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Constricciones a agujeros negros primordiales con distribución de masa monocromática debido a las distorsiones espectrales del fondo de radiación cósmico de microondas

CMB Spectral Distortions Constraints on Primordial Black Holes with Monochromatic Mass Distribution

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RESUMEN

Agujeros negros primordiales (PBH) fueron teorizados primero por Zeldovich y Novikov en 1967 y luego por Hawking en 1972. Se prevé que PBH inyecten energía en el universo temprano debido a la radiación Hawking, esto generaría distorsiones en el espectro de cuerpo negro del fondo cósmico de microondas (CMB). En este trabajo las distorsiones espectrales del CMB debido a PBH son estudiadas con el objetivo de obtener constricciones a las propiedades de PBH. El código CLASS ha sido utilizado para calcular las distorsiones espectrales del CMB. PBH tipo Schwaszchild han sido considerados en el intervalo de masas entre 10^{11} y 10^{13} g con una distribución de masa monocromática. La abundancia de PBH $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$ fue considerada entre 10^{-5} y 1. Los datos del fondo de radiación cósmico de microondas por COBE-FIRAS fueron utilizados para calcular constricciones a PBH. Los resultados obtenidos tienen gran correspondencia con los reportados en trabajos previos. Dos mapas muy descriptivos de amplitudes de distorsiones tipo $|\mu|$ y $|y|$ son presentados. Las constricciones a PBH debido las distorsiones espectrales del CMB considerando una distribución de masa extendida es pospuesta a futuros trabajos.

ABSTRACT

Primordial black holes (PBH) were first theorized by Zeldovich and Novikov in 1967 and then by Hawking in 1972. It is expected that PBH will inject energy into the early universe due to Hawking radiation, this may lead to spectral distortions in the black body spectrum of the cosmic microwave background radiation (CMB). In this work, we studied the spectral distortions of CMB due to PBH, the objective is to obtain constraints on the PBH properties. We used the CLASS code to compute the spectral distortion of CMB. Schwaszchild's PBH were considered at the mass interval of 10^{11} and 10^{13} g with a monochromatic mass distribution. The abundance of PBH $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$ were considered between 10^{-5} and 1. The CMB data from COBE-FIRAS was used to compute the PBH constraints. The obtained results do agree with the results reported in previous works. We present two very descriptive maps of the μ and y type spectral distortion amplitudes. The CMB spectral distortions constraints considering an extended mass distribution of PBH is left for future works.

PALABRAS CLAVES

Agujeros negros primordiales, fondo cósmico de microondas, distorsiones espectrales.

KEYWORDS

Primordial black holes, cosmic microwave background, spectral distortions.

I | INTRODUCTION

The first hypotheses of PBH arose due to Zeldovich and Novikov (1967) and Hawking (1971). They suggested the possibility of a numerous gravitational collapses of objects with masses greater than 10^{-5} g due to energy fluctuations of the early universe, this would yield to the formation of low-mass black holes compared to stellar black holes whose minimum mass is about three solar masses according to Tolman (1939), Oppenheimer and Volkoff (1939).

After Zeldovich, Novikov and Hawking suggestions, different proposals of PBH as dark matter appeared. Chapline (1975) proposed that PBH should be part of dark matter due to its almost unobservable nature. In the same year, Mezaroz (1975) proposed a scheme of galaxy formation in which part of the mass of the universe is considered to be PBH of about one solar mass. However, most of the research focused on weakly interacting massive particles (WIMP) with little attention to PBH (Bernal, Bellomo, Raccanelli, & Verde, 2017).

After the LIGO + VIRGO detection of gravitational waves emitted by a two black holes collision (Abbott et al., 2016), new interest in PBH arose (Green & Kavanagh, 2021). There is strong suspicion that the black holes detected by LIGO + VIRGO are primordial. This idea arises due to the observations of the high merger rate, unusual masses, and low angular momentum (Ali-Haimoud et al., 2019). After the LIGO + VIRGO results, new suggestions about the role of PBH as dark matter have emerged (Bernal et al., 2017; Bird et al., 2016; Carr & Kühnel, 2020; Chapline, 1975; Clesse & García-Bellido, 2017; Green & Kavanagh, 2021; Mezaroz, 1975; Sasaki, Suyama, Tanaka, & Yokoyama, 2016).

