Extended Higgs Sector in Singlet-Triplet Fermionic Model for Dark Matter and Neutrino Mass

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JHEP 11 (2022) 133, G. Belanger, S. Choubey, R. M. Godbole, S. Khan, M. Mitra, A. Roy

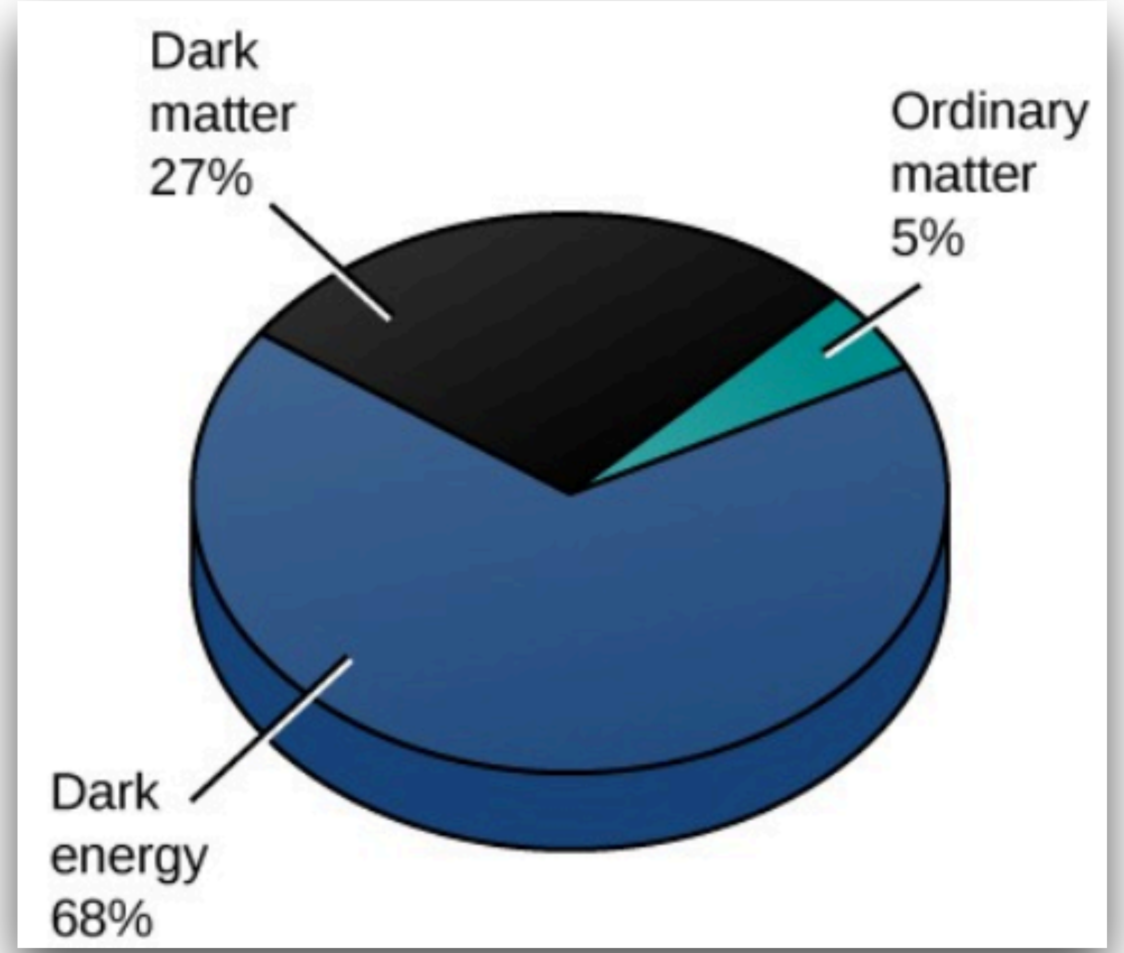
Major Questions in Modern Particle Physics ?

Dark Matter?

Relic density

$$\Omega h^2 = 0.1186 \pm 0.0020$$

Planck collaboration, 2018



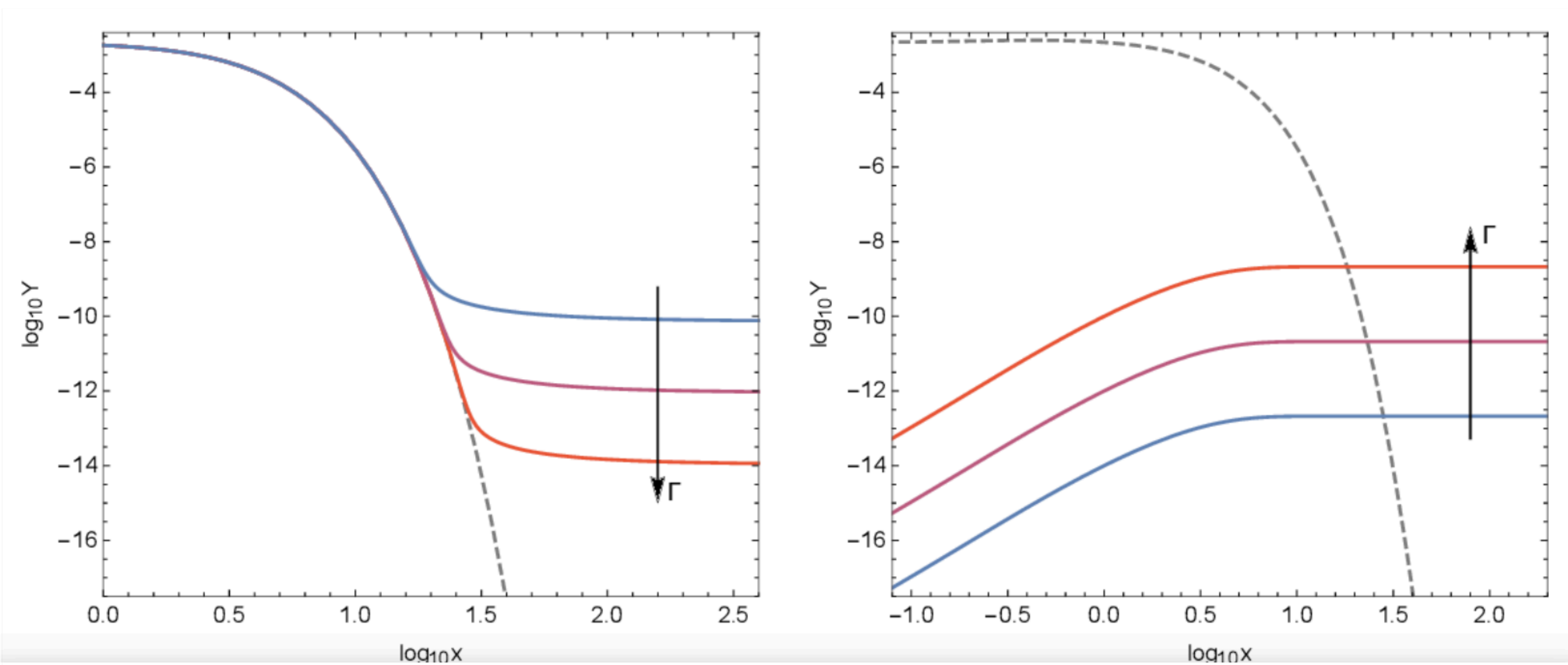
- Weakly interacting massive particle
- Feebly interacting massive particle
- Other production mechanisms, such as conversion driven freeze out, dark sector number changing processes

Theoretical description for particle dark matter??

Testing DM and associated BSM descriptions in experiments??

DarkMatter Production

- **Weakly interacting massive particle**
- **Feebly interacting massive particle**



Singlet-Triplet Fermionic Model

Renormalizable Lagrangian

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

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

Higgs triplet is necessary

$\rho_{1,2}$ **for neutrino mass**

ρ_3, N' **for dark matter**

Nucl. Phys. B394 (1993) 35, Eur. Phys. J. C78 (2018) 302 [1711.08888], *JHEP* 11 (2022) 133

BSM fields

$N' \to SU(3)_c \times SU(2)_L \times U(1)_Y$ — Singlet field

$\rho \to SU(3)_c \times SU(2)_L \times U(1)_Y \to (1,3,0)$ — Triplet field

Fermionic fields

ϕ_h → **SM scalar doublet**

$\Delta \to SU(3)_c \times SU(2)_L \times U(1)_Y \to (1,3,0)$ — **Scalar triplet field**

$$\Delta = \begin{pmatrix} \frac{\Delta^0}{2} & \frac{\Delta^+}{\sqrt{2}} \\ \frac{\Delta^-}{\sqrt{2}} & -\frac{\Delta^0}{2} \end{pmatrix}.$$

$$\rho_i = \begin{pmatrix} \frac{\rho_i^0}{2} & \frac{\rho_i^+}{\sqrt{2}} \\ \frac{\rho_i^-}{\sqrt{2}} & -\frac{\rho_i^0}{2} \end{pmatrix}, \; i = 1, 2, 3\,.$$

Induced vev

$$\langle \Delta^0 \rangle = v_\Delta \propto \mu v^2 / M_\Delta^2$$

$\mu \phi_h^\dagger \Delta \phi_h$

$M_\Delta^2 Tr(\Delta^\dagger \Delta)$

- **With a Z_2 symmetry, DM can be stable**

Scalar Spectrum

CP even neutral scalars → H_1, H_2

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

$\sin\alpha$ → CP even neutral Higgs mixing

M_{H_1}, M_{H_2} → Mass of the two Higgs

H_1 → SM like Higgs

Goldstone ↓

Charged Higgs ↓

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

$\tan\delta = 2v_{\Delta}/v$ → Charged Higgs mixing

$M_{H^{\pm}}^2 = \mu v/(\sin\delta\cos\delta)$ → Charged Higgs mass

We choose $\alpha = \delta$

Dark Matter

Mixing between singlet and triplet states due to $Y_{\rho\Delta} Tr(\bar{\rho}_3 \Delta) N'$ ↔

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

N', ρ_3 **are the gauge basis**

$$Y_{\rho\Delta} = \frac{\Delta M_{\rho N} \sin 2\beta}{2 v_\Delta}$$

Mass splitting between the two fermions

$$\Delta M_{\rho N} = M_\rho - M_N$$

M_ρ, M_N → **Mass of the two fermions**

$Y_{\rho\Delta} \sim \mathcal{O}(10^{-10}) - \mathcal{O}(10^{-12})$ → $\beta \sim 0$

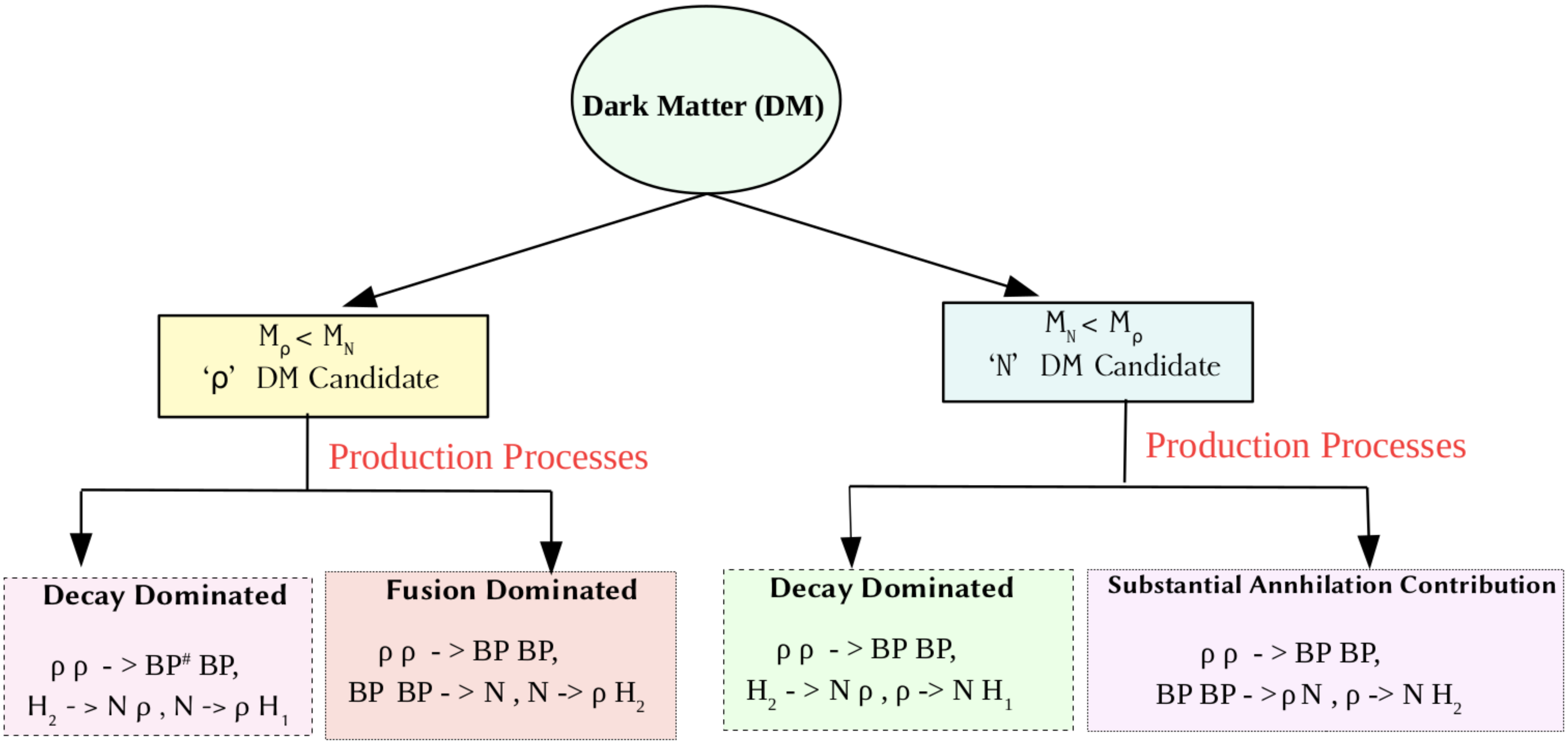
$$M_N \sim M_{N'}, \quad M_\rho \sim M_{\rho_3}$$

