Cosmological constraints on light flavons

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The SM and beyond

SM predictions confirmed:

- the W & Z (1983)
- the top quark (1995)
- the tau neutrino (2000)
- "a" Higgs boson (2012)

What is missing:

- Fermion mass hierarchy explanation
- Dark Matter candidate

⇒ Non-minimal Higgs frameworks

The Froggatt-Nielsen mechanism

Yukawa interactions as effective operators:

$$\mathcal{L}_Y \supset c_{ij} \left(\frac{\Phi}{\Lambda}\right)^{n_{ij}} \bar{f}_{L,i} f_{R,j} H \qquad \text{where} \qquad H = \begin{pmatrix} 0 \\ \frac{v_h + h}{\sqrt{2}} \end{pmatrix}, \; \Phi = \left(\frac{v_\phi + \phi}{\sqrt{2}}\right)$$

U(1) charges: $q_{\bar{L},i} + q_{R,j} + q_h + q_\phi n_{ij} = 0$

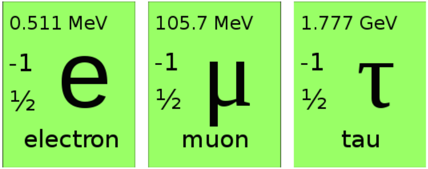
$$\begin{cases} q_\phi = -1 \\ q_h = 0 \end{cases} \Rightarrow \; Y_{ij} = c_{ij} \left(\frac{v_\phi}{\sqrt{2}\Lambda}\right)^{(q_{\bar{L},i} + q_{R,j})} \equiv c_{ij}\; \epsilon^{n_{ij}}$$

Leading to flavour violating interactions

$$\mathcal{L}_Y \supset \frac{v_h}{\sqrt{2}}\; Y_{ij} \left(1 + \frac{h}{v_h} + n_{ij} \frac{\phi}{v_\phi}\right) \bar{f}_{L,i} f_{R,j}$$

$$\tilde{\kappa}_{ij} = \frac{1}{v_\phi} \frac{v_h}{\sqrt{2}} (Y_{ij} \cdot n_{ij})$$

A leptophilic flavon



$$Y \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^4 \\ \epsilon^5 & \epsilon^4 & \epsilon^3 \\ \epsilon^4 & \epsilon^3 & \epsilon^2 \end{pmatrix} \quad \text{and} \quad \widetilde{\kappa} \sim \frac{1}{v_\phi} \begin{pmatrix} m_e & m_\mu\,\epsilon & m_\tau\,\epsilon^2 \\ m_\mu\,\epsilon & m_\mu & m_\tau\,\epsilon \\ m_\tau\,\epsilon^2 & m_\tau\,\epsilon & m_\tau \end{pmatrix}$$

$\bar{e}_L$	e_R	$\bar{\mu}_L$	μ_R	$\bar{\tau}_L$	τ_R	H	Φ
3	3	2	2	1	1	0	-1

The softly broken scalar potential

$$V = -\frac{\mu_h^2}{2}(H^\dagger H) + \frac{\lambda_h}{2}(H^\dagger H)^2 - \frac{\mu_\phi^2}{2}(\Phi^\dagger \Phi) + \frac{\lambda_\phi}{2}(\Phi^\dagger\Phi)^2 + \lambda_{h\phi}(H^\dagger H)(\Phi^\dagger\Phi) - \frac{{\mu'}_\phi^2}{4}(\Phi^2 + {\Phi^\dagger}^2).$$

$$H = \begin{pmatrix} 0 \\ \frac{v_h + h}{\sqrt{2}} \end{pmatrix}, \qquad \Phi = \left(\frac{v_\phi + \phi}{\sqrt{2}}\right), \quad \text{with} \quad \phi = \sigma + i\,\eta$$

