

When gas goes beyond:

Exploring the power of oriented SZ stacking

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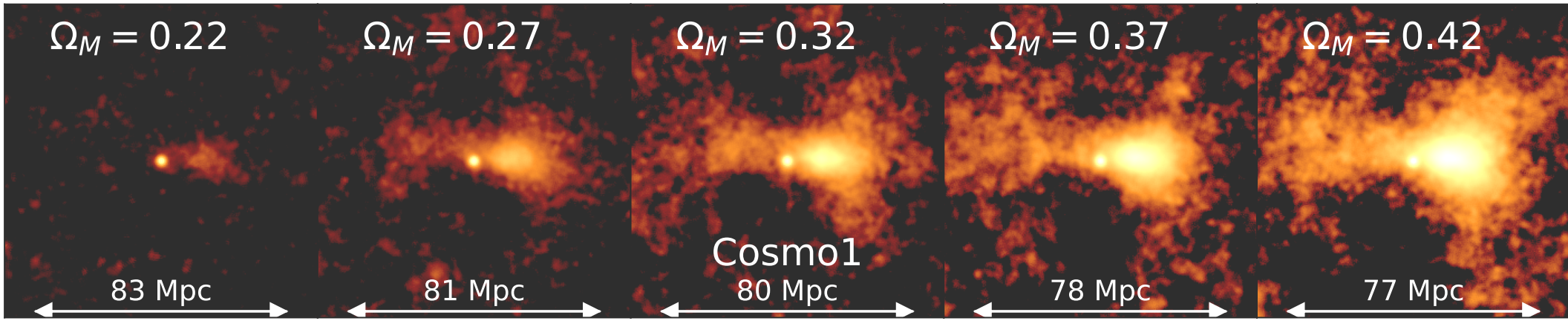
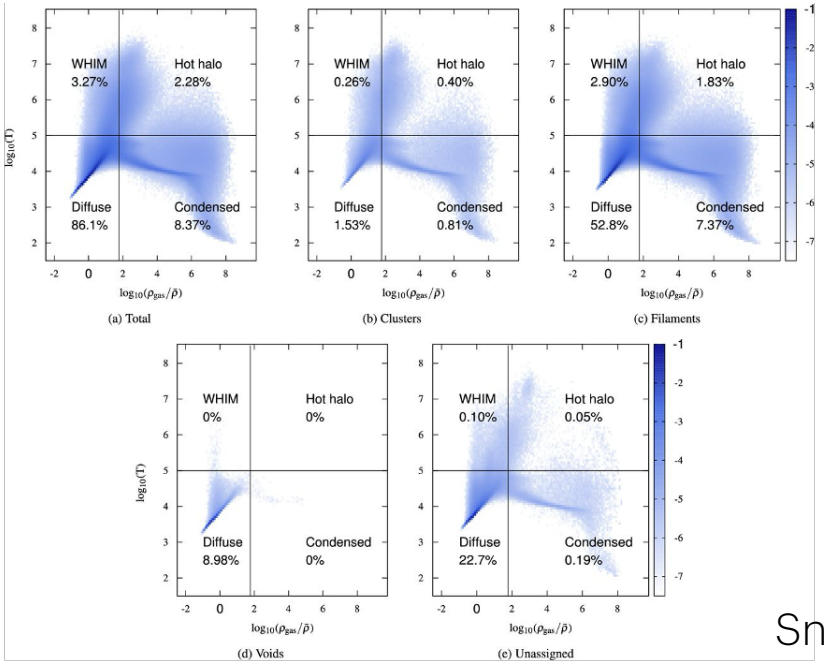
LBNL CMB Lunch



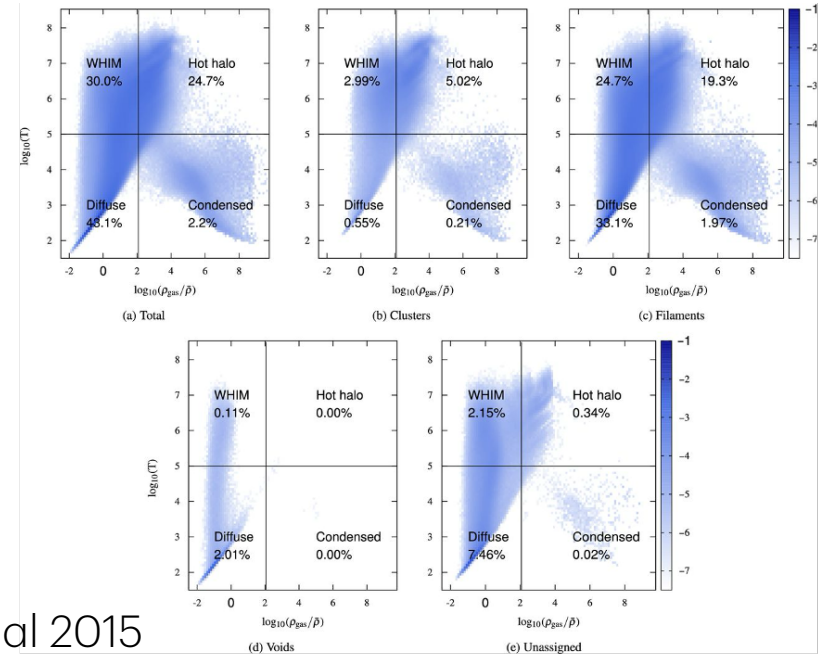
Motivation

- History of the gas: diffuse IGM —> multiphase, mix of diffuse + halos
- By z~1: Mix of hot galaxy clusters, warm-hot filaments and CGM, complex superclusters with mixture of states, etc

z=3.2



z=0



Snedden et al 2015

Mon Not R Astron Soc, Volume 455, Issue 3, 21 January 2016, Pages 2804–2825, https://doi.org/10.1093/mnras/stv2421

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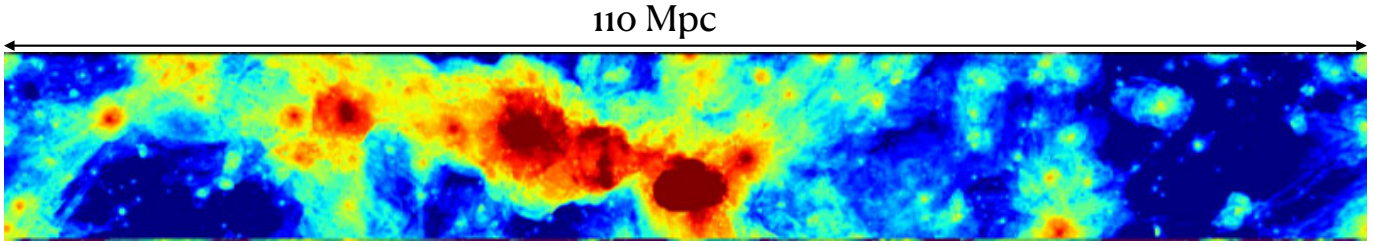
Motivation

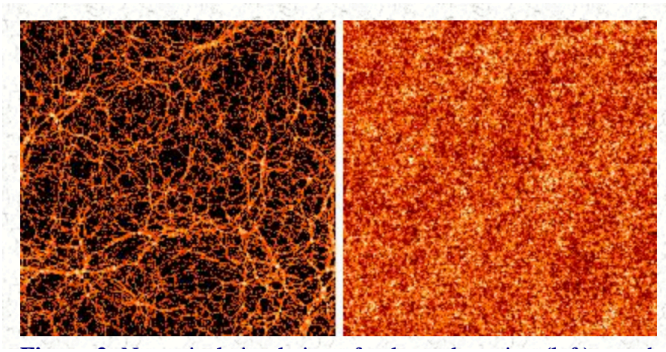


Illustris TNG 2021

- In reality, even at lower redshifts the gas is a continuous field, with complex morphology
- Imprints of late-time gas in the CMB often treated as discrete, unclustered objects disconnected to local environment
- Examples:
  - **Cluster counts** (discrete objects, usually assumed to be spherical and unclustered)
  - **tSZ power spectrum** (No environmental nor anisotropic dependence); usually modelled with halos
  - **Unoriented stacking** (Analysis usually centres on the 1-halo term)
- Approximations are OK for some regimes (esp. low-z, high-mass clusters), but breaks down elsewhere

Motivation

- Beyond power spectrum/cross-correlations: increased cosmological constraining power from non-Gaussianity
  - E.g. Minkowski functionals aid cosmological constraints even without clustering (Sabyr et al. 2024)
- Local anisotropy tells us about:
  - Influence of tidal fields in shaping superclusters and filaments
  - Interplay between dark energy and dark matter in triaxial collapse at late times