N is primarily singlet and ρ is primarily triplet state

M_ρ , M_N , M_{H_2} , $Y_{\rho\Delta}$, $\sin\alpha$ → **free parameter of the model**

ρ, N can be dark matter depending on the mass

Dark Matter Production



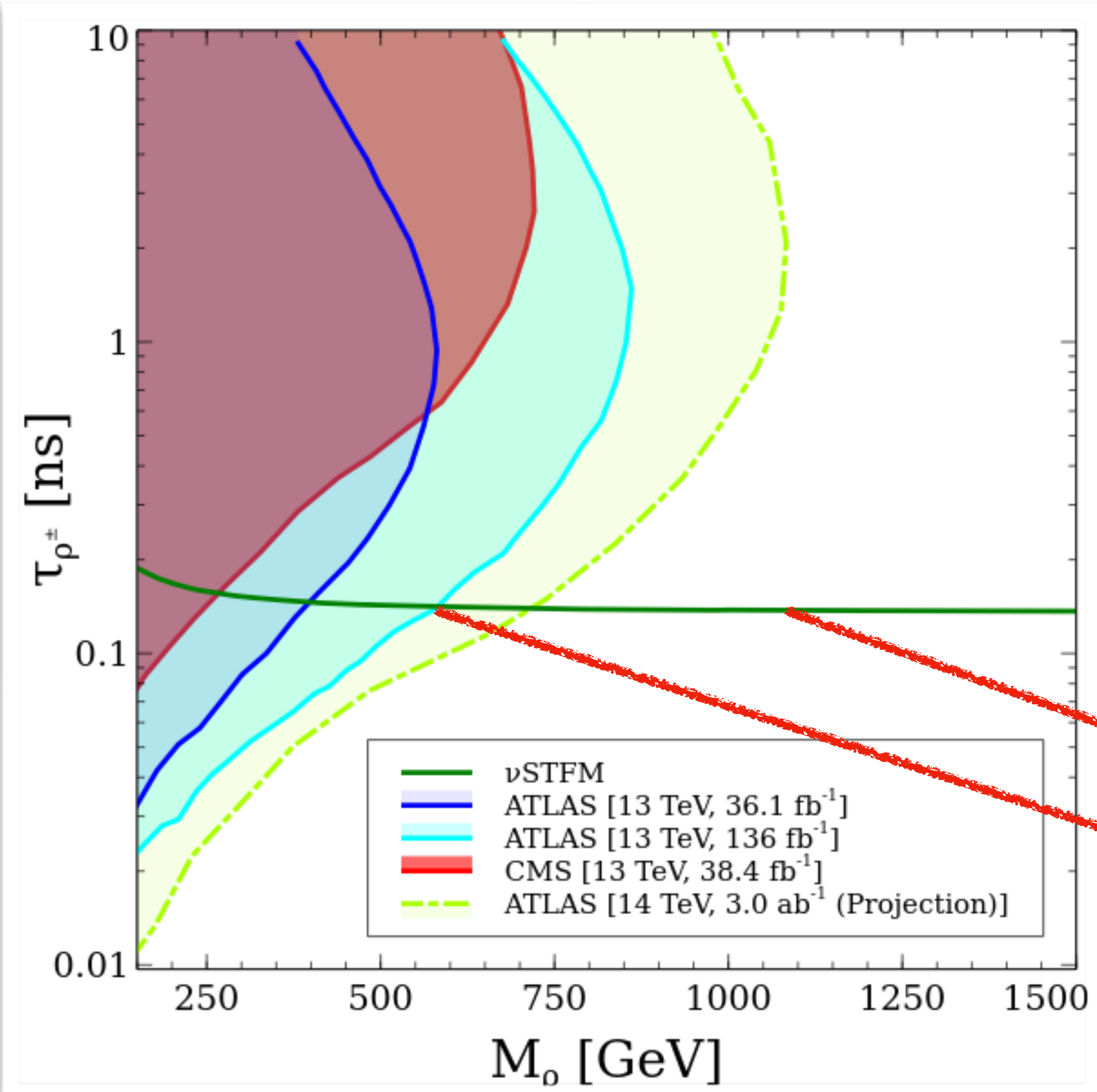
BP = Bath Particle

- **WIMP Dark Matter**
- **DM is in thermal bath**
- **Annihilation of bath particles, decay of H_2 and late decay of N play substantial role**

- **FIMP Dark Matter as $Y_{\rho\Delta} < \mathcal{O}(10^{-10})$**
- **N is non-thermal**
- **Freeze in production (decay, annihilation) +late decay of ρ contributes to relic density**

