UNIVERSITY OF TORONTO

Anisotropic Superclustering of Cosmic Gas

An analysis with ACT+*Planck* and DES data

Martine Lokken

In collaboration with Renée Hložek, Dick Bond, Alex van Engelen,
Mat Madhavacheril, George Stein, Zhiqi Huang, Bhuv Jain, Shivam Pandey
ACT + DES collaborations

Aug 2022, Cosmo'22, Rio de Janeiro

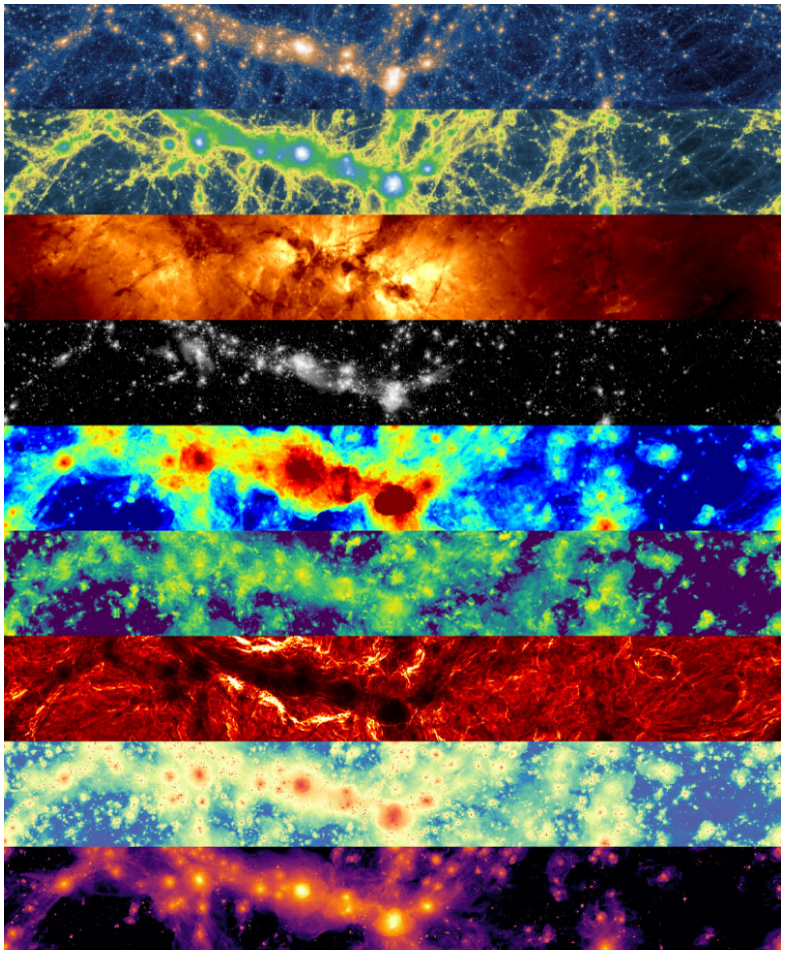
Overview

- Background: anisotropic superclustering
- Measurements of superclustering with tSZ
- Theoretical predictions
- Observational results
- Comparing tracers
- Conclusions and next steps

Overview

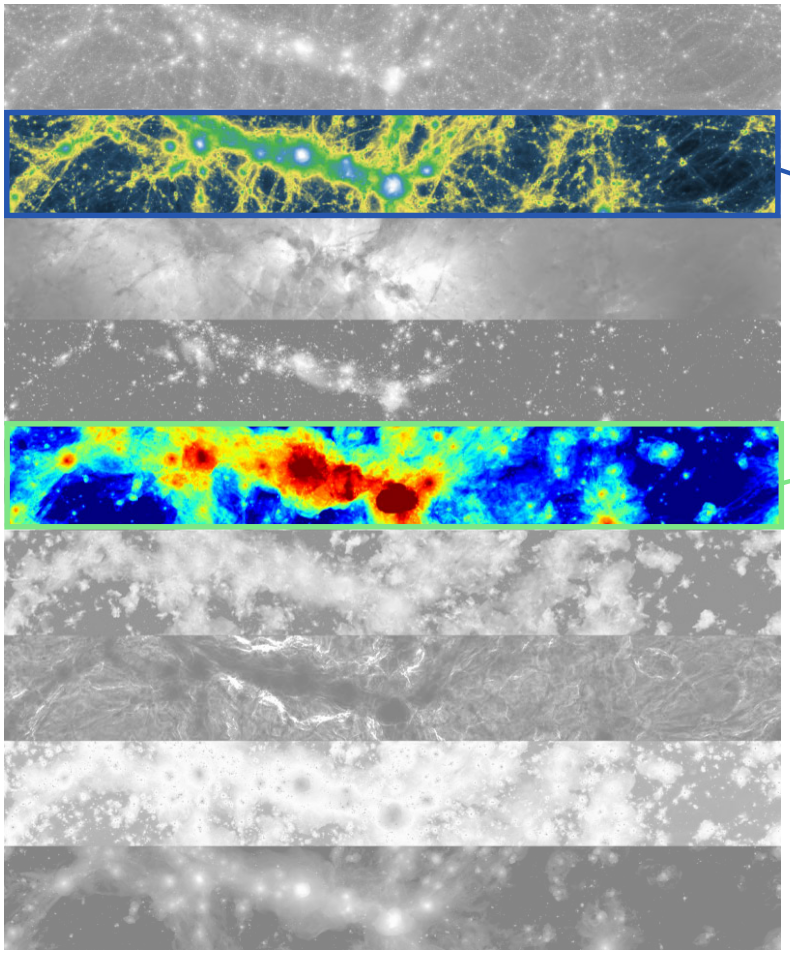
- **Background: anisotropic superclustering**
- Measurements of superclustering with tSZ
- Theoretical predictions
- Observational results
- Comparing tracers
- Conclusions and next steps

Anisotropic superclustering



Illustris TNG 2021

Anisotropic superclustering



gas density

gas temperature

thermal Sunyaev-Zel'dovich:
foreground effect in CMB maps

$$y = \int \left(n_e \frac{k_B T_e}{m_e c^2} \sigma_T \right) dl$$

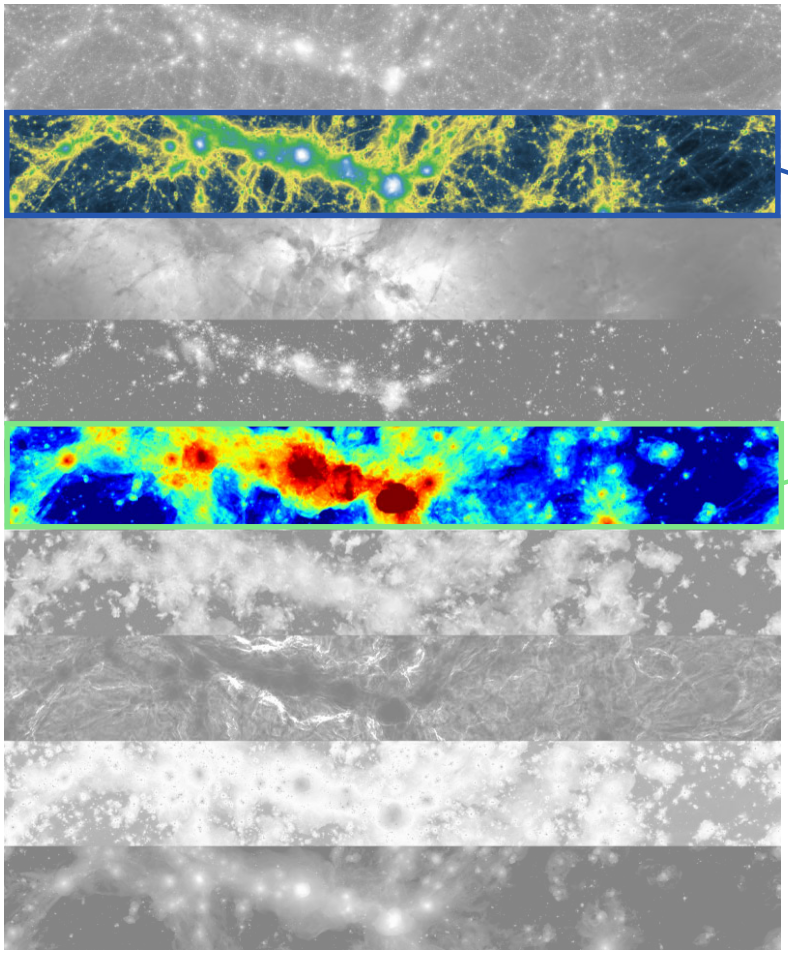
Advantages

- independent of redshift
- Measures thermal history of universe

Challenge: baryonic feedback

Illustris TNG 2021

Anisotropic superclustering



gas density

gas temperature

thermal Sunyaev-Zel'dovich:
foreground effect in CMB maps

$$y = \int \left(n_e \frac{k_B T_e}{m_e c^2} \sigma_T \right) dl$$

Atacama Cosmology Telescope *y* maps

Madhavacheril, Hill et al. 2020
Coulton et al. (in prep)

