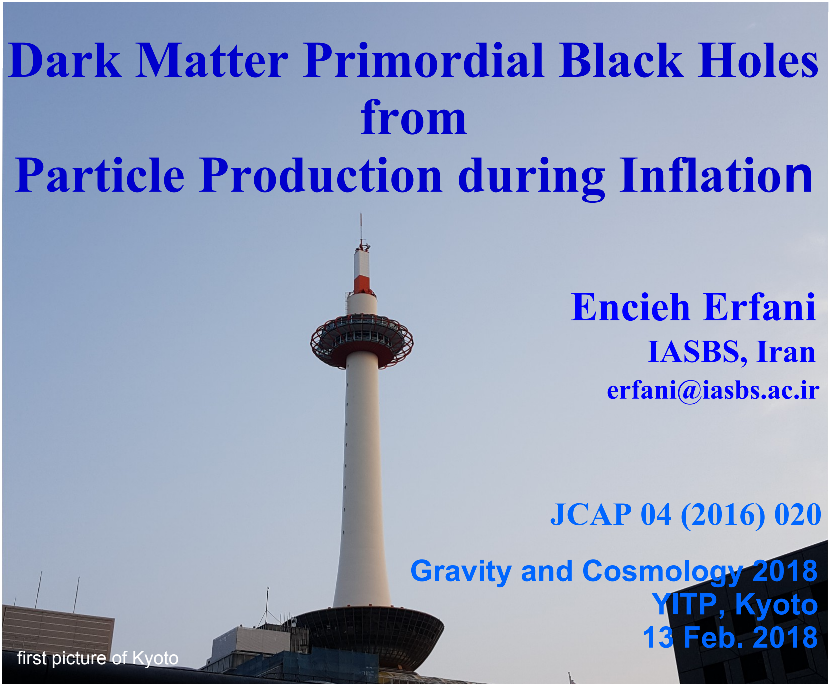
Dark Matter Primordial Black Holes from Particle Production during Inflation



first picture of Kyoto

Encieh Erfani
IASBS, Iran
erfani@iasbs.ac.ir

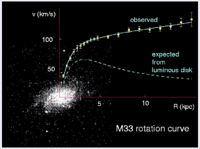
JCAP 04 (2016) 020

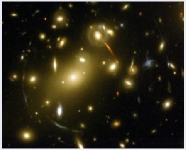
Gravity and Cosmology 2018
YITP, Kyoto
13 Feb. 2018

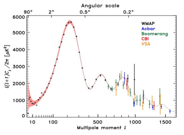
Outline

Dark Matter

Evidences







Properties

- stable
- neutral
- weakly interacting
- right relic density

Candidates

- Axions
- Sterile neutrinos
- WIMPs
- Primordial Black Holes (PBHs)

Primordial Black Holes

Definition

A PBH is a type of black hole that is **not** formed by the gravitational collapse of a star, but by the extreme density of matter present during the Universe's early expansion.

PBHs properties

Mass: $M_{\mathrm{BH}} = 10^{15}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)\,\mathrm{g}$

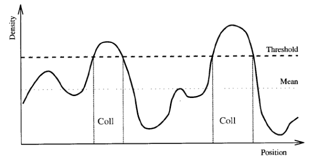
Temperature: $T_{\mathrm{BH}} \approx 10^{-7}\left(\frac{M}{M_\odot}\right)^{-1}\,\mathrm{K}$

Lifetime: $\tau_{\mathrm{BH}} \approx 10^{64}\left(\frac{M}{M_\odot}\right)^{3}\,\mathrm{y}$

$M_\odot \simeq 2\times 10^{33}\,\mathrm{g}$

M_{BH}	τ_{BH}
A man	$10^{-12}\,\mathrm{s}$
A building	$1\,\mathrm{s}$
$10^{15}\,\mathrm{g}$	$10^{10}\,\mathrm{y}$
The Earth	$10^{49}\,\mathrm{y}$
The Sun	$10^{66}\,\mathrm{y}$
The Galaxy	$10^{99}\,\mathrm{y}$

Press-Schechter Formalism

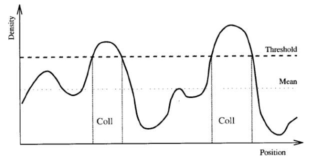


The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.

$$f(\geq M) = \gamma \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$$

Press-Schechter Formalism

The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.

