WIMP and FIMP Dark Matter in Singlet-Triplet Fermionic Model

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LHC Higgs Working Group WG3 (BSM) -- Extended Higgs Sector subgroup meeting

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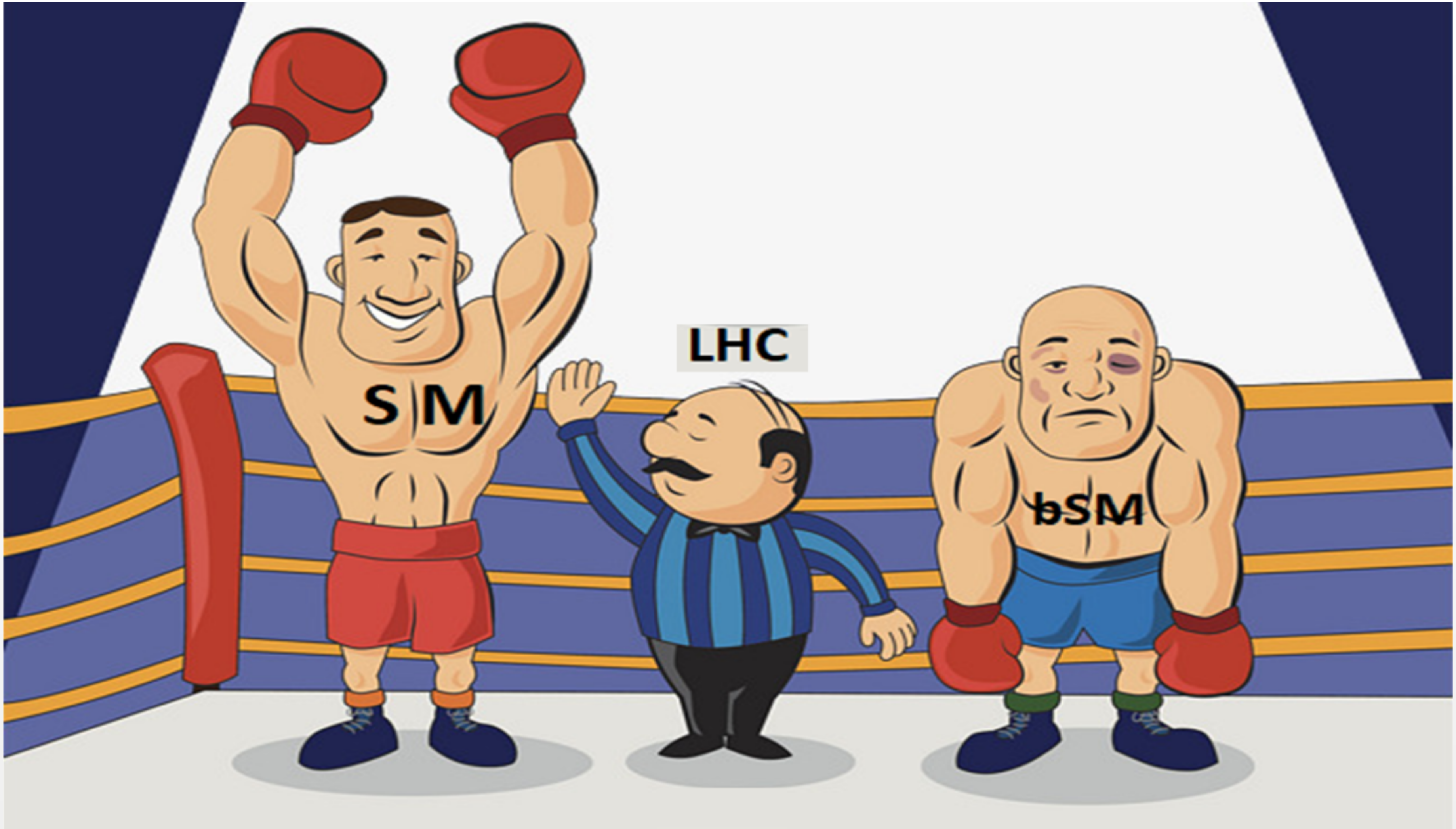
Outline

- Introduction
- Model Introduction and Motivation
- Constraints
- Dark Matter Production Mechanism
- Results based on STFM
- Summary



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

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

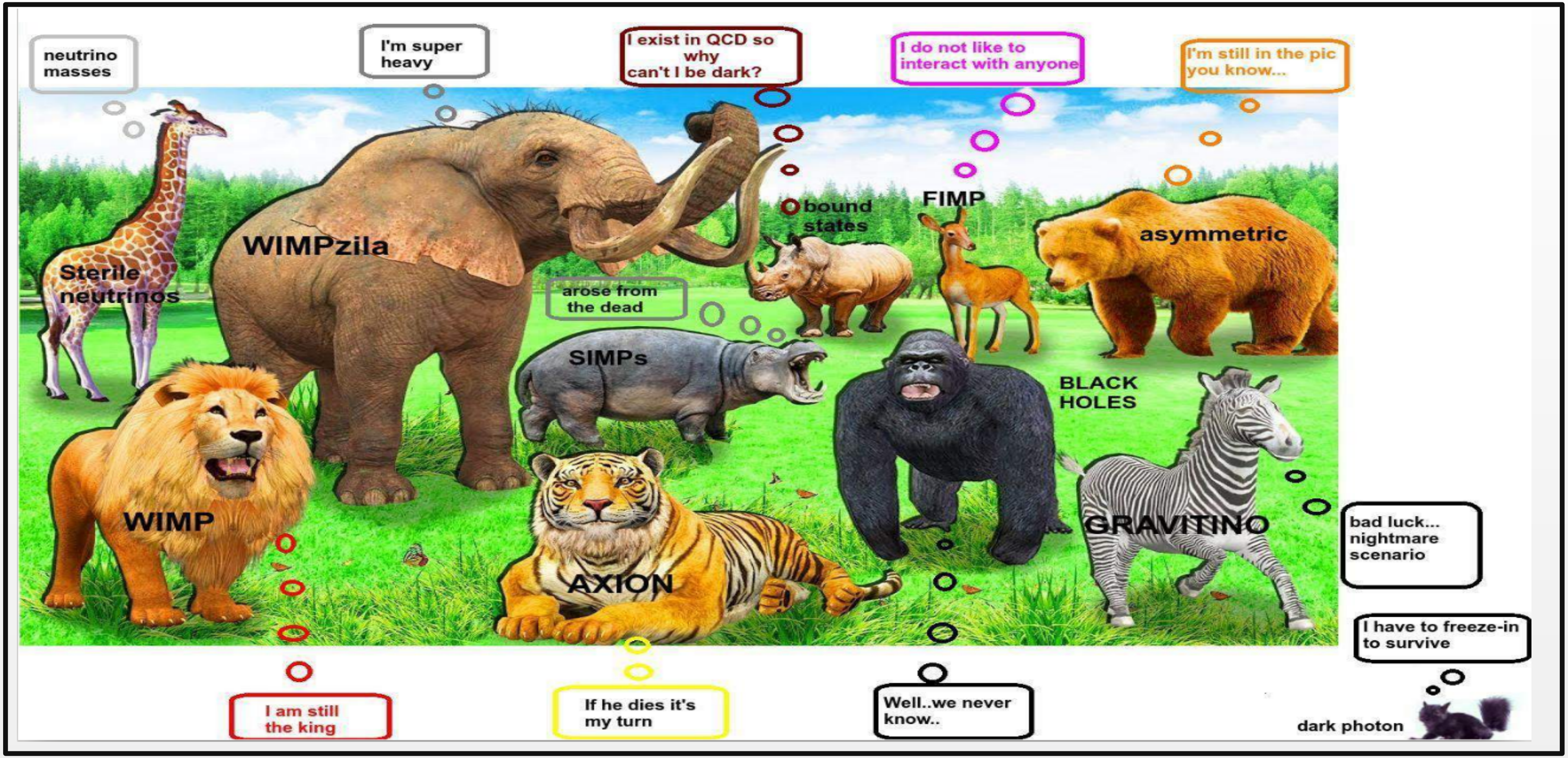


Image credit: Google

STFM 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
$\mathbb{Z}_2$	+	+	+	+	+	−	+	+	−	+	+

Particle content and their corresponding charges under various symmetry groups.

