Light Dirac neutrino portal dark matter with gauged $U(1)_{B-L}$ symmetry

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Collaborator - Dr. Debasish Borah

Nayan Das

Department of Physics
Indian Institute of Technology Guwahati

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Introduction and Motivation

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Motivation

- Search for beyond Standard model (BSM) particles is one of the main objective in particle physics.
- BSM particles can have weak coupling, difficult to detect them in terrestrial experiments.
- Precision cosmology, with various current and upcoming cosmological experiments, provide excellent opportunity to study BSM physics.
- BSM particles in early universe can leave their signatures.
- These signatures can be detected via cosmological experiments like Cosmic Microwave Background experiments.
- Dark matter (DM) can be weakly (WIMP) interacting or Feebly interacting (FIMP).
- Nature of neutrino : Dirac or Majorana.

Motivation

- If Dirac, CMB experiment can help in detection prospect due to light nature.
- Define -

$$\rho_r = \rho_\gamma + \rho_{\nu_L} + \rho_{\rm BSM} = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right)\rho_\gamma . \quad (1)$$

- $N_{eff} \implies$ effective number of relativistic species.
- Incorporate all possible light BSM particles.
- $N_{eff} = N_{eff}^{SM} + \Delta N_{eff}$.
- For the Standard Model, $N_{eff} = N_{eff}^{SM} = 3.045$ [1606.06986].
- Current CMB bound (2σ) from Planck 2018 data,
  $N_{eff} = 2.99^{+0.34}_{-0.33} \implies \Delta N_{eff} = 0.284$ [1807.06209].
- Future expected CMB bound (2σ) from CMB-S4, $\Delta N_{eff} = 0.06$ [1907.04473].

The Model

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The Model

- Here origin of DM is related to Dirac nature of neutrino.
- Dirac neutrino takes the role of mediating interactions with DM and SM bath.
- To realise, we consider a UV complete gauged B-L model.
- SM is extended by - ϕ_1, ϕ_2, ψ and ν_R with B-L charges 1, 3, 0, -1.

The Model

Scalar part

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger D_\mu \Phi + (D^\mu \phi_1)^\dagger D_\mu \phi_1 + (D^\mu \phi_2)^\dagger D_\mu \phi_2 - V(\Phi, \phi_1, \phi_2), \quad (2)$$

$$D_\mu \Phi = \left(\partial_\mu - i\frac{g}{2}\tau_a W_\mu^a - i\frac{g'}{2}B_\mu\right)\Phi\,; \qquad D_\mu \phi_1 = \left(\partial_\mu - i g_{BL} B'_\mu\right)\phi_1; \qquad D_\mu \phi_2 = \left(\partial_\mu - i3 g_{BL} B'_\mu\right)\phi_2,$$

$$\begin{aligned} V(\Phi, \phi_1, \phi_2) &= -\mu^2(\Phi^\dagger \Phi) + \mu_1^2(\phi_1^\dagger \phi_1) - \mu_2^2(\phi_2^\dagger \phi_2) \\ &+ \lambda(\Phi^\dagger \Phi)^2 + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 \\ &+ \lambda_{H\phi_1}(\Phi^\dagger \Phi)(\phi_1^\dagger \phi_1) + \lambda_{H\phi_2}(\Phi^\dagger \Phi)(\phi_2^\dagger \phi_2) + \lambda_{\phi_1\phi_2}(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2). \end{aligned} \quad (3)$$

Yukawa part

$$-\mathcal{L}_Y \supset Y_\nu \bar{L}\tilde{\Phi}\nu_R + y_{\phi_1}\overline{\psi}\phi_1\nu_R + m_\psi \overline{\psi}\psi \quad (4)$$

The Model

- ϕ_2 accuires vev and give mass to B-L gauge boson.
- ϕ_1 does not get vev, remain heavier than ψ making ψ stable.
- ψ is a fermionic dark matter.
- ϕ_1, ψ and ν_R interact through yukawa coupling y_{ϕ_1}.
- Relevant parameters are Relevant parameters - $m_{\phi_1}, m_{Z'}, m_{\psi}, \lambda_{H\phi_1}, g_{BL}, y_{\phi_1}$.
- Depending on y_{ϕ_1}, we can have both FIMP or WIMP type DM.

