Dark matter and entropy dilution

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ν Dark workshop
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Dark Matter

stability

Discrete symmetries

- MSSM & R-parity

Z_2 symmetries

- extended Higgs
  Inert Higgs doublet

talk by Steffen

Discrete symmetries

- MSSM & R-parity
- extended Higgs
  Inert Higgs doublet

Z_2 symmetries

talk by Steffen

Small couplings and or large scales

- small couplings (Dirac Yukawa)
- large scales (extended gauge symmetry)
  i.e. small masses (e.g. axion)

$\Gamma_\mu \propto m_\mu^5/M_W^4$

$m_{DM} \ll \Lambda$

talk by Redondo

Neutrino mass vs. Dark Matter

- new physics needed for neutrino mass talk by Schwetz

Neutrino mass vs. Dark Matter

- new physics needed for neutrino mass, same for DM?

Neutrino mass vs. Dark Matter

- small couplings (Dirac Yukawa) ν_S

νMSM

$$\tau_{\nu_S} \simeq \tau_\mu \left(\frac{m_\mu}{m_S}\right)^5 \frac{m_S}{m_\nu}$$

Dodelson, Widrow ’93,...

can’t do justice to the field

$$m_{\nu_S} \lesssim 20 \text{ keV}$$

talk by Drewes

Neutrino mass vs. Dark Matter

- small couplings (Dirac Yukawa) ν_S

νMSM

$$\tau_{\nu_S} \simeq \tau_\mu \left(\frac{m_\mu}{m_S}\right)^5 \frac{m_S}{m_\nu}$$

Dodelson, Widrow '93,...
can't do justice to the field

$$m_{\nu_S} \lesssim 20 \text{ keV}$$

- large scales and small masses N_i

Left-Right

no direct channels below m_π , only mixing

Bezrukov,
Hettmansperger,
Lindner '09

$$m_{N_1} \simeq \text{keV} \qquad M_{W_R} \gtrsim 14 \text{ TeV}$$

a possible window $M_{W_R} \in (4, 7)$ TeV

MN, Senjanović, Zhang '12

DM predicts mass and flavor of N_i

Left-Right the minimal model $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- understanding the SM asymmetry...

Pati, Salam ’74
Mohapatra, Pati ’75

...through spontaneous breaking

Senjanović, Mohapatra ’75

$$W_L \qquad Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad L_L = \begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$$

$$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \qquad L_R = \begin{pmatrix} e_R \\ \nu_R \end{pmatrix} \qquad W_R$$

Left-Right the minimal model

- understanding the SM asymmetry...

Pati, Salam ’74
Mohapatra, Pati ’75

...through spontaneous breaking

Senjanović, Mohapatra ’75

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \Phi(2,2,0) \qquad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$W_L \qquad\qquad\qquad\qquad\qquad\qquad\qquad W_R$$

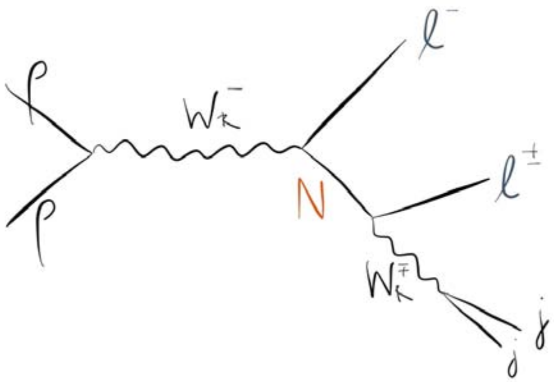
$$L_L = \begin{pmatrix} e_L \\ \nu_L \end{pmatrix} \qquad \Delta_L(3,1,2) \qquad \Delta_R(1,3,2) \qquad L_R = \begin{pmatrix} e_R \\ \nu_R \end{pmatrix}$$

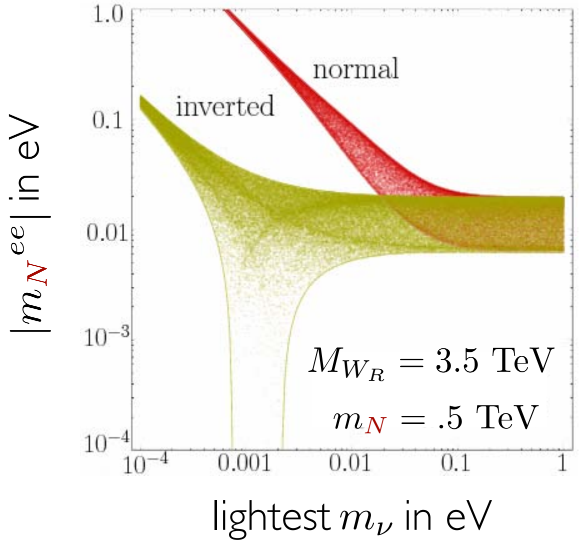
- seesaw

Minkowski ’79
Senjanović, Mohapatra ’79

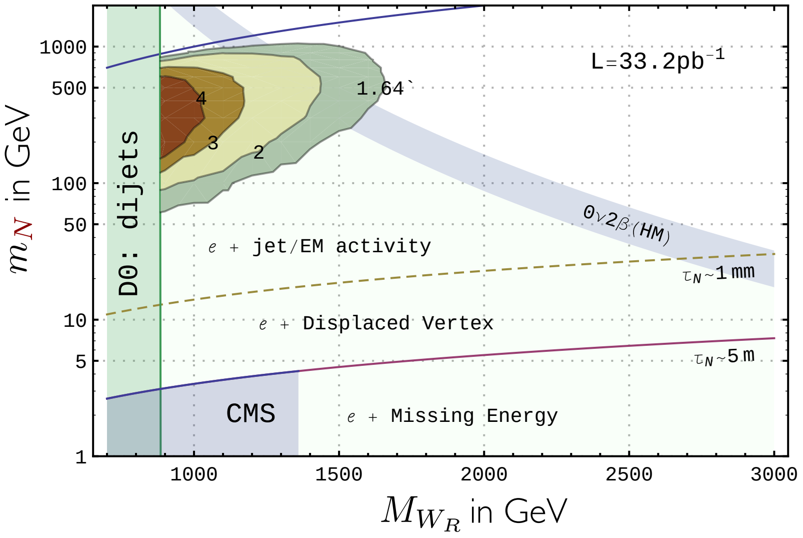
- rich phenomenology: LNV, LFV at colliders, $0\nu2\beta$

Left-Right $0\nu2\beta$ vs. LHC





Senjanović, Mohapatra ’82
Tello, MN, Nesti,
Senjanović, Vissani ’10

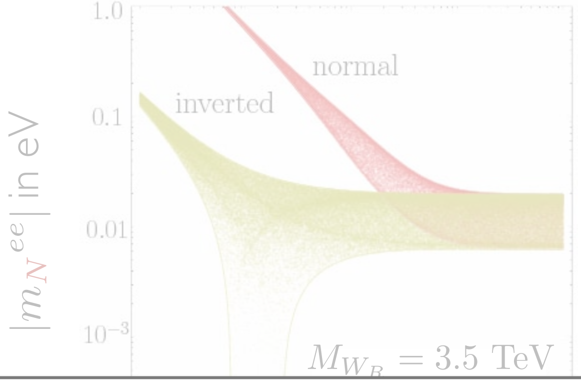


Keung, Senjanović ’83
MN, Nesti, Senjanović,
Zhang ’11

- mass origin in Higgs decays $h \to N_i N_i$

Maiezza, MN, Nesti, ’15

Left-Right $0\nu2\beta$ vs. LHC



Senjanović, Mohapatra '82
Tello, MN, Nesti,
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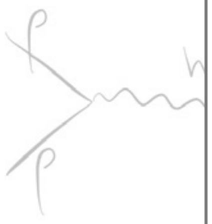
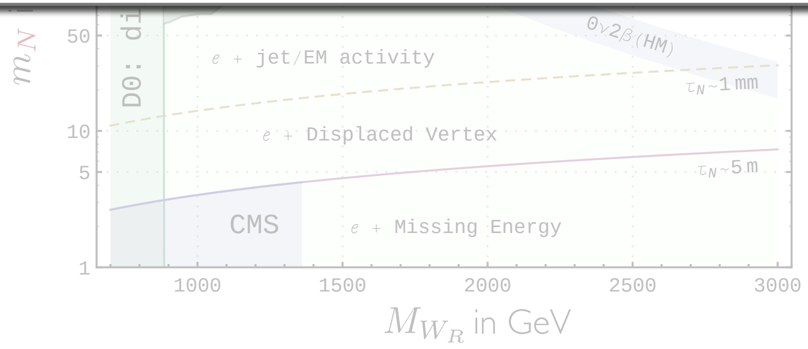


