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Composite Asymmetric Dark Matter from Primordial Black Holes

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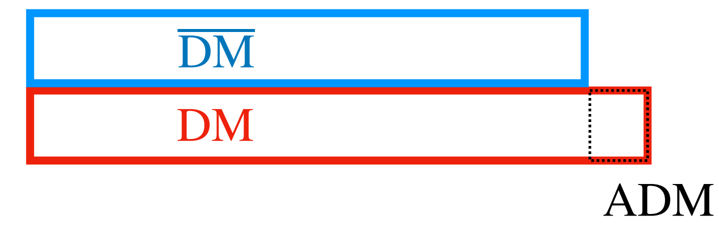
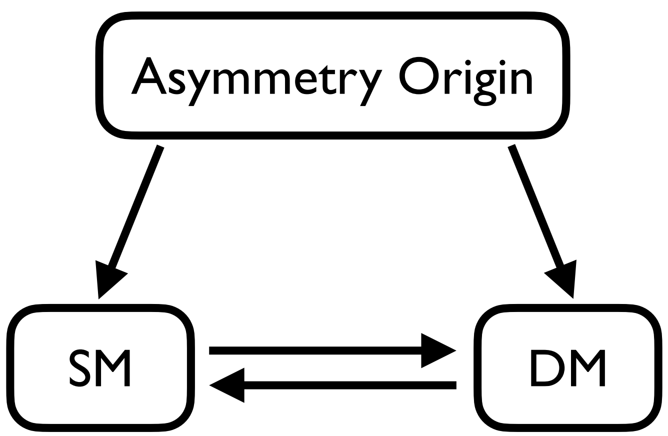
Asymmetric Dark Matter

Nushinov (1985), Barr Chivukula Farhi (1990), D.B.Kaplan (1992), Kuzmin (1998), Kitano Low (2005), D. E. Kaplan Luty Zurek (2009)

✓ particle-antiparticle asymmetries



$$\eta_B \equiv \frac{n_B - \bar{n}_B}{n_\gamma} \quad \text{and} \quad \eta_{\mathrm{DM}} \equiv \frac{n_{\mathrm{DM}} - \bar{n}_{\mathrm{DM}}}{n_\gamma}$$



- baryogenesis (leptogenesis) and sharing mechanism (or dark-genesis)
- cogenesis

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_B} = \frac{m_{\mathrm{DM}}\,\eta_{\mathrm{DM}}}{m_B\,\eta_B} \sim 5$$: DM mass ~ O(1) GeV

✓ Weak constraints from astrophysical/cosmological constraints

No anti-DM particles in the late-time Universe

-> No production of SM particles via pair annihilation

and consistent with the constraints from BBN/CMB/cosmic-ray

Why Compositeness?

ADM scenarios require

- large annihilation cross section
- DM mass O(1) GeV
- DM number conservation

SM baryons have

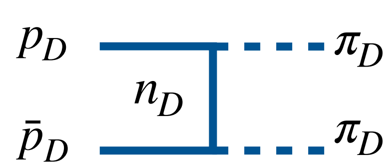
✓ large annihilation into pion

✓ nucleon with mass of 1GeV

✓ Baryon number conservation

Dark QCD seems to be a good candidate of ADM

- dark-baryon efficiently depleted into dark-pion



$$\sigma v \sim \frac{4\pi}{m_{n_D}^2}$$

- DM mass : dimensional transmutation
- DM number = dark baryon number

‣ How to generate an asymmetry and to share the asymmetry?
‣ stable dark pions can be problematic.

Cogenesis of Asymmetries

TK, Y. Uchida (2025)

PBH evaporation (Hawking rad.)

