Flavonic Dark Matter

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Outline

- Axion-like dark matter from flavon?
- Discrete flavor symmetry & axial flavon DM.
- Flavor structure with Dirac neutrinos
- Phenomenological implication: FCNC & DM-photon coupling.

Froggatt-Nielsen mechanism

- $U(1)_{\rm FN}$ symmetry under which SM fields are charged:

$$-\mathcal{L}_{\rm Yuk} = y_{ij}\left(\frac{\phi}{\Lambda}\right)^{n_{ij}} H\psi_i\psi_j + h.c. \qquad n_{ij} = |x_i + x_j + x_H| \text{ \with } x_\phi = \pm 1$$

- Arrange the FN charges for the flavor structure:

$$\Rightarrow y_{ij}\epsilon^{n_{ij}} H\psi_i\psi_j + h.c. \qquad \boxed{\epsilon = \frac{\langle\phi\rangle}{\Lambda} \sim 0.22}$$

- Anomaly-free after UV completion:

  e.g., Green-Schwarz mechanism in string theory.

Leurer, Nir & Seiberg, 1993
Ibanez & Ross, 1993
EJC & Lukas, 9605377
Choi, Hwang, EJC, 9811363

- $U(1)_{\rm FN}$ as a Peccei-Quinn symmetry.

Ema, et.al., 1612.05492
Calibbi, et.al, 1612.08040

Flavor structure

- Quark masses and mixing

$$(m_t, m_c, m_u) \sim (1, \epsilon^4, \epsilon^8)$$

$$(m_b, m_s, m_d) \sim (1, \epsilon^2, \epsilon^4) \cdot \epsilon^3$$

$$V_{\mathrm{CKM}} \sim \begin{bmatrix} 1 & \epsilon & \epsilon^3 \\ & 1 & \epsilon^2 \\ & & 1 \end{bmatrix}$$

- Lepton masses and mixing

$$(m_\tau, m_\mu, m_e) \sim (1, \epsilon^2, \epsilon^6)$$

$$(m_{\nu_3}, m_{\nu_2}, m_{\nu_1}) \sim (1, \epsilon, \epsilon^{1+n}) \cdot \epsilon^{19}$$

Dirac vs. Majorana

$$U_{\mathrm{PMNS}} \sim \begin{bmatrix} 0.83 & 0.55 & 0.15 \\ & & 0.71 \\ & & 0.71 \end{bmatrix}$$

Z_N discrete flavor symmetry

- Z_N extendable to U(1) except the potential:

$$\phi = \frac{v_F}{\sqrt{2}} e^{i\frac{a}{v_F}}$$

$$V_{Z_N} = -\lambda \frac{\phi^N}{\Lambda^{N-4}} + h.c. \Rightarrow -\frac{1}{4}|\lambda|\, \epsilon^{N-4} v_F^4 \cos\left(N\frac{a}{v_F} + \alpha\right)$$

$$m_a^2 = \frac{1}{8}|\lambda|\, N^2 \epsilon^{N-4}\, v_F^2$$

- CDM of pNGB from misalignment $\theta_0 \equiv \frac{a_0}{v_F/N}$:

$$\ddot{a} + 3H\,\dot{a} + m_a^2 a \approx 0$$

$$\rho_a(t) \approx 0.37 \frac{m_a^2 v_F^2 \theta_0^2/N^2}{(m_a t)^{3/2}}$$

$$\rho_a(t_{eq}) \approx 0.24\ \mathrm{eV}^4 \Rightarrow$$

$$v_F \approx 2.5 \times 10^7 \left(\frac{N^6}{\theta_0^8 |\lambda| \epsilon^{N-4}}\right)^{\frac{1}{10}} \mathrm{GeV}$$

$$m_a \approx 10^{16} \left(\epsilon^{N-4} N^4 \frac{|\lambda|}{\theta_0^2}\right)^{\frac{2}{5}} \mathrm{eV}$$

A model: $Z_8 \times Z_{22}$

Abbas, 1807.04783

Fields	$\mathcal{Z}_8$	$\mathcal{Z}_{22}$	Fields	$\mathcal{Z}_8$	$\mathcal{Z}_{22}$	Fields	$\mathcal{Z}_8$	$\mathcal{Z}_{22}$	Fields	$\mathcal{Z}_8$	$\mathcal{Z}_{22}$	Fields	$\mathcal{Z}_8$	$\mathcal{Z}_{22}$
u_R	ω^2	ω'^2	c_R	ω^5	ω'^5	t_R	ω^6	ω'^6	d_R	ω^3	ω'^3	s_R	ω^4	ω'^4
b_R	ω^4	ω'^4	$\psi^q_{L,1}$	ω^2	ω'^{10}	$\psi^q_{L,2}$	ω	ω'^9	$\psi^q_{L,3}$	ω^7	ω'^7	$\psi^\ell_{L,1}$	ω^3	ω'^3
$\psi^\ell_{L,2}$	ω^2	ω'^2	$\psi^\ell_{L,3}$	ω^2	ω'^2	e_R	ω^2	ω'^{16}	μ_R	ω^5	ω'^{19}	τ_R	ω^7	ω'^{21}
ν_{e_R}	ω^2	1	ν_{μ_R}	ω^5	ω'^3	ν_{τ_R}	ω^6	ω'^4	ϕ	ω	ω'	H	1	1

- Sufficiently large LCM: $N = 88$ leading to $v_F \sim 10^{14}$GeV & $m_a \sim$ meV.
- Flavor structure exploiting the freedom of order one y_{ij}.
- Better fit to Dirac neutrino mass matrix.
- Generalization to different values of N.
- Issues of FCNC & DM longevity.