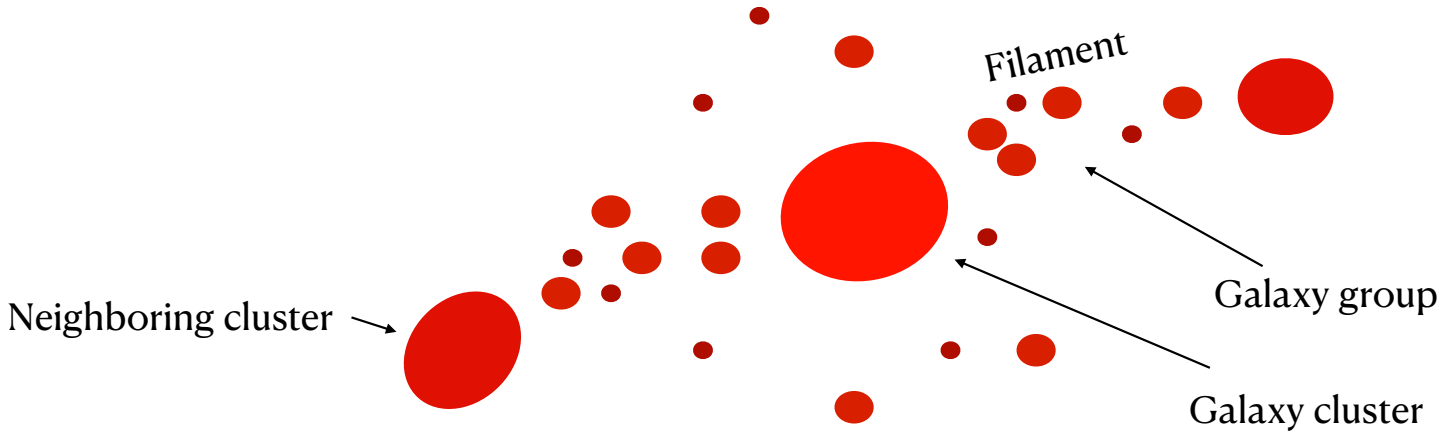
Illustris TNG 2021

Anisotropic superclustering of tSZ

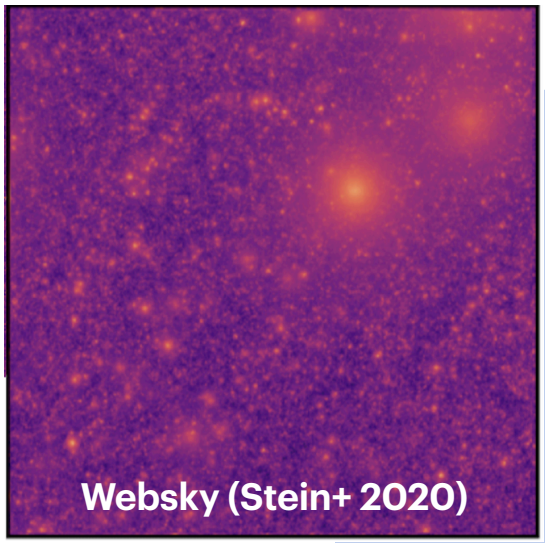
Modeling: Halo prescription

Within the halo model,

- $Y \propto M^{5/3}$ for $M \gtrsim 10^{14} M_{\odot}$
- Deviations at lower masses due to non-gravitational processes, i.e., astrophysical feedback



Anisotropic superclustering of tSZ



Modeling: Halo prescription

Websky (Stein et al 2020) **/**
Buzzard (deRose et al 2019)

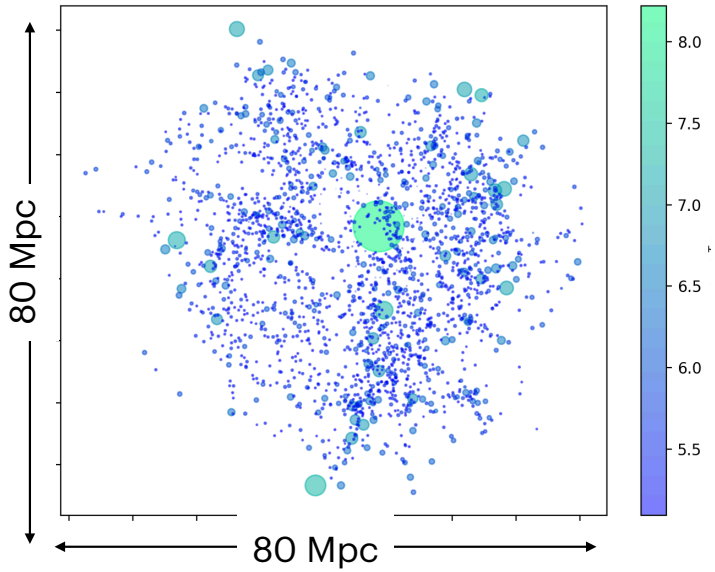
- Dark matter only simulation —> halo catalogue
- Galaxies from halo occupation distribution or subhalo abundance matching model
- Pressure profiles pasted for $M > 10^{12} M_{\odot}$ halos using fits from hydro sims (Battaglia+ 2012)

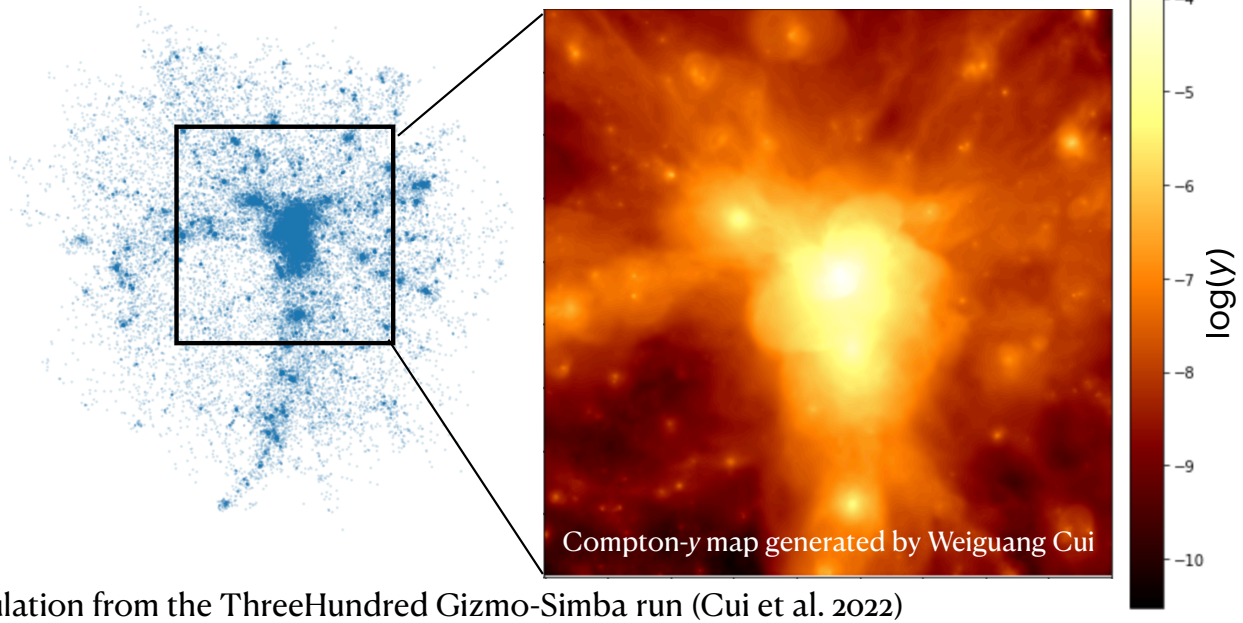
Anisotropic superclustering of tSZ

Theoretical context

Hydrodynamic simulations show:

- Diffuse dark matter and gas
- State of the unbound gas depends on feedback mechanisms





Plots of one cluster zoom simulation from the ThreeHundred Gizmo-Simba run (Cui et al. 2022)

Key Questions

Within the halo prescription

- How does gas pressure profile depend on halo mass & redshift?
- Are modifications needed at low-mass end?
- How far to extend the gas profiles?

