Post-Reheating Inflaton-Mediated Dark and Visible Matter Scatterings: A Cosmological Perspective

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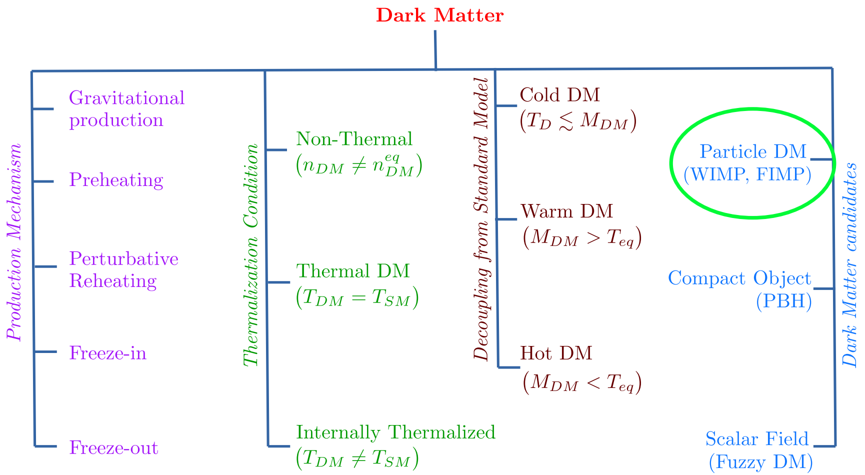
Classification of Dark Matter

Dark Matter

- *Production Mechanism*
  - Gravitational production
  - Preheating
  - Perturbative Reheating
  - Freeze-in
  - Freeze-out
- *Thermalization Condition*
  - Non-Thermal ($n_{DM} \neq n^{eq}_{DM}$)
  - Thermal DM ($T_{DM} = T_{SM}$)
  - Internally Thermalized ($T_{DM} \neq T_{SM}$)
- *Decoupling from Standard Model*
  - Cold DM ($T_D \lesssim M_{DM}$)
  - Warm DM ($M_{DM} > T_{eq}$)
  - Hot DM ($M_{DM} < T_{eq}$)
- *Dark Matter candidates*
  - Particle DM (WIMP, FIMP)
  - Compact Object (PBH)
  - Scalar Field (Fuzzy DM)

Classification of Dark Matter



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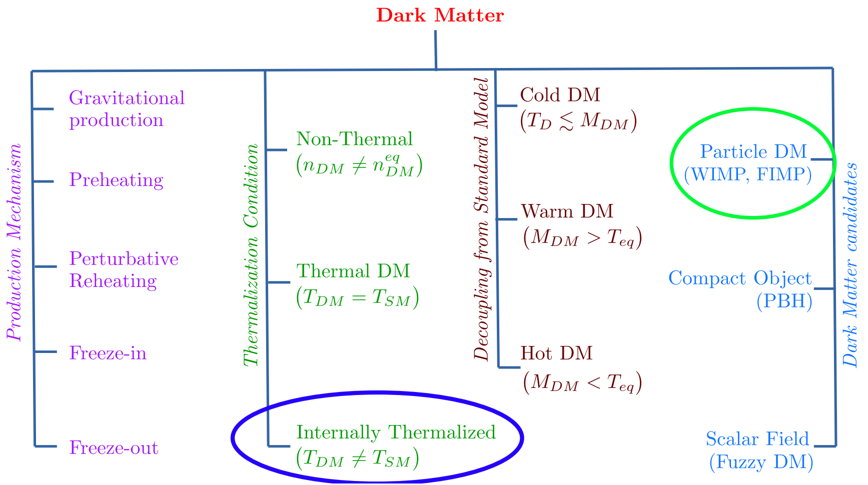


Dynamics of Dark Matter : Boltzmann equation

Consider this interaction : $1+2+...+k \to a+b$. The Boltzmann equation for determining the evolution of phase-space density of particle i, $f_i(\mathbf{p}_i, t)$:

$$\frac{\partial f_i(\mathbf{p}_i, t)}{\partial t} - H\mathbf{p}_i.\nabla_{\mathbf{p}_i} f_i(\mathbf{p}_i, t) = C[f_i] \tag{1}$$

The collision term, $C[f_i]$ includes all interactions involving i^{th} particle :

$$C[f_i] = \frac{1}{2E_i} \int \prod_{\substack{\alpha=1 \\ \alpha \neq i}}^{k} d\Pi_\alpha (2\pi)^4 \delta\left(p_1 + p_2 + ... + p_k - p_a - p_b\right) |\mathcal{M}|^2_{k\to 2} \tag{2}$$
$$\times \left[f_a(\mathbf{p}_a)\, f_b(\mathbf{p}_b) - f_1(\mathbf{p}_1)\, f_2(\mathbf{p}_2) \, . \, . \, . \, f_k(\mathbf{p}_k) \right]$$

