Baryogenesis from Non-thermal WIMP

[Based on the work with Jongkuk Kim and Sinkyu Kim]

arXiv:1803.00820

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30th May, 2018 at CTPU, IBS

Contents

Matter and anti-matter

Antiparticle: the same mass as particle but opposite charge

electron - positron	neutron - antineutron
proton - antiproton	hydrogen - antihydrogen

First predicted by Dirac in 1928, and then positron discovered by Anderson in 1932, antiproton in 1955, antineutron in 1956 at Bevatron antihydrogen in 1990s at accelerators.

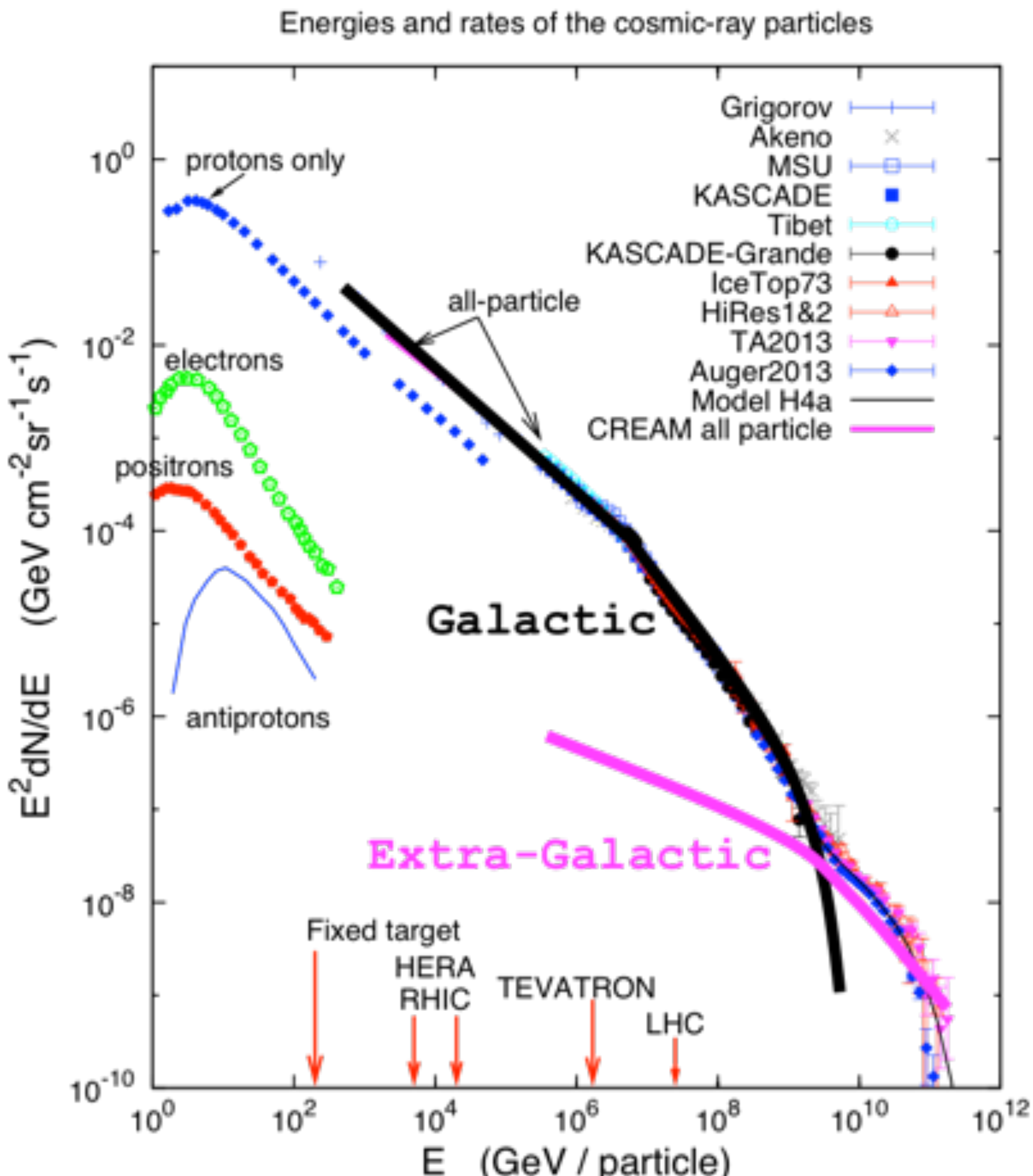
Matter >> anti-matter

We see only matters on Earth, and in the Universe.
Anti-matters are rare. They exist only in the laboratories or in the cosmic rays with small amount

Why there are more matters than anti-matter?
The amount of matter compared to the entropy (or photon):

$$\boxed{Y_B \equiv \frac{n_B}{s} \simeq 0.86 \times 10^{-10}} \qquad s \simeq 7.04 n_\gamma$$

*Y is conserved quantity when s and n decreases as 1/a^3.



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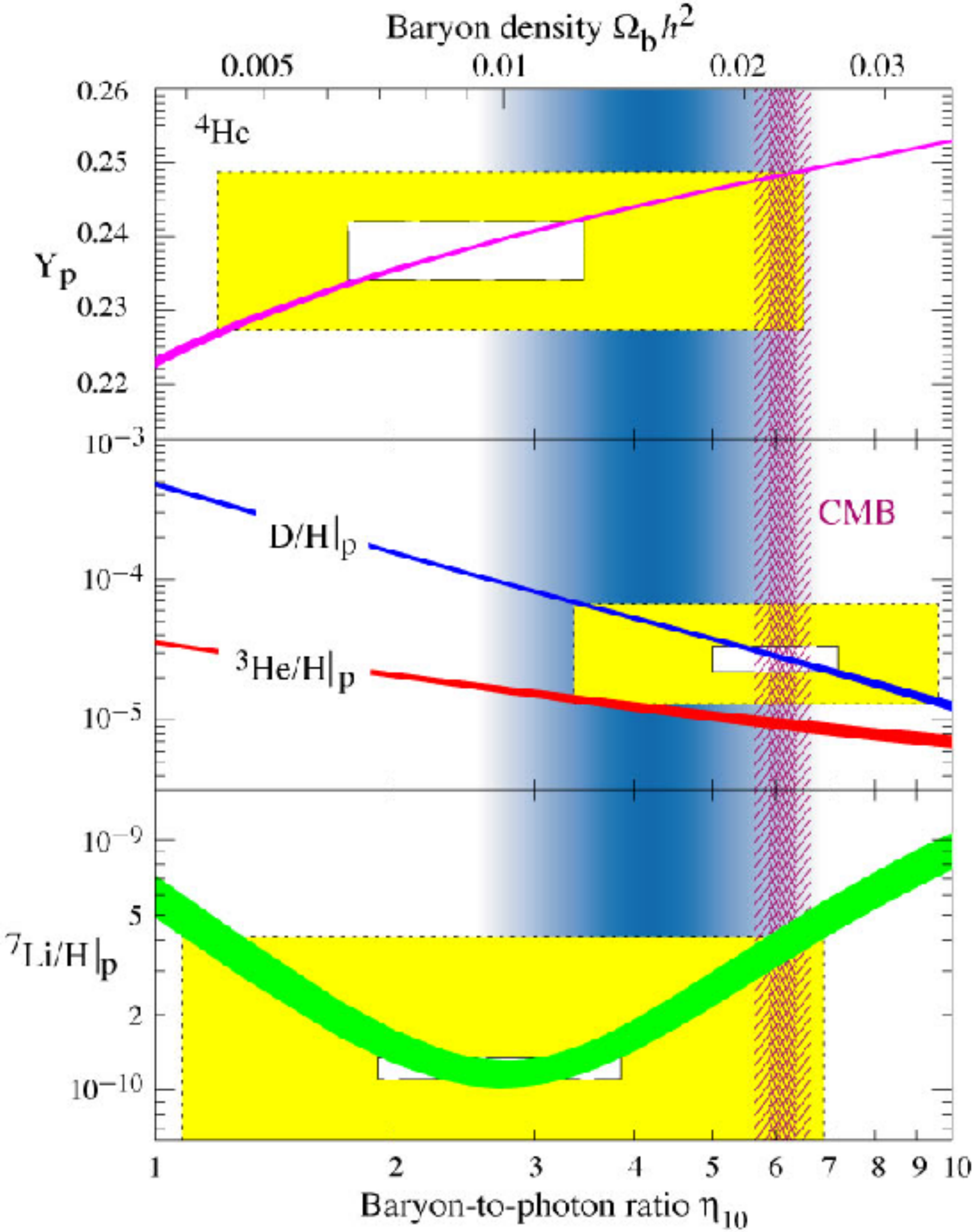


BBN and CMB for baryon density

The comparison between the observed light element abundances and the theoretical calculation shows that the baryon-to-photon ratio is

$$\eta_{10} = \frac{n_b}{n_\gamma} \times 10^{10} \sim 6$$

or

$$Y_B \equiv \frac{n_B}{s} \simeq 0.86 \times 10^{-10}$$

Baryon energy density in the Universe

$$\rho_b = 4 \times 10^{-31}\, g/cm^3$$

corresponds to the baryon density

$$\Omega_b\, h^2 \simeq 0.02$$

Evolution of Baryon Density

$T \gg 100\,\mathrm{MeV}$

The quarks are in the state of plasma and quark and antiquark coexist in the thermal equilibrium. $n_q \simeq n_{\bar{q}} \simeq n_\gamma$

The difference between them gives the Baryon asymmetry

$$Y_B = \frac{n_B - n_{\bar{B}}}{s}$$

$T \ll 100\,\mathrm{MeV}$

During the QCD phase transition, the anti-quarks annihilate and the difference only remains ad result in the present baryons

$n_B \gg n_{\bar{B}}$ and $Y_B = \frac{n_B - n_{\bar{B}}}{s} \simeq \frac{n_B}{s}$

Baryogenesis

The asymmetry between matter and ant-matter must have existed before Big Bang Nucleosynthesis.

The mechanism to explain this matter-anti matter asymmetry and the abundance in the early Universe before BBN.

1. Initial condition: it was like that from the first.

2. Initially the asymmetry was different from now. Or it could be symmetric. However, by some way, the asymmetry was generated.