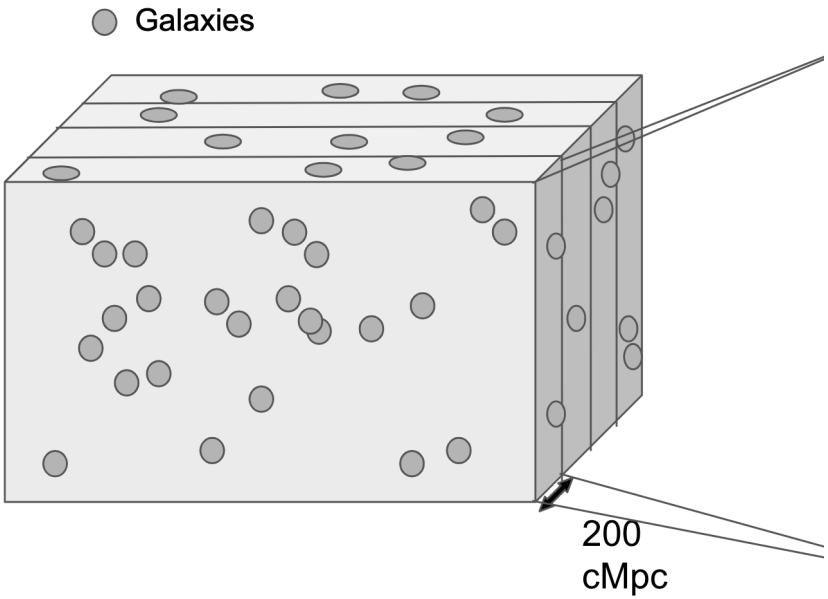


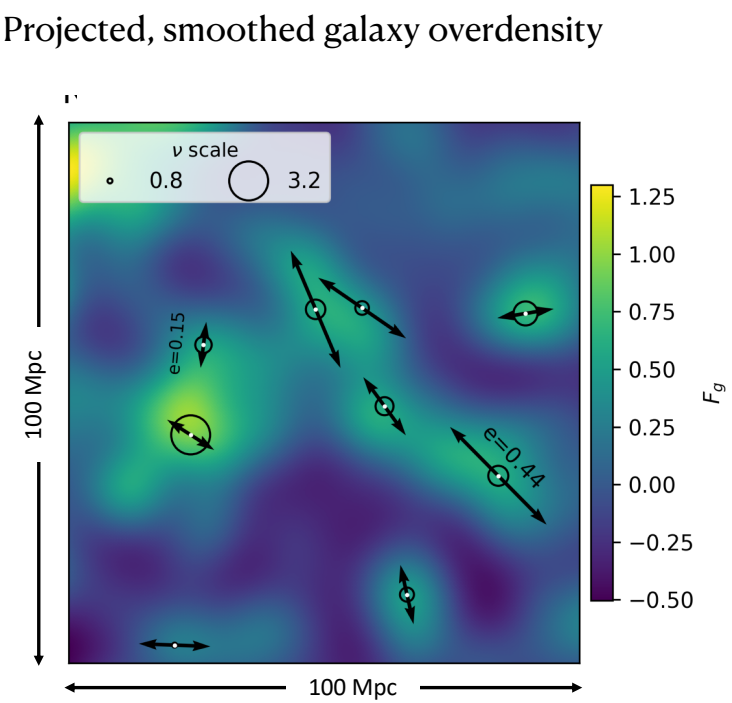
These two fields have the same power spectrum [Coles 2001]

Key questions

- As we push to higher *z*, can we improve cosmological constraints from tSZ and kSZ by:
    1. Focusing on the clustering
    2. Including environmental information
    3. Accounting for anisotropic clustering
- To be robust to gas uncertainties, do we need to treat gas as extended and continuous?
- In certain scales & environmental regimes, can we learn more about the gas physics from anisotropic analysis + modeling?

Constrained oriented stacking





(1) Select objects by mass or other properties from a catalog

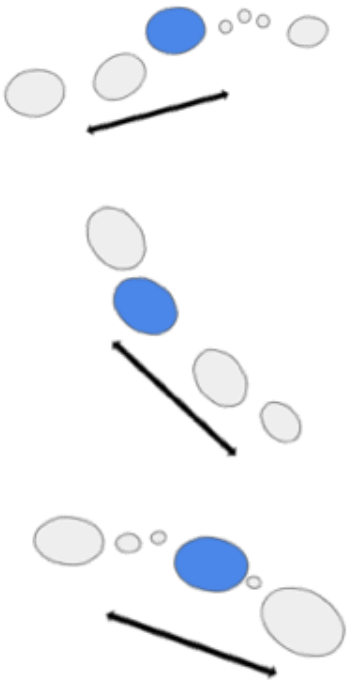
(2) Sub-select those with properties of galaxy field at some scale, e.g. excursion...

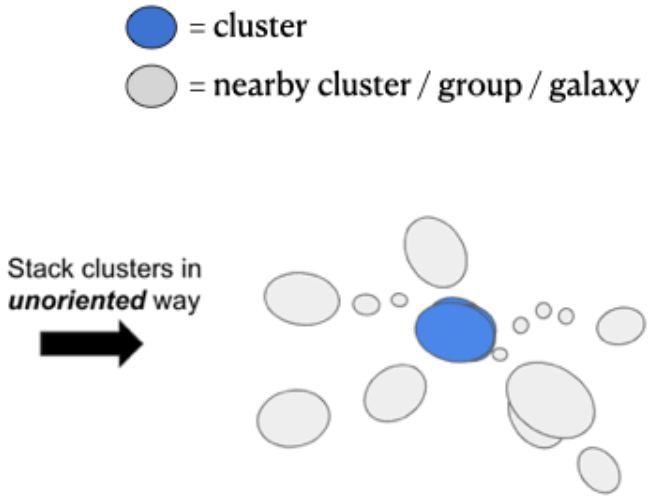
$$\nu = \frac{F_g}{\sigma}$$

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

Constrained **oriented** stacking

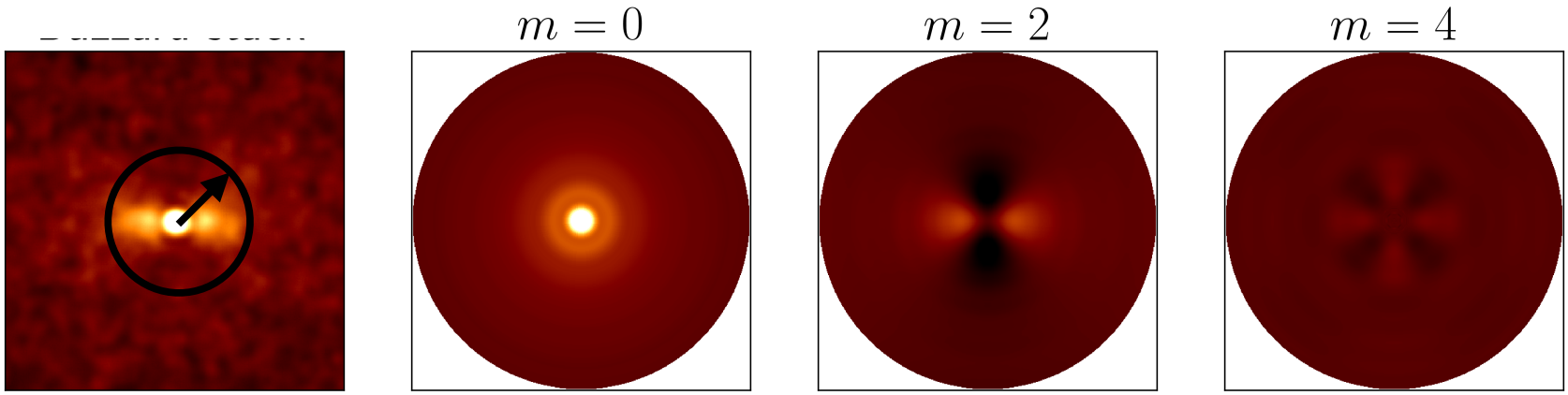
- Orientations from eigenvectors of local Hessian matrix of the smoothed galaxy field
- Asymmetries from gradients along eigenvector directions





Constrained oriented stacking

Summary statistics



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

The summary statistics

- Asymmetric stacks also have nonzero odd moments

Constrained oriented stacking

Unique features

- Use of multi-scale environmental information —> sensitivity to different regimes of the cosmic web
- SNR boost from stacking halos extends beyond the one-halo regime
- Expected to include information related to tidal fields, anisotropic collapse

