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

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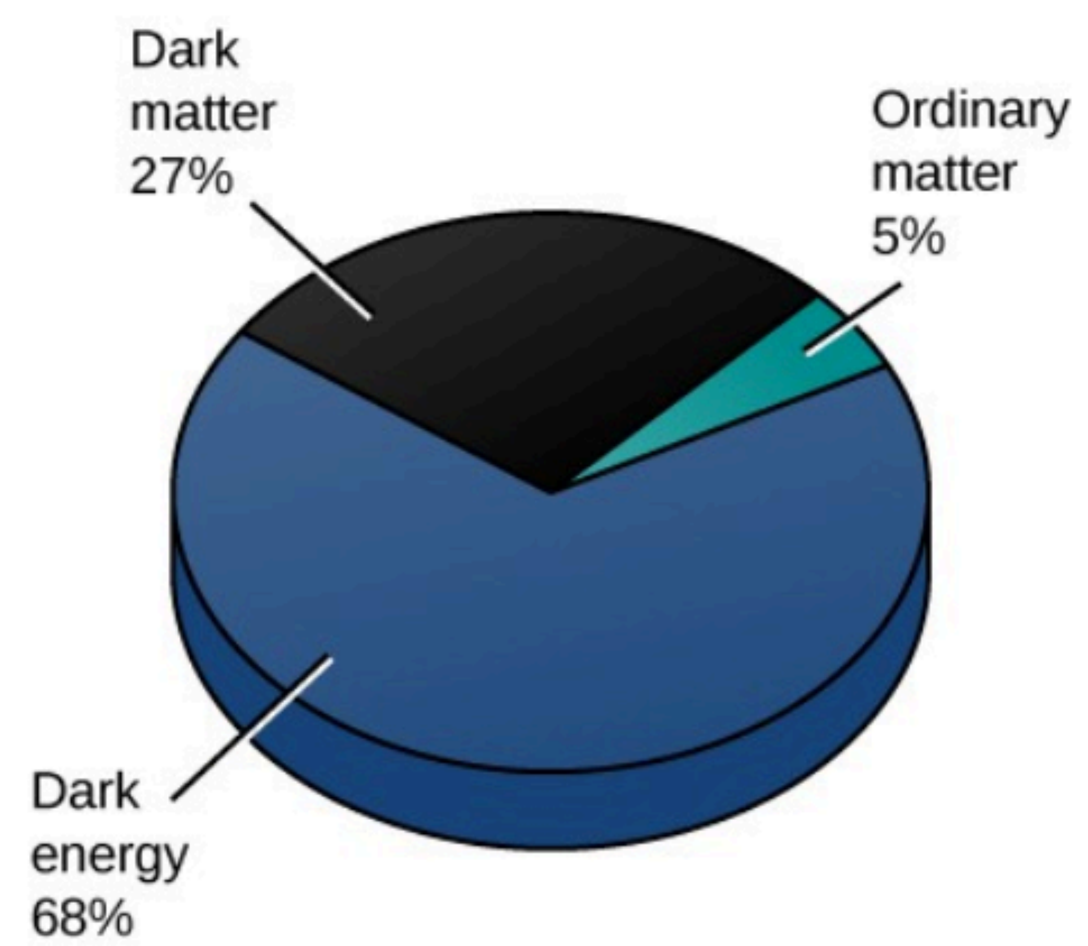
15/05/2024

Roadmap for Dark Matter Models for Run 3, CERN

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

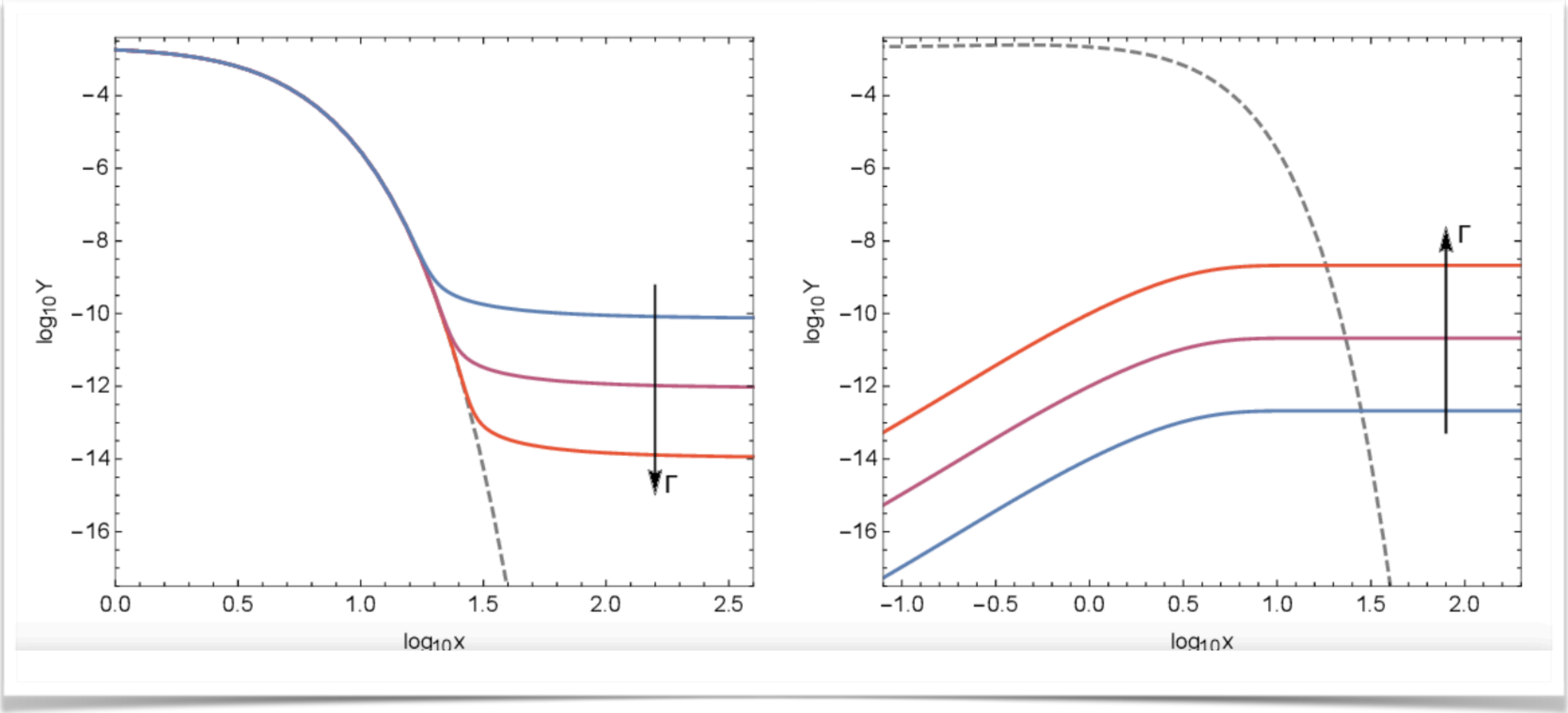
- Weakly interacting massive particle
- Feebly interacting massive particle
- Other production mechanisms, such as conversion driven freeze out, dark sector number changing processes

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

Higgs triplet is necessary

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

$\rho_{1,2}$ **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

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

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

Fermionic fields

ϕ_h

SM scalar doublet

$\Delta \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow (1,3,0)$ **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

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

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

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

H_1 → **SM like Higgs**

Goldstone ↓ **Charged Higgs** ↓

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

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

$\boxed{M^2_{H^\pm} = \mu v/(\sin\delta\cos\delta)}$ → **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