It is expected that PBH will inject energy into the early universe due to Hawking radiation, this may lead to spectral distortions in the CMB. Spectral distortions are deviations of the CMB intensity spectrum from a perfect blackbody. Spectral distortions are created wherever the energy density or photon number density of the early universe's plasma is modified, leaving out the thermodynamic equilibrium (Lucca, Schöneberg, Hooper, Lesgourgues, & Chluba, 2020). Because of that, PBH can be studied through its direct effect on the CMB intensity spectrum.

The spectral distortions of the CMB have not yet been experimentally observed. This is the reason why numerical studies have become relevant at the last times.

In this work we have performed a numerical study of the CMB spectral distortions using CLASS, the main objective is to obtain constraints on the mass $M_{\rm PBH}$ and the abundance of PBH $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$ (also called the "PBH - dark matter density fraction") using COBE-FIRAS data in Fixsen et al. (1996).

The present work is organized as follows: In section II we present the employed methods. In section III we show the results and their discussion. Finally in section IV we expose the conclusion and recommendations.

II | METHODS

In order to obtain the CMB spectral distortions due to PBH we used the version 3.0 of the Cosmic Linear Anisotropy Solving System (CLASS) code (Blas, Lesgourgues, & Tram, 2011). CLASS is an open source Boltzmann code for cosmological calculations. CLASS allows the calculation of numerous cosmological observables including the CMB spectral distortions of type μ and y.

CLASS consider Schwarzschild PBHs whose emitted Hawking radiation evolves according to

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -5.34 \times 10^{25} \frac{g}{s} \frac{F(M)}{M^2}, \tag{1}$$

where M is the mass of the PBH and the function $F(M)$ represents the effective number of particles species emitted (see Appendix C.2 of Lucca et al. (2020) for more details). The energy injected in the early universe plasma in CLASS will be given by the following equation

$$\dot{Q} = \frac{dE}{dtdV} = \rho_{\mathrm{cdm}} f_{\mathrm{frac}} f_{\mathrm{eff}} \frac{\dot{M}}{M}, \tag{2}$$

where f_{eff} is the energy efficiency parameter that determines how much of the heating is deposited at all, this function strongly depends on the PBH emission process and the characteristics of the universe, such as transparency and energy densities at the time of emission, the approximation used by CLASS can be found in the Appendix C.2 of Lucca et al. (2020).
Based in the PBH energy deposition in equation (1) and (2), CLASS evolves the Boltzmann equation for the photon distribution function $f(\nu,t)$ for a ΛCDM + PBH universe (see Lucca et al. (2020)). The CMB intensity spectrum in term of this distribution function will be given by

$$I = \frac{2h\nu^3}{c^2} f(\nu,t), \tag{3}$$

where ν is the photon frequencies.
We ran CLASS for the mass interval of PBH M_{PBH} between 10^{11} and 10^{13} g. The PBH - dark matter density fraction $f_{\mathrm{frac}} = \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$ were considered between 10^{-5} and 1. Our sample consist in nine values between each order of magnitude for the last PBH masses and abundances intervals.
For compute the PBH constrains we use the COBE-FIRAS (Fixsen et al., 1996) experimental limit of

$$\frac{\delta I}{I} < 5 \times 10^{-5}, \tag{4}$$

which even today is best measurement of the CMB intensity spectrum. The prohibited PBH masses and abundances will be those for which the CMB intensity spectrum do not satisfy the inequality in (4).
In addition to the limit set on the total CMB intensity spectrum, the COBE-FIRAS data in Fixsen et al. (1996) also set limits on the μ and y spectral distortions amplitudes