The complete Lagrangian for the model:-

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{3} Tr\left[\bar{\rho}_i\, i\,\gamma^\mu D_\mu \rho_i\right] + \bar{N'}\, i\,\gamma^\mu D_\mu N' + Tr[(D_\mu\Delta)^\dagger (D^\mu\Delta)] - V(\phi_h, \Delta)$$

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

Yukawa interaction term for neutrino mass generation in the Type III seesaw mechanism.

Higgs triplet is necessary

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

- ϕ_h accquires vev and EWSB takes place.
- Δ_0 acquires an 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.

$$H_1 = \cos\alpha \, H + \sin\alpha \, \Delta^0$$
$$H_2 = -\sin\alpha \, H + \cos\alpha \, \Delta^0$$

SM like Higgs

CP even neutral Higgs mixing

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

$$G^\pm = \cos\delta \, \phi^\pm + \sin\delta \, \Delta^\pm$$
$$H^\pm = -\sin\delta \, \phi^\pm + \cos\delta \, \Delta^\pm$$

Charged Higgs

$$\tan\delta = \frac{2 \, v_\Delta}{v}$$

Charged Higgs mixing

Dark Sector

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

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

Mixing between singlet and triplet states due to $Y_{\rho\Delta}\ Tr[\bar{\rho}_3\,\Delta]\,N'$

where the mixing angle is,

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

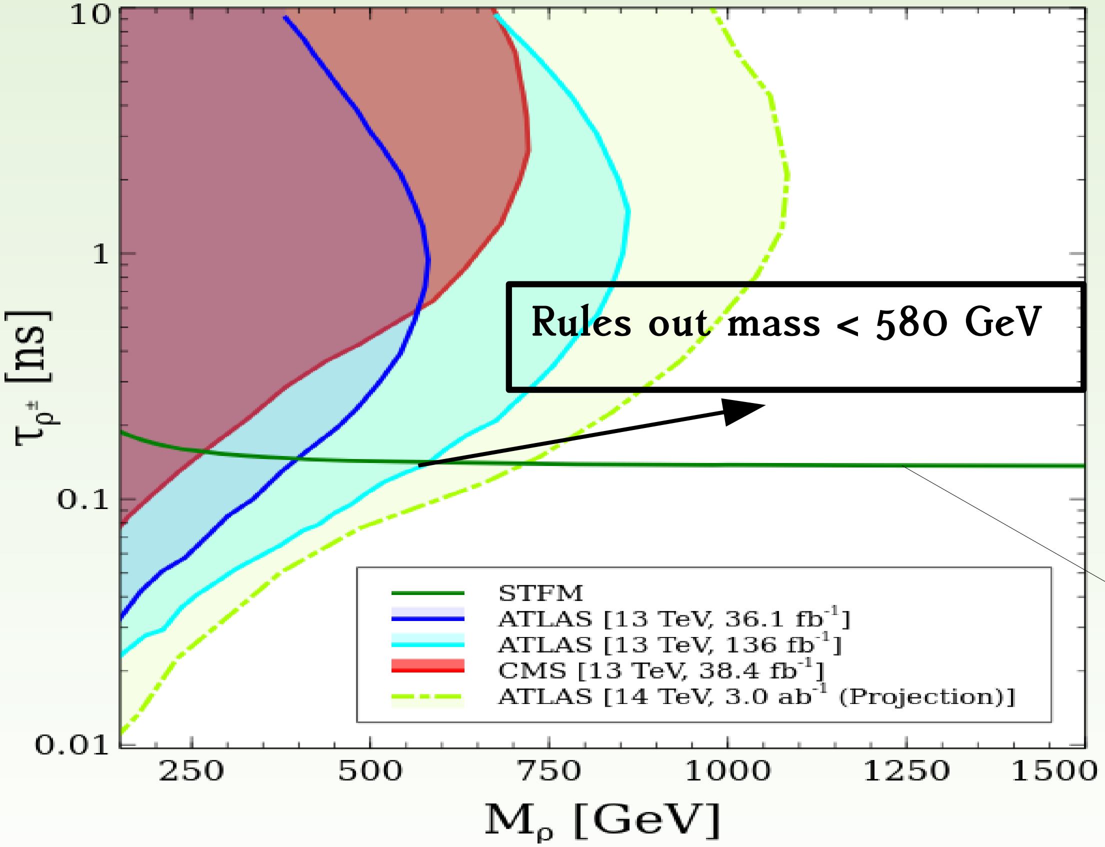
In the limit $Y_{\rho\Delta} \sim \mathcal{O}(10^{-10})$,

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

N is primarily singlet and ρ is primarily triplet states

DM Constraints:-

Collider constraints on ρ :-



ρ contains ρ^0 and $\rho^\pm$

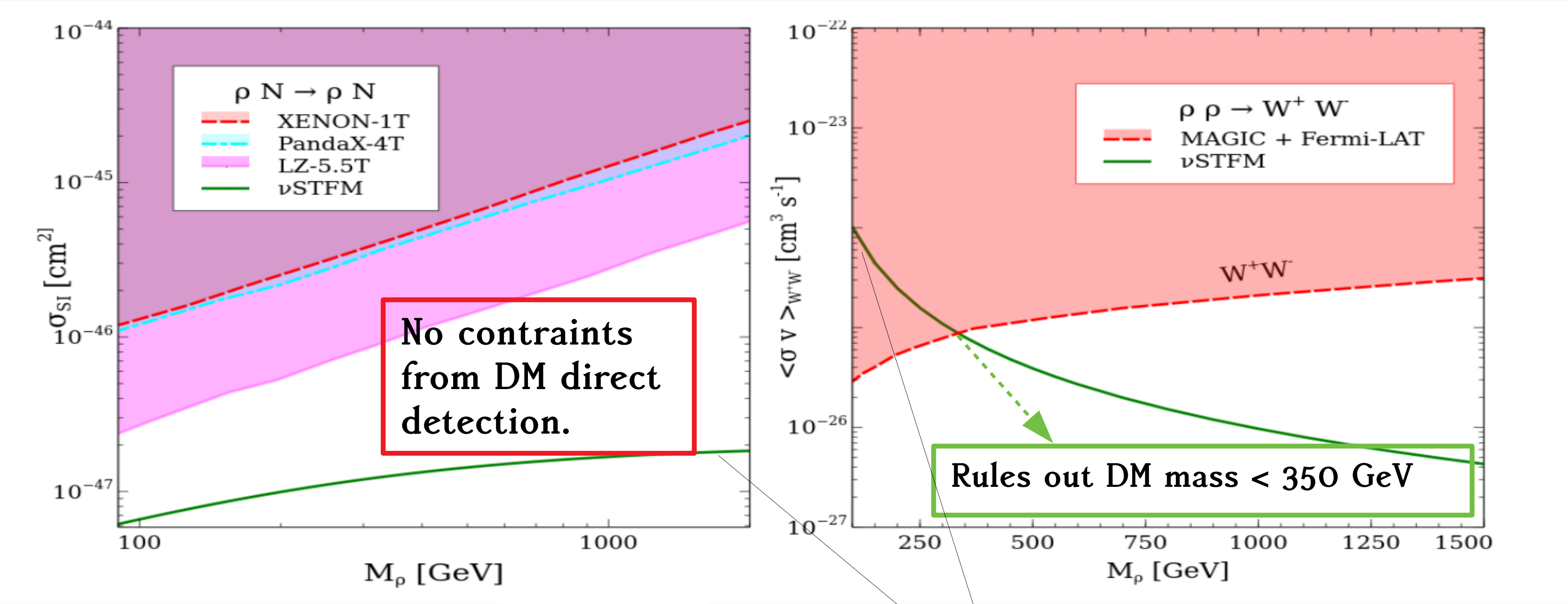
$$\Delta M = M_{\rho^\pm} - M_{\rho^0} = 167\ MeV$$