Key questions

- As we push to higher *z*, can we improve cosmological constraints from tSZ and kSZ by:

  1. **Focusing on the clustering**

  2. **Including environmental information**

  3. **Accounting for anisotropic clustering**

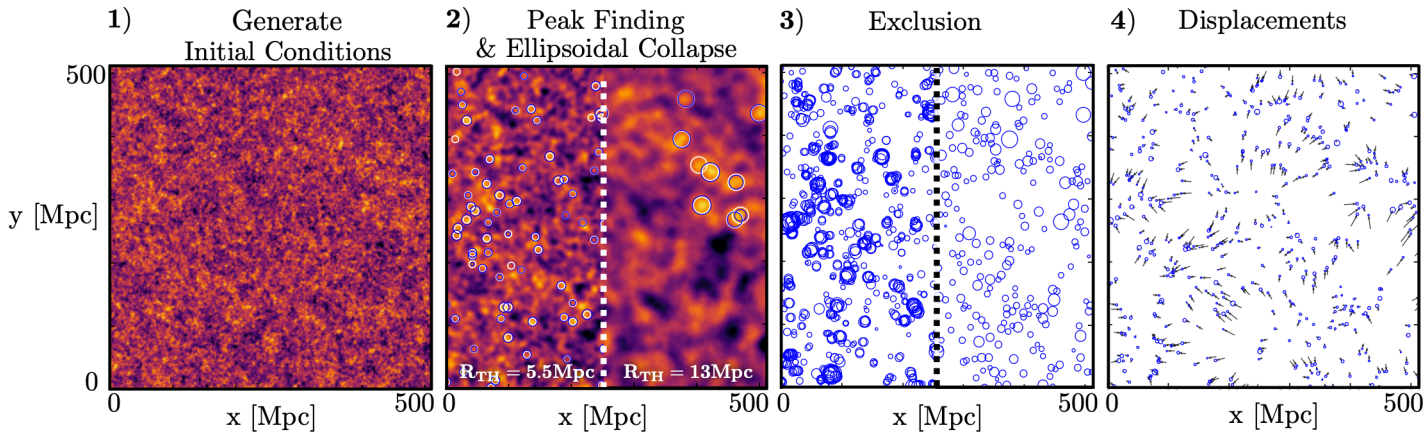
- To be robust to gas uncertainties, do we need to treat gas as extended and continuous?

- In certain scales & environmental regimes, can we learn more about the gas physics from anisotropic analysis + modeling?

Investigate for large scales, high-mass, high-density environments with Websky

Studying cosmology dependence with Websky

- Ran Websky simulations with 2 sets of 5 ΛCDM parameter variations
- 5 different Ω_M values per suite
- Realistic clustering
- Large-volume: 1/4 of sky to z=0.7

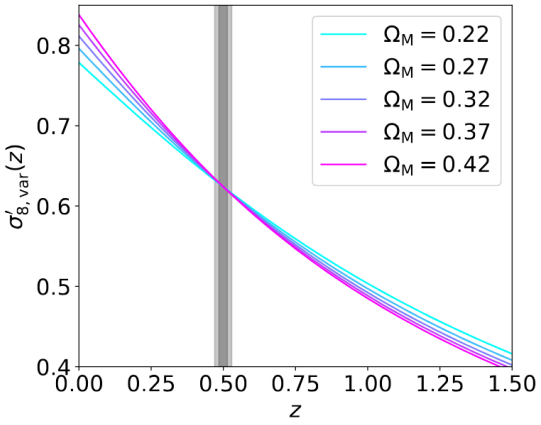


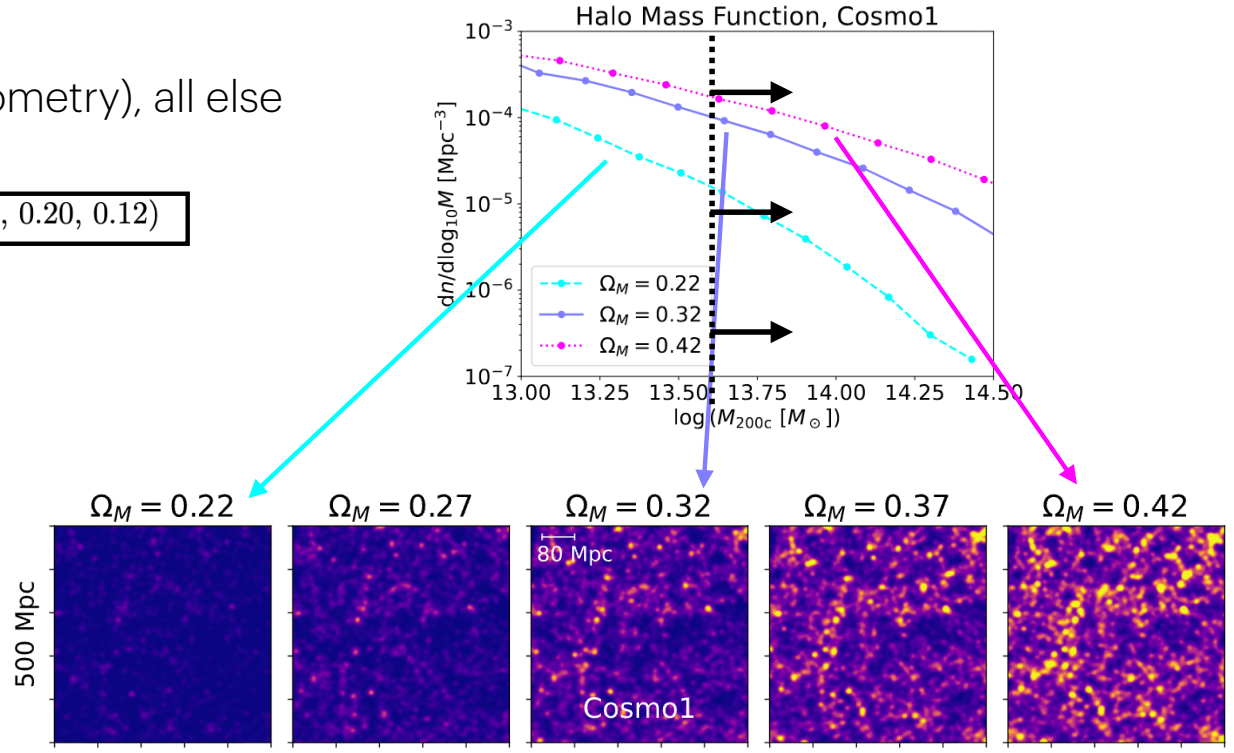
Peak-Patch and Websky algorithms: Stein, Bond, Myers et al 2019, 2020, 1996

Studying cosmology dependence with Websky

- Vary Ω_M* (and Ω_Λ to maintain flat geometry), all else fixed
  - z of matter-Λ equality: $(0.54, 0.40, 0.29, 0.20, 0.12)$
- Choose one redshift to analyze: z=0.5

