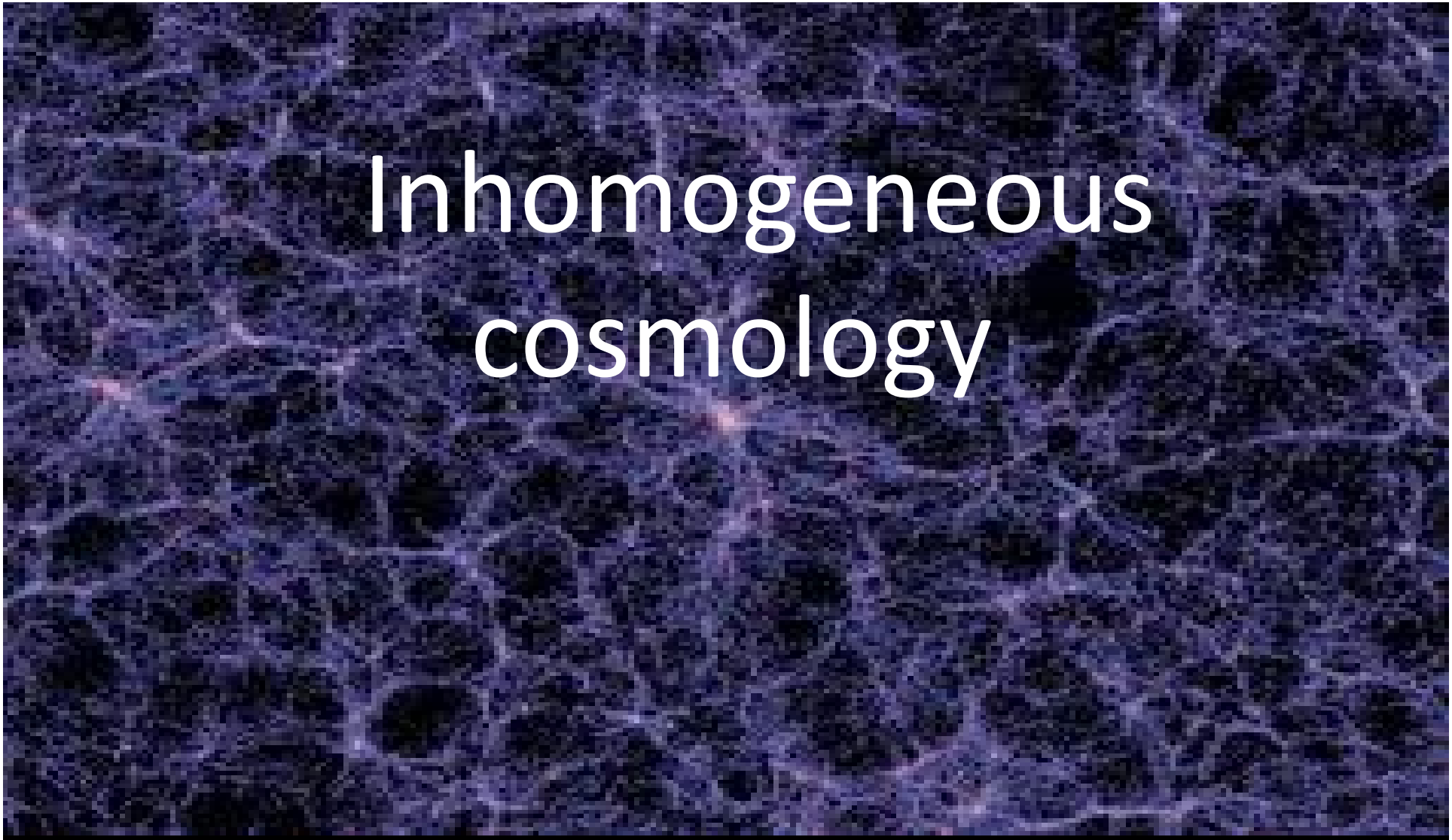


Inhomogeneous cosmology

David L Wiltshire

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Outline of talk

- 10-year bet with T Padamanabhan conceded
- Concepts of coarse-graining, averaging, backreaction
- What is dark energy?:
  Dark energy is a misidentification of gradients in quasilocal gravitational energy in inhomogeneous geometry
- Ideas/ present and future tests of timescape cosmology
- “Modified Geometry” rather than “Modified Gravity”
- Frontiers:
  - relativistic Lagrangian perturbation theory
  - fully general relativistic computational cosmology
- New bet offered: will Euclid satellite see non-Euclidean geometry? *(See final slide)*

TEXAS IN AUSTRALIA
XXIII TEXAS SYMPOSIUM ON RELATIVISTIC ASTROPHYSICS
2006
MELBOURNE UNIVERSITY
11-15 DECEMBER 2006

TERMS OF BET BETWEEN T. PADMANABHAN AND D.L. WILTSHIRE

WHEREAS Thanu Padmanabhan is convinced of the theoretical beauty of the cosmological constant and believes that observational data will ultimately show that a nonzero cosmological constant is driving the current accelerated expansion of the universe; AND

WHEREAS David Wiltshire, while accepting that a cosmological term may have relevance at some scale, is equally convinced that present epoch dark energy will in future be observationally shown to be an historical accident arising from our misinterpretation of gravitational energy, which is non-local,

WE HEREBY WAGER that if in 10 years time (by 15 December 2016) the observationally verified model of cosmology corresponds to a solution of Einstein's equations with an energy-momentum tensor with a term

$$T_{\mu\nu} = \Lambda g_{\mu\nu}, \quad \Lambda = \text{constant},$$

contributing at least 10% to the total energy-momentum over redshifts $0<z<8$, then DLW shall purchase for TP a lamp of TP's choice to help him better illuminate his calculations of the darkness of the Universe. On the other hand if this is not the case, then TP shall purchase for DLW a clock of DLW's choice to help him keep better track of the lack of constancy of cosmological ideas. The value of the "objet d'art" shall not exceed US$200 or 10% of the loser's net monthly salary, whichever is lower. Either party is free to concede the bet at any time before the 10 years are up.

Signed

David Wiltshire

DAVID L. WILTSHIRE

Padmanabhan

THANU PADMANABHAN

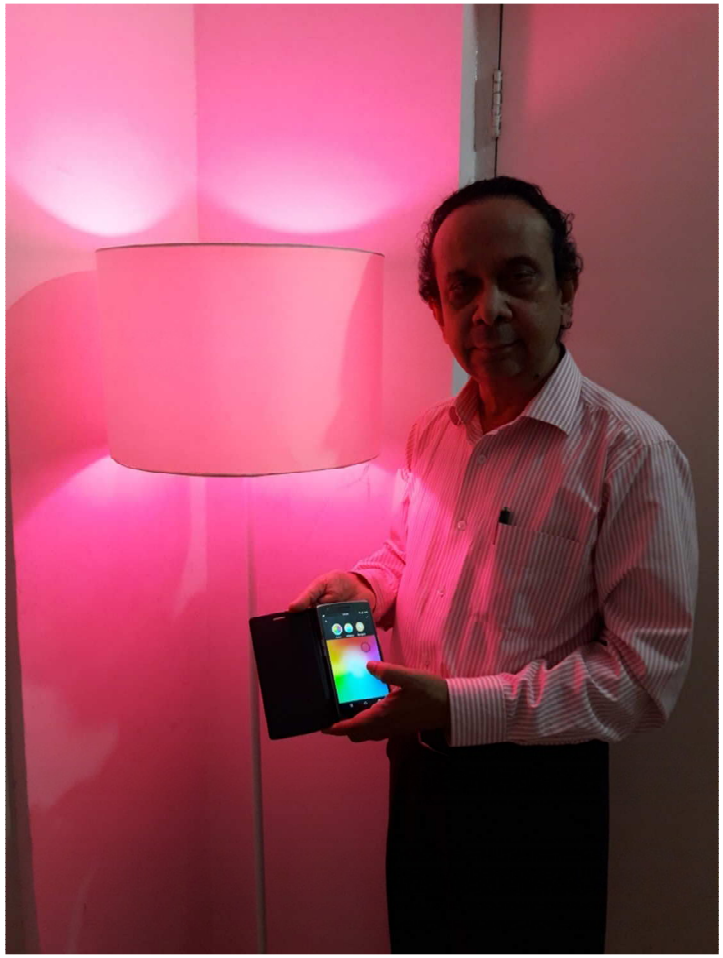
Witnessed by

A. Melatos

PROF. A. MELATOS

PROF. R. WEBSTER

[*Note*: This bet was made on the basis of a challenge in T. Padmanabhan's lecture delivered on 15 December 2006 at the 23rd Texas Symposium, that he had not met a physicist willing to make a wager against his claim that "w=-1".]



26 November 2016: T Padmanabhan and winnings - lamp with smart phone app, adjustable redshift feature

Cosmic web: typical structures

- Galaxy clusters, 2 – 10 h^{-1}Mpc, form filaments and sheets or “walls” that thread and surround voids
- Universe is void dominated (60–80%) by volume, with distribution peaked at a particular scale (40% of total volume):

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

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

Statistical homogeneity scale (SHS)

- Modulo debate (SDSS Hogg et al 2005, Sylos Labini et al 2009; WiggleZ Scrimgeour et al, 2012), *some notion* of statistical homogeneity reached on 70–100 h^{-1}Mpc scales based on 2–point galaxy correlation function
- Also observe $\delta\rho/\rho \sim 0.07$ on scales $\gtrsim 100\,h^{-1}$Mpc (bounded) in largest survey volumes; no evidence yet for $\langle \delta\rho/\rho \rangle_{\mathcal{D}} \to \epsilon \ll 1$ as $\mathrm{vol}(\mathcal{D}) \to \infty$
- BAO scale close to SHS; in galaxy clustering BAO scale determination is treated in near linear regime in ΛCDM
- No direct evidence for FLRW spatial geometry below SHS (although assumed, e.g., defining boost of Local Group wrt CMB rest frame)

