Cosmological gravitational particle production and primordial black holes

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Objectives and motivations

- Dark matter that interacts only with gravity!

- Study the interplay among two different **gravitational** production mechanisms:

Primordial Black Holes (PBHs)

+

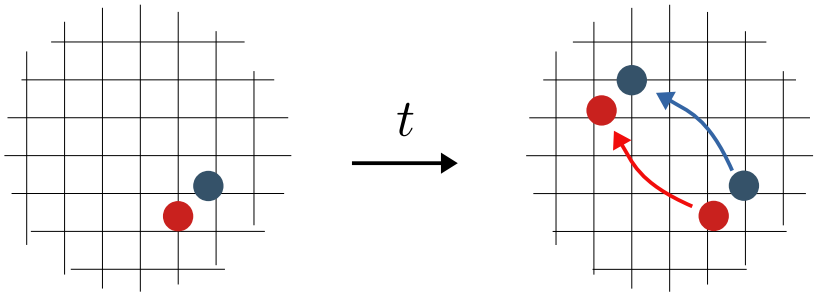
Cosmological Gravitational Particle Production (CGPP)

CGPP

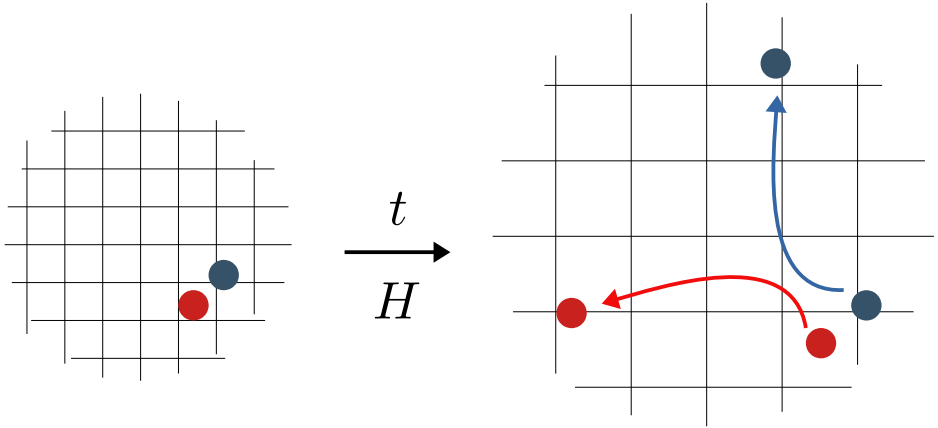
[Parker, 1968, 1969, 1971]
[Ford, 2021]
[Kolb, Long, 2023]

- Particles that are produced by the expansion of the universe (QFT in curved space-time effect);

- CGPP is efficient up to $m \lesssim H$.



Minkowski space-time



FLRW space-time

CGPP

- Compute the number of fluctuations of a particle χ in the classical FLRW background:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \mathscr{L}_\chi\right] \implies \chi_k''(\eta) + \omega_k^2(\eta)\chi_k(\eta) = 0$$

- Total comoving number:

$$na^3 = \int \frac{\mathrm{d}k}{k}\frac{k^3}{2\pi^2}\left[\frac{\omega_k}{2}|\chi_k|^2 + \frac{|\chi_k'|^2}{2\omega_k} - \frac{1}{2}\right]_{\eta\to\infty}$$

Including PBHs

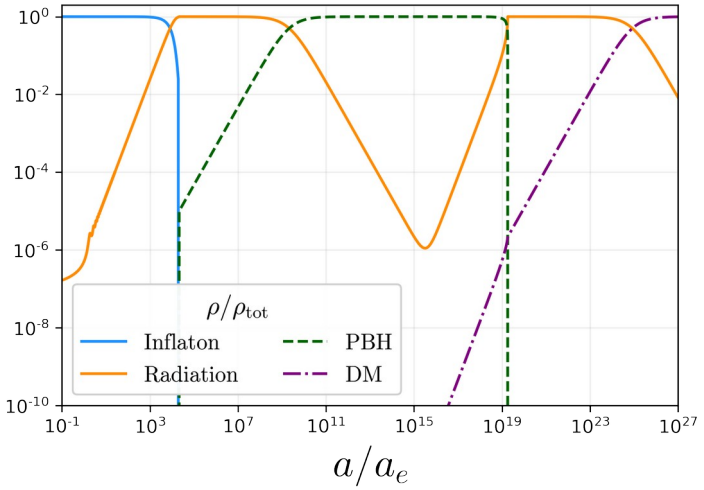
- PBHs affect the comological evolution:

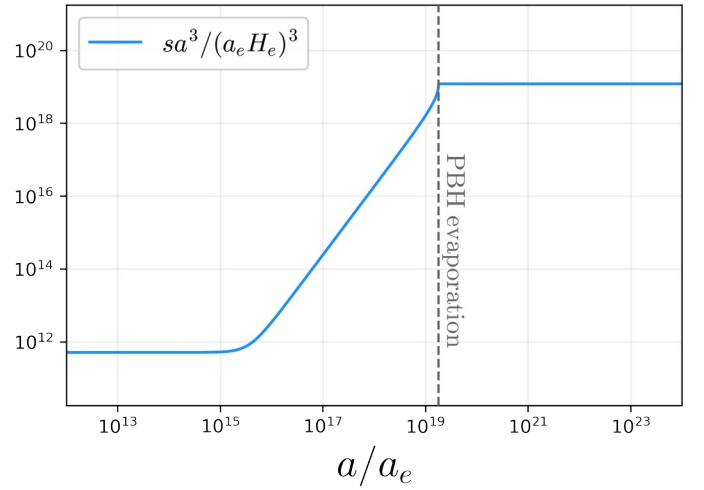
$$1\,\mathrm{g} \lesssim M_{\mathrm{BH}} \lesssim 10^{8}\,\mathrm{g}$$

1) Can dominate the energy density;

2) Emit *all particles* through evaporation;

