PECULIAR VELOCITIES OF CLUSTERS AT HIGH REDSHIFT

ROMAN JUSZKIEWICZ

COPERNICUS CENTER, WARSAW
& UNIVERSITY OF ZIELONA GÓRA,
POLAND

NONLINEAR COSMOLOGY WORKSHOP
NICE, JANUARY 2006

VELOCITY FIELDS, MASS DENSITY FIELDS & THEIR POWER SPECTRA

$\delta(\vec{x}, t)$ = MASS DENSITY

$$\rho(\vec{x}, t) = \langle \rho \rangle (1 + \delta(\vec{x}, t))$$

$\vec{U}$ = VELOCITY

$\vec{v}$ = PECULIAR VELOCITY

$$\vec{U}(\vec{x}, t) = H\vec{r} + \vec{v}$$

$\vec{r} = a(t)\,\vec{x}$; $a = (1+z)^{-1}$ - expansion factor

$$\delta_k \equiv (2\pi)^{-3} \int e^{i\vec{k}\cdot\vec{x}}\, \delta(\vec{x})\, d^3x$$

$$\vec{v}_k \equiv (2\pi)^{-3} \int e^{i\vec{k}\cdot\vec{x}}\, \vec{v}(\vec{x})\, d^3x$$

$$\langle \delta_k \delta_{k'} \rangle = P(k)\, \delta_D(\vec{k} + \vec{k}')$$

$$\langle \vec{v}_k \vec{v}_{k'} \rangle = P_{vv}(k)\, \delta_D(\vec{k} + \vec{k}')$$

LINEAR PERTURBATION THEORY

– GROWING MODE

$$\delta(\vec{x},t) = \delta(\vec{x})\,D(t)$$

$$\frac{\vec{\nabla}\cdot\vec{v}}{a} = -Hf\delta$$

$$f(\Omega_M, \Omega_\Lambda, z) \equiv \frac{a}{D}\frac{dD}{da}$$

Ω_Λ DEGENERACY AT $z = 0$

$$f(z=0) \simeq \Omega_M^{0.6}$$

$$\vec{v}_k = -\frac{i\vec{k}}{k^2} H a f \delta_k$$

$$|v_k|^2 \equiv P_{vv}(k) = H^2 a^2 f^2 P(k)/k^2$$

$$\langle v^2(R)\rangle = \frac{1}{2\pi^2}\int_0^\infty H^2 a^2 f^2 P(k)\,|W(kR)|^2\,dk$$

