Title: The not-so-homogeneous universe

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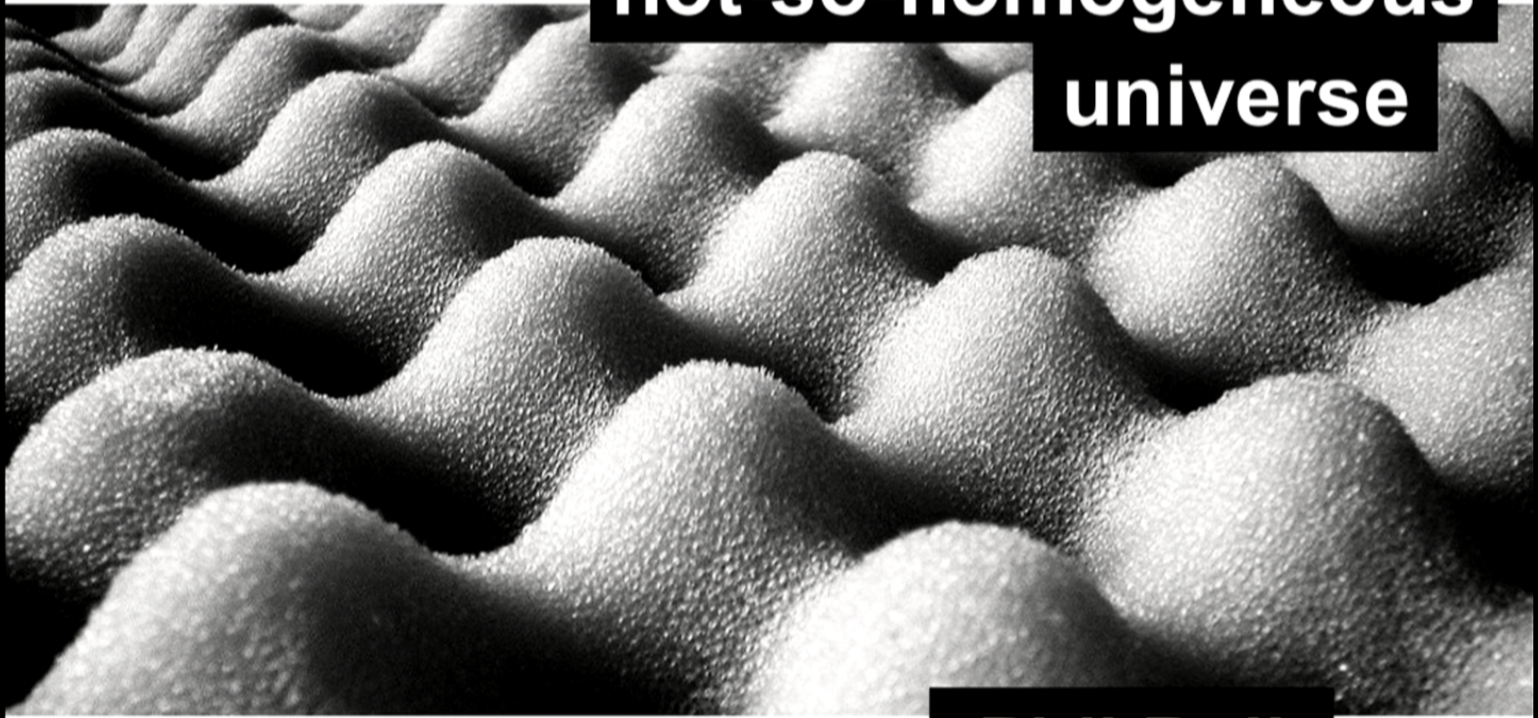
Abstract: The assumption of spatial homogeneity lies at the heart of the concordance cosmological model. But as I will discuss, truly solid empirical evidence for global (statistical) homogeneity is lacking, and tricky theoretical issues abound. I review a few recent advances in understanding the role inhomogeneity plays in cosmology, including some unexpected effects on light propagation, the death (and rebirth) of backreaction, and impending observational annoyances related to the lumpy local Universe. I'll also talk about some near-future observations that can give us a handle on these effects

The not-so-homogeneous universe



Phil Bull

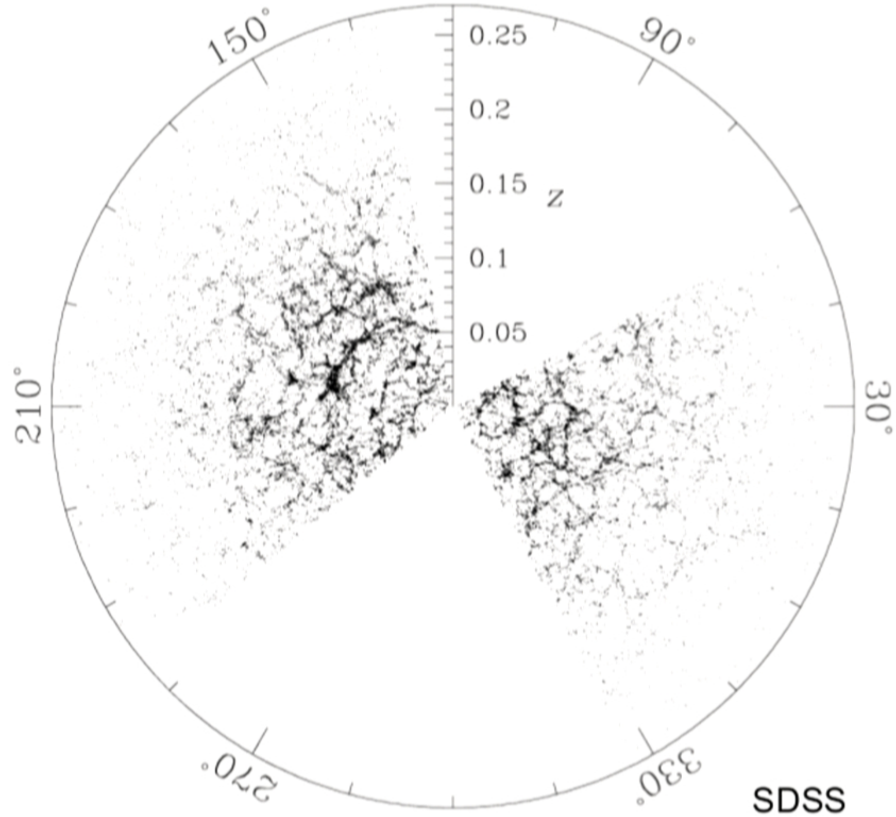
University of Oslo

Planck strikes back!

