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Non-thermal WIMPy Baryogenesis with Primordial Black Hole

Based on arXiv: 2309.16122

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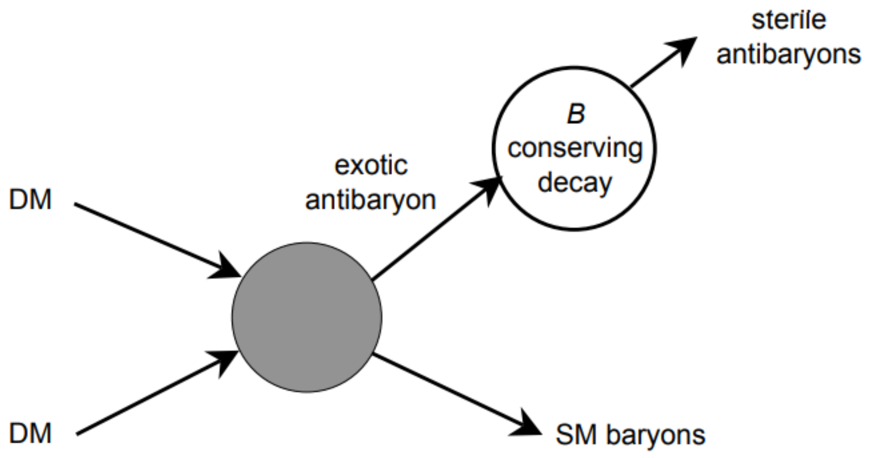
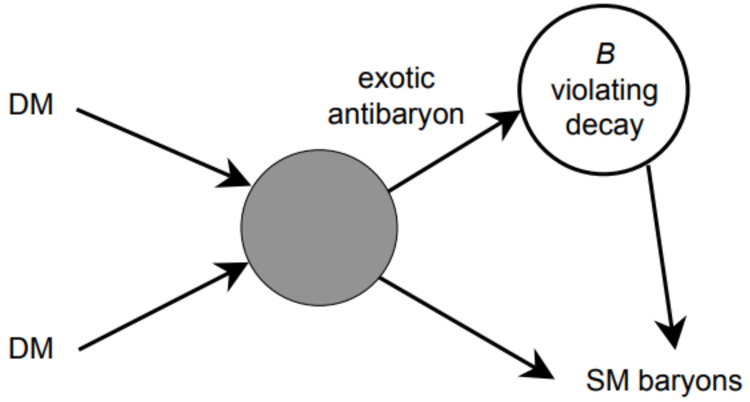
INTRODUCTION: WIMPY BARYOGENESIS

- ☐ **The particle nature of DM is not yet known.**
- ☐ **The SM fails to satisfy Sakharov's condition to generate BAU.**





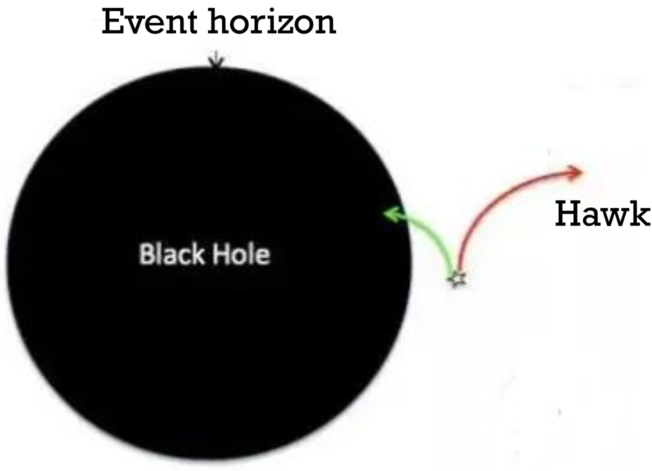
[Cui, Randall, Shuve, JHEP 1204 (2012) 075]

- ✓ 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 DM annihilation is directly responsible for Baryon Asymmetry.

PRESENCE OF PBH

- PBH could have produced in the early Universe due the collapse of large density perturbations during the radiation dominated era at the end of inflation. [Carr, et al. 2002.12778]



$$R_s = 2GM_{PBH}$$

"Particle Factory"

Hawking radiation → **SM**, **BSM**

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

Initial mass of the PBH is evaluated as :

$$M_{\rm in} = \gamma M_{\rm H} = \gamma M_p^2 t_{\rm in}$$

Numerical factor ~ 0.2 (γ)

Particle horizon mass ($M_{\rm H}$)

Formation time ($t_{\rm in}$)

$$\boxed{M_{\rm in} = \gamma \frac{4\pi}{3} \frac{\rho(T_{\rm in})}{H^3(T_{\rm in})}}$$

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

PBH EVAPORATION

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

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

[HAWKING1974, HAWKING1975]

The rate of PBH mass loss :

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

[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 $(E \gg T_{BH})$:

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

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

PBH evaporation temperature:

$$T_{\rm ev}|_{\rm RD} \simeq 30\ {\rm GeV} \left(\frac{10^6\ {\rm g}}{M_{\rm in}}\right)^{3/2}$$

PBH CONSTRAINTS

- **Upper mass bound :**

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

[Kawasaki, et al. Astro-ph/0002127; Hannestad 0403291]

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

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

- **Lower mass bound :**

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

[Planck 2018]

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

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

- **The initial energy density of PBHs normalized to the radiation energy density:** $\left(\beta = \frac{\rho_{\rm PBH}}{\rho_{\rm rad}}\right)$

$$\beta < 1.1\times10^{-6} \left(\frac{0.2}{\gamma}\right)^{1/2} \left(\frac{g_*(T_{\rm BH})}{108}\right)^{17/48} \left(\frac{g_*(T_{\rm ev})}{106.75}\right)^{1/16} \left(\frac{10^4\ {\rm g}}{M_{\rm in}}\right)^{17/24}$$

[Domenech, Lin, Sasaki, JCAP 04(2021)062]