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

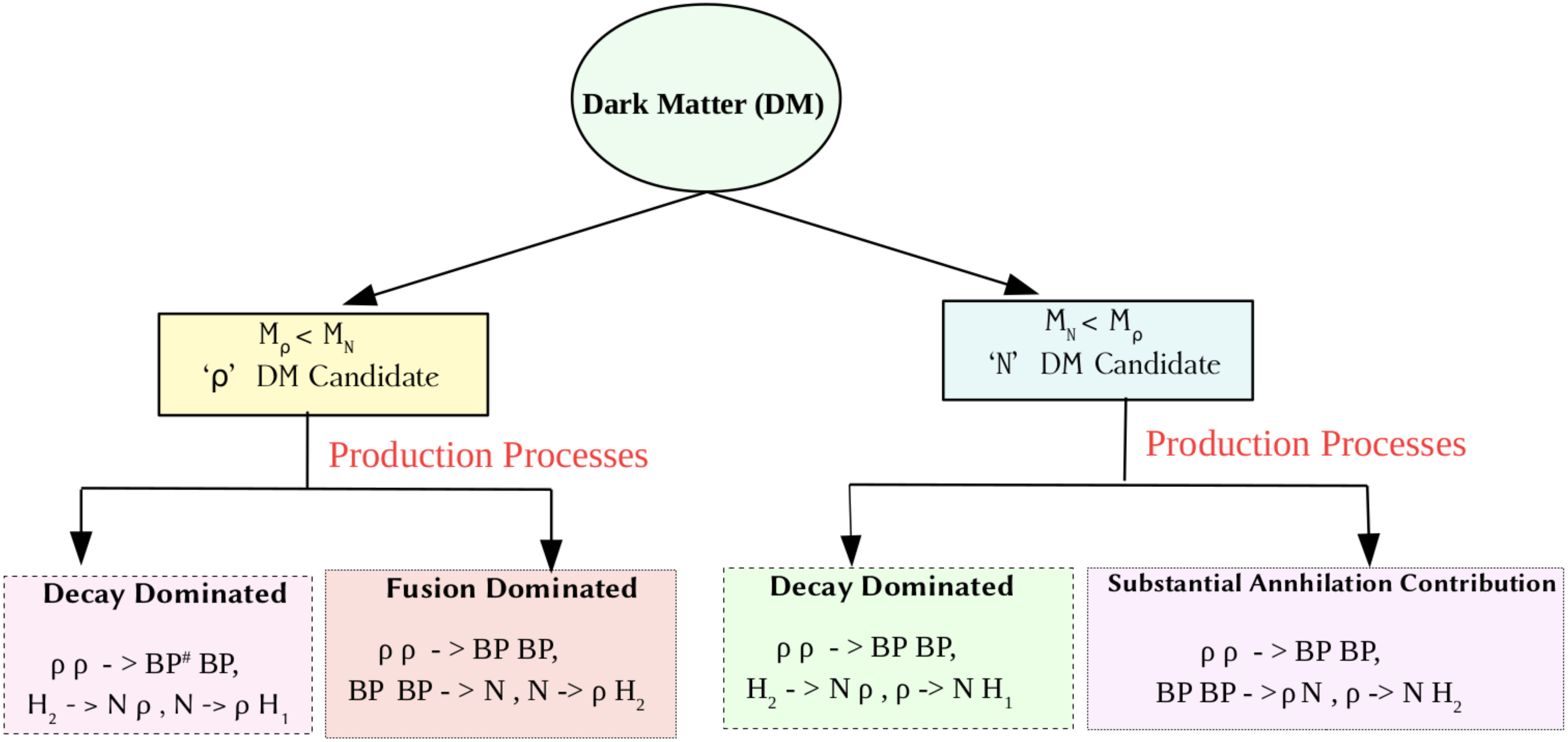
$$M_N \sim M_{N'}, \quad M_\rho \sim M_{\rho_3}$$

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



Dark Matter (DM)

$M_\rho < M_N$
'ρ' DM Candidate

Production Processes

Decay Dominated

$\rho\,\rho \to BP^{\#}\,BP$,
$H_2 \to N\,\rho$, $N \to \rho\,H_1$

Fusion Dominated

$\rho\,\rho \to BP\,BP$,
$BP\,BP \to N$, $N \to \rho\,H_2$

$M_N < M_\rho$
'N' DM Candidate

Production Processes

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

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

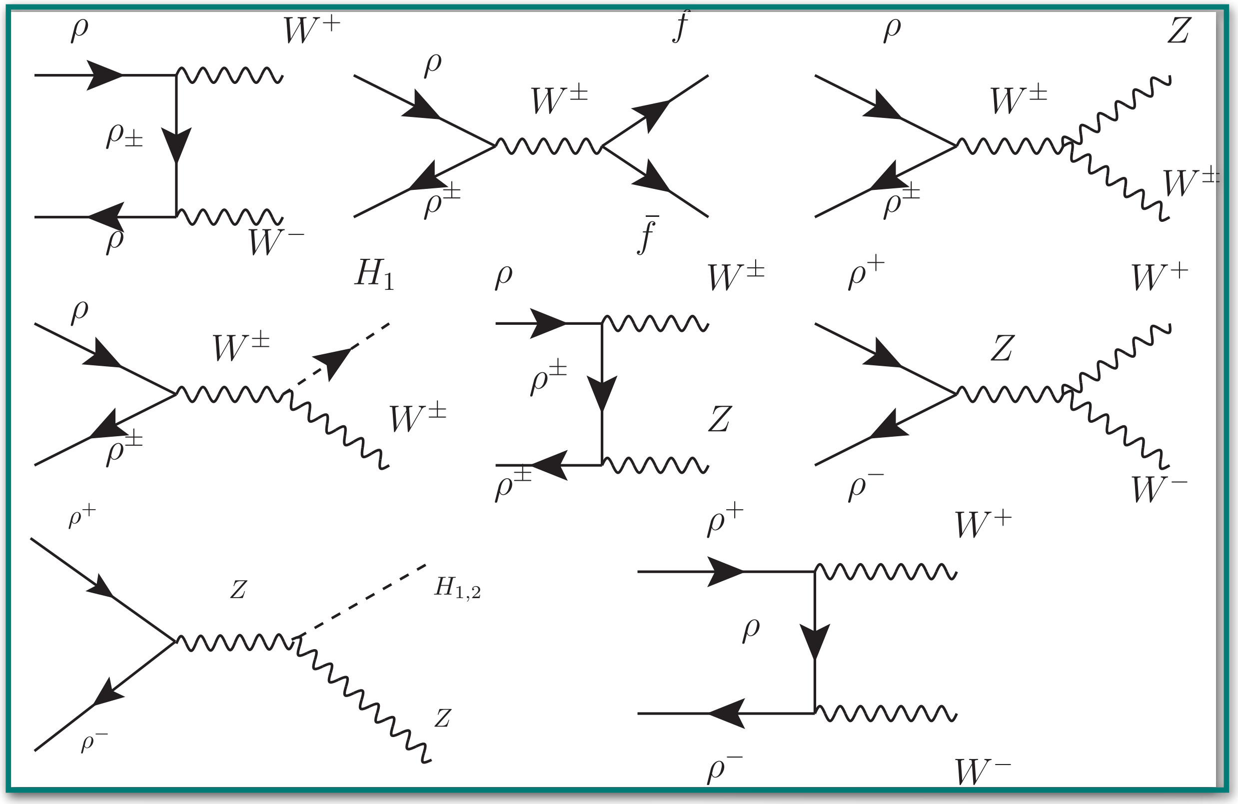
- **FIMP Dark Matter as $Y_{\rho\Delta} < \mathcal{O}(10^{-10})$**
- **N is non-thermal**
- **Freeze in production (decay, annihilation)**

+late decay of ρ contributes to relic density

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**



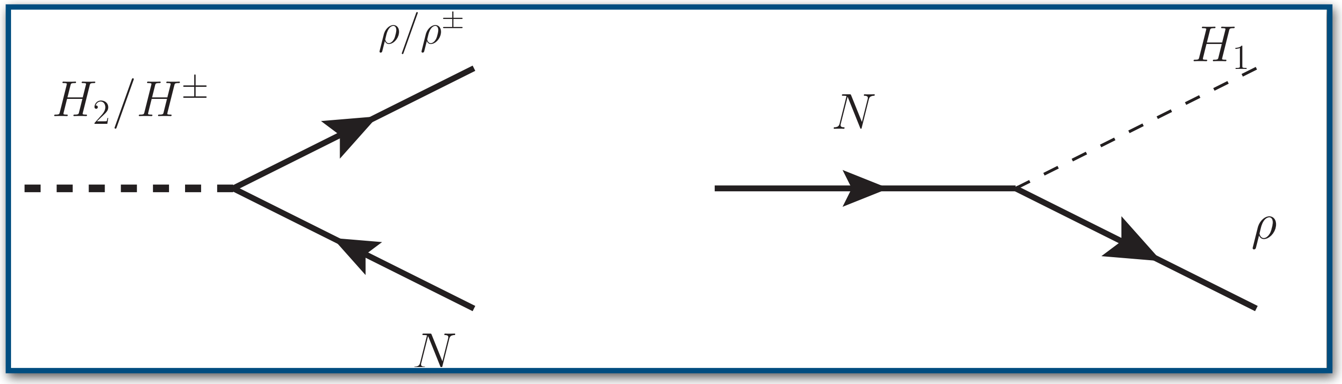
Under-abundant dark matter unless $M_\rho = 2400$ GeV or large