Ignazio Pillitteri

Questions

The Universe is clearly inhomogeneous on some scales



SDSS

Questions

The Universe is clearly inhomogeneous on some scales

Is it statistically homogeneous?

(Satisfies the cosmological principle on large scales)

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Is it statistically homogeneous?

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Is it well-described by FLRW?

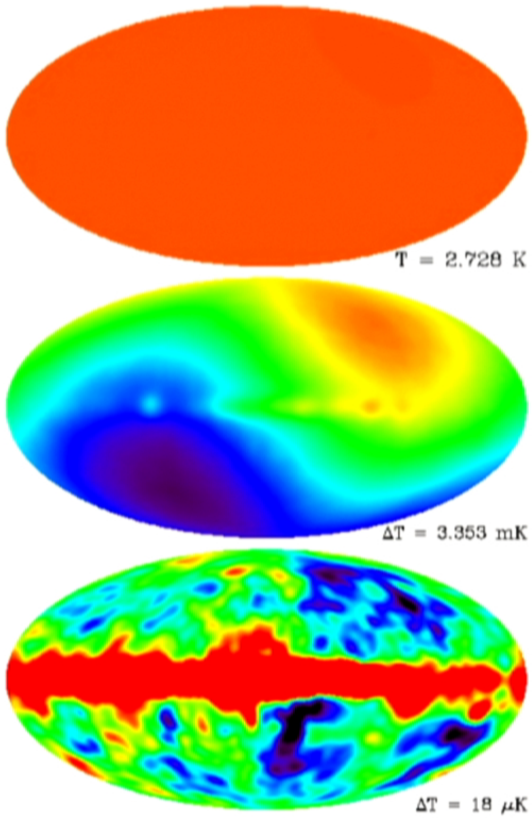
(Is our “background” physical model sensible?)

Evidence for CP

Observed isotropy

- Distant sources are distributed isotropically:
  - CMB
  - Radio sources
  - Galaxy distribution
- Naturally implies homogeneity

  What else explains it?



COBE

Is isotropy enough?

- Ehlers-Geren-Sachs theorem (1968)

Isotropy of the CMB implies homogeneity

(EGS) Radiation isotropy → FLRW

In a region, if

- collisionless radiation is exactly isotropic,
- the radiation four-velocity is geodesic and expanding,
- there is dust matter and dark energy in the form of Λ, quintessence or a perfect fluid,

then the metric is FLRW in that region.

Clarkson & Maartens (2010)

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Clarkson & Maartens (2010)

- Depends on **Copernican Principle** (we aren't special)
- Numerous examples of isotropic but inhomogeneous *non-Copernican* spacetimes

Generalised EGS theorems

- Is EGS stable to perturbations?

  i.e. does *almost*-isotropy imply *almost*-homogeneity?

- **Almost!**

  Stoeger, Maartens, Ellis (1995): departures from homogeneity are same order as departures from isotropy

  Rasanen (2009): Depends on smallness of spacetime derivatives of the temperature monopole

  → **not** necessarily satisfied in the real Universe!

- Rescued by the Copernican Principle again

Do we need the CP?

- Can we avoid the Copernican Principle?

  Yes, but it's hard work

Matter lightcone-isotropy → spatial isotropy
If one fundamental observer comoving with the matter measures isotropic area distances, number counts, bulk peculiar velocities, and lensing, in an expanding dust Universe with Λ, then the spacetime is isotropic about the observer's worldline.

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Includes *transverse* velocities

Only shear (magnification is fine)

Reconstruct metric + matter evolution on past lightcone → **Cauchy surface**

Observed homogeneity?

- We have **not** observed homogeneity yet
- Tantalising hints, but it's not good enough (need to assume too much)

But is there an alternative?

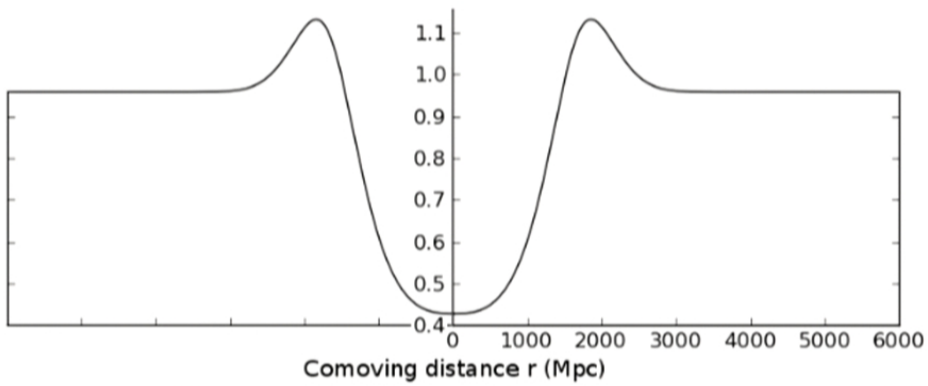
Lightcone degeneracy

- Mustapha, Hellaby, Ellis (1998):

