Dark energy from cosmic structure

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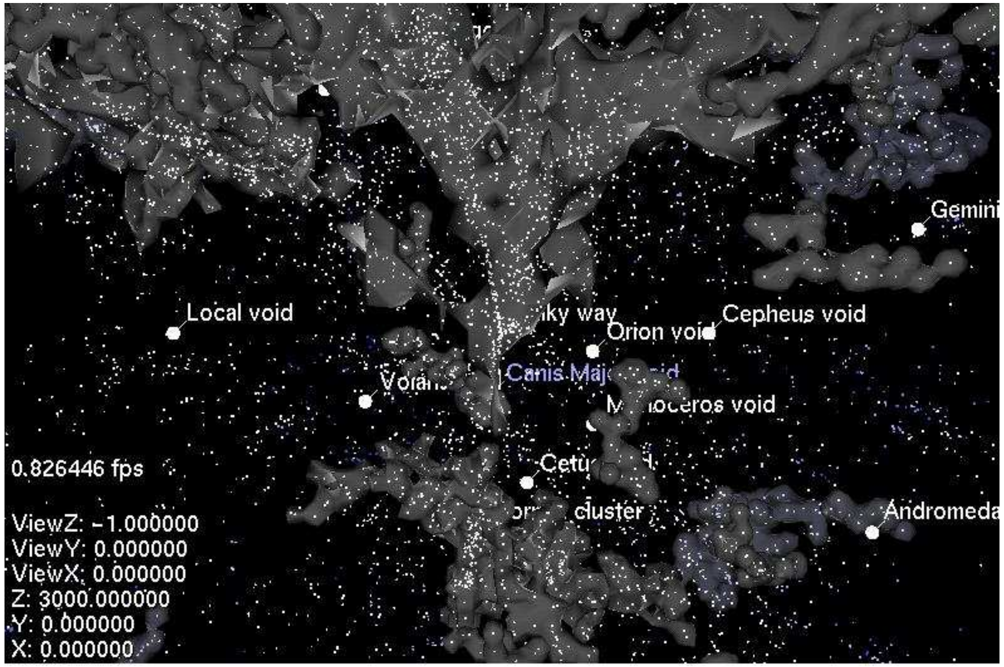


DLW: **New J. Phys. 9 (2007) 377**

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**

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: in preparation

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, . . .
- 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).

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]

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

Dilemma of gravitational energy. . .

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

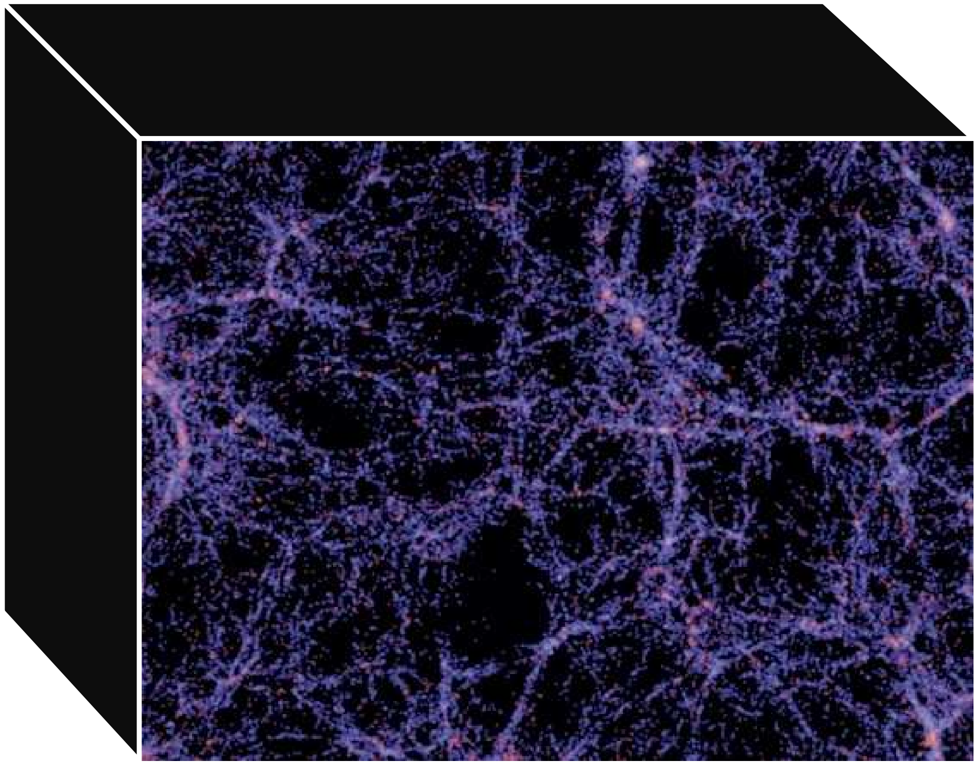
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

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)

