Cosmology

with the

Kinetic Sunyaev–Zeldovich (KSZ) Effect

Hume A. Feldman
University of Kansas

SZ Effect

CMB photons Compton scatter on hot electrons in clusters.

- SZE observations could yield distances to galaxy clusters when combined with X-ray data.

Thermal SZE:

The high T (~keV) e^- increase E_γ => non-thermal spectrum

Kinetic SZE:

The bulk motion of the cluster red- or blue-shifts scattered γ

kSZ Effect

The Doppler effect of line of sight cluster velocity leads to an observed shift of the CMB spectrum.

In the nonrelativistic limit, the spectral signature of the kinetic SZE is a pure thermal distortion of magnitude of the CMB signal:

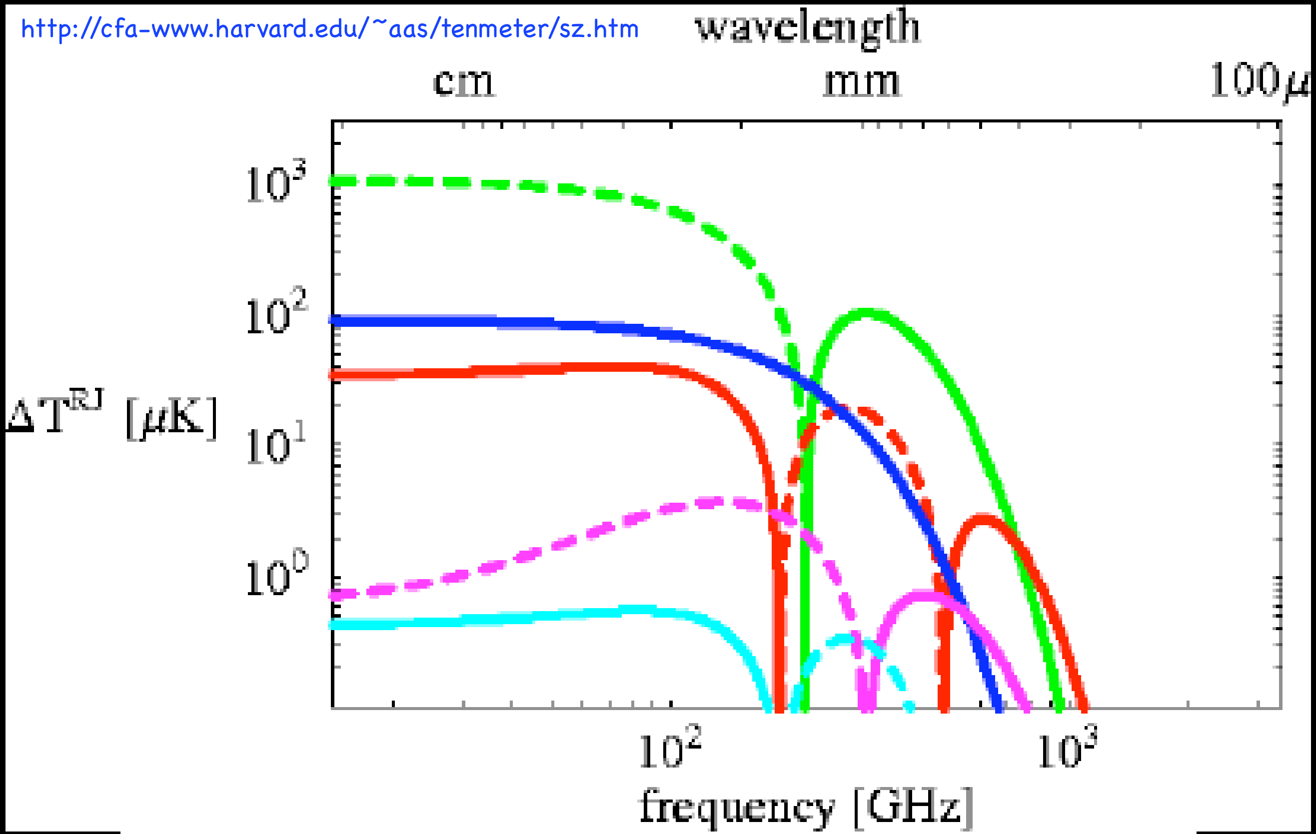
$$\frac{\Delta T_{\rm SZE}}{T_{\rm CMB}} = -\tau_e \left(\frac{v_{\rm pec}}{c}\right)$$

τ_e probability of CMB photons interacting with an energetic ICM electron

Velocity residuals in an all-sky peculiar velocity map of a fair volume of the Universe will point directly to mass concentrations.

