Non-thermal Hot Dark Matter from Inflaton/ Moduli Decay

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Motivation

Modular Cosmology

- Inflation
- Reheating I
- Radiation Domination
- Modulas Domination
- Reheating II
- Radiation Domination
- Today

Standard Cosmology

- Inflation
  - Reheating
  - Radiation Domination
  - Today

- Moduli domination continues until it decays

- Non-thermal sterile DM

\[ \tau_{\text{mod}} \approx \frac{16 \pi M_{\text{pl}}^2}{m^3} \]
The decay products have a characteristic energy distribution dependent on the decay mechanism.

Focus is on the hot DM and its effects on the CMB & LSS.

The SP is a result due to 1 -> 2 decays of the massive scalar with branching ratio $B_{sp}$.

\[
\dot{\rho}_{\text{mat}} + 3H \rho_{\text{mat}} = -\frac{\rho_{\text{mat}}}{\tau},
\]

\[
\dot{\rho}_{\text{rad}} + 4H \rho_{\text{rad}} = +\frac{\rho_{\text{mat}}}{\tau},
\]

\[
H = \left(\frac{\dot{a}}{a}\right) = \sqrt{\frac{\rho_{\text{mat}} + \rho_{\text{rad}}}{3M_{\text{pl}}^2}}.
\]

\[
\theta = \frac{t}{\tau}, \quad \dot{s}(\theta) = a(\tau \theta),
\]

\[
e_{\text{mat}}(\theta) = \frac{\tau^2 \rho_{\text{mat}}(\tau \theta)}{M_{\text{pl}}^2}, \quad e_{\text{rad}}(\theta) = \frac{\tau^2 \rho_{\text{rad}}(\tau \theta)}{M_{\text{pl}}^2}.
\]

\[
\rho_{\text{mat}}(0) = \frac{4\alpha}{3} \frac{M_{\text{pl}}^2}{\tau^2} \quad \text{i.e.} \quad e_{\text{mat}}(0) = \frac{4}{3} \alpha,
\]
**Comoving modulus number density**

**Number density at \( t=0 \)**

**Number density at of the SP**

**SP spectrum at \( t \)**

**Dimensionless variable**

\[
N = N(0)e^{-t/\tau}
\]

\[
N(0) = \frac{\rho_{\text{mat}}(0)}{m_\varphi} = \frac{4\alpha M_{\text{pl}}^2}{3\tau^2 m_\varphi}
\]

\[
dN = \frac{2B_{\text{sp}}}{\tau} N(0)e^{-t_\tau/\tau} dt_\tau.
\]

\[
dN_t = \frac{1}{s^3(\theta)} 2N(0) B_{\text{sp}} \frac{e^{-\dot{s}^{-1}(y)}}{\dot{H}(\ddot{s}^{-1}(y))} dE \equiv \tilde{n}_t(E) dE.
\]

\[
y = \frac{E\dot{s}(\theta)}{\dot{E}}
\]
The Momentum Distribution

Momentum distribution at early time

Momentum distribution today

Range of momentum of SP

Momentum distribution in terms of $T_{\text{ncdm},0}$

Momentum distribution in terms of the decay

Momentum distribution in terms of dimensionless variable

\[
dN_t = \frac{\vec{n}_t(|\vec{p}|)}{4\pi|\vec{p}|^2} d^3p \equiv n_t(\vec{p})d^3p.
\]

\[
n_{t_0}(\vec{p}) = n_{t^*} \left( \frac{a(t_0)}{a(t^*)} \vec{p} \right).
\]

\[
\frac{\hat{E}}{a(t_0)} < |\vec{p}| < \frac{\hat{E}a(t^*)}{a(t_0)}.
\]

\[
T_{\text{ncdm},0} = \frac{\hat{E} a(t^*)}{4 a(t_0)} = \frac{1}{8} m_\phi \left( \frac{g(t_0)}{g(t^*)} \right)^{\frac{1}{3}} \left( \frac{T(t_0)}{T(t^*)} \right).
\]

\[
T_{\text{ncdm},0} = 0.418 \left( \frac{m_\phi^2 \tau}{M_{\text{pl}}} \right)^{1/2} \frac{T_{\text{cmb}}}{(1 - B_{\text{sp}})^{1/4}} \equiv \zeta T_{\text{cmb}}
\]

\[
f(q) = \frac{32}{\pi \hat{E}^3} \left( \frac{N(0)B_{\text{sp}}}{\hat{s}^3(\theta^*)} \right) \frac{e^{-\hat{s}^{-1}(y)}}{q^3 \hat{H}(\hat{s}^{-1}(y))}
\]
The Momentum Distribution

\[ n_{sp} = 1.13 \left[ \frac{43 \pi^4}{45.3 \zeta(3)} \right] \frac{3}{\pi^{1/2} g_*^{1/4} (T(t^*))} \left( \frac{5}{2} \right)^{1/4} \]

\[ \times \frac{B_{sp}}{(1 - B_{sp})^{3/4}} \left( \frac{M_{pl}}{\tau m_\varphi^2} \right)^{1/2} n_\nu. \]

\[ w_{sp} = \frac{m_{sp}}{94.05 \text{eV}} \frac{62.1}{g_*^{1/4} (T(t^*))} \frac{B_{sp}}{(1 - B_{sp})^{3/4}} \left( \frac{M_{pl}}{\tau m_\varphi^2} \right)^{1/2} \]
Effects on Cosmological Observables

- Linear matter power spectra gets much less suppression for the hot DM compared to standard thermalised neutrinos of same mass.
- At higher $l$ (small scales) of CMB anisotropy different effects.
Hot DM produced from moduli/ inflation decay.
Characteristic momentum distribution of the hot DM is deduced.
Effects on CMB and LSS is studied.
Higher value of the hot DM mass is consistent with linear matter power spectra observations.
Features at low $l$ of CMB power spectra related to the phase difference due to supersonic transmission of hot DM through the photon-baryon plasma before they turn non-relativistic.
A detailed MCMC analysis is under progress which will reveal deeper cosmological implications.
Structure formation needs to be studied in details for this non-thermal distribution.
Effect on Hubble anomaly could be really interesting.