WIMP and FIMP dark matter in Singlet-Triplet Fermionic Model

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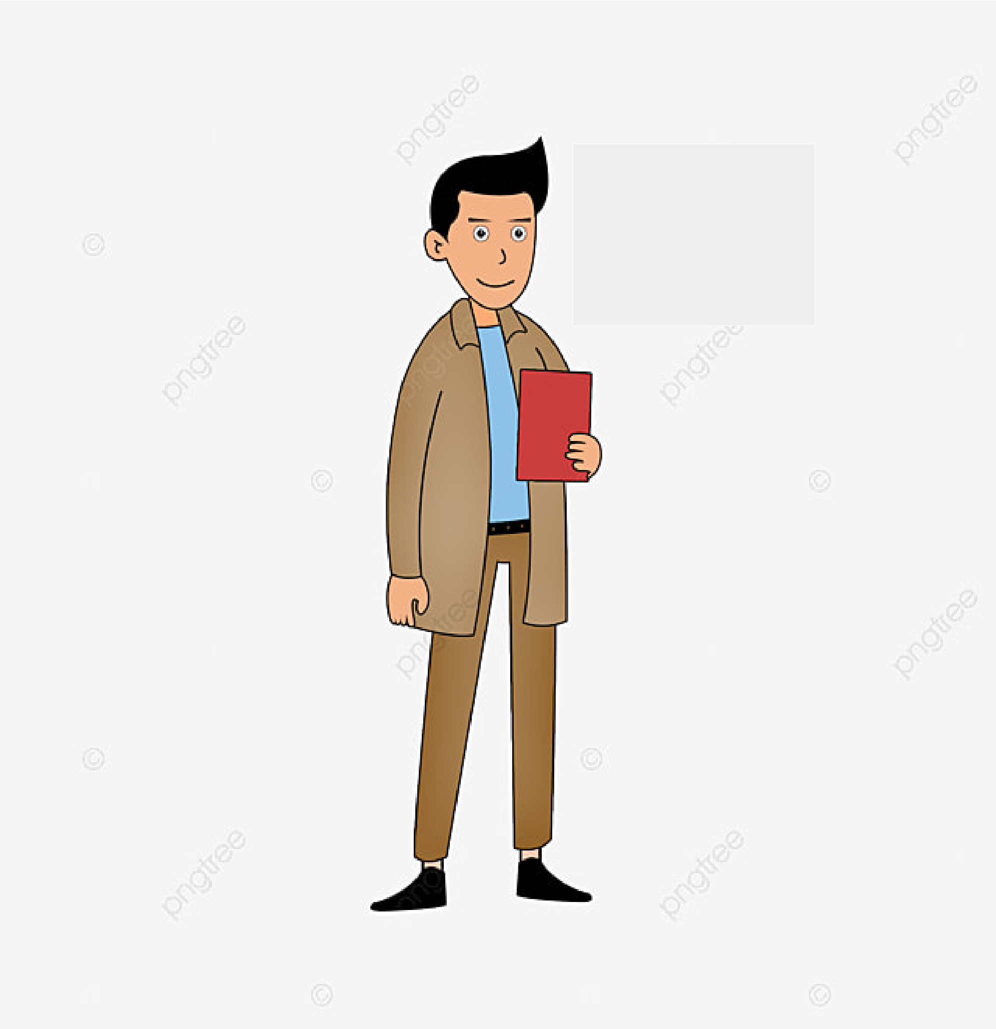
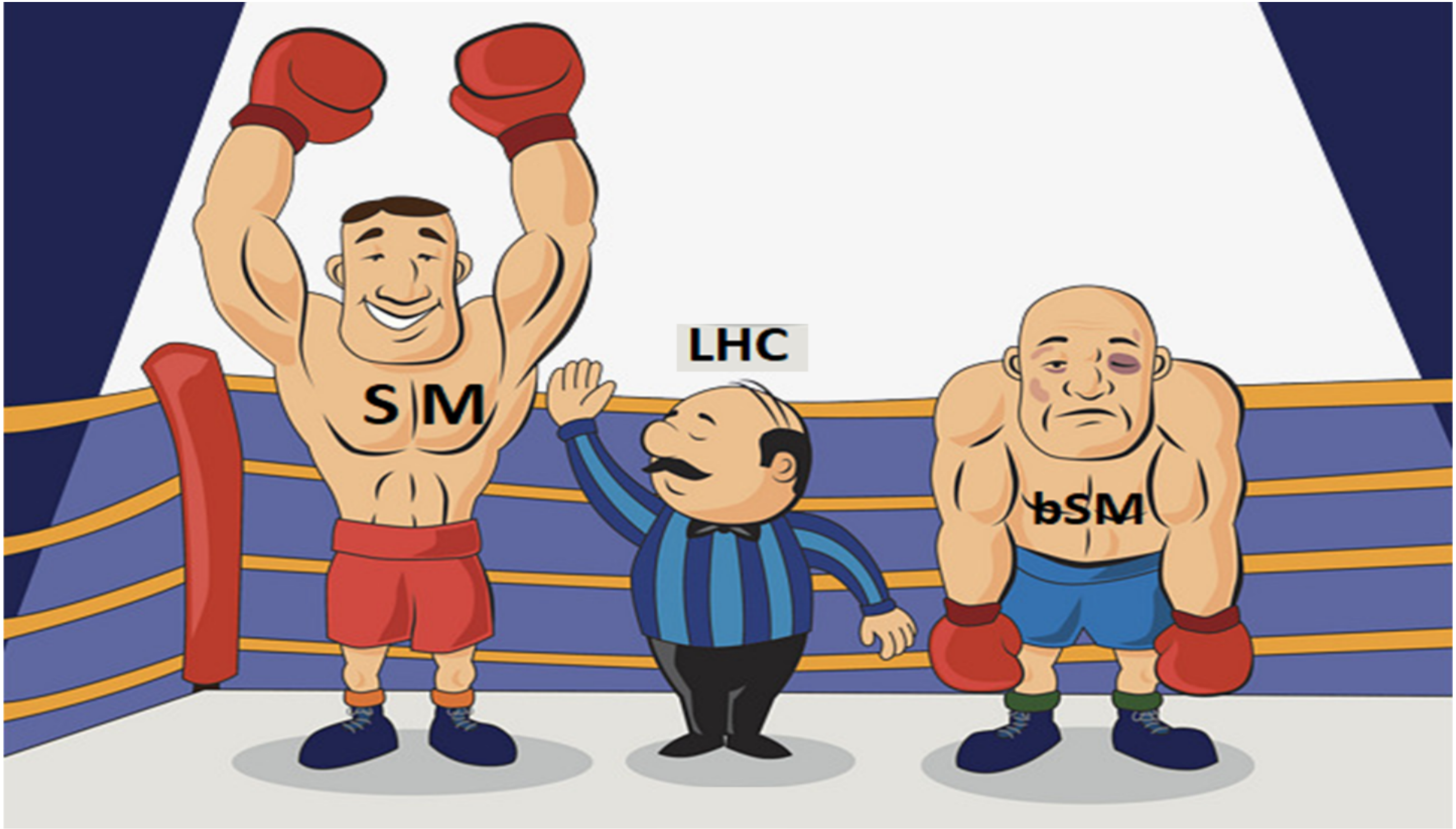
Talk Plan

- Introduction
- Model
- Results based on SFTM
- Conclusion

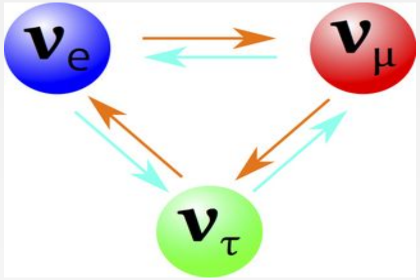




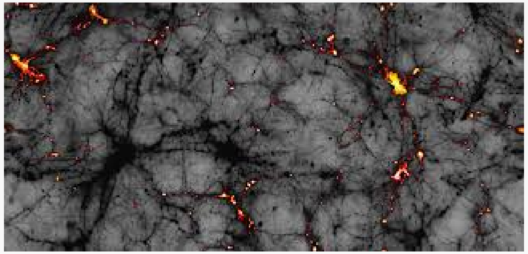
LHC results able to confirm the validity of the SM, with no signatures of new physics.

Problems in the SM

- SM fails to explain neutrino mass and mixings.



- SM doesn't have DM candidate.



- SM fails to explain observed baryon asymmetry.

Who can be a DM ?

- Should be massive
- Should be electrically neutral
- Should be present in early universe
- Should be stable or at least with half life greater than the age of the universe

