PROCEEDINGS OF SCIENCE

PoS(KMI2013)045

Constraining isocurvature perturbations with the 21cm emission from minihaloes

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We investigate the effects of isocurvature perturbations on the 21cm radiation from minihaloes (MHs) at high redshifts and examine constraints on the isocurvature fluctuations with the next generation of radio surveys. We find that there is a realistic prospect of observing the isocurvature imprints in the 21cm emission from MHs, but only if the isocurvature spectral index is close to 3 (*i.e.* the spectrum is blue). When the isocurvature fraction increases beyond $\sim 10\%$ of the adiabatic component, we observe an unexpected decline in the 21cm fluctuations from small-mass MHs, which can be explained by the incorporation of small MHs into larger haloes. We perform a detailed Fisher-matrix analysis, and conclude that the combination of future CMB and 21cm experiments is ideal in constraining the isocurvature parameters, and can distinguish between CDM and baryon types of isocurvature perturbations if the isocurvature fraction is large and the spectrum is blue.

KMI International Symposium 2013 on âĂIJQuest for the Origin of Particles and the Universe",
11-13 December, 2013
Nagoya University, Japan

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[†] This talk is based on [1]. We should note that [2] investigates the effect of MHs in isocurvature fluctuations to the epoch of reionization and which is significantly overlaps with our work.

1. Introduction

Recent measurements of the anisotropies in the cosmic microwave background (CMB) by the *Planck* satellite have placed constraints of unprecedented accuracy on the amplitude of the primordial density fluctuations. Planck also revealed that these fluctuations are consistent with having originated from *adiabatic* initial conditions, characterized by the constancy of the ratios of density contrasts of various particle species in the early Universe. On the other hand, if the aforementioned ratios of density contrasts are *not* constant, the fluctuations are said to be generated from *isocurvature* initial conditions. Constraints from Planck limit any isocurvature contributions to the CMB temperature anisotropies to less than ~ 10 percent.

We here present a new probe of isocurvature fluctuations using the 21cm signal from MHs. We will show that the fluctuations in the 21cm emission from MHs are a viable probe of isocurvature fluctuations. We also give forecasts on the isocurvature fluctuations using the next generation of large arrays of radio interferometers, which are expected to measure the cosmic 21cm signals over a wide range of redshifts, from the cosmic Dark Ages down to the Epoch of Reionization (EoR).

There have only been a handful of works exploring the link between 21cm cosmology and isocurvature perturbations: [3] and [4] discussed the prospects for differentiating between the CDM and baryon isocurvature fluctuations using 21cm signals. Further work by [5] showed that 21cm surveys can effectively probe the difference between CDM and baryon isocurvature fluctuations if the spectrum of isocurvature perturbations is strongly blue tilted.

The simplest model of inflation involving a single, slowly rolling scalar field predicts that density fluctuations are generated from purely adiabatic initial conditions. Hence, the detection of any isocurvature contribution would be a window to physical mechanisms in the inflationary era.

As a preliminary step, we define the primordial power spectrum for isocurvature fluctuations S_i in imitation of the adiabatic fluctuations as $\mathscr{P}_{S_i}(k) \equiv \mathscr{P}_{S_i}(k_0)\,(k/k_0)^{n_s^{\rm iso}-1}$, where $i = c$ or b, which indicates CDM or baryon isocurvature mode, $\mathscr{P}_{S_i}(k_0)$ and $n_s^{\rm iso}$ are respectively the amplitude and the spectral index for the mode i defined at reference scale k_0. Then, we introduce primordial isocurvature fractions to the adiabatic fluctuations ζ as $r_{\rm cdm} \equiv \mathscr{P}_{S_c}(k_0)/\mathscr{P}_\zeta(k_0)$ and $r_{\rm bar} \equiv \mathscr{P}_{S_b}(k_0)/\mathscr{P}_\zeta(k_0)$ for CDM and baryon isocurvature modes, respectively.

