From the Planck scale to the electroweak scale: PLANCK 2025

Cogenesis of baryon and dark matter from ultra-light Primordial Black Hole

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Motivation

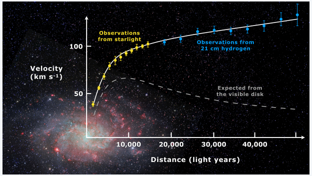
Dark Matter

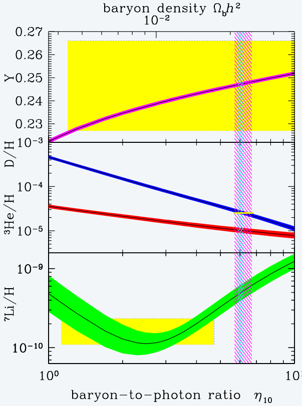
- No evidence of WIMP so far.
- Does DM interact only gravitationally?
- Production a) Gravity-mediated scattering.
  b) Black Hole as DM.
  c) Evaporation of BH.

Matter anti-matter asymmetry

- No evidence of anti-matter from cosmic-rays, gamma-rays.
- Mechanism : Leptogenesis, Affleck-Dine etc.

Role of BH for their common origin?





pdg data group

Primordial Black Hole

- Black holes in the early Universe $\Longrightarrow$ Primordial Black Hole.
- PBH can form due to
  - a) collapse of primordial overdensities
  - b) collapse of inflaton fields
  - c) collapse of topological defects
  - d) collapse from bubble collision etc.
- Here, we are agnostic about formation mechanism.
- 2 free parameters
  - a) PBH initial mass, $M_{\rm in}$.
  - b) Initial fractional energy density, $\beta \equiv \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_R(T_{\rm in})}$.
- We consider monochromatic mass distribution and zero spin.
- PBH can play interesting role in production of cogenesis. [1812.10606, 2104.14496]

Evaporation of PBH

- After formation, PBH emits particles due to QM effect.

Semi-Classical Effect

- Hawking evaporation $$\frac{d^2N}{dtdE} = \frac{1}{2\pi}\frac{\Gamma(E, M_{\rm BH}, s)}{e^{\frac{E}{M_P^2/M_{\rm BH}}} - (-1)^{2s}},$$

  Hawking temperature $T_{\rm BH} = \frac{M_P^2}{M_{\rm BH}}$ $\quad \Gamma(E,\, M_{\rm BH},\, s) \to$ Greybody factors
- Integrating wrt E,

$$\frac{dM_{\rm BH}}{dt} = -\epsilon \frac{M_P^4}{M_{\rm BH}^2}, \qquad \epsilon = \frac{27}{4}\frac{\pi g_{*,H}(T_{\rm BH})}{480} \tag{1}$$

- Mass evolution

$$M_{\rm BH}(t) = M_{\rm in}\left(1 - \frac{3\,\epsilon\, M_P^4}{M_{\rm in}^3}(t - t_{\rm in})\right)^{1/3}. \tag{2}$$

Evaporation of PBH

- However, SC assumptions may not be self consistent.
- It ignores back-reaction of emissions on the quantum state of BH.
- Semi-classical assumption is valid approximately $\{M_{\rm in}, qM_{\rm in}\}; q \approx 0.5.$

Memory-Burden Effect

- Recent studies suggest that information loaded in a BH resists its decay.
- Known as Memory-Burden effect. [2006.00011, 2402.14069]
- Expected to be valid for $\{qM_{\rm in}, 0\}; q \approx 0.5$
- Mass loss rate

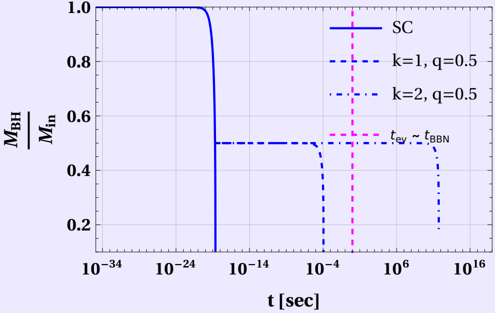
$$\frac{dM_{\rm BH}}{dt} = -\frac{\epsilon}{[S(M_{\rm BH})]^k}\frac{M_P^4}{M_{\rm BH}^2}, \quad k > 0. \tag{3}$$