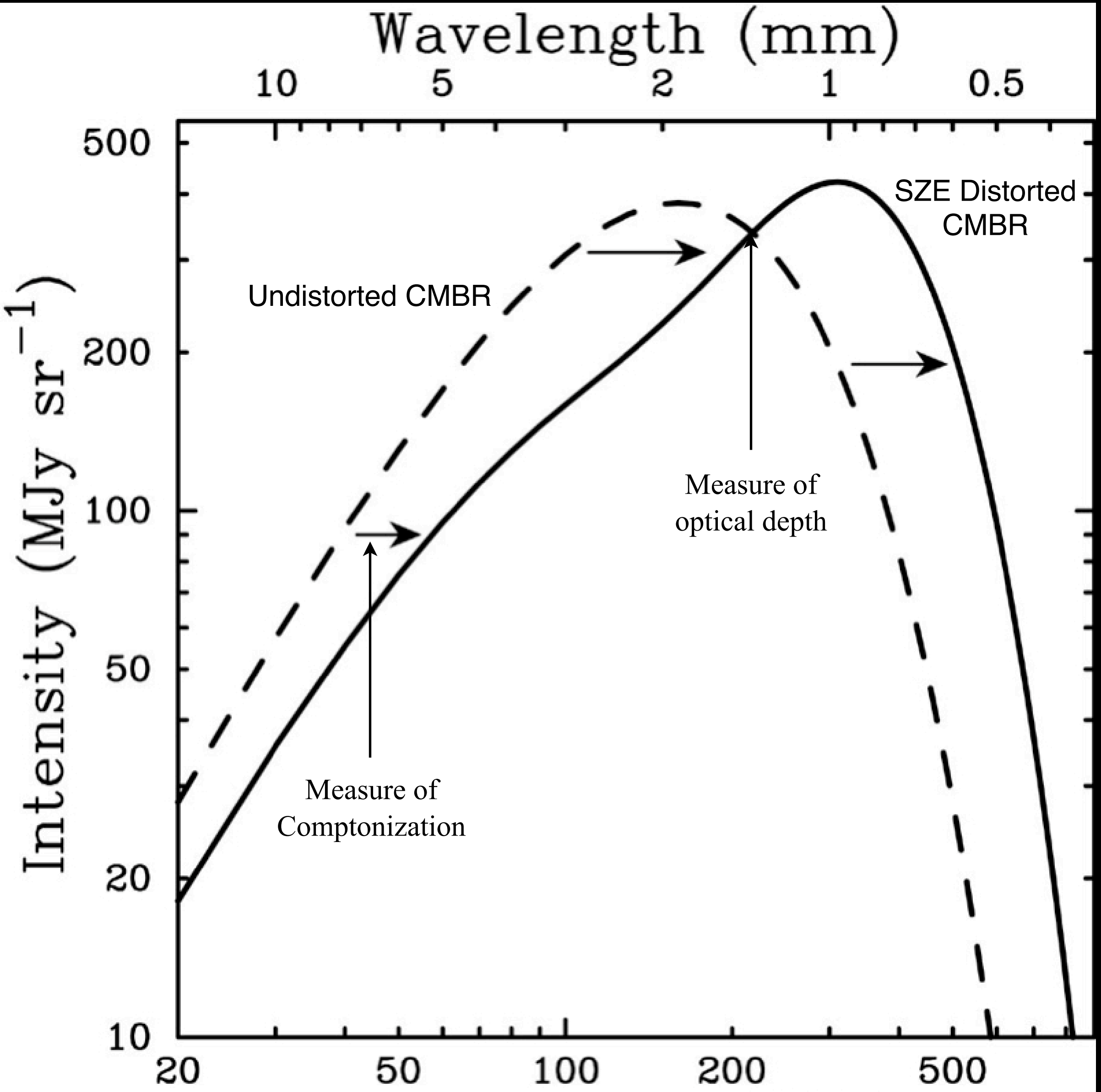
Obtain an estimate for the mass distribution in the Universe on the largest scales.

SZ Effect



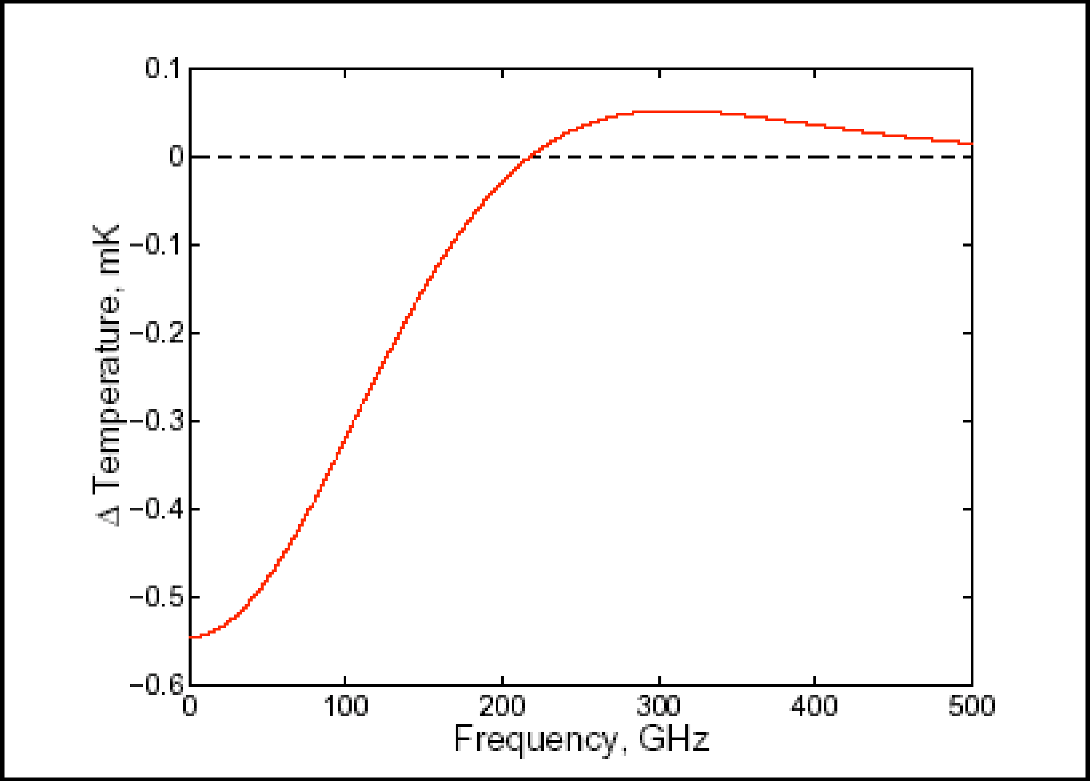
1. *the classical thermal S-Z effect*
2. *the classical kinetic S-Z effect*
3. *relativistic corrections to (1)*
4. *thermal corrections to (2)*
5. *finite optical depth corrections.*

