Dark energy without dark energy

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

Phys. Rev. Lett. 99 (2007) 251101

arXiv:0712.3984

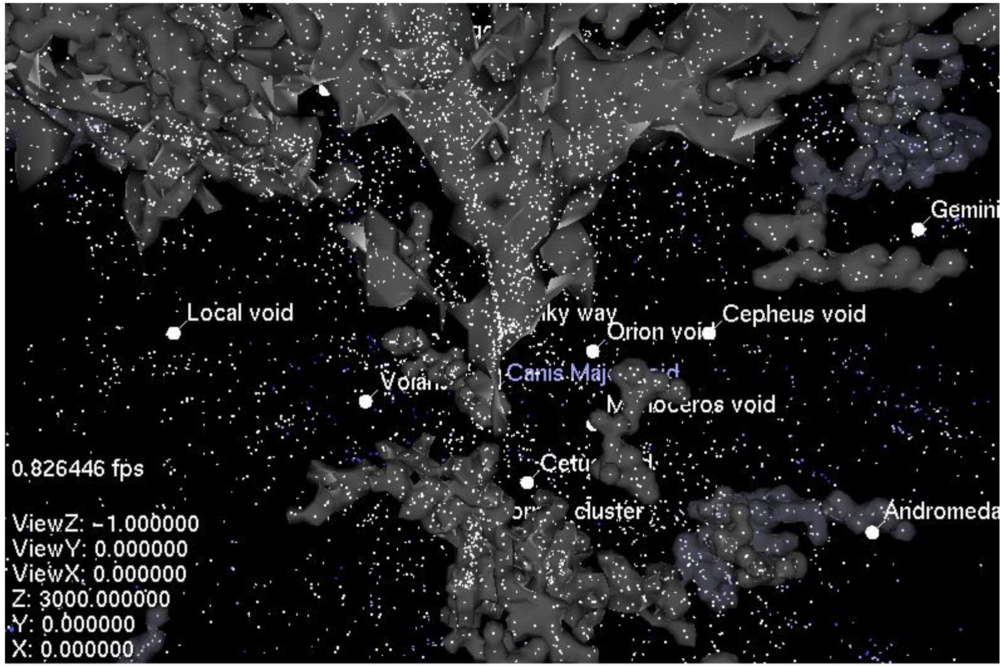
Phys. Rev. D78 (2008) 084032

Phys. Rev. D80 (2009) in press,

[arXiv:0909.0749]

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

ApJ 672 (2008) L91



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, Λ, $w = -1$.
- *Cosmic coincidence*: Why now? Why $\Omega_{\Lambda 0} \sim 2\Omega_{M0}$, 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

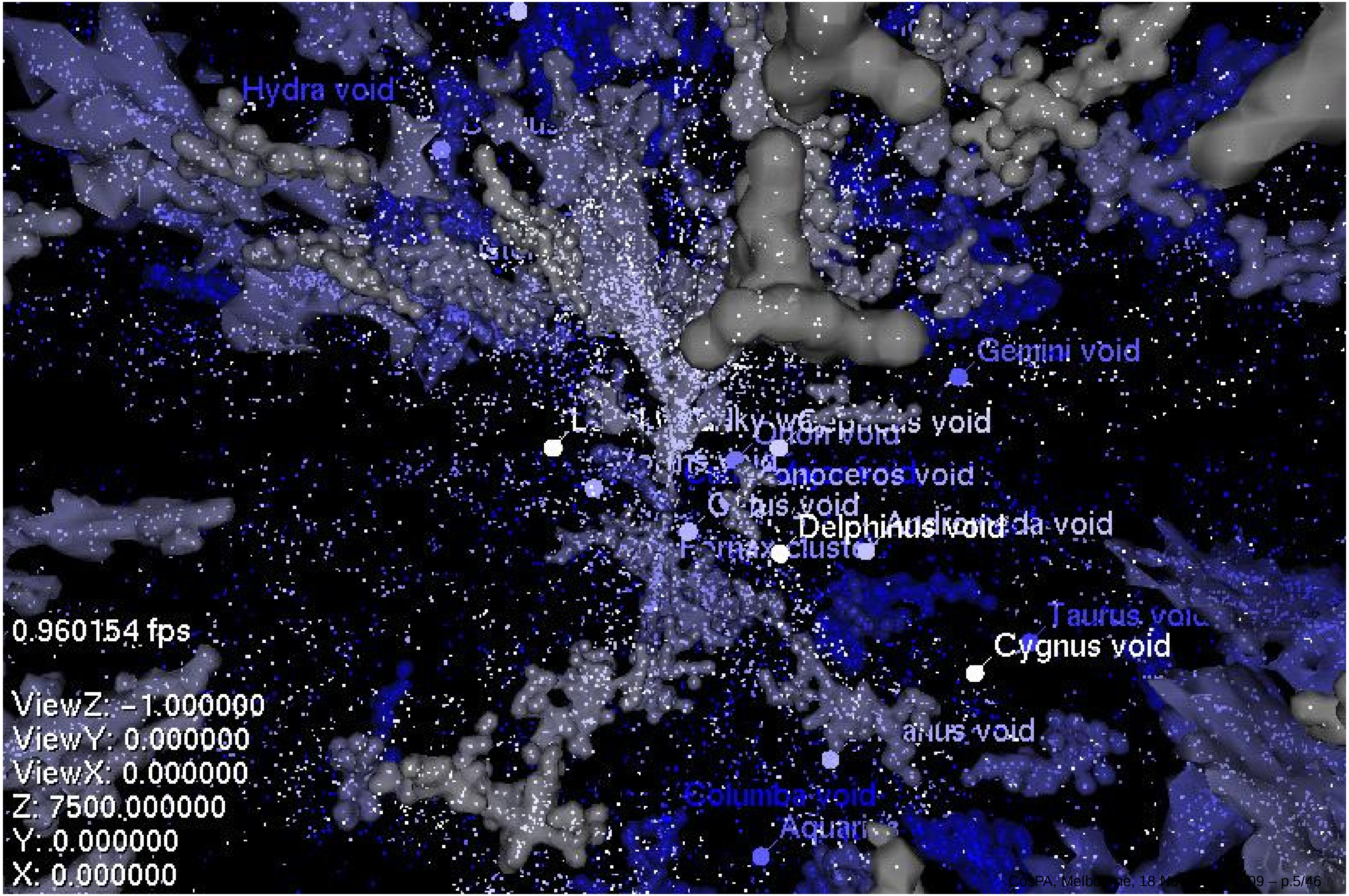
From smooth to lumpy

- 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 $H_0 = 100h$ km s^{-1} 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 ~ 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 ΛCDM parameters (Axenides & Perivolaropoulos 2002).

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



Approach 1: Exact solutions

- Much work has been done on spherically symmetric dust Lemaître–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 ΛCDM, 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 $\bar{\mathbf{G}}_{\mu\nu}(\mathbf{g}_{\alpha\beta}) \neq \mathbf{G}_{\mu\nu}(\bar{\mathbf{g}}_{\alpha\beta})$; and $\rho_{\rm cr} \neq 3H^2_{\rm av}/(8\pi G)$
- 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

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

Back-reaction

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

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

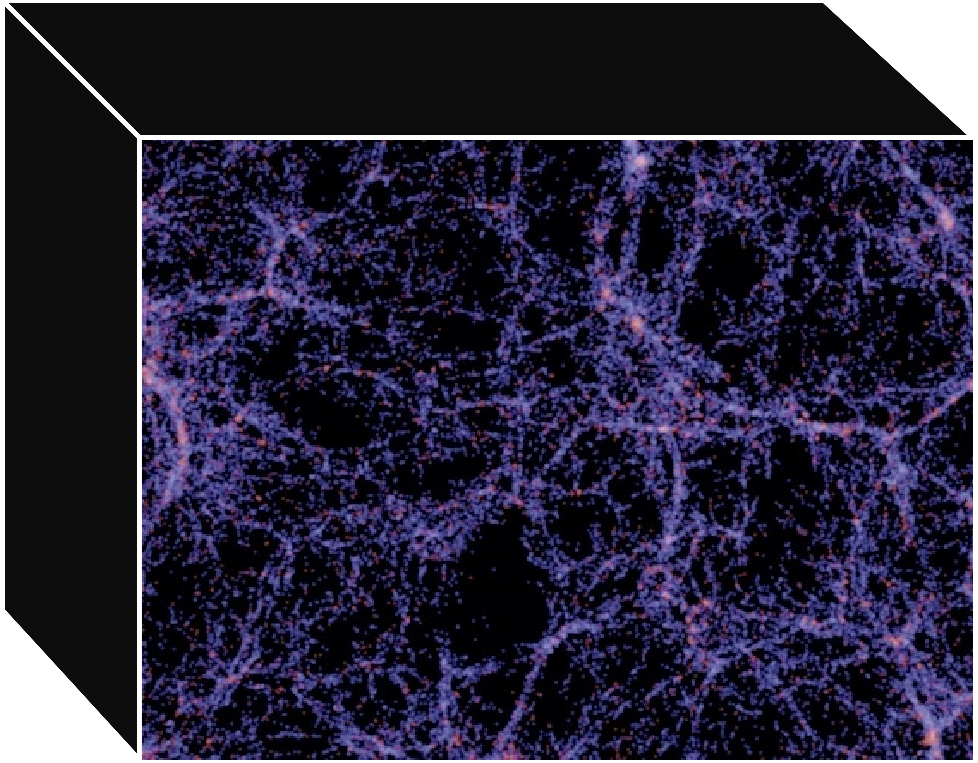
$$\langle \theta \rangle = 3 \frac{\dot{\bar{a}}}{\bar{a}}$$

Generally for any scalar Ψ,

$$\frac{\mathrm{d}}{\mathrm{d}t} \langle \Psi \rangle - \langle \frac{\mathrm{d}\Psi}{\mathrm{d}t} \rangle = \langle \Psi \theta \rangle - \langle \theta \rangle \langle \Psi \rangle$$

