Nelson Barr ultra-light DM

Wolfram Ratzinger

with

Michel Dine, Inbar Savoray and Gilad Perez

arXiv: 2405.06744

DPF-Pheno 2024

מכון ויצמן למדע

WEIZMANN INSTITUTE OF SCIENCE

The strong CP-Problem

SM admits two CP-violating operators:

Phase of CKM matrix

$$\theta_{CKM} = \arg(\det(y_u y_u^\dagger, y_d y_d^\dagger))$$

Observed value: O(1)

Strong CP phase

$$\overline{\theta} = \theta_{G\tilde{G}} + \arg(\det(y_u y_d))$$

$\overline{\theta} \lesssim 10^{-10}$ (neutron EDM)

The Nelson Barr solution

- Start from $\theta_{CKM} = \bar{\theta} = 0$ (CP is UV symmetry)

- New physics breaks CP $\theta_{CKM} = \mathcal{O}(1)$
  while additional symmetries ensure $\bar{\theta} = 0$ at tree-level

- As a consequence $\theta_{CKM} \to \theta_{CKM} + \frac{\phi}{f}$ is dynamical field

A minimal Model Bento, Branca, Parada '91

- Introduce:
  - -complex scalar, gauge singlet Φ
  - -vector like fermion, same charges as RH up-quark q

$$\mathcal{L} \supset \mu \bar{q} q + (g_i \Phi + \tilde{g}_i \Phi^*) \bar{u}_i q + y^u_{ij} \tilde{H} Q_i \bar{u}_j + y^d_{ij} H Q_i \bar{d}_j + \ldots$$

- All couplings are real, but CP breaking from

$$\Phi = \frac{f}{\sqrt{2}} \exp(i\phi/f) \ , \quad < \phi > \neq 0$$

1) Avoids strong CP violation

$$\mathcal{M}_u = \begin{pmatrix} \mu & B \\ 0 & m_u \end{pmatrix} , \quad m_u = y^u v, \ B_i = (g_i \Phi + \tilde{g}_i \Phi^*) \Rightarrow \det(\mathcal{M}_u) = \mu \det(m_u) \in \mathbb{R}$$

0 caused by absence of $\mathcal{L} \supset \tilde{H} Q \bar{q}$, ensured by $\mathbb{Z}_2; \ \ \Phi, q, \bar{q}$ odd

A minimal Model Bento, Branca, Parada '91

- Introduce:

  -complex scalar, gauge singlet Φ

  -vector like fermion, same charges as RH up-quark q

$$\mathcal{L} \supset \mu \bar{q} q + (g_i \Phi + \tilde{g}_i \Phi^*) \bar{u}_i q + y^u_{ij} \tilde{H} Q_i \bar{u}_j + y^d_{ij} H Q_i \bar{d}_j + \ldots$$

- All couplings are real, but CP breaking from

$$\Phi = \frac{f}{\sqrt{2}} \exp(i\phi/f) \ , \quad <\phi> \neq 0$$

2) Generates CKM phase, after integrating out q

$$(\tilde{m}_u \tilde{m}_u^\dagger)_{ij} = \left((m_u m_u^T)_{ij} - \frac{(m_u)_{ik} B_k^\dagger B_\ell (m_u^T)_{\ell j}}{\mu^2 + |B|^2} \right)$$

If $g_i \nparallel \tilde{g}_i, \ \mu \lesssim |B|, \ \phi/f \sim 1$ one finds $\theta_{CKM} = \mathcal{O}(1)$

Nelson Barr, axion-like pheno

$$\mathcal{L} \supset \mu \bar{q} q + (g_i \Phi + \tilde{g}_i \Phi^*) \bar{u}_i q + y^u_{ij} \tilde{H} Q_i \bar{u}_j + y^d_{ij} H Q_i \bar{d}_j + \ldots$$

- Assume approximate flavor symmetry such that $g \propto (1,0,0), \;\tilde{g} \propto (0,1,0)$

- Then ϕ is a pseudo Nambu-Goldstone boson

  Tree-level couplings:

  -CKM phase $\theta_{CKM} \sim \phi/f$

  -mixing angles $|V_{u/c,D}| \supset \cos(\phi/f)$

Requires phase and 1,2 rotation to diagonalize

$$\tilde{m}_u \tilde{m}_u^\dagger = m_u \left[\mathbb{1} + r \begin{pmatrix} 1 & \exp(i\phi/f) & 0 \\ \exp(-i\phi/f) & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] m_u^T$$

If ϕ displaced from minimum of potential → ϕ is DM + CKM elements oscillate!

Oscillating CKM elements

- How large is the effect?

