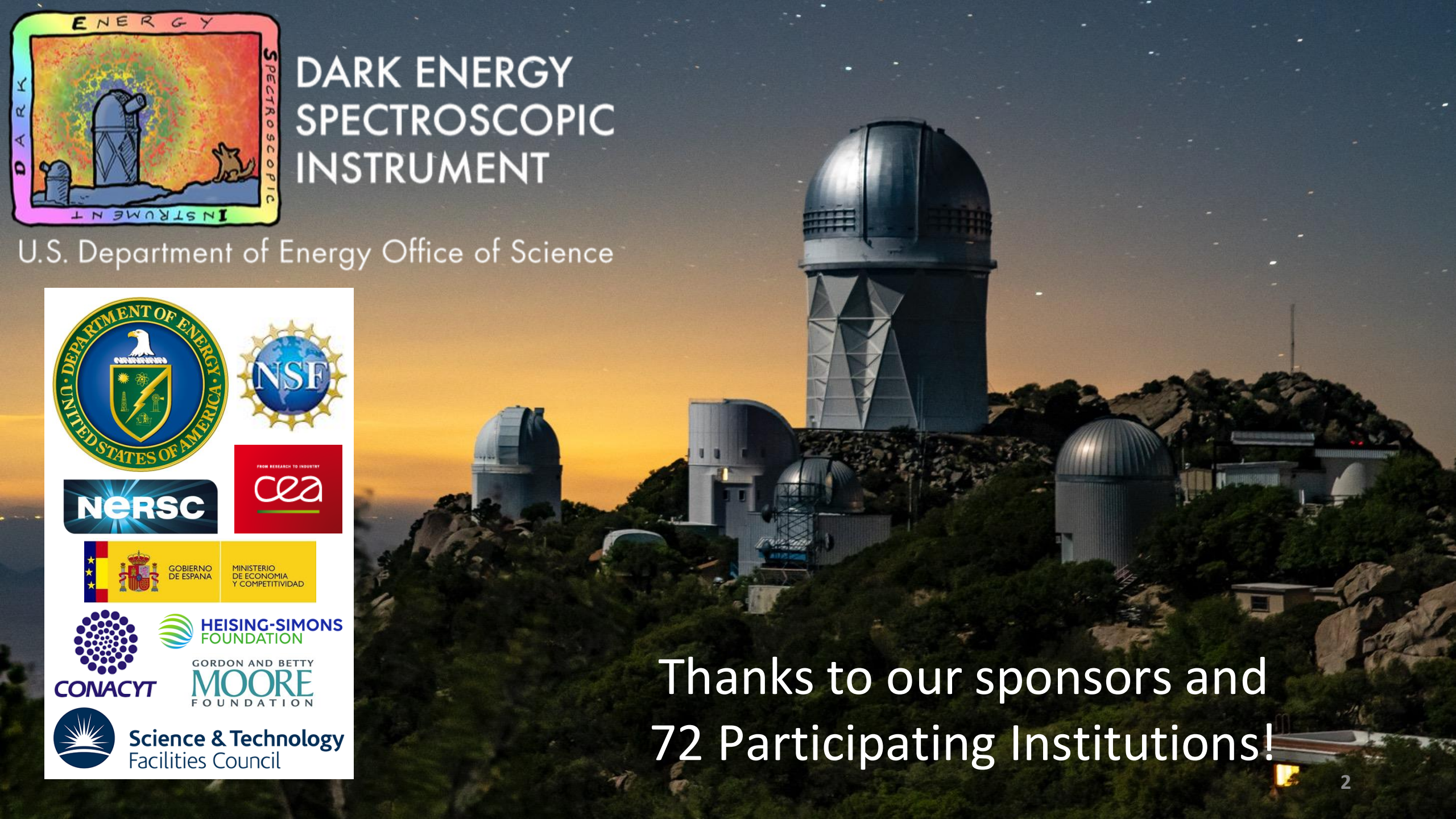
tSZ-split clustering of DESI Luminous Red Galaxies

