WARM DARK MATTER AND LOW SCALE LEFT-RIGHT SYMMETRY?

Yue Zhang,

ICTP, Trieste

Based on M. Nemevsek, G. Senjanovic, YZ, 1204.xxxx

Parity restoration and Seesaw

☐ Motivations of Left-Right Symmetric Model (LRSM).

Pati, Salam, 74′, 75′; Mohapatra, Pati, 75′; Senjanovic, Mohapatra, 75′

☐ Parity symmetry restoration at high scale.

☐ Broken spontaneously and Maximally -- break the degeneracy between left- and right-handed neutrinos -- Seesaw mechanism.

☐ Predict the Majorana nature of neutrinos -- lepton number violation processes.

☐ Nuclear physics energy scale, neutrino-less double beta decay.

Senjanovic, Mohapatra, 75′

☐ High-energy collider, like-sign di-lepton processes.

Keung, Senjanovic, 83′

Left-Right Symmetric Model

☐ Gauge symmetry:

$$\frac{SU(2)_L \times SU(2)_R \times U(1)_{B-L}}{\begin{pmatrix} u_L \\ d_L \end{pmatrix}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}}$$

☐ SM fermions form LH or RH doublets.

☐ Yukawa coupling need Higgs bi-doublet $\Phi = (H_1, H_2) \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$

$$\mathcal{L} = \bar{F}_L Y \Phi F_R + \bar{F}_L \tilde{Y} (i\sigma_2) \Phi^* (i\sigma_2) F_R \qquad (F = Q, L)$$

☐ Higgs triplet charged under B-L gauge symmetry:

- ☐ break the new gauge symmetry
- ☐ give neutrino masses

☐ Majorana-like Yukawa coupling $\mathcal{L} = Y_\Delta (L_L^T \Delta_L L_L + L_R^T \Delta_R L_R)$

Symmetry Breaking

☐ Maximal parity symmetry breaking

$$\langle \Delta_R \rangle \gg \langle \Delta_L \rangle$$

☐ Different Majorana mass for LH and RH neutrinos -- Seesaw.

☐ Interpretation of electric charge

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

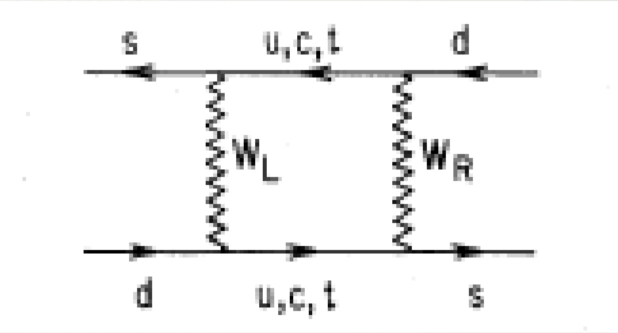
☐ New gauge boson masses relation:

$$M_{Z'} \approx \sqrt{3} M_{W_R}, \quad \text{for } g_L = g_R$$

$$\begin{tikzcd}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \arrow[d, "\langle \Delta_R \rangle"] \\
SU(2)_L \times U(1)_Y \arrow[d, "\langle \Phi \rangle"] \\
U(1)_{em}
\end{tikzcd}$$

Neutral Currents

- RH gauge interaction leads to neutral currents at one-loop level.
- A generic constraint: box diagram contribution to Kaon mixing.
  - No GIM suppression in Wilson coefficients
  - Chiral enhancement in the hadronic matrix element



$$M_{W_R} > 2.5\,\mathrm{TeV}$$

YZ, An, Ji, Mohapatra, 0704.1662, 0712.4218

- CP violation constraints could be evaded.

Maiezza, Nemevsek, Nesti, Senjanovic, 1105.5160

- Two Higgs doublets, couple to both u and d type quarks,
  - Tree-level flavor-changing neutral current -- require second Higgs doublet heavier than 10 TeV -- only one Higgs doublet near EW scale.

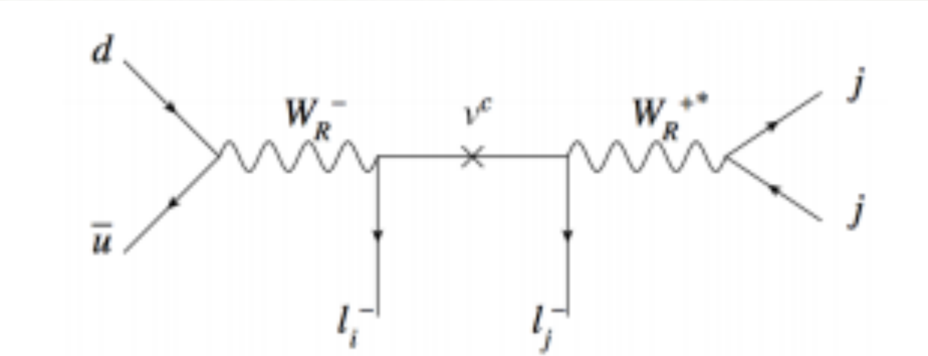
Why TeV scale?

☐ Seesaw mechanism is no better than simple Weinberg operator, if the RH neutrinos are too heavy. $(LH)^2/\Lambda$

☐ Need to correlate the seesaw scale with other phenomena.

☐ Same-sign di-lepton signal at LHC

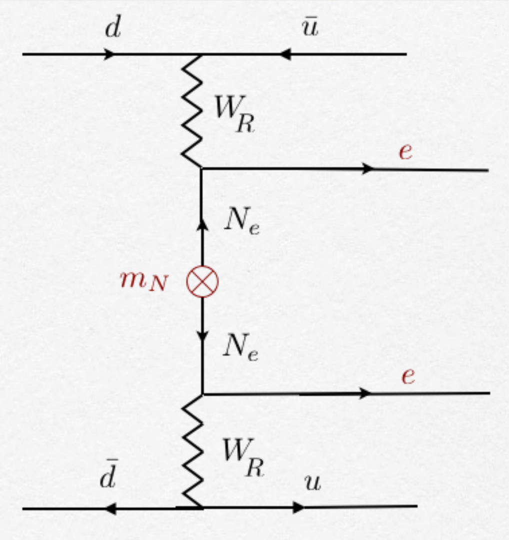
  ☐ ATLAS: $M_{W_R} > 2.5\,\mathrm{TeV}$ with $2.1\,\mathrm{fb}^{-1}$



Keung, Mohapatra, 83′

☐ Neutrino-less double beta decay

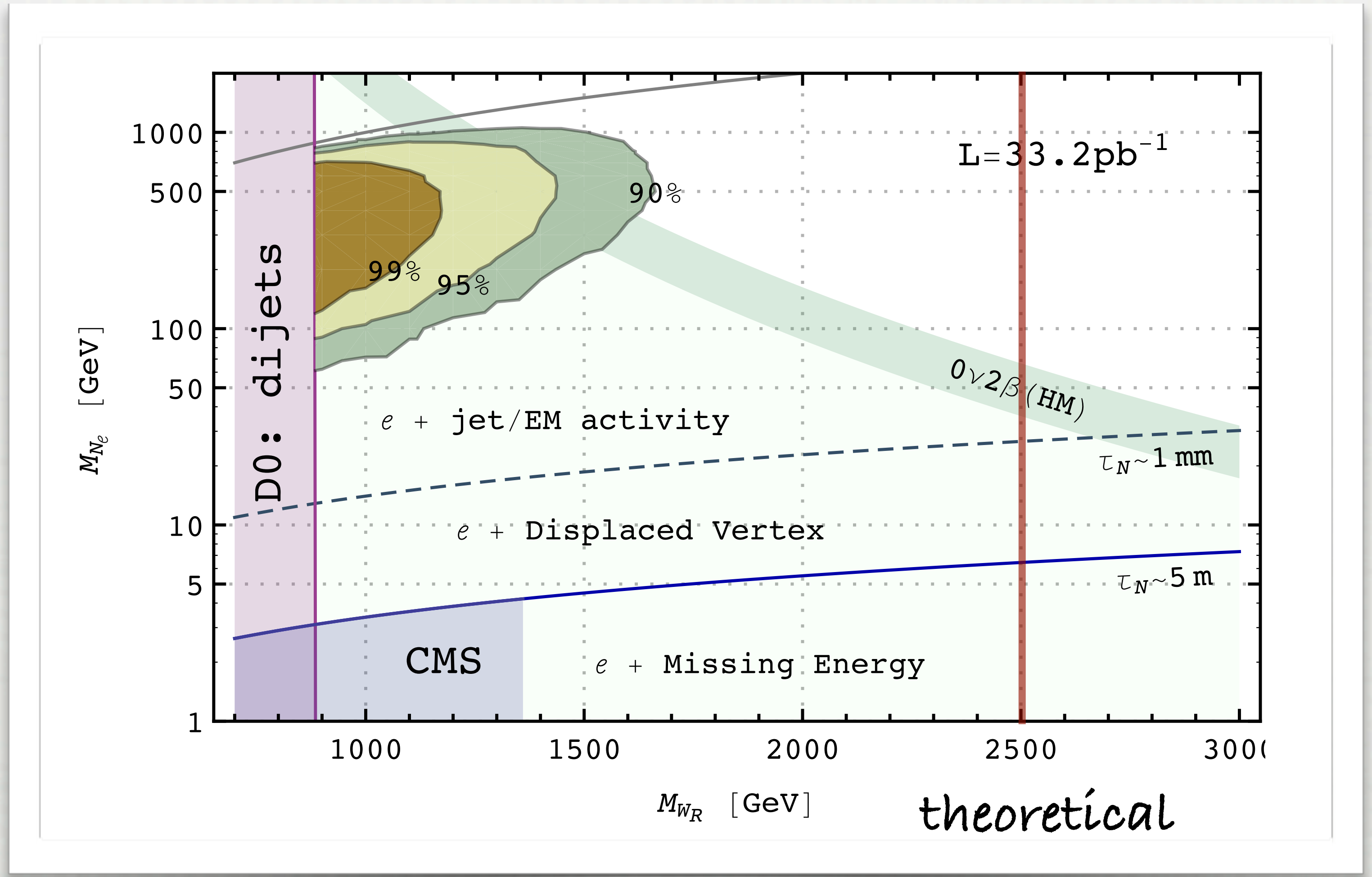
$$\mathcal{M}_{0\nu2\beta} \sim \frac{1}{M_W^4}\frac{m_\nu}{\underset{\underset{\text{100 MeV}}{\uparrow}}{p^2}} + \frac{1}{\underset{\underset{\text{TeV}}{\uparrow}}{M_{W_R}^4}}\frac{1}{\underset{\underset{\text{TeV}}{\uparrow}}{m_N}}$$



Senjanovic, Mohapatra, 75′

A summary of Limits

☐ We are therefore primarily interested in LR symmetry realized near TeV scale.



Nemevsek, Nesti, Senjanovic, YZ, 1103.1627

Updated in March 2012, stay tuned..

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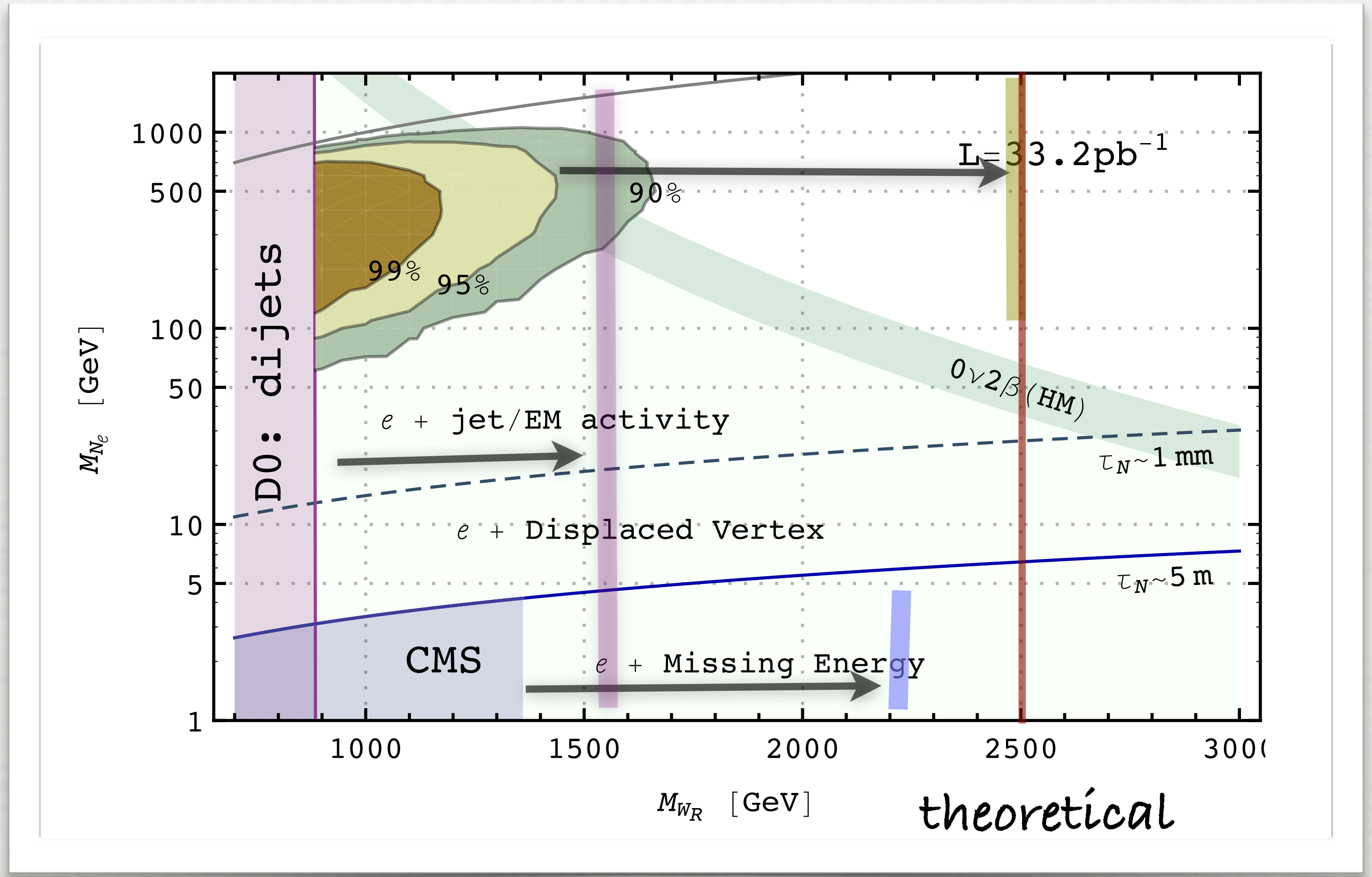


Nemevsek, Nesti, Senjanovic, YZ, 1103.1627

Updated in March 2012, stay tuned..

Dark Matter in the universe

☐ Evidences of DM: flat rotational curves, gravitional lensing, bullet cluster, large scale structure, etc.

☐ Desired Properties of DM: cosmologically stable, cold/warm, at most weakly interacting.

☐ Standard Model cannot accommodate such a candidate.

☐ Can TeV scale LRSM? -- Main motivation of this work.

☐ If there is such candidate, need to examine how it is generated in the early universe.

Dark matter candidate?

☐ In the minimal LRSM, there is no completely stable candidate.

☐ There are two types singlets under SM symmetry: right-handed (RH) neutrinos and the “Higgs” for $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ symmetry breaking.

☐ $\mathrm{Re}\Delta_R^0$ as dark matter: only compatible with high scale LR, connection to GUT?

$$\Gamma_{\Delta_R^0 \to \gamma\gamma} \simeq 10^{-50}\,\mathrm{GeV}\left(\frac{m_\Delta}{\mathrm{keV}}\right)^3 \left(\frac{1.86 \times 10^{12}\,\mathrm{GeV}}{M_{W_R}}\right)^2$$

☐ RH neutrino could be a viable candidate, which we will focus on below.

