Baryogenesis via left-right asymmetry generated by Affleck-Dine mechanism in Dirac neutrino model

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Contents

1. Introduction: neutrino mass

- Neutrino mass: very small

$$\Delta m^2_{\rm sol} \simeq 7.9 \times 10^{-5}{\rm eV}^2,\ \Delta m^2_{\rm atm} \simeq 2.4 \times 10^{-3}{\rm eV}^2\ \text{(neutrino oscillation)}$$

$$\sum_i |m_i| < 0.68{\rm eV}\ ({\rm WMAP} + {\rm LSS} + {\rm SN})$$

- seesaw mechanism

$\nu_R:$ right-handed (RH) neutrino

Majorana mass: $M\bar{\nu}_R\nu_R$ Dirac mass: $m\bar{L}\nu_R$

$\longrightarrow$ lighter mass eigenvalue $\sim \dfrac{m^2}{M}$

$m \sim \mathcal{O}(1) \times v \sim \mathcal{O}(100){\rm GeV} \longrightarrow M \gtrsim \mathcal{O}(10^{14}){\rm GeV}$

$v:$ Higgs VEV

intermediate scale mass

- pure Dirac mass

$y_\nu \bar{L} H_u \nu_R \longrightarrow m_\nu \sim y_\nu v$

$\longrightarrow y_\nu \lesssim 10^{-12}$ small Yukawa coupling

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$$\longrightarrow y_\nu \lesssim 10^{-12}$$

small Yukawa coupling

1 . Introduction: baryon asymmetry

- baryon-to-entropy ratio: $\frac{n_B}{s} = 8.7^{+0.3}_{-0.4} \times 10^{-11}$ (WMAP)

  - B -violating process
  - C- and CP-asymmetry
  - out-of-equilibrium process

* Majorana mass term ⟶ L -violating

in seesaw models, baryon asymmetry can be explained leptogenesis, via decays of heavy right-handed neutrinos, for example

Minimal Supersymmetric Standard Model (MSSM)
+ right-handed (RH) neutrino (Dirac neutrino mass)

⟶ can explain baryon asymmetry production

- without $B-L$ violation
- without B, L violation (except for sphaleron process)

S.Abel and V.Page, JHEP05,(2006)024

1. Introduction: outline of the model

- production of left-right asymmetry via Affleck-Dine mechanism
- production of baryon number via sphaleron process

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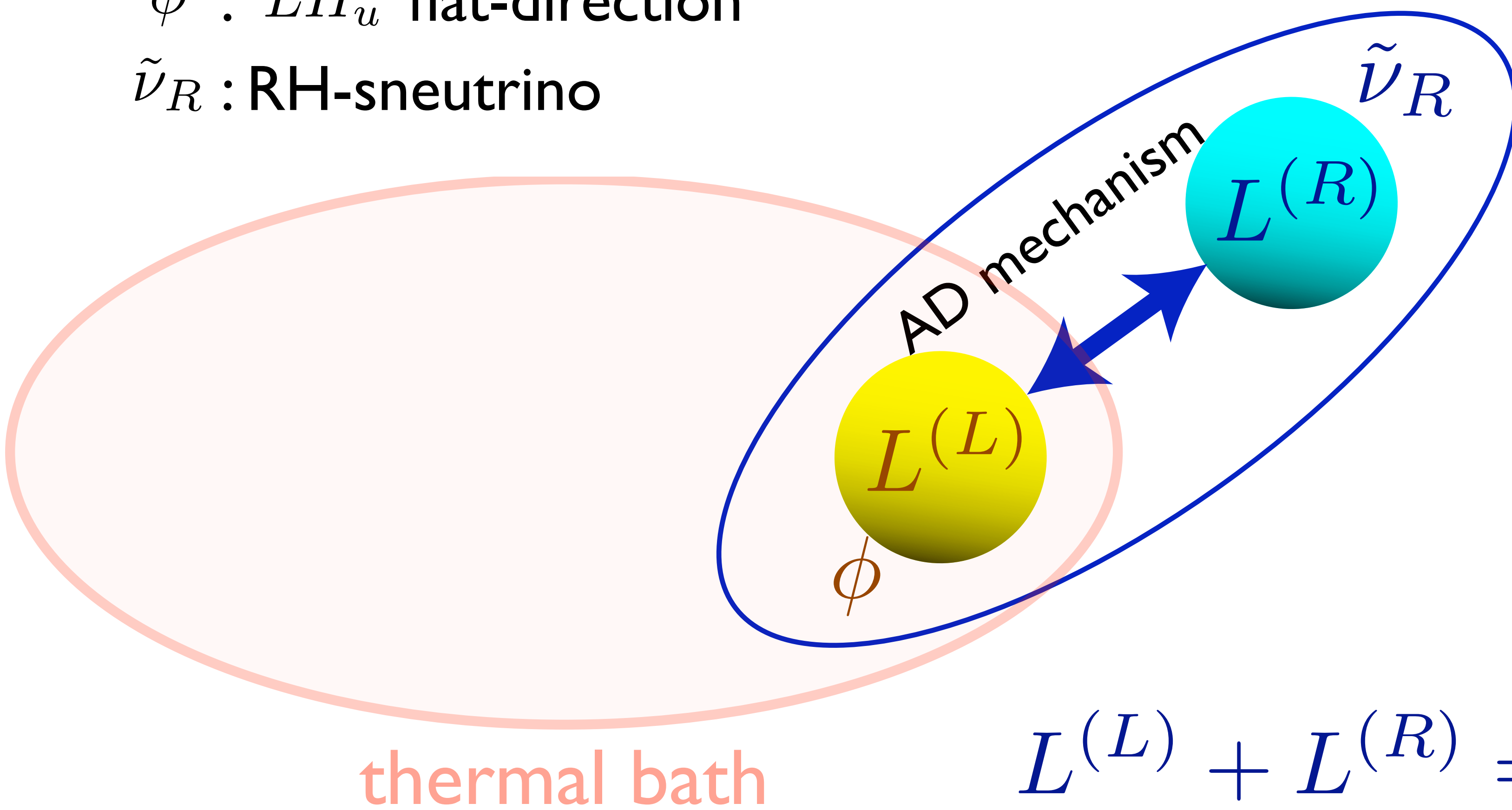
superpotential: $W = W_{\rm MSSM} + y_\nu \bar{L} H_u \nu_R$

ϕ : LH_u flat-direction

$\tilde{\nu}_R$: RH-sneutrino



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total lepton number ($L = L^{(L)} + L^{(R)}$) : conserved

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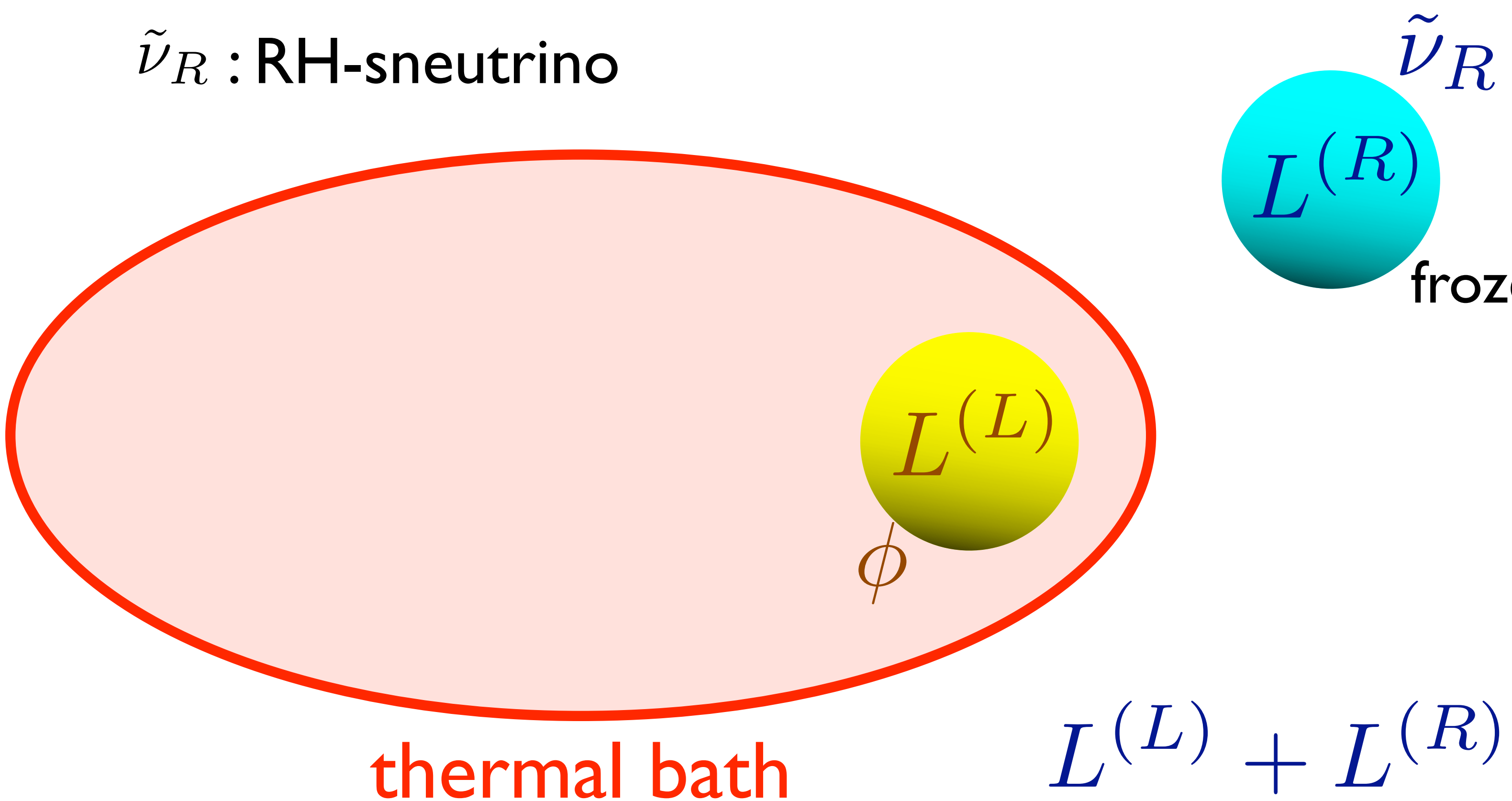

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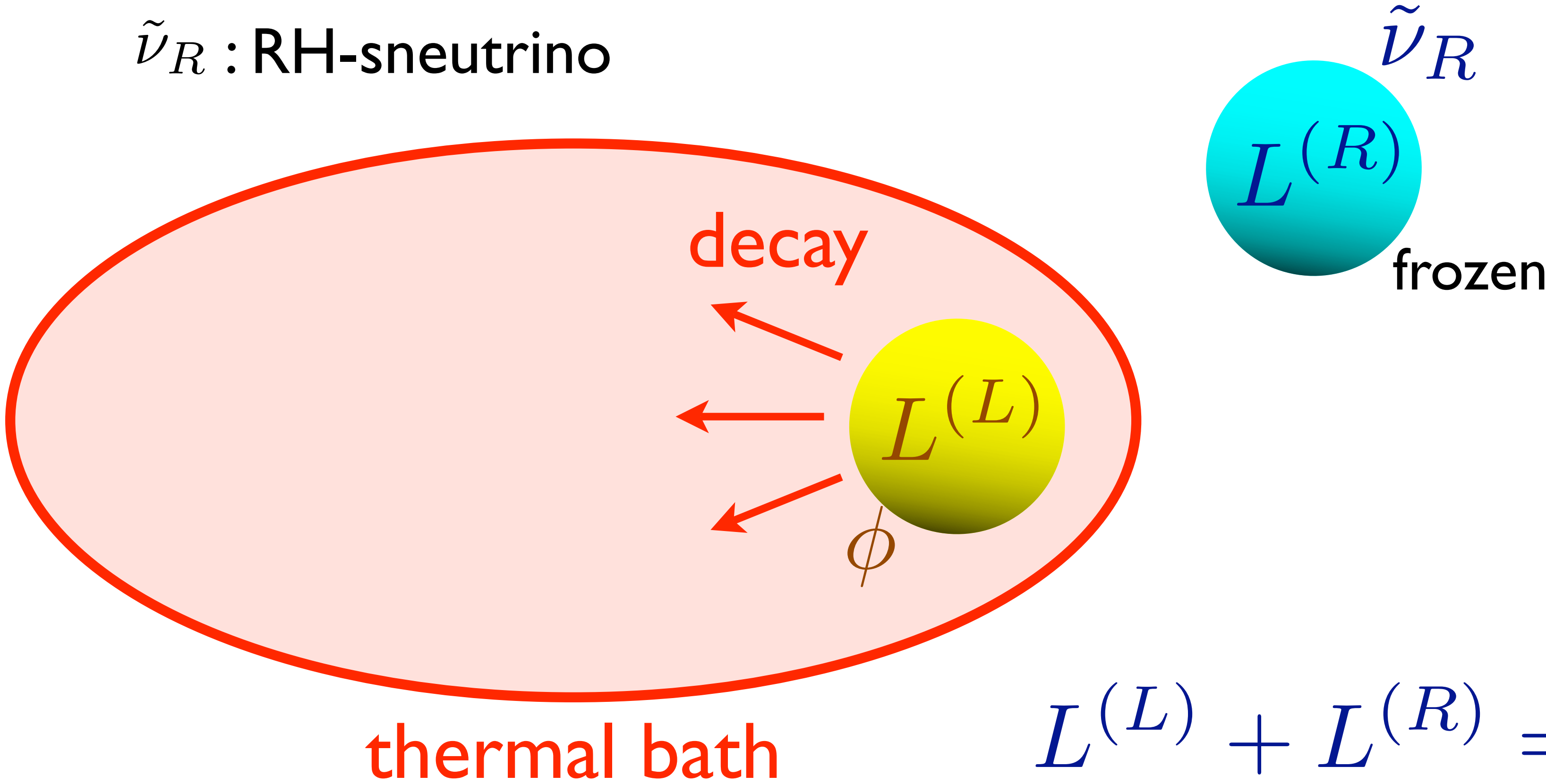

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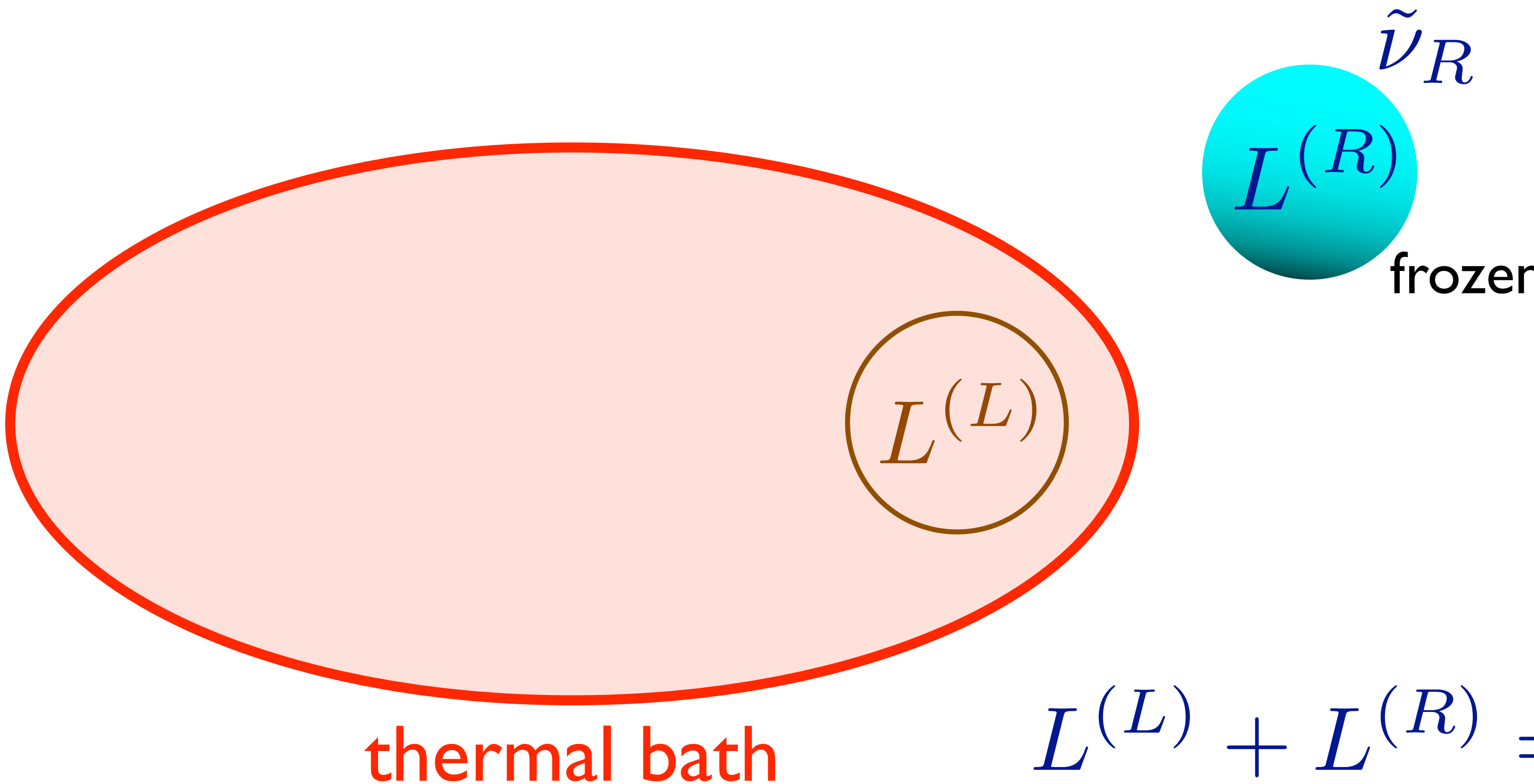

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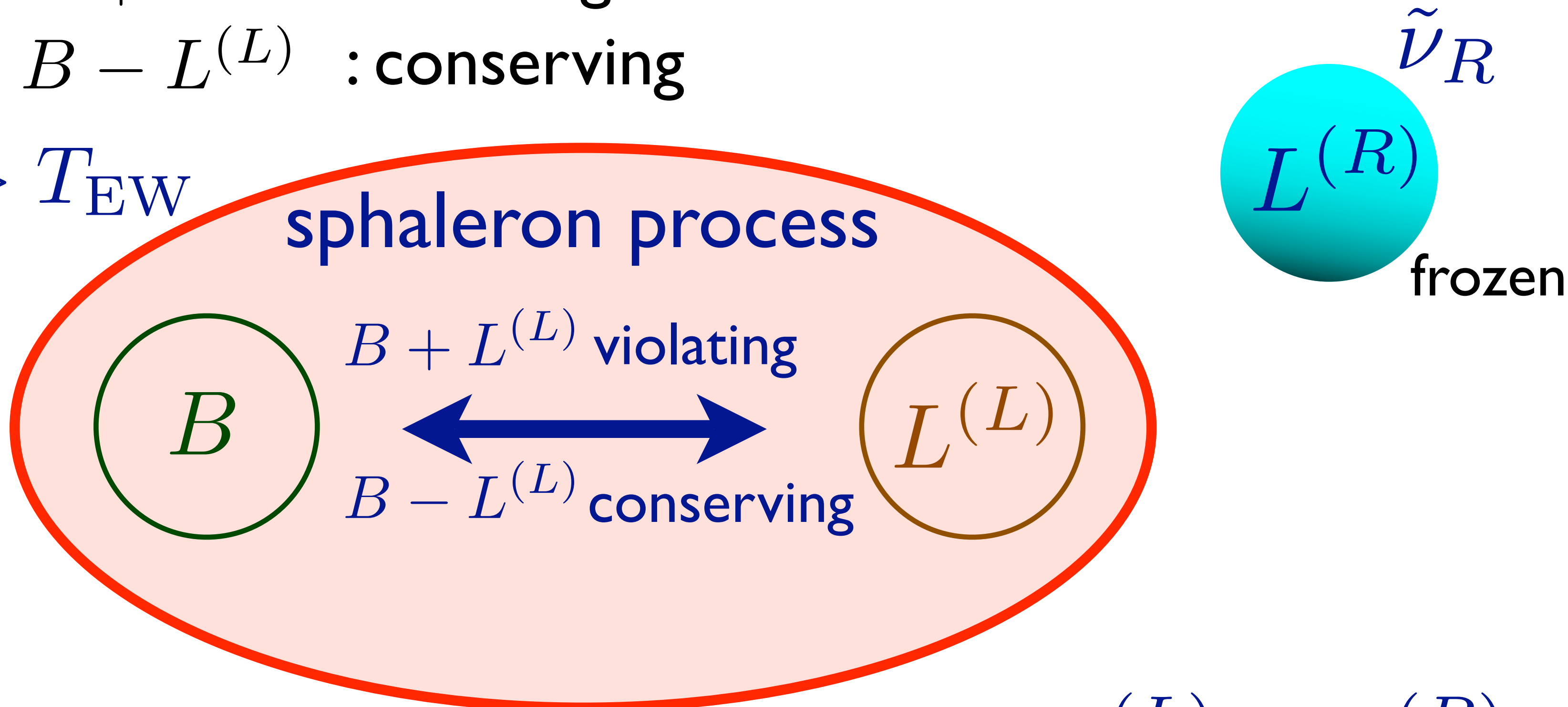
1. Introduction: outline of the model