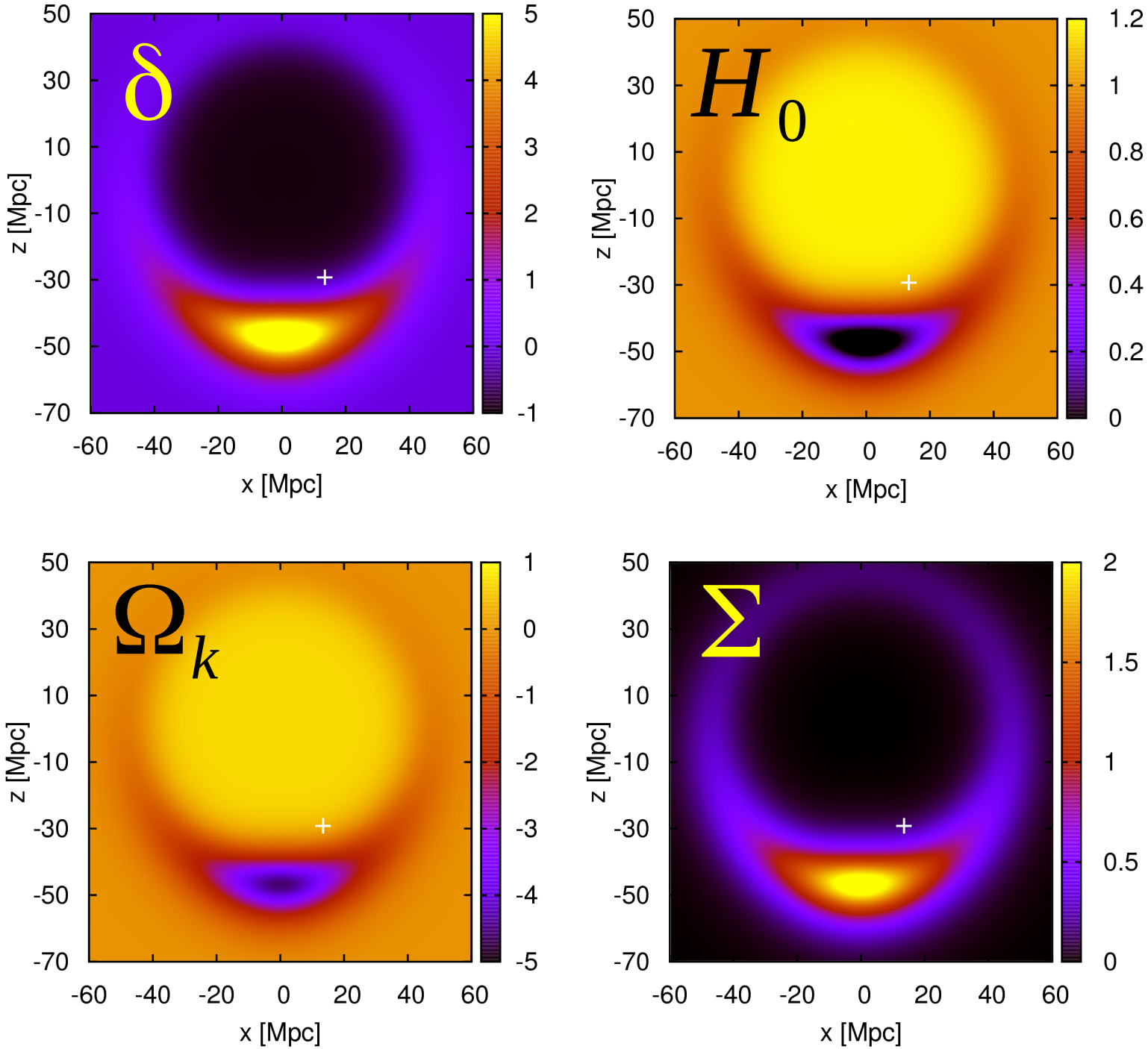
Inhomogeneity below SHS

- Non-Copernican large void Lemaître-Tolman-Bondi toy models considered widely as DE solution - unrealistic
- Exact Λ–Szekeres solutions: Planck ΛCDM on $\gtrsim 100\,h^{-1}$Mpc, Szekeres inhomogeneity inside, K Bolejko, MA Nazer, DLW JCAP 06 (2016) 035
- Potential insights about
  - convergence of “bulk flows” (see also Kraljic & Sarkar, JCAP 10 (2016) 016)
  - H_0 tension
  - Models for large angle CMB “anomalies” in future

$$\Delta T_{\text{nk-hel}} = \frac{T_{\text{model}}}{\gamma_{\text{LG}}(1-\boldsymbol{\beta}_{\text{LG}}\cdot\hat{\mathbf{n}}_{\text{hel}})} - \frac{T_0}{\gamma_{\text{CMB}}(1-\boldsymbol{\beta}_{\text{CMB}}\cdot\hat{\mathbf{n}}_{\text{hel}})}$$

$$T_{\text{model}} = \frac{T_{\text{dec}}}{1+z_{\text{model}}(\hat{\mathbf{n}}_{\text{LG}})}\,, \quad T_0 = \frac{T_{\text{dec}}}{1+z_{\text{dec}}}$$

Szekeres model



General relativity: theory

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad U^\nu \nabla_\nu U^\mu = 0$$

- *Matter tells space how to curve; Space tells matter how to move*
- Matter and geometry are dynamically coupled

$$\nabla^\nu T_{\mu\nu} = 0$$

- *Energy is not absolutely conserved*: rather energy-momentum tensor is covariantly conserved
- On account of the strong equivalence principle, $T_{\mu\nu}$ contains localizable energy–momentum only
- Gravitational energy is dynamical, nonlocal; integrated over a region it is *quasilocal*

Standard cosmology: practice

$$\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2} - \frac{1}{3}\Lambda c^2 = \frac{8\pi G\rho}{3}$$

- *Friedmann tells space how to curve;* (rigidly)

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

- *Newton tells matter how to move;* non-linearly in N-body simulations
- Dynamical energy of background fixed; Newtonian gravitational energy conserved
- Dynamical coupling of matter and geometry on small scales assumed irrelevant for cosmology

What is a cosmological particle (dust)?

- In FLRW one takes observers "comoving with the dust"
- Traditionally galaxies were regarded as dust. However,
  - Galaxies, clusters not 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]

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

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **23** (2006) 235–250 doi:10.1088/0264-9381/23/1/012

Can the acceleration of our universe be explained by the effects of inhomogeneities?

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Abstract

No. It is simply not plausible that cosmic acceleration could arise within the context of general relativity from a back-reaction effect of inhomogeneities in our universe, without the presence of a cosmological constant or ``dark energy." We point out that our universe appears to be described very accurately on all scales by a Newtonianly perturbed FLRW metric. (This assertion is entirely consistent with the fact that we commonly encounter $\delta\rho/\rho > 10^{30}$.) If the universe is accurately described by a Newtonianly perturbed FLRW metric, then the back-reaction of inhomogeneities on the dynamics of the universe is negligible. If not, then it is the burden of an alternative model to account for the observed properties of our universe. We emphasize with concrete examples that it is {\it not} adequate to attempt to justify a model by merely showing that some spatially averaged quantities

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Class. Quantum Grav. 31 (2014) 234003 (16pp) doi:10.1088/0264-9381/31/23/234003

How well is our Universe described by an FLRW model?

Stephen R Green[1] **and Robert M Wald**[2]

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Abstract

Extremely well! In the ΛCDM model, the spacetime metric, g_{ab}, of our Universe is approximated by an FLRW metric, $g_{ab}^{(0)}$, to about one part in 10^4 or better on both large and small scales, except in the immediate vicinity of very strong field objects, such as black holes. However, derivatives of g_{ab} are not close to derivatives of $g_{ab}^{(0)}$, so there can be significant differences in the

IOP Publishing Classical and Quantum Gravity
Class. Quantum Grav. 32 (2015) 215021 (38pp) doi:10.1088/0264-9381/32/21/215021

Is there proof that backreaction of inhomogeneities is irrelevant in cosmology?

T Buchert[1,13], M Carfora[2,3], G F R Ellis[4], E W Kolb[5], M A H MacCallum[6], J J Ostrowski[1,7], S Räsänen[8], B F Roukema[1,7], L Andersson[9,10], A A Coley[11] and D L Wiltshire[12]

Abstract

No. In a number of papers, Green and Wald argue that the standard FLRW model approximates our Universe extremely well on all scales, except close to strong-field astrophysical objects. In particular, they argue that the effect of inhomogeneities on average properties of the Universe (backreaction) is irrelevant. We show that this latter claim is not valid. Specifically, we demonstrate, referring to their recent review paper, that (i) their two-dimensional example used to illustrate the fitting problem differs from the actual problem in important respects, and it assumes what is to be proven; (ii) the proof of the trace-free property of backreaction is unphysical and the theorem about it fails to be a mathematically general statement; (iii) the scheme that

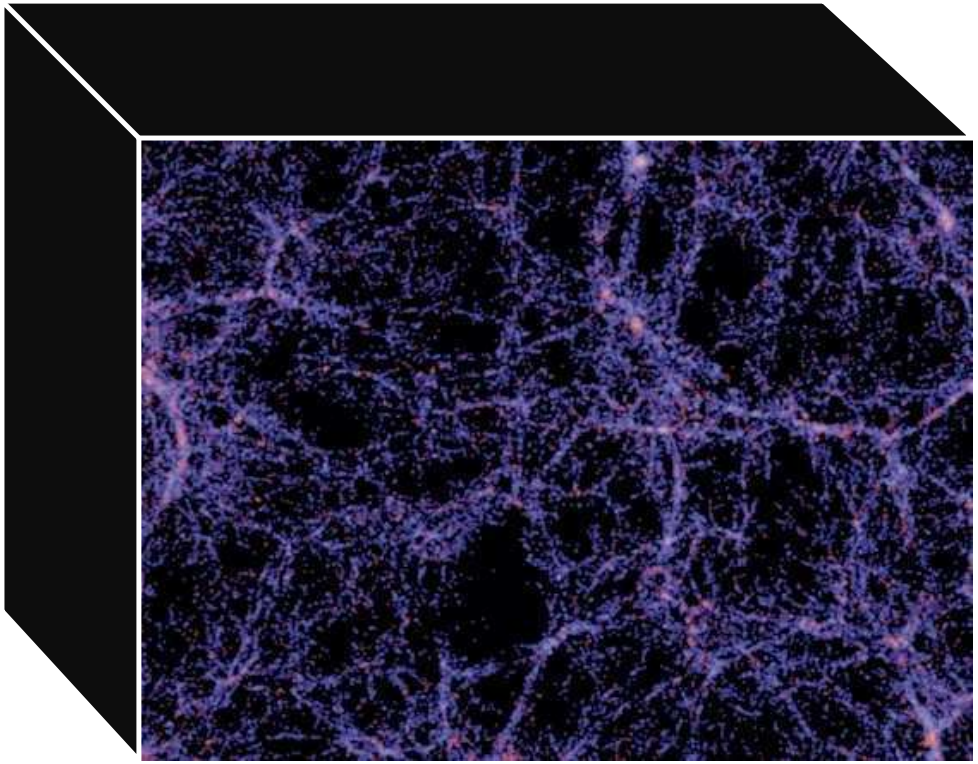
Averaging and backreaction

- *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 $\langle G^{\mu}{}_{\nu}(g_{\alpha\beta})\rangle \neq G^{\mu}{}_{\nu}(\langle g_{\alpha\beta}\rangle)$
- *Weak backreaction*: *Assume* global average is an exact solution of Einstein's equations on large scale
- *Strong backreaction*: Fully nonlinear; assume alternative solution for homogeneity at last scattering
  - Einstein's equations are causal; no need for them on scales larger than light has time to propagate
  - Inflation becomes more a quantum geometry phenomenon, impact in present spacetime structure