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

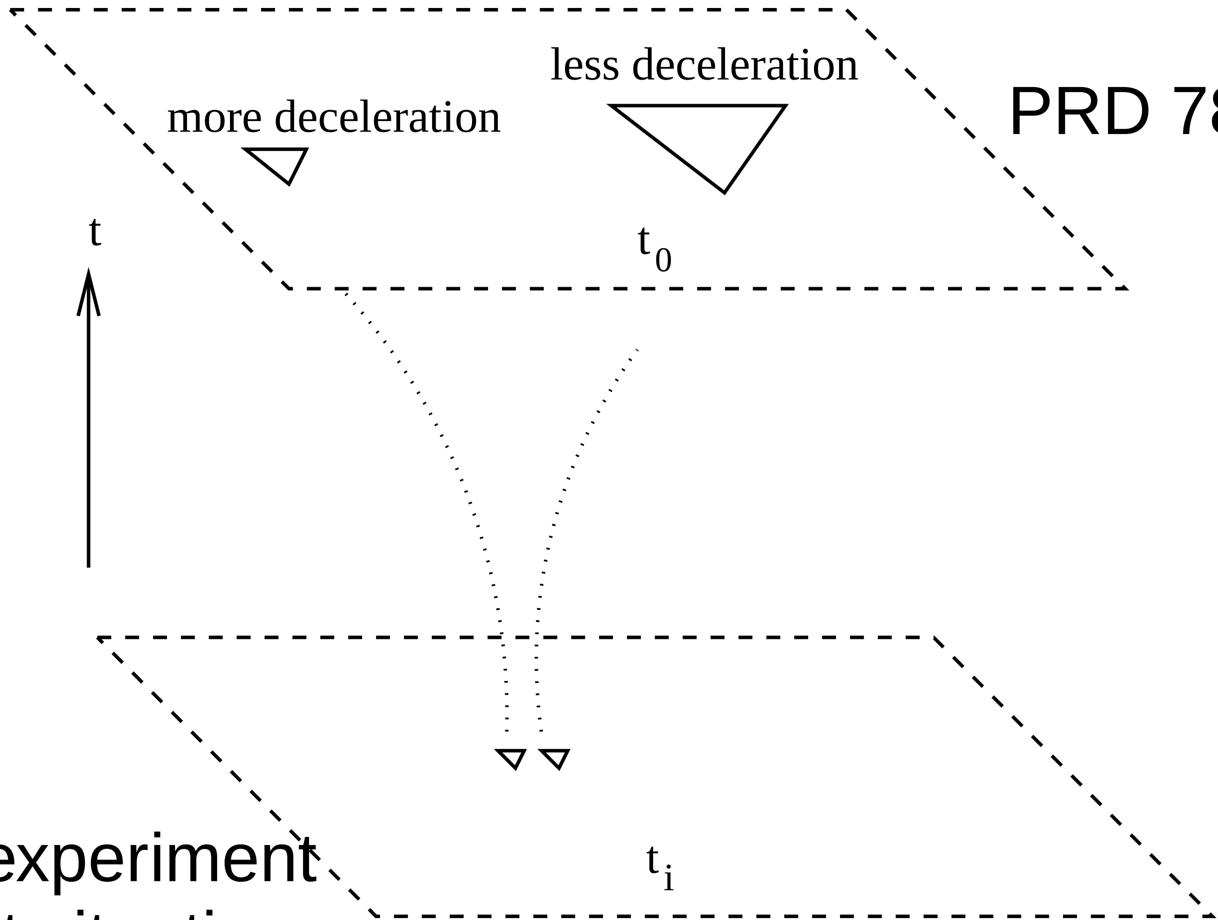
Cosmological Equivalence Principle

- *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*,

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

- 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

Cosmological Equivalence Principle

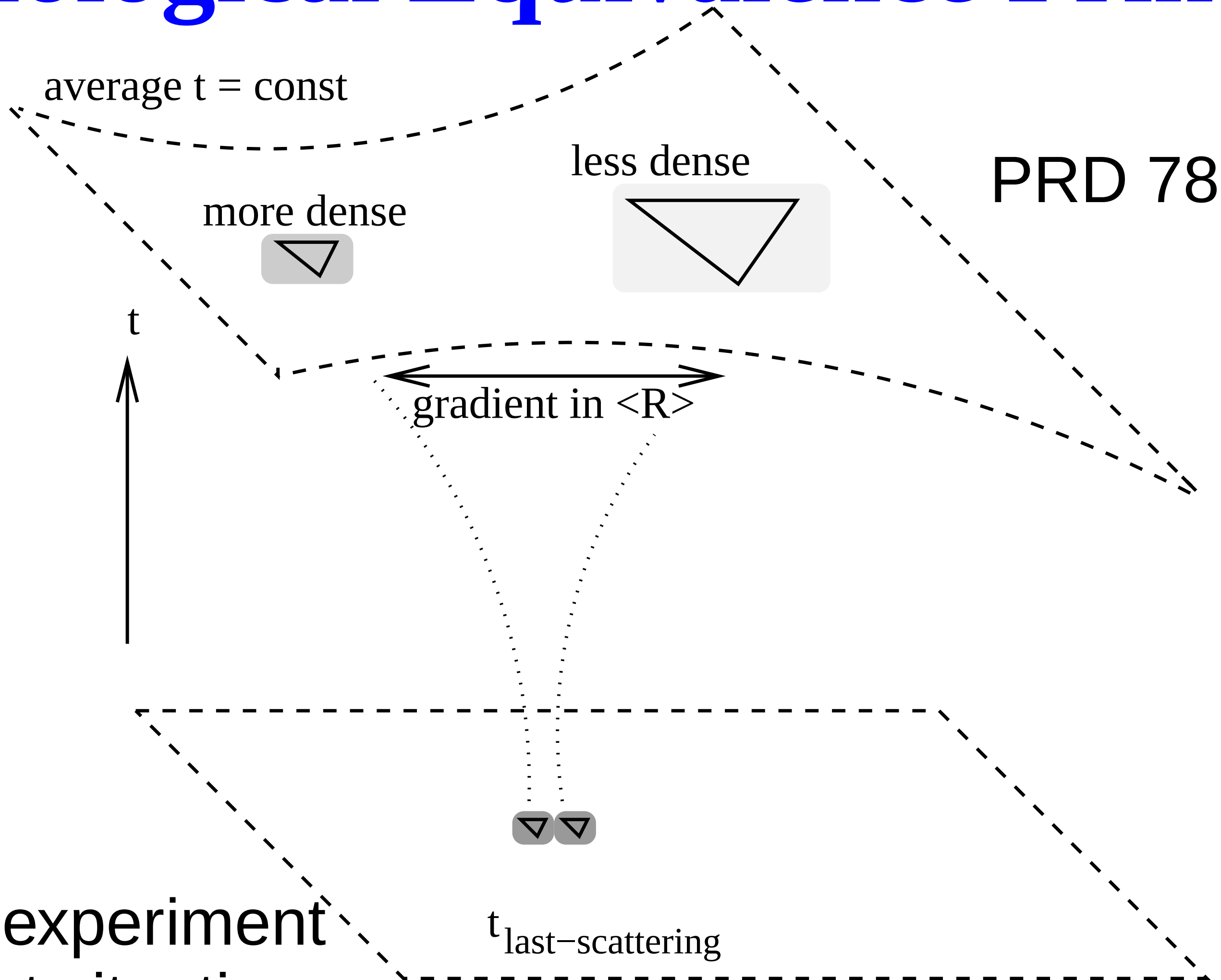


PRD 78, 084032 (2008)

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



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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

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

- 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_{av} on large scales with respect to *any one set of clocks* will differ from $\bar{H}$

Two/three scale "timescape" model

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

- Split statistical volume average into *spatially flat* walls (containing galaxies), $f_{\rm w}$, and negatively curved voids with fraction, $f_{\rm v} = 1 - f_{\rm w}$.
- 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, $\bar{\Omega}_M + \bar{\Omega}_k + \bar{\Omega}_{\mathcal{Q}} = 1$, 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

$$\begin{aligned} \mathrm{d}s^2_{\mathcal{F}_I} &= -\mathrm{d}\tau_{\rm w}^2 + {a_{\rm w}}^2(\tau_{\rm w})\left[\mathrm{d}\eta_{\rm w}^2 + \eta_{\rm w}^2\mathrm{d}\Omega^2\right] \\ \to \mathrm{d}s^2 &= -\mathrm{d}\tau_{\rm w}^2 + a^2\left[\mathrm{d}\bar\eta^2 + r_{\rm w}^2(\bar\eta,\tau_{\rm w})\,\mathrm{d}\Omega^2\right] \end{aligned}$$

where $a \equiv \bar a/\bar\gamma_{\rm w}$, $r_{\rm w} \equiv \bar\gamma_{\rm w}\,(1-f_{\rm v})^{1/3}\,{f_{\rm wi}}^{-1/3}\eta_{\rm w}(\bar\eta,\tau_{\rm w})$, and volume–average conformal time $\mathrm{d}\bar\eta = \mathrm{d}t/\bar a = \bar\gamma_{\rm w}\,\mathrm{d}\tau_{\rm w}/\bar a$.

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

$$\Omega_M = \bar\gamma_{\rm w}^3\bar\Omega_M\,.$$

Tracker solution PRL 99, 251101

- General exact solution possesses a “tracker limit”

$$\bar a = \frac{\bar a_0 (3\bar H_0 t)^{2/3}}{2+f_{v0}}\left[3f_{v0}\bar H_0 t + (1-f_{v0})(2+f_{v0})\right]^{1/3}$$

$$f_v = \frac{3f_{v0}\bar H_0 t}{3f_{v0}\bar H_0 t + (1-f_{v0})(2+f_{v0})},$$

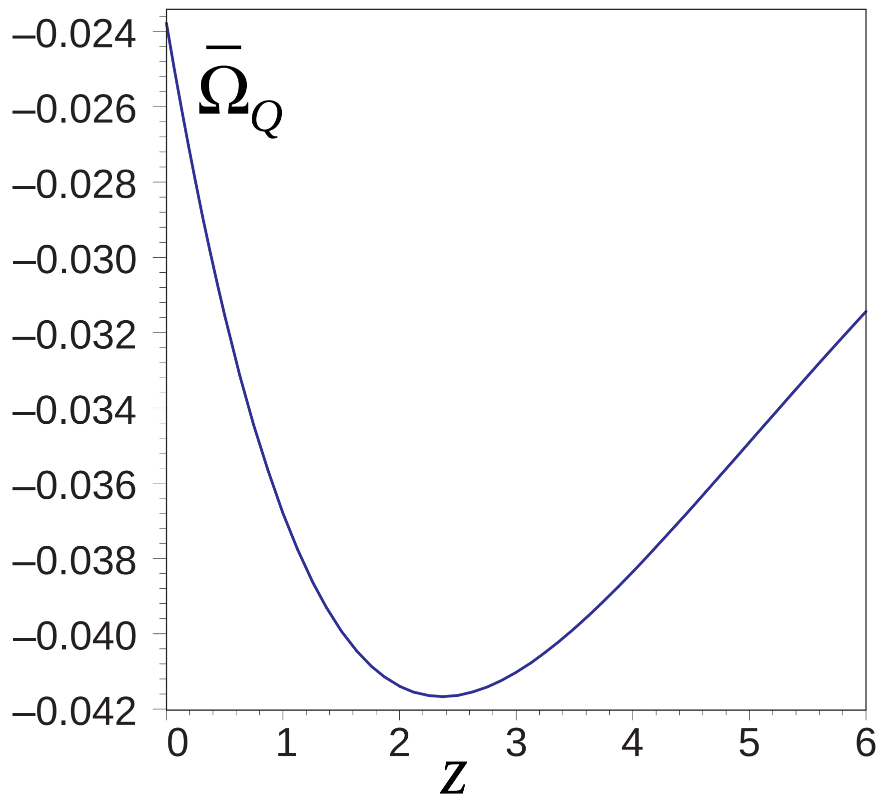
- Void fraction $f_v(t)$ determines many parameters:

$$\bar\gamma_w = 1 + \tfrac{1}{2}f_v = \tfrac{3}{2}\bar H t$$

$$\tau_w = \tfrac{2}{3}t + \frac{2(1-f_{v0})(2+f_{v0})}{27 f_{v0}\bar H_0}\ln\left(1+\frac{9f_{v0}\bar H_0 t}{2(1-f_{v0})(2+f_{v0})}\right)$$