BOLTZMANN EQUATIONS

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

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

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

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

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

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

The fraction of SM particles from evaporation

The momentum-integrated emission rate

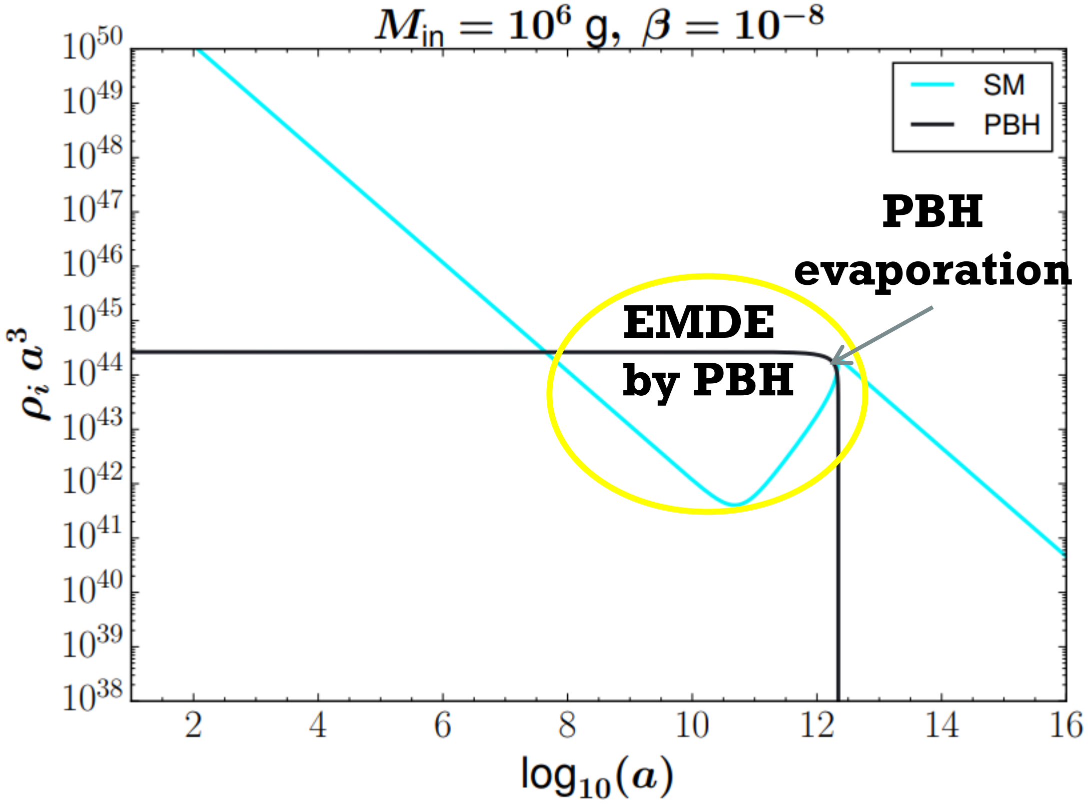
DM annihilation cross-section

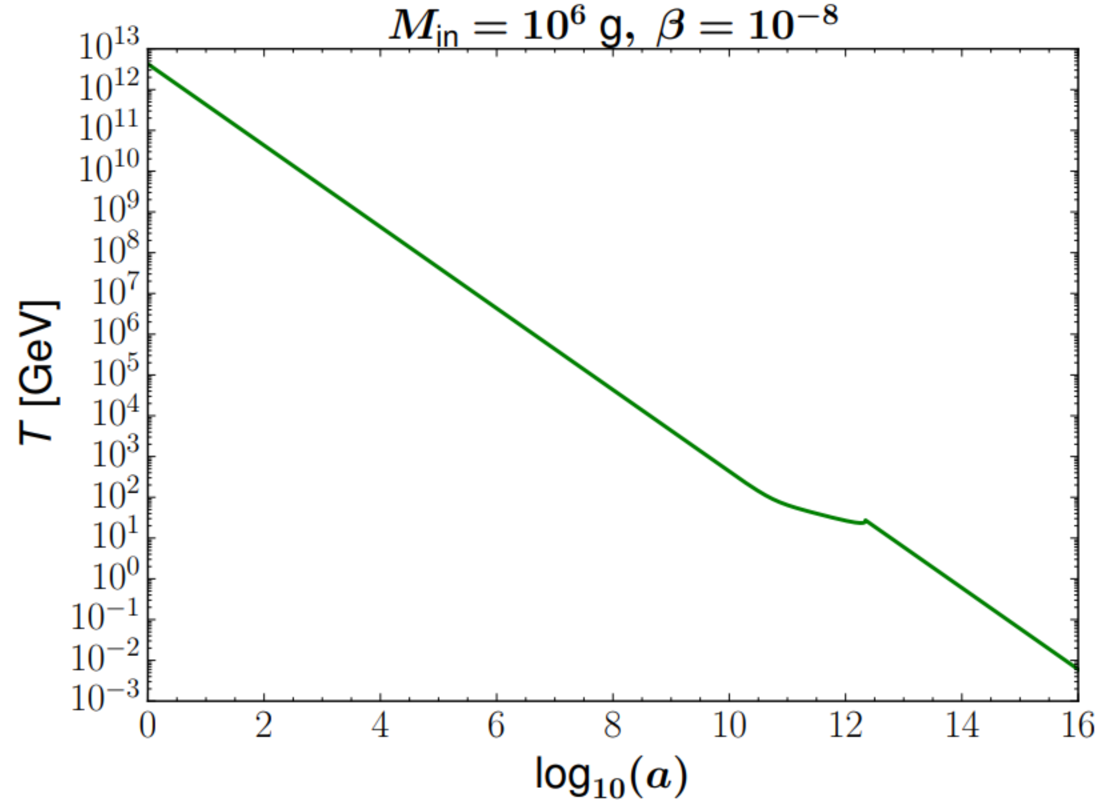
B-number violating cross-section of DM annihilation