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

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

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

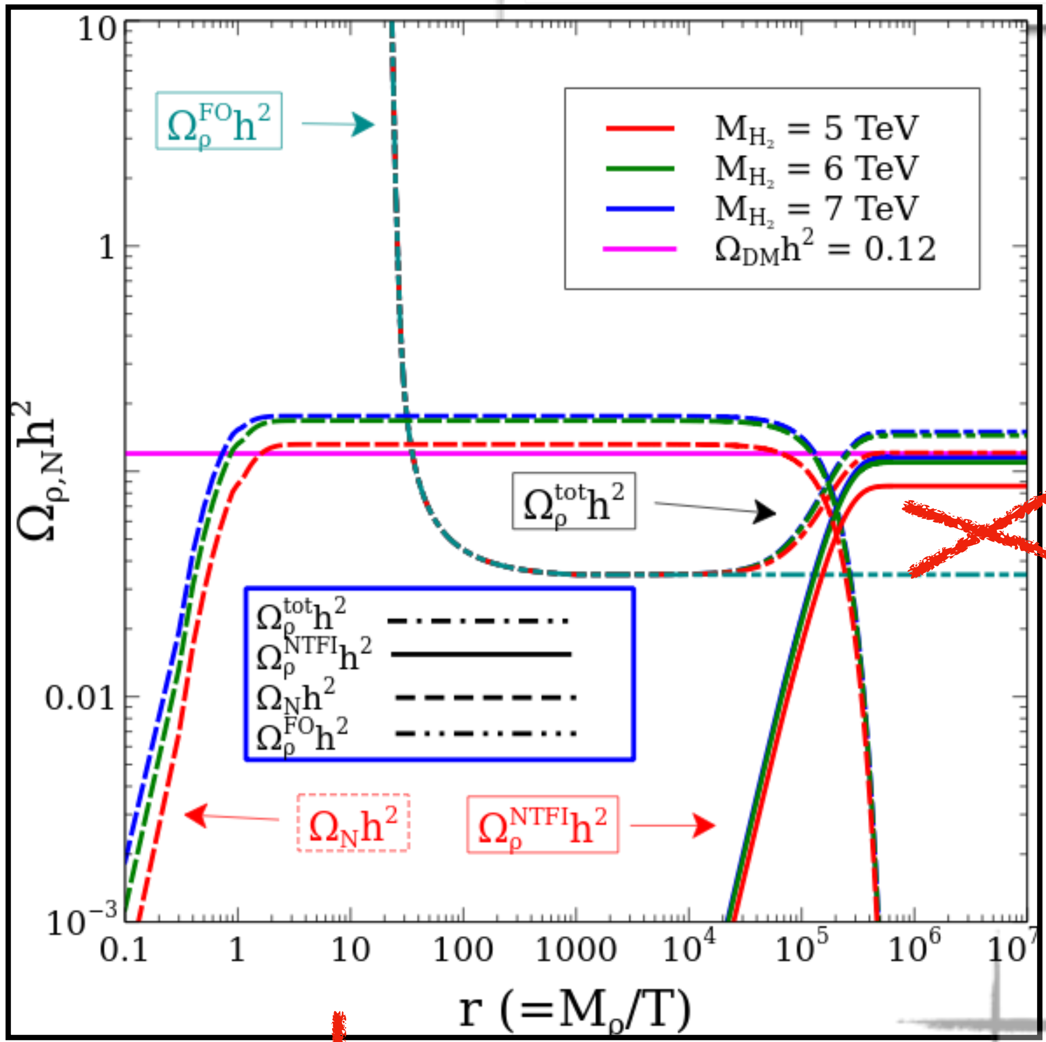
- **H_2 is a thermal particle**
- **$H_2 \to \rho N$ produces N**
- **Late decay of $N \to \rho H_1$ for correct relic density**
- **BBN constraint on lifetime of N**



Boltzmann equation for ρ and N

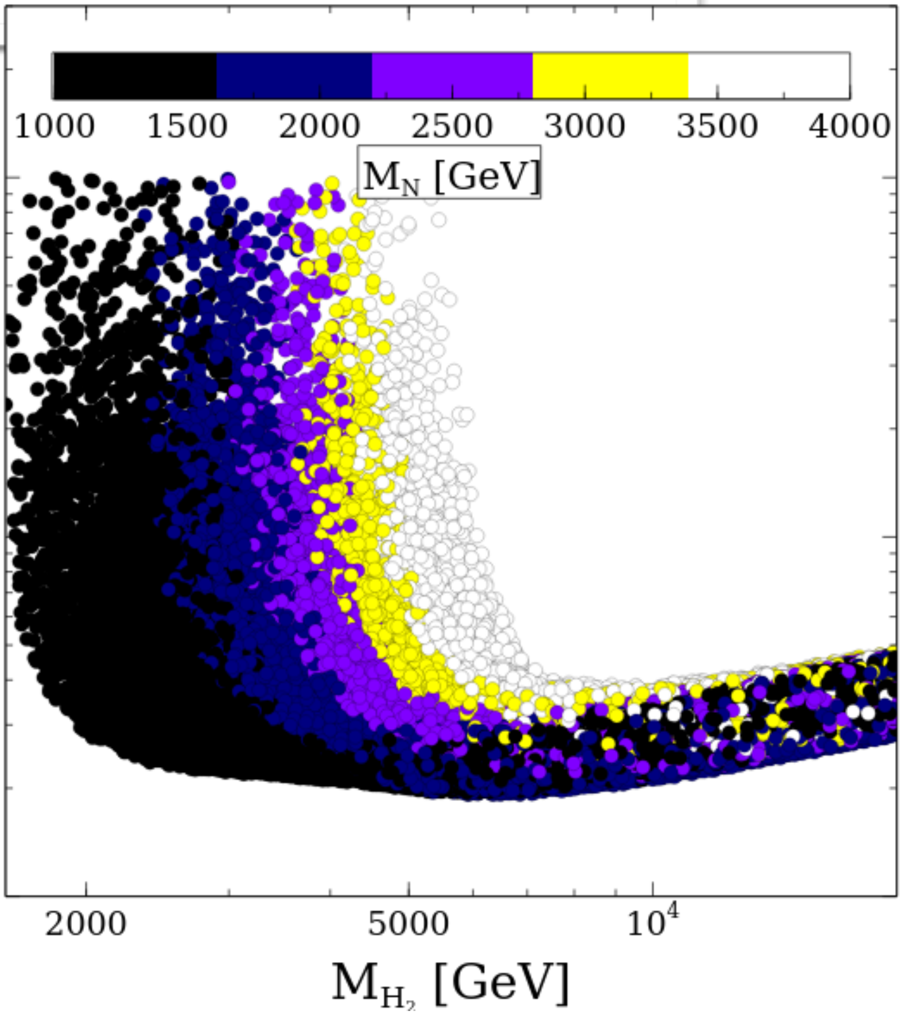
$$\hat{L} f_N = \mathcal{C}^{H_2\to N\rho} + \mathcal{C}^{AB\to N\rho} + \mathcal{C}^{N\to\ all}\,,$$

