kSZ and Voids

What does the kSZ effect really tell us about homogeneity on large scales?

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Overview

1) Giant voids and observations

2) The kSZ effect as a killer observable?

3) Bang time: inhomogeneous early universe

4) Observables and the bang time

5) Are voids dead?

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Lemaître-Tolman-Bondi

- Spherically-symmetric, inhomogeneous
- Two arbitrary radial functions

$$\left(\frac{\dot{a}_1}{a_1}\right)^2 = \frac{8\pi G}{3}\frac{m(r)}{a_1^3} - \frac{k(r)}{a_1^2} + \Lambda$$

Integrate to get third radial function, $t_B(r)$

Supernovae

LTB models allow temporal *and spatial* variations in expansion rate

Almost any distance-redshift relation can be constructed

Fit depends on properties of spatial curvature profile (simple Gaussian not too bad)

(Clifton, Ferreira, Land 2008)

CMB + H_0

Need to assume:

- Asymptotic FLRW region (at large-r)
- Physical properties at last scattering surface (photon-baryon ratio etc.)
- Form of initial power spectrum

Difficult to treat ISW (need perturbation theory)

CMB + H_0

Summarise properties of small-angle CMB with $d_{A,LS}$, H_{LS}, z_{LS}

$d_A(z_{LS})$: Need positive spatial curvature in asymptotic region

$H(z_{LS})$: Need low local Hubble rate

$H_0 \sim 50$ km/s/Mpc

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Isotropy?

Global isotropy implies homogeneity

(Ehlers, Geren, Sachs 1968)

Almost-isotropy implies almost-homogeneity

(Stoeger, Maartens, Ellis 1994)

Strongly anisotropic CMB means non-FLRW

Kinematic SZ

Bulk motion of hot electrons (cluster "peculiar velocity") with respect to CMB

Scattering electrons see dipole in incident CMB radiation – spectral distortion

$$\left(\frac{\Delta T}{T}\right)_{dipole} = \beta$$

Measuring kSZ

Confusion with primary anisotropies and sub-mm galaxies; Big error bars

Only upper-limits available so far

(Benson et. al. 2003) [SuZIE II]

(Hall et. al. 2009) [SPT]

(Das et. al. 2010) [ACT]

(Dunkley et. al. 2010) [ACT]

Off-Centre Observers

Away from centre of symmetry, redshift to last scattering depends on direction

Observers see strongly anisotropic sky

Dipole dominates – large kSZ effect

(Goodman 1995)