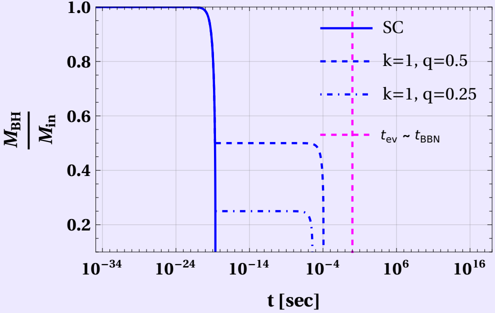
BH Entropy $$S(M_{\rm BH}) = \frac{1}{2}\left(\frac{M_{\rm BH}}{M_P}\right)^2 = \frac{1}{2}\left(\frac{M_P}{T_{\rm BH}}\right)^2.$$

Evaporation of PBH

- Free parameters : k and q.

Mass evolution

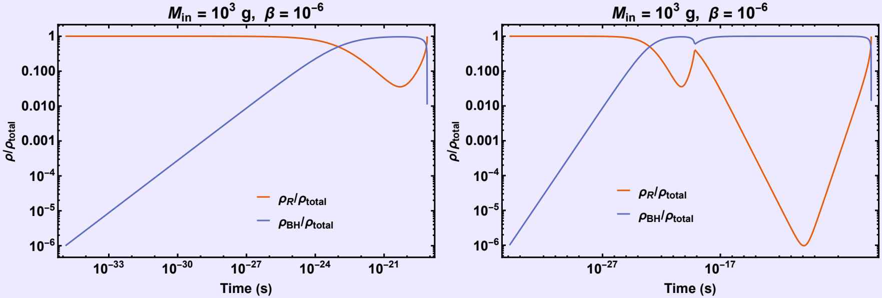




- Evaporation temperature $T_{\rm ev} = M_P \left(\frac{4}{3\alpha}\right)^{1/4} \left(\frac{3\times 2^k (3+2k)\epsilon \left(\frac{M_P}{M_{\rm in}}\right)^{3+2k}}{3\times q^{3+2k} + (1-q^3) 2^k (3+2k) \left(\frac{M_P}{M_{\rm in}}\right)^{2k}} \right)^{1/2}.$

Evaporation of PBH

Energy density evolution



Semi-Classical   Memory-burdened ($k = 1, q = 0.5$)

- PBH domination : $\beta > \beta_c = \left(\frac{(3+2k)2^k\epsilon}{8\,q^3\pi\gamma}\right)^{1/2}\left(\frac{M_P}{qM_{in}}\right)^{1+k}$.

Can we have cogenesis parameter space for SC as well as MB PBH?

Production of Dark Matter

- PBH evaporation produces all particles democratically.

$$N_j \simeq \frac{27}{128}\frac{\xi g_j \zeta(3)}{\pi^3 \epsilon} \begin{cases} \left(\frac{M_{\rm in}}{M_P}\right)^2 , & \text{if } m_j < T_{\rm BH}^{\rm in} \\ \left(\frac{M_P}{m_j}\right)^2 , & \text{if } m_j > T_{\rm BH}^{\rm in}. \end{cases} \tag{4}$$

- N_j is independent of memory-burdened parameters.
- We consider a real singlet scalar to be DM.

Structure formation constraint

- Comparison with thermal warm DM gives $\langle E_{\rm DM}(t_{\rm eq})\rangle \lesssim 10^{-4}\, m_{\rm DM}$.

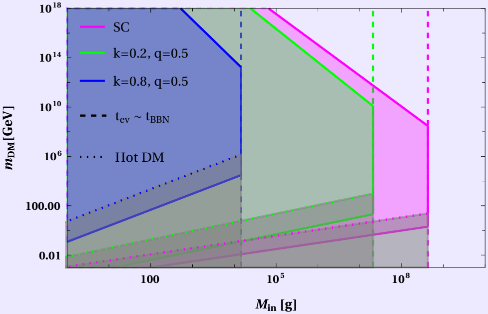
$$\langle E_{\rm DM}(t_{\rm eq})\rangle \approx 2\times 10^{-9}\text{GeV}\frac{M_{\rm P}}{qM_{\rm in}}\frac{\sqrt{3\times q^{3+2k}+(1-q^3)2^k(3+2k)\left(\frac{M_P}{M_{\rm in}}\right)^{2k}}}{\sqrt{3\times 2^k(3+2k)\epsilon\left(\frac{M_P}{M_{\rm in}}\right)^{3+2k}}}\left(\frac{g_{*s}(T_{\rm eq})}{g_{*s}(T_{\rm ev})}\right)^{1/3}.$$

