Primordial Black Holes from Pre-Big Bang

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Why PBHs?

Firstly studied by Carr & Hawking in '70 as objects formed by gravitational collapse of large inhomogeneities in the early universe.

- New access to the early universe. An important instrument to study the inflationary epoch.
- Primordial black holes give us an important alternative to the dark matter research.
  - Advantage of not needing (necessarily) new physics.

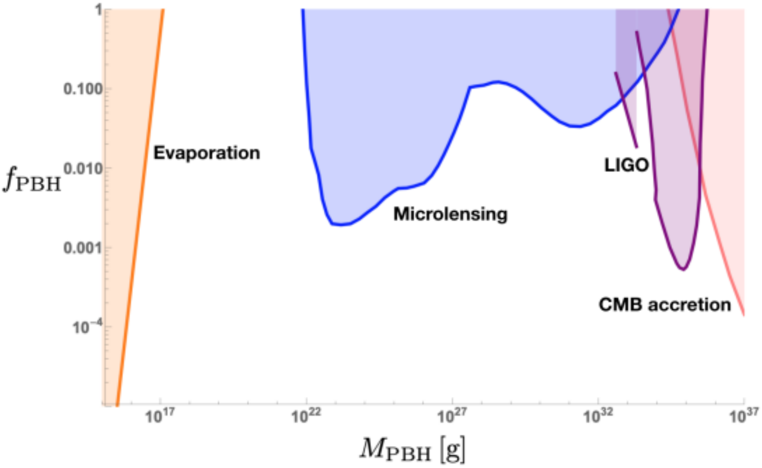

Figure: from arXiv:2112.05716.

Pre-Big Bang Scenario

It is a scenario obtained from string theory[1].
It is described by an effective low-energy action

$$g_s \ll 1\,, \quad H^2\alpha' \ll 1\,, \quad \alpha' = \lambda_s^2/2\pi$$

$$\boxed{S = -\frac{1}{2\lambda_s^{d-1}} \int d^{d+1}\sqrt{|g|}e^{-\phi}\Big[R + (\boldsymbol{\nabla}\phi)^2 - \frac{1}{12}\mathcal{H}^2_{\mu\nu\rho}\Big]}$$

where R is the Ricci scalar, ϕ is the dilatonic field and

$\mathcal{H}_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \partial_\nu B_{\rho\mu} + \partial_\rho B_{\mu\nu}$, $B_{\mu\nu}$ is NS-NS 2-form

$$\mathcal{H}^{\mu\nu\rho} = \frac{e^\phi}{\sqrt{|g|}}\epsilon^{\mu\nu\rho\lambda}\partial_\lambda\sigma \qquad \text{in 4-D}$$

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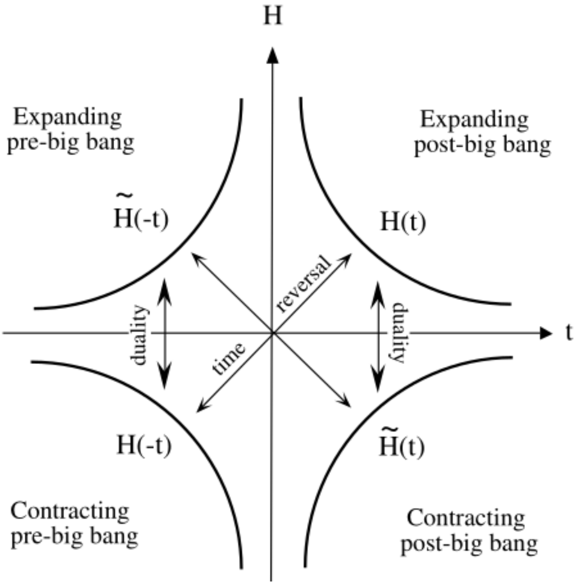
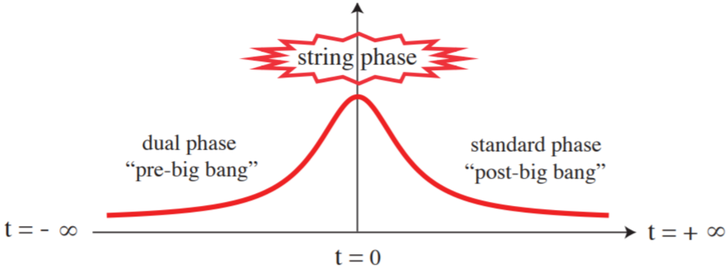
[1] M. Gasperini, G. Veneziano, *"The pre-big bang scenario in string cosmology"*, Physics Reports, Volume 373, 2003.



