



# What is “dark energy”?

- Usual explanation: a homogeneous isotropic form of “stuff” which violates the strong energy condition.  
(Locally pressure  $P = w\rho c^2$ ,  $w < -\frac{1}{3}$ .)  
Best-fit close to cosmological constant,  $\Lambda$ ,  $w = -1$ .
- *Cosmic coincidence*: Why now? Why  $\Omega_{\Lambda 0} \sim 2\Omega_{M 0}$ , so that a universe which has been decelerating for much of its history began accelerating only at  $z \sim 0.7$ ?
- Onset of acceleration coincides also with the nonlinear growth of large structures
- Are we oversimplifying the geometry?
- Hypothesis: must understand nonlinear evolution with backreaction, AND gravitational energy gradients within the inhomogeneous geometry

# 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 is very lumpy or inhomogeneous today.
- Recent surveys estimate that 40–50% of the volume of the universe is contained in voids of diameter  $30h^{-1}$  Mpc. [Hubble constant  $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ ] (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.

# The Sandage-de Vaucouleurs paradox...

- Matter homogeneity only observed at  $\gtrsim 200$  Mpc scales
- If “the coins on the balloon” are galaxies, their peculiar velocities should show great statistical scatter on scale much smaller than  $\sim 200$  Mpc
- However, a nearly linear Hubble law flow begins at scales above 1.5–2 Mpc from barycentre of local group.
- Moreover, the local flow is statistically “quiet”; despite a possible 100–200 Mpc Hubble bubble feature.
- Peculiar velocities are isotropized in FLRW universes which expand forever (regardless of dark energy); but attempts to explain the paradox not a good fit to  $\Lambda$ CDM parameters (Axenides & Perivolaropoulos 2002).



# Approach 1: Exact solutions

- Much work has been done on spherically symmetric dust Lemaitre–Tolman–Bondi models (Célérier 2000, Tomita 2001, . . . MANY researchers. . .)
- Violates Copernican principle.
- With 2 free functions can fit any luminosity distance relation, at cost of introducing very large voids or humps
- Distinguishable from  $\Lambda$ CDM, e.g., inhomogeneity test function (Clarkson, Bassett & Lu 2008), cosmic shear (Garcia-Bellido & Haugboelle 2008), . . .
- Unlikely symmetry for whole universe; difficult to reconcile with initial conditions at last scattering and structure formation
- Cut-and-paste exact solutions – *Swiss cheese* – invariably retain FLRW evolution at some level

# Approach 2: Weak backreaction

- Much argument about backreaction from perturbation theory near a FLRW background (e.g., Kolb *et al.* 2006)
- Debate is largely about mathematical consistency, and conclusions vary with assumptions made
- Debate shows a potential problem – perturbation theory does not converge – and if backreaction changes the background, then any FLRW model may simply be the wrong background at present epoch
- Noh, Jeong & Hwang [PRL 103, 021301 (2009)] find the pure Einstein gravity contribution appearing in the 3rd order perturbation leads to an infrared divergence

# Approach 3: Strong backreaction

- Nonlinear averaging of full inhomogeneous Einstein equations leads to modified evolution equations
- Many approaches, with different assumptions; generally  $\bar{G}_{\mu\nu}(\mathbf{g}_{\alpha\beta}) \neq G_{\mu\nu}(\bar{\mathbf{g}}_{\alpha\beta})$ ; and  $\rho_{\text{cr}} \neq 3H_{\text{av}}^2 / (8\pi G)$
- Do we average tensors on curves of observers? (Zalaletdinov 1992, 1993) ... (Also studied by Coley, Pelavas, van den Hoogen, Paranjape, Singh...)
- Can we get away with averaging scalars (density, pressure, shear...)? (Buchert 2000, 2001) ... (MANY papers, e.g. Buchert, Carfora, Räsänen, Schwarz ...)
- Other new and interesting approaches (e.g., Larena 2009; Brown, Behrend & Malik 2009; Korzynski, 2009)
- Interpretation of observations is an additional problem. I address this using Buchert formalism...



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

For irrotational dust cosmologies, with energy density,  $\rho(t, \mathbf{x})$ , expansion,  $\theta(t, \mathbf{x})$ , and shear,  $\sigma(t, \mathbf{x})$ , on a compact domain,  $\mathcal{D}$ , of a suitably defined spatial hypersurface of constant average time,  $t$ , and spatial 3-metric, average cosmic evolution described by exact equations

$$3 \frac{\dot{a}^2}{\bar{a}^2} = 8\pi G \langle \rho \rangle - \frac{1}{2} \langle \mathcal{R} \rangle - \frac{1}{2} \mathcal{Q}$$

$$3 \frac{\ddot{\bar{a}}}{\bar{a}} = -4\pi G \langle \rho \rangle + \mathcal{Q}$$

$$\partial_t \langle \rho \rangle + 3 \frac{\dot{\bar{a}}}{\bar{a}} \langle \rho \rangle = 0$$

$$\partial_t (\bar{a}^6 \mathcal{Q}) + \bar{a}^4 \partial_t (\bar{a}^2 \langle \mathcal{R} \rangle) = 0.$$

$$\mathcal{Q} \equiv \frac{2}{3} (\langle \theta^2 \rangle - \langle \theta \rangle^2) - 2 \langle \sigma^2 \rangle$$

# Back-reaction

Angle brackets denote the spatial volume average, e.g.,

$$\langle \mathcal{R} \rangle \equiv \left( \int_{\mathcal{D}} d^3x \sqrt{\det^3 g} \mathcal{R}(t, \mathbf{x}) \right) / \mathcal{V}(t)$$

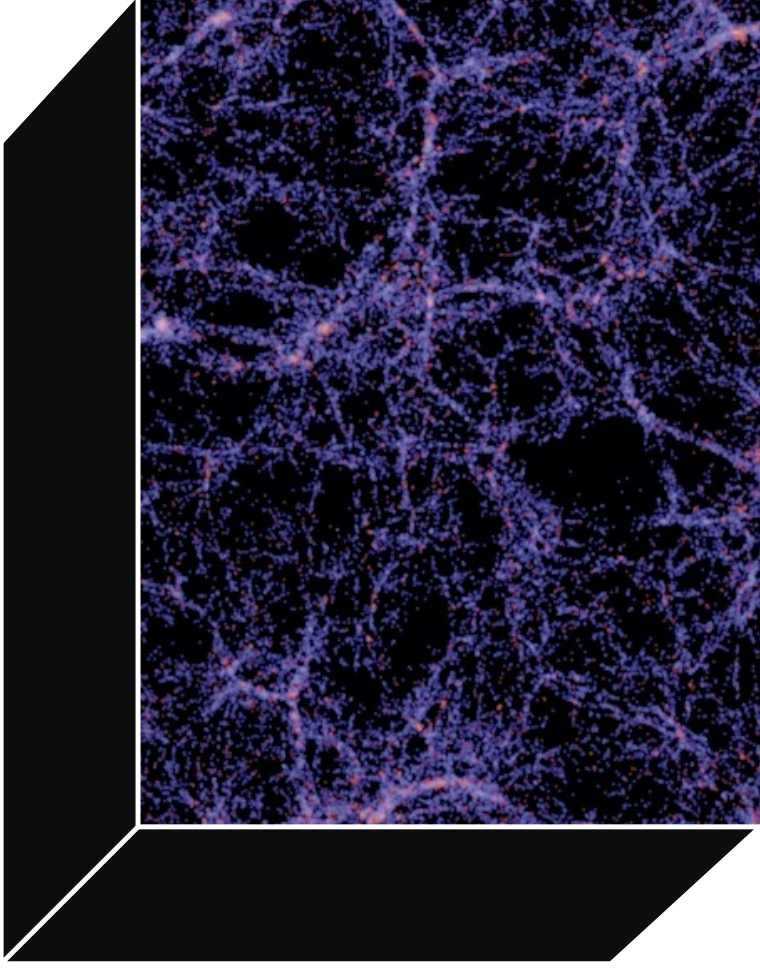
$$\langle \theta \rangle = 3 \frac{\dot{a}}{a}$$

Generally for any scalar  $\Psi$ ,

$$\frac{d}{dt} \langle \Psi \rangle - \left\langle \frac{d\Psi}{dt} \right\rangle = \langle \Psi \theta \rangle - \langle \theta \rangle \langle \Psi \rangle$$

- 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).

# 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 rods and 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) can differ significantly from volume-average environment (void)

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

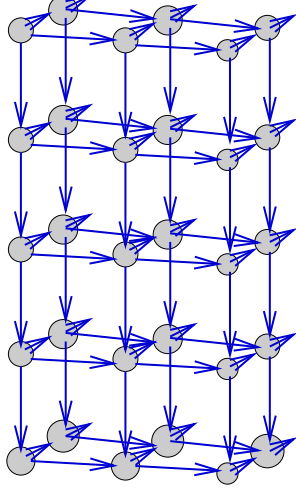
# Cosmological Equivalence Principle

- *At any event, always and everywhere, it is possible to choose a suitably defined spacetime neighbourhood, the cosmological inertial frame, in which average motions (timelike and null) can be described by geodesics in a geometry which is Minkowski up to some time-dependent conformal transformation,*

$$ds_{\text{CIF}}^2 = a^2(\eta) [-d\eta^2 + dr^2 + r^2 d\Omega^2],$$

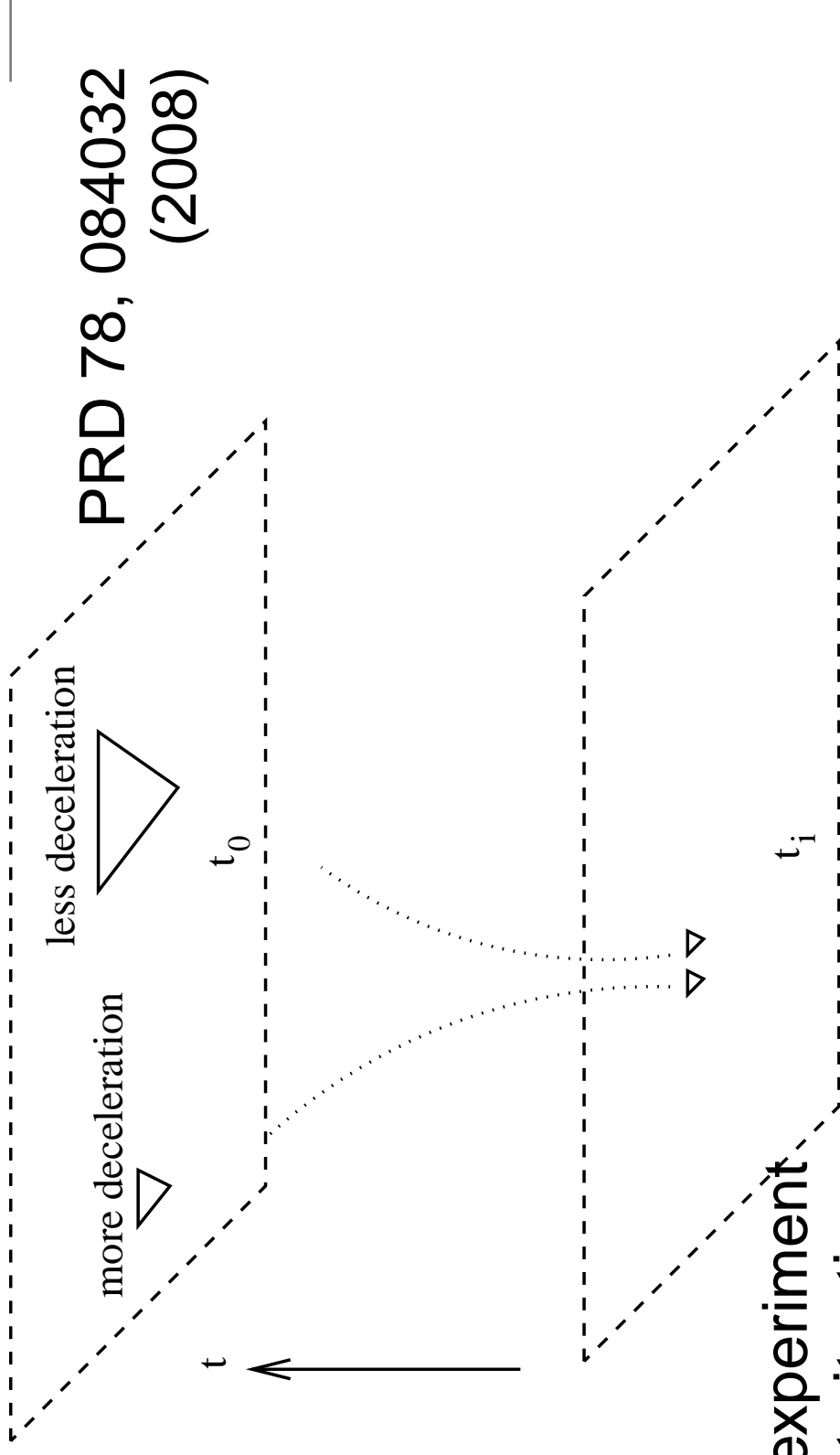
- **Defines Cosmological Inertial Frame (CIF)**
- **Accounts for regional average effect of density in terms of frames for which the state of rest in an expanding space is indistinguishable from decelerating expansion of particles moving in a static space**

