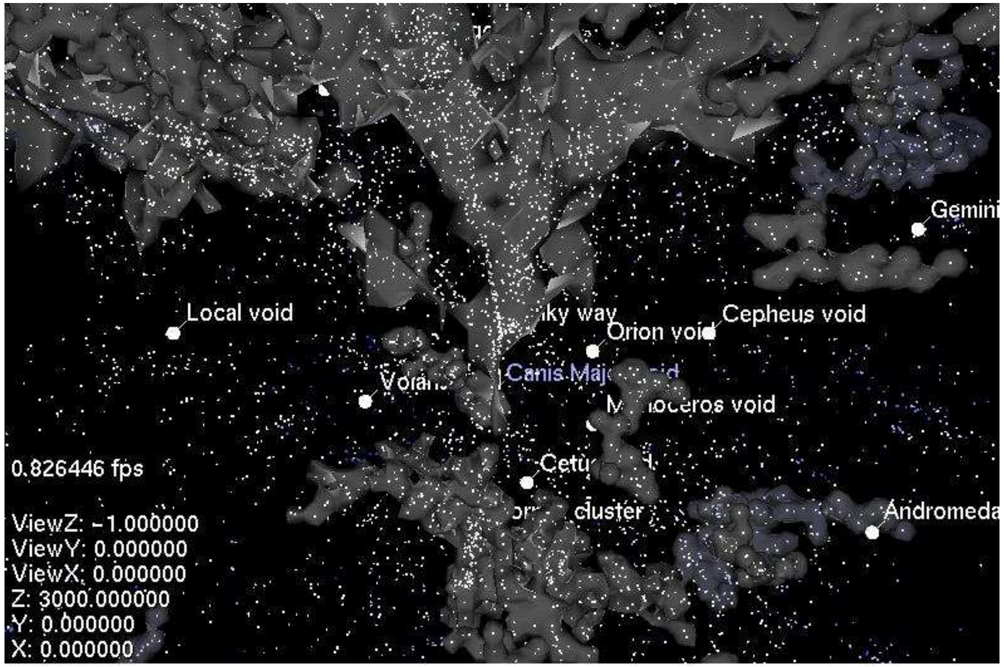
Timescape: observations, challenges

David L. Wiltshire (University of Canterbury, NZ)



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. Quan. Grav. 30 (2013) 175006**

M.A. Nazer & DLW: **Phys. Rev. D91 (2015) 063519**

L.H. Dam, A. Heinesen & DLW: **arXiv:1706.07236** **Lecture Notes: arXiv:1311.3787**

Outline of talk

- What is dark energy?:
  Dark energy is a misidentification of gradients in quasilocal gravitational energy in the geometry of a complex evolving structure of matter inhomogeneities
- Conceptual basis
- Present and future tests of timescape cosmology:
  - Supernovae, BAO, CMB, ...
  - Clarkson-Bassett-Lu test, redshift-time drift, ...
- Frontiers:
  - relativistic Lagrangian perturbation theory

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)

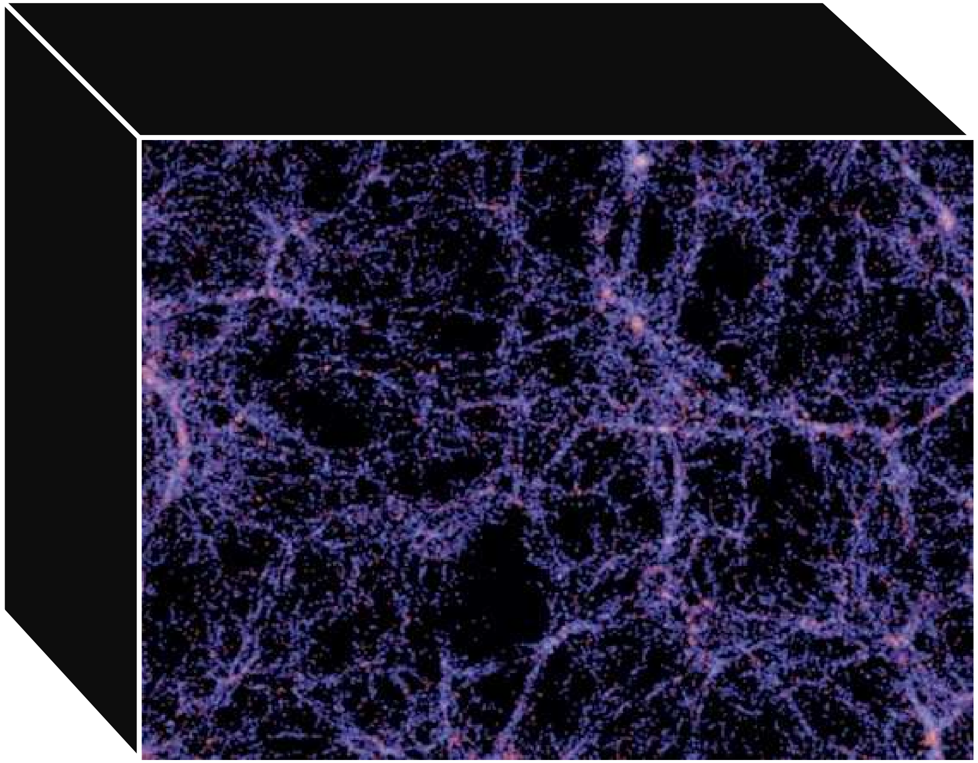
- Modulo debate (SDSS Hogg et al 2005, Sylos Labini et al 2009; WiggleZ Scrimgeour et al, 2012), *some notion* of statistical homogeneity reached on 70–100 h^{-1}Mpc scales based on 2–point galaxy correlation function
- Also observe $\delta\rho/\rho \sim 0.07$ on scales $\gtrsim 100\, h^{-1}$Mpc (bounded) 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)

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]

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

SHS average cell…

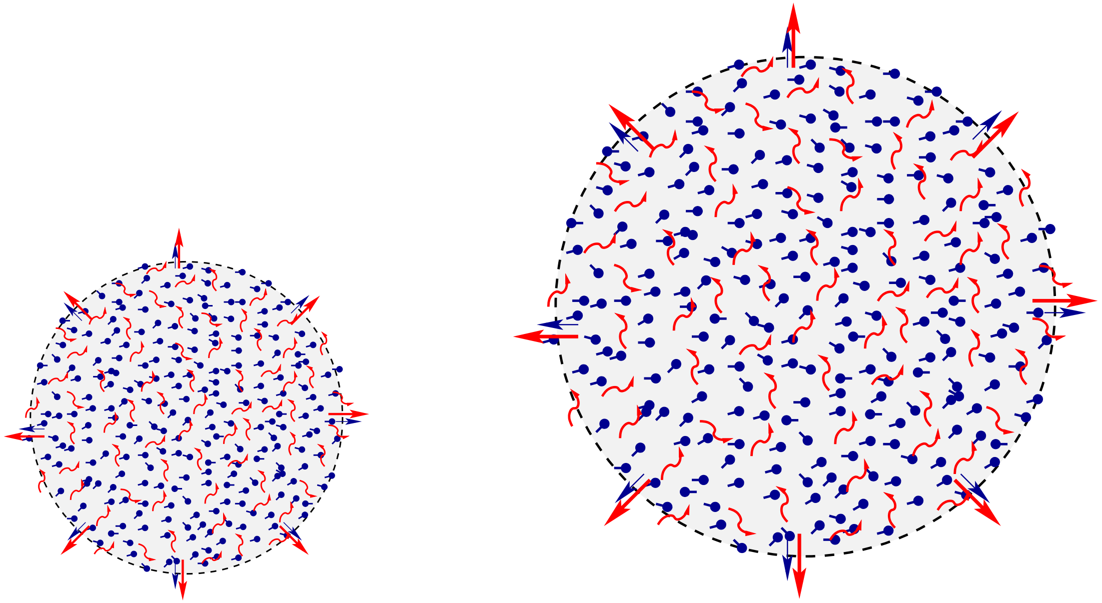


- Need to consider relative position of observers over scales of tens of Mpc over which $\delta\rho/\rho \sim -1$.
- Gradients in spatial curvature and gravitational energy can lead to calibration differences between rulers & clocks of bound structures and volume average

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)

Relative volume deceleration. . .



- Two fluids, 4-velocities U^μ, $\tilde{U}^\mu$, $U^\mu S_\mu = 0$, $\tilde{U}^\mu \tilde{S}_\mu = 0$, relative tilt $\gamma = (1-\beta^2)^{-1/2}$, $\beta \equiv v/c$),

$$U^\mu = \gamma(\tilde{U}^\mu + \beta\tilde{S}^\mu), \qquad S^\mu = \gamma(\tilde{S}^\mu + \beta U^\mu),$$

- Integrate on compact spherical boundary – average tilt $\langle\gamma\rangle$– time derivative relative volume deceleration.
- Integrated relative *clock rate drift*.

