

Connecting the Missing Dots: From Neutrinos to the Dark Universe

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11/09/2026

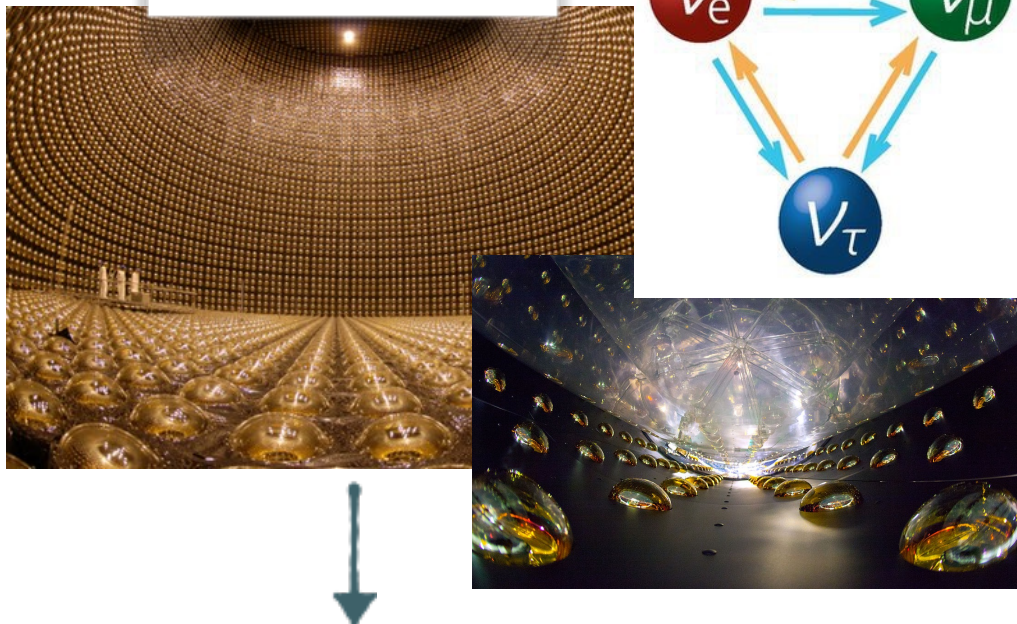
SWPNIOE 2026, Shiv Nadar Institute of Eminence, Delhi NCR

Experimental Observations

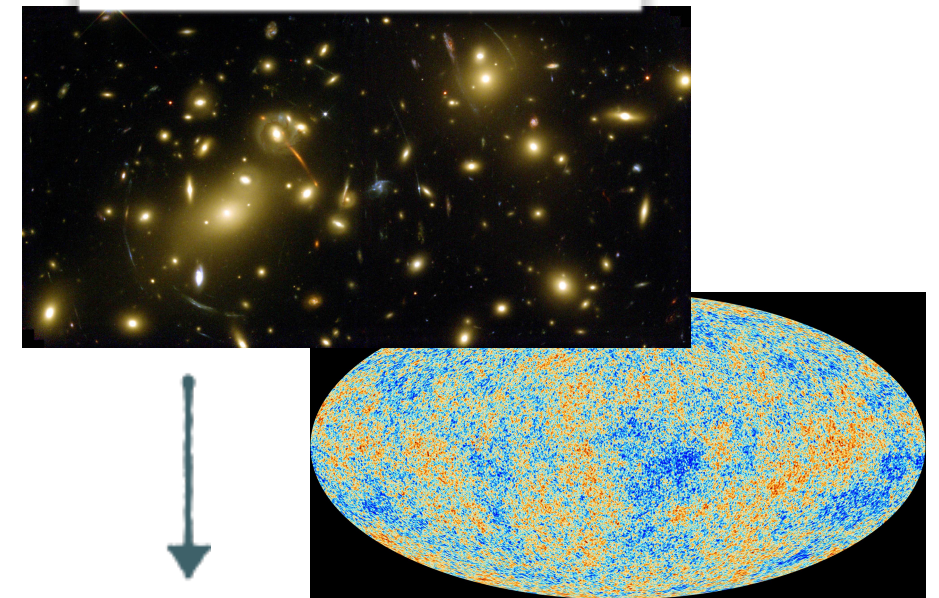
eV neutrino mass and mixing from oscillation and non-oscillation experiments

$$\nu_1, \nu_2, \nu_3 \longrightarrow m_1, m_2, m_3$$

Oscillation



Non-Oscillation



Mass square differences and mixings

$$\Delta m_{21}^2 = (6.92 - 8.05) \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{31}^2 = (2.46 - 2.60) \times 10^{-3} \text{ eV}^2$$

Large angle $\theta_{12} \sim 33.6^\circ, \theta_{23} \sim 48.5^\circ$

Non-zero $\theta_{13} \sim 8.5^\circ$ (DAYA BAY, RENO)

Sum of neutrino masses

Bound from cosmology

$$\Sigma m_i < \mathcal{O}(0.12 - 0.72) \text{ eV}$$

(Planck Collaboration, arXiv 1807.06209)

Beta decay and Neutrinoless double beta decay

$$m_\beta < 0.45 \text{ eV}, |m_{ee}| < (28 - 122) \text{ meV}$$

KATRIN Collaboration 2024 and KAMLND-Zen 2024

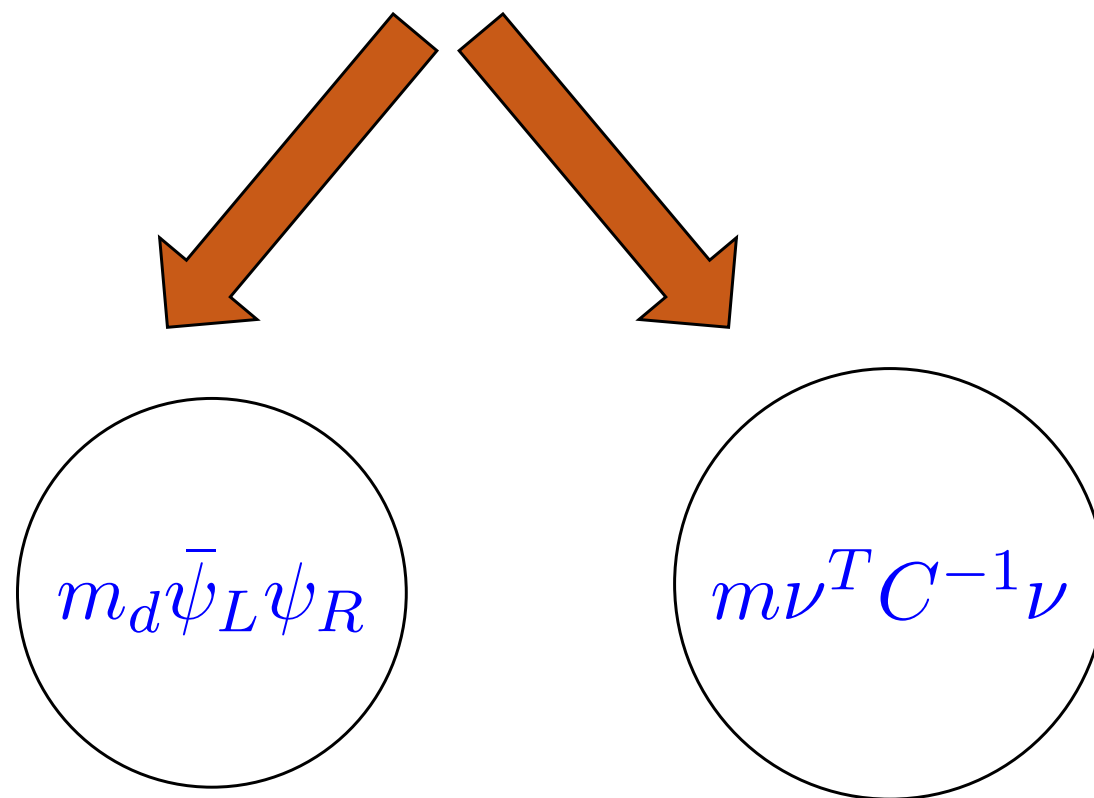
I. Esteban et al., JHEP 12 (2024) 216,
JHEP 09 (2020) 178

**Can not be explained with SM
without adding any additional particle**

Why BSM?

The experimental observation of neutrino mass and mixing demands Beyond Standard Model physics

Neutrinos could be Dirac or Majorana



Dirac mass

Majorana mass

ψ_R is missing in the Standard Model

Not gauge invariant

Origin of Neutrino Mass

Seesaw

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979,
Yanagida 1979, Mohapatra, Senjanovic 1980

Majorana mass of the standard model neutrino is generated
from higher dimensional operator

Neutrinos $\sim$ eV mass??

Majorana mass from d=5 operator



Seesaw

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979,
Yanagida 1979, Mohapatra, Senjanovic 1980

$\mathcal{L}_f(\phi, \chi)$ at higher scale $\xrightarrow{\chi \text{ integrated out}}$ $\mathcal{L}_{\text{eff}}(\phi)$ at lower scale

$$\hat{O}_5 = \frac{LLHH}{M}$$

► **Violates $B - L$ by 2 units**

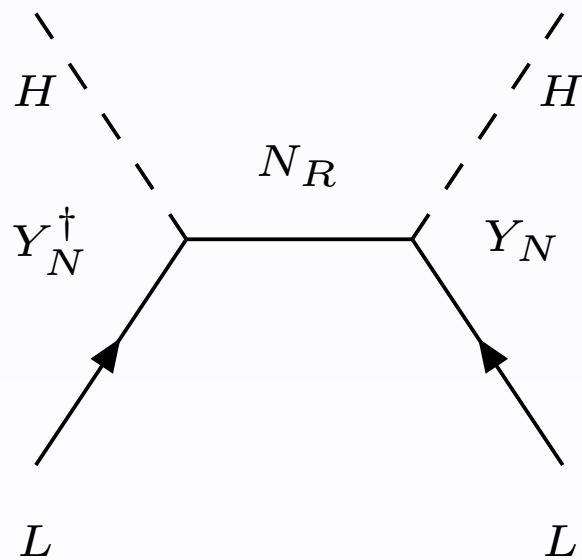
► Gauge invariance (Weinberg, PRL 43, 1979)

$$\frac{y^2 LL \langle H \rangle \langle H \rangle}{M} \Rightarrow m_\nu = \nu^T C^{-1} \nu$$

$$m_\nu \propto \frac{y^2 v^2}{\boxed{M}} \rightarrow \text{eV neutrino due to heavy } M$$

Type-I

SM gauge singlet



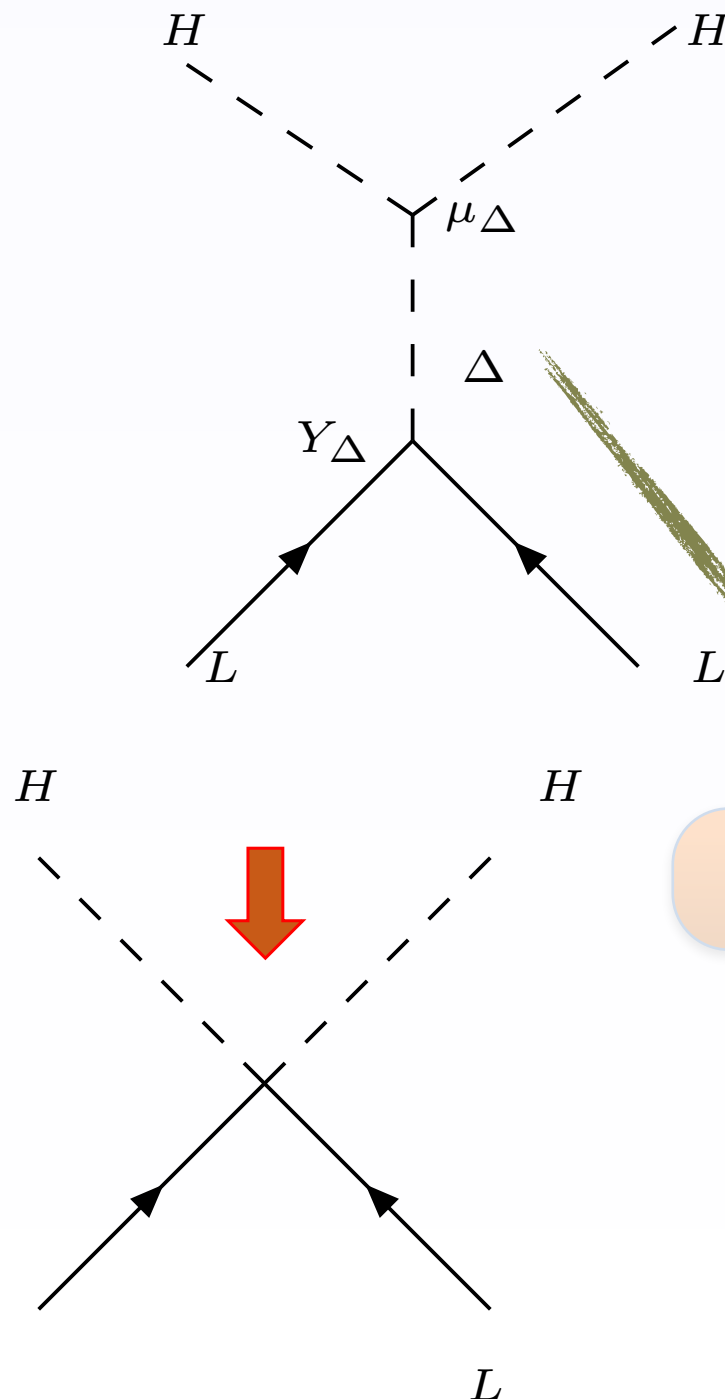
interaction of N with other SM particles is proportional to the active-sterile mixing



Suppressed

Type-II

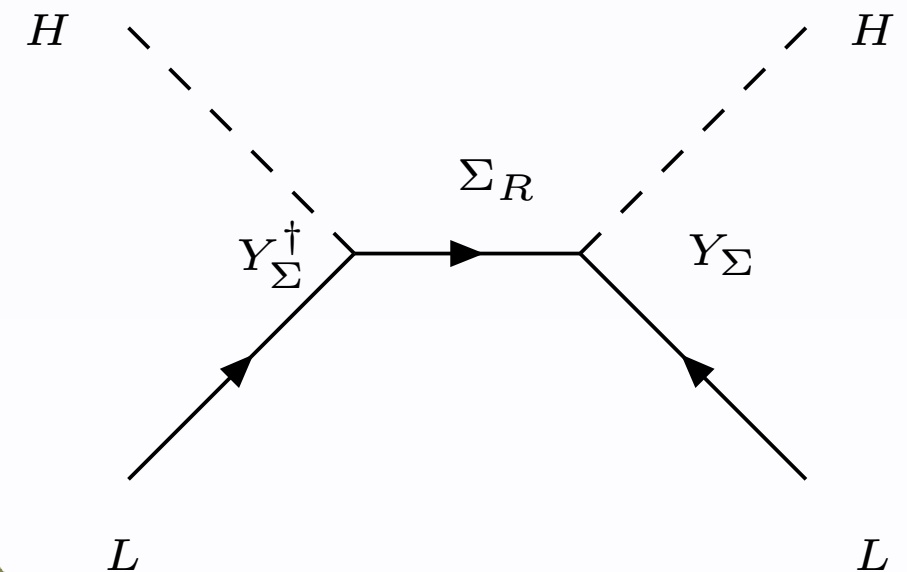
$SU(2)$ Triplet, $Y = 2$



Type-III

$SU(2)$ Triplet, $Y = 0$

$\Sigma_R \rightarrow$ Gauge interaction



H^{++} Doubly charged Higgs

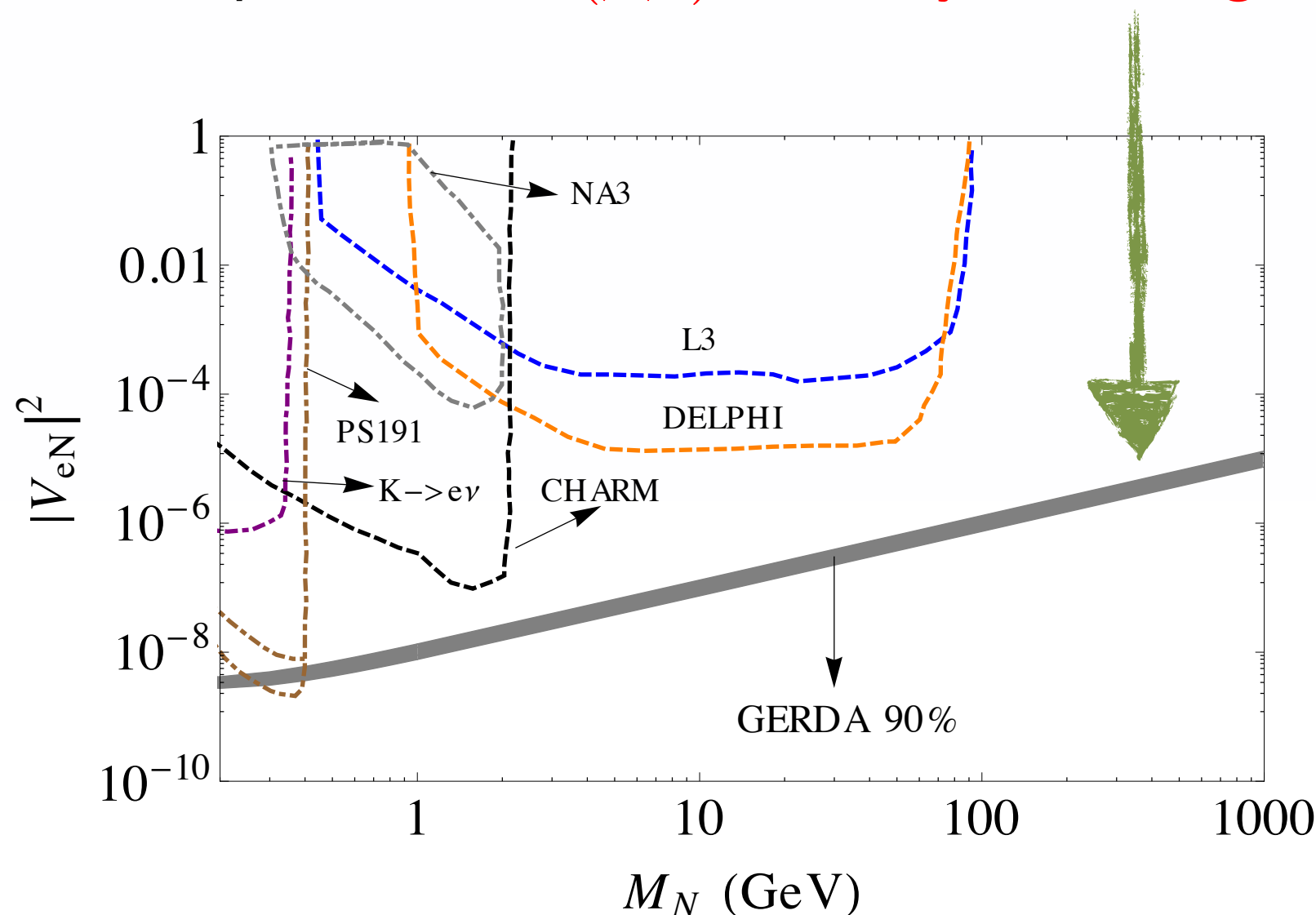
Heavy modes integrate out

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979, Yanagida 1979, Mohapatra, Senjanovic 1980; Magg, Wetterich, 1980; Foot et al., 1989

Bounds:

Limits on active-sterile neutrino mixing V from [neutrino mass](#), $(\beta\beta)_{0\nu}$ -decay, beam dump experiments and others...

- ▶ [Light neutrino mass](#) $V \sim 10^{-5}/\sqrt{M}$.
- ▶ [For \$M = 100\$ GeV, \$V \sim 10^{-6} \rightarrow\$ extremely small](#)
- ▶ Experimental constraints $\rightarrow (\beta\beta)_{0\nu}$ -decay, beam dump experiments. $(\beta\beta)_{0\nu}$ -decay $\rightarrow$ [stringent](#).



Mitra, Pascoli, Wong, 2013 ;

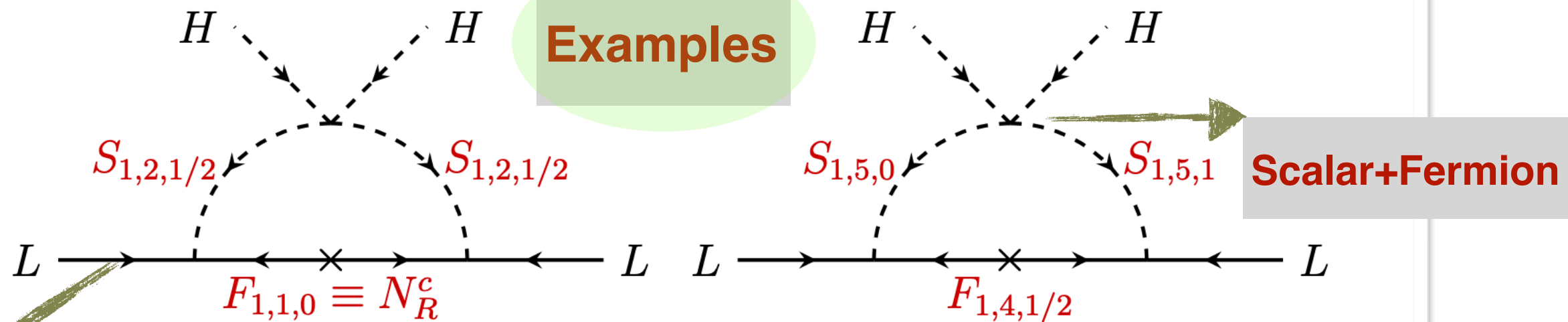
Atre et al., JHEP **0905**, 030 (2009) ;

Mitra et al., NPB **856**, 26 (2012)

Loop Generated Neutrino Mass (Weinberg operator)

The d=5 Weinberg operator can be generated via loop

Examples



Ernest Ma et al., *Phys.Lett.B* 642 (2006) 18-23

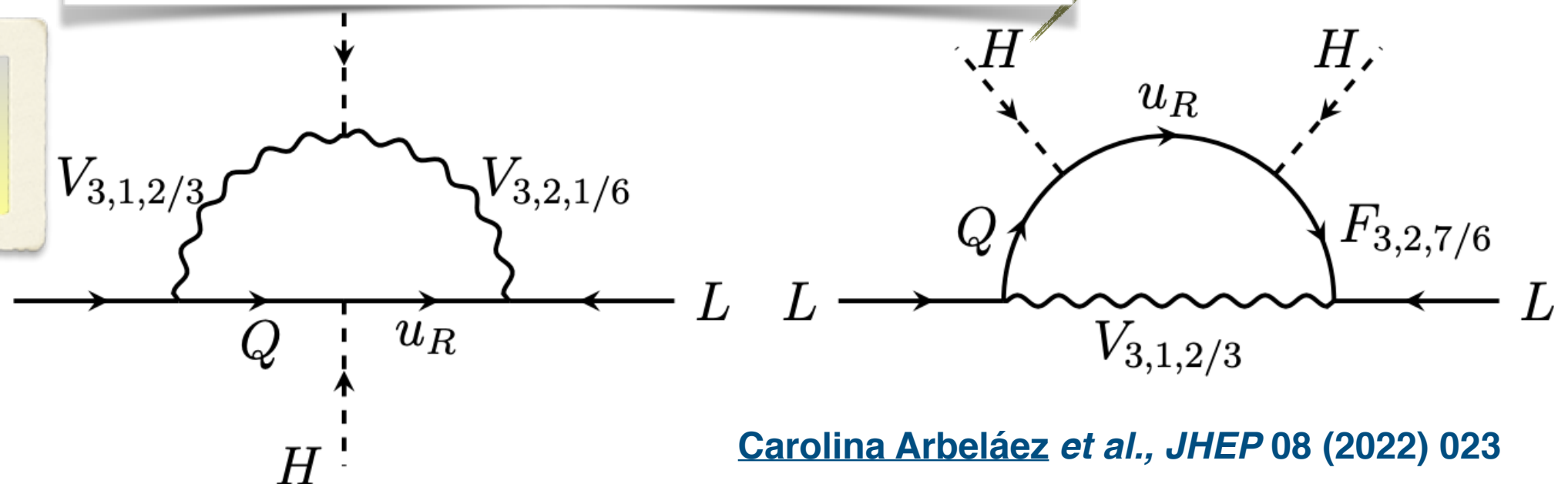
Scotogenic extension

Contain inert Higgs doublet and singlet fermion (HNL)

Provide suitable dark matter candidate

Close connection with Dark Matter

Vector+Fermion



Carolina Arbeláez et al., *JHEP* 08 (2022) 023

Non-trivial SU(2) or SU(3) multiplets (scalar/gauge bosons, fermion) required.

