

Reheating the Universe Once More: The Dissipation of Acoustic Waves as a Novel Probe of Primordial Inhomogeneities on Even Smaller Scales

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We provide a simple but robust bound on the primordial curvature perturbation in the range $10^4 \text{ Mpc}^{-1} < k < 10^5 \text{ Mpc}^{-1}$, which has not been constrained so far unlike low-wave-number modes. Perturbations on these scales dissipate the energy of their acoustic oscillations by the Silk damping after primordial nucleosynthesis but before the redshift $z \sim 2 \times 10^6$ and reheat the photon bath without invoking cosmic microwave background distortions. This acoustic reheating results in the decrease of the baryon-photon ratio. By combining independent measurements probing the nucleosynthesis era and around the recombination epoch, we find an upper bound on the amplitude of the curvature perturbation over the above wave number range as $\mathcal{P}_\zeta < 0.06$. Implications for supermassive black holes are also discussed.

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Introduction.—Primordial inhomogeneities have been intensively investigated by cosmic microwave background (CMB) [1,2] or large scale structures of the Universe. However, the perturbation scales relevant to these probes are limited to $O(\text{Mpc})$ to $O(\text{Gpc})$ and information of fluctuations on smaller scales is relatively scarce. On the other hand, some models of the early universe predict enhancement of the power spectrum of fluctuations on small scales [3–16], so investigating small scale perturbations is important. Given this situation, several methods to probe small scale fluctuations have been studied such as primordial black holes (PBHs) [17,18], ultracompact minihalos [19–23], and CMB spectral distortions [24–33].

In this Letter, we propose a novel method to probe perturbations on smaller scales than those probed by CMB spectral distortions ($10^4 \text{ Mpc}^{-1} < k$). This method is based on a phenomenon we call “acoustic reheating.” During the radiation-dominated era, perturbations are damped after the horizon crossing (diffusion damping or Silk damping [34,35]), injecting energy into the background universe. Before the μ era, the era when energy release leads to CMB μ distortions, any energy injection only causes increase in the average photon temperature, without invoking any spectral distortions [36–38]. If this energy injection takes place after the big bang nucleosynthesis (BBN), it increases the number density of photons n_γ , without changing the number density of baryons n_b , and so decreases the baryon-photon ratio $\eta \equiv n_b/n_\gamma$. Since the value of η is independently inferred by BBN [39] and CMB observation [40], we can put constraints on the amount of energy injection [41], or primordial perturbation amplitude (see also [42]).

Calculation of energy injection.—The basic equations can be found in [26] [by Chuba, Erickcek, and Ben-Dayan (CEB)]. The total energy release due to the damping of acoustic waves from the redshift z_2 to z_1 ($< z_2$) is given by

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = \int_{z_1}^{z_2} \frac{1}{a^4\rho_\gamma} \frac{d(a^4Q_{\text{ac}})}{dz} dz, \quad (1)$$

with

$$\frac{1}{a^4\rho_\gamma} \frac{d(a^4Q_{\text{ac}})}{dz} \sim 9.4a \int \frac{kdk}{k_D^2} \mathcal{P}_\zeta(k) 2\sin^2(kr_s) e^{-2k^2/k_D^2}, \quad (2)$$

where $r_s \sim 2.7 \times 10^5 (1+z)^{-1} \text{ Mpc}$ is the sound horizon and $k_D \sim 4.0 \times 10^{-6} (1+z)^{3/2} \text{ Mpc}^{-1}$ is the damping scale determined by the diffusion of photons.

The largest contributions to the energy release at a redshift z come from the modes around $k \sim k_D(z)$ and so we can safely approximate $\sin^2(kr_s) \sim 1/2$, since $k_D(z)r_s(z) \sim (1+z)^{1/2} \gg 1$. Let us consider a top-hat power spectrum: $\mathcal{P}_\zeta(k) = A_\zeta(k_1 < k < k_2), 0$ (otherwise), noting that the effects of acoustic reheating are most significant when the width of the enhanced part of the power spectrum is widest. We set $k_1 = 10^4 \text{ Mpc}^{-1}$, since the power spectrum is severely constrained for $k_1 < 10^4 \text{ Mpc}^{-1}$ by μ distortion [26]. On the other hand, the modes $10^5 \text{ Mpc}^{-1} < k$ dissipate before the neutrino decoupling due to the neutrino diffusion. The comoving wave number for the neutrino diffusion becomes $k = 10^5 \text{ Mpc}^{-1}$ at the time of neutrino decoupling, which is close to the horizon scale at that time [43]. Since what can be

probed by the consistency between BBN and CMB is only energy injection *after* BBN, taking place shortly after the neutrino decoupling, modes shorter than $k = 10^5 \text{ Mpc}^{-1}$ cannot be constrained and so we set $k_2 = 10^5 \text{ Mpc}^{-1}$.