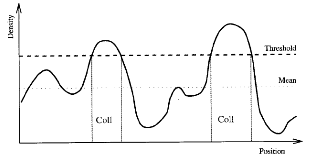


$$f(\geq M) = \gamma \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$$

$\delta_{\rm th} = 0.4135$

Press-Schechter Formalism

The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.



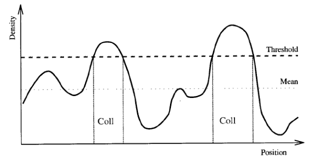
$$f(\geq M) = \gamma \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$$

$\delta_{\rm th} = 0.4135$

Gaussian PDF: $P_{\rm G}(\delta;\, R) = \frac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\frac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$

Press-Schechter Formalism

The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.



$$f(\geq M) = \gamma \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$$

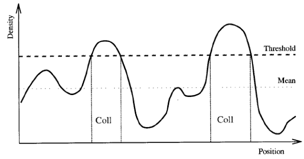
$\delta_{\rm th} = 0.4135$

Gaussian PDF: $P_{\rm G}(\delta;\, R) = \frac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\frac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$

$$\delta^2(k,t) \equiv \mathcal{P}_\delta(k,t) = \frac{4(1+w)^2}{(5+3w)^2}\left(\frac{k}{aH}\right)^4 \mathcal{P}_{\mathcal{R}_c}(k) \qquad w = 1/3$$

Press-Schechter Formalism

The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.



$$f(\geq M) = \gamma \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$$

$\delta_{\rm th} = 0.4135$

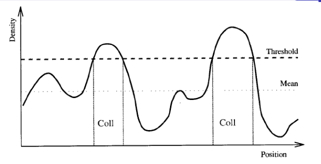
Gaussian PDF: $P_{\rm G}(\delta;\, R) = \dfrac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\dfrac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$

$$\delta^2(k,t) \equiv \mathcal{P}_\delta(k,t) = \frac{4(1+w)^2}{(5+3w)^2}\left(\frac{k}{aH}\right)^4 \mathcal{P}_{\mathcal{R}_c}(k) \qquad w = 1/3$$

$$\mathcal{P}_{\mathcal{R}_c}(k) = \mathcal{P}_{\mathcal{R}_c}(k_0)\left(\frac{k}{k_0}\right)^{n(k)-1}$$

Press-Schechter Formalism

The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.



$$f(\geq M) = \gamma \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$$

$\delta_{\rm th} = 0.4135$

Gaussian PDF: $P_{\rm G}(\delta;\, R) = \frac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\frac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$

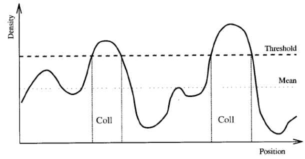
$$\delta^2(k,t) \equiv \mathcal{P}_\delta(k,t) = \frac{4(1+w)^2}{(5+3w)^2}\left(\frac{k}{aH}\right)^4 \mathcal{P}_{\mathcal{R}_c}(k) \qquad w = 1/3$$

$$\mathcal{P}_{\mathcal{R}_c}(k) = \mathcal{P}_{\mathcal{R}_c}(k_0)\left(\frac{k}{k_0}\right)^{n(k)-1}$$

$$\sigma_\delta^2(R) = \int_0^\infty W^2(kR)\mathcal{P}_\delta(k)\frac{\mathrm{d}k}{k} \qquad W(kR) = \exp\left(-k^2R^2/2\right)$$

Press-Schechter Formalism

The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.