SHS average cell…



- Need to consider relative position of observers over scales of tens of Mpc over which $\delta\rho/\rho \sim -1$.
- Gradients in spatial curvature and gravitational energy can lead to calibration differences between rulers & clocks of bound structures and volume average

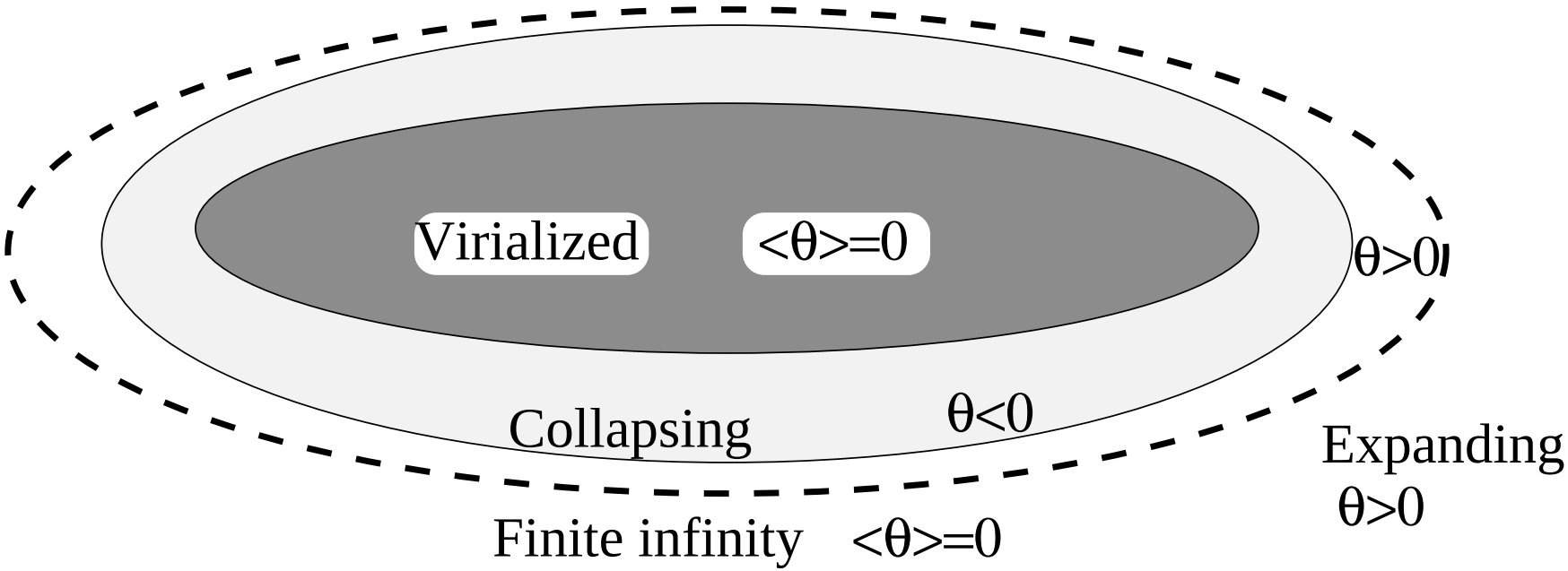
Cosmological Equivalence Principle

- *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*,

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

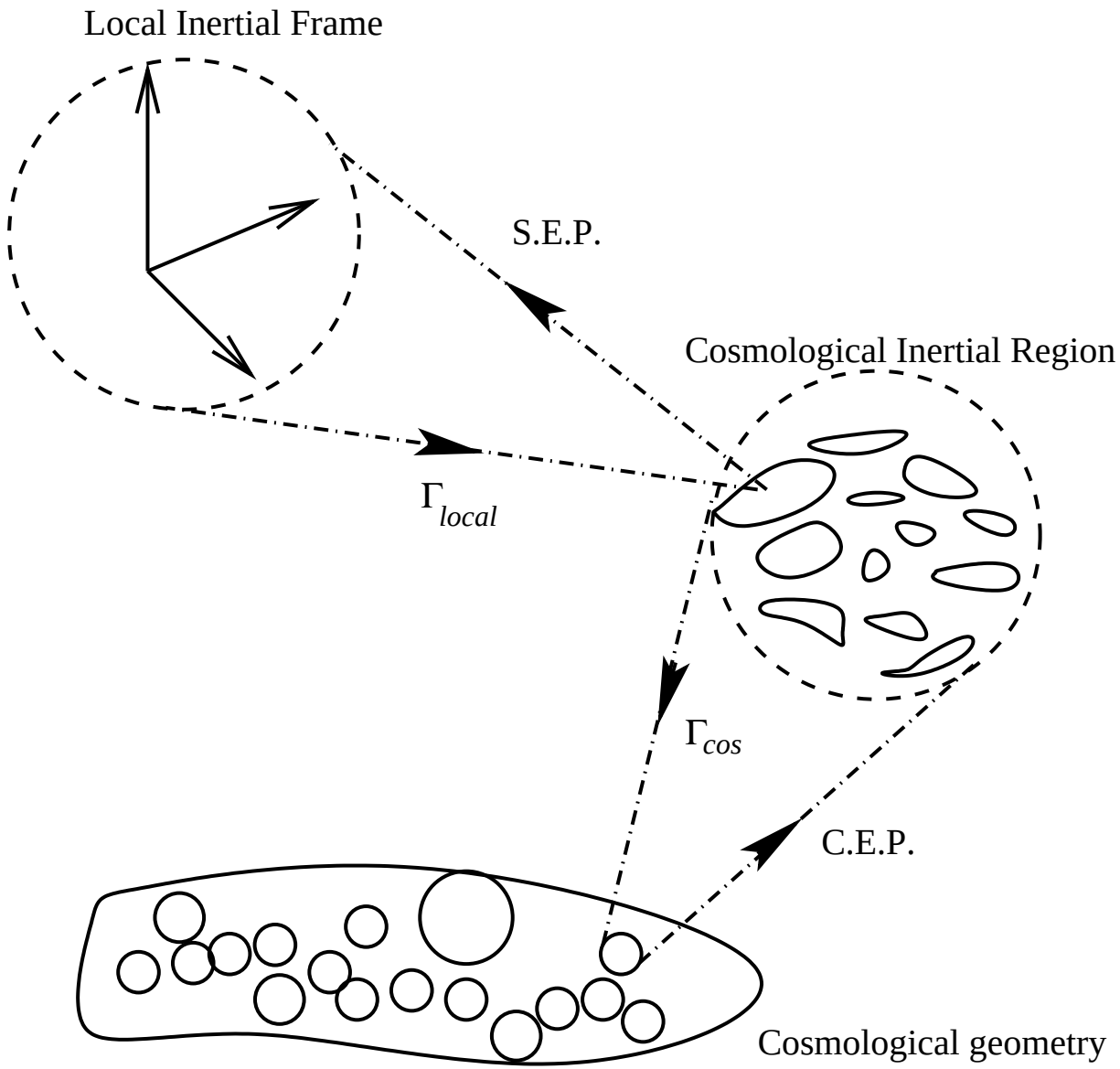
- Defines Cosmological Inertial Region (CIR) in which *regionally isotropic* volume expansion is equivalent to a velocity in special relativity
- Such velocities integrated on a bounding 2-sphere define *"kinetic energy of expansion"*: globally it has gradients

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…

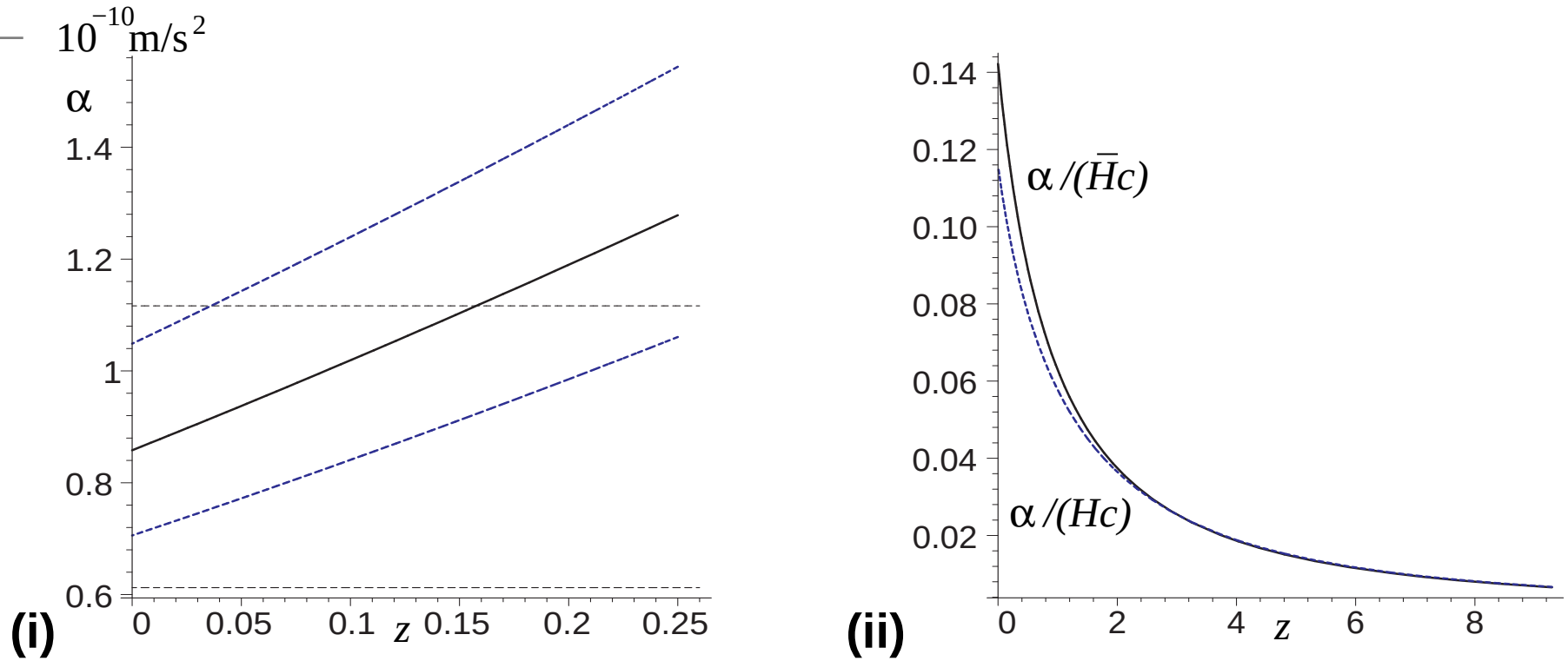


Timescape phenomenology

$$\mathrm{d}s^2 = -(1+2\Phi)c^2\mathrm{d}t^2 + a^2(1-2\Psi)g_{ij}\mathrm{d}x^i\mathrm{d}x^j$$