2. 21cm emission from minihaloes with isocurvature fluctuations

According to our current understanding of cosmology, inflation-stretched primordial quantum fluctuations subsequently grow via gravitational instability into the observed cosmic structures. One of the earliest cosmic structures to form were MHs, which are virialized haloes of dark and baryonic matter with typical mass $10^4 - 10^8\ M_\odot$, and temperature $\lesssim 10^4$ K, at very high redshift.

MHs typically host a high density of neutral hydrogen, which can be detected by the 21cm absorption/emission line due to the transition of the hydrogen atom from a parallel to anti-parallel spin state. MHs are typically at such high temperatures that their 21cm signal appears in emission with respect to the CMB [6]. The 21cm signals from MHs give us information on the small-scale density fluctuations at high redshifts, and their detection will therefore lead to a deeper understand-

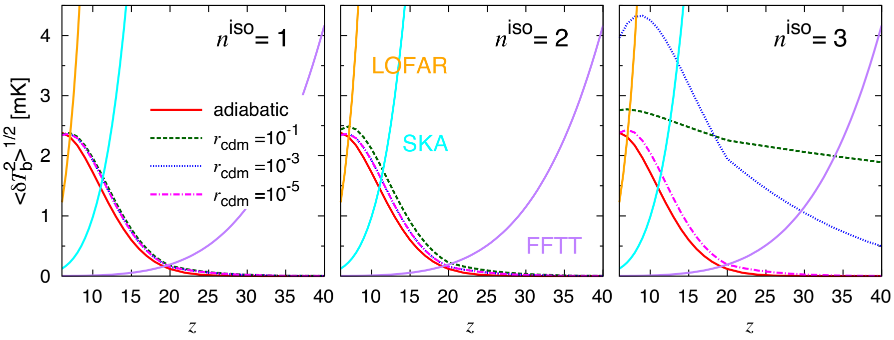

Figure 1: The *rms* fluctuations in the 21cm emission from MHs $\langle \delta {T_{\rm b}}^2\rangle^{1/2}$ and the sensitivity curves for LOFAR (orange), SKA (cyan) and FFTT (purple). Unusual trends in the right panel is discussed in the text.

ing of small-scale physics during the earliest structure-formation epoch.

The amplitude of the 21cm signal from a virialized halo depends on the density profile, velocity and temperature of the halo. We adopt as our model the *truncated isothermal sphere* (TIS) [7, 8]. In this model, each minihalo is modeled as a non-singular sphere of dark matter and baryons in virial and hydrostatic equilibrium.

The mean 21cm emission from an ensemble of MHs in the mass range $[M_{\rm min}, M_{\rm max}]$ is given by [6]

$$\overline{\delta T_{\rm b}} = \frac{c(1+z)^4}{\nu_0 H(z)} \int_{M_{\rm min}}^{M_{\rm max}} \Delta\nu_{\rm eff} \delta T_{\rm b}(M) A \frac{dn}{dM} dM \ , \tag{2.1}$$

where $\delta T_{\rm b}(M)$ is the differential 21cm brightness temperature measured with respect to the CMB temperature and averaged over the halo cross-section A. $\nu_{\rm eff}$ is the effective redshifted line width.

Then, the *rms* fluctuations in the 21cm emission for a pencil-beam survey with bandwidth $\Delta\nu$ and angular size $\Delta\theta$ is given by

$$\langle \delta T_{\rm b}^2 \rangle^{1/2} = \sigma_{\rm p}(z, \Delta\nu, \Delta\theta) \beta(z) \overline{\delta T_{\rm b}}(z) \ , \tag{2.2}$$

where $\sigma_{\rm p}$ is the variance in a cylinder and β is the flux-weighted average of the halo bias.

In Figure 1, we show the *rms* fluctuations in the 21cm emission from MHs and the sensitivity curves for some radio surveys. If the isocurvature spectrum is very blue ($n_s^{\rm iso} = 3$)[1], large differences can be seen, especially at high redshifts. However, a slight trend reversal is seen around $z \lesssim 20$, where $r_{\rm cdm} = 10^{-3}$ boosts the signal more effectively than when $r_{\rm cdm} = 10^{-1}$. This can be understood in terms of the incorporation of small-mass MHs into larger haloes.

