Higgs Parity, Strong CP, Dark Matter

&

Leptogenesis

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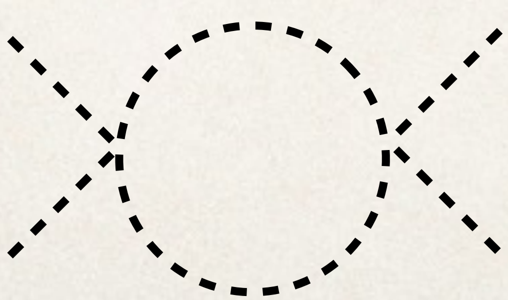
arXiv:1902.07726
arXiv:2001.xxxxx

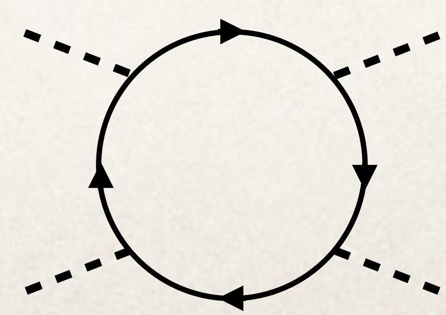
The Higgs Quartic

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

- 1967: $\langle H \rangle = v$ Weinberg
- 2012: m, λ ATLAS, CMS
- Measured value λ of appears special



$\lambda \uparrow$



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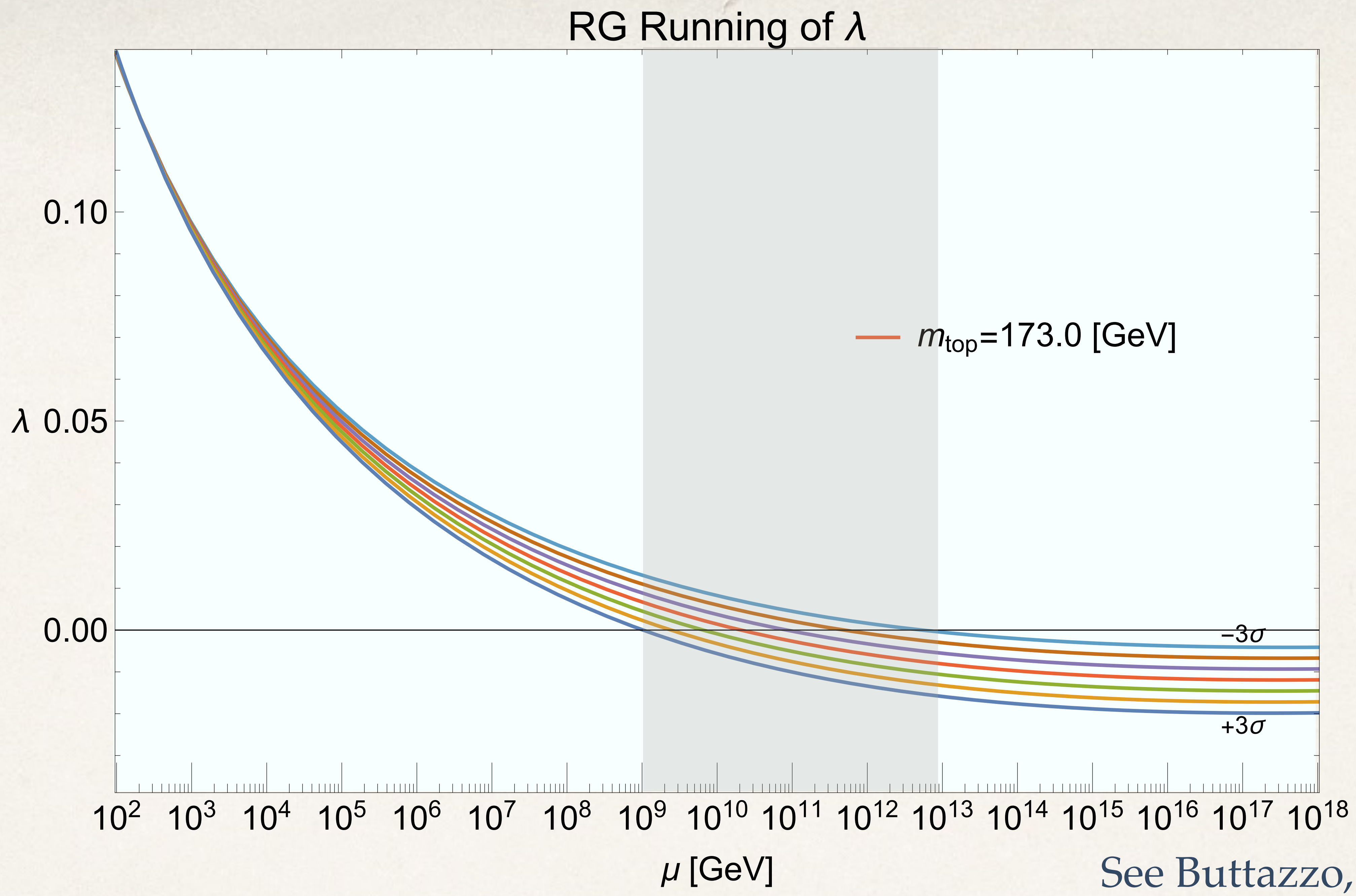

See Buttazzo, et al (2013)

- Why is $\lambda \sim .01$ above 10^9 GeV?
- Why λ crosses 0 between $10^9 - 10^{13}$?
- Vanishing of λ hint of new physics?

Vanishing of Higgs Quartic by a Z_2

- Consider a Z_2

$$SU(2) \leftrightarrow SU(2)'$$

$$\underset{(2,1)}{H} \leftrightarrow \underset{(1,2)}{H'}$$

Vanishing of Higgs Quartic by a Z_2

- Consider a Z_2
$$\begin{gathered} SU(2) \leftrightarrow SU(2)' \\ \underset{(2,1)}{H} \leftrightarrow \underset{(1,2)}{H'} \end{gathered}$$

- Most general potential
$$V(H, H') = -m^2(|H|^2 + |H'|^2) + \frac{\lambda}{2}(|H|^2 + |H'|^2)^2 + \lambda' |H|^2 |H'|^2$$

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Integrate out H'

$$\langle H' \rangle^2 \equiv v'^2 = \frac{m^2}{\lambda} \gg \underset{(174\,\mathrm{GeV})^2}{v^2}$$

$$V_{\mathrm{LE}}(H) = \lambda' v'^2 |H|^2 - \lambda' \left(1 + \frac{\lambda'}{2\lambda}\right) |H|^4$$

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$\downarrow$ $\qquad\qquad \uparrow$ $(174\,\mathrm{GeV})^2$