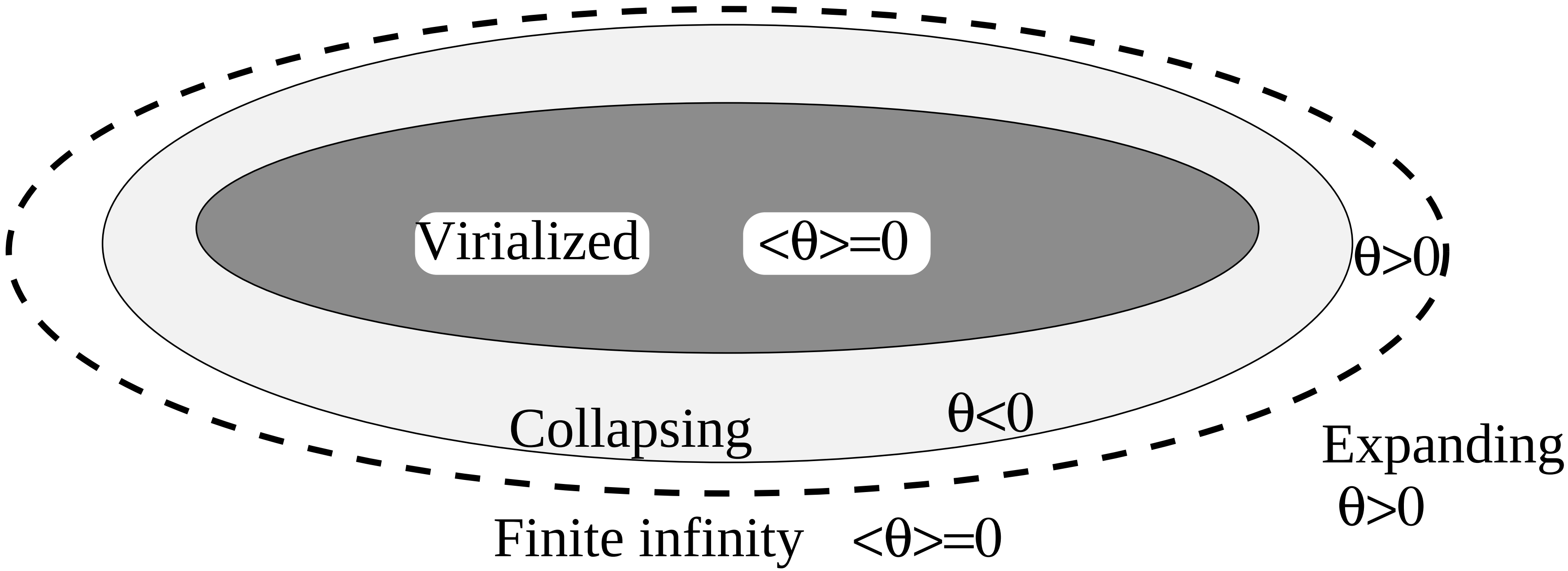
Cosmological Equivalence Principle

- *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*,

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

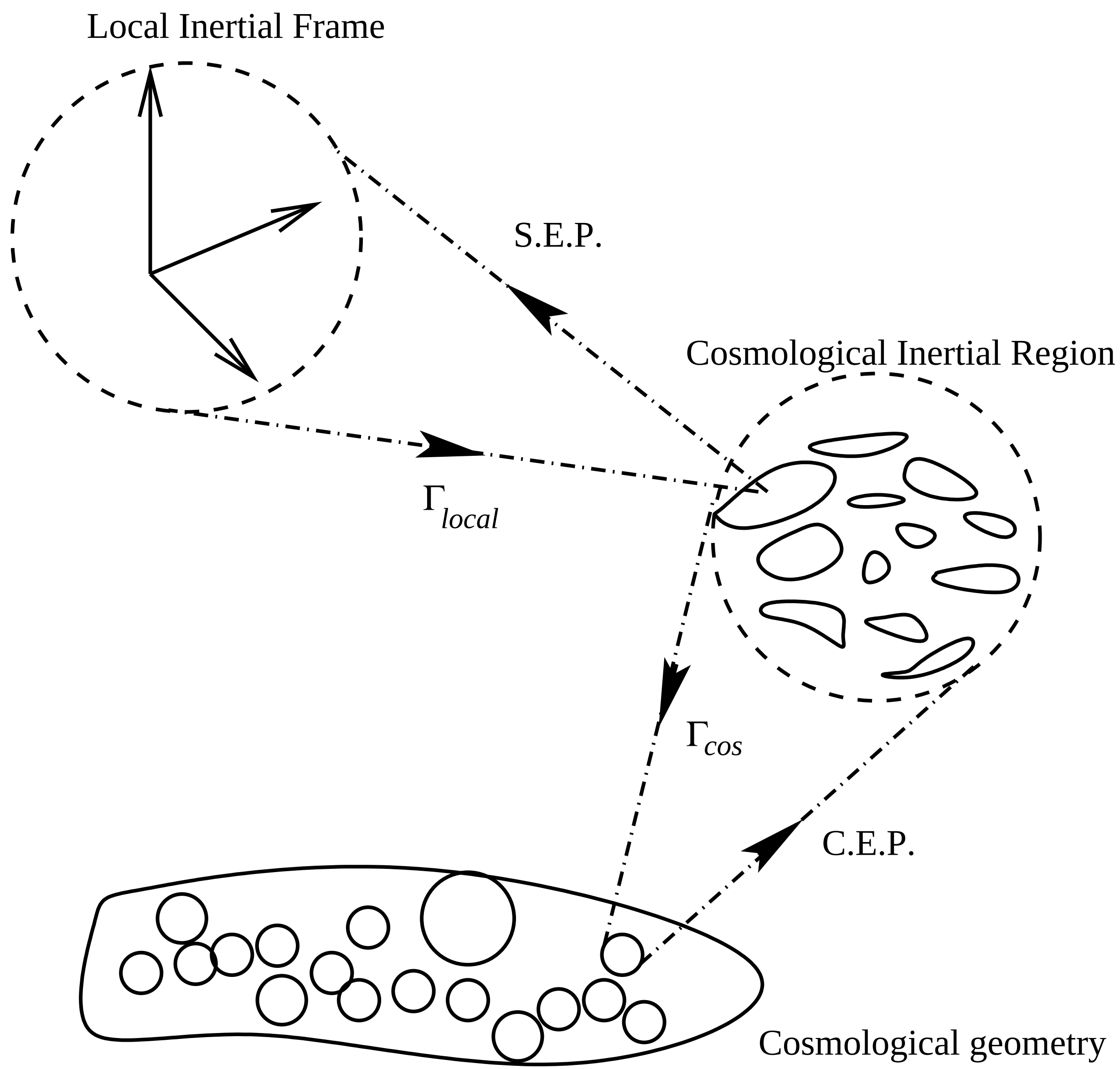
- Defines Cosmological Inertial Region (CIR) in which *regionally isotropic* volume expansion is equivalent to a velocity in special relativity
- Such velocities integrated on a bounding 2-sphere define *“kinetic energy of expansion”*: globally it has gradients

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. . .



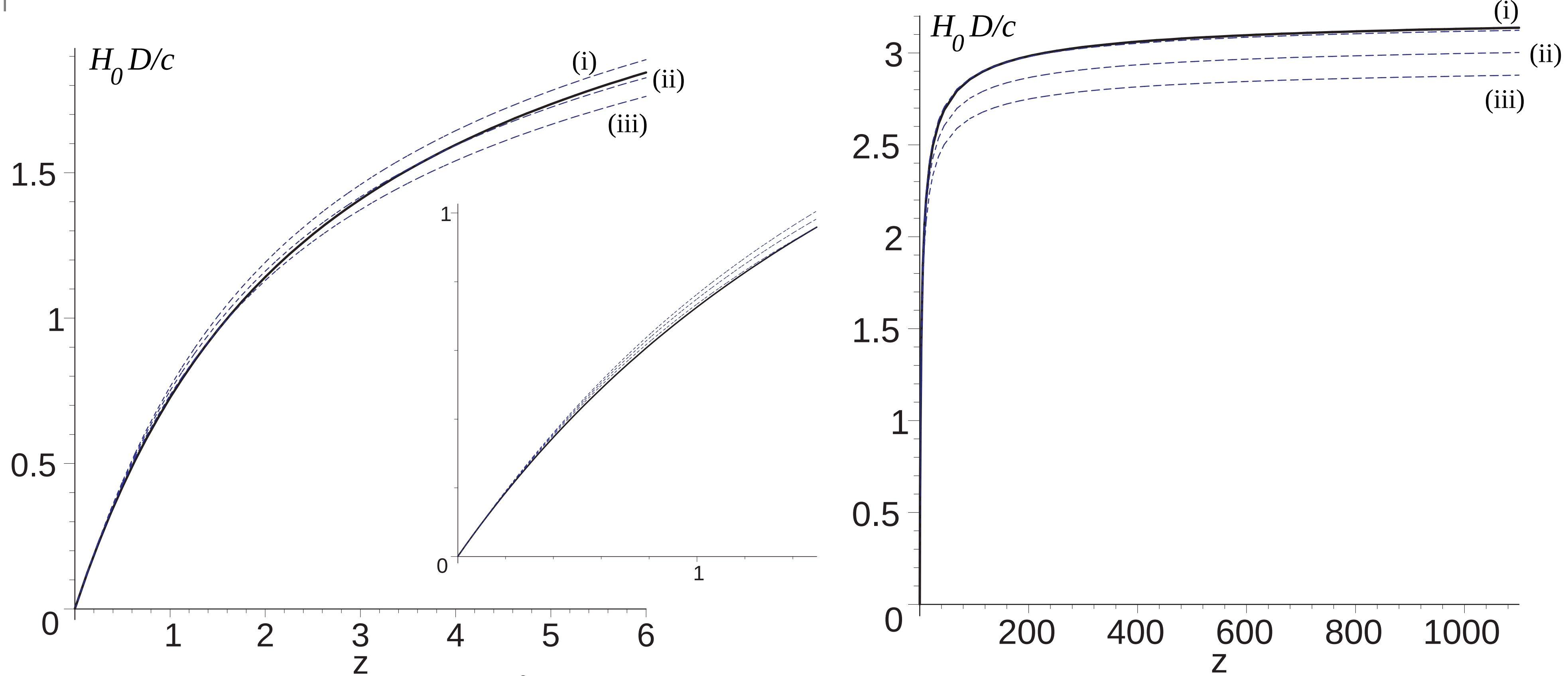
Why is ΛCDM so successful?

- 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* $\bar{H}$, $\bar{\Omega}_M$, $\bar{\Omega}_R$, $\bar{\Omega}_k$, $\bar{\Omega}_{\mathcal{Q}}$, $\ldots$
- *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, $\ldots$

Dressed "comoving distance" $D(z)$



TS model, with $f_{v0} = 0.695$, **(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)** $\Omega_{M0} = 0.388$.

