Non-thermal WIMP baryogenesis

Based on PLB 782 (2018) 657 arXiv: 1803.00820
Collaboration with Ki-Young Choi(SKKU) and Sin Kyu Kang(Seoul-tech)

Jongkuk Kim(SKKU)

Aug 30, 2018

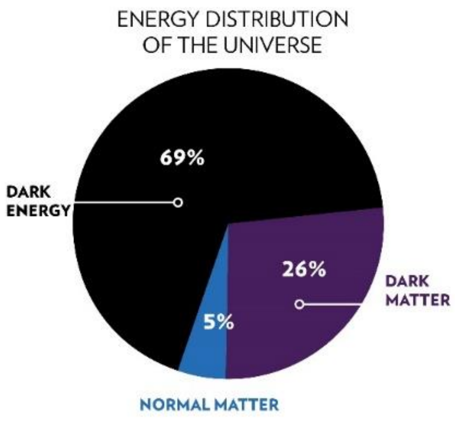
Daejeon, Korea

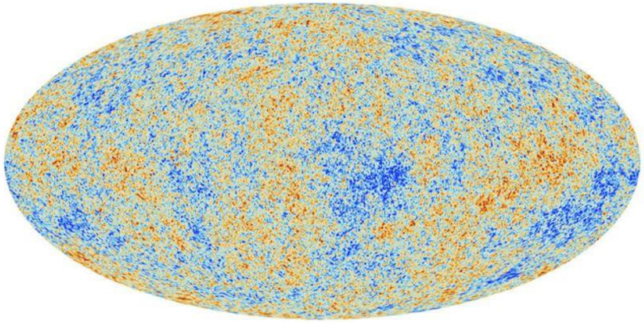
contents

- Introduction
- (Thermal) WIMPy Baryogenesis
- Non-thermal WIMP Baryogenesis
- Conclusions

Introduction

- Properties of DM
  - DM has existed from early Universe
  - Cold : Massive, Non-relativistic
  - non-luminous
    - Does not couple to photon
  - Stable or lifetime longer than the age of Universe
    - Additional Symmetry
  - ~26% of the present energy density of the Universe
    - $\Omega_{\rm DM}\, h^2 = 0.1186(20)$ Planck, 2015

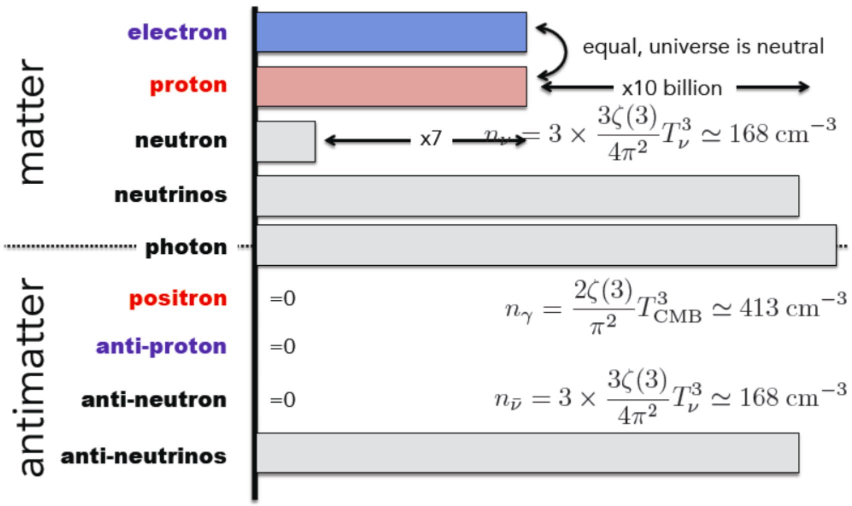




Introduction

- Matter-antimatter asymmetry
  - Matters are dominant in the Universe

- New mechanisms
  - Baryogenesis
  - Leptogenesis
  - …



From Andrew Long's lecture note

- Y is conserved quantity
  - entropy decreases as a^{-3}
  - Number density decreases as a^{-3}

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

Sakharov conditions

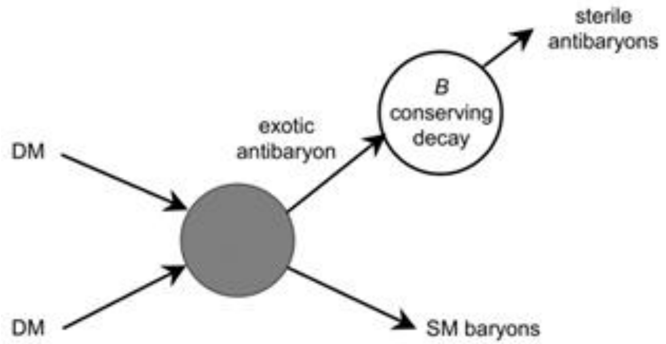
Sakharov, 1967

- Baryon number violation
  - A violation of baryon number
  - Interaction terms have B number violation
- C & CP violation
  - Bias the production of matter over antimatter
  - Interference term between tree level and one-loop level
- Departure from thermal equilibrium
  - Baryon-violating interaction goes out of thermal equilibrium