Vary initial power spectrum amplitude to ensure same σ_8 at z=0.5



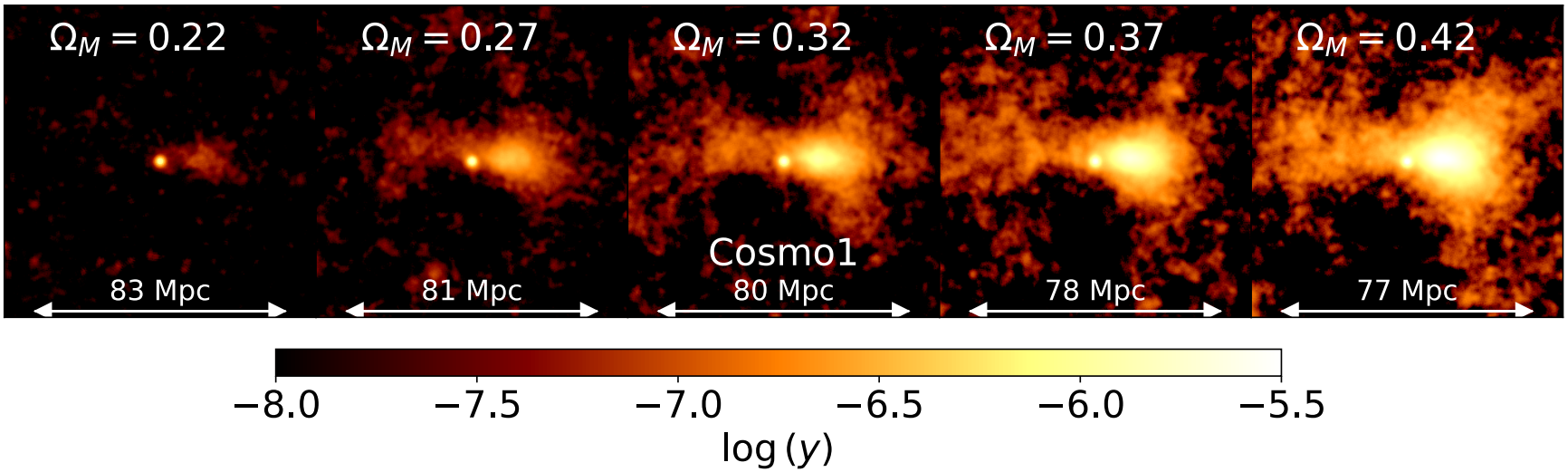


ML, Bond, Hlozek+ arXiv: 2510.08331

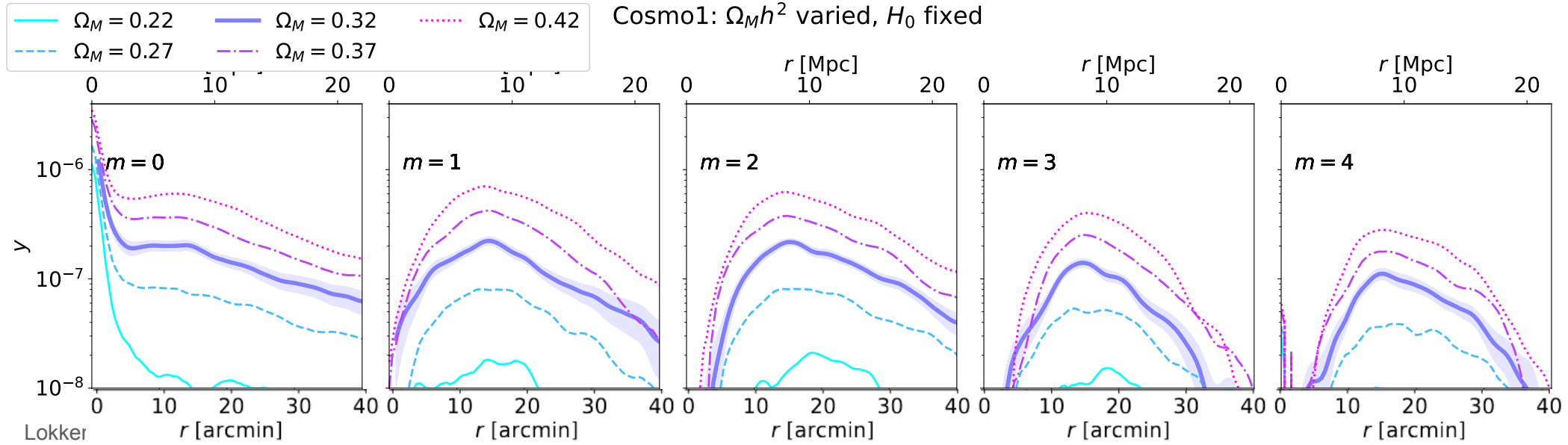
*In a second suite of simulations, we vary Ω_M and H_0 to fix $\Omega_M h^2$

Studying cosmology dependence with Websky

- Create mock y maps with fiducial gas model (Battaglia+ 2012) pasted on halos (no anisotropic gas)
- Select $M > 5 \times 10^{13} M_{\odot}$ halos in superclusters using halo field filtered at 20 Mpc FWHM
- Stack with orientation

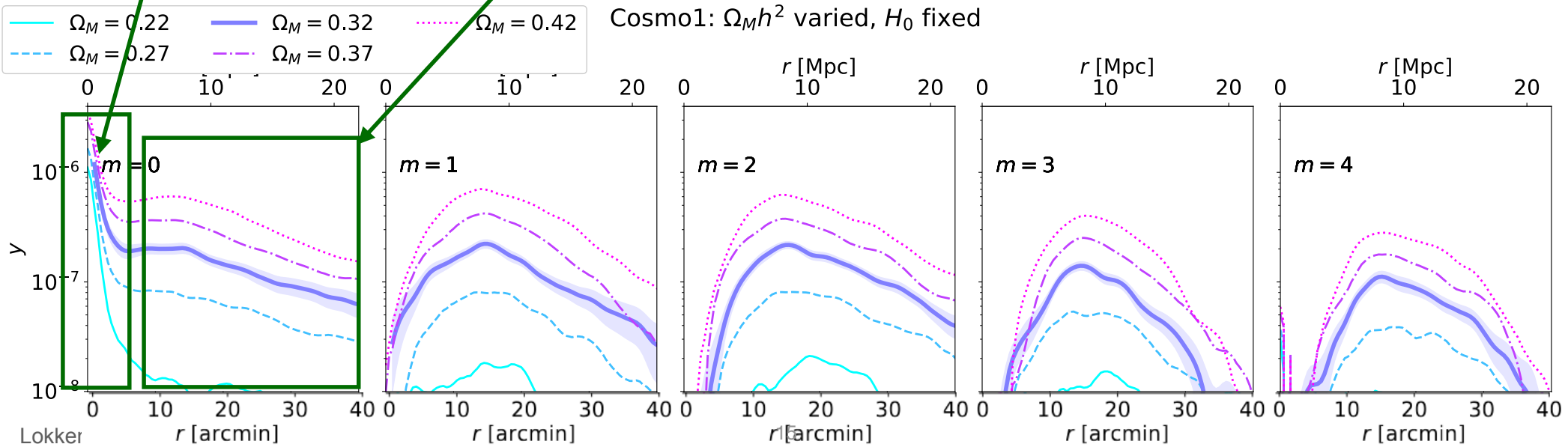


- Clear sensitivity in all cosine moments
- Sensitivity in amplitude and shape coming from:
  - Different HMFs —> changing bias of stacked sample and neighbors
  - Different levels of non-Gaussianity by z=0.5 —> affects selection of rare elongated peaks
  - Different matter power spectra