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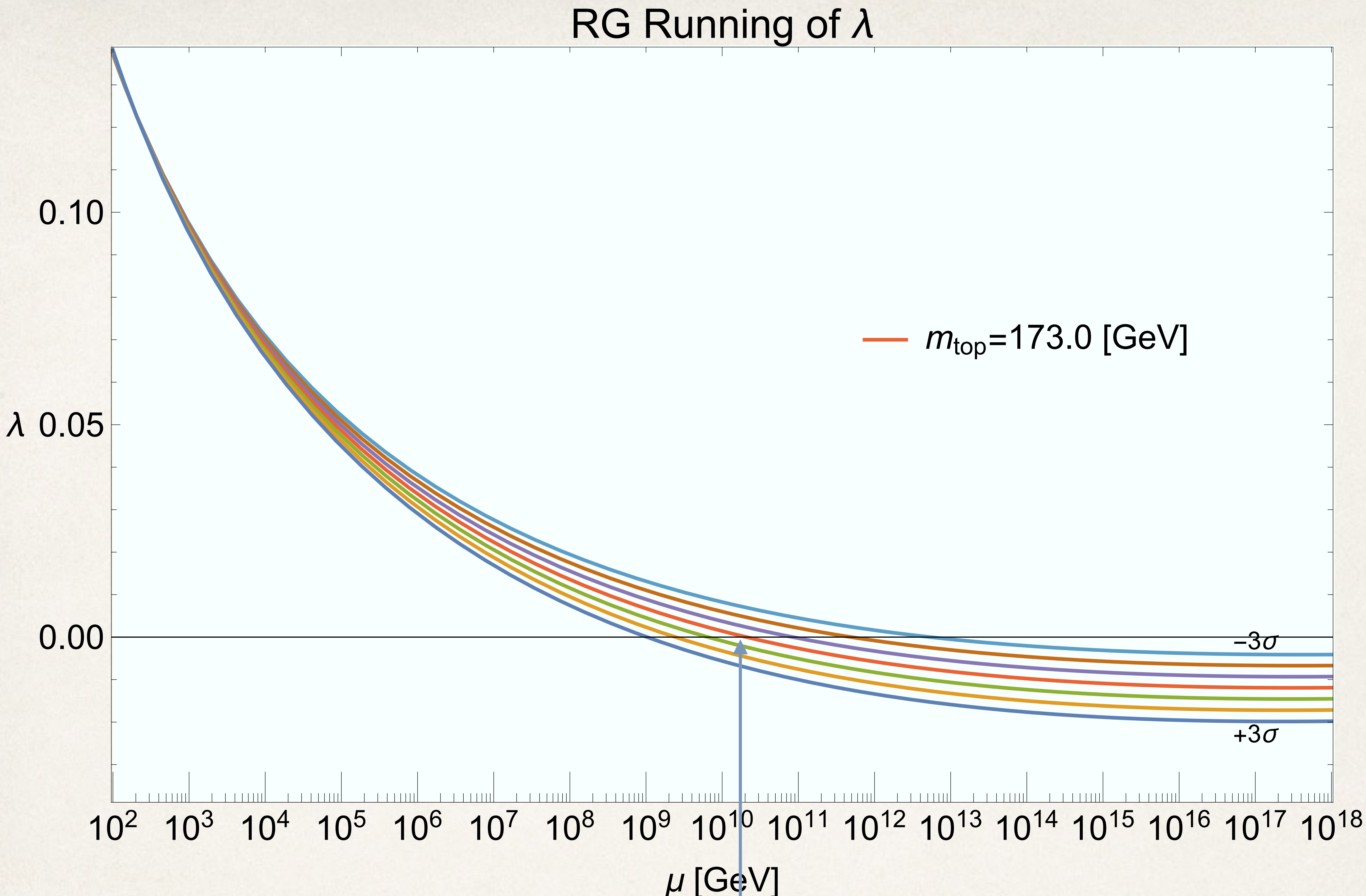
- Requiring $v \ll v'$ $\longrightarrow$ $\lambda' \ll 1$ $\longrightarrow$ $\lambda_{\mathrm{SM}} \approx 0$



$$10^9 \lesssim v' \lesssim 10^{13}$$

Fine-Tuning

- Fine tuning required, but same as SM

$$\frac{v^2}{m^2} \times \frac{m^2}{\Lambda^2} = \frac{v^2}{\Lambda^2}$$

Tuning of λ'

Tuning of v'

Model 1

The Mirror Electroweak Sector

- (1) Extend Z_2 to mirror electroweak sector
- (2) Identify Z_2 with spacetime parity

$$SU(2) \times U(1) \leftrightarrow SU(2)' \times U(1)'$$

$$\vec{x} \leftrightarrow -\vec{x}$$

$$q, \bar{u}, \bar{d}, l, \bar{e} \leftrightarrow (q', \bar{u}', \bar{d}', l', \bar{e}')^\dagger$$

$$H \leftrightarrow H'$$

The Mirror Electroweak Sector

- (1) Extend Z_2 to mirror electroweak sector
- (2) Identify Z_2 with spacetime parity

$$SU(3)_c \times (SU(2)_L \times U(1)_Y) \times (SU(2)'_L \times U(1)'_Y) \times Z_2$$

$$\Big\downarrow \langle H' \rangle = v'$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'_{\rm EM}$$

$$\Big\downarrow \langle H \rangle = v$$

$$SU(3)_c \times U(1)_{\rm EM} \times U(1)'_{\rm EM}$$

- Implications?

Solves Strong CP Problem

- $SU(3) \times (SU(2) \times U(1)) \times (SU(2)' \times U(1)')$ solves strong CP

