Differential expansion of space and the Hubble flow anisotropy

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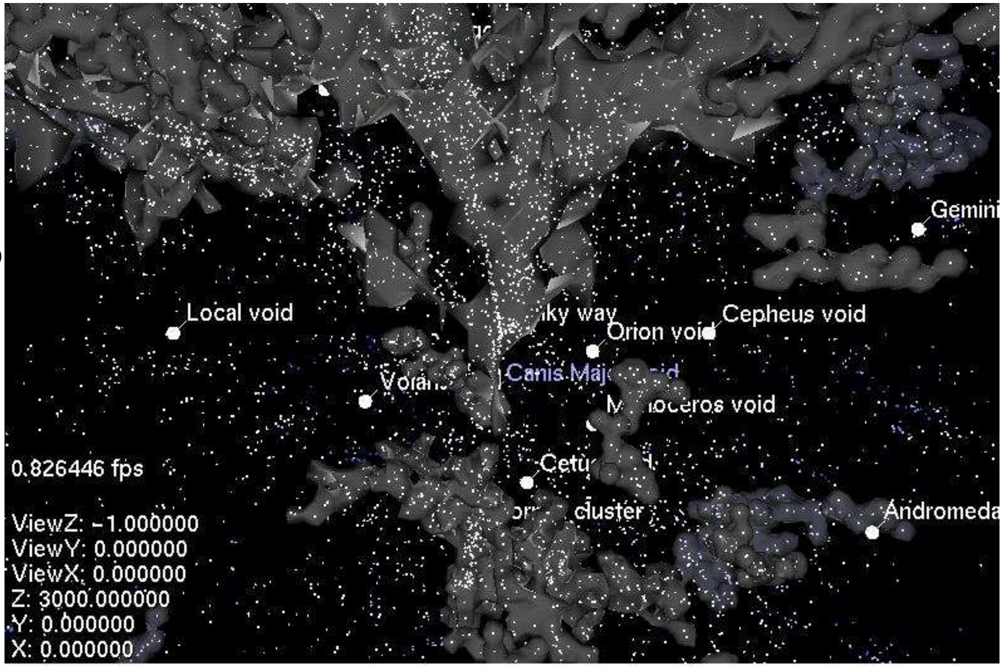
J H McKay & DLW: **MNRAS 457 (2016) 3285**

K Bolejko, M A Nazer & DLW:

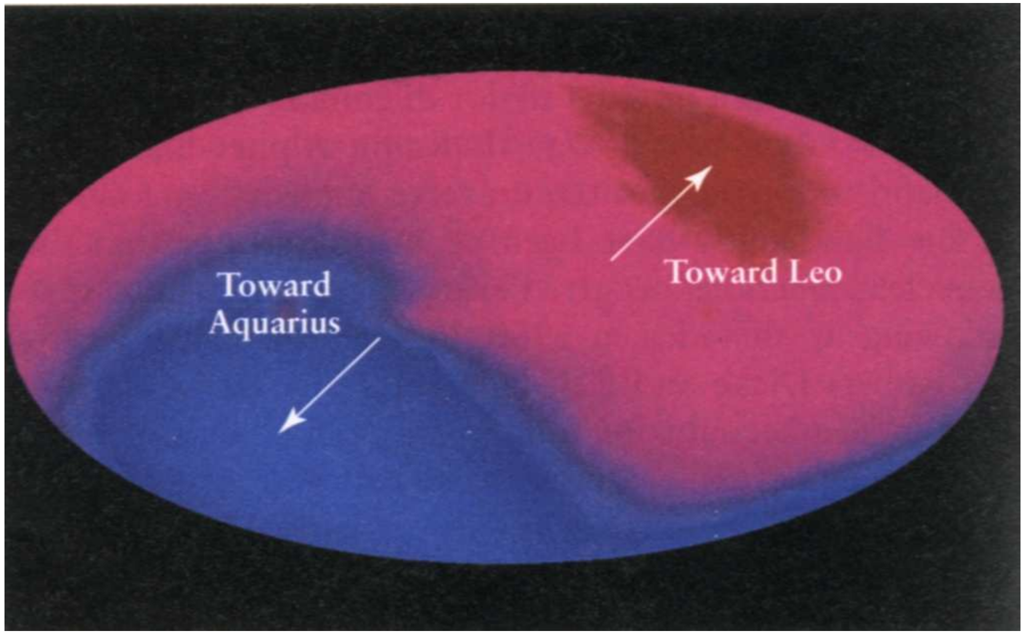
JCAP 06 (2016) 035



Outline of talk

- Test of FLRW on $\lesssim 100\,h^{-1}$Mpc scales
  Result: alternative to large bulk flows - GR differential expansion on $\lesssim 65\,h^{-1}$Mpc scales, supported by simulations, with proposal to test impact on large angle CMB anomalies
- Use exact inhomogeneous solutions of Einstein's equations for structures on $\lesssim 70\,h^{-1}$Mpc scales; asymptotic to Planck normalized FLRW model on larger scales: *effective* model for large scale light propagation
- Use Szekeres model: most general dust solution, reduces to spherically symmetric inhomoneity (Lemaître–Tolman–Bondi (LTB) model) in a limit
- Trace rays from CMB and mock COMPOSITE catalogues for 4534 galaxy clusters

Cosmic Microwave Background dipole



- Special Relativity: motion in a thermal bath of photons

$$T' = \frac{T_0}{\gamma(1 - (v/c)\cos\theta')}$$

- 3.37 mK dipole: $v_{\text{Sun-CMB}} = 371$ km s^{-1} to $(264.14°, 48.26°)$; splits as $v_{\text{Sun-LG}} = 318.6$ km s^{-1} to $(106°, -6°)$ and $v_{\text{LG-CMB}} = 635 \pm 38$ km s^{-1} to $(276.4°, 29.3°) \pm 3.2°$

