Sterile Neutrino Dark Matter in Left-Right Theories

Jeff Dror, **David Dunsky**, Lawrence Hall, Keisuke Harigaya

arXiv:2004.09511 ddunsky@berkeley.edu

Why Left-Right Symmetry?

- Grand-Unification

  Georgi, Fritzsch, Minkowsi, Nanopolous (1974-79)

$$SO(10) \rightarrow SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$
$$\xrightarrow{v_R} SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Can solve Strong CP Problem

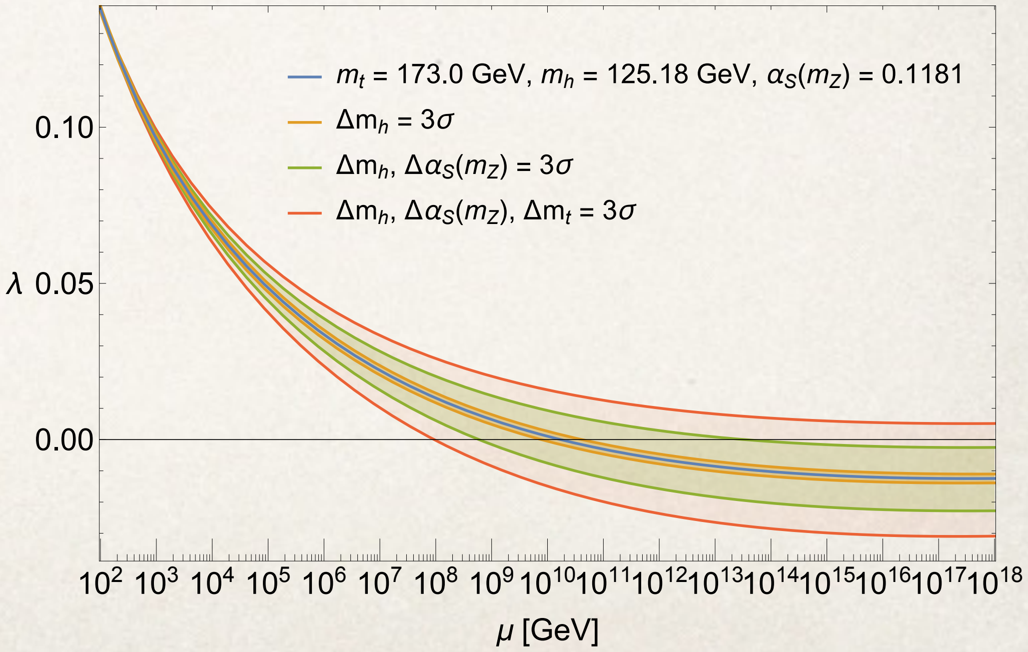
  Mohapatra, Senjanovic, Babu, Beg, Tsao (1978,89)

Parity restored symmetry

- Explain vanishing of Higgs quartic

  Hall, Harigaya (2018)

"Higgs Parity"



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  "Higgs Parity"

- Predicts right-handed neutrinos

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \leftrightarrow \begin{pmatrix} N \\ e \end{pmatrix}_R$$

- N SM gauge singlets. If long-lived, N_1 can be dark matter

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Cosmology

- Production mechanisms:
- 1) Yukawa coupling $yN\ell H$
    - Problem! In tension with x-ray and structure bounds

      Perez et.al (2017)
- 2) In LR theories, N_1 can also be produced via W_R exchange

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Relativistic Freeze-Out and Dilution

- When reheat temperature after inflation is large, N's in thermal equilibrium then decouple relativistically
- Overproduction problem! $\Omega_{N_1} \approx 20 \times \Omega_{\mathrm{DM}} \left(\frac{M_1}{2\,\mathrm{keV}} \right)$
- However, N_2 also thermally produced

↓

If long-lived can produce entropy upon decay

↓

Dilute N_1 to the dark matter abundance

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Neutrino Masses

- Stability of N_1 (to be DM) and semi-stability of N_2 (to be the diluter) will constrain form of neutrino masses
- In the conventional LR or two Higgs doublet LR theories, the general, effective Lagrangian below v_R is

$$-\mathcal{L}_{\mathrm{LR,eff}} \supset \underset{\substack{\uparrow \\ \text{Dirac mass}}}{y_{ij}\ell_i N_j H} + \underset{\substack{\uparrow \\ N \text{ Majorana} \\ \text{mass}}}{y'^{*}_{ij} v_R N_i N_j} + \underset{\substack{\uparrow \\ \nu \text{ Majorana} \\ \text{mass}}}{\frac{c y'_{ij}}{v_R} \ell_i \ell_j H^2}$$

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$$\begin{pmatrix} \nu_i & N_i \end{pmatrix} \begin{pmatrix} cM_{ij}\, v^2/v_R^2 & y_{ij}v \\ y_{ji}v & M_{ij}^{(*)} \end{pmatrix} \begin{pmatrix} \nu_j \\ N_j \end{pmatrix}$$

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- Semi-stability of N_2 guarantees

$$M_2 = \mu \left(\frac{v_R}{v} \right)^2 c^{-1} \qquad \begin{cases} \mu \simeq (0.01 - 0.10)\,\mathrm{eV} \\ c \lesssim 1 \end{cases}$$

