Superradiant Production of Heavy Dark Matter from Primordial Black Holes

Yong Xu

based on 2205.11522 [Phys.Rev.D 106 (2022) 1, 015020]
with N. Bernal and Y. F. Perez-Gonzalez

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UNIVERSITÄT BONN
bctp
Bethe Center for Theoretical Physics

Outline

PBH and Hawking Evaporation

PBHs could have been formed in early Universe

- mass $M_{\rm in} \simeq \frac{4\pi}{3}\rho \cdot \left(\frac{1}{H}\right)^3 \simeq 10^{15}\left(\frac{t}{10^{-23}\ \rm s}\right)\ \rm g$
- spin $a_\star \equiv 8\pi\, J\, M_P^2/M_{\rm BH}^2$
- abundance $\beta = \rho_{\rm BH}(T_{\rm in})/\rho_R(T_{\rm in})$
- charge Q (focus on Q=0 Kerr BH here)

PBHs emit particles via Hawking evaporation

$$\frac{dM_{\rm BH}}{dt} = -\varepsilon \frac{M_P^4}{M_{\rm BH}^2}\,; \qquad \frac{da_\star}{dt} = -a_\star\,(\gamma - 2\varepsilon)\,\frac{M_P^4}{M_{\rm BH}^3}$$

Temperature after PBHs have fully evaporated:

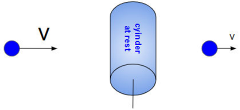
$$T_{\rm ev} \simeq \left(\frac{g_\star}{640}\right)^{1/4}\left(\frac{M_P^5}{M_{\rm in}^3}\right)^{1/2}$$

Remarks:

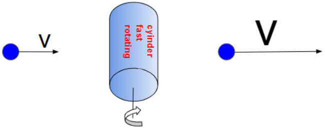
- if $\beta > \beta_c \equiv T_{\rm ev}/T_{\rm in} \Rightarrow$ PBHs domination phase
- CMB: $r < 0.035 \Rightarrow T_{\rm ev} \lesssim \mathcal{O}(10^{16})$ GeV $\Rightarrow M_{\rm in} \gtrsim \mathcal{O}(0.1)$ g
- BBN: $T_{\rm ev} \gtrsim 4$ MeV $\Rightarrow M_{\rm in} \lesssim \mathcal{O}(10^9)\ g$

Superradiance in a Nutshell

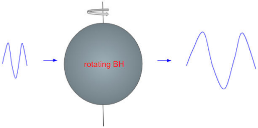
- Ball scatters off a cylinder with lossy surface:
  - slows down if cylinder at rest



  - speeds up if cylinder fast rotating



- Particles/Wave ($\phi \sim e^{-i\omega t}$) scatter with rotating BH (with angular frequency Ω)



- Superradiance condition: $\omega < m\Omega$ [Brito, Cardoso, Pani 1501.06570]

Superradiance: Scalar DM around Kerr BHs

Klein-Gordon equation:

$$\left(g_{\mu\nu}\nabla^{\mu}\nabla^{\nu} - m_{\rm dm}^2\right)\phi = 0$$

Separating variables (Hydrogen atom in QM):

$$\phi(t,r,\theta,\varphi) = \sum_{\omega,n,l,m} e^{-i\omega t + im\varphi} S_{lm}(\theta) R_{nlm}(r)$$

- $\mathfrak{Im}(\omega) > 0 \Rightarrow \phi$ exponentially grows
- Radial component R:

$$\Delta\partial_r\left(\partial_r R\right) - \Delta\left[m_{\rm dm}^2 r^2 + a_\star^2 r_g^2 \omega^2 - 2\omega\, m\, a_\star r_g\, r + \left(\omega\left(r^2 + a_\star^2 r_g^2\right) - m\, a_\star r_g\right)^2 + \lambda\right] R = 0$$

- Superradiance rate [Detweiler 1980]:

$$\Gamma_{\rm sr} \equiv \mathfrak{Im}(\omega) = \frac{m_{\rm dm}}{24}\left(m_{\rm dm} M\right)^8\left(a_\star - 2 m_{\rm dm}\, r_+\right)$$

with $r_+ = r_g\left(1 + \sqrt{1 - a_\star^2}\right)$ being event horizon and $r_g = GM$.