Peculiar velocity formalism

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

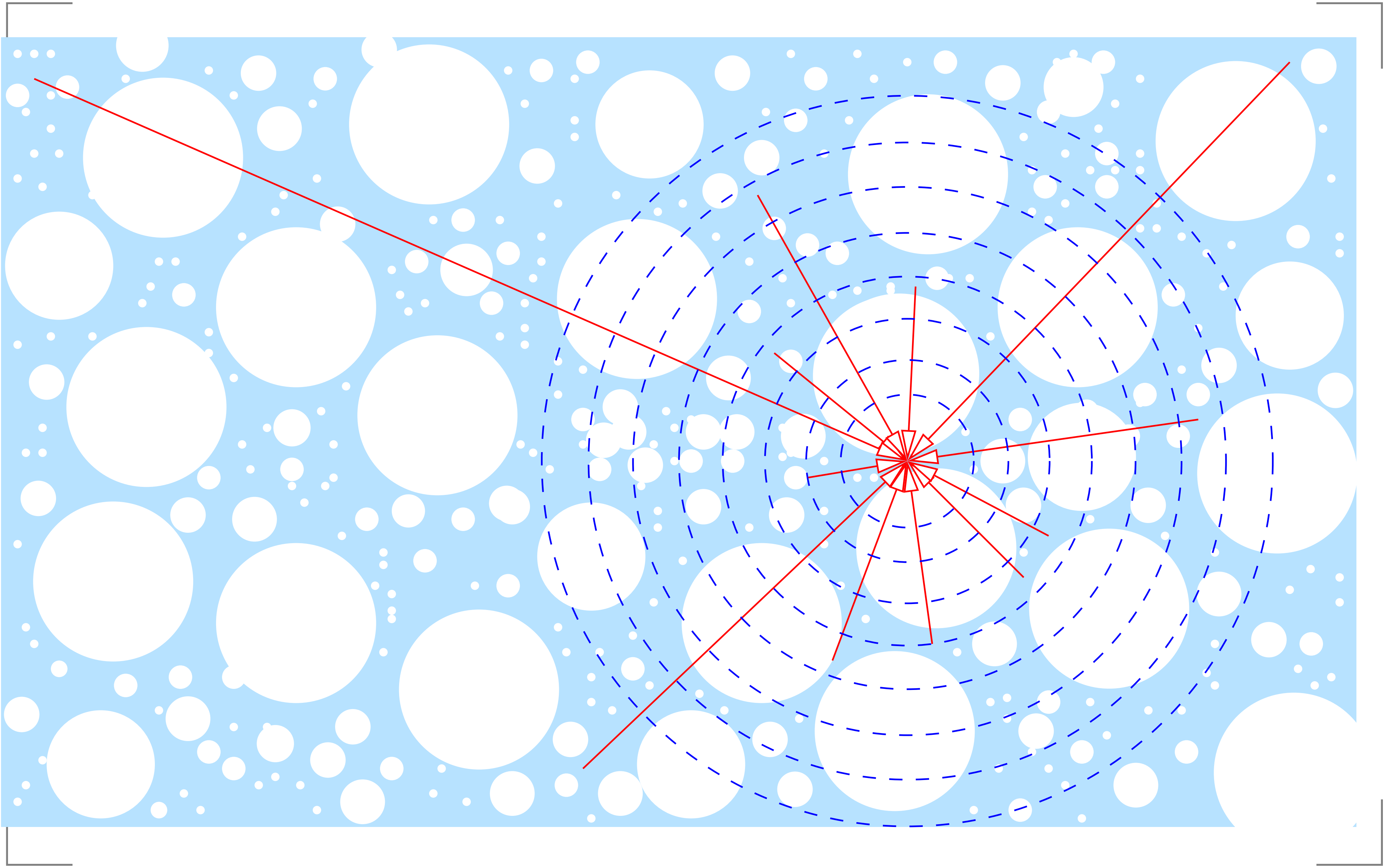
$$v_{\rm pec} = cz - H_0 r$$

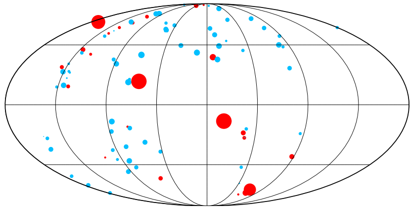
generated by

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

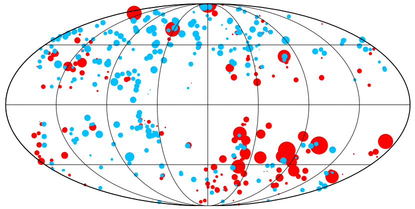
- 3 decades of debate on convergence of $\mathbf{v}(\mathbf{r})$ to velocity of LG w.r.t. CMB frame; Direction agreed, not amplitude or scale (Lavaux et al 2010; Bilicki et al 2011. . .)
- The debate continues: Hess & Kitaura arXiv:1412.7310, Springob et al arXiv:1511.04849, . . .

Apparent Hubble flow variation

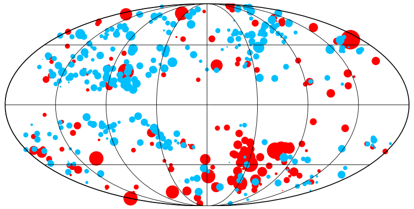




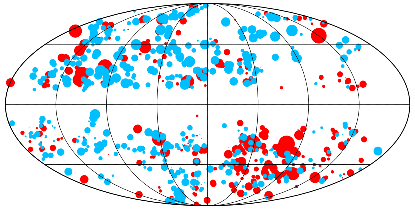
(a) 1: $0 - 12.5\ h^{-1}$ Mpc $N = 92$.



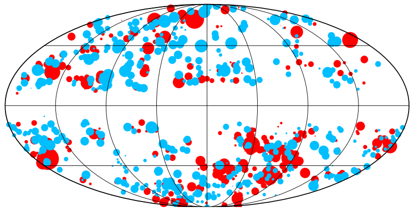
(b) 2: $12.5 - 25\ h^{-1}$ Mpc $N = 505$.



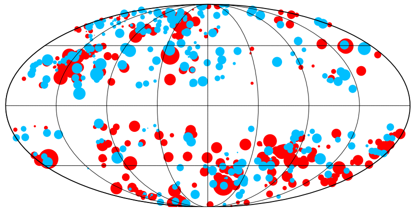
(c) 3: $25 - 37.5\ h^{-1}$ Mpc $N = 514$.



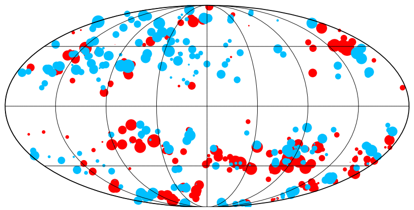
(d) 4: $37.5 - 50\ h^{-1}$ Mpc $N = 731$.



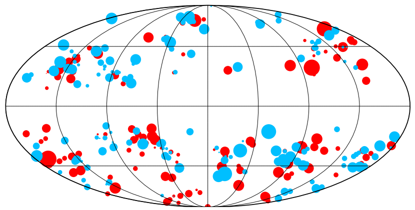
(e) 5: $50 - 62.5\ h^{-1}$ Mpc $N = 819$.



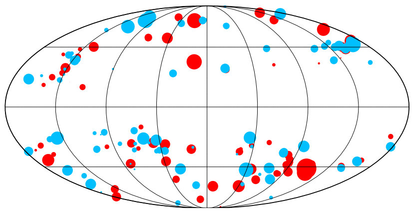
(f) 6: $62.5 - 75\ h^{-1}$ Mpc $N = 562$.



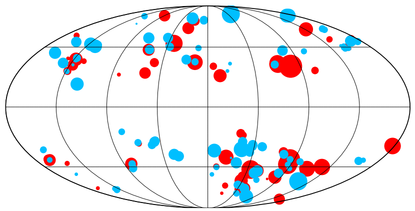
(g) 7: $75 - 87.5\ h^{-1}$ Mpc $N = 414$.



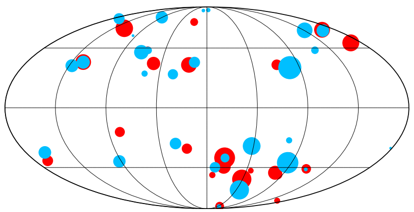
(h) 8: $87.5 - 100\ h^{-1}$ Mpc $N = 304$.



(i) 9: $100 - 112.5\ h^{-1}$ Mpc $N = 222$.

