Reheating and Leptogenesis in Peccei-Quinn Inflation

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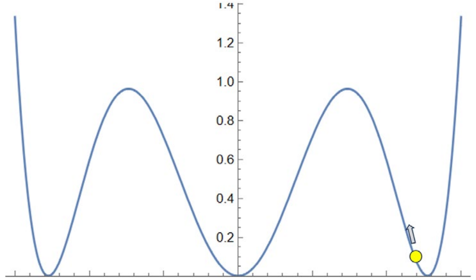
[Peccei-Quinn Inflation at the Pole and Axion Kinetic Misalignment,
H.M Lee, A.G. Menkara, M.J Seong, J.H Song Oct 26, 2023]
High1 Workshop on Particle, String and Cosmology

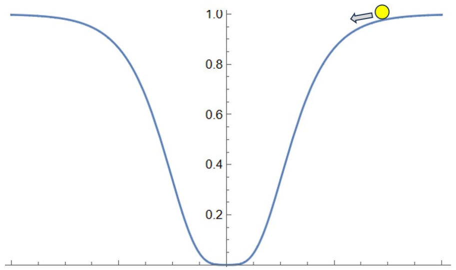
Peccei-Quinn inflation $U(1)_{PQ}$

$$\Phi = \frac{1}{\sqrt{2}}\rho\, e^{i\theta}$$



$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = -\frac{1}{2}M_P^2\,\Omega(\Phi)R(g_J) + |\partial_\mu\Phi|^2 - \Omega^2(\Phi)V_E(\Phi)$$

Jordan frame



$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}M_P^2 R + \frac{1}{2}(\partial_\mu\phi)^2 + 3M_P^2\sinh^2\left(\frac{\phi}{\sqrt{6}M_P}\right)(\partial_\mu\theta)^2 - V_E(\phi,\theta)$$

$$V_E(\phi,\theta) \;=\; V_{\rm PQ}(\phi) + V_{\rm PQV}(\rho,\theta)$$

Einstein frame

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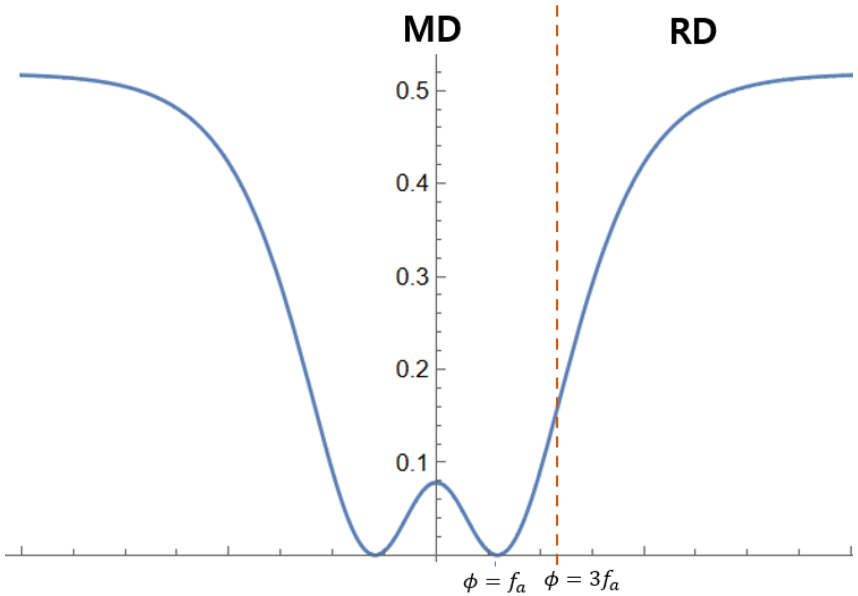
KSVZ model

