Hubble flow variance and the cosmic rest frame

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DLW, P R Smale, T Mattsson and R Watkins

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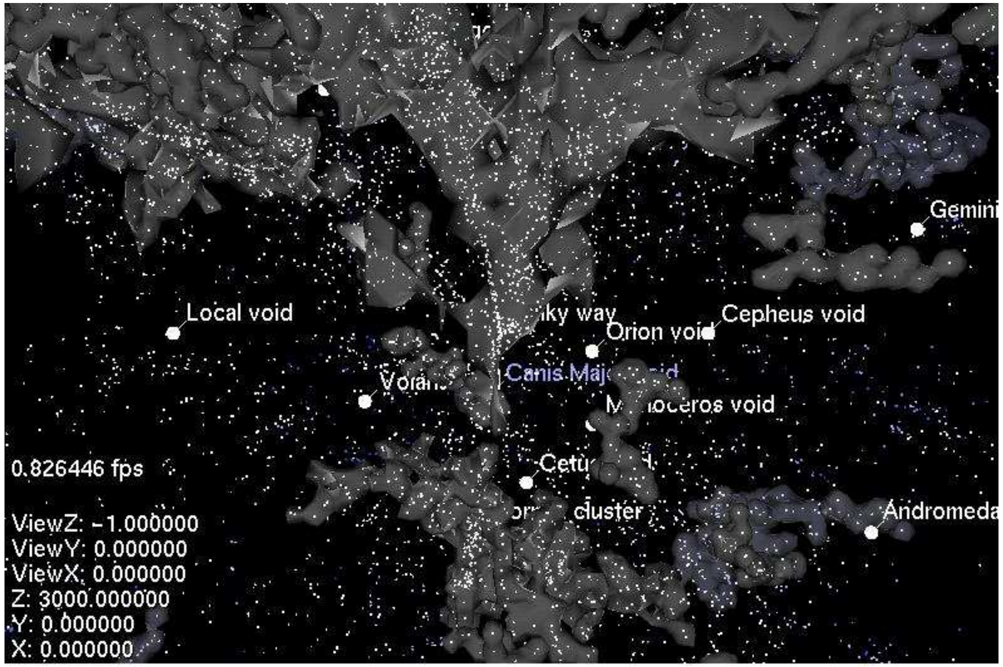
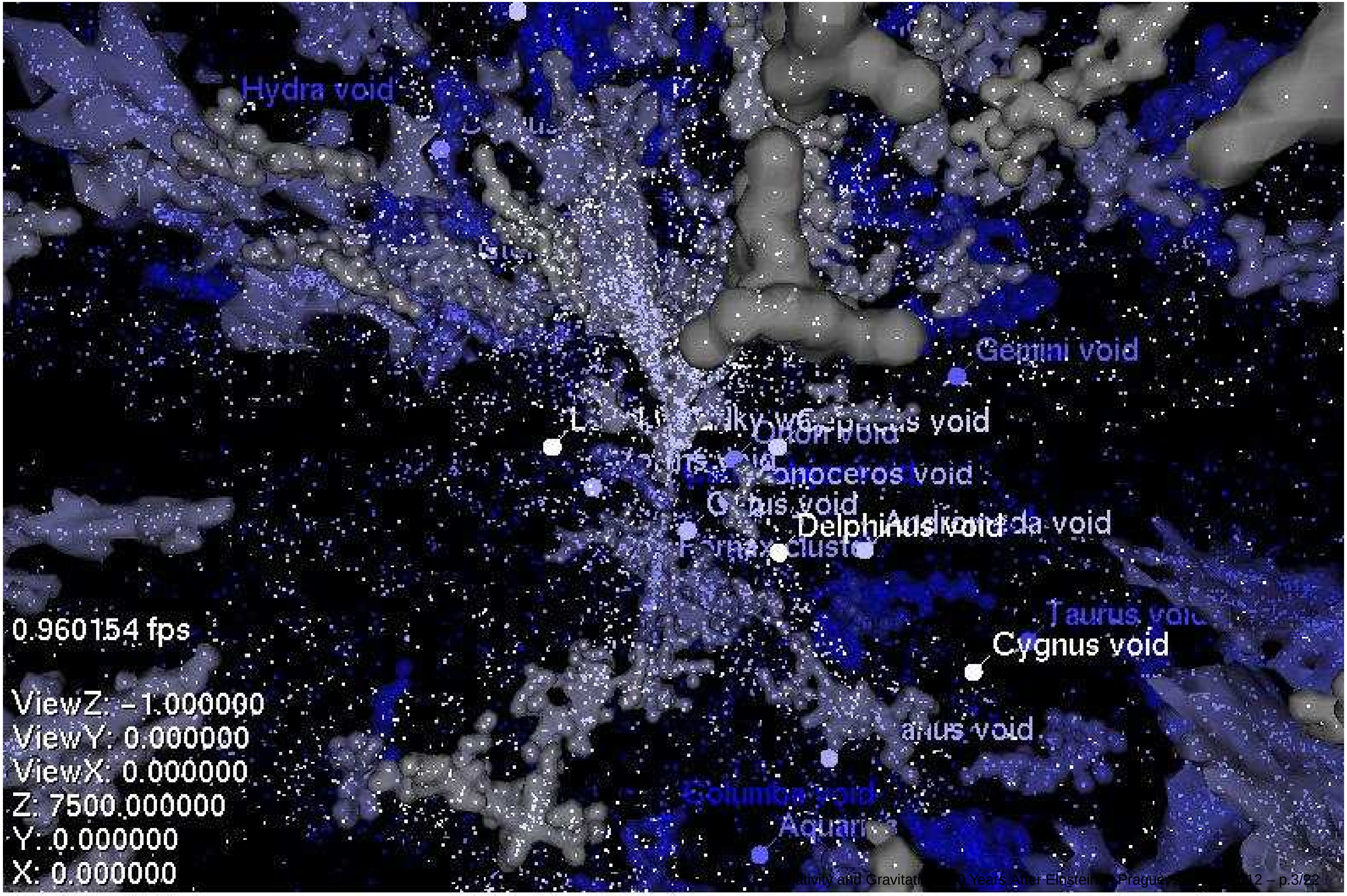


From smooth to lumpy

- Universe was very smooth at time of last scattering; fluctuations in the fluid were tiny ($\delta\rho/\rho \sim 10^{-5}$ in photons and baryons; $\sim 10^{-4}$,10^{-3} in non–baryonic dark matter).
- FLRW approximation very good early on.
- Universe inhomogeneous today on scales $\lesssim 100h^{-1}$Mpc
- Recent surveys estimate that 40–50% of the volume of the universe is contained in voids of diameter $30h^{-1}$ Mpc. [Hubble constant $H_0 = 100h$ km/s/Mpc] (Hoyle & Vogeley, ApJ 566 (2002) 641; 607 (2004) 751)
- Add some larger voids, and many smaller minivoids, and the universe is *void–dominated* at present epoch.
- Clusters of galaxies are strung in filaments and bubbles around these voids.