Sakharov Condition

[Sakharov, 1967]

1. Baryon number violation

2. C-symmetry and CP-symmetry violation

3. Interactions out of thermal equilibrium

    * wash-out effect

C-symmetry and CP-symmetry violation

$p^+ \to e^+\gamma,$ and $p^- \to e^-\gamma$

$$\begin{tikzcd}[column sep=huge, row sep=huge]
\Gamma\left(p_L^+ \to e_R^+\gamma_L\right) \arrow[r, leftrightarrow, "\text{Charge Conjugation}"] \arrow[d, leftrightarrow, "\text{Parity}"'] \arrow[dr, leftrightarrow, "\text{CP}"] & \Gamma(p_L^- \to e_R^-\gamma_L) \arrow[dl, leftrightarrow] \\
\Gamma(p_R^+ \to e_L^+\gamma_R) & \Gamma(p_R^- \to e_L^-\gamma_R)
\end{tikzcd}$$

$$\Gamma\left(p_R^+ \to e_L^+\gamma_R\right) + \Gamma\left(p_L^+ \to e_R^+\gamma_L\right) = \Gamma(p_L^- \to e_R^-\gamma_L) + \Gamma(p_R^- \to e_L^-\gamma_R)$$

Out-of thermal Equilibrium

[Kolb, Wolfram, 1980]

Unitarity

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(j \to i)|^2$$

CPT+Unitarity

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(j \to \bar{i})|^2 = \sum_j |\mathcal{M}(j \to i)|^2$$

$$\begin{tikzcd} \mathcal{M}(i \to j) \arrow[r, leftrightarrow, "\text{CP}"] \arrow[dr, leftrightarrow, "\text{CPT}"] & \mathcal{M}(\bar{i} \to \bar{j}) \\ \mathcal{M}(j \to i) \arrow[r, leftrightarrow] & \mathcal{M}(\bar{j} \to \bar{i}) \end{tikzcd}$$

In thermal equilibrium, the same number of particles and antiparticles are produced.

Destruction of initial asymmetry in the thermal Equilibrium

Unitarity

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(j \to i)|^2$$

CPT

$$= \sum_j |\mathcal{M}(\bar{\imath} \to j)|^2$$

The excess of particles over anti-particles are diminished by the over destruction but the same amount are produced from thermal equilibrium.

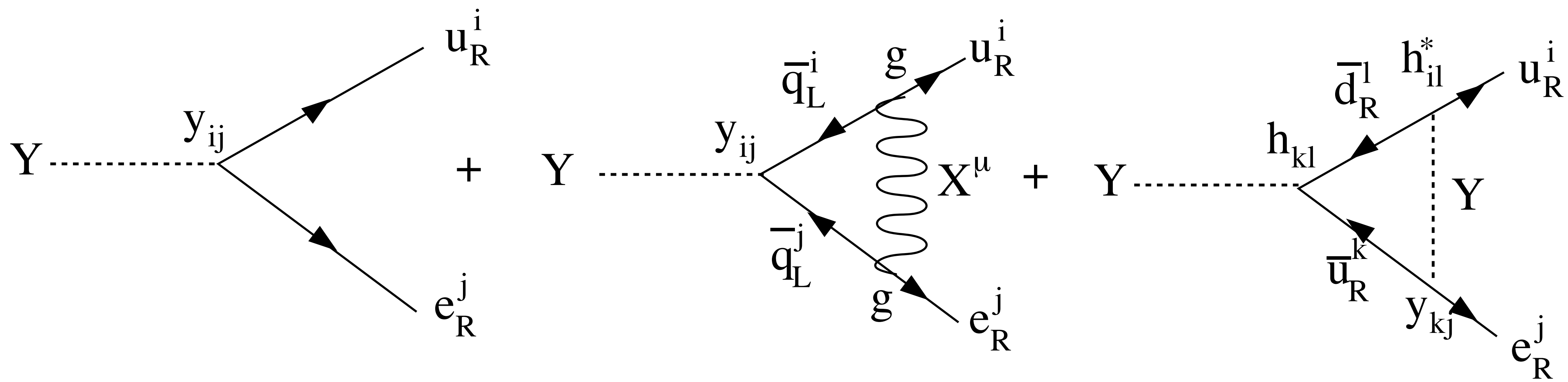
Boltzmann Equation

$$\frac{dn_B}{dt} = \sum_j \int |M(j \to B)|^2 f_j(1 - f_B) - \sum_j \int |M(B \to j)|^2 f_B(1 - f_j)$$

$$\frac{dn_{\bar{B}}}{dt} = \sum_j \int |M(j \to \bar{B})|^2 f_j(1 - f_{\bar{B}}) - \sum_j \int |M(\bar{B} \to j)|^2 f_{\bar{B}}(1 - f_j)$$

$$\frac{d(n_B - n_{\bar{B}})}{dt} =$$

Heavy Particle Decay



$$\begin{aligned}\mathcal{M}(Y \to eu) &= y + yF_X + \tilde{y}F_Y \\ \mathcal{M}(\bar{Y} \to \bar{e}\bar{u}) &= y^* + y^*F_X + \tilde{y}^*F_Y\end{aligned}$$

$$\tilde{y} \equiv h^* h^T y$$

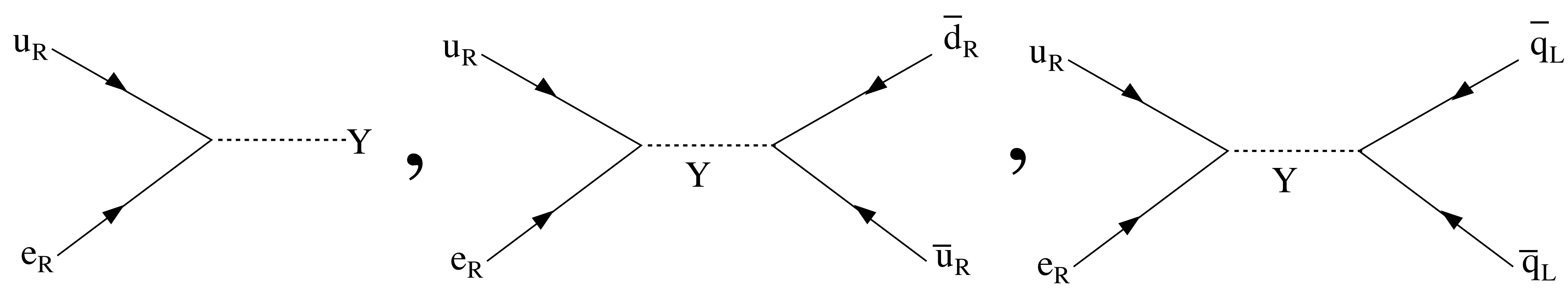
$$I_Y = \mathrm{Im}(F_Y)$$

$$\begin{aligned}|\mathcal{M}_{Y\to eu}|^2 - |\mathcal{M}_{\bar{Y}\to\bar{e}\bar{u}}|^2 &= y^*\tilde{y}F_Y + \tilde{y}^*yF_Y^* - y\tilde{y}^*F_Y - \tilde{y}y^*F_Y^* \\ &= -4\mathrm{Im}\,\mathrm{tr}(h^*h^T yy^\dagger)I_y\end{aligned}$$

[Review of Cline, 2006]

We need imaginary Loop function and imaginary couplings to generate asymmetry.

Wash-out Effect



, , , ...

Reduces the baryon asymmetry generated.

$$\dot{Y}_B = \Gamma_X(\epsilon - \bar{\epsilon})\left[Y_X - Y_{\rm eq}\right] - 2Y_B\left[\Gamma_X Y_{X,\rm eq} + \Gamma_{bb\leftrightarrow\bar{b}\bar{b}}\right]$$

wash-out

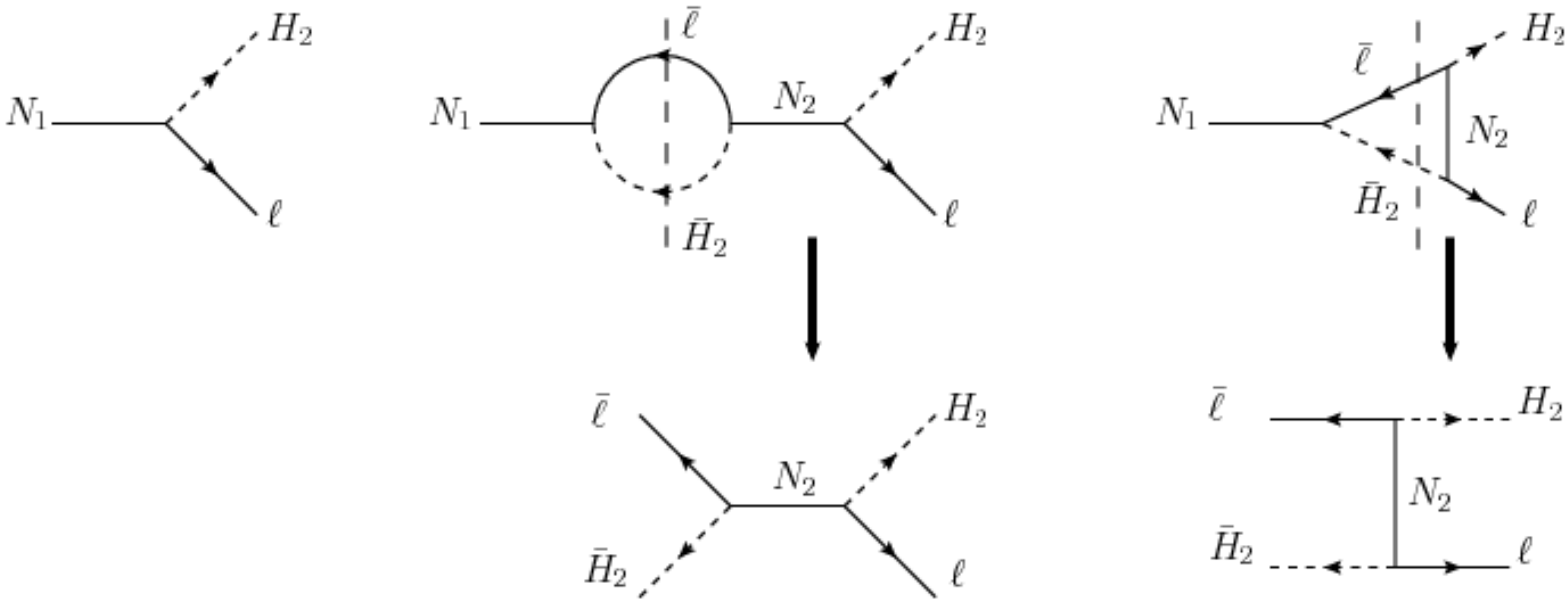
Leptogenesis

Leptogenesis uses the decay of RH heavy neutrino, with lepton number violating mass.

$$y_{ij}\bar{\nu}_{R,i}HL_j + \mathrm{h.c.} - \frac{1}{2}\left(M_{ij}\bar{\nu}^c_{R,i}\nu_{R,j} + \mathrm{h.c.}\right)$$

The lepton asymmetry generated is converted to the baryon asymmetry through the Sphaleron process.

Leptogenesis



Lepton asymmetry from the decay of heavy RH neutrinos, is converted to the baryon asymmetry.

