Cosmology of Flavons

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"The Flavor of Cosmology"

with M. Ratz, T. M. P. Tait, *and* S. Trojanowski

arXiv:1804.03662

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Models of Flavons

- Explain form of Yukawa matrix: $y^u_{ij}\overline{Q}_i \Phi u_j \longrightarrow \left(\frac{S}{\Lambda}\right)^n \overline{Q}_i \Phi u_j$
- Froggatt–Nielsen:
  - $\mathcal{L}_{\text{FN}} \sim \left(\frac{S}{\Lambda}\right)^{n^u_{ij}} \overline{Q}_i \Phi u_j + \left(\frac{S}{\Lambda}\right)^{n^d_{ij}} \overline{Q}_i \widetilde{\Phi} d_j$
  - Dimension-5 effective operators with scale Λ:

$$S \longrightarrow \frac{v_S + \sigma + i\rho}{\sqrt{2}}$$

radial mode (flavon)

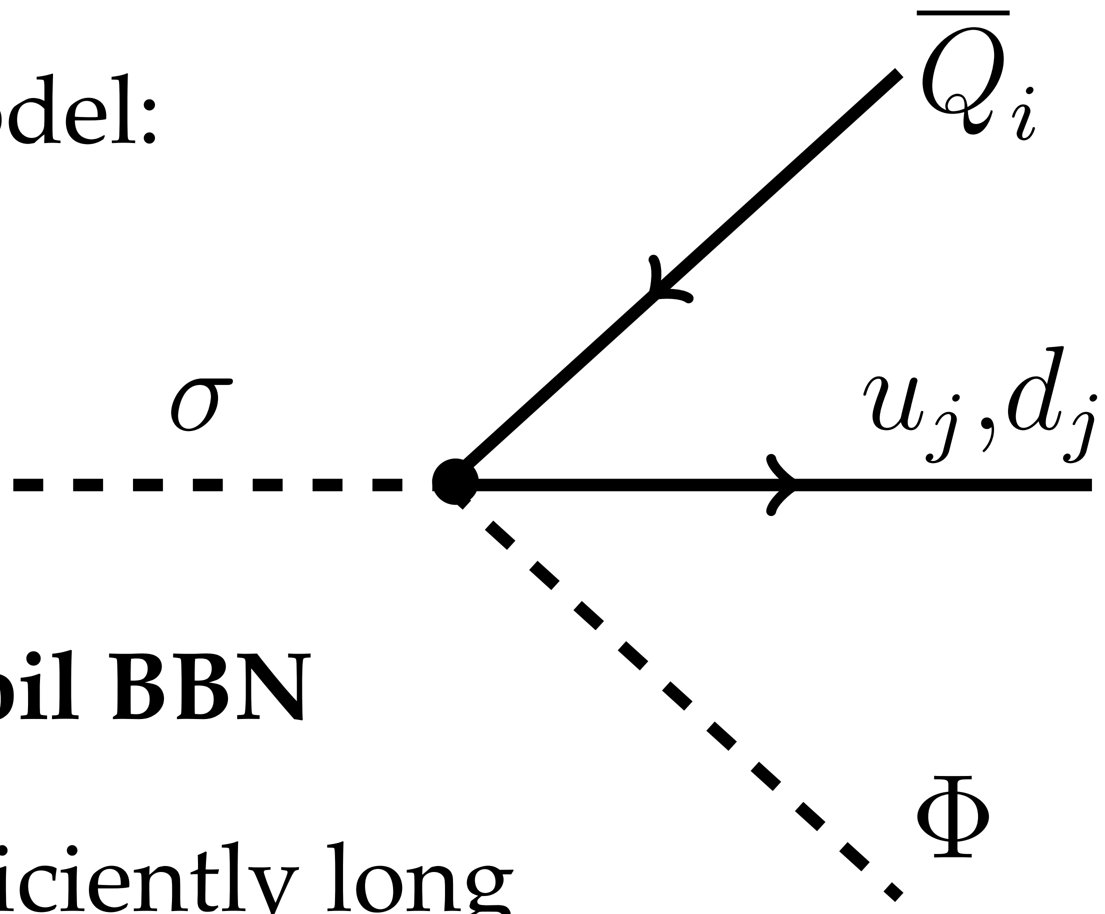
$$\mathcal{L}_{\text{FN}} \sim n\epsilon^{n-1} \frac{\sigma \overline{Q}_i \Phi u_j}{\Lambda}$$

