Primordial Black Holes and Second-Order Gravitational Waves in Axion-Like Hybrid Inflation

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Waqas Ahmed, Anish Ghoshal, Umer Zubair
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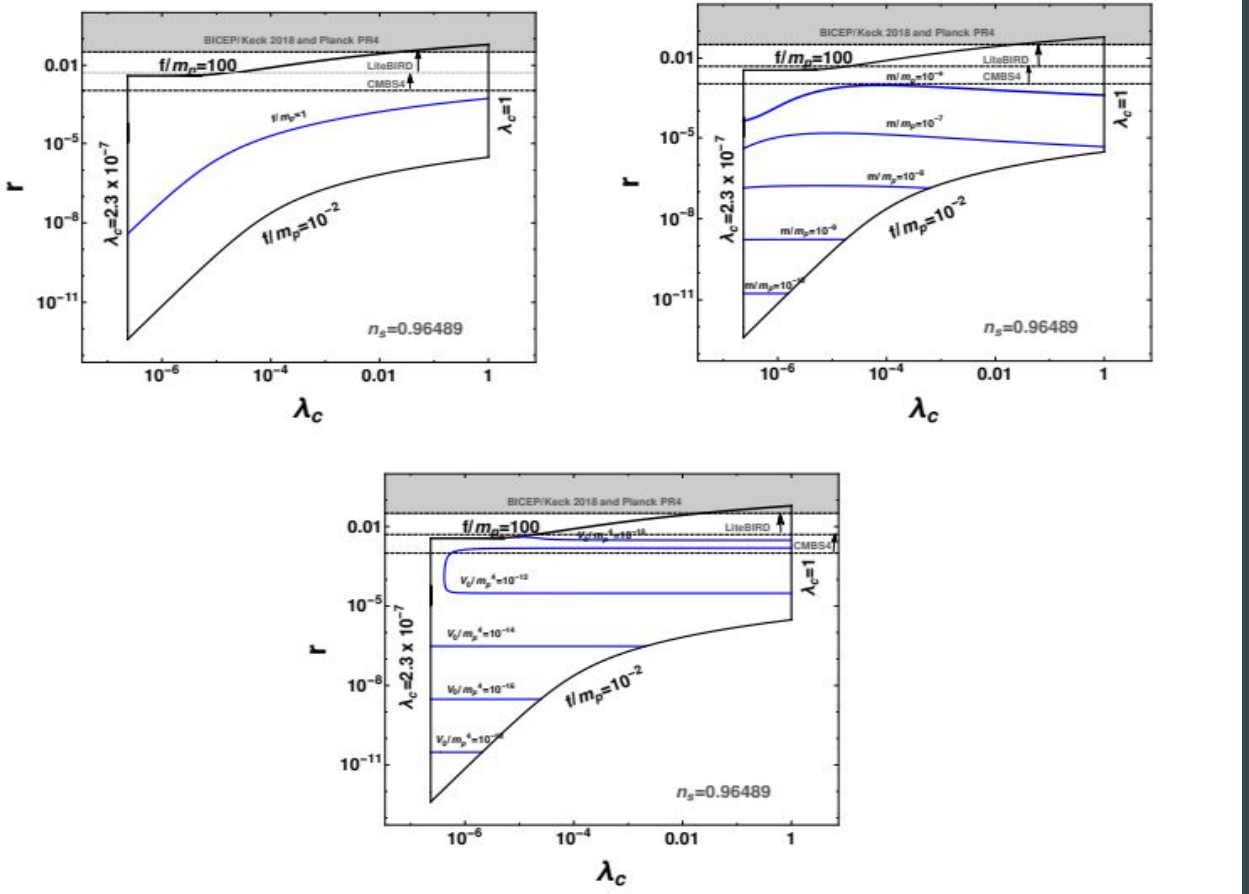
Introduction

- Peaks in amplitude of scalar perturbations can lead to the formation of Primordial Black Holes (PBHs) at small scales.
    - (Small scales are scales smaller than the Cosmic Microwave Background (CMB), and Hubble scale)
- This PBH formation could explain the observed black hole mergers detected by LIGO-VIRGO-KAGRA
- Axion-like particles (ALPs) exist past the standard QCD axion paradigm and these particles coupling affects early universe dynamics.
- **Main Objective:** Investigate relationship between ALP mass, PBH mass, and gravitational wave spectrum