3. Constraints on isocurvature fluctuations

We now perform a Fisher-matrix analysis on the cosmological parameters derived from measurements of the CMB and the fluctuations in the 21cm signal from MHs. In Figure 2, we show the constraints in the $r_{\rm cdm} - r_{\rm bar}$ parameter space expected from future the CMB (CMBPol) and the 21cm (FFTT) line surveys.

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[1] Some physical models which predict very blue isocurvature spectrum with $n_s^{\rm iso} = 2$ - 4 are discussed in [9].

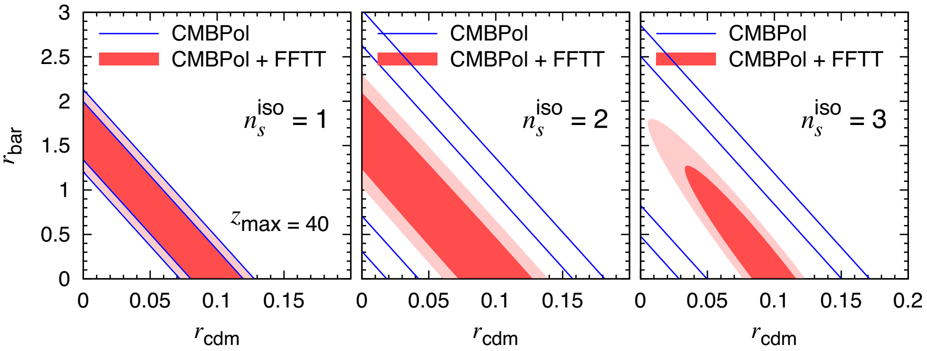

Figure 2: Projected 1σ (68 %) and 2σ (95 %) constraints in the $r_{\rm cdm}$ - $r_{\rm bar}$ plane from the CMB (CMBPol) alone (solid/blue) and the combination with 21cm line from MHs (FFTT) (shaded/red). For the fiducial model, we used $n_s^{\rm iso} = 1$, 2 and 3 (from left to right) and the isocurvature fractions of $(r_{\rm cdm}, r_{\rm bar}) = (0.1, 0)$ in all cases.

As shown in the previous section, the contribution from a scale-invariant ($n_s^{\rm iso} = 1$) isocurvature spectrum to the 21cm MH signal is small. This is also evident from the contours, which are only modestly tightened by when 21cm constraints are added to those from CMBPol. The improvement is more dramatic for bluer isocurvature spectra, where we can see that it is possible to break parameter degeneracies by the combining CMB and 21cm constraints.

4. Summary

We have investigated the effects of isocurvature perturbations on the 21cm emission from MHs at high redshifts. Our results showed that if the isocurvature power spectrum is flat, the 21cm MH signal, measured by the *rms* differential brightness temperature, changes only by less than a few percent around its peak. However, strongly blue-tilted spectrum gives rise to a significant increase in the amplitude of the 21cm signal compared with the adiabatic case. The next generation of huge radio surveys such as SKA and FFTT has the potential to detect these 21cm imprints from a blue isocurvature spectrum.

The characteristic signatures of isocurvature perturbations on the MH abundances were explored in detail. In particular, we found an unexpected deficit in small-mass MHs when the isocurvature fraction increases beyond a certain threshold. We explained this phenomenon in terms of the incorporation of small-mass MHs into larger haloes.

A detailed Fisher-matrix analysis was performed to study quantitatively how the 21cm signals from MHs can constrain the isocurvature amplitude and spectral index. We found that if the isocurvature spectrum is flat, 1) the combination of CMB and 21cm experiments fares no better than the CMB alone, 2) the CDM and baryon types of isocurvature fluctuations are unlikely to be distinguishable, even with the futuristic CMBPol+FFTT specifications.

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