Misha Rashkovetskyi
CCAPP Fellow

CCAPP Symposium
Columbus, OH, 17 Sep 2025

arxiv.org/abs/2508.20904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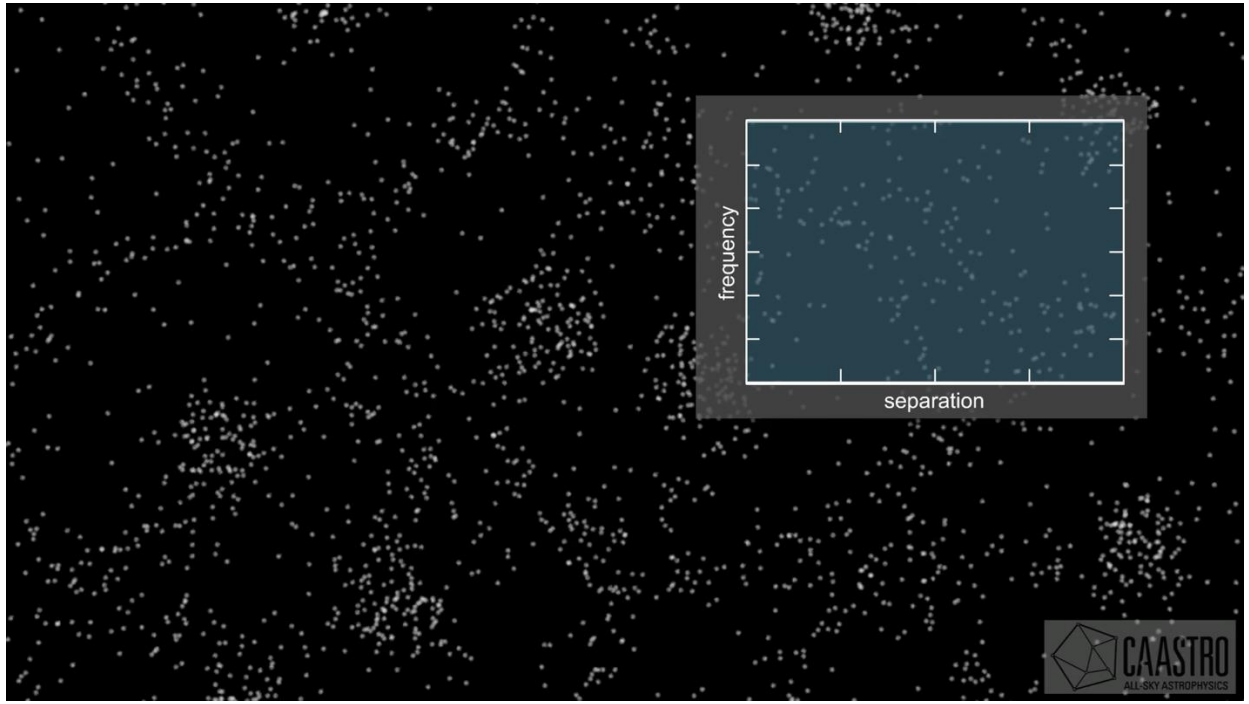
2-point galaxy clustering

2-pt correlation function (2PCF) of galaxies describes the excess probability of finding two galaxies separated by a certain distance (compared to random scatter)
Count pairs of D – galaxies (data) and
R – random points (rep. mean density)

$$\xi(s) = \frac{DD(s) - 2DR(s) + RR(s)}{RR(s)}$$



Measuring clustering (incl. power spectrum) – one of the key tools of DESI http://caastro.org