  Can find always find an LTB model (Λ=0) that fits any H(z) and $D_A(z)$

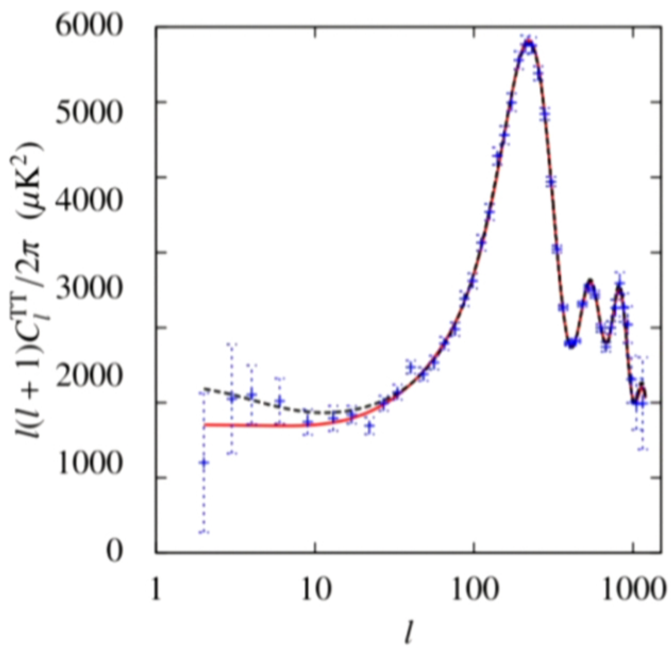
$$ds^2 = dt^2 - \frac{a_2^2(r,t)}{1-k(r)r^2}dr^2 - a_1^2(r,t)r^2 d\Omega^2$$

- Giant voids look like they are accelerating



Lightcone degeneracy

- Void models can fit SN Ia data, CMB, H_0...

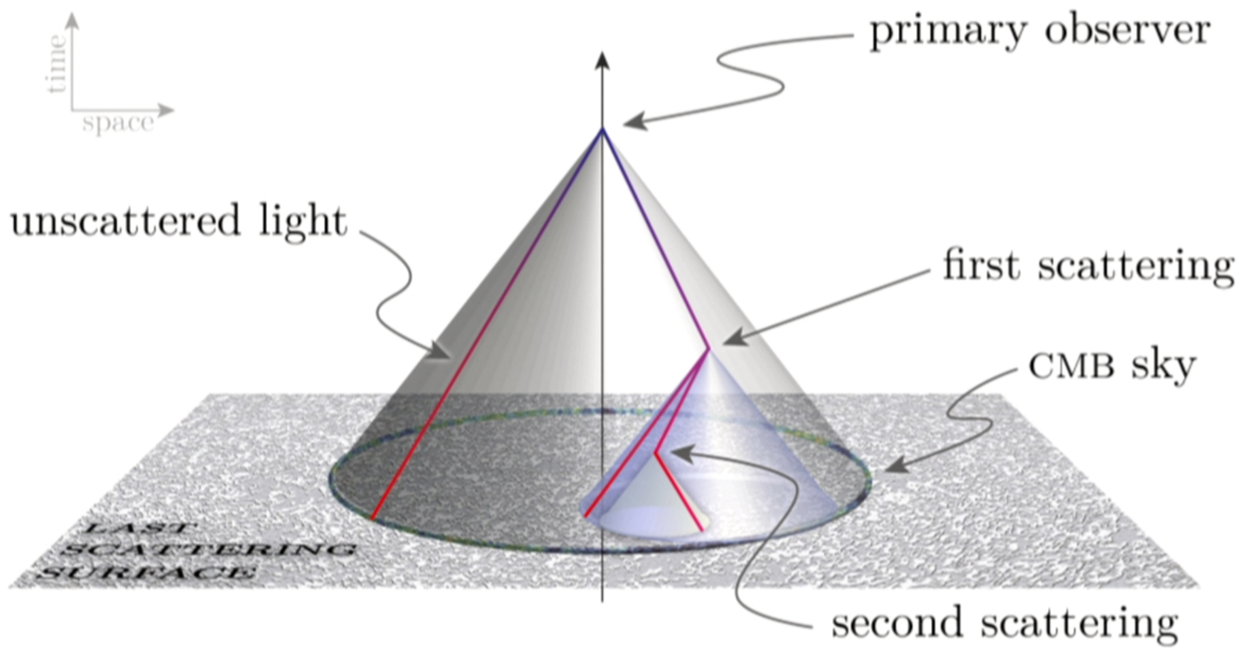


Nadathur & Sarkar (2011)

How can we distinguish models with identical past lightcones?

Scattering processes

- Probe *inside* the past lightcone
- Scattered light allows us to do this



KSZ effect

- Sunyaev-Zel'dovich effect:

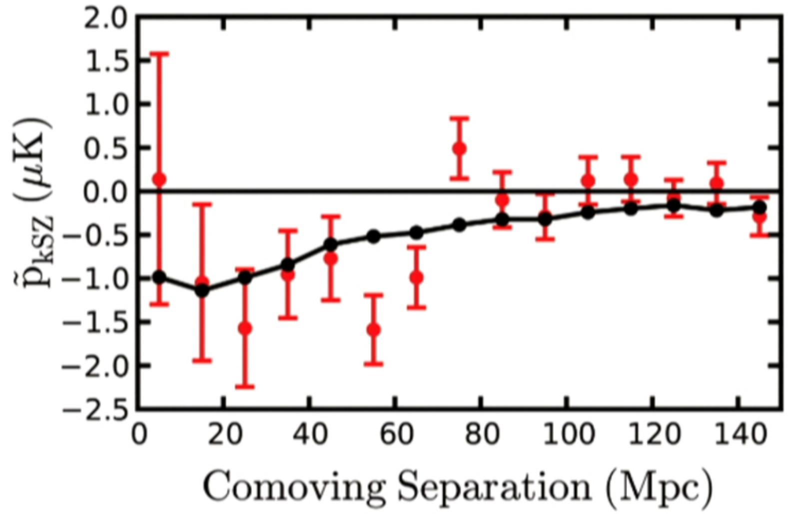
  Ionised gas in galaxy clusters scatters CMB photons

Kinetic SZ effect:

- Can be used to probe peculiar velocities
- Sensitive to *any* dipole
- Probes anisotropy about the scattering cluster