☐ SM + 3 RH neutrino WDM scenario has been widely studied.

Dodelson, Widrow, 93′; Abazajian, Fuller, Tucker, 01′;Asaka, Blanchet, Shaposhnikov, 05′; Asaka, Kusenko, Shaposhnikov, 06′; Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, 05′; Seljak, Makarov, McDonald, Trac, 06;

Stability of RH neutrino

- There is no Z_2 symmetry, broken by
  - RH charge-current interactions
  - Yukawa couplings -- can be made small.
- For low scale M_{W_R}, close to the current lower limit, a few TeV, freeze out temperature T_f ~ a few hundred MeV.
- Usual WIMP picture does not work, $m_{\rm WIMP} \simeq 20\,T_f$ -- a RH neutrino heavier than GeV decays too fast due to RH gauge interaction.
- To be cosmologically stable, a RH neutrino (N_1) must satisfy

$$m_{N_1} \ll 100\,\mathrm{MeV}$$

Thermal (over) production

- Gauge interactions in LRSM can keep RH neutrinos in thermal equilibrium, decouple like SM neutrinos.

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

- Certainly over-produced if as populated as SM neutrinos,

Olive, Turner, 82′

- Cosmological lower bound on DM mass, 0.1-1 KeV -- still over-close the universe.

$$\Omega_{N_1} \simeq 3.3 \times \left(\frac{m_{N_1}}{1\,\mathrm{keV}}\right)\left(\frac{70}{g_*(T_{f1})}\right)$$

- WMAP fit at 3-sigma: $\Omega_{\mathrm{DM}} = 0.228 \pm 0.039$ Need to dilute by factor of $12.5 \times (m_{N_1}/1\,\mathrm{keV})$
- Bottom line: point to keV-scale dark matter -- Warm.

Entropy production & Dilution

- How to dilute? Produce more photons/neutrinos but not DM after freeze out -- “heavy” particle decay.

Scherrer, Turner, 85′

- If some particle FO when relativistic $Y_N \simeq \frac{135\,\zeta(3)}{4\pi^4\, g_*(T_f)}$ and later become heavy, and dominates the universe over a period.
- Dilution factor S: $\mathcal{S} \simeq 1.8\,(g_*(T_r))^{1/4}\,\frac{Y_{N_2} m_{N_2}}{\sqrt{\Gamma_{N_2} M_\mathrm{p}}}$
- The other RH neutrino N_2 can be such a candidate.
  - naively the heavier and more long-lived the better.
- BBN constraints lifetime less than around 1 second, or “reheating” temperature $T_r \gtrsim 1\,\mathrm{MeV}$

$$T_r \simeq 0.78(g_*(T_r))^{-1/4}\sqrt{\Gamma_{N_2} M_\mathrm{p}} \simeq 1.22\,\mathrm{MeV}\left(\frac{1\,\mathrm{sec}}{\tau_{N_2}}\right)^{1/2}$$

Constraints in LRSM

- The constraint from LRSM: RH neutrinos share common gauge interactions, freeze out at similar temperatures
- The diluter N_2 must be also relativistic during FO, otherwise its number density gets Boltzmann suppressed.
- After dilution, relic density of (N_1) DM candidate

$$\hat{\Omega}_{N_1} \simeq (0.228 + 0.039) \times \left(\frac{m_{N_1}}{1\,\mathrm{keV}}\right)\left(\frac{1.85\,\mathrm{GeV}}{m_{N_2}}\right)\left(\frac{1\,\mathrm{sec}}{\tau_{N_2}}\right)^{1/2}\left(\frac{g_*(T_{f2})}{g_*(T_{f1})}\right)$$

- Questions need to answer:
  - Options: stick to heavy (>2GeV) N_2 or find large difference in $g_*(T_{f1,2})$?
  - Can N_2 with such mass be long-lived enough (lifetime~one second)

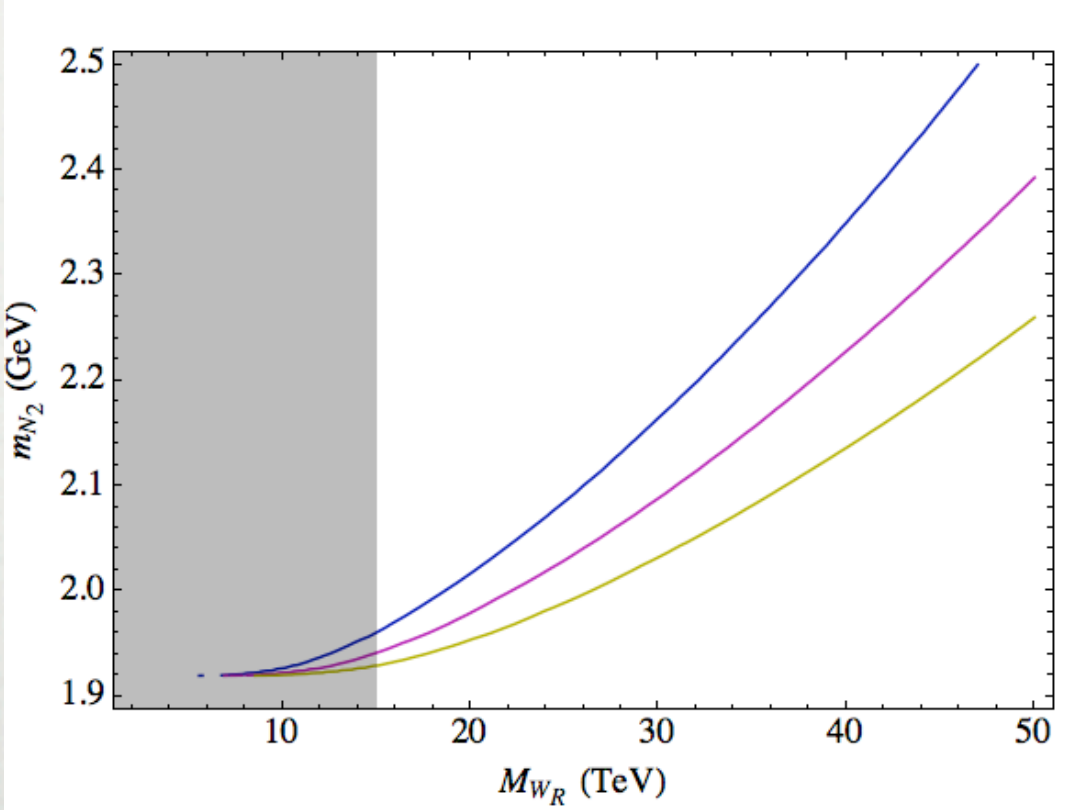
Late decay

- Decay channels: If enough heavy $N_2 \to \ell jj,\ \ell\ell' N_1$
- If close to the threshold, phase space suppression $N_2 \to \ell\pi$
- Light W_R possible if pionic decay channel dominates.
- If N_2 couples only to τ, and lives right above threshold $\tau + \pi$, two main decay channels:

$$N_2 \to \tau^{\pm}\pi^{\mp}$$

$$N_2 \to \tau^{\pm}\mu^{\mp}N_1$$

- Possibly appreciable branching ratio to N_1.



Two drawbacks for $m_{N_2} > \mathrm{GeV}$

- Consider the free-streaming length of N_1

$$\lambda_{fs} = R_0 \int_{1\,\mathrm{sec}}^{t_{eq}} dt' \frac{v(t')}{R(t')} \simeq 1\,\mathrm{Mpc} \frac{\langle p_{N_1} \rangle}{\langle p_\nu \rangle} \left(\frac{\mathrm{keV}}{m_{N_1}} \right) \mathcal{S}^{-1/3}$$

  - Large scale structure: cannot suppress too much structures > Mpc.
  - For N_1 from N_2 decay, average momentum >> MeV: $\langle p_{N_1} \rangle \gg \langle p_\nu \rangle$
  - With appreciable BR: erase too much structures unless N_1 is heavier than keV, which is a disaster for relic density.

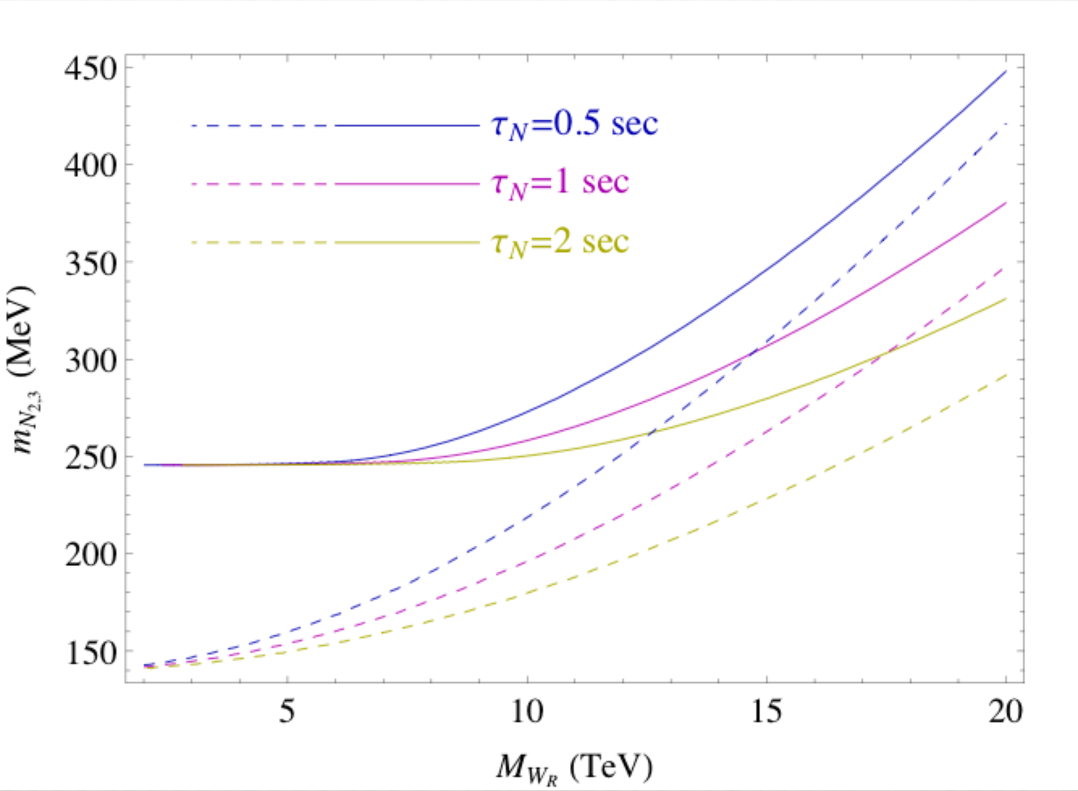
- For $m_{N_2} \approx 2\,\mathrm{GeV}$, freeze out when relativistic implies $M_{W_R} > 15\,\mathrm{TeV}$

Bezrukov, Hettmansperger, Lindner, 0912.4415

  - Disfavored by our motivation to have low scale LR symmetry.

Flavor Structure & spectrum

- Must couple N_1 to τ lepton, structure formation safe, light W_R.
- Have to shift N_2 mass to the next threshold, $\mu^{\pm} + \pi^{\mp}$, much lighter, 250-300 MeV.
- N_2 decaying into $\tau + \mu + N_1$ is kinematically forbidden.
- Notice for $M_{W_R} \lesssim 5 - 6\,\mathrm{TeV}$, the decay momentum is less than 5 MeV.



Can still dilute enough?

- Yes, when both below are satisfied:
  - If N_3 also dilutes, sits at electron+pion threshold. Fix the spectrum.
  - If there is large enough different between g*: $g_*(T_{f2}) \ll g_*(T_{f1})$

$$\boxed{\hat{\Omega}_{N_1} \simeq (0.228 + 0.039) \times \left(\frac{m_{N_1}}{1\,\mathrm{keV}}\right)\left(\frac{1.85\,\mathrm{GeV}}{m_{N_2}}\right)\left(\frac{1\,\mathrm{sec}}{\tau_{N_2}}\right)^{1/2}\left(\frac{g_*(T_{f2})}{g_*(T_{f1})}\right)}$$

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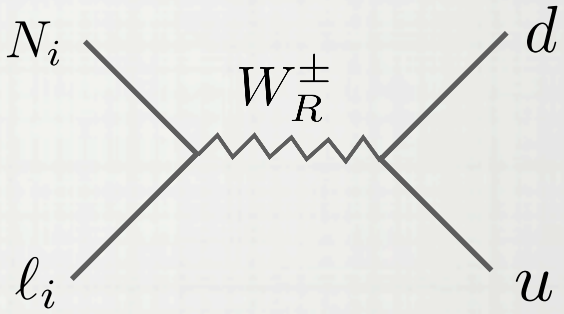
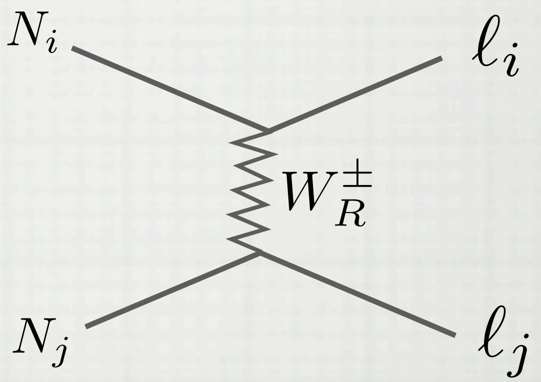
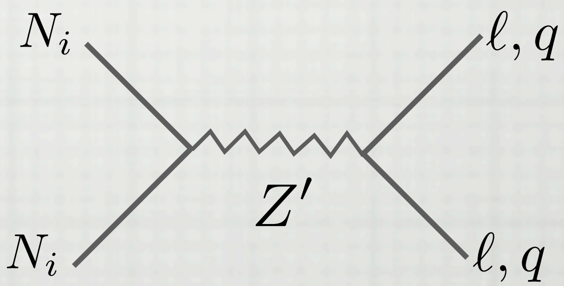
Annihilations during FO

- Major annihilation channels of RH neutrinos.
  - Dominant: single-N annihilation via W_R
  - Subdominant: pair annihilation via W_R and Z'
- Difference from SM neutrino decoupling, quarks/pions still present -- color factor.
- For freeze out temperature below 500 MeV, there is no τ lepton in the plasma (heavy).
- Lack of charge-current interaction, N_1 could freeze out earlier than $N_{2,3}$