$$|\mu| < 9 \times 10^{-5} \quad , \quad |y| < 15 \times 10^{-6}. \tag{5}$$

To obtain the PBH's mass M_{PBH} and PBH - dark matter density fraction f_{frac} constrains due to μ-type spectral distortions, the spectral distortions amplitudes $|\mu|$ were calculated using the simulated data from CLASS and the following equation

$$|\mu| \approx \left| \frac{\Delta I_\mu}{\frac{2h\nu^3}{c^2} \frac{xe^x}{(e^x-1)^2} \left(\frac{1}{x} + 0.4561\right)} \right|, \tag{6}$$

where $x = h\nu/T_0$.
The computed spectral distortions amplitudes $|\mu|$ were compared with the COBE-FIRAS experimental limit in (5). The values of M_{PBH} and f_{frac} whose spectral distortions amplitudes $|\mu|$ does not satisfy inequality in (5) are forbidden.
To obtain the PBH's mass M_{PBH} and PBH - dark matter density fraction f_{frac} constrains due to y-type spectral distortions, the spectral distortions amplitudes $|y|$ were calculated using the simulated data from CLASS and the following equation

$$|y| \approx \left| \frac{\Delta I_y}{\frac{2h\nu^3}{c^2} \frac{xe^x}{(e^x-1)^2} \left[x\frac{e^x+1}{e^x-1} - 4\right]} \right|, \tag{7}$$

where $x = h\nu/T_0$.

Once computed the spectral distortions amplitudes $|y|$, it is possible to obtain the values the PBH mass $M_{\rm PBH}$ and PBH - dark matter density fraction $f_{\rm frac}$ whose spectral distortions amplitudes $|y|$ do not satisfy the experimental limits of COBE-FIRAS in (5), when this happend the values of the PBH mass $M_{\rm PBH}$ and PBH - dark matter density fraction $f_{\rm frac}$ are prohibited.

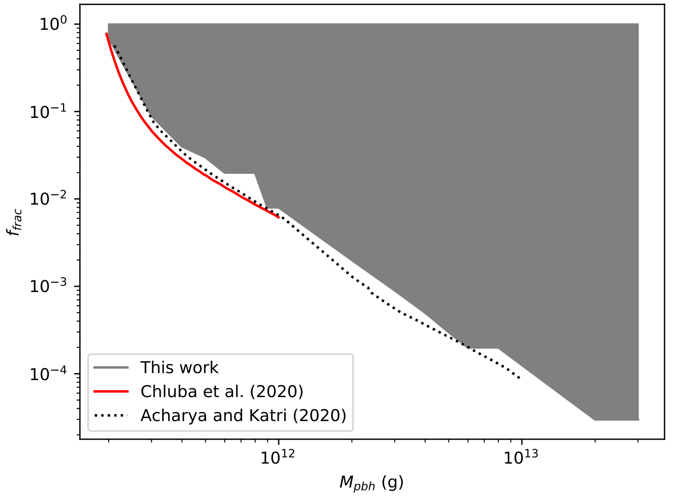

Figure 1: CMB spectral distortions constraints on PBH mass M_{PBH} and PBH - dark matter density fraction f_{frac}. The gray region shows forbidden values of M_{PBH} and f_{frac} due to the experimental limit $\delta I/I = 5\times10^{-5}$ set by the COBE-FIRAS data in Fixsen et al. (1996).

III | RESULTS AND DISCUSSION

CMB spectral distortions constraints on PBH's mass $M_{\rm PBH}$ and PBH - dark matter density fraction $f_{\rm frac}$ can be found in Figure 1. Constraints due Acharya and Khatri (2020b) and Chluba, Ravenni, and Acharya (2020) come from COBE-FIRAS data as in this work. Energy injection was considered entirely by PBH's Hawking radiation, and matter accretion was neglected. Monochromatic mass distribution of Schwarzchild's PBH was consider in Acharya and Khatri (2020b) and Chluba et al. (2020).

PBH's spectral distortions constrains by Chluba et al. (2020), Acharya and Khatri (2020b) and this work show the same trend. No significant differences were found considering a second particle cascade as in Acharya and Khatri (2020b).