$$\mathcal{L}_{Q,\rm int} = -y_Q\Phi\bar{Q}_R Q_L + \text{h.c.}$$

$$\mathcal{L}_{\rm gluons} = \frac{g_s^2}{32\pi^2}\left(\bar{\theta} + \xi\frac{a}{f_a}\right)G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\begin{aligned}
\Omega(\Phi) &= 1 - \frac{1}{3M_P^2}|\Phi|^2 \\
V_{\rm PQ}(\phi) &= V_0 + \frac{1}{4}\lambda_\Phi\left(6M_P^2\tanh^2\left(\frac{\phi}{\sqrt{6}M_P}\right) - f_a^2\right)^2 \\
V_{\rm PQV}(\rho,\theta) &= 3^{n/2}M_P^4\tanh^n\left(\frac{\phi}{\sqrt{6}M_P}\right)\sum_{k=0}^{[n/2]}|c_k|\cos\left((n-2k)\theta + A_k\right)
\end{aligned}$$

Anharmonic Inflaton Potential



$$V_{PQ} = \frac{\lambda_\phi}{4}(\phi^2 - f_a^2)^2$$

$$\phi = \phi_0(t)\mathcal{P}(t) \qquad \mathcal{P}(t) = \sum_{n=-\infty}^{\infty} \mathcal{P}_n \, e^{-in\omega t}$$

$$\omega = m_\phi \sqrt{\frac{\pi m}{2m-1}} \frac{\Gamma\left(\frac{1}{2} + \frac{1}{2m}\right)}{\Gamma\left(\frac{1}{2m}\right)}$$

$$m_\phi^2 = V_E''(\phi_0) = 2\alpha_m m(2m-1)\phi_0^{2m-2}$$

m=1 => quadratic potential

m=2 => quartic potential

Constraints

CMB normalization

$$3^{n/2}|c_k| \lesssim 10^{-10}$$

$$\lambda_\Phi = 1.1 \times 10^{-11}$$

$$V_{\rm PQ}(\phi) = V_0 + \frac{1}{4}\lambda_\Phi\left(6M_P^2 \tanh^2\left(\frac{\phi}{\sqrt{6}M_P}\right) - f_a^2\right)^2$$

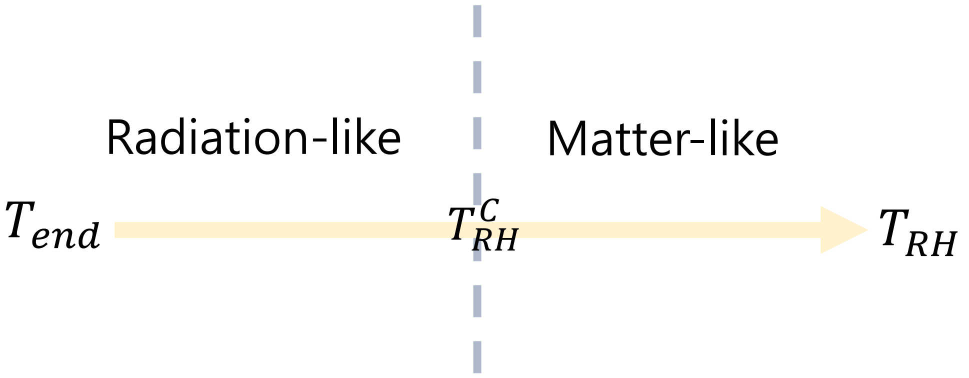
EDM Bound Condition

$$|\theta_{\rm eff}| = \left|\bar{\theta} + \xi\frac{\langle a\rangle}{f_a}\right| < 10^{-10}$$

