Viable Voids?

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Overview

1) Dark energy, giant voids and homogeneity

2) Testing voids with kSZ

3) Inhomogeneous early universe?

4) Peculiar velocities

Dark energy problem

Expansion of universe seems to be accelerating

Dark energy? Cosmological constant? Modified gravity?

Maybe FRW metric isn't the right choice?

Homogeneity

Global isotropy implies homogeneity

(Ehlers, Geren, Sachs 1968)

Almost-isotropy implies almost-homogeneity

(Stoeger, Maartens, Ellis 1994)

Universe FRW if we use Copernican principle

Lemaitre-Tolman-Bondi

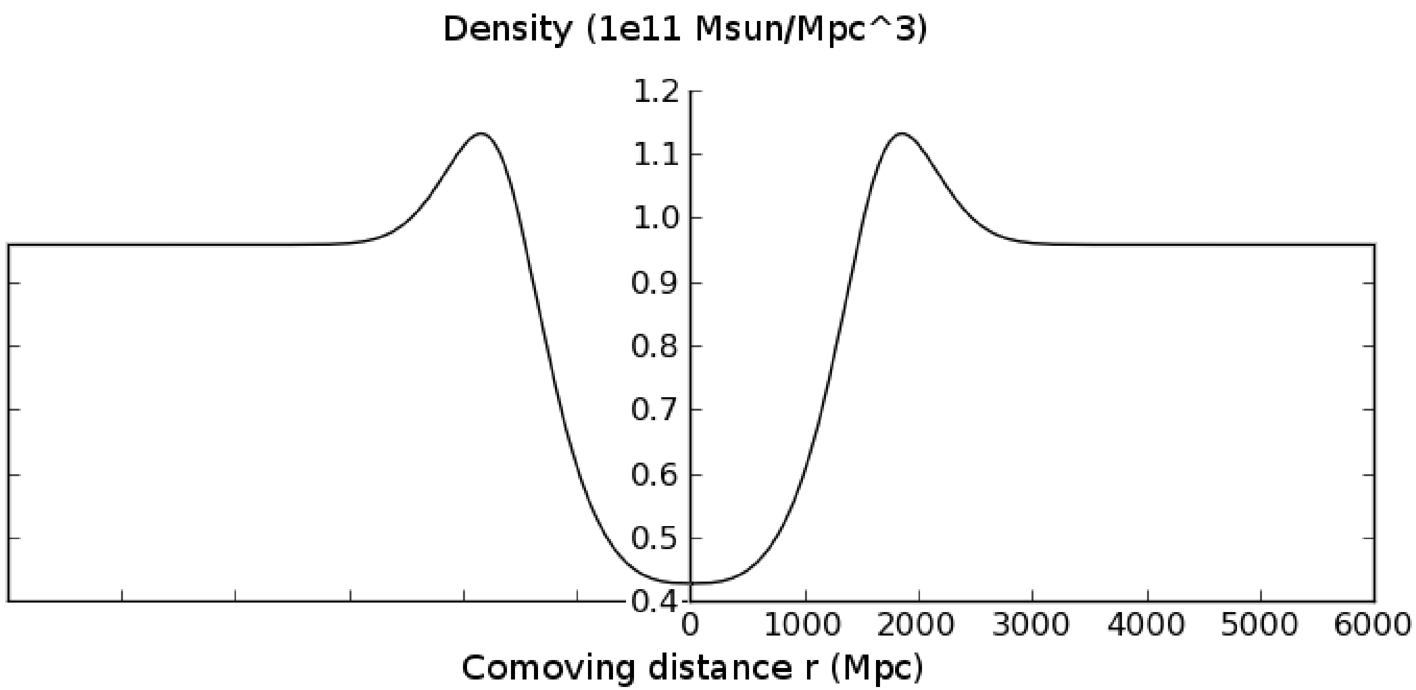
- Spherically-symmetric, inhomogeneous
- Exact solution to Einstein's equations
- Two arbitrary radial functions

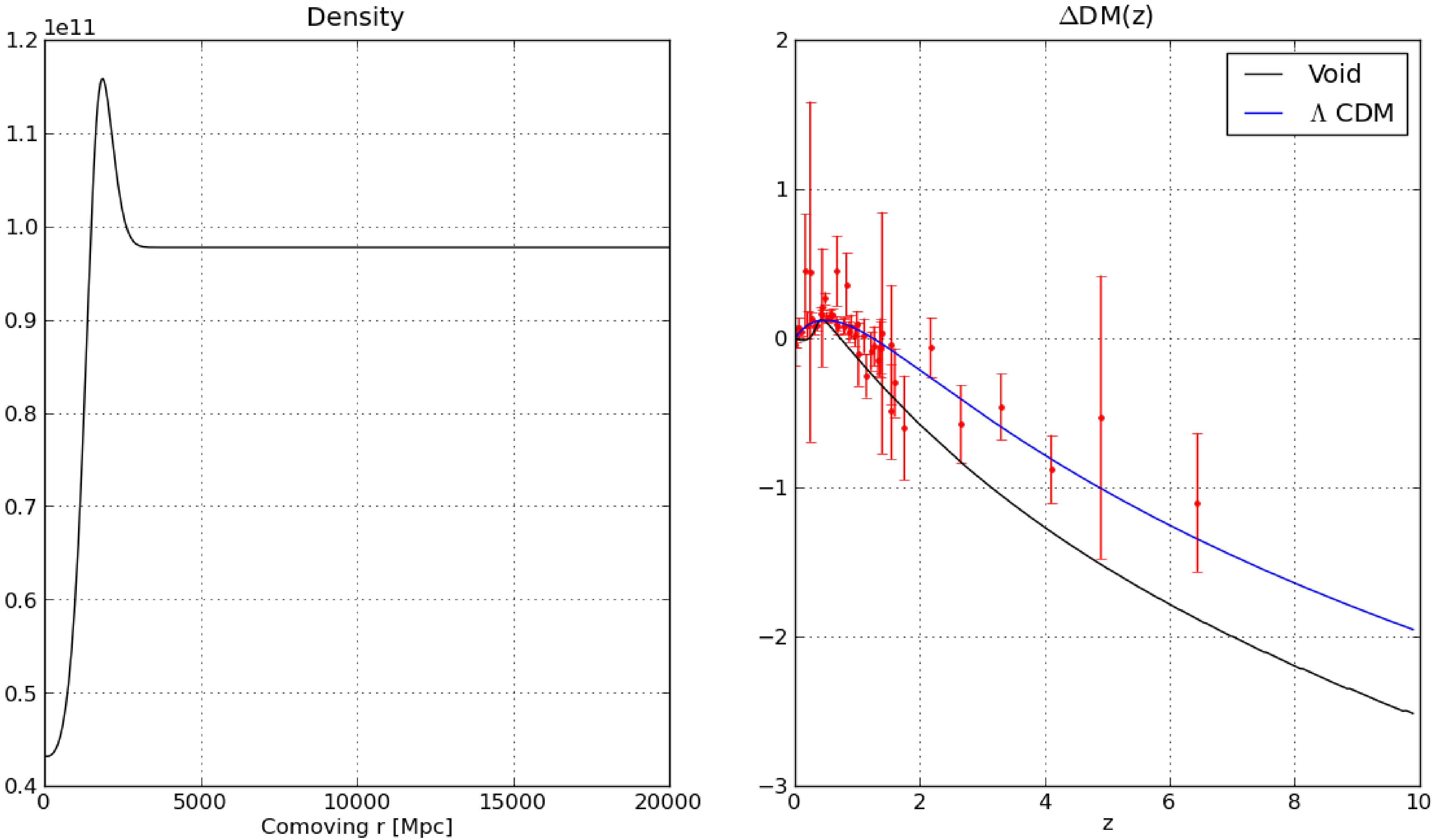
$$ds^2 = dt^2 - \frac{a_2^2(r,t)}{1-k(r)r^2}dr^2 - a_1^2(r,t)r^2 d\Omega^2$$