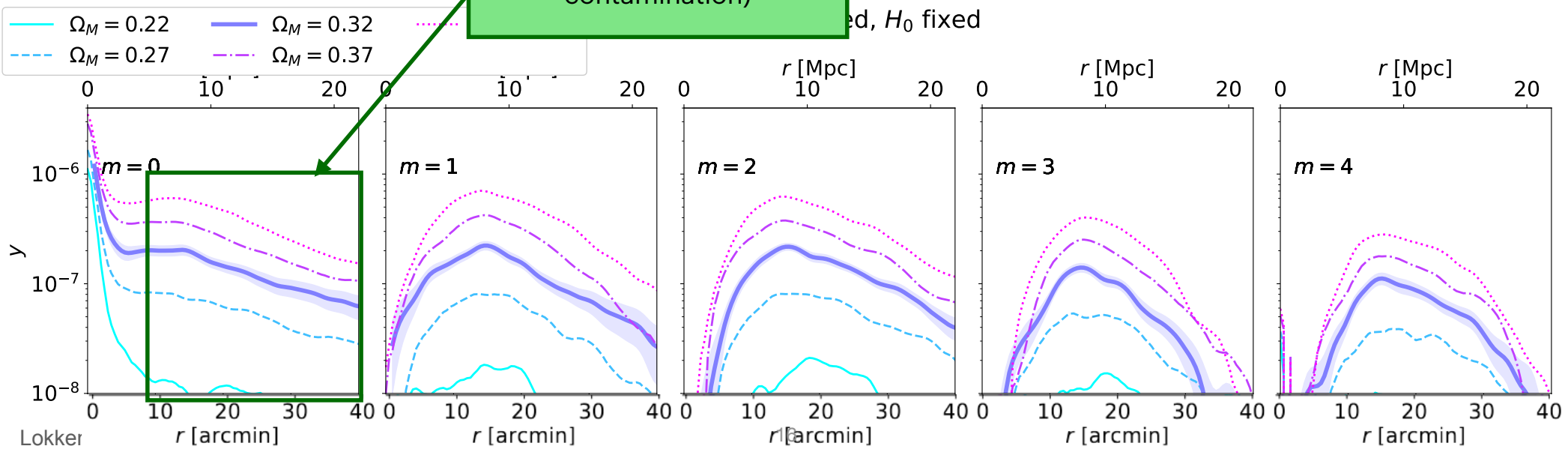


One-halo regime: the amplitude scales with ~$\Omega_M^{1.8}$

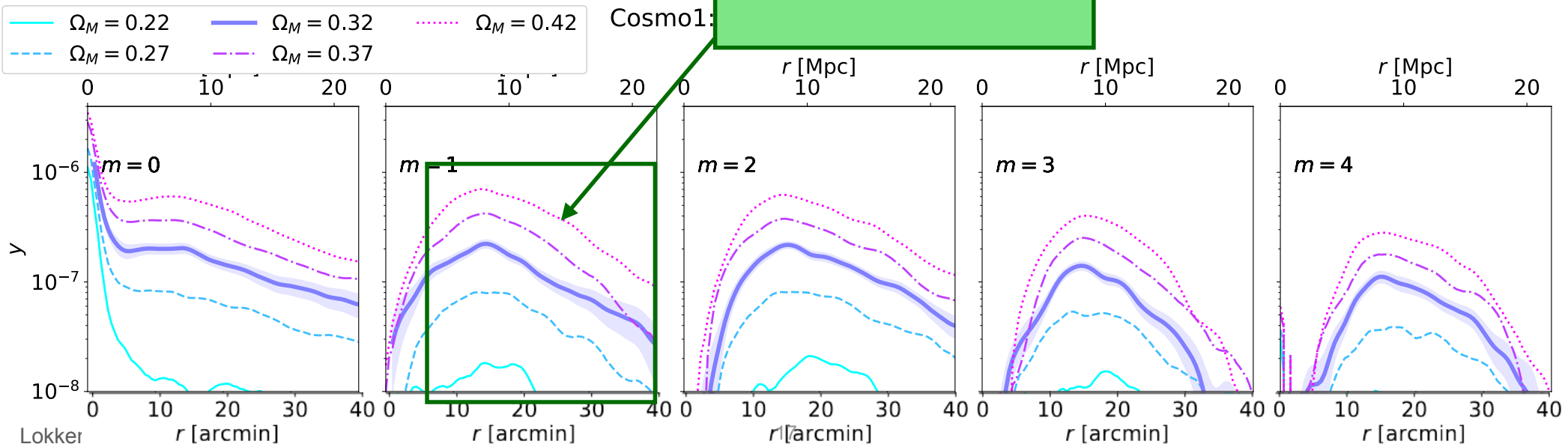
Clustering regime: ~$\Omega_M^{4.5}$



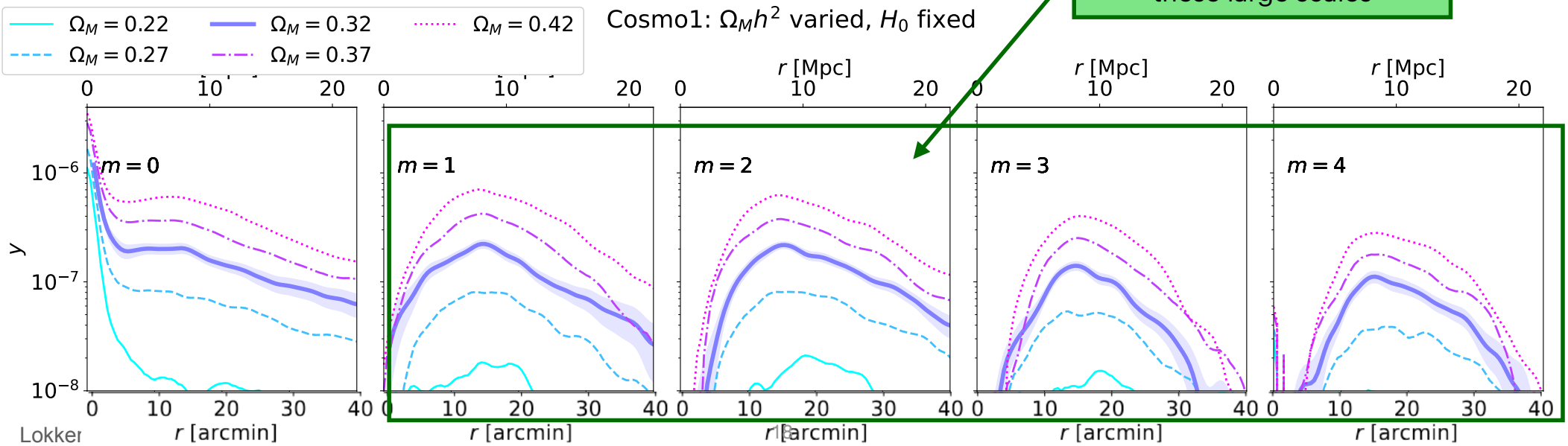
Hard to measure in the real data because: noise + additive biases (e.g., long-wavelength CMB contamination)



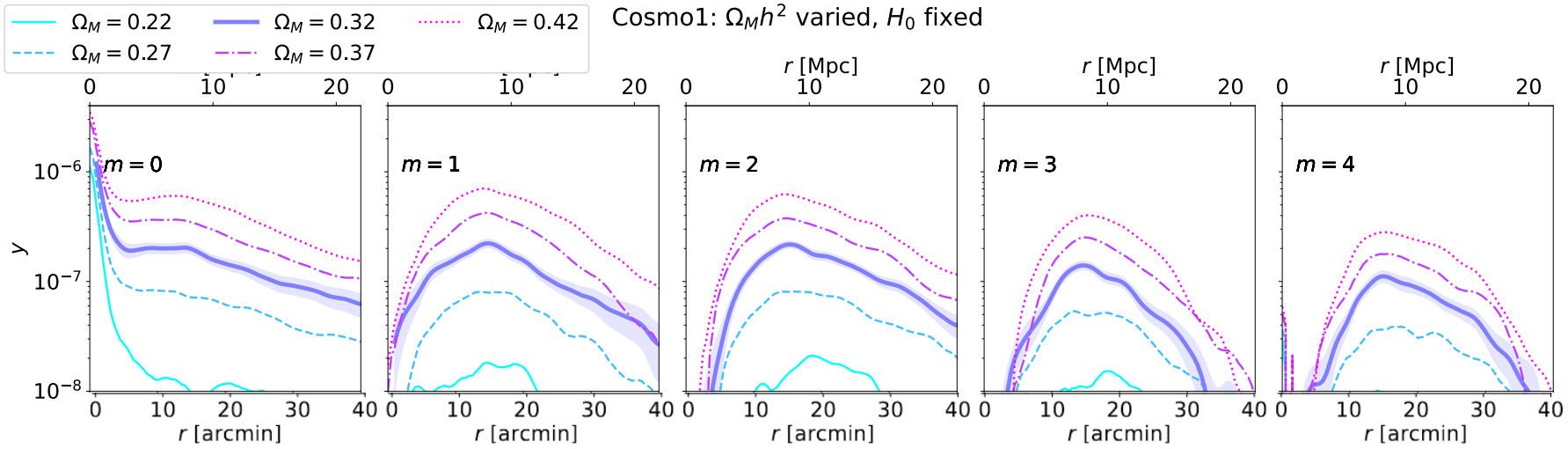
Easier to measure in the higher-order moments (not affected by additive biases)



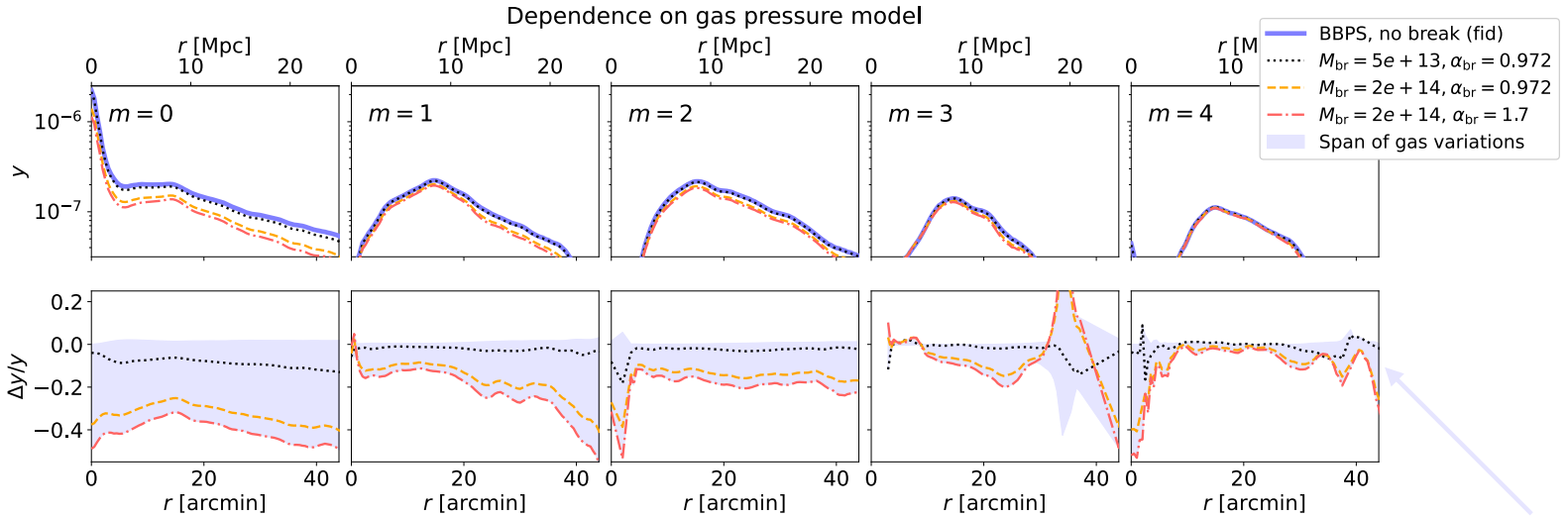
Similar dependence in the higher-order moments as in m=0 —> shape information not adding much cosmological sensitivity for these large scales