# Semi-tethered lattice



- Extend to decelerating motion over long time intervals by Minkowski space analogue (semi-tethered lattice - indefinitely long tethers with one end fixed, one free end on spool, apply brakes synchronously at each site)
- Brakes convert kinetic energy of expansion to heat and so to other forms
- Brake impulse can be arbitrary pre-determined function of local proper time; but provided it is synchronous deceleration remains homogeneous and isotropic: *no net force on any lattice observer.*
- Deceleration preserves inertia, by symmetry

# Cosmological Equivalence Principle

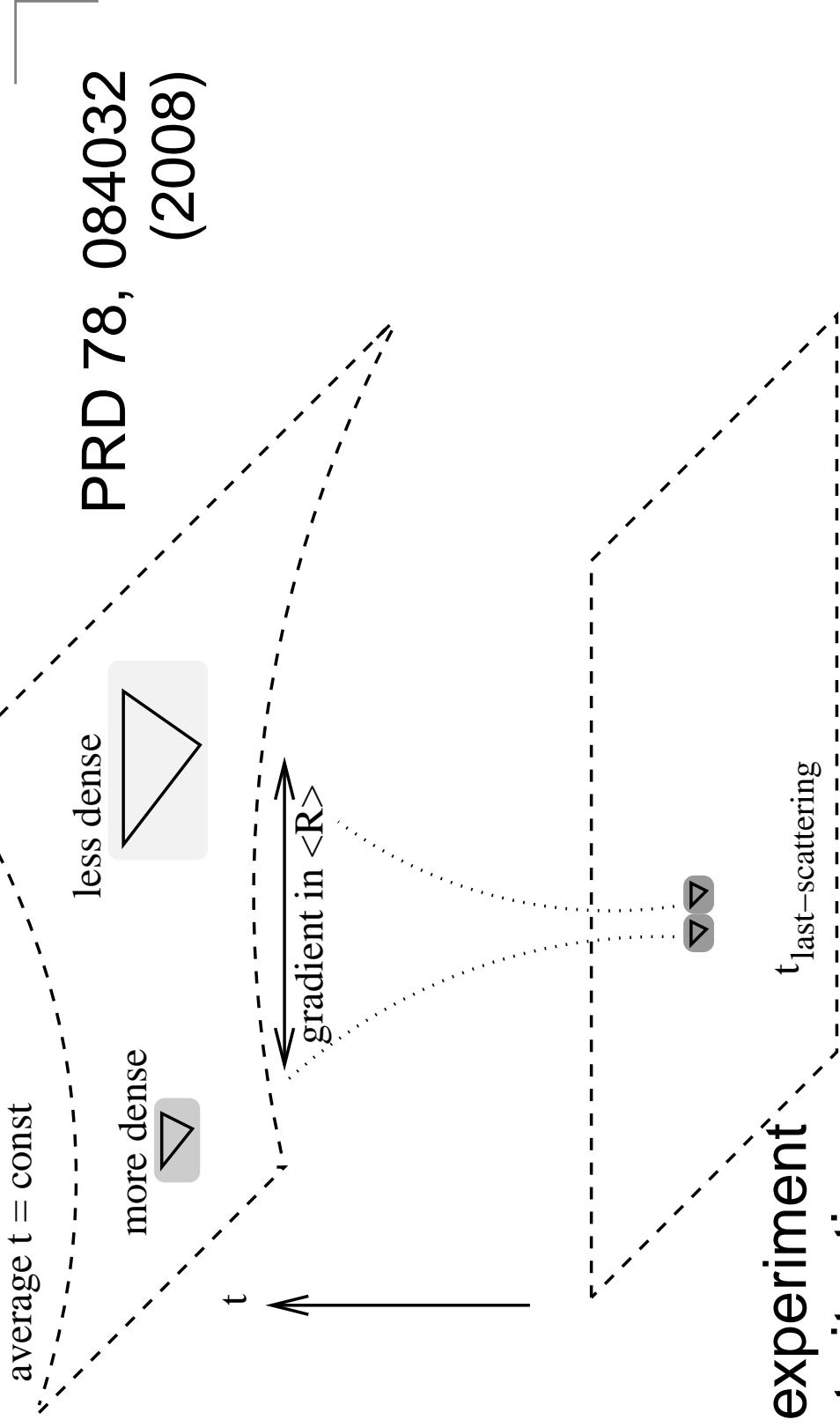


Thought experiment:  
equivalent situations:

- SR: observers in disjoint regional semi-tethered lattices volume decelerate at different rates
- Those who decelerate more age less



# Cosmological Equivalence Principle



Thought experiment equivalent situations:

- GR: regions of different density have different volume deceleration (for same initial conditions)
- Those in denser region age less

# Cosmic rest frame

- Patch together CIFs for observers who see an isotropic CMB by taking surfaces of uniform volume expansion

$$\left\langle \frac{1}{\ell_r(\tau)} \frac{d\ell_r(\tau)}{d\tau} \right\rangle = \frac{1}{3} \langle \theta \rangle_1 = \frac{1}{3} \langle \theta \rangle_2 = \dots = \bar{H}(\tau)$$

- Average over regions in which (i) spatial curvature is zero or negative; (ii) space is expanding at the boundaries, at least marginally.
- Solves the Sandage–de Vaucouleurs paradox implicitly.
- Voids appear to expand faster; but their local clocks tick faster, locally measured expansion can still be uniform.
- Global average  $H_{\text{av}}$  on large scales with respect to *any* one set of clocks will differ from  $\bar{H}$

# Two/three scale ‘timescape’ model

$$\bar{a}^3 = f_{\text{wi}} a_{\text{w}}^3 + f_{\text{vi}} a_{\text{v}}^3 \equiv \bar{a}^3 (f_{\text{w}} + f_{\text{v}})$$

- Split statistical volume average into *spatially flat walls* (containing galaxies),  $f_{\text{w}}$ , and negatively curved voids with fraction,  $f_{\text{v}} = 1 - f_{\text{w}}$ .
- Solve Buchert equations, and construct a spherically symmetric average geometry (LTB metric NOT LTB solution) by radial null cone average
- Volume-average Buchert cosmological parameters,  $\bar{\Omega}_M + \bar{\Omega}_k + \bar{\Omega}_Q = 1$ , defined w.r.t. coarse-grained 100/h Mpc cell with average (negative) spatial curvature
- Match to local spatially flat geometry within expanding wall regions by conformally matching radial null geodesics with uniform bare Hubble flow condition

# Dressed cosmological parameters

- Conventional parameters for “wall observers” in galaxies: defined by assumption (no longer true) that others in entire observable universe have synchronous clocks and same local spatial curvature

$$\begin{aligned} ds_{\mathcal{F}_I}^2 &= -d\tau_w^2 + a_w^2(\tau_w) [d\eta_w^2 + \eta_w^2 d\Omega^2] \\ \rightarrow ds^2 &= -d\tau_w^2 + a^2 [d\bar{\eta}^2 + r_w^2(\bar{\eta}, \tau_w) d\Omega^2] \end{aligned}$$

where  $a \equiv \bar{a}/\bar{\gamma}_w$ ,  $r_w \equiv \bar{\gamma}_w (1 - f_v)^{1/3} f_{wi}^{-1/3} \eta_w(\bar{\eta}, \tau_w)$ , and volume-average conformal time  $d\bar{\eta} = dt/\bar{a} = \bar{\gamma}_w d\tau_w/\bar{a}$ .

- This leads to conventional dressed parameters which do not sum to 1, e.g.,

$$\Omega_M = \bar{\gamma}_w^3 \bar{\Omega}_M.$$

# Tracker solution PRL 99, 251101

- General exact solution possesses a “tracker limit”

$$\bar{a} = \frac{\bar{a}_0(3\bar{H}_0 t)^{2/3}}{2 + f_{v0}} \left[ 3f_{v0}\bar{H}_0 t + (1 - f_{v0})(2 + f_{v0}) \right]^{1/3}$$

$$f_v = \frac{3f_{v0}\bar{H}_0 t}{3f_{v0}\bar{H}_0 t + (1 - f_{v0})(2 + f_{v0})},$$

