Scalar Spectral Index in the Presence of PBHs.

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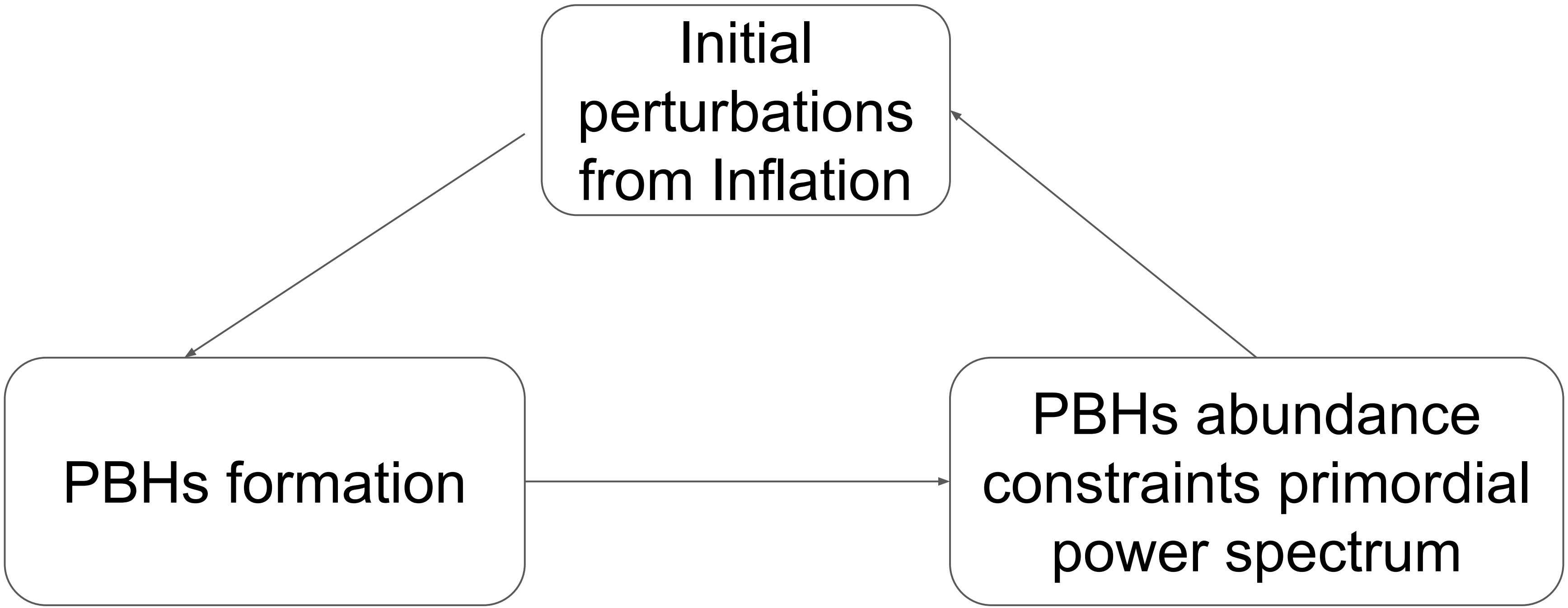
Motivation


Initial perturbations from Inflation
PBHs formation
PBHs abundance constraints primordial power spectrum

Primordial black holes

- Early universe was to a high degree homogeneous and isotropic.
- Tiny fluctuations are believed to have been generated during the inflation due to quantum fluctuations in the inflaton field.
- Primordial Black Holes (PBHs) are formed due to the collapse of the inhomogeneities that were generated during inflation.
- Can also be generated due to topological defects and bubble collisions in the early Universe.

PBHs formation mechanism

- When the size of density perturbations are of the order of horizon scale with amplitude above a certain critical threshold

- During the radiation dominated epoch, a few regions become sufficiently compressed and collapse to a black hole.

Gravity overpowers pressure forces and expansion rate.

The PBH mass at the time of its formation can be estimated to be

$$M_H \approx 10^{15} \left(\frac{t}{10^{-23} s} \right) g$$

A range of different masses are possible in the case of PBHs.

PBHs and Hawking radiation

Hawking radiation: A black body radiation being emitted from a black hole at a temperature which is inversely proportional to its mass.

$$T(M_{\mathrm{BH}}) = \frac{1}{8\pi G M_{\mathrm{BH}}} \approx 1.0 \left(\frac{M_{\mathrm{BH}}}{10^{13} g} \right)^{-1} GeV$$

Lifetime of PBHs

$$t_1 = \left(\frac{M}{10^{15} g} \right)^3 t_{now}$$

Energy injected by PBHs

- In the early universe, the PBHs inject energy (due to Hawking radiation) into photon-baryon fluid.