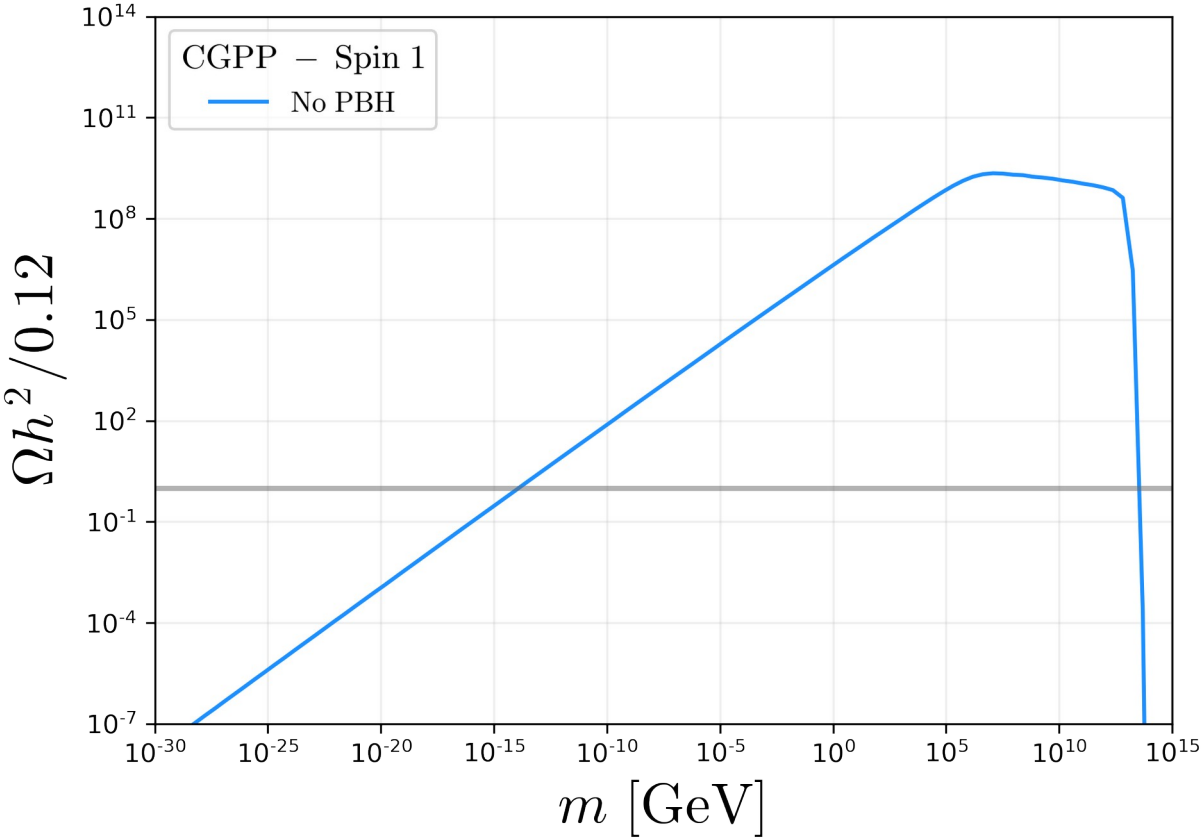
3) Dilute abundance by entropy injection.





Results – Spin-1 DM

- Abundance sensitive to when $m \simeq H$;