Need a symmetry

Singlet Scalar

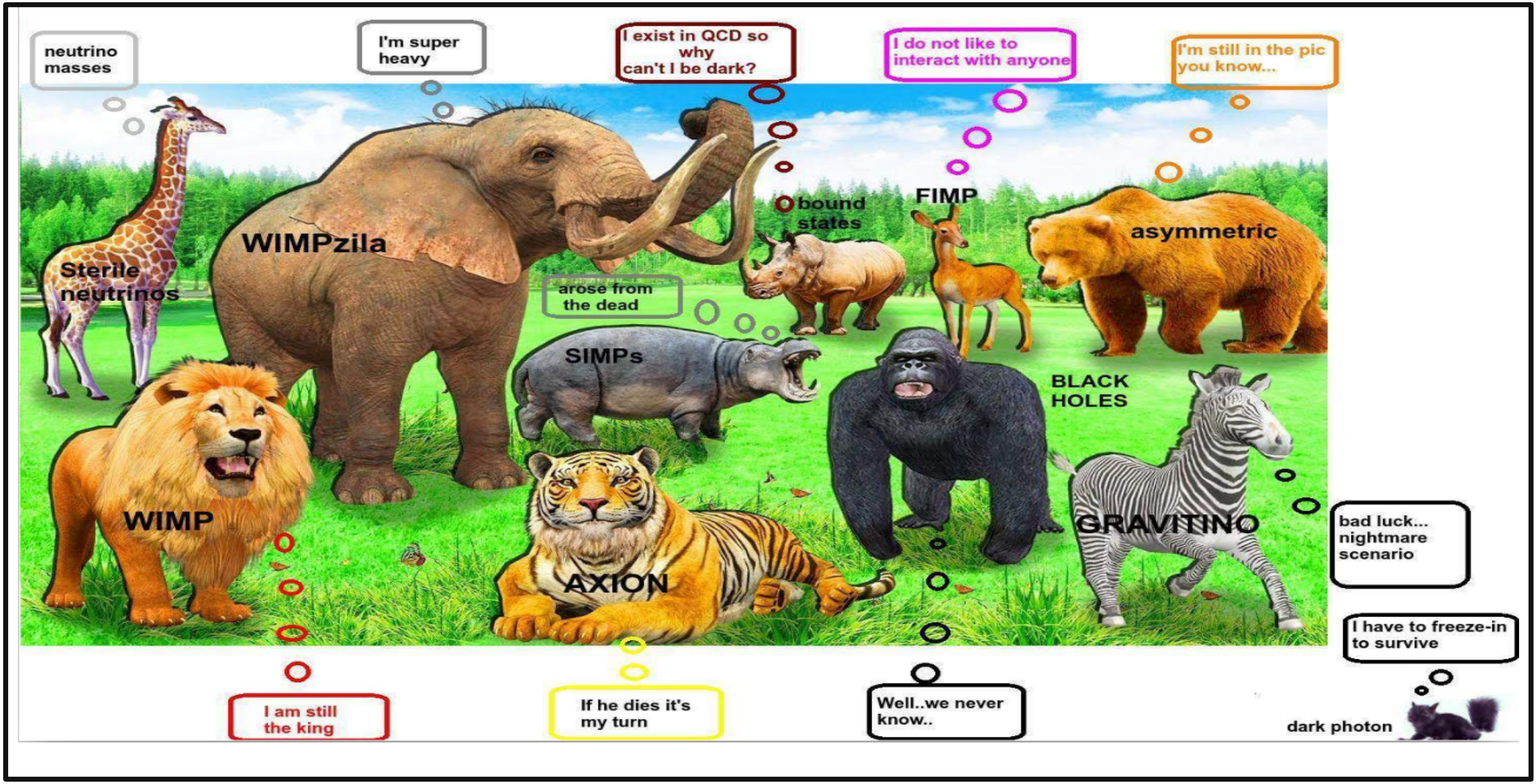
Singlet Fermion

Scalar in triplet repn

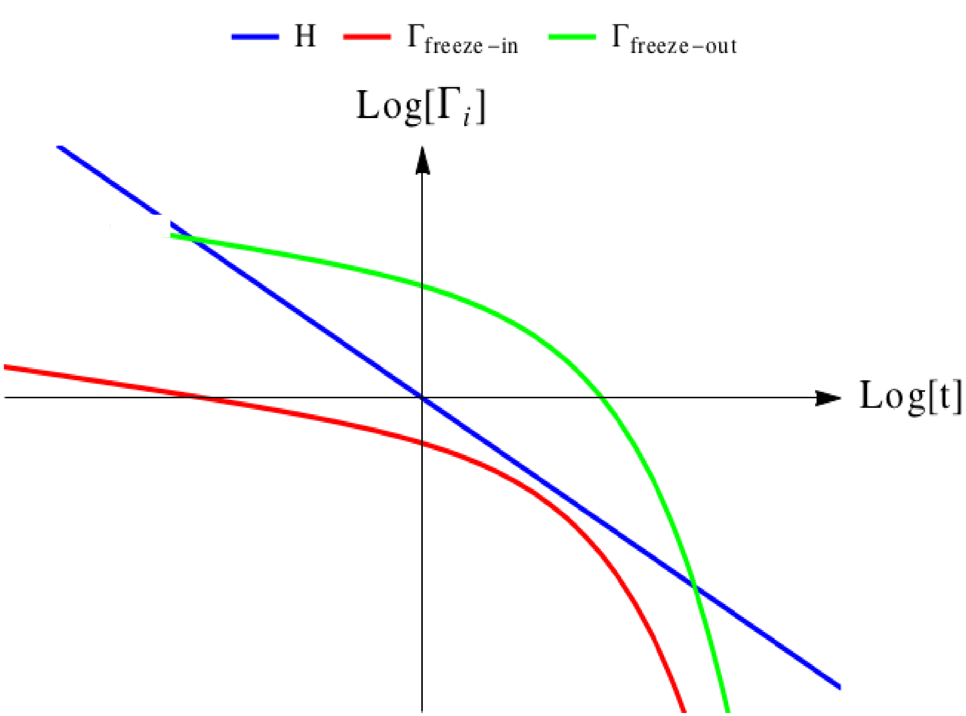
Fermion in triplet repn

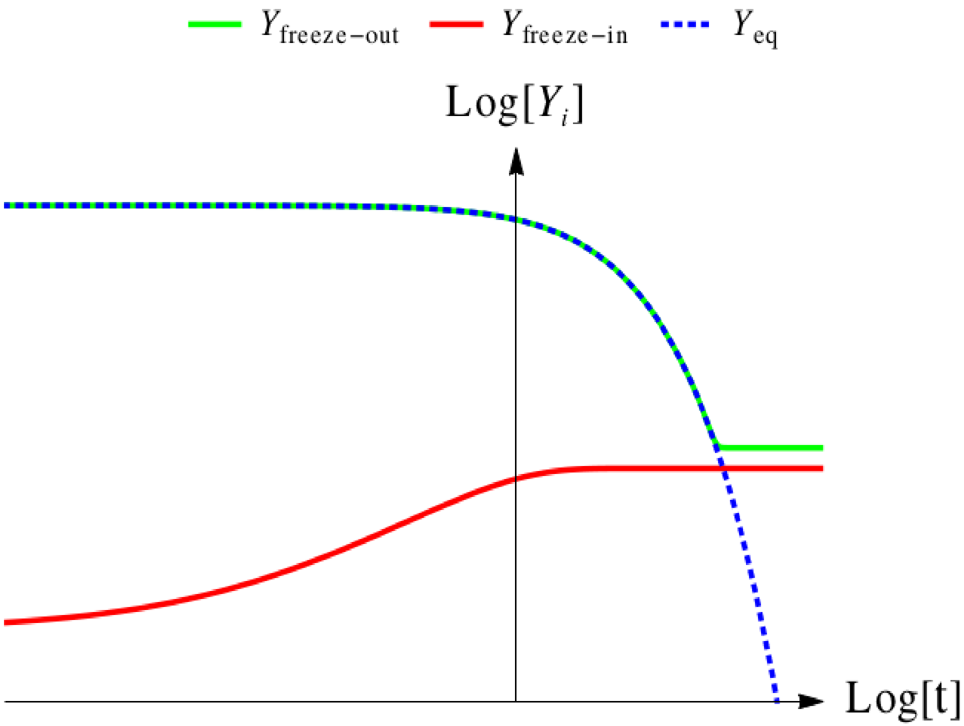
...and many more

Zoo of Dark Matter Candidates



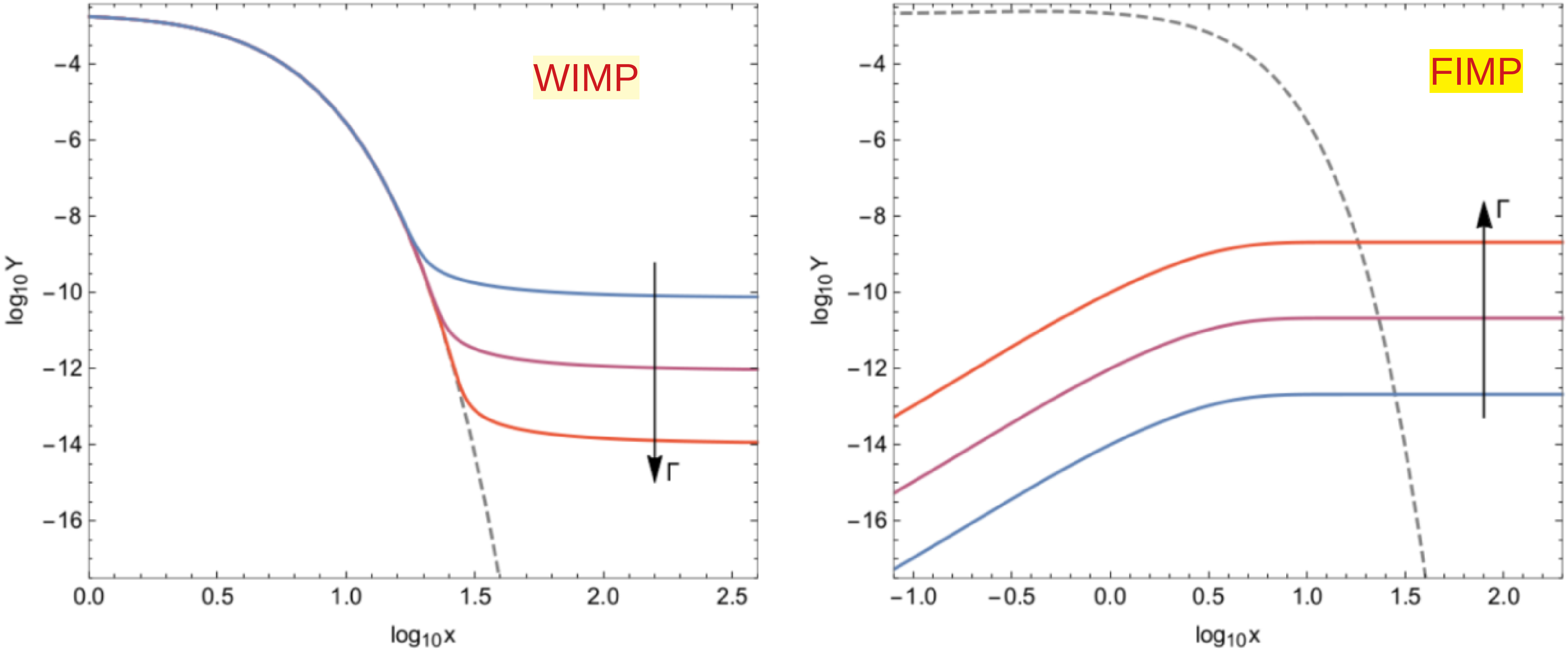
Overview WIMP and FIMP Mechanism



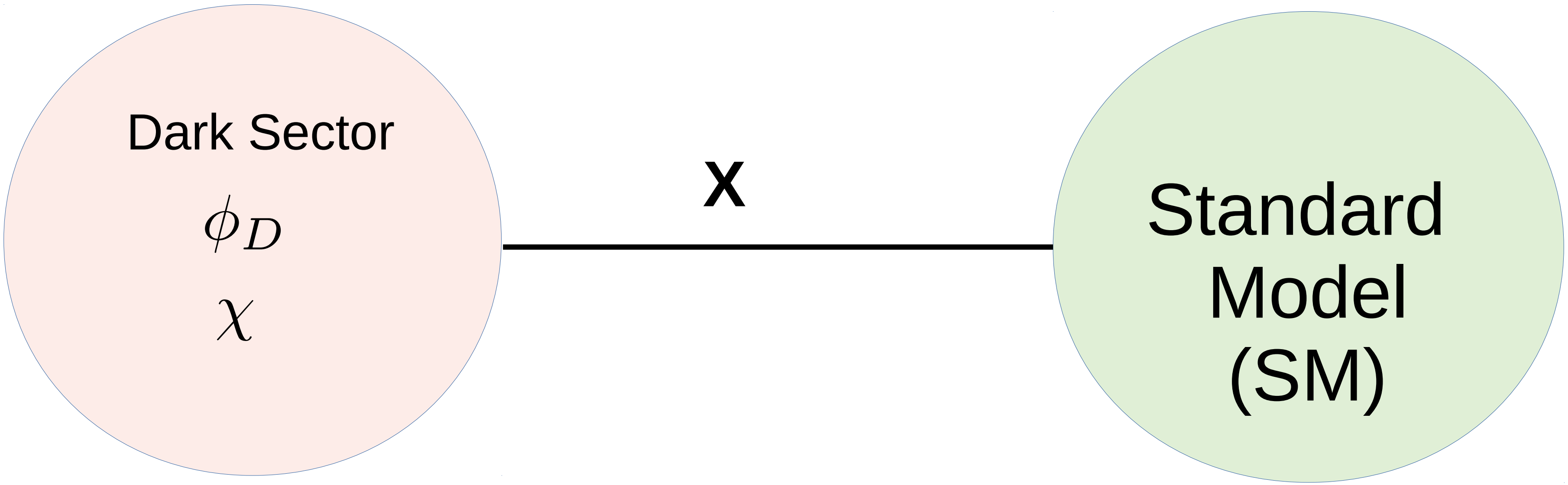


WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$



Overview SUPER-Wimp Mechanism



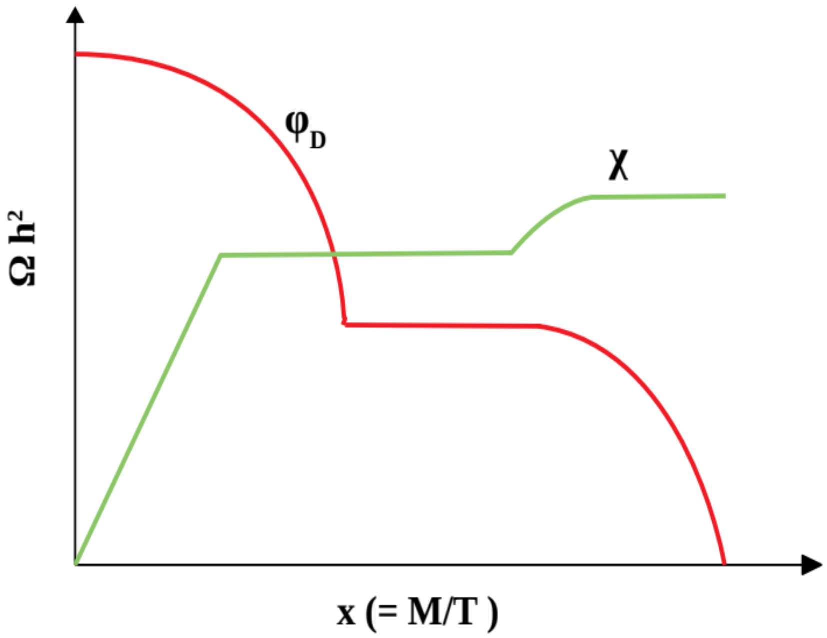
Assumptions:-

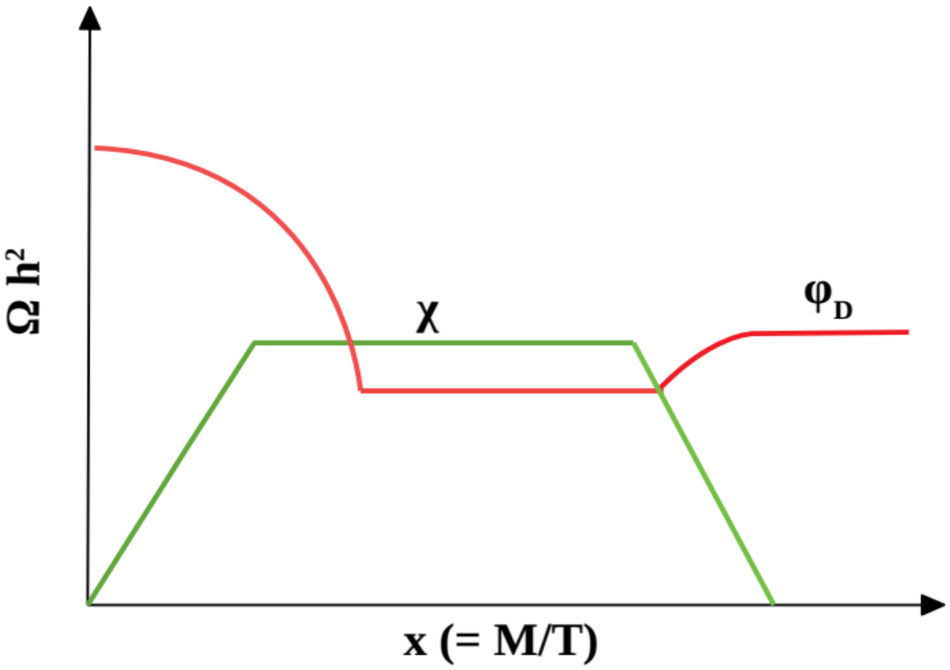
- ϕ_D is thermalized with the thermal bath due to gauge interactions.
- χ being singlet and having feeble interaction never thermalizes.

Overview SUPER-Wimp Mechanism

χ is a DM candidate

ϕ_D is a DM candidate





SFTM to explain DM and neutrino mass

New Particles

Symmetry Group	Baryon Fields			Fermion Fields						Scalar Fields	
	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	N'	ρ_1	ρ_2	ρ_3	ϕ_h	Δ
$SU(3)_c$	3	3	3	1	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	3	3	3	2	3
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	0	0	0	1/2	0
$\mathbb{Z}_2$	+	+	+	+	+	−	+	+	−	+	+

Table 1: Particle content and their corresponding charges under various symmetry groups.

The complete Lagrangian for the model:-

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{3} Tr\left[\bar{\rho}_i\, i\,\gamma^\mu D_\mu \rho_i\right] + \bar{N'}\, i\,\gamma^\mu D_\mu N' + Tr[(D_\mu\Delta)^\dagger(D^\mu\Delta)] - V(\phi_h, \Delta)$$
$$- \sum_{(i,j)=(1,1)}^{(3,2)} \lambda_{ij}\bar{L}_i\phi_h\rho_j^c - Y_{\rho\Delta}\left(Tr[\bar{\rho}_3\,\Delta]\,N' + h.c.\right) - \sum_{i=1}^{3} M_{\rho_i}\,Tr[\bar{\rho_i^c}\rho_i] - M_{N'}\,\bar{N'^c}N'$$

$$V(\phi_h, \Delta) = -\mu_h^2\phi_h^\dagger\phi_h + \frac{\lambda_h}{4}(\phi_h^\dagger\phi_h)^2 + \mu_\Delta^2 Tr[\Delta^\dagger\Delta] + \lambda_\Delta(\Delta^\dagger\Delta)^2 + \lambda_1(\phi_h^\dagger\phi_h)\,\mathrm{Tr}\,[\Delta^\dagger\Delta]$$
$$+\lambda_2\left(Tr[\Delta^\dagger\Delta]\right)^2 + \lambda_3\,Tr[(\Delta^\dagger\Delta)^2] + \lambda_4\,\phi_h^\dagger\Delta\Delta^\dagger\phi_h + (\mu\phi_h^\dagger\Delta\phi_h + h.c.)$$

- ϕ_h accquires vev and EWSB takes place.
- Δ_0 Acquires an induced vev and takes the following form,

$$\phi_h = \begin{pmatrix} \phi^+ \\ \frac{v + H + i\xi}{\sqrt{2}} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{\Delta^0 + v_\Delta}{2} & \frac{\Delta^+}{\sqrt{2}} \\ \frac{\Delta^-}{\sqrt{2}} & -\frac{\Delta^0 + v_\Delta}{2} \end{pmatrix} .$$

$$\langle \Delta^0 \rangle = v_\Delta = \frac{\mu v^2}{2\left(\mu_\Delta^2 + (\lambda_4 + 2\lambda_1)\frac{v^2}{4} + (\lambda_3 + 2\lambda_2)\frac{v_\Delta^2}{2}\right)}$$

After symmetry breaking, CP even neutral Higgs mixes with each other.

$$\begin{aligned} H_1 &= \cos\alpha\, H + \sin\alpha\, \Delta^0 \\ H_2 &= -\sin\alpha\, H + \cos\alpha\, \Delta^0 \end{aligned}$$

The charged scalar also mixes with each other after EWSB takes the following form,

$$\begin{aligned} G^{\pm} &= \cos\delta\,\phi^{\pm} + \sin\delta\,\Delta^{\pm} \\ H^{\pm} &= -\sin\delta\,\phi^{\pm} + \cos\delta\,\Delta^{\pm} \end{aligned}$$

Dark Matter(DM) Mass:-

Two neutral fermion states ρ_3^0 and N' also mixes.