Quark masses and mixing

$$\mathcal{M}_u = \frac{v}{\sqrt{2}} \begin{pmatrix} y^u_{11}\epsilon^8 & y^u_{12}\epsilon^5 & y^u_{13}\epsilon^4 \\ y^u_{21}\epsilon^7 & y^u_{22}\epsilon^4 & y^u_{23}\epsilon^3 \\ y^u_{31}\epsilon^5 & y^u_{32}\epsilon^2 & y^u_{33}\epsilon \end{pmatrix}$$

$$\mathcal{M}_d = \frac{v}{\sqrt{2}} \begin{pmatrix} y^d_{11}\epsilon^7 & y^d_{12}\epsilon^6 & y^d_{13}\epsilon^6 \\ y^d_{21}\epsilon^6 & y^d_{22}\epsilon^5 & y^d_{23}\epsilon^5 \\ y^d_{31}\epsilon^4 & y^d_{32}\epsilon^3 & y^d_{33}\epsilon^3 \end{pmatrix}$$

$$(m_t, m_c, m_u) \sim (\epsilon, \epsilon^4, \epsilon^8)$$

$$(m_b, m_s, m_d) \sim (\epsilon^3, \epsilon^5, \epsilon^7)$$

$$V_{\text{CKM}} \sim \begin{bmatrix} 1 & \epsilon & \epsilon^3 \\ & 1 & \epsilon^2 \\ & & 1 \end{bmatrix}$$

Lepton masses and mixing

$$\mathcal{M}_\ell = \frac{v}{\sqrt{2}} \begin{pmatrix} y^\ell_{11}\epsilon^9 & y^\ell_{12}\epsilon^6 & y^\ell_{13}\epsilon^4 \\ y^\ell_{21}\epsilon^8 & y^\ell_{22}\epsilon^5 & y^\ell_{23}\epsilon^3 \\ y^\ell_{31}\epsilon^8 & y^\ell_{32}\epsilon^5 & y^\ell_{33}\epsilon^3 \end{pmatrix}$$

$$\mathcal{M}_\mathcal{D} = \frac{v}{\sqrt{2}} \begin{pmatrix} y^\nu_{11}\epsilon^{25} & y^\nu_{12}\epsilon^{22} & y^\nu_{13}\epsilon^{21} \\ y^\nu_{21}\epsilon^{24} & y^\nu_{22}\epsilon^{21} & y^\nu_{23}\epsilon^{20} \\ y^\nu_{31}\epsilon^{24} & y^\nu_{32}\epsilon^{21} & y^\nu_{33}\epsilon^{20} \end{pmatrix}$$

Fit to Dirac neutrinos

$$(m_\tau, m_\mu, m_e) \sim (\epsilon^3, \epsilon^5, \epsilon^9)$$

$$(m_{\nu_3}, m_{\nu_2}, m_{\nu_1}) \sim (\epsilon^{20}, \epsilon^{21}, \epsilon^{25})$$

$$\sin\theta_{12} \simeq \left| \frac{y^\ell_{12}}{y^\ell_{22}} - \frac{y^\nu_{12}}{y^\nu_{22}} \right| \epsilon, \quad \sin\theta_{13} \simeq \left| \frac{y^\ell_{13}}{y^\ell_{33}} - \frac{y^\nu_{12} y^\ell_{23}}{y^\nu_{22} y^\ell_{33}} - \frac{y^\nu_{13}}{y^\nu_{33}} \right| \epsilon$$

$$\sin\theta_{23} \simeq \left| \frac{y^\ell_{23}}{y^\ell_{33}} - \frac{y^\nu_{23}}{y^\nu_{33}} \right|,$$

$$\text{Fit to } U_{\text{PMNS}} \sim \begin{bmatrix} 0.83 & 0.55 & 0.15 \\ & & 0.71 \\ & & 0.71 \end{bmatrix}$$

Phenomenology of Flavonic DM

- $Z_{N_1} \times Z_{N_2} \rightarrow U(1)$ for Yukawa interaction:

$$x_i^q = (4,3,1),\ x_i^u = (-4,-1,0),\ x_i^d = (-3,-2,-2),\ x_i^l = (3,2,2),\ \text{and } x_i^e = (-6,-3,-1),$$

- pNBG couplings to fermions:

Bjorkeroth, EJC & King 1711.07241

$$-\mathcal{L}_{aff} = \frac{\partial_\mu a}{v_F} \sum_{f,i} x_i^f\ \bar{\psi}_i^f \gamma^\mu \psi_i^f$$