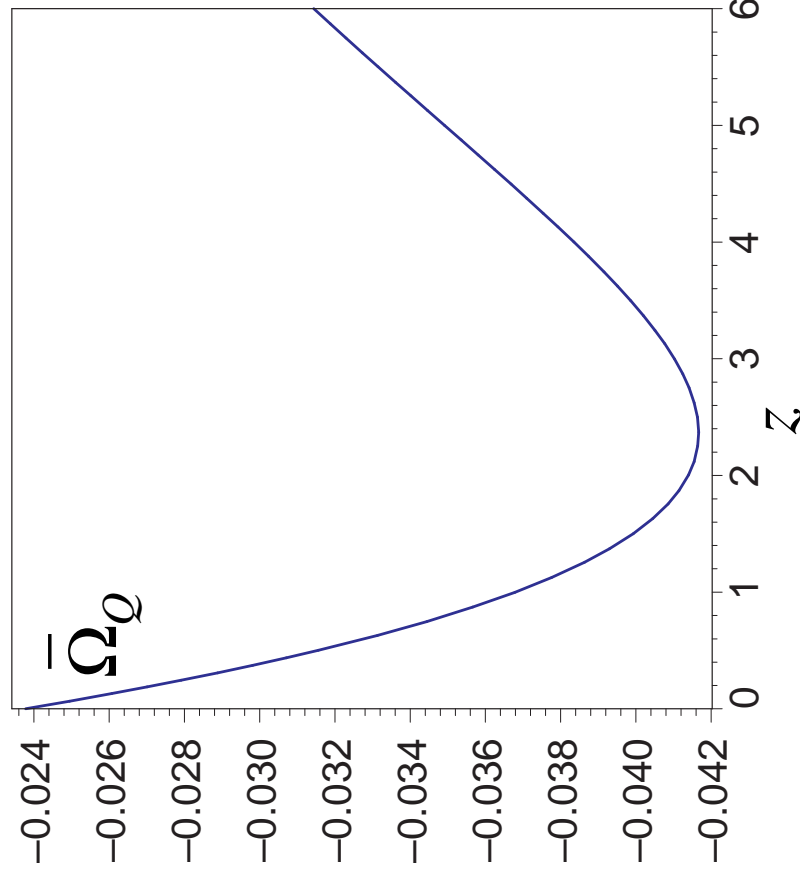
- Void fraction  $f_v(t)$  determines many parameters:

$$\bar{\gamma}_w = 1 + \frac{1}{2}f_v = \frac{3}{2}\bar{H}t$$

$$\tau_w = \frac{2}{3}t + \frac{2(1 - f_{v0})(2 + f_{v0})}{27f_{v0}\bar{H}_0} \ln \left( 1 + \frac{9f_{v0}\bar{H}_0 t}{2(1 - f_{v0})(2 + f_{v0})} \right)$$

$$H \equiv \frac{1}{a} \frac{da}{d\tau_w} = \bar{\gamma}_w \bar{H} - \dot{\bar{\gamma}}_w = \bar{\gamma}_w \bar{H} - \bar{\gamma}_w^{-1} \frac{d}{d\tau_w} \bar{\gamma}_w$$

# Magnitude of backreaction



- Magnitude of  $\bar{\Omega}_Q$  determines departure from FLRW evolution and variance of density of “statistically average” coarse-grained cells
- This of order 4–5% at most

# Apparent cosmic acceleration

- Volume average observer sees no apparent cosmic acceleration

$$\bar{q} = \frac{2(1 - f_v)^2}{(2 + f_v)^2}.$$

As  $t \rightarrow \infty$ ,  $f_v \rightarrow 1$  and  $\bar{q} \rightarrow 0^+$ .

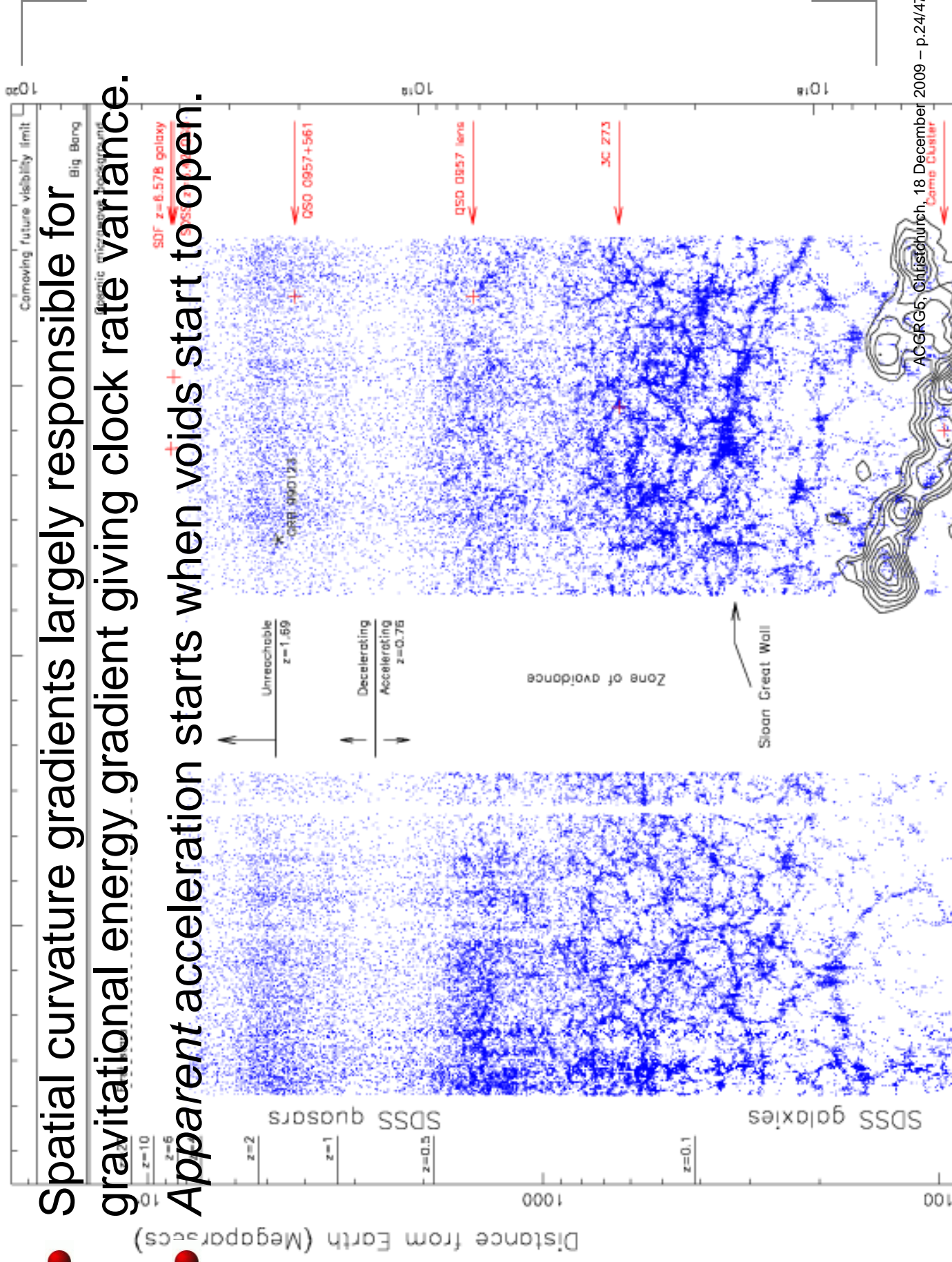
- A wall observer registers apparent cosmic acceleration

$$q = \frac{-(1 - f_v)(8f_v^3 + 39f_v^2 - 12f_v - 8)}{(4 + f_v + 4f_v^2)^2},$$

Effective deceleration parameter starts at  $q \sim \frac{1}{2}$ , for small  $f_v$ ; changes sign when  $f_v = 0.58670773\dots$ , and approaches  $q \rightarrow 0^-$  at late times.

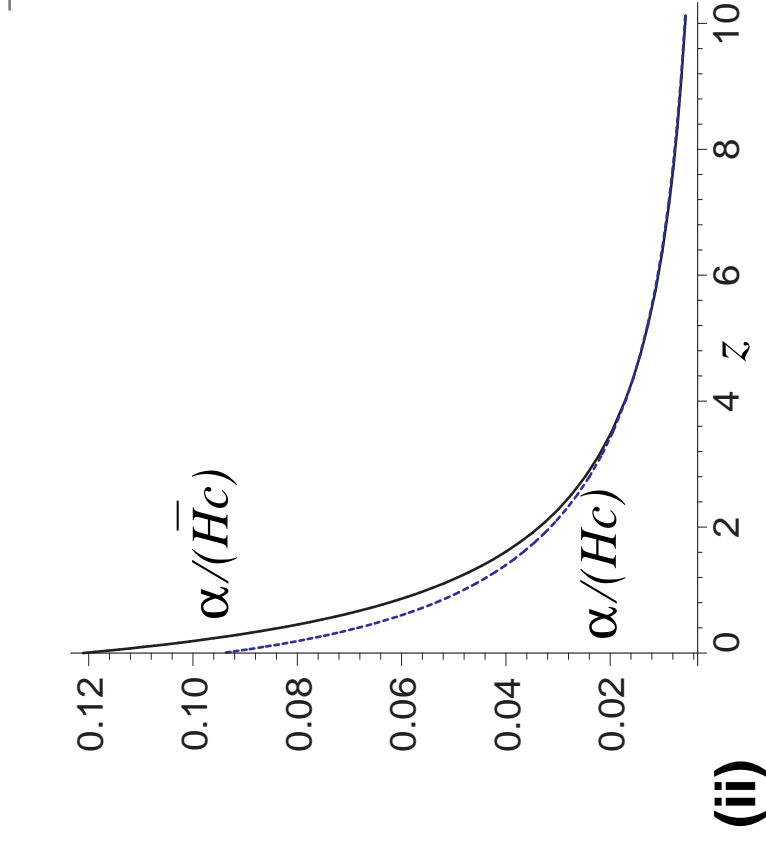
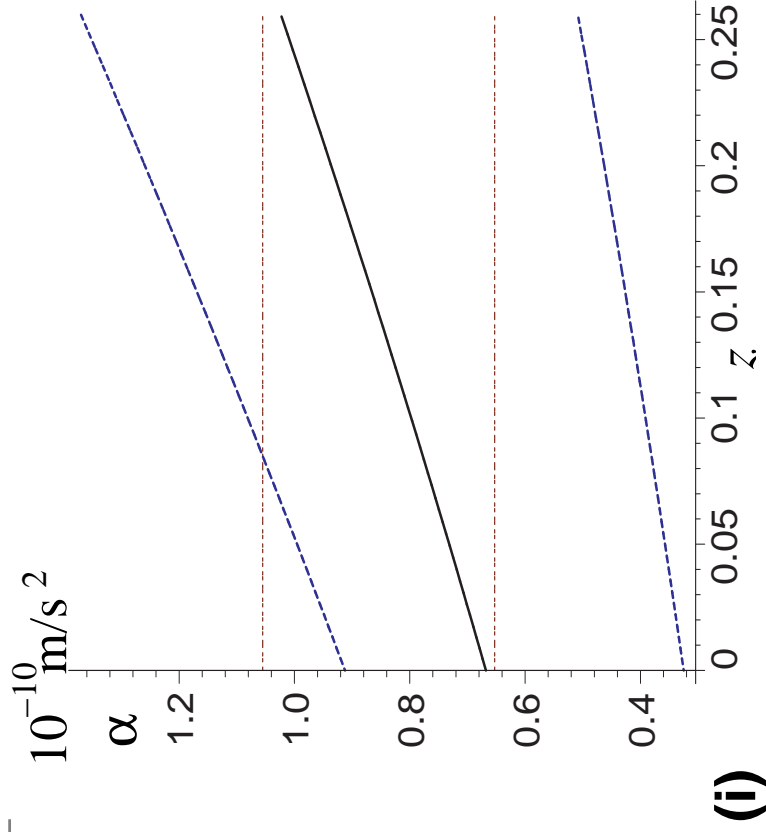
# Cosmic coincidence problem solved