  Best observables $\propto \frac{\phi}{f} = \frac{\sqrt{\rho_{DM}}}{m_\phi f}\cos(m_\phi t) \approx 10^{-5} \times \frac{10^{14}\ \mathrm{GeV}}{f} \times \frac{10^{-21}\ \mathrm{eV}}{m_\phi}\cos(m_\phi t)$

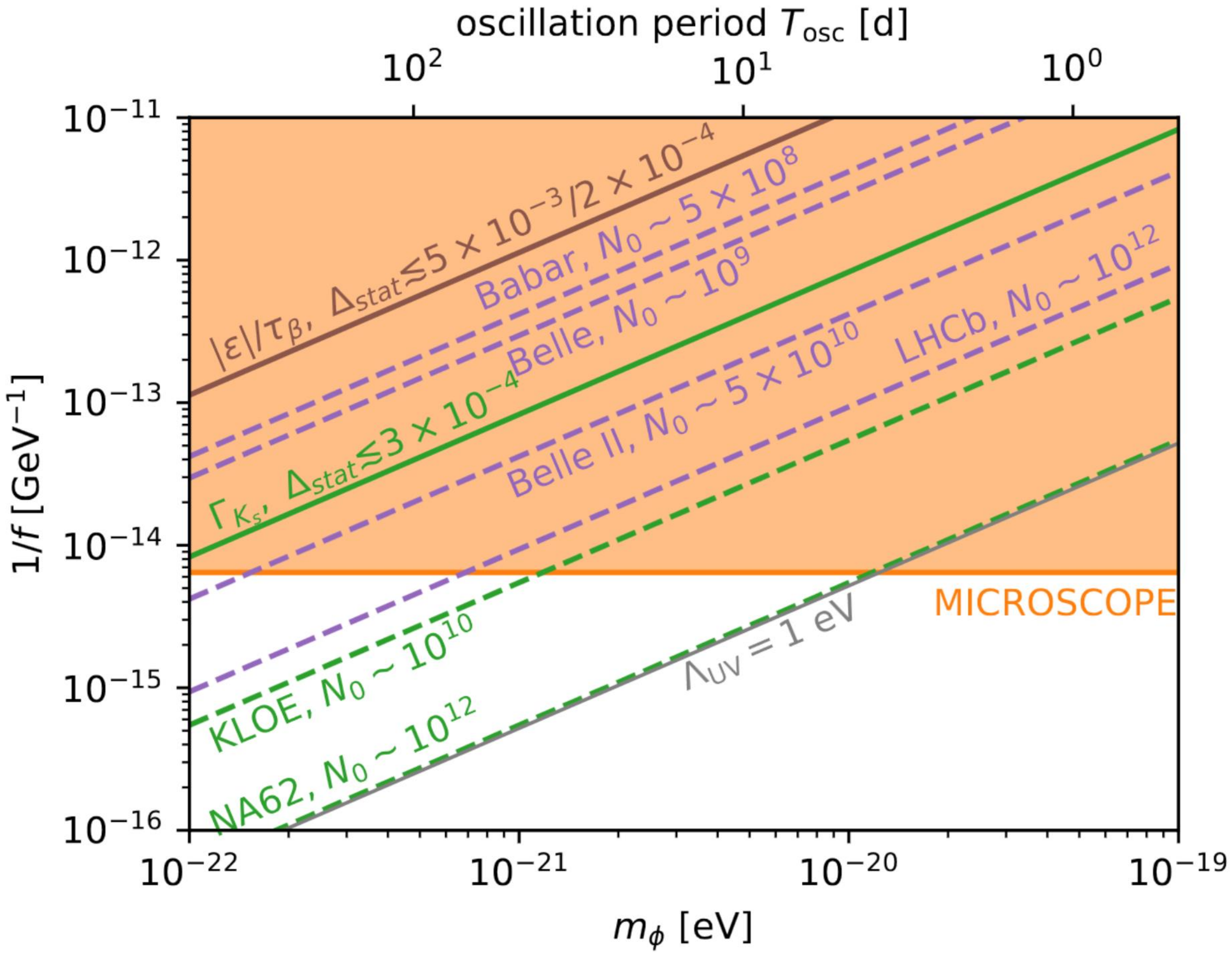
- Prime Candidates for luminosity frontier search:

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

  $\frac{\delta \theta_{\mathrm{KM}}}{\theta_{\mathrm{KM}}} \Rightarrow$ oscillating CP violation

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

Oscillating CKM elements

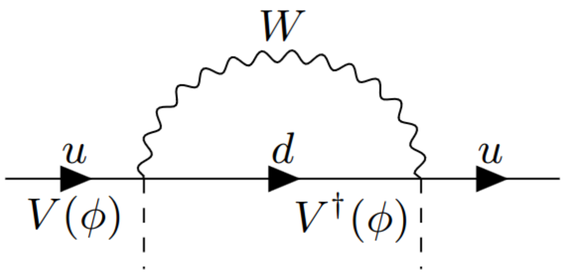


Further signatures

- At 1 loop, coupling to quark masses

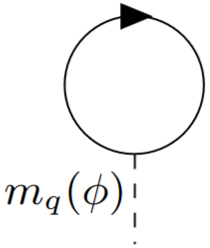
$$\frac{\Delta m_u}{m_u} \approx -\frac{3}{32\pi^2}|V_{us}^{SM}|^2 \tilde{y}_s^2 \log\left(\frac{\Lambda_{\rm UV}}{M_W}\right) \frac{\phi}{f}$$

