Testing cosmological foundations

David L Wiltshire

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

Outline of talk

- Cosmology: Quest for 2 numbers H_0, q_0 now a quest for 2 functions: $H(z)$, $D(z)$
- Can test foundations: e.g., Friedmann equation
- What is dark energy? Hypothesis:
  Dark energy is a misidentification of gradients in quasilocal gravitational energy in the geometry of a complex evolving structure of matter inhomogeneities
- Present and future tests of timescape cosmology:
  - Supernovae, BAO, CMB, . . .
  - Clarkson-Bassett-Lu test, redshift-time drift, . . .
- Tests below statistical homogeneity scale . . .

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)

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

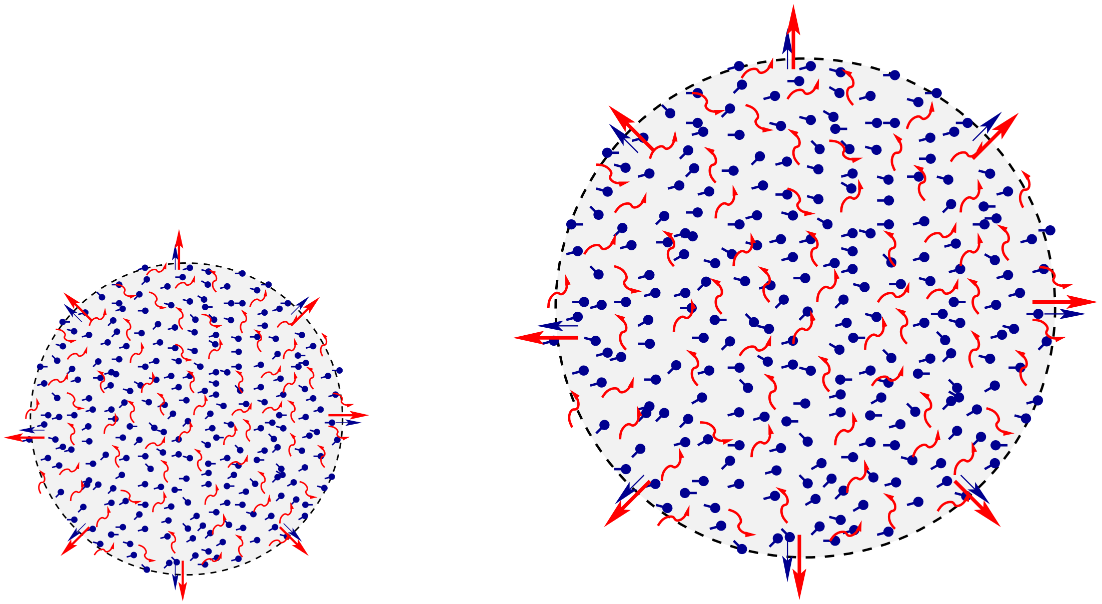
$$\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2} - \frac{1}{3}\Lambda c^2 = \frac{8\pi G\rho}{3}$$

- *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

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*.

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]

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

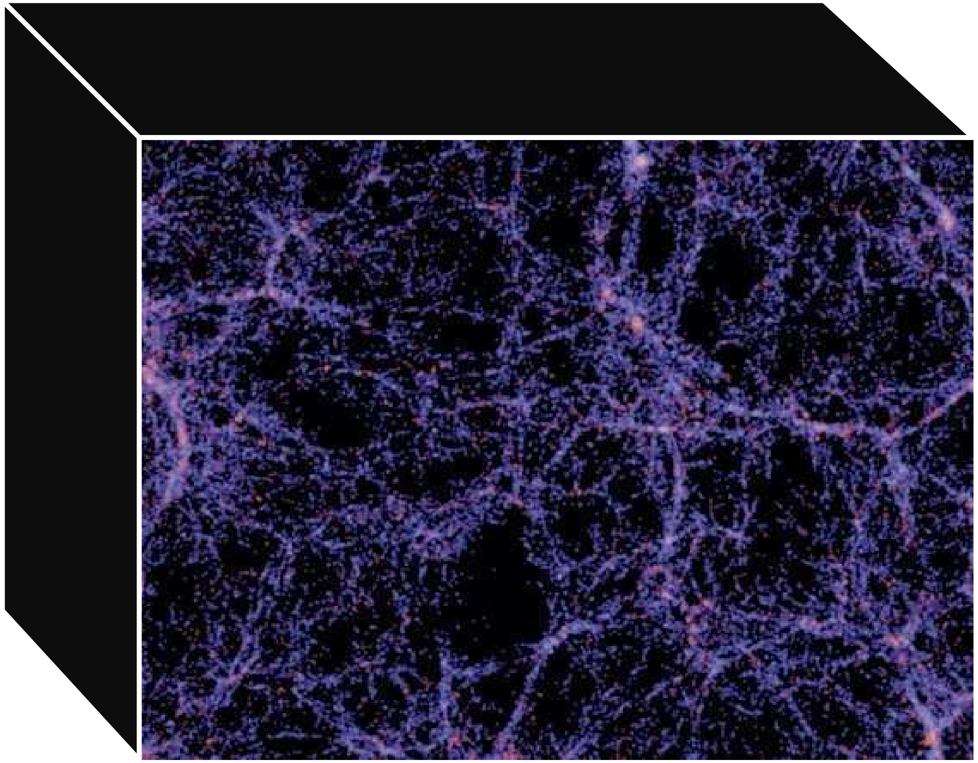
Averaging and backreaction

- *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

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)

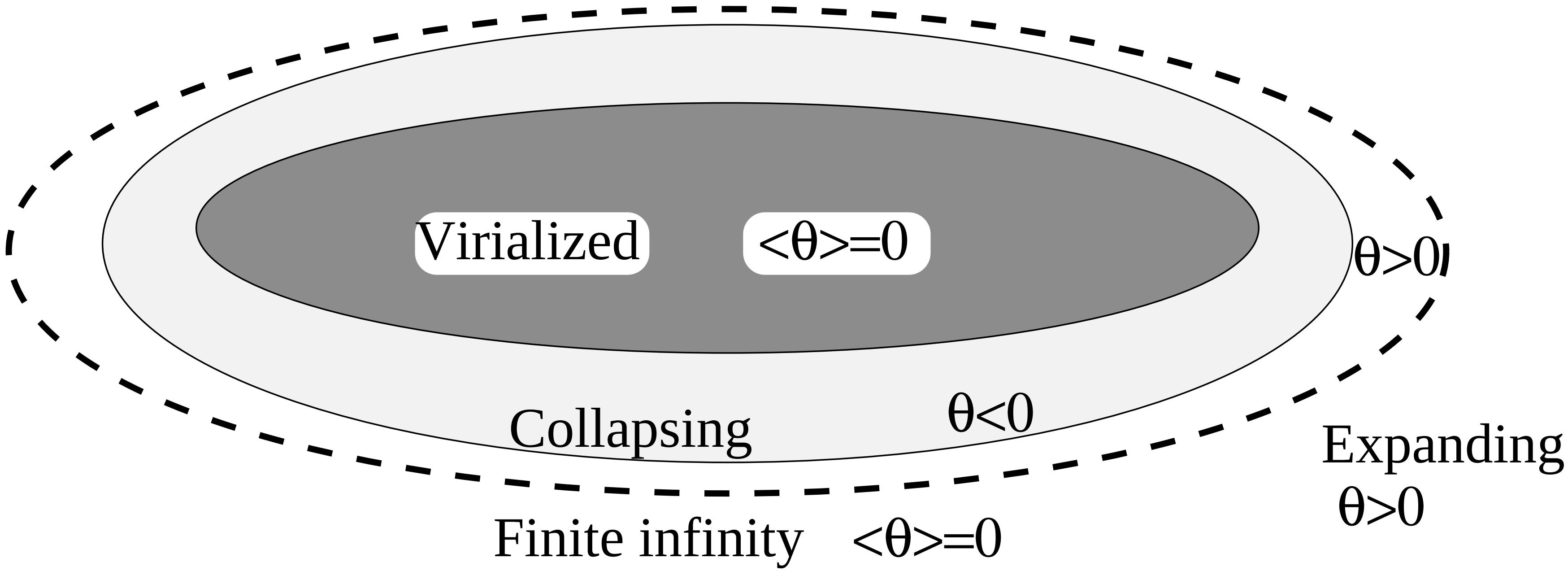
Cosmological Equivalence Principle

- *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*,

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

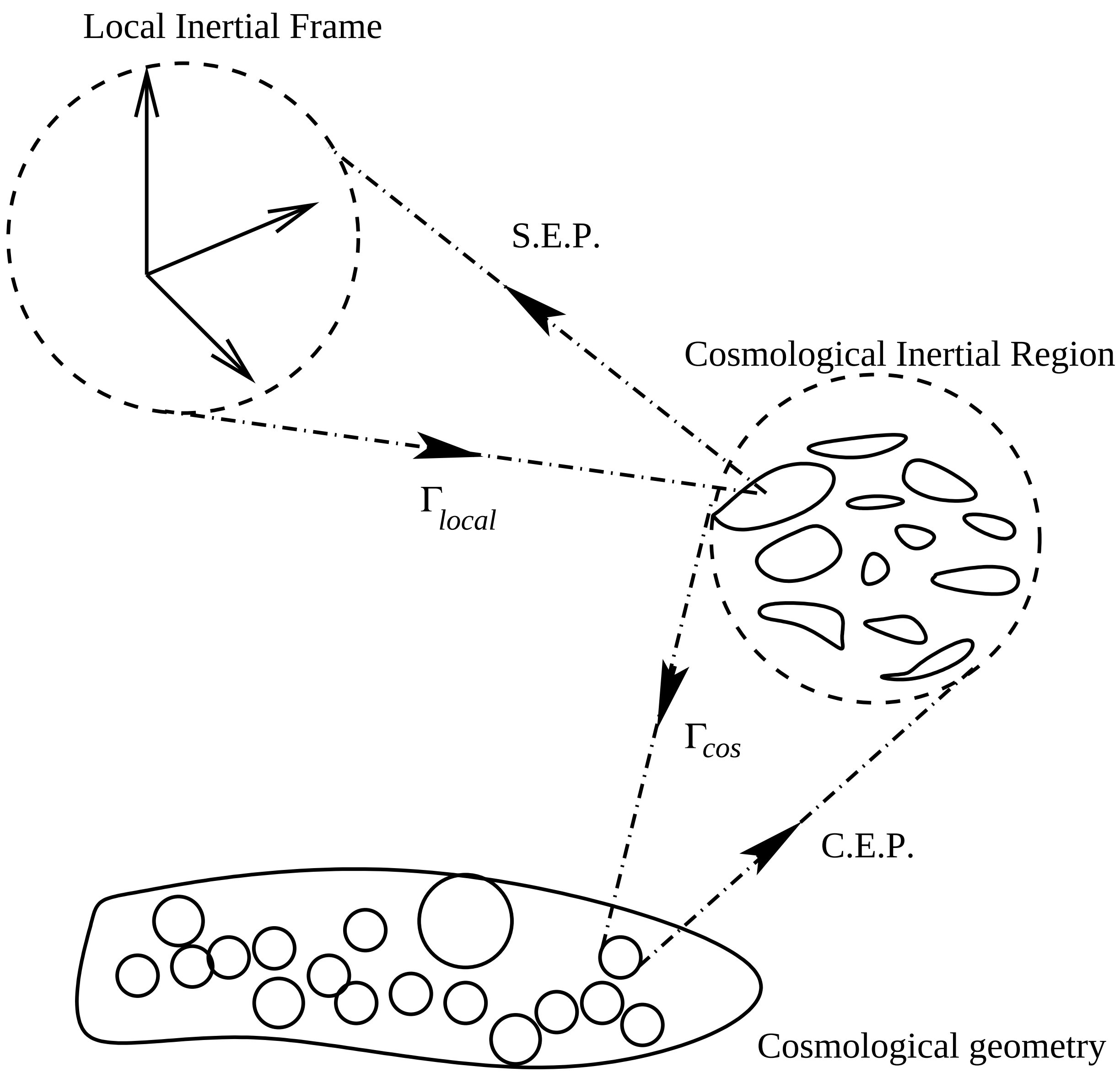
- Defines Cosmological Inertial Region (CIR) in which *regionally isotropic* volume expansion is equivalent to a velocity in special relativity
- Such velocities integrated on a bounding 2-sphere define *"kinetic energy of expansion"*: globally it has gradients

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. . .

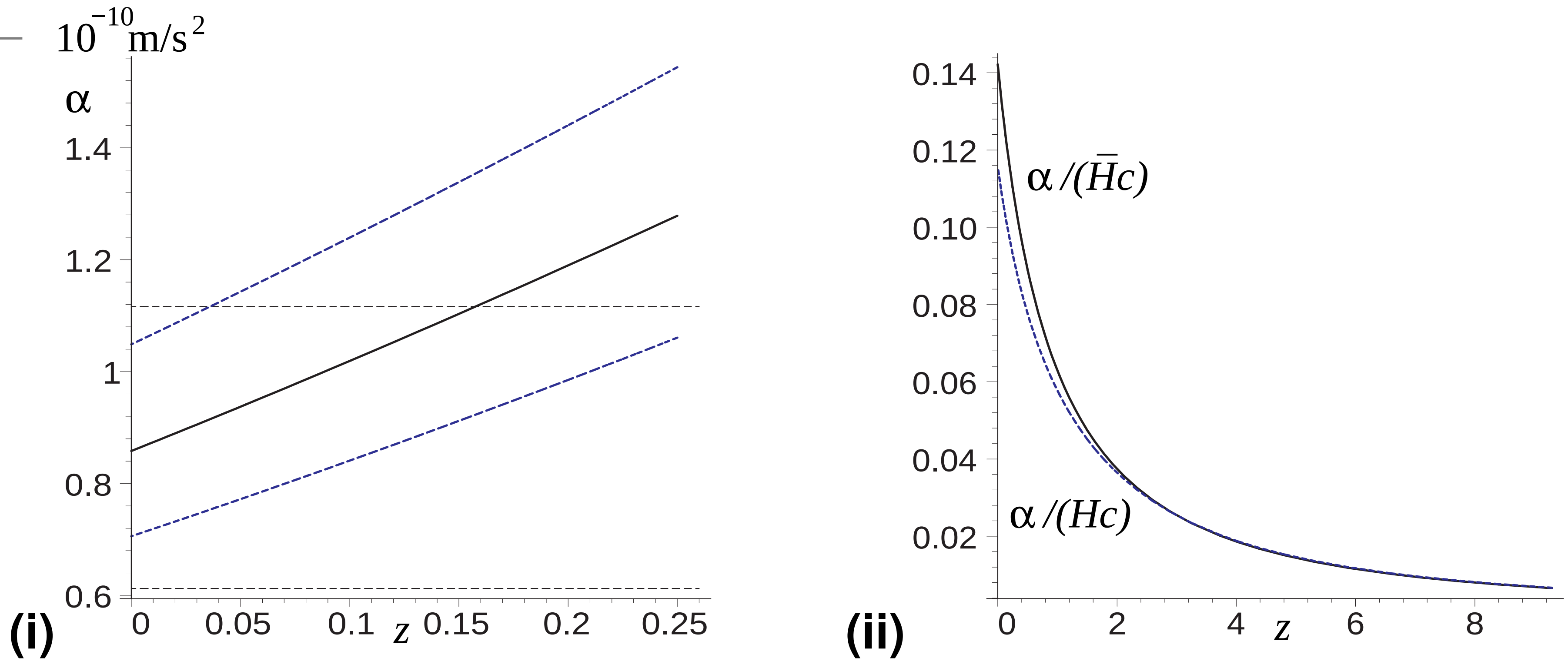


Timescape phenomenology

$$ds^2 = -(1 + 2\Phi)c^2 dt^2 + a^2(1 - 2\Psi) g_{ij} dx^i dx^j$$

- Global statistical metric by Buchert average not a solution of Einstein equations; solve for ensemble of void and finite infinity (wall) regions
- *Assuming uniform quasilocal Hubble flow condition*, 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 over age of universe
- Difference in *bare* (statistical or volume–average) and *dressed* (regional or finite–infinity) parameters