- Energy injection before the CMB distortion era the fluid can achieve black-body spectrum via double Compton scattering and Bremsstrahlung.

- This results in increase of photon number, while the total number of baryons remains unchanged.

Baryon-photon ratio decreases $\eta \equiv n_b/n_\gamma$

$$z_\mu = 2 \times 10^6 < z < z_i = 1 \times 10^9$$

This redshift range corresponds to energy injections of those PBHs whose mass range at the time of their formation lies between

$$10^9 g < M_{BH} < 10^{11} g$$

If a process pumps energy in a redshift interval *z* and *z* + *dz*, fractional density excess

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = \int dz \frac{1}{\rho_\gamma(z)} \frac{dQ}{dz} \qquad (1)$$

ρ_γ (*z*) is background energy density of photons which scales as $(1+z)^4$

$$\frac{\eta_{CMB}}{\eta_{BBN}} = \left(1 - \frac{3}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma}\right)$$

Nakama et al. obtained an upper bound on the density fraction of the injected energy as

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} < 7.71 \times 10^{-2} \quad (2)$$

- We calculate the fractional density excess for PBHs evaporation.
- This fractional density excess depends on n_s.
- Using observational bound on density fraction eq.(2) we place a bound on n_s

The gauge-invariant curvature perturbation ζ on the uniform-density hyper surface is

$$\zeta = \mathcal{R} - H\frac{\delta\rho}{\dot{\rho}}$$

Green et. al derived the relation between the threshold value of density perturbations and the threshold value of ζ_{th}

We assume a power-law primordial power spectrum

$$\mathcal{P}_{\mathcal{R}} = \mathcal{R}_c(k/k_0)^{n_s - 1}$$

When the density fields smoothed by a Gaussian window function with comoving size R, the peak theory gives the comoving number density of the peaks

$$n(\nu, R) = \frac{1}{(2\pi)^2} \frac{(n_s - 1)^{3/2}}{6^{3/2} R^3} (\nu^2 - 1) \exp\left(-\frac{\nu^2}{2}\right)$$

where,

$$\nu = \left[\frac{2(k_0 R)^{n_s - 1}}{\mathcal{R}_c \Gamma((n_s - 1)/2)}\right]^{1/2} \zeta_{\mathrm{th}}$$

The comoving number density of PBHs formed is deduced from the collapse of overdense regions with scale R=1/aH

Estimation of injected energy via PBHs evaporation

Consider a Schwarzschild black hole with mass M_{BH} which emits particles near the horizon with spin 's'

The rate of total energy emitted between *E* and *E*+*dE* per degree of freedom is given by

$$\frac{dN_{emit}}{dtdE}dE = \frac{\Gamma_s}{2\pi\hbar}\left[\exp\left(\frac{E}{kT(M_{\rm BH})}\right) - (-1)^{2s}\right]^{-1} dE$$

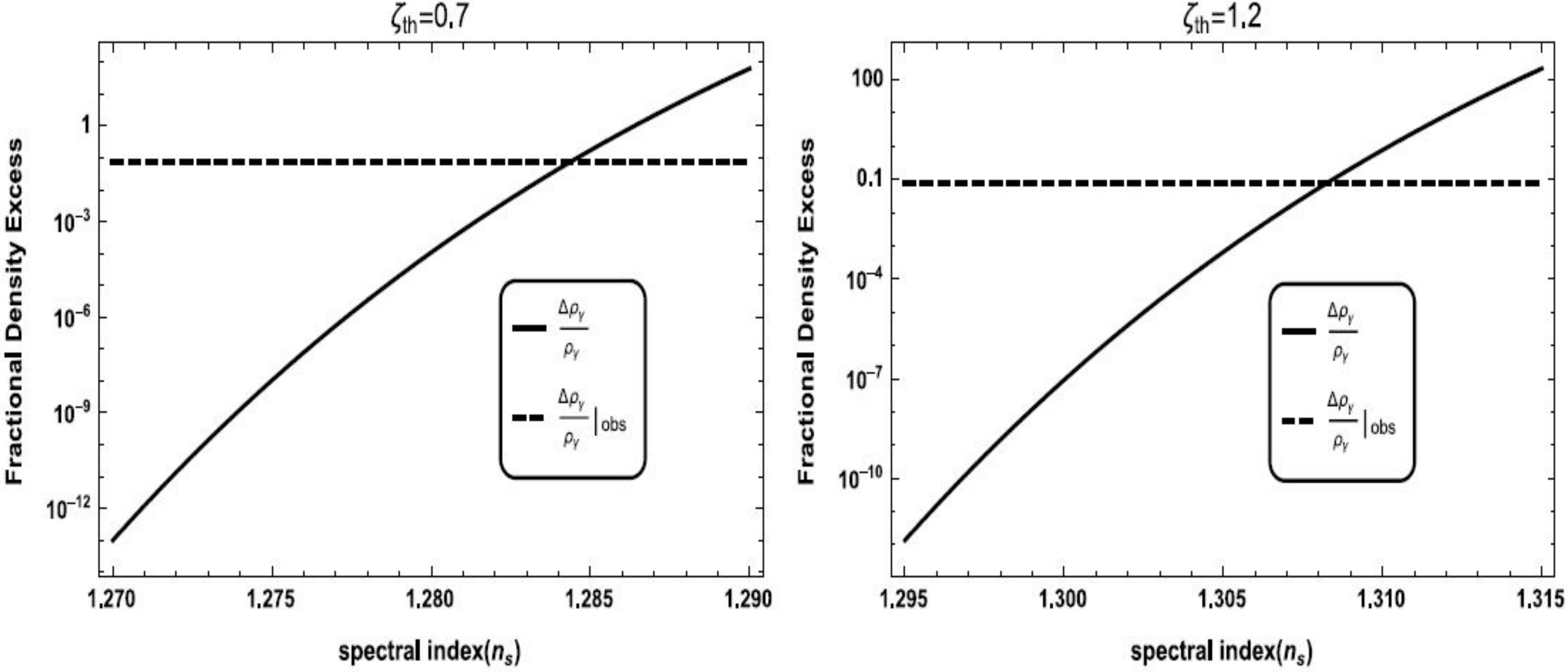
We can express the energy injection rate due to evaporating PBHs as