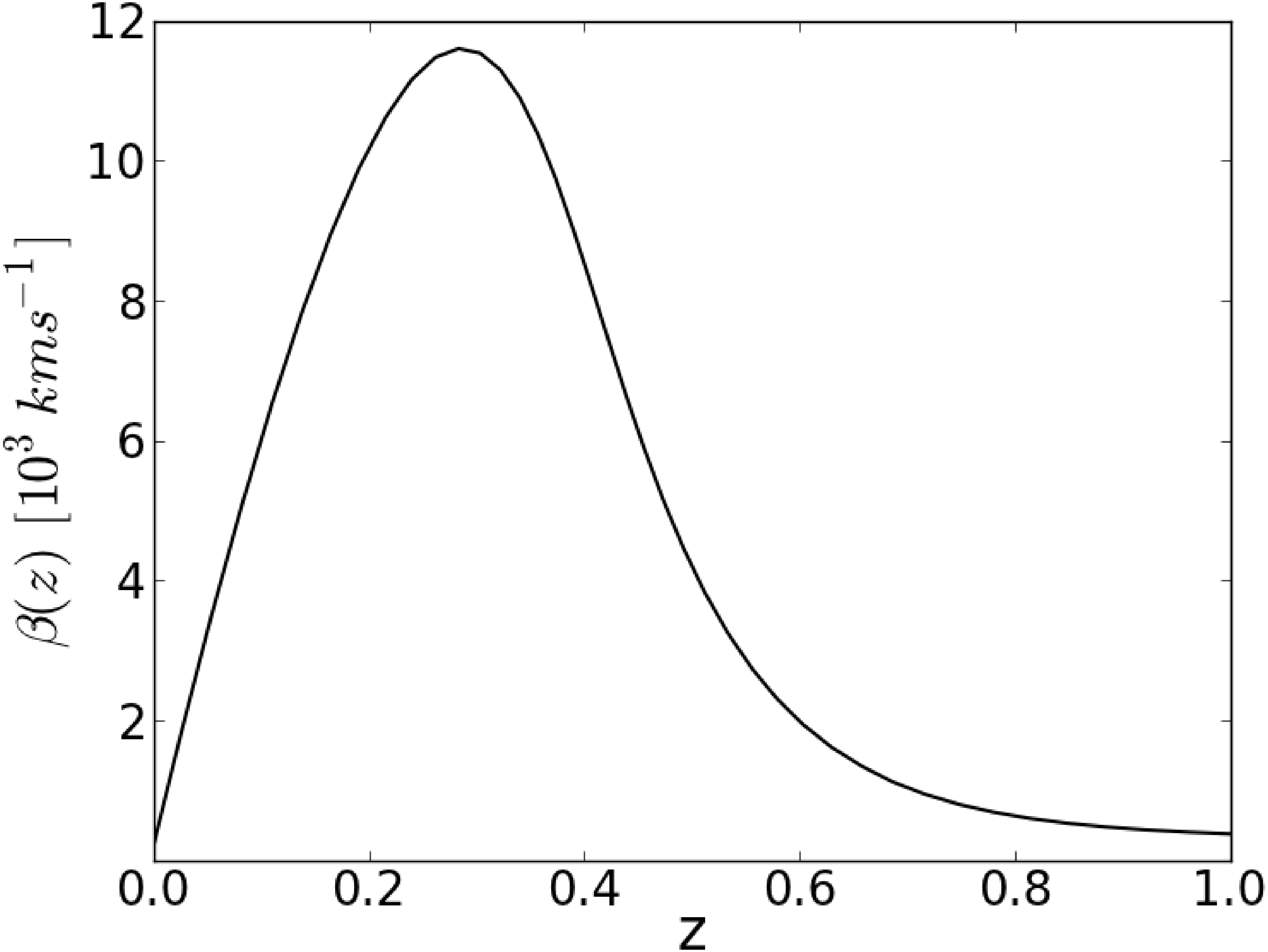
(García-Bellido, Haugbølle 2008)

Calculating kSZ in Voids

Approximate dipole using Δz_{LS} between ingoing/outgoing *radial* null geodesics

$$\beta = \frac{\Delta T}{T} = \frac{z_{in} - z_{out}}{2 + z_{in} + z_{out}}$$

$$1 + z = exp\left\{\int H_r(r(t), t)dt\right\}$$



12
10
8
6
4
2
0.0
0.2
0.4
0.6
0.8
1.0
z
$\beta(z)\ [10^3\ kms^{-1}]$

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Extra Freedom

Bang time typically set to constant, but this is an assumption

Makes Universe inhomogeneous at early times (CMB? Inflation?)

Need varying bang time to invert observables and fully specify LTB model

(Mustapha, Hellaby, Ellis 1997)