Beyond the halo model

- Is more needed to describe the diffuse gas in filaments?
- How does the anisotropy of the gas relate to anisotropy of galaxies, matter?

Combining it all

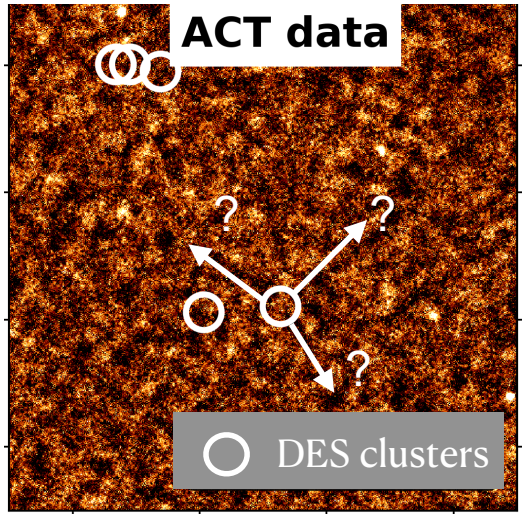
- Can these measurements provide stronger precision constraints on cosmology?

Overview

- Background: the thermal Sunyaev-Zel'dovich effect for cosmology
- **Measurements of superclustering with tSZ**
- Theoretical predictions
- Observational results
- Comparing to galaxies
- Conclusions and next steps

The challenge with tSZ

- *y* maps are projected, and current maps are noisy
- Need to identify the most elongated axis by some other measure — use galaxy maps from the **Dark Energy Survey**
- Combine measurements along this predetermined axis — *stack*

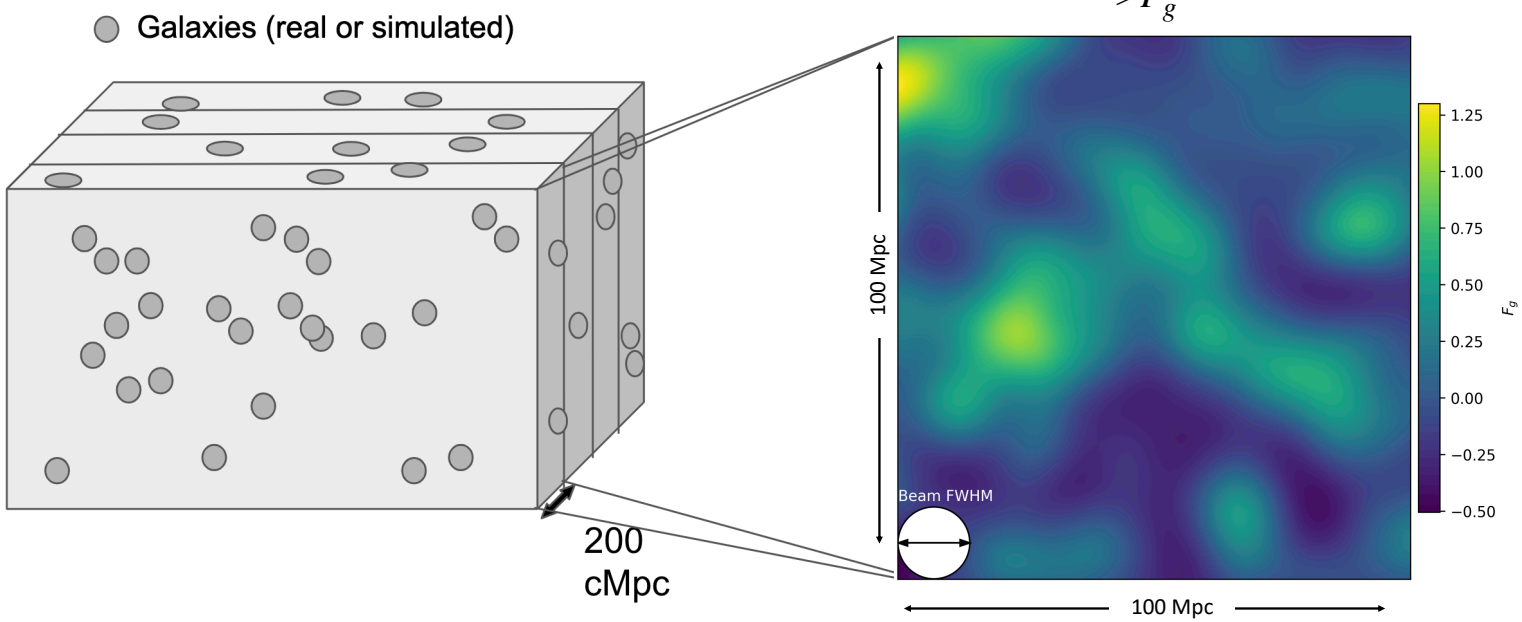


Compton-*y* map from Madhavacheril+ 2019

Atacama Cosmology Telescope

How to measure?
Identifying regions of high superclustering

Projected galaxy overdensity δ
—> smooth with Gaussian beam (here FWHM = 14 Mpc)
—> F_g



Hessian matrix

$$\begin{bmatrix} \frac{\partial^2}{\partial x^2}(F_g) & \frac{\partial^2}{\partial x \partial y}(F_g) \\ \frac{\partial^2}{\partial y \partial x}(F_g) & \frac{\partial^2}{\partial y^2}(F_g) \end{bmatrix}$$

Eigenvectors v_1, v_2 give orientation

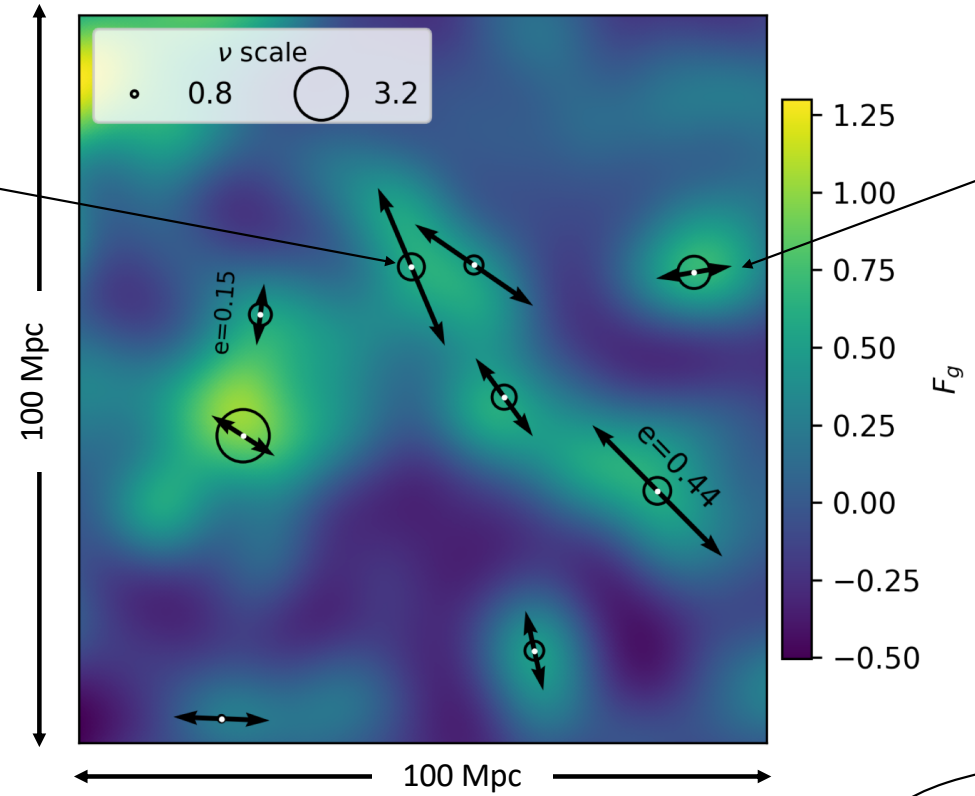
Eigenvalues λ_1, λ_2 provide additional info

Identifying regions of high superclustering

Define $|\lambda_1| > |\lambda_2|$

Galaxy clusters (white points)

Headless vector is along v2 axis (slowest change)