$$\rho^\pm \rightarrow \rho^0 \pi^\pm$$

Decay of $\rho^\pm$ manifest itself as disappearing track signal

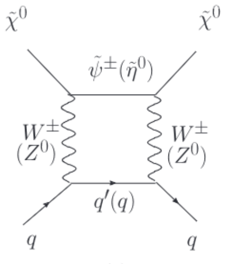
Theory Prediction

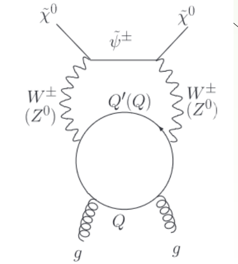
DM direct and Indirect Detection



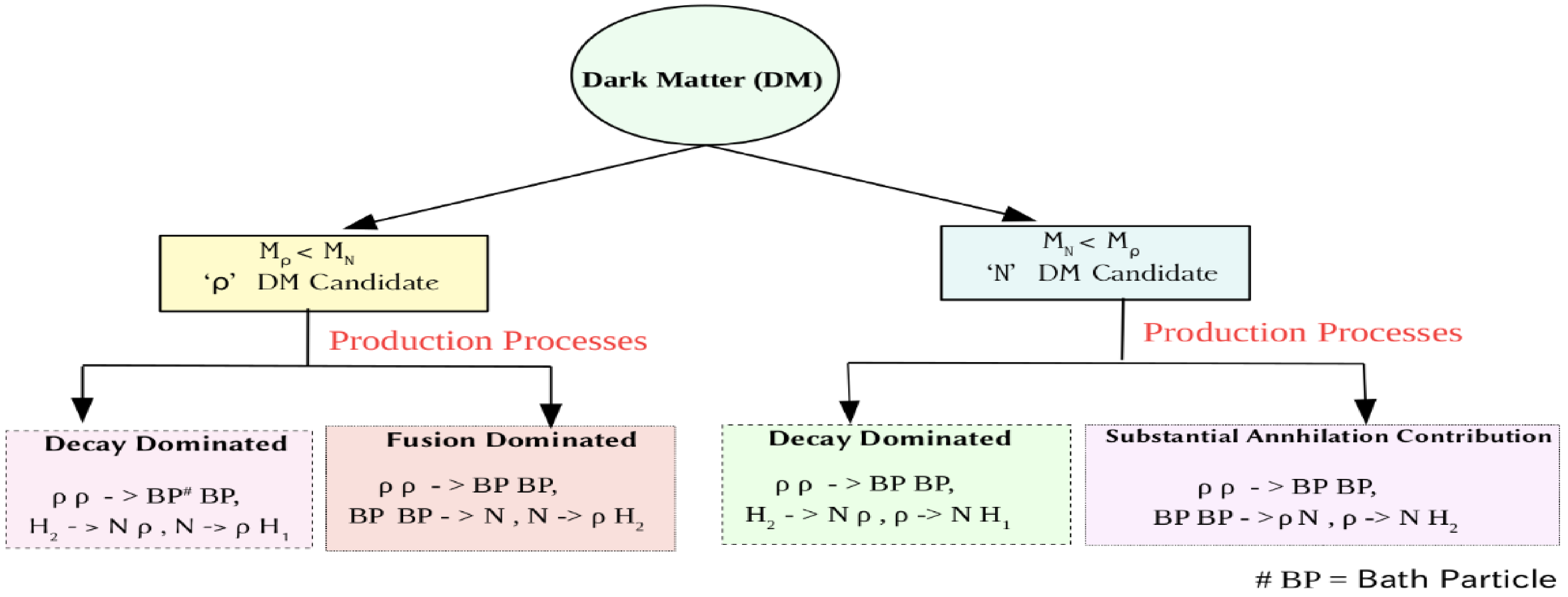
- No tree level diagram
- One loop mediated by W and two loop gluons

[JHEP07(2011)005]





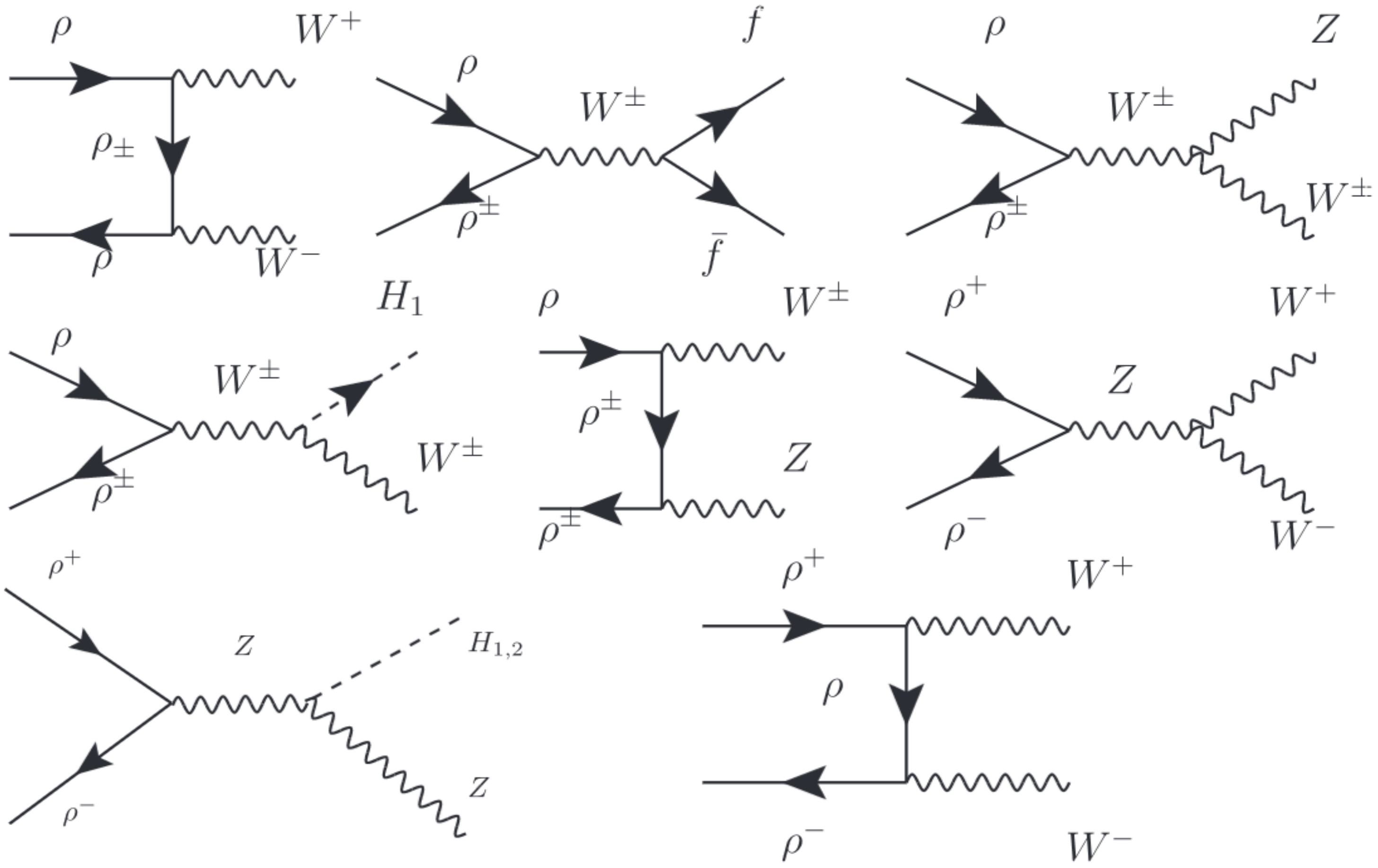
Theory Prediction



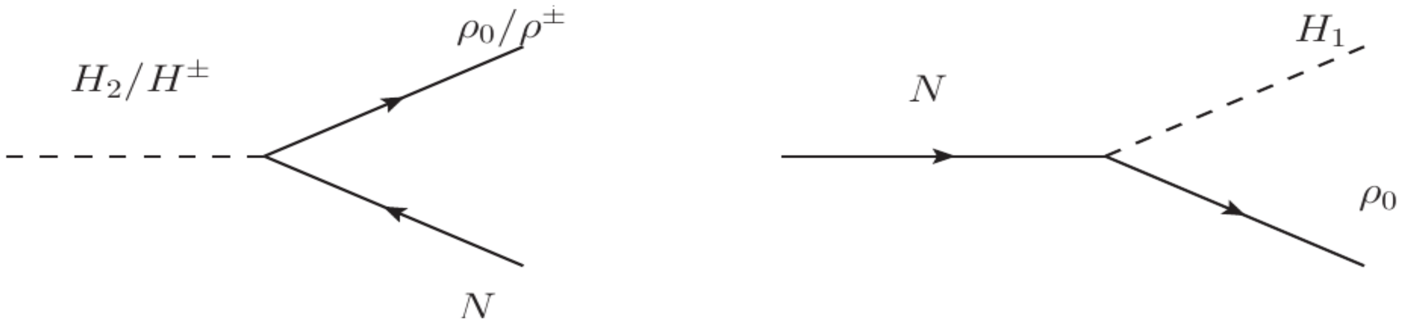
- WIMP Dark Matter
- DM is in thermal bath
- Annihilation of bath particles, decay of H_2 and late decay of N plays important role.