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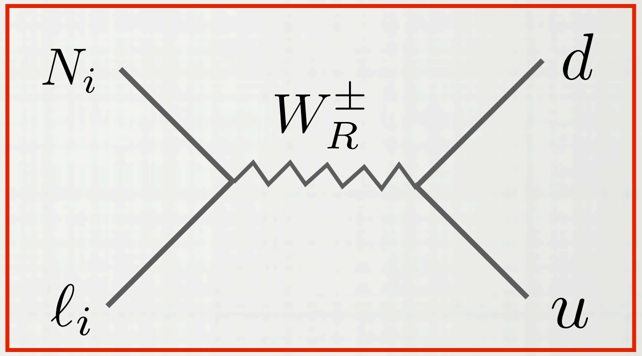
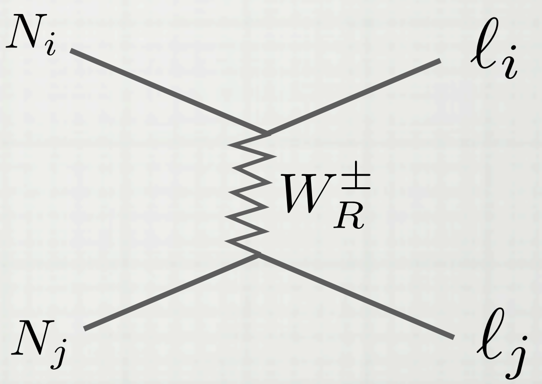
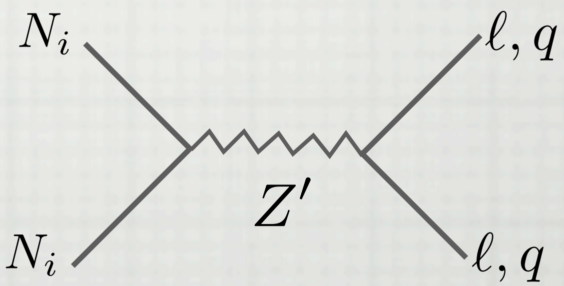
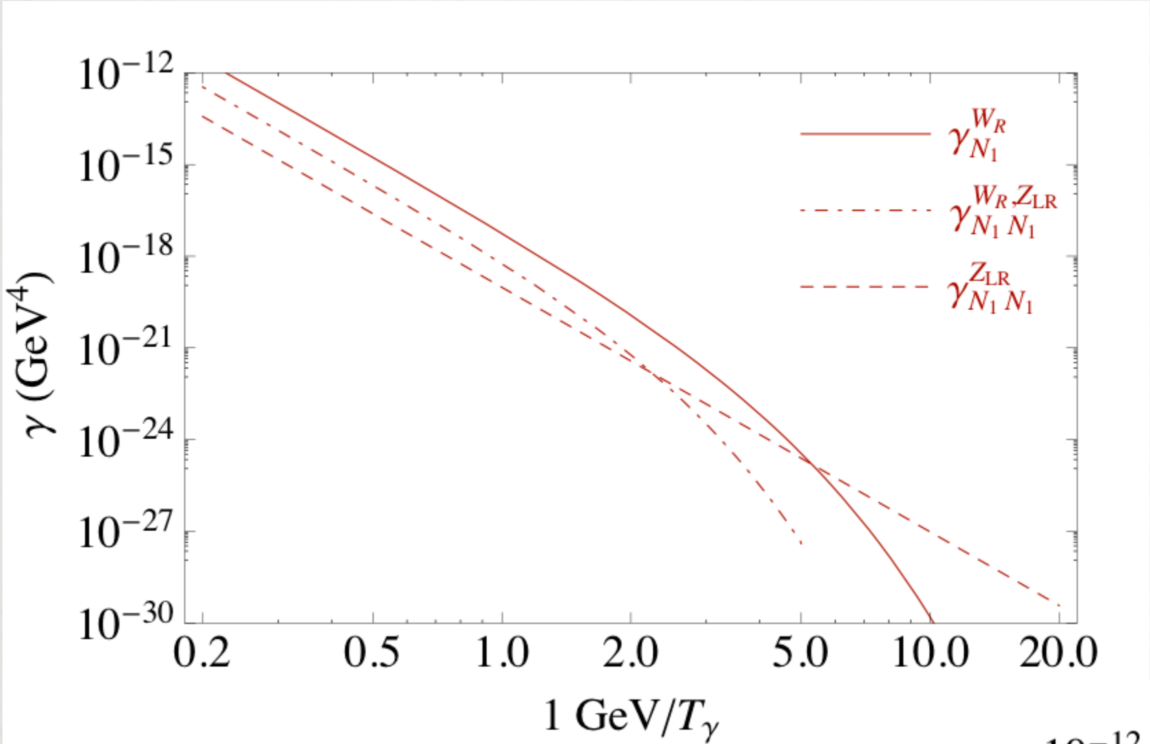
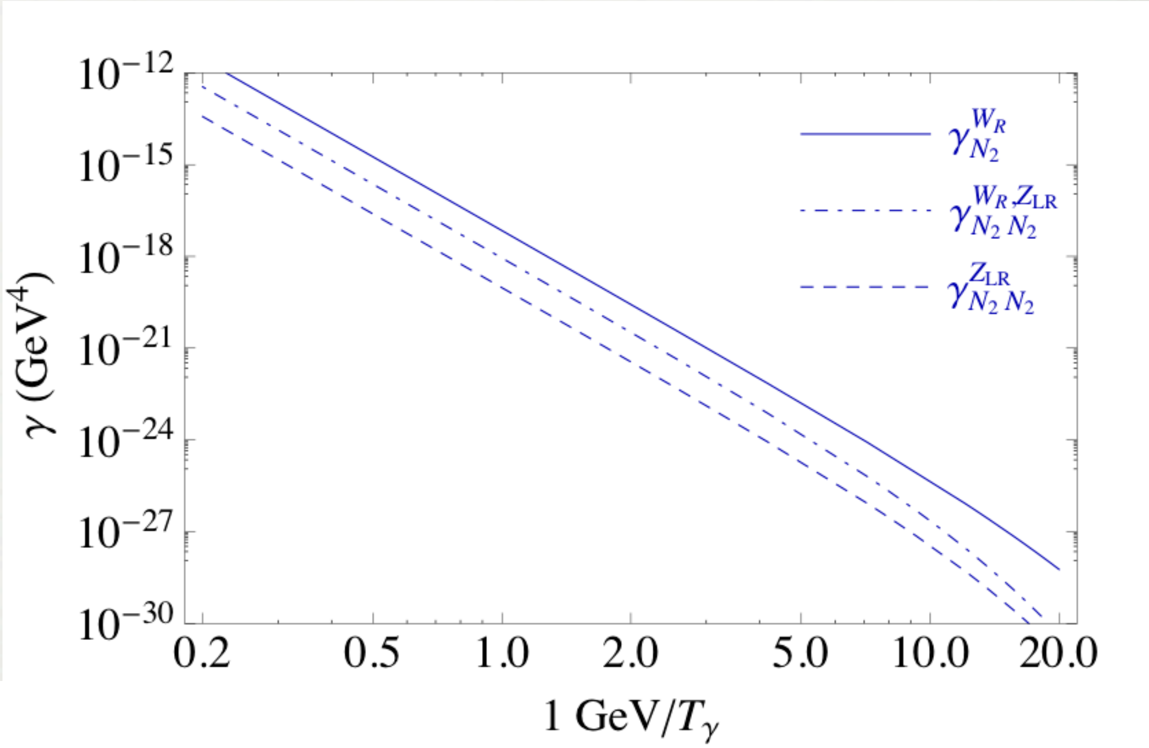






Reaction rates





- ☐ Interactions of N_1 are suppressed when τ becomes heavy.

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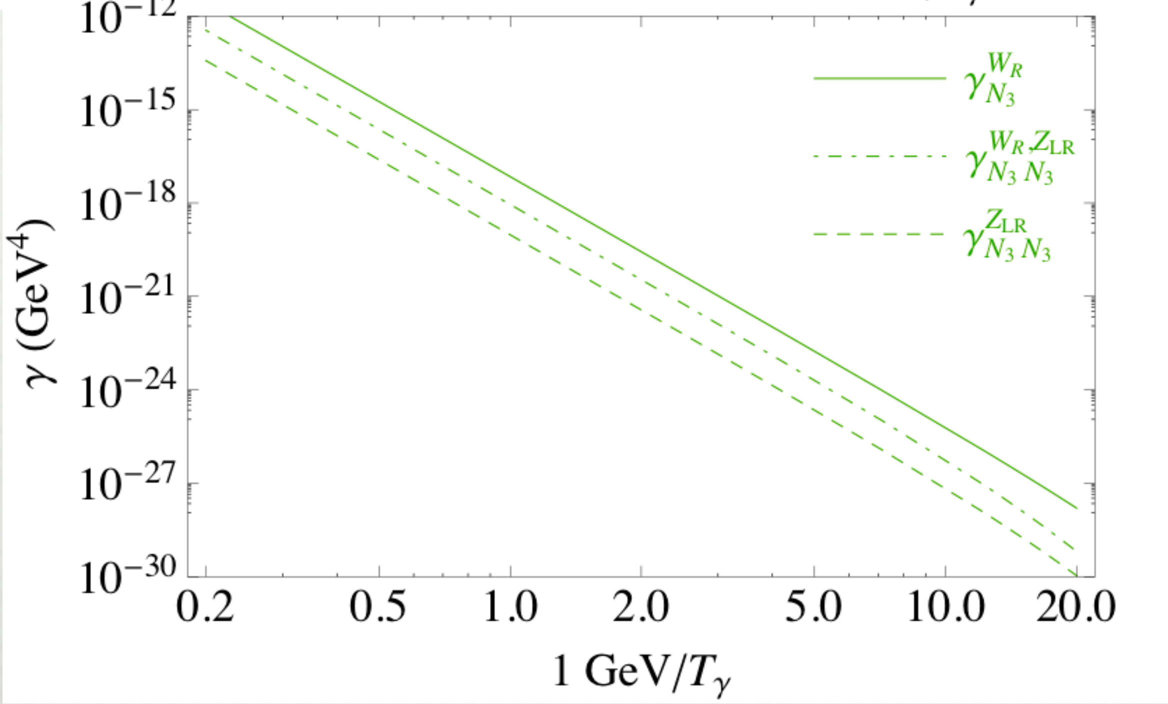
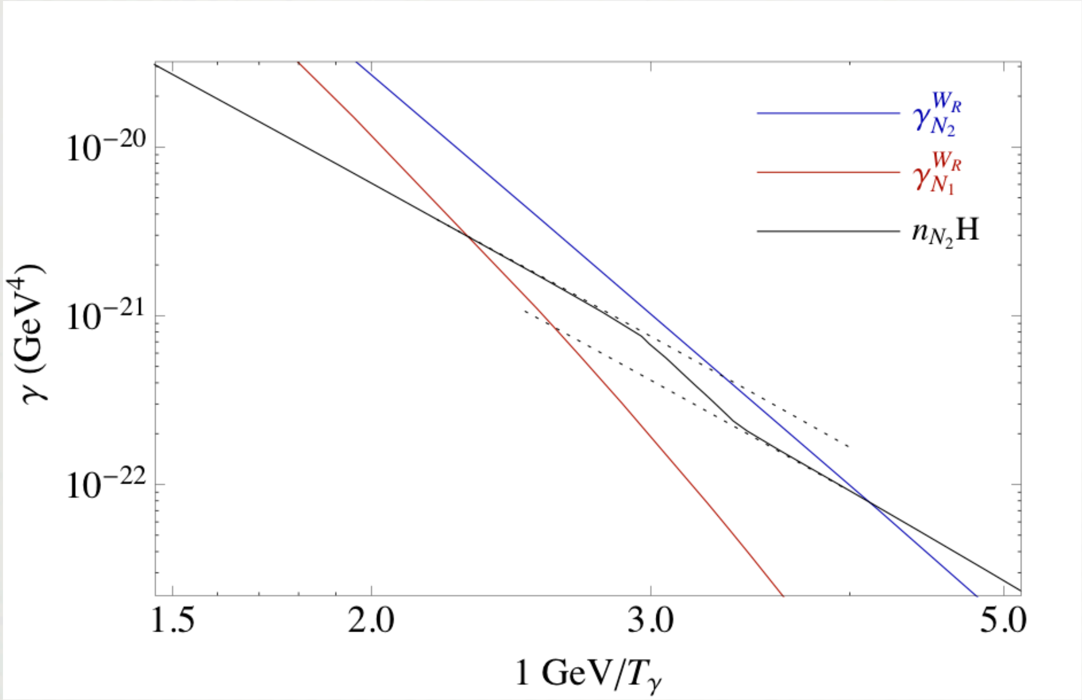


g* in QCD Phase Transition



- Freeze out temperature different at most 200 MeV.
- Number of degree of freedom g* changes dramatically during QCD phase transition.

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- Large difference in g*: N_1 FO before and N_2 after the transition.

$$\hat{\Omega}_{N_1} \simeq (0.228+0.039) \times \left(\frac{m_{N_1}}{1\,\mathrm{keV}}\right)\left(\frac{1.85\,\mathrm{GeV}}{m_{N_2}}\right)\left(\frac{1\,\mathrm{sec}}{\tau_{N_2}}\right)^{1/2}\left(\frac{g_*(T_{f2})}{g_*(T_{f1})}\right)$$

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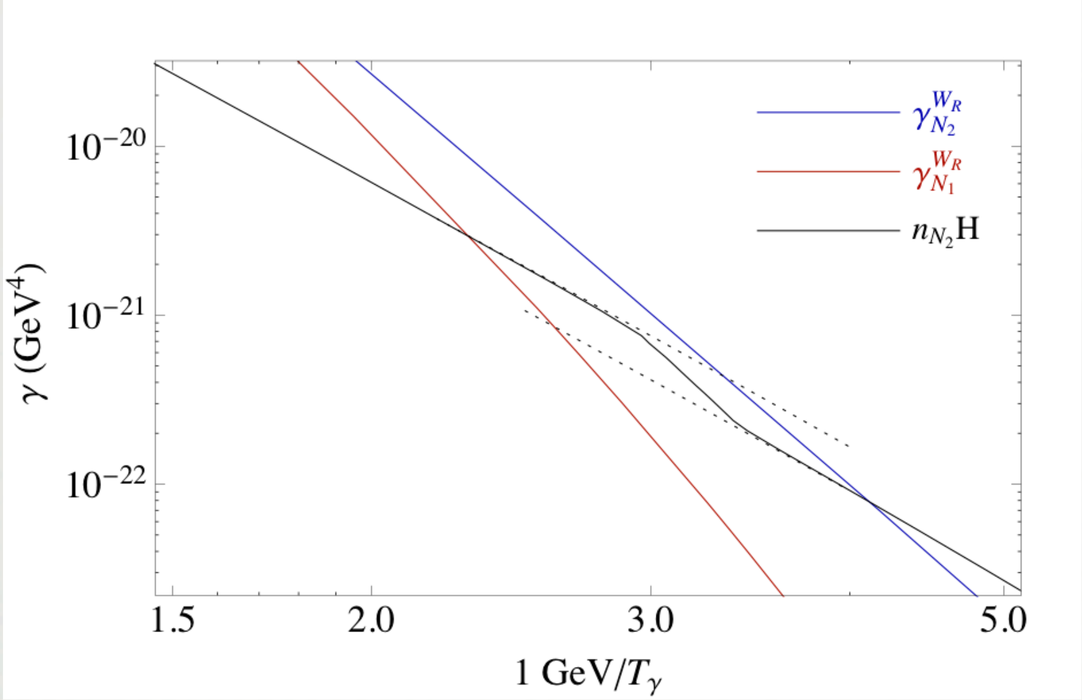

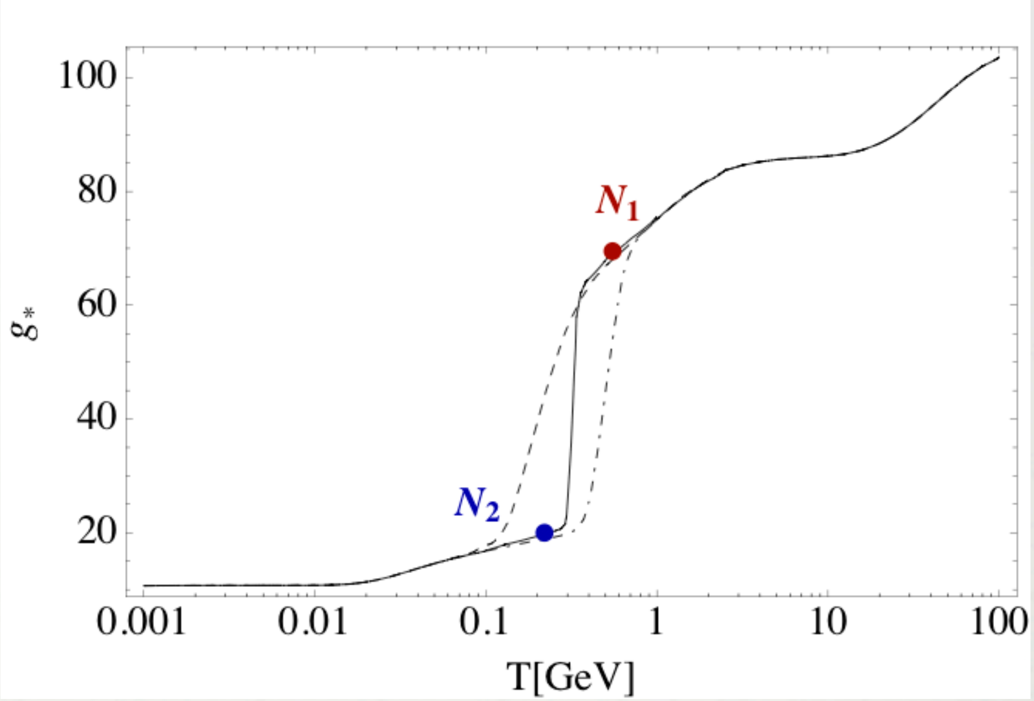

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Late Decay Boltzmann Equations

- Assume the decay products quickly thermalize.
- Energy release from decay completely transfer into heat

$$dS = dQ/T = \Gamma\,\rho\,dt/T$$

- No entropy produced into N_1. Dilution factor can be calculated

$$\mathcal{S} = \frac{s(t_\mathrm{f})}{s(t_\mathrm{m})}\frac{V(t_\mathrm{f})}{V(t_\mathrm{m})} = \left[\frac{\rho_R(t_\mathrm{f})}{\rho_R(t_\mathrm{m})}\right]^{3/4}\left[\frac{\rho_{N_1}(t_\mathrm{f})}{\rho_{N_1}(t_\mathrm{m})}\right]^{3/4}$$

- “Reheat” temperature can be inferred from later energy density of radiation (R).