SZ Effect



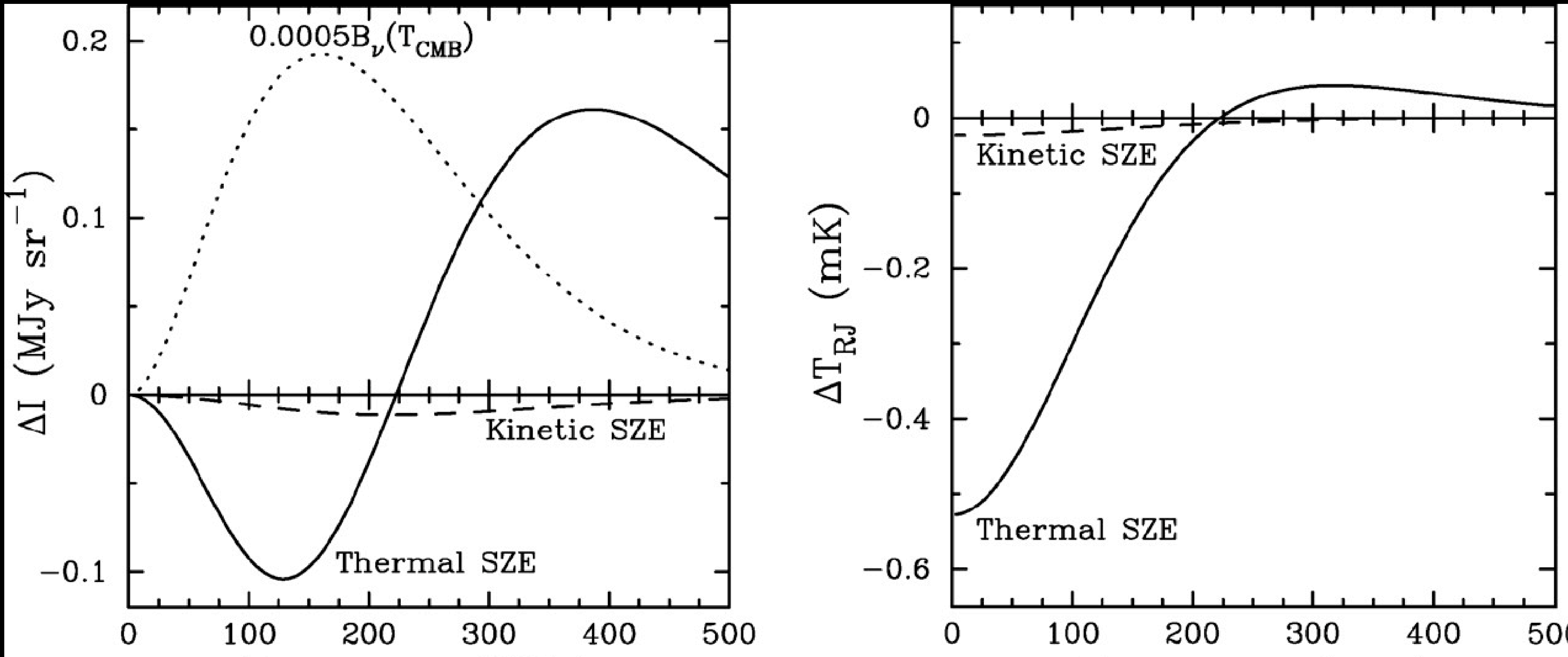
Carlstrom etal 2002

SZ Effect



- SZE Spectral Distortion of the CMBR due to hot ionized gas associated with a cluster of galaxies

SZ Effect



Carlstrom etal 2002

$$T_{e^-} = 10kev \qquad y = 10^{-4} \qquad v_{pec} = 500km/s$$

Measuring

the

Peculiar Velocity Power Spectrum

with the

Kinetic Sunyaev–Zeldovich (KSZ) Effect

Zhang, Juszkievicz, Stebbins, HAF

Astro-ph/0410637

In KSZ surveys

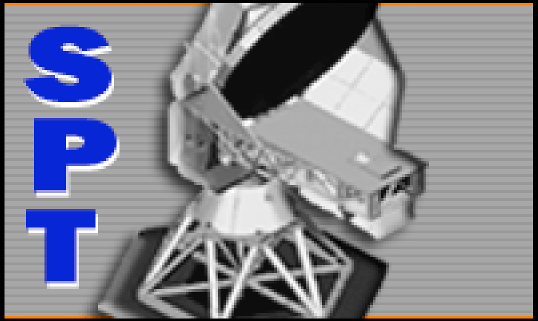
the direct observable is the KSZ flux

Contaminations have different clustering properties

===> Vanish

South Pole Telescope (http://spt.uchicago.edu/)

A new 10 meter diameter telescope is being constructed for deployment at the NSF South Pole research station.