More Baryogenesis

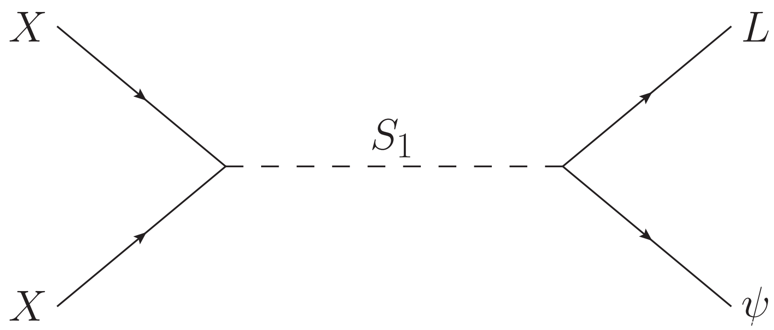
Affleck-Dine mechanism

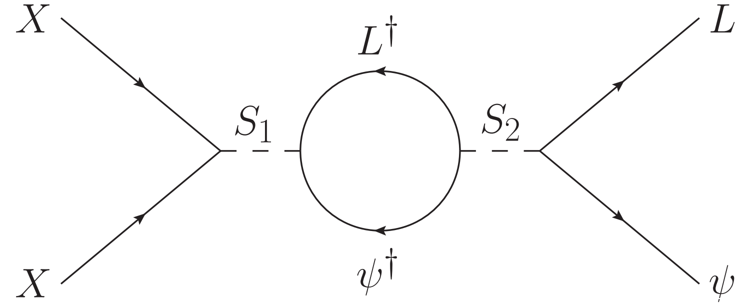
Electro-weak baryogengesis

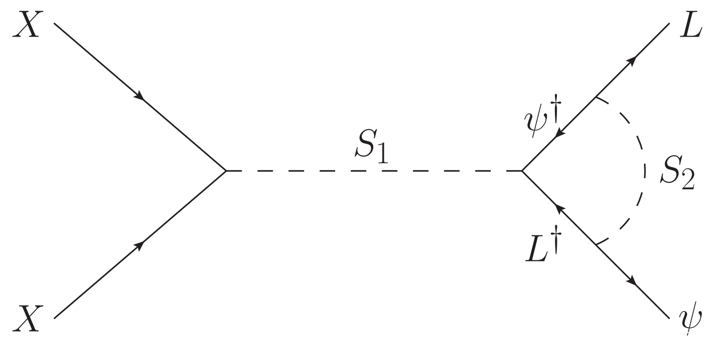
…….

WIMPy Baryogenesis (Leptogenesis)

[Cui, Randall, Shuve, 2012]



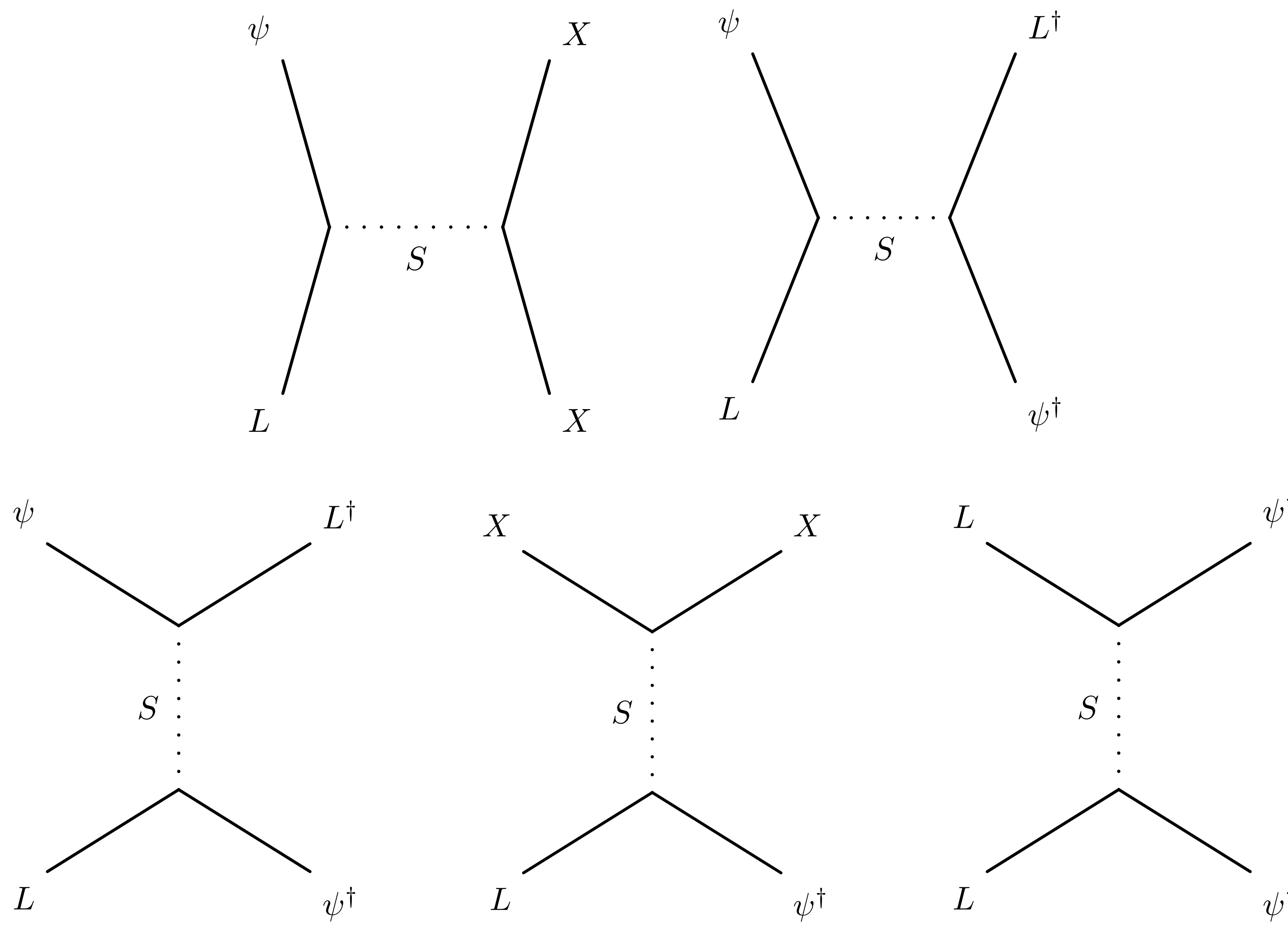




Freeze-out of WIMPs is the process of out-of-equilibrium.

Lepton (baryon) asymmetry from the annihilation of WIMPs during the freeze-out process.

Wash-out



“if washout processes freeze out before WIMP freeze-out, then a large baryon asymmetry may accumulate, and its final value is proportional to the WIMP abundance at the time that washout becomes inefficient.”

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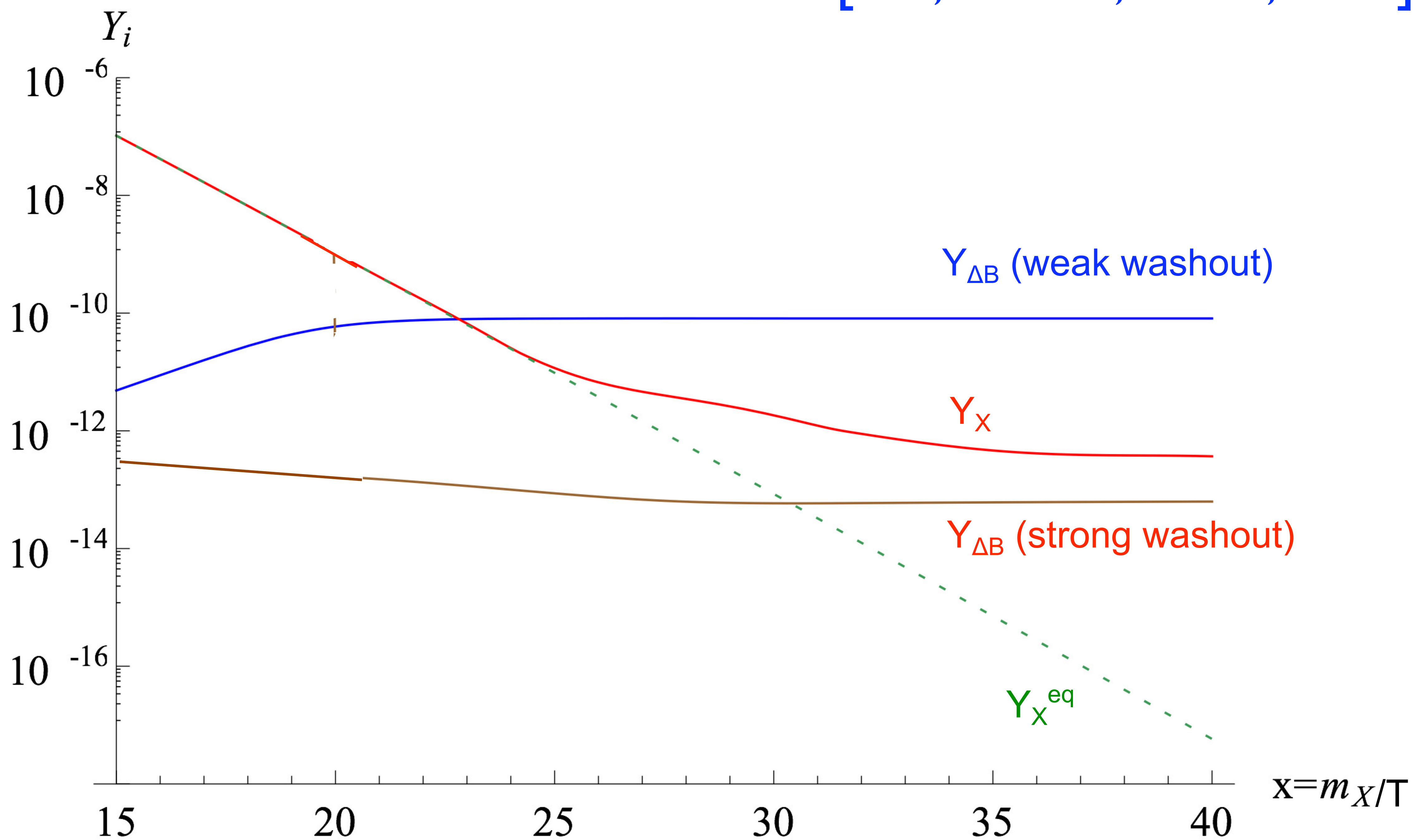
WIMPy Baryogenesis

[Cui, Randall, Shuve, 2012]



Non-thermal WIMP Baryogenesis

- Baryogenesis with WIMP

- Applicable with low-reheating temperature

- Relic density of WIMP as dark matter

Reheating

Reheating after inflation (curvaton, moduli, heavy particle…)

The energy of the decaying particle is converted to the production of the light particles.

The particles are thermalized and the Universe is heated to some temperature. Reheating temperature is the highest temperature when the radiation-domination starts.

