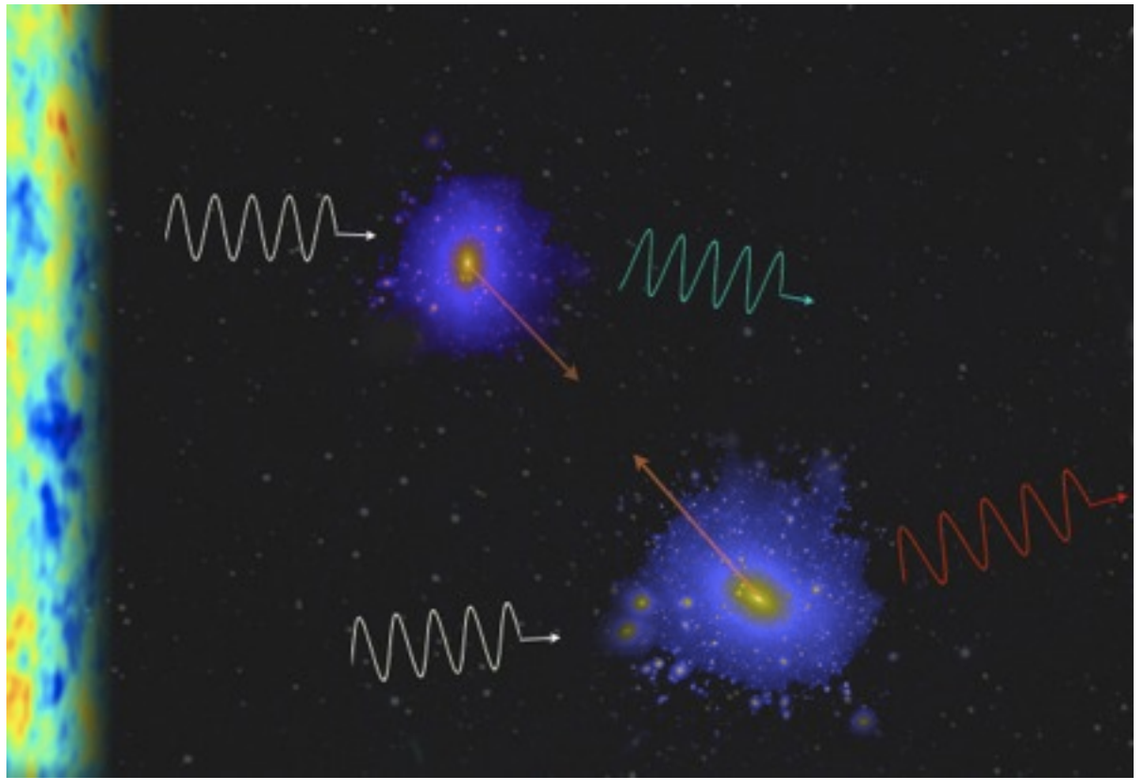
Detection of galaxy cluster motions with data from the Atacama Cosmology Telescope and BOSS



Nick Hand

UC Berkeley

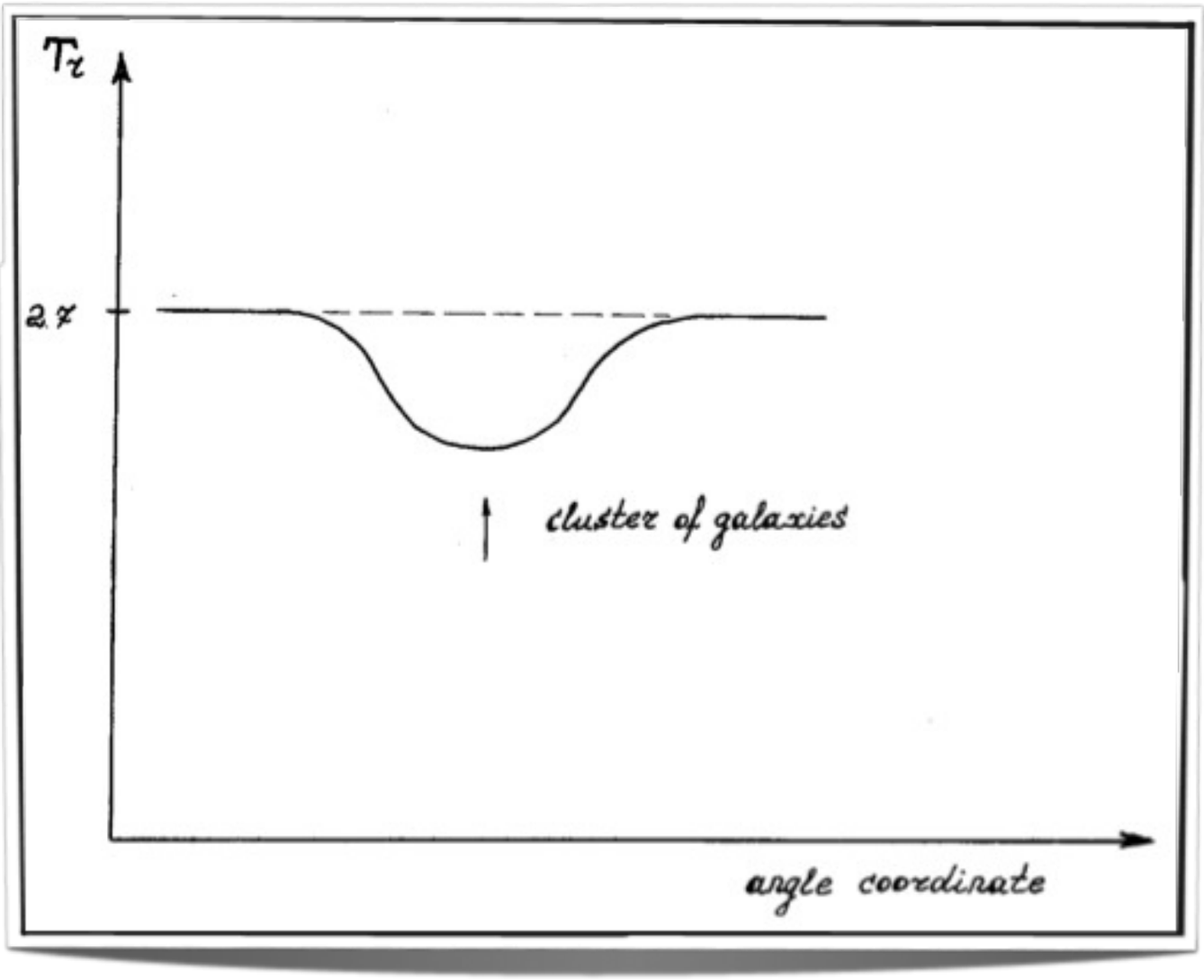
INPA Journal Club
March 30, 2012

Hand et al. 1203.4219

Outline

- SZ background information
- order of magnitude estimates
- breakdown of Hand et al. 1203.4219
  - methodology
  - results
- applications / future work

Some historical context ...



Sunyaev & Zel'dovich (1972)

How to explain the observed 'hole' in the Coma cluster?