No difference among particles from PBH evap.
(as T_{BH} is larger than their mass)

SM Sector

Dark Sector

Baryogenesis

Decay of heavy scalars with C/CPV
=> generation of particle-antiparticle asymmetry

Dark Baryogenesis

$\mathscr{T} \to \bar{u}\bar{d}$

$\mathscr{T}' \to \bar{u}'\bar{d}'$

portal to release excessive entropy in DS (dark pions)

massive dark photon

DM mass is determined by: number densities of heavy scalars and CPV of their decay

$$\frac{m_{\rm DM}}{m_B} = \frac{\rho_{\rm DM}}{\rho_B} \cdot \frac{\eta_B}{\eta_{\rm DM}} = 5.45 \frac{\varepsilon_{\mathscr{T}} \rho_{\mathscr{T}} m_{\mathscr{T}'}}{\varepsilon_{\mathscr{T}'} \rho_{\mathscr{T}'} m_{\mathscr{T}}}$$

PBH Evaporation

The PBH initial mass

$$M_{\rm BH}^{\rm in} = \gamma \rho_R \frac{4\pi}{3} \frac{1}{H^3}$$

H: Hubble parameter

ρ_R: energy density of radiation

γ: numerical factor ~ 0.2 (formation)

Plasma temperature at PBH formation: $3M_{\rm Pl}^2 H^2 = \rho_R$

$$T_{\rm in} \simeq 1.3 \times 10^{12}\ {\rm GeV} \left(\frac{106.75}{g_{*\rho}}\right)^{1/4} \left(\frac{10^7\ {\rm g}}{M_{\rm BH}^{\rm in}}\right)^{1/2}$$

PBH mass-loss function

$$\frac{{\rm d}M_{\rm BH}}{{\rm d}t} = -5.34 \times 10^{25}\, \epsilon(M_{\rm BH}) \left(\frac{1{\rm g}}{M_{\rm BH}}\right)^2\ {\rm g\, s^{-1}}$$

Evaporation function $\epsilon(M_{\rm BH})$

J. H. McGibbons, B. R. Webber (1990)
J. H. McGibbons (1991)

c.f.) Black-body radiation

$$\frac{{\rm d}E}{{\rm d}t} = -\sigma_S A T^4$$

$\sigma_S = \dfrac{\pi^2}{60}$: Stefan-Boltzmann constant

BH case,

$$E = M_{\rm BH}, \quad A = 4\pi r_s^2 = 16\pi \left(\frac{M_{\rm BH}^2}{M_{\rm Pl}^4}\right), \quad T = T_{\rm BH} = \frac{M_{\rm Pl}^2}{M_{\rm BH}}$$

light PBH: hot and efficiently radiates

Coupled Boltzmann equations for energy densities

$$\begin{cases} aH\dfrac{\mathrm{d}\varrho_{\mathrm{R},i}}{\mathrm{d}a} = -f_{\mathrm{R},i}\dfrac{\mathrm{d}\ln M_{\mathrm{BH}}}{\mathrm{d}t}a\varrho_{\mathrm{BH}} \\ aH\dfrac{\mathrm{d}\varrho_{\mathrm{BH}}}{\mathrm{d}a} = \dfrac{\mathrm{d}\ln M_{\mathrm{BH}}}{\mathrm{d}t}\varrho_{\mathrm{BH}} \\ H^2 = \dfrac{1}{3M_{\mathrm{Pl}}^2}\left(\dfrac{\varrho_{\mathrm{BH}}}{a^3} + \dfrac{\sum_i \varrho_{\mathrm{R},i}}{a^4}\right) \end{cases}$$

Comoving energy density

$$\varrho_{\mathrm{R},i} = a^4\rho_{\mathrm{R},i}\,, \quad \varrho_{\mathrm{BH}} = a^3\rho_{\mathrm{BH}}$$

$$\rho_{\mathrm{R},i} = \{\rho_{\mathrm{SM}}, \rho_T, \rho_{T'}, \rho_{\mathrm{DM}}\}$$

Ratio of evaporation functions:

$$f_{\mathrm{R},i} = \frac{\{\epsilon_{\mathrm{SM}}, \epsilon_T, \epsilon_{T'}, \epsilon_{\mathrm{DM}}\}}{\epsilon_{\mathrm{tot}}}$$

