3rd GUTPC
13th April 2026

Matter-genesis via Heavy Particle Decay from PBHs

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arXiv:2511.16354

Matter Asymmetry

Particle-antiparticle asymmetry:

key for explaining cosmological abundance of particles

- **baryogenesis/leptogenesis**
- **asymmetric dark matter**
- **etc.**

Sakharov's conditions for number asymmetry generation

- C/CP violation
- Particle number violation
- out of thermal equilibrium condition

GUT Baryogenesis

✦ baryon-number asymmetry via GUT-particle decay

$$\eta_B \equiv \frac{n_B - \bar{n}_B}{n_\gamma} \sim 10^{-10}$$

- via decays of extra gauge bosons and extra higgs

✳ very high reheating temperature ~ 10^{16} GeV

✳ washout by sphaleron process (B-L violation required)

alternative scenarios for the heavy particle production

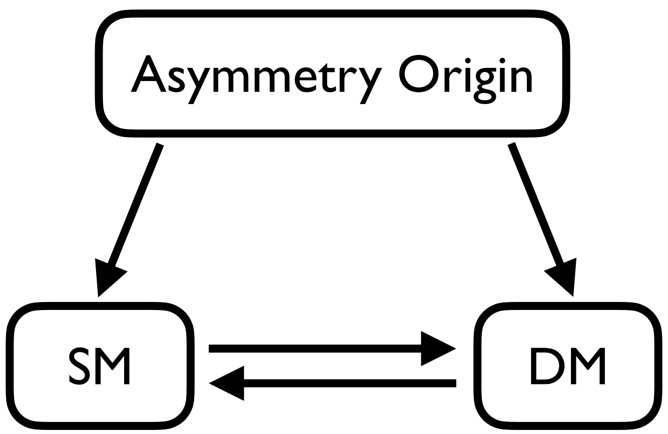
- freeze-in
- inflaton decay
- decay of macroscopic objects (defects, primordial BH)
- etc..

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

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



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

$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_{\rm DM}\,\eta_{\rm DM}}{m_B\,\eta_B} \sim 5$$: 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

Composite Asymmetric DM

ADM scenarios require

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

SM baryons have

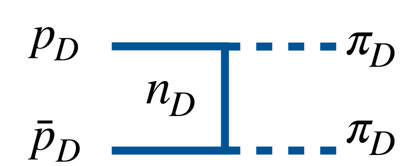
✓ large annihilation into pion

✓ 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

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

Primordial Black Holes

Primordial Black Holes (PBHs) = BHs formed before star formation

How formed? Collapse from/of

- **density inhomogeneities** (primordial fluctuations from inflation)
- **bubble collisions** (1st order phase transition)
- **cosmic string loop/closed domain walls**
- **scalar condensate** (such as Q-ball)
- so on

