Boosted Dark Matter: Relic Density Aspects

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Based On

• **Viability of Boosted Light Dark Matter in a Two-Component Scenario**,
Arindam Basu, Amit Chakraborty, Nilanjana Kumar, Soumya Sadhukhan,
2310.09349 [hep-ph]

• Masters project report on
Cosmic Ray Boosted Dark Matter,
Arindam Basu, Soumya Sadhukhan

Background: non-Standard DM

• Dark Matter: we know it exists, yet to figure out what it is..

• Weakly interacting massive particles (WIMPs) are the most popular dark matter candidates: with TeV scale mass and coupling strength of 'weak interaction' produces exact relic.

• No WIMP at the TeV scale is observed in the collider, direct and indirect DM detectors up to now.

• We look beyond any dark sector at TeV scale:

- **Light Dark Matter**: MeV-GeV scale DM
- Primordial Black Holes (at a higher scale)
- Axions, Sterile neutrinos etc (at an ultralight scale)

• Other non-standard DM scenarios like SIMP, FIMP DM etc among others...

Why Boosted Dark Matter?

• Detection of Dark Matter: DM scatters off a nucleon or an electron and DM is detected through the measurement of nuclear/electron recoil.

• All DM direct detection experiments (e.g. Xenon-nT, LUX-Zeplin) have their own threshold energy: nuclear recoil has to be greater than that to have observed any event.

• Inside the Milky way galaxy halo, DM particles are usually non-relativistic ($v \sim 10^{-3}c$). Therefore any sub-GeV scale DM cannot make a nucleus recoil.

• Proposal: We need a Lorentz boost for our light(-er) DM candidate.

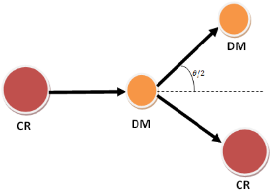
• Boosted Dark Matter case is interesting:

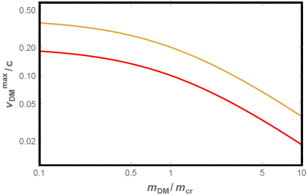
- The light DM can receive sufficient energy for a nuclear recoil when it is boosted.
- In large range of light DM: detection prospect gets better with the boost.

Possible Boost Mechanisms

- Cosmic ray boosted dark matter:

In this scenario cosmic ray and DM exchange their energy through collision: the boosted DM becomes relativistic. R. Laha et al





- Blazar Boosted DM
  D. Sachdeva et al
- Supernovae boosted DM
  R. Srivastava et al
- **Two component boosted DM**
  Agashe et al

Cosmic ray particle velocity $v_{\rm cr} = 0.1c$ (red plot) and $v_{\rm cr} = 0.1c$ (yellow plot) for dark matter χ.

- velocity of the boosted DM:

$$v_\chi = \frac{2m_{\rm cr}v_{\rm cr}}{m_{\rm cr} + m_\chi}$$

Motivation: Two Component Boosted Dark matter

Another boosted DM paradigm: Two component dark matter.

• Similar to the visible sector : Dark sector can in general consists of multiple dark particles.

• Two component dark sector is explored and interesting as a minimal version of extended dark sector.

• One interesting case: Hierarchical two component DM scenario, one dark matter component is heavier and the second dark matter candidate is orders of magnitude lighter.

• One heavy TeV scale WIMP dark matter can annihilate to lighter ($\sim$ MeV scale) DM. The lighter DM component in this case is the boosted DM.

Required: a popular BSM case with similar two-component boosted DM.

Boosted DM: Exact Model Scenario

• A modified neutrinophilic 2HDM (ν2HDM) scenario can have two component DM set up.

- A fermionic DM, a vectorlike fermion χ_1 with mass $\sim$ 100 GeV.
- A light ($\sim$ 10 MeV) DM which is a scalar, ϕ_3.

• ν2HDM has a light scalar mediator, which is a window to light scalar DM physics.

• Presence of a light scalar in ν2HDM puts stringent constraints on oblique corrections, forcing the S to large negative values. vectorlike fermions ease the constraints.

• Vectorlike fermions add positive contributions to S,T parameters: ease the constraints. Godbole et al

• Two DM components also interact among themselves, e.g. heavier one can annihilate to lighter one: provides boosted DM.