Dark Matter?

vić '83
janović,
ang '11



- mass origin in Higgs decays $h \to N_i N_i$

Maiezza, MN, Nesti, '15

Dark Matter

(over)production

Left-Right freeze-out part I

- gauge interactions keep thermal equilibrium
- suppressed rate compared to SM neutrinos

$$\Gamma_N \simeq \Gamma_\nu \left(\frac{M_W}{M_{W_R}}\right)^4 \simeq G_F^2 \left(\frac{M_W}{M_{W_R}}\right)^4 T^5$$

thermal freeze-out

$$\left(\frac{M_W}{M_{W_R}}\right)^4 T^5 \simeq \sqrt{G} T^2$$

around the QCD
phase transition

$$T_f \simeq 400 \text{ MeV} \left(\frac{g_*(T_f)}{70}\right)^{1/6} \left(\frac{M_{W_R}}{5 \text{ TeV}}\right)^{4/3}$$

Left-Right over-abundance

- freeze-out relativistic, no Boltzmann suppression

$$T_f > m_N \sim \mathrm{keV}$$

- freeze-out relativistic, no Boltzmann suppression

$$Y_N \equiv \frac{n_N}{s} \simeq \frac{135\,\zeta(3)}{4\pi^4 g_*(T_f)}$$

- Y_N conserved, evolve to present times

$$\begin{aligned}\Omega_{N_1} &= Y_{N_1} m_{N_1} \frac{s}{\rho_c} \\ &= 3.3 \left(\frac{m_{N_1}}{\mathrm{keV}}\right) \left(\frac{70}{g_*(T_f)}\right) \\ &\simeq \boxed{13\,\Omega_{DM}}\end{aligned}$$

- many species, not in LRSM

$$g_* < 1000$$

- ~~$m_{N_1} < 0.08\ \mathrm{keV}$~~ astrophysics, ...

Dark Matter

dilution

Decaying particles in the early universe

Scherrer, Turner ’85

- massive late decaying particle
- decays heat up radiation, dilutes the rest $\equiv$ diluter
- applied to sterile neutrinos

Asaka, Shaposhnikov, Kusenko ’06

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Left-Right candidates

- Higgs sector heavy & unstable
- next-to-lightest $N_{2,3}$ the only remaining candidates

Diluting with N_2 part I

Scherrer, Turner '85

- sudden decay approximation (works for $\rho_m \gg \rho_\gamma$)

$$t \leq \tau_2$$

matter dominance

$$H^2 = \Gamma_2^2 = \frac{8\pi}{3M_P^2} \, (Y_2 m_{N_2}) \, \frac{2\pi^2 g_*}{45} T_<^3$$

$$T_< = 0.65 \left(\frac{\Gamma_2^2 M_P^2}{Y_2 m_2 g_*} \right)^{1/3}$$

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$t \geq \tau_2$

radiation dominance

$$H = \Gamma_2 = 1.66\,\frac{g_*^{1/2}}{M_P} T_>^2$$

$$T_> \simeq 0.78\, g_*^{-1/4} \sqrt{\Gamma_2 M_P}$$

$$\simeq 1.22 \text{ MeV} \sqrt{\frac{1 \text{ sec}}{\tau_2}}$$

needed
for BBN

Diluting with N_2 part I

Scherrer, Turner ’85

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needed for BBN

Dilution factor $$\mathcal{S} = \left(\frac{T_>}{T_<}\right)^3 \simeq 1.7\,\frac{T(\tau_2)^{1/4}\, Y_2\, m_2}{\sqrt{\Gamma_2 M_P}}$$

$$\boxed{\mathcal{S} \propto m_2\sqrt{\tau_2}}$$

Diluting with N_2 part I

- how much dilution?

$$\boxed{\Omega_{N_1} \simeq .228 \left(\frac{m_{N_1}}{\mathrm{keV}}\right)\left(\frac{1.85\ \mathrm{GeV}}{m_{N_2}}\right)\left(\frac{\mathrm{sec}}{\tau_2}\right)\left(\frac{g_*(T_{f2})}{g_*(T_{f1})}\right)}$$

Boltzmann
suppressed

$$T_{f1} \simeq 400\ \mathrm{MeV}$$

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Boltzmann
suppressed

$$T_{f1} \simeq 400 \text{ MeV}$$

- 1sec lifetime near the $m_\pi + m_\ell$ threshold, τ disfavored

$$\tau(N_2 \to \ell\pi) = \text{sec}\left(\frac{250 \text{ MeV}}{m_{N_2}}\right)^3 \left(\frac{M_{W_R}}{5 \text{ TeV}}\right)^4 \left(\frac{0.002}{f(x_\ell, x_\pi)}\right)^3 \qquad \ell = e, \mu$$

Diluting with N_2 part I

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- 1sec lifetime near the $m_\pi + m_\ell$ threshold, τ disfavored

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- freeze-out flavor dependent

$m_{N_1} \sim \text{keV}$ $V_{Re1} \simeq 0$ SN cooling

Raffelt, Seckel '88
Barbieri, Mohapatra '89

'turn off' W_R $V_{R\tau 1} \simeq 1$ $T_{f1} > T_{f2}$

Mass spectrum of DM in Left-Right

- mass and flavor fixed

DM couples to τ

$$V_R \simeq \begin{pmatrix} 0 & 0 & \textcircled{1} \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \qquad m_{N_1} \simeq \mathrm{keV}$$

Mass spectrum of DM in Left-Right

- mass and flavor fixed

$$V_R \simeq \begin{pmatrix} 0 & 0 & 1 \\ 0 & \textcircled{1} & 0 \\ \textcircled{1} & 0 & 0 \end{pmatrix}$$