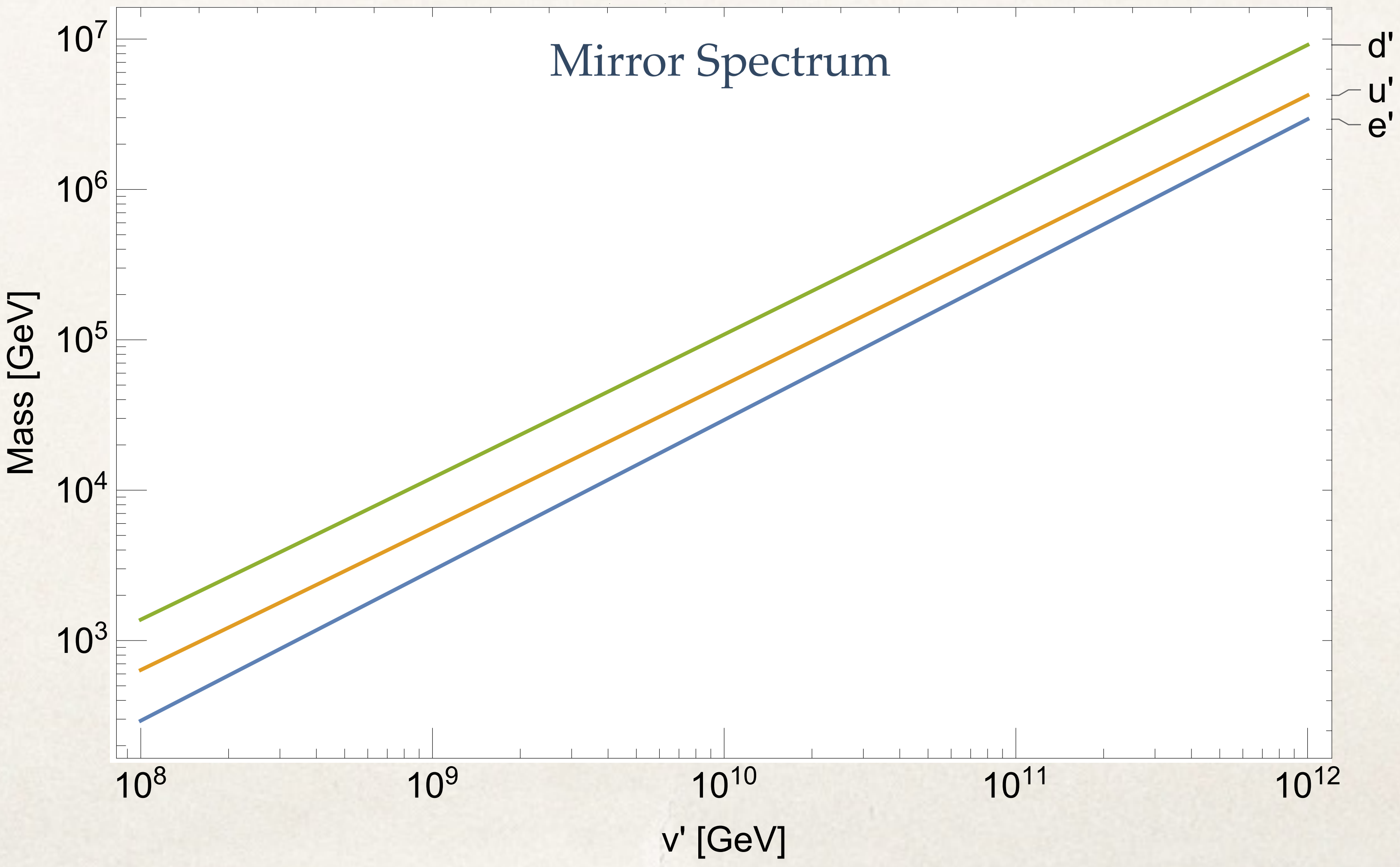
Babu, Chang, Senjanovic (1991)
Hall, Harigaya (2018)

- Parity *is* a symmetry
    - $\dfrac{\theta}{32\pi^2} G\tilde{G}$ forbidden
- No contribution from Yukawa sectors

$$\arg\det \begin{pmatrix} y_{u,d}\, v & 0 \\ 0 & y^*_{u,d}\, v' \end{pmatrix} = 0$$

Mirror Dark Matter

- Natural DM candidate lightest $U(1)'_{\rm EM}$ particle, e'
- DM mass $m_{e'} = y_{e'} v' = m_e \dfrac{v'}{v}$ (1-10^4 TeV)



Signals: Neutron EDM

- Higher dimensional operators generate θ

- $$\mathcal{L}_6 = \frac{C}{M_{Pl}^2}\left(|H|^2 - |H'|^2\right) G\tilde{G}$$

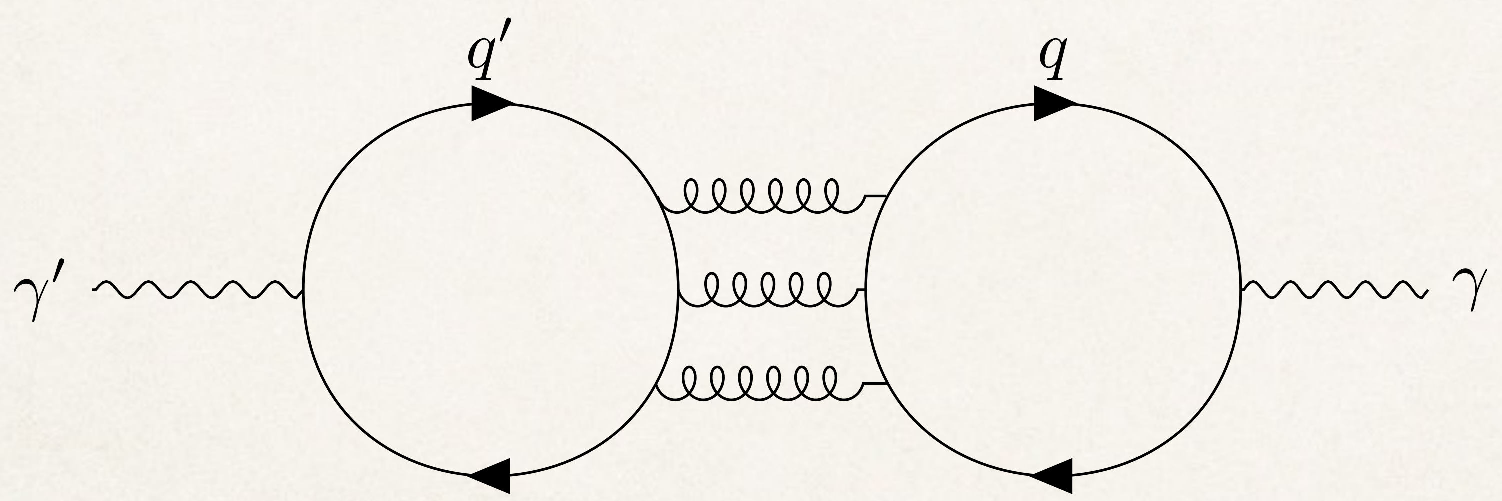
$$\downarrow$$

$$\theta = 32\pi^2 C\left(\frac{v'}{M_{Pl}}\right)^2 = 5\times 10^{-11} C\left(\frac{v'}{10^{12}\ \mathrm{GeV}}\right)^2$$

- Current neutron EDM limit $\theta < 10^{-10}$ Baker, et al (2006)

Signals: Kinetic Mixing

- $\mathcal{L} \supset -\frac{\epsilon_B}{2} B^{\mu\nu} B'_{\mu\nu}$ allowed
- Generated by