Mass matrix takes the following form,

$$M_F = \begin{pmatrix} M_{\rho 3} & \frac{Y_{\rho\Delta} v_\Delta}{2} \\ \frac{Y_{\rho\Delta} v_\Delta}{2} & M_{N'} \end{pmatrix} .$$

The mass eigenstates and weak eigenstates takes the following form,

$$\rho = \cos\beta\, \rho_3^0 + \sin\beta\, N'^c$$
$$N = -\sin\beta\, \rho_3^0 + \cos\beta\, N'^c\,.$$

where the mixing angle is,

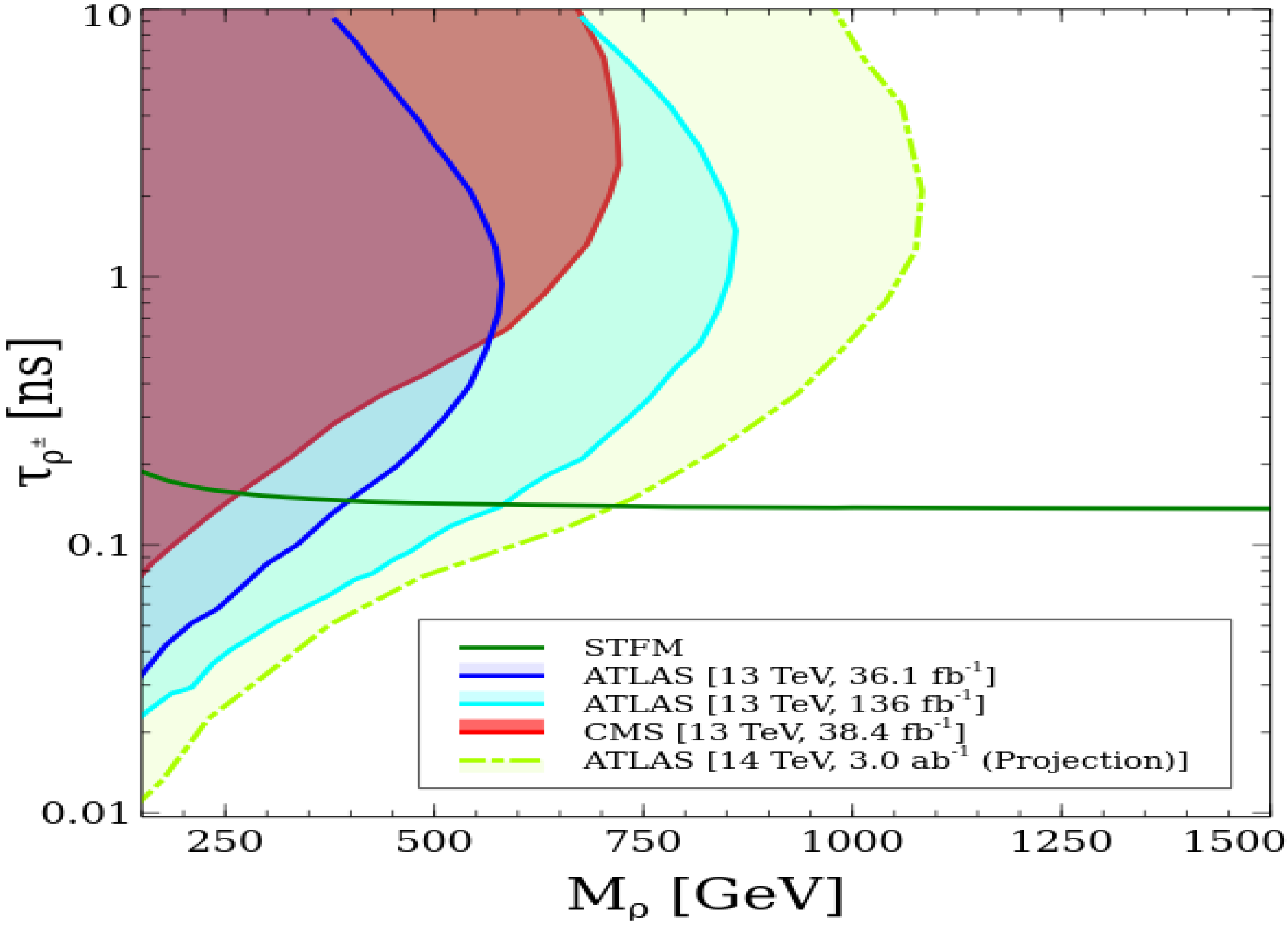
$$\tan 2\beta = \frac{Y_{\rho\Delta} v_\Delta}{M_{\rho_3} - M_{N'}}\,.$$

In the limit $Y_{\rho\Delta} \sim \mathcal{O}(10^{-10})$,

$$M_N \sim M_{N'}, \quad M_\rho \sim M_{\rho_3}$$

DM Constraints:-

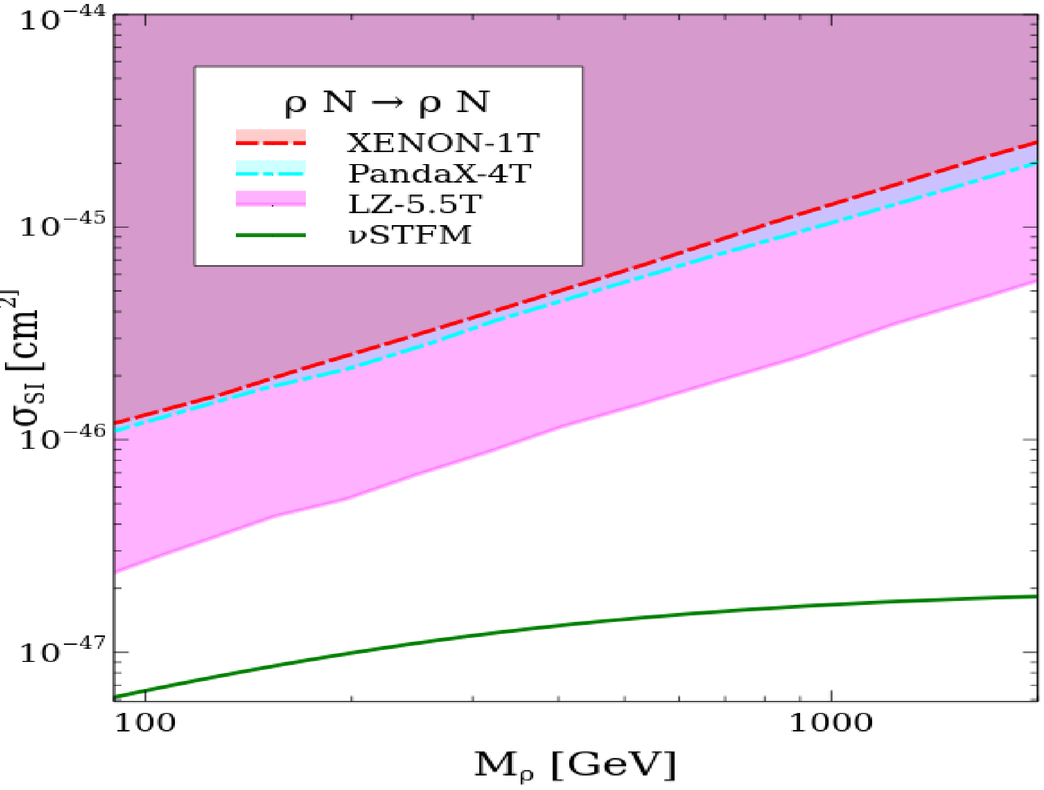
Collider constraints on ρ :-

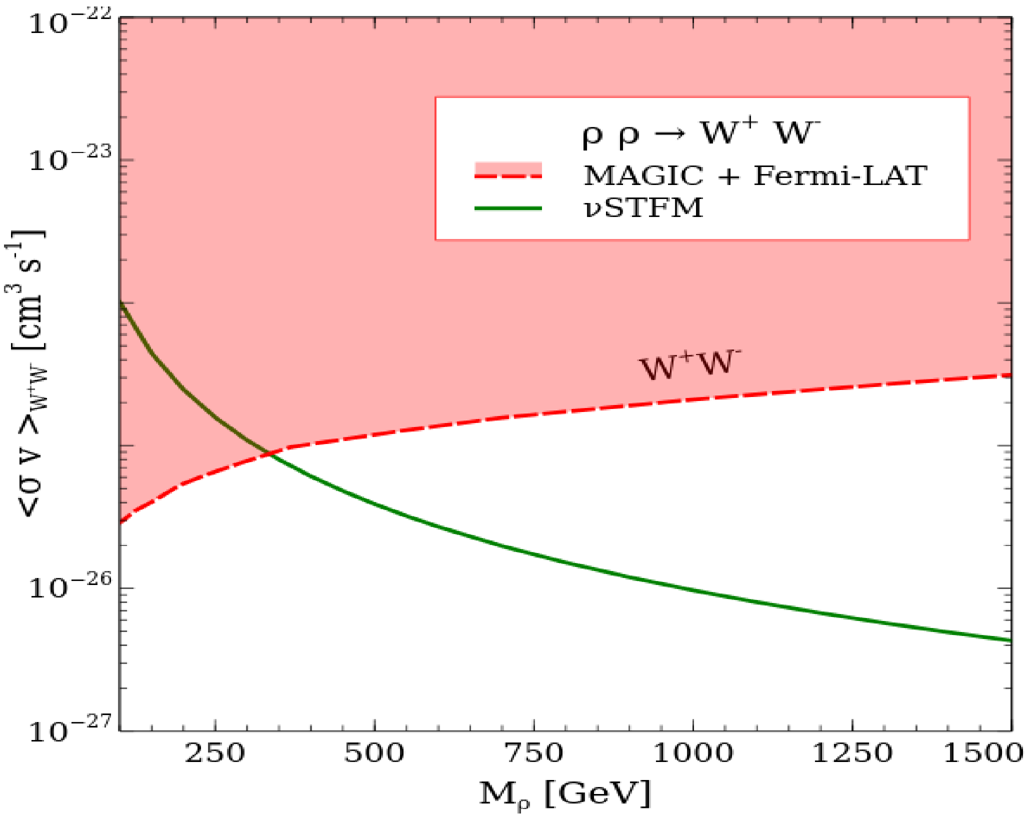


- Recent bound on DM mass from 136 fb^{-1} data of 13 TeV run is M_ρ > 580 GeV.

- In future at 14 TeV run and for 3 ab^{-1} luminosity, it can explore M_ρ upto 750 GeV.

DM direct and Indirect Detection



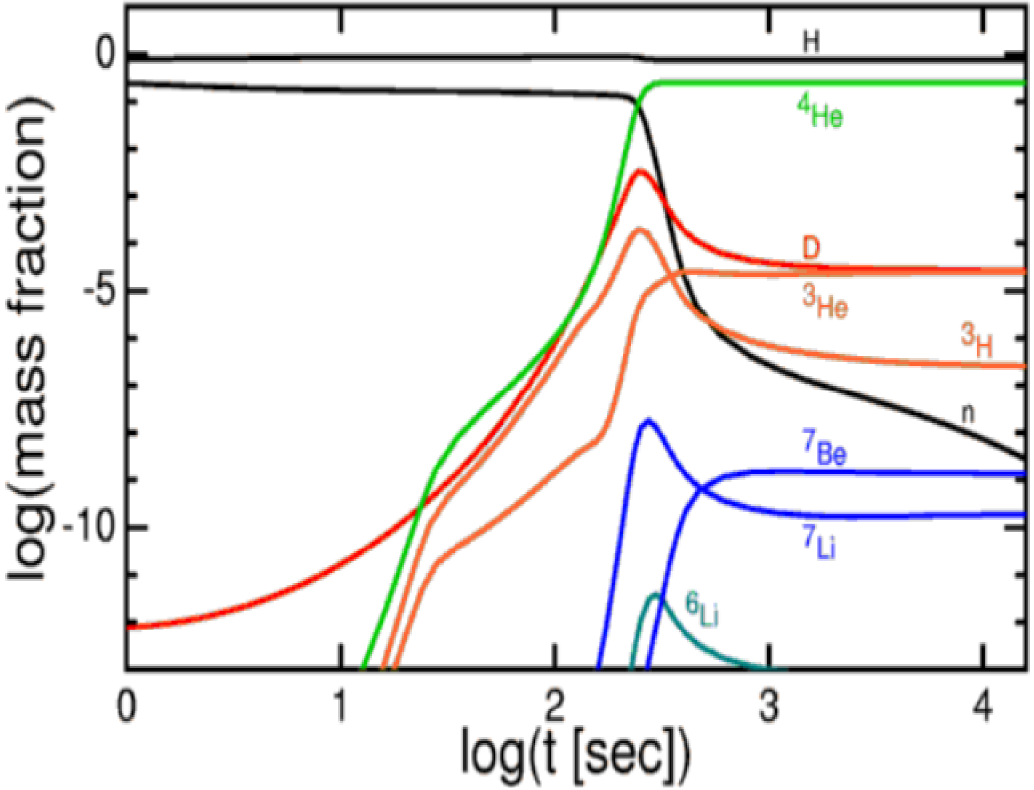


- In the LP DD suppression happens due to the 2-loop gluonic contributions.
- RP gives bound on DM mass from its annihilation to $W^+ W^-$ which is M_ρ > 300 GeV.

BBN Constraint

- Primordial elements nucleosynthesis occurs approximately between 1 and 1000 secs.

- The long lived particles decaying after 1 sec can inject energy to thermal bath and perturb the primordial elements.



