Dark energy from cosmic structure

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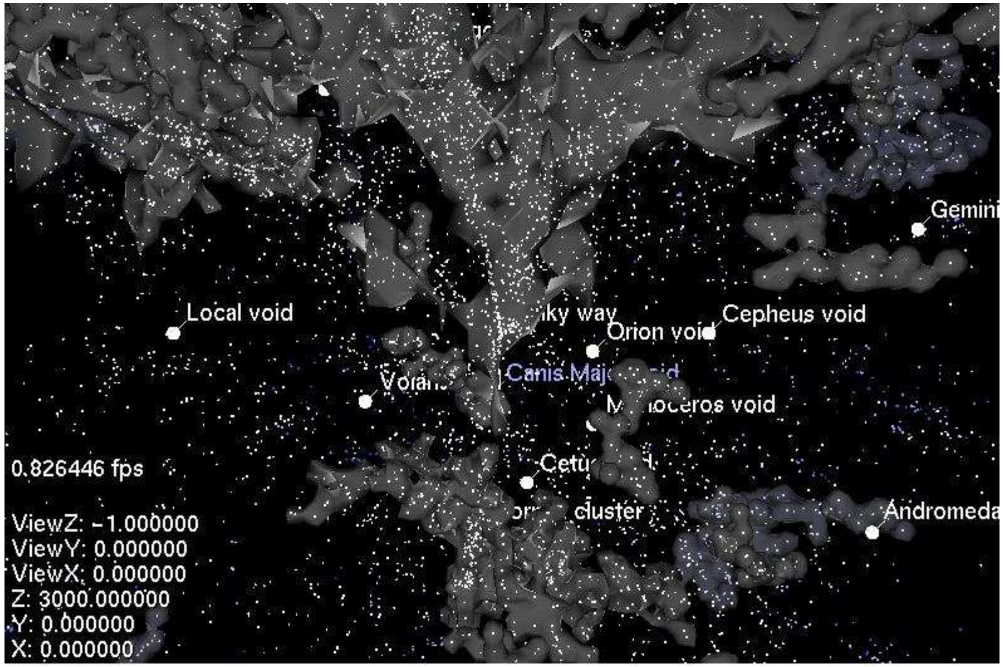


DLW: **New J. Phys. 9 (2007) 377**

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**

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

M.A. Nazer & DLW: **arXiv:1410.3470**

Recent summer school lectures: **arXiv:1311.3787**

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*
- Overview of current status of cosmological tests
  - SneIa, BAO, CMB (Ahsan Nazer), . . .
  - H_0 variance (James McKay), 'local'/global H_0 . . .
- Future tests
  - Timescape and ΛCDM distinguishable with *Euclid*

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

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

Backreaction in Buchert averaging

- *Kinematic backreaction* term can also be written

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

  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]

$$\left. \begin{array}{c} g^{\rm stellar}_{\mu\nu} \longrightarrow g^{\rm galaxy}_{\mu\nu} \longrightarrow g^{\rm cluster}_{\mu\nu} \longrightarrow g^{\rm wall}_{\mu\nu} \\ \vdots \\ g^{\rm void}_{\mu\nu} \end{array} \right\} \longrightarrow g^{\rm universe}_{\mu\nu}$$

Dilemma of gravitational energy…

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

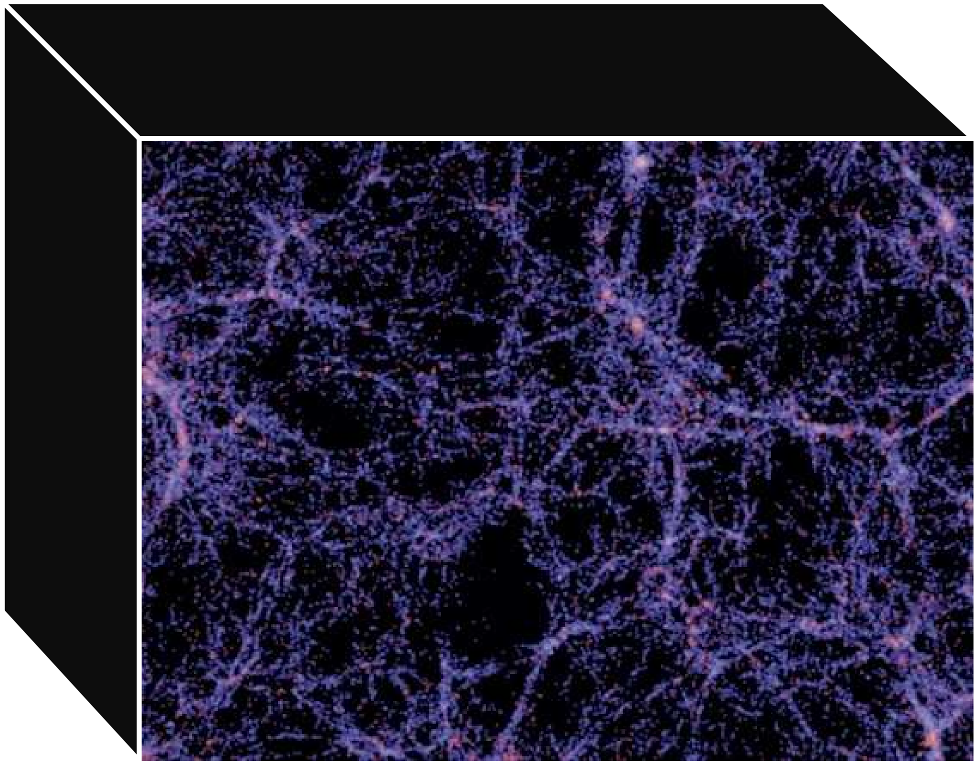
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- 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)