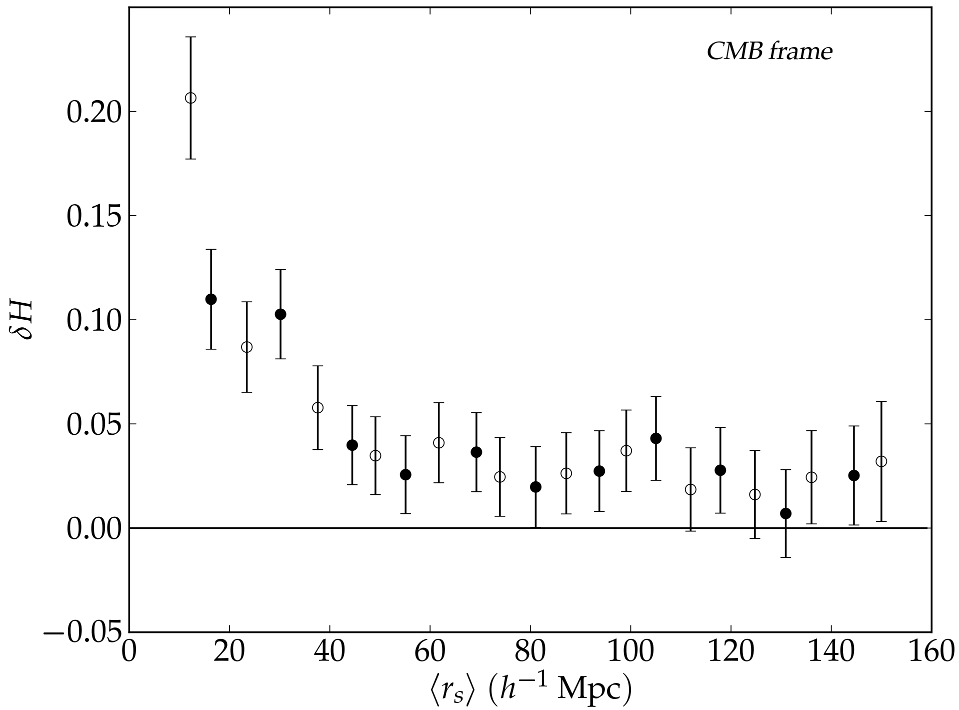


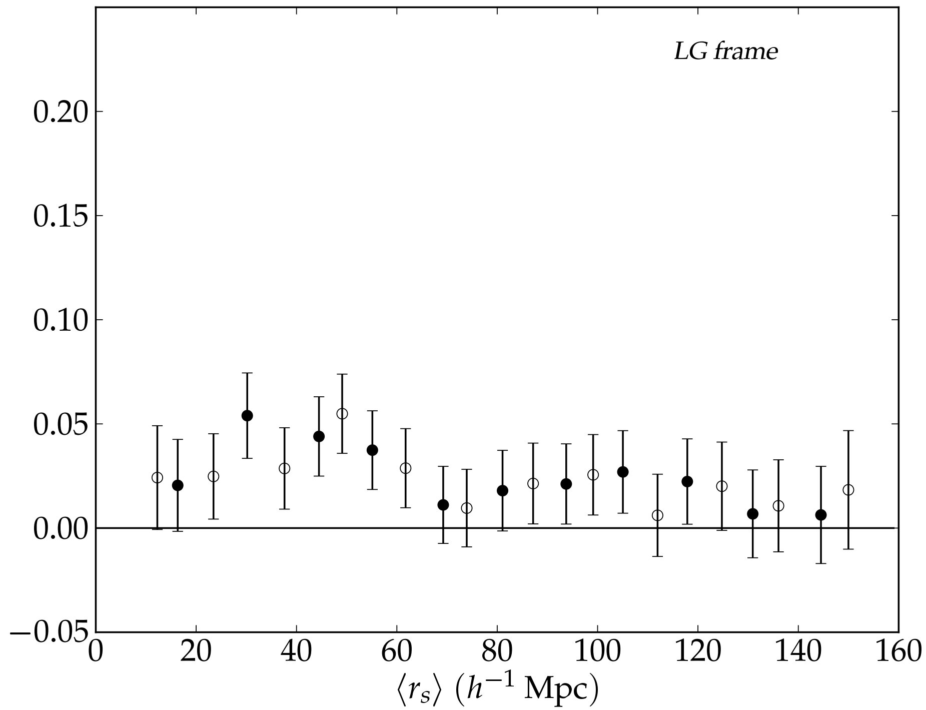
(j) 10: $112.5 - 156.25\ h^{-1}$ Mpc $N = 280$.



(k) 11: $156.25 - 417.4\ h^{-1}$ Mpc $N = 91$.

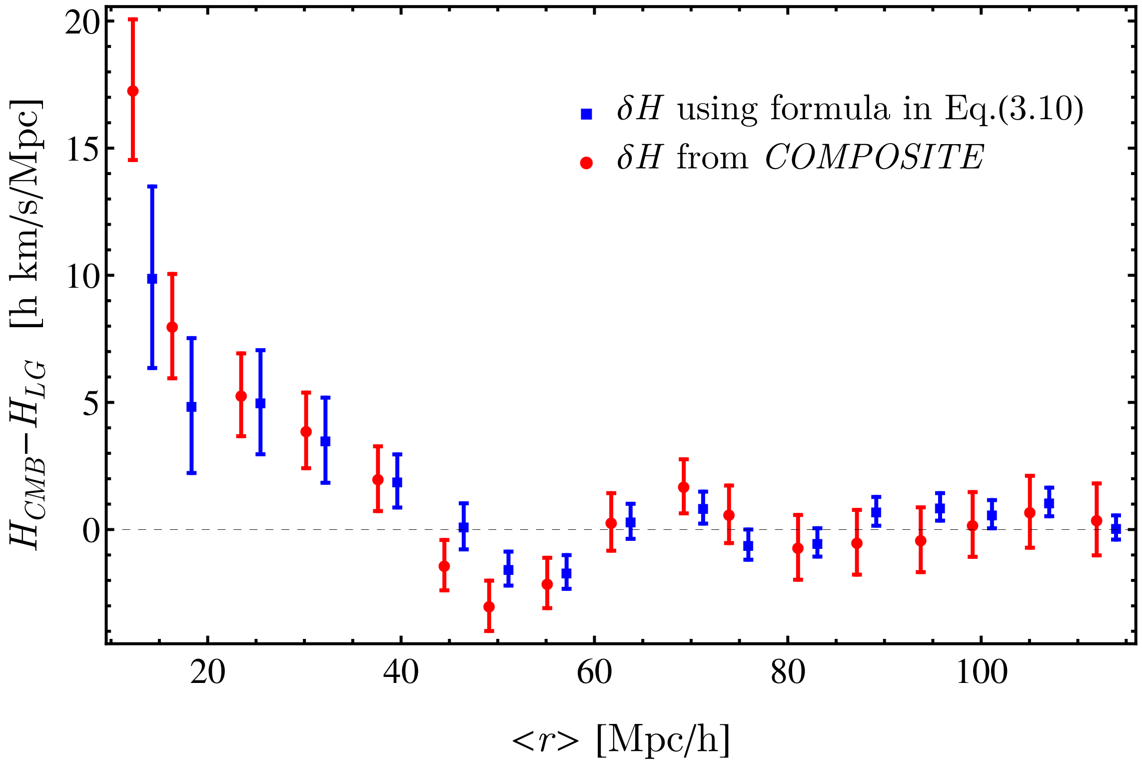
Radial variation $\delta H_s = (H_s - H_0)/H_0$





- Two choices of shell boundaries (closed and open circles); for each choice data points uncorrelated
- Result: Hubble expansion is very significantly more uniform in LG frame than in CMB frame: $\ln B > 5$; (except for $40 \lesssim r \lesssim 60\, h^{-1}$Mpc).

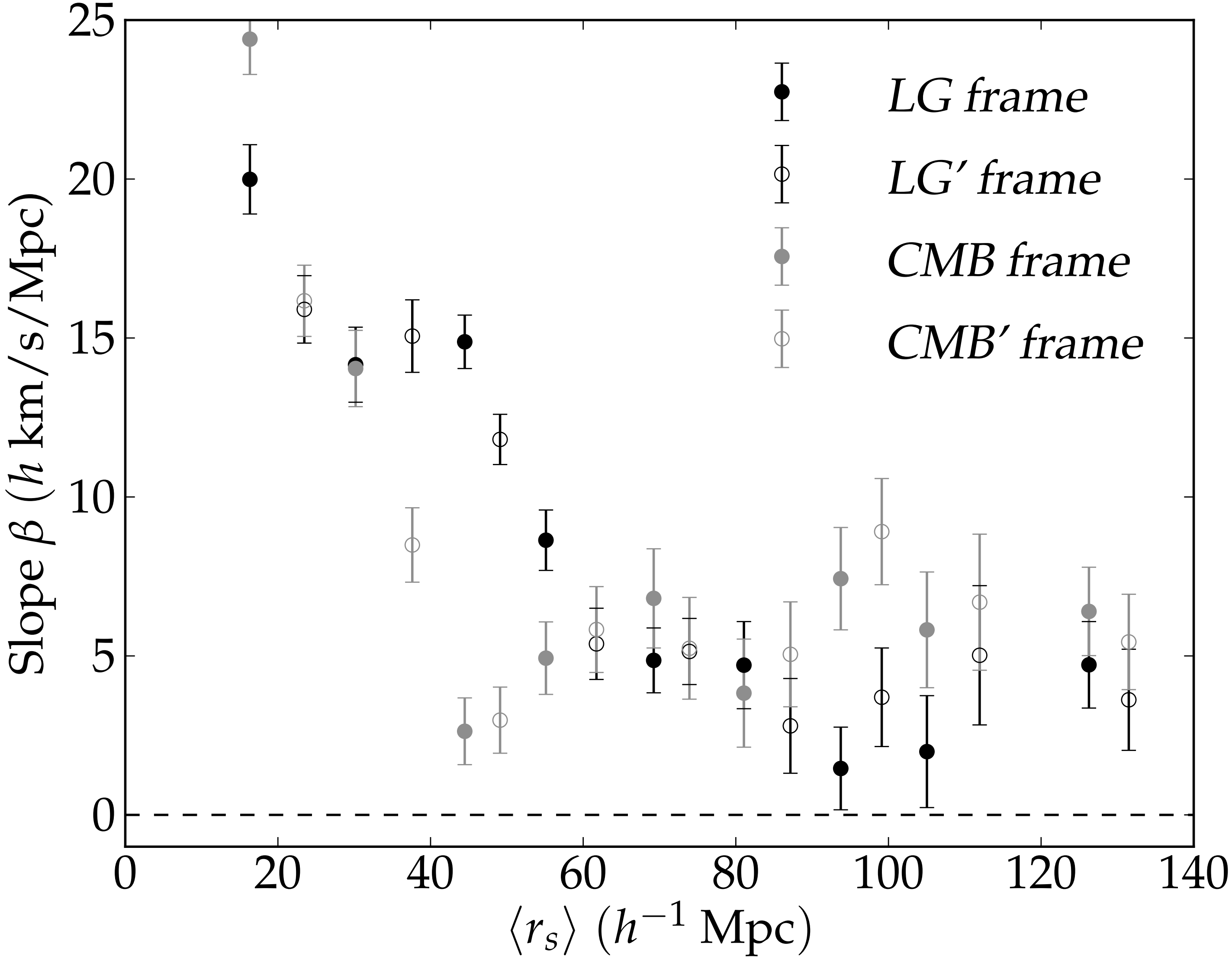
Boost offset and deviation



- Kraljic and Sarkar (2016, to appear). FLRW + Newtonian N-body simulation with bulk flow $\mathbf{v}_{\rm bulk}(r)$

$$H'_s - H_s \sim \frac{|\mathbf{v}|^2 - 2\mathbf{v}\cdot\mathbf{v}_{\rm bulk}(r)}{3H_0\langle r^2\rangle}$$

