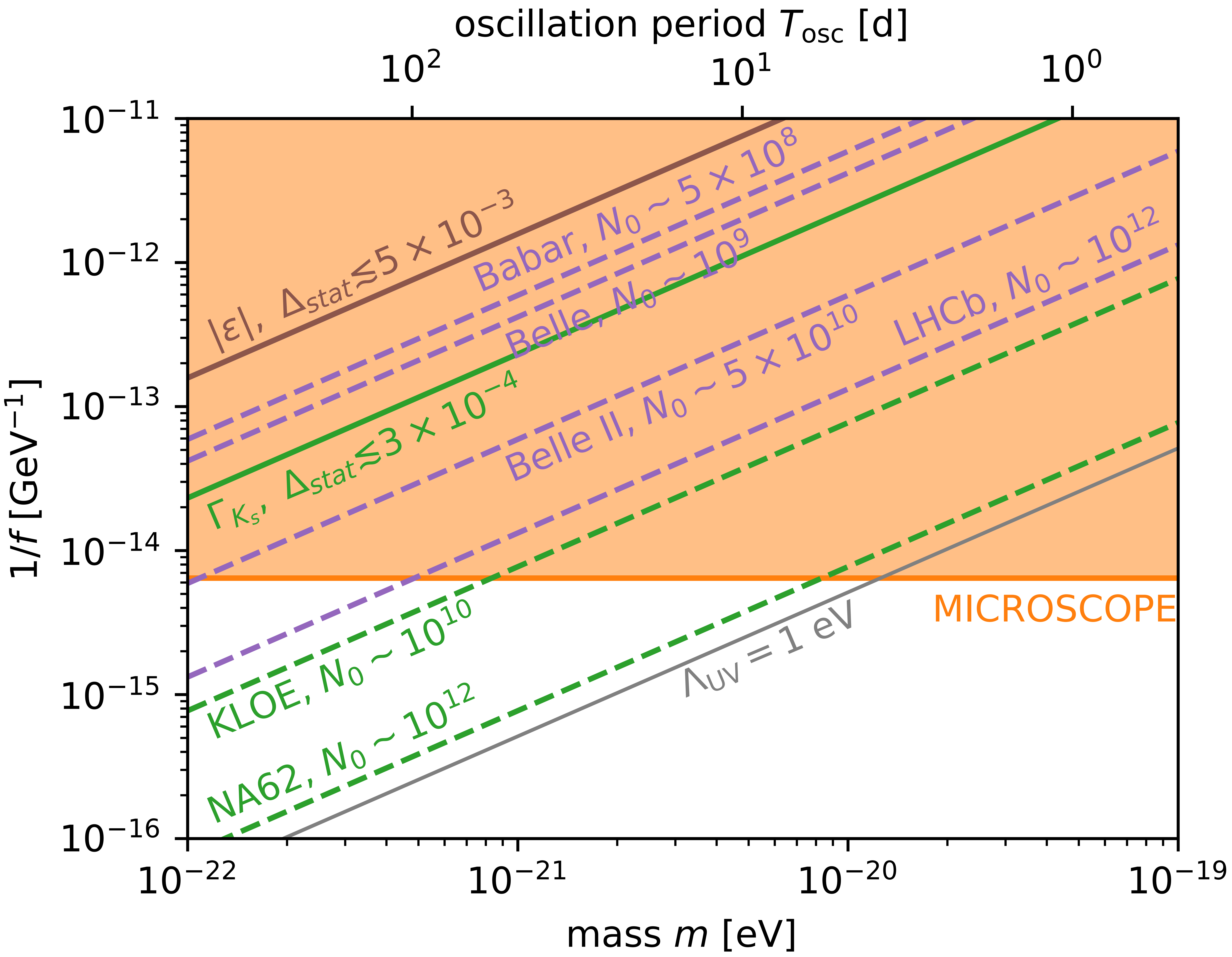
(i) Luminosity frontier: oscillating CP violation + oscillating CKM angles:

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

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

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

NB-UDM signature & parameter space

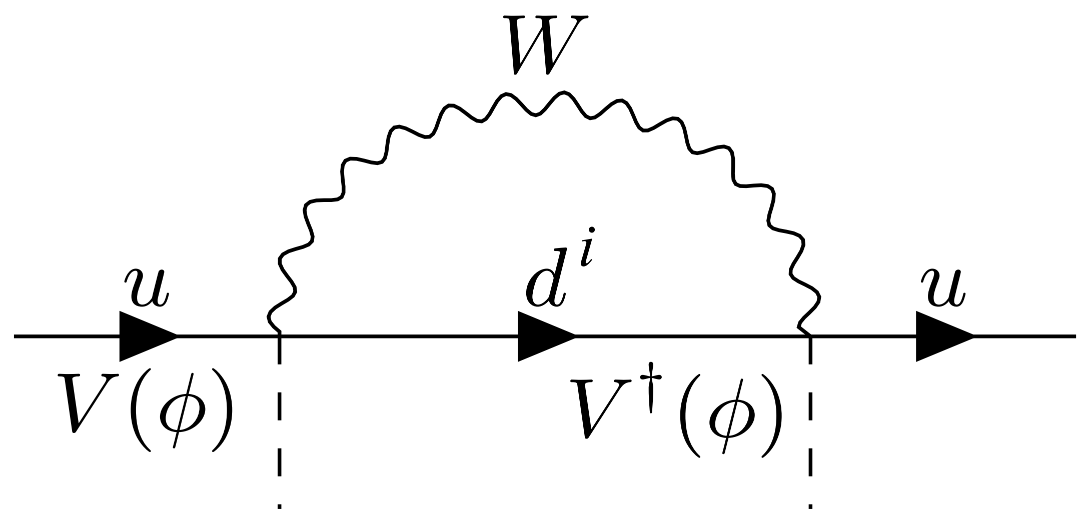


NB-UDM signature & parameter space

- How to search such signal?