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

Giant void models

- Temporal *and* radial variations in expansion rate
- Recover “accelerating expansion” result
- Lose large-scale homogeneity





Density
1e11
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
5000
10000
15000
20000
Comoving r [Mpc]
ΔDM(z)
2
1
0
−1
−2
−3
0
2
4
6
8
10
z
Void
Λ CDM

Testing voids

Two arbitrary radial functions – lots of freedom

Can fit two sets of observations, e.g. luminosity, number counts, stellar ages

(Mustapha, Hellaby, Ellis 1997)

(Bolejko, Hellaby, Alfedeel 2011)

Testing voids

Other data difficult to interpret / have large errors / assume a lot / are unconstraining

BAO, H_0, BBN, CMB, Compton y-distortion

(Garcia-Bellido and Haugbolle 2008)

(Moss, Zibin, Scott 2010)

(Biswas, Notari, Valkenburg 2010)

Sunyaev-Zel'dovich effect

Hot electrons Compton-upscatter CMB, get redshift-independent temperature change

(Sunyaev and Zel'dovich 1970, 1972)

(Rephaeli 1995)

$$\frac{\Delta T_t}{T_0} = y\left[\frac{x(e^x+1)}{e^x-1} - 4\right]$$

$$y = \int \left(\frac{kT_e}{m_e c^2}\right) n_e \sigma_T dl$$

Kinematic SZ

Bulk motion of electrons (cluster peculiar velocity)

Scattering electrons see dipole in incident CMB radiation

$$\frac{\Delta T_k}{T_0} = -\left(\frac{v_p}{c}\right)\tau$$

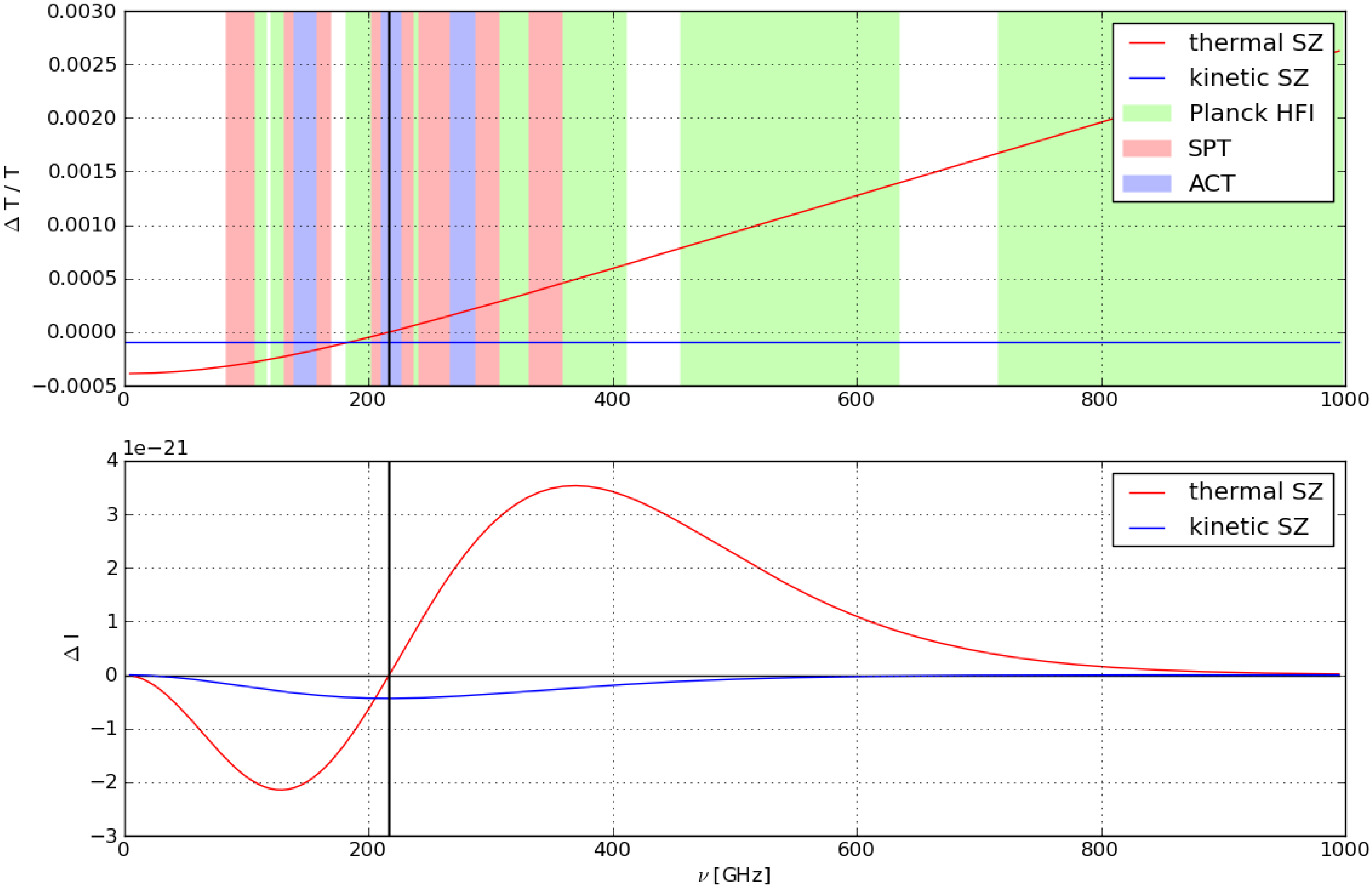
Measuring kSZ

Null at 217 GHz in tSZ corresponds to maximum in kSZ

$$\frac{\Delta T_t}{T_0} = y\left[\frac{x(e^x+1)}{e^x-1} - 4\right]$$

Dependence on cluster properties (T_e, τ)

