Detection of the kinetic Sunyaev-Zel'dovich effect in galaxy clusters

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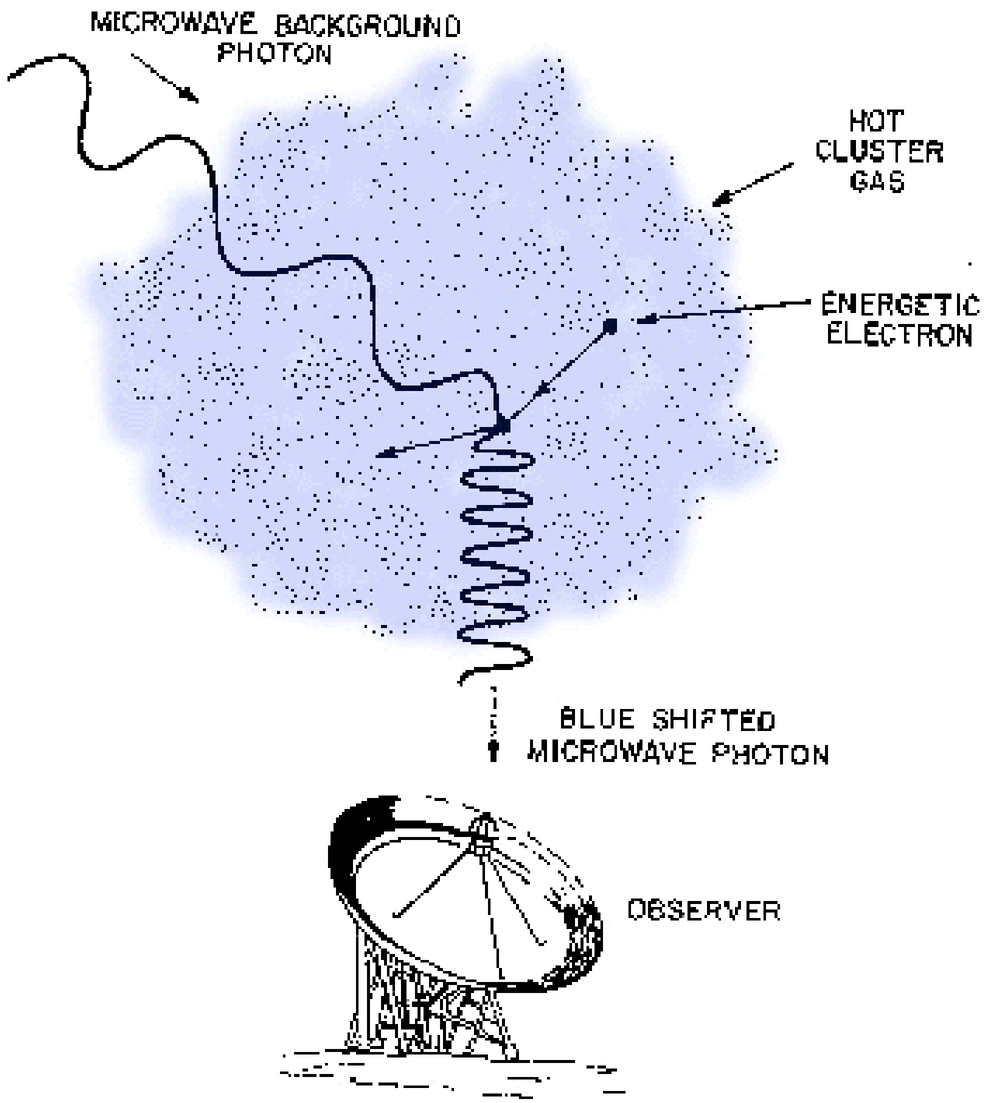
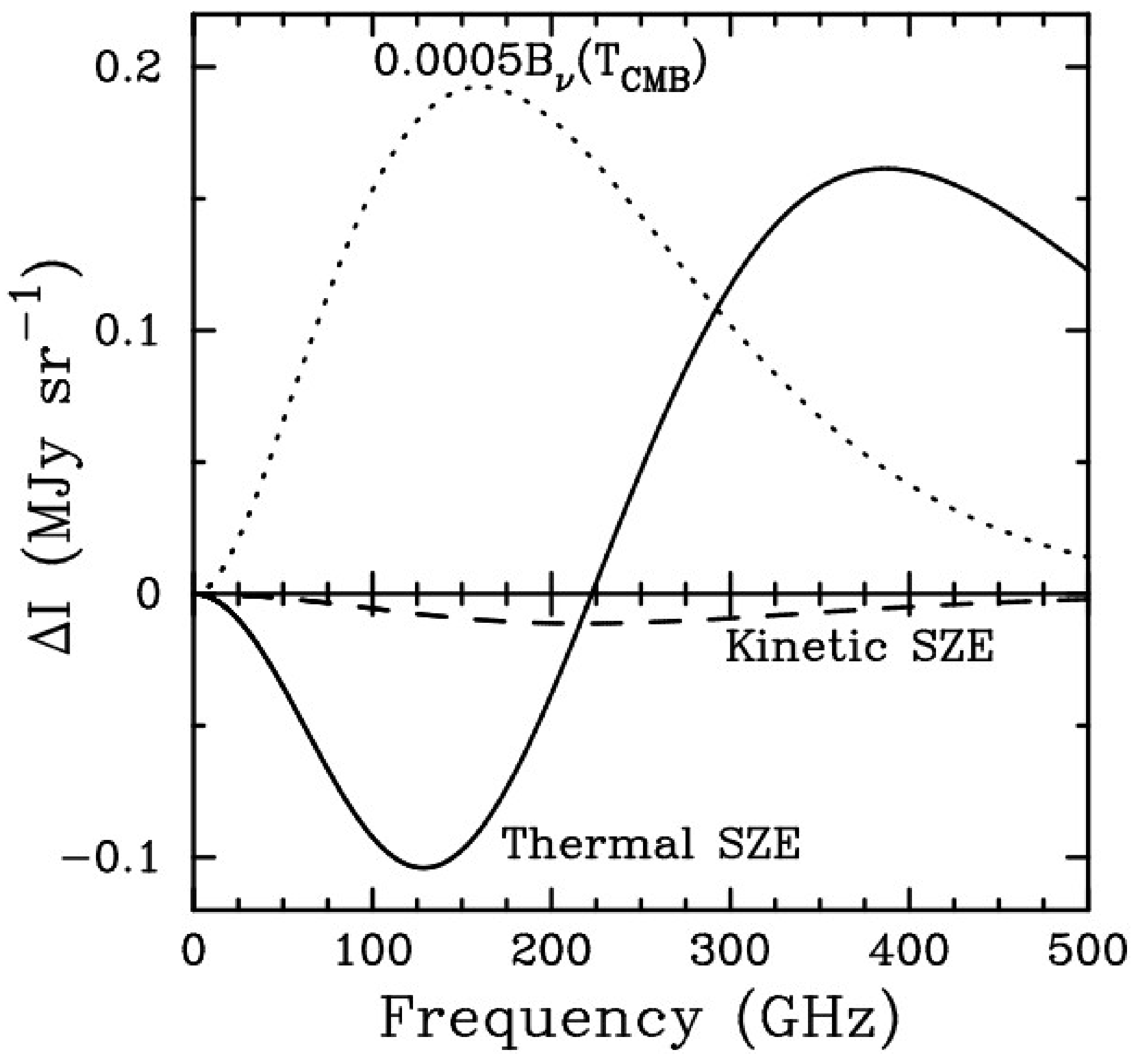
Sunyaev-Zel'dovich(SZ) Effect