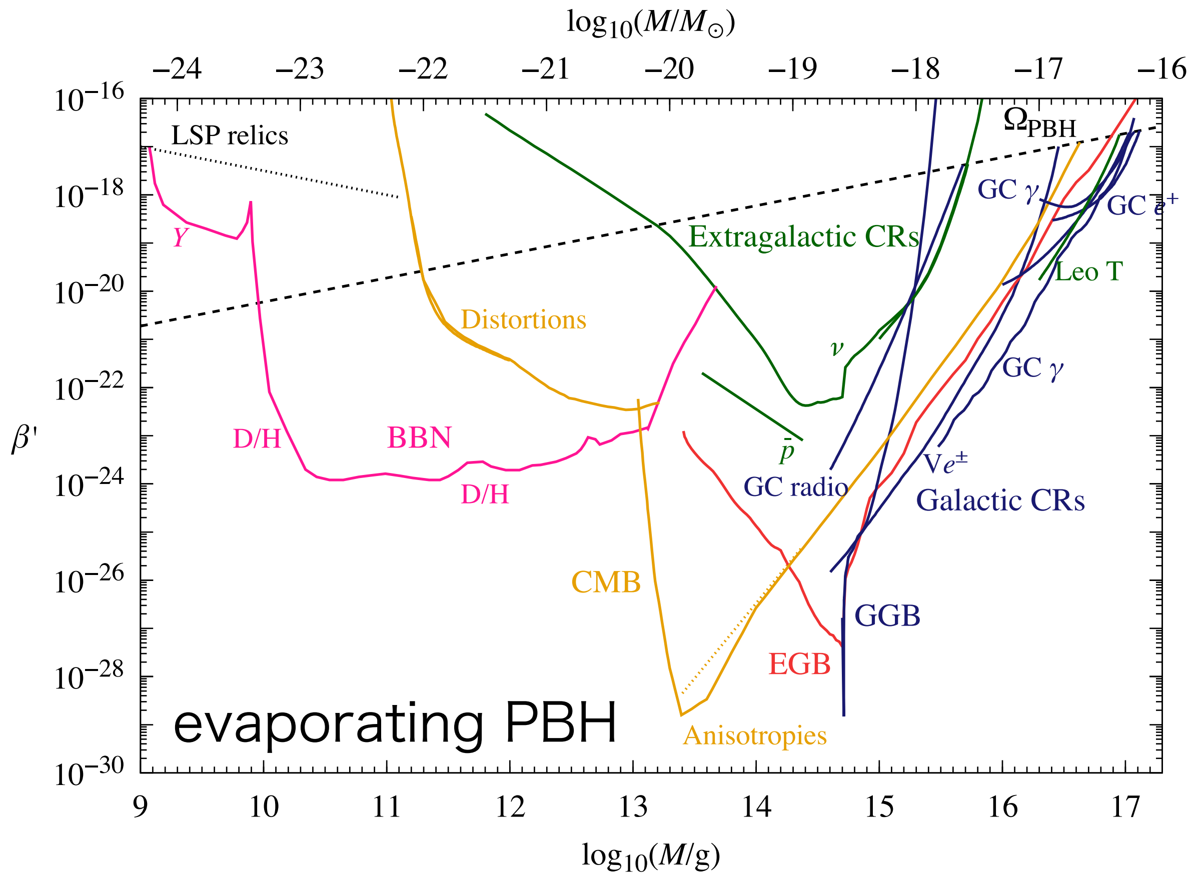
not specified in this talk

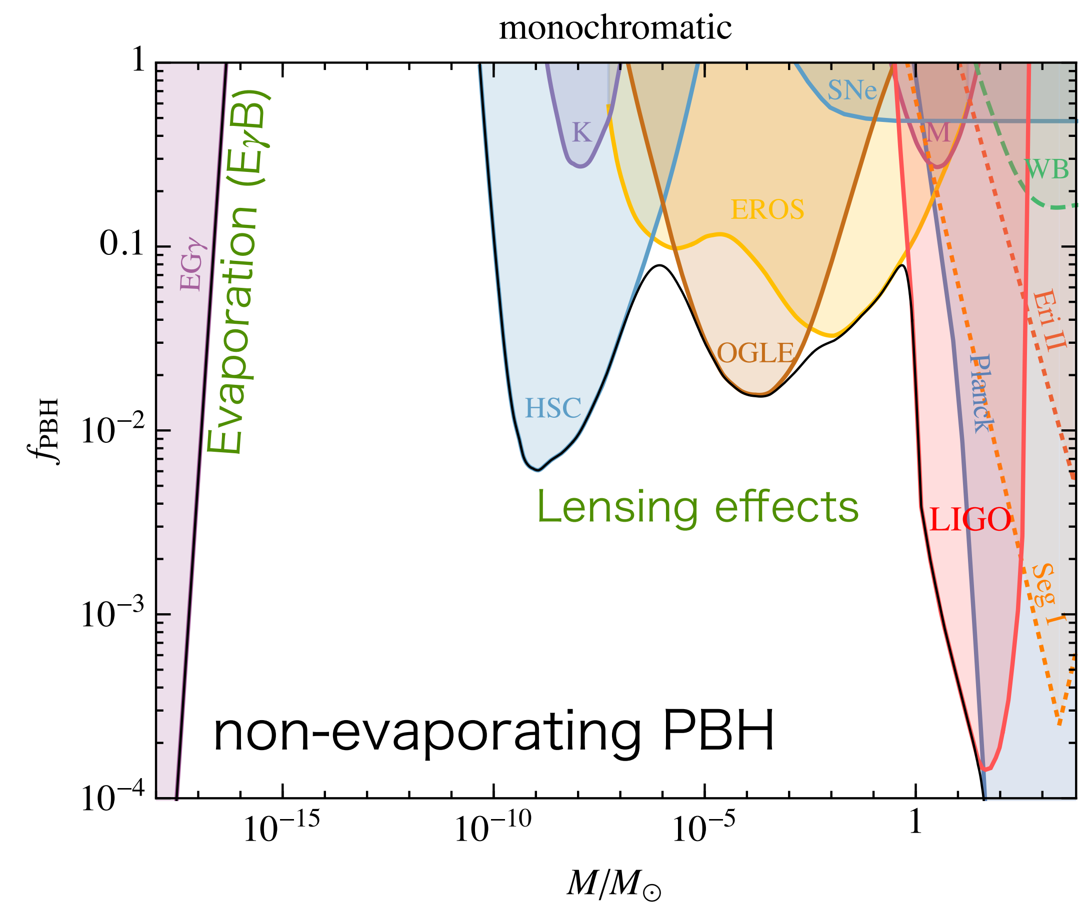
Mass range: $10^{-5}\,\mathrm{g}$ (= Planck scale) to astrophysical scale (much larger than $10^{6} M_{\odot} \simeq 10^{40}\,\mathrm{g}$)