Field ellipticity

$$e = \frac{\lambda_1 - \lambda_2}{2(\lambda_1 + \lambda_2)}$$

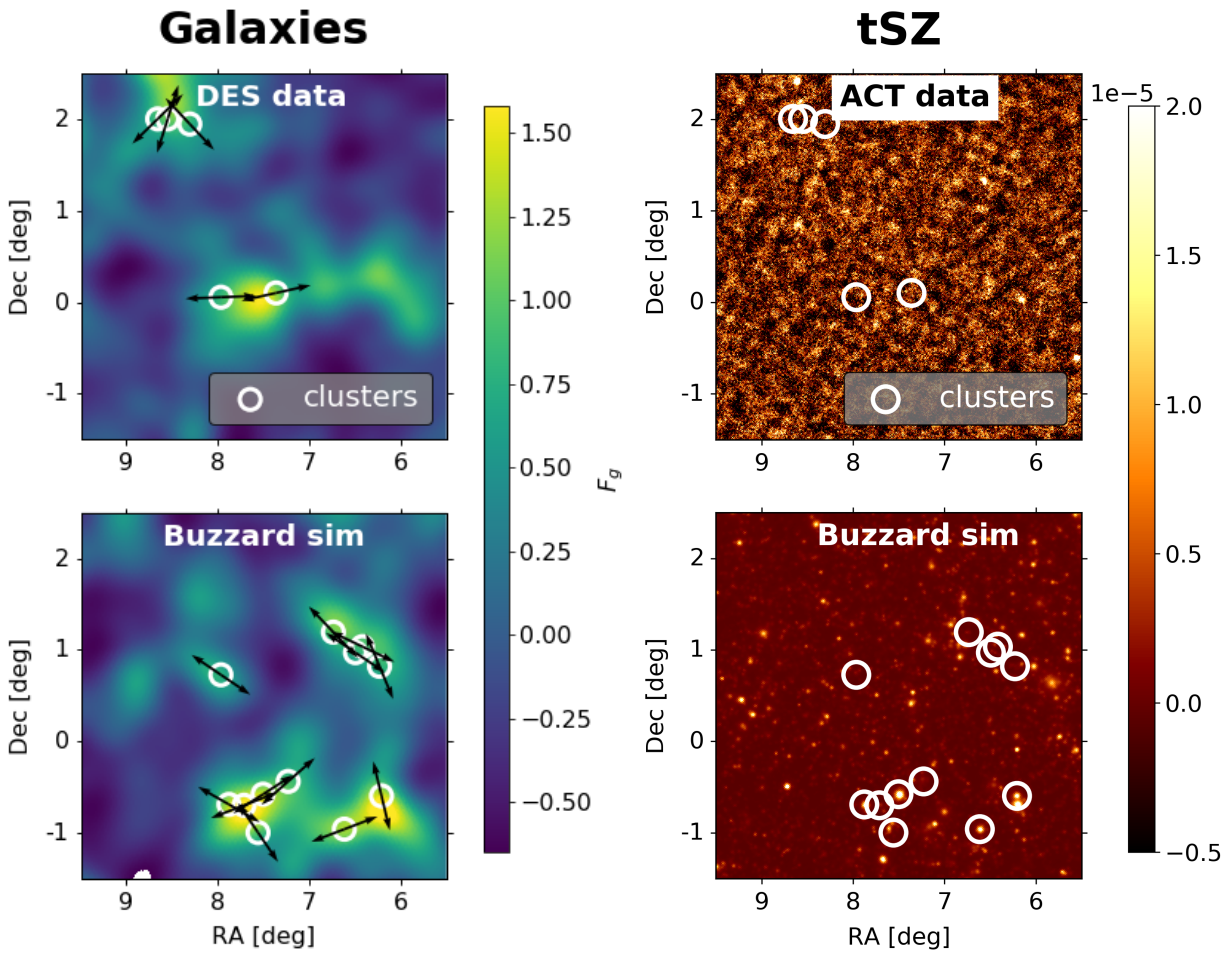
Field excursion

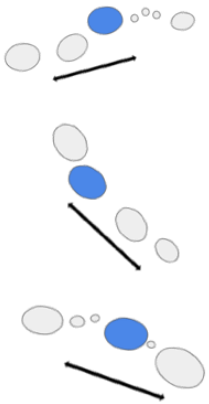
$$\nu = \frac{F_g}{\sigma}$$

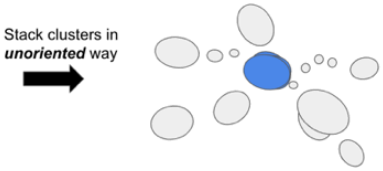
Where σ is the root mean square of F

$$\nu > 2 \quad e > 0.3$$

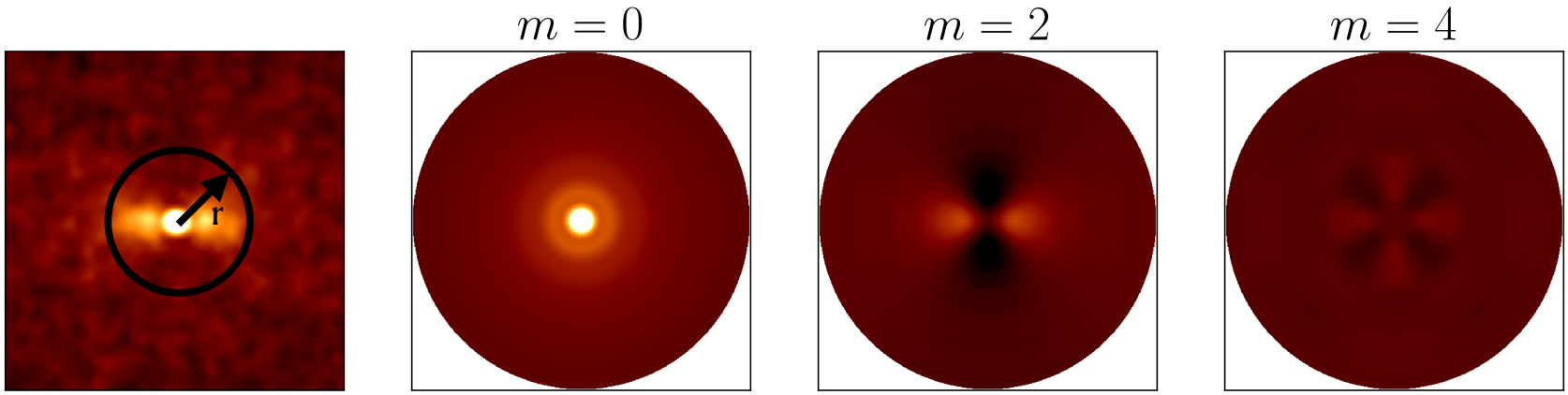
Measuring the signatures of superclustering in maps







Multipole Decomposition



$$F(\theta, r) = \sum_m \left(C_m(r)\cos(m\theta) + S_m(r)\sin(m\theta) \right)$$

What we will plot

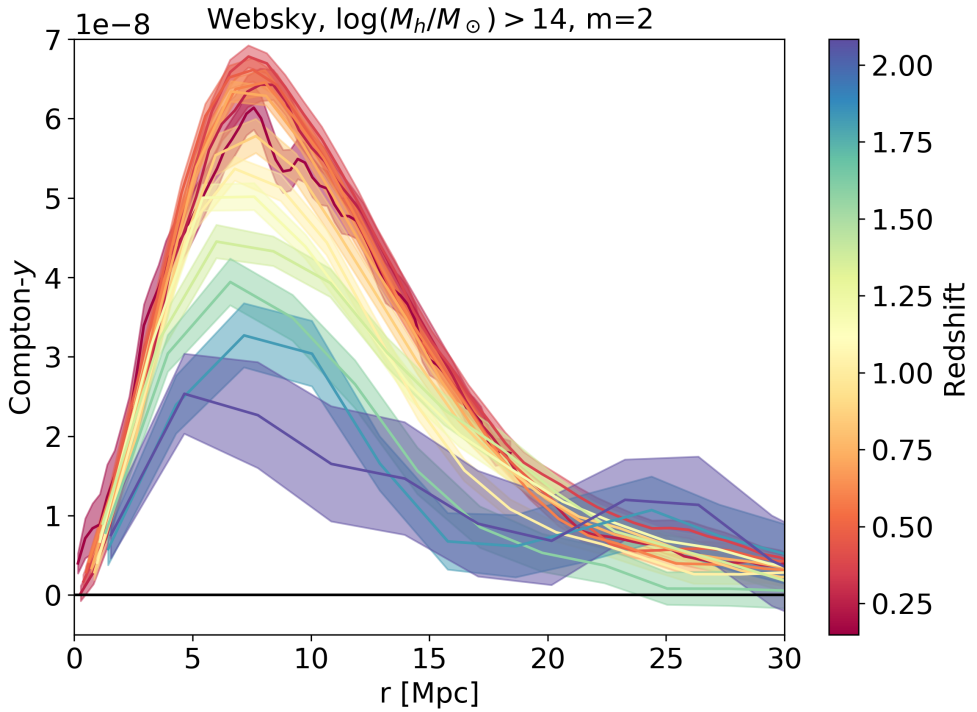
A noise term

Overview

- Background: the thermal Sunyaev-Zel'dovich effect for cosmology
- Measurements of superclustering with tSZ
- **Theoretical predictions with halo prescription**
- Observational results
- Comparing to galaxies
- Conclusions and next steps