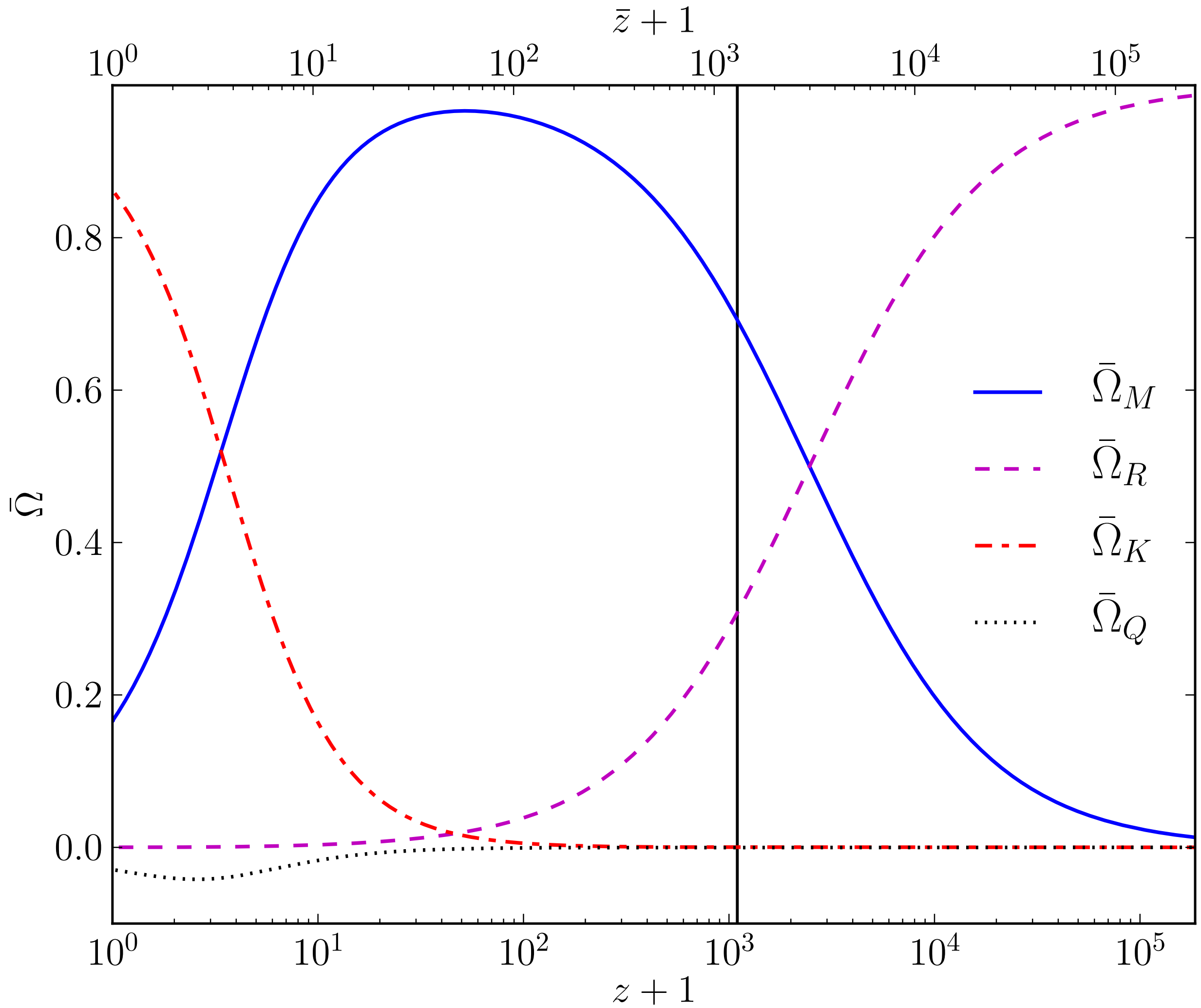
Relative deceleration scale



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



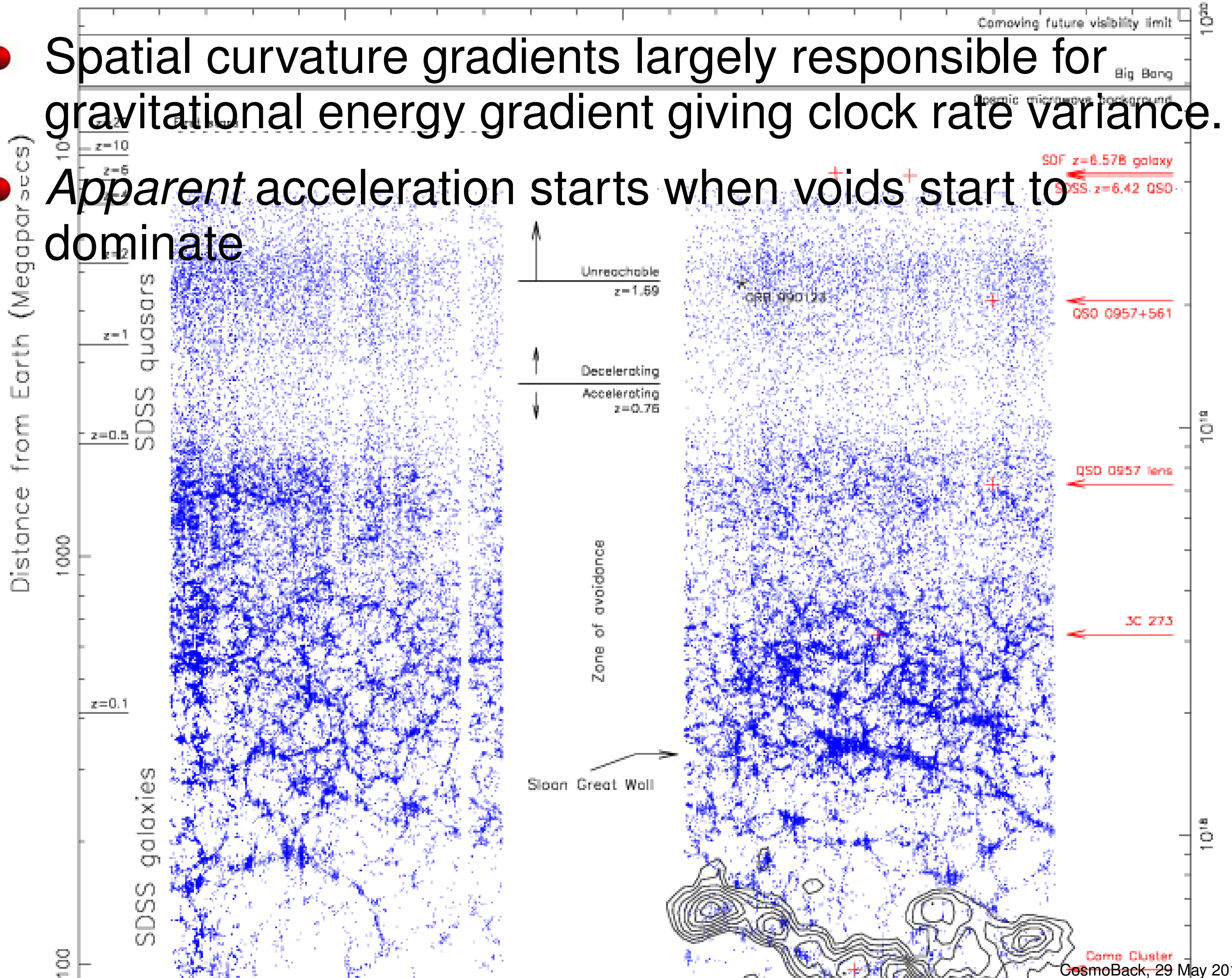
J.A.G. Duley, M.A. Nazer & DLW, CQG 30 (2013) 175006: full numerical solution with matter, radiation

Apparent cosmic acceleration

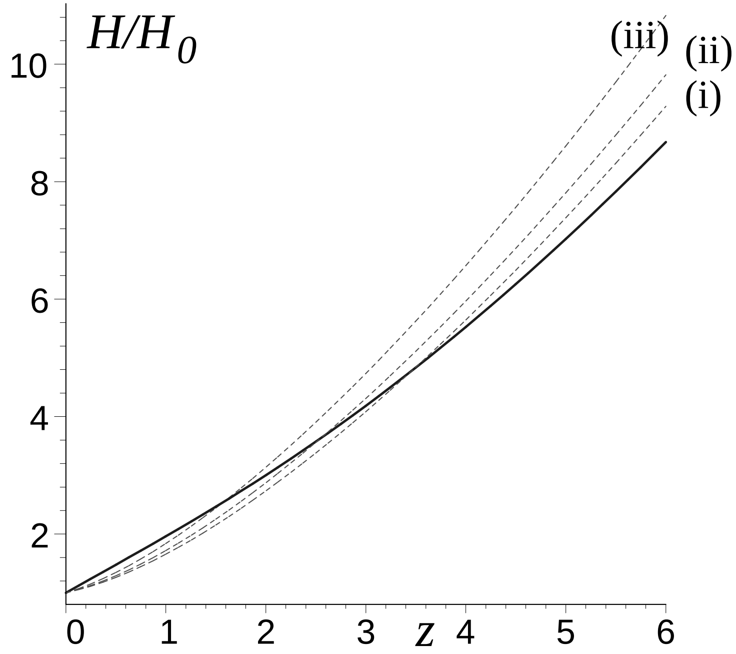
- Volume average observer sees no apparent cosmic acceleration
$$\bar{q} = \frac{2\,(1-f_{\rm v})^2}{(2+f_{\rm v})^2}\,.$$
As $t \to \infty$, $f_{\rm v} \to 1$ and $\bar{q} \to 0^+$.
- A wall observer registers apparent cosmic acceleration
$$q = \frac{-\,(1-f_{\rm v})\,(8f_{\rm v}{}^3 + 39f_{\rm v}{}^2 - 12f_{\rm v} - 8)}{\left(4 + f_{\rm v} + 4f_{\rm v}{}^2\right)^2}\,,$$
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



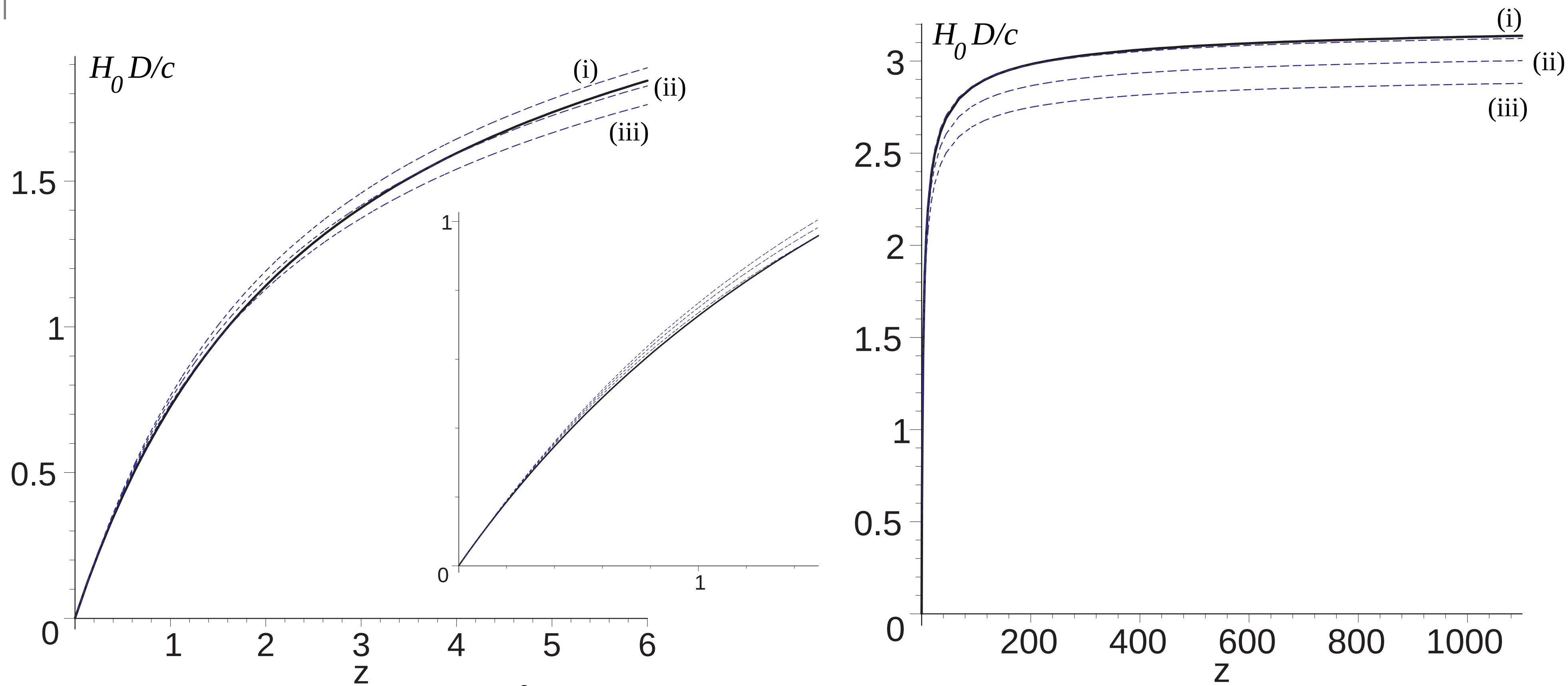
$H(z)/H_0$



$H(z)/H_0$ for $f_{v0} = 0.762$ (solid line) is compared to three spatially flat ΛCDM models: **(i)** $(\Omega_{M0}, \Omega_{\Lambda0}) = (0.249, 0.751)$; **(ii)** $(\Omega_{M0}, \Omega_{\Lambda0}) = (0.279, 0.721)$ **(iii)** $(\Omega_{M0}, \Omega_{\Lambda0}) = (0.34, 0.66)$;.