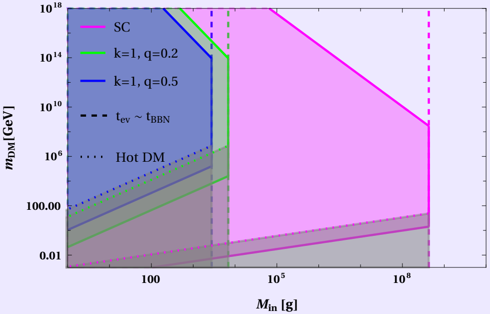
Production of Dark Matter

DM Relic

- DM abundance

$$\Omega_{\rm DM}h^2 = 1.6\times 10^8 \frac{g_{*s}(T_0)}{g_{*s}(T_{\rm ev})}\frac{n_{\rm BH}(T_{\rm ev})}{T_{\rm ev}^3}\frac{m_{\rm DM}}{\rm GeV}N_{\rm DM}. \tag{5}$$



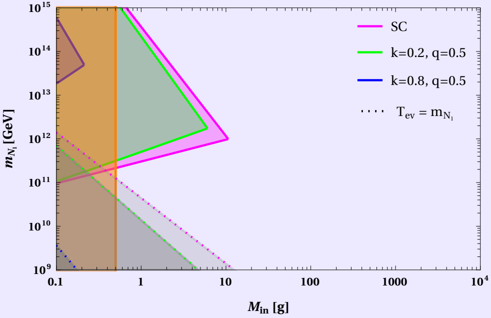


$m_j < T_{\rm BH}^{\rm in}$ excluded from warm DM criteria.

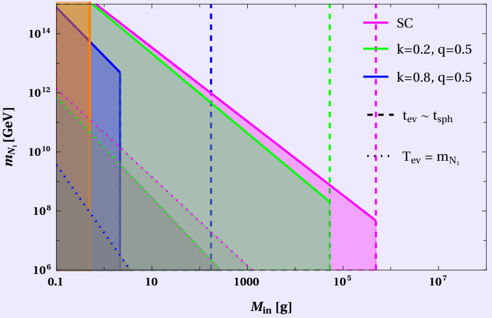
Production of Visible Matter

Leptogenesis from PBH

- Consider presence of RHN : $-\mathcal{L} \supset y_{\alpha i}\overline{L_\alpha}\tilde{H}N_i + \frac{1}{2}M_{N_i}\overline{N_i^c}N_i + \text{h.c.}$
- Final baryon asymmetry : $Y_{\rm B}^{\Delta L}(T_0) = \epsilon_1^{\Delta L}\, a_{\rm sph}\,\frac{n_{\rm BH}(a_{\rm ev})}{s(a_{\rm ev})}N_{N_1}$
- Hierarchical : $\epsilon_1^{\Delta L} = \frac{3M_{N_1}\sqrt{(\Delta m_{\rm atm})^2}}{4\pi v^2}$; Resonant : $\epsilon^{\Delta L} \sim 0.1$



Hierarchical



Resonant

Production of Visible Matter

Baryogenesis from PBH

- Advantage : Can be produced until $t_{\rm BBN}$, unlike Leptogenesis.
- Introduce two scalars $S_{1,2}$ $(3, 1, 2/3)$ and a fermion ψ $(1, 1, 0)$.
- Relevant Lagrangian : [1504.07196, 1712.02713]

$$-\mathcal{L} \supset \lambda_{\alpha i}\, S_\alpha\, \psi\, u_i^c + \lambda'_{\alpha ij}\, S_\alpha^\star\, d_i^c\, d_j^c + \frac{1}{2} m_\psi\, \overline{\psi^c}\, \psi + \text{h.c.} \tag{6}$$

