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Sterile Neutrino Dark Matter and Leptogenesis in Parity symmetric theory

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Dror, Dunsky, Hall and KH [2004.09511]
Dunsky, Hall and KH [2007.12711]

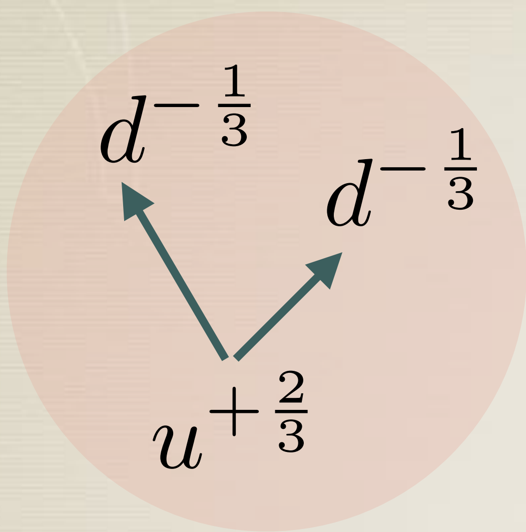
Summary

* Parity symmetry can solve the strong CP problem
* Dark matter and baryon asymmetry can be explained for a range of parity symmetry breaking scales
* The symmetry breaking scale is correlated with the top quark mass and the strong coupling constant
* The parameter space can be probed by the warmness of dark matter and measurements of SM parameters

Outline

* Introduction : the strong CP problem and parity
* Minimal fermions or Higgses models
* Sterile neutrino dark matter
* Leptogenesis
* Top quark mass and strong coupling constant

The strong CP problem



Neutron Electric Dipole Moment

$$H = d_n \vec{E} \cdot \vec{S}$$

$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm ?}$$

$$d_n/e < 2.9 \times 10^{-26} \text{ cm}$$ Baker et.al (2006)

Suggests CP symmetry forbidding $H = d_n \vec{E} \cdot \vec{S}$

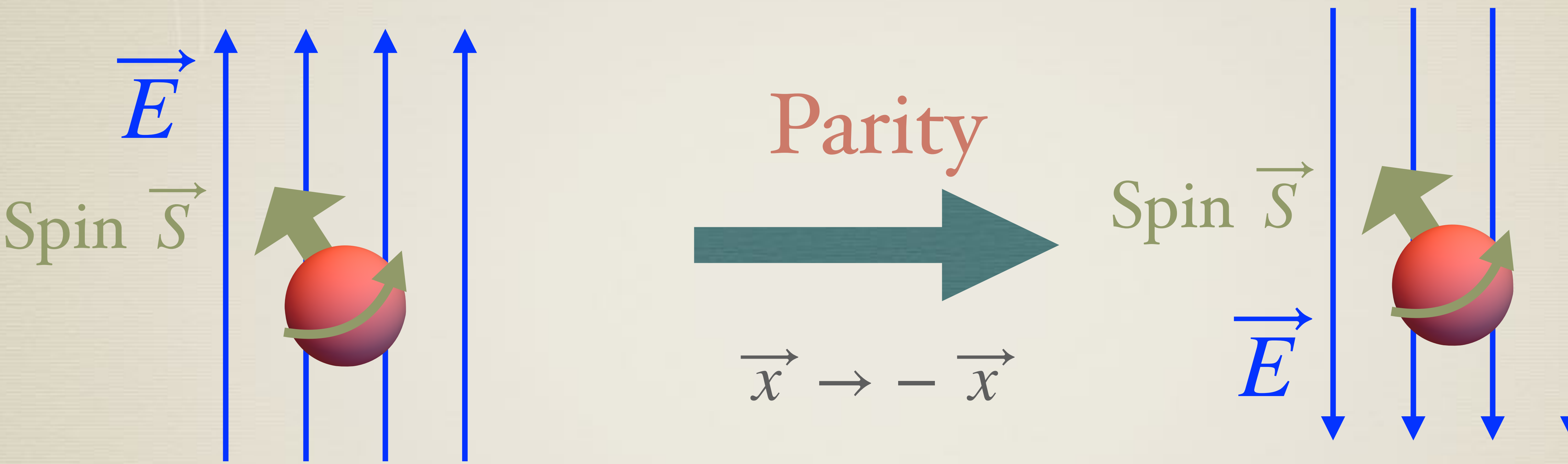
But CP violation from quark masses is essential for CKM phase

Strong CP problem

't Hooft (1976)

Parity solution

Mohapatra and Senjanovic (1978), Beg and Tsao (1978), Babu and Mohapatra (1989)



$$\vec{S} = \text{“}\vec{x} \times \vec{v}\text{”}$$

$$\cancel{H = d_n \vec{E} \cdot \vec{S}}$$

Parity solution

Fermions

Left Right

$$u_i(t,x) \leftrightarrow \bar{u}_i^\dagger(t,-x)$$

$$u_i m_{ij} \bar{u}_j + u_i^\dagger m_{ij}^* \bar{u}_j^\dagger$$

$$u_j^\dagger m_{ij} \bar{u}_i^\dagger + u_j m_{ij}^* \bar{u}_i$$

Hermitian mass

(CP is violated!)

Gluons

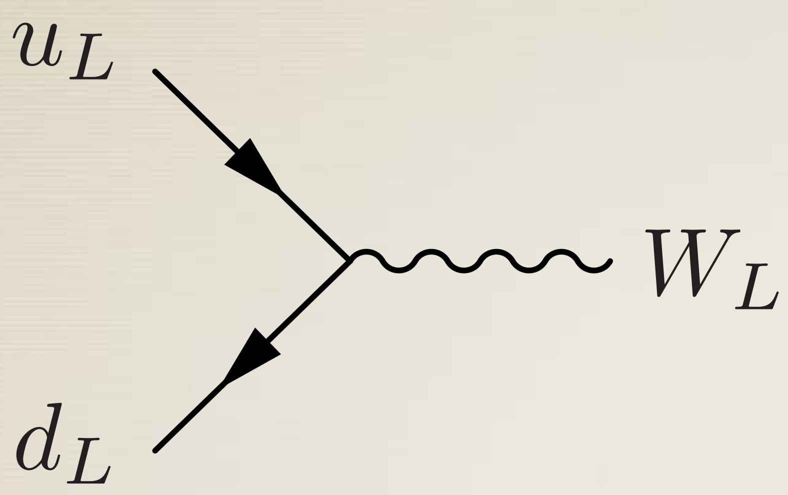
$$G_{01} \to -G_{01}$$

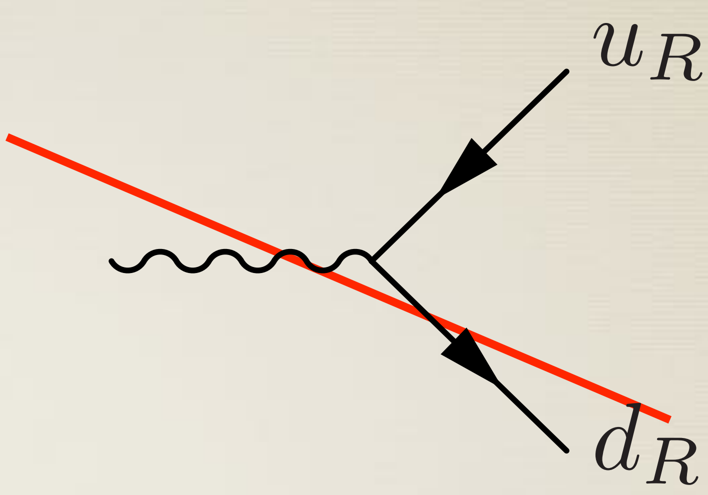
$$G_{23} \to G_{23} \quad \text{etc}$$

$$\cancel{\theta_{\rm QCD} G\tilde{G}}$$

$$\theta_{\rm CPV} = \theta_{\rm QCD} + \arg(\det m_{ij}) = 0$$

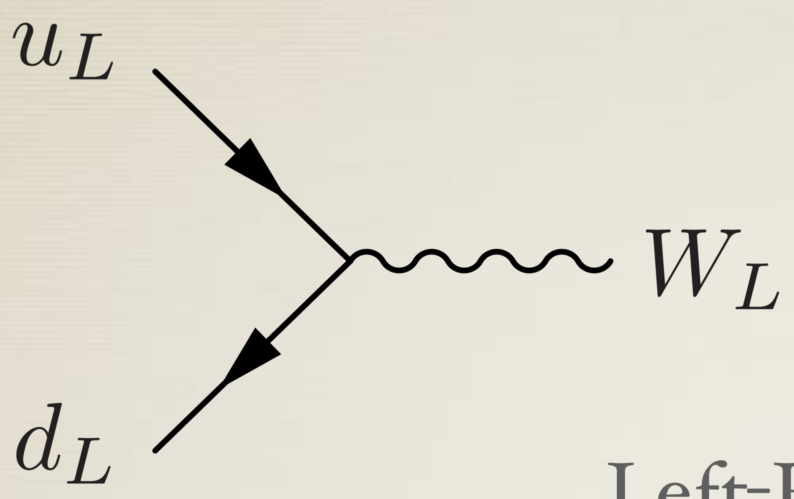
Parity is broken

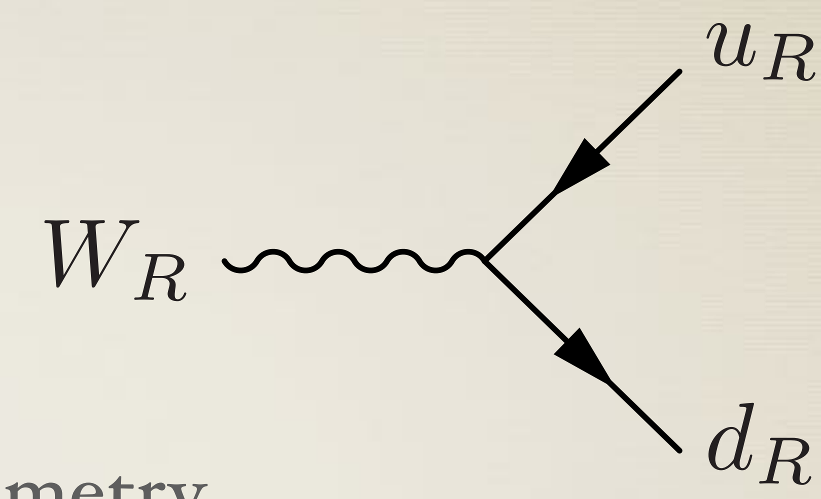




Lee and Yang (1956), Wu (1957)

New gauge bosons





Left-Right symmetry

$SU(2)_L \Longleftrightarrow SU(2)_R$

$m_{W_L} \ll m_{W_R}$ by spontaneous breaking of the LR symmetry

Lee (1973), Pati and Salam (1975),
Moahapatra and Pati (1975), Senjanovic and Mohapatra (1975)

The strong CP phase may arise again
after the spontaneous breaking

(I will detail more later)

Right-handed neutrinos

$$\ell = (\nu, e) \leftrightarrow \bar{\ell} = (N, \bar{e})$$

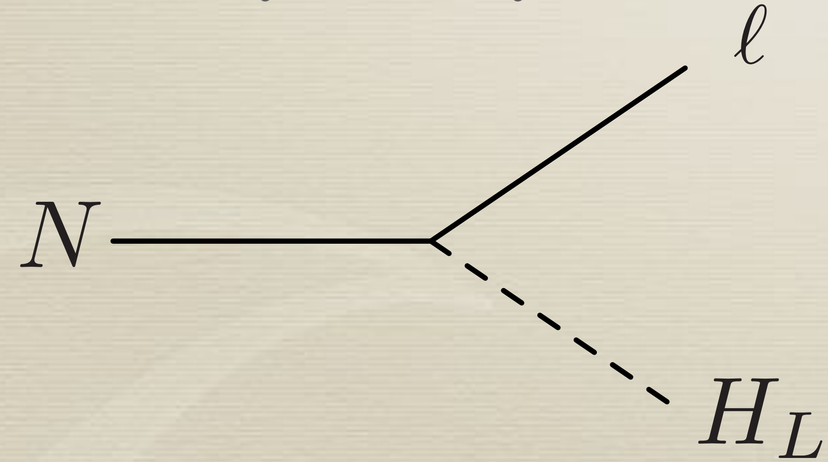
* Dark matter

  N is neutral and may be stable enough

  Sterile neutrino dark matter

  Dodelson and Widrow (1993)
  Khail and Seto (2008)
  Bezrukov, Hettmansperger and Lindner (2009)
  Dror, Dunsky, Hall and KH (2020)

* Baryon asymmetry



Leptogenesis

Fukugita and Yanagida (1986)
Dunsky, Hall and KH (2020)

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* Leptogenesis
* Top quark mass and strong coupling constant

Minimal fermion model

Mohapatra and Senjanovic (1978)
Beg and Tsao (1978)

$SU(2)_L$ $\qquad$ $SU(2)_R$

$q = (u, d)$ $\qquad$ Parity $\longleftrightarrow$ $\qquad$ $\bar{q} = (\bar{u}, \bar{d})$

$\ell = (\nu, e)$ $\qquad$ $\bar{\ell} = (N, \bar{e})$

$$q(t, x) \leftrightarrow i\sigma_2 \bar{q}^*(t, -x)$$

Higgses

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

$$\downarrow$$

$T_R(1,1,3,1)$ parity $T_L(1,3,1,1)$

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

$$\downarrow$$

$\Phi(1,2,2,0)$ parity Φ^*

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

Yukawa couplings

Let us concentrate on quarks

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

$$q(3,2,1,1/6) \qquad \Phi(1,2,2,0) \qquad \bar{q}(\bar{3},1,2,-1/6)$$

$$y_{ij} q_i \Phi \bar{q}_j + y'_{ij} q_i \Phi^* \bar{q}_j + \mathrm{h.c.}$$

Parity
$\Phi \leftrightarrow \Phi^*$

yukawa couplings are Hermitian because of the parity symmetry

$\det(y), \det(y')$ are real

The strong CP problem is solved??

Wait, what about the phases of Higgs vev?

Yukawa couplings

$$y_{ij} q_i \Phi \bar{q}_j + y'_{ij} q_i \Phi^* \bar{q}_j + \mathrm{h.c.}$$

$$\Phi(1,2,2,0)$$

$$\Phi = (H, \epsilon H^*)$$

Suppose Φ is pseudo-real : $\epsilon \Phi^* \epsilon = \Phi$

$$y_{ij} q_i \Phi \bar{q}_j + \mathrm{h.c.} \quad \text{with} \quad \Phi = \begin{pmatrix} v & 0 \\ 0 & v^* \end{pmatrix}$$

$$m_{u,ij} = y_{ij} v, \quad m_{d,ij} = y_{ij} v^*$$

$\det(m_u) \times \det(m_d)$ is real, but

$$m_u = m_d, \; m_c = m_s, \; m_t = m_b$$

Yukawa couplings

$$y_{ij} q_i \Phi \bar{q}_j + y'_{ij} q_i \Phi^* \bar{q}_j + \mathrm{h.c.}$$

$$\Phi(1,2,2,0)$$

$$\Phi = (H_1,\ H_2^*)$$

Suppose Φ is complex

$$\Phi = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix}$$

$$m_{u,ij} = y_{ij} v_1 + y'_{ij} v_2^*, \quad m_{d,ij} = y_{ij} v_2 + y'_{ij} v_1^*$$

Realistic quark masses can be obtained, but

$\det(m_u) \times \det(m_d)$ is NOT real unless $\arg(v_2) = -\arg(v_1)$

Phase of Higgs VEV

Most of the parameters of the Higgs potential are real because of Hermiticity and parity

$\Phi \leftrightarrow \Phi^*$

$$|\Phi|^4,\ |\Phi|^2,\ \Phi^2 + \Phi^{*2}$$

However, we must introduce $SU(2)_R$ symmetry breaking field T_R and its parity partner T_L

$$e^{i\alpha}|T_R|^2\Phi^2 + e^{i\alpha}|T_L|^2\Phi^{*2}$$
$$+e^{-i\alpha}|T_R|^2\Phi^{*2} + e^{-i\alpha}|T_L|^2\Phi^2$$

$T_R \gg T_L$

$$\Longrightarrow \quad e^{i\alpha}\Phi^2 + e^{-i\alpha}\Phi^{*2} \supset e^{i\alpha}v_1 v_2 + \mathrm{h.c.}$$

Way out

$$e^{i\alpha}|T_R|^2\Phi^2 + e^{i\alpha}|T_L|^2\Phi^{*2}$$
$$+e^{-i\alpha}|T_R|^2\Phi^{*2} + e^{-i\alpha}|T_L|^2\Phi^2$$

We must forbid these quartic couplings

Ex. supersymmetry

Kuchimanchi (1995), Mohapatra and Rasin (1995)

Minimal Higgs model

Babu and Mohapatra(1989)

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

$$\downarrow \quad H_R(1,1,2,-1/2)$$

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

parity

$$\downarrow \quad H_L(1,2,1,1/2)$$

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

Fermion sector?

$SU(2)_L$	Parity	$SU(2)_R$
$q = (u, d)$	$\Longleftrightarrow$	$\bar{q} = (\bar{u}, \bar{d})$
$(3,2,1,1/6)$		$(\bar{3},1,2,-1/6)$
$\ell = (\nu, e)$		$\bar{\ell} = (N, \bar{e})$
$(1,2,1,-1/2)$		$(1,1,2,1/2)$

But yukawa couplings are forbidden

$$\cancel{q\bar{q}H_L}$$

Yukawa couplings

Babu and Mohapatra(1989)

$$y_{ij} q_i H_L \bar{U}_j + y_{ij}^* \bar{q}_i H_R U_j + M_{ij} U_i \bar{U}_j$$

$M \gg y v_R$ $\Rightarrow$ $\dfrac{y^2}{M} q \bar{q} H_L H_R$

right-handed quarks $\simeq \bar{q}$

(not viable for top)

$M \ll y v_R$ $\Rightarrow$ right-handed quarks $\simeq \bar{U}$

Yukawa couplings

Babu and Mohapatra(1989)

$$y_{ij} q_i H_L \bar{U}_j + y_{ij}^* \bar{q}_i H_R U_j + M_{ij} U_i \bar{U}_j$$

$$\begin{pmatrix} q & U \end{pmatrix} \begin{pmatrix} 0 & y v_L \\ y^\dagger v_R & M \end{pmatrix} \begin{pmatrix} \bar{q} \\ \bar{U} \end{pmatrix}$$

$$\det(m_u) \propto \det(y y^\dagger) \qquad \text{is real}$$

Strong CP problem is solved!