Major Questions in Modern Particle Physics

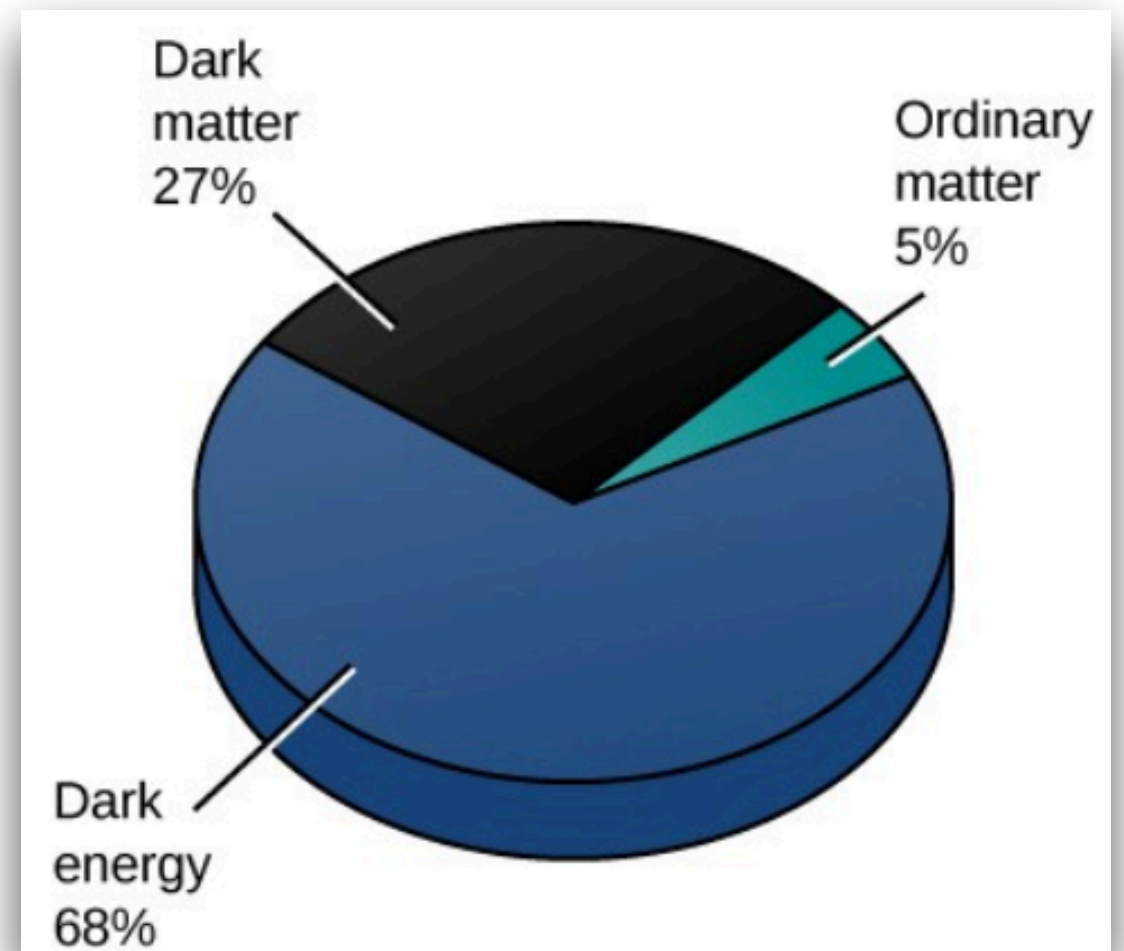


Dark Matter?

Relic density

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

Planck collaboration, 2018



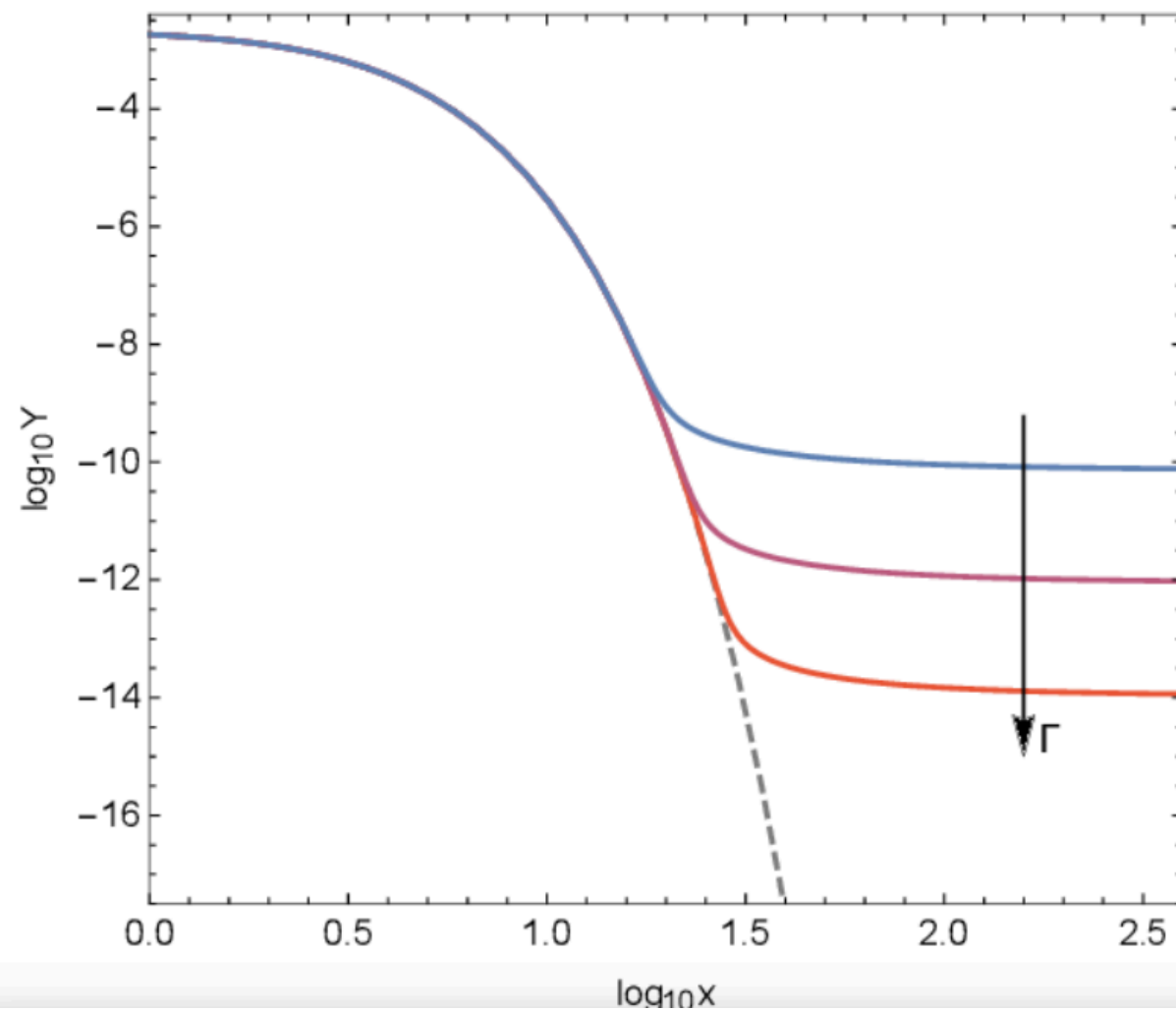
- ❖ Weakly interacting massive particle
- ❖ Feebly interacting massive particle
- ❖ Other production mechanisms, such as conversion driven freeze out, dark sector number changing processes

Theoretical description for particle dark matter??

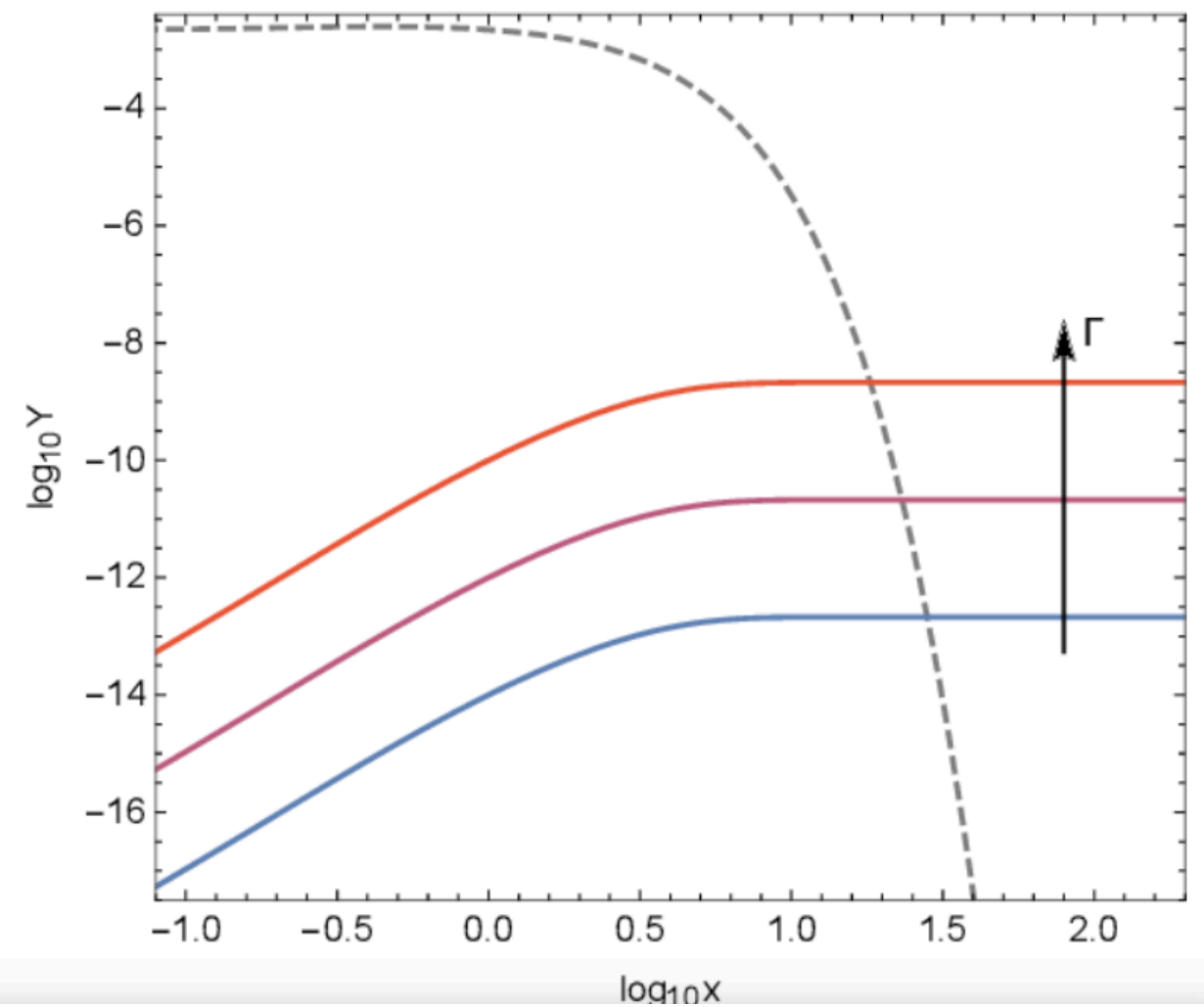
Testing DM and associated BSM descriptions in experiments??

DarkMatter Production

❖ Weakly interacting massive particle



❖ Feebly interacting massive particle



HNL as WIMP: Dynamic Scotogenic Model with Global B-L Extension

$$-\mathcal{L}_Y \supset Y_{ij}^\ell \bar{L}_i \Phi \ell_{Rj} + Y_{ij}^\nu \bar{L}_i \tilde{\eta} N_j + \frac{1}{2} Y_{ij}^N \sigma \bar{N}_i^c N_j + h.c.,$$

Vev of σ breaks global B-L

V. De Romeri, et al, arXiv:2210.07706 [hep-ph]; E.J. Chun, A. Roy, S.Mandal, and M. Mitra, *JHEP* 08 (2023) 130

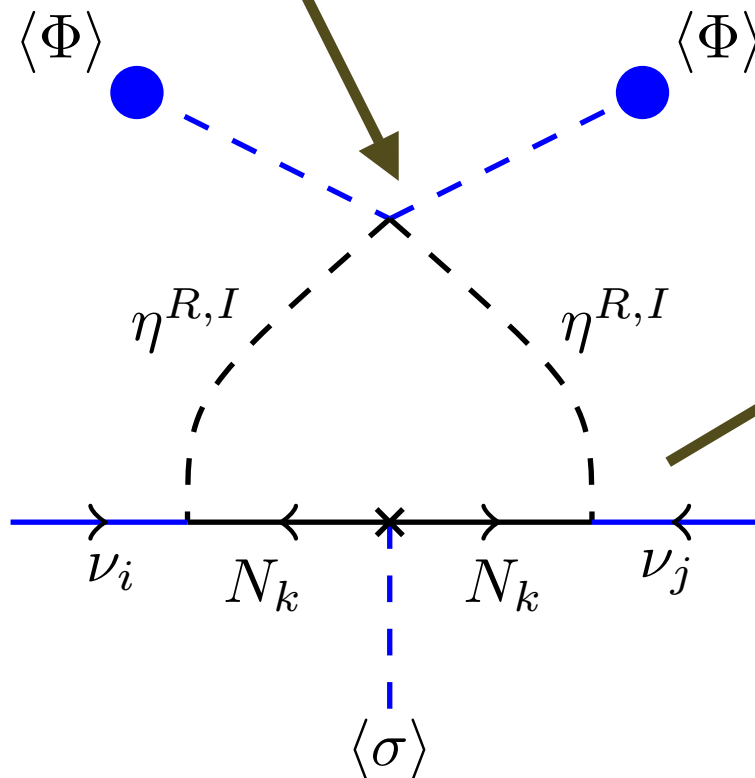
$$V = m_\Phi^2 \Phi^\dagger \Phi + m_\eta^2 \eta^\dagger \eta + m_\sigma^2 \sigma^* \sigma + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_\eta (\eta^\dagger \eta)^2 + \lambda_3 (\eta^\dagger \eta) (\Phi^\dagger \Phi) + \lambda_4 (\eta^\dagger \Phi) (\Phi^\dagger \eta) + \frac{\lambda_5}{2} [(\eta^\dagger \Phi)^2 + h.c] + \lambda_\sigma (\sigma^* \sigma)^2 + \lambda_{\Phi\sigma} (\Phi^\dagger \Phi) (\sigma^* \sigma) + \lambda_{\eta\sigma} (\eta^\dagger \eta) (\sigma^* \sigma).$$

Majoron state J

HNL N as the DM

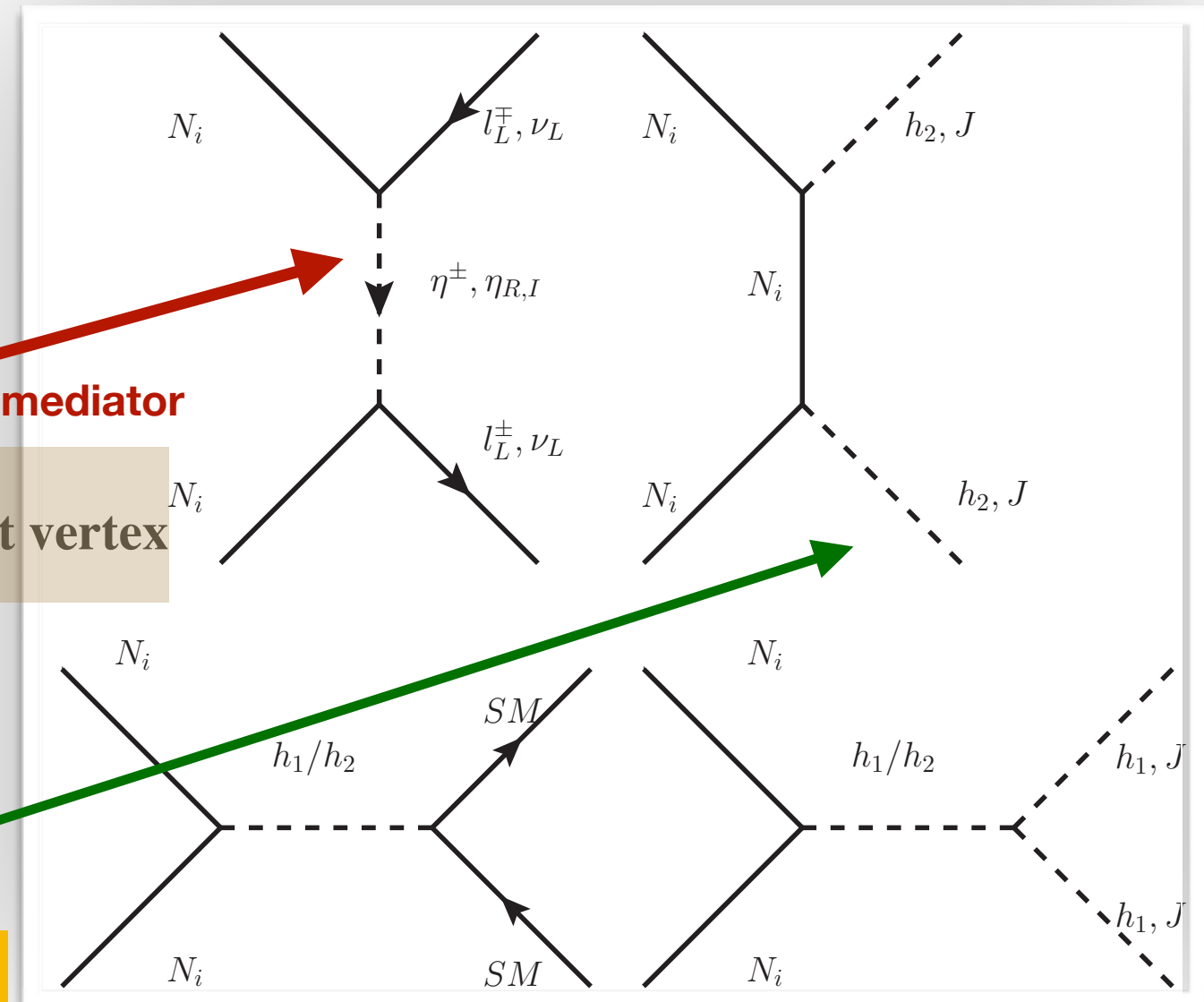
N, η are odd under Z_2

Neutrino mass generated in loop



Inert doublet as mediator

Y^ν dependent vertex



DM DM annihilation to Majoron state, $NN \rightarrow JJ$ can play significant role in determining relic abundance

Little details about light neutrino mass

$$-\mathcal{L}_Y \supset Y_{ij}^\ell \bar{L}_i \Phi \ell_{Rj} + Y_{ij}^\nu \bar{L}_i \tilde{\eta} N_j + \frac{1}{2} Y_{ij}^N \sigma \bar{N}_i^c N_j + h.c.,$$

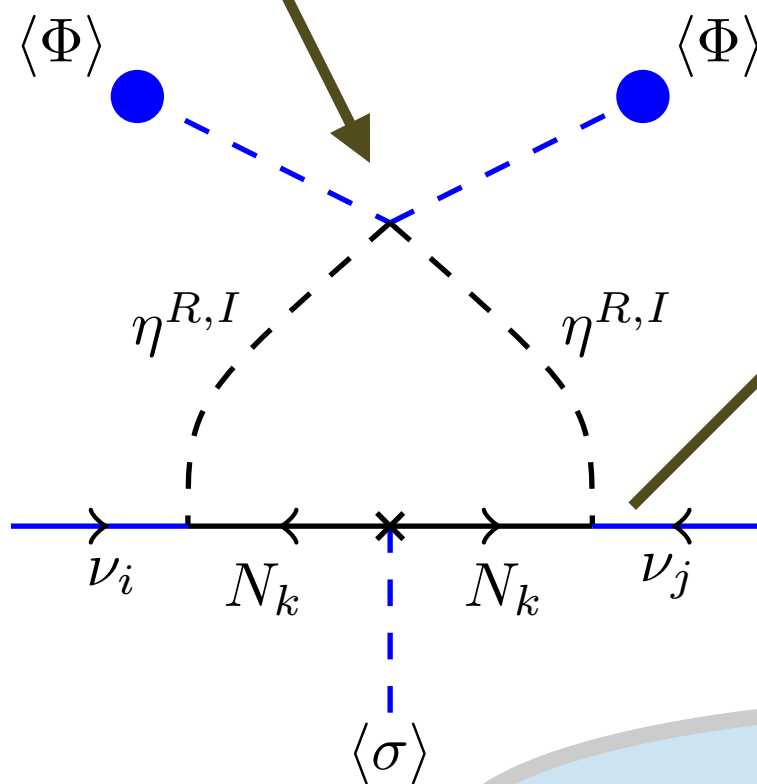
Phys. Rev. D 107, 095019

• Vev of σ breaks global B-L

Majoron state J

$$V = m_\Phi^2 \Phi^\dagger \Phi + m_\eta^2 \eta^\dagger \eta + m_\sigma^2 \sigma^* \sigma + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_\eta (\eta^\dagger \eta)^2 + \lambda_3 (\eta^\dagger \eta) (\Phi^\dagger \Phi) + \lambda_4 (\eta^\dagger \Phi) (\Phi^\dagger \eta) + \frac{\lambda_5}{2} [(\eta^\dagger \Phi)^2 + h.c] + \lambda_\sigma (\sigma^* \sigma)^2 + \lambda_{\Phi\sigma} (\Phi^\dagger \Phi) (\sigma^* \sigma) + \lambda_{\eta\sigma} (\eta^\dagger \eta) (\sigma^* \sigma).$$

Neutrino mass generated in loop



Y^ν dependent vertex

$$(m_\nu)_{ij} = \sum_{k=1}^3 \frac{Y_\nu^{ik} Y_\nu^{kj} M_{N_k}}{32\pi^2} \left[\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_{N_k}^2} \log \frac{m_{\eta_R}^2}{M_{N_k}^2} - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{N_k}^2} \log \frac{m_{\eta_I}^2}{M_{N_k}^2} \right] \equiv (Y_\nu^T \Lambda Y_\nu)_{ij},$$

Key parameters to govern neutrino masses

$Y^\nu, \lambda_5, Y^N_{\nu\sigma} \sim$ dark matter mass **and** mass of η^0

Enlarged Higgs sector

$$\Phi = \begin{pmatrix} \phi^+ \\ (v_\Phi + h_\Phi + i\eta_\Phi)/\sqrt{2} \end{pmatrix}, \quad \eta = \begin{pmatrix} \eta^+ \\ (\eta^R + i\eta^I)/\sqrt{2} \end{pmatrix} \text{ and } \sigma = (v_\sigma + h_\sigma + iJ)/\sqrt{2}.$$

$$\begin{aligned} m_{\eta^R}^2 &= m_\eta^2 + \frac{1}{2}\lambda_{\eta\sigma}v_\sigma^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v_\Phi^2, \\ m_{\eta^I}^2 &= m_\eta^2 + \frac{1}{2}\lambda_{\eta\sigma}v_\sigma^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v_\Phi^2, \\ m_{\eta^+}^2 &= m_\eta^2 + \frac{1}{2}\lambda_{\eta\sigma}v_\sigma^2 + \frac{1}{2}\lambda_3v_\Phi^2. \end{aligned}$$

(Φ, σ) mix with each other

η is secluded

(h_Φ, h_σ) basis

$$M_R^2 = \begin{bmatrix} 2\lambda_\Phi v_\Phi^2 & \lambda_{\Phi\sigma} v_\Phi v_\sigma \\ \lambda_{\Phi\sigma} v_\Phi v_\sigma & 2\lambda_\sigma v_\sigma^2 \end{bmatrix},$$

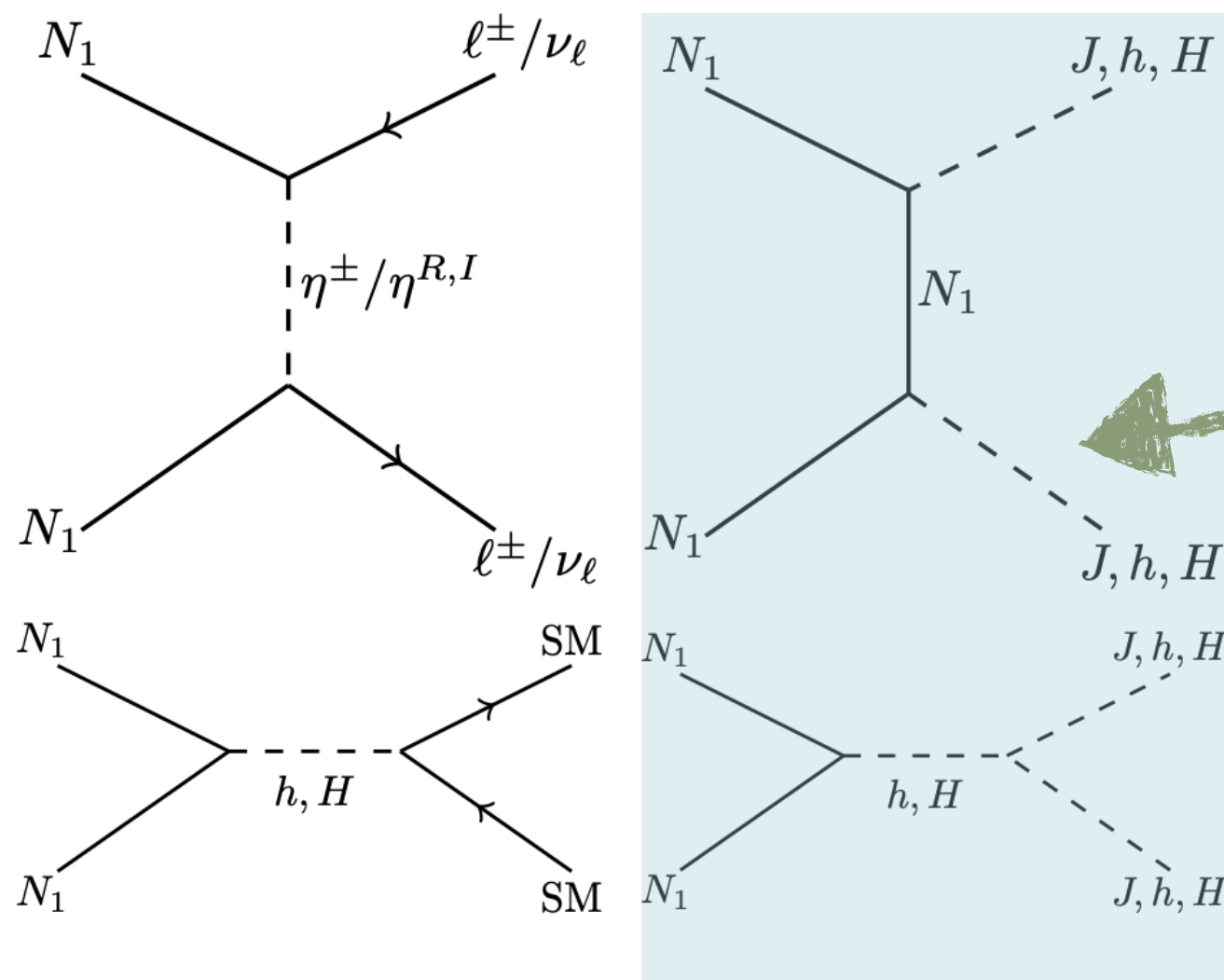
$$m_{h,H}^2 = \lambda_\Phi v_\Phi^2 + \lambda_\sigma v_\sigma^2 \mp \sqrt{(\lambda_\Phi v_\Phi^2 - \lambda_\sigma v_\sigma^2)^2 + \lambda_{\Phi\sigma}^2 v_\Phi^2 v_\sigma^2},$$