WIMPy baryogenesis

L. Randall et al, 2012

- DM relic density is obtained as usual in WIMP paradigm

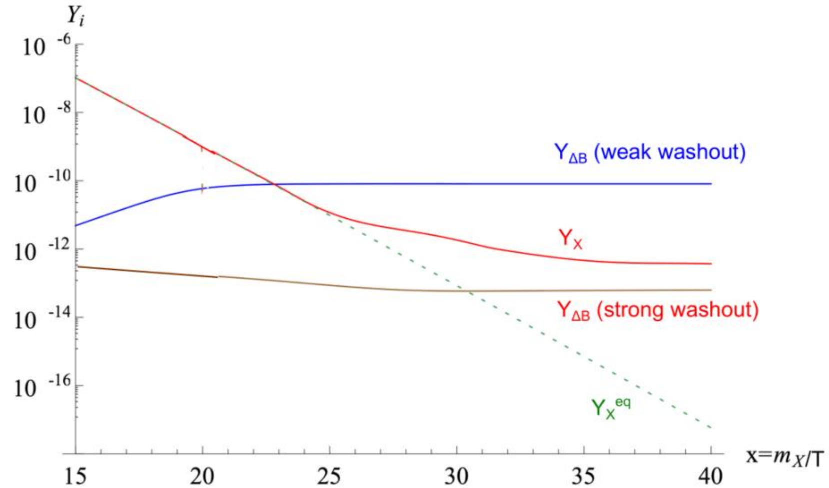


- DM annihilation generates more baryons during thermal freeze-out
  - Washout process should be suppressed
- Simultaneously solve the observed baryon asymmetry and the Dark Matter relic abundance

WIMPy baryogenesis

L. Randall et al, 2012

- Evolution of the comoving density of Dark Matter & baryon number asymmetry
  - Dark Matter freeze-out → baryon asymmetry freeze out
- strong washout
  - Mass relation: $m_\psi < m_X$
  - washout becomes effective
  - Too small
- weak washout
  - Mass relation: $m_X < m_\psi < 2\, m_X$
  - washout freezes out well before DM freeze-out
  - Baryon asymmetry accumulated



$$Y_{\Delta B}(\infty) \approx \frac{\epsilon}{2} Y_X(x_{\rm washout}) < \frac{\epsilon}{2} Y_X^{\rm eq}(15) \approx \epsilon \times 10^{-8}$$

Early matter domination

- Reheating temperature
  - The energy of the decaying particle is converted to the energy of the light particles
  - The hottest temperature when RD begins
  - Matter density is equal to Radiation density : $T_{\rm reh} \simeq \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma M_P}$
- T above ~eV, the energy density was dominated by radiation
  - The most stringent constraint comes from BBN
  - CMB+BBN+LSS: T_R > 4.7 MeV Salas, Lattanzi, Mangano, Miele, Pastor, Pisanti, 2015
- In BSM, it often occurs that the energy density of the universe is dominated by a non-relativistic matter
  - Interact very weakly with visible sector and decay very late time in the Universe
  - Reheating temperature can be low enough: 20GeV
  - Primordial asymmetry is diluted during the late time reheating → New generation needed

Non-thermal WIMP baryogenesis

- Boltzmann equations which govern the evolution

$$H^2 = \frac{1}{3M_{\mathrm{P}}^2}(\rho_\phi + \rho_r + \rho_\chi),$$: Total sum of the energy density

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

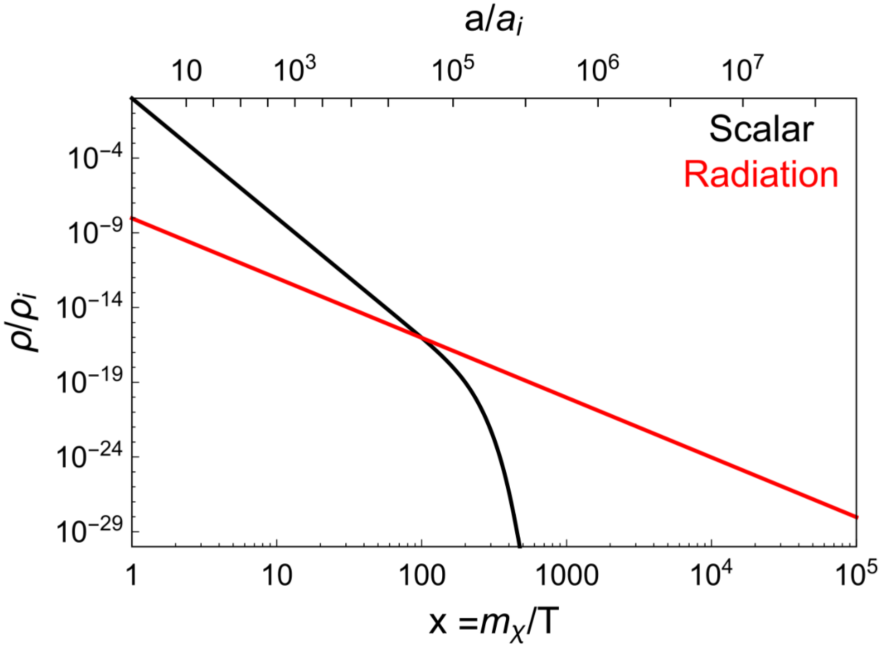
$$\dot{\rho}_r + 4H\rho_r = (1 - f_\chi)\Gamma_\phi \rho_\phi + 2\langle\sigma_A v\rangle\left(\frac{m_\phi}{2}\right) n_\chi n_{\bar{\chi}}\,,$$

