UNIVERSITY OF TORONTO

Anisotropic Superclustering of Cosmic Gas

An analysis with ACT+*Planck* and DES data

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ACT + DES collaborations

July 2022, Cosmo From Home Conference

Overview

- Background: the thermal Sunyaev-Zel'dovich effect for cosmology
- Measurements of superclustering with tSZ
- Theoretical predictions
- Observational results
- Comparing to galaxies
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thermal Sunyaev-Zel'dovich (tSZ) effect

Foreground effect in CMB maps dependent on the
electron number density and temperature

Parametrized by Compton-*y*:

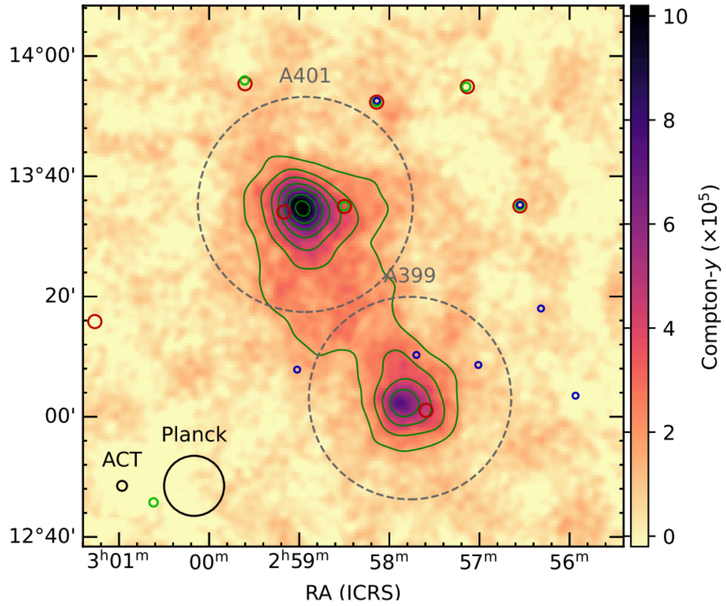
$$y = \int \left(n_e \frac{k_B T_e}{m_e c^2} \sigma_T \right) dl$$

- Advantage: independent of redshift
- Uses for cosmology: cluster number counts, power spectrum
- Uses for astrophysics: measuring the physics of the intracluster medium, typically through *stacking*
- ***But:*** the distribution of hot gas around clusters is typically *anisotropic*
  - *Cosmological and astrophysical information is missed by isotropic measures*

tSZ for cosmology

Why study anisotropic superclustering?

- Filaments and superclusters are sensitive to…
  - parameters within the standard model (k, σ_8 (Cen+1993), Ω_Λ (Kolokotroni+2002, Basilakos+2001)
  - The form of dark matter — e.g., cold vs. warm vs. fuzzy (Mocz+ 2019)
  - Modified gravity (Ho et al 2018)
  - Bias of the tracers (Bharadwaj+ 2004)
- Information that is not contained in 2-point statistics



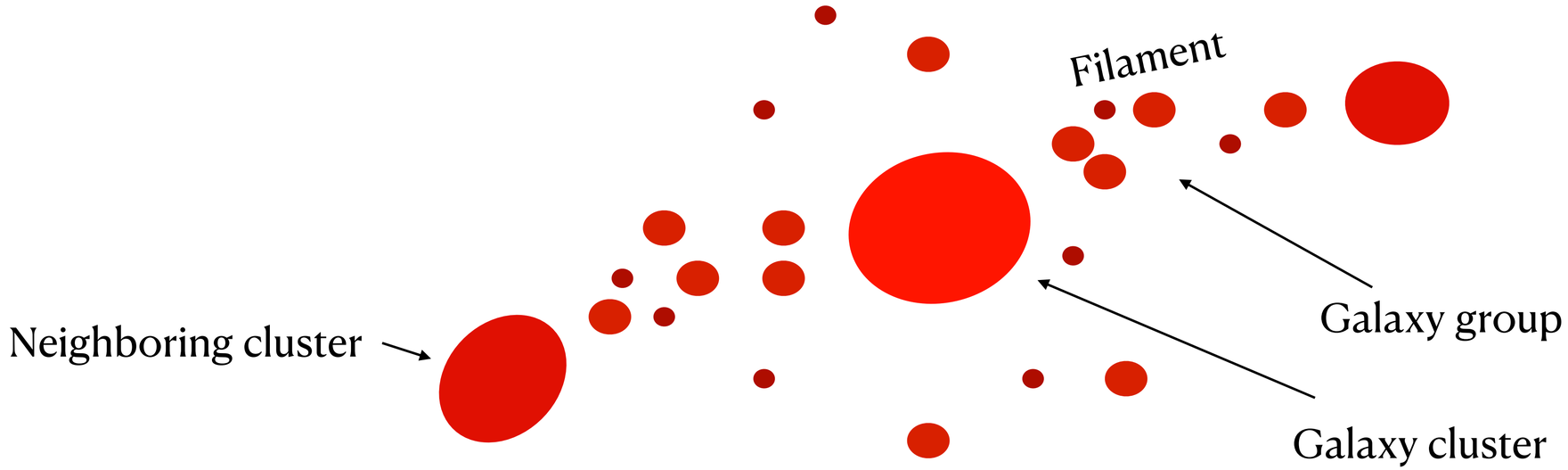
Two clusters in a pre-merger phase shown in ACT+*Planck* data (Hincks et al. 2021)

tSZ for cosmology

Comparing to theory

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
- Applying gas to DM-only simulations: fits to hydrodynamic simulations of massive clusters with AGN feedback [e.g., Battaglia+ 2012]

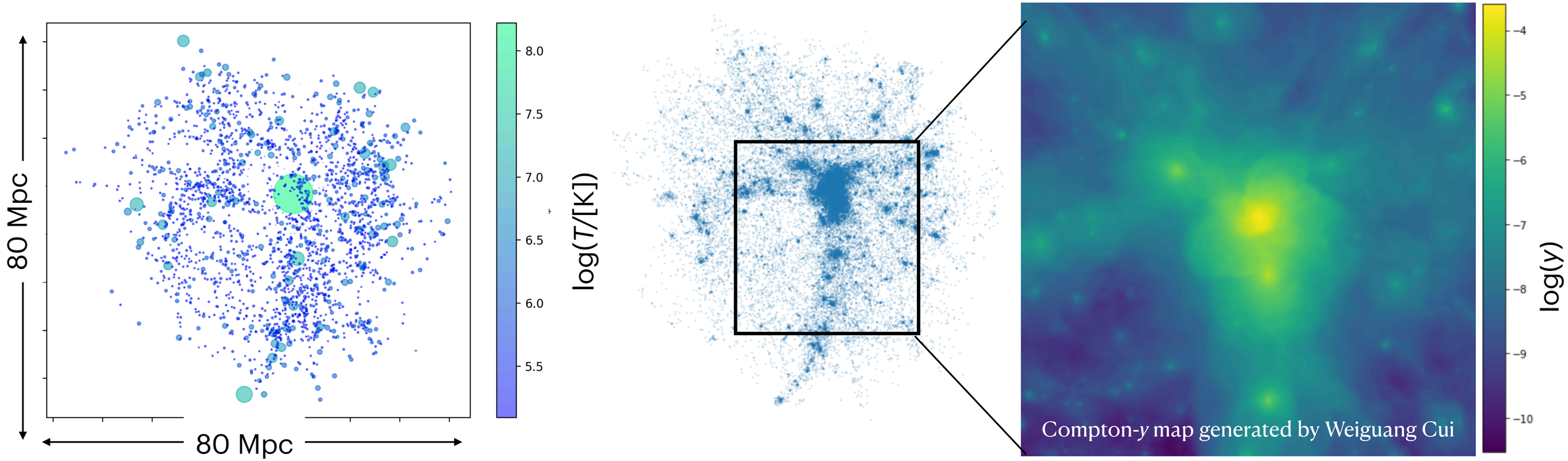


tSZ for cosmology

Comparing to theory

Going beyond the halo model

- Diffuse dark matter and gas
- State of the gas in the warm-hot intergalactic medium



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

Key Questions

**Anisotropy of the gas in superclusters,
comparison to galaxy and matter distributions**

Within the halo model

- 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

- What is the state of 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?