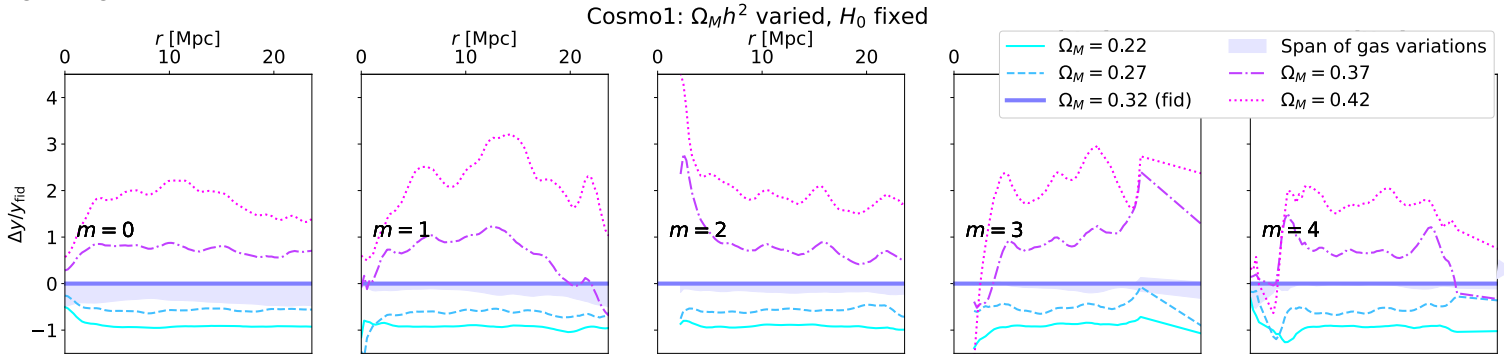
- Takeaways:
  - The clustering regime holds additional cosmological information, but usually can't be well-measured
  - Oriented stacking allows more robust access to that regime



Gas modeling variations affect signal as function of m



The gas effects decrease with m, whereas cosmology impacts remain consistent with m



Shaded purple regions are identical

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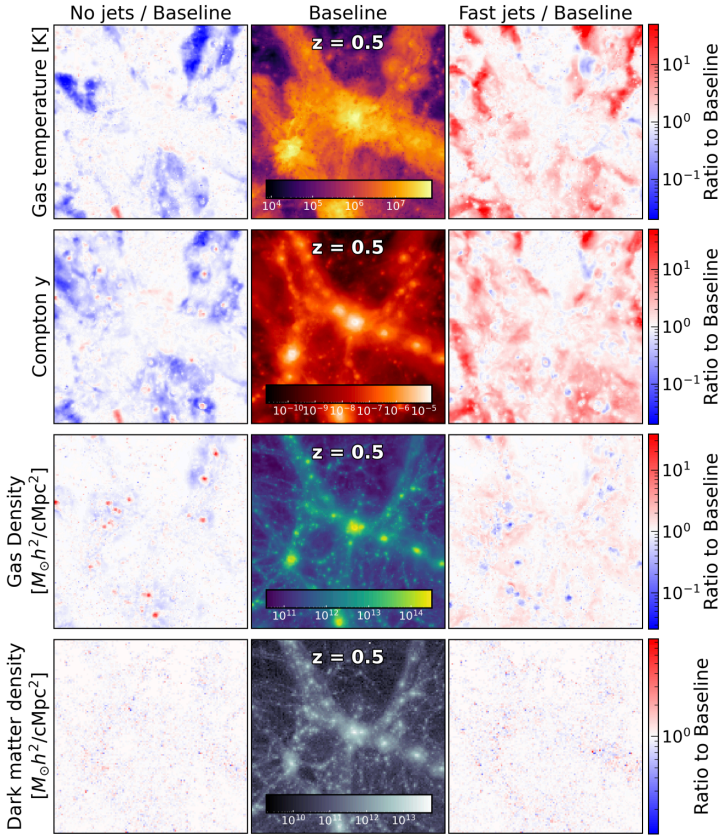
Does more accurate gas modeling complicate the picture?

The ThreeHundred Clusters

- Re-simulate several zoom regions of galaxy clusters (30h-1 Mpc) with varied jet strength and orientation
- As in Websky, feedback variations affect 2-halo term
- Potential additional effects from anisotropic gas outflows or infalls correlated with large-scale structure





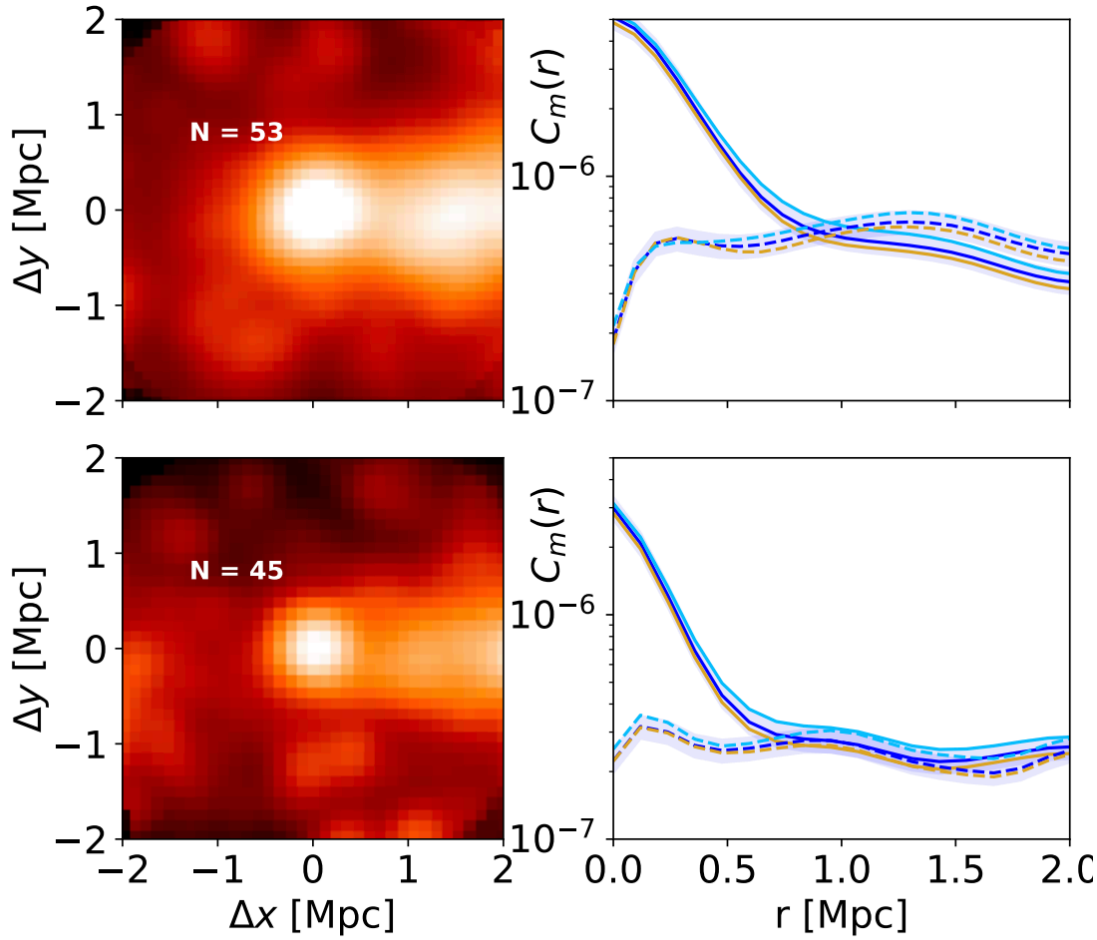
Rosenberg, ML, Hlozek et al,
Submitted to A&A 2026

Does more accurate gas modeling complicate the picture?