Late Decay Boltzmann Equations

$$\begin{aligned}
\frac{d\rho_R}{dt} + 4H\rho_R &= \Gamma_2\rho_2 + \Gamma_3\rho_3 \ , \\
\frac{d\rho_{N_1}}{dt} + 4H\rho_{N_1} &= 0 \ , \\
\frac{d\rho_{N_2}}{dt} + 3H\rho_{N_2} &= -\Gamma_2\rho_2 \ , \\
\frac{d\rho_{N_3}}{dt} + 3H\rho_{N_3} &= -\Gamma_3\rho_3
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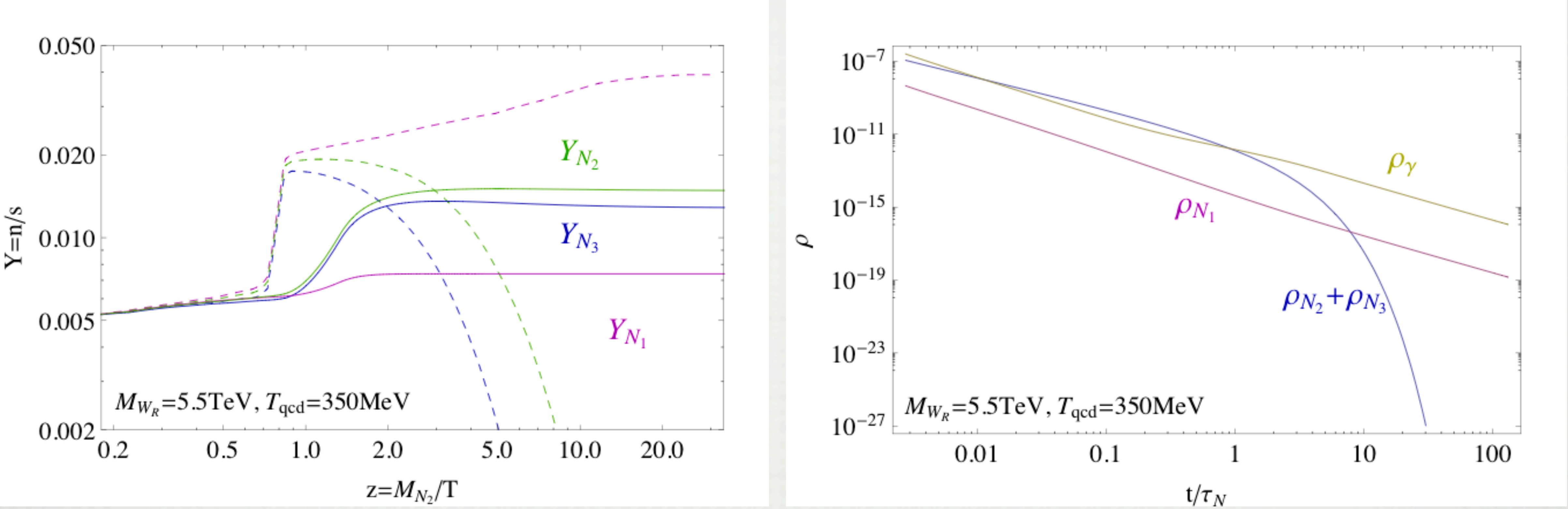
A sample point and solution



☐ Fix the flavor structure $V_{\tau 1} = V_{\mu 2} = V_{e3} = 1$ fix the masses so that $\tau_{N_2} = \tau_{N_3} = 1.5\,\mathrm{sec}$

☐ Match the solution to Boltzmann Eqns for FO and late decay

☐ Obtain: $\mathcal{S} = 7.2$ and $T_r = 0.7\,\mathrm{MeV}$

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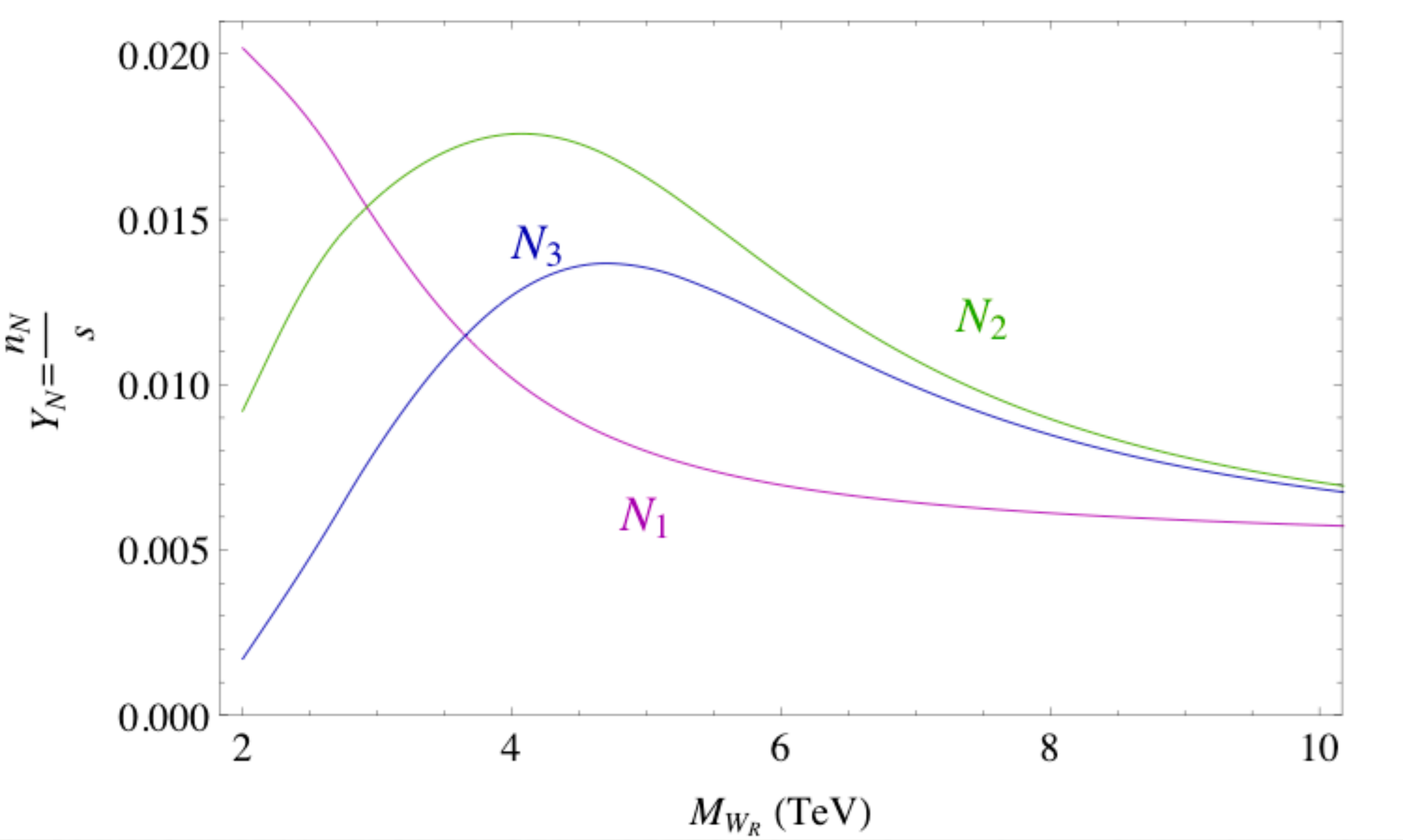
Yields of DM versus Diluter



- ☐ Light W_R enhancement: freeze out after QCD transition.
- ☐ Very light W_R suppression for $N_{2,3}$: Boltzmann suppression.

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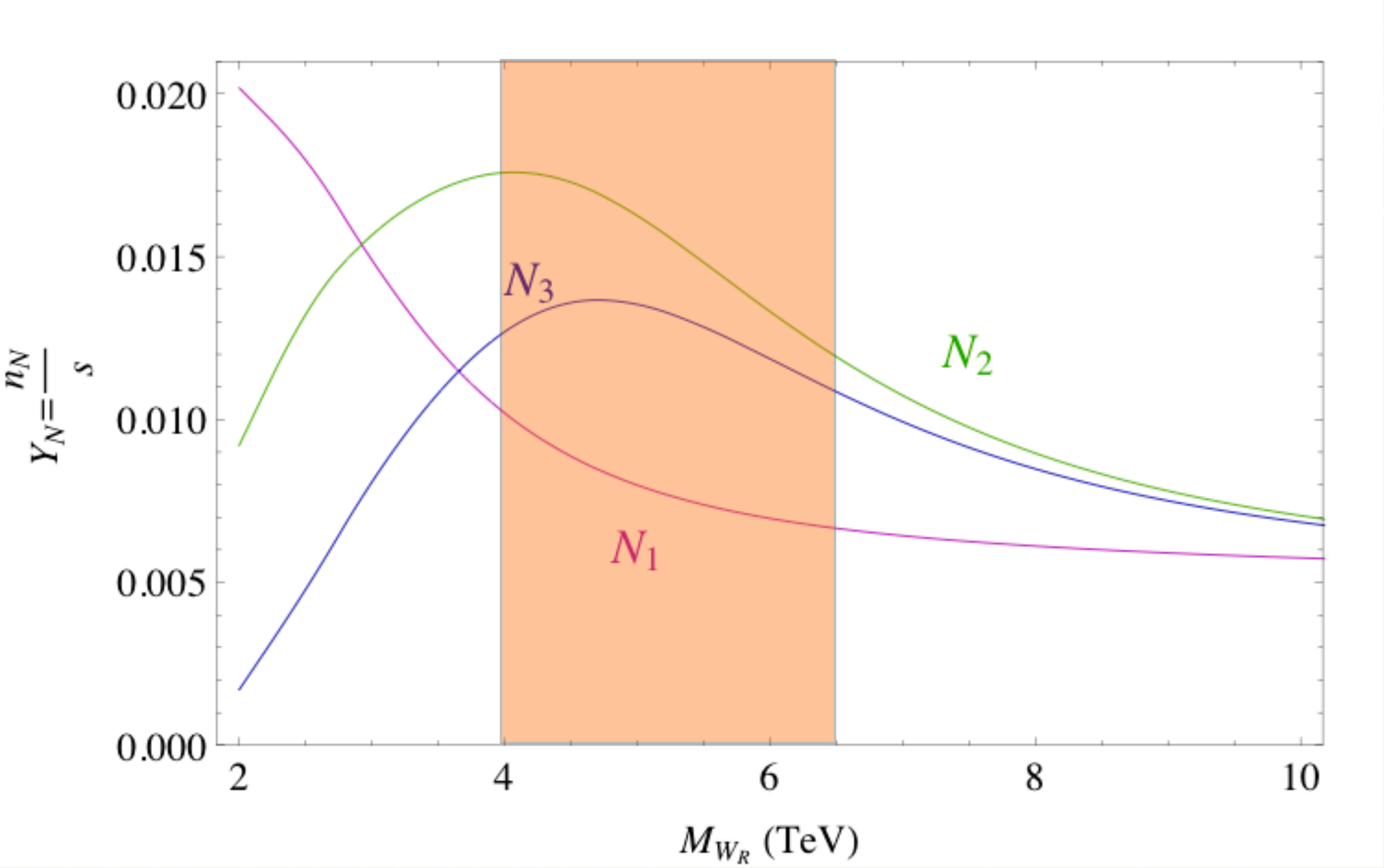

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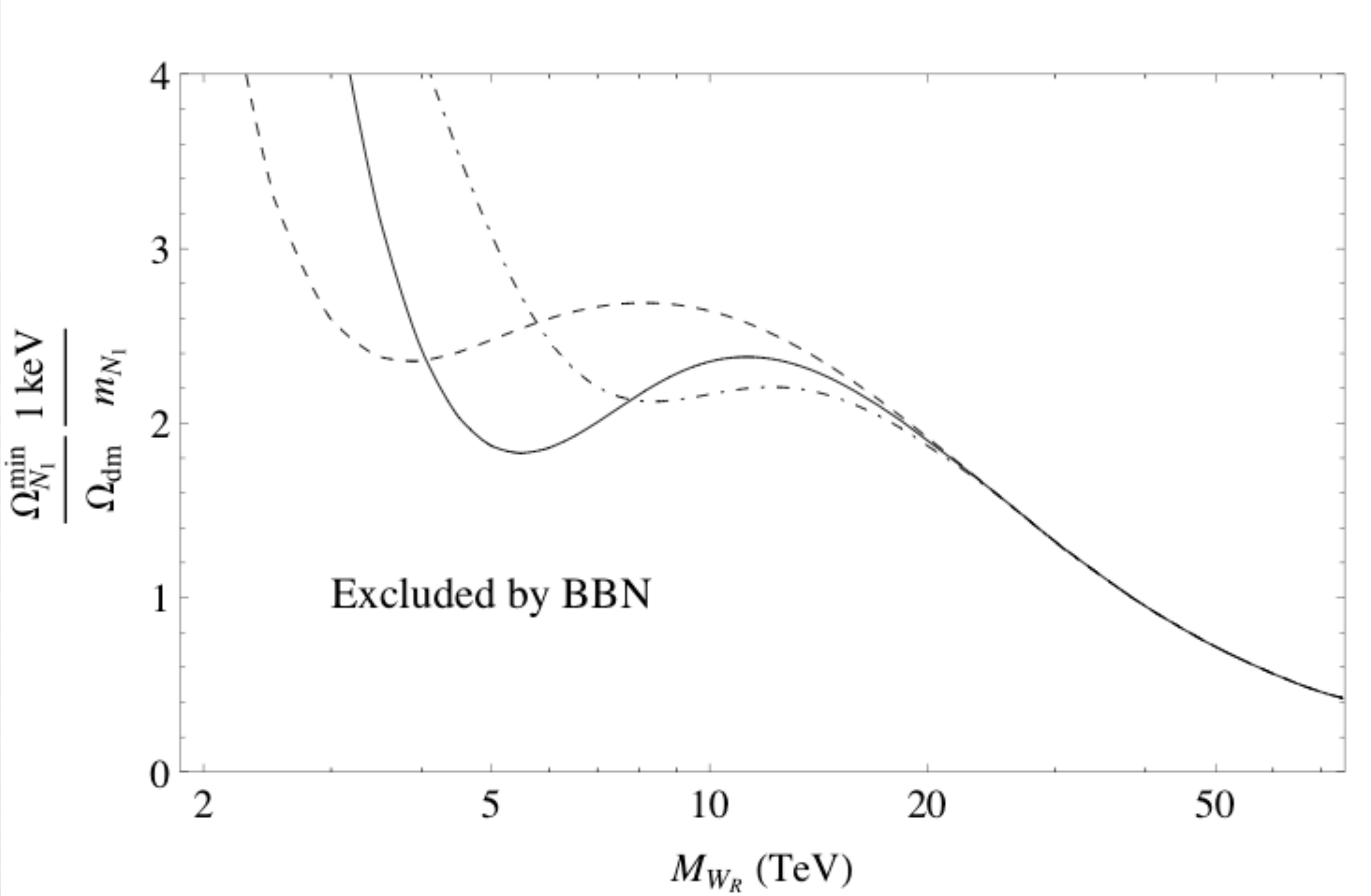
A TeV scale Window



- The tilde in the lower bound curves reflect QCD transition impact.
- If N_1 mass 0.5 keV, there is a light W_R window between 4-7 TeV.