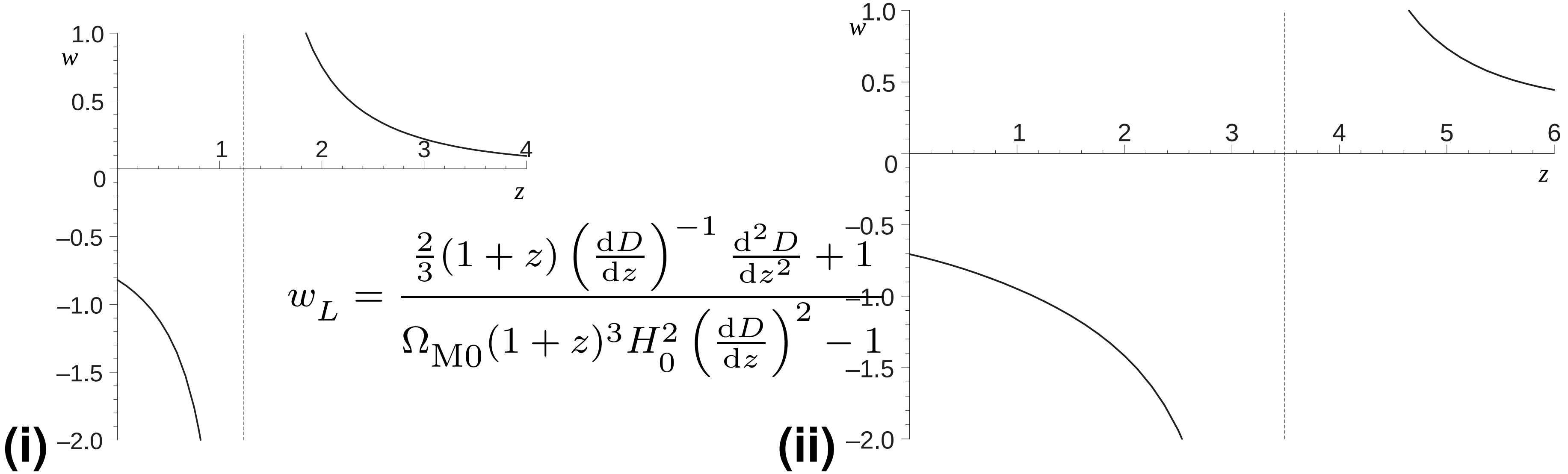
- Function $H(z)/H_0$ displays quite different characteristics
- For $0 < z \lesssim 1.7$, $H(z)/H_0$ is larger for TS model, but value of H_0 assumed also affects $H(z)$ numerical value

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”?

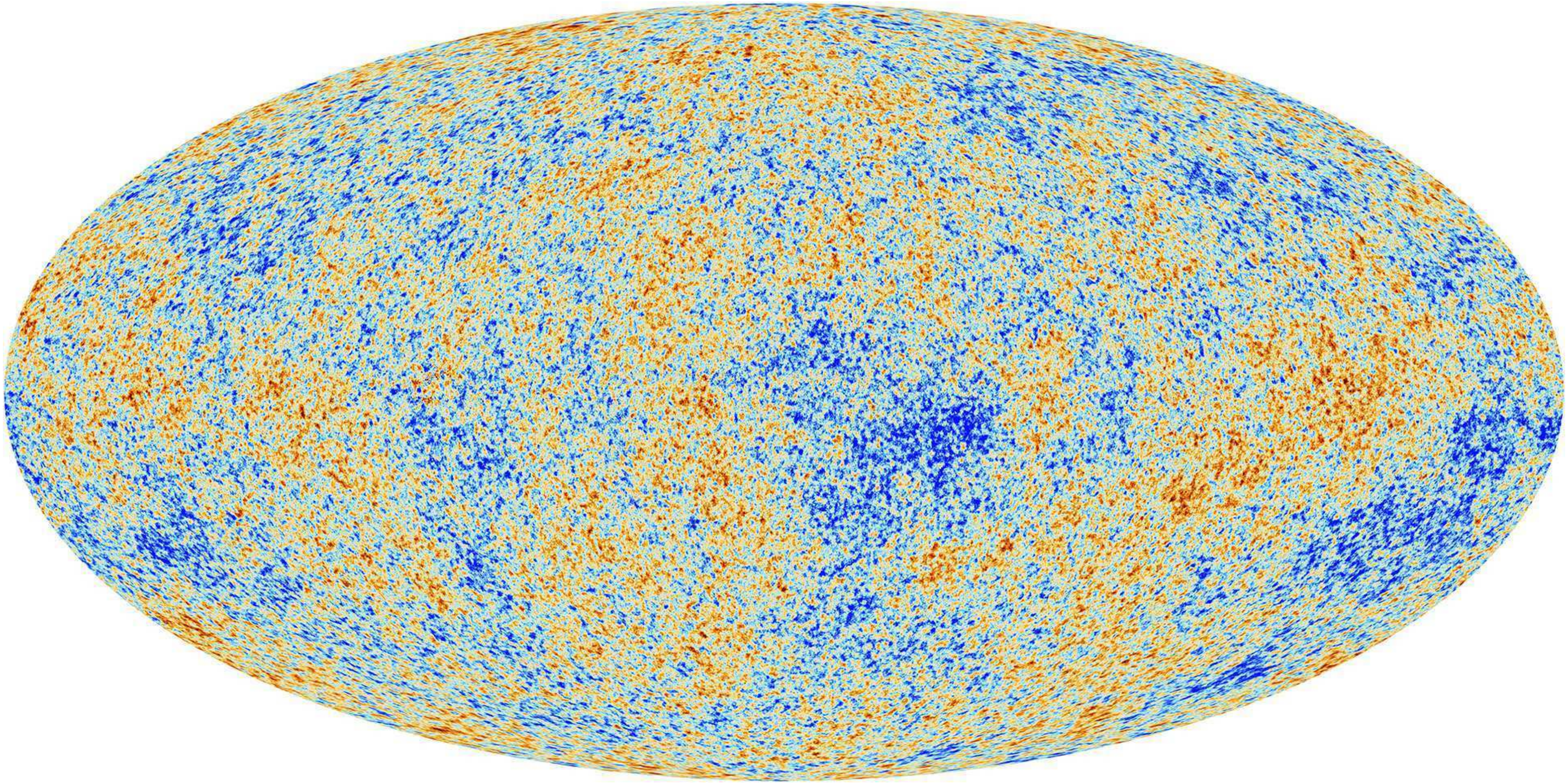


$$w_L = \frac{\frac{2}{3}(1+z)\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^{-1}\frac{\mathrm{d}^2D}{\mathrm{d}z^2}+1}{\Omega_{M0}(1+z)^3H_0^2\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^2-1}$$

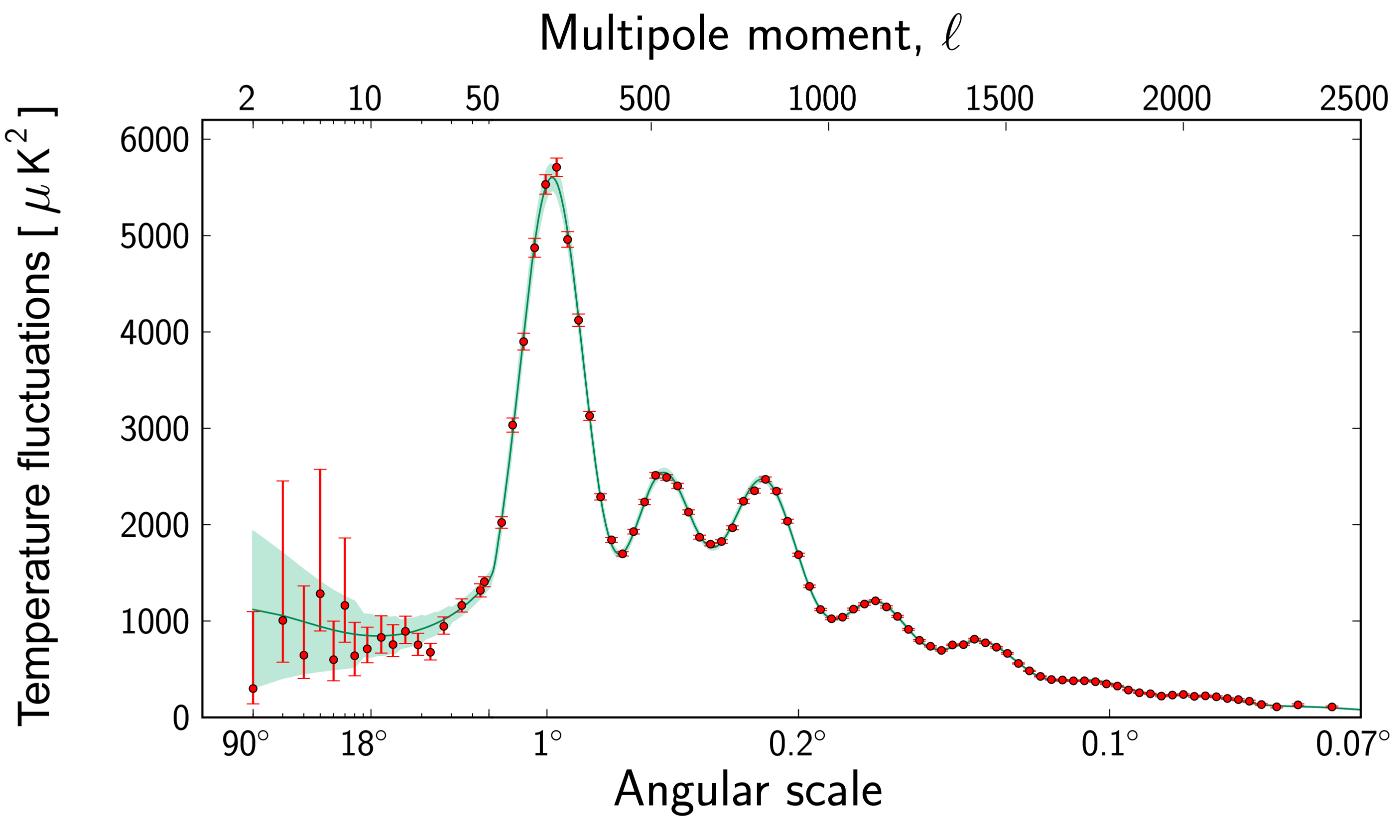
A formal “dark energy equation of state” $w_L(z)$ for the TS model, with $f_{v0} = 0.695$, calculated directly from $r_w(z)$: **(i)** $\Omega_{M0} = 0.41$; **(ii)** $\Omega_{M0} = 0.3175$.

- 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.

Observational data fitting: CMB



Planck data ΛCDM parametric fit



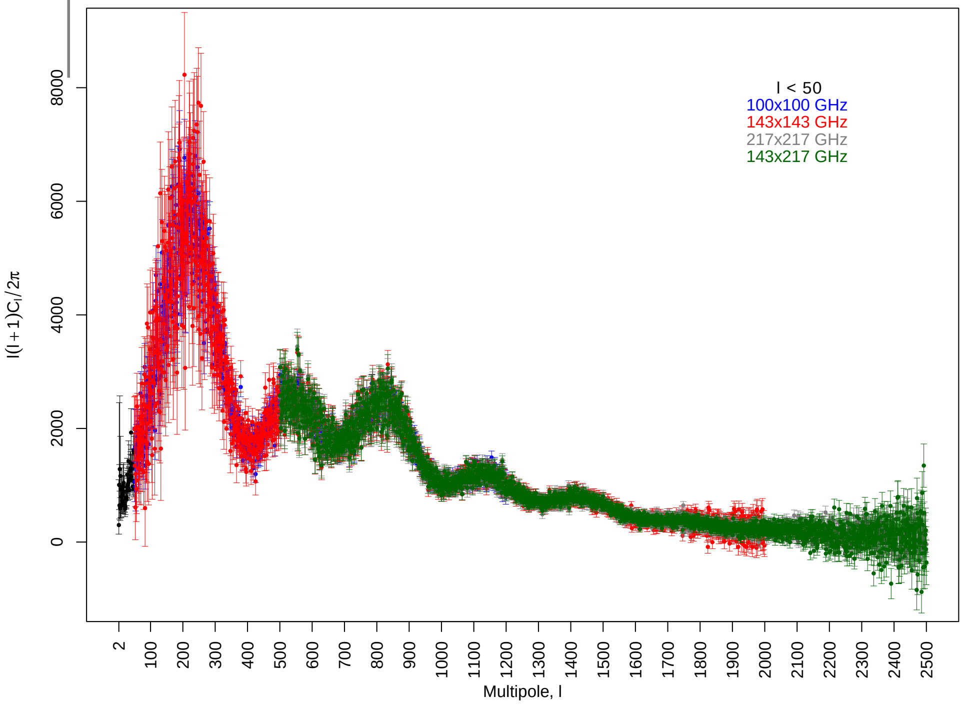
Duley, Nazer + DLW, CQG 30 (2013) 175006:

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

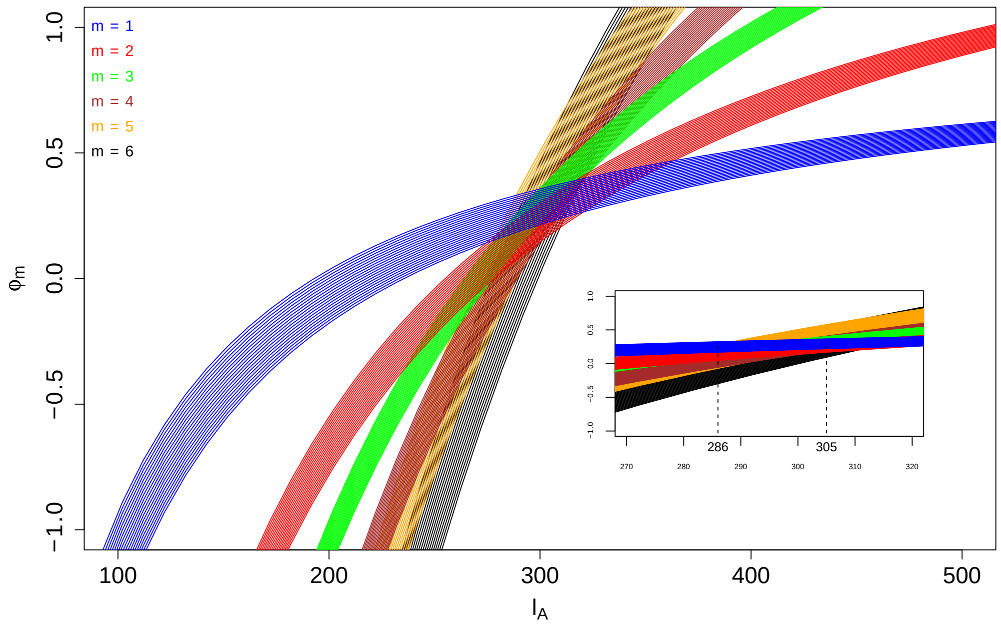
Planck constraints $D_A + r_{drag}$

- Dressed Hubble constant $H_0 = 61.7 \pm 3.0$ km/s/Mpc
- Bare Hubble constant $H_{\rm w0} = \bar{H}_0 = 50.1 \pm 1.7$ 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 $z_{\rm acc} = 0.46^{+0.26}_{-0.25}$