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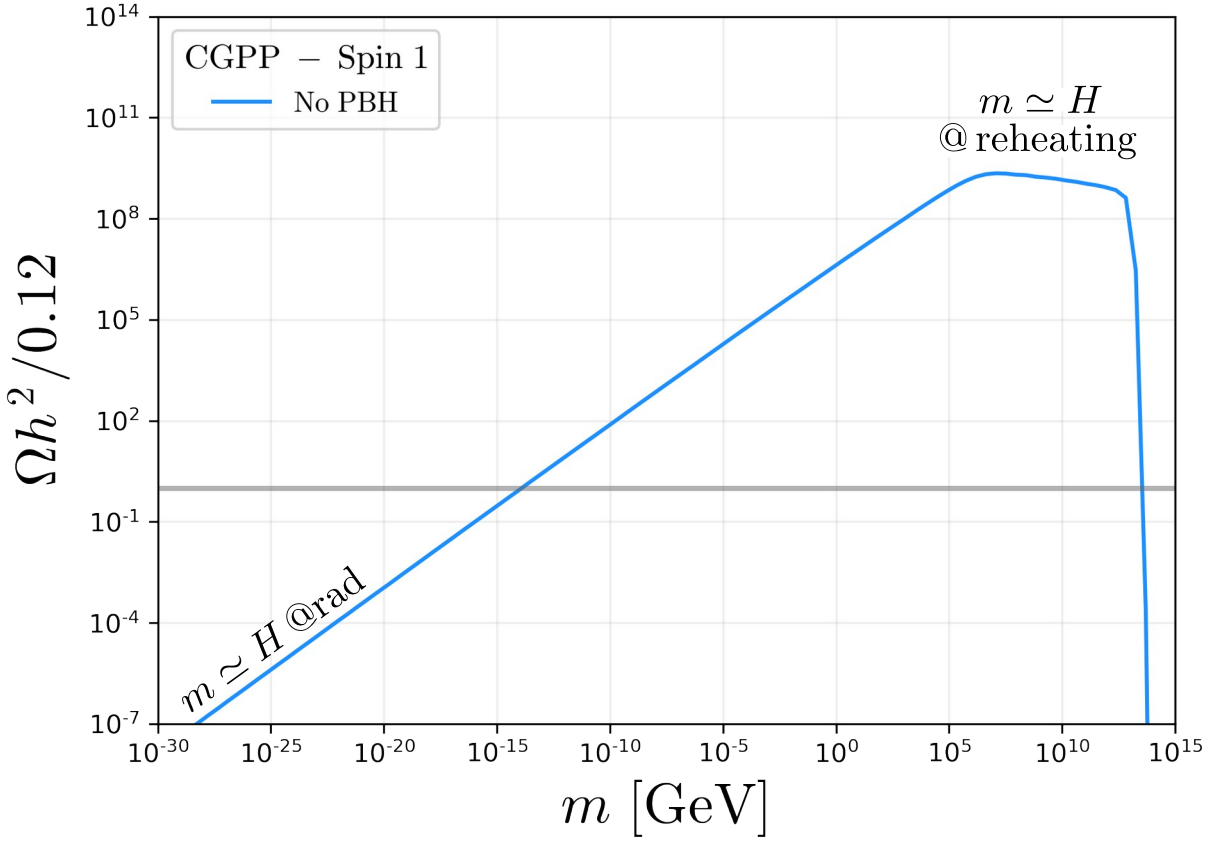
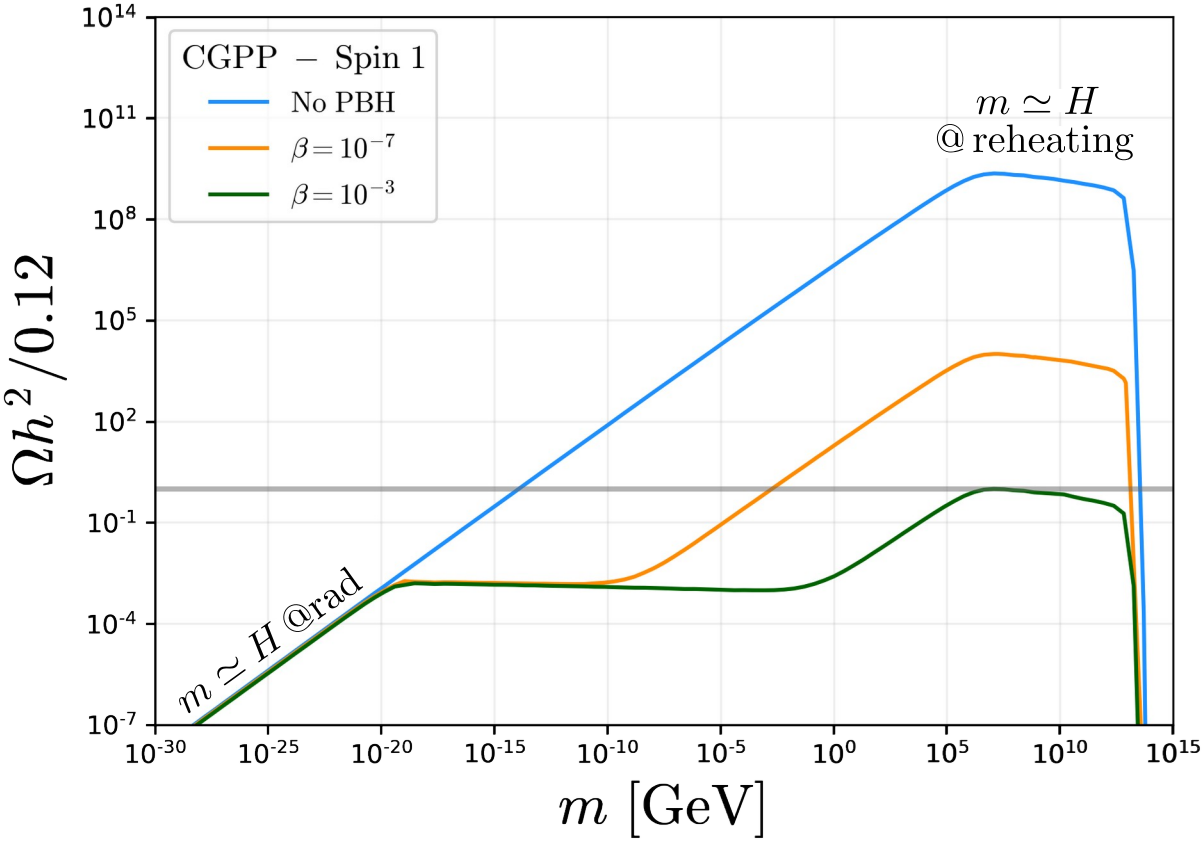


Results – Spin-1 DM

- Abundance sensitive to when $m \simeq H$;
- Strong modifications due to PBHs!
- "Decoupling" of PBH dynamics for low masses.