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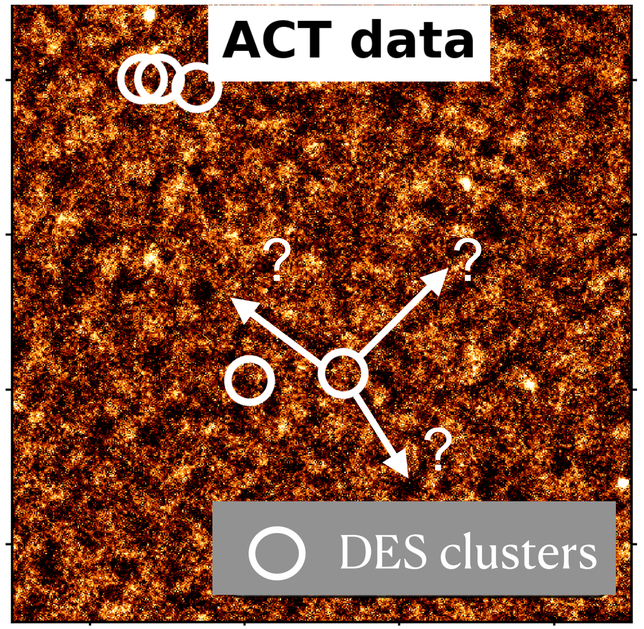
The challenge with tSZ

- 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*

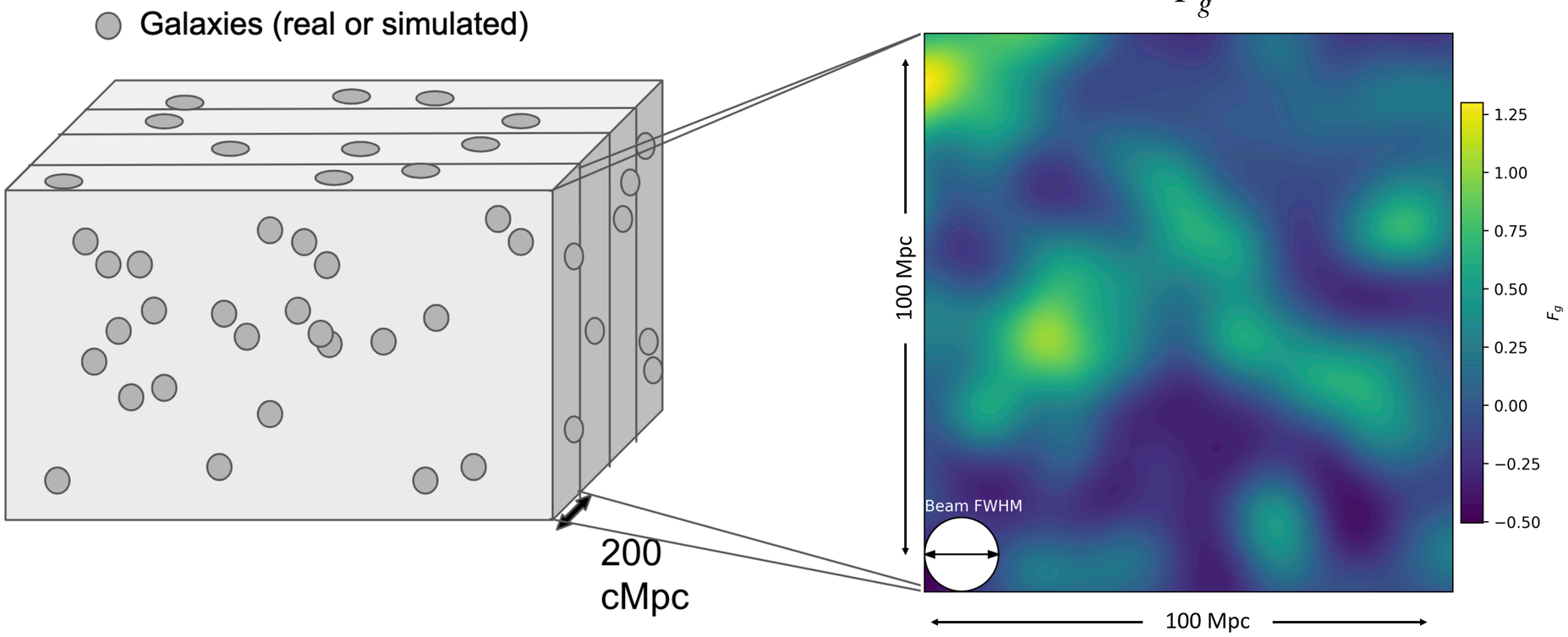


Compton-*y* map from Madhavacheril+ 2019

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

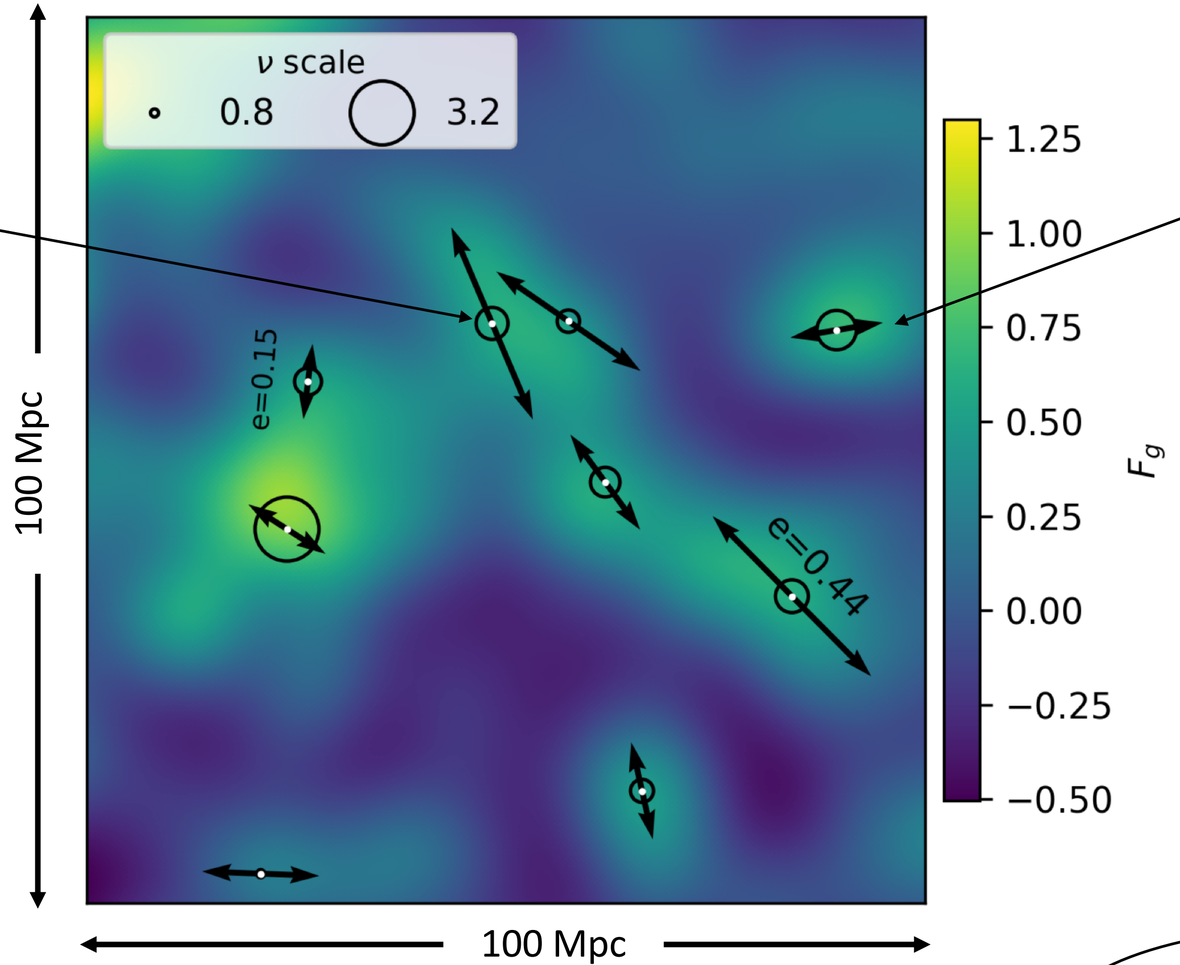
Eigenvalues λ_1, λ_2 provide additional info