The thermal Sunyaev-Zel'dovich effect

Menanteau et al. (2012)

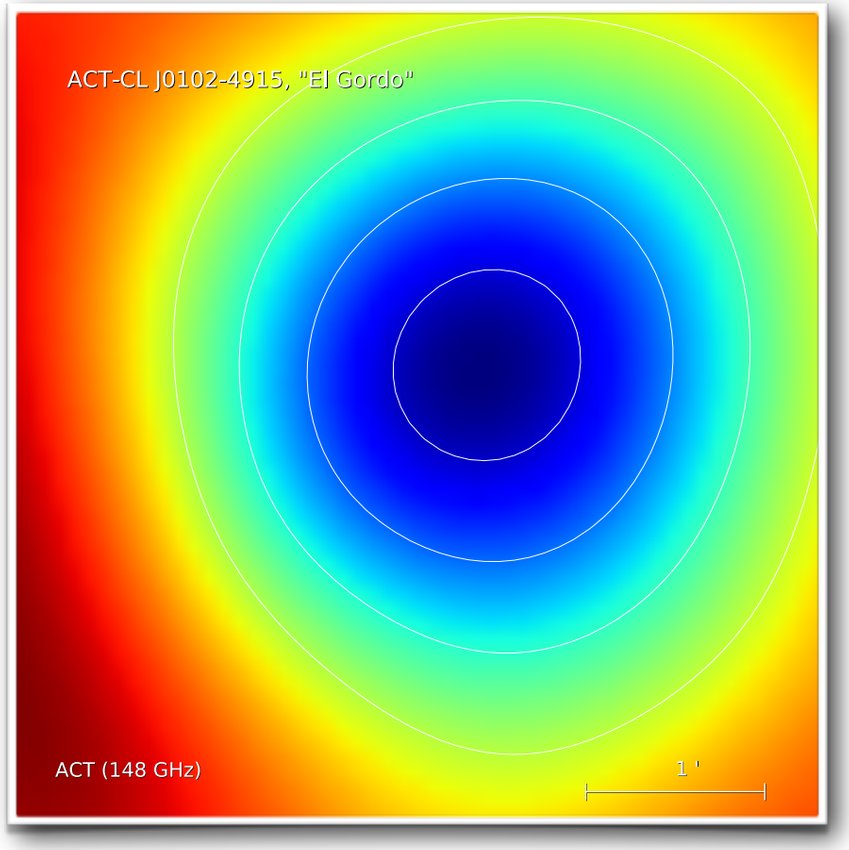
- inverse Compton scattering between free electrons and CMB photons
- arcminute-scale decrement at 148 GHz
- measures the thermal content
- nearly independent of redshift

electron gas pressure

$$\frac{\delta T_{\rm tSZ}}{T_{\rm CMB}} = f(x)y = \boxed{\left(\frac{x(e^x+1)}{e^x-1} - 4\right)} \int \sigma_T \frac{\boxed{n_e k T_e}}{m_e c^2} \mathrm{d}\ell$$

unique frequency dependence

The thermal Sunyaev-Zel'dovich effect



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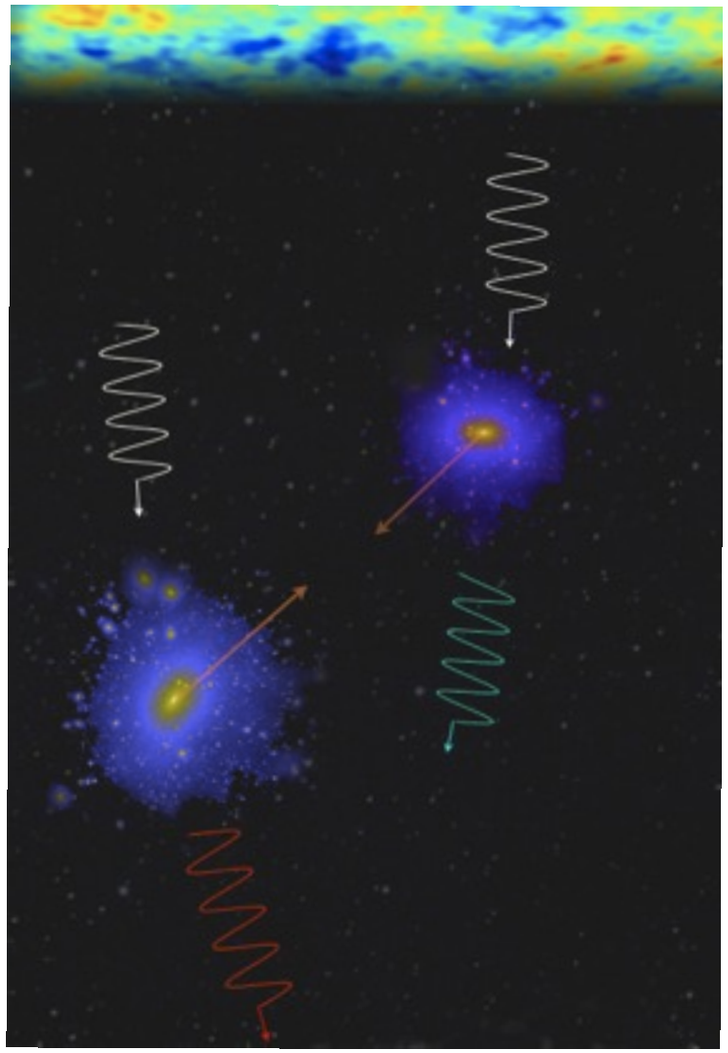
unique frequency dependence

The kinematic Sunyaev-Zel'dovich effect

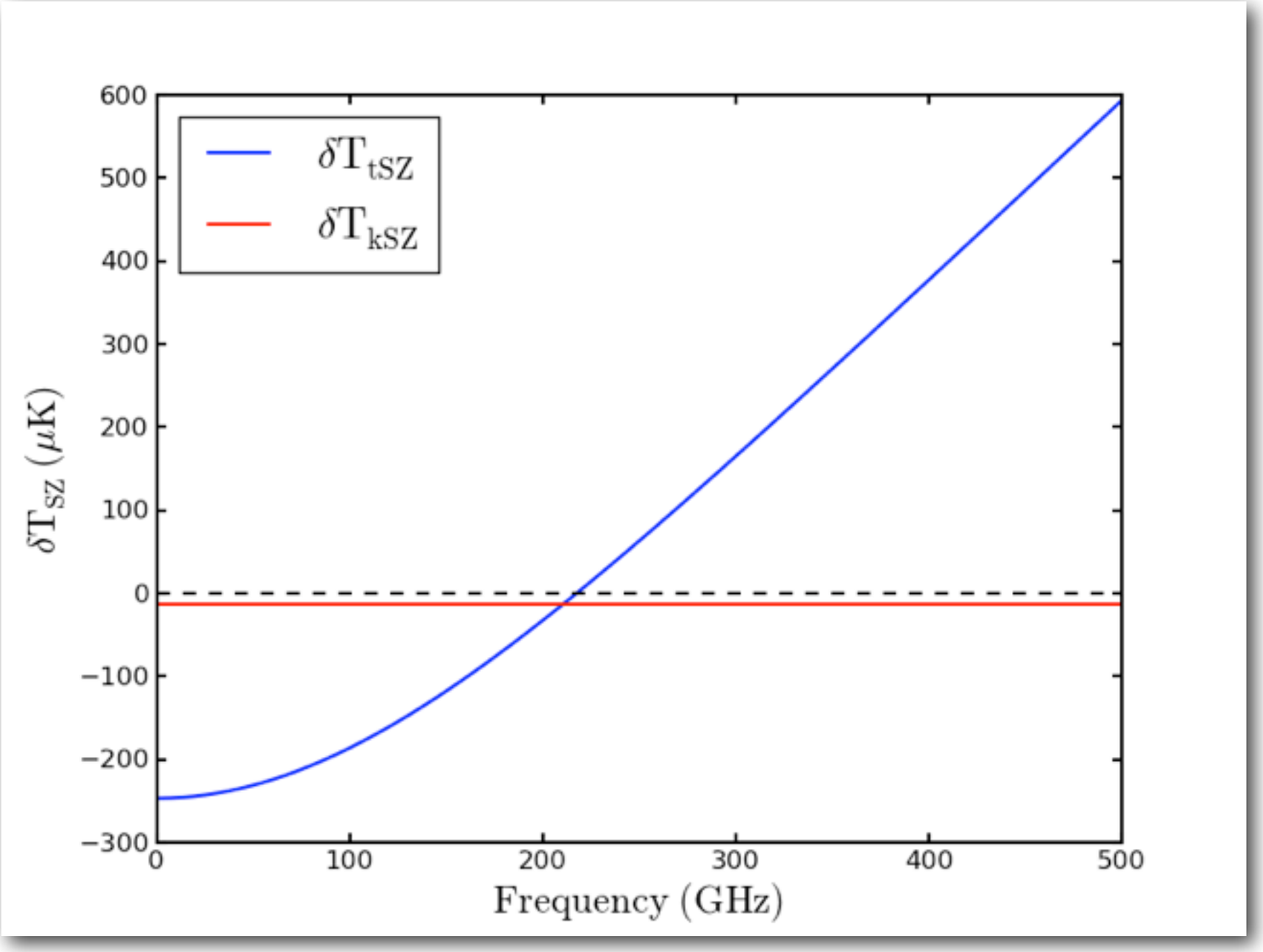


- Doppler-induced temperature distortion of CMB photons
- measures integrated momentum
- no frequency dependence for temperature distortion
- also nearly independent of redshift

electron gas momentum

$$\frac{\delta T_{\rm kSZ}}{T_{\rm CMB}} = -\tau\left(\frac{v_{\rm pec}}{c}\right) = -\int \sigma_T \frac{n_e v_{\rm pec}}{c} {\rm d}\ell$$