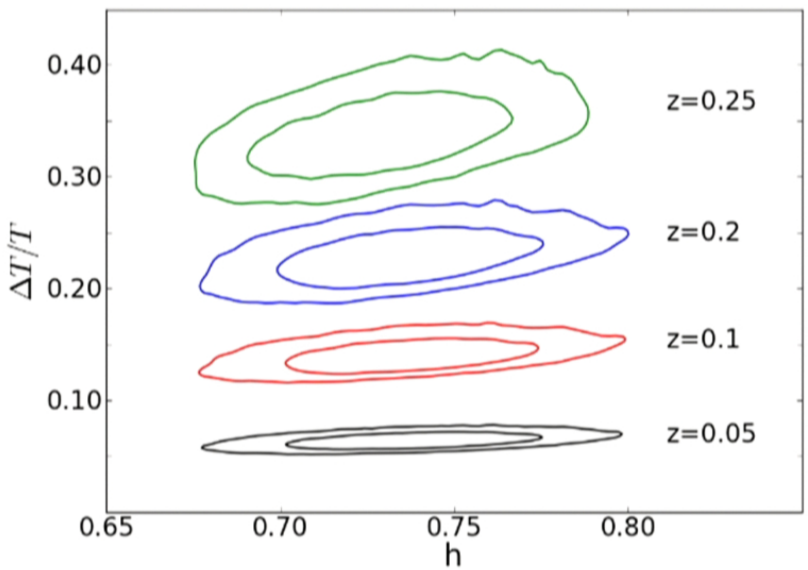
$$\left.\frac{\Delta T}{T}\right|_{KSZ} = -\frac{v_p}{c}\sigma_T \int n_e(l)dl$$

ACT / Hand et al. (2012)



KSZ in voids

- Off-centre observers see highly anisotropic sky
  $\rightarrow$ large dipole
- KSZ effect is huge



Bull, Clifton, Ferreira (2012)

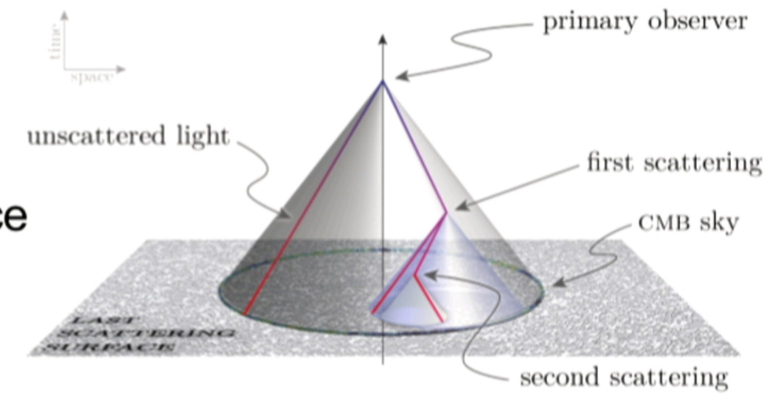
Spectral distortions

- Consider *general* distortion of the CMB spectrum
  - Scattering of anisotropic radiation field gives a superposition of blackbodies of different temperatures
  - Sum of different blackbodies is not blackbody

- **Alternative EGS theorem**
  - Blackbody CMB
  - Photons scattered at least twice

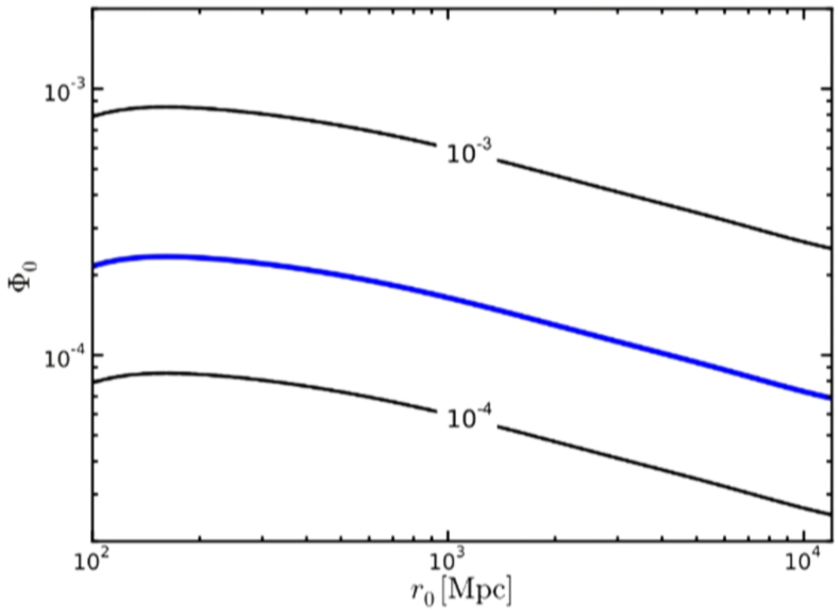
  → FLRW region

  Clifton, Clarkson, Bull (2012)



Local inhomogeneity

- Don't need a *giant* void to cause havoc...
  - Evidence is building that we live in an underdensity
  - Biases determination of cosmological parameters (*consider if H_0 is lower inside the void)*