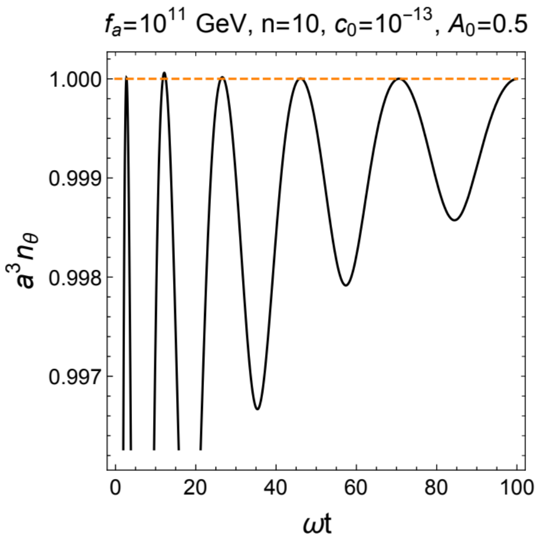
$$\left(\frac{f_a}{M_P}\right)^n \lesssim \frac{2^{n/2}\xi}{(n-2k)|c_k|}\left(\frac{\Lambda_{\rm QCD}}{M_P}\right)^4$$

$$V_{\rm PQV}(\rho,\theta) = 3^{n/2}M_P^4 \tanh^n\left(\frac{\phi}{\sqrt{6}M_P}\right)\sum_{k=0}^{[n/2]}|c_k|\cos\left((n-2k)\theta + A_k\right)$$

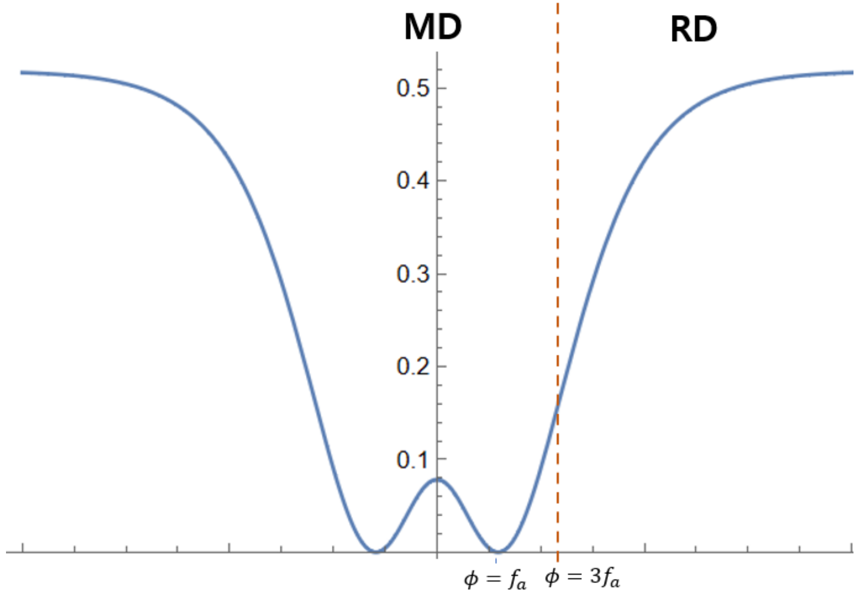
Axion Kinetic misalignment



Initial axial velocity : $\dot{\theta} \simeq -\frac{1}{3H} \frac{\frac{\partial V_E}{\partial \theta}}{6M_P^2 \sinh^2\left(\frac{\phi}{\sqrt{6}M_P}\right)}$



