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WIMPy Baryogenesis with Primordial Black Hole

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INTRODUCTION

Dark Matter:

- ✓ Existed from early Universe
- ✓ Non-luminous (does not couple to the photon)
- ✓ Stable within the age of the Universe
- ✓ Relative abundance is around 27%

$$\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$$ [Planck 2018]

Baryonic matter:

- ✓ Asymmetric (BAU)
- ✓ The excess of baryons over anti-baryons

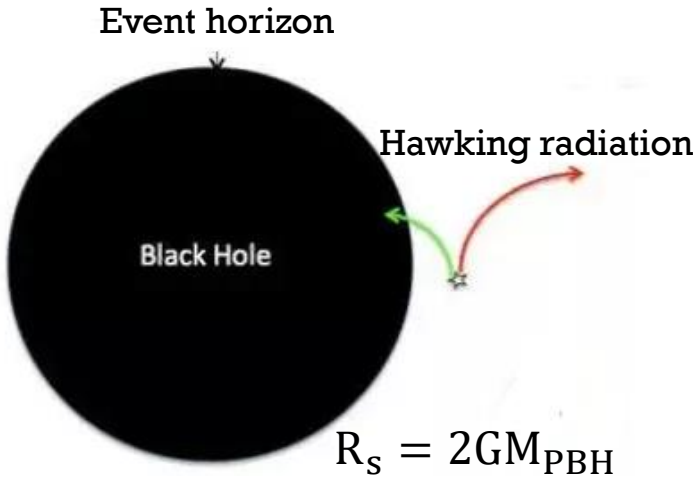
$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} \simeq 6.2 \times 10^{-10}\,, Y_B \simeq 8.7 \times 10^{-11}\,.$$ [Planck 2018, PDG 2020]

The SM fails to explain the nature of DM particles and satisfy the criteria of BAU.

WIMPY Baryogenesis: [Cui, Randall, Shuve 1112.2704]

- ✓ WIMP annihilations violate baryon number
- ✓ WIMP couplings to the SM particles violate CP
- ✓ Net DM annihilation begins around temperature $T \leq m_{DM}$ (deviation from equilibrium)
- ❖ WIMP annihilation can generate a baryon asymmetry during the freeze-out process.
- ❖ Suppression of the washout effect prior to DM freeze-out.

THE PRESENCE OF PBH



$$R_s = 2GM_{PBH}$$

$$M_{\rm in} = \gamma \frac{4\pi}{3} \frac{\rho_i}{H^3}$$

- A hypothetical type of BH which formed less than one second after the Big Bang when a large density collapses and the fluctuations re-enter the event horizon

[Carr, et al. 0912.5297, 2002.12778, 2110.02821; Pablo, et al. 2103.12087]

PBHs evaporate into all particles (SM + DM particles)

$$m_{BSM} \lesssim T_{\rm BH} = \frac{M_p^2}{M_{\rm BH}} \simeq 10^7 {\rm GeV} \left(\frac{10^6 \ {\rm g}}{M_{\rm BH}} \right)$$

[Gondolo, et al. 2009.02424
Morrison, et al. 1812.10606
Masina 2004.04730]

The emission rate of particles with momentum by a Schwarzschild BH:

$$\frac{d^2 N_i}{dp \ dt} = \frac{g_i}{2\pi^2} \frac{\sigma_{s_i}(M_{\rm BH}, \mu_i, p)}{e^{E_i(p)/T_{\rm BH}} - (-1)^{2s_i}} \frac{p^3}{E_i(p)}$$

[Ukwatta, et al. 1510.04372
Cecilia, et al. 1910.07864
Yuber, et al. 2010.03565]

PBH GENERATION AND EVAPORATION

The rate of PBH mass loss :

$$\frac{dM_{\rm BH}}{dt} = -\sum_i \int_0^\infty E_i \frac{d^2N_i}{dp\ dt} dp = -\varepsilon(M_{\rm BH}) \frac{\left(8\pi M_p^2\right)^2}{M_{\rm BH}^2}$$

[Cheek et al, Phys. Rev. D 105, 015022
Phys. Rev. D 105, 015023]

Evaporation function depending on the grey-body factor

In Geometric-optic limit ($E \gg T_{BH}$) :

$$\frac{dM_{\rm BH}}{dt} = -\frac{27\pi}{4} \frac{g_*(T_{\rm BH})}{480} \frac{M_p^4}{M_{\rm BH}^2}$$