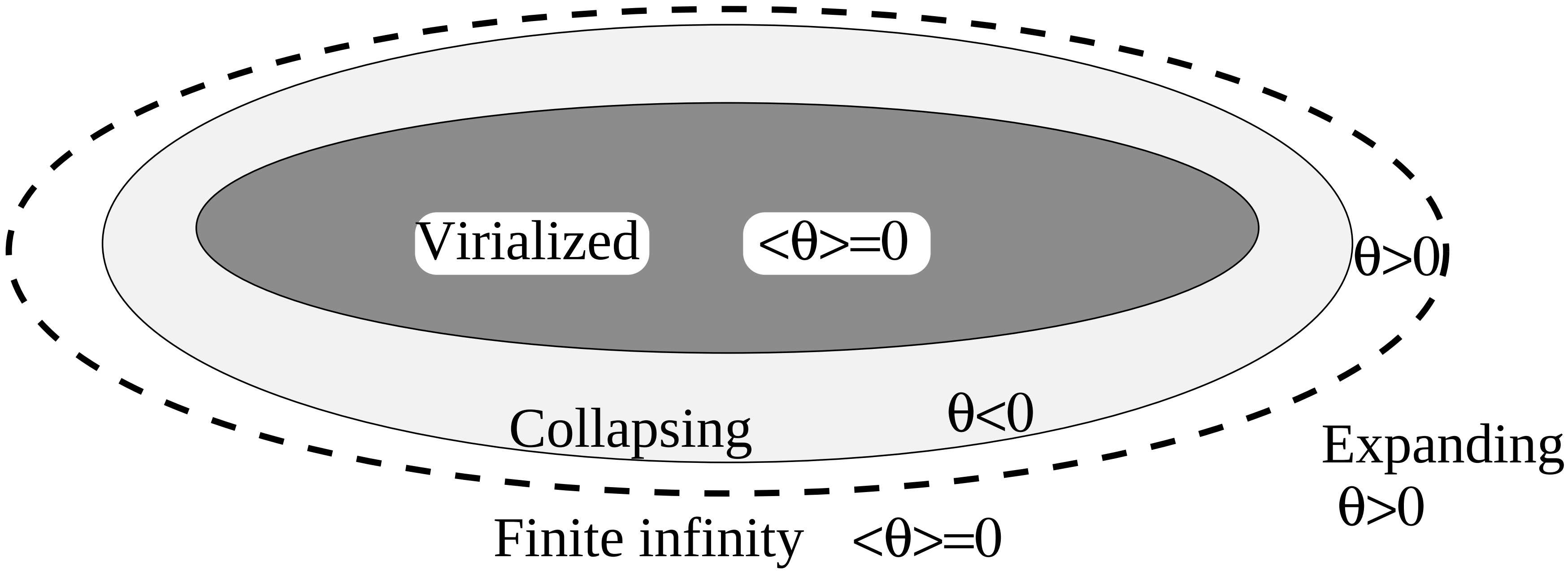
Cosmological Equivalence Principle

- *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*,

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

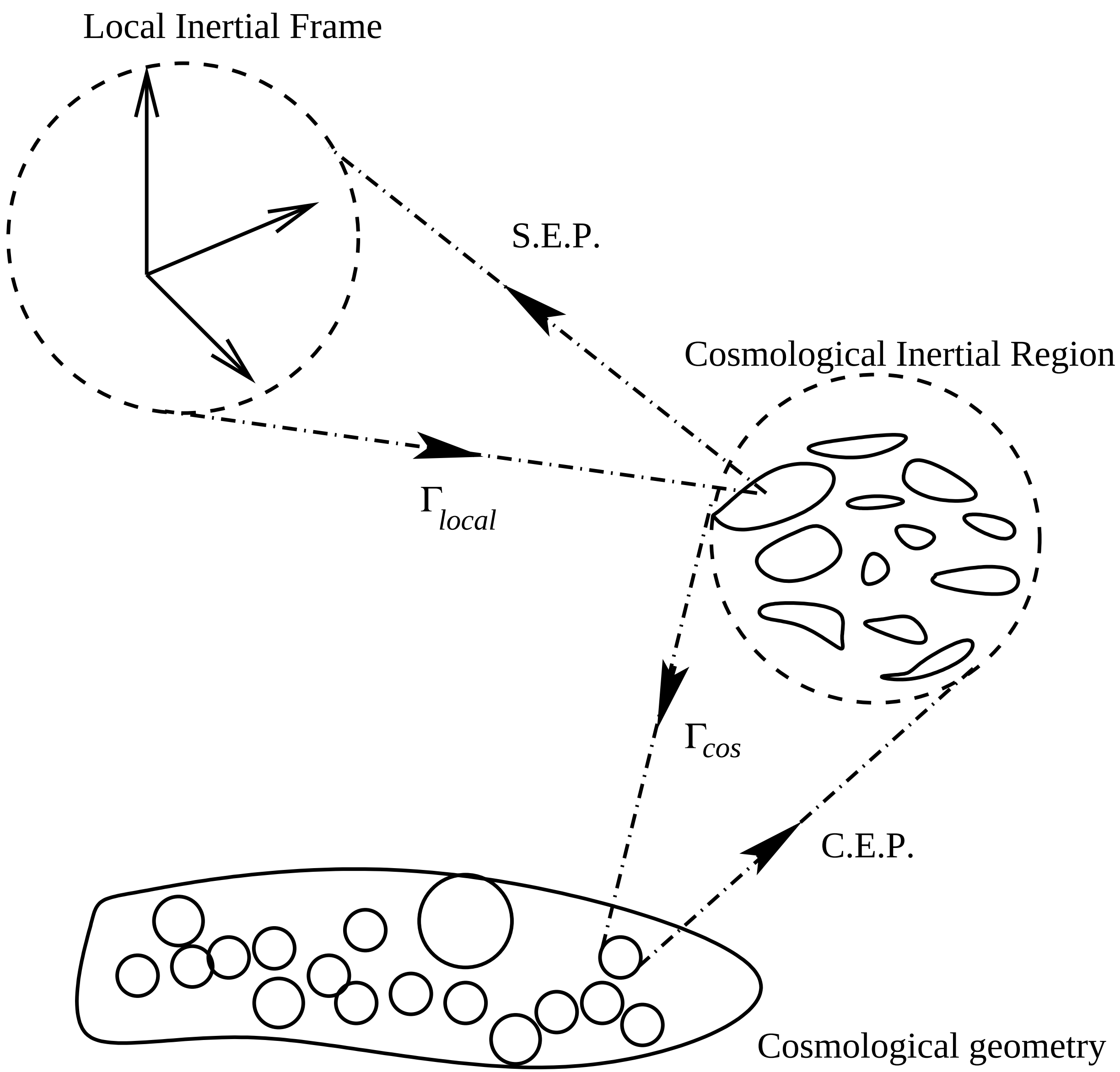
- Defines Cosmological Inertial Region (CIR) in which *regionally isotropic* volume expansion is equivalent to a velocity in special relativity
- Such velocities integrated on a bounding 2-sphere define *"kinetic energy of expansion"*: globally it has gradients

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.