- production of baryon number via sphaleron process

・ sphaleron process: $SU(2)_L$ non-perturbative effect

$$\begin{cases} B + L^{(L)} & \text{: violating} \\ B - L^{(L)} & \text{: conserving} \end{cases}$$

$T > T_{\mathrm{EW}}$



thermal bath $B - (L^{(L)} + L^{(R)}) = 0$

⟶ in chemical equilibrium: $B \neq 0, \ (B - L^{(L)}) - L^{(R)} = 0$

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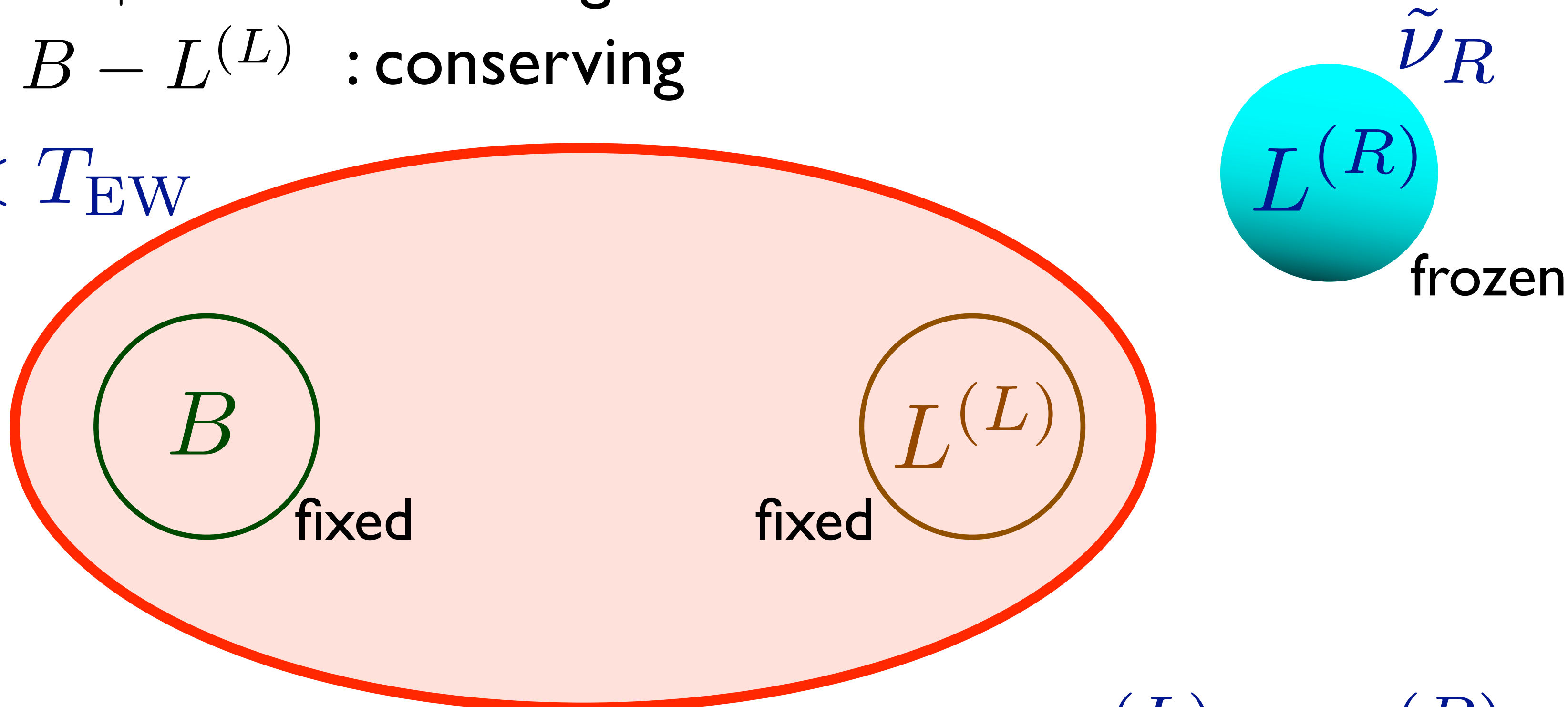

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• after sphaleron process becomes ineffective, B is fixed

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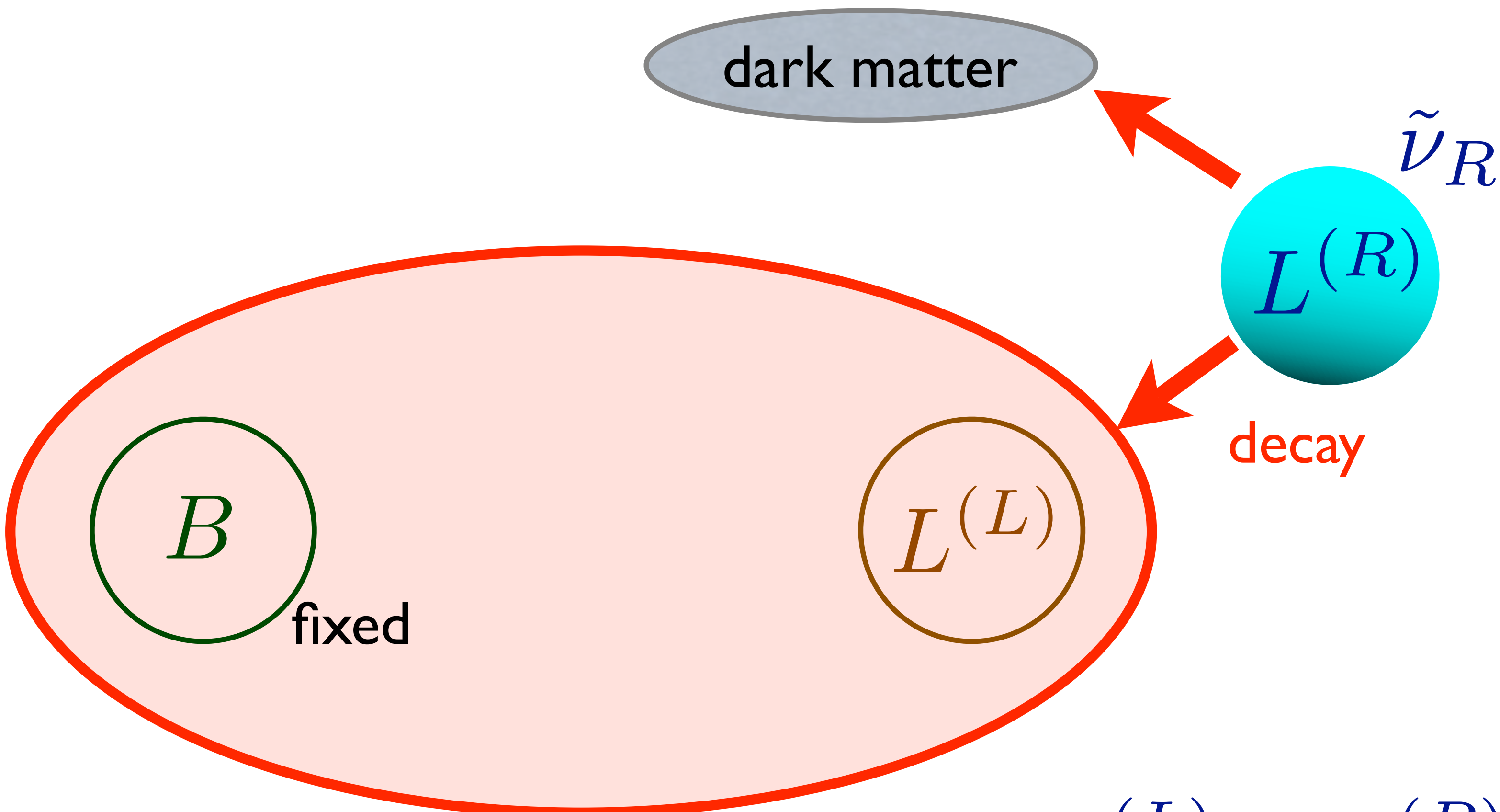

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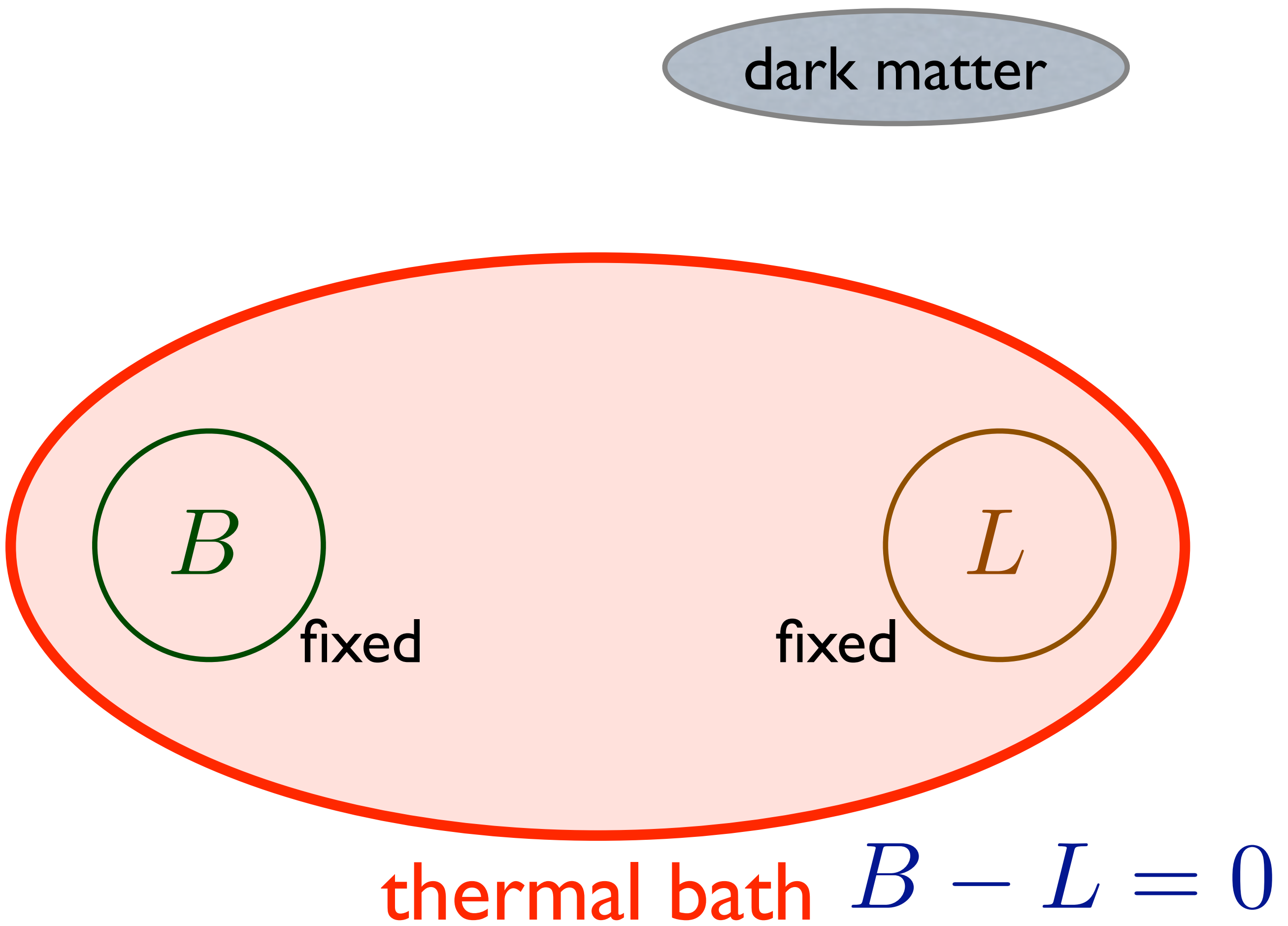


- after sphaleron process becomes ineffective, B is fixed

1. Introduction: Affleck-Dine mechanism

- complex scalar field ϕ with baryon (or lepton) number 1

total baryon (or lepton) number in homogeneous condensate of ϕ

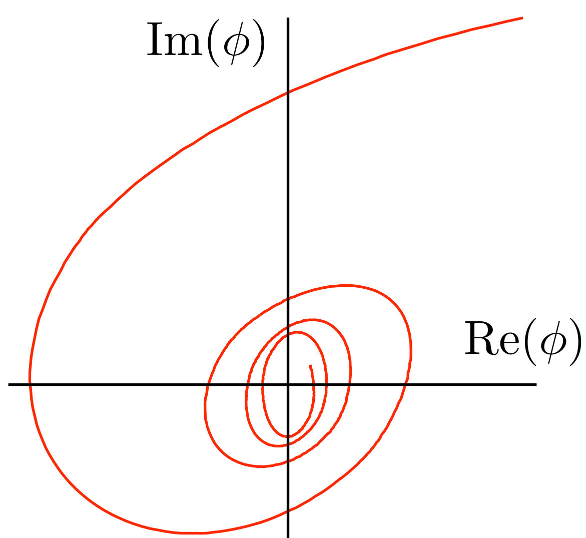
$$n = n_\phi - \bar{n}_\phi = i(\dot{\phi}^* \phi - \phi^* \dot{\phi}) = 2|\phi|^2 \dot{\theta}$$

$\phi = |\phi| e^{i\theta}$

"angular momentum" of ϕ ⟶ baryon (lepton) number

- ϕ has large vacuum expectation value during inflation
- CP-violating effects (e.g. a-term) $\quad \mathrm{Im}\left(\frac{\partial V}{\partial \phi}\phi\right) \neq 0$
- charge-violating effects

⟶ rotational motion after inflation



⟷

baryon (lepton) number in ϕ condensate

↓ B- (L-) conserving decay

baryon (lepton) number in SM particles

2. Set-up of the model: superpotential

- set-up: superpotential $W = W_{\rm MSSM} + y_\nu \bar{L} H_u \nu_R$

L : LH-lepton superfield　　H_u : up-type Higgs superfield

ν_R : RH-neutrino superfield (SM gauge singlet)

- Dirac neutrino mass from Higgs mechanism　$y_\nu \lesssim 10^{-12}$
- relevant scalar potential

ϕ : LH_u flat-direction

$$L = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi \\ 0 \end{pmatrix}, \quad H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix}$$

$\tilde{\nu}_R$: RH-sneutrino

$$V = \frac{y_\nu^2}{4} |\phi|^4 + y_\nu^2 |\tilde{\nu}_R \phi|^2$$

F-term potential

$$+ m_\phi^2 |\phi|^2 + m_{\tilde{\nu}_R}^2 |\tilde{\nu}_R|^2 + (y_\nu a m_{3/2} \phi^2 \tilde{\nu}_R + h.c.)$$

soft SUSY-breaking mass
+ A-term

$$- c_\phi H^2 |\phi|^2 - c_{\tilde{\nu}_R} H^2 |\tilde{\nu}_R|^2 + (y_\nu A H \phi^2 \tilde{\nu}_R + h.c.)$$

Hubble-induced SUSY-breaking mass (negative)
+ A-term

2 . Set-up of the model: thermal corrections

- thermal corrections (not included by AP)

  before reheating, there is thermal bath with $T \sim (H M_{\rm Pl} T_R^2)^{\frac{1}{4}}$

for ϕ

thermal-mass terms from MSSM particles in thermal equilibrium

$$\sum_{f_k|\phi|<T} c_k f_k^2 T^2 |\phi|^2$$

$$\begin{pmatrix} f_k \\ c_k \end{pmatrix} = \underset{\text{lepton}}{\begin{pmatrix} y_l/\sqrt{2} \\ 1/4 \end{pmatrix}}, \underset{\text{quark}}{\begin{pmatrix} y_q/\sqrt{2} \\ 3/4 \end{pmatrix}}, \underset{\text{W-boson}}{\begin{pmatrix} g_2/\sqrt{2} \\ 1/2 \end{pmatrix}}, \underset{\text{Z-boson}}{\begin{pmatrix} \sqrt{g_1^2 + g_2^2/2} \\ 1/4 \end{pmatrix}}$$

thermal-log terms from the running of the strong gauge coupling

$$0.47 \times \left(\sum_{\rm massive} \frac{1}{2} \right) \alpha_s^2 T^4 \ln\left(\frac{|\phi|^2}{T^2} \right)$$

for $\tilde{\nu}_R$

$\tilde{\nu}_R$: decoupled ⟶ no thermal corrections

2 . Set-up of the model: initial condition

we consider evolution of AD fields before the reheating

⟶ matter-dominant background is assumed

■ initial condition

- during inflation, Hubble-induced SUSY breaking terms are dominant
- after minimizing phase directions, potential for $|\tilde{\nu}_R|$

$$V_{\tilde{\nu}_R} = y_\nu^2 |\phi \tilde{\nu}_R|^2 + (m_{\tilde{\nu}_R}^2 \underline{- c_{\tilde{\nu}_R} H^2)|\tilde{\nu}_R|^2} - 2|y_\nu (a m_{3/2} + AH)||\phi|^2 |\tilde{\nu}_R|$$

* obviously, $V \to -\infty \ (|\tilde{\nu}_R| \to \infty)$

⟶ we must introduce some stabilizing potential

⟷ Abel & Page (AP): initially at the local minimum

$$|\phi|_{\min}(t) \simeq \sqrt{\frac{c_\phi}{2}} \frac{H(t)}{y_\nu}, \quad |\tilde{\nu}_R|_{\min}(t) \simeq \begin{cases} \dfrac{-c_\phi}{2c_{\tilde{\nu}_R} - c_\phi} \dfrac{|a|}{y_\nu} & (c_H H \ll |a|) \\ \dfrac{-c_\phi}{2c_{\tilde{\nu}_R} - c_\phi} \dfrac{H(t)}{y_\nu} & (c_H H \gg |a|) \end{cases}$$

2. Set-up of the model: stabilizing potential

- stabilizing potential:

  at higher energy scale, we assume extra gauge symmetry cf: GUT

  → D-term potential

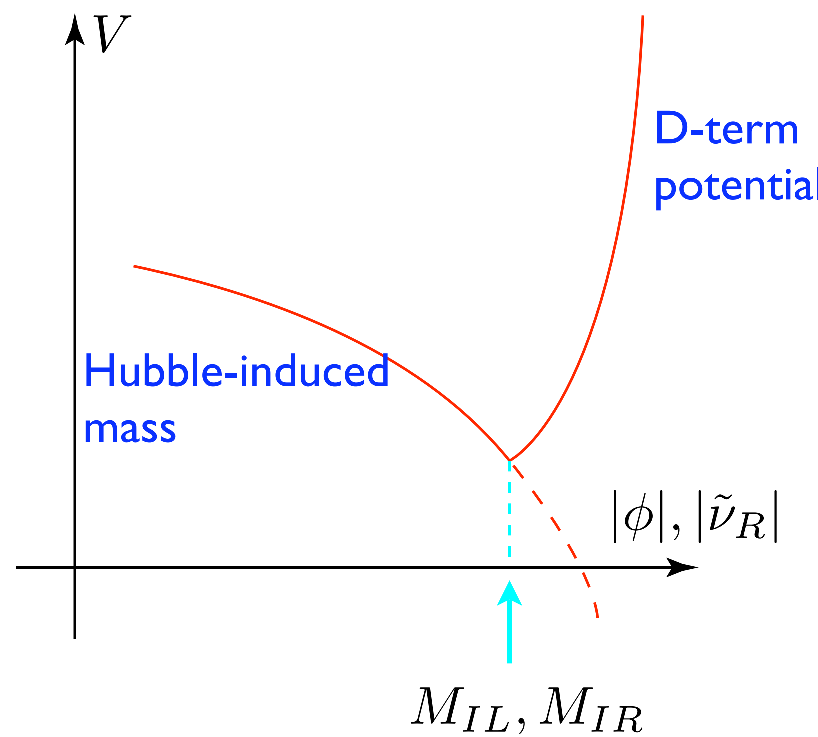
assumption: initial configuration at large H

