Non-Decoupling Dark Matter

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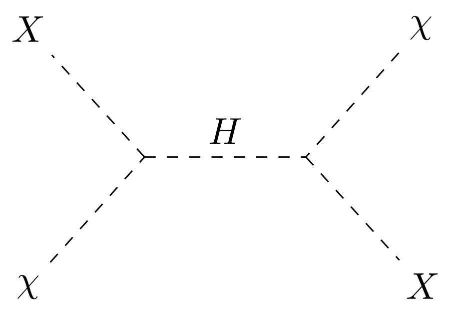
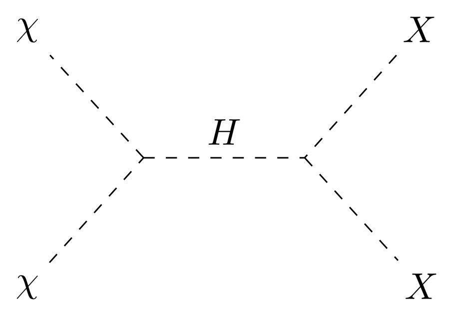
Introduction

- Non-decoupling particles whose majority source of mass is from Higgs vacuum expectation energy are called Loryons.
- Low energy Effective Field Theory (EFT) is described by Higgs EFT (HEFT) instead of Standard Model EFT (SMEFT). [1][2]
- HEFT parameter space can be constrained by Higgs decay data from LHC, including $h\gamma\gamma, hgg, h \to$ inivisble/untagged. [1] [2]
- In addition to collider physics data constraint, Loryons can be natural Dark Matter (DM) candidates. [1] [4] [5]
- Thermal DM relic from early universe obeys Boltzmann equation, and the leftover DM Cosmic Abundance can be measured. [4] [5]
- Cosmic Abundance then further bound Loryon parameters.

Thermal Dark Matter

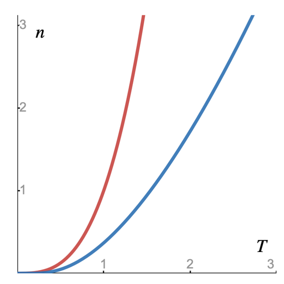


Inelastic:
DM annihilation changes DM number density (Relativistic)



Elastic:
DM scattering conserves DM number density (Non-relativistic)

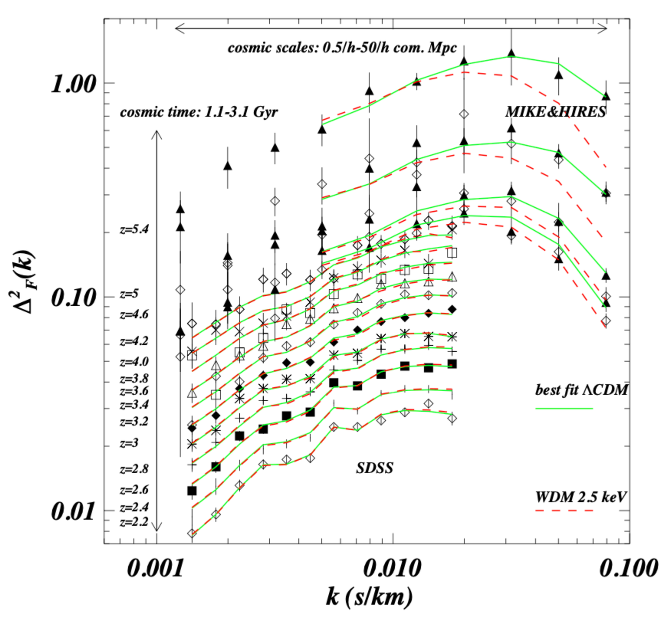
- Annihilation and scattering were in equilibrium in early universe.
- The inelastic process stops before the elastic process stops.
- "Freeze out" happens when inelastic process terminates due to $\Gamma_{el} \sim H$.
- Both processes terminate when $\Gamma_{el,nel} \sim H$, where H is the Hubble rate.
- DM decouples with everything after $\Gamma_{el,nel} \sim H$



Elastic $\propto T^3$
Inelastic $\propto T^{3/2}e^{-m_\chi/T}$

Cosmic Abundance

- Kinetic decoupling happens when elastic scattering stops.
- DM fully decouples, we can predict the relic content.