The SZ shifts for a massive cluster

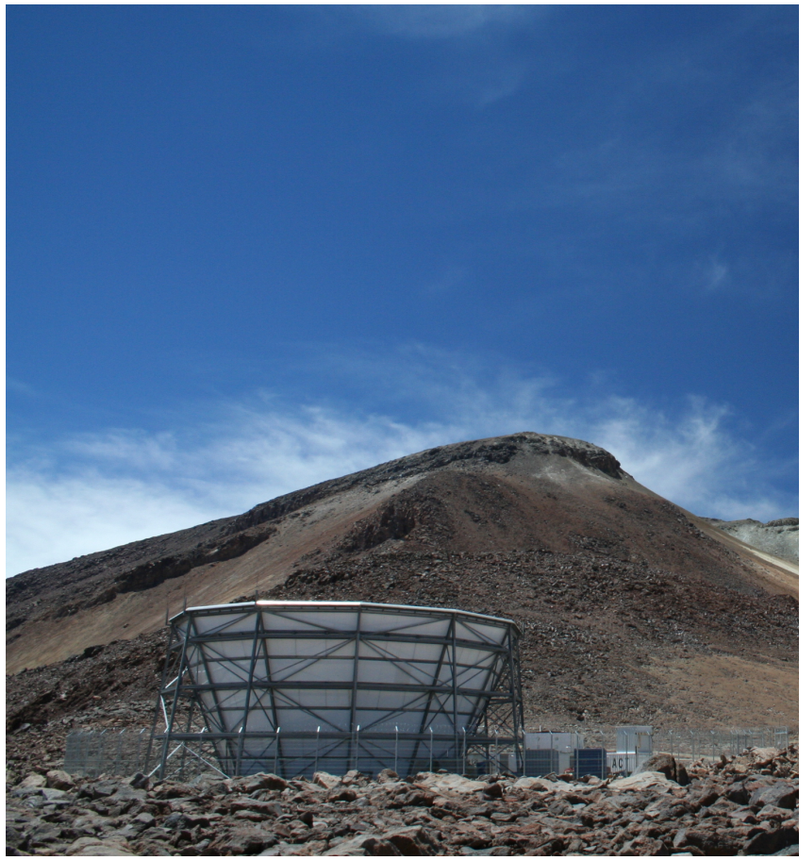


kSZ signal is smaller by an order of magnitude!

assumes $kT_e = 5$ keV, $v_{pec} = 300$ km/s

Measuring the kSZ effect with ACT

- PI: Lyman Page, Princeton
- 80 scientists on 5 continents
- 6-meter telescope on Cerro Tocco (5200 m) in the Atacama Desert.
- Observing the sky at 148, 218 and 277 GHz



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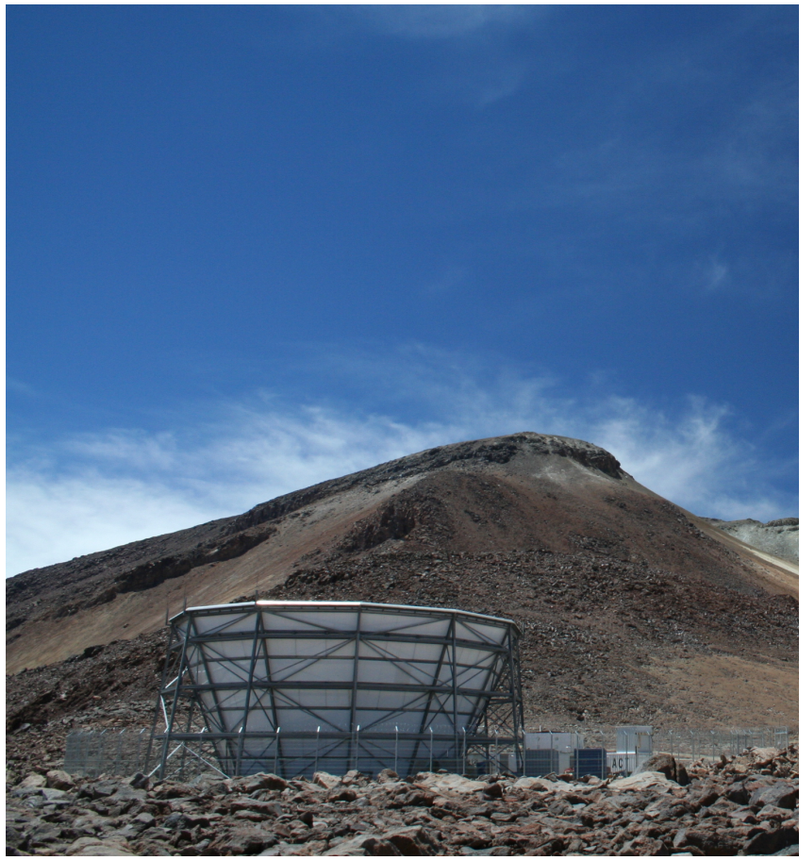
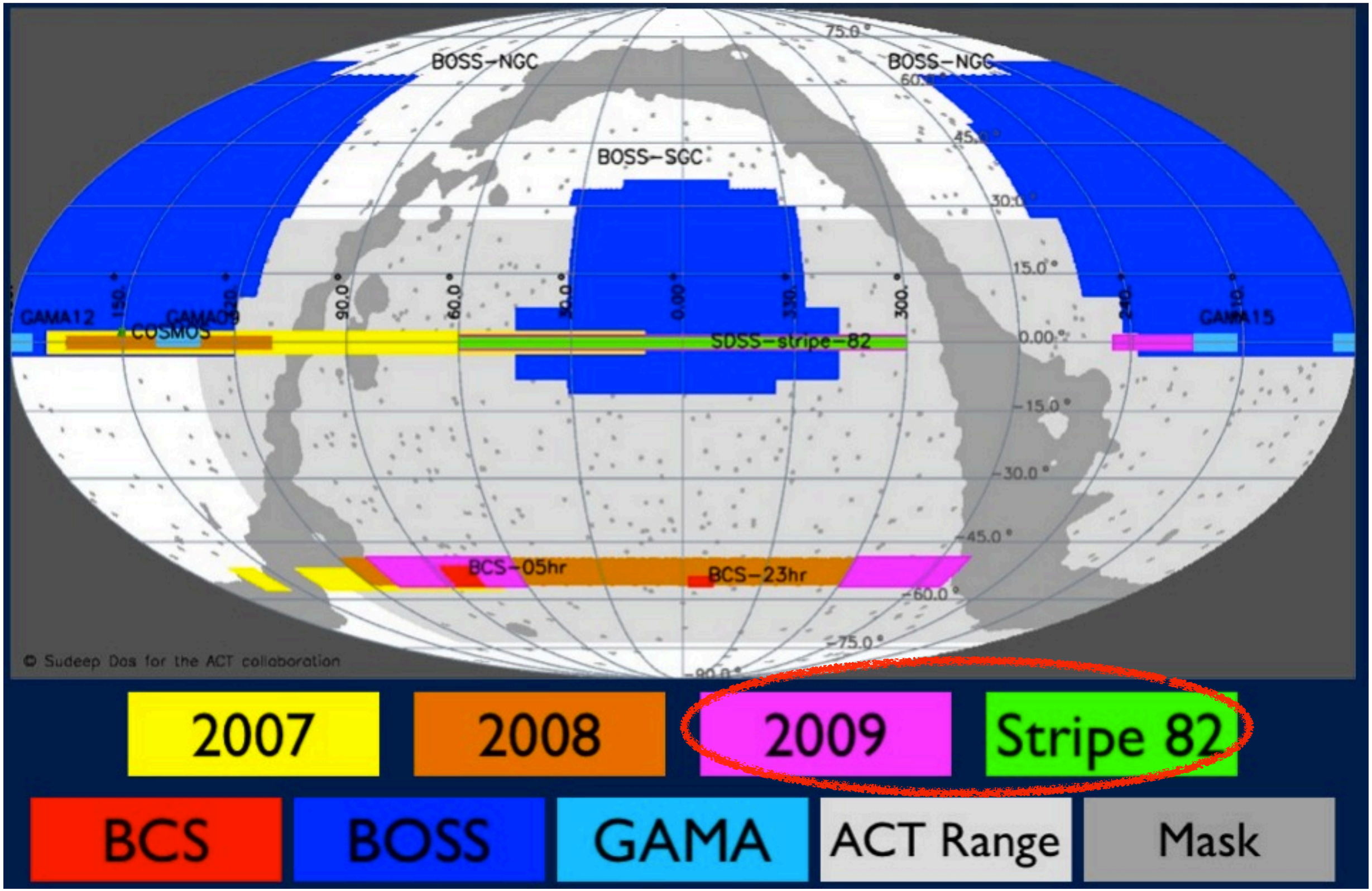