α-Attractor Axionic Hybrid Inflation

- This inflationary model integrates hybrid inflation with ALPs.
- Involves inflation (ϕ) and waterfall (ψ) fields where ϕ is the main driver and ψ triggers the end of inflation.
- Uses slow roll parameters (ϵ_V, η_V) to predict spectral index (n_s) and tensor-to-scalar ratio (r) values of:
  - $n_s = 1 - 6\epsilon_V + 2\eta_V = 0.964$
  - $r = 16\epsilon_V = 0.003$
- These values align with CMB observations found by previous experiments

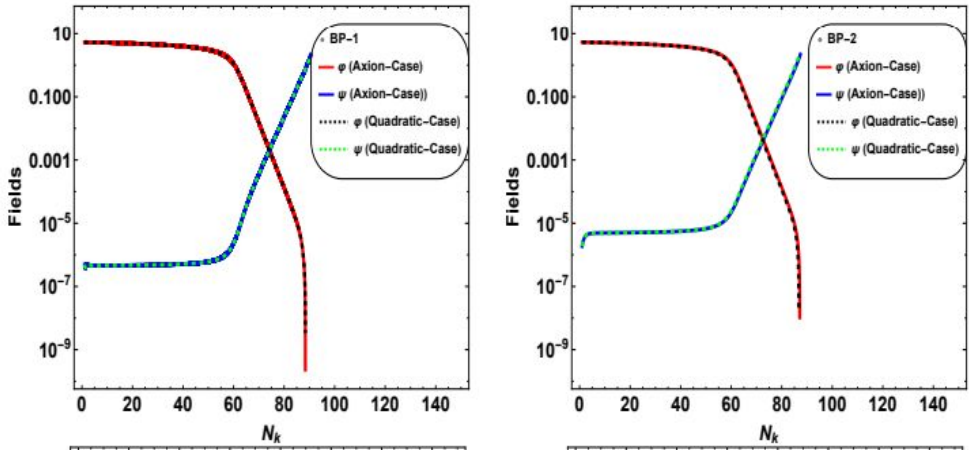
α-Attractor Axionic Hybrid Inflation

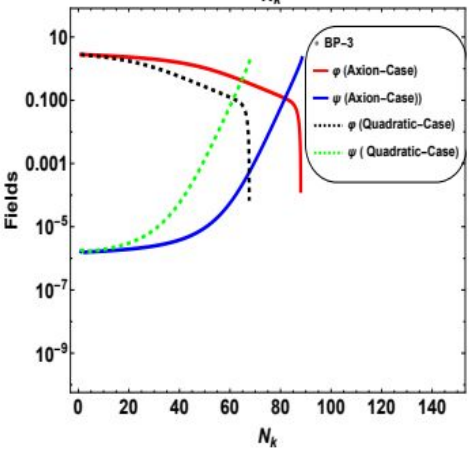


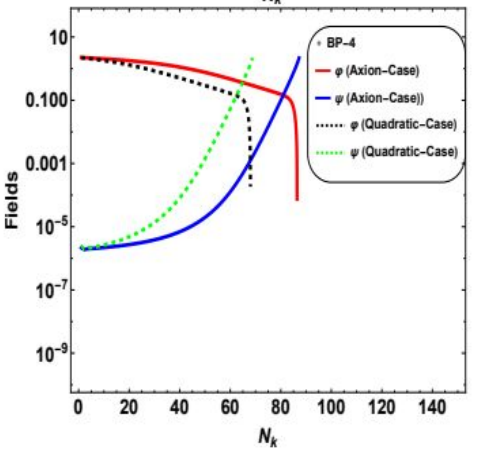
Scalar Spectra

- The scalar power spectrum ($P_s(k)$) is critical for formation of PBHs when perturbations re-enter the horizon.
- The waterfall transition leads to rapid growth of ψ significantly amplifying perturbations.
- These enhanced perturbations create large density fluctuations, giving conditions for PBH formation.

