

QCD Masterclass 2021

Minimal warm inflation with complete medium response

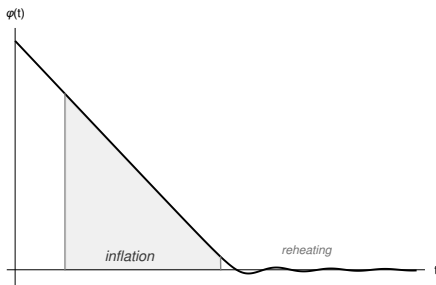
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Minimal warm inflation

- ▶ many models
- ▶ simplest case: scalar field $\varphi = \varphi(t)$, $\vec{\nabla}\varphi = 0$
potential $V(\varphi) = \frac{1}{2}m^2\varphi^2$



Minimal warm inflation

- ▶ scalar field $\varphi = \varphi(t)$, $\vec{\nabla}\varphi = 0$
- ▶ medium with increasing temperature $\dot{T} > 0$, $T(0) \sim 0$
- ▶ friction transfer energy from φ to medium

\Rightarrow many time scales to take care of
thermal, vacuum, ...

- ▶ How is φ coupled to the heat bath?

Minimal warm inflation

impose symmetry $\Rightarrow \varphi$ pseudoscalar

\Rightarrow Axion-like coupling: medium thermalizes

$$\mathcal{L} = \frac{1}{2} (\partial^\mu \varphi \partial_\mu \varphi - m^2 \varphi^2) - \varphi J + \mathcal{L}_{\text{bath}} \quad (1)$$

$$J = \frac{g^2}{f_a} \frac{\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}^c F_{\rho\sigma}^c}{64\pi^2},$$

$$g \text{ YM coupling, } \alpha = \frac{g^2}{4\pi}$$

f_a decay constant

$$c \in \{1, \dots, N_c^2 - 1\}$$

\mathbf{u}^b

$$\mathcal{L} = \frac{1}{2} (\partial^\mu \varphi \partial_\mu \varphi - m^2 \varphi^2) - \varphi J + \mathcal{L}_{\text{bath}} \quad (1)$$

Procedure:

- ▶ local Minkowskian frame
- ▶ covariant field equation
- ▶ expanding FLRW universe

$$\mathcal{L} = \frac{1}{2} (\partial^\mu \varphi \partial_\mu \varphi - m^2 \varphi^2) - \varphi J + \mathcal{L}_{\text{bath}} \quad (1)$$

Procedure:

- ▶ local Minkowskian frame

$$\begin{array}{c} \downarrow \\ \ddot{\varphi} + m^2 \varphi + \underbrace{\langle J(t) \rangle}_{?} = 0 \end{array}$$

\mathbf{u}^b

$\langle J(t) \rangle$?

Hamiltonian: $\hat{H} = \hat{H}_{\text{bath}} + \varphi \hat{J}$

Heat bath density matrix: $\hat{\rho}(t)$, $[\hat{H}_{\text{bath}}, \hat{\rho}(0)] = 0$

$$i\partial_t \hat{\rho}(t) = [\hat{H}(t), \hat{\rho}(t)]$$

$$\Rightarrow \langle \hat{J}(t) \rangle = - \int_0^t dt' \varphi(t') C_R(t-t') + \mathcal{O}(J^3) \quad (2)$$

\mathbf{u}^b

$$\overset{\text{eom}}{\curvearrowright} \quad \ddot{\varphi}(t) + m^2\varphi(t) - \int_0^\infty dt' C_R(t-t')\varphi(t') = 0, \quad t \geq 0$$

$$\downarrow$$

$$\omega$$

$$\downarrow$$

$$\varphi(t)\theta(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{e^{-i\omega t}}{\omega^2 - m^2 + C_R(\omega)} \mathcal{G}[\omega, \varphi^{(n)}(0)] \quad (3)$$

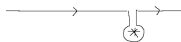
$$\mathbf{u}^b$$

$$\varphi(t)\theta(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{e^{-i\omega t}}{\omega^2 - m^2 + C_R(\omega)} \mathcal{G}[\omega, \varphi^{(n)}(0)] \quad (3)$$

► $t \gg 0$

► deform integration contour into H_-

► compute poles iteratively from $\omega = \pm m$



*

$$\Rightarrow \boxed{\ddot{\varphi} + \Upsilon \dot{\varphi} + m_T^2 \varphi^2 \approx 0} \quad (4)$$

$$\Upsilon \approx \frac{\text{Im}C_R(m)}{m}, \quad m_T^2 \approx m^2 - \text{Re}C_R(m)$$

\mathbf{u}^b

$C_R(\omega)$?

