Non-thermal dark matter at reheating: production & evolution

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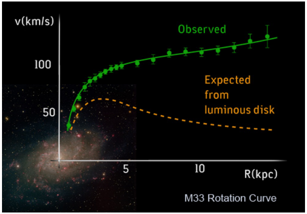
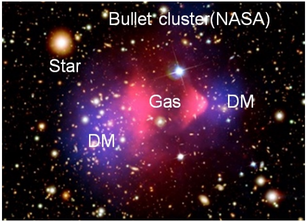
Dark Matter: Evidences

- 1933, Coma Cluster: Virial Theorem suggests a mass larger than the luminous mass of the galaxy.
- 1970, Andromeda Galaxy: Rotational velocity of the stars orbiting the galaxy
- 2000, Bullet clusters: Centre-of-mass of colliding pair of galaxy clusters are away from the hot, luminous region of the gas
- CMB angular power spectrum, matter power spectrum etc.





Todays universe: $\Omega_\Lambda \simeq 0.70, \Omega_{\rm DM} \simeq 0.26, \Omega_B \simeq 0.04.$

Dark Matter: Classification

- Based on how the present density of the DM is set we have two broad classes:

  - Thermal:
  - • Weakly Interacting Massive Particles (WIMPs),
  - • Strongly Interacting Massive Particles (SIMPs),
  - • ELastically DEcoupling Relics (ELDERs),

  and many more ....

  - Non-Thermal:
  - • Freeze-in (FIMPs),
  - • Misalignment mechanism,
  - • Production from Inflaton,

  and many more ....

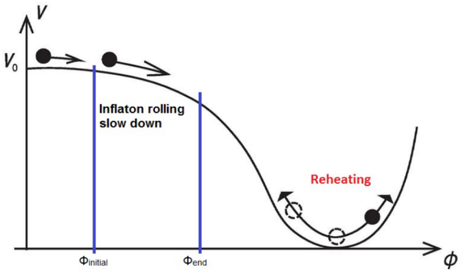
- Thermal paradigm is quite predictive
  $\rightarrow$ number density, phase-space distributions, ...
- Non-thermal DM candidates,
  $\rightarrow$ properties are highly model dependent !

Here, we shall consider the DM production from inflaton decay during reheating

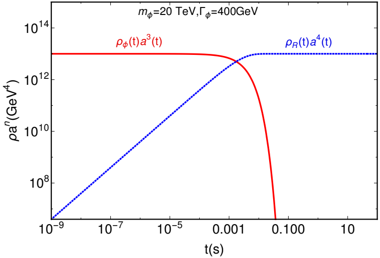
Inflation & Reheating

- Issues with hot big-bang cosmology:
  - Identical properties of causally disconnected regions of the CMB sky (Horizon Problem)
  - Universe is spatially flat on large scales: $|\Omega_K| = \frac{|K|}{a^2 H^2} \ll 1$ (Flatness Problem)
  - Production of primordial perturbations that lead to the structure formation

- Solved if the Universe has undergone a phase of exponential expansion $\rightarrow$ Inflation
  - Velocity of the scalar field ϕ (Inflaton) is much smaller than its Potential energy: $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$
  - The potential is nearly constant: $V(\phi) \simeq$ const.
  - Followed by a phase of coherent oscillations of ϕ and it's decays to radiation: Reheating



Inflation & Reheating



Evolution of $\rho_\phi(t)$ and $\rho_R(t)$ during reheating

- Reheating ends when $\Gamma_\phi \simeq H$

  $\Rightarrow$ reheating temperature: $T_{\rm R} = \left(\frac{90}{\pi^2\, g_*(T_{\rm R})}\right)^{1/4}\sqrt{M_{\rm Pl}\Gamma_\phi}$

- Duration of reheating: In terms of $r = a(t_{\rm end})/a(t_R)$ we have,

$$r^3\, e^{r^{3/2}} \simeq \frac{g^*(T_{\rm R})\pi^2 e T_{\rm R}^4}{\rho_\phi(t_{\rm end})}$$

$\rightarrow$ with $\rho_\phi(t_{\rm end}) \lesssim (10^{16}\,{\rm GeV})^4$ and $T_{\rm R} = 1\,{\rm TeV}$ we obtain, $r \geq 10^{-17}$

$\Rightarrow$ during reheating Universe may expand by ~ 40 e-foldings!!

