Impact of EDGES 21cm Global Signal on Primordial Power Spectrum

Shintaro Yoshiura\textsuperscript{a}, Keitaro Takahashi\textsuperscript{a}, and Tomo Takahashi\textsuperscript{b}

\textsuperscript{a}Faculty of Advanced Science and Technology, Kumamoto University, Kumamoto, Japan
\textsuperscript{b}Department of Physics, Saga University, Saga 840-8502, Japan

Abstract

We investigate the impact of the recent observation of the 21cm global signal by EDGES on primordial power spectrum, particularly focusing on the running parameters $\alpha_s$ and $\beta_s$ which characterize the detailed scale dependence of the primordial spectrum. When primordial power spectrum is enhanced/suppressed on small scales, the structure formation proceeds faster/slower and changes the abundance of small size halos, which affects the sources of Lyman $\alpha$ radiation at high redshifts to alter the position of the absorption line. Recent observation of EDGES detected the 21cm absorption line at $z = 17.2$ and this result also indicates that the brightness temperature is consistent with zero for $z \lesssim 14$ and $z \gtrsim 22$, which can exclude a scenario giving the absorption line at such redshifts. We argue that the bound on the running parameters can be obtained by requiring that the absorption line should not exceed observational bounds at such redshift ranges and found that some parameter space of $\alpha_s$ and $\beta_s$ allowed by Planck may be disfavored.
1 Introduction

The nature of primordial fluctuations reflects the physical mechanism behind the inflationary Universe and hence a great deal of effort has been made to understand it both from observational and theoretical viewpoints. Current cosmological observations such as cosmic microwave background (CMB) from Planck satellite have measured primordial power spectrum, in particular, its amplitude and the spectral index $n_s$ very accurately [1, 2], and together with the bound on the amplitude of primordial gravitational waves such as from CMB B-mode observations like BICEP2/KECK [3], the inflationary models are now severely tested. Nevertheless there remains a large variety of inflationary models consistent with those observations and we are still far from a thorough understanding of the inflationary Universe. Therefore it is imperative to go further to probe primordial fluctuations.

One direction would be to measure the primordial power spectrum more precisely. For this purpose, it is common to adopt the following parametrization for the primordial spectrum:

$$P_\zeta(k) = A_s(k_{\text{ref}}) \left( \frac{k}{k_{\text{ref}}} \right)^{n_s - 1 + \frac{1}{2} \alpha_s \ln(k/k_{\text{ref}}) + \frac{1}{2} \beta_s \ln^2(k/k_{\text{ref}})} ,$$

(1.1)

where $A_s(k_{\text{ref}})$ is the amplitude at the reference scale $k_{\text{ref}}$, $n_s$ is the spectral index, $\alpha_s$ and $\beta_s$ are the so-called running parameters and represent the scale dependence of $n_s$ as

$$\alpha_s = \frac{dn_s}{d \ln k} , \quad \beta_s = \frac{d^2 n_s}{d \ln k^2} .$$

(1.2)

Although one can obtain the bounds on the running parameters from Planck data, they are not so severe and thus it is worth exploring a possibility of probing the runnings by using yet another observation to measure them more accurately.

When one wishes to determine the runnings precisely, probing the power spectrum on a wide range of scales would be helpful. Since CMB measures cosmic fluctuations on large scales, one needs observations on small scales. As such, expected constraints from future observations of 21cm fluctuations of neutral hydrogen from intergalactic medium [4, 5] and minihalos [6], and CMB spectral $\mu$ distortions [7–9] have been studied.