(Quantum corrections are found to be small enough)

Hall, KH (2018)

I will consider the minimal Higgs model in the following

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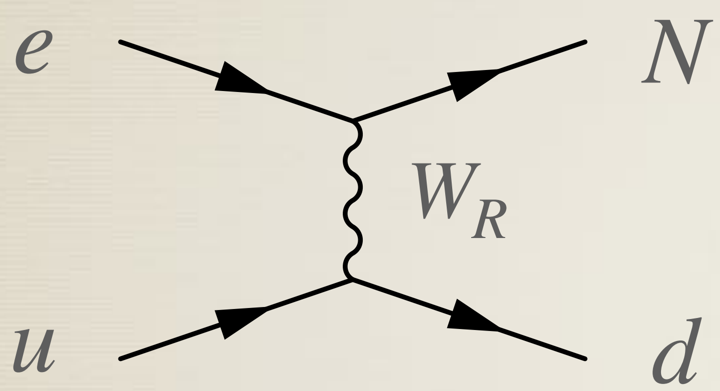
Production of dark matter

Relativistic freeze-out + dilution



Decouple at

$$T = 10^8 \text{ GeV} \left(\frac{v_R}{10^{10} \text{ GeV}} \right)^{4/3}$$

Too much unless $m_N \lesssim 100$ eV, for which dark matter is too warm

→ larger m_N and dilution

Bezrukov, Hettmansperger and Lindner (2009)
Asaka, Shaposhnikov and Kusenko (2006)
Nemevsek, Senjanovic and Zhang (2012)
Dror, Dunsky, Hall and KH (2020)

Other possibility includes freeze-in:

Khail and Seto (2008), Kusenko, Takahashi and Yanagida (2010), ...
Dror, Dunsky, Hall and KH (2020)

Dilution by heavy right-handed neutrino

Three right-handed neutrinos N_i with masses M_i

(The numbering not necessarily corresponds to the numbering of SM neutrinos)

N_1 : Dark matter
N_2 : Long-lived, dominate the universe, decay, and dilute dark matter
N_3 : (Provide quantum correction required for leptogenesis)

$$\frac{\Omega_{\mathrm{N}_1}}{\Omega_{\mathrm{DM}}} \simeq \frac{M_1}{10\ \mathrm{keV}} \frac{300\ \mathrm{GeV}}{M_2} \frac{T_{\mathrm{dec}}}{10\ \mathrm{MeV}}$$

Don't disturb BBN : $T_{\mathrm{dec}} > 4\ \mathrm{MeV}$

➡ Large enough M_2 is required

Right-handed neutrino mass?

$$\ell = (\nu, e), \quad \bar{\ell} = (N, \bar{e})$$

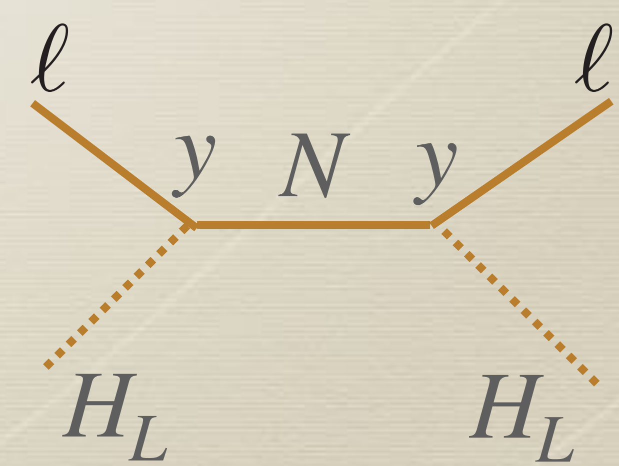
$$\frac{c_i}{2\Lambda}\ell_i\ell_i H_L H_L + \frac{c_i}{2\Lambda}\bar{\ell}_i\bar{\ell}_i H_R H_R + \frac{d_{ij}}{\Lambda}\ell_i\bar{\ell}_j H_L H_R$$

$$M_i = \frac{c_i}{\Lambda}{v_R}^2$$

$$y_{ij} = \frac{v_R}{\Lambda}d_{ij}$$

$$\frac{c_i}{2\Lambda}\ell_i\ell_i H_L H_L + \frac{M_i}{2}N_i N_i + y_{ij}\ell_i N_j H_L$$

$$m_{\nu,ij} = \delta_{ij}M_i\left(\frac{v_L}{v_R}\right)^2 - \frac{y_{ik}y_{jk}v_L^2}{M_k}$$

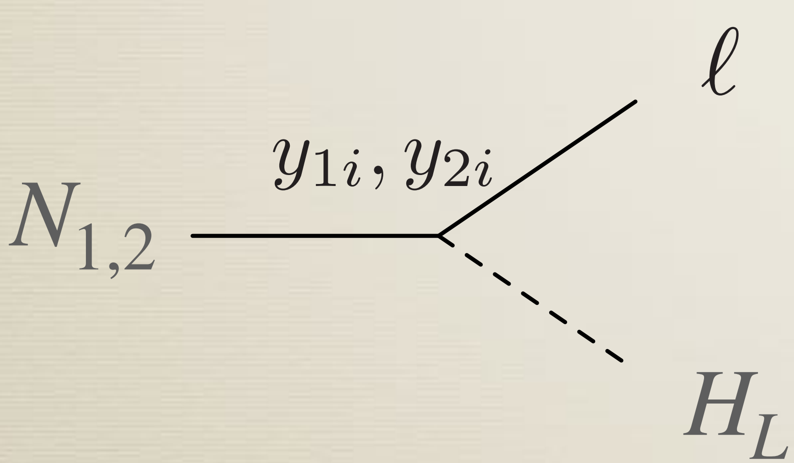


Right-handed neutrino mass?

$$\begin{pmatrix} \left(\frac{v_L}{v_R}\right)^2 M_1 - \frac{y_{1i}^2}{M_i} v_L^2 & -\frac{y_{2i} y_{1i}}{M_i} v_L^2 & -\frac{y_{1i} y_{3i}}{M_i} v_L^2 \\ -\frac{y_{2i} y_{1i}}{M_i} & \left(\frac{v_L}{v_R}\right)^2 M_2 - \frac{y_{2i}^2}{M_i} v_L^2 & -\frac{y_{2i} y_{3i}}{M_i} v_L^2 \\ -\frac{y_{1i} y_{3i}}{M_i} v_L^2 & -\frac{y_{2i} y_{3i}}{M_i} v_L^2 & \left(\frac{v_L}{v_R}\right)^2 M_3 - \frac{y_{3i}^2}{M_i} v_L^2 \end{pmatrix}$$

Right-handed neutrino mass?

$$\begin{pmatrix} \cancel{\left(\frac{v_L}{v_R}\right)^2 M_1 - \frac{y_{1i}^2}{M_i} v_L^2} & \cancel{-\frac{y_{2i}y_{1i}}{M_i} v_L^2} & \cancel{-\frac{y_{1i}y_{3i}}{M_i} v_L^2} \\ \cancel{-\frac{y_{2i}y_{1i}}{M_i}} & \left(\frac{v_L}{v_R}\right)^2 M_2 - \cancel{\frac{y_{2i}^2}{M_i} v_L^2} & \cancel{-\frac{y_{2i}y_{3i}}{M_i} v_L^2} \\ \cancel{-\frac{y_{1i}y_{3i}}{M_i} v_L^2} & \cancel{-\frac{y_{2i}y_{3i}}{M_i} v_L^2} & \left(\frac{v_L}{v_R}\right)^2 M_3 - \frac{y_{33}^2}{M_3} v_L^2 \end{pmatrix}$$

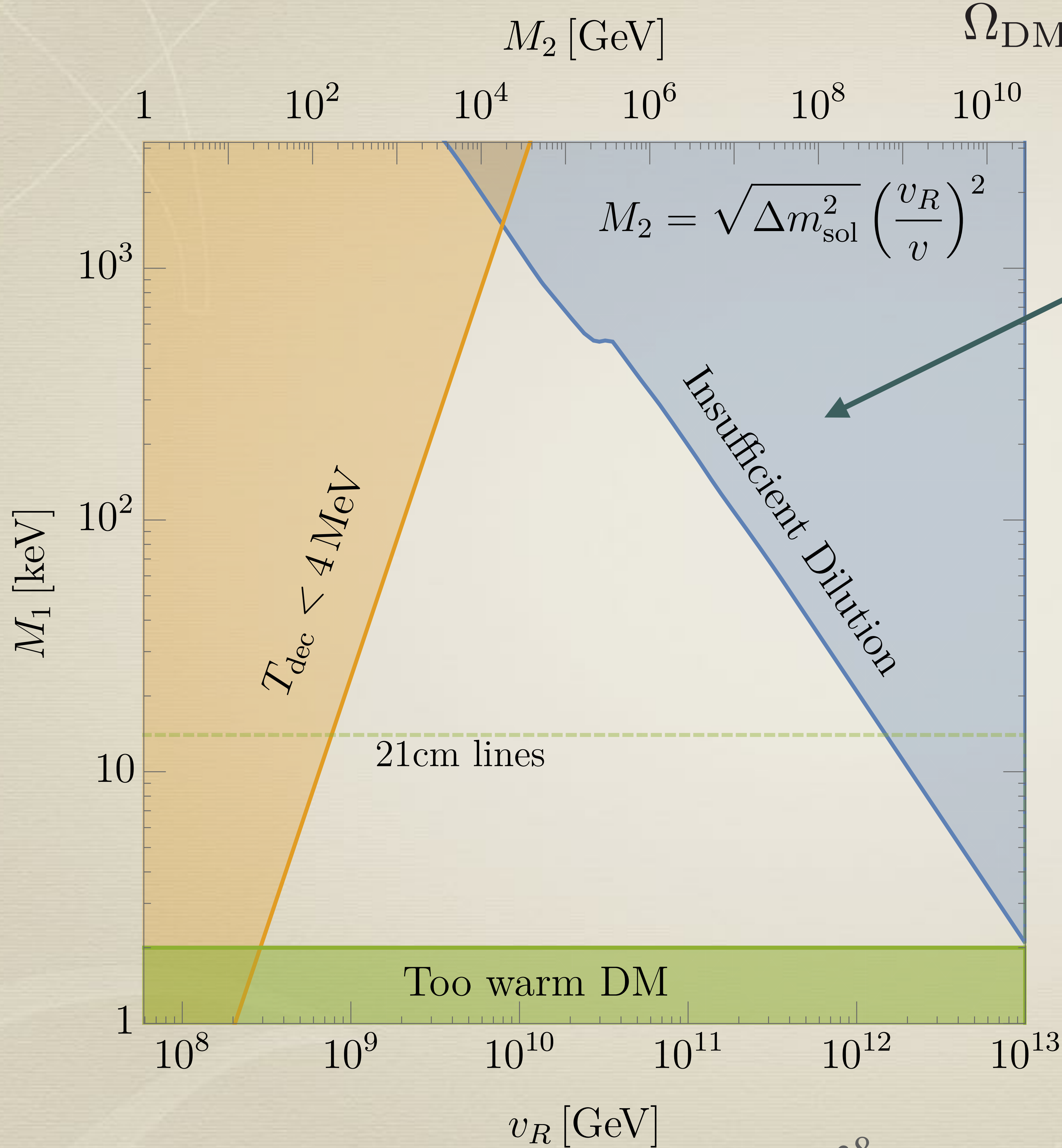


Enough stability of $N_{1,2}$

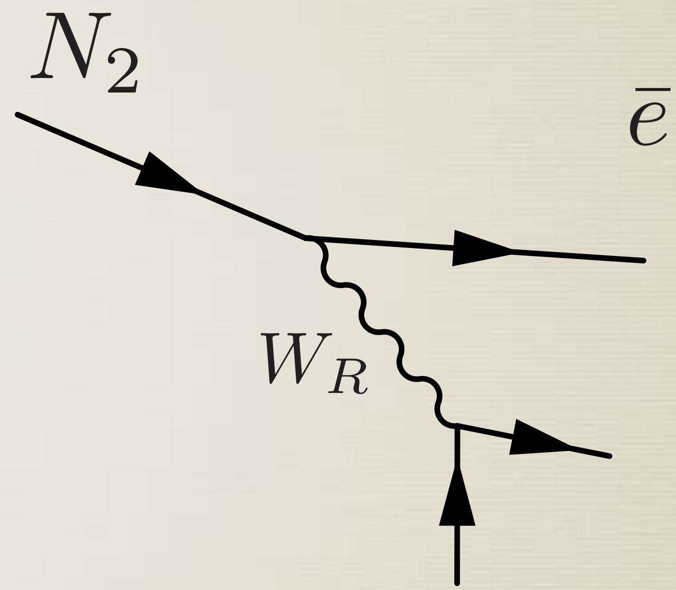
$$\boxed{M_2 = \left(\frac{v_R}{v_L}\right)^2 \times (\text{observed SM neutrino mass})}$$

Dror, Dunsky, Hall and KH (2020)

$$\frac{\Omega_{N_1}}{\Omega_{DM}} \simeq \frac{M_1}{10\ \mathrm{keV}} \frac{300\ \mathrm{GeV}}{M_2} \frac{T_{dec}}{10\ \mathrm{MeV}}$$



Too early decay of N_2 by W_R



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

Dror, Dunsky, Hall and KH (2020)
Dunsky, Hall and KH (2020)

$M_2 \propto \sqrt{\Delta m^2_{atm}}$: backup

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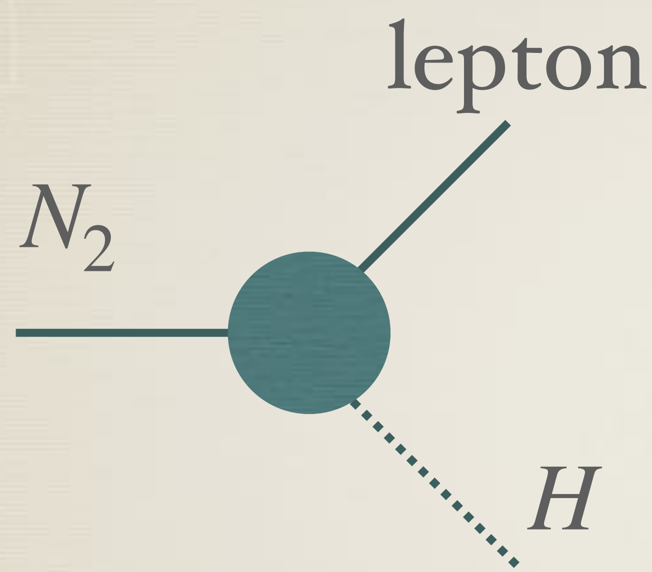
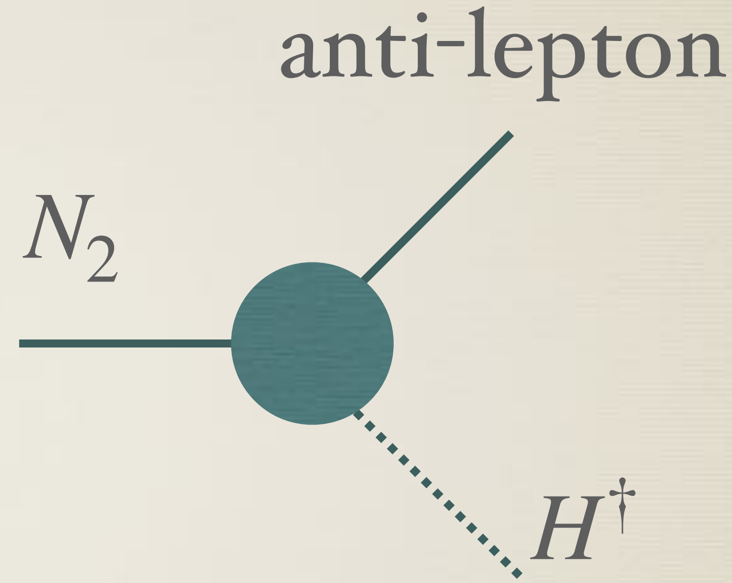
Leptogenesis

Fukugita and Yanagida (1986)



$\neq$

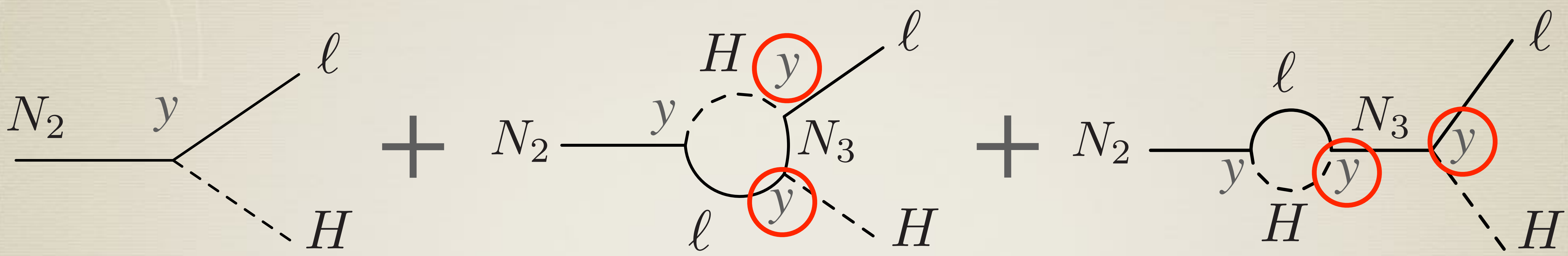


Lepton asymmetry

non-perturbative
weak process
(sphaleron)

Baryon asymmetry

Efficient?



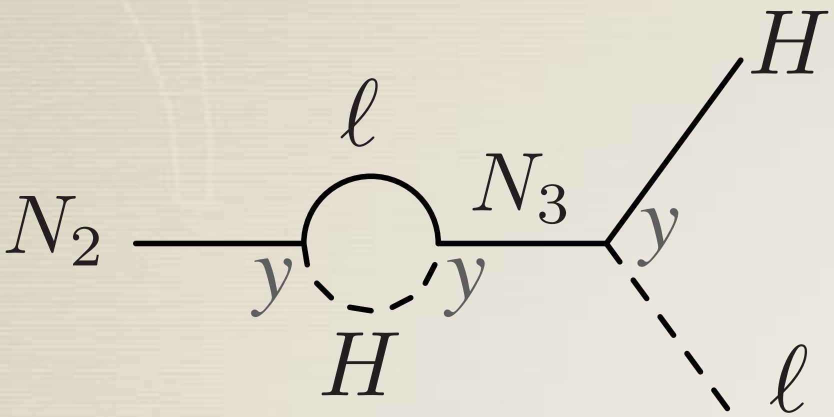
y_{1i}, y_{2i} are small ➡

$$(\text{asymmetry}) \propto y_{33}^2 < \frac{m_\nu M_3}{v_L^2} < \frac{m_\nu^2 v_R^2}{v_L^4}$$

$$m_{\nu,33} = -\frac{y_{3k} y_{3k} v_L^2}{M_k} + M_3 \left(\frac{v_L}{v_R}\right)^2$$

Leptogenesis favors large v_R, which is however disfavored by DM production

Resonant leptogenesis?



$$(\text{asymmetry}) \propto \frac{1}{M_2 - M_3}$$

Flanz, Paschos and Sarkar (1995)

Achieved by approximate symmetry that imposes $M_2 \simeq M_3$

e.g., $SU(2)_{\text{flavor}}$ of $(\bar{\ell}_2, \bar{\ell}_3)$

This is necessarily broken by the charged lepton yukawa

$\neq$

Cancelation ?