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





# CEP relative deceleration scale



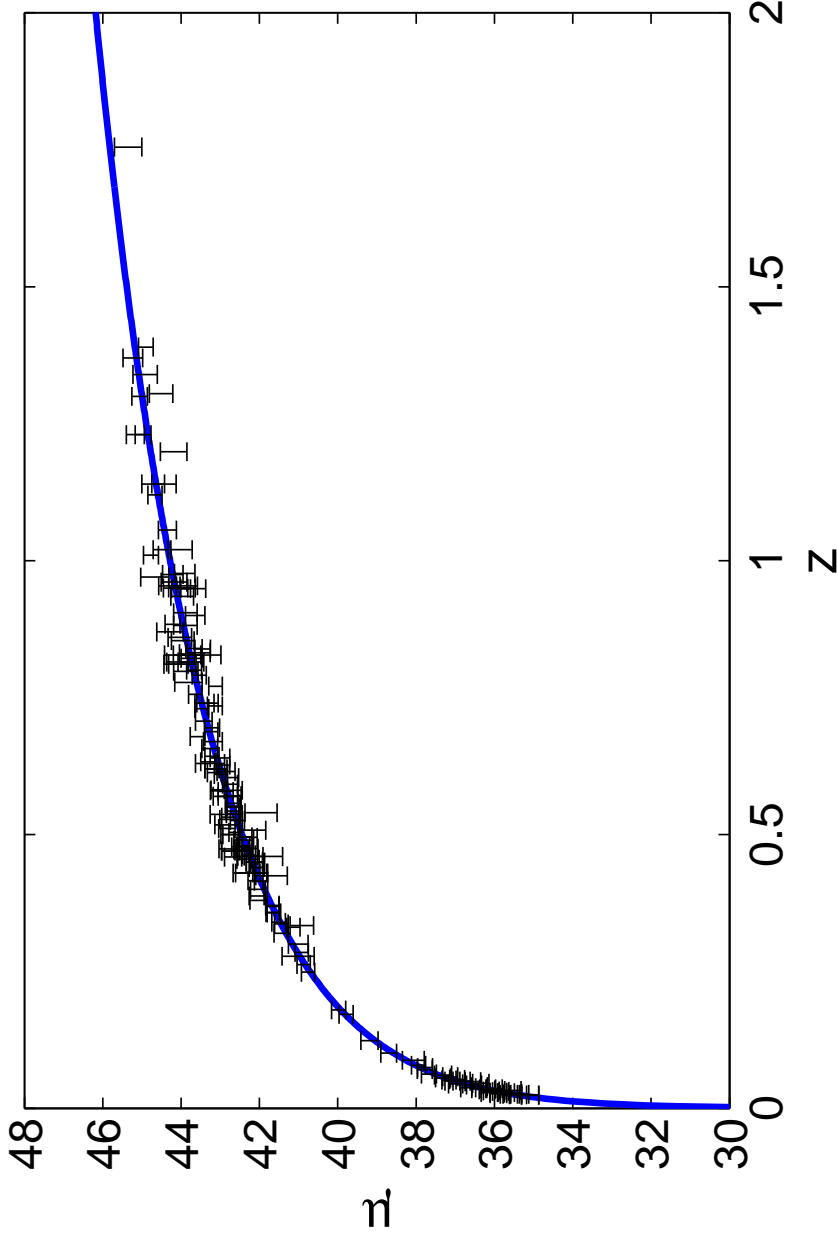
By equivalence principle the instantaneous relative deceleration of backgrounds gives an instantaneous 4-acceleration of magnitude  $\alpha = H_0 c \bar{\gamma}_w \dot{\gamma}_w / (\sqrt{\bar{\gamma}_w^2 - 1})$  beyond which *weak field cosmological general relativity* will be changed from Newtonian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

● For  $z \lesssim 0.25$ , coincides with empirical MOND scale

$$\alpha_0 = 1.2^{+0.3}_{-0.2} \times 10^{-10} \text{ ms}^{-2} h_{75}^2 = 8.1^{+2.5}_{-1.6} \times 10^{-11} \text{ ms}^{-2} \text{ for}$$

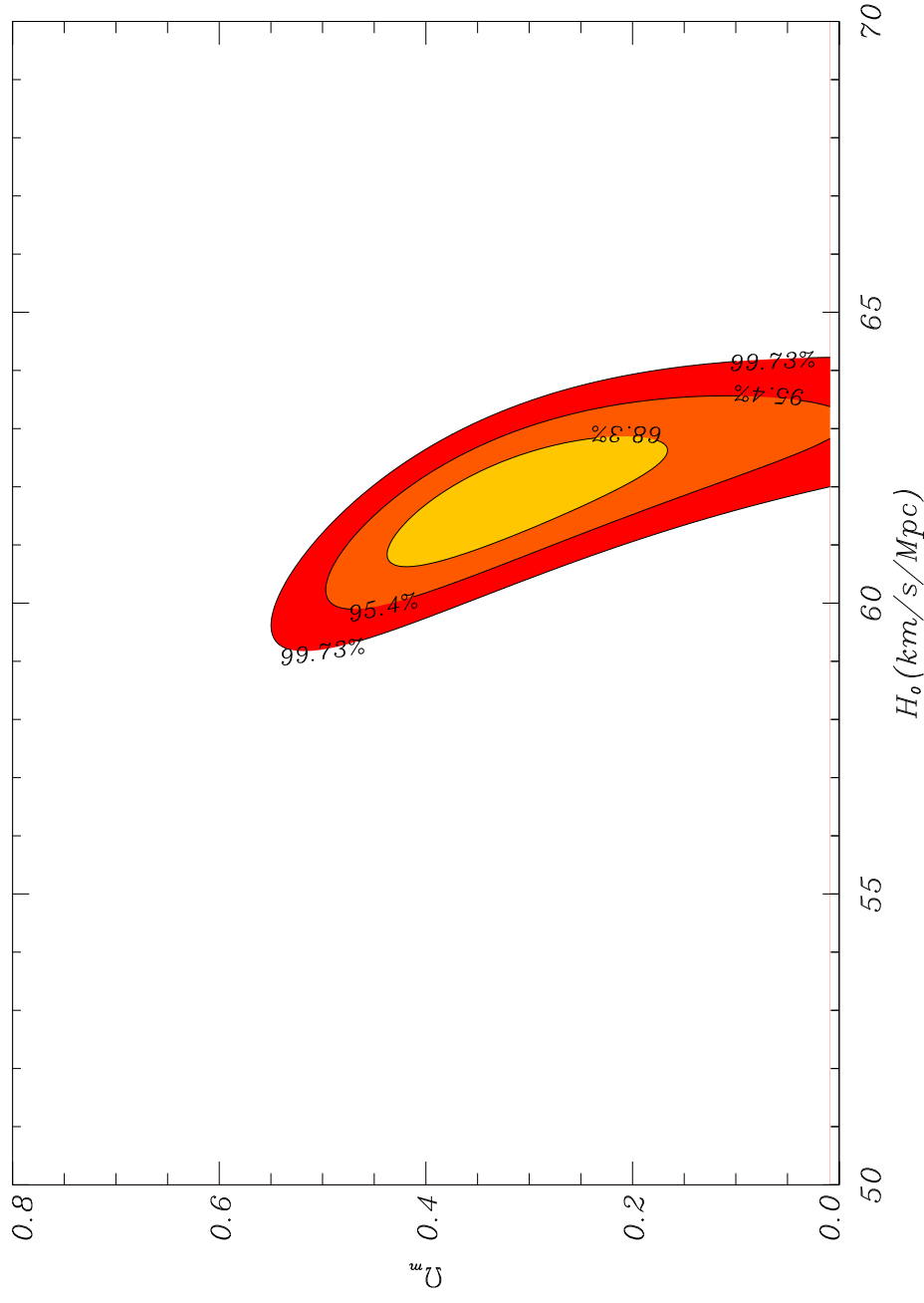
$$H_0 = 61.7 \text{ km s}^{-1} \text{ Mpc}^{-1}.$$

# Test 1: Snela luminosity distances



- Type Ia supernovae of Riess 2007 Gold data set fit with  $\chi^2$  per degree of freedom = 0.9
- Type Ia supernovae of Hicken 2009 MLC17 set fit with  $\chi^2$  per degree of freedom = 1.08

# Test 1: Snela luminosity distances



Two free parameters  $H_0$  versus  $\Omega_{M0}$  (dressed shown here),  
or alternatively “bare values”, constrained by Riess07 Gold  
data fit

# Best fit parameters

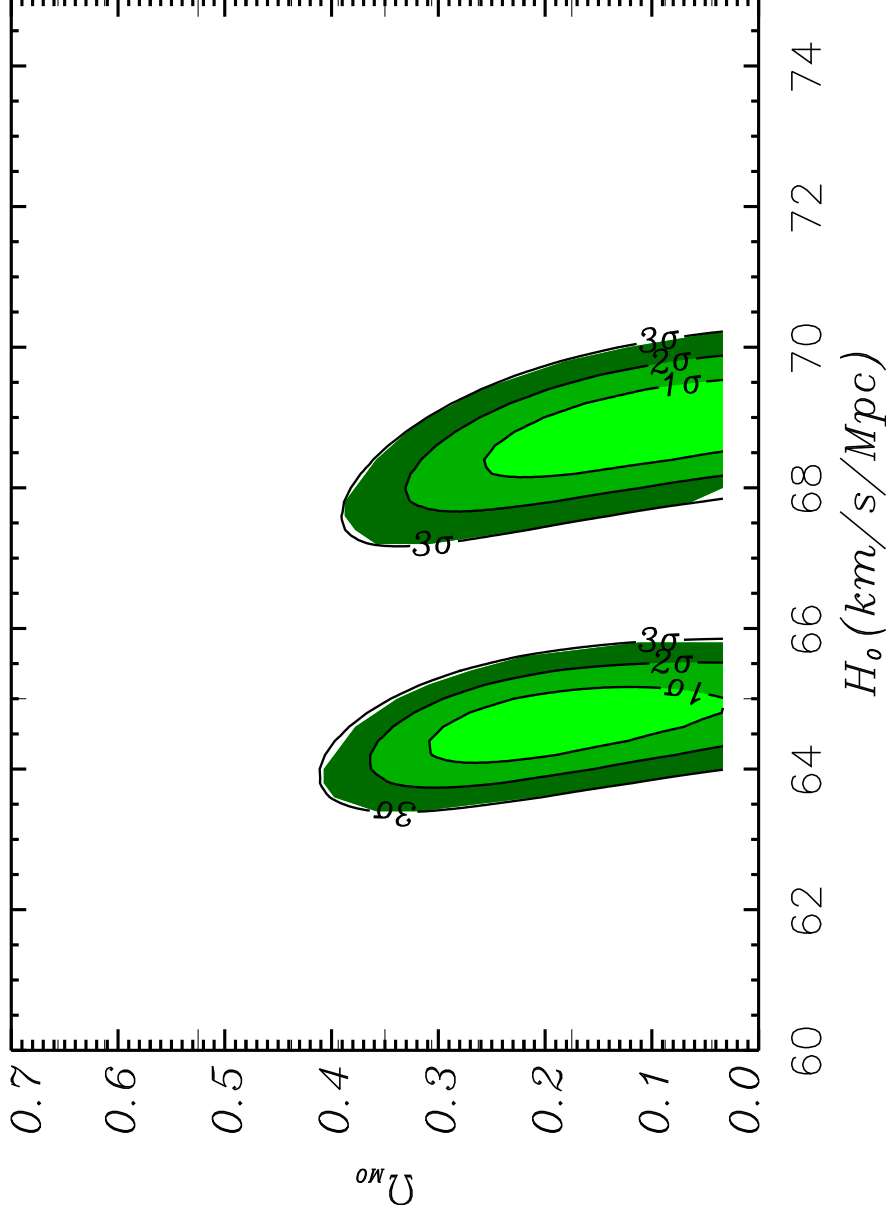
- Hubble constant  $H_0 = 61.7^{+1.2}_{-1.1} \text{ km s}^{-1} \text{ Mpc}^{-1}$
- present void volume fraction  $f_{v0} = 0.76^{+0.12}_{-0.09}$
- bare density parameter  $\bar{\Omega}_{M0} = 0.125^{+0.060}_{-0.069}$
- dressed density parameter  $\Omega_{M0} = 0.33^{+0.11}_{-0.16}$
- non-baryonic dark matter / baryonic matter mass ratio  $(\bar{\Omega}_{M0} - \bar{\Omega}_{B0}) / \bar{\Omega}_{B0} = 3.1^{+2.5}_{-2.4}$
- bare Hubble constant  $\bar{H}_0 = 48.2^{+2.0}_{-2.4} \text{ km s}^{-1} \text{ Mpc}^{-1}$
- mean lapse function  $\bar{\gamma}_0 = 1.381^{+0.061}_{-0.046}$
- deceleration parameter  $q_0 = -0.0428^{+0.0120}_{-0.0002}$
- wall age universe  $\tau_0 = 14.7^{+0.7}_{-0.5} \text{ Gyr}$