How to achieve necessary S/N for a kSZ measurement?

Cross-correlate ACT with BOSS!



Mapping 'Luminous Galaxies' with BOSS

BOSS in process of obtaining spectra for 1.5 million luminous galaxies

Two galaxy samples in upcoming DR9 release

LOZ: $0.2 < z < 0.4$, $z_{med} \sim 0.3$

CMASS: $0.4 < z < 0.7$, $z_{med} \sim 0.57$

Preferentially sit in massive halos: $\sim 10^{13} - 10^{14}\ M_{sun}$

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Two relevant questions:

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1. What tSZ/kSZ amplitude should we expect in this halo mass range?

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Redshifts/sky locations for thousands of potential clusters

Two relevant questions:

1. What tSZ/kSZ amplitude should we expect in this halo mass range?
2. How many galaxies to achieve a given S/N?

SZ vs halo mass: order of magnitude scaling

Thermal SZ

$$\delta T_{\rm tSZ} \propto \tau(M) T_e(M)$$

$\rightarrow$ $T_e \propto M^{2/3}$

$\rightarrow$ $\tau \propto M$

$$\boxed{\delta T_{\rm tSZ} \propto M^{5/3}}$$

Kinematic SZ

$$\delta T_{\rm kSZ} \propto \tau(M)$$

$\rightarrow$ $\tau \propto M$

$$\boxed{\delta T_{\rm kSZ} \propto M}$$

If $|\delta T_{\rm tSZ}| = 10\ |\delta T_{\rm kSZ}|$ at $M = 10^{15}\ M_{\rm sun}$:

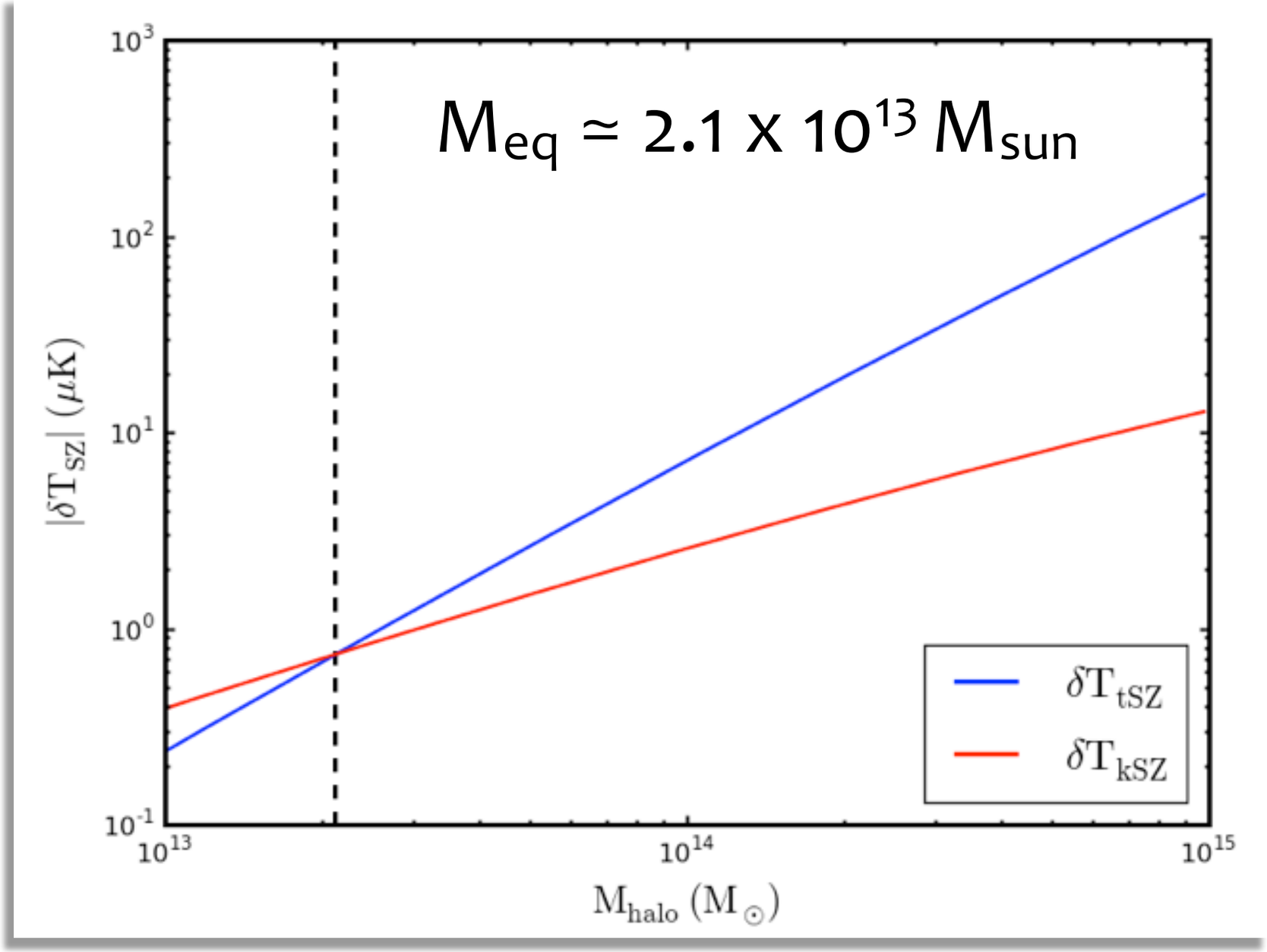
SZ signals equal at $M_{\rm eq} \simeq 3 \times 10^{13}\ M_{\rm sun}$

a little more quantitatively ...

