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Primordial black holes from inflaton and spectator field perturbations in a matter-dominated era

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Talk based on arXiv:1706.03746

COSMO'17
28/9/2017

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Primordial Black Holes (PBHs) – How do they form?

- PBHs can easily form in the early Universe from sufficiently large density perturbations – already within the GR
- In a radiation-dominated Universe, they can form when large enough perturbations ($\delta \gtrsim 0.5$) enter the horizon (tails of the Gaussian $\delta_{\mathbf{k}}$'s).
- In a matter-dominated Universe, perturbations grow as $\delta \propto a$ $\Rightarrow$ if there was enough time, even small perturbations can grow large, $\delta \sim 1$.

Primordial Black Holes – FAQ

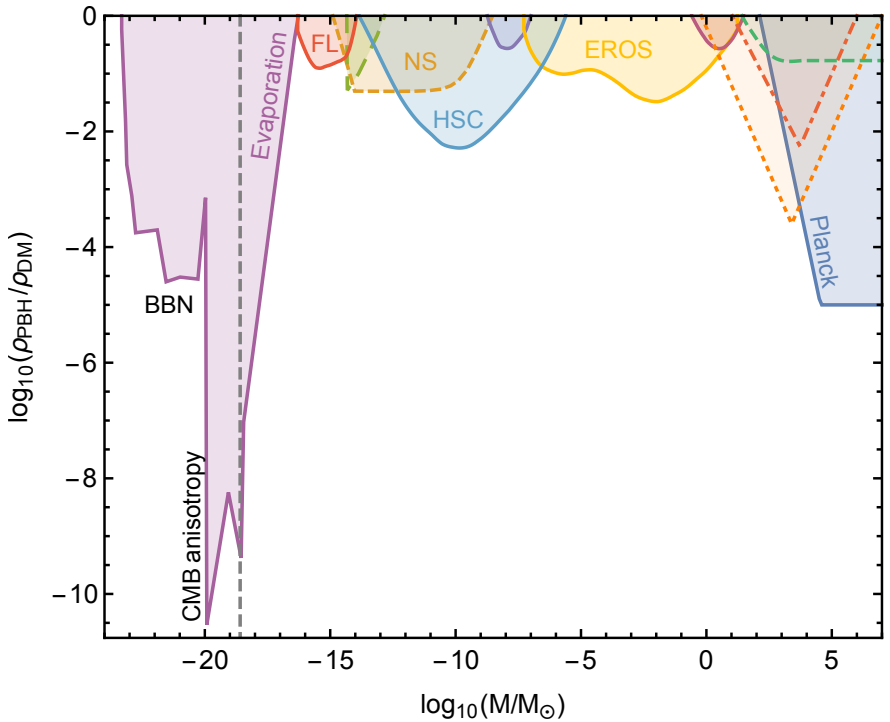
- Q: OK, but isn't that gauge-dependent?
  A: It is. Most importantly, in a matter-dominated Universe the Jeans pressure does not prevent PBHs from forming.

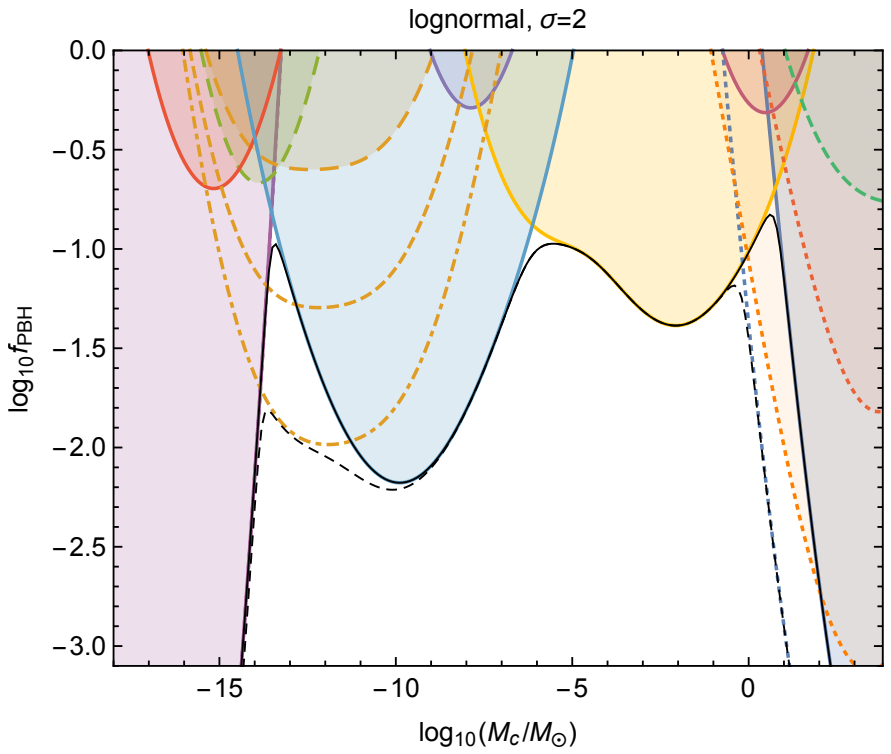
- Q: Why do not all regions collapse?
  A: Initial asphericities will be amplified and this prevents BH formation.