6df: voids & bubble walls (A. Fairall, UCT)



Peculiar velocity formalism

- Standard framework, FLRW + Newtonian perturbations, assumes peculiar velocity field

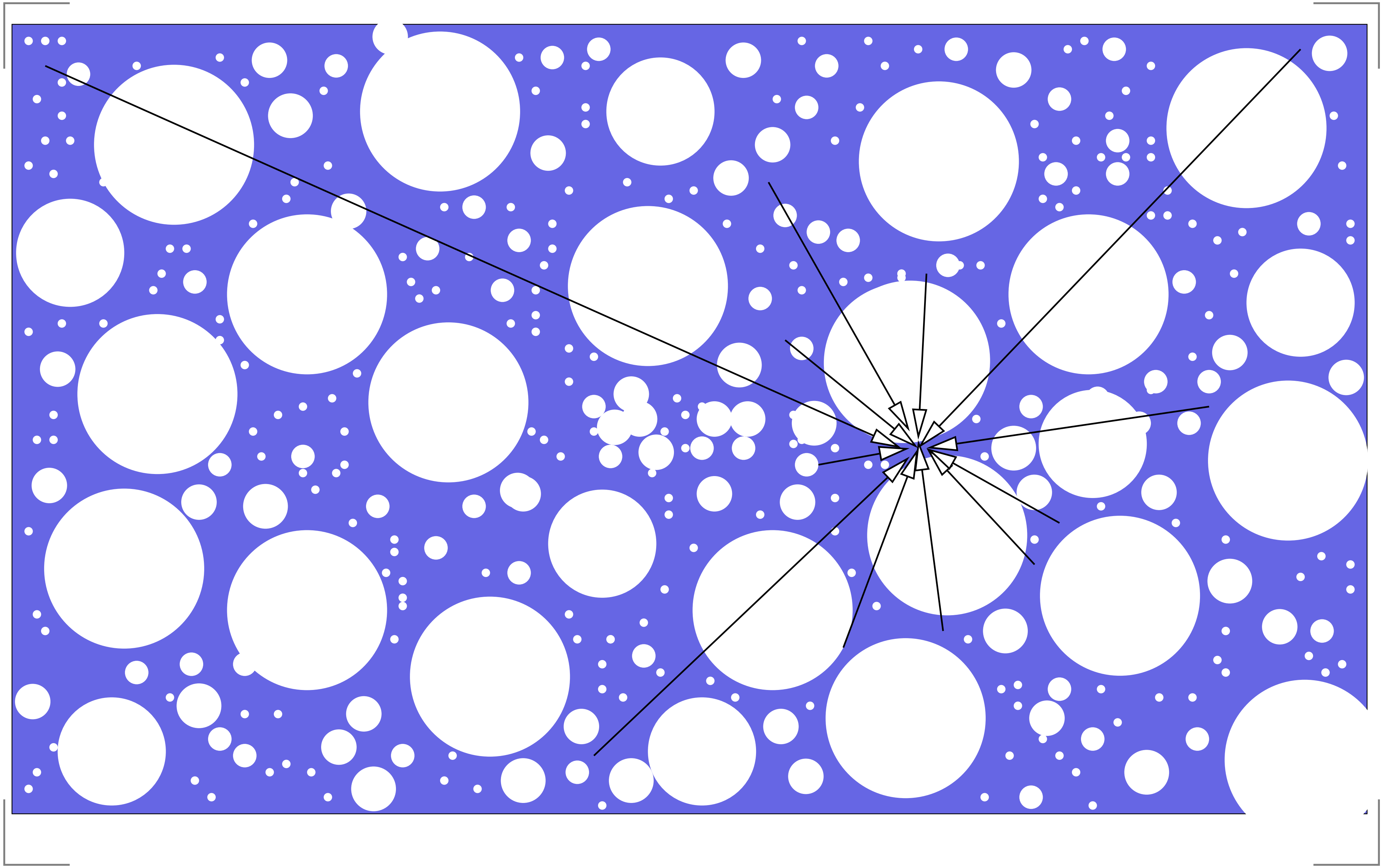
$$v_{\rm pec} = cz - H_0 r$$

generated by

$$\mathbf{v}(\mathbf{r}) = \frac{H_0 \Omega_{M0}^{0.55}}{4\pi} \int \mathrm{d}^3\mathbf{r}'\, \delta_m(\mathbf{r}')\, \frac{(\mathbf{r}' - \mathbf{r})}{|\mathbf{r}' - \mathbf{r}|^3}$$

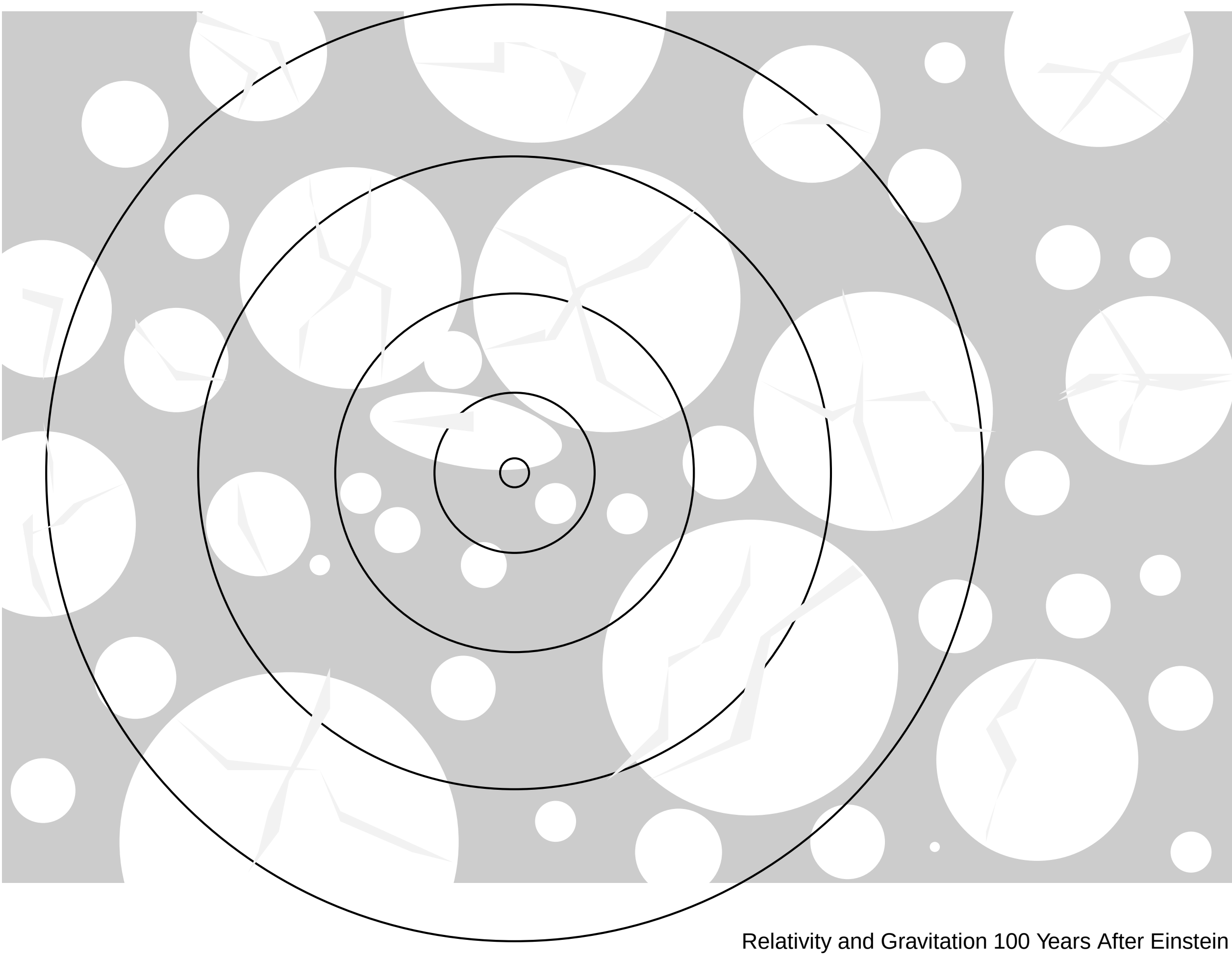
- After 3 decades of work, despite contradictory claims, the $\mathbf{v}(\mathbf{r})$ is not found to converge to LG velocity w.r.t. CMB frame
- Agreement on direction, not amplitude or scale (Lavaux et al 2010; Bilicki et al 2011; . . .)