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

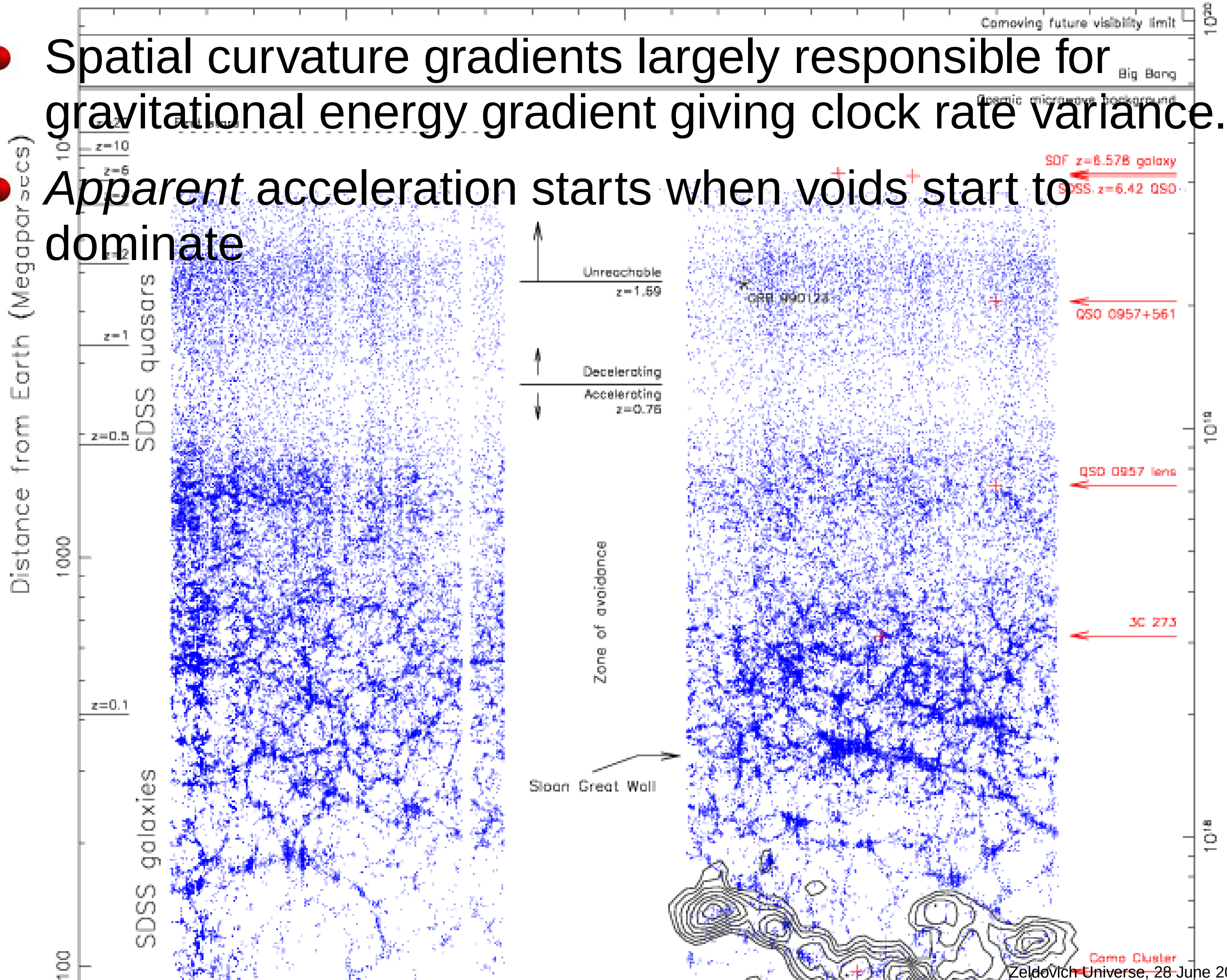
- A wall observer registers apparent cosmic acceleration

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

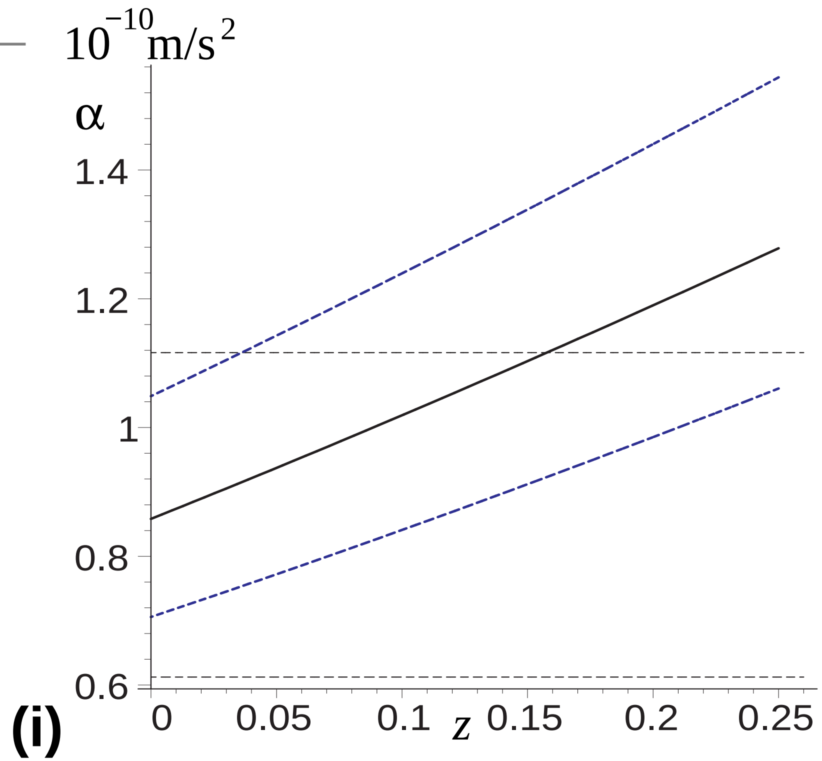
Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small $f_{\rm v}$; changes sign when $f_{\rm v} = 0.5867\ldots$, and approaches $q \to 0^-$ at late times.