Identifying regions of high superclustering

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

Headless vector is along v2 axis (slowest change)

Galaxy clusters (white points)



Field ellipticity

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

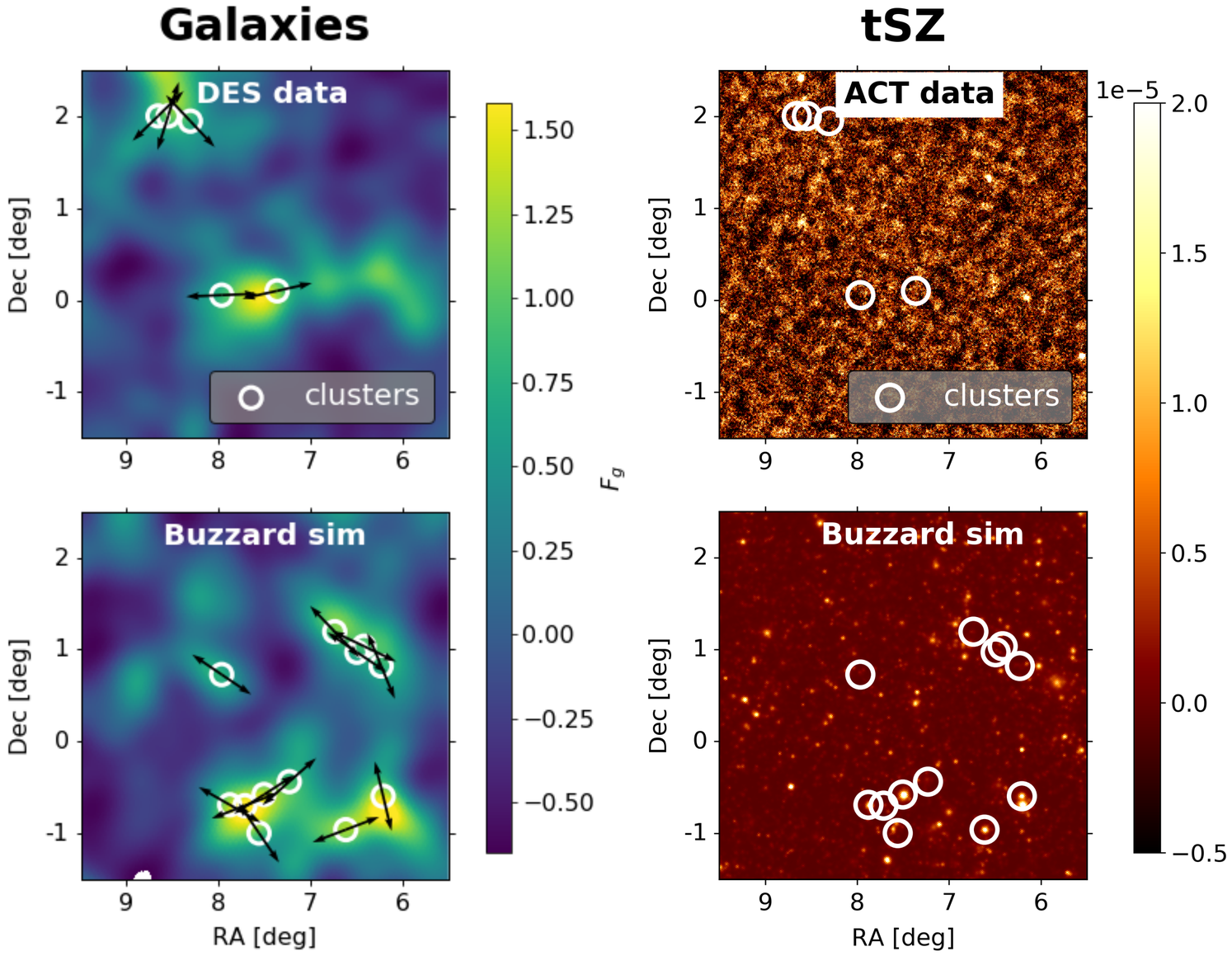
Field excursion

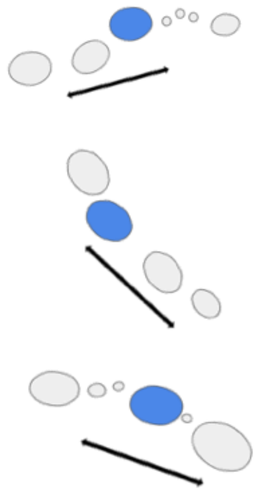
$$\nu = \frac{F_g}{\sigma}$$

Where σ is the root mean square of F