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

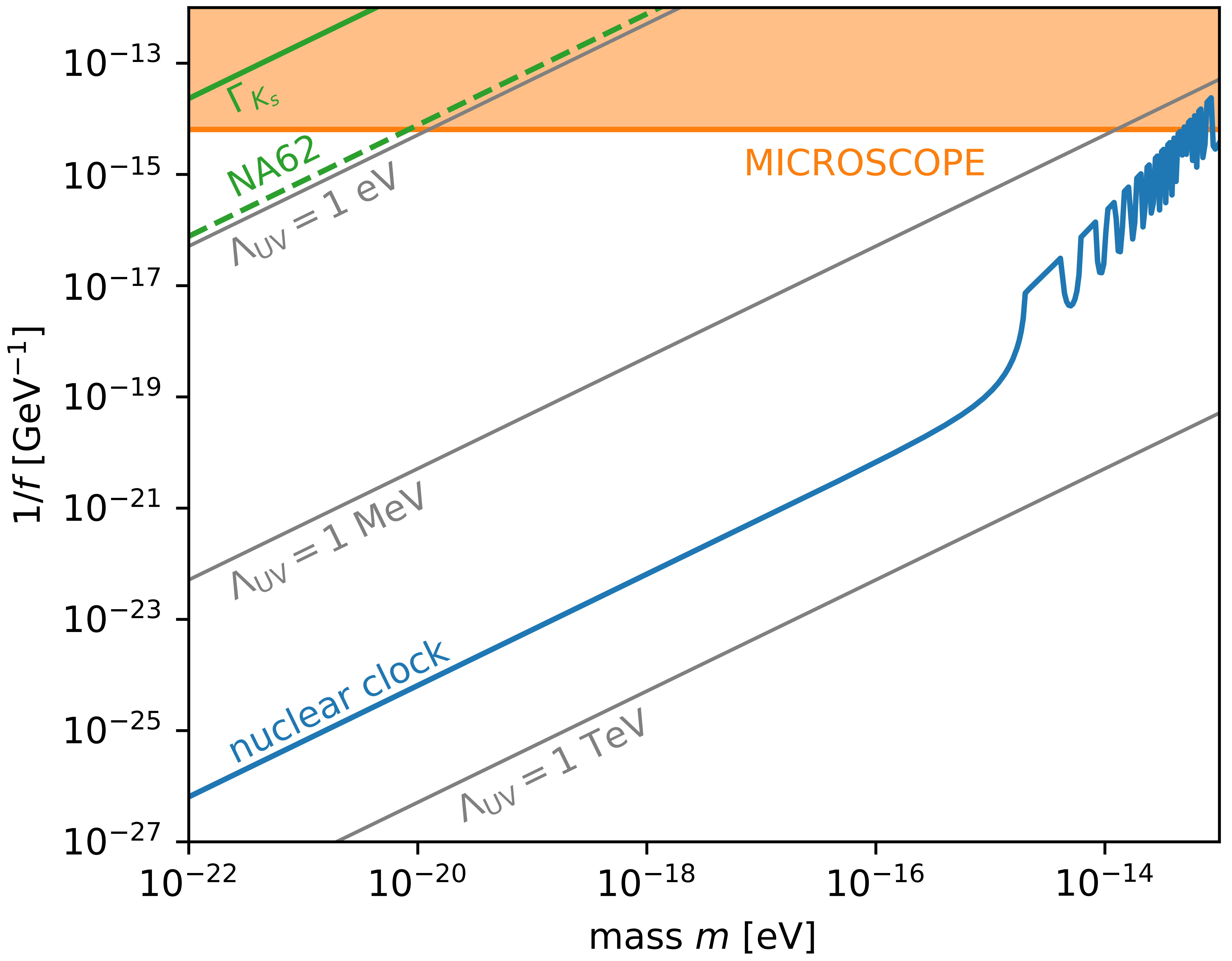
$$\frac{\Delta m_u}{m_u} \approx \frac{3}{32\pi^2} y_s^2 \;\; V_{us}^{\rm SM} \;\; {}^{2} \frac{a}{f}$$



- EP $\Rightarrow f \gtrsim 10^{14}\,\mathrm{GeV}$

- 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



Challenges

- Minimal misalignment DM bound, can't be satisfied: $f \gtrsim 10^{15}\,\mathrm{GeV}\left(\frac{10^{-19}\,\mathrm{eV}}{m_\phi}\right)^{\frac{1}{4}}$, but pretty close …

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

- 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

- Scalar ultralight dark matter (UDM): challenge for natural dilaton UDM
- 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
- May be probed by the K/B-factories & (nuclear)-clocks

Backups

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)

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

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
$\frac{\left\lvert d_{m_e}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\left\lvert d_{m_e}^{(1)}\right\rvert \lesssim 2\times 10^{-3}$ [58]	DDM Oscillations
$i\frac{\left\lvert \tilde{d}_{m_e}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\left\lvert \tilde{d}_{m_e}^{(1)}\right\rvert \lesssim 7\times 10^{8}$ [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
$\frac{\left\lvert d_{m_N}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\left\lvert d_{m_N}^{(1)}\right\rvert \lesssim 2\times 10^{-6}$ [67]	EP test: MICROSCOPE
$i\frac{\left\lvert \tilde{d}_{m_N}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\left\lvert \tilde{d}_{m_N}^{(1)}\right\rvert \lesssim 4$ [69]	Oscillating neutron EDM

DDM = direct dark matter searches

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