- Q: Why do not PBHs form in today's Universe?
  A: They could, but the formation probability is negligible, $\rho_{\rm PBH}(M)/\rho_{\rm tot} \simeq 0.01\,\delta_0^5(M)$.

Primordial Black Holes – Why are they interesting?

- Especially the LIGO observation of $\mathcal{O}(10)M_\odot$ BH mergers and seeds for supermassive BHs are interesting for PBHs
- PBHs might constitute all DM, although this possibility is very constrained (see 1705.05567 and the talk by V. Vaskonen)





Constraining Primordial Power Spectrum

- In any case, PBHs provide for an effective way to constrain curvature perturbations at small scales

- Let us assume that the are two components that contribute to the curvature power spectrum: the inflaton φ and a spectator field s

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R},\varphi}(k) + \mathcal{P}_{\mathcal{R},s}(k)$$

Primordial Power Spectrum with two components

- The inflaton perturbations produce a nearly flat spectrum at small k,

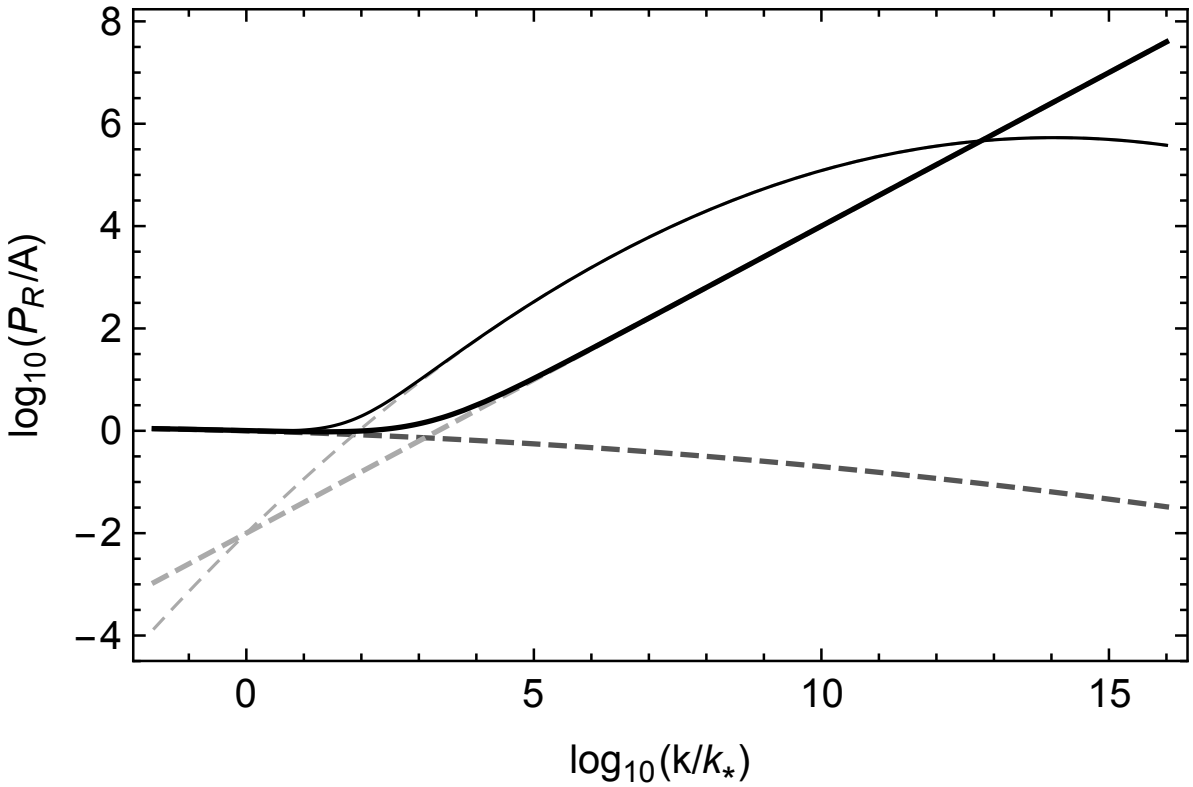
$$\mathcal{P}_{\mathcal{R},\varphi}(k) = A\left(\frac{k}{k_*}\right)^{n-1+\frac{1}{2}\mathrm{d}n/\mathrm{dln}k\,\ln\left(\frac{k}{k_*}\right)},$$