- FIMP Dark Matter
- N is non thermal
- Freeze-in production through decay and annihilation of bath particles.
- Late Decay of ρ also contributes substantially.

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



Annhilation and co-annihilation channels of ρ in the early Universe .



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'

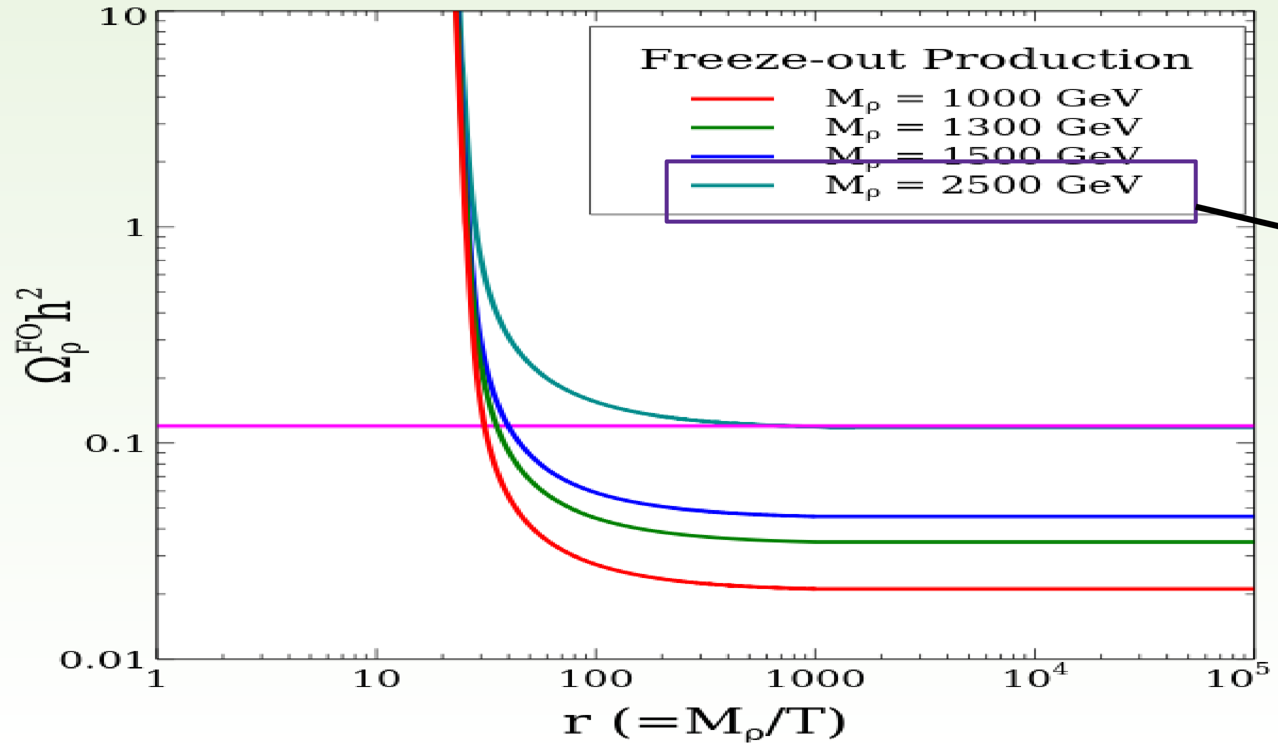
where,

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

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

B.eqn for the evolution of DM:

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

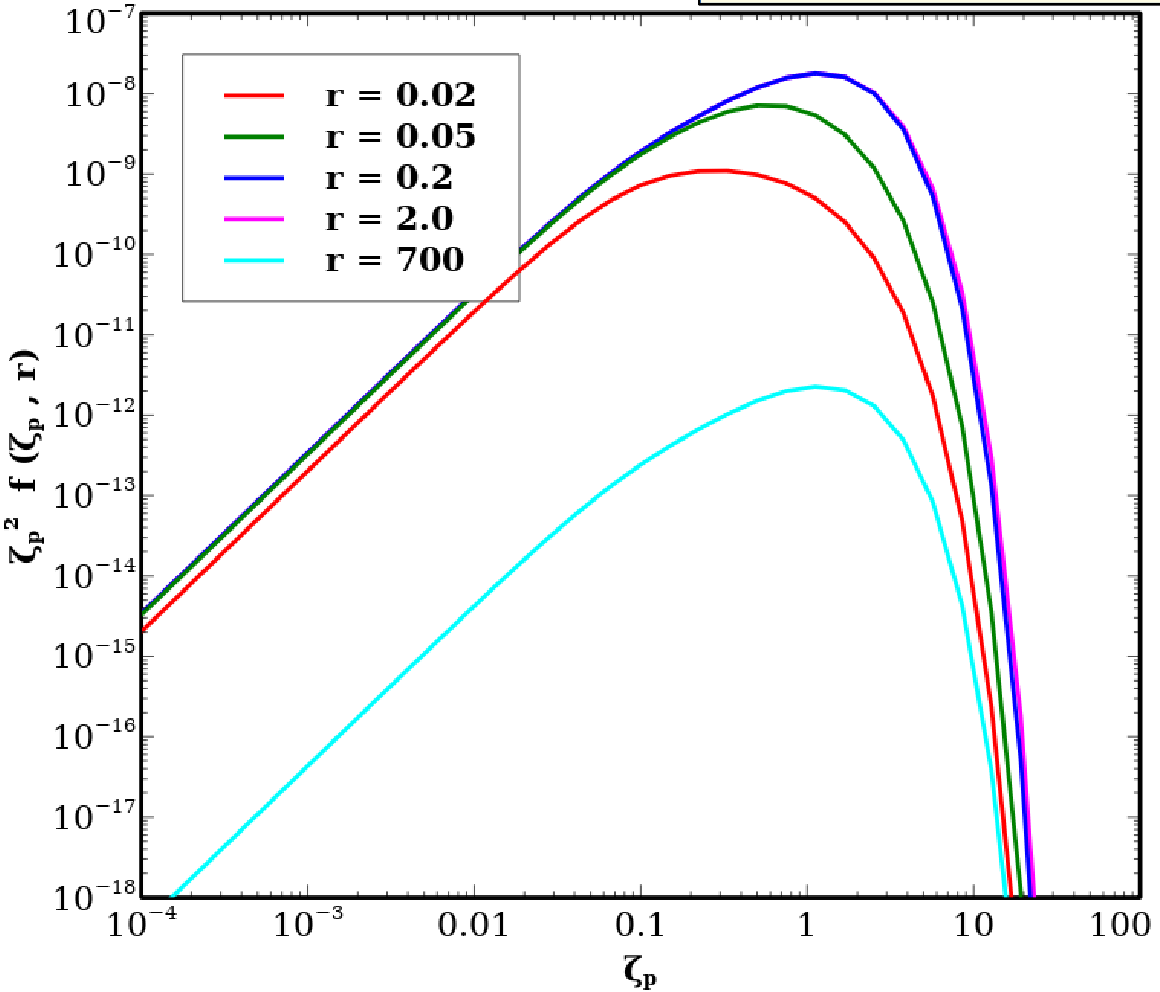


Satisfy the observed DM relic density

Evolution of distribution function for 'N'