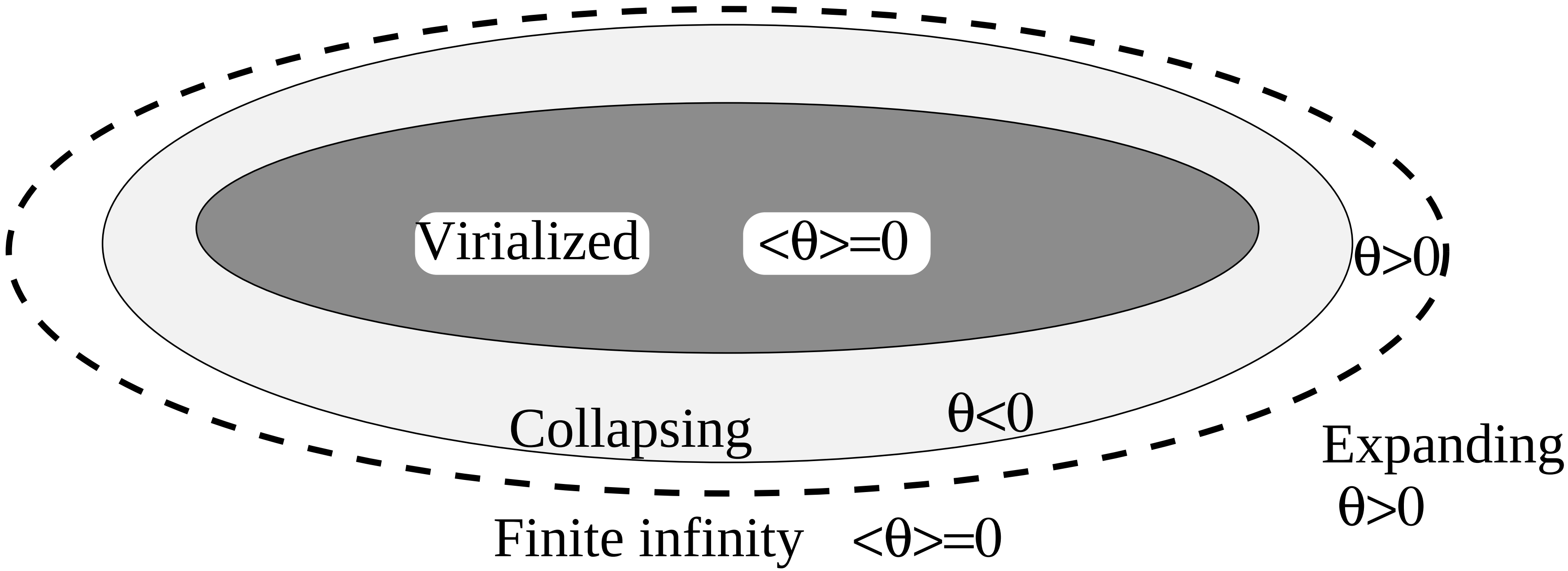
Cosmological Equivalence Principle

- *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*,

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

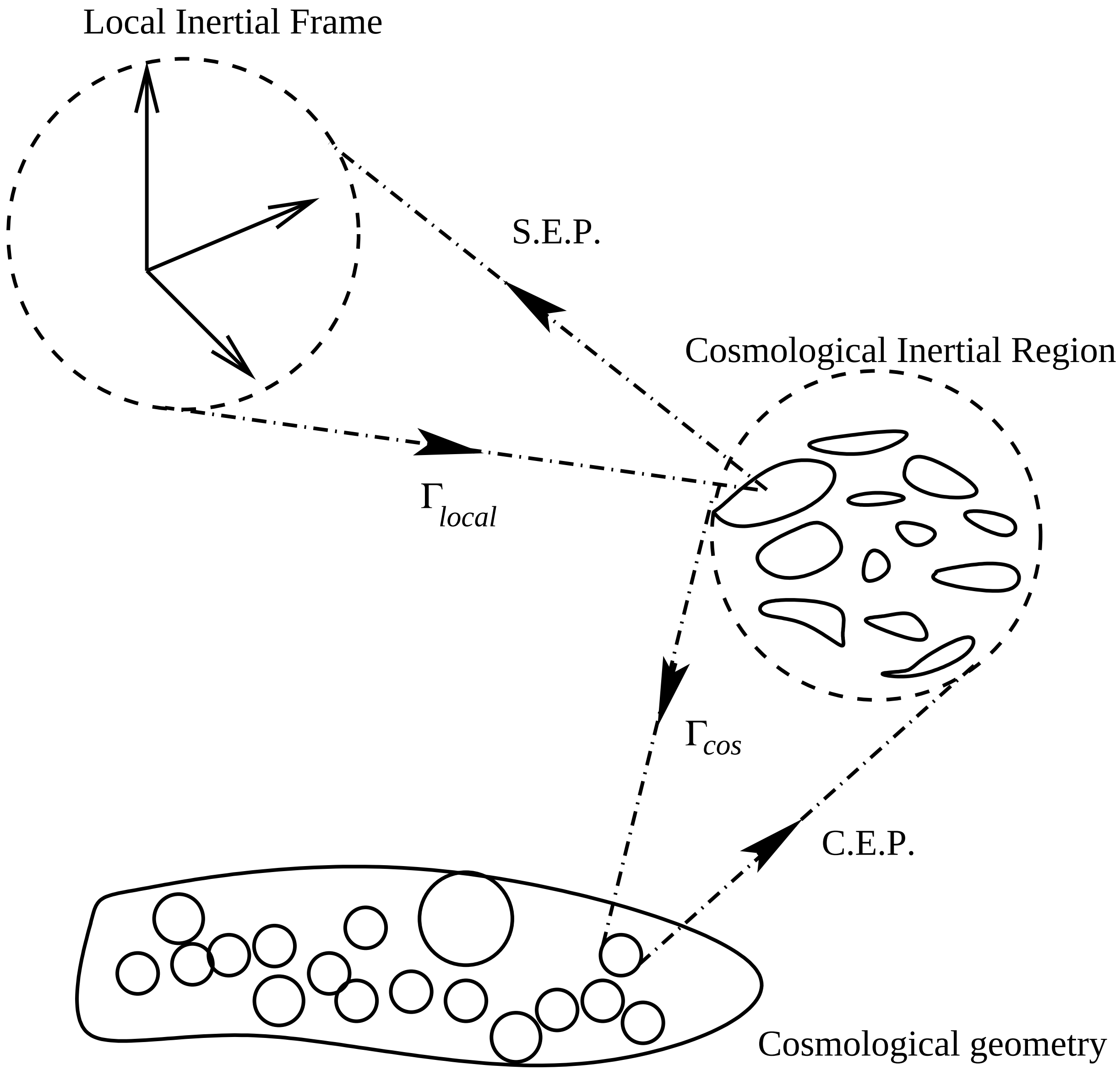
- Defines Cosmological Inertial Region (CIR) in which *regionally isotropic* volume expansion is equivalent to a velocity in special relativity
- Such velocities integrated on a bounding 2-sphere define *“kinetic energy of expansion”*: globally it has gradients

Finite infinity



- Define *finite infinity*, "*fi*" as boundary to *connected* region in which *average expansion* vanishes $\langle\theta\rangle = 0$ with $\theta > 0$ outside. [NOT global cosmological $\langle\rangle$ here]
- Shape of *fi* boundary irrelevant (minimal surface generally): could typically contain a galaxy cluster.

Statistical geometry. . .



Two/three scale "time-scape" model

- Split spatial volume $\mathcal{V} = \mathcal{V}_i \bar{a}^3$ as disjoint union of negatively curved void fraction with scale factor $a_{\rm v}$ and spatially flat "wall" fraction with scale factor $a_{\rm w}$.