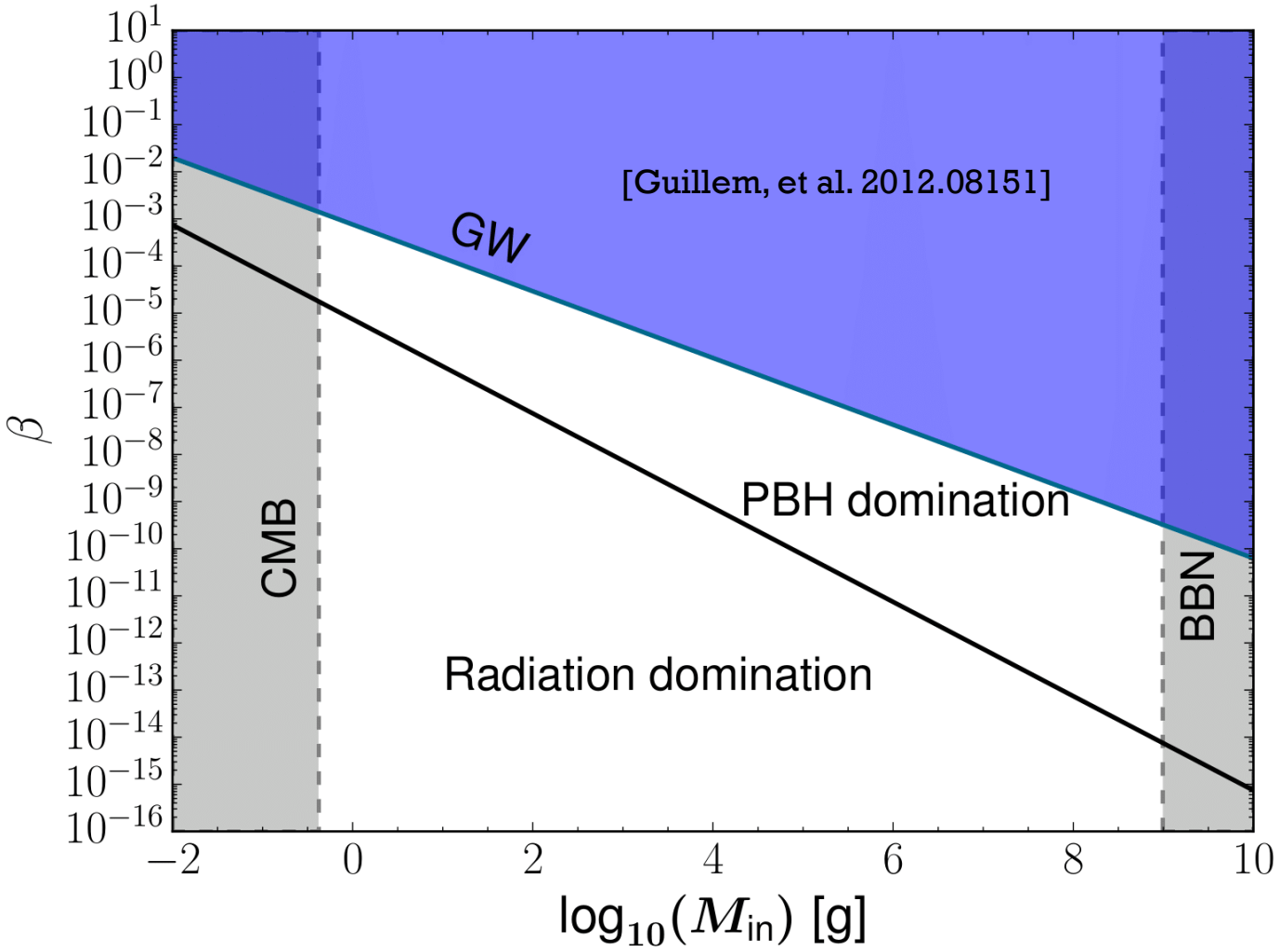
The PBH lifetime :

$$\tau = \frac{4}{27\,\pi} \frac{160\ M_{\rm in}^3}{g_*(T_{\rm BH}) M_p^4}$$

The PBH evaporation temperature :

$$T_{\rm ev}|_{RD} \equiv \left(\frac{45 M_p^2}{2\pi^2 g_*(T_{\rm ev})\tau^2}\right)^{1/4} \simeq 30\ {\rm GeV} \left(\frac{10^6\ {\rm g}}{M_{\rm in}}\right)^{3/2}$$