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

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

- f_χ : branching ratio of decay to DM: $\phi \rightarrow \chi\bar{\chi}$
- $<\sigma_A v>$: thermal averaged DM total annihilation

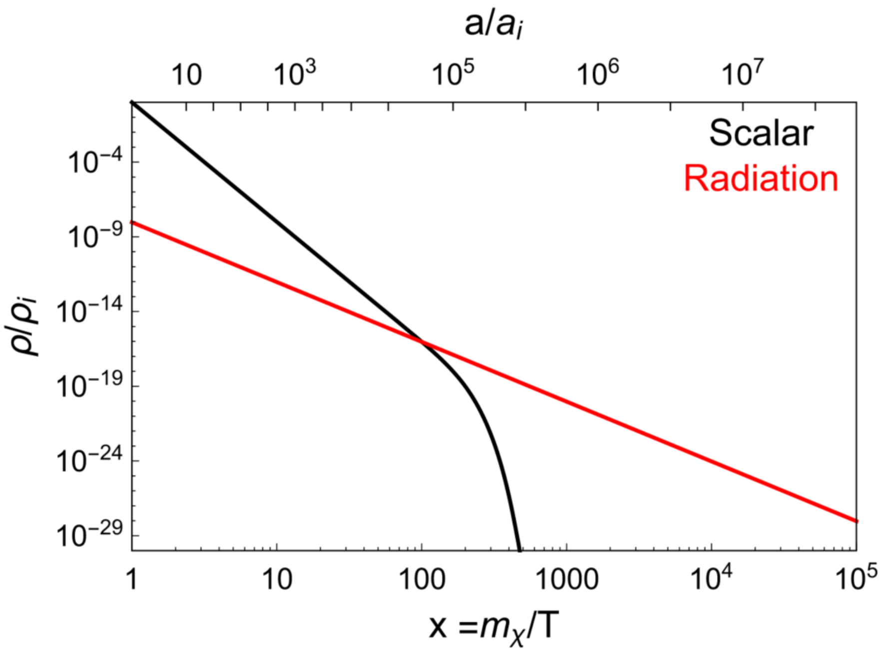
Non-thermal WIMP baryogenesis



m_ϕ = 5TeV,
m_χ = 2TeV, T_R = 20 GeV

- Long-lived heavy particle was dominated in early Universe
- Decay continuously
  - DMs and relativistic particles are produced

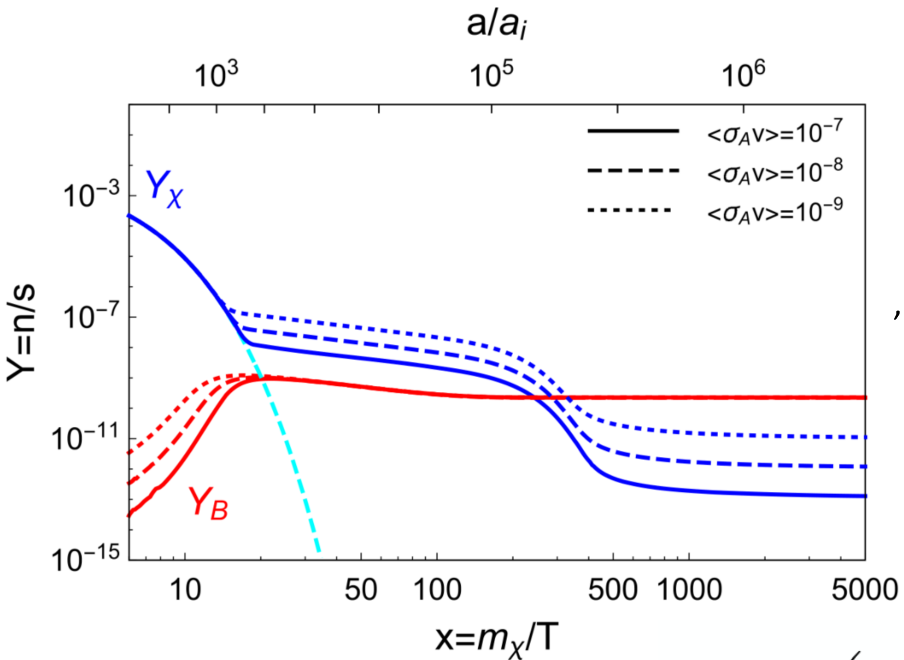
Non-thermal WIMP baryogenesis



m_ϕ = 5TeV,
m_X = 2TeV, T_R = 20 GeV

- Right after the production
  - Non-thermal with the energy of E ~ $m_\phi/2$
  - SM particles quickly settle down to thermal equilibrium : gauge interactions and large Yukawa
  - DM scatterings relatively slow and do not lead to thermal equilibrium: out-of-equilibrium