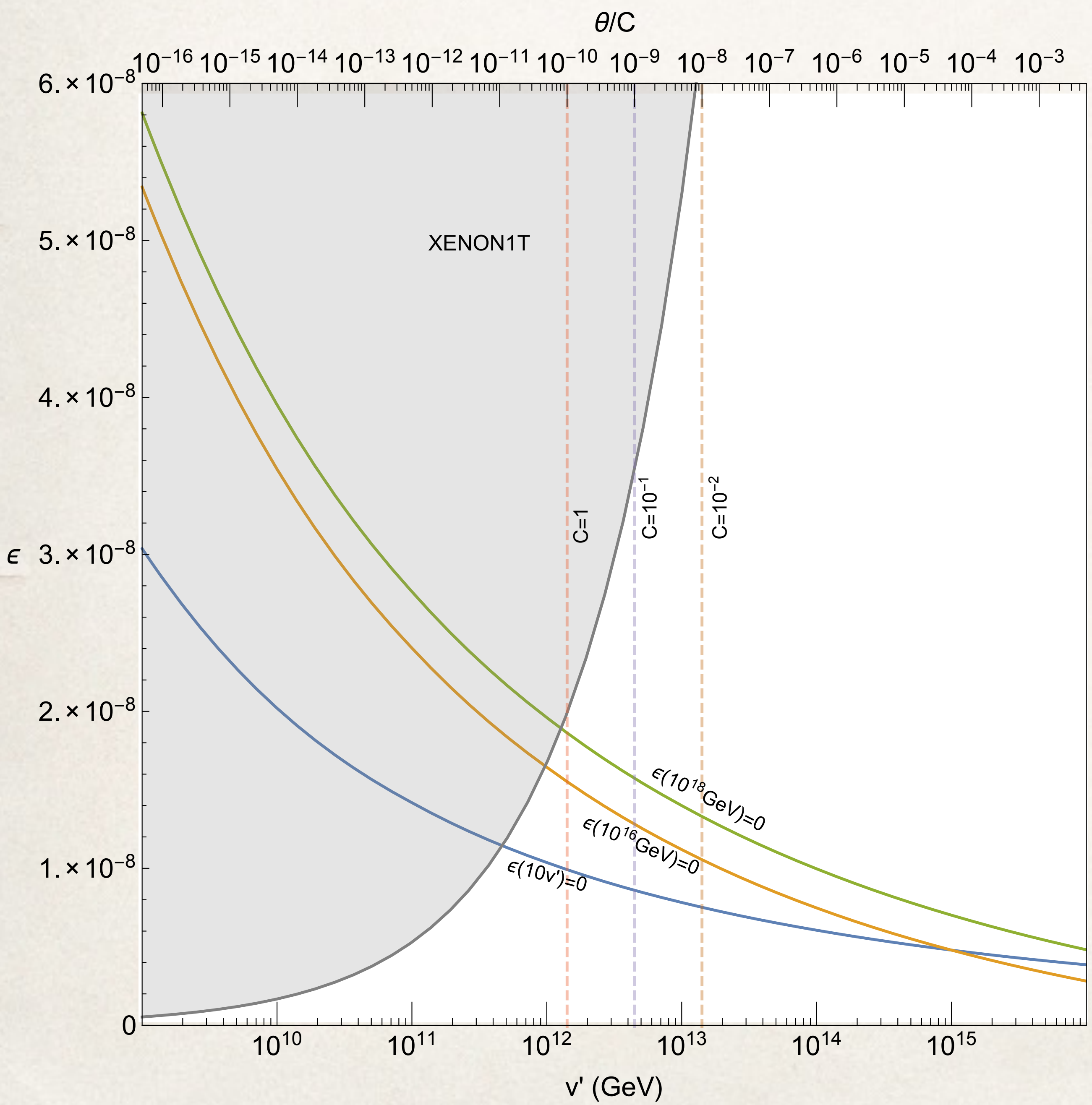


$\approx 10^{-8}$

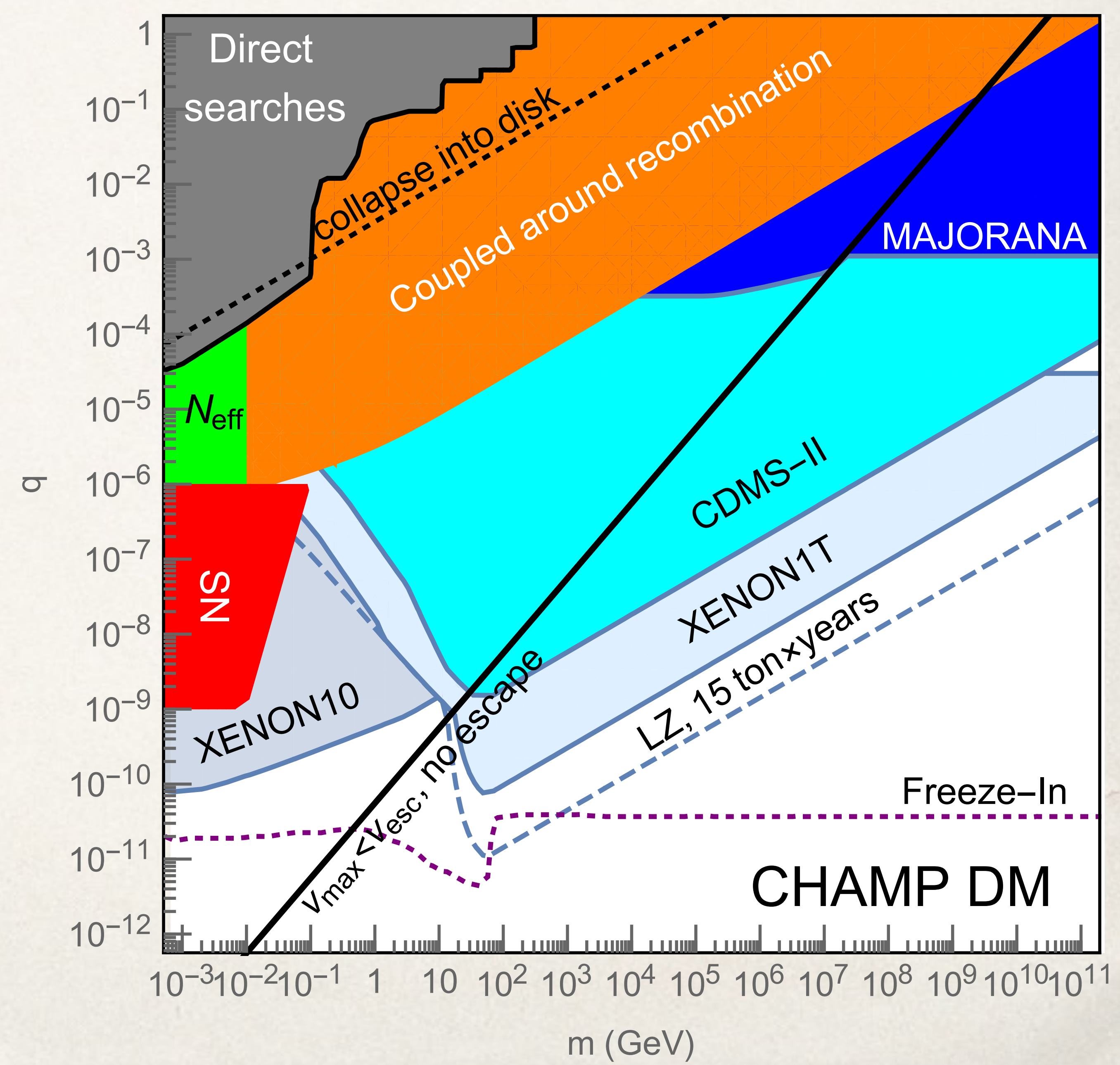
(Calculable from 4-loop QCD beta function)