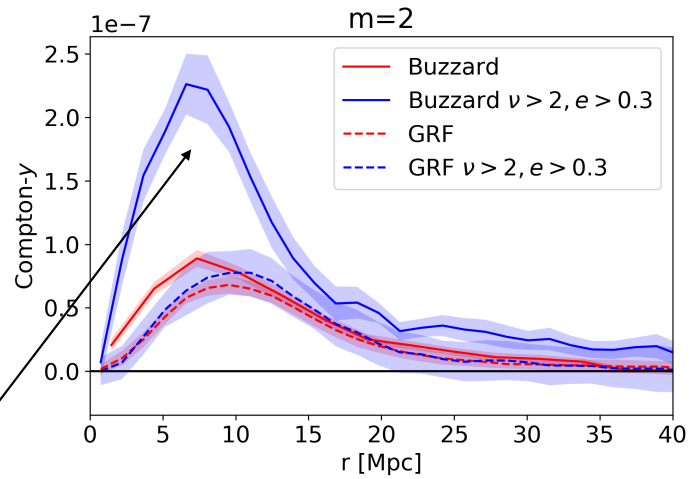
Evolution with cosmic time

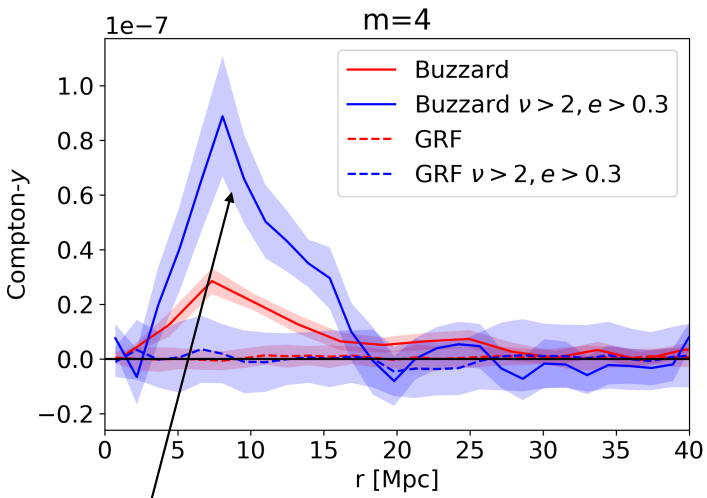
Expected redshift dependence from simulations (Websky)



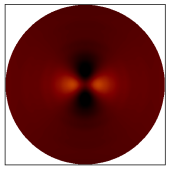
Lokken et al. 2022 (ApJ; arXiv: 2107.05523)

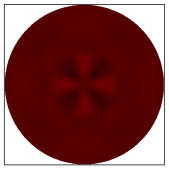
Signs of non-Gaussianity





Many more high-superclustering regions in a realistic, non-Gaussian late-time universe
—> stronger anisotropic tSZ signal





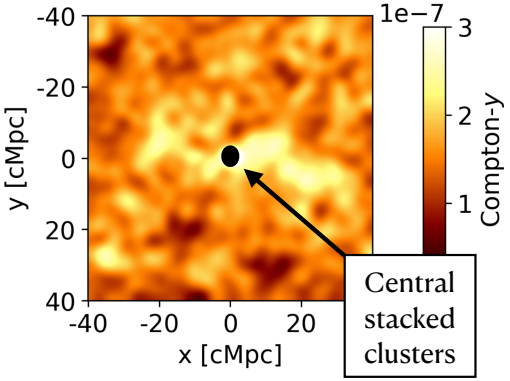
m=4 signal is only present in the non-Gaussian field stacks
Measure of how 'squashed' filaments are

Overview

- Background: the thermal Sunyaev-Zel'dovich effect for cosmology
- Measurements of superclustering with tSZ
- Theoretical predictions
- **Observational results**
- Comparing to galaxies
- Conclusions and next steps

Results

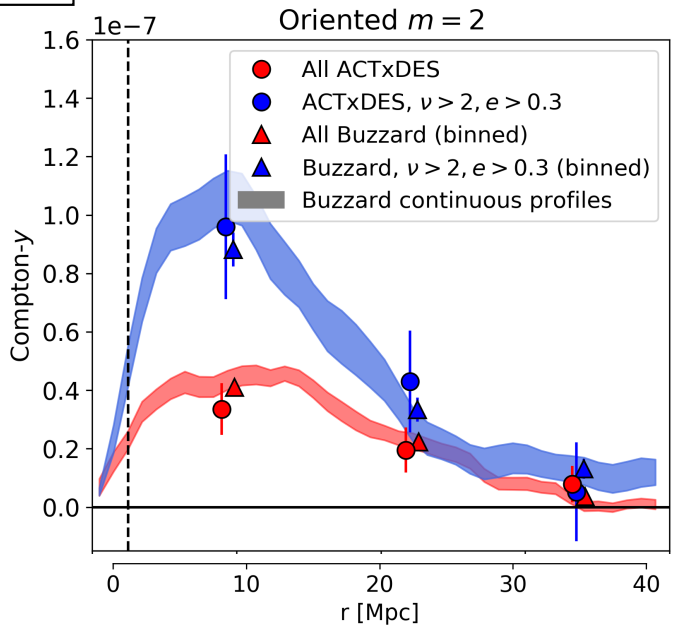
Deep56 y-map (fractional overlap with DES)

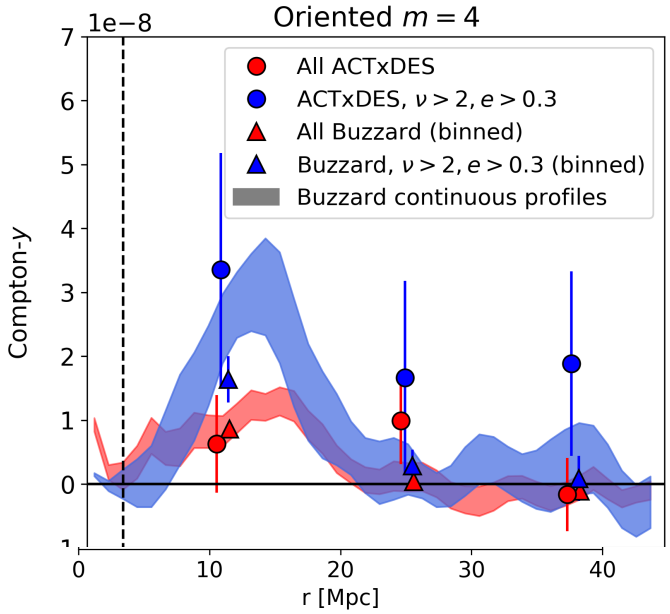


3.5σ result for m=2

All clusters (5,500)

Clusters in high-superclustering regions (1,000)