$$m_{N_2} \simeq m_\pi + m_\mu$$

$$m_{N_3} \simeq m_\pi + m_e$$

Diluters couple to e and μ

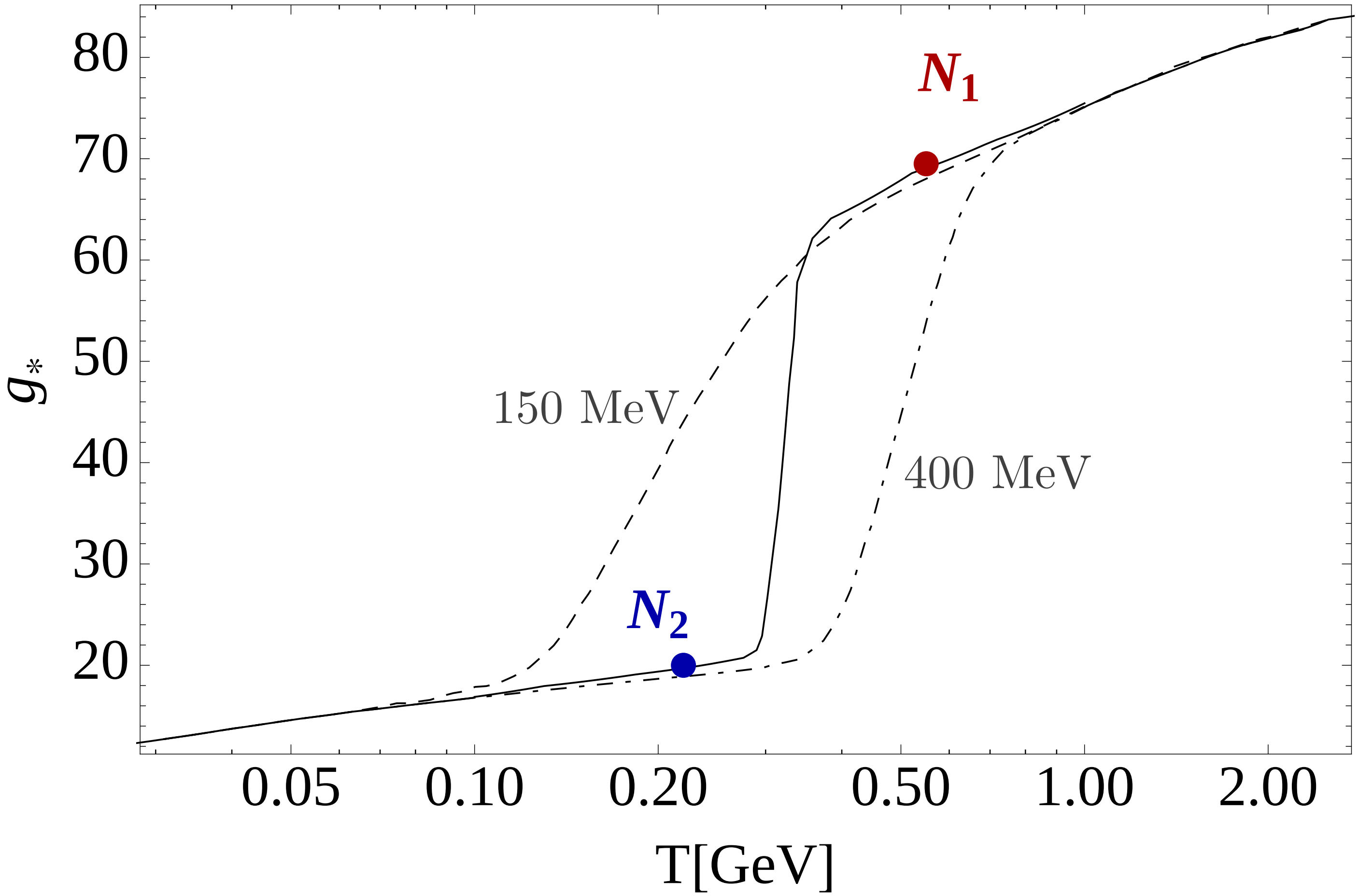
Dark Matter

freeze-out pt. 2

Left-Right freeze-out part II

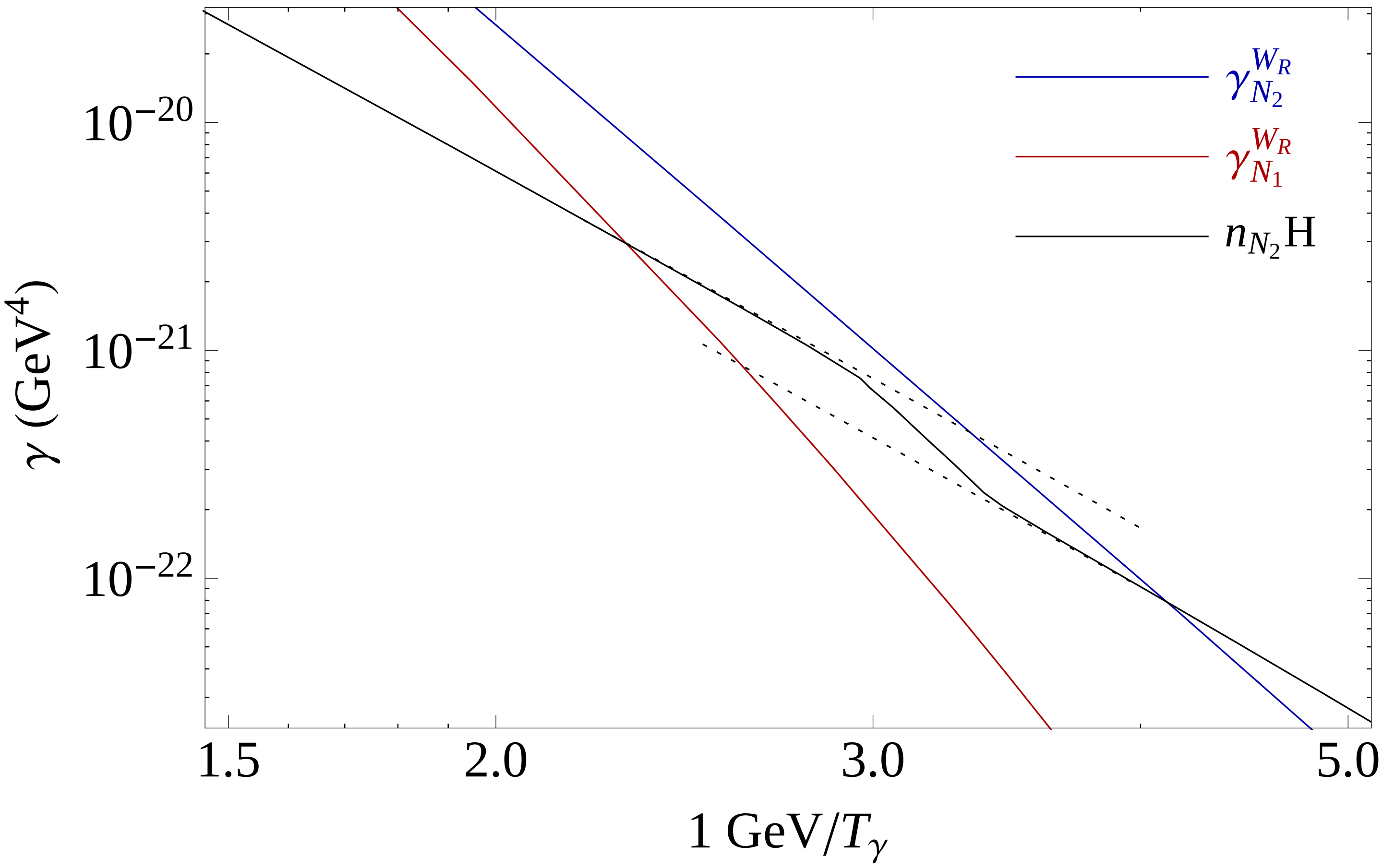
- drop in g_*

$$\frac{Y_{N_2}}{Y_{N_1}} \simeq \frac{g_*(T_{f1})}{g_*(T_{f2})} \sim 3-4$$



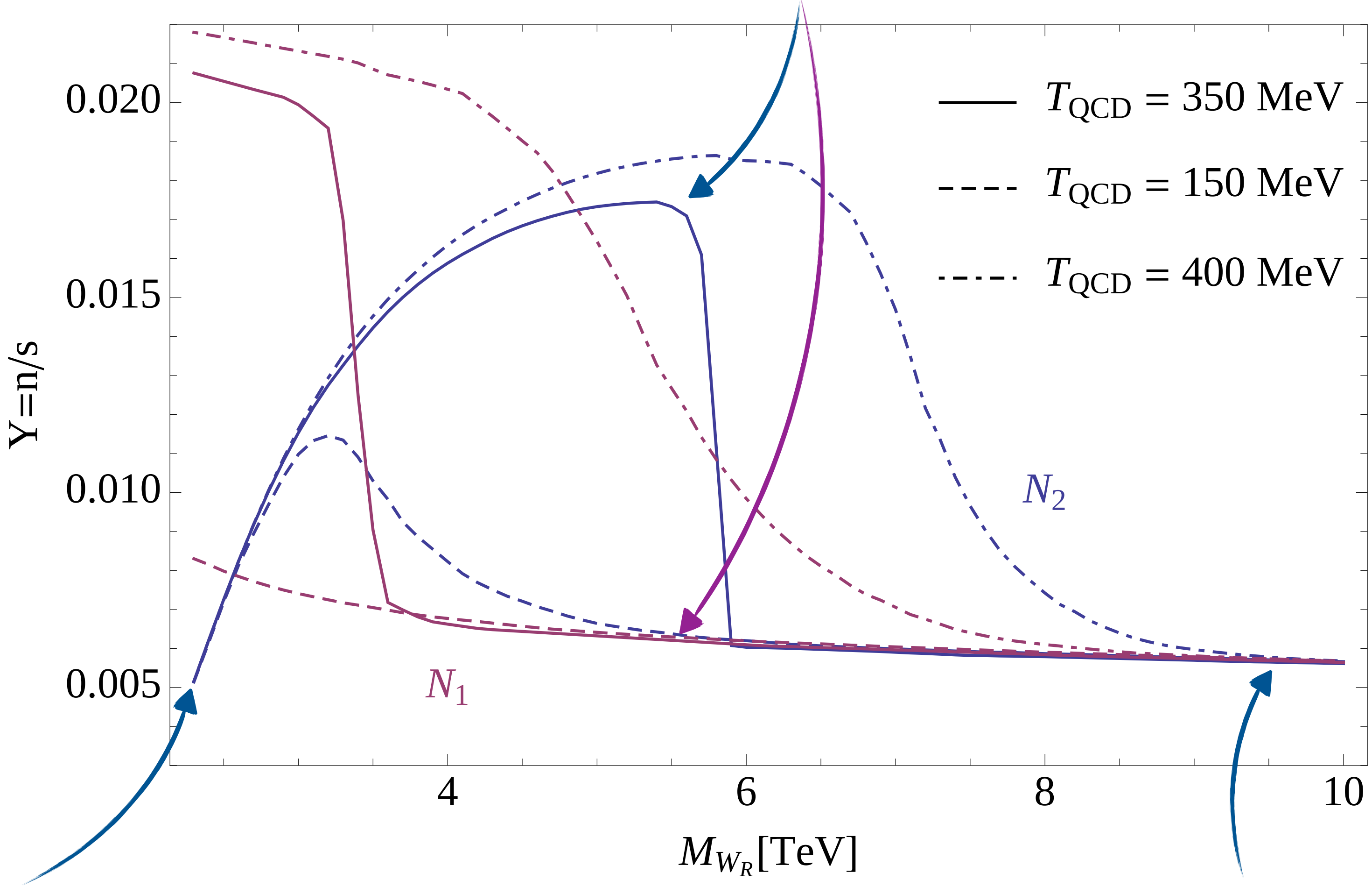
Left-Right freeze-out part II

- pair $N_i N_i \to \ell^+ \ell^-,\ u\overline{u},\ d\overline{d}$
- single $N_i \ell^- \to \overline{u} d,\ N_i u \to \ell^+ d,\ N_i d \to \overline{\ell}^+ u$