PBH GENERATION AND EVAPORATION



- **Upper bound :** [Baumann, et al. 0703250]

$$T_{\rm ev} > T_{\rm BBN} \simeq 4 \text{ MeV}$$

$$\frac{M_{\rm in}}{M_p} \lesssim 10.4 \times 10^{13} \left(\frac{g_*^2(T_{\rm BH})}{g_*(T_{\rm ev})} \right)^{1/6}$$

$$\Rightarrow \quad \boxed{M_{\rm in}^{\rm max} \lesssim 9.7 \times 10^8 \text{ g.}}$$

- **Lower bound :** [Planck 2018]

$$H \leq 2.5 \times 10^{-5} M_p$$

$$M_{\rm in} > \frac{4\pi\gamma M_p}{2.5 \times 10^{-5}} \simeq \left(\frac{\gamma}{0.2} \right) 0.4 \text{ g}$$

$$\Rightarrow \quad \boxed{M_{\rm in}^{\rm min} \gtrsim 0.4 \text{ g.}}$$

NON-THERMAL WIMP BARYOGENESIS

$$H^2 = \frac{8\pi}{3M_{\rm pl}^2}(\rho_r + \rho_{\rm BH})$$

$$\frac{dM_{\rm BH}}{dt} = -\varepsilon(M_{\rm BH})\frac{(8\pi M_p^2)^2}{M_{\rm BH}^2}$$

$$\dot{\rho}_{\rm BH} + 3H\rho_{\rm BH} = \frac{\rho_{\rm BH}}{M_{\rm BH}}\frac{dM_{\rm BH}}{dt},$$

$$\dot{\rho}_{\rm r} + 4H\rho_{\rm r} = -\frac{\varepsilon_{\rm SM}(M_{\rm BH})}{\varepsilon(M_{\rm BH})}\frac{\rho_{\rm BH}}{M_{\rm BH}}\frac{dM_{\rm BH}}{dt}$$

$$\dot{n}_\chi + 3Hn_\chi = \frac{\rho_{\rm BH}}{M_{\rm BH}}\Gamma_{{\rm BH}\to\chi} - \langle\sigma_{\rm ann}\upsilon\rangle(n_\chi^2 - n_{\chi,{\rm eq}}^2),$$

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

The fraction of SM particles from evaporation

Emission rate of NT DM from PBH

DM annihilation cross-section

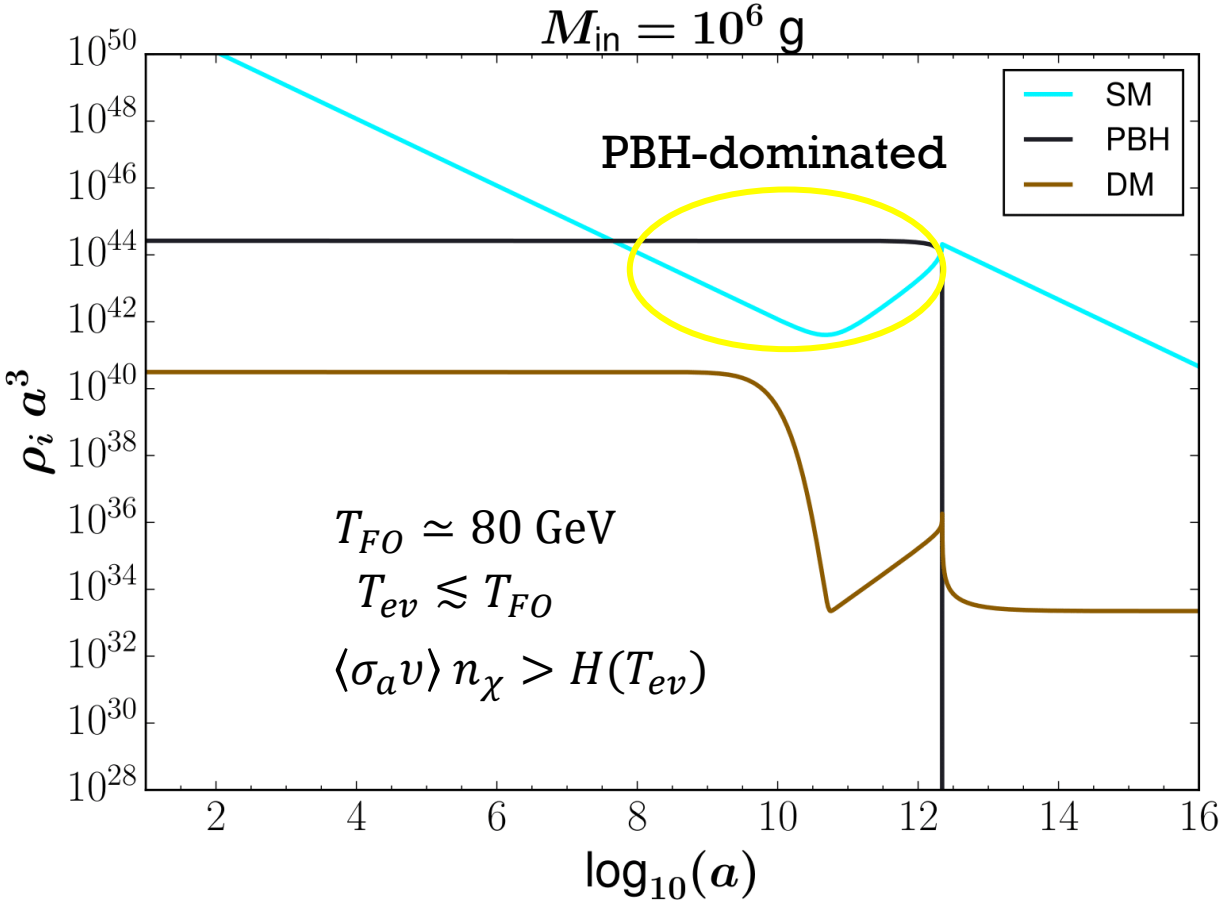
B-number violating cross-section of DM annihilation

