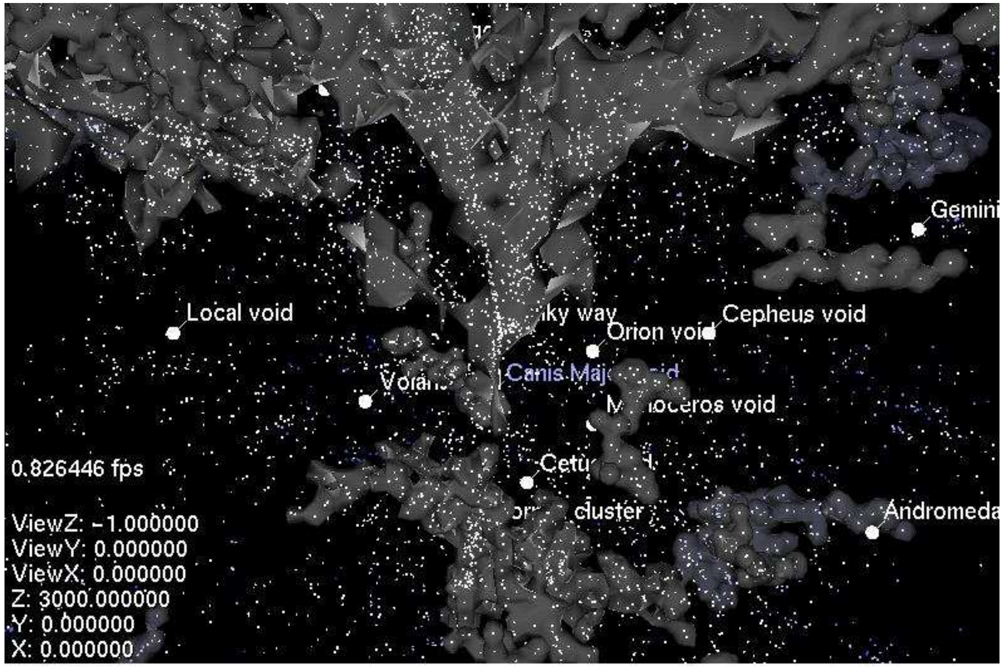
Dark energy from cosmic structure

David L. Wiltshire (University of Canterbury, NZ)



DLW: **New J. Phys. 9 (2007) 377**

Phys. Rev. Lett. 99 (2007) 251101

Phys. Rev. D78 (2008) 084032

Phys. Rev. D80 (2009) 123512

Class. Quan. Grav. 28 (2011) 164006

B.M. Leith, S.C.C. Ng & DLW:

ApJ 672 (2008) L91

P.R. Smale & DLW, **MNRAS 413 (2011) 367**

P.R. Smale, **MNRAS 418 (2011) 2779**

DLW, P.R. Smale, T. Mattsson & R. Watkins, **Phys. Rev. D88 (2013) 083529**

J.A.G. Duley, M.A. Nazer & DLW: **Class. Quan. Grav. 30 (2013) 175006**

M.A. Nazer & DLW: **arXiv: 1410.3470** *Review article* – DLW: **arXiv: 1311.3797**

Outline of talk

- What is dark energy?:

  Dark energy is a misidentification of gradients in quasilocal kinetic energy of expansion of space

  (in presence of density and spatial curvature gradients on scales $\lesssim 100\,h^{-1}$Mpc which also alter average cosmic expansion).
- Ideas and principles of *timescape scenario*
- Cosmological tests of average expansion history
  - SneIa, BAO, CMB, . . .
  - Timescape and ΛCDM distinguishable with *Euclid*
- Hubble expansion variance
  - Local / global H_0

Averaging and backreaction

- *Fitting problem* (Ellis 1984):
  On what scale are Einstein's field equations valid?

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- In general $\langle G^{\mu}{}_{\nu}(g_{\alpha\beta})\rangle \neq G^{\mu}{}_{\nu}(\langle g_{\alpha\beta}\rangle)$
- Inhomogeneity in expansion (on $\lesssim 100\,h^{-1}$Mpc scales) may make average non–Friedmann as structure grows
- *Weak backreaction*: Perturb about a given background
- *Strong backreaction*: fully nonlinear
  - Spacetime averages (R. Zalaletdinov 1992, 1993);
  - Spatial averages on hypersurfaces based on a $1+3$ foliation (T. Buchert 2000, 2001).

Buchert-Ehlers-Carfora-Piotrkowska -Russ-Soffel-Kasai-Börner equations

For irrotational dust cosmologies, with energy density, $\rho(t,\mathbf{x})$, expansion scalar, $\vartheta(t,\mathbf{x})$, and shear scalar, $\sigma(t,\mathbf{x})$, where $\sigma^2=\frac{1}{2}\sigma_{\mu\nu}\sigma^{\mu\nu}$, **defining** $3\dot{\bar{a}}/\bar{a}\equiv\langle\vartheta\rangle$, we find average cosmic evolution described by exact Buchert equations

$$
\begin{aligned}
&(1) & 3\frac{\dot{\bar{a}}^2}{\bar{a}^2} &= 8\pi G\langle\rho\rangle-\tfrac{1}{2}\langle\mathcal{R}\rangle-\tfrac{1}{2}\mathcal{Q}\\
&(2) & 3\frac{\ddot{\bar{a}}}{\bar{a}} &= -4\pi G\langle\rho\rangle+\mathcal{Q}\\
&(3) & \partial_t\langle\rho\rangle &+ 3\frac{\dot{\bar{a}}}{\bar{a}}\langle\rho\rangle=0\\
&(4) & \partial_t\left(\bar{a}^6\mathcal{Q}\right) &+ \bar{a}^4\partial_t\left(\bar{a}^2\langle\mathcal{R}\rangle\right)=0\\
& & \mathcal{Q} &\equiv \frac{2}{3}\left(\langle\vartheta^2\rangle-\langle\vartheta\rangle^2\right)-2\langle\sigma^2\rangle
\end{aligned}
$$

Backreaction in Buchert averaging

- *Kinematic backreaction* term can also be written

$$\mathcal{Q} = \tfrac{2}{3}\langle(\delta\vartheta)^2\rangle - 2\langle\sigma^2\rangle$$

  i.e., combines variance of expansion, and shear.
- Eq. (6) is required to ensure (3) is an integral of (4).
- Buchert equations look deceptively like Friedmann equations, but deal with *statistical* quantities
- The extent to which the back–reaction, $\mathcal{Q}$, can lead to apparent cosmic acceleration or not has been the subject of much debate (e.g., Ishibashi & Wald 2006):
  - How do statistical quantities relate to observables?
  - What about the time slicing?
  - How big is $\mathcal{Q}$ given reasonable initial conditions?

What is a cosmological particle (dust)?

- In FLRW one takes observers "comoving with the dust"
- Traditionally galaxies were regarded as dust. However,
  - Neither galaxies nor galaxy clusters are homogeneously distributed today
  - Dust particles should have (on average) invariant masses over the timescale of the problem
- Must coarse-grain over expanding fluid elements larger than the largest typical structures [voids of diameter $30\,h^{-1}$Mpc with $\delta_\rho \sim -0.95$ are $\gtrsim 40\%$ of $z=0$ universe]

$$\left.\begin{array}{c} g_{\mu\nu}^{\rm stellar} \to g_{\mu\nu}^{\rm galaxy} \to g_{\mu\nu}^{\rm cluster} \to g_{\mu\nu}^{\rm wall} \\ \hfill \vdots \hfill \\ \hfill g_{\mu\nu}^{\rm void} \end{array}\right\} \to g_{\mu\nu}^{\rm universe}$$

Largest typical structures

Survey	Void diameter	Density contrast
PSCz	$(29.8 \pm 3.5)h^{-1}$Mpc	$\delta_\rho = -0.92 \pm 0.03$
UZC	$(29.2 \pm 2.7)h^{-1}$Mpc	$\delta_\rho = -0.96 \pm 0.01$
2dF NGP	$(29.8 \pm 5.3)h^{-1}$Mpc	$\delta_\rho = -0.94 \pm 0.02$
2dF SGP	$(31.2 \pm 5.3)h^{-1}$Mpc	$\delta_\rho = -0.94 \pm 0.02$

Dominant void statistics in the Point Source Catalogue Survey (PSCz), the Updated Zwicky Catalogue (UZC), and the 2 degree Field Survey (2dF) North Galactic Pole (NGP) and South Galactic Pole (SGP), (Hoyle and Vogeley 2002,2004). More recent results of Pan et al. (2011) using SDSS Data Release 7 similar.

- Particle size should be a few times greater than largest typical structures (voids with $\delta_\rho \equiv (\rho - \bar{\rho})/\bar{\rho} \sim -1$)
- Coarse grain dust “particles” – fluid elements – at Scale of Statistical Homogeneity (SSH) $\sim 100/h$ Mpc

Dilemma of gravitational energy…

- In GR spacetime carries *energy* & *angular momentum*

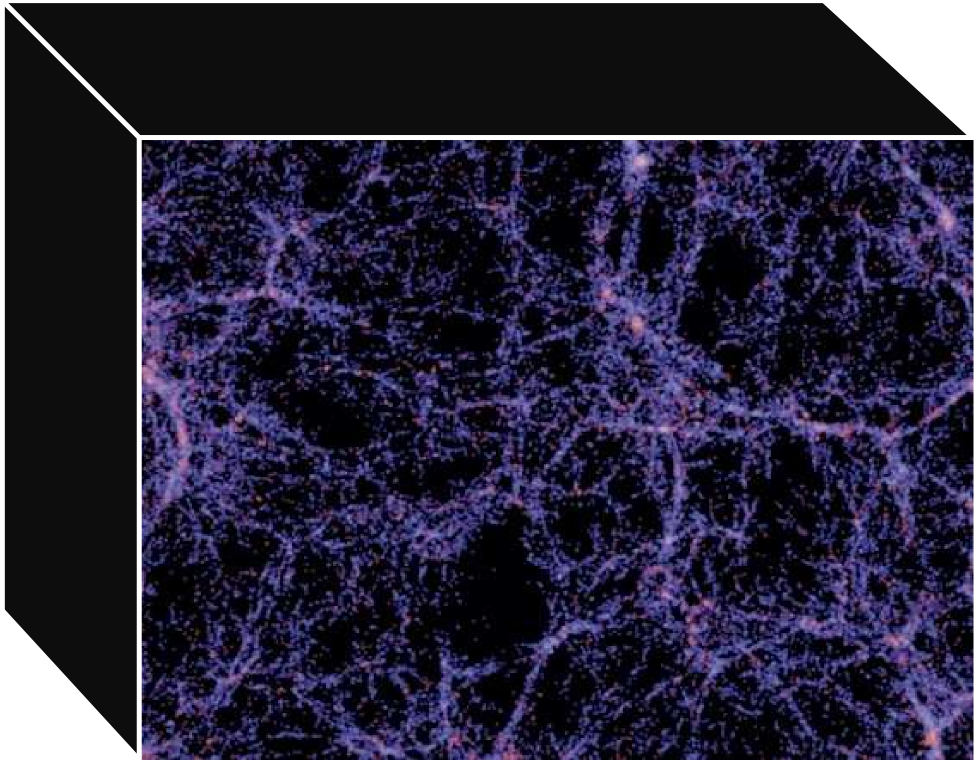
$$G_{\mu\nu}=\frac{8\pi G}{c^4}T_{\mu\nu}$$

- On account of the strong equivalence principle, $T_{\mu\nu}$ contains localizable energy–momentum only
- Kinetic energy and energy associated with spatial curvature are in $G_{\mu\nu}$: variations are “quasilocal”!
- Newtonian version, $T-U=-V$, of Friedmann equation

$$\frac{\dot a^2}{a^2}+\frac{kc^2}{a^2}=\frac{8\pi G\rho}{3}$$

where $T=\frac{1}{2}m\dot a^2x^2$, $U=-\frac{1}{2}kmc^2x^2$, $V=-\frac{4}{3}\pi G\rho a^2x^2m$; $\mathbf{r}=a(t)\mathbf{x}$.