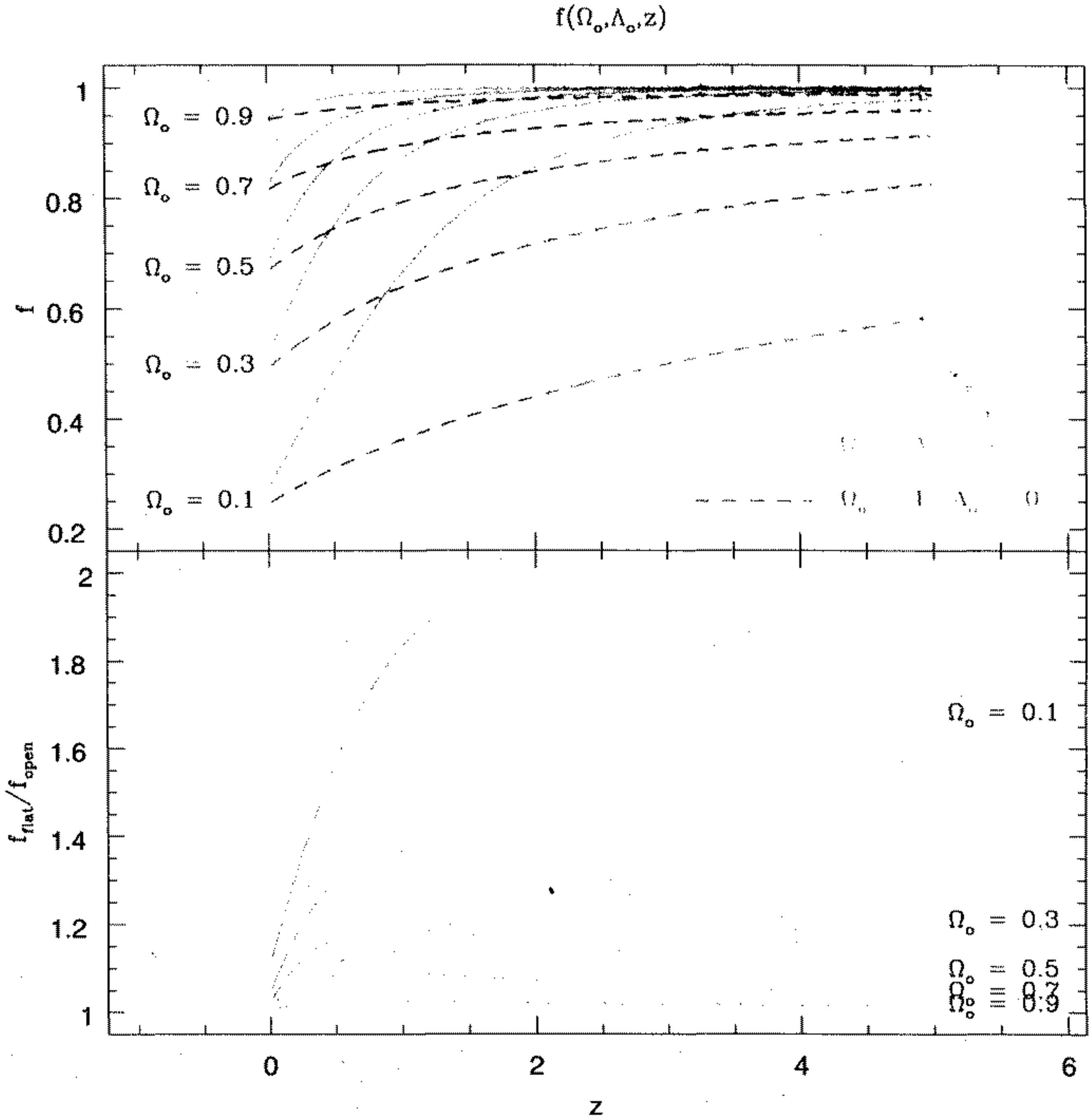
$$|W(kR)|^2 = e^{-k^2R^2}$$

FOR A GAUSSIAN SPATIAL FILTER

POWER PER OCTAVE

$$\Delta_Q^2 \equiv \frac{P_Q(k,z)\,k^3}{2\pi^2}$$

$$\langle Q^2 \rangle = \int_{-\infty}^{\infty} \Delta_Q^2(k)\,\frac{dk}{k}$$



f(Ωo,Λo,z)
Ωo = 0.9
Ωo = 0.7
Ωo = 0.5
Ωo = 0.3
Ωo = 0.1
f
fflat/fopen
Ωo = 0.1
Ωo = 0.3
Ωo = 0.5
Ωo = 0.7
Ωo = 0.9
z