DM number density n_χ with g_χ degrees of freedom is

$$n_\chi = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3}\, f_\chi(\mathbf{p}, t). \tag{3}$$

Write the distribution function as : $f_\chi = (n_\chi / n_\chi^{eq})\ f_\chi^{eq}$

Evolution equation for the DM number density integrating (1) w.r.t $\mathbf{p}_i$: **[D. Bhatia and S. Mukhopadhyay, JHEP 03, 133 (2021)]**

$$\frac{dn_\chi(t)}{dt} + 3Hn_\chi(t) = g_\chi \int \frac{d^3\mathbf{p}_i}{(2\pi)^3} C[f_\chi] = (\Delta n_\chi) n_a n_b \langle \sigma_{2\to k} v_{rel} \rangle \left[\frac{n_a n_b}{n_a^{eq} n_b^{eq}} - \frac{n_1 n_2 \ldots n_k}{n_1^{eq} n_2^{eq} \ldots n_k^{eq}} \right] \tag{4}$$

where $\langle \sigma_{2\to k} v_{rel} \rangle$ means the thermal averaged cross-section over the distribution functions :

$$\langle \sigma_{2\to k} v_{rel} \rangle = \frac{\int d^3p_a\ d^3p_b\ f_a^{eq}\ f_b^{eq}\ (\sigma_{2\to k} v_{rel})}{\int d^3p_a\ d^3p_b\ f_a^{eq}\ f_b^{eq}} \tag{5}$$

Thermodynamics of Dark Matter : Evolution of Temperature

Define the temperature of a species as the average of $|\mathbf{p}|^2/3E$ over its distribution function :

$$T_\chi \equiv \frac{g_\chi}{n_\chi} \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{|\mathbf{p}|^2}{3E} f_\chi(\mathbf{p}, t). \qquad (6)$$

Taking the moment of (1) with $|\mathbf{p}|^2/3E$, the evolution equation for the DM temperature is :

$$\frac{dT_\chi}{dt} + 2HT_\chi + \frac{T_\chi}{n_\chi}\left(\frac{dn_\chi}{dt} + 3Hn_\chi\right) - \frac{H}{3}\left\langle \frac{|\mathbf{p}|^4}{E^3} \right\rangle = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{|\mathbf{p}|^2}{3E} C[f_\chi] \qquad (7)$$

Reheating after Inflation

Inflation : Exponential expansion of the universe, $a \propto e^{Ht}$, H$\simeq$constant.
Universe dominated by a scalar field, called *'Inflaton'*.

Inflaton decay and particle production :

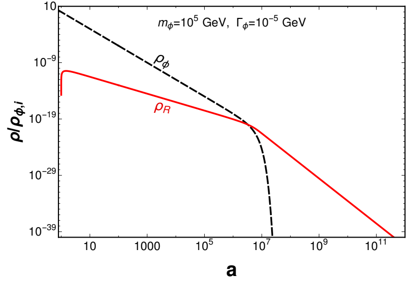
Inflaton decays into SM particles to enter radiation dominated universe : $\phi \xrightarrow{\Gamma_\phi} SM \quad \Rightarrow \quad$ Reheating

Evolution of energy density of inflaton and SM :

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\frac{d\rho_{SM}}{dt} + 4H\rho_{SM} = \Gamma_\phi \rho_\phi$$

Evolution of inflaton field : $\rho_\phi(t) = \rho_\phi(t_i).\frac{a(t_i)^3}{a(t)^3} e^{-\Gamma_\phi(t-t_i)}$



Reheating : $\Gamma_\phi \simeq H \implies T_R = \left(\frac{90}{\pi^2 G_{*SM}}\right)^{1/4} \sqrt{\Gamma_\phi M_P}$

Two sector Reheating : an Effective Theory

Two sector reheating : Inflaton ϕ decays perturbatively to both SM and DM (χ) particles.