SZ effect is the distortion of the CMB spectrum
caused by high energy electrons in galaxy clusters.



tSZ: Thermal motion of gas in galaxy clusters
kSZ: Peculiar velocity of galaxy clusters



Spectral distortion of the CMB by a galaxy cluster
with T=10 keV, y=1e-4, Vpec=500 km/s (Carlstrom et al 2002)

Motivation

$$\frac{\Delta T_{\mathrm{ksz}}}{T_{\mathrm{CMB}}} = -\tau_{\mathrm{e}} \frac{v_{\mathrm{pec} //}}{c}$$

(Cosmological)

1, Given an optical depth, we can obtain a peculiar velocity.

→ kSZ can be used to trace the growth of velocities (structure) along the cosmic time.
But our result was not sensitive to the cosmological parameter.

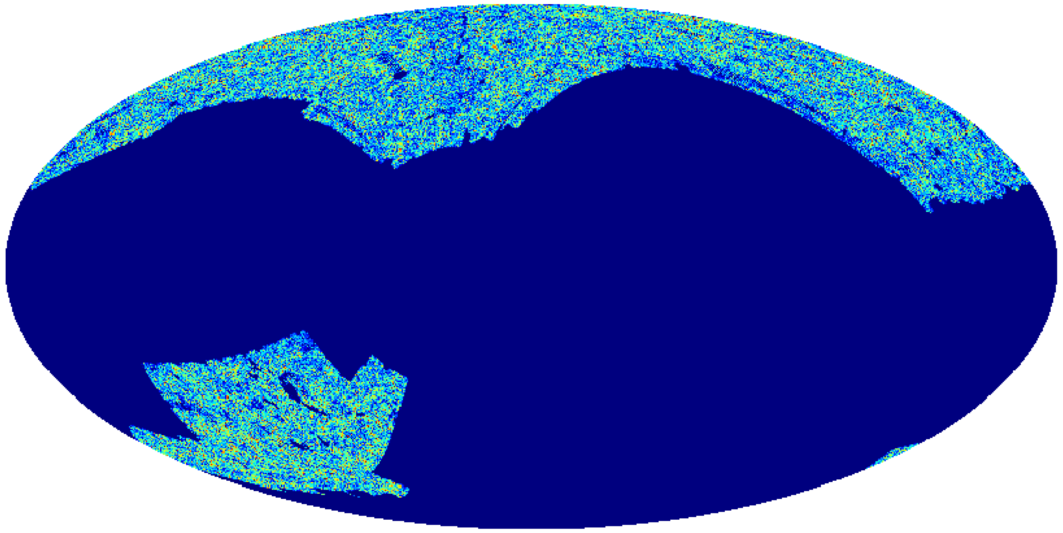
(Astrophysical)

2, Given a peculiar velocity, we can obtain an optical depth.

→ kSZ can be used to trace the distribution of gas in and around galaxy clusters.
It helps to probe baryonic effects such as AGN feedback.

Data set

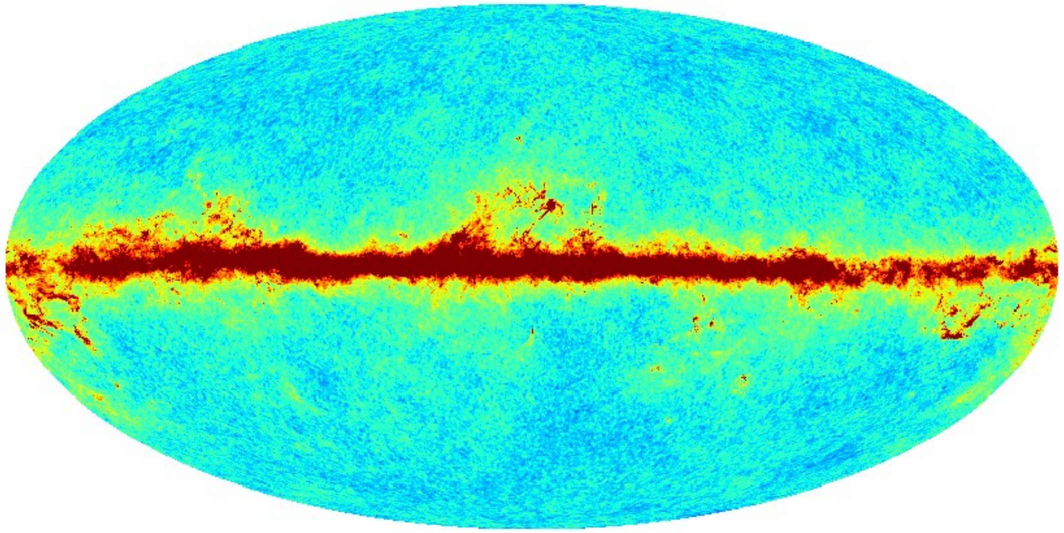
Galaxy clusters from SDSS survey



~30,000 WHL galaxy clusters
Halo mass: $M_{500} \sim 1.0 \times 10^{14}$ Msun
Redshift: $0.25 < z < 0.55$