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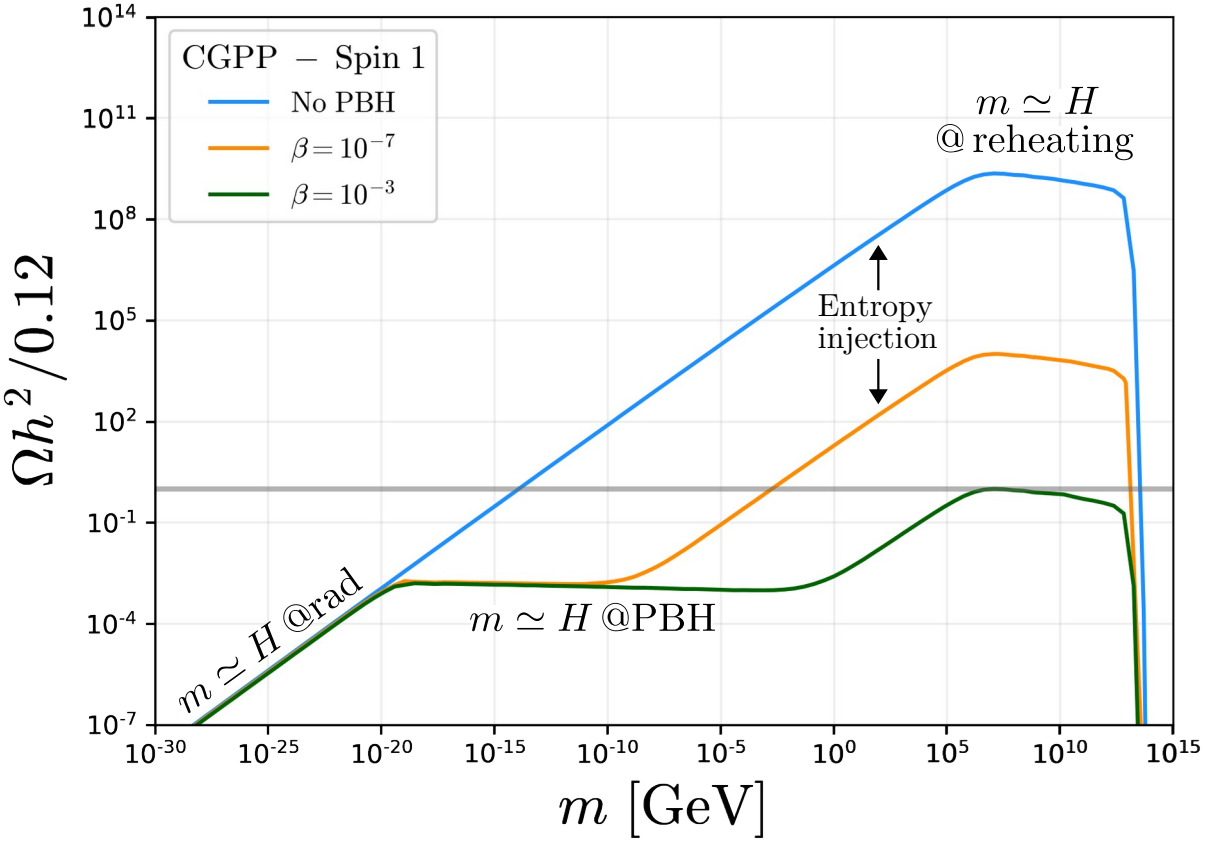
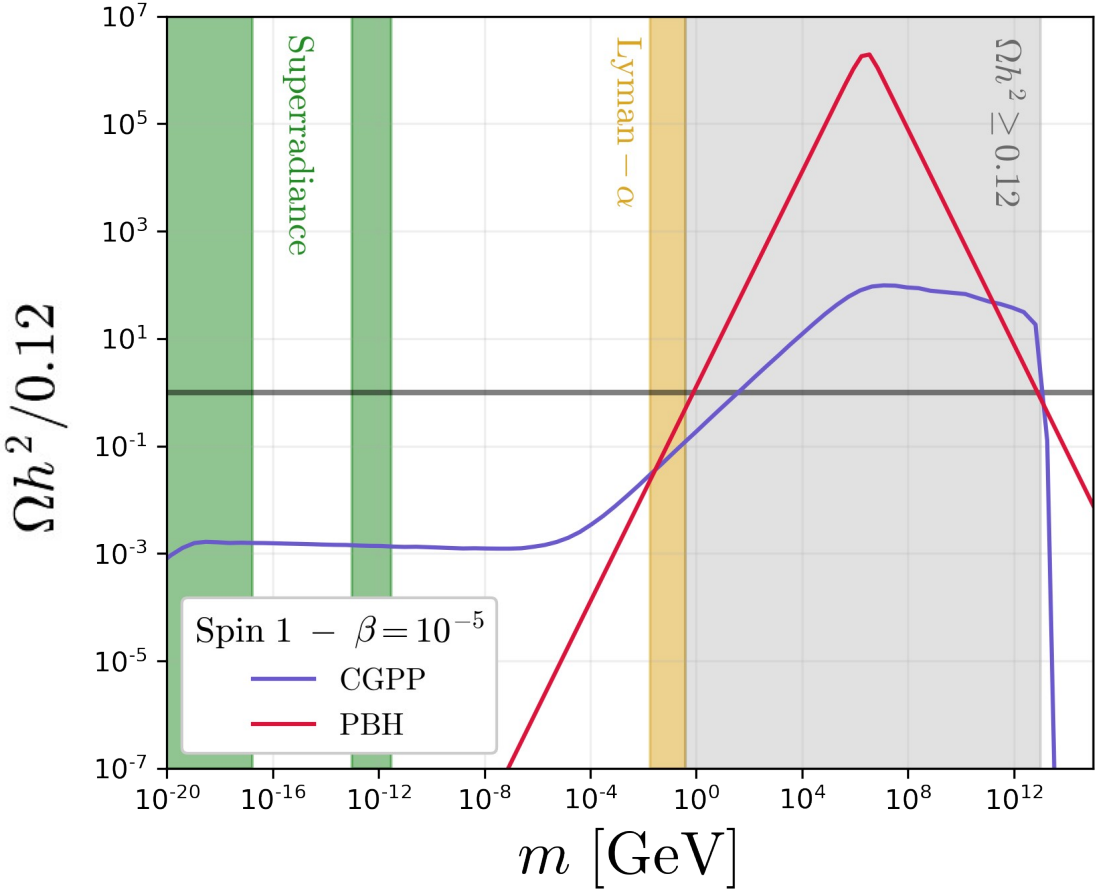


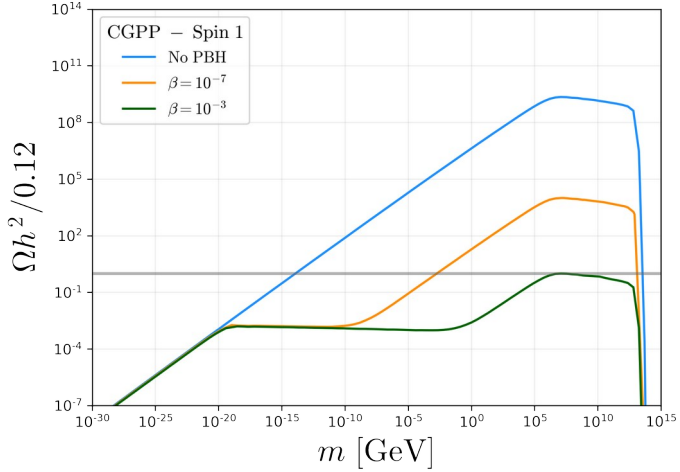
Results – Spin-1 DM

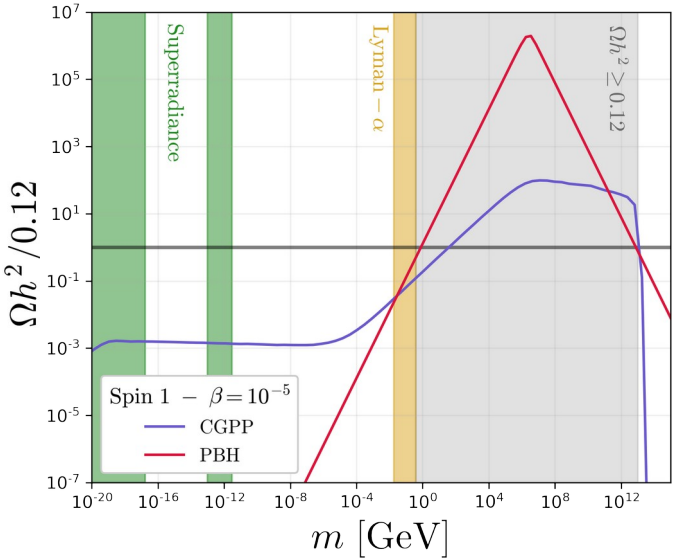
- Add the contribution from evaporation;
- Relevant contraints from superradiance, warm DM and overabundance.