Constraint 1: N_1 Warmness

- In general, light N_1

  ↓

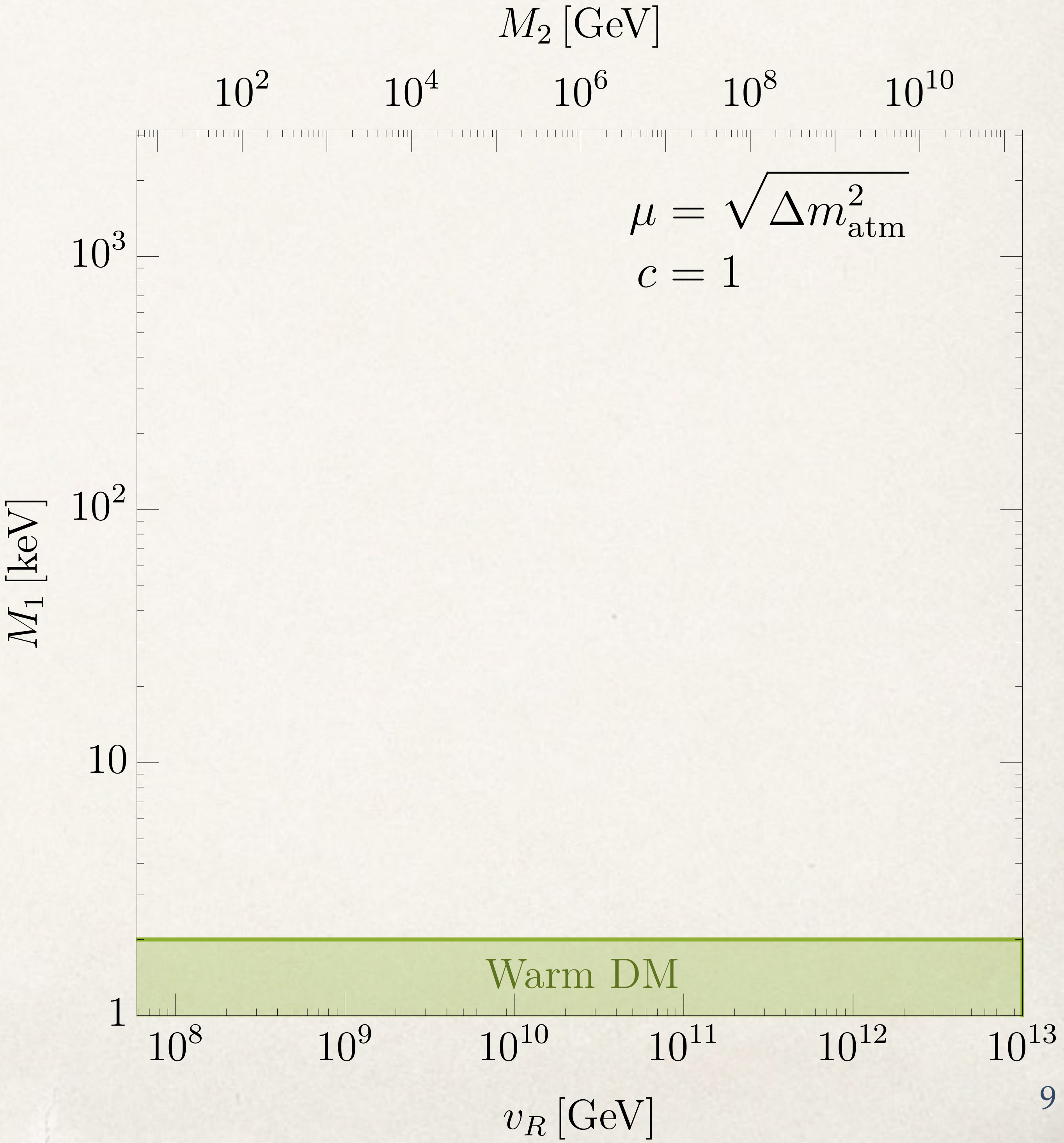
  Large free-streaming length

  ↓

  Matter power-spectrum suppression

- Current limits from LSS surveys & Lyman-alpha photons require $M_1 \gtrsim 2$ keV

  Drews et. al. (2016)