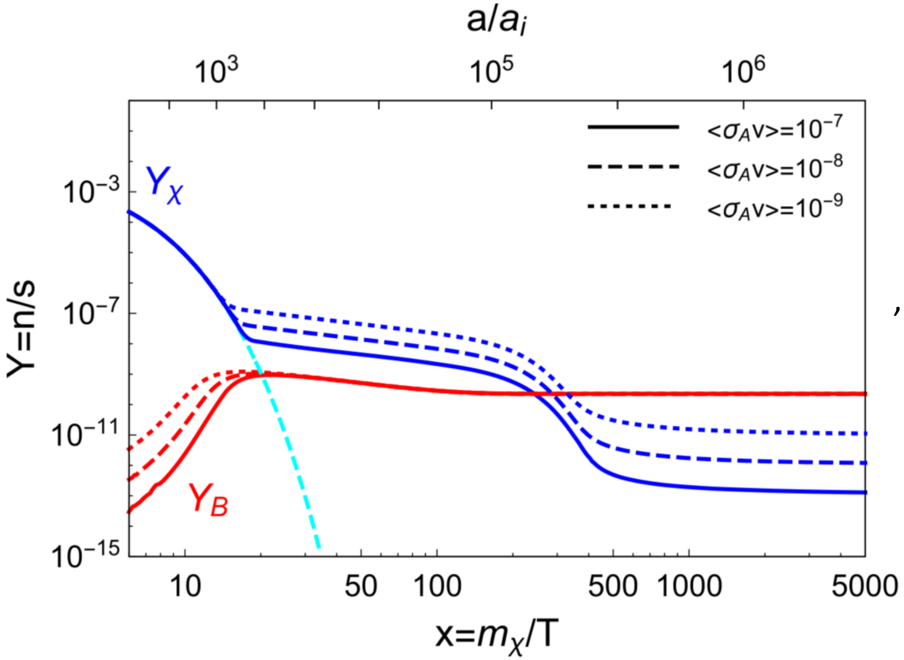
Non-thermal WIMP baryogenesis



m_ϕ=5TeV, m_χ=2TeV, T_R=20GeV, ϵ=0.001, $\langle\sigma_A v\rangle / \langle\sigma_B v\rangle$=5*e-3

- DM was in thermal equilibrium (non-relativistic) $n_\chi = g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$
- Thermal DM becomes frozen at x ~ 20
- Non-thermal DM are soon dominated

Non-thermal WIMP baryogenesis

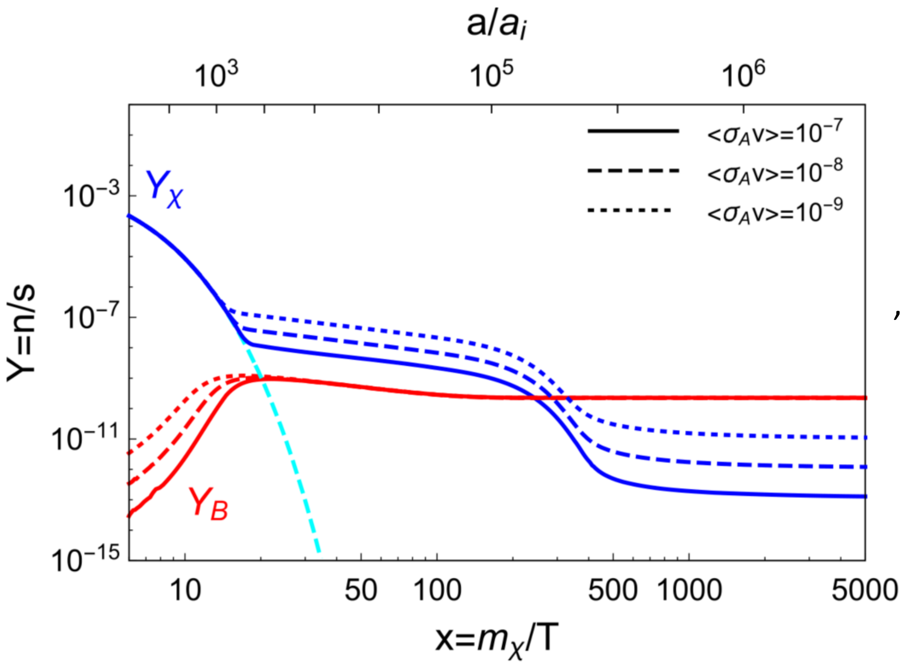


m_ϕ=5TeV, m_χ=2TeV, T_R=20GeV
, ε=0.001, $<\sigma_A v>/<\sigma_B v>$=5*e-3

- Quasi-stable
  - DM production from decay equals to DM annihilation
- Scaling solution:

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

Non-thermal WIMP baryogenesis



m_ϕ=5TeV, m_χ=2TeV, T_R=20GeV
, ε=0.001, $<\sigma_A v>/< \sigma_B v >$=5*e-3

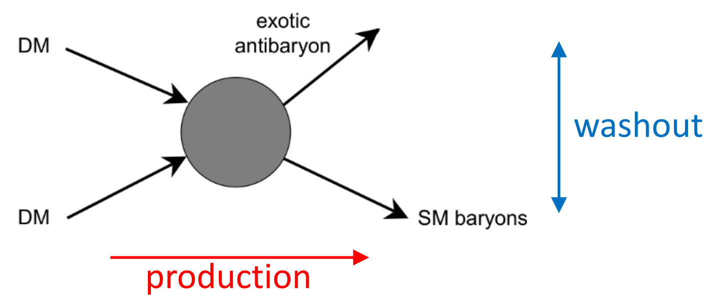
- After reheating, no more production of non-thermal DM → DM annihilation
- DM Freeze-out: Decoupled & remain constant
- Comoving number density: $Y_\chi \equiv \frac{n_\chi}{s} \simeq \frac{H(T_{\rm reh})}{\langle \sigma_{\rm A} v \rangle s} \simeq \frac{1}{4}\left(\frac{90}{\pi^2 g_*}\right)^{1/2} \frac{1}{\langle \sigma_{\rm A} v \rangle M_{\rm P} T_{\rm reh}}$

Non-thermal WIMP baryogenesis

- The Boltzmann equation for the baryon asymmetry
  - Non-thermal DMs are out-of-equilibrium

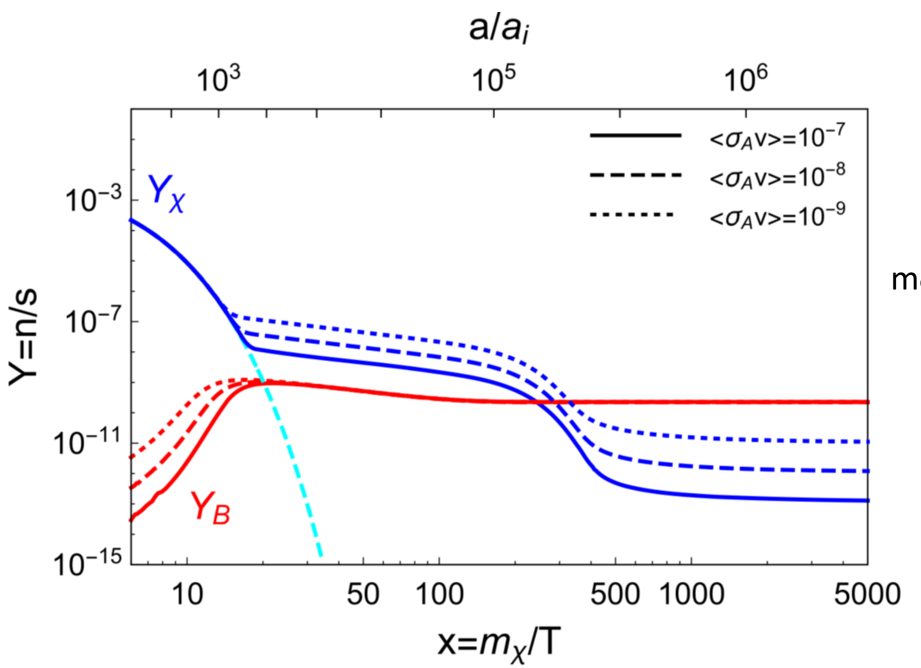
$$\dot{n}_B + 3Hn_B = \boxed{\epsilon\langle\sigma_{\not{B}}v\rangle(n_\chi^2 - (n_\chi^{\rm eq})^2)} - \langle\sigma_{\rm washout}v\rangle n_B \boxed{n_{\rm eq}}$$

- B number violating process:



- Washout effect is expected to be the same order as the B number violating interaction
  - Must be suppressed: $\dfrac{\langle\sigma_{\rm washout}v\rangle n_B n_{\rm eq}}{\epsilon\langle\sigma_{\not{B}}v\rangle n_\chi^2} \ll 1$

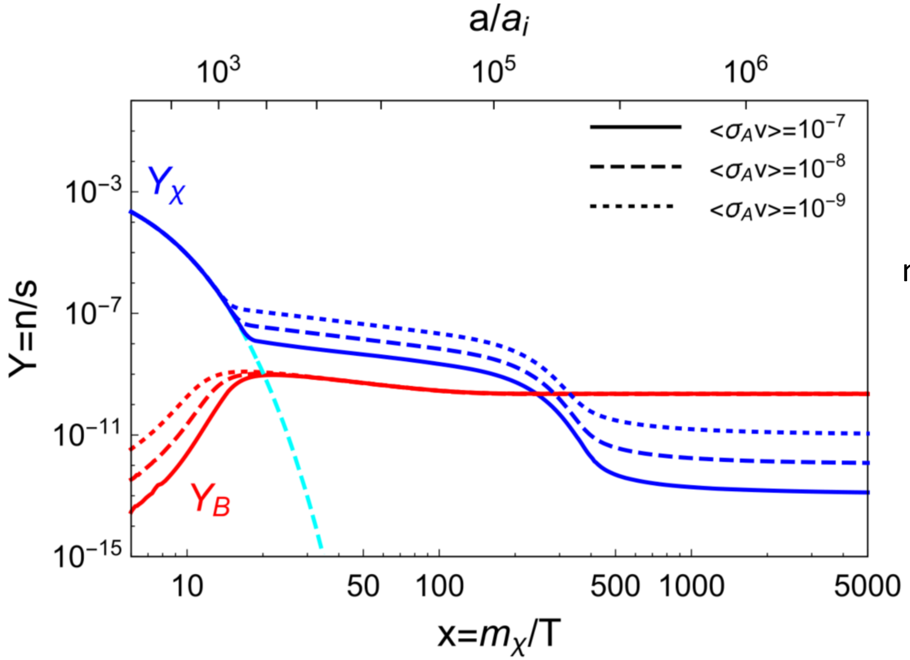
Non-thermal WIMP baryogenesis



m_ϕ=5TeV, m_χ=2TeV, T_R=20GeV , m_ψ=3TeV, ϵ=0.001, f_χ=0.01, $\langle\sigma_A v\rangle / \langle\sigma_B v\rangle$=5*e-3