# More recent results

Sample	# Snela	$\ln B$	favours...
Riess 2007 Gold	182	0.27	indeterminate
Hicken 2009 MLCS31	366	-1.47	$\Lambda$ CDM
Hicken 2009 MLCS17	372	4.16	TS

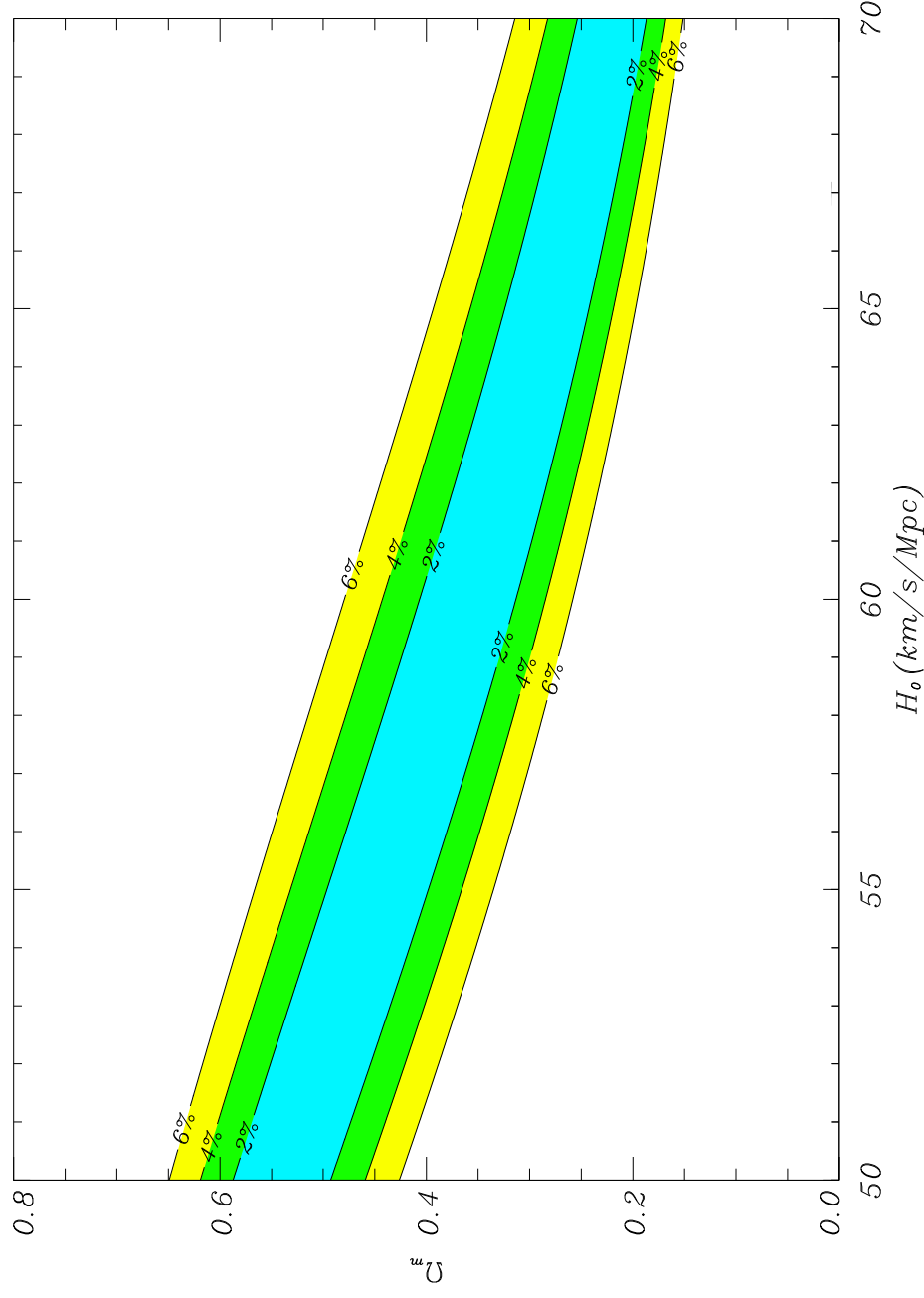
- Bayesian comparison for MLCS reductions with priors  $55 \leq H_0 \leq 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $0.01 \leq \Omega_{M0} \leq 0.5$ .
- Currently enough data to distinguish models; but systematic uncertainties need to be understood first.
- SALT reduced data (Union, Constitution) trickier, as cosmology is mixed with empirical light curve parameters in data reduction (talk by P Smale)

# Test 1: Snela luminosity distances



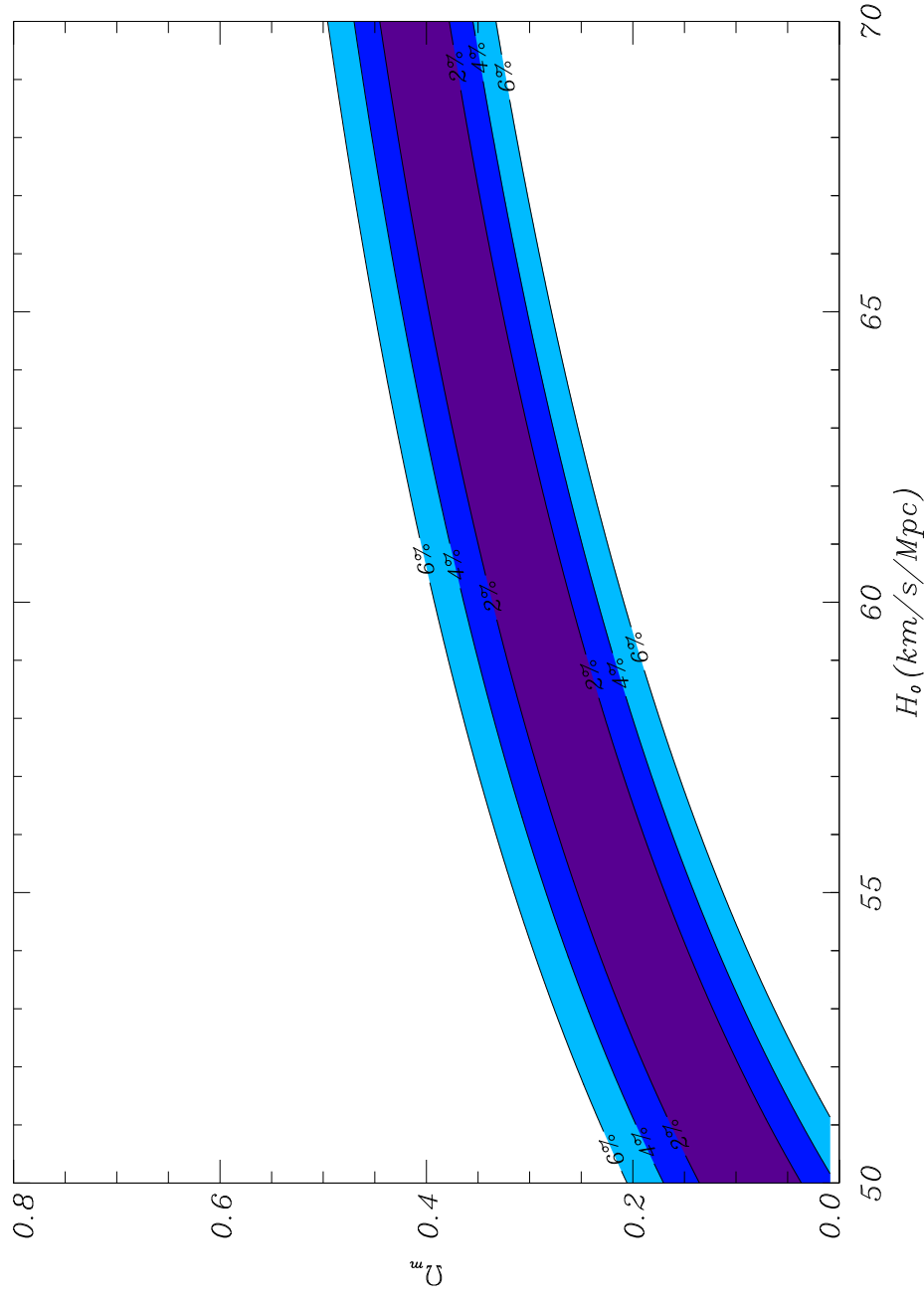
Left: fit to 372 MLCs17 Snela of Hicken *et al.*; right fit to 307 Union Snela.

# Test 2: Angular scale of CMB Doppler peaks



Parameters within the  $(\Omega_m, H_0)$  plane which fit the angular scale of the sound horizon  $\delta = 0.01$  rad deduced for WMAP, to within 2%, 4% and 6%.

# Test 3: Baryon acoustic oscillation scale

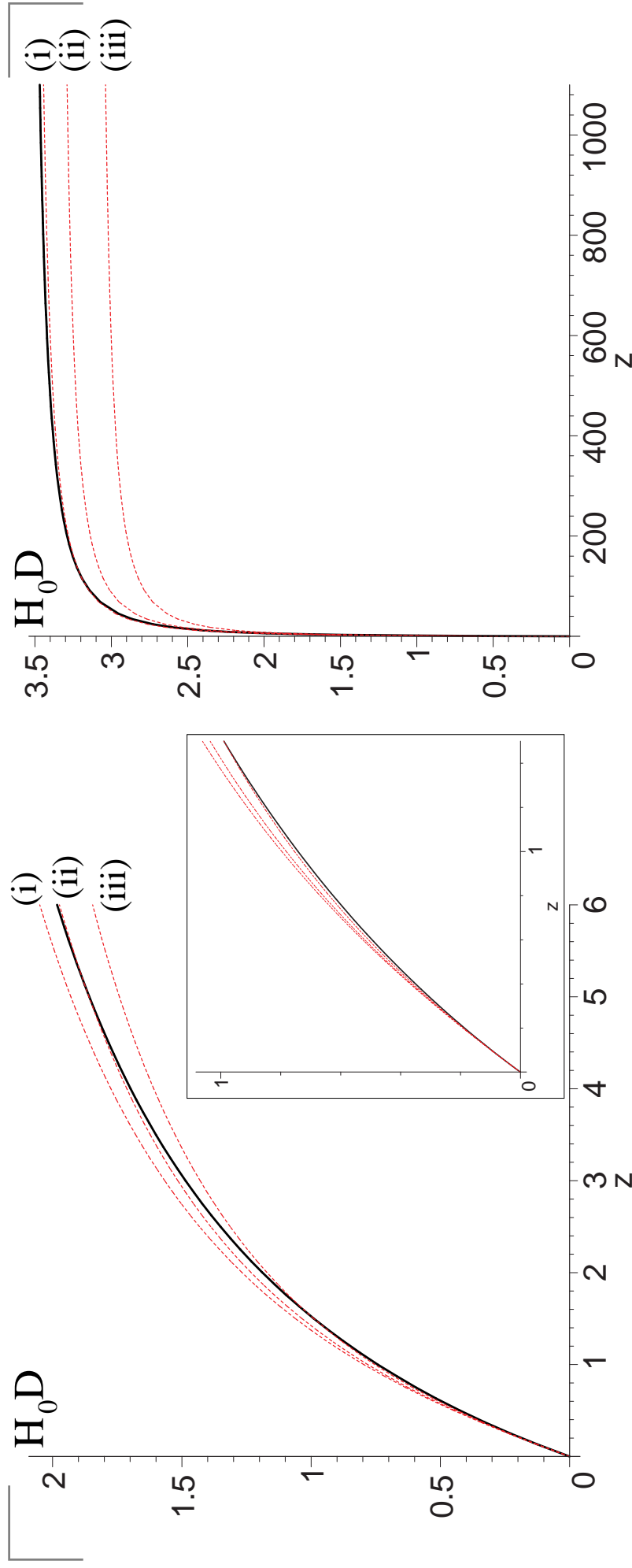


Parameters within the  $(\Omega_m, H_0)$  plane which fit the effective comoving baryon acoustic oscillation scale of  $104h^{-1}$  Mpc, as seen in 2dF and SDSS.