- Ratio $\langle S \rangle / \Lambda = \epsilon \simeq 0.23$ determines Yukawa couplings: for lighter quarks, $y \sim \epsilon^n$.

Decays of Flavons

- Flavons decay to Standard Model:

$$\Gamma_\sigma \sim \frac{m_\sigma^3}{64\pi^3\Lambda^2}$$

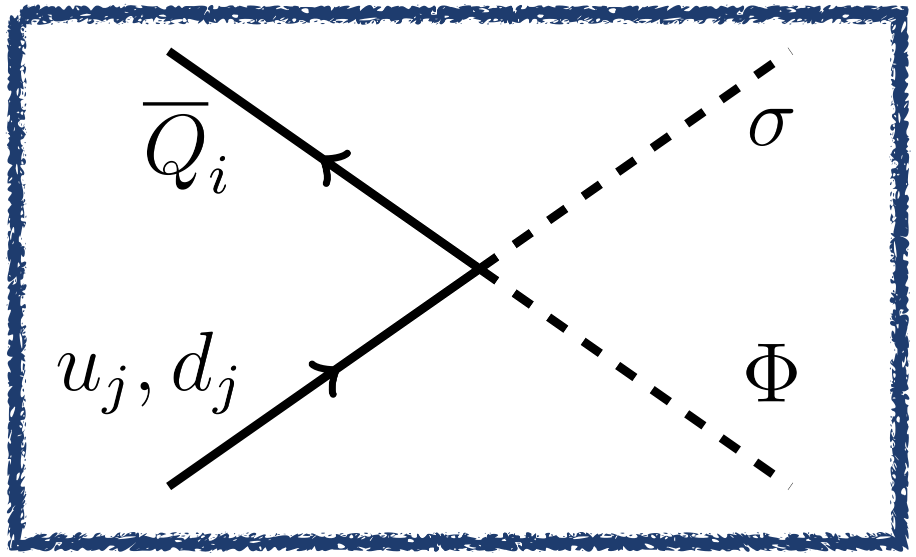


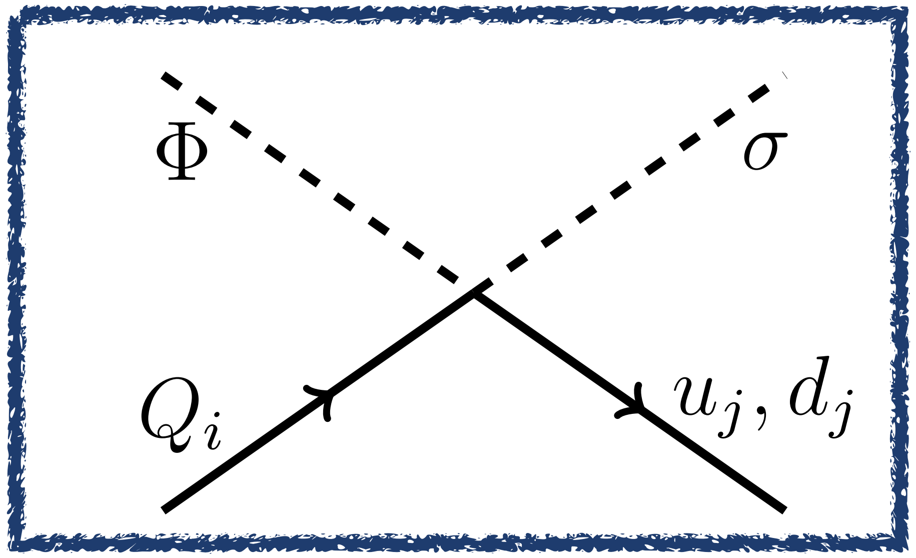
- **Late-decaying flavons can spoil BBN**
  - **IF** Flavon lifetime is sufficiently long
  - **AND** Enough flavons are produced