~ 1,300,000 SDSS DR12 galaxies

Planck HFI 217 GHz

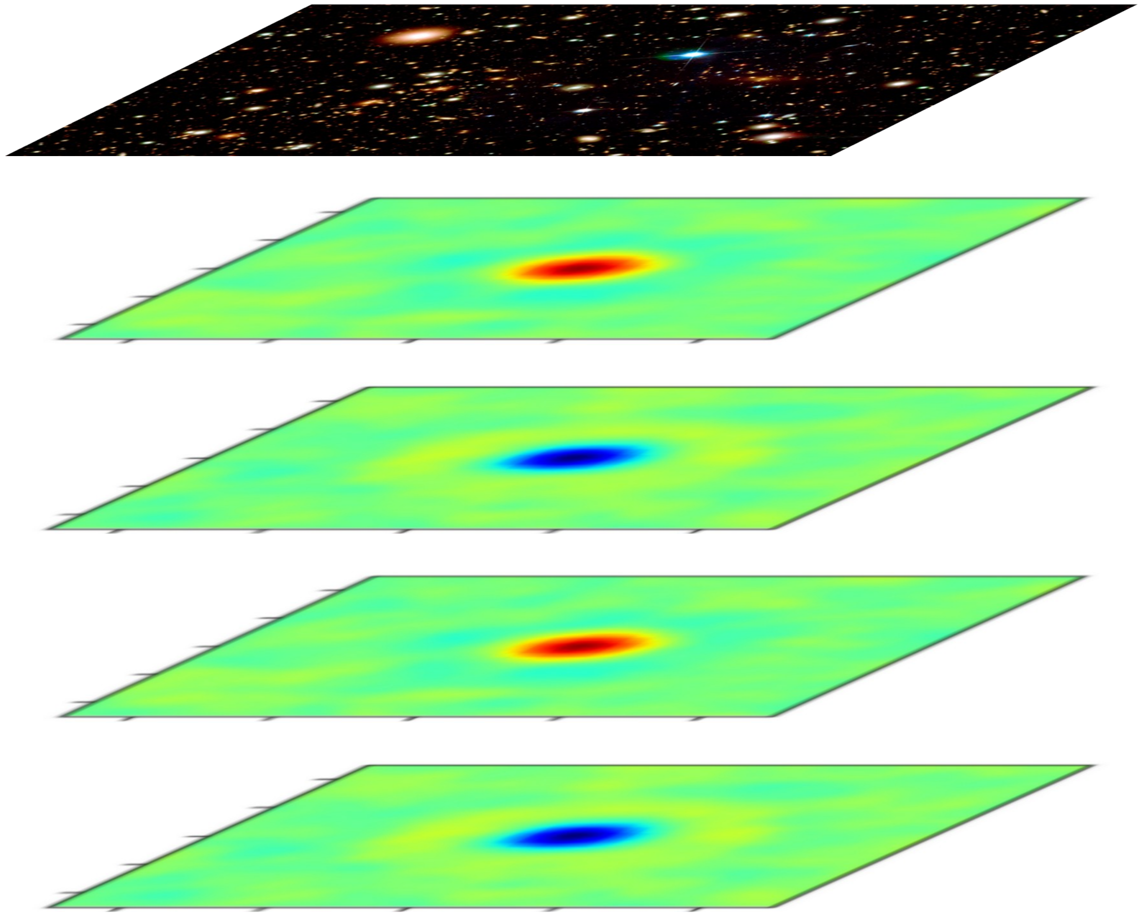


At 217 GHz, tSZ signal is null.

Methodology (Stacking)

Issue 1, kSZ is weak,
Two orders of magnitude lower than the primary CMB fluctuation and typically one order of magnitude lower than the tSZ.

(Galaxy cluster)



(Planck 217 GHz and Planck CMB map)

Issue 2,
Because the kSZ is proportional to the radial peculiar velocities of galaxy clusters, simple stacking method leads to cancellation of the signal.

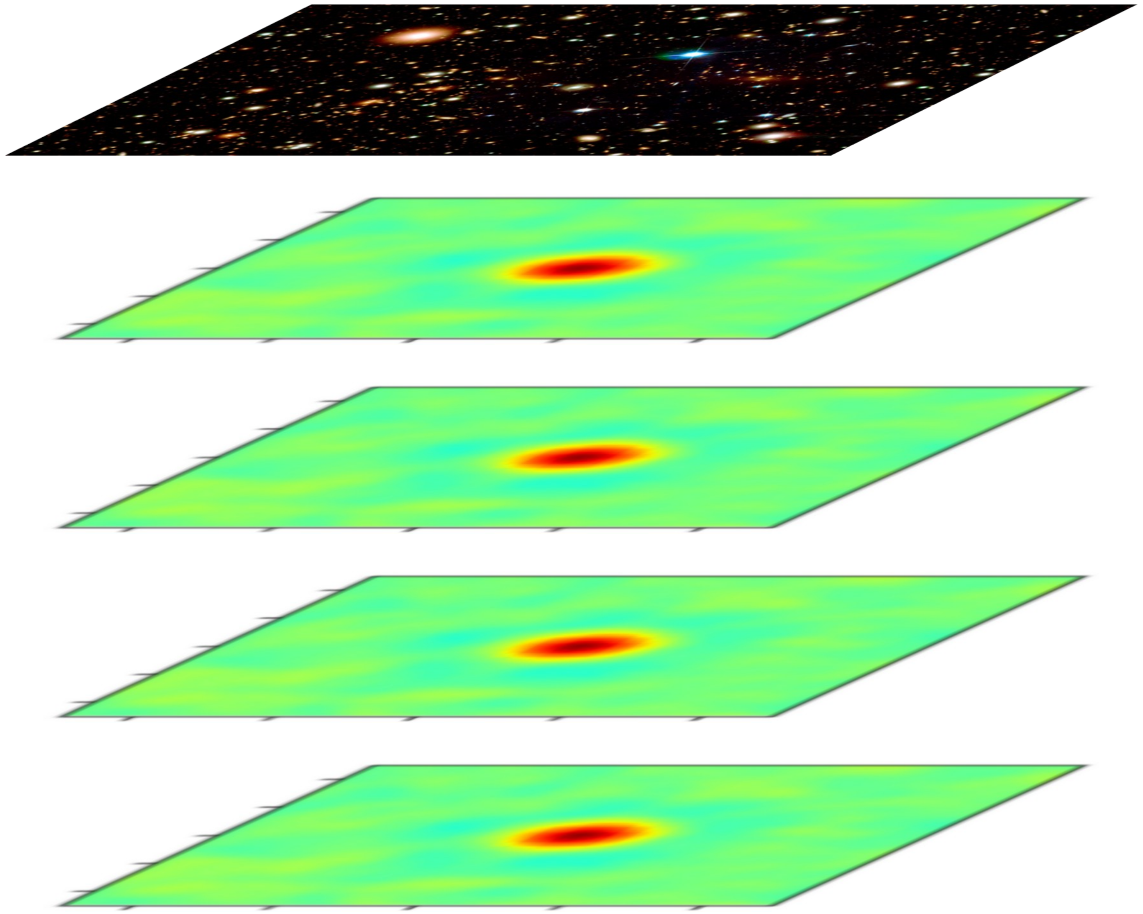
Issue 3, Foreground and background emissions

Issue 4, Planck beam (5 arcmin)

Methodology (Stacking)

Issue 1, kSZ is weak,
Two orders of magnitude lower than the primary CMB fluctuation and typically one order of magnitude lower than the tSZ.
→ We stack the Planck 217 GHz at the positions of galaxy clusters.
→ The large-scale modes (>15’, ell<720) are filtered out.

(Galaxy cluster)



(Planck 217 GHz and Planck CMB map)

Issue 2,
Because the kSZ is proportional to the radial peculiar velocities of galaxy clusters, simple stacking method leads to cancellation of the signal.
→ We stack the galaxy clusters, depending on the direction of the radial peculiar velocities.

Issue 3, Foreground and background emissions
→ These are canceled out by the flipping of sign. and we do not find a significant contamination. (It will be shown later.)

