Hubble Expansion Variance and the Cosmic Rest Frame

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Average homogeneity is only reached on scales greater than 70–100h^{-1}Mpc yet standard peculiar velocity approaches assume an most Euclidean geometry below this scale. Furthermore, the Friedmann equation is applied in the nonlinear regime, although this has no motivation in the fundamental principles of general relativity. We investigate the variance of the Hubble expansion in a manner which makes no prior geometrical assumptions, other than the existence of a suitably averaged linear Hubble law. We use the COMPOSITE data set of 4534 galaxies [Watkins, Feldman and Hudson (2009)].

Spherical shell averages

- Monopole variation of average expansion is determined in 11 independent spherical shells of minimum width 12.5h^{-1}Mpc, (for two separate choices of shell boundaries). The Hubble constant H_s for a linear expansion law, computed for the sth shell is

$$H_s = \left(\sum_{i=1}^{N_s} \frac{(cz_i)^2}{\sigma_i^2} \right) \left(\sum_{i=1}^{N_s} \frac{cz_i r_i}{\sigma_i^2} \right)^{-1} \qquad (1)$$

  where distances r_i and their uncertainties σ_i are in h^{-1}Mpc.
- The difference of H_s for each shell relative to the asymptotic value $\bar{H}_0$ (at $r > 156h^{-1}$Mpc) is determined as a relative fraction $\delta H_s = \left(H_s - \bar{H}_0\right)/\bar{H}_0$.
- The analysis is carried out in the CMB, Local Group and Local Sheet frames.
- We find with **extremely strong** Bayesian evidence ($\ln B \gg 5$) that the Hubble constant, when averaged in these spherical shells, is closer to its asymptotic value when referred to the rest frame of the LG, rather than the CMB.

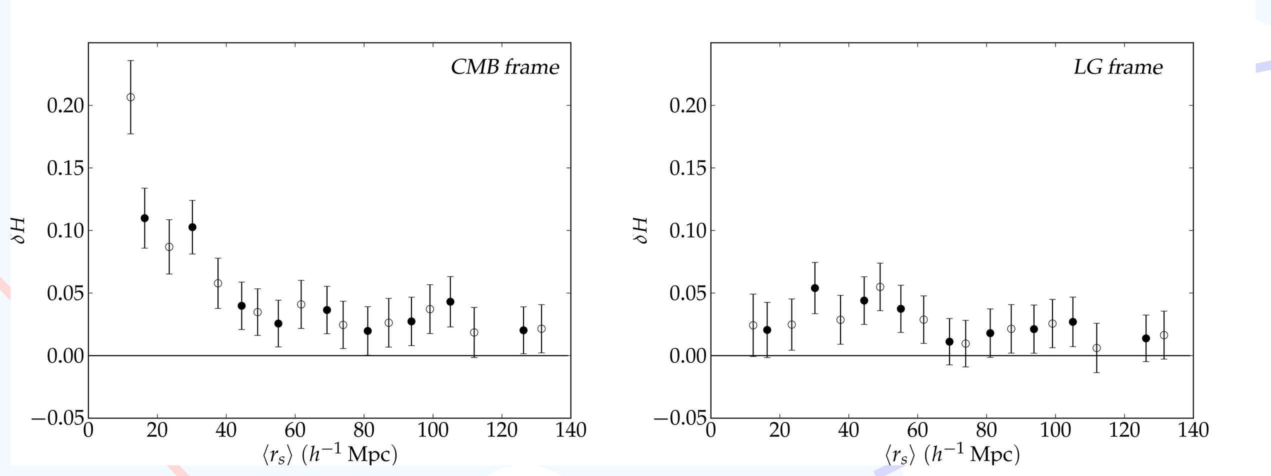

Figure 1. Variation in the Hubble expansion in spherical shells as a function of the weighted mean shell distance for the CMB frame (*left*) and the Local Group frame (*right*). The LG frame value is lower except for $40h^{-1} \lesssim r \lesssim 60h^{-1}$Mpc.