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



FO contribution

Late decay contribution



$M_\rho = 1.3\ TeV, M_N = 2\ TeV, Y_{\rho\Delta} = 2.5\times10^{-12}$

DM abundance increases with a heavier BSM Higgs state

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

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

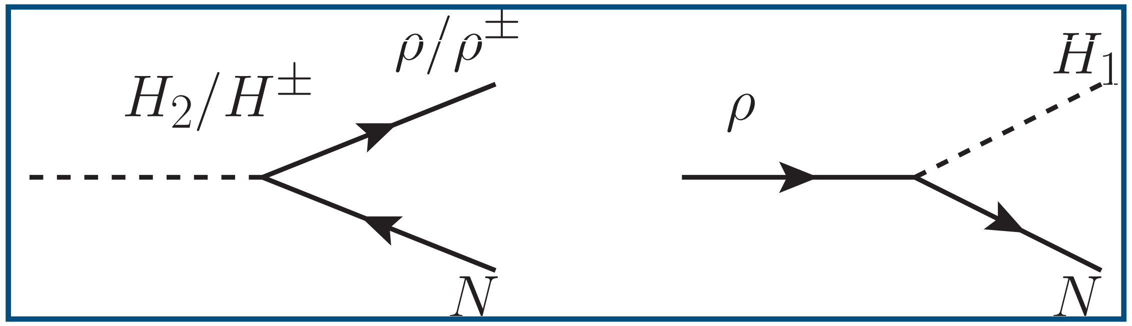
$125\ GeV < M_N - M_\rho < 3000\ GeV$

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

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

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)**

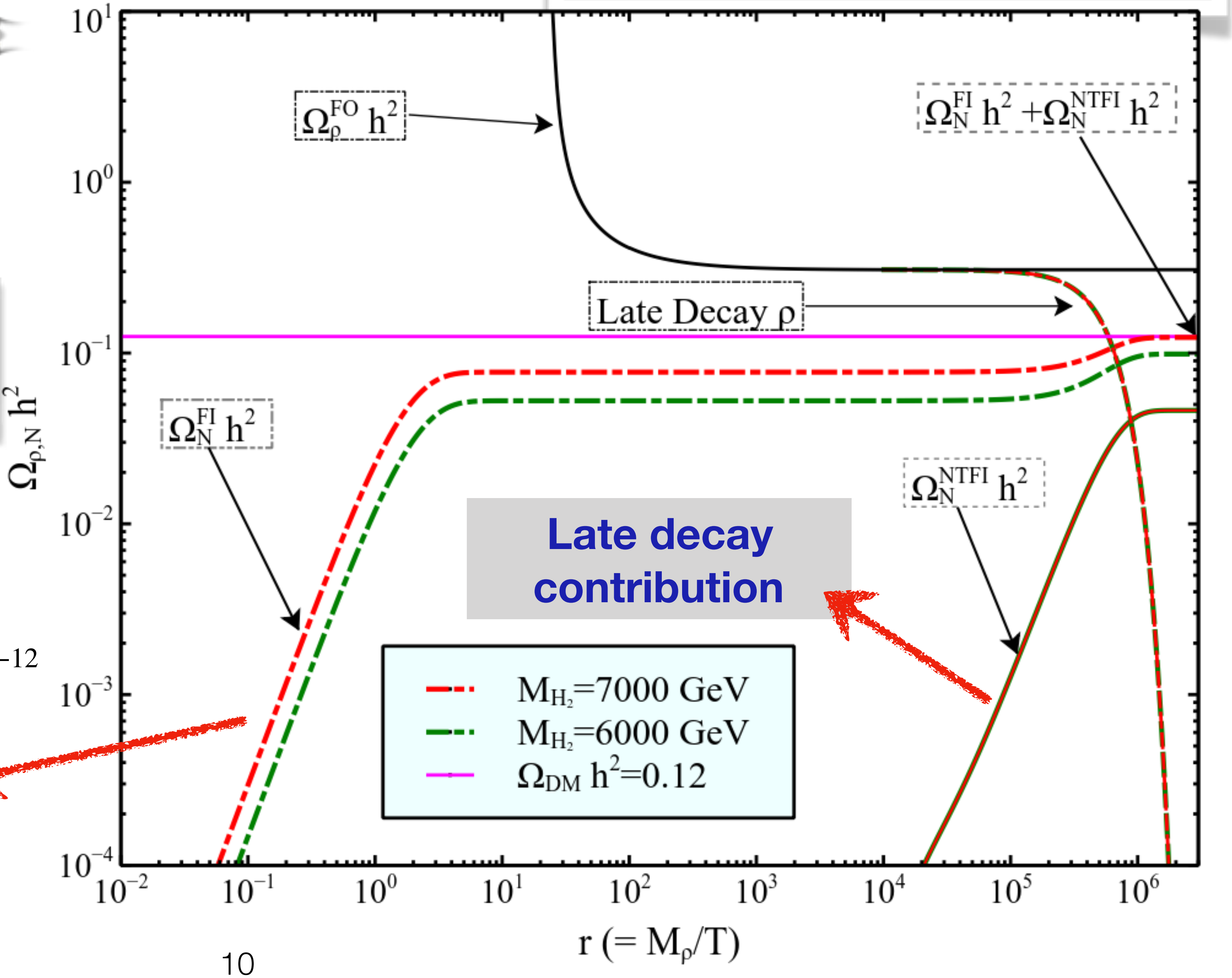