We in this paper investigate how the nature of primordial power spectrum affects the 21cm global signal and the impact of the recent EDGES result [10] on the running parameters. EDGES has reported that the absorption peak is observed at the frequency corresponding to $z = 17.2$ and its brightness temperature relative to CMB is $T_b = -500^{+200}_{-500}$ mK (99\% C.L.), whose value is too low to be explained in the standard cosmological and astrophysical scenarios\footnote{See, however, Ref. [11] for the discussion on the analysis and its interpretation.}. This result has stimulated many works which aim to explain its non-standard value by resorting to dark matter (DM) interactions to cool the gas (baryon) [12–19], which could be confronted with other cosmological/astrophysical observations [20–22]. Other possibilities to explain the signal have been discussed in models with producing photons at radio wavelength [23–28], dark sector properties [29–31] and so on. On the other hand, there have been
several works to derive constraints on DM and primordial black holes by using the EDGES result [32–40]. Implications of the EDGES result for 21cm power spectrum have also been investigated [41, 42].

One should notice that the EDGES result also indicates that there is no absorption signal at the redshift regions $\zappa 14$ and $\zapp 22$, which can constrain the running parameters of primordial power spectrum. Since the runnings $\alpha_s$ and $\beta_s$ directly affect the matter power on small scales, the structure formation should change depending on these parameters. For too positively (negatively) large values of $\alpha_s$ and $\beta_s$, the matter power on small scales are enhanced (suppressed) and the structure formation is affected. When the structure formation proceeds faster (slower) due to the enhanced (suppressed) matter power spectrum on small scales, which switches on the source of Lyman $\alpha$ radiations earlier (later), then the absorption line is shifted to a higher (lower) redshift. If the absorption line appears at the redshift ranges $\zappa 14$ or $\zapp 22$, it is inconsistent with the EDGES result and such parameter values are disfavored. By adopting this argument, we can obtain the bound on the running parameters $\alpha_s$ and $\beta_s$ from EDGES, which is the main purpose of this paper.

The organization of this paper is the following. In the next section, we briefly describe the procedure to compute the 21cm brightness temperature and discuss the effects of the runnings on the global signal of 21cm line. Then in Section 3, we investigate the bound on the running parameters from EDGES by requiring that the absorption line should not appear at the redshift ranges $\zappa 14$ and $\zapp 22$. The effects of astrophysical parameters on the 21cm global signal and constraints on the running parameters are discussed in Section 4. The final section is devoted to conclusion of this paper.

2 21cm global signal and primordial power spectrum

Here we briefly discuss how the nature of primordial power spectrum affects the global signal of 21cm line of neutral hydrogen.

The 21cm global signal, averaged differential brightness temperature relative to CMB radiation, is given by (see, e.g., the reviews [44, 45])

$$T_b \simeq 27 x_{\text{HI}} \left( \frac{\Omega_b h^2}{0.023} \right) \left( \frac{0.15}{\Omega_m h^2} \right)^{1/2} \left( \frac{1 + z}{10} \right)^{1/2} \left( \frac{T_s - T_{\text{CMB}}}{T_s} \right) \text{mK},$$

where $\Omega_b, \Omega_m$ are density parameters for baryon and (total) matter, $h$ is the Hubble parameter in units of $100 \text{km s}^{-1} \text{Mpc}^{-1}$, $T_s$ is the spin temperature of neutral hydrogen, $T_{\text{CMB}} = 2.725/(1 + z)$ is the temperature of CMB photon. The spin temperature $T_s$ can be given by

$$T_s^{-1} = \frac{T_{\text{CMB}}^{-1} + x_\alpha T_{\alpha}^{-1} + x_c T_{c}^{-1}}{1 + x_\alpha + x_c},$$

#2 When the running parameters are too negative where the matter power on small scales is suppressed, its effects are similar to the case with warm dark matter [39, 43].
where $T_\alpha$ and $T_K$ respectively are the color temperature and gas temperature, respectively. $x_\alpha$ and $x_c$ are the coupling coefficients characterizing the scattering of Lyman $\alpha$ photons and the atomic collisions. For the detailed discussion of the evolution of the spin temperature, see e.g., Refs. [44, 45].