For the top-hat power spectrum ranging from k_1 to k_2 , the energy release given by Eq. (2) becomes

$$\frac{1}{a^4 \rho_\gamma} \frac{d(a^4 Q_{\text{ac}})}{dz} \sim \frac{2.4 A_\zeta}{1+z} \left[\exp \left\{ -2 \left(\frac{1+z_{*,1}}{1+z} \right)^3 \right\} - \exp \left\{ -2 \left(\frac{1+z_{*,2}}{1+z} \right)^3 \right\} \right], \quad (3)$$

where $k_* \equiv 4 \times 10^{-6} \text{ Mpc}^{-1}$ and

$$z_{*,i} \equiv \left(\frac{k_i}{k_*} \right)^{2/3} \quad (i = 1, 2) \quad (4)$$

is the redshift when the mode k_i dissipates. The total energy release then becomes

$$\frac{\Delta \rho_\gamma}{\rho_\gamma} \sim 0.8 A_\zeta \left[\text{Ei} \left(-2 \left(\frac{1+z_{*,1}}{1+z} \right)^3 \right) - \text{Ei} \left(-2 \left(\frac{1+z_{*,2}}{1+z} \right)^3 \right) \right]_{z_2}^{z_1} \sim 2.3 A_\zeta, \quad (5)$$

where Ei denotes an exponential integral. We choose $z_{*,1} = 2 \times 10^6$, the onset of the μ era, and $z_{*,2} = 8.5 \times 10^6$, around when the mode $k = 10^5 \text{ Mpc}^{-1}$ dissipates, assuming it dissipates due to the diffusion of photons.

Constraints on A_ζ obtained by the baryon-photon ratio.—The baryon-photon ratio η has been determined independently by BBN and CMB, so the damping should not increase the number of photons too much (or equivalently should not decrease η too much) after BBN, from which constraints on A_ζ can be obtained. To be consistent with observation, we require (noting $n_\gamma \propto T^3$, $\rho_\gamma \propto T^4$)

$$\frac{\eta_{\text{CMB}}}{\eta_{\text{BBN}}} = \left(1 - \frac{3 \Delta \rho_\gamma}{4 \rho_\gamma} \right) > \frac{\eta_{\text{CMB,obs}}}{\eta_{\text{BBN,obs}}}, \quad (6)$$

where η_{BBN} and η_{CMB} are the baryon-photon ratios at the time of BBN and after the onset of the μ era (η becomes constant after this moment since we only consider energy injection before the μ era) and the subscript “obs” implies a value determined by observation. Using (5), this inequality is rewritten as a constraint on A_ζ :

$$A_\zeta \lesssim 0.6 \left(1 - \frac{\eta_{\text{CMB,obs}}}{\eta_{\text{BBN,obs}}} \right). \quad (7)$$

As the observed values, we follow [39], in which $\eta = (6.11 \pm 0.08) \times 10^{-10}$ for CMB and $\eta = (6.19 \pm 0.21) \times 10^{-10}$ for BBN were adopted. For 1σ constraint, we

conservatively set $\eta_{\text{CMB,obs}} = (6.11 - 0.08) \times 10^{-10}$ and $\eta_{\text{BBN,obs}} = (6.19 + 0.21) \times 10^{-10}$ (and 2σ constraints are considered similarly). Then, the constraint on A_ζ is

$$A_\zeta \lesssim 0.03(1\sigma), \quad 0.06(2\sigma). \quad (8)$$

Discussion.—The constraints on the amplitude of the curvature perturbation have also been obtained to avoid overproduction of PBHs to be consistent with observations [44–46]. If we follow [18] (see also [17]), considering the disruption of wide binaries, which is relevant to the scales accessible by acoustic reheating, we obtain a constraint by PBHs as $A_\zeta \lesssim 0.05$.

Although the order of magnitude of these constraints is the same, we may not compare the two directly for several reasons. First a constraint imposed by PBH refers to the average of peaked curvature fluctuations over one e -fold of wave number, and it is obtained under the assumption that there is one-to-one correspondence between the mass of PBHs and the comoving scale of perturbation. But this is not true since the critical phenomenon [47,48] has been observed, which results in formation of a number of PBHs with their mass much smaller than the comoving horizon mass. Furthermore, since PBHs are created at high- σ peaks, possible non-Gaussian distribution may change their abundance in a model-dependent manner [3,5,11]. In particular, when non-Gaussianity is extremely large, it can change constraints to avoid overproduction of PBHs [49,50]. (Note that $f_{NL}^{\text{local}} = O(1)$ corresponds to a case with extremely large non-Gaussianity for PBH formation whose relevant amplitude of fluctuation is $O(0.1)$ and the ratio of the linear-to-second-order term is as large as 0.1 for $f_{NL}^{\text{local}} = O(1)$.)

On the other hand, acoustic reheating considered here is insensitive to the assumption of Gaussianity (as is also pointed out in CEB) and is relatively easy to quantify precisely as well as relate to observations. Furthermore, what is interesting about constraints on the amplitude of primordial fluctuations obtained by acoustic reheating is that they can improve almost in proportion to potential future decrease in error bars associated with the determination of η .

Though our constraints apply only in a relatively narrow range $10^4 \text{ Mpc}^{-1} < k < 10^5 \text{ Mpc}^{-1}$, this technique will have profound implications. For example, if the constraints from acoustic reheating become tighter in future, PBHs in the corresponding comoving horizon mass range $10^3 M_\odot < M < 10^5 M_\odot$ will be severely constrained (note that PBHs bigger than $10^5 M_\odot$ are severely constrained by μ distortion [51]). This mass range is particularly interesting in the context of scenarios of PBHs as the seeds of supermassive black holes.

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