Washout processes must freeze-out before WIMP freeze-out

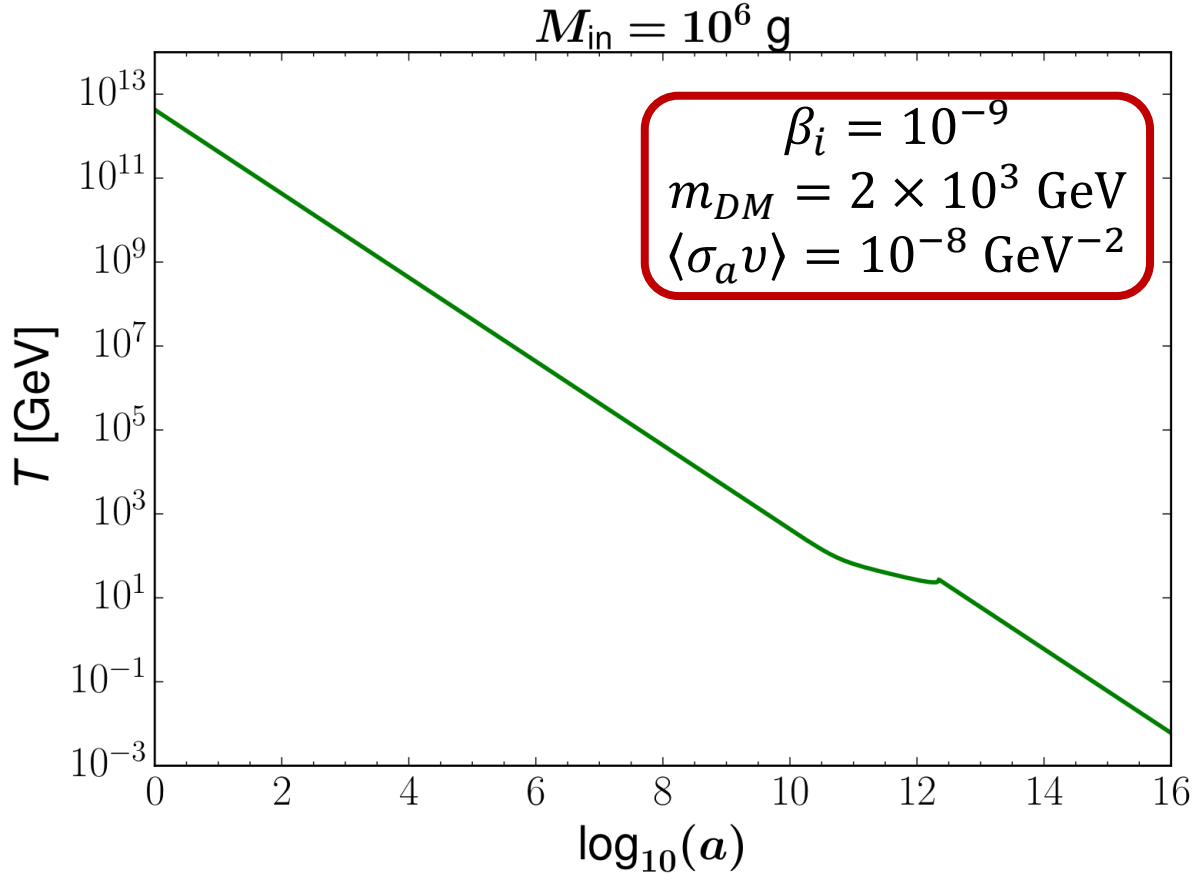
[Ki-Young, et al. 1803.00820
Barman, et al. 2204.10339]