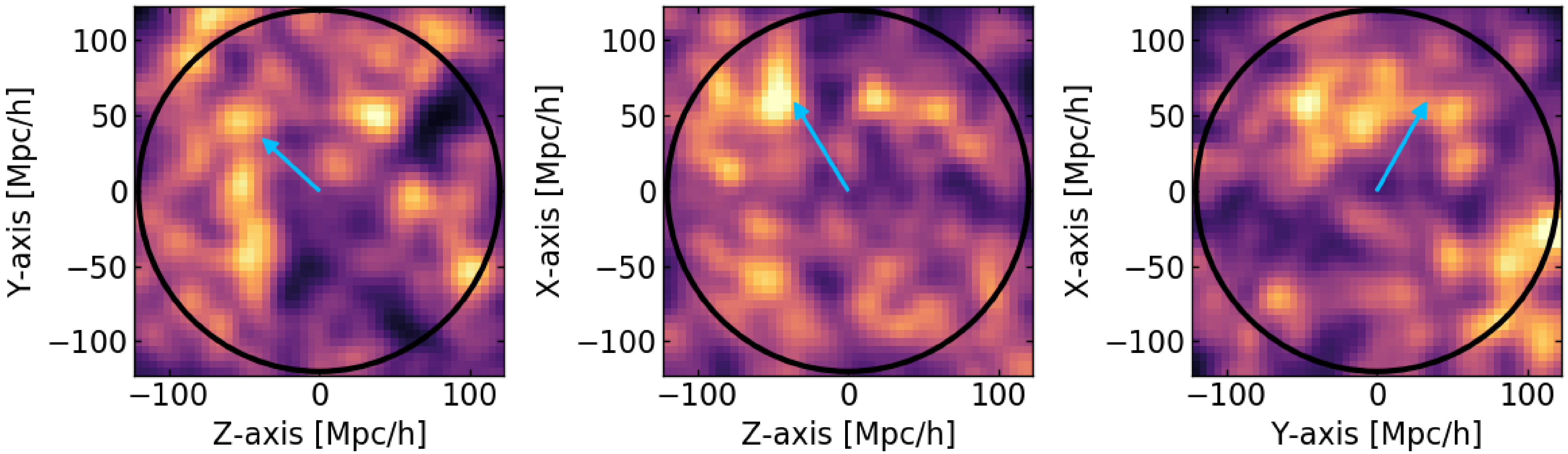
Issue 4, Planck beam (5 arcmin)

Methodology (velocity estimate)

$$\boldsymbol{v}(\boldsymbol{x},t) = \frac{f(\Omega)aH(a)}{4\pi}\int d^3y\,\delta(\boldsymbol{y},t)\,\frac{\boldsymbol{y}-\boldsymbol{x}}{|\boldsymbol{y}-\boldsymbol{x}|^3}$$

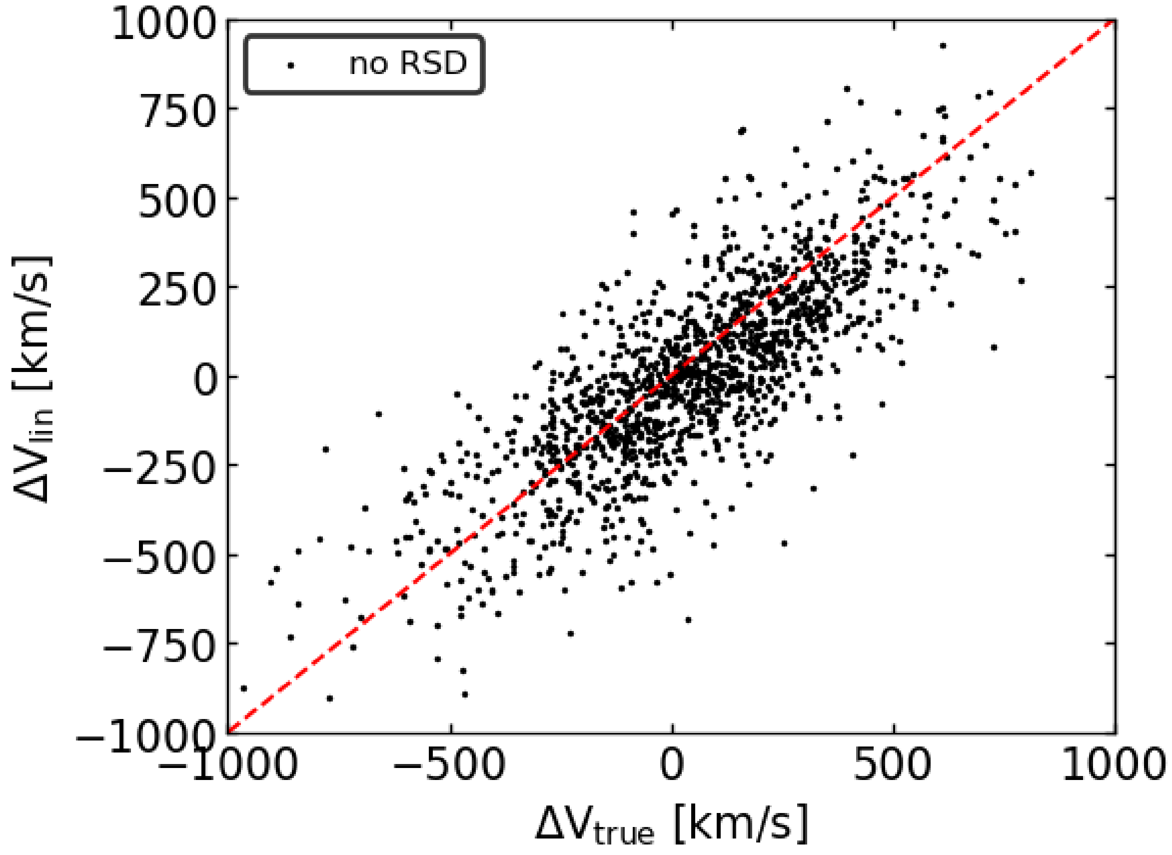
(x: position of galaxy cluster, y: positions around the galaxy cluster)