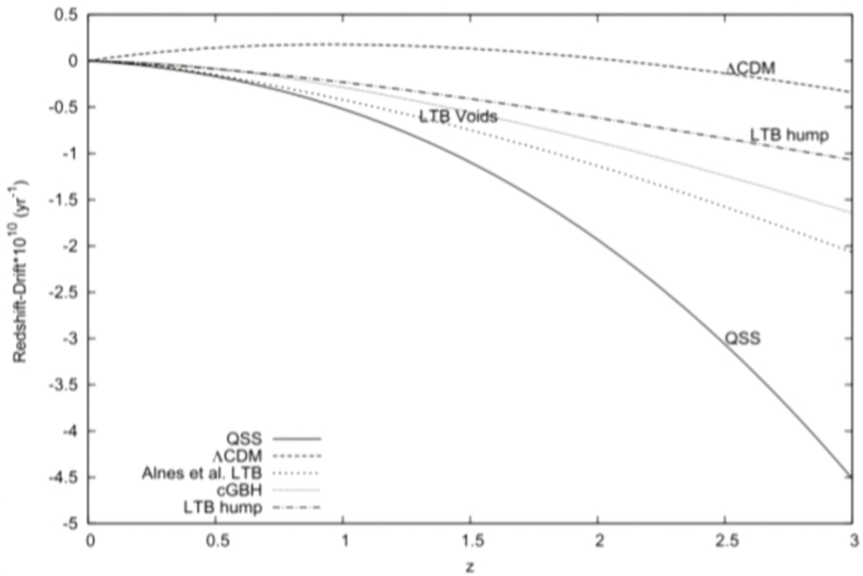


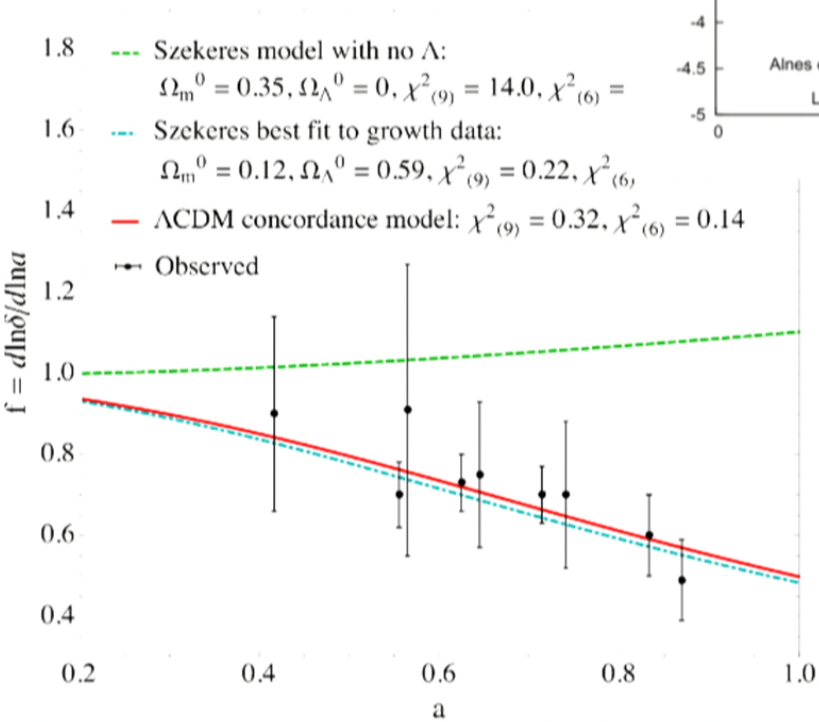
Even a small local inhomogeneity is enough to severely bias curvature

Bull & Kamionkowski (2013)

Redshift drift

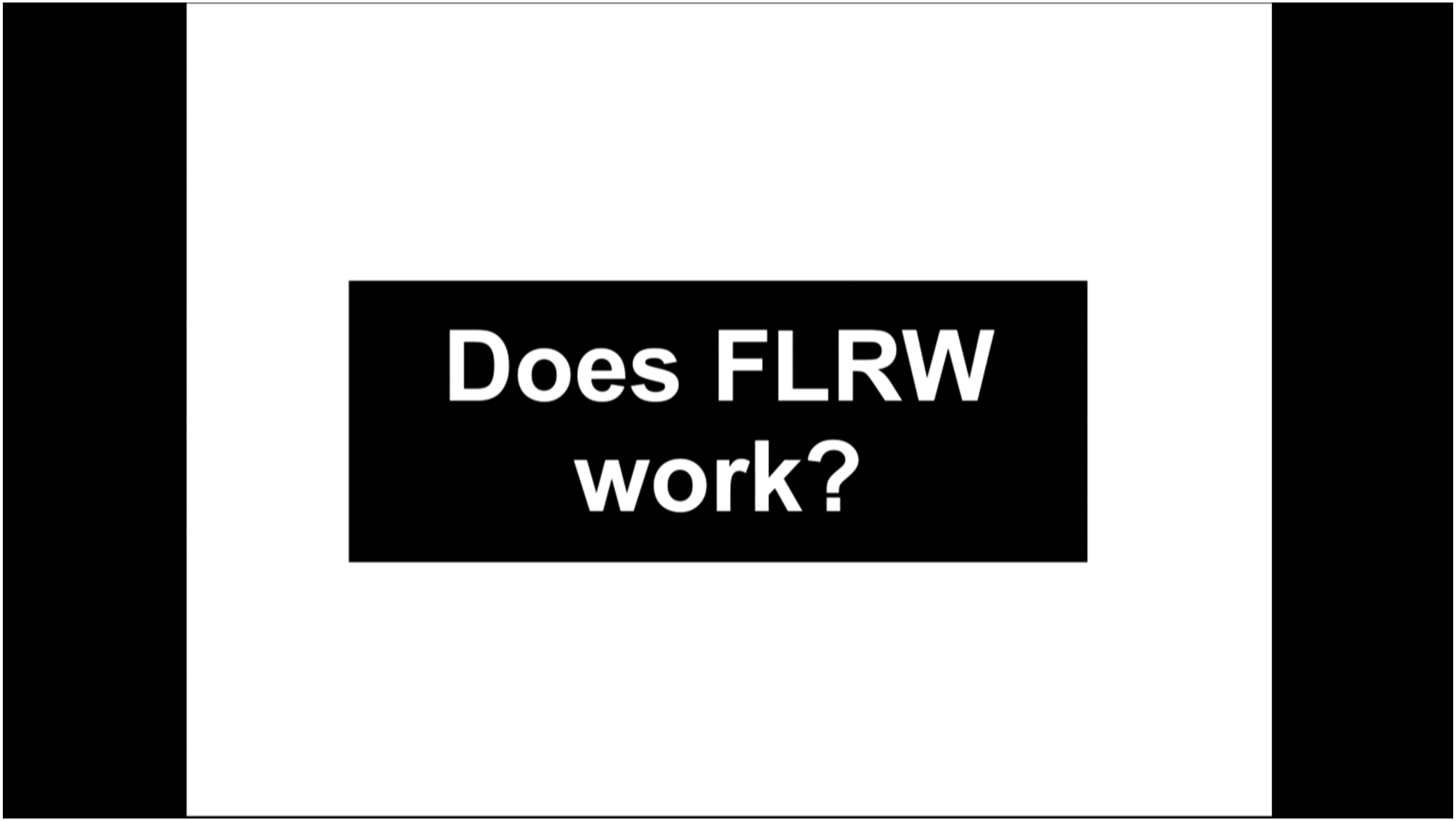
Mishra et al. (2013)