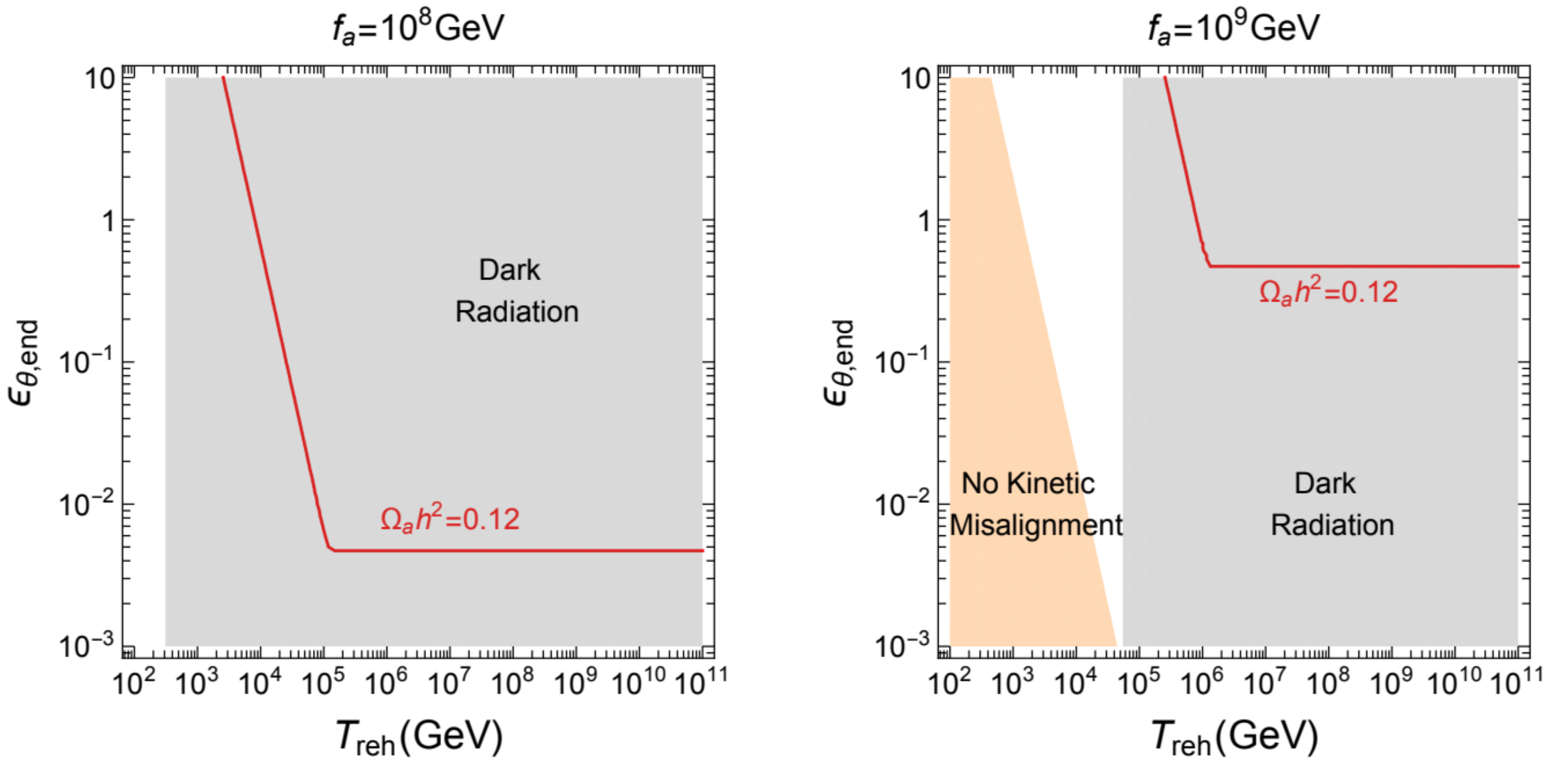
$$a^3 n_\theta = a^3 \phi^2 \dot{\theta} \simeq \text{const}$$



$$n_\theta(T_{\rm RH}) = n_{\theta,\rm end} \left(\frac{\pi^2 g_*(T_{\rm RH}) T_{\rm RH}^4}{45 V_E(\phi_{\rm end})}\right)^{3/4} \left(\frac{T_{\rm RH}}{T_{\rm RH}^c}\right)$$

$$\Omega_a h^2 = 0.12 \left(\frac{10^9\,\text{GeV}}{f_a}\right)\left(\frac{Y_\theta}{40}\right)$$

Axion Kinetic misalignment



$$\Omega_a h^2 = 0.12\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)\left(\frac{Y_\theta}{40}\right)$$

Interaction terms in reheating

Sub-dominant about Reheating

$$\mathcal{L}_{Q,\text{int}} = -y_Q \Phi \bar{Q}_R Q_L + \text{h.c.}$$

$$\mathcal{L}_{\text{gluons}} = \frac{g_s^2}{32\pi^2}\left(\bar{\theta} + \xi \frac{a}{f_a}\right) G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Due to Strong CP problem!