Statistical geometry. . .



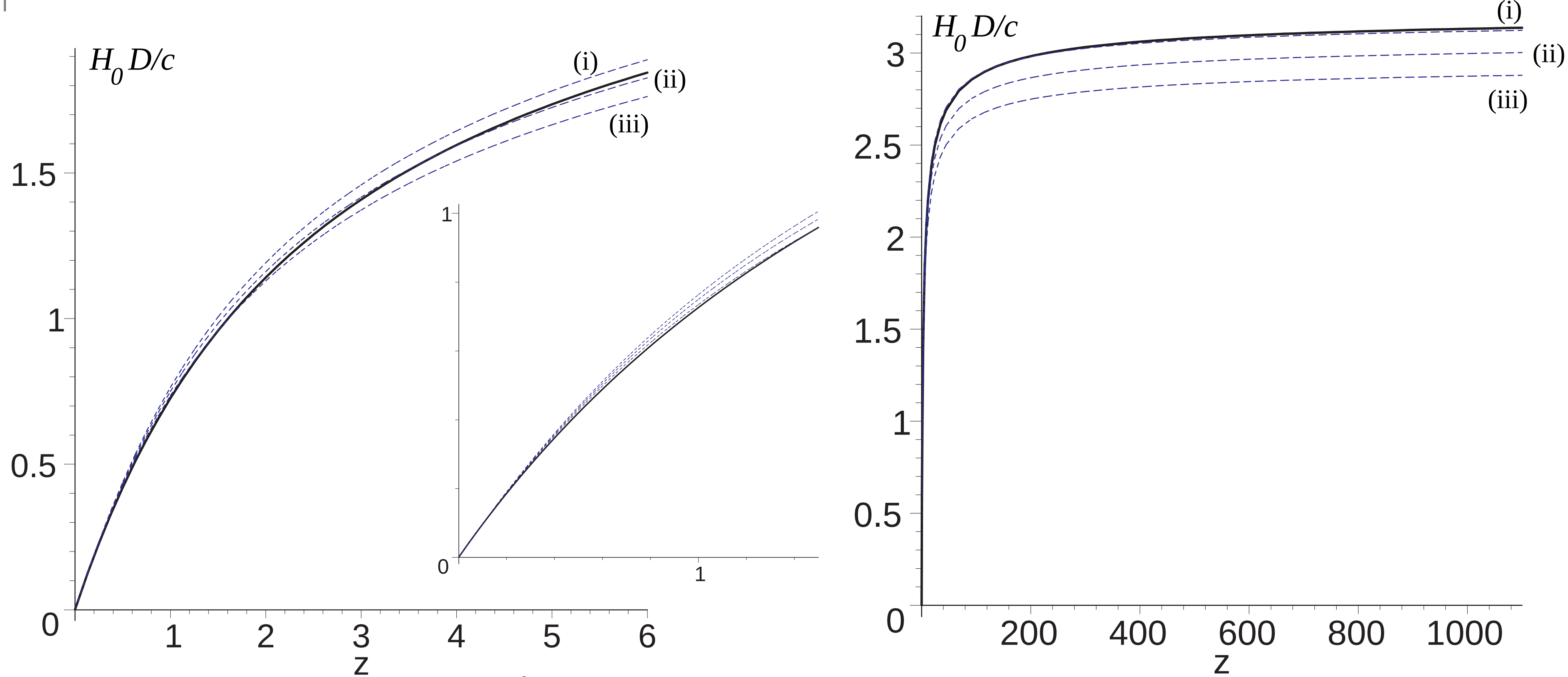
Why is ΛCDM so successful?

- 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

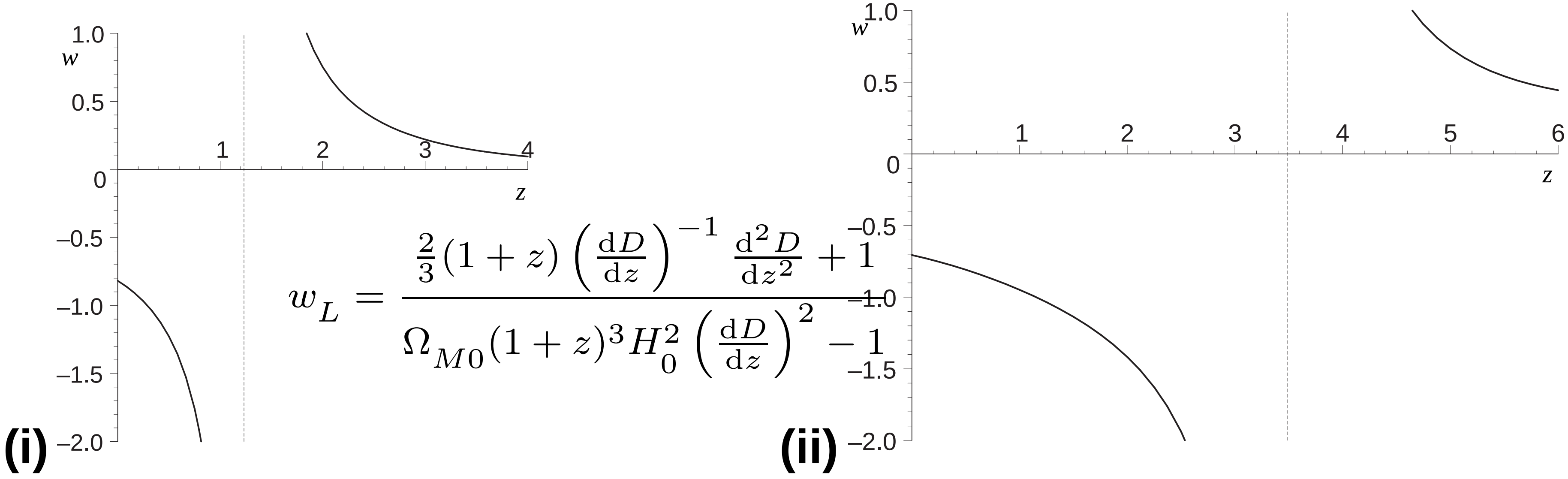
- Take *horizon volume average* of two populations:
  - *voids*: negatively curved, volume fraction, $f_{\rm v}$
  - *"walls"* $=\ \cup\{$*sheets*, *filaments*, *knots*$\}$ coarse grained as spatially flat, volume fraction, $f_{\rm w}=1-f_{\rm v}$
- *Solve Buchert equations*:
  Buchert time parameter, 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”?



