SEWM 2021

Minimal warm inflation with complete medium response

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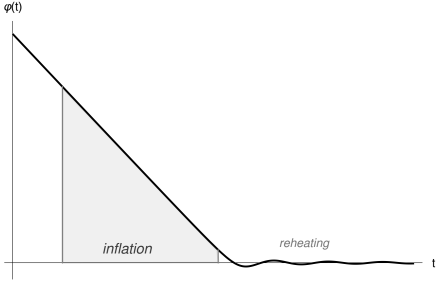
Minimal warm $\underbrace{\textit{inflation}}$

- many models
- simplest case: scalar field $\varphi = \varphi(t)$, $\vec{\nabla}\varphi = 0$

potential $V(\varphi) = \frac{1}{2}m^2\varphi^2$



Minimal $\underbrace{\text{warm inflation}}$

- 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

$$\Rightarrow \quad \underbrace{\text{many time scales}}_{\text{thermal, vacuum, ...}} \text{ to take care of}$$

- How is φ coupled to the heat bath?

Minimal warm inflation

impose symmetry $\Rightarrow$ φ pseudoscalar

$\Rightarrow$ Axion-like coupling: medium thermalizes

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

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

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

f_a decay constant

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

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

Procedure:

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

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

Procedure:

- local Minkowskian frame

$$\downarrow$$

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

$\langle J(t) \rangle$?

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

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

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

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

$$\downarrow$$

$$\omega$$

$$\downarrow$$

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

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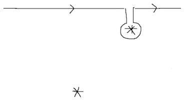


- $t \gg 0$
- deform integration contour into H_-
- compute poles iteratively from $\omega = \pm m$

$$\Rightarrow \boxed{\ddot{\varphi} + \Upsilon \dot{\varphi} + m_{\rm T}^2 \varphi^2 \approx 0} \qquad (4)$$

$$\Upsilon \approx \frac{\mathrm{Im}\, C_{\rm R}(m)}{m} \,, \qquad m_{\rm T}^2 \approx m^2 - \mathrm{Re}\, C_{\rm R}(m)$$

$C_R(\omega)$?

- $\omega \gg \pi T$: vacuum part dominates[1] $\leftarrow$
- $\omega \sim \pi T$: thermal modifications[2]
- $\omega \sim gT$: plasma excitations and Debye screening[2]
- $\omega \ll \alpha^2 T$: non-perturbative dynamics[3] $\leftarrow$

$$C_R \approx C_R^{\text{vac}} + C_R^{\text{IR}} \tag{5}$$

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

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

[3] G. 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] :

$$\mathrm{Im}\, C_{\mathrm{R}}^{\mathrm{vac}}(\omega) \propto \frac{\alpha^2 \omega^4}{f_a^2} \tag{6}$$

- Decay width of $\varphi \rightarrow gg$
- $\mathrm{Re}\, C_{\mathrm{R}}^{\mathrm{vac}}(\omega)$: mass correction

$$C_{\mathrm{R}}^{\mathrm{IR}}(\omega) \simeq -\frac{\omega \Delta \Upsilon_{\mathrm{IR}}}{\omega + i\Delta} \qquad (7)$$

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

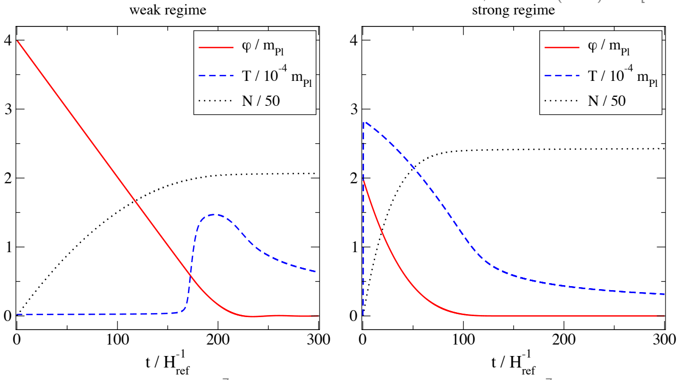
$$\mathrm{Im}\, C_{\mathrm{R}}^{\mathrm{IR}}(\omega) \longrightarrow \textit{transport coefficient},$$
$$\Upsilon_{\mathrm{IR}} \longleftrightarrow \textit{sphaleron rate}$$

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

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

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

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

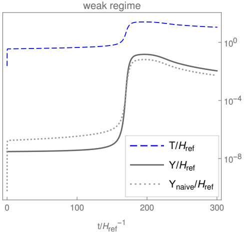


$m = 7 \times 10^{-7} m_{pl}$, $f_a = 8 \times 10^{-7} m_{pl}$, $\varphi(0) = 4 m_{pl}$

$m = 7 \times 10^{-7} m_{pl}$, $f_a = 2 \times 10^{-7} m_{pl}$, $\varphi(0) = 2 m_{pl}$

Conclusions:

- previously[4]: $\Upsilon \sim T^x$, $\quad x \in \mathbb{R}^+$
- we find $\boxed{\Upsilon \approx \underbrace{\Upsilon_{\text{vac}}}_{\sim const.} + \underbrace{\Upsilon_{\text{IR}}}_{\sim T^3}}$



Outlook:

- *thermally* $\rightarrow$ estimate Δ
- *phenomenologically* $\rightarrow$ observational constraints (n_s, A, r, ...)

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[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. Reyimuaji and X. Zhang, JCAP04 (2021) 077 [2012.07329]