Non-parametric CMB constraints



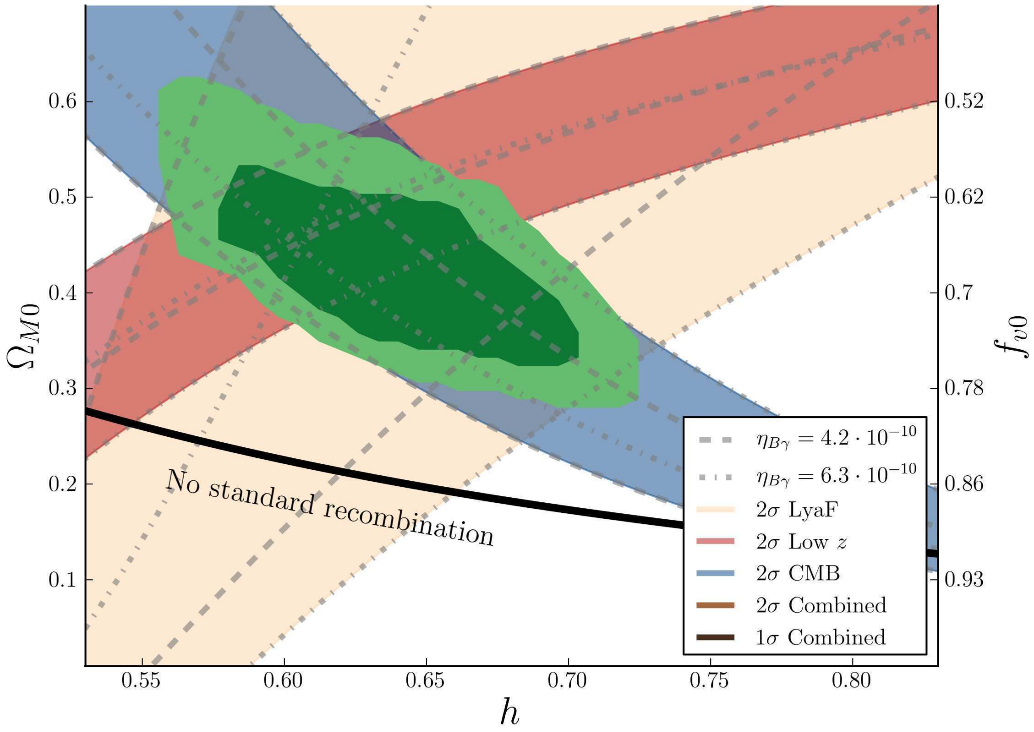
Raw Planck data



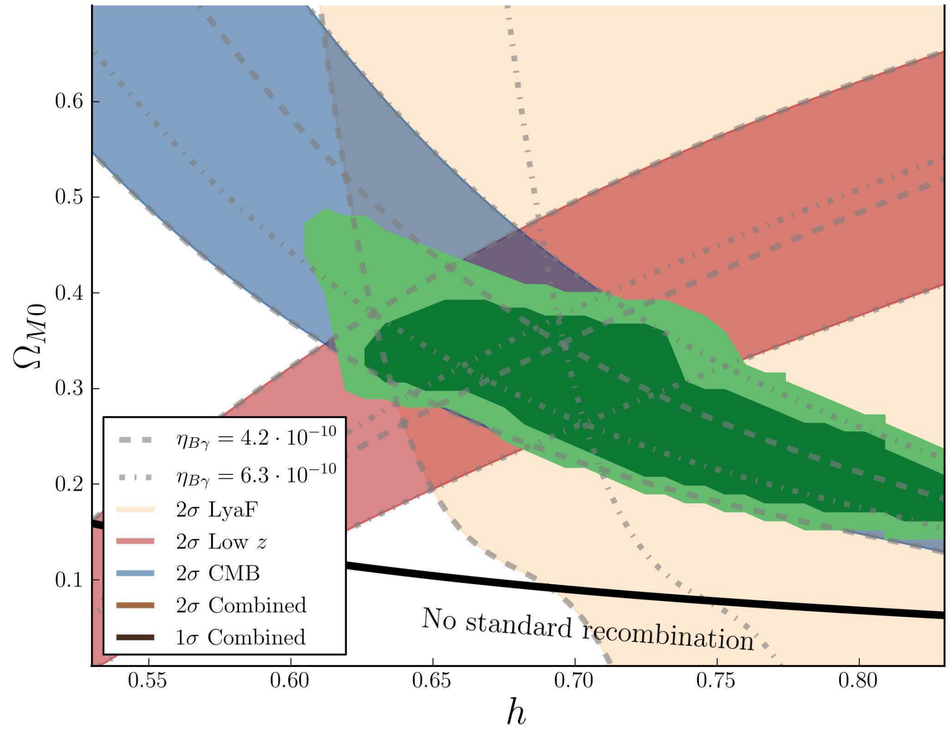
Fit to angular scale from 6 peaks

- 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



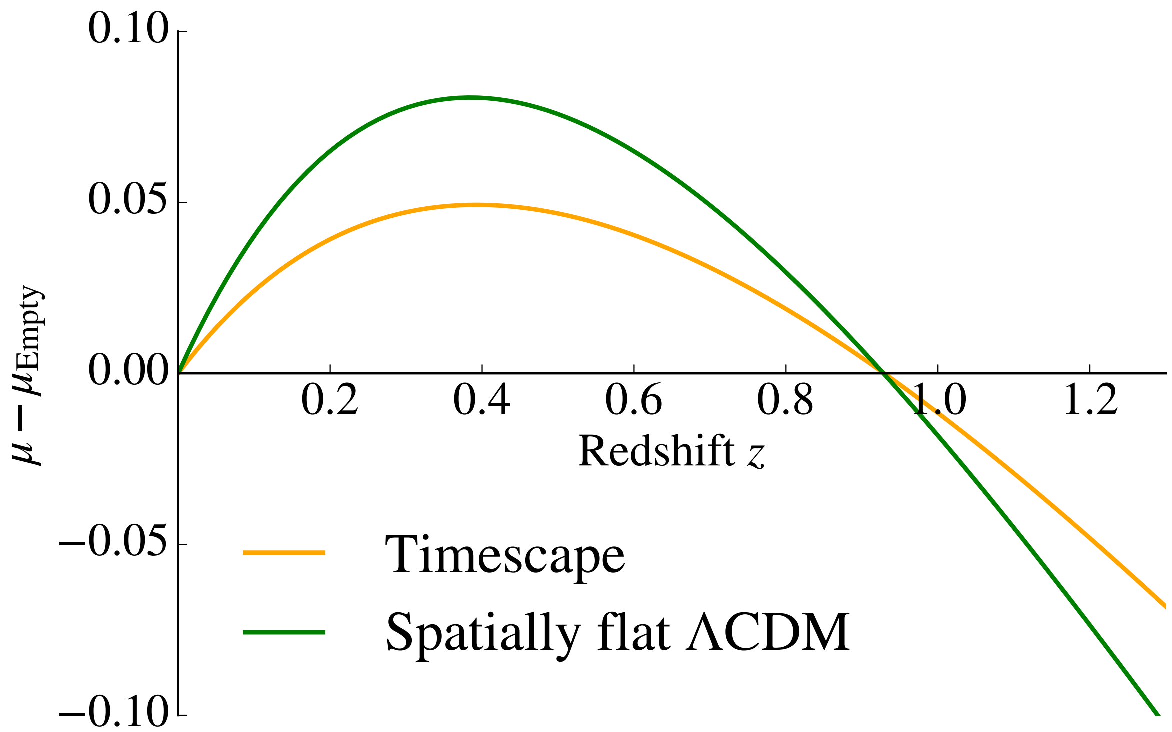
Timescape parameter constraints



Spatially flat ΛCDM parameter constraints

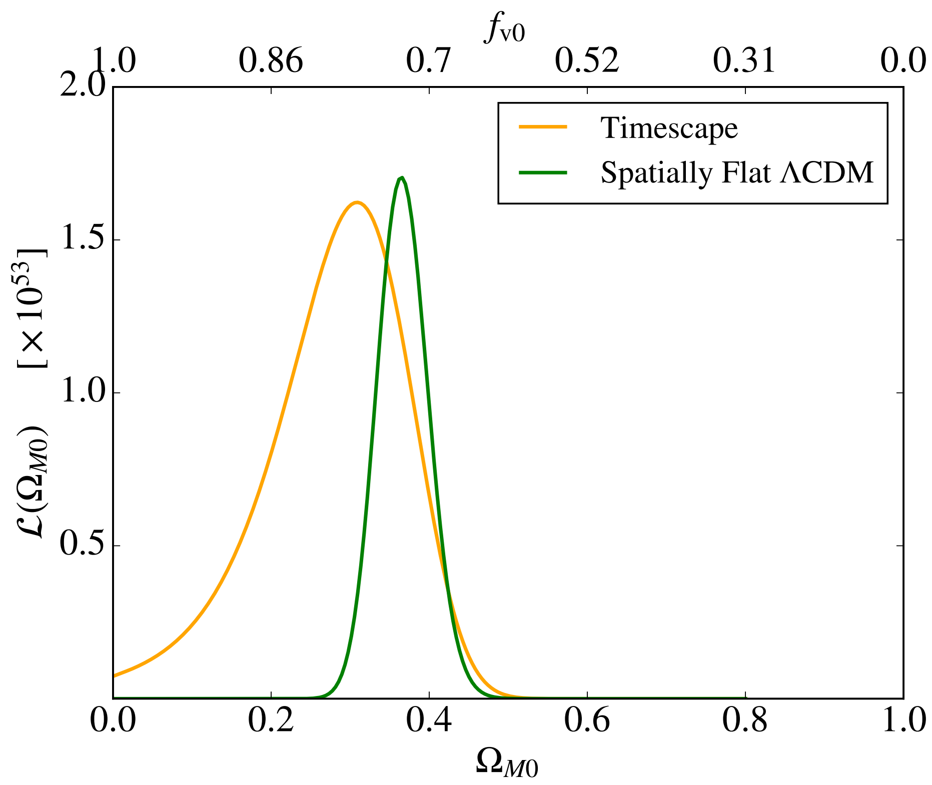
- Non-parametric CMB angular scale constraint (blue, 2σ)
- Baryon acoustic oscillations from BOSS (using FLRW model!) - galaxy clustering statistics $z = 0.38, 0.51, 0.61$ (red, 2σ); Lyman α forest $z = 2.34$ (pink, 2σ)

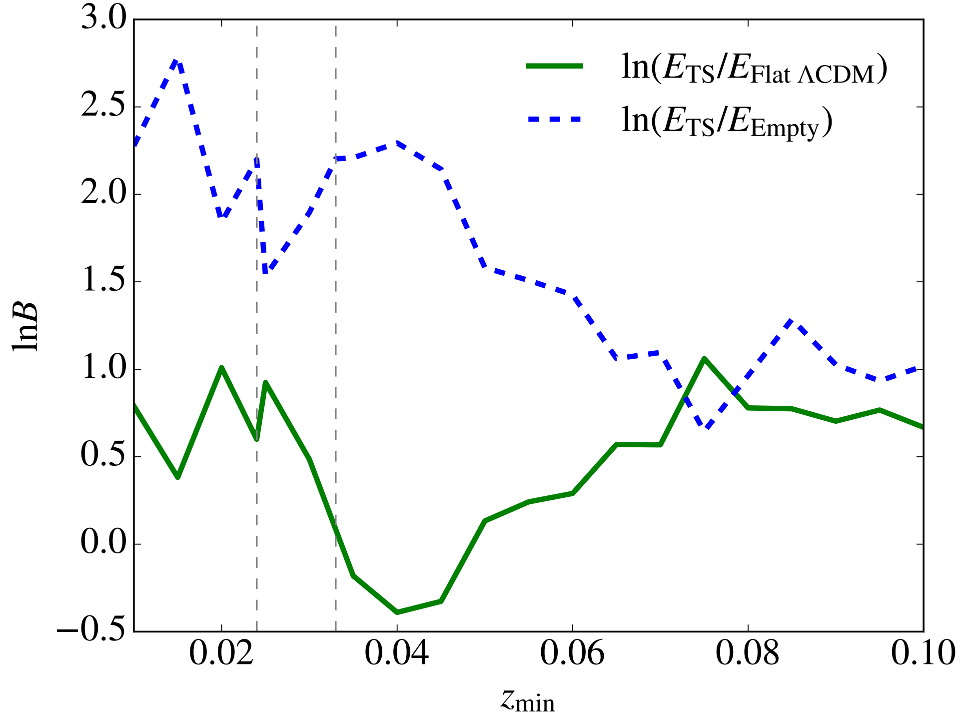
Supernovae Ia: data fits



- Dam, Heinesen + DLW, MNRAS 472 (2017) 835: SALT2 on JLA data (Betouille et al 2014), 740 SneIa, with methodology Nielsen, Guffanti & Sarkar Sci. Rep. 6 (2016) 35596

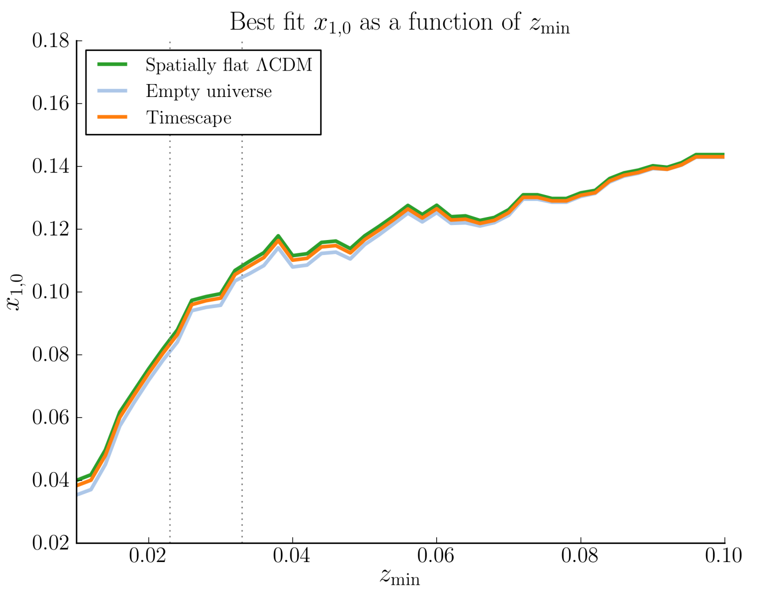
Dam, Heinesen & DLW, arXiv:1706.07236

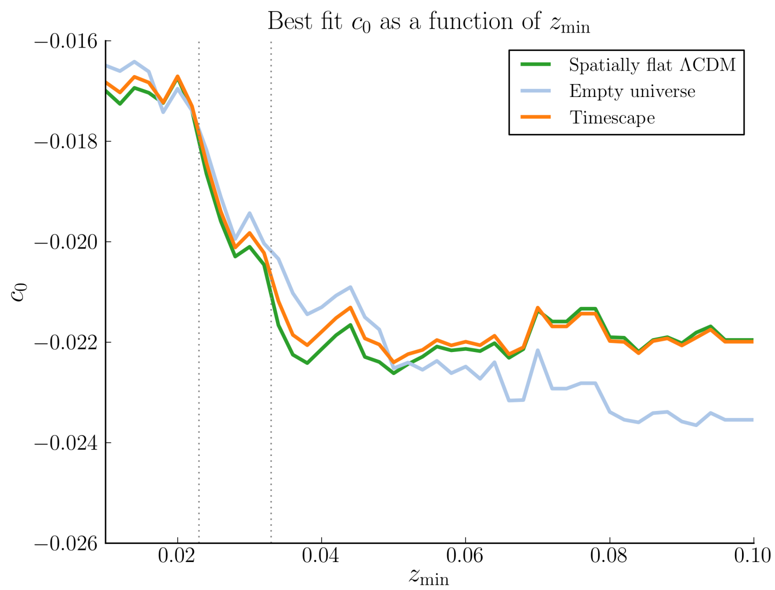




- Timescape / ΛCDM statistically indistinguishable, $\ln B =$ 0.60, 0.08 $z_{min} = 0.024, 0.033$
- Best fit $f_{v0} = 0.778^{+0.063}_{-0.056}$ (or $\Omega_{M0} = 0.33^{+0.06}_{-0.08}$) same as Leith, Ng & DLW, ApJ 672 (2008) L91 fit to Riess07 data