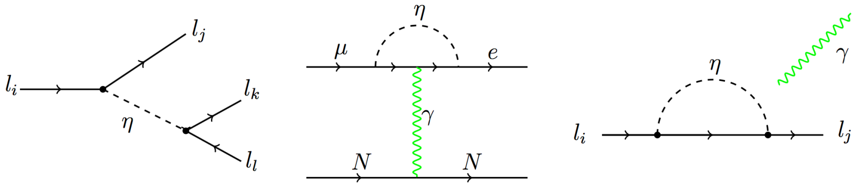
The physical states H_1, H_2

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \equiv \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \sigma \end{pmatrix}$$

with $m_{H_2} \approx m_{H_1} = 125$ GeV and a light η

CLFV processes mediated by light η

$$m_{H_1} = 125\text{GeV}, \quad m_{H_2} = 500\text{GeV}, \quad m_\eta < 2m_e$$

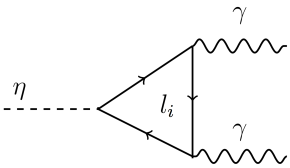


$$BR(\mu \to e\gamma) < 4.2 \times 10^{-13} \Rightarrow v_\phi > 14.4 \text{ TeV}$$

The MEG collaboration, Hyperfine Interact. 239 (2018) no.1, 58

Lifetime of η ($m_\eta < 2m_e$)

$$\tau_\eta = \frac{1}{\Gamma_{\eta\to\gamma\gamma}} = \frac{32\pi m_\eta}{|\mathcal{M}_{\eta\to\gamma\gamma}|^2} > 10^{17} s$$ age of the universe

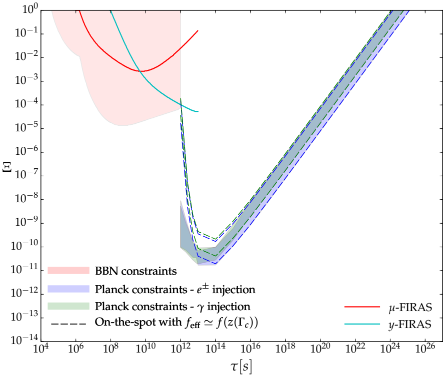


$$|\mathcal{M}_{\eta\to\gamma\gamma}|^2 = \frac{e^4}{32\pi^4}\, m_\eta^4 \left(\frac{\tilde{\kappa}_{ee}}{m_e} + \frac{\tilde{\kappa}_{\mu\mu}}{m_\mu} + \frac{\tilde{\kappa}_{\tau\tau}}{m_\tau}\right)^2$$

- for $m_\eta = 10$ KeV $\Rightarrow v_\phi \sim 10^6 GeV$
- for $m_\eta = 1$ MeV $\Rightarrow v_\phi \sim 10^{13} GeV$

CMB constraints on long-lived decaying η

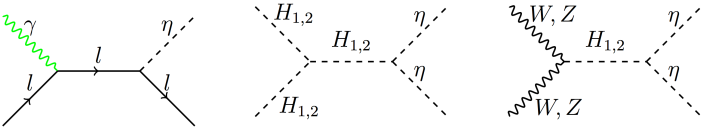
$$\text{for } \tau_\eta \sim 10^{17} s \;\Rightarrow\; \Omega_\eta h^2 \lesssim 10^{-8}\, \Omega_{DM} h^2$$

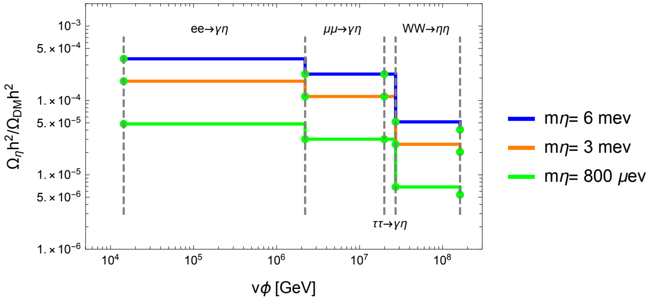


$$\text{For } \Omega_\eta h^2 = \Omega_{DM} h^2 \;\Rightarrow \begin{cases} m_\eta = 10 \text{ KeV} \to v_\phi \sim 10^{10} \text{ GeV} \\ m_\eta = 1 \text{ MeV} \to v_\phi \sim 10^{17} \text{ GeV} \end{cases}$$