Evaporation function $\epsilon(M_{\mathrm{BH}})$ J. H. McGibbons, B. R. Webber (1990), J. H. McGibbons (1991)

$$\epsilon_{\mathrm{tot}}(M_{\mathrm{BH}}) = \epsilon_{\mathrm{SM}}(M_{\mathrm{BH}}) + \epsilon_{\mathrm{DS}}(M_{\mathrm{BH}}) + \epsilon_H(M_{\mathrm{BH}})$$

$$\epsilon_{\mathrm{SM}}(M_{\mathrm{BH}}) = 2f_1 + 2\times 3f_{1/2}^0 + 2\times 2f_{1/2}^1\left(\sum_\ell e^{-\frac{1}{\beta_{1/2}}\frac{m_\ell}{T_{\mathrm{BH}}}} + 3\sum_q e^{-\frac{1}{\beta_{1/2}}\frac{m_q}{T_{\mathrm{BH}}}}\right)$$
$$+2\times 8f_1 e^{-\frac{1}{\beta_1}\frac{m_g}{T_{\mathrm{BH}}}} + 3f_1\left(2e^{-\frac{1}{\beta_1}\frac{m_W}{T_{\mathrm{BH}}}} + e^{-\frac{1}{\beta_1}\frac{m_Z}{T_{\mathrm{BH}}}}\right) + f_0 e^{-\frac{1}{\beta_0}\frac{m_h}{T_{\mathrm{BH}}}}$$

$$\epsilon_{\mathrm{DS}}(M_{\mathrm{BH}}) = 12f_{1/2}^1\sum_{q'} e^{-\frac{m_{q'}}{\beta_{1/2}T_{\mathrm{BH}}}} + 16f_1\, e^{-\frac{m_{g'}}{\beta_1 T_{\mathrm{BH}}}} + 3f_1\, e^{-\frac{m_{A'}}{\beta_1 T_{\mathrm{BH}}}} + f_0\, e^{-\frac{m_{H'}}{\beta_0 T_{\mathrm{BH}}}}$$

$$\epsilon_H(M_{\mathrm{BH}}) = 6f_0\, e^{-\frac{m_{\mathcal{T}}}{\beta_0 T_{\mathrm{BH}}}} + 6f_0\, e^{-\frac{m_{\mathcal{T}'}}{\beta_0 T_{\mathrm{BH}}}}$$

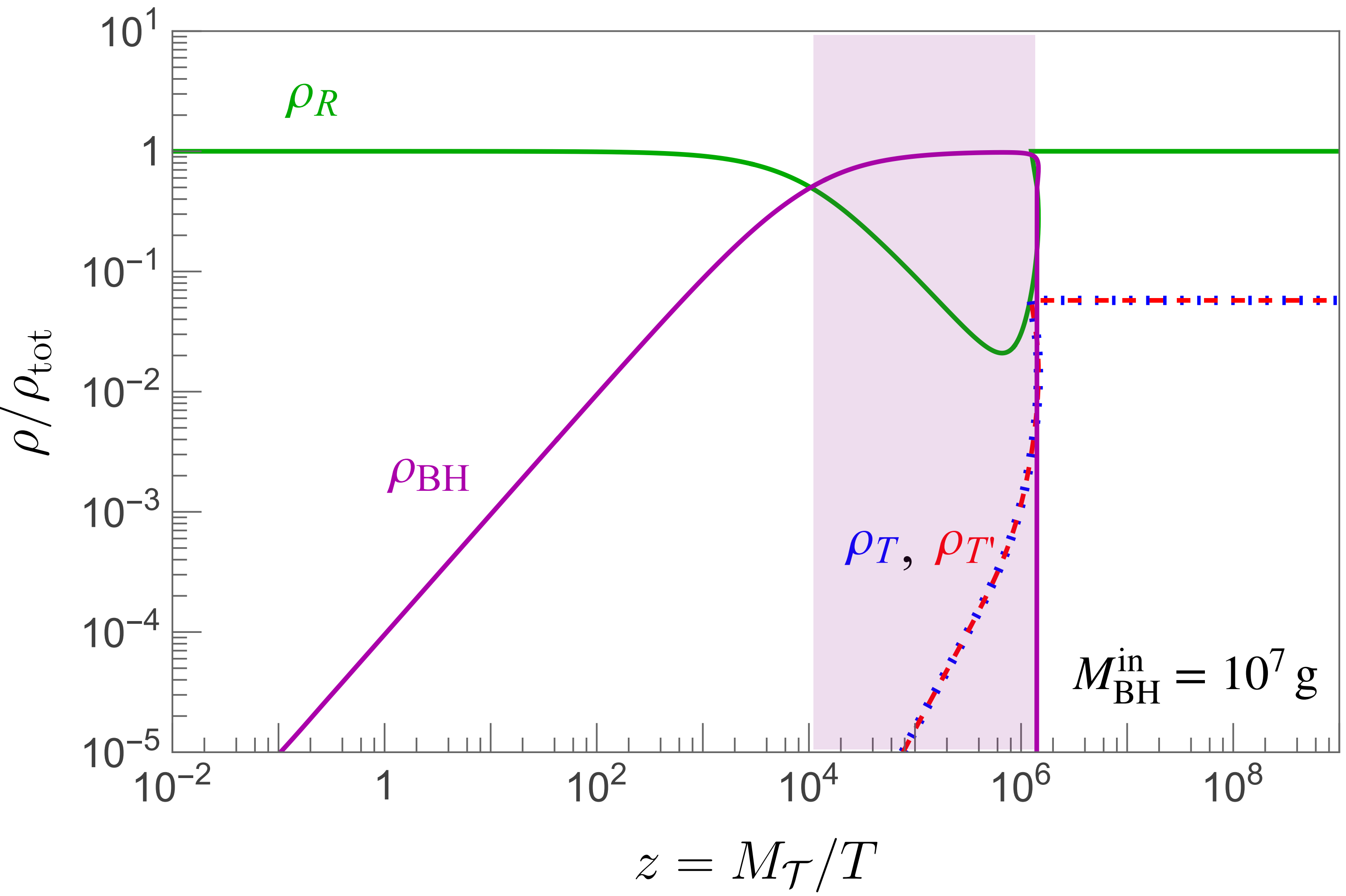
$$\beta_i = \begin{cases} 2.66 & (s=0) \\ 4.53 & (s=1/2) \\ 6.04 & (s=1) \end{cases}$$