Even taking into account the criticized consideration made by Lucca et al. (2020) where all PBH injected energy goes towards non-relativistic μ and y distortions (Acharya & Khatri, 2020b; Carr, Kohri, Sendouda, & Yokoyama, 2010), no large deviations were found between this work and Acharya and Khatri (2020b). Taking into account the nonthermal spectral distortions in Acharya and Khatri (2020b), weaker constraints were found for PBH masses greater than 10^{12} g. This arises because at redshifts less than 10^5, thermalization is less efficient due to Compton scattering decoupling (Acharya & Khatri, 2020b).

CMB spectral distortions constraints on f_{frac} are stronger as the PBH mass increases (see figure 1). This is because PBH with large masses evaporates at lower redshift and the ratio between CMB injected energy density and CMB energy density is higher (Acharya & Khatri, 2020b). The energy density injected by the CMB due to PBH behaves as $(1+z)^3$ and the CMB energy density behaves as $(1+z)^4$. The ratio between them goes as $(1+z)^{-1}$ which is higher at lower redshift when higher mass PBH are evaporated (Acharya & Khatri, 2020b).

PBH with masses between 10^{11} and 10^{13} g are expected to evaporate at redshifts between 10^6 and 10^3, just at the era of formation of the μ and y distortions (Acharya & Khatri, 2020b). For this reason, strong spectral distortions are expected due to the evaporation of PBH with masses between 10^{11} and 10^{13} g (Carr et al., 2010; Tashiro & Sugiyama, 2008). In this work, strong constraints were found for the masses of PBH between 2×10^{11} and 3×10^{13} g. The mass range obtained was very similar to that found in Tashiro and Sugiyama (2008) between 2.7×10^{11} and 3.5×10^{13} g.

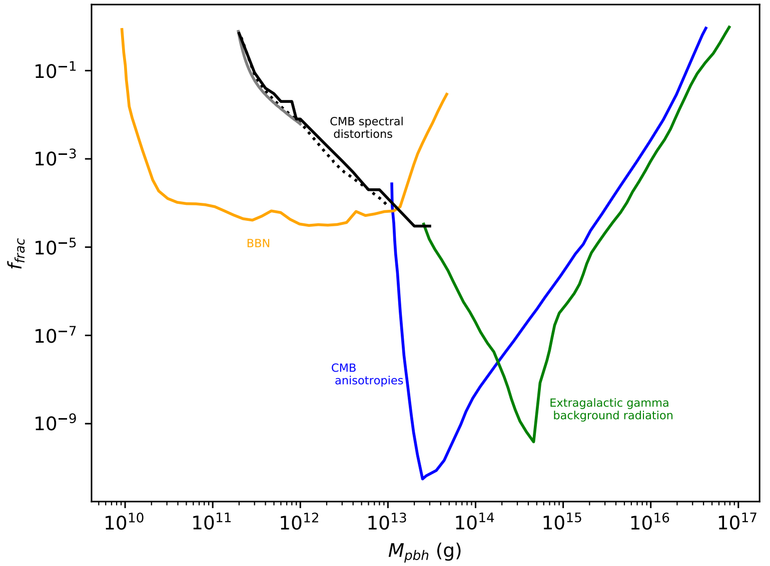

Figure 2: Constraints on PBH mass M_{PBH} and PBH - dark matter density fraction f_{frac} due to different cosmological observables. The region above the curves is prohibited. The big bang nucleosynthesis constraints are due to Carr et al. (2010), CMB anisotropies constraints are due to Acharya and Khatri (2020a), extragalactic gamma background radiation constraints are due to Carr et al. (2010), for the CMB spectral distortions constraints, the black dotted line shows those found in Acharya and Khatri (2020b), the solid gray line shows those found in Chluba et al. (2020). The solid black line shows the constraints obtained in this work.

PBH between 2×10^{11} and 3×10^{13} g have no other CMB constraints except for spectral distortions. CMB anisotropies constraints are outside this mass range (Lucca et al., 2020), for this reason spectral distortions constraints parameter window are considered a complement to CMB anisotropies constraints (Lucca et al., 2020).