δT_{tSZ} at 148 GHz

δT_{kSZ} uses
v_{pec} = 300 km/s

$|\delta T_{tSZ}| \sim |\delta T_{kSZ}|$
$\sim 1\ \mu K$
in relevant halo
mass range for BOSS



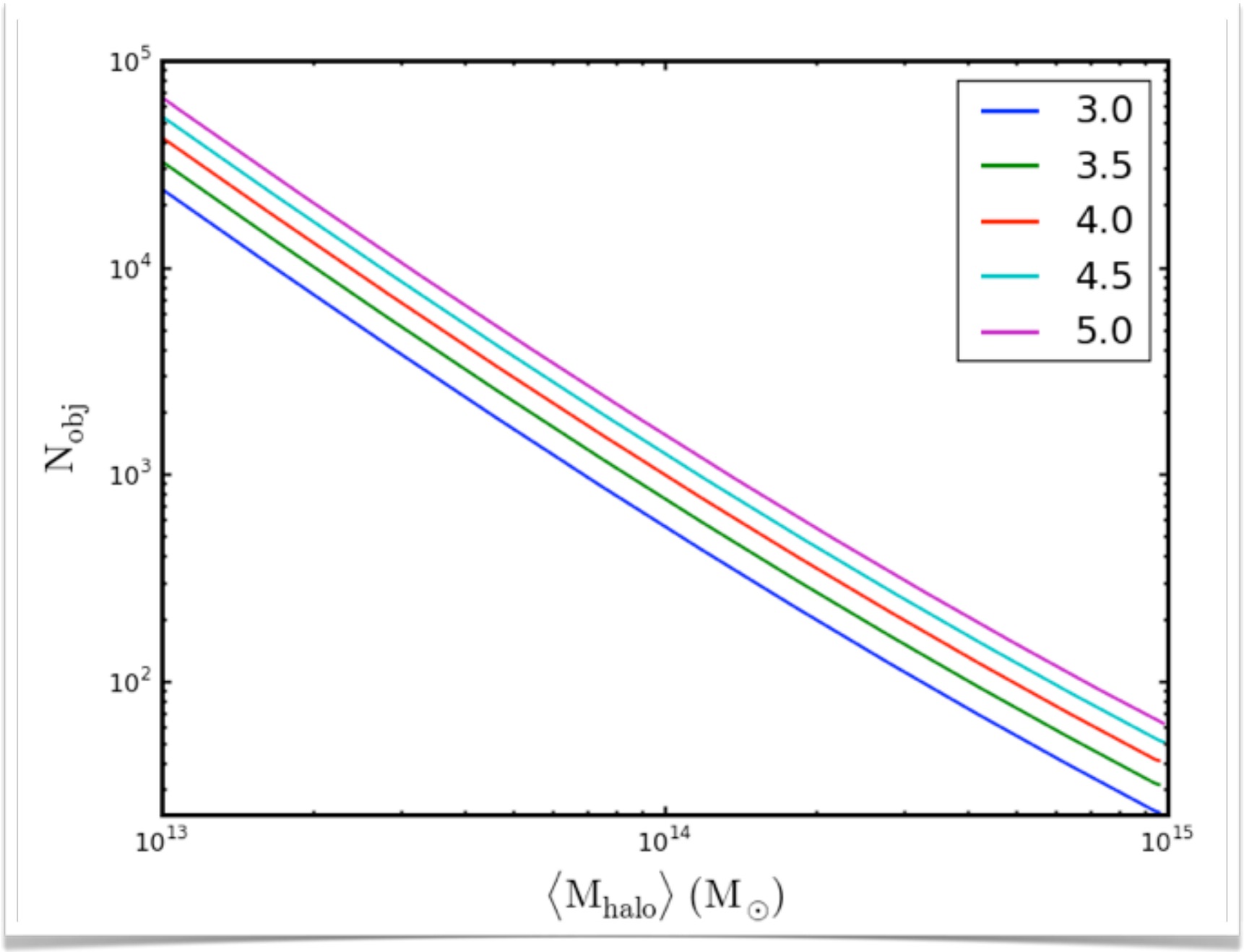
How many galaxies for a given kSZ S/N?

- Consider Poisson noise in N_{obj}: $N_{\rm poisson} \propto (N_{\rm obj})^{-1/2}$
- Estimate the ACT pixel noise: $\sigma_{\rm ACT} \simeq 20\ \mu{\rm K/pixel}$

order of magnitude estimate:

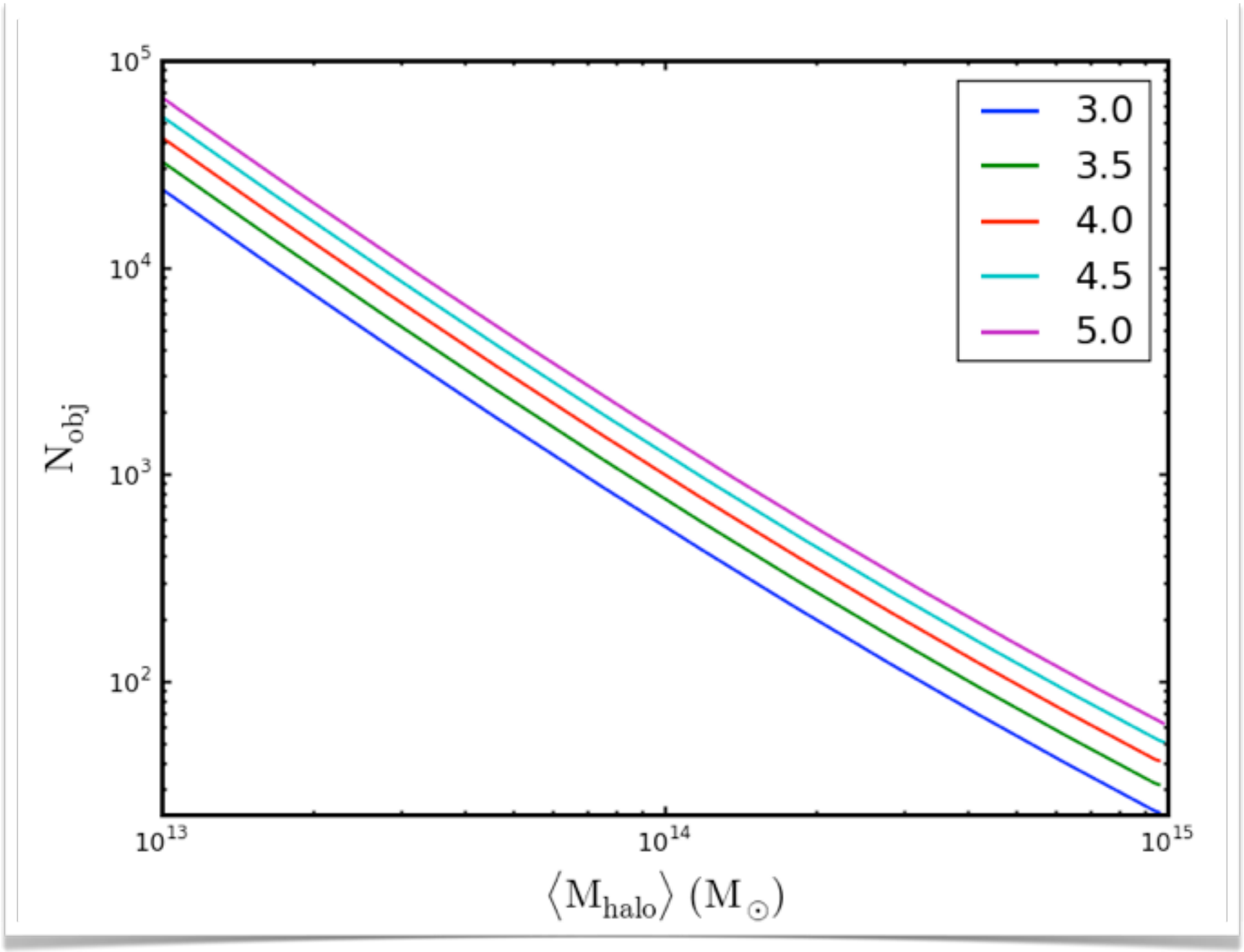
$$N_{\rm obj} \sim \left[\frac{(S/N)\sigma_{\rm ACT}}{\delta T_{\rm kSZ}(M)}\right]^2$$

How many galaxies for a given kSZ S/N?



5,000 - 10,000 galaxies needed for ~4σ detection at average mass ~4 x 10^{13} M_{sun}

How many galaxies for a given kSZ S/N?