Conclusions

- CGPP is an irreducible contribution to DM abundance;
- PBHs can affect it in an interesting and non-trivial way;
- This interplay deeply impacts the final DM abundance.





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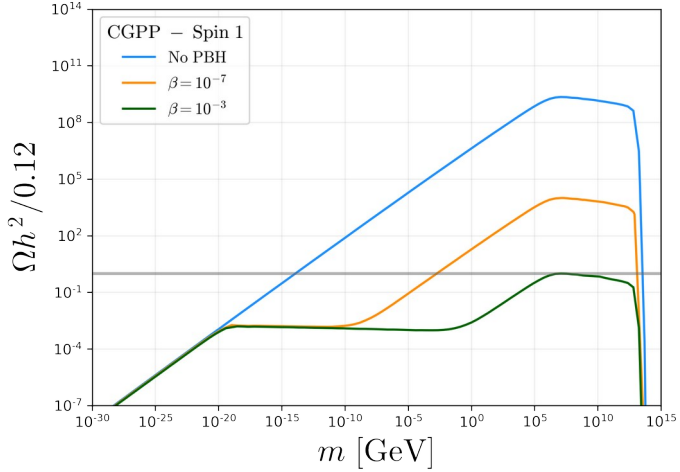
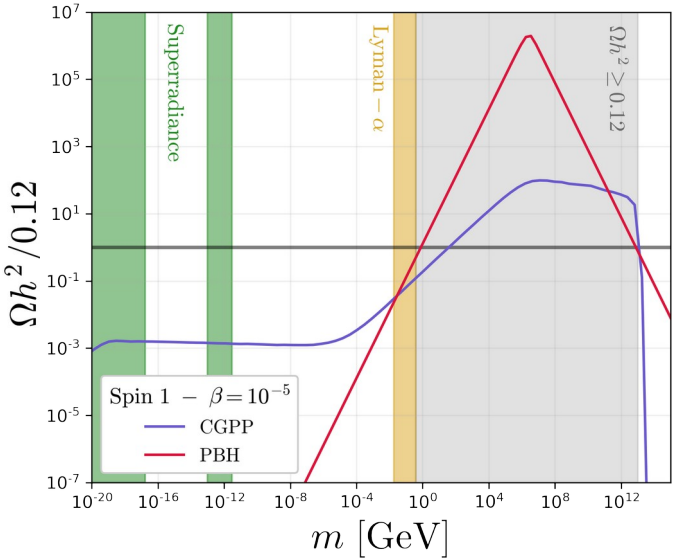
Thank you!





Backup

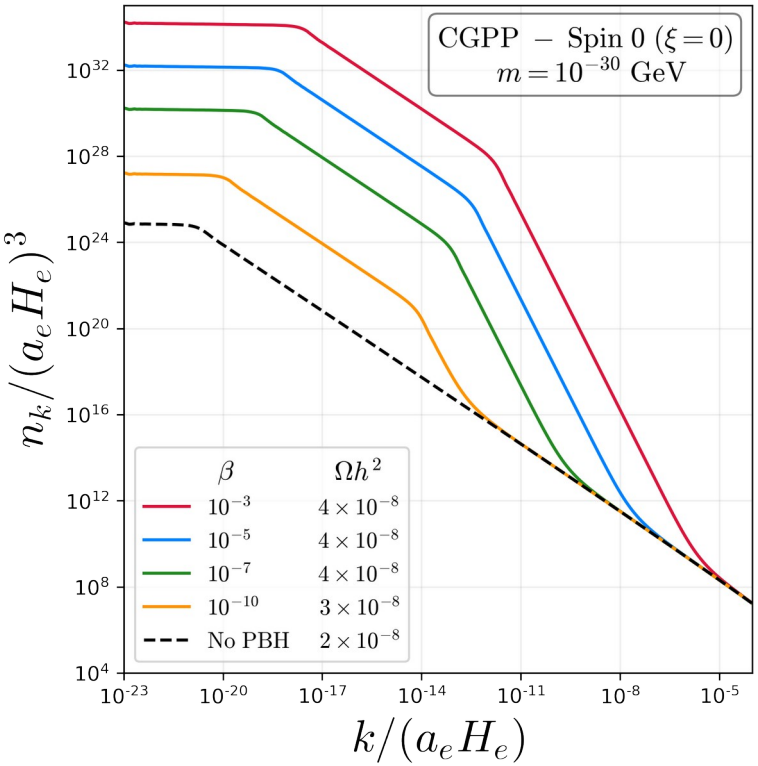
CGPP

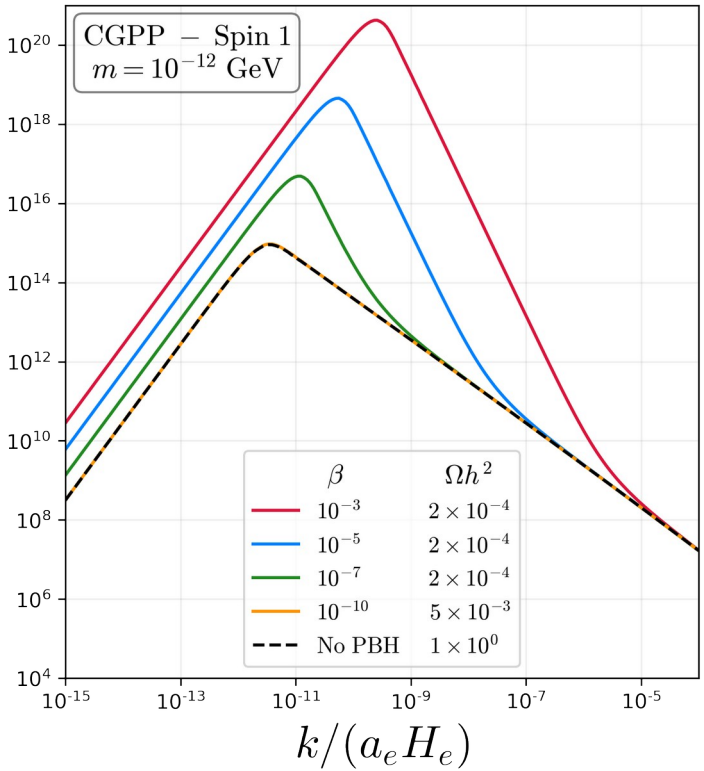
- Equations of motion: $\chi_k''(\eta) + \omega_k^2(\eta)\chi_k(\eta) = 0$