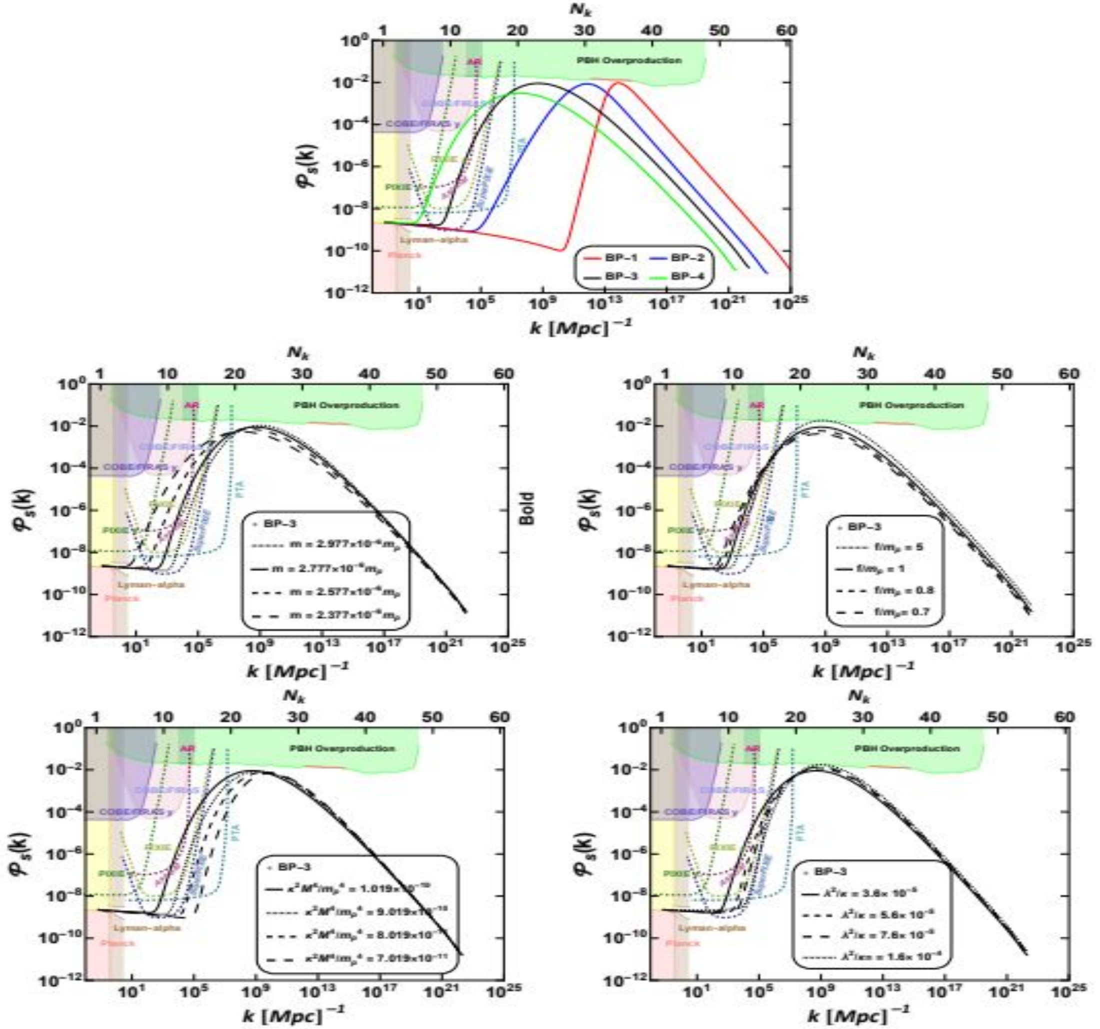
Scalar Spectra





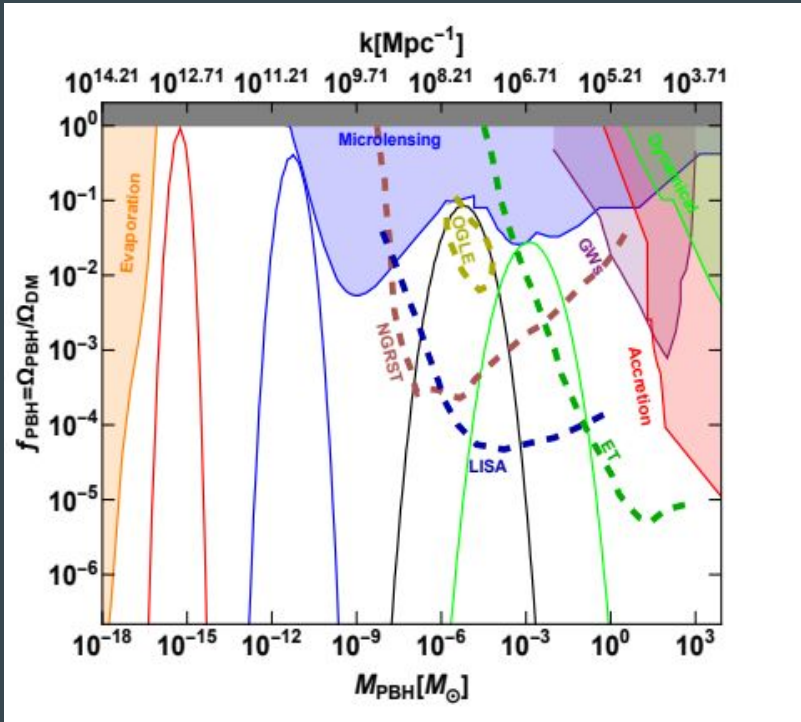


Scalar Spectra



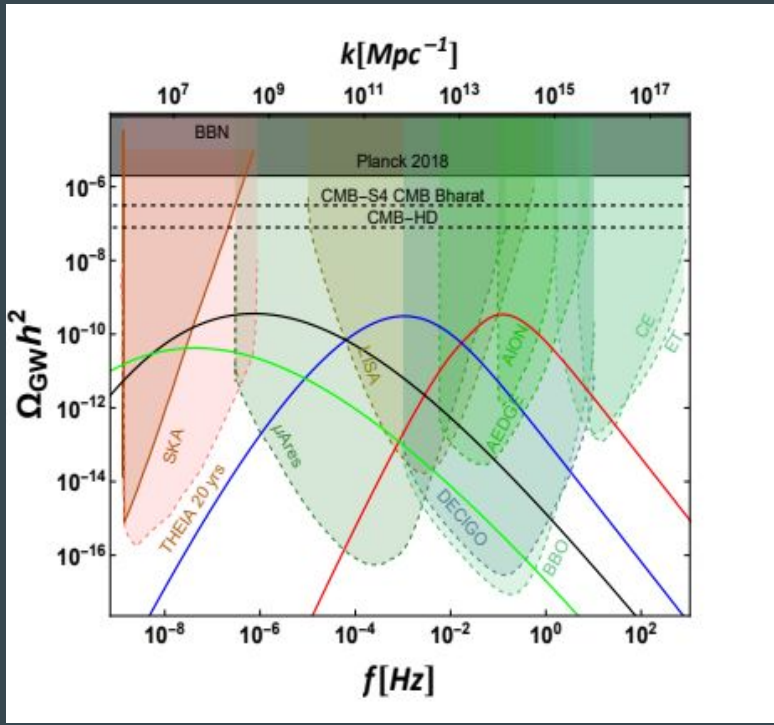
Primordial Black Hole Formation

- PBHs form when enhanced density perturbations re-enter the horizon.
- A region will undergo gravitational collapse when a perturbations density contrast exceeds its critical threshold.
- This collapse is followed by PBH formation



Scaler-Induced Gravitational Wave

- Scalar perturbations during inflation produce gravitational waves (GWs) known as second-order GWs.
- The spectrum of these GWs correlates with PBH formation.



Reheating Estimates

- After inflation ends axions decay into SM particles, leading to universe reheating.
- Using the decay width of the inflation field, estimated reheating temperature to be from 10^6 to 10^7 GeV
- This estimate is consistent with BBN constraints and provides a reasonable post-inflationary scenario for PBH formation.

Conclusions

- Axion-Driven hybrid inflation models can produce PBHs, which accounts for a large fraction of dark matter
- Predicted observable signatures of second-order gravitational waves to be tested by future experiments.