Axion Dark Matter in the Time of PBHs

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Outline

1. Mini Overview of PBHs and Phenomenology
2. QCD Axion DM with PBHs

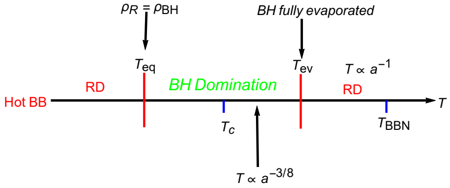
PBH: a mini overview

- PBHs could have been formed in early Universe [Hawking 1971, Carr 1974]
  - Mass
$$M_{\rm BH} \simeq \frac{4\pi}{3}\rho\cdot\left(\frac{1}{H}\right)^3 \simeq 10^{15}\left(\frac{t}{10^{-23}\ {\rm s}}\right)\ {\rm g}$$
e.g. $t = 10^{-43}s \Rightarrow M_{\rm BH} \sim \mathcal{O}(10^{-5})g$; $t = 10^{-4}s \Rightarrow M_{\rm BH} \sim \mathcal{O}(10)M_\odot$
  - Horizon temperature [Hawking 1975]
$$T_{\rm BH} = \frac{M_P^2}{M_{\rm BH}} \simeq 10^{13}\,{\rm GeV}\left(\frac{1\,{\rm g}}{M_{\rm BH}}\right)$$
$\Rightarrow$ particles $m \lesssim T_{\rm BH}$ can be produced
  - Lifetime [Hawking 1974]
$$\tau_{\rm BH} \sim \frac{\hbar c^4}{G^2 M_{\rm BH}^3} \sim 10^{64}\left(\frac{M_{\rm BH}}{M_\odot}\right)^3 {\rm y}$$
$M_{\rm BH} \lesssim 10^{15}g \Rightarrow \tau_{\rm BH} \lesssim 10^{10}{\rm y} \Rightarrow$ fully evaporated and disappeared

Phenomenology with PBHs

- Massive $M_{\rm BH} > 10^{15} g$ $\Rightarrow$ long live and CDM candidate [review 2006.02838]
- Phenomenology with Light PBHs:
  - Particle DM [1401.1909, 2009.02424, ...]
  - Baryogenesis [hep-th/0703250, 1610.02586, ...]
  - Neutrinos [1910.07864, ...]
  - Dark radiation [1905.01301, ...]
  - ALPs [2107.03420]
  - ....
  - Axions (this talk)

Cosmological History with an early PBHs Epoch



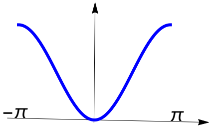
- Modified expansion:

$$H(T) \simeq \begin{cases} H_R(T) & \text{for } T \geq T_{eq} \,, \\ H_R(T_{eq}) \left[\frac{g_{\star s}(T)}{g_{\star s}(T_{eq})} \left(\frac{T}{T_{eq}} \right)^3 \right]^{1/2} & \text{for } T_{eq} \geq T \geq T_c \,, \\ H_R(T_{ev}) \left[1 - \frac{720}{\pi \, g_\star(T_{in})} \frac{M_{in}^3}{M_P^4} \frac{H_R^2(T_{ev}) - H_R^2(T)}{H_R(T_{ev})} \right] & \text{for } T_c \geq T \geq T_{ev} \,, \\ H_R(T) & \text{for } T_{ev} \geq T \,, \end{cases}$$

- Implications for Axion DM Phenomenology?

Misalignment and QCD Axion DM in Standard Cosmo

- Axion potential: $V(\theta) = \tilde{m}_a^2(T) f_a^2 (1 - \cos\theta)$
- EoM: $\ddot{\theta} + 3H(T)\dot{\theta} + \tilde{m}_a^2(T) f_a^2 \theta = 0$
- Energy density:
  $\rho_a(T_0) = m_a n_a(T_0) = m_a \frac{\rho_a(T_{osc})}{\tilde{m}_a(T_{osc})} \frac{s(T_0)}{s(T_{osc})}$
- Zero Tem mass: $m_a \simeq 5.7 \times 10^{-6} \left(\frac{10^{12}\ \text{GeV}}{f_a}\right) \text{eV}$

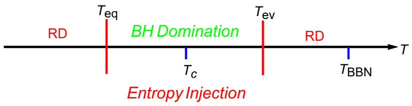


Relic density:

$$\Omega_a h^2 \equiv \frac{\rho_a(T_0)}{\rho_c/h^2} \simeq 0.12 \left(\frac{\theta_i}{10^{-3}}\right)^2 \times \left(\frac{m_a}{\mathcal{O}(10^{-11})\ \text{eV}}\right)^{-\frac{7}{6}}$$

$\Omega_a h^2 = 0.12$ with $\theta_i \sim \mathcal{O}(1) \Rightarrow m_a \sim \mathcal{O}(10^{-5})$ eV or $f_a \sim 10^{12}$ GeV!