Washout process

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

EVOLUTION OF ENERGY DENSITY & TEMPERATURE





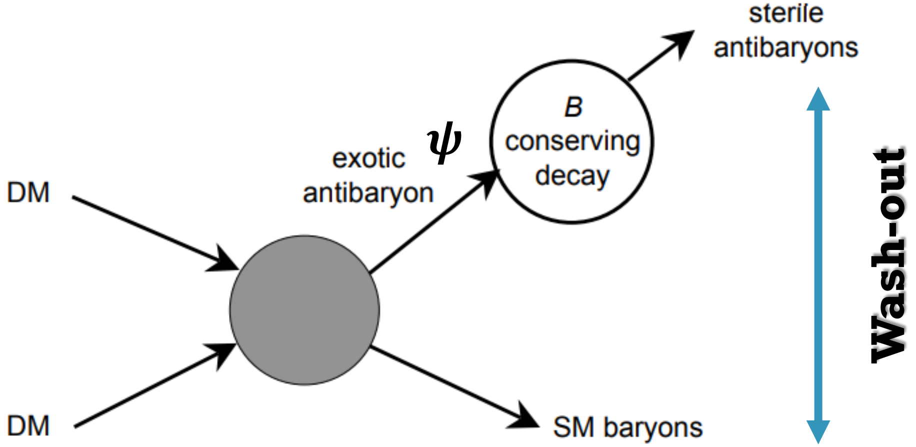
$$\rho_{\rm BH}(T) = \rho_{\rm BH}(T_{\rm in})\left(\frac{a_i}{a}\right)^3 \exp[-\varepsilon(M_{\rm BH})64\pi^2 M_p^4/M_{\rm BH}^3(T - T_{\rm in})] \boxed{\propto a^{-3}}$$

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

NON-THERMAL WIMPY BARYOGENESIS

$$\frac{dn_B}{dt} + 3Hn_B = \epsilon \left\langle \sigma_B v \right\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right) - \langle \sigma_{\mathrm{wo}} v \rangle n_B n_{\psi,\mathrm{eq}}$$

$\boxed{\chi\chi \to \psi\bar{u}}$



$$\epsilon = \frac{\sigma_B(\chi\chi \to \cdots) - \sigma_B(\bar{\chi}\bar{\chi} \to \cdots)}{\sigma_B(\chi\chi \to \cdots) + \sigma_B(\bar{\chi}\bar{\chi} \to \cdots)}$$

$$n_{\psi,\mathrm{eq}} = \frac{g_\psi}{2\pi^2} m_\psi^2 T K_2(m_\psi/T), \quad m_\psi = 3\ \mathrm{TeV}$$

$$\langle \sigma_a v \rangle \geq \langle \sigma_B v \rangle \sim \langle \sigma_{\mathrm{wo}} v \rangle$$

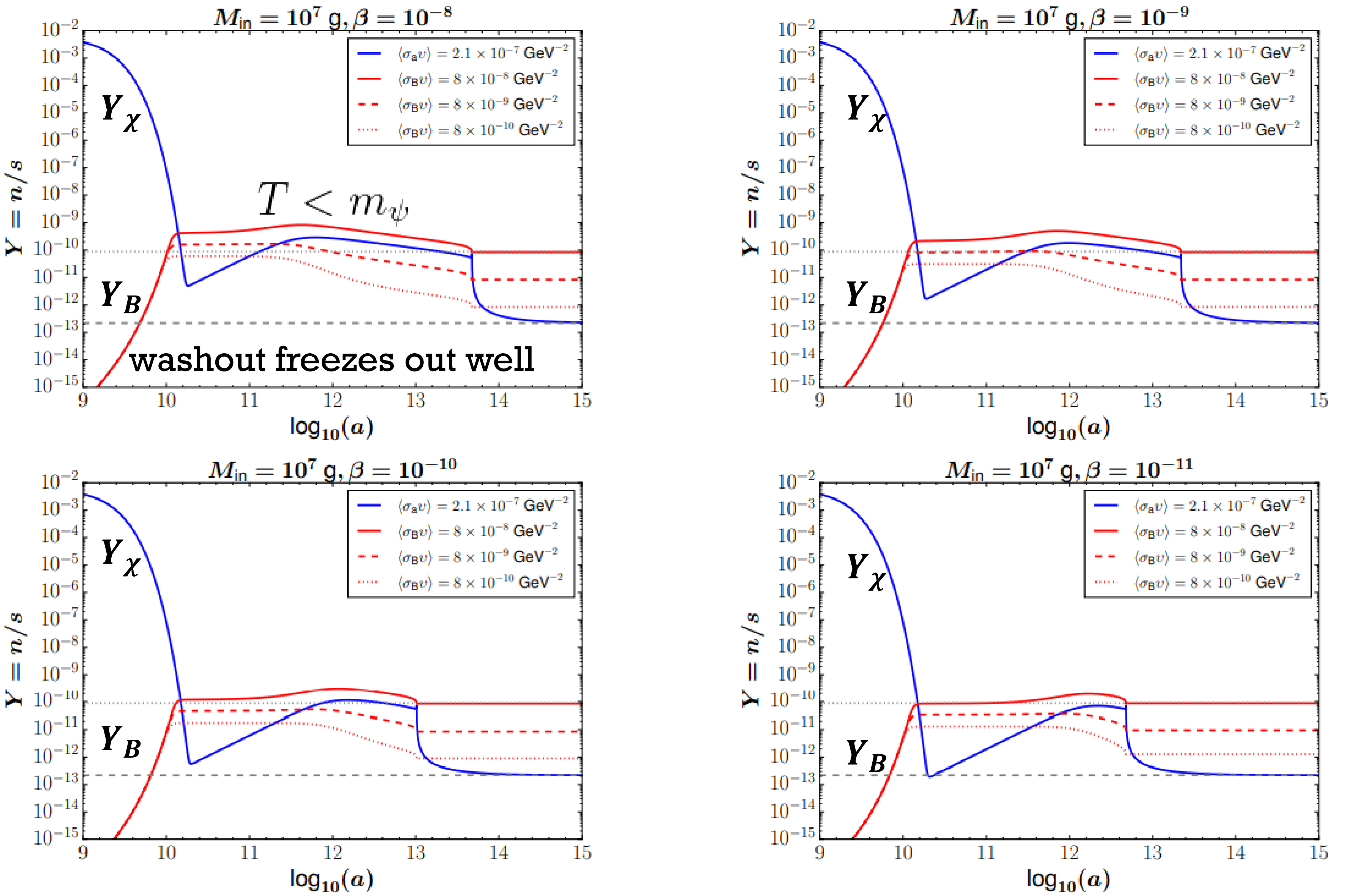
During the EMDE by PBH, ignoring the wash-out effect, the approximate scaling solution for baryon asymmetry can be found as:

$$n_B = \frac{2}{3H} \epsilon \left\langle \sigma_B v \right\rangle n_\chi^2 = \frac{2}{\sqrt{3}} \epsilon \Gamma_{\mathrm{BH}\to\chi} \frac{\langle \sigma_B v \rangle}{\langle \sigma_a v \rangle} \frac{M_p}{M_{\mathrm{BH}}} \sqrt{\rho_{\mathrm{BH}}} \boxed{\propto a^{-3/2}}$$

$$\boxed{Y_B \simeq 8.7 \times 10^{-11} \left(\frac{\epsilon}{0.1}\right) \left(\frac{f_\sigma}{0.15}\right) \left(\frac{100}{g_*(T_{\mathrm{ev}})}\right)^{1/2} \left(\frac{10^6 \mathrm{g}}{M_{\mathrm{in}}}\right)^{1/2}} \quad f_\sigma = \langle \sigma_B v \rangle / \langle \sigma_a v \rangle$$

NON-THERMAL WIMPY BARYOGENESIS

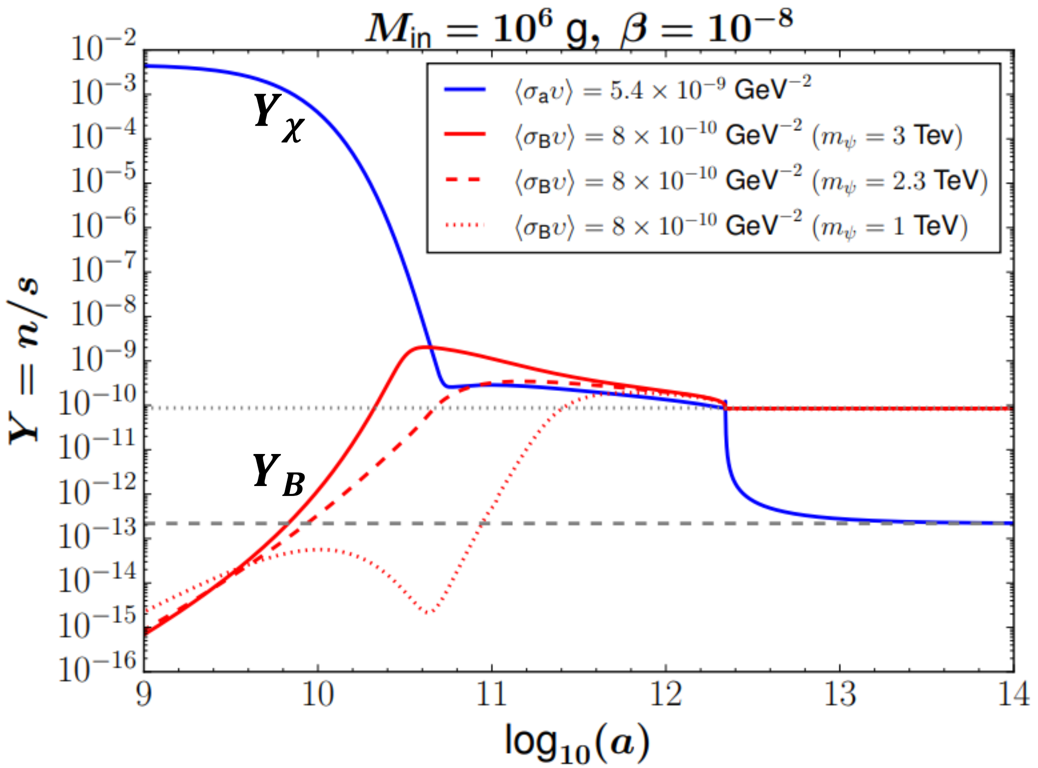
$\epsilon = 0.1$
$m_\psi = 3$ TeV

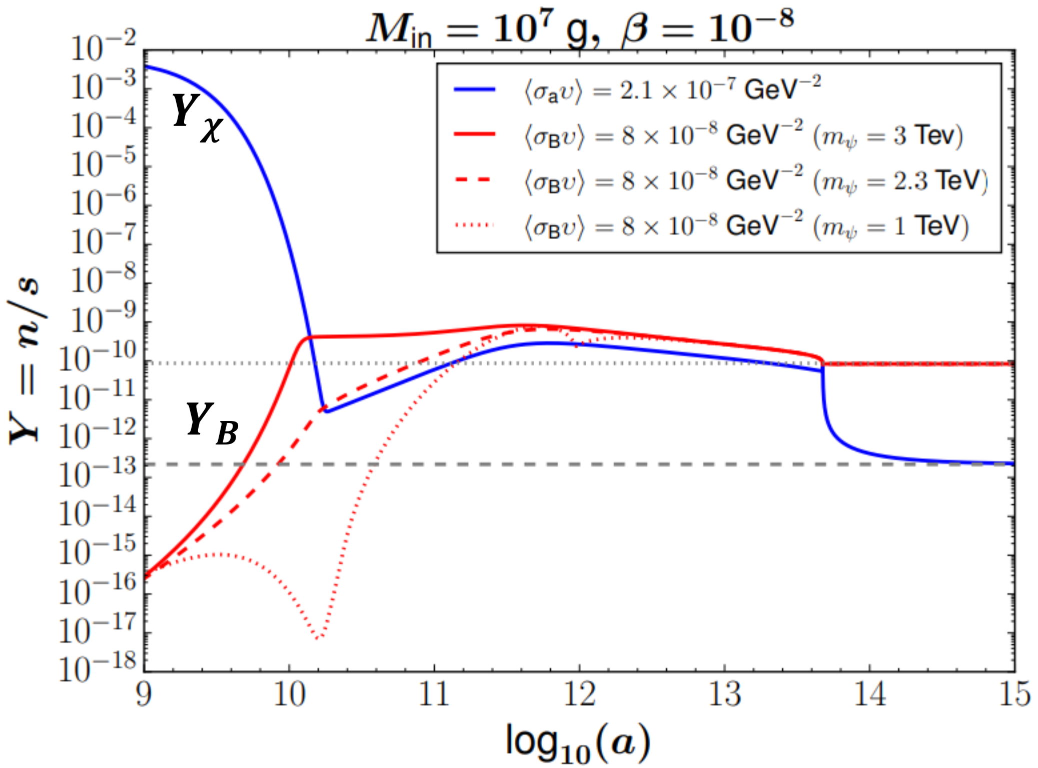


- ❖ β-independent during EMDE

NON-THERMAL WIMPY BARYOGENESIS

The wash-out effect: $T_{\text{ev}} < m_\psi < 2m_{\text{DM}}$

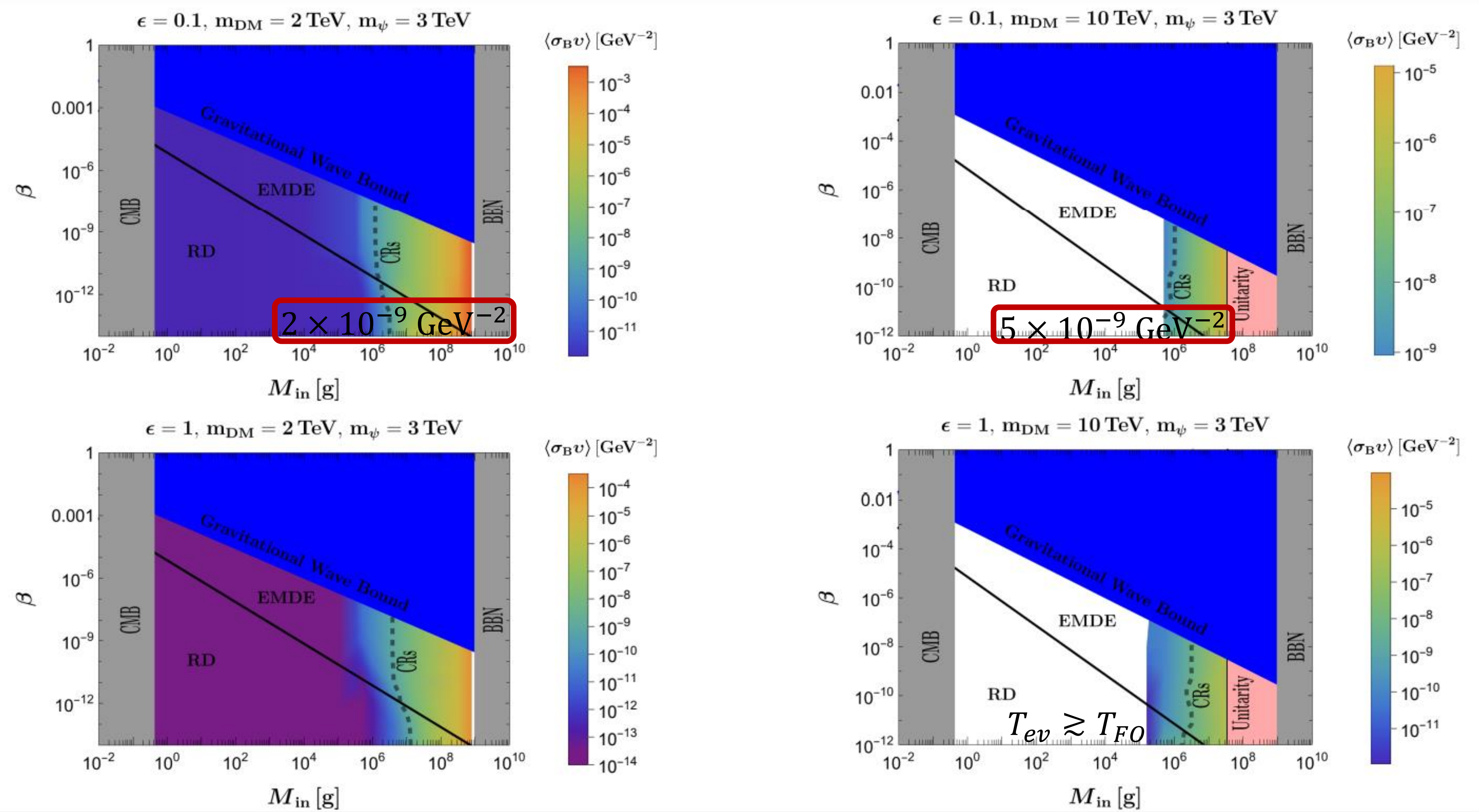




- ❖ The washout effect can be Boltzmann suppressed at large mass of ψ than PBH evaporation temperature
- ❖ The washout is effective before the PBH evaporation time, afterwards the washout is suppressed and Y_B can be sizeable as giving the correct relic for baryon asymmetry.