- High temperature: No baryon asymmetry due to washout
- Baryon asymmetry are accumulated after washout processes freeze out

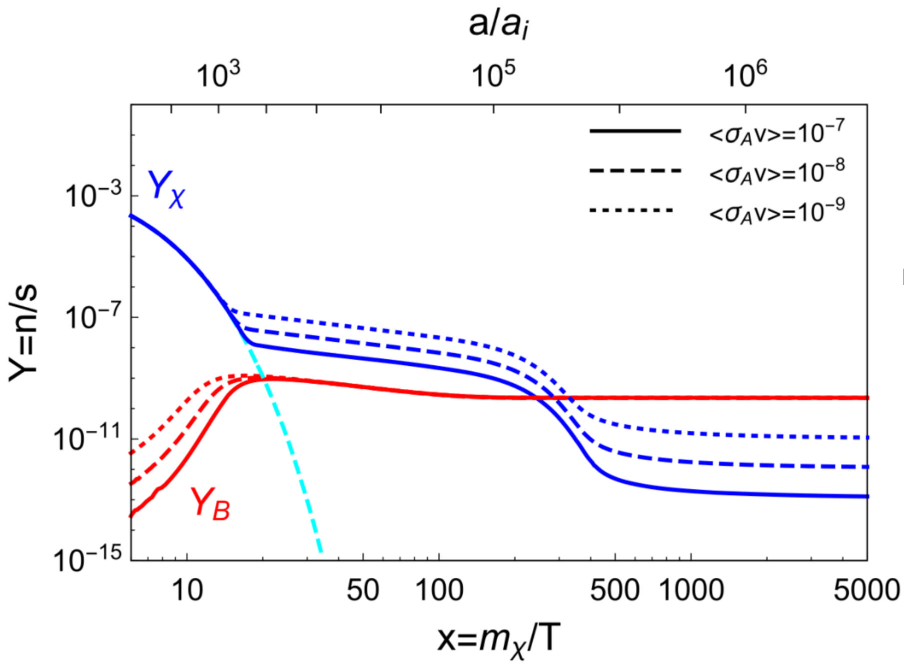
Non-thermal WIMP baryogenesis



m_ϕ=5TeV, m_χ=2TeV, T_R=20GeV, m_ψ=3TeV, ϵ=0.001, f_χ=0.01, $<\sigma_A v>/<\sigma_B v>$=5*e-3

- quasi-stable state
- Scaling solution: $n_B = \epsilon\langle\sigma_{\not B} v\rangle n_\chi^2 \frac{2}{3H} = \frac{2\epsilon f_\chi \Gamma_\phi M_P}{\sqrt{3} m_\phi}\frac{\langle\sigma_{\not B} v\rangle}{\langle\sigma_A v\rangle}\rho_\phi^{1/2} \propto a^{-3/2}$ (ignoring washout effects)

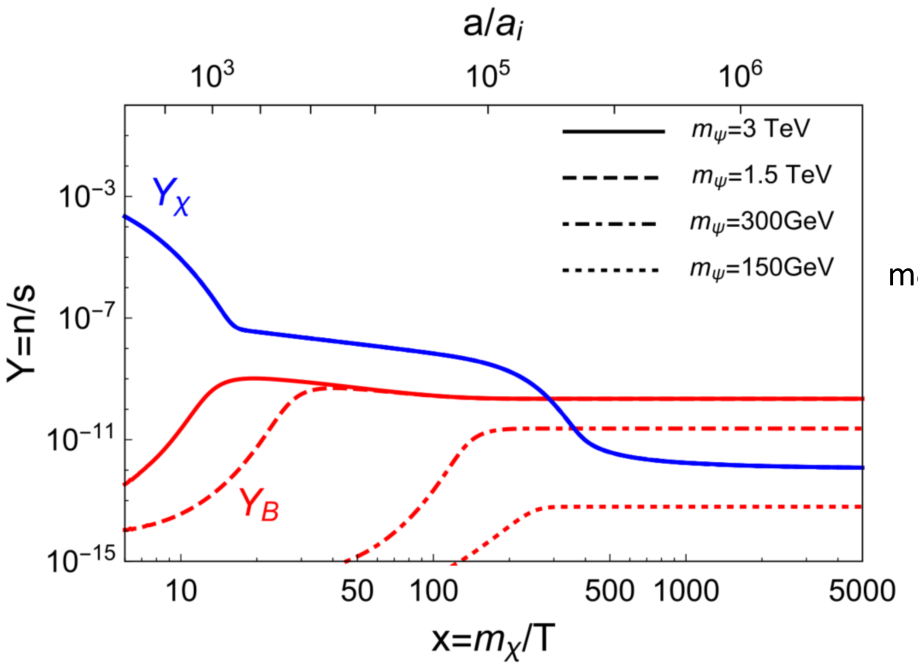
Non-thermal WIMP baryogenesis



m_ϕ=5TeV, m_χ=2TeV, T_R=20GeV, m_ψ=3TeV, ϵ=0.001, f_χ=0.01, $<\sigma_A v>/<\sigma_B v>$=5*e-3