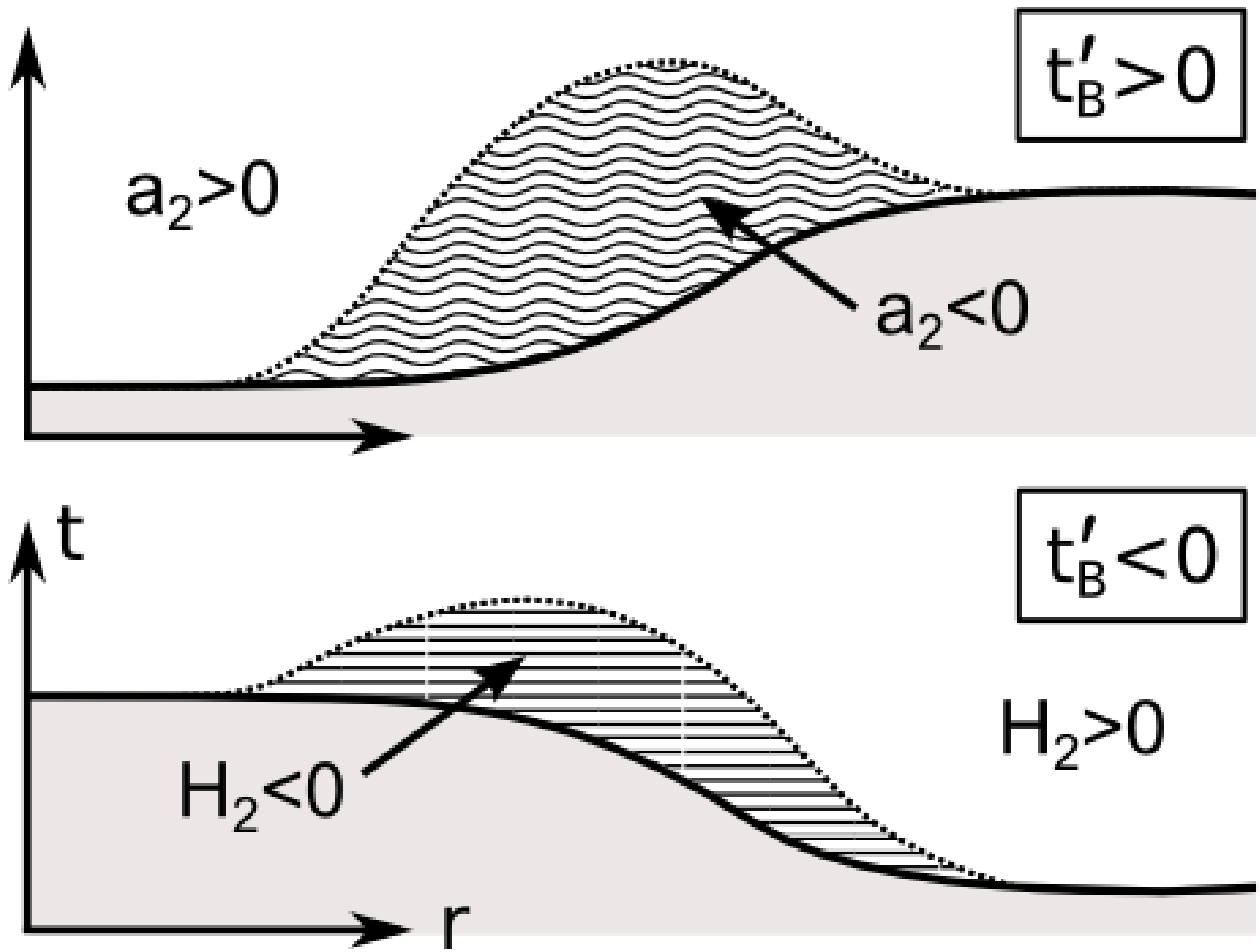
Decaying Modes

Bang time like a decaying mode (Silk 1977). Conflicts with CMB observations?

Choose profile such that $\partial_r t_B(r) \to 0$ near our surface of last scattering

Equivalent to making model asymptotically FLRW at large radii

Get shell crossings or negative Hubble rate when $t \to t_B(r)$ *(Hellaby, Lake 1984)*