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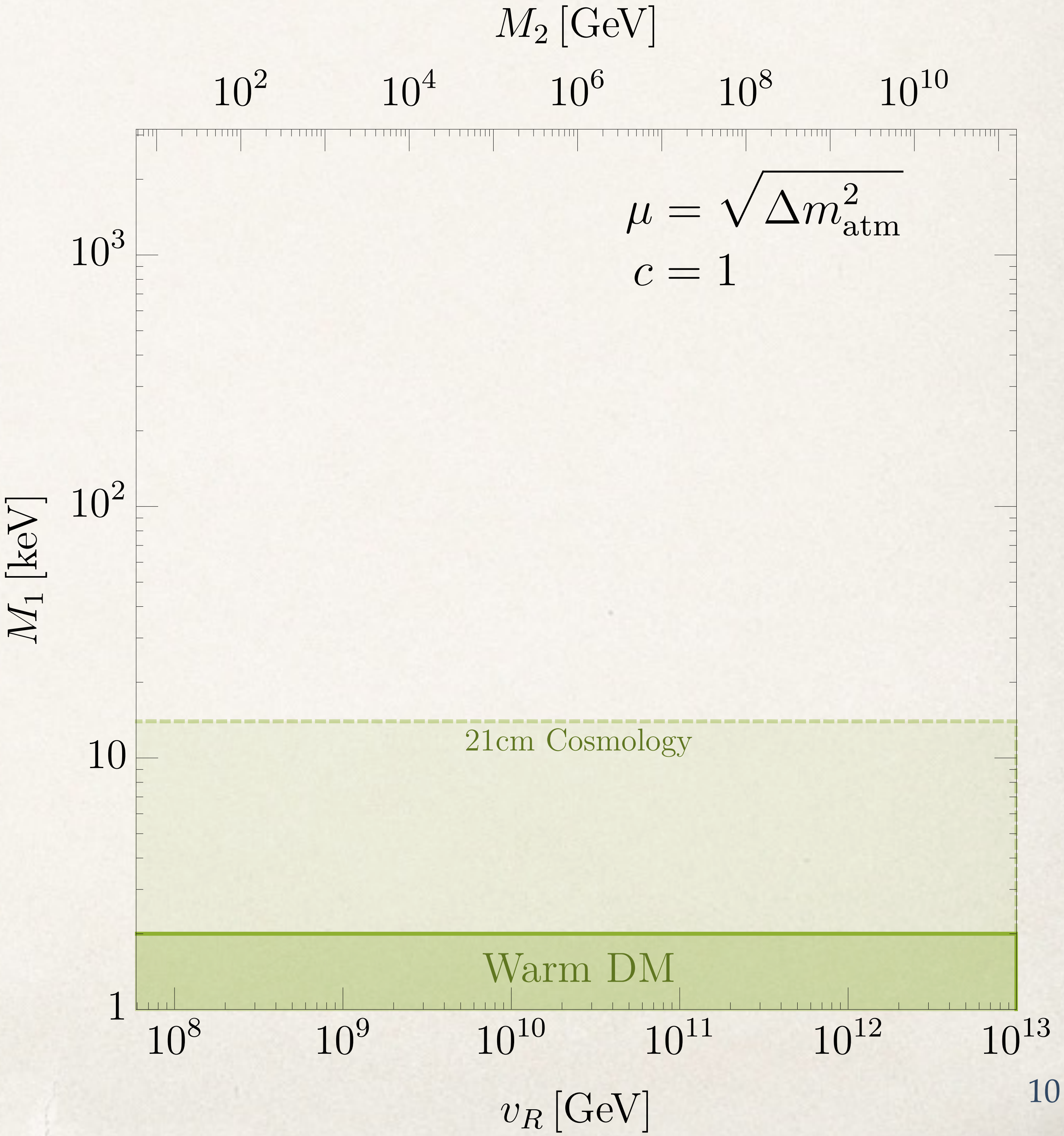
Signal: 21cm Cosmology

- Future 21-cm cosmology experiments can trace early star and galaxy formation at cosmic dawn

- Can probe matter power spectrum at smaller scales up to $M_1 \simeq 14\,\mathrm{keV}$

Muoz, Dvorkin, Cyr-Racine (2020)



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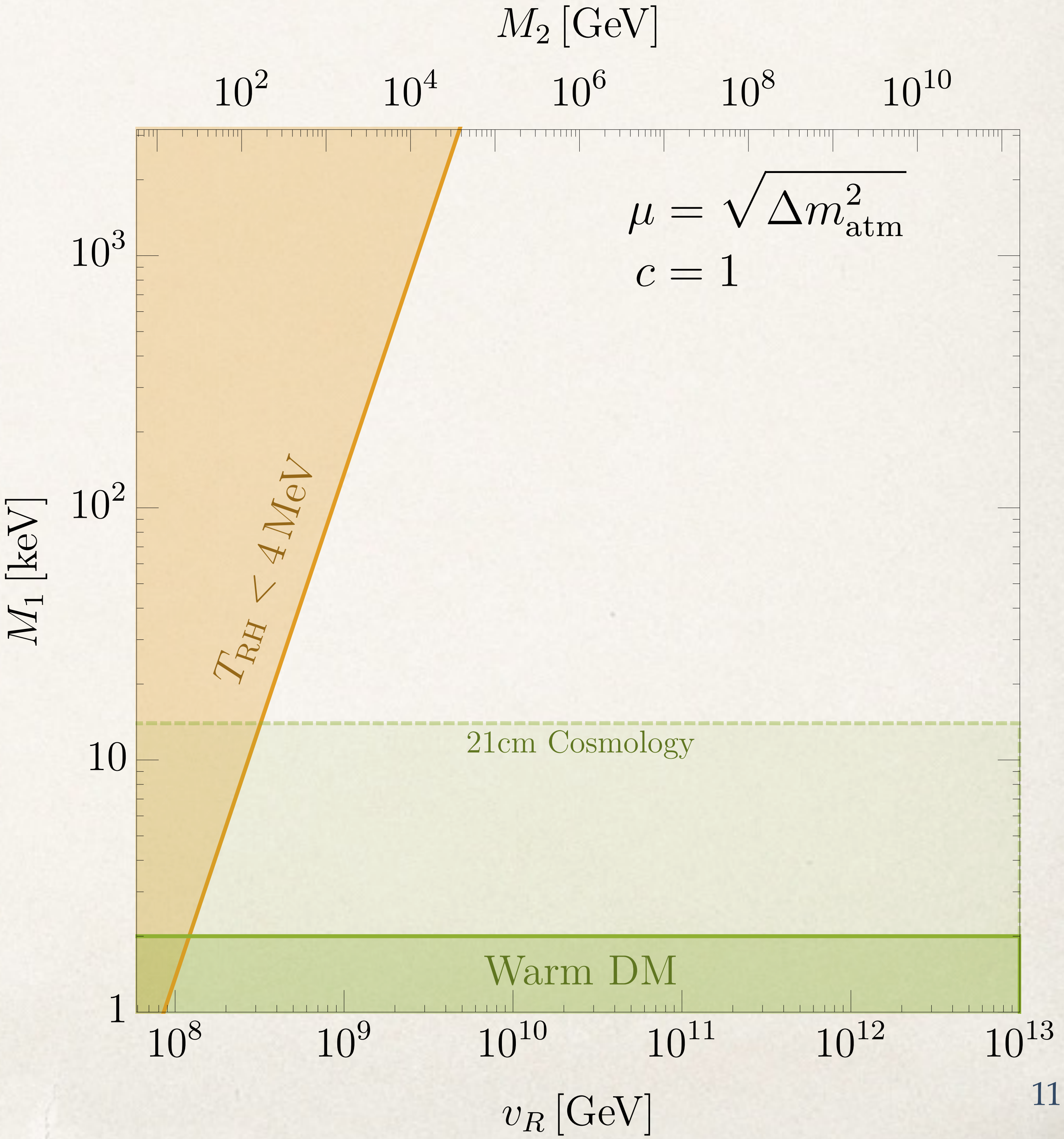
Constraint 2: N_2 Decaying after BBN