B. Lillard, M. Ratz, T. M. P. Tait, and S. Trojanowski, "The Flavor of Cosmology," arXiv:1804.03662 [hep-ph].

Flavon Production 1: Freeze-In

- Out-of-equilibrium flavon production
  - Solve Boltzmann equation
- Dominated by **high-temperature** limit
  - Flavon yield Y_σ scales linearly with T_R
  - $Y_\sigma^{\text{FI}} \sim \dfrac{M_P T_R}{\Lambda^2}$





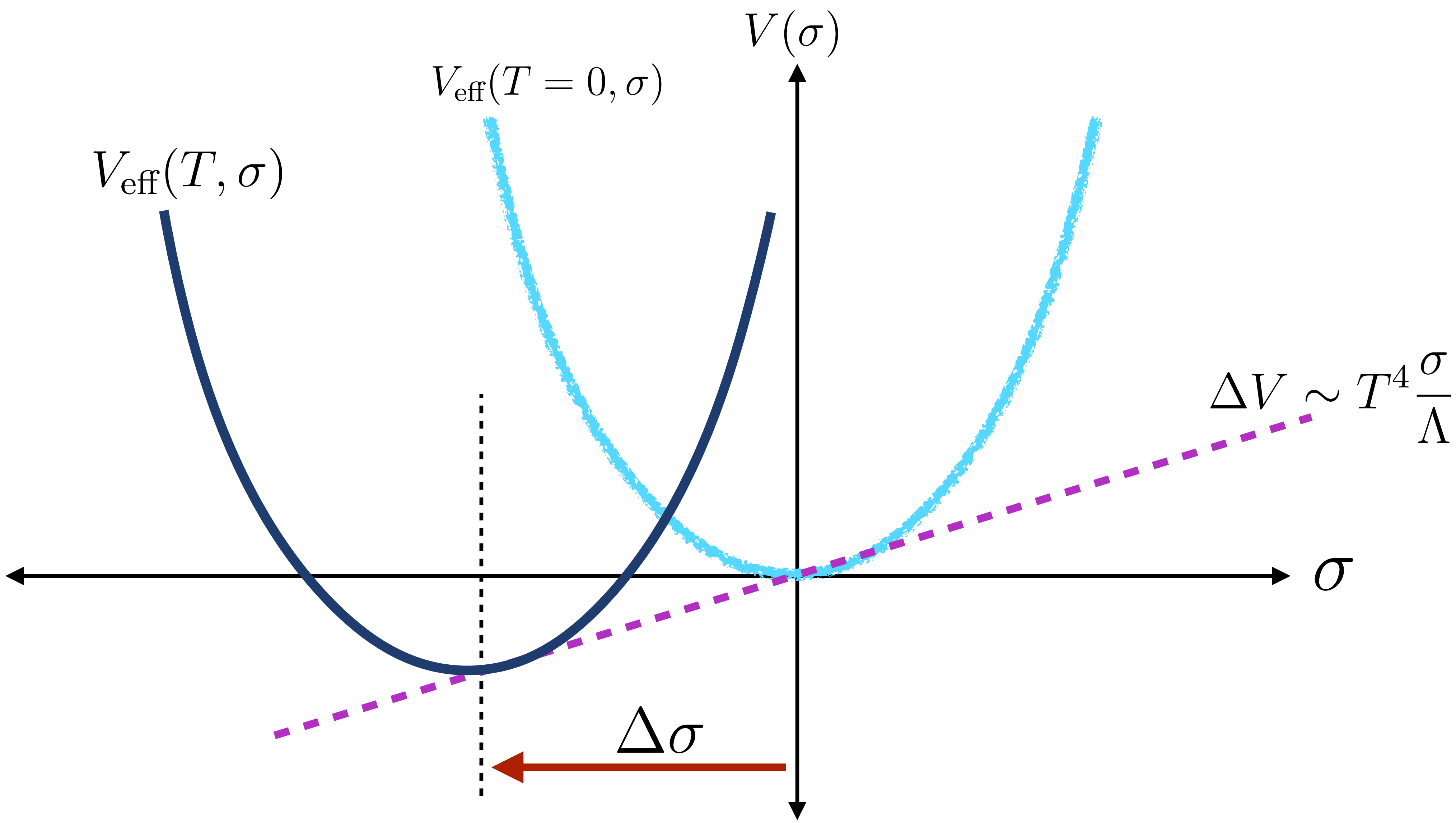
$$Y_\sigma = \frac{n_\sigma}{S}$$

Flavon Production 2: Scalar Potential