To investigate how the running parameters $\alpha_s$ and $\beta_s$ affect the brightness temperature, we have computed the evolution of the spin temperature by using 21cmFAST [46, 47]. To calculate its evolution, we also need to specify astrophysical parameters such as the minimum virial temperature of star forming sources $T_{\text{vir}}$, the fraction of baryons converted to stars $f_*$ and the number of X-ray photons emitted from stars $\zeta_X$. The evolution of the spin temperature is also sensitive to these astrophysical parameters. We discuss how these parameters affects the absorption line in Section 4.

In Fig. 1, we show the evolutions of $T_s, T_K$ and $T_{\text{CMB}}$ (left panel) and the differential brightness temperature $T_b$ (right panel) for several parameter sets of $(n_s, \alpha_s, \beta_s)$, whose values are indicated in the figure. The astrophysical parameters mentioned above are assumed as $T_{\text{vir}} = 10^4$ K, $f_* = 0.05$ and $\zeta_X = 2 \times 10^{56}/M_\odot$. The cosmological parameters are taken as $\sigma_8 = 0.831, \Omega_b h^2 = 0.02225, \Omega_m = 0.3156, h = 0.6727$ where $\sigma_8$ is the amplitude of matter fluctuations at $8h^{-1}$ Mpc. As mentioned in the introduction, when $\alpha_s$ and $\beta_s$ are positively (negatively) large, the matter power on small scales are enhanced (suppressed), and thus the structure formation proceeds faster (slower) and the sources of Lyman $\alpha$ background are switched on earlier (later). Therefore positively (negatively) larger values of $\alpha_s$ and $\beta_s$ drive the spin temperature to approach the gas temperature earlier (later), which shifts the absorption line to a higher (lower) redshift. On the other hand, the recent EDGES result indicates that the absorption line appears at around $z = 17.2$ and the brightness temperature goes to zero for $z \lesssim 14$ and $z \gtrsim 22$, therefore too large positive or negative values of the runnings are expected to be disfavored in the light of recent EDGES result. In the next section, we investigate the bound on the runnings $\alpha_s$ and $\beta_s$ from the requirement that the redshift (frequency) of the absorption line should be consistent with the EDGES result, i.e., it should not appear at $z \lesssim 14$ and $z \gtrsim 22$.

3 Bounds on primordial power spectrum from EDGES 21cm global signal

Now in this section, we study the bound on the running parameters $\alpha_s$ and $\beta_s$ of primordial power spectrum by demanding that the absorption line should appear in the redshift range of $14 < z < 22$ indicated by the EDGES result. In practice, we conservatively require that the brightness temperature should be $T_b > -100$ mK for the redshift range $z < 14$ and $z > 22$. We note that, since EDGES does not give data for $z \gtrsim 27$, we do not constrain the case where the absorption trough appears at redshifts $z > 27$.

In Fig. 2, color panels of the redshift of the peak position of the absorption trough $z_{\text{peak}}$ and allowed region from EDGES are shown in the $\alpha_s-\beta_s$ plane. We consider a $\Lambda$CDM model and fixed other cosmological parameters as $\sigma_8 = 0.831, \Omega_b h^2 = 0.02225, \Omega_m = 0.3156, h =$
$\alpha_s = 0.009, \beta_s = -0.025$

$\alpha_s = 0.0, \beta_s = 0$

$\alpha_s = 0.009, \beta_s = 0.025$

$T_s, T_k$ (solid), $T_b$ (dashed) and $T_{\text{CMB}}$ (dotted). Cases with $(n_s, \alpha_s, \beta_s) = (0.9586, 0, 0)$ (red), $(0.9586, 0.009, 0.025)$ (blue) and $(0.9586, -0.009, -0.025)$ (green) are shown. Light blue hatched regions correspond to the ones inconsistent with the EDGES result. Black hatched one indicates that there is no data in the redshift range.