Covers 217Ghz 4000 deg^2 at arcmin resolution

Large-area millimeter and sub-millimeter wave surveys of faint, low contrast emission to map primary and secondary anisotropies in the cosmic microwave background.

ACT

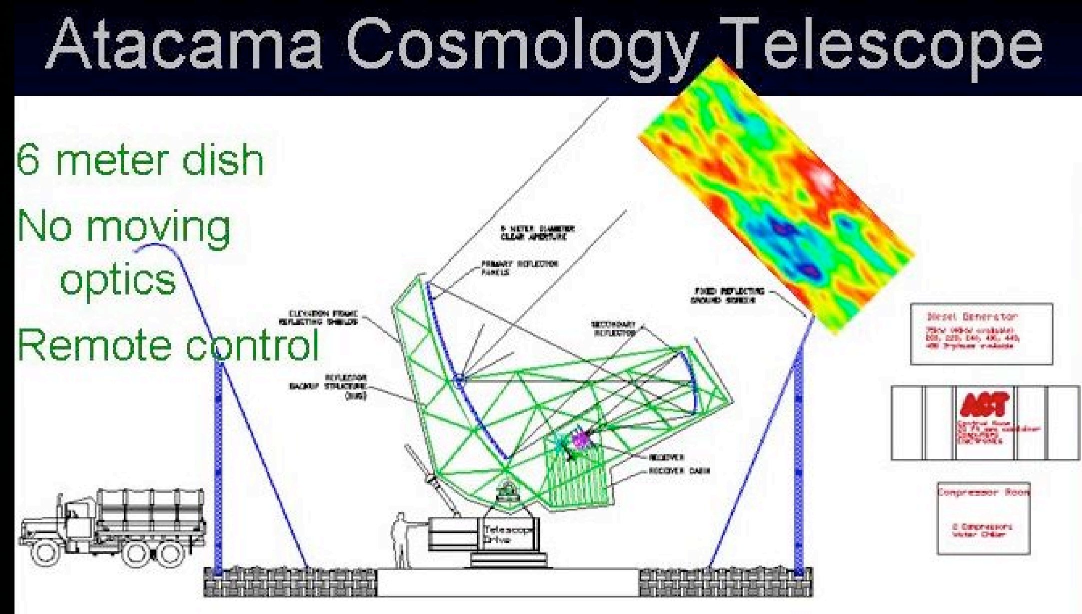
Atacama Cosmology Telescope

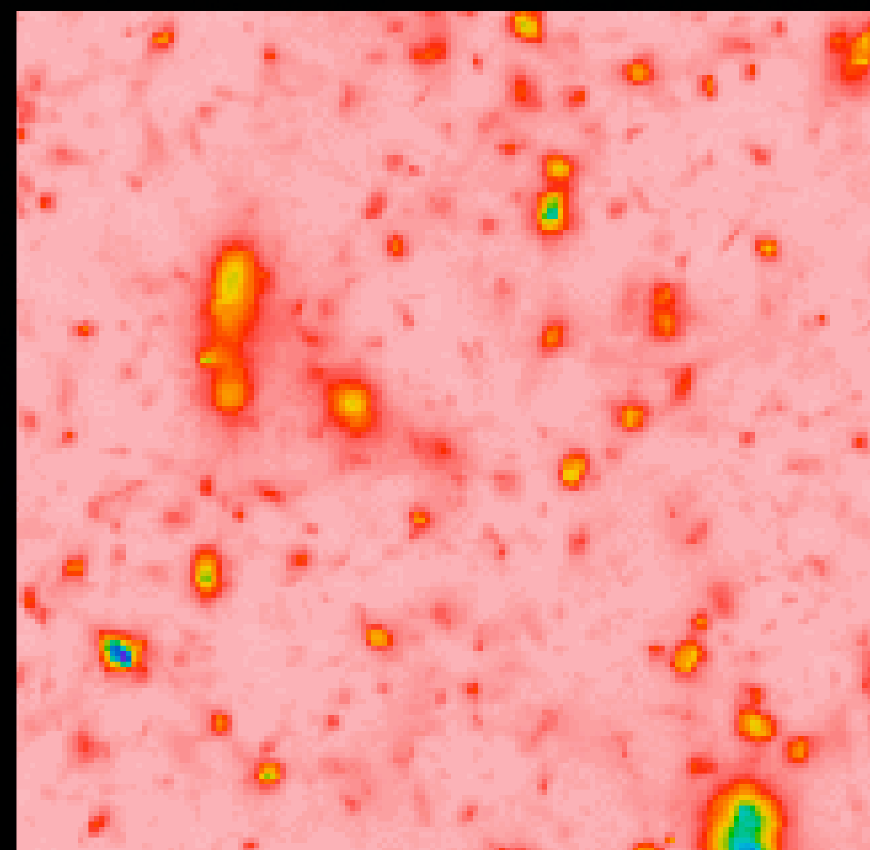
- Map the CMB ΔT/T over 100 deg^2 beyond the resolution limits of the WMAP and Planck, with an error of 2 μK/pixel for 1.7'x1.7' pixels.