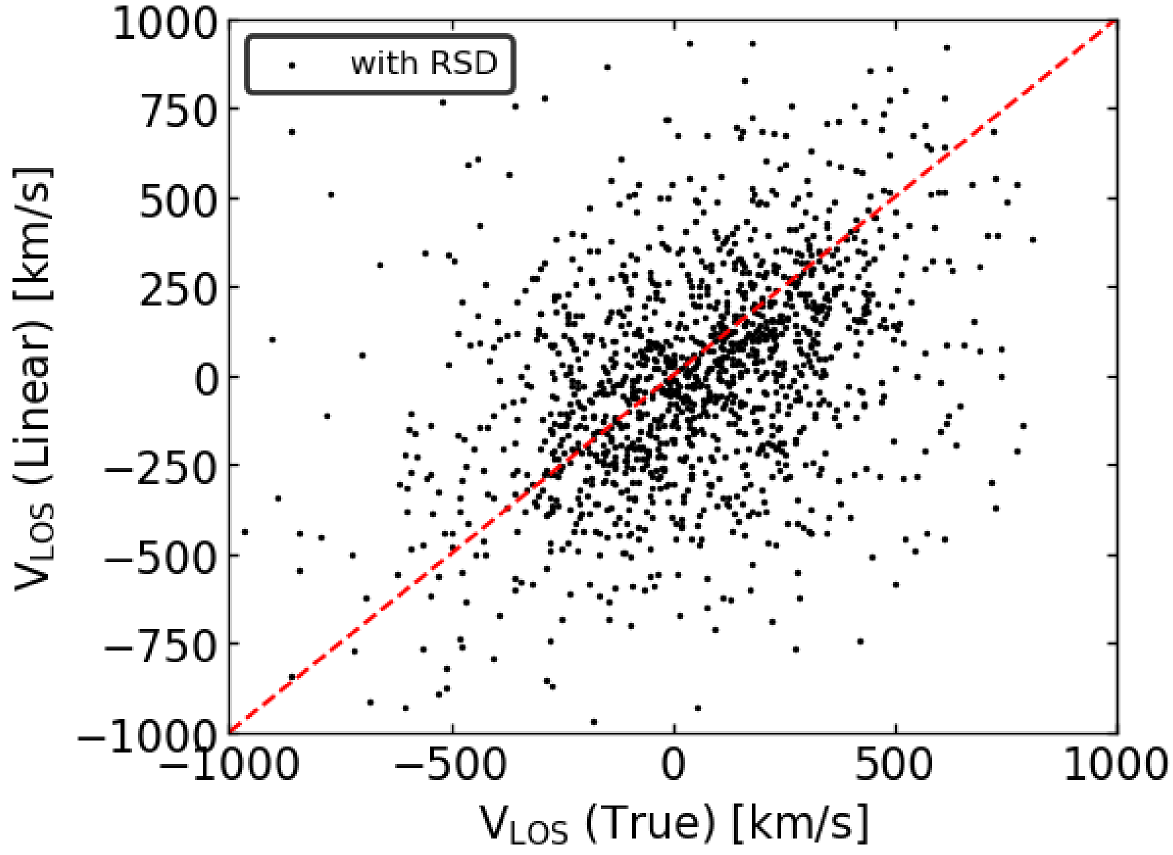
- Overdensity is calculated based on a galaxy density field (SDSS DR12 galaxies), assuming the galaxy bias of 2 (Parejko et al 2013, White et al 2011 and Nuza et al 2013).
- Velocity is calculated using the density field within R < 120 Mpc/h.



Uncertainty of radial velocities

The uncertainty of the radial velocities is estimated
using the Magneticum simulations with mock galaxy catalog and cluster catalog.



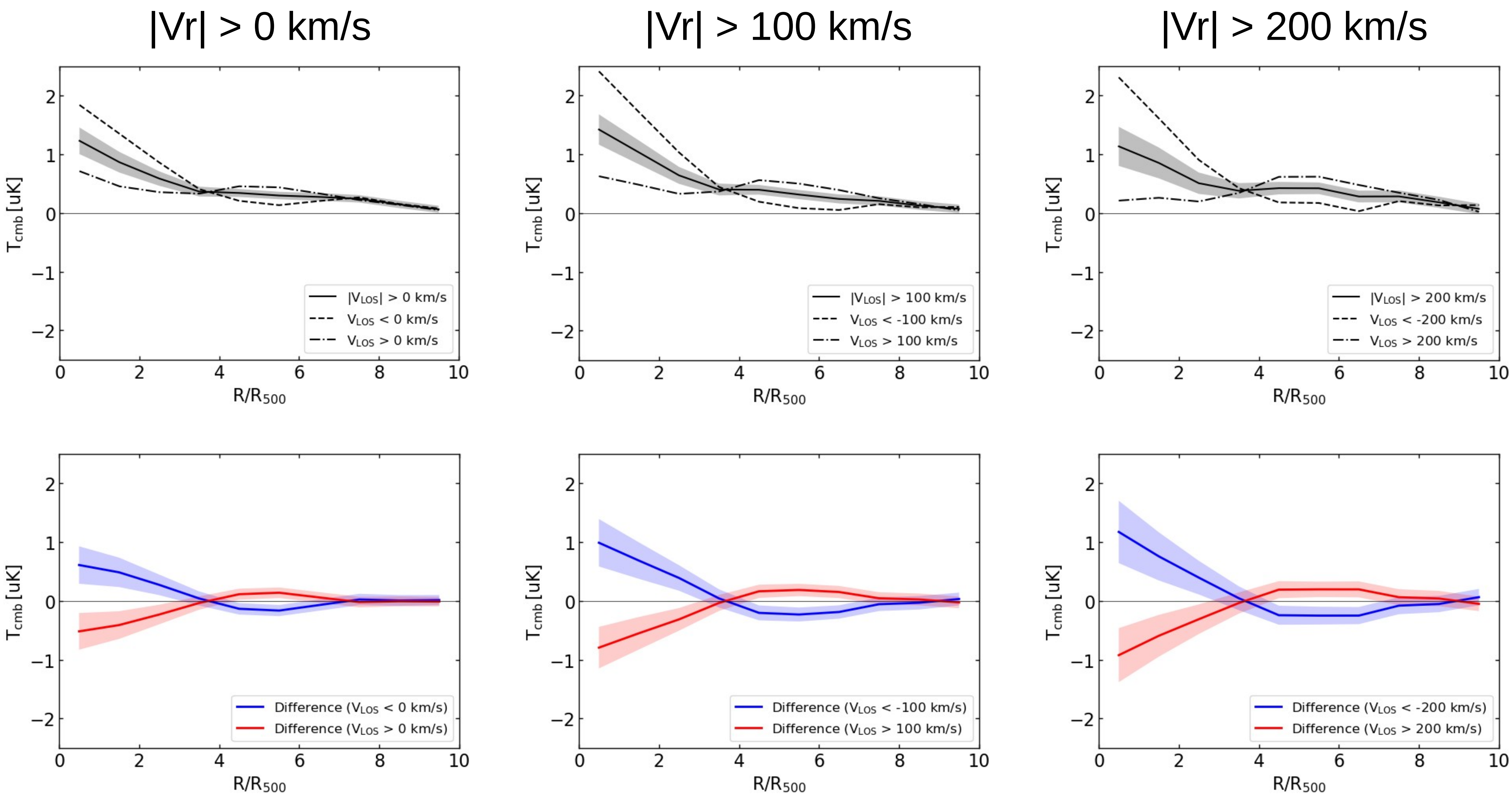


σv ~ 180 km/s

σv ~ 260 km/s

The larger the uncertainty of the radial velocities, the more the observed kSZ signal is suppressed.