5,000 - 10,000 galaxies needed for ~4σ detection at average mass ~4 x 10^{13} M_{sun}

possible with ACT x BOSS correlation

ACT Data

- 148 GHz sky map taken from 2008-2010
- strip 3° wide and 110° long centered on celestial equator
- 1.4′ angular resolution
- noise per pixel: 15 - 25 μK

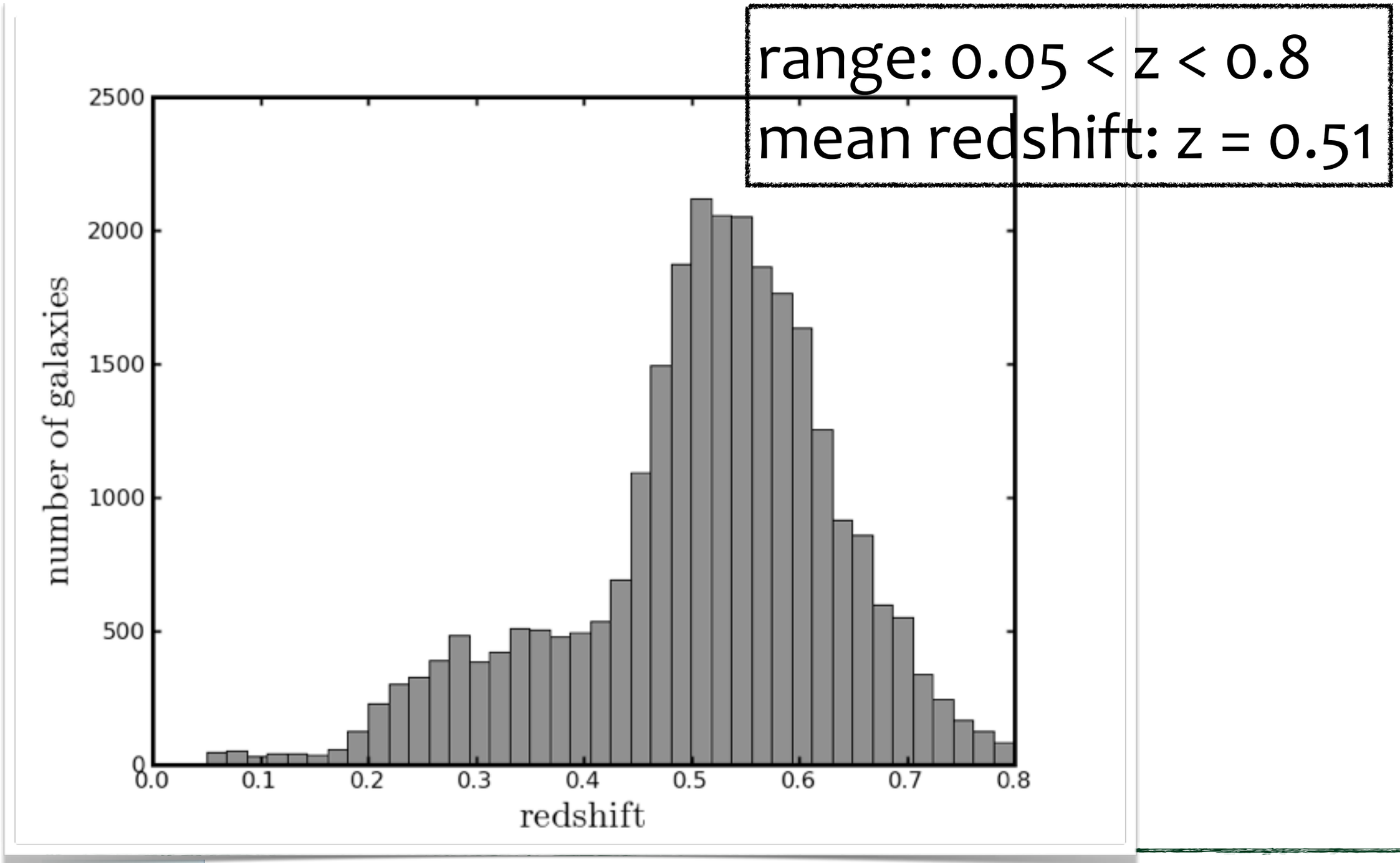
BOSS Data

- galaxies drawn from both CMASS and LOZ DR9 samples
- right ascension slightly smaller than ACT footprint:

$$-43° < \alpha < 45°$$

- 27,291 BOSS galaxies in overlap region
- about 100 galaxies per sq. degree on sky
- exclude any galaxies falling within 1′ of 1.4 GHz FIRST radio source

Sample redshift distribution



Verifying the galaxy sample traces massive halos ...

First, stack filtered ACT data at galaxy locations to compute tSZ signal

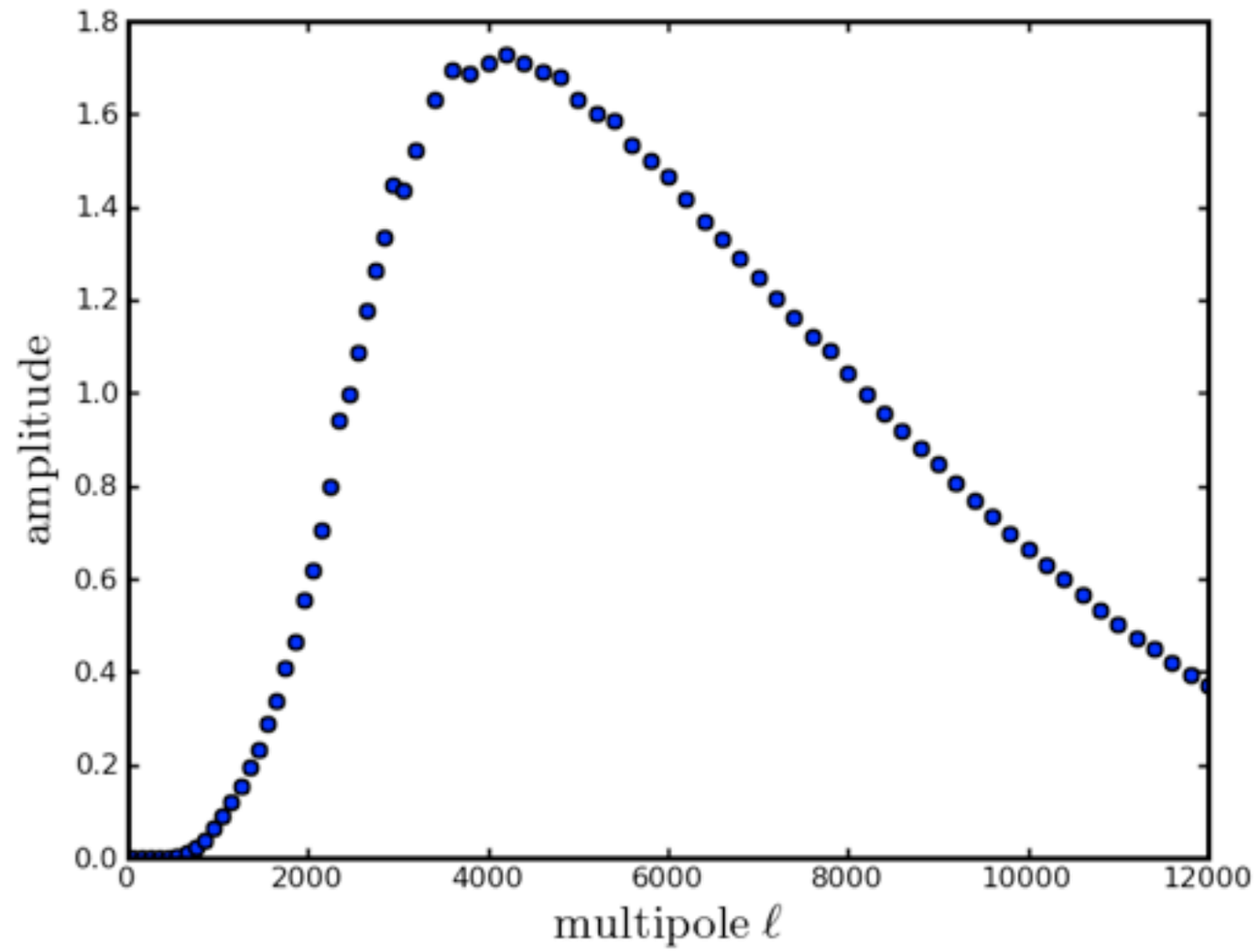
- Filtering process identical to *Hand et al., ApJ (2011)*
- Before applying the filter:
    - Mask point sources with S/N > 5 in ACT data
    - weight map by $\sqrt{N_{\rm obs}(x)/N_{\rm obs,max}}$

Verifying the galaxy sample traces massive halos ...