  where k_* is a pivot scale, $A \simeq 10^{-9}$, and $n \simeq 0.968$.

- Perturbations in the s field dominate at large k

$$\mathcal{P}_{\mathcal{R},s}(k) = A_s\left(\frac{k}{k_*}\right)^{n_s-1+\frac{1}{2}\mathrm{d}n_s/\mathrm{dln}k\,\ln\left(\frac{k}{k_*}\right)}$$

The total power spectrum



The total curvature power spectrum (**black solid lines**).

Black dashed line: inflaton. **Grey dashed lines**: spectator field for different choices of parameters.

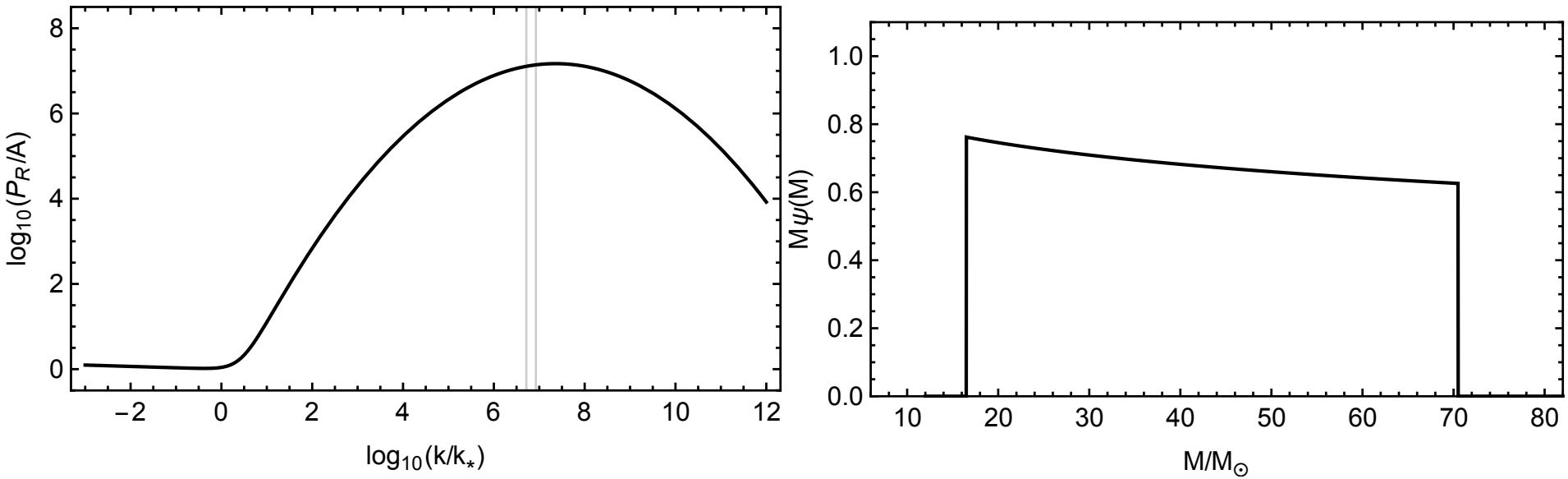
Primordial Black Hole formation: theory

- Assume there was an early matter-dominated phase (MD) at $T > T_{\rm BBN} \simeq \mathcal{O}(1)$ MeV.
- Possible cause: reheating, massive metastable particles...
- PBH formation starts when δ grows large enough[1] ($\delta \sim 1$) and ends when the MD ends
- In MD, PBHs form with an energy $\rho_{\rm PBH}(M)/\rho_{\rm tot} \simeq 0.01\delta_0^5(M)$

[1] Recall that in MD $\delta \propto a$ in Newtonian gauge.

