Scalar multiplet dark matter in non standard Universe.

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Abstract

We examine the impact of a faster expanding Universe on the phenomenology of scalar dark matter (DM) associated with SU(2) multiplets. Earlier works with radiation dominated Universe have reported the presence of desert region for both inert SU(2) doublet and triplet DM candidates where the DM is under abundant. We find that the existence of a faster expanding component before BBN can revive a major part of the desert parameter space consistent with relic density requirements and other direct and indirect search bounds. We also review the possible collider search prospects of the newly obtained parameter space and predict that such region can be probed at the future colliders with improved sensitivity via a disappearing/stable charged track.

Inert Doublet and Triplet dark matter

1. Inert doublet [1]: Φ, with hypercharge $Y=0$

$$V(H,\Phi) = -\mu_H^2|H|^2 + \lambda_H|H|^4 + \mu_\Phi^2(\Phi^\dagger\Phi) + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_1(H^\dagger H)(\Phi^\dagger\Phi) + \lambda_2(H^\dagger\Phi)(\Phi^\dagger H) + \frac{\lambda_3}{2}\left[(H^\dagger\Phi)^2 + h.c.\right]$$

with

$$H = \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}, \quad \Phi = \begin{pmatrix} H^\pm \\ \frac{H^0+iA^0}{\sqrt{2}} \end{pmatrix}$$

Independent parameters:
m_H^0, $\lambda_L = \frac{1}{2}(\lambda_1+\lambda_2+\lambda_3)$, $\Delta M_1 = m_A^0 - m_H^0$, $\Delta M_2 = m_{H^\pm} - m_H^0$.

2. Inert Triplet [2]: Δ with hypercharge $Y=0$.

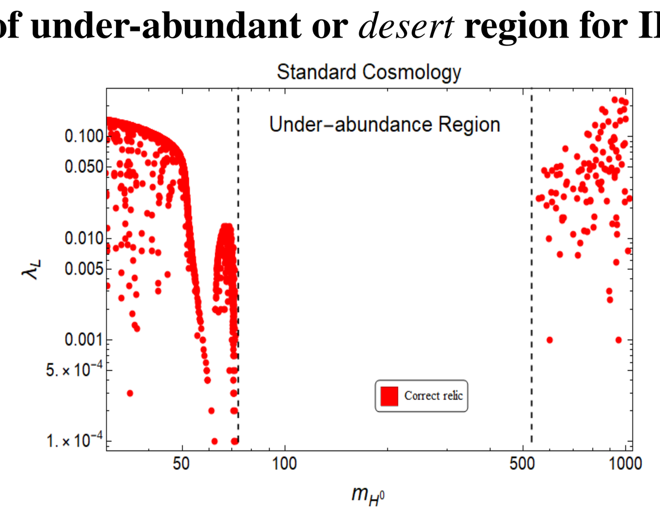
$$V(H,T) \supset \mu_H^2|H|^2 + \lambda_H|H|^4 + \frac{\mu_T^2}{2}\mathrm{Tr}\left[T^2\right] + \frac{\lambda_T}{4!}\left(\mathrm{Tr}\left[T^2\right]\right)^2 + \frac{\lambda_{HT}}{2}|H|^2\,\mathrm{Tr}\left[T^2\right], \tag{1}$$

where H is the SM-like Higgs doublet and the triplet T is parameterized as

$$T = \begin{pmatrix} T^0/\sqrt{2} & -T^+ \\ -T^- & -T^0/\sqrt{2} \end{pmatrix}. \tag{2}$$

Independent prameters:
$m^2_{T^0,T^\pm} = \mu_T^2 + \frac{\lambda_{HT}}{2}v^2$, λ_{HT}