$$y = \int \left(\frac{kT_e}{m_e c^2}\right) n_e \sigma_T dl$$



v_p = 1000 km/s T_e = 10 keV τ = 0.01

Measuring kSZ

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

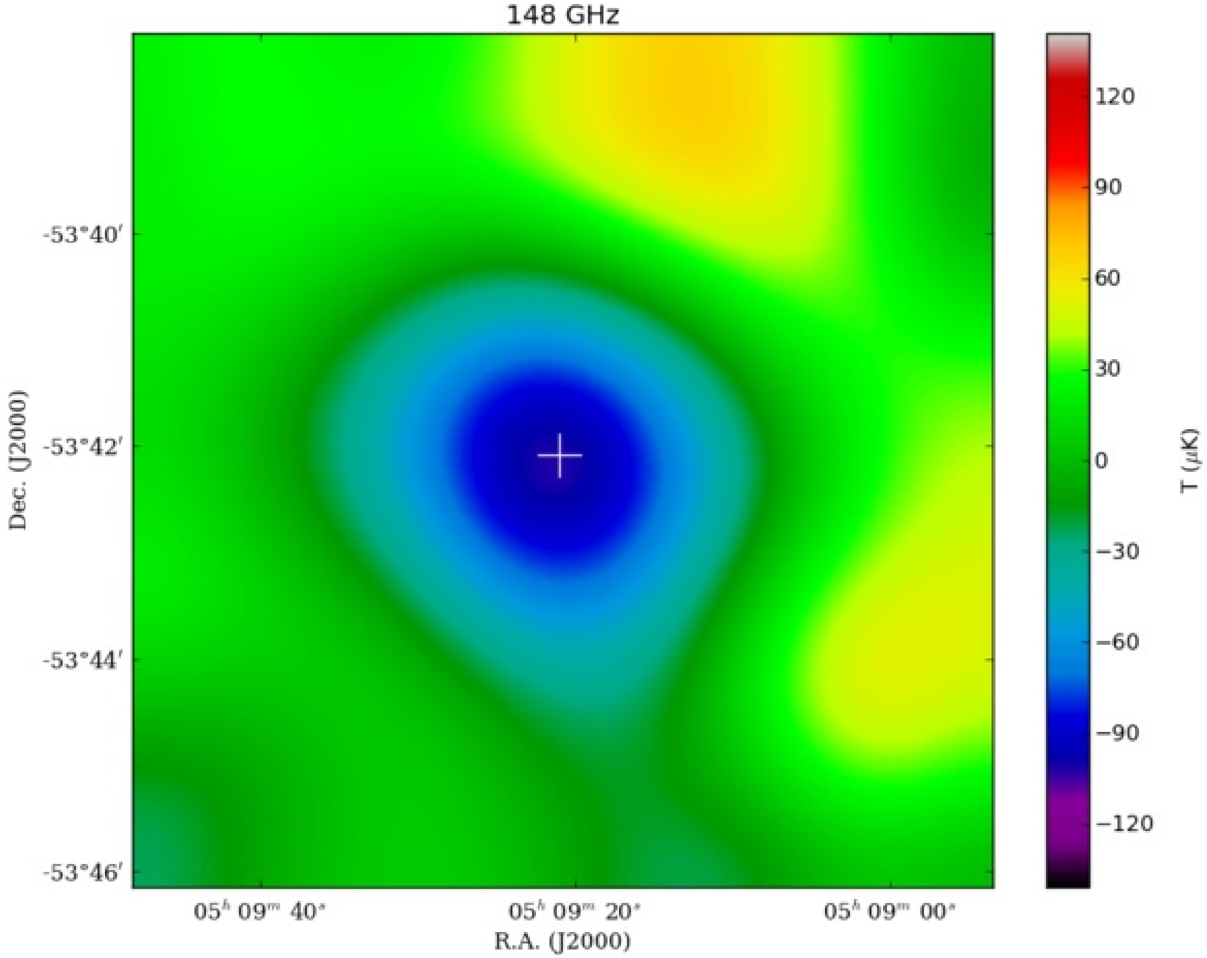
Only upper-limits available so far

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

(Hall et. al. 2009 arXiv:0912.4315) [SPT]

(Das et. al. 2010 arXiv:1009.0847) [ACT]

(Dunkley et. al. 2010 arXiv:1009.0866) [ACT]



ACT cluster CL J0509-5341
(from http://lambda.gsfc.nasa.gov)