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Low-H_0 Problem Resolved

MCMC study, simple parameterised profiles

Fit SN + CMB + H_0 very well

Best-fit H_0: 73.6 km/s/Mpc

$$\Delta\chi^2|_{\Lambda CDM} = +4.5$$

Bang time: 1 Gyr older in centre, 8 Gpc wide

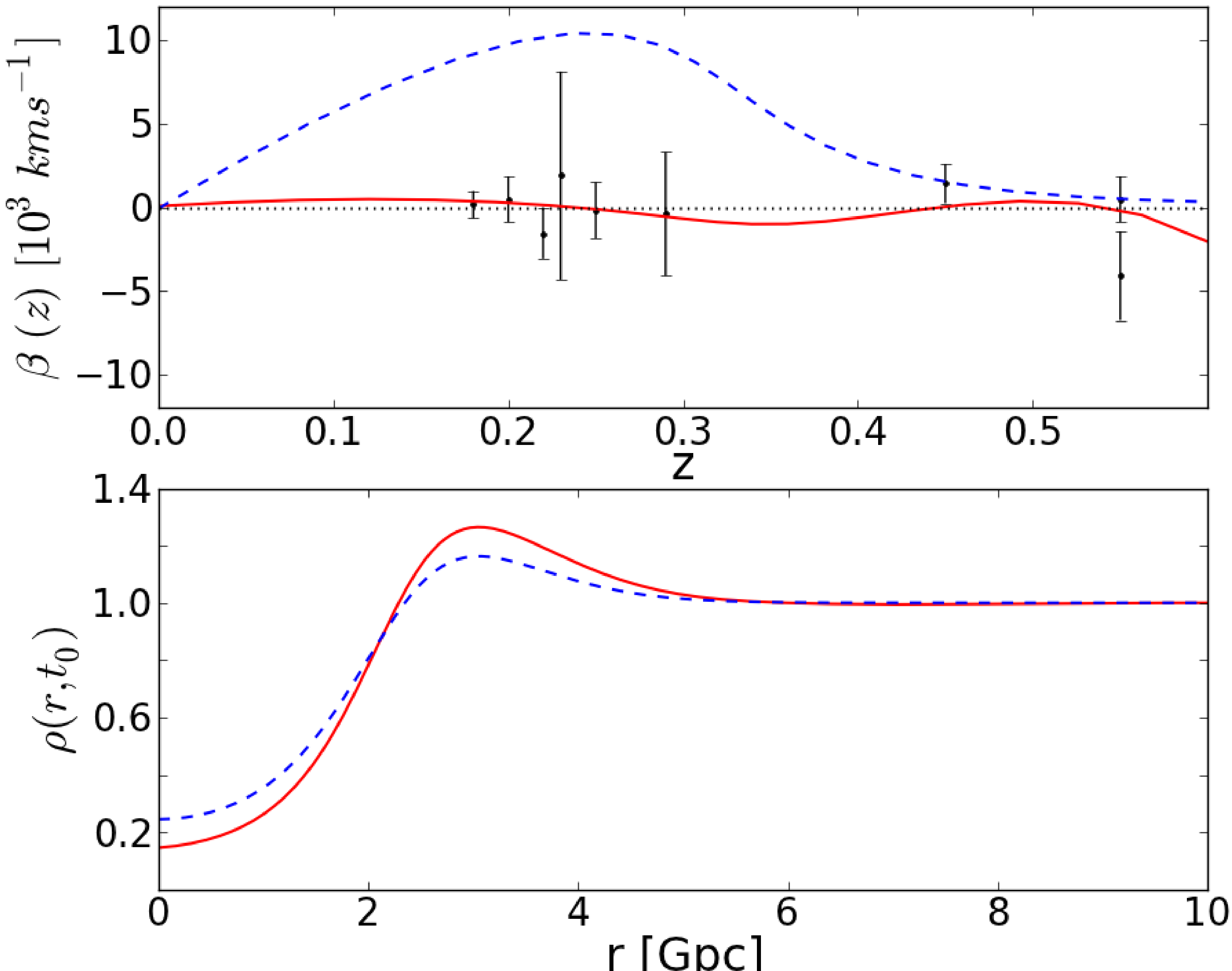
(Shell crossings at early times!)