The energy released through late decay of long lived particle takes the following form,

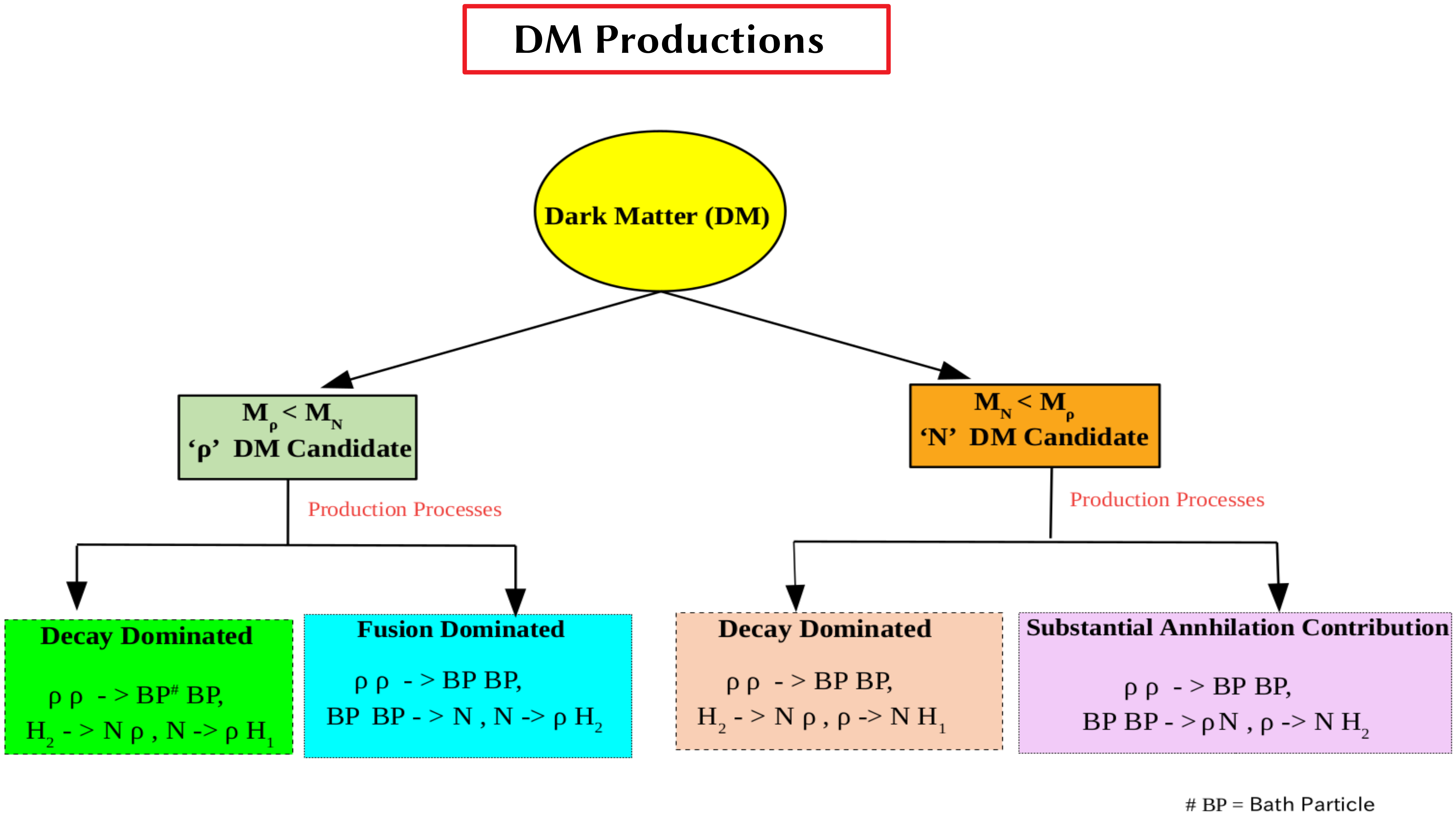
$$\zeta_{had} = E_{vis} B_{had} Y_{NLOP},$$

Yield of NLOP before its decay

where,

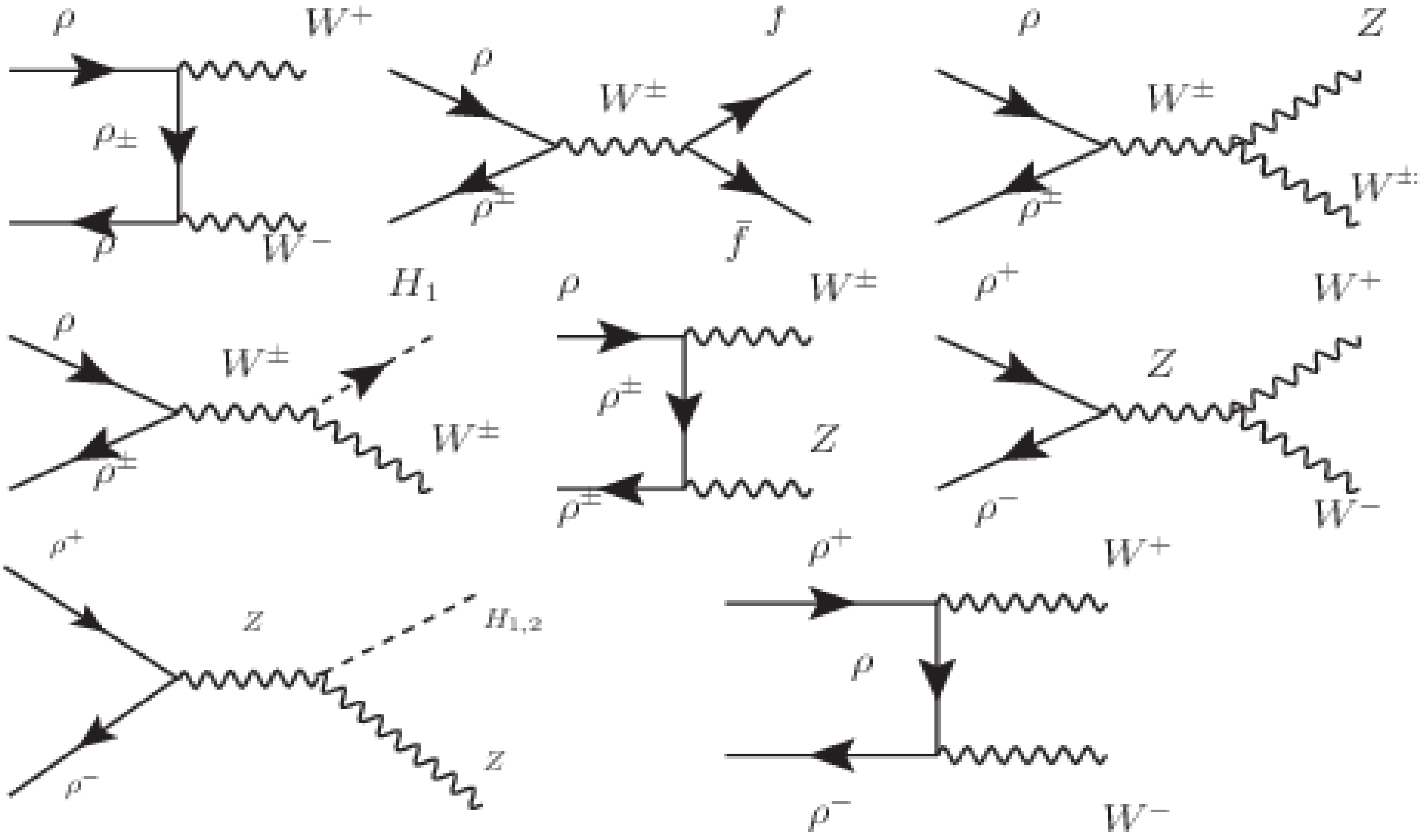
$$B_{had} \approx \frac{\sum_i \Gamma(NLOP \to DM\ X_i) Br(X_i)}{\Gamma^{total}_{NLOP}}, \quad X_i \in B/SM$$

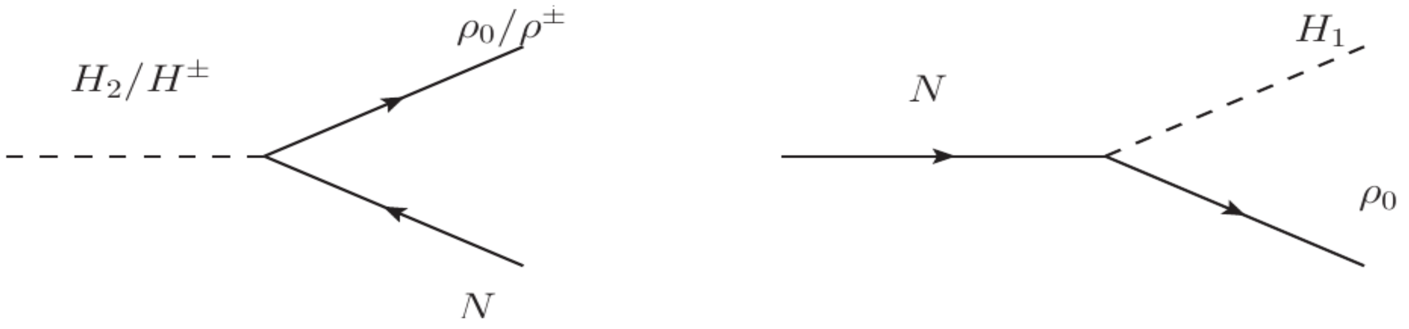
$$E_{vis} \approx \frac{M^2_{NLOP} - M^2_{DM}}{2M_{NLOP}},$$



DM Productions
Dark Matter (DM)
$M_\rho < M_N$
'ρ' DM Candidate
$M_N < M_\rho$
'N' DM Candidate
Production Processes
Production Processes
Decay Dominated
$\rho\,\rho \to BP^{\#}\,BP$,
$H_2 \to N\,\rho$, $N \to \rho\,H_1$
Fusion Dominated
$\rho\,\rho \to BP\,BP$,
$BP\,BP \to N$, $N \to \rho\,H_2$
Decay Dominated
$\rho\,\rho \to BP\,BP$,
$H_2 \to N\,\rho$, $\rho \to N\,H_1$
Substantial Annhilation Contribution
$\rho\,\rho \to BP\,BP$,
$BP\,BP \to \rho\,N$, $\rho \to N\,H_2$
BP = Bath Particle

Scenario I → $M_N > M_\rho$ → ρ is DM candidate.





Feynmann diag. for the dominant production of N as well its late decay to DM.

Boltzmann Equation for DM and NLOP:

$$\hat{L} f_N = \sum_{i=1,2} \mathcal{C}^{H_i \to N\rho} + \mathcal{C}^{AB \to N\rho} + \mathcal{C}^{N \to \, all} \,,$$

→ B.eqn to determine the distribution function of 'N'

where,

$$\hat{L} = r\,H \left(1 + \frac{T g_s'}{3 g_s}\right)^{-1} \frac{\partial}{\partial\, r}$$

$$r = \frac{M_{sc}}{T}, \quad \xi_p = \left(\frac{g_s(T_0)}{g_s(T)}\right)^{1/3} \frac{p}{T}$$

Collision functions

$$\mathcal{C}^{h_i \to N\rho} = \frac{r}{16\pi M_{sc}} \frac{\mathcal{B}^{-1}(r)\,|M|^2}{\xi_p \sqrt{\xi_p^2 \mathcal{B}(r)^2 + \left(\frac{M_N\, r}{M_{sc}}\right)^2}} \times \left(e^{-\sqrt{\left(\xi_k^{\min}\right)^2 \mathcal{B}(r)^2 + \left(\frac{M_{H_2}\, r}{M_{sc}}\right)^2}} - e^{-\sqrt{\left(\xi_k^{\max}\right)^2 \mathcal{B}(r)^2 + \left(\frac{M_{H_2}\, r}{M_{sc}}\right)^2}} \right)$$

The amplitude for the process $h_2 \to N\rho$ can be expressed as,

$$|M|^2 = 2\lambda_{N\rho h_i}^2 M_{h_i}^2 \left(1 - x^2\right) \theta(1 - x)$$

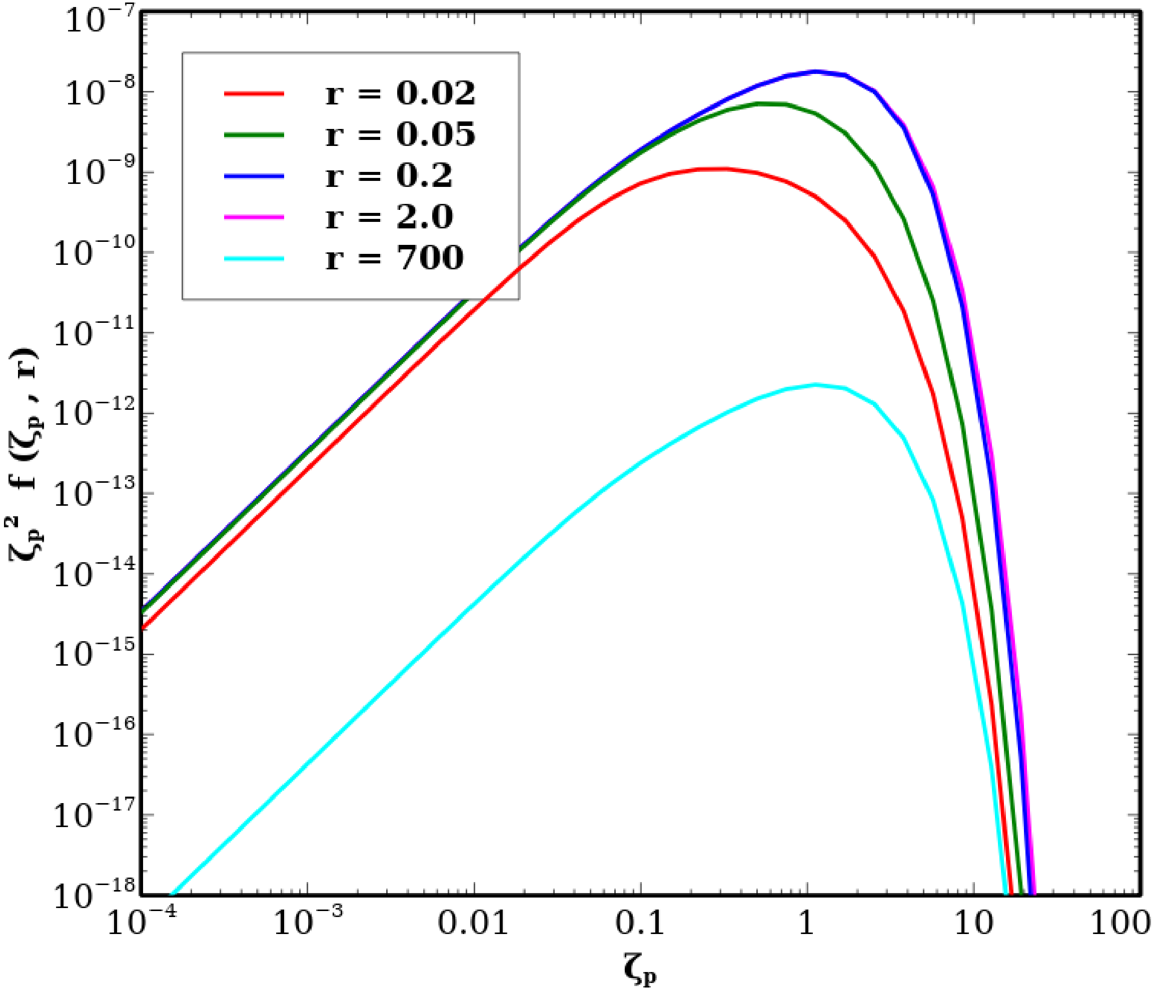
where $x = \frac{M_\rho + M_N}{M_{H_2}}$, $\lambda_{N\rho h_2} = Y_{\rho\Delta} \cos\theta$ and $\lambda_{N\rho h_1} = Y_{\rho\Delta} \sin\theta$. The parameters ξ_k^{min} and ξ_k^{max} can be expressed as,

$$\xi_k^{\min}(\xi_p, r) = \frac{M_{sc}}{2\,\mathcal{B}(r)\, r\, M_N} \left| \eta(\xi_p, r) - \frac{\mathcal{B}(r) \times M_{H_2}^2}{M_N \times M_{sc}} \xi_p\, r \right| ,$$

$$\xi_k^{\max}(\xi_p, r) = \frac{M_{sc}}{2\,\mathcal{B}(r)\, r\, M_N} \left(\eta(\xi_p, r) + \frac{\mathcal{B}(r) \times M_{H_2}^2}{M_N \times M_{sc}} \xi_p\, r \right) ,$$

$$\eta(\xi_p, r) = \left(\frac{M_{H_2}\, r}{M_{sc}}\right) \sqrt{\frac{M_{H_2}^2}{M_N^2} - 4} \sqrt{\xi_p^2\, \mathcal{B}(r)^2 + \left(\frac{M_N\, r}{M_{sc}}\right)^2} .$$