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

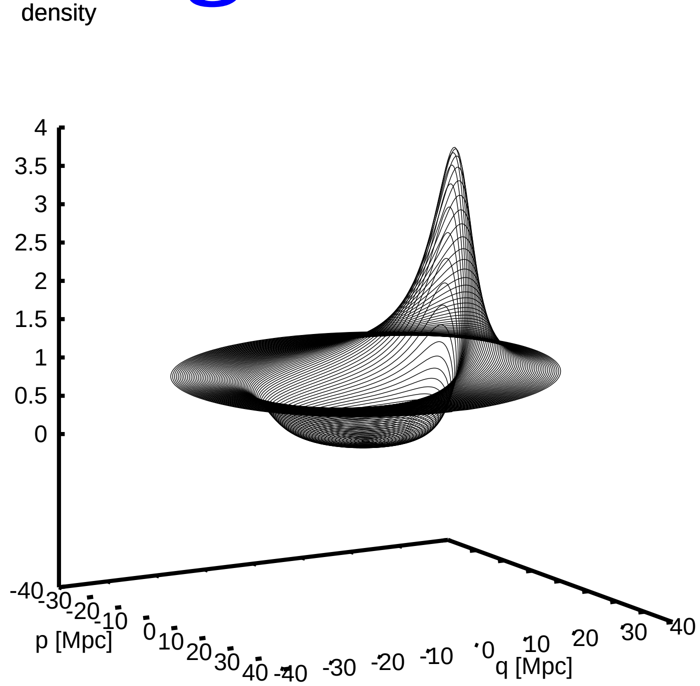


Ray tracing: Szekeres model (1975)

$$\begin{aligned}
\mathrm{d}s^2 &= c^2\mathrm{d}t^2 - \frac{\left(R' - R\frac{\mathcal{E}'}{\mathcal{E}}\right)^2}{1-k}\mathrm{d}r^2 - \frac{R^2}{\mathcal{E}^2}(\mathrm{d}p^2 + \mathrm{d}q^2), \\
\mathcal{E}(r,p,q) &= \frac{1}{2S}(p^2+q^2) - \frac{P}{S}p - \frac{Q}{S}q + \frac{P^2}{2S} + \frac{Q^2}{2S} + \frac{S}{2}, \\
\dot{R}^2 &= -k(r) + \frac{2M(r)}{R} + \frac{1}{3}\Lambda R^2, \\
t &- t_B(r) = \int\limits_0^R \mathrm{d}\widetilde{R}\left[-k + 2M/\widetilde{R} + \frac{1}{3}\Lambda\widetilde{R}^2\right]^{-1/2}, \\
\kappa\rho &= \frac{2\left(M' - 3M\mathcal{E}'/\mathcal{E}\right)}{R^2\left(R' - R\mathcal{E}'/\mathcal{E}\right)}.
\end{aligned}$$

where $' \equiv \partial/\partial r$, $\dot{} \equiv \partial/\partial t$, $R = R(t,r)$, $k = k(r) \leq 1$, $S = S(r)$, $P = P(r)$, $Q = Q(r)$, $M = M(r)$. Above eqns satisfied but functions are otherwise arbitrary. We take $t_B(r) = 0$.

Ray tracing: Szekeres model

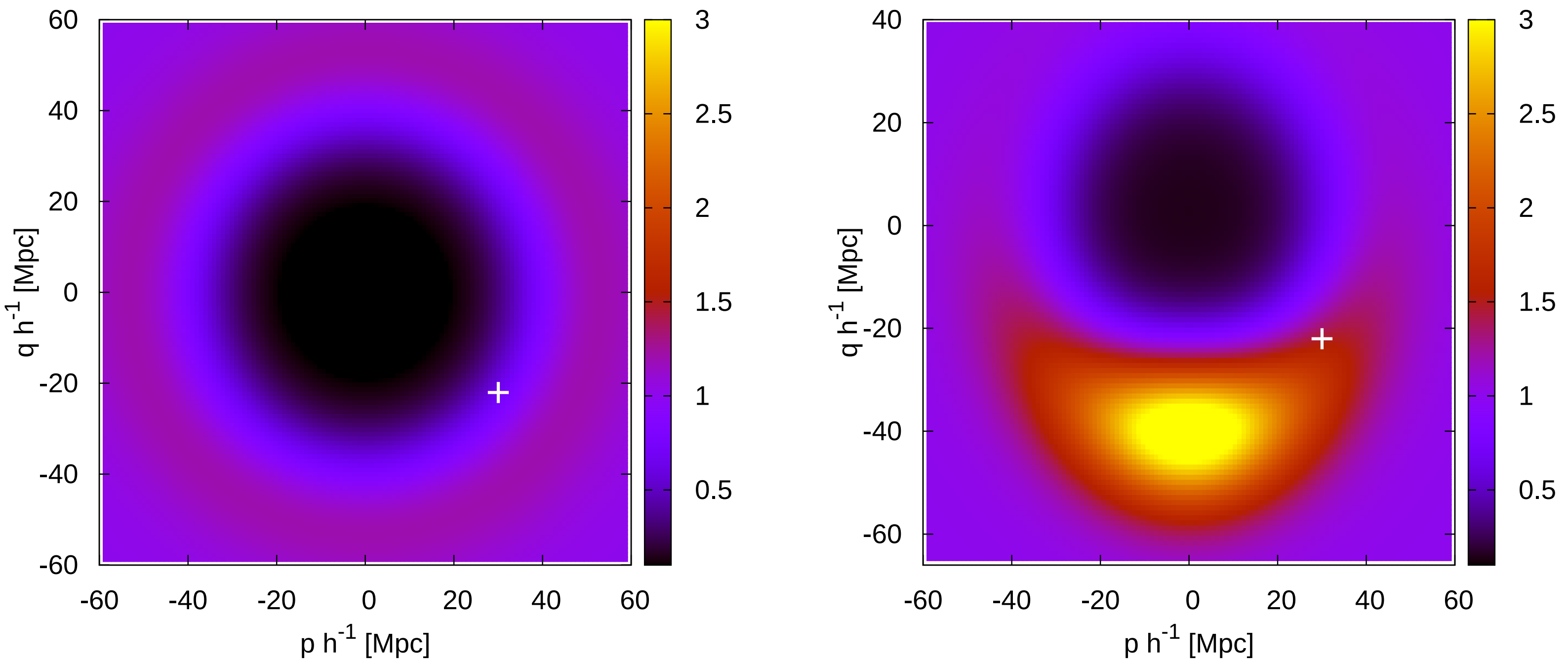


Simplify to $P = Q = 0$; $\quad S = r\left(\frac{r}{1h^{-1}\mathrm{Mpc}}\right)^{\alpha-1}$

$$
\begin{aligned}
M &= M_0 r^3 \left[1 + \delta_M(r)\right], \\
\delta_M(r) &= \frac{1}{2}\delta_0\left(1 - \tanh\frac{r - r_0}{2\Delta r}\right),
\end{aligned}
$$

$-1 \le \delta_0 < 0$ underdensity at $r \to 0$; $\delta_M \to 0$ as $r \to \infty$.

LTB and Szekeres profiles



- Fix $\Delta r = 0.1 r_0$, $\varphi_{obs} = 0.5\pi$
- LTB parameters: $\alpha = 0$, $\delta_0 = -0.95$, $r_0 = 45.5\ h^{-1}$ Mpc; $r_{obs} = 28\, h^{-1}$Mpc, $\vartheta_{obs} =$ any
- Szekeres parameters: $\alpha = 0.86$, $\delta_0 = -0.86$; $r_{obs} = 38.5\ h^{-1}$ Mpc; $r_{obs} = 25 h^{-1}$ Mpc, $\vartheta_{obs} = 0.705\pi$.