Apparent Hubble flow variance



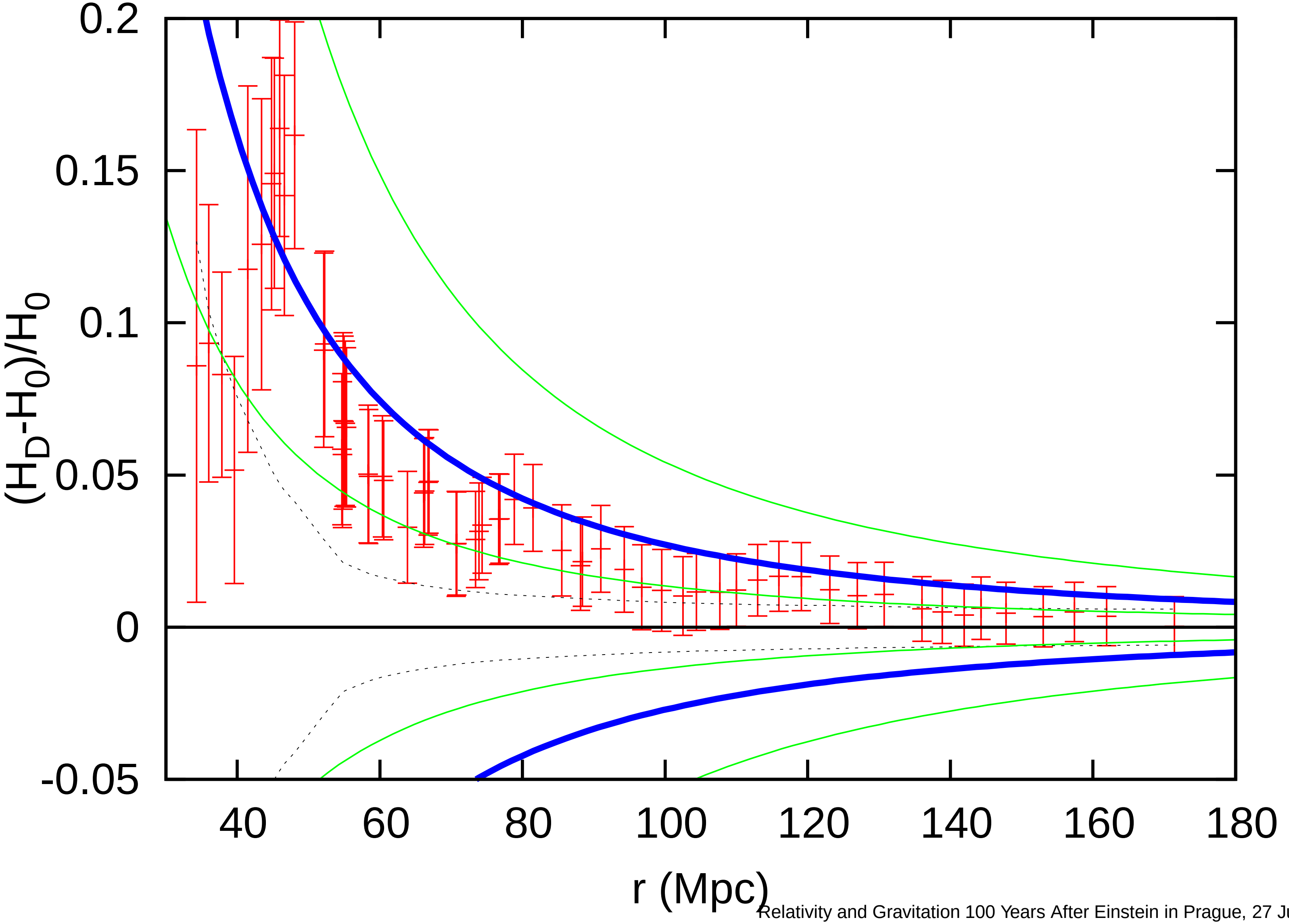
Spherical averages

- Determine variation in Hubble flow by determining best-fit linear Hubble law in spherical shells