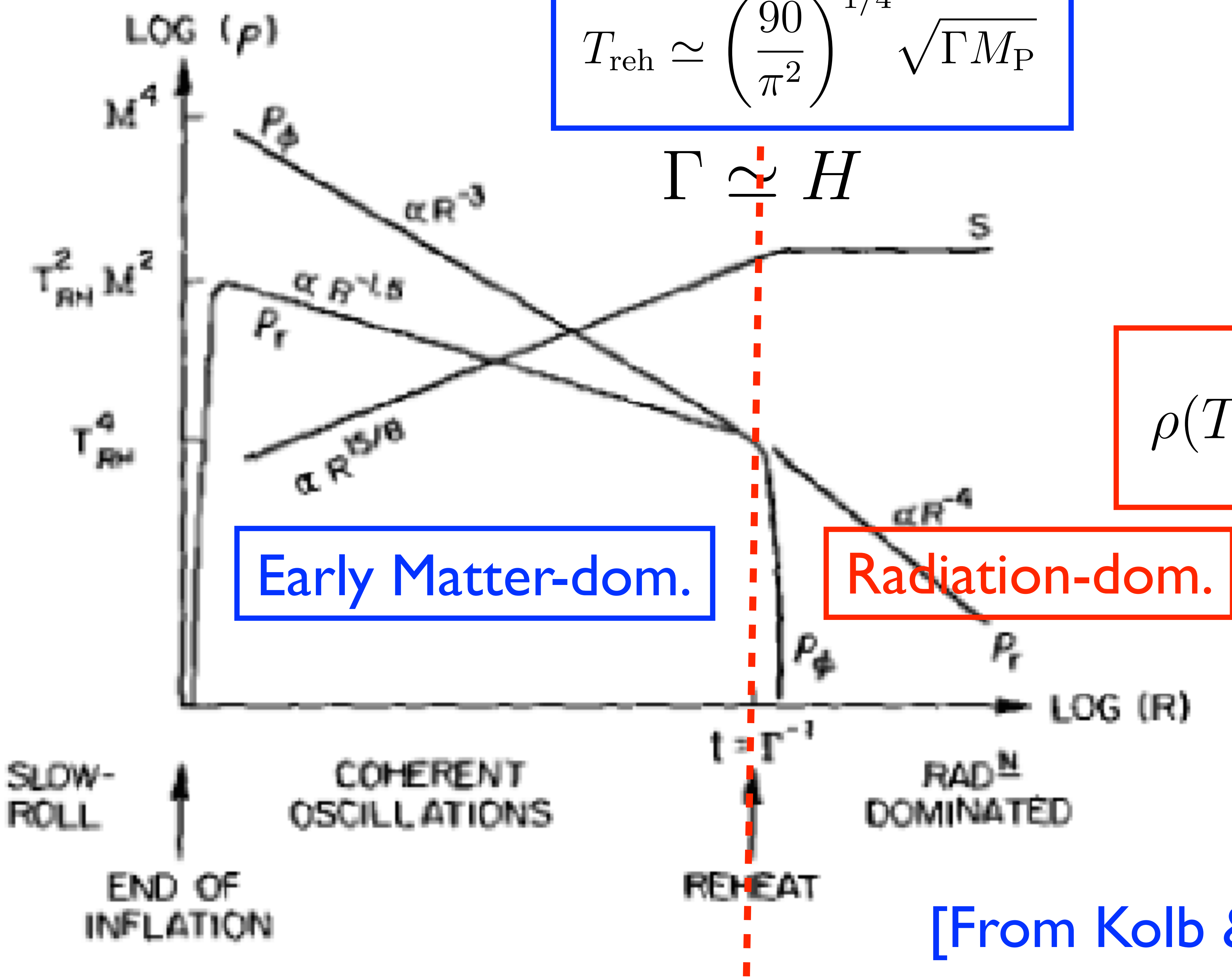
Early matter domination (eMD) before the reheating

Early Matter Domination and Reheating

$$T_{\rm reh} \simeq \left(\frac{90}{\pi^2}\right)^{1/4} \sqrt{\Gamma M_{\rm P}}$$

$$\Gamma \simeq H$$

$$\rho(T) = \frac{\pi^2}{30} g_* T^4$$



[From Kolb & Turner]

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Early Matter-Domination and Reheating

Reheating and early matter-domination also happen in the scenarios of Moduli, curvaton, thermal inflation, axino, gravitino, ...

$$\boxed{T_{\rm reh} \simeq \left(\frac{90}{\pi^2}\right)^{1/4} \sqrt{\Gamma M_{\rm P}}}$$

When decoupled heavy particles are very weakly interacting, they decay very late in the early Universe.

Temperature ~ MeV - GeV

Low bound on Reheating Temperature

1. Big Bang Nucleosynthesis

: at low-reheating temperature, neutrinos are not fully thermalised and the light element abundances are changed,

$$T_{\mathrm{reh}} \gtrsim 0.5 - 0.7\,\mathrm{MeV}$$

$$T_{\mathrm{reh}} \gtrsim 2.5\,\mathrm{MeV} - 4\,\mathrm{MeV}$$ for hadronic decays

[Kwasaki, Kohri, Sugiyama, 1999, 2000]

2. BBN+CMB

: precise calculation of the cosmic neutrino background and CMB

$$T_{\mathrm{reh}} \gtrsim 4.7\,\mathrm{MeV}$$

[Salas, Lattanzi, Mangano, Miele, Pastor, Pisanti, 2015]

New bound on low-reheating temperature

3. Dark matter halos

: density perturbation during early matter-domination and no observation of small scale DM halos.

$$\boxed{T_{\rm reh} \gtrsim 10\,\mathrm{MeV} - 100\,\mathrm{MeV}}$$

[KYChoi, Tomo Takahashi, 1705.01200]

Thermalization during Reheating

$$\phi \rightarrow 2X, \quad E_X \simeq \frac{m_\phi}{2}$$

$\boxed{\text{out-of-thermal equilibrium}}$

[Hamada et.al.,2016]
Leptogenesis during reheating

X: SM particles
:quickly thermalized

$$\rho_r = \frac{\pi^2}{30} g_* T^4$$

[Our work, 2018]
Baryogenesis during annihilation

X: particles
relatively slowly thermalized

and X-X annihilation

Freeze-out of Dark Matter

For thermal DM, $n_\chi = n_\chi^{eq}$

$T > T_{\rm fr}$ $n_\chi \langle \sigma_{\rm A} v \rangle > H,$ DMs are in thermal eq.

$T < T_{\rm fr}$ $n_\chi \langle \sigma_{\rm A} v \rangle < H$ DMs are frozen $T_{\rm fr} \simeq m_\chi / 20$

For non-thermal DM, $n_\chi = n_\phi \times Br(\phi \to X\bar{X}) \gg n_X^{eq}$

Even for $T_{\rm reh} \ll T_{\rm fr}$

$n_\chi \langle \sigma_{\rm A} v \rangle > H,$ and DM can annihilate.

Boltzmann Equations

$$H^2 = \frac{1}{3M_{\mathrm{P}}^2}(\rho_\phi + \rho_r + \rho_\chi),$$

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi \,,$$

$$\dot{\rho}_r + 4H\rho_r = (1 - f_\chi)\Gamma_\phi\rho_\phi + 2\langle\sigma_A v\rangle\left(\frac{m_\phi}{2}\right)n_\chi n_{\bar{\chi}} \,,$$

$$\dot{n}_\chi + 3Hn_\chi = f_\chi\Gamma_\phi\frac{\rho_\phi}{m_\phi} - \langle\sigma_A v\rangle(n_\chi n_{\bar{\chi}} - n_\chi^{\mathrm{eq}} n_{\bar{\chi}}^{\mathrm{eq}}) \,,$$

$$\dot{n}_{\bar{\chi}} + 3Hn_{\bar{\chi}} = f_\chi\Gamma_\phi\frac{\rho_\phi}{m_\phi} - \langle\sigma_A v\rangle(n_\chi n_{\bar{\chi}} - n_\chi^{\mathrm{eq}} n_{\bar{\chi}}^{\mathrm{eq}}) \,,$$

Boltzmann Equations

$$H^2 = \frac{1}{3M_{\rm P}^2}(\rho_\phi + \rho_r + \rho_\chi),$$

Decay of heavy particle

$$\dot\rho_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi,$$

Branching ratio to DM decay

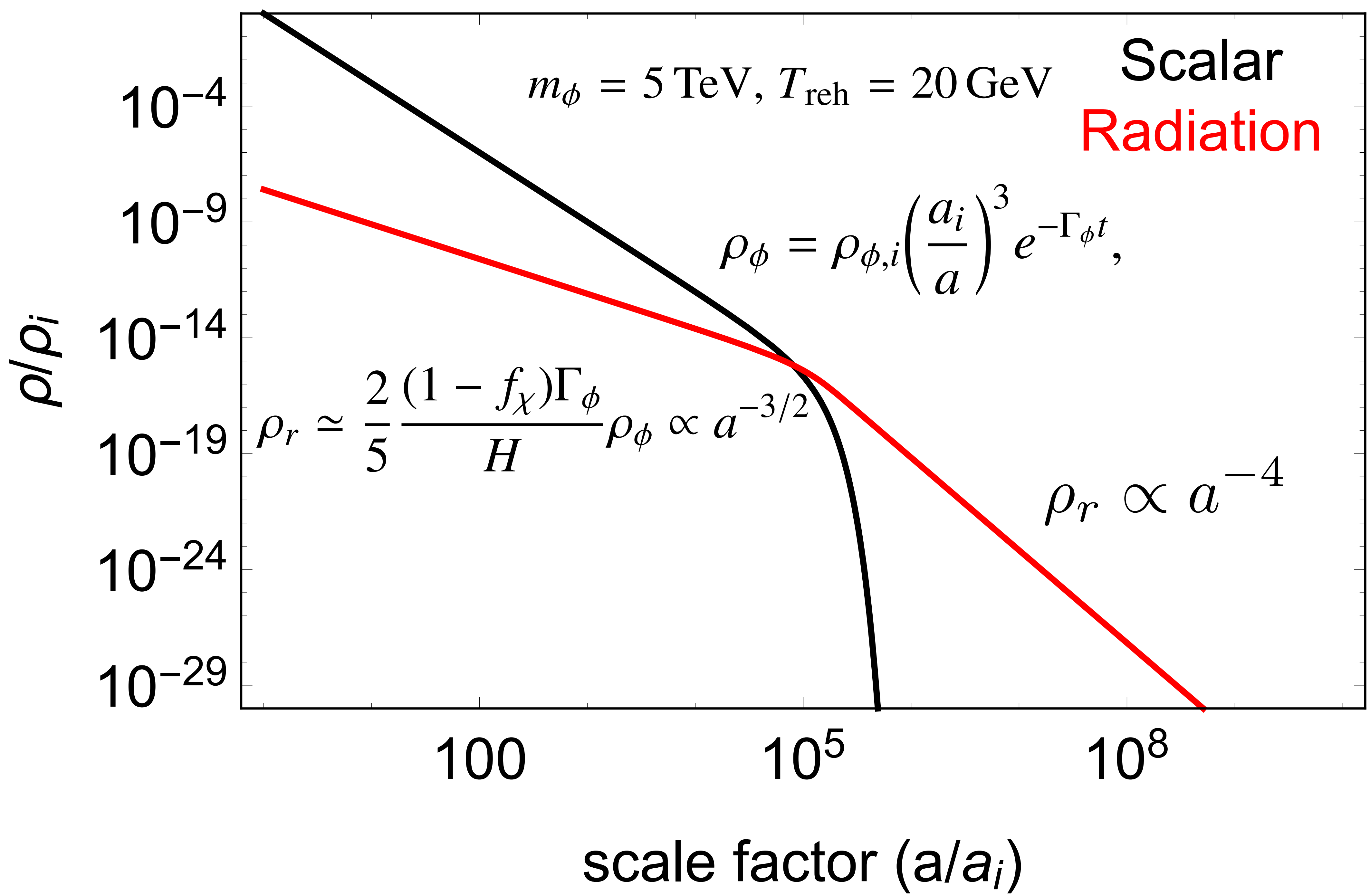
$$\dot\rho_r + 4H\rho_r = (1-f_\chi)\Gamma_\phi\rho_\phi + 2\langle\sigma_A v\rangle\left(\frac{m_\phi}{2}\right)n_\chi n_{\bar\chi}\,,$$