$\alpha_s = 0.009 \pm 0.010, \quad \beta_s = 0.025 \pm 0.013,$

which is also indicated in Fig. 2. Interestingly, some parameter region for $\alpha_s$ and $\beta_s$ allowed by Planck at $1\sigma$ is now ruled out by the EDGES, which shows that the 21cm global signal is powerful in constraining the runnings of primordial power spectrum although some of the parameter space cannot be constrained since the EDGES measures the redshift range of $14 \lesssim z \lesssim 27$. We should also note that, although the recent result from EDGES may need to be confirmed by other observations of the 21cm global signal, as far as the frequency range of the absorption trough persists (even if the size of the absorption signal is weakened), the constraint obtained in this paper will still be valid.

Here it should also be mentioned that in obtaining the constraint shown in Fig. 2, we have fixed the astrophysical parameters such as $T_{\text{vir}}, f_*$ and $\zeta_X$, however, as briefly mentioned in
Figure 2: Allowed region from the EDGES result and the peak redshift of the absorption trough $z_{\text{peak}}$ are shown with a color panel for the cases with $n_s = 0.9586$ (left) and $n_s = 0.9530$ (right) with $T_{\text{vir}} = 10^4$ K. Red point shows Planck best fit value with 1 sigma error bars. When the peak redshift of the absorption line is in the range of $z > 27$ or $T_b > -100$ mK at $z = 27$, no constraint can be obtained from EDGES, which is indicated by black hatched.

Sec. 2, these parameters can also affect the global signal. Therefore constraints on $\alpha_s$ and $\beta_s$ also depend on the values of these parameters. In the next section, we discuss effects of the astrophysical parameters on the evolution of the brightness temperature and the constraints.

4 Effects of Astrophysical Parameters

As discussed in the previous section, our analysis indicates that some parameter space of $\alpha_s$ and $\beta_s$ allowed by Planck tend to be disfavored by the EDGES result for some fixed astrophysical parameters. However, the 21cm global signal also strongly depends on the astrophysical parameters used in 21cmFAST. Here we discuss in some detail how the astrophysical parameters such as $T_{\text{vir}}$, $f_*$ and $\zeta_X$ affect the 21cm absorption signal.

In Fig. 3, we show the evolution of the brightness temperature $T_b$ by varying the values of $T_{\text{vir}}$ (top panel), $f_*$ (middle panel) and $\zeta_X$ (bottom panel). Since $T_{\text{vir}}$ and $f_*$ affect the WF coupling and gas heating in the same way, the effects of these parameters on the 21cm global signal are degenerate. But on the other hand, $\zeta_X$ only affects gas heating, and hence the variation of $\zeta_X$ is not degenerate with the other parameters.

Concerning $T_{\text{vir}}$, a negative feedback effect such as Lyman-Werner radiation at high redshifts leads to the suppression of the star formation in halos [48], which results in a larger value of $T_{\text{vir}}$ and the reduction of X-ray and Lyman-\(\alpha\) photons from small halos, then the absorption line shifts to a lower redshift. The fraction of baryon converted to stars $f_*$ also alters the number of X-ray and Lyman-\(\alpha\) photons. Smaller values of $f_*$ make the WF coupling less effective at higher redshifts and gas heating occur later, and thus the absorption peak shifts to a lower redshift, whose effect is quite similar to the one for $T_{\text{vir}}$. Therefore, as can be seen from Fig. 3, the change in $T_{\text{vir}}$ and $f_*$ give a degenerate effect on the evolution of $T_b$. 
Figure 3: Evolution of the brightness temperature for various sets of astrophysical parameters. We show the impact of minimum virial temperature, $T_{\text{vir}}$ (top), fraction of baryon converted to stars, $f_*$ (middle) and X-ray heating efficiency, $\zeta_X$ (bottom). Here we assume $n_s = 0.9586$, $\alpha_s = 0.009$, $\beta_s = 0.025$ for the spectral index and its runnings. Light blue hatched regions correspond to the ones inconsistent with the EDGES result. Black hatched one indicates that there is no data in the redshift range.
In Fig. 4, we show constraints on $\alpha_s$ and $\beta_s$ from EDGES for the case with $T_{\text{vir}} = 3 \times 10^4$ K. As seen from the figure, since we take a larger value for $T_{\text{vir}}$ than that assumed in Fig. 2, the whole allowed region from EDGES shifts to the parameter space with larger $\alpha_s$ and $\beta_s$. Due to the degeneracy between $T_{\text{vir}}$ and $f_*$, if $f_*$ is assumed to be smaller than $f_* = 0.05$ which is the fiducial value in our analysis, the whole allowed region would also be shifted to the direction of larger $\alpha_s$ and $\beta_s$. On the other hand, when we take smaller $T_{\text{vir}}$, which is depicted in Fig. 5, the allowed region shifts to the direction of smaller $\alpha_s$ and $\beta_s$. In this case, the allowed values from Planck are now in the region where the EDGES cannot constrain the running parameters since the absorption trough goes outside the measured redshift range. Therefore, we cannot say anything about the consistency of the constraints between Planck and EDGES in this case.