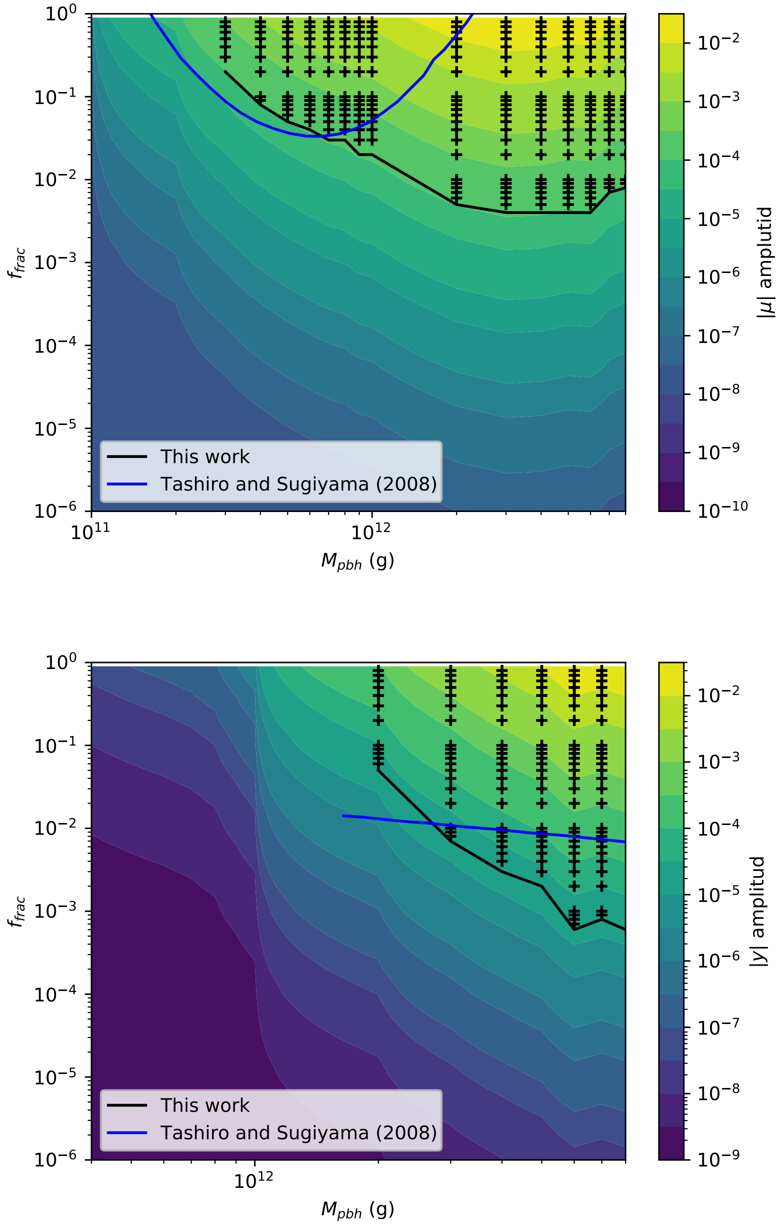

Figure 3: Constraints on PBH mass M_{PBH} and PBH - dark matter density fraction f_{frac} due to the CMB spectral distortions of type μ (top) and y (below). The region above the blue and black line is forbidden by the COBE-FIRAS data in Fixsen et al. (1996). The prohibited sample values are represented by +.

Spectral distortions constraints on PBH due to different mechanisms can be found in figure 2. The masses between 9.2×10^9 and 4.7×10^{13} g have big bang nucleosynthesis constraints (Carr et al., 2010). Masses between 9.2×10^9 and 4.7×10^{13} g have CMB anisotropies constraints (Acharya & Khatri, 2020a). Masses between 2.7×10^{13} and 7.9×10^{16} g have extragalactic background gamma radiation constraints (Carr et al., 2010). Constraints on f_{frac} in the mass parameter window of CMB anisotropies and extragalactic gamma rays outweigh the big bang nucleosynthesis and spectral distortions constraints by nearly three orders of magnitude.