# Dressed “comoving distance” $D(z)$



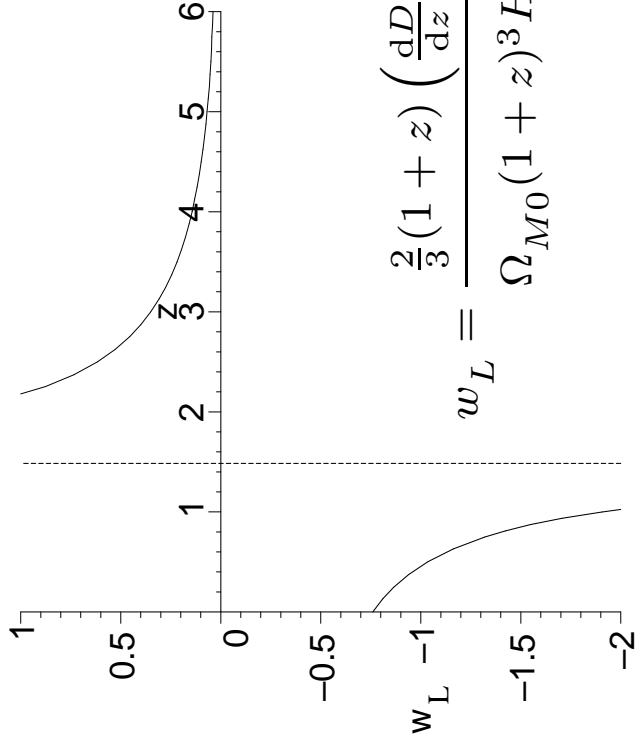
Best-fit timescape model (**red line**) compared to 3 spatially

flat  $\Lambda$ CDM models: **(i)** best-fit to WMAP5 only ( $\Omega_\Lambda = 0.75$ );

**(ii)** joint WMAP5 + BAO + Snella fit ( $\Omega_\Lambda = 0.72$ );

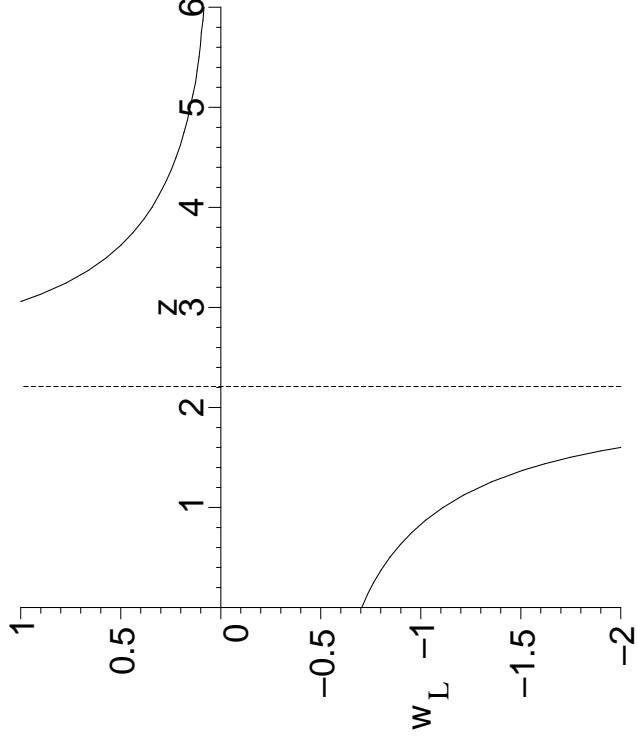
**(iii)** best flat fit to (Riess07) Snella only ( $\Omega_\Lambda = 0.66$ ).

# Equivalent “equation of state”?



(i)

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

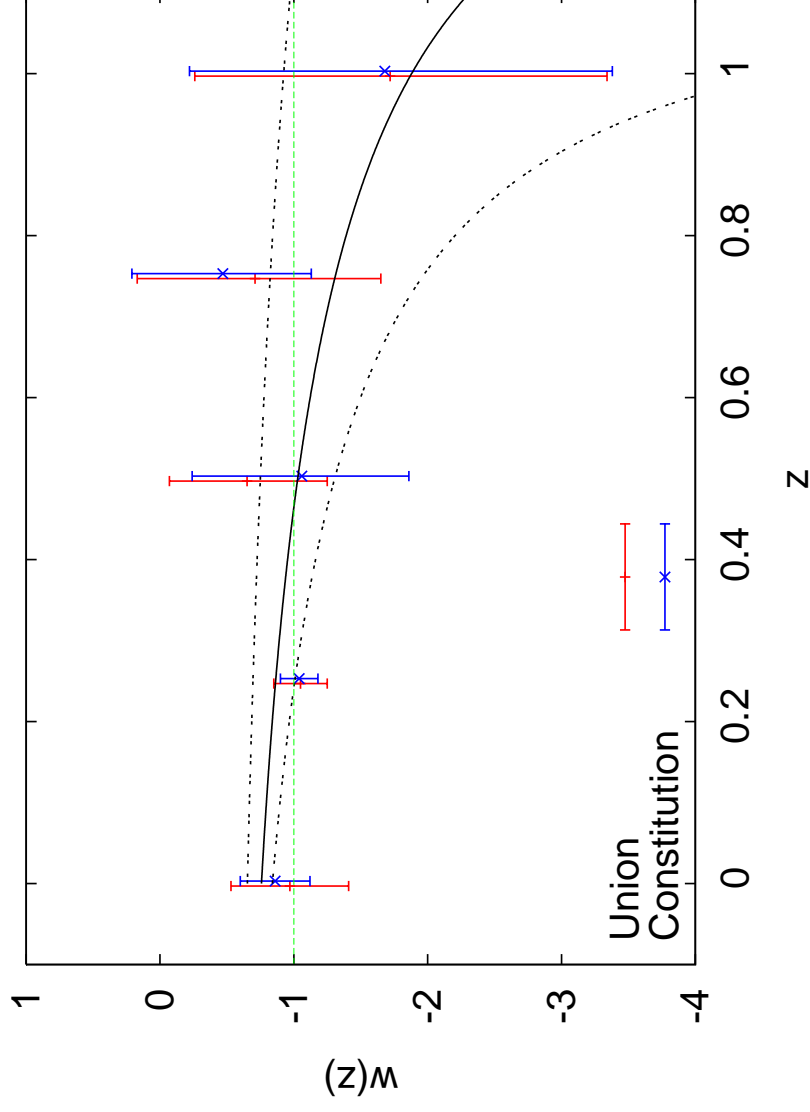


(ii)

A formal “dark energy equation of state”  $w_L(z)$  for the best-fit timescape model,  $f_{v0} = 0.76$ , calculated directly from  $r_w(z)$ : **(i)**  $\Omega_{M0} = 0.33$ ; **(ii)**  $\Omega_{M0} = 0.279$ .

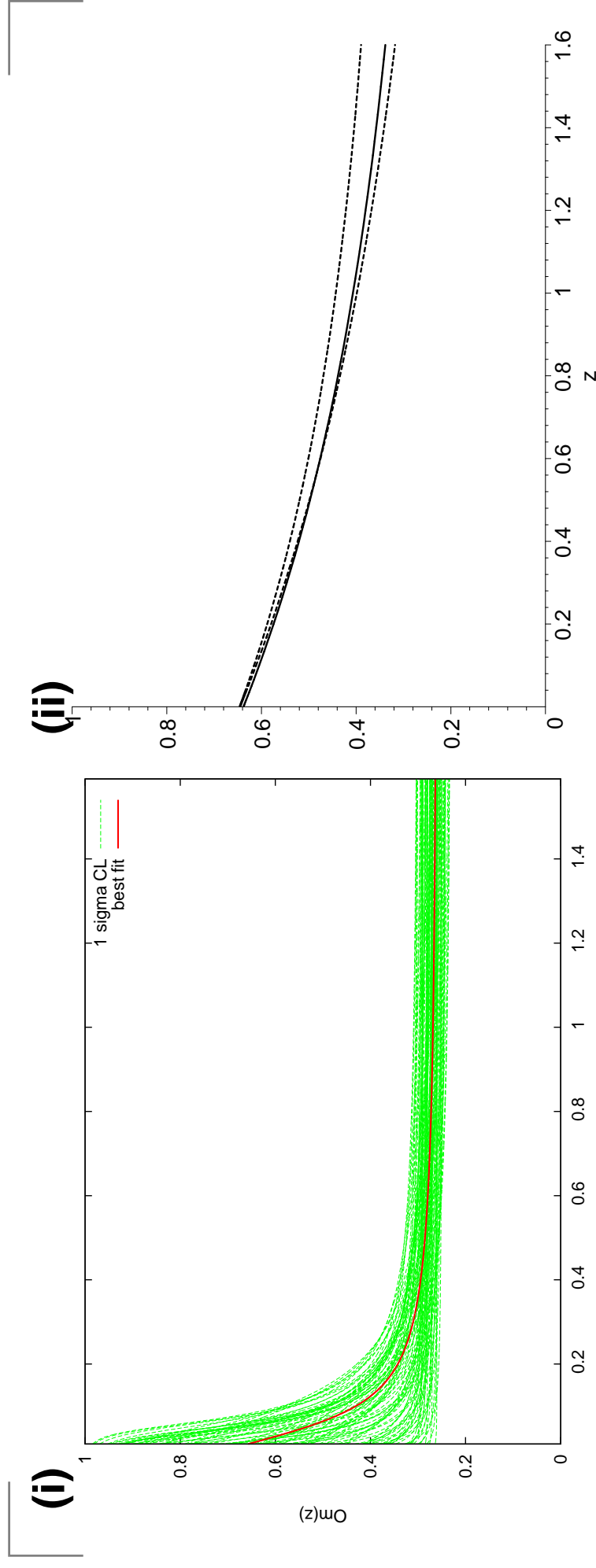
- Description by a “dark energy equation of state” makes no sense when there’s no physics behind it; but average value  $w_L \simeq -1$  for  $z < 0.7$  makes empirical sense.