Dark matter production during Reheating

- In addition to the SM particles the inflaton may also couple to the fermionic DM and produces both DM and SM particles during reheating
- The necessary part of the Lagrangian is:

$$\mathcal{L}_{\rm int} \supset -\mu_H\, H^\dagger H\, \phi - \lambda \bar{\psi}\psi\, \phi$$

Decay rates: $\Gamma_\phi \simeq \Gamma_H(\phi \to hh) \simeq \mu_H^2/32\pi\, m_\phi$, $\Gamma_\psi(\phi \to \psi\bar{\psi}) \simeq \lambda^2\, m_\phi/8\pi$

- Instantaneous decay approximation: Inflaton decays to DM instantaneously at $t = t_R$

$\rightarrow$ DM number density at t_R: $n_\psi(t_R) = 2 \times {\rm Br}(\phi \to \psi)\, n_\phi(t_R) \simeq 2 \times \frac{\Gamma_\psi}{\Gamma_\phi} \times \frac{\rho_R(t_R)}{m_\phi}$

- The momentum distribution of the produced DM particles at $t = t_R$:

$$f_\psi(k, t_R) = \frac{16\pi^2}{g_\psi^2\, m_\phi^3}\, \frac{\Gamma_\psi}{\Gamma_\phi} \rho_R(t_R)\delta(m_\phi/2 - k)$$

$\rightarrow$ Dirac-delta function

- Here, radiation energy density at reheating: $\rho_R(t_R) = \frac{\pi^2\, g_{*,\rho}(T_{\rm R})}{30}\, T_{\rm R}^4$

Dark matter production during Reheating

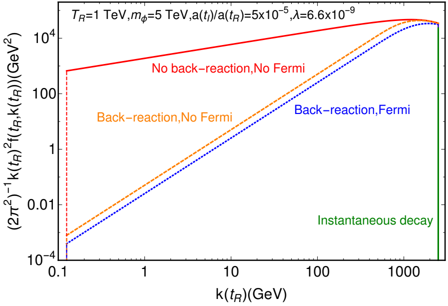
If we relax the 'instantaneous' approximation:

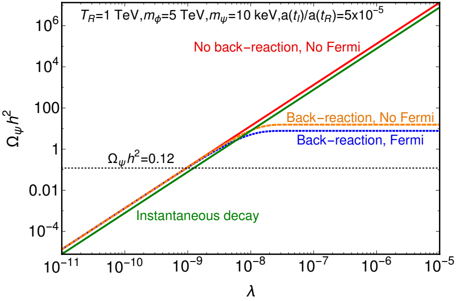
- Three possible cases (t_p is time of production):

  Case 1: $f_{\psi\,(1)}(t_p,t) = \bar{f}(t_p)\,\Theta(m_\phi/2 - k(t))$ (Back reaction and quantum statistics not included)

  Case 2: $f_{\psi\,(2)}(t_p,t) = \tanh\left(\bar{f}(t_p)\right)\,\Theta(m_\phi/2 - k(t))$(Only back reaction included)

  Case 3: $f_{\psi(3)}(t_p,t) = \frac{1}{2}\left(1 - e^{-2\bar{f}(t_p)}\right)\,\Theta(m_\phi/2 - k(t))$(Back reaction and quantum statistics both included)

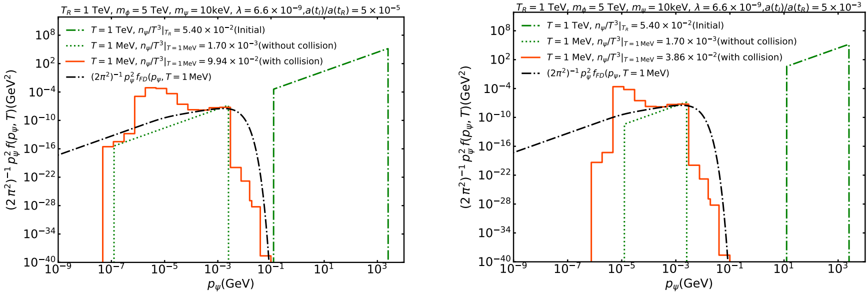




Evolution of f_ψ: effect of inflaton mediated scatterings

- It is usually assumed that the phase-space distribution of ψ is "frozen" at reheating
  $\Rightarrow$ It only redshifts till matter-radiation equality ($t_{\rm EQ}$)
- Inflaton couples to both SM and DM
  $\Rightarrow$ Inflaton mediated s-channel and t-channel scatterigs are inevitable
  $\rightarrow$ Such scatterings may redistribute energies between DM and SM and affect f_ψ
  $\rightarrow$ f_ψ has important implications for structure formation
- Three possible scattering processes:
  s-channel inelastic: $h\,h \leftrightarrow \psi\bar{\psi} \Rightarrow n_\psi$ increases and energy transfer with SM
  t-channel inelastic: $h\,\psi(\bar{\psi}) \leftrightarrow h\,\psi(\bar{\psi}) \Rightarrow$ energy transfer with SM
  self-scatterings: $\psi\bar{\psi} \leftrightarrow \psi\bar{\psi}$: $\Rightarrow$ energy redistribute among DM particles
- DM-SM scatterings are only active in the range $m_h \lesssim T \lesssim T_{\rm R}$
  $\Rightarrow$ below this temperature h does not remain in the thermal bath
- Self scatterings may be effective even for $T \lesssim m_h$, for large values of λ