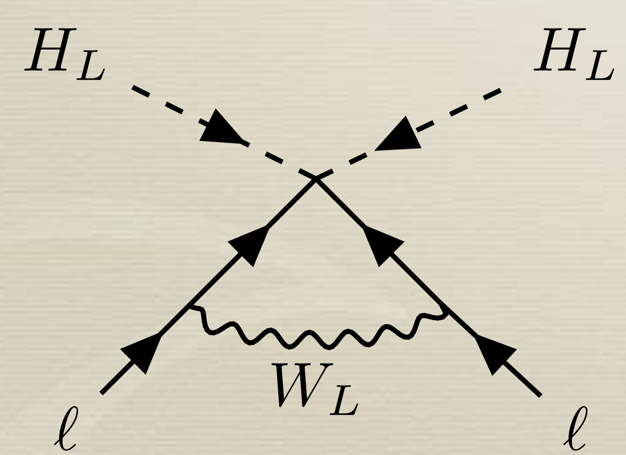
Consider the following UV completion of the dim-5 operators:

$$\lambda S(\ell H_L + \bar{\ell} H_R) + \frac{1}{2} m_S S^2 \quad \Rightarrow \quad \frac{\lambda^2}{m_S}(\ell H_L + \bar{\ell} H_R)^2$$

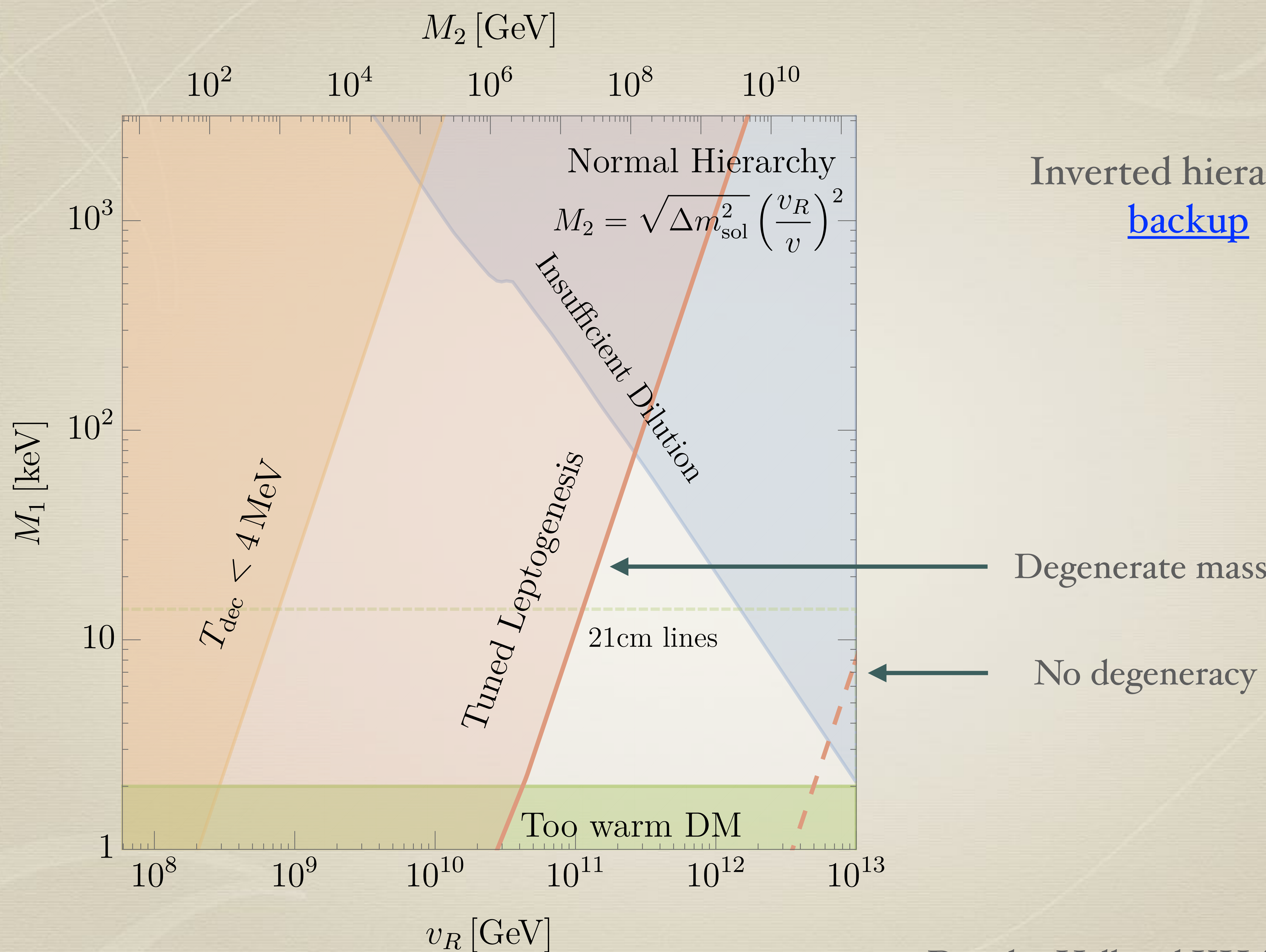
Only a linear combination of ν and N obtains a mass

$$m_\nu = -\frac{y^2 v_L^2}{M} + M\left(\frac{v_L}{v_R}\right)^2 = 0$$

Still, quantum correction generates a non-zero neutrino mass



$\Rightarrow$ Not as efficient as the resonant case



Inverted hierarchy:
backup

Dunsky, Hall and KH (2020)

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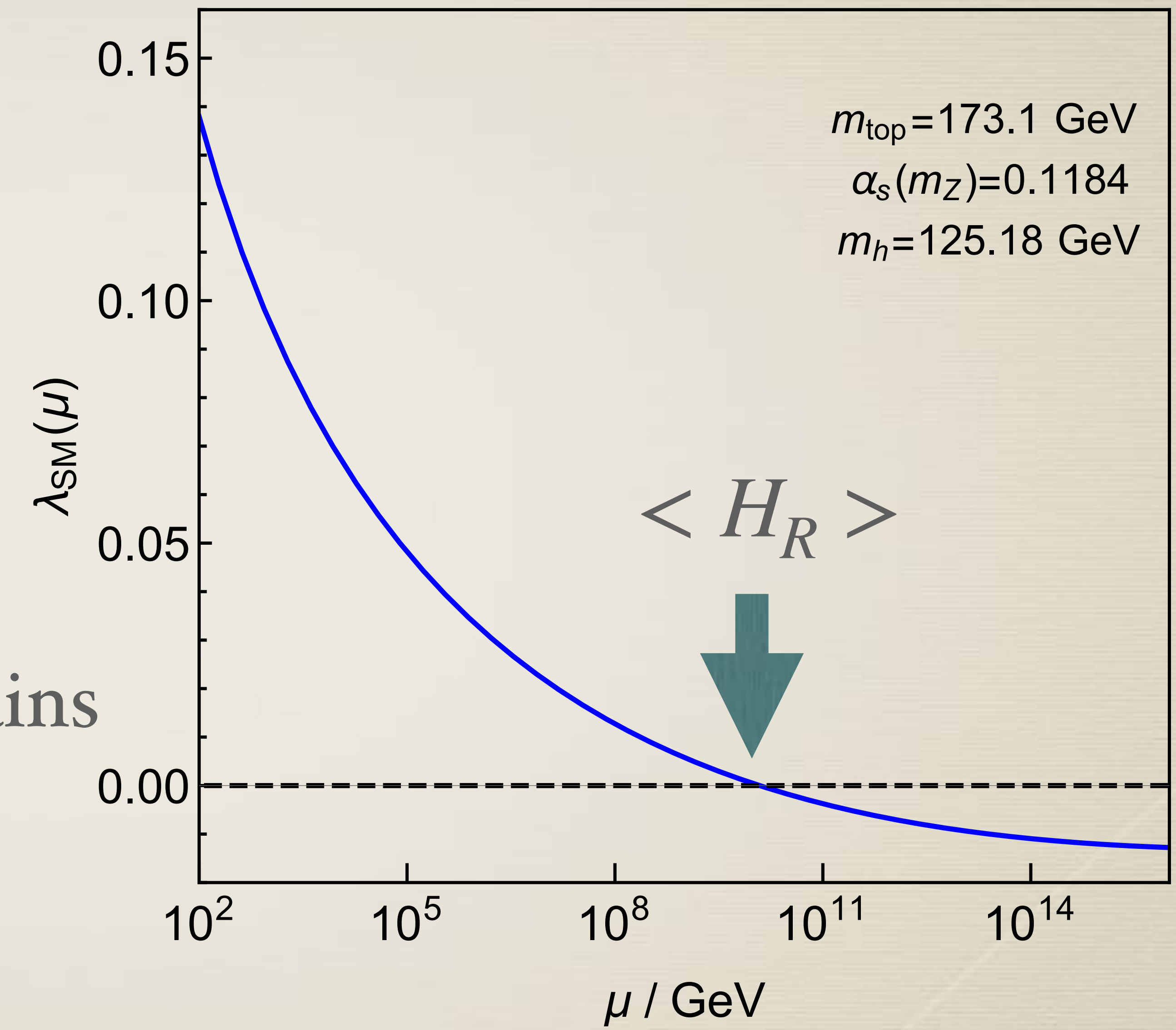
Vanishing quartic

I will show that

$$\lambda_{\mathrm{SM}}(< H_R >) \simeq 0$$

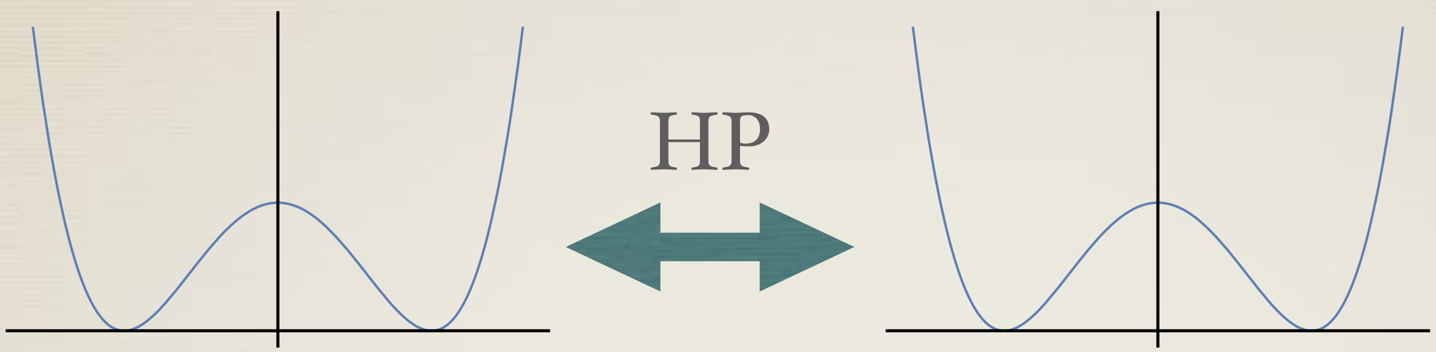
because the Z2 symmetry constrains the potential of HL and HR



Generically applicable to a theory with $H \leftrightarrow H'$

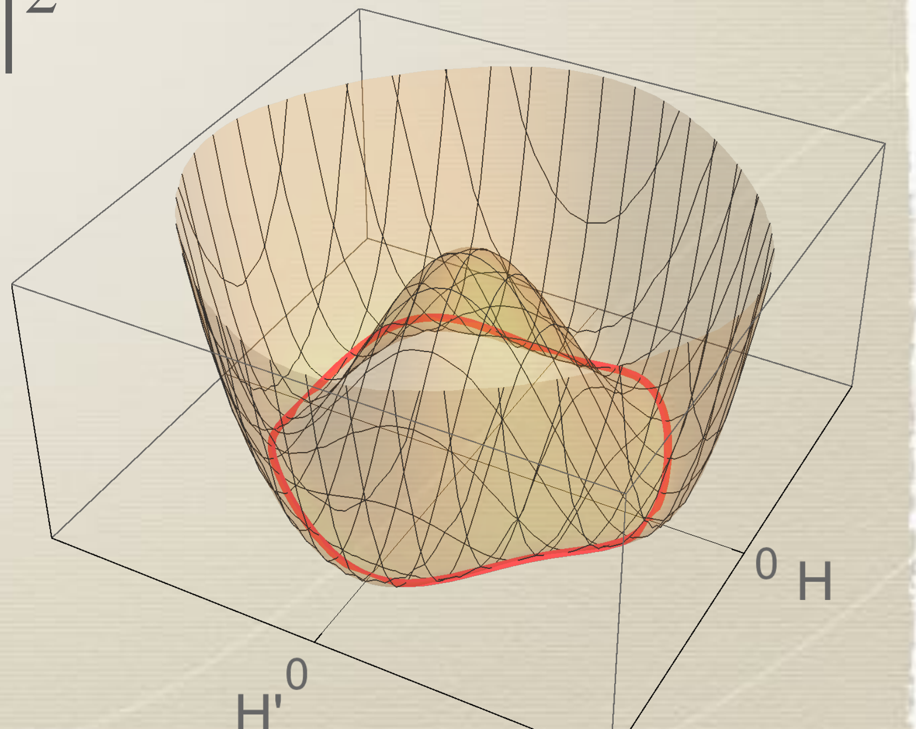
For LR symmetric theories, $H = H_L,\ \ H' = H_R$

Higgs potential



$$V = \left(\lambda |H|^4 - m^2 |H|^2\right) + \left(\lambda |H'|^4 - m^2 |H'|^2\right) + \tilde{y}\, |H|^2 |H'|^2$$