Hubble-induced negative mass terms dominate the low-energy potential

$|\phi|$: fixed at M_{IL}

$|\tilde{\nu}_R|$: fixed at M_{IR}

phase-direction:
fixed at the minimum of
Hubble-induced A-term



2. Set-up of the model: comparison with AP

- in Abel & Page
  - initial condition is not appropriate
  - subsequent evolution is incorrect
  - thermal corrections is not taken into account

    low reheating temperature is favored

- our work
  - introduction of intermediate scale physics

    → stabilization of initial condition
      larger parameter region ($M_{IL} \neq M_{IR}$ case)
      possible solution of dark matter overproduction of this model

  - thermal correction is taken into account

    → high reheating temperature can give $n_B/s \sim 10^{-10}$

3 . Evolution of AD fields: left-right asymmetry

- AD mechanism ⟶ left-right asymmetry production
  - LH- / RH-lepton number

$$\begin{cases} L^{(L)} = n_L^{(L)} = \dfrac{i}{2}(\dot{\phi}^* \phi - \phi^* \dot{\phi}) \\ L^{(R)} = -n_L^{(R)} = -i(\dot{\tilde{\nu}}_R^* \tilde{\nu}_R - \tilde{\nu}_R^* \dot{\tilde{\nu}}_R) \end{cases}$$

  - evolution of scalar fields

↓

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi^*} = 0, \quad \ddot{\tilde{\nu}}_R + 3H\dot{\tilde{\nu}}_R + \frac{\partial V}{\partial \tilde{\nu}_R^*} = 0$$

  - evolution of total lepton number and left-right asymmetry

$$\begin{cases} \dfrac{d}{dt}(L^{(L)} + L^{(R)}) + 3H(L^{(L)} + L^{(R)}) = 0 \\ \dfrac{d}{dt}(L^{(L)} - L^{(R)}) + 3H(L^{(L)} - L^{(R)}) = 4\mathrm{Im}\{y_\nu (a m_{3/2} + AH)\phi^2 \tilde{\nu}_R\} \end{cases}$$

total lepton number conservation

CP -violating A-term ⟶ left-right asymmetry

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↓

  - evolution of total lepton number and left-right asymmetry

$$\frac{d}{dt}(L^{(L)} + L^{(R)}) + 3H(L^{(L)} + L^{(R)}) = 0$$

total lepton number conservation

$$\frac{d}{dt}(L^{(L)} - L^{(R)}) + 3H(L^{(L)} - L^{(R)}) = 4\mathrm{Im}\{y_\nu (a m_{3/2} + AH)\phi^2 \tilde{\nu}_R\}$$

CP-violating A-term ⟶ left-right asymmetry

3. Evolution of AD fields: left-right asymmetry

- evolution of the left-right asymmetry can be reduced into

$$\frac{d}{dt}(R^3 n_{LR}) = \underline{R^3 \mathrm{Im}(a m_{3/2} y_\nu \phi^2 \tilde{\nu}_R)}$$

source term

$R:$ scale factor, $n_{LR} \equiv L^{(L)} - L^{(R)}$

* we assume phase direction minimizes the Hubble-induced A-term

- source term $= 0$: $n_{LR} \propto R^{-3}$ (simply scaling)
- source term is not oscillating,
  and the motion of phase directions are negligible: $(a m_{3/2} \ll AH)$

asymptotic solutions: for $|\phi|^2 |\tilde{\nu}_R| \propto t^\gamma$

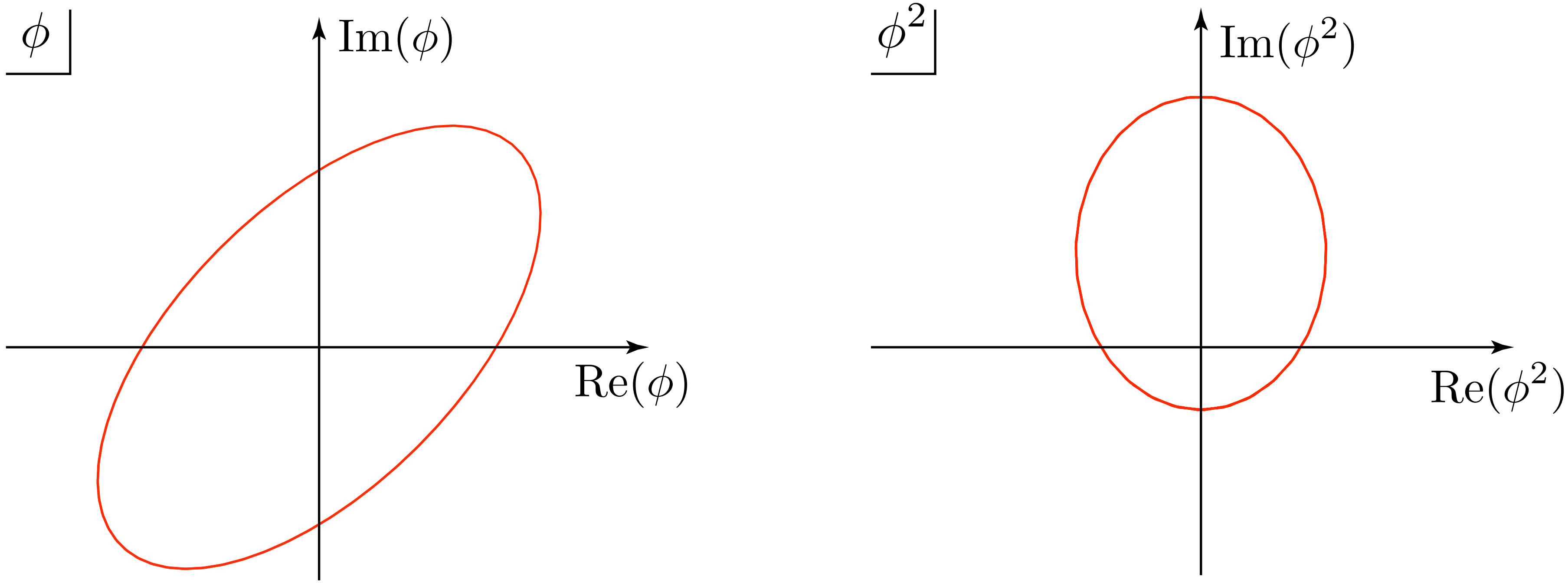
$$\gamma > -3 \longrightarrow n_{LR} \propto \frac{1}{H} a m_{3/2} y_\nu |\phi^2||\tilde{\nu_R}|\delta_{\mathrm{eff}}$$

$\delta_{\mathrm{eff}} \lesssim 1$: phase factor

$$\gamma < -3 \longrightarrow n_{LR} \propto R^{-3}$$

3 . Evolution of AD fields: left-right asymmetry

- ϕ is oscillating, $\tilde{\nu}_R$ is fixed: $\longrightarrow$ generally, trajectory is elliptical



on average, $\mathrm{Im}(am_{3/2}y_\nu\phi^2\tilde{\nu}_R) \neq 0$ $\longrightarrow$ growth of n_{LR}

evolution is estimated
by scaling of the amplitude: $\langle|\phi|\rangle \propto t^{\gamma'}$ $\longrightarrow$ $\gamma = 2\gamma'$

- $\tilde{\nu}_R$ is oscillating:

on average, $\mathrm{Im}(am_{3/2}y_\nu\phi^2\tilde{\nu}_R) = 0$ $\longrightarrow$ $n_{LR} \propto R^{-3}$

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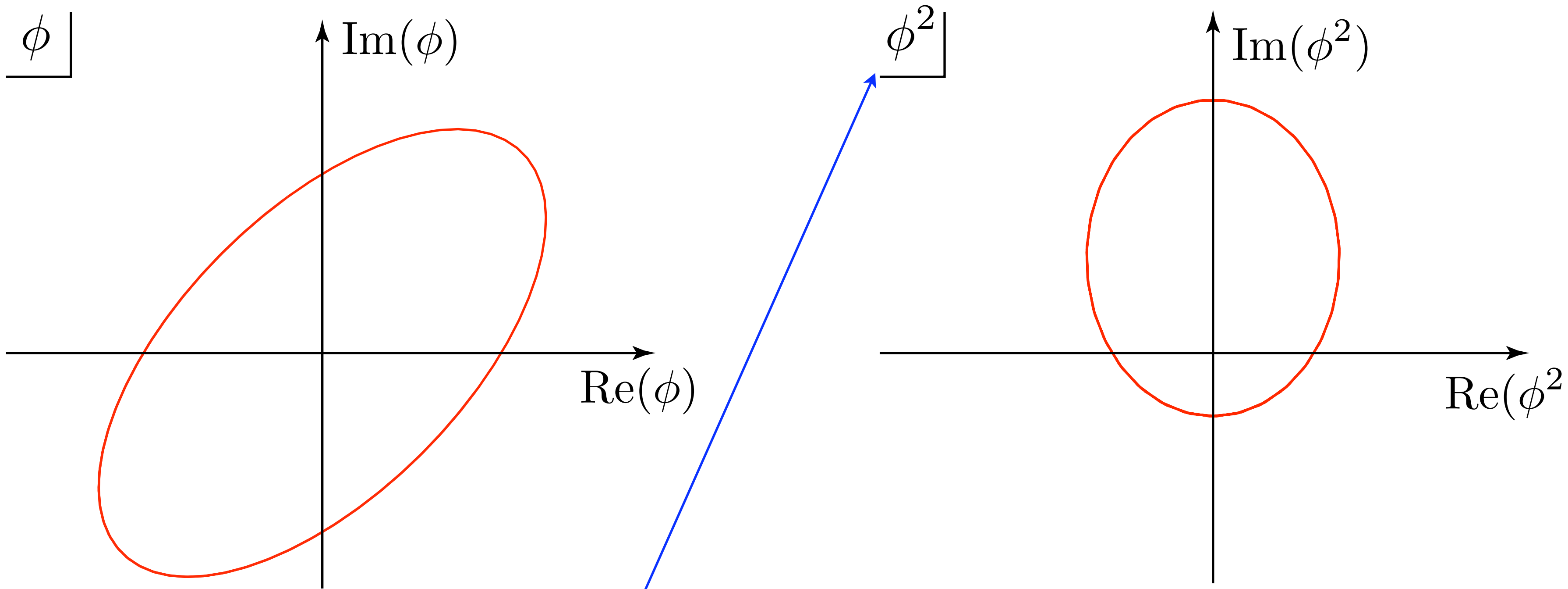

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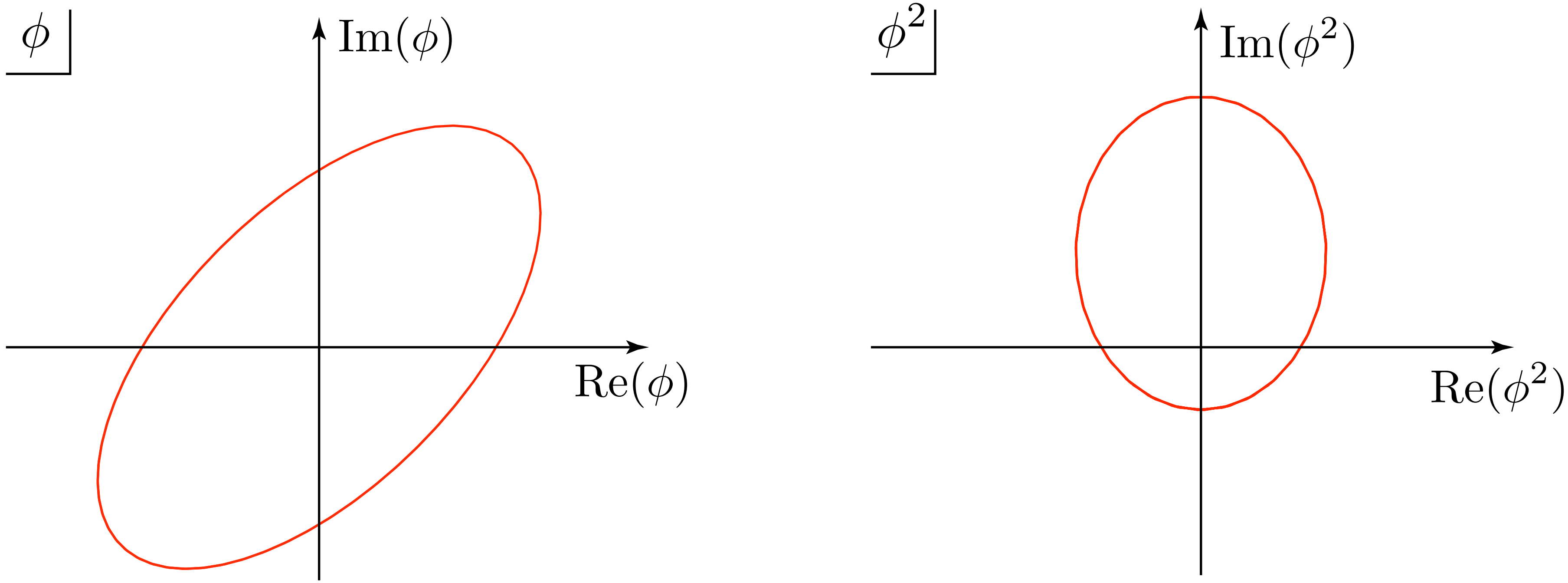

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- $\tilde{\nu}_R$ is oscillating:

on average, $\mathrm{Im}(a m_{3/2} y_\nu \phi^2 \tilde{\nu}_R) = 0$ ⟶ $n_{LR} \propto R^{-3}$

3 . Evolution of AD fields: left-right asymmetry

in summary,

a) source term is simply scaling with $|\phi|^2|\tilde{\nu}_R| \propto t^\gamma$, $\gamma > -3$
and the motion of phase directions are negligible

b) only ϕ is oscillating, trajectory is elliptical,
direction of trajectory does not change significantly,
amplitude is scaling with $\langle|\phi|\rangle \propto \gamma'$, $\gamma' > -3/2$

⟶ $R^3 n_{LR}$ is growing

c) the same as a) or b), but scaling is $\gamma < -3$ $(\gamma' < -3/2)$

d) $\tilde{\nu}_R$ is oscillating

⟶ $R^3 n_{LR}$ is fixed $(n_{LR} \propto R^{-3})$

3 . Evolution of AD fields: destabilization

- destabilization takes place when

$$\left.\frac{\partial V}{\partial|\phi|}\right|_{|\phi|=M_{IL}} = \Big(-2c_\phi H^2 + 2m_\phi^2 + M_{IL}^2 + 2M_{IR}^2 + M_{IL}^{-1}\frac{\partial V_{\rm thermal}}{\partial|\phi|} + \cdots\Big)M_{IL} > 0$$

$$\left.\frac{\partial V}{\partial|\tilde{\nu}_R|}\right|_{|\tilde{\nu}_R|=M_{IR}} = \Big(-2c_{\tilde{\nu}_R}H^2 + 2m_{\tilde{\nu}_R}^2 + 2M_{IL}^2 + \cdots\Big)M_{IR} > 0$$

* hereafter, we assume $m_\phi \sim m_{\tilde{\nu}_R} \sim m_{3/2}$

- large soft-mass or M_{IL}^2 ⟶ $|\phi|$ and $|\tilde{\nu}_R|$ are destabilized almost at the same time

- large thermal-corrections or M_{IR}^2

  ⟶ first, $|\phi|$ is destabilized

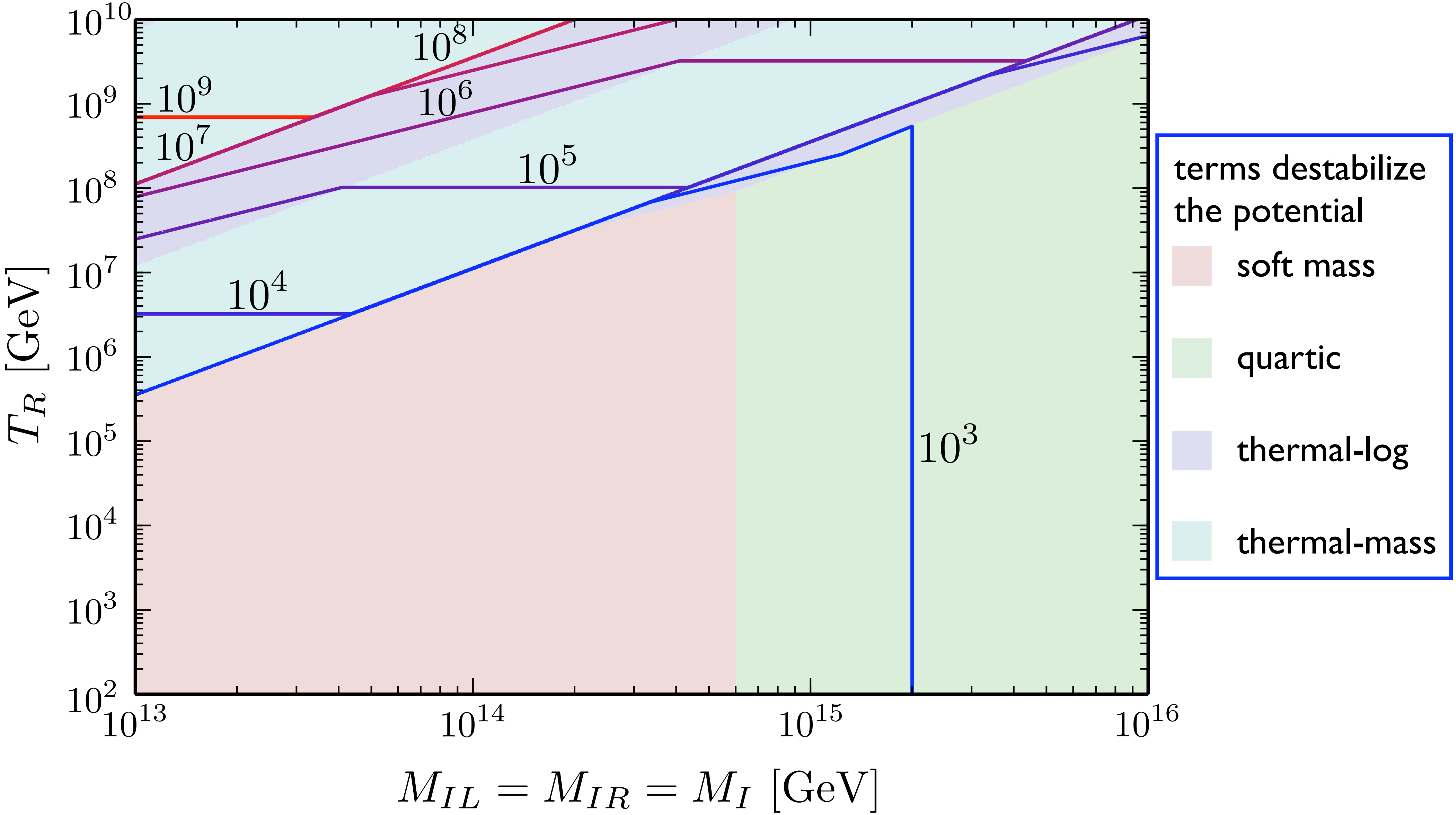
  then, $|\tilde{\nu}_R|$ is destabilized at $H \sim m_{\tilde{\nu}_R}$

3. Evolution of AD fields: destabilization

contour plot of $H_{\rm osc}$ [GeV]