Lower kSZ Effect

Assume surface of last scattering is constant density hypersurface

Can choose bang time to cancel-out kSZ

Needs more complicated profile than Gaussian



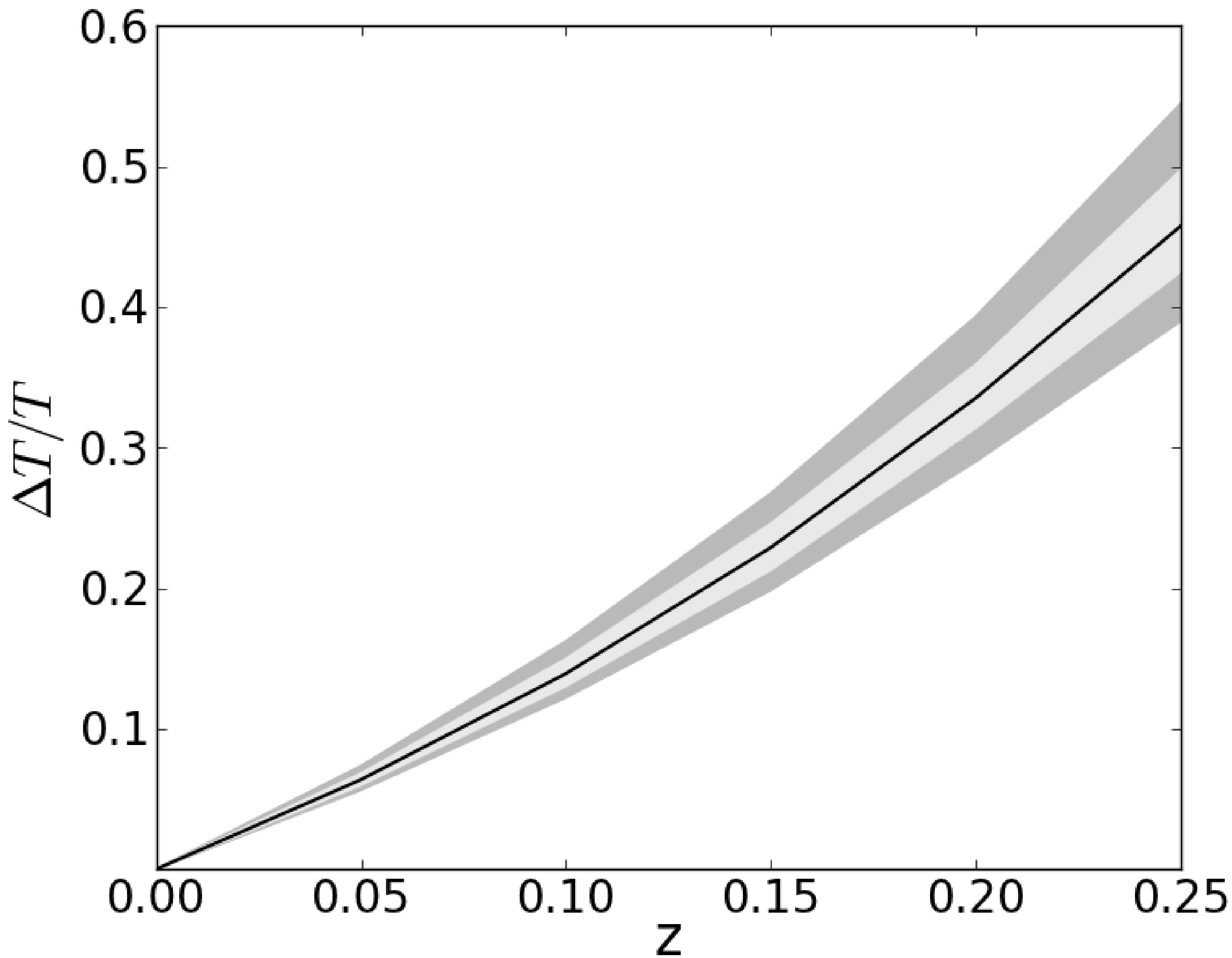
$\beta\ (z)\ [10^3\ km s^{-1}]$
10
5
0
−5
−10
0.0
0.1
0.2
0.3
0.4
0.5
z
1.4
1.0
0.6
0.2
$\rho(r, t_0)$
0
2
4
6
8
10
r [Gpc]

SN + H_0 + CMB + kSZ?