- Global statistical metric by Buchert average not a solution of Einstein equations
- Solve for Buchert equations for ensemble of void and finite infinity (wall) regions; conformally match radial null geodesics of finite infinity and statistical geometries, fit to observations
- Relative regional volume deceleration integrates to a substantial difference in clock calibration of bound system observers relative to volume average over age of universe
- Difference in *bare* (statistical or volume–average) and *dressed* (regional or finite–infinity) parameters

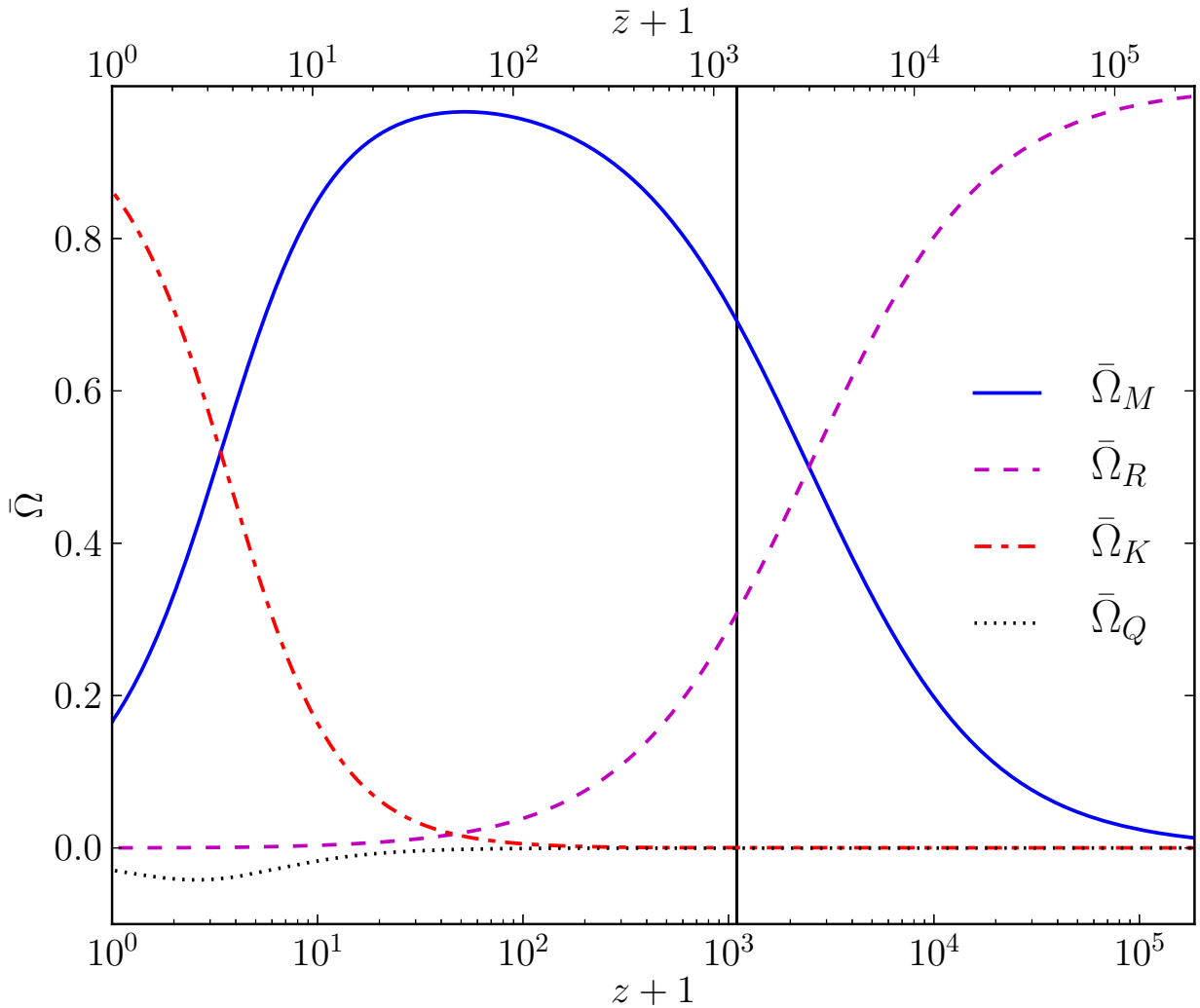
Relative deceleration scale



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 $\mathrm{d}t = \bar{\gamma}_{\mathrm{w}}\,\mathrm{d}\tau_{\mathrm{w}}$ ($\rightarrow\sim 35\%$)

Bare cosmological parameters



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

Apparent cosmic acceleration

- Volume average observer sees no apparent cosmic acceleration

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

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

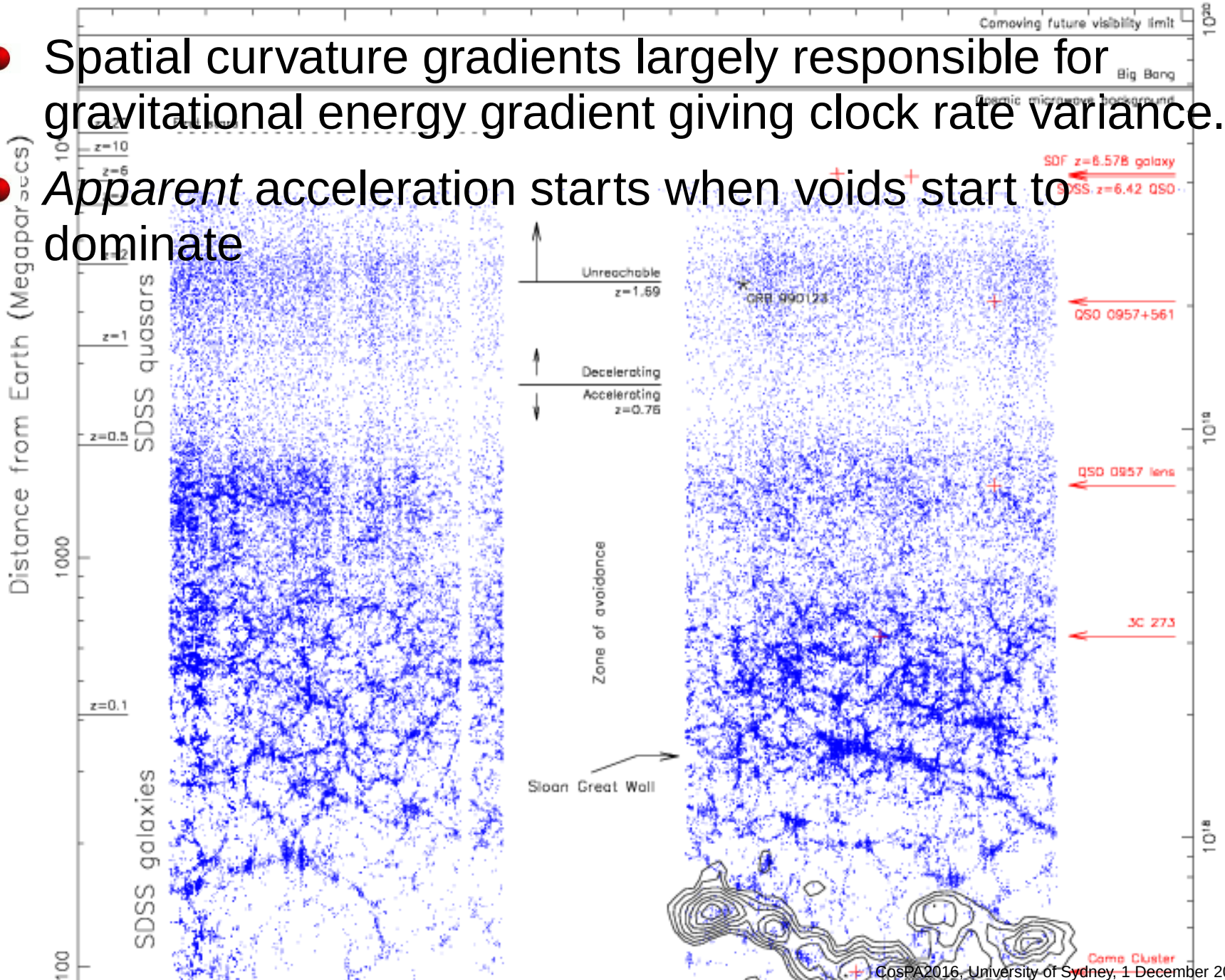
- A wall observer registers apparent cosmic acceleration

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

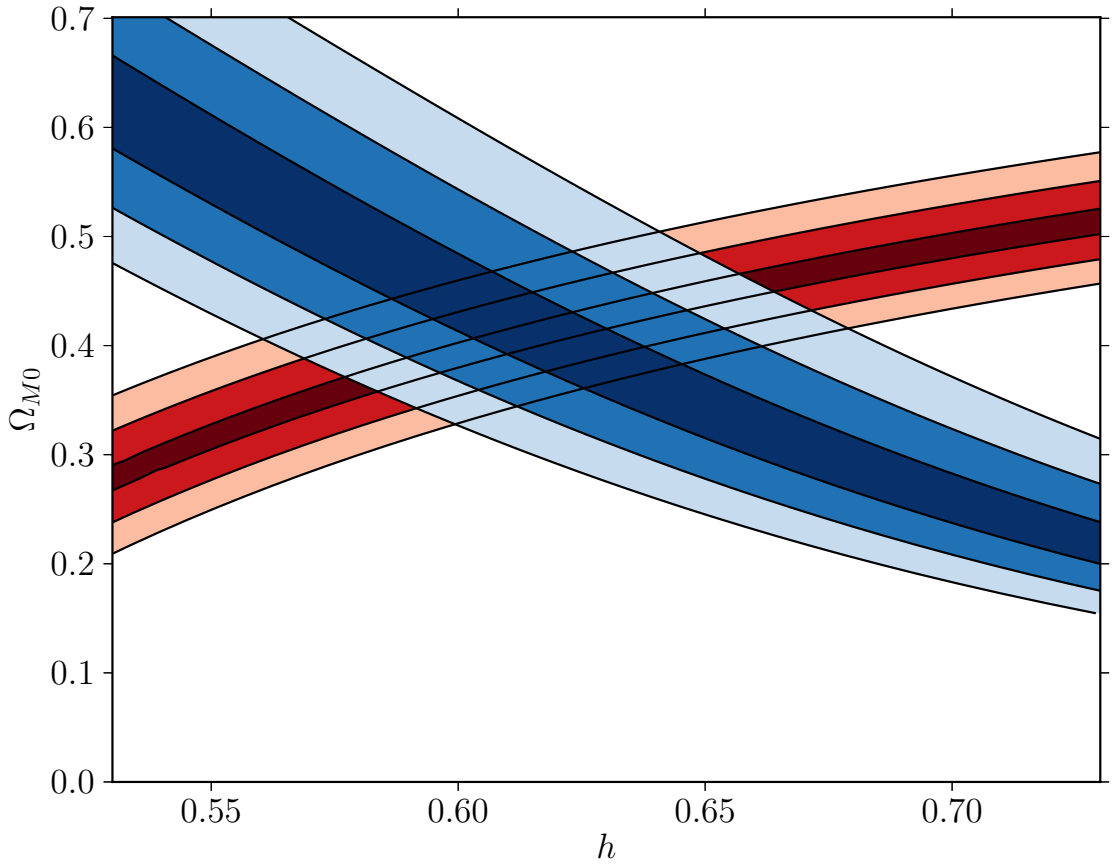
Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small $f_{\rm v}$; changes sign when $f_{\rm v} = 0.5867\ldots$, and approaches $q \to 0^-$ at late times.