CONVENTIONAL DISTANCE INDICATORS

$D_n - \sigma$, TF, SBF

DISTANCE ERROR $\boxed{\Delta r = \varepsilon r}$

$\varepsilon = 10\% - 25\%$

$v = 500 - 600 \text{ km s}^{-1}$

LIMITING DISTANCE

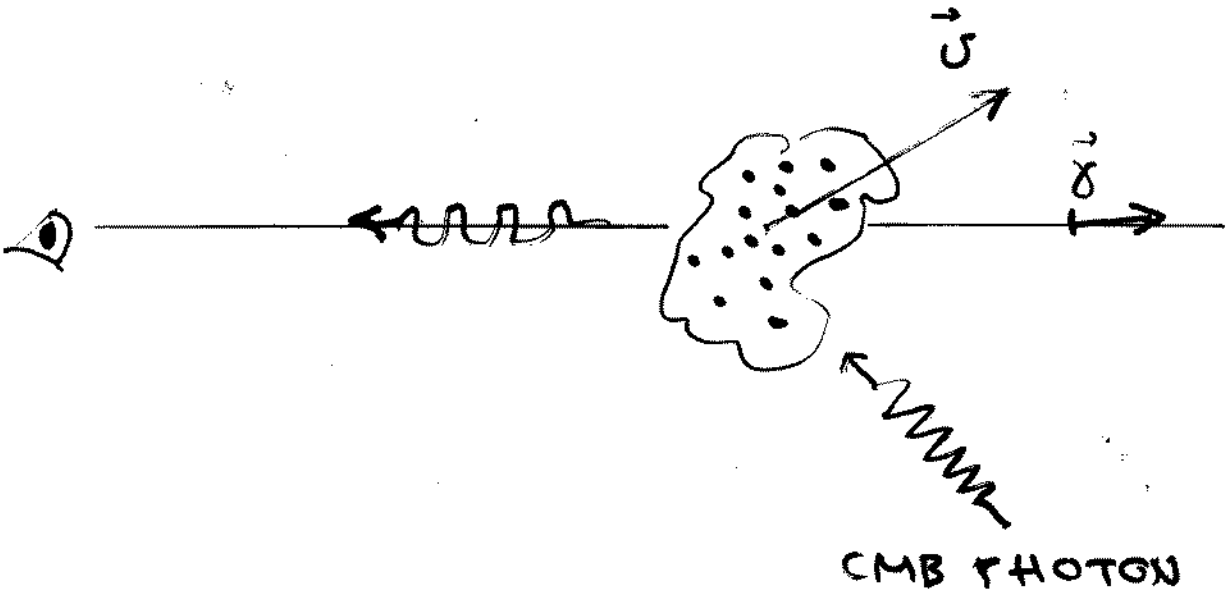
$r_{max} \cong 70 h^{-1}$ Mpc

$z_{MAX} \cong 0.024$!!!

$$\boxed{\begin{array}{l}\text{kSZ DISTANCES} \\ \Delta r \lesssim \dfrac{200 \text{ km s}^{-1}}{H_0}\end{array}}$$

THE KINETIC SZ EFFECT (kSZ)

$$\frac{\Delta T}{T}(\vec{\gamma}) = \int dl\, e^{-\tau} n_e \sigma_T\, \vec{\gamma} \cdot \vec{v}$$



kSZ flux S_{kSZ}

Planck function $B_\nu(T)$

$\nu \simeq 217\,\mathrm{GHz}$ – tSZ vanishes

$$S_{kSZ} = \frac{\partial B_\nu}{\partial T} \Delta T_{kSZ}$$

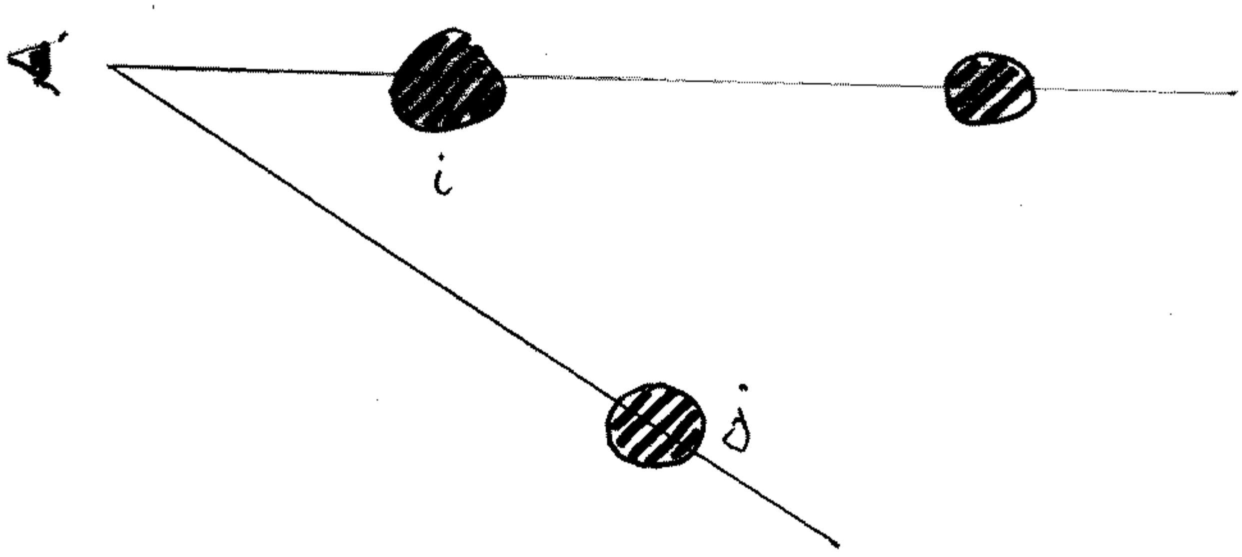
$$\Delta T_{kSZ} \simeq 9\,\mu K \; \frac{\vec{v} \cdot \vec{\gamma}}{100\,\mathrm{km\,s^{-1}}} \cdot \frac{\langle \tau \rangle}{0.01}$$