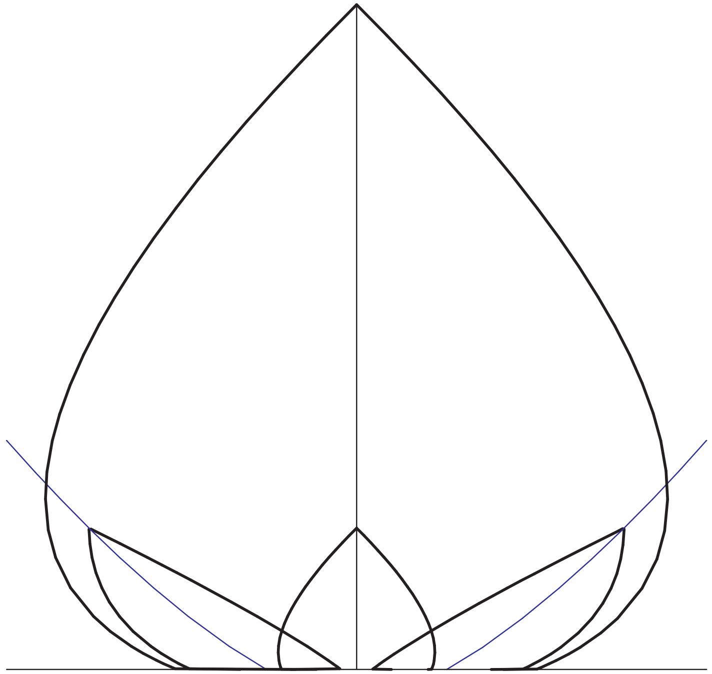
$$\begin{aligned} \bar{a}^3 &= f_{\rm wi} a_{\rm w}{}^3 + f_{\rm vi} a_{\rm v}{}^3 \equiv \bar{a}^3 (f_{\rm w} + f_{\rm v}) \\ f_{\rm w} &\equiv f_{\rm wi} a_{\rm w}{}^3 / \bar{a}^3, \qquad f_{\rm v} \equiv f_{\rm vi} a_{\rm v}{}^3 / \bar{a}^3 \end{aligned}$$

- $f_{\rm vi} = 1 - f_{\rm wi}$ is the fraction of present epoch horizon volume which was in uncompensated underdense perturbations at last scattering.

$$\bar{H}(t) = \frac{\dot{\bar{a}}}{\bar{a}} = f_{\rm w} H_{\rm w} + f_{\rm v} H_{\rm v}; \qquad H_{\rm w} \equiv \frac{1}{a_{\rm w}} \frac{{\rm d}a_{\rm w}}{{\rm d}t}, \quad H_{\rm v} \equiv \frac{1}{a_{\rm v}} \frac{{\rm d}a_{\rm v}}{{\rm d}t}$$

- Here t is the Buchert time parameter, considered as a collective coordinate of dust cell coarse-grained at SHS.

Past light cone average



- Interpret solution of Buchert equations by radial null cone average

$$ds^2 = -dt^2 + \bar{a}^2(t)\,d\bar{\eta}^2 + A(\bar{\eta},t)\,d\Omega^2,$$

where $\int_0^{\bar{\eta}_\mathcal{H}} d\bar{\eta}\, A(\bar{\eta},t) = \bar{a}^2(t)\mathcal{V}_\mathrm{i}(\bar{\eta}_\mathcal{H})/(4\pi)$.

- LTB metric but NOT an LTB solution

Physical interpretation

- Conformally match radial null geodesics of spherical Buchert geometry to those of finite infinity geometry with *uniform quasilocal Hubble flow* condition $\mathrm{d}t = \bar{a}\,\mathrm{d}\bar{\eta}$ and $\mathrm{d}\tau_{\mathrm{w}} = a_{\mathrm{w}}\mathrm{d}\eta_{\mathrm{w}}$. But $\mathrm{d}t = \bar{\gamma}\mathrm{d}\tau_{\mathrm{w}}$ and $a_{\mathrm{w}} = {f_{\mathrm{wi}}}^{-1/3}\,(1 - f_{\mathrm{v}})\,\bar{a}$. Hence *on radial null geodesics*

$$\mathrm{d}\eta_{\mathrm{w}} = \frac{{f_{\mathrm{wi}}}^{1/3}\mathrm{d}\bar{\eta}}{\bar{\gamma}\,(1 - f_{\mathrm{v}})^{1/3}}$$

  Define η_{w} by integral of above on radial null-geodesics.

- Extend spatially flat wall geometry to dressed geometry

$$\mathrm{d}s^2 = -\mathrm{d}\tau_{\mathrm{w}}^2 + a^2(\tau_{\mathrm{w}})\left[\mathrm{d}\bar{\eta}^2 + r_{\mathrm{w}}^2(\bar{\eta},\tau_{\mathrm{w}})\,\mathrm{d}\Omega^2\right]$$

  where $r_{\mathrm{w}} \equiv \bar{\gamma}\,(1 - f_{\mathrm{v}})^{1/3}\,{f_{\mathrm{wi}}}^{-1/3}\eta_{\mathrm{w}}(\bar{\eta},\tau_{\mathrm{w}})$, $a = \bar{a}/\bar{\gamma}$.

Dressed cosmological parameters

- N.B. The extension is NOT an isometry

$$\text{N.B.}\qquad \begin{aligned} ds^2_{fi} &= -d\tau_w^2 + a_w{}^2(\tau_w)\left[d\eta_w^2 + \eta_w^2 d\Omega^2\right] \\ \to ds^2 &= -d\tau_w^2 + a^2\left[d\bar\eta^2 + r_w^2(\bar\eta,\tau_w)\,d\Omega^2\right] \end{aligned}$$

- Extended metric is an effective "spherical Buchert geometry" adapted to wall rulers and clocks.
- Since $d\bar\eta = dt/\bar a = \bar\gamma\, d\tau_w/\bar a = d\tau_w/a$, this leads to *dressed parameters* which do not sum to 1, e.g.,

$$\Omega_M = \bar\gamma^3 \bar\Omega_M\,.$$

- Dressed average Hubble parameter

$$H = \frac{1}{a}\frac{da}{d\tau_w} = \frac{1}{\bar a}\frac{d\bar a}{d\tau_w} - \frac{1}{\bar\gamma}\frac{d\bar\gamma}{d\tau_w}$$

Dressed cosmological parameters

- H is greater than wall Hubble rate; smaller than void Hubble rate measured by wall (or any one set of) clocks

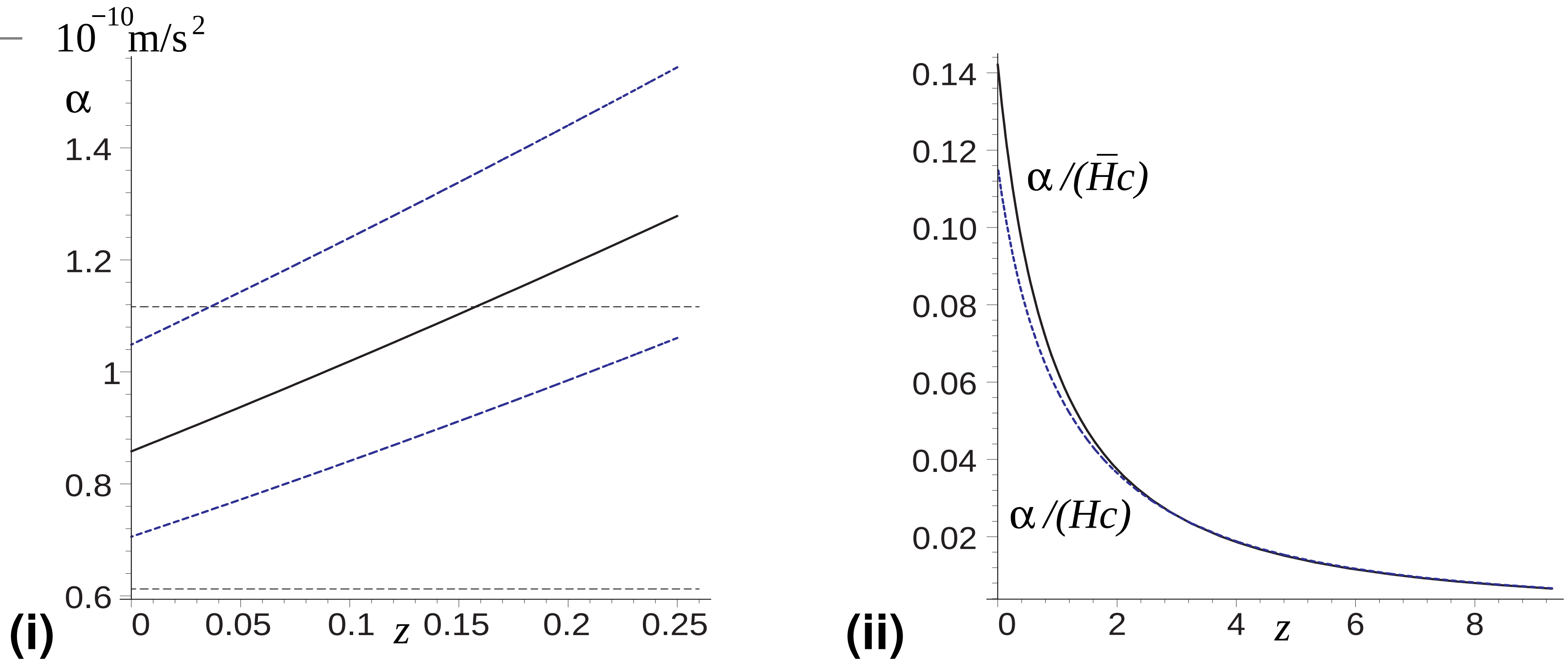
$$\bar{H}(t) = \frac{1}{\bar{a}}\frac{\mathrm{d}\bar{a}}{\mathrm{d}t} = \frac{1}{a_{\mathrm{v}}}\frac{\mathrm{d}a_{\mathrm{v}}}{\mathrm{d}\tau_{\mathrm{v}}} = \frac{1}{a_{\mathrm{w}}}\frac{\mathrm{d}a_{\mathrm{w}}}{\mathrm{d}\tau_{\mathrm{w}}} < H < \frac{1}{a_{\mathrm{v}}}\frac{\mathrm{d}a_{\mathrm{v}}}{\mathrm{d}\tau_{\mathrm{w}}}$$

- For tracker solution $H = (4{f_{\mathrm{v}}}^2 + f_{\mathrm{v}} + 4)/6t$
- Dressed average deceleration parameter

$$q = \frac{-1}{H^2 a^2}\frac{\mathrm{d}^2 a}{\mathrm{d}\tau_{\mathrm{w}}^2}$$

Can have $q < 0$ even though $\bar{q} = \frac{-1}{\bar{H}^2 \bar{a}^2}\frac{\mathrm{d}^2\bar{a}}{\mathrm{d}t^2} > 0$; difference of clocks important.