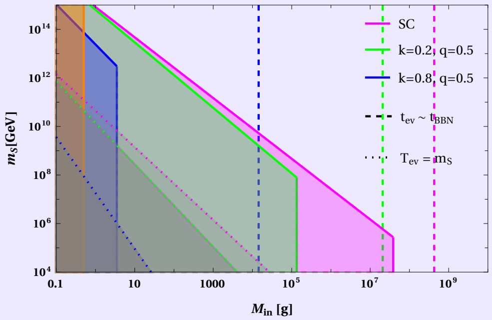
- CP asymmetry parameter

$$\epsilon_\alpha \;=\; \frac{1}{8\pi} \frac{\sum_{ijk} \mathrm{Im}(\lambda^*_{\alpha k}\lambda_{\beta k}\lambda'^*_{\alpha ij}\lambda'_{\beta ij})}{\sum_i |\lambda_{\alpha i}|^2 + \sum_{ij} |\lambda'_{\alpha ij}|^2} \times \frac{(m^2_{S_\alpha} - m^2_{S_\beta}) m_{S_\alpha} m_{S_\beta}}{(m^2_{S_\alpha} - m^2_{S_\beta})^2 + m^2_{S_\alpha} \Gamma^2_{S_\beta}} \tag{7}$$

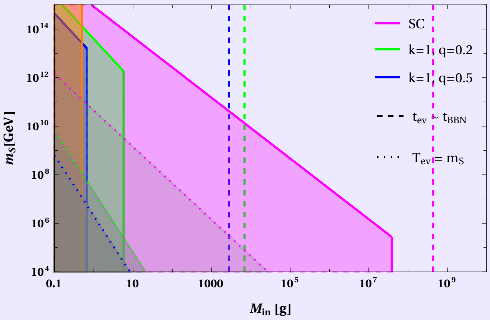
- Baryon asymmetry : $Y_B(T_0) \equiv Y_B(T_{\rm ev}) = (\epsilon_1 + \epsilon_2) N_S \frac{n_{\rm BH}(T_{\rm ev})}{s(T_{\rm ev})}$.

Production of Visible Matter

Baryogenesis from PBH



Varying *k*



Varying *q*

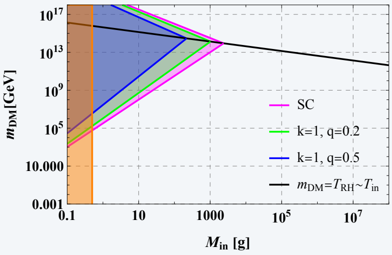
$m_S < T_{\rm ev}$ is inconsistent with non-thermal requirement.

Production from gravity mediated process

- Unavoidable production from gravity mediated process.
- 2-to-2 annihilations of SM particles via exchange of massless gravitons. [1803.01866].

$$Y_j = \frac{45 \times \delta}{2\,\pi^3\, g_{*\,s}} \sqrt{\frac{10}{g_*}} \begin{cases} \frac{T_{\rm RH}^3}{M_{\rm P}^3} & \text{for } m_j < T_{\rm RH}, \\ \frac{T_{\rm RH}^7}{M_{\rm P}^3 m_j^4} & \text{for } m_j > T_{\rm RH}. \end{cases} \quad (8)$$

- Y_j will get diluted due to PBH evaporation.



$\beta = 10^{-4}$

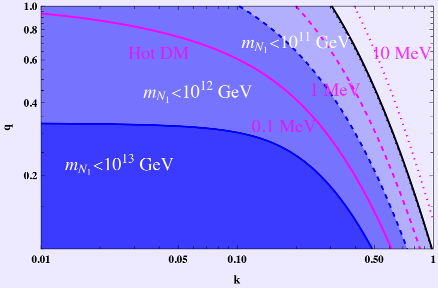
Comparison with production from PBH evaporation

- Contribution from gravity mediated process is subdominant for $T_{\rm RH} = T_{\rm in}$.
- Prodcution of baryon asymmetry requires $M_{\rm in} < 10^{-2}$ g.

Cogenesis of Dark and Visible Matter

Cogenesis with Heirarchical Leptogenesis

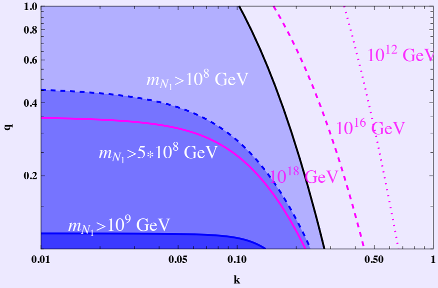
- A common parameter space require $m_{\rm DM} < 1$ GeV.
- Ruled out from structure formation constraint. [2405.15858].