Left-Right freeze-out part II

DM-diluter separation window



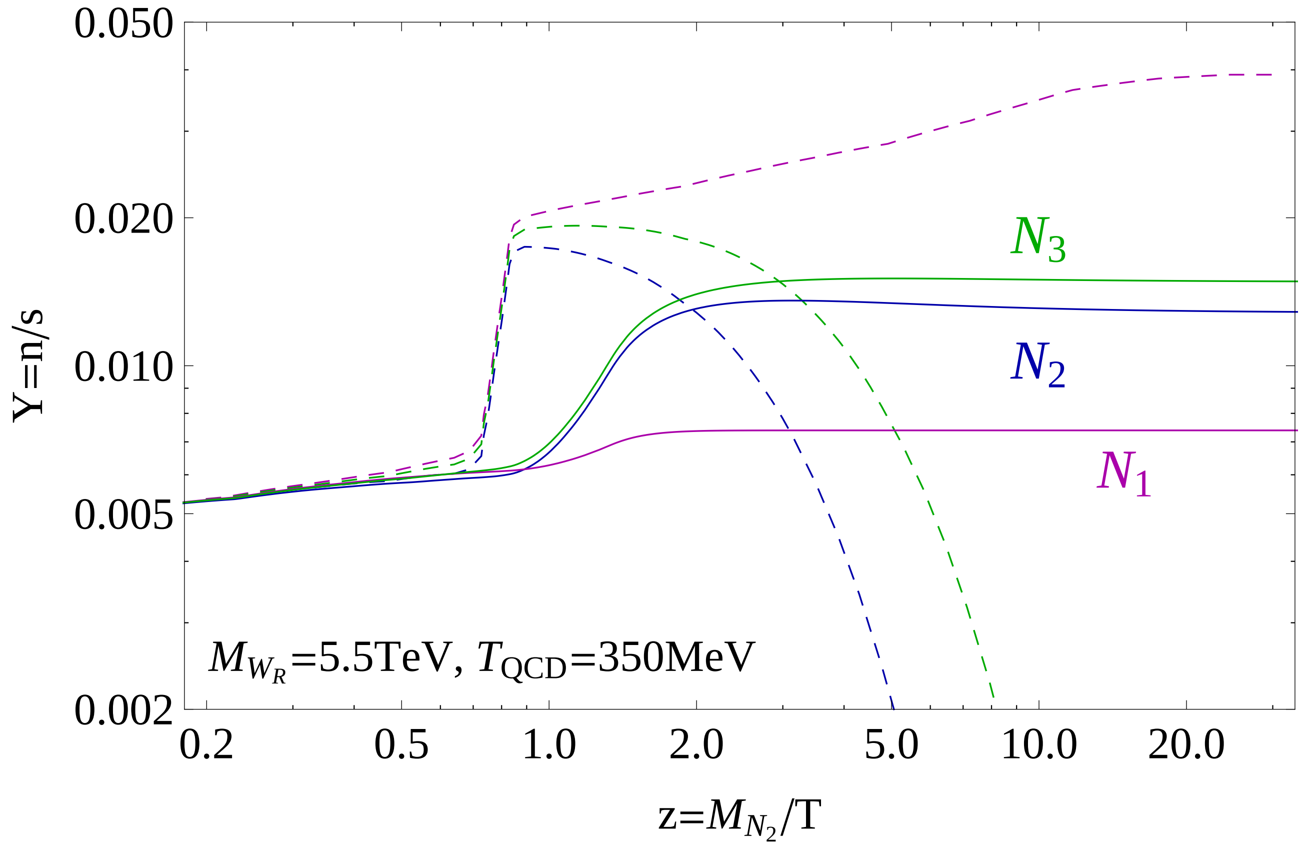
Boltzmann suppressed

universal freeze-out

Left-Right freeze-out part II

- coupled Boltzmann equations $i = 1, 2, 3$

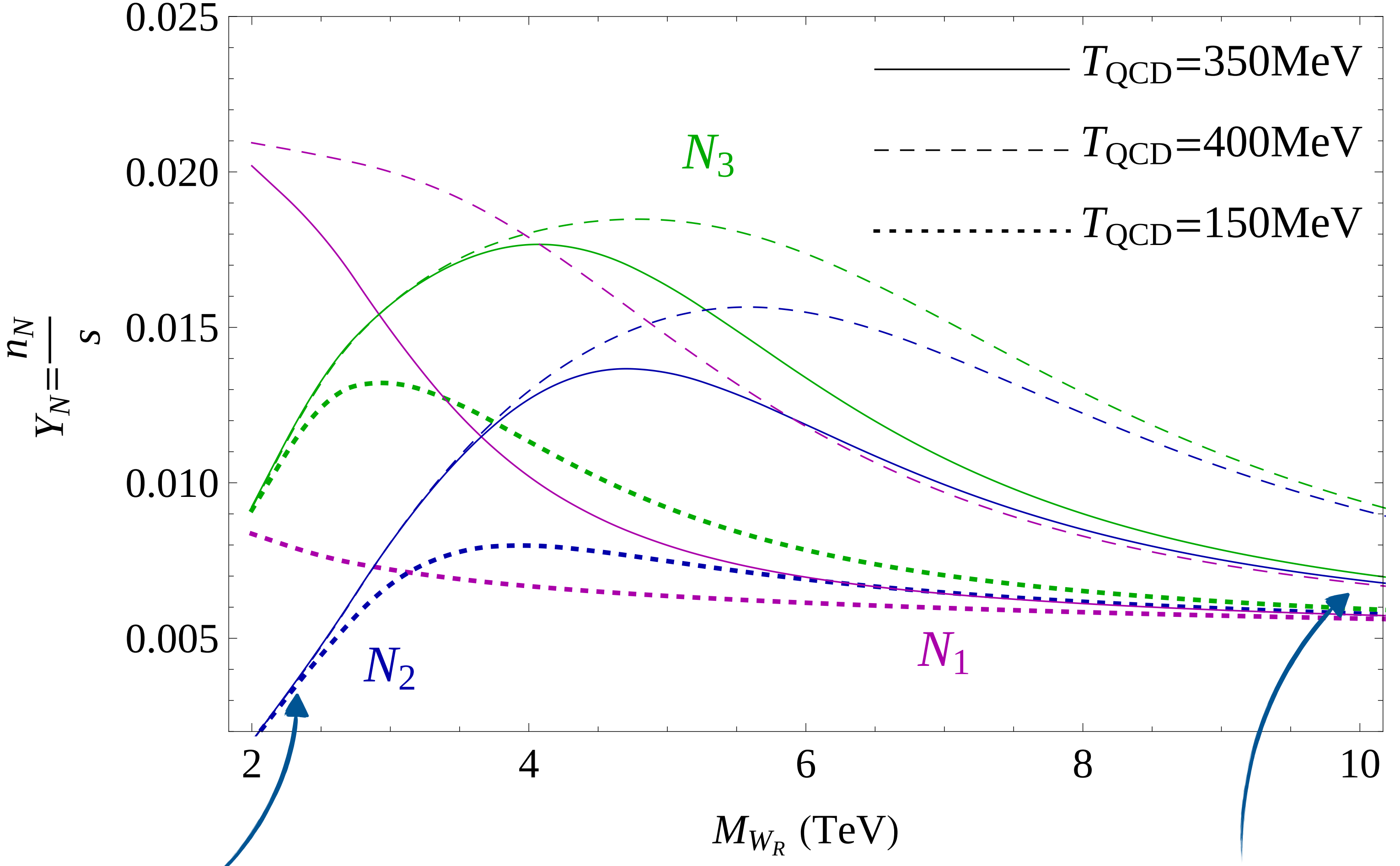
$$sHz\frac{dY_{N_i}}{dz} = -\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}} - 1\right)\gamma^{W_R}_{N_i} - \left(\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}}\right)^2 - 1\right)\left(\gamma^{W_R}_{N_iN_i} + \gamma^{Z_{LR}}_{N_iN_i}\right)$$