$$f_s = \begin{cases} 0.267 & (s=0) \\ 0.060 & (s=1) \end{cases}$$

$$f_{1/2}^q = \begin{cases} 0.147 & (q=0:\text{neutral}) \\ 0.142 & (q=1:\text{charged}) \end{cases}$$

Particles start to be emitted once BH temperature exceeds its mass

Early PBH dominant Epoch



The initial ratio of densities: $\beta \equiv \rho_{\rm BH}(T_{\rm in})/\rho_R(T_{\rm in})$

Choose β so that PBH dominates the universe;

$$\beta \simeq \frac{T_{\rm RH}}{T_{\rm in}} \frac{\rho_{\rm BH}(T_{\rm RH})}{\rho_R(T_{\rm RH})} \gtrsim \beta_{\rm min} \simeq 3 \times 10^{-12} \left(\frac{10^6\,{\rm g}}{M_{\rm BH}^{\rm in}} \right) \left(\frac{g_{*\rho}}{106.75} \right)^{1/2}$$

approx $T_{\rm RH}$

$$T_{\rm RH} \simeq \left(\frac{90\, g_{*\rho}}{10240} \right)^{1/4} \frac{M_{\rm Pl}^{5/2}}{(M_{\rm BH}^{\rm in})^{3/2}}$$

Temperature and Entropy

Plasma is reheated by BH evaporation:

$$\Delta \equiv 1 + \frac{T}{3 g_s(T)} + \frac{\mathrm{d} g_s(T)}{\mathrm{d} T}$$

$$aH \frac{\mathrm{d}T}{\mathrm{d}a} = -\frac{T}{\Delta} \left\{ H + \frac{\epsilon_{\rm SM}(M_{\rm BH})}{\epsilon_{\rm tot}(M_{\rm BH})} \frac{\mathrm{d} \ln M_{\rm BH}}{\mathrm{d}t} \frac{g_\rho(T)}{g_s(T)} \frac{a \varrho_{\rm BH}}{4 \varrho_{\rm R}} \right\}$$