Constraints on PBH abundance

Different constraints on PBHs, remained or evaporated in the current Universe

Carr, Kohri, Sendouda, Yokoyama (2020)





$$\beta'(M) \equiv \gamma^{1/2} \left(\frac{g_*}{106.75} \right)^{-1/4} \left(\frac{h}{0.67} \right) \frac{\rho_{\rm PBH}(t_i)}{\rho_R(t_i)}$$

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$

Evaporation completed before BBN for $M \lesssim 10^9\,\mathrm{g}$

PBH Evaporation

The PBH initial mass (formed during radiation-dominated era)

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

Mass in Hubble Volume

H: Hubble parameter

ρ_R: energy density of radiation

γ: numerical factor ~ 0.2 (formation dep.)

Plasma temperature at PBH formation: $3M_{\rm Pl}^2 H^2 = \rho_R = \frac{\pi^2}{30} g_{*\rho} T_{\rm in}^4$

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

Light PBH should be formed in the very early Universe

PBH mass-loss function

A BH loses its energy by Hawking radiation

S. W. Hawking (1974)

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

$\epsilon(M_{\mathrm{BH}})$: Evaporation function

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

spin/electric potential are taken into account

c.f.) Black-body radiation

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

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

BH case,

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

Key: Light PBH is hot and efficiently radiates
→ **heavy particle production at the last stage of evaporation**

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)

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

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

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

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

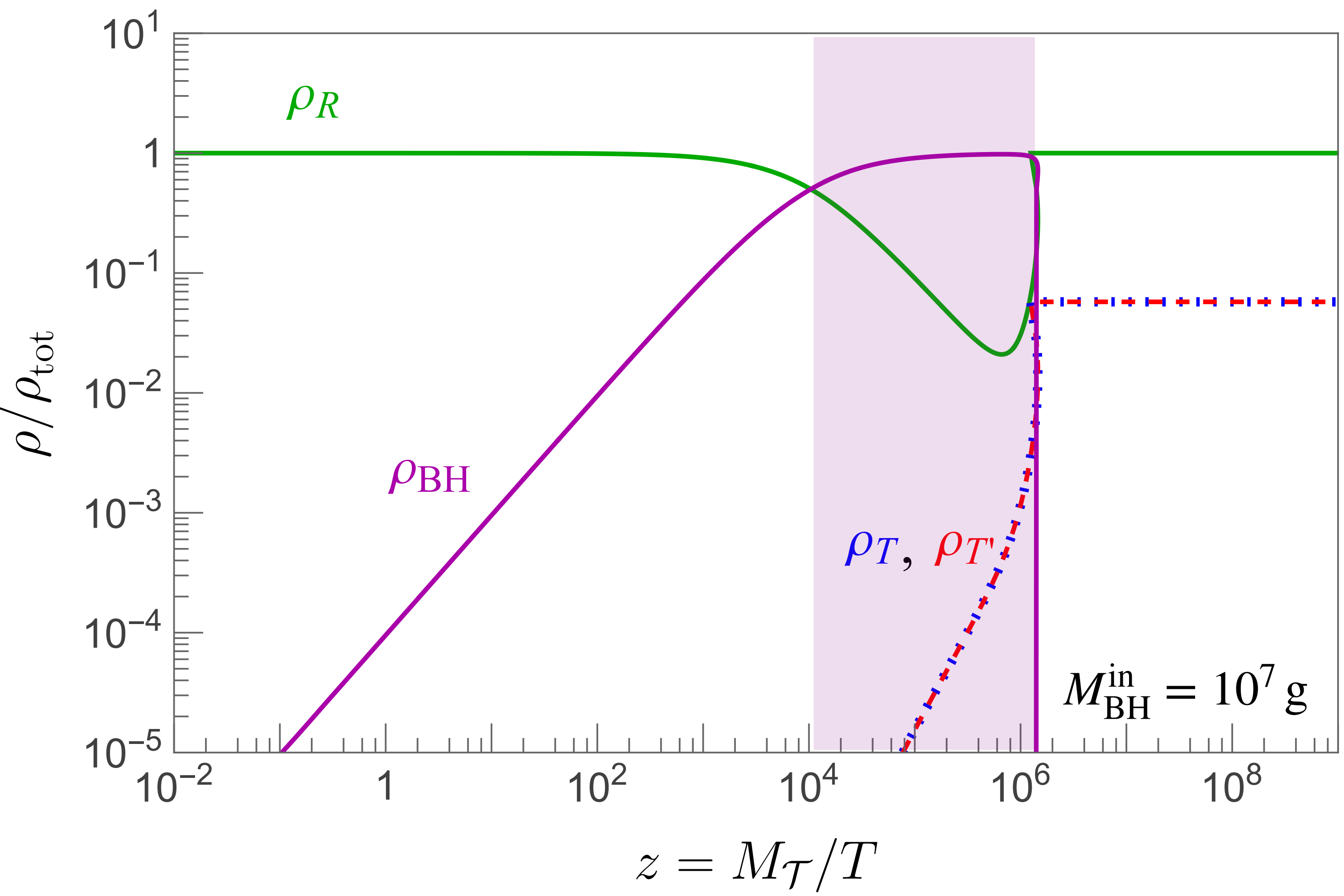
$$\beta_i = \begin{cases} 2.66 & (s=0) \\ 4.53 & (s=1/2) \\ 6.04 & (s=1) \end{cases}$$