Regarding $\zeta_X$, since the number of X-ray photons emitted from stars $\zeta_X$ affects gas heating, but not the WF coupling, the evolution of $T_b$ at high redshift is not much affected by the change in $\zeta_X$ as seen from the bottom panel of Fig. 3. At lower redshift, the change of $\zeta_X$ gives a different efficiency of gas heating, which affects the lower part of the absorption trough. For example, by assuming a smaller value for $\zeta_X$, $T_b$ gets cooler due to less heating, which shifts the peak redshift of the absorption line to a lower one. Therefore, with smaller $\zeta_X$, only the lower bound of the constraint on $\alpha_s$ and $\beta_s$ would be shifted to more larger values, while the upper bounds are unaffected. On the other hand, powerful heating due to the higher value of $\zeta_X$ can increase $T_b$ at lower redshifts. We also note that $\zeta_X$ affects the ionization history, it would give a very important effect when we look at lower redshift as $z \lesssim 10$, which however is not important in the redshift range we consider in this paper.

Here we should also mention that there are other parameters which affect the X-ray heating, such as the minimum energy of X-ray heating, $E_0$, and the spectral index of X-ray radiation, $\alpha_X$. Effects of these parameters on the behavior of 21cm global signal have been discussed in [49], from which one can see that their impact on the evolution of $T_b$ is similar to the one by $\zeta_X$, but weaker than $\zeta_X$. Thus, we do not show the dependence of 21cm global signal on $E_0$ and $\alpha_X$ here.

Before closing this section, we make a comment on a possibility of constraining primordial power spectrum from the 21cm global signal at lower redshifts. The running parameters can also be constrained via the information of the signal at lower redshifts, especially from the argument of the ionization history. However, the evolution of ionization fraction depends on other additional parameters such as the escape fraction of ionizing photon, ionization efficiency, maximum mean free path of ionizing photon and $T_{\text{vir}}$ during the EoR era. It would be worth investigating an attainable constraint on the running parameters by using the information at such lower redshifts, however, we need to take account of the effect of various astrophysical parameters mentioned above, which is computationally very demanding. We leave this for future work.

#3 For a work on constraints on ionization history at low-redshift motivated by the EDGES result, see [50].
Figure 4: Same as Figure 2, but with $T_{\text{vir}} = 3 \times 10^4$ K.

Figure 5: Same as Figure 2, but for the cases with $n_s = 0.9586$ (left) and $n_s = 0.9642$ (right) with $T_{\text{vir}} = 5 \times 10^3$ K.
5 Conclusion

We have investigated the impact of the recent EDGES result on primordial power spectrum, particularly focusing on the running parameters $\alpha_s$ and $\beta_s$. EDGES has detected the absorption line at the frequency corresponding to $z = 17.2$ and also indicates that the absorption line should not appear in the redshift range of $z < 14$ and $z > 22$. Since large values of the runnings $\alpha_s$ and $\beta_s$ directly enhance/suppress the matter power on small scales, the process of the structure formation is much affected, which changes the position of the absorption trough of the 21cm global signal. By requiring that the absorption line should appear at the frequency consistent with the EDGES result, we have obtained the bounds on the running parameters $\alpha_s$ and $\beta_s$. In particular, for some values of astrophysical parameters such as $T_{\text{vir}}$, $f_*$ and $\zeta_X$, the parameter space of $\alpha_s$ and $\beta_s$ allowed by Planck can be excluded in the light of the EDGES result.