- The longer N_2 lives, the greater dilution it can provide
- $$\frac{\rho_{N_1}}{s} = \frac{M_1 Y_{\rm therm}}{D} \approx \frac{M_1}{M_2} T_{\rm RH}$$
- If $T_{\rm RH} < T_{\rm BBN} \simeq 4\,{\rm MeV}$ N_2 decays after BBN



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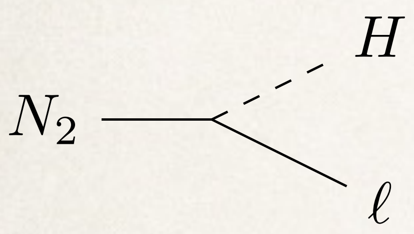
Constraint 3: Insufficient Dilution

- If N_2 decays too early

↓

Insufficient dilution

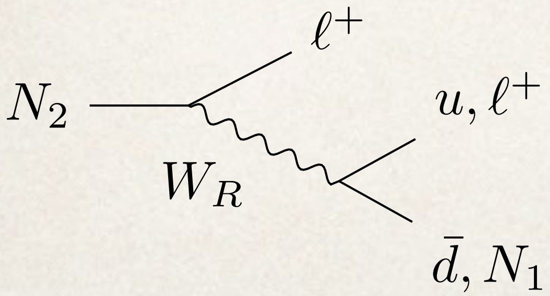
1)



$$\propto \sum |y_{2i}|^2 M_2$$

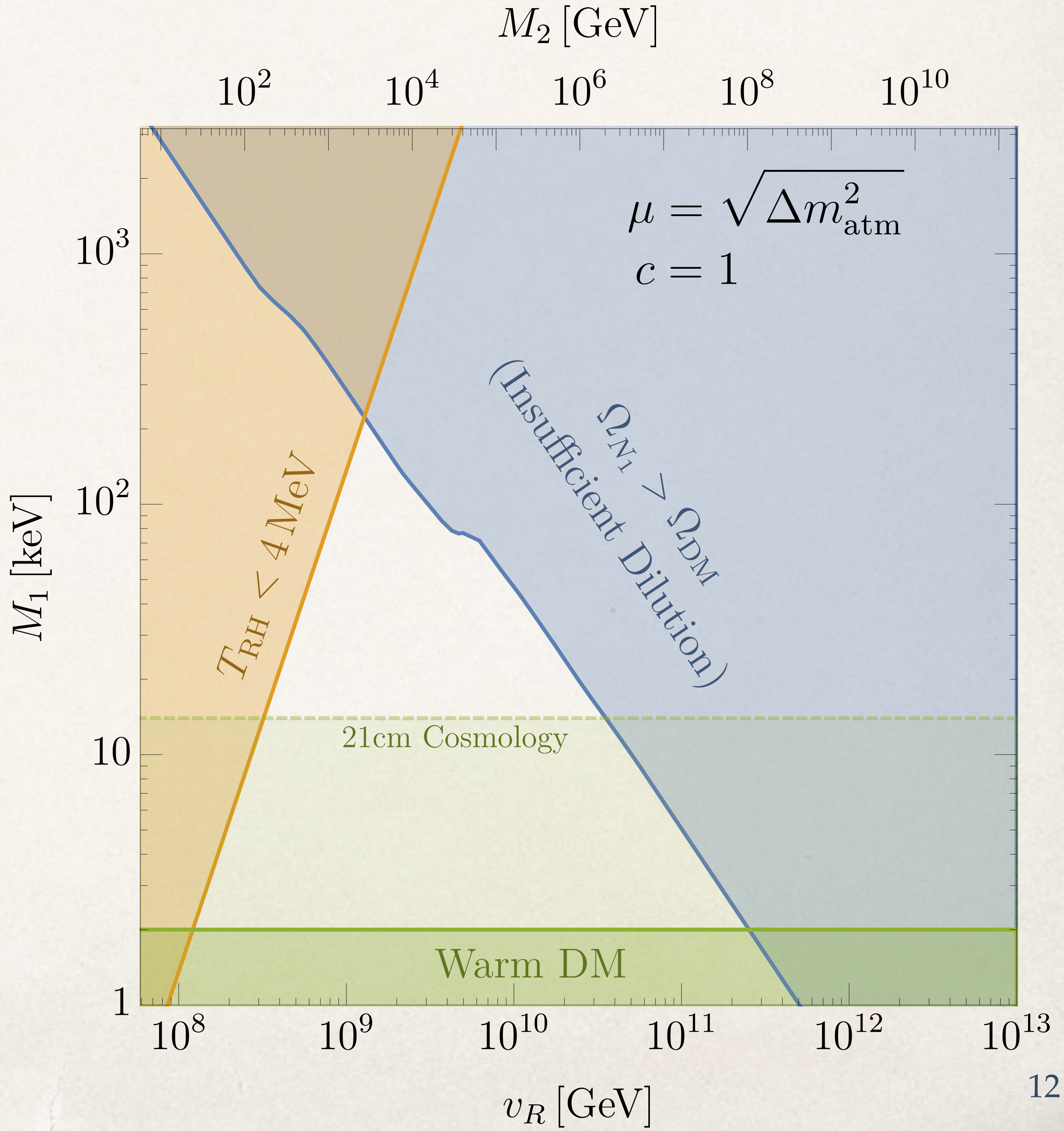
Choose y_{2i} to get DM abundance (white region)