Superradiance Phenomenology

- $\alpha \equiv \frac{r_g}{\lambda_C} = G\, M_{\rm BH}\, m_{\rm dm} \sim \left(\frac{M_{\rm BH}}{10^7\ {\rm g}}\right)\left(\frac{m_{\rm dm}}{10^7\ {\rm GeV}}\right)$

$$M_{\rm BH} \lesssim 10^9\ {\rm g} \Rightarrow m_{\rm dm} \gtrsim 1{\rm TeV} \ \Rightarrow {\rm Heavy\ \ DM}$$

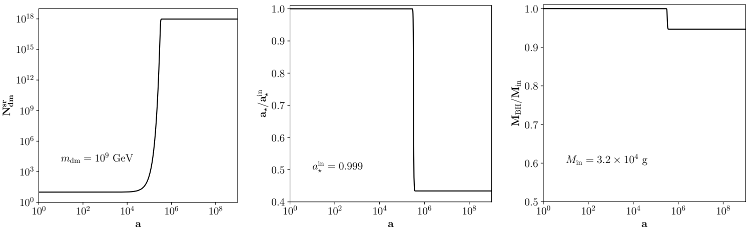
- Evolution Eqs [Brito, Cardoso, Pani 1501.06570]:

$$\frac{dN^{\rm sr}_{\rm dm}}{dt} = \Gamma_{\rm sr}\, N^{\rm sr}_{\rm dm}$$

$$\frac{dM_{\rm BH}}{dt} = -m_{\rm dm}\, \Gamma_{\rm sr}\, N^{\rm sr}_{\rm dm}$$

$$\frac{da_\star}{dt} = -8\pi \left[\sqrt{2} - 2\alpha\, a_\star\right] \Gamma_{\rm sr}\, N^{\rm sr}_{\rm dm}\, \frac{M_P^2}{M_{\rm BH}^2}$$

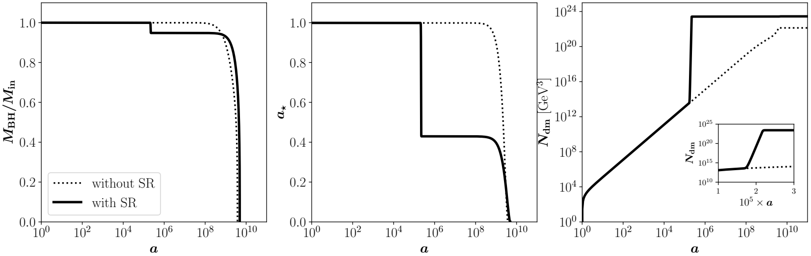
Superradiance Phenomenology



- Superradiance manifests significantly when $t \simeq \frac{1}{\Gamma_{\rm sr}} \iff a \sim 10^5$
- Final DM numbers:

$$N_{\rm dm}^{\rm sr}(\mathrm{end}) \simeq N_{\rm dm}^{\rm sr}(\mathrm{in}) + \mathcal{O}\left(10^{19}\right)\left(\frac{M_{\rm BH}}{10^5\ \mathrm{g}}\right)^2$$

PBHs with and without Superradiance



$$\frac{dN_{dm}^{sr}}{dt} = \Gamma_{sr}\, N_{dm}^{sr}$$

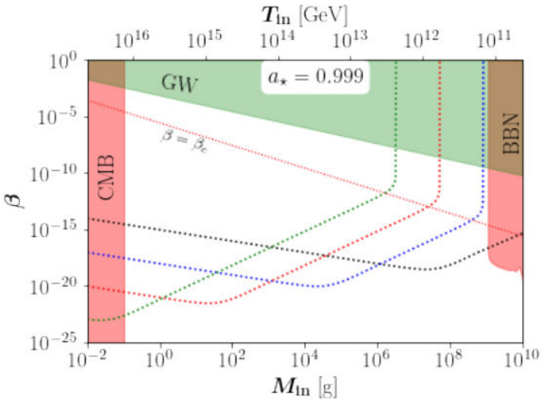
$$\frac{dM_{BH}}{dt} = -\varepsilon\, \frac{M_P^4}{M_{BH}^2} - m_{dm}\, \Gamma_{sr}\, N_{dm}^{sr}$$

$$\frac{da_\star}{dt} = -a_\star \left[\gamma - 2\varepsilon\right] \frac{M_P^4}{M_{BH}^3} - 8\pi \left[\sqrt{2} - 2\alpha\, a_\star\right] \Gamma_{sr}\, N_{dm}^{sr}\, \frac{M_P^2}{M_{BH}^2}$$

$$\frac{dn_{dm}}{dt} + 3H\, n_{dm} = n_{BH} \left[\Gamma_{BH\to DM} + \Gamma_{sr}\, N_{dm}^{sr}\right]$$