$$f(\geq M) = \gamma \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$$

$\delta_{\rm th} = 0.4135$

Gaussian PDF: $P_{\rm G}(\delta;\, R) = \dfrac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\dfrac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$

$$\delta^2(k,t) \equiv \mathcal{P}_\delta(k,t) = \frac{4(1+w)^2}{(5+3w)^2}\left(\frac{k}{aH}\right)^4 \mathcal{P}_{\mathcal{R}_c}(k) \qquad w = 1/3$$

$$\mathcal{P}_{\mathcal{R}_c}(k) = \mathcal{P}_{\mathcal{R}_c}(k_0)\left(\frac{k}{k_0}\right)^{n(k)-1}$$

$$\sigma_\delta^2(R) = \int_0^\infty W^2(kR)\mathcal{P}_\delta(k)\frac{\mathrm{d}k}{k} \qquad W(kR) = \exp\left(-k^2R^2/2\right)$$

$$M_{\rm PBH} = \gamma M_{\rm PH} \xrightarrow{\gamma = w^{3/2}} \frac{R}{1\,{\rm Mpc}} = 5.5\times 10^{-24}\gamma^{-\frac{1}{2}}\left(\frac{M_{\rm PBH}}{1\,{\rm g}}\right)^{1/2}\left(\frac{g_*}{3.36}\right)^{1/6}$$

Gaussian PDF:

$$P_{\rm G}(\delta;\, R) = \frac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\frac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$$

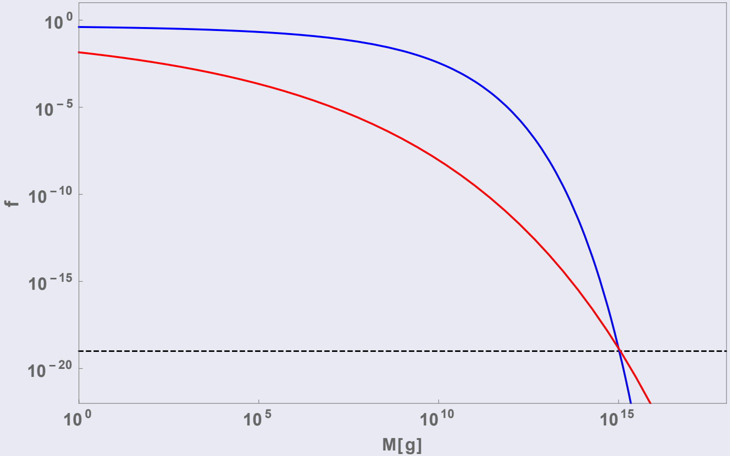
$$f_{\rm G} = \frac{1}{2}\,\mathrm{erfc}\left(\delta_{\rm th}/\sqrt{2\sigma_\delta^2(R)}\right)$$

non-Gaussian PDF:

$$P_{\rm NG}(\delta;\, R) = \frac{1}{\sqrt{2\pi\left(\delta + \sigma_g^2(R)\right)}\,\sigma_g(R)} \exp\left(-\frac{\delta + \sigma_g^2(R)}{2\sigma_g^2(R)}\right)$$

$$f_{\rm NG} = \mathrm{erfc}\left(\sqrt{\delta_{\rm th} + \sigma_g^2(R)}/\sqrt{2\sigma_g^2(R)}\right)$$

$f(\geq M)$ diagram for the mass range $10^0 - 10^{20}\,\mathrm{g}$



Result

$n_s(k_{\rm PBH}) \geq 1.418 \quad \Rightarrow \quad \mathcal{P}_\zeta \simeq 2 \times 10^{-2}$ for Gaussian PDF

$n_s(k_{\rm PBH}) \geq 1.322 \quad \Rightarrow \quad \mathcal{P}_\zeta \simeq 4 \times 10^{-4}$ for non-Gaussian PDF

Inflation

Inflation parameters

$$\mathcal{P}_{\zeta,\,\mathrm{vac.}}(k) = \mathcal{P}_{\zeta,\,\mathrm{vac.}}(k_0)\left(\frac{k}{k_0}\right)^{n_\mathrm{s}(k)-1}$$

$$n_\mathrm{s}(k_0) - 1 \equiv \frac{d\ln \mathcal{P}_{\zeta,\,\mathrm{vac.}}(k)}{d\ln k}$$

$$r = \frac{\mathcal{P}_\mathrm{t}(k)}{\mathcal{P}_\zeta(k)}\,, \qquad \mathcal{P}_{\mathrm{t},\,\mathrm{vac.}}(k) = \frac{2}{\pi^2}\left(\frac{H}{M_\mathrm{P}}\right)^2\left(\frac{k}{k_0}\right)^{n_\mathrm{t}}$$