H
Expanding
pre-big bang
Expanding
post-big bang
$\tilde{H}(-t)$
H(t)
reversal
duality
duality
t
time
H(-t)
$\tilde{H}(t)$
Contracting
pre-big bang
Contracting
post-big bang



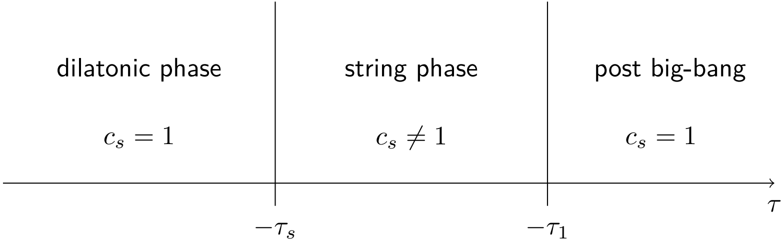
The Pre-Big Bang solution has a singularity in the future $(t \to 0_-)$; $H, g_s \to \infty$. The action needs to be corrected:

$$S = S_0 + S_{\alpha'} + S_{loop} \ ,$$

- α' corrections in the action, high derivative terms.
- loop corrections, as correction in powers of g_s.

Such corrections generate a non-trivial sound speed on the perturbations.

Two inflationary phases



Perturbations follow the Mukhanov-Sasaki equation in terms of the canonical variable $v = z\mathcal{R}$:

$$v'' - \left(c_s^2\nabla^2 + \frac{z''}{z}\right)v = 0$$

We apply a matching procedure in the transition hypersurfaces:

$$\mathcal{R}_k^i(-\tau_t) = \mathcal{R}_k^{i+1}(-\tau_t) \quad \wedge \quad \mathcal{R}_k'^i(-\tau_t) = \mathcal{R}_k'^{i+1}(-\tau_t)$$

We can evaluate the power spectrum at re-entry $k = aH$:

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2} \left|\mathcal{R}_k^3\right|^2_{|k\tau|=1}$$

Obtaining the complete spectrum:

$$\begin{aligned}
\mathcal{P}_{\mathcal{R}}(k) \quad & \sim \left(\frac{H_1}{M_P}\right)^2 \left(\frac{k}{k_1}\right)^{3-2|\nu_2|} c_s^{-1-2|\nu_2|}, && k_s/c_s < k < k_1/c_s, \\
& \sim \left(\frac{H_1}{M_P}\right)^2 \left(\frac{k_s}{k_1}\right)^{3-2|\nu_2|} \left(\frac{k}{k_s}\right)^{4}, && k_s < k < k_s/c_s \\
& \sim \left(\frac{H_1}{M_P}\right)^2 \left(\frac{k_s}{k_1}\right)^{3-2|\nu_2|} \left(\frac{k}{k_s}\right)^{3-2|\nu_1|} && k < k_s
\end{aligned}$$

Non-trivial sound speed c_s dependence on the high frequency band $\Longrightarrow$ enhancement of the spectrum.