dominant about Reheating

$$\Delta V_E = \lambda_{H\Phi} |\Phi|^2 |H|^2$$

$$\mathcal{L}_{\text{int}} = -\frac{1}{2}\lambda_\Phi \phi^2 a^2$$

$$\frac{\Gamma_{\phi\phi\to aa}}{\Gamma_{\phi\phi\to HH}} \simeq \frac{\lambda_\Phi^2}{2\lambda_{H\Phi}^2}$$

$$\lambda_{H\Phi} \gtrsim \frac{1}{\sqrt{2}}\lambda_\Phi$$

Reheating condition

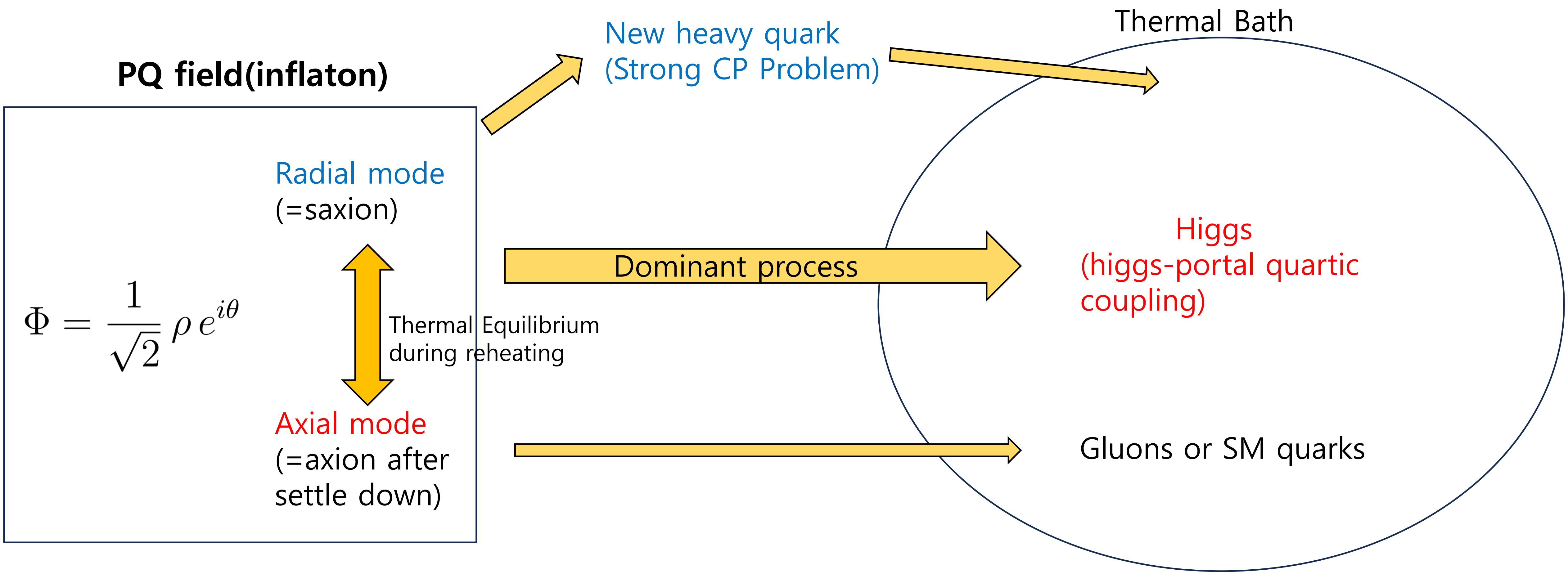
Decay, Scattering Rate

$$\langle\Gamma_{\phi\phi\to HH}\rangle = \frac{\lambda_{H\Phi}^2\phi_0^2\omega}{\pi m_\phi^2}(m+1)(2m-1)\Sigma_m^H\left\langle\left(1-\frac{m_H^2}{\omega^2 n^2}\right)^{1/2}\right\rangle \qquad \Sigma_m^H = \sum_{n=1}^\infty n|(\mathcal{P}^2)_n|^2$$