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

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

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

Energy densities of heavy particles $\rho_{\mathcal{T}^{(\prime)}}$

increases at the last stage of evaporation

Temperature and Entropy

Plasma is reheated by BH evaporation:

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

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

expansion of universe

PBH evaporation

mass-loss function

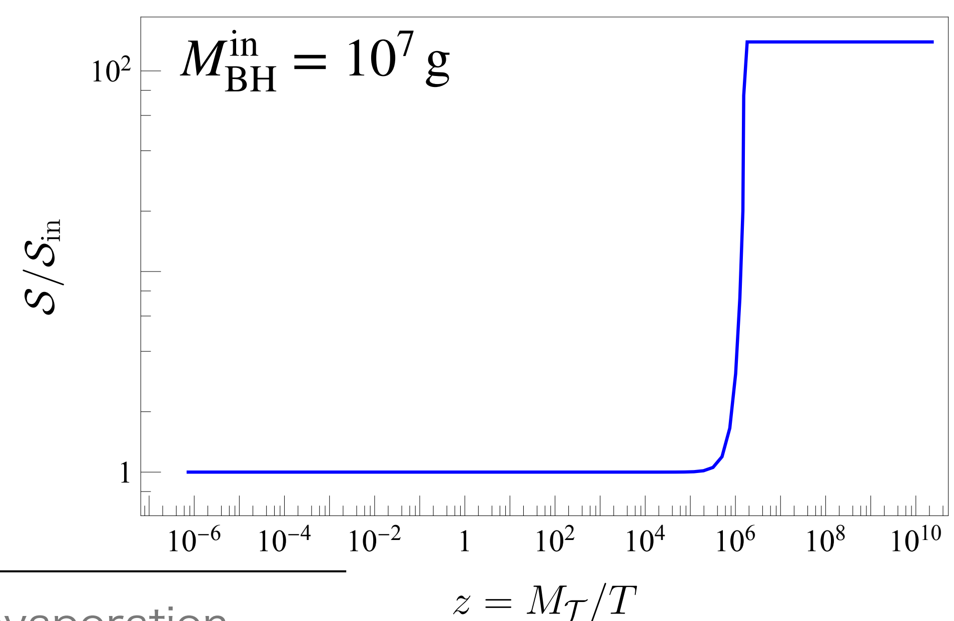
$$\frac{\mathrm{d}\ln M_{\mathrm{BH}}}{\mathrm{d}t} < 0$$

resists temperature decrease by the Universe expansion

comoving entropy density:

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

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



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

- positive contribution from PBH evap.

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

- dilute the existing asymmetries

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

Successful "GUT-like" Baryogenesis

D. Hooper, G. Krnjaic (2021)
TK, Y. Uchida (2025)

Colored scalar fields $\mathscr{T}(\mathbf{3},\mathbf{1})_{-1/3}$

$$\mathscr{L}_{\rm int} = y^L_{\mathscr{T}_i 1}\epsilon_{\alpha\beta\gamma}\epsilon^{rs}\mathscr{T}^{\alpha}_{i}Q^{\beta}_{r}Q^{\gamma}_{s} + y^R_{\mathscr{T}_i 1}\mathscr{T}^{\alpha}_{i}\overline{u}_{\alpha}\overline{e} + y^L_{\mathscr{T}_i 2}\mathscr{T}^{*}_{i\alpha}Q^{\alpha}L + y^R_{\mathscr{T}_i 2}\epsilon^{\alpha\beta\gamma}\mathscr{T}^{*}_{i\alpha}\overline{u}_{\beta}\overline{d}_{\gamma} + {\rm h.c.}$$

CP-violating decay of $\mathscr{T}$ provides a generation of baryon asymmetry

$$\varepsilon_{\mathscr{T}} \simeq \frac{\Gamma(\mathscr{T}\to ud) - \Gamma(\overline{\mathscr{T}}\to \overline{u}\overline{d})}{\Gamma_{\rm total}}$$