2)



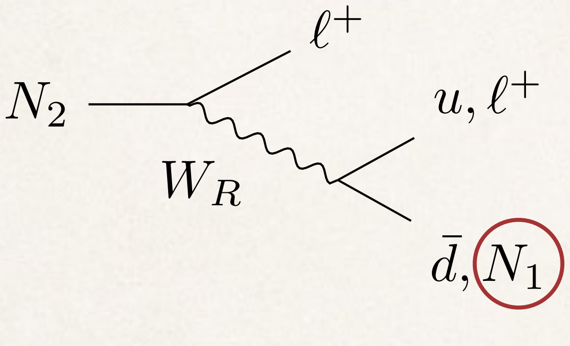
$$\propto \frac{M_2^5}{v_R^4} \propto v_R^6$$

Unavoidable decay (blue region)

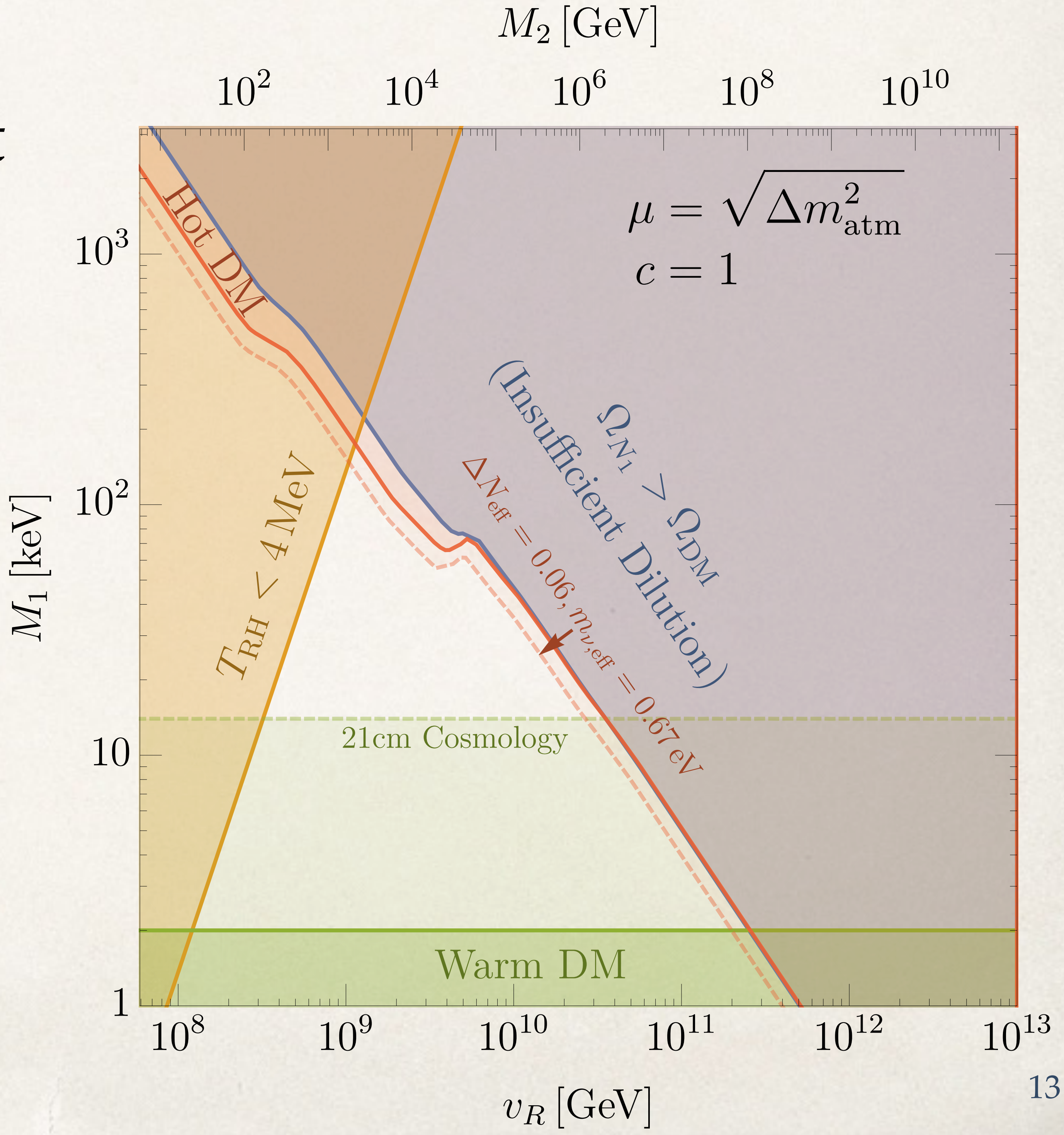


Signal: Hot Dark Matter

- Subdominant component of N_1 DM produced from N_2 beta decay



- These N_1 become non-relativistic around eV era, and constitute hot DM



Summary

- Parameter space of sterile neutrino DM in LR theories bounded