- match filter ACT data in Fourier space:

$$\delta T_{\rm filt}(k) = \frac{\tilde{B}^\star(k)\ |\delta\tilde{T}_{\rm other}(k)|^{-2}\ \delta\tilde{T}(k)}{\int \tilde{B}^\star(k')\ |\delta\tilde{T}_{\rm other}(k')|^{-2}\ \tilde{B}(k')dk'}$$

signal profile $B(\theta)$ chosen to be equal to ACT 148 GHz beam function ($\theta = 1.4'$)



tSZ Stacking Methods

- Verify that galaxy luminosity correlates with halo mass
    - Bin galaxy sample by *r*-band luminosity, as in *Hand et al., ApJ (2011)*
    - luminosities computed from CMODEL magnitudes
- Perform weighted sum of filtered ACT 10′ x 10′ submaps centered on each galaxy

Bin	$N_{\rm gal}$	$\langle L_{0.1r} \rangle$ $10^{10} L_\odot$	$L_{0.1r}$ Range $10^{10} L_\odot$	$\langle z \rangle$
1	225	21.4	15.9 – 61.4	0.66
2	1326	11.8	9.9 – 15.9	0.62
3	4100	8.1	6.9 – 9.9	0.57
4	8467	5.8	5.0 – 6.9	0.52
5	13173	3.7	0.01 – 5.0	0.48
total	27291	5.7	0.01 – 61.4	0.51

tSZ Stacking Results

Bin	δT_{148} μK	δT_{218} μK	$\delta T_{\rm tSZ}$ μK
1	-5.25 ± 1.76	$+1.90 \pm 2.62$	-5.87 ± 1.96
2	-1.09 ± 0.73	$+2.07 \pm 1.06$	-1.76 ± 0.81
3	-0.04 ± 0.39	$+2.77 \pm 0.59$	-0.94 ± 0.43
4	$+0.29 \pm 0.27$	$+1.97 \pm 0.42$	-0.35 ± 0.30
5	$+0.39 \pm 0.22$	$+1.60 \pm 0.34$	-0.13 ± 0.25
total	$+0.17 \pm 0.16$	$+1.92 \pm 0.23$	-0.45 ± 0.18

148 GHz results

218 GHz results

'dust-subtracted' 148 GHz results

$$\delta T_{\rm tSZ} \equiv \delta T_{148} - 0.325\ \delta T_{218}$$

see Hall et al., 2010 (SPT power spectra)

now on to measuring the kSZ signal ...

The pairwise momentum statistic

now have thousands of cluster line-of-sight momenta, from kSZ temperature shift in ACT data

- compute the mean pairwise momentum:

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

- $p_{pair} < 0$ when two objects moving towards each other
- measures the mean tendency of objects to approach each other due to gravitational attraction

The pairwise momentum statistic

- we can estimate p_{pair} using only line-of-sight momenta:

$$\tilde{p}_{\rm pair}(r) = \frac{\sum_{i<j}(\boldsymbol{p}_i \cdot \hat{\boldsymbol{r}}_i - \boldsymbol{p}_j \cdot \hat{\boldsymbol{r}}_j)c_{ij}}{\sum_{i<j} c_{ij}^2}$$

see e.g., *Ferreira et al. (1999)*

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

- 'collinearity' c_{ij} is geometric weight:
  - $c_{ij} = 0$, if objects are equidistant from observer
  - $c_{ij} = \pm 1$, if objects are aligned along line-of-sight
- related to familiar mean pairwise velocity:

$$p_{\rm pair} = \langle M_{\rm halo} \rangle\, v_{\rm pair}$$

Pairwise Momentum from the kSZ Shift

- relate line-of-sight momenta to measured kSZ temperature shift in ACT data

$$T_{\mathrm{kSZ},i} \equiv -N_{\mathrm{kSZ}}\ \boldsymbol{p}_i \cdot \hat{\boldsymbol{r}}_i$$

- N_{kSZ} depends on ACT pixel scale, beam size, cluster profile

estimate N_{kSZ} from Seghal et al. (2010) microwave sky simulations

v_{pec} = 200 km/s, $M_{200} = 10^{13}\ M_{sun}$:
$|T_{kSZ}| \simeq 0.9\ \mu K$
v_{pec} = 200 km/s, $M_{200} = 10^{14}\ M_{sun}$:
$|T_{kSZ}| \simeq 2.2\ \mu K$

Possible Contamination Sources

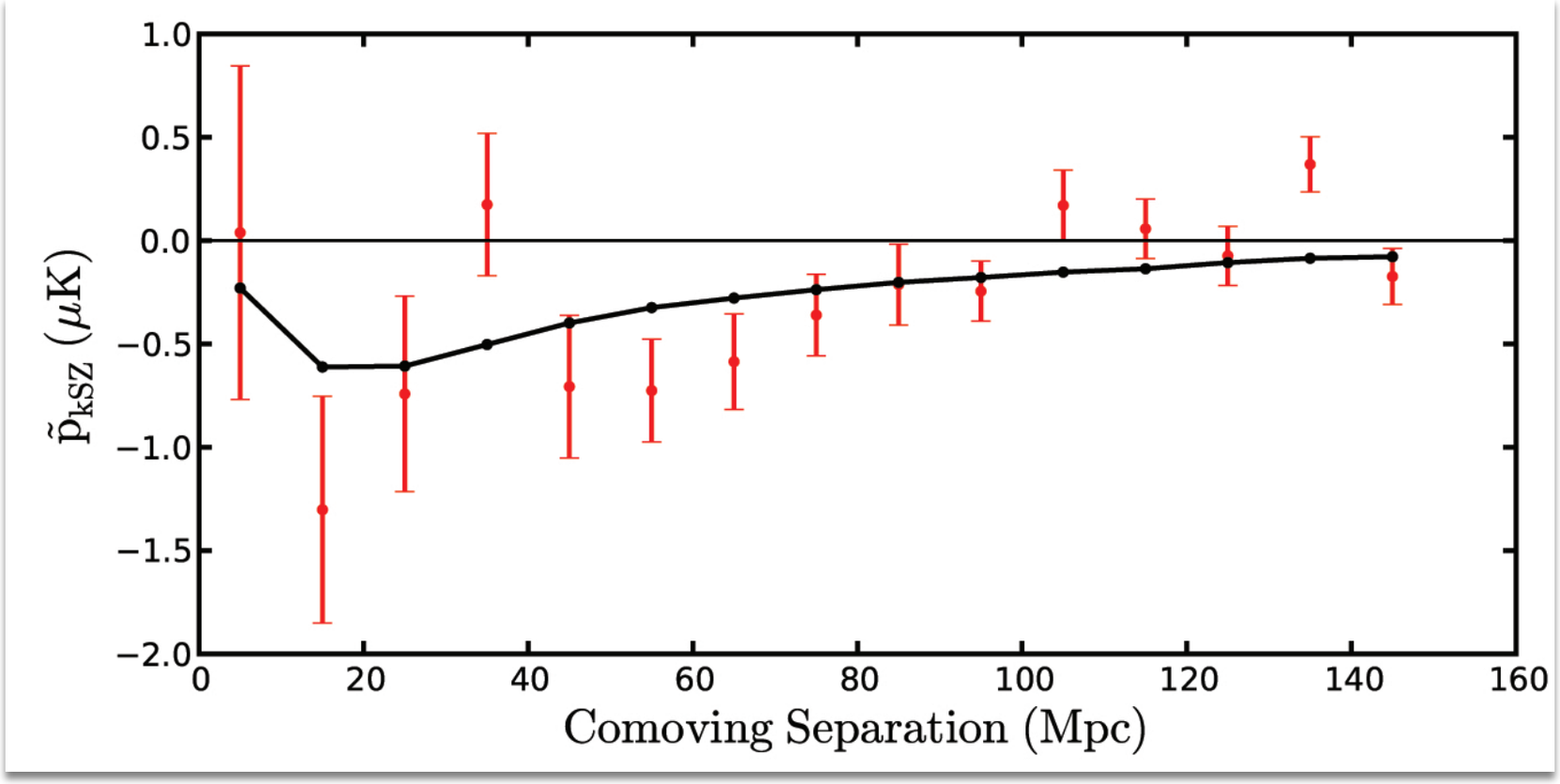
- advantageous systematic error properties
    - linear and differential
- tSZ signal from individuals clusters will subtract out