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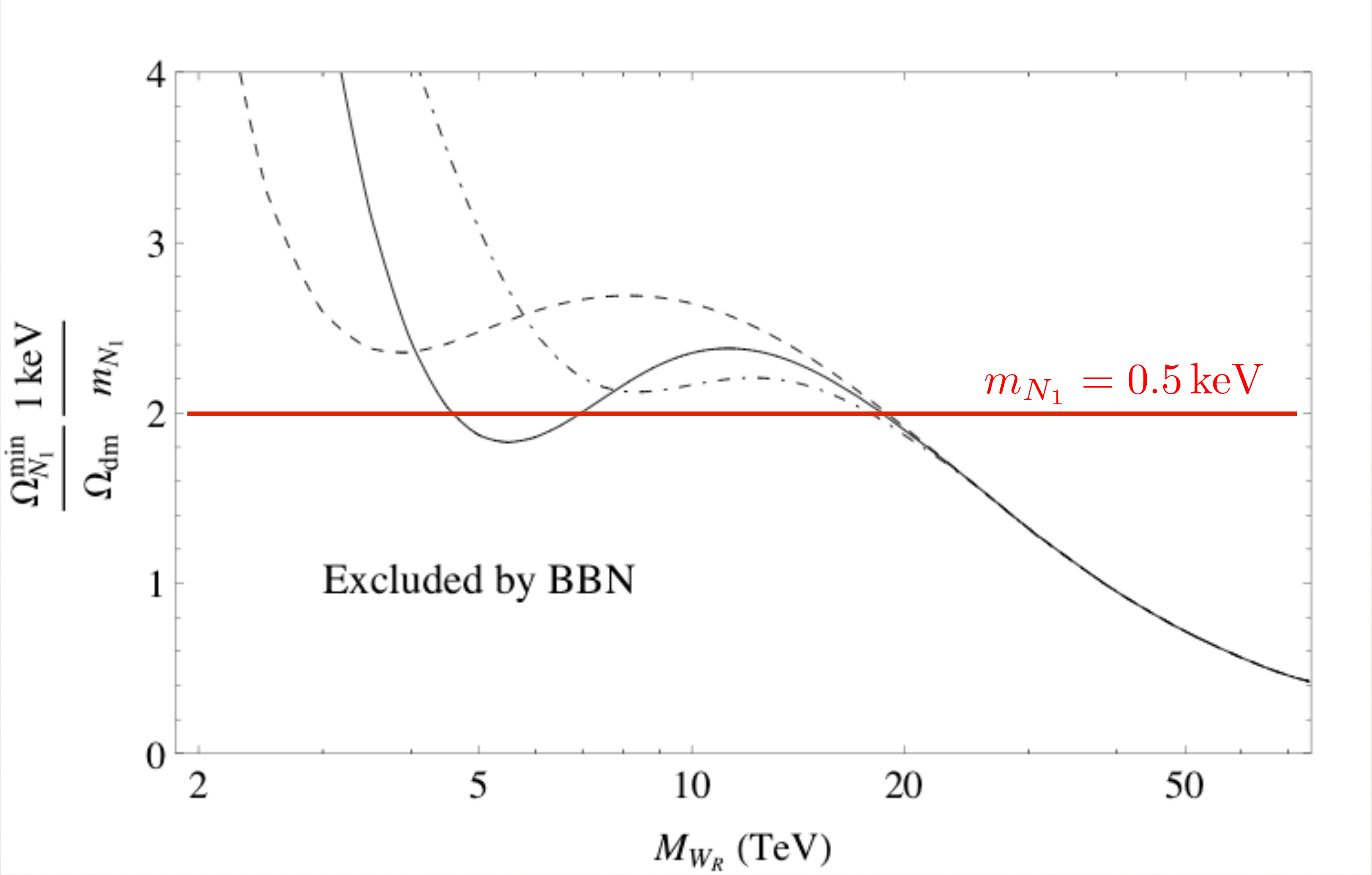

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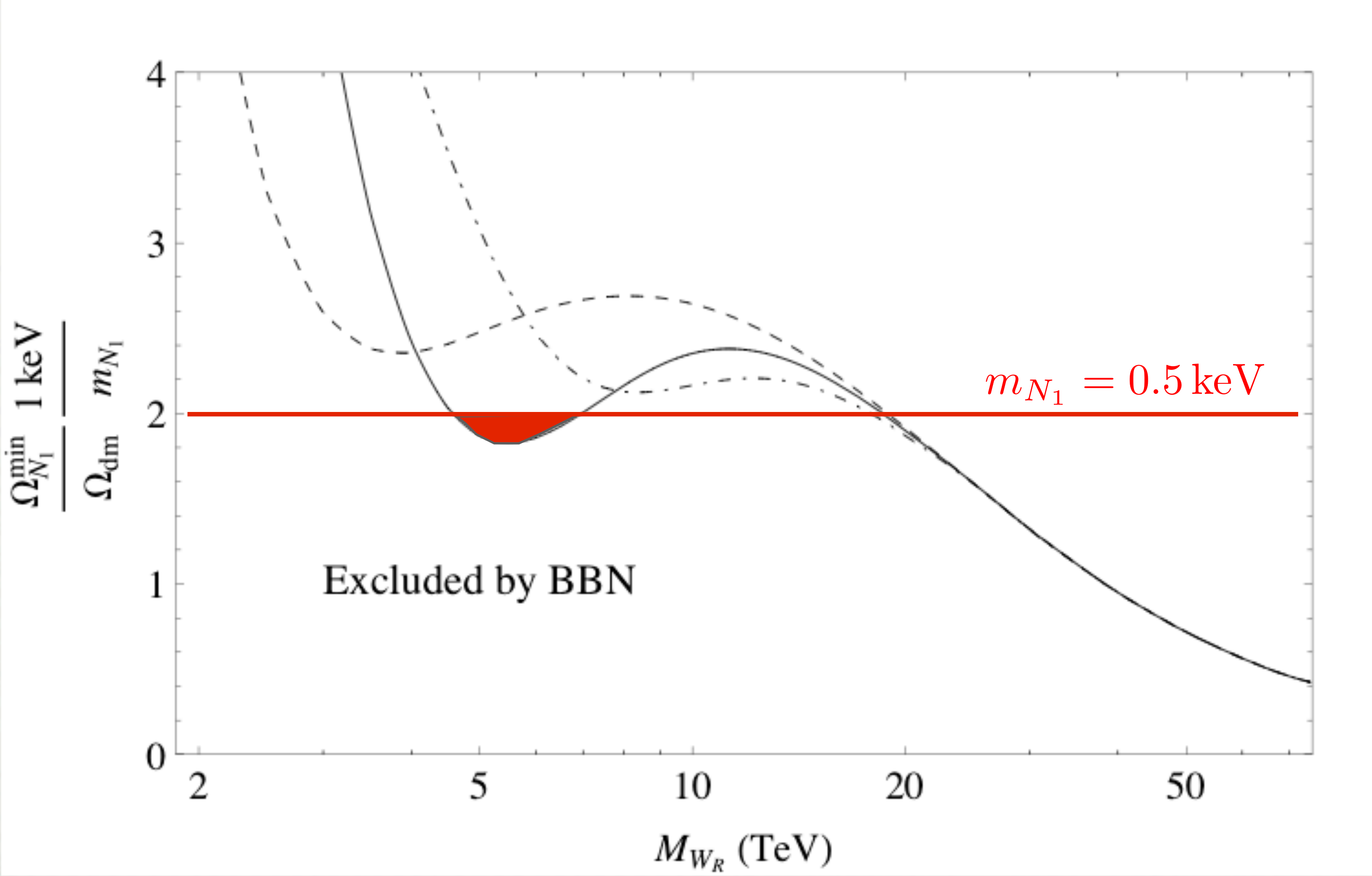

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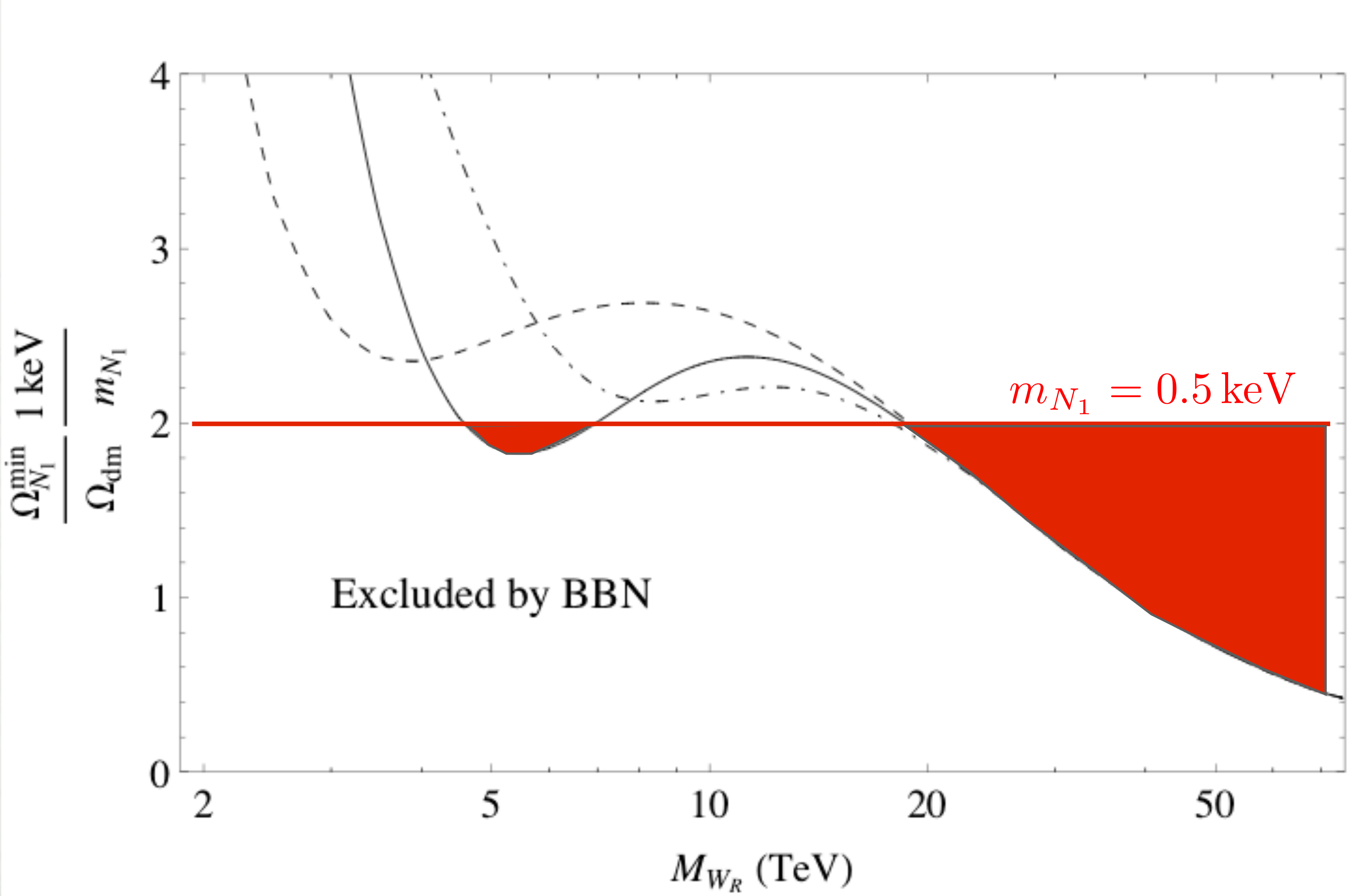

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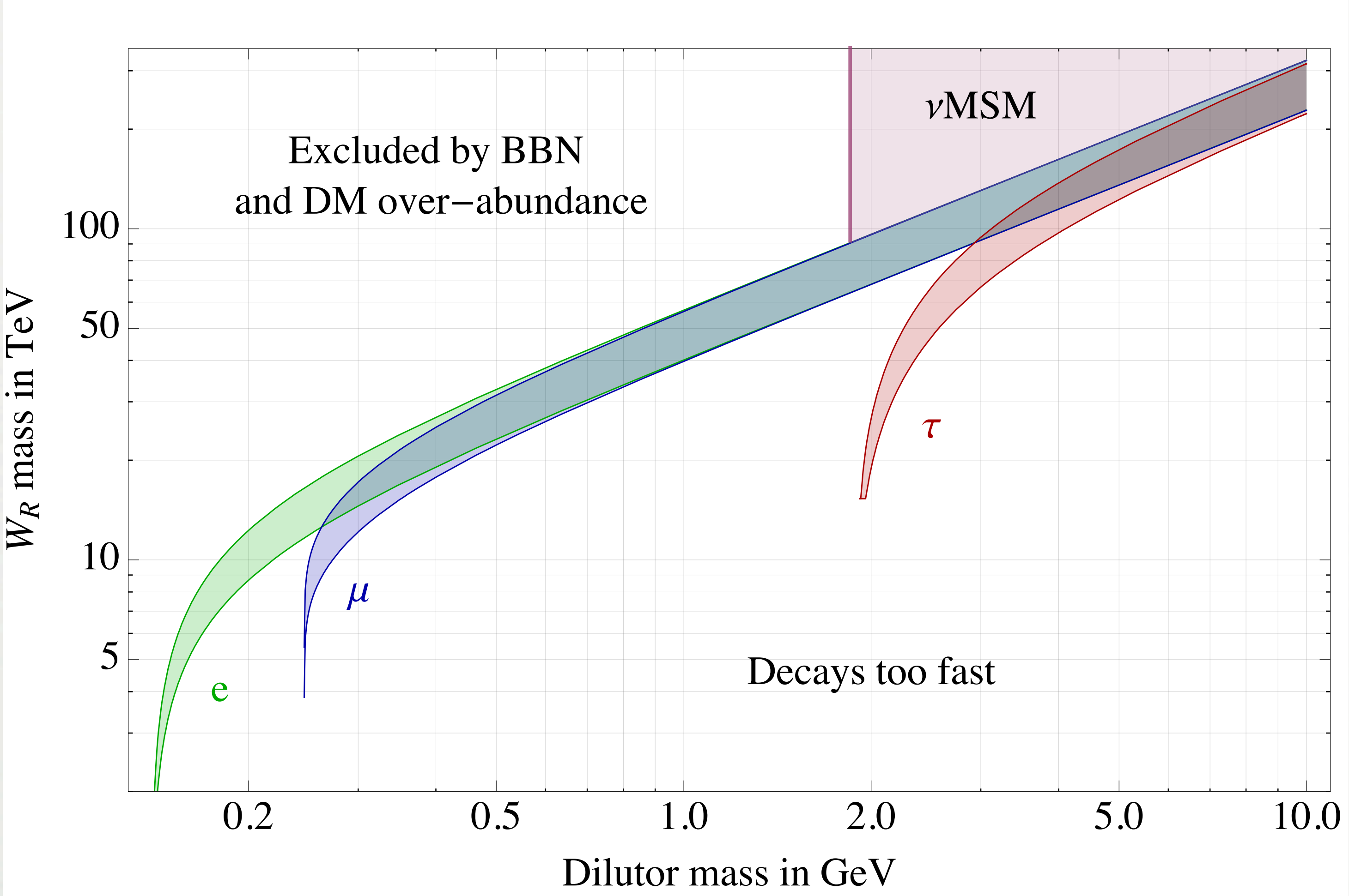
A global picture



- ☐ Major parameters relevant to our picture: DM mass m_{N_1}, lifetime of diluter $\tau_{N_{2,3}}$, scale of LR symmetry M_{W_R} .
- ☐ Next survey a list of constraints.