Evolution of distribution function for 'N'



$$n_N(r) = \frac{g\,T^3}{2\pi^2}\,\mathcal{B}(r)^3 \int d\xi_p\,\xi_p^2\,f_N(\xi_p,\,r)$$

This gives number density of 'N' at values of r.

where,

$$\mathcal{B}(r) = \left(\frac{g_s(T_0)}{g_s(T)}\right)^{1/3} = \left(\frac{g_s(M_{sc}/r)}{g_s(M_{sc}/r_0)}\right)^{1/3} .$$

B.eqn for the evolution of DM:

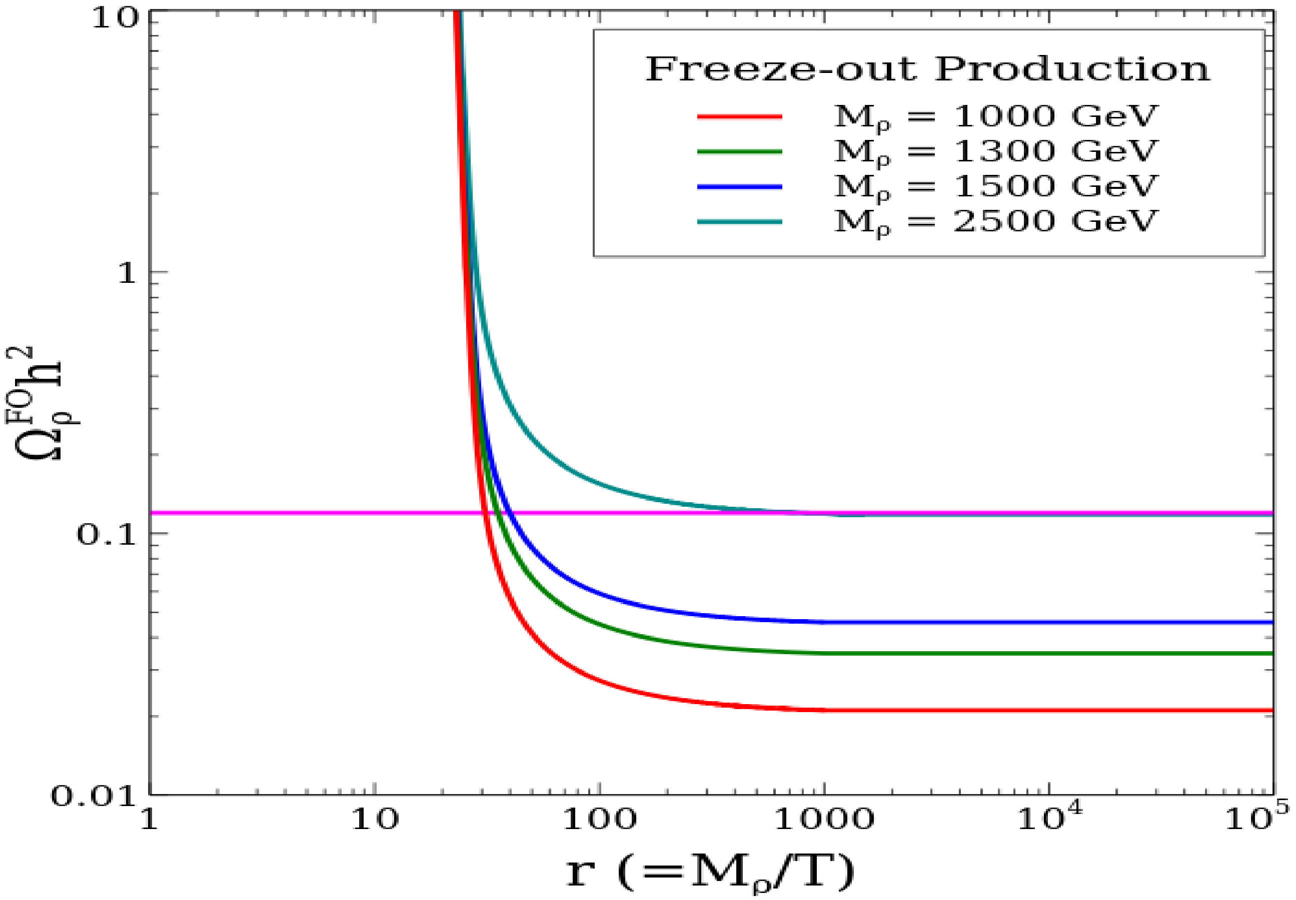
$$\frac{dY_\rho}{dr} = -\sqrt{\frac{\pi}{45G}}\frac{M_{Pl}\sqrt{g_*(r)}}{r^2}\langle\sigma_{eff}|v|\rangle\left(Y_\rho^2 - (Y_\rho^{eq})^2\right)$$
$$+\frac{M_{Pl}\, r\,\sqrt{g_\star(r)}}{1.66\, M_{sc}^2\, g_s(r)}\left[\langle\Gamma_{H_2\to N\rho}\rangle(Y_{H_2} - Y_N Y_\rho) + \langle\Gamma_{N\to\rho A}\rangle_{NTH}\,(Y_N - Y_\rho Y_A)\right]$$

where,

$$\langle\Gamma_{H_2\to N\,\rho}\rangle = \Gamma_{H_2\to N\,\rho}\,\frac{K_1\left(r\,\frac{M_{H_2}}{M_{sc}}\right)}{K_2\left(r\,\frac{M_{H_2}}{M_{sc}}\right)}\,,$$

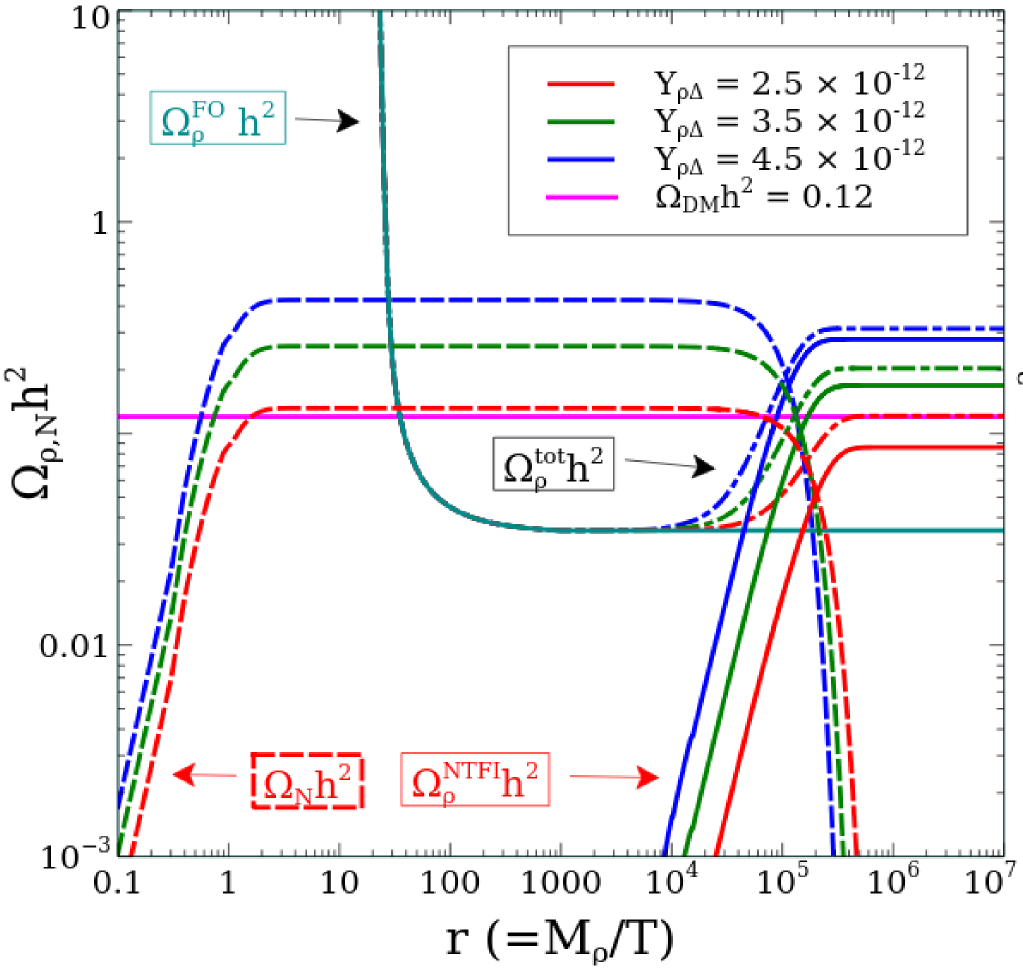
$$\langle\Gamma_{N\to\rho A}\rangle_{NTH} = M_N\Gamma_{N\to\rho A}\frac{\int\frac{f_N(p)}{\sqrt{p^2+M_N^2}}d^3p}{\int f_N(p)d^3p}\,.$$

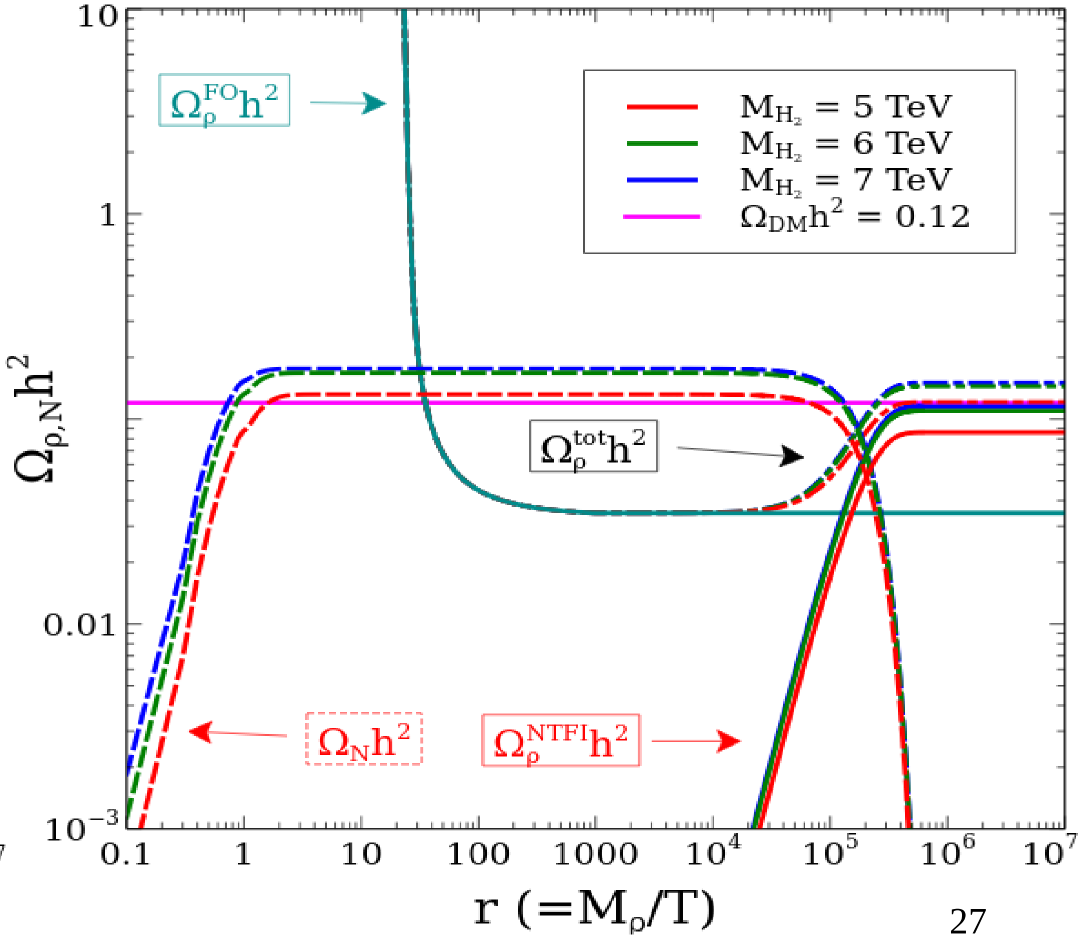
Results:-



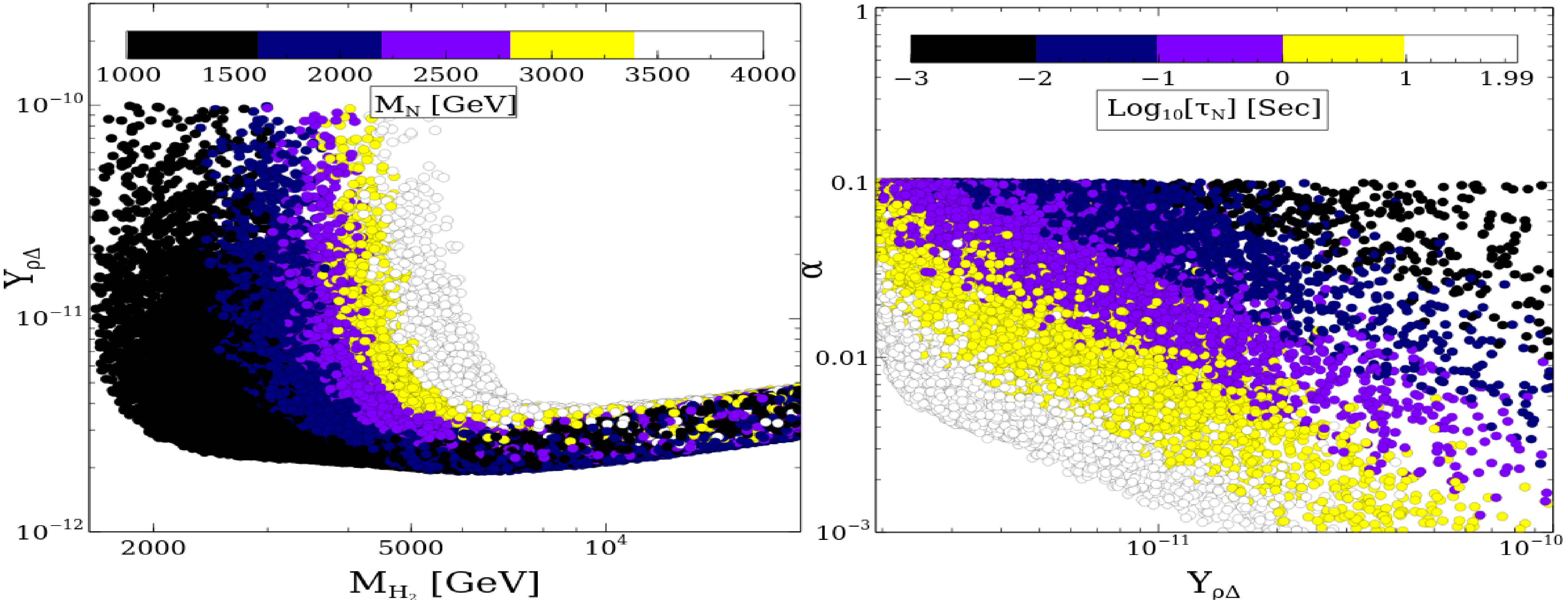
Relic density satisfies around 2.5 TeV.