Within a statistically average cell

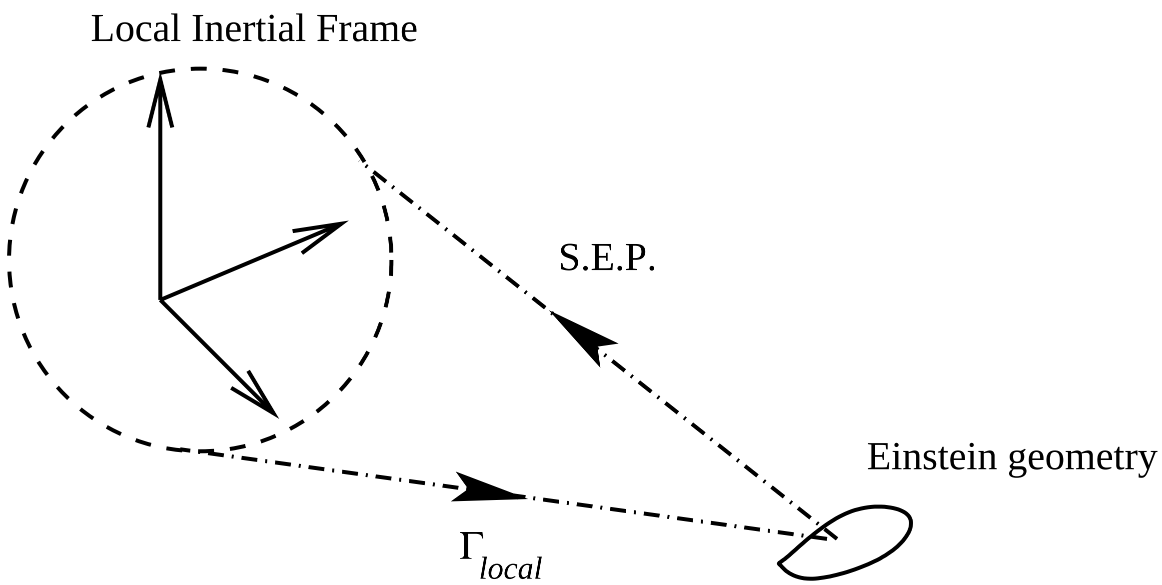


- Need to consider relative position of observers over scales of tens of Mpc over which $\delta\rho/\rho \sim -1$.
- GR is a local theory: gradients in spatial curvature and gravitational energy can lead to calibration differences between our rulers & clocks and volume average ones

The Copernican principle

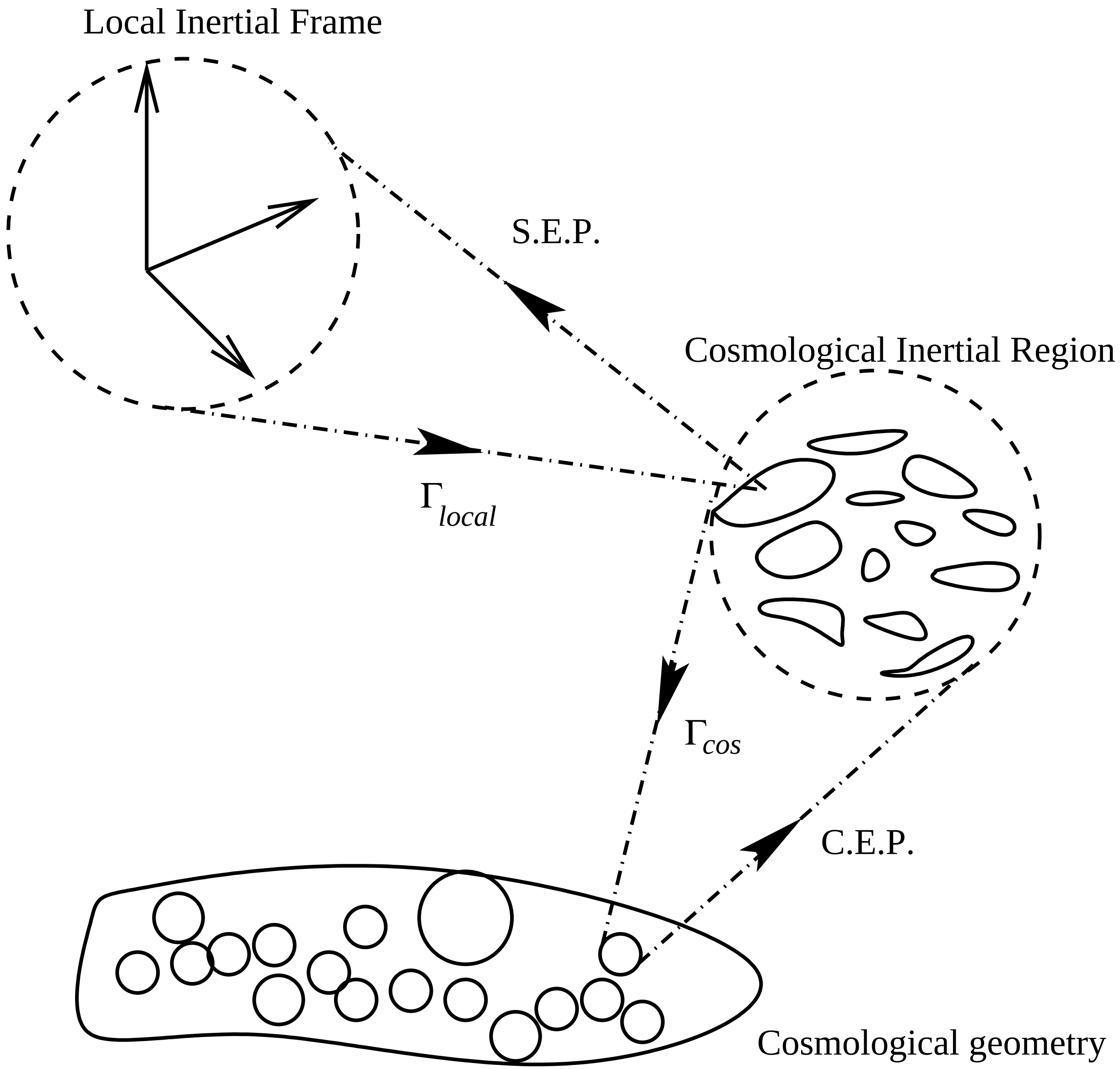
- Retain Copernican Principle - we are at an average position *for observers in a galaxy*
- Observers in bound systems are not at a volume average position in freely expanding space
- By Copernican principle other average observers should see an isotropic CMB
- BUT *nothing in theory, principle nor observation demands that such observers measure the same mean CMB temperature nor the same angular scales in the CMB anisotropies*
- Average mass environment (galaxy) will differ significantly from volume–average environment (void)

Back to first principles…



- Need to address Mach's principle: *"Local inertial frames are determined through the distributions of energy and momentum in the universe by some weighted average of the apparent motions"*
- Need to separate non-propagating d.o.f., in particular regional density, from propagating modes: shape d.o.f.
- Need to specify relevant asymptotic scale of "fixed stars" for local/regional mass definitions

Statistical geometry. . .



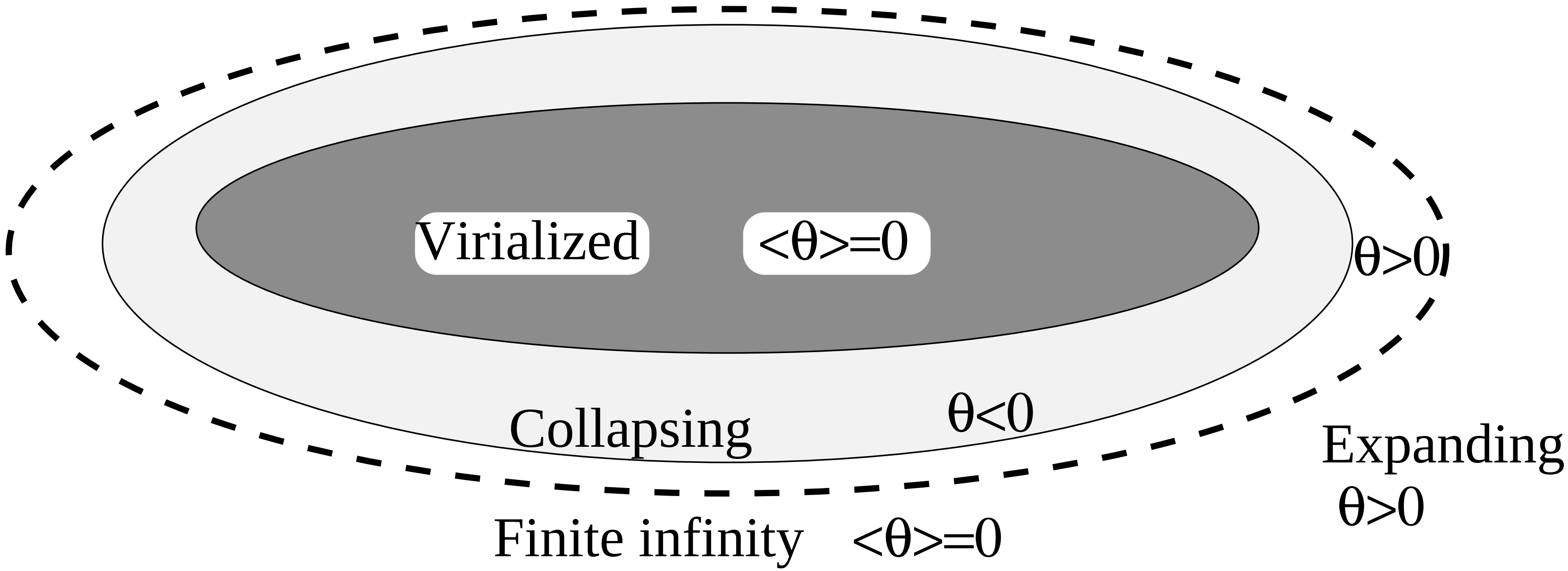
Cosmological Equivalence Principle

- *In cosmological averages it is always possible to choose a suitably defined spacetime region, the cosmological inertial region, on whose boundary average motions (timelike and null) can be described by geodesics in a geometry which is Minkowski up to some time-dependent conformal transformation*,

$$\mathrm{d}s^2_{\mathrm{CIR}} = a^2(\eta)\left[-\mathrm{d}\eta^2 + \mathrm{d}r^2 + r^2\mathrm{d}\Omega^2\right],$$

- Defines Cosmological Inertial Region (CIR) in which *regionally isotropic* volume expansion is equivalent to a velocity in special relativity
- Such velocities integrated on a bounding 2-sphere define *"kinetic energy of expansion"*: globally it has gradients

Finite infinity



- Define *finite infinity*, "*fi*" as boundary to *connected* region within which *average expansion* vanishes $\langle\vartheta\rangle = 0$ and expansion is positive outside.
- Shape of *fi* boundary irrelevant (minimal surface generally): could typically contain a galaxy cluster.

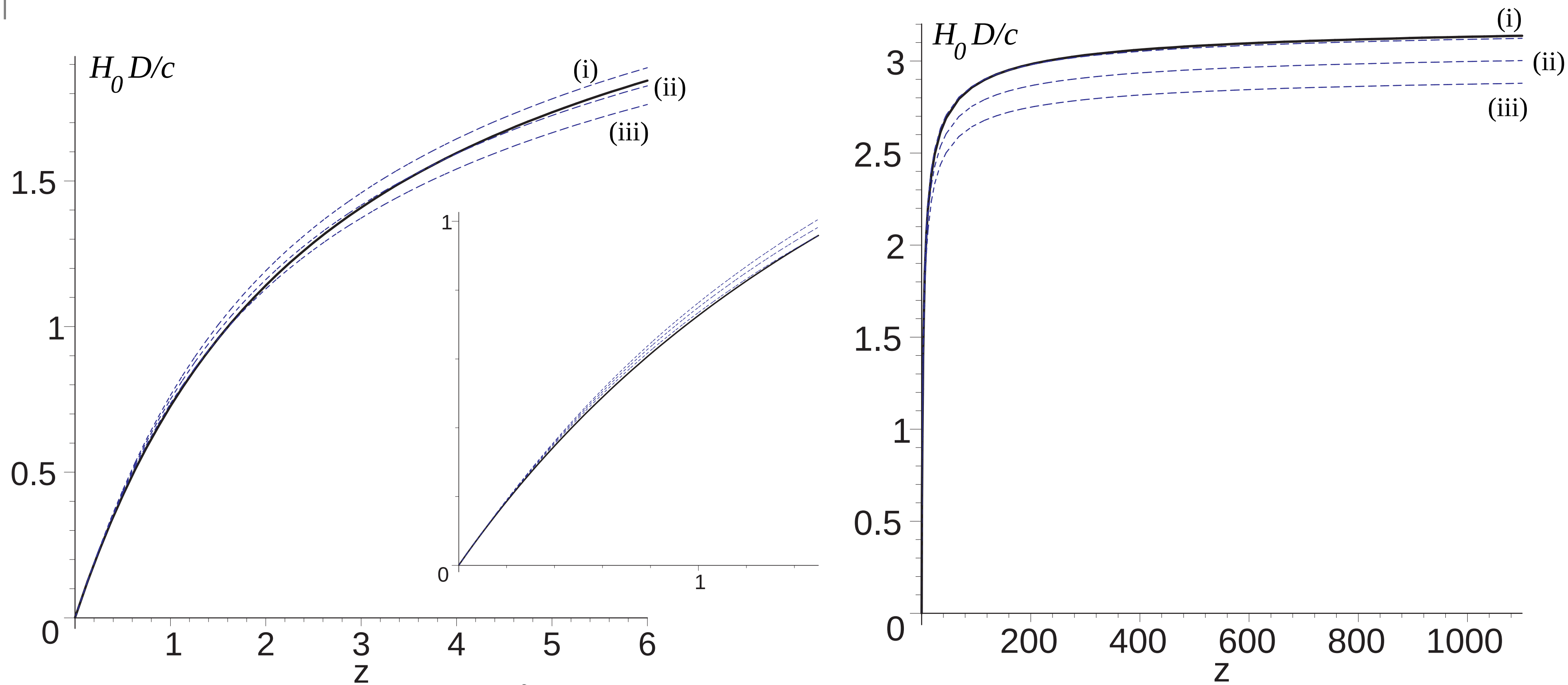
Why is ΛCDM so successful?