Systematic Boost Offset

- The variance observed in the CMB frame can be almost entirely explained as a systematic boost offset. If H_s is the value of the Hubble constant in the sth shell in a frame in which the spherical Hubble variance is minimized, and H'_s is the value in any frame with relative velocity v, then the difference is found to be

$$\Delta H_s \equiv H'_s - H_s \approx \left(\sum_{i=1}^{N_s} \frac{(v\cos\phi_i)^2}{\sigma_i^2} \right) \left(\sum_{i=1}^{N_s} \frac{cz_i r_i}{\sigma_i^2} \right)^{-1} = \frac{<(v\cos\phi_i)^2>_s}{<cz_i r_i>_s} \approx \frac{v^2}{2\bar{H}_0 <r_i^2>_s} \qquad (2)$$

  where $<\cdot>$ denotes a weighted average and $\bar{H}_0$ is the asymptotic Hubble constant.
- Fitting a power law, $\Delta H_s = aY^b$, $Y \equiv <r_i^2>_s$ gives a value of $b = -1.0 \pm 0.2$ as expected.

Frame of Minimum H_0 Variance (with J.H. McKay)

- In which frame of reference is spherically averaged linear Hubble law the *most* uniform?
- There is a degenerate set of possible minimum variances frames, all boosted from the Local Group in the plane of the galaxy. The magnitude of this boost from the LG is consistent with zero, thus not ruling out the LG frame. The lack of a systematic boost offset between these degenerate frames further supports this claim. Correlation between the CMB temperature dipole and the Hubble variance is also considered as an independent test.
- Further analysis will test the hypothesis that the lack of data in the Zone of Avoidance is responsible for the large uncertainty in this boost velocity and thus the cause of the degeneracy.

Angular Averages

- In order to associate variance in the Hubble law with foreground structures angular information is also required.
- Angular averages were studied by two methods: (i) Gaussian window averages; (ii) fitting a simple linear dipole law

$$\frac{cz}{r} = H_d + \beta\cos\phi \qquad (3)$$

  in the same spherical shells, in LG and CMB rest frames. In each case ϕ is the angle on the sky between each galaxy and the direction of the best fit dipole axis, (l_d, b_d). H_d, β, l_d and b_d are determined using a least squares fit. Figure 2 shows the value of β in each shell.
- The dipole magnitudes coincide at $\bar{r} = 30.2h^{-1}$Mpc and $\bar{r} = 61.7h^{-1}$Mpc yet exhibit very different behavior in-between these distances.
- Analysis of this phenomena leads to the conclusion that the boost from the LG to the CMB frame is compensating for structures in the range $30h^{-1} \lesssim r \lesssim 62h^{-1}$Mpc.
- The transition occurs in the only range in which the spherical average also produces a better fit in the CMB than LG frame; i.e., the differential expansion *almost (but not exactly)* has the character of a local boost.

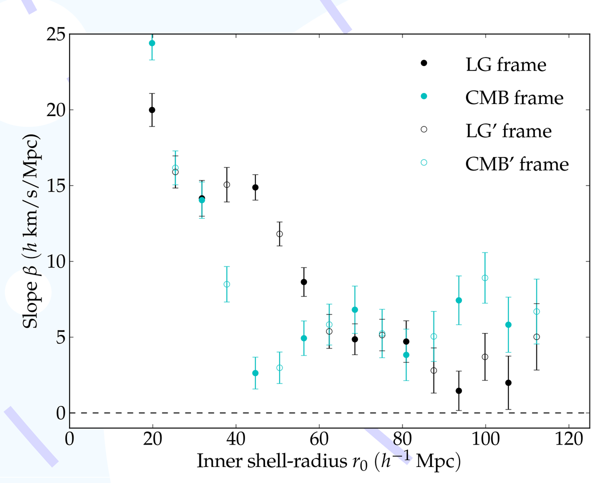

Figure 2: The slope β of the linear dipole relation is plotted by shell in the CMB and LG rest frames. The filled and unfilled circles correspond to the two different choices of shell boundaries.