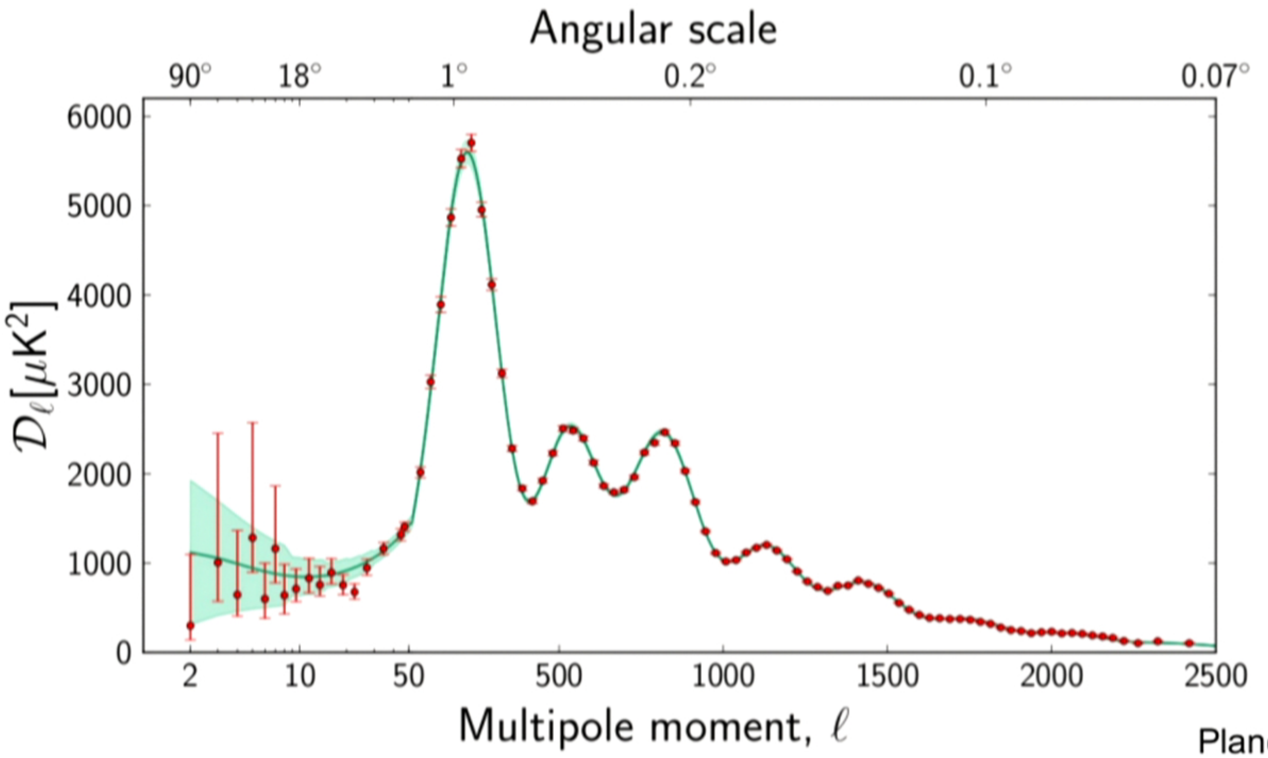
Growth rate

Ishak, Peel, Troxel (2013)


Does FLRW
work?

If the model fits...

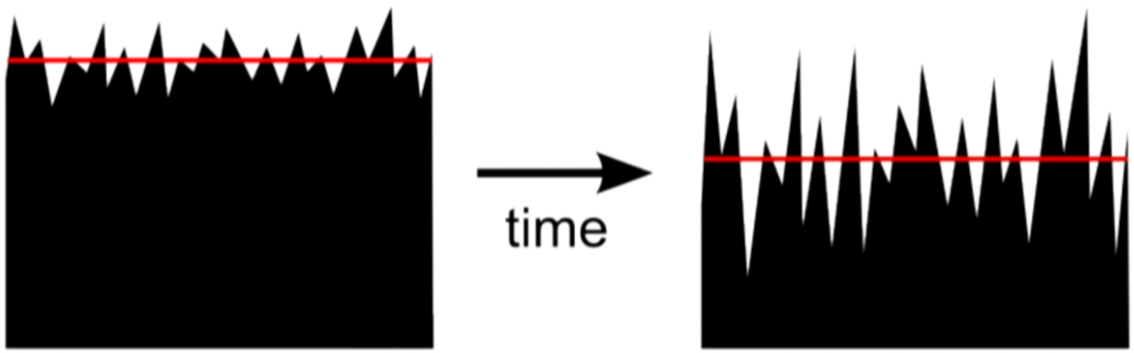
- FLRW models are remarkably successful
- ΛCDM: 6 parameters fits pretty much everything



Planck (2013)

Background = average?

- Want to find a map between real, inhomogeneous spacetime and a **descriptive** homogeneous model



- The averaged spacetime should correspond to a **background** FLRW model

How to average

- How do you average a spacetime?

- Fundamental geometrical quantities are tensors

  $\rightarrow$ how to average a tensor covariantly?

Extra structure needed to define parallel transport

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- How do you average a spacetime?

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  Extra structure needed to define parallel transport

- Only want a spatial average – time evolution stays in

  → foliation dependence?

  Covariant, but choice of foliation is ambiguous

Backreaction

- Averaged metric doesn't correspond to averaged EFEs

$$\begin{aligned} \langle G(g) \rangle &= 8\pi G \, \langle T \rangle \\ &\neq G(\langle g \rangle). \end{aligned}$$

- Introduce correlation tensor to describe mismatch

$$C_{ab} = G_{ab}(\langle g \rangle) - 8\pi G \, \langle T_{ab} \rangle$$

- Correlation tensor **must** appear in averaged spacetime. But is it negligible?