- Baryon asymmetry freezes out
- $$Y_B \sim \epsilon \frac{\langle \sigma_{\not B} v\rangle}{\langle \sigma_A v\rangle} Y_\chi = \epsilon f_\chi \frac{\langle \sigma_{\not B} v\rangle}{\langle \sigma_A v\rangle} \frac{n_\phi}{s}$$
$$\sim 10^{-10}\left(\frac{\epsilon}{10^{-3}}\right)\left(\frac{f_\chi}{10^{-2}}\right)\left(\frac{\langle \sigma_{\not B} v\rangle/\langle \sigma_A v\rangle}{10^{-2}}\right)\left(\frac{T_{\rm reh}/m_\phi}{10^{-3}}\right)$$

Non-thermal WIMP baryogenesis



m_ϕ=5TeV, m_χ=2TeV, T_R=20GeV, ε=0.001, f_χ=0.01, $\langle\sigma_A v\rangle/\langle\sigma_B v\rangle$=5*e-3

- Washout effects are strong or weak
  - Depending on mass of ψ particle
- Y_χ is independent of the washout effect

Conclusion

We suggested non-thermal WIMP baryogenesis.

Dark matter is non-thermally produced during an reheating epoch generated by the long-lived heavy particle.

The re-annihilation of dark matter provides the observed baryon asymmetry as well as the correct relic abundance of dark matter.

We investigated how washout can have an effect on the creation of the baryon asymmetry.

We found that total annihilation cross section of dark matter can be larger than that adopted in the usual thermal WIMP baryogenesis.

Conclusion

We suggested non-thermal WIMP baryogenesis.

Dark matter is non-thermally produced during an reheating epoch generated by the long-lived heavy particle.

The re-annihilation of dark matter provides the observed baryon asymmetry as well as the correct relic abundance of dark matter.

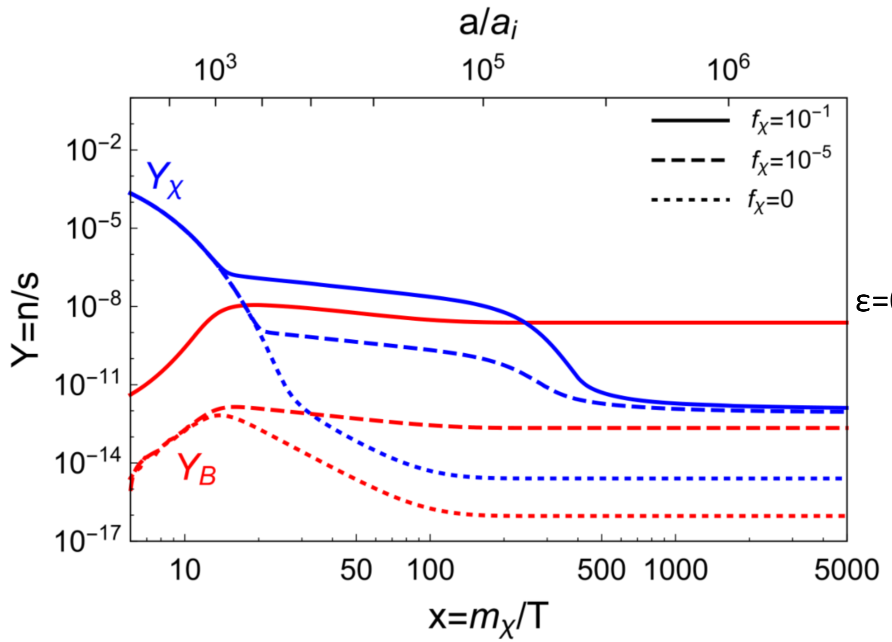
We investigated how washout can have an effect on the creation of the baryon asymmetry.

We found that total annihilation cross section of dark matter can be larger than that adopted in the usual thermal WIMP baryogenesis.