Scientific motivation: dark energy, Hubble tension, dark matter, gravity +++

Not only the BAO peak position, but also full shape of clustering

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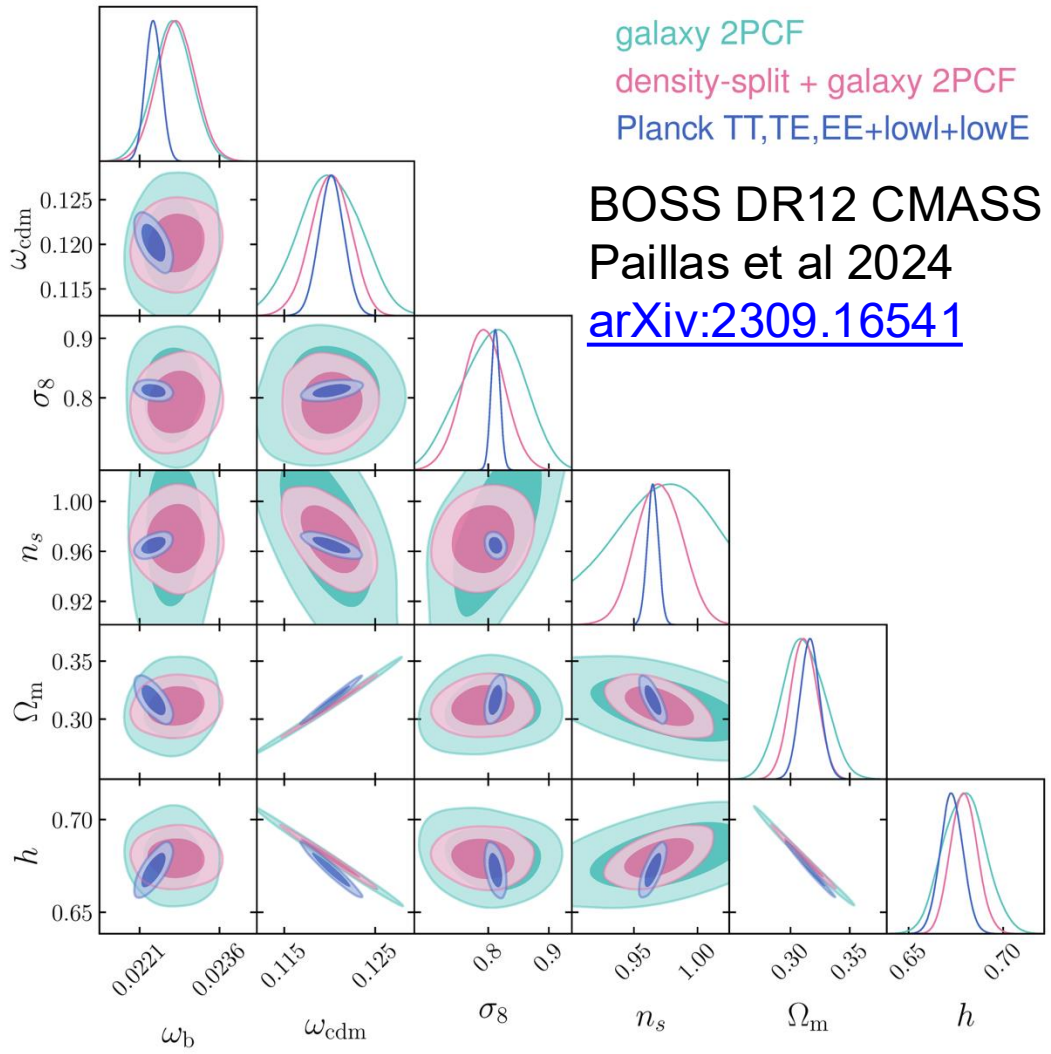
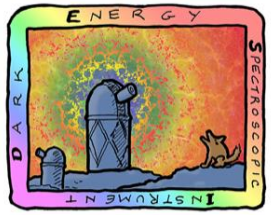
More info from different environments

- 2-pt clustering statistics do not contain all information about non-linear/non-Gaussian Universe
- Can add a “dimension” without more points: density-split and density-marked (weighted)
- Tighter constraints —>
- But harder to model: rely on simulations
- May be prone to assumptions/systematics