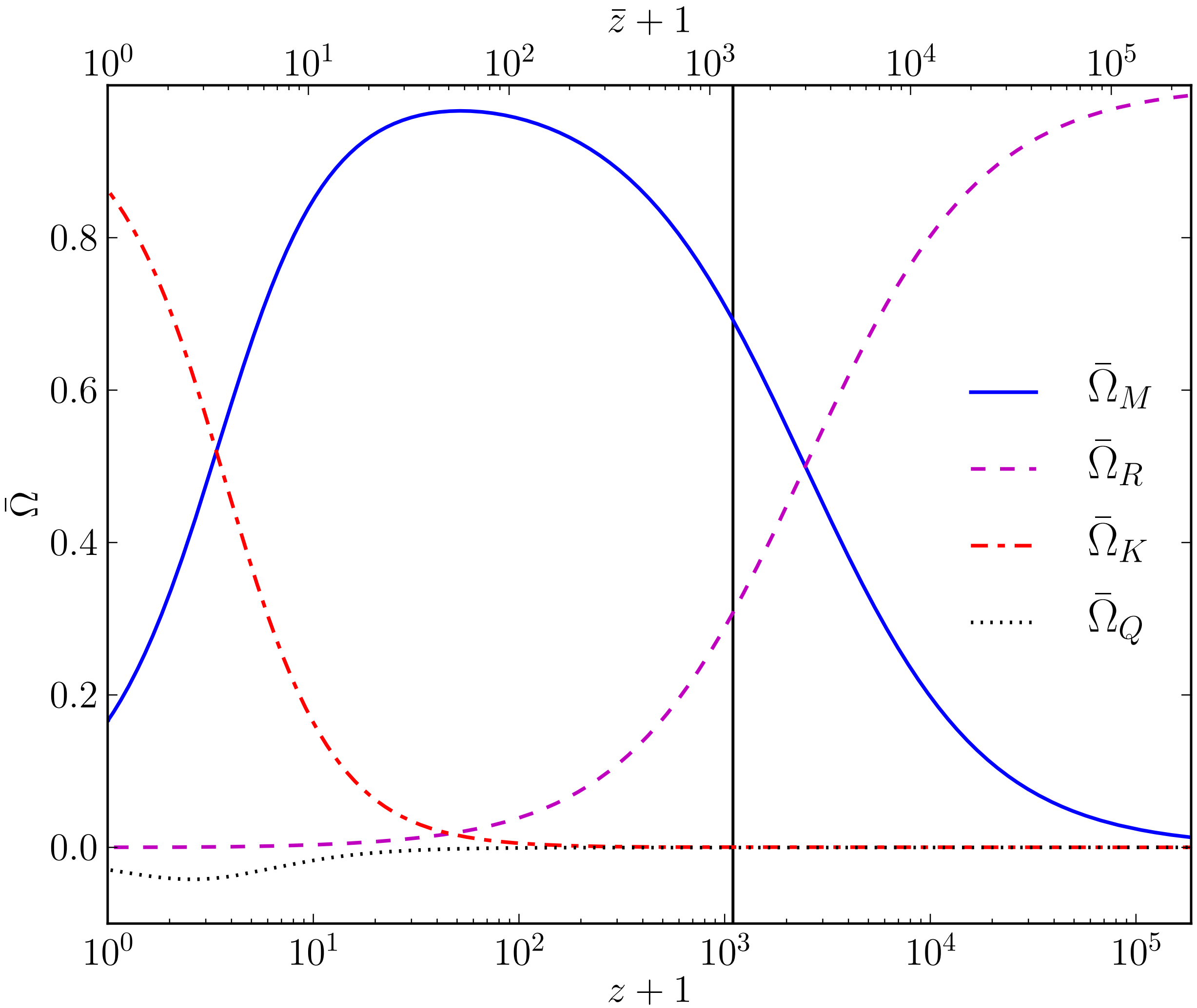
Relative deceleration scale



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

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

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

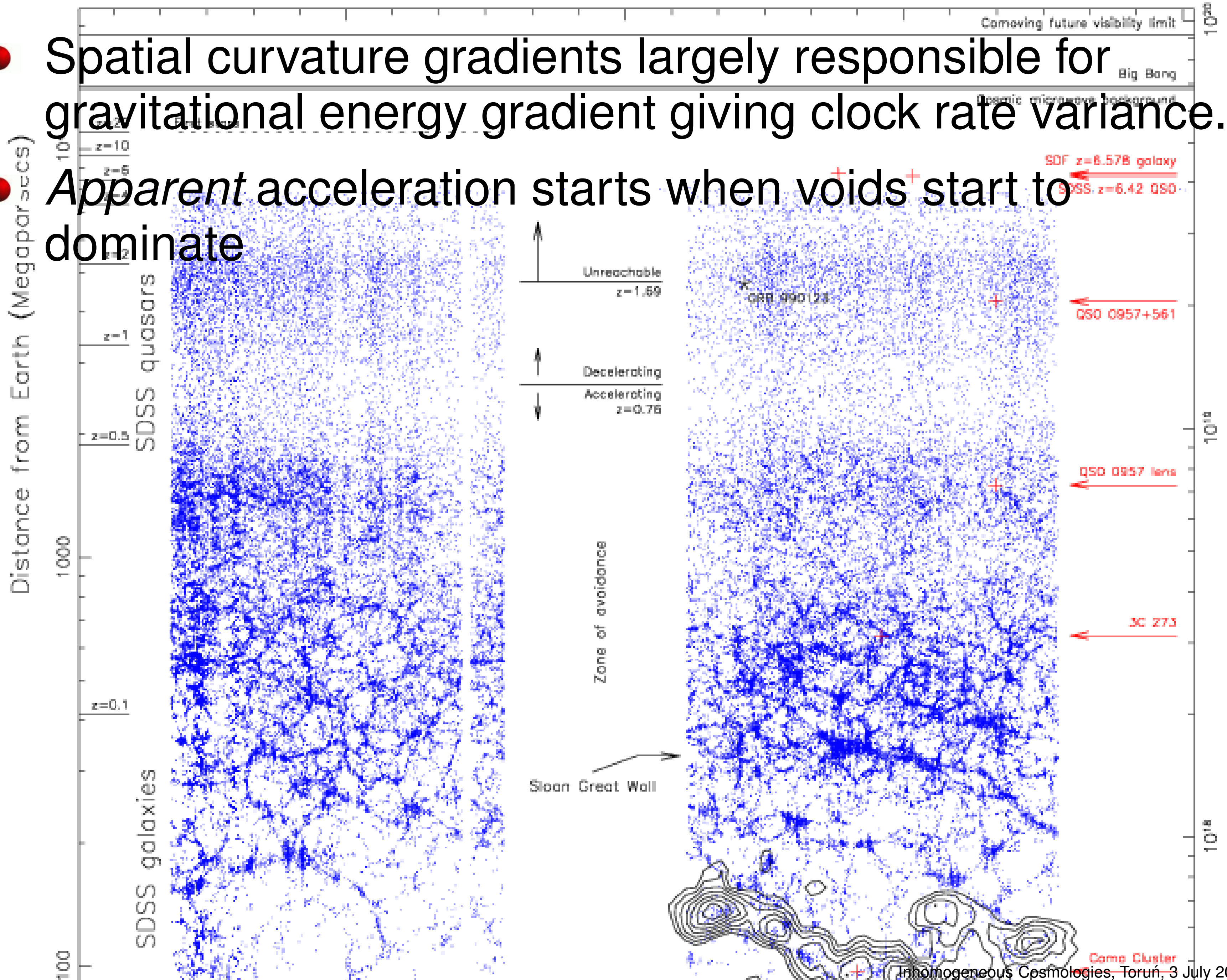
- A wall observer registers apparent cosmic acceleration