- Spin 0: $\omega_k^2(\eta) = k^2 + a^2 m^2 + \left(\frac{1}{6} - \xi\right) a^2 R$
  - $\xi = 0$ is minimal coupling
  - $\xi = 1/6$ is conformal coupling

- Spin 1: $\omega_k^2(\eta) = k^2 + a^2 m^2 + \frac{k^2 a^2 R/6}{k^2 + a^2 m^2} + \frac{3k^2 a^4 m^2 H^2}{(k^2 + a^2 m^2)^2}$

Results – Momentum spectrum



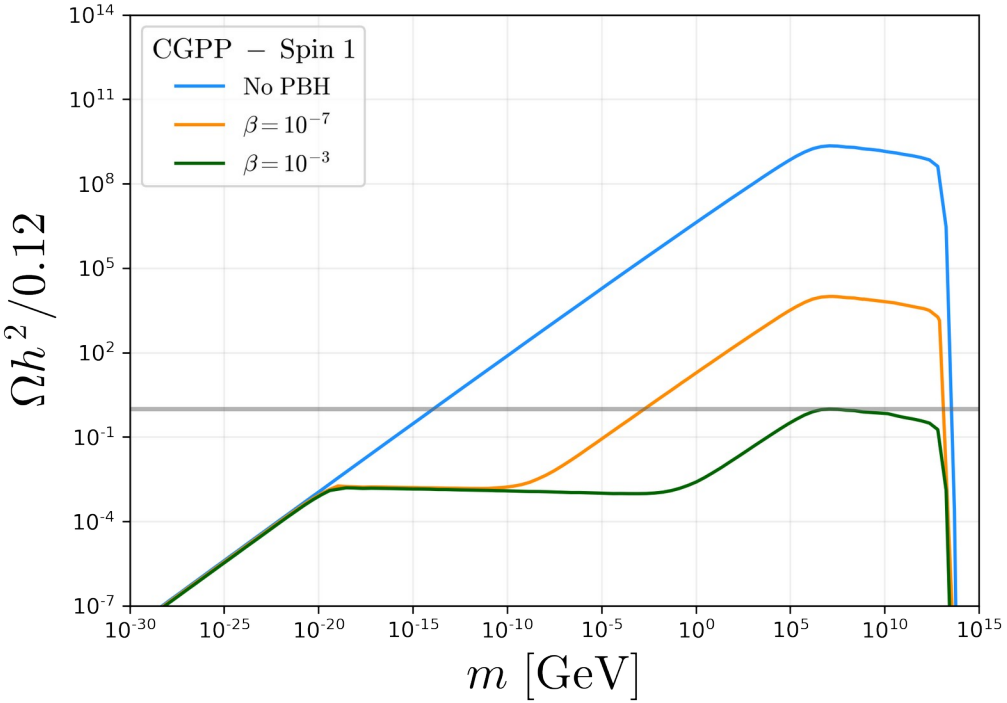


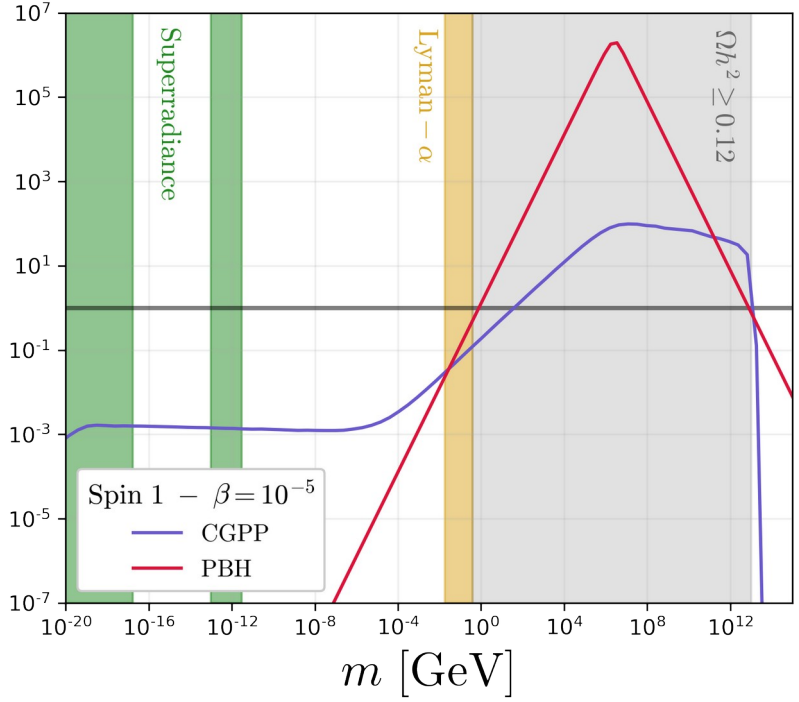
- Number per comoving momentum:

$$n_k = \frac{k^3}{2\pi^2} \times \left[\frac{\omega_k}{2} |\chi_k|^2 + \frac{|\chi_k'|^2}{2\omega_k} - \frac{1}{2} \right]$$

