Cold Dark Matter Production

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May 2021

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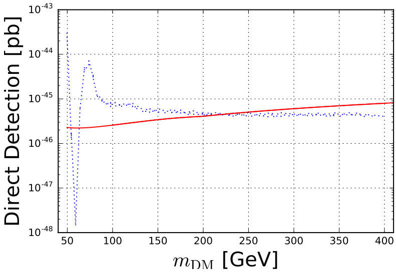
Motivation



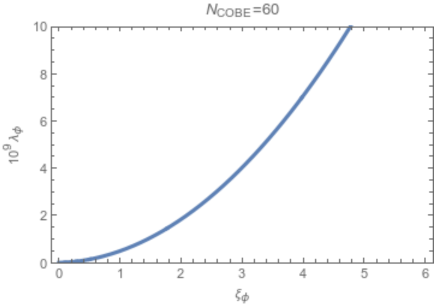


Figure: WIMP & FIMPLATON

Inflation

- Einstein field equation

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$$

Inflation

- Einstein field equation

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- FLRW metric

$$\begin{aligned} ds^2 &= dx^\mu dx^\nu g_{\mu\nu} \\ &= dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2 \right) \right) \end{aligned}$$

- Friedman equation

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho + \Lambda c^2}{3} - K\frac{c^2}{a^2}$$

$$3\frac{\ddot{a}}{a} = \Lambda c^2 - 4\pi G\left(\rho + \frac{3p}{c^2}\right)$$

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$$3\frac{\ddot{a}}{a} = \Lambda c^2 - 4\pi G\left(\rho + \frac{3p}{c^2}\right)$$

- Accelerate

$$\frac{d}{dt}(aH)^{-1} = \frac{d}{dt}(\dot{a})^{-1} = -\frac{\ddot{a}}{(\dot{a})^{-1}},$$

$$\frac{d^2a}{dt^2} > 0$$

Slow roll-inflation

- Klein-Gordon

$$\ddot{\phi} + 3H\dot{\phi} + \partial_{\phi} V(\phi) = 0$$

Slow roll-inflation

- Klein-Gordon

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V(\phi) = 0$$

- Flat potential

$$\dot{\phi} = -\frac{1}{3H}\partial_\phi V$$

Slow Roll parameters

$$\epsilon_V \equiv \frac{1}{2}\left(\frac{\partial_\phi V}{V}\right)^2 ,$$

$$\eta_V \equiv \frac{\partial_\phi^2 V}{V} .$$

End of inflation

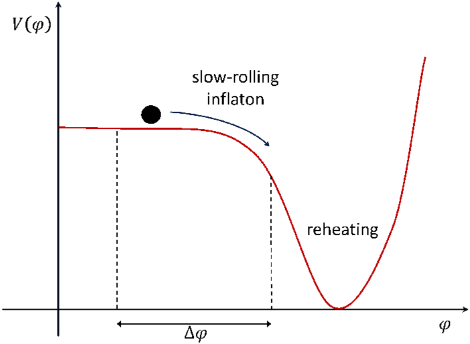


Figure: Reheating epoch starts. Inflaton decays into ordinary matter.

Reheating process

Trans-Plankian energy scale

$$N = \int_{t_*}^{t_{\text{end}}} H\, dt \simeq \frac{1}{M_p^2} \int_{\phi_{\text{end}}}^{\phi_*} \frac{V}{V_\phi}\, d\phi \simeq \frac{1}{4}\left(\frac{\phi_*}{M_p}\right)^2$$

with

$$\phi_* \gg \phi_{\text{end}}.$$

Reheating

Once the trans plankian scale is computed one can calculate the inflation observables; tensor to scalar ratio r, and spectral index n_s and contrast the model with CMB measurements.

$$n_s \approx 1 - 6\,\epsilon_V^\star + 2\,\eta_V^\star$$
$$r \approx 16\,\epsilon_V^\star\,.$$

DM production

Scalar singlet extension ϕ (or **S**):

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu_\phi^2\phi^2 - \frac{1}{2}\lambda_{\mathsf{HS}}\phi^2 H^\dagger H - \frac{\lambda_\phi}{4!}\phi^4\,, \tag{1}$$

with μ_ϕ as the mass parameter, H Higgs doublet and λ_{HS} coupling to Higgs.

