Flavour Cosmology: Dynamical Yukawas in the Froggatt-Nielsen Mechanism

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Short review of the matter-antimatter asymmetry puzzle and electroweak baryogenesis

Some new ideas on the flavour puzzle and varying Yukawas in electroweak baryogenesis
The matter-antimatter asymmetry

CMB (in agreement with BBN):

\[ Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (0.86 \pm 0.02) \times 10^{-10} \]

- In a symmetric universe \( n_b/s = n_{\bar{b}}/s \approx 10^{-20} \)
- The post-inflation causal volume is too small for baryons/antibaryons to be sufficiently separated
  \( (n_b/s = n_{\bar{b}}/s \approx 10^{-10} \) would be reached at \( T \approx 40 \text{ MeV} \) when \( M_{H^{-3}} \approx 10^{-7} M_\odot \)).
- We seek a mechanism to generate the asymmetry

Sakharov Conditions

1. B violation
2. C and CP violation
3. Departure from thermal equilibrium (or spontaneously broken CPT)
Baryogenesis

Sakharov Conditions

1. B violation
2. C and CP violation
3. Departure from thermal equilibrium (or spontaneously broken CPT)

SM + FRLW

1. (B+L) violation present in symmetric phase at $T \gtrsim 100$ GeV from non-perturbative EW sphaleron process.
2. CP violation observed in quark sector (but not strong enough).
3. Can be driven by expansion (but SM EW phase transition is a crossover).

Almost there...
Focus here is EW baryogenesis (but also remember Leptogenesis, Affleck-Dine baryogenesis, Spontaneous baryogenesis, ...)
Electroweak baryogenesis - basic picture

CP violating collisions with the bubble walls lead to a chiral asymmetry.

Sphalerons convert this to a Baryon Asymmetry.

This is swept into the expanding bubble where sphalerons are suppressed.
Electroweak baryogenesis requires:

- A strong first order phase transition \( (\phi_c / T_c \gtrsim 1) \)
- Sufficient CP violation

However in the SM:

- The Higgs mass is too large
- Quark masses are too small

We require new (EW-scale) physics!
Electroweak phase transition

Lattice calculations show the SM Higgs mass is too large.

\[ R_{HW} \equiv \frac{m_H}{m_W} \]

Endpoint at:
\[ m_H \approx 67 \text{ GeV} \]

- Csikor, Fodor, Heitger, Phys. Rev. Lett. 82, 21 (1999)

Higgs mass is too large in the SM. The Higgs potential must be modified.
Require a modification of the Higgs potential

\[ V(H) = m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{1}{f^2}|\Phi|^6 \]

Other options:
- Singlet models/tree level barriers
- Thermal barriers from bosonic loops
- Multi-step transitions

Successful electroweak baryogenesis requires:

\[ \Gamma_{\text{sph}} \sim 10^{1\div4} \left( \frac{\alpha_W T}{4\pi} \right)^4 \left( \frac{2M_W(\phi)}{\alpha_W T} \right)^7 \text{Exp} \left[ -\frac{3.2M_W(\phi)}{\alpha_W T} \right] \lesssim H \Rightarrow \frac{\phi_c}{T_c} \gtrsim 1 \]

- Delaunay, Grojean, Wells [0711.2511]
Collider signatures - example

Correlation between $T_c$ and triple Higgs couplings $g_{111}h^3$ in a singlet model. - Profumo, Ramsey-Musolf, Wainwright, Winslow [1407.5342]

- Example of how the Higgs potential can be probed by experiment.
- This would also constrain the parameter $f$ in the previous example.
- Other signals can also be found in the literature e.g. $h \rightarrow \gamma\gamma$ in inert 2HDM models. - Blinov, Profumo, Stefaniak [1504.05949]
Baryogenesis from charge transport with SM CP violation

\[ R_{LR} = \ldots \]

\[ \epsilon_{\text{CP}} \sim \frac{1}{M_W^6 T_c^6} \prod_{i>j}^{u,c,t} (m_i^2 - m_j^2) \prod_{i>j}^{d,s,b} (m_i^2 - m_j^2) J_{\text{CP}} \]

- Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289],
- Huet, Sather [hep-ph/9404302].