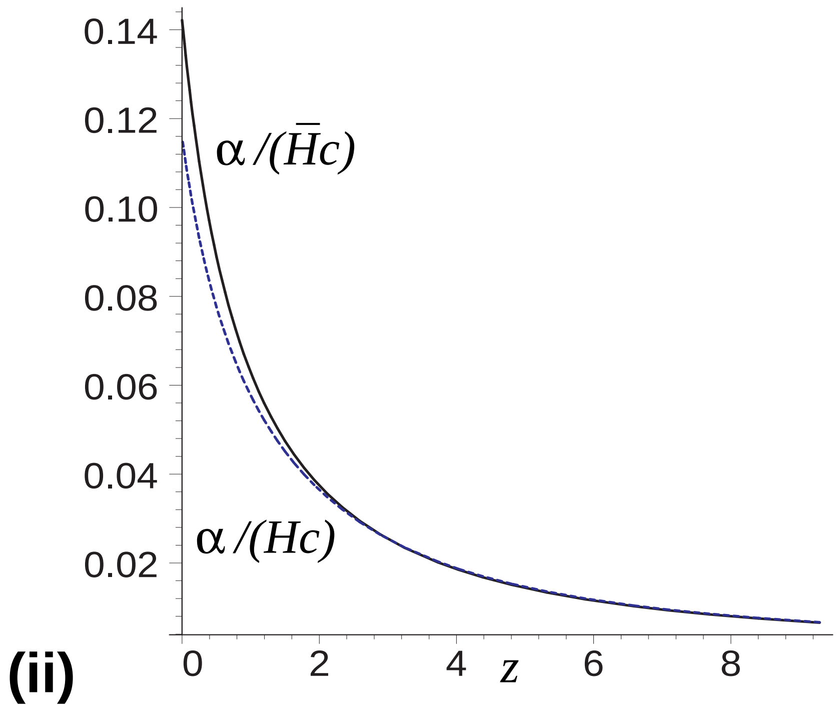
Cosmic coincidence problem solved

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



Relative deceleration scale





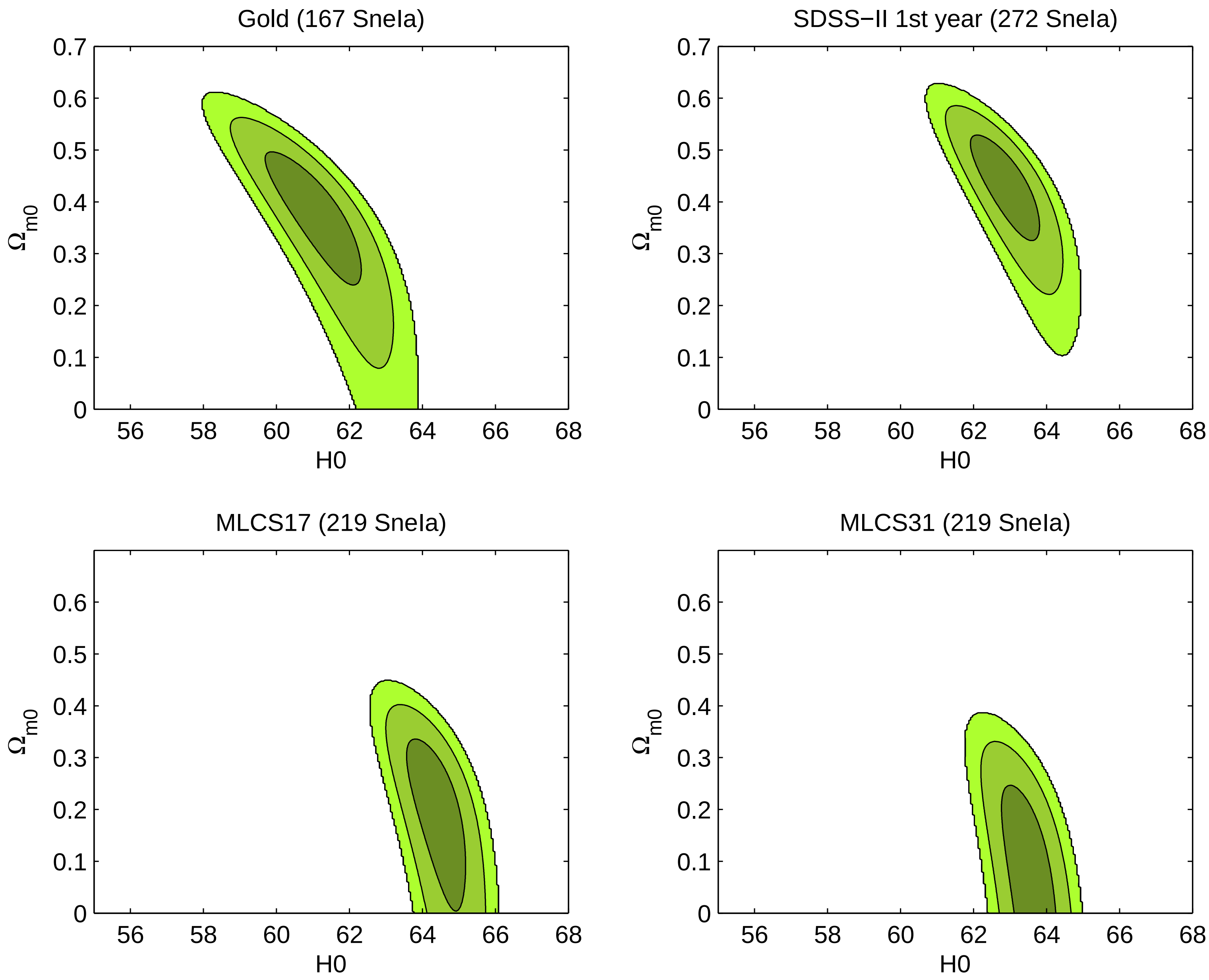
By cosmological equivalence principle the instantaneous relative deceleration of backgrounds gives an instantaneous 4-acceleration of magnitude $\alpha = H_0 c\bar{\gamma}\dot{\bar{\gamma}}/(\sqrt{\bar{\gamma}^2 - 1})$ beyond which *weak field cosmological general relativity* will be changed from Newtonian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