- The early Universe was extremely close to homogeneous and isotropic
- Finite infinity geometry (2 – $15\,h^{-1}$Mpc) is close to spatially flat (Einstein–de Sitter at late times) – N–body simulations successful *for bound structure*
- At late epochs there is a simplifying principle – Cosmological Equivalence Principle
- Hubble parameter (first derivative of statistical metric; i.e., connection) is to some extent a “gauge choice”
  - Affects local/global H_0 issue
  - Has contributed to fights (e.g., Sandage vs de Vaucouleurs) depending on measurement scale
- *Even on small scales there is a notion of uniform Hubble flow at expense of calibration of rulers AND CLOCKS*

Model detail

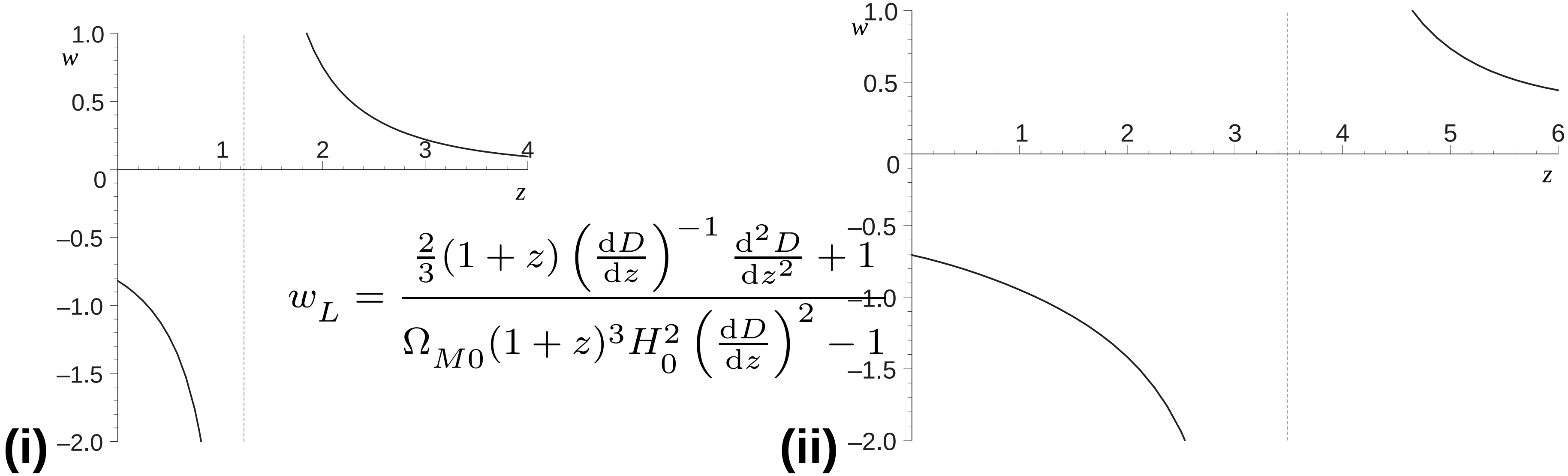
- Take *horizon volume average* of two populations:
  - *voids*: negatively curved, volume fraction, $f_{\rm v}$
  - *"walls"* $= \cup\{$*sheets*, *filaments*, *knots*$\}$ coarse grained as spatially flat, volume fraction, $f_{\rm w} = 1 - f_{\rm v}$
- *Solve Buchert equations*:
  Buchert time parameter, t, is a collective coordinate of fluid cell coarse-grained at $\sim 100\,h^{-1}$Mpc, giving *bare cosmological parameters* $\bar{H}$, $\bar{\Omega}_M$, $\bar{\Omega}_R$, $\bar{\Omega}_k$, $\bar{\Omega}_{\mathcal{Q}}$, …
- *Relate statistical solutions to local ("wall") geometry*:
  Conformally match radial null geodesics to spatially flat finite infinity geometry on spherically averaged past light cone using uniform quasilocal Hubble flow condition, giving *dressed cosmological parameters* H, Ω_M, …

Dressed "comoving distance" $D(z)$



TS model, with $f_{\mathrm{v}0} = 0.695$, **(black)** compared to 3 spatially flat ΛCDM models (blue): **(i)** $\Omega_{M0} = 0.3175$ (best-fit ΛCDM model to Planck); (ii) $\Omega_{M0} = 0.35$; **(iii)** $\Omega_{M0} = 0.388$.

Equivalent "equation of state"?

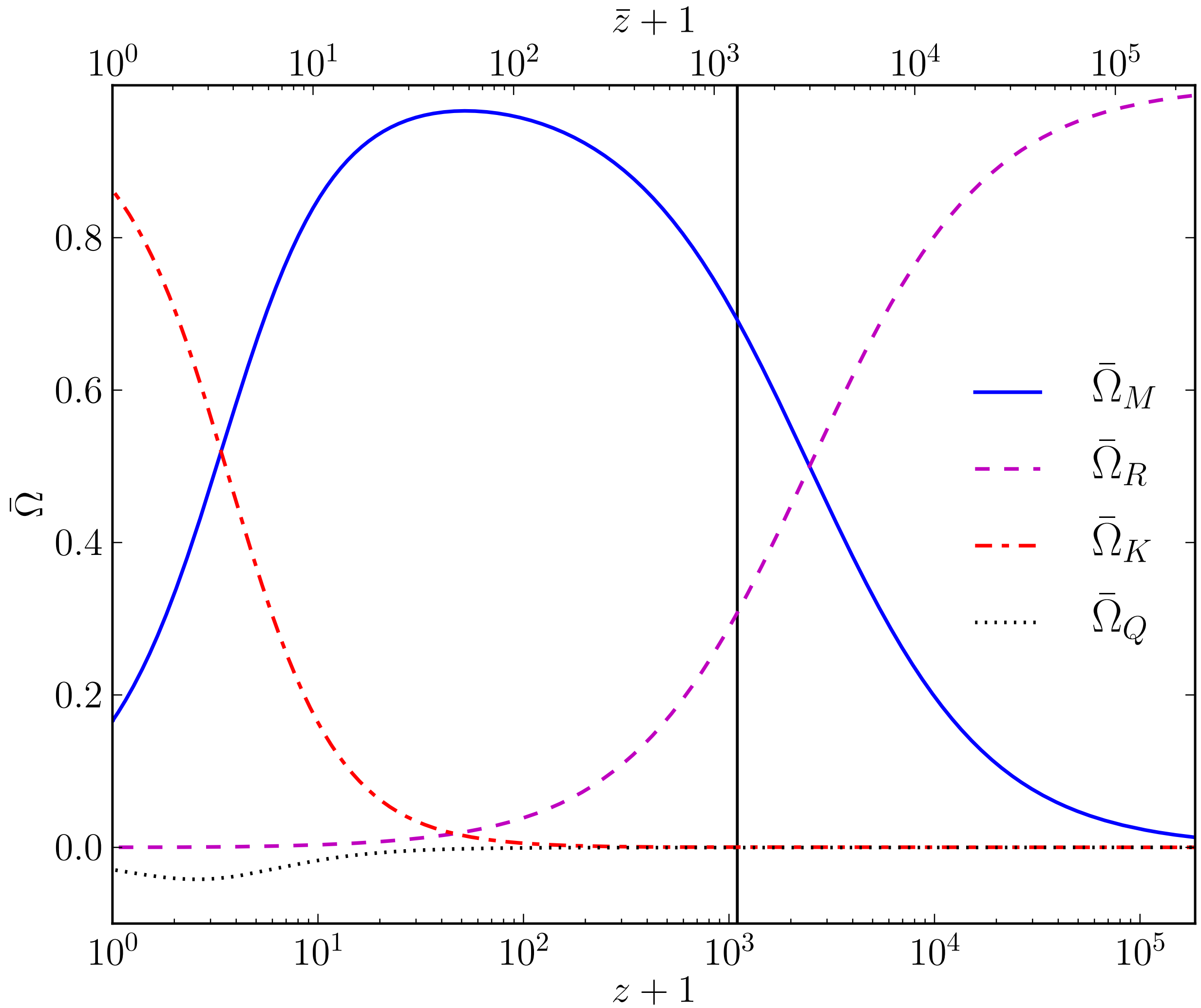


$$w_L = \frac{\frac{2}{3}(1+z)\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^{-1}\frac{\mathrm{d}^2D}{\mathrm{d}z^2}+1}{\Omega_{M0}(1+z)^3H_0^2\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^2-1}$$

A formal "dark energy equation of state" $w_L(z)$ for the TS model, with $f_{\mathrm{v}0} = 0.695$, calculated directly from $r_w(z)$: **(i)** $\Omega_{M0} = 0.695$; **(ii)** $\Omega_{M0} = 0.3175$.

- Description by a "dark energy equation of state" makes no sense when there's no physics behind it; but average value $w_L \simeq -1$ for $z < 0.7$ makes empirical sense.

Bare cosmological parameters



J.A.G. Duley, M.A. Nazer & DLW, CQG 30 (2013) 175006: full numerical solution with matter, radiation

Apparent cosmic acceleration

- Volume average observer sees no apparent cosmic acceleration

$$\bar{q} = \frac{2\left(1 - f_{\rm v}\right)^2}{(2 + f_{\rm v})^2} .$$

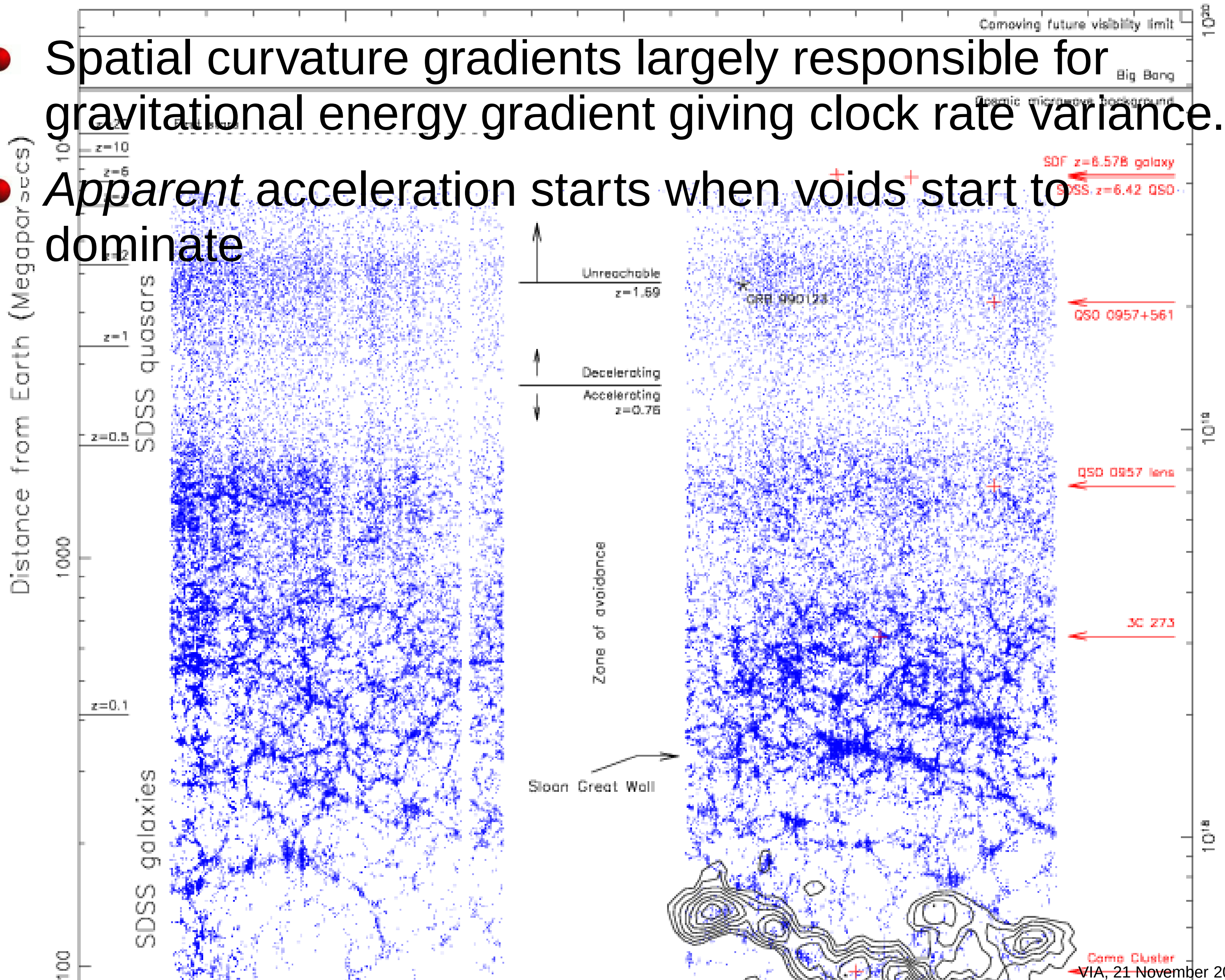
As $t \to \infty$, $f_{\rm v} \to 1$ and $\bar{q} \to 0^+$.