- Find and study all galaxy clusters with M > $3 \times 10^{14}\ \mathrm{M}_\odot$ in the CMB map region through the Sunyaev-Zel'dovich effect and determine the spectroscopic redshifts of over 400 clusters.

- Measure the masses of the clusters with X-ray observations and with galaxy velocity dispersions.

http://www.hep.upenn.edu/act/





Measurement:

Spatial correlation of Cluster KSZ flux

$\Longrightarrow$ Cluster Peculiar Velocity PS to $\sim 10\%$

without:

Thermal SZ (TSZ) signal

T_{X-ray}

Systematic errors are subdominant to statistical errors on all scales (k) and redshifts (z)

KSZ cluster surveys directly measure:

Cluster KSZ flux $S_{\rm KSZ}$

and various contaminants:

- Intracluster gas internal flow
- Radio and IR point sources
- Primary cosmic microwave background (CMB)
- Cosmic infrared background (CIB)

The Signal

$$S_{\mathrm{KSZ}} = \frac{\partial B_\nu(T)}{\partial T} \Delta T_{\mathrm{KSZ}}$$

Sunyaev & Zeldovich 1980, MNRAS, 190, 413

$B_\nu(T)$ is the Planck Function

$$\partial B/\partial T|_{\nu \sim 217\mathrm{Ghz}} = 540 \text{ Jy sr}^{-1} \ \mu K^{-1}$$

and

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

$< \tau >$ Optical Depth averaged over the solid angle ω

$v_{100} \equiv v_p/(100\mathrm{km}/s)$ Peculiar velocity

$S_{100} \equiv S_{\mathrm{KSZ}}(v_p)/S_{\mathrm{KSZ}}(100 \, \mathrm{km}/s)$ KSZ Flux

Measure cluster z with uncertainty <0.01.

(Dark Energy Survey)

$\Longrightarrow$ Auto correlation of measured cluster KSZ flux

$$\xi_S(r) \equiv \langle (S_i - \bar{I}\omega_i)(S_j - \bar{I}\omega_j) \rangle$$
$$= \langle S_{\mathrm{KSZ},i} S_{\mathrm{KSZ},j} \rangle + \cdots$$

$S_i = S_{\mathrm{KSZ},i} + \cdots$ Total Flux

$S_{\mathrm{KSZ},i}$ KSZ signal

ω_i Solid angle subtended by the i^{th} cluster

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

The signal is $\langle S_{\mathrm{KSZ},i} S_{\mathrm{KSZ},j} \rangle \propto \Delta_v^2$

Where $\Delta_Q^2 \equiv P_Q(k,z) k^3/(2\pi^2)$

k is the comoving wavenumber

P_Q is the PS of the random field Q

Variance $\langle Q^2 \rangle = \int_0^\infty dk\, \Delta_Q^2/k$

Other Contaminations to the Cluster Bulk Flow Velocity such as

- Internal Flows
- Instrumental Noise

Are uncorrelated and thus vanish in the correlation measurement

In fact all systematic errors are either:

Subdominant

or

Can be subtracted directly

KSZ flux correlation is cluster number density weighted

$$\langle S_{\mathrm{KSZ},i} S_{\mathrm{KSZ},j} \rangle \propto$$

$$\langle (1+\delta_C(M_1))v_1(1+\delta_C(M_2))v_2 \rangle$$

Where

$$\delta_C(M) = b_n(M)\delta$$

Mo & White, 1996, MNRAS, 282, 347

Cluster number overdensity

Cluster mass dependent bias

KSZ signal

$$\Delta^2_{\mathrm{KSZ}}(k) = s_0^2\left(\Delta^2_v(k) + \overline{b_n}^2\Delta^2_{v\delta}\right)$$

$\langle v_1 v_2\rangle$ $\langle v_1 v_2 \delta_1 \delta_2\rangle$

Logarithmic power spectra of spatial correlation functions

where

$$s_N \equiv \int_{M_*\sim 10^{14}M_\odot}^{\infty} b_n^N(M)S(M)(dn/dM)dM,\ N=0,1$$

Cluster Mass Fn.

and

$$\overline{b_n} \equiv s_1/s_0$$

The Effective Cluster Bias

Mo & White, 1996

$$b_n(M) = 1 + (\nu^2 - 1)/(\delta_c/D)$$

where

linear density growth factor

$$\delta_c \simeq 1.686 \quad \text{and} \quad \nu = \delta_c/(D\sigma(M))$$

rms Density Fluctuation

Approximate

$$\sigma(M_*) \equiv \sigma_8 = 0.9$$

$$\overline{b_n} = b_n(M_*) = b_n(M_8) \approx 3$$

In linear theory

$$\Delta_v(k,z) \;=\; f\,H\,a\,\Delta_m / \,H_0\,k\,\sqrt{3}$$

Where

$$f \equiv \frac{d\ln D}{d\ln a}$$ and $$H = H(z)$$

Δ_m^2 is the logarithmic power spectrum of the Dark Matter

BBKS, 1986

Since $\overline{b_n}$ is large $\langle \delta_1 v_1 \delta_2 v_2 \rangle > \langle v_1 v_2 \rangle$