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

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.

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 $\bar{q} \to 0^+$.

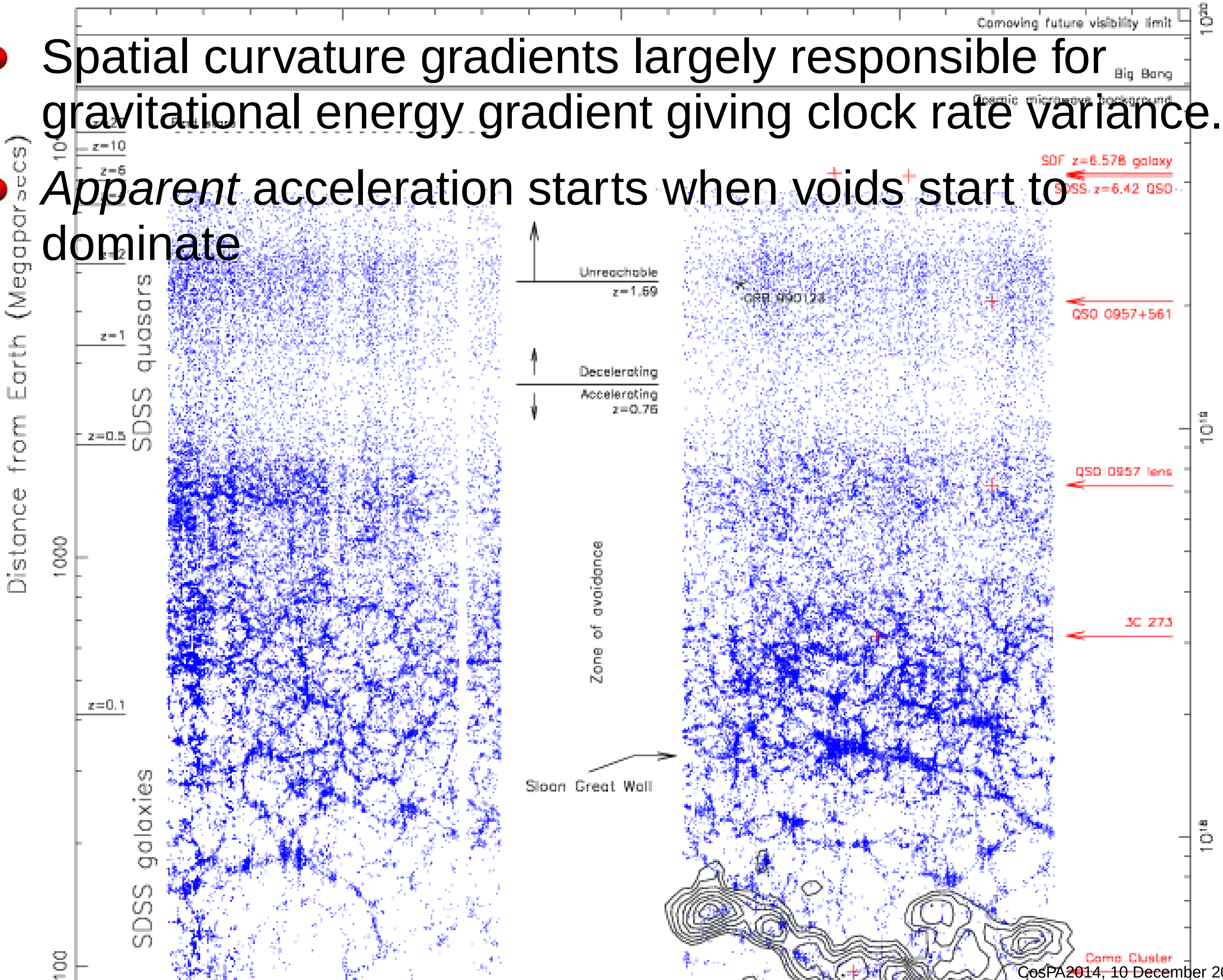
- A wall observer registers apparent cosmic acceleration

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

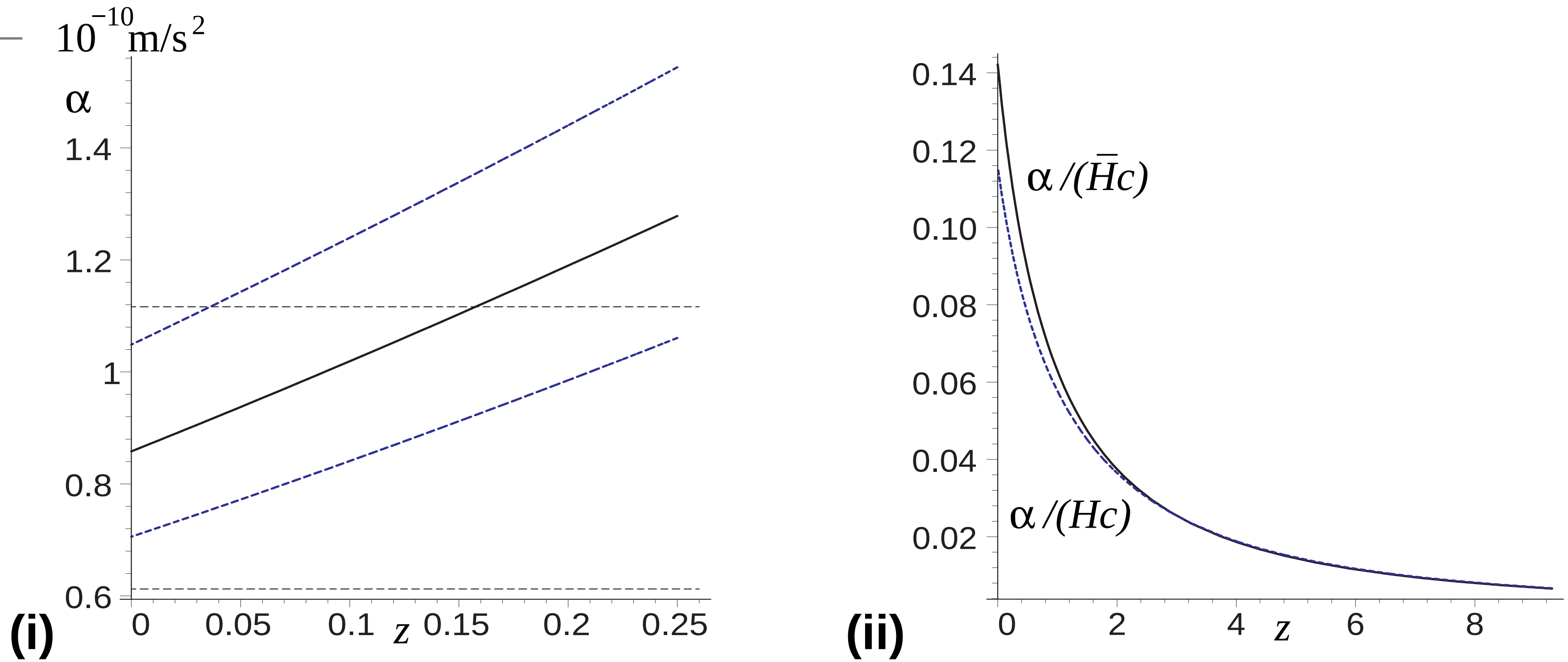
Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small $f_{\rm v}$; changes sign when $f_{\rm v} = 0.5867\ldots$, and approaches $q \to 0^-$ at late times.