Thank you

Back-up Slide

Non-thermal WIMP baryogenesis

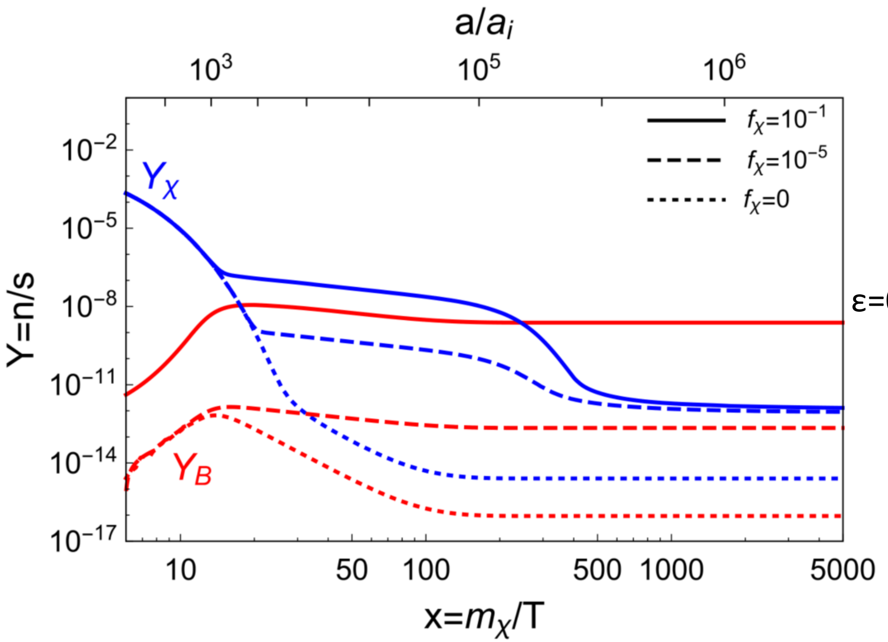


mϕ=5TeV, mχ=2TeV, TR=20GeV, mψ=3TeV,
ε=0.001, <σAv>=1e^-8, <σAv>/< σBv >=5*e-3

- The dependence of Branching ratio: $Y_B \sim \epsilon \frac{\langle \sigma_{\not B} v \rangle}{\langle \sigma_A v \rangle} Y_\chi = \epsilon f_\chi \frac{\langle \sigma_{\not B} v \rangle}{\langle \sigma_A v \rangle} \frac{n_\phi}{s}$

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

Non-thermal WIMP baryogenesis



mϕ=5TeV, mχ=2TeV, TR=20GeV, mψ=3TeV,
ε=0.001, <σAv>=1e^-8, <σAv>/< σBv >=5*e-3

- fχ → 0 limit
  - Yχ ~ 10^-14, YB ~ 10^-16
  - Too small to explain baryon asymmetry and dark matter relic density

Non-thermal WIMP baryogenesis

L. Randall et al, 2012

- Toy model
  - A vectorlike gauge singlet DM: $X, \bar{X}$
  - Singlet pseudoscalars: S_α
  - vectorlike exotic quark color triplets: ψ, $\bar{\psi}$
- Interaction term

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

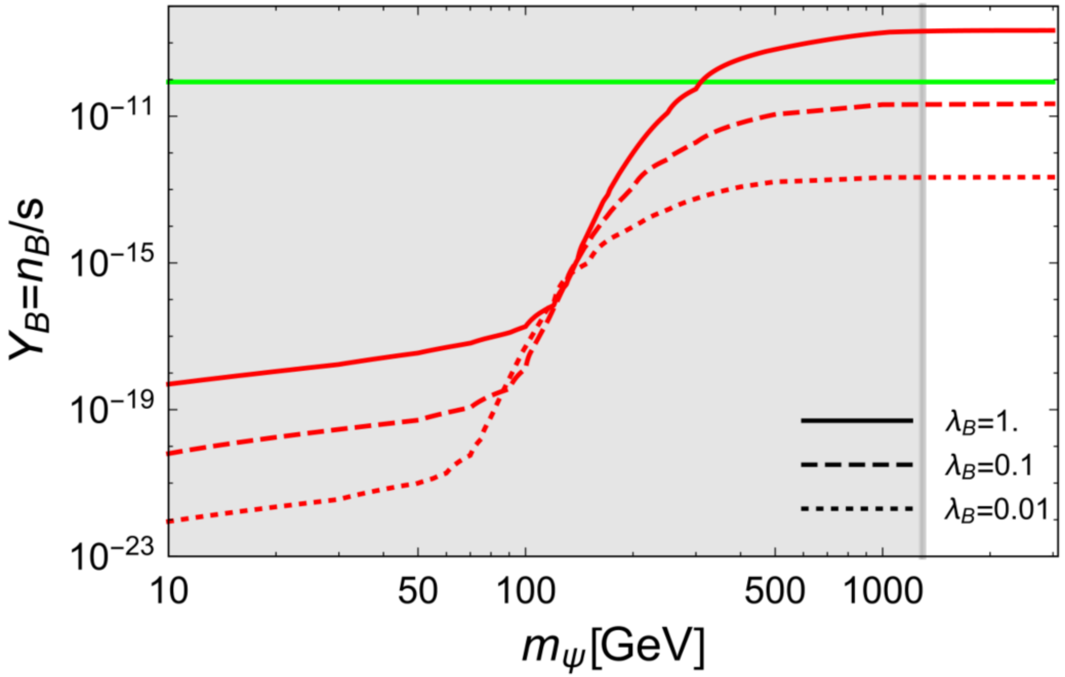
- B-number violating DM annihilation

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

- washout process
  - The same of order with B-number violating cross section

$$\sigma_{\not B} \sim (\lambda_X\lambda_B)^2\frac{1}{m_S^2}$$

Non-thermal WIMP baryogenesis



- Washout suppressed when mψ is heavy
- Green horizontal line: the observed baryon asymmetry
- Shade region: ruled out from LHC color charged particle search