Physical Higgs, h, H

$$\tan 2\theta = \frac{\lambda_{\Phi\sigma} v_\Phi v_\sigma}{\lambda_\Phi v_\Phi^2 - \lambda_\sigma v_\sigma^2}.$$

Presence of massless Majoron mode J

Dark Matter Relic Abundance



- In typical Scotogenic model only 1st diagram is present
- In dynamical Scotogenic model, additional s-channel or t-channel diagram will also contribute
- Dark matter annihilation to Majoron is significant

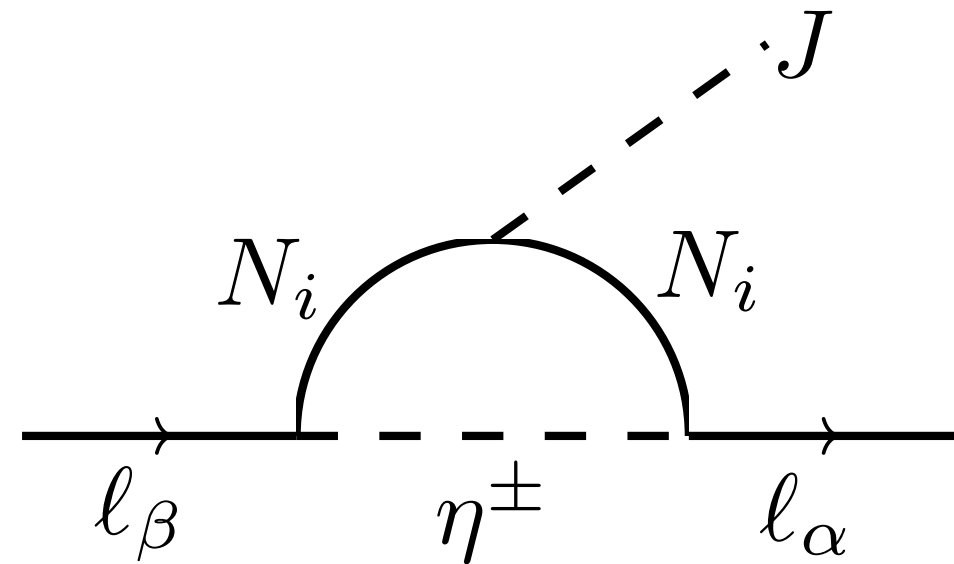
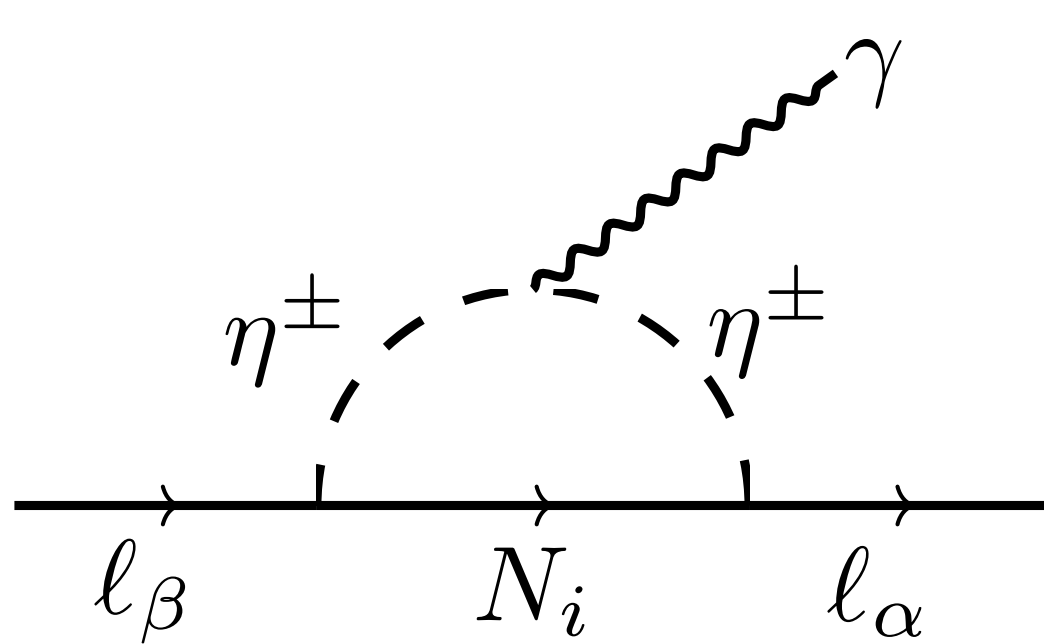
Initial state		Final state		Scaling with couplings
N_1	N_1	l^-	l^+	$Y^{\nu 4}$ 't' channel processes
		ν	$\bar{\nu}$	
N_1	N_1	J	J	$Y^{N 4}$ 't' channel processes
		h, H	h, H	
		J	h, H	
N_1	N_1	Z, W^+	Z, W^-	$Y^{N 2}$'s' channel processes
		q	q	
		h, H	h, H	
		J	J	

$$-\mathcal{L}_Y \supset Y_{ij}^\ell \bar{L}_i \Phi \ell_{Rj} + Y_{ij}^\nu \bar{L}_i \tilde{\eta} N_j + \frac{1}{2} Y_{ij}^N \sigma \bar{N}_i^c N_j + h.c.,$$

Governs light neutrino mass

Governs Dark matter mass (together with vev of σ)

Lepton flavour violation



Presence of charged scalar and HNL -> $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \tau \rightarrow e\gamma$

Presence of charged scalar, HNL, and Majoron -> $\mu \rightarrow eJ$

$$\text{Br}(\ell_\beta \rightarrow \ell_\alpha \gamma) = \frac{3\alpha_{\text{em}}}{64\pi G_F^2 m_{\eta^\pm}^4} \left| \sum_{i=1}^3 Y_{\alpha i}^\nu Y_{\beta i}^{\nu*} F_2(M_{N_i}^2/m_{\eta^\pm}^2) \right|^2 \text{Br}(\ell_\beta \rightarrow \ell_\alpha \nu_\beta \bar{\nu}_\alpha)$$

$$F_2(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6(1 - x)^4}$$

$$\mathcal{L}_{Jl_\alpha l_\beta} = J \bar{l}_\beta (S_L^{\beta\alpha} P_L + S_R^{\beta\alpha} P_R) l_\alpha + h.c.$$

$$S_L = \frac{-i}{16\pi^2 v_\sigma} M_l Y^{\nu\dagger} \Gamma Y^\nu, \quad S_R = \frac{i}{16\pi^2 v_\sigma} Y^{\nu\dagger} \Gamma Y^\nu M_l.$$

For $l_i \rightarrow l_j J$

For $l_i \rightarrow l_j \gamma$

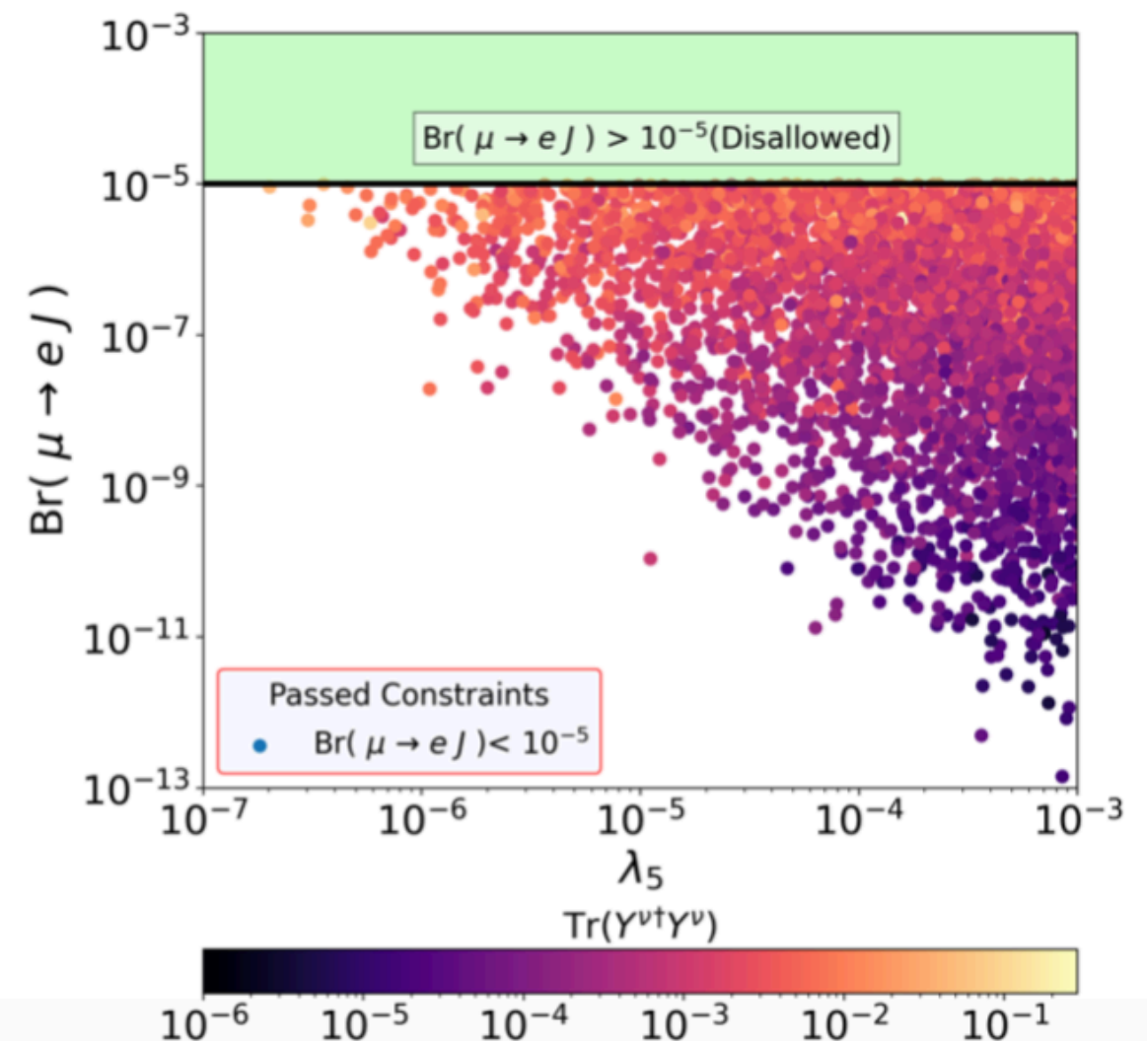
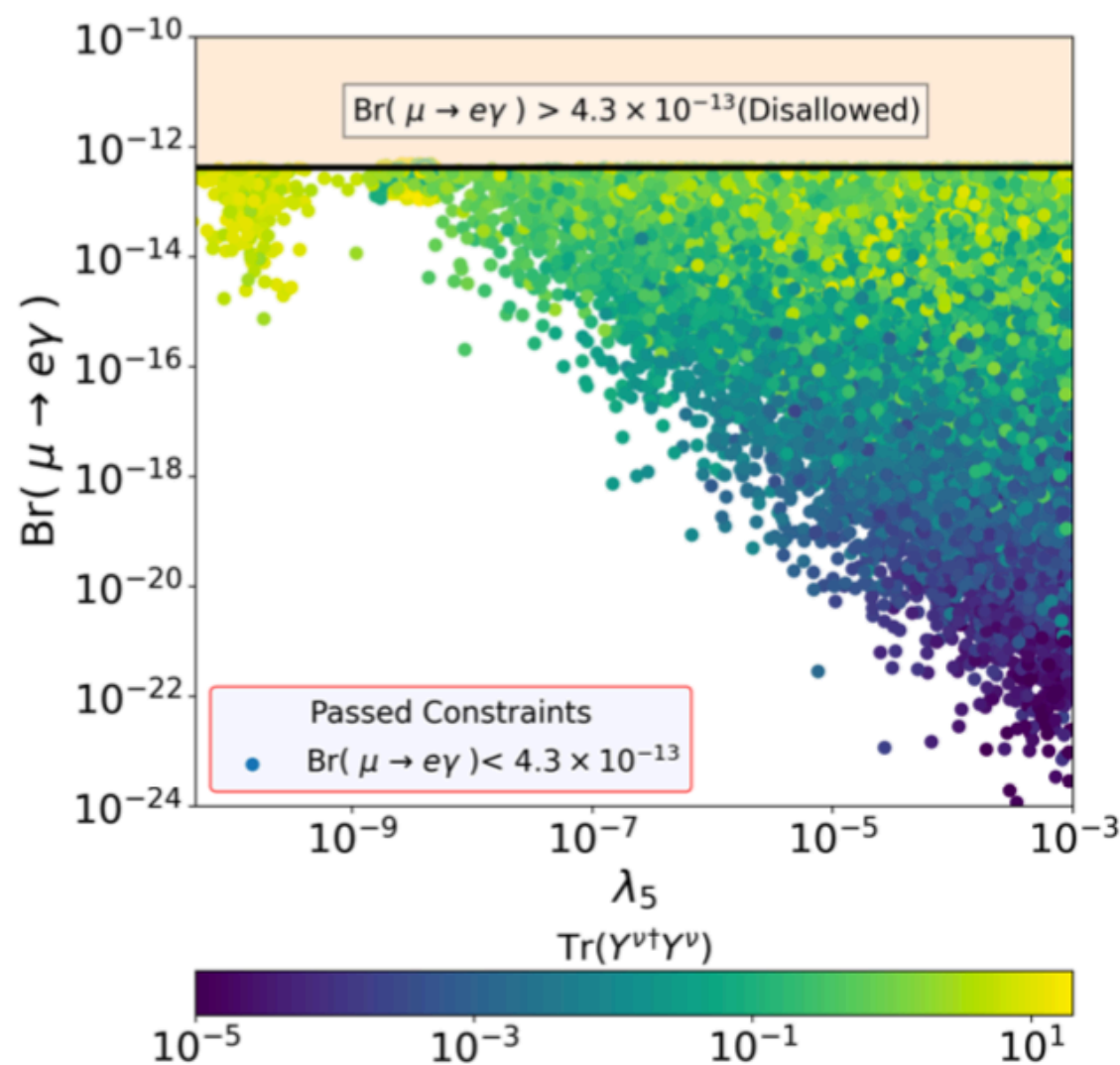
Strong dependency on Yukawa Y^ν

Lepton flavour violation

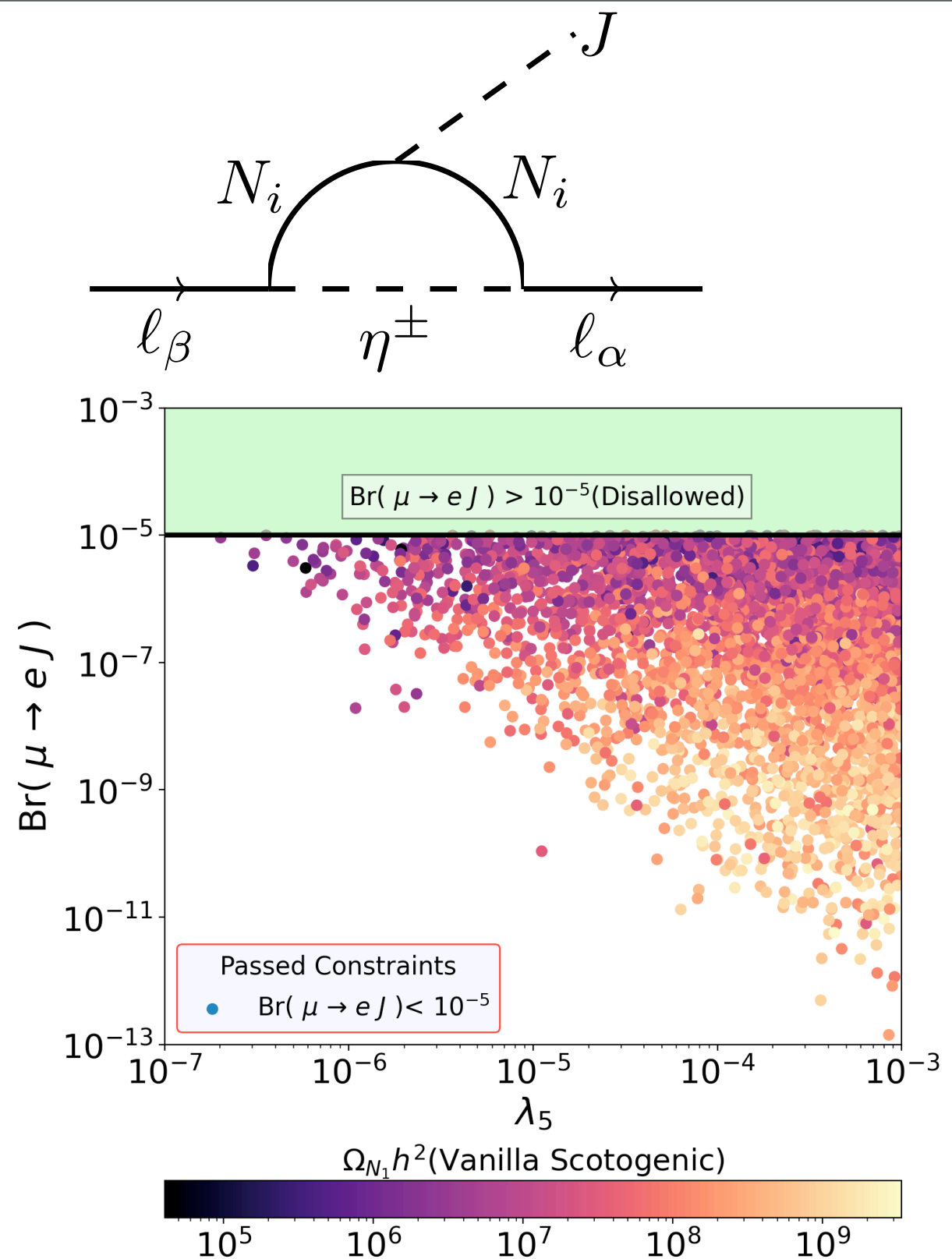
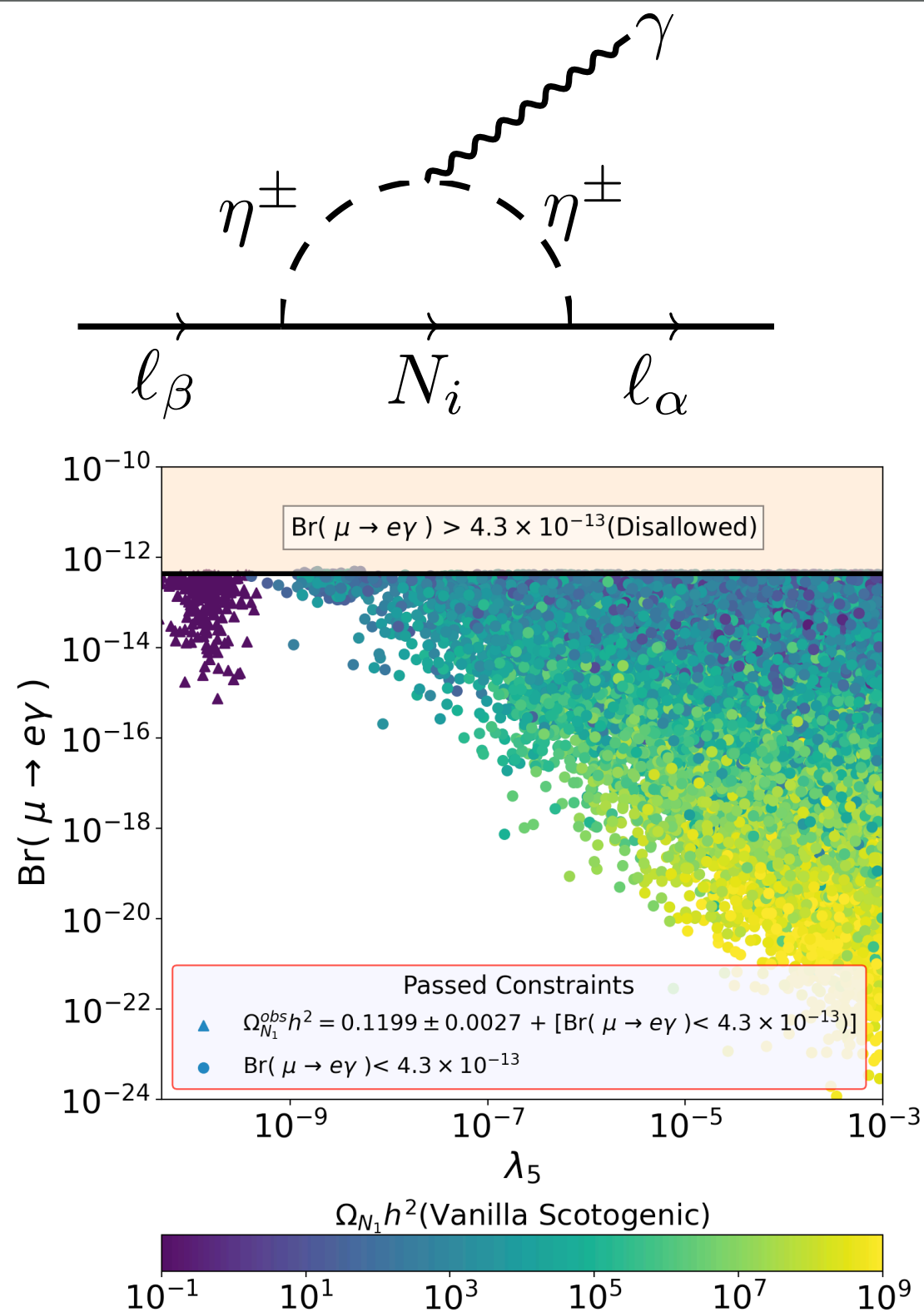
$$(m_\nu)_{ij} \approx \frac{\lambda_5 v_\Phi^2}{32\pi^2} \sum_{k=1}^3 \frac{Y_\nu^{ik} Y_\nu^{kj}}{M_{N_k}} \left[\frac{M_{N_k}^2}{m_0^2 - M_{N_k}^2} + \frac{M_{N_k}^4}{(m_0^2 - M_{N_k}^2)^2} \log \frac{M_{N_k}^2}{m_0^2} \right],$$

Neutrino mass constraint: a smaller λ_5 will be accompanied by larger Yukawa coupling Y^ν

However, a larger Y^ν will be disallowed from CLFV



CLFV-> Impact on Relic Abundance (without co-annihilation)



A smaller λ_5 satisfies DM relic abundance in vanilla Scotogenic model

$\mu \rightarrow eJ$ impose even more stringent constraint

Stellar Cooling constraint

The massless relativistic particle majoron gets stringent constraints from the stellar objects such as Red Giants (RD), White Dwarfs (WD) and Horizontal Stars (HS)