Collider Constraint on ρ

Applicable irrespective of triplet is a DM or NLOP



ρ **contains** $\rho^\pm$ **and** ρ^0

$\Delta M \sim 167$ **MeV**

$\rho^\pm \to \rho^0 \pi^\mp$

Soft Pion, difficult to reconstruct due to small momentum

Theoretical prediction

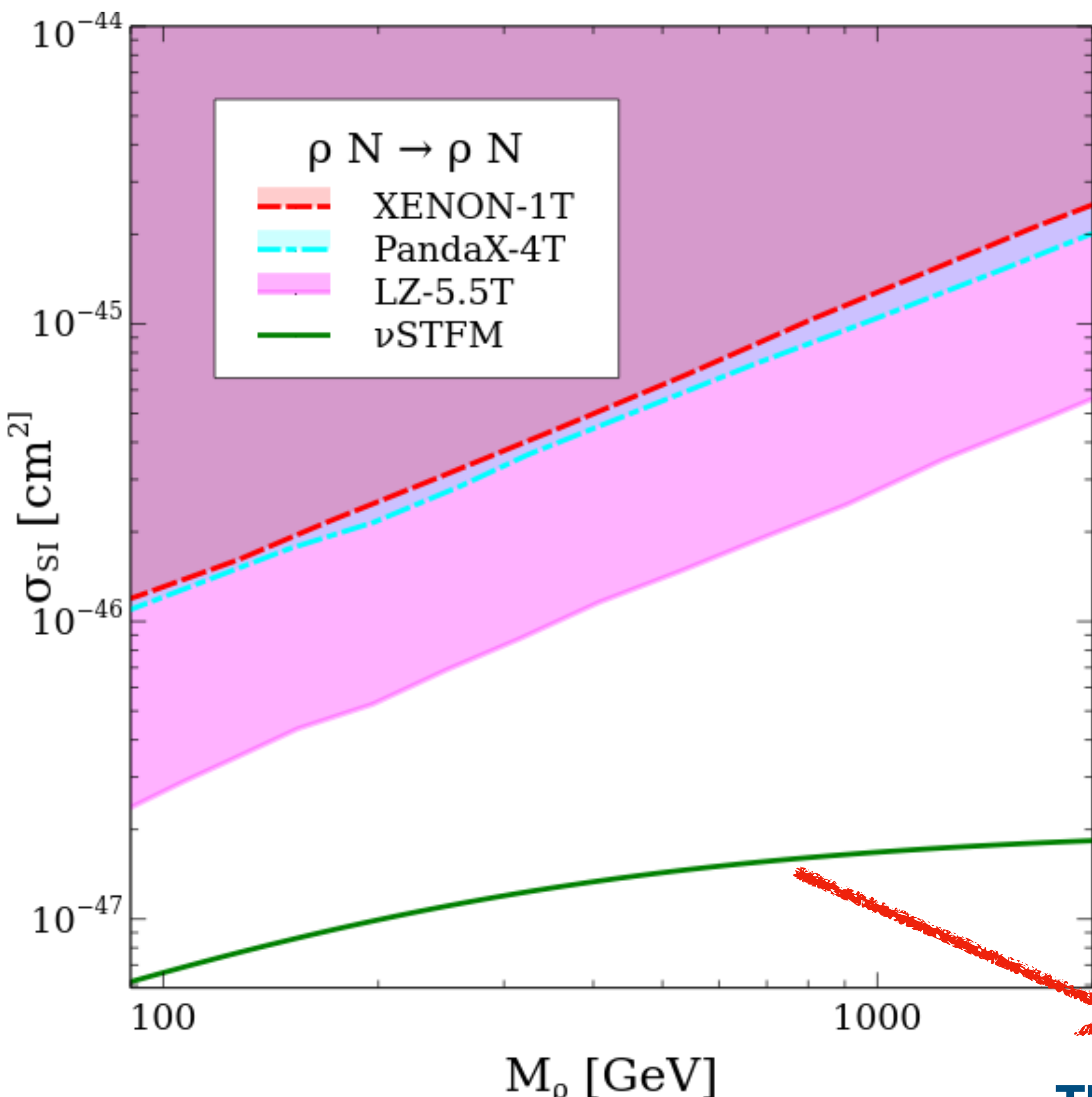
$M_\rho > 580$ **GeV**

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

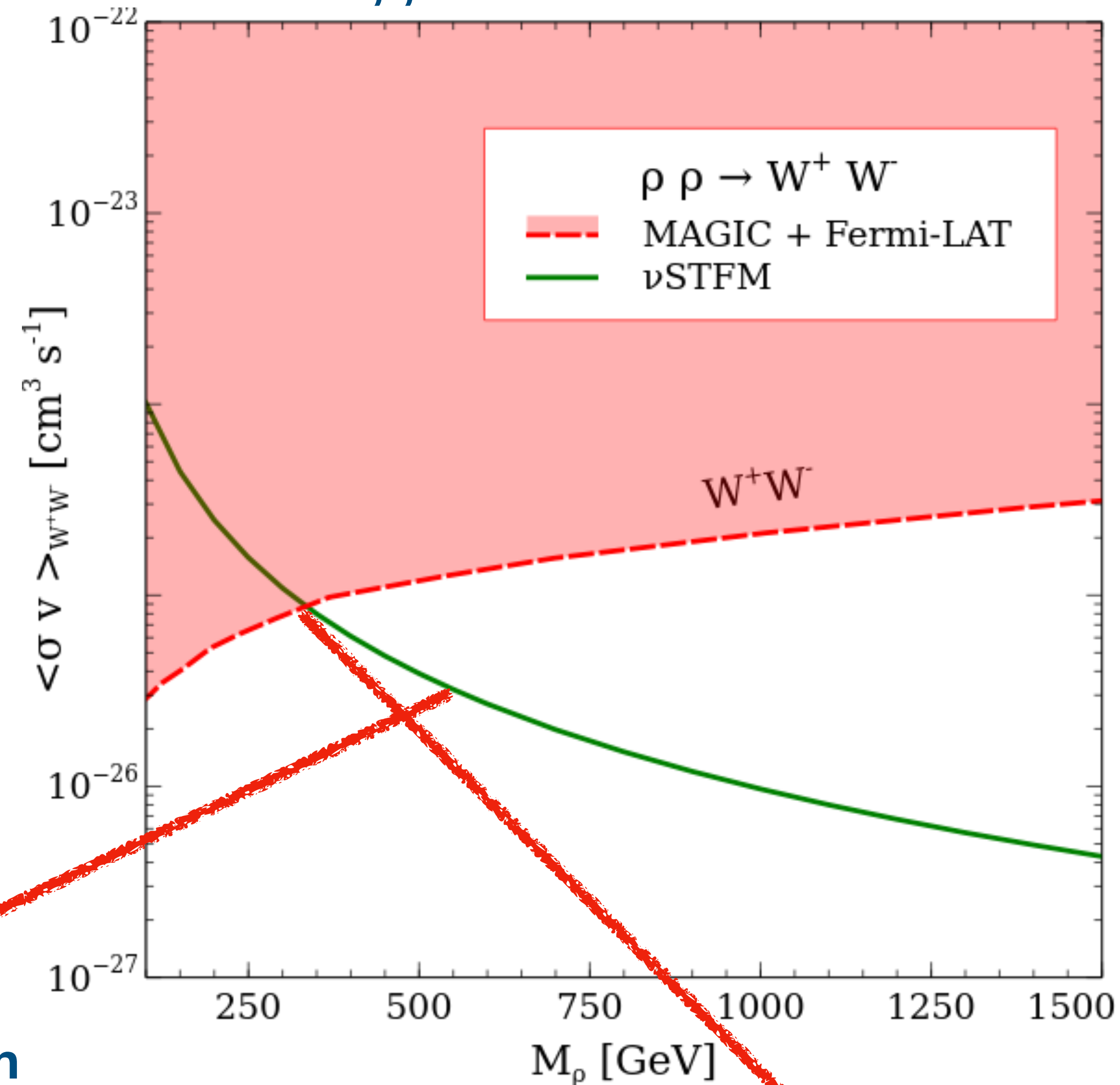
Direct and Indirect Constraint on ρ

Applicable only if triplet is DM

$\rho N \to \rho N$



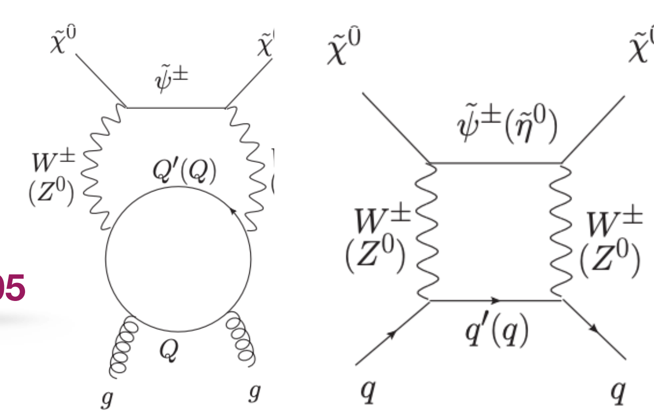
$\rho\rho \to SM + SM$



Theory prediction

Relaxed constraint

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

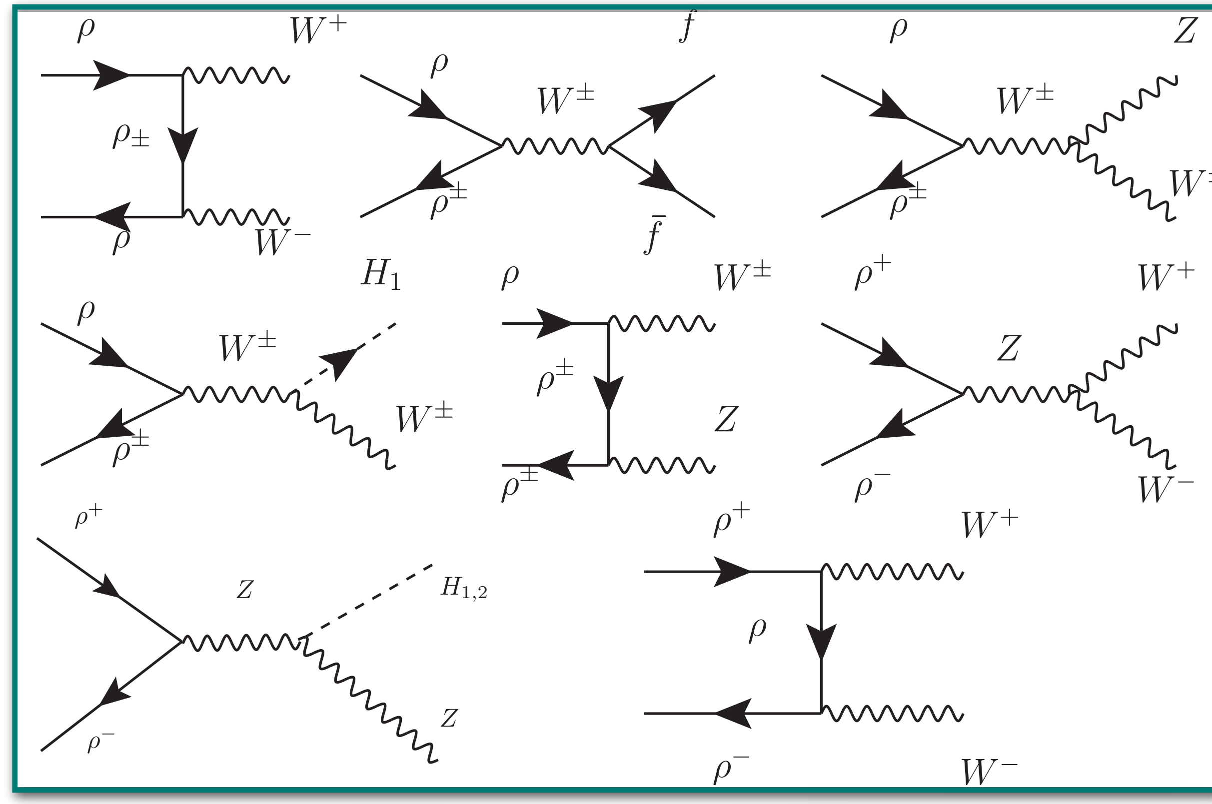


Hisano et al, JHEP 07 (2011) 005

Dark Matter Production - Scenario I (ρ as Dark Matter)

$M_\rho > 580\ GeV$ from disappearing track searches [ATLAS collaboration, Eur. Phys. J. C 82 (2022) 606]

- Heavy BSM Higgs sector ~ few TeV
- Triplet state ρ is lighter and singlet N is NLOP
- ρ has gauge interaction, hence thermal



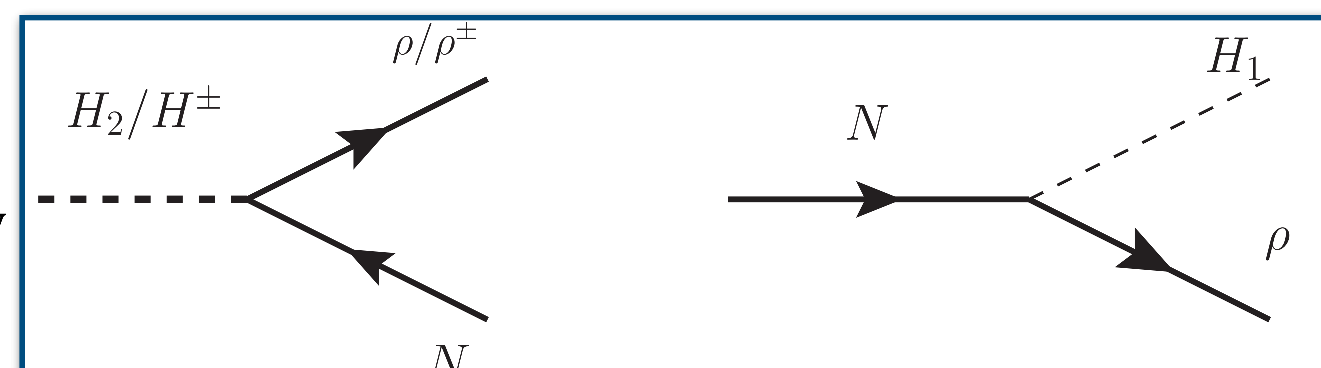
Under-abundant dark matter unless $M_\rho = 2400$ GeV or large

E. Ma, Mod.Phys.Lett.A24:583-589,2009

With additional decay dominated production channels, the under abundance can be compensated

- **Decay dominated scenario, $H_2 \to \rho N, N \to \rho H_1$**

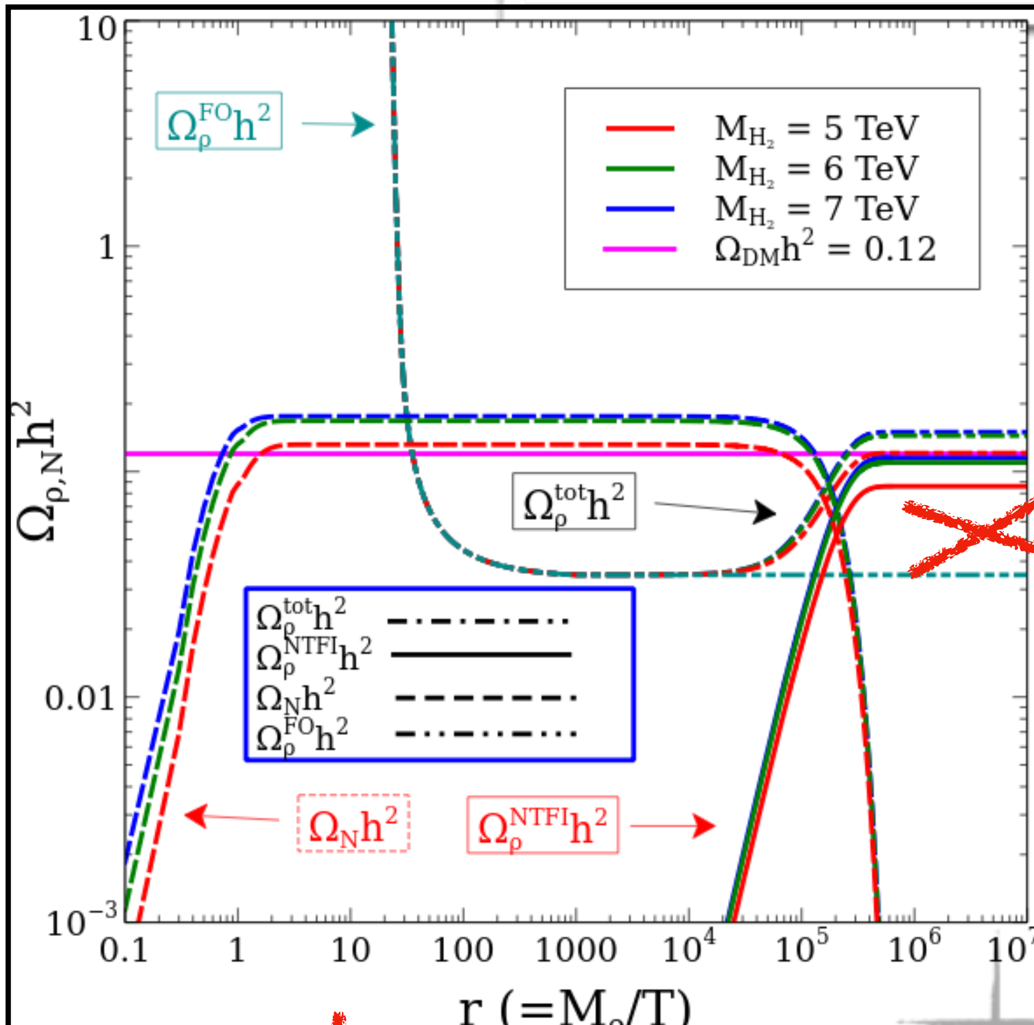
- H_2 is a thermal particle
- $H_2 \to \rho N$ produces N
- Late decay of $N \to \rho H_1$ for correct relic density
- BBN constraint on lifetime of N



Boltzmann equation for ρ and N

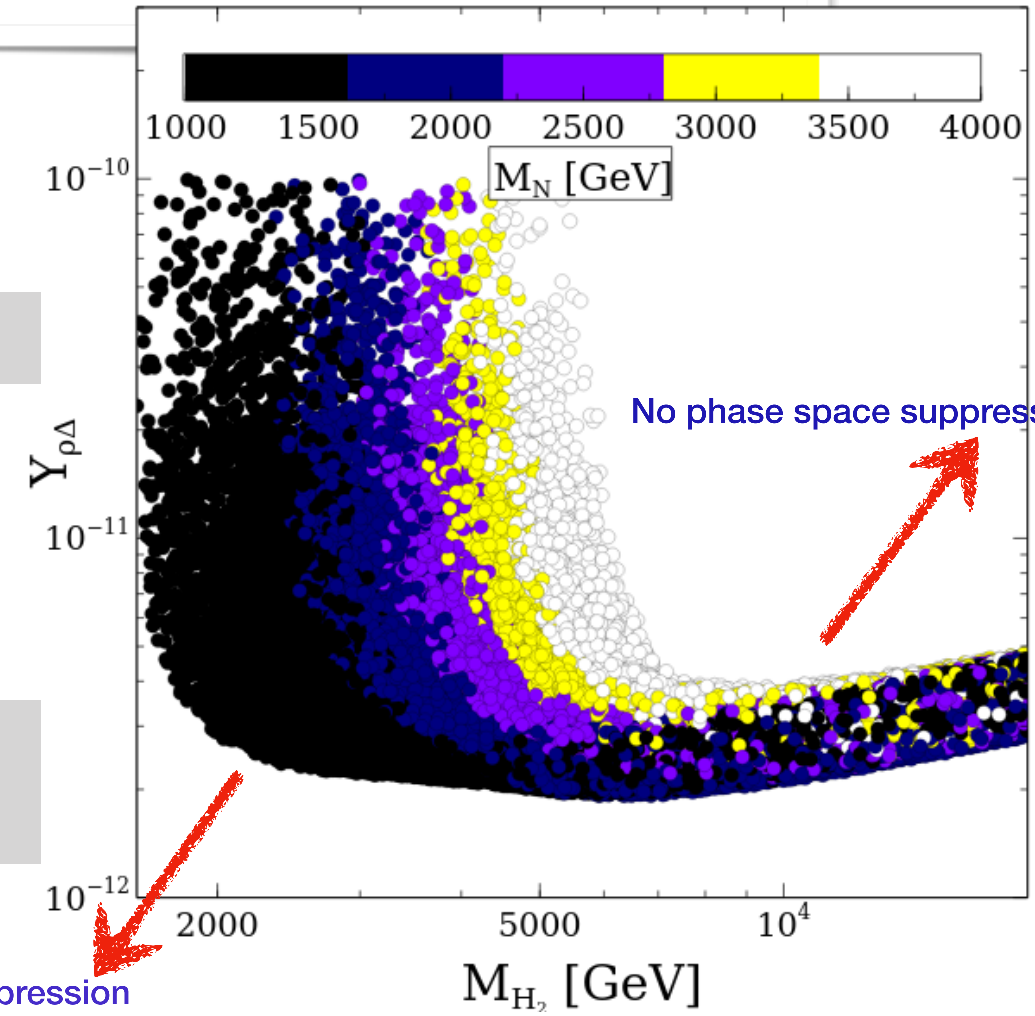
$$\hat{L} f_N = \mathcal{C}^{H_2 \to N\rho} + \mathcal{C}^{AB \to N\rho} + \mathcal{C}^{N \to\, all},$$