$$= \lambda \left(|H|^2 + |H'|^2 - v'^2 \right)^2 + y |H|^2 |H'|^2$$

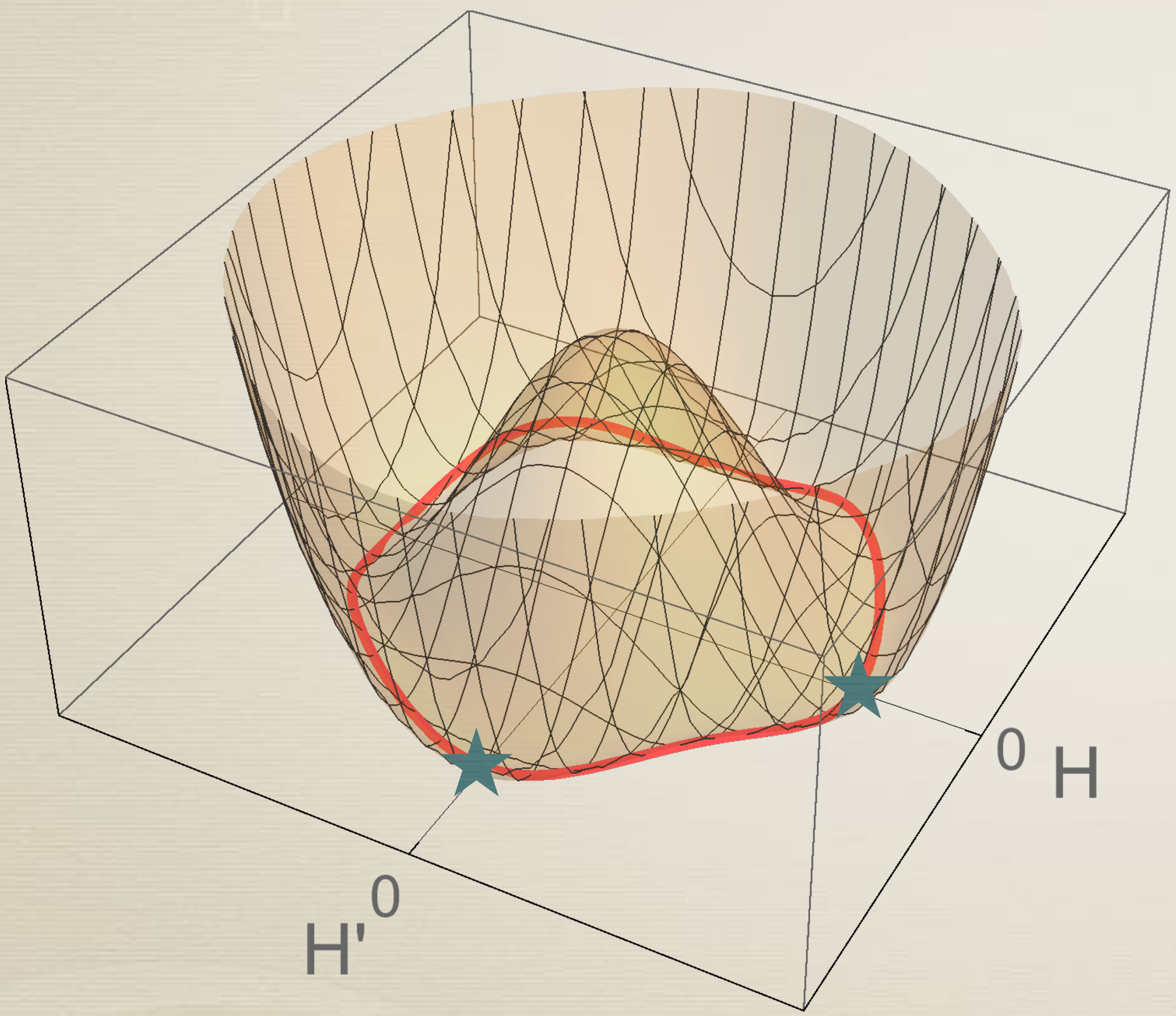


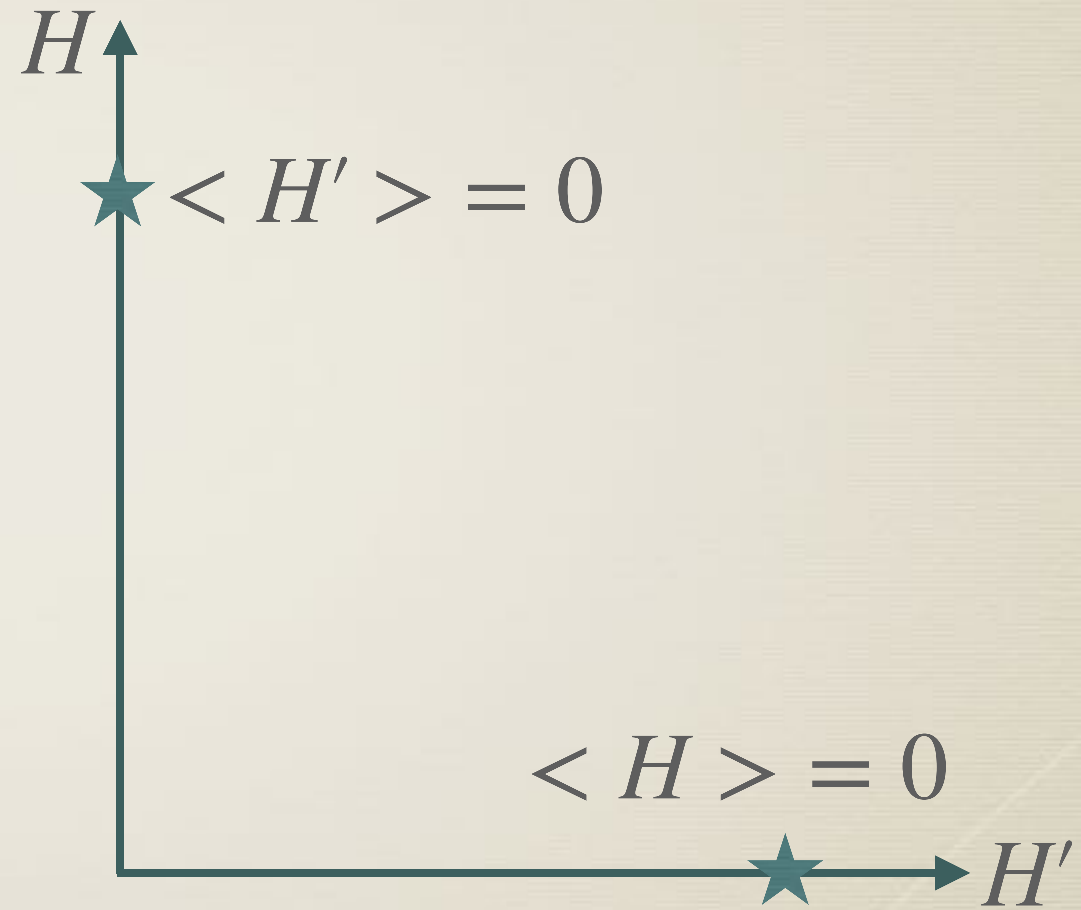
Can we find the minimum with

$$\langle H \rangle \ll \langle H' \rangle \; ?$$

$y > 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

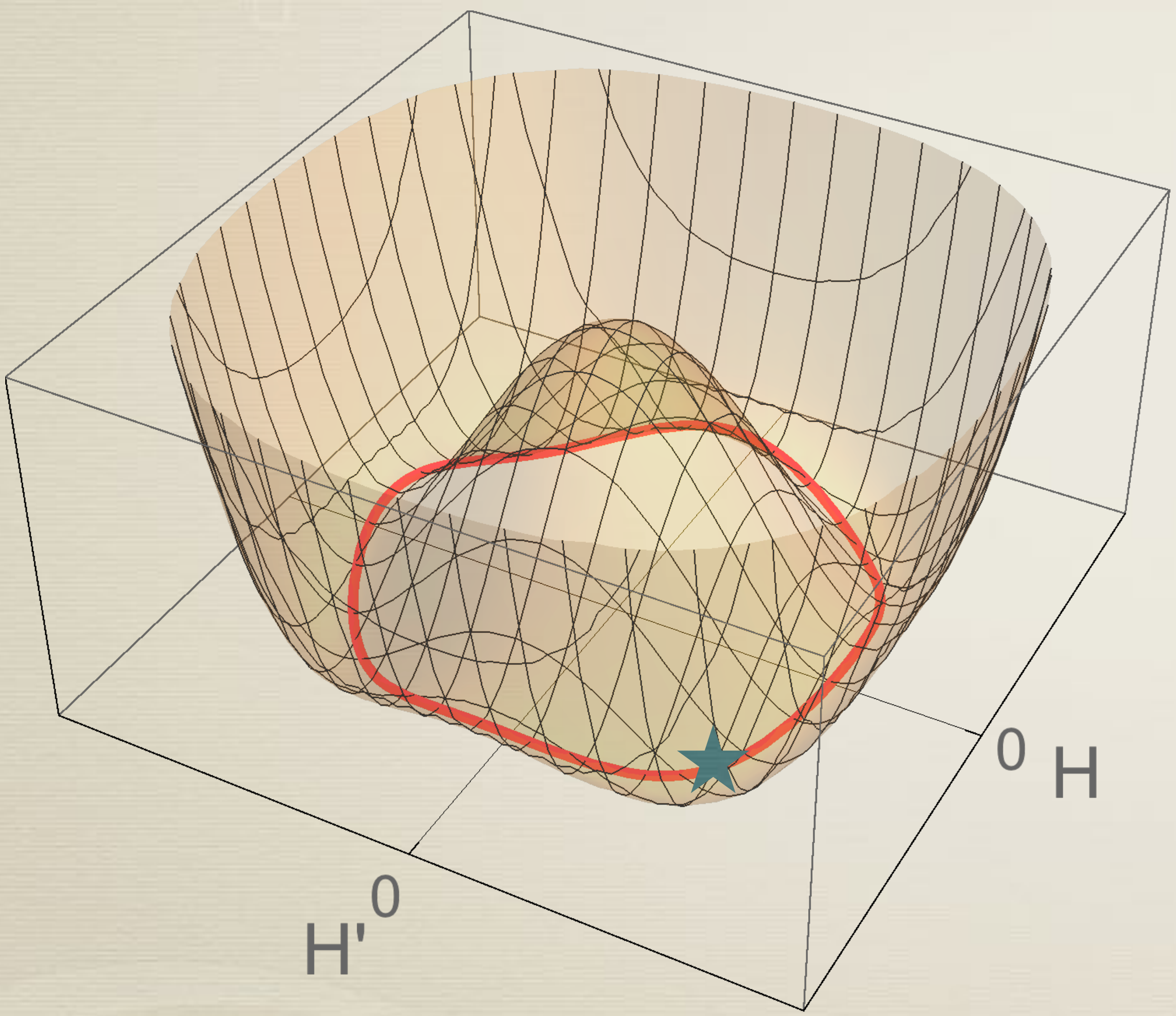


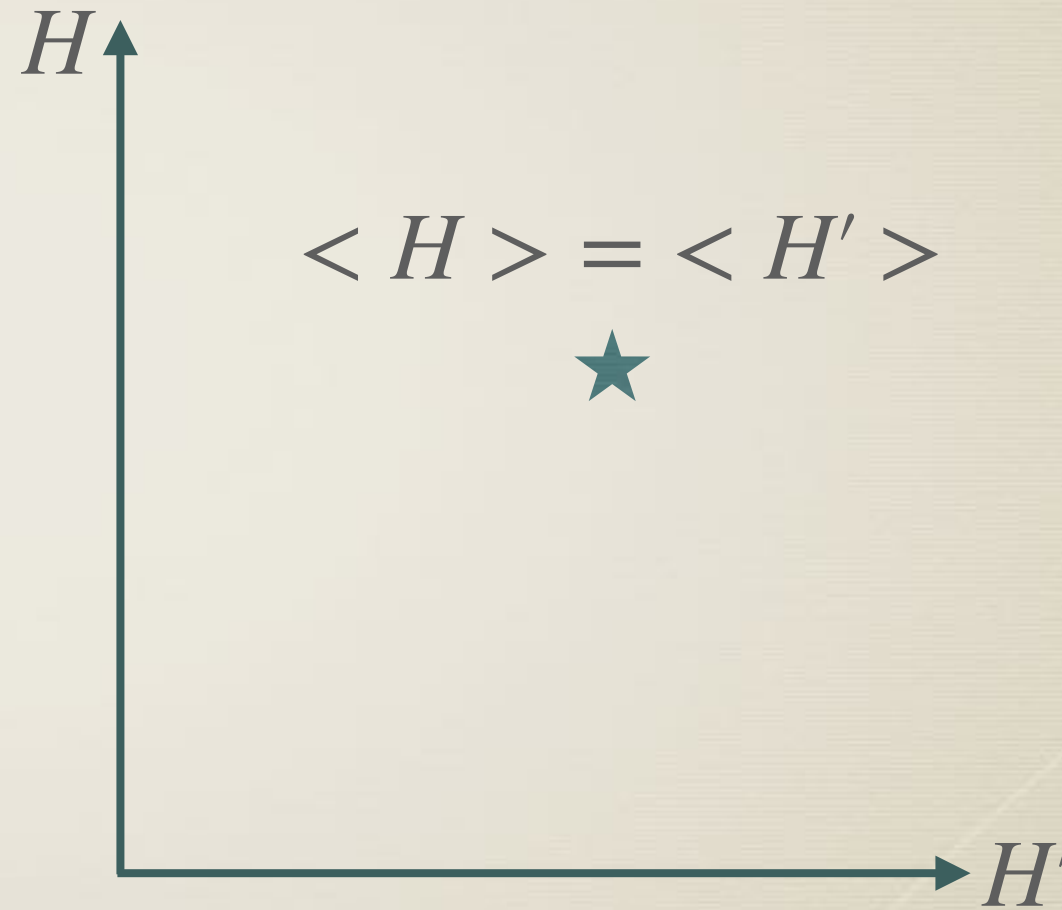


$$\cancel{0 \neq \langle H \rangle \ll \langle H' \rangle}$$

$y < 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

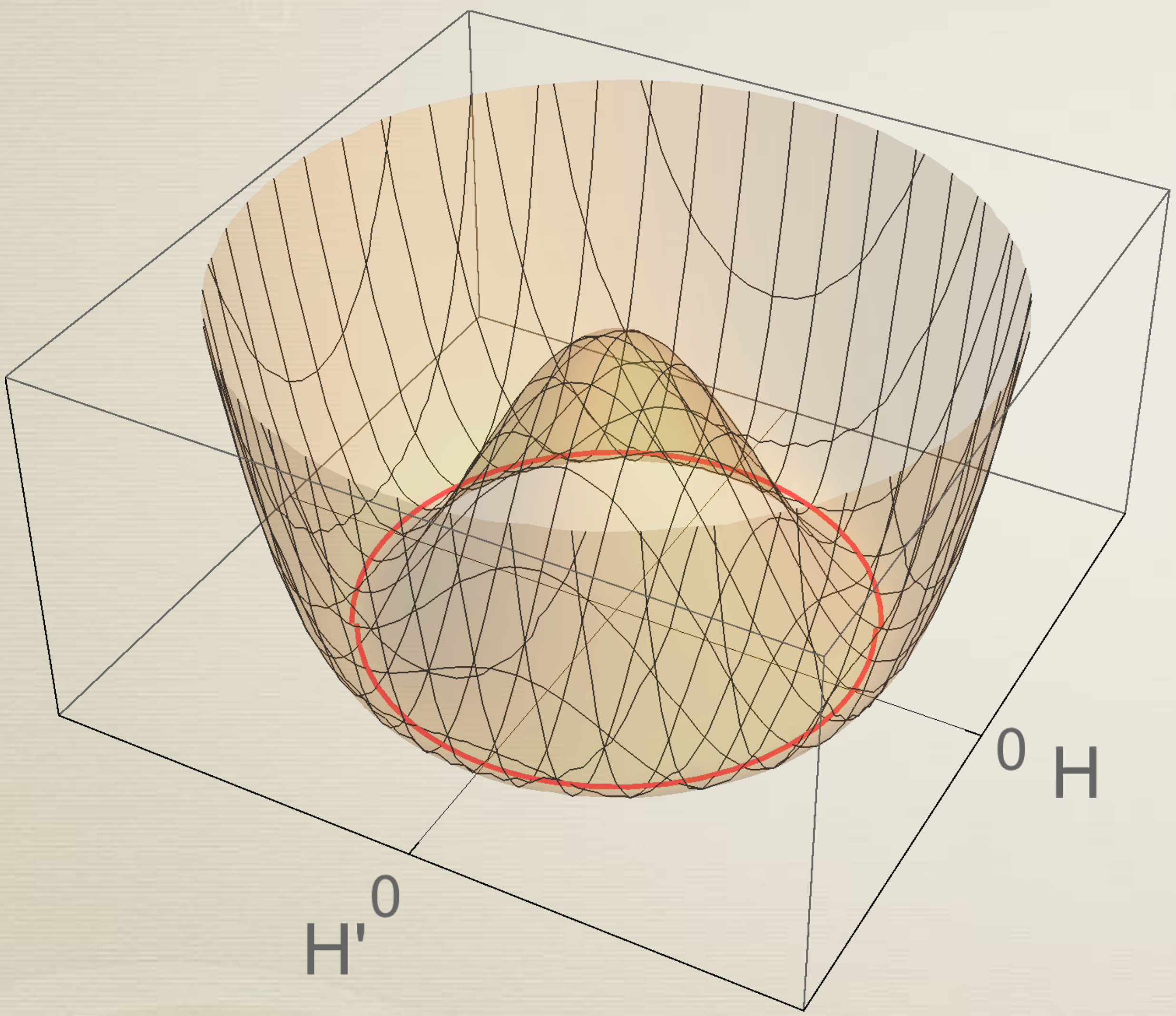


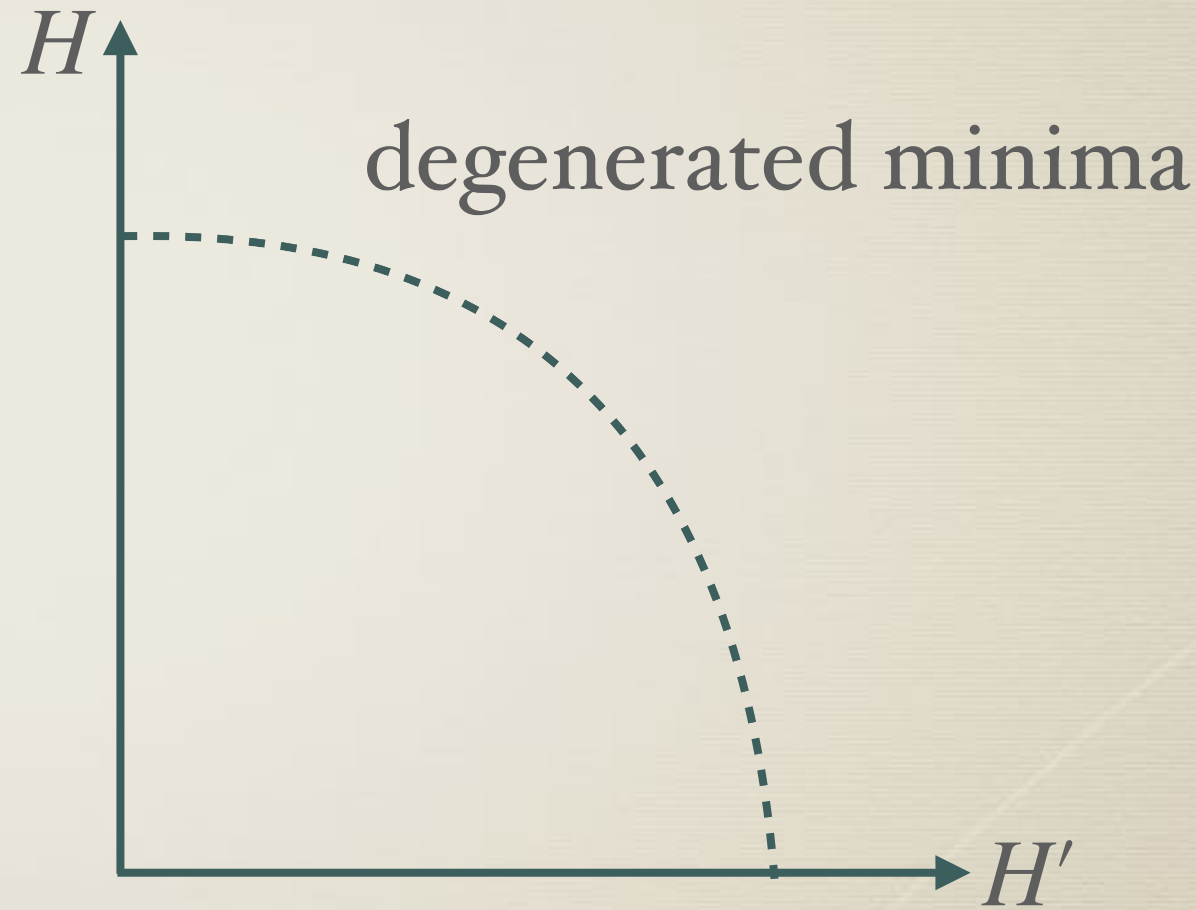


$$\cancel{\langle H \rangle \ll \langle H' \rangle}$$

$y \simeq 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + \cancel{y|H|^2|H'|^2}$$



