Diffuse gas in filaments and superclusters with SZ stacking analysis

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Hot/warm gas

“Warm-Hot Intergalactic Medium” (WHIM) is the gas with $10^5 - 10^7$ K.

Connection to the structure formation, galaxy evolution, baryonic feedback process.

Hydrodynamic simulations predict:
- the gas density is $\delta=10-100$ (signal is weak)
- a large fraction of the WHIM resides in the cosmic web (morphology is complicated)
Sunyaev-Zel'dovich (SZ) Effect

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

SZ effect can be used to study the physical state (pressure) of diffuse gas in galaxy clusters, which is invisible by optical observations.

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Hot/warm gas in filaments through the SZ effect

Planck produces all-sky SZ map, but the expected signal level ($y \sim 10^{-8}$) is lower than the noise level ($y \sim 10^{-6}$). We use a stacking method to detect low-dense gas in filaments.

1. $\sim 260,000$ short filaments with 6 - 10 Mpc/h identified between pairs of SDSS DR12 LRGs

2. $\sim 24,000$ long filaments with 30 - 100 Mpc identified with SDSS DR12 galaxies by DisPerSE (Malavasi et al. 2020)

3. Intercluster gas in $\sim 670$ superclusters identified with SDSS DR7 galaxies (Liivamägi et al. 2012)
1, Stacking LRG pairs

1, We stack ~260,000 LRG pairs. $(0.05<z<0.40, M_*>10^{11.3} \text{ Msun})$

6 - 10 Mpc/h (>27’)

2, Halo signals are removed assuming they have a spherical shape (circularly symmetric In 2D)

$y = (1.31\pm0.25) \times 10^{-8} \text{ (~5.3σ)}$
Comparison to BAHAMAS hydro simulations

We perform the same analysis on large-scale hydro simulations and find a somewhat smaller signal, but reasonably consistent result:

$$y = (0.84 \pm 0.24) \times 10^{-8}$$

By modeling a filament geometry, (cylinder shape with constant temperature and a density profile from a simulation), we derive the following constraint:

$$\delta_c \left( \frac{T_e}{0.82 \times 10^7 \text{ K}} \right) \left( \frac{r_c}{0.5h^{-1} \text{ Mpc}} \right) = 3.2 \pm 0.6$$

$\delta_c$: over-density at the core of filaments
$r_c$: core radius of filaments
$T_e$: electron temperature

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Comparison with other statistical studies

(Lensing)
Filaments between 135,000 SDSS DR7 LRG pairs 6-14 Mpc/h using SDSS galaxies (Clampitt et al. 2016) → 4.5σ detection

Filaments between 23,000 BOSS LRG pairs 6-10 Mpc/h using CFHTLenS (Epps & Hudson 2017) → 5σ detection, δ~4,

Filaments between 11,000 BOSS LRG pairs 3-5 Mpc/h using CFHTLenS, RCSLenS, KiDS (Xia et al. 2019) → 3.4σ detection, δcore~15 for beta-profile

Filaments between 70,000 BOSS CMASS galaxy pairs 6-14 Mpc/h using Subaru HSC (Kondo et al. 2020) → 3.9σ detection

(SZ)
Filaments between 1,000,000 BOSS CMASS galaxy pairs 6-14 Mpc/h using Planck SZ map and Planck CMB lensing map (de Graaff et al. 2019) → 2.9σ detection, δ=5.5±2.9, T=(2.7±1.7)×10^6 K

Filaments between 260,000 BOSS LOWZ galaxy pairs 6-10 Mpc/h using Planck SZ (Our work) → 5.3σ detection, δ=3.2±0.6, T=8×10^6 K

Assumption: galaxy pairs are “all” connected by “straight” filaments.
2, Stacking cosmic-web filaments

1. Using filaments identified by DisPerSE (Malavasi et al 2020), a radial profile is computed on a 2D map by following a filament spine.

2. The average of ~24000 filament profiles (0.2<z<0.6, 30-100 Mpc) is calculated.

Filament SZ profile (~4.4σ)
Filament CMB lensing profile (~8.1σ)
Density profile in filaments

We fit the average SZ profile and lensing profile at the same time, for an isothermal filament with a beta-model or constant density distribution. (assuming $\delta_{\text{gas}} \sim \delta_{\text{m}}$)

Reduced $\chi^2$ are 0.9 for both.
We can not determine the density profile due to the angular resolution of the CMB lensing map. (Planck SZ map: 10 arcmin FWHM, Planck CMB lensing map: cut at $l \sim 400$ (30 arcmin))
Interpretation (MCMC)

(Constant density model)

\[ \delta = 6.3^{+0.9}_{-0.8} \quad T_e = 1.3^{+0.4}_{-0.4} \times 10^6 \text{ K} \]

(\(\beta\)-model)

\[ \delta = 19.0^{+27.3}_{-12.1} \quad T_e = 1.4^{+0.4}_{-0.4} \times 10^6 \text{ K} \quad r_c = 1.5^{+1.8}_{-0.7} \text{ Mpc} \]
3, Internal filaments in superclusters

Superclusters compose of multiple galaxy groups and clusters inside, and they are connected by galaxy chains of filaments (Einasto et al. 2007, 2011). → most likely also by gas
3, Stacking superclusters

To probe intercluster gas in superclusters, we mask galaxy groups and clusters from SDSS, ROSAT X-ray and Planck SZ down to $1 \times 10^{13}$ Msun.

Detection of intercluster gas in superclusters at 2.5$\sigma$. Assuming a uniform distribution of gas,

$$\delta_e \times \left( \frac{T_e}{8 \times 10^6 \text{ K}} \right) = 10.6 \pm 4.0$$
Summary

1, Small-scale filaments (6-10 Mpc/h, z~0.3)
We detect the SZ signal between SDSS LRG pairs \((y \sim 1.3 \times 10^{-8})\) at 5.3\(\sigma\).
\(\rightarrow\) \(\delta \sim 3.2\) and \(T_e \sim 8 \times 10^6\) K (with hydrodynamic simulations)

2, Large-scale filaments (30-100 Mpc, z~0.5)
We detect the SZ signal at 4.4\(\sigma\) and lensing signal at 8.1\(\sigma\)
\(\rightarrow\) \(\delta \sim 6.3\) and \(T_e \sim 1.3 \times 10^6\) K (by combining with lensing data and assuming \(\delta m \sim \delta e\))

3, Intercluster gas in superclusters (~20 Mpc, z~0.1)
We detect the SZ signal at 2.5\(\sigma\).
\(\rightarrow\) \(\delta \sim 10\) for \(T_e \sim 8 \times 10^6\) K (reference to my result 1)