Evolution of f_ψ: effect of inflaton mediated scatterings



Evolution of f_ψ due to inflaton mediated scatterings

- Scatterings change the shape of the distribution: populate lower as well as higher momentum modes

  $\rightarrow$ f_ψ is still non-thermal, i.e., DM is non-thermal

- Effects are most prominent for larger duration of reheating (r); since more lower momentum modes are populated at T_R: scattering probability increases

  $\Rightarrow$ Ω_ψ increases $\sim$ 58 times for $r = 5\times10^{-5}$
  Ω_ψ increases $\sim$ 23 times for $r = 5\times10^{-3}$

Lyman-α forest constraints

- Photons emitted by distant galaxies and quasars

  $\rightarrow$ redshift while passing through the neutral H_2 gas constituting the inter-galactic medium (IGM)

  $\rightarrow$ When reaches $\lambda = 1216\mathring{A}$, get absorbed by IGM

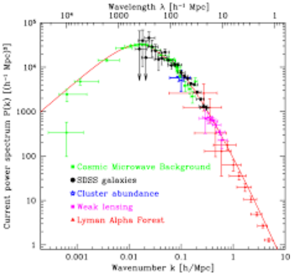
  $\rightarrow$ Series of absorption lines are observed in the quasar spectra

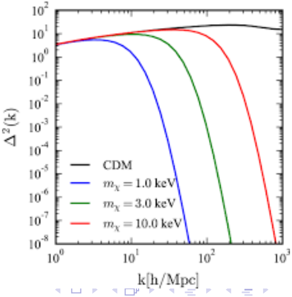
  $\Rightarrow$ Lyman-α forest

- The intensities of these absorption lines

  $\rightarrow$ the column density of H_2 along the line of sight

  $\Rightarrow$ used to measure the matter power spectrum or matter density fluctuations along the line of sight





Dark matter free-streaming

- Observation suggests that power is suppressed at low scale

  $\Rightarrow$ DM may not be completely cold

- Warm dark matter (WDM) decouples when they are relativistic

  $\Rightarrow$ decoupled WDM particles traverse large distances by matter-radiation equality ($t_{\rm EQ}$)

  $\Rightarrow$ Such DM particles move from overdense to underdense regions, thereby smoothing out inhomogeneities

  $\Rightarrow$ Causes suppression of power on small scales

- This is characterized by the comoving free-streaming horizon:

$$\lambda_{\rm FSH} = \int_{t_{\rm dec}}^{t_{\rm EQ}} \frac{\langle v(t) \rangle}{a(t)} dt$$

where, $t_{\rm dec}$ is the time of decoupling

$\Rightarrow$ For a WDM species we have $0.01\,{\rm Mpc} \lesssim \lambda_{\rm FSH} \lesssim 0.1\,{\rm Mpc}$

Dark matter free-streaming

- The average velocity,

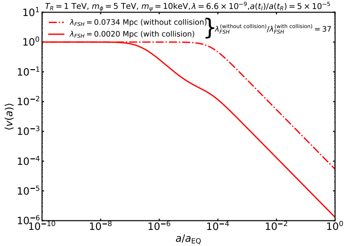
$$\langle v(t)\rangle = \left(\int \frac{d^3\vec{p}}{(2\pi)^3}\frac{p}{\sqrt{p^2+m_\psi^2}} f_\psi(p,t)\right) \Big/ \left(\int \frac{d^3\vec{p}}{(2\pi)^3} f_\psi(p,t)\right)$$

determines $\lambda_{\rm FSH}$ and is dependent on $f_\psi(p,t)$

- For non-thermal DM this $f_\psi(p,t)$ has no particular form
  $\Rightarrow$ $\lambda_{\rm FSH}$ for non-thermal DM may be quite different from thermal WDM

- Effects of the inflaton mediated scatterings:
  - DM become non-relativistic earlier
  - More than an order of magnitude decrease in $\lambda_{\rm FSH}$

  $\Rightarrow$ Lyman-α constraint on m_ψ weakens



Evolution of the DM average velocity

Conclusions

- Perturbative decay of inflaton to SM radiation "reheats" the Universe and in a minimalistic scenario capable to explain dark matter: $\Rightarrow$ DM is also produced from inflaton decay during reheating
- Usually the DM is assumed to be "non-thermal" whose phase-space distribution is assumed to be frozen and simply redshifts with the expansion of the Universe
- Since the inflaton couples to both the DM and the SM, inflaton mediated scatterings between DM and SM are inevitable
- For certain choices of the associated parameters such scatterings may increase the comoving number density of the DM by a factor of ~ 60 !!
- Change in the shape of the phase-space distribution may reduce the free-streaming horizon by a factor of ~ 40 !!

  $\Rightarrow$ Weaking of the Lyman-α constraint on the DM mass

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  $\Rightarrow$ Weaking of the Lyman-α constraint on the DM mass