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

Magnitude of backreaction



- Magnitude of $\bar{\Omega}_{\mathcal{Q}}$ 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

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

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

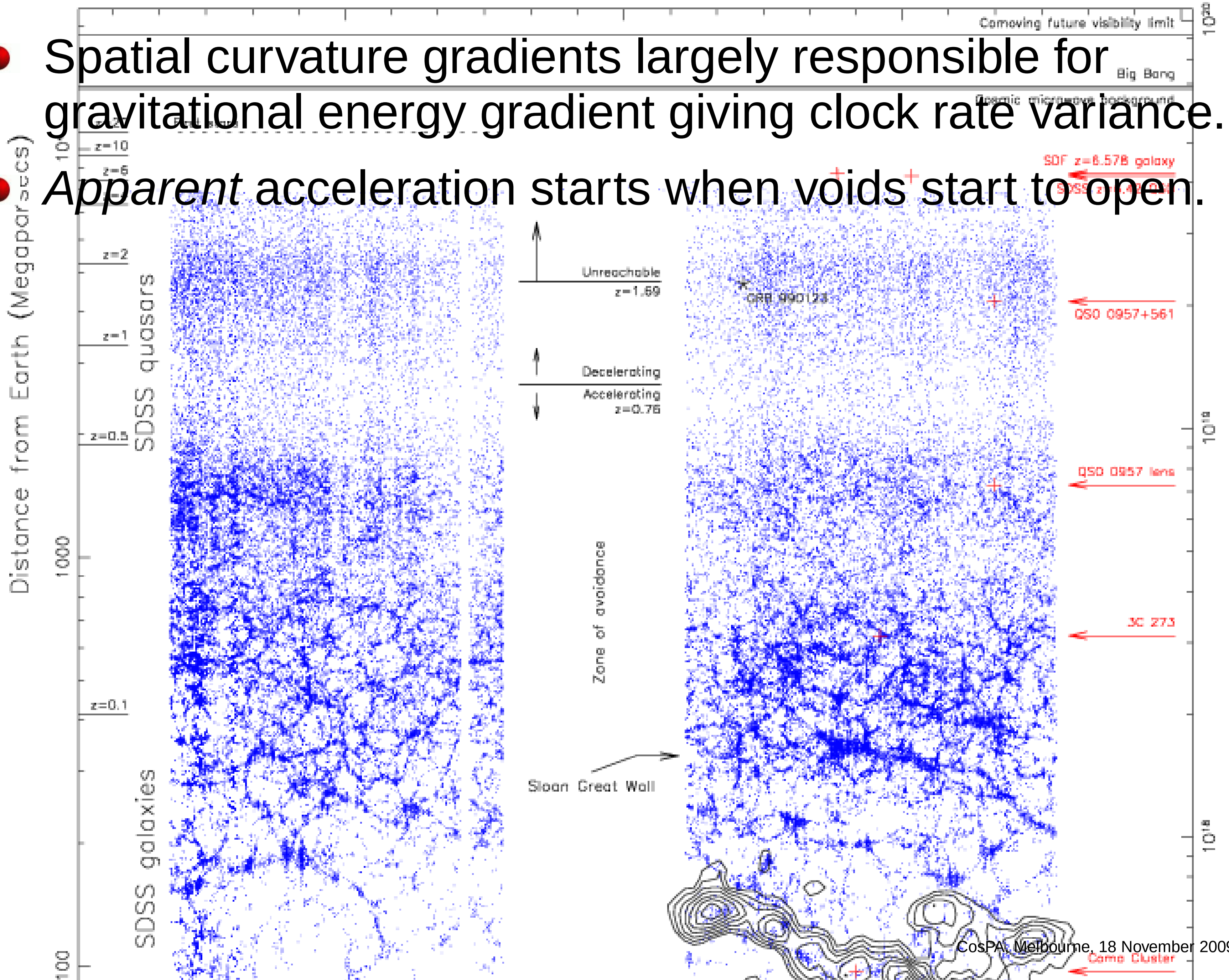
- A wall observer registers apparent cosmic acceleration

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

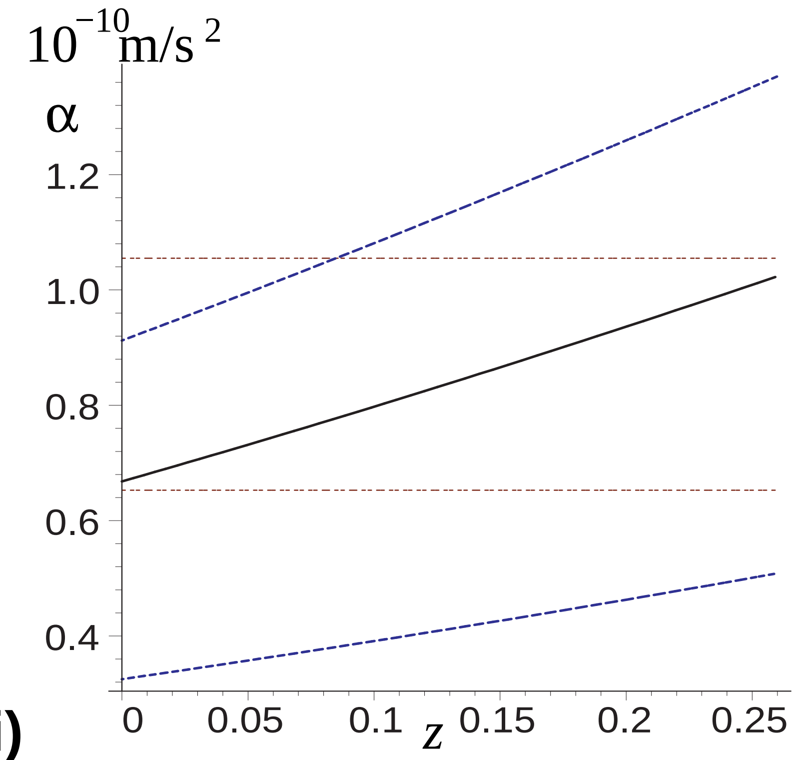
Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small $f_{\rm v}$; changes sign when $f_{\rm v} = 0.58670773\ldots$, and approaches $q \to 0^-$ at late times.

Cosmic coincidence problem solved

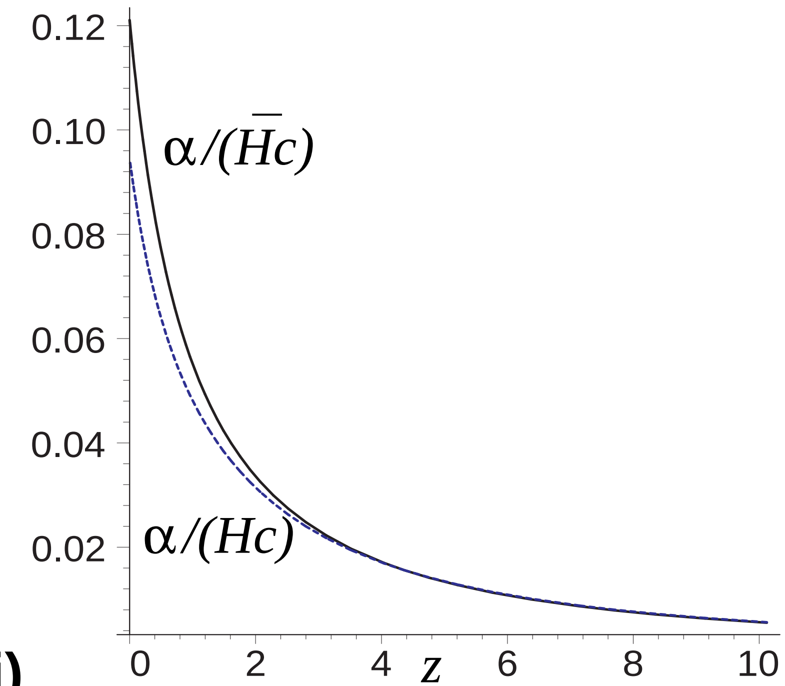
- Spatial curvature gradients largely responsible for gravitational energy gradient giving clock rate variance.
- *Apparent* acceleration starts when voids start to open.



CEP relative deceleration scale



(i)

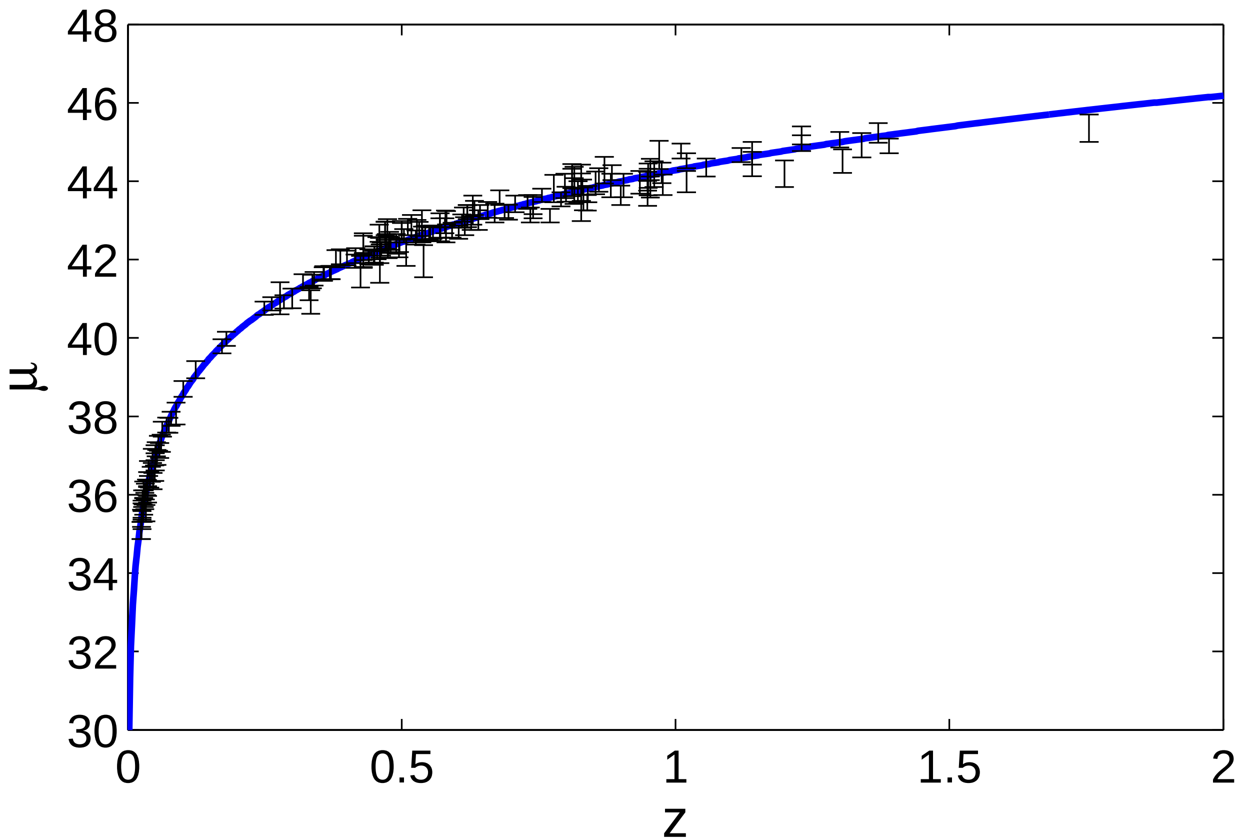


(ii)

By equivalence principle the instantaneous relative deceleration of backgrounds gives an instantaneous 4-acceleration of magnitude $\alpha = H_0 c\bar{\gamma}_{\rm w}\dot{\bar{\gamma}}_{\rm w}/(\sqrt{\bar{\gamma}_{\rm w}^2 - 1})$ 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.