- Prediction of $2\,\mathrm{keV} \lesssim M_1 \lesssim 500\,\mathrm{keV}\,,\ \ 10^8\,\mathrm{GeV} \lesssim v_R \lesssim 10^{13}\,\mathrm{GeV}$
- Interestingly, v_R compatible with Grand Unification or Higgs Parity

  Rizzo, Senjanovic (1982), Siringo (2013), Hall, Harigaya (2018)
- 21-cm cosmology and CMB telescopes can probe much of parameter space
- N_2 can also provide leptogenesis besides diluting (future work)

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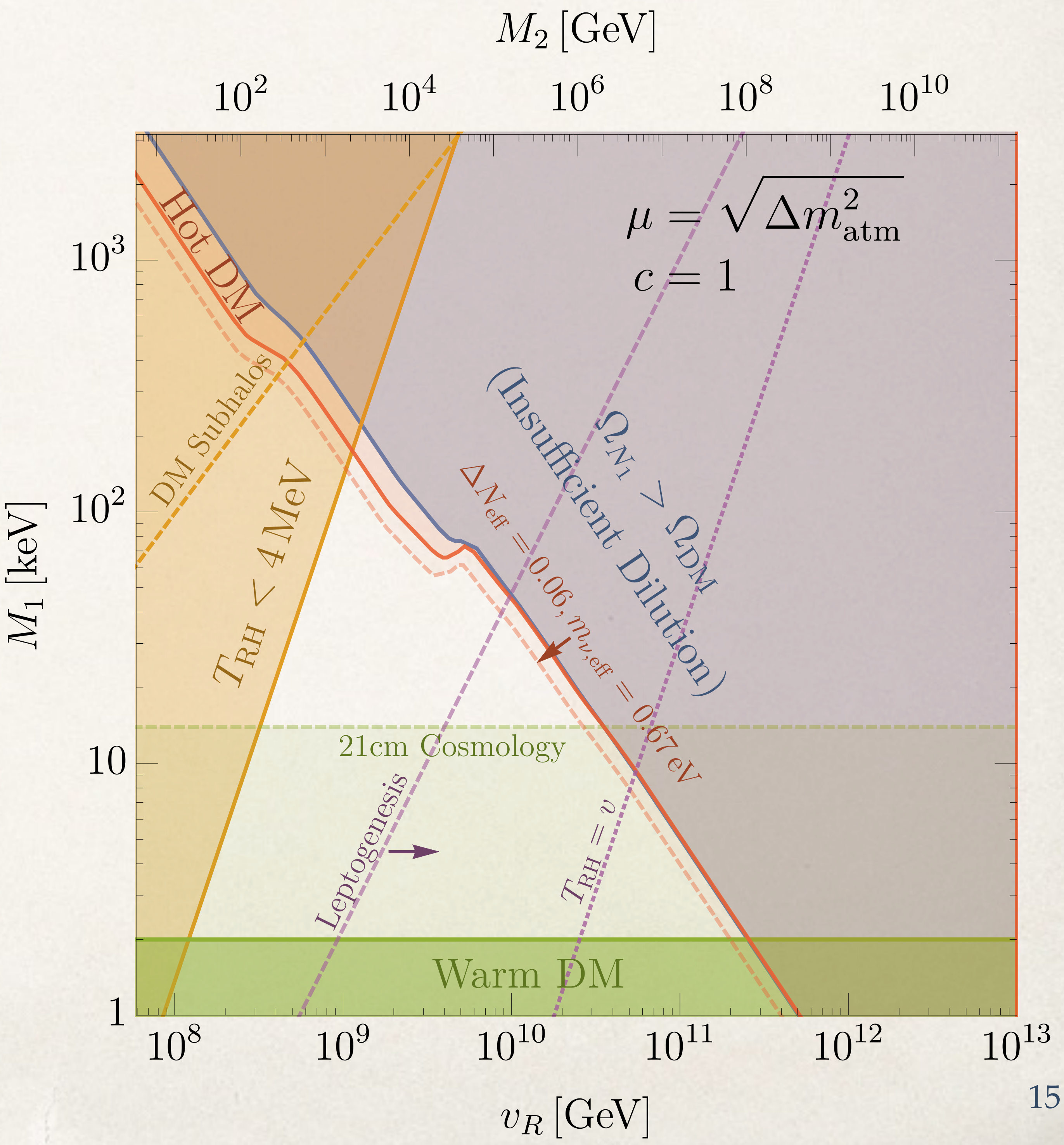
Signal: Leptogenesis