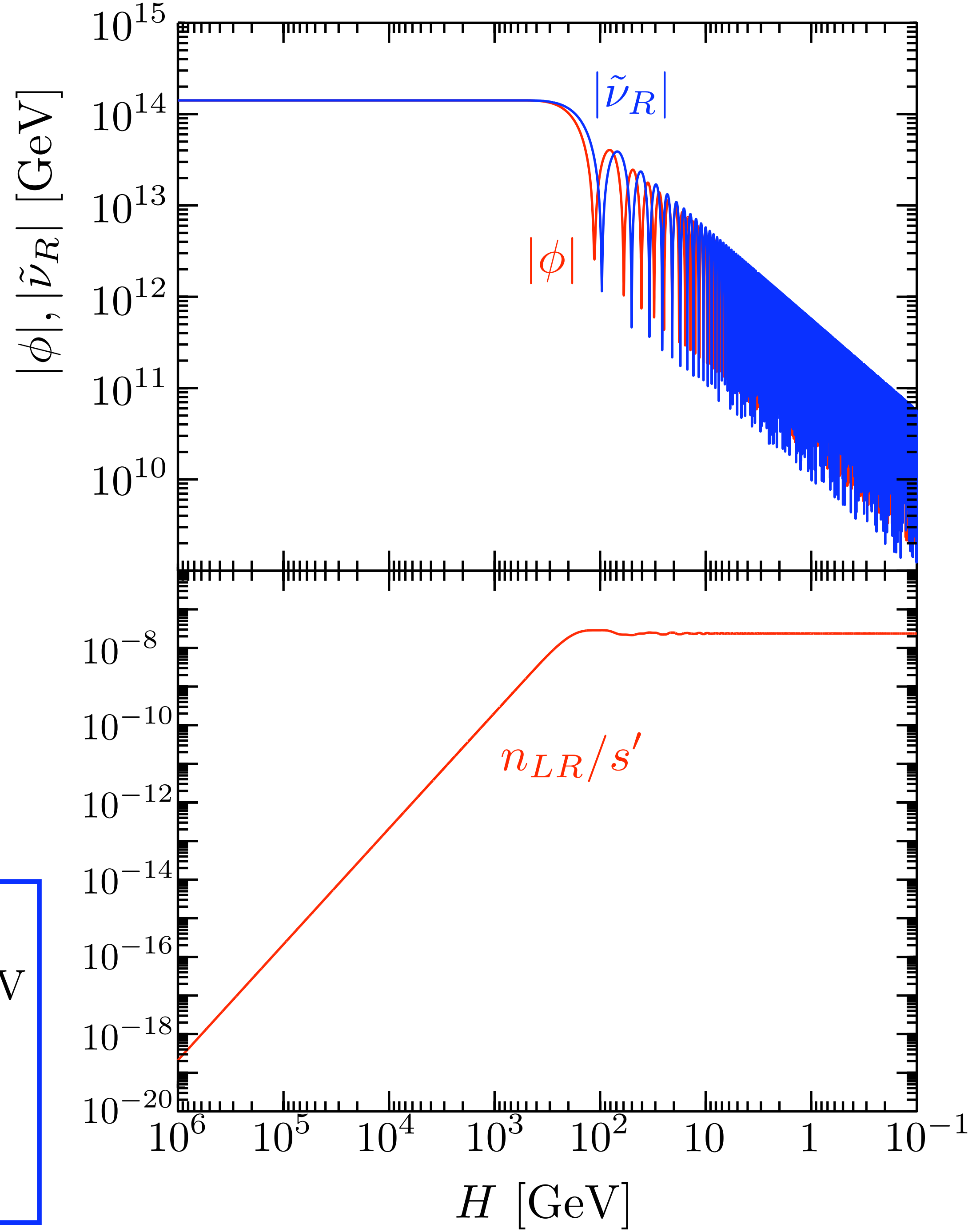
$y_\nu = 1.0 \times 10^{-12}, m_\phi = 600\text{GeV}, m_{\tilde{\nu}_R} = 500\text{GeV},$

$m_{3/2} = 100\text{GeV}, c_\phi = 1.0, c_{\tilde{\nu}_R} = 0.8$



3. Evolution of AD fields: case-I

- soft SUSY-breaking mass term



* $s' \equiv \dfrac{T_R}{4H^2 M_{Pl}^2}$, fixed value of n_{LR}/s' corresponds to n_{LR}/s after the reheating

note: $R^3 n_{LR} \propto n_{LR}/s'$

parameters for numerical calculation

$y_\nu = 1.0 \times 10^{-12}, m_\phi = 600\text{GeV}, m_{\tilde{\nu}_R} = 500\text{GeV}$

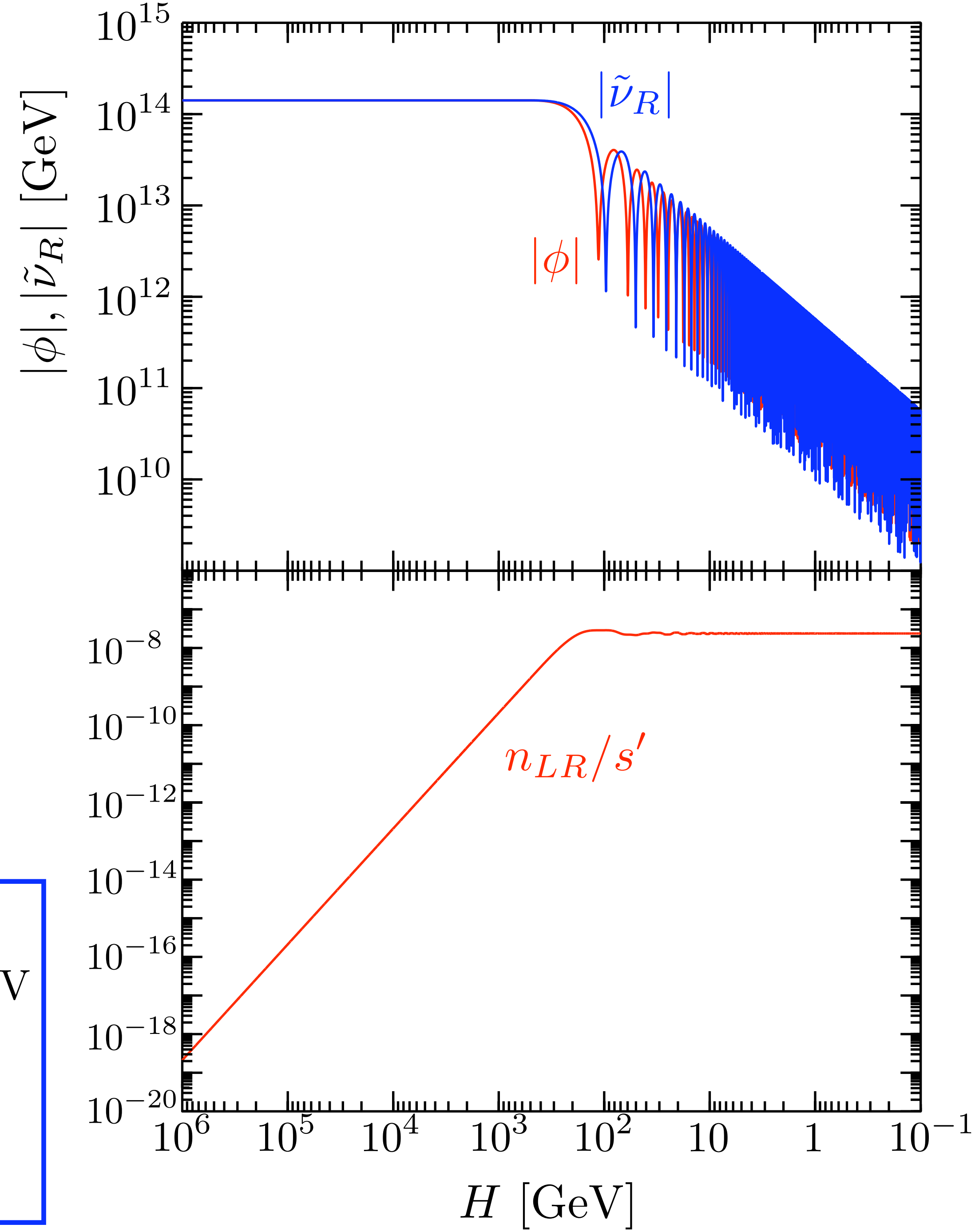
$m_{3/2} = 100\text{GeV}$

$M_{IL} = M_{IR} = 10^{14}, T_R = 10^5\text{GeV}$

$c_\phi = 1.0, c_{\tilde{\nu}_R} = 0.8, a = e^{0.6i}, A = -0.5$

3. Evolution of AD fields: case-I

- soft SUSY-breaking mass term
  - until $H \sim m_\phi \sim m_{\tilde{\nu}_R}$



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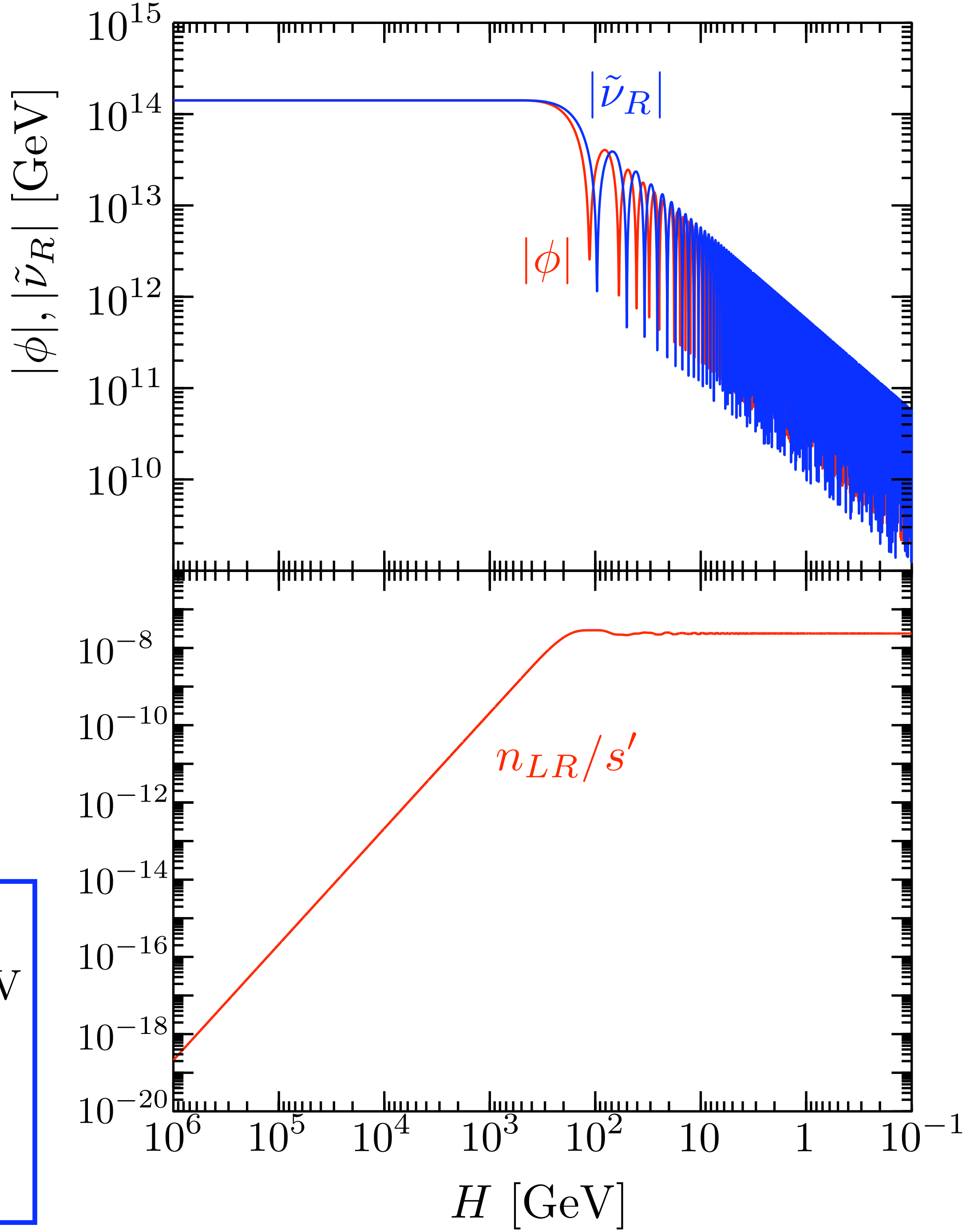
- soft SUSY-breaking mass term
  - until $H \sim m_\phi \sim m_{\tilde{\nu}_R}$ fields are fixed at

$$|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$$

$\longrightarrow$ $R^3 n_{LR}$ is growing



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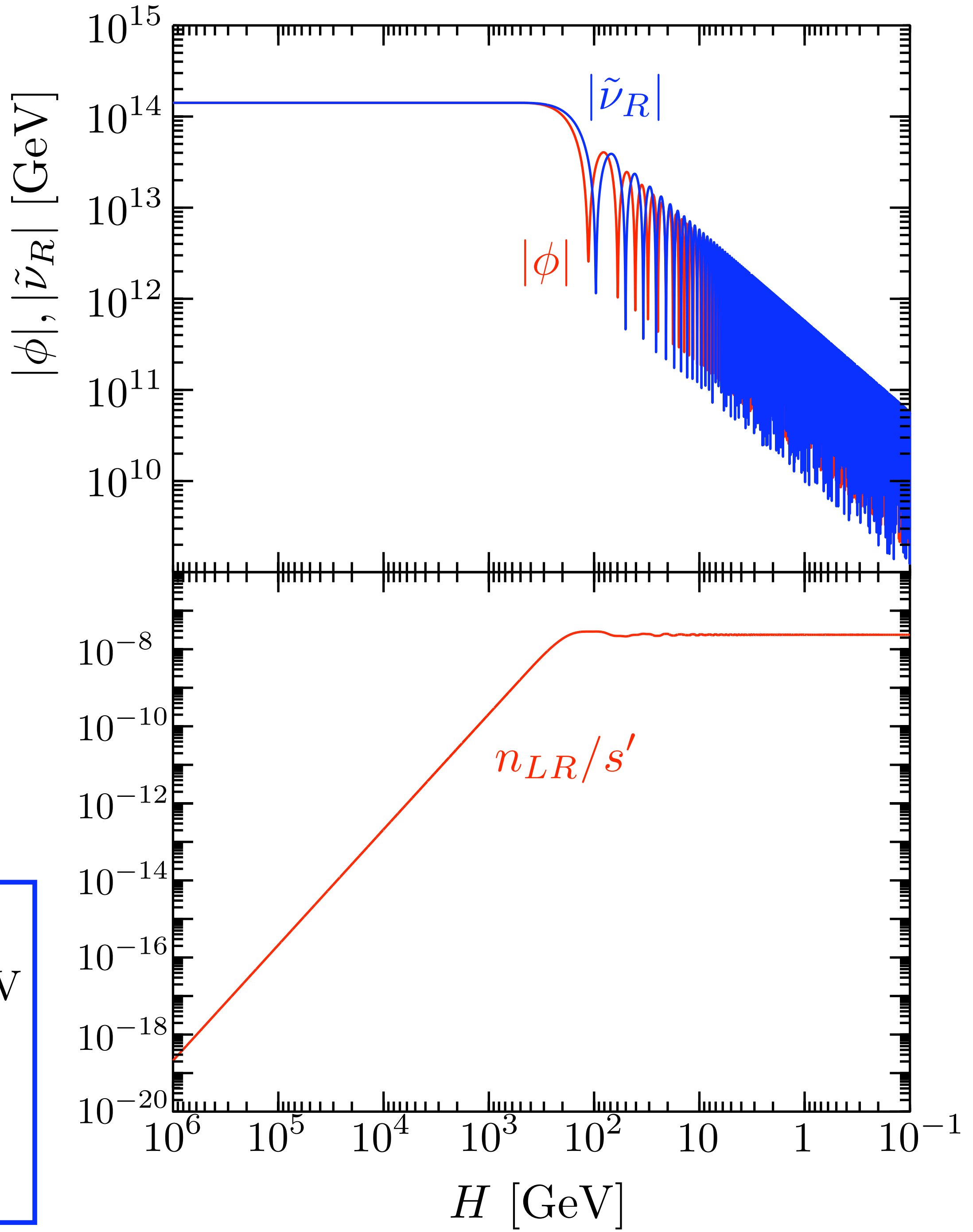
3 . Evolution of AD fields: case-I

■ soft SUSY-breaking mass term

- until $H \sim m_\phi \sim m_{\tilde{\nu}_R}$
  fields are fixed at
  $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$
  ⟶ $R^3 n_{LR}$ is growing
- at $H \sim m_\phi \sim m_{\tilde{\nu}_R}$



* $s' \equiv \frac{T_R}{4H^2 M_{Pl}^2}$, fixed value of n_{LR}/s' corresponds to n_{LR}/s after the reheating

note: $R^3 n_{LR} \propto n_{LR}/s'$

parameters for numerical calculation

$y_\nu = 1.0 \times 10^{-12}, m_\phi = 600\text{GeV}, m_{\tilde{\nu}_R} = 500\text{GeV}$

$m_{3/2} = 100\text{GeV}$

$M_{IL} = M_{IR} = 10^{14}, T_R = 10^5\text{GeV}$

$c_\phi = 1.0, c_{\tilde{\nu}_R} = 0.8, a = e^{0.6i}, A = -0.5$

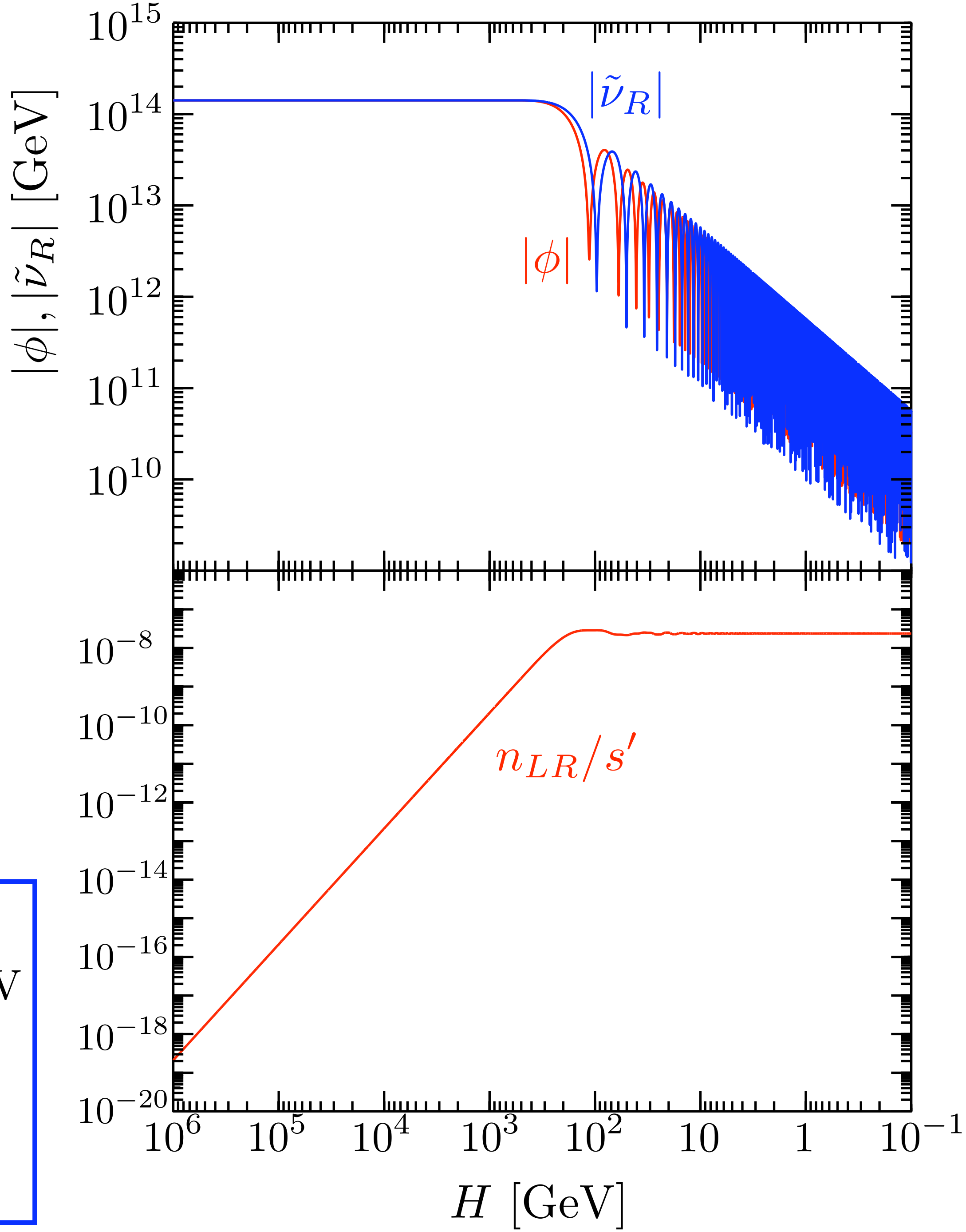
3. Evolution of AD fields: case-1

■ soft SUSY-breaking mass term

- until $H \sim m_\phi \sim m_{\tilde{\nu}_R}$
  fields are fixed at
  $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$
  ⟶ $R^3 n_{LR}$ is growing
- at $H \sim m_\phi \sim m_{\tilde{\nu}_R}$
  both ϕ and $\tilde{\nu}_R$ begin oscillation
  ⟶ $R^3 n_{LR}$ is fixed

* $s' \equiv \frac{T_R}{4H^2 M_{Pl}^2}$, fixed value of n_{LR}/s' corresponds to n_{LR}/s after the reheating

note: $R^3 n_{LR} \propto n_{LR}/s'$



parameters for numerical calculation

$y_\nu = 1.0 \times 10^{-12}, m_\phi = 600\text{GeV}, m_{\tilde{\nu}_R} = 500\text{GeV}$