Benchmark Point

$M_N = 2000\ \text{GeV},\ M_\rho = 1300\ \text{GeV},\ Y_{\rho\Delta} = 2.5 \times 10^{-12}.$



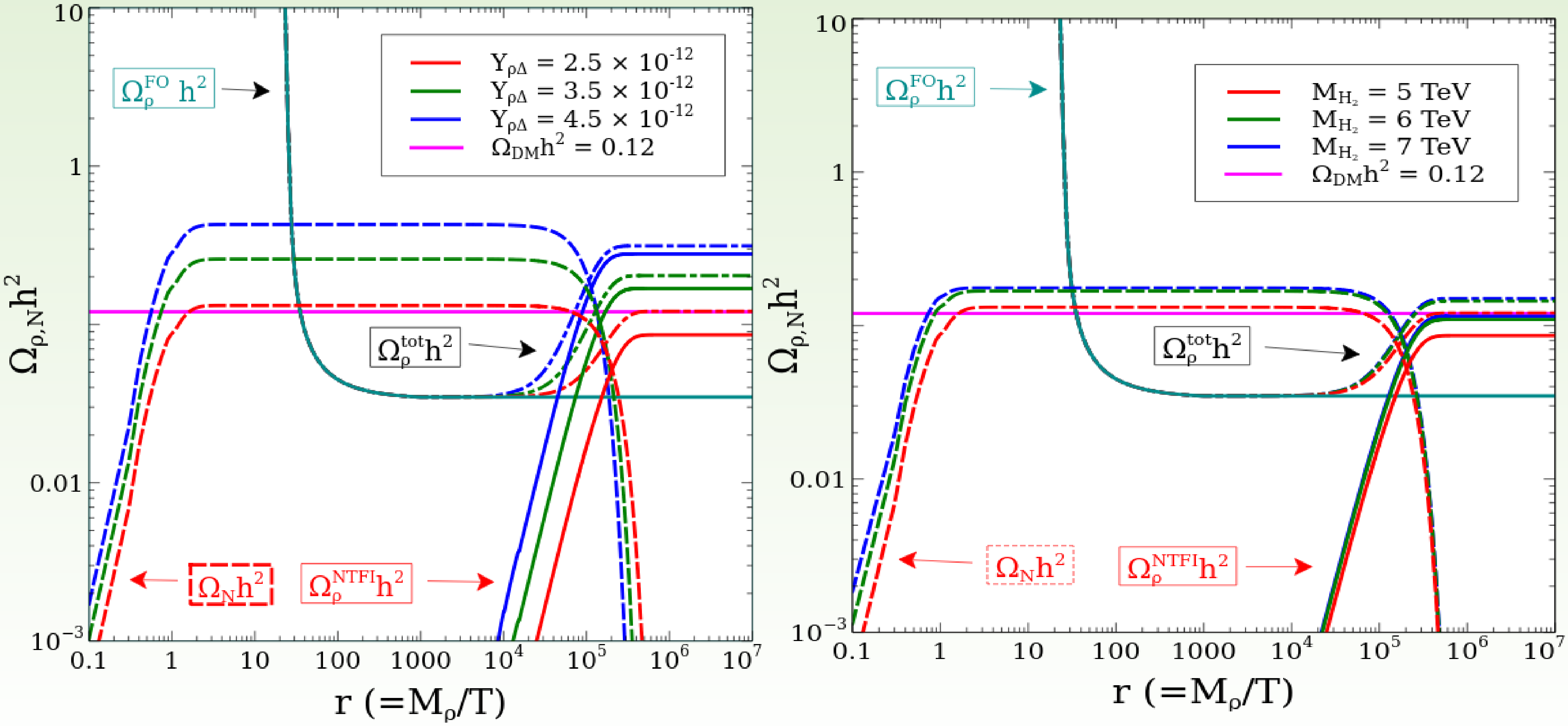
$$n_N(r) = \frac{g\,T^3}{2\pi^2}\,\mathcal{B}(r)^3 \int d\xi_p\, \xi_p^2\, f_N(\xi_p, r)$$

