Roads to right-handed neutrino Dark Matter

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Based on

G.A., S. Profumo, F. S. Queiroz and C. Siqueira JCAP 12 (2020) 030

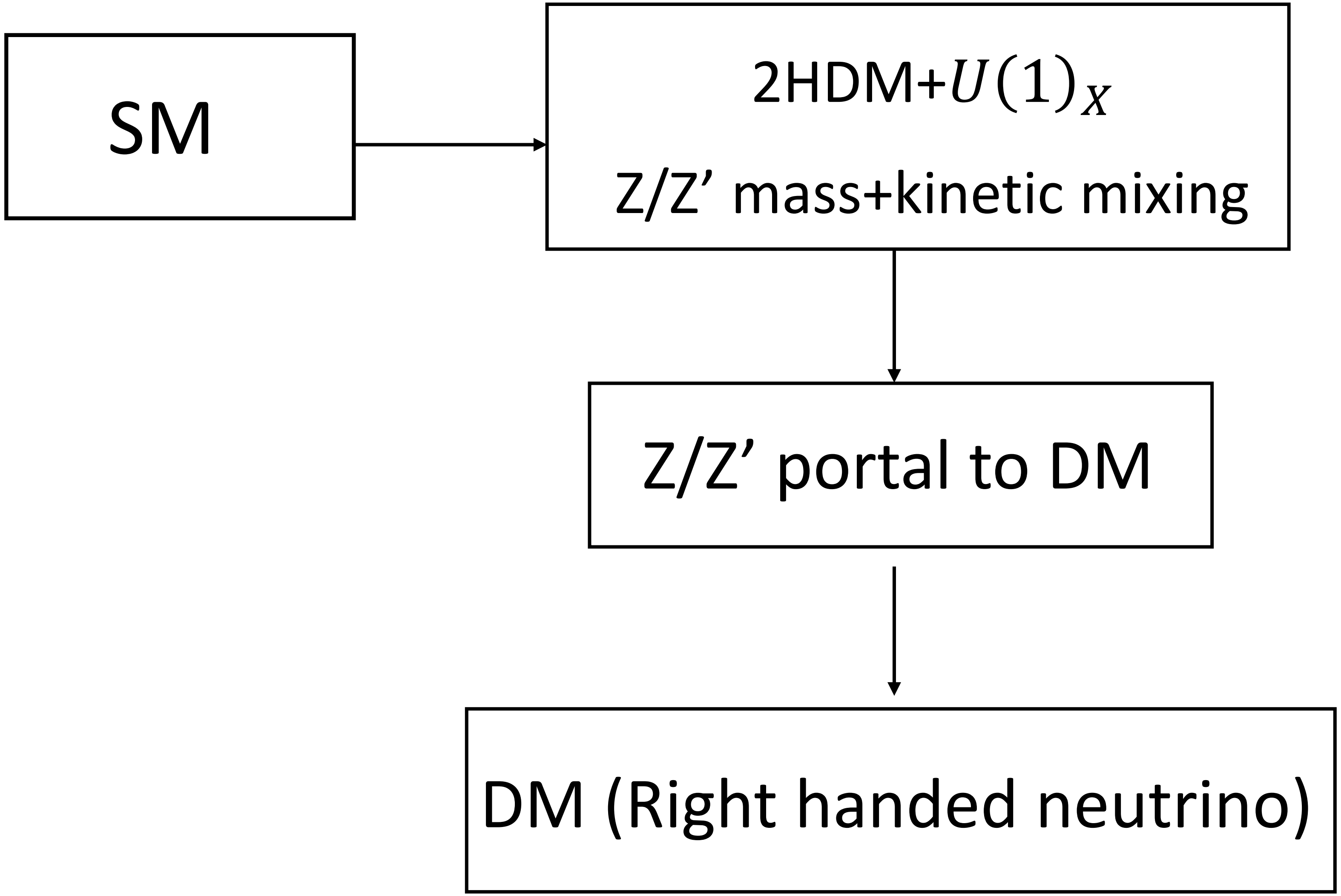
G.A., J. P. Neto, F. S. Queiroz and C. Siqueira PRD 105 (2022) 035016

Motivation

Propose an extension of the 2HDM:

- Accommodates the a viable DM candidate
- Accommodates generation of neutrino masses
- Automatically addresses the flavor problem