NON-THERMAL WIMP BARYOGENESIS

Evolution of energy density

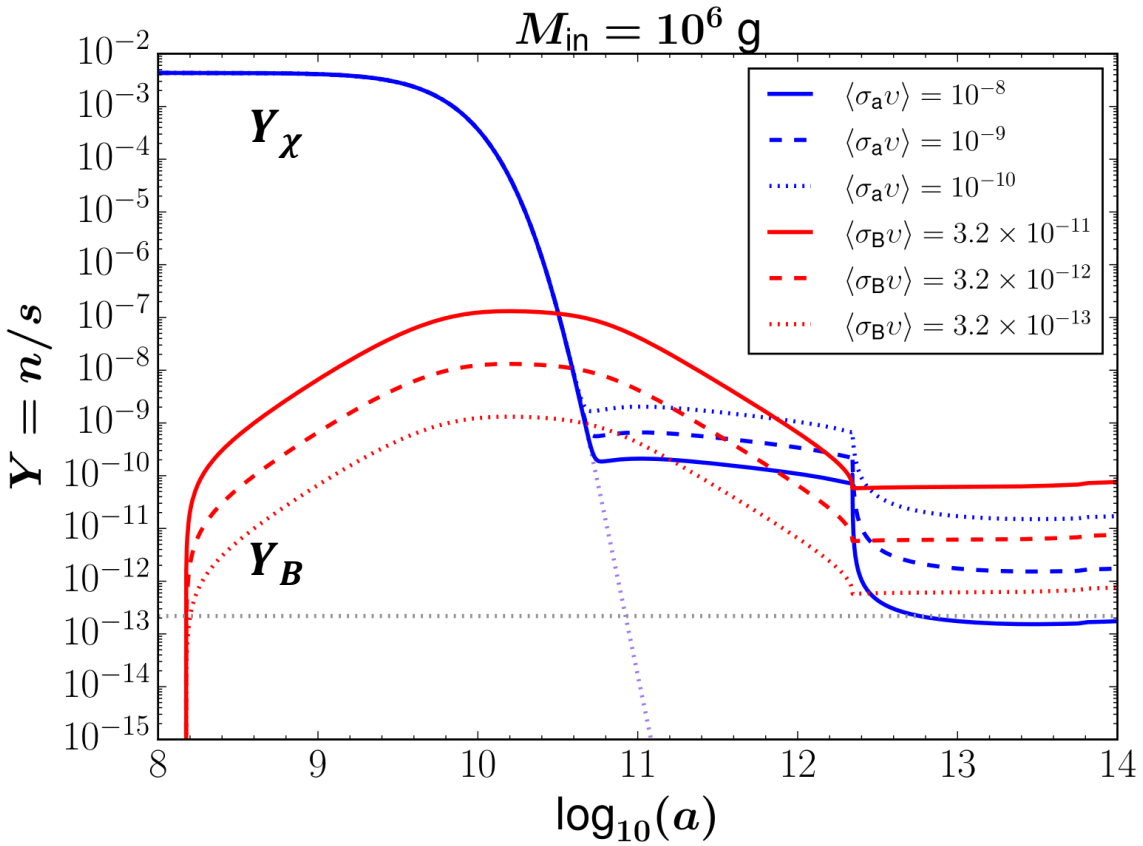


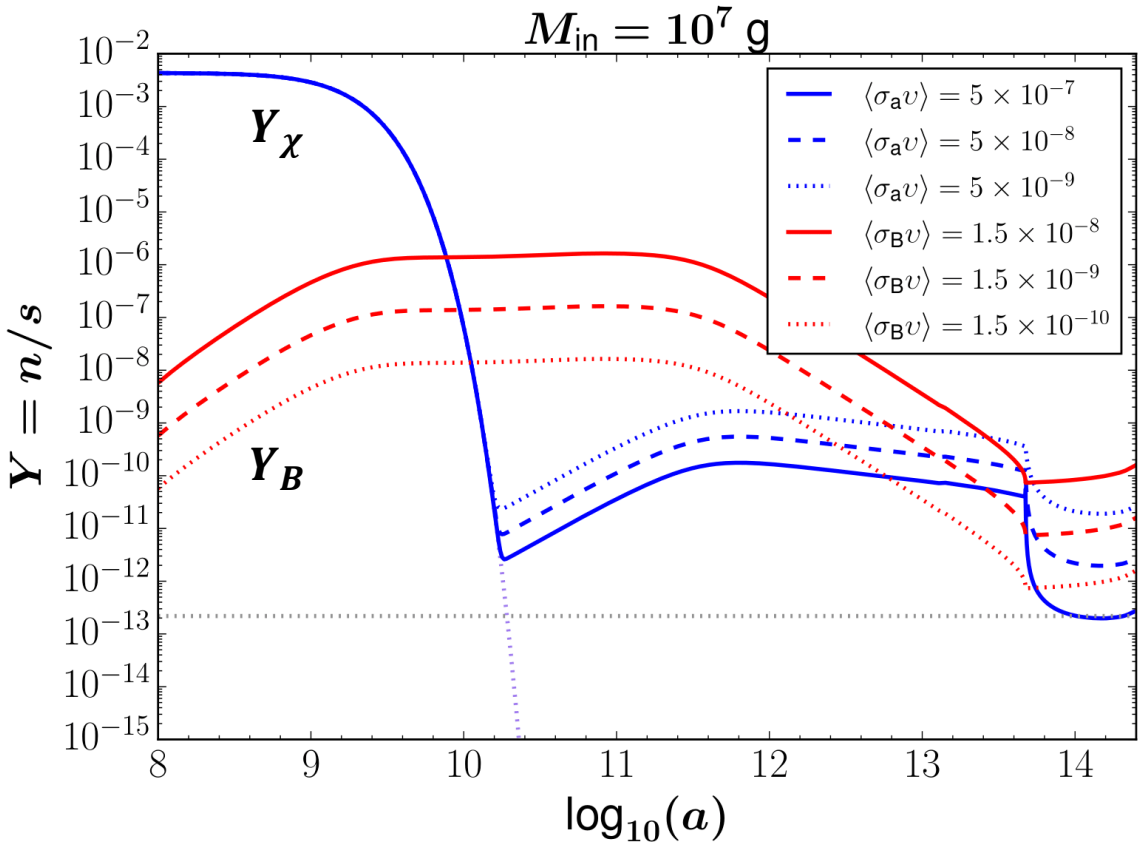
Plasma temperature



$$\rho_R(t) \simeq \frac{2\sqrt{3}}{5}\varepsilon_{\rm SM}\sqrt{\rho_{\rm BH}(t_i)}\frac{64\pi^2 M_p^5}{M_{\rm BH}^3}\left(\frac{a_i}{a}\right)^{3/2}\left[1-\left(\frac{a_i}{a}\right)^{5/2}\right] \propto a^{-3/2}.$$

NON-THERMAL WIMP BARYOGENESIS





$$\Omega_\chi^{\rm ann} h^2 \simeq 0.11 \sqrt{\frac{100}{g_*(T_{\rm ev})}} \left(\frac{10^{-8}\ {\rm GeV}^{-2}}{\langle\sigma_a v\rangle}\right) \left(\frac{30\ {\rm GeV}}{T_{\rm ev}}\right) \left(\frac{m_\chi}{2\ {\rm TeV}}\right)$$