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

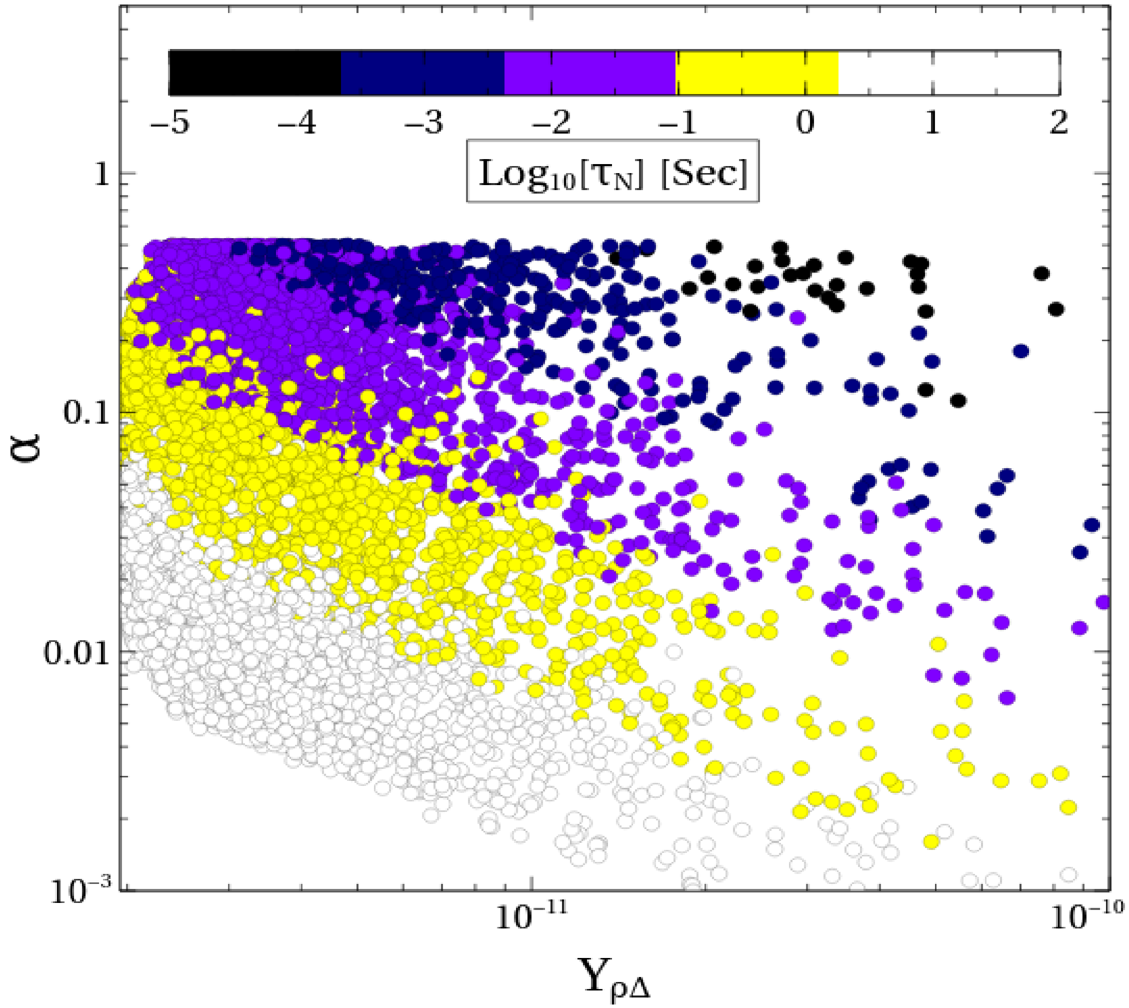
where,

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

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



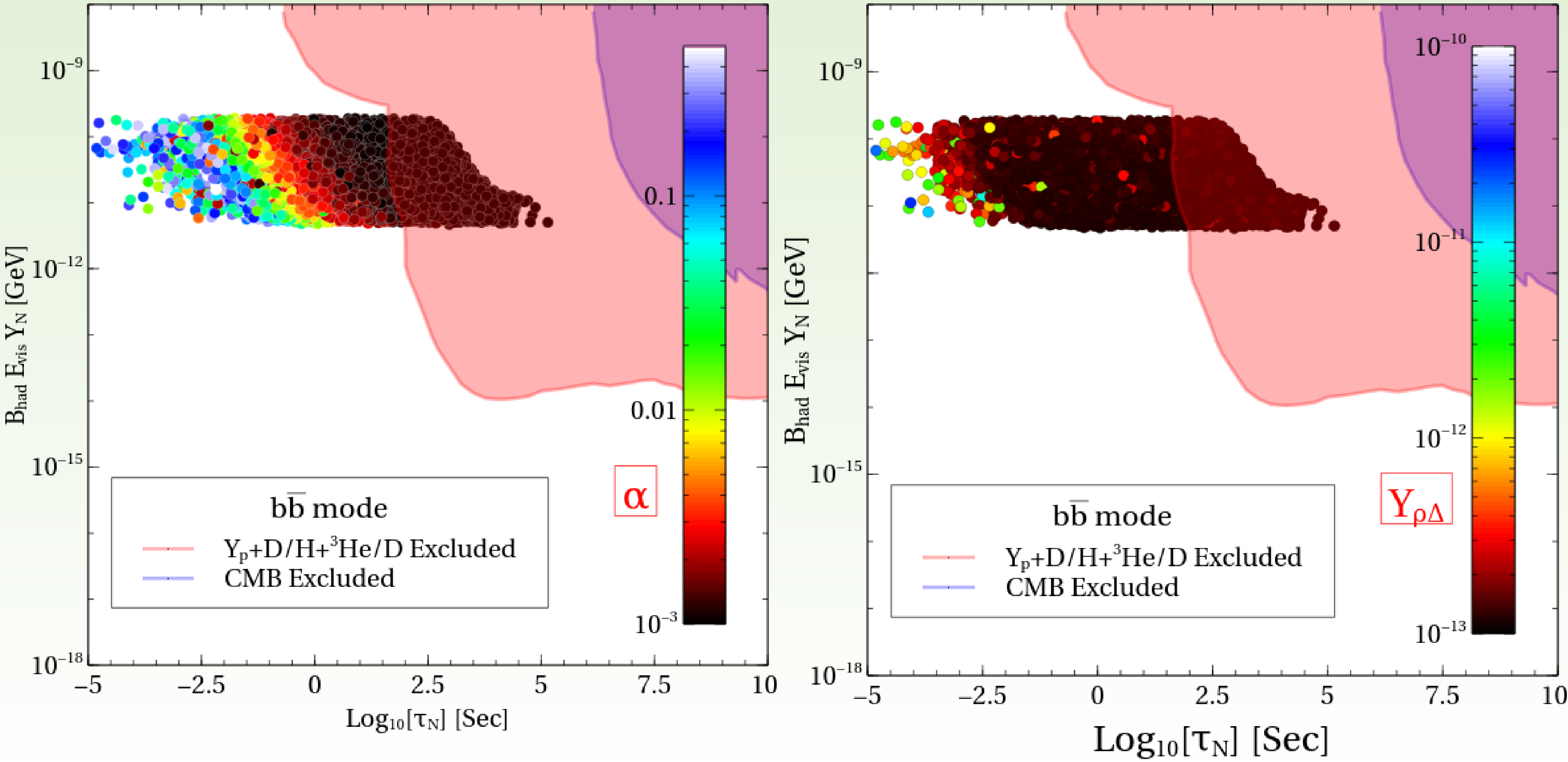
Results:-



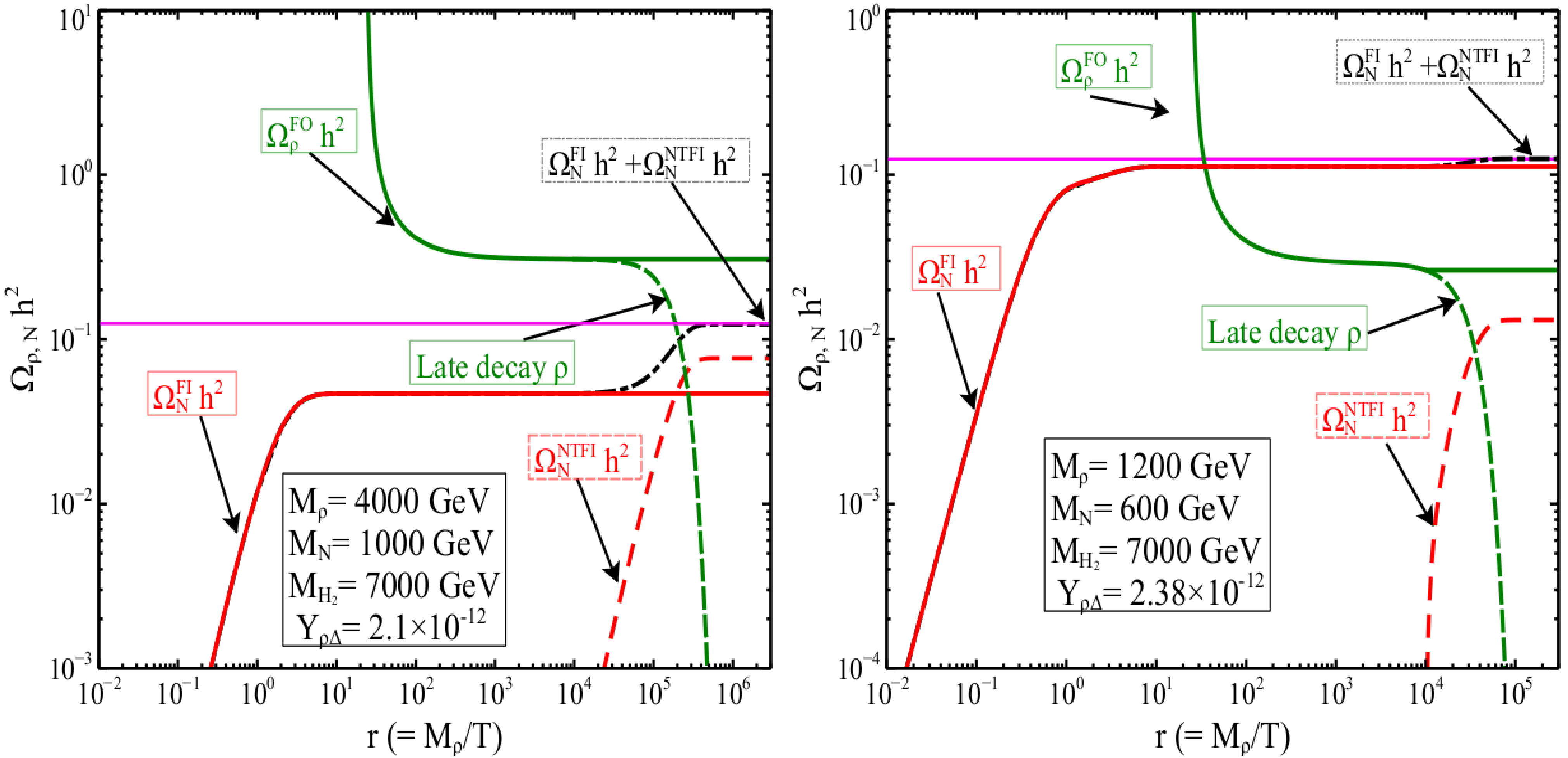
Parameters Varied

$$
\begin{aligned}
700 \text{ GeV} &< \quad M_\rho \quad < 1500 \text{ GeV}, \\
125 \text{ GeV} &< M_N - M_\rho < 3000 \text{ GeV}, \\
1500 \text{ GeV} &< \quad M_{H_2} \quad < 20000 \text{ GeV}, \\
10^{-13} &< \quad Y_{\rho\Delta} \quad < 10^{-10} \\
10^{-3} &< \quad \alpha \quad < 0.5 .
\end{aligned}
$$