The CMB dipole and differential expansion

- Does the Hubble law dipole correlate with the component of the CMB temperature dipole that is usually attributed to the motion of the Local Group? (635km/s towards $(\ell, b) = (276.4°, 29.3°)$).
- We compute the correlation of the residual CMB temperature skymap with a Gaussian window averaged skymap (on scales $\geq 15h^{-1}$ Mpc. Figure 3 shows these sky maps with the dipole clearly evident.)
- A Pearson correlation coefficient of -0.92 is found, indicating a strong anti-correlation.
- Calculations show that a 0.5% differential expansion of space on scales $\lesssim 60h^{-1}$Mpc is what is required to account for all the putative 635 km/s "local motion" of the Local Group
- In every exact general relativistic model cosmology (other than the FLRW model) differential expansion, which cannot be reduced to a local boost, is the norm.
- Realistic CMB spectra for dipole, quadrupole, have been produced by ray-tracing in with nonlinear foreground inhomogeneities using the Lemaître–Tolman and Szekeres models (K. Bolejko, M.A. Nazer, D.L. Wiltshire, in preparation)

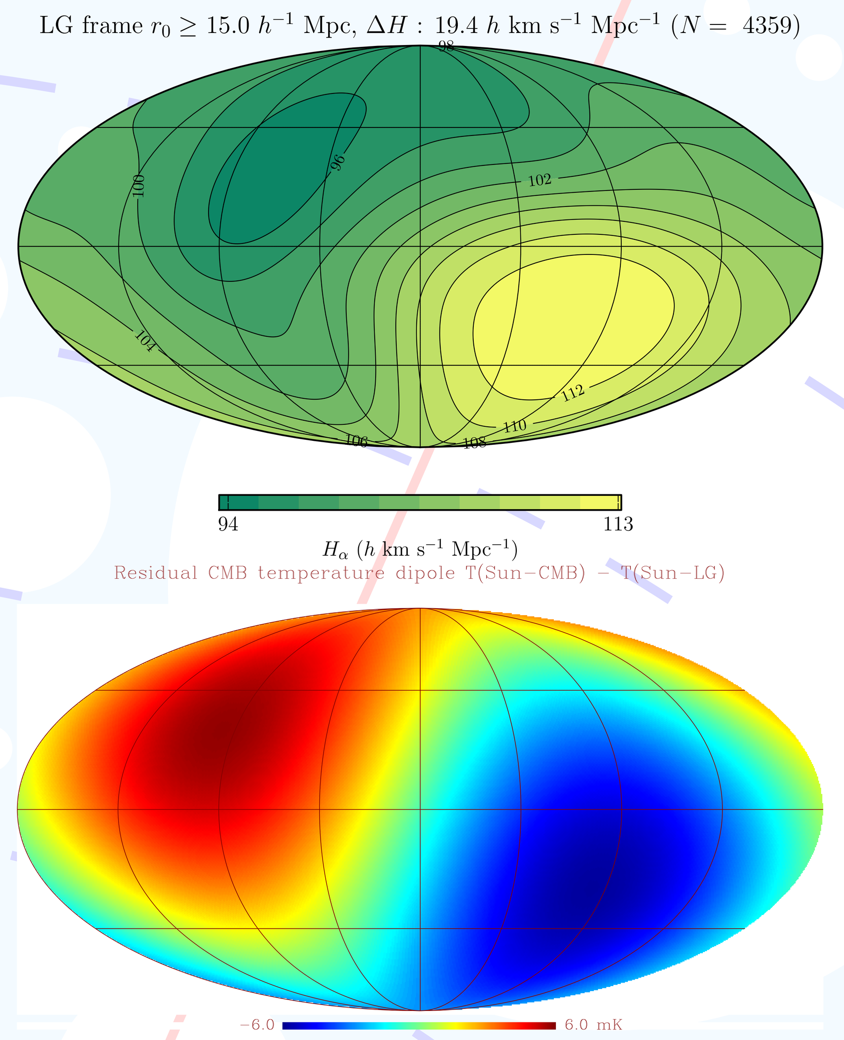

Figure 3: LG frame Hubble flow variance map for $r > 15h^{-1}$Mpc (*top*) compared to the residual CMB temperature dipole in the LG frame (*bottom*). N.B. Galactic longitudes $l = 0°, 180°, 360°$ are on the right, centre and left respectively.