- Thermal effects add terms to scalar potential:

$$\mathscr{V}_{\text{eff}}(\sigma, T) \;=\; \gamma\, T_Y\, T^4 + \alpha\, T^4 \frac{\sigma}{\Lambda} + \frac{m_\sigma^2(T)}{2}\,\sigma^2 + \frac{\kappa}{3!}\,\sigma^3 + \frac{\lambda_S}{4}\,\sigma^4$$

Free energy of a Yukawa gas depends on coupling y^2; expansion includes radial mode σ.



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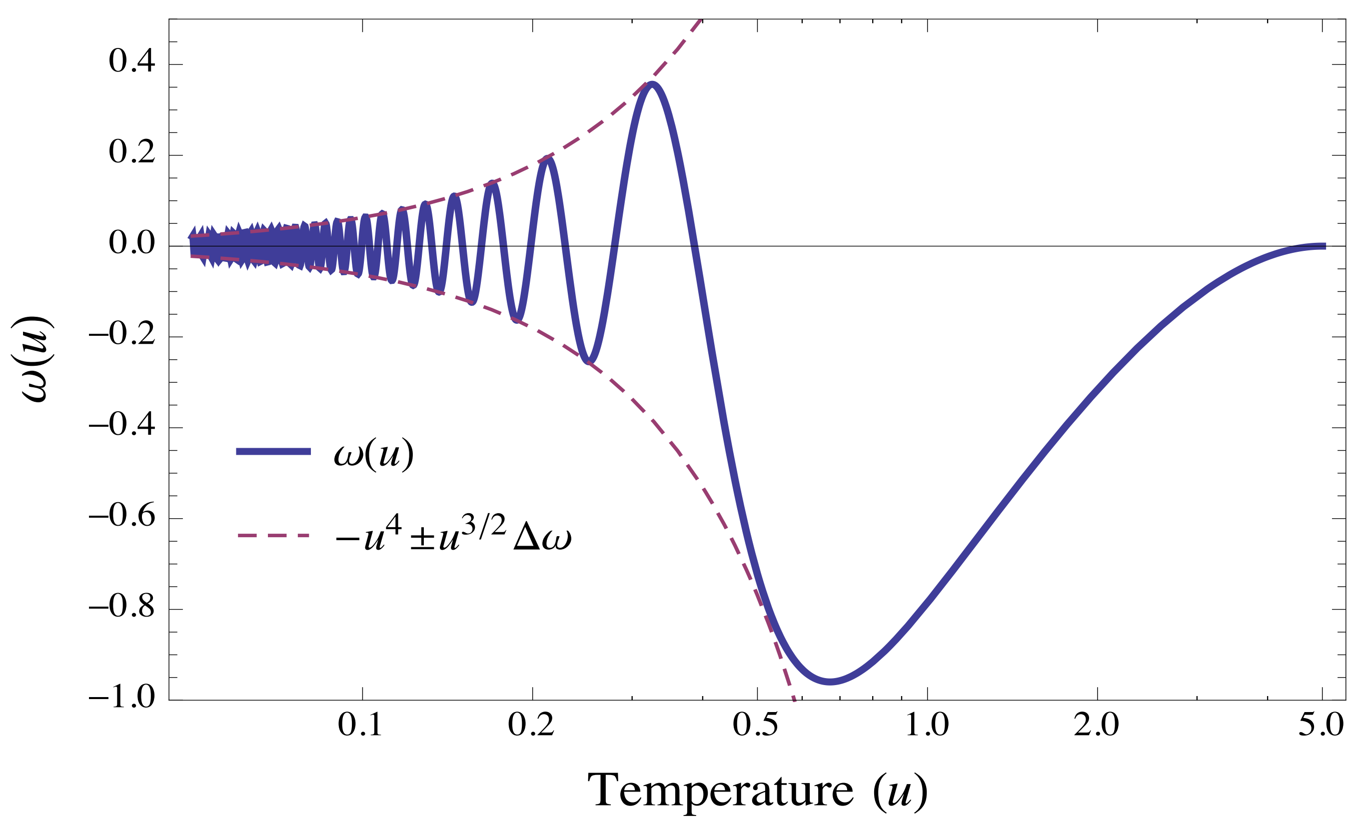
shifts flavon away from its T=0 minimum