kSZ in voids

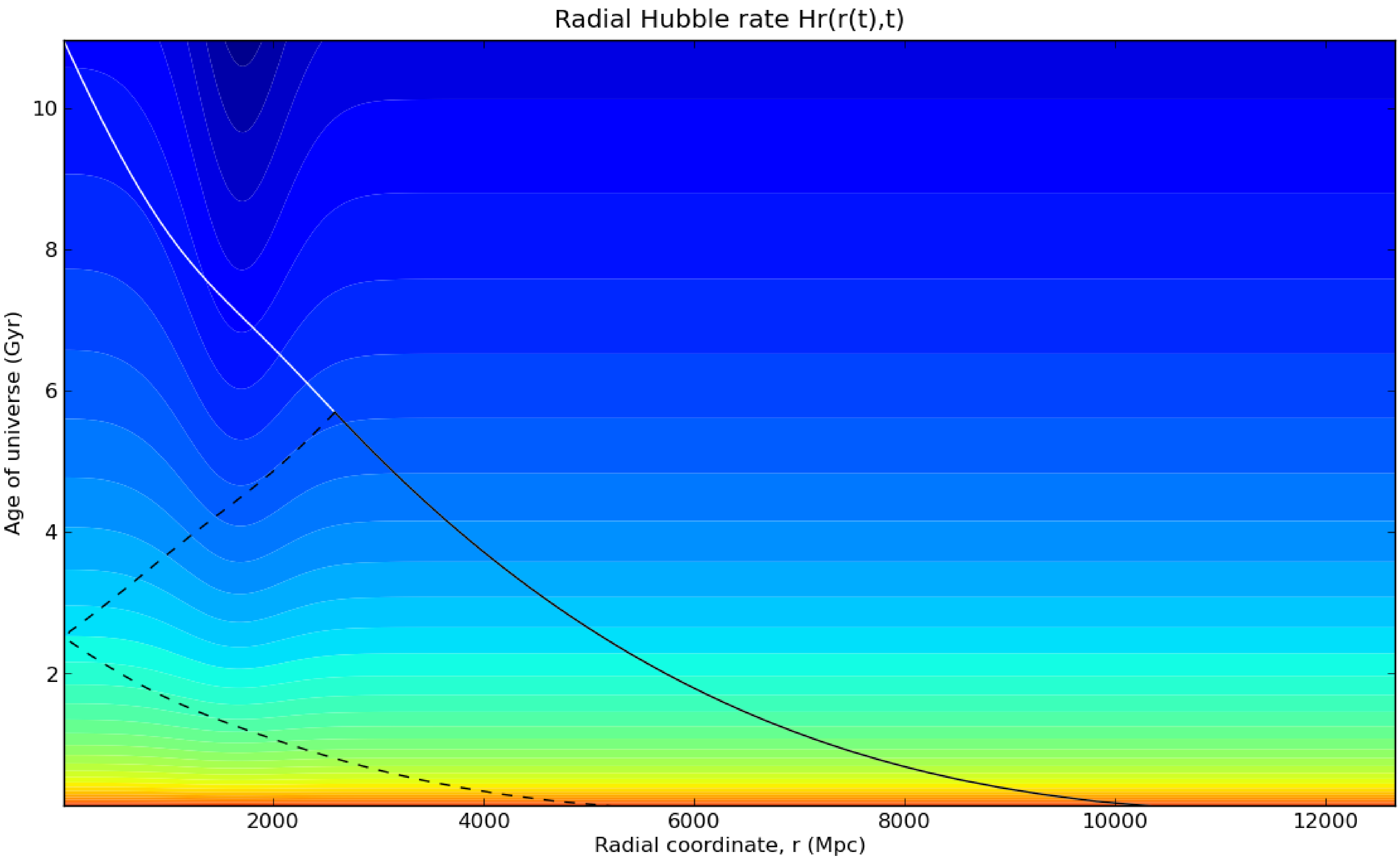
Off-centre observers see *void-induced* dipole in CMB

Due to different expansion rates along ingoing/outgoing null geodesics

$$\left(\frac{\Delta T}{T}\right)_{dipole} = \tau\left(\frac{v_p}{c}\right)$$

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

kSZ probes inside our lightcone



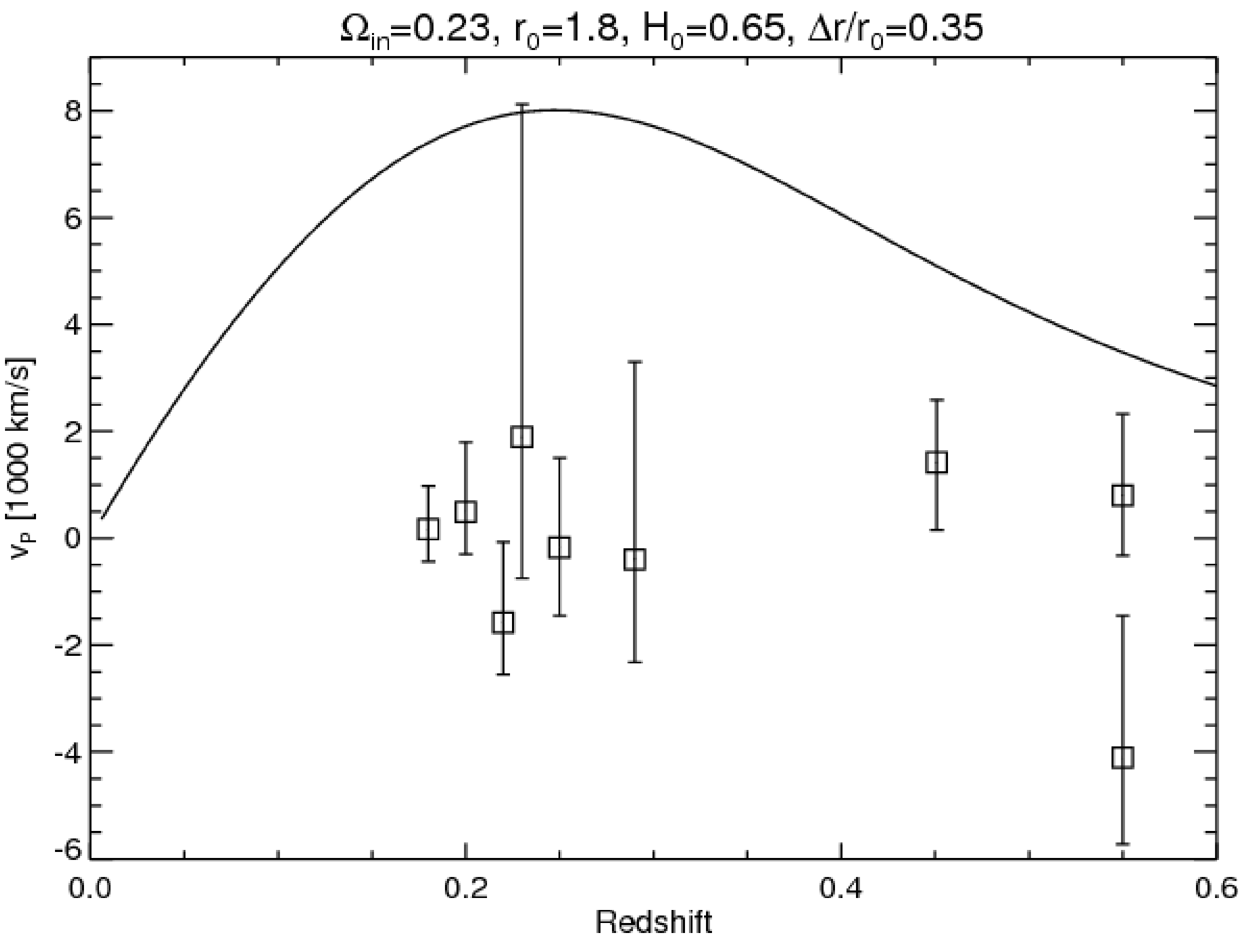
Voids ruled-out?