FIMP type DM

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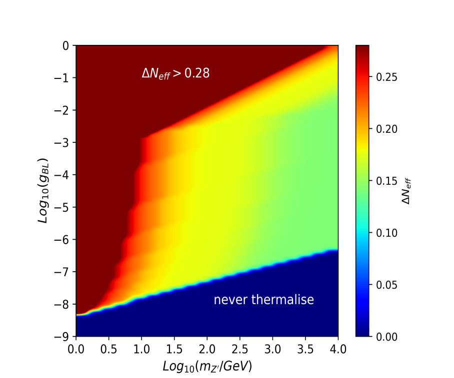
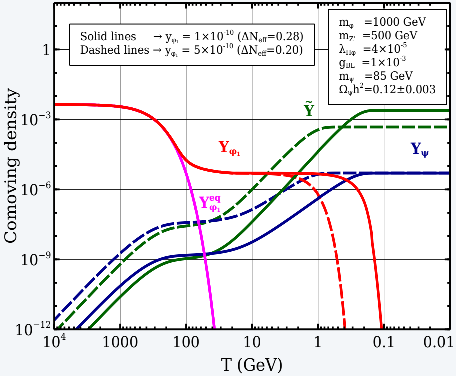
FIMP type DM

- Due to small yukawa, DM and ν_R are produced non-thermally.
- Thermal ν_R is also possible via $f\bar{f} \leftrightarrow \nu_R \bar{\nu}_R$ (resonant) via Z' gauge boson.
- $\Delta N_{\rm eff} = \Delta N_{\rm eff}^{\rm th} + \Delta N_{\rm eff}^{\rm non-th}$.
- $\Delta N_{\rm eff}^{\rm th} = \frac{7}{8} \times 2 \times 0.027 \left(\frac{106.75}{g_*(T_{\rm dec})}\right)^{4/3}$.



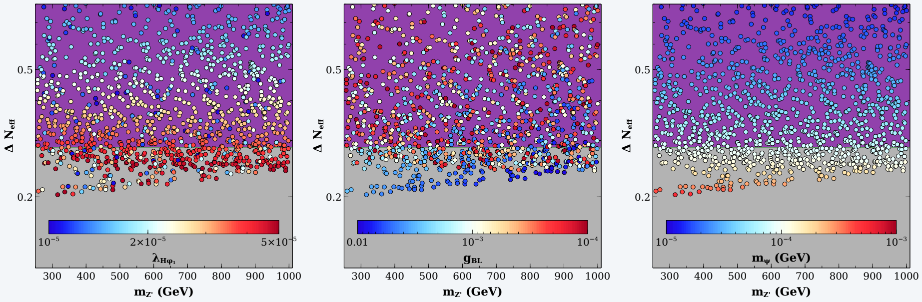
FIMP type DM

- Non - thermal production : ϕ_1 decays to DM, ψ and ν_R.
- Solve Boltzmann equation for $Y_{\phi_1} = \frac{n_{\phi_1}}{s}$, $Y_\psi = \frac{n_\psi}{s}$ and $Y_{\nu_R} = \frac{\rho_{\nu_R}}{s^{4/3}}$.
- ϕ_1 freeze-out is determined by : $\lambda_{H\phi_1}$ and g_{BL}.
- Decay width : y_{ϕ_1}.



FIMP type DM

- $$250\,\text{GeV} < m_{Z'} < 1000\,\text{GeV}, \qquad 10^{-5} < \lambda_{H\phi_1} < 5\times10^{-5},$$
  $$10^{-4} < g_{BL} < 10^{-2}, \qquad 10\,\text{keV} < m_\psi < 1000\,\text{keV}.$$