SM quark masses are too small!
EDMs

Additional CP violation

\[ \mathcal{L} \supset y_{ij} \bar{Q}_i \Phi u_j + x_{ij} \frac{(\Phi^\dagger \Phi)}{\Lambda_{\text{CP}}^2} \bar{Q}_i \Phi u_j \]

- Huber, Pospelov, Ritz [hep-ph/0610003], Konstandin [1302.6713]

Neutron EDM: \( |d_n| < 3 \times 10^{-26} \text{ e cm} \)

- Such operators are constrained from EDMs and FCNCs.
- Constraint from neutron EDM:
  \( \Lambda_{\text{CP}} \gtrsim \sqrt{\text{Im}[x_{33}]} \times 750 \text{ GeV.} \)
- Small \( \Lambda_{\text{CP}} \) possible with \( x_{ij} \sim y_{ij} \).
EDMs

Additional CP violation

\[ \mathcal{L} \supset y_{ij} \overline{Q_i} \Phi u_j + x_{ij} \frac{(\Phi^\dagger \Phi)}{\Lambda_{CP}^2} \overline{Q_i} \Phi u_j \]

Plots for \( \Lambda \equiv f = \Lambda_{CP} \). Left: top only \( (x_{33}) \). Right: MFV.
- Huber, Pospelov, Ritz [hep-ph/0610003]

Common constraint on EWBG!
Could the solution be linked to flavour?

Yukawa interactions:

\[ y_{ij} \bar{f}_L^i \Phi^{(c)} f_R^j \]

Possible solutions

- Froggatt-Nielsen
- Composite Higgs
- Randall-Sundrum Scenario

Froggatt-Nielsen Yukawas:

\[ y_{ij} \sim \left( \frac{\chi}{\Lambda} \right)^{-q_i + q_j + q_H} = \left( \frac{\chi(\phi)}{\Lambda} \right)^{-q_i + q_j + q_H} \]

Some previous work: Baryogenesis from the Kobayashi-Maskawa phase
- Berkooz, Nir, Volansky - Phys. Rev. Lett. 93 (2004) 051301

Split fermions baryogenesis from the Kobayashi-Maskawa phase
- Perez, Volansky - Phys. Rev. D 72 (2005) 103522
We postulate varying Yukawas

Study the strength of the EWPT with varying Yukawas in a _model independent_ way. Assume $\chi(\phi)$. - IB, Konstandin, Servant (1604.04526)

**Ansatz**

$$y(\phi) = \begin{cases} 
    y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for } \phi \leq v, \\
    y_0 & \text{for } \phi \geq v.
\end{cases}$$
Effective Potential

Thermal correction

\[ V_{\text{eff}} \supset -\frac{g_* \pi^2}{90} T^4 \]
Effective Potential - SM case

Crossover transition $T_c = 163$ GeV.

$$V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T)$$
Effective Potential - Varying Yukawas

Strong first order phase transition

\[ \phi_c = 230 \text{ GeV}, \quad T_c = 128 \text{ GeV}, \quad \phi_c / T_c = 1.8 \]
Effective Potential - \( T = 0 \) terms

\[
V_{\text{eff}} = V_{\text{tree}}(\phi) + V_0^1(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T)
\]

\[
V_{\text{tree}}(\phi) = -\frac{\mu^2}{2} \phi^2 + \frac{\lambda}{4} \phi^4
\]

\[
V_0^1(\phi) = \sum_i \frac{g_i(-1)^F}{64\pi^2} \left\{ m_i^4(\phi) \left( \log \left[ \frac{m_i^2(\phi)}{m_i^2(\nu)} \right] - \frac{3}{2} \right) + 2m_i^2(\phi)m_i^2(\nu) \right\}
\]

Gives a large negative contribution to the \( \phi^4 \) term.

- Can lead to a new minimum between \( \phi = 0 \) and \( \phi = 246 \text{ GeV} \).
- Not an issue for previous \( y_1 = 1, n = 1 \) example.
- Can make phase transition weaker.
Effective Potential - one-loop \( T \neq 0 \) correction

\[
V_1^T(\phi, T) = \sum_i g_i (-1)^F \frac{T^4}{2\pi^2} \times \int_0^\infty y^2 \log \left( 1 - (-1)^F e^{-\sqrt{y^2 + m_i^2(\phi)/T^2}} \right) dy
\]

\[
V_f^T(\phi, T) = -\frac{gT^4}{2\pi^2} J_f \left( \frac{m_f(\phi)^2}{T^2} \right)
\]