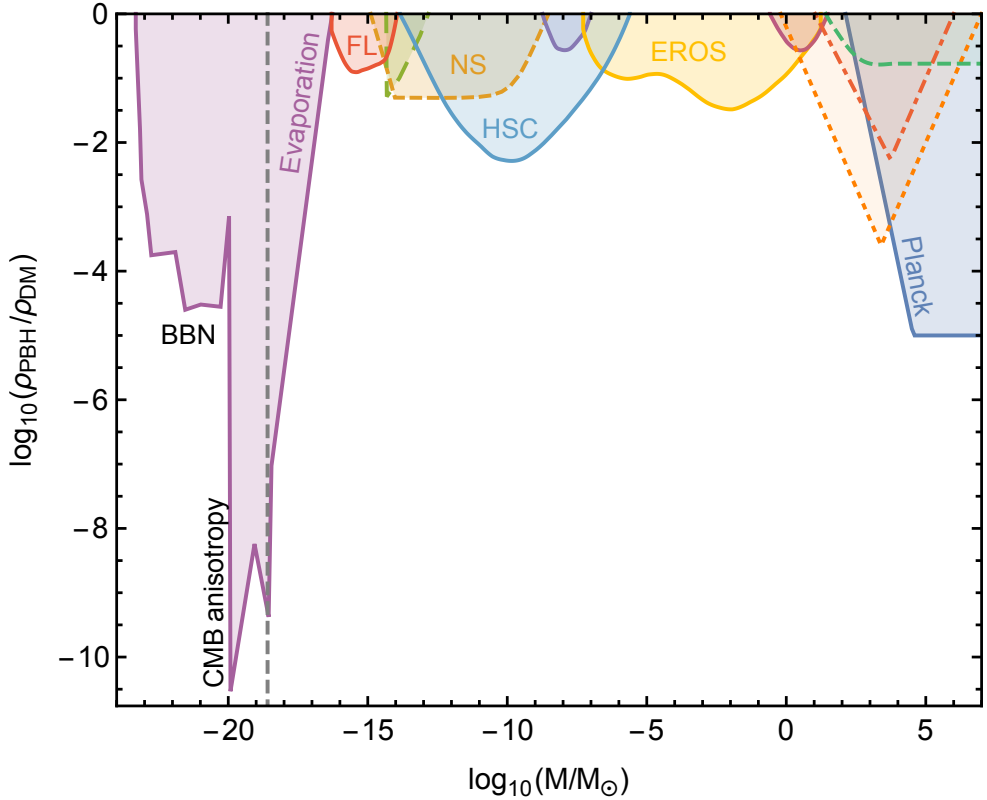
Primordial Black Hole formation: results

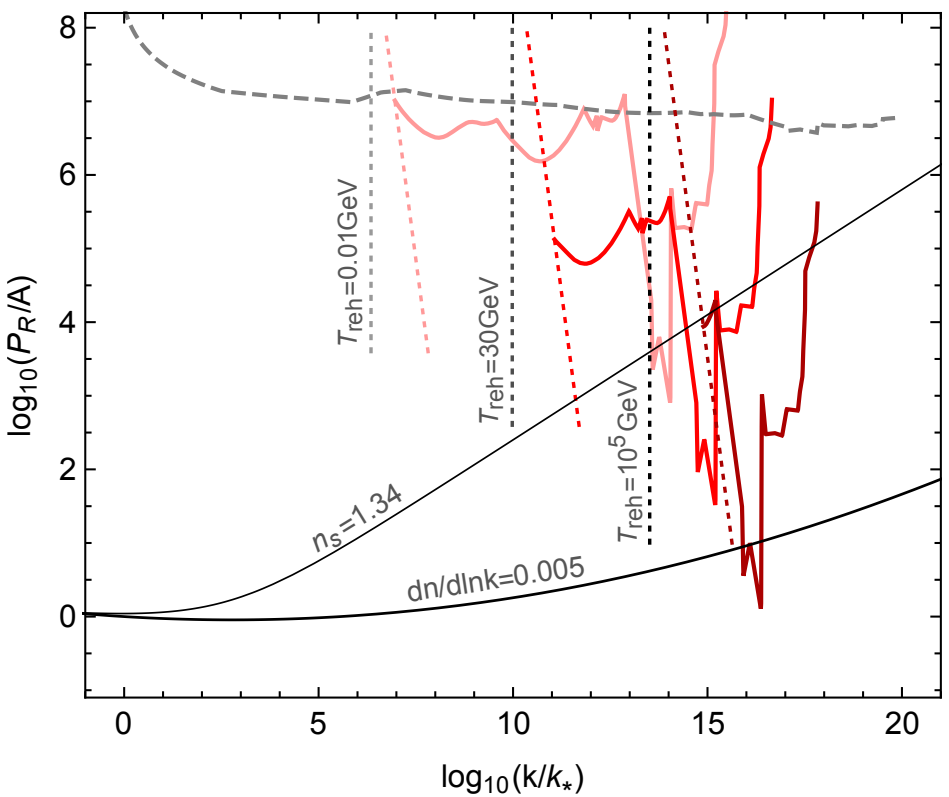
- Five parameters: A_s, n_s, $\mathrm{d}n_s/\mathrm{dln}k$, T_{MD}, T_{reh} (+ $\mathrm{d}n/\mathrm{dln}k$)