Scalar averaging

- Can average scalar quantities on a spacelike hypersurface

$$\langle S \rangle = V_{\mathcal{D}}^{-1} \int_{\mathcal{D}} S(\vec{x}, t) \sqrt{-h}\ d^3x$$

- Spatial averaging and time evolution don't commute

$$\partial_t \langle S \rangle - \langle \partial_t S \rangle = \langle \Theta S \rangle - \langle \Theta \rangle \langle S \rangle$$

- Correction to Friedmann/Raychaudhuri equations:

$$3H_{\mathcal{D}}^2 \;=\; 8\pi G \langle \rho \rangle + \Lambda - \frac{1}{2}\left(Q_{\mathcal{D}} + \langle {}^{(3)}\mathcal{R} \rangle \right)$$

$$3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} \;=\; -8\pi G \langle \rho \rangle + \Lambda + Q_{\mathcal{D}}$$

Acceleration from backreaction

- Correction is large if (e.g.) variance in expansion rate is large → only when nonlinearities important
- Solves coincidence problem
- Numerous toy models have been shown to have accelerating averages

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Is backreaction important?

YES

- **Averages of LTB models**

  Scalar average of void models can accelerate

  e.g. Rasanen (2004), Moffat (2006)

NO

- **Matched swiss-cheese models**

  LTB regions properly embedded in FLRW background show negligible backreaction

  Mattsson & Mattsson (2011)

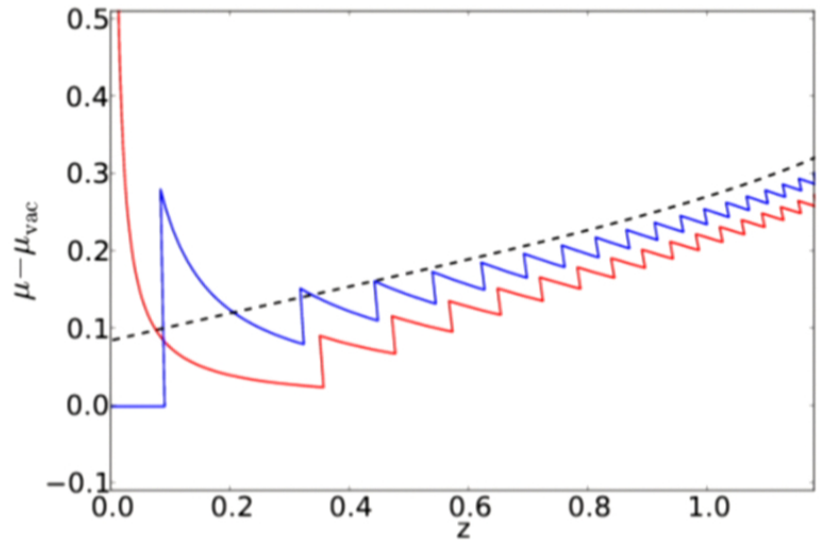
What's the answer?

- The **NO** camp tend to use perturbative analyses or toy models with lots of symmetry
- The **YES** camp depend on unrealistic or unrepresentative models, or unobservables
- Can we find backreaction in a model that's:
  - Non-perturbative (exact solution)?
  - Statistically-homogeneous (meaningful average)?

  And if so, does it matter for observations?

Disjoint FLRW model

- Consider a light ray passing through alternating expanding/collapsing FLRW regions

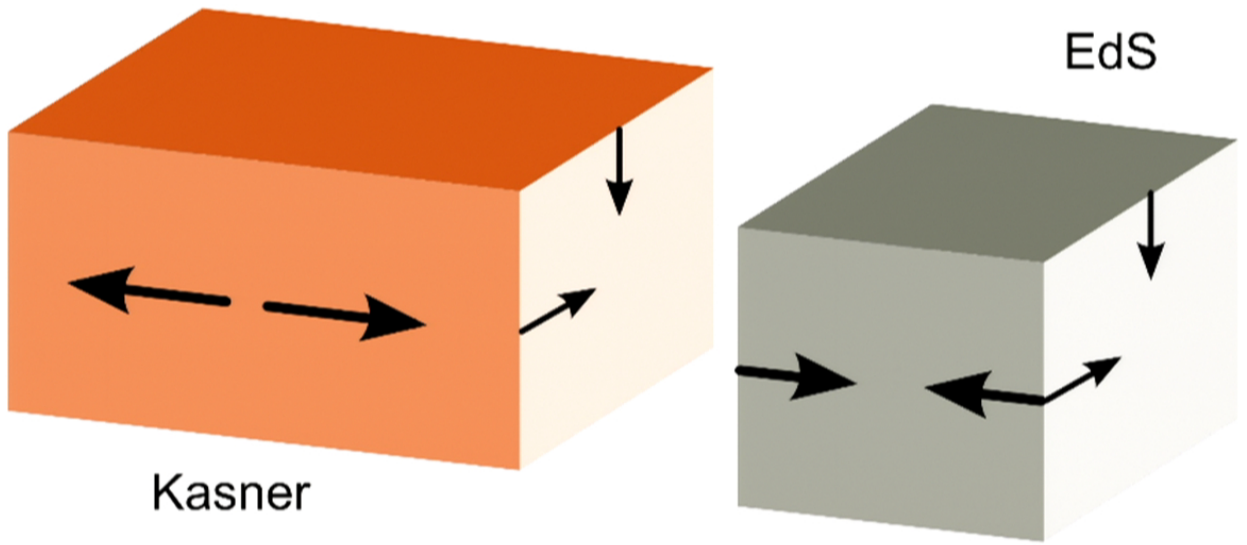


Bull & Clifton (2012)

- Overall **observed** trend looks like acceleration
- Variance in Hubble rate is large too