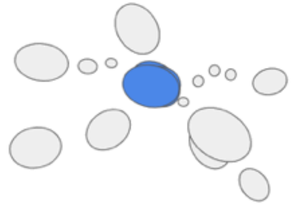
$\nu > 2 \quad e > 0.3$

Measuring the signatures of superclustering in maps

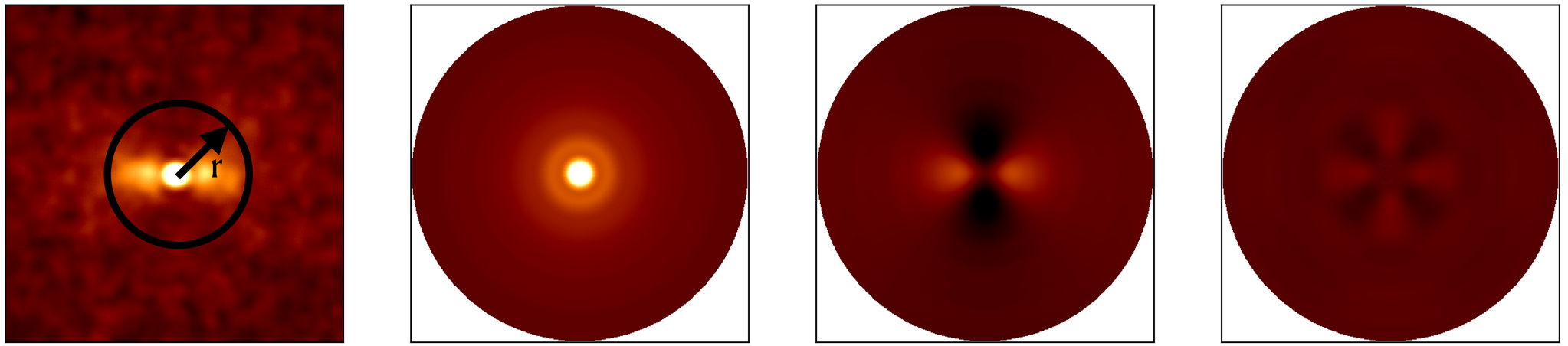




Stack clusters in ***unoriented*** way



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

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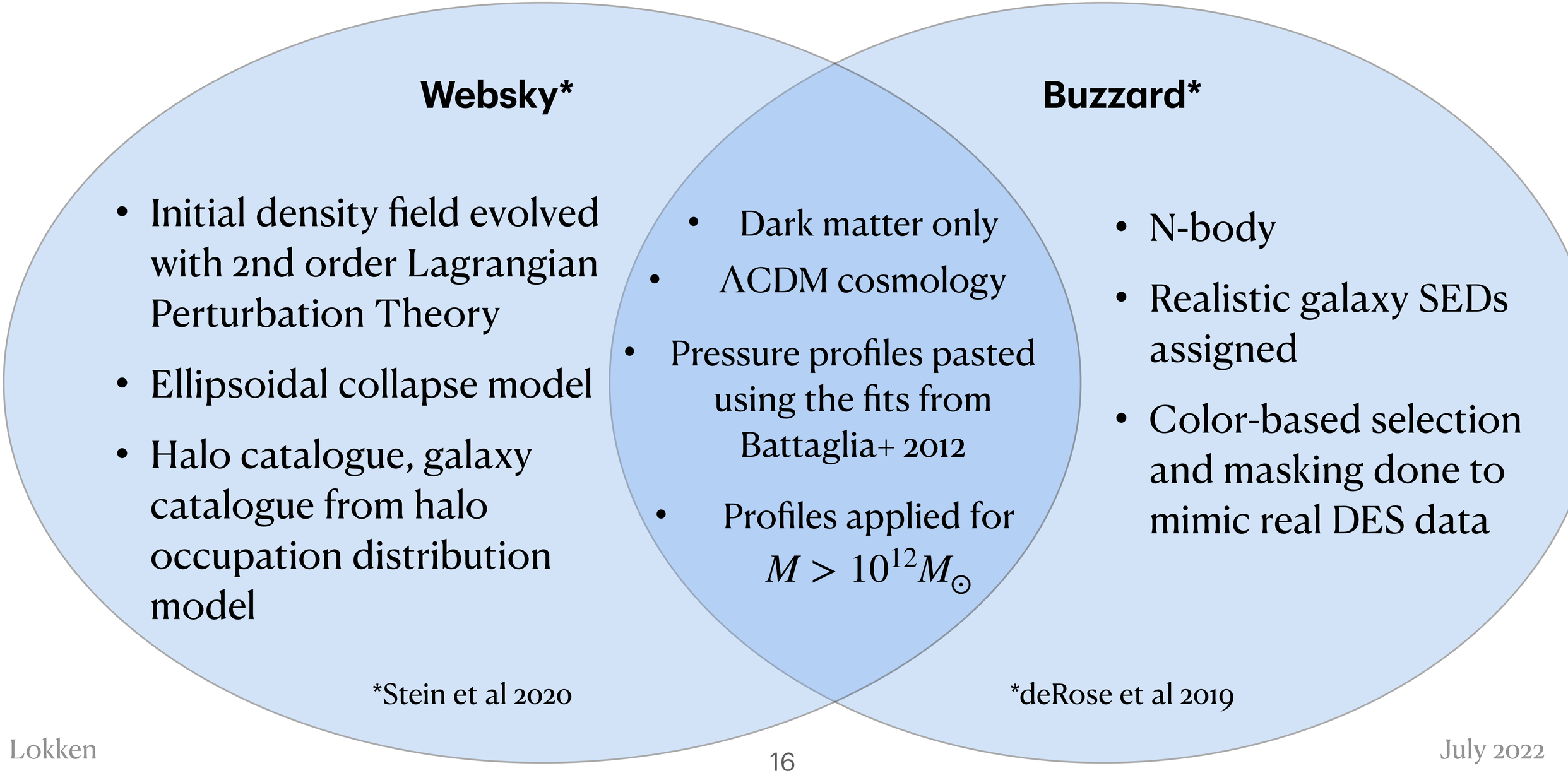
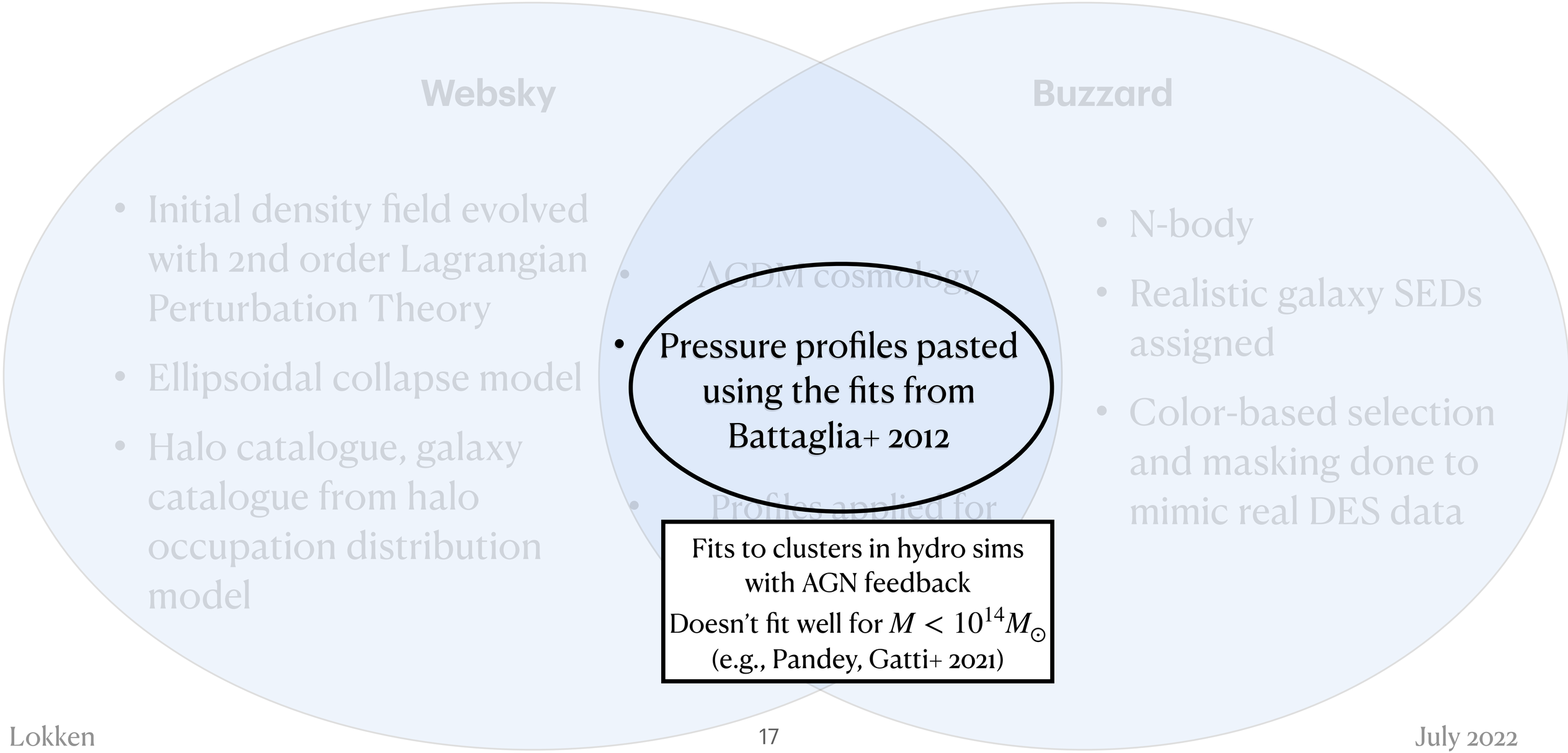
Predictions from simulations: the halo model