To boost or not to boost?: CMB anomalies

- Since data is routinely transformed to the CMB, our result has obvious implications for all observational cosmology.
- A differential expansion dipole can differ subtly from a boost dipole. Dipole subtraction and foreground galaxy cleaning require reanalysis (and it is hard).
- Aghanim N. *et al* 2013, arXiv:1303.5087, claim to have measured the effects of aberration and modulation in the Planck data. However, the claim only works for small angles. For large angles the putative boost direction moves away from its correct direction to point in the direction of maximum anomaly.
- Such a scale-dependence may be the precise signature of an effect we claim and will principally affect large angle multipoles only.

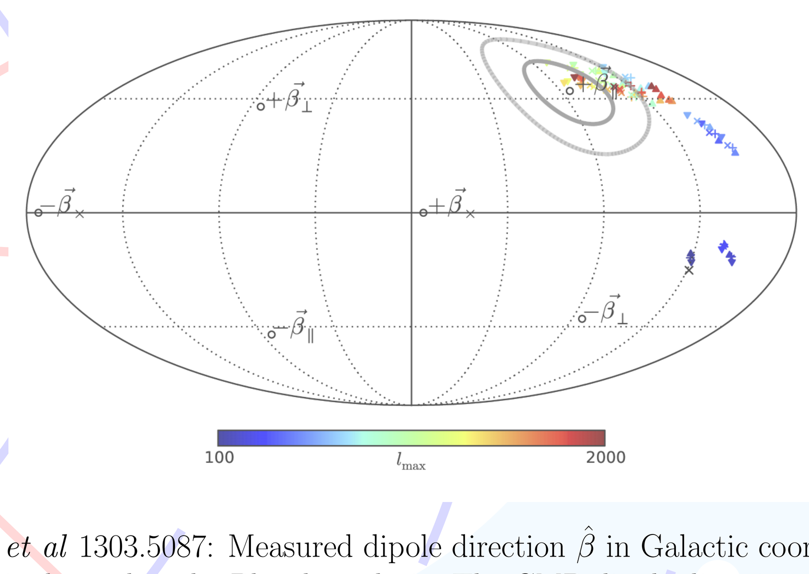

Figure 4. From Aghanim N *et al* 1303.5087: Measured dipole direction $\hat{\beta}$ in Galactic coordinates as a function of the maximum temperature multipole used in the Planck analysis. The CMB dipole direction $\beta_{\|}$ has been highlighted with 14° and 26° radius circles, which correspond roughly to our expected uncertainty on the dipole direction. The black cross in the lower hemisphere is the modulation dipole anomaly direction found for WMAP at $l_{max} = 64$.
N.B. Galactic longitudes $l = 0$ is at the center of this map.

Local/global H_0 (with K. Bolejko, M.A. Nazer, R. Watkins)

- Since Planck 2013 the values of local and global H_0 measurements are an issue, even for ΛCDM
- Riess et al (2009,2011) estimate H_0 by fitting an O(z^3) spatially flat Friedmann luminosity distance to SneIa in the range $0.23 < z < 0.1$, *assuming given values* of $q_0 = -0.55$, $j_0 = 1$.
- If foreground inhomogeneities in the nonlinear regime do not obey the Friedmann equation such a fit can give H_0 values which differ depending on the redshift range used, even for $z > 0.23$. (This is seen in our data.)
- Ray-tracing to galaxies through nonlinear foreground voids by using exact solutions of Einstein's equations that match asymptotically to a Planck-fit LCDM background show that the difference between "local" and "global" values can be potentially resolved. A paper will appear shortly.

References

[1] Wiltshire D L, Smale P R, Mattsson T, and Watkins R 2013 *Phys. Rev.* D **88** 083529