# Detection of the Kinematic Sunyaev-Zeldovich Effect

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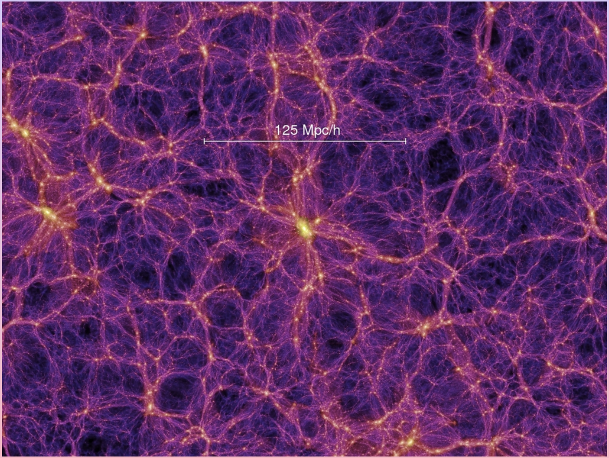

125 Mpc/h

Peculiar velocities are a generic result of structure growth in the universe

# How to Measure Velocities: Doppler Shift

$$\frac{\Delta\nu}{\nu_0} = \frac{v_{\rm los}}{c}$$

or

$$v_{\rm los} = cz, \qquad 1 + z \equiv \frac{\nu}{\nu_0}$$

# How to Measure Velocities In Cosmology

Peculiar velocity = (redshift velocity) - (Hubble velocity)

$$v_{\rm los} = cz - H_0 d$$

Typical $v_{\rm los} \simeq 300\,{\rm km/s} \ = 10^{-3} c$

For $z = 0.1$, need error on $d$ much less than 1% to measure $v_{\rm los}$ via Doppler shift

# Kinematic Sunyaev-Zeldovich Effect

Alternate velocity measurement: for a blob of ionized gas,

$$\frac{\Delta T}{T} \propto M_{\rm gas} v_{\rm los} \qquad (1)$$

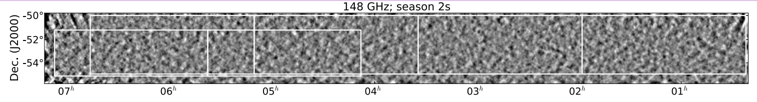
Measures $v$ with respect to CMB rest frame directly, independent of distance (Sunyaev and Zeldovich 1972)

# Size of kSZ Effect

For a galaxy cluster with $M = 3 \times 10^{14}\, M_\odot$ and $v_{\rm los} = 300$ km/s, kSZ distortion is a few $\mu$K over a region of 1 square arcmin.

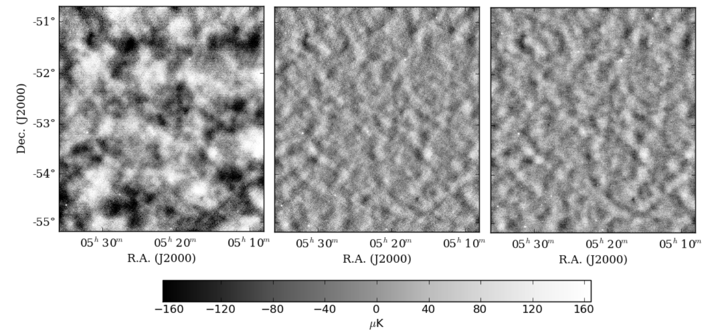
(Also, thermal SZ distortion is a few $\times$ 10 $\mu$K,
$y \propto M_{\rm gas} T_{\rm gas} \propto M^{5/3}$)

# Atacama Cosmology Telescope



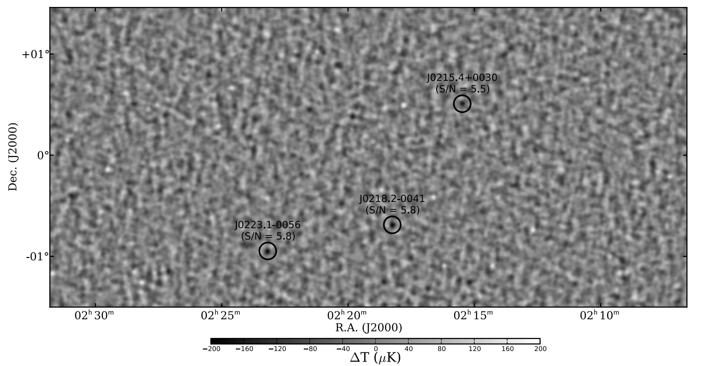

Map sensitivity 20 to 30 $\mu$K arcmin, angular resolution 1.4 arcmin at 148 GHz (S. Das et al. 2013)