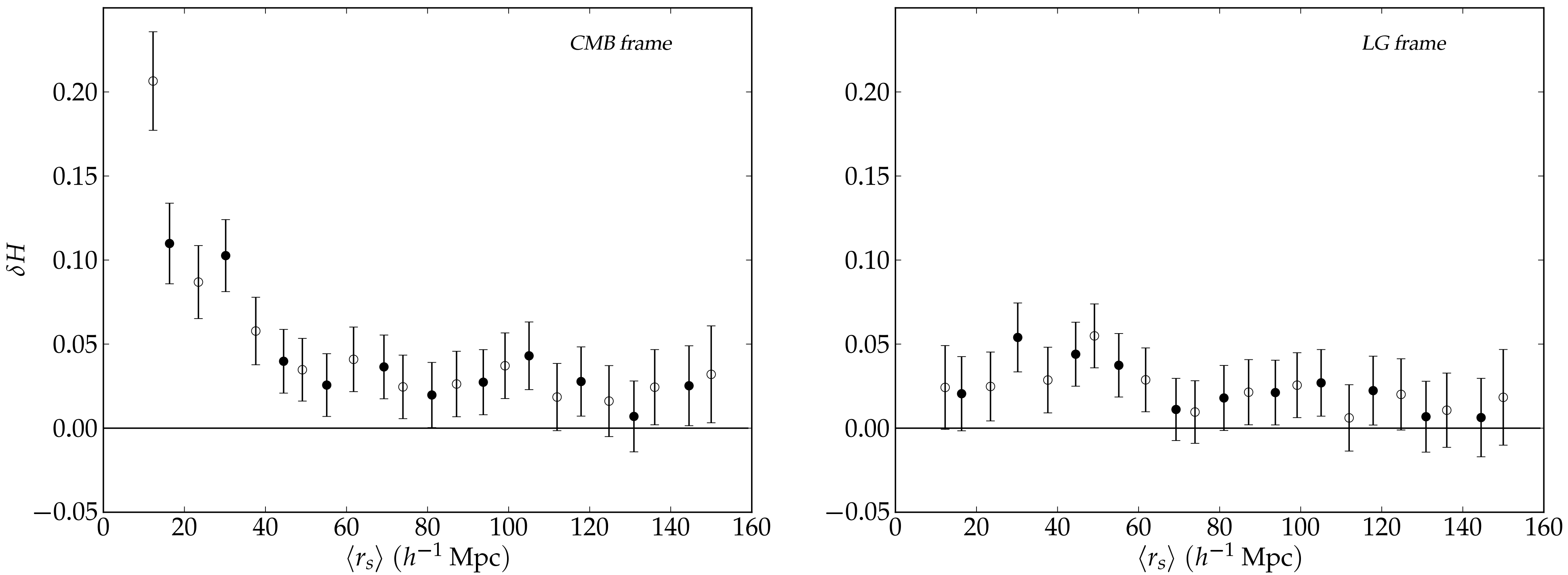
N. Li & D. Schwarz, PRD 78, 083531

HST key data: 68 points, single shell (all points within r Mpc as r varied) – correlated result



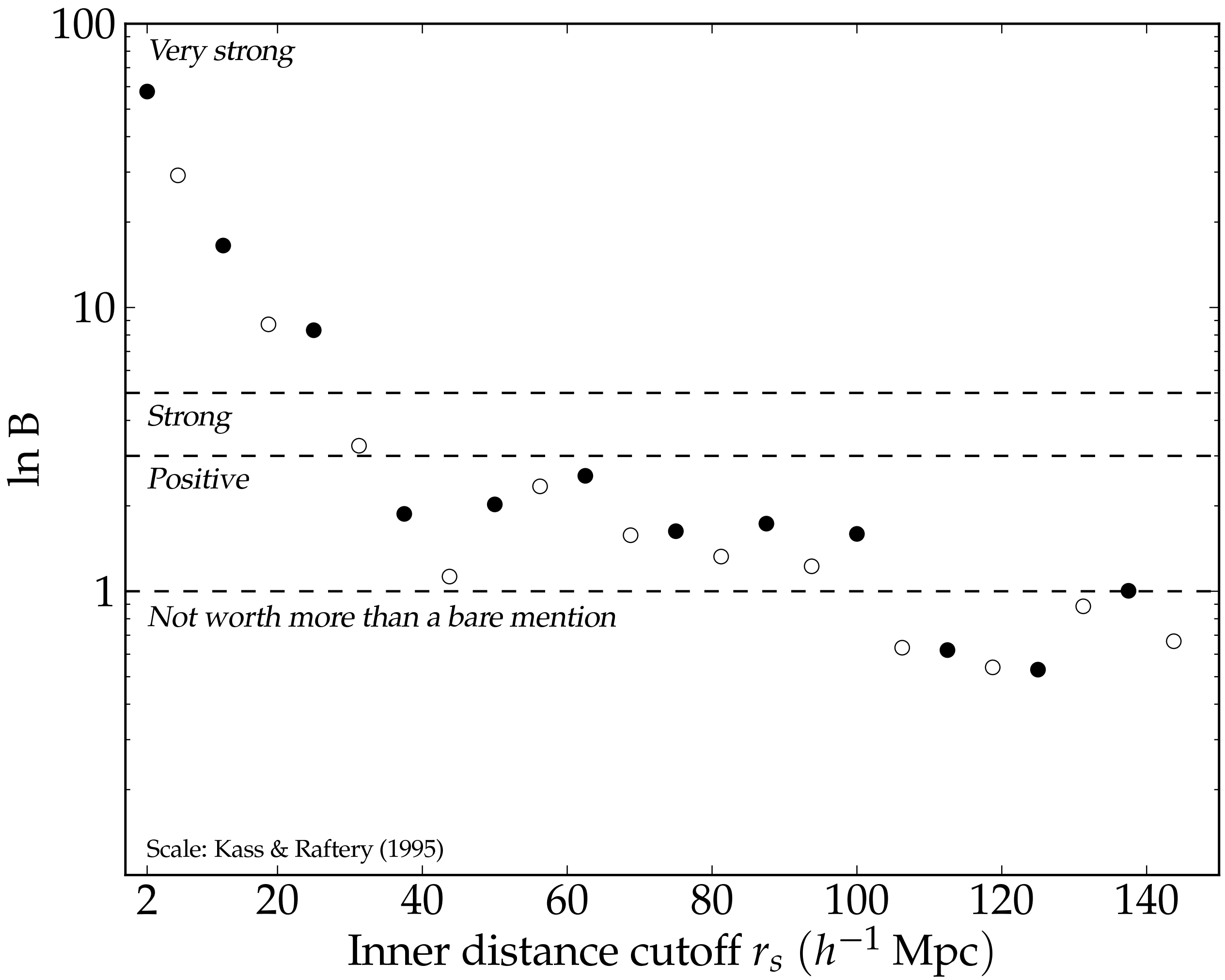
Radial variance $\delta H_s = (H_s - H_0)/H_0$

- COMPOSITE sample (R. Watkins et al; 4,534 galaxies): average in independent shells