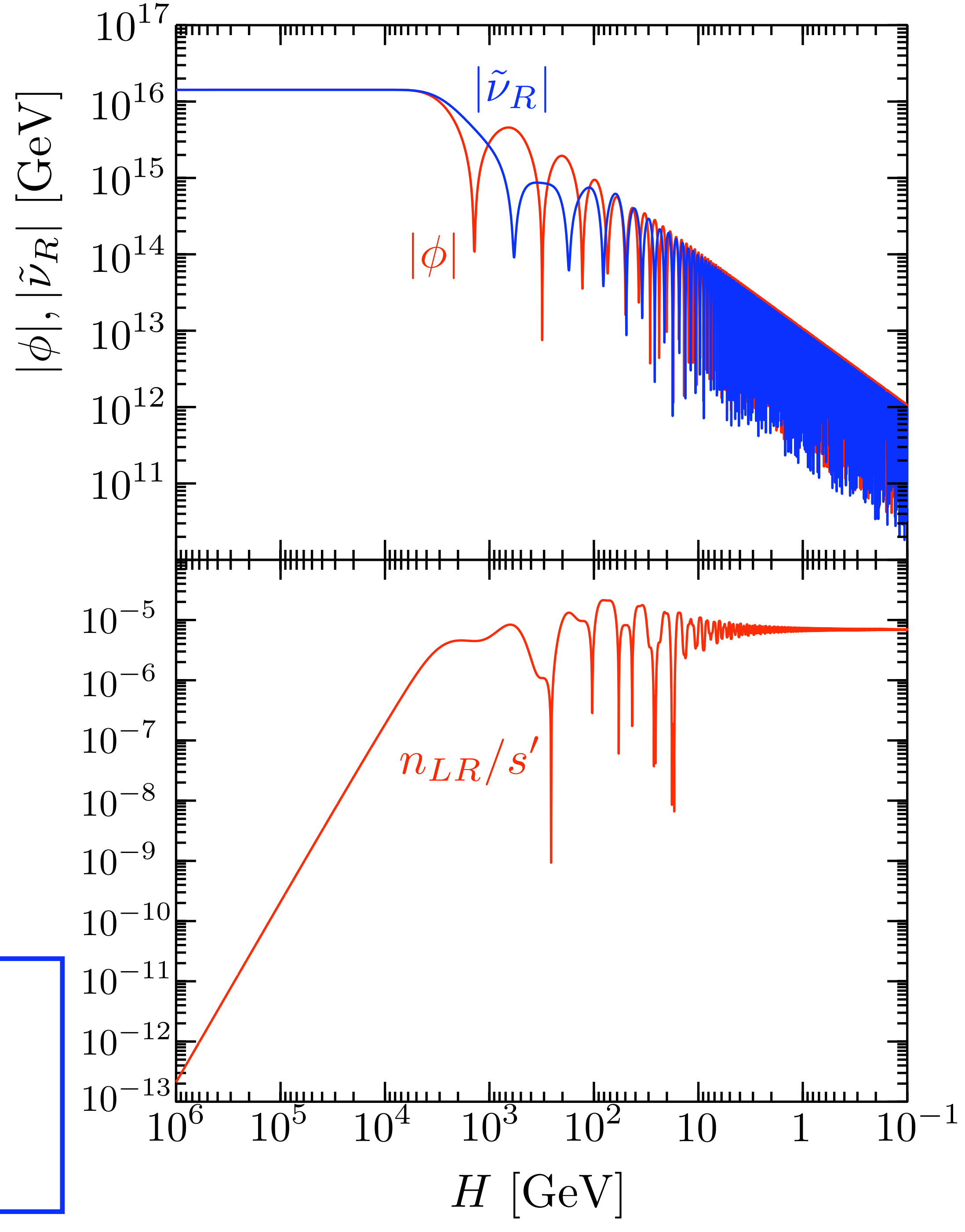
$m_{3/2} = 100\text{GeV}$

$M_{IL} = M_{IR} = 10^{14}, T_R = 10^5\text{GeV}$

$c_\phi = 1.0, c_{\tilde{\nu}_R} = 0.8, a = e^{0.6i}, A = -0.5$

3 . Evolution of AD fields: case-II

- quartic term $(M_{IL} \geq M_{IR})$



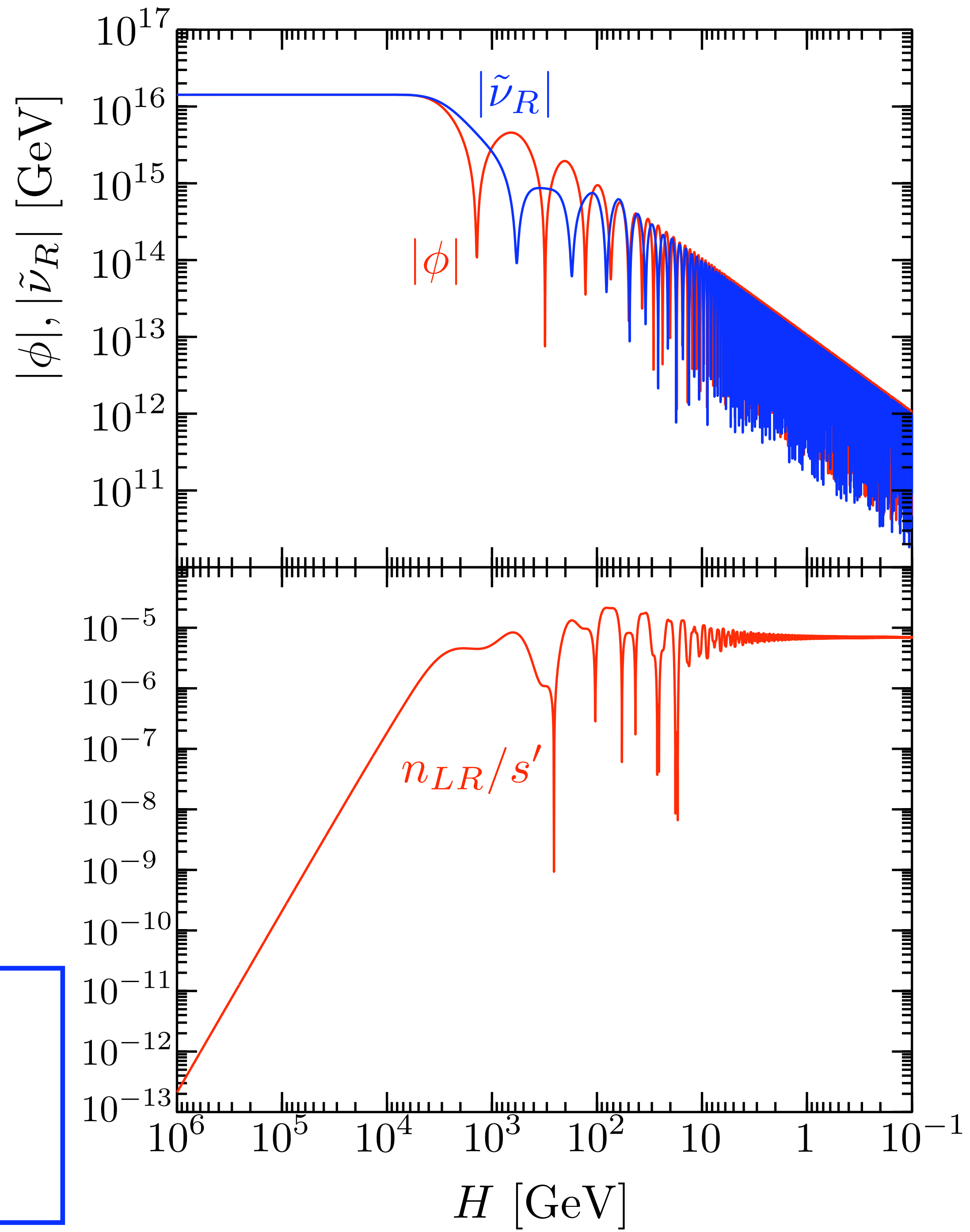
parameters for numerical calculation:

the same for the previous, except for

$M_{IL} = M_{IR} = 10^{16}\text{GeV},\ T_R = 10^5\text{GeV}$

3 . Evolution of AD fields: case-II

- quartic term $(M_{IL} \geq M_{IR})$
  - until $H \sim y_\nu M_{IL}/2$



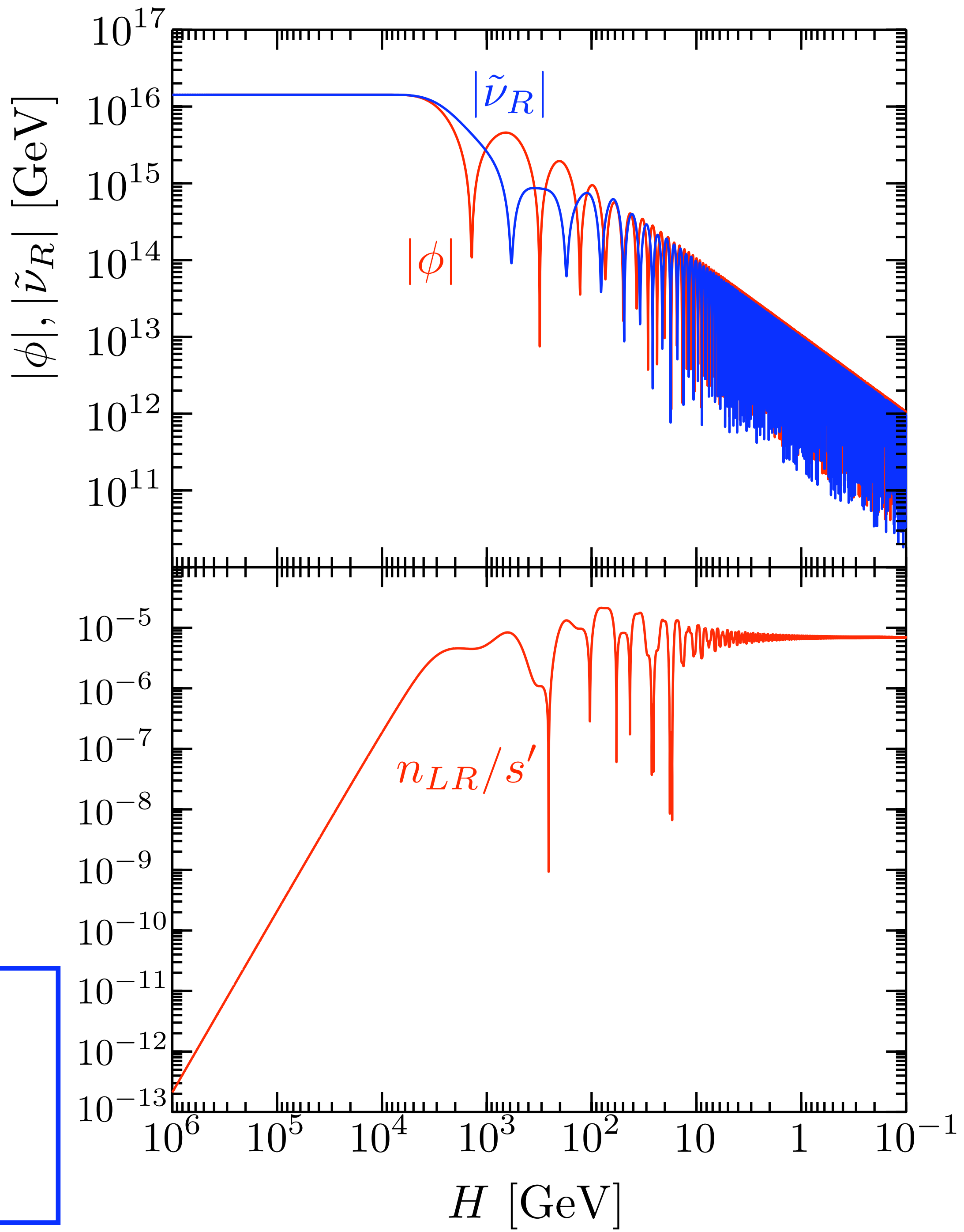
parameters for numerical calculation:

the same for the previous, except for

$M_{IL} = M_{IR} = 10^{16}\mathrm{GeV},\ T_R = 10^5\mathrm{GeV}$

3. Evolution of AD fields: case-II

- quartic term $(M_{IL} \geq M_{IR})$
  - until $H \sim y_\nu M_{IL}/2$ fields are fixed at $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$
    $\longrightarrow$ $R^3 n_{LR}$ is growing



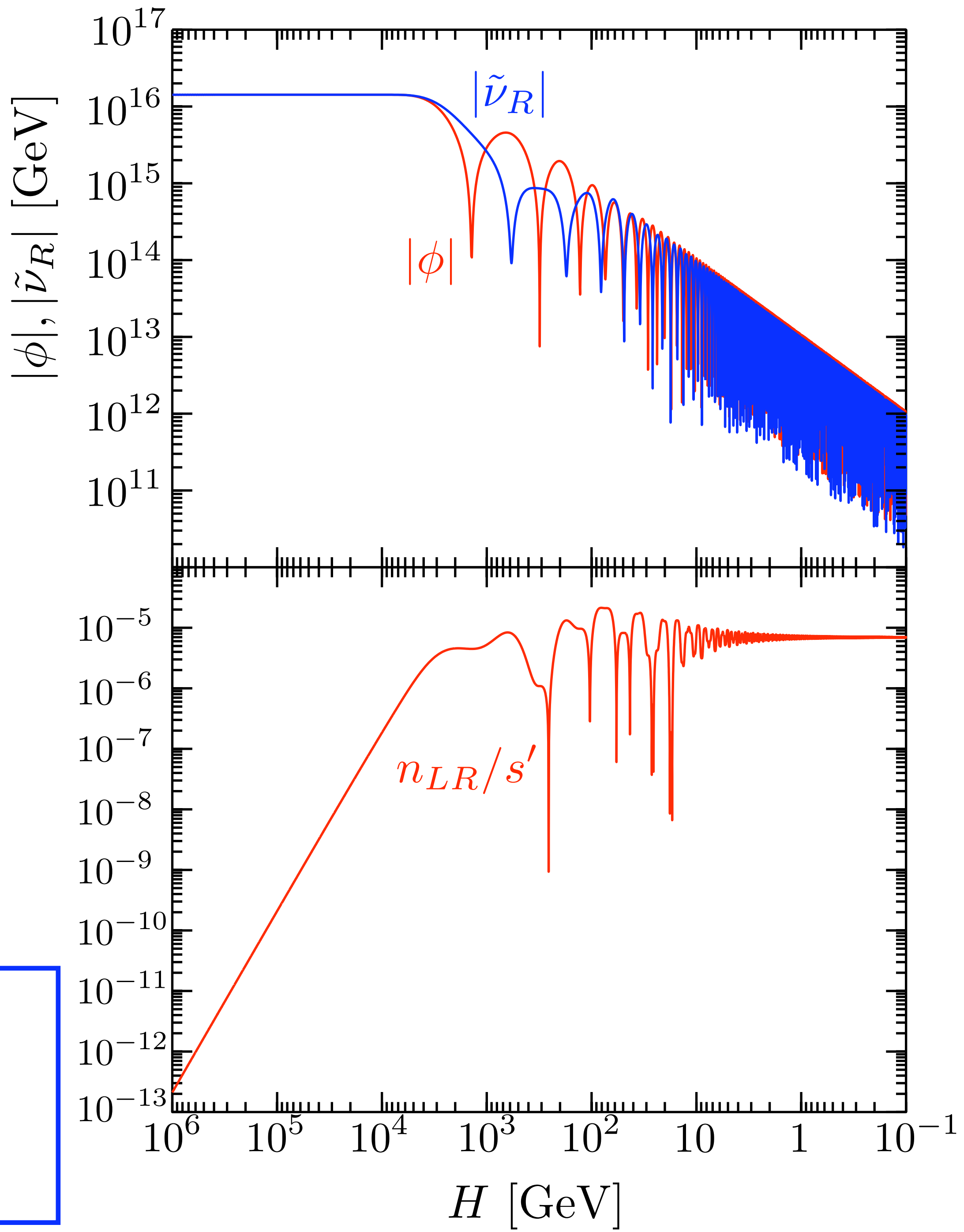
parameters for numerical calculation:

the same for the previous, except for

$M_{IL} = M_{IR} = 10^{16}\text{GeV},\ T_R = 10^5\text{GeV}$

3 . Evolution of AD fields: case-II

- quartic term $(M_{IL} \geq M_{IR})$
  - until $H \sim y_\nu M_{IL}/2$ fields are fixed at $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$
    $\longrightarrow$ $R^3 n_{LR}$ is growing
  - at $H \sim y_\nu M_{IL}/2$



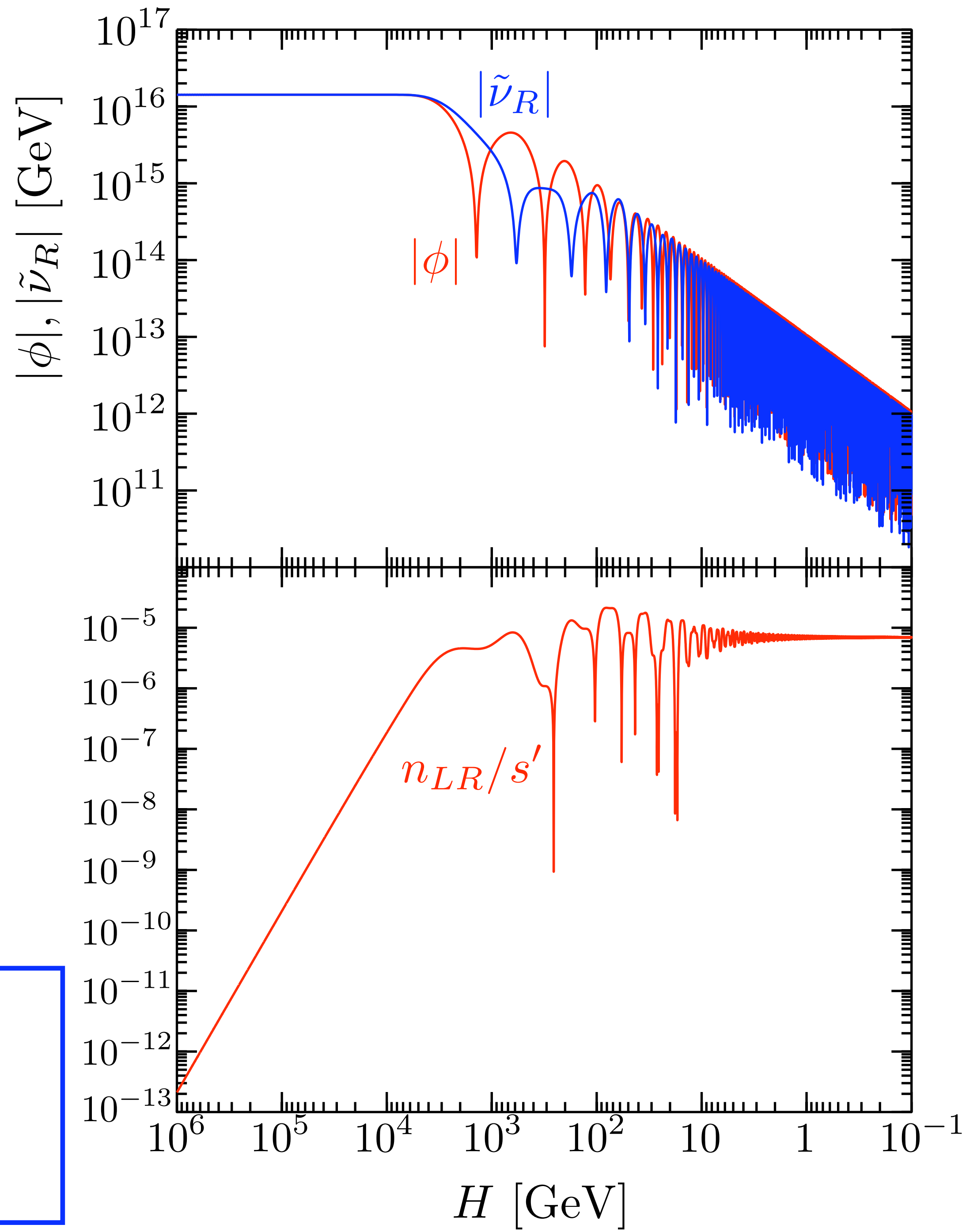
parameters for numerical calculation:

the same for the previous, except for

$M_{IL} = M_{IR} = 10^{16}\text{GeV}, \ T_R = 10^5\text{GeV}$

3. Evolution of AD fields: case-II

- quartic term $(M_{IL} \geq M_{IR})$
  - until $H \sim y_\nu M_{IL}/2$ fields are fixed at $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$
    ⟶ $R^3 n_{LR}$ is growing
  - at $H \sim y_\nu M_{IL}/2$ both ϕ and $\tilde{\nu}_R$ begin oscillation
    ⟶ order of $R^3 n_{LR}$ is not changed