\[
J_f \left( \frac{m_f(\phi)^2}{T^2} \right) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24} \left( \frac{m}{T} \right)^2 - \frac{1}{32} \left( \frac{m}{T} \right)^4 \log \left[ \frac{m^2}{13.9 T^2} \right], \quad \text{for} \quad \frac{m^2}{T^2} \ll 1,
\]

\[
\delta V \equiv V_f^T(\phi, T) - V_f^T(0, T)
\]

\[
\approx \frac{gT^2 \phi^2[y(\phi)]^2}{96}
\]
Effective Potential - daisy correction

\[ V_{\text{Daisy}}(\phi, T) = \frac{T}{12\pi} \left\{ m_{\phi}^3(\phi) - \left[ m_{\phi}^2(\phi) + \Pi_{\phi}(\phi, T) \right]^{3/2} \right\} \]

\[ \Pi_{\phi}(\phi, T) = \left( \frac{3}{16} g_2^2 + \frac{1}{16} g_Y^2 + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{g y(\phi)^2}{48} \right) T^2 \]
Strength of the phase transition with varying Yukawas

\[ y(\phi) = y_1 \left( 1 - \left[ \frac{\phi}{\nu} \right]^n \right) + y_0 \quad \text{for} \quad \phi \leq \nu \]
Including the flavon

Flavor Cosmology: Dynamical Yukawas in the Froggatt-Nielsen Mechanism
- IB, Konstandin, Servant (1608.03254)

- Have to take into account constraints from flavour physics.
- Flavon dof also affects $\phi_c / T_c$.
- Generic prediction: light flavon with mass below the EW scale.

We have implemented this idea in some non-standard Froggatt-Nielsen scenarios.
Including the flavon: Froggatt-Nielsen Mechanism

**Froggatt-Nielsen**

\[
\mathcal{L} = \tilde{y}_{ij} \left( \frac{S}{\Lambda_s} \right)^{n_{ij}} \bar{U}_i \tilde{\Phi} Q_j + y_{ij} \left( \frac{S}{\Lambda_s} \right)^{m_{ij}} \bar{D}_i \Phi Q_j \\
+ \tilde{f}_{ij} \left( \frac{X}{\Lambda_{\chi}} \right)^{2n_{ij}} \bar{U}_i \tilde{\Phi} Q_j + f_{ij} \left( \frac{X}{\Lambda_{\chi}} \right)^{2m_{ij}} \bar{D}_i \Phi Q_j + H.c.
\]

Under \( U(1)_{FN} \): \( S (-1) \) and \( X (-1/2) \). Define \( \epsilon_s \equiv \langle S \rangle / \Lambda_s \), \( \epsilon_{\chi} \equiv \langle X \rangle / \Lambda_{\chi} \).

**Charges and resulting Yukawas and mixings**

| \( Q_3 \) (0), | \( Q_2 \) (+2), | \( Q_1 \) (+3), | \( y_t \sim 1 \), | \( y_c \sim \epsilon_s^3 \), | \( y_u \sim \epsilon_s^7 \), |
| --- | --- | --- | --- | --- | --- |
| \( \bar{U}_3 \) (0), | \( \bar{U}_2 \) (+1), | \( \bar{U}_1 \) (+4), | \( y_b \sim \epsilon_s^2 \), | \( y_s \sim \epsilon_s^4 \), | \( y_d \sim \epsilon_s^6 \), |
| \( \bar{D}_3 \) (+2), | \( \bar{D}_2 \) (+2), | \( \bar{D}_1 \) (+3), | \( s_{12} \sim \epsilon_s \), | \( s_{23} \sim \epsilon_s^2 \), | \( s_{13} \sim \epsilon_s^3 \). |
Consider the term

$$y_{31} \left( \frac{S}{\Lambda_s} \right)^3 Q_{3L} \phi D_{1L}$$

For the UV-completion we require vector-like quarks which transform under $U(1)_{FN}$. Here $F \sim d_R$ under $G_{SM}$ and one takes $M \approx \Lambda_s$.

$$\mathcal{L} \supset \Phi Q_{3L} F^0_R + SF^2_L D_{1R} + SF^0_R F^1_L + MF^0_R F^0_L + MF^1_R F^1_L + \ldots$$

The current limits from the LHC imply $M \gtrsim 1$ TeV.
Symmetry breaking

\[ \Phi \rightarrow \frac{1}{\sqrt{2}} \left( G_1 + iG_2 \right) \left( v_\phi + \phi + iG_3 \right), \quad S \rightarrow \frac{v_s + \sigma + i\rho}{\sqrt{2}}, \quad X \rightarrow \frac{v_\chi + \chi + i\eta}{\sqrt{2}}. \]