Results:- $M_N = 2000$ GeV, $M_\rho = 1300$ GeV, $Y_{\rho\Delta} = 2.5 \times 10^{-12}$. → **Parameter choosen unless varied**



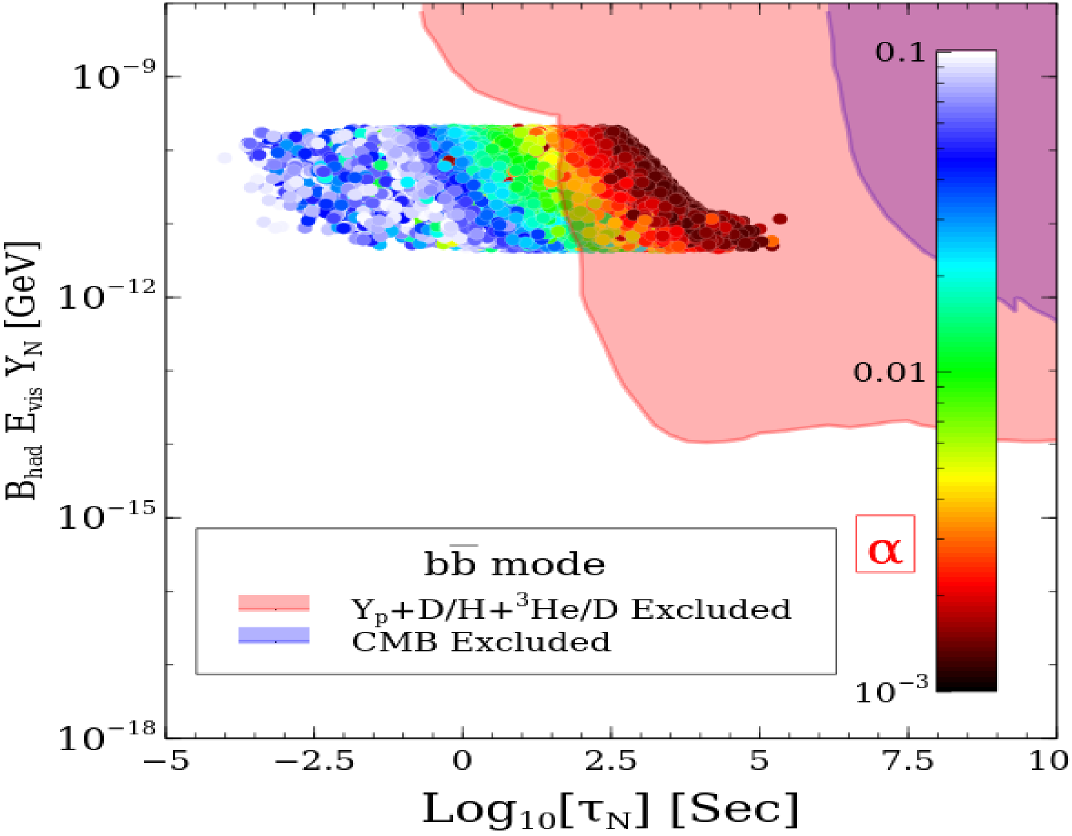


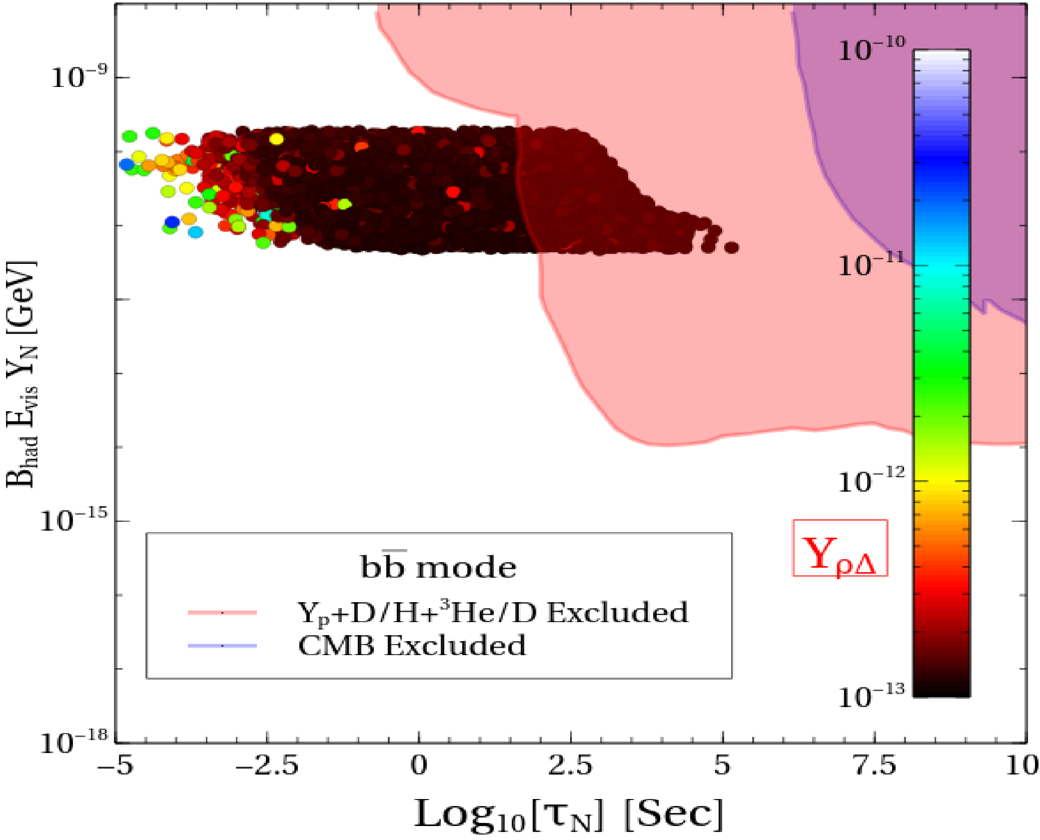
Results:-



- All the points in LP and RP satisfy relic density and BBN bound.
- In LP, M_{H2} < 7 TeV, there is effect of phase space suppression arises from the decay of $H_2 \rightarrow \rho N$ decay. To counter the suppression, the portal coupling is increased. This is in turn decreases the life time of N which is shown in RP.

BBN Constraint





- All the points in LP and RP satisfy observed DM relix density.
- Lower value of $Y_{\rho\Delta}$ and sin α gets rules out from BBN due to excess hadronic injection to plasma at late times.

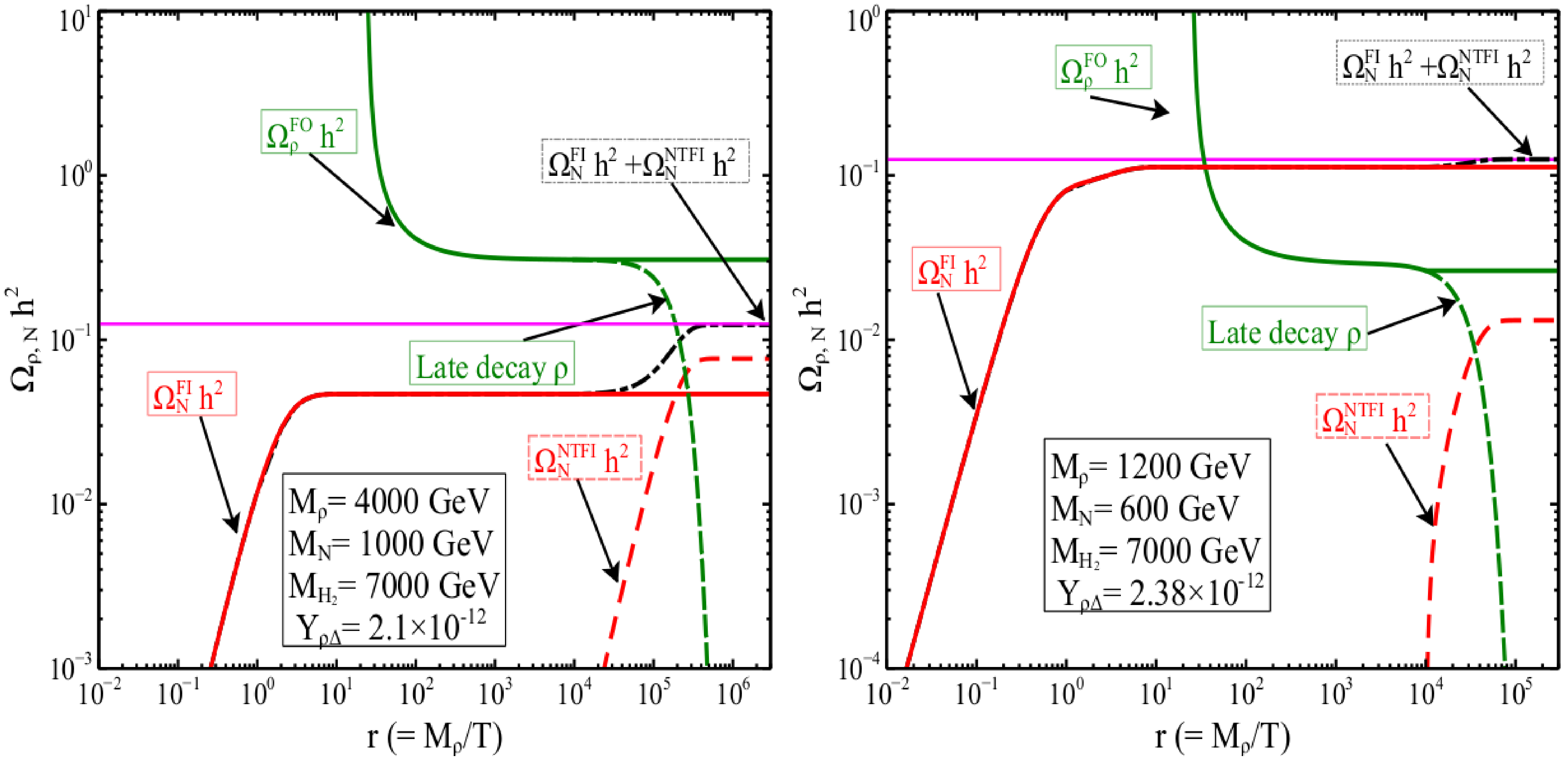
Scenario II → $M_\rho > M_N$ → 'N' is dark matter candidate.

Boltzmann Equation for the evolution of DM and NLOP:-

$$\frac{dY_\rho}{dr} = \kappa(r)\theta(M_{H_2/H_2^\pm} - (M_N + M_{\rho/\rho^\pm}))\langle\Gamma_{H_2/H_2^\pm \to N\,\rho/\rho^\pm}\rangle(Y_{H_2} - Y_N Y_\rho)$$
$$-\kappa(r)\theta(M_\rho - (M_N + M_A))\langle\Gamma_{\rho\to N A}\rangle\,(Y_\rho - Y_N Y_A)$$
$$-\sqrt{\frac{\pi}{45G}}\frac{M_{Pl}\sqrt{g_*(r)}}{r^2}\langle\sigma_{eff}|v|\rangle\left(Y_\rho^2 - (Y_\rho^{eq})^2\right)$$

$$\frac{dY_N}{dr} = \kappa(r)\theta(M_{H_2/H_2^\pm} - (M_N + M_{\rho/\rho^\pm}))\left[\langle\Gamma_{H_2/H_2^\pm \to N\,\rho/\rho^\pm}\rangle(Y_{H_2} - Y_N Y_\rho)\right] +$$
$$\kappa(r)\langle\Gamma_{\rho^\pm/\rho^0 \to N H_2^\pm/H_2}\rangle\,(Y_\rho - Y_N Y_{H_2^\pm/H_2}) +$$
$$\kappa(r)\theta(M_\rho - (M_N + M_A))\langle\Gamma_{\rho\to N A}\rangle\,(Y_\rho - Y_N Y_A)\,.$$