$$\langle\Gamma_{\phi\phi\to aa}\rangle = \frac{\lambda_{\Phi}^2\phi_0^2\omega}{2\pi m_\phi^2}(m+1)(2m-1)\Sigma_m^a\left\langle\left(1-\frac{m_a^2}{\omega^2 n^2}\right)^{1/2}\right\rangle \qquad \Sigma_m^a = \sum_{n=1}^\infty n|(\mathcal{P}^2)_n|^2$$

$$\langle\Gamma_{\phi\to f\bar{f}}\rangle = \frac{N_c y_f^2\omega^3}{8\pi m_\phi^2}(m+1)(2m-1)\Sigma_m^f\left\langle\left(1-\frac{4m_f^2}{\omega^2 n^2}\right)^{3/2}\right\rangle \qquad \Sigma_m^f = \sum_{n=1}^\infty n^3|\mathcal{P}_n|^2$$

Reheating


PQ field(inflaton)
$\Phi = \frac{1}{\sqrt{2}} \rho e^{i\theta}$
Radial mode
(=saxion)
Thermal Equilibrium
during reheating
Axial mode
(=axion after
settle down)
New heavy quark
(Strong CP Problem)
Thermal Bath
Dominant process
Higgs
(higgs-portal quartic
coupling)
Gluons or SM quarks

Reheating

$$\ddot{\phi} + 3H\dot{\phi} - \phi\,\dot{\theta}^2 \simeq -\frac{\partial V_E}{\partial \phi}$$

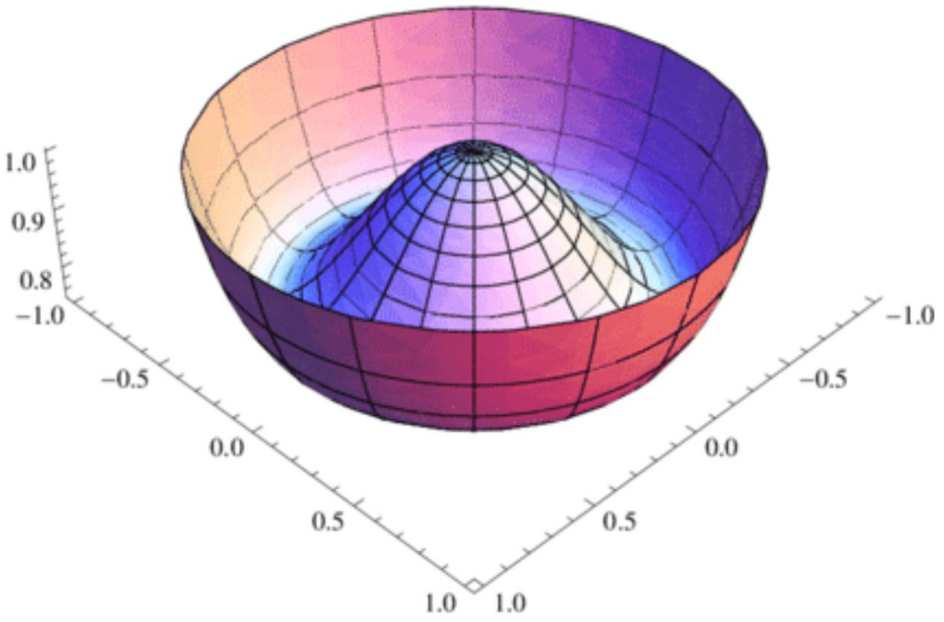
$$\phi^2(\ddot{\theta} + 3H\dot{\theta}) + 2\phi\dot{\phi}\,\dot{\theta} \simeq -\frac{\partial V_E}{\partial \theta}$$

$$\rho_R' + 4H\rho_R \simeq (\Gamma_{\phi\phi\to HH} + \Gamma_{\phi\to ff})\rho_\phi$$