Voids matching SNe data would give generically-large kSZ signal

(Garcia-Bellido and Haugbolle 2008)

ACT and SPT kSZ power spectrum measurements already rule out giant voids

(Zhang and Stebbins 2010)



Taken from Garcia-Bellido and Haugbolle 2008

Wriggle room

- Single parameterised model is used
- Only use one functional degree of freedom and fix the other to be constant
- Assumed homogeneous at early times

Inhomogeneous LSS

$$T_{LSS} = T(r) \qquad \eta_{LSS} = \eta(r)$$

(Yoo, Nakao, Sasaki 2010)

Two-fluid solutions

(Regis and Clarkson 2010)

Equivalent to isocurvature perturbations

Bang time

Big Bang hypersurface is an arbitrary radial function in LTB

Introduces inhomogeneous physics in the early universe

Decaying modes (Silk 1977)

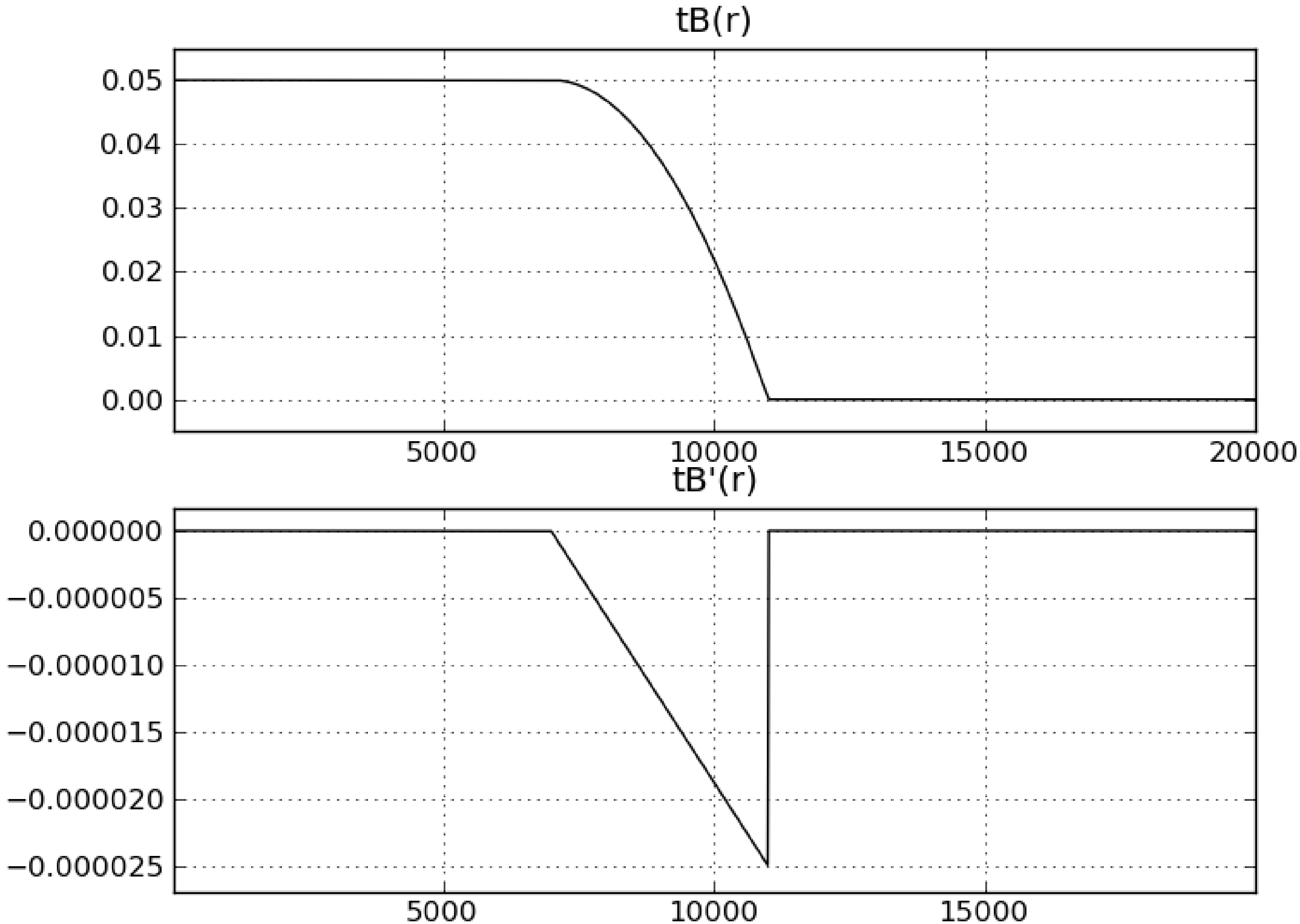
$t_B(r)$ near our LSS

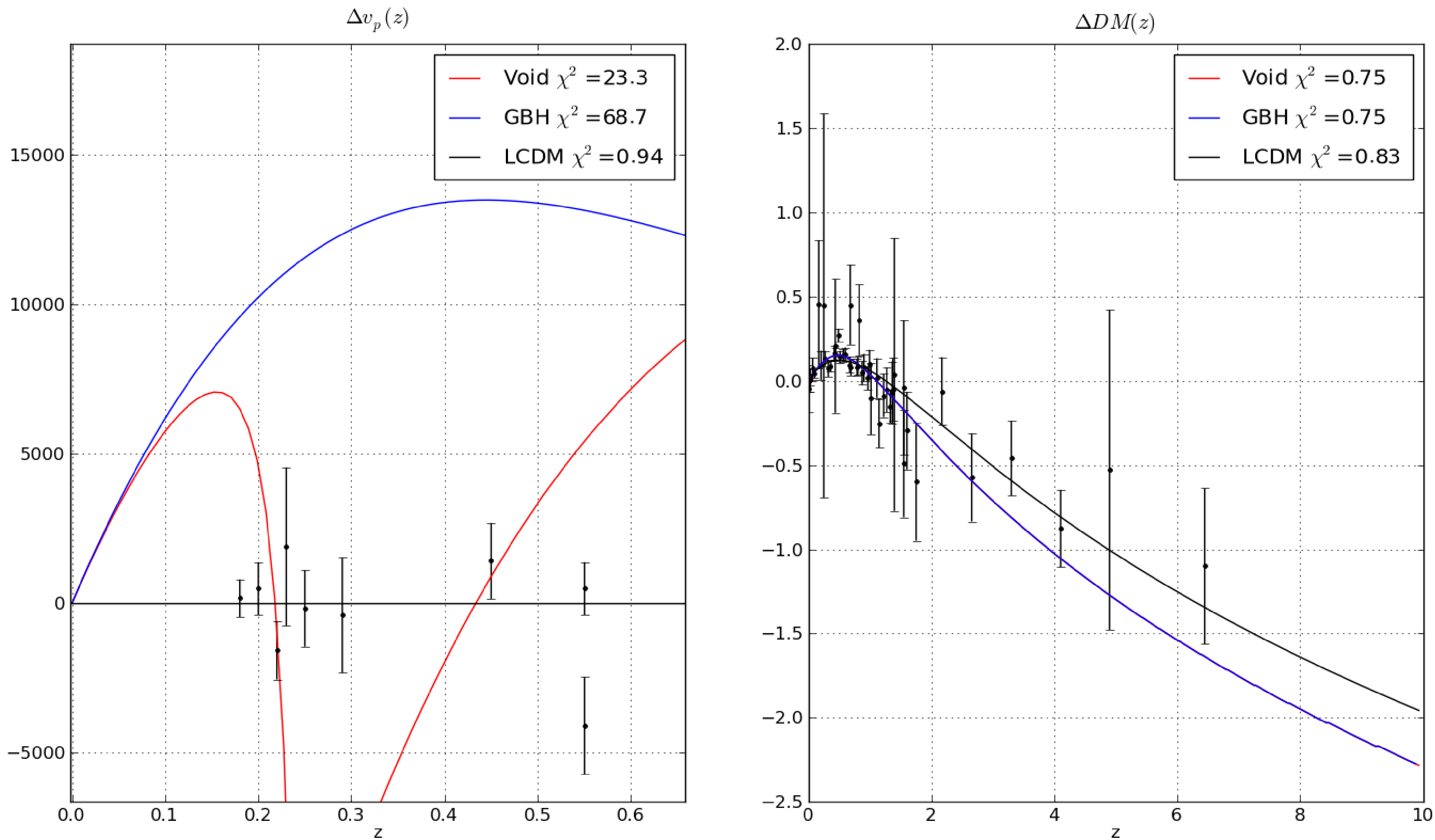
Only small variations ($\sim t_{dec}$) required