The Model


SM
2HDM+$U(1)_X$
Z/Z' mass+kinetic mixing
Z/Z' portal to DM
DM (Right handed neutrino)

$$-\mathcal{L}_{Y_1} = y^d_{ab}\bar{Q}_a\Phi_2 d_{bR} + y^u_{ab}\bar{Q}_a\widetilde{\Phi}_2 u_{bR} + y^e_{ab}\bar{L}_a\Phi_2 e_{bR} + h.c.$$

$$-\mathcal{L}_{Y_2} \supset y_{ab}\bar{L}_a\widetilde{\Phi}_2 N_{bR} + y^M_{ab}\overline{(N_{aR})^c}\Phi_s N_{bR} + h.c.$$

The lightest neutrino N_{1R} is odd under a Z_2 simmetry and hence the DM candidate.

$$(\nu\, N)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$

$$m_D = \frac{y v_2}{2\sqrt{2}} \qquad M_R = \frac{y^M v_s}{2\sqrt{2}}$$

The other two neutrinos generate light neutrino masses via See-Saw

$$\mathcal{L} = (D^\mu \phi_1)^\dagger (D_\mu \phi_1) + (D^\mu \phi_2)^\dagger (D_\mu \phi_2) + (D^\mu \phi_s)^\dagger (D_\mu \phi_s) =$$
$$+ \frac{1}{4} g^2 v^2 W^{-\,\mu} W^+_\mu + \frac{1}{8} g_Z^2 v^2 Z^{0\,\mu} Z^0_\mu - \frac{1}{4} g_Z (G_{X_1} v_1^2 + G_{X_2} v_2^2) Z^{0\,\mu} X_\mu$$
$$+ \frac{1}{8} (v_1^2 G_{X_1}^2 + v_2^2 G_{X_2}^2 v_2^2 + v_s^2 Q_{X_s}^2 g_X^2) X^\mu X_\mu$$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \rho_i + i\eta_i)/\sqrt{2} \end{pmatrix} \qquad \Phi_s = \frac{1}{\sqrt{2}} (v_s + \rho_s + i\eta_s)$$

$$\mathcal{L}_{\rm NC} = - e J^\mu_{\rm em} A_\mu - \frac{g}{2\cos\theta_W} \cos\xi J^\mu_{NC} Z_\mu - \sin\xi \left(\epsilon e J^\mu_{em} + \epsilon_Z \frac{g}{2\cos\theta_W} J^\mu_{NC} \right) Z'_\mu +$$
$$+ \frac{1}{4} g_X \sin\xi \left[\left(Q^R_{Xf} + Q^L_{Xf}\right) \bar{\psi}_f \gamma^\mu \psi_f + \left(Q^R_{Xf} - Q^L_{Xf}\right) \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f \right] Z_\mu +$$
$$- \frac{1}{4} g_X \cos\xi \left[\left(Q^R_{Xf} + Q^L_{Xf}\right) \bar{\psi}_f \gamma^\mu \psi_f - \left(Q^L_{Xf} - Q^R_{Xf}\right) \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f \right] Z'_\mu +$$
$$- \frac{1}{4} Q_{N_1} g_X \cos\xi \cos\xi N_1 \gamma^\mu \gamma_5 N_1 Z'_\mu + \frac{1}{4} Q_{N_1} g_X \sin\xi N_1 \gamma^\mu \gamma_5 N_1 Z_\mu,$$

Constraints

DM Direct Detection

$$\bar{N}_1\gamma^\mu\gamma_5 N_1\bar{q}\gamma_\mu q \rightarrow 2v_N^\perp\cdot\vec{S}_N + 2i\vec{S}_N\cdot\left(\vec{S}_n\times\frac{\vec{q}}{m_N}\right)$$

No dependence on nucleon spin. Coherent enhanchement at the nuclear level.

$$\bar{N}_1\gamma^\mu\gamma_5 N_1\bar{q}\gamma_\mu\gamma_5 q$$

Conventional SD Interaction (induced by Z/Z' mixing)

$$\sigma^{\rm SD}_{\rm N_1p}=\frac{\mu^2_{N_1p}}{4\pi}\left|\left(\frac{g^A_{Zu}g_{ZN_1}}{m_Z^2}+\frac{g^A_{Z'u}g_{Z'N_1}}{m_{Z'}^2}\right)\Delta^p_u+\left(\frac{g^A_{Zd}g_{ZN_1}}{m_Z^2}+\frac{g^A_{Z'd}g_{Z'N_1}}{m_{Z'}^2}\right)(\Delta^p_d+\Delta^p_s)\right|^2$$

Atomic Parity violation

$$\mathcal{L}_{\rm APV}=\left(\frac{g^A_{Ze}g^V_{Zu}}{m_Z^2}+\frac{g^A_{Z'e}g^V_{Z'u}}{m_{Z'}^2}\right)\bar{e}\gamma^\mu\gamma_5 e\bar{u}\gamma_\mu u+\left(\frac{g^A_{Ze}g^V_{Zd}}{m_Z^2}+\frac{g^A_{Z'e}g^V_{Z'd}}{m_{Z'}^2}\right)\bar{e}\gamma^\mu\gamma_5 e\bar{d}\gamma_\mu d$$

$\longrightarrow$ $$\Delta Q_W=-59.84\delta^2-220\delta\sin\theta_W\cos\theta_W\epsilon\frac{m_Z}{m_{Z'}}-133\delta^2\tan\beta^2$$

$$|\Delta Q_W|<0.6$$

Limits from searches of $H^{\pm}$ and $b\rightarrow s\gamma$.