$$\Omega_N^{NTFI} h^2 = \frac{M_N}{M_\rho} \Omega_\rho^{FO} h^2$$

Dark matter abundance

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

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

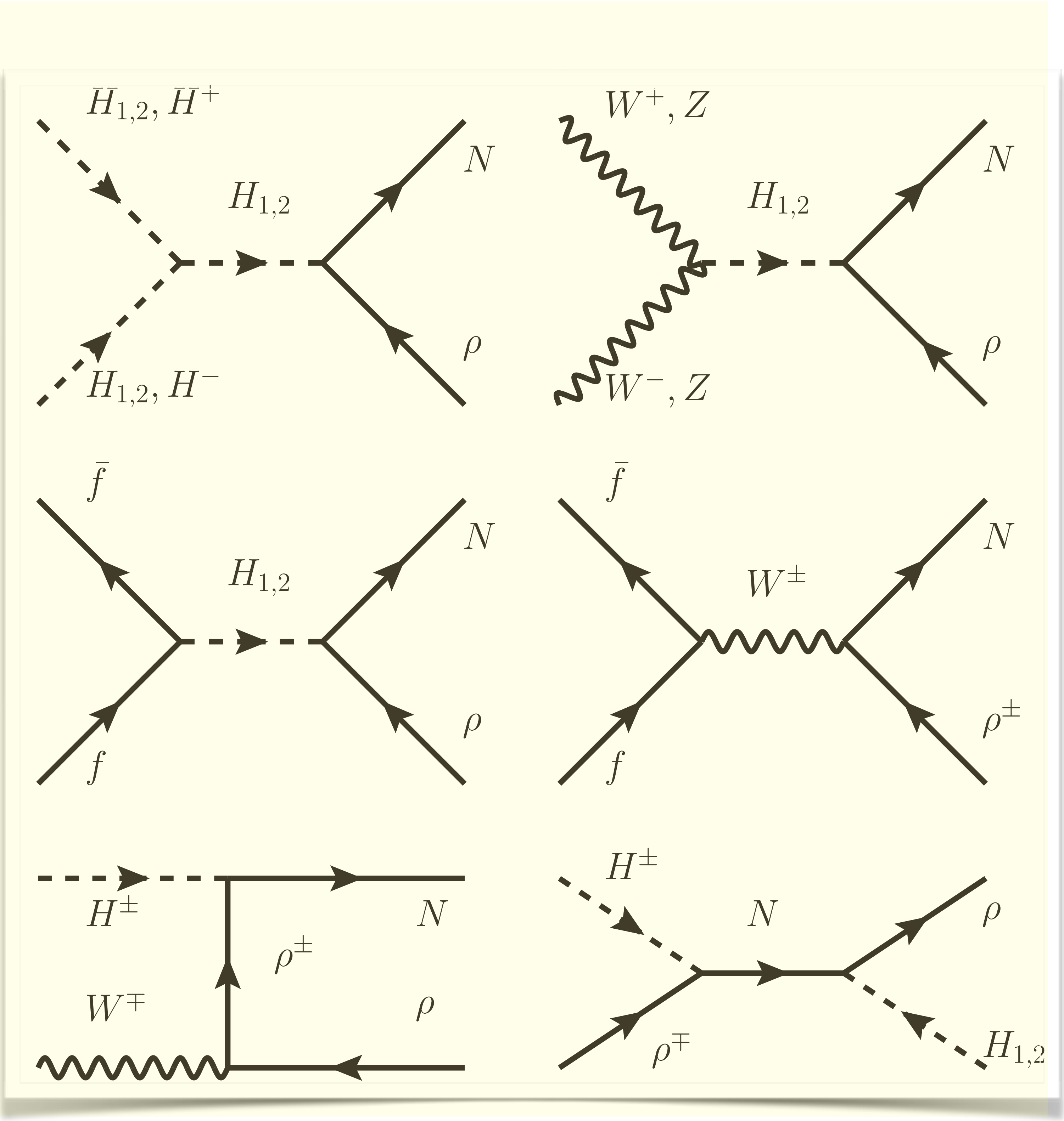


Late decay contribution

Thermal Freeze in contribution

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**

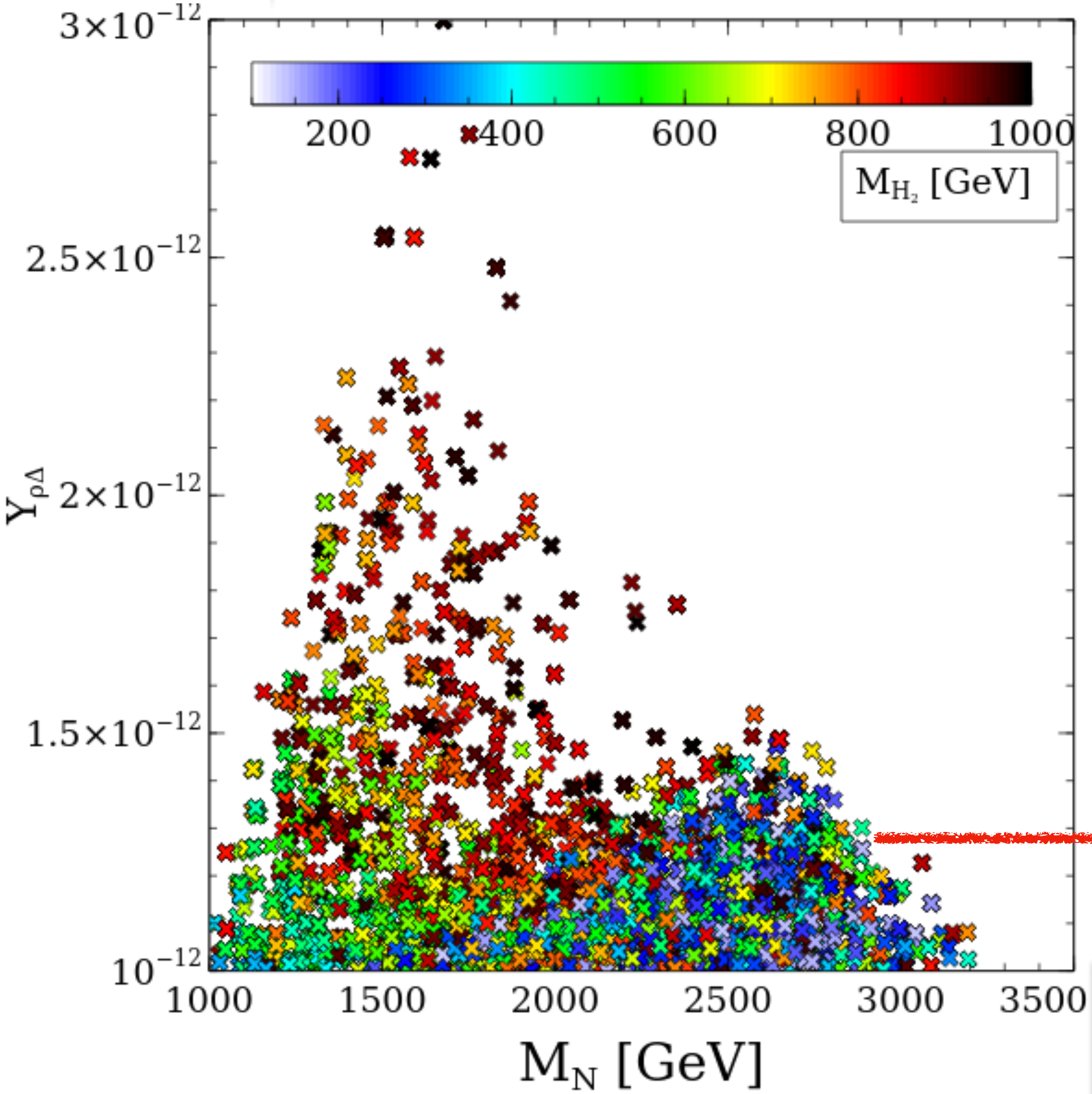
Dark Matter Production with lighter H_2

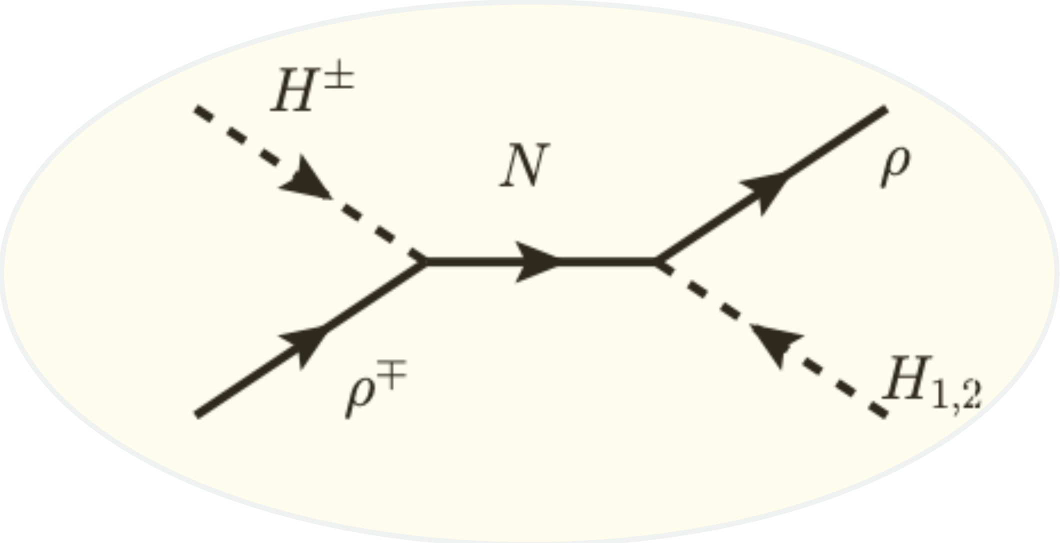
Fusion dominated scenario

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

- ρ is DM -> thermal particle.