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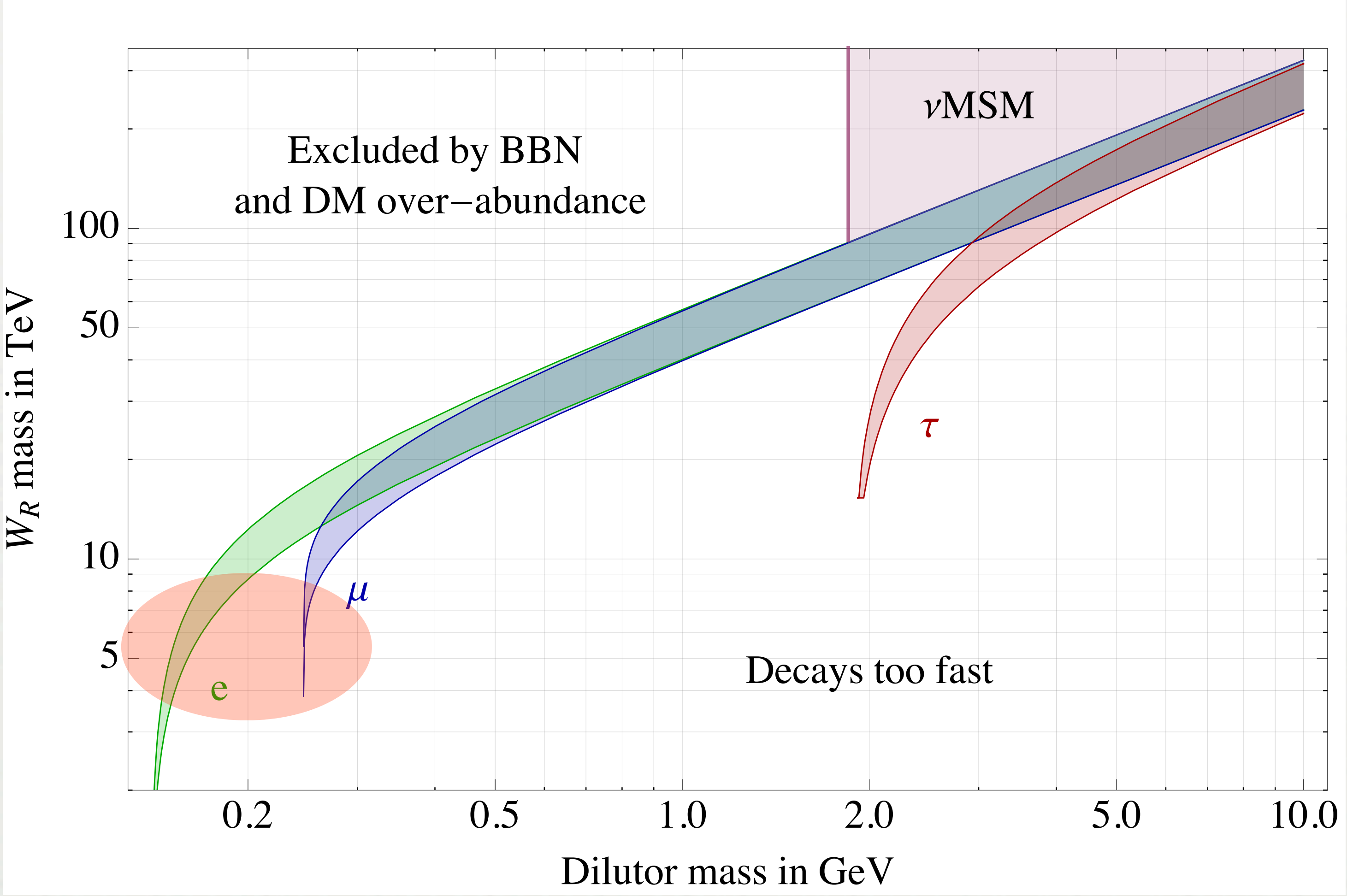


- ☐ Major parameters relevant to our picture: DM mass m_{N_1}, lifetime of diluter $\tau_{N_{2,3}}$, scale of LR symmetry M_{W_R} .
- ☐ Next survey a list of constraints.

Nemevsek, Senjanovic, YZ, 1204.xxxx

Constraints on DM mass

Dwarf Galaxies

- Consider degenerate Fermi gas, for a non-relativistic particle.

$$v_F = \frac{\pi\hbar}{m}\left(\frac{6N}{g\pi V}\right)^{1/3} = \hbar\left(\frac{9\pi M}{2gR^3m}\right)^{1/3}$$

- Apply the bound to observed dwarf spheroidal satellites, with mass M and radius R.
- Lighter DM (small m) leads to larger N, higher velocity at Fermi surface -- but should be less than the escape velocity.
- Lower bound on DM mass, derived from “Canes Venatici II”,

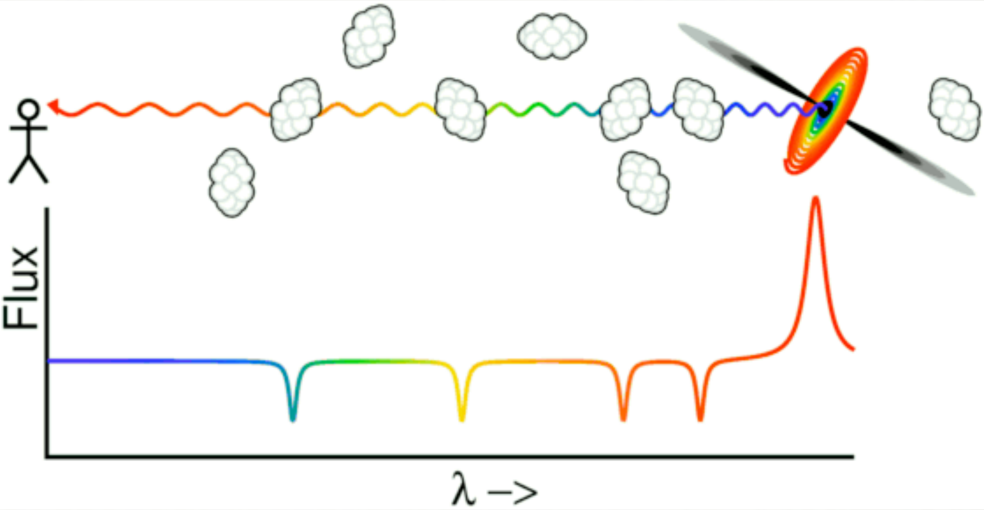
$$m_{DM} \gtrsim 0.468^{+0.137}_{-0.082}$$

- More sophisticated method using maximal phase space density, gives similar lower bounds.

$$m_{DM} \gtrsim 0.557^{+0.163}_{-0.097}$$

Tremaine, Gunn, 79'
Boyarsky, Ruchayshiy, Iakubovskyi, 0808.3902
Gorbunov, Khmelnitsky, Rubakov, 0808.3910

Lyman-alpha forest



- Quasars: very bright object (active nucleus) in the early universe ($z \sim 2-5$).
- Light traveling to us get redshifted, and absorbed from Lyman-alpha transition when passing through Hydrogen gas -- absorption line reflect structures.
- For $z \sim 2-3$, scale of structure is around Mpc -- infer lower bound on warm DM mass (not erased too much).
- Approaching non-linear growth regime, larger uncertainties.
- A recent analysis find 0.75 keV fits well.

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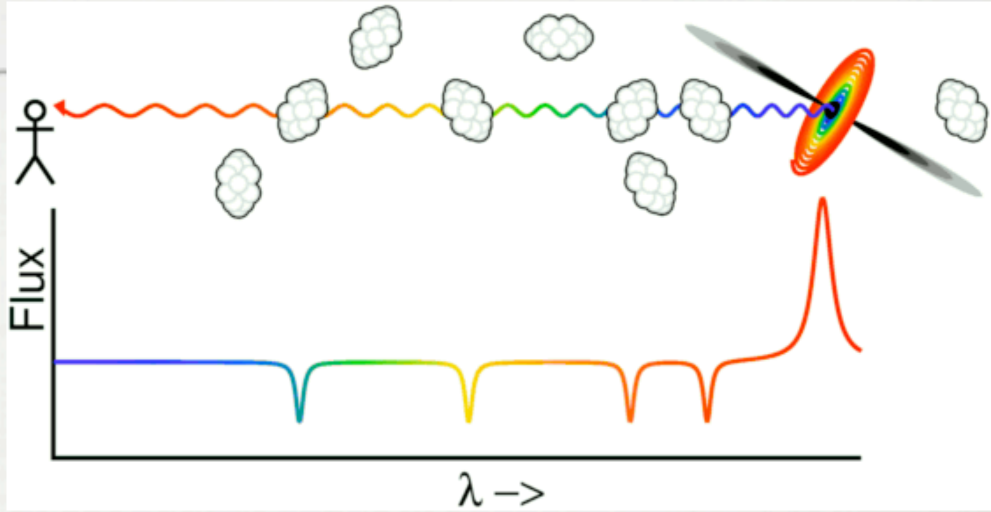

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$$m_{DM} \gtrsim \mathcal{O}(1)\,\mathrm{keV}$$

Constraints on Diluter $N_{2,3}$ lifetime

CMB

- Main constraints from measuring effective number of neutrinos.
- Progress in WMAP: $\mathrm{WMAP\ 5}: N_{\mathrm{eff}} = 4.4 \pm 1.5 \,@\, 68\%\mathrm{CL} \quad (3.77 \pm 0.67)$

  $\mathrm{WMAP\ 7}: N_{\mathrm{eff}} = 4.34^{+0.86}_{-0.88} \,@\, 68\%\mathrm{CL}$
- For low reheating temperature, weak interactions already fell out of equilibrium.
- SM neutrinos may not be completely thermalized -- reduce N_{eff} .
- N2,3 decays produce final states rich in neutrinos

$$N_2 \to \mu^+\pi^- \to \bar{\nu}_\mu e^+ \nu_e + \bar{\nu}_\mu \nu_\mu e \bar{\nu}_e$$

$$N_3 \to e^+\pi^- \to e^+ + \bar{\nu}_\mu \nu_\mu e \bar{\nu}_e$$

- Average energy about 20-30 MeV. What will these energetic neutrinos do?

Neutrino Thermalization

- Simply counting number of neutrinos from decay gives $N_{\rm eff} \approx 3-4$
- Energetic neutrinos have stronger weak interactions.
  - Down scatter with electron in the plasma $\sigma \sim E_\nu$
  - Self annihilation dominates $\sigma \sim E_\nu^2$

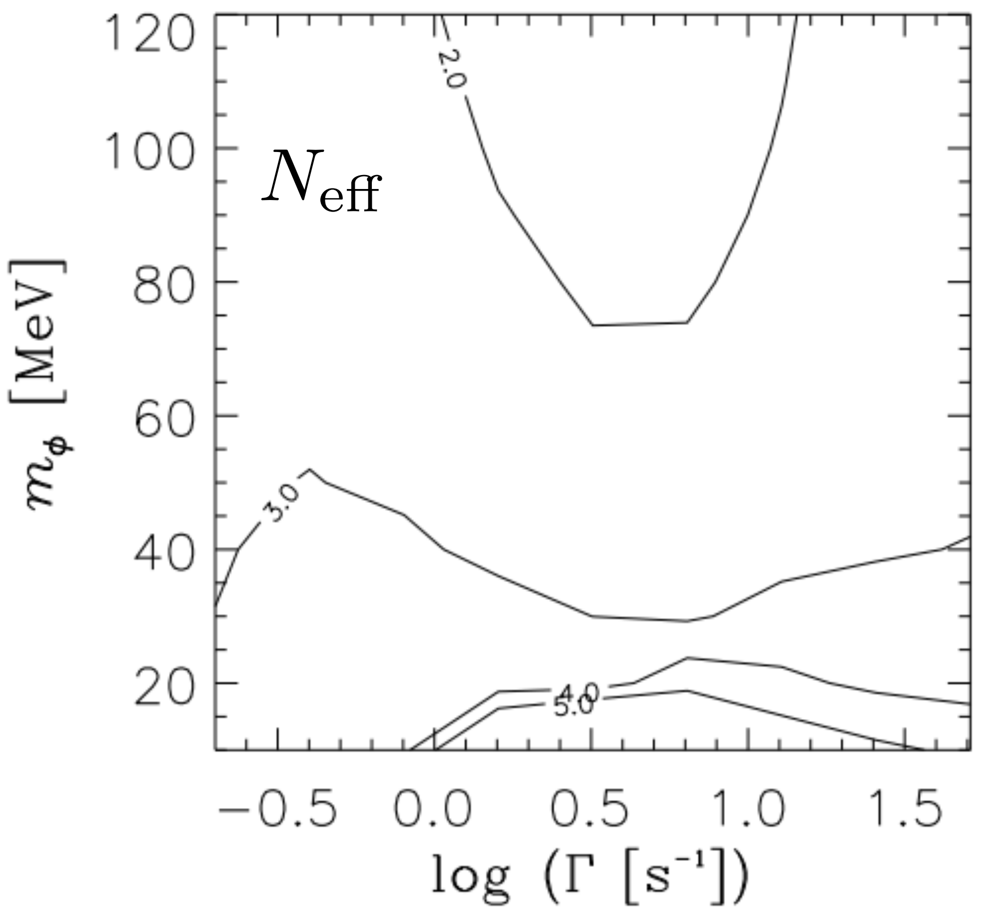
Fuller, Kishimoto, Kusenko, 1110.6479

Hannestad. 04’

- Effective neutrino number is likely

$$\boxed{N_{\rm eff} \approx 2-3}$$

- Agree with CMB within $3\,\sigma$.



BBN

- Helium abundance determined by proton-neutron ratio.
  - Reheating temperature T_r : Hubble and weak interaction rates.
  - For low scale LR symmetry, N2,3 light, decay to very soft pions ($E_\pi \lesssim 5\,\mathrm{MeV}$), which decays before the interaction $\pi^+ n \to p\pi^0$, electromagnetic nature.
  - Very energetic neutrino could also convert proton to neutron, depend on their spectrum in the late decay.