Predictions from simulations: the halo model

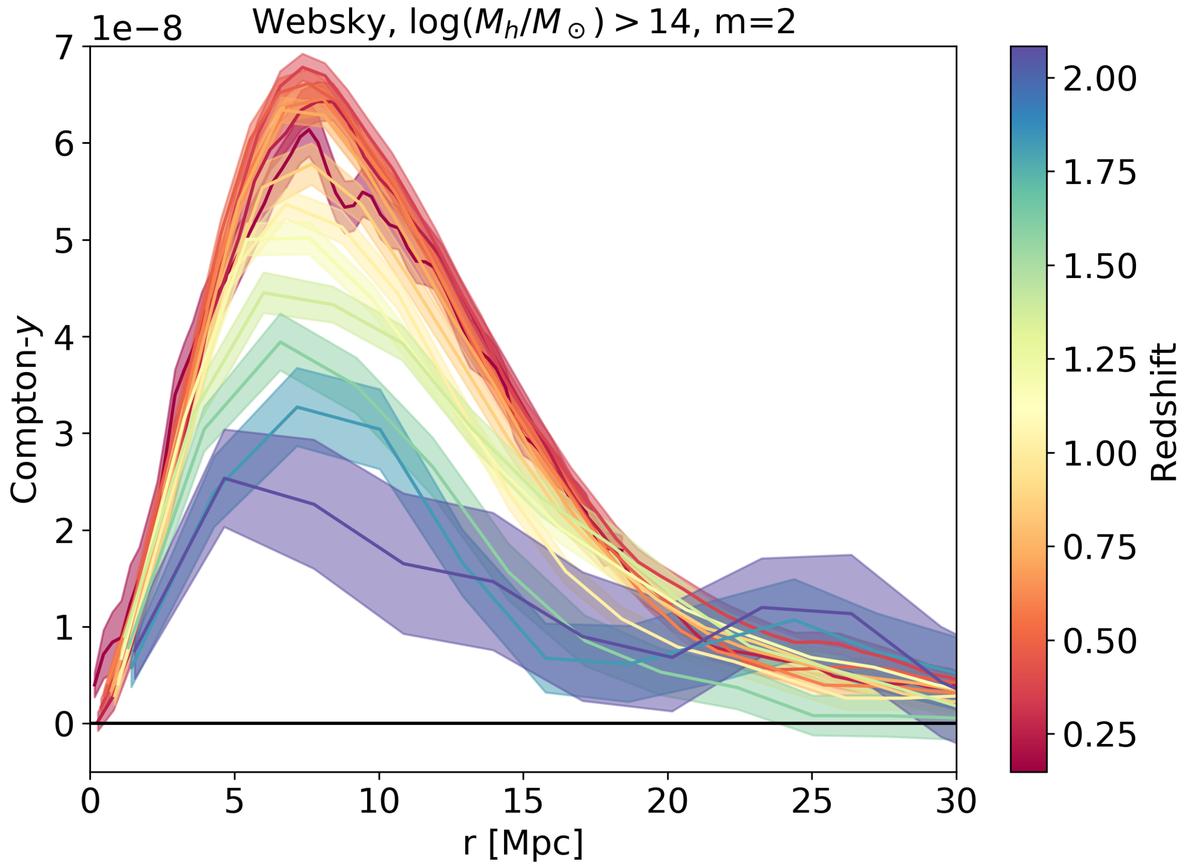


Fits to clusters in hydro sims with AGN feedback

Doesn't fit well for $M < 10^{14} M_{\odot}$ (e.g., Pandey, Gatti+ 2021)

Evolution with cosmic time

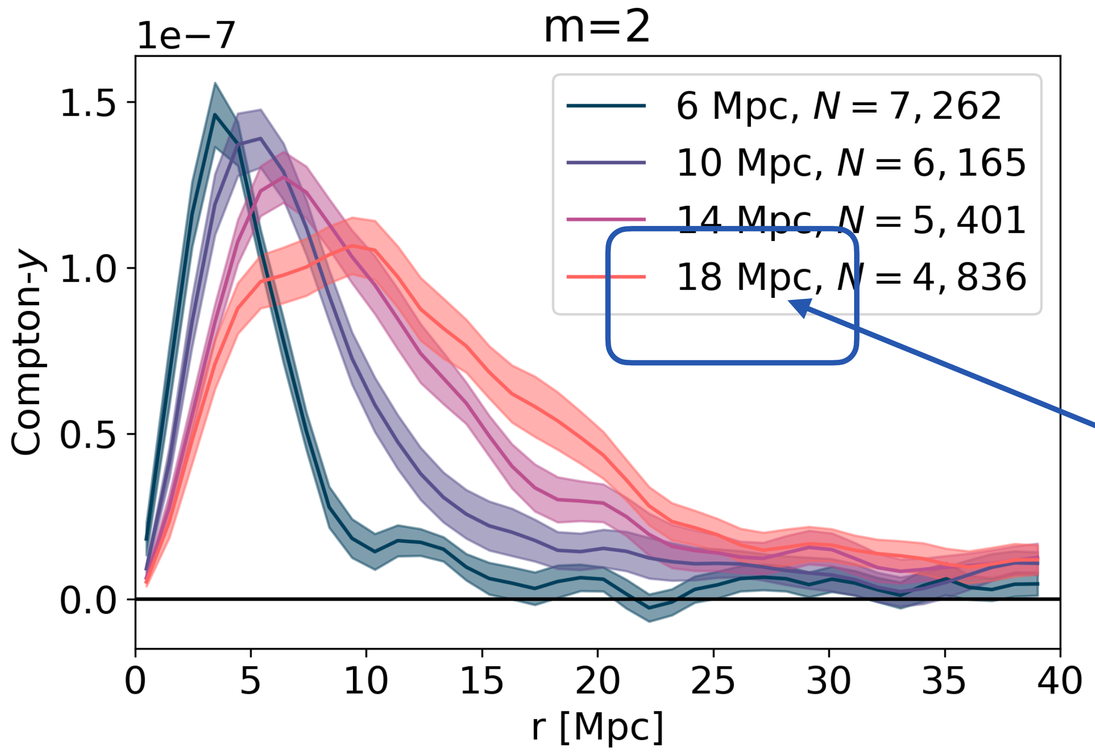
Expected redshift dependence from simulations (Websky)



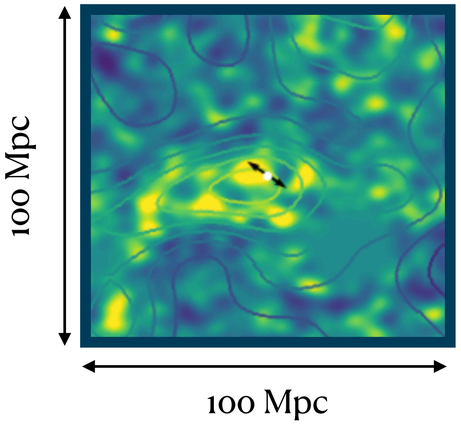
Lokken et al. 2022 (ApJ; arXiv: 2107.05523)

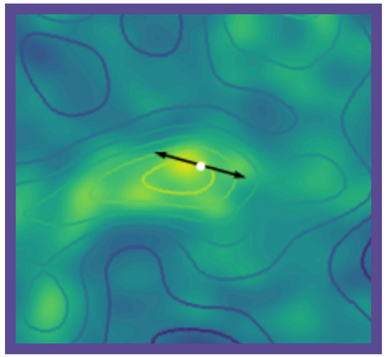
Dependence on scale

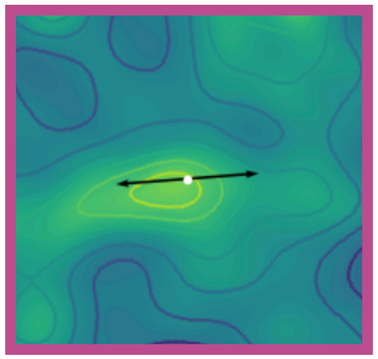
(from Buzzard simulations)