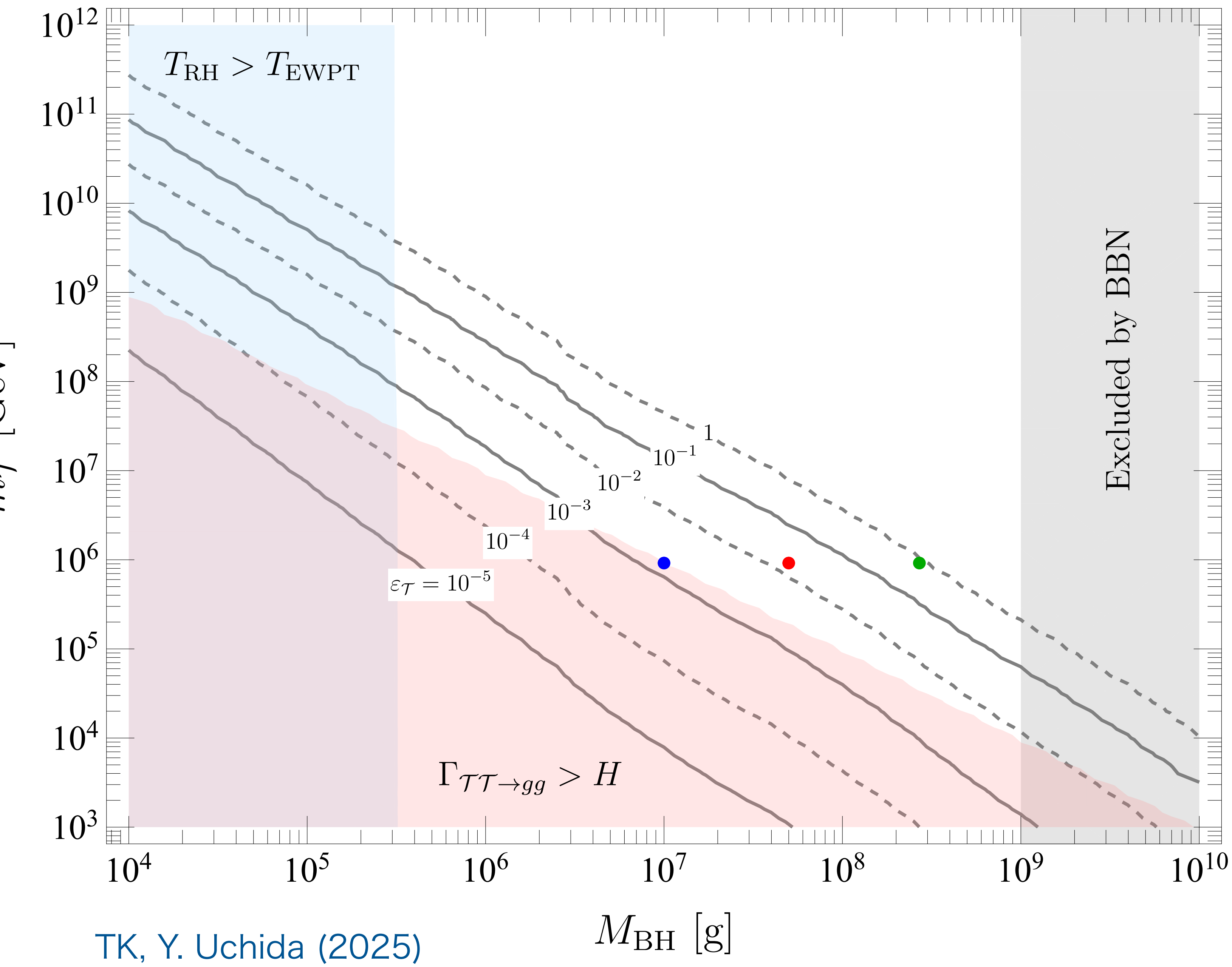
Constraints on the Yukawa couplings from proton decay

$$\Gamma(p\to e^+\pi^0) \simeq \frac{1}{64\pi}(|y^R_{\mathscr{T}1}y^R_{\mathscr{T}2}|^2 + |y^L_{\mathscr{T}1}y^L_{\mathscr{T}2}|^2)\frac{m_p}{m^4_{\mathscr{T}}}|W|^2$$

$$\simeq (4.2\times 10^{36}\,{\rm years})^{-1}\left(\frac{y_{\mathscr{T}}}{10^{-10}}\right)^4\left(\frac{10^6\,{\rm GeV}}{m_{\mathscr{T}}}\right)^4$$

unification with the higgs doublet?