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



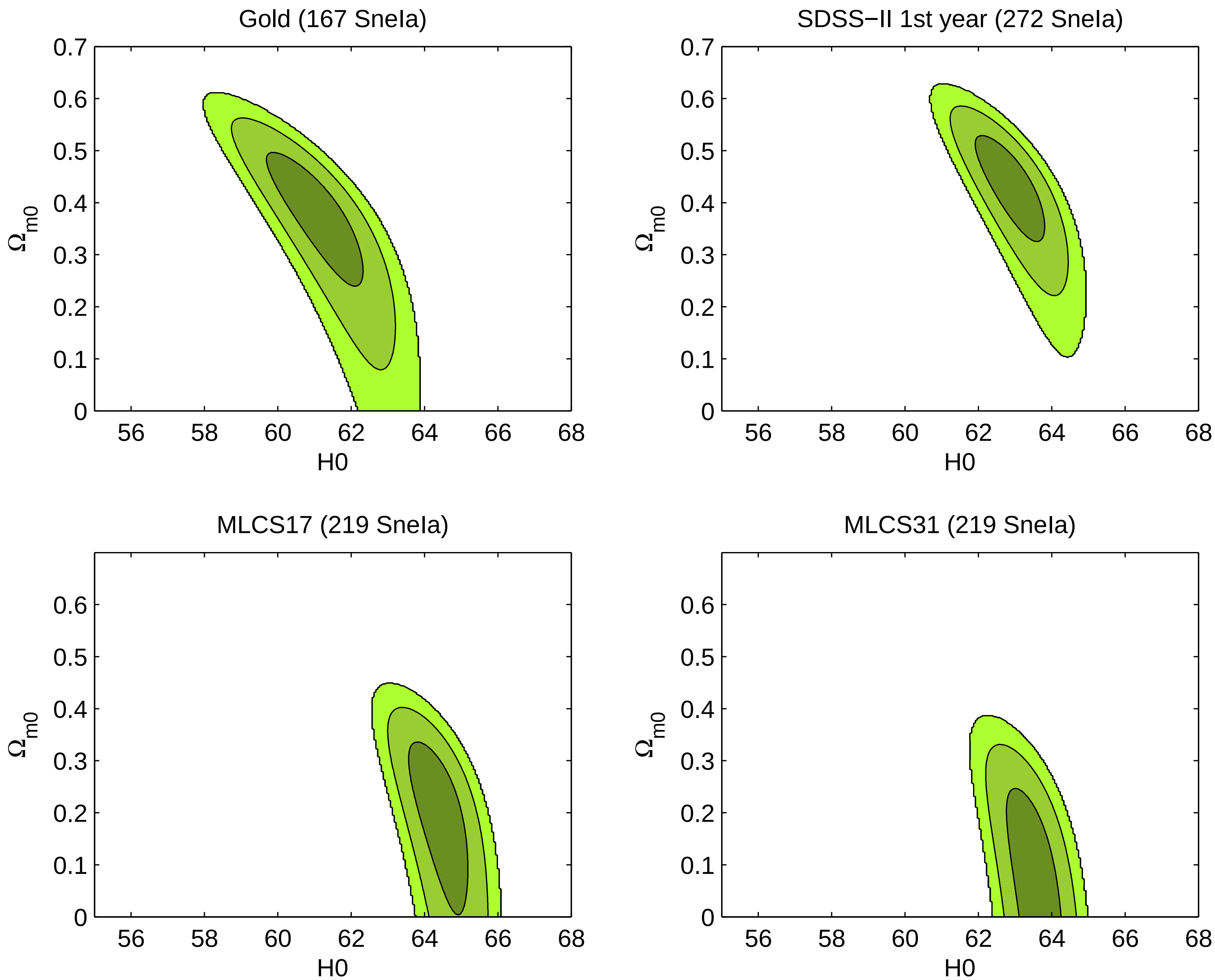
By cosmological equivalence principle the instantaneous relative deceleration of backgrounds gives an instantaneous 4-acceleration of magnitude $\alpha = H_0 c\bar{\gamma}\dot{\bar{\gamma}}/(\sqrt{\bar{\gamma}^2 - 1})$ beyond which *weak field cosmological general relativity* will be changed from Newtonian 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 $\mathrm{d}t = \bar{\gamma}_{\mathrm{w}}\, \mathrm{d}\tau_{\mathrm{w}}$ ($\rightarrow \sim 35$%)