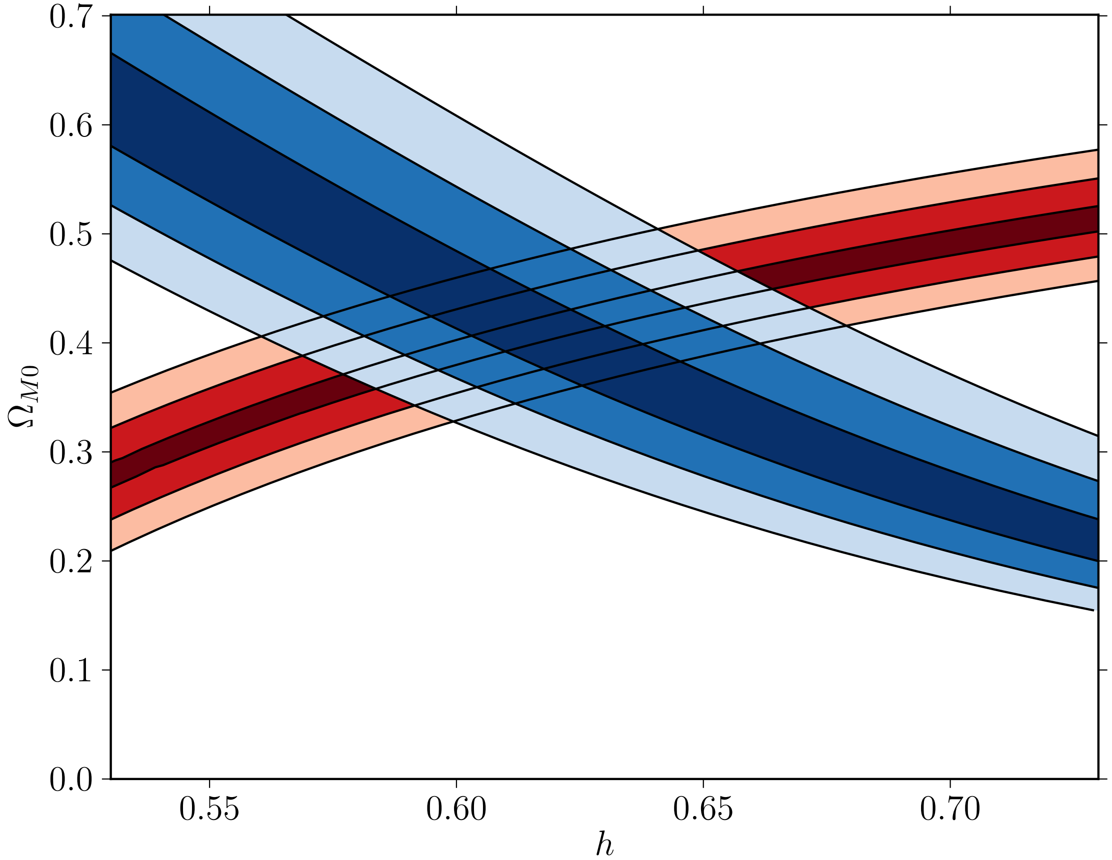
Smale + DLW, MNRAS 413 (2011) 367

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

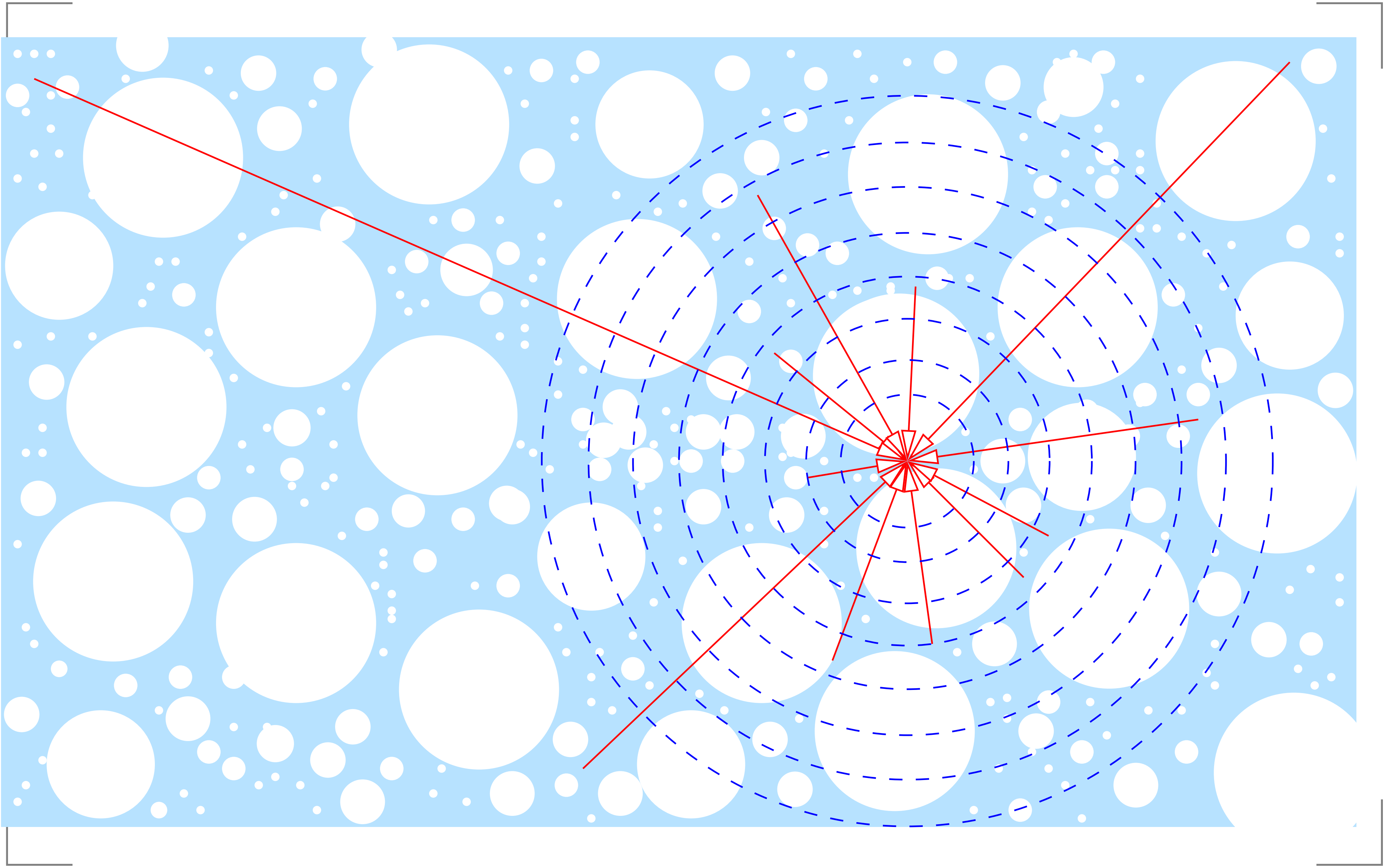


Parameters within the (Ω_{M0},H_0) plane which fit the angular scale of the sound horizon $\theta_* = 0.0104139$ (blue), and its comoving scale at the baryon drag epoch as compared to Planck value $98.88\,h^{-1}$ Mpc (red) to within 2%, 4% and 6%, with photon-baryon ratio $\eta_{B\gamma} = 4.6$–5.6×10^{-10} 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 $z_{\rm acc} = 0.46^{+0.26}_{-0.25}$

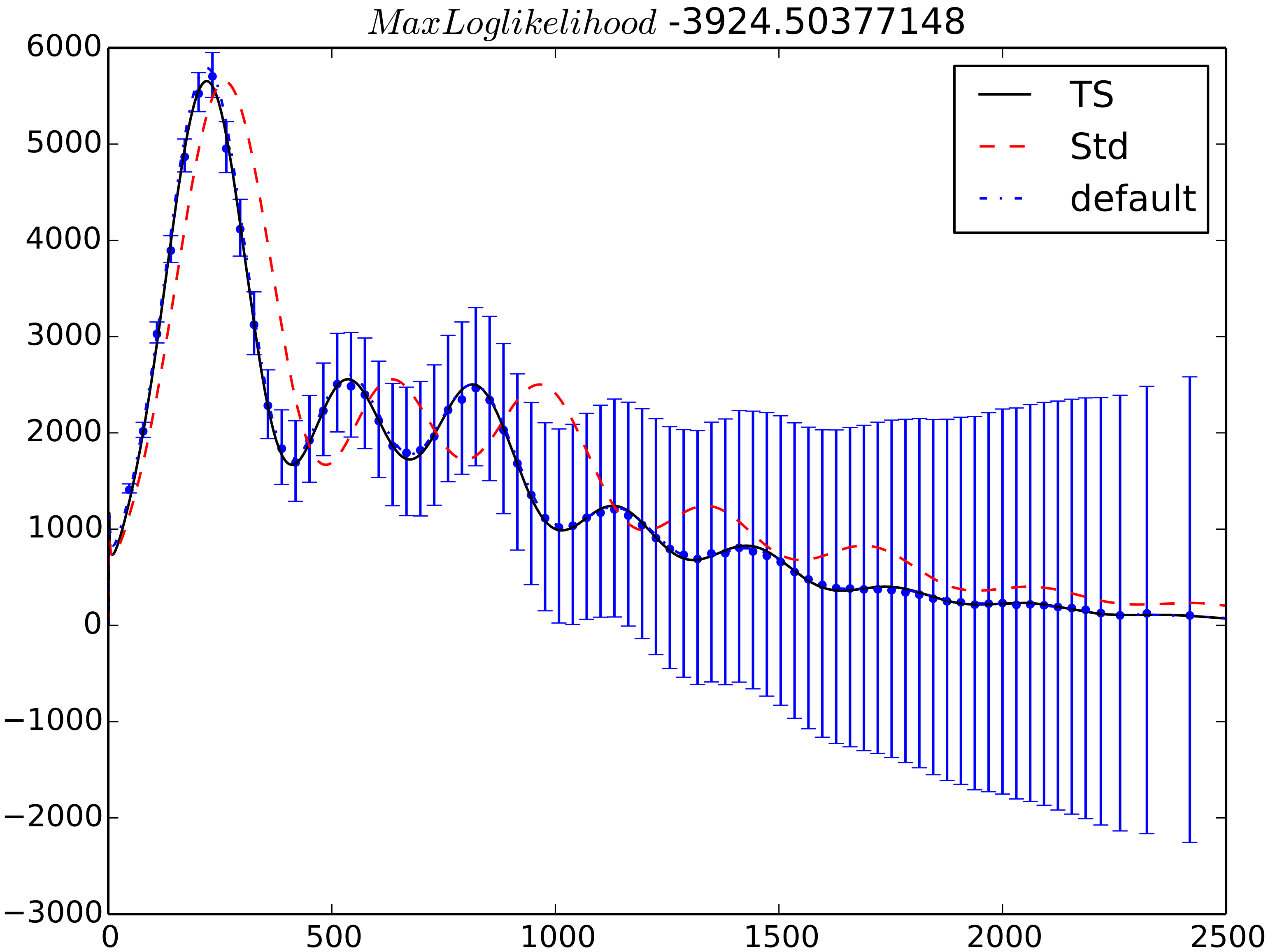
Apparent Hubble expansion variance



Baryon acoustic oscillations

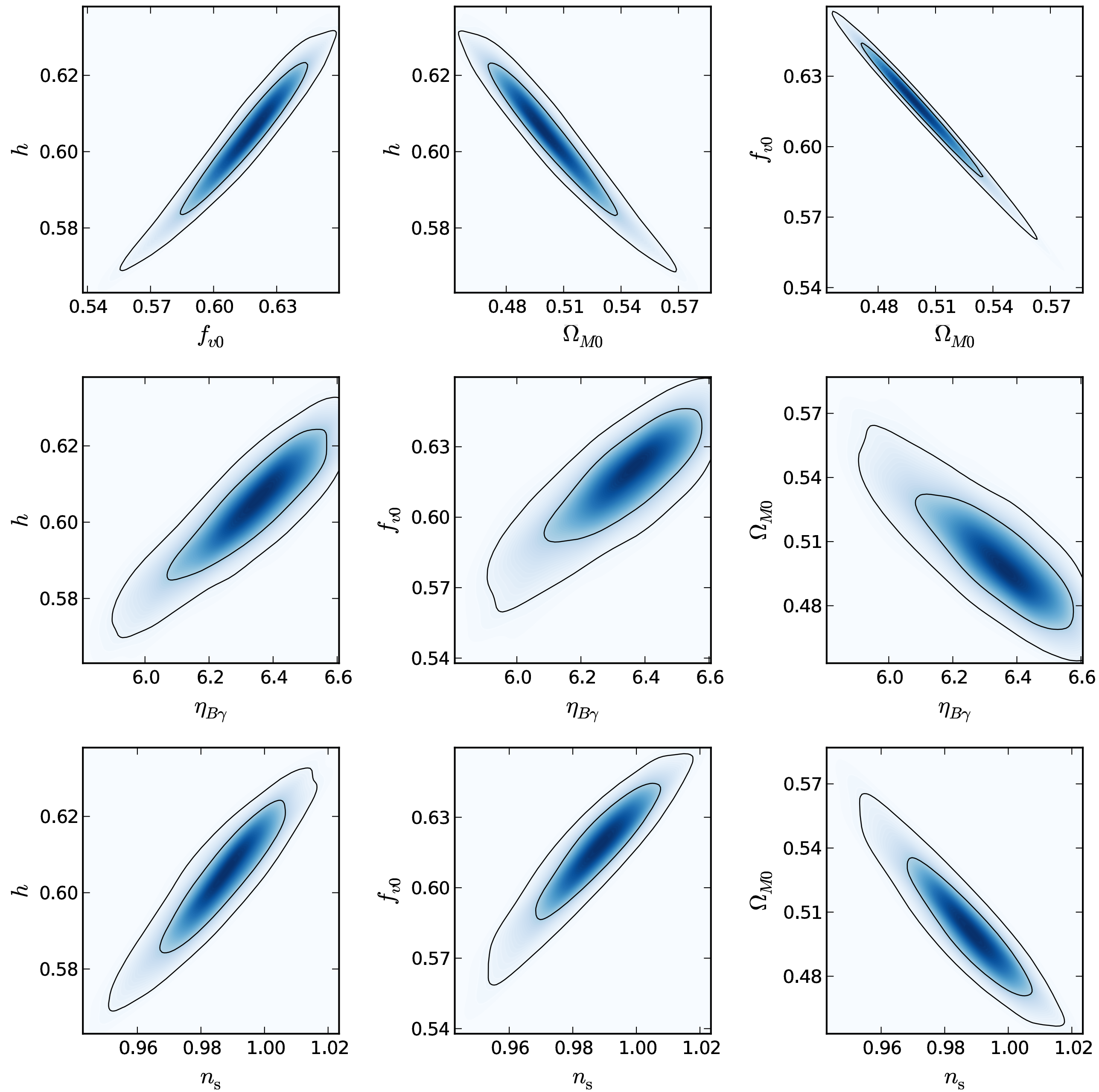
- Commonly used measure $D_V = \left[\frac{zD^2}{H(z)}\right]^{1/3}$ gives results which differ very little between ΛCDM and timescape (both within uncertainty)
- Alcock–Paczyński test which separates angular and radial scales is a better model discriminator
- BOSS arXiv:1404.1801 finds 2.5σ tension for ΛCDM in Ly-α forest measurement at $z = 2.34$.
- 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 Planck fit