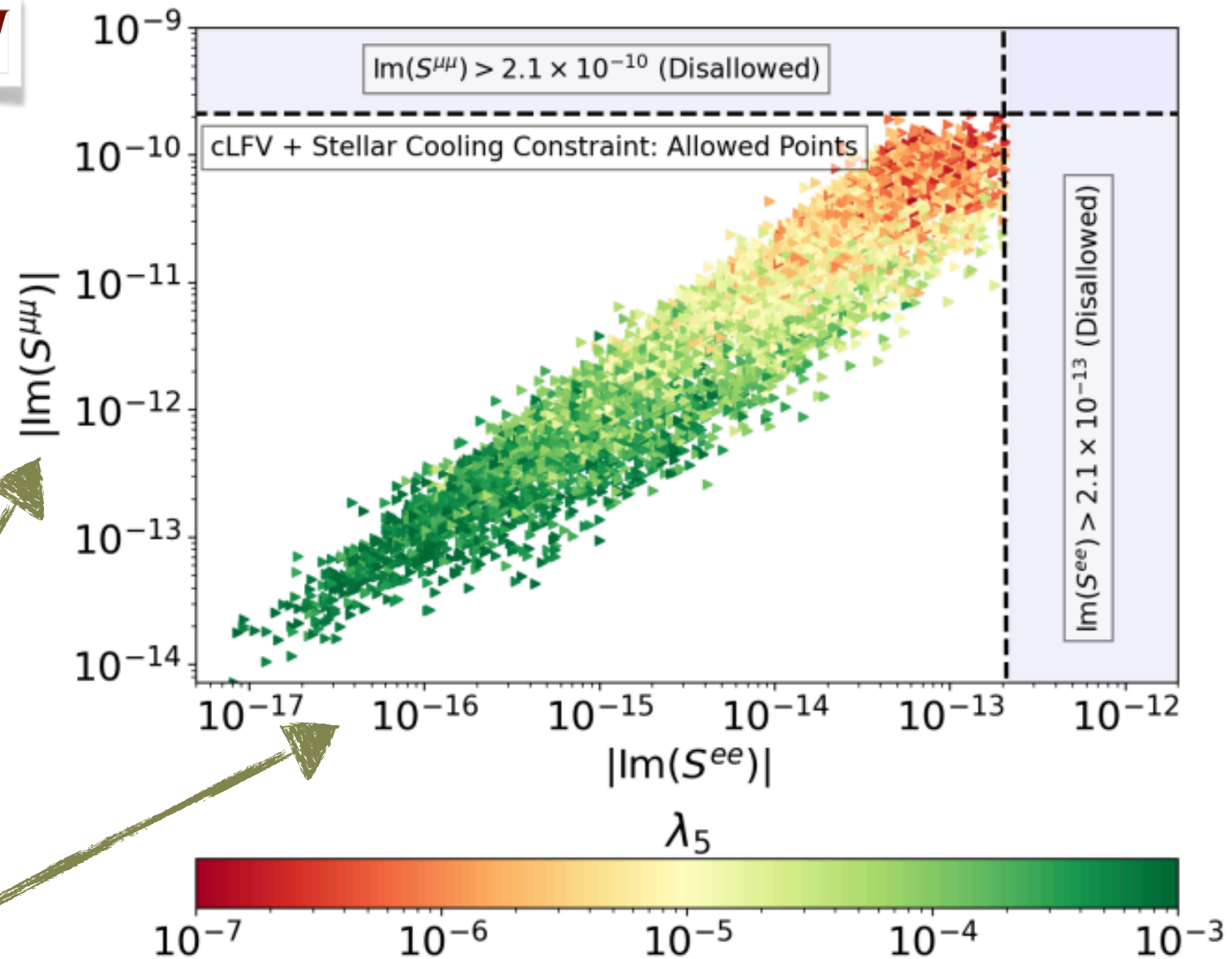
$$l + \gamma \rightarrow l + J, l + l \rightarrow l + l + J$$

Production of majoron impact the stellar cooling of compact stars



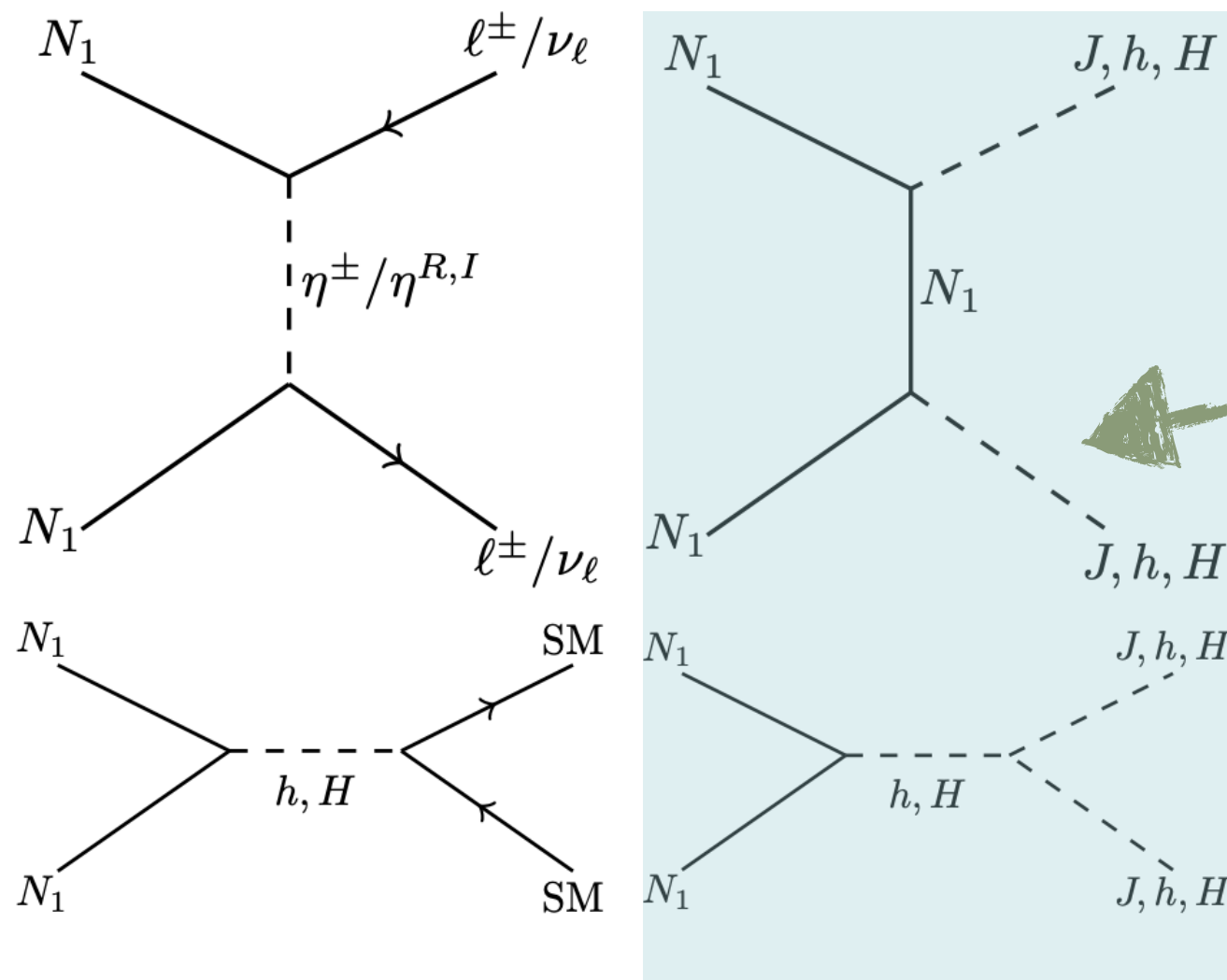
Impact in observed luminosity

A larger Yukawa Y^ν is constrained



Together with CLFV -> constraint on λ_5

Dark Matter Relic Abundance



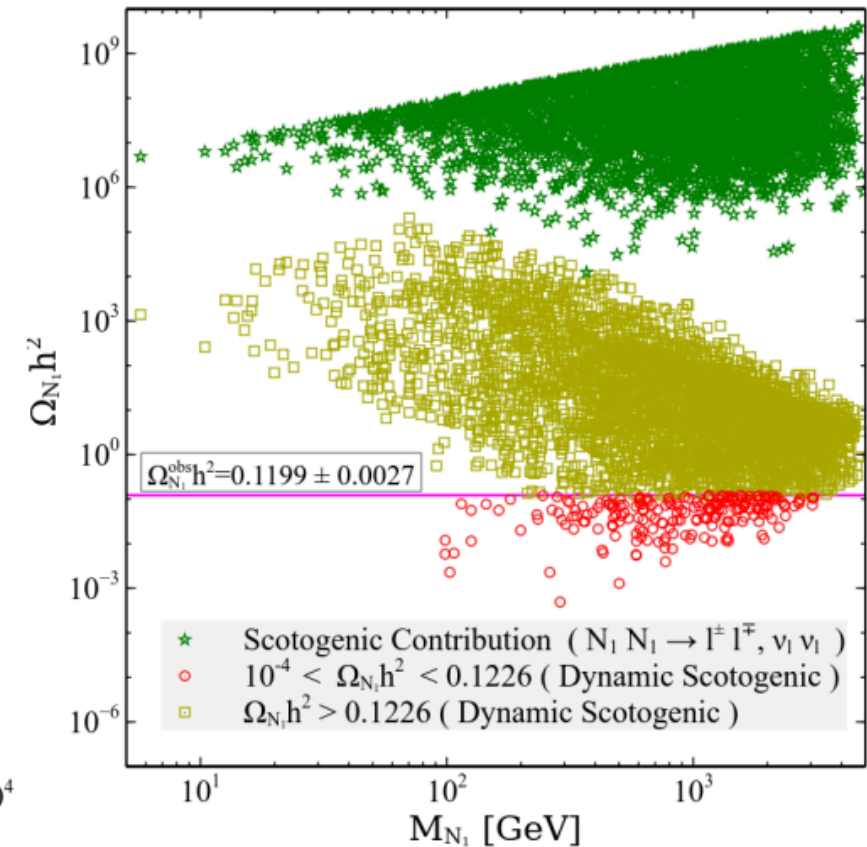
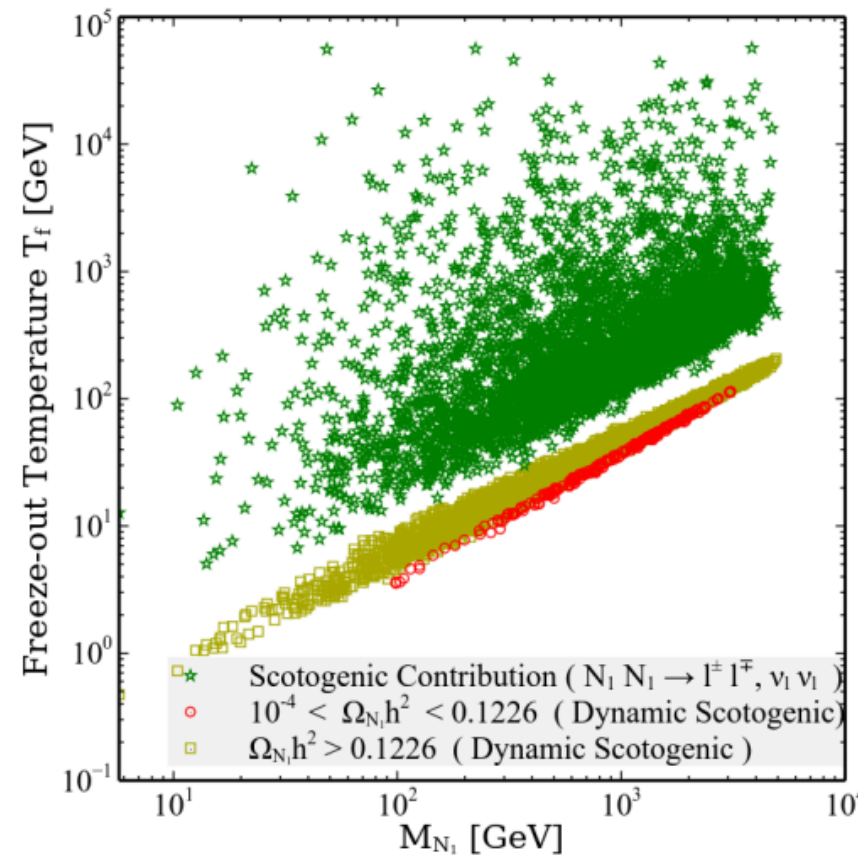
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$$-\mathcal{L}_Y \supset Y_{ij}^\ell \bar{L}_i \Phi \ell_{Rj} + Y_{ij}^\nu \bar{L}_i \tilde{\eta} N_j + \frac{1}{2} Y_{ij}^N \sigma \bar{N}_i^c N_j + h.c.,$$

Relic abundance in dynamical Scotogenic model

Parameter	Scanned range
m_H [GeV]	[500 , 1500]
m_η [GeV]	$[10^2 , 10^4]$
v_σ [GeV]	$[500 , 10^4]$
λ_5	$[10^{-11} , 10^{-3}]$
$Y_{N_{1,2,3}}$	[0.1 , 2]
$\sin \theta$	$[10^{-3} , 10^{-1}]$
$\theta_{x,y,z}^R$	$[0 , 2\pi]$
$\theta_{x,y,z}^I$	$[0 , 2\pi]$

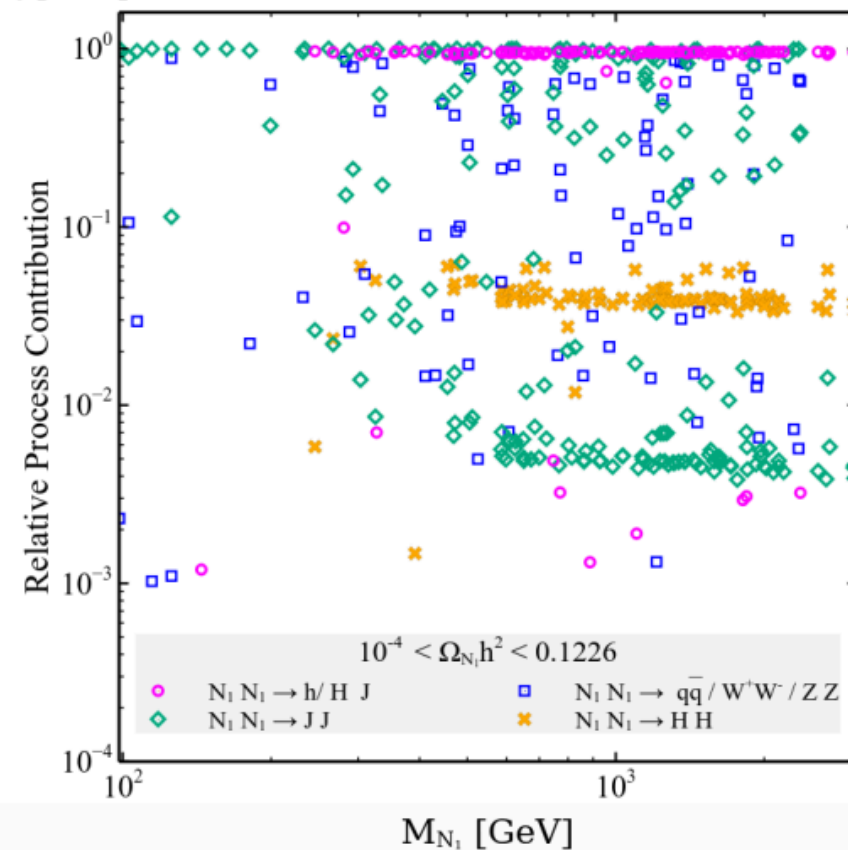


Freeze-out temperature is large for vanilla Scotogenic model (due to smaller Yukawa coupling Y^ν)



Relic abundance is over-abundant

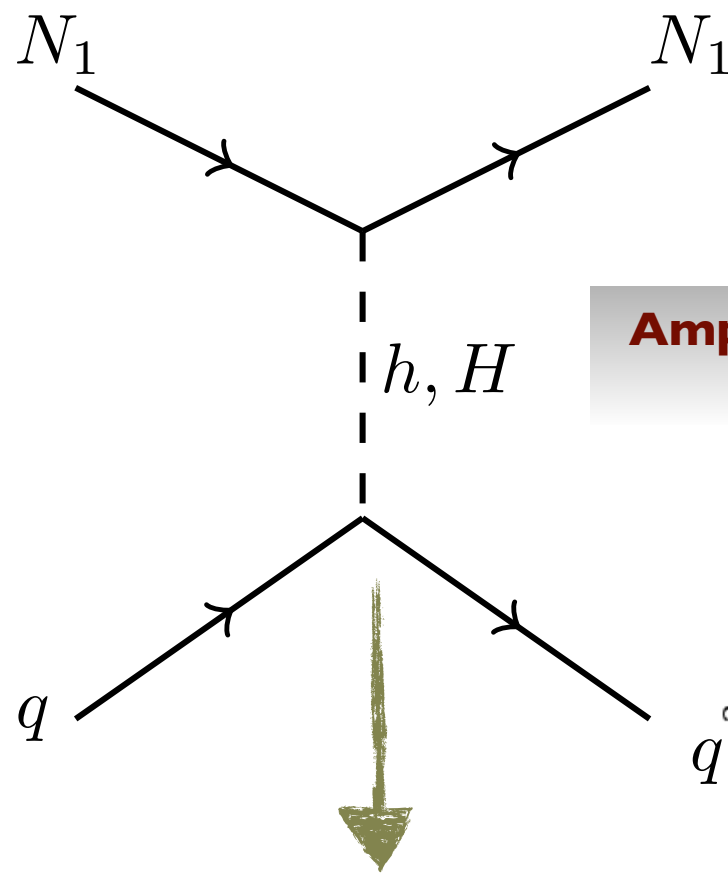
For dynamical Scotogenic model, $T_f \sim (1 - 100)\text{GeV}$, as additional Y^ν independent channel emerges



Correct relic abundance

Dark Matter Direct Detection Signature

DM elastic scattering on nucleons (X is a nucleon)

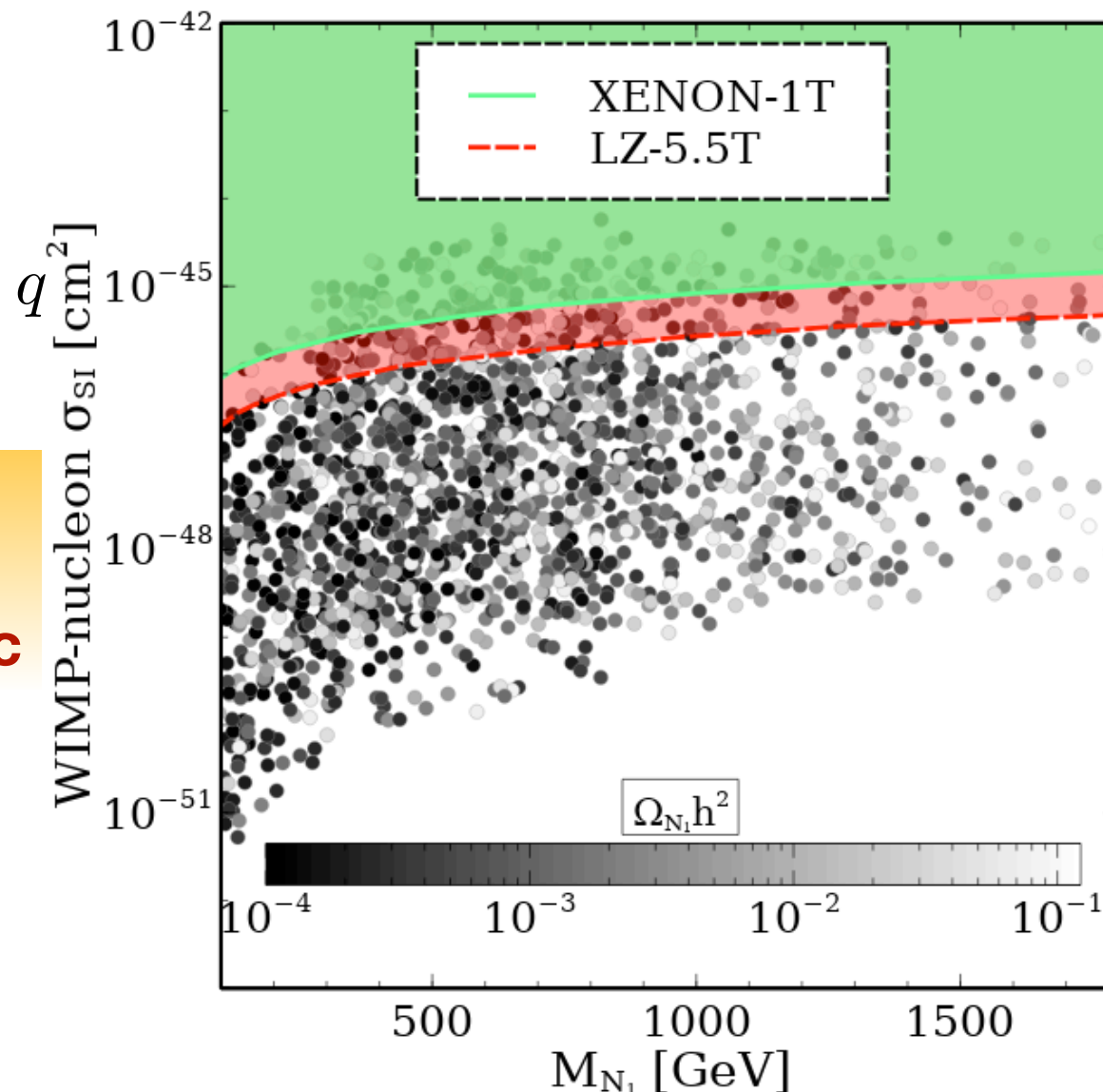


$$N + X \rightarrow N + X$$

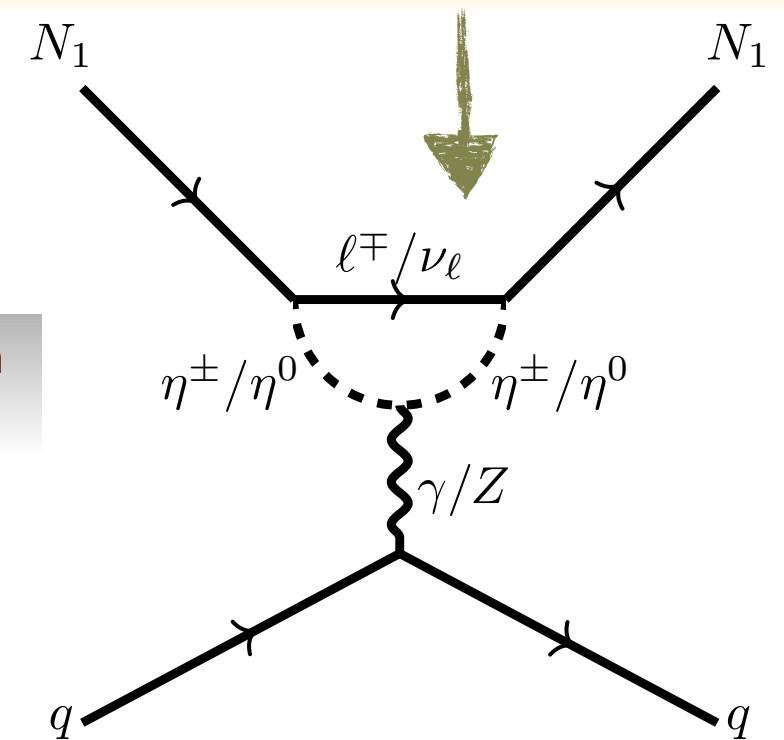
$$\sigma_{SI} = \frac{4}{\pi} \mu_r |A^{SI}|^2$$

Amplitude A_{SI} depends on the DM interaction with the nucleons, and the nuclear form factor

Additional contribution in dynamical Scotogenic



Vanilla Scotogenic only



All points are allowed from

- Neutrino mass
- CLFV
- Astrophysical constraint
- Dark matter relic density

Strong correlation between neutrino and dark matter physics

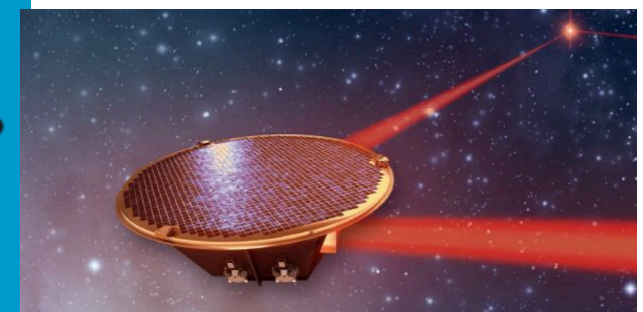
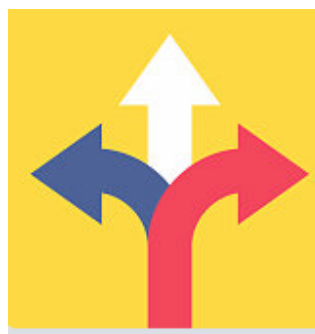
Summary



- *Few major observations in nature ~ Neutrino masses and mixings, Dark Matter, and Baryon Asymmetry in the Universe*
- *Other than standard tree level seesaw realisation, loop level generation of Majorana mass of light neutrinos offer appealing alternatives*
- *low scale neutrino mass models with heavy neutral lepton offer wide detection prospects at different experiments*
- *Strong correlation between neutrino mass and dark matter physics for Scotogenic extension*

~ Neutrino oscillation physics
~ Dark matter phenomenology
~ Collider, precision experiments

*Neutrino Mass Models
at
Energy, Intensity, Cosmic frontiers*



Thank You

Right handed neutrinos, TeV scale BSM neutral Higgs boson, and FIMP dark matter in an EFT framework