  - Equivalence principle bound $f \gtrsim 10^{14}\,\mathrm{GeV}$
  - Search with nuclear clock

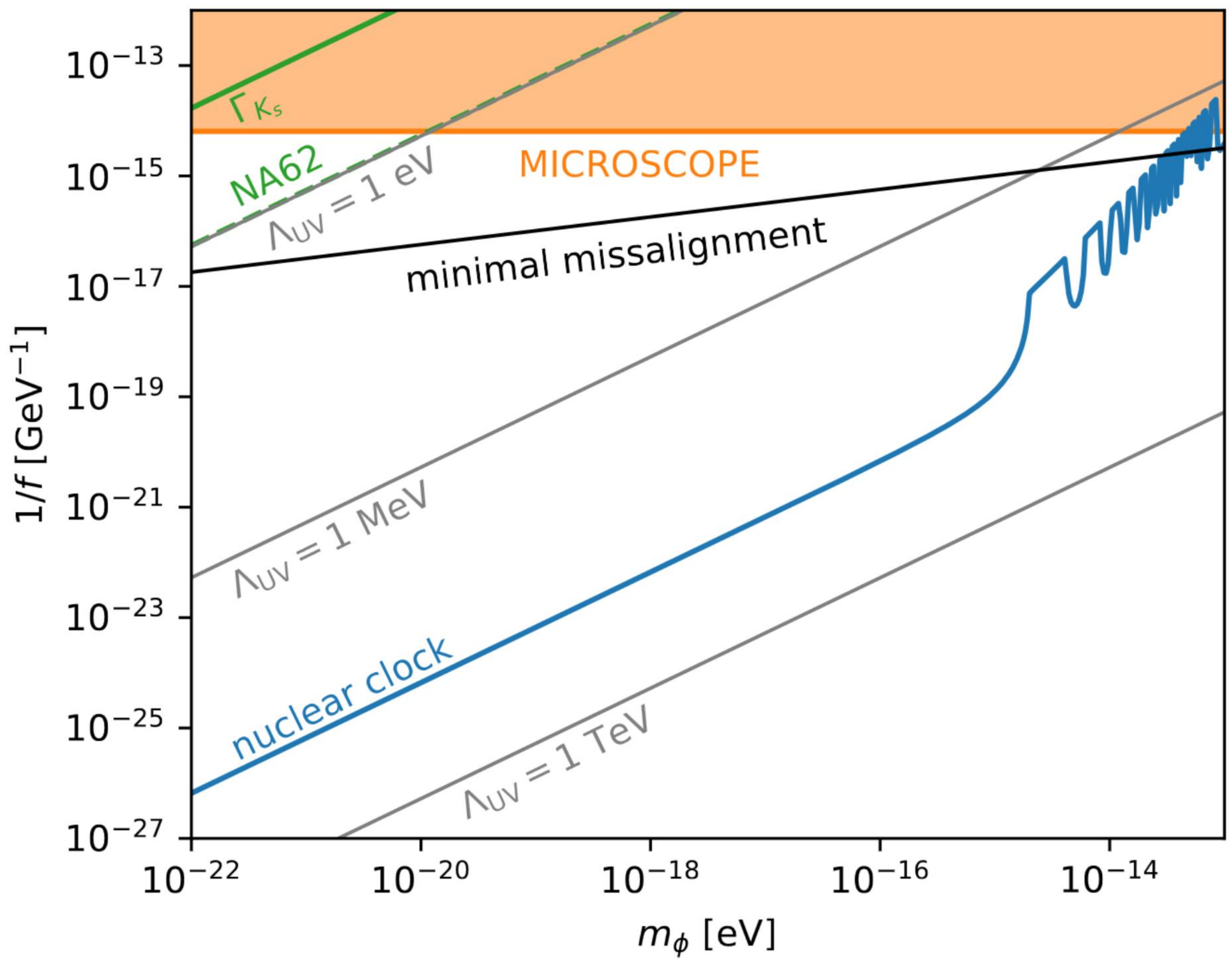


- At 2 loop, correction to potential + mass of ϕ

$$\Delta m_\phi \simeq \frac{3}{16\pi^2}|V_{cb}|^2 y_c y_b \frac{v\Lambda_{\rm UV}}{f}$$



Further signatures



Thanks!