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

M.A. Nazer + DLW, in preparation



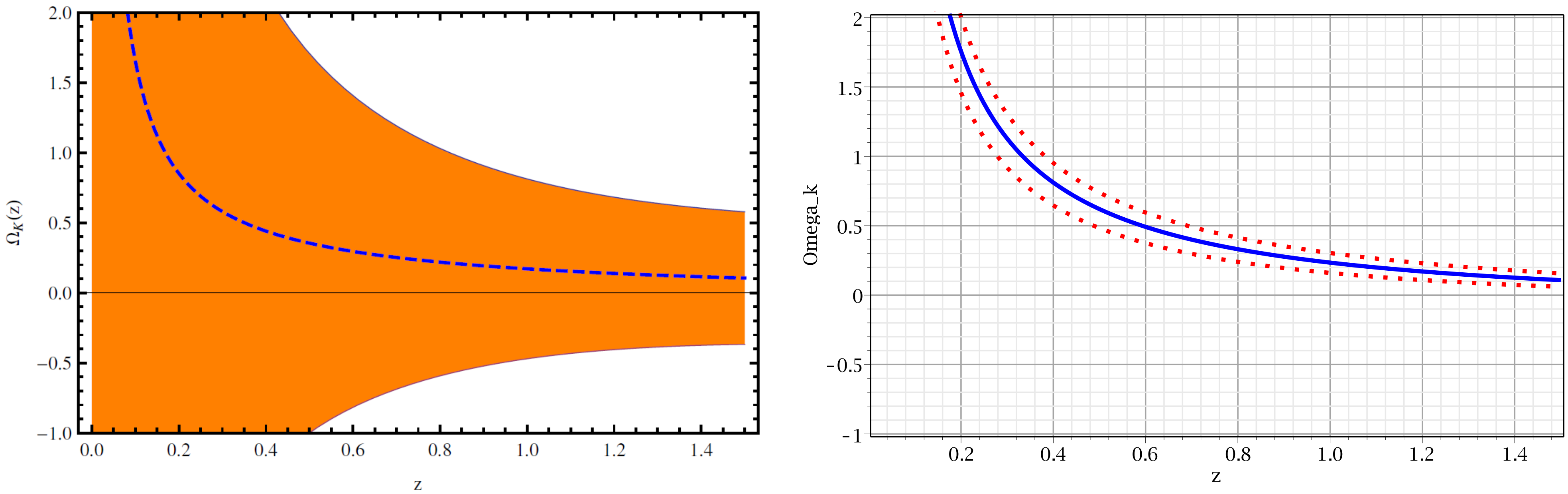
CMB acoustic peaks: preliminary results

- Standard ΛCDM model assumed for evolution of perturbations and acoustic waves in plasma. [Vonlanthen et al (2010) procedure used to map timescape model d_A to FLRW reference d'_A ($\ell > 50$)]
- Previous D_A + r_{drag} constraints [arXiv:1306.3208] give concordance for baryon–to–photon ratio $\eta_{B\gamma} = (5.1 \pm 0.5) \times 10^{-10}$ with no primordial ^{7}Li anomaly.
- Full fit – driven by 2nd/3rd peak height ratio – forces $\eta_{B\gamma} = (6.32 \pm 0.16) \times 10^{-10}$, driven by ratio $\Omega_{C0}/\Omega_{\rm B0}$.
- With bestfit, $f_{\rm v0} = 0.612$, $h = 0.603$, primordial ^{7}Li anomalous and BOSS $z = 2.34$ result in tension again
- BUT backreaction in plasma neglected; may affect perturbations differently to background

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

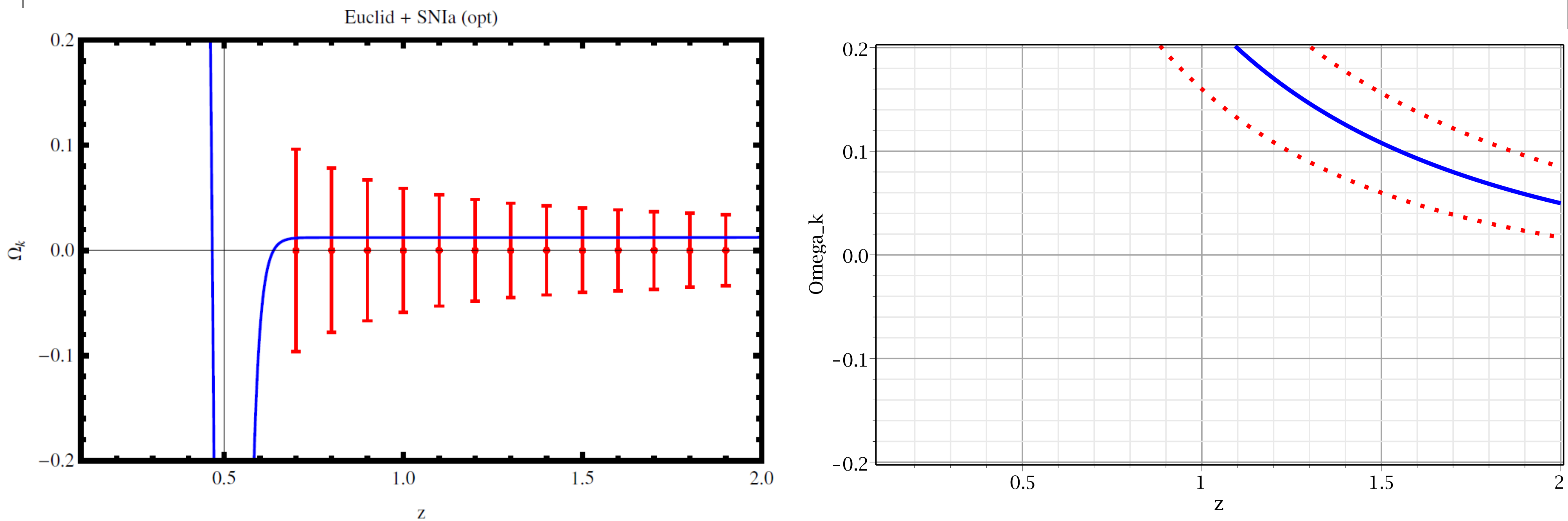
$$\Omega_{k0} = \Omega_k(z) = \frac{[c^{-1}H(z)D'(z)]^2 - 1}{[c^{-1}H_0 D(z)]^2}$$



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 $H(z)$.