$$\dot{Q}(t) = \int_{M_{min}(t)}^{M_H(t)} dM_{\rm BH} \frac{dn}{dM_{\rm BH}} \int_0^\infty dE a^{-3}(t) E \frac{dN_{emit}}{dtdE}$$

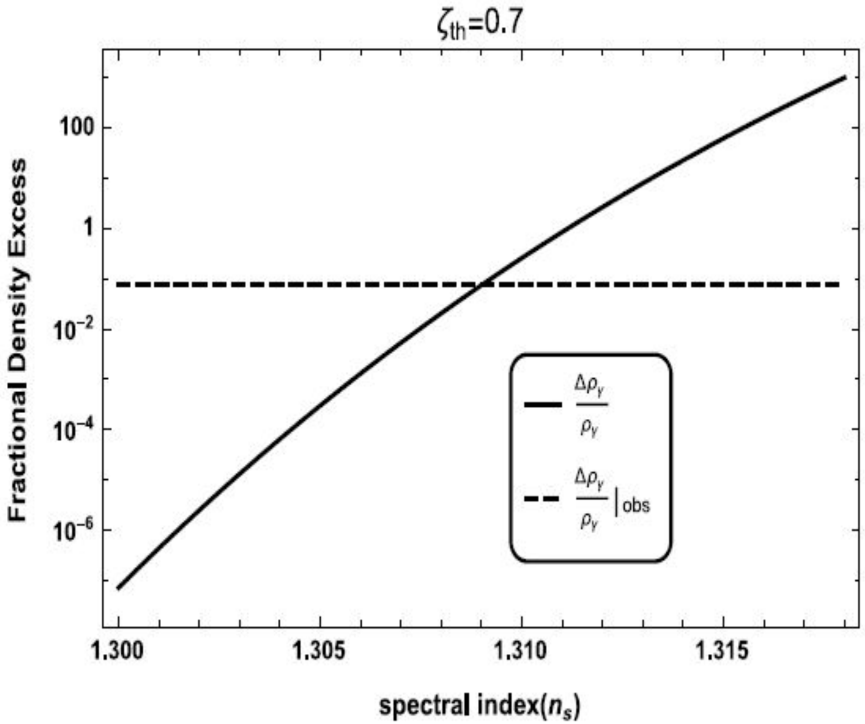
We estimate the total energy dissipated by evaporating PBHs into the background fluid between the redshifts z_μ and z_i