Cold DM relic
Warm DM relic

- Better agreement between Cold DM and Lyman α
- Warm DM decouples sooner than Cold DM

- Calculate cold abundance using Boltzmann equation [3]

Covariant change = Collisional change

$$\frac{dn}{dt} + 3Hn = -\sum_{spins}\int [f_1 f_2 (1 \pm f_3)(1 \pm f_4)\,|M_{12\to 34}|^2$$
$$+ f_3 f_4 (1 \pm f_1)(1 \pm f_2)\,|M_{34\to 12}|^2](2\pi)^3 \delta(\Delta p) d^4\Pi$$

- [3] Assume kinetic equilibrium, low temperature, SM in thermal photon equilibrium.

$$\Omega_\chi \approx \frac{m s_{today} Y_{today}}{\rho_{critical}} \approx \frac{10^{-26} cm^3/2}{\langle \sigma v \rangle}.$$

- Ω_χ is the fraction of critical density contributed by DM and $Y = n/s$ is density/entropy.
- Today's accepted value $\Omega_\chi h^2 \sim 0.3$.

Loryon Candidates

- Loryons are particles that do not decouple.
- Most of their mass are from Higgs vacuum expectation energy.
- Loryon mass is bounded above by unitarity, lives in finite parameter space.
- Parameter space constraint by Higgs measurement and Cosmic abundance
- Focus on scalar Loryon candidates that preserve custodial symmetry [1]
- Define $[L, R]_Y$ as the representation under custodial symmetry
- $[L, R]_Y$ suppresses colour information

SM Reps	$(1,1)_Y$	$(1,2)_Y$	$(1,3)_Y$	$(1,4)_Y$	$(1,L)_Y$	$(3,1)_Y$	$(3,2)_Y$
Field	S_Y	Φ_{2Y}	Ξ_Y	Θ_{2Y}	$X_{L,Y}$	$\omega_{\lvert 3Y \rvert}$	$\Pi_{\lvert 6Y \rvert}$

Table 1. Enumeration of Loryon candidates and their respective symmetry and field [1]

- For each $[L, R]_Y$ with field Φ and
- $U_{L,R}$ is the chosen representation of $SU(2)_{L,R}$
- Transforms $\Phi \to U_L \Phi U_R^\dagger$
- The explicit mass term of the scalar Loryon is

$$\mathscr{L} \supset -\frac{m_{ex}^2}{2^\rho} tr(\Phi^\dagger \Phi)$$

- The Higgs interaction term contributes $\lambda_{h\Phi} v^2/2$ to the mass

$$\mathscr{L} \supset -\frac{\lambda_{h\Phi}}{2^\rho} tr(\Phi^\dagger \Phi) tr(H^\dagger H)$$

- We are interested in the BSM case with most of the mass from $\lambda_{h\Phi} v^2/2$. [1]
- Loryons as DM candidate constrained by Cosmic Abundance.

Case Study of Singlet Scalar

- Singlet scalar Loryon $(1,1)_Y$ coupled with Higgs through [4]

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_0^2}{2} S^2 - \frac{\lambda_S}{2} S^4 - \lambda S^2 H^\dagger H$$

- The Lagrangian assumes $\mathbb{Z}_2$ symmetry and that S is the only relevant degree of freedom.
- The two parameters m_0, λ_S characterises the massive and self-coupling strength.

$$\sigma v \propto \frac{\lambda^2 m_s^2}{m_h^4}, m_s \ll m_h \quad \text{and} \quad \sigma v \approx \frac{\lambda^2}{4\pi m_s^2}, m_s \gg m_h$$

- Demand perturbative regime $\lambda \sim \frac{m_S}{10\text{TeV}}$ bounds mass $m_S < 10$TeV.

Outlook

- This project has so far recreated result for singlet and doublet, and aims to explore the possibility of triplet candidate and beyond.
- Non-decoupling particles has parameter space confined by both Cosmic Abundance and Higgs decay measurement means improved precision of Higgs coupling precision through HL-LHC can point towards potential discovery of Loryons and DM candidate by interpreting constraints on Higgs Effective Field Theory (HEFT) parameter space. [1] [2]
- We assumed the flavour contribution is minimised, which could be loosen for the possibility of new signatures. [1]

Citation

[1] Ian Banta, Timothy Cohen, Nathaniel Craig, Xiaochuan Lu, and Dave Sutherland. Non-decoupling new particles. *Journal of High Energy Physics*, 2022(2), feb 2022.
[2] Timothy Cohen, Nathaniel Craig, Xiaochuan Lu, and Dave Sutherland. Is SMEFT enough? *Journal of High Energy Physics*, 2021(3), mar 2021.
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[4] C.P. Burgess, Maxim Pospelov, and Tonnis ter Veldhuis. The minimal model of nonbaryonic dark matter: a singlet scalar. *Nuclear Physics B*, 619(1-3):709–728, dec 2001.
[5] Vanda Silveira and A. Zee. Scalar phantoms. *Physics Letters B*, 161(1):136– 140, 1985.

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