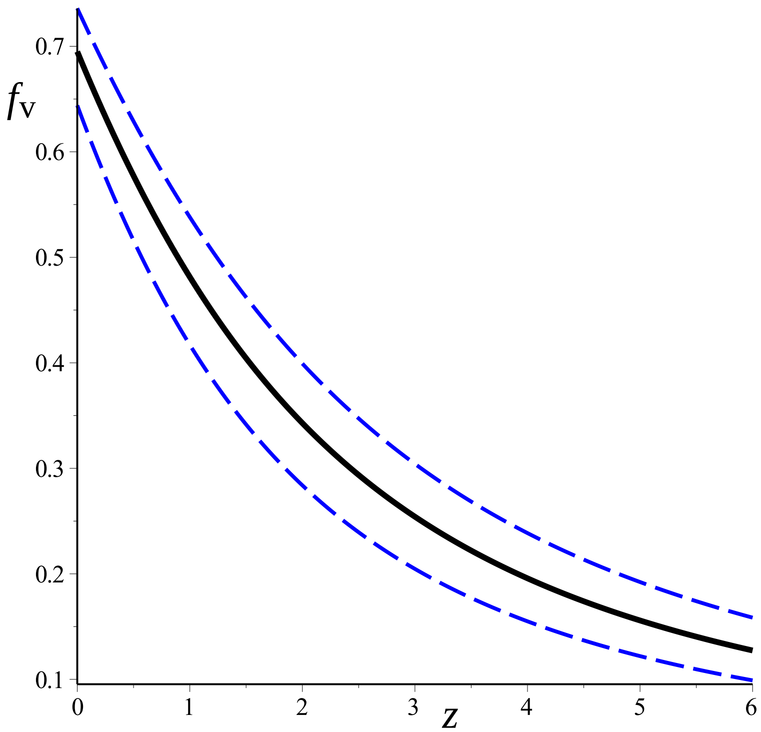
Right panel: TS prediction, with $f_{\rm v0} = 0.695^{+0.041}_{-0.051}$.

Clarkson Bassett Lu test with *Euclid*



- Left panel: Projected uncertainties for ΛCDM model with *Euclid* and 1000 SneIa. (Blue line is a comparison non-Copernican Gpc void model. From Sapone, Majerotto and Nesseris arXiv:1402.2236v1 Fig 10)
- Right panel. Timescape prediction becomes greater than uncertainties for $z \lesssim 1.5$. (Falsfiable.)

Void fraction: potential test?

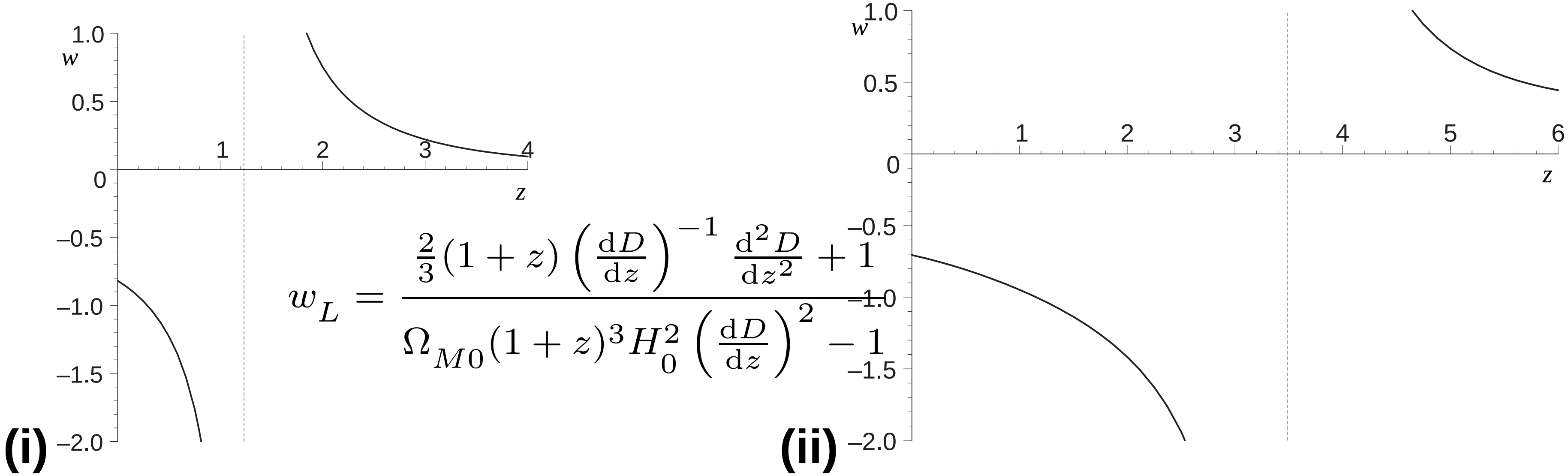


- Growth of structure difficult to parameterize as effective FLRW model, as not based on this geometry
- Bound system measures below finite infinity likely to be close to standard GR (Einstein-de Sitter) prediction
- Void volume fraction $f_v(z)$ itself provides a measurable constraint. Ly–α tomography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

Equivalent “equation of state”?

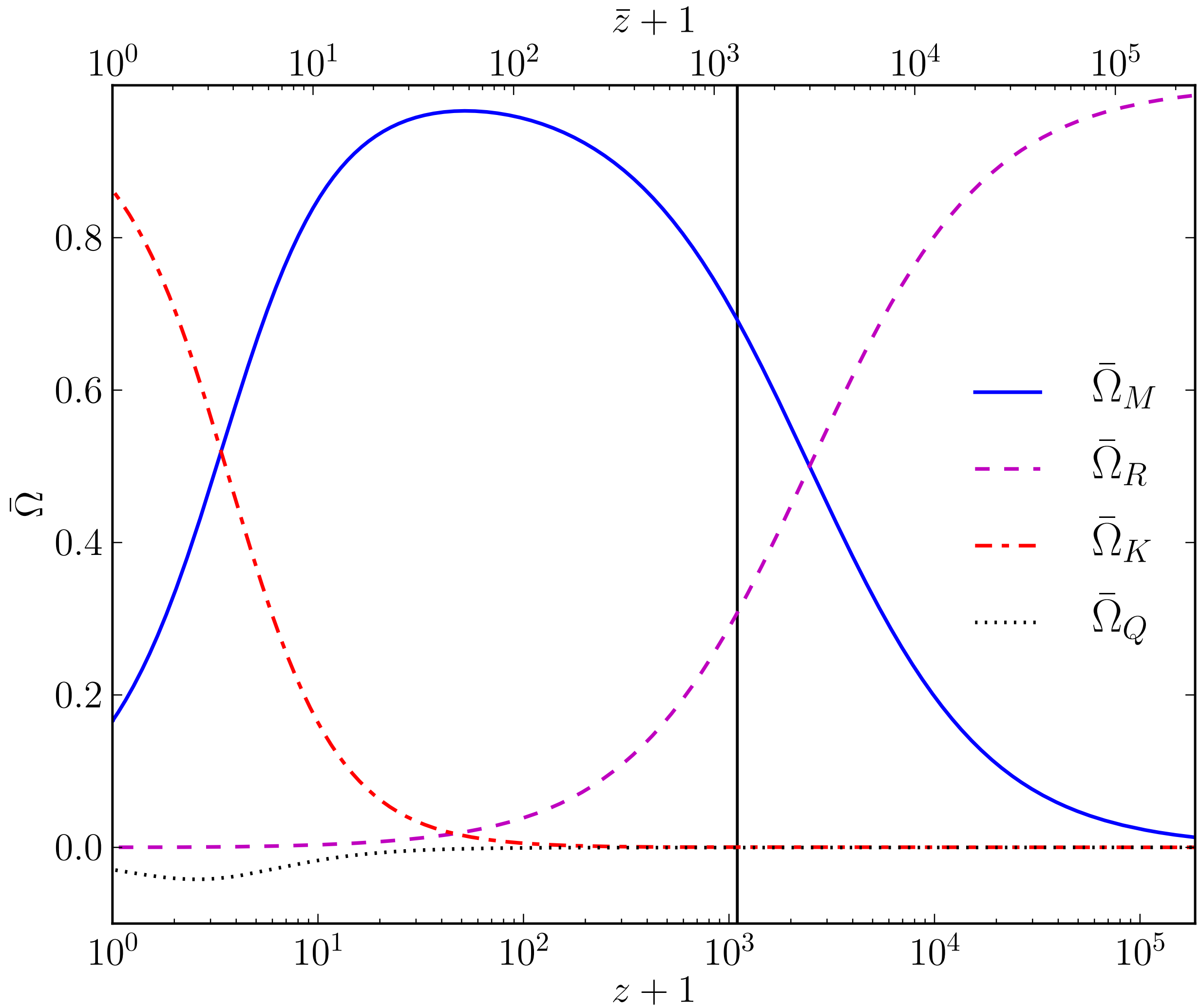


$$w_L = \frac{\frac{2}{3}(1+z)\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^{-1}\frac{\mathrm{d}^2D}{\mathrm{d}z^2}+1}{\Omega_{M0}(1+z)^3H_0^2\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^2-1}$$