$$\dot n_\chi + 3Hn_\chi = f_\chi\Gamma_\phi\frac{\rho_\phi}{m_\phi} - \langle\sigma_A v\rangle(n_\chi n_{\bar\chi} - n_\chi^{\rm eq}n_{\bar\chi}^{\rm eq})\,,$$

$$\dot n_{\bar\chi} + 3Hn_{\bar\chi} = f_\chi\Gamma_\phi\frac{\rho_\phi}{m_\phi} - \langle\sigma_A v\rangle(n_\chi n_{\bar\chi} - n_\chi^{\rm eq}n_{\bar\chi}^{\rm eq})\,,$$

Annihilation of DM

Background Energy Density



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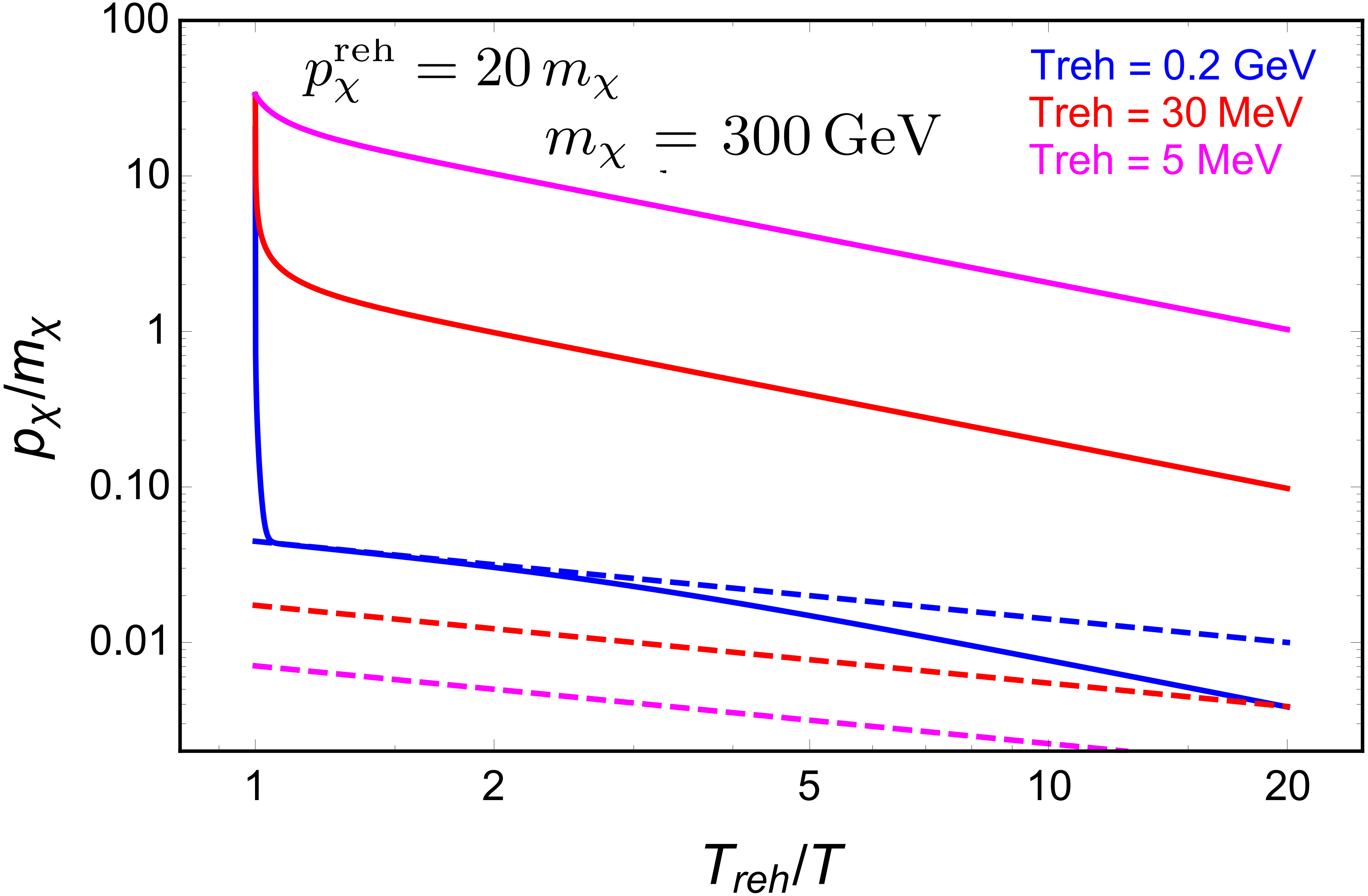
Evolution of momentum of WIMP

[Kim, Hong, Shin, 2017]



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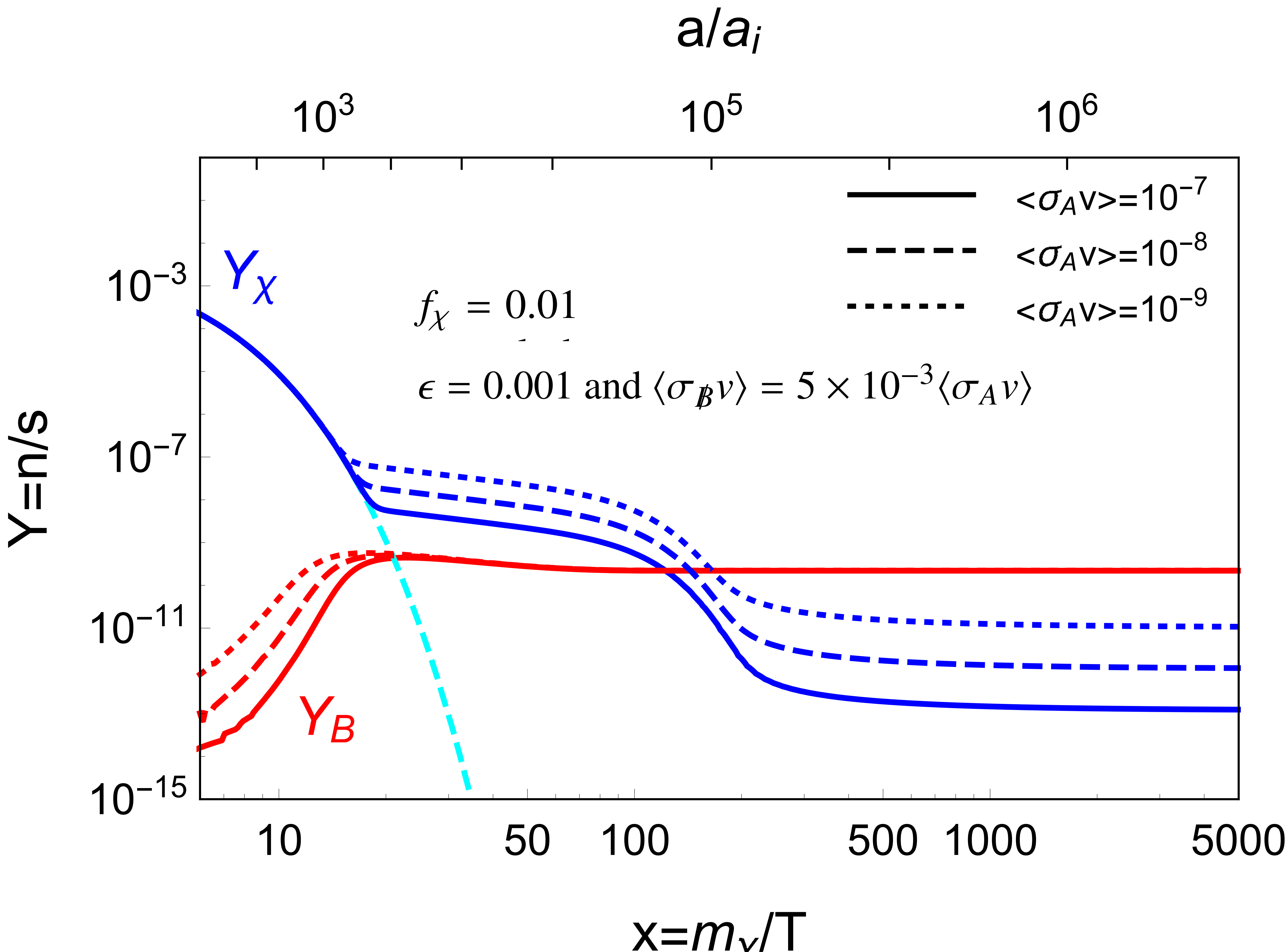
Evolution of DM and Baryon Asymmetry