- Results: Effects are not likely to be detectable in this regime with SO
- Therefore, cosmology with anisotropic high-clustering regions (e.g. superclusters) may be robust to gas uncertainties
- Caveats: smaller-volume zoom simulations

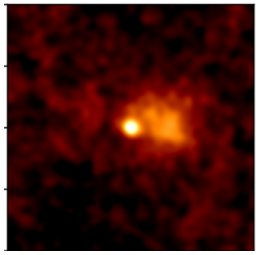
z=0.5

z=1

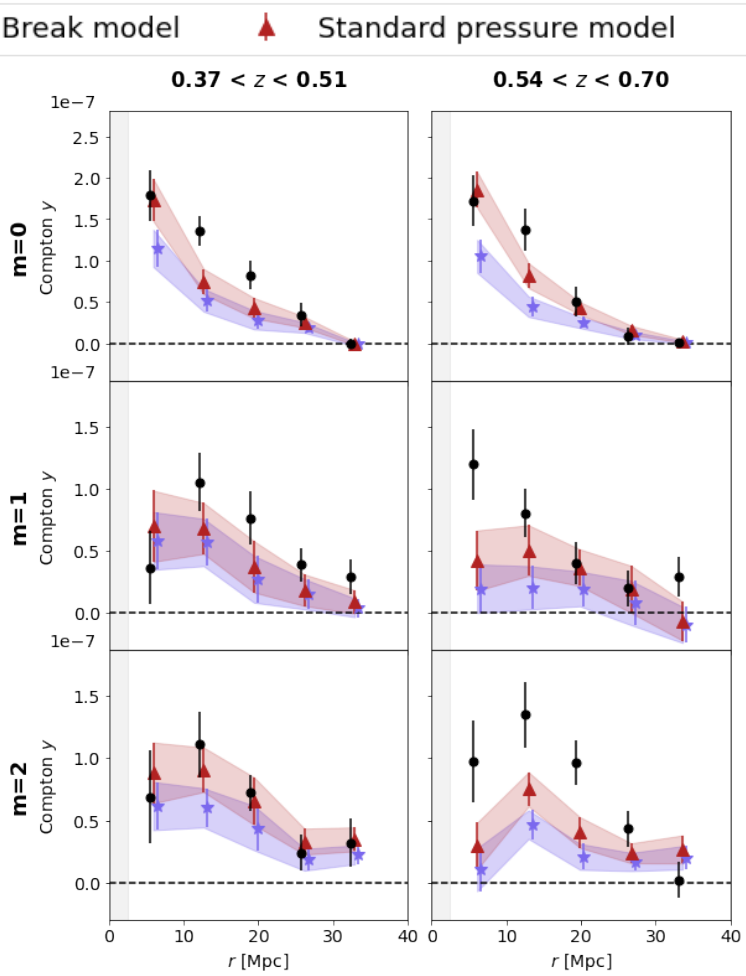


Applications to data

ACT tSZ (DR6)



Amplitude of the cosine components



Distance from stack center

- ACT DR6 x DES Y3 showed high-SNR measurements of higher-order moments
- Analysis at fixed cosmology and several gas models
- Future: SO x Rubin, or SO x DESI + joint cosmological+gas variations

ML, van Engelen, Bond, Hlozek, ACT, DES
ApJ 2024, arXiv:2409.04535

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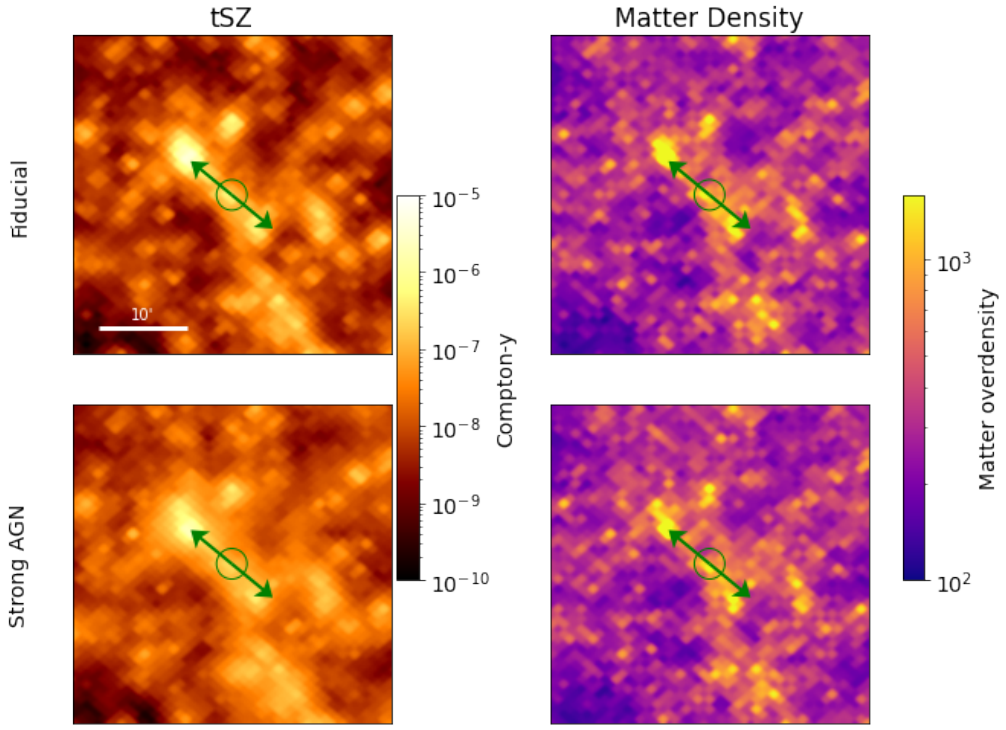
- **In certain scales & environmental regimes, can we learn more about the gas physics from anisotropic analysis + modeling?**

Investigate for intermediate-scale, average environments in Flamingo

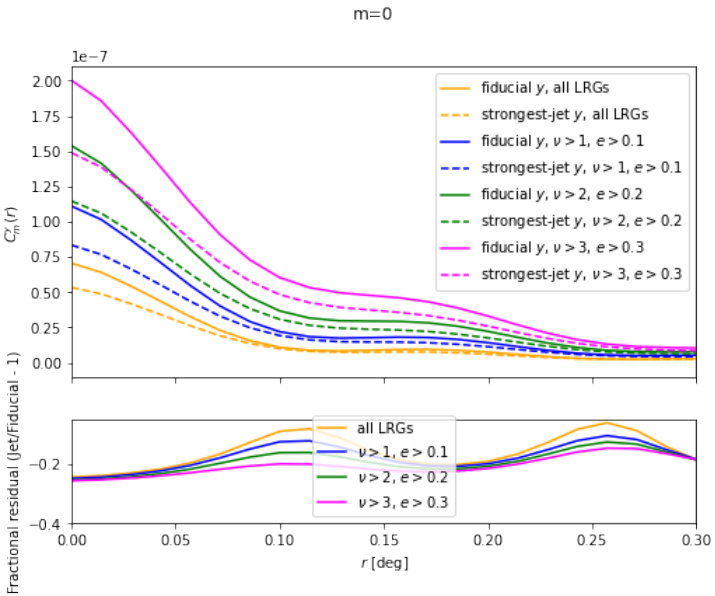
Oriented stacking for feedback physics

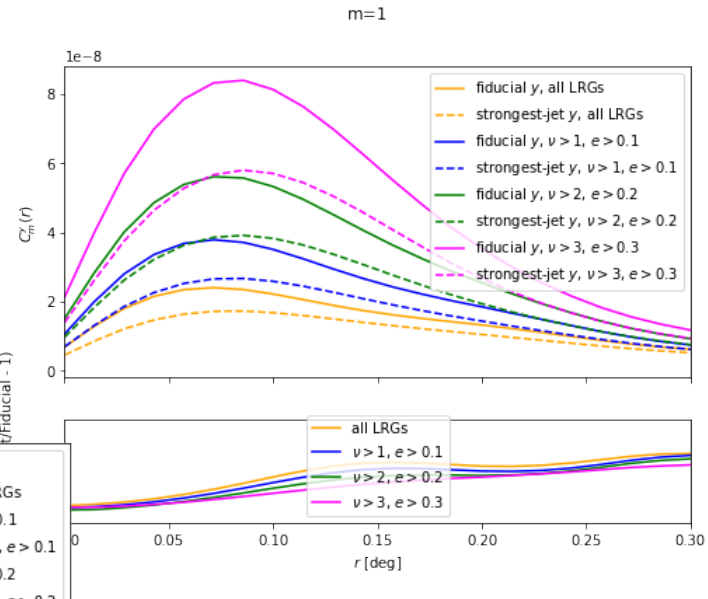
Do different feedback models affect anisotropic signal in lower-density environments, for smaller-scales?