NON-THERMAL WIMPY BARYOGENESIS

Contour plot of the B-violating annihilation cross section wrt the observed relic abundance for BA:



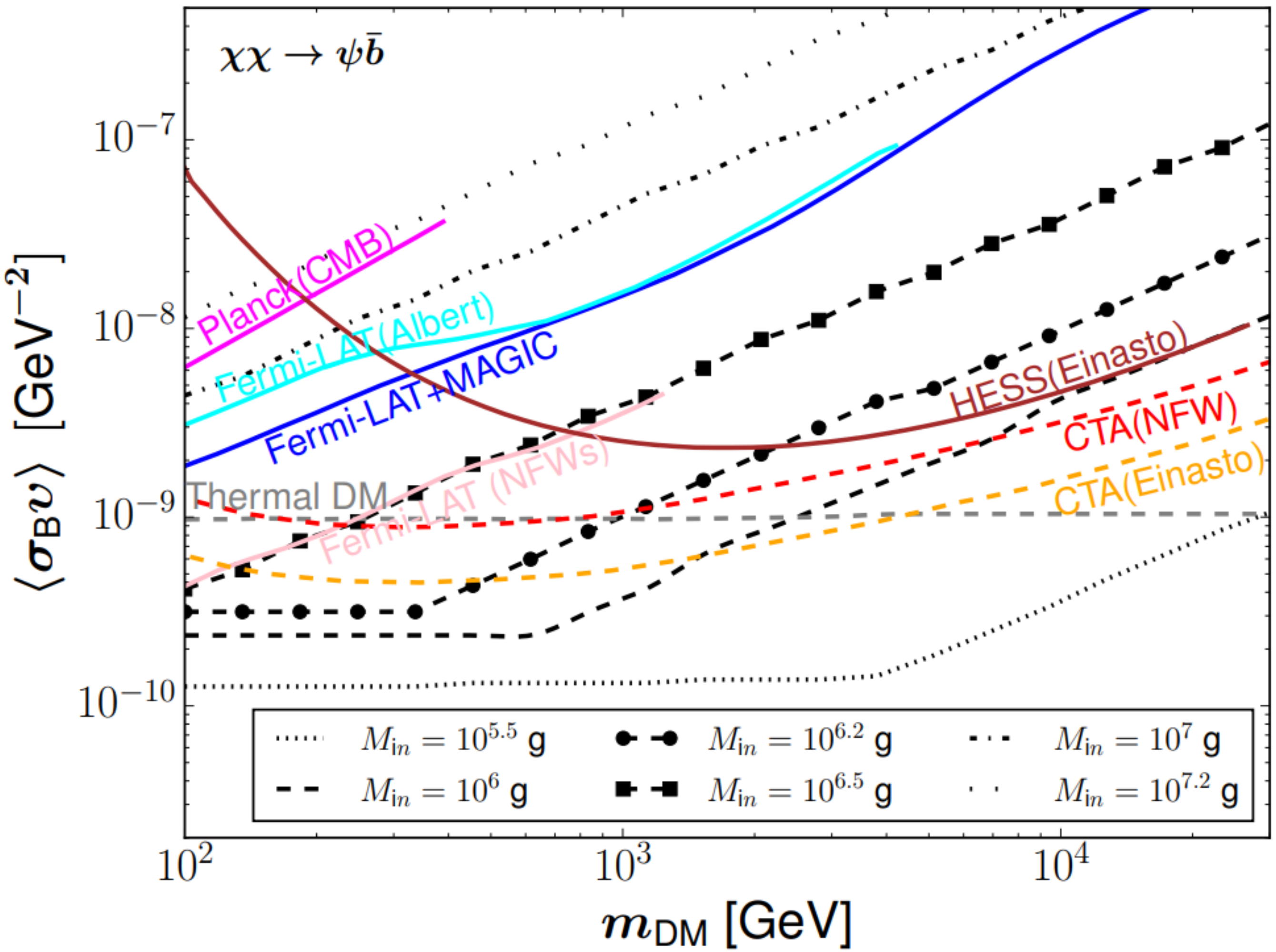
2×10^{-9} GeV^{-2}

5×10^{-9} GeV^{-2}

$T_{ev} \gtrsim T_{FO}$

SIGNALS IN THE INDIRECT DETECTION OF DM

The B-number violating annihilation cross section:



Only one quark is produced from DM annihilation with energy around:

$$E \simeq m_{\rm DM} - \frac{m_\psi^2}{4m_{\rm DM}}$$

CONCLUSION & OUTLOOK

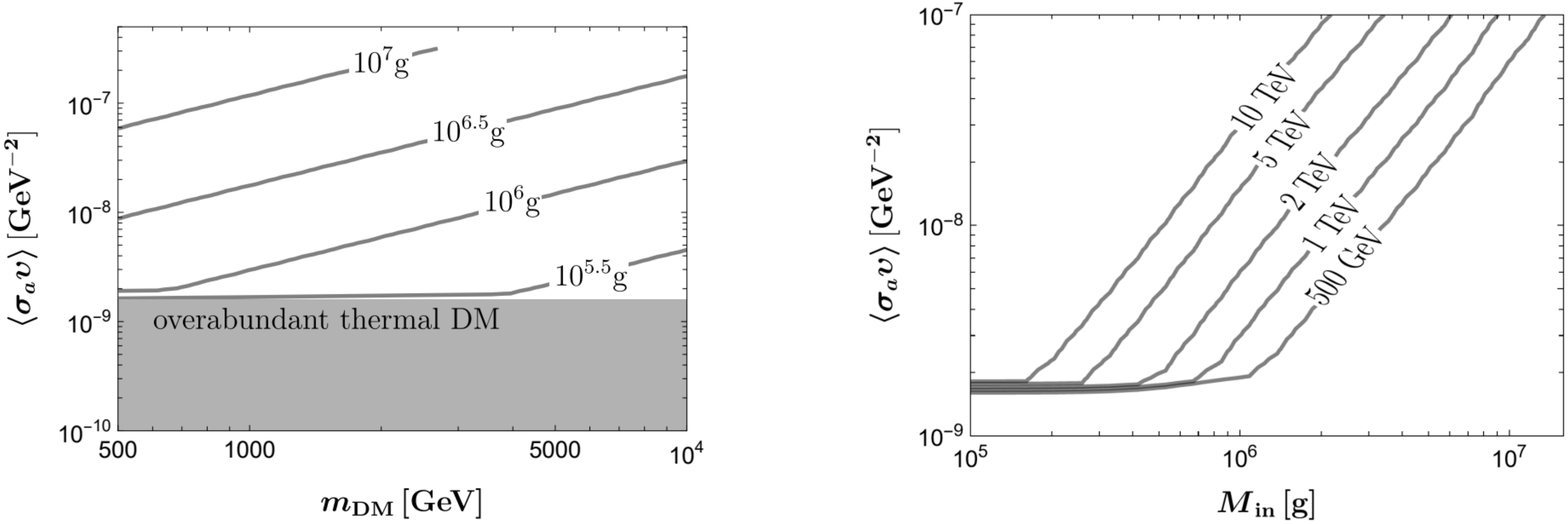
We consider a new model of non-thermal WIMPy baryogenesis with PBH.