Can be converted into limits on the mass of the Z'.

LHC searches of Z'

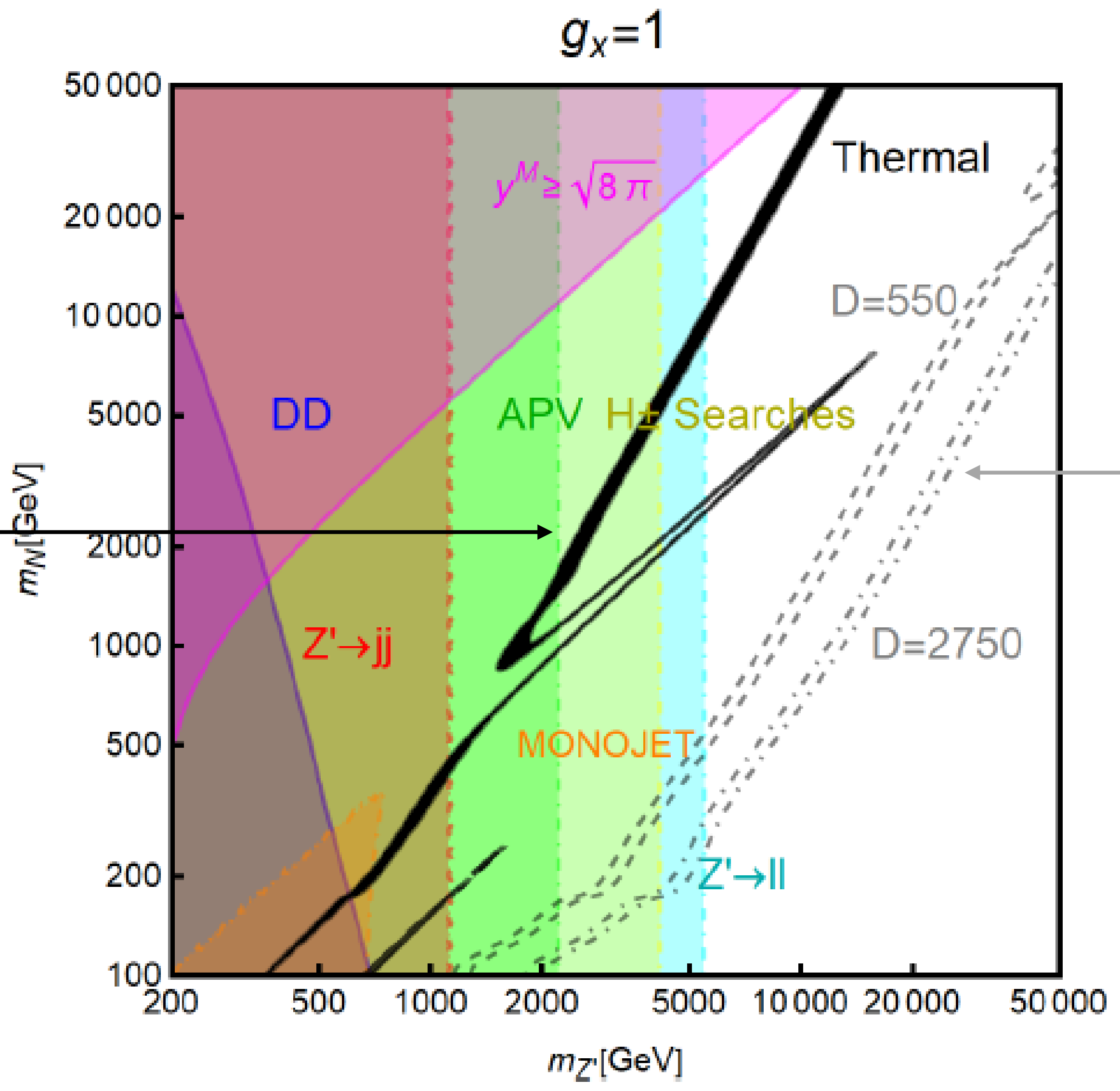
- Searches for heavy $(M_{Z'} = 1\,TeV)$ dijet resonances.
- Searches for light (down to $M_{Z'} = 45\,GeV$) dijet resonances.
- Searches of heavy $(M_{Z'} = 600\,GeV)$ dilepton resonances.
- Monojets.