Kawasaki, Hohri, Sugiyama, 00'
Hannestad. 04'

- Upper limit on late decay lifetime or lower limit on T_r :

$$\begin{aligned} T_r > 0.7\,\mathrm{MeV}, &\quad \text{electromagnetic decay} \\ 4\,\mathrm{MeV}, &\quad \text{hadronic decay} \end{aligned}$$

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Kawasaki, Hohri, Sugiyama, 00′
Hannestad. 04′

- ☐ Upper limit on late decay lifetime or lower limit on T_r :

$$\boxed{T_r > 0.7\,\mathrm{MeV}, \quad \text{electromagnetic decay}} \qquad \boxed{\tau_{N_{2,3}} \lesssim 1.5\,\mathrm{sec}}$$

$$4\,\mathrm{MeV}, \quad \text{hadronic decay}$$

Constraints on LR symmetry scale M_{W_R}

Supernovae emission

- With new gauge interactions in LRSM, RH neutrino emission could be efficient if:

Raffelt, Seckel, 88'
Barbieri, Mohapatra, 89';

  - Lighter than a few MeV.
  - Couples to electron flavor.
- If this happens, implies a severe lower bound $M_{W_R} > 23\,\mathrm{TeV}$
- In our case, with $V_{e3} = 1$, N_3 is constrained to be heavier than 100 MeV, while typical temperature of supernovae ~10 MeV.
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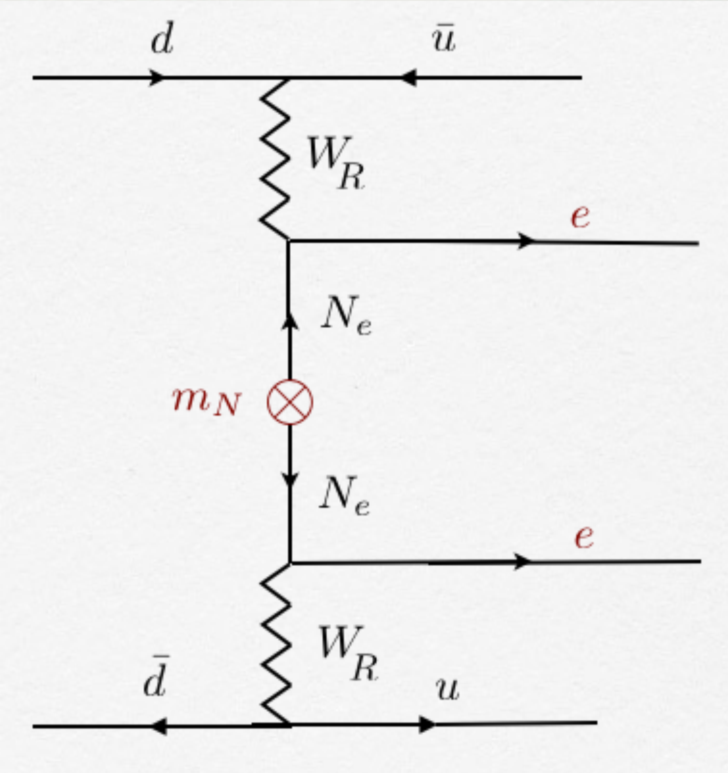
Nu-less Double Beta Decay

- In LRSM with WDM, N_3 with mass 140-150 MeV couples dominantly to electron.
- Typical nuclear momentum transfer: $p \sim 100 - 200\,\mathrm{MeV}$.
- In the intermediate regime between

$$\mathcal{M}_{0\nu 2\beta} \sim \frac{1}{M_W^4}\frac{m_\nu}{p^2} + \frac{1}{M_{W_R}^4}\frac{1}{m_N}$$

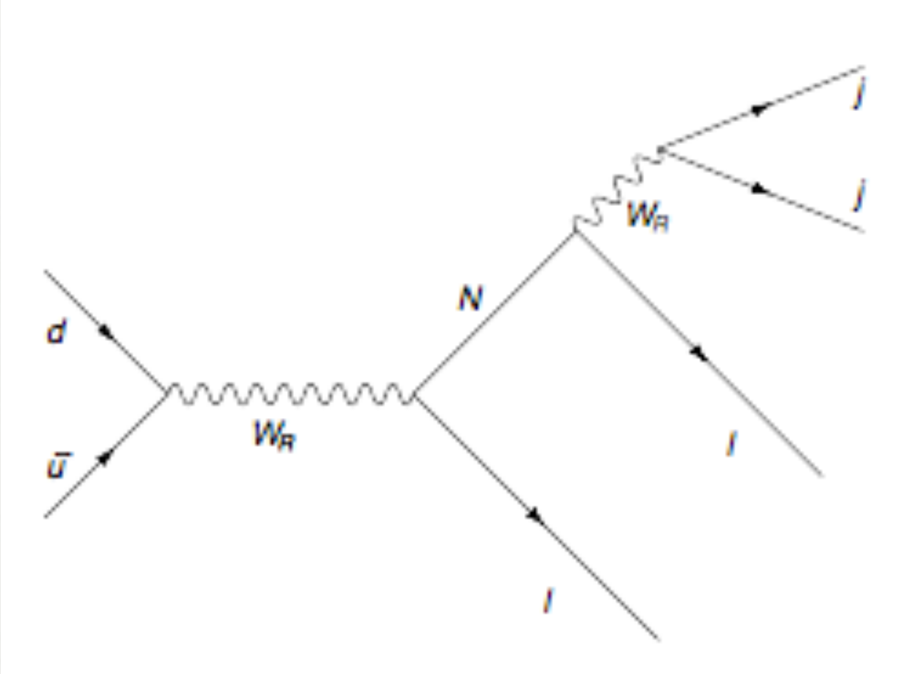
- Barring uncertainties in form factor

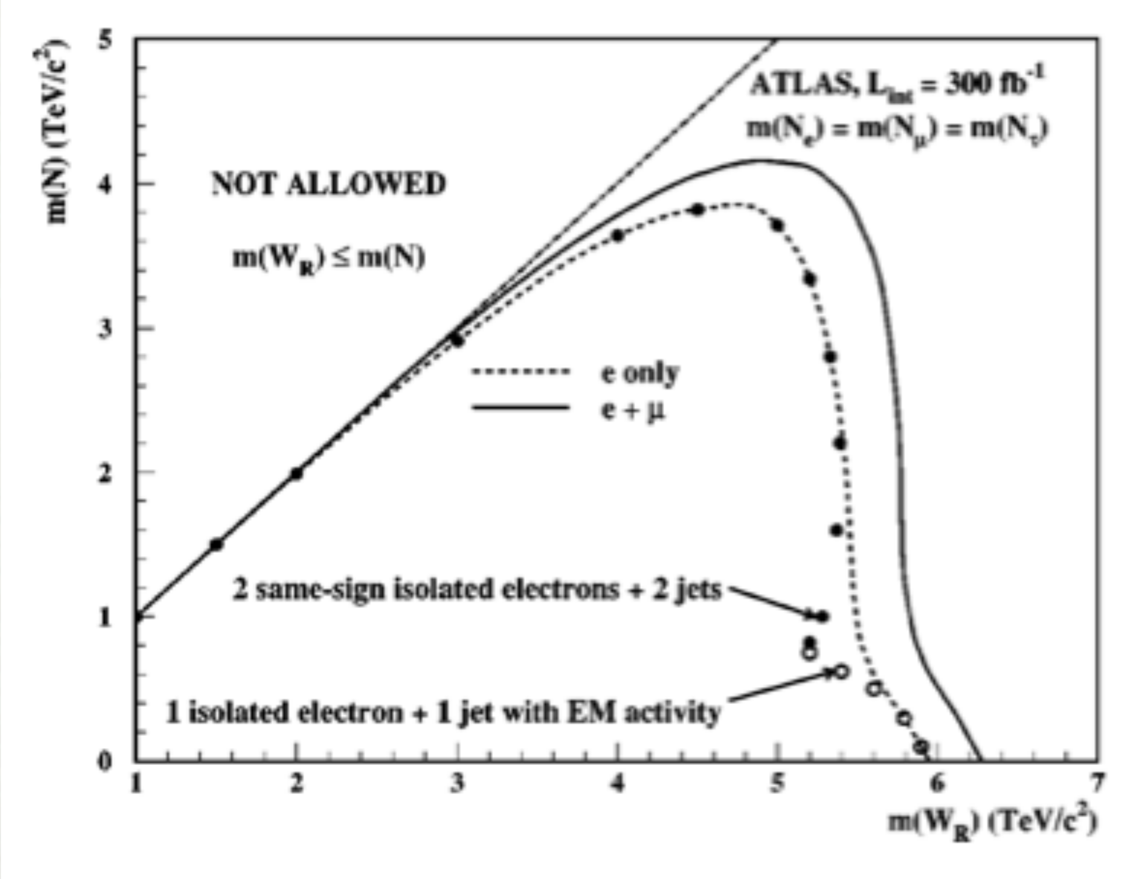
$$M_{W_R} \gtrsim 5 - 7\,\mathrm{TeV}$$



Gomez-Cadenas, Martin-Albo, Mezzetto, Monrabal, Sorel, 1109.5515
Tello, Nemevsek, Nesti, Senjanovic, Vissani, 1011.3522, 1112.3601

LHC reach





Ferrari, Collot, Andrieux, Belhorma, Saintignon, Hostachy, Martin, Wielers, 00′
Gninenko, Kirsanov, Krasnikov, Matveev, 07′

- Major signal at LHC: e/mu + missing energy.
- W_R boson with mass below 6.3 TeV can be found with 14 TeV.

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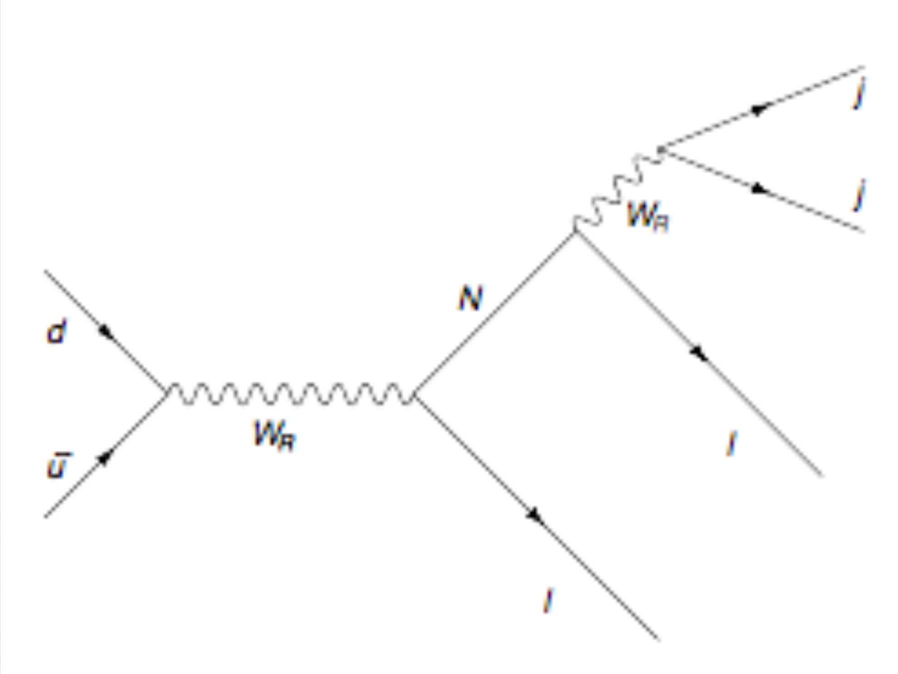

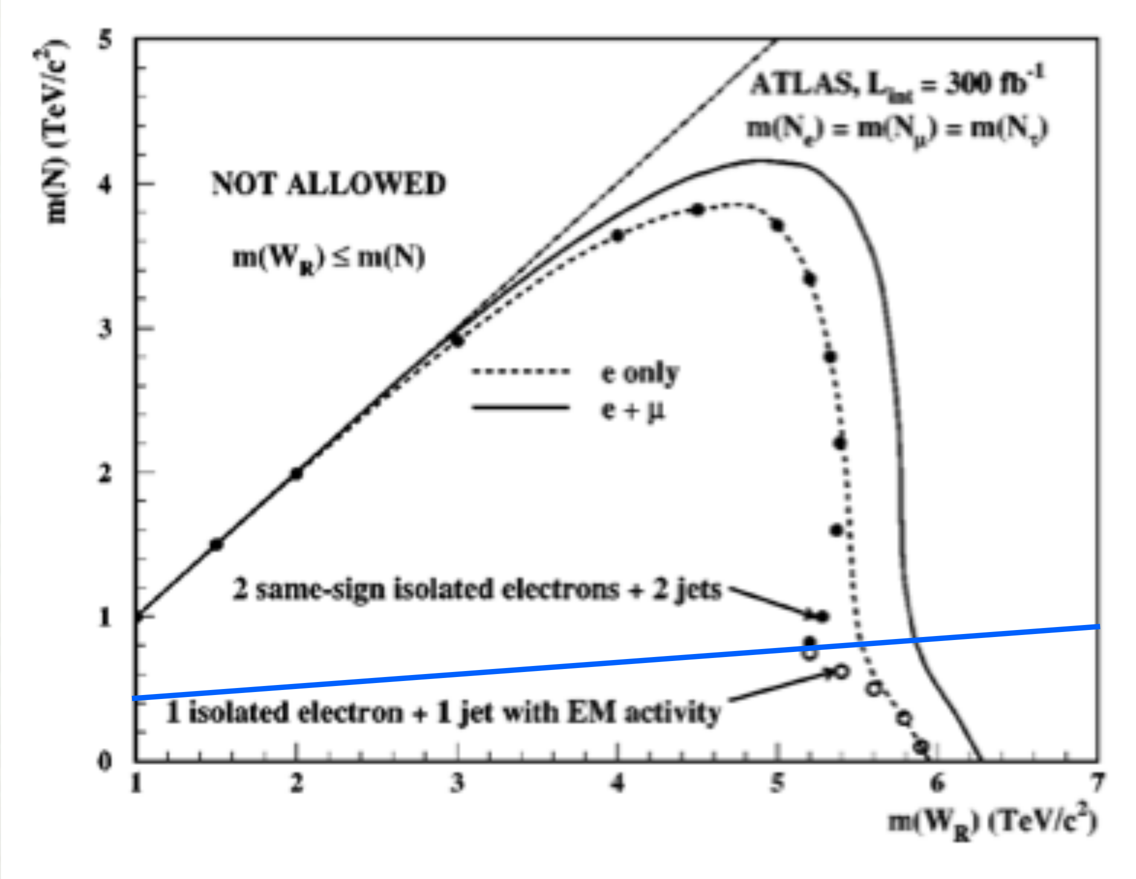

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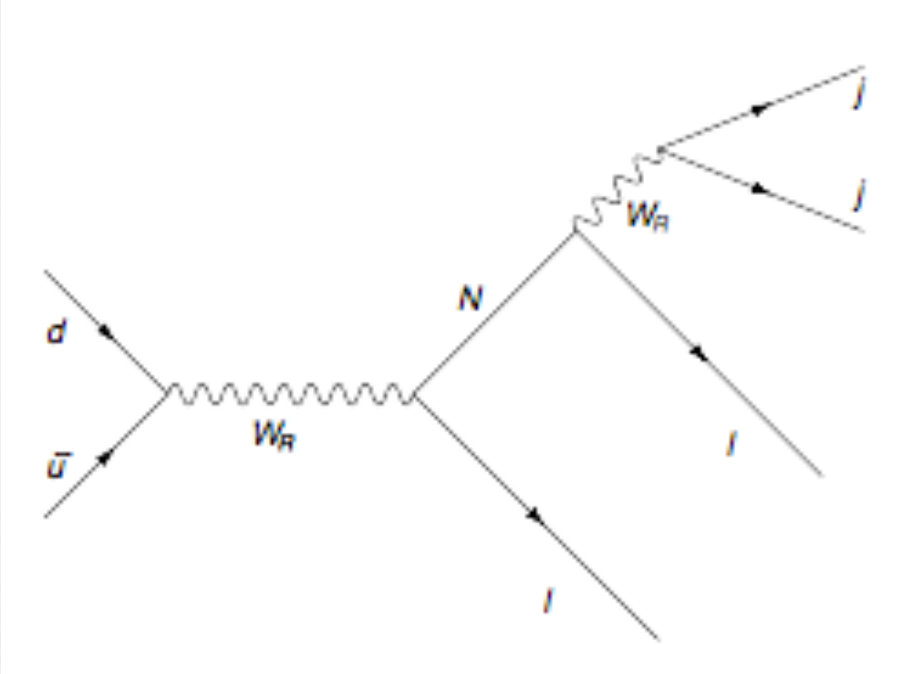