Cosmic coincidence not a problem

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



CMB: sound horizon + baryon drag

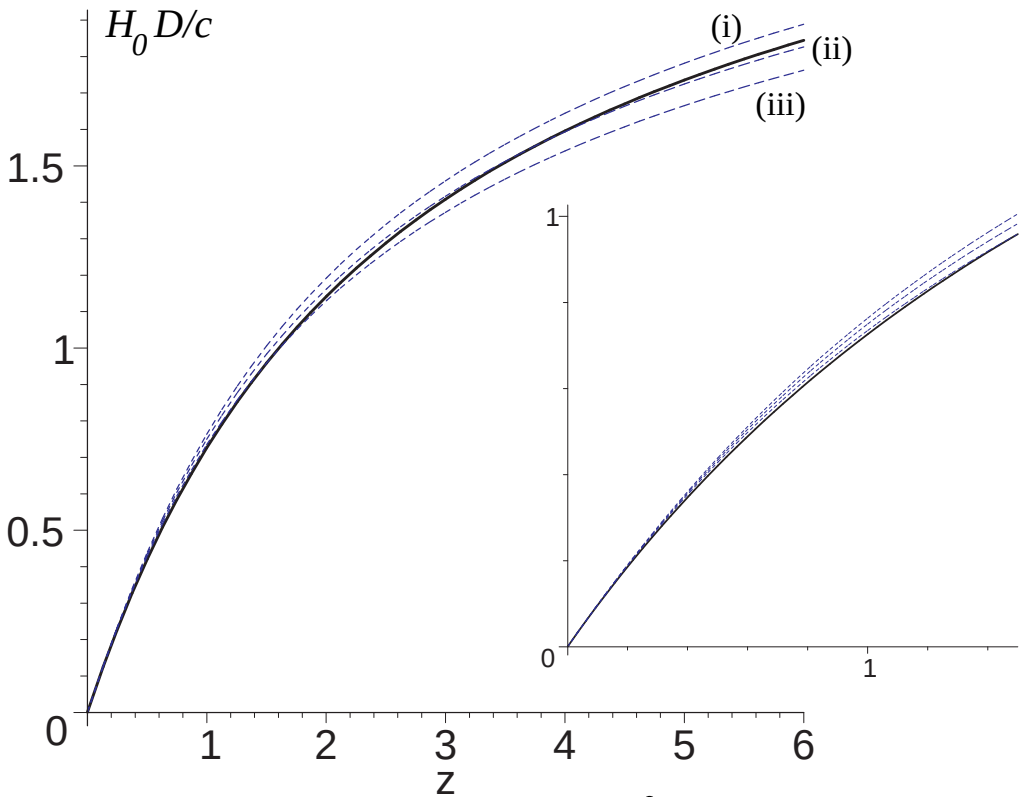


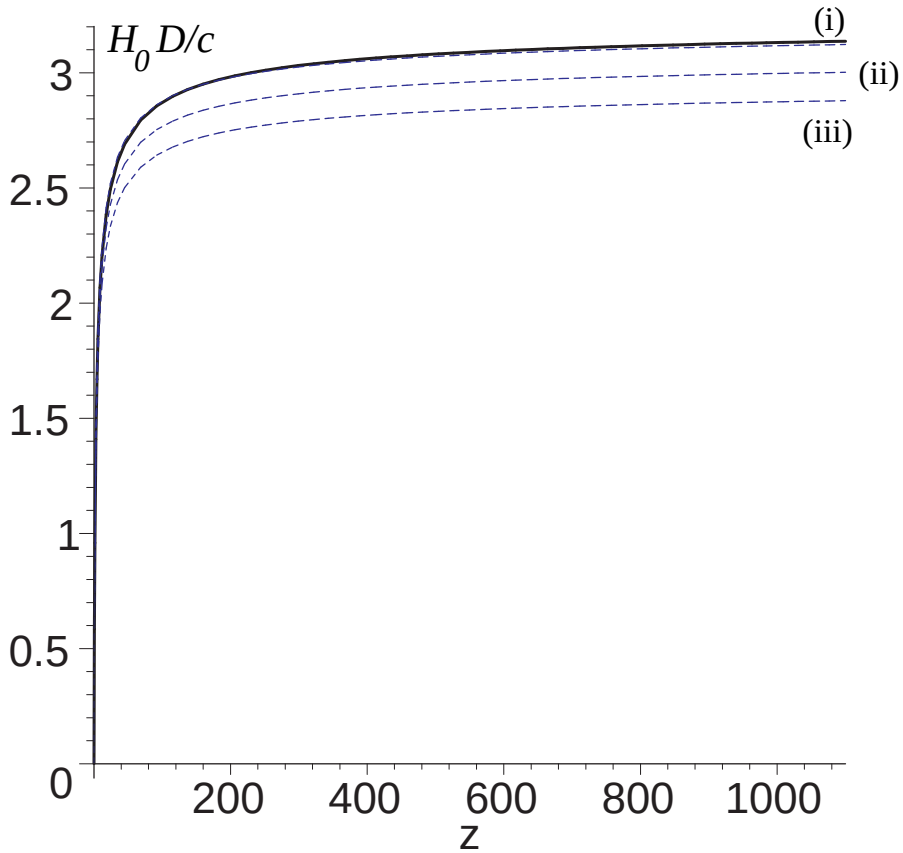
Parameters within the (Ω_{M0},H_0) plane which fit the angular scale of the sound horizon $\theta_* = 0.0104139$ (blue), and its comoving scale at the baryon drag epoch as compared to Planck value $98.88\,h^{-1}$Mpc (red) to within 2%, 4% and 6%, with photon-baryon ratio $\eta_{B\gamma} = 4.6$–5.6×10^{-10} 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 $\bar{\Omega}_{\rm M0} = 0.167^{+0.036}_{-0.037}$
- Dressed matter density parameter $\Omega_{\rm M0} = 0.41^{+0.06}_{-0.05}$
- Dressed baryon density parameter $\Omega_{\rm B0} = 0.074^{+0.013}_{-0.011}$
- Nonbaryonic/baryonic matter ratio $\Omega_{\rm C0}/\Omega_{\rm B0} = 4.6^{+2.5}_{-2.1}$
- 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 $z_{\rm acc} = 0.46^{+0.26}_{-0.25}$

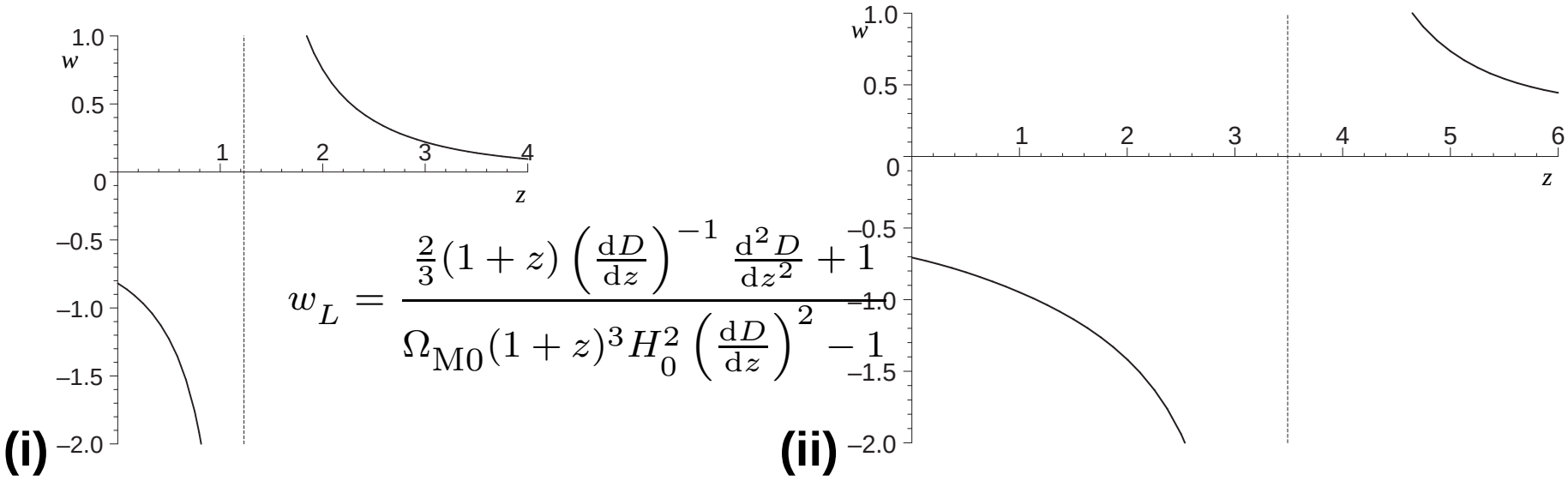
Dressed "comoving distance" $D(z)$





TS model, with $f_{\rm v0} = 0.695$, **(black)** compared to 3 spatially flat ΛCDM models (blue): **(i)** $\Omega_{\rm M0} = 0.3175$ (best-fit ΛCDM model to Planck); (ii) $\Omega_{\rm M0} = 0.35$; **(iii)** $\Omega_{\rm M0} = 0.388$.

Equivalent “equation of state”?