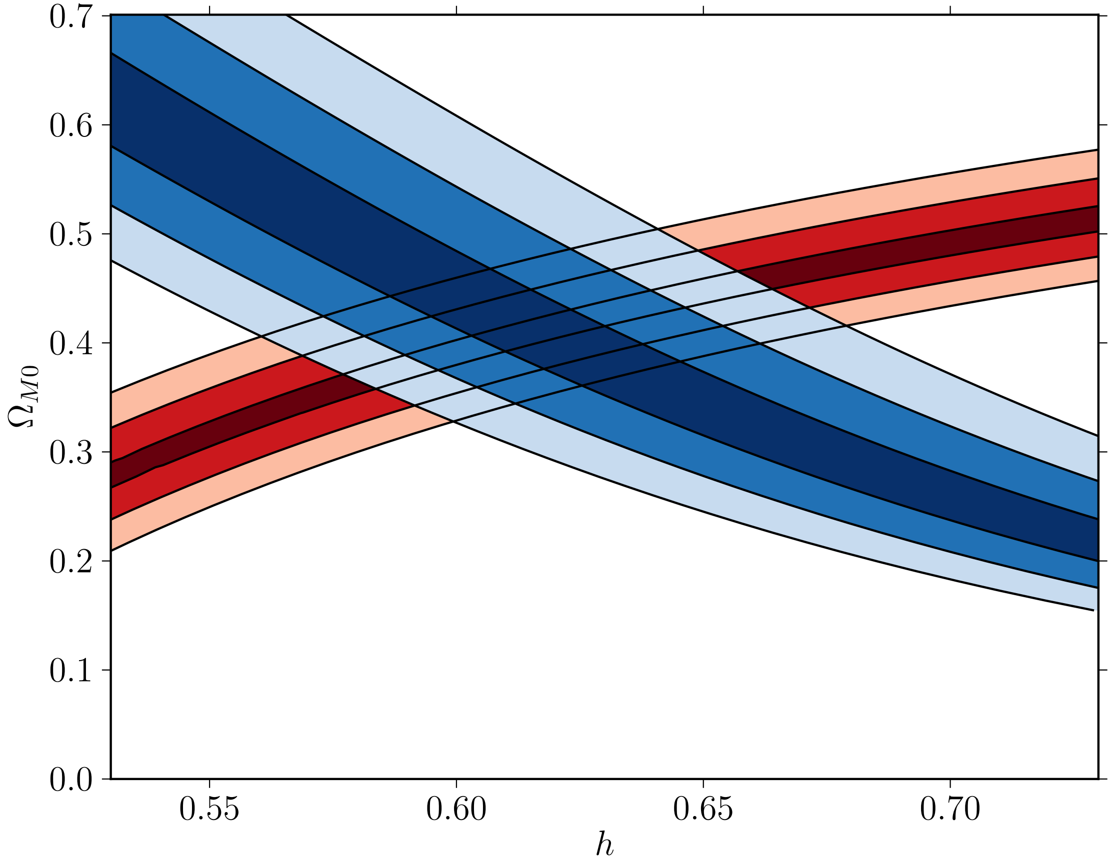
Smale + DLW, MNRAS 413 (2011) 367

- SALT/SALTII fits (Constitution,SALT2,Union2) favour ΛCDM over TS: $\ln B_{\mathrm{TS:}\Lambda\mathrm{CDM}} = -1.06, -1.55, -3.46$
- MLCS2k2 (fits MLCS17,MLCS31,SDSS-II) favour TS over ΛCDM: $\ln B_{\mathrm{TS:}\Lambda\mathrm{CDM}} = 1.37, 1.55, 0.53$
- 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

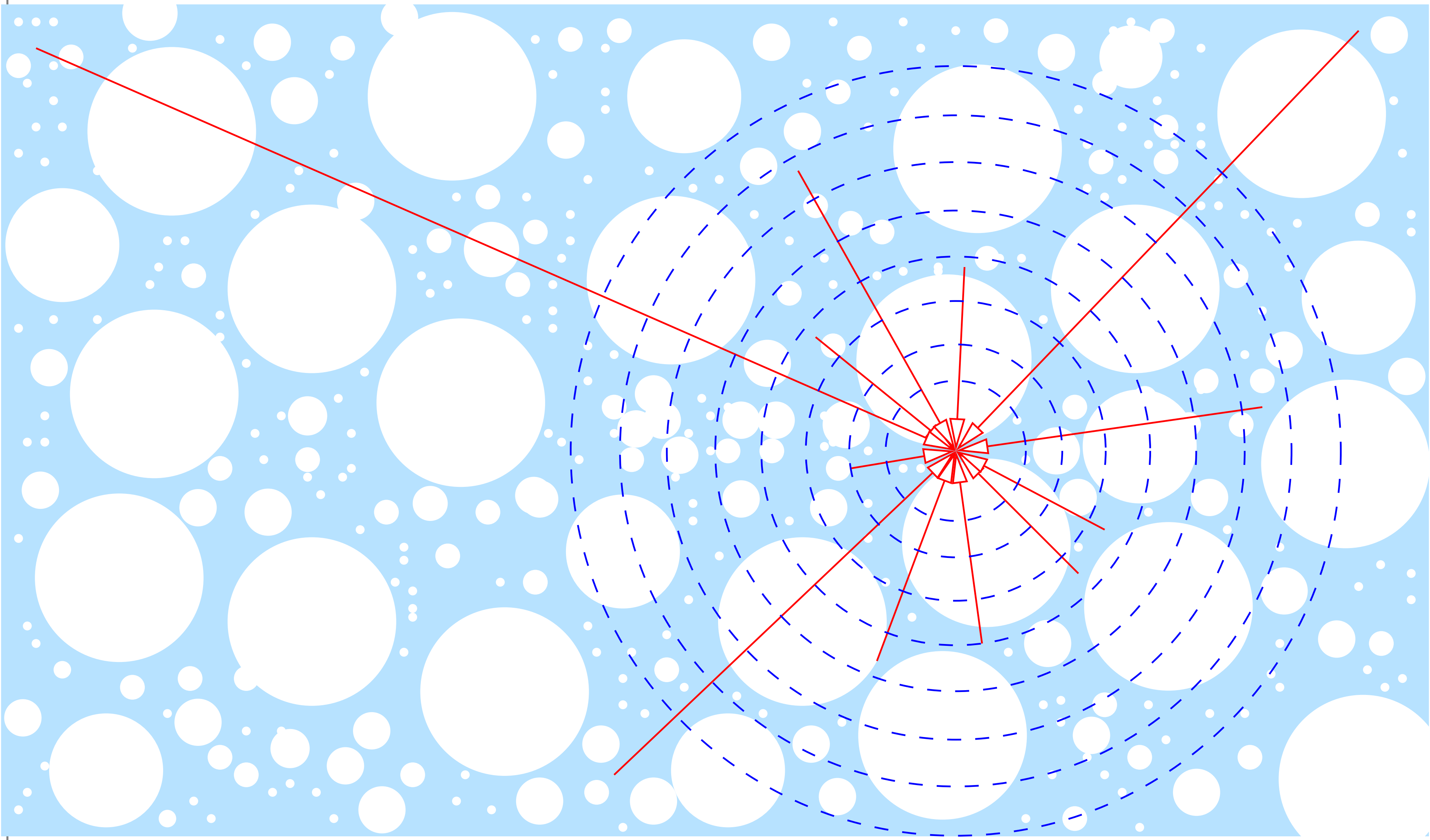
Planck constraints $D_A + r_{drag}$

- 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 $f_{\rm v0} = 0.695^{+0.041}_{-0.051}$
- 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 $z_{\rm acc} = 0.46^{+0.26}_{-0.25}$
- BUT . . . TALK BY AHSAN NAZER (arXiv:1410.3470)

