Gravitational wave background from vacuum and thermal fluctuations during axion-like inflation

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Gravitational waves constrain Axion-like inflation

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V_0(\varphi) - G_{\mu\nu}G^{\mu\nu} - \frac{\varphi}{f_a}\chi \qquad \chi = \frac{\alpha_s}{16\pi}\widetilde{G}_{\mu\nu}G^{\mu\nu}$$

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What about non-Abelian case?

Non-Abelian gauge bosons can thermalize

- Inflaton $\phi \to gg$ decays can sustain non-diluting gauge sector
- If gauge sector thermalizes, universe heats during inflation
  $\Rightarrow$ Warm inflation:

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = \quad -\Gamma\dot{\phi}$$
$$\dot{e} + 3H(e+p) = \quad \underbrace{+\Gamma\dot{\phi}^2}_{\phi\to gg \text{ friction}} \quad \underbrace{+T(\partial_t + 3H)V_T}_{\text{thermal potential}}$$

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$\Rightarrow$ **Qualitatively different GW production**

Warm inflation GW background

Master formula primordial tensor power spectrum:

$$P_T(k) = \underbrace{32G\frac{H_\star^2}{2\pi}}_{\text{vacuum fluctuations}} + \underbrace{(32G)^2 k^3 \int_{-\infty}^{t_e} dt' \Delta_k^2(t_e, t')\Pi_k(T(t'))}_{\text{thermal fluctuations}}$$

Π_k = thermal production rate / $H_\star(k)$ = Hubble rate at Horizon exit / t_e = inflation end time / G = Newton const.

Our work:

- We combined vacuum and thermal fluctuations
- We extended propagator Δ_k from DeSitter to general background solution

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But what is T_{max}?

CMB constrains model parameters

We fix T_{max} for minimal scenario:

- QCD-like gauge fields
- Thermal cosine potential $V = (m_0^2 + m_T^2) f_b^2 \, (1 - \cos \phi/f_b)$

$\Rightarrow$ Fit mass m_0 and decay constant f_b to CMB power spectra (scalar amplitude A_s, spectral tilt n_s, tensor-to-scalar ratio r)

CMB reference frequency $f \ll 10^{-15}\,\mathrm{Hz}$

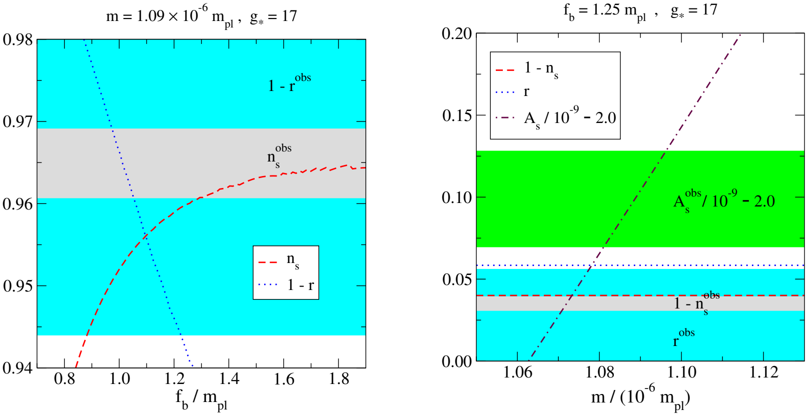
(Horizon exit 60 e-folds before end of inflation)

$\Rightarrow$ thermal effects only impact background solution:

$$A_S = \frac{H_\star^4}{4\pi^2 \dot{\phi}_\star^2} \,, \qquad n_S = 1 + \frac{4\dot{H}_\star}{H_\star^2} \,, \qquad r = \frac{A_T}{A_S} = 64\pi G \frac{\dot{\phi}_\star^2}{H_\star^2}$$

$H_\star$, $\dot{\phi}_\star$ = Horizon exit Hubble rate, field velocity in full background solution

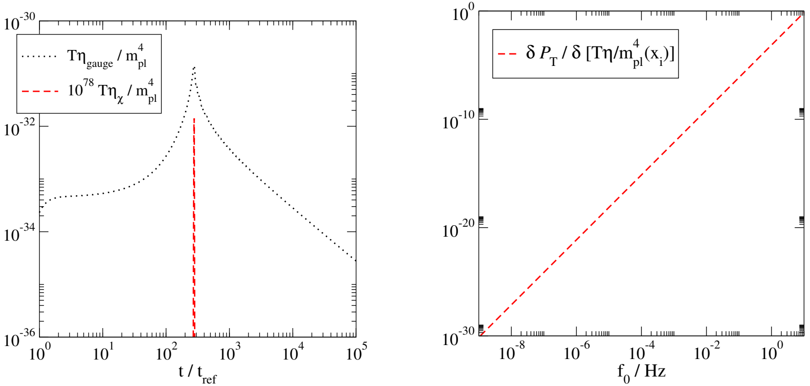
Minimal model predicts $T_{\max} \approx 5 \cdot 10^{-9} m_{\rm pl}$



- CMB constraints fix $f \approx 1.25 m_{\rm pl}$ and $m = 1.09 \cdot 10^{-6} m_{\rm pl}$

$\overset{g_\star = 17}{\Longrightarrow}$ Background solution predicts $T_{\max}$

No overproduction of gravitational waves



- T_{max} too small to produce observable signal
- $T \ll m_{ALP} \Rightarrow$ Gauge bosons dominate shear viscosity $\eta \propto T^3$

Summary and Outlook

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- We identified benchmark point for minimal axion-like warm inflation:

$$f_b = 1.25 m_{\text{pl}} \qquad\qquad m = 1.09 \cdot 10^{-6} m_{\text{pl}}$$

$\Rightarrow$ Realistic estimate $T_{\text{max}} \overset{g_\star = 17}{\approx} 4 \cdot 10^{-9} m_{\text{pl}}$

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Further prospects: Out-of-equilibrium corrections,
Higher T_{max} (cf. arXiv:2303.17973)

Thank you for your attention!

Backup slides