JCAP 1703 (2017) no.03, 043

Production of η in the early universe

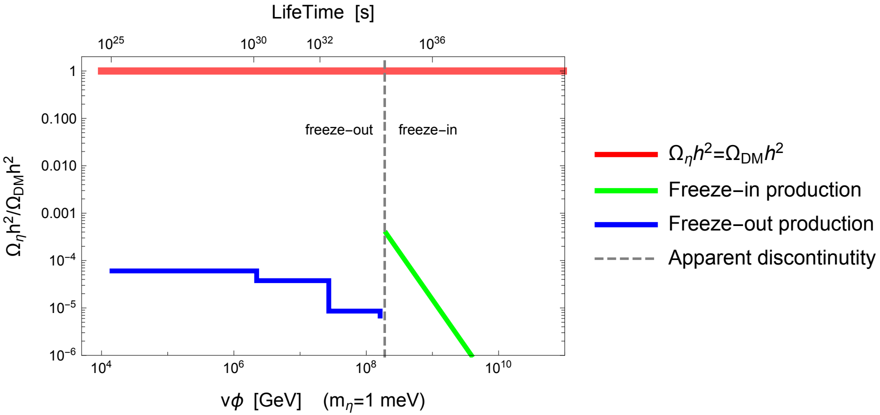




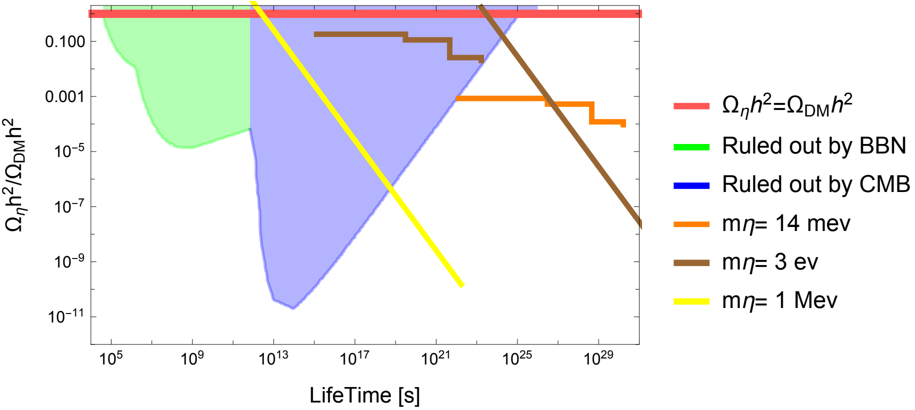
for $v_\phi \sim \mathcal{O}(10^4 - 10^8)$ GeV $\Rightarrow$ $\Gamma_{\alpha x \to \eta y}(T_{fo}) = H(T_{fo})$ where $T_{fo} \sim m_\alpha$

Production of η in the early universe

$$\text{for } v_\phi \gtrsim 10^8 \text{ GeV} \;\Rightarrow\; \eta \text{ does not thermalise}$$

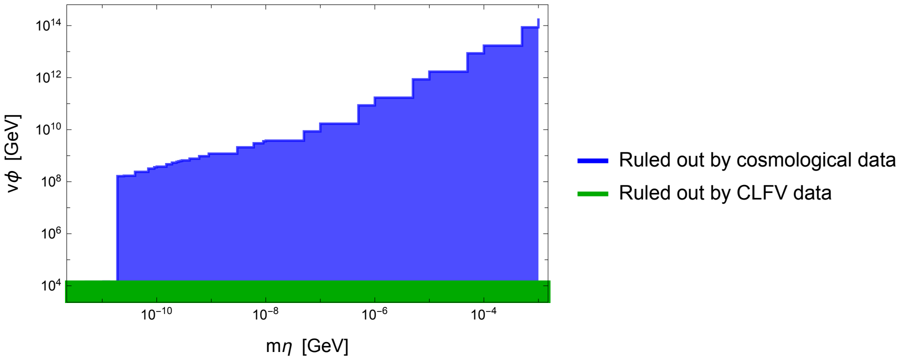


Cosmological constraints on the abundance of η



- $m_\eta \leq 14$ meV: no cosmological constraints
- 14 meV $< m_\eta < 3$ eV: hot relic, moderately constrained
- 3 eV$< m_\eta < 2m_e$: severely constrained

Cosmological constraints on the abundance of η



Summary

- Froggatt-Nielsen mechanism predicts a complex flavon responsible for producing the SM fermion Yukawa couplings.
- The real part of flavon mixes with the higgs and leads to CLFV processes.
- The abundance of the imaginary part of flavon is constrained by BBN, CMB and small scale structure observations.