- ❖ Non-thermal dark matter can be produced from PBH evaporation.
- ❖ When the decay rate of non-thermal dark matter is greater than Hubble rate at PBH evaporation time, non-thermal DM can re-annihilate into the lighter particles.
- ❖ The re-annihilation of non-thermal DM can satisfy Sakharov conditions and simultaneously explain a net baryon asymmetry and the observed DM relic abundance.
- ❖ In baryon asymmetry, there is an enhancement in the presence of PBH compared to the usual thermal case.
- ❖ PBH with mass less than 10^7g is a good candidate as source of TeV dark matter with the total annihilation cross section $\langle \sigma_a v \rangle \lesssim 10^{-7}\ \mathrm{GeV}^{-2}$, and the B-violating cross section including one quark $\langle \sigma_B v \rangle \lesssim 2 \times 10^{-9}\ \mathrm{GeV}^{-2}$.
- ❖ This upper bound comes from the gamma-ray search produced by DM annihilation in our galaxy.
- ❖ This indirect detection of the gamma-ray or cosmic rays also provide good methods to probe the other parameter space in our model in the near future.

Thank you!

BACKUP: NON-THERMAL DARK MATTER

Contour plot of the correct relic abundance for DM:

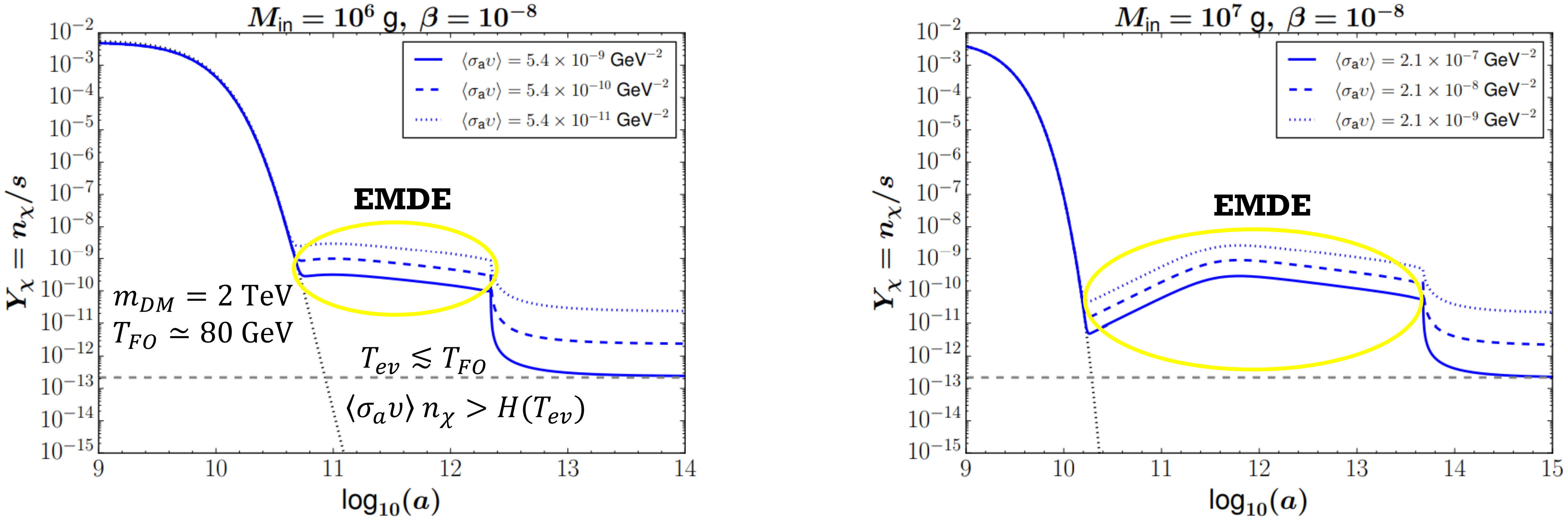


$$\Omega_\chi^{\rm ann} h^2 \simeq 0.115 \sqrt{\frac{100}{g_*(T_{\rm ev})}} \left(\frac{10^{-8}\ {\rm GeV}^{-2}}{\langle\sigma_a v\rangle}\right) \left(\frac{M_{\rm in}}{10^6 {\rm g}}\right)^{3/2} \left(\frac{m_\chi}{2\ {\rm TeV}}\right)$$

- When either PBH or DM masses are light, DM is produced dominantly by the usual thermal FO.