van Ritbergen, Vermaseren, Larin (1997)

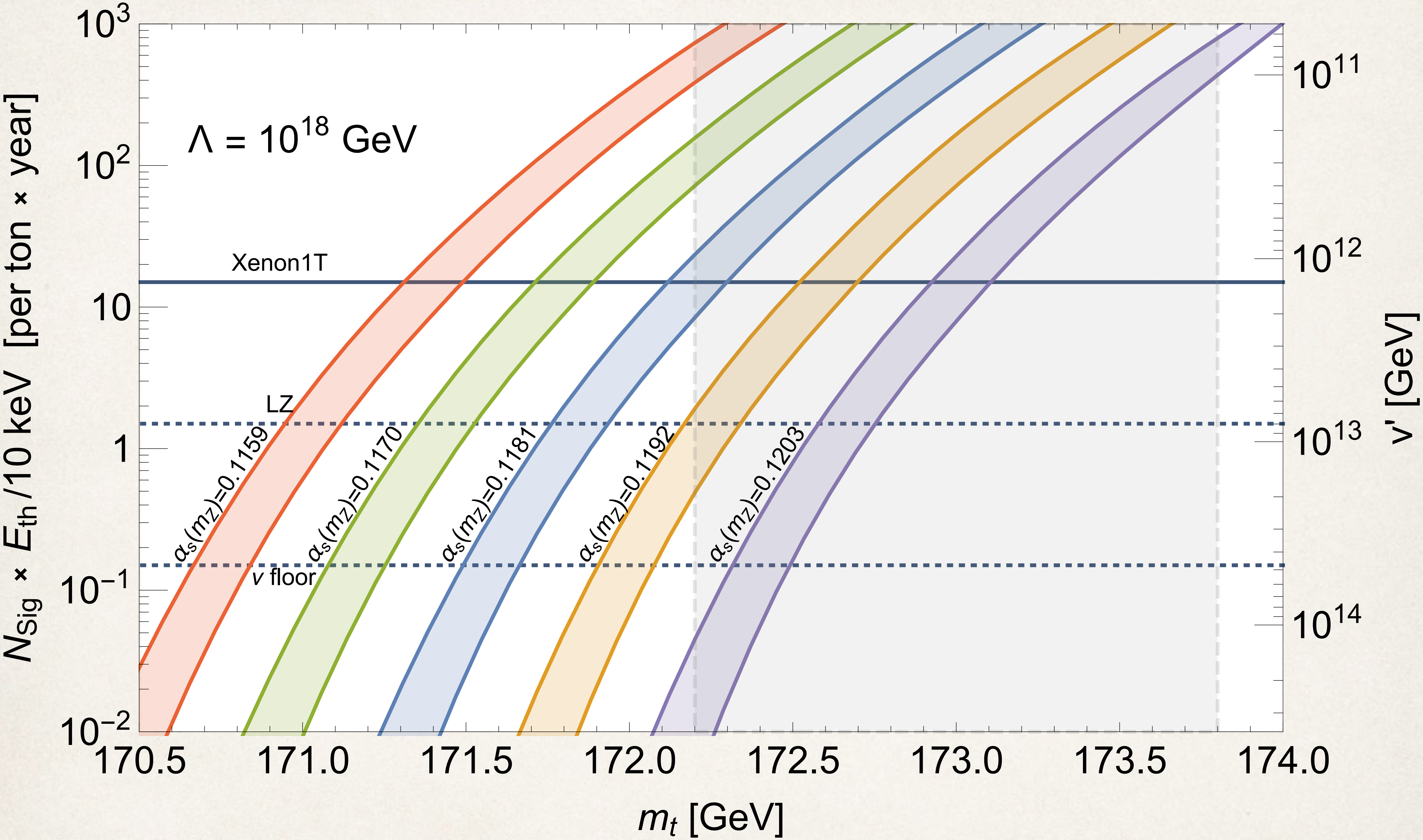
Signals: Kinetic Mixing



Dunsky, Hall, Harigaya (2018) arXiv:1812.11116



e' DM Direct Detection Rate

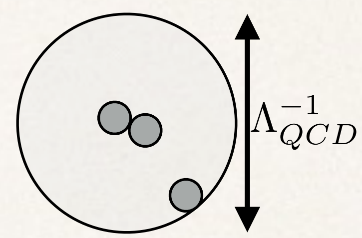


Other Higgs Parity Models

- $SU(3) \times (SU(2) \times U(1)) \times (SU(2)' \times U(1)')$ not unique

- For ex, $(SU(3) \times SU(2) \times U(1)) \times ((SU(3)' \times SU(2)' \times U(1)')$

  Dunsky, Hall, Harigaya (2019) arXiv:1908.02756

  - No dangerous mixed hadrons 

$u'u'q$

  - Gravitational wave signatures from $N_f = 0$ QCD' PT

  - Needs axion to solve Strong CP

Model 2

Left-Right Higgs Parity

- (1) Extend Z_2 to RH weak sector
- (2) Identify Z_2 with spacetime parity

$$SU(2)_L \leftrightarrow SU(2)_R$$
$$\vec{x} \leftrightarrow -\vec{x}$$
$$q,\ l \leftrightarrow (\bar{q},\ \bar{l})^\dagger$$
$$H_L \leftrightarrow H_R$$

Left-Right Higgs Parity

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- (2) Identify Z_2 with spacetime parity

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times Z_2$$

$$\big\downarrow \langle H_R \rangle = v_R$$

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

$$\big\downarrow \langle H_L \rangle = v$$

$$SU(3)_c \times U(1)_{\mathrm{EM}}$$

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- Parity *is* a symmetry
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- No contribution from (Hermitian) Yukawa sectors

$$\arg\det \mathbf{M}_{u,d} = \arg\det \mathbf{M}^{\dagger}{}_{u,d} = 0$$

- Same Neutron EDM Signal $\mathcal{L}_6 = \frac{C}{M_{Pl}^2}\left(|H_L|^2 - |H_R|^2\right) G\tilde{G}$

Dark Matter Candidate?