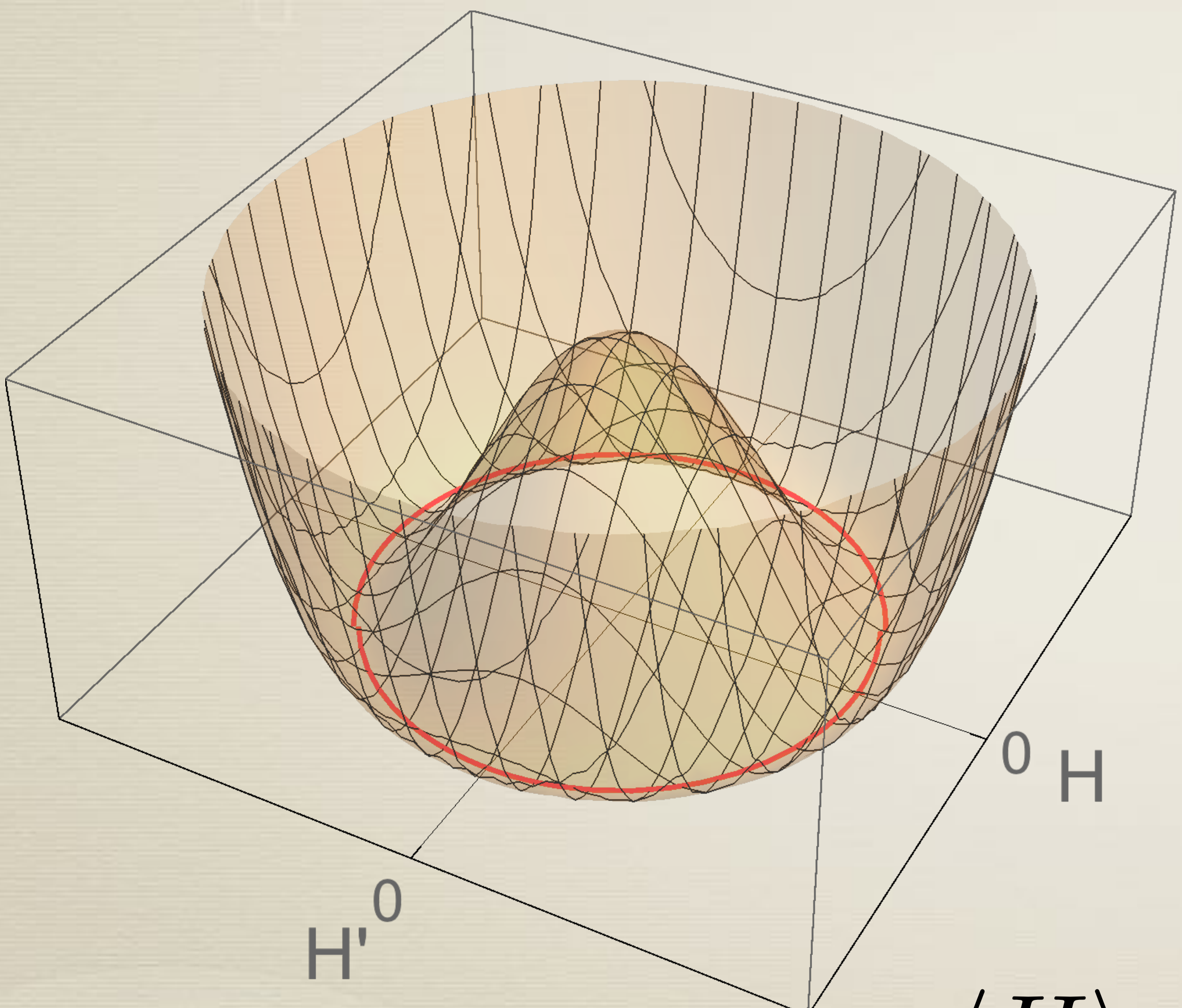


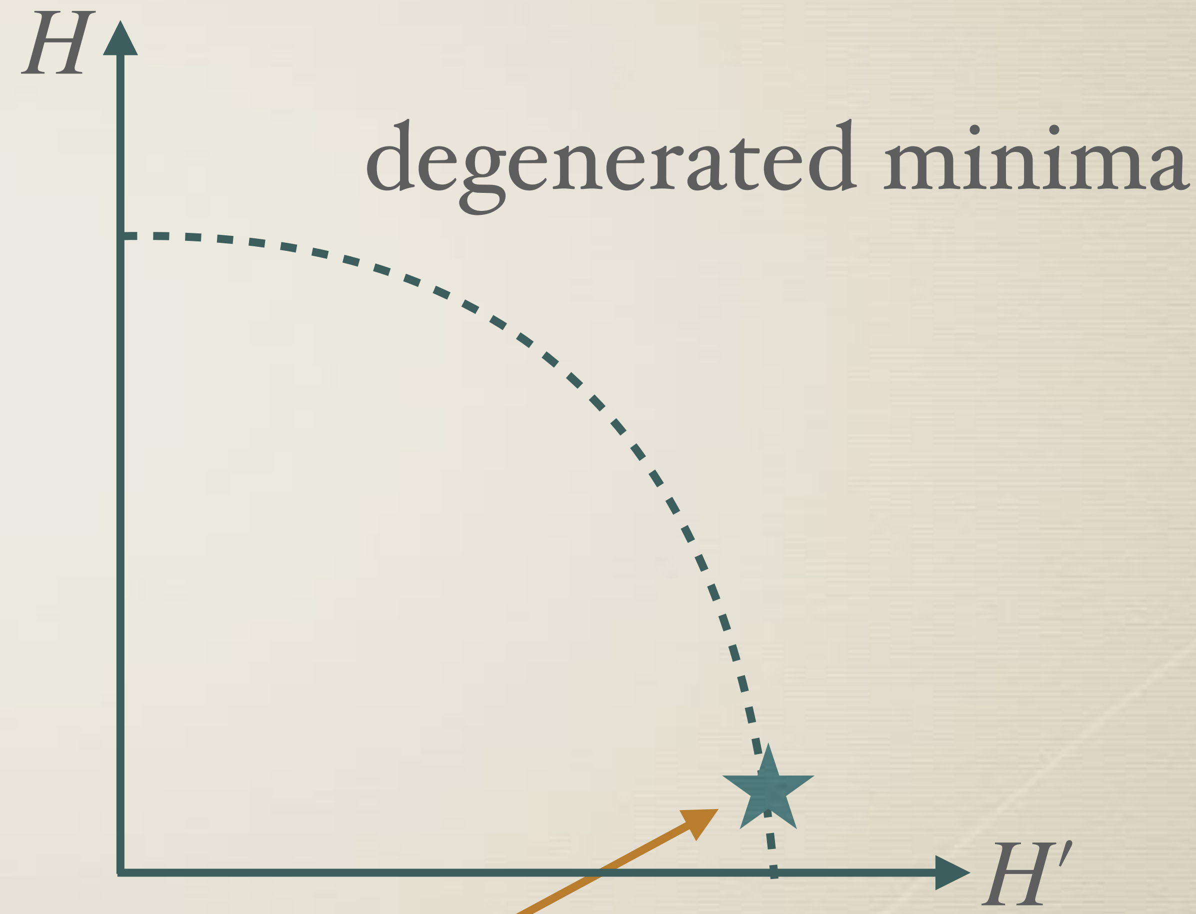
symmetry rotating the vector

(H, H')

$$y \simeq 0$$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + \cancel{y|H|^2|H'|^2}$$



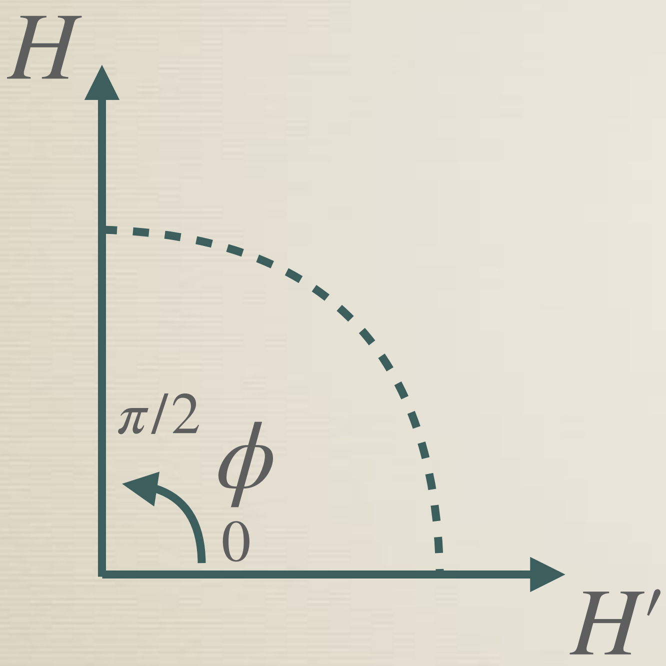


$$\langle H \rangle \ll \langle H' \rangle \,?$$

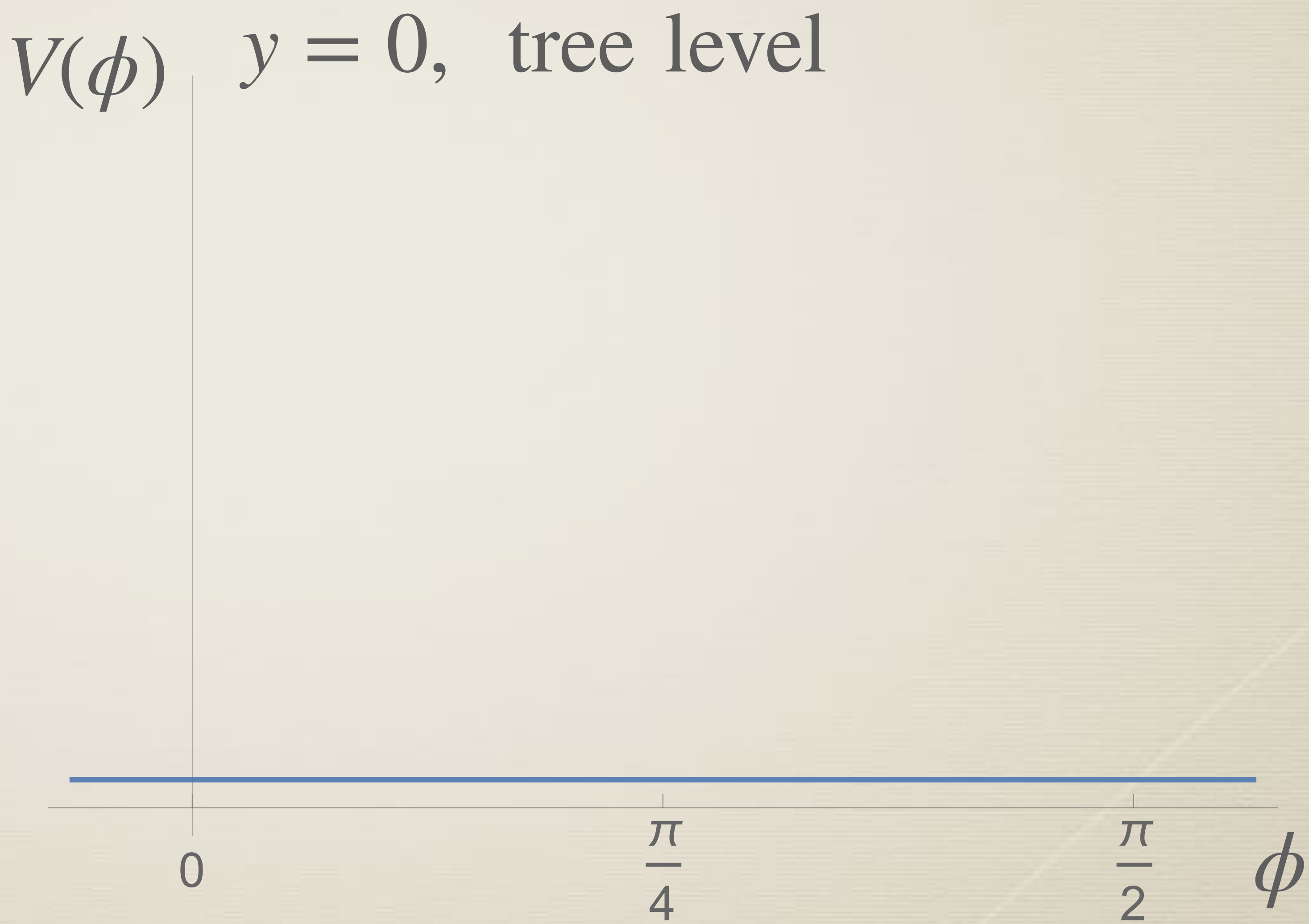
Degeneracy is resolved by quantum corrections

$y \simeq 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2$$



angular direction ϕ

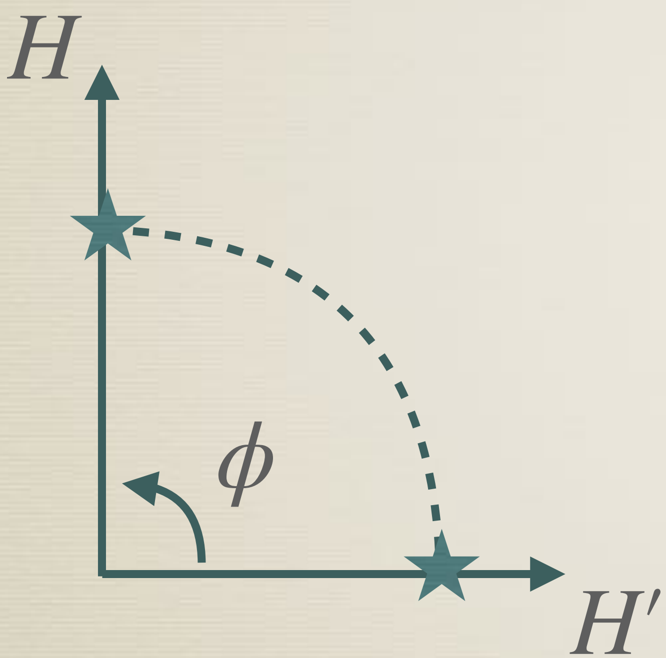


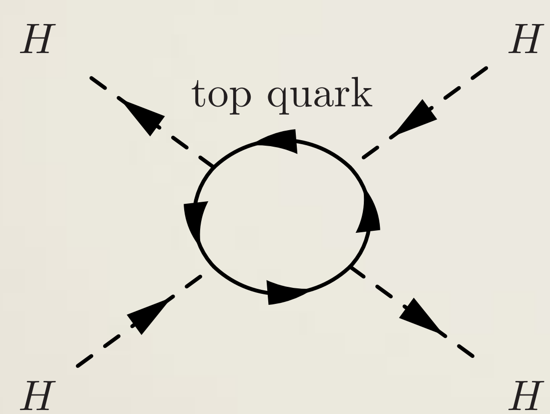
$y \simeq 0$

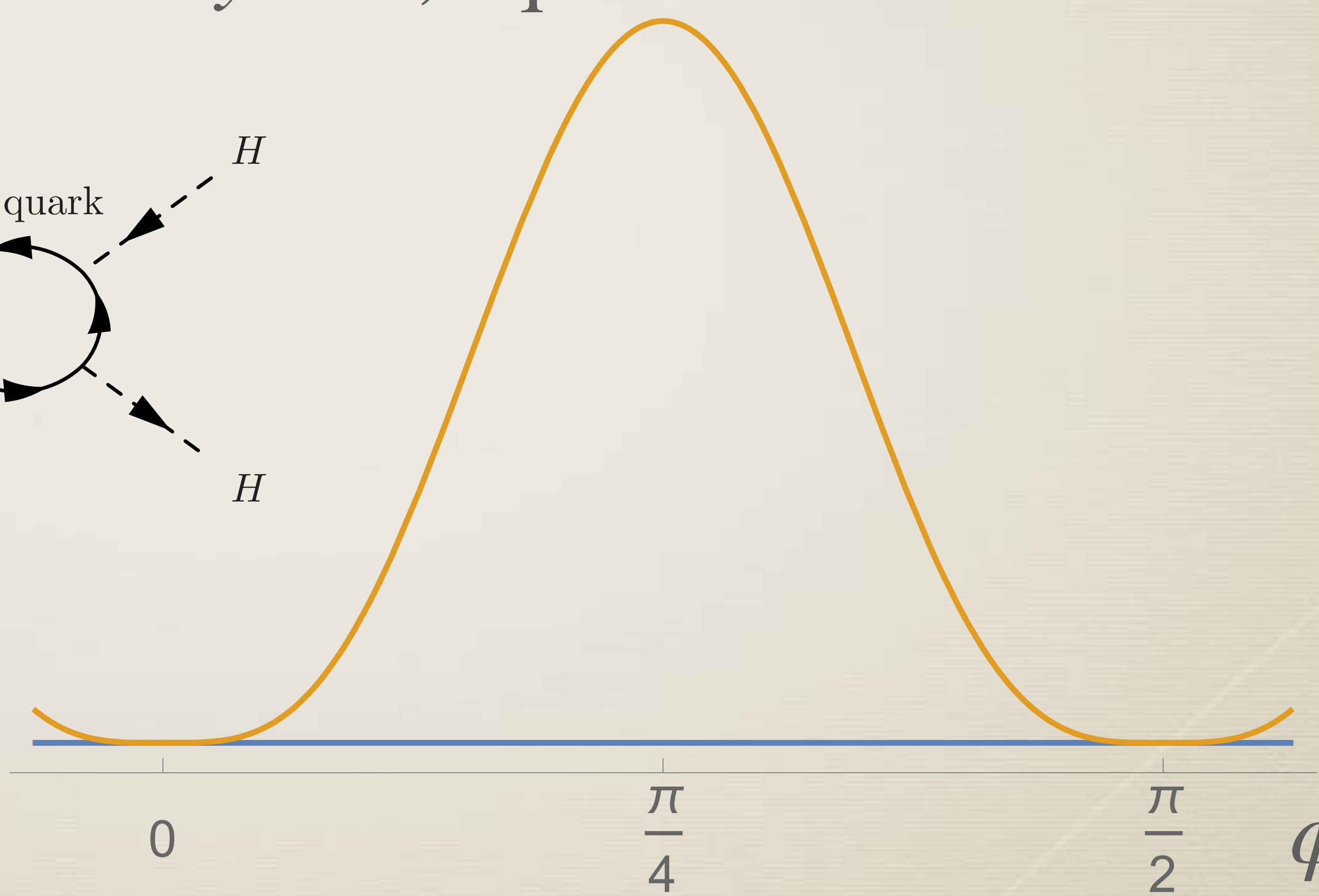
Coleman-Weinberg potential

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + V_{\text{quantum}}(H, H')$$

$y = 0, \;\; \text{quantum correction}$





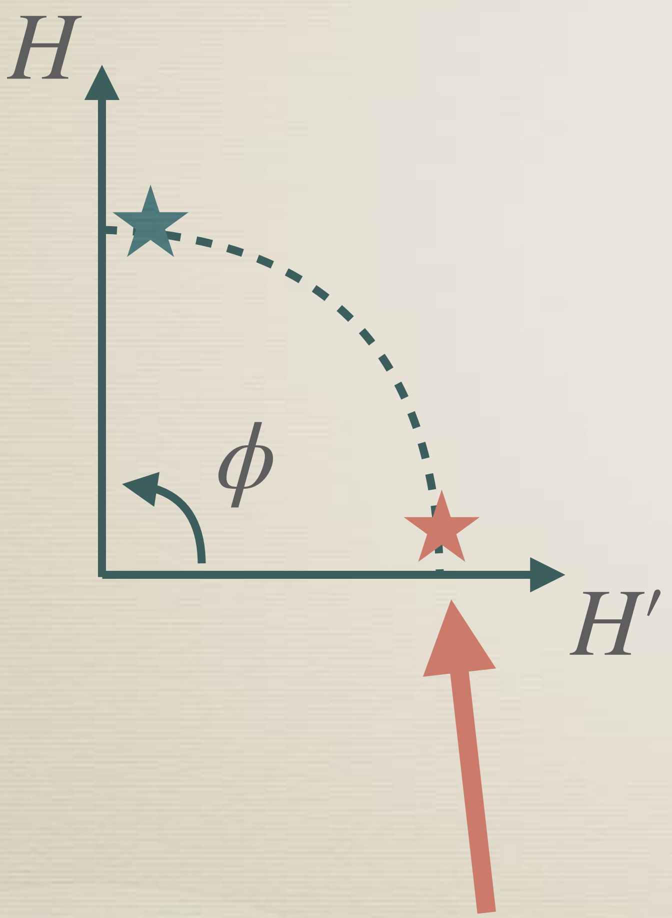


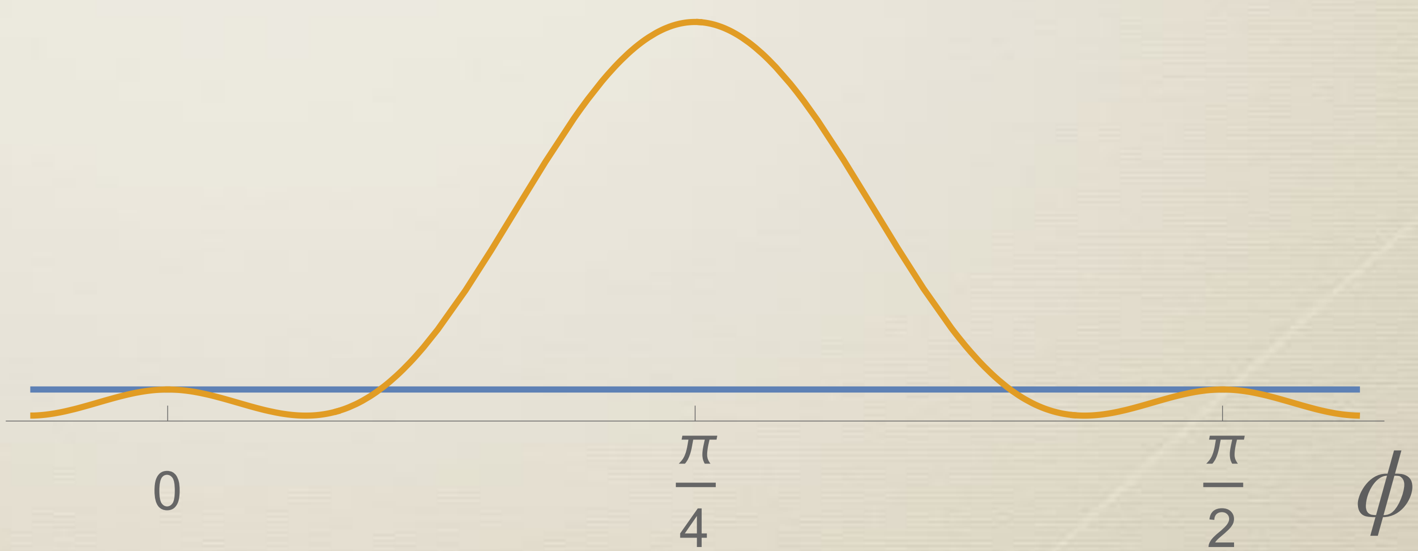
$y \simeq 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + V_{\text{quantum}}(H, H') + y|H|^2|H'|^2$$

$$y \simeq -\frac{v^2}{v'^2} + \text{quantum correction}$$

(fine-tuned Higgs mass)