It is possible to observe that big bang nucleosynthesis constraints coincide with spectral distortions constraints window mass parameters and also have much stronger constraints (see figure 2). However, future experiments like PIXIE are expected to improve PBH constraints between masses of 10^{10} and $10^{13.5}$ g between 1 and 3 orders of magnitude. Higher improvements are expected for PRISM (Lucca et al., 2020).

Type μ spectral distortions constraints can be found in the upper part of figure 3. These constraints are due to COBE-FIRAS data in equation (5). Theoretically, a perfect CMB blackbody spectrum is expected up to a redshift of 10^6 when double Compton scattering decouples (Carr et al., 2010; Tashiro & Sugiyama, 2008). Redshift less than 10^6 correspond to the evaporation of PBH masses greater than 10^{11} g (Carr et al., 2010), this corresponds to μ type spectral distortions constraints obtained in this work. As shown in figure 3, for masses less than 10^{12} g, constraints found in this work and those obtained by Tashiro and Sugiyama (2008) show the same trend. Discrepancies are found for PBH masses greater than 10^{12} g where there are no significant constraints due to Tashiro and Sugiyama (2008).

After the double Compton scattering decoupling, the Compton scattering decoupling occurs at redshift of 10^5. The rapid expansion of the universe allows the photon thermalization process to be inefficient, which leads to the emergence of the y type spectral distortions (Tashiro & Sugiyama, 2008) .

Type y spectral distortions constrains are shown in the lower part of the figure 3, in same figure it is shown the constrains due to Tashiro and Sugiyama (2008). These constraints are due to COBE-FIRAS limits in equation (5). It is theorized that at redshifts less than 10^5, PBH with masses greater than 10^{12} g are evaporated, generating spectral distortions of type y (Carr et al., 2010). The y type spectral distortions constraints mass window found in this work does agree with that in Carr et al. (2010) where constrains were found for masses greater than 10^{12} g.

IV | CONCLUSIONS AND RECOMMENDATIONS

We have performed a study of the CMB spectral distortions due to PBH in order to constrains PBH masses and abundances. The sample under study was consider between 10^{11} and 10^{13} g with monochromatic mass distribution and PBH - dark matter density fraction between 10^{-5} and 1.

We used the Cosmic Linear Anosotropy Solving System CLASS code to obtain the spectral distortions of the CMB due to exotic PBH energy injections. The calculation of the CMB spectral distortions allows us to corroborate that the PBH mass window whose energy injection generates spectral distortions is between 10^{11} and 10^{13} g. These PBH will be evaporated at redshift between 10^6 and 10^3 as reported in Tashiro and Sugiyama (2008).

We found strong constrains in the mass M_{PBH} and f_{frac} of PBH due to CMB spectral distortions using the COBE-FIRAS experimental uncertainty in Fixsen et al. (1996) to were found. In the mass range under study there are no other constraints on PBH due to CMB. The method to obtain PBH masses and abundances constraints using spectral distortions of the CMB is presented and could be replicated using the open source code CLASS.

The constraints obtained in this work have a strong correspondence with those reported by Acharya and Khatri (2020b) and Chluba et al. (2020). The observed trend consists of stronger constrains for f_{frac} as the PBH mass increases. This trend corresponds to the expected behavior of f_{frac}. Constrains three or more orders of magnitude larger than COBE-FIRAS are expected due to PIXIE Acharya and Khatri (2020b) and the next generations of CMB intensity spectrum experiments.

We exposed a method to constrains PBH masses and abundances using the spectral distortions of type μ and y. Likewise, two very descriptive amplitude maps of μ and y type spectral distortions. Strong μ distortions were found for masses greater than 10^{11} g and strong y type distortions were obtained at masses greater than 10^{12} g in agreement with previously reported by Tashiro and Sugiyama (2008).

The implementation of an extended mass distribution and the study of the effect of PBH on other cosmological observables are left for future work.

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