For $M_{\rm in} = 1g$

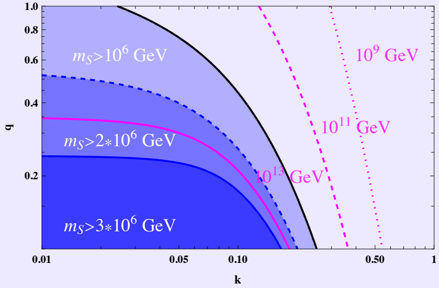
Cogenesis of Dark and Visible Matter

With Resnonant Leptogenesis



For $M_{\text{in}} = 10^5 g$

With Baryogenesis

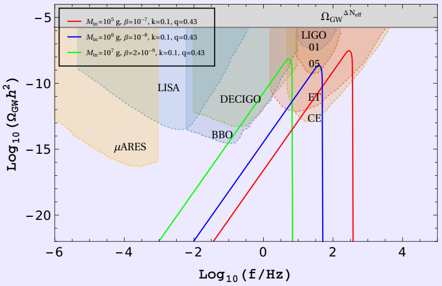


For $M_{\text{in}} = 10^7 g$

Observational Probes

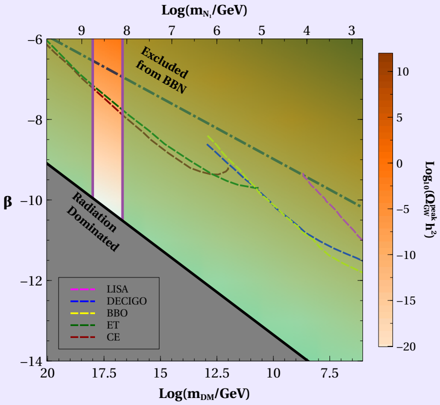
Gravitational Waves

- PBHs are distributed inhomogeneously that induce GWs at second order during PBH evaporation. [2012.08151, 2403.14309]
- $$\Omega_{\rm GW,ev}^{\rm peak} \simeq \frac{q^4}{4133^{\frac{4}{3+2k}}} \left(\frac{3+2k}{3}\right)^{-\frac{7}{3}+\frac{4}{9+6k}} \frac{\beta^{16/3}\exp[8{\rm k}(7-\frac{4}{3+2{\rm k}})]}{2.3\times 10^{-20}} \left(\frac{qM_{\rm in}}{1{\rm g}}\right)^{\frac{2}{3}(1+k)(7-\frac{4}{3+2k})}$$
- Peak frequency $$f_{\rm UV} \simeq 4.8\times 10^6\,{\rm Hz}\,{\rm e}^{-4{\rm k}} \left(\frac{3+2{\rm k}}{3}\right)^{1/6} \left(\frac{1\,{\rm g}}{{\rm q}\,{\rm M_{in}}}\right)^{\frac{5}{6}+\frac{{\rm k}}{3}} .$$



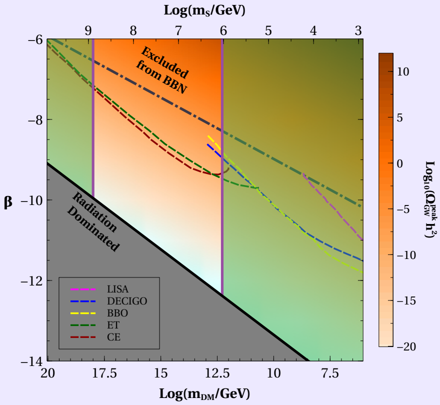
Observational Probes

With Resnonant Leptogenesis



$k = 0.1$ and $q = 0.43$

With Baryogenesis



$k = 0.1$ and $q = 0.43$

Conclusion

- Evaporation of PBH can produce dark matter and baryon asymmetry non-thermally.
- Cogenesis with heirarchical leptogenesis is not possible due to constraint from structure formation.
- We show viability of cogenesis with resonant leptogenesis and baryogenesis.
- This requires memory-burdened parameter space in the range $0 \leq k < 1$.
- These two scenarios can give signatures in future gravitational waves observations and can also be potentially distinguished.
- The roles of gravity-mediated processes are not significant for $T_{\rm RH} = T_{\rm in}$.

Thank you for your attention