A formal “dark energy equation of state” $w_L(z)$ for the TS model, with $f_{\rm v0} = 0.695$, calculated directly from $r_w(z)$: **(i)** $\Omega_{M0} = 0.695$; **(ii)** $\Omega_{M0} = 0.3175$.

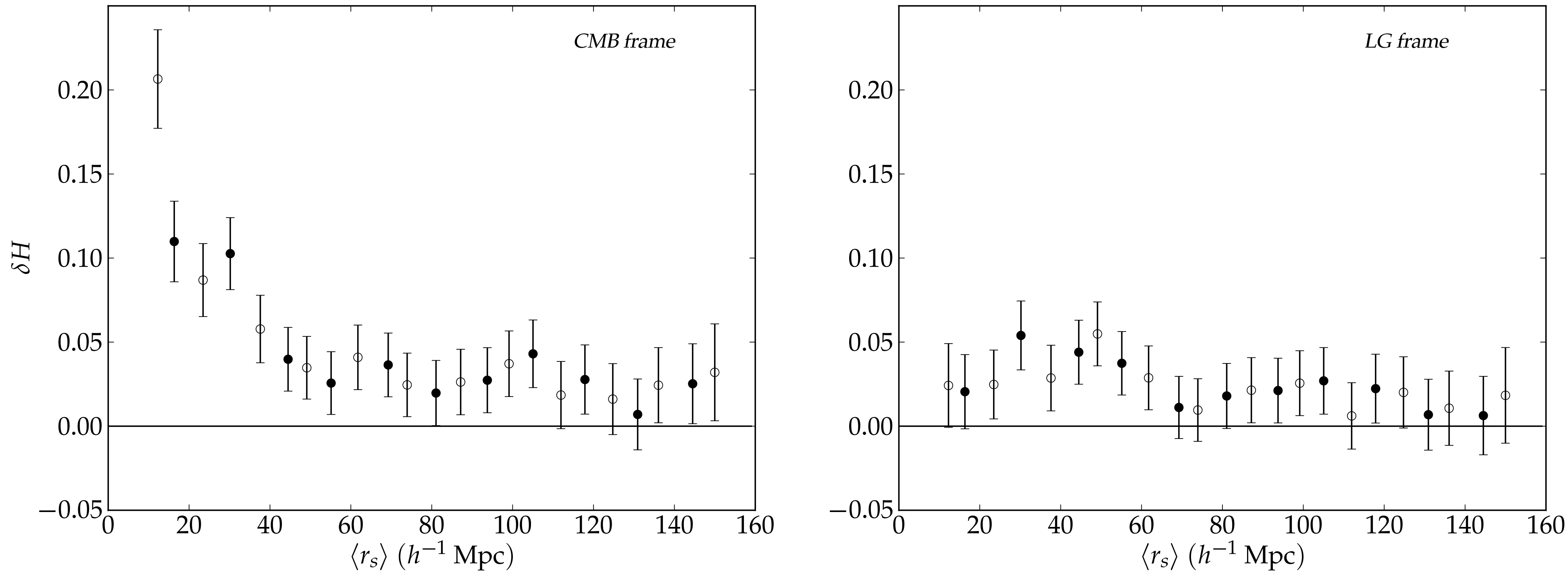
- Description by a “dark energy equation of state” makes no sense when there’s no physics behind it; but average value $w_L \simeq -1$ for $z < 0.7$ makes empirical sense.

Bare cosmological parameters



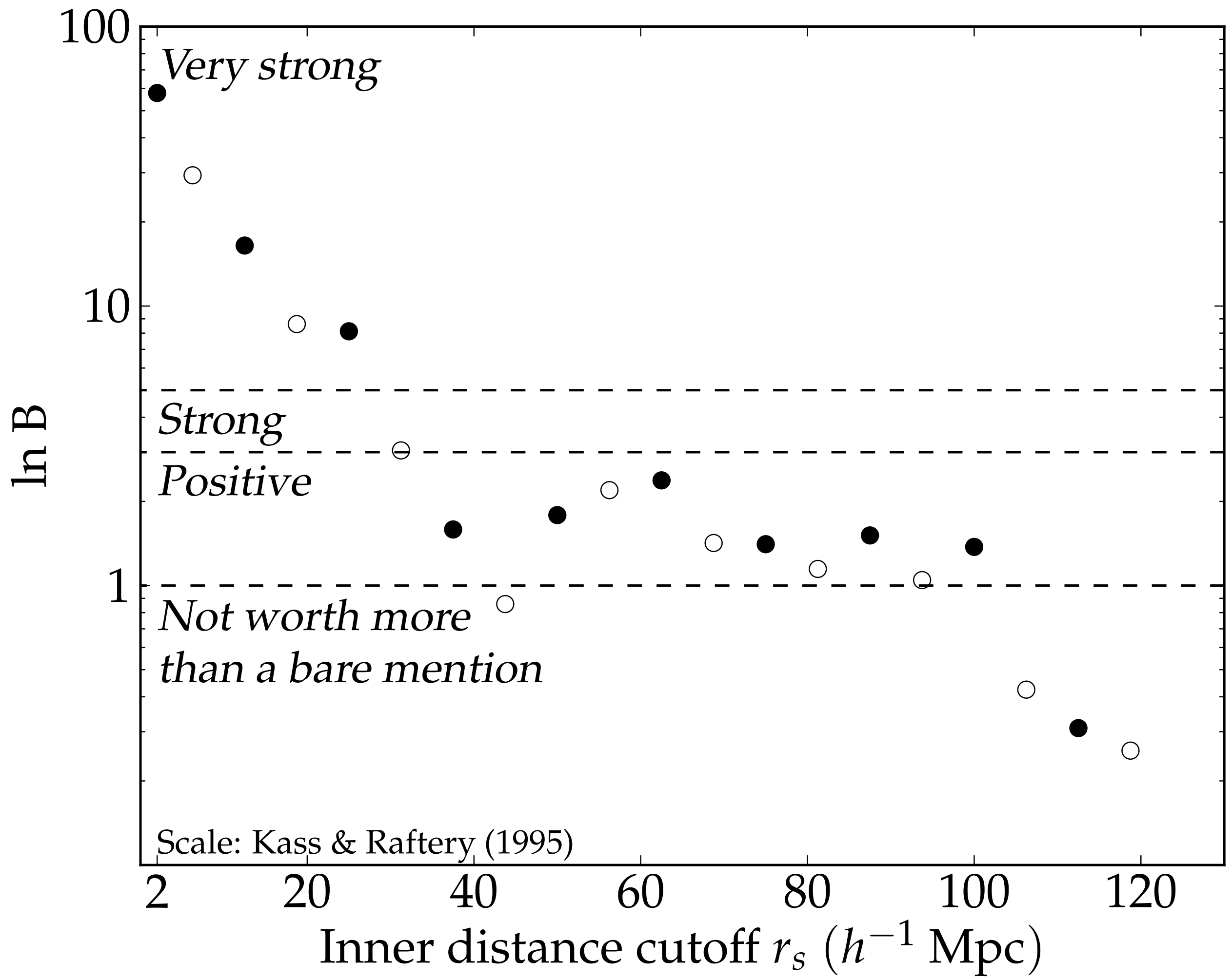
J.A.G. Duley, M.A. Nazer & DLW, CQG 30 (2013) 175006: full numerical solution with matter, radiation

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



- 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

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