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

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Workshop on Particle Production in the Early Universe

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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

- Efficient $\phi \to gg$ decays can sustain non-diluting heat bath
- Thermalizing gauge bosons $\Rightarrow$ Warm inflation:

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

Γ = inflaton friction / H = Hubble rate / $V_T = \partial_T V$ / $V_\phi = \partial_\phi V$

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No preheating $\Rightarrow$ qualitatively different GW background

Master formula for warm inflation GW production

Primordial tensor perturbation power spectrum:

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

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Our work:

- We derive formula combining vacuum with thermal fluctuations
- We show universal $\propto f^3$ scaling of modes that exit horizon (including LISA frequencies $f < 10^{-1}\,\mathrm{Hz}$)

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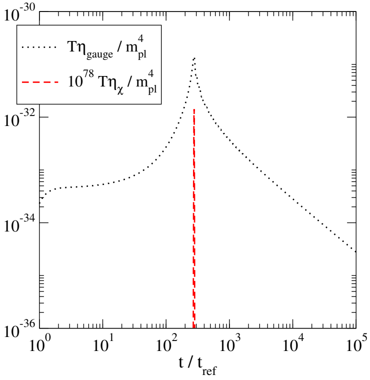
We fix T evolution in minimal setup:

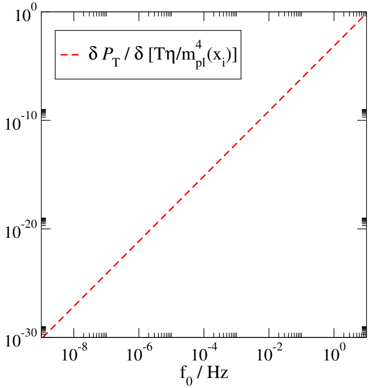
- QCD-like gauge group, no fermions
- Cosine potential $V_T = (m_0^2 + m_T^2) f_a^2 \left(1 - \cos \phi/f_a\right)$

$\Rightarrow$ CMB constrains benchmark point:

$$f_a = 1.25 m_{\rm pl} \qquad m = 1.09 \cdot 10^{-6} m_{\rm pl} \qquad \Rightarrow T_{\rm max} \overset{g_\star = 17}{\approx} 5 \cdot 10^{-9} m_{\rm pl}$$

Small T_{max} implies no GW overproduction





- $m_{ALP} \gg T_{max} \Rightarrow$ Gauge bosons dominate shear viscosity
- Higher temperatures possible in non-minimal Axion-like models

  (cf. arXiv:2303.17973 / arXiv:2406.10345)

Summary and Outlook

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- **Future prosect:** Out-of-equilibrium fluctuations

Thank you for your attention!

Backup slides