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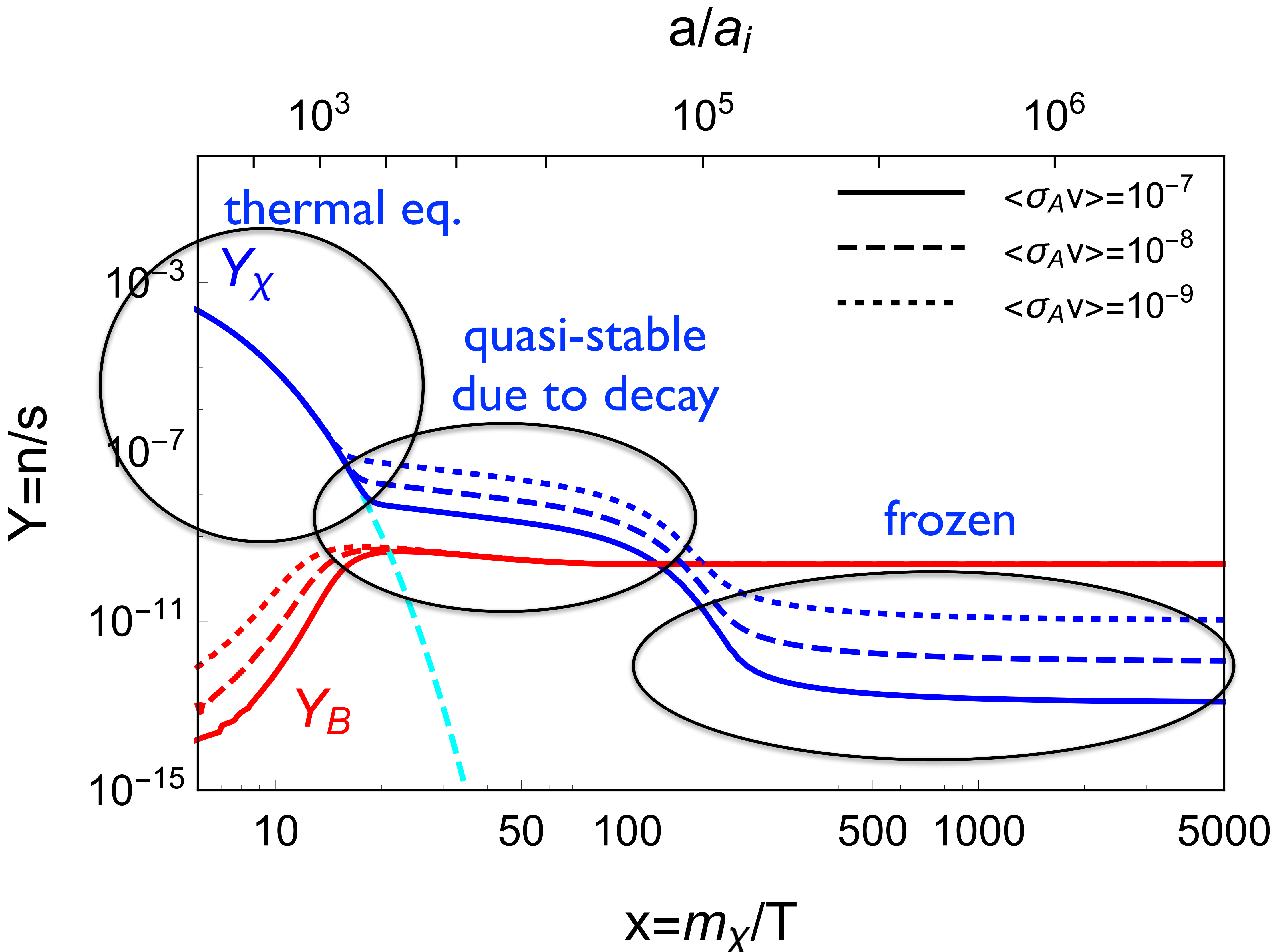
Evolution of DM



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Evolution of DM

thermal equilibrium: equilibrium solution

$$n_\chi = g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$$

quasi-stable due to decay: scaling solution

$$n_\chi \simeq n_{\bar{\chi}} \simeq \left(\frac{f_\chi \Gamma_\phi \rho_\phi}{\langle \sigma_A v \rangle m_\phi}\right)^{1/2} \propto a^{-3/2}$$

after frozen: DM relic abundance

$$Y_\chi \equiv \frac{n_\chi}{s} \simeq \frac{H(T_{\rm reh})}{\langle \sigma_{\rm A} v \rangle s} \simeq \frac{1}{4}\left(\frac{90}{\pi^2 g_*}\right)^{1/2} \frac{1}{\langle \sigma_{\rm A} v \rangle M_{\rm P} T_{\rm reh}}$$

Evolution of Baryon Asymmetry

$$\dot{n}_B + 3Hn_B = \epsilon\langle\sigma_{\not B} v\rangle(n_\chi^2 - (n_\chi^{\mathrm{eq}})^2) - \langle\sigma_{\mathrm{washout}} v\rangle n_B n_{\mathrm{eq}}$$

CP asymmetry generated via B-violating DM annihilations

$$\epsilon = \frac{\sigma_{\not B}(\chi\chi \to \cdots) - \sigma_{\not B}(\bar\chi\bar\chi \to \cdots)}{\sigma_{\not B}(\chi\chi \to \cdots) + \sigma_{\not B}(\bar\chi\bar\chi \to \cdots)}$$

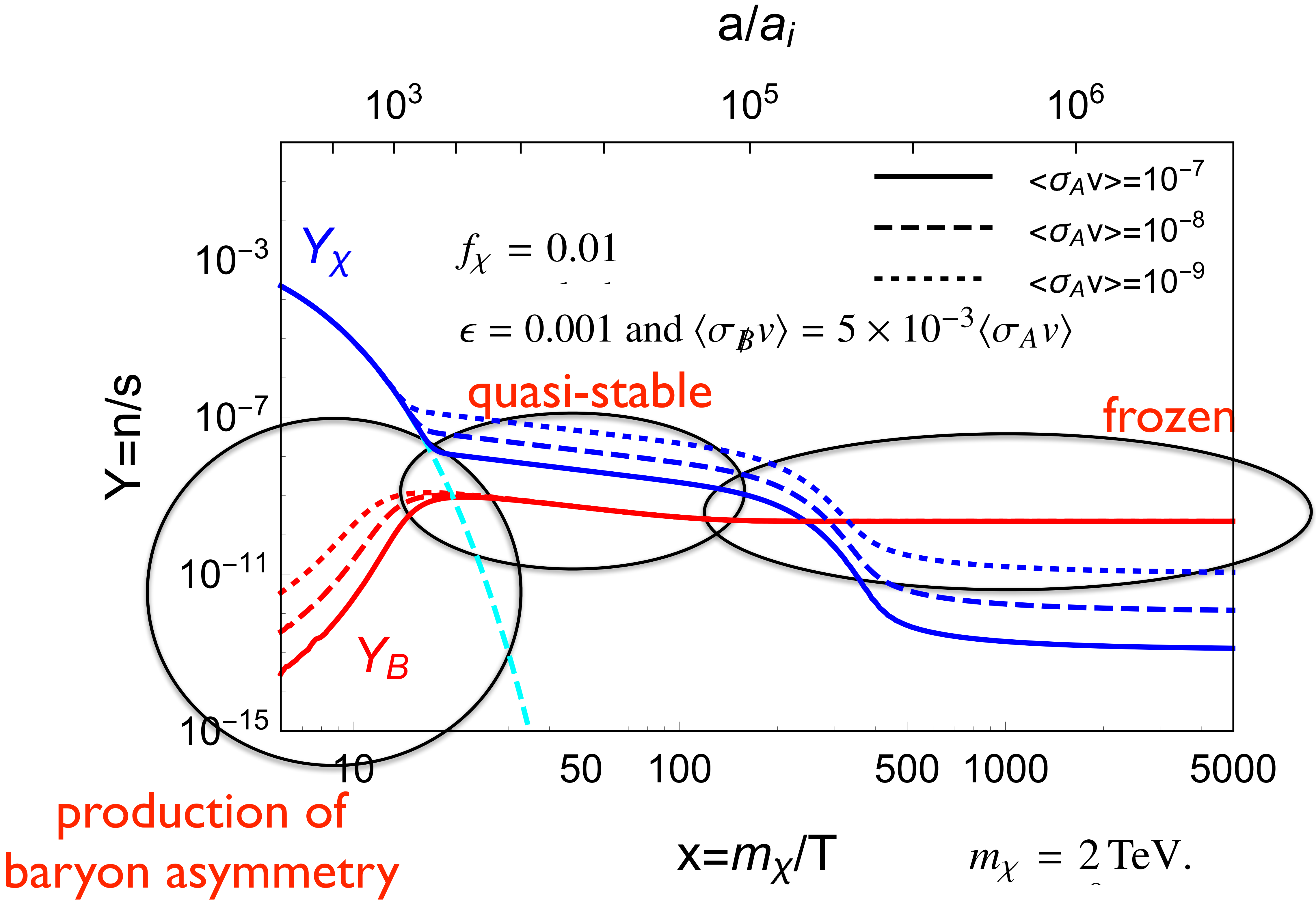
with total B-violating annihilation cross section

$$\sigma_{\not B} = \sigma_{\not B}(\chi\chi \to \cdots) + \sigma_{\not B}(\bar\chi\bar\chi \to \cdots)$$

$$\langle\sigma_{\not B} v\rangle \lesssim \langle\sigma_A v\rangle$$

and wash-out $\quad \sigma_{\mathrm{washout}} \sim \sigma_{\not B}$

Evolution of Baryon Asymmetry



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Evolution of Baryon Asymmetry

Initially at high temperature: no generation due to wash-out

quasi-stable from DM annihilation: scaling solution

$$n_B = \epsilon \langle \sigma_{\not B} v \rangle n_\chi^2 \frac{2}{3H} = \frac{2\epsilon f_\chi \Gamma_\phi M_{\rm P}}{\sqrt{3} m_\phi} \frac{\langle \sigma_{\not B} v \rangle}{\langle \sigma_A v \rangle} \rho_\phi^{1/2} \propto a^{-3/2}$$