PBHs production

A fluctuation with frequency ω_M, which re-enters at the scale $H_M \rightarrow$ PBH with mass:

$$M \sim \frac{{M_P}^2}{H_M}.$$

We define the PBHs abundance: $$\beta \equiv \frac{\rho_{PBH}}{\rho_{tot}}\bigg|_{at formation}.$$

and we connect the PBHs with the dark matter abundance by the parameter f_{pbh}:

$$f_{pbh} \equiv \frac{\Omega_{pbh}}{\Omega_{cdm}} \qquad \Longrightarrow \qquad \begin{aligned} f_{pbh}^{RD} &\sim \beta \frac{\Omega_\gamma^0}{\Omega_{cdm}^0}\frac{T_k}{T_0} \\ f_{pbh}^{MD} &\sim \beta \frac{\Omega_\gamma^0}{\Omega_{cdm}^0}\frac{T_d}{T_0} \end{aligned}$$

Formation in radiation dominated era

$$\beta = \frac{2}{\sqrt{2\pi\sigma^2}} \int_{\delta_c}^{\infty} \exp\left\{ \frac{-\delta^2}{2\sigma^2} \right\} = \mathrm{Erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma} \right)$$

where the density contrast δ is related to $\mathcal{R}$ by

$$\delta = \frac{2(1+\omega)}{5+3\omega}\mathcal{R} \qquad \Rightarrow \qquad \sigma^2 \sim \mathcal{P}_\delta \sim \frac{16}{81}\mathcal{P}_\mathcal{R}$$

If DM is made of PBHs then $f_{pbh} \sim 1 \rightarrow$ constraints on the primordial spectrum:

$$f_{pbh} \sim 1 \quad \Rightarrow \quad \mathcal{P}_\mathcal{R} \gtrsim 10^{-2}$$

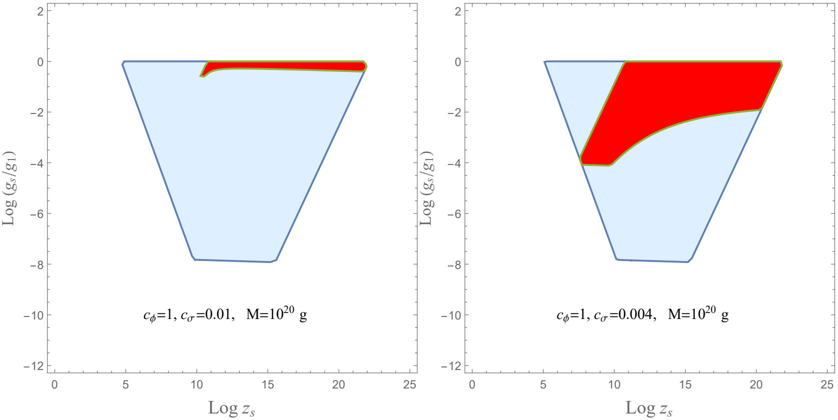


Figure: Production of Pbhs in RD era at varying axion sound speed.

Formation in matter era

When the collapse happens in matter era asphericities in the collapsing region should be taken into account [2]

$$\beta_0 \sim 0.056\sigma^5\,, \qquad \sigma > 0.005$$

$$\beta_0 \sim 10^{-7}\sigma^2 \exp\left\{\left(-\frac{0.15}{\sigma^{2/3}}\right)\right\}, \qquad \sigma < 0.005$$

where $\sigma < \sigma_{ang} \sim 0.005$ angular momentum of the collapsing region should be taken into account.

$$f_{pbh}^{MD} \sim \left(\frac{\beta_0}{5.5 \times 10^{-15}}\right)\left(\frac{T_d}{10^5 GeV}\right)$$

[2] T. Harada, C. Yoo, K. Kohri, and K. Nakao, Phys. Rev. D 96, 083517 (2017)