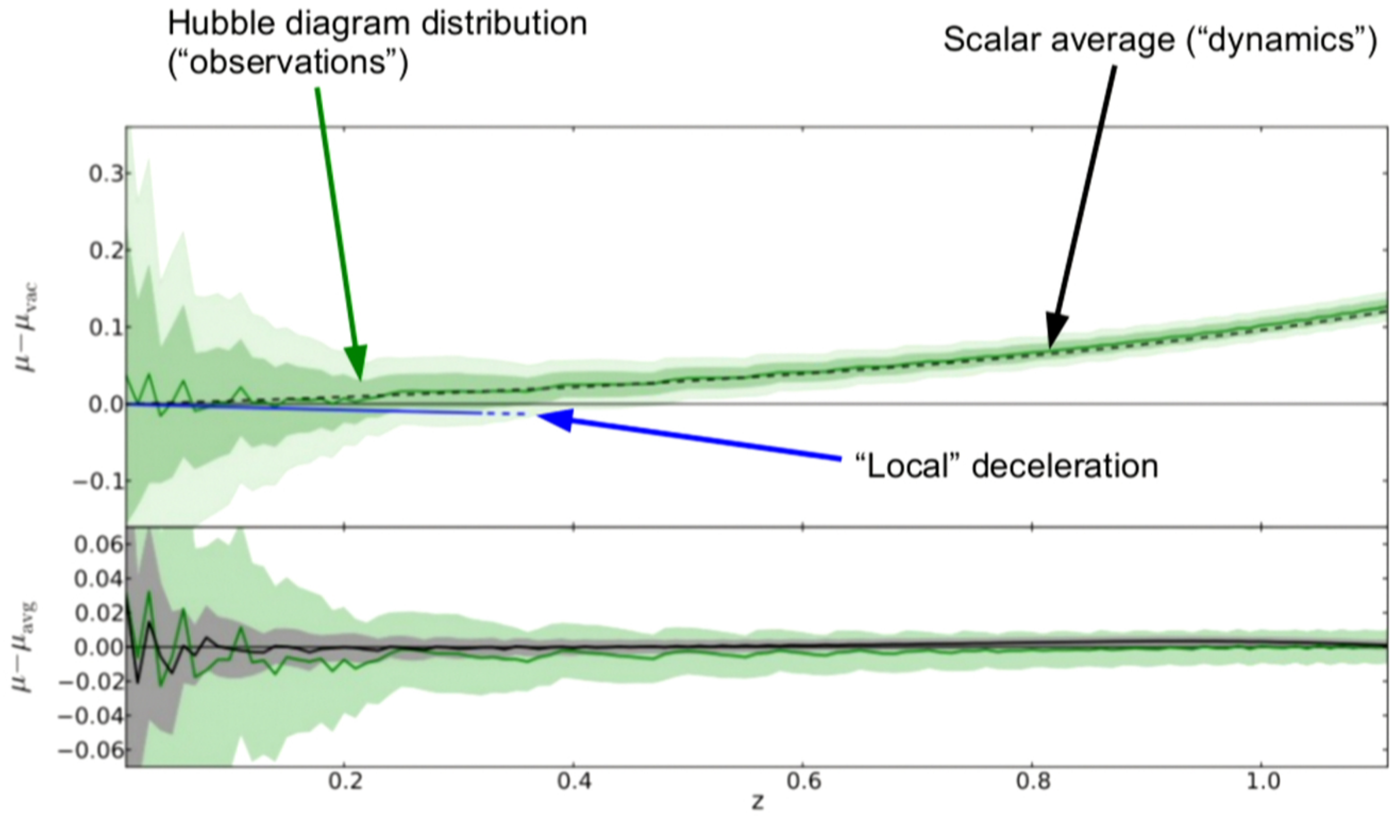
Exact solution

- Construct a similar scenario using matched Kasner and EdS regions
- Forms exact, non-perturbative solution of EFEs



Bull & Clifton (2012)

Observable backreaction



Bull & Clifton (2012)

Observable backreaction

- **Successes**
  - Non-perturbative, statistically-homogeneous, exact solution
  - Backreaction is observable and representative of dynamics
- **Failures**
  - Too simple; can't describe real density distribution
  - Planar; not truly isotropic

What next?

- Difficult to construct more realistic exact solutions

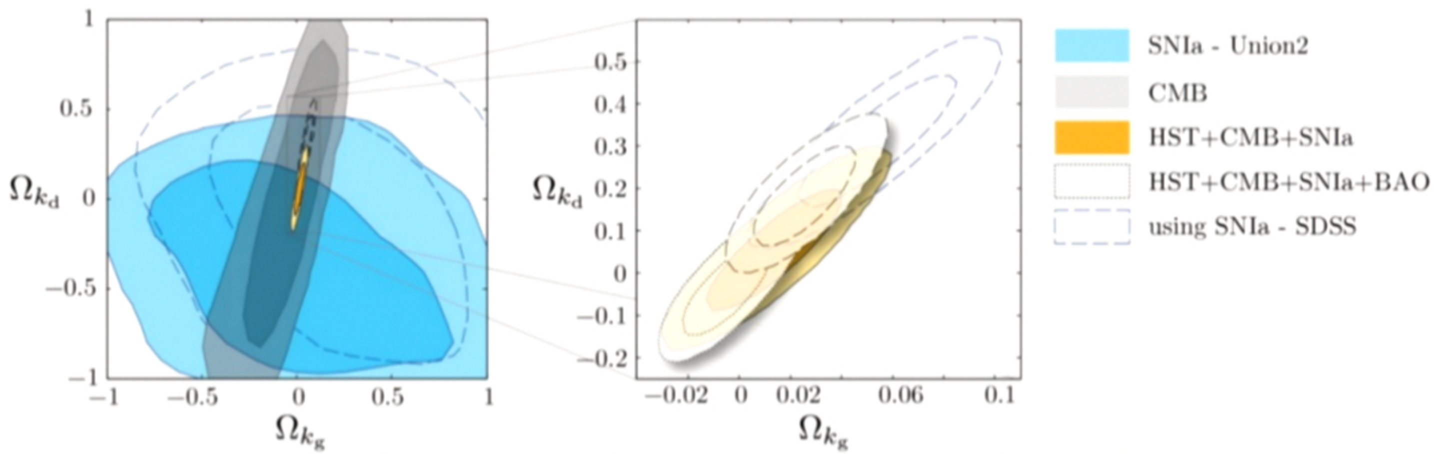
  Full-GR simulations? (No backreaction in Newtonian gravity)

- Higher-order perturbation theory?

  Tedious, and still not definitive

- Phenomenology of correlation tensor?

  Curvature mismatch (Clarkson et al. 2012)



Summary

- We currently **assume** homogeneity
  (but we **can** test it)

- Observations **off the lightcone** are powerful

- The backreaction issue has still **not been settled**
  (but it's probably not dark energy)