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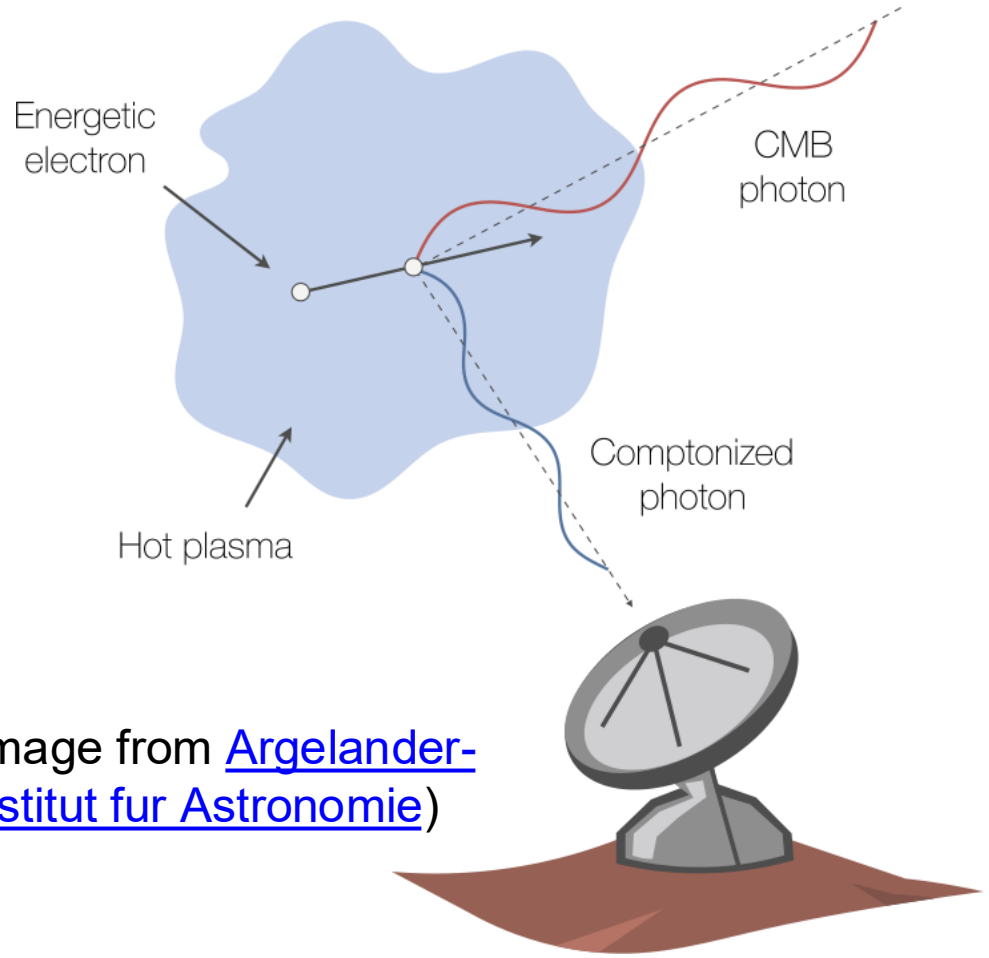
(Thermal) Sunyaev-Zeldovich (tSZ) effect

- Inverse Compton scattering of CMB photons on free (thermal) electrons
- Relative net increase in photon energy:

$$y \sim \int \frac{k_B T_e}{m_e c^2} \sigma_T n_e dl$$

- Mostly ionized hot and dense gas in/around galaxy clusters
  - Distinct environment
- Independent => can cross-check and uncover tensions



(image from Argelander-Institut fur Astronomie)

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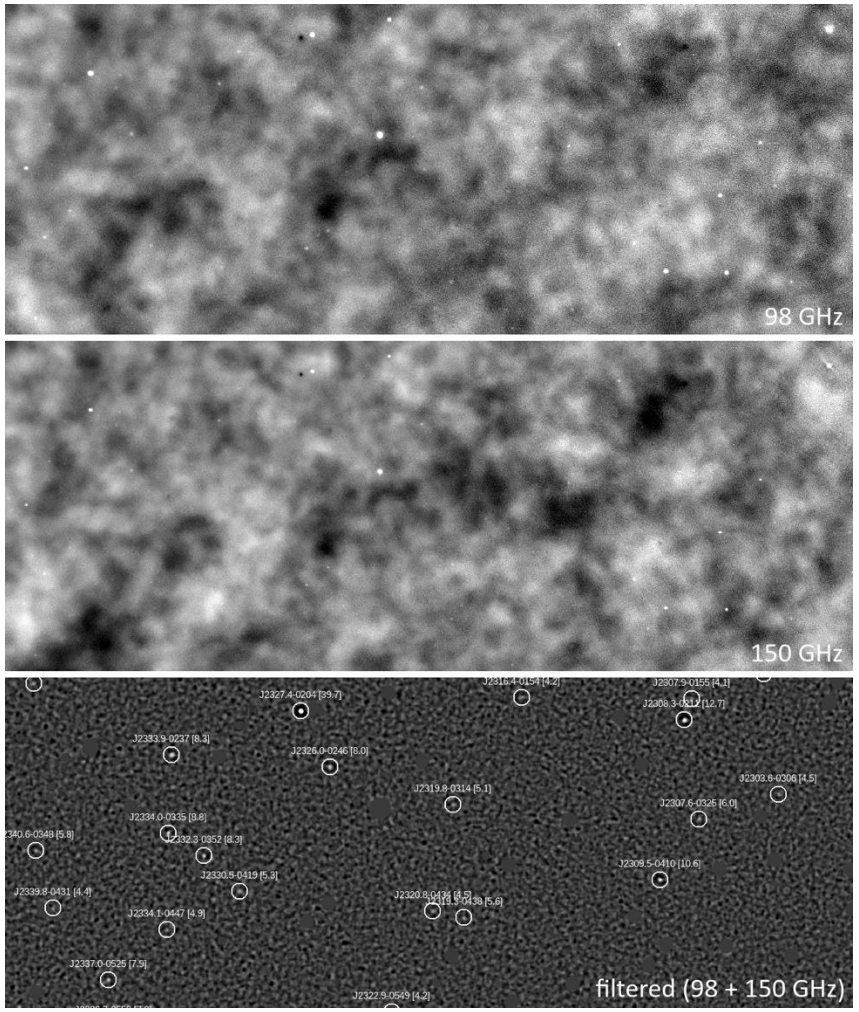
SZ clusters and beyond