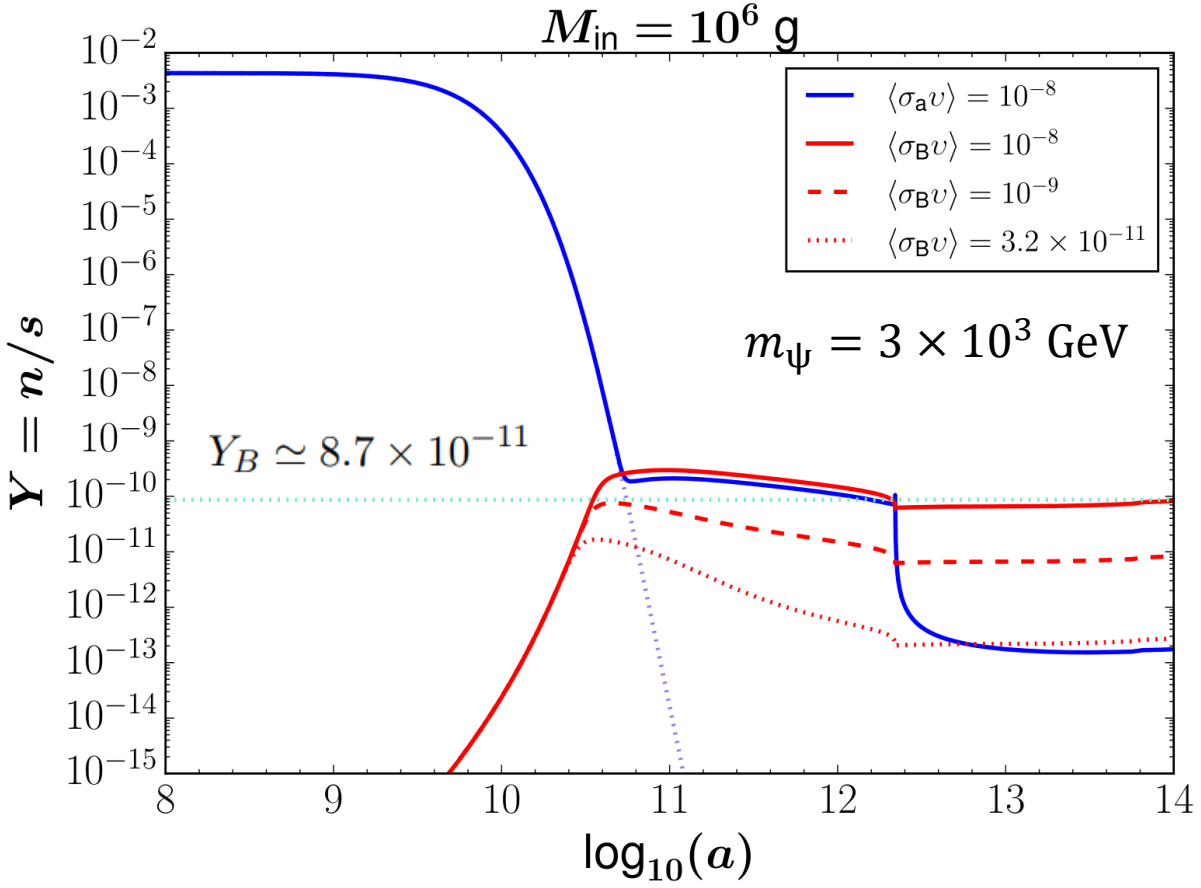
$$Y_B \sim \epsilon \frac{\langle\sigma_B v\rangle}{\langle\sigma_a v\rangle} Y_{\rm DM}$$