- ▶ $\omega \gg \pi T$: vacuum part dominates¹ ←
- ▶ $\omega \sim \pi T$: thermal modifications²
- ▶ $\omega \sim gT$: plasma excitations and Debye screening²
- ▶ $\omega \ll \alpha^2 T$: non-perturbative dynamics³ ←

$$C_R \approx C_R^{\text{vac}} + C_R^{\text{IR}} \quad (5)$$

¹S. Caron-Huot, Phys. Rev. D 79 (2009) 125009 [0903.3958]

²M. Laine, A. Vuorinen and Y. Zhu, JHEP 09 (2011) 084 [1108.1259]

³G. D. Moore and M. Tassler, JHEP 02 (2011) 105 [1011.1167]

A. L. Kataev, N. V. Krasnikov and A. A. Pivovarov, Nucl. Phys. B. 490 (1997) 505 (E) [hep-ph/9612326] ,
M. Laine, M. Vepsäläinen and A. Vuorinen, JHEP 10 (2010) 010 [1008.3263] :

$$\text{Im}C_R^{\text{vac}}(\omega) \propto \frac{\alpha^2 \omega^4}{f_a^2} \quad (6)$$

- ▶ Decay width of $\varphi \rightarrow gg$
- ▶ $\text{Re}C_R^{\text{vac}}(\omega)$: mass correction

$$C_R^{\text{IR}}(\omega) \simeq -\frac{\omega \Delta \Upsilon_{\text{IR}}}{\omega + i\Delta} \quad (7)$$

- $\omega \rightarrow 0$: G. D. Moore and M. Tassler, JHEP 02 (2011) 105 [1011.1167]

$$\begin{aligned} \text{Im} C_R^{\text{IR}}(\omega) &\longrightarrow \textit{transport coefficient} , \\ \Upsilon_{\text{IR}} &\longleftrightarrow \textit{sphaleron rate} \end{aligned}$$

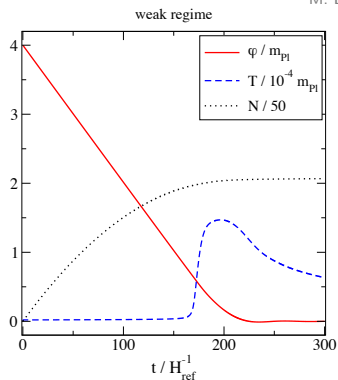
- $\omega \sim \alpha^2 T$: Lorentzian shape (?)

$$\Delta \approx c \alpha^2 T \quad \text{YM thermalization rate} , \quad c \simeq 10$$

\mathbf{u}^b

$$C_R \rightsquigarrow \ddot{\varphi} + \Upsilon \dot{\varphi} + m_T^2 \varphi^2 \approx 0 \quad (4)$$

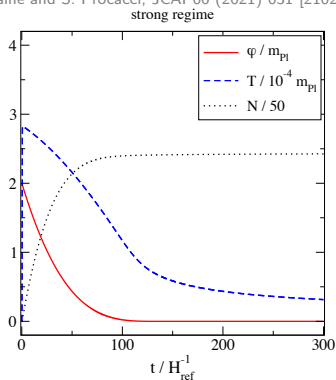
M. Laine and S. Procacci, JCAP06 (2021) 031 [2102.09913v2]



$$m = 7 \times 10^{-7} m_{\text{pl}}$$

$$f_a = 8 \times 10^{-7} m_{\text{pl}}$$

$$\varphi(0) = 4 m_{\text{pl}}$$



$$m = 7 \times 10^{-7} m_{\text{pl}}$$

$$f_a = 2 \times 10^{-7} m_{\text{pl}}$$

$$\varphi(0) = 2 m_{\text{pl}}$$

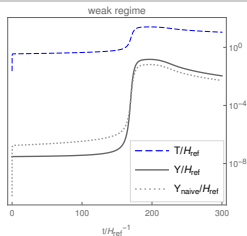
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Conclusions:

▶ previously⁴: $\Upsilon \sim T^x$, $x \in \mathbb{R}^+$

▶ we find

$$\Upsilon \approx \underbrace{\Upsilon_{\text{vac}}}_{\sim \text{const.}} + \underbrace{\Upsilon_{\text{IR}}}_{\sim T^3}$$



Outlook:

▶ *thermally* \rightarrow estimate Δ

▶ *phenomenologically* \rightarrow observational constraints (n_s , A , r , ...)

⁴ see e.g.

K. V. Berghaus, P. W. Graham and D. E. Kaplan, JCAP03 (2020) 034 [1910.07525]
 K. V. Berghaus and T. Karwal, Phys. Rev. D 101 (2020) 083537 [1911.06281]
 D. Suratna, G. Goswami and C. Krishnan Phys. Rev. D 101 (2020) 103529 [1911.00323]
 Y. Reymuaji and X. Zhang, JCAP04 (2021) 077 [2012.07329]