ν2HDM Model & Modifications

- Well studied ν2HDM (Machado et al) + Our modifications

Particle Name	$SU(2)_L$ Charges	$U(1)_Y$ Charges	Z_2^{D} Charges
Scalar Fields			
Φ_1	2	1	1
Φ_2	2	1	1
ϕ_3	1	0	-1
Fermionic Fields			
N	2	-1	-1
χ	1	0	-1

- the mass basis of the SM neutrinos are written as,

$$\mathcal{L}_{\mathcal{N_R}} = y_i \bar{L}_i \tilde{\Phi}_2 N_R + \frac{m_{N_R}}{2} N_R N_R .$$

- Low scale seesaw happens Neutrinophilic seesaw. E. Ma et al
- N and χ mix among themselves:

$$L_{VLL} = m_N \bar{N} N + m_\chi \bar{\chi}\chi + y_N \bar{N}\tilde{\Phi}_1 \chi + h.c.$$

Constraints: Boosted DM

• Due to light spectrum known particle widths will be important constraints.

- Light mediator particle (H) and light scalar DM candidate: additional contribution to Higgs width $h \to HH$ and $h \to \phi_3\phi_3$. Total invisible BR $\sim 10\%$: consistent with LHC.
- Invisible Z and W widths are also satisfied.

• Charged scalars decay through $H^\pm \to l^\pm \nu$: LEP limit on charged Higgs given as $m_{H^\pm} \geq 80$ GeV. We take $m_{H^\pm} = m_A = 500$ GeV.

• CP-even H is light, other scalar particles heavy: the oblique parameters (S, T, U) will constrain the parameter space.

- the S parameter is highly sensitive to the new physics effects at scales lower than M_Z.
- while T controls the breaking of the custodial symmetry.

Boltzmann Equation Formalism

• Single Component Boltzmann Equation:

$$\frac{dn_{\phi_3}}{dt} + 3Hn_{\phi_3} = -\langle\sigma_{\phi_3} v\rangle(n^2_{\phi_3} - n^2_{\phi_3,\mathrm{eq}})$$

Here $\sigma_{\phi_3}, \sigma_{\chi_1}$ is the annihilation cross section of the scalar dark matter candidate, when ϕ_3 annihilates to the visible sector

• Coupled Boltzmann Equation: (For multi-component DM)

$$\frac{dn_{\chi_1}}{dt} + 3Hn_{\chi_1} = -\frac{1}{2}\langle\sigma_{\chi_1\phi_3} v\rangle(n^2_{\chi_1} - n^2_{\phi_3}\frac{n^2_{\chi_1,\mathrm{eq}}}{n^2_{\phi_3,\mathrm{eq}}}) - \frac{1}{2}\langle\sigma_{\chi_1} v\rangle(n^2_{\chi_1} - n^2_{\chi_1,\mathrm{eq}})$$

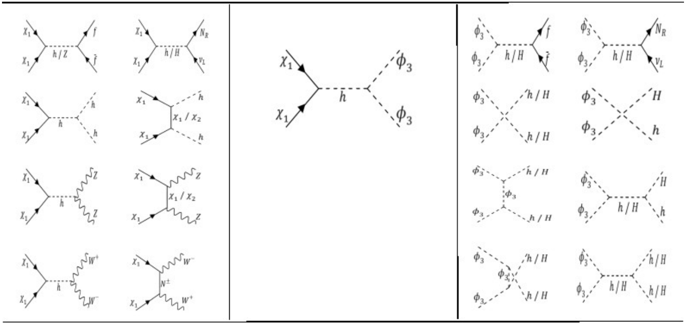
$$\frac{dn_{\phi_3}}{dt} + 3Hn_{\phi_3} = -\langle\sigma_{\phi_3} v\rangle(n^2_{\phi_3} - n^2_{\phi_3,\mathrm{eq}}) - \langle\sigma_{\phi_3\chi_1} v\rangle(n^2_{\phi_3} - n^2_{\chi_1}\frac{n^2_{\phi_3,\mathrm{eq}}}{n^2_{\chi_1,\mathrm{eq}}})$$

$n_{\chi_1,\mathrm{eq}}, n_{\phi_3,\mathrm{eq}}$ are equilibrium density of χ_1 and ϕ_3 respectively.