at $k > 0.06h/\mathrm{Mpc}$

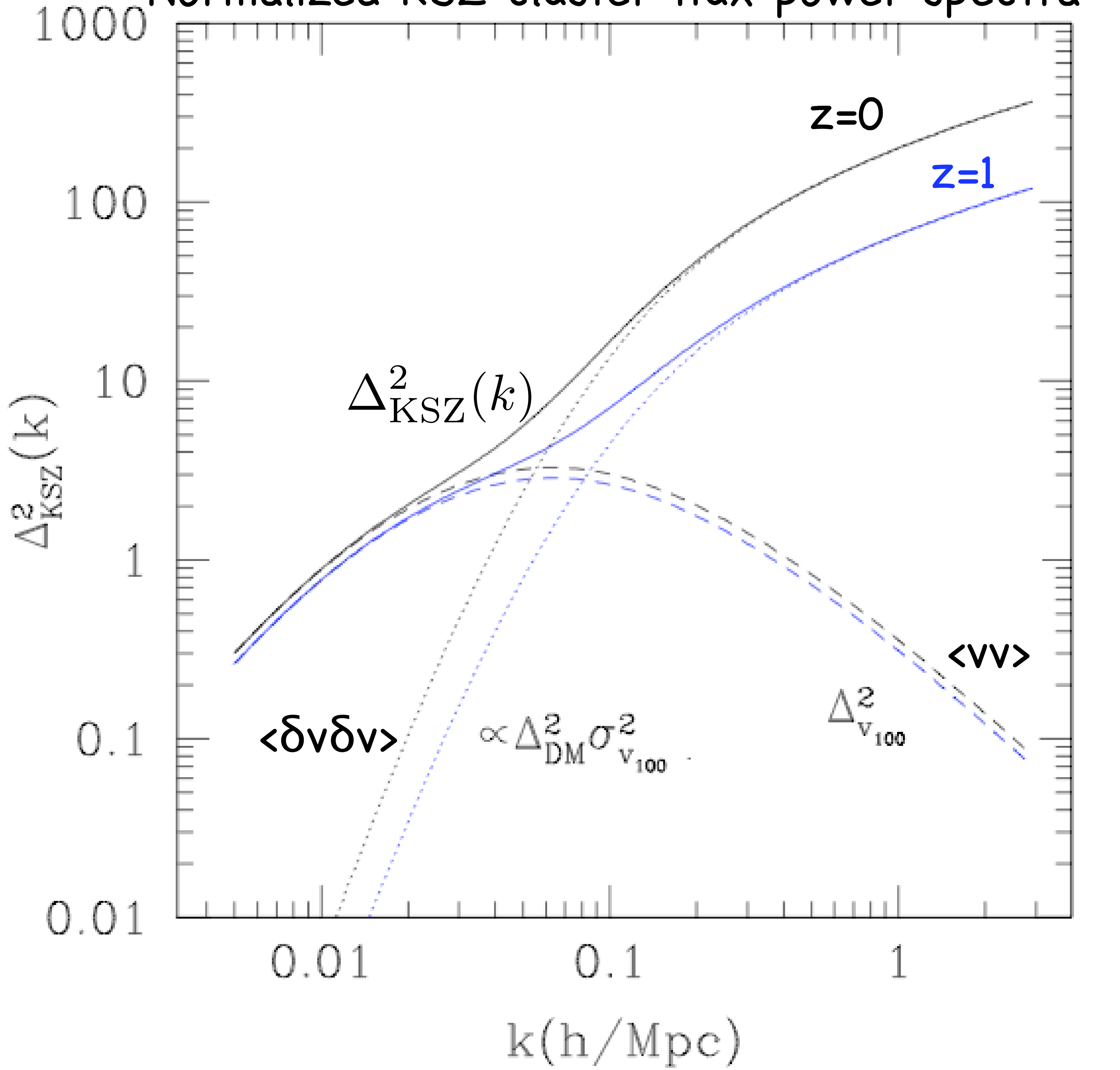
$$k_{\mathrm{NL}}(z \sim 1) \simeq 0.5h/\mathrm{Mpc}$$

For $k > 0.15h/\mathrm{Mpc}$ Ma & Fry, 2002 PRL 88 211301

$$\Delta^2_{v\delta}(k,z) \approx 2\,\Delta^2_m\,\sigma^2_v$$

$$\sigma_v^2 = \int_0^\infty dk\,\Delta_v^2/3k$$ Line-of-sight velocity dispersion

Normalized KSZ cluster flux power spectra



Error Sources

Diffuse Foreground and Background

Cluster Bulk Flows $\Delta T_{\rm KSZ} \sim \frac{20\mu K \langle\tau\rangle}{0.01}$

Primary CMB $\Delta T_{\rm CMB} \sim 100\mu{\rm K}$

Primary CIB $\Delta T_{\rm CIB} \sim 20\mu{\rm K}$

Cluster size ~ few arcmin. $\Rightarrow \ell > 3 \times 10^3$

Dominant CMB Signal Peak $\Rightarrow \ell \sim 1.5 \times 10^3$

KSZ Profile Filter:
Zero integrated area @ 217Ghz

- Dominant CMB Signal
- Galactic Synchrotron
- Free—Free Foregrounds
- Galactic Dust Emission
- Radio Background
- TSZ Background

Negligible due to their frequency or scale dependence

Bennett et al. 2003, ApJs, 148, 97
Wright, 1998, ApJ, 496, 1

Constructing Optimal Filter

Electron density profile $n_e(r) \propto (1 + r^2/r_c^2)^{-1}$

Gaussian Filter $W_\ell = 6(\ell/\ell_f)^2 \exp(-(\ell/\ell_f)^2)$

$\tilde{\Delta}_{\rm KSZ}$ Peaks at $\ell_f \approx 1.1/\theta_c \approx 3800(1'/\theta_c)$