Presence of under-abundant or *desert* region for IDM



Presence of under-abundant or *desert* region for ITDM

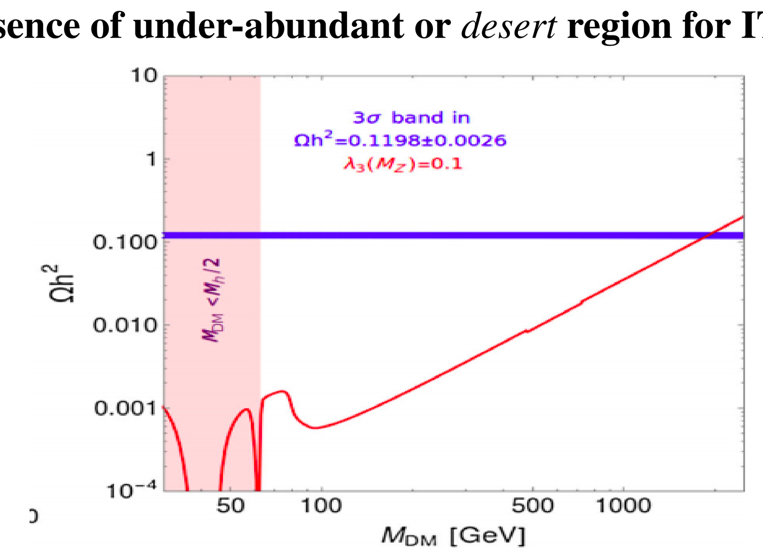


Figure picked from [3].

Motivation for our work

The underabundant region for IDM is $80\text{ GeV} \lesssim m_{H^0} \lesssim 525$ GeV and for ITDM is $m_T^0 \lesssim 1.9$ TeV .

Can a non standard Universe, revive the desert region?

Kinaton or faster than kinaton

The equation of state for a particular component is given by:

$$p = \omega\rho, \tag{3}$$

where p stands for the pressure of that component. For radiation, $\omega_R = \frac{1}{3}$.

The $\omega_\eta = 0$ case is familiar as early matter domination and $\omega_\eta = 1$ is dubbed as fast expanding universe. One can also obtain $\rho_\eta \propto a(t)^{-(4+n)}$, for radiation $n=0$. In this work, we consider early Universe to be dominated by fluids having $n \geq 2$.

The total energy density at any temperature ($T > T_R$) as [4]

$$\rho(T) = \rho_{rad}(T) + \rho_\eta(T) \tag{4}$$

$$= \rho_{rad}(T)\left[1 + \frac{g_*(T_R)}{g_*(T)}\left(\frac{g_{*s}(T)}{g_{*s}(T_R)}\right)^{(4+n)/3}\left(\frac{T}{T_R}\right)^n\right] \tag{5}$$

The temperature T_R is an unknown parameter ($> T_{\rm BBN}$) and can be safely assumed as the point of equality of two respective energy densities: $\rho_\eta(T_R) = \rho_{\rm rad}(T_R)$. From the above equation, it is evident that the energy density of the universe at any arbitrary temperature ($T > T_R$), is dominated by η component. The standard Friedmann equation connecting the Hubble parameter with the energy density of the universe is given by:

$$\mathcal{H}^2 = \frac{\rho}{3M_{\rm Pl}^2}, \tag{6}$$

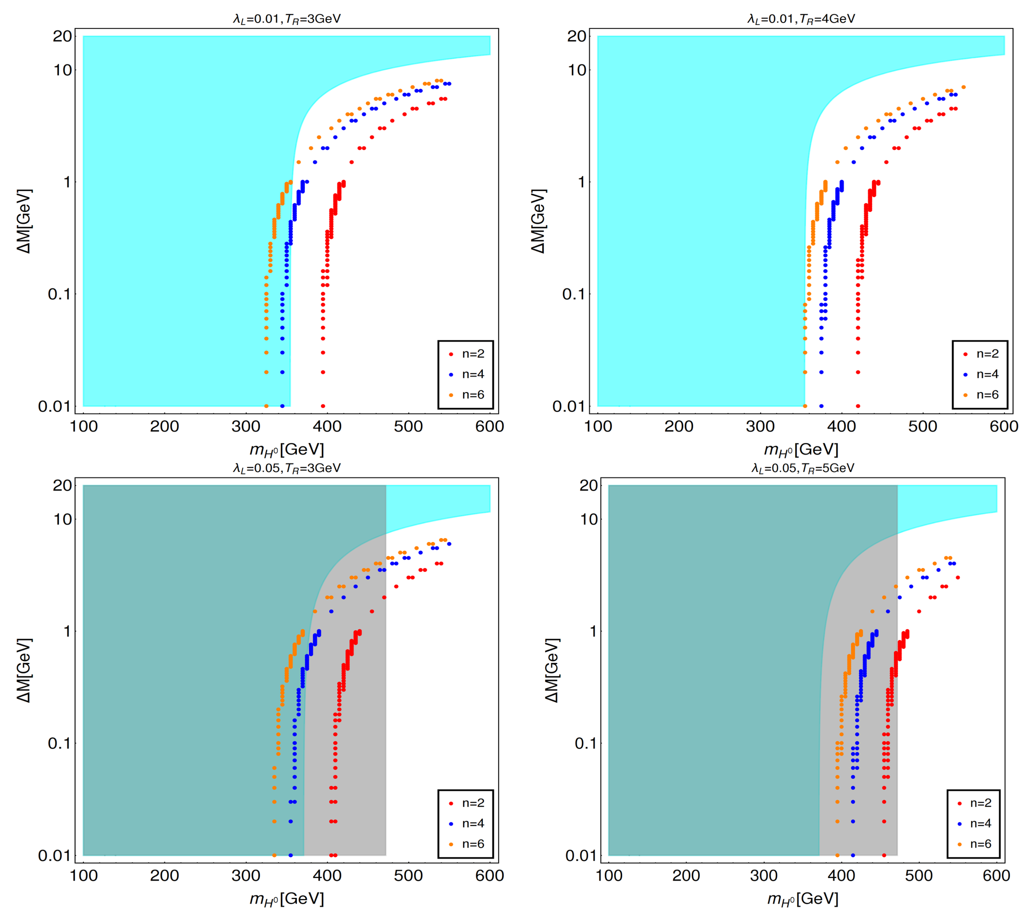
where $M_{\rm Pl} = 2.4\times10^{18}$ GeV being the Planck mass.

Boltzman equation

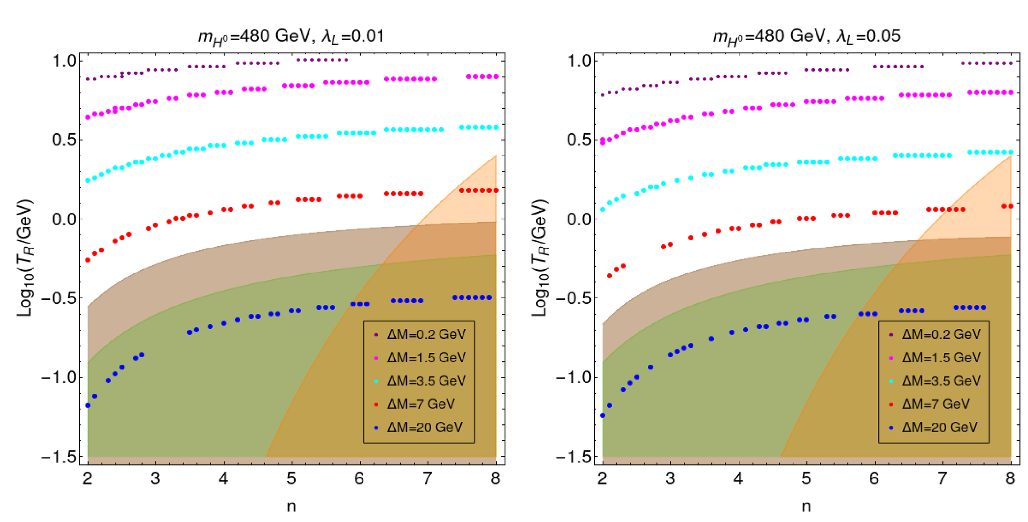
The Boltzmann equation (BEQ) that governs the evolution of comoving number density of the DM, in the standard radiation dominated universe has the familiar form (assuming DM thermalises in the early Universe)

$$\frac{dY_{\rm DM}}{dx} = -\frac{\langle\sigma v\rangle s}{\mathcal{H}(T)x}\left(Y_{\rm DM}^2 - Y_{\rm DM}^{\rm eq^2}\right), \tag{7}$$