Long range forces must be suppressed by introducing explicit breaking of \( U(1)_{\text{FN}} \).

\[ V(S) \supset -\mu_s^2 S^\dagger S + \lambda_s (S^\dagger S)^2 - A^2 (SS + S^\dagger S^\dagger) \]

Minimisation of the potential gives the relations

\[ m_\sigma^2 = 2\mu_s^2 + 4A^2 = 2\lambda_s v_s^2, \quad m_\rho^2 = 4A^2. \]

We will take \( m_\rho > m_\sigma \) for simplicity below.
What if Froggatt-Nielsen dynamics takes place close to the EW scale? Can this lead to variation of Yukawa couplings during the EWPT?

We begin with a renormalizable tree-level potential

$$V = \frac{\mu^2}{2} \phi^2 + \frac{\lambda\phi}{4} \phi^4 + \frac{\lambda_s}{4} \phi^2 \sigma^2 + \frac{\mu^2_s}{2} \sigma^2 + \frac{\lambda_s}{4} \sigma^4$$

Rewrite the above potential in the form

$$V = \frac{\mu^2_s}{2} \phi^2 + \frac{\lambda\phi}{4} \phi^4 + \frac{\lambda_s}{4} \left(\sigma^2 - \Lambda_s^2 \left[1 - C \frac{\phi^2}{v^2}\right]\right)^2 - \frac{\lambda_s \Lambda_s^4}{4} \left[1 - C \frac{\phi^2}{v^2}\right]^2$$

$C \sim 0.9$ is dimensionless and

$$\mu^2_s = -\lambda_s \Lambda_s^2$$

$$\lambda_{\phi s} = \frac{2C\Lambda_s^2}{v^2} \lambda_s.$$
Mass of the flavon

\[ V = \frac{\mu^2}{2} \phi^2 + \frac{\lambda_\phi}{4} \phi^4 + \frac{\lambda_s}{4} \left( \sigma^2 - \Lambda_s^2 \left[ 1 - C \frac{\phi^2}{v^2_\phi} \right] \right)^2 - \frac{\lambda_s \Lambda_s^4}{4} \left[ 1 - C \frac{\phi^2}{v^2_\phi} \right]^2 \]

Consistency requires \( \lambda_{\phi s}^2 < 4 \lambda_s \lambda_\phi \).
One can combine various relations to show:

\[ m_\sigma \lesssim \frac{2 \sqrt{\lambda_\phi \epsilon_s v^2_\phi}}{C \Lambda_s} \]

The potential must be quite flat for \( \Delta \phi \sim 100 \text{ GeV} \) to induce \( \Delta \chi \sim 1000 \text{ GeV} \).

For Yukawa variation we need \( m_\sigma \sim v^2_\phi / \Lambda_s \).
Froggatt-Nielsen Mechanism - Constraints (Model A-1)

\[ H = C_{sd}^2 (\bar{s}Ld)^2 + \tilde{C}_{sd}^2 (\bar{s}Rd)^2 + C_{sd}^4 (\bar{s}Ld)(\bar{s}Rd) + H.c. \]

\[ C_{sd}^2 = \left( \frac{5\epsilon_s^4 v_\phi y_{21}}{2\Lambda_s m_\sigma} \right)^2 \]
\[ \tilde{C}_{sd}^2 = \left( \frac{5\epsilon_s^4 v_\phi y_{12}^*}{2\Lambda_s m_\sigma} \right)^2 \]
\[ C_{sd}^4 = y_{12} y_{21}^* \left( \frac{5\epsilon_s^4 v_\phi}{2\Lambda_s m_\sigma} \right)^2 \]

\[ \Rightarrow \sqrt{\Lambda_s m_\sigma} \gtrsim \text{few} \times \text{TeV}. \text{ For Yukawa variation we need } m_\sigma \sim \frac{v_\phi^2}{\Lambda_s}. \]
Couple a flavon to each mass eigenstate - Knapen, Robinson (1507.00009). This allows one to avoid limits from neutral meson oscillations.