# Tests of ‘equation of state’



- Zhao and Zhang arXiv:0908.1568 find mild 95% evidence in favour of  $w(z)$  crossing the phantom divide from  $w > -1$  to  $w < -1$  in the range  $0.25 < w < 0.75$
- Serra *et al.* arXiv:0908.3186 find “no evidence” of dynamical dark, but their data analysis shown above is also consistent with timescape

# Sahni, Shafieloo and Starobinsky $\Omega_m(z)$



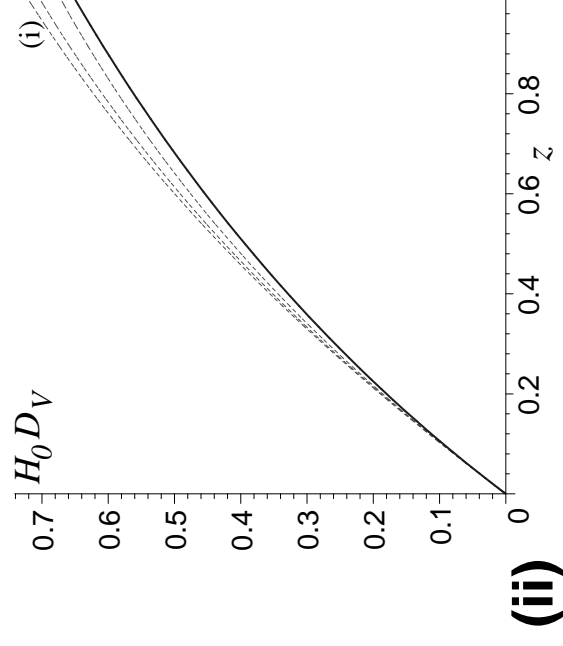
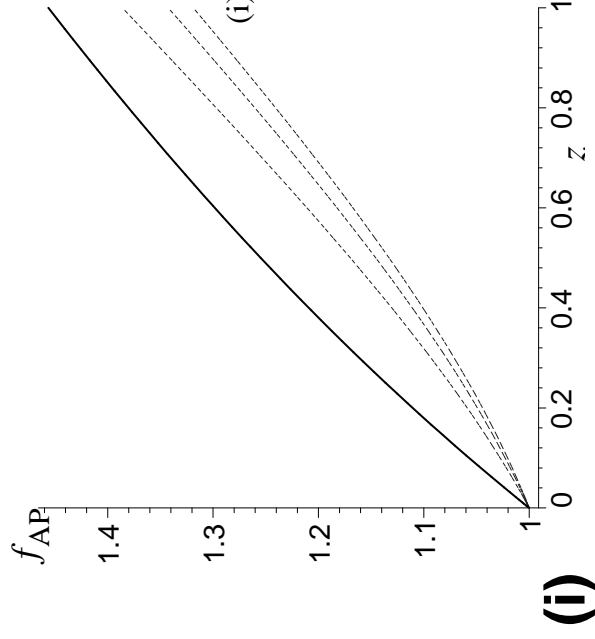
(i)  $\Omega_m(z)$  fit by Shafieloo *et al.* to SN+BAO+CMB with  $w(z) = -\frac{1}{2} [1 + \tanh((z - z_t) \Delta)]$ ;

(ii) TS model prediction for  $\Omega_m(z)$  (NOT same  $w(z)$ ) – best-fit and  $1\sigma$  uncertainties

● Shafieloo *et al.*, arxiv:0903.5141, fit  $\Omega_m(z)$  with hint that “dark energy is decaying” .

● Intercept  $\Omega_m(0)$  agrees well with TS model expectation

# Baryon acoustic oscillation measures

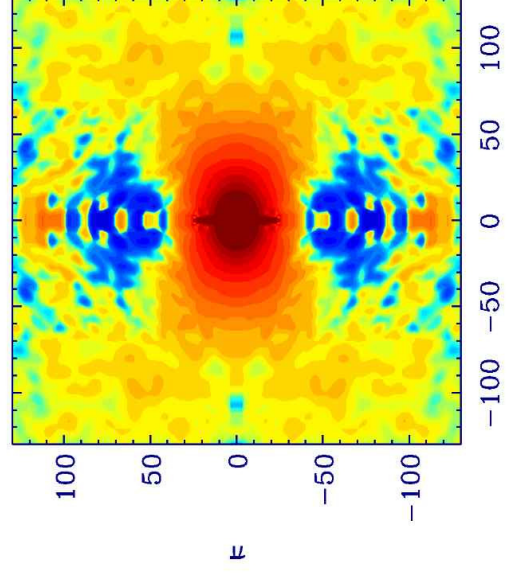
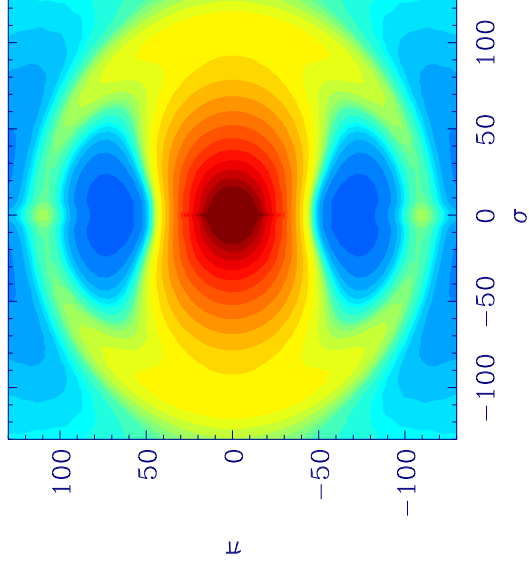
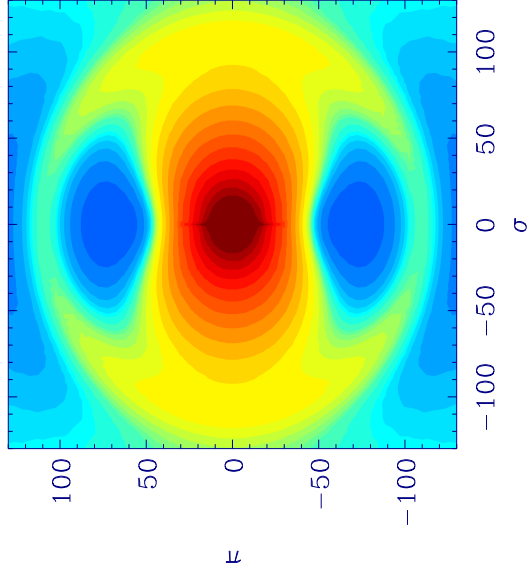


Best-fit timescape model (red line) compared to 3 spatially flat  $\Lambda$ CDM models as earlier: (i)

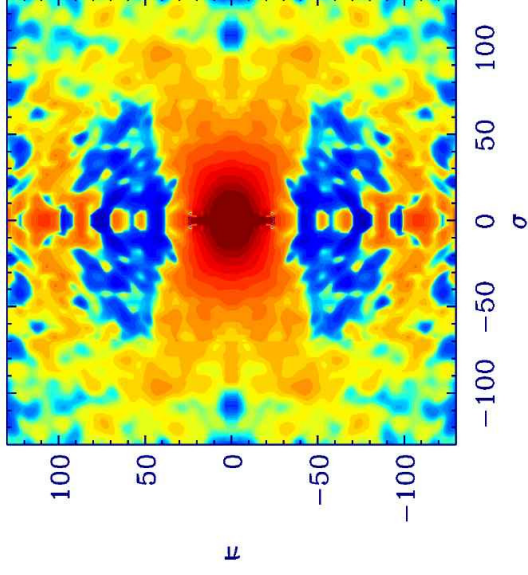
Alcock-Paczynski test; (ii)  $D_V$  measure.

- BAO signal detected in galaxy clustering statistics
- Current  $D_V$  measure averages over radial and transverse directions; little leverage for  $z \lesssim 1$
- Alcock-Paczynski measure - needs separate radial and transverse measures - a greater discriminator for  $z \lesssim 1$

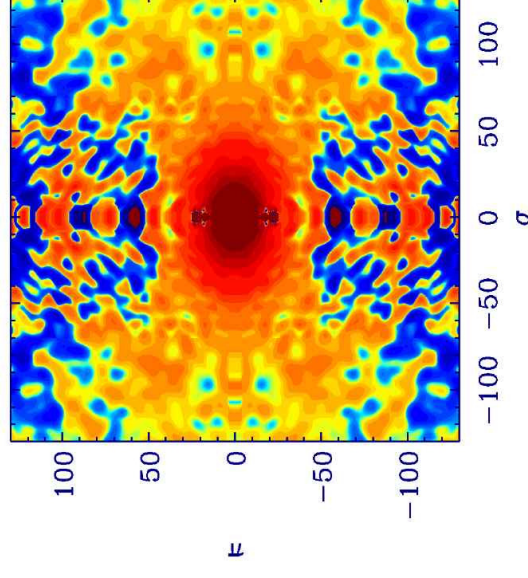
# Gaztañaga, Cabre and Hui 0807.3551



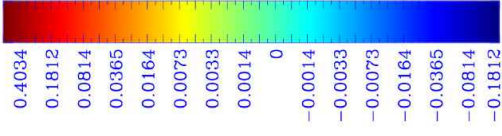
$z = 0.15-0.47$



$z = 0.15-0.30$



$z = 0.40-0.47$



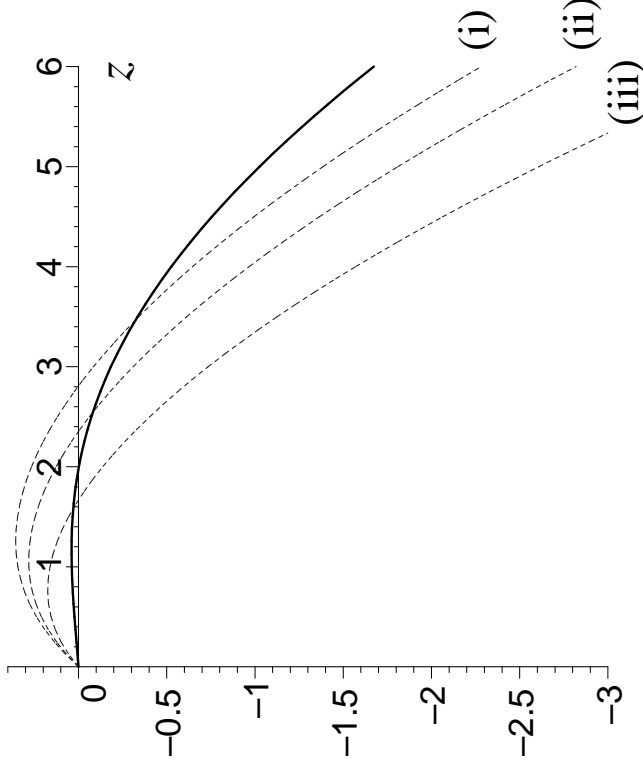
# Gaztañaga, Cabre and Hui 0807.3551

redshift range	$\Omega_{M0}h^2$	$\Omega_{B0}h^2$	$\Omega_{C0}/\Omega_{B0}$
0.15-0.30	0.132	0.028	3.7
0.15-0.47	0.12	0.026	3.6
0.40-0.47	0.124	0.04	2.1

- Tension with WMAP5 fit  $\Omega_{B0} \simeq 0.045$ ,  $\Omega_{C0}/\Omega_{B0} \simeq 6.1$  for LCDM model.
- GCH bestfit:  $\Omega_{B0} = 0.079 \pm 0.025$ ,  $\Omega_{C0}/\Omega_{B0} \simeq 3.6$ .
- TS prediction  $\Omega_{B0} = 0.080^{+0.021}_{-0.013}$ ,  $\Omega_{C0}/\Omega_{B0} = 3.1^{+1.8}_{-1.3}$  with match to WMAP5 sound horizon within 4% and no  $^7\text{Li}$  anomaly.