Bernal, Perez-Gonzalez and YX [2205.11522]

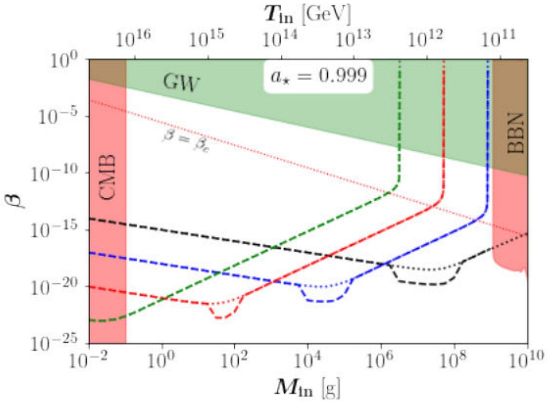
Pure Hawking evaporation



$m_{\rm dm} = 10^{15}$ GeV; $m_{\rm dm} = 10^{12}$ GeV; $m_{\rm dm} = 10^{9}$ GeV; $m_{\rm dm} = 10^{6}$ GeV

Bernal, Perez-Gonzalez and YX [2205.11522]

Hawking evaporation + Superradiance



$m_{\rm dm} = 10^{15}$ GeV; $m_{\rm dm} = 10^{12}$ GeV; $m_{\rm dm} = 10^{9}$ GeV; $m_{\rm dm} = 10^{6}$ GeV

$$\alpha \equiv r_g/\lambda_C \sim \left(M_{\rm BH}/10^7\ {\rm g}\right)\left(m_{\rm dm}/10^7\ {\rm GeV}\right)$$

Bernal, Perez-Gonzalez and YX [2205.11522]

Summary

- Superradiance enhances DM production from PBH $\Rightarrow$ a new non-thermal gravitational channel for DM

- Less PBHs, hence smaller β are needed compared to pure Hawking evaporation

Thank you for your attention!

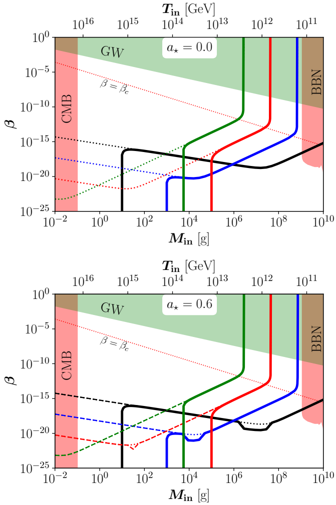
Backup: Kerr Metric

Line element:

$$ds^2 = -dt^2 + \frac{2\, r_g\, r}{\Sigma} \left(dt - a_\star\, r_g\, \sin^2\theta\, d\varphi \right)^2 + \frac{\Sigma}{\Delta}\, dr^2 + \Sigma\, d\theta^2 + \left(r^2 + a_\star^2\, r_g^2 \right) \sin\theta^2\, d\varphi^2$$

- $\Sigma \equiv r^2 + a_\star^2\, r_g^2\, \cos^2\theta$
- $\Delta \equiv r^2 - 2\, r_g\, r + a_\star^2\, r_g^2,$
- coordinate singularity: $\Delta = 0 \Rightarrow r_\pm = r_g \left(1 \pm \sqrt{1 - a_\star^2} \right)$
- r_+: Event horizon; r_-: Cauchy horizon
- ergosphere: $r_+ \leq r \leq r_t$ with $r_t \equiv r_g \left(1 + \sqrt{1 - a_\star^2 \cos^2\theta} \right)$

Backup: Varying BH spin



Backup: bound on PBH mass for superradiance

PBH lifetime:

$$\tau = \frac{160}{\pi g_\star} \frac{M_{\rm in}^3}{M_P^4}$$

Typical timescale for superradiance:

$$t_{\rm sr} \sim \frac{1}{\Gamma_{\rm sr}} \simeq \frac{24}{m_{\rm dm}} \left(\frac{8\pi\, M_P^2}{M_{\rm in}\, m_{\rm dm}} \right)^8 \frac{1}{a_\star}$$

To develop superradiance, $t_{\rm sr} < \tau$ is required, leading to

$$M_{\rm in} \gtrsim 70 \left(\frac{1}{a_\star} \right)^{1/11} \left(\frac{10^{11}\ \text{GeV}}{m_{\rm dm}} \right)^{9/11} \ \text{g}$$