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



FO contribution

Late decay contribution



No phase space suppression

Phase space suppression

$M_\rho = 1.3\ TeV, M_N = 2\ TeV, Y_{\rho\Delta} = 2.5 \times 10^{-12}$

DM abundance increases with a heavier BSM Higgs state

$700\ GeV < M_\rho < 1500\ GeV$

$1500\ GeV < M_{H_2} < 20\ TeV$

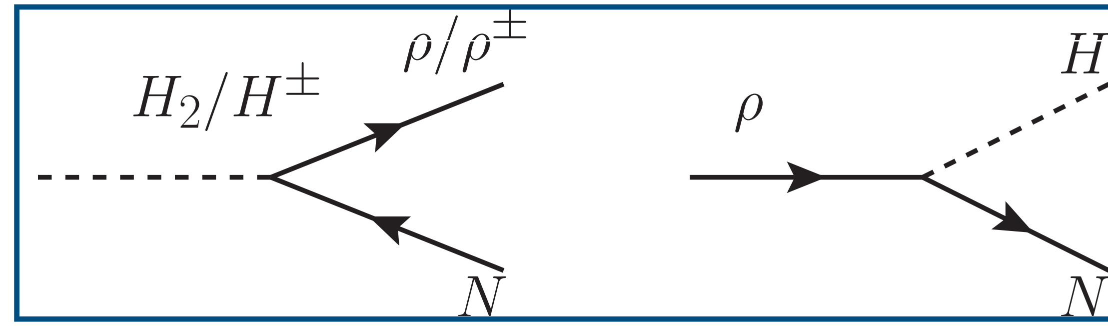
$125\ GeV < M_N - M_\rho < 3000\ GeV$

$10^{-13} < Y_{\rho\Delta} < 10^{-10}$

$10^{-3} < \alpha < 0.1$

Dark Matter Production - Scenario II (*N* as Dark Matter)

- **Heavy BSM Higgs sector ~ few TeV thermal particle**
- **Triplet state ρ is heavier and singlet N is the Dark Matter**
- ***N* is non-thermal particle**
- **Dark matter production is via thermal freeze-in and late decay of NLOP (non-thermal production)**

