Braneworld Cosmological Effect on Freeze-In Dark Matter Density and Lifetime Frontier

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Freeze-in DM

- DM possibly never in thermal equilibrium with SM particle plasma.
- Instead, DM relic density determined by "Freeze-in" mechanism [1].
- Thermal DM case: $Y = Y_{eq}$ for $x \ll 1,\ x = m/T$

$$\frac{dY}{dx} = -\frac{s(T=m)}{H(T=m)}\frac{\langle \sigma v_{rel} \rangle}{x^2}(Y^2 - Y_{EQ}^2)$$

- Freeze-in case: $Y(x_{RH}) = 0$ leads to

$$\frac{dY}{dx} \simeq \frac{s(m)}{H(m)}\frac{\langle \sigma v_{rel} \rangle}{x^2} Y_{EQ}^2 \simeq 0.698 \frac{g_{DM}^2}{g_*^{3/2}} m M_P \frac{\langle \sigma v_{rel} \rangle}{x^2}$$

- In both cases, DM density determined as

$$\Omega_{DM} h^2 = \frac{m Y(\infty) s_0}{\rho_c / h^2}$$

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[1] Hall et al., 2010

Freeze-in DM

- Given $\langle \sigma v_{rel} \rangle$ as a function of x, Boltzmann equation can be integrated up to $x = 1$ (kinematic boundary)
- Example: light vector-boson mediator

$$\langle \sigma v_{rel} \rangle = \frac{g_V^4}{128\pi} \frac{x^2}{m^2}$$

leads to DM density of

$$\Omega_{DM} h^2 = \frac{mY(x=\infty)s_0}{\rho_c/h^2} \backsimeq \frac{mY(x=1)s_0}{\rho_c/h^2} \backsimeq 1.16 \times 10^{24} \frac{g_{DM}^2}{g_*^{3/2}} g_V^4$$

- Observed DM density of $\Omega_{DM} h^2 \backsimeq 0.12$ [2] reproduced by $g_V = 2.31 \times 10^{-6}$

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[2] Planck Collaboration, 2018

Braneworld Cosmologies

- **Modified Friedmann Equation**
  - For $T/T_t < 1$, standard Big Bang cosmology is reproduced.
  - For $T/T_t > 1$, the universe evolves differently. Parametrize modified Friedmann equation as

$$H = H_{st}(T) \times F(T)$$

  - We assume the following form for $F(T)$ for $T/T_t > 1$

$$\boxed{F(T/T_t) = \left(\frac{T}{T_t}\right)^{\gamma} = \left(\frac{x_t}{x}\right)^{\gamma}}$$

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Braneworld Cosmologies

- Apply adjusted Hubble parameters to Boltzmann equation. The effective change is

$$\langle \sigma v_{rel} \rangle \to \left(\frac{\langle \sigma v_{rel} \rangle}{F(x_t/x)} \right) = \langle \sigma v_{rel} \rangle \left(\frac{x_t}{x} \right)^{-\gamma}$$

  - DM relic abundance enhanced (reduced) for $\gamma < 0 \, (\gamma > 0)$
- For vector boson mediated process:

$$\Omega_{DM} h^2 = \frac{mY(x=\infty)s_0}{\rho_c/h^2} \backsimeq \frac{mY(x=1)s_0}{\rho_c/h^2} \backsimeq 1.16 \times 10^{24} \frac{g_{DM}^2}{g_*^{3/2}} g_V^4 \times \boxed{\frac{x_t^{-\gamma}}{\gamma+1}}$$

$$\boxed{\Omega_{DM} h^2 = 0.12 \Rightarrow g_V \to g_V \times \left(\frac{x_t^{-\gamma}}{\gamma+1} \right)^{-\frac{1}{4}}}$$

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Braneworld Cosmologies

- **Randall-Sundrum (RS) II Model**
  - Friedmann equation for a spatially flat universe [2] yields:

$$H^2 = \frac{\rho}{3M_P^2}\left(1 + \frac{\rho}{\rho_{RS}}\right) \Rightarrow H \backsimeq H_{st}\sqrt{\frac{\rho}{\rho_{RS}}} = \boxed{H_{st} \times \left(\frac{x_t}{x}\right)^2}$$

- **Gauss Bonnet (GB) Model**
  - Found by adding higher curvature terms to RS action [3].
  - Phenomenological requirements fix free parameters.
  - Friedmann equation in highest temperature epoch becomes:

$$H \backsimeq \left(\frac{1+\beta}{4\beta}\frac{\mu}{M_P^2}\rho\right)^{\frac{1}{3}} \backsimeq H_{st} \times \left(\frac{\rho}{\rho_{GB}}\right)^{-\frac{1}{6}} = \boxed{H_{st} \times \left(\frac{x_t}{x}\right)^{-\frac{2}{3}}}$$

[3] Binetruy, Deffayet, & Langlois, 2000
[4] Kim et al., 2000

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Application to Z' portal DM with RHN

- Minimal B-L SM Extension with RHN as a DM candidate [5]
  - RHN DM communicates with SM via Higgs-mediated (Higgs-portal) or Z' mediated (Z'-portal) processes.
  - DM experiments and LHC have narrowed parameter space for Z' mediated RHN freeze-in DM [6].