- redshift-dependent signals can lead to erroneous signal
    - subtract out mean temperature at given redshift

$$\tilde{p}_{\rm kSZ}(r) = -\frac{\sum_{i<j} c_{ij}\left[(T_i - \mathcal{T}(z_i)) - (T_j - \boxed{\mathcal{T}(z_j)})\right]}{\sum_{i<j} c_{ij}^2}$$

mean, Gaussian smoothed temperature around redshift z_j

Mean Pairwise Momentum Detection



compute p_{kSZ} for 7500 most luminous galaxies

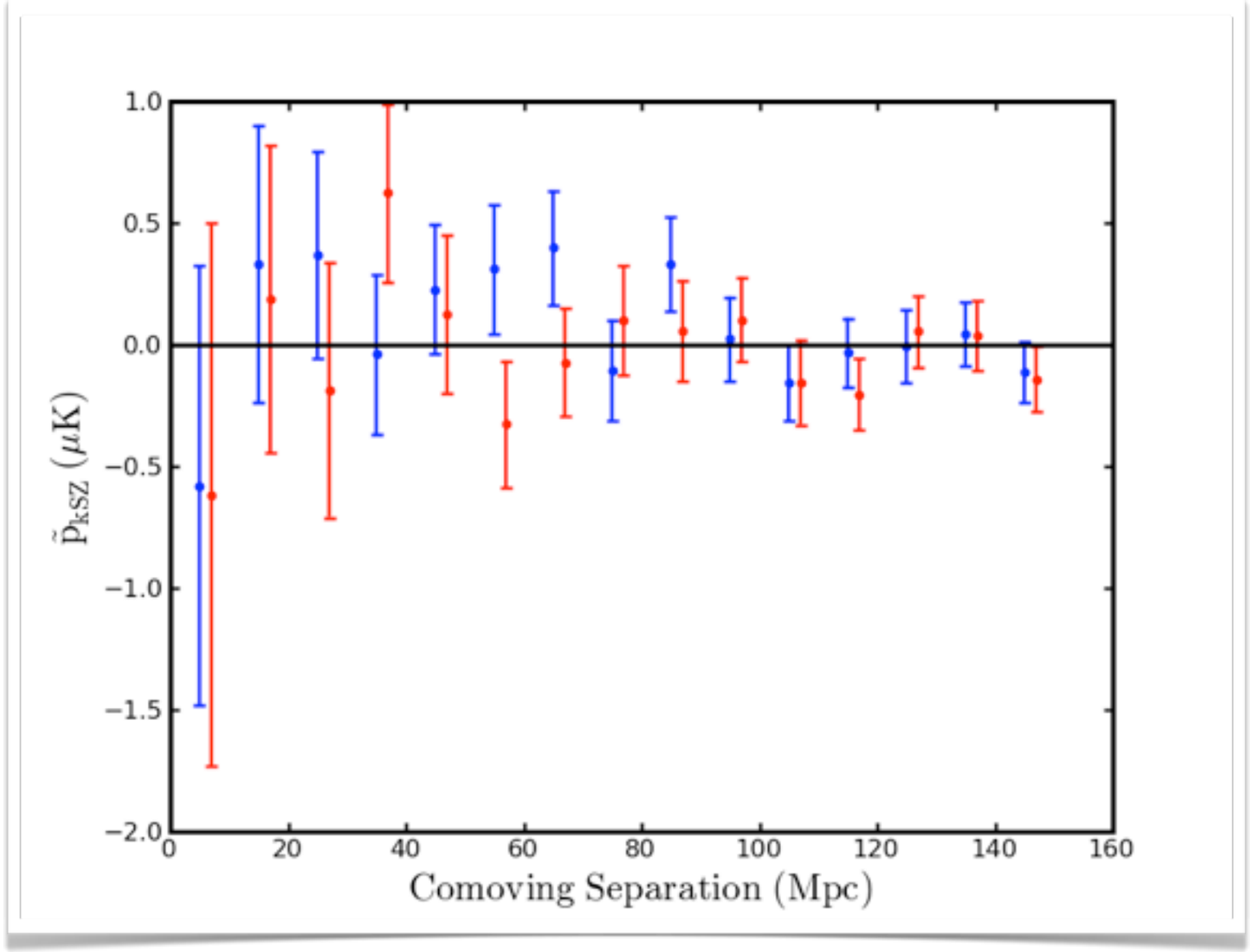
using ACT 148 data, filtered at scale $\theta = 4.2'$

- bin errors computed by bootstrap resampling
- 3.8σ away from zero, including correlations between bins

Null Tests

compute same summation for p_{kSZ} but:

1. using random sky locations (blue)
2. changing the sign in the 2nd term of p_{kSZ} from negative to positive (red)



both tests consistent with zero

Fitting for the average halo mass

- we can relate the kSZ momentum estimator to the mean pairwise velocity:

$$p_{\rm kSZ}(r) = N_{\rm kSZ}\ \langle M_{\rm halo}\rangle\ \boxed{f_b}\ v_{\rm pair}(r)$$

baryon fraction

- assume f_b equal to cosmological value
- vary <M_{halo}> in Seghal et al. simulations to get best fit to data results:

$$\langle M_{200}\rangle \simeq 4.0\times 10^{13}\ M_\odot \qquad M_{200,\rm cut} \simeq 2.5\times 10^{13}\ M_\odot$$

roughly consistent with BOSS clustering masses

Missing Baryon Problem

- baryon fraction known at high redshift from Big Bang nucleosynthesis and at $z \simeq 3$ from studies of Lyα lines
- census of baryons at low redshift

➡ only 1/10 of amount at high redshift

'missing' baryons believed to be gas filaments connecting virialized groups and clusters (~0.5 - 10 x 10^6 K)

Using p_{kSZ} to measure the baryon fraction?

- kSZ effect is proportional to electron gas number density
- no dependence on temperature (unlike tSZ effect)

ACT maps filtered at scale 4.2′, corresponds to ~1 Mpc at z= 0.5

→ p_{kSZ} is measuring f_b on Mpc scales in groups/clusters

Need to carefully compute $\langle M_{halo} \rangle$ and $\langle b \rangle$ for galaxy sample:

$$p_{\rm kSZ}(r) = N_{\rm kSZ}\ \langle M_{\rm halo} \rangle\ f_b\ v_{\rm pair}(r)$$

compute $v_{pair}(r)$ using <b>, assuming fiducial ΛCDM model

measure f_b from the amplitude of p_{kSZ}

Summary

- kSZ effect sensitive to cluster motions on cosmological scales ⟶ unique probe of large scale structure
- combination of ACT and BOSS data sets has detected galaxy cluster motions using the kSZ effect
- kSZ effect probes electron distribution around groups / clusters ⟶ finding the missing baryons?
- future improved measurements:

  ACTPol: increased sensitivity, larger sky coverage

  BigBOSS: deeper with increased sky coverage
- kSZ effect opening new window into the large scale structure

Thank You