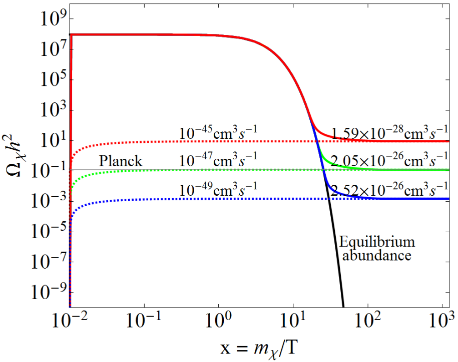
DM production

When the electroweak symmetry is spontaneously broken, the phenomenology of the model is completely determined by :

$$\mu_\phi^2 = m_\phi^2 - \frac{1}{2}\lambda_{\mathrm{HS}} v_0^2 \,, \qquad (2)$$

where m_ϕ represents the mass of the scalar singlet with expected value of vacuum $v_0 = 246,2$ GeV.

Regimes



$10^{-45}\text{cm}^3 s^{-1}$
$1.59\times10^{-28}\text{cm}^3 s^{-1}$
Planck
$10^{-47}\text{cm}^3 s^{-1}$
$2.05\times10^{-26}\text{cm}^3 s^{-1}$
$10^{-49}\text{cm}^3 s^{-1}$
$2.52\times10^{-26}\text{cm}^3 s^{-1}$
Equilibrium abundance
$\Omega_\chi h^2$
$x = m_\chi/T$

Dark matter in a matter dominated era

Cold Dark Matter Production: non instantaneous reheating

$$\dot{n}_\phi + 3Hn_\phi + \Gamma_\phi n_\phi = 0\,,$$
$$\dot{\rho}_R + 4H\rho_R - \Gamma_\phi n_\phi m_\phi \Delta_\phi - 2m_\chi \langle \sigma v \rangle (n_\chi^2 - n_{\chi eq}^2) = 0\,,$$
$$\dot{n}_\chi + 3Hn_\chi + \langle \sigma v \rangle (n_\chi^2 - n_{\chi eq}^2) - \Gamma_\phi N_\chi n_\phi = 0\,,$$

where dots represents cosmic time derivative, $\Delta_\phi = (m_\phi - N_\chi m_\chi)/m_\phi$ is a shorthand, $\langle \sigma v \rangle$ is the thermal average cross section [1].

Cold Dark Matter Production: non instantaneous reheating

he equilibrium number density of χ particles can be expressed in terms of the modified Bessel Function of second kind, K_2:

$$n_{\mathrm{eq}\chi} = \frac{gT^3}{2\pi^2}\left(\frac{m_\chi}{T}\right)^2 K_2\left(\frac{m_\chi}{T}\right) \qquad (3)$$
$$\longrightarrow \frac{gT^3}{\pi^2}(T \gg m_\chi)$$
$$\longrightarrow g\left(\frac{m_\chi}{T}\right)^{3/2} e^{-m_\chi/T}(T \ll m_\chi),$$

where $g = 2$ are the degrees of freedom of χ particles.

Considerations

Hubble parameter

$$H^2 = \frac{8\pi}{3M_\mathrm{p}^2}(\rho_\phi + \rho_R + \rho_\chi)\,, \tag{4}$$

$\Gamma_\phi \sim H$

$$\Gamma_\phi = 2\sqrt{\frac{\pi^3 g_{\rho*}(T_R)}{45}}\frac{T_R^2}{M_\mathrm{p}} \tag{5}$$

Numerical solution

o solve the Boltzmann equations set, it is more convenient to express the variables in terms of dimensionless quantities as follows:

$$\Phi = n_\phi A^3 \,, \qquad R = \rho_R A^4 \,, \qquad \chi_{[eq]} = n_{\chi_{[eq]}} A^3 \,, \tag{6}$$

where $A = HA_I$, represents the scalar factor

Parameters

Parameters		
Quantity	WIMP	FIMP
m_ϕ [GeV]	1×10^6	1×10^{13}
m_χ [GeV]	410	410
T_R [GeV]	5	5
$\langle \sigma v \rangle$ $[\mathrm{GeV}]^{-2}$	1×10^{-10}	8.5×10^{-30}
N_χ	1.4×10^{-7}	1.4×10^{-7}
$g_{\rho *}$	10.88	3.36
$g_{s *}$	10.85	3.96

Table: Parameters used to test the matter dominated era model in WIMP and FIMP frameworks.