BACKUP SLIDES

Yukawa interactions

$$\mathcal{L}_{eff} \supset \frac{v_h}{\sqrt{2}} \; Y_{ij} \left(1 + \frac{h}{v_h} + n_{ij}\frac{\phi}{v_\phi}\right) \bar{l}'_{L,i} l'_{R,j}$$

Diagonalising the Yukawa matrix

$$Y_{\rm diag} = U_L \; Y_{ij} \; U_R^\dagger$$

In the lepton mass basis

$$\mathcal{L}_{eff} \supset \bar{l}_L M_{\rm diag} l_R + \frac{h}{\sqrt{2}} \bar{l}_L Y_{\rm diag} l_R + \frac{v_h}{v_\phi}\frac{\phi}{\sqrt{2}} \bar{l}_{L,i} \kappa_{ij} l_{R,j} + h.c.$$

CLFV processes with coupling

$$\tilde{\kappa}_{ij} = \frac{v_h \kappa_{ij}}{\sqrt{2} v_\phi} = \left[y_j \sum_{k=1}^{3} q_{\bar{L},k} (U_L)_{ik} (U_L)^*_{jk} + y_i \sum_{k=1}^{3} q_{R,k} (U_R)_{ik} (U_R)^*_{jk} \right]$$

The scalar potential

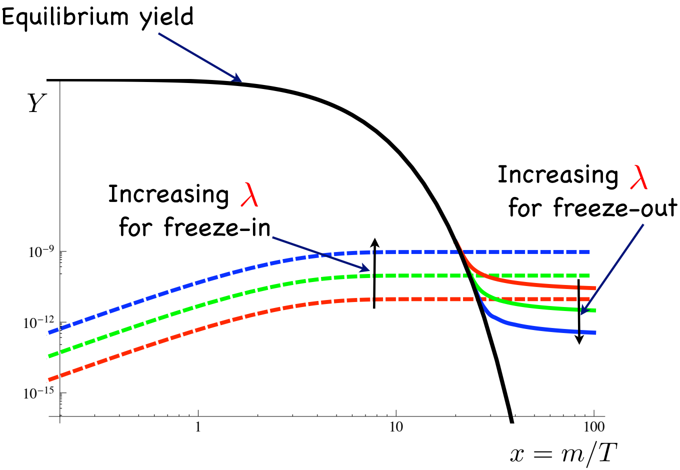
$$V = -\frac{\mu_h^2}{2}(H^\dagger H) + \frac{\lambda_h}{2}(H^\dagger H)^2 - \frac{\mu_\phi^2}{2}(\Phi^\dagger \Phi) + \frac{\lambda_\phi}{2}(\Phi^\dagger \Phi)^2 + \lambda_{h\phi}(H^\dagger H)(\Phi^\dagger \Phi) - \frac{\mu'^2_\phi}{4}(\Phi^2 + \Phi^{\dagger 2}).$$

$$H = \begin{pmatrix} 0 \\ \frac{v_h + h}{\sqrt{2}} \end{pmatrix}, \qquad \Phi = \left(\frac{v_\phi + \phi}{\sqrt{2}} \right), \quad \text{with} \quad \phi = \sigma + i\,\eta$$

The physical states H_1, H_2 (mixture of h and σ) and η

$$\mathcal{L} \supset \left[\cos\theta \, \frac{Y_{ij}^{\rm diag}}{\sqrt{2}} + \sin\theta \, \widetilde{\kappa}_{ij} \right] \bar{l}_i P_R l_j \, H_1 + \left[-\sin\theta \, \frac{Y_{ij}^{\rm diag}}{\sqrt{2}} + \cos\theta \, \widetilde{\kappa}_{ij} \right] \bar{l}_i P_R l_j \, H_2 + i\widetilde{\kappa}_{ij} \, \bar{l}_i P_R l_j \, \eta + \text{h.c.}$$

Freeze-in vs. Freeze-out



(borrowed from S. West's talk in ULB in 2010)