More freedom for $\epsilon_s$

$$\epsilon_s \equiv \frac{\langle \sigma \rangle}{\sqrt{2} \Lambda_s}$$

$$\mathcal{L} \supset \frac{\gamma_b}{\sqrt{2}} \left( \frac{\sigma}{\sqrt{2} \Lambda_s} \right)^2 \phi \bar{b}b$$

We assume a simple polynomial scalar potential up to dimension four + FN style coupling to $b$'s.
Upsilon and K decays

\[ \epsilon_s \equiv \frac{\langle \sigma \rangle}{\sqrt{2} \Lambda_s} \]

\[ \mathcal{L} \supset \frac{y_b}{\sqrt{2}} \left( \frac{\sigma}{\sqrt{2} \Lambda_s} \right)^2 \phi \bar{b}b \]

Limits now come from light scalar searches. The flavon mixes with the Higgs but has an enhanced coupling to \( b \)'s.
Experimental signatures - Model A-2

\[ \mathcal{L} \supset \frac{y_b}{\sqrt{2}} \left( \frac{\sigma}{\sqrt{2}\Lambda_s} \right)^2 \phi \bar{b}b \quad \text{Br}(\phi \to \bar{b}b\sigma) = 1.1\% \left( \frac{0.1}{\epsilon_s} \right)^2 \left( \frac{1\ TeV}{\Lambda_s} \right)^2 \]
Model A-2: Disentangled hierarchy and mixing mechanism

\[ \Lambda_s = 10 \text{ TeV}, \ m_\sigma = 0.03 \text{ GeV}, \ \epsilon_s = 0.12, \ y_b = 1.7, \ \lambda_{\phi s} = 10^{-6.3}, \ \lambda_s = 1.6 \times 10^{-10}. \]

Here we assume a simple polynomial scalar potential up to dimension four augmented with a \( \sigma \) dependent Yukawa term.

\[ \epsilon_s \equiv \frac{\langle \sigma \rangle}{\sqrt{2} \Lambda_s} \quad \mathcal{L} \supset \frac{y_b}{\sqrt{2}} \left( \frac{\sigma}{\sqrt{2} \Lambda_s} \right)^2 \bar{\phi}bb \]
Models B

Two FN fields

\[ \mathcal{L} = \tilde{y}_{ij} \left( \frac{S}{\Lambda_s} \right)^{\tilde{\eta}_{ij}} \bar{Q}_i \Phi U_j + y_{ij} \left( \frac{S}{\Lambda_s} \right)^{\eta_{ij}} \bar{Q}_i \Phi D_j \]

\[ + \tilde{f}_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{\tilde{m}_{ij}} \bar{Q}_i \Phi U_j + f_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{m_{ij}} \bar{Q}_i \Phi D_j \]

We assume a small VEV for the second FN field today: \( \langle X \rangle \simeq 0 \).
The VEV \( \langle S \rangle \) sets the Yukawas today while \( \langle X \rangle \) varies during the EWPT.

Model B-1: \( Q_{\text{FN}}(X) = -1/2 \)

\( \Lambda_\chi \gtrsim 700 \text{ GeV} \) \((K - \bar{K})\)

\( \Lambda_\chi \gtrsim 250 \text{ GeV} \) \((B_s - \bar{B}_s)\)

Model B-2: \( Q_{\text{FN}}(X) = -1 \)

\( \Lambda_\chi \gtrsim 2.5 \text{ TeV} \) \((K - \bar{K})\)

\[ \sqrt{\Lambda_\chi m_\chi} \gtrsim 500 \text{ GeV} \) \((D - \bar{D})\)
Models B: Yukawa variation at tree level - renormalisable potential

\[ V = \frac{\mu^2}{2} \phi^2 + \frac{\lambda \phi}{4} \phi^4 + \frac{\mu^2}{2} \chi^2 + \frac{\lambda \chi}{4} \chi^4 + \frac{\lambda \phi \chi}{4} \phi^2 \chi^2. \]

**VEV conditions**

\[ \mu^2 \chi + \lambda \chi v^2 = 0, \]
\[ \mu^2 \phi + \lambda \phi v^2 = 0. \]

**Theoretical Constraints**

\[ m^2 = \mu^2 \chi + \frac{\lambda \phi \chi v^2}{2} = -\lambda \chi v^2 + \frac{\lambda \phi \chi v^2}{2} > 0 \]

\[ \lambda \chi < \lambda \phi \left( \frac{v \phi}{v \chi} \right)^4 = 4.7 \times 10^{-4} \left( \frac{1 \text{ TeV}}{v \chi} \right)^4 \]
Model B-1: $Q_{FN}(X) = -1/2$ - Constraints