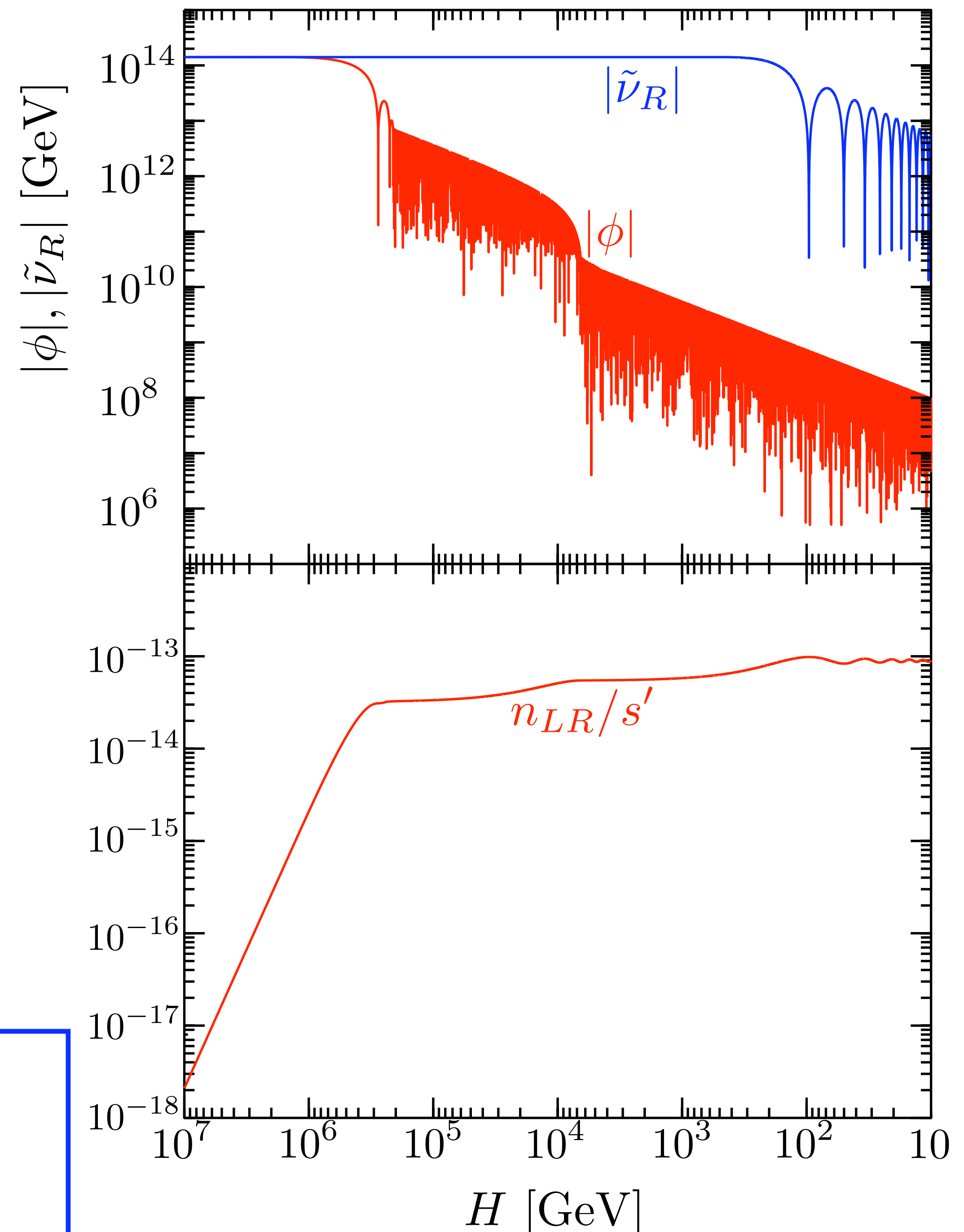
parameters for numerical calculation:

the same for the previous, except for

$M_{IL} = M_{IR} = 10^{16}\text{GeV}, \ T_R = 10^5\text{GeV}$

3 . Evolution of AD fields: case-III

- thermal corrections



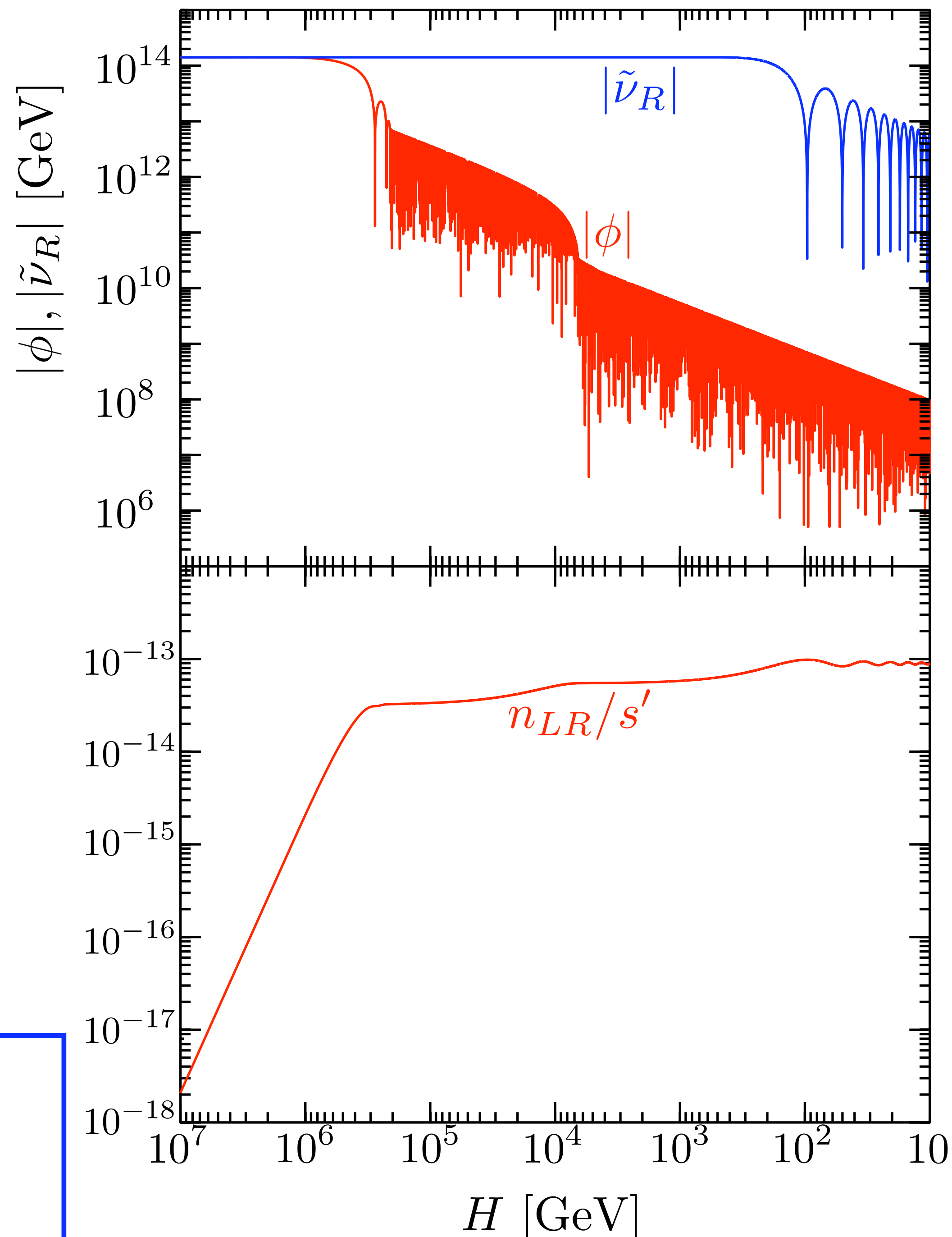
parameters for numerical calculation:

the same for the soft-mass case, except for

$M_{IR} = M_{IL} = 10^{14}\mathrm{GeV}, T_R = 10^{9}\mathrm{GeV}$

3 . Evolution of AD fields: case-III

- thermal corrections
  - until thermal-terms dominate,



parameters for numerical calculation:

the same for the soft-mass case, except for

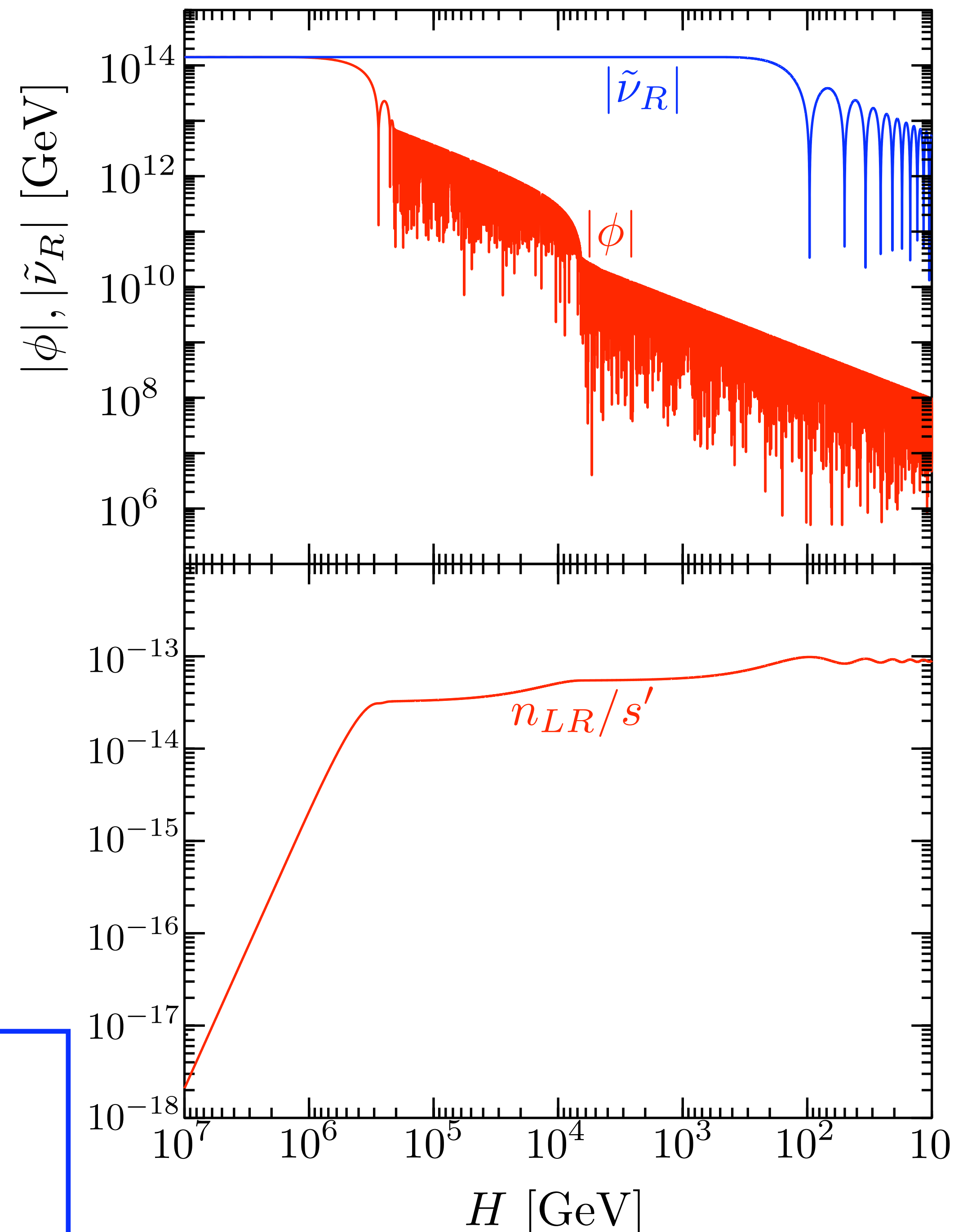
$M_{IR} = M_{IL} = 10^{14}\mathrm{GeV}, T_R = 10^9\mathrm{GeV}$

3. Evolution of AD fields: case-III

- thermal corrections
  - until thermal-terms dominate, fields are fixed at

$$|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$$

$\longrightarrow$ $R^3 n_{LR}$ is growing



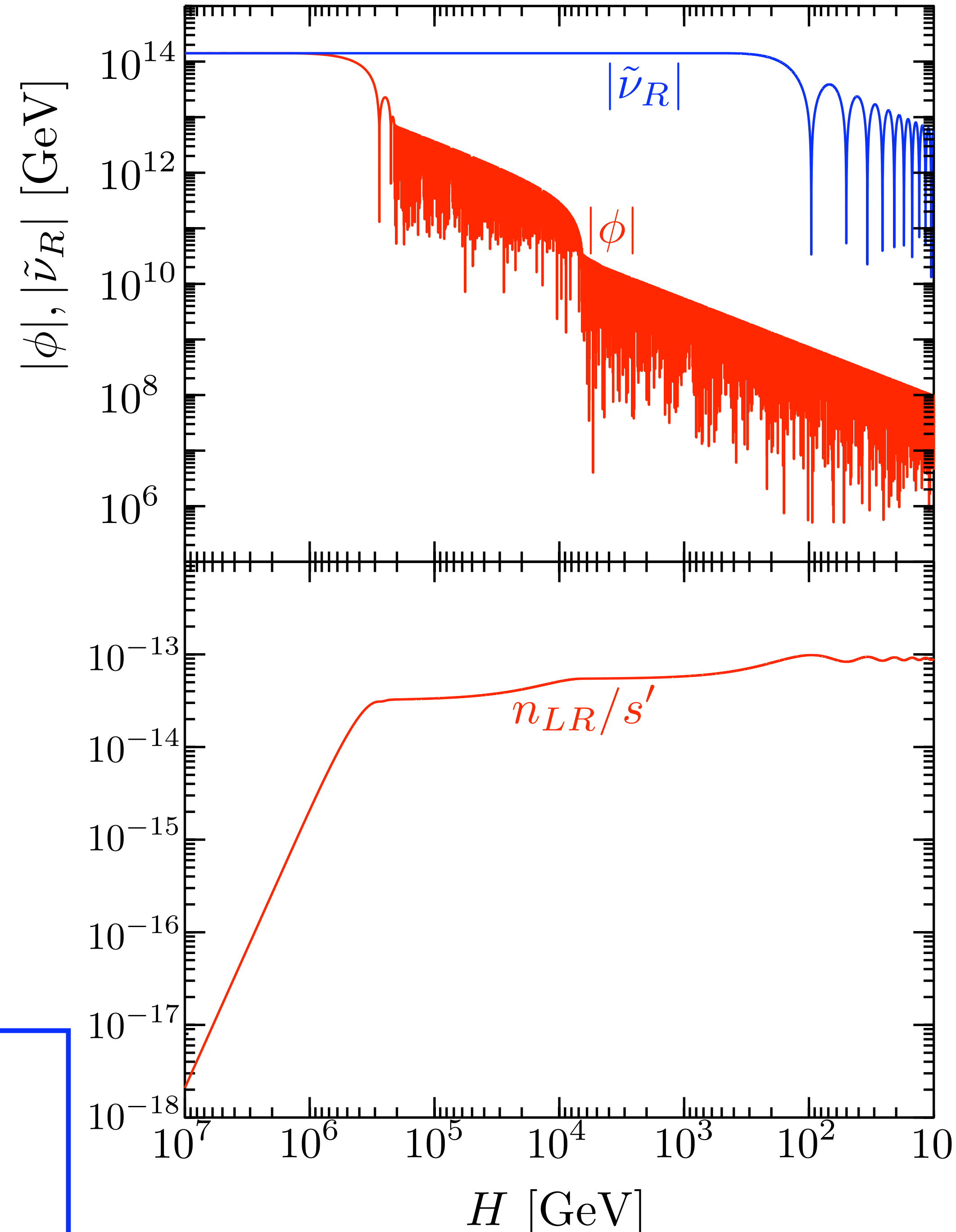
parameters for numerical calculation:

the same for the soft-mass case, except for

$M_{IR} = M_{IL} = 10^{14}\text{GeV}, T_R = 10^9\text{GeV}$

3 . Evolution of AD fields: case-III

- thermal corrections
  - until thermal-terms dominate, fields are fixed at
    $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$
    $\longrightarrow$ $R^3 n_{LR}$ is growing
  - after thermal-terms dominate,



parameters for numerical calculation:

the same for the soft-mass case, except for

$M_{IR} = M_{IL} = 10^{14}\mathrm{GeV}, T_R = 10^9\mathrm{GeV}$

3 . Evolution of AD fields: case-III

- thermal corrections
  - until thermal-terms dominate, fields are fixed at

    $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$

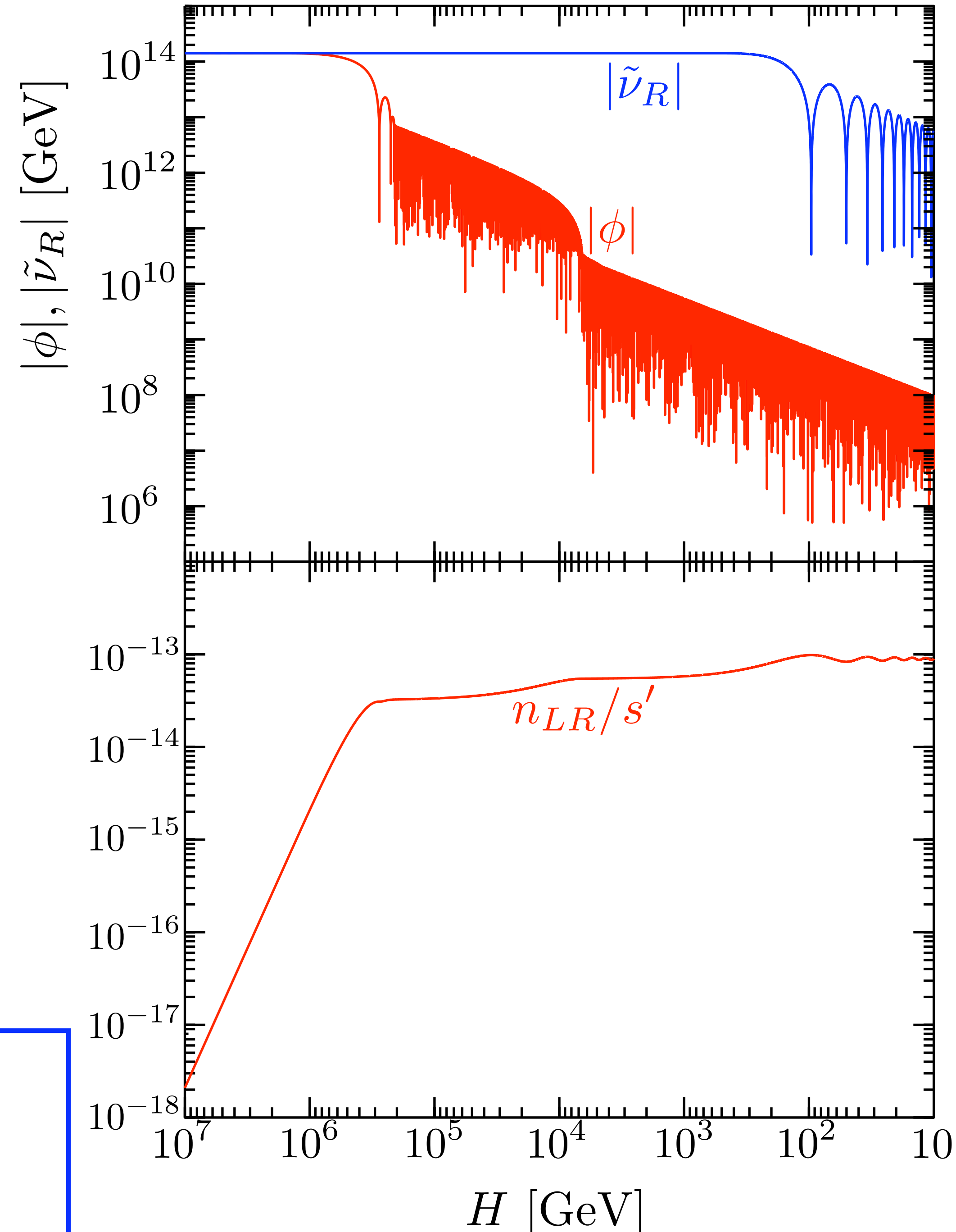
    ⟶ $R^3 n_{LR}$ is growing
  - after thermal-terms dominate, only ϕ begins oscillation