Cluster angular core radius

Comoving Angular distance

$$\theta_c = 0.4h^{-1}{\rm Mpc}/\chi(z)$$

The Peak Value

$$\tilde{\Delta}T_{\rm KSZ} \simeq \Delta T_{\rm KSZ} \simeq 9v_{100}[\langle\tau\rangle/0.01]\mu K$$

Correlations of Filtered Backgrounds

Dark Matter Correlation

$$\tilde{\xi}_b(r) \approx \left[\int \omega(M)\, dn(M)\right]^2 \left[1 + \overline{b_n}^2 \xi_m(r)\right] \tilde{w}_b(\theta)$$

Cluster solid angle

Filtered Background Angular Correlation

$$\theta = r/\chi$$

CMB contaminants are known and can be subtracted

$\Longrightarrow$ Only statistical intrinsic CMB fluctuations remain.

CIB Power Spectrum

$$C_\ell^{(1)}\ell^2/(2\pi) \simeq (4\mu\mathrm{K})^2(\ell/10^3)^{0.7}$$

KSZ power spectrum

$$C_\ell^{(2)}\ell^2/(2\pi) \simeq (2.7\mu\mathrm{K})^2$$

Upper Limit on the Fractional Systematic Error

$$\eta(k) \approx \frac{(1+A_k)\sum_{j=1,2} C_\ell^{(j)} W_\ell^2 \ell^2}{2\pi\, B_k\, [9(\langle\tau\rangle/0.01)\mu K]^2}$$

$$A_k \equiv \overline{b_n}^2 \Delta_m^2$$

$$B_k \equiv \Delta_{v100}^2 + \overline{b_n}^2 \Delta_{v\delta 100}^2$$

$$\ell = k\chi$$

Other (pesky) Contaminants

The filter cannot remove contaminants associated with clusters

Cluster Sources

Local processes => no large-scale correlations

=> No Systematic Errors, only Statistical.

Other (pesky) Contaminants

Radio & IR Sources $\sim 10^3 \mathrm{Jy/sr} \;\; at \;\; 217\mathrm{Ghz}$

Aghanim, Hansen & Lagache, astro-ph/0402571

At 217Ghz the non-relativistic TSZ vanishes.

Cluster TSZ Relativistic Correction:

Residual Signal @ 217Ghz band

Correction is few % of TSZ at

Rayleigh-Jeans regime $< 10^3$ Jy/sr

Flux Contribution

Itoh, Kohyama, & Nozawa, 1998, ApJ, 502, 7

Other (pesky) Contaminants

The Expected Fractional Error

$$\eta(k) \approx 5 \times 10^{-3} \frac{\langle \delta S_{\rm cl}^2 \rangle}{z S_{100}^2} \sqrt{\frac{\Delta z}{0.2} \frac{\Delta k / k}{0.4}}$$

where

S_{100}^2 The normalized mean flux of these sources

$\langle \delta S_{\rm cl}^2 \rangle$ The mean square of the flux fluctuations

Since $\langle \delta S_{\rm cl}^2 \rangle^{1/2} \leq \langle S_{\rm cl} \rangle$

$\eta(k)$ is negligible for all k and z

Cosmic Variance and Shot Noise

Intrinsic cosmic variance dominates at large scales.

$N_{\rm cluster}$ is small $\Longrightarrow$ shot noise is large

The shot noise power spectrum

$$\tilde{\Delta}^2_{\rm shot} = \frac{k^3}{\bar{n} 2\pi^2} \sum_{j=1}^{5} \tilde{\sigma}_j^2 \, ,$$

Five dominant sources of shot noise.