We assume $\langle \chi \rangle \simeq 0$ today.

\[
\left| C_2^{bs} \right| \approx \left( \frac{|f_{23}| v_\phi}{2 \Lambda_\chi^4} \right)^2 \left\{ \frac{1}{(8\pi)^3} \Lambda_\chi^4 \right\}
\]

\[\Lambda_\chi \gtrsim 700 \text{ GeV (}K - \bar{K})\] \[\Lambda_\chi \gtrsim 250 \text{ GeV (}B_s - \bar{B}_s)\]
Model B-1: \( Q_{FN}(X) = -\frac{1}{2} \) - phase transition strength

Here we assume a simple polynomial scalar potential up to dimension four + the Yukawa sector.

\[ \Lambda_{\chi} = 1 \text{ TeV}, \lambda_{\chi} = 10^{-4}, \lambda_{\phi\chi} = 10^{-2}, m_{\chi} = 14 \text{ GeV} \]

\[ \Gamma(\chi \rightarrow \bar{c}c) \approx 10^{-12} \text{ GeV} \left( \frac{m_{\chi}}{10 \text{ GeV}} \right) \left( \frac{\nu_{\chi}^{\text{today}}}{1 \text{ GeV}} \right)^2 \left( \frac{1 \text{ TeV}}{\Lambda_{\chi}} \right)^4 \]
Model B-1: $Q_{\text{FN}}(X) = -1/2$ - phase transition strength

Yukawa sector

\[
\mathcal{L} \supset \tilde{f}_{ij} \left( \frac{X}{\Lambda_\chi} \right) \tilde{m}_{ij} \overline{Q}_i \tilde{\Phi} U_j + f_{ij} \left( \frac{X}{\Lambda_\chi} \right) m_{ij} \overline{Q}_i \Phi D_j + H.c.
\]
The $Z_2$ symmetry may be softly broken, allowing $\chi$ to decay. (Alternatively new annihilation channels may also be present.)

e.g. $\frac{X^\dagger X \bar{N}^c N}{\Lambda}$
Model B-2: \( Q_{FN}(X) = -1 \) - Constraints

The bounds are stronger because there are less \( \chi \)'s involved.

There is also a dangerous tree level constraint from the up-type quark sector due to \( \chi \phi t_L c_R \).

\[
\Lambda_\chi \gtrsim 2 \text{ TeV } (B - \bar{B}) \\
\Lambda_\chi \gtrsim 2.5 \text{ TeV } (K - \bar{K}) \\
\sqrt{\Lambda_\chi m_\chi} \gtrsim 500 \text{ GeV } (D - \bar{D})
\]
Model B-2: $Q_{FN}(X) = -1$ - phase transition strength

This is for $\Lambda_{\chi} = 1$ TeV. In tension with the flavour constraints.
Model B-2: $Q_{\text{FN}}(X) = -1$ - phase transition strength

Yukawa sector

$$\mathcal{L} \supset \tilde{f}_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{\tilde{m}_{ij}} \bar{Q}_i \bar{\Phi} U_j + f_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{m_{ij}} \bar{Q}_i \Phi D_j + H.c.$$
CP violation with varying Yukawas

Consider the source

\[ S \sim \text{Im} \left[ W_q^\dagger m^{\dagger''} m W_q \right]_{ii} \]

- \( W_q \) is the Unitary matrix which diagonalizes \( m\dagger m \).
- Prime denotes the derivative with respect to the spatial coordinate across the wall.
- \( S \sim \text{Im} \left[ W_q^\dagger m^{\dagger''} m W_q \right]_{ii} = \left[ W_q^\dagger y^{\dagger''} y W_q \right]_{ii} \phi'' \phi = 0 \) for constant Yukawas.
- One needs to solve a set of coupled diffusion equations.

Details are being studied in the Kadanoff-Baym formalism - Bruggisser, Konstandin, Servant (in preparation)
Conclusions

Electroweak baryogenesis and flavour physics may be closely related.

Yukawa variation may allow us to address:
- The lack of a strong first order phase transition in the SM
- The insufficient CP violation for EW baryogenesis.
  - Bruggisser, Konstandin, Servant (in preparation)
- The related limits on EDMs (this approach leads to a lack of EDM signals)

This offers additional motivation to consider low scale flavour models and their cosmology.