expansion of universe

PBH evaporation

mass-loss function

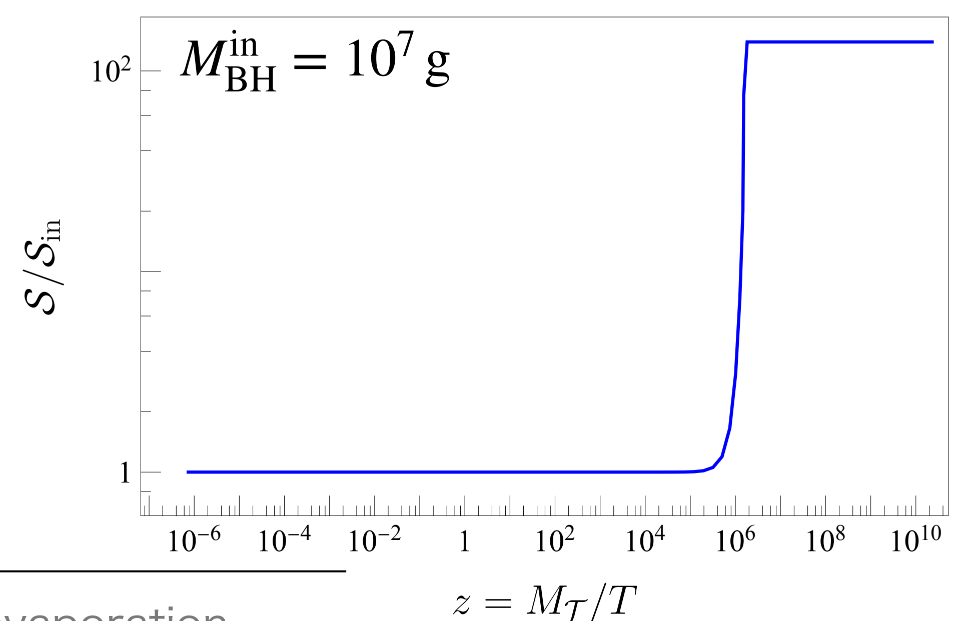
$$\frac{\mathrm{d} \ln M_{\rm BH}}{\mathrm{d}t} < 0$$

resists temperature decrease by the Universe expansion

comoving entropy density:

$$\frac{\mathrm{d}\mathcal{S}}{\mathrm{d}t} = - f_{\rm SM} \frac{\mathrm{d} \ln M_{\rm PBH}}{\mathrm{d}t} \frac{\varrho_{\rm PBH}}{T}$$

$$\mathcal{S} = a^3 s \qquad s = \frac{2\pi^2}{45} g_s T^3$$



$\mathcal{S}$ is conserved when there is no source for injecting entropy

- positive contribution from PBH evap.

$$\frac{\mathrm{d} \ln M_{\rm BH}}{\mathrm{d}t} < 0$$

- dilute the existing asymmetries

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s}, \quad Y_{\rm DM} \equiv \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{s}$$