Scenario I: Thermal Relic density

For definiteness we have considered X=B-L

$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

Thermal relic density strongly constrained by experiments



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Entropy dilution from Early Matter domination (more details in the following).

Alternative Roads for Dark Matter Relic Density

Modified Cosmological History

We include an additional exotic component which can dominate the energy density of the Universe. (We assume, for simplicity, that such additional component does not produce non-thermally DM).

$$\frac{d\rho_\phi}{dt} = -3(1+\omega)H\rho_\phi - \Gamma_\phi \rho_\phi$$

$$\frac{ds}{dt} = -3Hs + \frac{\Gamma_\phi \rho_\phi}{T} + 2\frac{E}{T}\langle \sigma v \rangle (n^2 - n_{eq}^2)$$

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2)$$

Considered scenarios

Freeze-before Early Matter Domination

$$Y_{DM} = \frac{Y_{DM,thermal}}{D}$$

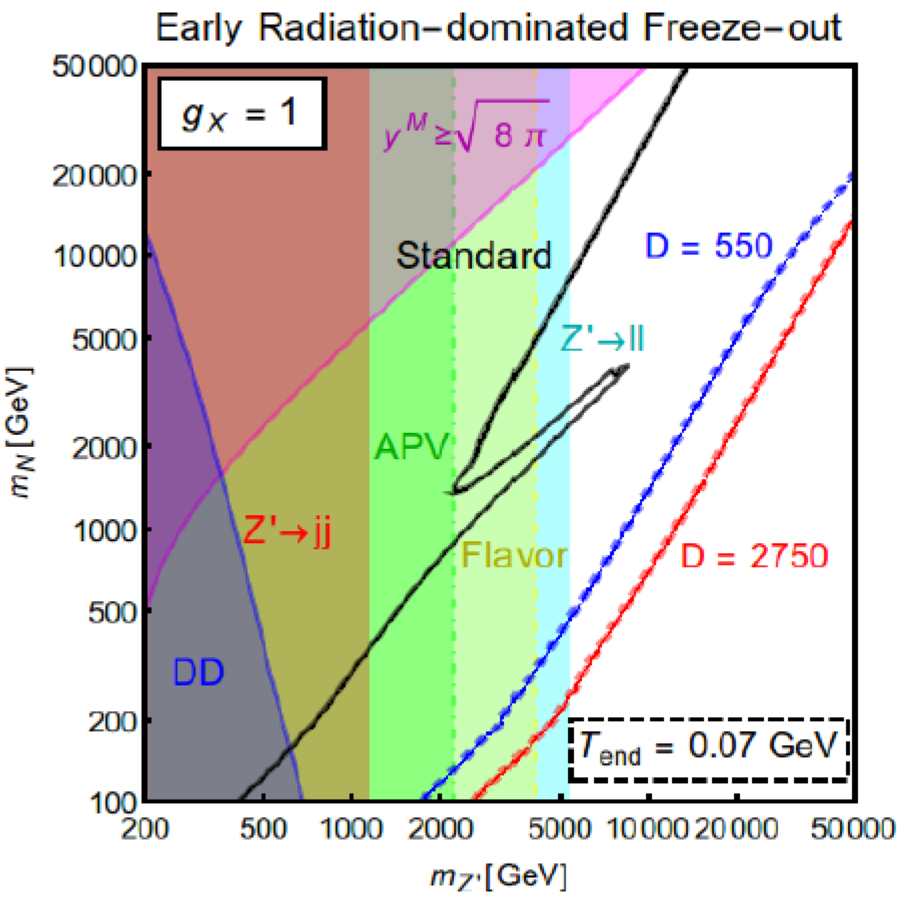
Freeze-out during Early Matter Domination