- A wall observer registers apparent cosmic acceleration

$$q = \frac{-\left(1 - f_{\rm v}\right)\left(8f_{\rm v}{}^3 + 39f_{\rm v}{}^2 - 12f_{\rm v} - 8\right)}{\left(4 + f_{\rm v} + 4f_{\rm v}{}^2\right)^2} ,$$

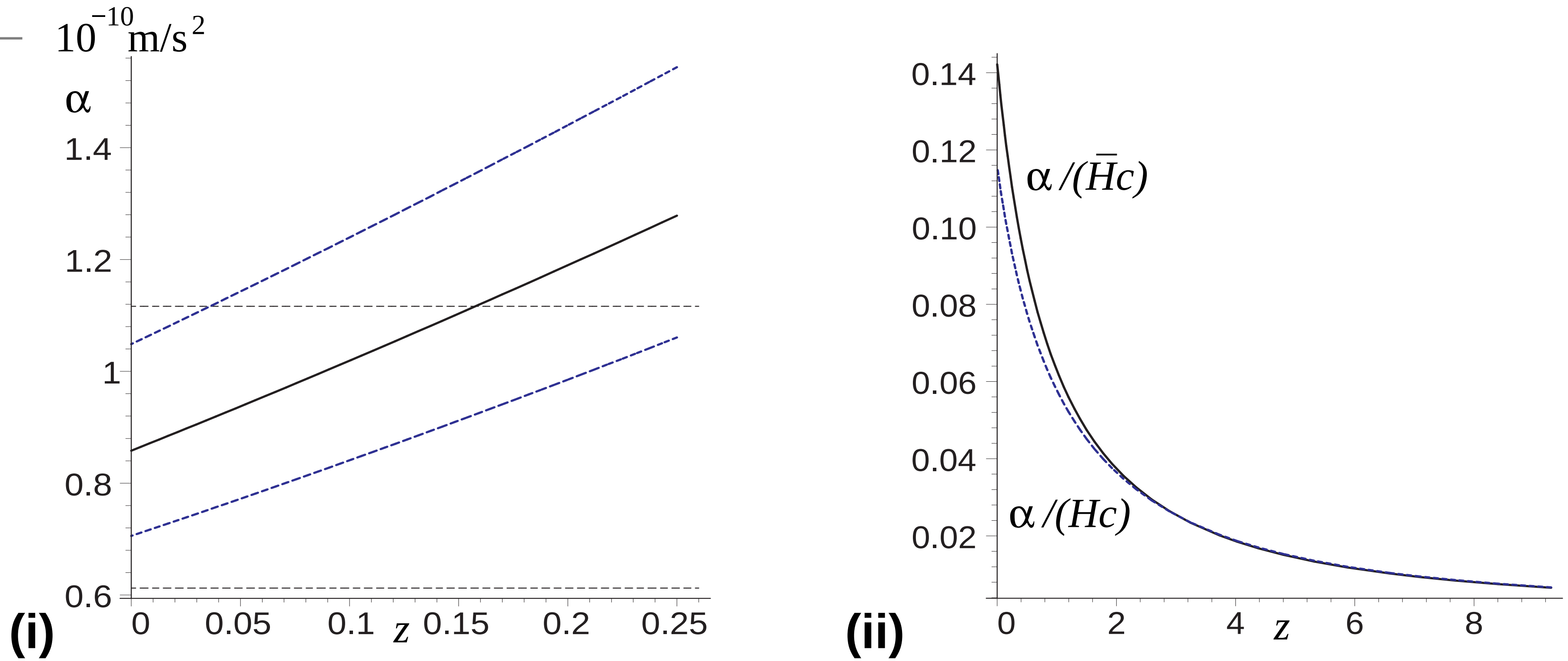
Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small $f_{\rm v}$; changes sign when $f_{\rm v} = 0.5867\ldots$, and approaches $q \to 0^-$ at late times.

Cosmic coincidence problem solved



- Spatial curvature gradients largely responsible for gravitational energy gradient giving clock rate variance.
- *Apparent* acceleration starts when voids start to dominate

Relative deceleration scale



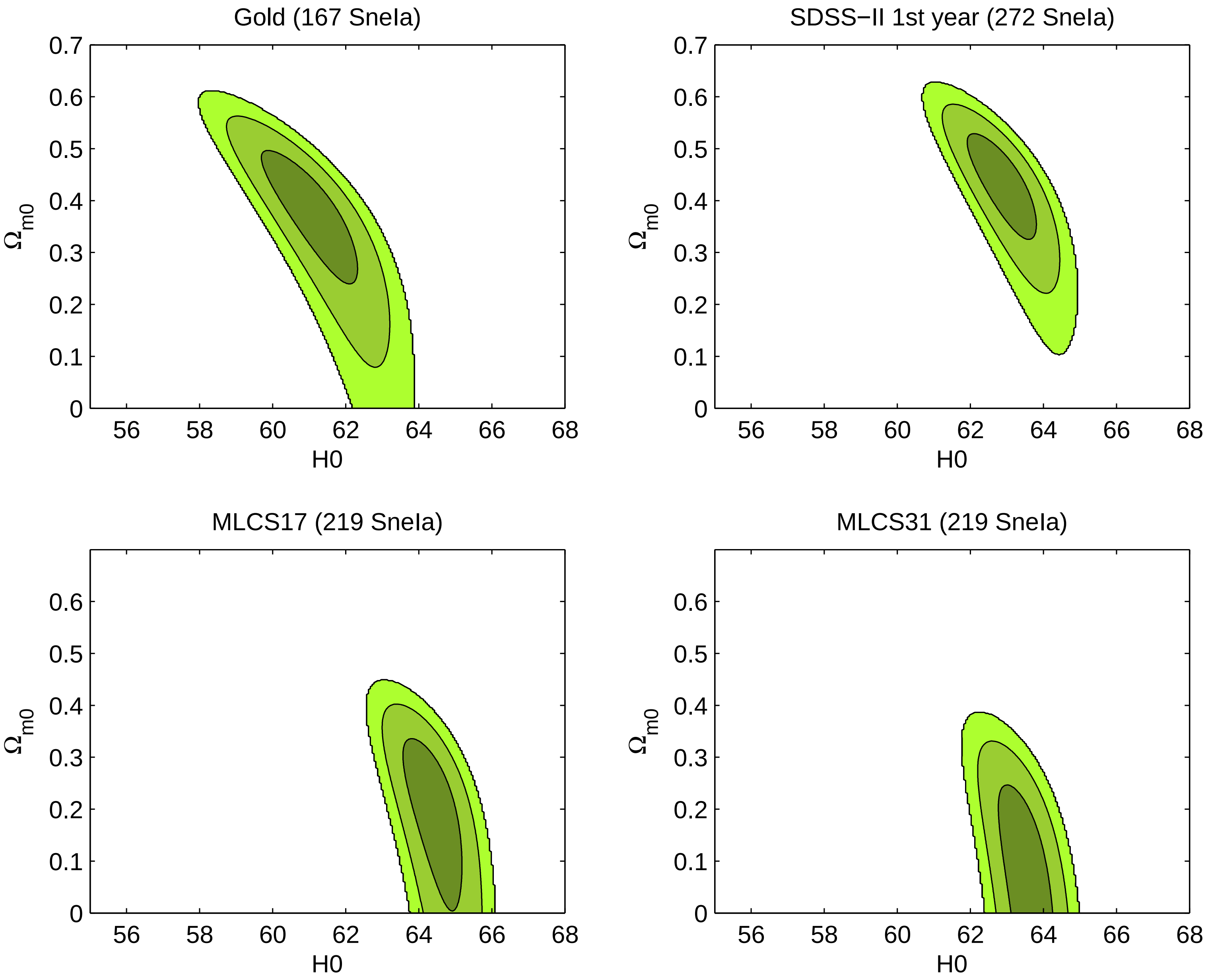
By cosmological equivalence principle the instantaneous relative deceleration of backgrounds gives an instantaneous 4-acceleration of magnitude $\alpha = H_0 c\bar{\gamma}\dot{\bar{\gamma}}/(\sqrt{\bar{\gamma}^2 - 1})$ beyond which *weak field cosmological general relativity* will be changed from Newtonian expectations: **(i)** as absolute scale nearby; **(ii)** divided by Hubble parameter to large z.

- Relative *volume* deceleration of expanding regions of different local density/curvature, leads cumulatively to canonical clocks differing by $\mathrm{d}t = \bar{\gamma}_{\mathrm{w}}\, \mathrm{d}\tau_{\mathrm{w}}$ ($\to\sim 35$%)

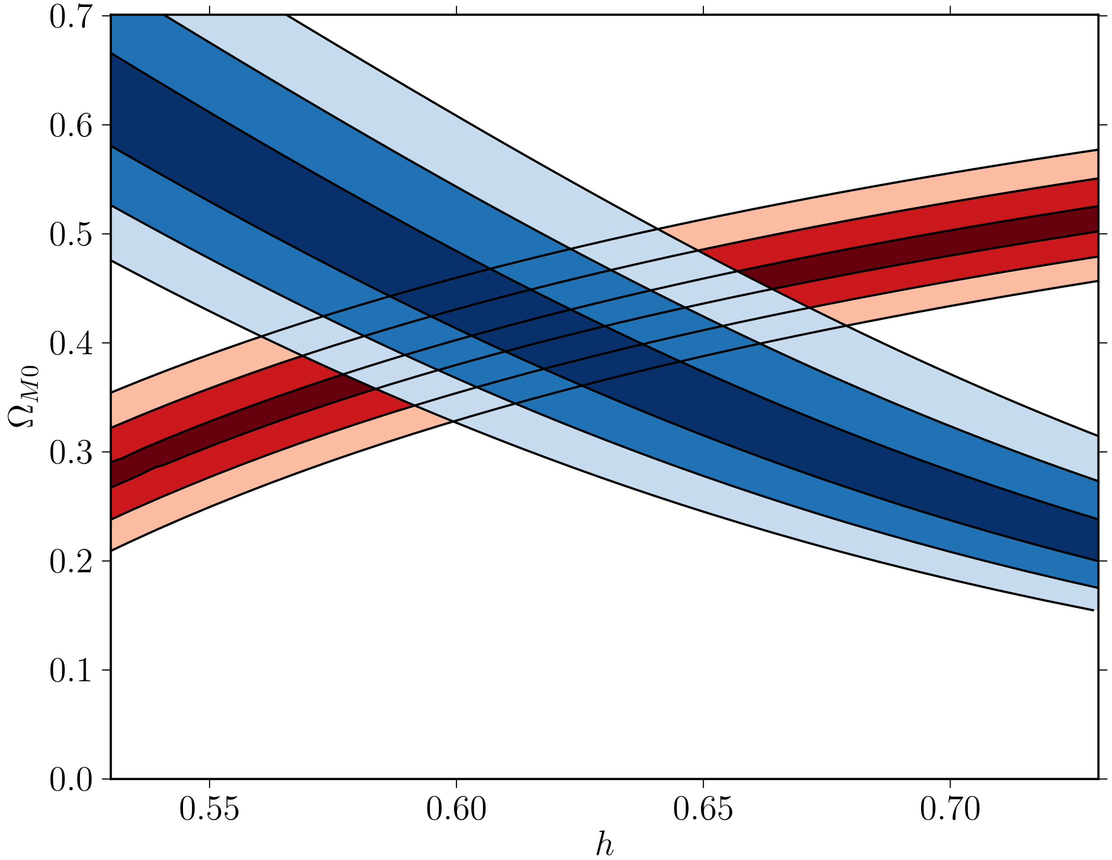
Smale + DLW, MNRAS 413 (2011) 367

- SALT/SALTII fits (Constitution,SALT2,Union2) favour ΛCDM over TS: $\ln B_{\mathrm{TS:\Lambda CDM}} = -1.06, -1.55, -3.46$
- MLCS2k2 (fits MLCS17,MLCS31,SDSS-II) favour TS over ΛCDM: $\ln B_{\mathrm{TS:\Lambda CDM}} = 1.37, 1.55, 0.53$
- Different MLCS fitters give different best-fit parameters; e.g. with cut at statistical homogeneity scale, for MLCS31 (Hicken et al 2009) $\Omega_{M0} = 0.12^{+0.12}_{-0.11}$;
MLCS17 (Hicken et al 2009) $\Omega_{M0} = 0.19^{+0.14}_{-0.18}$;
SDSS-II (Kessler et al 2009) $\Omega_{M0} = 0.42^{+0.10}_{-0.10}$
- Supernovae systematics (reddening/extinction, intrinsic colour variations) must be understood to distinguish models
- Inclusion of SneIa below $100\,h^{-1}$Mpc an important issue