- **Equations of motion for σ depend on temperature**

  Surprisingly, has analytic solution when cubic and quartic terms are dropped

- Flavon yield:

$$Y_\sigma^{\text{osc}} \sim \frac{T_R^5}{\Lambda^2 m_\sigma^3}$$

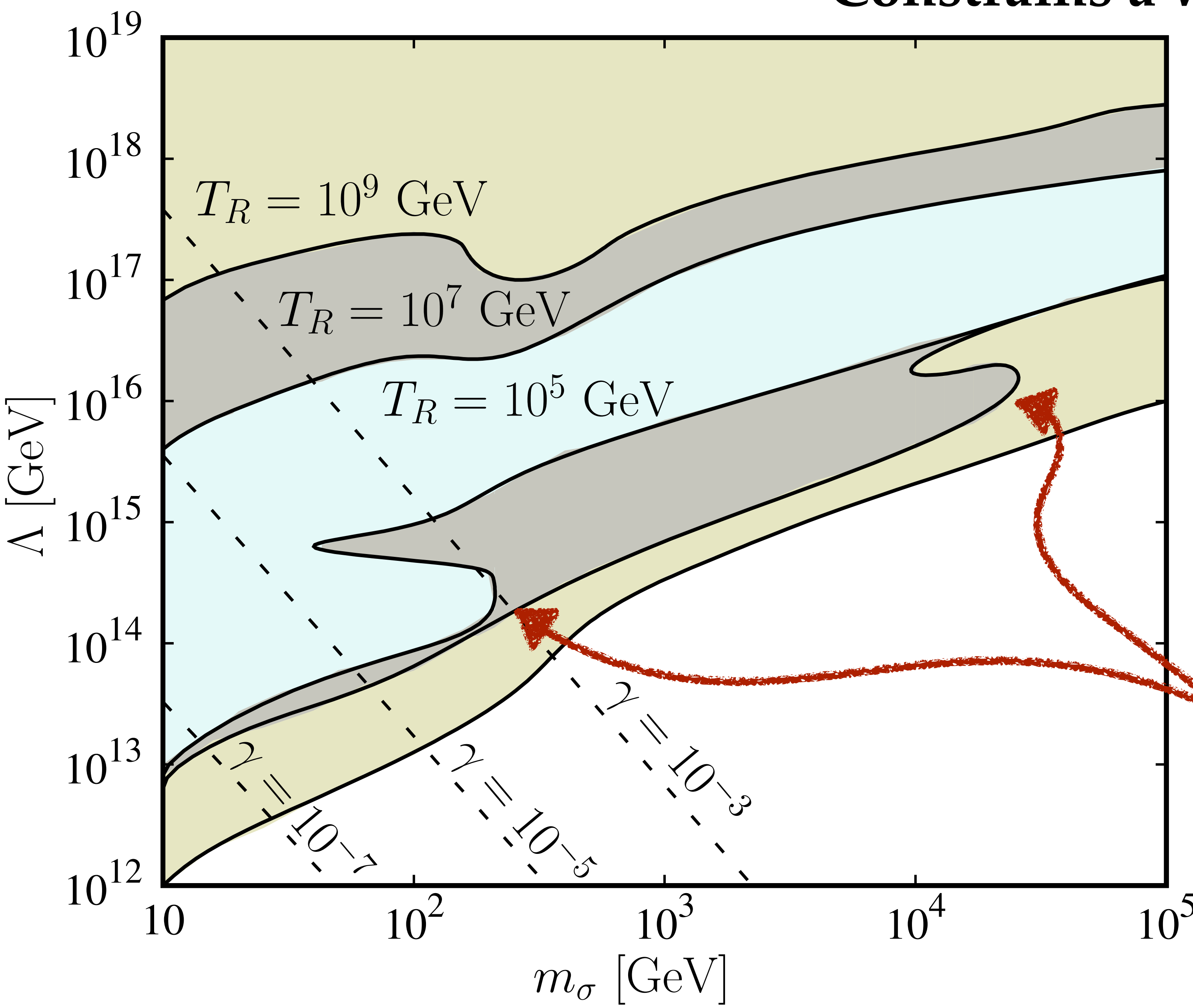


$$\omega \sim \frac{\Lambda}{M_P^2}\sigma$$

$$u \sim \frac{T}{\sqrt{m_\sigma M_P}}$$

Constraining the Flavon

- Larger Λ reduces the flavon yield, but increases lifetime:
  - **Constrains a window of Λ parameter space**