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

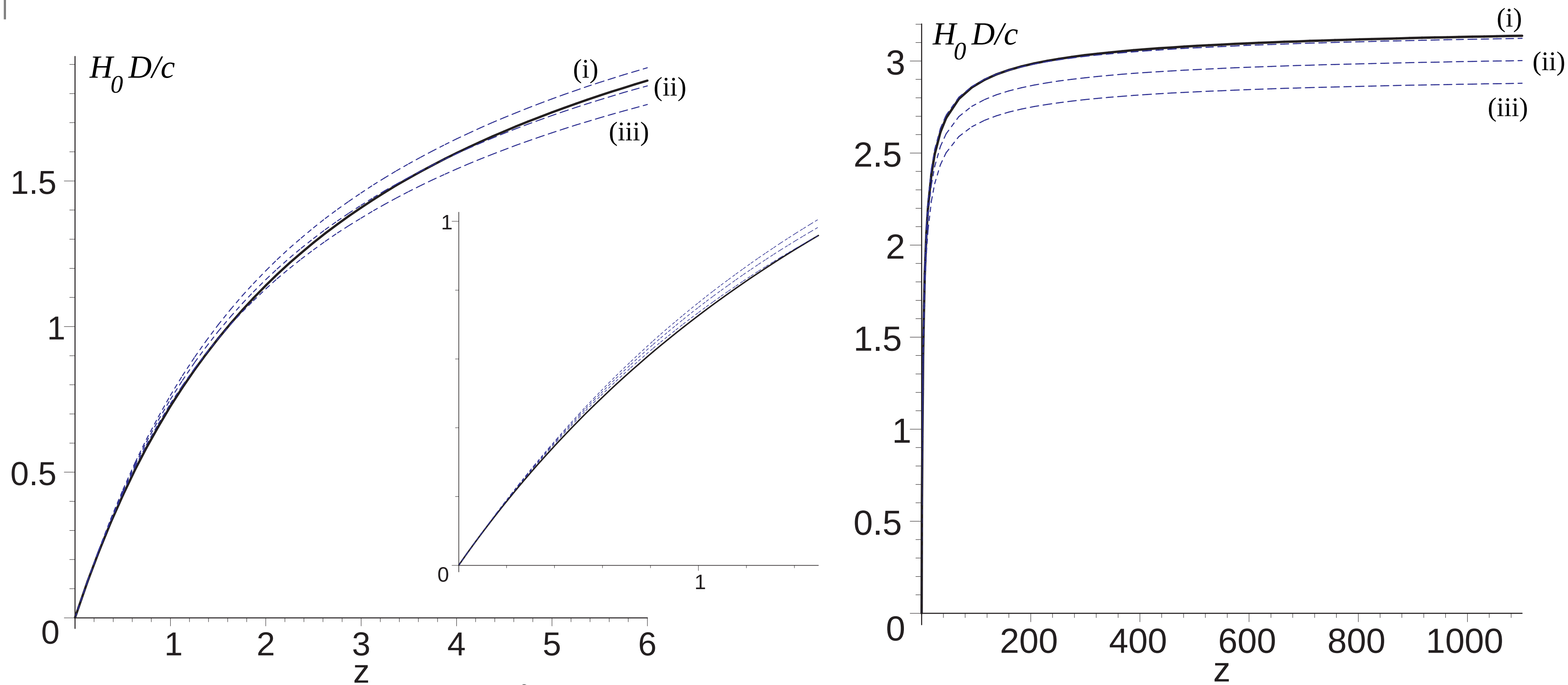
Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small $f_{\rm v}$; changes sign when $f_{\rm v} = 0.5867\ldots$, and approaches $q \to 0^-$ at late times.

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

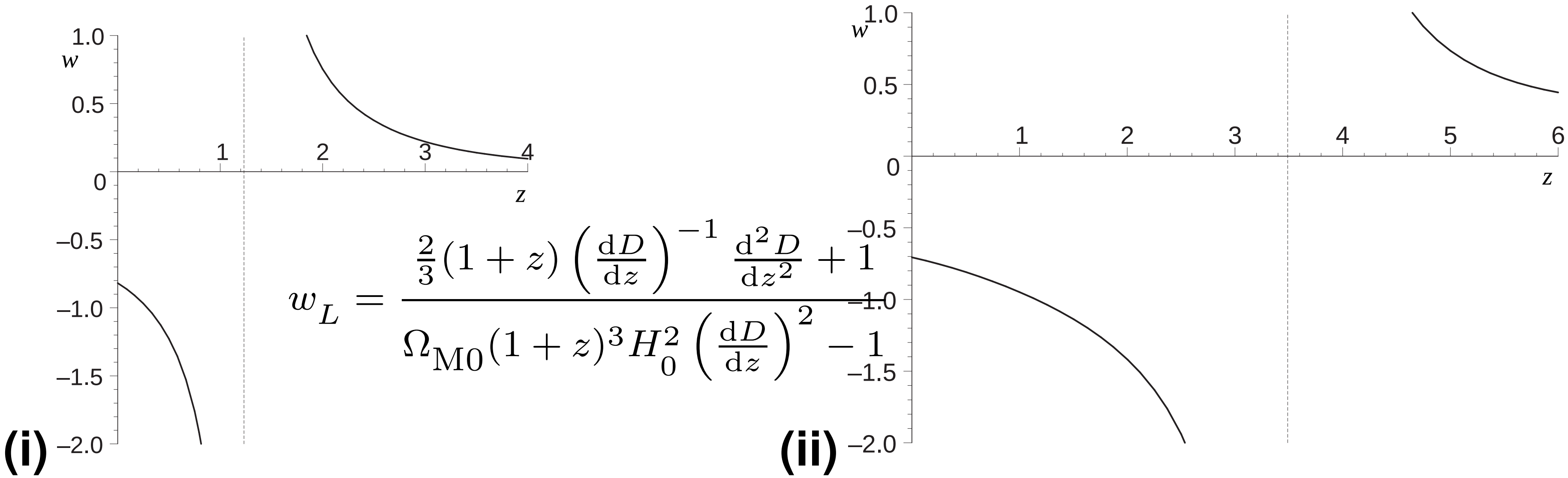


Dressed "comoving distance" $D(z)$



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)** $\Omega_{M0} = 0.388$.

Equivalent “equation of state”?

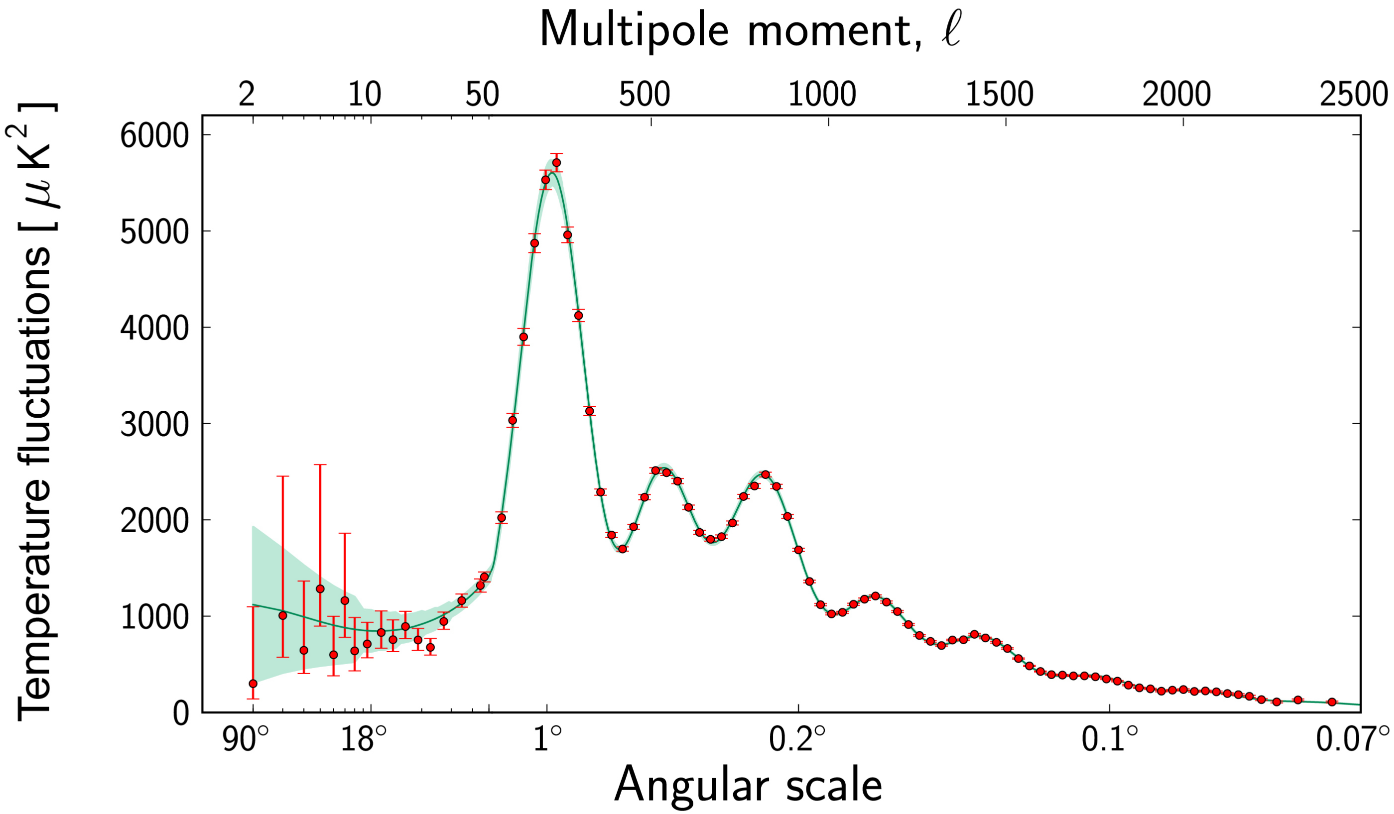


$$w_L = \frac{\frac{2}{3}(1+z)\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^{-1}\frac{\mathrm{d}^2 D}{\mathrm{d}z^2}+1}{\Omega_{\mathrm{M0}}(1+z)^3 H_0^2\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^2-1}$$

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.