BBN Constraint



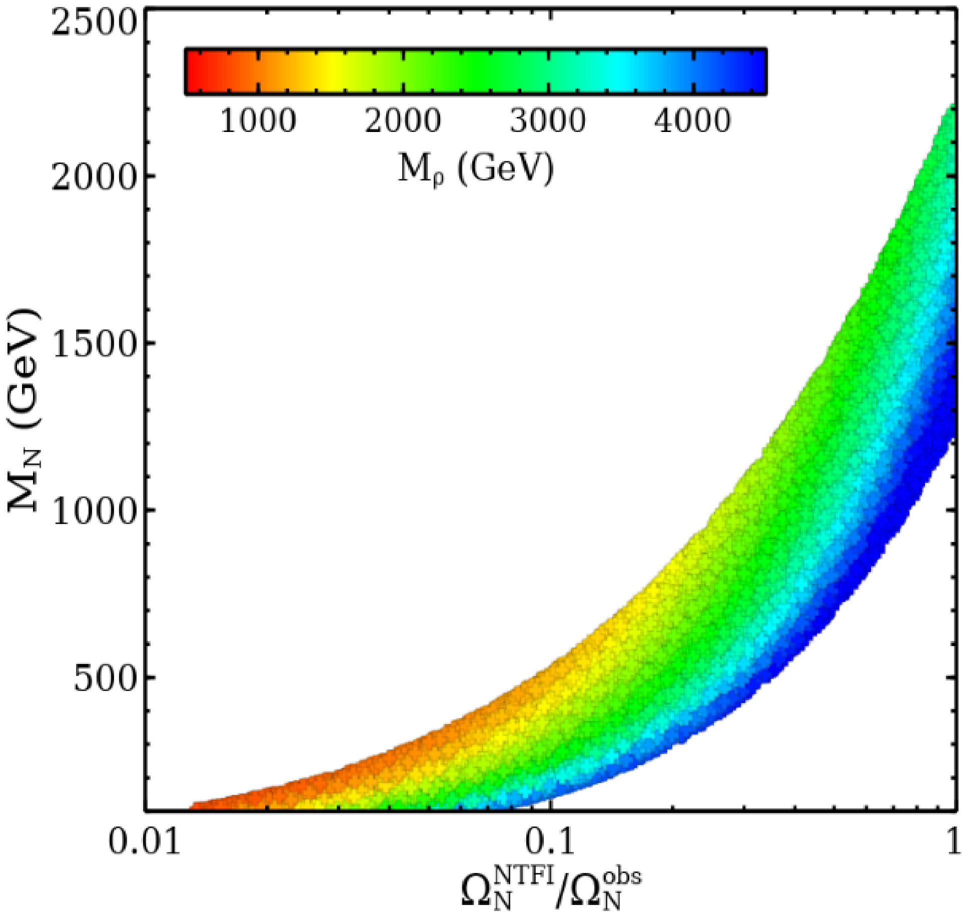
Scenario II → $M_\rho > M_N$ → 'N' is dark matter candidate.