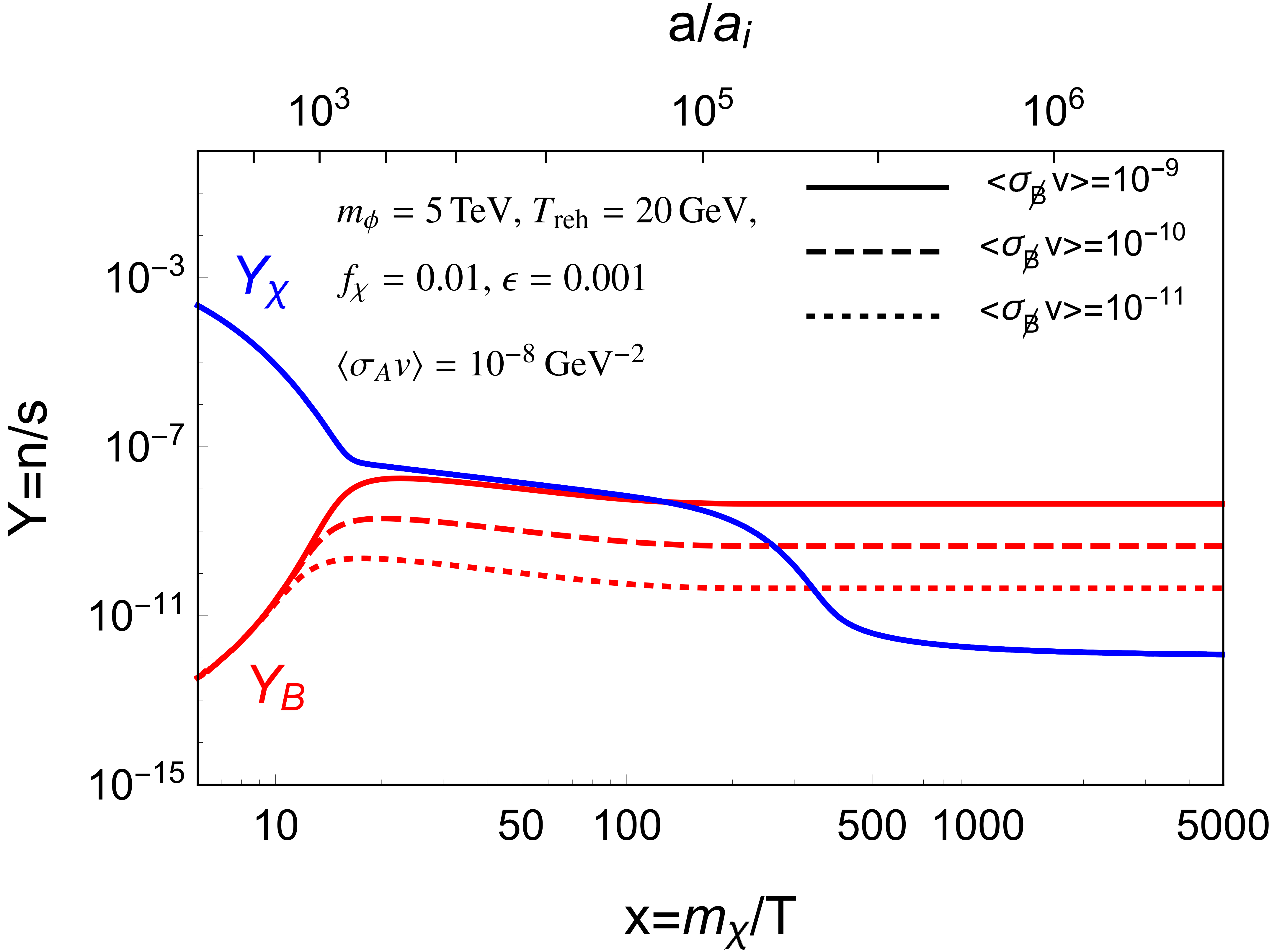
ignoring wash-out

after frozen:

$$Y_B \sim \epsilon \frac{\langle \sigma_{\not B} v \rangle}{\langle \sigma_A v \rangle} Y_\chi = \epsilon f_\chi \frac{\langle \sigma_{\not B} v \rangle}{\langle \sigma_A v \rangle} \frac{n_\phi}{s}$$

$$\sim 10^{-10} \left(\frac{\epsilon}{10^{-3}} \right) \left(\frac{f_\chi}{10^{-2}} \right) \left(\frac{\langle \sigma_{\not B} v \rangle / \langle \sigma_A v \rangle}{10^{-2}} \right) \left(\frac{T_{\rm reh}/m_\phi}{10^{-3}} \right),$$

Evolution of Baryon Asymmetry



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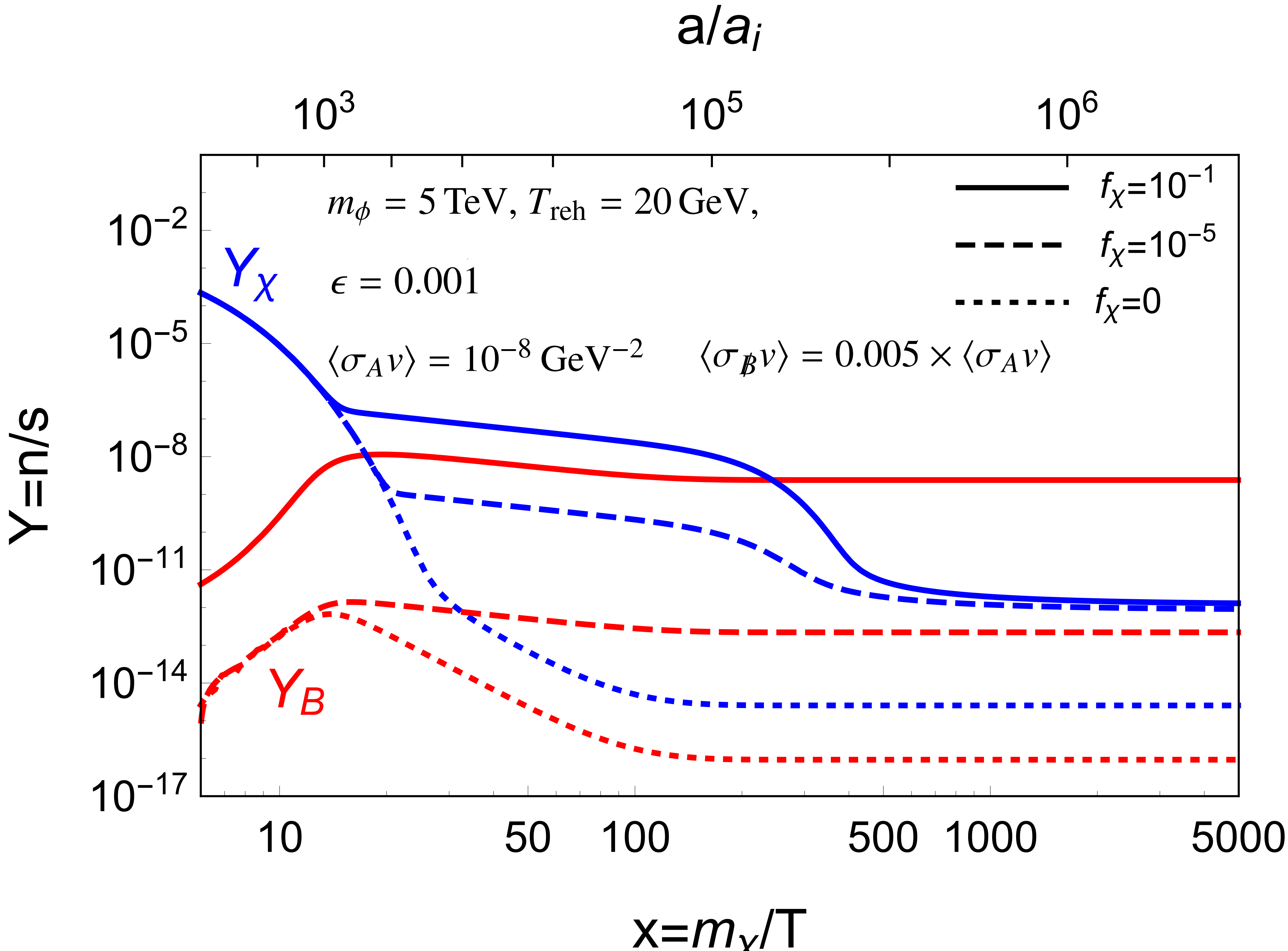
Evolution of Baryon Asymmetry



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Wash-out Effect

$$\dot{n}_B + 3Hn_B = \epsilon\langle\sigma_{\not{B}}v\rangle(n_\chi^2 - (n_\chi^{\rm eq})^2) - \langle\sigma_{\rm washout}v\rangle n_B n_{\rm eq}$$

Wash-out erases the baryon asymmetry produced

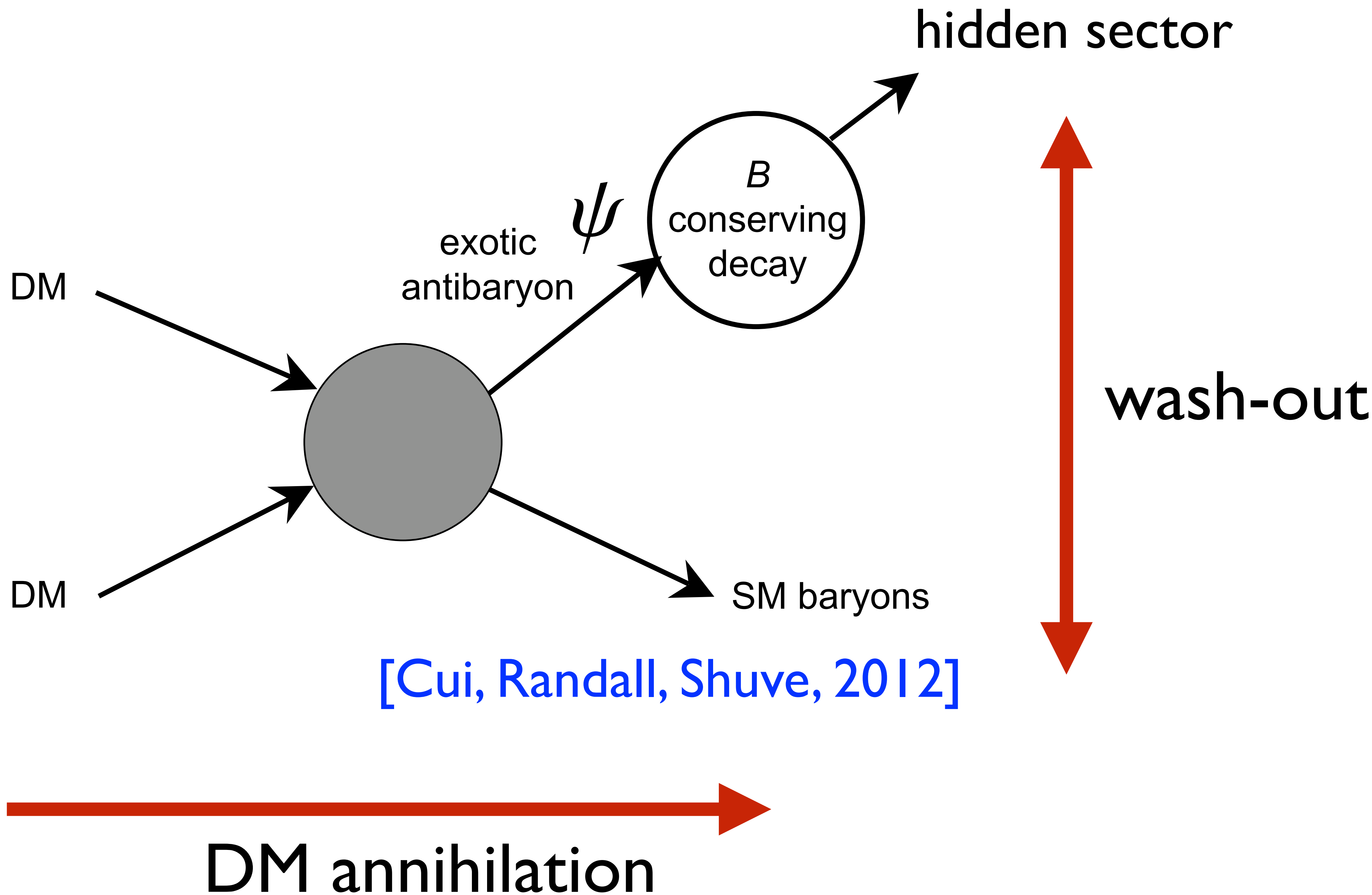
$$\sigma_{\rm washout} \sim \sigma_{\not{B}}$$

