cosmic probes of the early universe with axions and gravitational waves

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Outline

- Non standard cosmological background
- Axion CDM produced by the misalignment mechanism in non standard cosmological backgrounds.
- Axion CDM production by the addition of a network of Cosmic strings, in non standard cosmological backgrounds.
- Primordial gravitational wave relics from Axion string loops.

Non standard cosmological background

- effective equation of state for a scalar field Φ

$$w_{\rm eff} = \left\langle \frac{\dot{\Phi}^2 - 2V(\Phi)}{\dot{\Phi}^2 + 2V(\Phi)} \right\rangle, \tag{1}$$

- The governing Boltzmann equations which describes the particle exchange between the ρ_Φ, ρ_r

$$\begin{aligned} \dot{\rho_\Phi} + 3H(1 + w_{eff})\rho_\Phi &= -\Gamma\rho_\Phi & (2) \\ \dot{\rho}_r + 4H\rho_r &= \Gamma\rho_\Phi & (3) \\ H &= \sqrt{\frac{\sum_i \rho_i}{3M_{PL}^2}} & (4) \end{aligned}$$

- Once the evolution is deep within the ρ_Φ i.e $t << \Gamma^{-1}$ then

$$H = \sqrt{\frac{\rho_\Phi}{3M_{pl}^2}} \propto a(t)^{-\frac{3}{2}(1+w_{eff})} \tag{5}$$

Axions from the Strong CP problem

- The Strong CP problem is the discrepancy Between the theoretical prediction of CP violation, and the fact that it has not been experimentally found. Stringent condition for Strong CP violation from NEDM.

$$d_n \propto e\bar{\theta}\frac{m_q}{m_n^2} \tag{6}$$

unless $\bar{\theta} \leq 10^{-11}$.

- Peccei Quinn Solution by introducing a new symmetry breaking which yields a new pseudo-scalar goldstone Boson "i.e" the axion
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$$\mathcal{L}_a = -\frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \frac{g_s}{32\pi^2}\frac{a}{f_a/N}\mathcal{G}^a_{\mu\nu}\bar{\mathcal{G}}^{a\mu\nu} \tag{7}$$

Axion CDM produced by the misalignment mechanism in NSC background

$$\ddot{\theta}(t) + 3H\dot{\theta}(t) + m_a(T)^2 \sin\theta = 0. \quad (8)$$

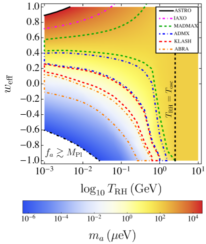

Figure: contour plot of ω_{eff}, T_{RH}, m_a with the various detector scopes and their mass ranges. With the exclusions from astrophysical limits and plank mass.

$$m_a(T_{osc}) \approx 3H(T_{osc}) \quad (9)$$

Cosmic strings as Topological defects

- Previous scenario holds as long the PQ symmetry breaks during an inflationary period that washes out any topological defects.
- Cosmic string networks form as a consequence of the Kibble mechanism at $T \propto f_a$ and dissipates which leads to the formation of Domain walls which decay instantly once they are formed at $T \propto T_{QCD}$
- Evolution of cosmic string networks, computationally complex due to the large range of length scales. $\rho_s = \rho_\infty + \rho_{loop}$ about 80% into long strings, and 20% into loops of various lengthscales from the string core to horizon size.

QCD-Axion CDM from the addition of a network of strings Results

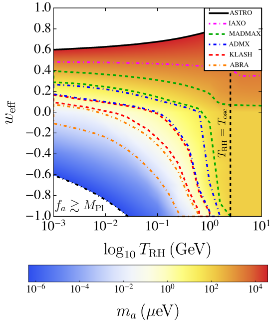

Figure: contour plot of ω_{eff}, T_{RH}, m_a with the various detector scopes of their mass ranges. With the exclusions from astrophysical limits and plank mass.

QCD Axion CDM results from both sections

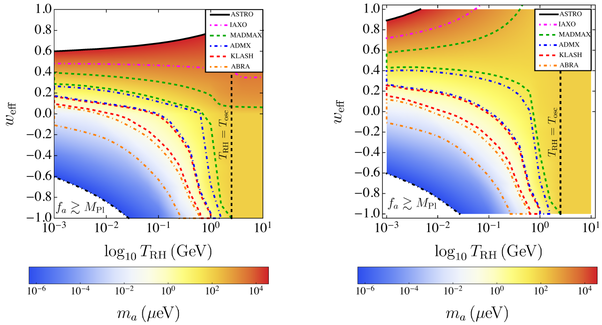

Figure: Left Figure the contour plot of the axion mass by the addition of the cosmic string network, right figure is from only the misalignment mechanism. Contour plot functions of the equation of state w_{eff}, T_{RH} with the various mass ranges of the detectors.

Primordial gravitational wave relics from Axion-string loops in NSC backgrounds 1

- The relic gravitational wave energy density at a given frequency and for a certain moment in time

$$\Omega_{GW}(t,f) = \frac{1}{\rho_c(t)}\frac{d\rho_{GW}}{d\ln k} \tag{10}$$

per logarithmic interval.

- The frequency $f' = \frac{2n}{l(t')}$ which is emitted at t' becomes redshifted by the expansion of the universe and the observed frequency f is

$$f = \frac{2n}{l(t_i) - \kappa(t - t_i)}\frac{a(t')}{a(t)} \tag{11}$$

- The spectrum is defined from the loop shrinking with some power spectrum.

$$P_{GW} = \Gamma_{GW}\sum_{n=1}^{\infty}\frac{l_n}{f'}n_l(l(t),t)P_n \tag{12}$$

Primordial gravitational wave relics from Axion-string loops in NSC backgrounds 2

- $$n_l(l(t), t) = \frac{\xi}{\alpha}\left(\frac{a(t)}{a(t_i)}\right)^3 \frac{1}{t_i^4} \tag{13}$$

- The power spectrum for gravitational waves used here is

$$P_n = \Gamma_{GW}\frac{n^{-4/3}}{\sum_n n^{-4/3}}. \tag{14}$$

where the spectral index $q = -4/3$ is for loops which has cusps in them

- $$\Omega_{GW}(t, f) = \sum_n P_n \Omega^n_{GW}(t, f) \tag{15}$$

Primordial gravitational wave relics from axion string loops in NSC backgrounds, Results

$$\Omega^{n}_{GW}(t,f) = \frac{1}{\rho_c(t)}\frac{2n}{f}\frac{\xi}{\alpha}\int_{t_s}^{t}\frac{G\mu_a(t')^2}{t_i^4} \tag{16}$$

$$\left(\frac{a(t')}{a(t)}\right)^5\left(\frac{a(t_i)}{a(t')}\right)^3 dt' \tag{17}$$

$$\Omega_{GW}(t_0,f_0) = \frac{\rho_c(t_{osc})}{\rho_c(t_0)}\left(\frac{a(t_{osc})}{a(t_0)}\right)^4\Omega_{GW}(t_{osc},f) \tag{18}$$

Primordial gravitational wave relics from axion string loops in NSC backgrounds, Results 2

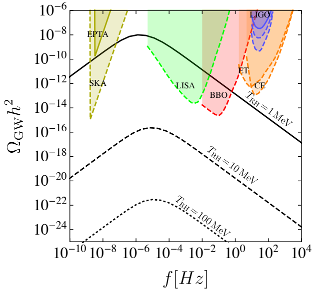

Figure: Plot of the relic gravitational wave energy density today yielded from a early matter dominated universe with different reheating temperatures.

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