• solution of these equation: Thermal evolution of DM number density (translated to Yield).

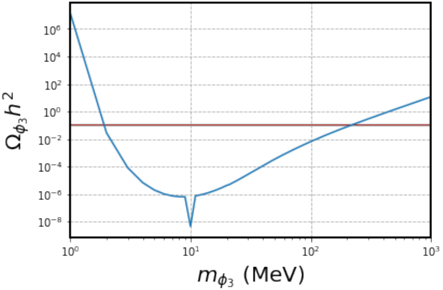
DM Annihilation Channels

- Different DM annihilation Feynman diagrams:



Thermal averaged annihilation cross section computed: $\langle \sigma_{\chi_1} v \rangle$ (left column), $\langle \sigma_{\chi_1 \phi_3} v \rangle$ (middle column) and $\langle \sigma_{\phi_3} v \rangle$ (right column)

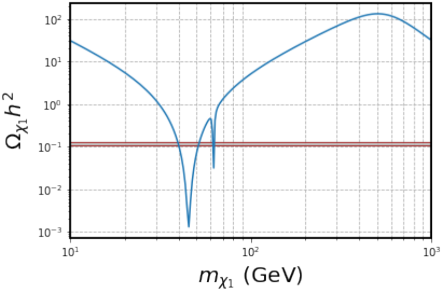
Single Component DM: Scalar



- Freeze-out phenomenon happens around $x \sim 10-30$, with the largest x obtained for the lightest scalar dark matter mass.

- Allowed region spans scalar DM mass of 5 MeV to less than 200 MeVs.
- The scalar dark matter for most of the allowed parameter space is severely underabundant: requirement of another DM candidate.

Single Component DM: Fermion

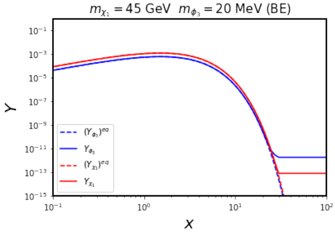


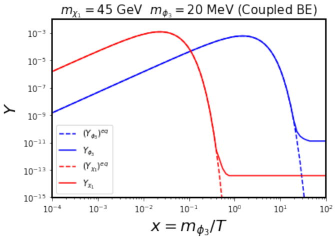
- The Z mediated resonant region around $m_{\chi_1} \sim 45$ GeV provides large DM annihilation, with under-abundant relic.
- The Higgs resonant annihilation is not that significant as the $h\chi_1\chi_1$ coupling is constrained to be small.

- Freeze-out phenomenon happens around $x \sim 20 - 30$, with the largest x obtained for the fermion DM mass in the Z-resonance region.

Multi-component DM: Scenario-I

- This is the case with $m_{\chi_1} = 45$ GeV and $m_{\phi_3} = 20$ MeV.

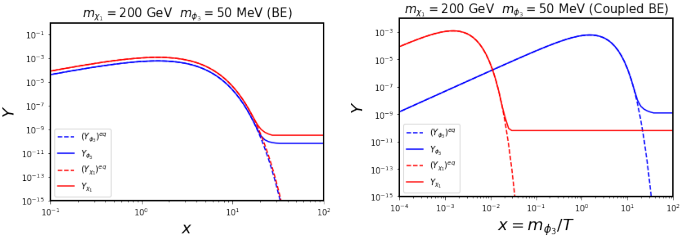




- The fermionic yield is smaller (but the relic density is somewhat larger) when we treat them individually.
- When they are coupled, gap in their yields widens which translates to both the components contributing almost equally to the total relic.

Multi-component DM: Scenario-II

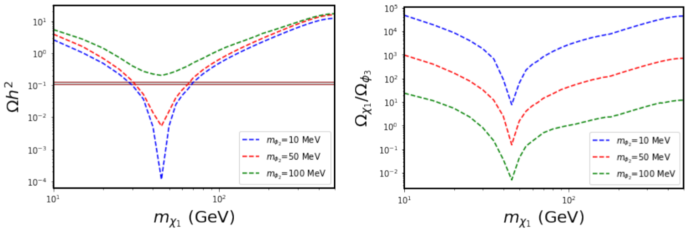
- This is the case with $m_{\chi_1} = 200$ GeV and $m_{\phi_3} = 50$ MeV.