An example of the **total curvature power spectrum** (left) and the corresponding **PBH mass function** (right).

Constraints on primordial perturbations





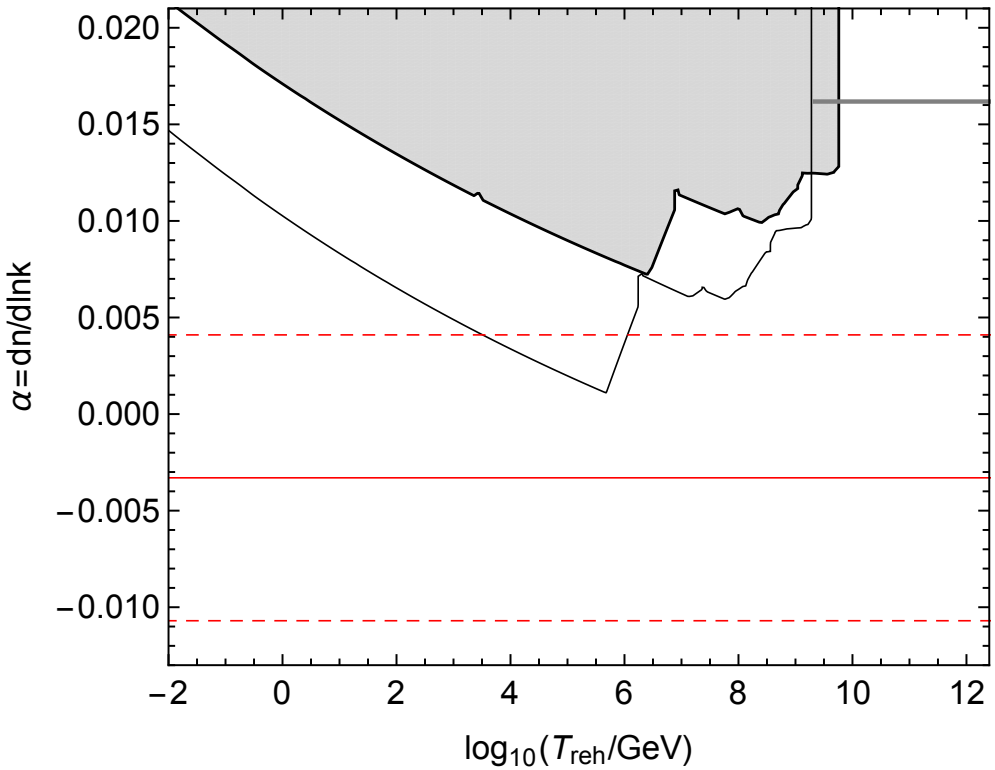
Left panel: Constraints on monochromatic PBH mass function.

Right panel: constraints on the amplitude of power spectrum. **Gray dashed line**: RD case. **Red lines**: MD case.

Thin black line: blue-tilted spectator field. **Thick black line**: inflaton with positive running.

Constraints on running of the spectral tilt

- We derive new constraints on the running of the inflaton field's spectral tilt. Red lines: Planck results.



- For constraints on spectral features of the spectator field and PBH DM, see 1706.03746.

Conclusions

- Primordial black holes are a compelling alternative to particle DM and may constitute all DM

- PBHs provide for an effective way to constrain curvature perturbations at small scales

  $\Rightarrow$ we placed new constraints on spectator fields and on the running of the spectral tilt, $\mathrm{d}n/\mathrm{dln}k \lesssim 0.001$.