Expansion rate larger at early times; small change in $t_{dec} \rightarrow$ big change in z_{LSS}

Negligible change in low-redshift observables

Inhomog. inside the horizon *at last scattering*


tB(r)
0.05
0.04
0.03
0.02
0.01
0.00
5000
10000
15000
20000
tB'(r)
0.000000
−0.000005
−0.000010
−0.000015
−0.000020
−0.000025
5000
10000
15000



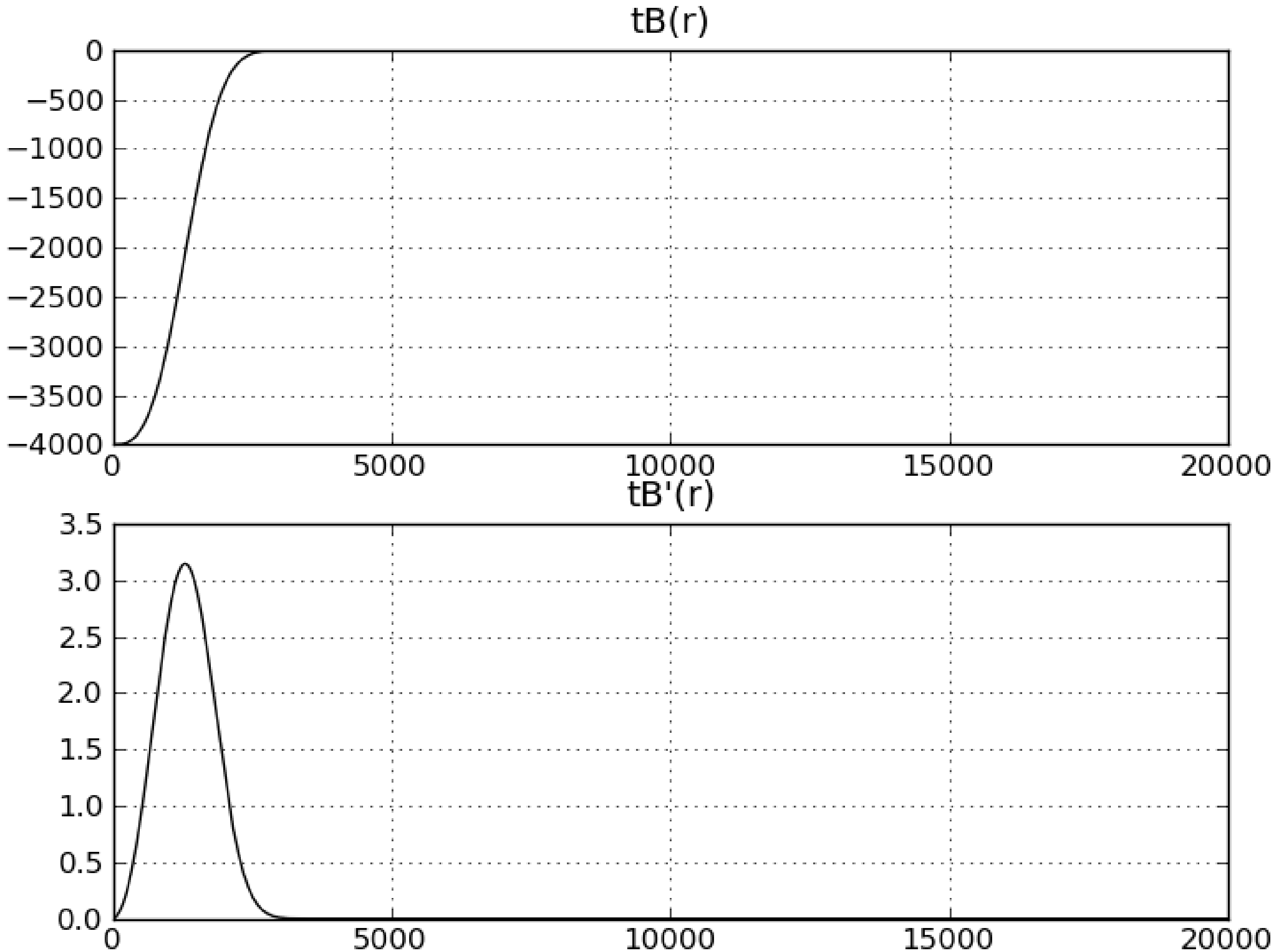
$\Delta v_p(z)$
Void χ^2 =23.3
GBH χ^2 =68.7
LCDM χ^2 =0.94
15000
10000
5000
0
−5000
0.0
0.1
0.2
0.3
0.4
0.5
0.6
z
$\Delta DM(z)$
Void χ^2 =0.75
GBH χ^2 =0.75
LCDM χ^2 =0.83
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
0
2
4
6
8
10
z