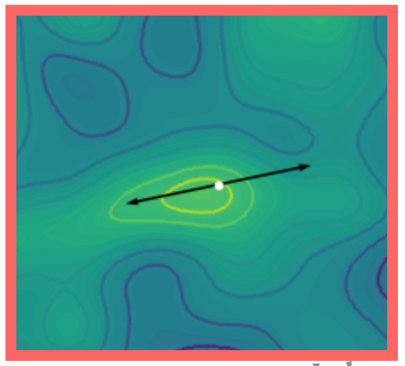


Sensitive to inter-cluster bridges

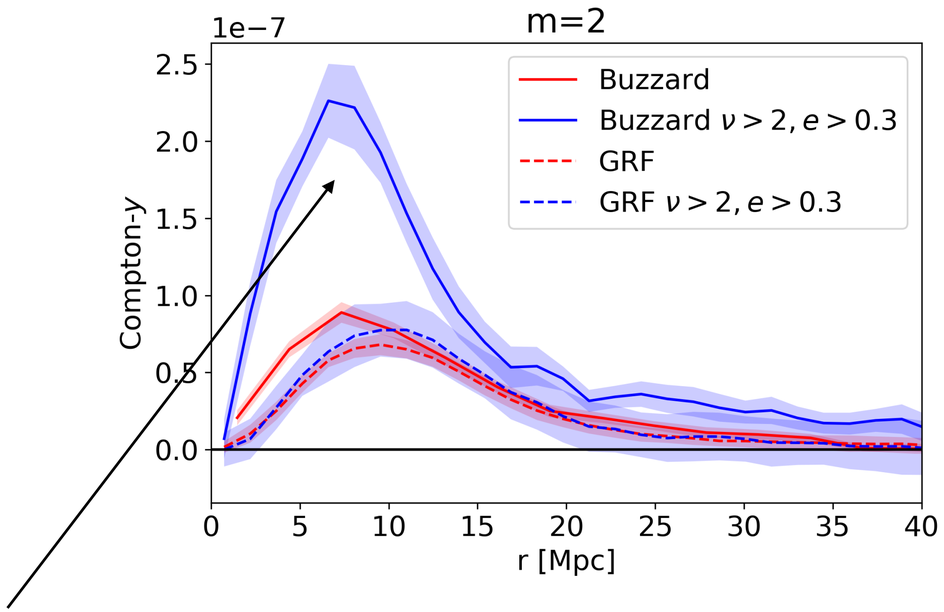


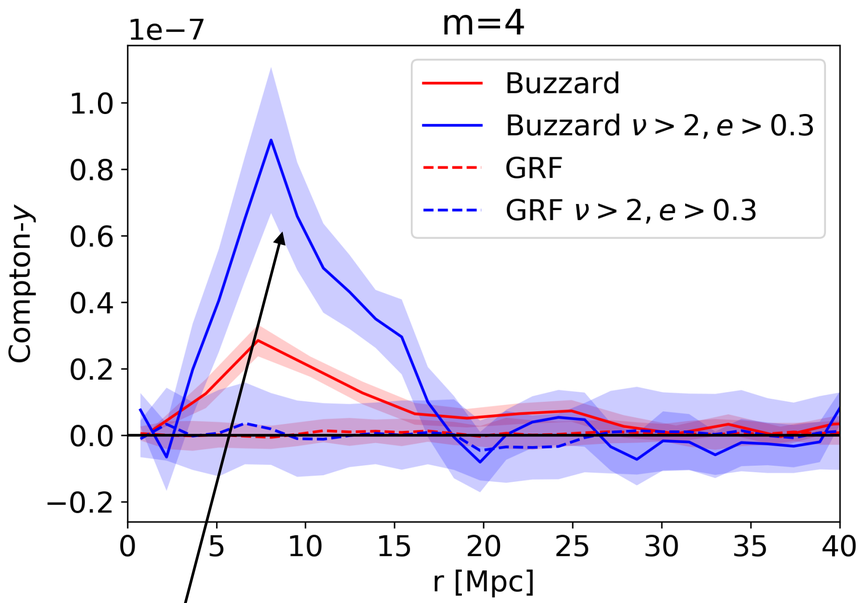




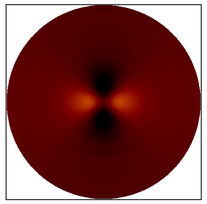


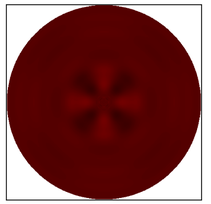
Signs of non-Gaussianity





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

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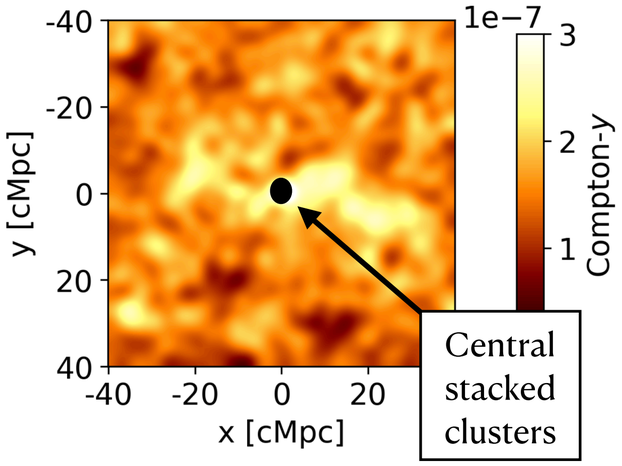
Results

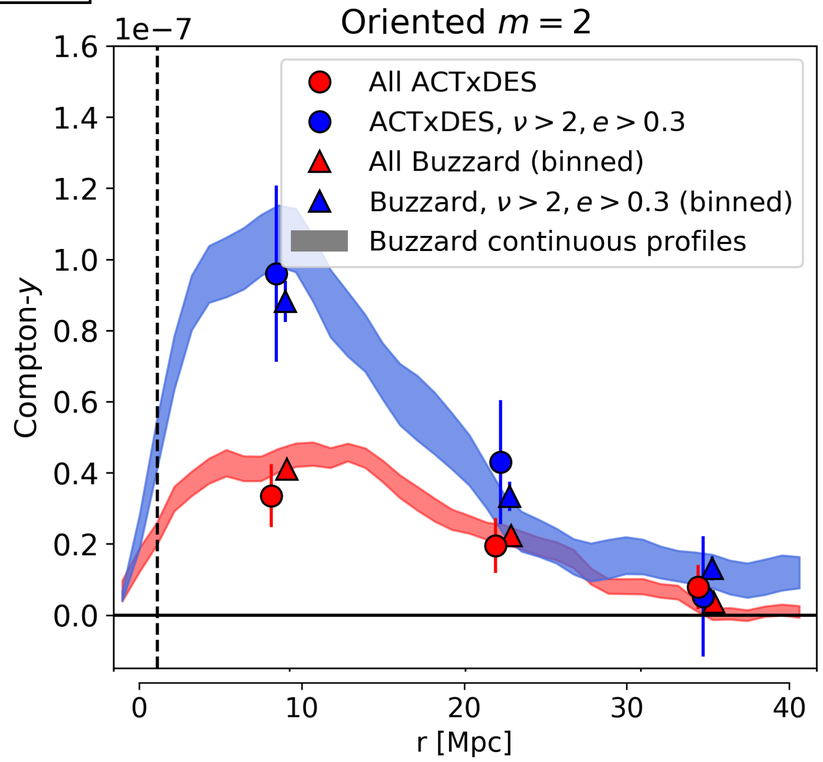
Deep56 y-map (fractional overlap with DES)

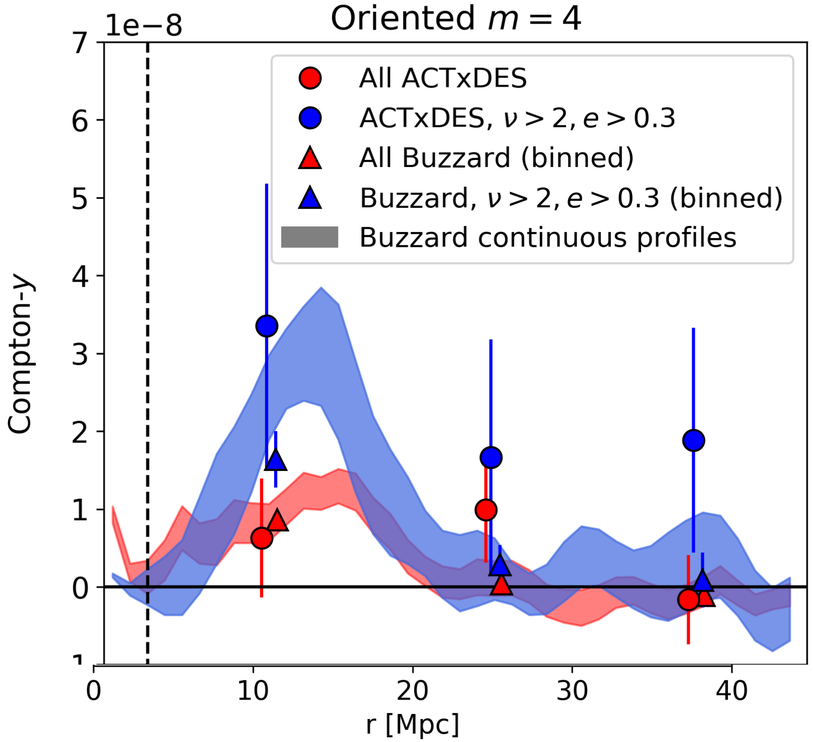


3.5σ result for m=2

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)