Results (stacked kSZ signal)



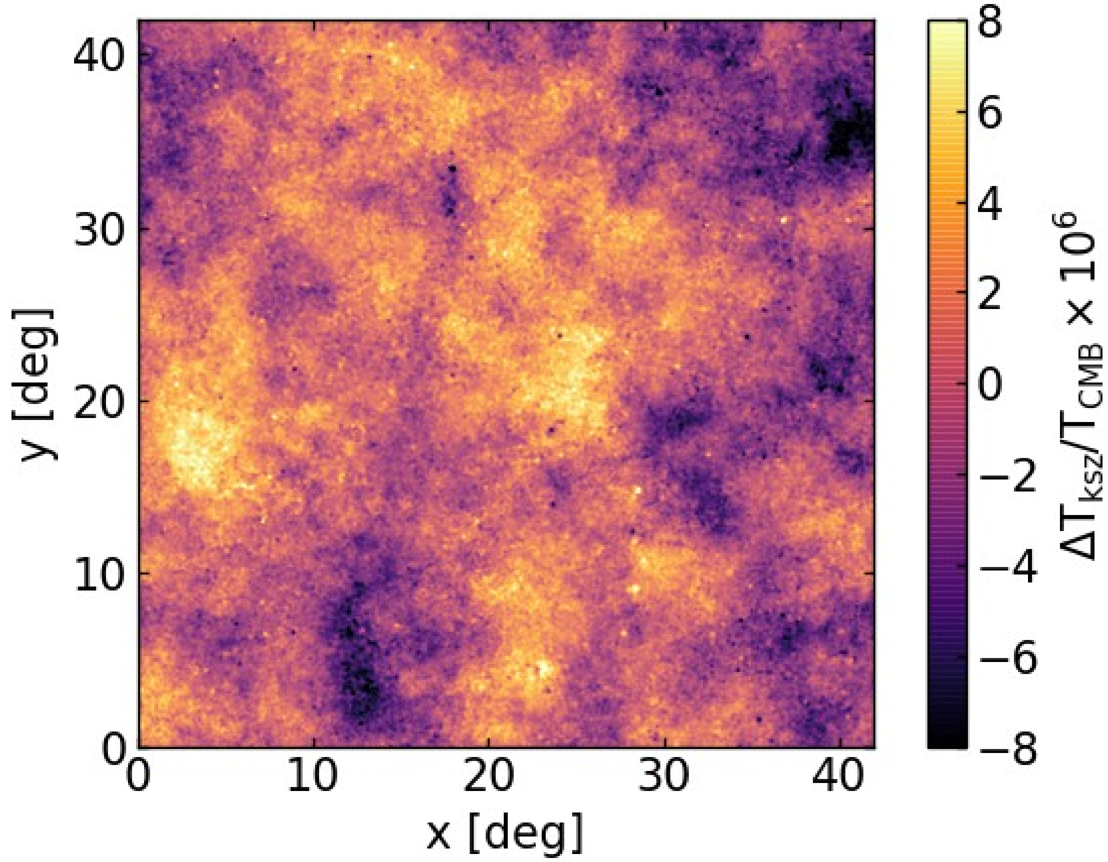
A clear correlation is seen between the amplitude of the radial velocities and kSZ signals.

Comparison with Magneticum simulations

- The Magneticum simulations are one of the largest cosmologi-cal hydrodynamical simulations with WMAP7 cosmology (Hirschmann et al. 2014; Dolag2015).

- The post-processed data of the galaxy catalog and the cluster catalog is provided from the full snapshot simulations with a cube box of 640^3 Mpc/h.

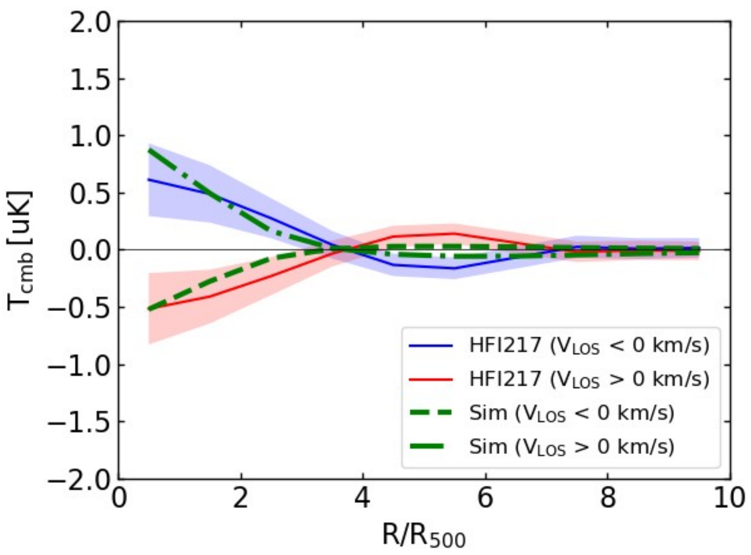
- The kSZ light-cone map with an area of ~1,600 deg^2 is provided with the corresponding cluster catalog with M500 > 3×10^{13} Msun/h.



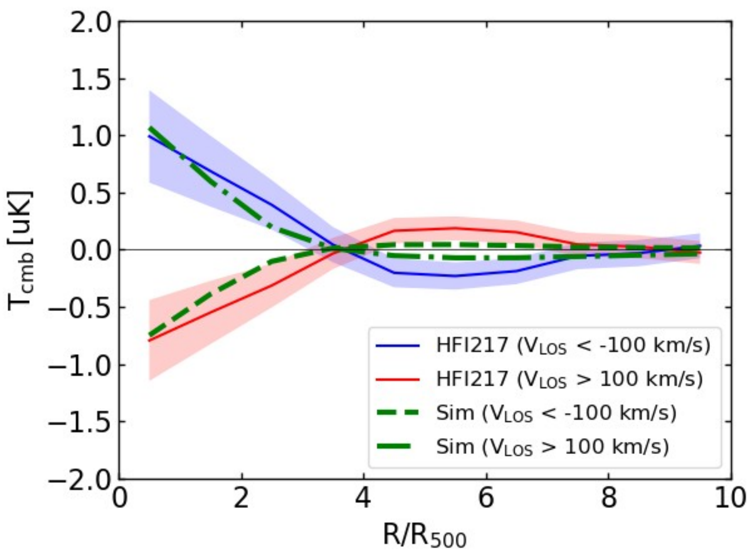
Comparison with Magneticum simulations

We perform the same stacking analysis with the kSZ lightcone map as we did with the real data.