The initial temperature ratio at the reheating : $(T_\chi/T_{SM})_i = g_{*SM}^{1/4}(T_R)\left(\frac{\Gamma_{\phi\to\chi\chi}}{\Gamma_{\phi\to SM\ SM}}\right)^{1/4}$

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Lagrangian for inflaton decay :

A scalar inflaton ϕ couples to scalar singlet DM χ and *SM* through $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant Lagrangian :

$$\mathcal{L} \supset \frac{\mu_\chi}{2}\phi\chi^2 + \frac{\lambda}{4}\phi^2\chi^2 + \mu_\phi\phi H^\dagger H + \frac{\lambda_\phi}{2}\phi^2 H^\dagger H + \frac{1}{\Lambda}\phi\bar{L}He_R + \frac{1}{\Lambda}\phi\bar{Q}\tilde{H}u_R + \frac{1}{\Lambda}\phi\bar{Q}Hd_R$$
$$+ \frac{1}{\Lambda}(\partial_\mu\phi)(g_L\bar{f}_L\gamma^\mu f_L + g_R\bar{f}_R\gamma^\mu f_R) + \frac{1}{\Lambda}\phi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda}\phi W^{a\mu\nu}W^a_{\mu\nu} + \frac{1}{\Lambda}\phi G^{a\mu\nu}G^a_{\mu\nu} \quad (8)$$

where, $\tilde{H} = i\sigma_2 H^*$.

Inflaton dominantly couples to the SM Higgs

Decay widths : $\Gamma_{\phi\rightarrow H^\dagger H} \simeq \frac{\mu_\phi^2}{8\pi m_\phi}$; $\Gamma_{\phi\rightarrow\chi\chi} \simeq \frac{\mu_\chi^2}{32\pi m_\phi}$

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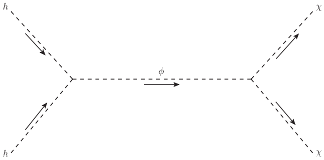

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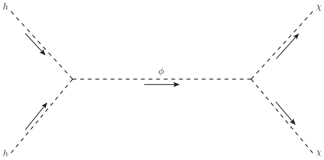

Inflaton mediated scatterings between DM and SM(Higgs) :

Electroweak Symmetry breaking scale, $T_{EW} \simeq 160$ GeV

[D'Onofrio et al. ,Phys. Rev. D 93, 025003 (2016)]

For $T > T_{EW}$: $\sigma_{\chi\chi\to H^\dagger H} = \frac{1}{8\pi}\frac{\mu_\chi^2\mu_\phi^2}{\sqrt{s(s-4m_\chi^2)}}\frac{1}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$

For $T < T_{EW}$: $\sigma_{\chi\chi\to hh} = \frac{1}{32\pi}\frac{\mu_\chi^2\mu_\phi^2}{\sqrt{s(s-4m_\chi^2)}}\frac{\sqrt{1-\frac{4m_h^2}{s}}}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$

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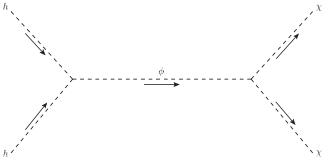

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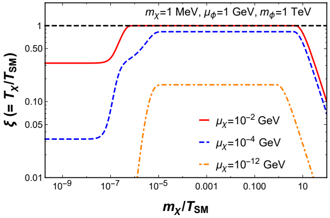
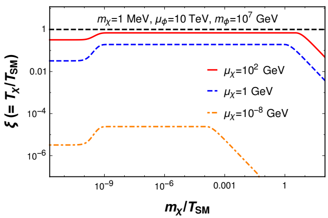
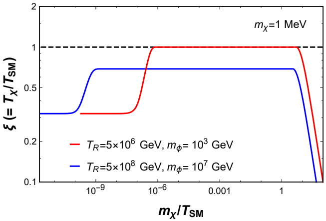


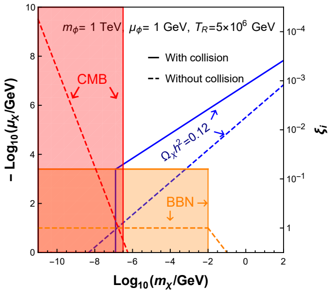
Effects of Inflaton mediated DM-Higgs scattering :

Variation of Inflaton mass :





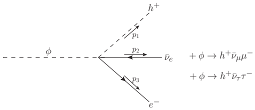
Relic density and allowed parameter space :



$$\mathcal{L} \supset \frac{1}{\Lambda}\phi\bar{L}He_R + \frac{1}{\Lambda}\phi\bar{Q}\tilde{H}u_R + \frac{1}{\Lambda}\phi\bar{Q}Hd_R + \frac{1}{\Lambda}(\partial_\mu\phi)(g_L\bar{f}_L\gamma^\mu f_L + g_R\bar{f}_R\gamma^\mu f_R)$$
$$+ \frac{1}{\Lambda}\phi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda}\phi W^{a\mu\nu}W^a_{\mu\nu} + \frac{1}{\Lambda}\phi G^{a\mu\nu}G^a_{\mu\nu}$$