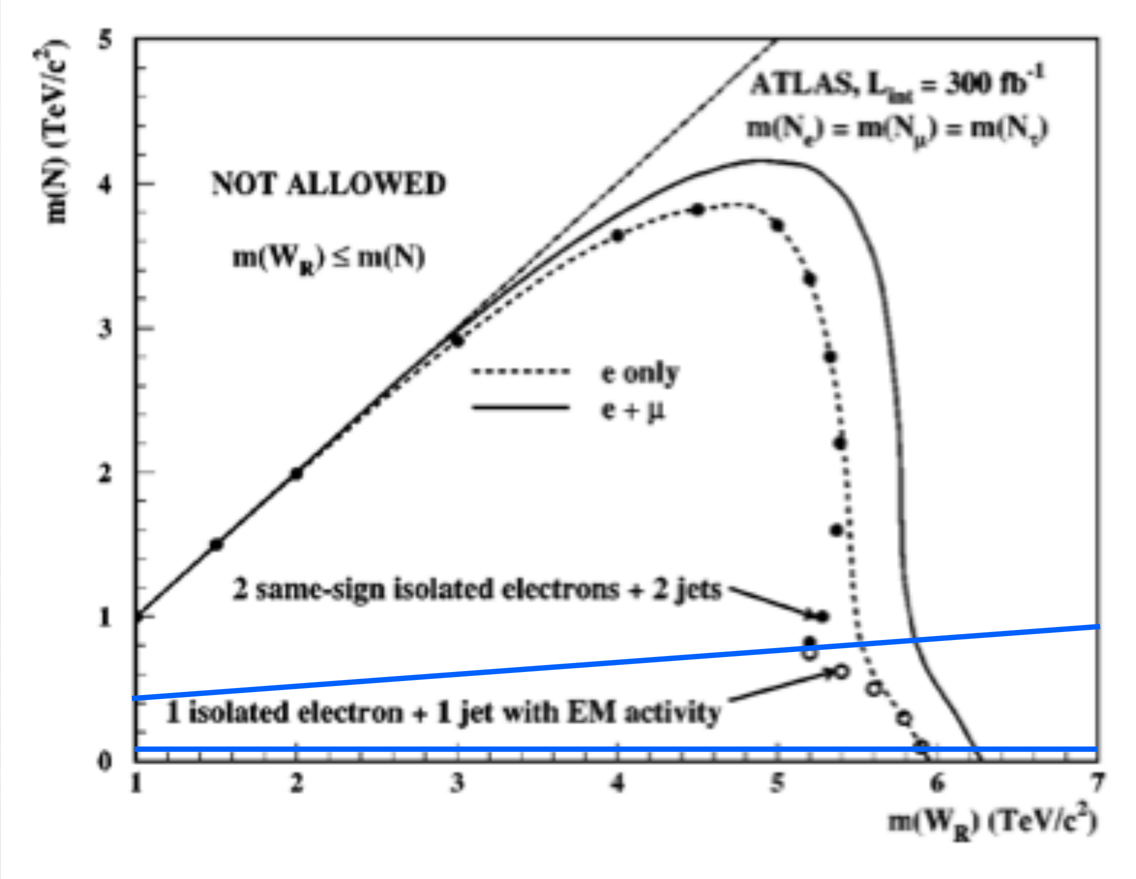

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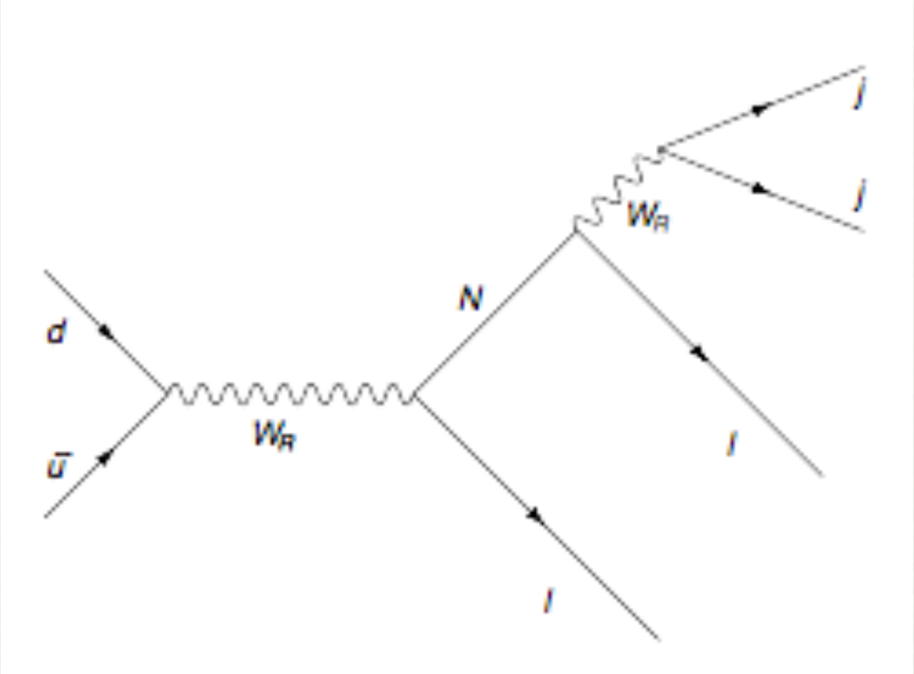

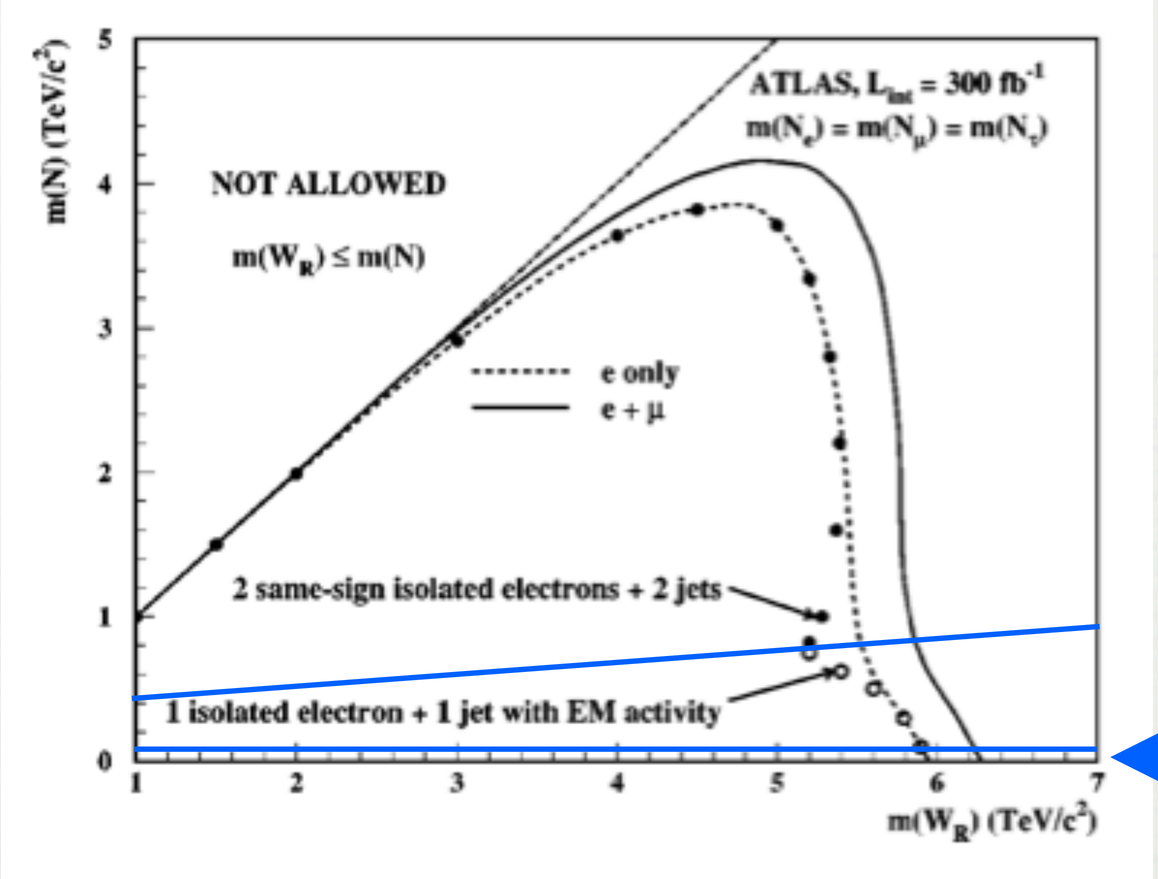

MISSING ENERGY

Ferrari, Collot, Andrieux, Belhorma, Saintignon, Hostachy, Martin, Wielers, 00'
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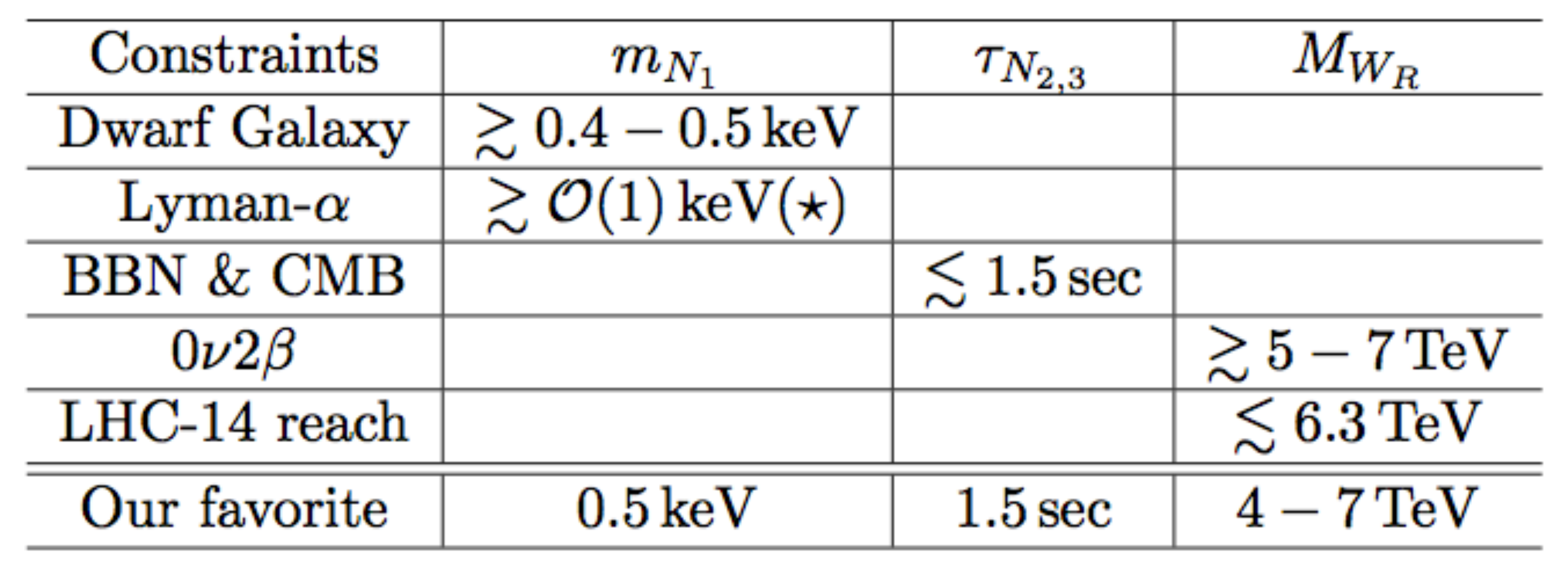
Summary of constraints



Constraints	m_{N_1}	$\tau_{N_{2,3}}$	M_{W_R}
Dwarf Galaxy	$\gtrsim 0.4 - 0.5\,\mathrm{keV}$		
Lyman-α	$\gtrsim \mathcal{O}(1)\,\mathrm{keV}(\star)$		
BBN & CMB		$\lesssim 1.5\,\mathrm{sec}$	
$0\nu 2\beta$			$\gtrsim 5 - 7\,\mathrm{TeV}$
LHC-14 reach			$\lesssim 6.3\,\mathrm{TeV}$
Our favorite	$0.5\,\mathrm{keV}$	$1.5\,\mathrm{sec}$	$4 - 7\,\mathrm{TeV}$

Nemevsek, Senjanovic, YZ, 1204.xxxx

Conclusion

☐ LRSM is a well motivated theory for neutrino mass -- Seesaw from maximal parity violation.

☐ Rich phenomenological when the theory lies near TeV.

☐ We show there could be a low-scale LRSM window for it to be a theory of warm dark matter.

☐ Relic density: take advantage of QCD phase transition. Require spectacular flavor structure and mass spectrum in this picture.

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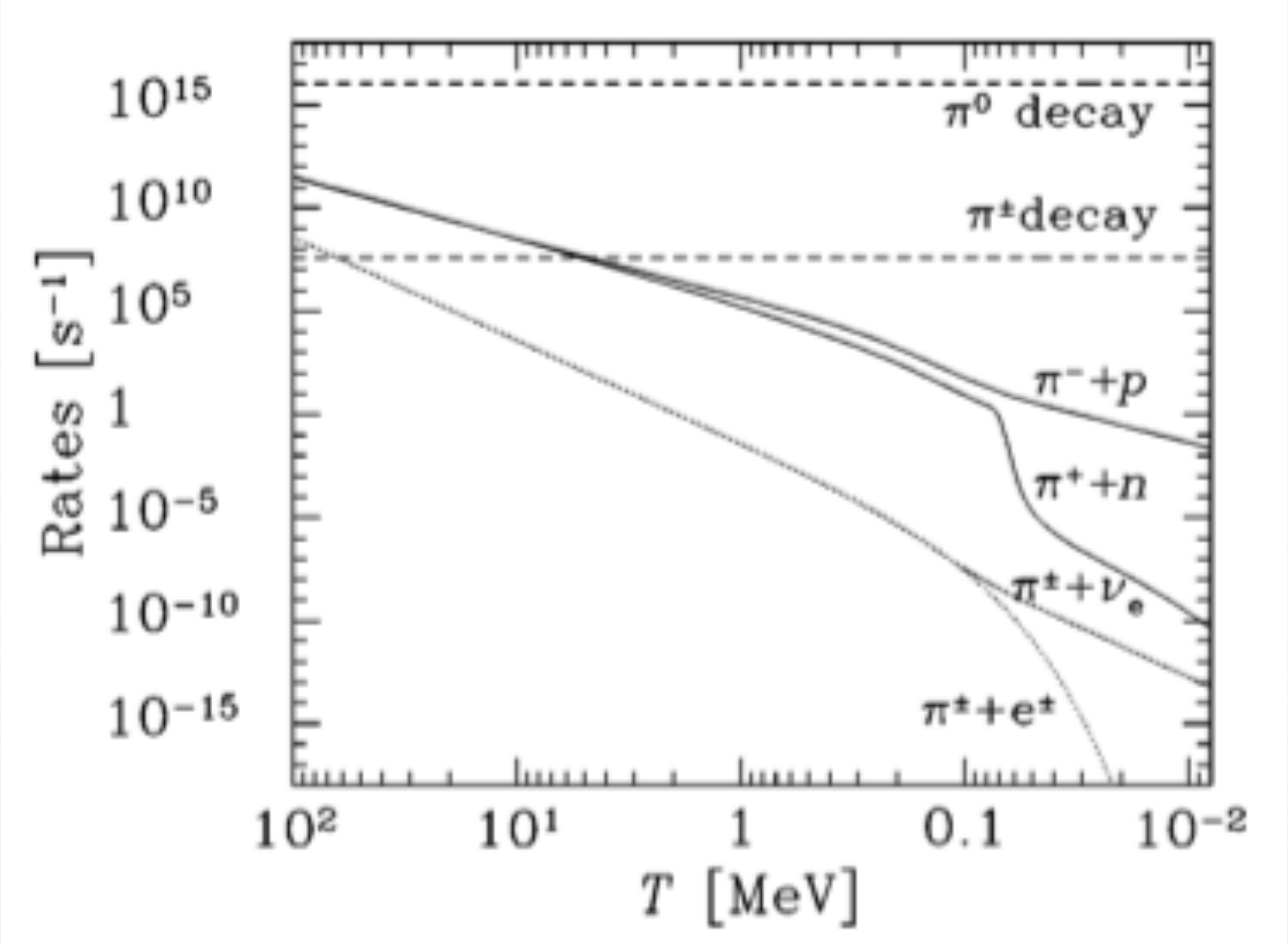
THANKS!

Backup slides

Pion-nucleon scattering



Rehm, Jedamzik, 00’