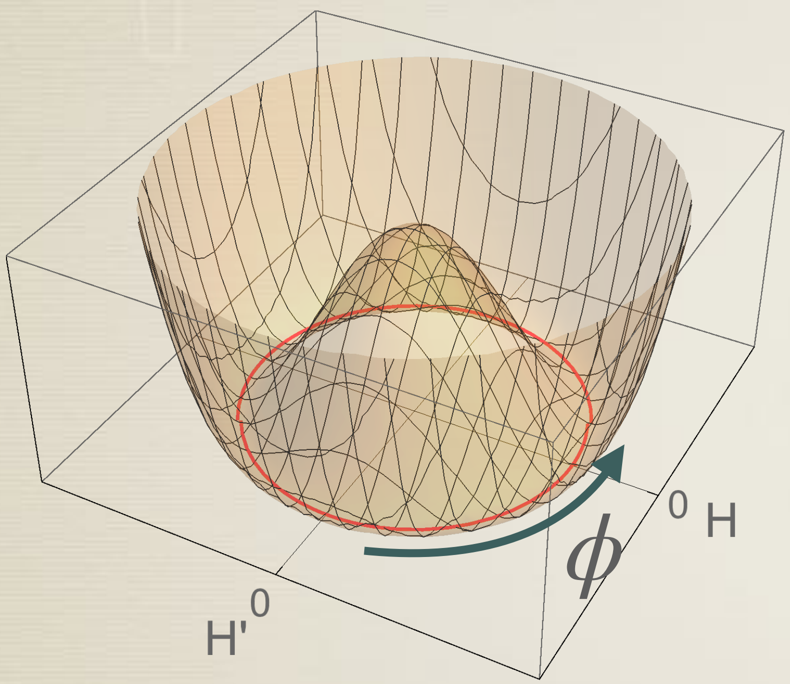
$$\langle H \rangle \ll \langle H' \rangle \quad \text{is achieved !}$$

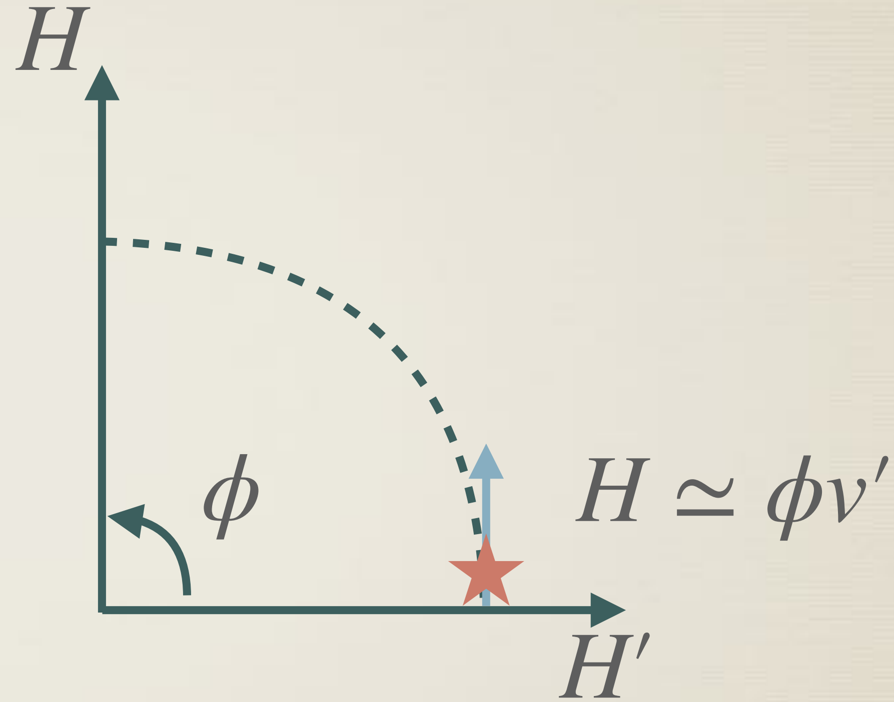
Hall, KH (2018)

Prediction on the quartic coupling

Hall, KH (2018)

$V \simeq \lambda(|H|^2 + |H'|^2 - v'^2)^2$ + small corrections





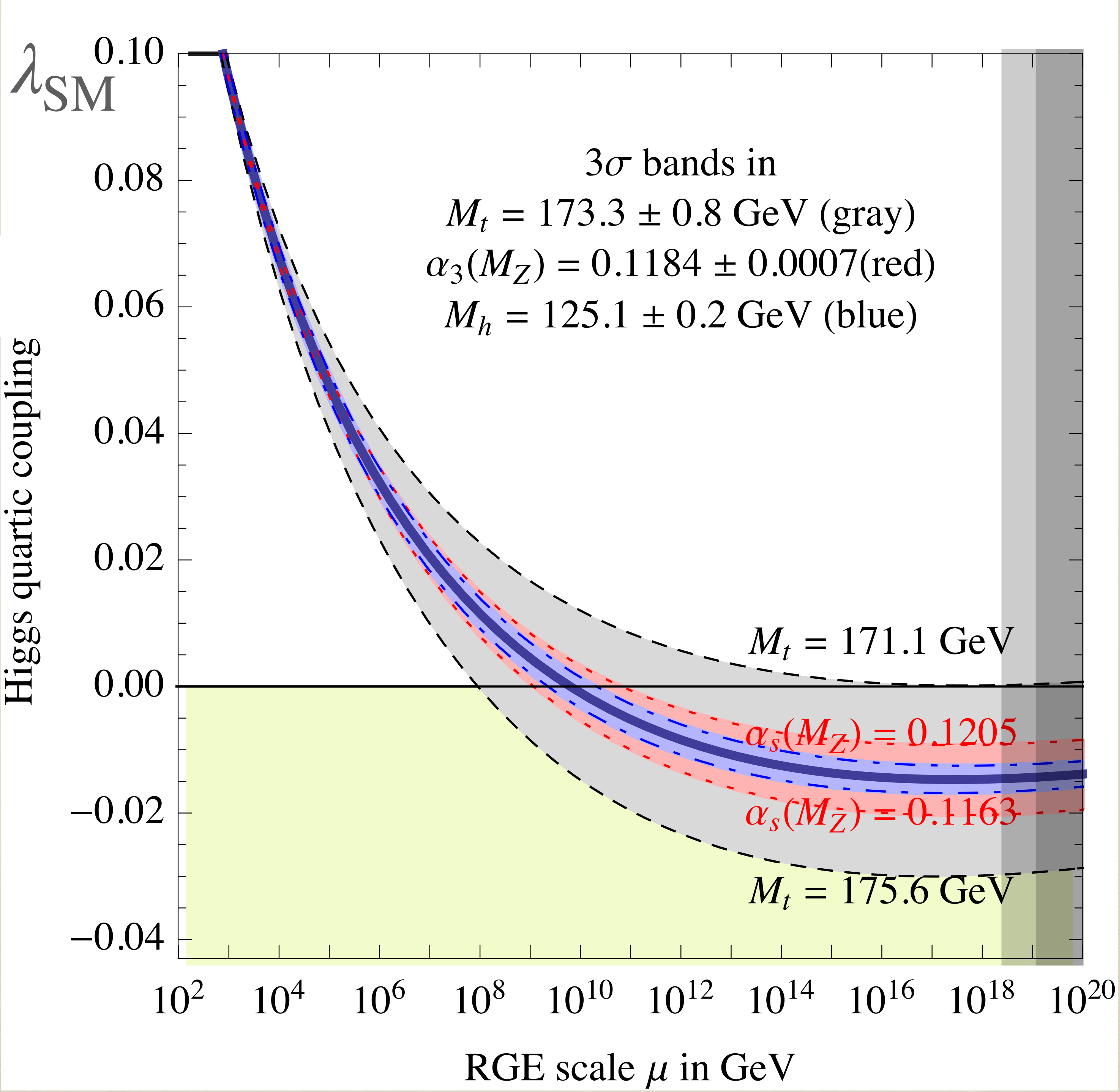
symmetry rotating the vector (H, H')

Standard Model Higgs is a (pseudo) Nambu-Goldstone boson associated with symmetry breaking by $\langle H' \rangle = v'$

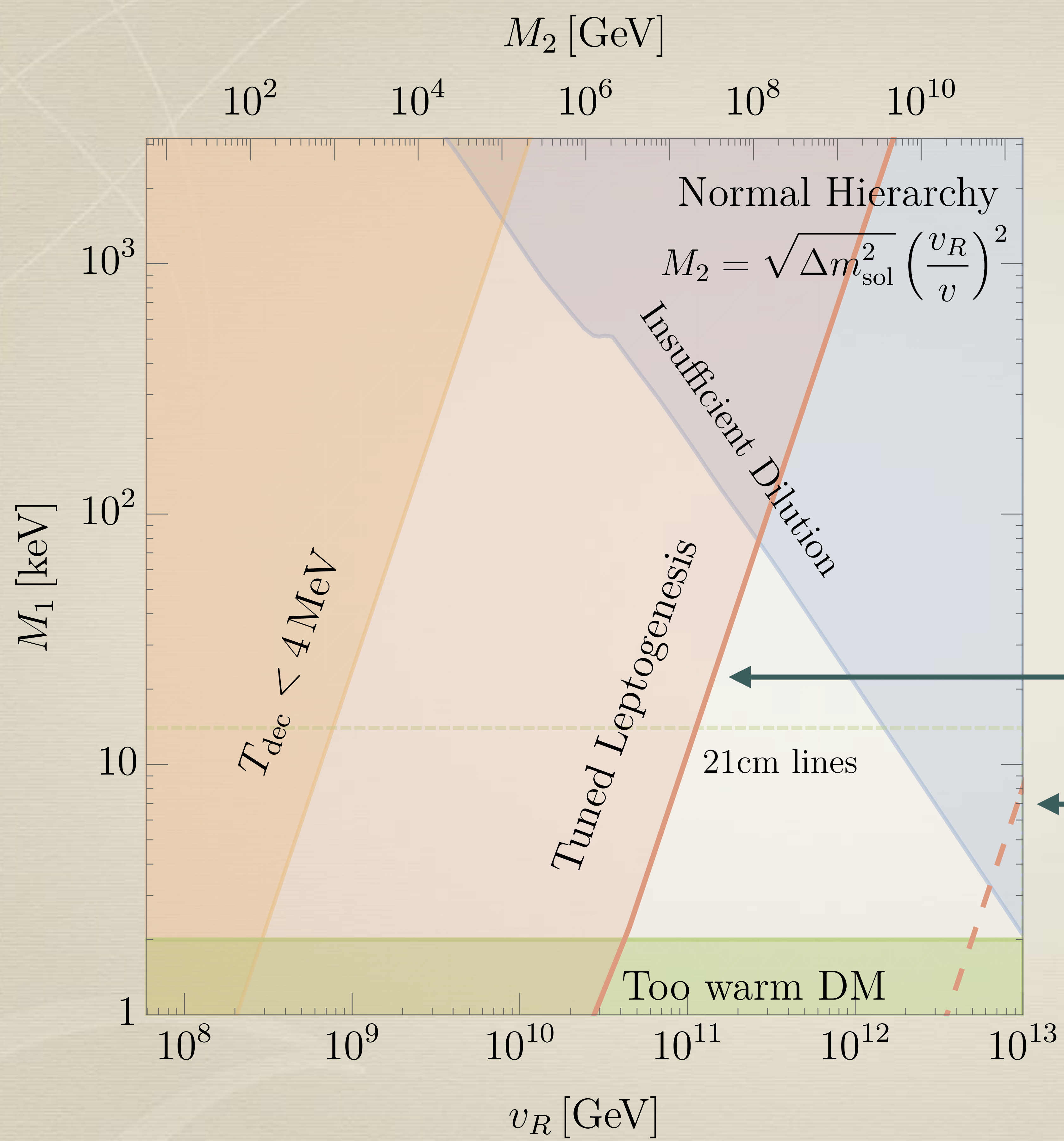
$$\boxed{\lambda_{\rm SM}(v') \simeq 0}$$

(up to calculable threshold correction)

Vanishing Higgs quartic



Buttazzo et.al (2013)

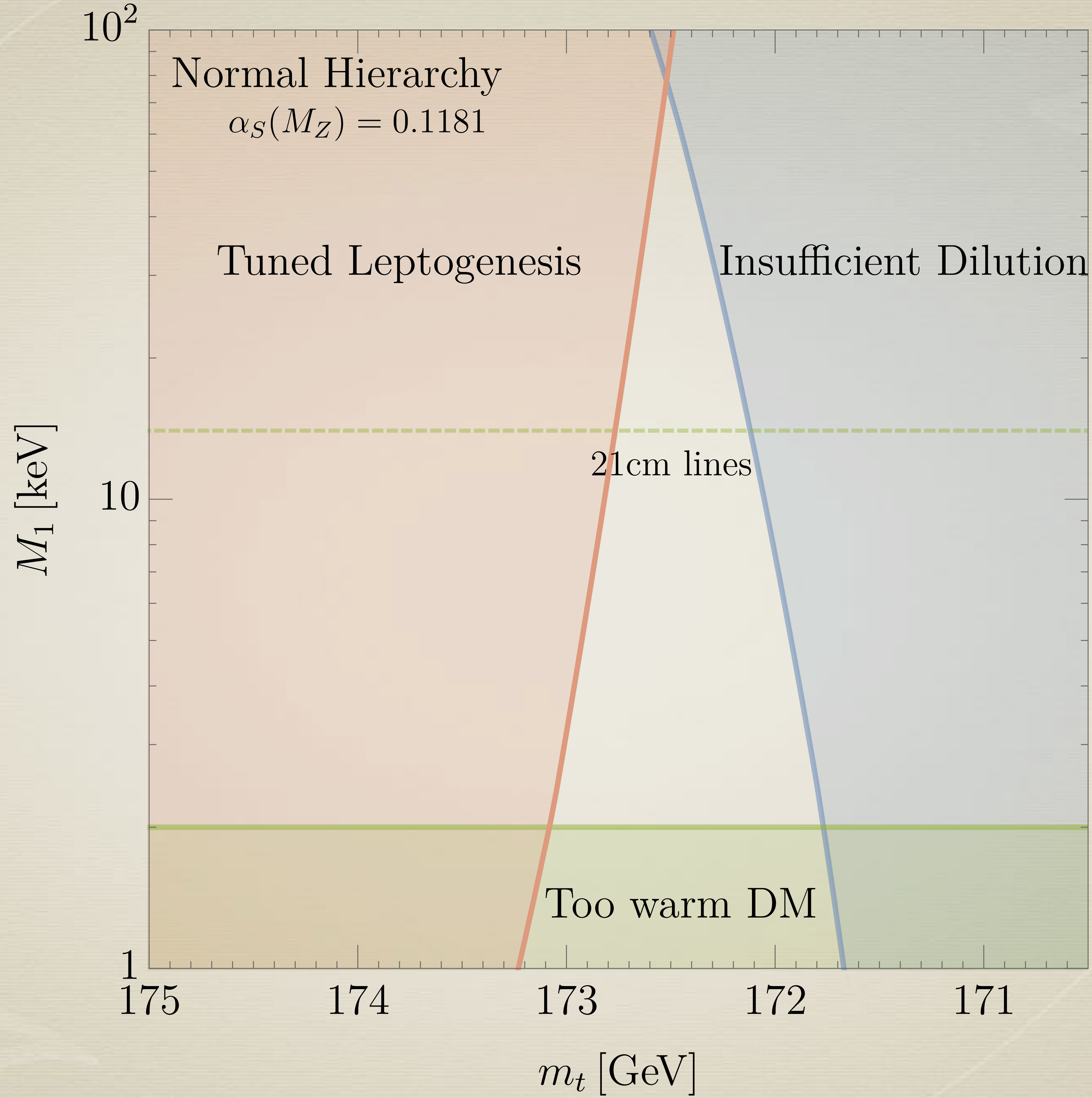


Inverted hierarchy:
backup

Degenerate mass

No degeneracy

Dunsky, Hall and KH (2020)



Inverted Hierarchy: backup

Dunsky, Hall and KH (2020)

Summary

* Parity symmetry can solve the strong CP problem
* Dark matter and baryon asymmetry can be explained for a range of parity symmetry breaking scales that is correlated with the top quark mass and the strong coupling constant
* The scenario is probed by the observation of the structure formation and the measurement of the standard model parameters

2004.09511

2007.12711

Discussion

The correlation between the SM parameters and the symmetry breaking scale is applicable to generic Z2 symmetric theories with $H \leftrightarrow H'$

- SO(10) gauge coupling unification and proton decay

  Hall, KH (2018)