Results – Spin 1

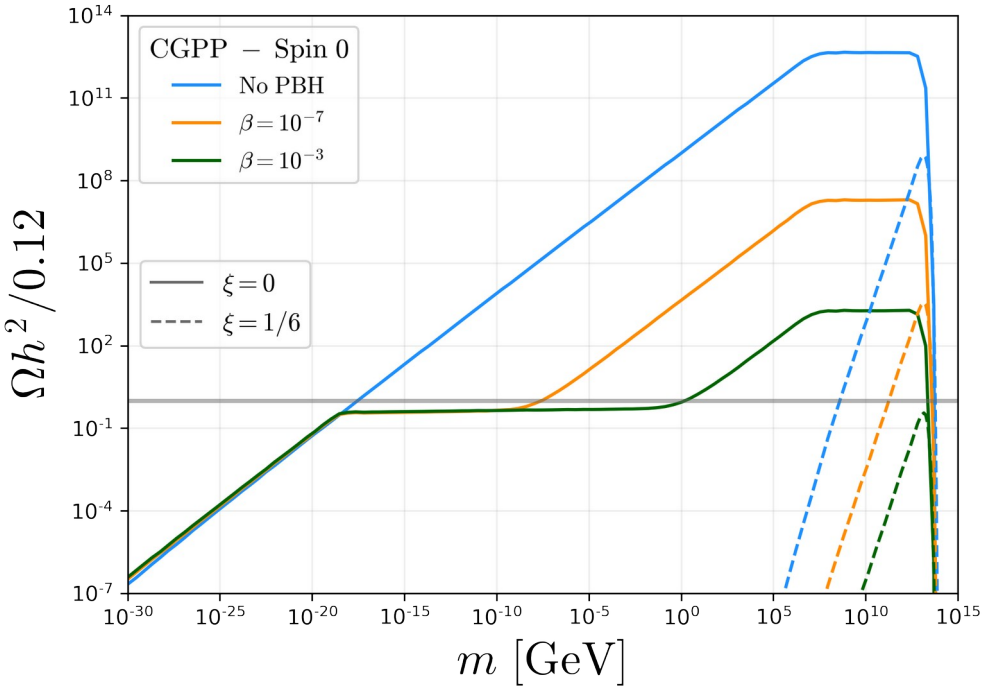
- Minimally coupled strongly constrained by isocurvature

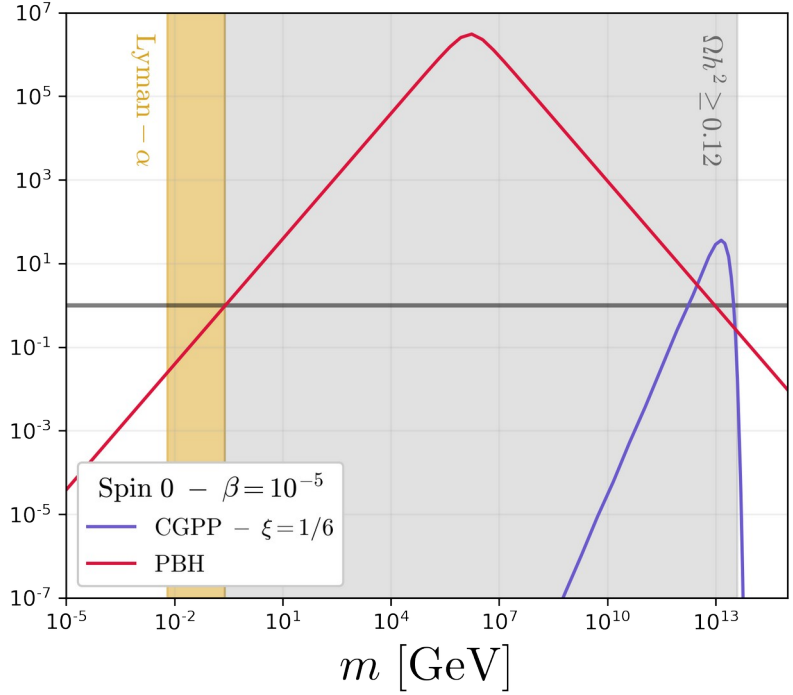




Results – Spin 0

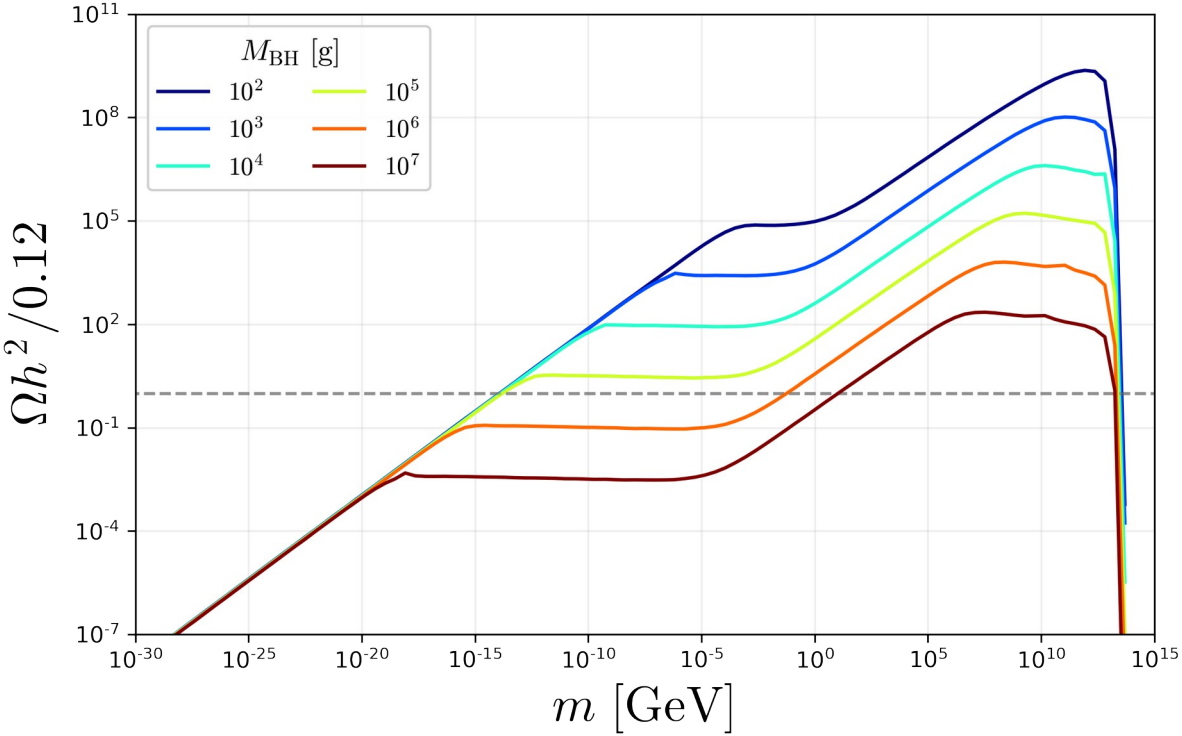
- Minimally coupled strongly constrained by isocurvature