# ACT and SPT



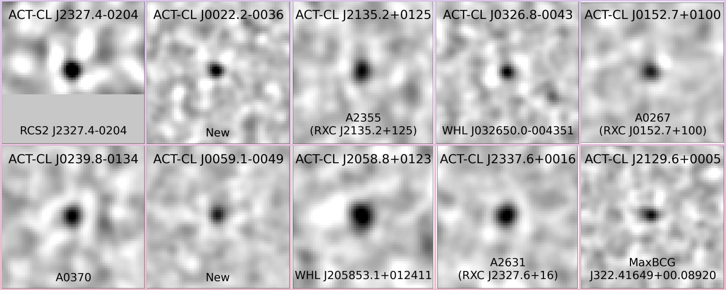

Left: ACT — Center: ACT filtered (S. Das et al. 2013) — Right: SPT

# Galaxy Clusters in Thermal SZ Effect




M. Hasselfield et al. 2013

# Galaxy Clusters in Thermal SZ Effect




M. Hasselfield et al. 2013

# Mean Pairwise Momentum

For galaxy clusters at positions $\mathbf{r}_i$ and momenta $\mathbf{p}_i$, consider

$$p_{\rm pair}(r) \equiv \langle (\mathbf{p}_i - \mathbf{p}_j) \cdot \hat{\mathbf{r}}_{ij} \rangle$$

with $\mathbf{r}_{ij} \equiv \mathbf{r}_i - \mathbf{r}_j$ and $r \equiv |\mathbf{r}_{ij}|$.

If a pair is moving towards each other, contribution is *negative* and if moving away from each other, contribution is *positive*.

Closely related to mean pairwise velocity (Davis and Peebles 1977)

# Line-of-Sight Estimator

$$p_{\rm pair}(r) \approx \frac{\sum_{i<j}(\mathbf{p}_i \cdot \hat{\mathbf{r}}_i - \mathbf{p}_j \cdot \hat{\mathbf{r}}_j) c_{ij}}{\sum_{i<j} c_{ij}^2}$$

$$c_{ij} \equiv \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2} = \frac{(r_i - r_j)(1+\cos\theta)}{2\sqrt{r_i^2 + r_j^2 - 2 r_i r_j \cos\theta}}$$

To use this estimator, need to know $r_i$, $p_{\rm los} = \mathbf{p}_i \cdot \hat{\mathbf{r}}_i$ and sky position for each cluster

# SDSS BOSS Survey in Stripe 82

Sky image from the SDSS-3 collaboration

# BOSS Galaxies

We use positions and redshifts of luminous galaxies in the SDSS Baryon Oscillation Spectroscopic Survey (BOSS) as tracers of galaxy clusters.

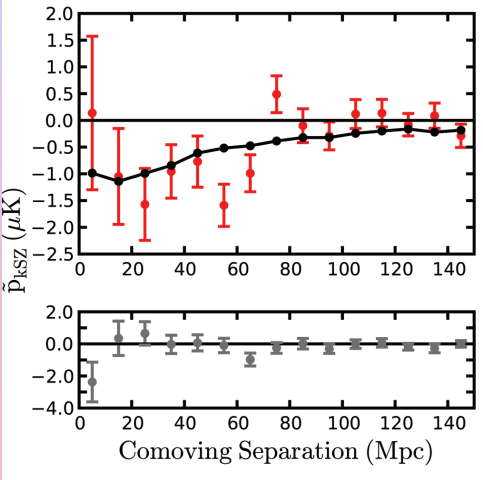
220 square degrees of overlap with ACT maps, 27381 galaxies. $0.05 < z < 0.8$, average $\bar{z} = 0.51$. Most halo masses around $10^{13}\, M_\odot$ with 10% in haloes of $10^{14}\, M_\odot$.

For estimator, use 5000 most luminous galaxies, $L > 8.1 \times 10^{10} L_\odot$

Cluster sky position from BOSS galaxy position

Cluster $r_i$ from BOSS redshift and standard cosmological model

Cluster $p_{\rm los}$ from temperature $T_i$ which is a noisy estimator of the kSZ signal plus other signals which average to zero




Model curve with cluster mass cutoff $M_{200} = 4.1 \times 10^{13} M_\odot$

Chance due to noise is $2 \times 10^{-3}$

N. Hand et al. 2012

First detection of the kinematic Sunyaev-Zeldovich Effect

Direct detection of motions at cosmological distances

Detection of “missing baryons” in galaxy groups

Signal dominated by Poisson and map noise, not systematic errors: linear, differential statistic