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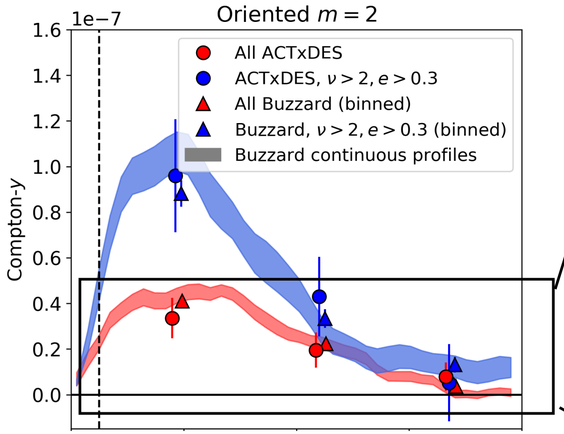
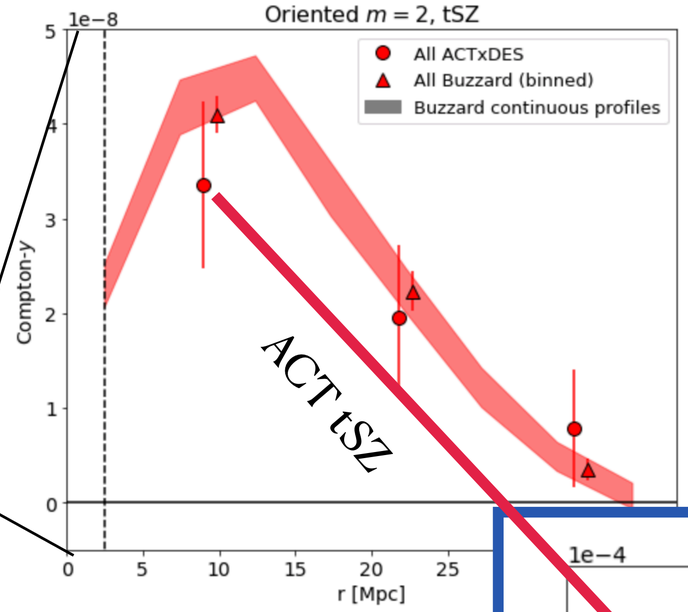
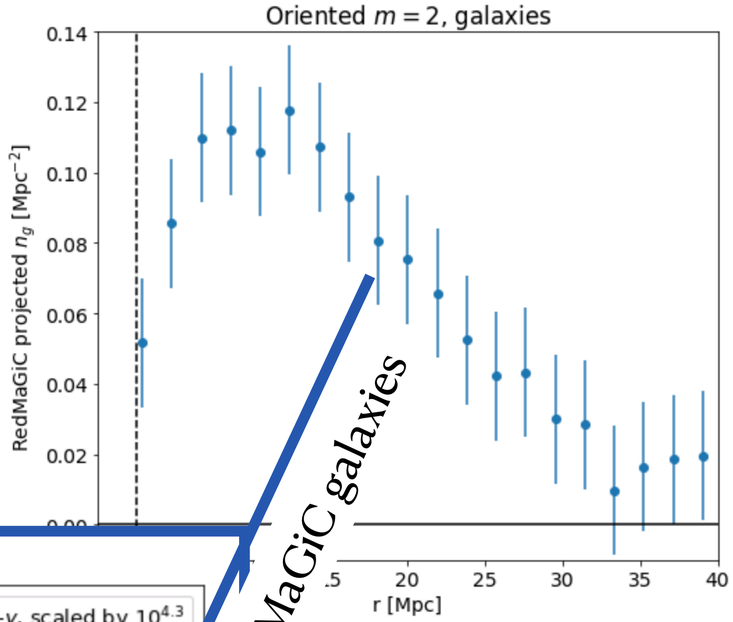
Comparing with galaxies