$H_2 \to \rho N$ kinematically forbidden





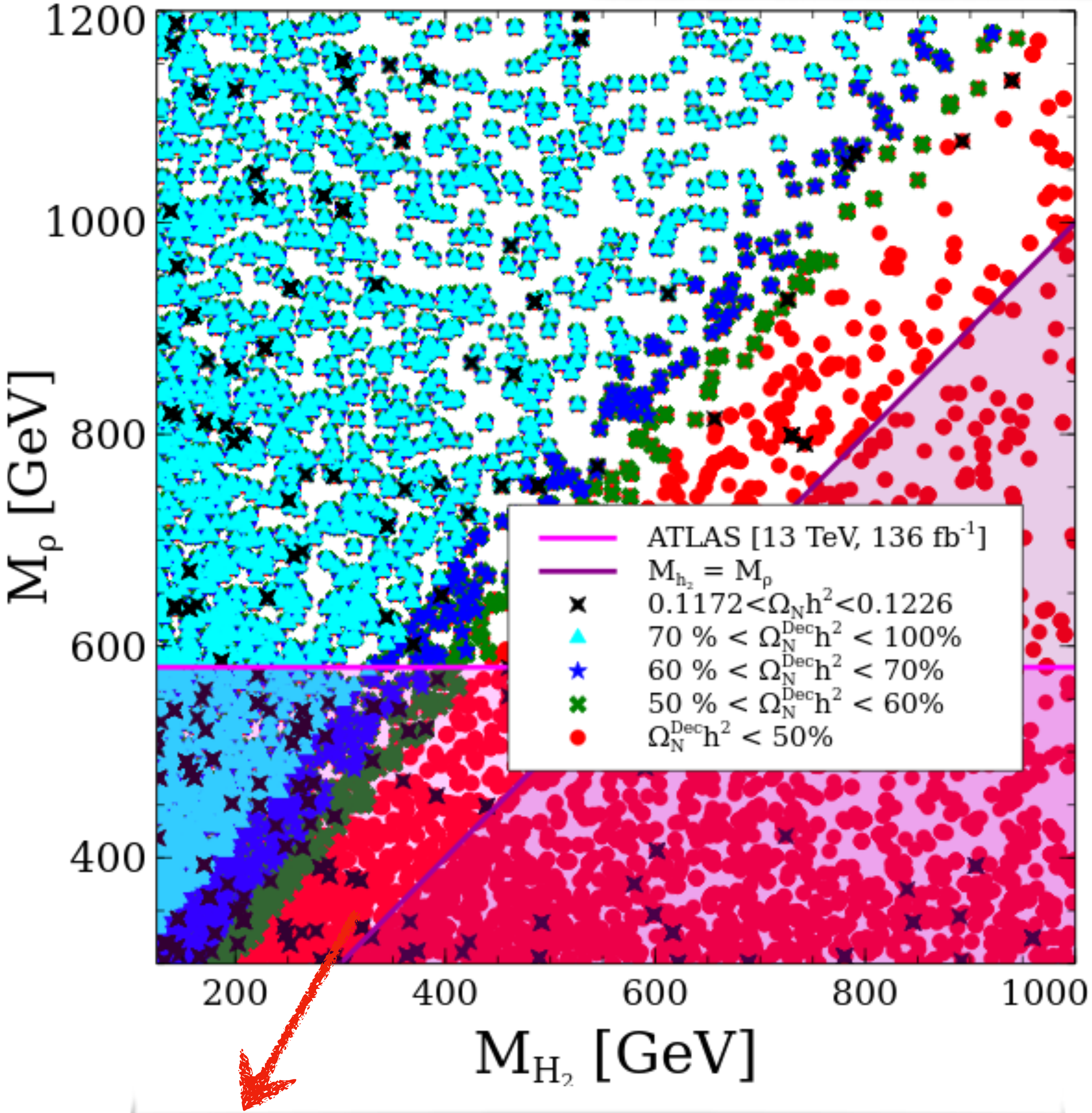
A lighter BSM Higgs can satisfy the relic abundance