$$Y_{N_{2,3}} > Y_{N_1}$$

Left-Right freeze-out part II

- final yields



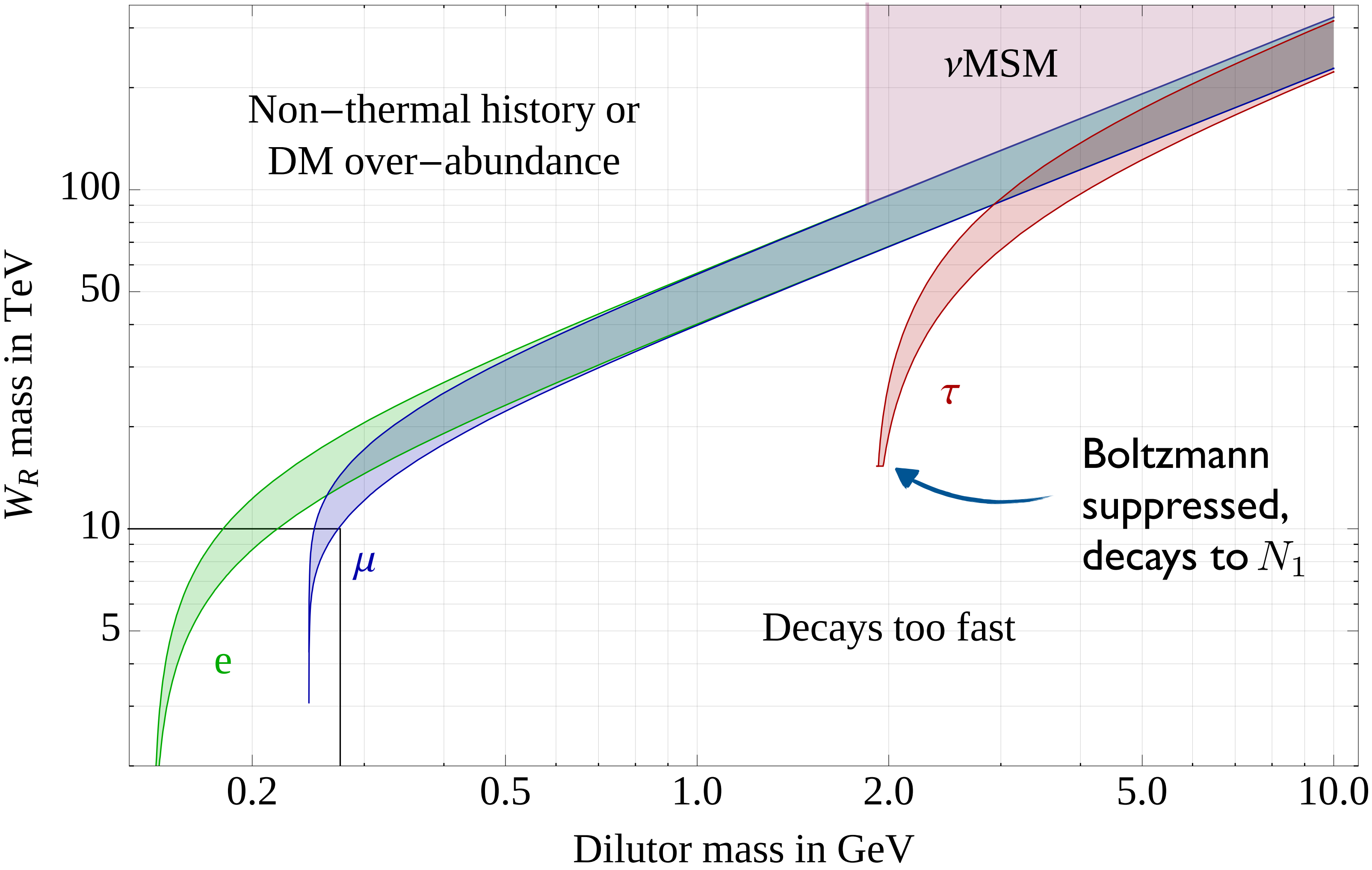
Boltzmann suppressed

universal freeze-out

Dark Matter

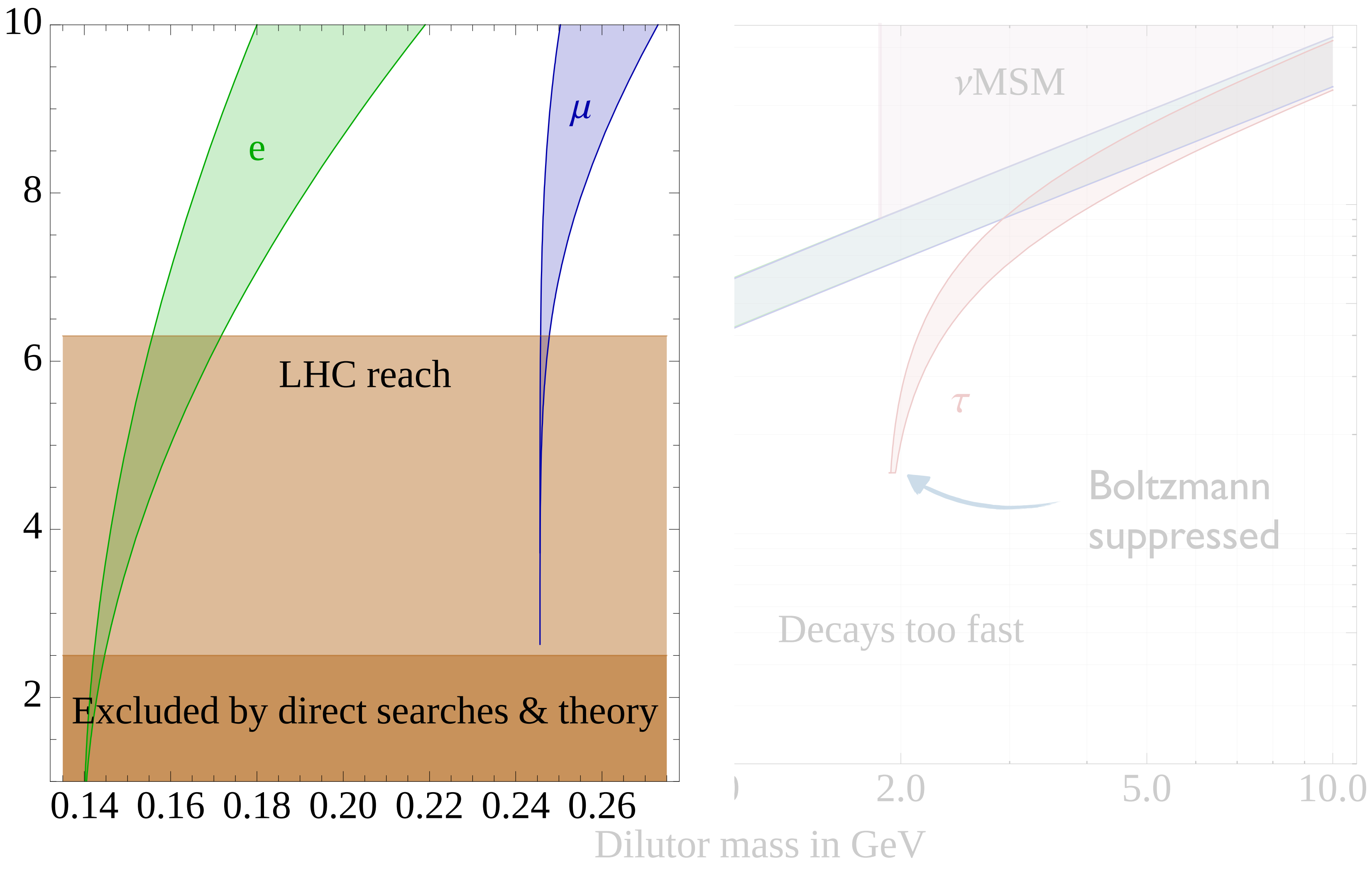
dilution pt. 2

Dilution phase space



Boltzmann suppressed, decays to N_1

Dilution phase space



Dilution part II

- coupled energy density evolution

radiation

$$\frac{d\rho_\gamma}{dt} + 4H\rho_\gamma = \Gamma_2\rho_2 + \Gamma_3\rho_3$$

matter

$$\frac{d\rho_{N_1}}{dt} + 4H\rho_{N_1} = 0$$

$$\frac{d\rho_{N_2}}{dt} + 4H\rho_{N_2} = -\Gamma_2\rho_2$$

$$\frac{d\rho_{N_3}}{dt} + 4H\rho_{N_3} = -\Gamma_3\rho_3$$

Dilution part II

- coupled energy density evolution

freeze-out

match