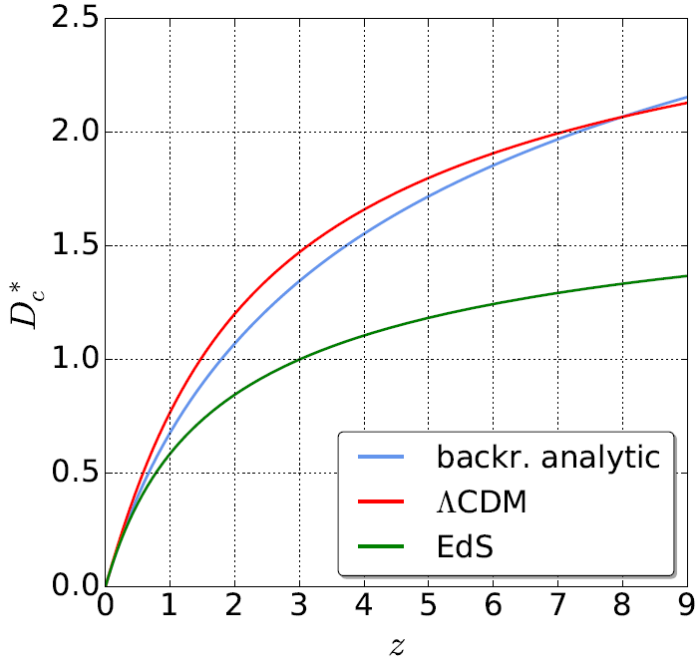


$$w_L = \frac{\frac{2}{3}(1+z)\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^{-1}\frac{\mathrm{d}^2 D}{\mathrm{d}z^2}+1}{\Omega_{\mathrm{M0}}(1+z)^3 H_0^2\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^2-1}$$

A formal “dark energy equation of state” $w_L(z)$ for the TS model, with $f_{\mathrm{v0}} = 0.695$, calculated directly from $r_w(z)$: **(i)** $\Omega_{\mathrm{M0}} = 0.41$; **(ii)** $\Omega_{\mathrm{M0}} = 0.3175$.

- 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.

Racz et al arXiv:1607.08797



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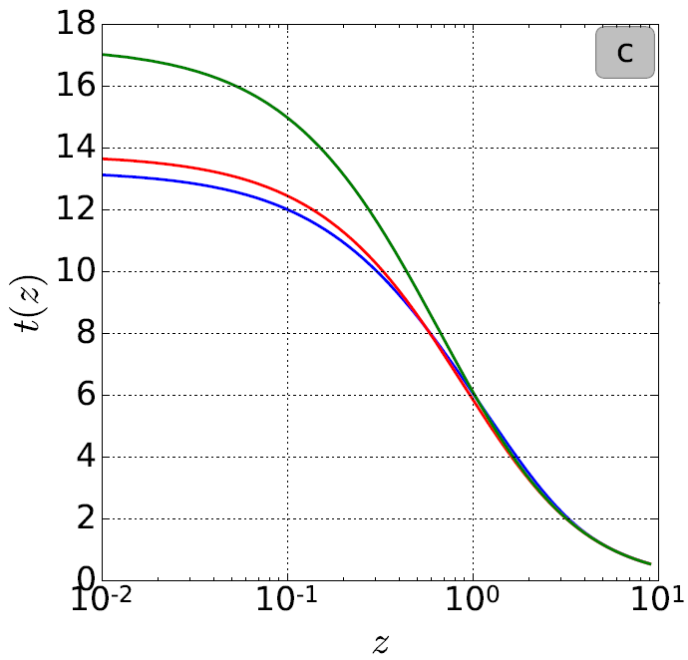


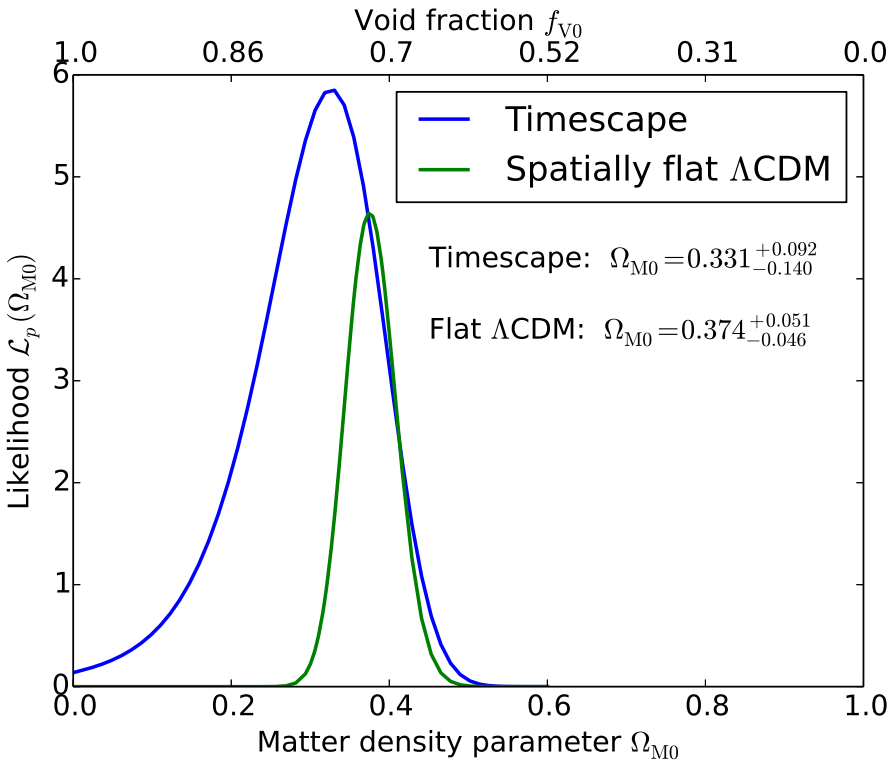
(5)

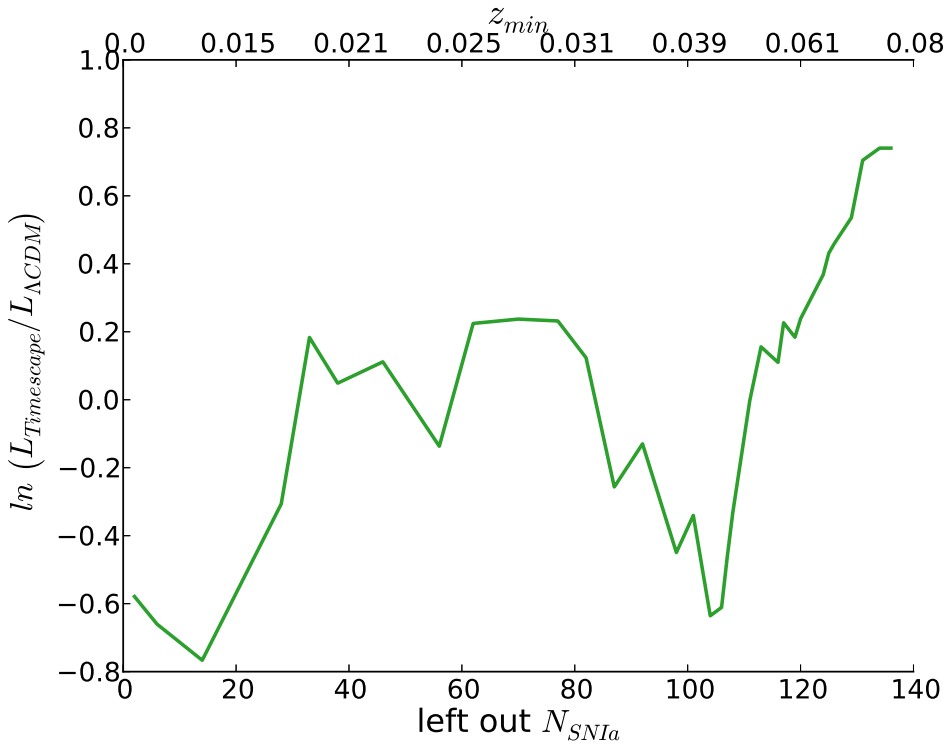
- Timescape numerically rediscovered in Newtonian N-body simulation, applying backreaction scheme to Planck LCDM EdS initial data at $z = 9$
- No light propagation formalism, no light cone average
- Different phenomenological interpretation; but ensemble averages $D_c^*(z)$, $t(z)$ of finite infinity close match to analytic solution DLW, PRL 99 (2007) 251101

SneIa: Smale + DLW, (2011), MNRAS 413

- 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) $\Omega_{\mathrm{M0}} = 0.12^{+0.12}_{-0.11}$;
  MLCS17 (Hicken et al 2009) $\Omega_{\mathrm{M0}} = 0.19^{+0.14}_{-0.18}$;
  SDSS-II (Kessler et al 2009) $\Omega_{\mathrm{M0}} = 0.42^{+0.10}_{-0.10}$
- Supernovae systematics (reddening/extinction, intrinsic colour variations) must be understood to distinguish models
- Foregrounds, and inclusion of SneIa below SSH an issue