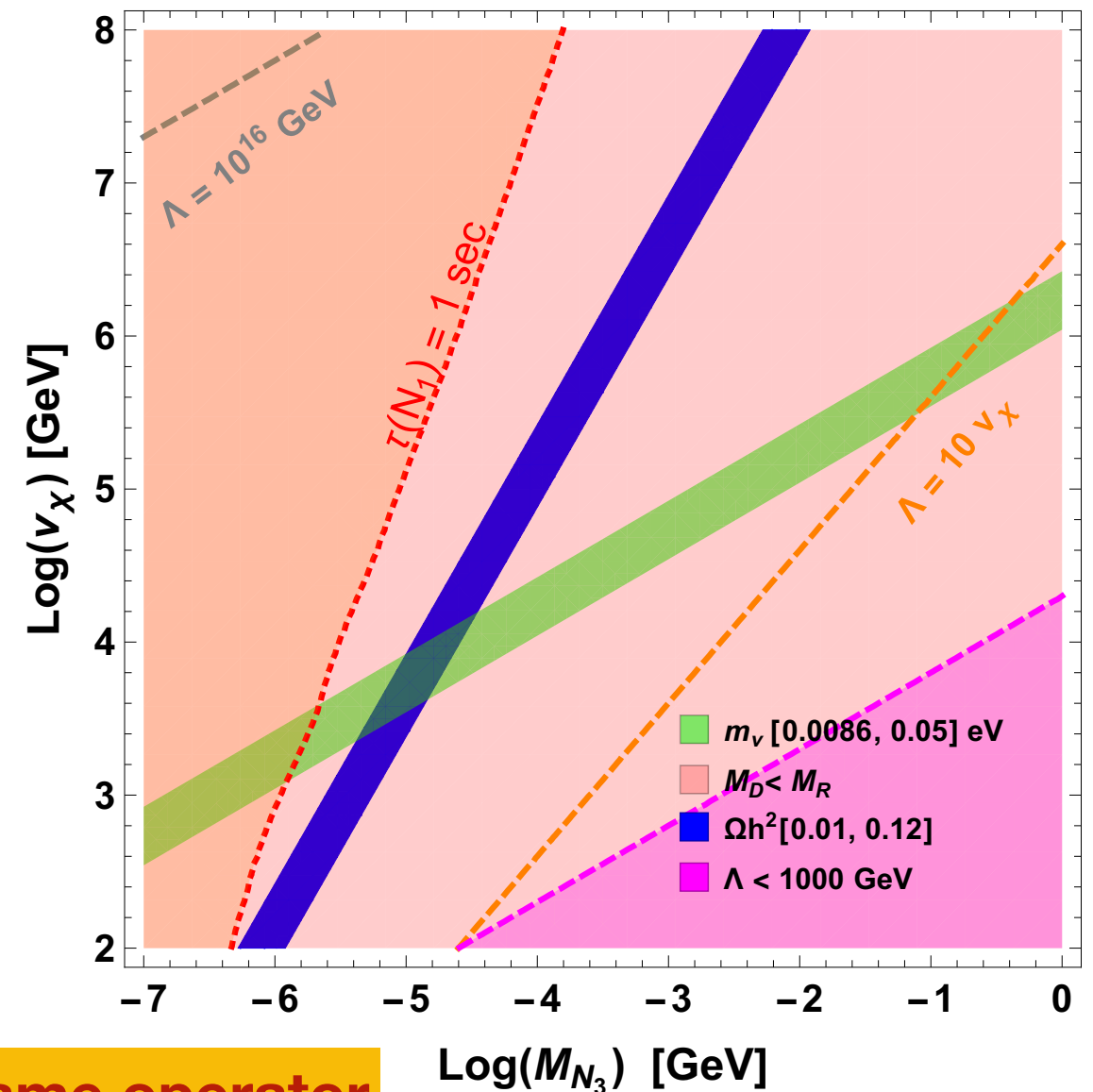
$$\mathcal{L}_{eff} = M_B N_i^T C^{-1} N_i + \frac{c_{ij}}{\Lambda} N_i^T C^{-1} N_j \chi^2 + \frac{c'_{ij}}{\Lambda} N_i^T C^{-1} N_j \Phi^\dagger \Phi + \frac{Y_{ij}}{\Lambda} \bar{L}_i \tilde{\Phi} N_j \chi + H.C.$$

$$M_B = 0$$

- Dimension-5 operators with HNL field (DM) N and SM gauge singlet scalar
- N_3 is Dark Matter
- Freeze-in production of N_3
- Correlation with the BSM Higgs state
- BSM Higgs mass $\sim \text{vev}$.

$$\langle \chi \rangle = v_\chi, \quad M_{N_3} = \frac{c}{\Lambda} v_\chi^2$$

Primary dark matter production $\chi \rightarrow N_3 N_3$



DM mass and production is governed by the same operator

BSM Higgs mass is $M_H^2 \sim v_\chi^2$

TeV scale BSM Higgs/vev requires DM in the KeV range

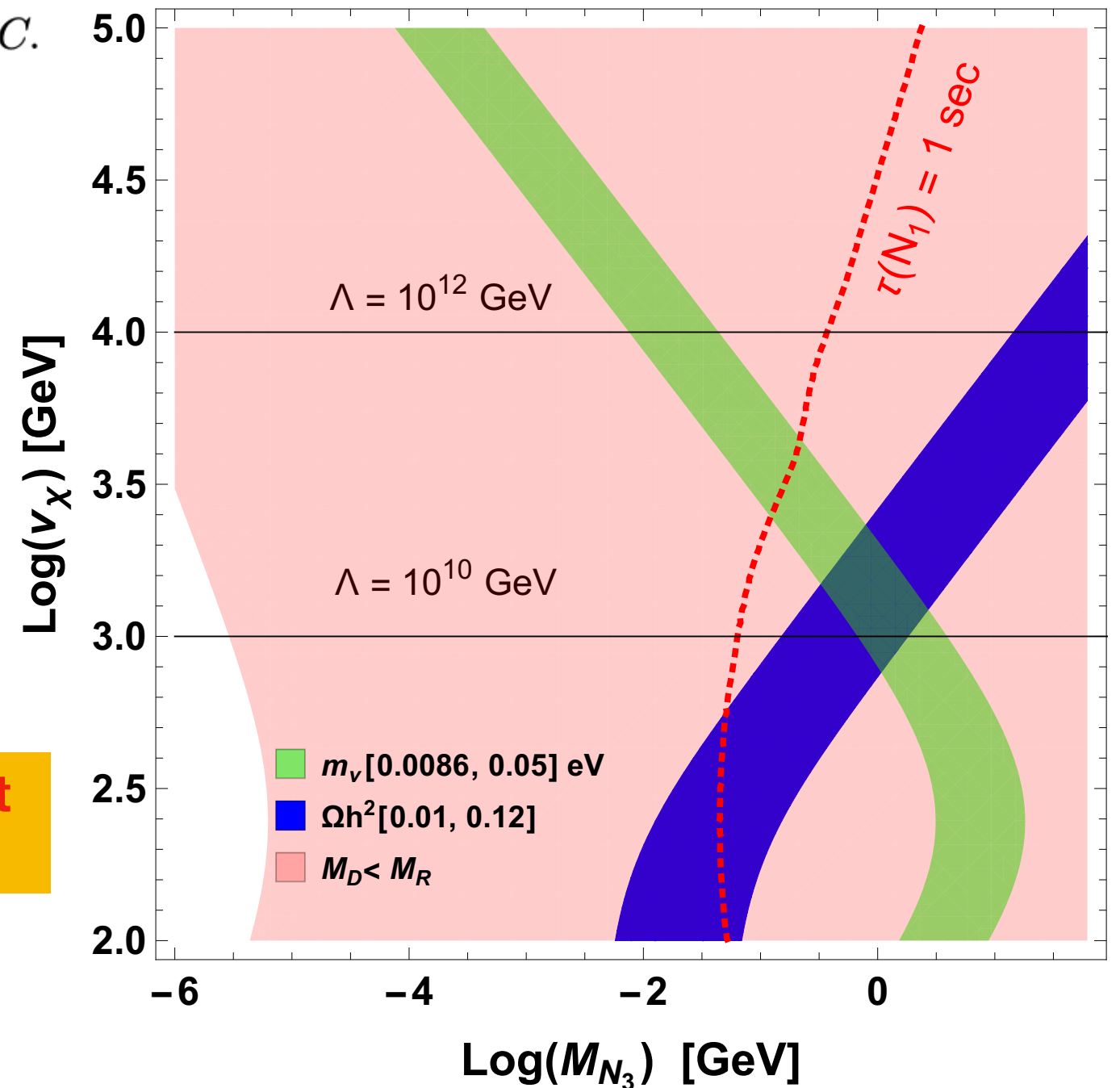
Belanger, Khan, Padhan, Mitra and Shil,
Phys.Rev.D 104 (2021) 5, 055047

Right handed neutrinos, TeV scale BSM neutral Higgs boson, and FIMP dark matter in an EFT framework

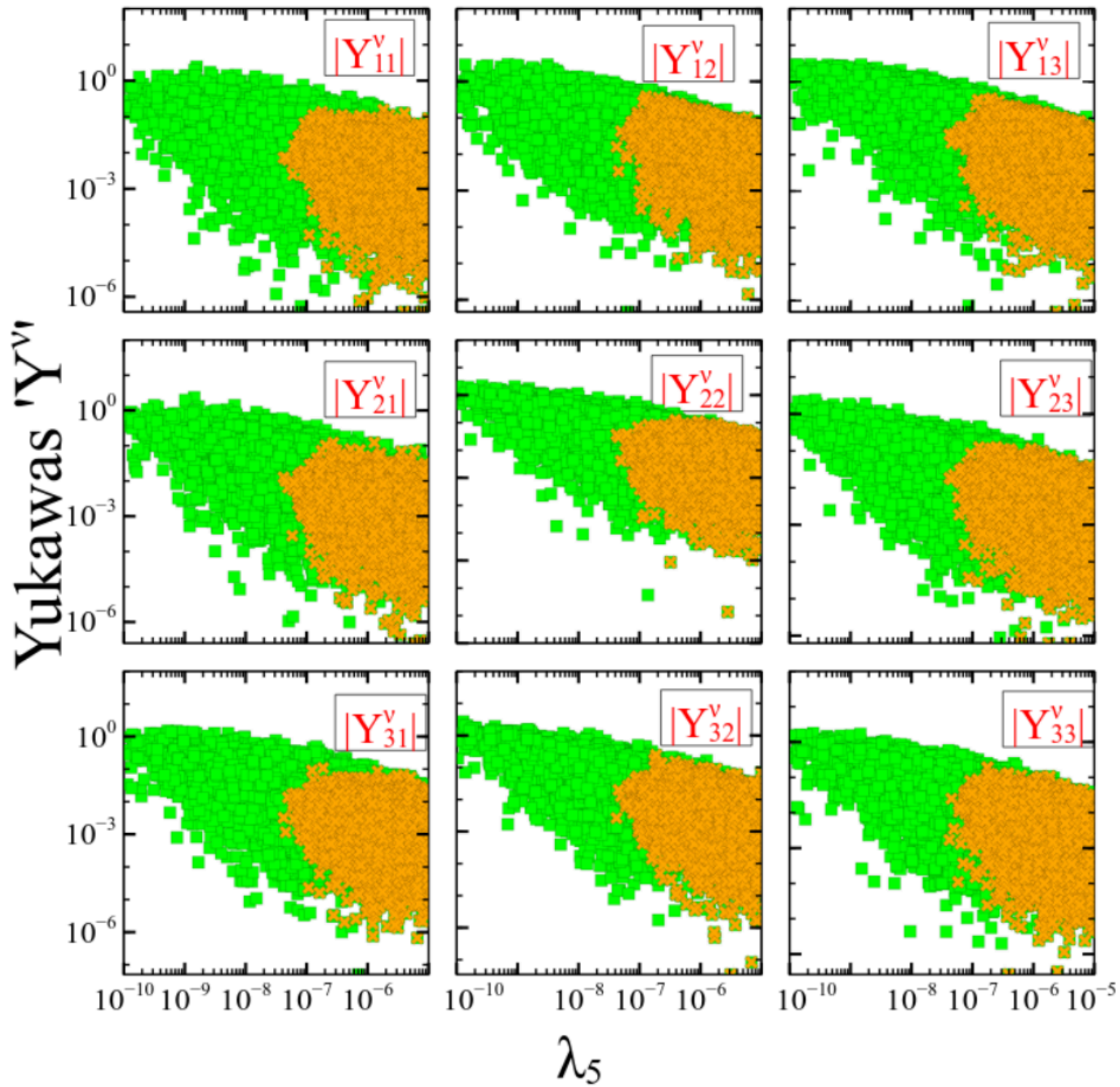
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With a non-zero bare mass term

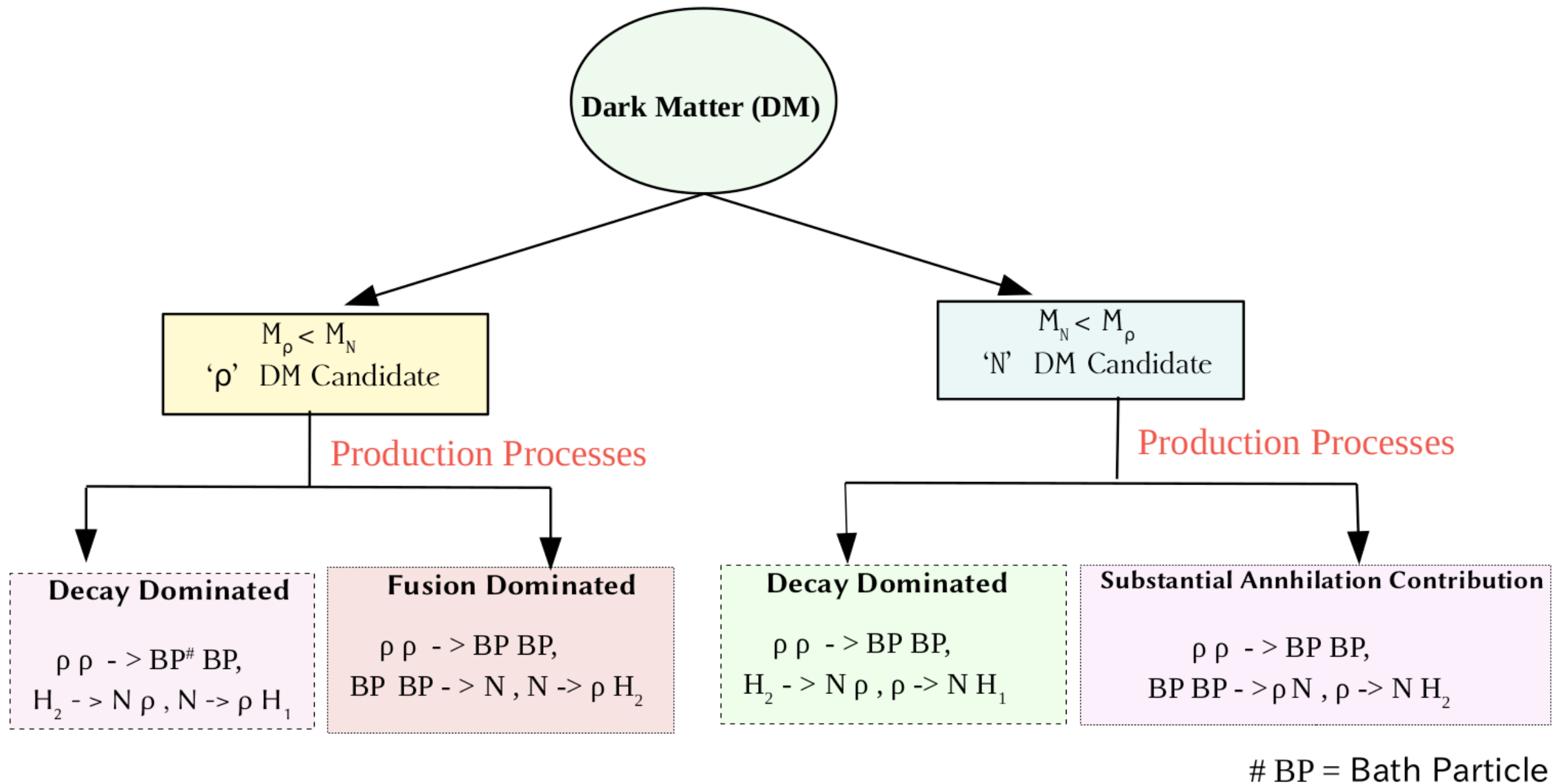
GeV scale DM mass is also consistent with a TeV scale BSM Higgs mass



Direct detection signature



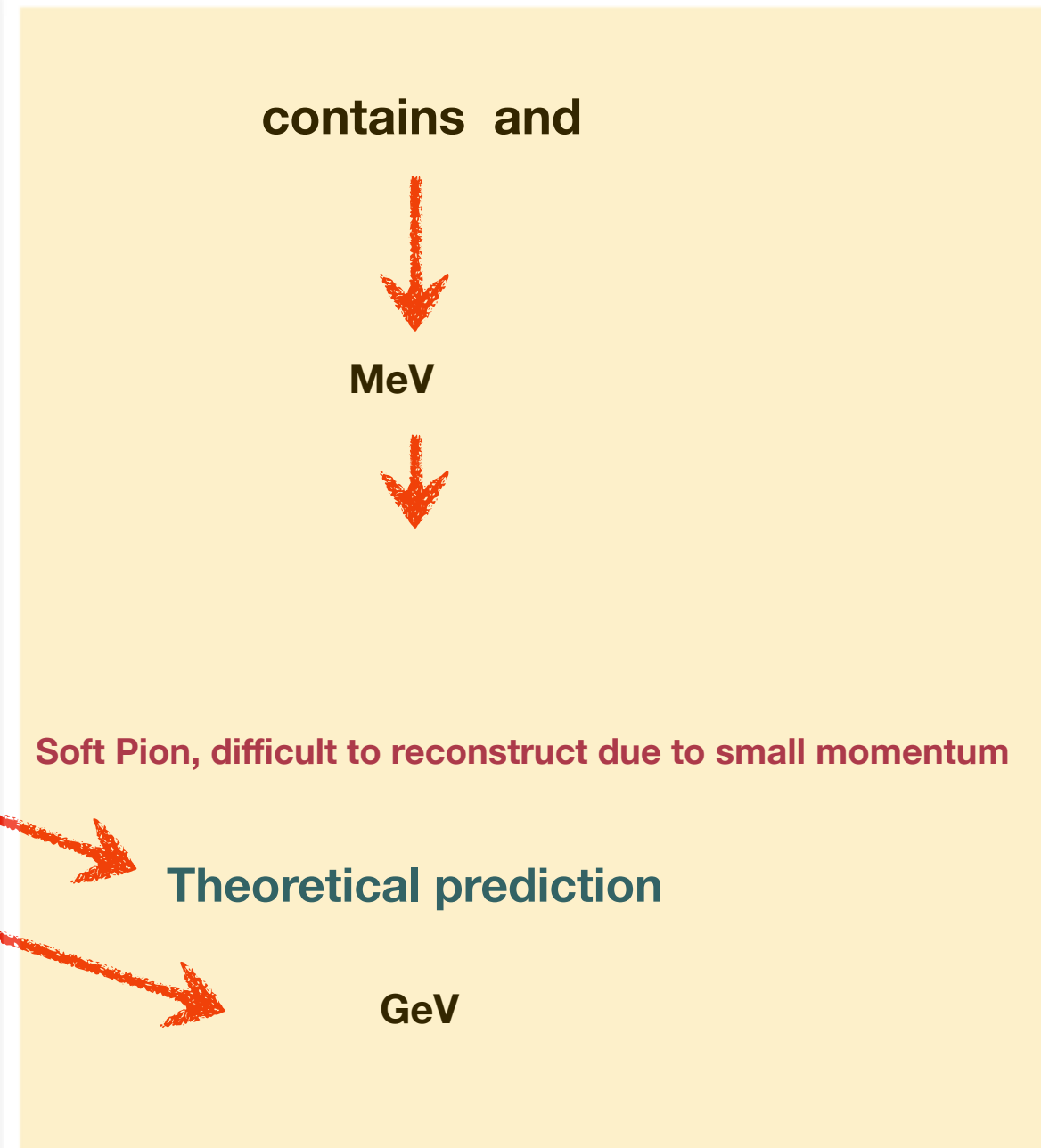
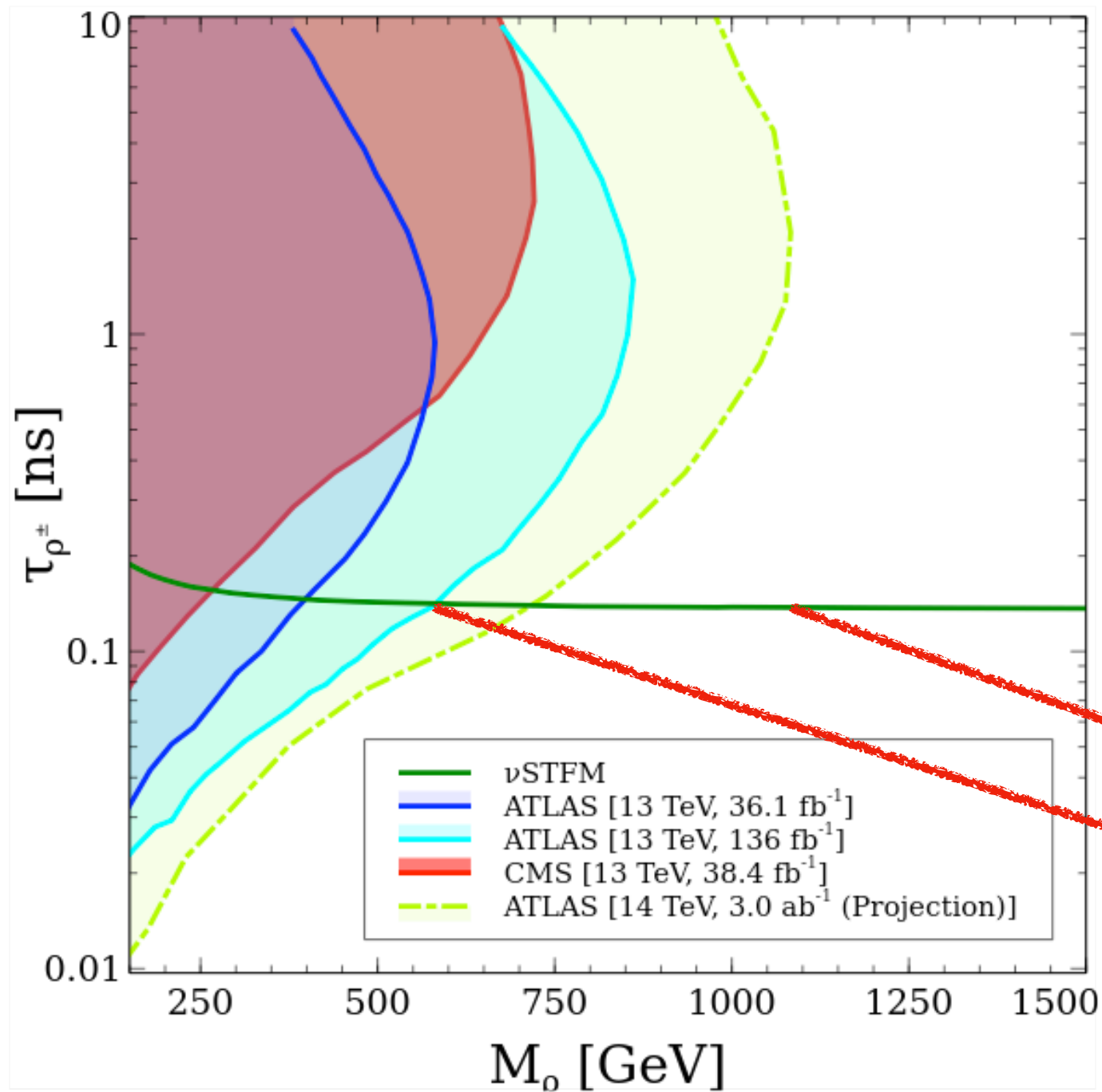
Dark Matter Production



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

- **FIMP Dark Matter as**
- **N is non-thermal**
- **Freeze in production (decay, annihilation) + late decay of contributes to relic density**