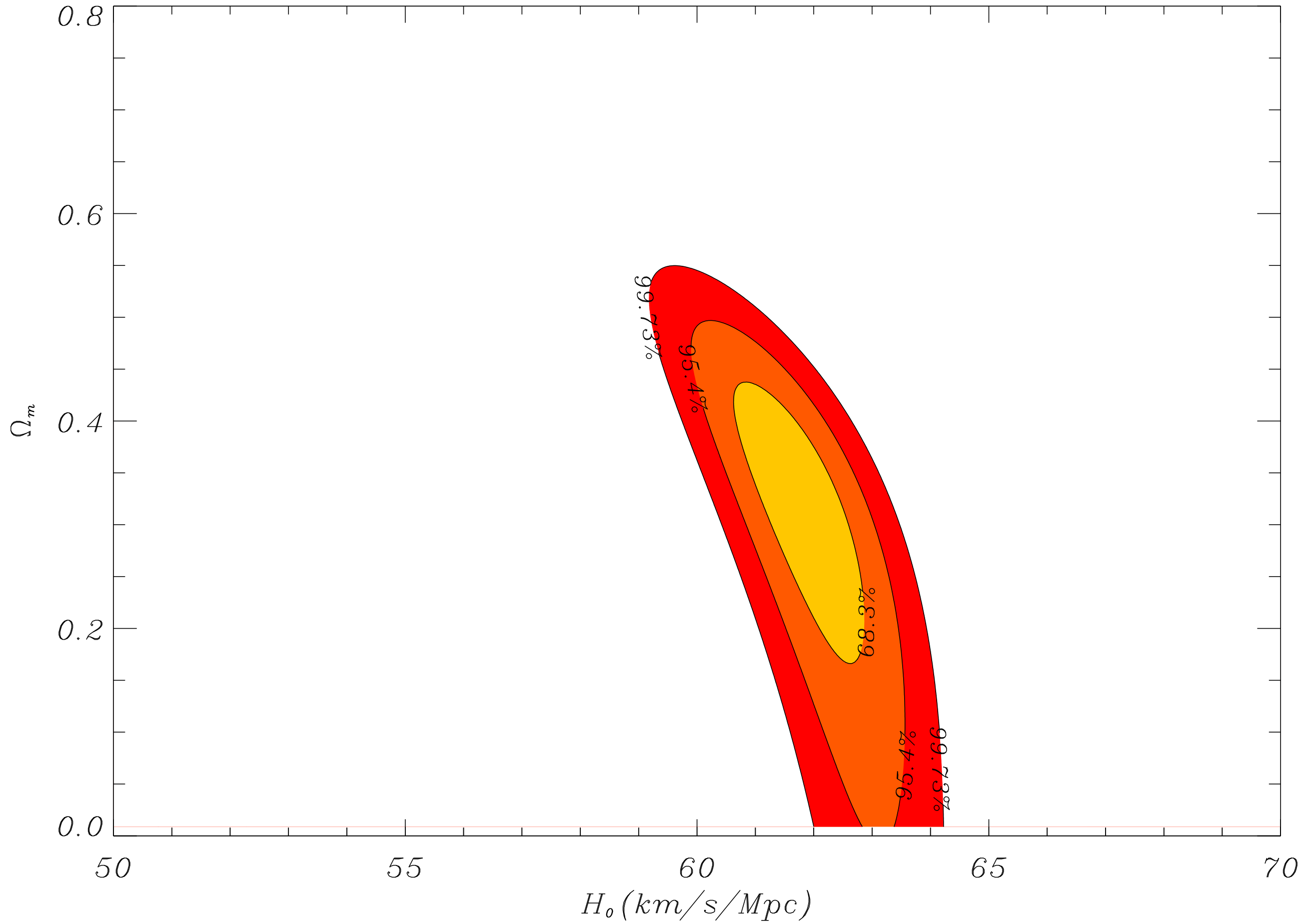
- For $z \lesssim 0.25$, coincides with empirical MOND scale $\alpha_0 = 1.2^{+0.3}_{-0.2} \times 10^{-10}$ ms$^{-2}h_{75}^2 = 8.1^{+2.5}_{-1.6} \times 10^{-11}$ms^{-2} for $H_0 = 61.7$ km s^{-1} Mpc^{-1}.

Test 1: SneIa luminosity distances



- Type Ia supernovae of Riess 2007 Gold data set fit with χ^2 per degree of freedom $= 0.9$
- Type Ia supernovae of Hicken 2009 MLCS17 set fit with χ^2 per degree of freedom $= 1.08$

Test 1: SneIa luminosity distances



Two free parameters H_0 versus Ω_{M0} (dressed shown here), or alternatively "bare values", constrained by Riess07 Gold data fit

Best fit parameters

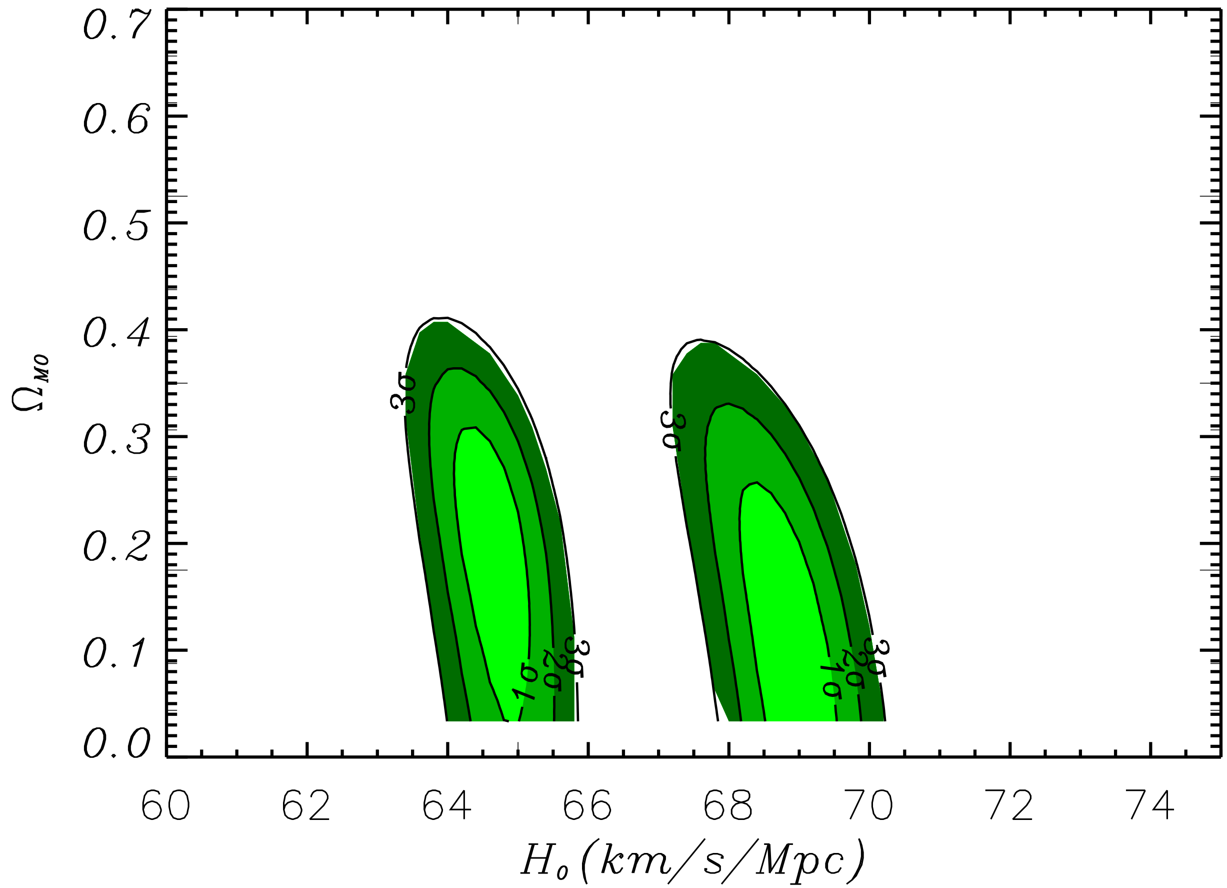
- Hubble constant $H_0 = 61.7^{+1.2}_{-1.1}$ km s^{-1} Mpc^{-1}
- present void volume fraction $f_{v0} = 0.76^{+0.12}_{-0.09}$
- bare density parameter $\bar{\Omega}_{M0} = 0.125^{+0.060}_{-0.069}$
- dressed density parameter $\Omega_{M0} = 0.33^{+0.11}_{-0.16}$
- non–baryonic dark matter / baryonic matter mass ratio $(\bar{\Omega}_{M0} - \bar{\Omega}_{B0})/\bar{\Omega}_{B0} = 3.1^{+2.5}_{-2.4}$
- bare Hubble constant $\bar{H}_0 = 48.2^{+2.0}_{-2.4}$ km s^{-1} 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 $\tau_0 = 14.7^{+0.7}_{-0.5}$ Gyr