- Previously, e' DM stabilized by unbroken $U(1)'_{\rm EM}$

- Now, three Higgs Parity partners to SM neutrinos

$$N_1,\ N_2,\ N_3$$

- Lightest sterile neutrino, N_1 , DM candidate if long-lived

Right-Handed Sterile Neutrinos

- In SM, exists one dim-5 operator: $\frac{c_i}{2}\frac{(l_i H_L)(l_i H_L)}{\mathcal{M}}$

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$\downarrow$ Diagonalize

- N_i dominantly $\bar{l}_i$

$$M_i \simeq c_i v_R^2/\mathcal{M}$$

- ν_i admixture

$$m_{\nu,ij} = \delta_{ij}\frac{v^2}{v_R^2}M_i - y_{ik}^T v\,\frac{1}{M_k}\,y_{kj}v$$

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- Long-lived N_1 requires small y_{1i}

Freeze-Out and Dilution of N_1 DM

- If $T_{\rm RH}$ high enough, N_i in thermal eq. from W_R exchange
- As T drops, N_i relativistically decouple, with abundance

$$\rho_{N_1}/s = M_1 Y_{\rm therm} = 0.4\,{\rm eV}\left(\frac{{\rm M}_1}{0.1\,{\rm keV}}\right)$$

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Problem!

ρ_{DM}/s

Freeze-Out and Dilution of N_1 DM

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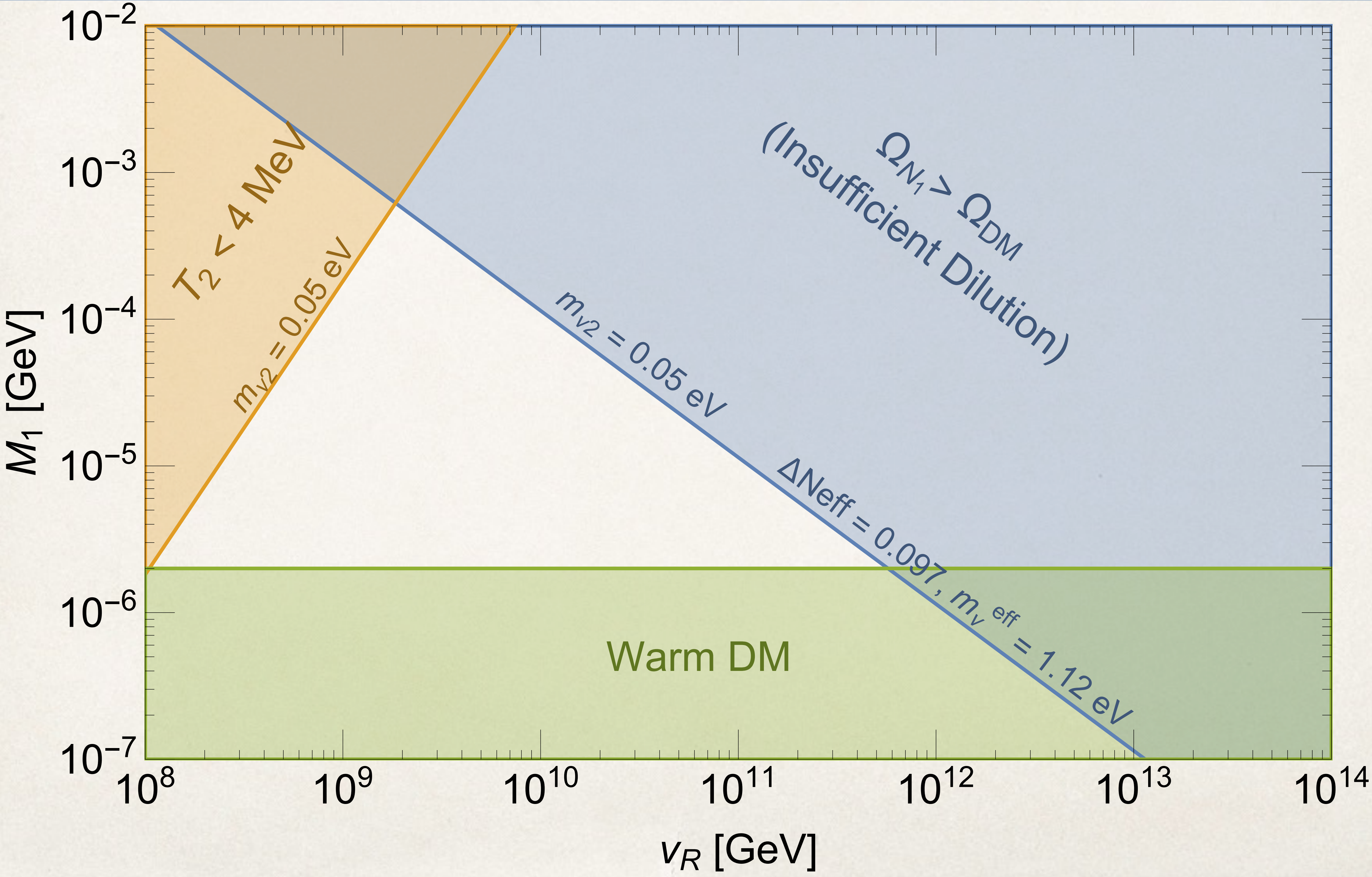
$$\uparrow$$
$$\rho_{\rm DM}/s$$

- Built-in solution: heavy $N_{2,3}$ can be:
  - Long-lived $\rightarrow$ dominate over $\rho_{\rm rad}$ $\rightarrow$ dilute N_1 upon decay