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

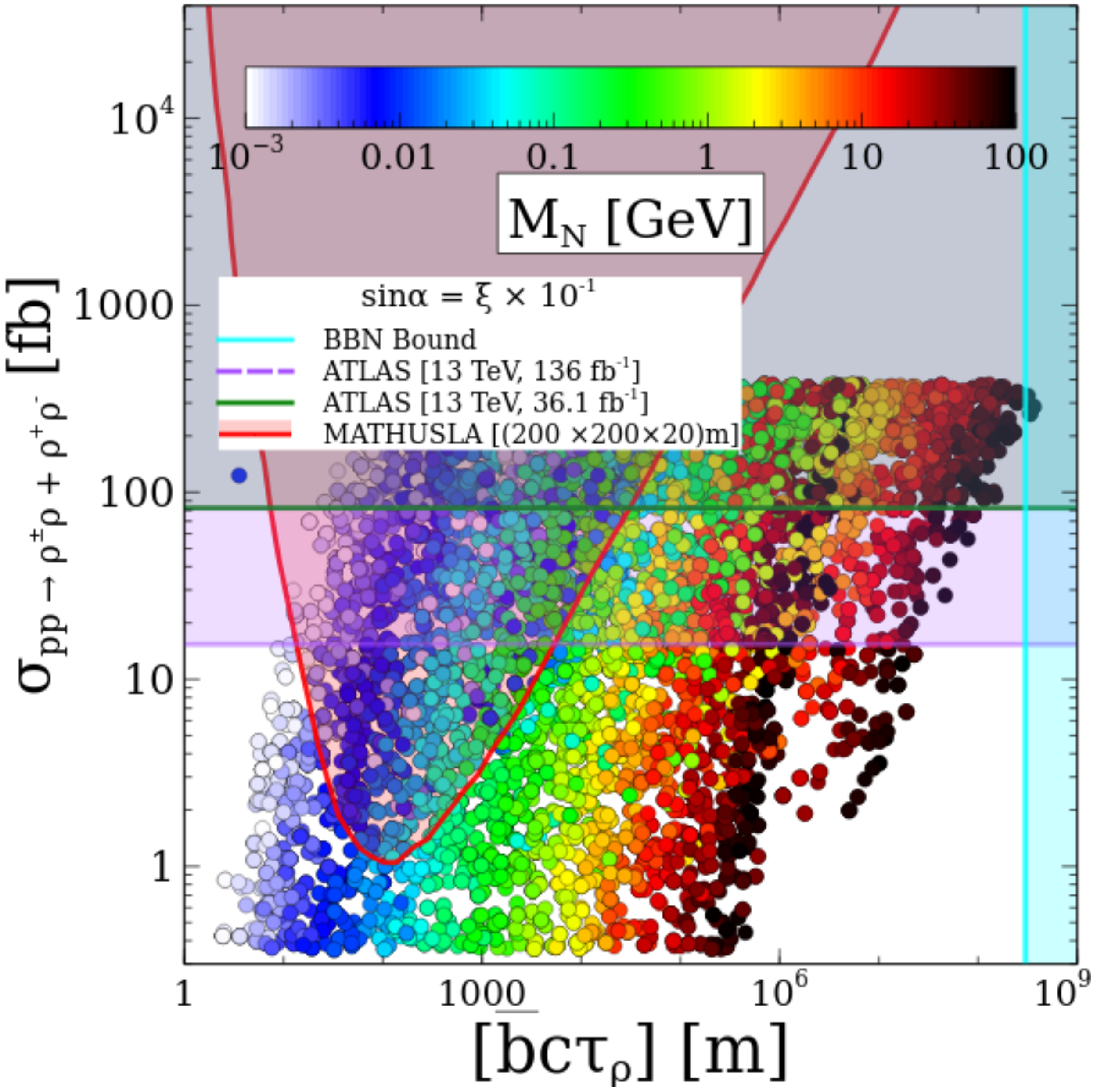
Substantial annihilation contribution

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

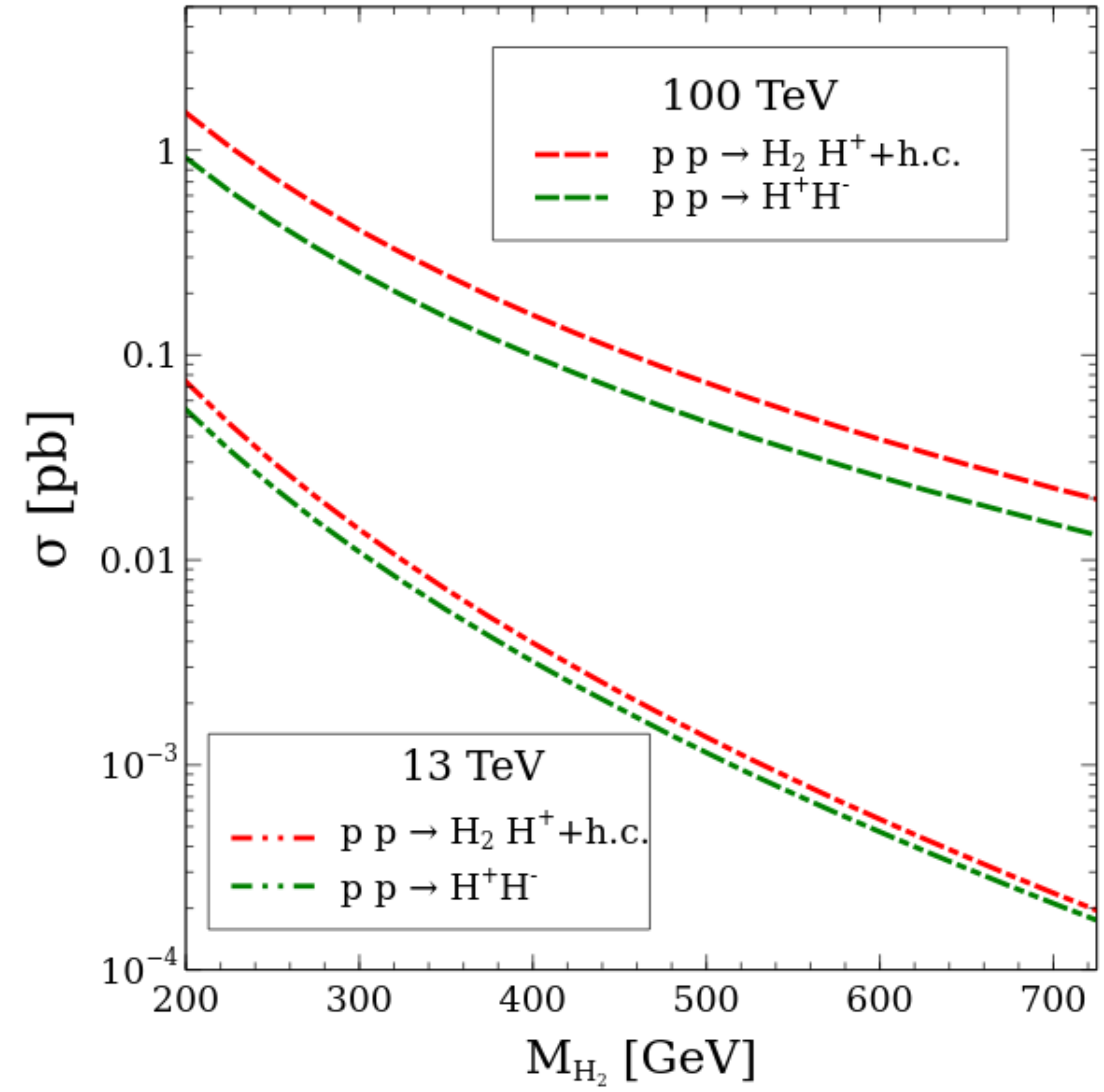
- **Standard freeze-in and late decay $\rho \to NH_2$**
- $AB \to \rho N, \quad AB = W^\pm, Z, \rho^\pm, H_{1,2}, H^\pm$ **large**

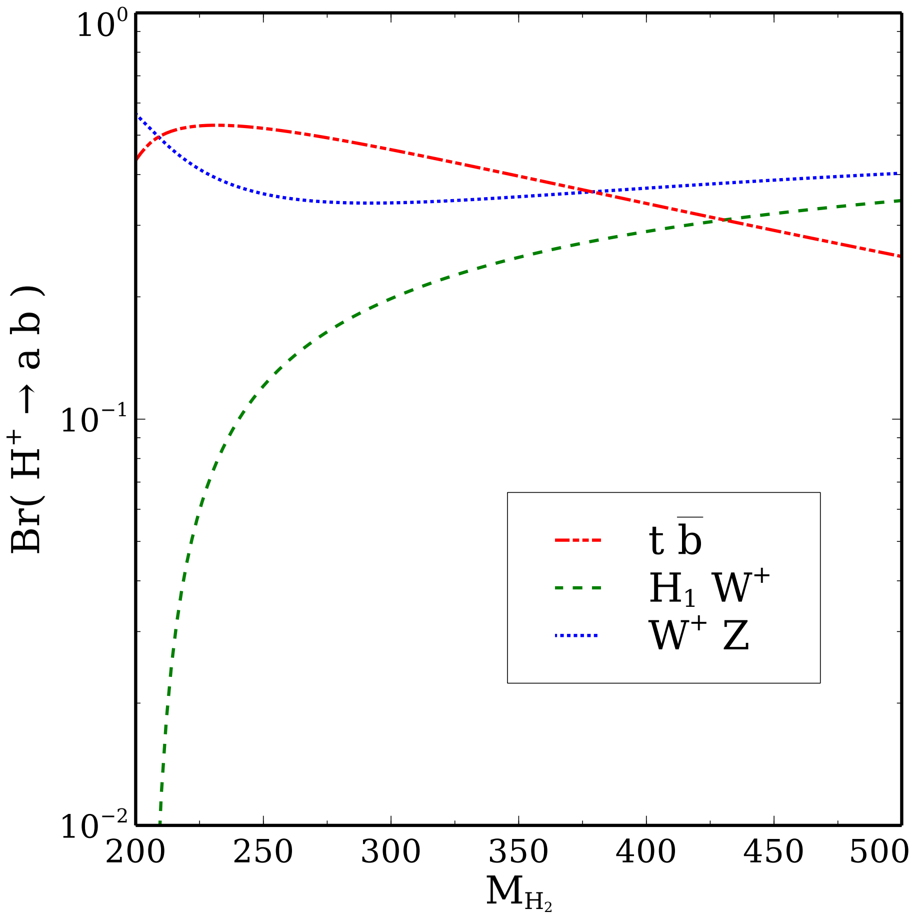


Decay contribution can be less than 50%



BSM Higgs H2 at the LHC



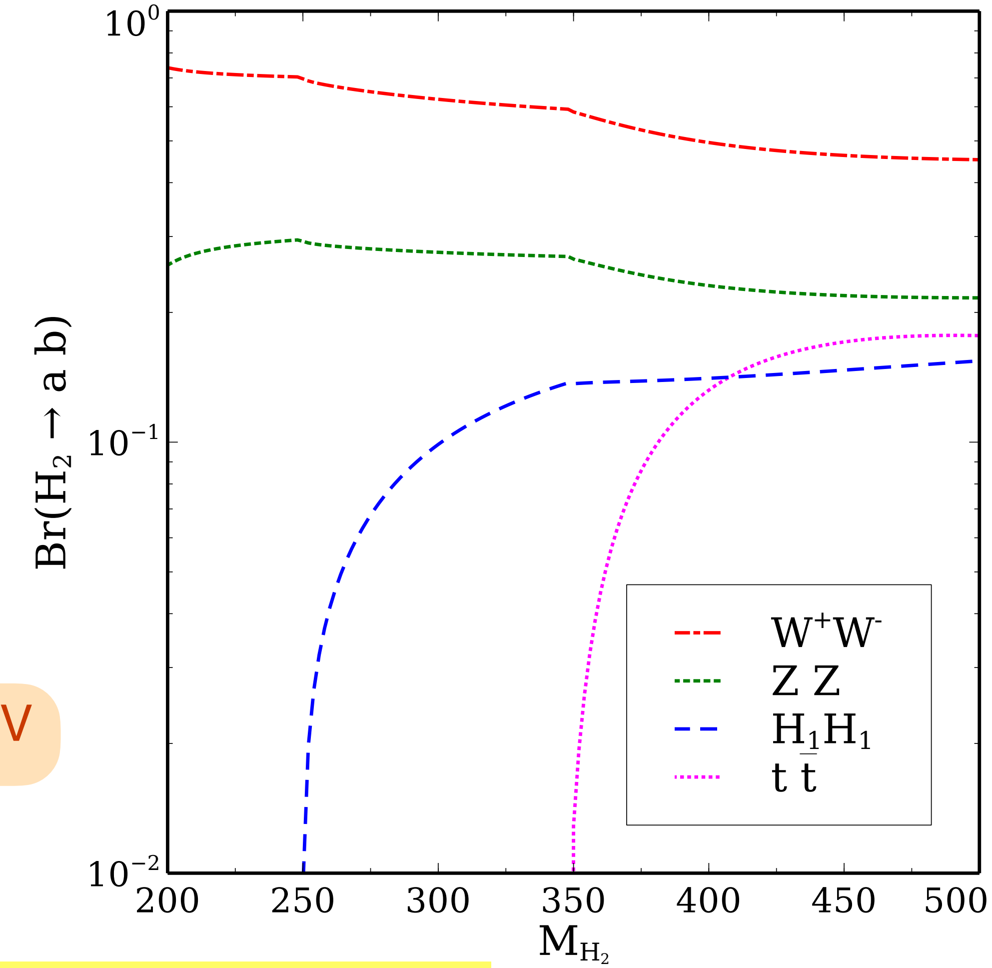


$$\sigma \sim 2.42\ (0.242)\ fb, M_{H_2} = 250\ GeV, \sin\alpha = 0.1$$

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

$pp \to H^+H^- \to 6l + MET,\ 2l + MET,\ 4j + 4l,\ 4j + MET$ 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