JLA data: SALT2 light curve parameters

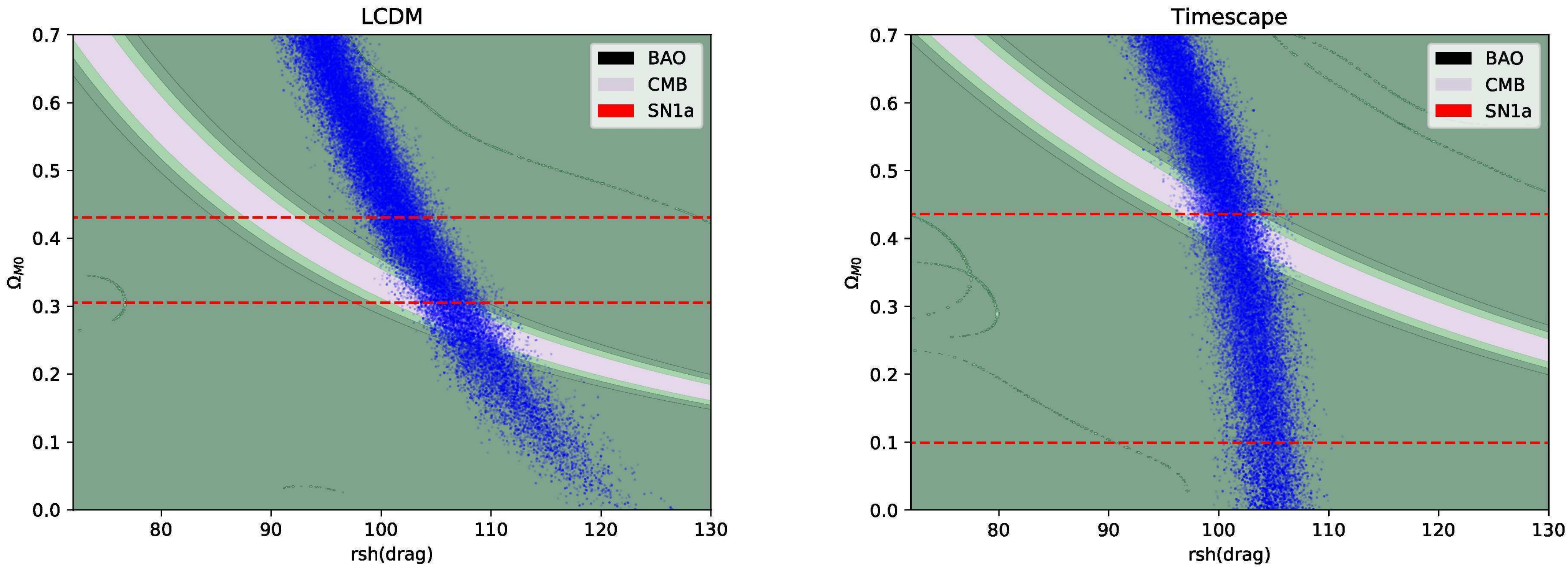




$x_{1,0}$ $\qquad$ c_0

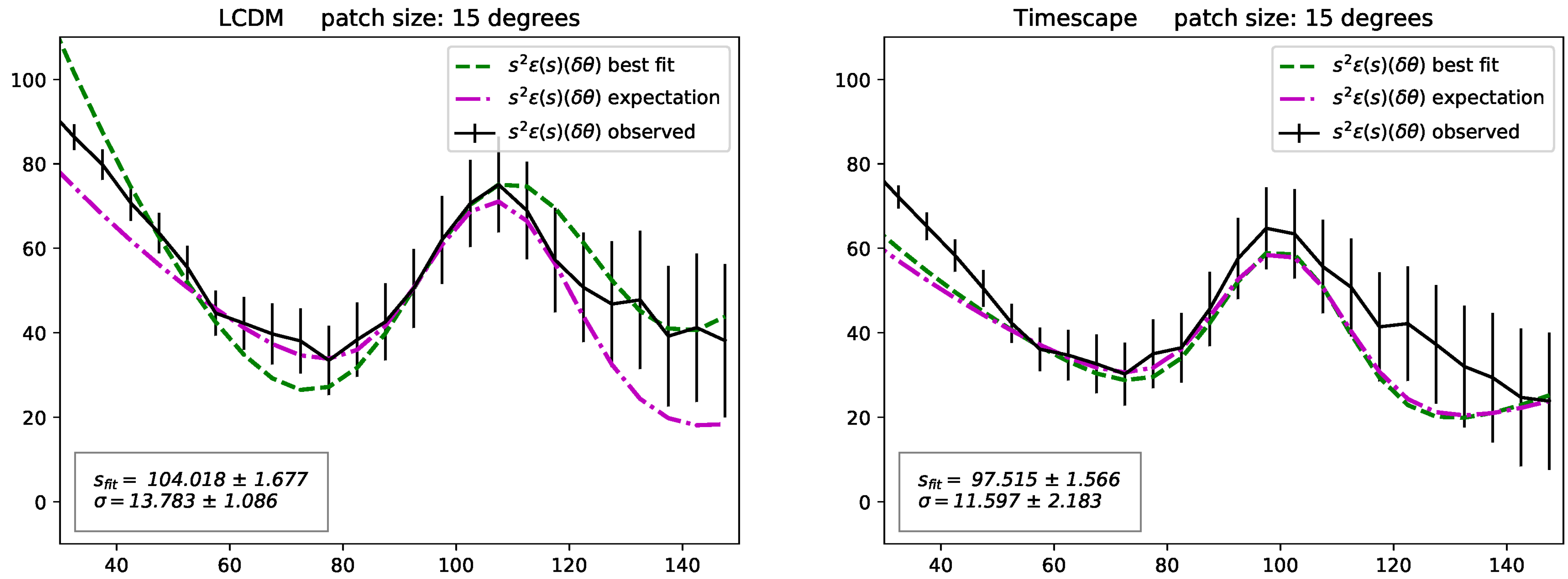
- Inclusion of SneIa below statistical homogeneity scale significant issue; along with SneI systematics (dust reddening/extinction, intrinsic colour variations)
- SHS is seen as a systematic *irrespective of model cosmology*

Goal: nonparametric BAO constraints



- Fit using angular correlation functions only *empirically* in $\Delta z = 0.02$ slices (Carvalho et al 2016, 2017)
- Relative evidence for timescape slightly increased but $\ln B < 1$ still AND systematic uncertainties underestimated

Preliminary: with C Blake, A Heinesen

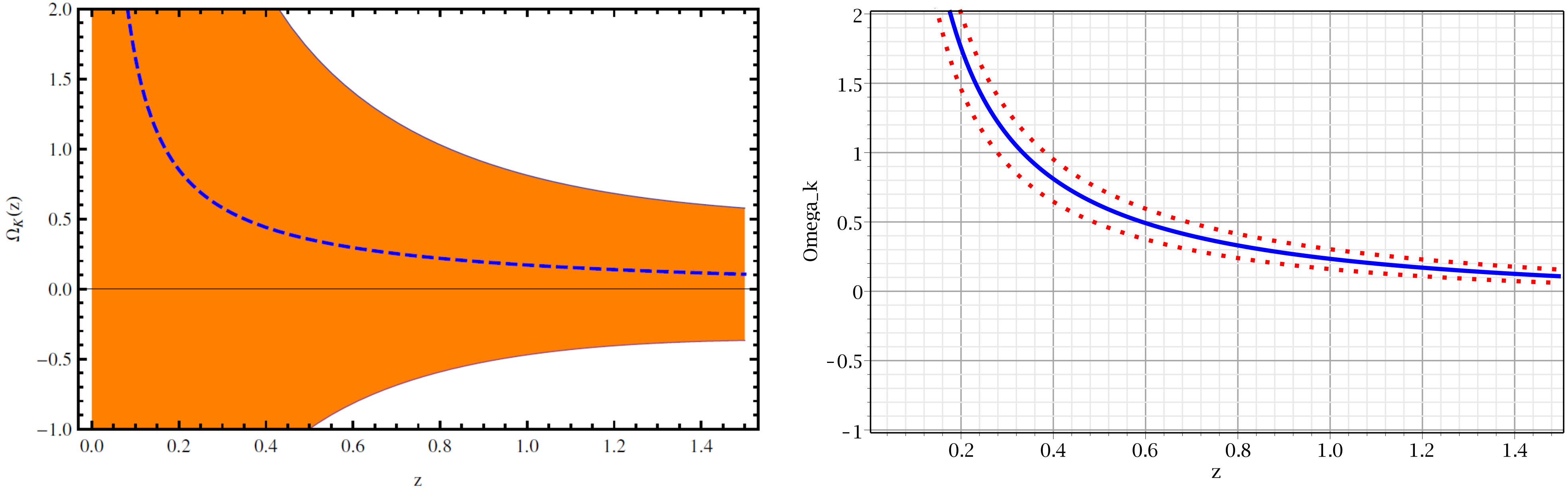


- Using BOSS-CMASS entire sample, radial + angular fit, approximations still in use (peak location slightly higher)
- Removing LCDM assumptions a coding challenge
- Angular/radial separation, parameter fits in progress

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

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

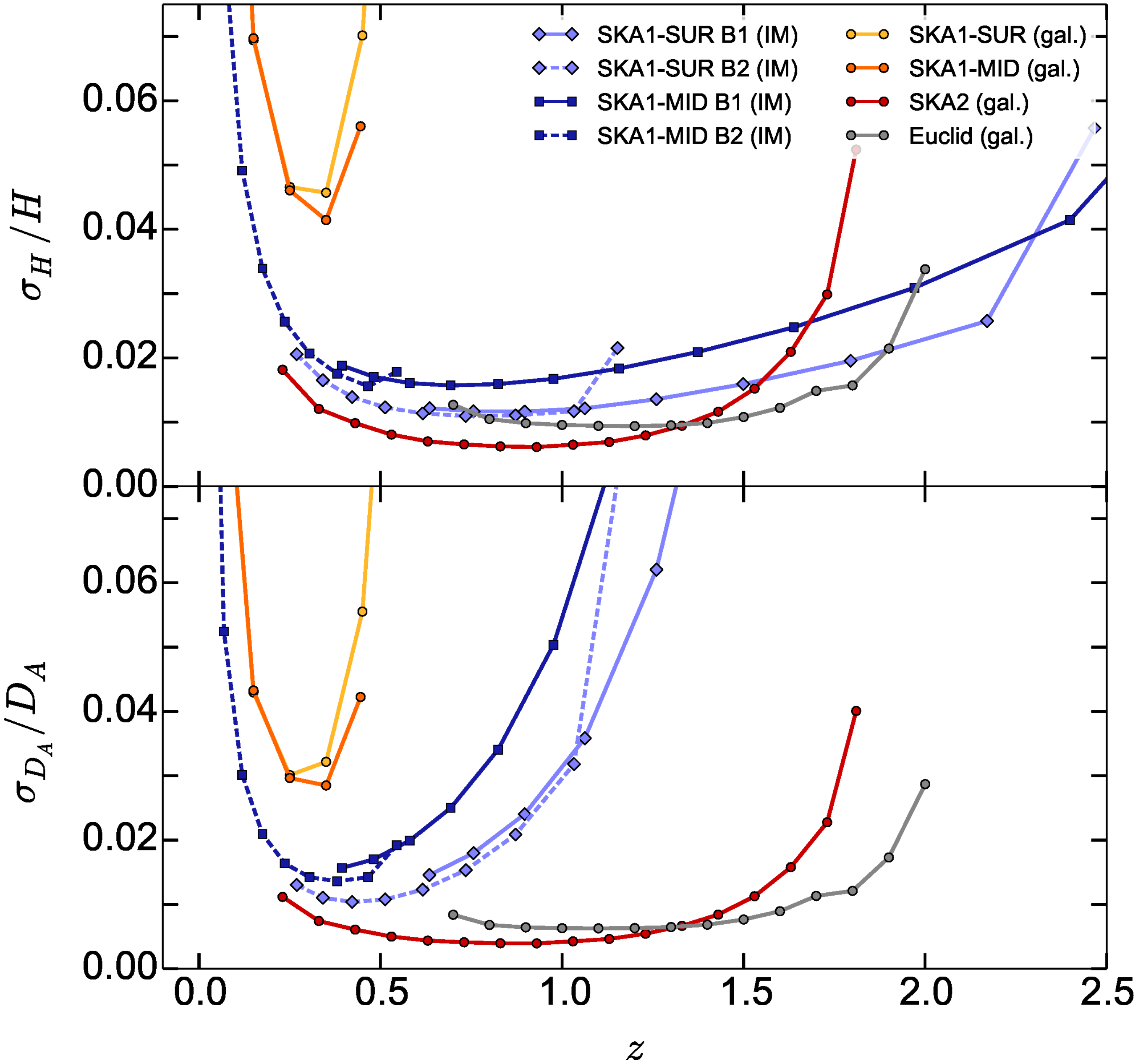


Left panel: CBL statistic from Sapone, Majerotto and Nesseris, PRD 90, 023012 (2014) Fig 8,

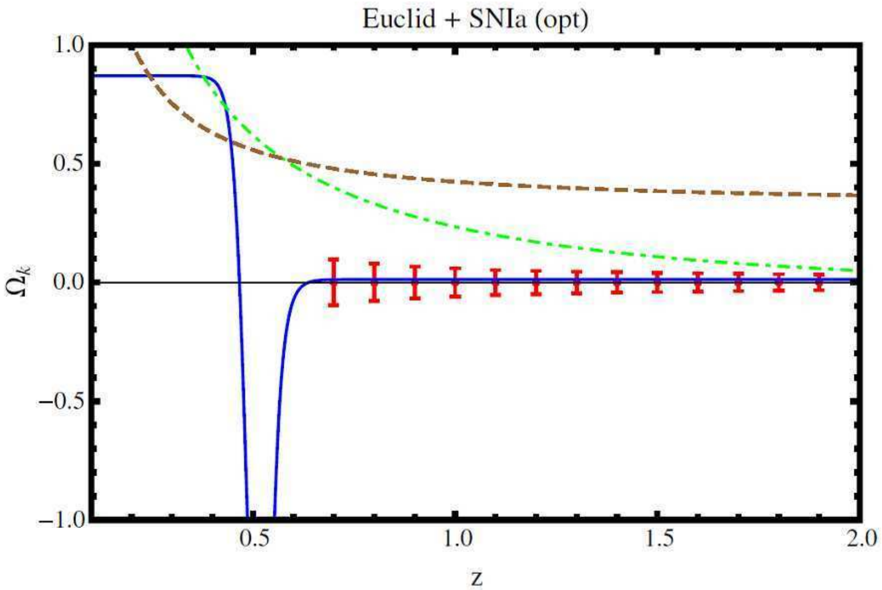
using existing data from SneIa (Union2) and passively evolving galaxies for $H(z)$.

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

Projections for Euclid, SKA

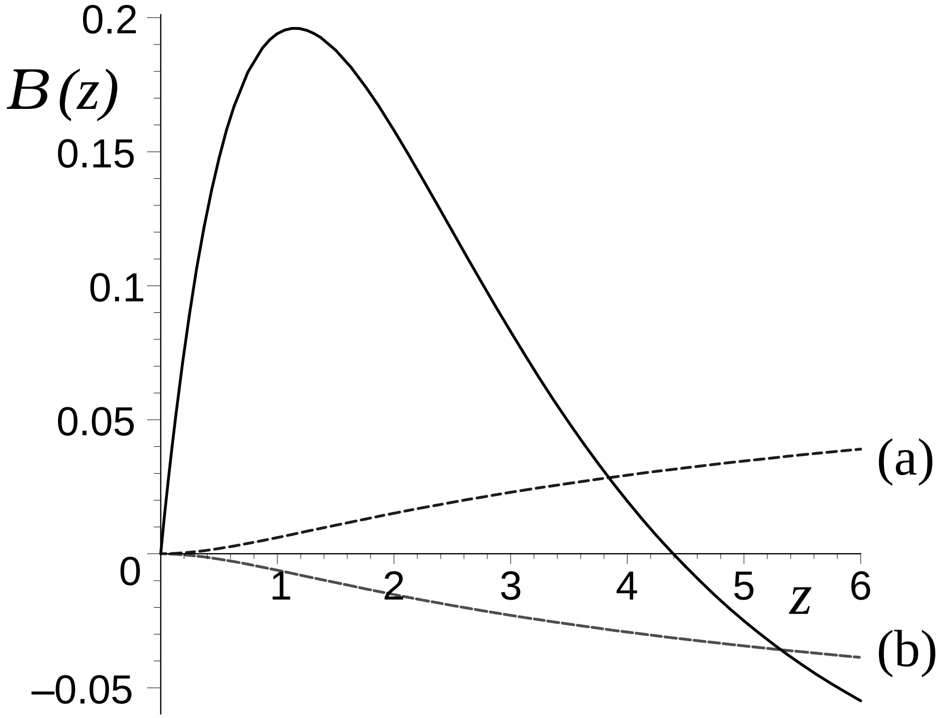


Clarkson Bassett Lu test with *Euclid*



- 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.)