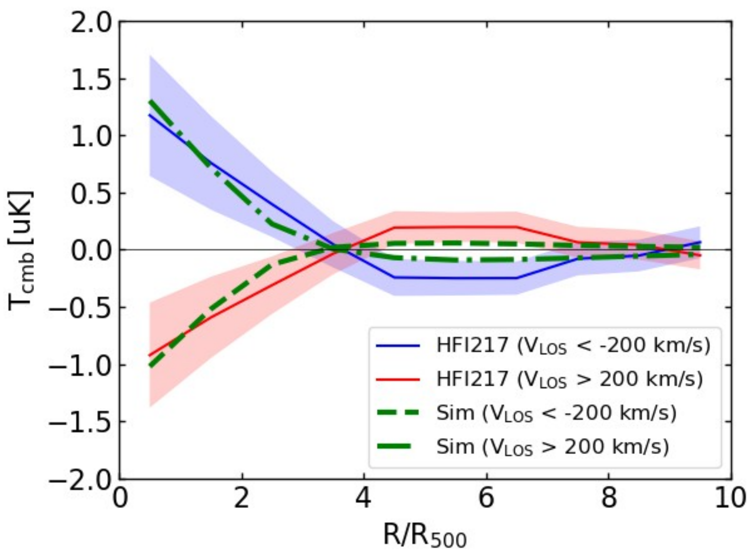
|Vr| > 0 km/s



|Vr| > 100 km/s



|Vr| > 200 km/s

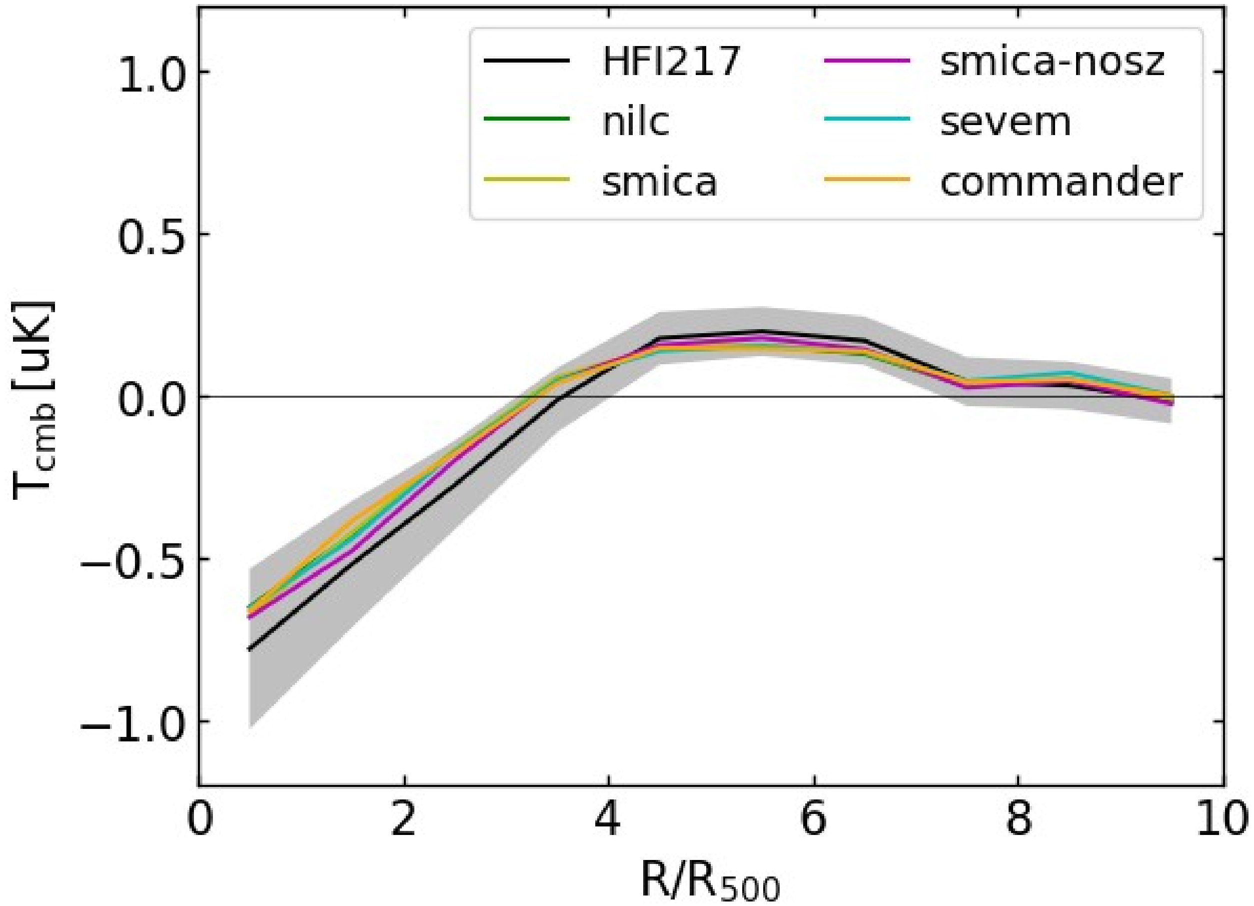


A similar correlation is seen between the amplitude of the radial velocities and kSZ signals.

Foreground and background contamination

We stack the Planck 217GHz and CMB maps at the positions of galaxy clusters with weighs from the radial peculiar velocities.

$$T(r) = \frac{\sum T_i(r) \times \boldsymbol{v}_{i,\mathrm{LOS}}}{\sum |\boldsymbol{v}_{i,\mathrm{LOS}}|}$$



Note that HFI 217 Map includes all the foreground and background emissions , while those are removed in the CMB maps.

→ This result show no significant contamination from the foreground and background in our analysis.

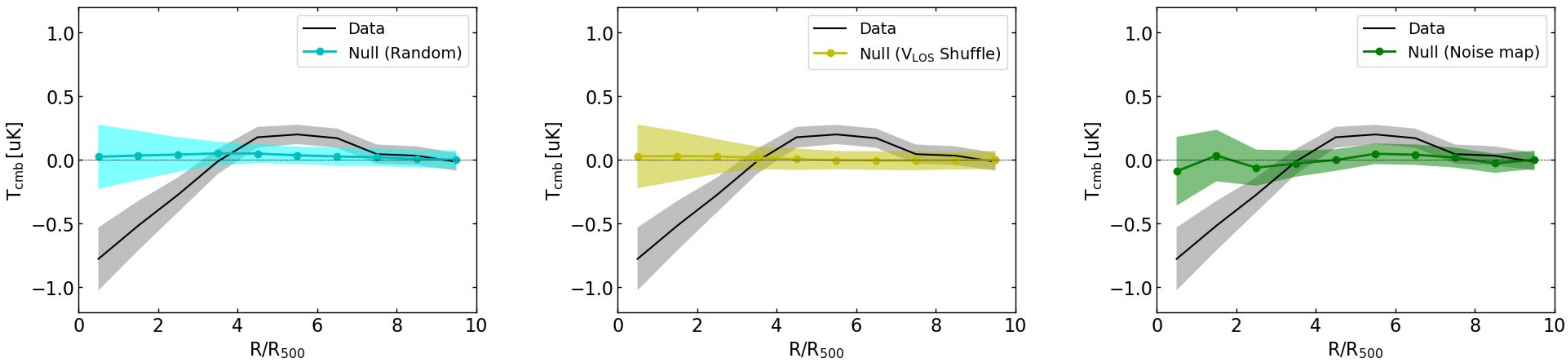
Null tests

We perform three null tests:

1, galaxy clusters are re-located at random positions

2, radial velocities of galaxy clusters are shuffled randomly

3, galaxy clusters are stacked with a noise map at 217 GHz

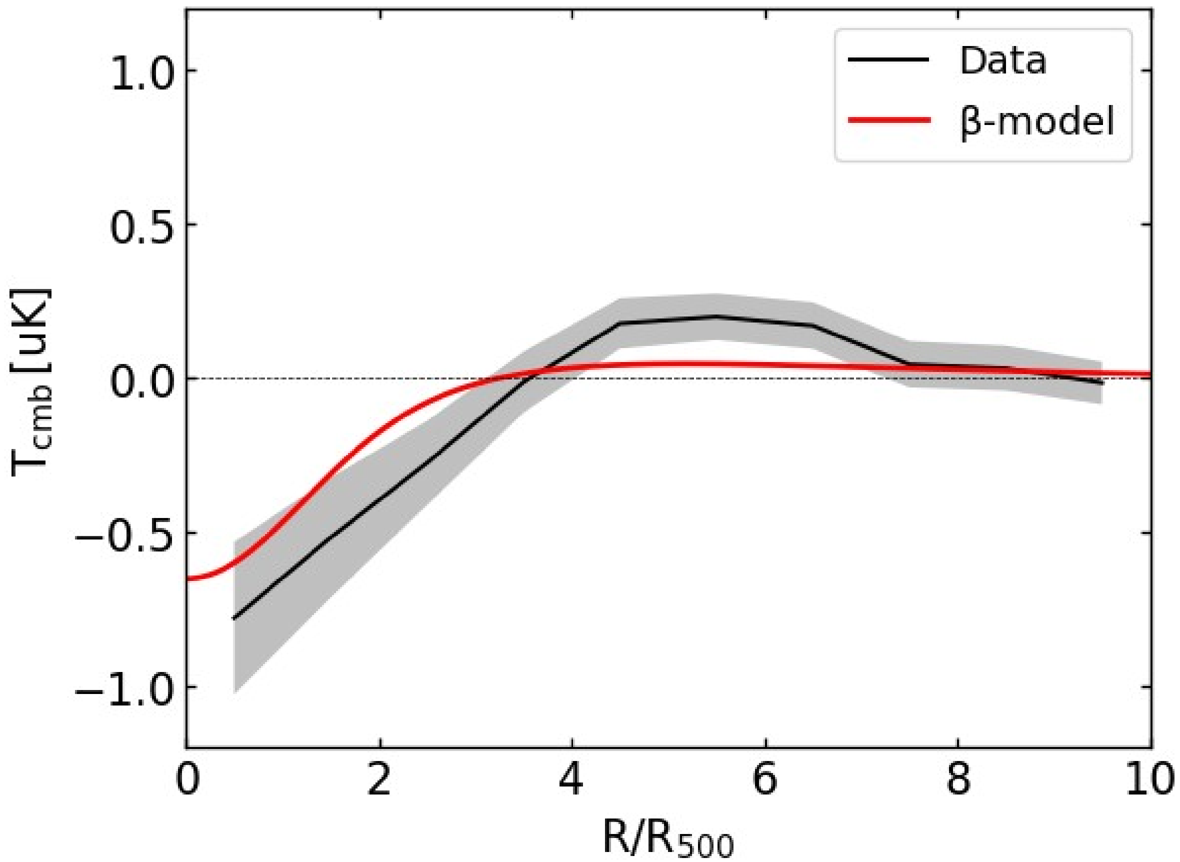


All the null tests are consistent with zero signal.

Using the null tests, we estimate the significance of the detected kSZ signal at 3.5σ.

Interpretation

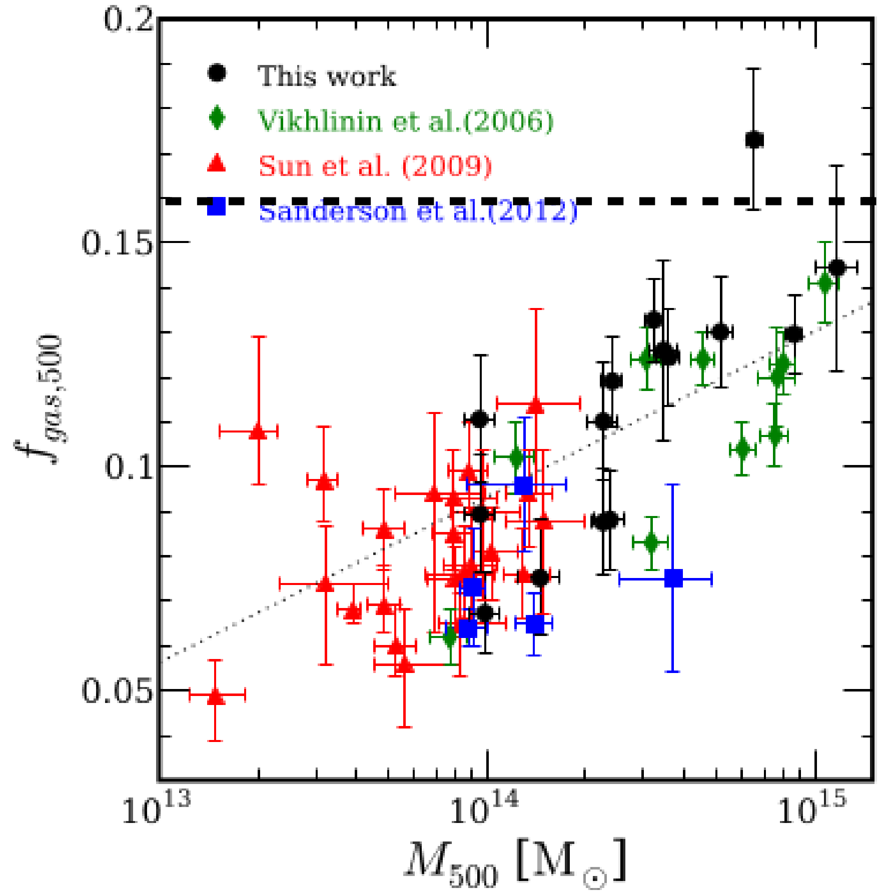
- We model the kSZ signal with a β-model density profile. $n_e(r) = n_e(0)\left[1+\left(\frac{r}{r_c}\right)^2\right]^{-\frac{3}{2}\beta}$
- We refer to Plagge et al 2010 (measurements with SPT clusters) for the core radius and spectral index, and fit the amplitude.



We measure the optical depth of the galaxy clusters ($M_{500} \sim 1.0 \times 10^{14}$ Msun),
$\tau_e = (3.0 \pm 0.9) \times 10^{-3}$
This results in the gas mass fraction of f_{gas} ($=M_{gas}/M_{total}$) ~ 0.12 ± 0.04.

Comparison with other measurements

- X-ray measurements from Gonzalez et al 2013



Cosmic baryon fraction (Ωb/Ωm)

- kSZ measurement from Soergel et al 2016 shows f_{gas} = 0.08 ± 0.02 (M_{500} ~ 1-3 ×10^{14} Msun)
- kSZ measurement from Lim et al 2020 shows fgas ~ 0.16 (cosmic fraction) down to $10^{12.3}$ Msun.

Our measurement is f_{gas} ~ 0.12 ± 0.04 and consistent with the cosmic fraction, but we need more precise measurements to confirm whether the gas fraction is cosmic fraction or not.

Summary

- We detect a kSZ signal around the WHL galaxy clusters ($M_{500} \sim 10^{14}$ Msun) at 3.5σ, beyond the virial radius.

- The measured kSZ profile agrees with the ones from the Magneticum simulation.

- We estimate the optical depth of $\tau_e = (3.0 \pm 0.9) \times 10^{3}$, and $f_{gas} \sim 0.12 \pm 0.04$.

  The gas fraction is consistent with the cosmic baryon fraction,
  but we need more precise measurements, for a better understanding of baryonic effects in galaxy clusters.