Szekeres model ray tracing constraints

- Require Planck satellite normalized FLRW model on scales $r \gtrsim 100\, h^{-1}$Mpc; i.e., spatially flat, $\Omega_m = 0.315$ and $H_0 = 67.3$ km/s/Mpc
- CMB temperature has a maximum $T_0 + \Delta T$, where

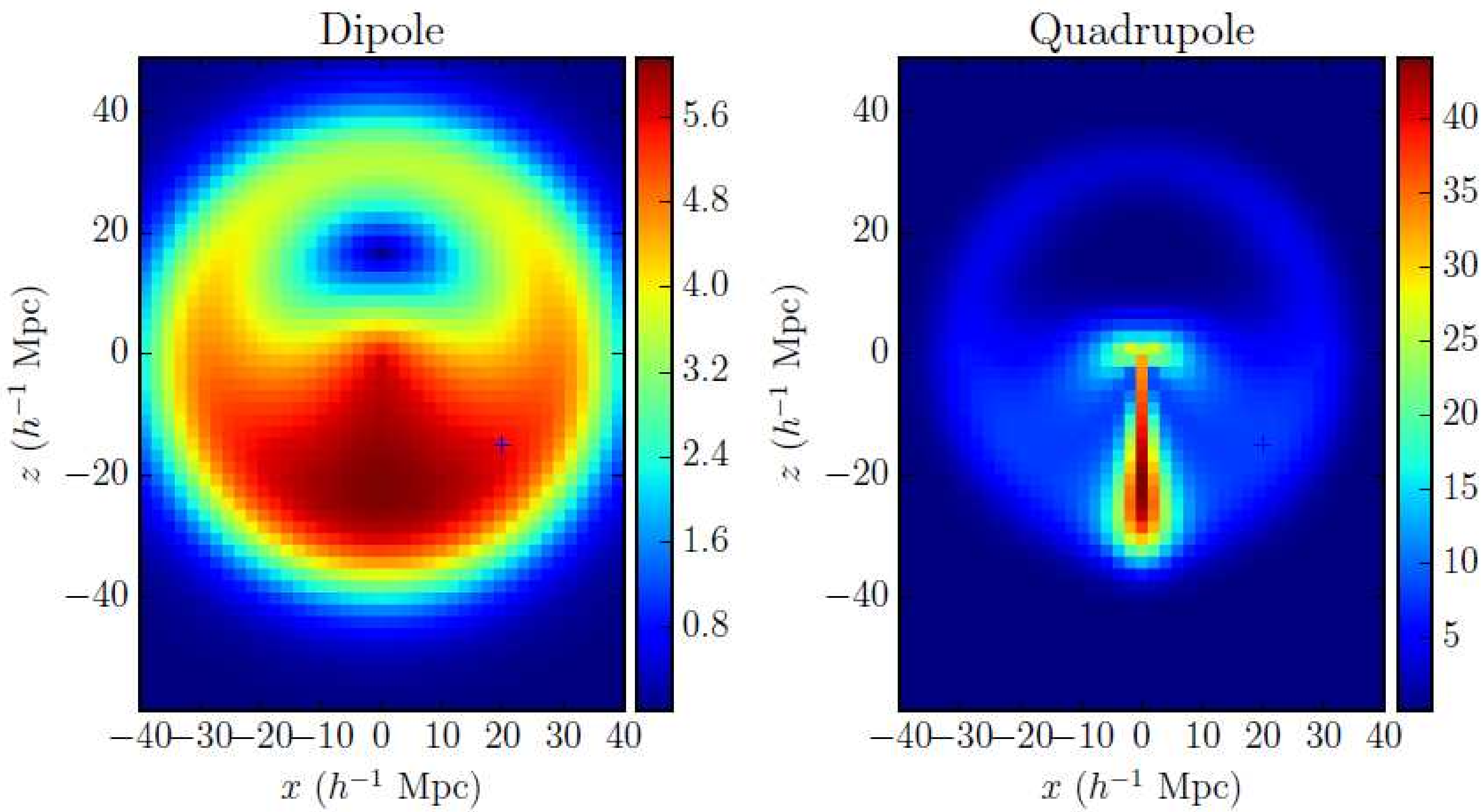
$$\Delta T(\ell = 276.4^\circ, b = 29.3^\circ) = 5.77 \pm 0.36 \text{ mK},$$

  matching dipole amplitude, direction in LG frame
- CMB quadrupole anisotropy lower than observed

$$C_{2,CMB} < 242.2^{+563.6}_{-140.1}\ \mu\text{K}^2.$$

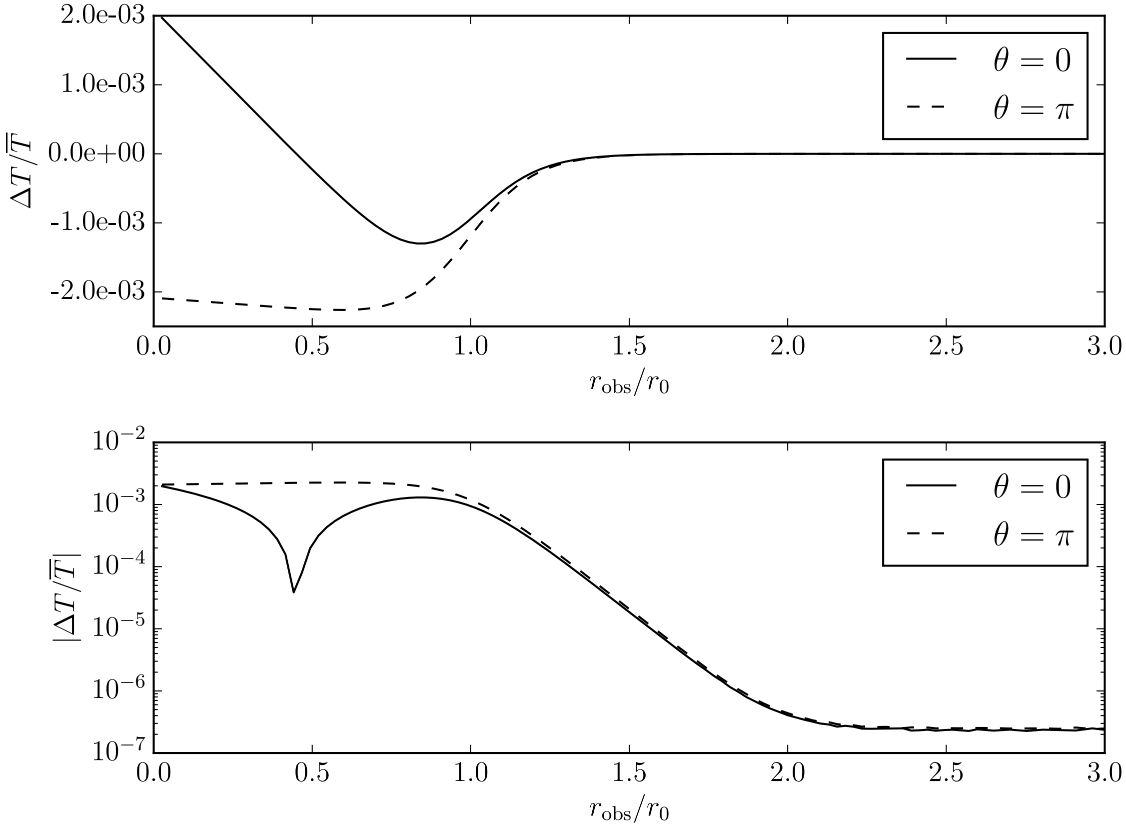
- Hubble expansion dipole (LG frame) matches COMPOSITE one at $z \to 0$, if possible up to $z \sim 0.045$
- Match COMPOSITE quadrupole similarly, if possible

CMB dipole, quadrupole examples



- Generate $z_{\rm ls}(\hat{\mathbf{n}})$ for each gridpoint
- $T = T_{\rm ls}/(1+z_{\rm ls})$; $(T_{\rm max} - T_{\rm min})/2$ left (mK); C_2 right (μK^2)

Peculiar potential not Rees–Sciama



- Rees–Sciama (and ISW) consider photon starting and finishing from *average* point
- Across structure $|\Delta T|/T \sim 2 \times 10^{-7}$
- Inside structure $|\Delta T|/T \sim 2 \times 10^{-3}$

Local expansion variation methodology

$$H_0(\ell, b, z) = \frac{\sum_i H_i w_{d,i} w_{z,i} w_{\theta,i}}{\sum_i w_{d,i} w_{z,i} w_{\theta,i}}, \qquad \langle H_0 \rangle = \frac{1}{4\pi} \int \mathrm{d}\Omega \; H_0(\ell, b, z)$$

$$\zeta_i = z_i + \frac{1}{2}(1 - q_0) z_i^2 - \frac{1}{6}(1 - q_0 - 3q_0^2 + j_0) z_i^3$$

$$H_i = c\zeta_i / d_i, \qquad w_{d,i} = c\zeta_i d_i / (\Delta d_i)^2,$$

$$w_{z,i} = \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left[-\frac{1}{2} \left(\frac{z - z_i}{\sigma_z} \right)^2 \right],$$