- N_2 can not only dilute N_1, but its decays can produce the baryon asymmetry via leptogenesis $Y_B \approx \epsilon Y_2$

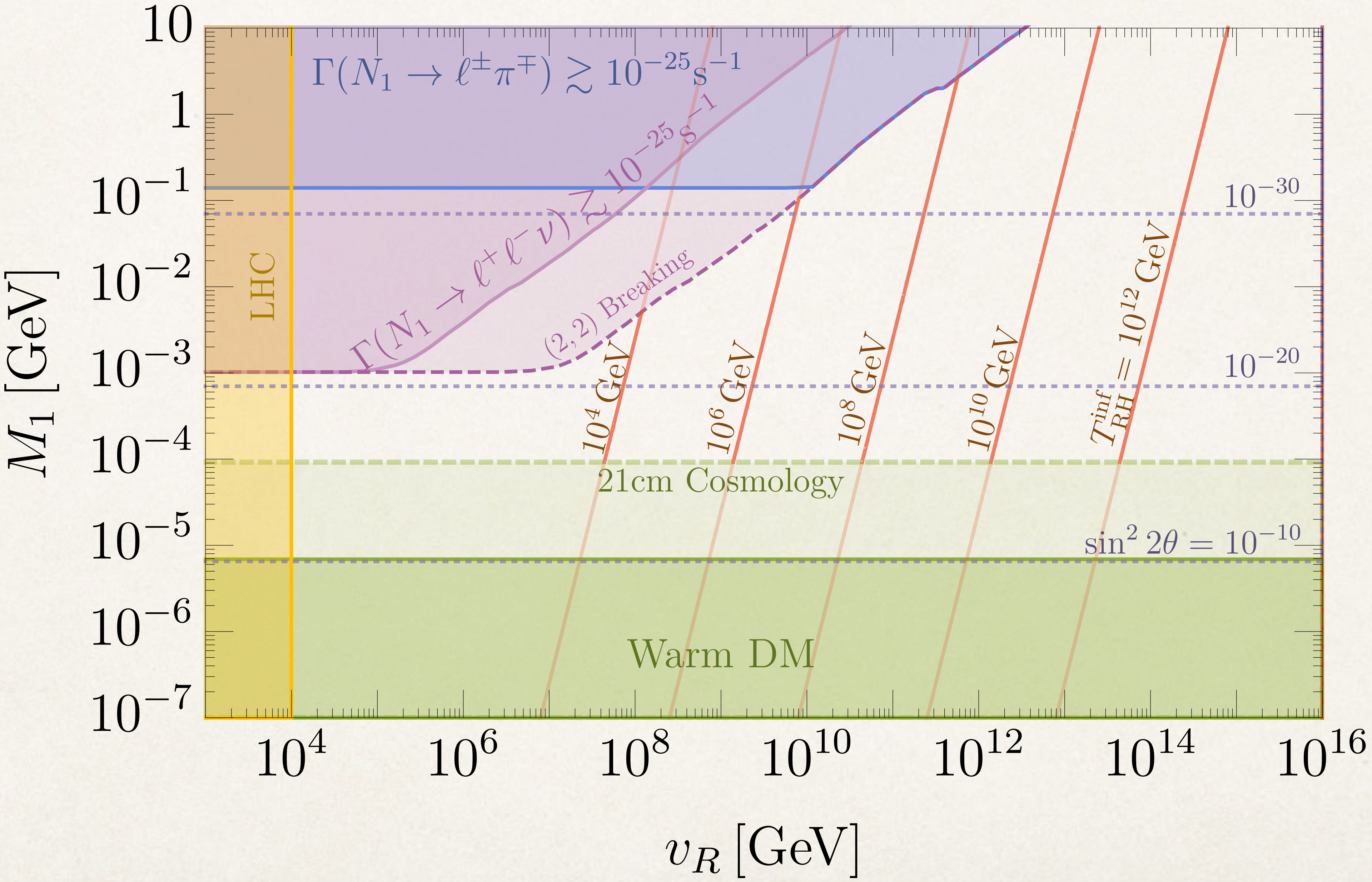
- Leptogenesis suppressed when $T_{\rm RH} < v$ by $(T_{\rm RH}/v)^2$

- Taking conservative $\epsilon = 1$ dashed line shows region where $Y_B \gtrsim 8 \times 10^{-11}$