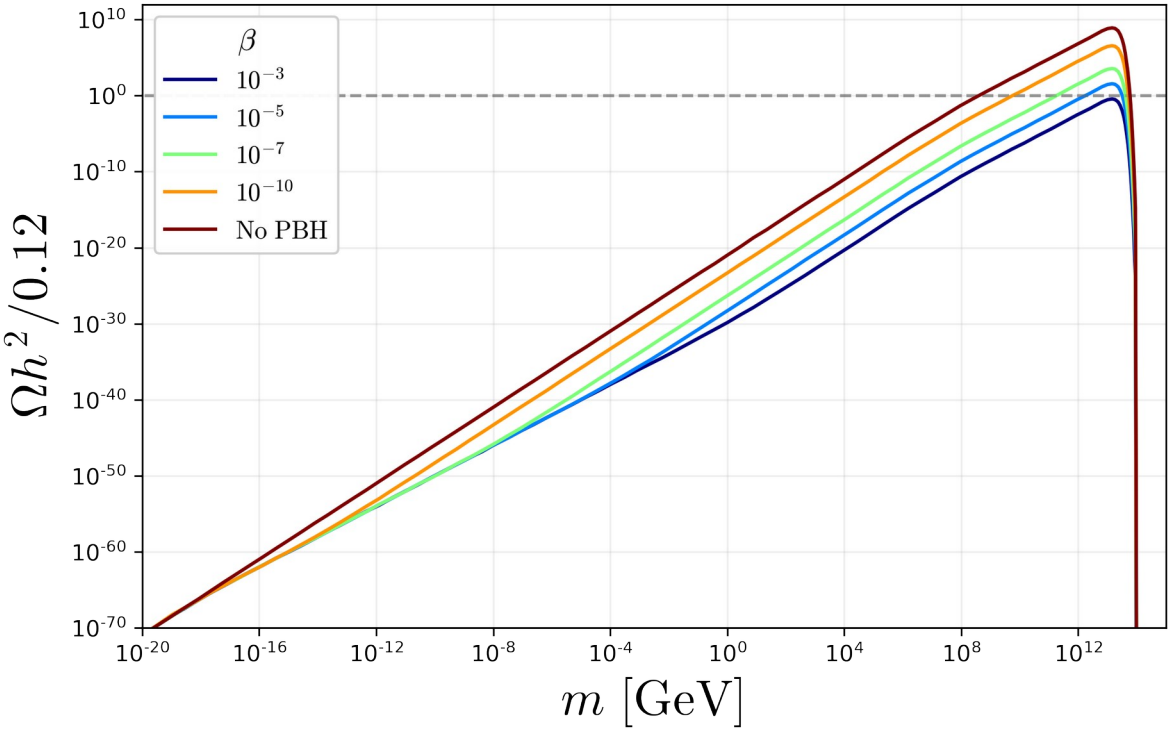
Results – Spin 1 – Varying mass

- Reheating temperature set by PBH mass:



Results – Conformally coupled Spin 0

- Similar behaviour, but very small abundance

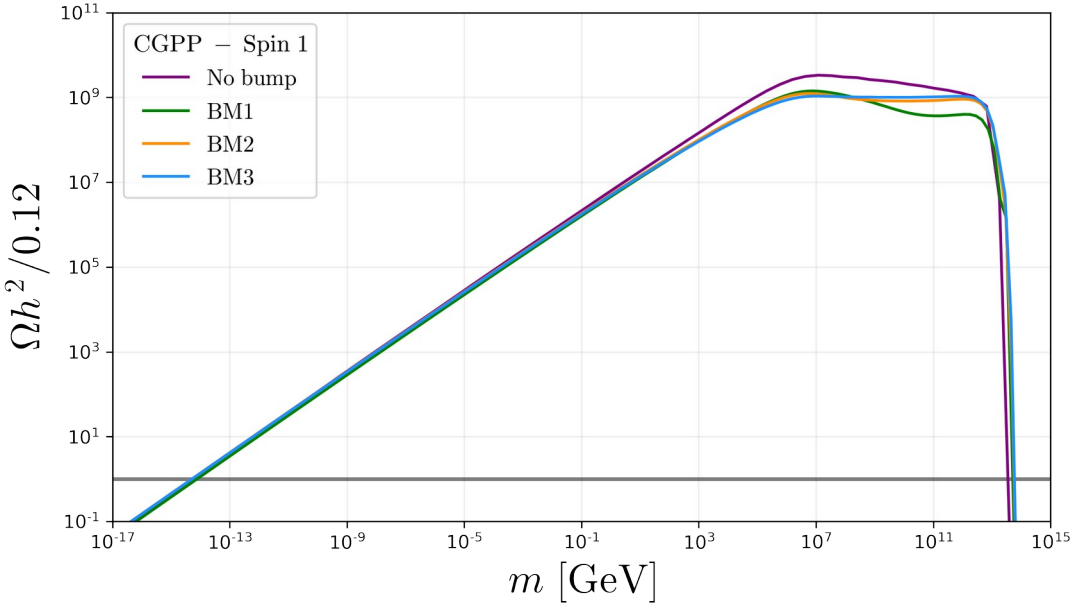


PBH production

- PBHs generated by ultra-slow roll of inflaton field:

$$V(\Phi) \to V(\Phi)(1+\epsilon(\Phi)), \qquad \epsilon(\Phi) = A \exp\left[-\frac{(\Phi-\Phi_0)^2}{\sigma^2}\right]$$

- Only mild effect in the reheating plateu:



PBH dynamics

- PBHs supposely formed during the early universe
- Formation through gravitational collapse of perturbations

$$M_{\mathrm{BH}}(T_i) = \frac{4\pi\gamma}{3}\frac{\rho(T_i)}{H(T_i)^3}$$

- Abundance controlled by

$$\beta = \frac{\rho_{\mathrm{BH}}(T_i)}{\rho(T_i)}$$