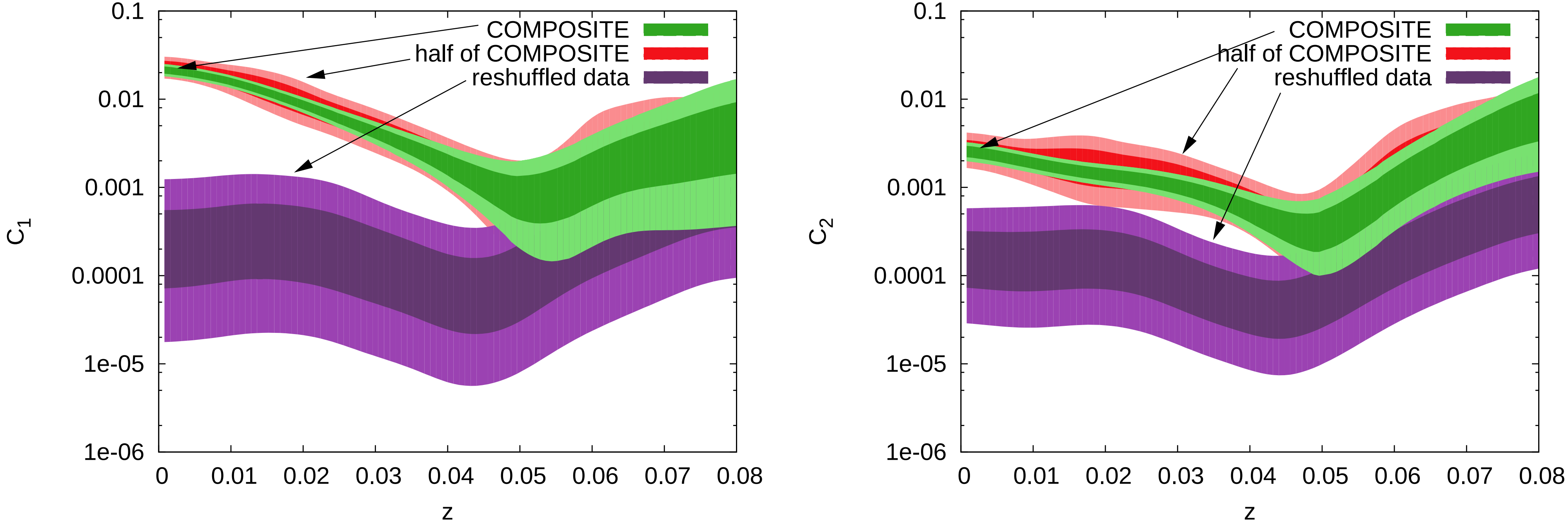
$$w_{\theta,i} = \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp\left[-\frac{1}{2} \left(\frac{\theta_i}{\sigma_\theta} \right)^2 \right],$$

$q_0 = -0.5275$, $j_0 = 1$ ($\Omega_m = 0.315$ ΛCDM); $\sigma_z = 0.01$,
$\sigma_\theta = 25^\circ$, $\theta_i =$ angle between each source and boost apex.

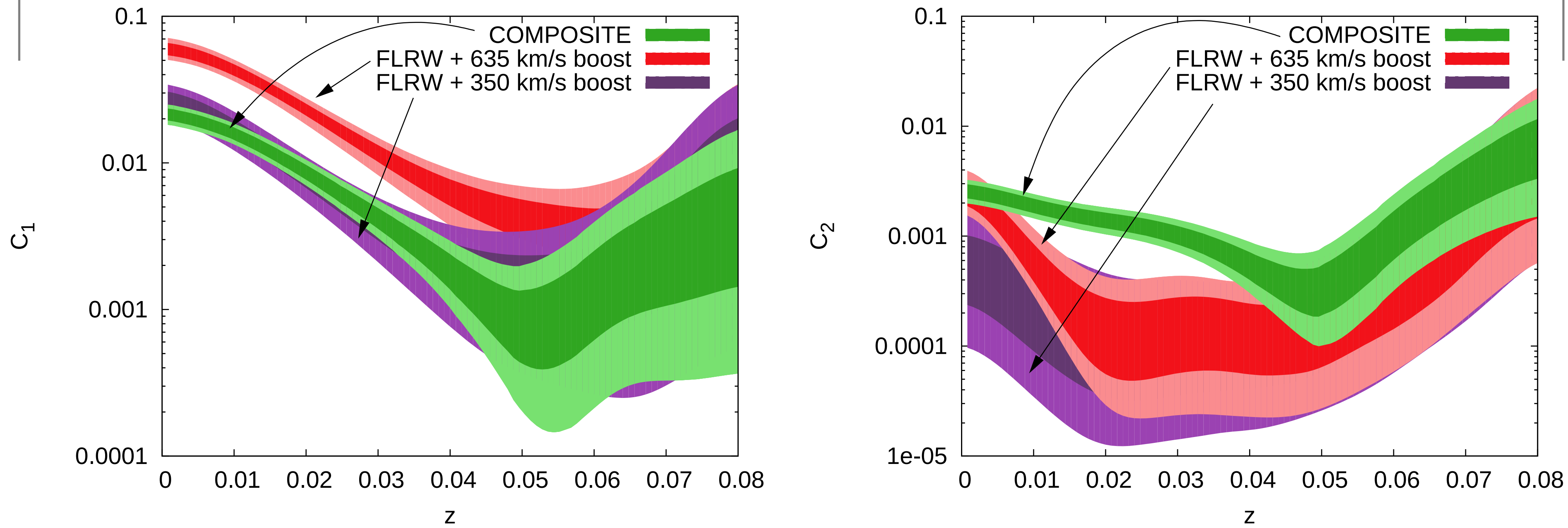
Method and COMPOSITE data

$$\frac{\Delta H_0}{\langle H_0\rangle} = \frac{H_0(l,b,z) - \langle H_0\rangle}{\langle H_0\rangle} = \sum_{l,m} a_{lm} Y_{lm},$$

Expand fractional Hubble expansion variation in multipoles, evaluate angular power spectrum: $C_\ell = \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2$