Since the absorption line detected by EDGES was somewhat unexpected, and hence further analysis with other instruments will be awaited to draw a more rigorous conclusion regarding constraints on primordial power spectrum. Especially, more systematic analysis for foreground removal would be inevitable. However, as our analysis demonstrates that the 21cm global signal is very powerful in constraining primordial power spectrum, future observational/theoretical studies of the 21cm global signal would bring us more insight to understand the primordial Universe.

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References

[1] P. A. R. Ade et al. [Planck Collaboration], Astron. Astrophys. 594, A13 (2016) [arXiv:1502.01589 [astro-ph.CO]].

[2] P. A. R. Ade et al. [Planck Collaboration], Astron. Astrophys. 594, A20 (2016) [arXiv:1502.02114 [astro-ph.CO]].

[3] P. A. R. Ade et al. [BICEP2 and Keck Array Collaborations], Phys. Rev. Lett. 116, 031302 (2016) [arXiv:1510.09217 [astro-ph.CO]].

[4] K. Kohri, Y. Oyama, T. Sekiguchi and T. Takahashi, JCAP 1310, 065 (2013) [arXiv:1303.1688 [astro-ph.CO]].

[5] J. B. Muñoz, E. D. Kovetz, A. Raccanelli, M. Kamionkowski and J. Silk, JCAP 1705, 032 (2017) [arXiv:1611.05883 [astro-ph.CO]].
[6] T. Sekiguchi, T. Takahashi, H. Tashiro and S. Yokoyama, JCAP 1802, no. 02, 053 (2018) [arXiv:1705.00405 [astro-ph.CO]].

[7] J. B. Dent, D. A. Easson and H. Tashiro, Phys. Rev. D 86, 023514 (2012) [arXiv:1202.6066 [astro-ph.CO]].

[8] G. Cabass, A. Melchiorri and E. Pajer, Phys. Rev. D 93, no. 8, 083515 (2016) [arXiv:1602.05578 [astro-ph.CO]].

[9] K. Kainulainen, J. Leskinen, S. Nurmi and T. Takahashi, JCAP 1711, no. 11, 002 (2017) [arXiv:1707.01300 [astro-ph.CO]].

[10] J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen and N. Mahesh, Nature 555, no. 7694, 67 (2018).

[11] R. Hills, G. Kulkarni, P. D. Meerburg and E. Puchwein, arXiv:1805.01421 [astro-ph.CO].

[12] R. Barkana, Nature 555, no. 7694, 71 (2018) [arXiv:1803.06698 [astro-ph.CO]].

[13] J. B. Muñoz and A. Loeb, arXiv:1802.10094 [astro-ph.CO].

[14] A. Fialkov, R. Barkana and A. Cohen, arXiv:1802.10577 [astro-ph.CO].

[15] Z. Kang, arXiv:1803.04928 [hep-ph].

[16] A. Falkowski and K. Petraki, arXiv:1803.10096 [hep-ph].

[17] G. Lambiase and S. Mohanty, arXiv:1804.05318 [hep-ph].

[18] L. B. Jia, arXiv:1804.07934 [hep-ph].

[19] P. Sikivie, arXiv:1805.05577 [astro-ph.CO].

[20] A. Berlin, D. Hooper, G. Krnjaic and S. D. McDermott, arXiv:1803.02804 [hep-ph].

[21] R. Barkana, N. J. Outmezguine, D. Redigolo and T. Volansky, arXiv:1803.03091 [hep-ph].