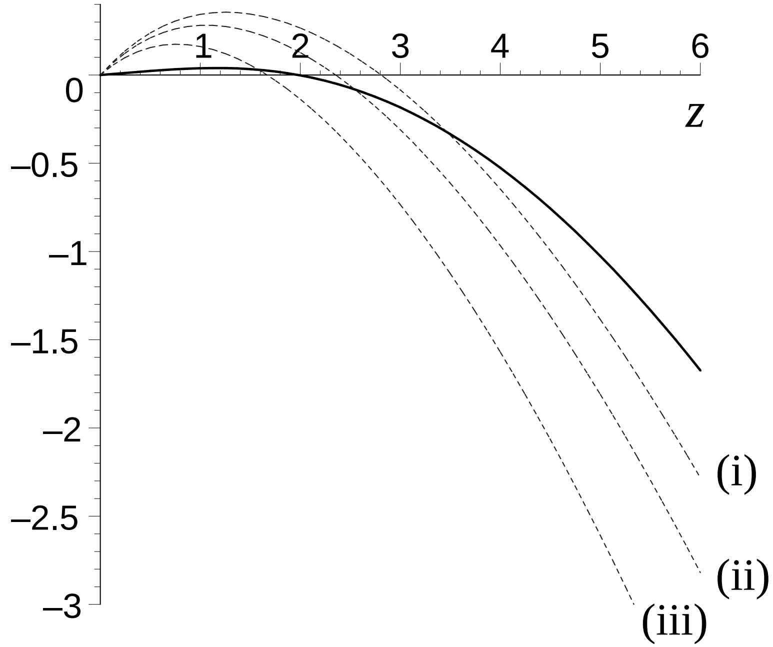
Clarkson, Bassett and Lu homogeneity test



e

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

Redshift time drift (Sandage–Loeb test)

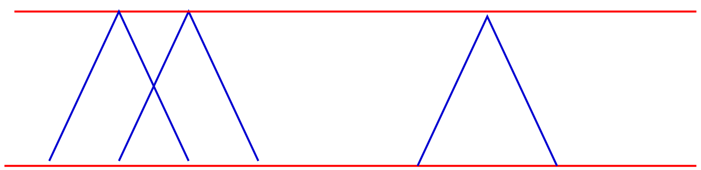


$H_0^{-1}\frac{\mathrm{d}z}{\mathrm{d}\tau}$ for the TS model with $f_{\mathrm{v}0} = 0.76$ (solid line) is compared to three spatially flat ΛCDM models.

- 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

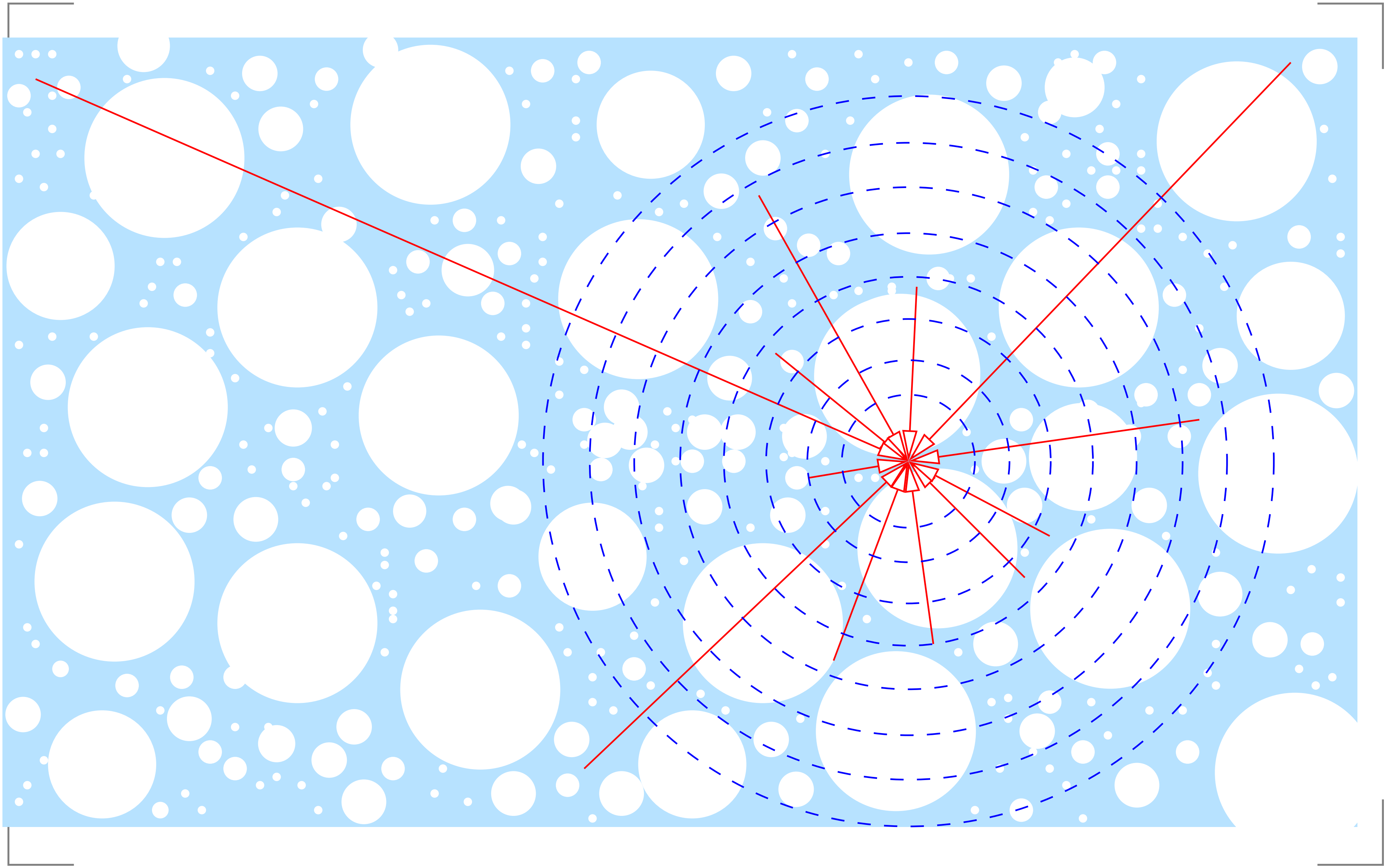
- Need CMB constraints of same precision as ΛCDM
- BUT backreaction in primordial plasma neglected
- Backreaction of similar order to density perturbations (10^{-5}); little influence on background but may influence growth of perturbations
- First step: add pressure to new "relativistic Lagrangian formalism": Buchert et al, PRD 86 (2012) 023520; PRD 87 (2013) 123503; Alles et al, PRD 92 (2015) 023512
- Rewrite whole of cosmological perturbation theory *without a single global background Einstein 4-geometry*
- Formalism adapted to fluid frames ("Lagrangian") not hypersurfaces ("Eulerian").

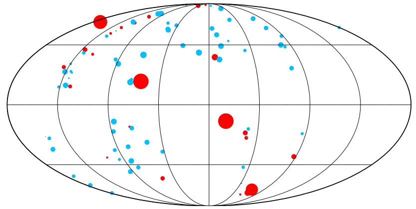


Inhomogeneity below SHS

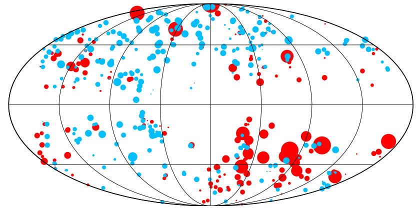
- Toy model Λ–Szekeres solutions: Planck ΛCDM on $\gtrsim 100\,h^{-1}$Mpc, Szekeres inhomogeneity inside, K Bolejko, MA Nazer, DLW JCAP 06 (2016) 035
- Potential insights about
  - convergence of “bulk flows” (see also Kraljic & Sarkar, JCAP 10 (2016) 016)
  - H_0 tension
  - Models for large angle CMB “anomalies” in future
- Standard sirens (GW170817 etc): will test this!

Apparent Hubble flow variation

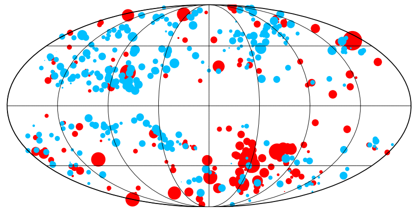




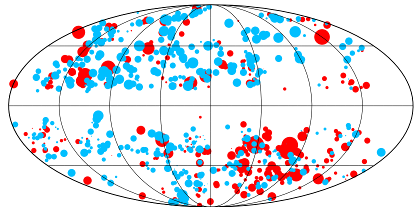
(a) 1: $0 - 12.5\ h^{-1}$ Mpc $N = 92$.



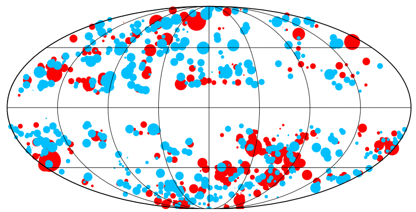
(b) 2: $12.5 - 25\ h^{-1}$ Mpc $N = 505$.



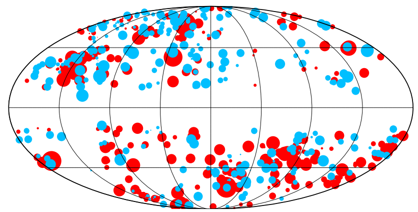
(c) 3: $25 - 37.5\ h^{-1}$ Mpc $N = 514$.



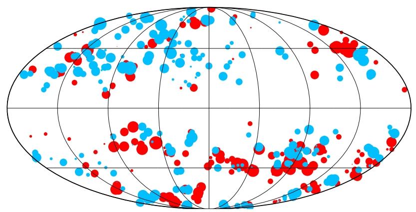
(d) 4: $37.5 - 50\ h^{-1}$ Mpc $N = 731$.



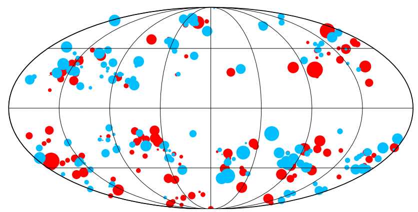
(e) 5: $50 - 62.5\ h^{-1}$ Mpc $N = 819$.



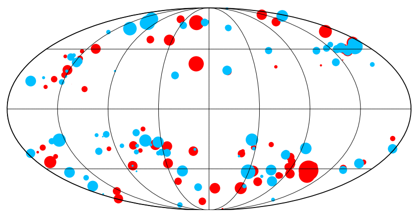
(f) 6: $62.5 - 75\ h^{-1}$ Mpc $N = 562$.



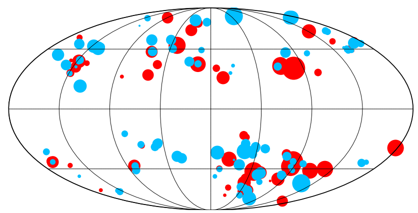
(g) 7: $75 - 87.5\ h^{-1}$ Mpc $N = 414$.



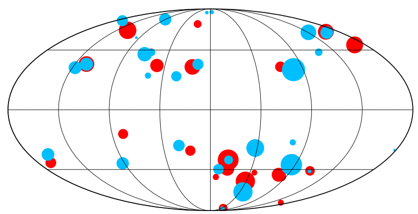
(h) 8: $87.5 - 100\ h^{-1}$ Mpc $N = 304$.



(i) 9: $100 - 112.5\ h^{-1}$ Mpc $N = 222$.

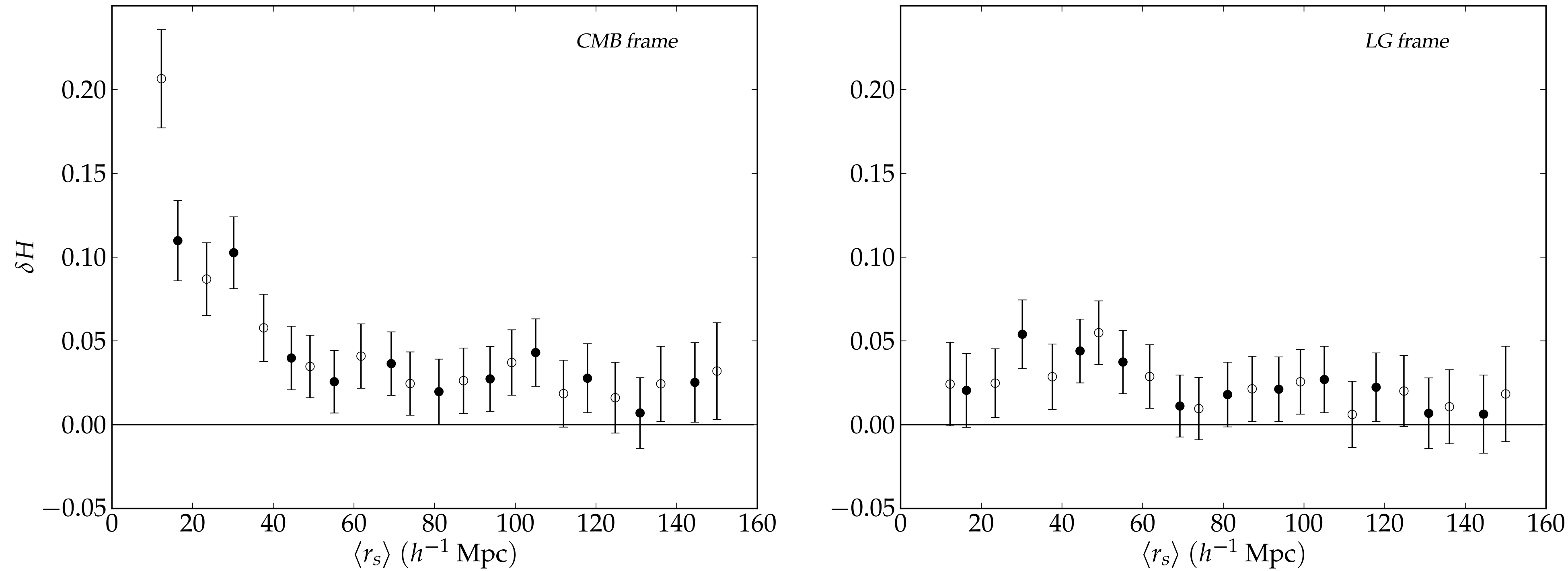


(j) 10: $112.5 - 156.25\ h^{-1}$ Mpc $N = 280$.