$$B_\zeta(k_1,\ k_2,\ k_3) = f_\mathrm{NL} F(k_1,\ k_2,\ k_3)$$

Observation

Planck XX, arXiv: 1502.01592

$$\ln(10^{10}\mathcal{P}_{\zeta,\,\mathrm{vac.}}(k_0)) = 3.094 \pm 0.034 \qquad k_0 = 0.05\ \mathrm{Mpc}^{-1}$$

$$n_\mathrm{s} = 0.9645 \pm 0.0049$$

$$r_{0.002} < 0.10 \qquad (95\,\%\,\mathrm{CL})$$

$$f_\mathrm{NL} = 22.7 \pm 25.5$$

PBHs formation from Particle Production

direct or gravitational coupling of the inflaton (ϕ) to another field (χ)

$$\mathcal{L}(\phi,\,\chi) = -\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) - \frac{1}{2}\partial_\mu\chi\,\partial^\mu\chi - U(\chi) + \mathcal{L}_{\rm int}(\phi,\chi)$$

The equations of motion for the inflaton field:

$$H^2 = \frac{1}{3M_{\rm P}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_\chi\right)$$

$$\ddot{\phi} + 3H\,\dot{\phi} + V'(\phi) = \frac{\partial\mathcal{L}_{\rm int}}{\partial\phi}$$

The inflaton fluctuations satisfy

$$\ddot{\delta\phi} + 3H\,\dot{\delta\phi} - \frac{\nabla^2}{a^2}\delta\phi + V''(\phi)\,\delta\phi = \delta\left(\frac{\partial\mathcal{L}_{\rm int}}{\partial\phi}\right)$$

PBHs formation from Particle Production

direct or gravitational coupling of the inflaton (ϕ) to another field (χ)

$$\mathcal{L}(\phi,\,\chi) = -\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) - \frac{1}{2}\partial_\mu\chi\,\partial^\mu\chi - U(\chi) + \mathcal{L}_{\rm int}(\phi,\chi)$$

The equations of motion for the inflaton field:

$$H^2 = \frac{1}{3M_{\rm P}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_\chi\right)$$

$$\ddot{\phi} + 3H\,\dot{\phi} + V'(\phi) = \frac{\partial\mathcal{L}_{\rm int}}{\partial\phi}$$

The inflaton fluctuations satisfy

$$\ddot{\delta\phi} + 3H\,\dot{\delta\phi} - \frac{\nabla^2}{a^2}\delta\phi + V''(\phi)\,\delta\phi = \delta\left(\frac{\partial\mathcal{L}_{\rm int}}{\partial\phi}\right)$$

Result

$$\mathcal{P}_\zeta(k) = \mathcal{P}_{\zeta,\,\rm vac.}(k) + \mathcal{P}_{\zeta,\,\rm src.}(k)$$

$$\mathcal{P}_{\rm t}(k) = \mathcal{P}_{\rm t,\,vac.}(k) + \mathcal{P}_{\rm t,\,src.}(k)$$

Gauge Production

$$\mathcal{L}_{\rm int} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\alpha}{4f} \Phi \, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Gauge Production

$$\mathcal{L}_{\rm int} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{4f}\Phi\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

direct coupling

$$\mathcal{P}_\zeta = \mathcal{P}_{\zeta,\,\rm vac.}\left(1 + 7.5\times 10^{-5}\,\epsilon^2\,\mathcal{P}_{\zeta,\,\rm vac.}X^2\right)$$

