## **Constraints on Pre-inflation Fluctuations in a Nearly Flat Open ACDM Cosmology**

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There is now a general consensus that we live in a nearly flat universe. The best fit of the combined CMB + HiL + BAO fit by the Planck collaboration [1] obtained a closure content of the universe to be  $\Omega_0 = 1.005^{+0.0062}_{-0.0065}$ implying a curvature content of  $\Omega_k \equiv 1 - \Omega_0 = -0.0005$ +0.0062 . This is indeed very close to exact flatness. Nevertheless, in this paper [2] we considered the possibility that the present universe is slightly open, i.e.  $\Omega_0 \ge 0.994$  at the 95 % confidence level. In this case any fluctuations that existed before inflation might now be visible on the horizon. In our paper [2], we determined what constraints can be placed on inhomogeneities in the pre-inflation universe based upon current cosmological observations. Such pre-inflation isocurvature fluctuations would appear as a distortion in the cosmic microwave background dipole moment and can be characterized as a cosmic dark flow velocity vDF.

We developed a simple analytical model in which the pre-inflation universe contained a plane-wave sinusoidal inhomogeneity as an isocurvature fluctuation.  $\phi(t, z) = \phi_i + \delta \phi_i \sin \frac{2\pi}{\lambda_i} (a_i z - t)$ . The wavelength of the fluctuation can then be parameterized by:  $\lambda_i = lH_i^{-1}$ , The pre-inflation universe is then characterized by: 1) the scale *l* of the fluctuation in the inflaton field; 2) the initial closure parameter of the universe  $\Omega_i$ ; and 3) the fraction of the energy density of the universe in the inflaton field *f* as the universe enters the inflationary epoch.

Figure 1 from [2] summarizes values for  $\Omega_i$  and l that satisfy the constraint f < 1 based upon the upper limit  $v_{\rm DF} = 254 \,\rm km \, s^{-1}$  from the *Planck* analysis of the KSZ effect, and the constraint that the quadrupole and higher moments not exceed the value from the observed CMB power spectrum. The upper region shows that only values of *l* near unity can satisfy this constraint while the the upper limit to the initial closure parameter is  $\Omega_i <$ 0.4 ( $\Omega_{k,i} > 0.6$ ) as  $f \rightarrow 1$ . Indeed, from these constraints alone we find that the pre inflation fluctuation in the power spectrum must reside at least ~80 times the current Hubble scale. Such fluctuations are also constrained by the near flatness of the current universe. Indeed, all together we find that the wavelength of the pre-inflation fluctuation must be of order the Hubble scale as inflation begins. Also, if there is a pre-inflation component to the current cosmic dipole moment, then the initial preinflation closure parameter could have been as large as  $\Omega_i$  $< 0.4 \ (\Omega_{k,i} > 0.6).$ 

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Figure 1: Constraints on the pre-inflation parameters as a function of the fraction *f* of the initial pre-inflation energy density in the inflaton field for a present dark flow velocity of 254 km s<sup>-1</sup> from the upper limit to the *Planck* analysis [3]. Lower shaded region shows allowed values for the initial closure parameter  $\Omega_i$ . Upper shaded region shows the allowed values of the wavelength parameter *l*.

## References

- [1] Planck Collaboration, Planck XVI: 2014, A&A, 566, A54.
- [2] Mathews, G. J., et al.: 2015, Phys. Rev. D, 92, 123514.
- [3] Planck Collaboration, Planck XIII: 2014, A&A, 561, A97.