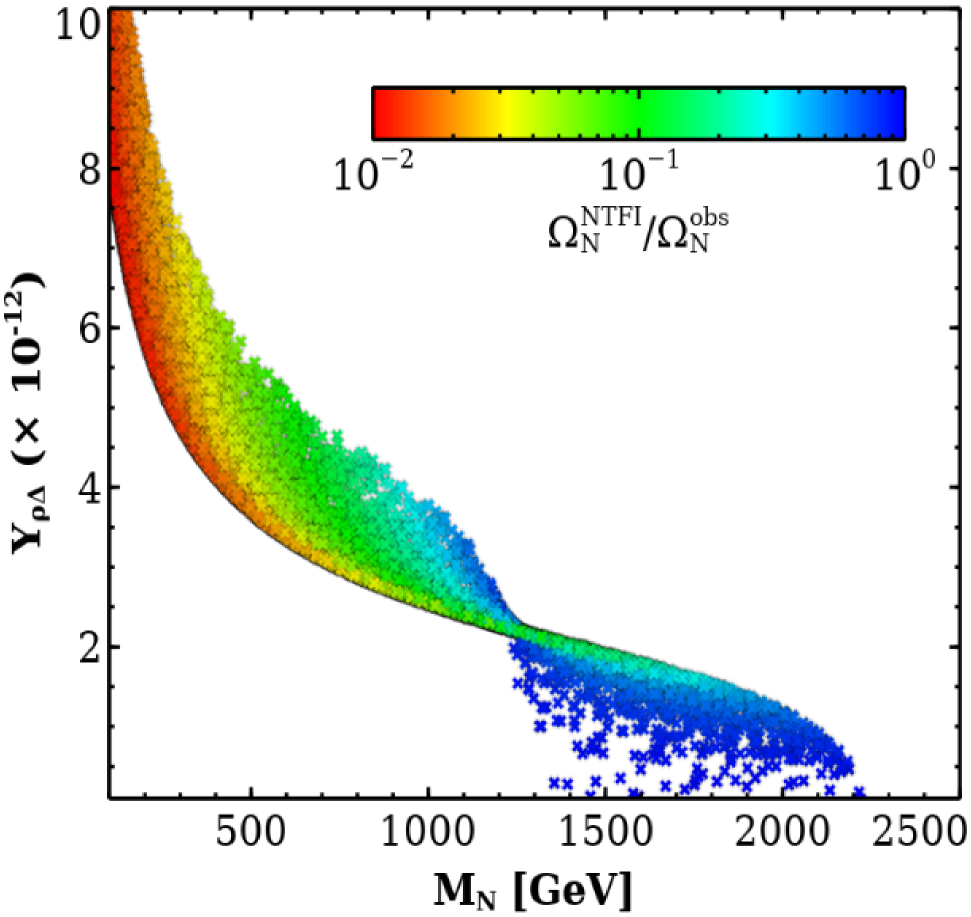


Results:-

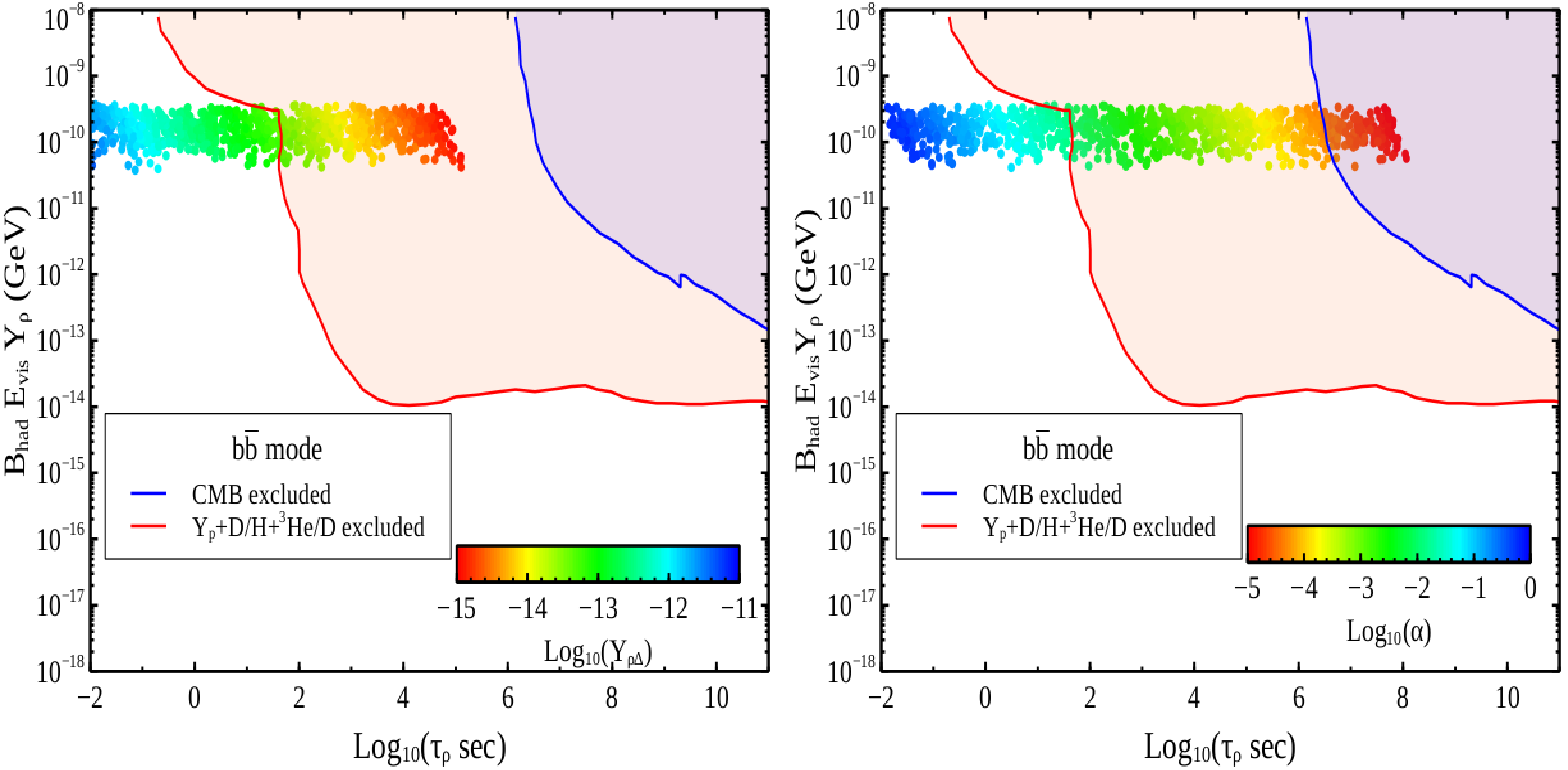
Parameters Varied

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



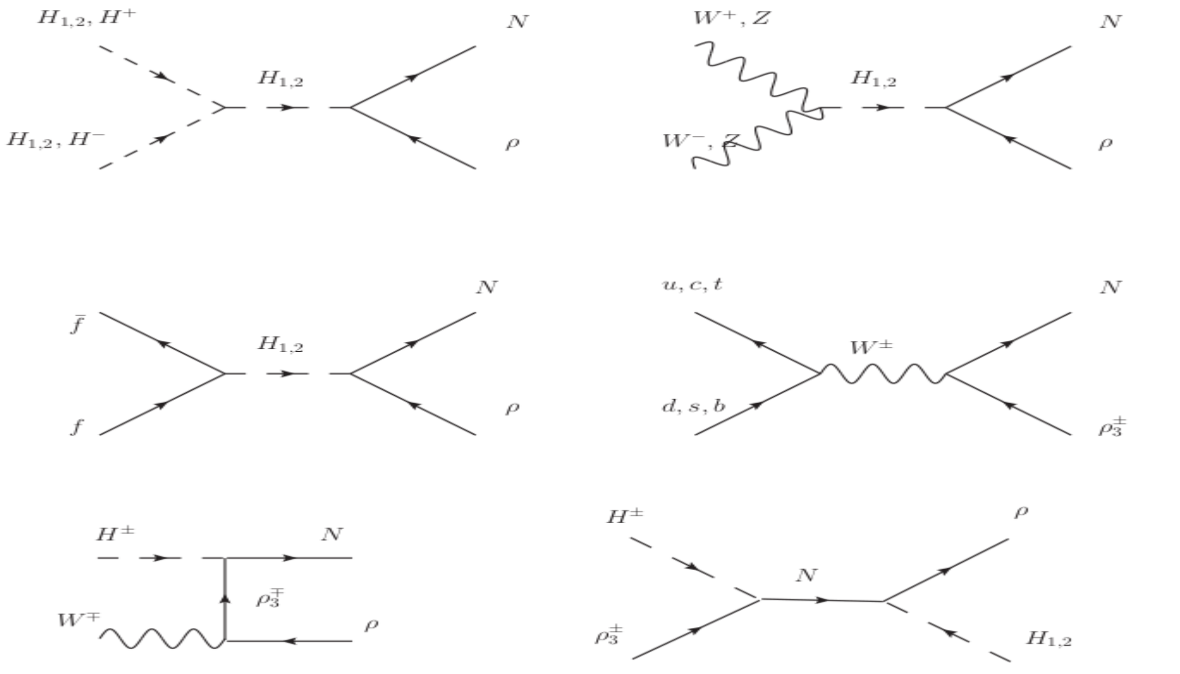


BBN Constraint:-



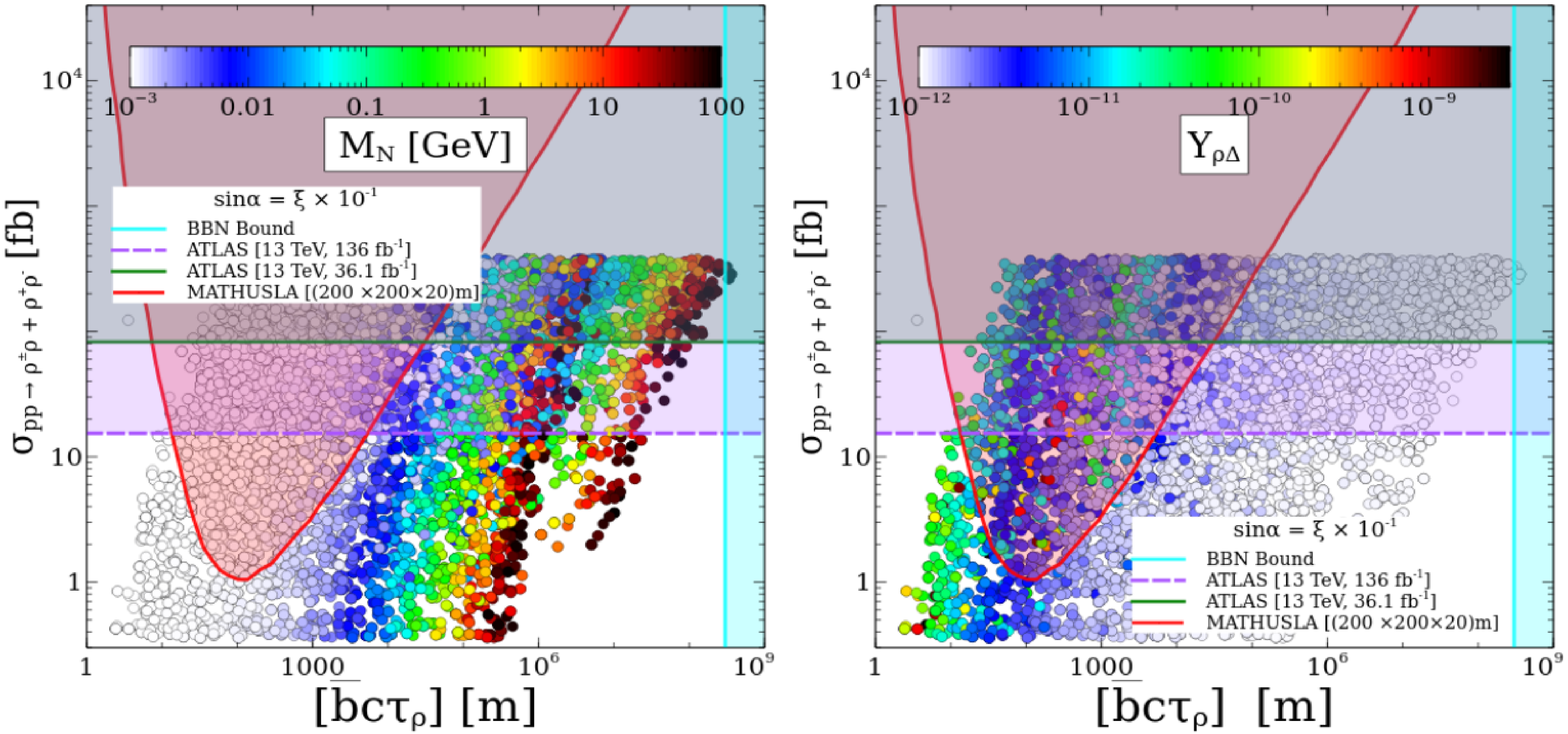
Results: allowing for a light scalar sector.

- 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.



Production channels for N.

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



Summary

- We extended SM with three fermion triplet, one singlet and one real triplet to explain DM and 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.

- If the channel $H_2 \to \rho N$ is kinematically forbidden, observed dark matter relic density can also be realised with a few hundred GeV BSM Higgs and such scenario can be probed in MATHUSLA.

THANK YOU
for your
ATTENTION!