$$\tau_\sigma \sim \frac{64\pi^3\Lambda^2}{m_\sigma^3}$$

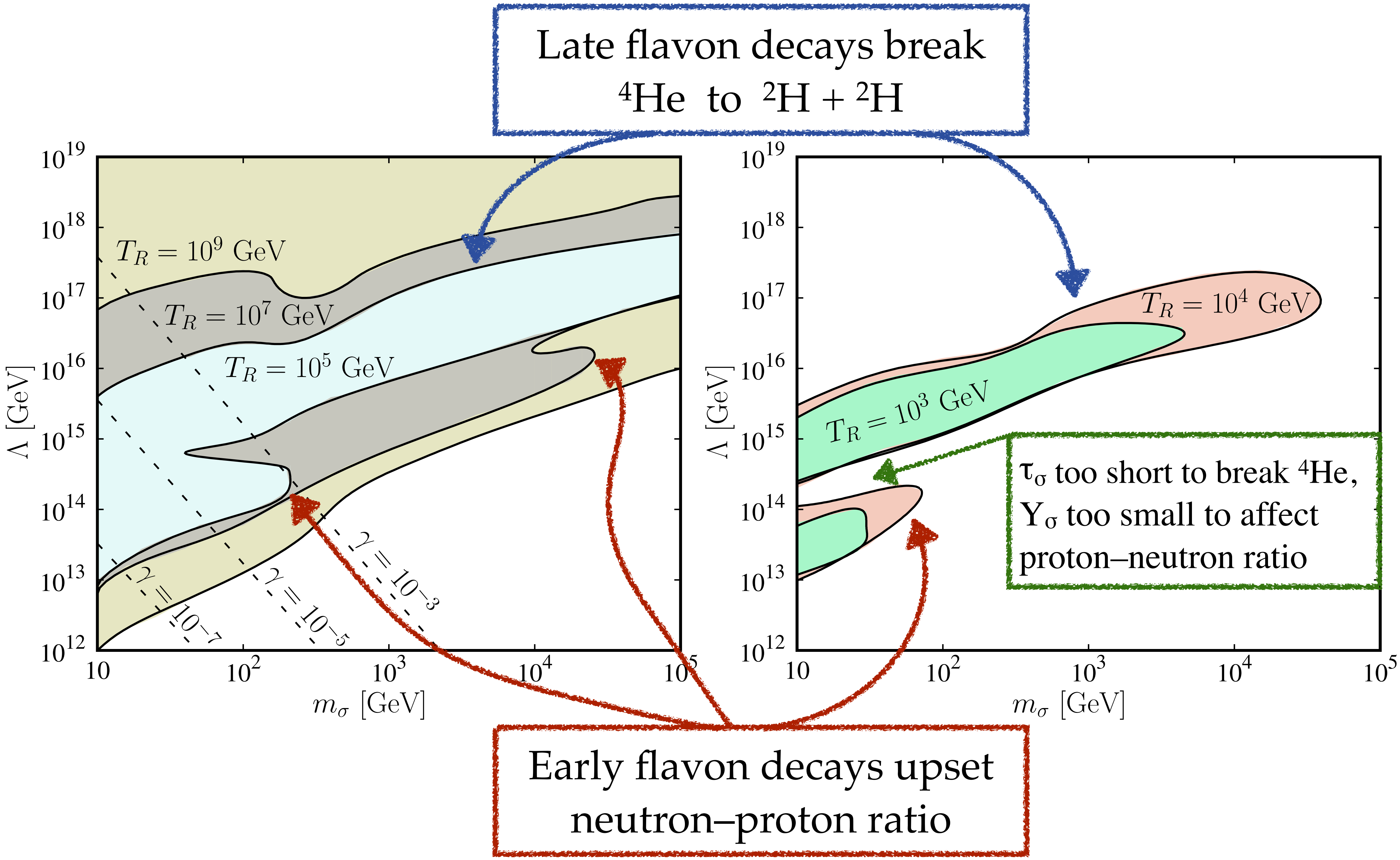
$$Y_\sigma^{\rm FI} \sim \frac{M_P T_R}{\Lambda^2}$$