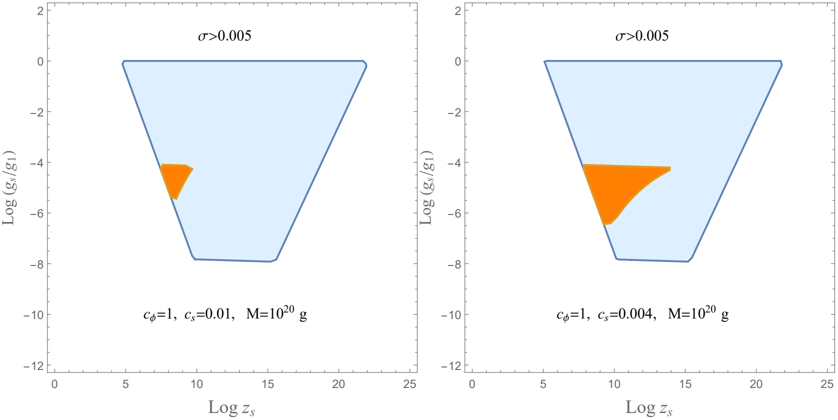


Figure: Production in matter era for $\sigma > \sigma_{ang}$.

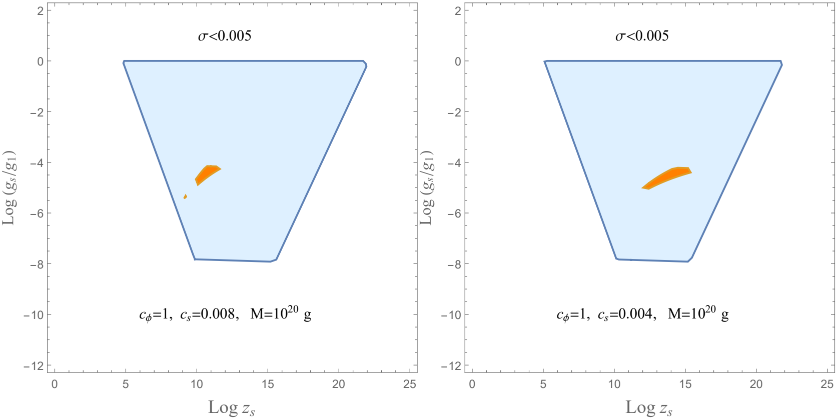
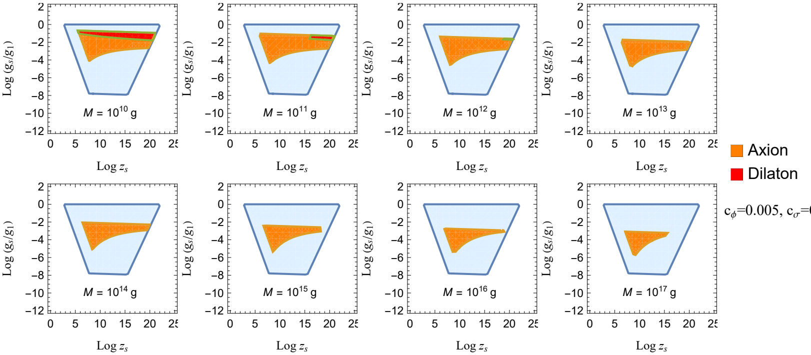


Figure: Production in matter era for $\sigma < \sigma_{ang}$

Light PBHs



c_ϕ=0.005, c_σ=0.004

Pre–Big Bang Scenario

- Conclusions

Conclusions

- Non trivial sound speed dependence.
- A possibility of PBHs formations by this effect, requiring $c_s \ll 1$. In the particular Pre-Big Bang we obtain a suitable PBHs production in order to produce the dark matter if we require $0.003 < c_s < 0.01$.[3][4]

Future prospects:

- Evaluate the case of $c_s(\tau)$ (motiveted by loop corrections).
- Calculus of perturbations to all olders in α' to obtain theoretical predictions on the value of c_s.
- Light PBHs impact on the model (eventually how to avoid them).

[3] P. Conzinu, M. Gasperini, and G. Marozzi, "*Primordial Black Holes from Pre-Big Bang inflation*," JCAP 08 (2020) 031.

[4] P. Conzinu and G. Marozzi, "*Primordial black holes formation in a early matter dominated era from the pre-big bang scenario*" [arXiv:2305.01430].

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Thank you for the attention

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