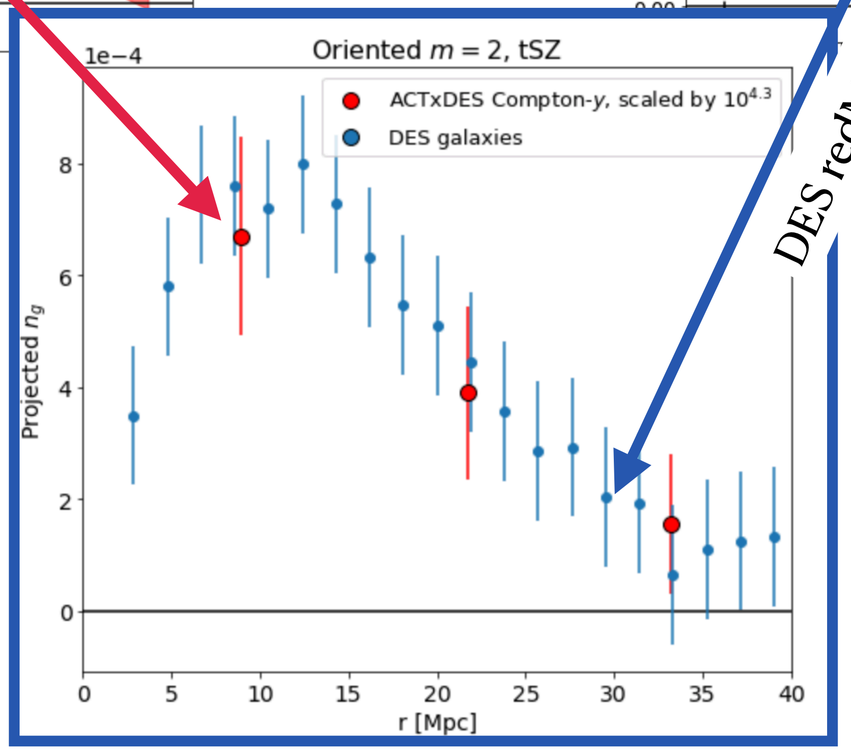




ACT tSZ



DES redMaGiC galaxies

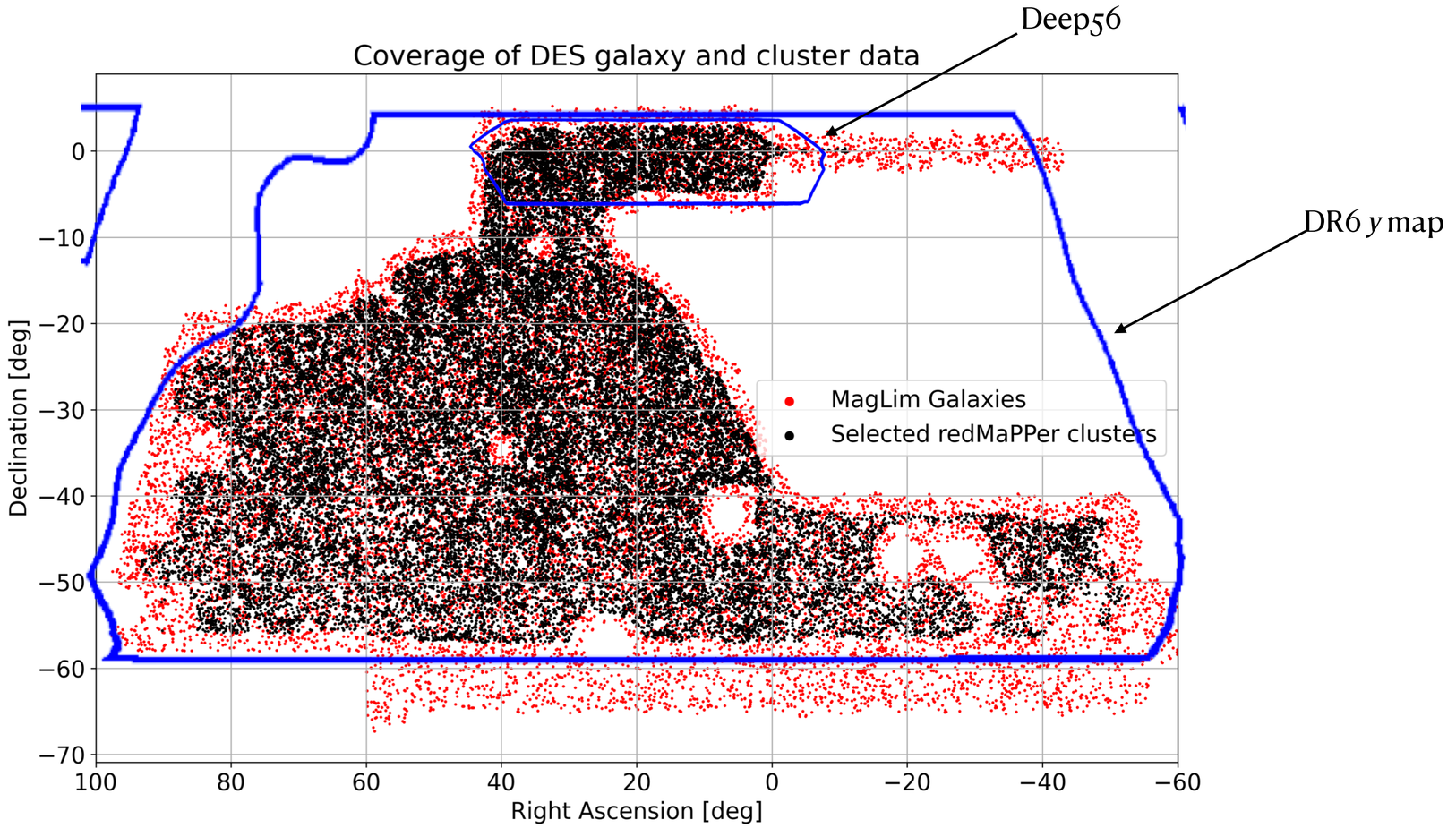


- Measuring the *relative anisotropic bias* between gas and galaxies
- DES weak lensing data —> absolute anisotropic bias

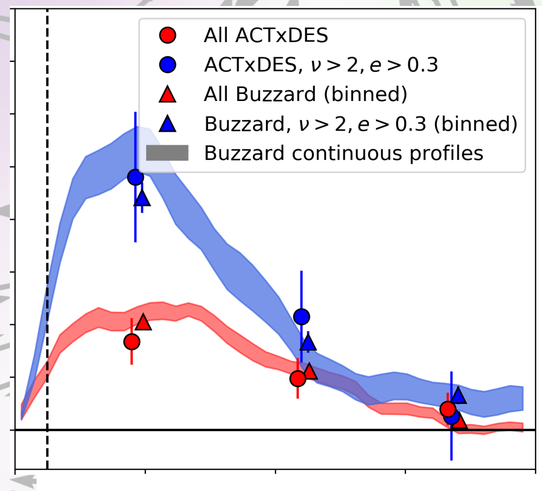
Preliminary

Expected Improvements from full DR6 Data

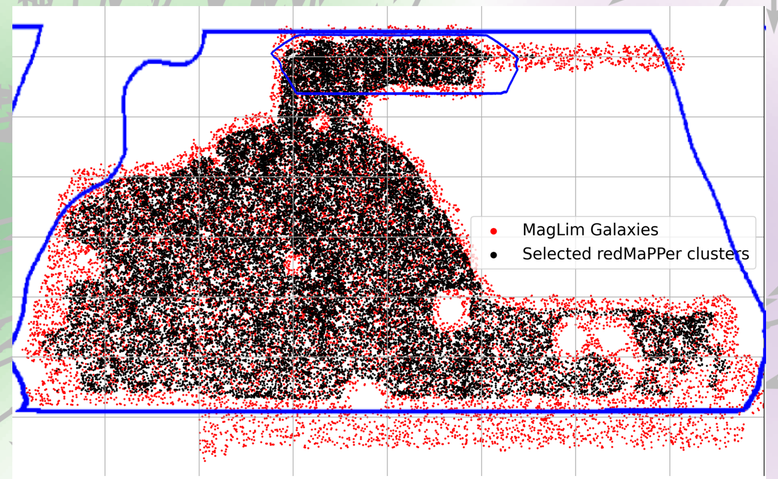
>**3x** improvement in SNR in tSZ, detection of late-time non Gaussianity, full comparisons with the DES galaxies!



Conclusions

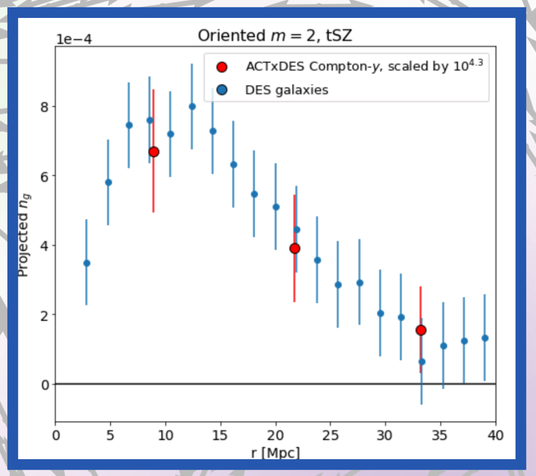


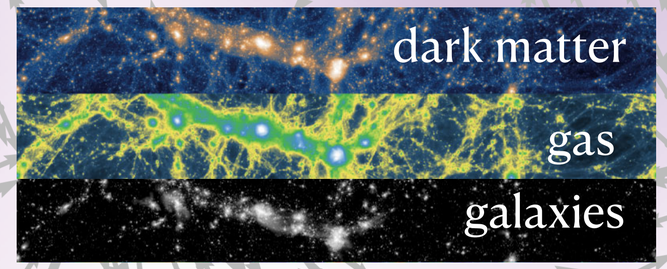
3.5σ evidence for extended anisotropy in the thermal energy content of superclusters



Expanded data:

significance expected to increase by ~3-4x

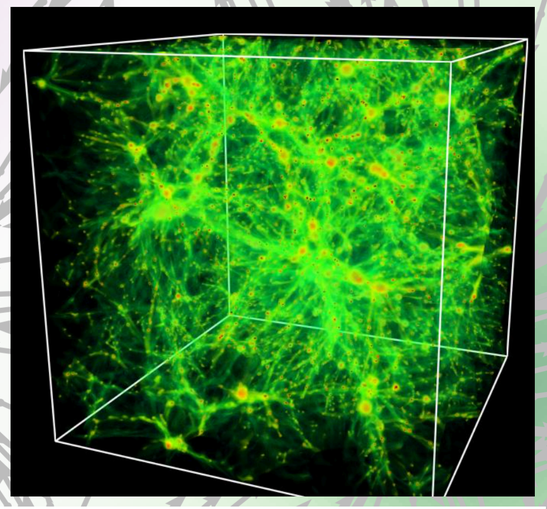




Credit: Illustris

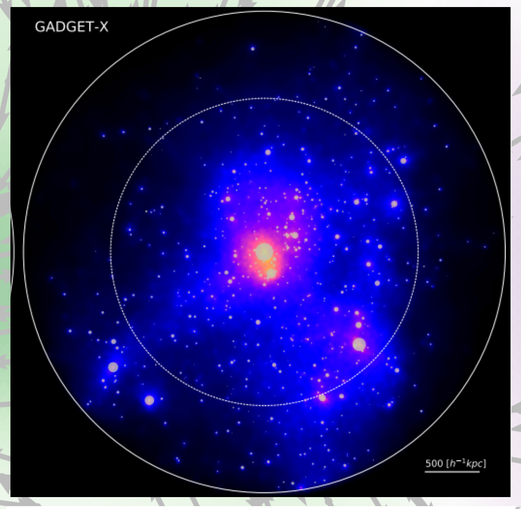
New data enables measurements of the how the dark matter, galaxies, and gas relate in anisotropic non-Gaussian structure

Future Work



Search for WHIM gas

- marginal evidence from cluster-pair filament stacking (de Graaff et al 2017)



AGN feedback impact on thermal energy anistropy

- the 300 project Gizmo-Simba runs (Cui, Davé, Knebe et al. 2022)

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

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