Planck data ΛCDM parametric fit



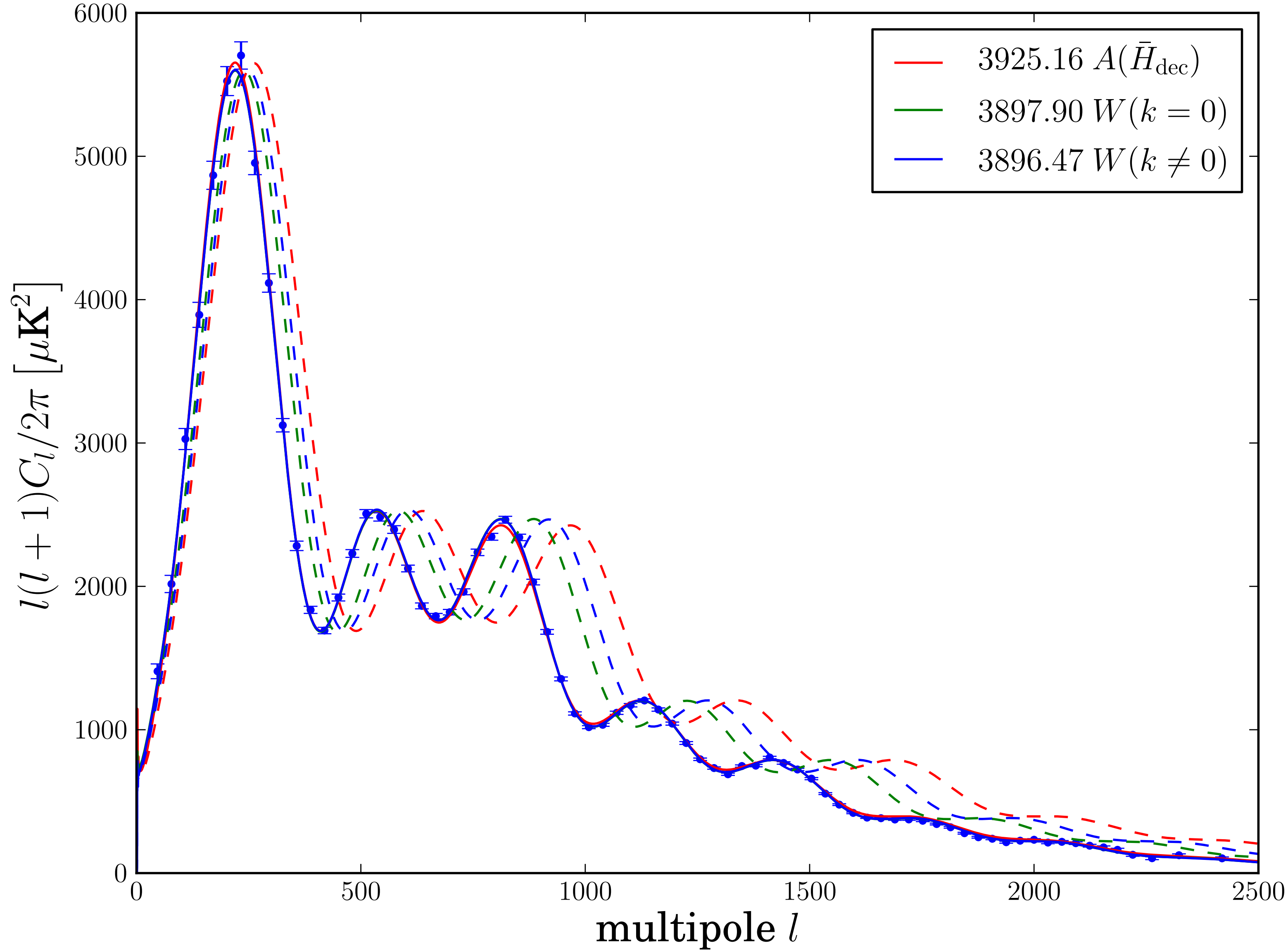
Duley, Nazer + DLW, CQG 30 (2013) 175006:

- Use angular scale, baryon drag scale from ΛCDM fit
- Baryon–photon ratio $\eta_{B\gamma} = 4.6$–5.6×10^{-10} within 2σ of all observed light element abundances (**including ^{7}Li**).

Planck constraints D_A + r_{drag}

- Dressed Hubble constant $H_0 = 61.7 \pm 3.0$ km/s/Mpc
- Bare Hubble constant $H_{\mathrm{w0}} = \bar{H}_0 = 50.1 \pm 1.7$ km/s/Mpc
- Local max Hubble constant $H_{\mathrm{v0}} = 75.2^{+2.0}_{-2.6}$ km/s/Mpc
- Present void fraction $f_{\mathrm{v0}} = 0.695^{+0.041}_{-0.051}$
- Bare matter density parameter $\bar{\Omega}_{\mathrm{M0}} = 0.167^{+0.036}_{-0.037}$
- Dressed matter density parameter $\Omega_{\mathrm{M0}} = 0.41^{+0.06}_{-0.05}$
- Dressed baryon density parameter $\Omega_{\mathrm{B0}} = 0.074^{+0.013}_{-0.011}$
- Nonbaryonic/baryonic matter ratio $\Omega_{\mathrm{C0}}/\Omega_{\mathrm{B0}} = 4.6^{+2.5}_{-2.1}$
- Age of universe (galaxy/wall) $\tau_{\mathrm{w0}} = 14.2 \pm 0.5$ Gyr
- Age of universe (volume-average) $t_0 = 17.5 \pm 0.6$ Gyr
- Apparent acceleration onset $z_{\mathrm{acc}} = 0.46^{+0.26}_{-0.25}$