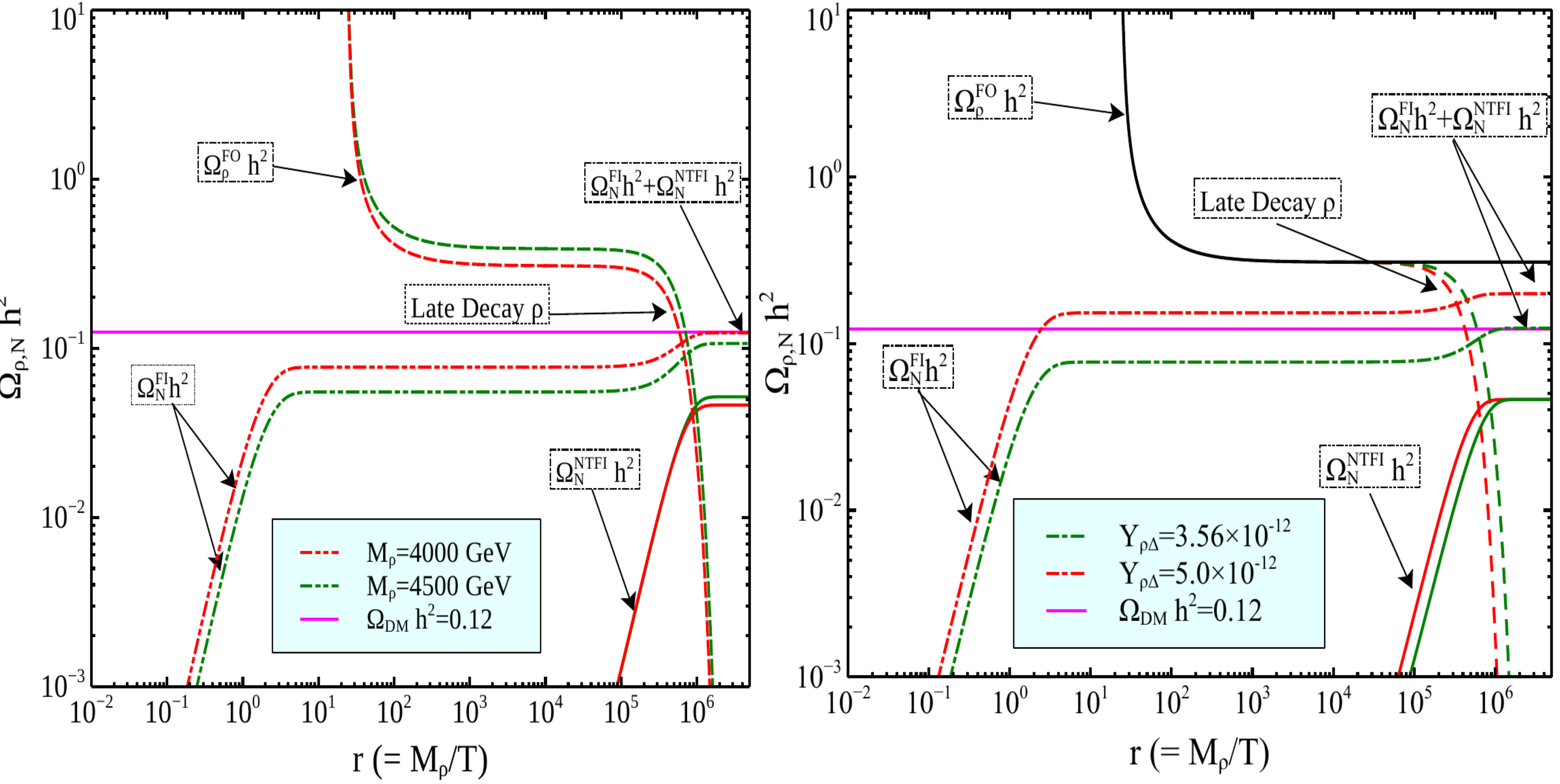
Results:-



$\Omega_\rho^{FO}\,h^2$
$\Omega_N^{FI}\,h^2 + \Omega_N^{NTFI}\,h^2$
Late decay ρ
$\Omega_N^{FI}\,h^2$
$\Omega_N^{NTFI}\,h^2$
M_ρ= 4000 GeV
M_N= 1000 GeV
M_{H_2}= 7000 GeV
$Y_{\rho\Delta}$= 2.1×10^{-12}
$\Omega_{\rho,N}\,h^2$
r (= M_ρ/T)
M_ρ= 1200 GeV
M_N= 600 GeV
M_{H_2}= 7000 GeV
$Y_{\rho\Delta}$= 2.38×10^{-12}

Results:-

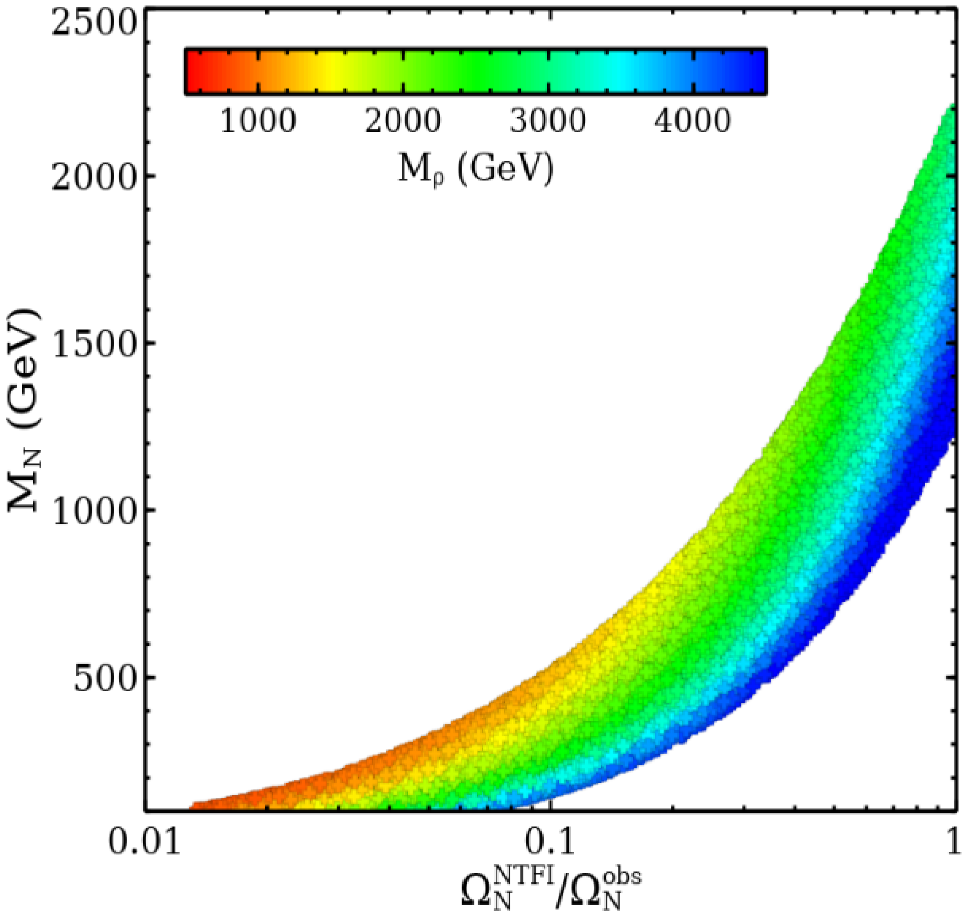
$M_\rho = 4000$ GeV, $M_N = 600$ GeV, $M_{H_2} = 7000$ GeV and $Y_{\rho\Delta} = 3.56 \times 10^{-12}$ → **Parameter fixed unless varied**

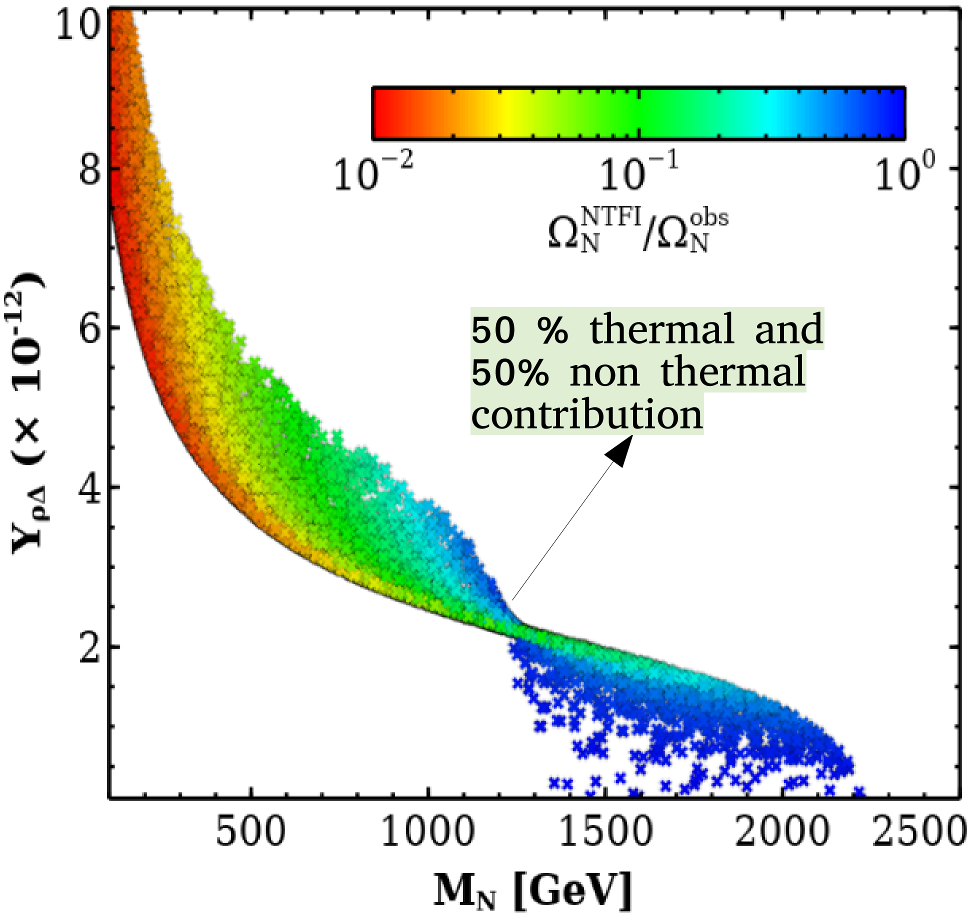


Results:-

Parameters Varied

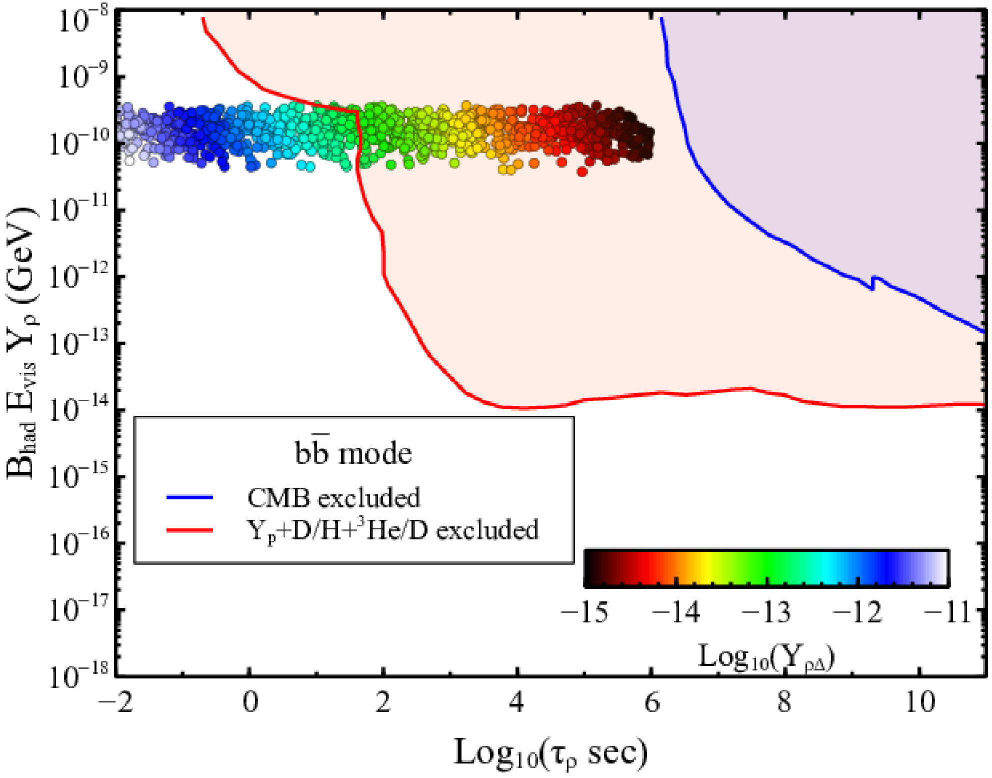
$10^{-11} < Y_{\rho\Delta} < 10^{-15}$, $100\,\text{GeV} \leq M_N \leq 1800$ GeV and $600\,\text{GeV} \leq M_\rho \leq 4500\,\text{GeV}$

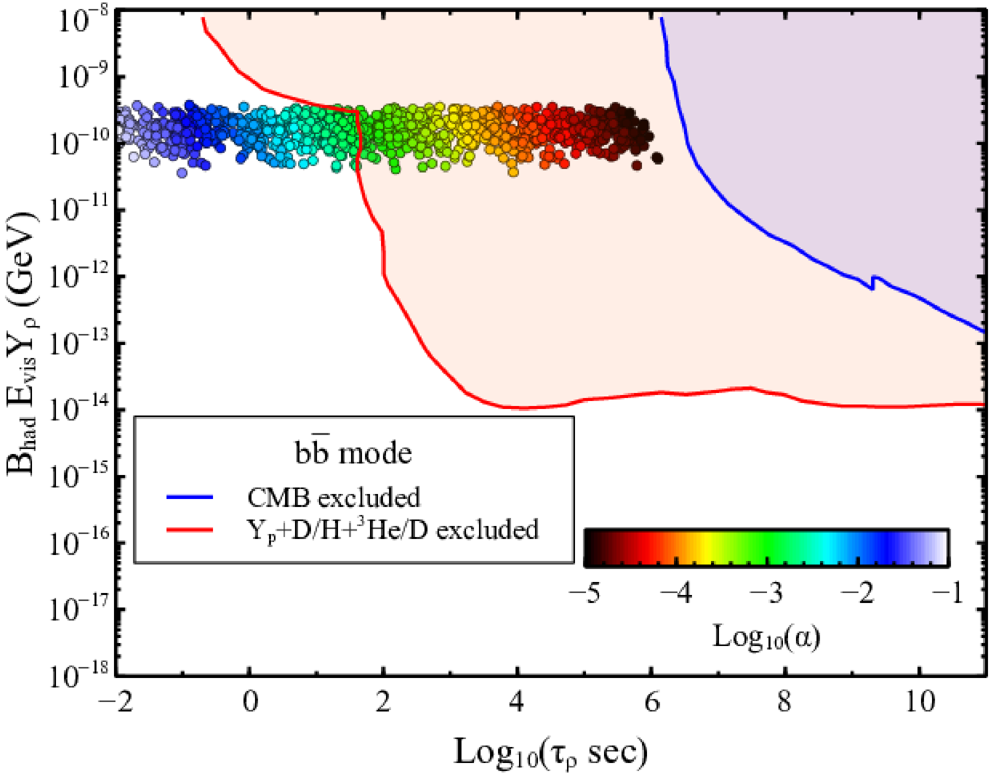




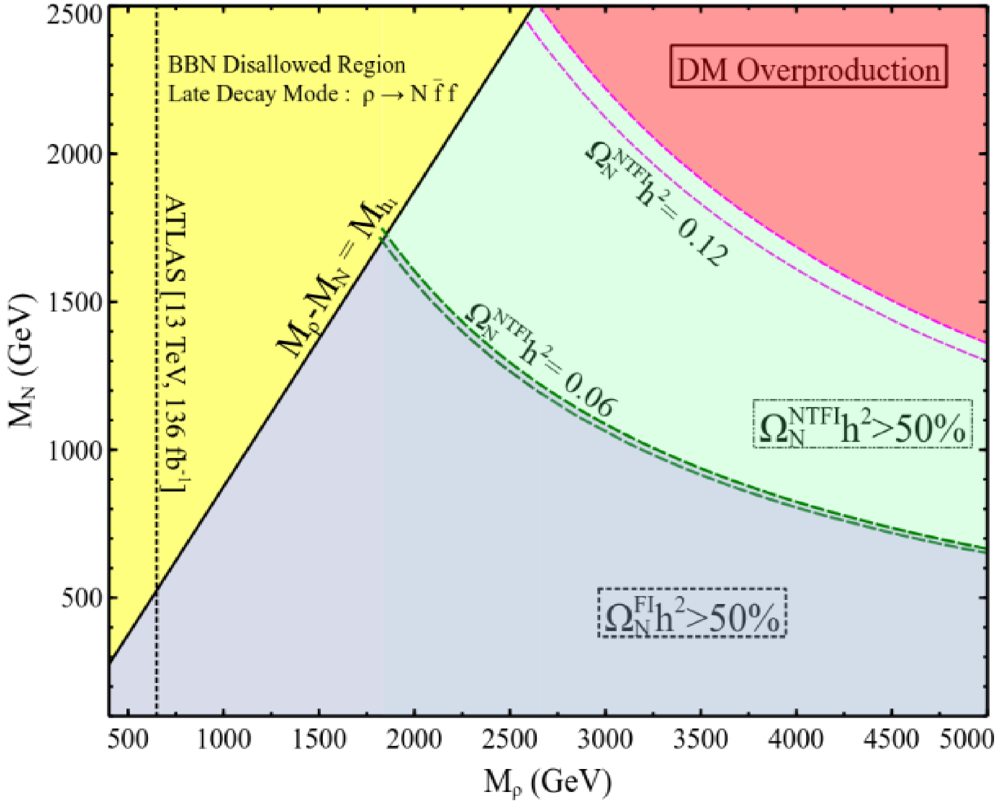
50 % thermal and
50% non thermal
contribution