    thermal-log: $\langle|\phi|\rangle \propto H^2$

    thermal-mass: $\langle|\phi|\rangle \propto H^{7/8}$

    while $\tilde{\nu}_R$ is fixed

    ⟶ $R^3 n_{LR}$ is still growing



parameters for numerical calculation:

the same for the soft-mass case, except for

$M_{IR} = M_{IL} = 10^{14}\text{GeV}, T_R = 10^9\text{GeV}$

3 . Evolution of AD fields: case-III

- thermal corrections
  - until thermal-terms dominate, fields are fixed at

    $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$

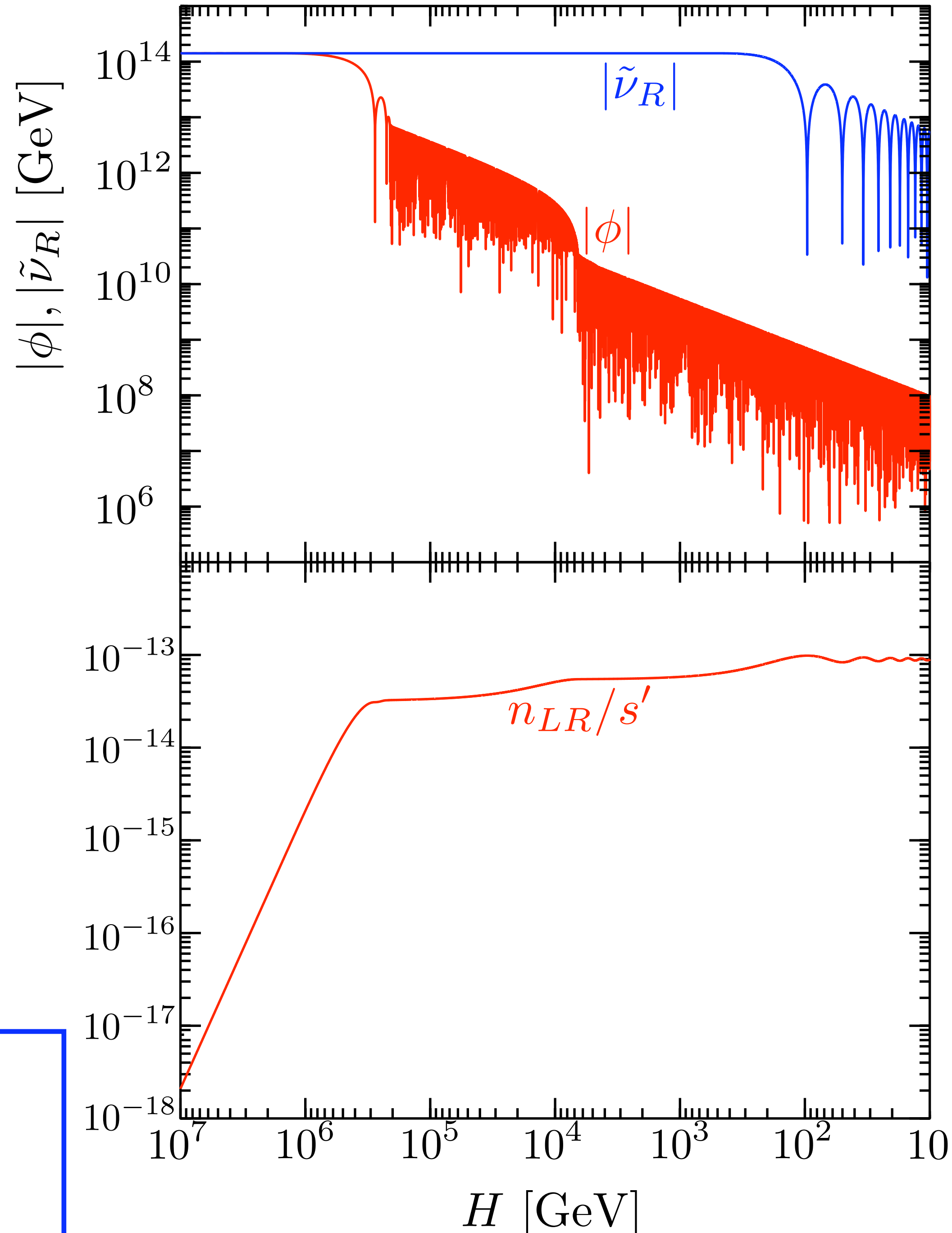
    $\longrightarrow$ $R^3 n_{LR}$ is growing
  - after thermal-terms dominate, only ϕ begins oscillation

    thermal-log: $\langle|\phi|\rangle \propto H^2$

    thermal-mass: $\langle|\phi|\rangle \propto H^{7/8}$

    while $\tilde{\nu}_R$ is fixed

    $\longrightarrow$ $R^3 n_{LR}$ is still growing
  - at $H \sim m_{\tilde{\nu}_R}$



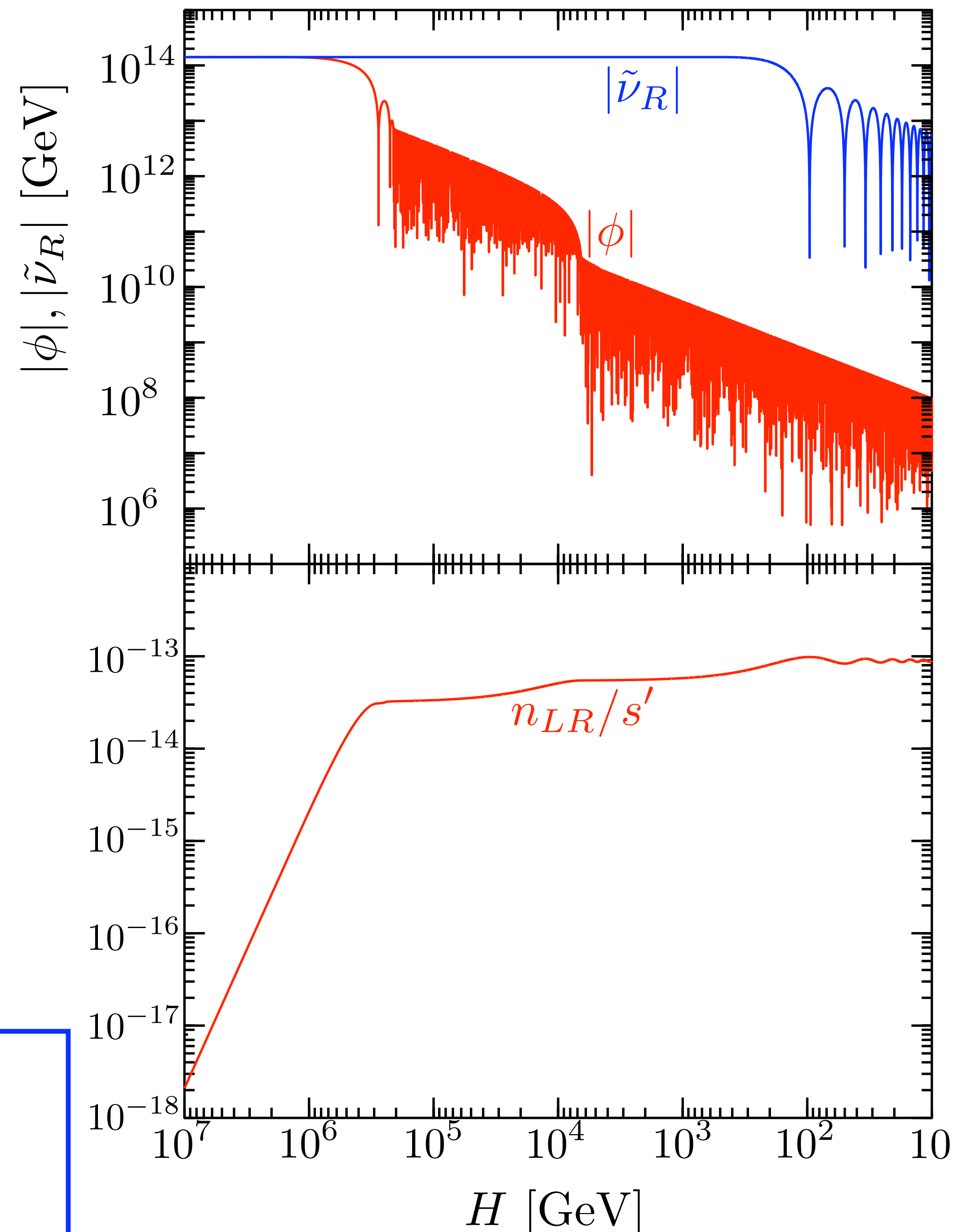
parameters for numerical calculation:

the same for the soft-mass case, except for

$M_{IR} = M_{IL} = 10^{14}\mathrm{GeV}, T_R = 10^9\mathrm{GeV}$

3 . Evolution of AD fields: case-III

- thermal corrections
  - until thermal-terms dominate, fields are fixed at
    $|\phi| = M_{IL}, |\tilde{\nu}_R| = M_{IR}$
    $\longrightarrow$ $R^3 n_{LR}$ is growing
  - after thermal-terms dominate, only ϕ begins oscillation
    thermal-log: $\langle|\phi|\rangle \propto H^2$
    thermal-mass: $\langle|\phi|\rangle \propto H^{7/8}$
    while $\tilde{\nu}_R$ is fixed
    $\longrightarrow$ $R^3 n_{LR}$ is still growing
  - at $H \sim m_{\tilde{\nu}_R}$
    $\tilde{\nu}_R$ begins oscillation
    $\longrightarrow$ $R^3 n_{LR}$ is fixed



parameters for numerical calculation:

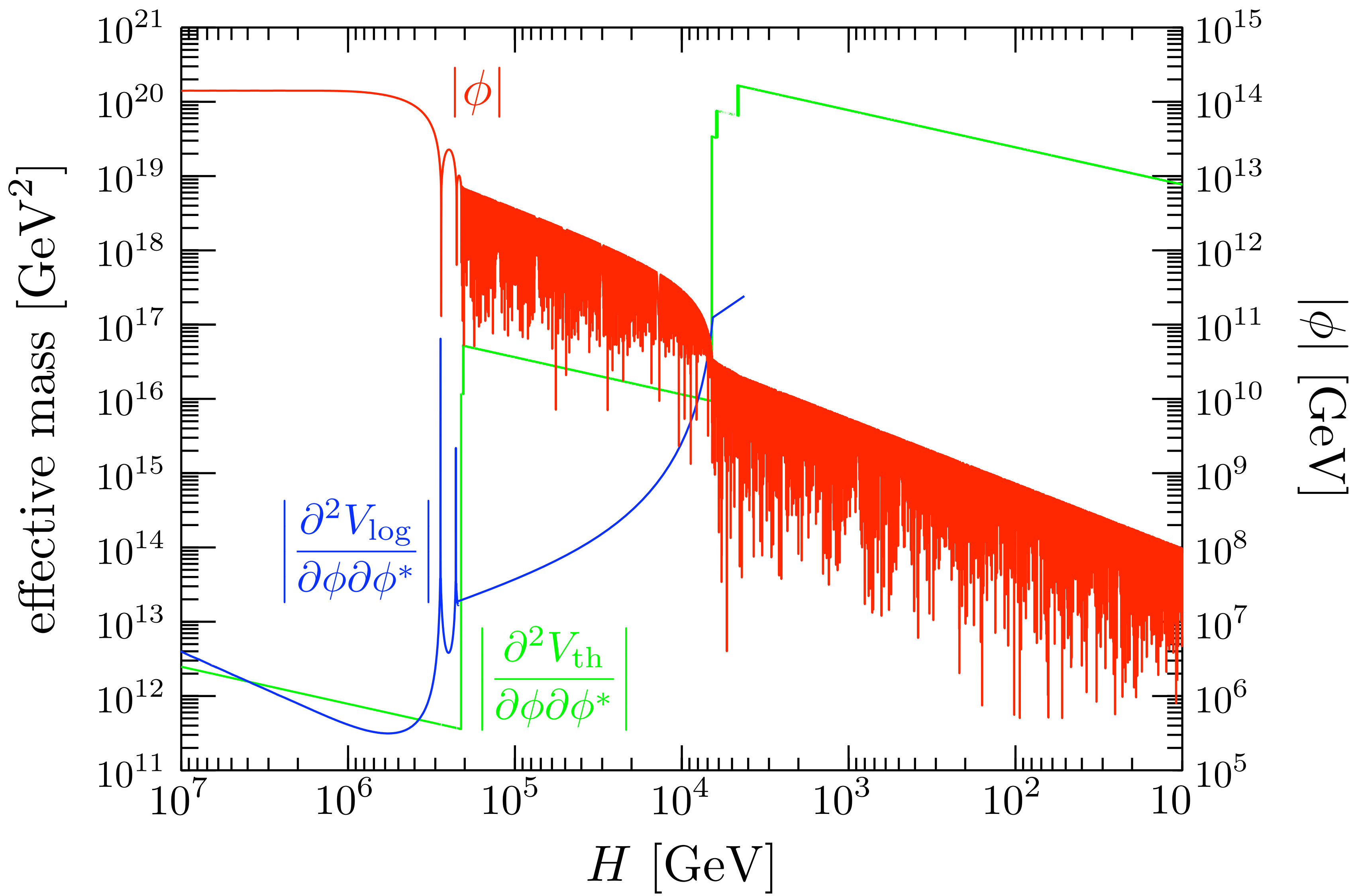
the same for the soft-mass case, except for

$M_{IR} = M_{IL} = 10^{14}\mathrm{GeV}, T_R = 10^9\mathrm{GeV}$

3 . Evolution of AD fields: case-III

- an example of the evolution of $|\phi|$ after thermal-log term destabilizes the potential

* effects of oscillation on effective masses are erased by hand for simplicity



4 . Baryon asymmetry: sphaleron process

- baryon number asymmetry
  - non-perturbative effect $SU(2)_L$

    $\longrightarrow$ $B + L^{(L)}$ violating process $\longrightarrow$ $B \neq 0$
  - RH-sneutrino is decoupled from thermal bath $\longrightarrow$ $L^{(R)}$ is fixed

    at $T > T_{\rm EW}$
    - equilibrium of $SU(2)_L$ non-perturbative effect
    - equilibrium of $SU(2)_L \times U(1)_Y$ and Yukawa interactions
    - total electric charge neutrality $\sum Q = 0$
    - total weak isospin neutrality $\sum Q_3 = 0$

$\longrightarrow$ **chemical equilibrium** $B = \frac{8}{23}(B - L^{(L)})_{\rm ini} = \frac{8}{23} L^{(R)}$

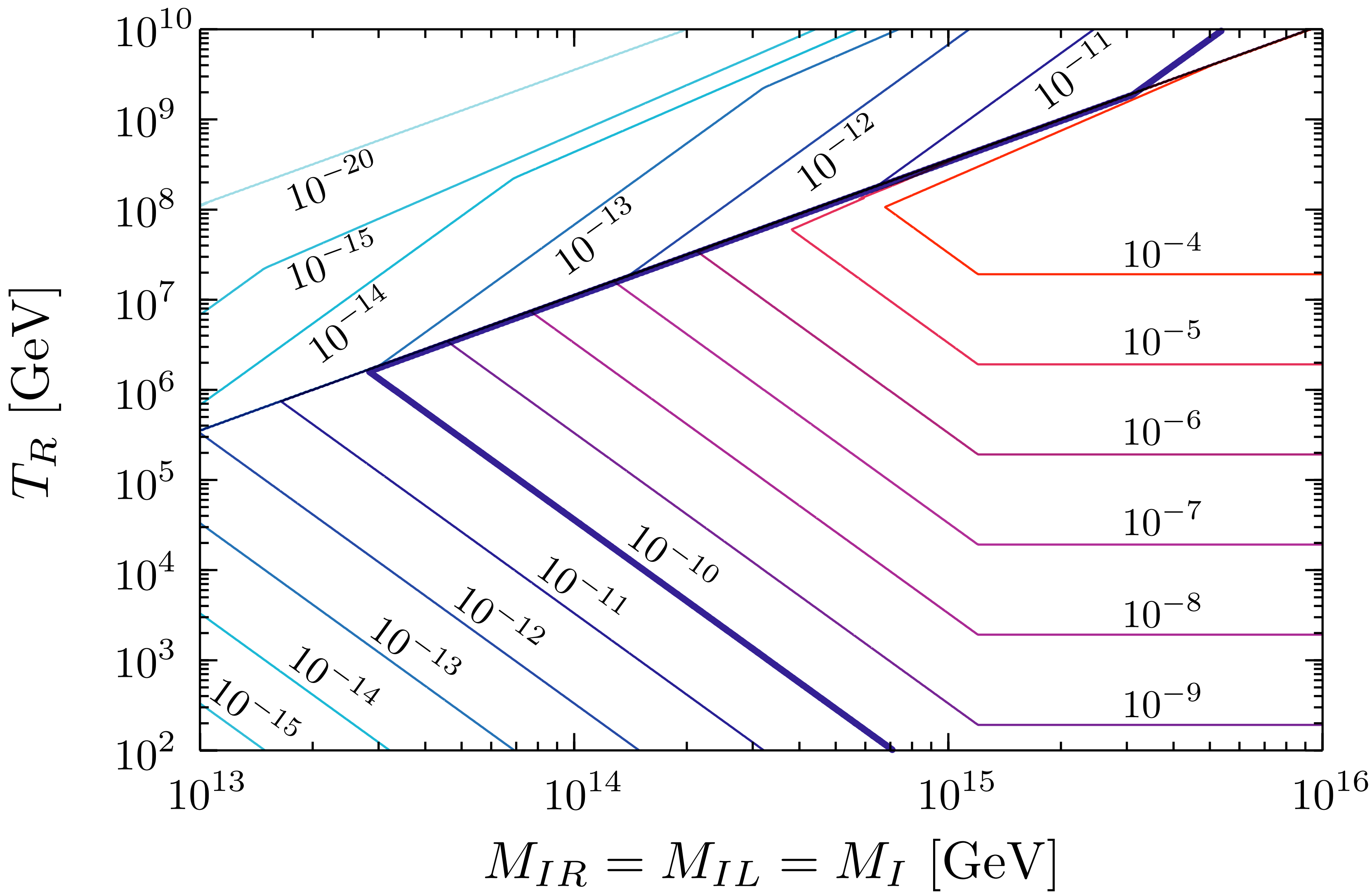
- RH-sneutrino $n_{\tilde{\nu}_R} = \frac{23}{8} B$ $\longrightarrow$ dark matter overproduction

  (we discuss later)

4. Baryon asymmetry: baryon-to-entropy ratio

- contour plot of n_B/s ($M_{IL} = M_{IR} = M_I$)

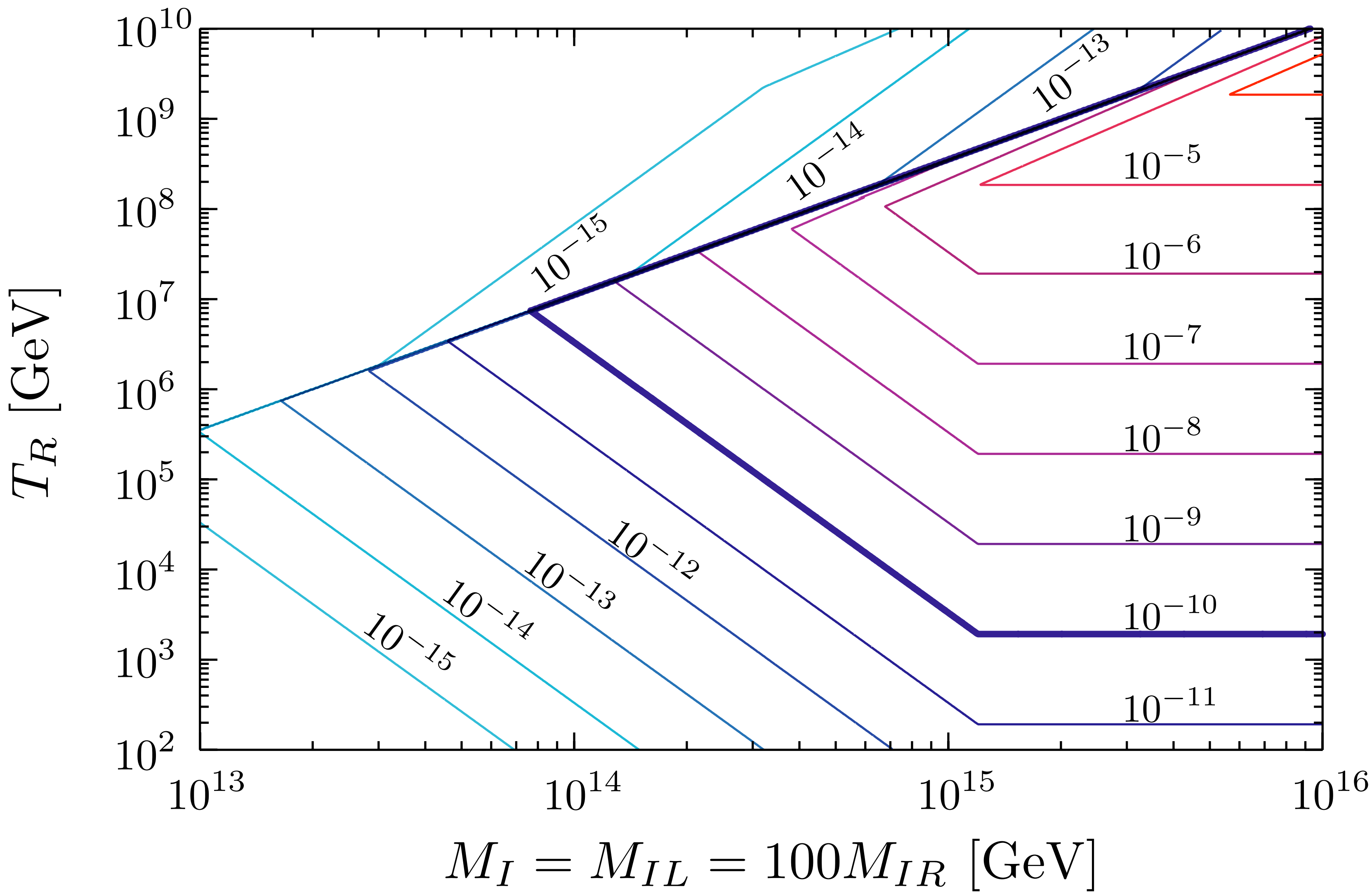
  if $M_{IL} > M_{IR}$, n_B/s is modified by a factor M_{IR}/M_{IL}