$t_B(r)$ far from our LSS

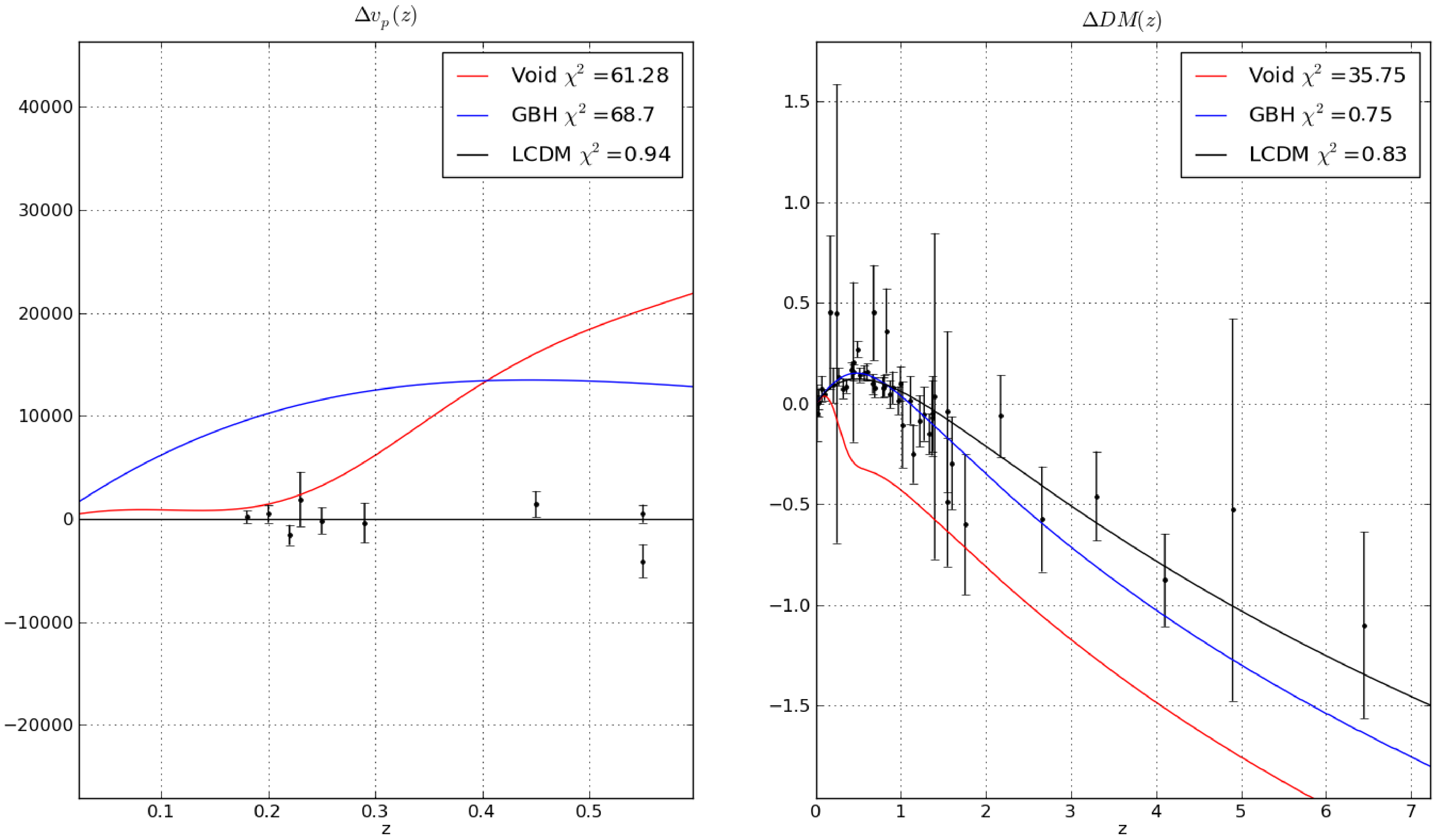
Changes $H(z)$ inside our past lightcone

Geodesics to offcentre observers pass through modified region

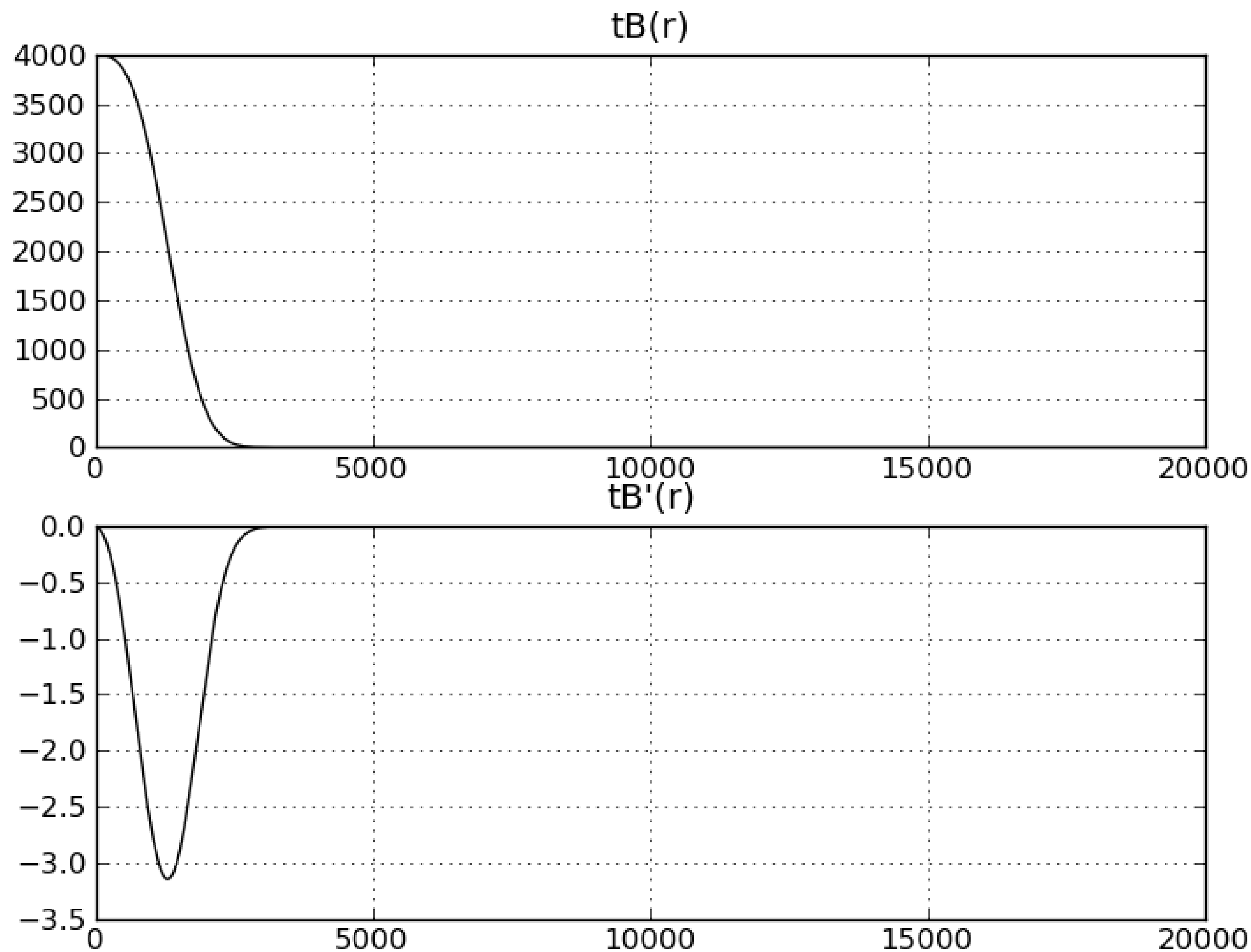
Affects central observer's H_0, $d_L(z)$ etc.