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 : $y_{\mathcal{T}} \lesssim 10^{-10} \left(\frac{10^6\,\mathrm{GeV}}{m_{\mathcal{T}}} \right)$

efficient depletion before decay

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

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

Dark Baryogenesis

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

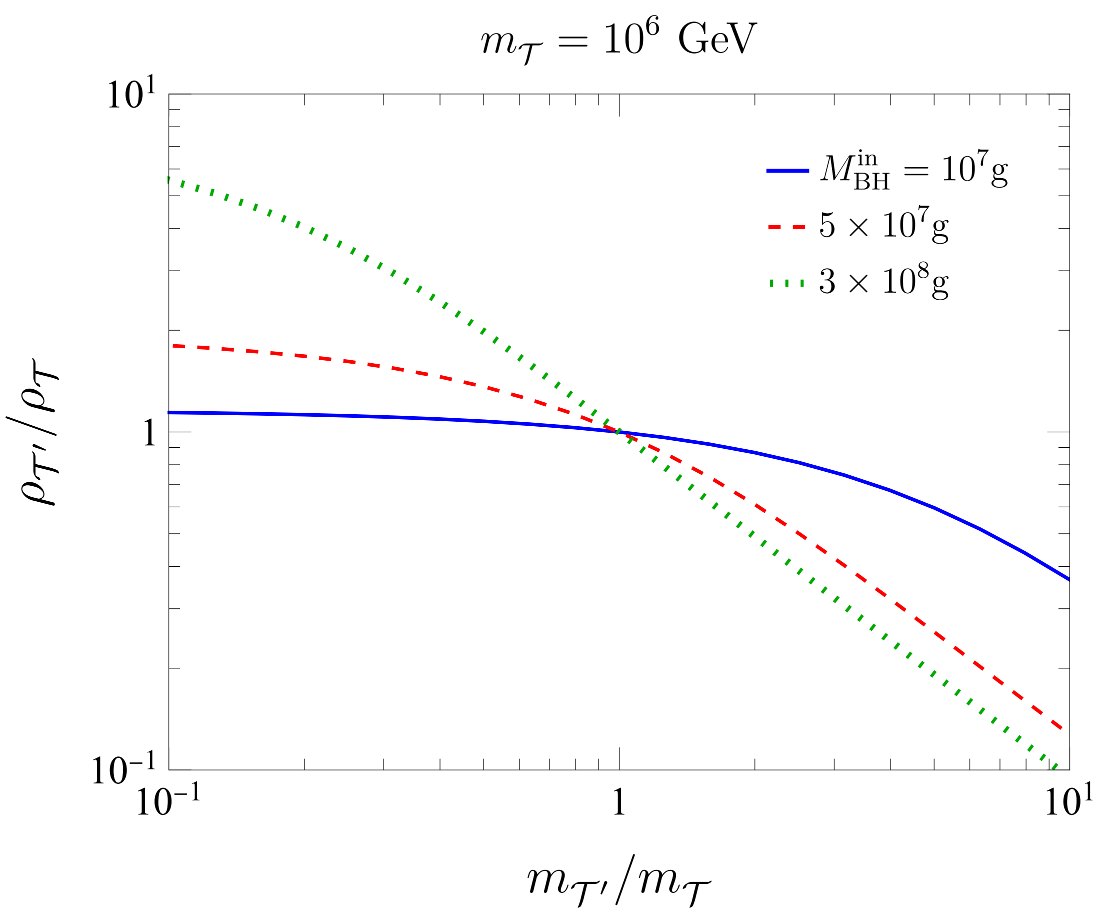
$$\mathcal{T}' \to \bar{u}'\bar{d}'$$

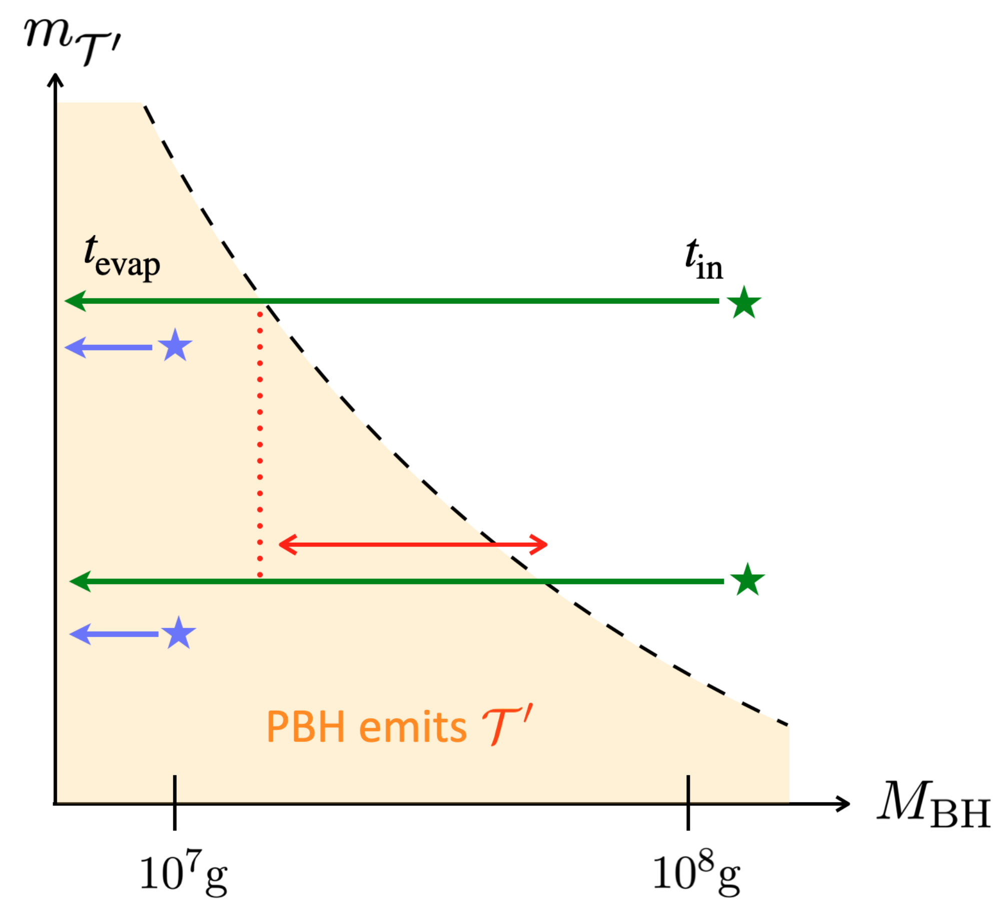
Key quantities: both energy densities of heavy scalars ($\rho_{\mathcal{T}}, \rho_{\mathcal{T}'}$) from PBH evaporation