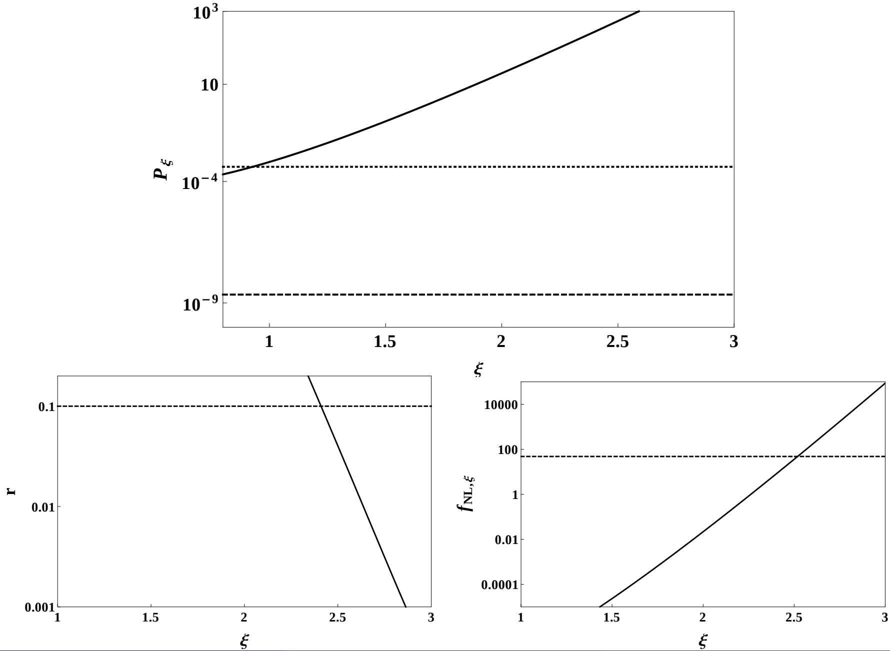
$$r = 16\epsilon\,\frac{1 + 2.2\times 10^{-7}\,\mathcal{P}_{\rm t,\,vac.}\,X^2}{1 + 7.5\times 10^{-5}\,\epsilon^2\,\mathcal{P}_{\zeta,\,\rm vac.}X^2}$$

$$f_{\rm NL,\,\zeta}^{\rm equil.} \approx 4.4\times 10^{10}\,\epsilon^3\,\mathcal{P}_{\zeta,\,\rm vac.}^3\,X^3$$

where

$$X \equiv \frac{e^{2\pi\xi}}{\xi^3} \qquad \xi \equiv \frac{\alpha}{2fH}\dot{\Phi}$$

Result



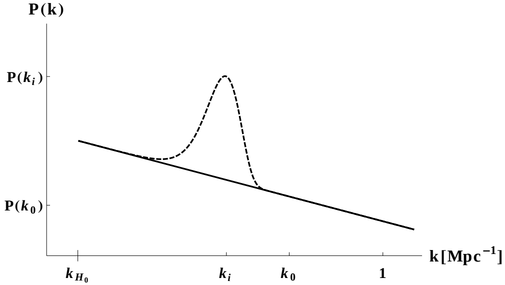
10^3
10
10^{-4}
10^{-9}
P_ξ
1
1.5
2
2.5
3
ξ
0.1
0.01
0.001
r
1
1.5
2
2.5
3
ξ
10000
100
1
0.01
0.0001
$f_{\mathrm{NL},\xi}$
1
1.5
2
2.5
3
ξ

Scalar Production

$$\mathcal{L}_{\rm int}(\phi,\,\chi) = -\frac{g^2}{2}\,(\phi-\phi_0)^2\,\chi^2$$

$$\mathcal{P}_{\zeta,\,{\rm src.}}(k) \sim A\,k^3 e^{-\frac{\pi}{2}\left(\frac{k}{k_i}\right)^2}$$

Result



$$A \lesssim 4\times 10^{-4}$$

Conclusions

- The fluctuation which arise at inflation are the most likely source of PBHs.
- The spectral index at scale of PBHs formation should be at least 1.418 (1.322) for Gaussian (non-Gaussian) PDF.
- The most stringent constraints on the gauge production parameter is derived from the non-production of DM PBHs at the end of inflation and the bounds from the bispectrum and the tensor-to-scalar ratio are weaker.
- In the scenario where the inflaton field coupled to a scalar field, the model is free of DM PBHs overproduction in the CMB observational range if the amplitude of the generated bump in the scalar power spectrum, A is less than 4×10^{-4}.


mount Everest mass ~ 10^{15} g
Thank you