1. Discrete Cluster Sources
2. Instrumental Noise
3. Flux fluctuations of primary CMB
4. CIB
5. Background KSZ

Cosmic Variance and Shot Noise

Mean number density of observed clusters

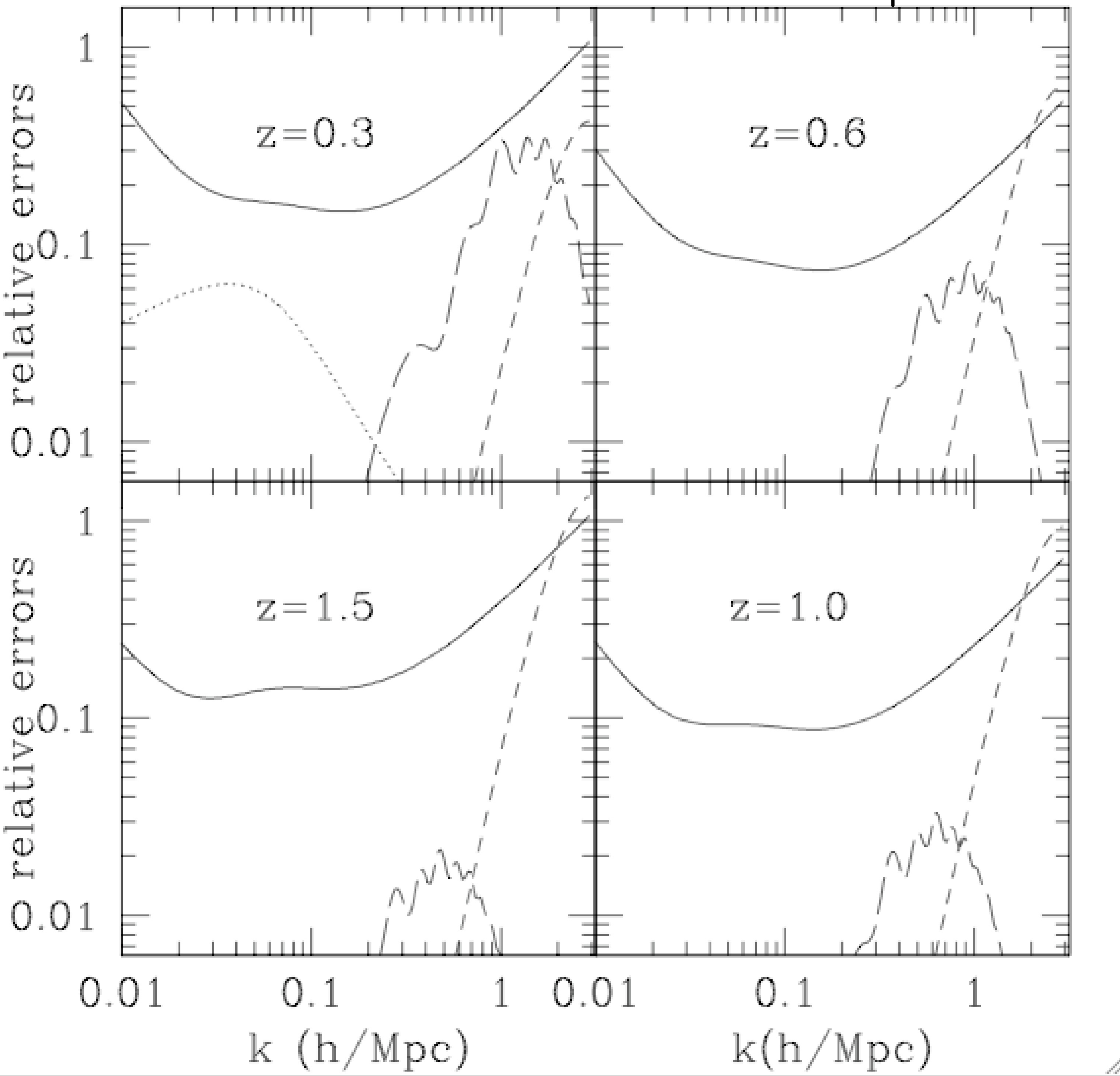
$$\bar{n}(z) = 3 \times 10^{-5}/(1+z)^3 (h/\mathrm{Mpc})^3$$

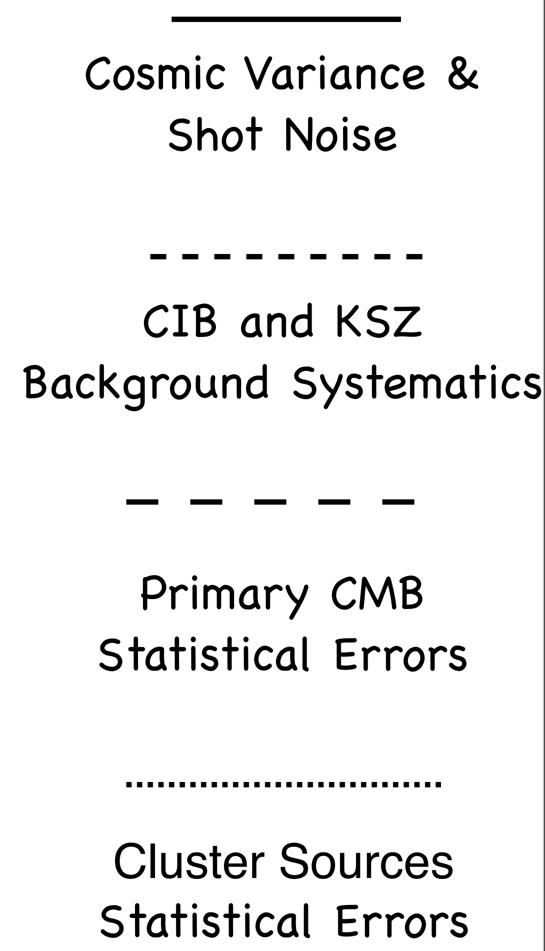
Contributions of the five noise sources

1. Discrete Cluster Sources $\tilde{\sigma}_1 \approx 5\mu K$
2. Instrumental noise
3. Flux fluctuations of primary CMB
4. CIB
5. Background KSZ

$$\tilde{\sigma}_{j=2,5} \approx 20\mu K$$

Dominant Errors of the Cluster KSZ Power Spectrum





For SPT

$$\sigma_{\rm cv+sn} \simeq 10\% \gg \sum_{j=1,5} \tilde{\sigma}_j$$

Direct autocorrelation of the cluster KSZ flux amplifies the signal (cluster bulk velocity correlation).

$$\xi_S(r)$$

The method is optimal to measure the cluster peculiar velocity power spectrum.

$$\Delta_v^2$$

$\sigma_{\rm Statistical} > \sigma_{\rm Systematic}$ for all k and z

For a future all–sky–survey $\sigma_{\rm Total} \approx$ few %