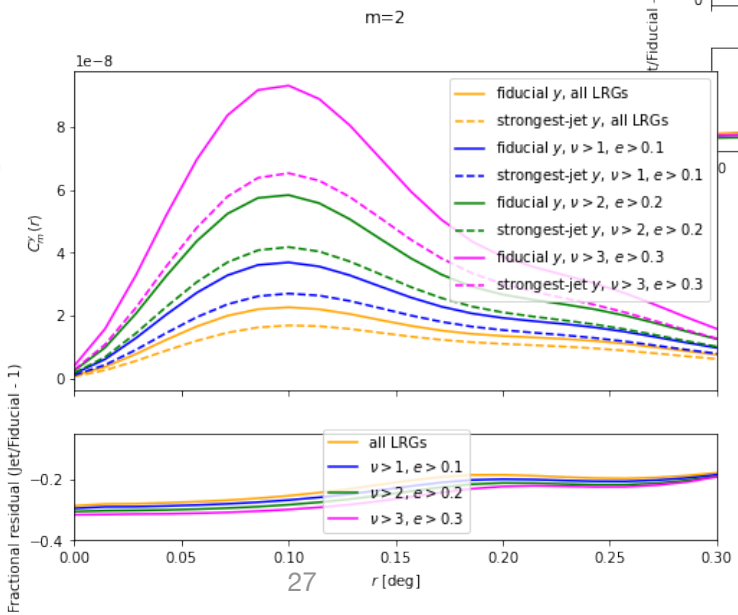


- Examine FLAMINGO simulations with varied AGN strengths

Oriented stacking for feedback physics



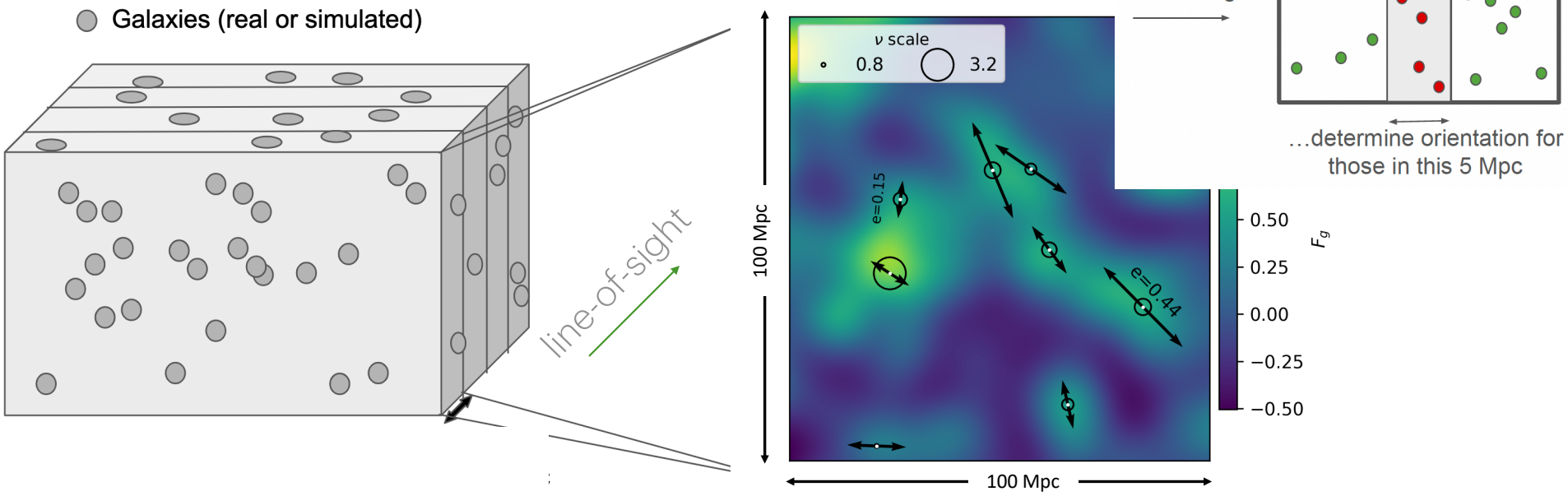




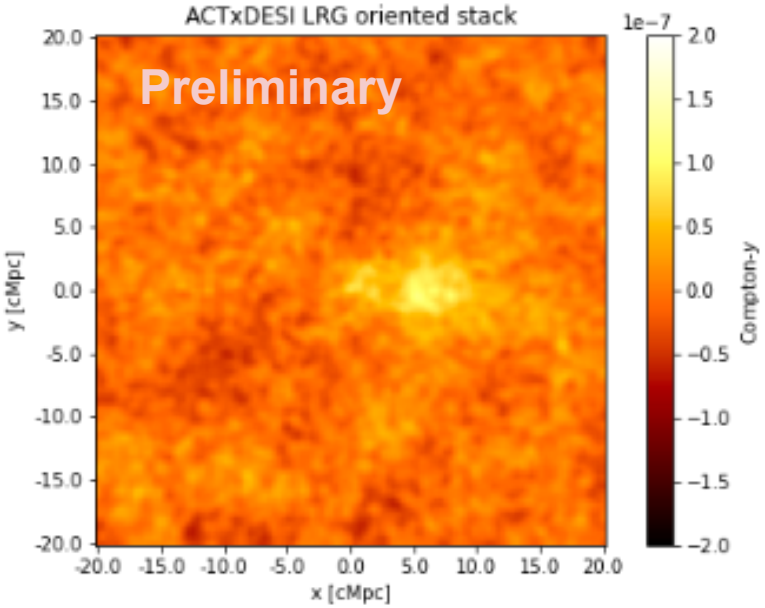
- Results: Significant impacts (~20-40%) at z~1, for thin-shell stacks

Oriented stacking for feedback physics

- Applications to data: Can we measure this with ACTxDESI? Using DESI spec-zs can:
  - reduce the line-of-sight binning significantly
  - isolate physically correlated structure much better
  - Therefore improving orientations



Oriented stacking for feedback physics

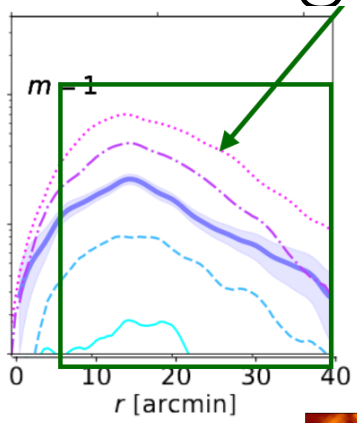


- However,
  - Real tSZ maps are noisy
  - Need to combine over many redshift bins to increase SNR
  - $0.7 < z < 1.0$

Power of constrained, oriented stacking

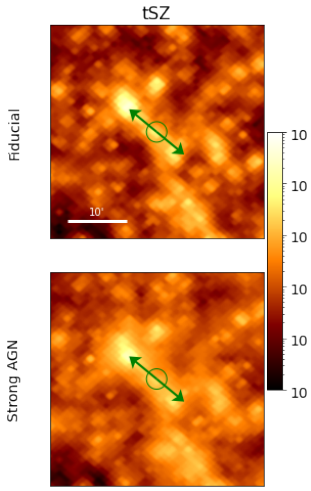
Cosmology Sensitivity (large scales)

- Including oriented information can enable measurements further into the two-halo regime



Gas Sensitivity (large scales)

- Higher-order moments less sensitive to variations than monopole
- Different sensitivity as a function of moment than cosmology can help break degeneracies



Gas Sensitivity (smaller scales)

- Moments can help distinguish feedback models

Observability

- Can measure anisotropic tSZ superclustering using photometric and spectroscopic galaxy data