Freeze-Out and Dilution of N_1 DM



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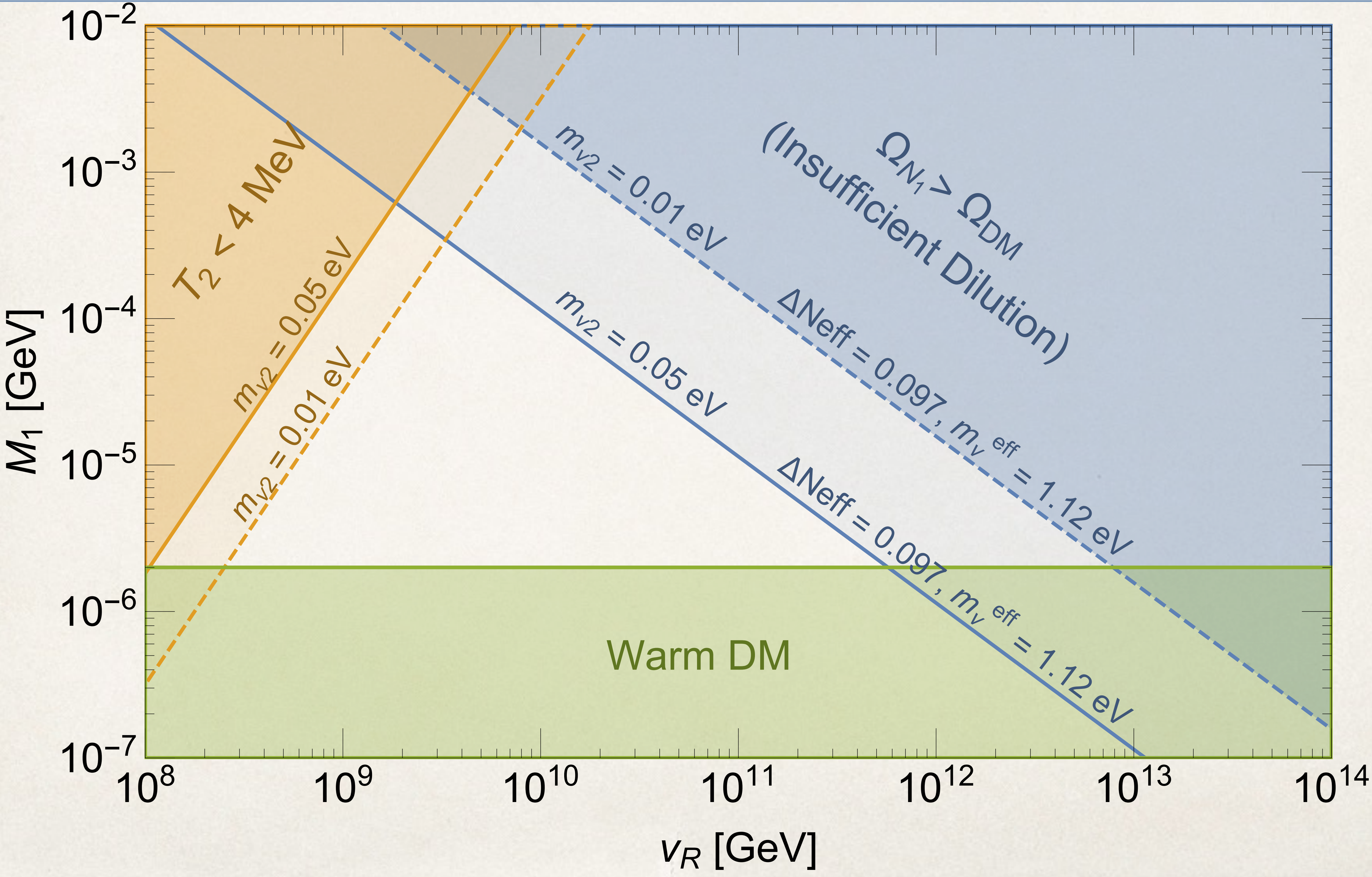


Leptogenesis

- N responsible for dilution upon decay can also generate lepton asymmetry

- Assuming $y_{22} < y_{33}$ (WLOG)
- Assuming $y_{22} < |y_{23}|$ (Maximize lepton asymmetry)

$$\epsilon_{N_2} \equiv \mathrm{Br}(N_2 \to l H_L) - \mathrm{Br}(N_2 \to l^\dagger H_L^\dagger) \simeq \frac{y_{33}^2}{8\pi} \delta g(x) \qquad x \equiv (M_3/M_2)^2$$

$$Y_B \simeq \frac{28}{79} \epsilon_{N_2} \frac{Y_{N_2}}{D} = \frac{28}{79} \epsilon_{N_2} \frac{0.4\mathrm{eV}}{M_1}$$ Must equal observed 8×10^{-11}

Fukugita, Yanagida (1986)

Generating a large lepton asymmetry

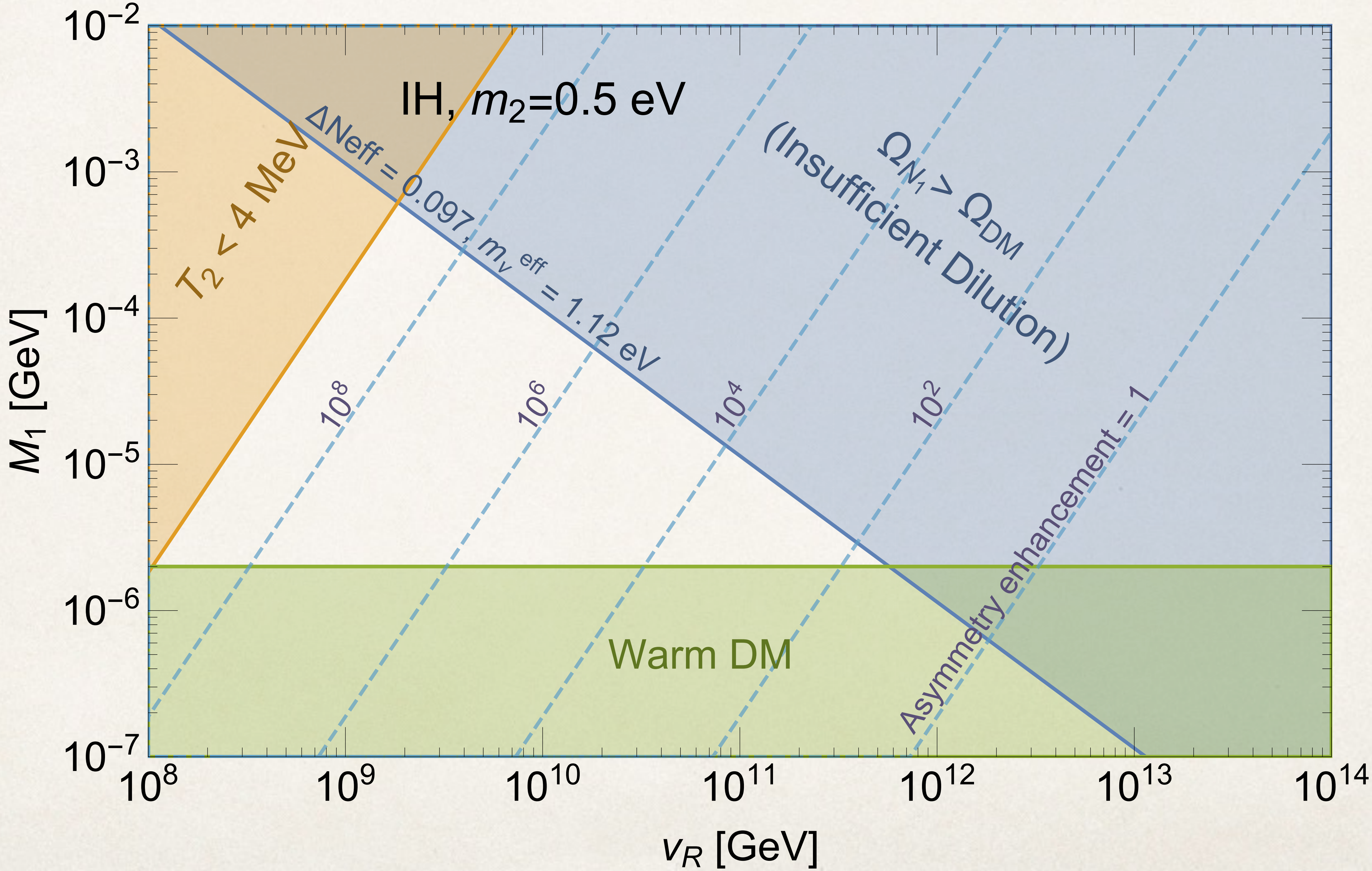
- $$Y_B \approx \frac{y_{33}^2}{8\pi}\delta g(x)\frac{0.4\,\mathrm{eV}}{M_1}$$