- Two choices of shell boundaries; for each choice data points uncorrelated

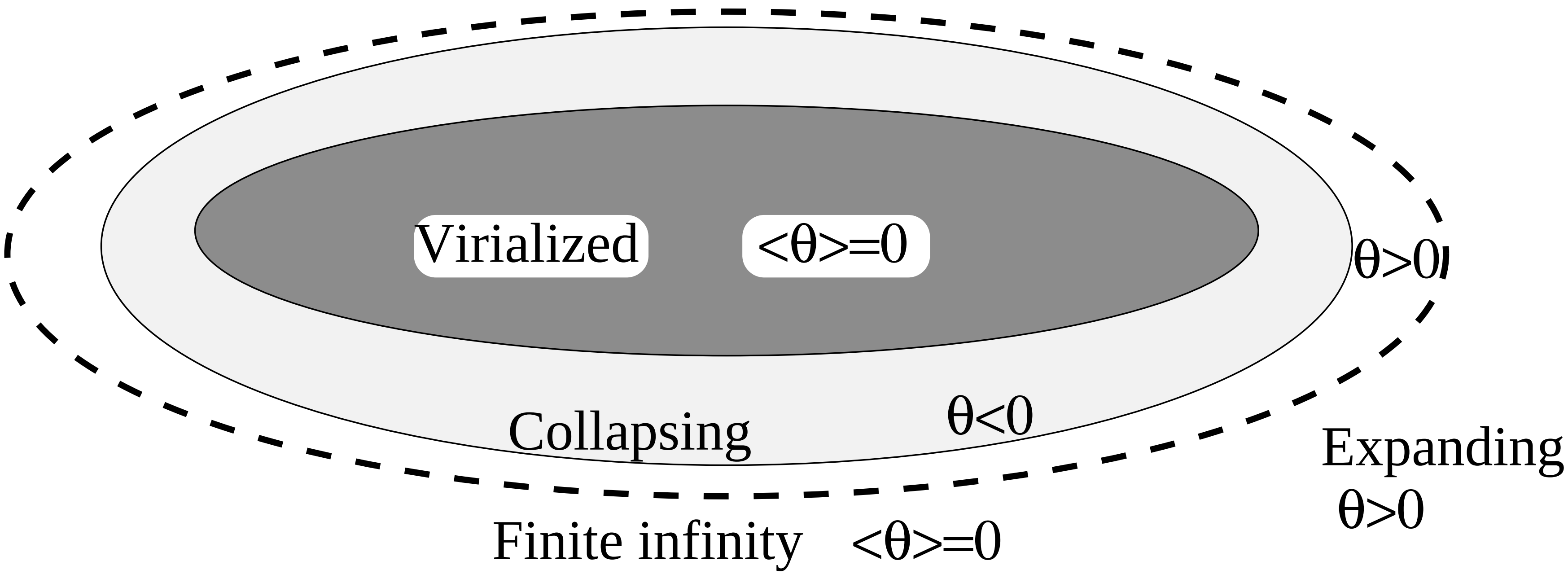
Bayesian comparison of uniformity



- Hubble flow more uniform in LG frame than CMB frame with very strong evidence

But why try the LG frame?

- From viewpoint of the timescape model (DLW 2007, 2009) and in particular the “Cosmological Equivalence Principle” (DLW 2008) in bound system the *finite infinity* region (or *matter horizon*) is the standard of rest



Boosts and spurious monopole variance

- H_s determined by linear regression in each shell

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

- Under boost $cz_i \to cz_i' = cz_i + v\cos\phi_i$ for uniformly distributed data, linear terms cancel on opposite sides of sky

$$\begin{aligned} H_s' - H_s &\sim \left(\sum_{i=1}^{N_s} \frac{(v\cos\phi_i)^2}{\sigma_i^2} \right) \left(\sum_{i=1}^{N_s} \frac{cz_i r_i}{\sigma_i^2} \right)^{-1} \\ &= \frac{\left\langle (v\cos\phi_i)^2 \right\rangle_s}{\left\langle cz_i r_i \right\rangle_s} \sim \frac{v^2}{2H_0 \left\langle r_i^2 \right\rangle_s} \end{aligned}$$

Dipole variance

Two approaches; take two inner ($r < r_o$) and outer ($r > r_o$) shells, varying r_o and fit

- **(i)**

$$\frac{cz}{r} = H_0 + b\cos\phi$$

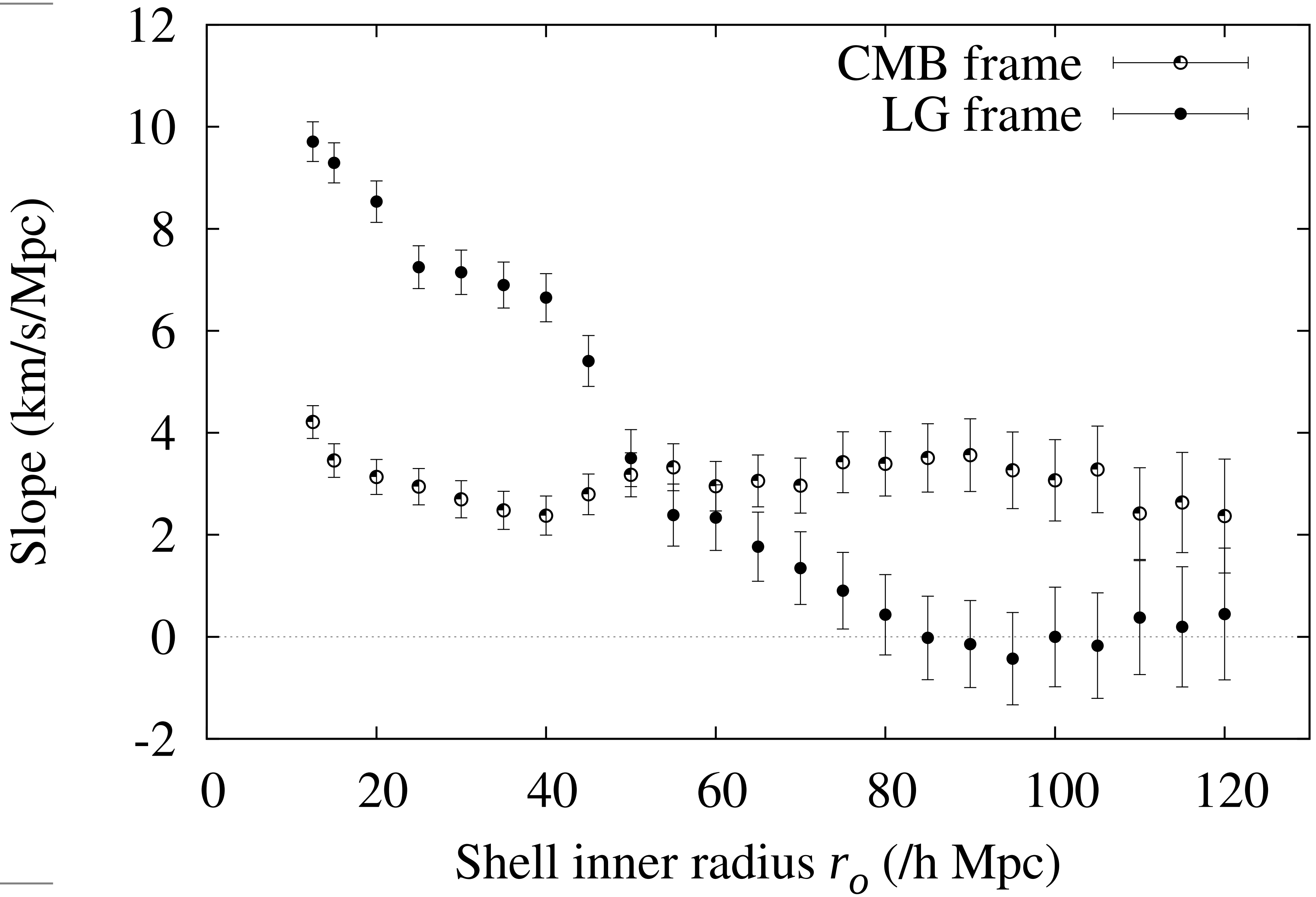
(ii) McClure and Dyer (2007) method

$$H_\alpha = \frac{\sum_{i=1}^{N} W_{i\,\alpha}\, cz_i\, r_i^{-1}}{\sum_{j=1}^{N} W_{j\,\alpha}}$$