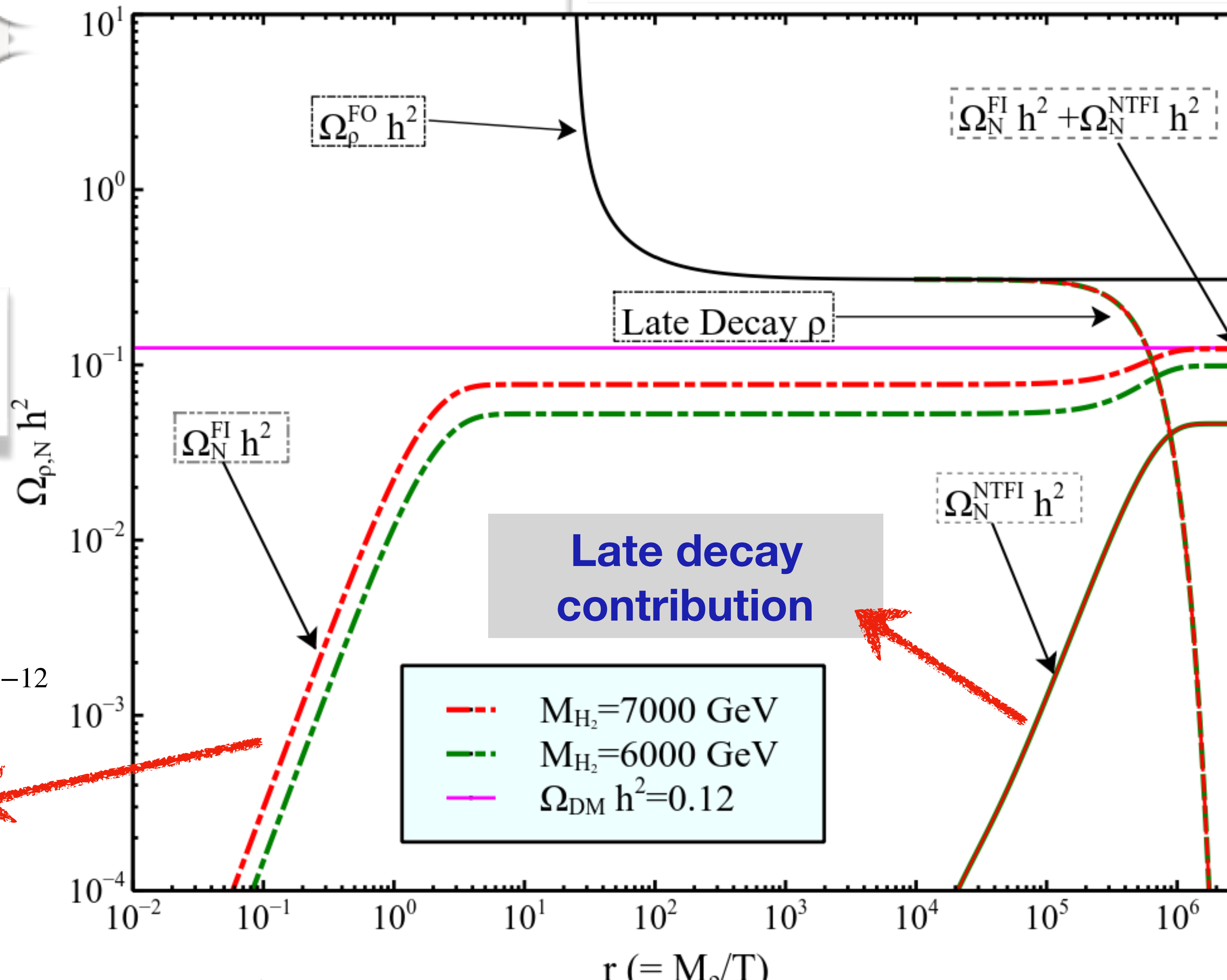


$$\Omega_N^{NTFI} h^2 = \frac{M_N}{M_\rho} \Omega_\rho^{FO} h^2$$

Dark matter abundance

$$\Omega_N h^2 = \Omega_N^{FI} h^2 + \Omega_N^{NTFI} h^2$$

$M_\rho = 4\ TeV, M_N = 600\ GeV, Y_{\rho\Delta} = 3.56 \times 10^{-12}$

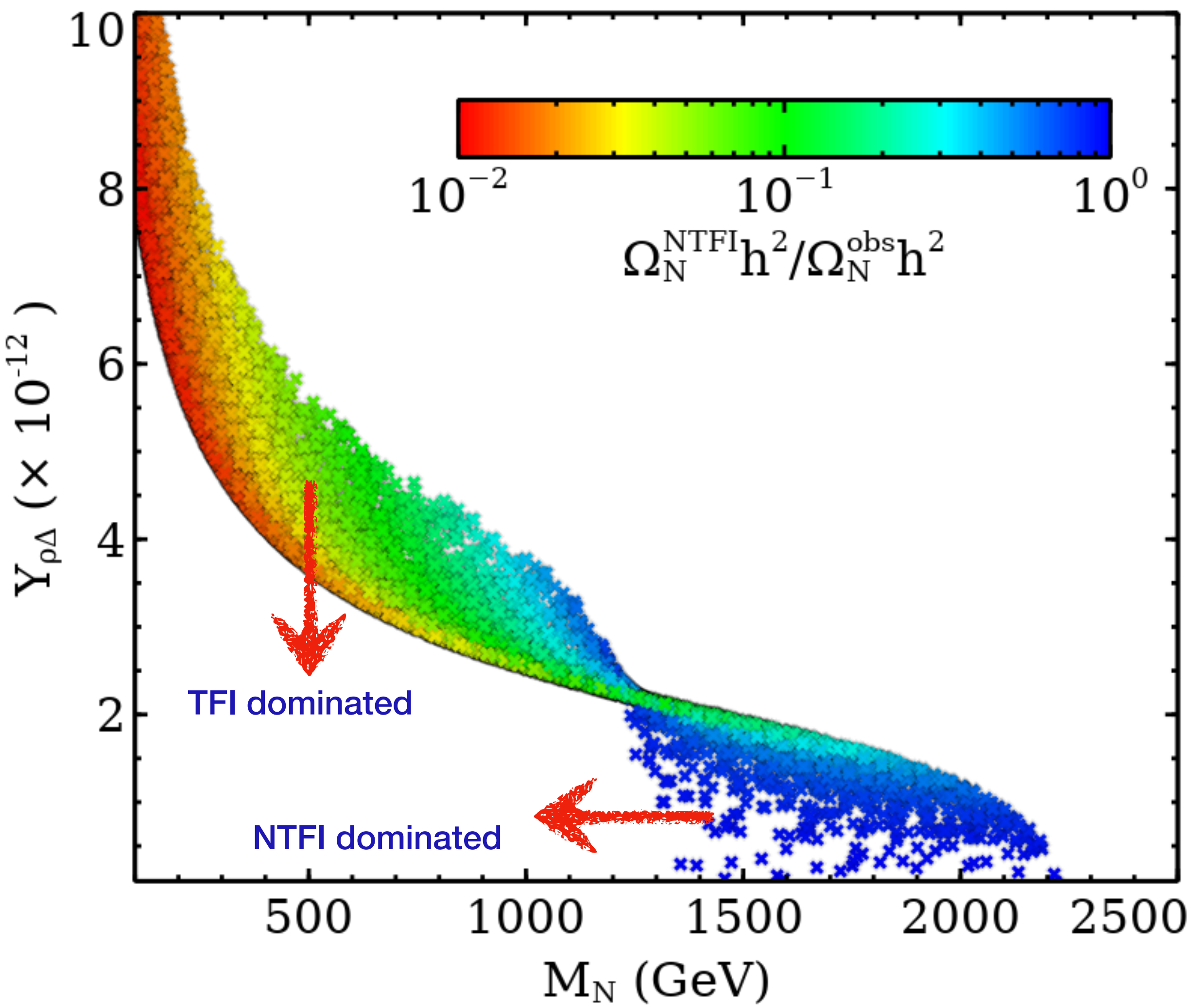


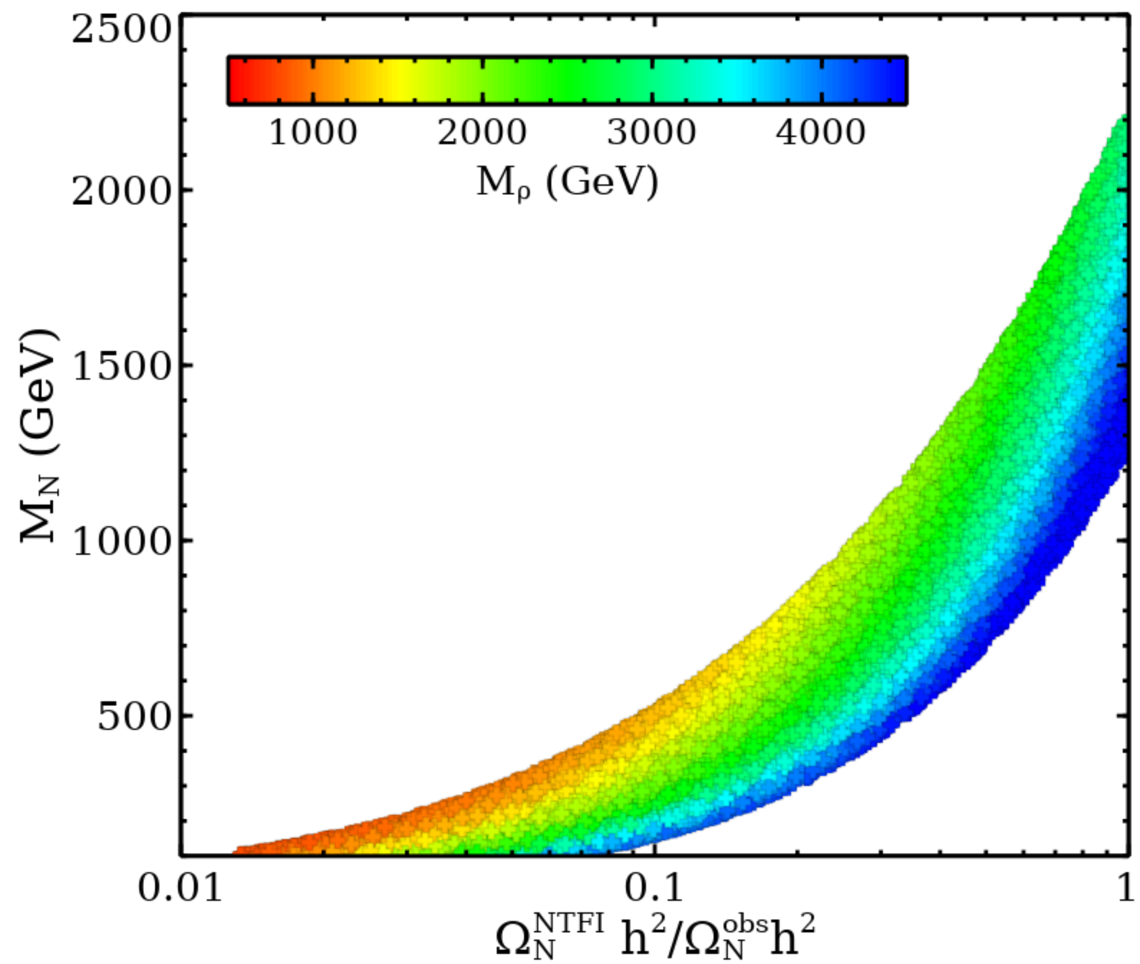
Thermal Freeze in contribution

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

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

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



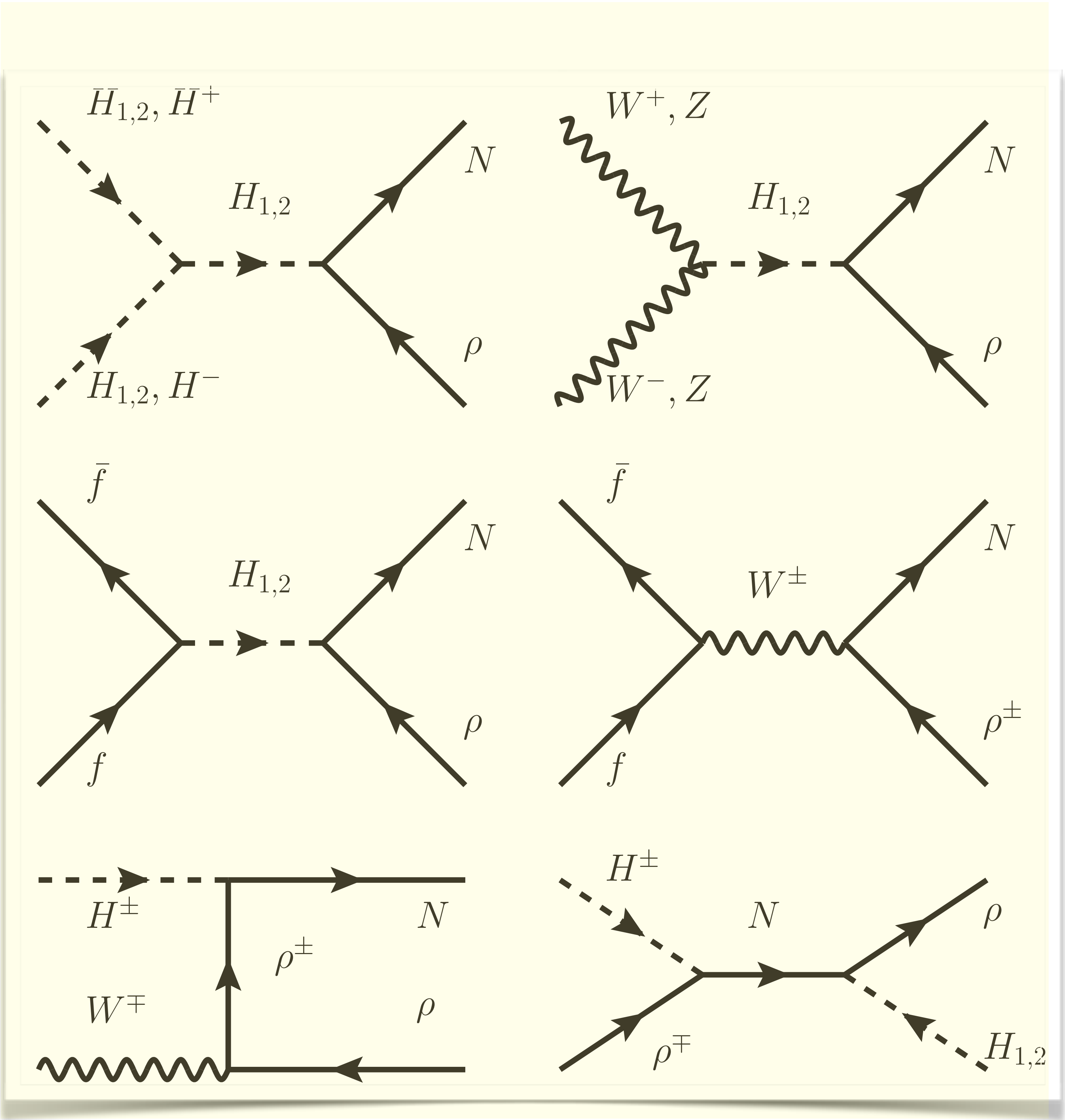


- As N becomes heavier, NTFI contribution increases

- As NLOP becomes heavier, NTFI contribution increases
- Large abundance of triplet as mass of triplet increases
- Mass of H2 set to 7 TeV

Dark Matter Production with Lighter H_2

H_2 is lighter (within the reach of LHC) and $H_2 \to \rho N$ is kinematically foreboded



A. $2 \to 1{,}1 \to 2$ **dominated scenario**

B. $2 \to 2$ **dominated scenario**

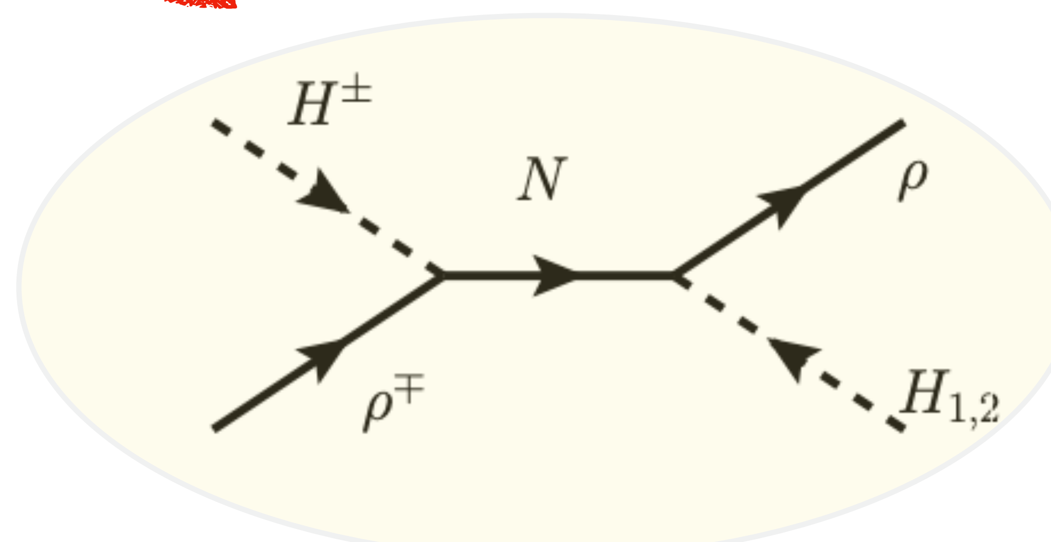
Dark Matter Production with Lighter H_2

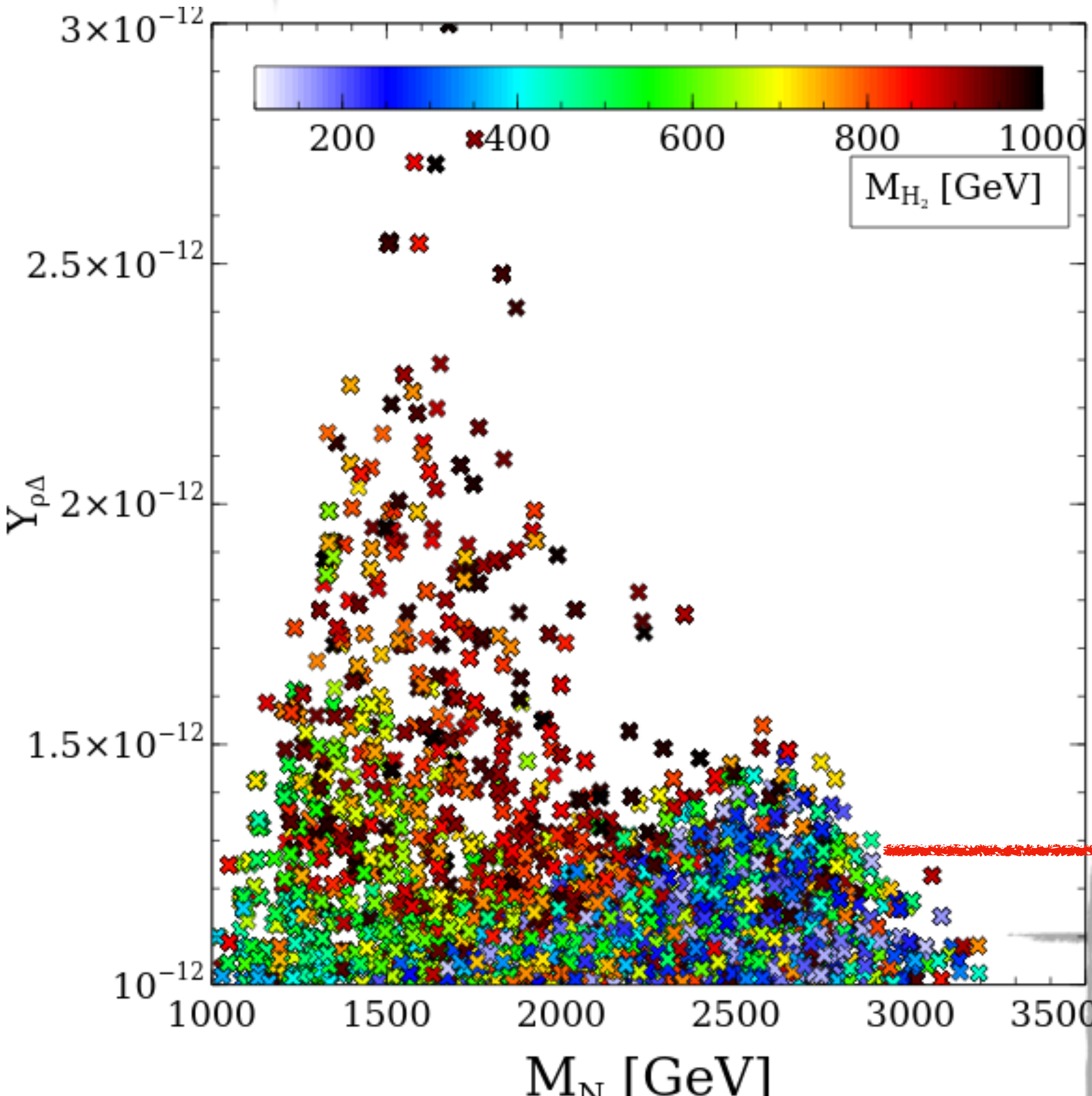
Fusion dominated scenario

$AB \to N \to \rho H_{1,2}, A, B = \rho, \rho^{\pm}, H_i$

- ρ **is DM -> thermal particle.**

$H_2 \to \rho N$ **kinematically forbidden**





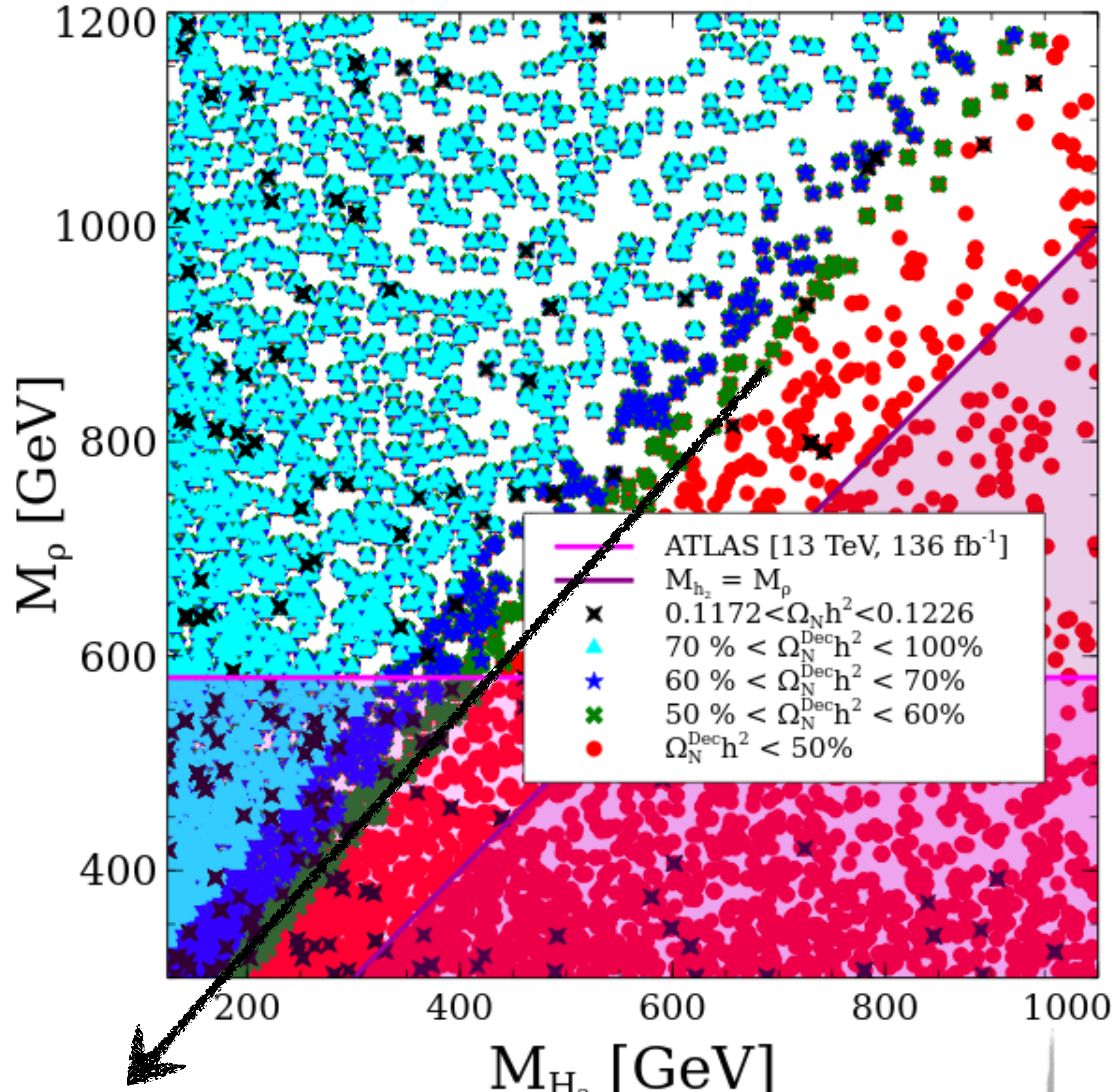
A lighter BSM Higgs can satisfy the relic abundance