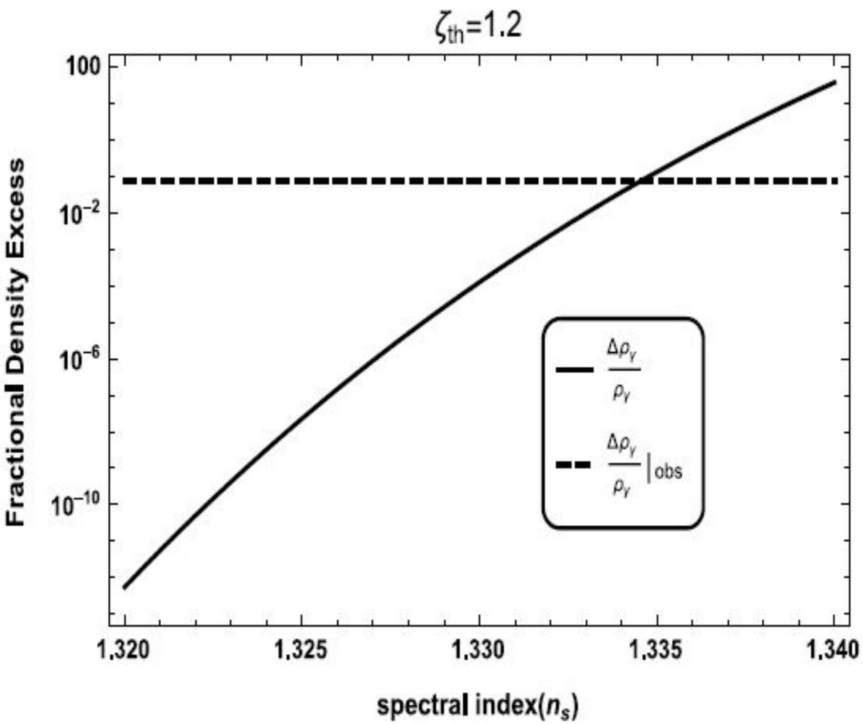
$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = \int dz \frac{1}{\rho_\gamma(z)} \frac{dQ}{dz}$$

Results



$$n_s < 1.284, \zeta_{\rm th} = 0.7 \qquad n_s < 1.308, \zeta_{\rm th} = 1.2$$

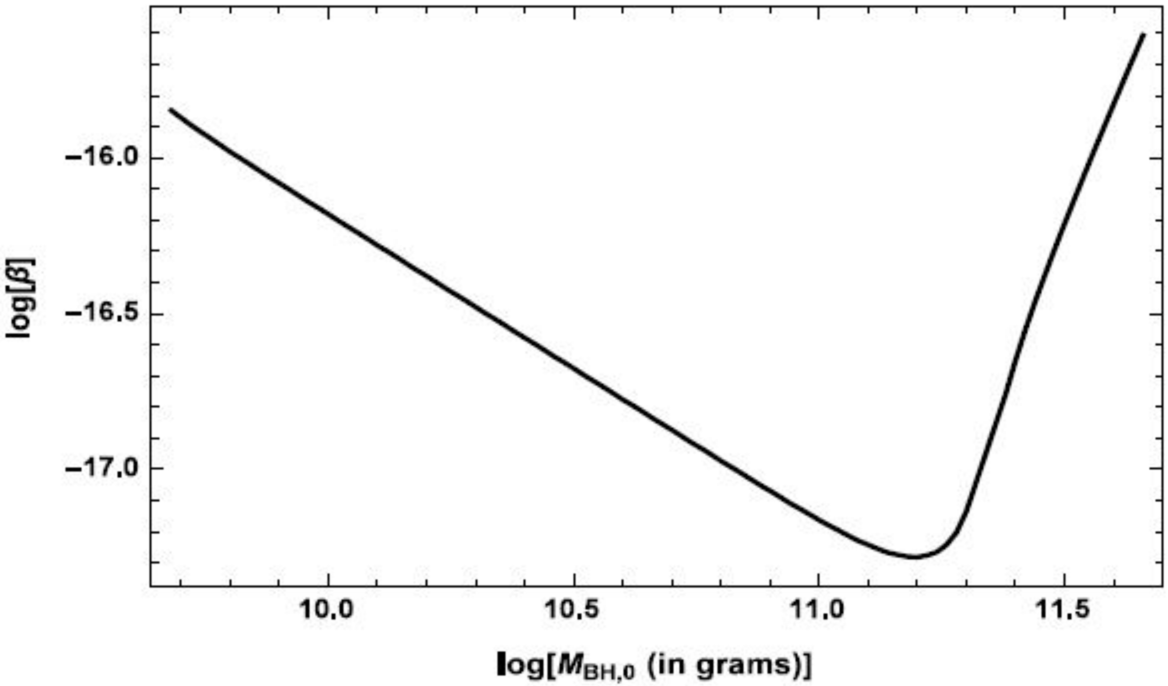




$$n_s < 1.309, \zeta_{\text{th}} = 0.7 \qquad n_s < 1.334, \zeta_{\text{th}} = 1.2$$

The PBH abundance which represents the fraction of total energy density which collapses to form the black holes

$$\beta(M_{\rm BH,0}) \equiv \frac{\rho_{\rm BH}(M_{\rm BH,0})}{\rho} = \frac{\int_{M_{\rm BH,0}}^{\infty} M_{\rm BH} dn(\nu, M_{\rm BH})}{\rho}$$



$$\beta < 10^{-17}$$

Summary

We use BBN and CMB constraints on η to obtain an upper bound on n_s of density fluctuations at small scales which are difficult to be probed through the observations of CMB anisotropies and distortions.

Thank You !