Cogenesis of Asymmetries

TK, Y. Uchida (2025)

mass ratio dependence of energy densities



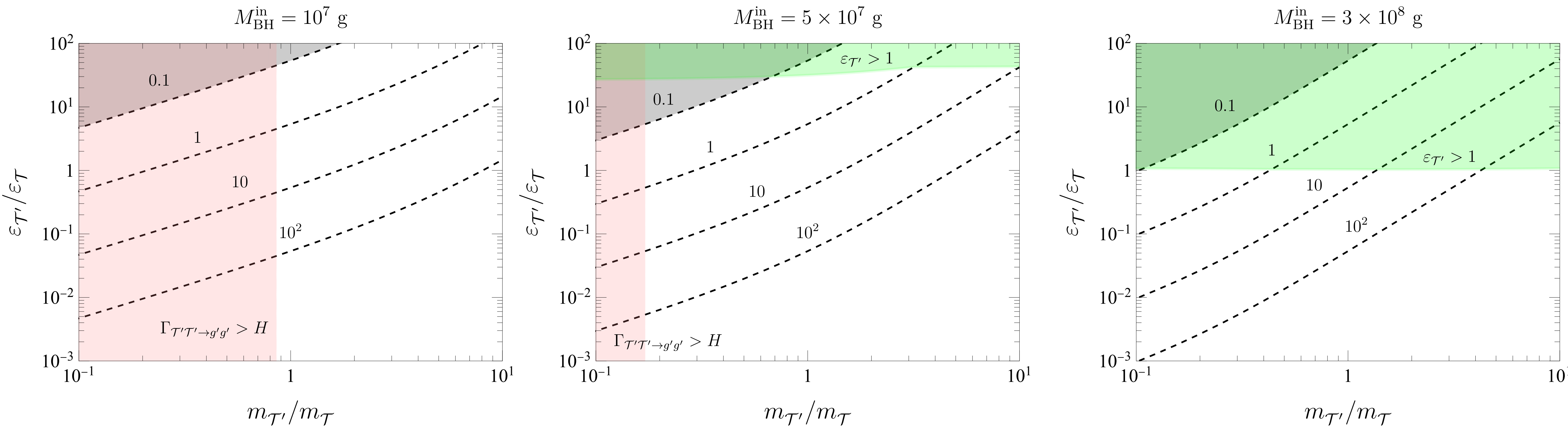


heavier (visible/dark) scalar leads to smaller (visible/dark) energy density for given $M_{\rm BH}$

= tends to reduce number asymmetry in the (visible/dark) sector

Cogenesis of Asymmetries

TK, Y. Uchida (2025)



We take benchmark points for successful B#: $(m_{\mathscr{T}}, \varepsilon_{\mathscr{T}})$

DM mass (in GeV): $\dfrac{m_{\rm DM}}{m_B} = 5.45\dfrac{\varepsilon_{\mathscr{T}}\rho_{\mathscr{T}}m_{\mathscr{T}'}}{\varepsilon_{\mathscr{T}'}\rho_{\mathscr{T}'}m_{\mathscr{T}}}$