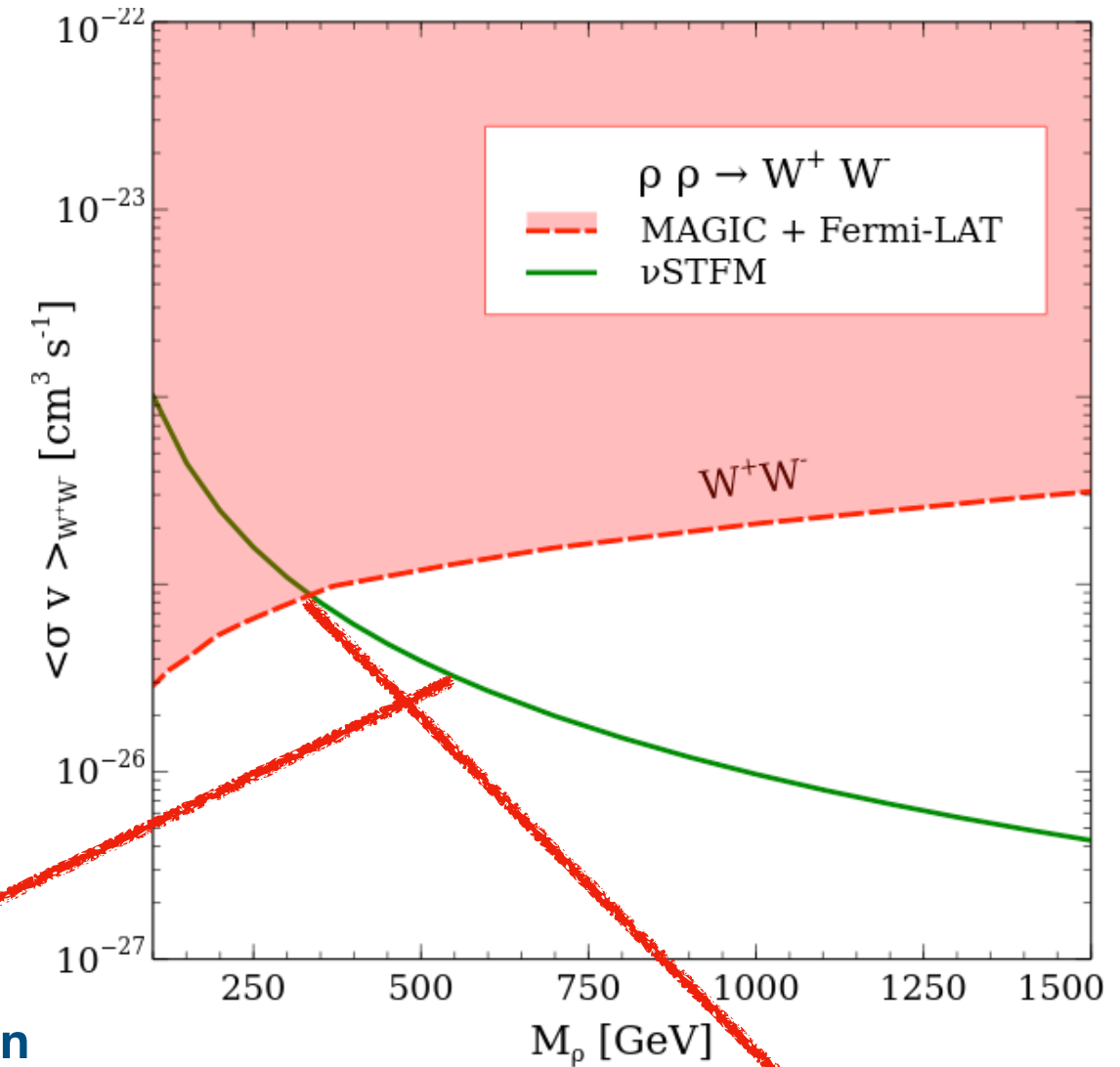
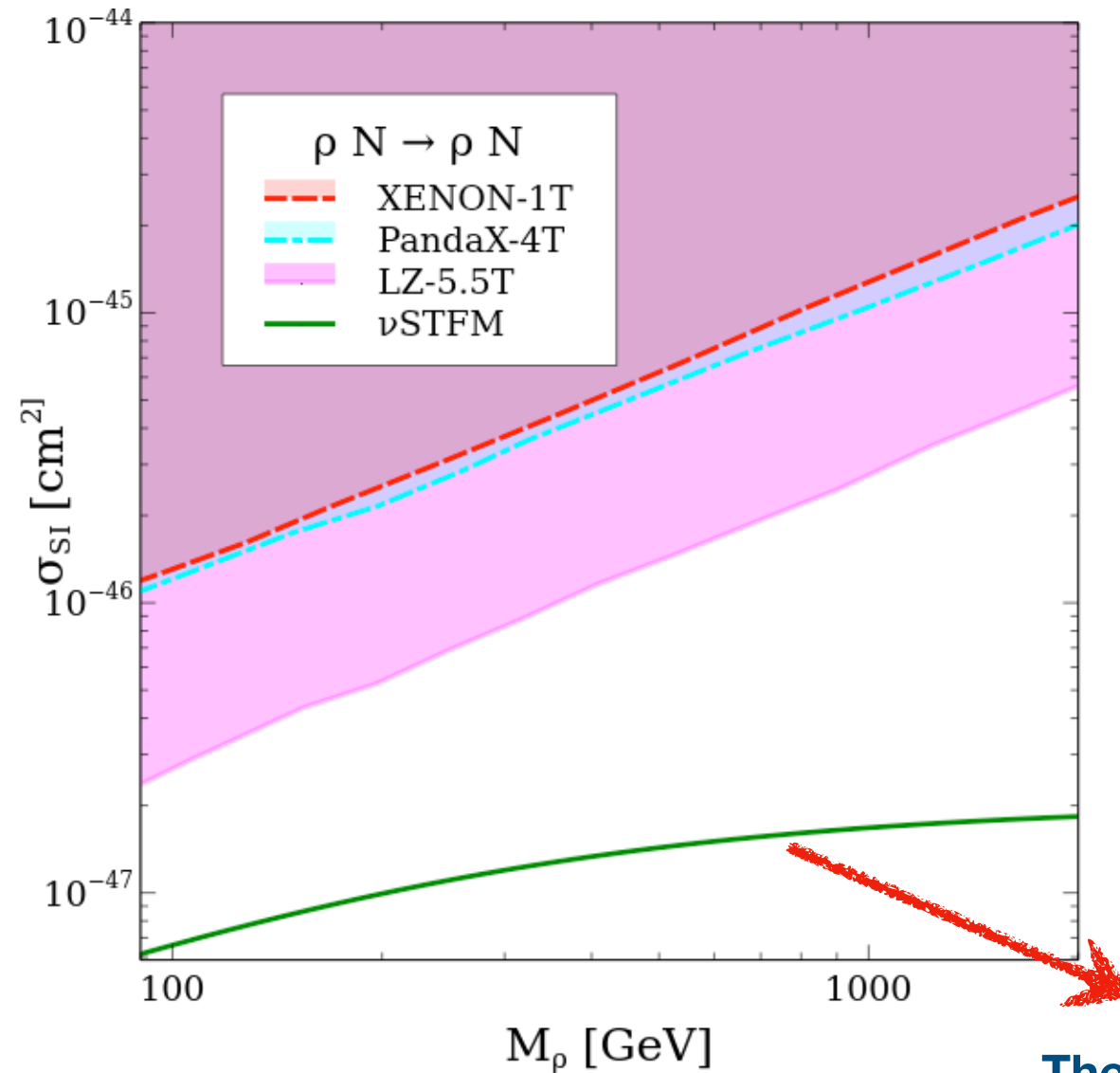
Applicable irrespective of triplet is a DM or NLOP



The decay of manifest itself as disappearing track signal

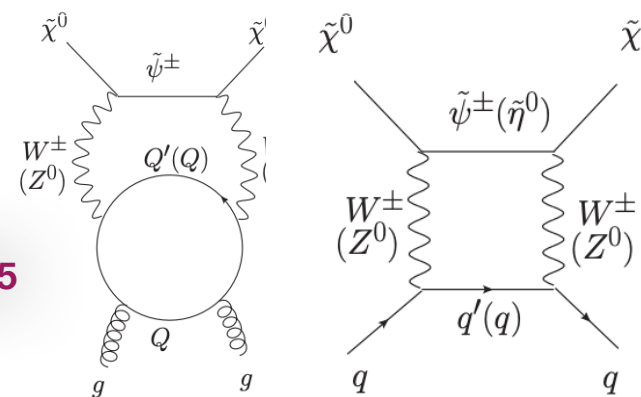
Direct and Indirect Constraint on

Applicable only if triplet is DM



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

Hisano et al, JHEP 07 (2011) 005



Dark Matter

Mixing between singlet and triplet states due to



$$\begin{aligned}\rho &= \cos \beta \rho_3^0 + \sin \beta N'^c \\ N &= -\sin \beta \rho_3^0 + \cos \beta N'^c.\end{aligned}$$

N', ρ_3

are the gauge basis

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

Mass splitting between the two fermions

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

M_ρ, M_N

Mass of the two fermions

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

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

N is primarily singlet and ρ is primarily triplet state

$$M_\rho, M_N, M_{H_2}, Y_{\rho\Delta}, \sin \alpha$$

free parameter of the model

can be dark matter depending on the mass

Dark Matter Production - Scenario I (as Dark Matter)

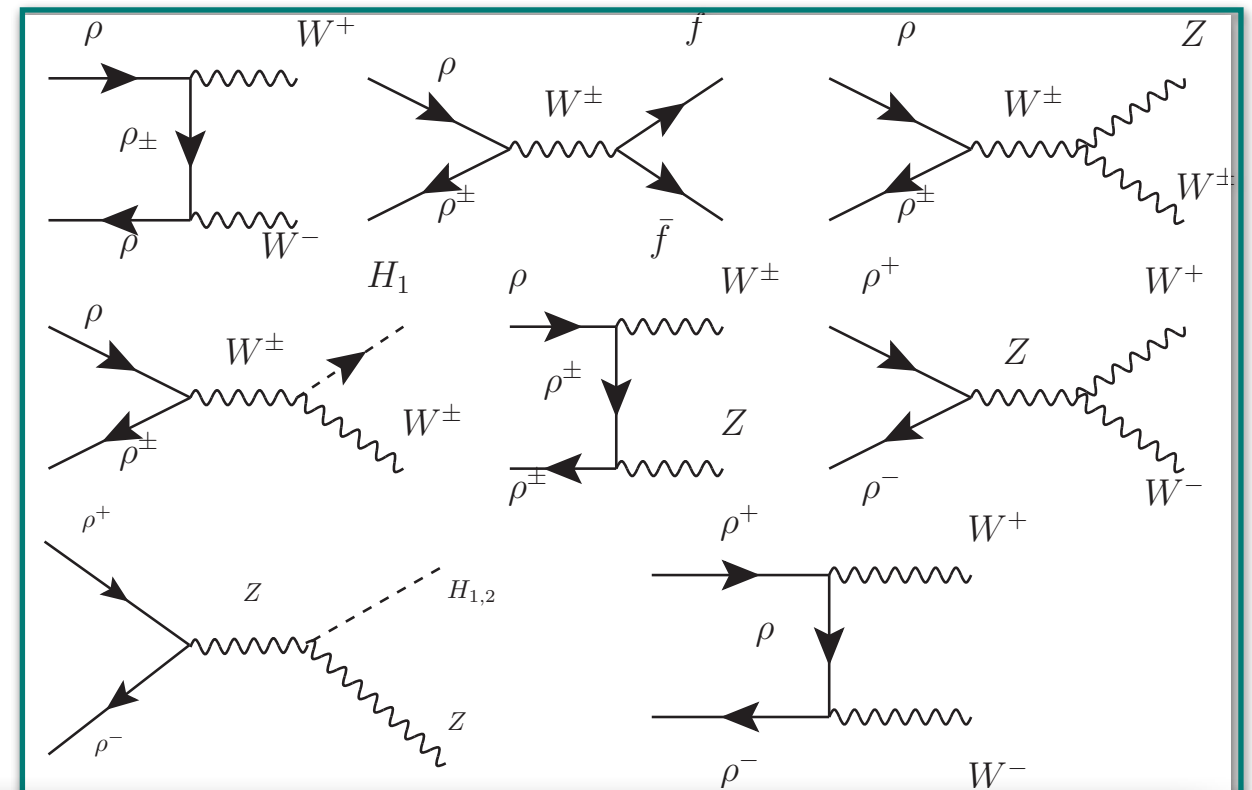
$$M_\rho > 580 \text{ GeV}$$

from disappearing track searches [ATLAS collaboration, Eur. Phys. J. C 82 (2022) 606]

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

Under-abundant dark matter
unless GeV or large

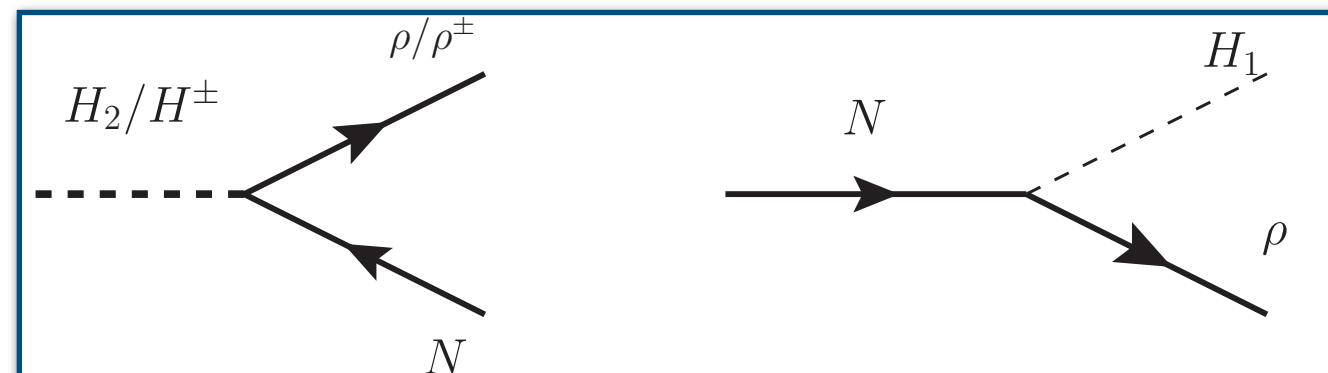
E. Ma, Mod.Phys.Lett.A24:583-589,2009



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

- Decay dominated scenario,

- is a thermal particle
- produces
- Late decay of for correct relic density
- BBN constraint on lifetime of



Scalar Spectrum

CP even neutral scalars



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

$\sin \alpha$



CP even neutral Higgs mixing

M_{H_1}, M_{H_2}



Mass of the two Higgs

H_1



SM like Higgs

Goldstone



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

Charged Higgs



$$\tan \delta = 2v_\Delta / v$$



Charged Higgs mixing

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



Charged Higgs mass

We choose

Singlet-Triplet Fermionic Model

Renormalizable Lagrangian

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

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

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

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

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

Singlet field

Fermionic fields

Triplet field

Scalar triplet field

SM scalar doublet

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

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

Induced vev

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

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

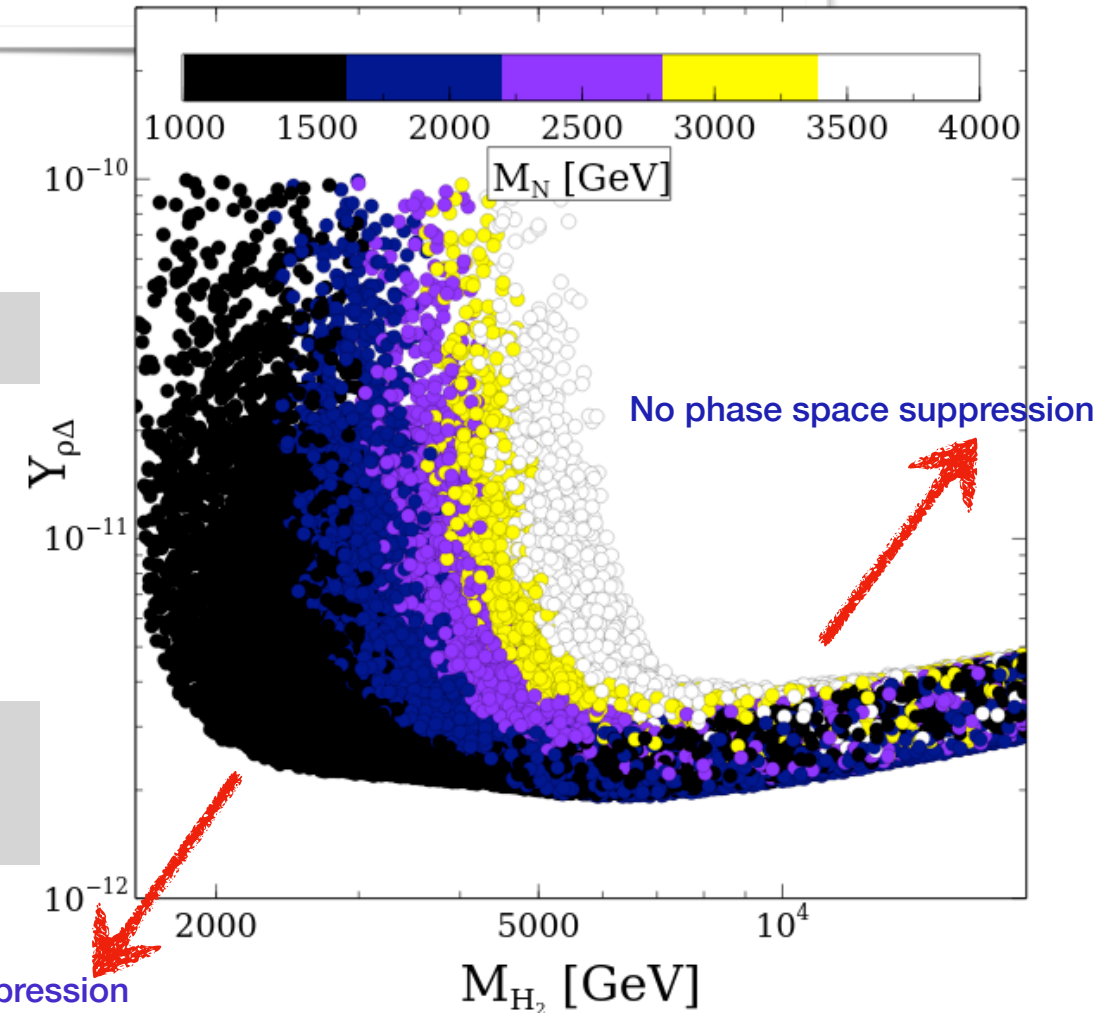
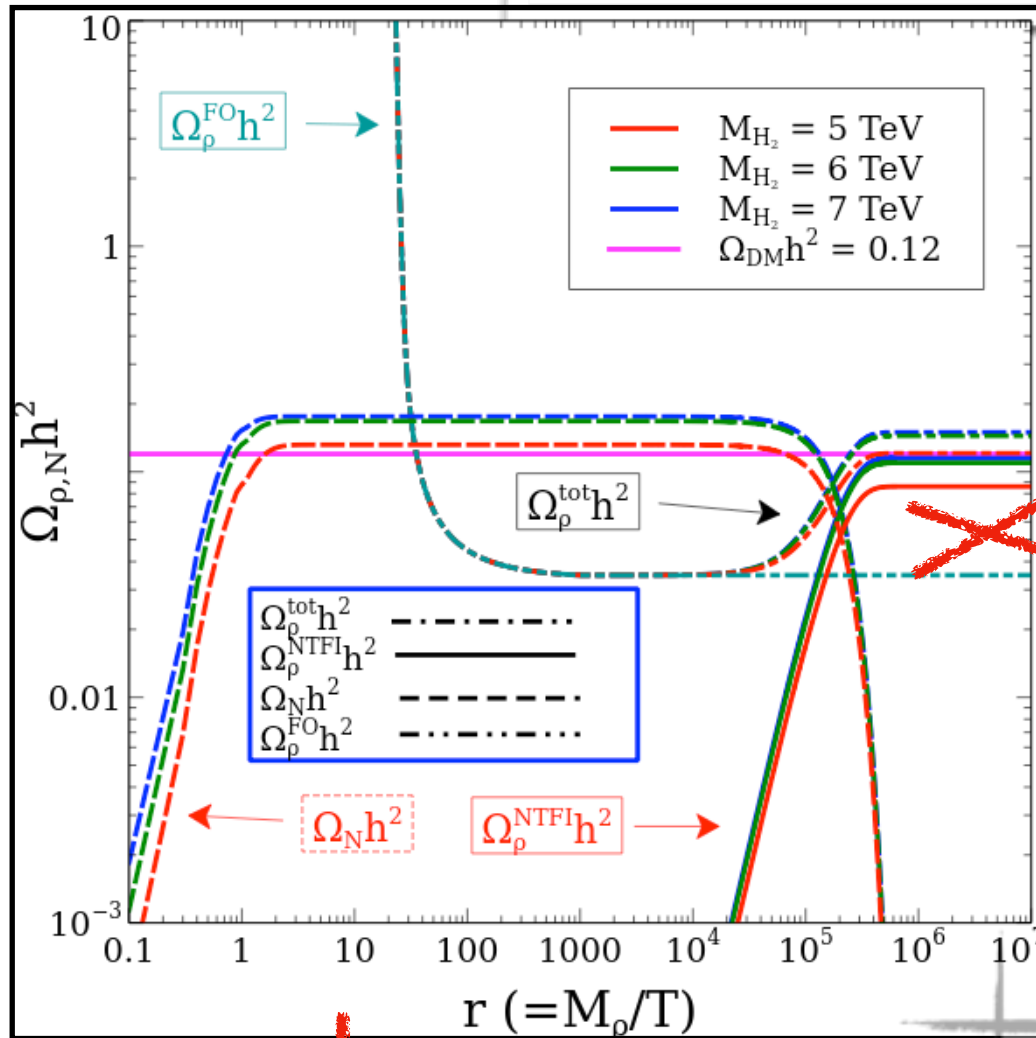
• With a symmetry, DM can be stable

$$M_\Delta^2 \text{Tr}(\Delta^\dagger \Delta)$$

Boltzmann equation for and

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

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



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

DM abundance increases with a heavier BSM Higgs state

$$700 \text{ GeV} < M_\rho < 1500 \text{ GeV}$$

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

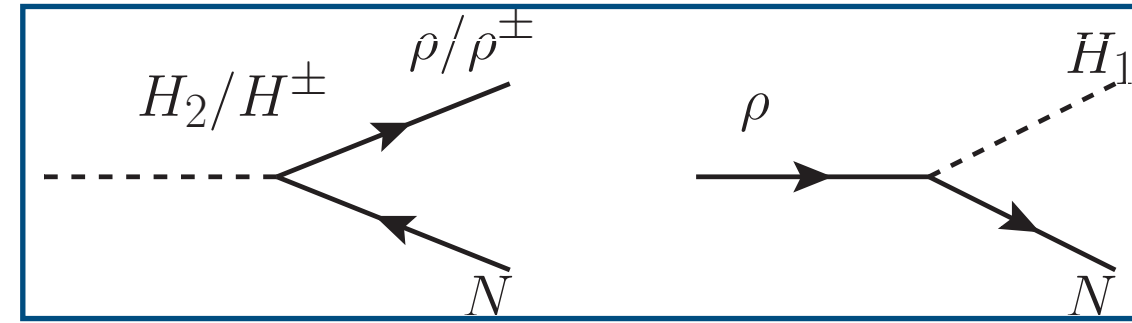
$$125 \text{ GeV} < M_N - M_\rho < 3000 \text{ GeV}$$

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

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

Dark Matter Production - Scenario II (as Dark Matter)

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



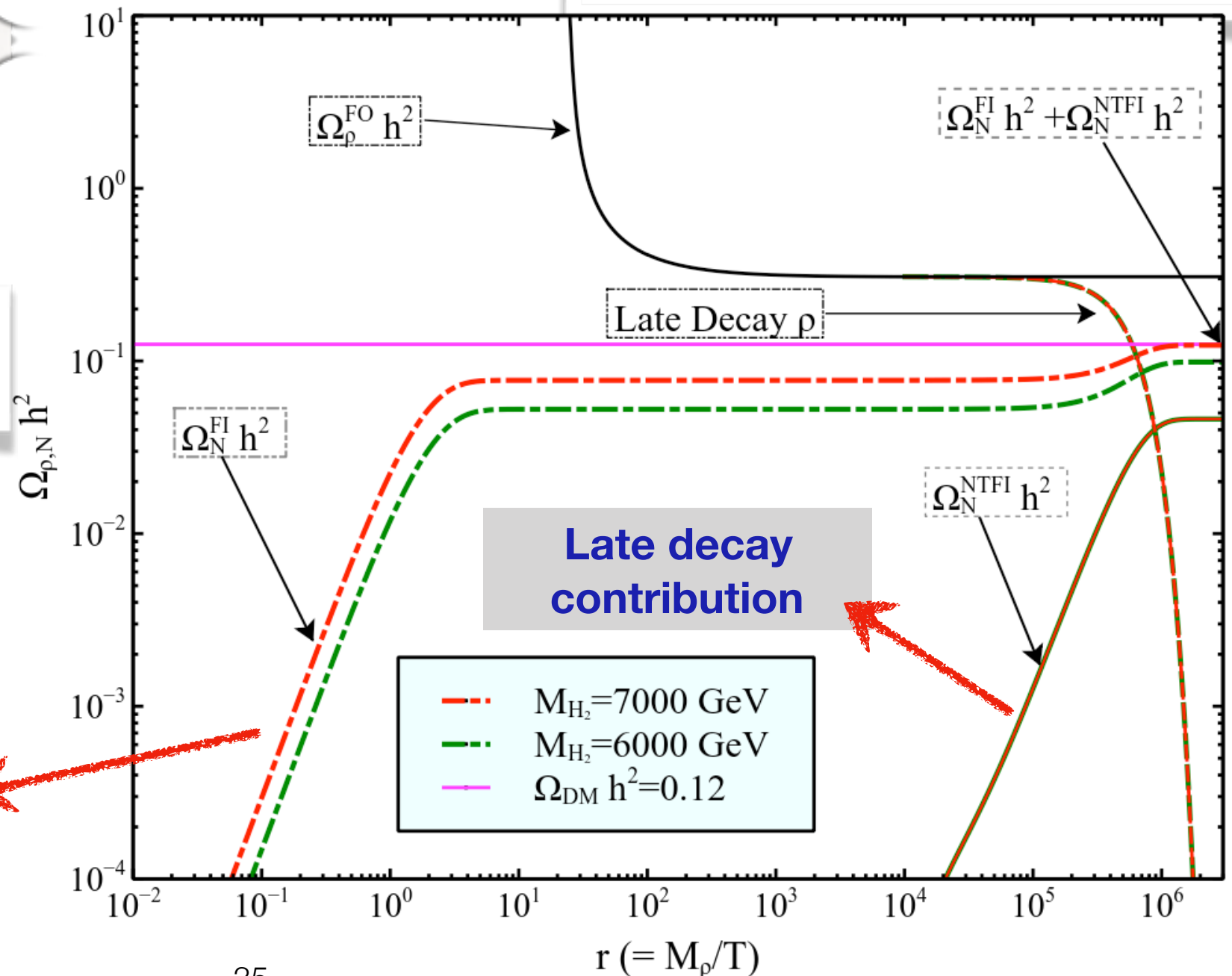
$$\Omega_N^{NTFI} h^2 = \frac{M_N}{M_\rho} \Omega_\rho^{FO} h^2$$

