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 È*S*Í*/* = *'* ƒ 0*.*23 **LEADER AND LEADER** dels of Flavon $\frac{1}{\sqrt{110}}$ **LFN** $\frac{1}{2}$

❖ Explain form of Yukawa matrix: *L*FN ≥ $u\overline{t}$ \overline{S} $\frac{1}{\sqrt{2}}$ $y_{i_1}^u$ $\frac{u}{ij}$ *Q*_{*i*}**D** $u_j \longrightarrow \left(\frac{S}{\Lambda}\right)$ Λ ◆*ⁿ* $Q_i \Phi u_j$

3*S*

*Qi*e*d^j*

4*n^u*

⇤

ij

❖ Froggatt–Nielsen:

$$
\mathcal{L}_{\text{FN}} \sim \left(\frac{S}{\Lambda}\right)^{n_{ij}^u} \overline{Q}_i \Phi u_j + \left(\frac{S}{\Lambda}\right)^{n_{ij}^d} \overline{Q}_i \widetilde{\Phi} d_j
$$

❖ Dimension-5 effective operators with scale Λ: *fective operators v ‡Qiu^j* \bullet Dimension-5 effective operators with scale Λ ^p² (1.3)

• Ratio $\langle S \rangle / \Lambda = \epsilon \simeq 0.23$ determines Yukawa couplings: for lighter quarks, $y \sim \epsilon^n$. *n* (1.7) $V = \frac{1}{2}$ ⇤ (1.5)

3*S*

⇤

v^S + *‡* + *ifl*

Qiu^j +

4*n^d*

 $\sqrt{1 + \frac{n}{n}}$

ij

*Qi*e*d^j* (1.1)

Decays of Flavons $\int_{\mathbb{R}^{d}} f \prod_{\alpha \neq \alpha}$ \int of Flavons 2 Feynman Diagrams

❖ Flavons decay to Standard Model:

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

[1] B. Lillard, M. Ratz, T. M. P. Tait, and S. Trojanowski, "The Flavor of Cosmology," arXiv:1804.03662 [hep-ph]. Internet *m*³ Cosn $\frac{1000000}{3/9}$

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

 σ

 $\Gamma_\sigma \sim$

 Q_i

 u_j , d_j

 $\left\langle \begin{array}{c} u_j, d_j \\ \hline \end{array} \right\rangle$

 Φ

Flavon Production 1: Freeze-In *Y* FI ⇠ ⇤² (2.7) q *ze* – In

- ❖ Out-of-equilibrium flavon production
	- ❖ Solve Boltzmann equation

- ❖ Dominated by **high-temperature** limit *s*
	- ❖ Flavon yield *Yσ* scales linearly with *TR* |
|avon r ield Y_{σ} scales linearly with T_{R} $\left\{\right.$ $\left\{\right.$ $\left.\right\}$ $\left\{\right.$ $\left\{\right.$ $\left\{\right.$ $\right\}$

$$
\;\ast\;\,Y^{\text{FI}}_{\sigma}\sim\frac{M_P T_R}{\Lambda^2}
$$

⇤

M^P T^R

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4

CALLAGE

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

T

u^j , d^j

Flavon Production 2: Scalar Potential *^F* ⁼ *^y*² *^T*⁴ ⁺ ↵ *^T*⁴ $\frac{1}{2}$ Flavon Production 2: Scalar Potential 7. Coo *ijQiu^j* ! ✓*^S* $\overline{\mathbf{S}}$ *v^S* + + *i*⇢ otential **V** (1011 **2**) Dealai 1 Ξ *)* lent <u>CHURI</u> *yu* $\overline{G_{\Omega}J_{\Omega}T}$ ⇤ ◆*ⁿ^u* Q^+Q^+ (I^2 $\frac{1}{\sqrt{1-\frac{1}{2}}}$ *S* !

❖ Thermal effects add terms to scalar potential: \mathcal{F} Thorm of \mathcal{F} a tei *v^S* + + *i*⇢

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

Free energy of a Yukawa gas depends on coupling *y*2; expansion includes radial mode *σ*. i ncludes radial mode σ . *Qiu^j* of a Yukawa gas depends on coupling y^2 ; expansion includes radial mode *Qi*e*d^j*

2 Feynman Diagrams

V () () A R . TO () (4) P () E (K (T) A . (N B ()

⇤

yu

ij

Flavon Production 2: Scalar Potential $\overline{}$ UUCLIOII Z. DCalal I OLCHLIAI $\nabla \Omega$ *s* Production 2: Scalar P

***** Thermal effects add terms to scalar potential Free energy of a Yukawa gas depends on coupling *y*2, expansion includes radial mode *σ*. F ree energy of ϵ *M^P T^R* ffects add terms to scalar potential

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

 σ^4 **b** shifts flavon away from its T=0 minimum *s*

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❖ **Equations of motion for** *σ* **depend on temperature Surprisingly, has analytic solution when cubic and quartic terms are dropped** \bullet **Equations of motion for** σ **d**
Surprisingly has analytic solution when e UCI
... *|M|*² *<u>on</u>* plisi
P **h**a ϵ urop

equation of motion, ¨ + (3*^H* ⁺) ˙ ⁺ @*V*e↵*/*@ = 0, which together with *^T*˙ ⇡ *H T*

arXiv:1804.03662 [hep-ph].

Constraining the Flavon

 \cdot Larger Λ reduces the flavon yield, but increases lifetime: P

!
" ¨ ¨ ¨ ¨

*M*²

FIG. 2. Big Bang Nucleosynthesis constraints on late time flavon decays in the (*m,*⇤) plane. In

Constraining the Flavon

In Conclusion: *T* $logic$

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

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In the left panel of Figure 2 we show the BBN constraints on the (*m,*⇤) plane for

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Nucleosynthesis (BBN) PSIS (RRN)

- Earlier flavon decay, $0.1\text{--}1\,\sec \lesssim \tau_{\sigma} \lesssim 100\,\sec$, $\left.\rule{0pt}{10pt}\right.^{\sqrt{Q}}$ changes the neutron–proton ratio
	- ❖ Affects the 4He mass fraction $i\Omega$ 0 a.u.c. 0 d.u.c. 11 sec 111 s
1 sec 111 sec 1

- \bullet Later flavon decay $100~\sec \lesssim \tau_\sigma$ breaks ⁴He into deuterium: $\ddot{\bullet}$ ⁴ $1_m:$ ${}^4\text{He} \longrightarrow {}^2\text{H} + {}^2\text{H}$ and the fill detection
	- Flavons are sufficiently long-lived if $m_{\sigma} \ll \Lambda$: $\tau_{\sigma} \sim$ $64\pi^3\Lambda^2$ m_σ^3

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• (2.1)