- Explore in upcoming paper

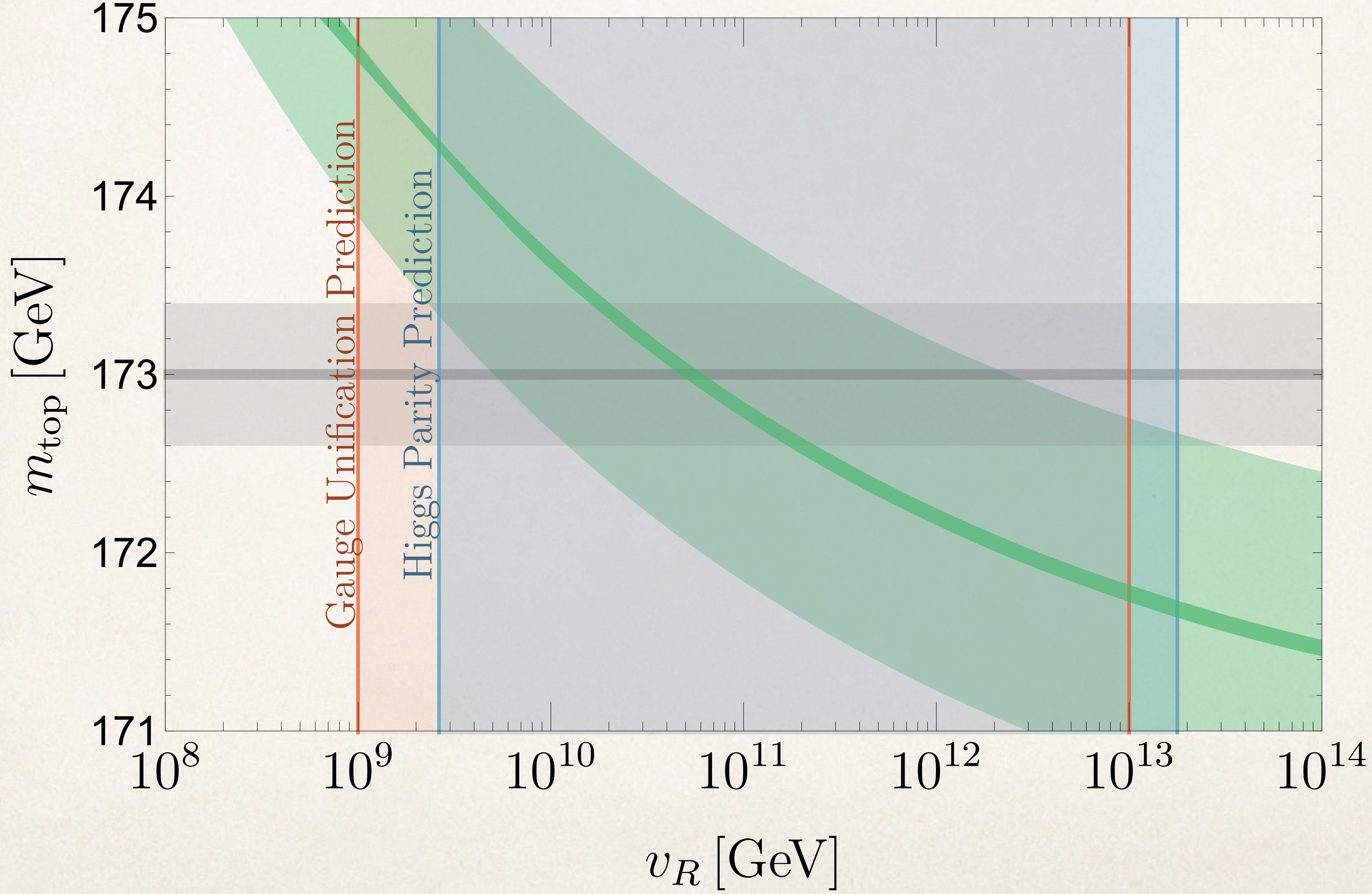


Freeze-In



$\Gamma(N_1 \to \ell^\pm \pi^\mp) \gtrsim 10^{-25}\mathrm{s}^{-1}$
$\Gamma(N_1 \to \ell^+ \ell^- \nu) \gtrsim 10^{-25}\mathrm{s}^{-1}$
(2,2) Breaking
LHC
10^{-30}
10^{-20}
10^4 GeV
10^6 GeV
10^8 GeV
10^{10} GeV
$T_{\mathrm{RH}}^{\mathrm{inf}} = 10^{12}$ GeV
21cm Cosmology
$\sin^2 2\theta = 10^{-10}$
Warm DM
M_1 [GeV]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
v_R [GeV]

Compatibility with GUTs and HP



Effective Lagrangian below v_R

- Conventional LR

$$-\mathcal{L}_{\rm LR} \supset y_{ij}\,(\ell_i\,\bar{\ell}_j)\,\Phi + y'_{ij}(\ell_i\,\ell_j)\,\Delta_L + y'^{(*)}_{ij}(\bar{\ell}_i\,\bar{\ell}_j)\,\Delta_R + \text{h.c.}$$

- Integrating out Δ_L via $\lambda_{LR}\,\Delta_L\Delta_R\Phi^\dagger\Phi$ leads to $\ell\ell H^2$ term

- Two Higgs doublet LR

$$-\mathcal{L}_{\rm LR} \supset f_{ij}\frac{1}{\Lambda}\,(\ell_i\,\bar{\ell}_j)\,H_L H_R + f'_{ij}\frac{1}{\Lambda}(\ell_i\,\ell_j)\,H_L^2 + f'^{(*)}_{ij}\frac{1}{\Lambda}(\bar{\ell}_i\,\bar{\ell}_j)\,H_R^2 + \text{h.c.}$$