Initial condition

$$\dot{\theta} \simeq -\frac{1}{3H}\frac{\frac{\partial V_E}{\partial \theta}}{6M_P^2\sinh^2\left(\frac{\phi}{\sqrt{6}M_P}\right)}$$

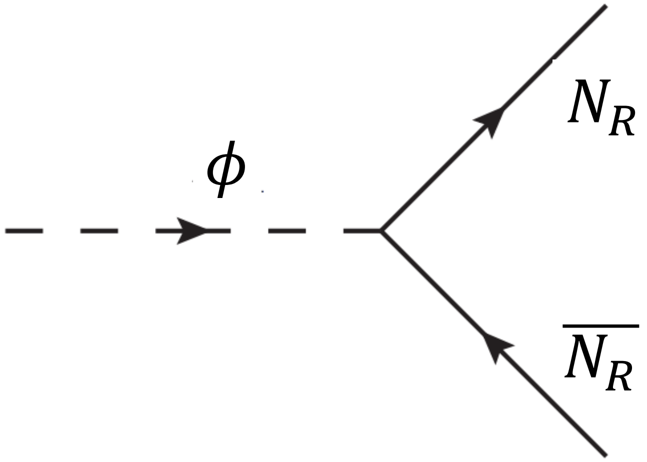
$$\phi_{\rm end} \simeq \sqrt{\frac{3}{8}}M_P \ln\left[\frac{1}{2} + \frac{2m}{3}\left(2m + \sqrt{4m^2+3}\right)\right]$$



$$T_{\rm RH}|_{\rm scattering} \simeq 6.0\times 10^{11}\,{\rm GeV}\left(\frac{100}{g_*(T_{\rm reh})}\right)^{1/4}\left(\frac{\max[\lambda_{H\Phi}, \sqrt{4N_c}y_f^2 m_f/\omega]}{10^{-7}}\right)^2\left(\frac{10^{-11}}{\lambda_\Phi}\right)^{3/4}$$

Leptogenesis

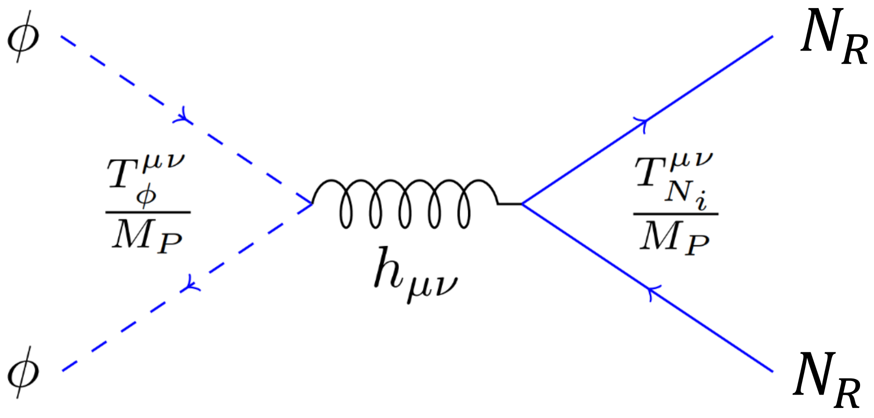
$$\mathcal{L} \supset i\overline{N}_R\gamma^\mu\partial_\mu N_R + h\bar{l}_L H N_R + M_N\overline{N}^c_R N_R + h.c$$



$$\mathcal{L}_{N,\text{int}} = -\frac{1}{2}\lambda_N \Phi \overline{N^c_L} N_R + \text{h.c.}$$

$$M_\phi \sim M_R$$

Dominant



$$\sqrt{-g}L^1_{int} \supset \frac{1}{2M_P} h_{\mu\nu}\left(T^{\mu\nu}_{SM} + T^{\mu\nu}_\phi + T^{\mu\nu}_N\right).$$

$$g_{\mu\nu} \cong \eta_{\mu\nu} + \frac{h_{\mu\nu}}{M_P}$$

Sub-Dominant