$$\downarrow \qquad \begin{aligned} z_m &= 30 \\ T_{\gamma,m} &\simeq 15\ \mathrm{MeV} \\ t_m &= 1/(2H) \end{aligned}$$

radiation

$$\frac{d\rho_\gamma}{dt} + 4H\rho_\gamma = \Gamma_2\rho_2 + \Gamma_3\rho_3$$

$$\rho_\gamma(t_m) = \frac{\pi^2}{30} g_*(T_{\gamma,m}) T_{\gamma,m}^4$$

matter

$$\frac{d\rho_{N_1}}{dt} + 4H\rho_{N_1} = 0$$

$$\frac{d\rho_{N_2}}{dt} + 4H\rho_{N_2} = -\Gamma_2\rho_2$$

$$\frac{d\rho_{N_3}}{dt} + 4H\rho_{N_3} = -\Gamma_3\rho_3$$

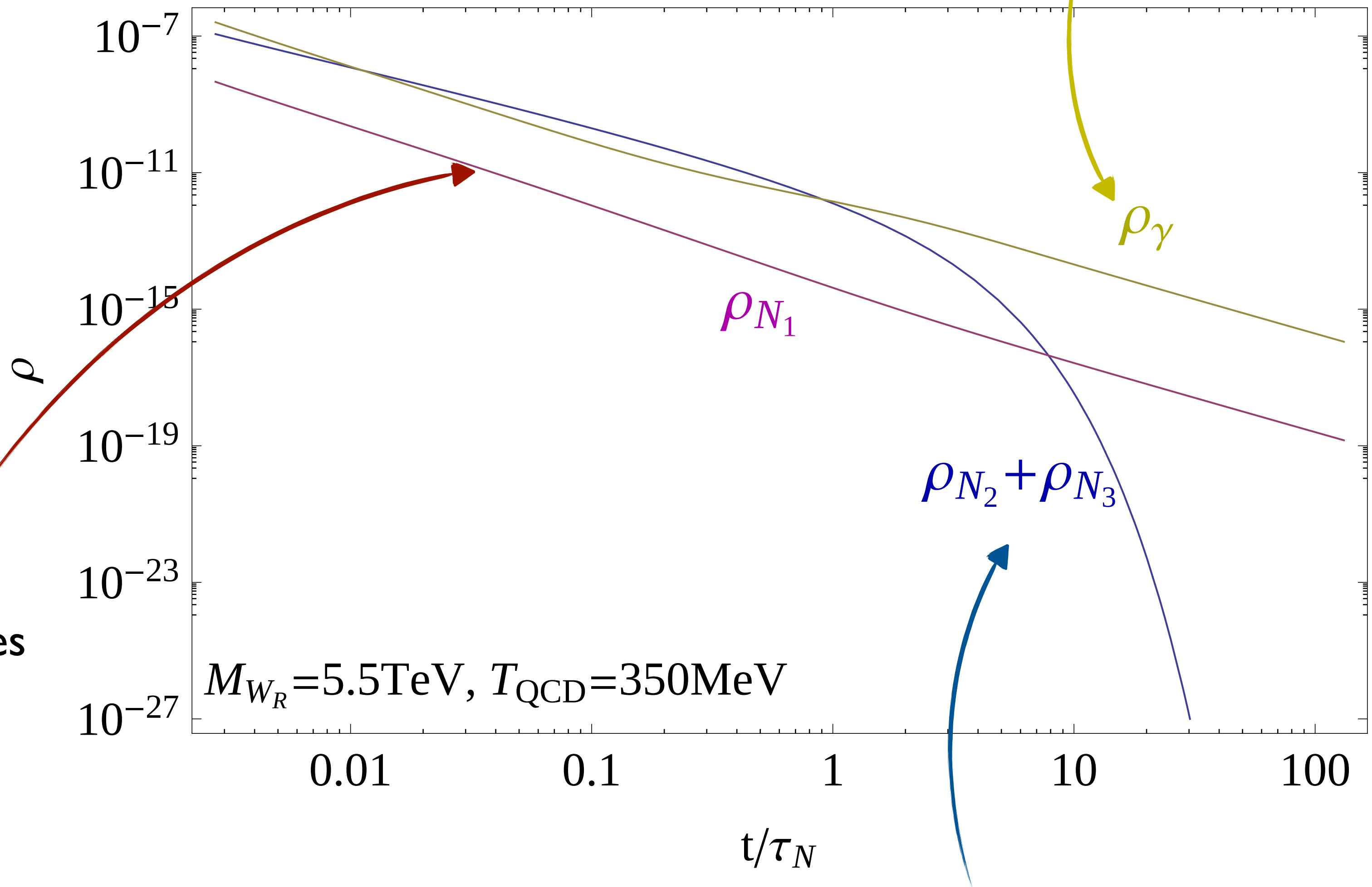
$$\rho_{N_1}(t_m) = \frac{7}{4}\frac{\pi^2}{30} g_*(T_{\gamma,m}) T_{N_1,m}^4$$

$$\rho_{N_2}(t_m) = m_{N_2} Y_{N_2}(z_m) \frac{2\pi^2}{45} g_*(T_{\gamma,m}) T_{\gamma,m}^3$$

$$\rho_{N_3}(t_m) = m_{N_3} Y_{N_3}(z_m) \frac{2\pi^2}{45} g_*(T_{\gamma,m}) T_{\gamma,m}^3$$