Supernovae systematics



CMB: sound horizon + baryon drag



Parameters within the (Ω_{M0}, H_0) plane which fit the angular scale of the sound horizon $\theta_* = 0.0104139$ (blue), and its comoving scale at the baryon drag epoch as compared to Planck value $98.88\,h^{-1}$ Mpc (red) to within 2%, 4% and 6%, with photon-baryon ratio $\eta_{B\gamma} = 4.6$–5.6×10^{-10} within 2σ of all observed light element abundances (including lithium-7). J.A.G. Duley, M.A. Nazer + DLW, Class. Qu. Grav. **30** (2013) 175006

Planck constraints $D_A + r_{drag}$

- Dressed Hubble constant $H_0 = 61.7 \pm 3.0$ km/s/Mpc
- Bare Hubble constant $H_{\rm w0} = \bar{H}_0 = 50.1 \pm 1.7$ km/s/Mpc
- Local max Hubble constant $H_{\rm v0} = 75.2^{+2.0}_{-2.6}$ km/s/Mpc
- Present void fraction $f_{\rm v0} = 0.695^{+0.041}_{-0.051}$
- Bare matter density parameter $\bar{\Omega}_{M0} = 0.167^{+0.036}_{-0.037}$
- Dressed matter density parameter $\Omega_{M0} = 0.41^{+0.06}_{-0.05}$
- Dressed baryon density parameter $\Omega_{\rm B0} = 0.074^{+0.013}_{-0.011}$
- Nonbaryonic/baryonic matter ratio $\Omega_{C0}/\Omega_{\rm B0} = 4.6^{+2.5}_{-2.1}$
- Age of universe (galaxy/wall) $\tau_{\rm w0} = 14.2 \pm 0.5$ Gyr
- Age of universe (volume-average) $t_0 = 17.5 \pm 0.6$ Gyr
- Apparent acceleration onset $z_{\rm acc} = 0.46^{+0.26}_{-0.25}$

Baryon acoustic oscillations

- Commonly used measure $D_V = \left[\frac{zD^2}{H(z)}\right]^{1/3}$ gives results which differ very little between ΛCDM and timescape (both within uncertainty)
- Alcock–Paczyński test – which separates angular and radial scales – better discriminates timescape from ΛCDM [Phys. Rev. D80 (2009) 123512]
- BOSS arXiv:1404.1801 finds 2.5σ tension for ΛCDM in Ly-α forest measurement at $z = 2.34$.
- PRELIMINARY: Timescape with $f_{\rm v0} = 0.695$, $h = 0.617$, agrees with BOSS angle, and $H(2.24) = 223$ km/s/Mpc agrees with BOSS value 222 ± 7 km/s/Mpc (BUT should be off by H_0 ratio?)

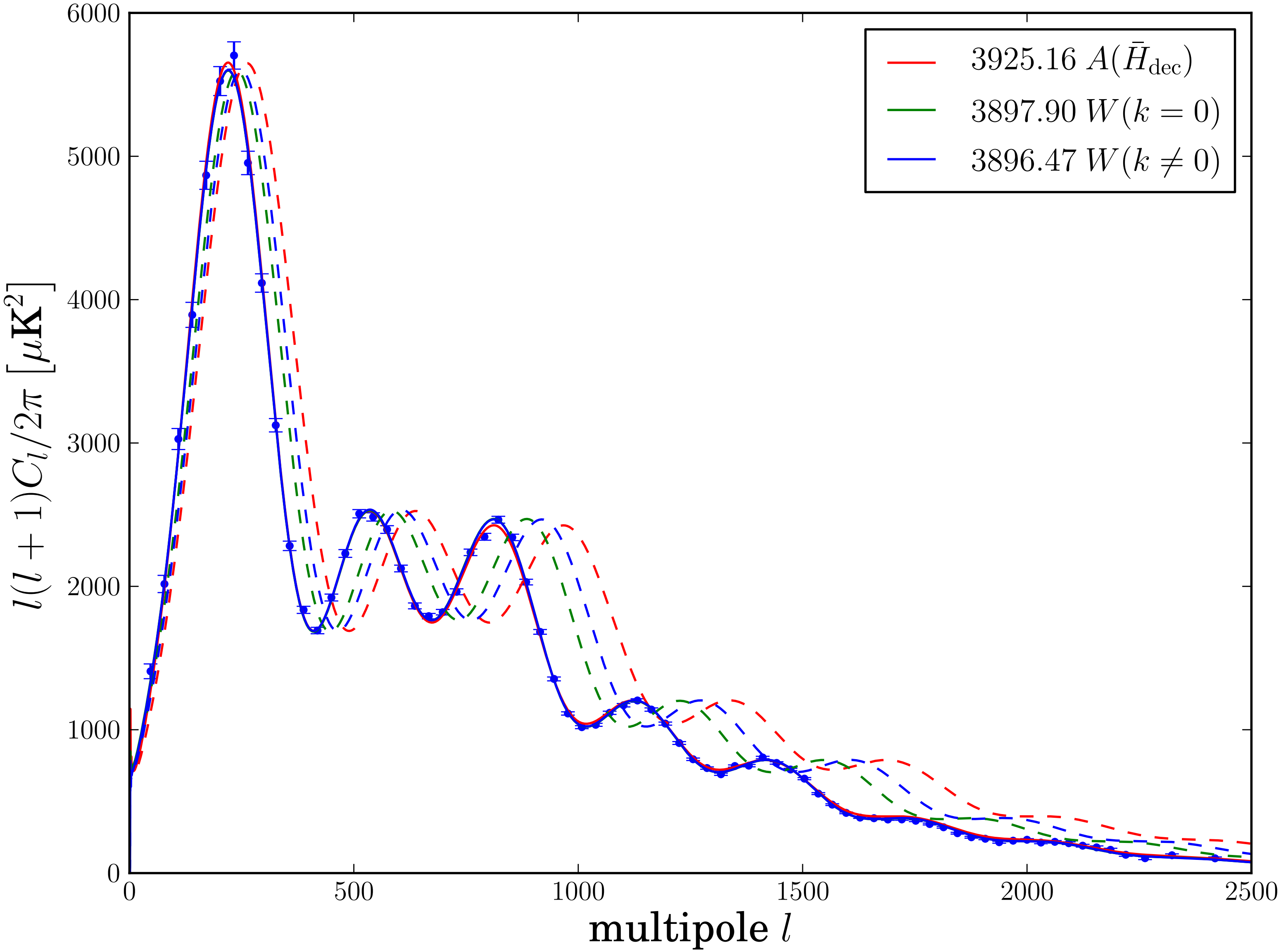
CMB acoustic peaks, full fit

- Use FLRW model prior to last scattering best matched to timescape equivalent parameters
- Use Vonlanthen, Räsänen, R. Durrer (2010) procedure to map timescape model d_A to FLRW reference d'_A

$$\begin{aligned} C_\ell &= \sum_{\tilde\ell} \frac{2\tilde\ell+1}{2} C'_{\tilde\ell} \int_0^\pi \sin\theta \, \mathrm{d}\theta \, P_{\tilde\ell}\left[\cos(\theta\, d_A/d'_A)\right] P_\ell(\cos\theta) \\ &\approx \left(\frac{d'_A}{d_A}\right)^2 C'_{\frac{d'_A}{d_A}\ell}\,, \qquad \ell > 50 \end{aligned}$$

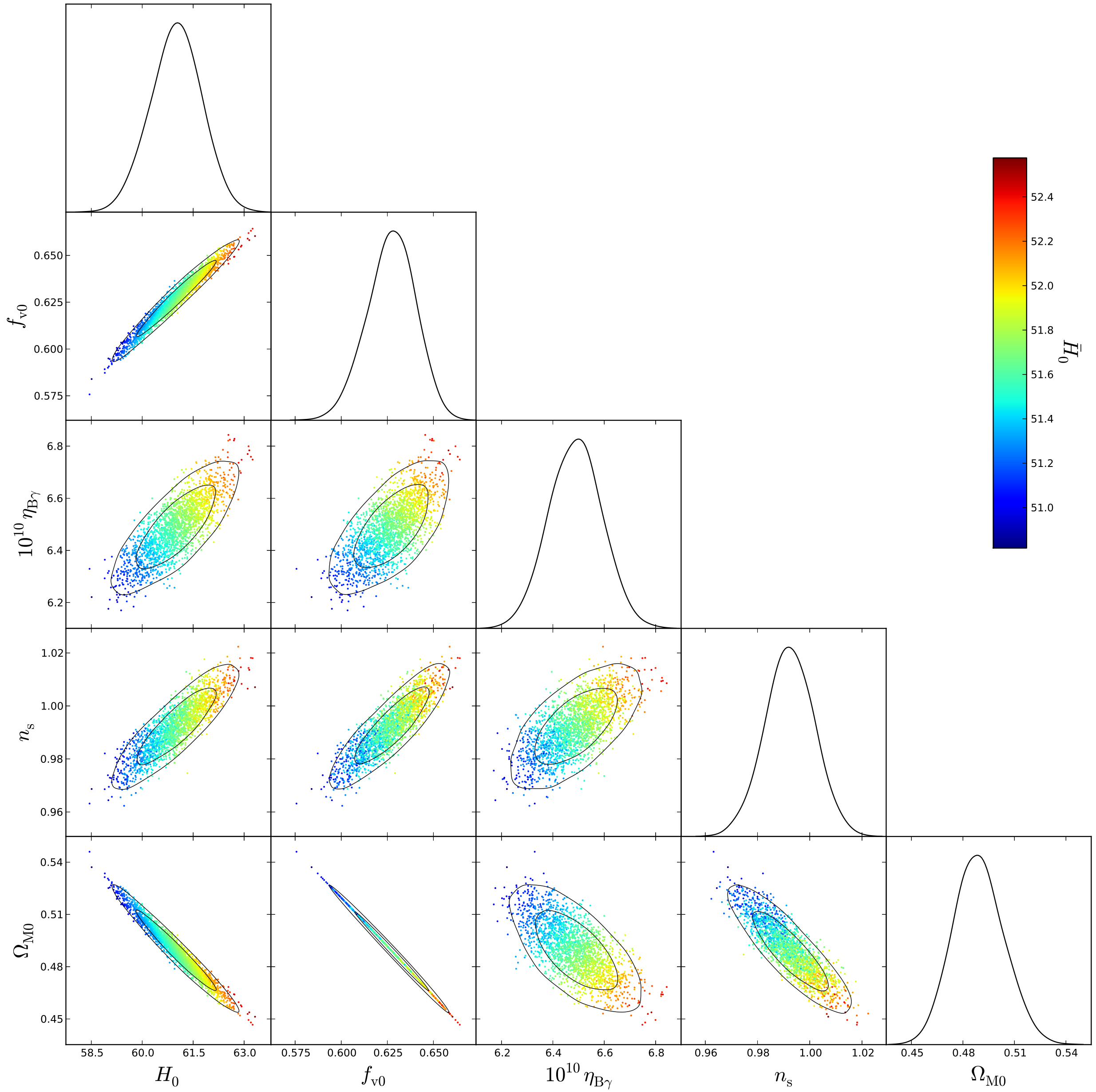
- Ignore $\ell < 50$ in fit (late ISW effect may well differ)
- Fit FLRW model that decelerates by same amount from last scattering til today (in volume-average time) – systematic uncertainties depending on method adopted

