Research Project-written report
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Paper Title: Signals of Primordial Black Holes at Gravitational Wave Interferometers

(a) an introduction on the paper and why your team chose it

The paper we are choosing is on the topic of detecting the gravitational waves generated from the first generations of black holes in the early Universe. Particularly, we studied the prospect of Gravitational-wave interferometers that are being used to investigate the GW created due to the collapse of primordial density perturbations. The two types of PBHs discussed within the paper are light evaporating PBHs, and long lived PBHs. During a BHD era, gravitational waves can be generated furthermore by the potential well of the black holes themselves, forming a 2nd order expansion.

We chose the paper because we were interested in the field of gravitational wave observational astronomy, and the primordial black holes introduced in this paper are conjectured to contribute to some proportion of the dark matter density, especially those PBHs that are massive enough to survive from Hawking evaporation. By studying this topic, we wished to be more prepared for the journey toward research in astrophysics and cosmology in the future.

(b) what methods did the authors use

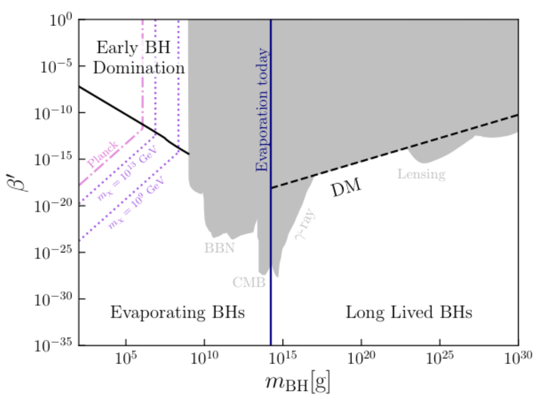
The terms curvature and density perturbations are introduced, where a density perturbation refers to certain regions in the universe being denser than other regions, and curvature perturbation refers to fluctuations in the curvature of spacetime. PBHs are formed from density perturbations, Which do not require stellar matter to collapse to form black holes. The authors characterized their studies and classifications of the black holes with the parameters β and $k_\star$, where beta represents the fraction of energy density of PBHs over the energy density of the entire universe, and $k_\star$ represents the comoving wavenumber associated with the curvature perturbations, defined in the comoving coordinates, where the universe and the CMB appears isotropic. The comoving distance between two objects is defined as constant, but when multiplied by the scale factor, gives the appropriate proper distance in current cosmological time. This comoving wavenumber is measured at the point where it enters the cosmological horizon, or in other words, at a point in time where causal events in spacetime can be observed, during the inflation of the universe|||. $k_\star$ is measured during the time right before freezeout occurs, where the length scale becomes larger than the hubble radius, making causal events unable to affect the curvature perturbations. For observational purposes, this $k_\star$ and a few orders of magnitude above it are the ones readily observable today.

To study PBHs, the authors studied the inflation perturbation model and the PBH mass spectrum. Experimentally, the authors referenced extremely sensitive interferometers, which can probe the mass range of the matter from 10g to 10^28g. They also did a clear comparison between the GW interferometer and other PBHs detectors by presenting the results with observational prospects along with some constraints.

(c) what are the major findings of the paper

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -a^2(1+2\Phi)\mathrm{d}\eta^2 + a^2\left((1-2\Psi)\delta_{ij} + \frac{1}{2}h_{ij}\right)\mathrm{d}x^i\mathrm{d}x^j,$$