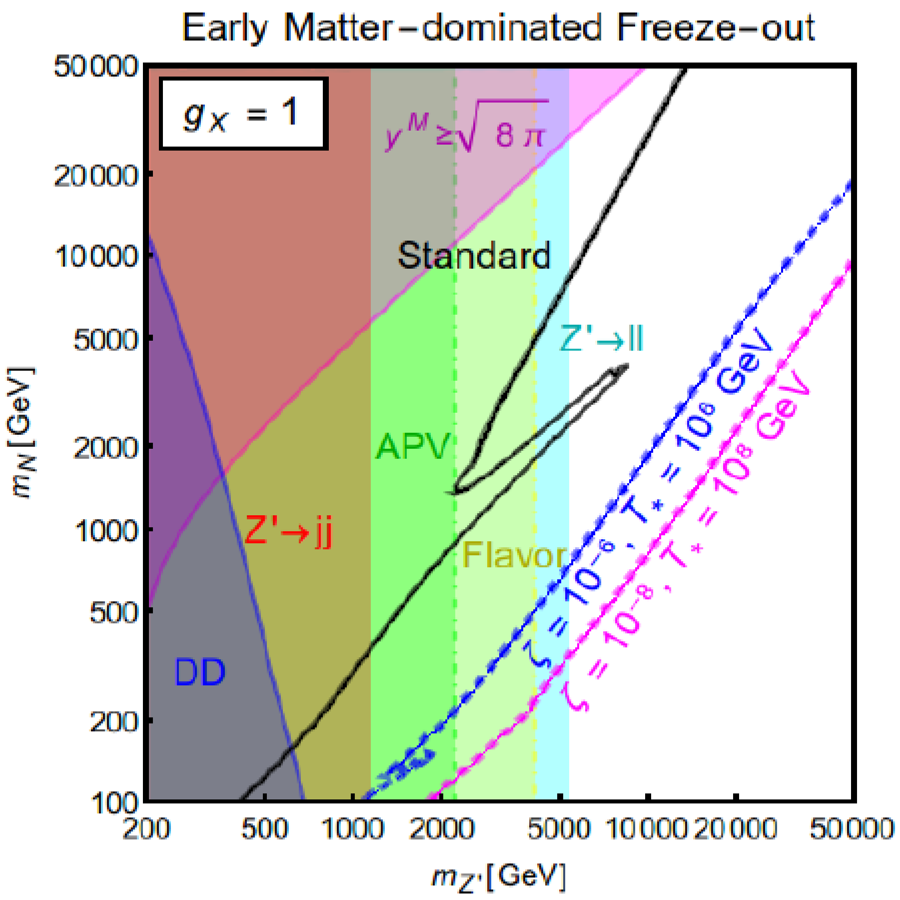
$$\rho_\phi \propto a^{-3} \qquad Y_{DM} = \zeta Y_{DM,MD} \qquad Y_{DM,MD} = \frac{3}{2}\sqrt{\frac{45}{\pi}}\frac{\sqrt{g_*}}{g_{*,s}}\frac{x_f}{m_{DM} M_{pl} \langle \sigma v \rangle x_*^{1/2}}$$

Phase of Faster Expansion

$$\rho_\phi \propto a^{-(4+n)} \qquad n \geq 2$$

$$Y_{DM} \simeq \frac{x_r}{m_{DM} M_{pl} \langle \sigma v \rangle}\left[\frac{2}{x_f} + \log\left(\frac{x}{x_f}\right)\right]^{-1} \qquad Y_{DM} \simeq \frac{x_r^{\frac{n}{2}}}{2 m_{DM} M_{pl} \langle \sigma v \rangle}\left[x_f^{\frac{n}{2}-2} + \frac{x^{\frac{n}{2}-1}}{n-1}\right]^{-1}$$