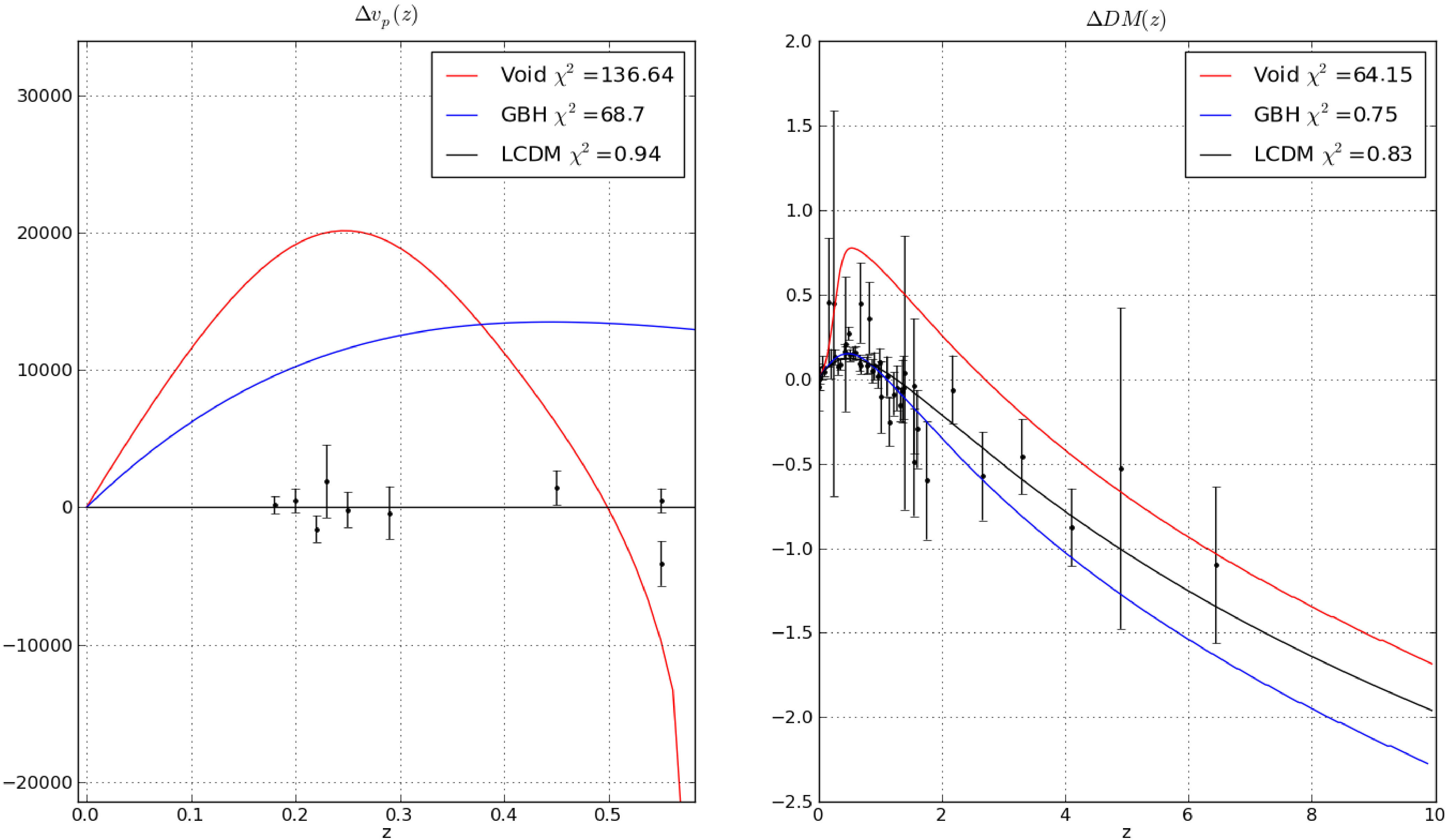


tB(r)
0
−500
−1000
−1500
−2000
−2500
−3000
−3500
−4000
0
5000
10000
15000
20000
tB'(r)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5000
10000
15000
20000



$\Delta v_p(z)$
Void χ^2 =61.28
GBH χ^2 =68.7
LCDM χ^2 =0.94
z
$\Delta DM(z)$
Void χ^2 =35.75
GBH χ^2 =0.75
LCDM χ^2 =0.83
z


tB(r)
4000
3500
3000
2500
2000
1500
1000
500
0
0
5000
10000
15000
20000
tB'(r)
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
0
5000
10000
15000
20000



$\Delta v_p(z)$
Void χ^2 =136.64
GBH χ^2 =68.7
LCDM χ^2 =0.94
30000
20000
10000
0
−10000
−20000
0.0
0.1
0.2
0.3
0.4
0.5
z
$\Delta DM(z)$
Void χ^2 =64.15
GBH χ^2 =0.75
LCDM χ^2 =0.83
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
0
2
4
6
8
10
z

Peculiar velocities

Very few cluster kSZ measurements

Peculiar velocities of clusters distort void kSZ curve

Why should peculiar velocities follow LCDM relations?

How to break the degeneracy?

Velocity mismatch

Comoving matter frame *is not* the frame where the CMB is isotropic any more

Ambiguous definition of peculiar velocity:

- Peculiar to Hubble flow [Tully-Fisher, SNe]
- Peculiar to CMB [kSZ]

$$\Delta v = v_{CMB} - v_m = v_{void}(z)$$

Velocity mismatch

Tully-Fisher errors proportional to z

kSZ cluster selection function peaks around z=0.4, Tully-Fisher z<0.1 (so far)

Sensitive to systematic offsets in one of the "peculiar" velocity measurements

Conclusion

kSZ is a powerful test, but voids aren't ruled out just yet

Inhomogeneous early universe provides extra freedom, but difficult physics

Tests are required which don't make assumptions about early homogeneity