SUB - mm experiments

- SOUTH POLE TELESCOPE

- ATACAMA COSMOLOGY TELESCOPE $\rightarrow$ $v(z)$
  + SOUTH AFRICAN LARGE TELESCOPE (SALT)
  $\rightarrow$ cluster redshifts (z)

- PLANCK



3-D FLUX AUTOCORRELATION FUNCTION

ω_i - SOLID ANGLE

$\bar{I} = \sum_i S_i / \sum \omega_i$ - mean flux

$$\boxed{\begin{aligned}\xi_S(\vec{r}_i - \vec{r}_j) &= \langle (S_i - \bar{I}\omega_i)(S_j - \bar{I}\omega_j) \rangle \\ &= \langle S_{kSZ,i}\, S_{kSZ,j} \rangle + \ldots\end{aligned}}$$

$S_i = S_{i\,kSZ} +$ NOISE

NOISE SOURCES:
- SHOT NOISE, COSMIC VARIANCE
- INTERNAL FLOWS
- INSTRUMENTAL NOISE
- DIFFUSE FOREGROUNDS & BACKGROUNDS - CIB, CMB

POWER PER OCTAVE

$$\Delta^2_{kSZ}(k) = S_0^2\left(\Delta^2_{vv}(k) + \bar{B}^2\,\Delta^2_{v\delta v\delta}(k)\right)$$

$$\bar{B} \equiv S_1/S_0$$

$$S_N = \int_{M_*}^{\infty} B^N(M)\,S(M)\,\frac{dn}{dM}\,dM \quad ; N = 0, 1$$

$$\boxed{\Delta^2_{v\delta v\delta} \simeq \frac{2}{3}\,\Delta^2_{\delta\delta}\,\sigma_v^2}$$

$$\langle S_i S_j \rangle \propto \langle (1+\delta_c(M_i)) v_{i\parallel} (1+\delta_c(M_j)) v_{j\parallel} \rangle$$

$$v_{i\parallel} = \vec{v}_i \cdot \hat{\gamma}_i$$

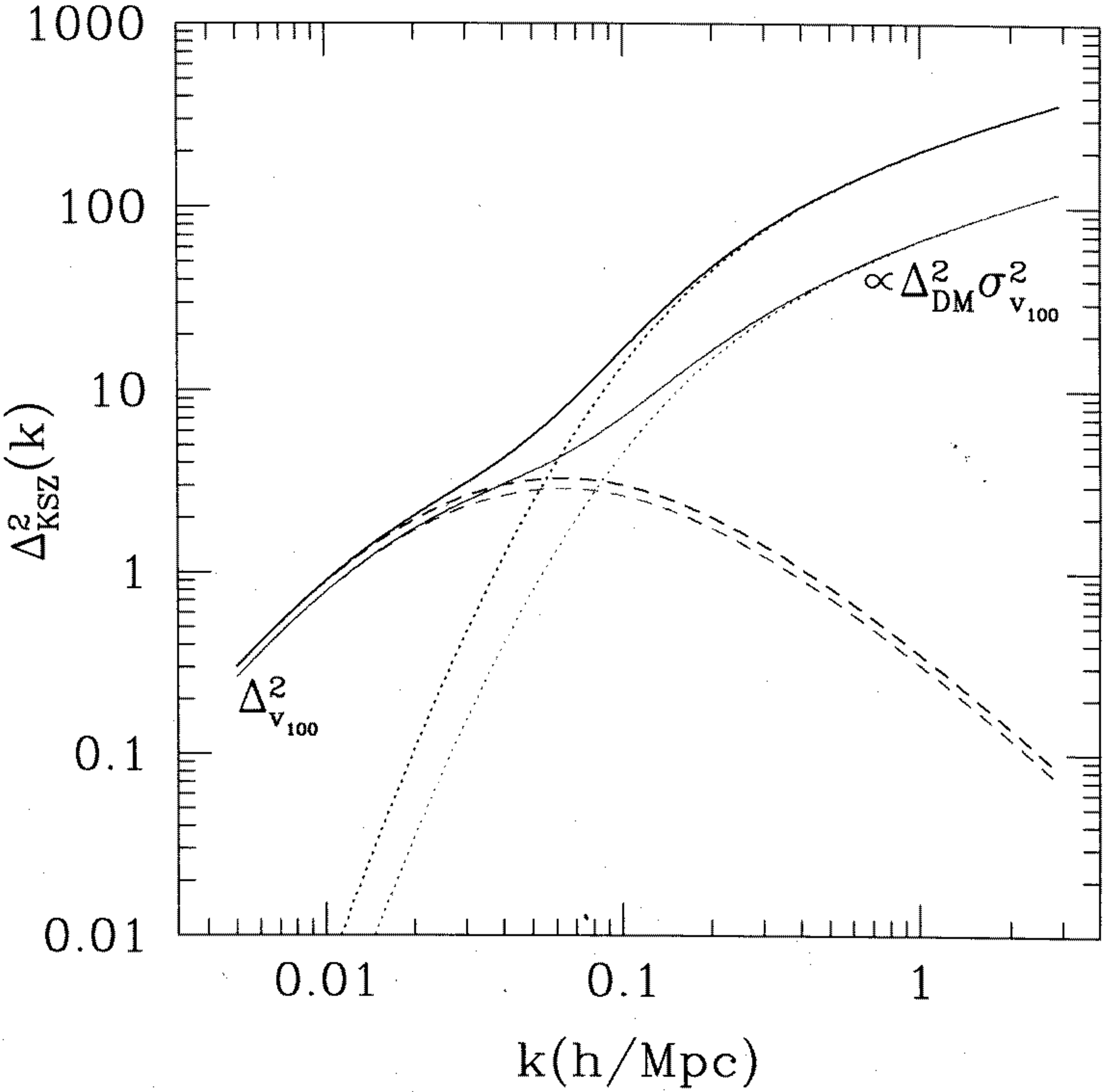
$\delta_c(M_i)$ - overdensity of clusters