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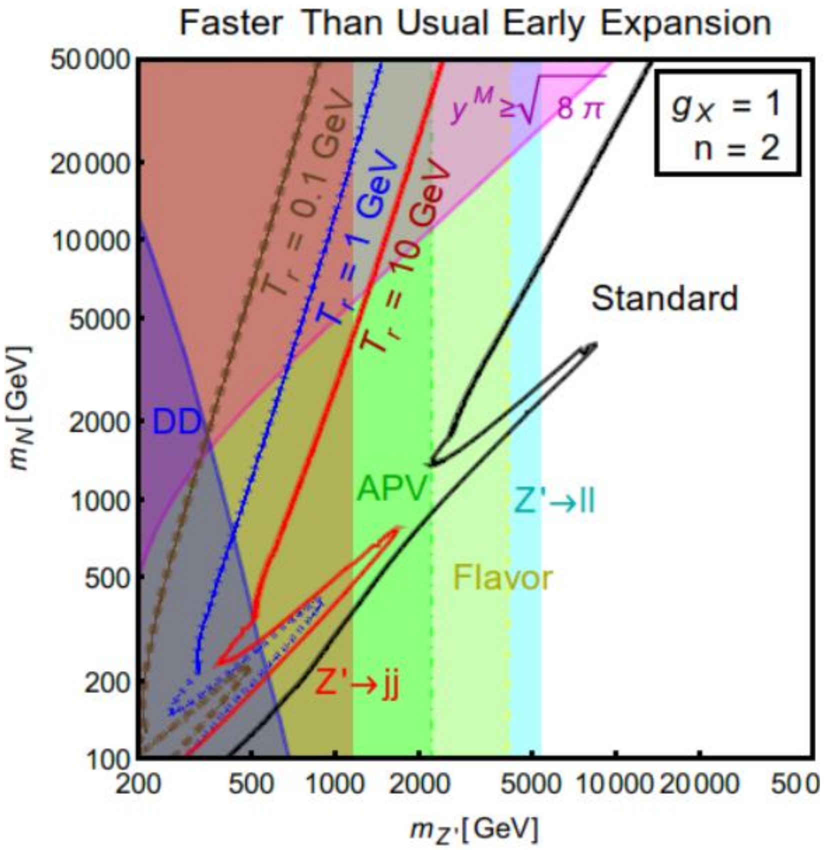
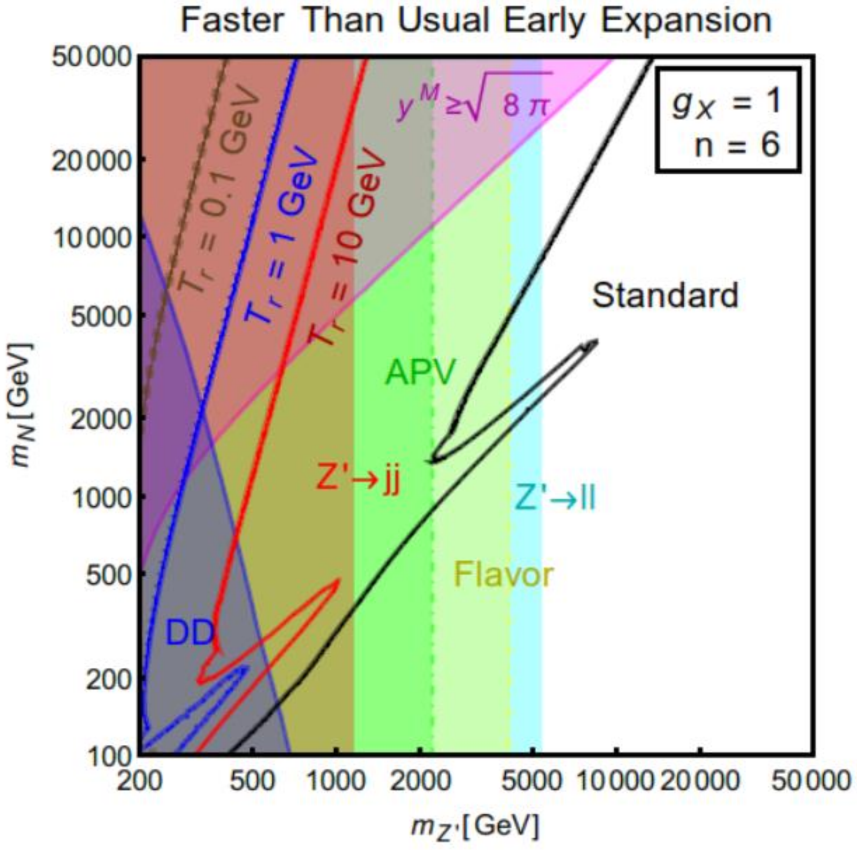
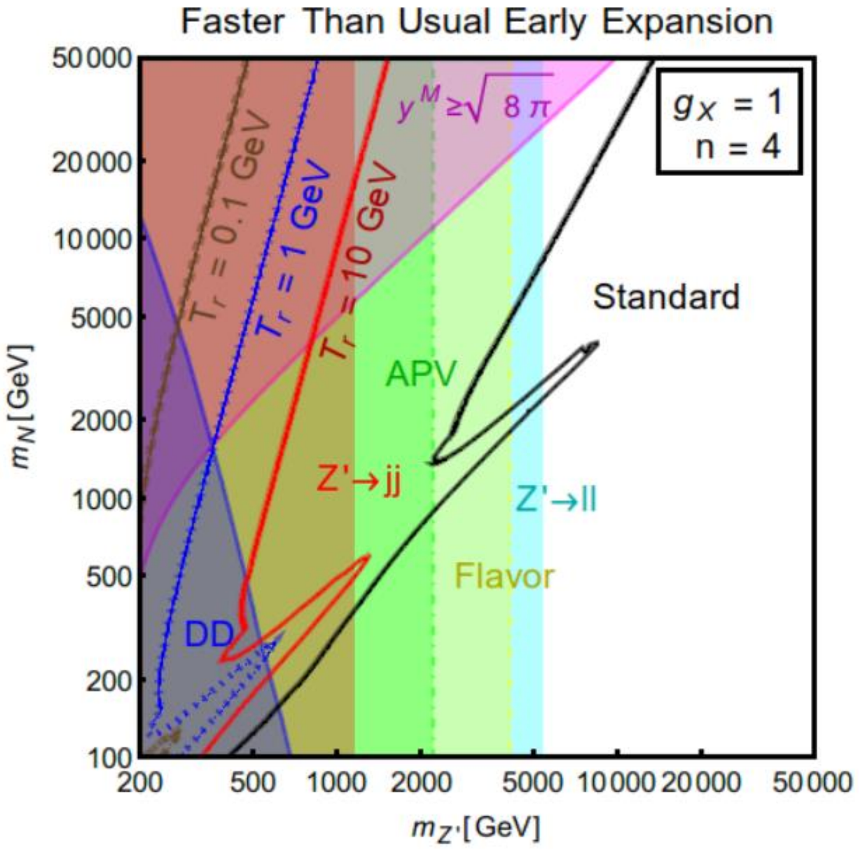