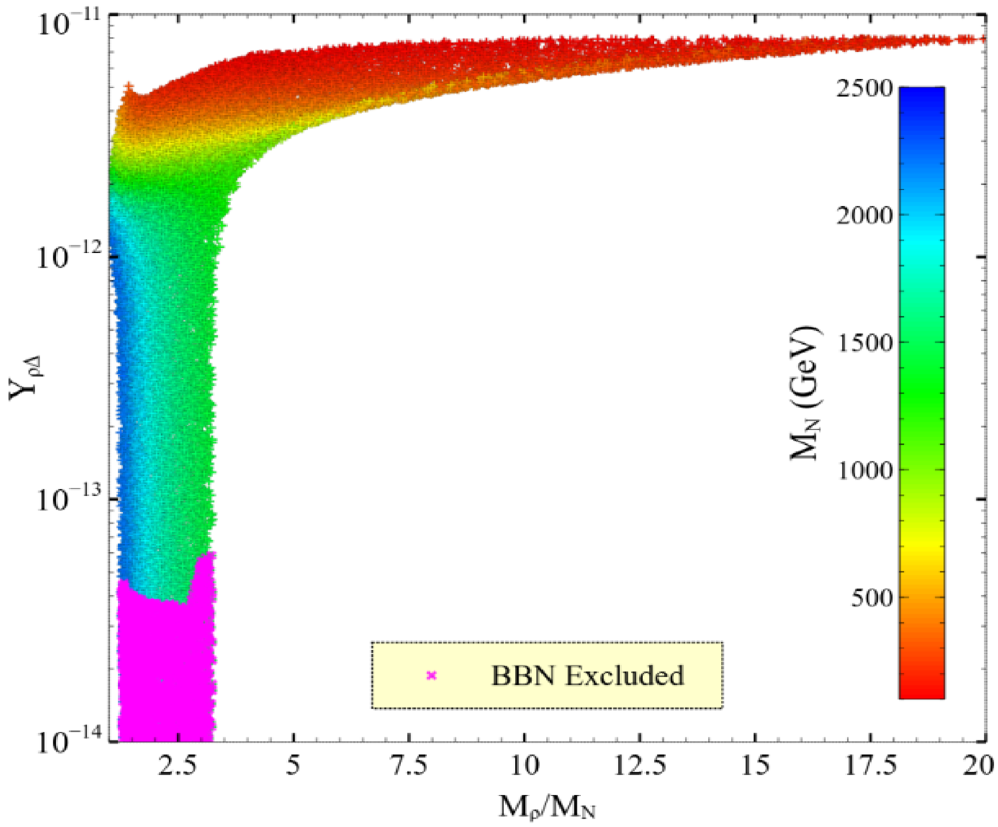
BBN Constraint:-





- All the points in LP and RP satisfy observed DM relix density.
- Lower value of YρΔ and sin α gets rules out from BBN due to excess hadronic injection to plasma at late times.

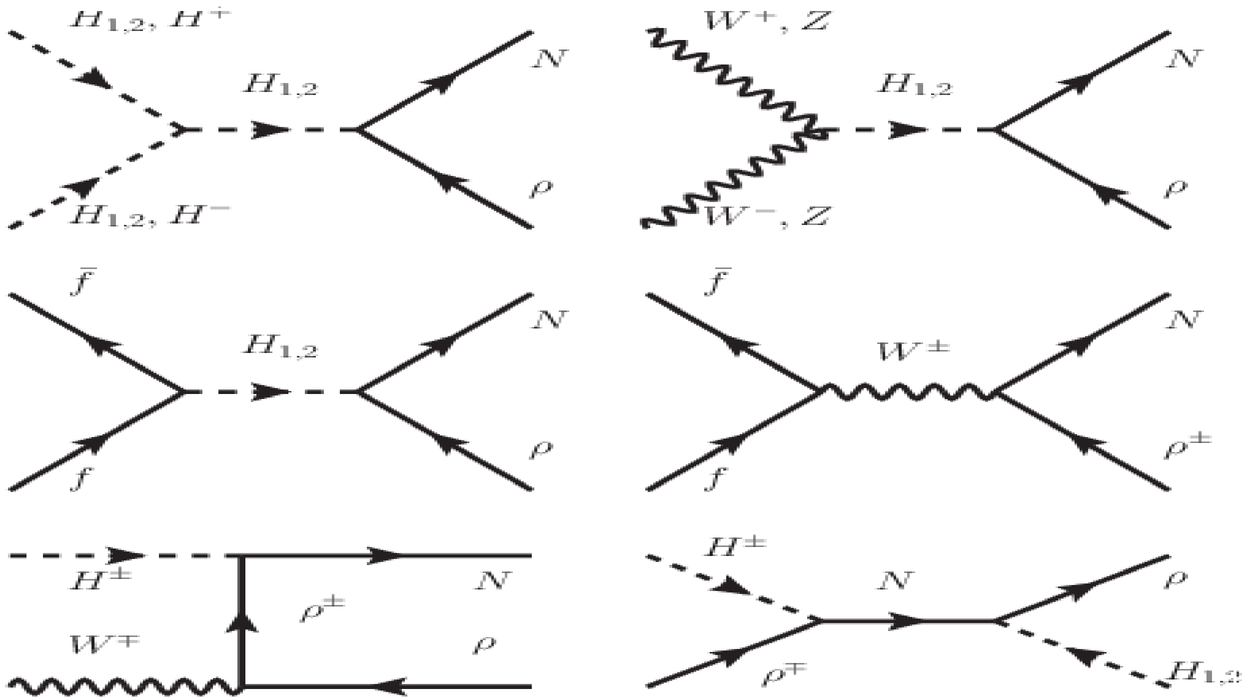




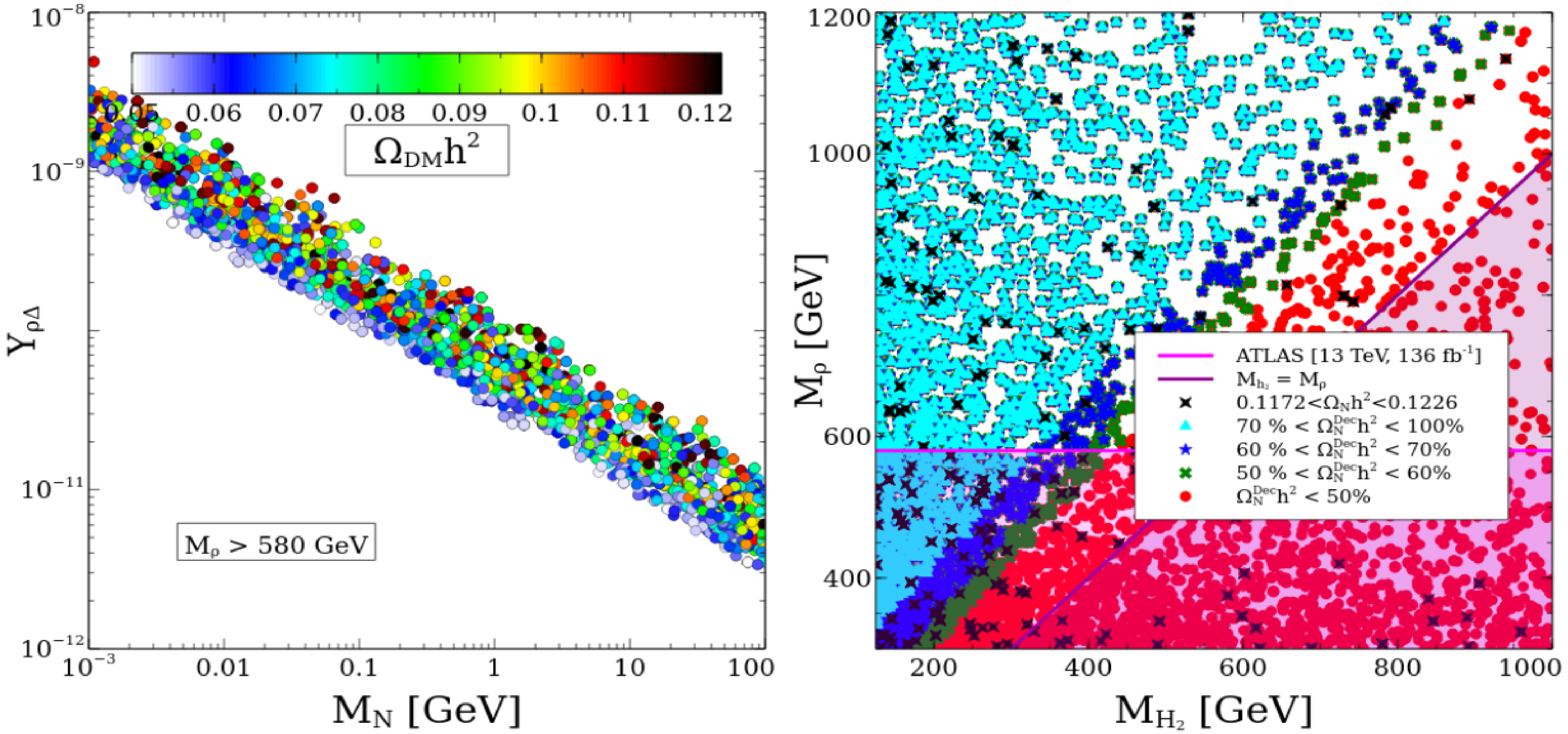
- LP: the yellow region is ruled out by the BBN bound, and the red region is overproduced because Mρ > 2400 GeV, the green region NTFI dominating and the grey region is FI dominating.
- RP: small ratio region contributes small mass splitting between N and ρ. This result in large non thermal contribution and less sensitive to YρΔ.

Results: allowing for a light scalar sector.

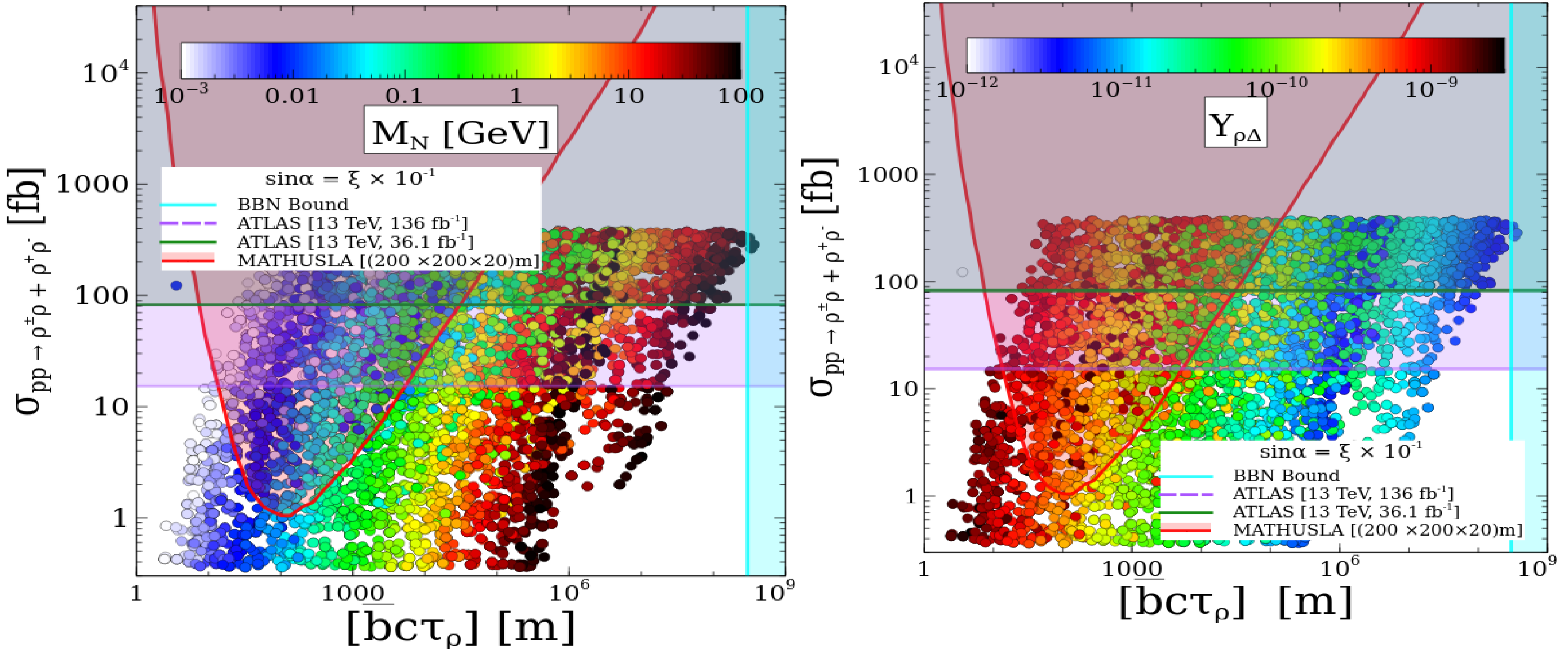
- In previous scenarious, ‘**N**’ is dominantly produced through decay at high temperature.
- Now, we assume ‘**N**’ is produced through annhilation of bath particles and production through decay is kinematically forbidden.



Fusion dominated scenario: $M_\rho < M_N$ **and** $M_{H_2} < M_\rho + M_N$



Substantial Annhilation Contribution: $M_N < M_\rho$ and $M_{H_2} < M_\rho + M_N$



- Large portion of the region is already ruled out by the ATLAS 136 fb^{-1} data.
- MATHUSLA can detect MeV to GeV range DM mass with the large coupling strength.

Conclusion:-

- The present work can solve two well-accepted SM problems namely a dark matter candidate and the origin of the neutrino mass.
- We investigated different production mechanism for the production of DM.
- We also constrained our model paramters through BBN and found the model to viable in large areas of parameter space.
- We investigated the possible detection prospects of FIMP DM at the MATHUSLA detector
- Detailed collider anaylsis and cosmological implication of our model is left for our future work.

THANK YOU
for your
ATTENTION!