Other models of flavour are worth looking at too (not just Froggatt-Nielsen). e.g. RS1 - von Harling, Servant [1612.02447]

New experimental signatures should then be accessible as we further probe the Higgs potential!
Higher dimensional terms

\[ V = \frac{\mu_\phi^2}{2} \phi^2 + \frac{\lambda_\phi}{4} \phi^4 + \frac{\lambda_\phi \chi}{4} \phi^2 \chi^2 + \frac{\mu_\chi^2}{2} \chi^2 + \frac{\lambda_\chi}{4} \chi^4 + \frac{1}{8f^2} \chi^6. \]

Choosing \( \lambda_\chi < 0 \). We check whether we can increase the flavon mass:

The other options, \( \phi^2 \chi^4 \), \( \phi^4 \chi^2 \) and \( \phi^6 \) also don’t help.
Knapen and Robinson Construction

\[ H^\dagger \bar{Q}_L \left\{ \frac{\lambda_t}{\Lambda_F} + \left[ \frac{\sigma_c}{\Lambda_H} \right]^{p_c} \frac{\lambda_c}{\Lambda_F} + \left[ \frac{\sigma_u}{\Lambda_H} \right]^{p_u} \frac{\lambda_u}{\Lambda_F} \right\} U_R \]

\[ + H \bar{Q}_L \left\{ \left[ \frac{\sigma_b}{\Lambda_H} \right]^{p_b} \frac{\lambda_b}{\Lambda_F} + \left[ \frac{\sigma_s}{\Lambda_H} \right]^{p_s} \frac{\lambda_s}{\Lambda_F} + \left[ \frac{\sigma_d}{\Lambda_H} \right]^{p_d} \frac{\lambda_d}{\Lambda_F} \right\} D_R. \]

Need the flavon matrices to be “aligned, spectrally disjoint and rank-1”.
Consistency of Yukawa variation in the UV picture

Consider a mass matrix of the form:

$$v_{\phi} \begin{pmatrix} c_L & t_L \end{pmatrix} \begin{pmatrix} \varepsilon_s^4 & \varepsilon_s^2 \\ \varepsilon_s^2 & 1 \end{pmatrix} \begin{pmatrix} c_R \\ t_R \end{pmatrix}$$

UV completion consists of vector-like quarks $G_i \sim u_R$ under $G_{SM}$.

$$\begin{pmatrix} G_{1R} \\ G_{2R} \\ G_{3R} \\ G_{4R} \\ t_R \\ c_R \end{pmatrix}^T \begin{pmatrix} M & S & 0 & 0 & 0 & 0 & \phi \\ S & M & S & 0 & 0 & 0 \\ 0 & S & M & S & \phi & 0 \\ 0 & 0 & S & M & 0 & 0 \\ 0 & S & 0 & S & \phi & 0 \\ 0 & S & 0 & S & 0 & 0 \end{pmatrix} \begin{pmatrix} G_{1L} \\ G_{2L} \\ G_{3L} \\ G_{4L} \\ t_L \\ c_L \end{pmatrix}$$
Consistency of Yukawa variation in the UV picture

\[
\begin{pmatrix}
G_{1R} \\
G_{2R} \\
G_{3R} \\
G_{4R} \\
t_R \\
c_R
\end{pmatrix}^T
\begin{pmatrix}
M & S & 0 & 0 & 0 & \phi \\
S & M & S & 0 & 0 & 0 \\
0 & S & M & S & \phi & 0 \\
0 & 0 & S & M & 0 & 0 \\
0 & S & 0 & S & \phi & 0 \\
0 & S & 0 & S & 0 & 0
\end{pmatrix}
\begin{pmatrix}
G_{1L} \\
G_{2L} \\
G_{3L} \\
G_{4L} \\
t_L \\
c_L
\end{pmatrix}
\]

Insert random coefficients \(re^{i\theta}\) with \(r \in [0.5, 1.5], \theta \in [-\pi, \pi]\).

- SeedRandom[690720]
- \(S=1000\) GeV, obtain masses:
  \{1728.21, 1701.2, 861.237, 777.839, 356.446, 196.85\} [GeV]
- \(S=200\) GeV, obtain masses:
  \{970.202, 937.018, 886.44, 786.23, 175.201, 20.9502\} [GeV]
- \(S=0\), obtain masses:
  \{1023.59, 889.184, 852.595, 786.338, 159.827, 0.\} [GeV]