More recent results

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

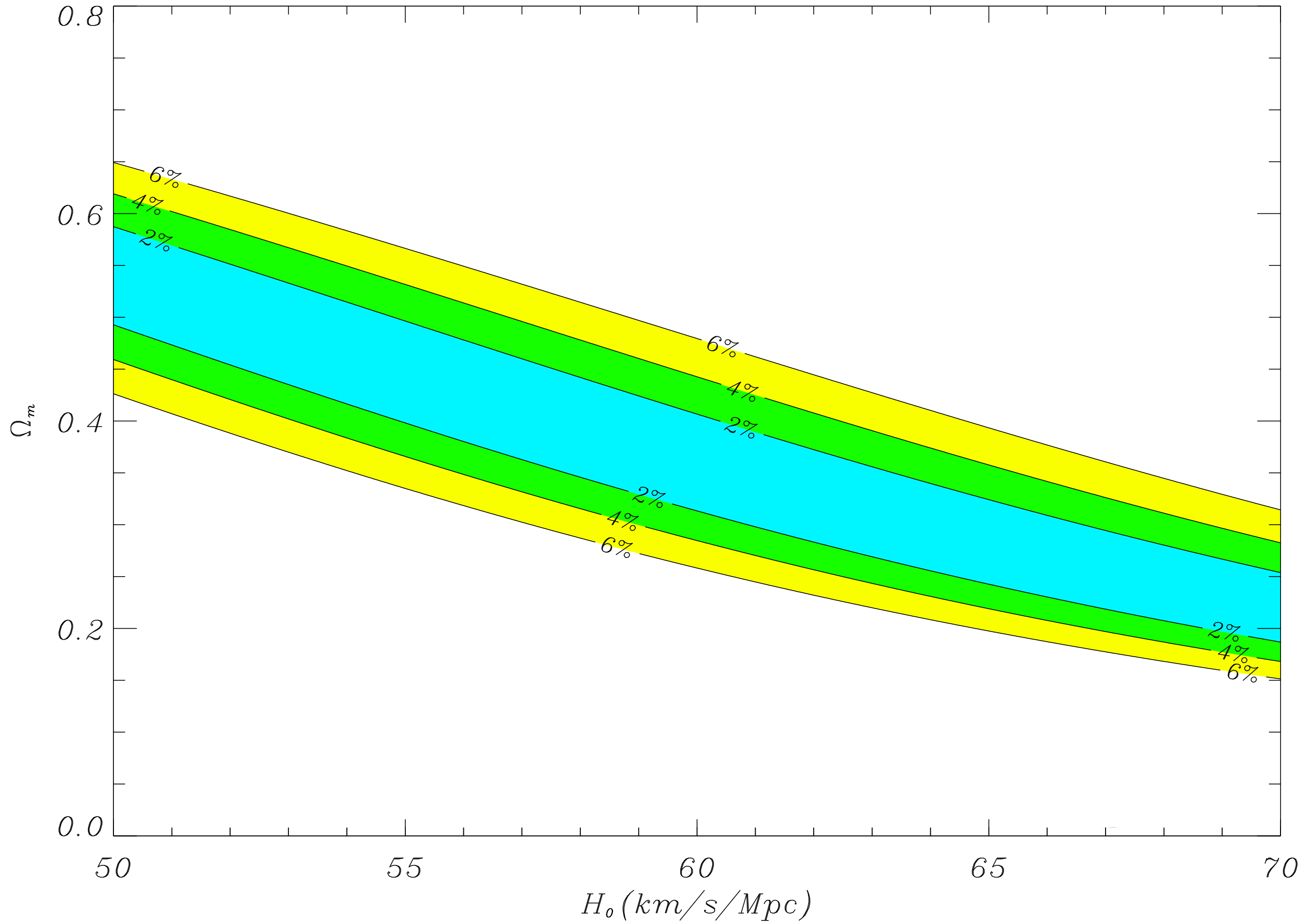
- Bayesian comparison for MLCS reductions with priors $55 \leq H_0 \leq 75$ km s^{-1} Mpc^{-1}, $0.01 \leq \Omega_{M0} \leq 0.5$.
- Currently enough data to distinguish models; but systematic uncertainties need to be understood first.
- SALT reduced data (Union, Constitution) trickier, as cosmology is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

Test 1: SneIa luminosity distances



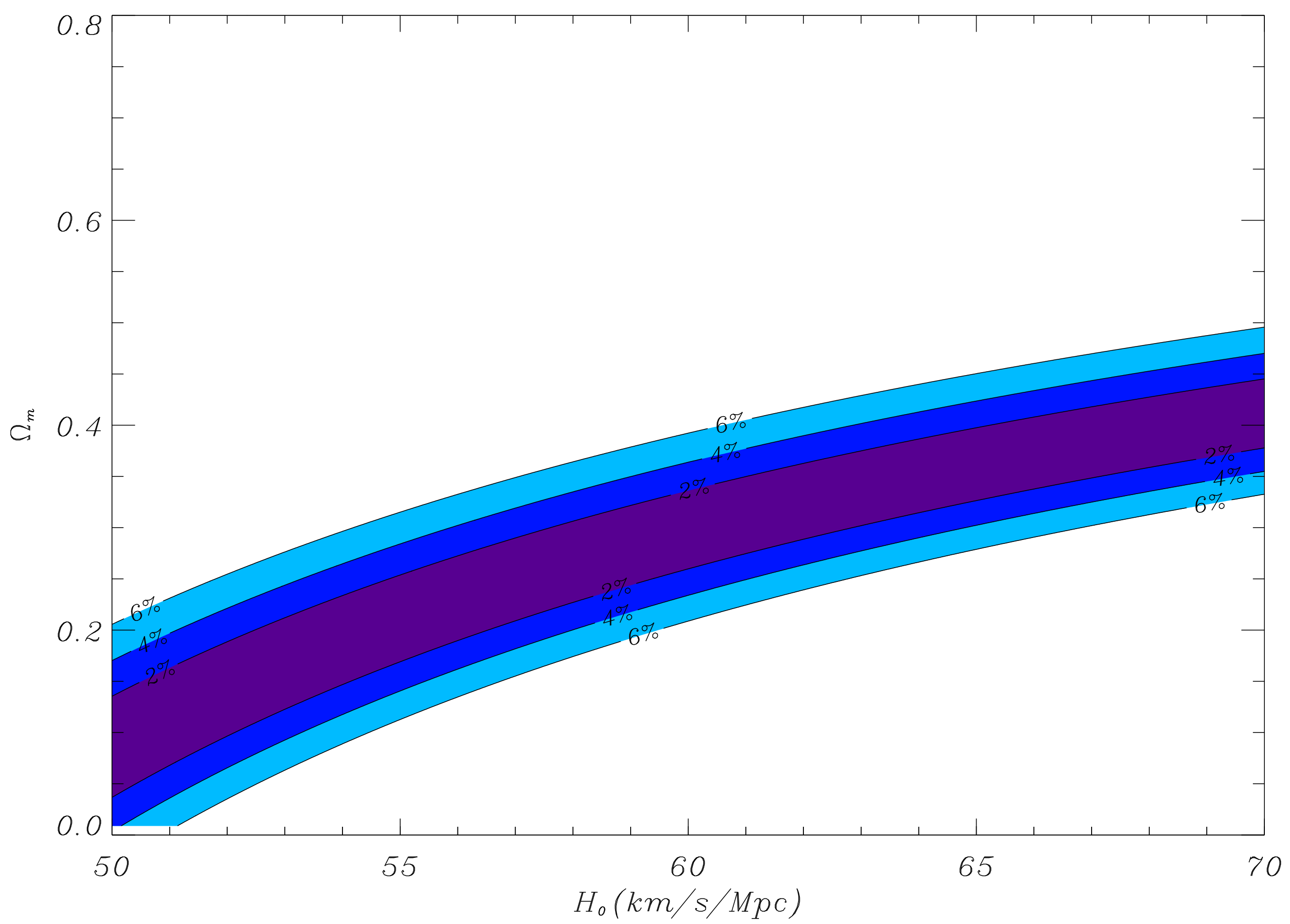
Left: fit to 372 MLCS17 SneIa of Hicken *et al.*; right fit to 307 Union SneIa.

Test 2: Angular scale of CMB Doppler peaks



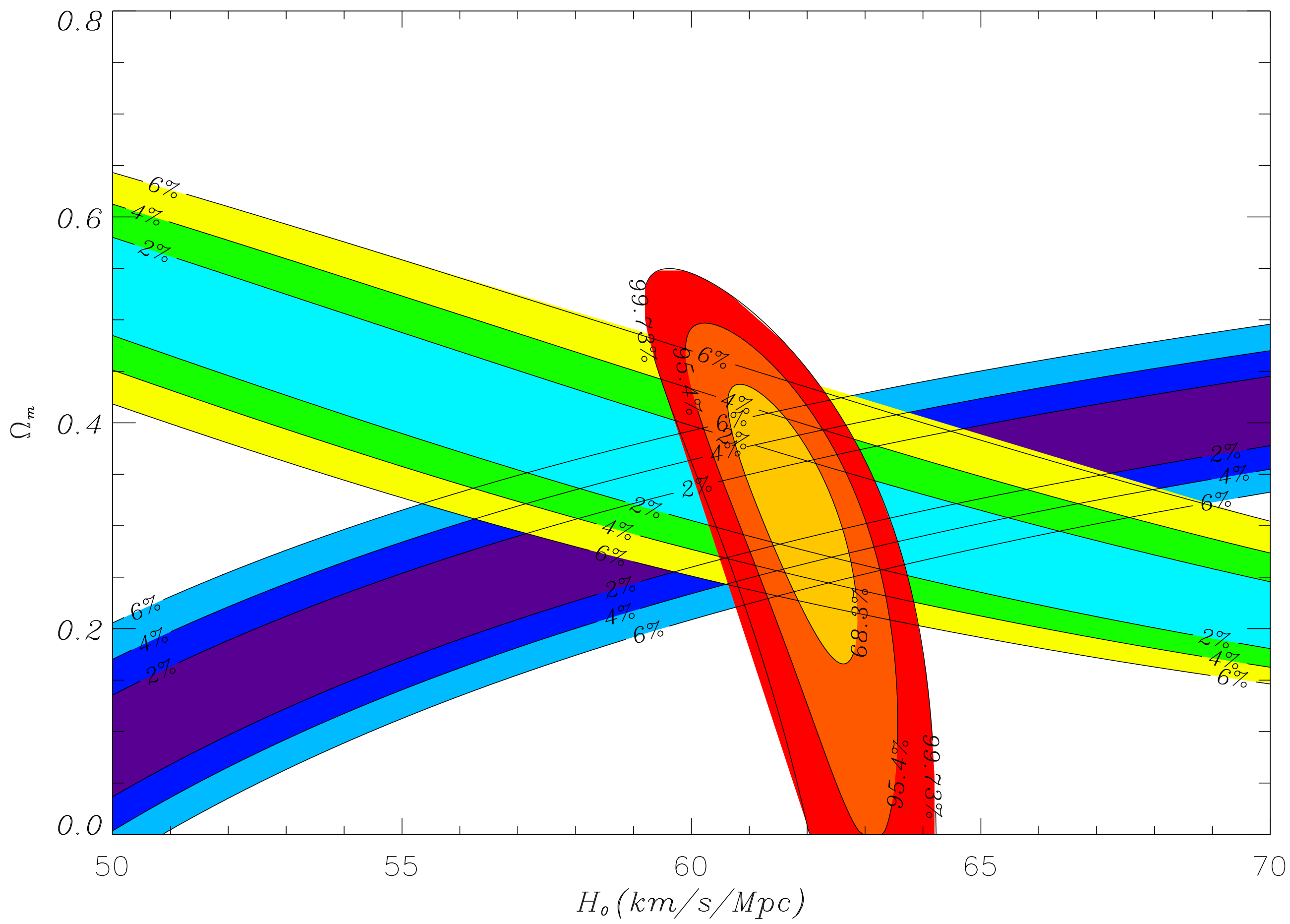
Parameters within the (Ω_m, H_0) plane which fit the angular scale of the sound horizon $\delta = 0.01$ rad deduced for WMAP, to within 2%, 4% and 6%.