CMB acoustic peaks, full Planck fit



MCMC coding by M.A. Nazer, adapting *CLASS*

M.A. Nazer + DLW, arXiv:1410.3470



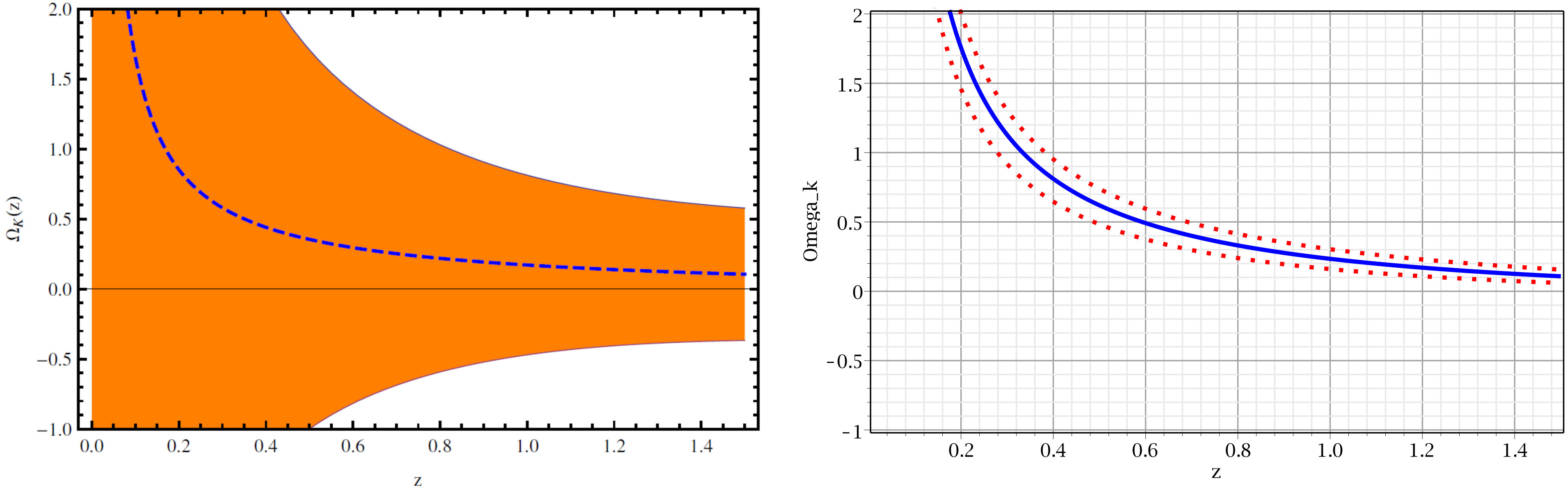
CMB acoustic peaks: arXiv:1410.3470

- $H_0 = 61.0$ km/s/Mpc (± 1.3% stat) (± 8% sys);
  $f_{\rm v0} = 0.627$ (± 2.33% stat) (± 13% sys).
- Previous D_A + r_{drag} constraints give concordance for baryon–to–photon ratio $10^{10}\eta_{B\gamma} = 5.1 \pm 0.5$ with no primordial ^{7}Li anomaly, $\Omega_{C0}/\Omega_{\rm B0}$ possibly 30% lower.
- Full fit – driven by 2nd/3rd peak heights, $\Omega_{C0}/\Omega_{\rm B0}$, ratio – gives $10^{10}\eta_{B\gamma} = 6.08$ (± 1.5% stat) (± 8.5% sys).
- With bestfit values, primordial ^{7}Li anomalous and BOSS $z = 2.34$ result in tension at level similar to ΛCDM
- BUT backreaction in primordial plasma neglected
- Backreaction of similar order to density perturbations (10^{-5}); little influence on background but may influence growth of perturbations

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

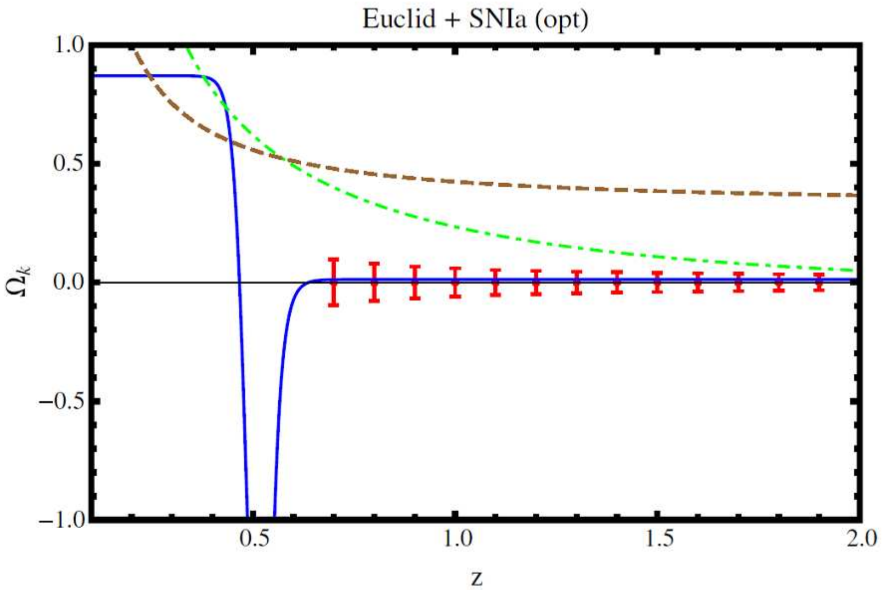
$$\Omega_{k0} = \Omega_k(z) = \frac{[c^{-1}H(z)D'(z)]^2 - 1}{[c^{-1}H_0 D(z)]^2}$$



Left panel: CBL statistic from Sapone, Majerotto and Nesseris, arXiv:1402.2236v1 Fig 8, using existing data from SneIa (Union2) and passively evolving galaxies for $H(z)$.

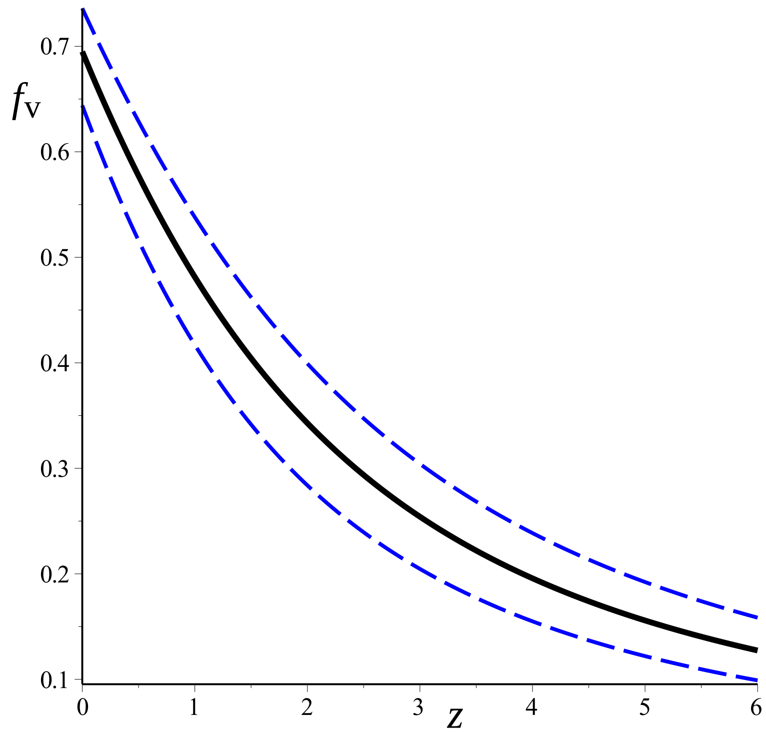
Right panel: TS prediction, with $f_{v0} = 0.695^{+0.041}_{-0.051}$.

Clarkson Bassett Lu test with *Euclid*



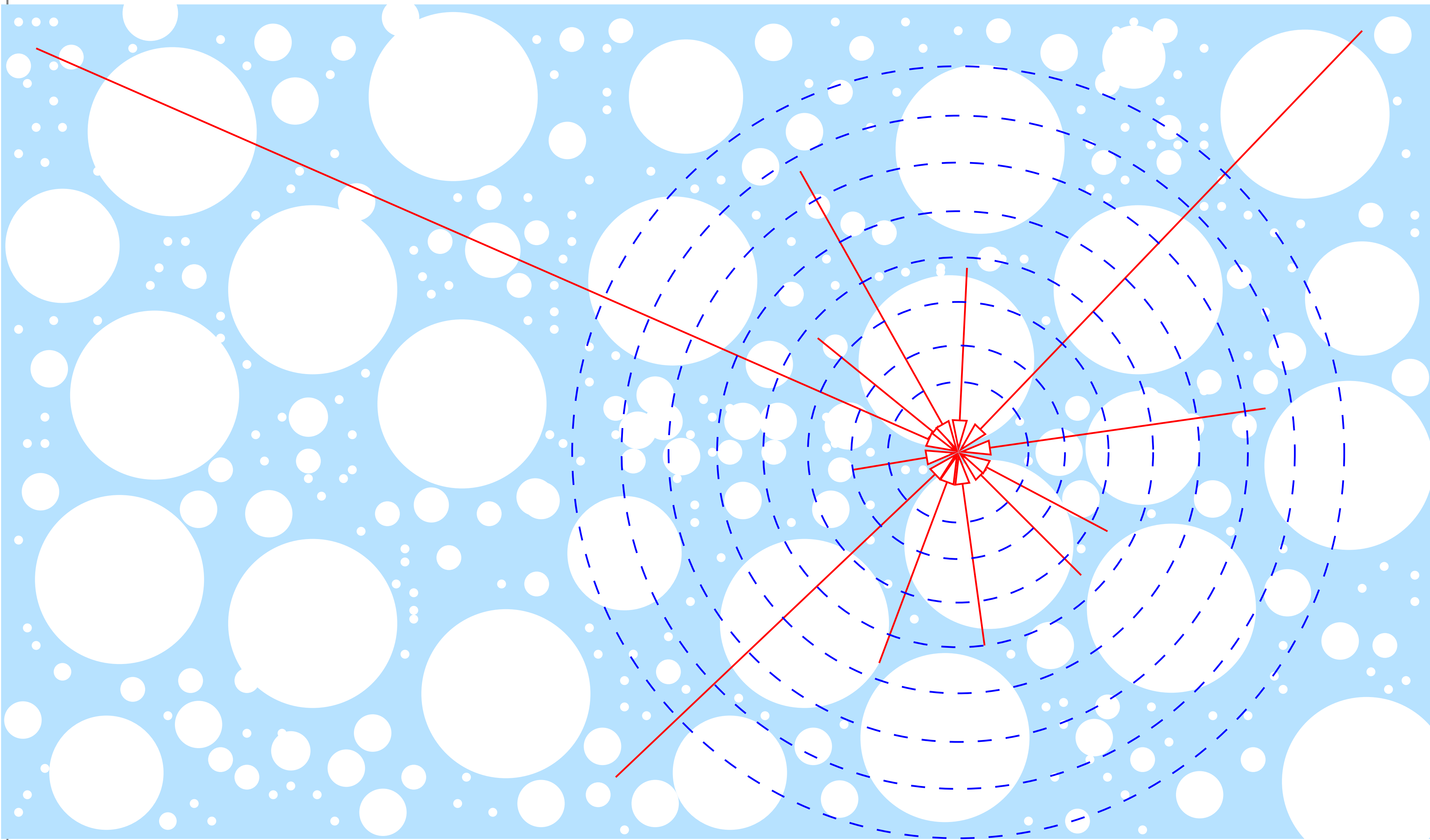
- Projected uncertainties for ΛCDM model with *Euclid* $+$ 1000 SneIa, Sapone *et al*, arXiv:1402.2236v2 Fig 10
- Timescape prediction (green), compared to non-Copernican Gpc void model (blue), and *tardis* cosmology, Lavinto *et al* arXiv:1308.6731 (brown).
- Timescape prediction becomes greater than uncertainties for $z \lesssim 1.5$. (Falsfiable.)

Void fraction: potential test?



- Growth of structure difficult to parameterize as effective FLRW model, as not based on this geometry
- Bound system measures below finite infinity likely to be close to standard GR (Einstein-de Sitter) prediction
- Void volume fraction $f_\mathrm{v}(z)$ itself provides a measurable constraint. Ly–α tomography at high z may help.

Apparent Hubble expansion variance



Peculiar velocity formalism

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

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

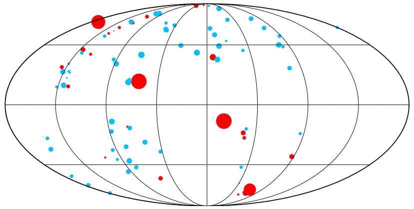
  generated by

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

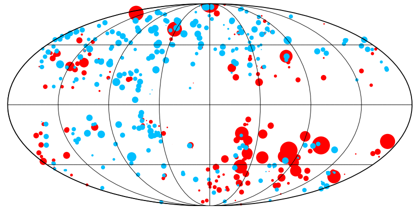
- After 3 decades of work, despite contradictory claims, the $\mathbf{v}(\mathbf{r})$ does not to converge to LG velocity w.r.t. CMB
- Agreement on direction, not amplitude or scale (Lavaux et al 2010; Bilicki et al 2011; Nusser & Davis 2011 . . .); debate about consistency of bulk flows and ΛCDM

Analysis of COMPOSITE sample

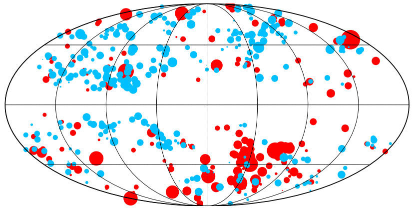
- Use COMPOSITE sample: Watkins, Feldman & Hudson 2009, 2010, with 4,534 galaxy redshifts and distances, includes most large surveys to 2009
- Distance methods: Tully Fisher, fundamental plane, surface brightness fluctuation; 103 SneIa distances.
- Average $d/(cz)$ in *independent spherical shells*
- Model independent – no large scale Euclidean geometry assumed
- Compute H_s in $12.5\,h^{-1}$Mpc shells; combine 3 shells $> 112.5\,h^{-1}$Mpc
- Use data beyond $156.25\,h^{-1}$Mpc as check on H_0 normalization – COMPOSITE sample is normalized to $100\,h$ km/s/Mpc



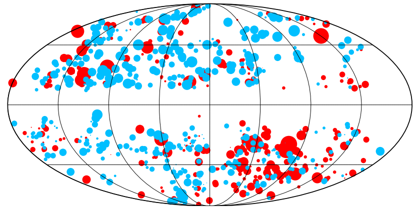
(a) 1: $0 - 12.5\ h^{-1}$ Mpc $N = 92$.