$\delta_c(M) = b(M)\, \delta \leftarrow$ mass overdensity

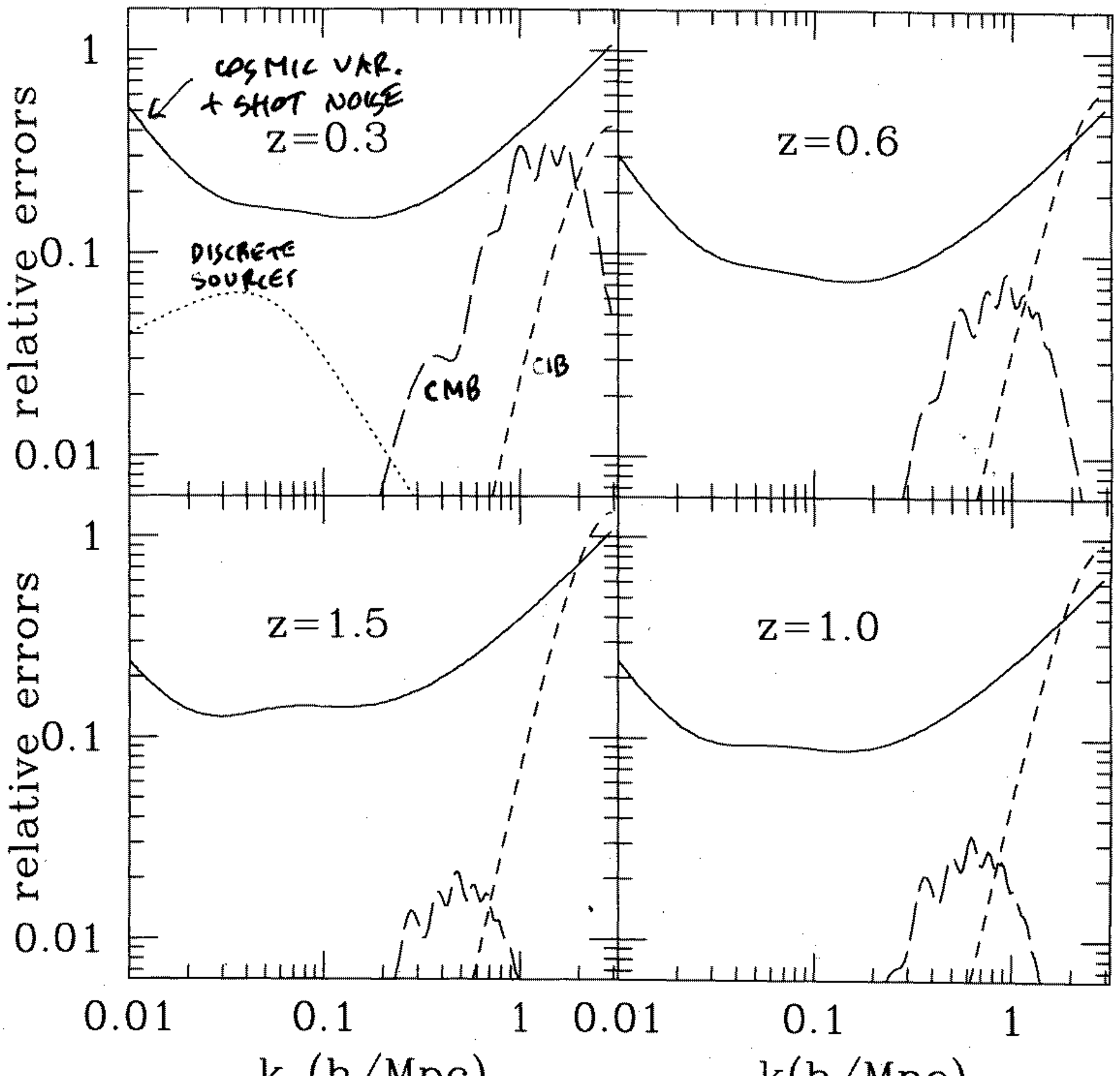
cluster bias from HALO MODEL
MO & WHITE (1996)