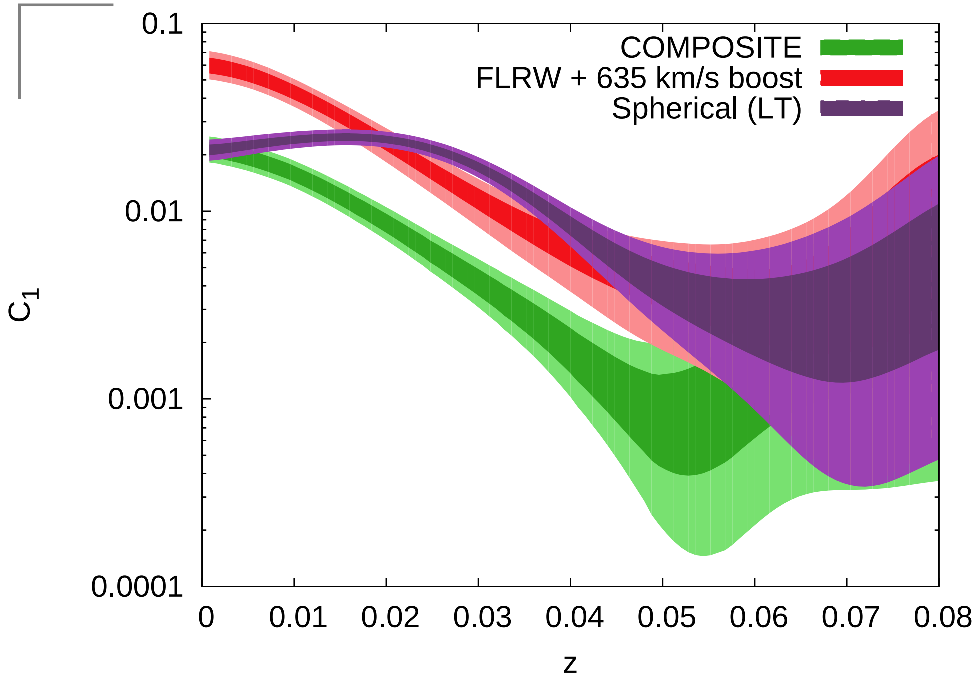


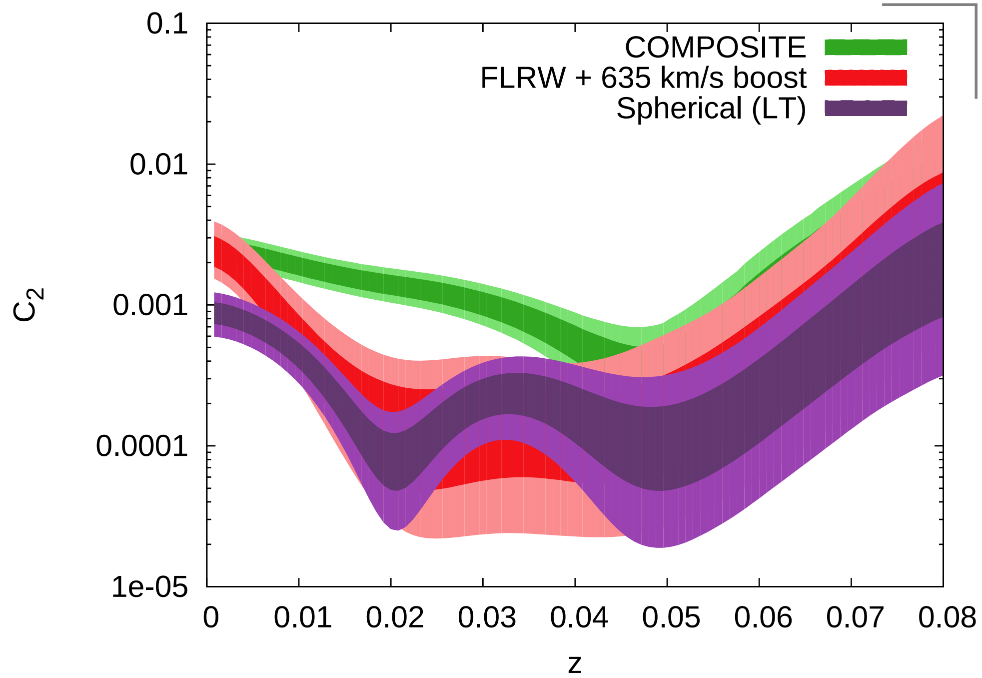
FLRW model in CMB frame + LG boost



- Result of 100,000 mock COMPOSITE catalogues with same distance uncertainties
- For standard kinematic CMB dipole, H_0 dipole too high over all $z < 0.045$; quadrupole OK only at $z \to 0$
- Dipole result: means bulk flow in standard approach

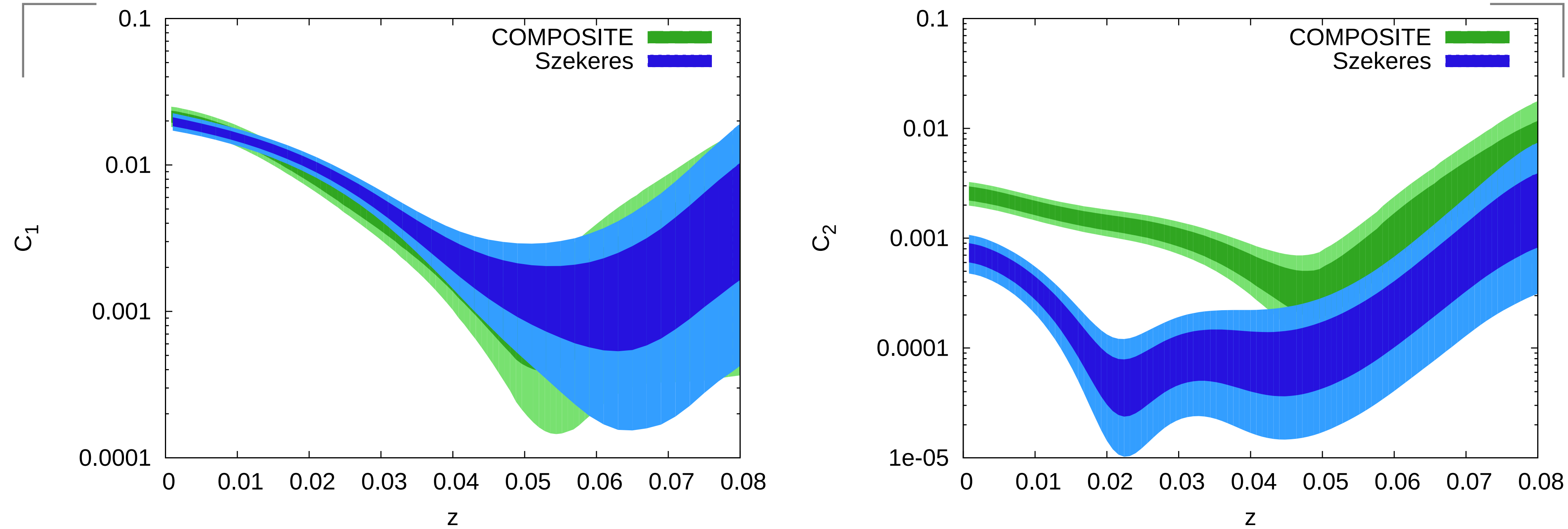
LTB fit: H dipole, quadrupole





- LTB dipole matches only at $z \to 0$, increases to close to FLRW plus boost case for larger z
- Smaller insignificant quadrupole
- Differential expansion radially only; effective point symmetry on scale larger than inhomogeneity

Best fit Szekeres: H dipole, quadrupole

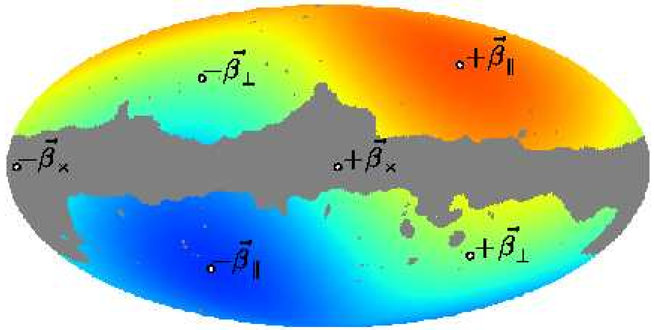


- Szekeres matches dipole on whole $z < 0.045$ range
- Smaller insignificant quadrupole
- Note $C_{2,CMB} = 8.26\ \mu\mathrm{K}^2$ 30 times smaller than observed
- Possible additional smaller amplitudes structures can add quadrupole (future work)

Association with known structures

- Our galaxy is in a local void complex on a filamentary sheet (Tully et al 2008) joined to Virgo cluster. Dominant overdensity $23\,h^{-1}$Mpc wide “Great Attractor”:
  - Near side Centaurus, $z_{\rm LG} = 0.0104 \pm 0.0001$, $(\ell, b) = (302.4°, 21.6°)$
  - Far side Norma, $z_{\rm LG} = 0.0141 \pm 0.0002$, $(\ell, b) = (325.3°, -7.3°)$
- Szekeres $\delta\rho/\rho > 2$ ellipsoidal overdense region, spans $0.003 \lesssim z_{\rm LG} \lesssim 0.013$ (or $16\,h^{-1} \lesssim D_L \lesssim 53\,h^{-1}$Mpc) and angles $220° < \ell < 320°$, $-60° < b < 40°$
- Centaurus lies inside; Norma just outside
- Adding structures at larger distances (Perseus–Pisces) will change far side alignment

Systematics for CMB



- Define nonkinematic foreground CMB anisotropies by

$$\Delta T_{\text{nk-hel}} = \frac{T_{\text{model}}}{\gamma_{\text{LG}}(1-\boldsymbol{\beta}_{\text{LG}}\cdot\hat{\mathbf{n}}_{\text{hel}})} - \frac{T_0}{\gamma_{\text{CMB}}(1-\boldsymbol{\beta}_{\text{CMB}}\cdot\hat{\mathbf{n}}_{\text{hel}})}$$

$$T_{\text{model}} = \frac{T_{\text{dec}}}{1+z_{\text{model}}(\hat{\mathbf{n}}_{\text{LG}})}, \qquad T_0 = \frac{T_{\text{dec}}}{1+z_{\text{dec}}}$$

$z_{\text{model}}(\hat{\mathbf{n}}_{\text{LG}})$ = anisotropic Szekeres LG frame redshift;
T_0 = present mean CMB temperature

- Constrain $\frac{T_{\text{model}}}{\gamma_{\text{LG}}(1-\boldsymbol{\beta}_{\text{LG}}\cdot\hat{\mathbf{n}}_{\text{hel}})} - T_{\text{obs}}$ by Planck with sky mask

Large angle CMB anomalies?

Anomalies (significance increased after Planck 2013):

- power asymmetry of northern/southern hemispheres
- alignment of the quadrupole and octupole etc;
- low quadrupole power;
- parity asymmetry; . . .

Critical re-examination required; e.g.