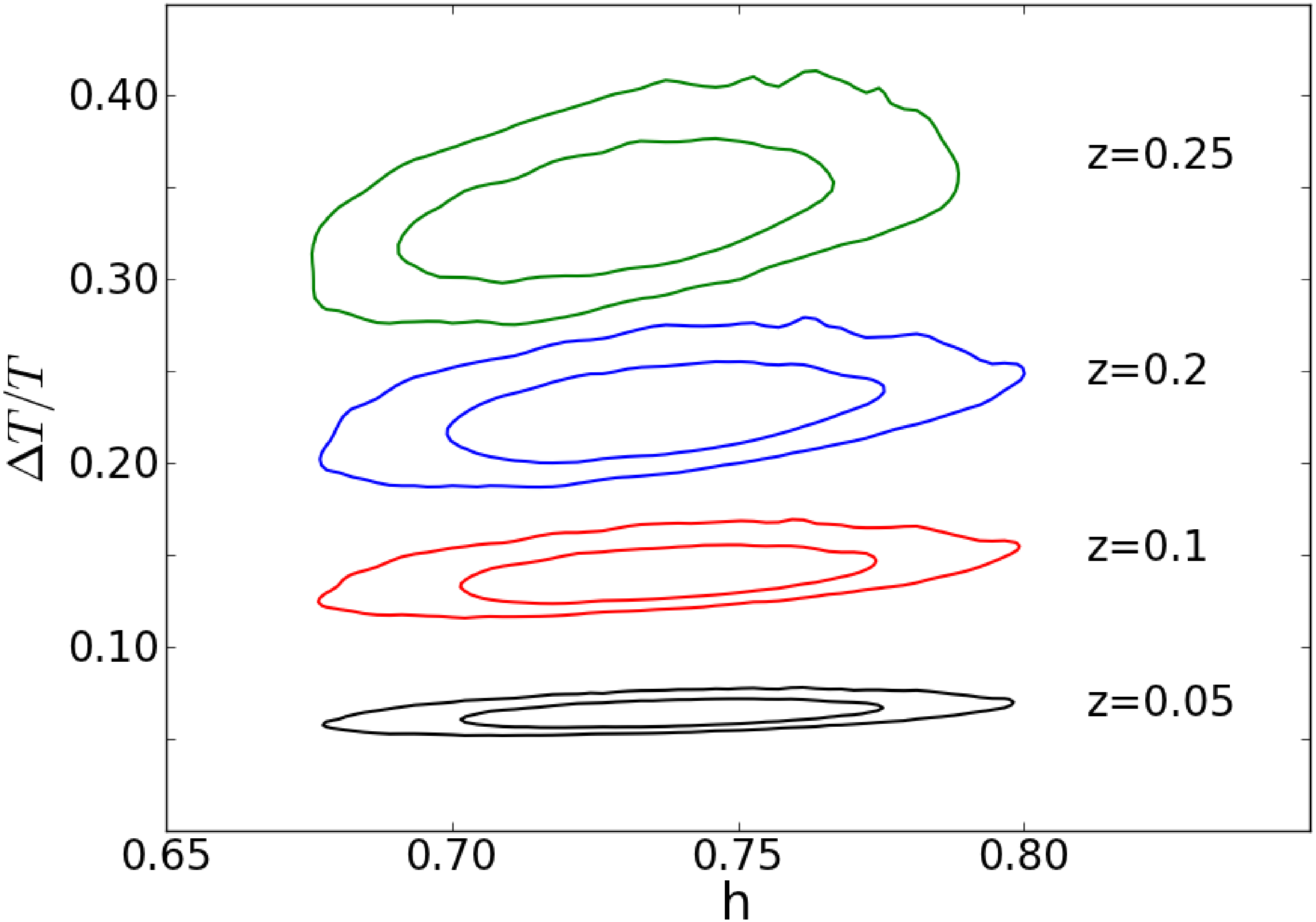
Calculate kSZ for models which fit the other observables

Always get an enormous dipole!

Because geodesics pass near shell crossing regions



High H_0 means high kSZ?



Profile Dependence?

Result might be an artefact of profile choice

Looked at “hump” model which fits ΛCDM $H(z)$ and $d_L(z)$

(Célérier, Bolejko, Krasiński 2010)

No shell crossings at early times, since:

$$\partial_r t_B(r) < 0$$

Profile Dependence?

Negative Hubble rate near inhomogeneous region.

$$1 + z = exp\left\{\int H_r(r(t), t)dt\right\}$$

$$\left(\frac{\Delta T}{T}\right)_{dipole} = \frac{z_{in} - z_{out}}{2 + z_{in} + z_{out}}$$

Also get very large dipole (in general)

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Lots of Caveats

Relies on approximate treatment of radiation at early times. Multi-fluid?

(Clarkson, Regis 2010)

(Yoo, Nakao, Sasaki 2010)

Consider more generally inhomogeneous space-times. Perturbations?

(Zibin, 2008)

(Clarkson, Clifton, February 2009)

Initial power spectrum?

(Nadathur, Sarkar 2010)

Conclusions

KSZ on its own not enough – need other observables

“General” LTB models strongly constrained

Not good enough to *prove* homogeneity

See arXiv:1108.2222

Statistical kSZ

$$\left.\frac{\Delta T(\hat{n})}{T}\right|_{kSZ} = \int_0^{z_*} \beta(z)\delta_e(\hat{n}, z)\frac{d\tau}{dz}dz$$

Large effect, but sensitive to matter power spectrum

(Zhang, Stebbins 2010)

(Moss, Zibin 2011)

Bang time: dipole should be big *somewhere*

But dipole approx. breaks down at large radii