CMB acoustic peaks, $\ell > 50$ fit

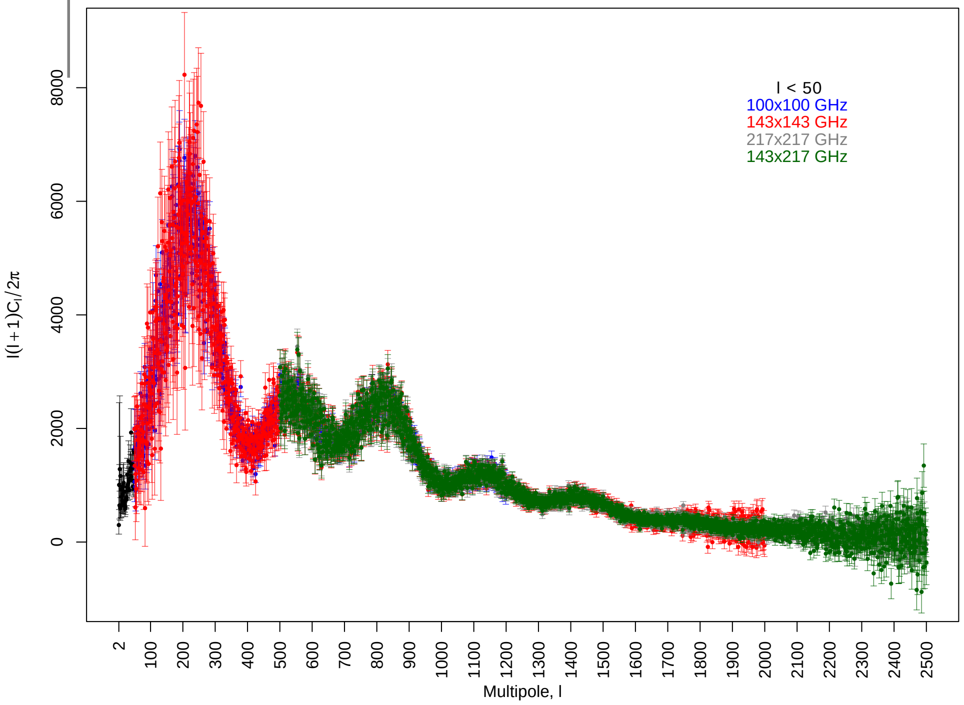


MCMC coding by M.A. Nazer, adapting *CLASS*

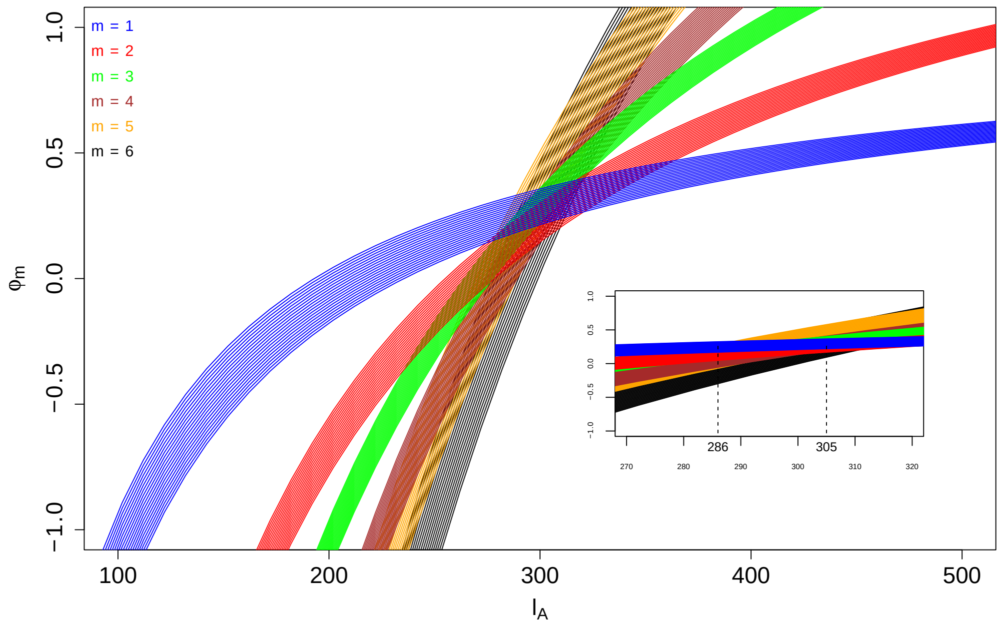
CMB acoustic peaks: results

- 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 $50 \le \ell \le 2500$, 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

Non-parametric CMB constraints



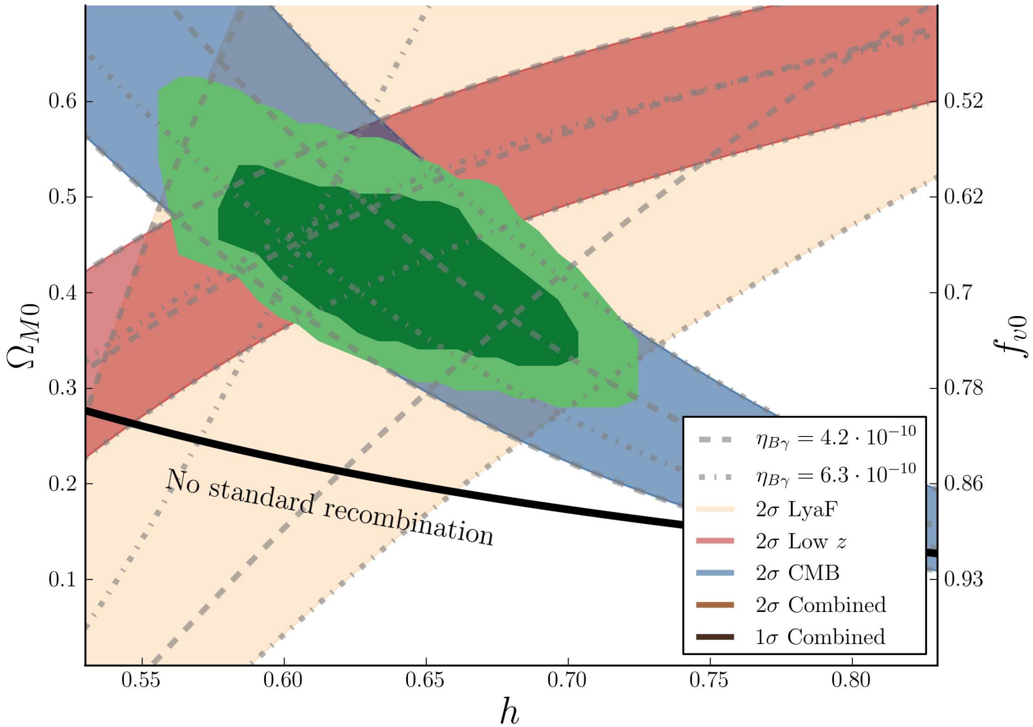
Raw Planck data



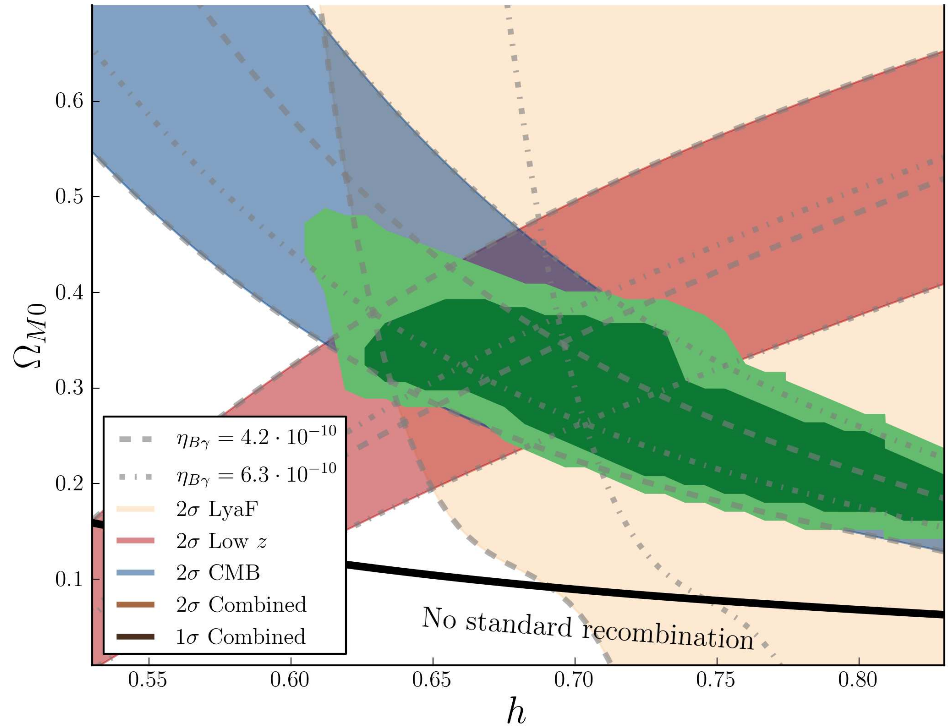
Fit to angular scale from 6 peaks

- What do we know without a cosmological model?
- $286 \leq \ell_A \leq 305$ at 95% confidence Aghamousa et al, JCAP 02(2015)007