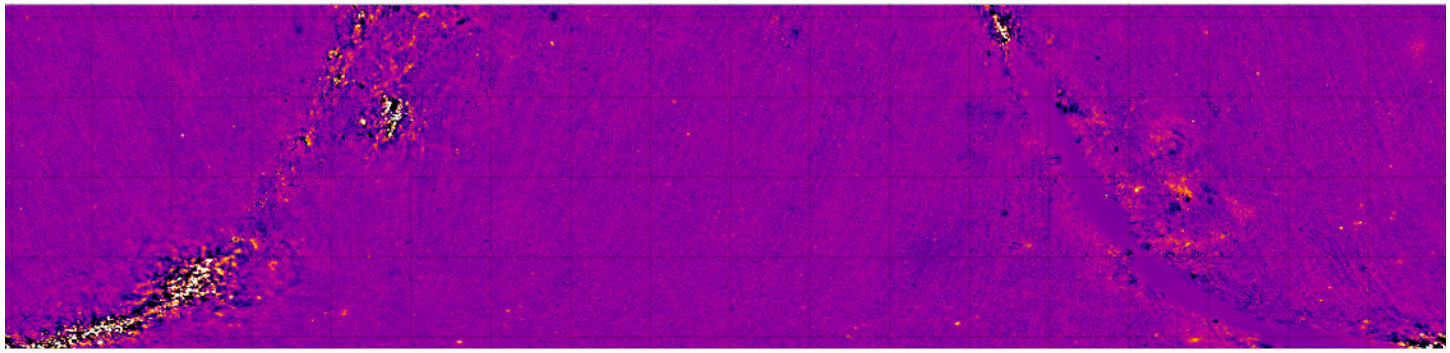


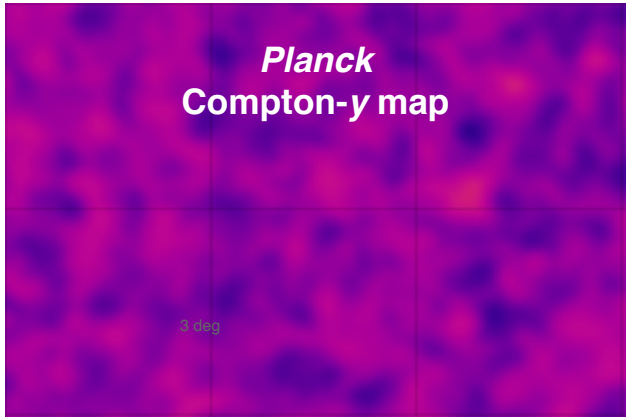


Statistically insignificant result for m=4

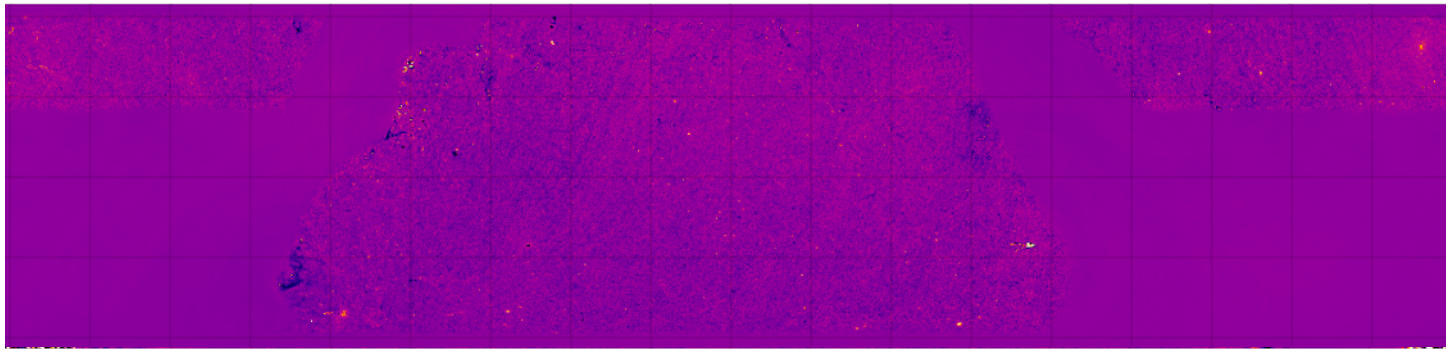
Lokken et al. 2022 (ApJ; arXiv: 2107.05523)