Test 3: Baryon acoustic oscillation scale



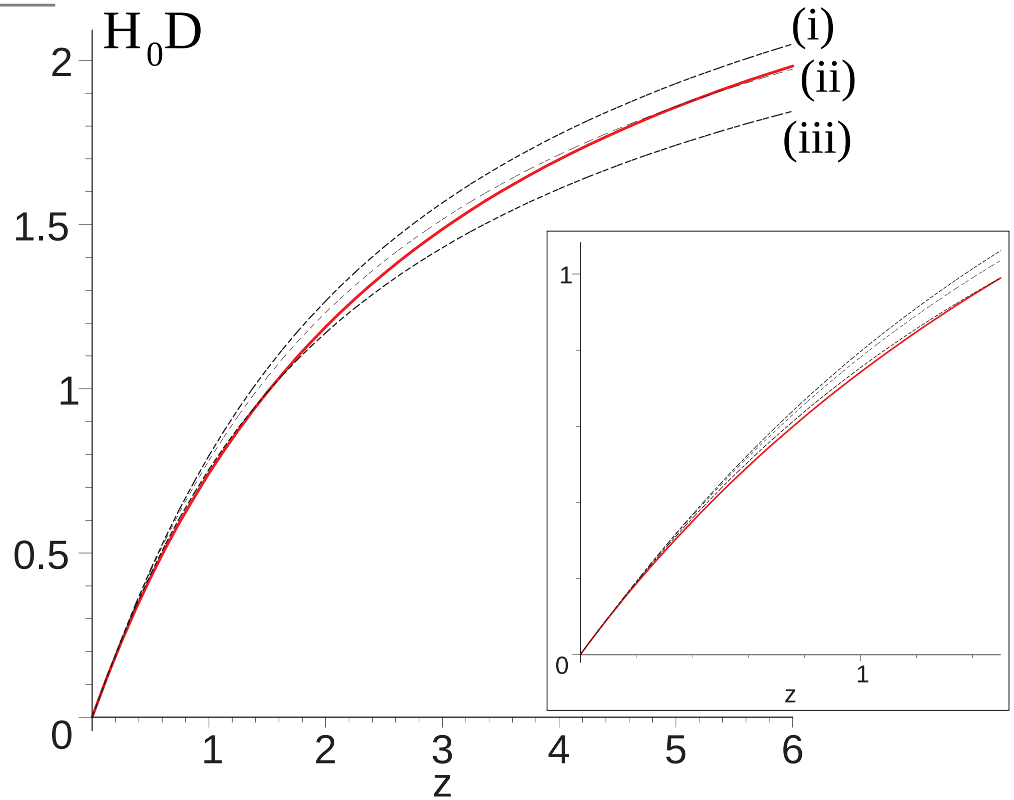
Parameters within the (Ω_m,H_0) plane which fit the effective comoving baryon acoustic oscillation scale of $104h^{-1}$ Mpc, as seen in 2dF and SDSS.

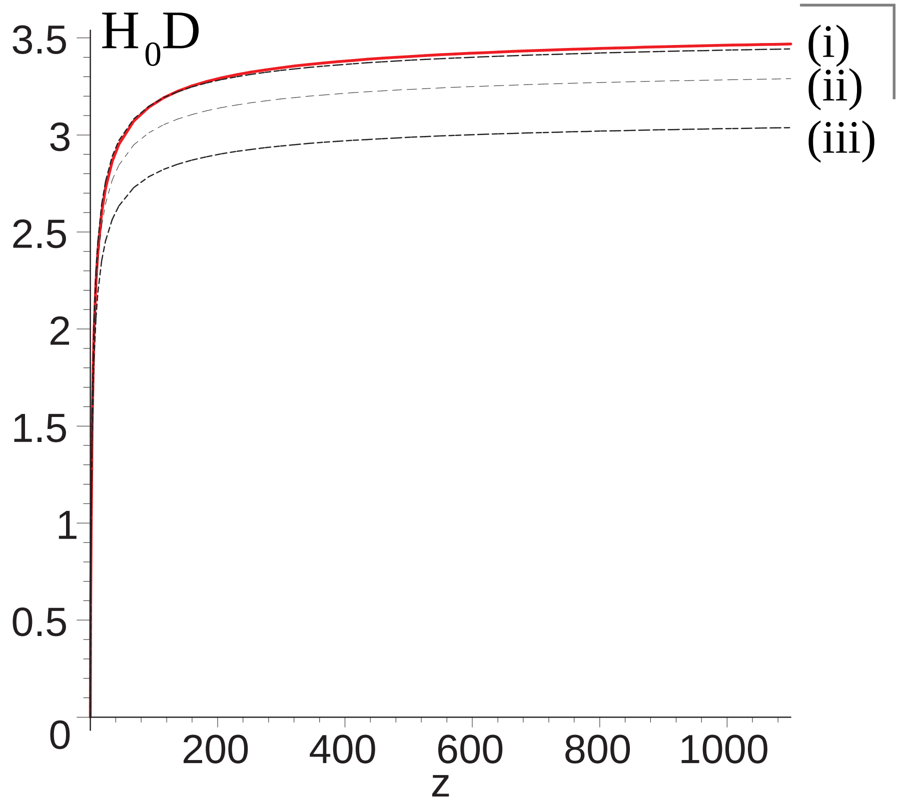
Agreement of independent tests



Best–fit parameters: $H_0 = 61.7^{+1.2}_{-1.1}$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.33^{+0.11}_{-0.16}$ (1σ errors for SneIa only) [Leith, Ng & Wiltshire, ApJ 672 (2008) L91]

Dressed "comoving distance" $D(z)$

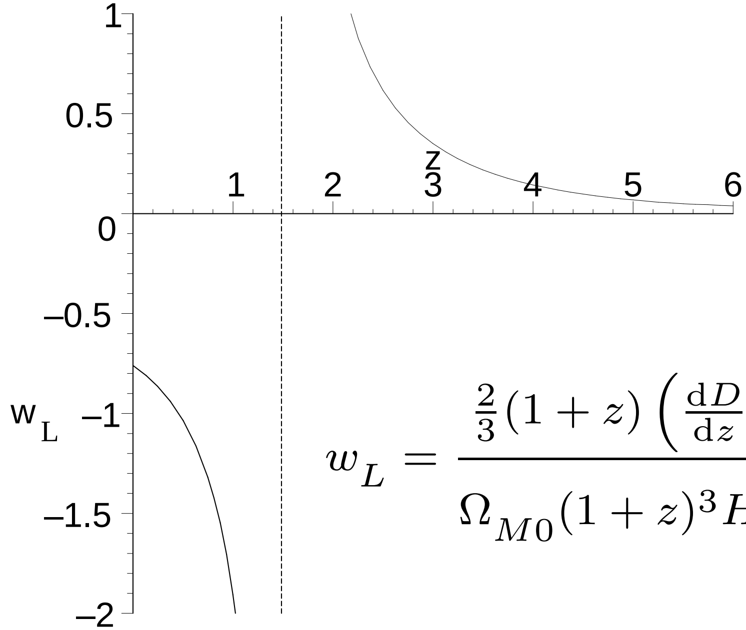




Best-fit timescape model **(red line)** compared to 3 spatially flat ΛCDM models: **(i)** best–fit to WMAP5 only ($\Omega_\Lambda = 0.75$); **(ii)** joint WMAP5 + BAO + SneIa fit ($\Omega_\Lambda = 0.72$); **(iii)** best flat fit to (Riess07) SneIa only ($\Omega_\Lambda = 0.66$).

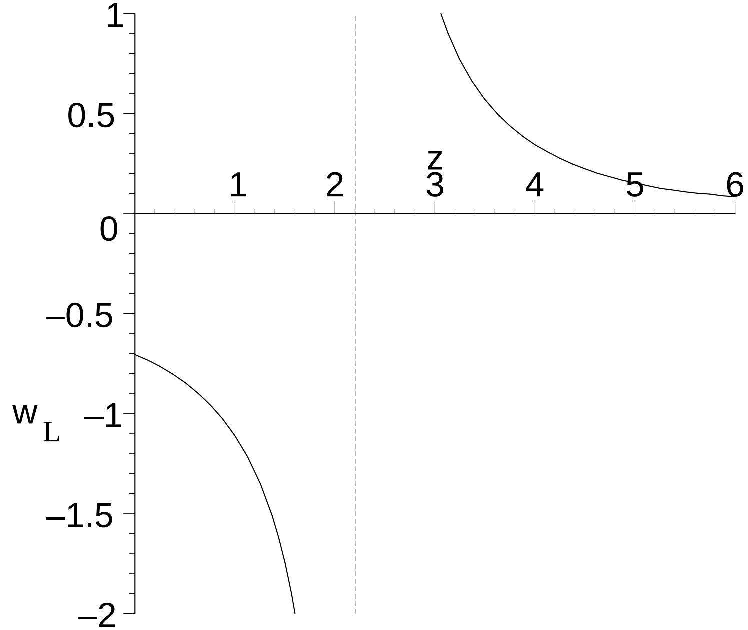
Equivalent “equation of state”?

(i)



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

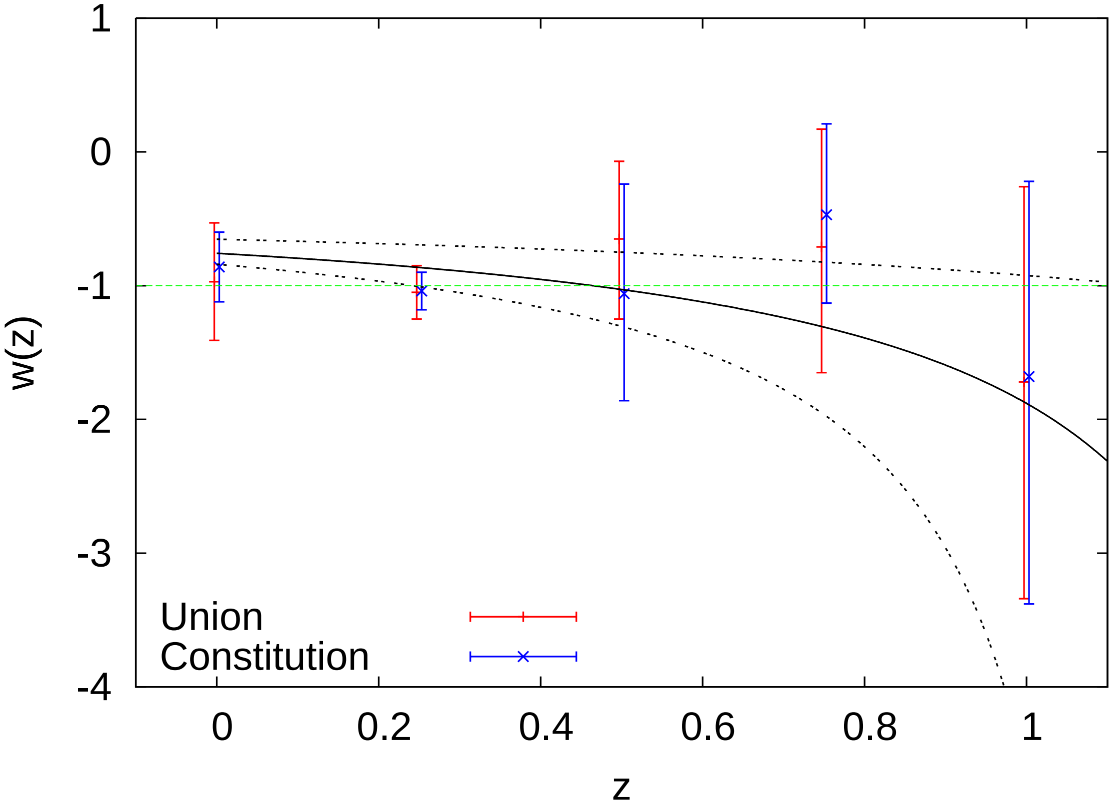
(ii)



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.