WIMPS

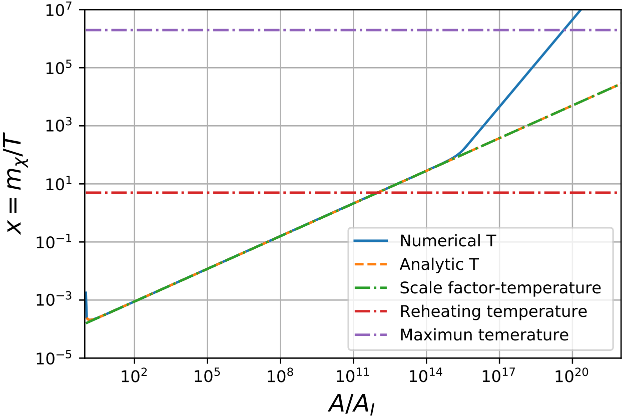


Figure: Numerical and analytic temperature behaviour. The graph includes the temperature behaviour obtained from the scale factor equation

Components evolution

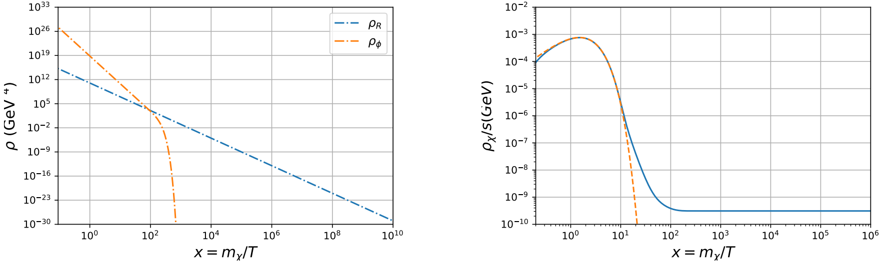


Figure: Evolution of the energy components

Cross sections

DD cross section			
λ_{HS}	σ_{SI} [pb]	$\langle \sigma v \rangle$ [pb]	Ωh^2
10^{-2}	2.130×10^{-11}	1.75×10^{-2}	3.62
10^{-3}	2.130×10^{-13}	1.75×10^{-4}	2.79×10^{2}
10^{-4}	2.213×10^{-15}	1.75×10^{-6}	1.98×10^{4}

Table: Direct detection cross section, thermal averaged cross section and relic density obtained for a fixed mass of 410 GeV using single scalar model implemented in micrOMEGAS

For WIMPS: thermal production

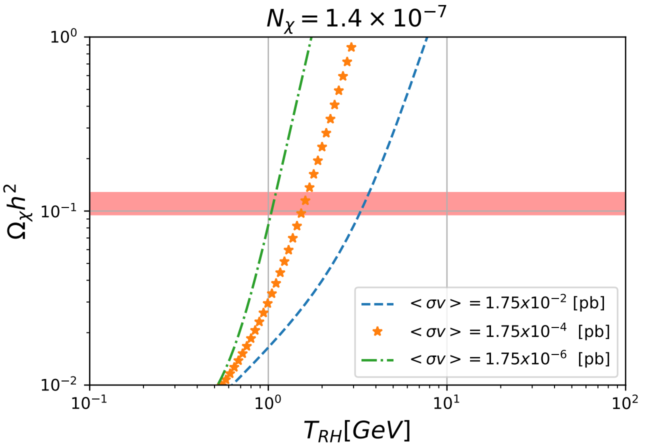


Figure: Dark matter abundance for excluded the thermal average cross sections from Direct detection [2]. The pink band represents the current dark matter abundance constrain $\Omega h^2 = 0.112^{+0.0161}_{-0.0181}$.

FIMP

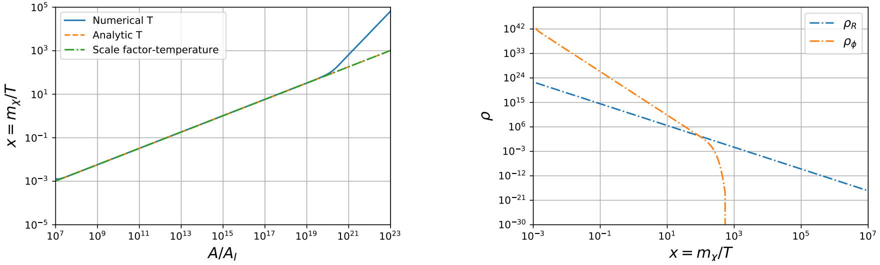


Figure: Evolution of the energy components

FIMP

- MicrOmegas funtion **vSigma** to find $\langle \sigma v \rangle$.
- We found $\langle \sigma v \rangle \propto 1/T^2$
- Interpolation function for $M_\chi = 550$ GeV

For FIMPs: non-thermal production

m_ϕ [GeV]	m_χ [GeV]	N_χ	T_R [GeV]	$\langle \sigma v \rangle$ $[\text{GeV}]^{-2}$
10^{13}	550	10^{-8}	10^{9}	10^{-36}