$$Y_\sigma^{\rm osc} \sim \frac{T_R^5}{\Lambda^2 m_\sigma^3}$$

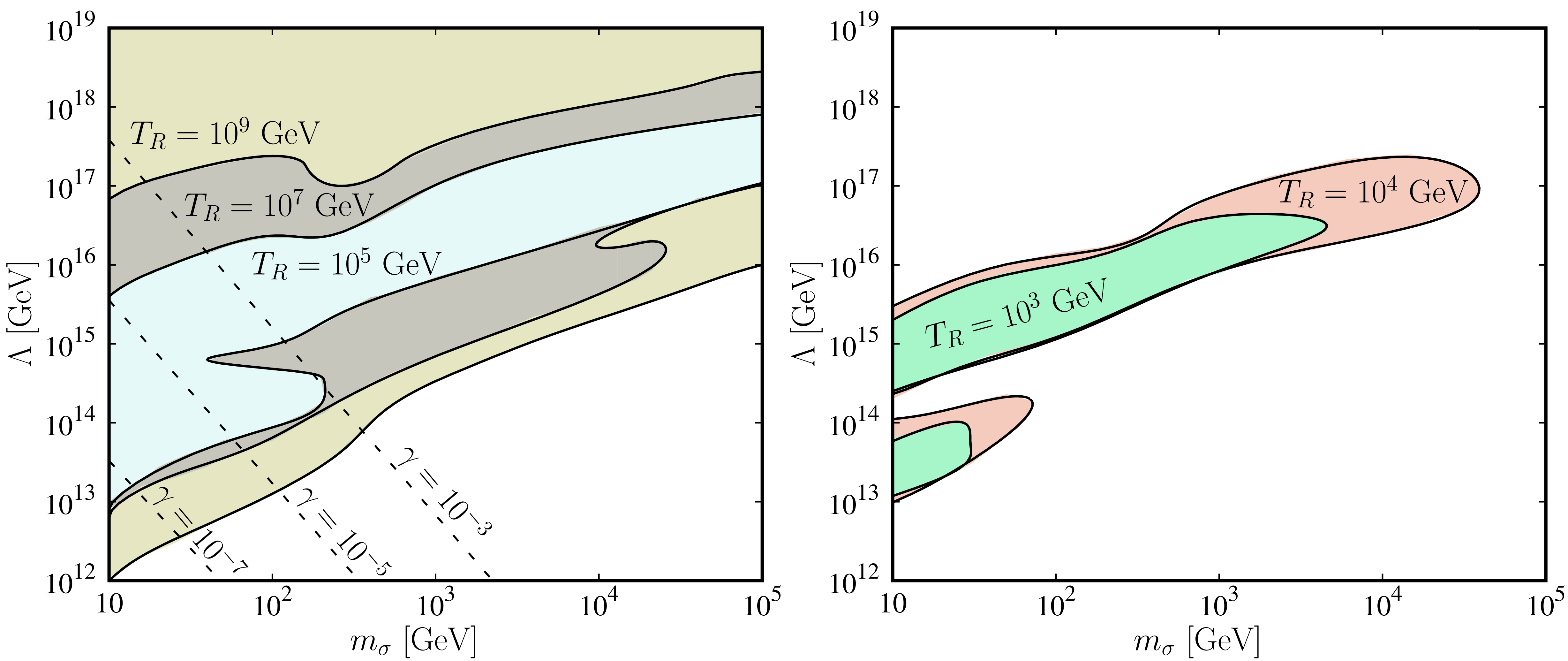
$$Y_\sigma = \frac{n_\sigma}{S}$$

BBN with decaying particles: 1709.01211 M. Kawasaki, K. Kohri, T. Moroi, Y. Takaesu

Constraining the Flavon



In Conclusion:



- Constraints apply to a general class of flavor models:

$$y \to \left(y + \frac{\sigma}{\Lambda} + \ldots\right)$$

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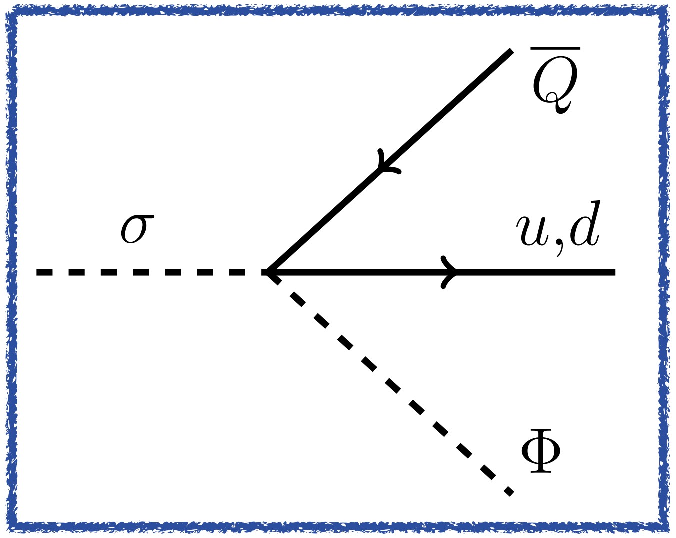
Nucleosynthesis (BBN)



- Earlier flavon decay, $0.1\text{–}1 \text{ sec} \lesssim \tau_\sigma \lesssim 100 \text{ sec}$, changes the neutron–proton ratio
    - Affects the ^{4}He mass fraction
- Later flavon decay $100 \text{ sec} \lesssim \tau_\sigma$ breaks ^{4}He into deuterium:
    - $^4\text{He} \longrightarrow {}^2\text{H} + {}^2\text{H}$
- Flavons are sufficiently long-lived if $m_\sigma \ll \Lambda$: $\tau_\sigma \sim \dfrac{64\pi^3\Lambda^2}{m_\sigma^3}$