$\phi \rightarrow$ SM Fermions :

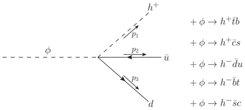
$$\frac{1}{\Lambda}\phi\bar{L}He_R = \frac{1}{\Lambda}\phi h^+\bar{\nu}_e e_R + \frac{1}{\Lambda}\phi h^0\bar{e}_L e_R + \mu,\tau \quad \text{before} \quad \text{EWSB}$$
$$= \frac{v}{\sqrt{2}\Lambda}\phi\bar{e}_L e_R + \frac{1}{\sqrt{2}\Lambda}\phi h\bar{e}_L e_R + \mu,\tau \quad \text{after} \quad \text{EWSB}$$



Decay widths :

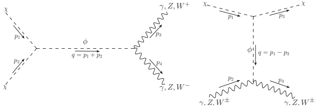
Before EWSB : $\Gamma_{\phi\rightarrow fermions+h} = \frac{3}{128\pi^3}\frac{m_\phi^3}{\Lambda^2}$

After EWSB : $\Gamma_{\phi\rightarrow f\bar{f}} = \frac{1}{16\pi}\frac{\sqrt{m_\phi^2-4m_f^2}}{\Lambda^2 m_\phi^2}\left(\frac{v^2}{4}(2m_\phi^2-5m_f^2)+8g_A^2 m_\phi^2 m_f^2\right)$



$\phi \rightarrow$ SM Fermions :

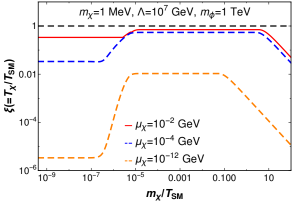
$$\sigma_{\chi\chi\rightarrow f\bar{f}}\Big|_{T<T_{EW}} = \frac{1}{32\pi s}\sqrt{\frac{s-4m_f^2}{s-4m_\chi^2}}\,\frac{16\mu_\chi^2}{\Lambda^2}\,\frac{\frac{v^2}{4}(2s-5m_f^2)+8g_A^2 m_f^2 s}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$$



$\phi \rightarrow$ SM Gauge bosons :

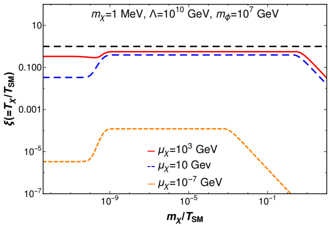
$$\sigma_{\chi\chi\rightarrow i\bar{i}}\Big|_{T>T_{EW}} = \frac{1}{g_s}\frac{1}{32\pi s}\sqrt{\frac{s}{s-4m_\chi^2}}\,\frac{8\mu_\chi^2}{\Lambda^2}\,\frac{s^2}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$$

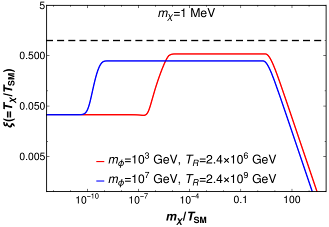
$$\sigma_{\chi\chi\rightarrow i\bar{i}}\Big|_{T<T_{EW}} = \frac{1}{g_s}\frac{1}{32\pi s}\sqrt{\frac{s-4m_i^2}{s-4m_\chi^2}}\,\frac{16\mu_\chi^2}{\Lambda^2}\,\frac{\frac{s^2}{2}-2m_i^2 s+3m_i^2}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$$



DM abundance and allowed parameter space

Variation of Inflaton mass :





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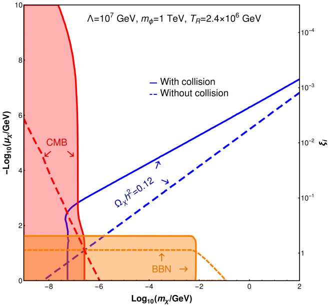

Summary

- The initial conditions (e.g. temperature ratio, co-moving abundance) for DM and SM sectors could be modified significantly by scatterings at later epochs if they both were produced from inflaton decay.
- Parameters that generate two thermally asymmetric sectors from the decay of inflaton, are also responsible to modify the temperature ratio significantly, altering late time dynamics of the dark matter.

Invitation to the Poster Session

To find more about this topic, please visit the poster session in the evening : **Foyer Floor 2**

Poster No. - 264

"Cosmological implications of inflaton-mediated dark and visible matter scatterings after reheating"

thank you

Back-up slides