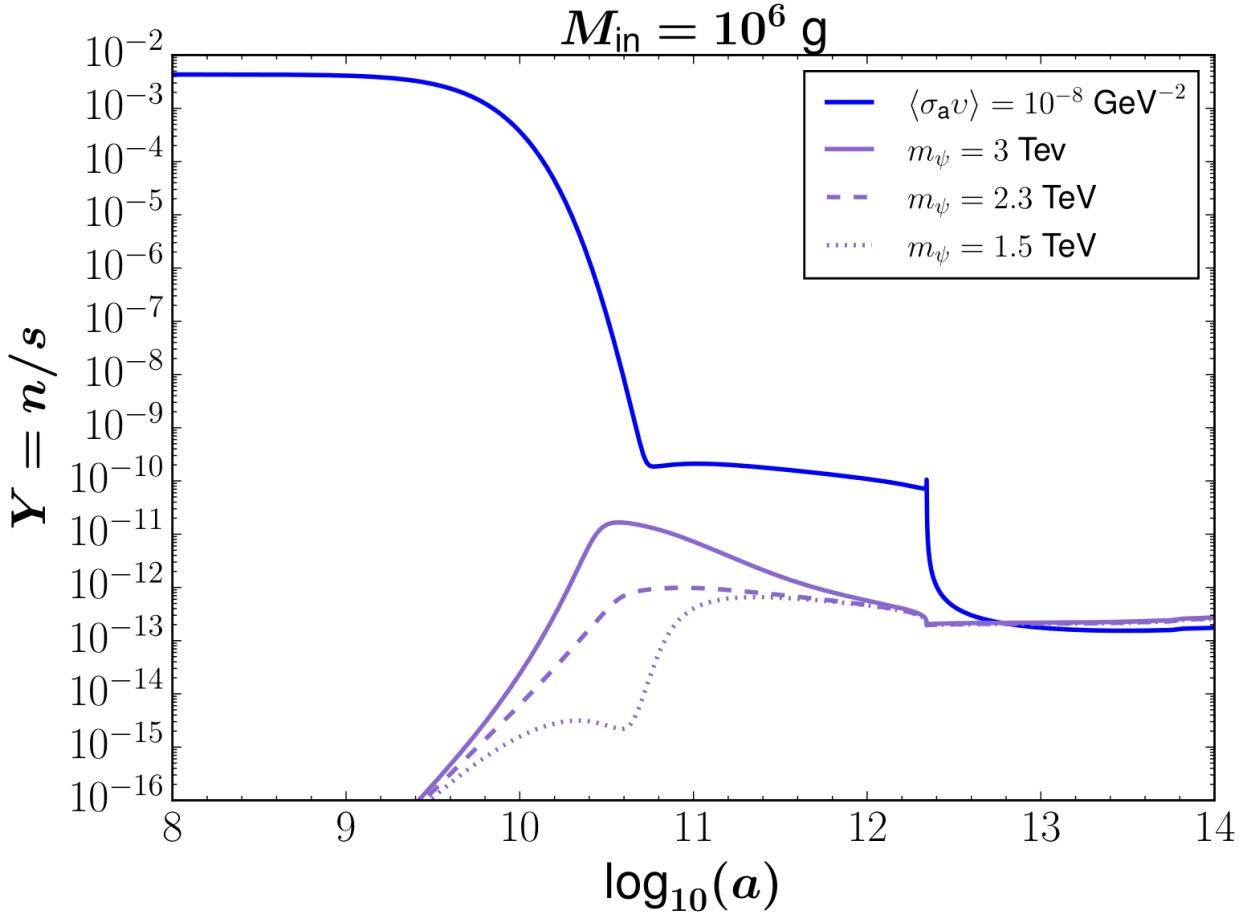
A MODEL WITH WASHOUT EFFECT

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

$$(\psi\bar{u} \to \chi\chi)$$
$$(\bar{u}\chi \to \chi^\dagger\psi^\dagger)$$

[Cui, Randall, Shuve 1112.2704
Bernal, et al. 1210.0094, 1307.6878]





CONCLUSION & OUTLOOK

We consider **a new model of the non-thermal WIMPy baryogenesis with PBH**.

- Non-thermal dark matter can be produced from PBH evaporation and ccan re-annihilate into the lighter particles as the decay rate of non-thermal dark matter is greater than Hubble rate at PBH evaporation time.
- The re-annihilation of DM can satisfy Sakharov conditions and leads to a net baryon asymmetry and the observed DM relic abundance.
- In baryon asymmetry, the washout effect is successfully suppressed.
- The enhancement of the annihilation cross section could be detected in the indirect DM detection.

Thank you!

BACKUP SLIDE:

Evaporation function:

$$\varepsilon_i(z) = -\frac{27 g_i}{8192\pi^5}\int_z^\infty \frac{\Psi_{s_i}(x)(x^2 - z^2)}{e^x - (-1)^{2s_i}} x dx$$

Definition of the ratio of the absorption cross section to the geometrical optics limit:

$$\Psi_{s_i}(E) = \frac{\sigma_{s_i(E)}}{27\pi G^2 M_{BH}^2}$$

The momentum-integrated emission rate :

$$\Gamma_{\mathrm{BH}\to\chi} = \int dp \frac{d^2 N_\chi}{dp\ dt} = \frac{27 g_i}{512\pi^4}\frac{M_p^2}{M_{\mathrm{BH}}}[z\ Li_2(e^{-z}) + Li_3(e^{-z})]$$

$$z = m_{\mathrm{DM}}/T_{\mathrm{BH}}$$