- In the individual case here fermionic DM yield is larger than the scalar one, indicating that the fermionic contribution dominates the total relic.
- The nature of the yield flips in this case when the DM components are coupled: even then the fermionic DM relic is larger compared to the scalar one.

Combined DM scenario

• The allowed fermionic DM mass region widens compared to individual vectorlike DM: 40-50 GeV vs 30-70 GeV now.

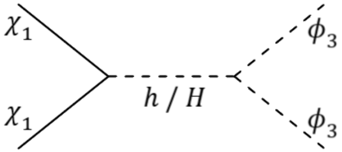


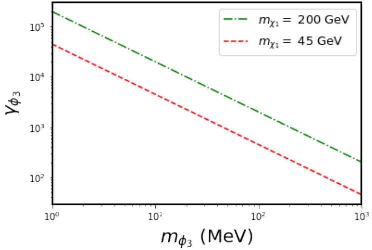
• Exact relic can be arranged when the scalar DM mass is slightly below 100 MeV, ruling out a scalar DM above that mass.
• Scalar DM gets more constrained as the factor $s = 4m_{\phi_3}^2$ modifies to $s \approx 8m_{\phi_3}^2$, diluting the resonant enhancement in the $(s - 4m_i^2)$ factors inside the DM annihilation cross section.

Amount of Boost

• The scalar DM achieves boost via the annihilation process $\chi_1\chi_1 \to \phi_3\phi_3$.
• Relativistic kinematic computation gives the boosted velocity of the scalar DM:

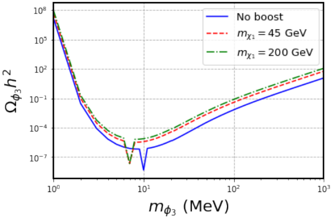
$$v_{\phi_3}^2 = 1 - \frac{m_{\phi_3}^2}{m_{\chi_1}^2}\left(1 - v_{\chi_1}^2\right) \quad \text{and the boost} \quad \gamma_{\phi_3} \sim \frac{m_{\chi_1}}{m_{\phi_3}}$$

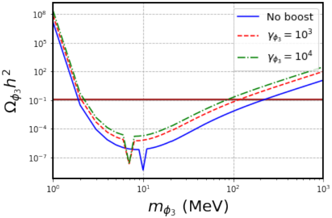




Boost Effects: Scalar DM

- Model dependent boost vs a general boost:





- In both the cases the overall nature of modification in boosted scalar DM phenomenology is similar with minor differences.
- Relic density behaviour of the boosted dark matter is independent of the mechanism through which the light DM is given boost.

DM Detection Possibility

• The vectorlike fermion DM is at masses around ~ 100 GeV, which even being non relativistic can scatter off a nucleus to have a significant recoil.

• For the light DM detection $\phi_3 N \to \phi_3 N$ or $\phi_3\ e \to \phi_3\ e$ scatterings can happen: result is a possible nuclear or electron recoil.

• For the boosted scalar DM the kinematics of these scattering will have relativistic boost factors, that will potentially result in high recoil energies.

• Boosted DM particles detection can happen at large volume terrestrial experiments that are designed for detecting neutrinos and/or proton decay, such as Super-K, Hyper-K, IceCube, PINGU, MICA, KM3NeT and ANTARES etc.

• In the lower mass region, the strong limit comes from the electron scattering experiments such as DarkSide, PICO-60, CRESST and a series of other DM detectors.

Conclusion

• Two component boosted DM scenario is one interesting case where multi component dark sector can be utilized to achieve something novel: a DM which is boosted.

• A neutrinophilic 2HDM has phenomenological aspects that make hierarchical two component scenario very natural in that model, which leads to a boosted DM.

• For the heavier DM component the relic density decreases due to extra annihilation channel, while for the boosted component the resonant annihilation becomes somewhat inefficient, producing a larger relic.

• In the combined fermion-scalar DM scenario, the boosted scalar component can form significant portion of the total DM relic, which makes the perfect case to look for its detection.

Thank You