→ FCNC, e.g., $K^+ \rightarrow \pi^+ a$

- pNBG coupling to photon:

$$-\mathcal{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma}\ aF\tilde{F} \qquad g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi v_F} \sum_{f,i} x_i^f Q_f^2$$

Phenomenology of Flavonic DM

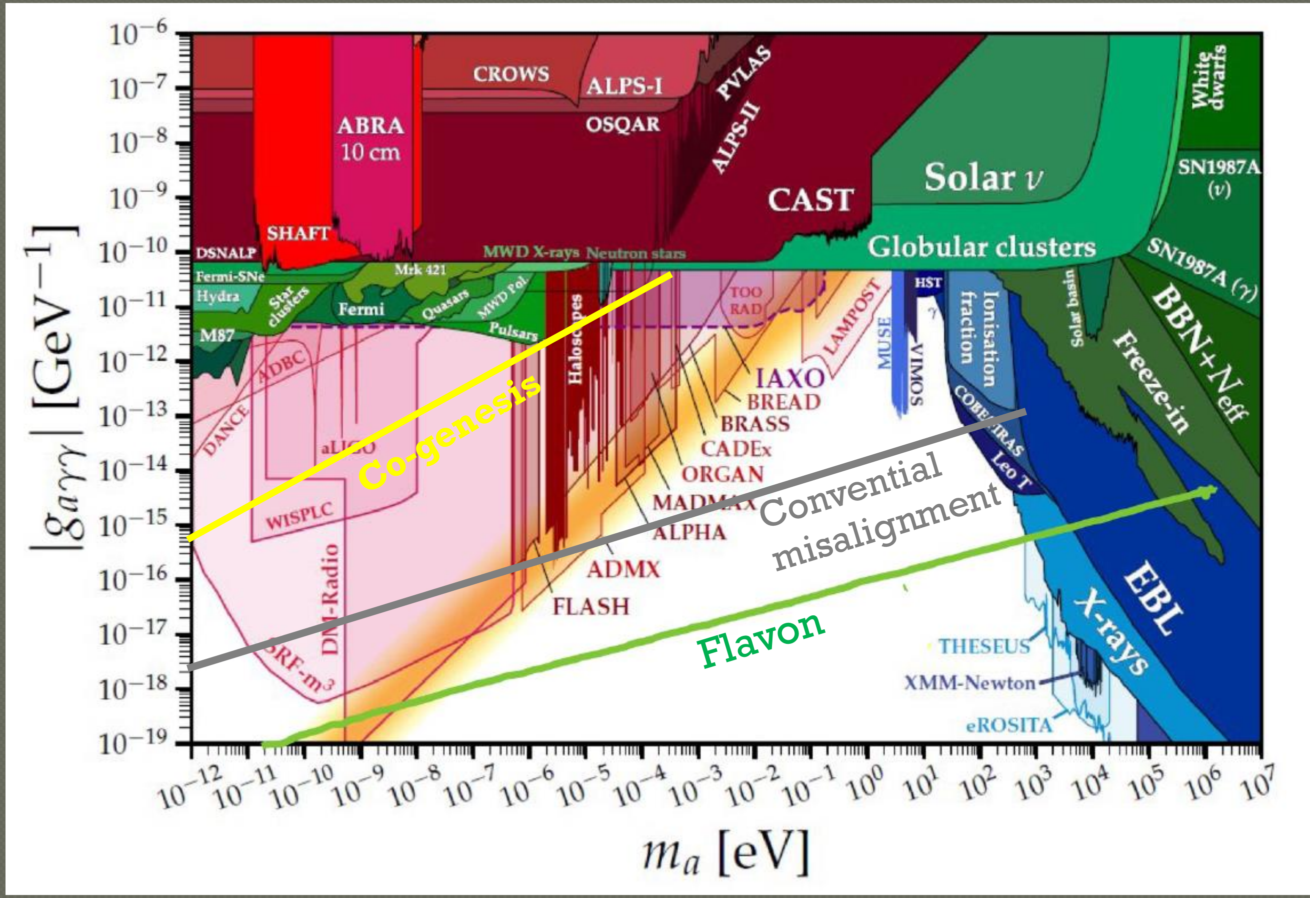
- FCNC bound from $K^+ \to \pi^+ a$

$$v_F > 7 \times 10^{11}\, V_{21}^d \mathrm{GeV} \sim 10^{11} \mathrm{GeV}$$

- DM longevity: $m_a < 2m_e \Rightarrow N > 53, v_F > 4 \times 10^{11} \mathrm{GeV}$

- X-ray bound: $m_a < \mathrm{keV} \Rightarrow N > 67, v_F > 4 \times 10^{12} \mathrm{GeV}$

Flavonic DM and ALP searches



Conclusion

- FN flavon is another example of ALP as CDM.
- It can be realized in the framework of discrete (abelian) flavor symmetry leading to a peculiar relation between the ALP mass and decay constant.
- Quark and lepton masses and mixing can be easily reproduced assuming Dirac neutrinos.
- The predicted photon couplings are well out of the current and future detectability except the mass around keV and neV.