[22] T. R. Slatyer and C. L. Wu, arXiv:1803.09734 [astro-ph.CO].

[23] A. Ewall-Wice, T. C. Chang, J. Lazio, O. Dore, M. Seiffert and R. A. Monsalve, arXiv:1803.01815 [astro-ph.CO].

[24] S. Fraser et al., arXiv:1803.03245 [hep-ph].

[25] Y. Yang, arXiv:1803.05803 [astro-ph.CO].

[26] M. Pospelov, J. Pradler, J. T. Ruderman and A. Urbano, arXiv:1803.07048 [hep-ph].
[27] K. Lawson and A. R. Zhitnitsky, arXiv:1804.07340 [hep-ph].
[28] T. Moroi, K. Nakayama and Y. Tang, arXiv:1804.10378 [hep-ph].
[29] A. A. Costa, R. C. G. Landim, B. Wang and E. Abdalla, arXiv:1803.06944 [astro-ph.CO].
[30] J. C. Hill and E. J. Baxter, arXiv:1803.07555 [astro-ph.CO].
[31] C. Li and Y. F. Cai, arXiv:1804.04816 [astro-ph.CO].
[32] G. D’Amico, P. Panci and A. Strumia, arXiv:1803.03629 [astro-ph.CO].
[33] M. Safarzadeh, E. Scannapieco and A. Babul, arXiv:1803.08039 [astro-ph.CO].
[34] S. Clark, B. Dutta, Y. Gao, Y. Z. Ma and L. E. Strigari, arXiv:1803.09390 [astro-ph.HE].
[35] K. Cheung, J. L. Kuo, K. W. Ng and Y. L. S. Tsai, arXiv:1803.09398 [astro-ph.CO].
[36] A. Hektor, G. Hutsi, L. Marzola, M. Raidal, V. Vaskonen and H. Veermae, arXiv:1803.09697 [astro-ph.CO].
[37] H. Liu and T. R. Slatyer, arXiv:1803.09739 [astro-ph.CO].
[38] A. Mitridate and A. Podo, arXiv:1803.11169 [hep-ph].
[39] A. Schneider, arXiv:1805.00021 [astro-ph.CO].
[40] A. Lidz and L. Hui, arXiv:1805.01253 [astro-ph.CO].
[41] J. B. Muñoz, C. Dvorkin and A. Loeb, arXiv:1804.01092 [astro-ph.CO].
[42] A. A. Kaurov, T. Venumadhav, L. Dai and M. Zaldarriaga, arXiv:1805.03254 [astro-ph.CO].
[43] M. Sitwell, A. Mesinger, Y. Z. Ma and K. Sigurdson, Mon. Not. Roy. Astron. Soc. 438, no. 3, 2664 (2014) [arXiv:1310.0029 [astro-ph.CO]].
[44] S. Furlanetto, S. P. Oh and F. Briggs, Phys. Rept. 433, 181 (2006) [astro-ph/0608032].
[45] J. R. Pritchard and A. Loeb, Rept. Prog. Phys. 75, 086901 (2012) [arXiv:1109.6012 [astro-ph.CO]].
[46] A. Mesinger and S. Furlanetto, Astrophys. J. 669, 663 (2007) [arXiv:0704.0946 [astro-ph]].
[47] A. Mesinger, S. Furlanetto and R. Cen, Mon. Not. Roy. Astron. Soc. 411, 955 (2011) [arXiv:1003.3878 [astro-ph.CO]].
[48] Z. Haiman, T. Abel and M. J. Rees, Astrophys. J. \textbf{534}, 11 (2000) [astro-ph/9903336].

[49] B. Greig, and A. Mesinger, Mon. Not. Roy. Astron. Soc. \textbf{472}, 2651 (2017) [astro-ph/1705.03471].

[50] S. Witte, P. Villanueva-Domingo, S. Gariazzo, O. Mena and S. Palomares-Ruiz, arXiv:1804.03888 [astro-ph.CO].