$$\langle ABCD \rangle = \langle AB \rangle \langle CD \rangle + \langle AC \rangle \langle BD \rangle + \langle AD \rangle \langle BC \rangle + \langle ABCD \rangle_c$$

- OSTRIKER & VISHNIAC (1986) - 2ND ORDER PERTURBATION THEORY
- PEEBLES & JUSZKIEWICZ (1998) - POISSON MODEL
- MA & FRY (2001) - NONLINEAR HALO MODEL



1000
100
10
1
0.1
0.01
$\Delta^2_{KSZ}(k)$
$\propto \Delta^2_{DM}\sigma^2_{v_{100}}$
$\Delta^2_{v_{100}}$
0.01
0.1
1
k(h/Mpc)



$P_{vv}(k)$ CAN BE MEASURED TO 10% ACCURACY FOR $k \lesssim (1\ h^{-1}\mathrm{Mpc})^{-1}$

DRAFT VERSION SEPTEMBER 29, 2005
Preprint typeset using LaTeX style emulateapj v. 7/15/03

PAPER TO APPEAR SOON
– DRAFT

A NEW METHOD OF MEASURING THE PECULIAR VELOCITY POWER SPECTRUM

PENGJIE ZHANG[1], ALBERT STEBBINS[1], ROMAN JUSZKIEWICZ[2,3], HUME A. FELDMAN[4]

Draft version September 29, 2005

ABSTRACT

We show that measurements of spatial correlations of the cluster kinetic Sunyaev Zeldovich (KSZ) flux can in principle allow the measurement of the cluster peculiar velocity power spectrum. We expect that future large sky coverage KSZ surveys may allow a peculiar velocity power spectrum estimate of an accuracy reaching $\sim 10\%$. In contrast with conventional techniques, our new method does not require measurements of the thermal SZ signal; the X-ray temperature measurement is also not needed. Moreover, this method is optimal in the sense that the expected systematic errors are always subdominant to statistical errors on all scales and redshifts of interest.
Subject headings: cosmology: large scale structure: theory-cosmic microwave background

1. INTRODUCTION

Peculiar-velocity-distance surveys have been successfully used in the past to constrain structure formation scenarios and power spectra of initial density fluctuations; they have been also used to estimate the cosmological density parameter, Ω_m (Vittorio et al. 1986; Groth et al. 1989; da Costa et al. 1998; Feldman et al. 2003a,b). For a broader background, see also an excellent review and conference proceedings, written and edited by Strauss & Willick (1995) and Courteau et al. (2000), respectively. However, all velocity-distance surveys are limited by errors in the distance estimators, in the range of 15 to 20% of the estimated distance. In contrast, for cluster peculiar velocities, v_p, derived from the kinetic Sunyaev Zeldovich (KSZ) effect, the errors grow much less rapidly with distance. Hence, KSZ cluster surveys may open new possibilities for studying large-scale flows (Haehnelt & Tegmark 1996; Kashlinsky & Atrio-Barandela 2000; Aghanim et al. 2001; Atrio-Barandela et al. 2004; Holder 2004). The currently established method of recovering v_p from the SZ data requires extra measurements of the cluster temperature and its Thomson optical depth, τ. Other sources of confusion are the thermal Sunyaev Zeldovich (TSZ) effect and the KSZ signal generated by internal motions, which is added to the signal from cluster's bulk velocity, resulting in a limit in accuracy in determining v_p, not less than ~ 200 km/s (Knox et al. 2003; Aghanim et al. 2004; Diaferio et al. 2005); for a more optimistic/pessimistic assesment, see (Nagai et al. 2003), or (Peel 2005), respectively.