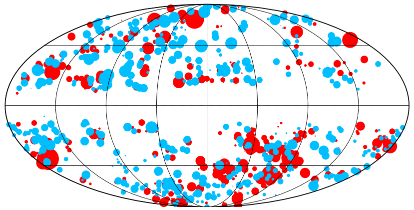
(b) 2: $12.5 - 25\ h^{-1}$ Mpc $N = 505$.



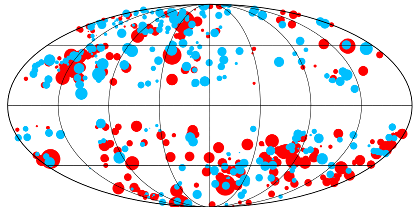
(c) 3: $25 - 37.5\ h^{-1}$ Mpc $N = 514$.



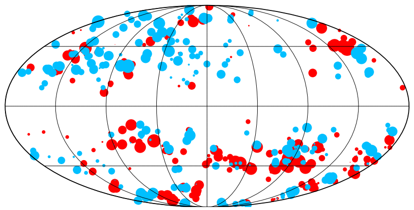
(d) 4: $37.5 - 50\ h^{-1}$ Mpc $N = 731$.



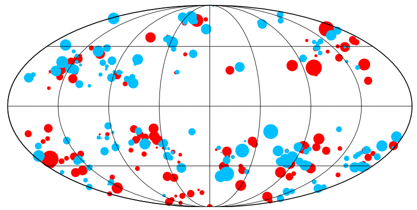
(e) 5: $50 - 62.5\ h^{-1}$ Mpc $N = 819$.



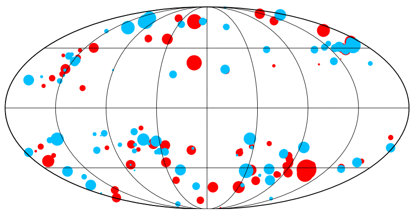
(f) 6: $62.5 - 75\ h^{-1}$ Mpc $N = 562$.



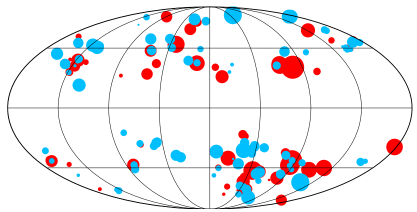
(g) 7: $75 - 87.5\ h^{-1}$ Mpc $N = 414$.



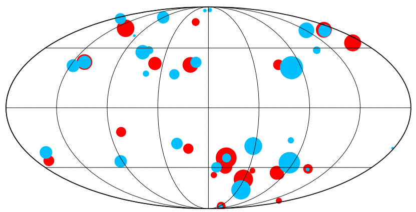
(h) 8: $87.5 - 100\ h^{-1}$ Mpc $N = 304$.



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

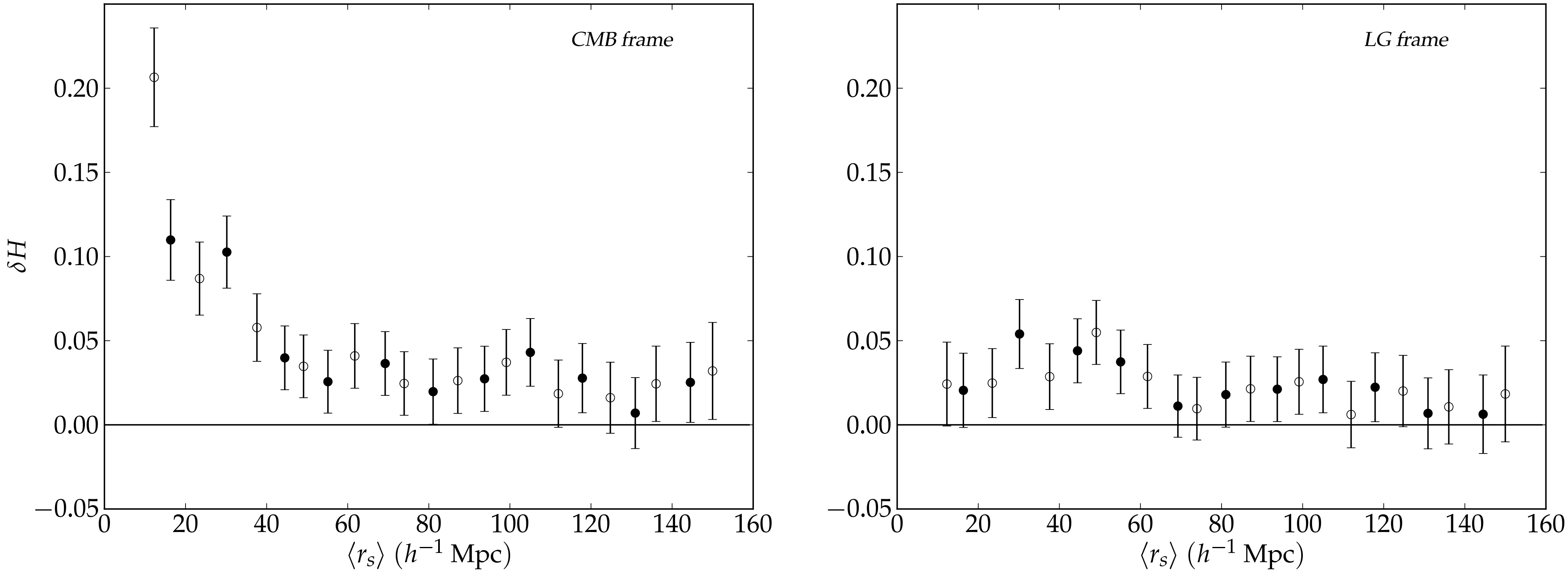


(j) 10: $112.5 - 156.25\ h^{-1}$ Mpc $N = 280$.



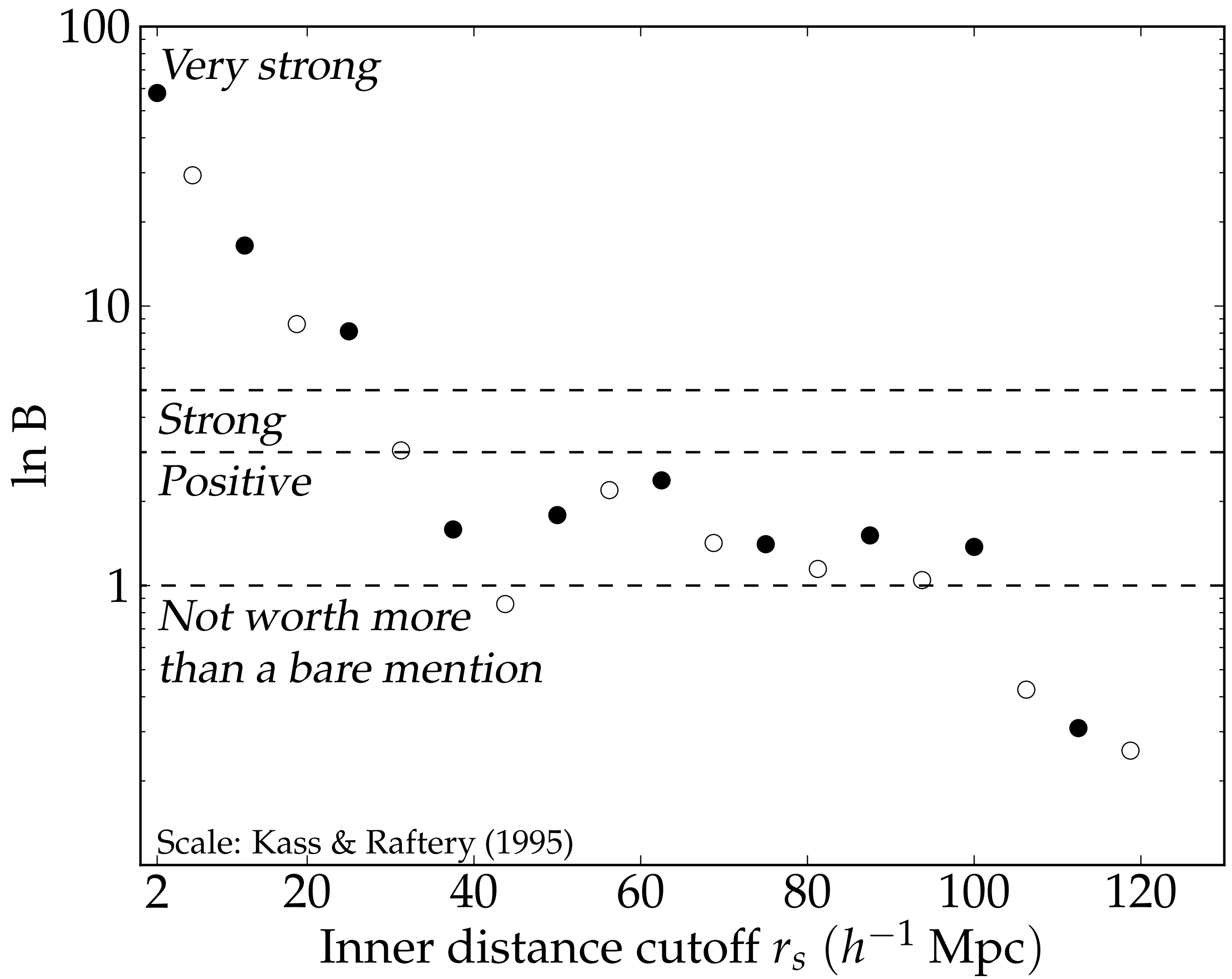
(k) 11: $156.25 - 417.4\ h^{-1}$ Mpc $N = 91$.

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



- Plot fractional difference relative to asymptotic H_0
- Two choices of shell boundaries (closed and open circles); for each choice data points uncorrelated
- Analyse linear Hubble relation in rest frame of CMB; Local Group (LG); Local Sheet (LS). LS result very close to LG result.

Bayesian comparison of uniformity



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

Boosts and spurious monopole variance

- H_s determined by linear regression in each shell

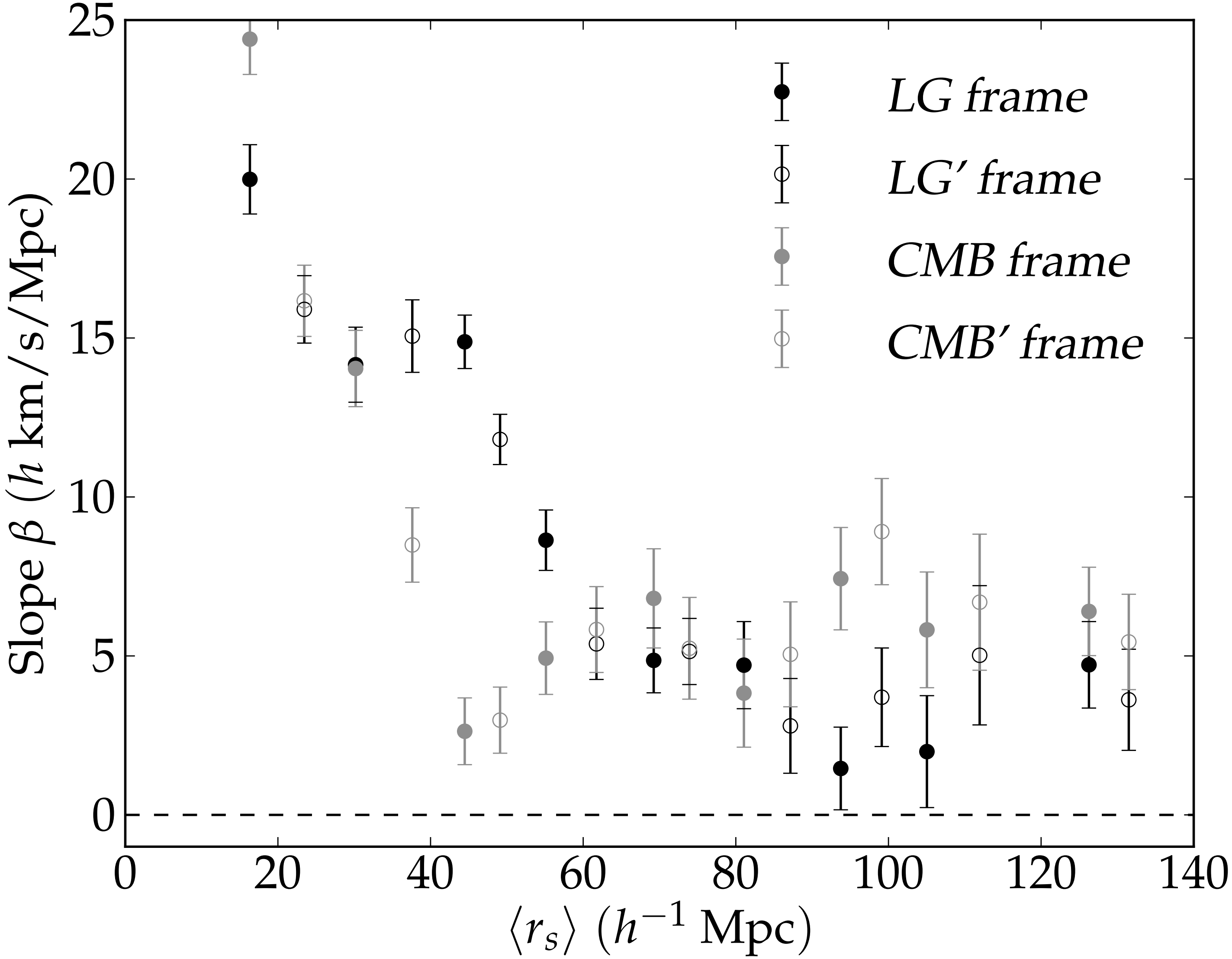
$$H_s = \left(\sum_{i=1}^{N_s} \frac{(cz_i)^2}{\sigma_i^2}\right)\left(\sum_{i=1}^{N_s} \frac{cz_i r_i}{\sigma_i^2}\right)^{-1},$$