CMB sound horizon + BAO LRG / Lyman α



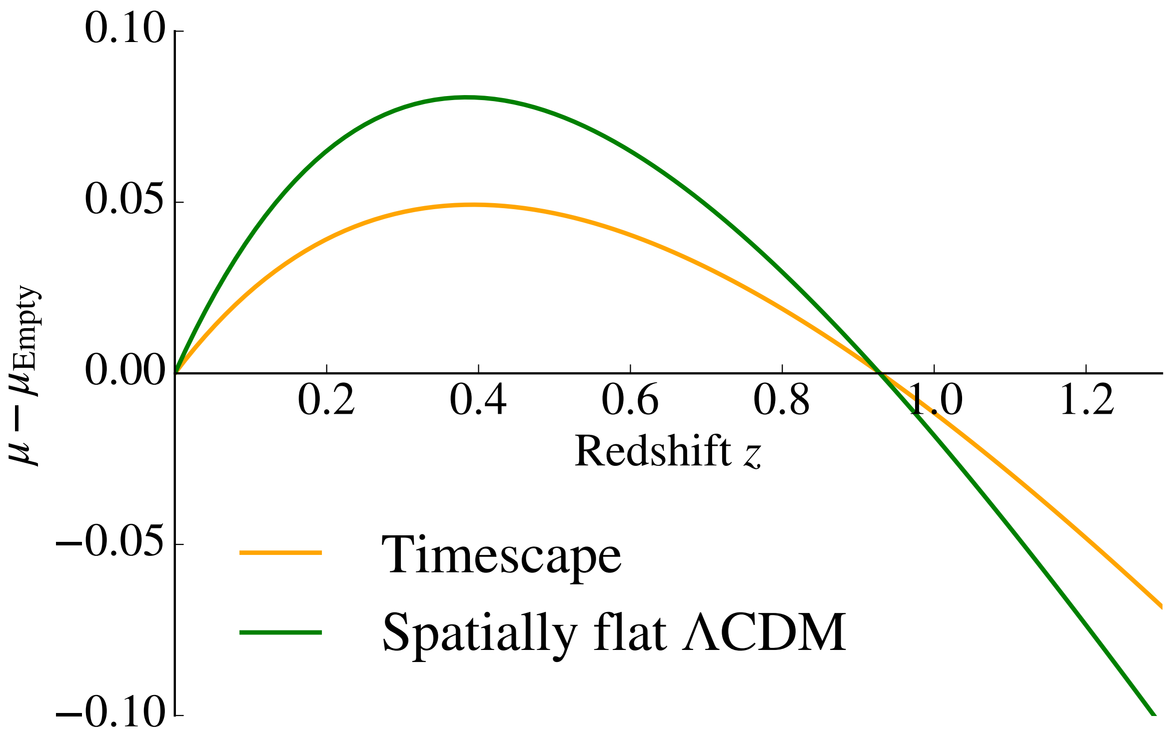
Timescape parameter constraints



Spatially flat ΛCDM parameter constraints

- Non-parametric CMB angular scale constraint (blue, 2σ)
- Baryon acoustic oscillations from BOSS (using FLRW model!) - galaxy clustering statistics $z = 0.38, 0.51, 0.61$ (red, 2σ); Lyman α forest $z = 2.34$ (pink, 2σ)

Supernovae: A Heinesen talk

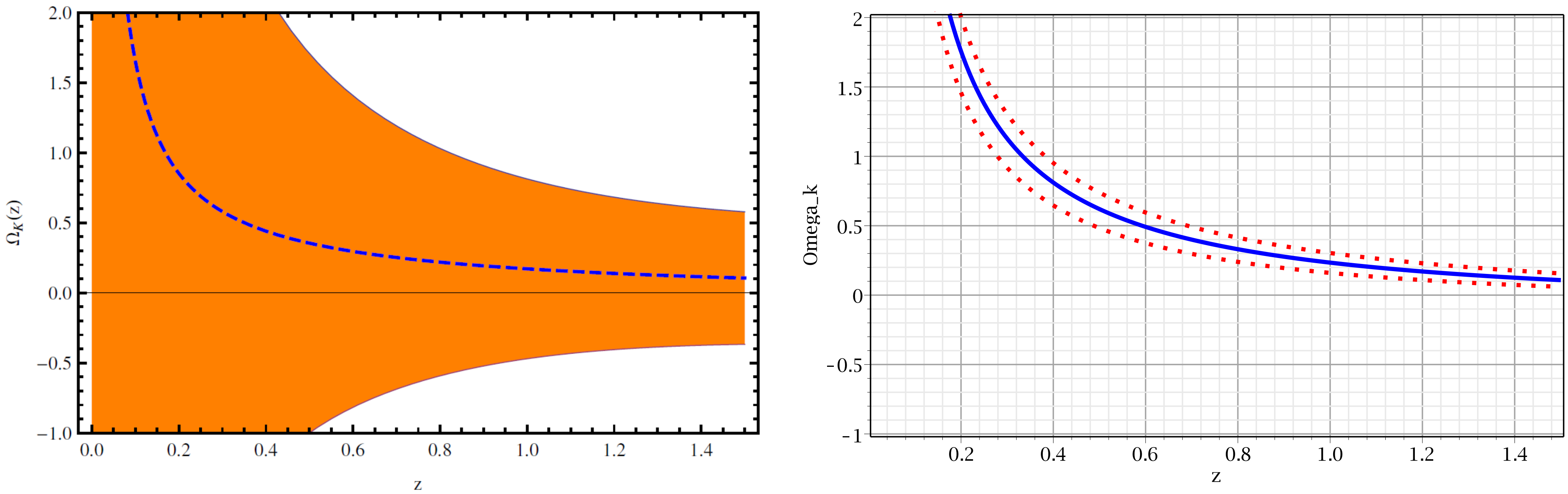


- Smale + DLW, 2011, MNRAS 413: Different light curve fitters MLCS2k2 versus SALT/SALT2 gave different answers for preference of TS versus ΛCDM
- Dam, Heinesen & DLW, arXiv:1706.07236: applying Nielsen, Guffanti, Sarkar 2016 methodology, SALT2 results now consistent. . . much to say about systematics

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

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

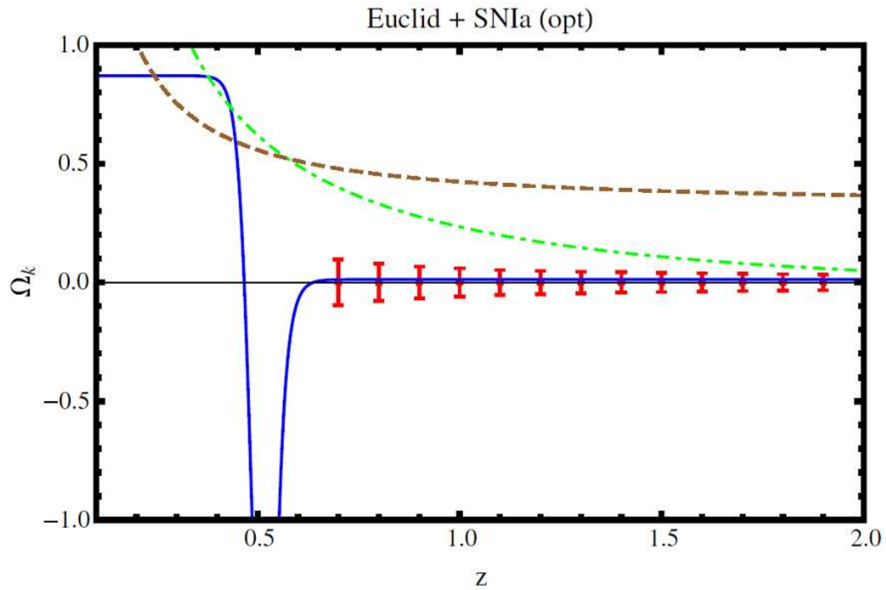


Left panel: CBL statistic from Sapone, Majerotto and Nesseris, PRD 90, 023012 (2014) Fig 8,

using existing data from SneIa (Union2) and passively evolving galaxies for $H(z)$.

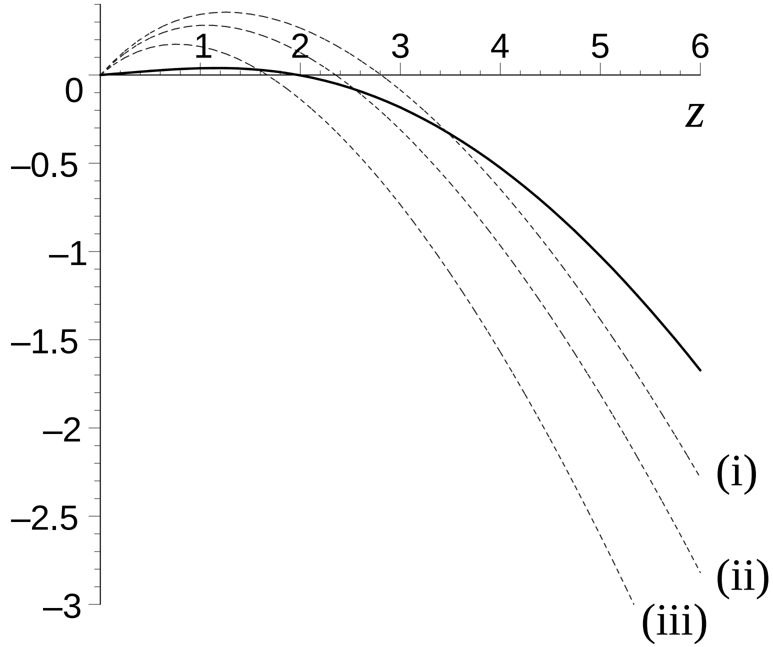
Right panel: TS prediction, with $f_{\mathrm{v0}} = 0.695^{+0.041}_{-0.051}$.

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)

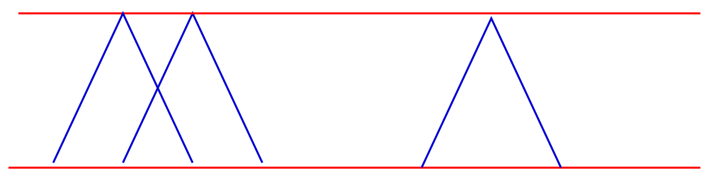


$H_0^{-1}\frac{\mathrm{d}z}{\mathrm{d}\tau}$ for the TS model with $f_{\mathrm{v}0} = 0.76$ (solid line) is compared to three spatially flat ΛCDM models.

- 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

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, PRD 95 (2017) 064028
- 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
- "Modified Geometry" rather than "Modified Gravity"