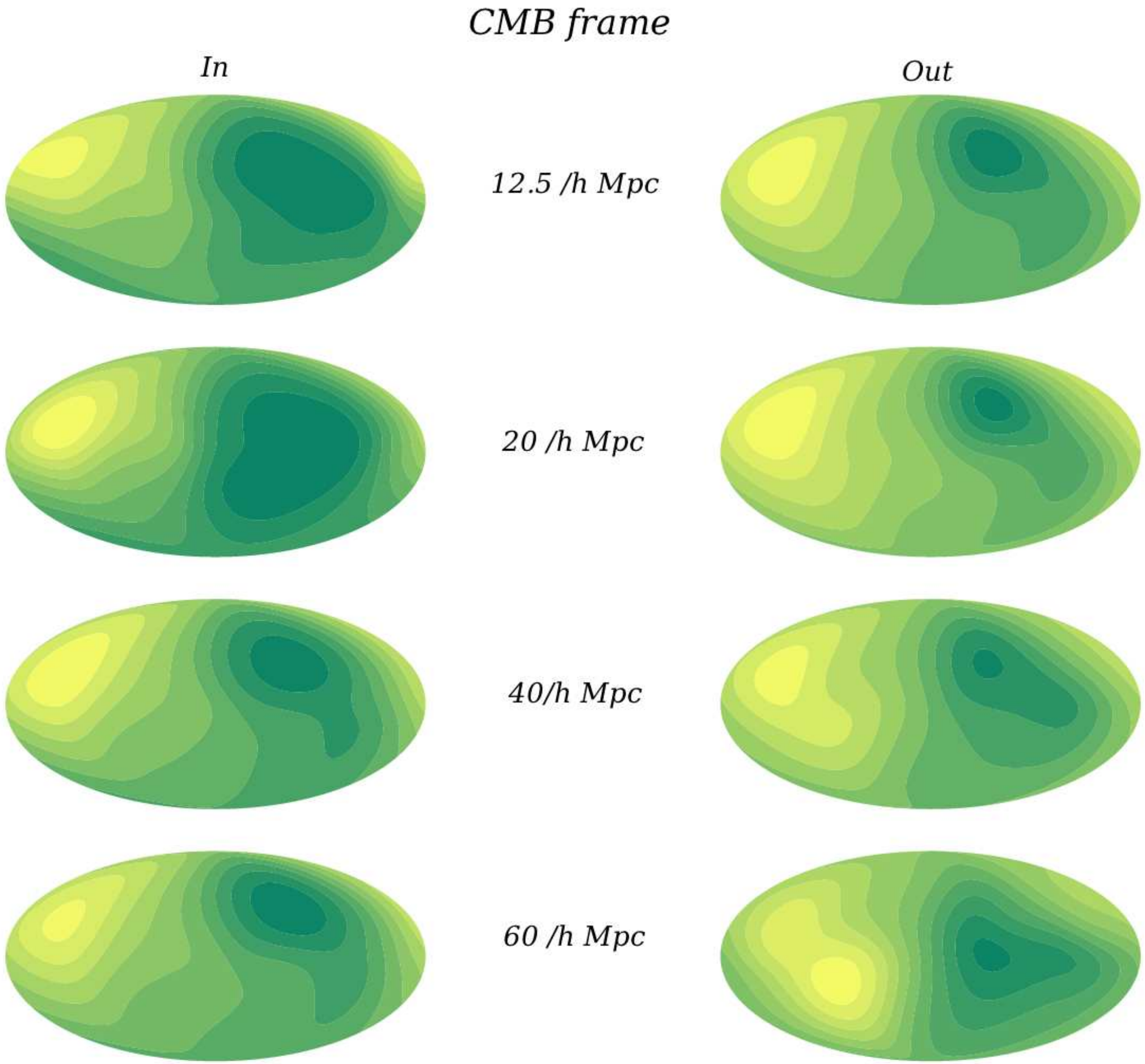
where with $\cos\theta_i = \vec{r}_{\rm grid}\cdot\vec{r_i}$, $\sigma_\theta = 25^\circ$ (typically)

$$W_{i\,\alpha} = \frac{1}{\sqrt{2\pi}\sigma_\theta}\exp\left(\frac{-\theta_i^2}{2\sigma_\theta^2}\right)$$

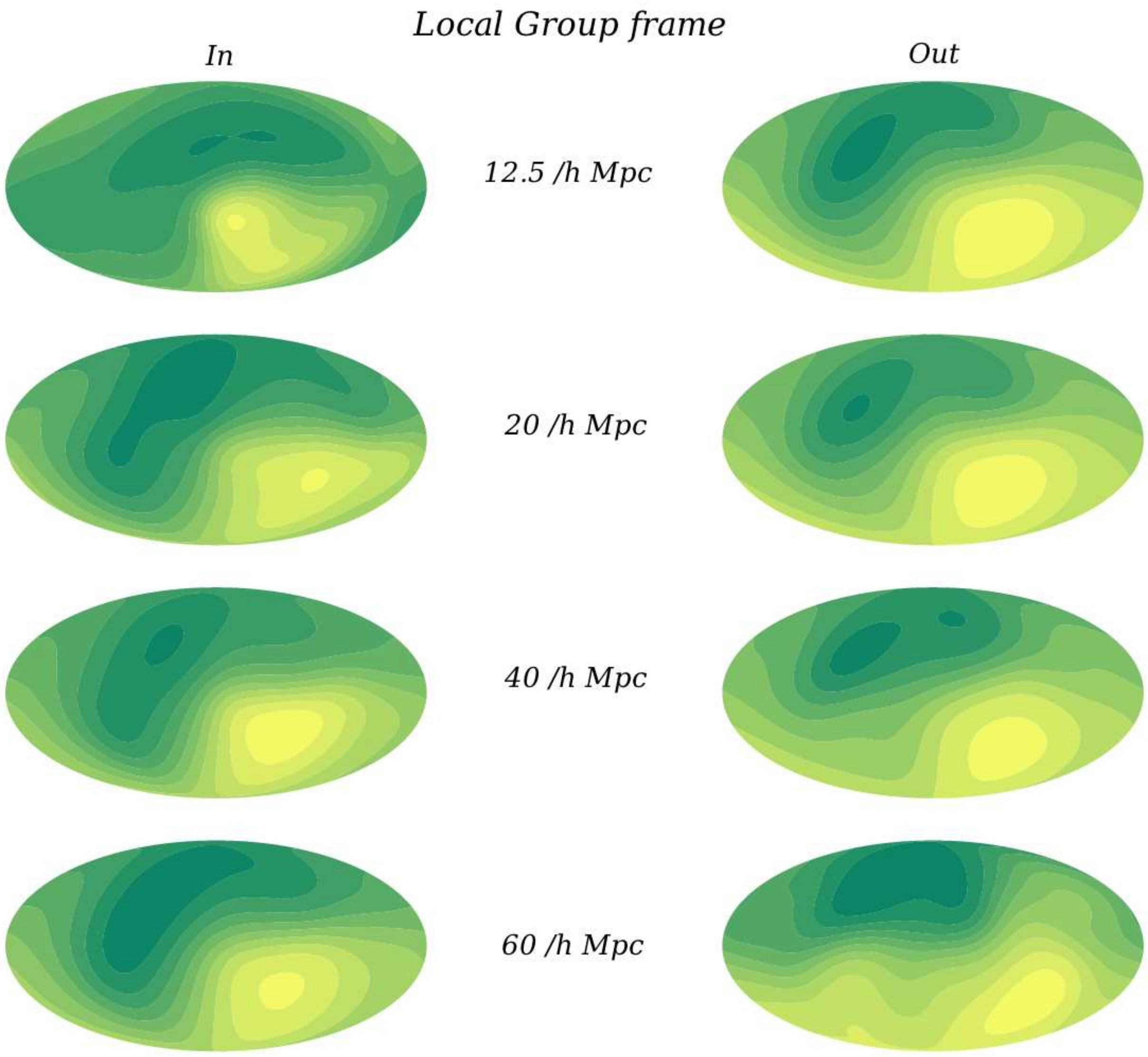
Value of b in $\frac{cz}{r} = H_0 + b\cos\phi$