Dilution part II

radiation decrease
slows down

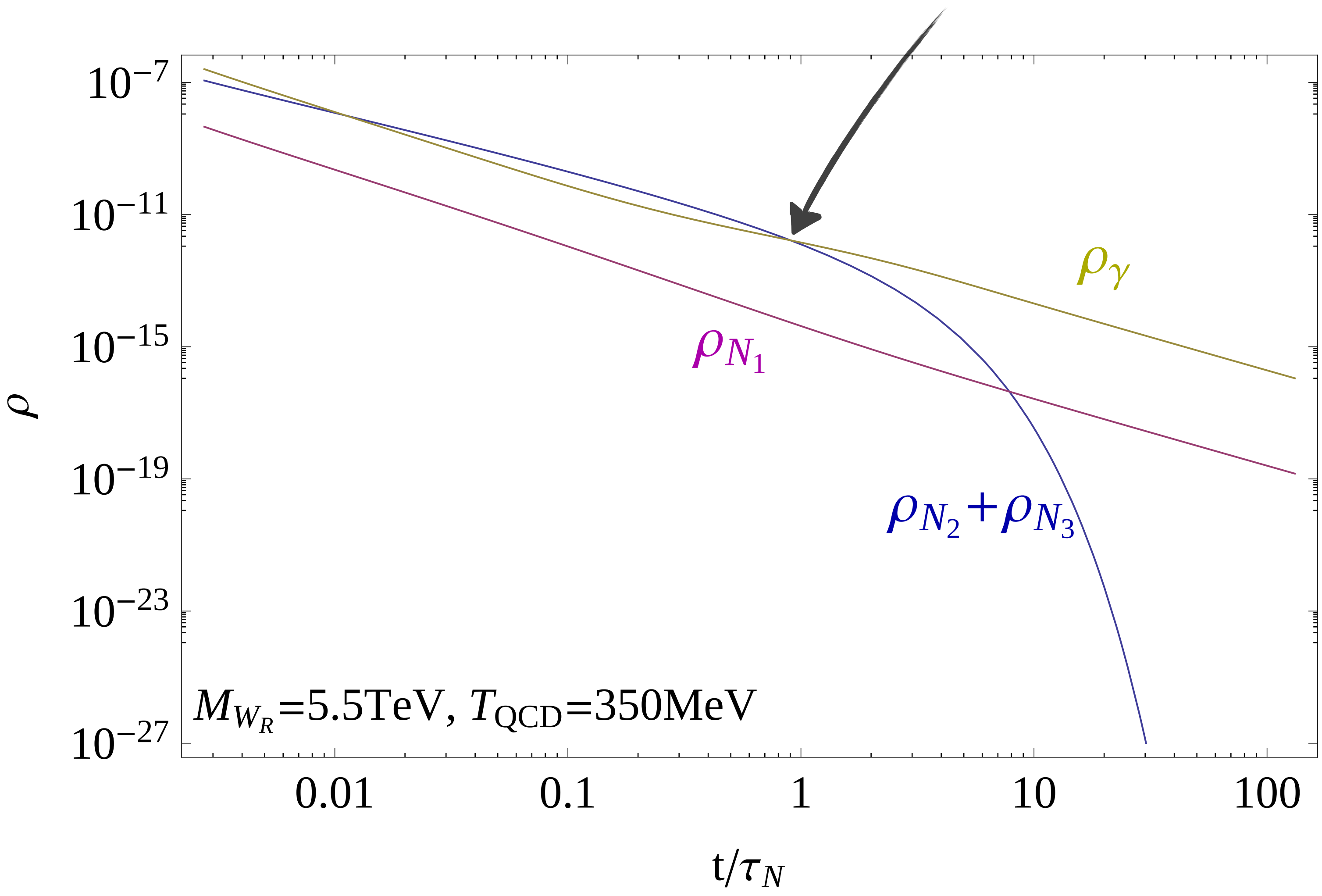


DM
decouples

diluters
decay

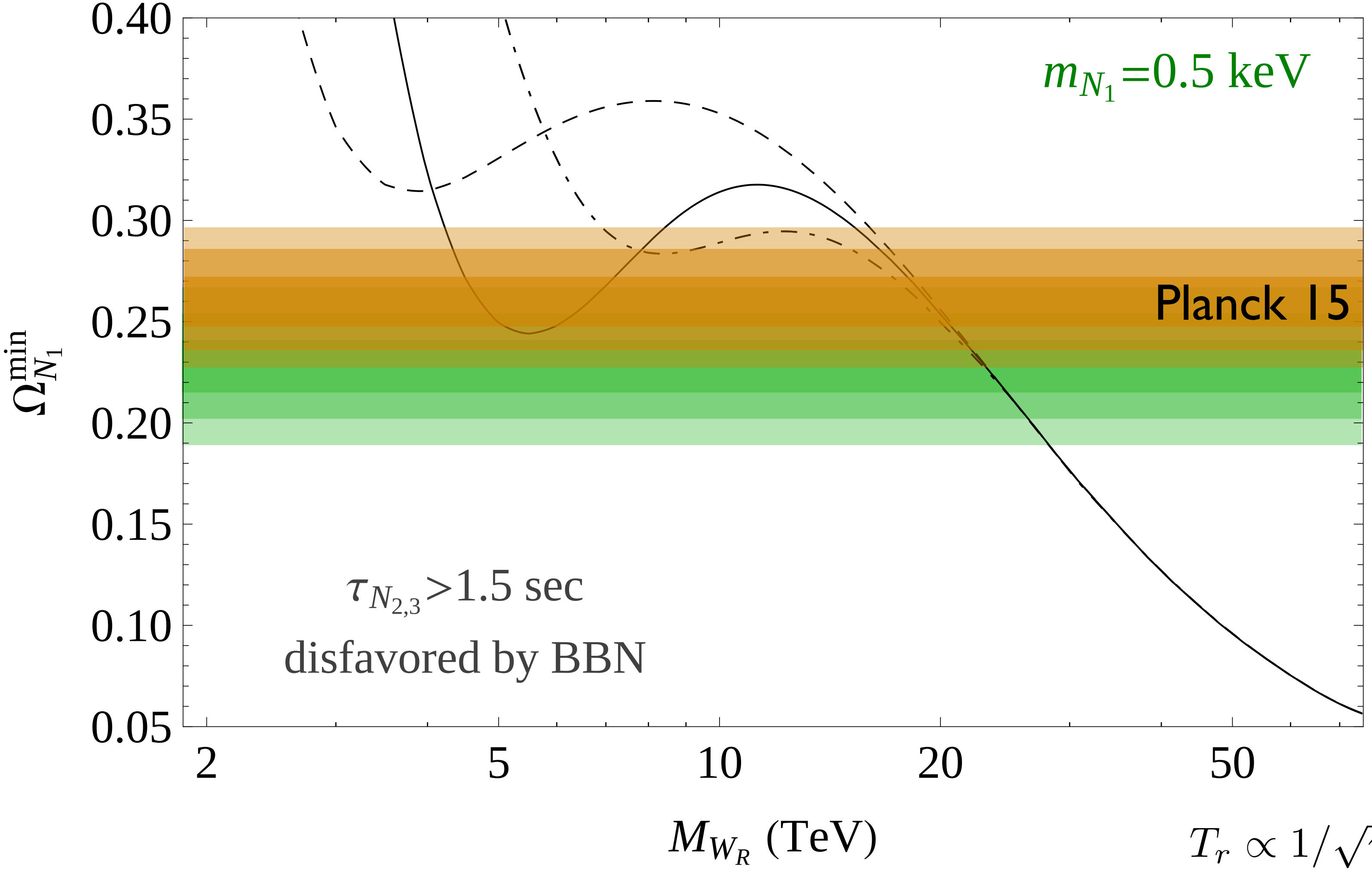
Dilution part II

$$\rho_{N_2} + \rho_{N_3} = \rho_\gamma = \frac{\pi^2}{30} g_*(T_r) T_r^4 \qquad T_r \gtrsim 0.7 \text{ MeV}$$



$$\mathcal{S} = \frac{S(t_f)}{S(t_m)} = \frac{s(t_f)}{s(t_m)} \frac{V(t_f)}{V(t_m)} = \left(\frac{\rho_\gamma(t_f)}{\rho_\gamma(t_m)}\right)^{3/4} \left(\frac{\rho_{N_1}(t_f)}{\rho_{N_1}(t_m)}\right)^{3/4}$$