Dark matter abundance

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

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

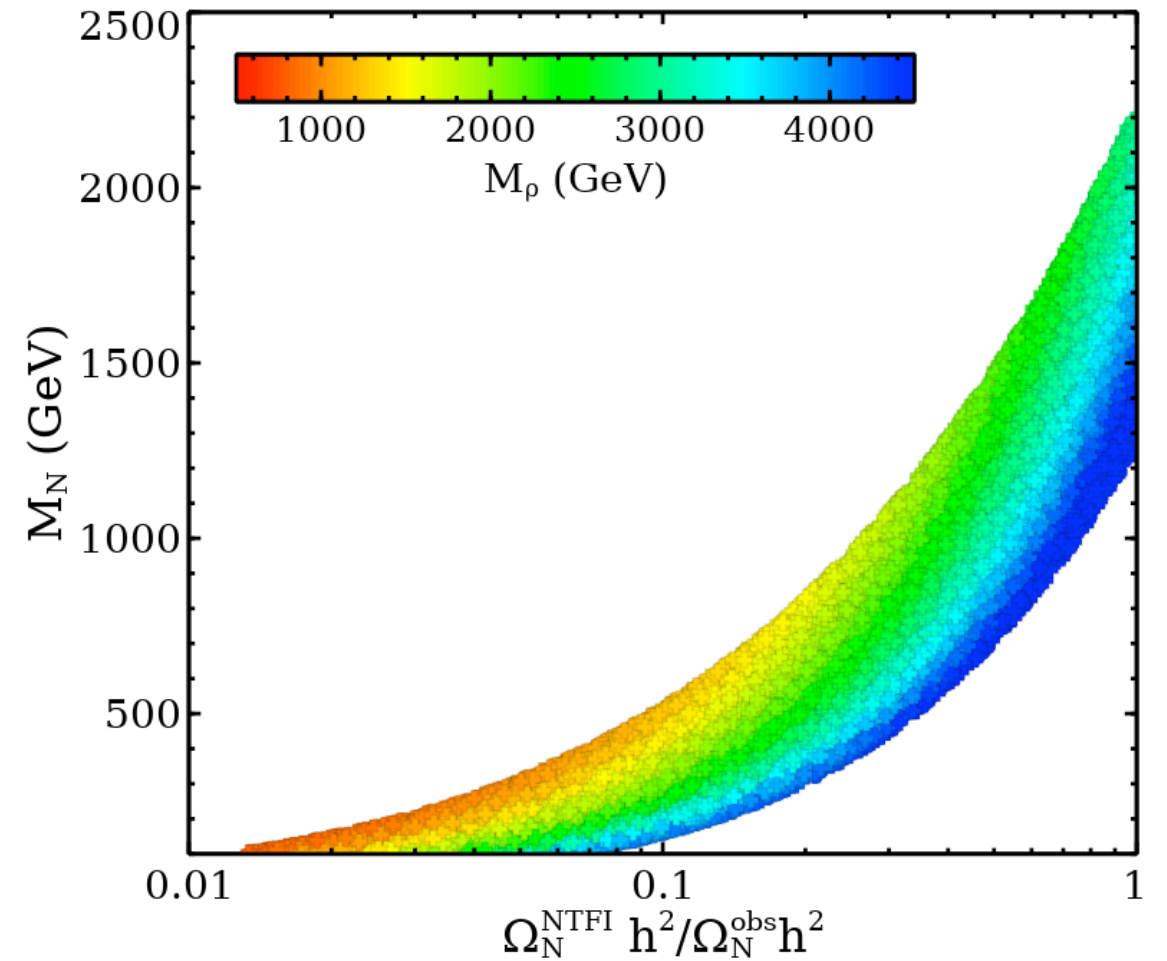
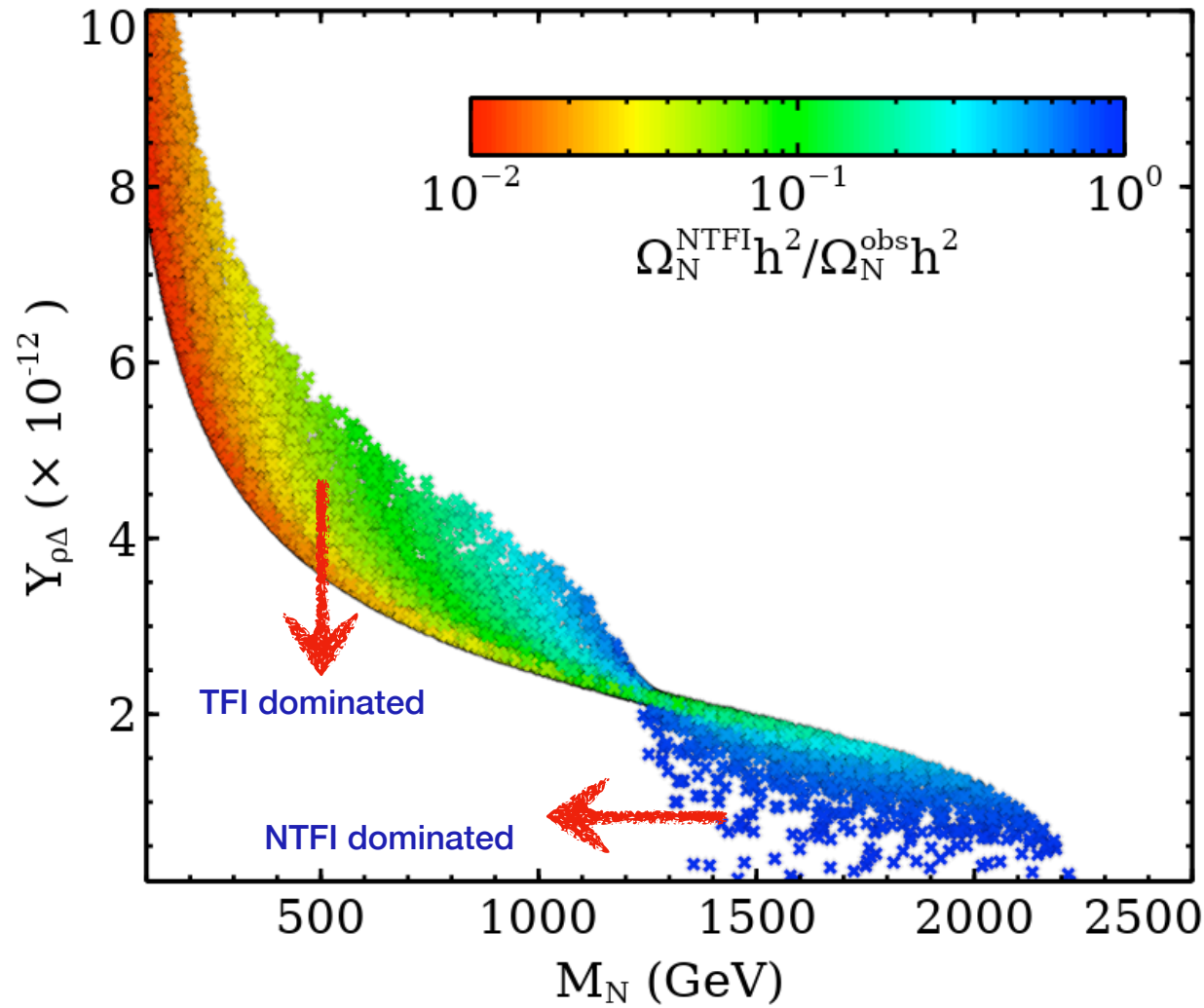
Thermal Freeze in contribution



$$\begin{aligned} \frac{dY_\rho}{dr} = & -\sqrt{\frac{\pi}{45G}} \frac{M_{Pl} \sqrt{g_*(r)}}{r^2} \langle \sigma_{eff} | v | \rangle (Y_\rho^2 - (Y_\rho^{eq})^2) \\ & + \kappa(r) \theta(M_{H_2/H^\pm} - (M_N + M_{\rho/\rho^\pm})) \langle \Gamma_{H_2/H^\pm \rightarrow N \rho/\rho^\pm} \rangle (Y_{H_2} - Y_N Y_\rho) \\ & - \kappa(r) \theta(M_\rho - (M_N + M_A)) \langle \Gamma_{\rho \rightarrow NA} \rangle (Y_\rho - Y_N Y_A) \end{aligned}$$

$$\begin{aligned} \frac{dY_N}{dr} = & \kappa(r) \theta(M_{H_2/H^\pm} - (M_N + M_{\rho/\rho^\pm})) \left[\langle \Gamma_{H_2/H^\pm \rightarrow N \rho/\rho^\pm} \rangle (Y_{H_2} - Y_N Y_\rho) \right] + \\ & \kappa(r) \theta(M_{\rho/\rho^\pm} - (M_N + M_{H_2/H^\pm})) \left[\langle \Gamma_{\rho^\pm/\rho^0 \rightarrow N H^\pm/H_2} \rangle (Y_\rho - Y_N Y_{H^\pm/H_2}) \right] + \\ & \kappa(r) \theta(M_\rho - (M_N + M_A)) \langle \Gamma_{\rho \rightarrow NA} \rangle (Y_\rho - Y_N Y_A) . \end{aligned}$$

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

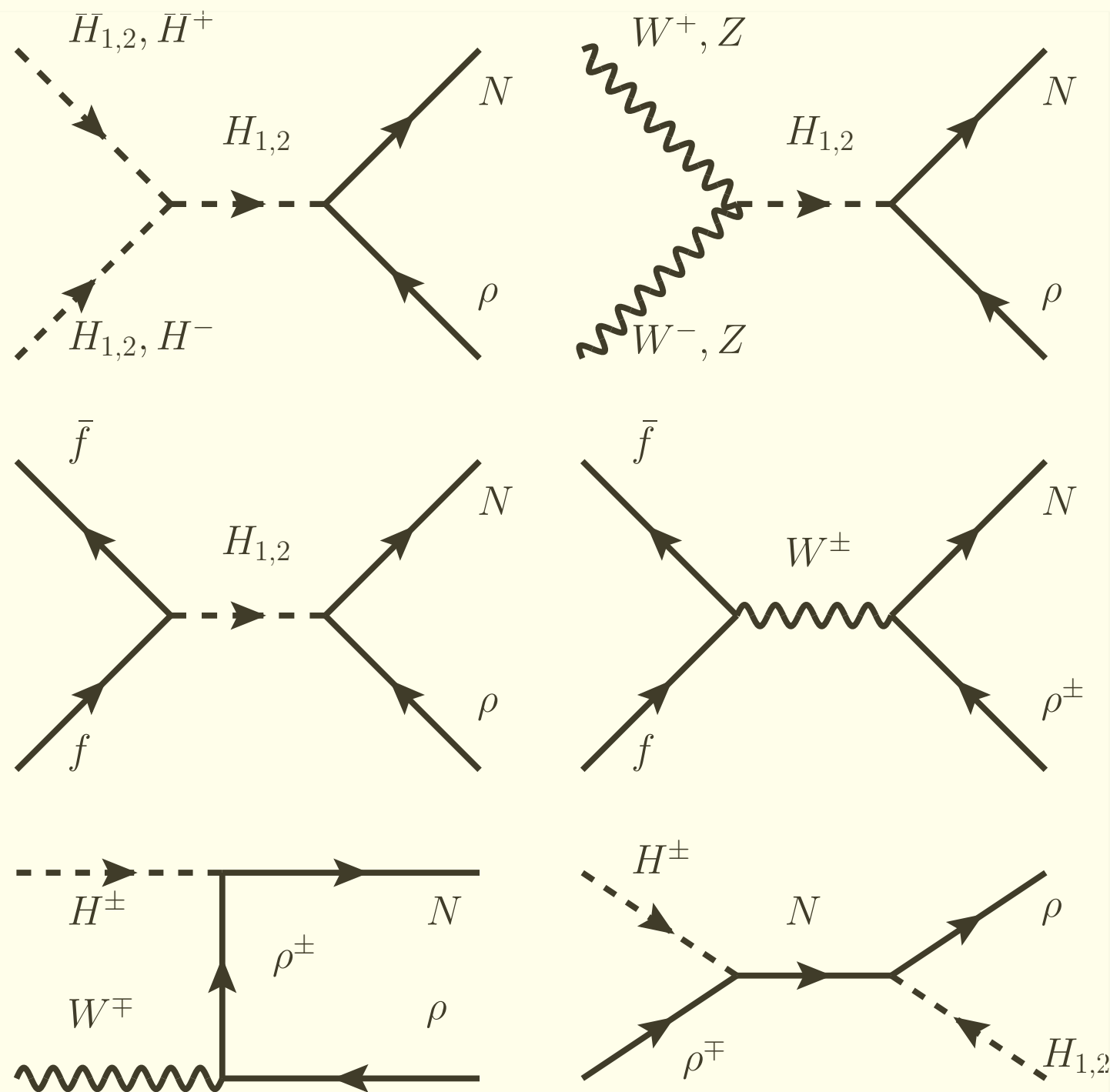


- As N becomes heavier, NTFI contribution increases

- 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

is lighter (within the reach of LHC) and is kinematically foreboded



A. dominated scenario

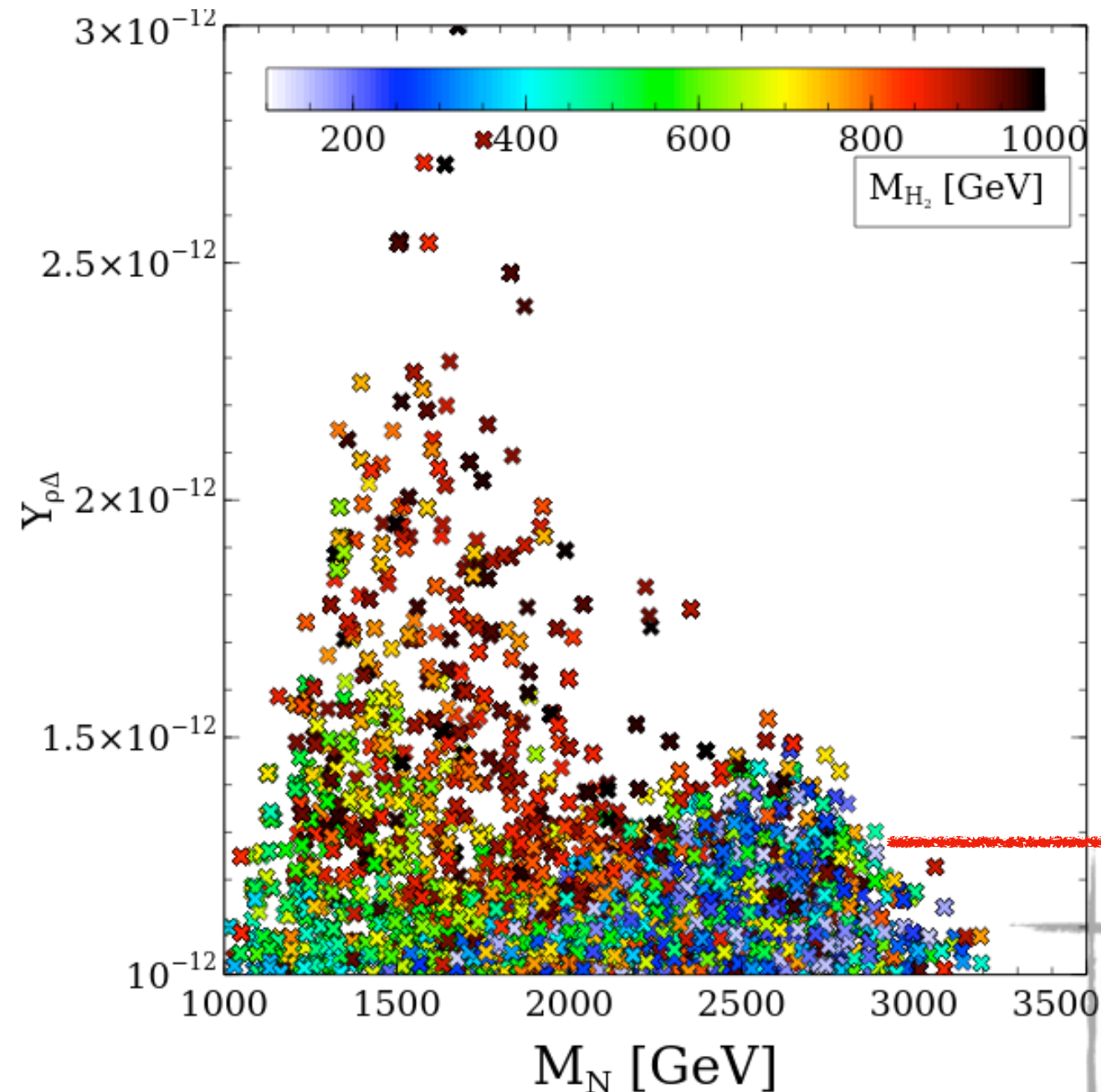
B. dominated scenario

Dark Matter Production with Lighter

Fusion dominated scenario

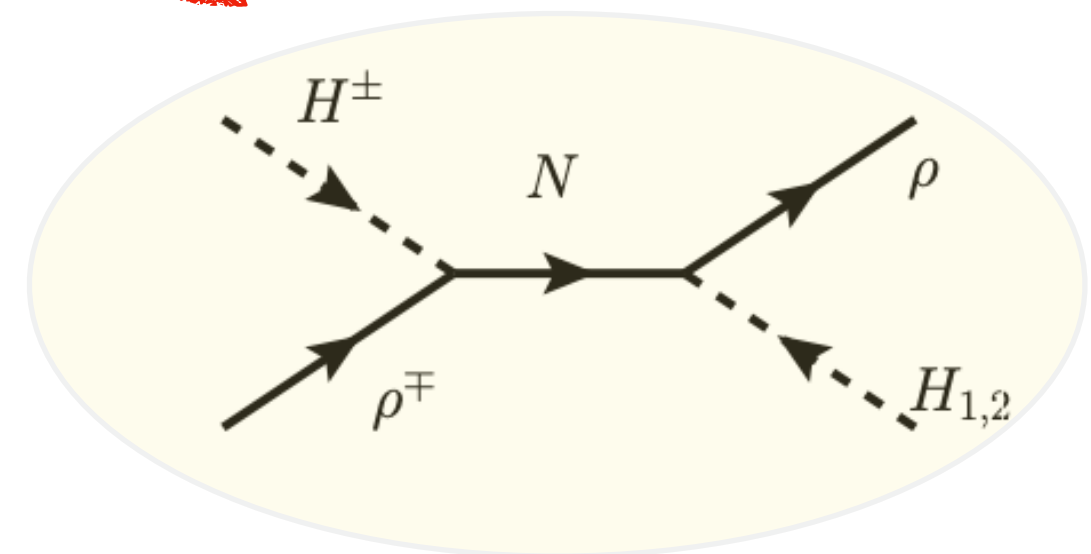
$$AB \rightarrow N \rightarrow \rho H_{1,2}, A, B = \rho, \rho^\pm, H_i$$

- is DM $\rightarrow$ thermal particle.



$$H_2 \rightarrow \rho N$$

kinematically forbidden



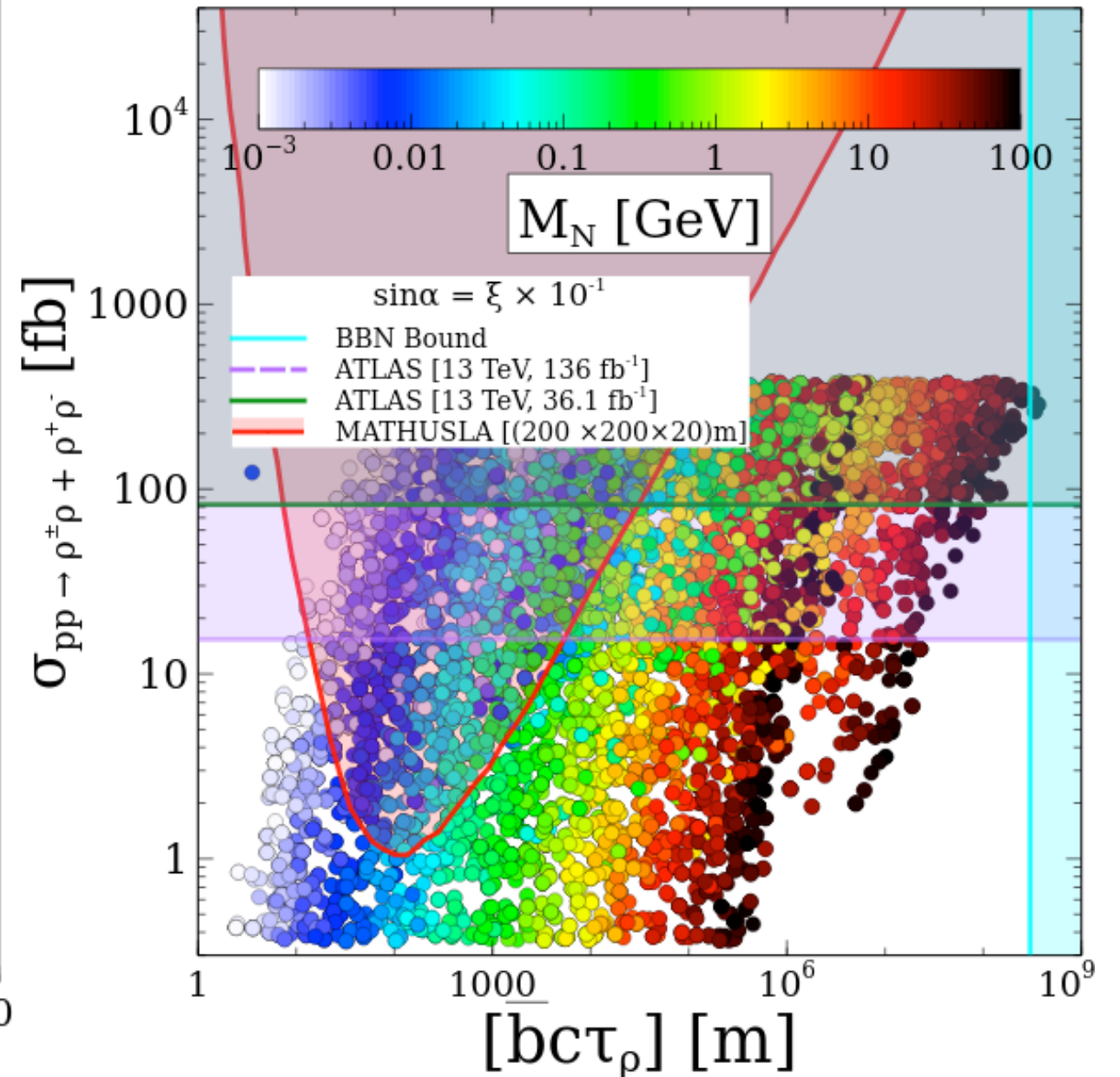
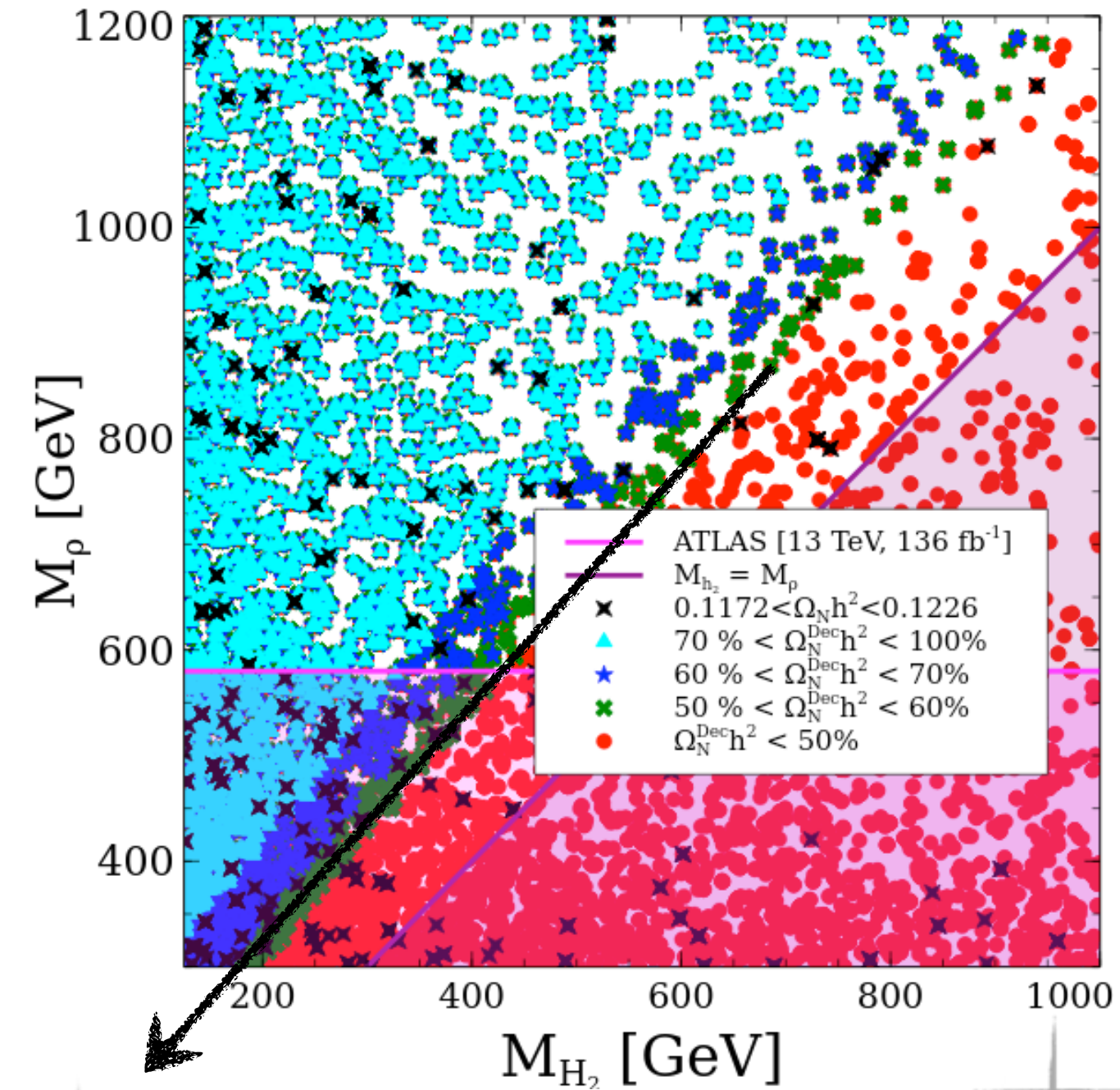
A lighter BSM Higgs can satisfy the relic abundance