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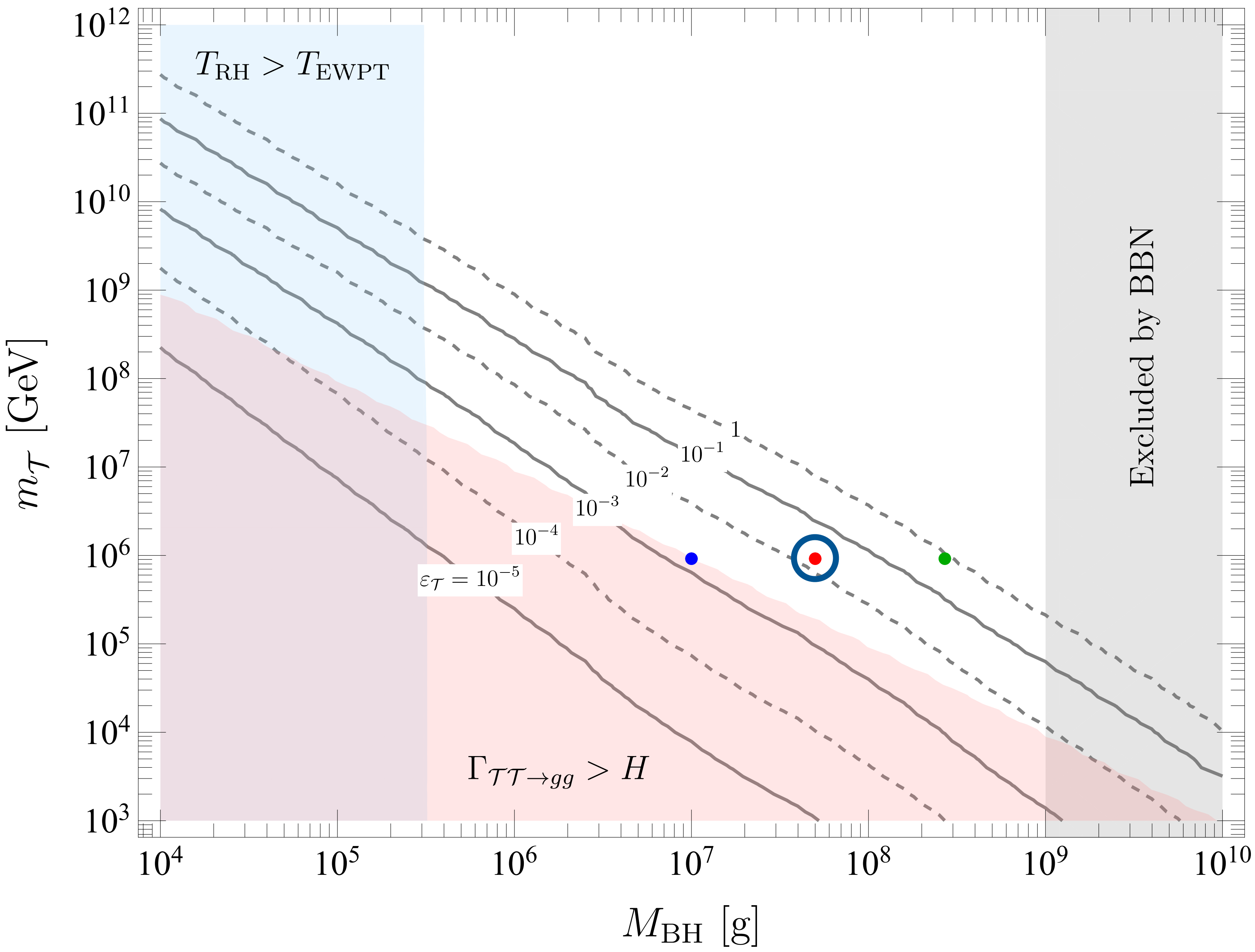
Successful "GUT-like" Baryogenesis

TK, Y. Uchida (2025)



evaporation

- after sphaleron decoupling
- before BBN

final yield

$$Y_B(T) = \frac{\varepsilon_{\mathcal{T}}}{m_{\mathcal{T}}} \frac{\rho_{\mathcal{T}}(T)}{s(T)}$$

$\mathcal{T}$ coupling restricted:

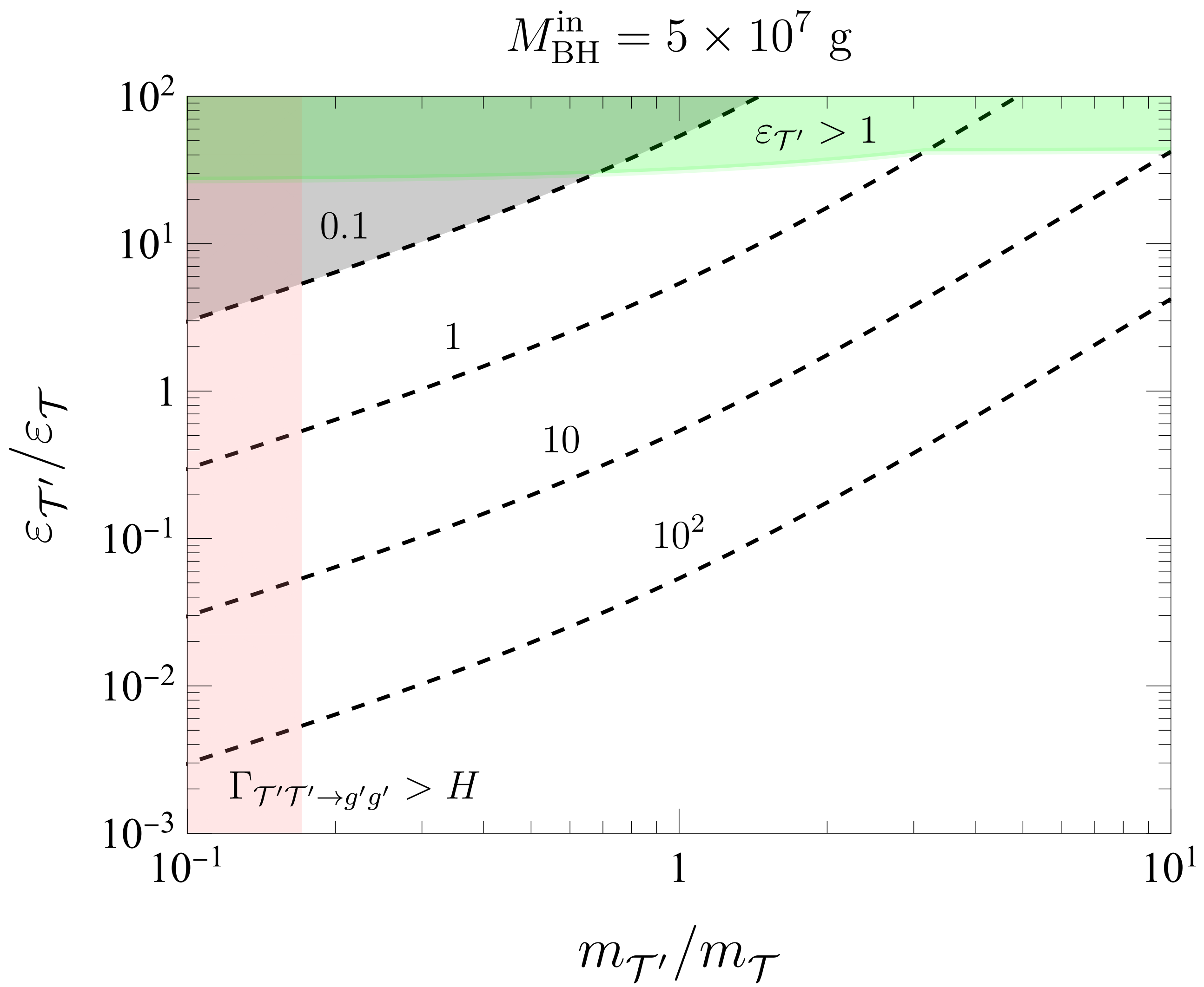
- proton decay (RH/no CKM mixing)

efficient depletion before decay

$$\Gamma(\mathcal{T}\mathcal{T} \to gg)/H > 1$$

Cogenesis of Asymmetries

TK, Y. Uchida (2025)



benchmark point for B# :

$$m_{\mathcal{T}} = 10^6\,\text{GeV}\,,\quad M_{\rm BH}^{\rm in} = 5\times 10^7\,\text{g}\,,$$

$$\varepsilon_{\mathcal{T}} \simeq 5\times 10^{-2}$$

DM mass

$$\frac{m_{\rm DM}}{m_B} = 5.45\frac{\varepsilon_{\mathcal{T}}\rho_{\mathcal{T}}m_{\mathcal{T}'}}{\varepsilon_{\mathcal{T}'}\rho_{\mathcal{T}'}m_{\mathcal{T}}}$$

similarly efficient depletion before decay

$$\Gamma(\mathcal{T}'\mathcal{T}' \to g'g')/H > 1$$

Summary and Discussions

Composite ADM with A' portal

- DM abundance by particle-antiparticle asymmetry
- Compositeness plays crucial role of providing key ingredients for ADM
- dark photon plays a role of releasing entropy in dark sector in early universe

Primordial Black Holes and Composite ADM

- PBH as a source for cogenesis
- CPV decay of heavy scalar particles produces net B# and DM#
- PBH mass of 10^6-10^9 g and Scalar masses of 10^4 - 10^{10} GeV

Backup Slides

Comparison with Hooper-Krnjaic

They integrate the formula below

$$\frac{\mathrm{d}N_{\mathscr{T}}}{\mathrm{d}t} = \pi r_s^2 \mathscr{G} g_H^{\mathscr{T}} \int \frac{\mathrm{d}E}{(2\pi)^3} \frac{4\pi^2 E^2}{e^{E/T_{\mathrm{BH}}} - 1}$$