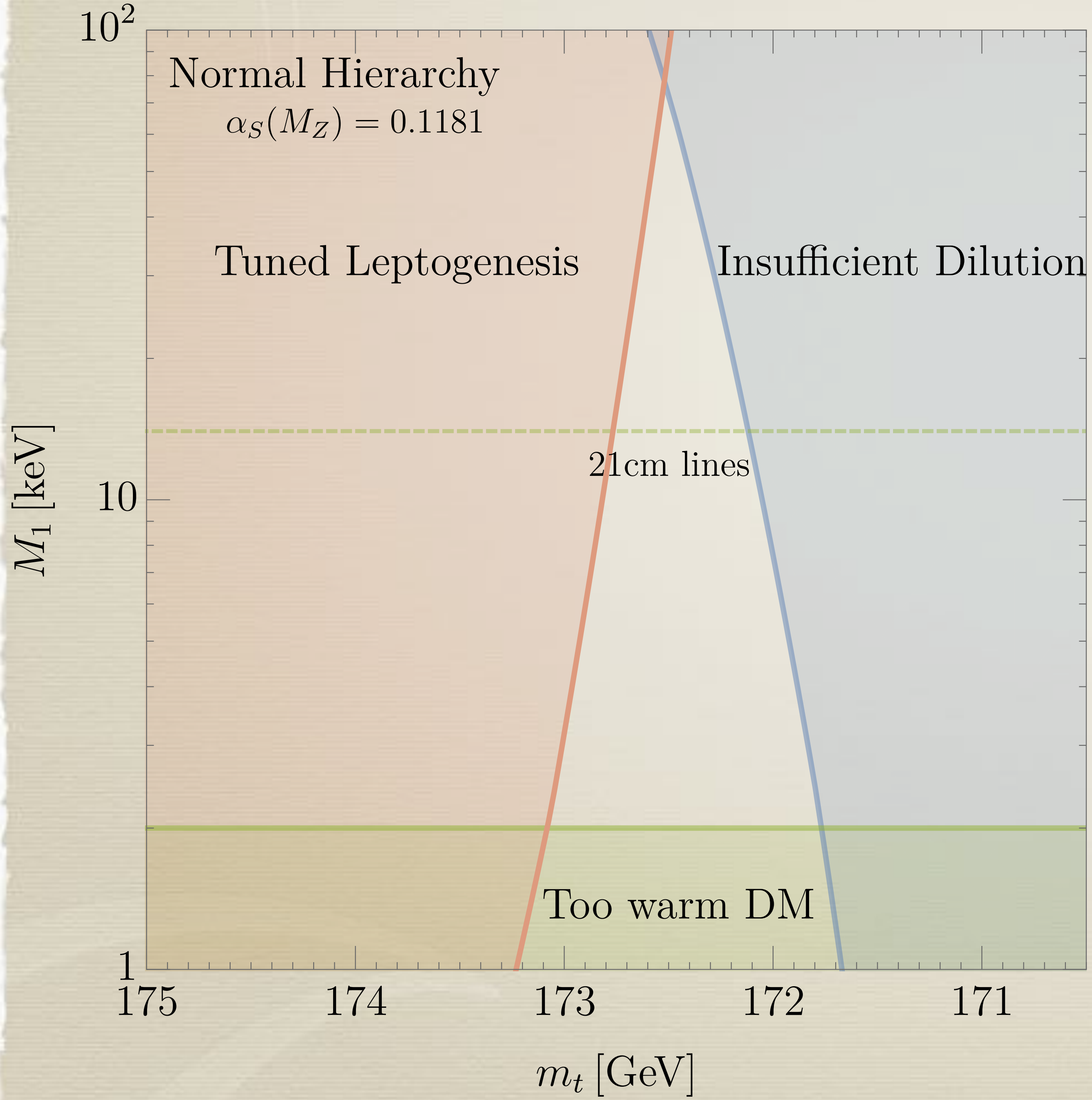
- Mirror dark matter and its direct detection rate

  Dunsky, Hall, KH (2018)

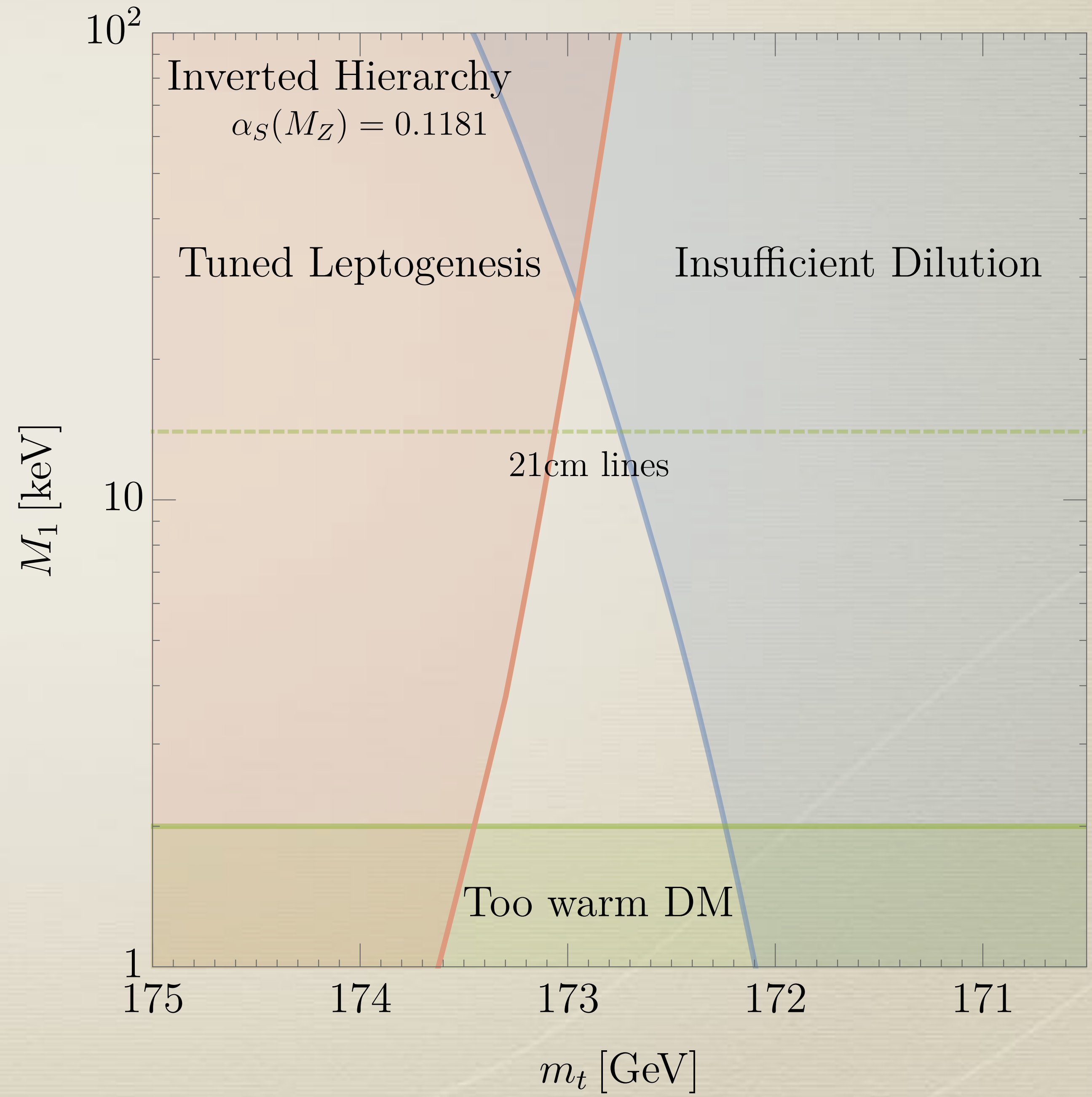
- Gravitational waves from mirror QCD phase transition

  Dunsky, Hall, KH (2018)

Summary



Normal Hierarchy
$\alpha_S(M_Z) = 0.1181$
Tuned Leptogenesis
Insufficient Dilution
21cm lines
Too warm DM
10^2
10
1
175
174
173
172
171
M_1 [keV]
m_t [GeV]



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10^2
10
1
175
174
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M_1 [keV]
m_t [GeV]

Backup

Enhancement of lepton asymmetry

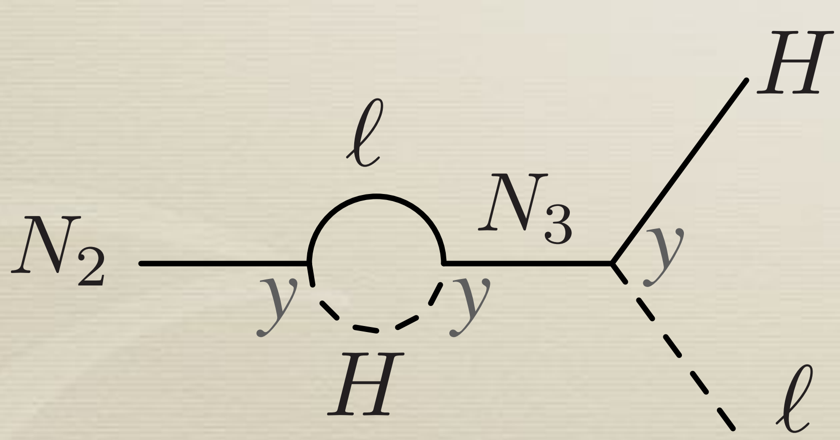
Two ways of enhancement

1. Cancellation between the two terms in m_ν

$$m_{\nu,33} = -\frac{y_{3k} y_{3k} v_L^2}{M_k} + M_3 \left(\frac{v_L}{v_R}\right)^2$$

2. Degenerate masses

Flanz, Paschos and Sarkar (1995)



$$\Rightarrow \quad \frac{M_{2,3}}{M_2 - M_3}$$

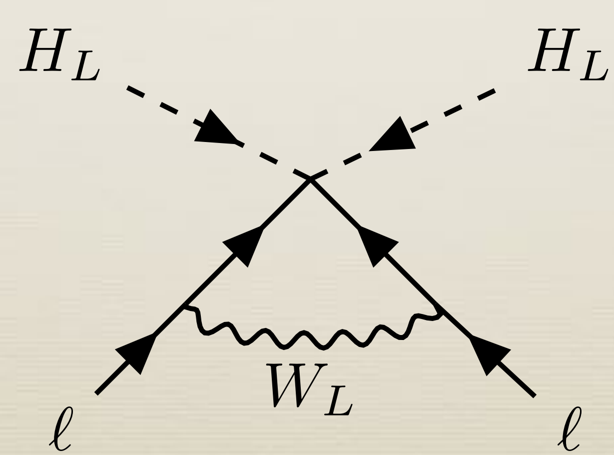
1. Cancelation

$$\lambda S(\ell H_L + \bar{\ell} H_R) + \frac{1}{2} m_S S^2 \quad \Longrightarrow \quad \frac{\lambda^2}{m_S}(\ell H_L + \bar{\ell} H_R)^2$$

Only a linear combination of ν and N obtains a mass

$$m_\nu = -\frac{y^2 v_L^2}{M} + M \left(\frac{v_L}{v_R} \right)^2 = 0$$

Still, quantum correction generates a non-zero neutrino mass

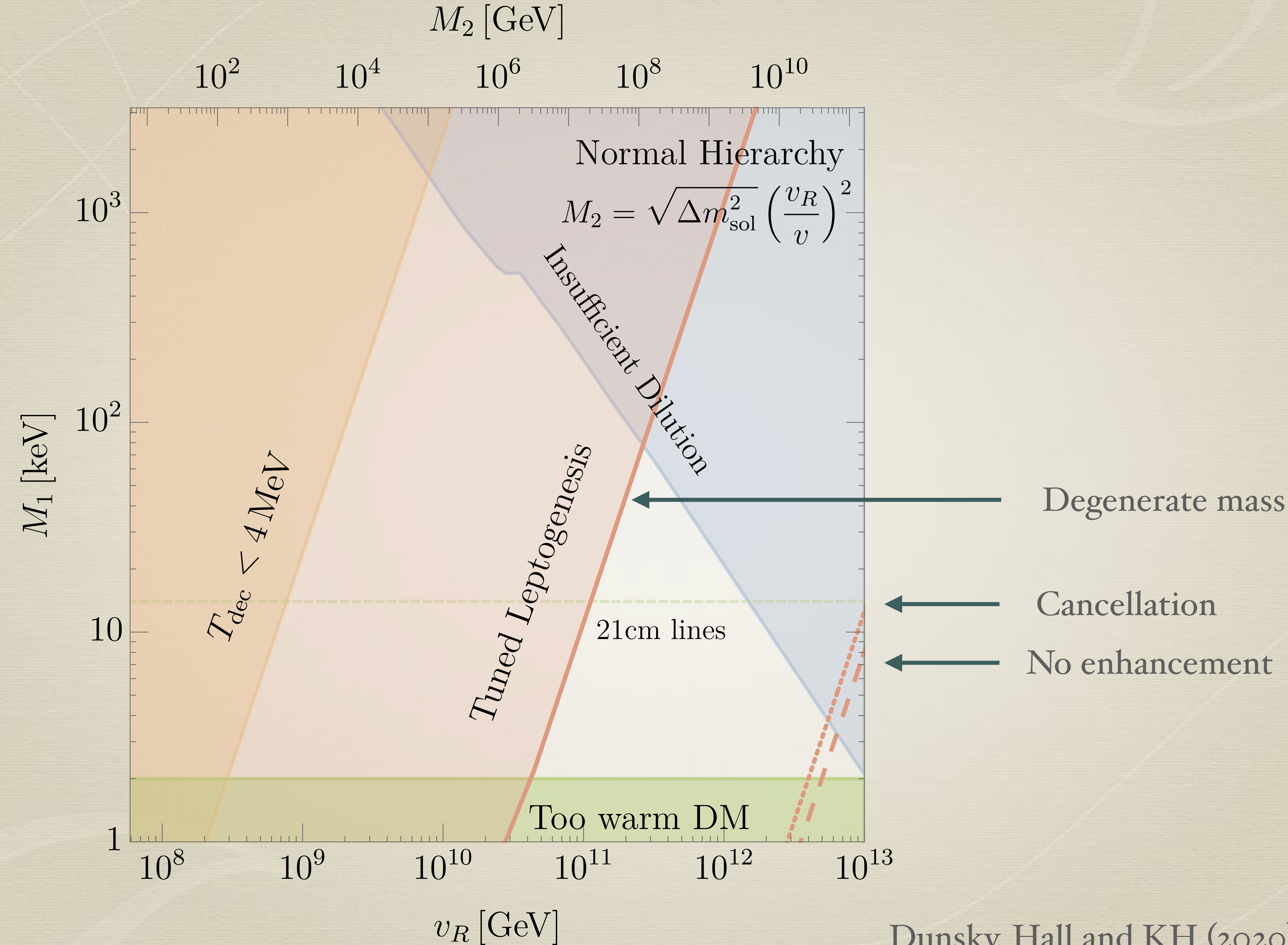


2. Degenerate masses

Approximate symmetry that ensures $M_2 \simeq M_3$

e.g., $SU(2)_{\text{flavor}}$ of $(\bar{\ell}_2, \bar{\ell}_3)$

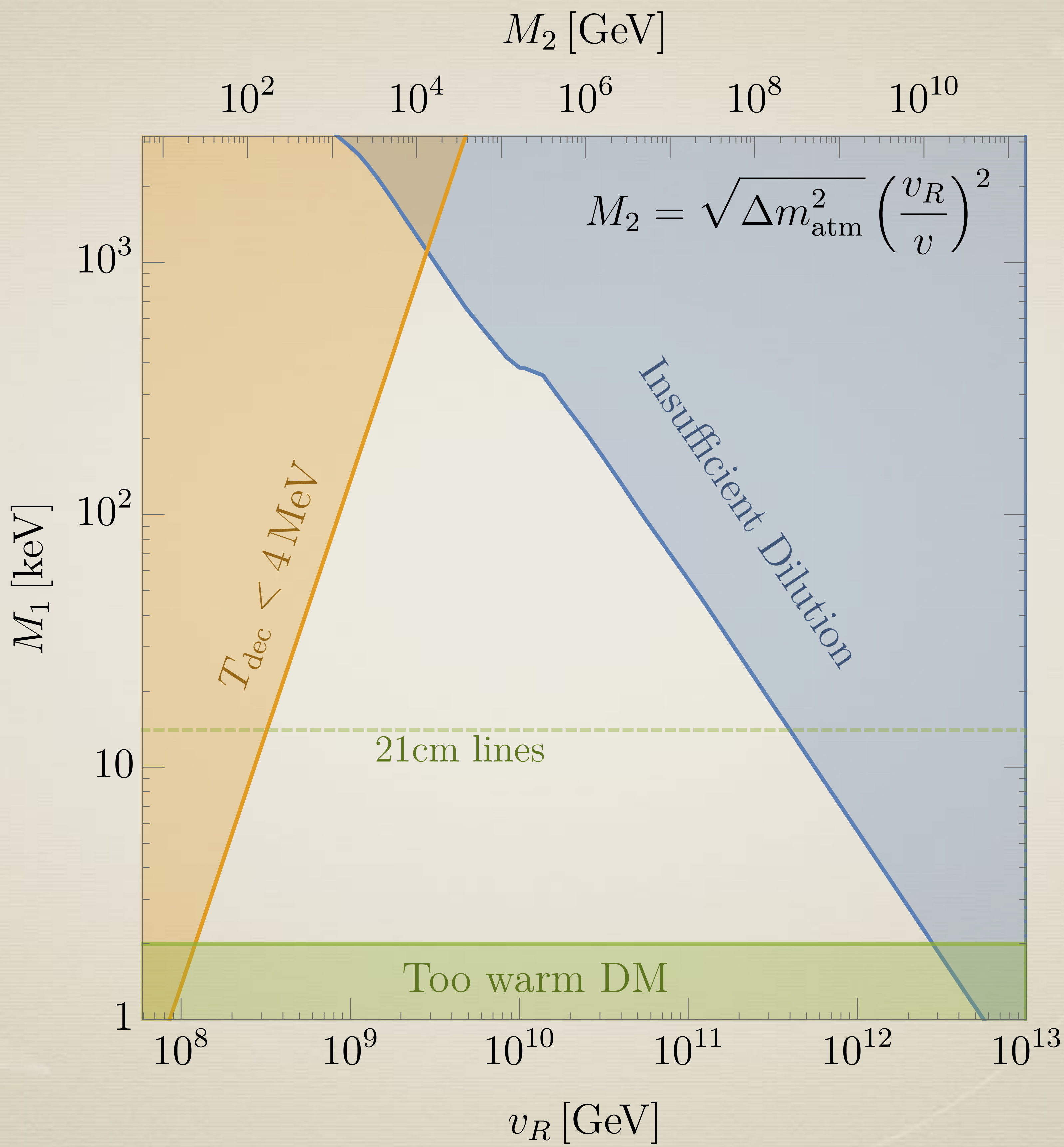
This is necessarily broken by the charged lepton yukawa