Summary

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

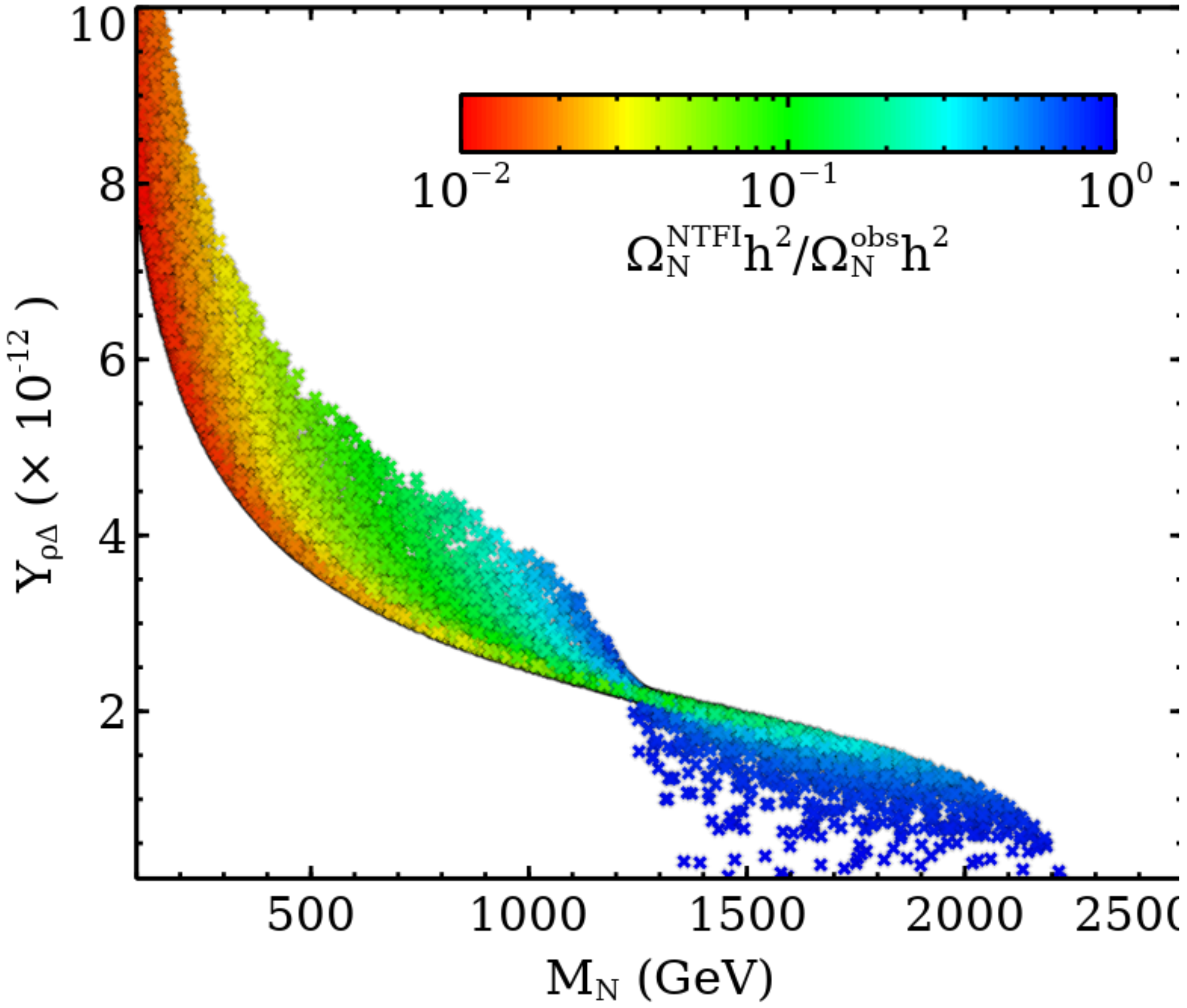
- **With $Y_{\rho\Delta} \sim \mathcal{O}(10^{-10})$ late decay contribution plays a significant role In determining relic abundance**

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

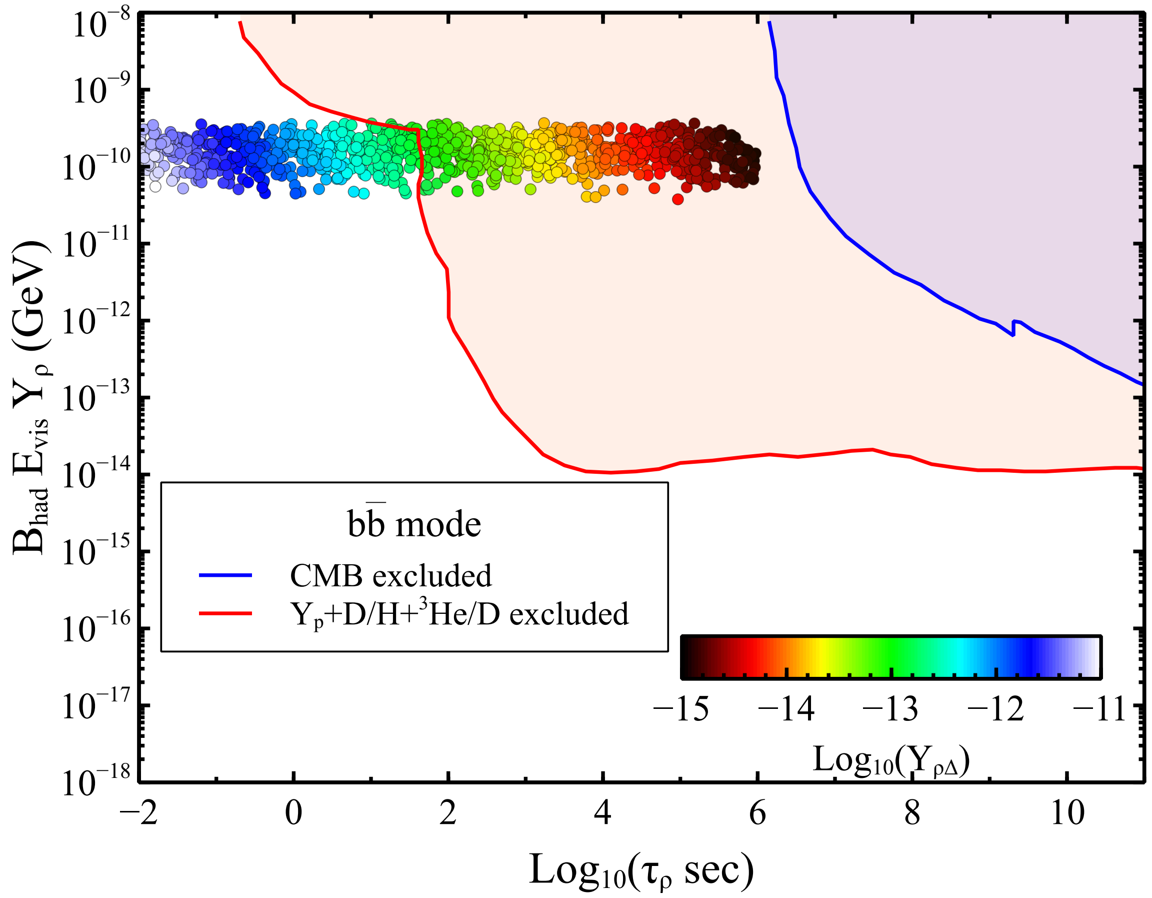
- **JET+MET, Multi-lepton+MET, Multi-lepton+Multi-jet channels can be powerful probe**

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

Thank You



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



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Fusion dominated scenario

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- ρ is DM -> thermal particle.

$H_2 \to \rho N$ kinematically forbidden