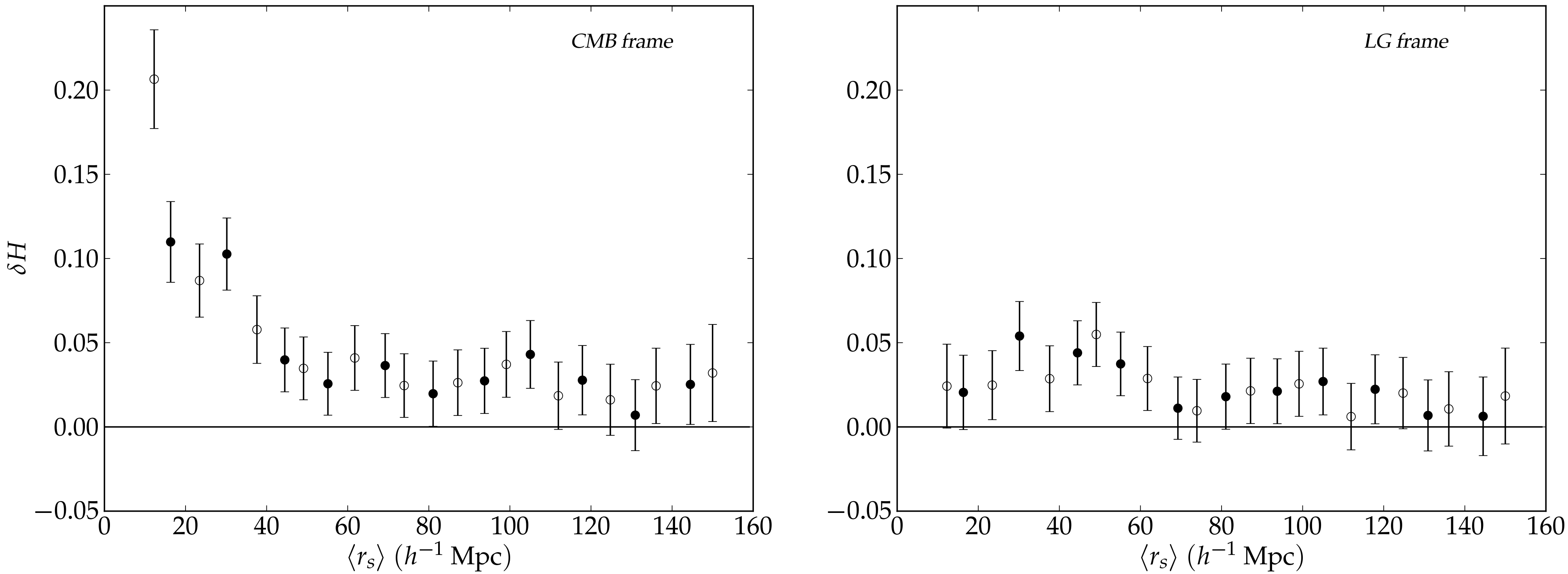
Baryon acoustic oscillations

- 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 is a better model discriminator
- BOSS arXiv:1404.1801 finds 2.5σ tension for ΛCDM in Ly-α forest measurement at $z = 2.34$.
- 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?) Full CMB fit (Ahsan Nazer's talk)– driven by 2nd/3rd peak heights, $\Omega_{C0}/\Omega_{\rm B0}$, ratio – gives BOSS $z = 2.34$ result in tension at level similar to ΛCDM

Apparent Hubble expansion variance



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



- Hubble expansion more uniform in LG frame than CMB frame with very strong Bayesian evidence $\ln B > 5$
- Monopole variation correlated with additional dipole variation (TALK BY JAMES McKAY)