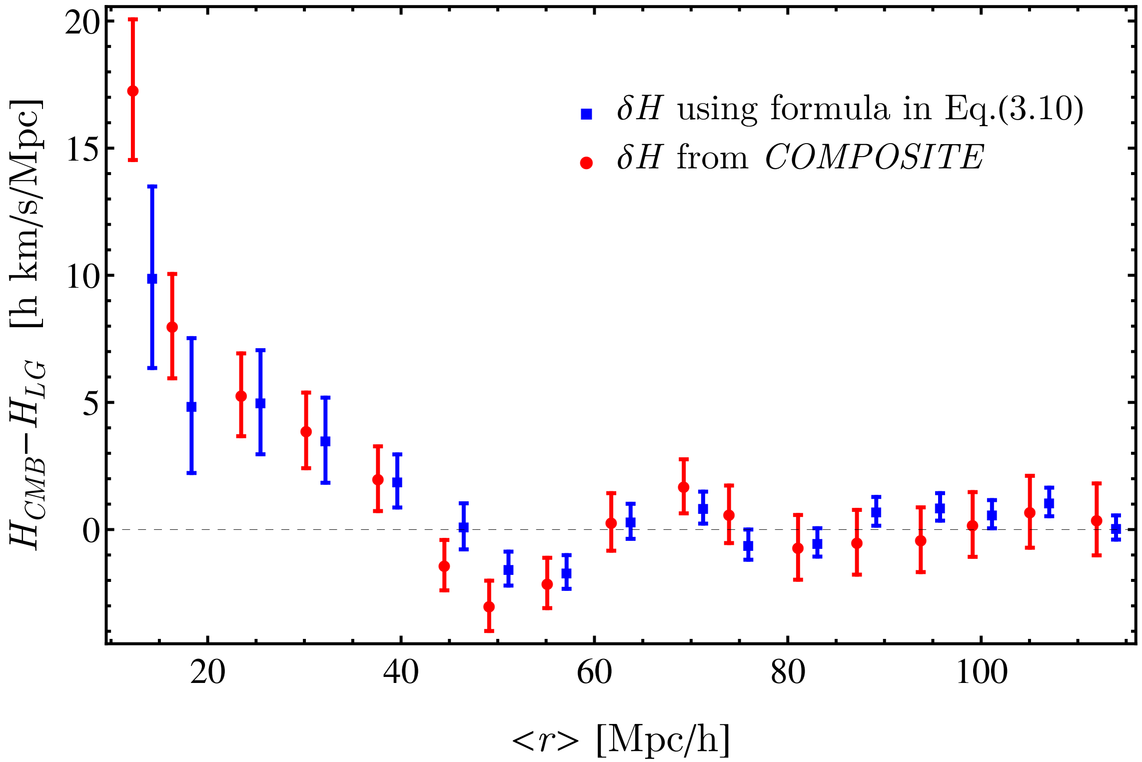
(k) 11: $156.25 - 417.4\ h^{-1}$ Mpc $N = 91$.

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



- Two choices of shell boundaries (closed and open circles); for each choice data points uncorrelated
- Result: Hubble expansion is very significantly more uniform in LG frame than in CMB frame: $\ln B > 5$; (except for $40 \lesssim r \lesssim 60\, h^{-1}$Mpc).

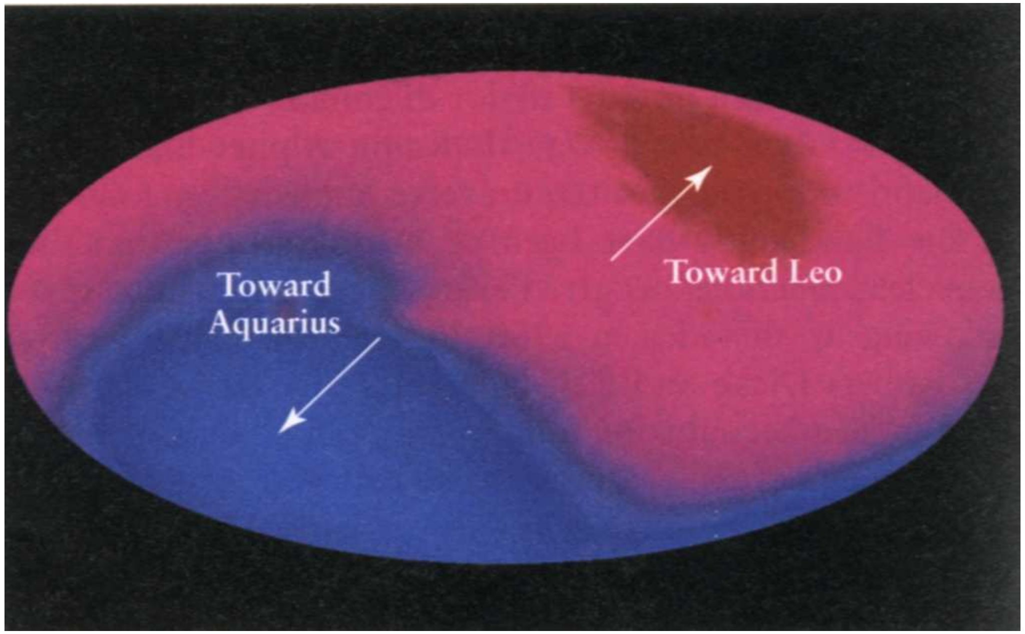
Boost offset and deviation



- Kraljic and Sarkar (JCAP 2016). FLRW + Newtonian N-body simulation with bulk flow $\mathbf{v}_{\text{bulk}}(r)$

$$H'_s - H_s \sim \frac{|\mathbf{v}|^2 - 2\mathbf{v}\cdot\mathbf{v}_{\text{bulk}}(r)}{3H_0\langle r^2\rangle}$$

Cosmic Microwave Background dipole

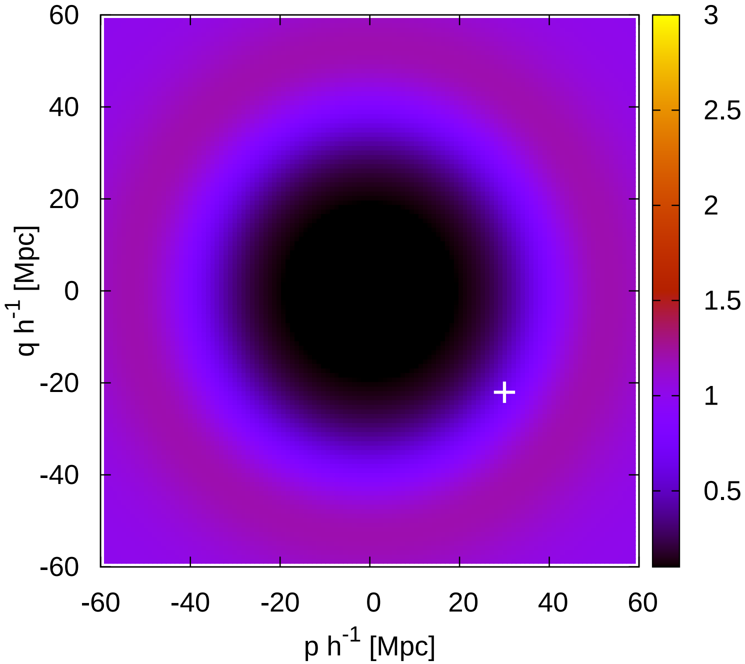


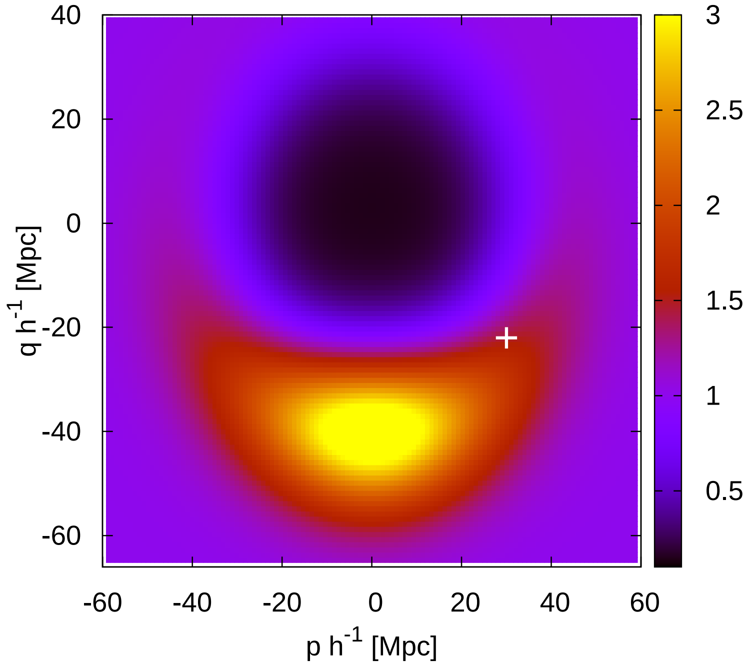
- Special Relativity: motion in a thermal bath of photons

$$T' = \frac{T_0}{\gamma(1 - (v/c)\cos\theta')}$$

- 3.37 mK dipole: $v_{\text{Sun-CMB}} = 371$ km s^{-1} to $(264.14°, 48.26°)$; splits as $v_{\text{Sun-LG}} = 318.6$ km s^{-1} to $(106°, -6°)$ and $v_{\text{LG-CMB}} = 635 \pm 38$ km s^{-1} to $(276.4°, 29.3°) \pm 3.2°$

LTB and Szekeres profiles





- Fix $\Delta r = 0.1 r_0$, $\varphi_{obs} = 0.5\pi$
- LTB parameters: $\alpha = 0$, $\delta_0 = -0.95$, $r_0 = 45.5\ h^{-1}$ Mpc; $r_{obs} = 28\, h^{-1}$Mpc, $\vartheta_{obs} =$ any
- Szekeres parameters: $\alpha = 0.86$, $\delta_0 = -0.86$; $r_{obs} = 38.5\ h^{-1}$ Mpc; $r_{obs} = 25h^{-1}$ Mpc, $\vartheta_{obs} = 0.705\pi$.

Szekeres model ray tracing constraints

- Require Planck satellite normalized FLRW model on scales $r \gtrsim 100\,h^{-1}$Mpc; i.e., spatially flat, $\Omega_m = 0.315$ and $H_0 = 67.3$ km/s/Mpc
- CMB temperature has a maximum $T_0 + \Delta T$, where

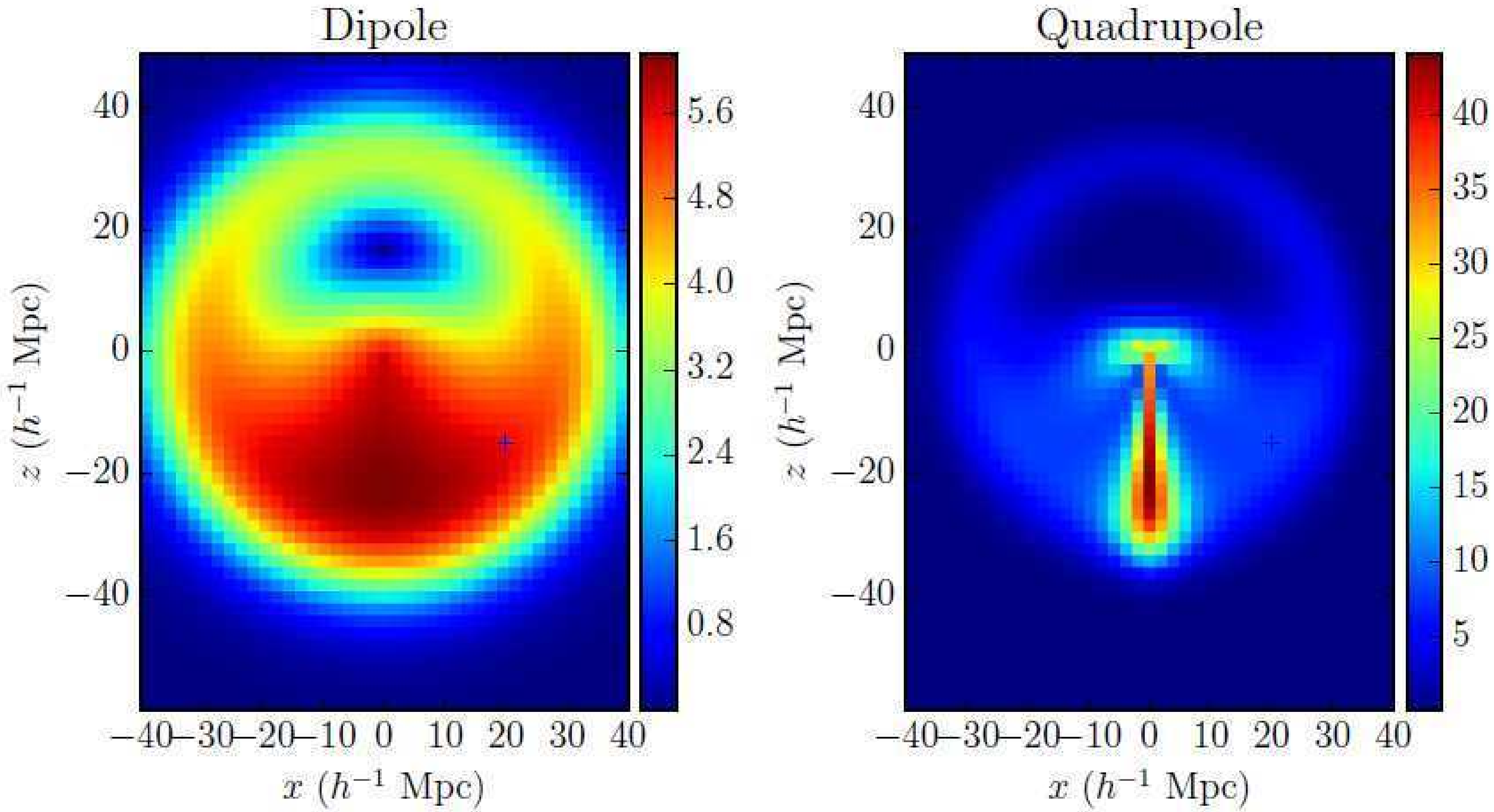
$$\Delta T(\ell = 276.4^\circ, b = 29.3^\circ) = 5.77 \pm 0.36 \text{ mK},$$

  matching dipole amplitude, direction in LG frame
- CMB quadrupole anisotropy lower than observed

$$C_{2,CMB} < 242.2^{+563.6}_{-140.1}\ \mu\text{K}^2.$$

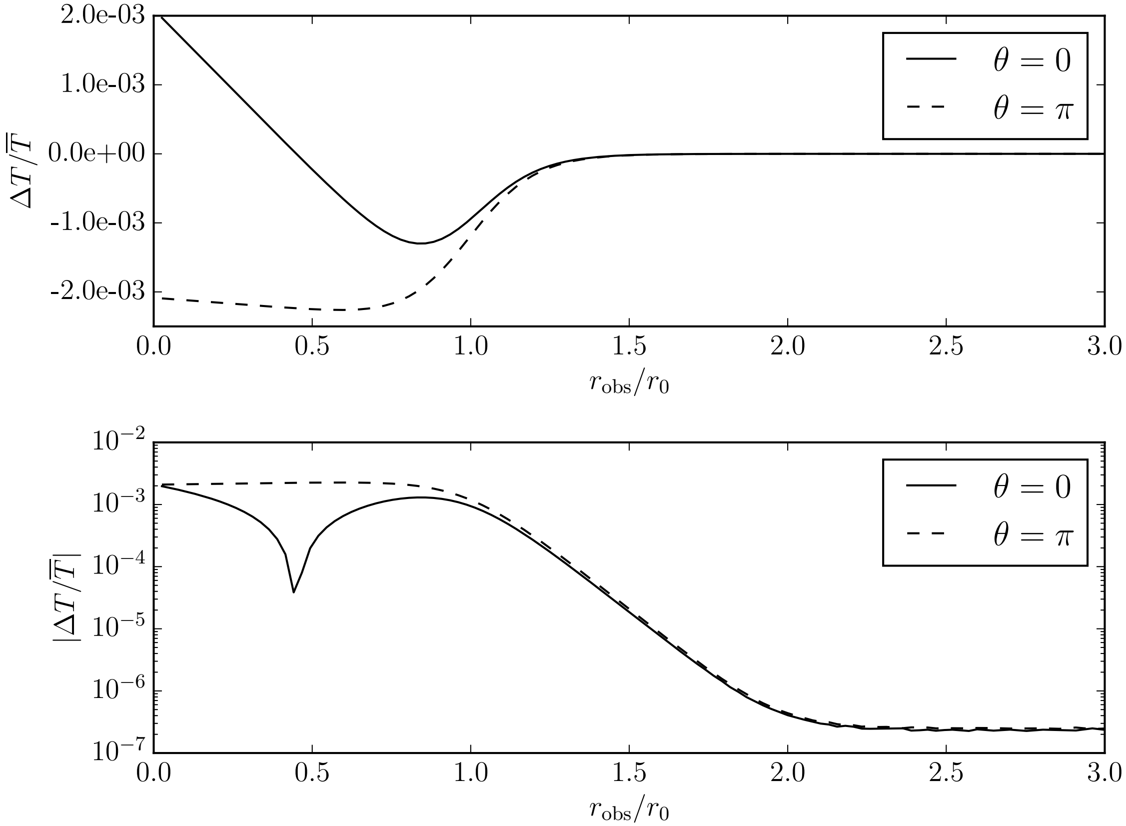
- Hubble expansion dipole (LG frame) matches COMPOSITE one at $z \to 0$, if possible up to $z \sim 0.045$
- Match COMPOSITE quadrupole similarly, if possible