Faster Than Usual Early Expansion
$g_X = 1$
n = 2
$T_r = 0.1$ GeV
$T_r = 1$ GeV
$T_r = 10$ GeV
$y^M \geq \sqrt{8\pi}$
Standard
DD
APV
Z'→ll
Flavor
Z'→jj
m_N [GeV]
$m_{Z'}$ [GeV]


Faster Than Usual Early Expansion
$g_X = 1$
n = 6
$T_r = 0.1$ GeV
$T_r = 1$ GeV
$T_r = 10$ GeV
$y^M \geq \sqrt{8\pi}$
Standard
APV
Z'→jj
Z'→ll
Flavor
DD
m_N [GeV]
$m_{Z'}$ [GeV]


Faster Than Usual Early Expansion
$g_X = 1$
n = 4
$T_r = 0.1$ GeV
$T_r = 1$ GeV
$T_r = 10$ GeV
$y^M \geq \sqrt{8\pi}$
Standard
APV
Z'→jj
Z'→ll
Flavor
DD
m_N [GeV]
$m_{Z'}$ [GeV]

Conclusions

We have discussed the Dark Matter phenomenology of a 2HDM+U(1) model.

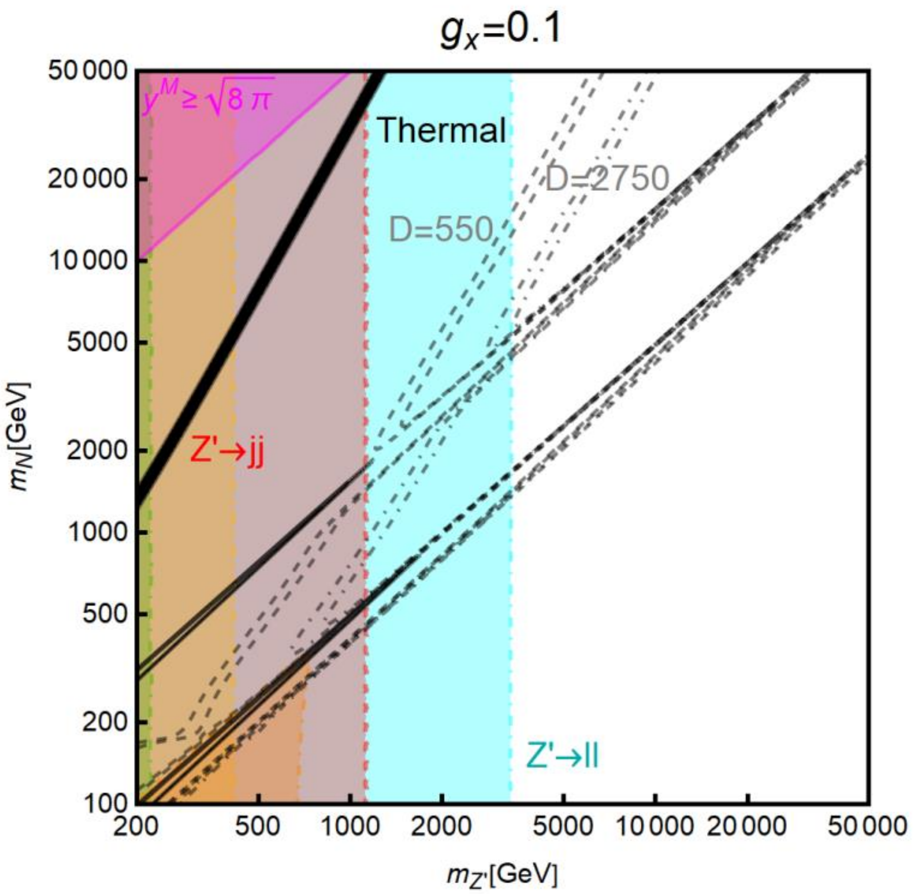
This model incorporates DM, neutrino masses and accommodates the absence of FCNC in the 2HDM.