- Under boost $cz_i \to cz_i' = cz_i + v\cos\phi_i$ for uniformly distributed data, opposing linear terms cancel

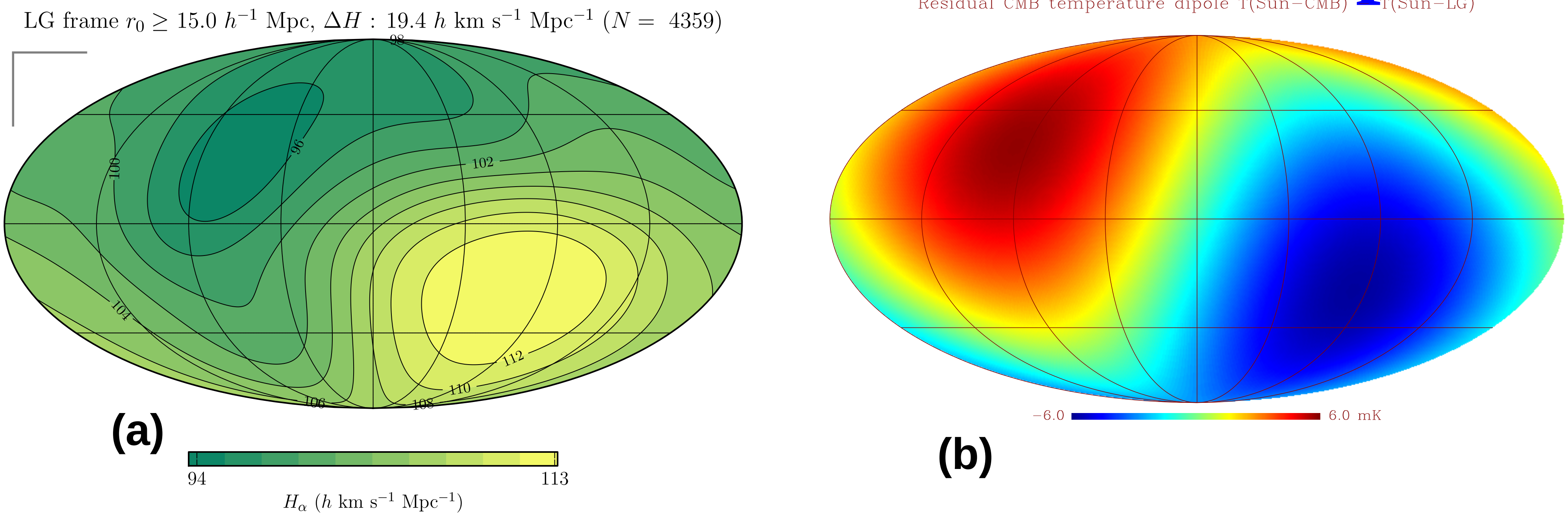
$$\begin{aligned} H_s' - H_s &\sim \left(\sum_{i=1}^{N_s} \frac{(v\cos\phi_i)^2}{\sigma_i^2}\right)\left(\sum_{i=1}^{N_s} \frac{cz_i r_i}{\sigma_i^2}\right)^{-1} \\ &= \frac{\langle (v\cos\phi_i)^2\rangle}{\langle cz_i r_i\rangle} \sim \frac{v^2}{2H_0\langle r_i^2\rangle} \end{aligned}$$

- Fitting a power law, $\Delta H_s = aY^b$, $Y \equiv <r_i^2>_s$ gives a value of $b = -1.0 \pm 0.2$ for CMB relative to LG frame

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



Correlation with residual CMB dipole



- Angular averaged Hubble flow vs LG frame CMB dipole

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

- $\rho_{HT} = -0.92$, (almost unchanged for $15^\circ < \sigma_\vartheta < 40^\circ$)
- Alternatively, t-test on raw data: null hypothesis that maps uncorrelated is rejected at 24.4σ.

Redshift-distance anisotropy

- **Proposal**: rather than originating in a boost the ± 5.77 mK LG frame dipole is due to a small anisotropy in the distance-redshift relation on scales $\lesssim 65\,h^{-1}$Mpc.
- 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
- For spatially flat ΛCDM with $\Omega_{M0} = 0.30$, 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 foreground structures within $65\,h^{-1}$Mpc then $\pm 0.35\,h^{-1}$Mpc represents a ± 0.5% effect
- I.e., no local bulk flow to Shapley concentration at $\gtrsim 138\,h^{-1}$Mpc > Scale of Statistical Homogeneity.

Why strong dipole / small quadrupole?

- Ray tracing studies in progress with K. Bolejko
- Alnes and Amarzguioui (2006) results give correct order of magnitude estimate, equivalent "peculiar velocity"

$$\frac{v_p}{c} = \frac{(h_{\rm in} - h_{\rm out})d_{\rm off}}{2998\,\text{Mpc}}$$

- Using observed $h_{\rm in} - h_{\rm out} = \beta h = (15.1 \pm 1.0)\,h$, $v_p = 635\,\text{km}\,\text{s}^{-1}$, we have $d_{\rm off} = (42 \pm 3)\,h^{-1}$Mpc: consistent.
- Quadrupole/dipole ratio

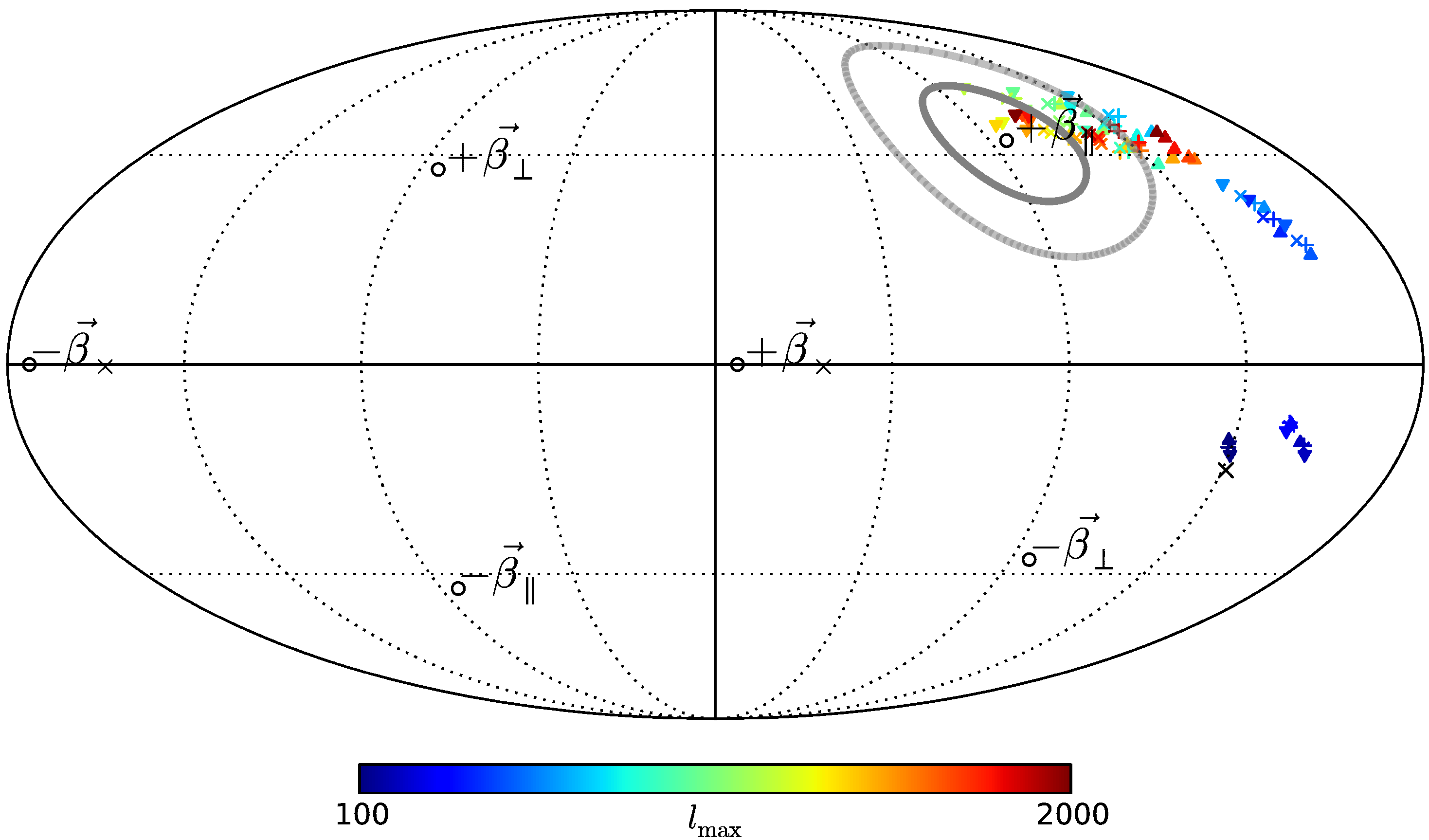
$$a_{20}/a_{10} = \sqrt{\tfrac{4}{15}}(h_{\rm in} - h_{\rm out})d_{\rm off}/\,(2998\,\text{Mpc})$$

- For above values $a_{20}/a_{10} = 0.001$ (i.e., 0.1%).
- Actual ray-tracing in Szekeres models $\lesssim 1$%.

Local / global H_0

- 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 fit of O(z^3) spatially flat FLRW luminosity distance to SneIa in range $0.23 < z < 0.1$, *assuming* $q_0 = -0.55$, $j_0 = 1$.
- 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 simulations through nonlinear foreground voids, using exact solutions of Einstein's equations matched asymptotically to a Planck-fit ΛCDM model show local/global H_0 potentially resolved. (K. Bolejko, M.A. Nazer, R. Watkins + DLW, in preparation)

Planck Doppler boosting 1303.5087



- Dipole direction consistent with CMB dipole $(\ell, b) = (263.99, 48.26^\circ)$ for small angle multipoles, $\ell_{\max} \sim 2000$
- When $\ell_{\max} \to 100$ shifts to WMAP power asymmetry modulation dipole $(\ell, b) = (224^\circ, -22^\circ) \pm 24^\circ$

Questions, consequences...

- Evidence for Doppler boosting of CMB sky seen at small angles in Planck data, but changes significantly when large angle multipoles included: arXiv:1303.5087
- Strong evidence for a non-kinematic dipole in radio galaxy data: Rubart and Schwarz, arXiv:1301.5559
- Clearly a significant non-kinematic component to the CMB dipole will impact large angle anomalies
- We find "Hubble bubble" (of reduced amplitude in LG frame) *independently* of SneIa
- SneIa Hubble bubble with MLCS if reddening by dust parameter $R_V = 3.1$ (Milky way value); not if $R_V = 1.7$
- Study independent of SneIa in 15 nearby galaxies gives $R_V = 2.77 \pm 0.41$ (Finkelman et al 2010, 2011)

Next steps: Modified Geometry

- Acoustic 2nd/3rd peak ratio – driven by ratio of CDM to baryonic matter before decoupling – forces $\eta_{B\gamma}$ to ΛCDM value even for timescape
- Timescape may now have parameter tension
- Backreaction in primordial plasma must be addressed; No detailed study yet as perturbative studies focus on backreaction on background in matter dominated epoch
- Need to characterize statistical geometry, quasilocal kinetic energy, binding energy
- Shape Dynamics (Gomes, Gryb and Koslowski 2011, 2012,...) – a CMC (Constant Mean extrinsic Curvature) formulation of gravity with 3d conformal invariance – might be adapted for statistical geometry, and early universe backreaction

Conclusion

- Apparent cosmic acceleration can be understood by
  - treating geometry of universe more realistically
  - understanding fundamental aspects of general relativity which have not been fully explored – *quasi–local gravitational energy*, of *gradients* in kinetic energy of expansion etc.
- "Timescape" model gives good fit to major independent tests of ΛCDM with new perspectives on many puzzles – e.g., local/global differences in H_0; primordial ^{7}Li ?
- Many tests can be done to distinguish from ΛCDM. Must be careful not to assume Friedmann equation in any data reduction.
- "Modified Geometry" rather than "Modified Gravity"