# Redshift time drift (Sandage–Loeb test)



$H_0^{-1} \frac{dz}{d\tau}$  for the timescape model with  $f_{v0} = 0.762$  (solid line) is compared to three spatially flat  $\Lambda$ CDM models with the same values of  $(\Omega_{M0}, \Omega_{\Lambda0})$  as in previous figures.

- Measurement is extremely challenging. May be feasible over a 10–20 year period by precision measurements of the Lyman- $\alpha$  forest over redshift  $2 < z < 5$  with next generation of Extremely Large Telescopes

# Clarkson, Bassett and Lu homogeneity test

- For FLRW equations, irrespective of dark energy model

$$\Omega_{k0} = \frac{\mathcal{B}}{[H_0 D(z)]^2} = \text{const}$$

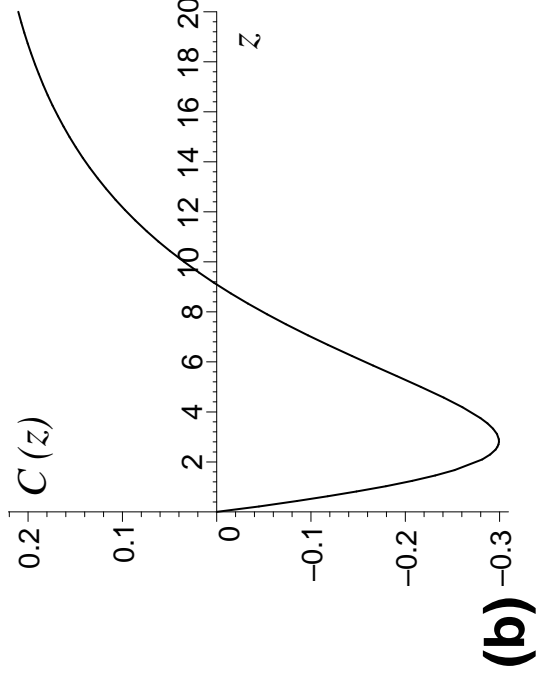
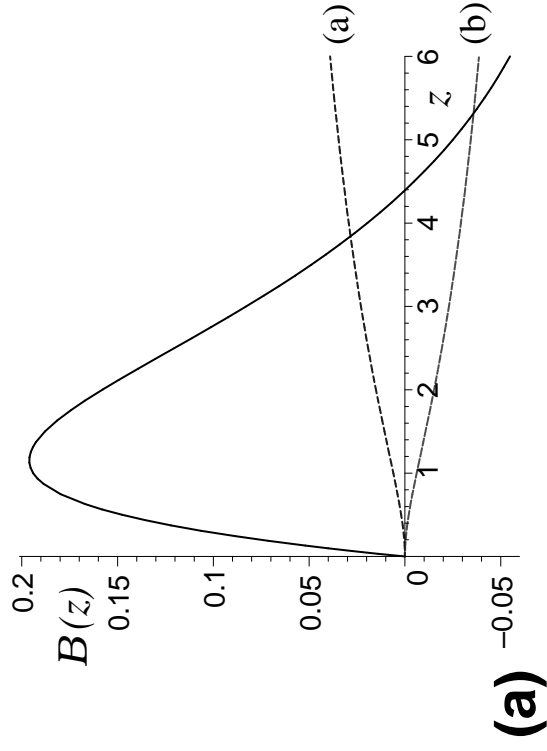
where  $\mathcal{B}(z) \equiv [H(z)D'(z)]^2 - 1$ . Thus

$$C(z) \equiv 1 + H^2(DD'' - D'^2) + HH'DD' = 0$$

for any homogeneous isotropic cosmology, irrespective of DE.

- Clarkson, Bassett and Lu [PRL 101 (2008) 011301] call this a “test of the Copernican principle”. However, it is really a test of Friedmann equation (cosmological principle).

# Clarkson, Bassett and Lu homogeneity test



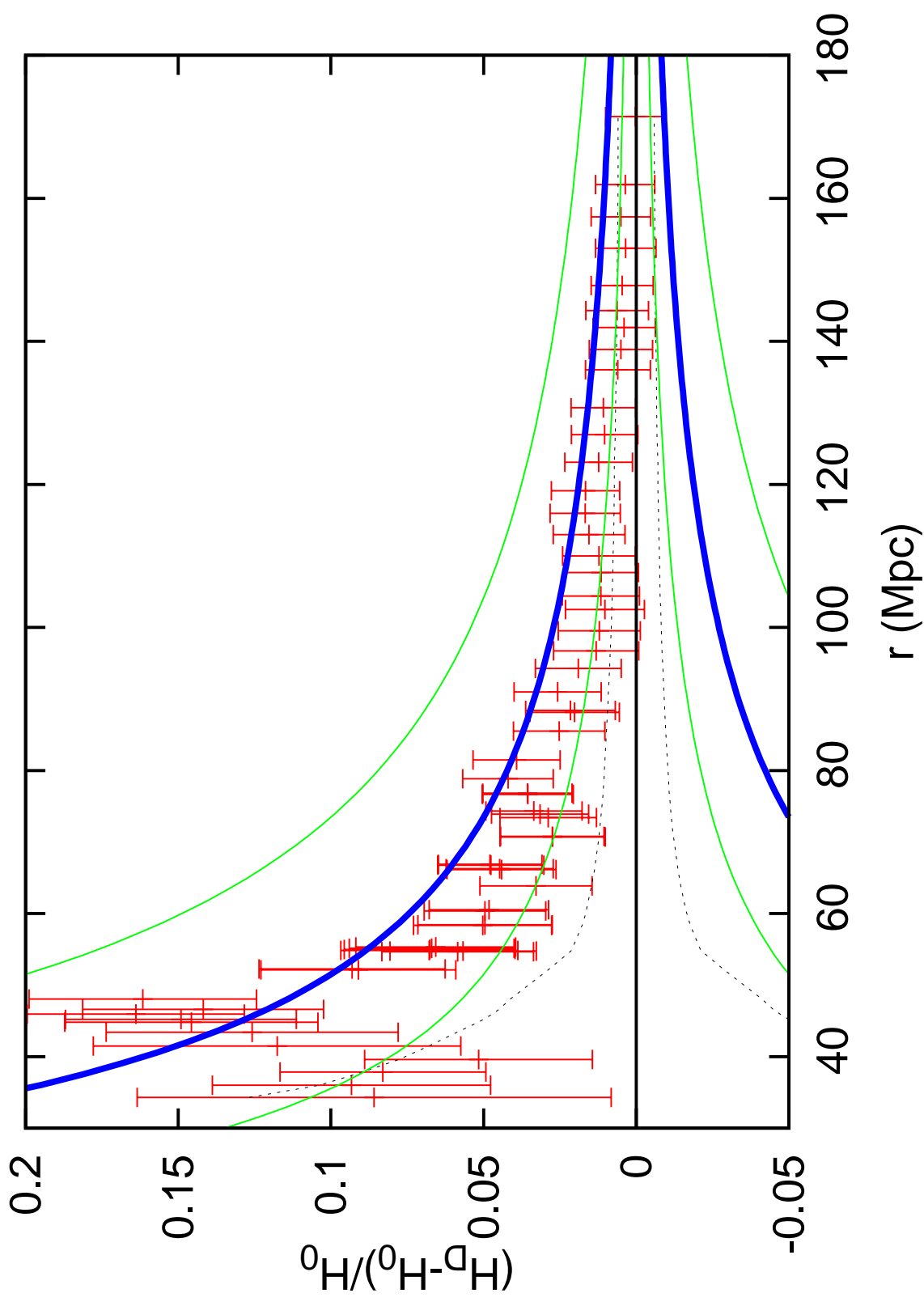
**(a)**  $\mathcal{B} \equiv [H(z)D'(z)]^2 - 1$  for timescape model with  $f_{v0} = 0.762$  (solid line) and two  $\Lambda$ CDM models (dashed lines): **(i)**  $\Omega_{M0} = 0.28$ ,  $\Omega_{\Lambda0} = 0.71$ ,  $\Omega_{k0} = 0.01$ ; **(ii)**  $\Omega_{M0} = 0.28$ ,  $\Omega_{\Lambda0} = 0.73$ ,  $\Omega_{k0} = -0.01$ ; **(b)**  $\mathcal{C}(z)$ .

- Will give a powerful test of FLRW assumption in future, with quantitatively different prediction for timescape model.

# Apparent Hubble flow variance

- As voids occupy largest volume of space expect to measure higher average Hubble constant locally until the global average relative volumes of walls and voids are sampled at scale of homogeneity; thus expect maximum  $H_0$  value for isotropic average on scale of dominant void diameter,  $30h^{-1}\text{Mpc}$ , then decreasing till levelling out by  $100h^{-1}\text{Mpc}$ .
- Consistent with observed Hubble bubble feature (Jha, Riess, Kirshner ApJ 659, 122 (2007)), which is unexplained (and problem for)  $\Lambda\text{CDM}$ .
- Intrinsic variance in apparent Hubble flow exposes a local scale dependence which may partly explain difficulties astronomers have had in converging on a value for  $H_0$ .

# N. Li & D. Schwarz, arxiv:0710.5073v1-2



# The value of $H_0$

Value of  $H_0 = 74.2 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$  of  $S_{H_0}$  ES survey (Riess *et al.*, 2009) calibrated by NGC4258 maser distance at 7.5 Mpc is a challenge for the timescape model.

However,

- Expect variance in Hubble flow below scale of homogeneity with typical higher value

$$H_0 = 72.3 \text{ km s}^{-1} \text{ Mpc}^{-1} \text{ at } 30h^{-1} \text{ Mpc scale}$$

- Latest FLRW BAO value:  $H_0 = 68.2 \pm 2.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (SDSS7: Percival *et al.*, arXiv:0907.1660)
- Megamaser project will give better geometric distances and independent  $H_0$  measure. First more distant maser galaxy NGC3789 at 49.5 Mpc gives [by 8 June NRAO press release]  $H_0 = 67.2 \pm 11.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

# Conclusion

- Apparent cosmic acceleration can be understood purely within general relativity; by (i) treating geometry of universe more realistically; (ii) understanding fundamental aspects of general relativity which have not been fully explored – *quasi-local gravitational energy*, of *gradients* in spatial curvature etc.
- “Timescape” model gives good fit to major independent tests of  $\Lambda$ CDM and may resolve significant puzzles – e.g., primordial lithium abundance anomaly
- Many tests can be done to distinguish from  $\Lambda$ CDM.
- It is crucial that  $\Lambda$ CDM assumptions such as Friedmann equation are not used in data reduction.
- Many details – averaging scheme etc – may change, but fundamental questions remain