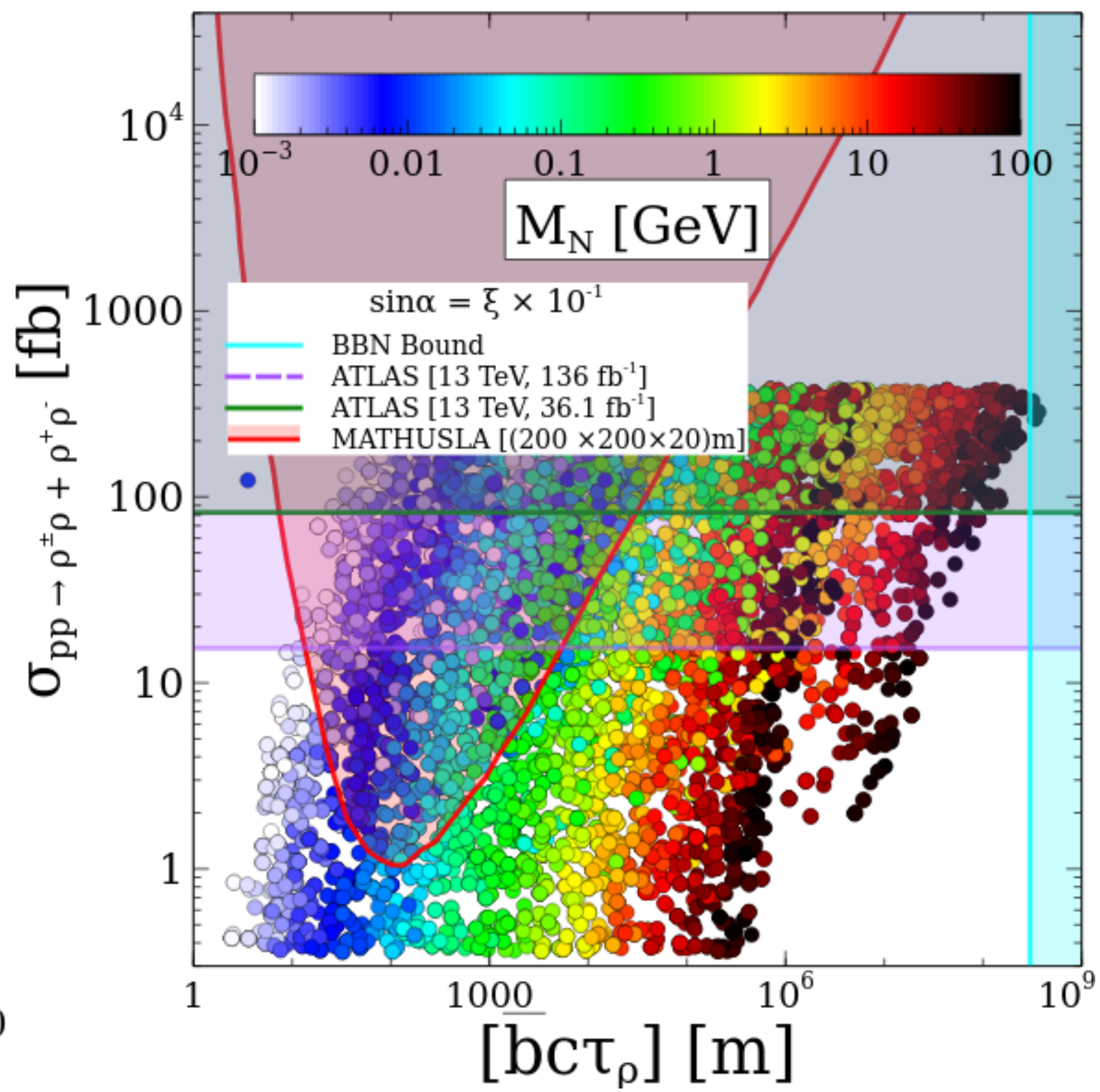
$10^{-12} \leq Y_{\rho\Delta} \leq 10^{-9}$, $10^{-3} \leq \sin\alpha \leq 10^{-1}$, 200 GeV $\leq \Delta M \leq$ 2000 GeV ,
700 GeV $\leq M_\rho \leq$ 1600 GeV , 125 GeV $\leq M_{H_2} \leq$ 1000 GeV .

Substantial annihilation contribution

$M_N < M_\rho, \quad M_{H_2} < M_\rho + M_N$

- **Standard freeze-in and late decay** $\rho \to NH_2$
- $AB \to \rho N, \quad AB = W^\pm, Z, \rho^\pm, H_{1,2}, H^\pm$ **large**

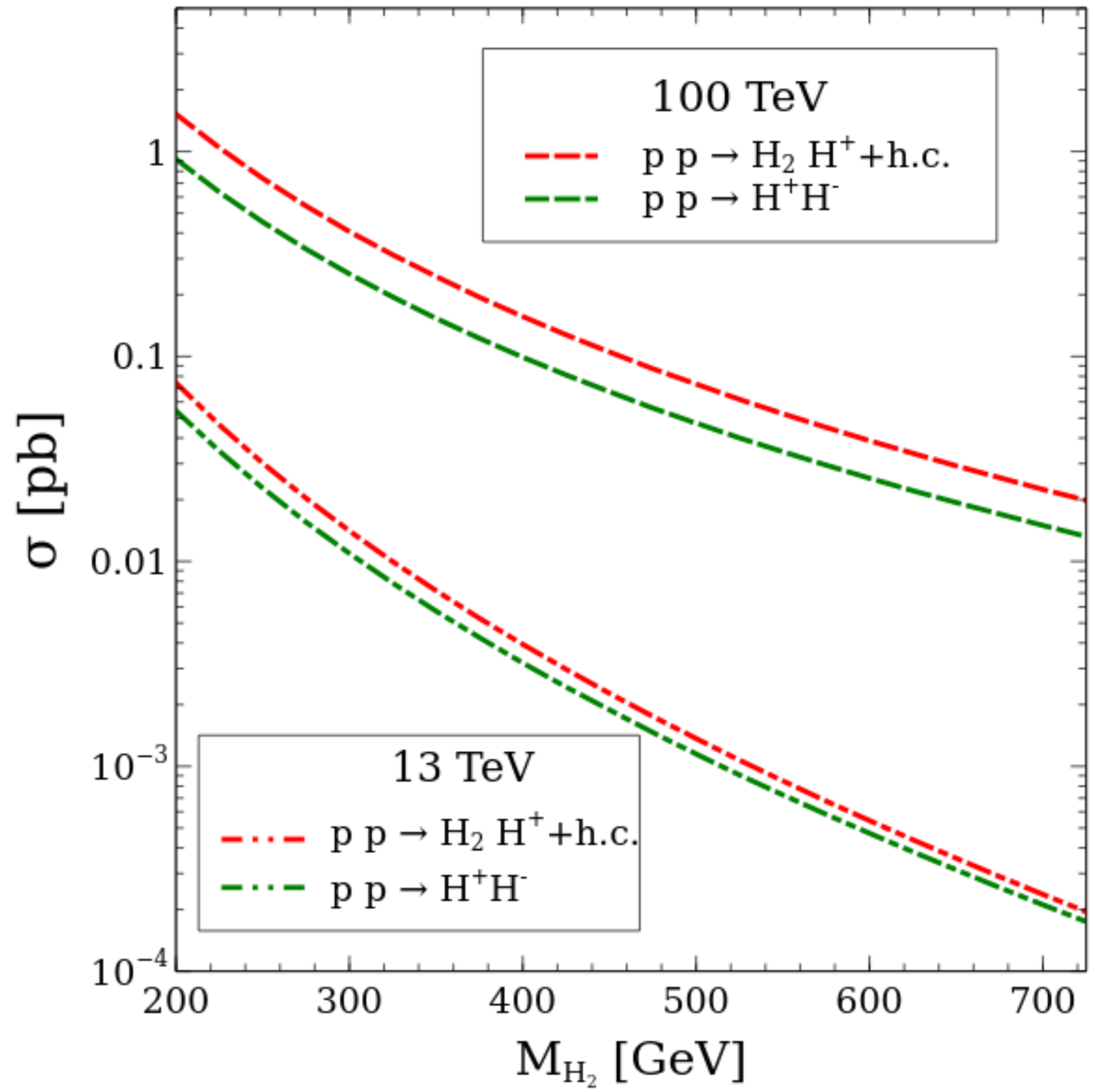


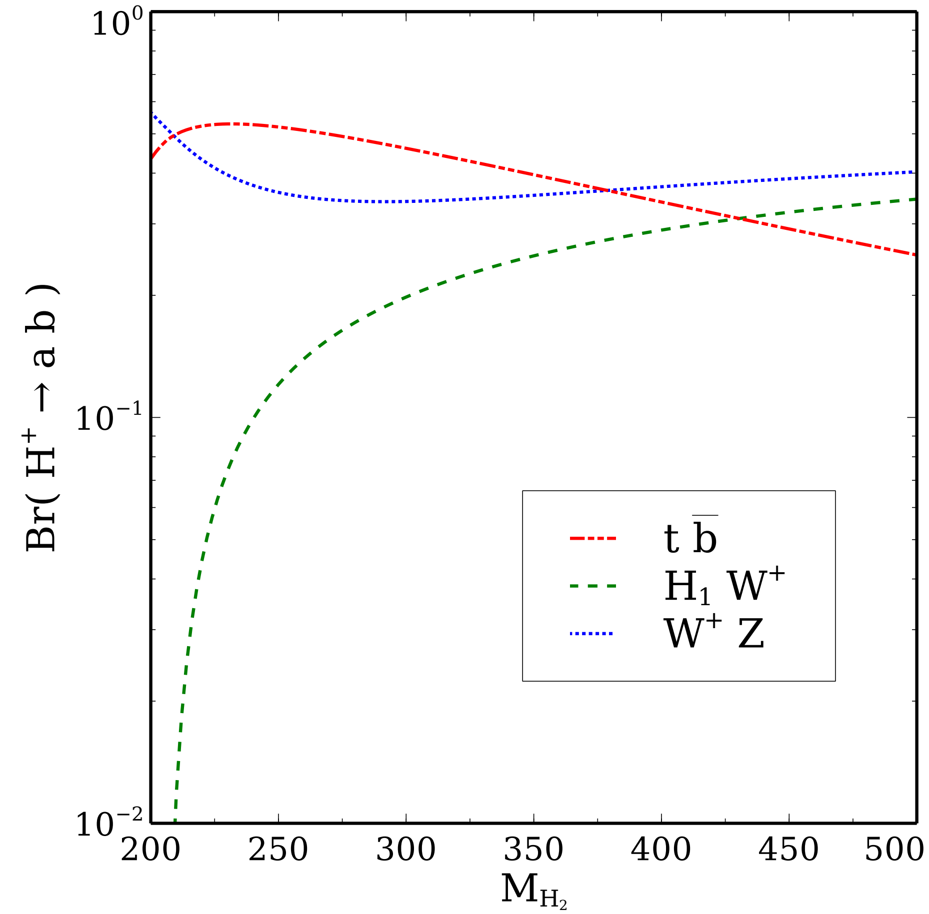


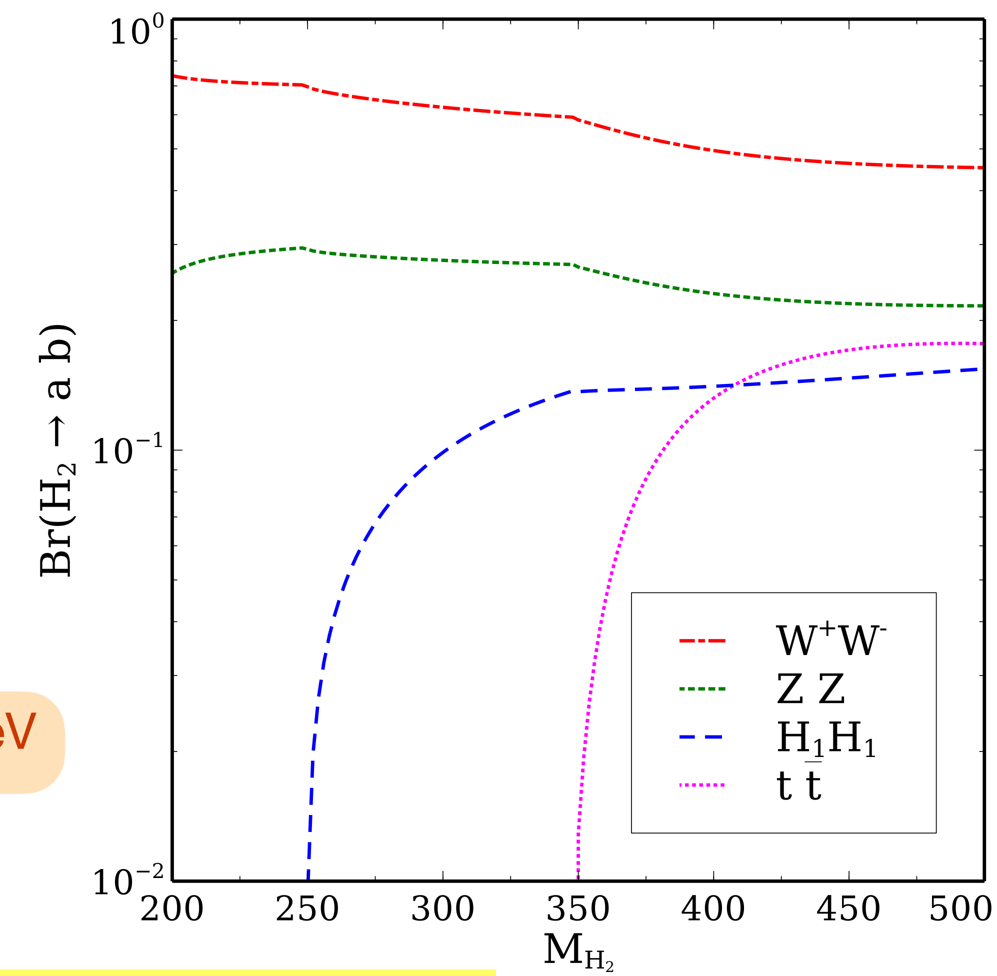
Decay contribution can be less than 50%

$10^{-12} \le Y_{\rho\Delta} \le 10^{-8}, \; 10^{-3} \le \sin\alpha \le 10^{-1}, \; 300 \text{ GeV} \le M_\rho \le 1200 \text{ GeV},$
$10^{-4} \text{ GeV} \le M_N \le 100 \text{ GeV}, \; 125 \text{ GeV} \le M_{H_2} \le 1000 \text{ GeV}.$