Results for IDM

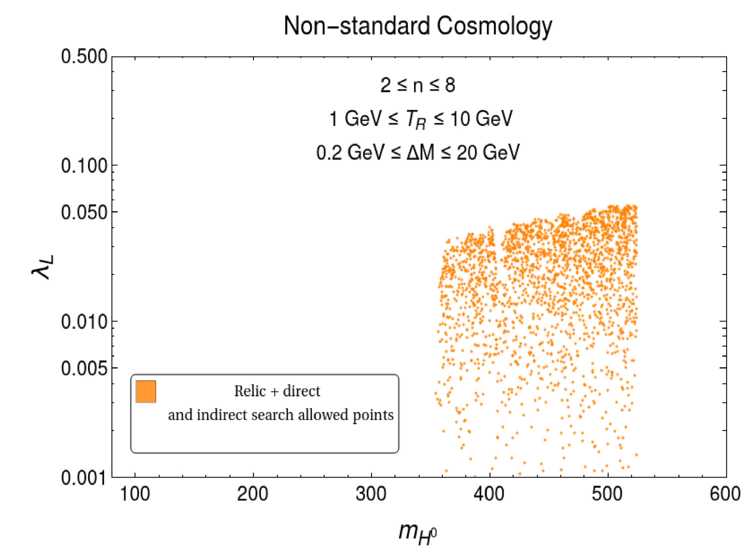


- Direct detection bound (ash color) is more stronger than the indirect search bound (light blue) for higher λ_L.
- A larger value of n requires smaller DM mass to satisfy the relic bound.



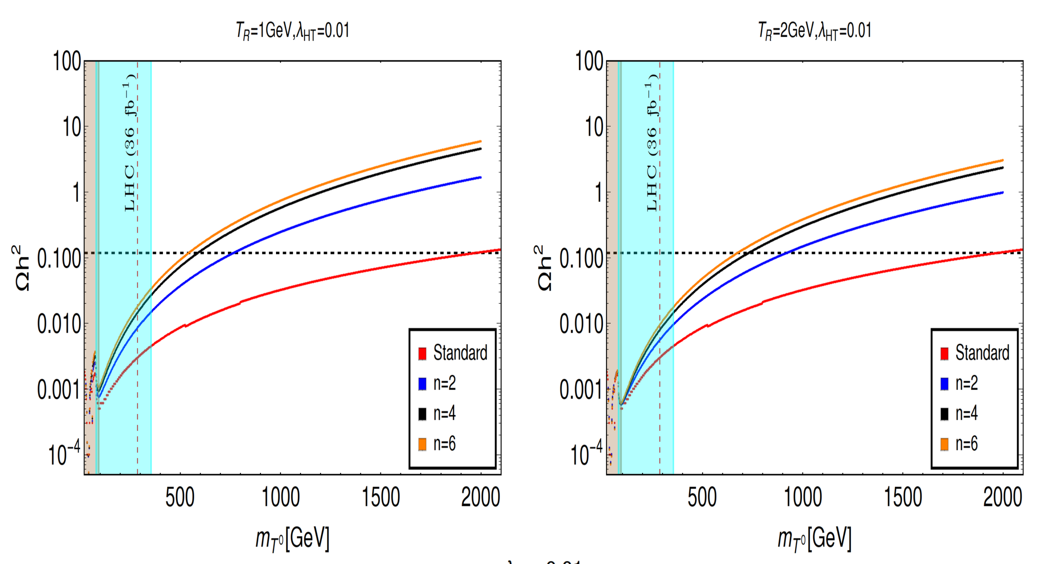
- With the increase in ΔM we see a smaller T_R is required to satisfy the observed relic abundance.
- Smaller value of T_R for a fixed n (and vice-versa) violating the limit are disfavoured from the BBN bound. This BBN-excluded region is shown (green) in either of the plots in green.
- The brown region indicates the disallowed space by indirect search constraint while the orange region is disfavored by the violation of DM thermalisation condition before weak scale.
- We also see that, for fixed ΔM and m_{H^0}, larger λ_L prefers low T_R (for a fixed n) or larger n (for a fixed T_R). This is typically attributed to the DM annihilation cross-section that has a quadratic dependence on λ_L.