SneIa: Dam, Heinesen & DLW preliminary



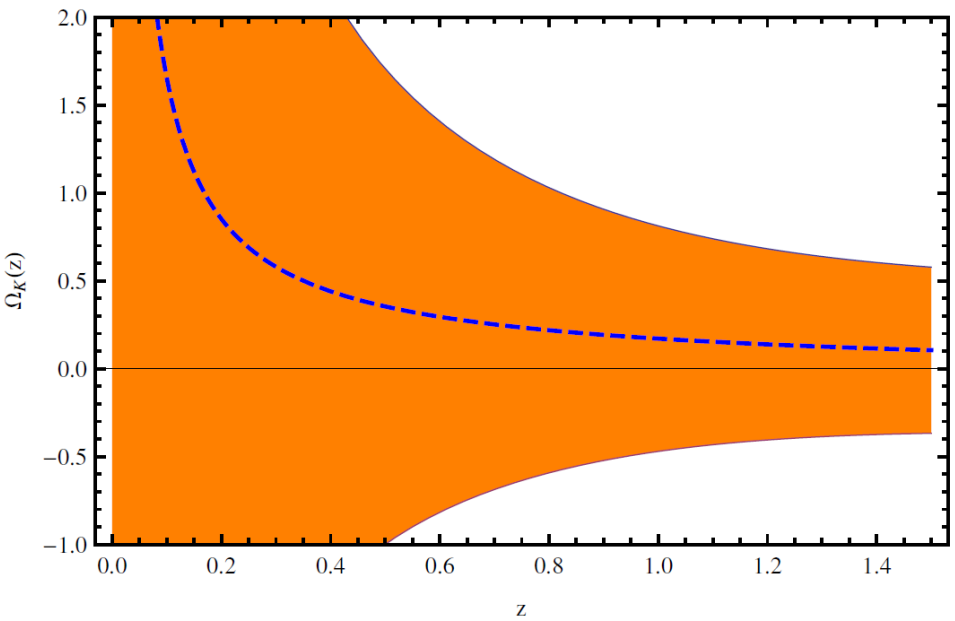


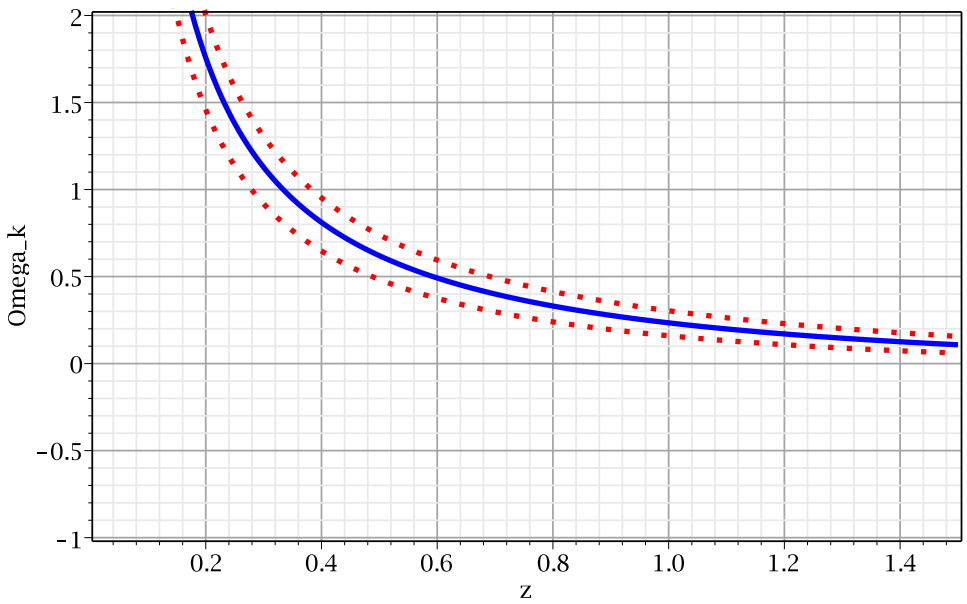
- Applying SALT2 to JLA data (Betouille et al 2014), 740 SneIa, with methodology Nielsen, Guffanti & Sarkar Sci. Rep. 6 (2016) 35596, timescape and spatially flat ΛCDM statistically indistinguishable
- Best fit $f_{v0} = 0.76^{+0.06}_{-0.05}$ (or $\Omega_{M0} = 0.33^{+0.06}_{-0.08}$) same as Leith, Ng & DLW, ApJ 672 (2008) L91 fit to Riess07 data

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

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

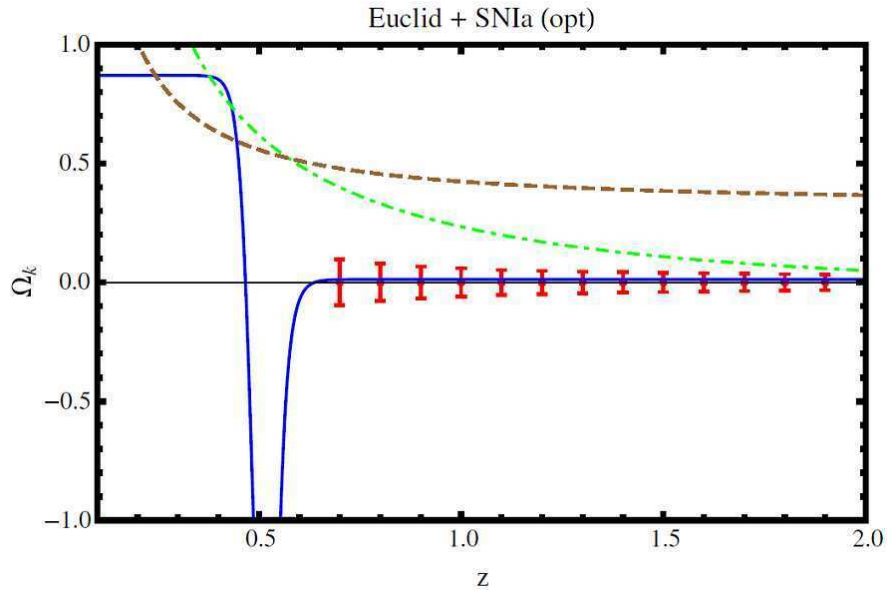




Left panel: CBL statistic from Sapone, Majerotto and Nesseris, PRD 90, 023012 (2014) Fig 8, using existing data from SneIa (Union2) and passively evolving galaxies for $H(z)$.

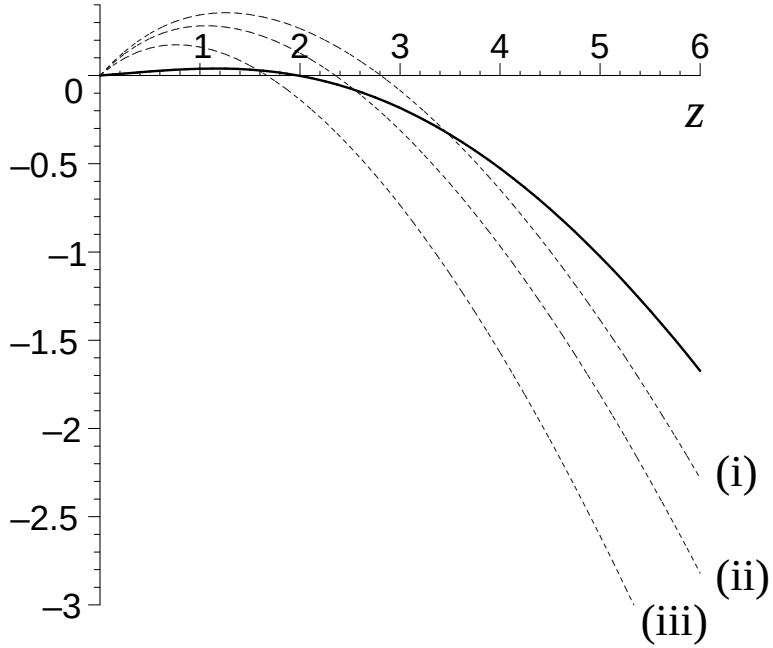
Right panel: TS prediction, with $f_{\rm v0} = 0.695^{+0.041}_{-0.051}$.

Clarkson Bassett Lu test with *Euclid*



- Projected uncertainties for ΛCDM, with *Euclid* $+$ 1000 SneIa, Sapone *et al*, PRD 90, 023012 (2014) Fig 10
- Timescape prediction (green), compared to non-Copernican Gpc void model (blue), and *tardis* cosmology, Lavinto *et al* JCAP 12 (2013) 051 (brown).
- Timescape prediction becomes greater than uncertainties for $z \lesssim 1.5$. (Falsfiable.)

Redshift time drift (Sandage–Loeb test)



$H_0^{-1}\frac{\mathrm{d}z}{\mathrm{d}\tau}$ for the TS model with $f_{\mathrm{v}0} = 0.76$ (solid line) is compared to three spatially flat ΛCDM models.

- 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

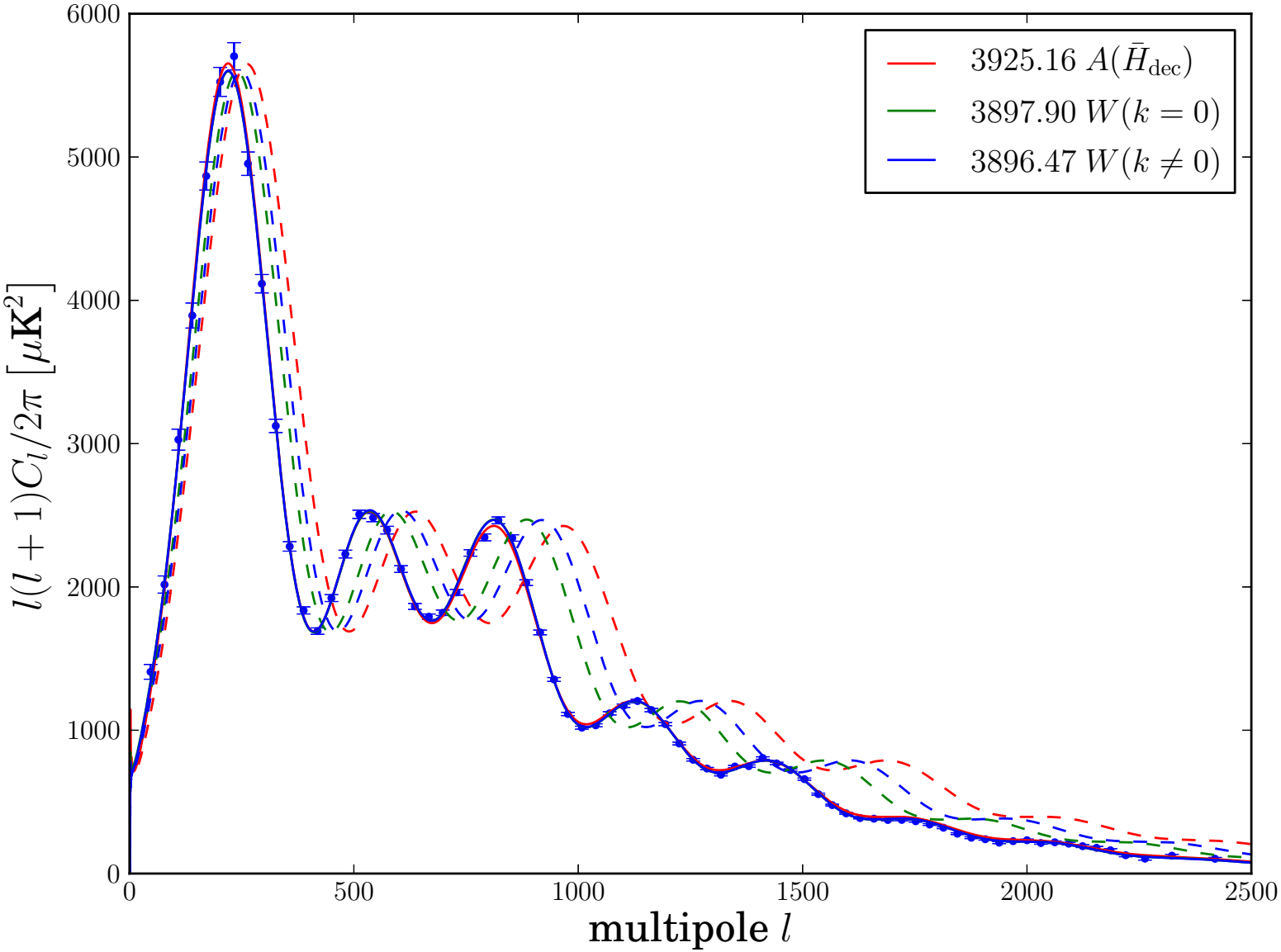
CMB acoustic peaks, $\ell > 50$, full fit