BACKUP: NON-THERMAL DARK MATTER

Relic abundance of DM:



$m_{DM} = 2$ TeV

$T_{FO} \simeq 80$ GeV

$T_{ev} \lesssim T_{FO}$

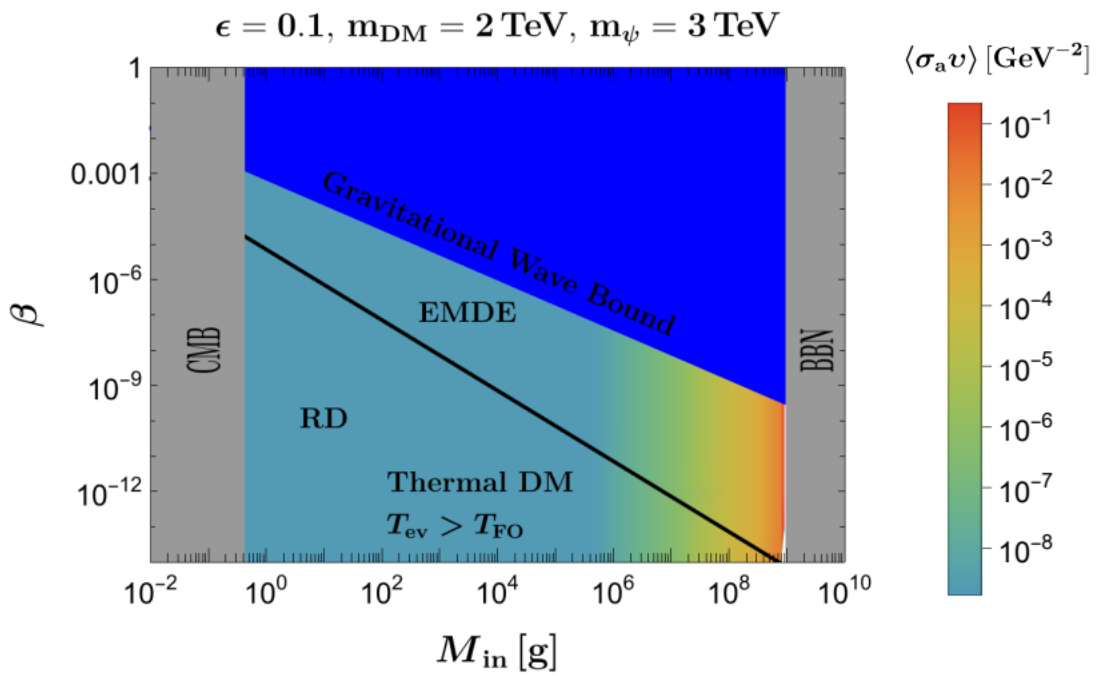
$\langle\sigma_a v\rangle\, n_\chi > H(T_{ev})$

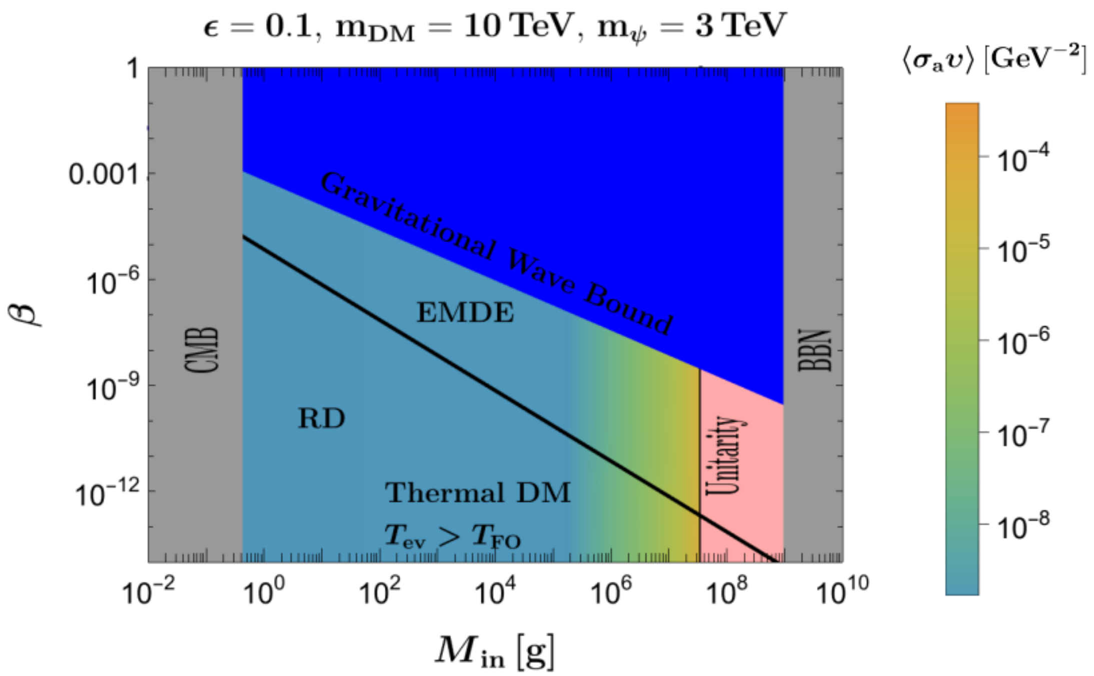
$$Y_\chi = \frac{n_\chi + n_{\bar\chi}}{s} \sim \frac{a^{-3/2}}{T^3} \boxed{\propto a^{-3/8}}$$

- ❖ Thermally produced DMs are already frozen
- ❖ The non-thermal DMs produced from PBH evaporation can re-annihilate into light particles
- ❖ PBH-dominated epoch lasts longer when the initial mass of PBHs increases

NON-THERMAL WIMPY BARYOGENESIS

Contour plot of total annihilation cross section wrt the correct relic abundance for DM:





The unitarity bound on the total annihilation cross section of DM:

[Griest, Kamionkowski, PRL. 64 (Feb, 1990)]

$$(\sigma v_{\rm rel})_{\rm max} = \frac{4\pi}{m_{\rm DM}^2 v_{\rm rel}} \qquad v_{\rm rel} = \sqrt{2T_{\rm ev}/m_{\rm DM}}$$