CMB dipole, quadrupole examples



- Generate $z_{\mathrm{ls}}(\hat{\mathbf{n}})$ for each gridpoint
- $T = T_{\mathrm{ls}}/(1 + z_{\mathrm{ls}})$; $(T_{\mathrm{max}} - T_{\mathrm{min}})/2$ left (mK); C_2 right (μK^2)

Peculiar potential not Rees–Sciama



- Rees–Sciama (and ISW) consider photon starting and finishing from *average* point
- Across structure $|\Delta T|/T \sim 2 \times 10^{-7}$
- Inside structure $|\Delta T|/T \sim 2 \times 10^{-3}$

Large angle CMB anomalies?

Anomalies (significance increased after Planck 2013):

- power asymmetry of northern/southern hemispheres
- alignment of the quadrupole and octupole etc;
- low quadrupole power;
- parity asymmetry; . . .

Critical re-examination required; e.g.

- light propagation through Hubble variance dipole foregrounds may differ subtly from Lorentz boost dipole
- dipole subtraction is an integral part of the map-making; is galaxy correctly cleaned?
- Freeman et al (2006): 1–2% change in dipole subtraction may resolve the power asymmetry anomaly.

Planck results arXiv:1303.5087

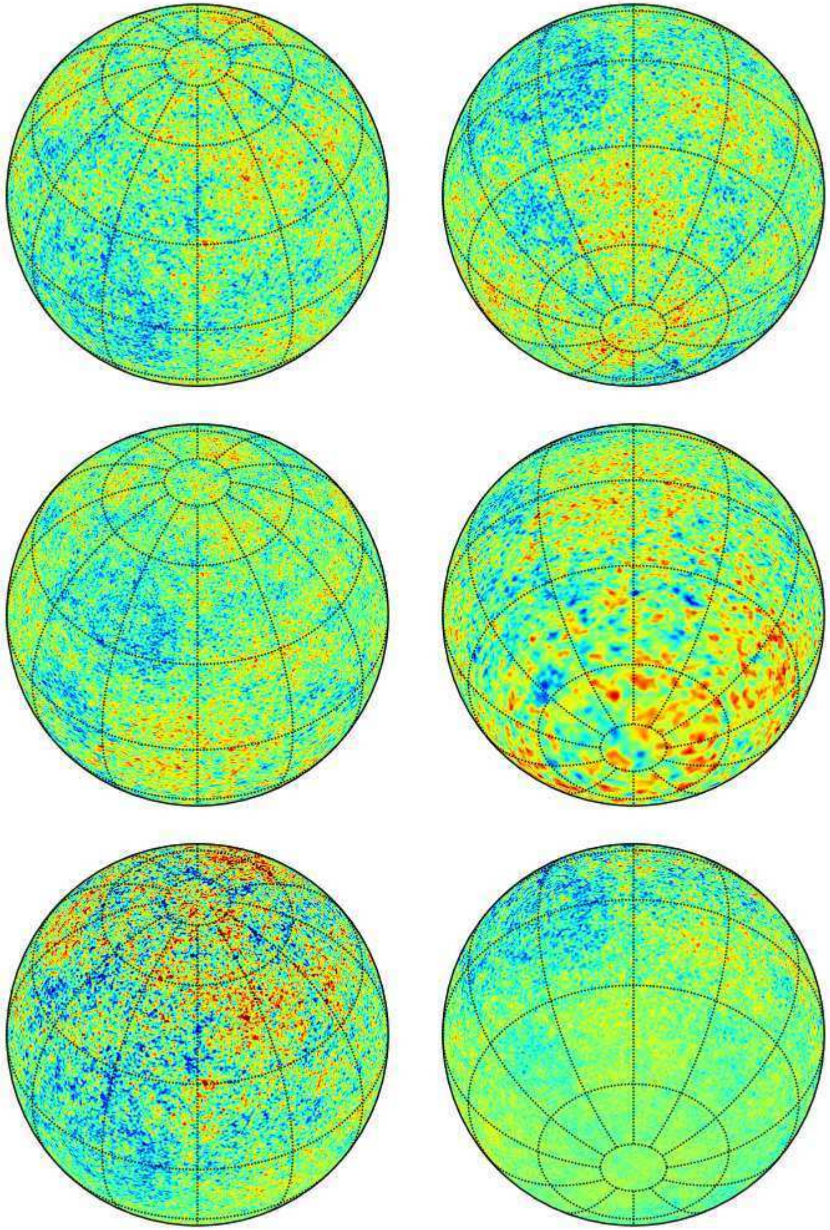
Boost dipole from second order effects

Original

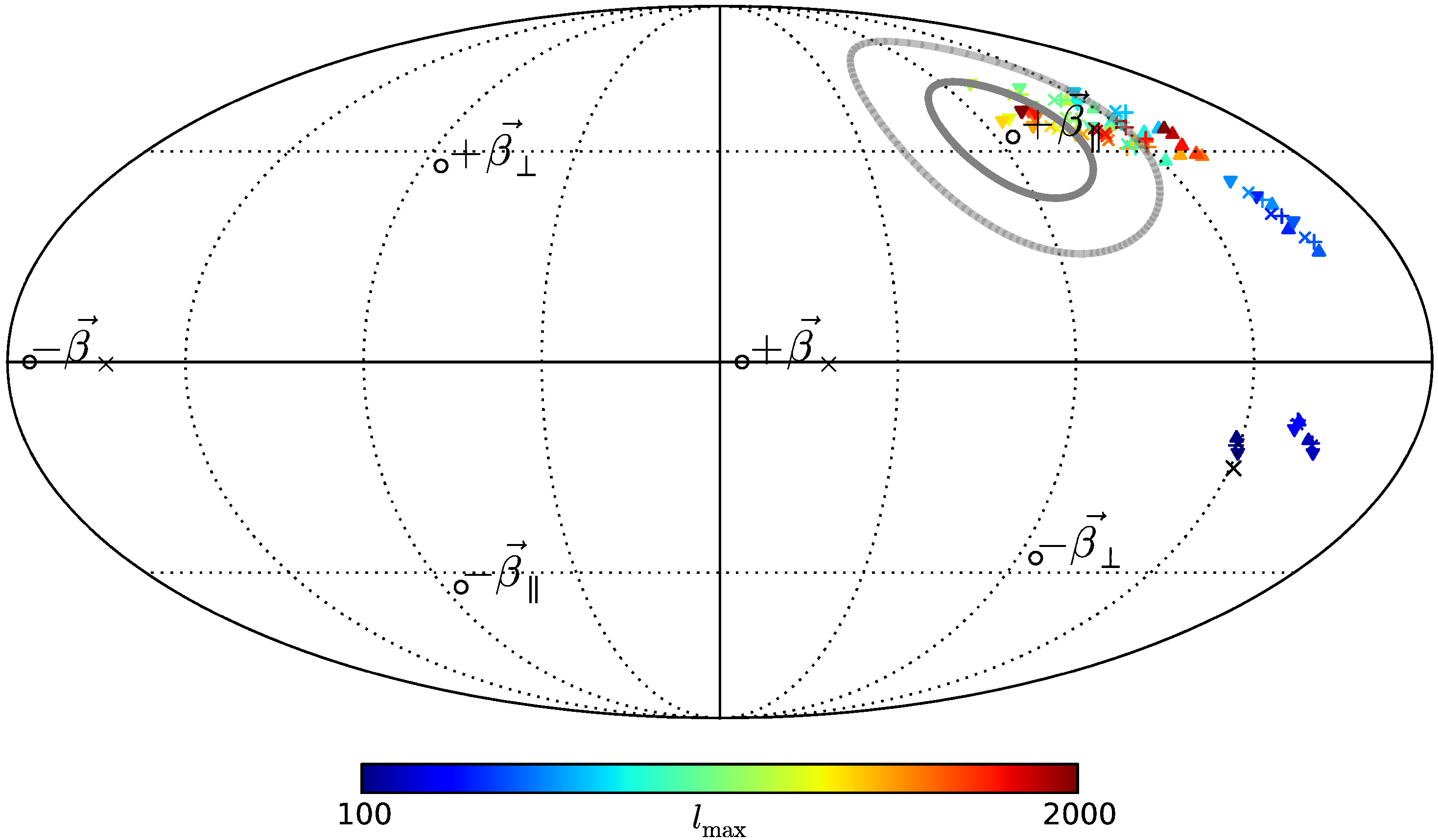
Aberration (Exaggerated)

Modulation (Exaggerated)

Eppur si muove?

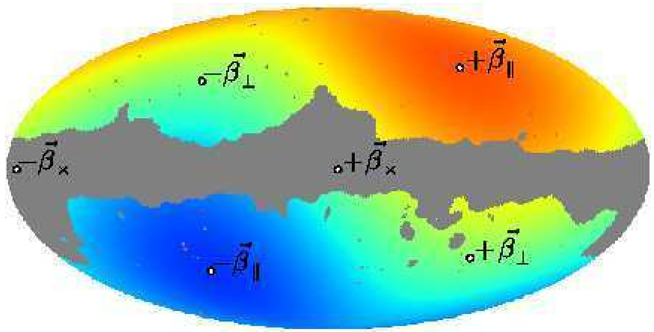


Planck Doppler boosting 1303.5087



- Dipole direction consistent with CMB dipole $(\ell, b) = (264°, 48°)$ for small angles, $l_{\min} = 500 < l < l_{\max} = 2000$
- When $l < l_{\max} = 100$, shifts to WMAP power asymmetry modulation dipole $(\ell, b) = (224°, -22°) \pm 24°$

Systematics for CMB



- Define nonkinematic foreground CMB anisotropies by

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

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

$z_{\text{model}}(\hat{\mathbf{n}}_{\text{LG}})$ = anisotropic Szekeres LG frame redshift; T_0 = present mean CMB temperature

- Constrain $\frac{T_{\text{model}}}{\gamma_{\text{LG}}(1-\boldsymbol{\beta}_{\text{LG}}\cdot\hat{\mathbf{n}}_{\text{hel}})} - T_{\text{obs}}$ by Planck with sky mask

Non-kinematic dipole in radio surveys

- Effects of aberration and frequency shift also testable in large radio galaxy surveys (number counts)
- Rubart and Schwarz, arXiv:1301.5559, have conducted a careful analysis to resolve earlier conflicting claims of Blake and Wall (2002) and Singal (2011)
- Rubart & Schwarz result: kinematic origin of radio galaxy dipole ruled out at 99.5% confidence
- Our smoothed Hubble variance dipole in LG frame $(180+\ell_d, -b_d) = (263^\circ \pm 6^\circ, 39^\circ \pm 3^\circ)$ for $r > r_o$ with $20\,h^{-1} \lesssim r_o \lesssim 45\,h^{-1}$Mpc, or $(\text{RA}, \text{dec}) = (162^\circ \pm 4^\circ, -14^\circ \pm 3^\circ)$, lies within error circle of NVSS survey dipole found by Rubart & Schwarz, $(\text{RA}, \text{dec}) = (154^\circ \pm 21^\circ, -2^\circ \pm 21^\circ)$

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*
- Test of the Friedmann equation possible with Euclid, 1000 SneIa, SKA2, . . .
- For theorists, Clarkson–Bassett–Lu test is tipping point

References

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

Phys. Rev. Lett. 99 (2007) 251101

Phys. Rev. D78 (2008) 084032

Phys. Rev. D80 (2009) 123512

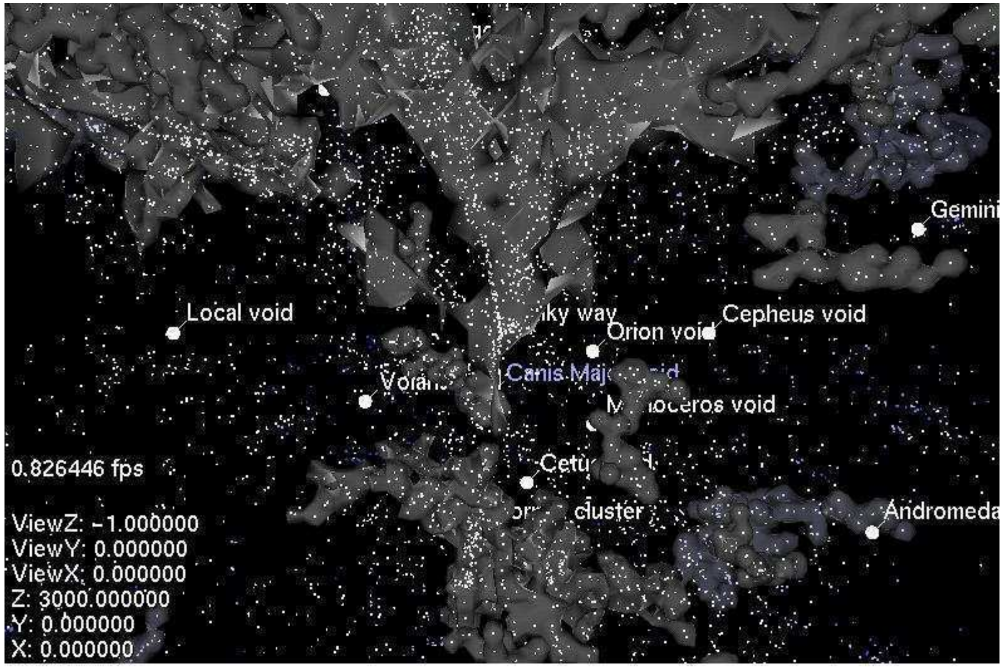
Class. Quan. Grav. 28 (2011) 164006

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** **Lecture Notes: arXiv:1311.3787**

L.H. Dam, A. Heinesen & DLW: **MNRAS 472 (2017) 835**