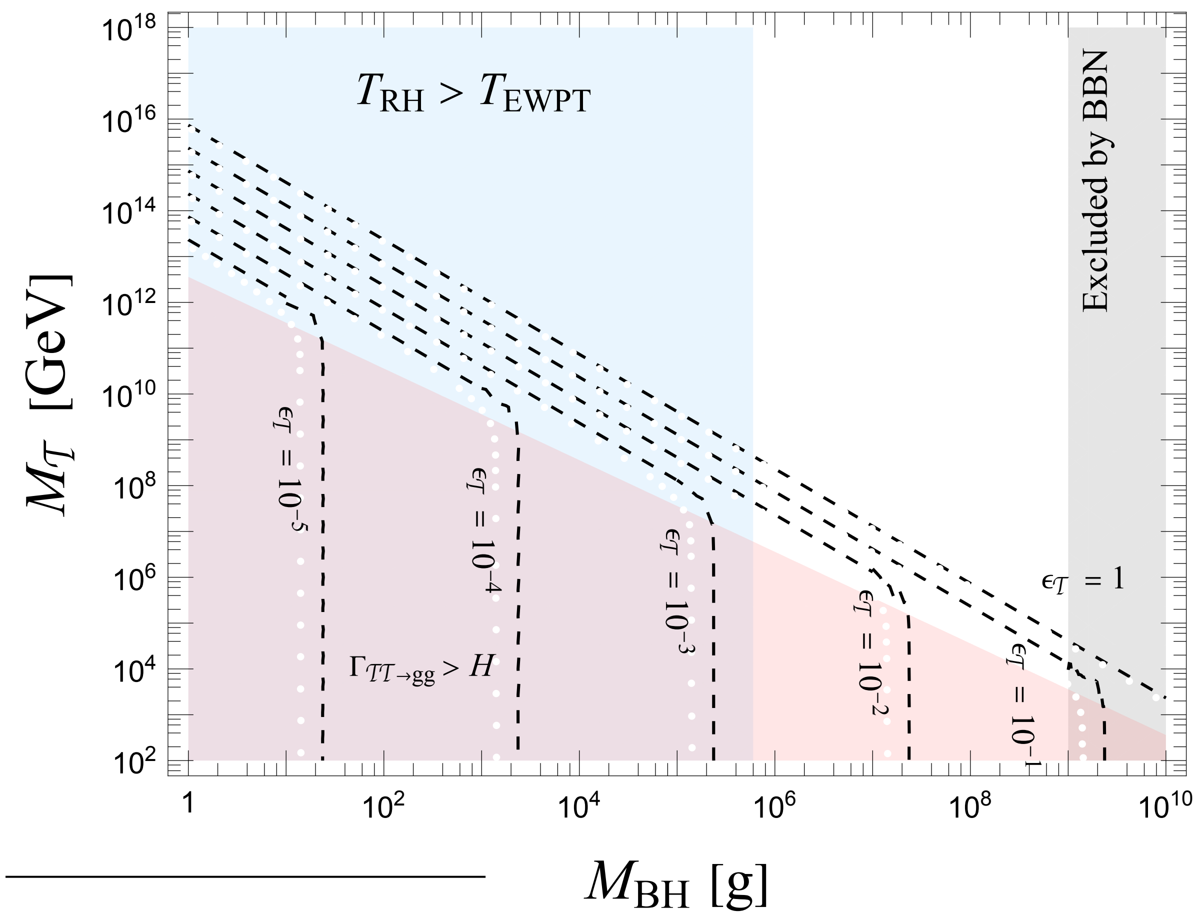
$\mathscr{G}$: graybody factor r_s : Schwarzschild radius

$g_H^{\mathscr{T}}$: the Hawking radiation weight per $\mathscr{T}$

We solve Boltzmann eq.

$$\begin{cases} aH\frac{\mathrm{d}\varrho_{\mathscr{T}}}{\mathrm{d}a} = -f_{\mathscr{T}}\frac{\mathrm{d}\ln M_{\mathrm{BH}}}{\mathrm{d}t}a\varrho_{\mathrm{BH}} \\ \vdots \end{cases}$$

PBH evaporation increases number density $n_{\mathscr{T}}$



PBH evaporation increases energy density $\rho_{\mathscr{T}}$