Instead of v_p, the direct observable in the KSZ surveys is the KSZ flux. Contaminations to the cluster KSZ flux have different clustering properties and can be applied to disentangle KSZ signal from contaminations. If one measures the spatial cluster KSZ flux autocorrelation directly, many contaminations vanish and most remaining contaminations can be subtracted. We will show that at $z \gtrsim 0.3$, the systematics become sub-dominant and the statistical errors, at $\sim 10\%$ level for South Pole Telescope (SPT[5]), dominate. Throughout this *letter*, we adopt the cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 1 - \Omega_m$ and a normalization parameter $\sigma_8 = 0.9$.

2. THE FLUX POWER SPECTRUM

The KSZ cluster surveys directly measure the sum of the cluster KSZ flux $S_{\rm KSZ}$ and various contaminants, such as intracluster gas internal flow, radio and IR point sources, primary cosmic microwave background (CMB), cosmic infrared background (CIB), etc. The signal is (Sunyaev & Zeldovich 1980)

$$S_{\rm KSZ} = \frac{\partial B_\nu(T)}{\partial T} \Delta T_{\rm KSZ}\ , \tag{1}$$

where $B_\nu(T)$ is the Planck function. At $\nu \sim 217$Ghz, $\partial B/\partial T = 540$ Jy sr^{-1} μK^{-1}. The KSZ temperature fluctuation can be expressed as

$$\Delta T_{\rm KSZ} = T_{\rm CMB} \langle\tau\rangle\, (v_p/c)\, \omega \equiv S_{100} v_{100}, \tag{2}$$

where $\langle\tau\rangle$ is the optical depth averaged over the solid angle ω, while $v_{100} \equiv v_p/(100{\rm km}/s)$ and $S_{100} \equiv S_{\rm KSZ}(v_p)/S_{\rm KSZ}(100\,{\rm km}/s)$ are the "normalized" peculiar velocity and the KSZ flux, scaled to $v_p = 100\,{\rm km}/s)$. This expression can be also rewritten as

$$\Delta T_{\rm KSZ} = 9\mu K\ v_{100}\, \langle\tau\rangle/0.01\ . \tag{3}$$

Since at $\nu \sim 217$ Ghz, the non-relativistic part of the TSZ effect, which is one of the major contaminations of the KSZ, vanishes (Zel'dovich & Sunyaev 1969). In this paper, we focus on this frequency. Optical follow-up of KSZ surveys such as dark energy survey[6] will measure cluster redshift z with uncertainty $\lesssim 0.005$.[7] The z information allows the measurement of the 3D auto correlation of measured cluster KSZ flux

$$\begin{aligned} \xi_S(r) &\equiv \langle (S_i - \bar{I}\omega_i)(S_j - \bar{I}\omega_j) \rangle \\ &= \langle S_{{\rm KSZ},i} S_{{\rm KSZ},j} \rangle + \cdots\ . \end{aligned} \tag{4}$$

Electronic address: zhangpj@fnal.gov, stebbins@fnal.gov, roman@camk.edu.pl, feldman@ku.edu
[1] NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500
[2] Institute of Astronomy, Zielona Góra University, Poland
[3] Copernicus Astronomical Center, 00-716 Warsaw, Poland
[4] Dept. of Physics & Astronomy, Univ. of Kansas, Lawrence, KS 66045, USA

[5] http://astro.uchicago.edu/spt
[6] http://www.darkenergysurvey.org/
[7] The photo-z of each galaxies has dispersion ~ 0.05. Clusters have $\gtrsim 100$ galaxies and thus the determined z dispersion is $\lesssim 0.005$.