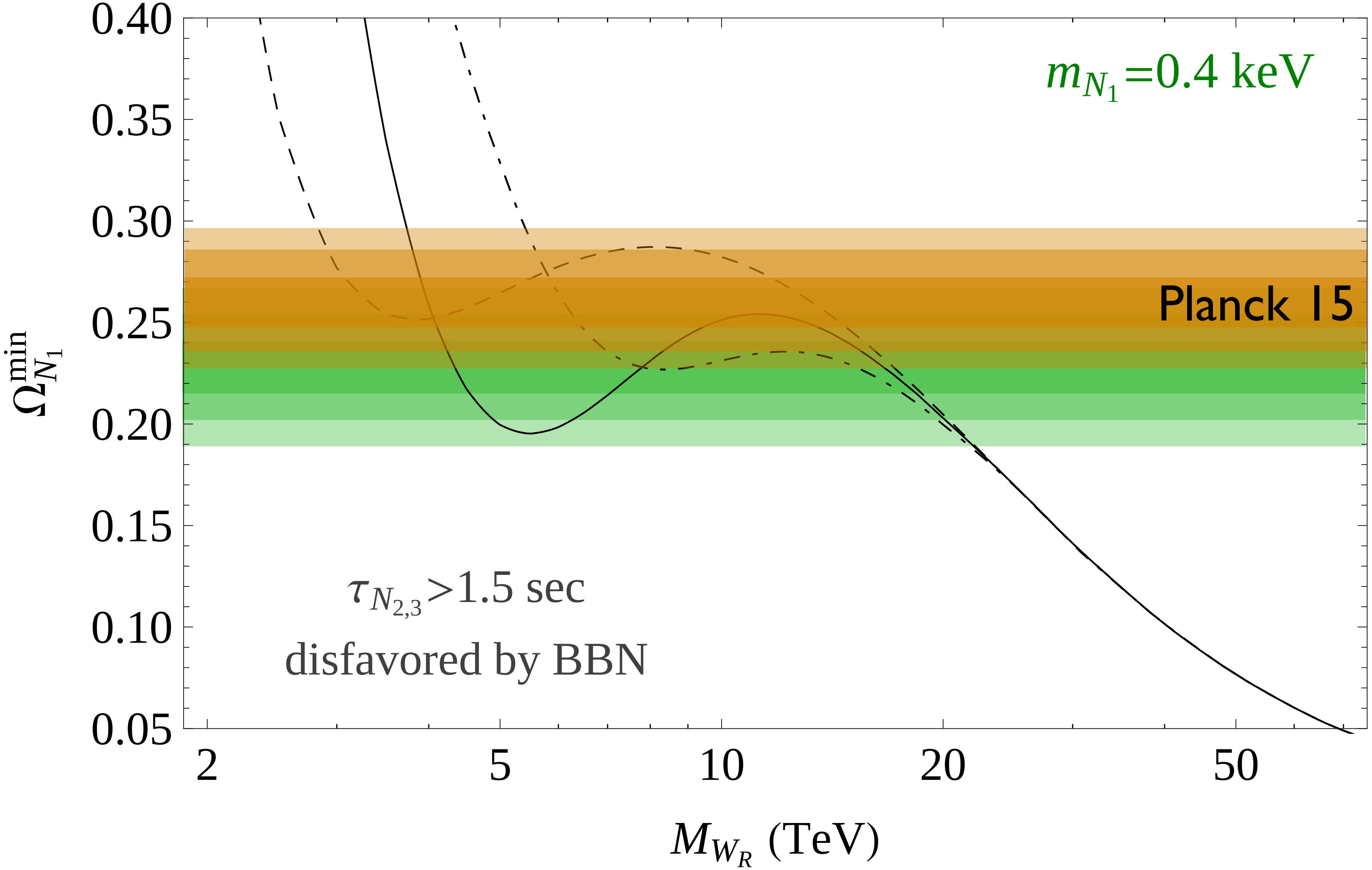
Left-Right low scale DM windows



$$T_r \propto 1/\sqrt{\tau_N}$$

$$\mathcal{S} \propto \sqrt{\tau_N}$$

Left-Right low scale DM windows



Left-Right low scale DM - further constraints

- dSPh $m_{N_1} \lesssim (0.4 - 0.5)\ \mathrm{keV}$
- diluted Ly-α $m_{N_1} \lesssim \mathcal{O}(\mathrm{keV})$
- CMB & N_{eff} repopulation
  $N_3 \to \pi^+ e^- \to e^+ e^- \nu_\mu \overline{\nu}_\mu \nu_e$
  $N_2 \to \pi^+ \mu^- \to e^+ e^- \nu_\mu \nu_\mu \overline{\nu}_\mu \nu_e \overline{\nu}_e$
  Fuller, Kishimoto, Kusenko '11
- X-ray observations $M_D\ , \xi_{LR}\ \&\ v_L$ Merle, Niro '13
- $0\nu 2\beta$ subject to uncertainties $M_{W_R} \gtrsim (5-7)\ \mathrm{TeV}$
  MN, Senjanović, Zhang '12
  Lopez-Pavon, Huang '13

Critical conclusion

pros

- RH neutrino keV DM candidate
- dilution possible in the minimal model
- window at the LHC
- X-ray limits

cons

- fairly low reheating vs. BBN and CMB
- light DM mass vs. Ly-α

Thank you

X-ray constraints

- Majorana vs. Dirac in Left-Right

MN, Senjanović, Tello '13

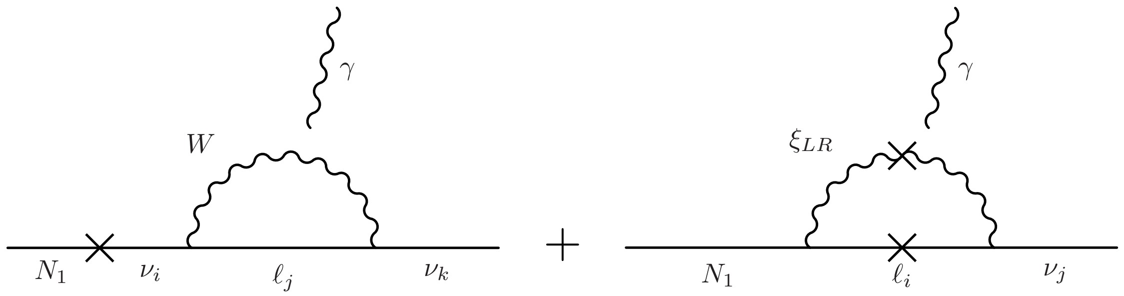
seesaw $M_\nu = -M_D^T M_N^{-1} M_D + \frac{v_L}{v_R} M_N$

parity $M_D = M_D^T$

$M_N = V_R^T m_N V_R$

$$M_D = i M_N \sqrt{M_N^{-1} M_\nu - \frac{v_L}{v_R}}$$

$\mathcal{A}_{N_1 \to \nu\gamma} =$



$$\boxed{\Gamma_{N_1 \to \nu\gamma} = \Gamma_\mu \left(\frac{m_{N_1}}{m_\mu}\right)^5 \left(\frac{\alpha}{4\pi}\right) 3 \sum_\ell \left| \theta_{LR\ell N_1} f_D + \xi_{LR} \frac{m_\ell}{m_{N_1}} f_{\xi_{LR}} \right|^2}$$

$0\nu2\beta$ constraints

$$m_{ee}^{N_3} = p^2 \left(\frac{M_W}{M_{W_R}}\right)^4 V_{Re3}^2 \frac{m_{N_3}}{p^2 + m_{N_3}^2}$$

MN, Nesti, Senjanović, Tello '11

- including the mixing

$$m_{ee}^{\nu N} = \left(\xi_{LR} + \eta \frac{M_W^2}{M_{W_R}^2}\right) p \left(M_N^{-1} M_D\right)_{ee}$$

MN, Senjanović, Tello '12

- see also

Lopez-Pavon, Huang '13
Barry, Rodejohann '13

- NME uncertainties

axial coupling

Barea, Kotila, Iachello '12, '13, '15