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

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

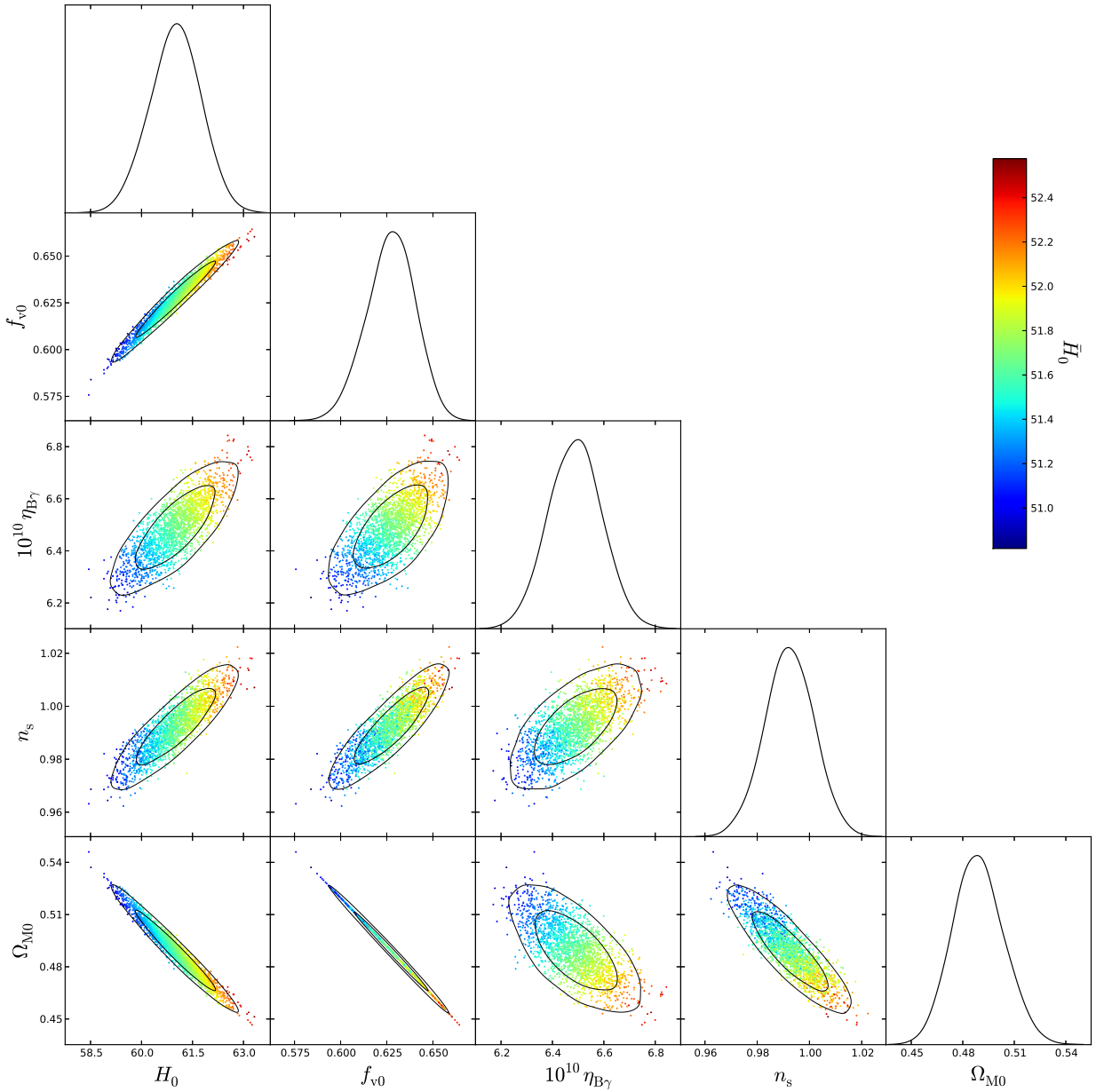
- Ignore $\ell < 50$ in fit (late ISW effect may well differ)
- Fit FLRW model that decelerates by same amount from last scattering til today (in volume-average time) – systematic uncertainties depending on method adopted

CMB acoustic peaks, full Planck fit



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

M.A. Nazer + DLW, arXiv:1410.3470

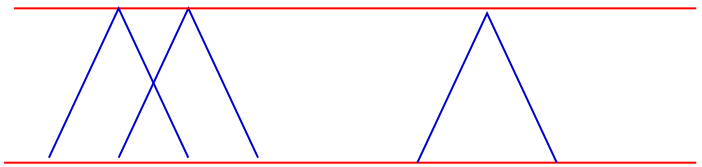


CMB acoustic peaks: arXiv:1410.3470

- Likelihood $-\ln\mathcal{L} = 3925.16$, 3897.90 and 3896.47 for A($\bar{H}_{\rm dec}$), W($k=0$) and W($k\neq 0$) methods respectively on $50 \leq \ell \leq 2500$, c.f., ΛCDM: 3895.5 using `MINUIT` or 3896.9 using `CosmoMC`.
- $H_0 = 61.0$ km/s/Mpc (± 1.3% stat) (± 8% sys); $f_{\rm v0} = 0.627$ (± 2.33% stat) (± 13% sys).
- Previous D_A + r_{drag} constraints give concordance for baryon–to–photon ratio $10^{10}\eta_{B\gamma} = 5.1 \pm 0.5$ with no primordial ^{7}Li anomaly, $\Omega_{\rm C0}/\Omega_{\rm B0}$ possibly 30% lower.
- Full fit – driven by 2nd/3rd peak heights, $\Omega_{\rm C0}/\Omega_{\rm B0}$, ratio – gives $10^{10}\eta_{B\gamma} = 6.08$ (± 1.5% stat) (± 8.5% sys).
- With bestfit values, primordial ^{7}Li anomalous and BOSS $z = 2.34$ result in tension at level similar to ΛCDM

Back to the early Universe

- BUT backreaction in primordial plasma neglected
- Backreaction of similar order to density perturbations (10^{-5}); little influence on background but may influence growth of perturbations
- First step: add pressure to new “relativistic Lagrangian formalism”: Buchert et al, PRD 86 (2012) 023520; PRD 87 (2013) 123503; Alles et al, PRD 92 (2015) 023512
- Rewrite whole of cosmological perturbation theory
- Formalism adapted to fluid frames (“Lagrangian”) not hypersurfaces (“Eulerian”). Backreaction effects small in early Universe – debates can be resolved!

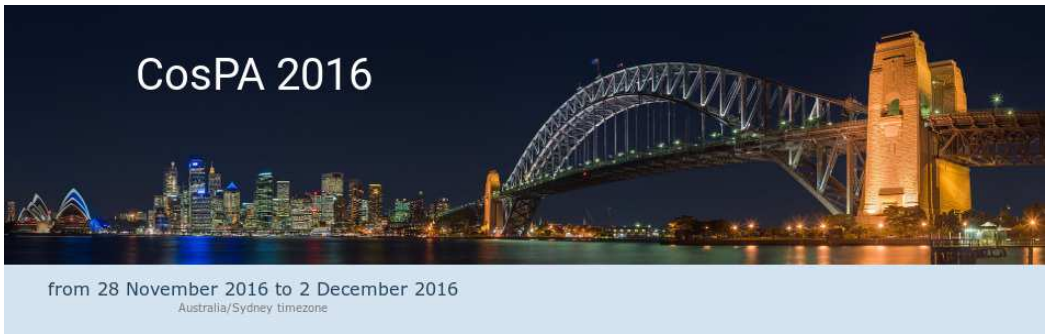


Relativistic computational cosmology

- Full general numerical simulations using (BSSN (Baumgarte-Shapiro-Shibata-Nakamura) formalism beginning
  - Mertens, Giblin, Starkman, PRL 116 (2016) 251301
  - Bruni, Bentivenga, PRL 116 (2016) 251302
  - Macpherson, Lasky, Price, arXiv:1611.05447
- Structures from faster than spherical collapse model
- Expect decades of development
- E.g., Bruni & Bentivenga must stop codes when $\delta\rho/\rho \sim 2$ in overdensities (at effective redshift $z = 260$), no chance for void dominated backreaction yet
- Consistent excision of collapsing region (finite infinity scale) a huge challenge; again a Lagrangian approach desirable

Conclusion: Why is ΛCDM so successful?

- Early Universe was extremely close to homogeneous and isotropic, leading to a simplifying principle – Cosmological Equivalence Principle
- 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*
- Hubble parameter (first derivative of statistical metric; i.e., connection) is to some extent observer dependent
- *Even on small scales there is a notion of uniform Hubble flow at expense of calibration of rulers AND CLOCKS*
- Testable alternative cosmologies – timescape or otherwise – are needed to change nature of debate, and better understand systematics, selection biases



WILL THE EUCLID SATELLITE SEE NON-EUCLIDEAN GEOMETRY?

TERMS OF BET BETWEEN D.L. WILTSHIRE AND X

WHEREAS David Wiltshire, believes that the era of precision cosmology will topple the cosmological constant from its current dominance of our models of the Universe, once the rigidly expanding nature of spatial geometry – that the dark energy assumption rests on – is put to the test; and

WHERAS X believes …

WE HEREBY WAGER that that once observations of the expansion history of the universe are sufficiently precise to perform the Clarkson-Bassett-Lu test [1] at the level of precision depicted by Sapone, Majerotto and Nesseris [2] Figure 10, right panel, (as projected for Euclid satellite measurements and 1000 supernovae, for example), then the result will show a failure of the Friedmann-Lemaitre-Robertson-Walker (FLRW) model at redshifts $z < 1$.

If the FLRW model tails the test, then X shall purchase for DLW a clock of DLW's choice to help him keep better track of the lack of constancy of cosmological ideas. If the FLRW model stands the test the DLW shall purchase for X …

The value of the "objet d'art" shall not exceed US$200 or 10% of the loser's net monthly salary, whichever is lower.

SIGNED:

WITNESSED:

References:

[1] Clarkson, C., Bassett, B.A. and Lu, T.H.-C., 2008, *"A general test of the Copernican Principle"*, Phys. Rev. Lett. **101**, 011301

[2] Sapone, D., Majerotto, E. and Nesseris S., 2014, *"Curvature vs distances: testing the FLRW cosmology"*, Phys. Rev. D **90**, 023012.

Note: This wager was offered by DLW at a talk in the CosPA2016 Conference, University of Sydney, on 1 December 2016, as a "precision cosmology" version of a more loosely worded 10 year wager he had entered into with T Padmanabhan on 15 December 2006, and conceded on 26 November 2016.