New map of Compton-*y*

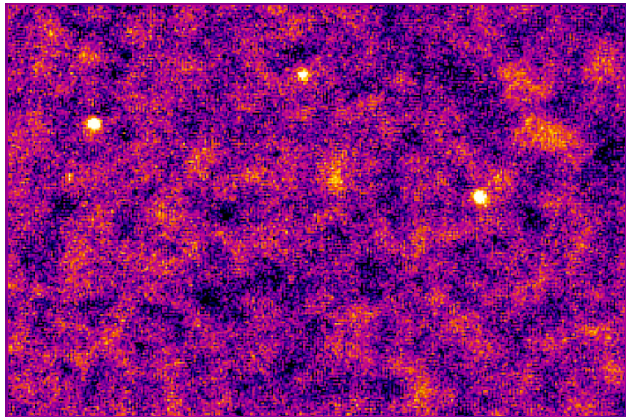




New map of Compton-*y*



***Planck* + ACT**
Compton-y map

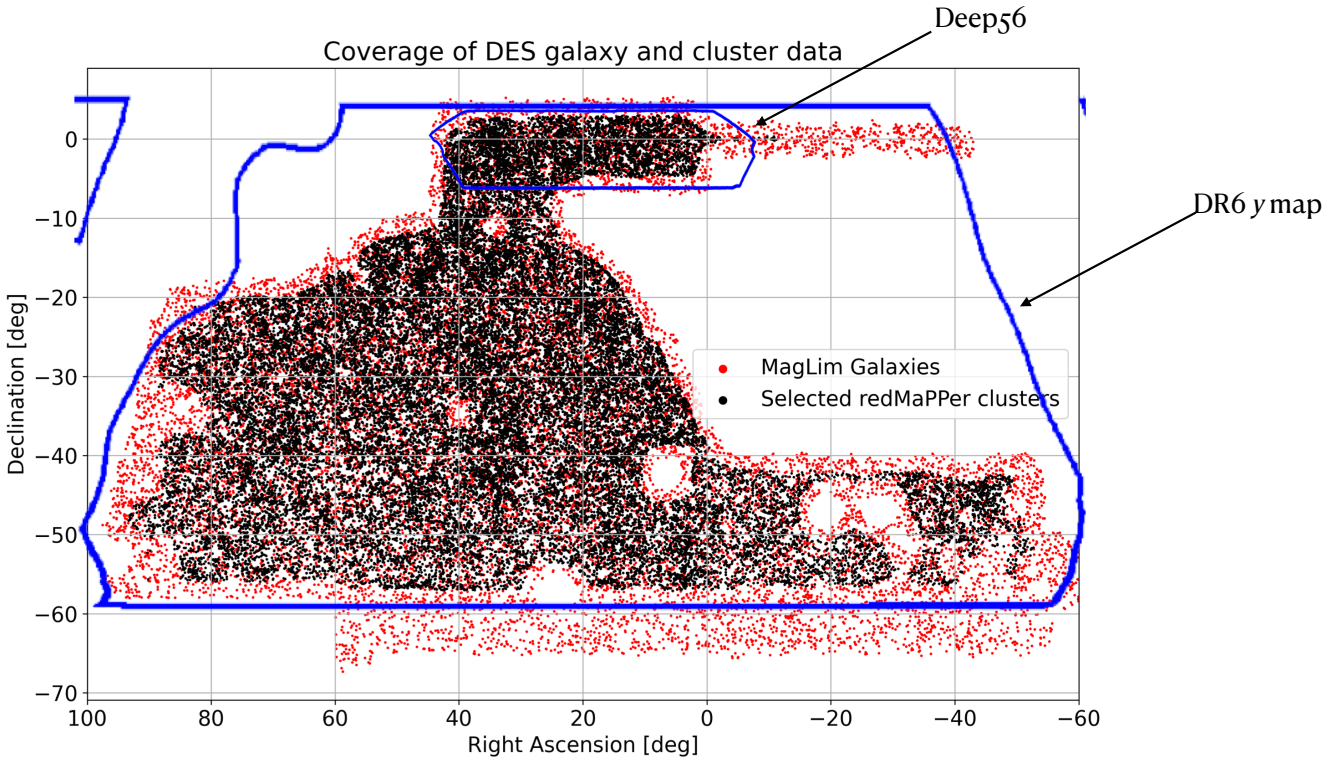


PRELIMINARY

Will Coulton

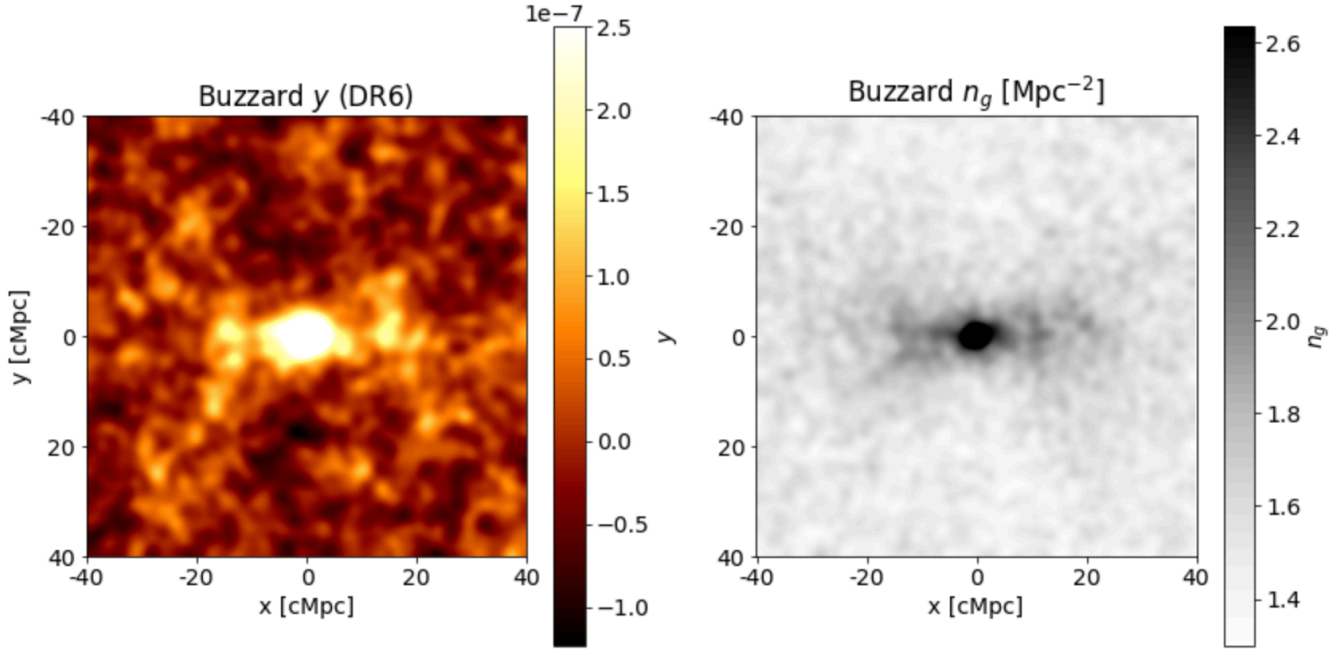
Expected Improvements from full DR6 Data

- >10x as many clusters overlapping!
- Increase in SNR of 3-4x



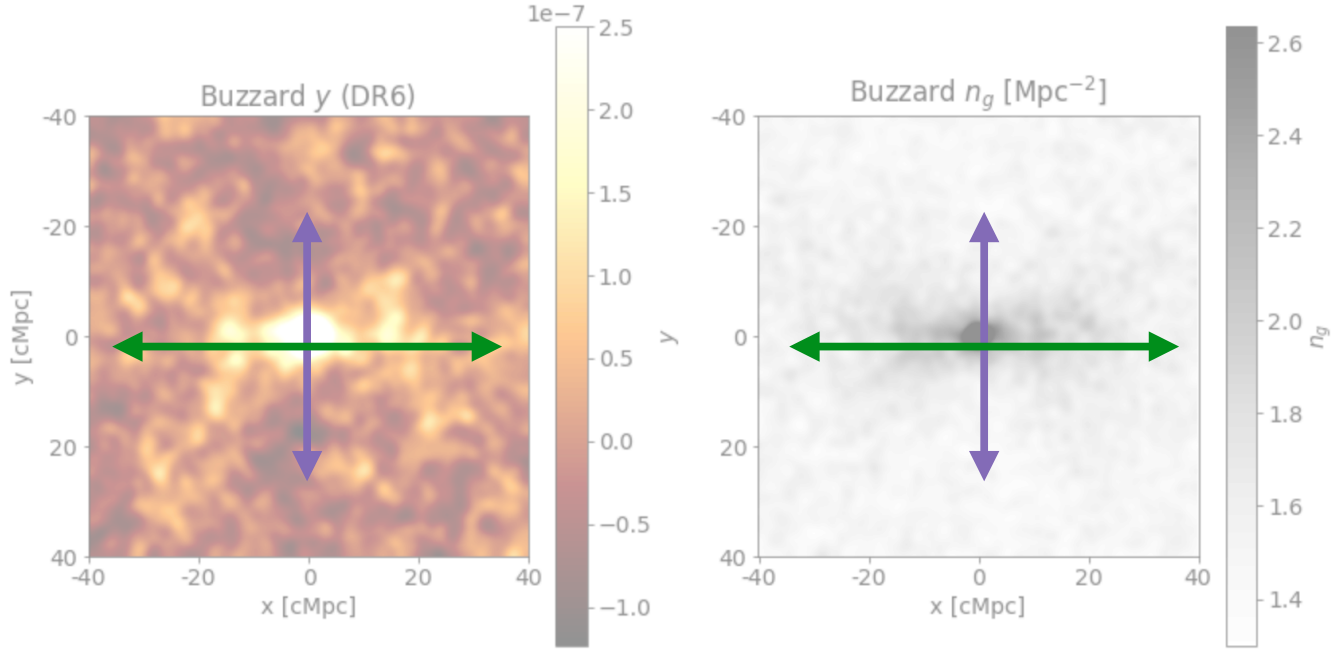
Relationships between fields

How are the gas thermal energy and galaxy number density related?



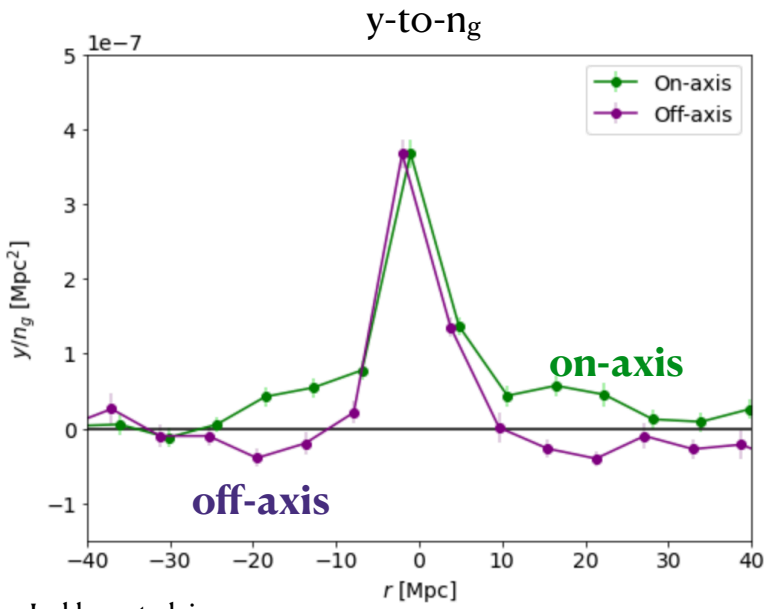
Relationships between fields

How are the gas thermal energy and galaxy number density related?

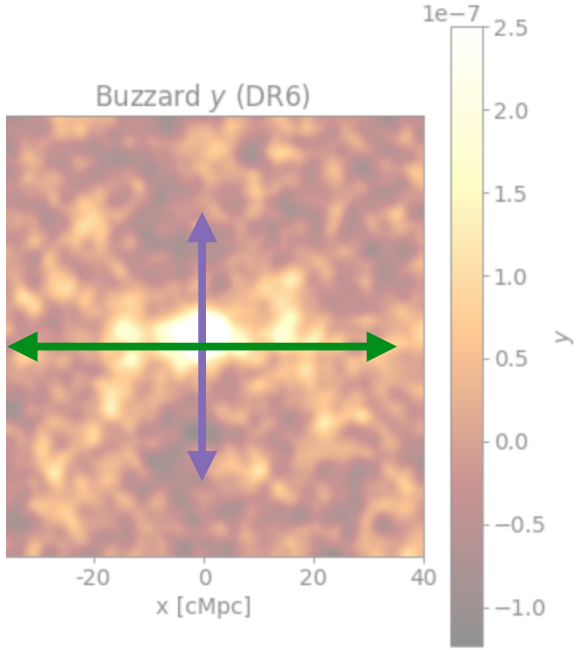


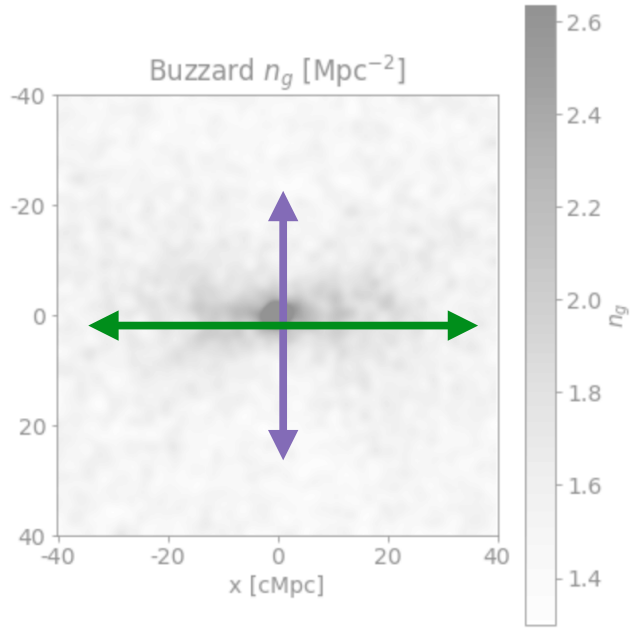
Relationships between fields

How are the gas thermal energy and galaxy number density related?