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	Z_2
q_L^i	**3**	**2**	$1/6$	$1/3$	$+$
u_R^i	**3**	**1**	$2/3$	$1/3$	$+$
d_R^i	**3**	**1**	$-1/3$	$1/3$	$+$
l_L^i	**1**	**2**	$-1/2$	-1	$+$
N_R^j	**1**	**1**	0	-1	$+$
N_R	**1**	**1**	0	-1	$-$
e_R^i	**1**	**1**	-1	-1	$+$
H	**1**	**2**	$-1/2$	0	$+$
Φ	**1**	**1**	0	2	$+$

[5] Okada et al., 2010
[6] Kaneta et. al., 2018

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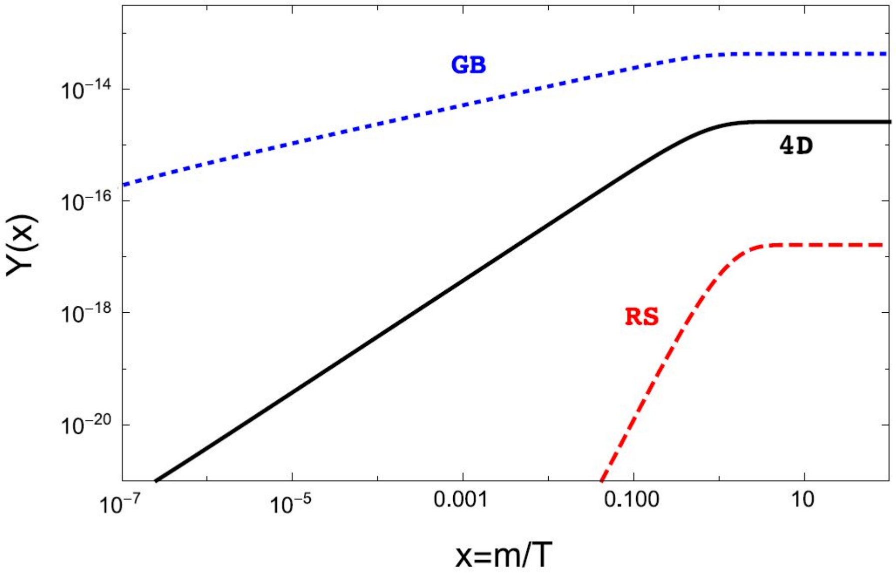
Application to Z’ portal DM with RHN

- Process: $f\overline{f} \to Z' \to NN$
- Numerically solved Boltzmann equations
  - GB Yield enhanced
  - RS Yield reduced
- Densities become:
  - GB: $\Omega_{DM}h^2 = 0.12$
  - 4D: $\Omega_{DM}h^2 = 7.2 \times 10^{-3}$
  - RS: $\Omega_{DM}h^2 = 4.5 \times 10^{-5}$

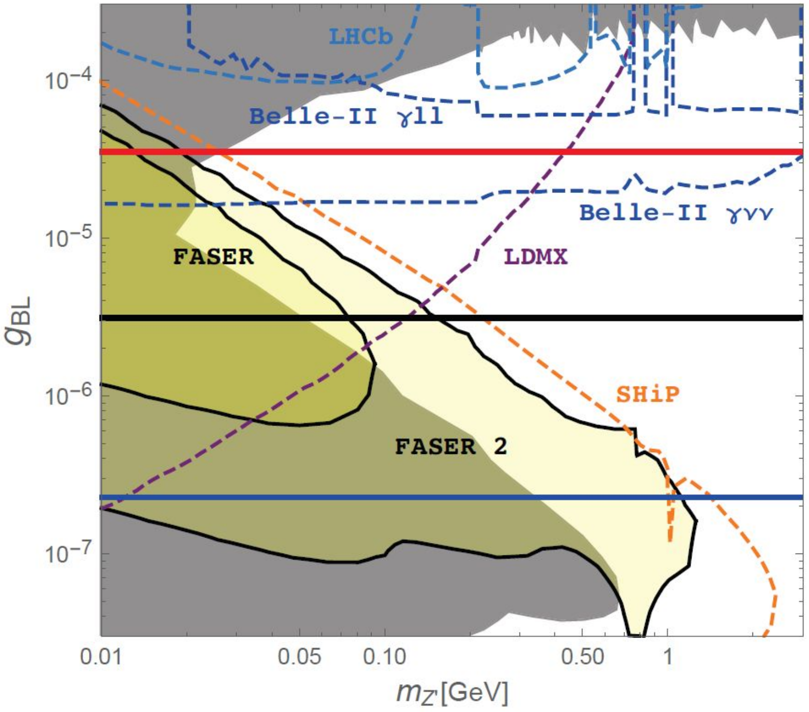


$m = 10$ TeV, $T_t = 1$ TeV, $m_{Z'} = 1$ GeV, $g_{BL} = 1.54 \times 10^{-6}$

V.B., Okada, & Okada arXiv: 1911.05344 [hep-ph]

Lifetime Frontier Experiments

- Reproducing $\Omega_{DM}h^2 \simeq 0.12$ requires different values of g_{BL} for the RS, GB, and standard cosmologies.
- Small $g_{BL} \Rightarrow$ long-lived Z’
- ForwArd Search ExpeRiment (FASER) for LHC Run-3 and FASER 2 at HL-LHC could search for such a Z’.



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Excluded regions taken from [7] Bauer et al., 2018

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Summary

- Considered “Freeze-In” DM in the context of 5D Braneworld cosmology.
- Friedmann equation modified in early universe, in turn modifying DM relic density for nonstandard cosmologies.
- For Z’-portal RHN DM in minimal B-L SM extension, braneworld effect affects value of coupling. Results from Lifetime Frontier Experiments directly inform possibilities for BSM physics and accurate cosmological description of the universe.

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