Suppression of wash-out when

$$\frac{\langle\sigma_{\rm washout}v\rangle n_B n_{\rm eq}}{\epsilon\langle\sigma_{\not{B}}v\rangle n_\chi^2} \ll 1$$

1. $\langle\sigma_{\rm washout}v\rangle \ll \langle\sigma_{\not{B}}v\rangle$ small wash-out interaction
2. $n_B n_{\rm eq} \ll n_\chi^2$ small number density of relevant particles for the wash-out

Suppressing Wash-out

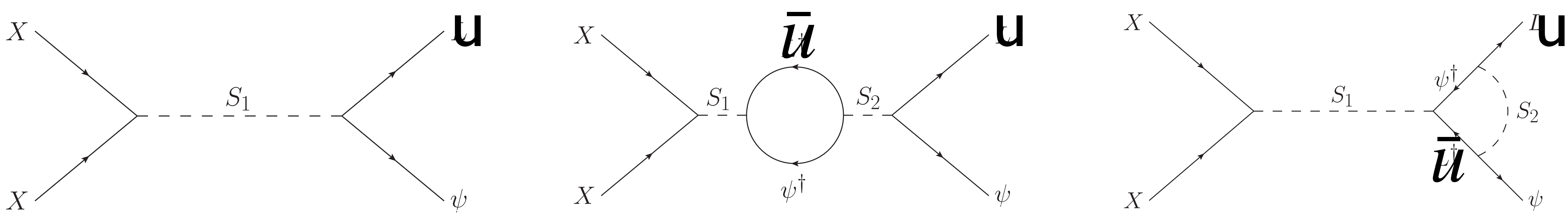


[Cui, Randall, Shuve, 2012]

Toy Model

$$\Delta\mathcal{L} = -\frac{i}{2}(\lambda_{X\alpha}X^2 + \lambda'_{X\alpha}\bar{X}^2)S_{\alpha} + i\lambda_{B\alpha}S_{\alpha}\bar{u}\psi.$$

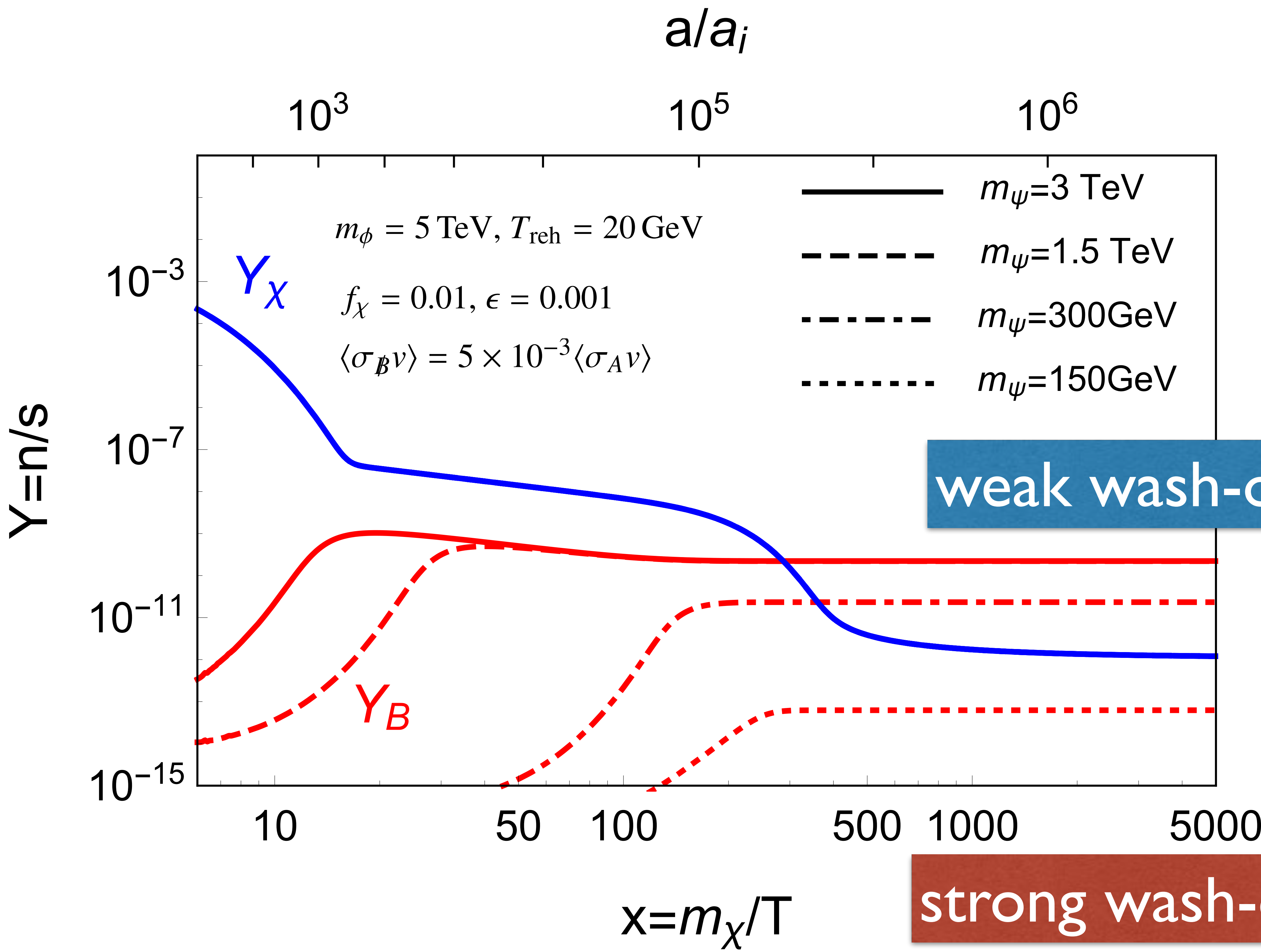
$$XX \to S^* \to \bar{u}\psi, \quad \text{and} \quad \bar{X}\bar{X} \to S^* \to u\psi^\dagger.$$



The wash-out can be suppressed with heavy mass of ψ than the reheating temperature.

$$2m_\chi > m_\psi > 25T_{\rm reh}$$

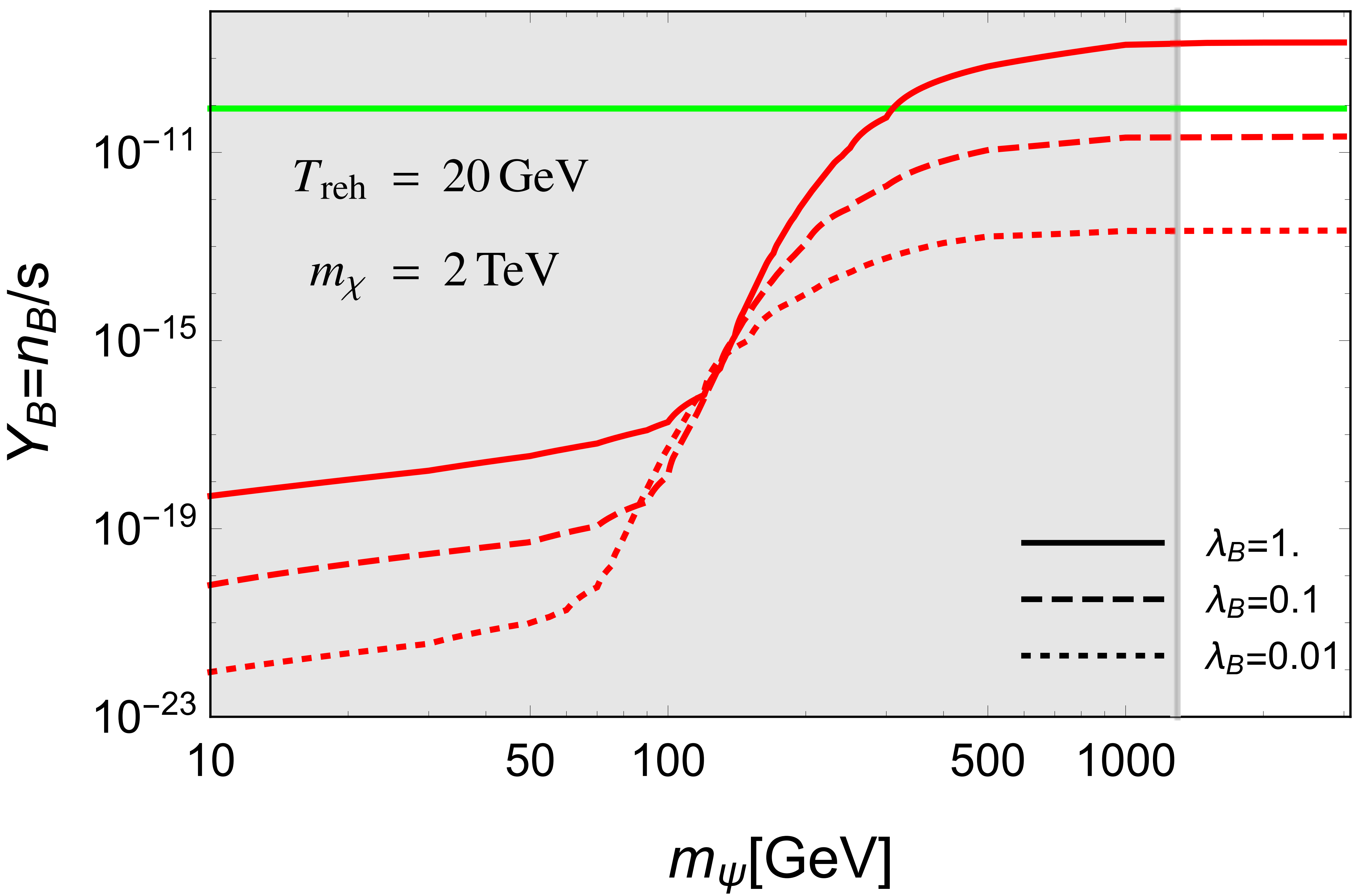
Baryon Asymmetry vs Wash-out



weak wash-out

strong wash-out

The effect of Wash-Out



Discussion

1. Baryogenesis to explain the asymmetry between matter and anti-matter in the present Universe

2. Non-thermal WIMP baryogengesis is a new model of baryogenesis, which can work at low-reheating temperature using WIMP annihilation.

Thank You!