- Typical values:

  - $m_{\nu 3}^{(5)} \sim m_{\nu 3}^{(ss)} \sim m_3 \simeq (0.01\,\mathrm{eV}\ \text{or}\ 0.05\,\mathrm{eV}) \longrightarrow y_{33}^2 \sim \frac{m_3^2 v_R^2}{v^4}$

  - $M_2 \sim M_3 \longrightarrow g(x) \sim 1$

Required Lepton Asymmetry



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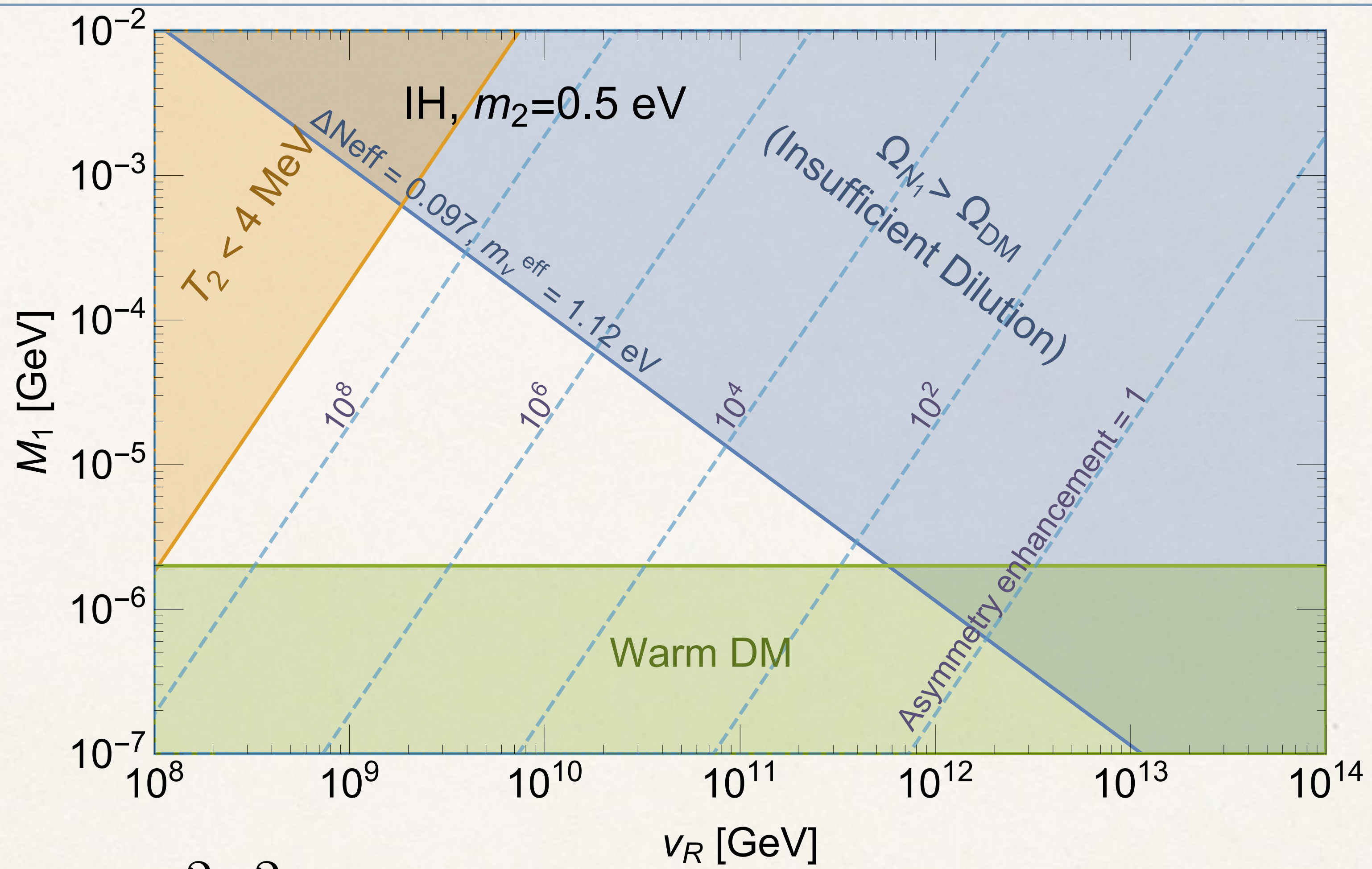

- Increase $y_{33}^2 \sim \dfrac{m_3^2 v_R^2}{v^4}$
  - Large v_R
  - Large $m_{\nu 3}^{(ss)} \gg m_3$

or

- Increase $g(x)$ (i.e $N_{2,3}$ degeneracy)
  - IH with $\left(\dfrac{M_3}{M_2}\right)^2 = \left(\dfrac{m_3 v_R^2/v^2}{m_2 v_R^2/v^2}\right)^2 \simeq 1$
  - Introduce $N_{2,3}$ symmetry

Summary

- Observed Higgs mass imply next symmetry breaking scale of nature?
- Motivated by Strong CP $\longrightarrow$ Higgs Parity, no QCD′
- Motivated by DM $\longrightarrow$ Mirror electroweak, $SU(2)_R$
- Same number of parameters as SM below v'
- Future measurements of $\{m_t, m_h, \alpha_s(M_Z)\}$ will hone in on v'
- Parameter space will be probed by future detectors