BSM Higgs H2 at the LHC







$\sigma \sim 2.42\ (0.242)\ fb, M_{H_2} = 250\ GeV, \sin\alpha = 0.1$

$pp \to H^+H^- \to 4j + 4b,\ \ 2l + 4b + MET$

$pp \to H^+H^- \to 6l + MET,\ 2l + MET,\ 4j + 4l,\ 4j + MET$ for > 375 GeV

$pp \to H^{\pm}H_2 \to 6j + 2b,\ 3l + 2b + MET,\ 5l + MET,\ 6j + MET$

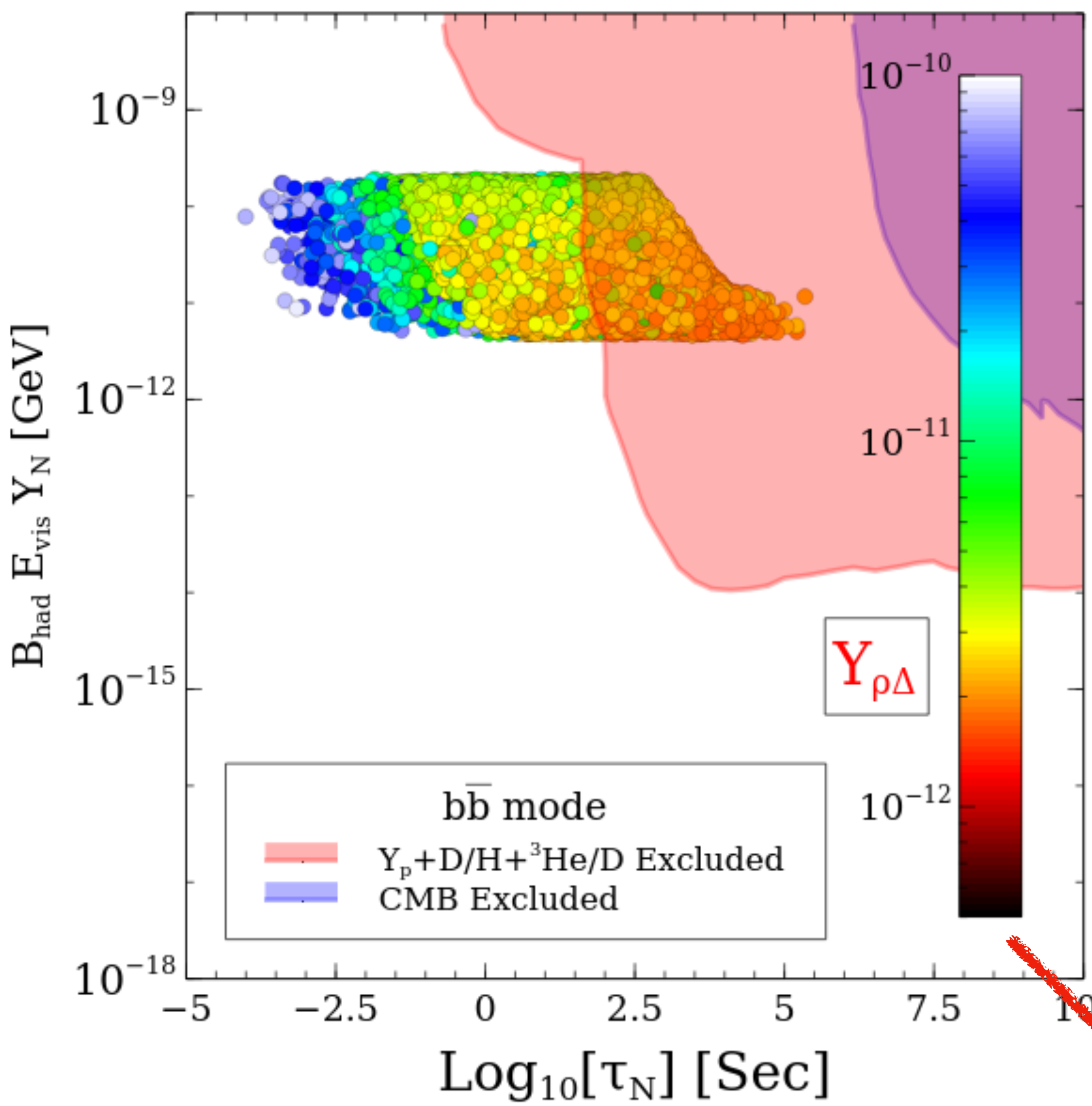
JET+MET, Multi-lepton+MET, Multi-lepton+Multi-jet channels can be powerful probe

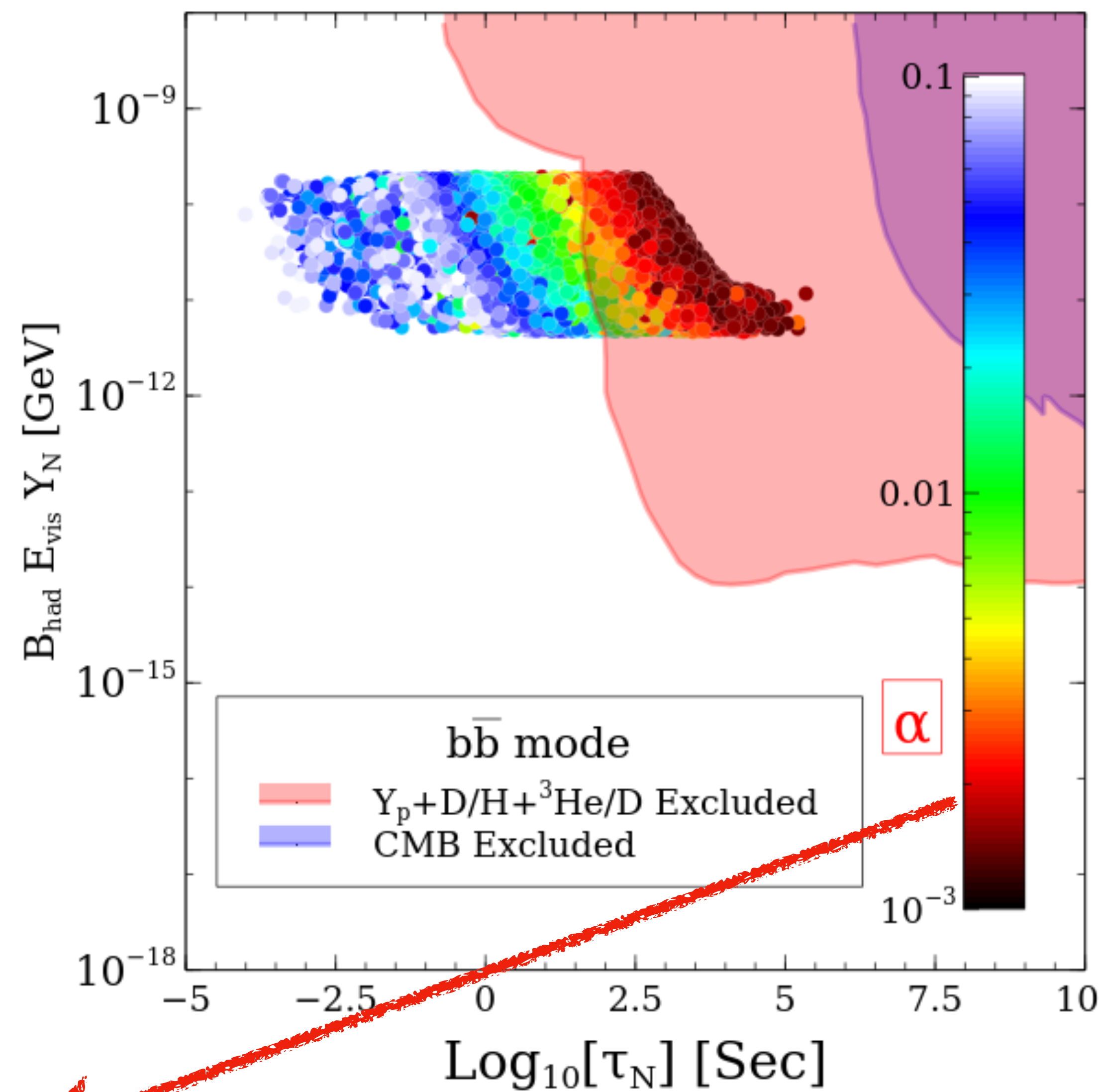
BBN constraint

Late decay of $N \to \rho H_1$ can influence Big Bang Nucleosynthesis

$$\tau_N = \frac{16\pi M_N}{Y_{\rho\Delta}^2 \sin^2\alpha \left((M_N + M_\rho)^2 - M_{H_1}^2\right)} \left[\left(1 - \left(\frac{M_\rho + M_{H_1}}{M_N}\right)^2\right)\left(1 - \left(\frac{M_\rho - M_{H_1}}{M_N}\right)^2\right)\right]^{-\frac{1}{2}} .$$

Depends on $\sin\alpha, Y_{\rho\Delta}$





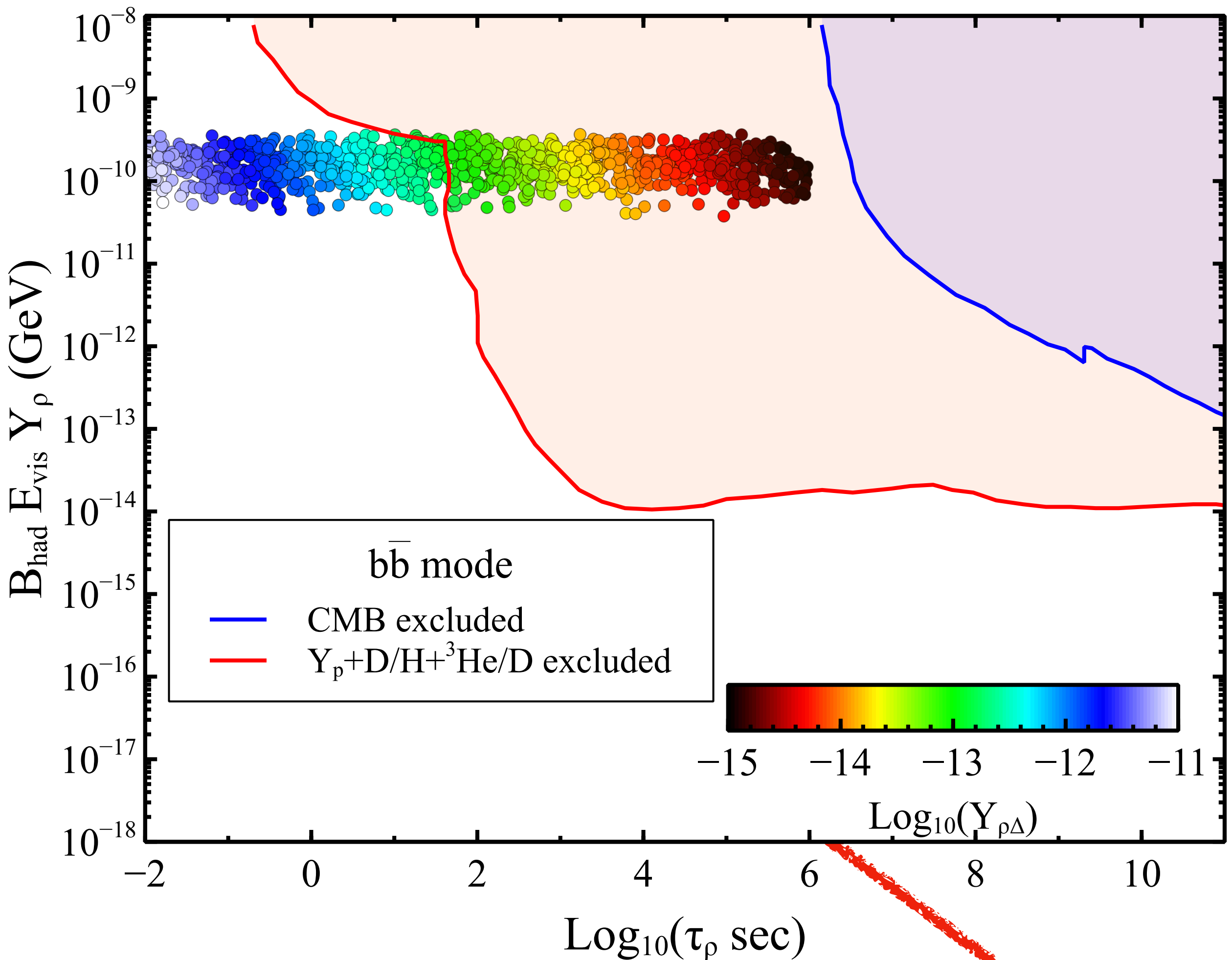
Small values of $\sin\alpha, Y_{\rho\Delta}$ **are ruled out**