- light propagation through Hubble variance dipole foregrounds may differ subtly from Lorentz boost dipole
- dipole subtraction is an integral part of the map-making; is galaxy correctly cleaned?
- Freeman et al (2006): 1–2% change in dipole subtraction may resolve the power asymmetry anomaly.

Planck results arXiv:1303.5087

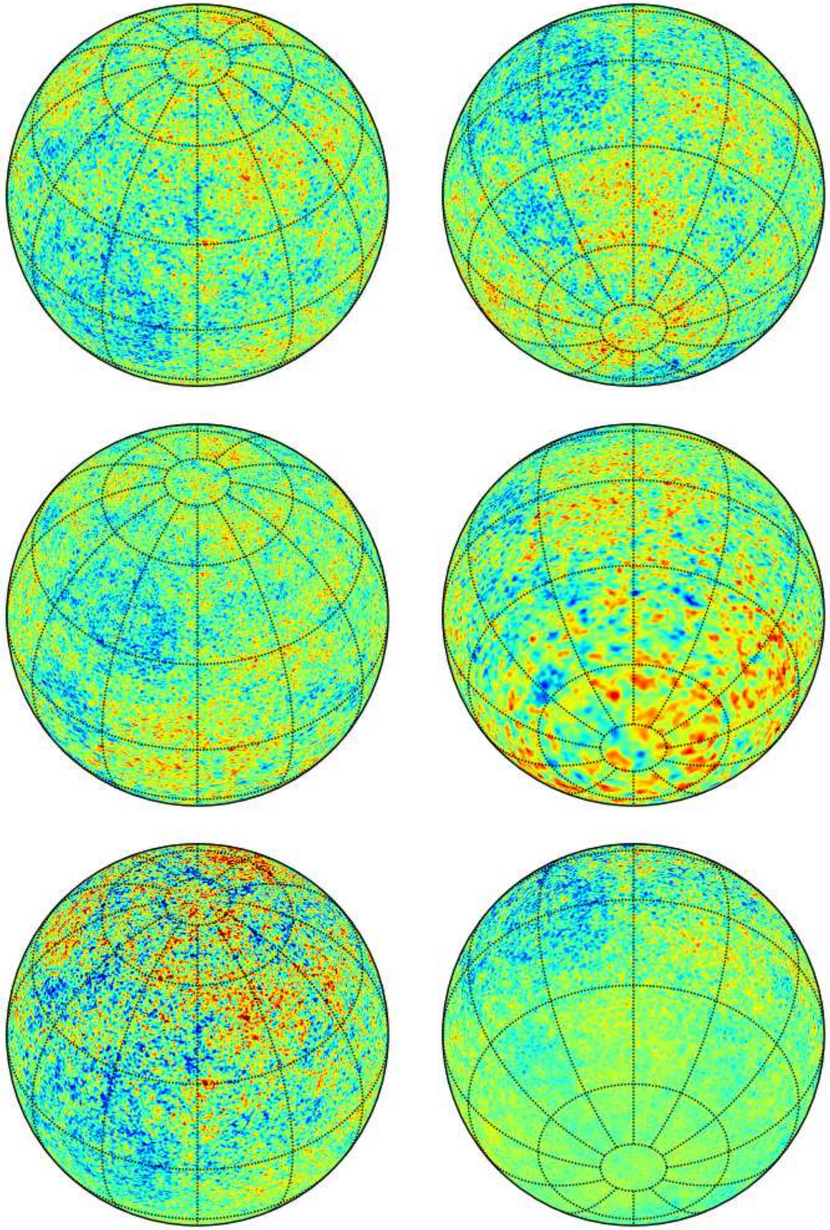
Boost dipole from second order effects

Original

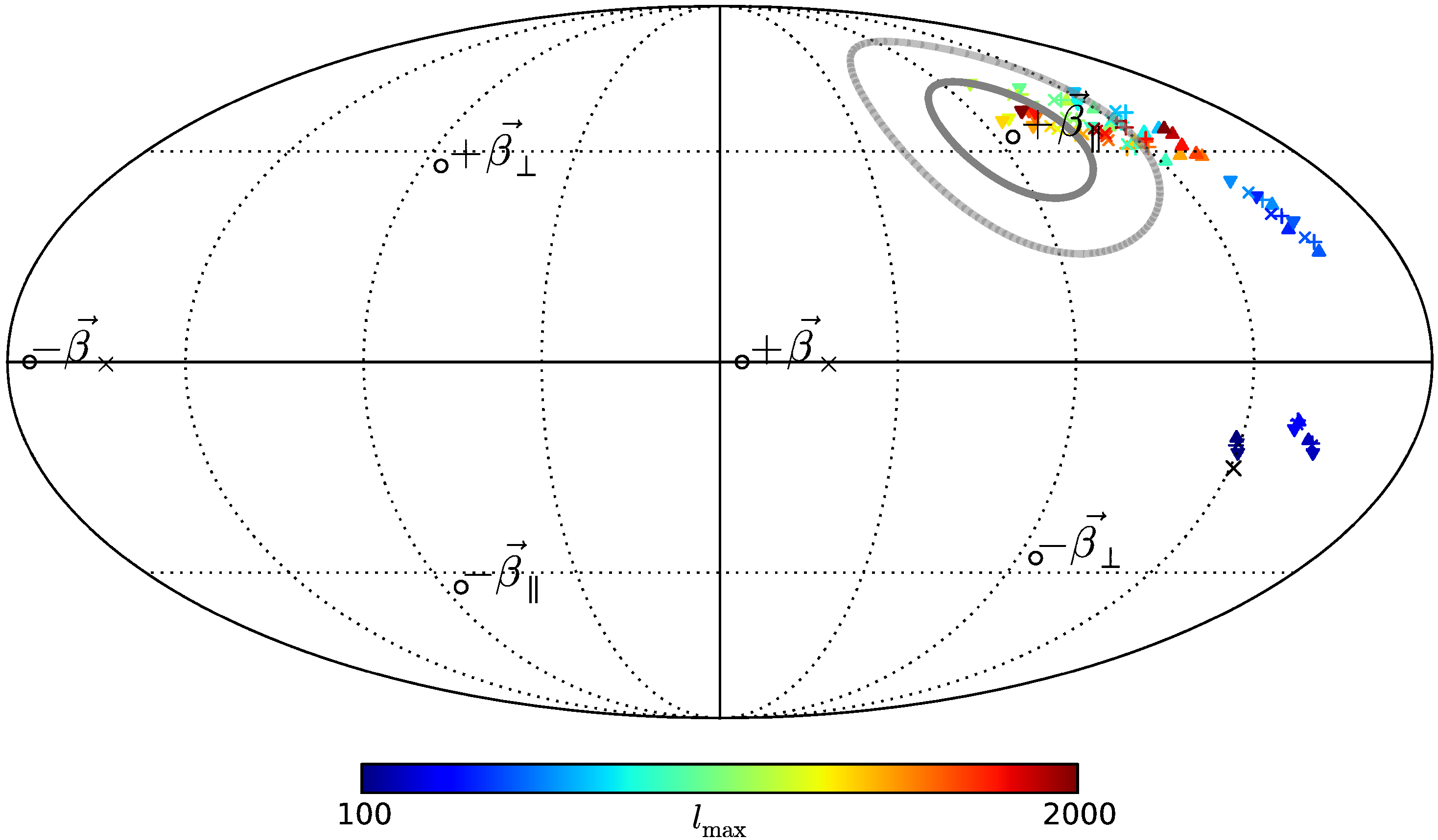
Aberration (Exaggerated)

Modulation (Exaggerated)

Eppur si muove?



Planck Doppler boosting 1303.5087



- Dipole direction consistent with CMB dipole $(\ell, b) = (264^\circ, 48^\circ)$ for small angles, $l_{\mathrm{min}} = 500 < l < l_{\mathrm{max}} = 2000$
- When $l < l_{\mathrm{max}} = 100$, shifts to WMAP power asymmetry modulation dipole $(\ell, b) = (224^\circ, -22^\circ) \pm 24^\circ$

Conclusion/Outlook

- Claim: GR below SHS can resolve bulk flow dilemmas
- Independently, kinematic dipole rejected at 99.5% confidence in radio galaxy number counts (Rubart & Schwarz 2013) – direction same
- A 0.5% nonkinematic anisotropy on $\lesssim 65\,h^{-1}$Mpc scales has profound implications for cosmology
- Local value of H_0 by Riess et al analysis higher than global value (Bolejko et al, to appear)
- CMB dipole subtraction *will be different* with modellable consequences for large angle anomalies
- Generalization for ensembles of realistic Szekeres models relevant for ISW amplitude calculation (needs assumptions about backreaction, averaging)