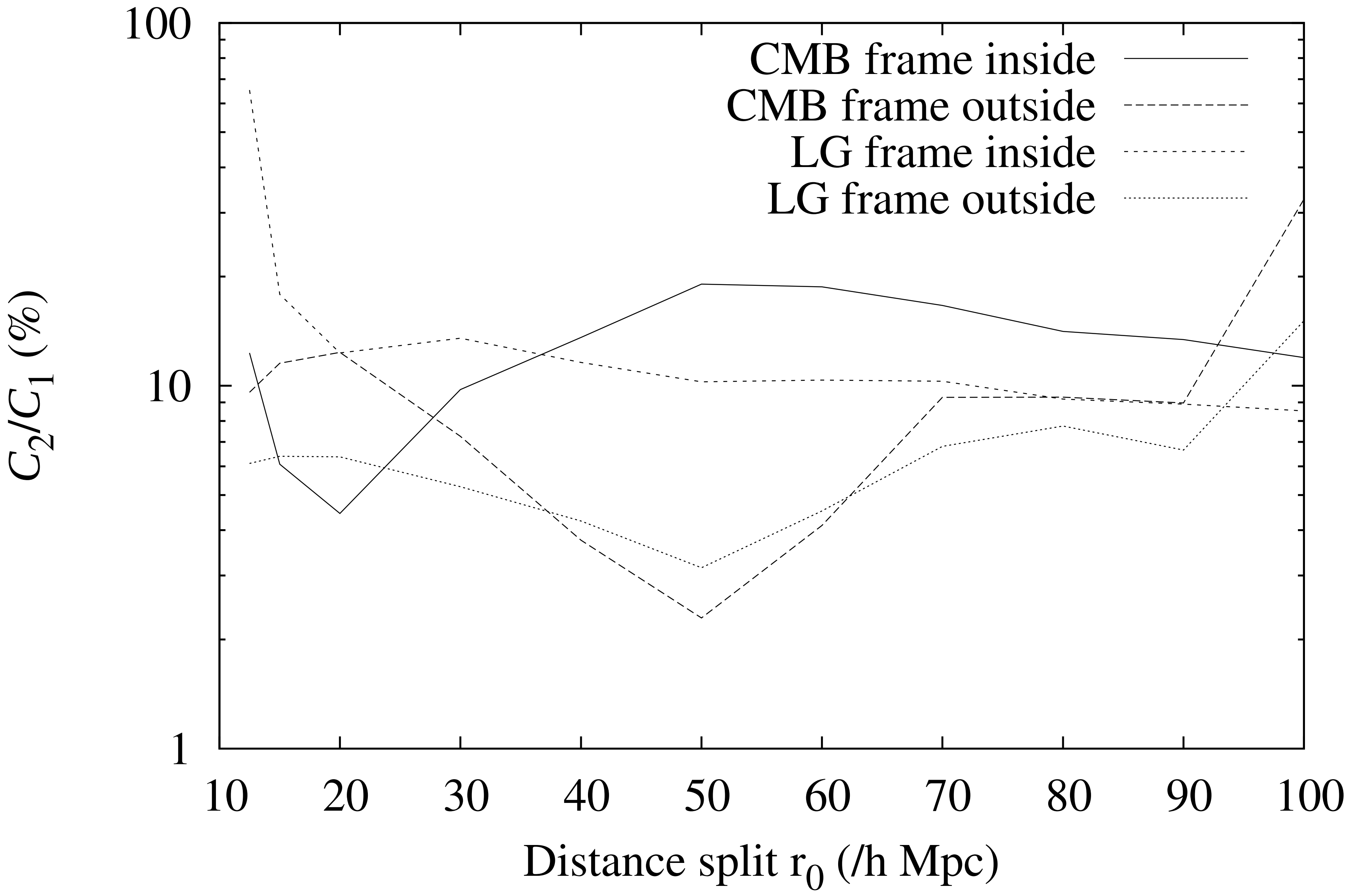
Hubble variance: CMB frame



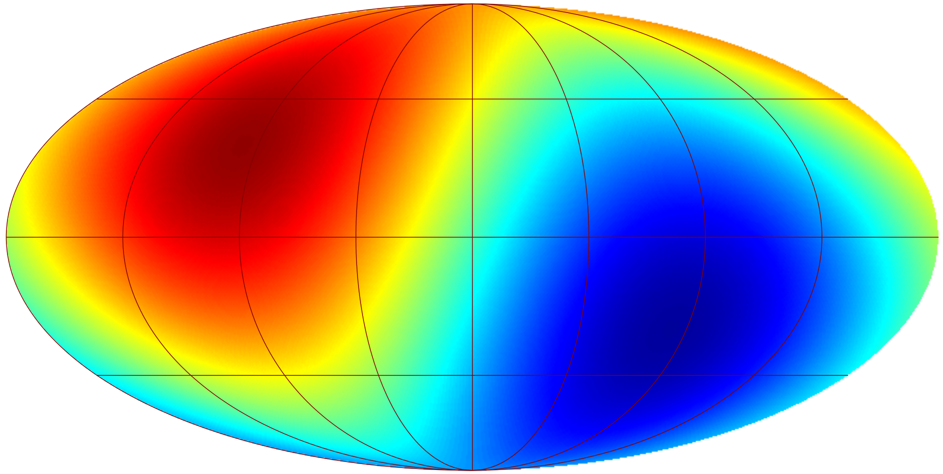
Hubble variance: LG frame



Hubble variance quadrupole/dipole ratios



Correlation with residual CMB dipole

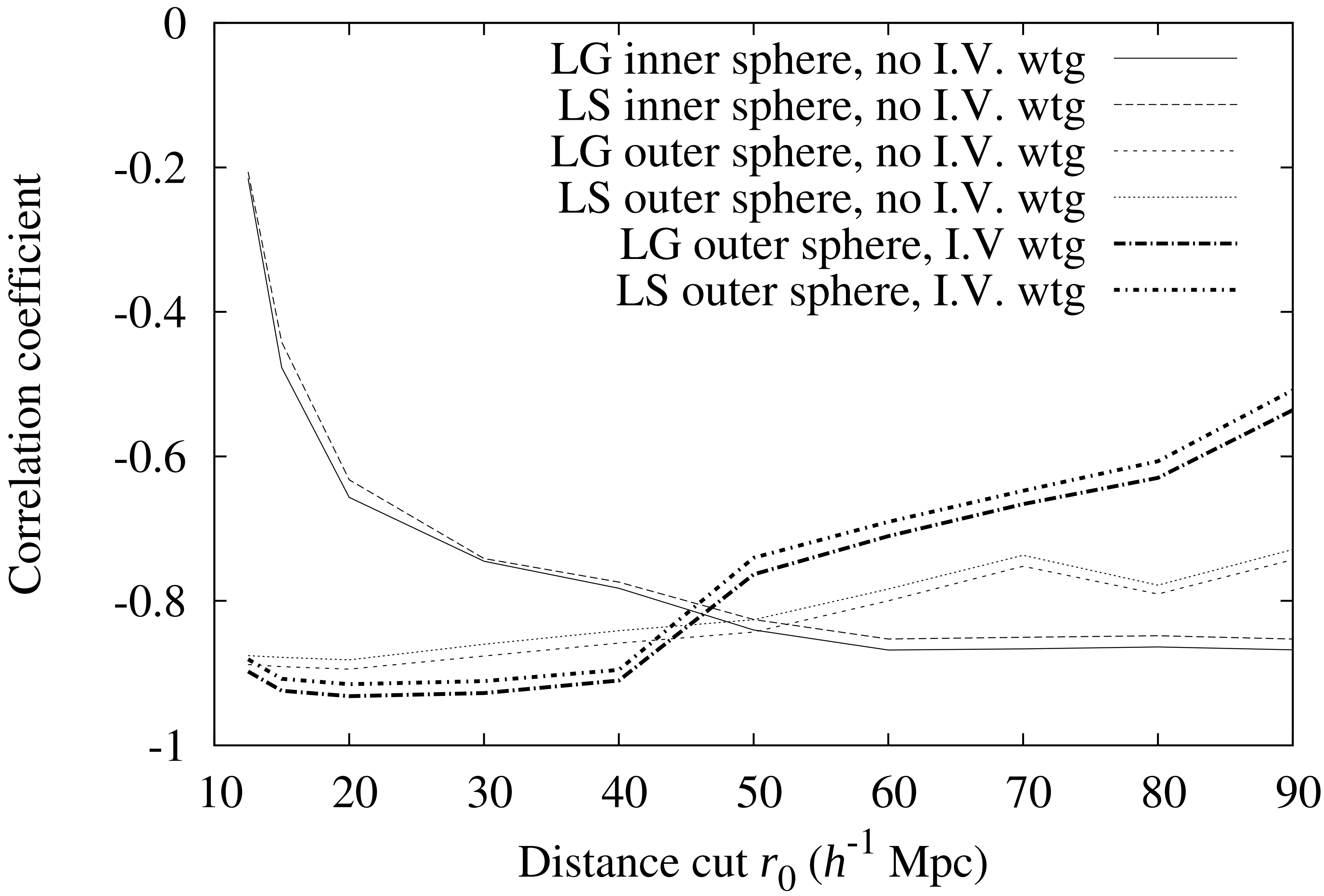


- Digitize skymaps with HEALPIX, compute

$$\rho_{HT} = \frac{\sqrt{N_p}\,\sum_\alpha \bar{\sigma}_\alpha^{-2}(H_\alpha - \bar{H})(T_\alpha - \bar{T})}{\sqrt{\left[\sum_\alpha \bar{\sigma}_\alpha^{-2}\right]\left[\sum_\alpha \bar{\sigma}_\alpha^{-2}(H_\alpha - \bar{H})^2\right]\left[\sum_\alpha (T_\alpha - \bar{T})^2\right]}}$$

- $\rho_{HT} = -0.92$, (almost unchanged for $15^\circ < \sigma_\theta < 40^\circ$)
- Alternatively, t-test on raw (unsmeared) data: null hypothesis that maps uncorrelated is rejected at 23.6σ.

Correlation with CMB dipole as r_o varied



Redshift-distance anisotropy

- As long as $T \propto 1/a$, where $a_0/a = 1 + z$ *for some appropriate average*, not necessarily FLRW, then small change, δz, in the redshift of the surface of photon decoupling – due to foreground structures – will induce a CMB temperature increment $T = T_0 + \delta T$, with

$$\frac{\delta T}{T_0} = \frac{-\delta z}{1 + z_{\rm dec}}$$

- With $z_{\rm dec} = 1089$, $\delta T = \pm(5.77 \pm 0.36)$ mK represents an increment $\delta z = \mp(2.31 \pm 0.15)$ to last scattering
- **Proposal**: rather than originating in a LG boost the ± 5.77 mK dipole is due to a small anisotropy in the distance-redshift relation on scales $\lesssim 65\, h^{-1}$Mpc.

Redshift-distance anisotropy

- For spatially flat ΛCDM

$$D = \frac{c}{H_0} \int_1^{1+z_{\rm dec}} \frac{{\rm d}x}{\sqrt{\Omega_{\Lambda 0} + \Omega_{M0} x^3 + \Omega_{R0} x^4}}$$