Lokken et al, in prep



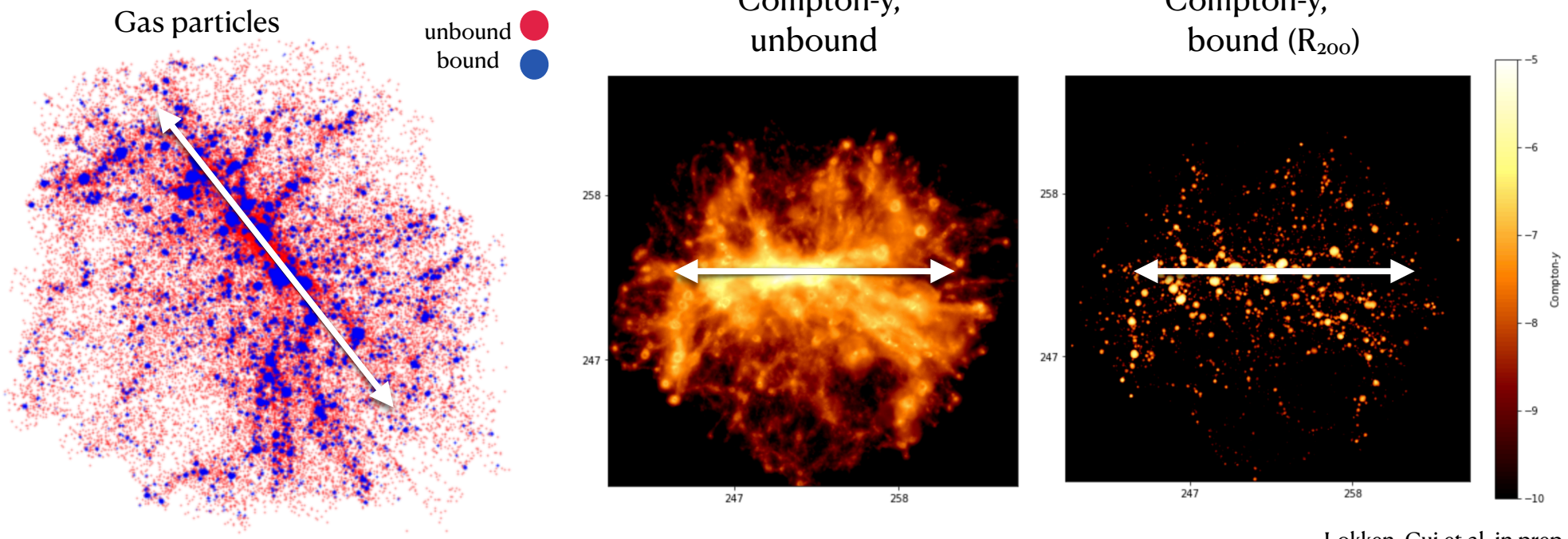


Takeaways

- More thermal energy per galaxy along the superclustering axis
- Larger halo masses on-axis boost Y more than they boost galaxy number

Probing diffuse gas

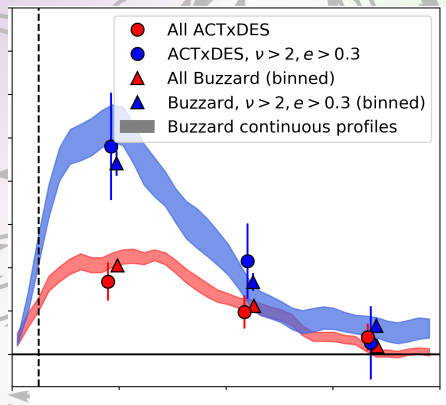
Gizmo-Simba ThreeHundred Hydrodynamic Simulations



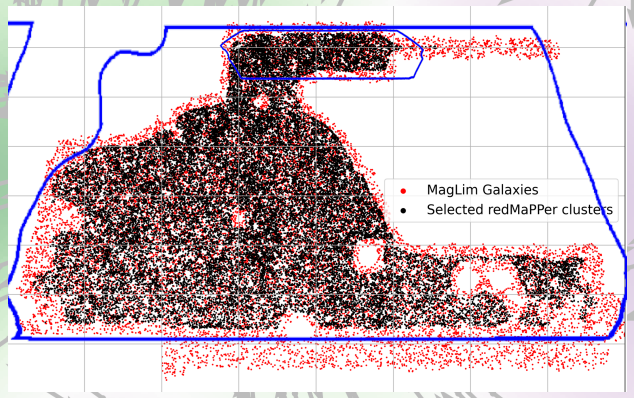
Lokken, Cui et al, in prep

Data from the ThreeHundred project Gizmo-Simba runs (Cui, Davé, Knebe et al. 2022)

Conclusions

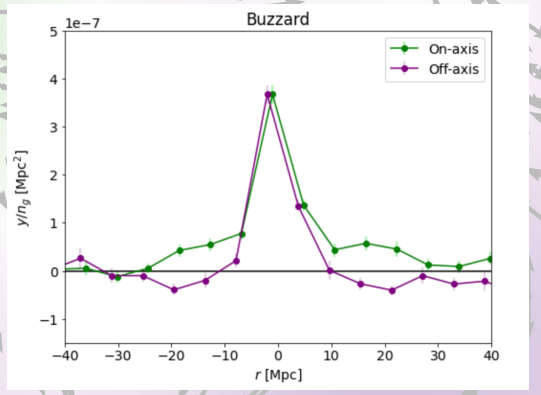


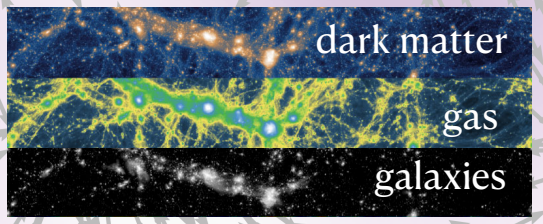
3.5σ evidence for extended anisotropy in the thermal energy content of superclusters



Expanded data:

significance increasing by ~3-4x

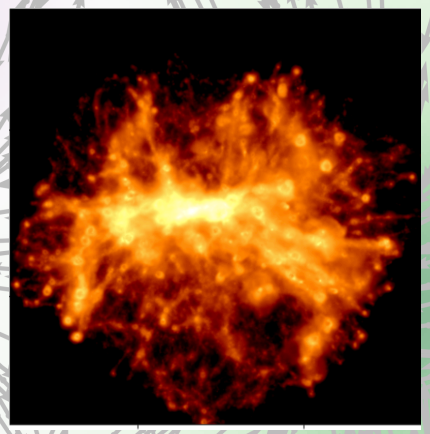




Credit: Illustris

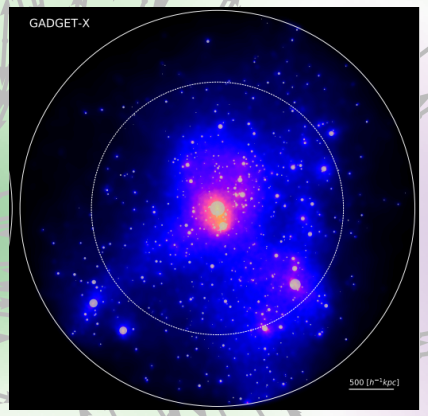
Measuring how dark matter, galaxies, and gas relate in anisotropic non-Gaussian structure

Ongoing & Future Work



Measure expectations for diffuse gas, search for evidence in data

Previous study found marginal detection in tSZ data (de Graaff et al)



AGN feedback impact on thermal energy anistropy

- Re-running the ThreeHundred simulations

How does the oriented signal vary with cosmology (e.g., *w*) in sims?

- Websky (Stein+ 2020), Quijote, (Villaescusa-Navarro+ 2019)