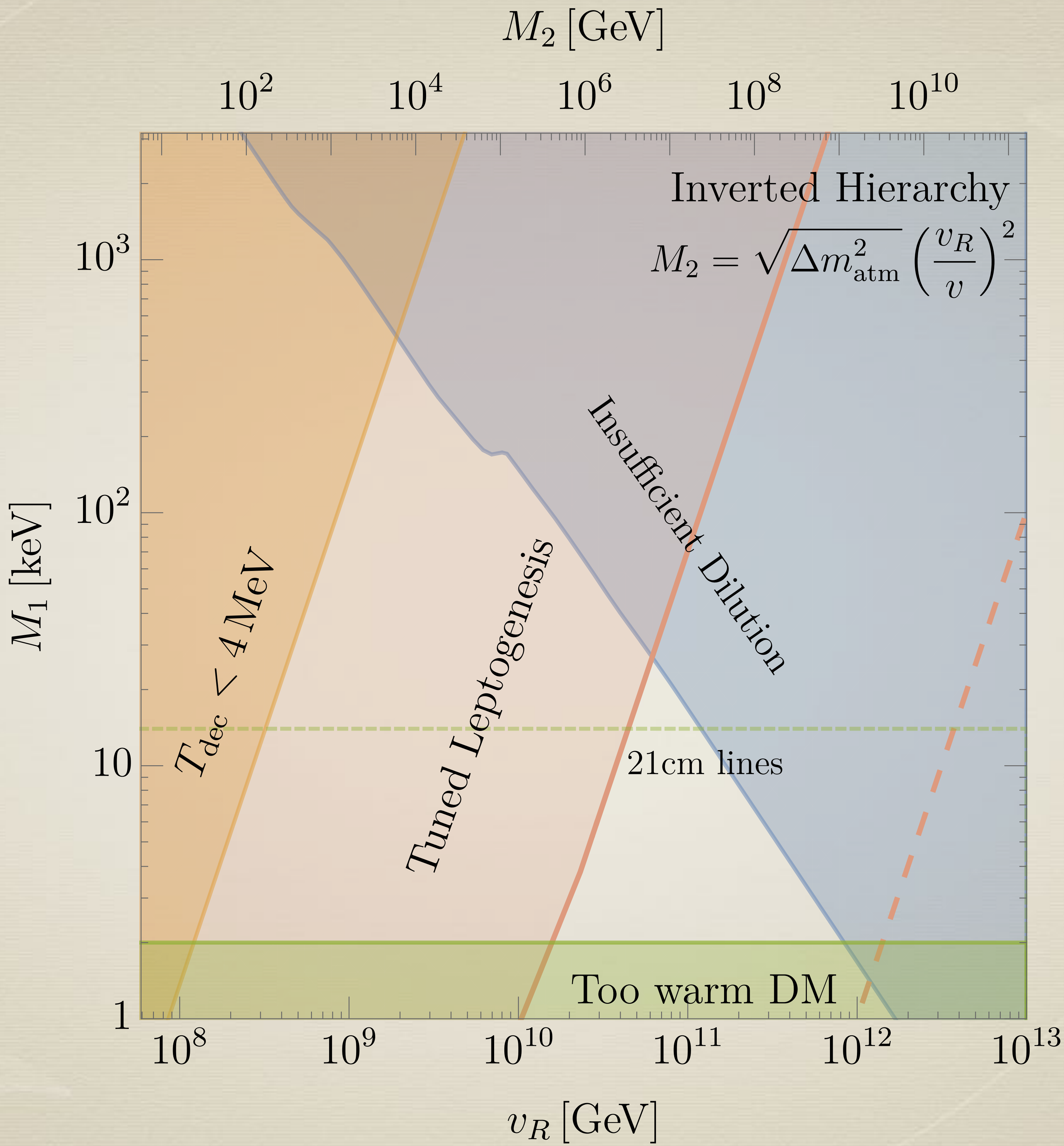
Dunsky, Hall and KH (2020)

Vanishing quartic

Additional figures



M_2 [GeV]
10^2
10^4
10^6
10^8
10^{10}
$M_2 = \sqrt{\Delta m^2_{\rm atm}}\left(\frac{v_R}{v}\right)^2$
10^3
10^2
10
1
M_1 [keV]
$T_{\rm dec} < 4\,{\rm MeV}$
Insufficient Dilution
21cm lines
Too warm DM
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
v_R [GeV]



M_2 [GeV]
10^2
10^4
10^6
10^8
10^{10}
Inverted Hierarchy
$M_2 = \sqrt{\Delta m^2_{\rm atm}} \left(\frac{v_R}{v}\right)^2$
10^3
10^2
10
1
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Insufficient Dilution
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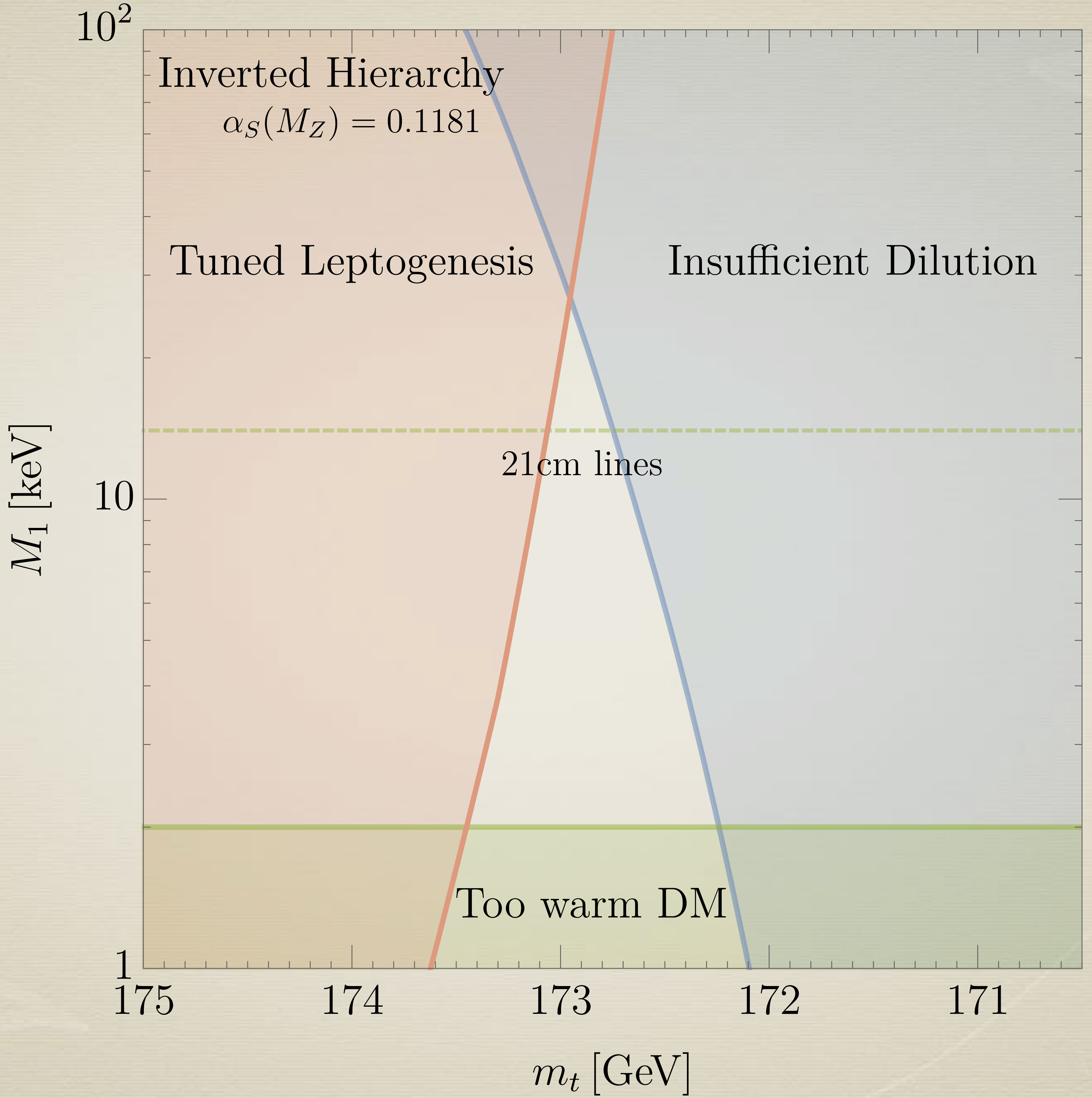
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
v_R [GeV]



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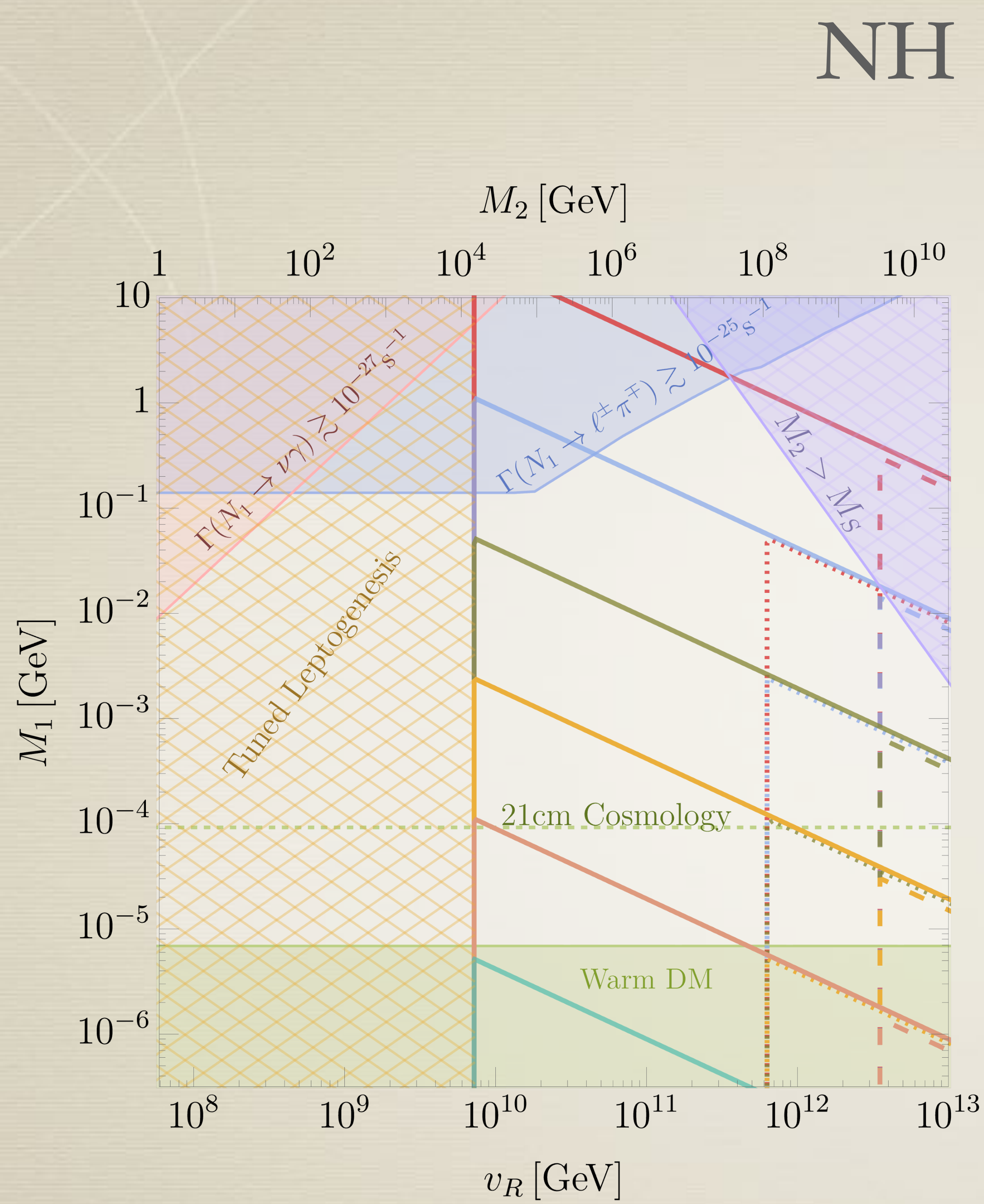
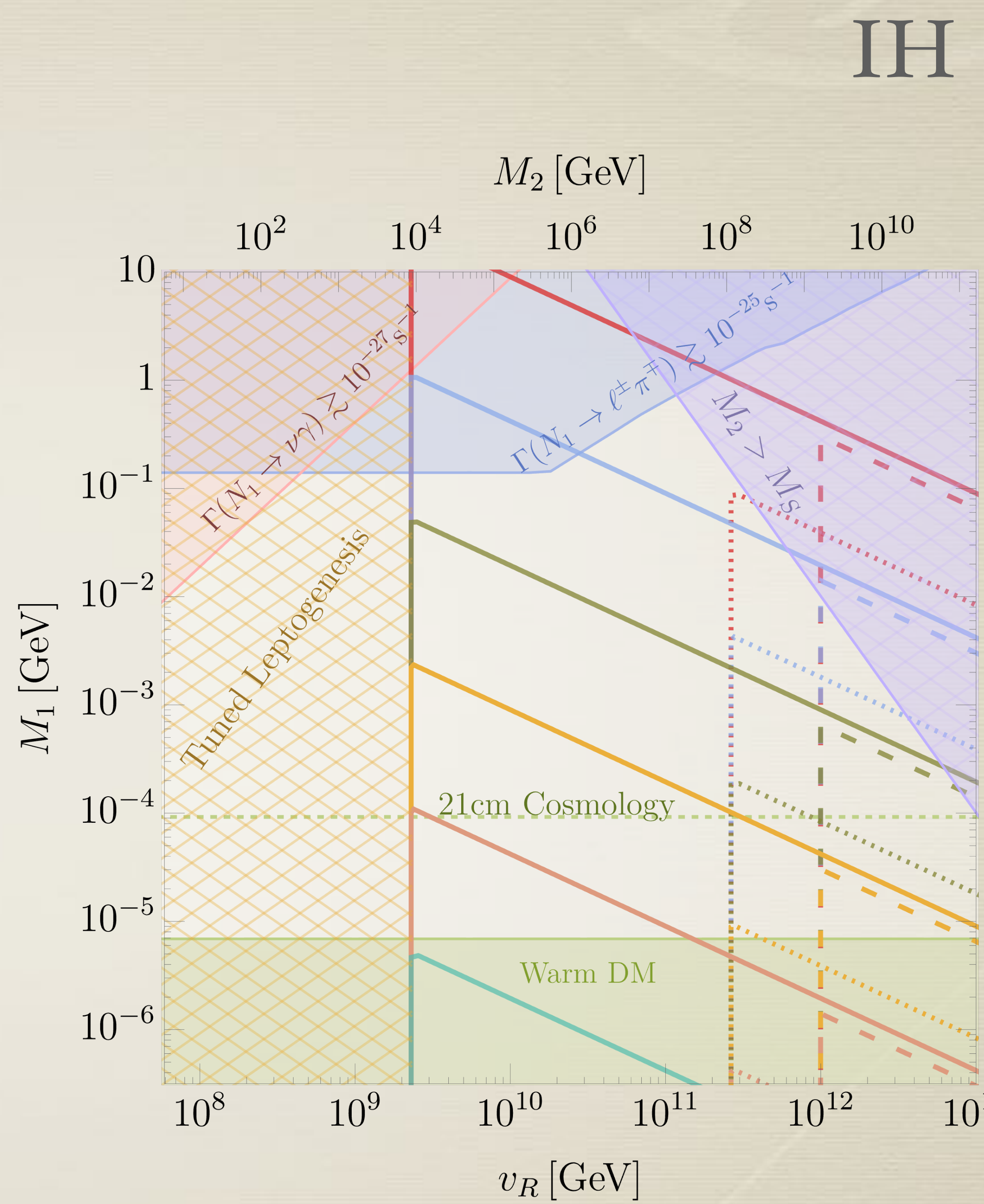
Too warm DM
10^2
10
1
175
174
173
172
171
M_1 [keV]
m_t [GeV]

Freeze-in


NH
M_2 [GeV]
1
10^2
10^4
10^6
10^8
10^{10}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
M_1 [GeV]
$\Gamma(N_1 \to \nu\gamma) \gtrsim 10^{-27}\,\mathrm{s}^{-1}$
$\Gamma(N_1 \to \ell^\pm\pi^\mp) \gtrsim 10^{-25}\,\mathrm{s}^{-1}$
$M_2 > M_S$
Tuned Leptogenesis
21cm Cosmology
Warm DM
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
v_R [GeV]


IH
M_2 [GeV]
10^2
10^4
10^6
10^8
10^{10}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
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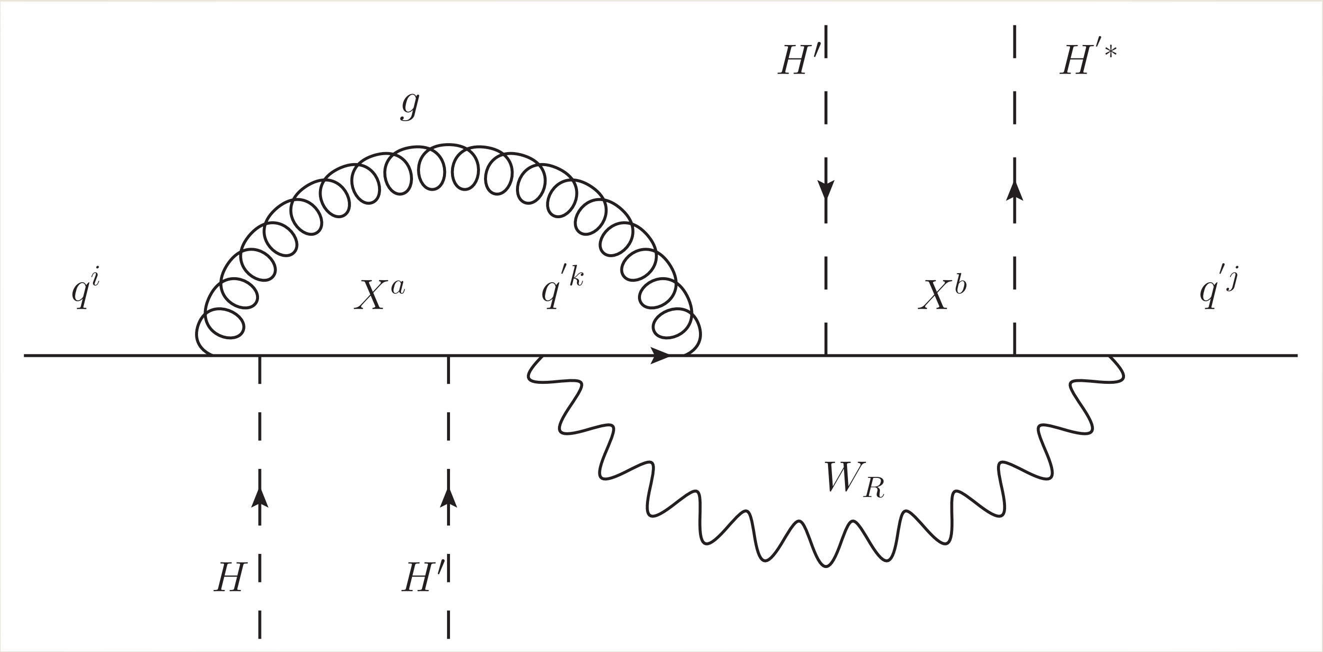
Tuned Leptogenesis
21cm Cosmology
Warm DM
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
v_R [GeV]

Non-zero theta term

Quantum corrections to the theta term

$$yH_Lq\bar{u} + M\bar{u}u + yH_R\bar{q}u$$

$M > yv_R$



$$\bar{\theta} \simeq \frac{g_2^2 g_3^2}{(16\pi^2)^2}\frac{y_b^3}{y_s}\theta_{23}^u\theta_{23}^d \lesssim \mathcal{O}(10^{-11})$$

Hall, KH (2018)

Quantum corrections to the theta term

$$yH_L q\bar{u} + M\bar{u}u + yH_R\bar{q}u$$

$M \ll yv_R$

$$\bar{\theta} \sim 10^{-19}$$

Ellis and Gaillard (1979)
Barr, Chang and Senjanović (1991)