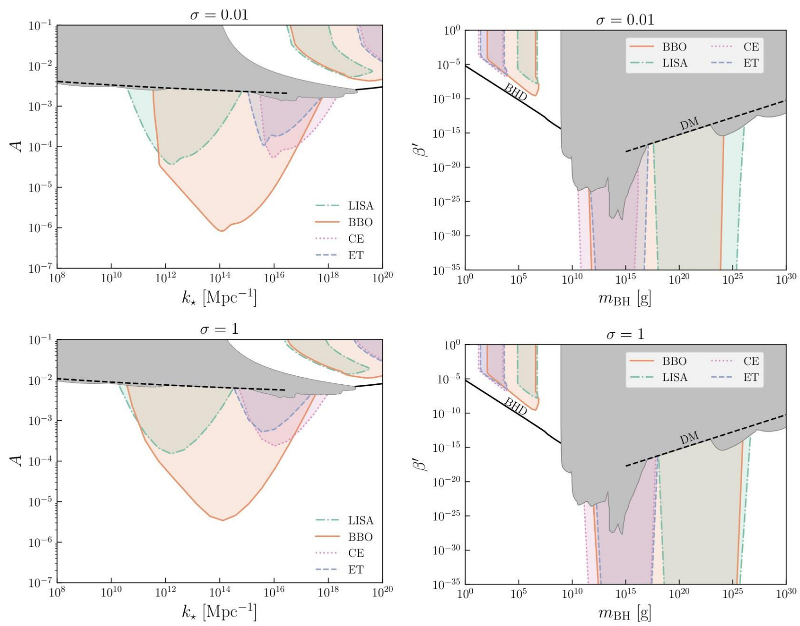
The paper uses the FRW metric to describe spacetime, along with the Newtonian gauge phi, which is the Newtonian Gravitational Potential energy. The differential eta represents the scalar term, while the $dx^i dx^j$ represents the tensor term affecting space, and h_{ij} represents the departure from the curvature of flat space. The tensor perturbations represent the effect of gravitational waves, which are negligible. The Scalar perturbations during inflation are the primary components that influence the expansion of the universe and further generate GWs.
Secondly, the figure below shows a range of PBHs mass and fractional energy density. The vertical blue line separates the PBHs that can avoid complete evaporation and the light evaporating black holes that would have evaporated now. The dashed line indicates the masses of long-lived black holes, and energy densities which would explain the current observed dark matter density in the universe, making them an attractive candidate for dark matter. The gray region represents the excluded bounds due to observational constraints ruling out the possibility of BHs in this region being responsible for gravitational wave generation. The purple lines indicate the ranges at which particle dark matter density can be generated by evaporating BHs, whose evaporation halts eventually due to quantum gravity effects.



Thirdly, a huge population of PBHs is formed due to the collapse of density fluctuations, particularly when strong scalar perturbations enter the cosmological horizon. These PBHs energy density and temperature are given by the following equations: (in a matter-dominated era):

$$T_{\rm RH} = 2.8\times 10^4\,\mathrm{GeV}\left(\frac{m_{\rm BH}}{10^4\mathrm{g}}\right)^{-3/2}, \qquad (8) \qquad \beta'_{\rm min} \simeq 3\times 10^{-10}\left(\frac{10^4\mathrm{g}}{m_{\rm BH}}\right). \qquad (9)$$

(d) a discussion of a few of the figures



β vs m_{BH} plot: on the top left corner of the RH plots the four colored regions are the predicted data collectable by 4 laboratories in one year, detail the predicted masses of the PBHs corresponding to their energy density signature. Notice on the top left, the masses of the black holes are much smaller, and the energy density ratio is close to one, this corresponds to a hypothetical era of PBH domination, where the PBHs accounted for most of the energy in the universe. On the bottom right for the four colored figures, corresponding to long-lived black holes, we see the beta value is much lower, which makes sense as well, since most of the PBHs that account for the higher energy would have either dissipated, or evaporated enough for β to drop significantly. On the LHS, where A is the amplitude of the curvature perturbations, is taken from the press-schechter formalism, which assumes a Gaussian distribution of curvature length scales, k can also be interpreted as momentum, and has units of curvature, and the idea is that curvature is proportional to gravitational energy, thus we see in the LHS diagrams, a reversal of the positions of the expected BHD era to the RHS in the top right corner, which spans the largest range of k values and hence a higher energy density fraction.

(e) what more work needs to be done on the topic

In order to treat the BHD era properly, beyond what has been found in this paper, more numerical results and data from different sources that created gravitational waves are required to be obtained in future studies (the possible sources include black hole fluid curvature perturbation, turbulence, nonlinear evolution, the sharp transition between BHD era to radiation eras, nonlinear evolution of BHD era, and mergers.) Furthermore, astrophysicists need to explore the detailed mechanisms of how PBHs constitute dark matter density and how their gravitational waves are able to consolidate the theory of inflation of space. Scientists also need to study how the prospective signals from PBHs (detected by Gamma-ray Space Telescope) will possibly contribute to evidence of string theory.

Work Cited

Kozaczuk, Jonathan, et al. “Signals of Primordial Black Holes at Gravitational Wave Interferometers.” *Physical Review D*, vol. 105, no. 12, 2022, https://doi.org/10.1103/physrevd.105.123023.