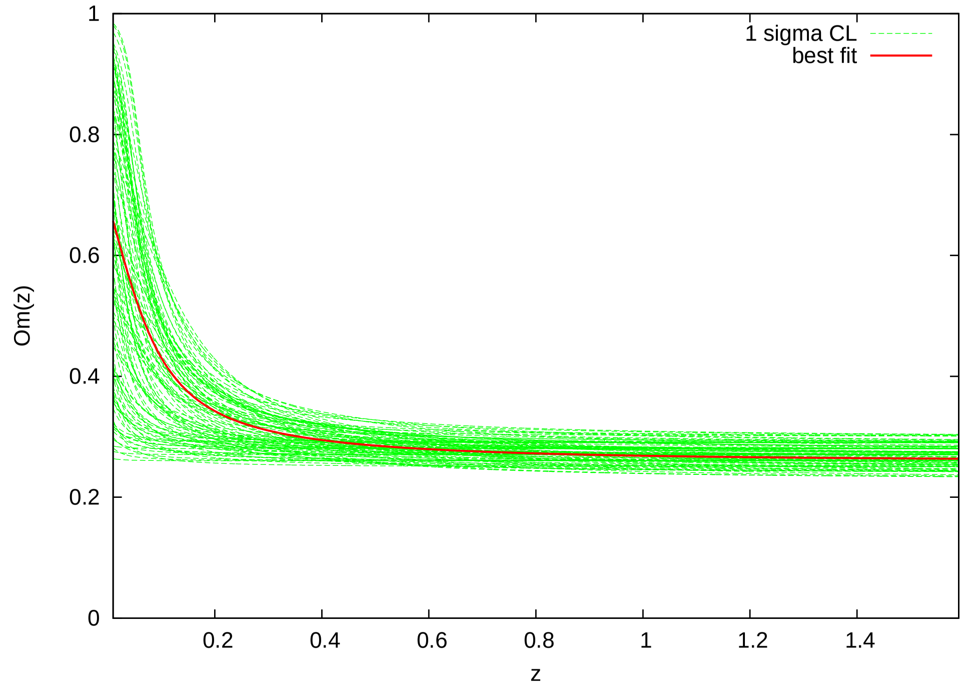
Tests of “equation of state”



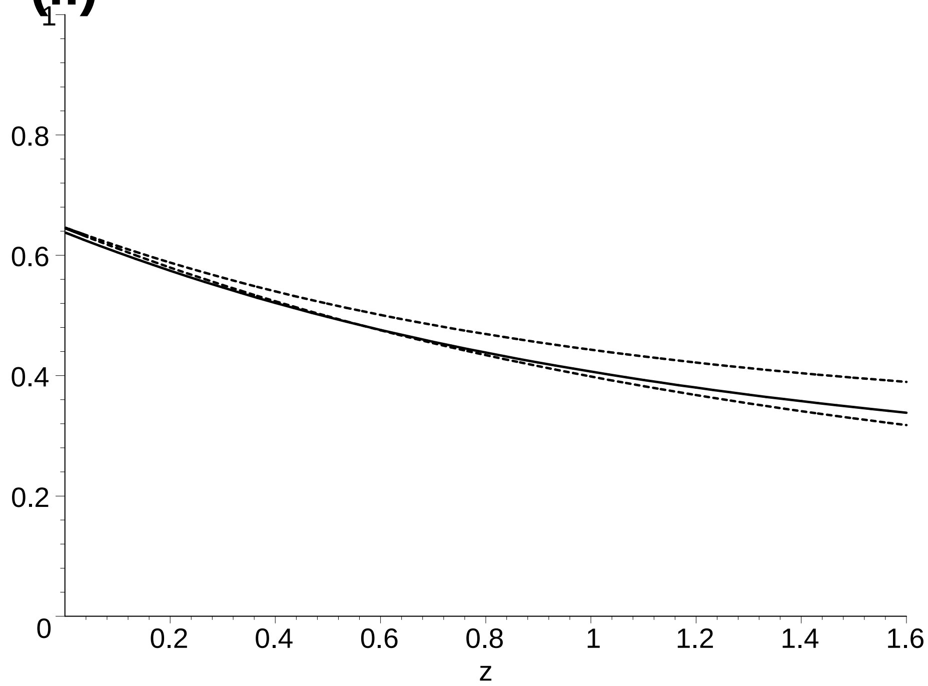
- Zhao and Zhang arXiv:0908.1568 find mild 95% evidence in favour of $w(z)$ crossing the phantom divide from $w > -1$ to $w < -1$ in the range $0.25 < w < 0.75$”
- Serra *et al*. arXiv:0908.3186 find “no evidence” of dynamical dark, but their data analysis shown above is also consistent with timescape

Sahni, Shafieloo and Starobinsky $Om(z)$

(i)



(ii)

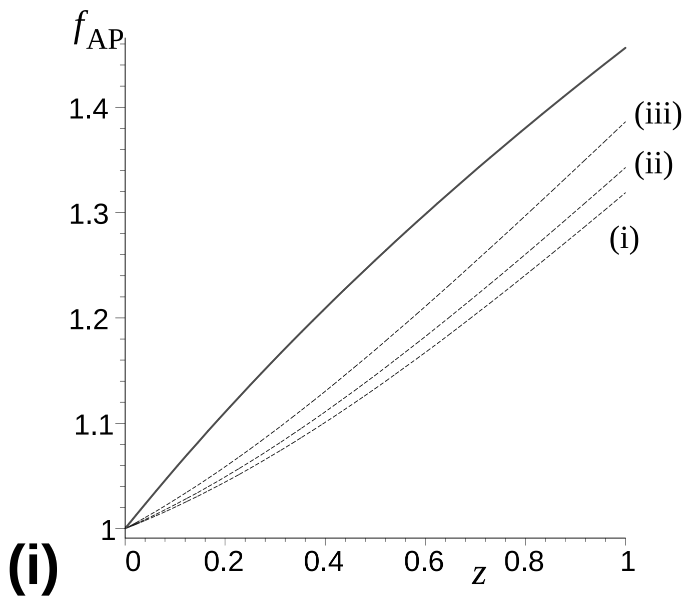


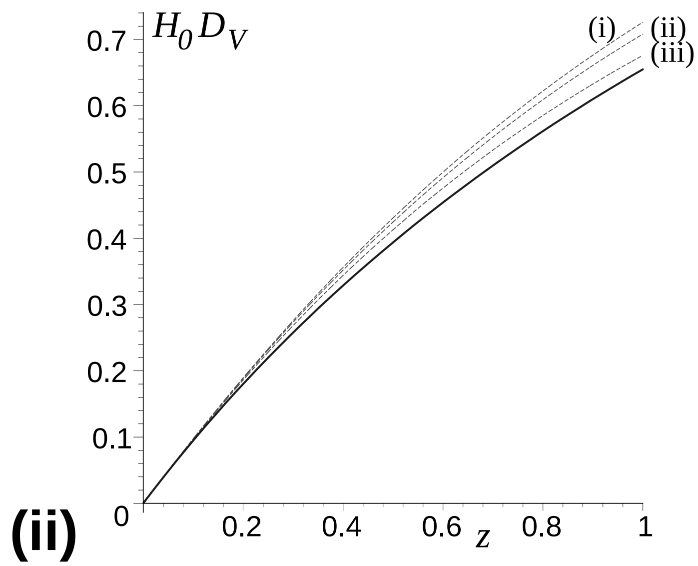
(i) Om(z) fit by Shafieloo *et al*. to SN+BAO+CMB with $w(z)=-\frac{1}{2}[1+\tanh((z-z_t)\Delta)]$;

(ii) TS model prediction for Om(z) (NOT same w(z)) – best-fit and 1σ uncertainties

- Shafieloo *et al*., arxiv:0903.5141, fit $Om(z)$ with hint that "dark energy is decaying".
- Intercept $Om(0)$ agrees well with TS model expectation

Baryon acoustic oscillation measures

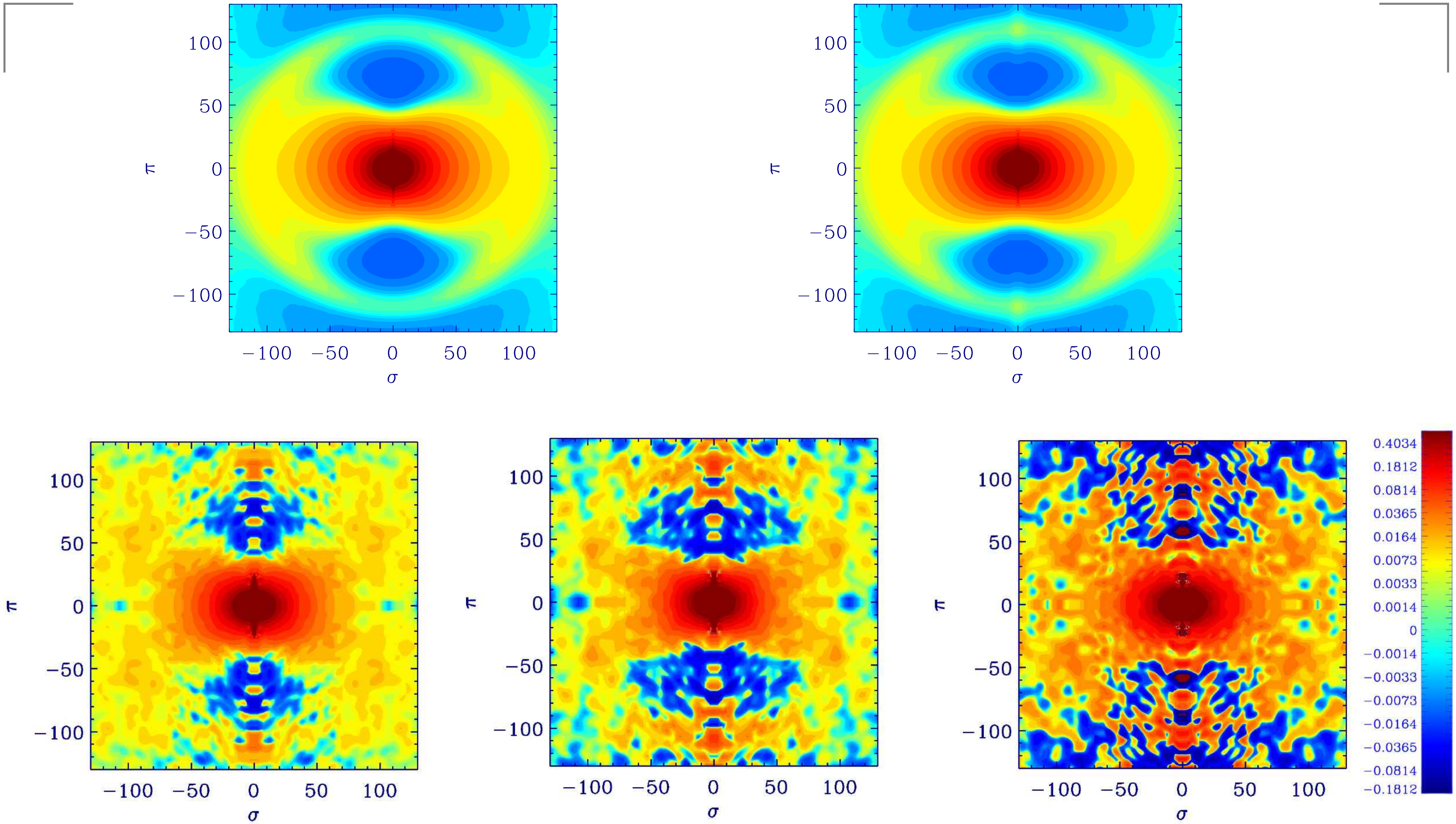




Best-fit timescape model **(red line)** compared to 3 spatially flat ΛCDM models as earlier: **(i)** Alcock–Paczyński test; **(ii)** D_V measure.