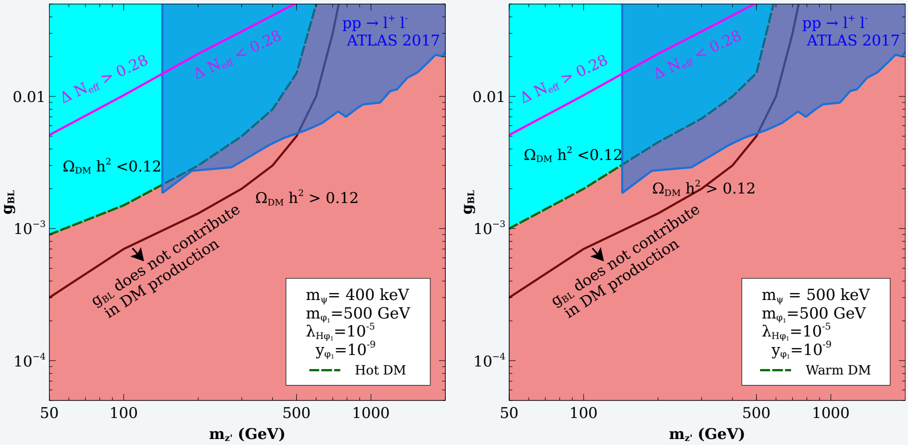


FIMP type DM : Structure formation

- Ability to form structure $\implies$ Depend on FSL of DM.
- FSL $\implies$ Distribution function $\implies$ Production mechanism.
- Cold Dark Matter (CDM) $\iff$ $\lambda_{\text{FSL}} < 0.01\text{Mpc}$.
- Warm Dark Matter (WDM) $\iff$ $0.01\text{Mpc} < \lambda_{\text{FSL}} < 0.1\text{Mpc}$.
- Hot Dark Matter (HDM) $\iff$ $\lambda_{\text{FSL}} > 0.1\text{Mpc}$. [1112.0330]
- $\lambda_{\text{fs}} = \int_{T_{\text{prod}}}^{T_{\text{eq}}} \frac{\langle v(T)\rangle}{a(T)} \frac{dt}{dT} dT, \qquad \langle v(T)\rangle = \frac{\int \frac{p_1}{E_1} \frac{d^3p_1}{(2\pi)^3} f_\psi(p_1, T)}{\int \frac{d^3p_1}{(2\pi)^3} f_\psi(p_1, T)}.$

	Parameters						$\Omega_{\text{DM}}\text{h}^2$	ΔN_{eff}	FSL(Mpc)
	m_{ϕ_1}(GeV)	$\lambda_{H\phi_1}$	y_{ϕ_1}	$m_{Z'}$(GeV)	g_{BL}	m_ψ(keV)			
BP I	1000	5×10^{-5}	10^{-10}	500	0.001	126	0.12	0.251	3.09
BP II	500	5×10^{-5}	10^{-10}	500	0.001	233	0.12	0.210	1.32
BP III	1000	2×10^{-4}	10^{-9}	500	0.001	970	0.12	0.184	0.06
BP IV	500	2×10^{-4}	10^{-9}	500	0.001	938	0.12	0.184	0.05

FIMP type DM : Summary plots



WIMP type DM

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WIMP type DM

- Here interaction between ϕ_1, ψ and ν_R is large (large y_{ϕ_1}).
- Form a dark sector (DS) among themselves.
- DS interact with SM via $\phi_1 X \to \phi_1 X$, $\phi_1 Z' \to \phi_1 Z'$ and $\nu_R X \to \nu_R X$.
- $T_{\rm dec}$ can be found -

$$\frac{\Gamma_{\rm total}}{\mathcal{H}} = \frac{1}{\mathcal{H}}\left[n_X^{\rm eq}\left(\langle\sigma v\rangle_{\phi_1 X\to\phi_1 X} + \langle\sigma v\rangle_{\phi_1 Z'\to\phi_1 Z'}\right) + n_{\nu_R}^{\rm eq}\langle\sigma v\rangle_{\nu_R\bar{\nu}_R\to X\bar{X}}\right]. \tag{5}$$

WIMP type DM

- After decoupling, DS evolves and have separate temperature.
- Define $\xi = \frac{T_{\rm DS}}{T}$.

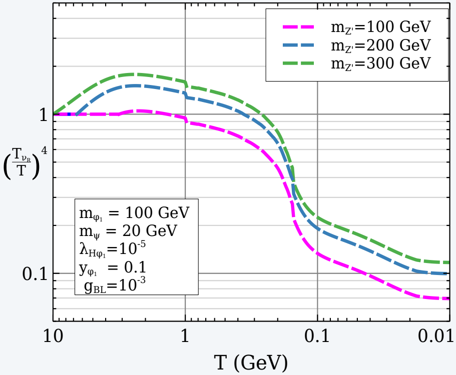
$$\frac{dY}{dx} = \frac{1}{2}\frac{\beta s}{Hx}\langle\sigma v\rangle_{\rm eff}\left((Y^{\rm eq})^2 - Y^2\right) \tag{6}$$

$$\frac{d\xi}{dx} = \frac{1}{x}\left(-\frac{1}{2}\frac{\beta x^4 s^2}{4\alpha\xi^3 H m_{\phi_1}^4}\langle E\sigma v\rangle_{eff}\left((Y^{\rm eq})^2 - Y^2\right) - (\beta-1)\xi\right).$$