For standard values $\Omega_{R0} = 4.15 h^{-2} \times 10^{-5}$, $h = 0.72$

- $\Omega_{M0} = 0.25$, find $\delta D = \mp(0.33 \pm 0.02)\, h^{-1}$Mpc;
- $\Omega_{M0} = 0.30$, find $\delta D = \mp(0.32 \pm 0.02)\, h^{-1}$Mpc;
- timescape model similar.
- Assuming that the redshift-distance relation anisotropy is due to forground structures within $65\, h^{-1}$Mpc then $\pm 0.35\, h^{-1}$Mpc represents a ± 0.5% effect

Why a strong CMB dipole?

- Ray tracing of CMB sky seen by off-centre observer in LTB void gives $|a_{10}| \gg |a_{20}| \gg |a_{30}|$ (Alnes and Amarzguioui 2006). E.g.,

$$\frac{a_{20}}{a_{10}} = \sqrt{\frac{15}{4}} \frac{(h_{\rm in} - h_{\rm out}) d_{\rm off}}{2998\,\text{Mpc}}$$

where $H_{\rm in\,0} = 100\, h_{\rm in}$ km/s/Mpc, $H_{\rm out\,0} = 100\, h_{\rm out}$ km/s/Mpc are Hubble constants inside/outside void, $d_{\rm off} =$ distance of the observer from centre in Mpc.

- Even for relatively large values $d_{\rm off} = 50\, h^{-1}$Mpc and $h_{\rm in} - h_{\rm out} = 0.2$, we have $a_{20}/a_{10} \lesssim$ 1%.

Conclusion/Outlook

- Variance of the Hubble flow over tens of megaparsecs cannot be reduced to a boost; i.e. *Eppur si espande!*, (Abramowicz et al 2007) space really is expanding
- Large CMB angle anomalies, and map-making procedures would need to be reconsidered ... are the cold spot etc foreground artifacts, or primordial
- “Dark flow” probably a systematic “error”
- Frame of minimum variance Hubble flow variance frame to be determined
- Impact of rest frame choice, e.g., on nearby measurements in setting distance scale etc, needs to be re-examined
- Opportunity to develop new formalism and approaches to observational cosmology