We tasted this parameters for ultraviolet reheating, and the for infrared reheating (variable thermal average cross section: fit with MicrOMEGAS) and we found a couplig of order $\lambda \approx 10^{-14}$

DM and inflation through dark portal

$$-\mathcal{L} \supset \frac{\lambda_\phi}{2}\left(\Phi^\dagger\Phi - \frac{v_\phi^2}{2}\right)^2 + \frac{\lambda_\sigma}{2}\left(\Sigma^\dagger\Sigma - \frac{v_\sigma^2}{2}\right)^2 + \delta\left(\Phi^\dagger\Phi - \frac{v_\phi^2}{2}\right)\left(\Sigma^\dagger\Sigma - \frac{v_\sigma^2}{2}\right),$$

where v_ϕ and v_σ are the vacuum expectation value of each field and the last term in the lagrangian represents the inflaton portal interaction, [4, 5].

$$\Phi = \frac{1}{\sqrt{2}}(v_\phi + \phi + iS_d)\,, \tag{7}$$

$$\Sigma = \frac{1}{\sqrt{2}}(v_\sigma + \sigma + iS_v)\,, \tag{8}$$

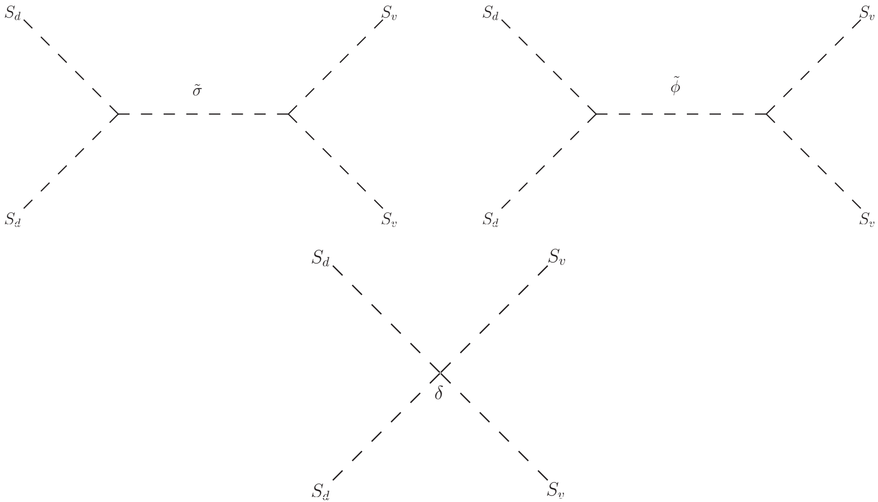


Figure: Diagrams leading dark sector annihilating into the visible sector.

To ensure single field inflation, we consider $m_\sigma^2 \geq H^2$. Also, to make sure that light excitation get watered down during inflation, Nambu-Goldstone bosons S_v and S_d, and the standard model are supposed to get effective Hubble masses.

$$V_{inf}(\phi) \propto (\phi^4 + 4v_\phi^2\phi^2 + 4v_\phi\phi^3)\,. \tag{9}$$

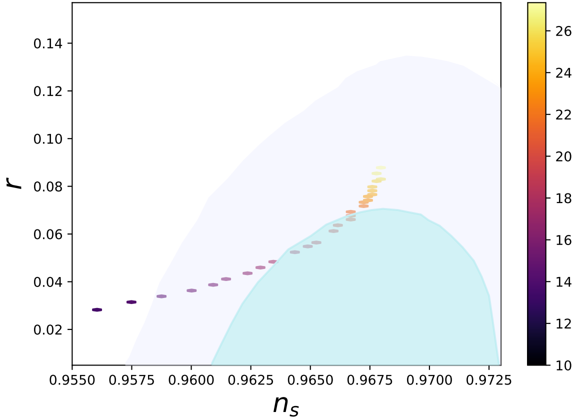


Figure: Inflaton observables for $N = 60$ and some vev v_ϕ corresponding to the color bar (times Planck mass). Contours represent Planck measurements [3]. From the plot we can obtain a $v_\phi \approx 20 M_P$

$$\langle \sigma v \rangle n_{eq}^2 = \frac{4\pi}{2} \frac{T}{32(2\pi)^6} \int_{4m_d^2}^{\infty} |\mathcal{M}|^2 \sqrt{s - 4m_d^2} K_1 \left(\frac{\sqrt{s}}{T} \right) ds \,.$$

We restrict dark matter production and found:

$$\Omega_{\text{non-thermal}} h^2 \approx 0.12 \left(\frac{\delta}{4.2 \times 10^{-12}} \right)^2 \,.$$

Thanks for your attention

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