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

Gaztañaga, Cabre and Hui 0807.3551



$z = 0.15\text{-}0.47$ $z = 0.15\text{-}0.30$ $z = 0.40\text{-}0.47$

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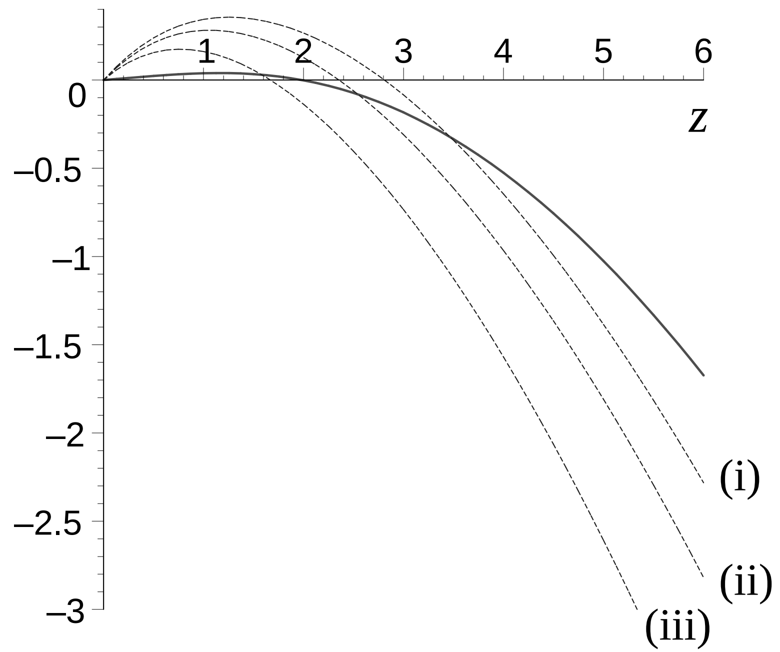
redshift range	$\Omega_{M0}h^2$	$\Omega_{B0}h^2$	Ω_{C0}/Ω_{B0}
0.15-0.30	0.132	0.028	3.7
0.15-0.47	0.12	0.026	3.6
0.40-0.47	0.124	0.04	2.1

- 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}Li anomaly.

Redshift time drift (Sandage–Loeb test)



$H_0^{-1}\frac{\mathrm{d}z}{\mathrm{d}\tau}$ for the timescape model with $f_{v0} = 0.762$ (solid line) is compared to three spatially flat ΛCDM models with the same values of $(\Omega_{M0}, \Omega_{\Lambda 0})$ as in previous figures.

- Measurement is extremely challenging. May be feasible over a 10–20 year period by precision measurements of the Lyman-α 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

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

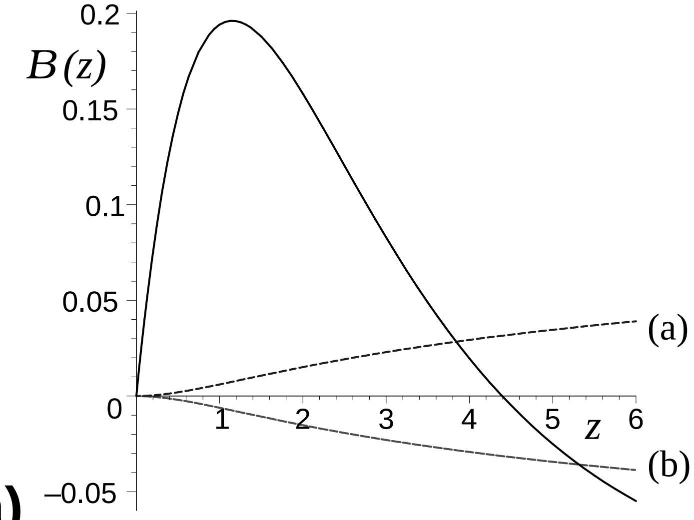
where $\mathcal{B}(z) \equiv [H(z)D'(z)]^2 - 1$. Thus

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

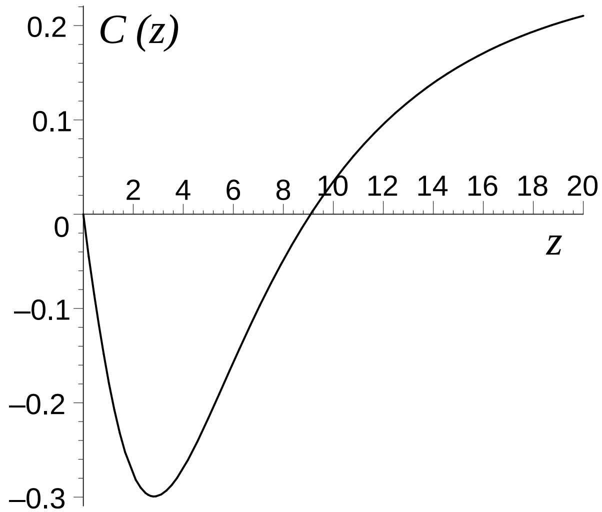
for any homogeneous isotropic cosmology, irrespective of DE.

- 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)



(b)

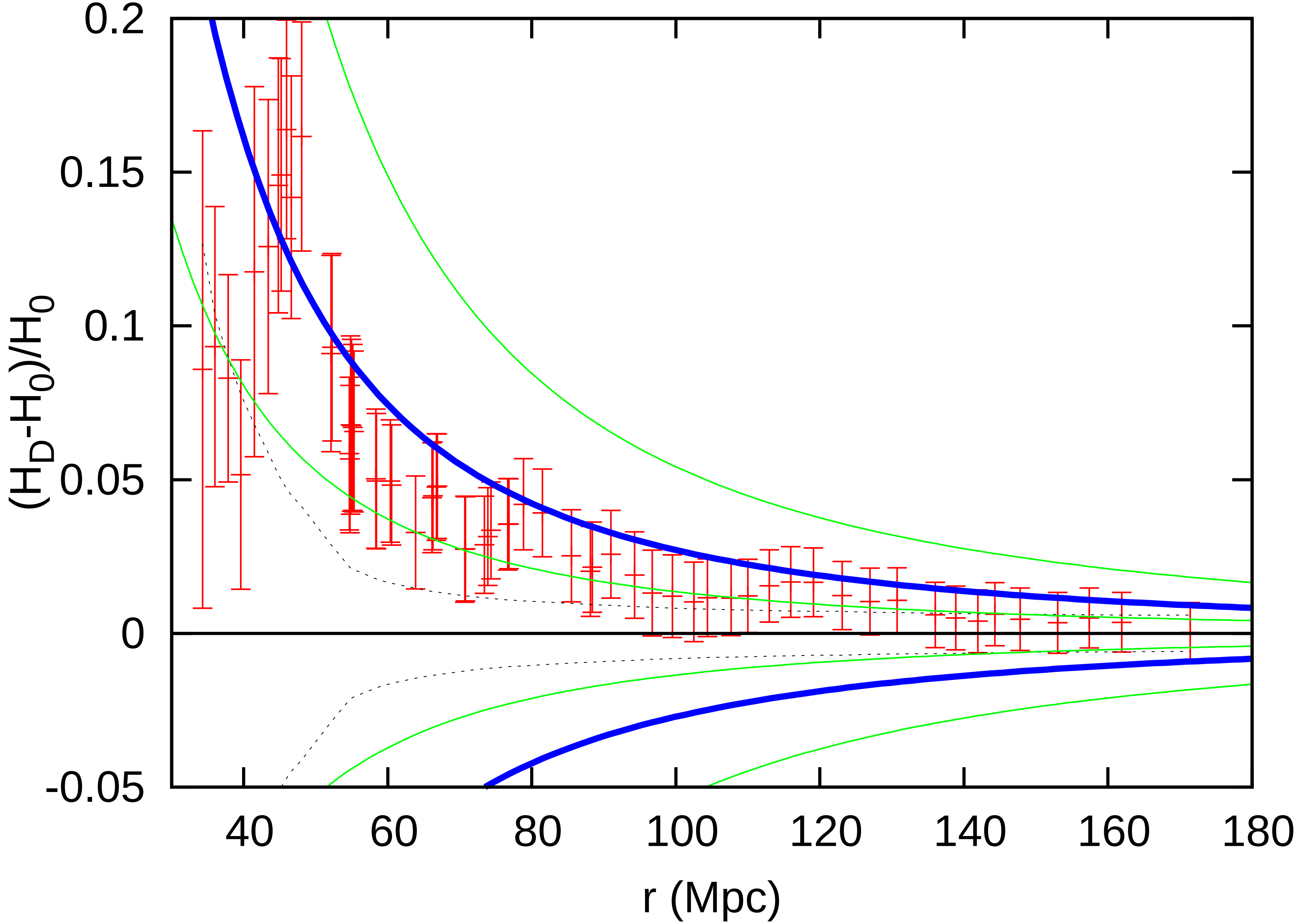
(a) $\mathcal{B} \equiv [H(z)D'(z)]^2 - 1$ for timescape model with $f_{v0} = 0.762$ (solid line) and two ΛCDM models (dashed lines): **(i)** $\Omega_{M0} = 0.28$, $\Omega_{\Lambda 0} = 0.71$, $\Omega_{k0} = 0.01$; **(ii)** $\Omega_{M0} = 0.28$, $\Omega_{\Lambda 0} = 0.73$, $\Omega_{k0} = -0.01$; **(b)** $\mathcal{C}(z)$.

- 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, $30h^{-1}$Mpc, then decreasing til levelling out by $100h^{-1}$Mpc.
- Consistent with observed Hubble bubble feature (Jha, Riess, Kirshner ApJ 659, 122 (2007)), which is unexplained (and problem for) ΛCDM.
- 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 $H_0 = 74.2 \pm 3.6$ km s^{-1} Mpc^{-1} of SH_0ES 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 $H_0 = 72.3$ km s^{-1} Mpc^{-1} at $30h^{-1}$ Mpc scale
- Latest FLRW BAO value: $H_0 = 68.2 \pm 2.2$ km s^{-1} 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] $H_0 = 67.2 \pm 11.4$ km s^{-1} 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 ΛCDM and may resolve significant puzzles – e.g., primordial lithium abundance anomaly
- Many tests can be done to distinguish from ΛCDM.
- It is crucial that ΛCDM assumptions such as Friedmann equation are not used in data reduction.
- Many details – averaging scheme etc – may change, but fundamental questions remain