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

Substantial annihilation contribution

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

- Standard freeze-in and late decay
- large



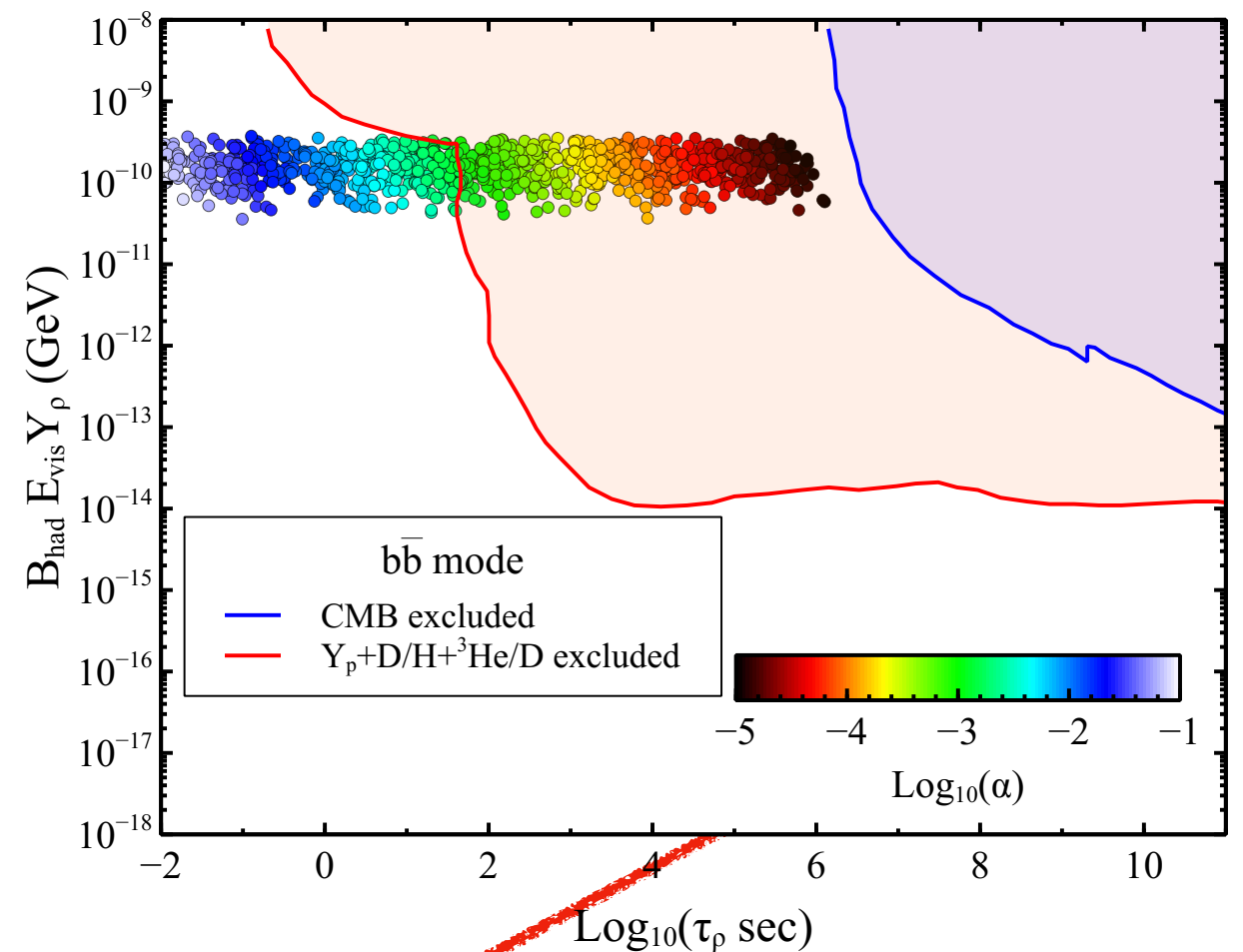
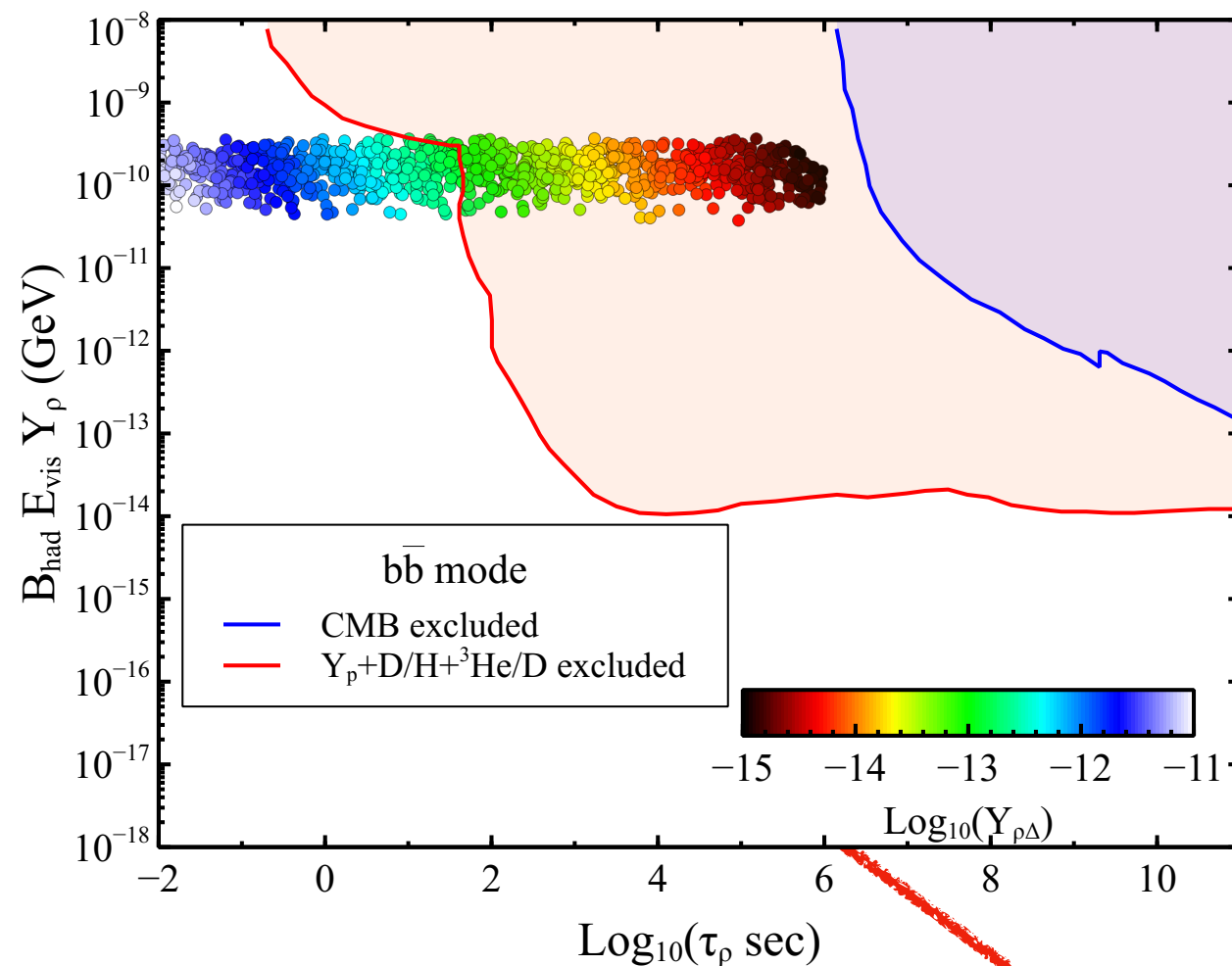
Decay contribution can be less than 50%

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

Late decay of ρ 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

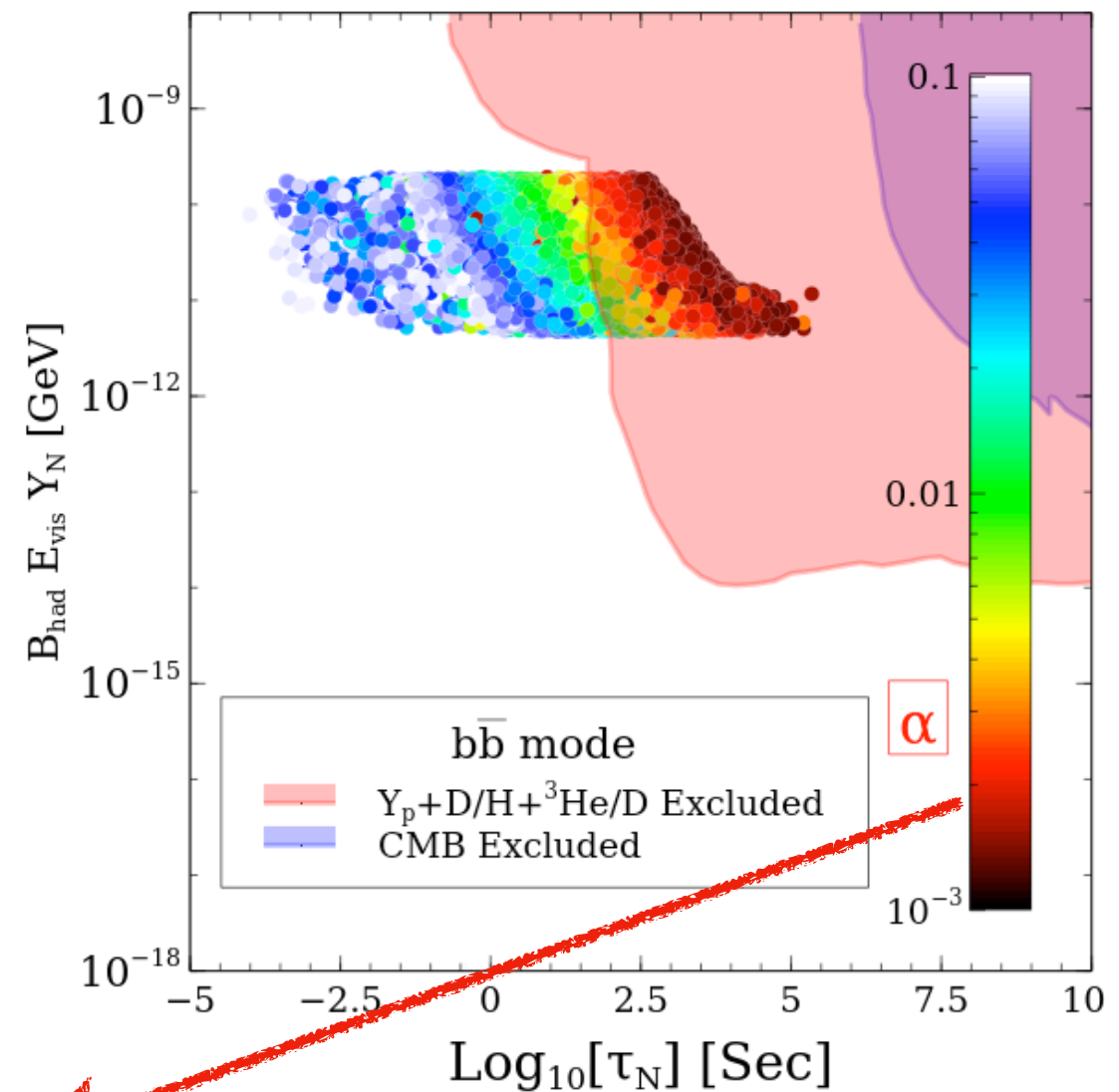
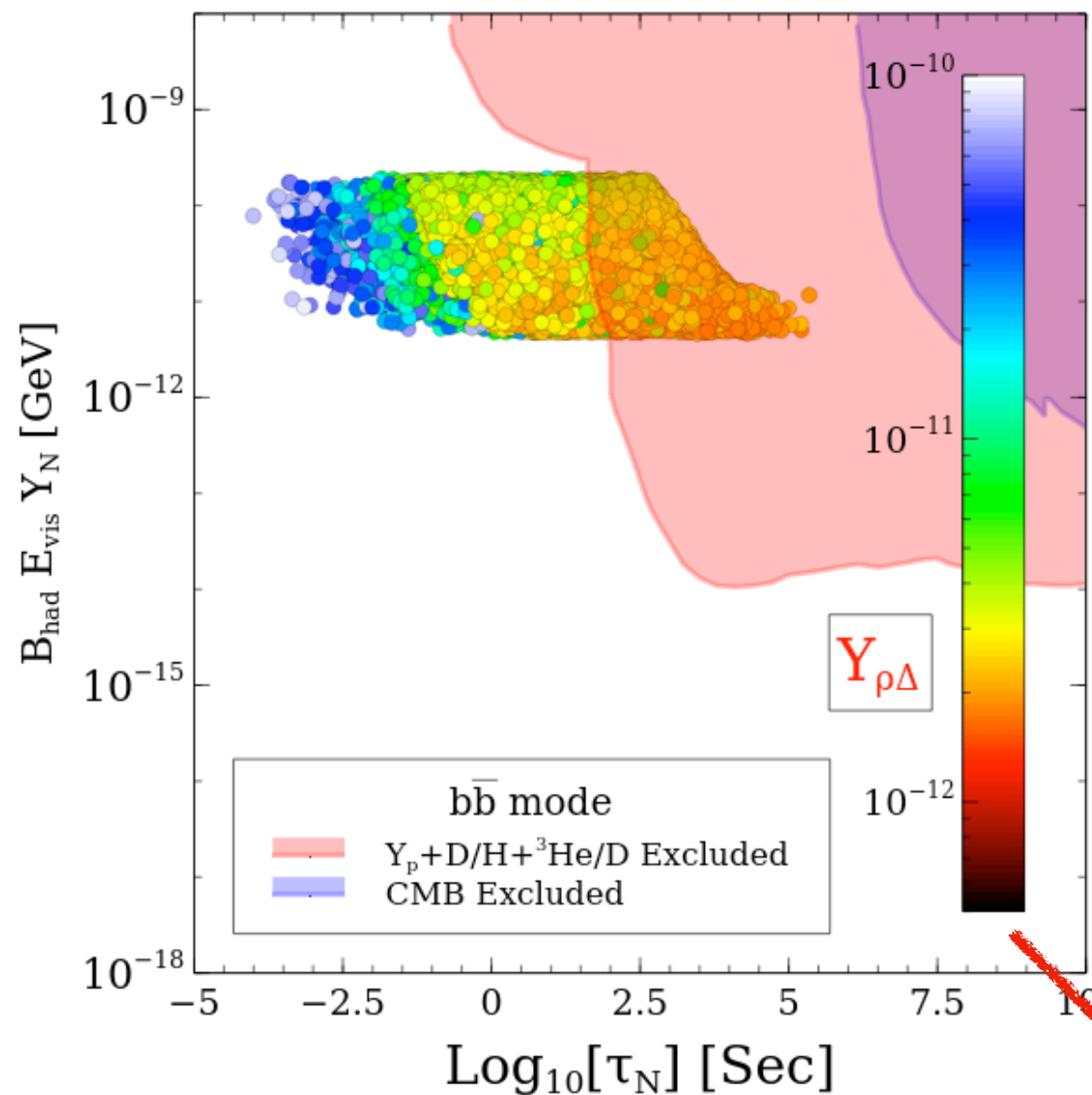


Small values of α are ruled out

Late decay of 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

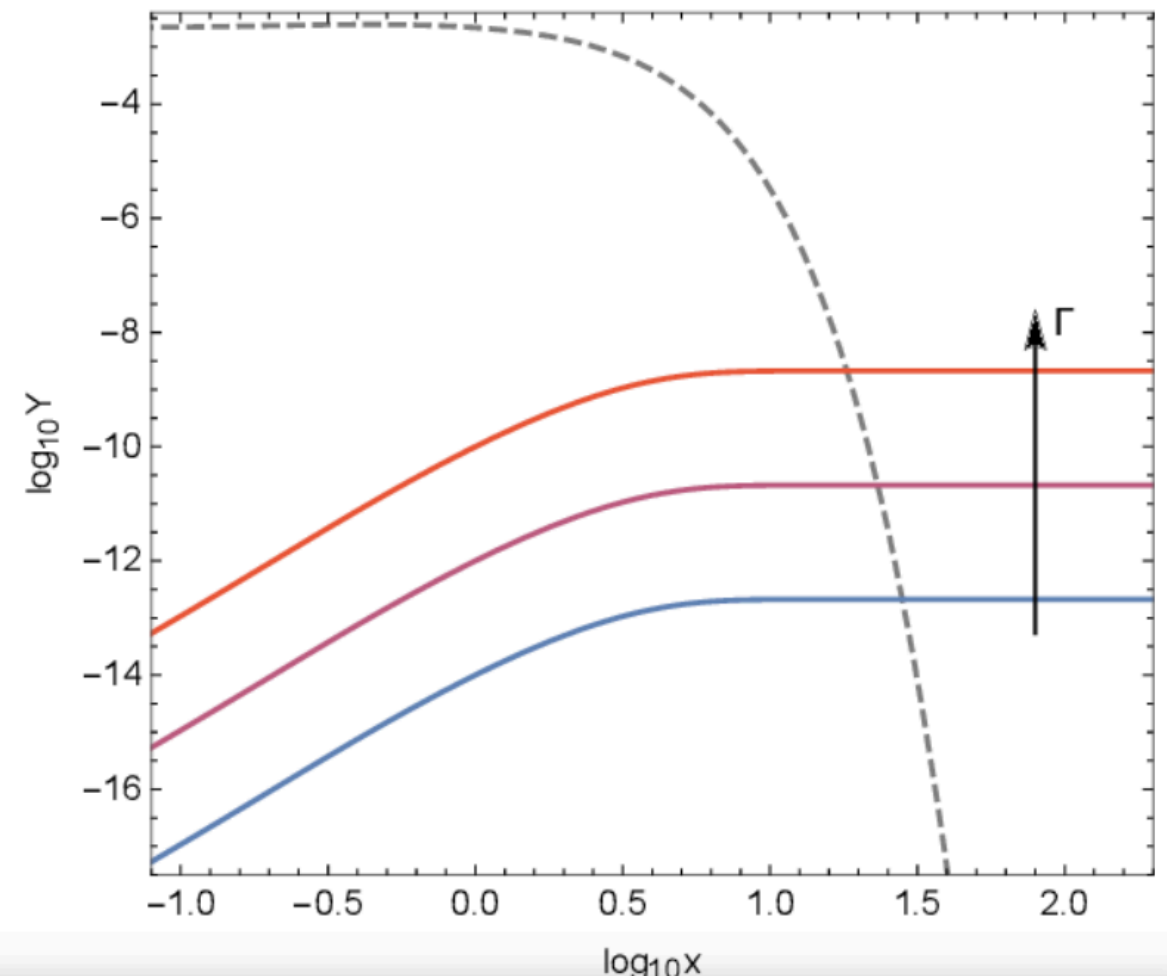
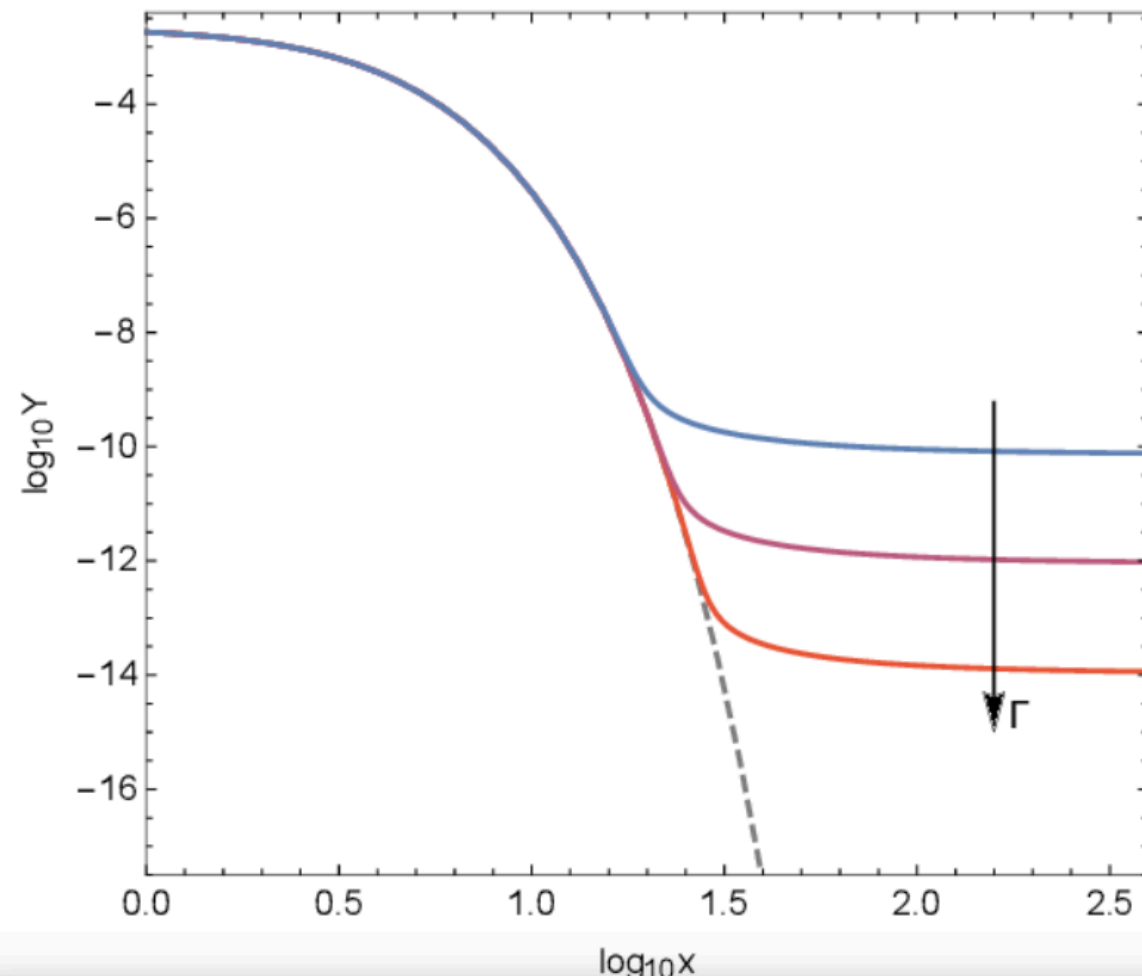


Small values of are ruled out

DarkMatter Production

❖ Weakly interacting massive particle

❖ Feebly interacting massive particle



• HNL as a FIMP

N is produced from decay or annihilation of thermal bath particles

• HNL as a WIMP

$N N \rightarrow \text{SM SM}, \text{BSM}$
BSM generates the relic abundance

• HNL as a NLOP and a SuperWimp

Late decay of N into DM + X contributes significantly to DM relic abundance