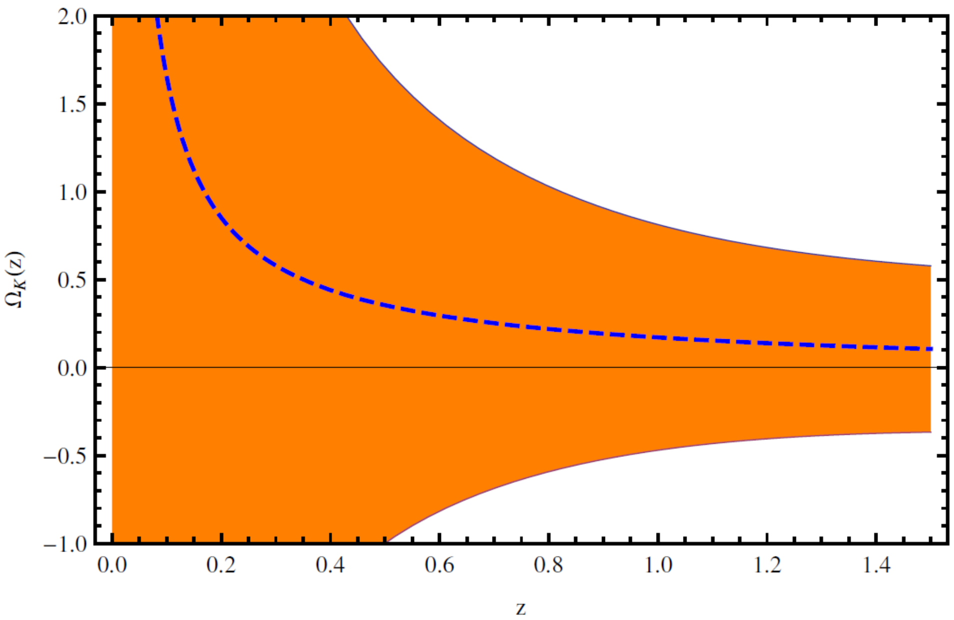
‘Local’ / global H_0

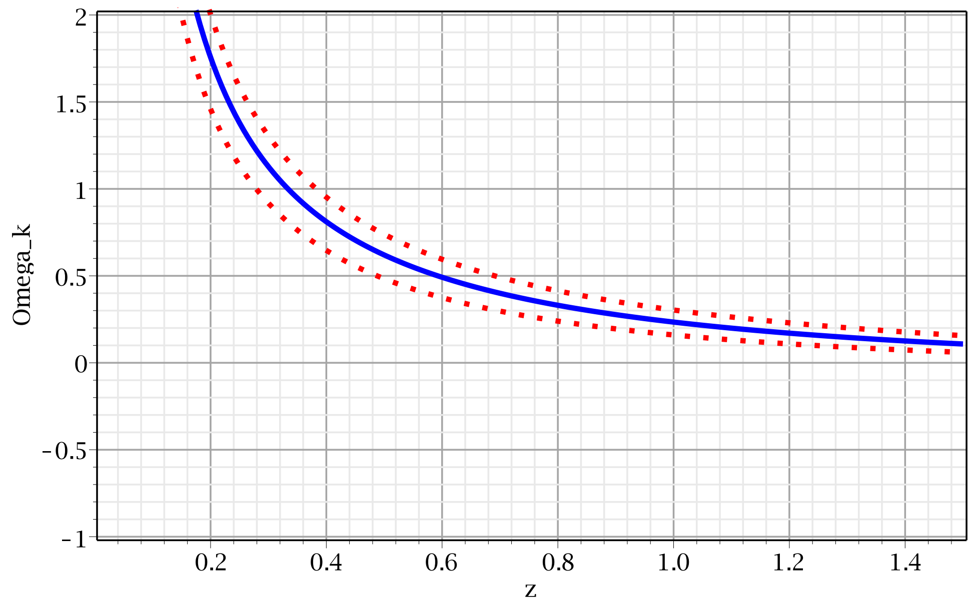
- Since Planck 2013 the values of ‘local’ and global H_0 measurements are an issue, even for ΛCDM
- Riess et al (2009, 2011) estimate H_0 by fit of O(z^3) spatially flat FLRW luminosity distance to SneIa in range $0.23 < z < 0.1$, *assuming* $q_0 = -0.55$, $j_0 = 1$.
- If “nonlinear regime” inhomogeneities on $\lesssim 65\,h^{-1}$Mpc scales do not obey the Friedmann equation such a fit gives H_0 values which vary with redshift range used, even for $z > 0.23$. (Seen in COMPOSITE 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)

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

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

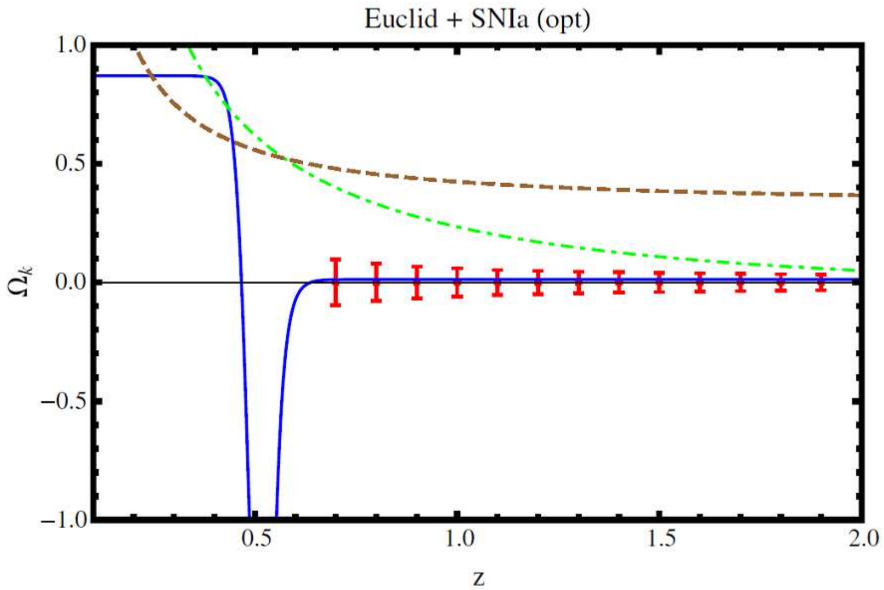




Left panel: CBL statistic from Sapone, Majerotto and Nesseris, arXiv:1402.2236v1 Fig 8, using existing data from SneIa (Union2) and passively evolving galaxies for $H(z)$.

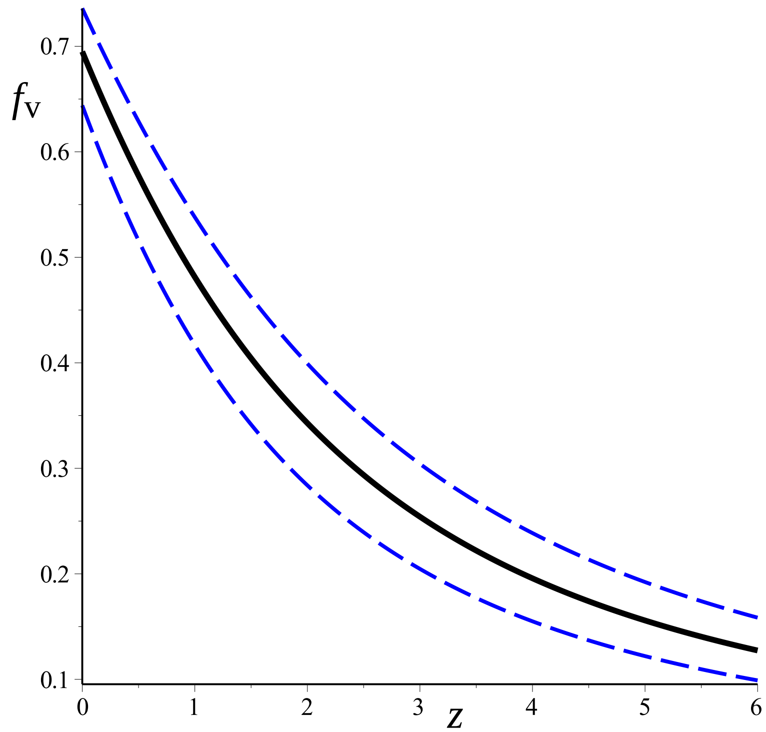
Right panel: TS prediction, with $f_{v0} = 0.695^{+0.041}_{-0.051}$.

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 $f_{\rm v}(z)$ itself provides a measurable constraint. Ly–α tomography at high z may help.

Conclusion: Modified Geometry

- 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”