Constraints (shaded area)

- similarly efficient depletion before decay
  $\Gamma(\mathscr{T}'\mathscr{T}' \to g'g')/H > 1$
- unphysical region for $\varepsilon_{\mathscr{T}'} > 1$
- Late-time heating ($\Delta N_{\rm eff}$) for $m_{A'} \lesssim 100\,{\rm MeV}$: $m_{A'} \lesssim m_{\pi'} \simeq 0.1 m_{N'}$

Summary

Heavy Particles from Primordial Black Holes

- Evaporating PBH ($M_{\rm BH} \lesssim 10^9\,{\rm g}$) can be the source for heavy particle production
- Matter-genesis via the heavy particle decay

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

Not investigated yet

★ Assumption for PBH Mass Function (Monochromatic or Extended?)

★ Detail of PBH evaporations (PBH hot spots/Memory-burdened/etc..)

Backup Slides

Comparison with Hooper-Krnjaic

They integrate the formula below

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

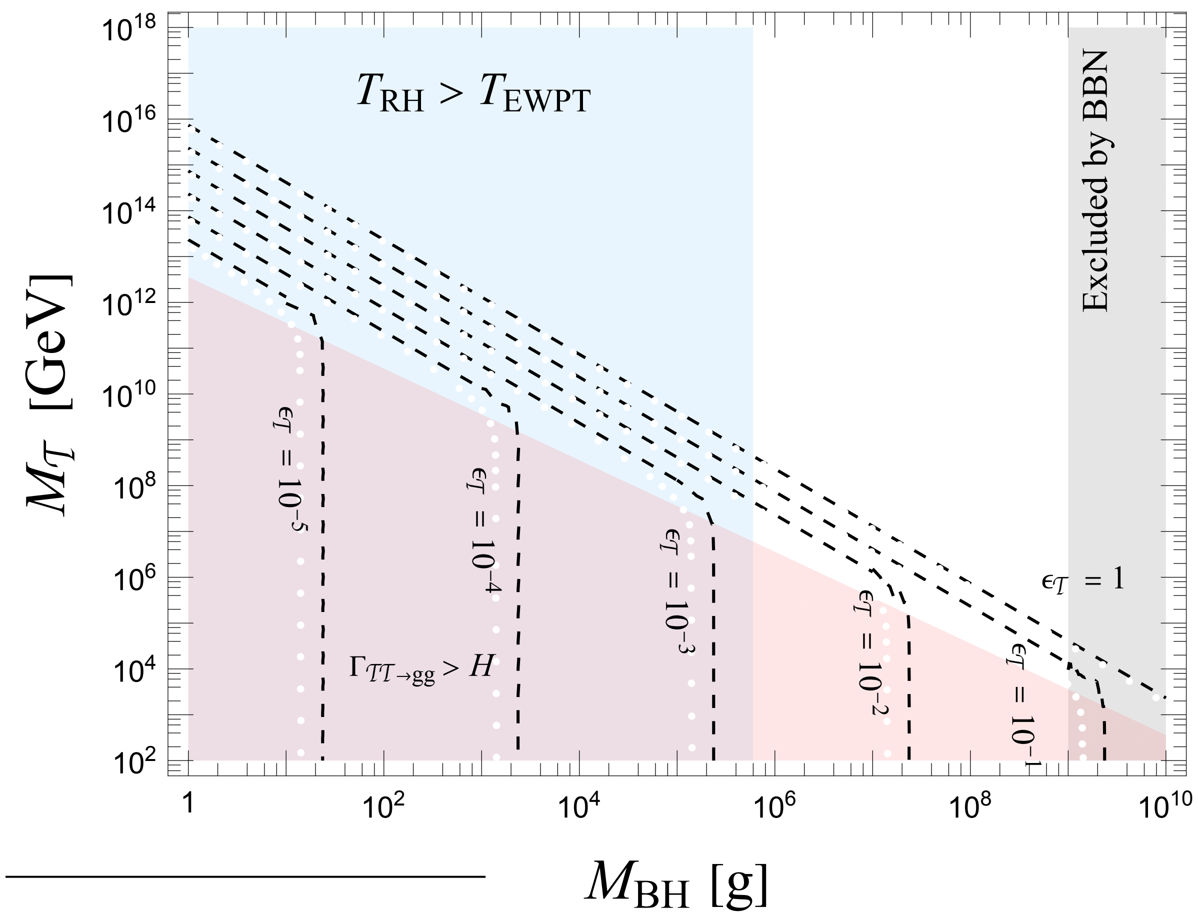
$\mathscr{G}$: graybody factor r_s : Schwarzschild radius

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

We solve Boltzmann eq.

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

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



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