We have focussed on DM production mechanism considering the Standard freeze-out paradigm as well as the production in non-Standard cosmological histories.

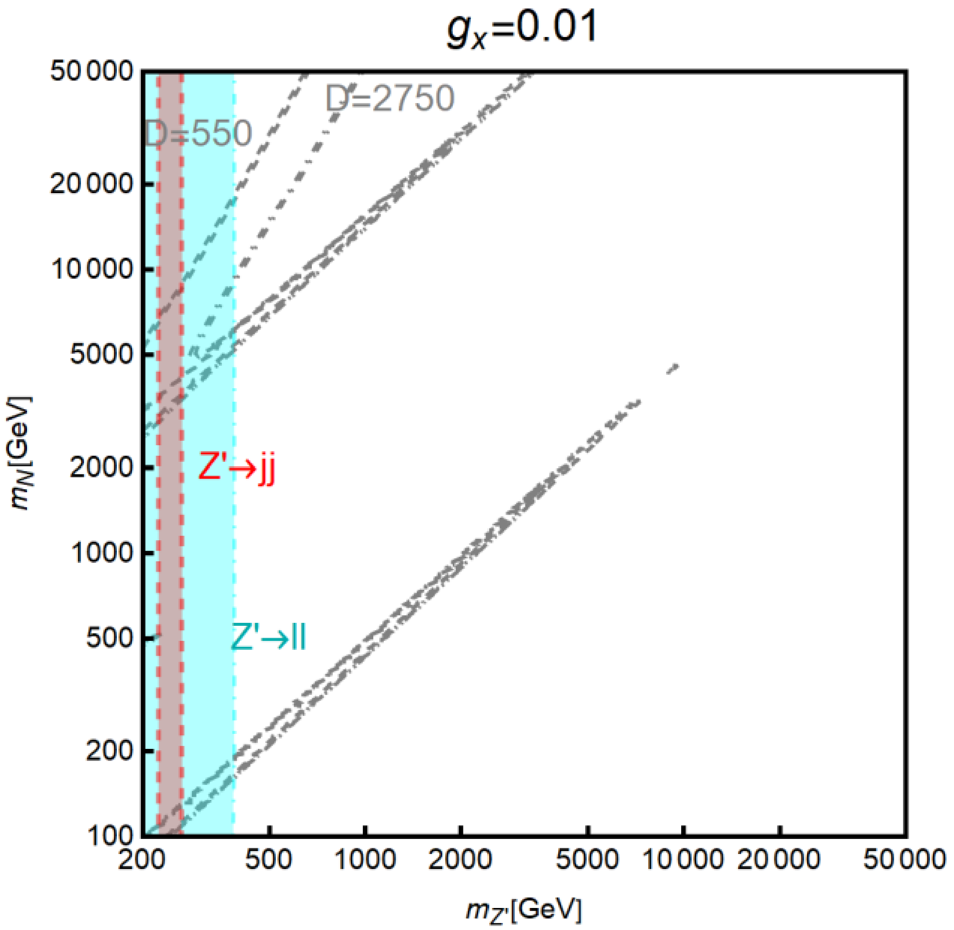
Back up

Fields	u_R	d_R	Q_L	L_L	e_R	N_R
$U(1)_X$	Q^u_X	Q^d_X	$\frac{(Q^u_X+Q^d_X)}{2}$	$\frac{-3(Q^u_X+Q^d_X)}{2}$	$-(2Q^u_X+Q^d_X)$	$-(Q^u_X+2Q^d_X)$
$U(1)_{B-L}$	$1/3$	$1/3$	$1/3$	-1	-1	-1

Fields	Φ_2	Φ_1
$U(1)_X$	$\frac{(Q^u_X-Q^d_X)}{2}$	$\frac{5Q^u_X}{2}+\frac{7Q^d_X}{2}$
$U(1)_{B-L}$	0	2



g_x=0.1
50 000
20 000
10 000
5000
2000
1000
500
200
100
$y^M \geq \sqrt{8\pi}$
Thermal
D=2750
D=550
Z'→jj
Z'→ll
m_N[GeV]
200
500
1000
2000
5000
10 000
20 000
50 000
$m_{Z'}$[GeV]



g_x=0.01
50 000
20 000
10 000
5000
2000
1000
500
200
100
D=2750
D=550
Z'→jj
Z'→ll
m_N[GeV]
200
500
1000
2000
5000
10 000
20 000
50 000
$m_{Z'}$[GeV]