4 . Baryon asymmetry: baryon-to-entropy ratio

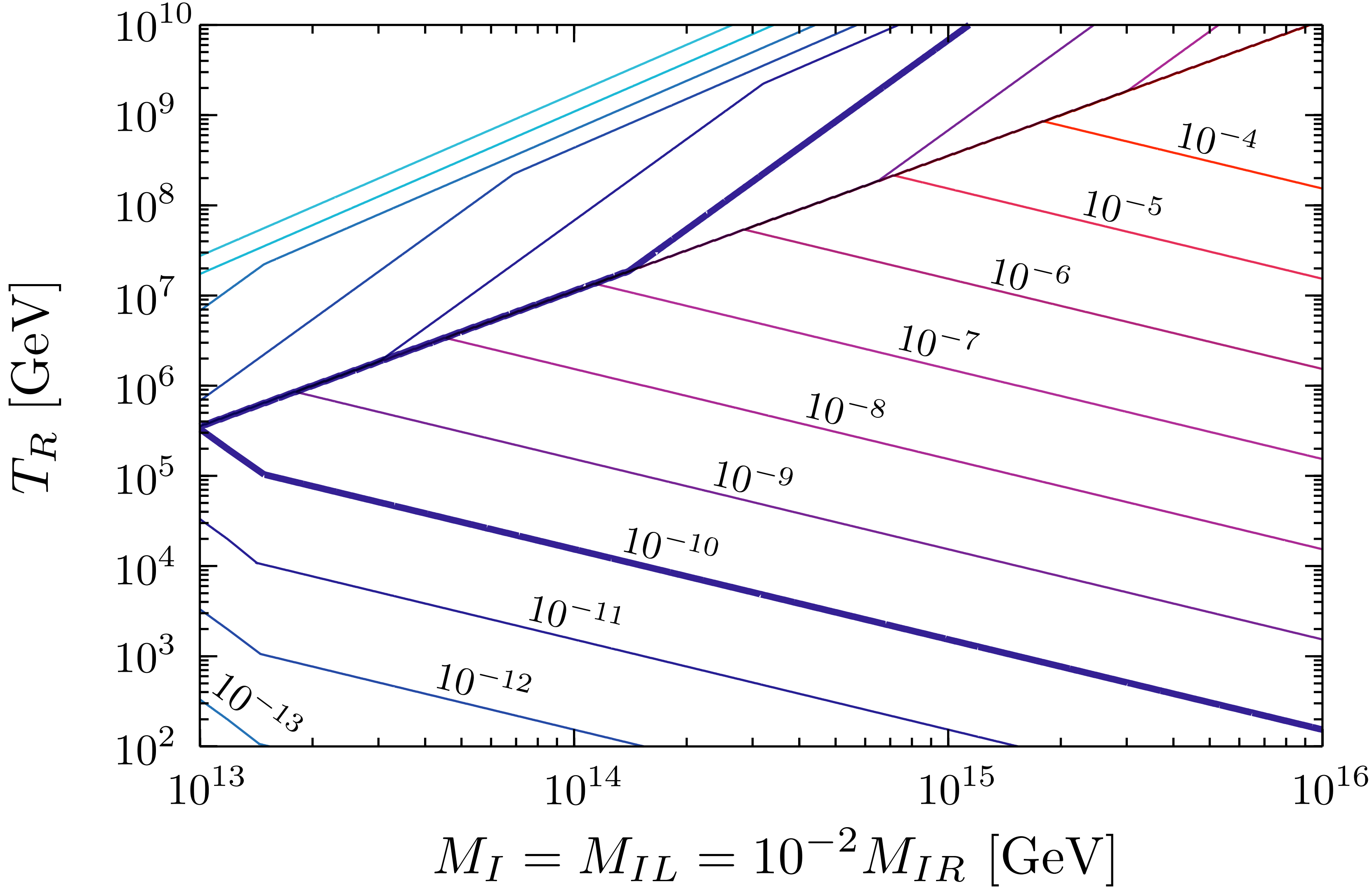
- contour plot of n_B/s ($M_I = M_{IL} = 100 M_{IR}$)

  if $M_{IL} > M_{IR}$, n_B/s is modified by a factor M_{IR}/M_{IL}



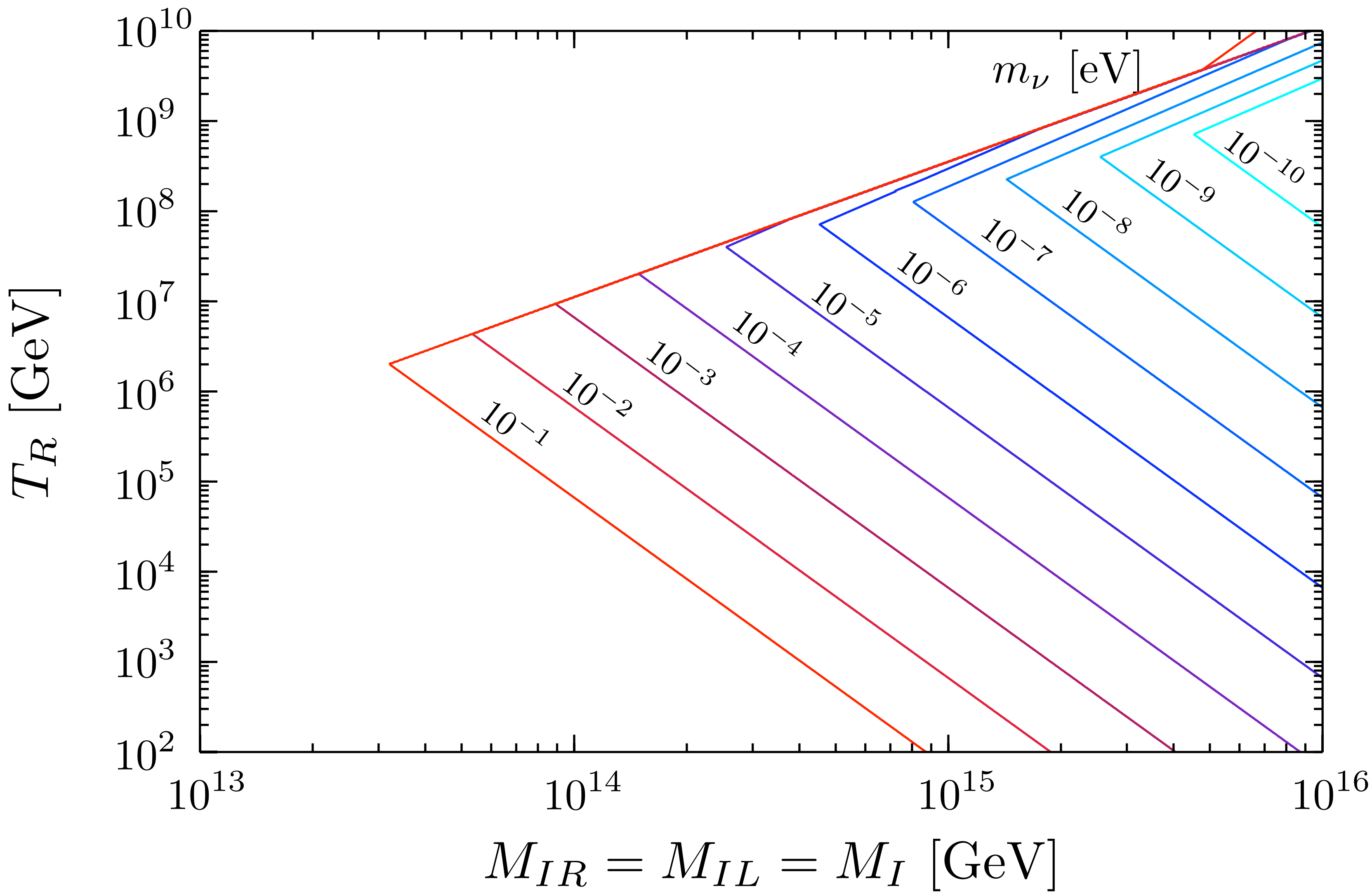
4. Baryon asymmetry: baryon-to-entropy ratio

- contour plot of n_B/s ($M_I = M_{IL} = 10^{-2} M_{IR}$)
  - for soft-mass case or thermal-correction case, n_B/s is modified by a factor M_{IR}/M_{IL} from previous result
  - for quartic term case, the result is further modified



4. Baryon asymmetry: baryon-to-entropy ratio

- $n_B/s = 10^{-10}$ contour for various neutrino mass m_ν [eV]
  - lower m_ν ⟶ higher T_R and M_I can give $n_B/s = 10^{-10}$



4 . Baryon asymmetry: discussion

- for the case soft SUSY-breaking mass terms destabilize the first

$$\frac{n_B}{s} = 6 \times 10^{-10} \times \left(\frac{y_\nu}{10^{-12}}\right)\left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)\left(\frac{m_\phi}{1\mathrm{TeV}}\right)^{-3}\left(\frac{M_{IL}}{10^{14}\mathrm{GeV}}\right)^2\left(\frac{M_{IR}}{10^{14}\mathrm{GeV}}\right)\left(\frac{T_R}{10^5\mathrm{GeV}}\right)|a|\delta_{\mathrm{eff}}$$

- for the case quartic terms destabilize the first

  if $M_{IL} \geq M_{IR}$

$$\frac{n_B}{s} = 5 \times 10^{-6} \times \left(\frac{y_\nu}{10^{-12}}\right)^{-2}\left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)\left(\frac{M_{IL}}{10^{16}\mathrm{GeV}}\right)^{-1}\left(\frac{M_{IR}}{10^{16}\mathrm{GeV}}\right)\left(\frac{T_R}{10^5\mathrm{GeV}}\right)|a|\delta_{\mathrm{eff}}$$

  if $M_{IL} < M_{IR}$

$$\frac{n_B}{s} = 8 \times 10^{-7} \times \left(\frac{y_\nu}{10^{-12}}\right)^{-1}\left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)\left(\frac{m_{\tilde{\nu}_R}}{1\mathrm{TeV}}\right)^{-1}\left(\frac{M_{IL}}{10^{16}\mathrm{GeV}}\right)^2\left(\frac{M_{IR}}{10^{18}\mathrm{GeV}}\right)^{-1}\left(\frac{T_R}{10^5\mathrm{GeV}}\right)|a|\delta_{\mathrm{eff}}$$

- for the thermal-terms terms destabilize the first (see contour plot)

- there are large parameter region allowed for sufficient baryon asymmetry
- for smaller neutrino mass, larger M_I and T_R can give $n_B/s = 10^{-10}$
- combined with constraint $T_R < 10^9\mathrm{GeV}$ from gravitino overproduction, some cases that thermal-terms dominate the dynamics are excluded unless M_{IR} is sufficiently large
- $T_R \lesssim 10^9\mathrm{GeV}$ can give $n_B/s = 10^{-10}$ for large M_{IR}

5 . Dark matter problem

■ over-abundance of dark matter

RH-sneutrino is produced in AD-mechanism $L^{(R)} = B - L^{(L)}$

⟶ RH-sneutrino number density $n_{\rm DM} = \frac{23}{8} n_B$

even if there are some dilution process after reheating, this relation is still held

- RH-sneutrinos are decoupled from thermal bath ⟶ no annihilation
- RH-sneutrinos decay via neutrino Yukawa coupling very slowly

$y_\nu \tilde{\nu}_R \tilde{H}_u \nu_L$ coupling ⟶ $T_{\rm dec} \sim 100{\rm MeV}$

■ possible solutions of this dark matter overproduction

- some additional interaction

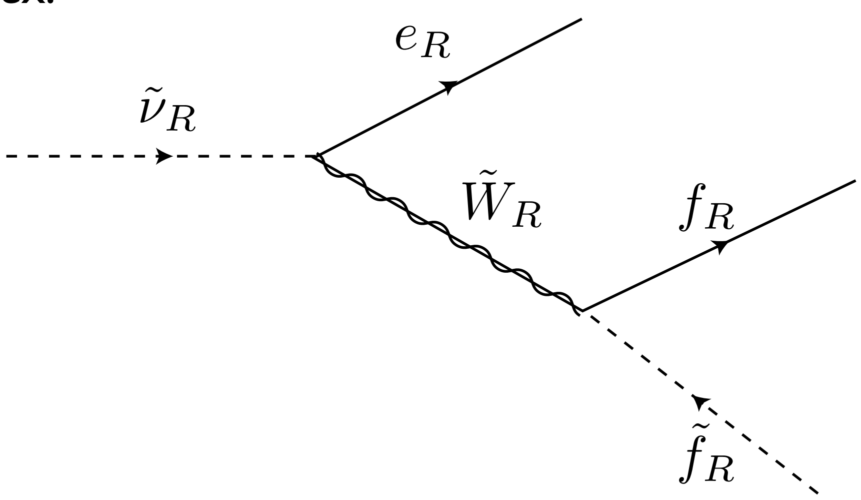
  ⟶ decay of $\tilde{\nu}_R$ before the freeze-out of LSP

- light LSP dark matter $m_{\rm DM} < \frac{8}{23} \frac{\Omega_{\rm DM}}{\Omega_b} m_p \sim 1{\rm GeV}$

5 . Dark matter problem: possible solution

- $SU(2)_R$ gauge coupling above some intermediate scale $M_{SU(2)_R}$

ex:



$$\Gamma \sim \frac{m_{\tilde{\nu}_R}^5}{M_{SU(2)_R}^4} > H \sim \frac{T_{\rm fr}^2}{M_{\rm Pl}}$$

$T_{\rm fr} \sim 5 - 50{\rm GeV}$: freeze-out temperature of LSP

$T_{\rm EW} > T_\Gamma$: decay after sphaleron process becomes ineffective

$\longrightarrow$ $M_{SU(2)_R} \lesssim 10^{7-8}{\rm GeV}$

- $\tilde{L}_{L\uparrow} = H_u^0 = \tilde{\nu}_R$ can be flat-direction

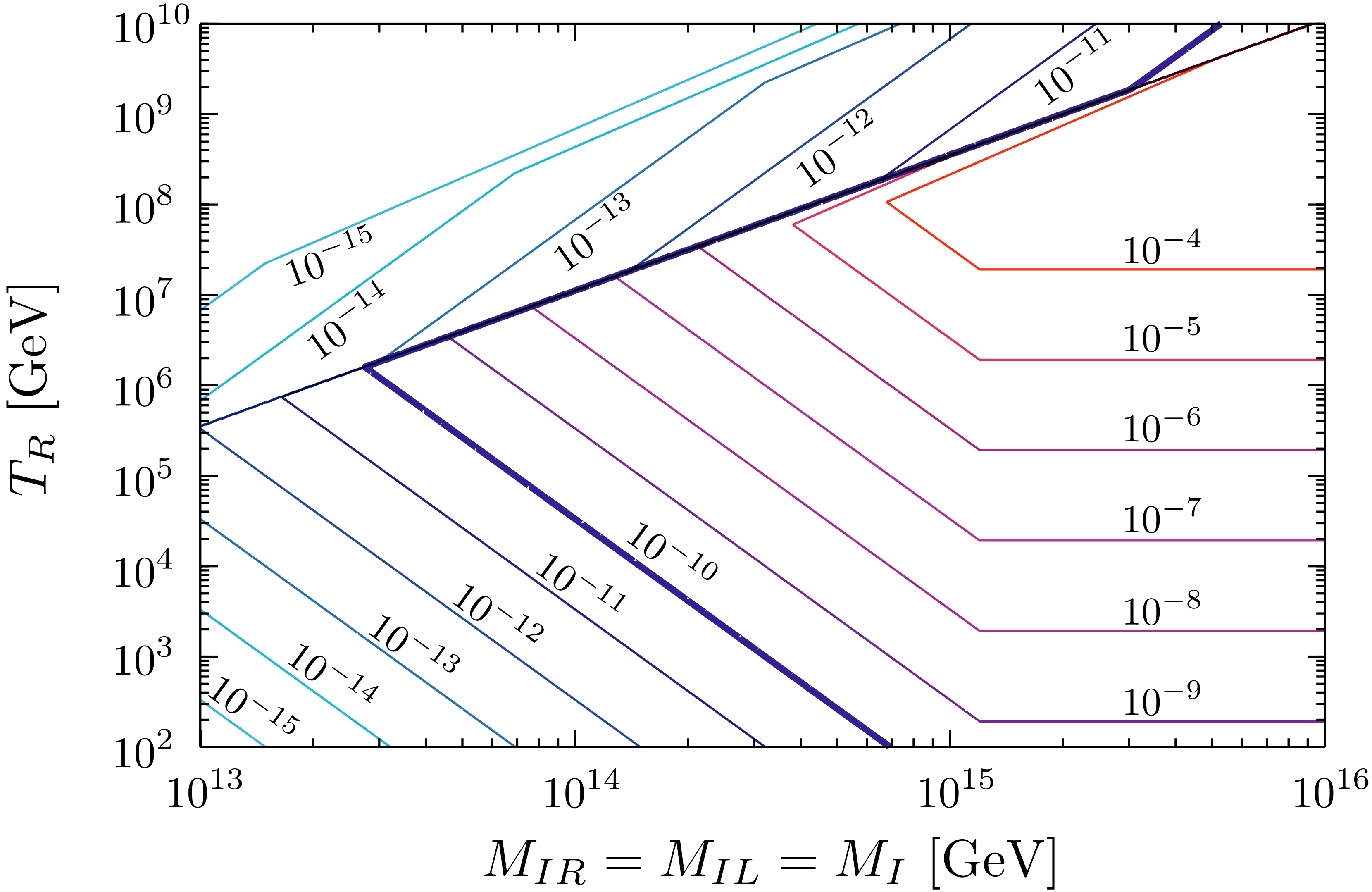
$\longrightarrow$ no D-term potential from $SU(2)_R$ gauge group

$\longrightarrow$ there is single scalar field in Affleck-Dine mechanism, but the result does not change significantly

> dark matter overproduction can be solved by adding $SU(2)_R$

5. Dark matter problem: possible solution

- for the case with $SU(2)_R$ symmetry: $\tilde{L}_{L\uparrow} = H_u^0 = \tilde{\nu}_R$ flat-direction



6 . Summary

- we reconsidered baryogenesis in Dirac neutrino model
  - baryon asymmetry is generated by sphaleron process,
    from left-right asymmetry generated by Affleck-Dine mechanism
  - we included thermal corrections
  - we also included extra gauge symmetry to stabilize the potential
  - we confirmed that the appropriate baryon asymmetry is produced
    for large parameter region

$$M_{IL} \sim 10^{14-16}\mathrm{GeV},\ M_{IR} \lesssim M_{IL},\ T_R \lesssim 10^5\mathrm{GeV}$$

for large M_{IR} , $T_R \lesssim 10^9\mathrm{GeV}$ can give $n_B/s \sim 10^{-10}$

  - this baryogenesis scenario prefers lower neutrino mass

for smaller y_ν , higher T_R gives $n_B/s \sim 10^{-10}$

- dark matter overproduction problem can be solved by introducing $SU(2)_R$ gauge symmetry