QCD Axion DM with PBHs



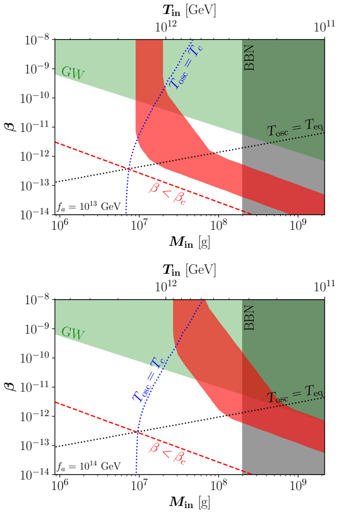
If $T > T_{\rm ev}$: $S(T) < S(T_{\rm ev})$

- Diluted the energy density:

$$\rho_a(T_0) = \left(\rho_a(T_{\rm osc}) \frac{m_a}{\tilde{m}_a(T_{\rm osc})} \frac{s(T_0)}{s(T_{\rm osc})}\right) \times \frac{S(T_{\rm osc})}{S(T_{\rm ev})}$$

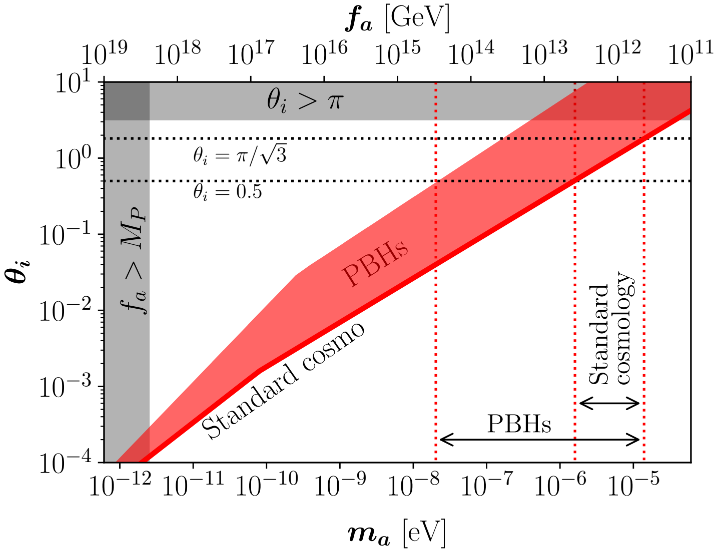
  - $\rho_a(T_{\rm osc}) \propto m_a^2(T_{\rm osc})\, f_a^2$ and $m_a \propto 1/f_a$
  - For $T_{\rm osc} > T_{\rm ev}$ with $\frac{S(T_{\rm osc})}{S(T_{\rm ev})} < 1 \Rightarrow$ larger f_a (smaller m_a) is allowed!

Misalignment with PBHs: $\Omega_a h^2 = f(\theta_i, m_a, \beta, M_{\rm in})$



- $\beta \equiv \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_R(T_{\rm in})} \Rightarrow$ abundance of PBHs
- $M_{\rm in} < 2 \times 10^8\ g \Rightarrow T_{\rm ev} \propto \left(\frac{M_P^5}{M_{\rm in}^3}\right)^{\frac{1}{2}} >$ 4MeV $\Rightarrow$ BBN
- Red band: $\Omega_a h^2 = 0.12$ with $\theta_i \in [1/2, \pi/\sqrt{3}]$
- upper: $f_a = 10^{13}$ GeV ($m_a \simeq 10^{-6}$ eV)
  lower: $f_a = 10^{14}$ GeV ($m_a \simeq 10^{-7}$ eV)

Full Parameter Space



Summary

- PBHs could have been copiously produced in the early Universe
- An early PBHs dominated era is possible (and phenomenologically interesting)
- In standard cosmology: $f_a \sim \mathcal{O}(10^{12})$ GeV $\Rightarrow \Omega_a h^2 \sim 0.12$ with $\theta_i \sim \mathcal{O}(1)$
- With an early PBHs epoch, $f_a \sim \mathcal{O}(10^{14})$ GeV is allowed even without fine tuning θ_i

Thank you for your attention!