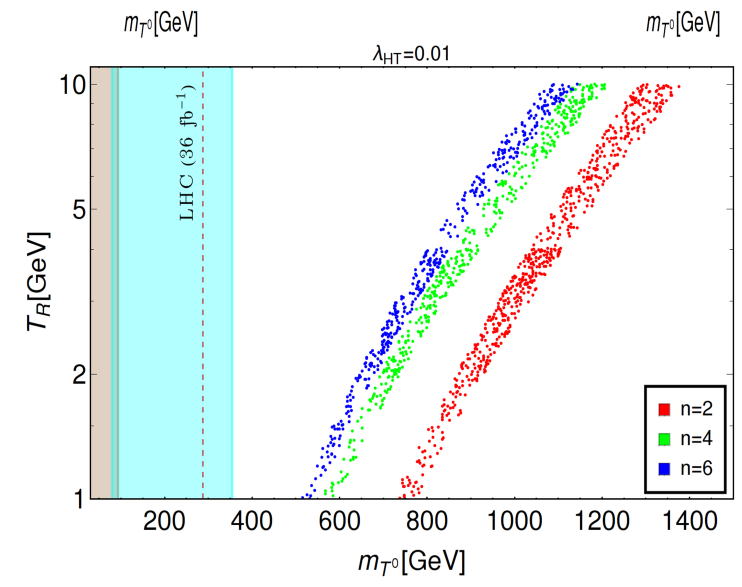
- With these outcomes, it is understandable that the fast expansion parameters are well restricted by all the combined constraints irrespective of the value of λ_L.



- A fast expanding Universe can recover $350\text{ GeV} \lesssim m_{H^0} \lesssim 525$ GeV out of $80\text{ GeV} \lesssim m_{H^0} \lesssim 525$.

Results for ITDM





- Brow and cyan region indicate the bounds coming from direct and indirect search. Taking all relevant constraints into account, we see from bottom panel, the region $m_{T^0} \gtrsim 450$ GeV can be recovered considering $2 \leq n \leq 6$ and $T_R \gtrsim 1$ GeV. We find, it is also possible to resurrect part of the parameter space below 450 GeV for $T_R < 1$ GeV ensuring the DM thermalizes in the early Universe depending on the choice of n. This is, however, in contrast to the case of IDM dark matter, where the lower bound on the allowed DM mass ($\gtrsim 350$ GeV), satisfying thermalization criteria, is almost independent of the fast expanding parameters.

Comment on Collider Probes

- We have seen that for IDM, even in presence of non-standard cosmology, the mass difference has to be very small (at most 10 GeV). Hence, its collider search is very challenging. The lower $\Delta M \sim 140-200$ MeV can be probed by the disappearing pion charge track where Br[$H^\pm \to H^0\pi^\pm$] is near about 100%.
- For smaller $\Delta M < 140$ MeV, only decay mode is $H^\pm \to l\nu_L H^0$. However the decay occurs outside the detector giving rise to a stable charged track.
- For $\Delta M > 200$ MeV, the Br[$H^\pm \to H^0\pi^\pm$] will come down from 100% and future improved sensitivities form CMS or ATLAS could put further constraints on the non standard cosmological parameters.
- The 13 TeV LHC excludes a real triplet lighter than $\{287, 608, 761\}$ GeV for $\mathcal{L} = \{36, 300, 3000\}$ fb^{-1} of luminosity via a disappearing charge track.

References:

1. JCAP 01 (2011) 002,[arXiv:1011.1411]
2. Phys. Rev. D 83 (2011) 075014,[arXiv:1102.4906]
3. Eur. Phys. J. C78 (2018) no.4, 341, arXiv:1610.03178
4. JCAP 05 (2017) 012, [arXiv:1703.04793].