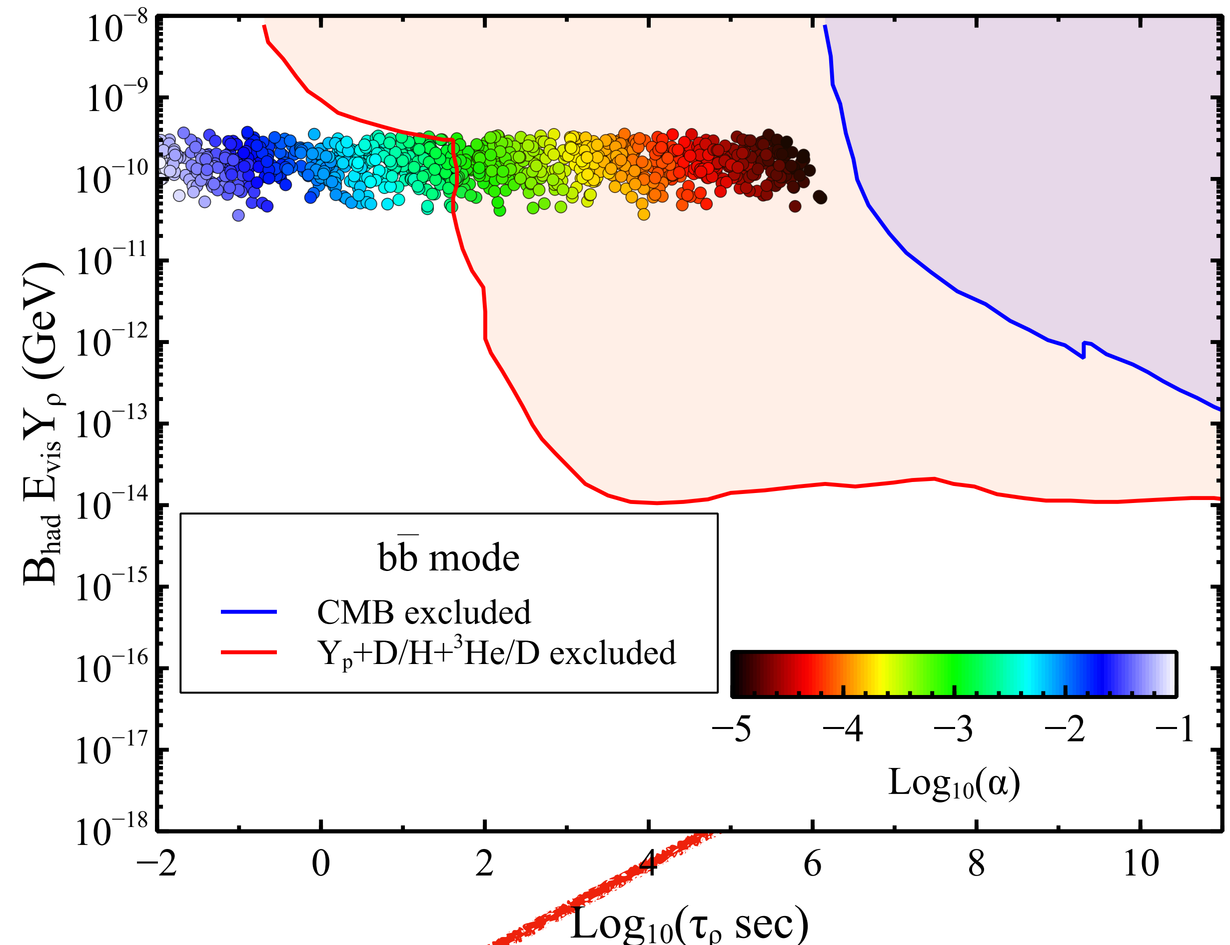
BBN Constraint

Late decay of $\rho \to NH_1$ can influence Big Bang Nucleosynthesis

$$\frac{1}{\tau_\rho} = \frac{Y_{\rho\Delta}^2 \sin^2\alpha}{16\pi M_\rho}\left((M_\rho + M_N)^2 - M_{H_1}^2\right)\sqrt{1 - \frac{2(M_{H_1}^2 + M_N^2)}{M_\rho^2} + \frac{(M_{H_1}^2 - M_N^2)^2}{M_\rho^4}}$$

Depends on $\sin\alpha, Y_{\rho\Delta}$





Small values of $\sin\alpha, Y_{\rho\Delta}$ **are ruled out**

Summary

- Singlet-triplet fermonic model is a viable model for neutrino mass generation and dark matter

- With $Y_{\rho\Delta} \sim \mathcal{O}(10^{-10})$ late decay contribution plays a significant role In determining relic abundance

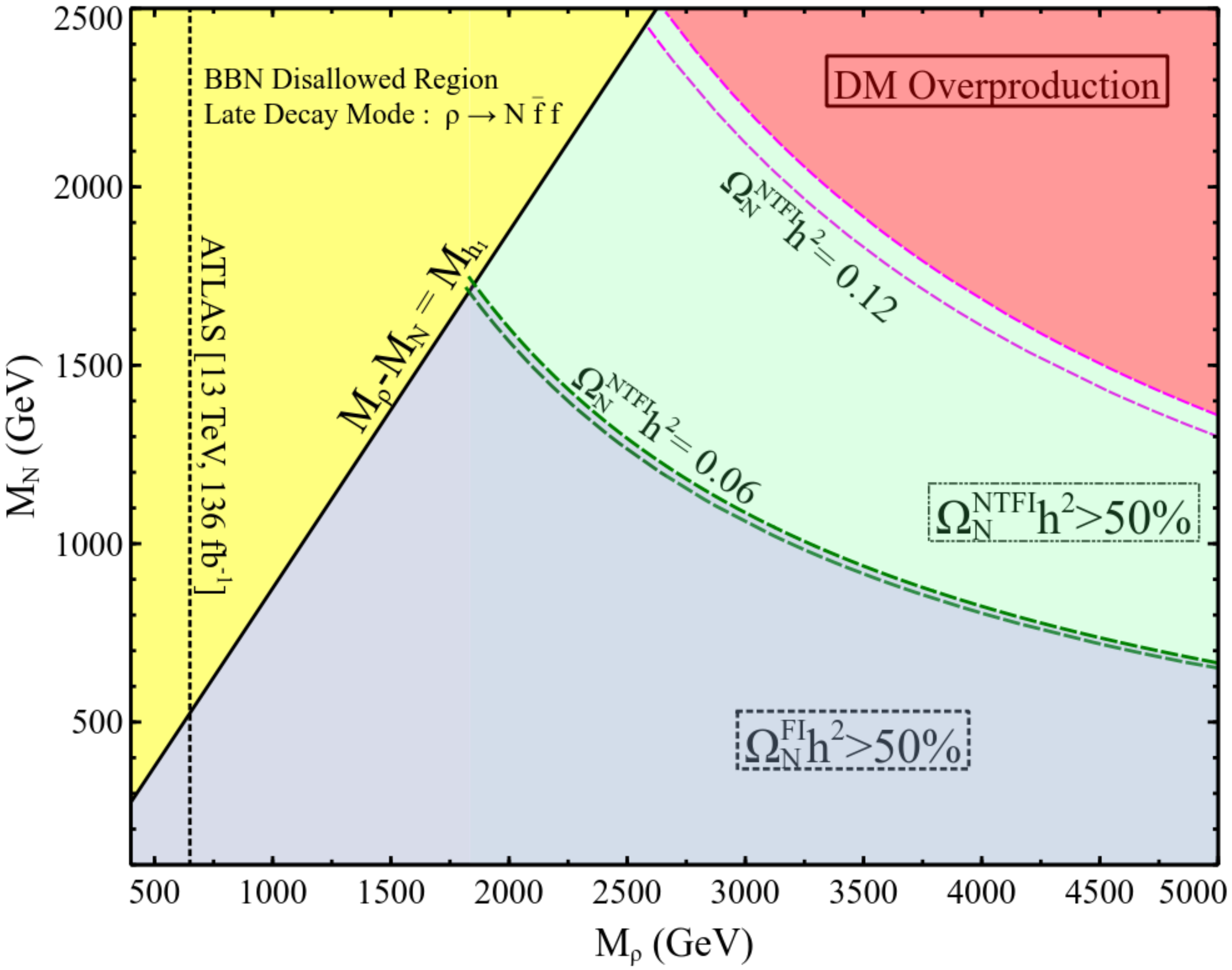
- If the channel $H_2 \to \rho N$ is closed, substantial fusion and annihilation contribution can be realised with a few hundred GeV BSM Higgs

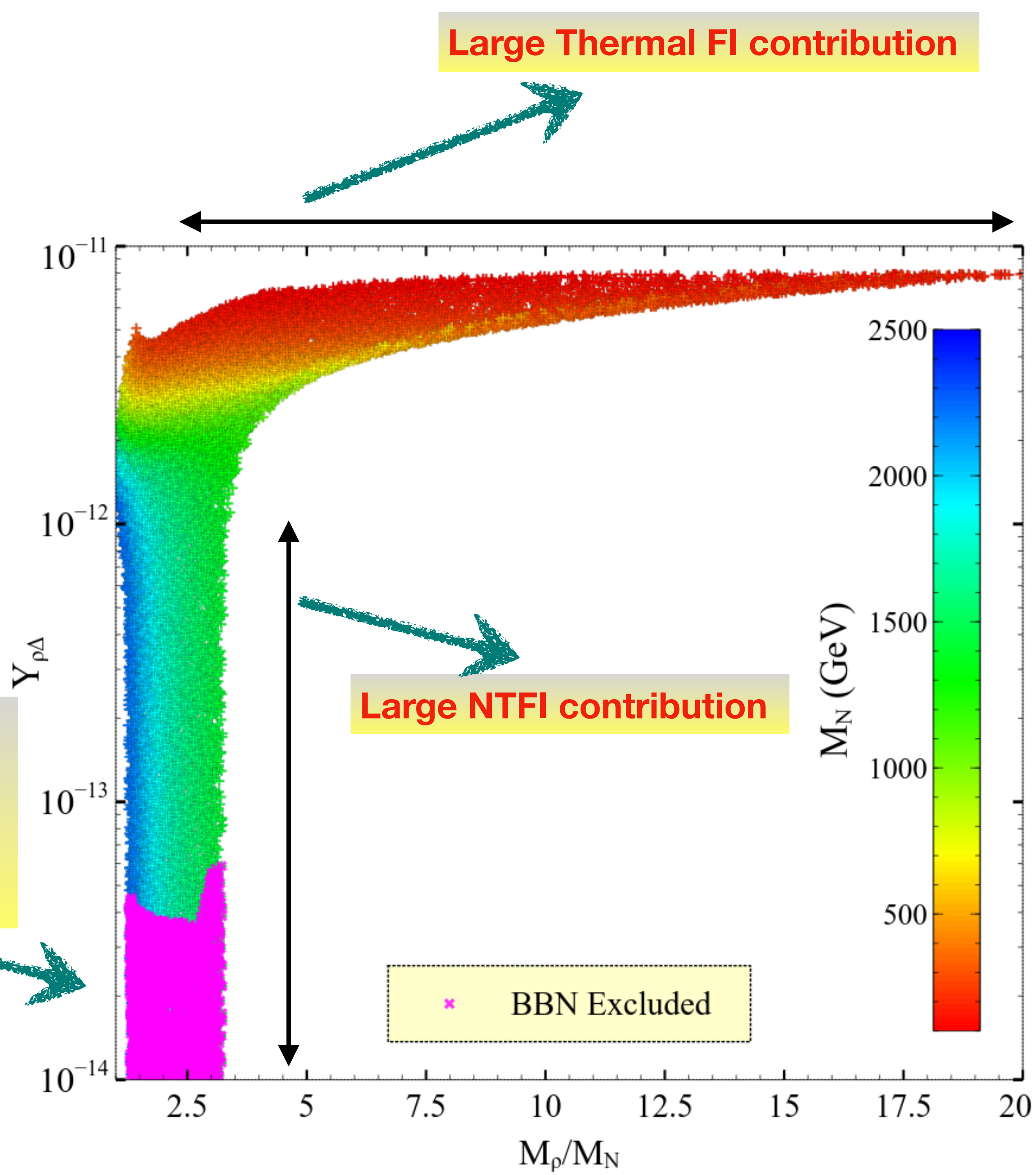
- JET+MET, Multi-lepton+MET, Multi-lepton+Multi-jet channels can be powerful probe

- Big Bang Nucleosynthesis constraint due to late decay of ρ, N

Thank You

BBN constraint





- As the ratio decreases, NTFI contribution increases
- Smaller Yukawa coupling to suppress the thermal contribution
- Smaller Yukawa coupling to give larger lifetime of triplet
- BBN exclusion