$$Y = Y_{\phi_1} + Y_{\psi}.$$

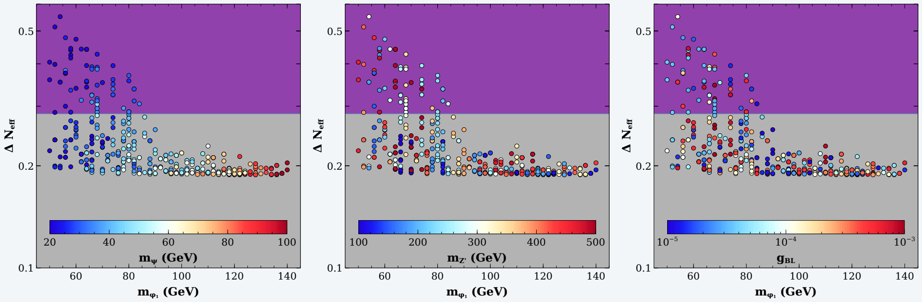
WIMP type DM

- We find increase in T_{DS} compared to T.
- Reason : annihilation of heavier DS particles to lighter DS particles.
- Gives strong constraint from ΔN_{eff}.

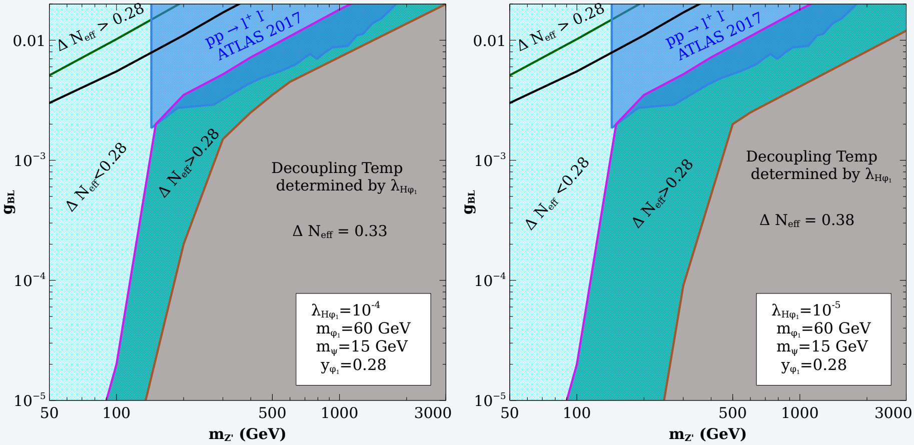


WIMP type DM

- $50\text{GeV} < m_{\phi_1} < 150\text{GeV}$, $100\text{GeV} < m_{Z'} < 500\text{GeV}$, $10\text{GeV} < m_\psi < 100\text{GeV}$
  $10^{-5} < \lambda_{H\phi_1} < 10^{-2}$, $10^{-5} < g_{BL} < 10^{-3}$, $0.2 < y_{\phi_1} < 0.3$.



WIMP type DM : Summary plots

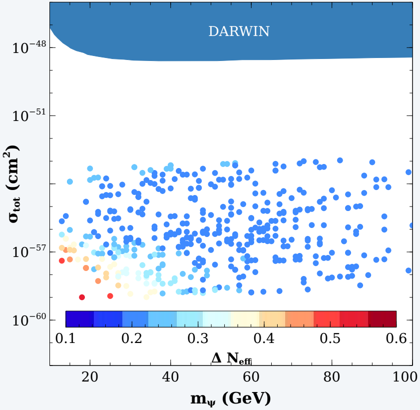


WIMP type DM : Direct Detection

- No tree level diagram.
- One loop - Higgs mediated and Z' mediated.
- Total DM-nucleon cross-section

$$\sigma_{\rm tot} = \frac{1}{\pi}\frac{m_N^2 m_\psi^2}{(m_N+m_\psi)^2}\left[\frac{m_N}{v}\frac{1}{m_h^2} g_{\psi\bar{\psi}h} f_N + \frac{g_{BL}}{3}\frac{1}{m_{Z'}^2} g_{\psi\bar{\psi}Z'} f_{Z'}\right]^2.$$

- Out of reach from future DD experiment. [1606.07001]



Conclusion

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Conclusion

- We study a possible UV completion of light DNPDM.
- Due to gauge $B - L$ interaction, detectable contribution to $\Delta N_{\rm eff}$.
- We study both thermal and non-thermal production of DM.
- We find that cosmological constraint (from structure formation and CMB) put stringent bound to the parameter space of the model: stronger than direct detection bound.

Thank you for your attention

Nayan Das

Department of Physics
Indian Institute of Technology Guwahati

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