- Sunyaev-Zeldovich maps have been used for cluster detection, mass determination, etc.
- But rigorously detected clusters candidates (>4σ) are rare: ≈21,300 in ≈16,300 deg^2 (Atacama Cosmology Telescope (ACT) DR6)
- We aim to extract more information from the lower signal-to-noise parts dominating the map

Hilton et al 2021 (arXiv:2009.11043)
10x4 deg patch from ACT DR5



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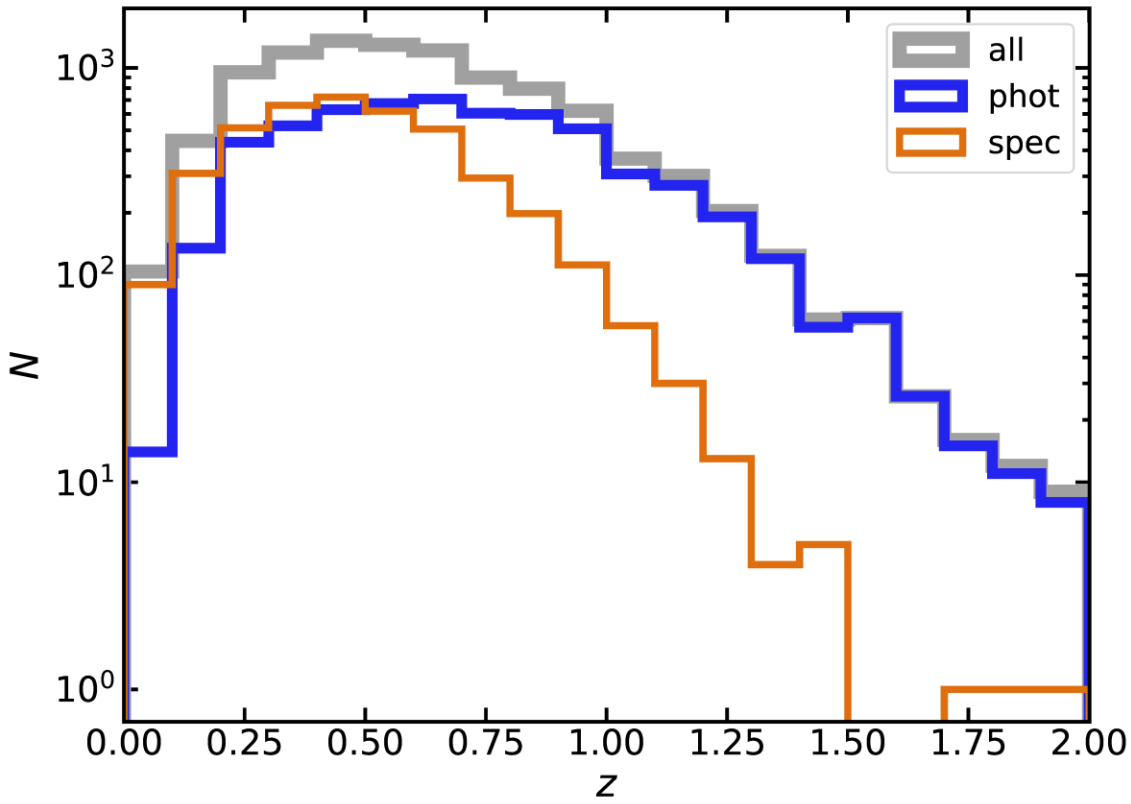
Data and methodology

- DESI DR1 luminous red galaxies (LRG)
  - Most likely to overlap with tSZ sources ->
  - Redshift range: z=0.4-0.85
- Matched to ACT DR6 (incl. *Planck*) tSZ Compton-y map
- "Binned" by pixel-level tSZ signal-to-noise ratio (*after simple filtering*)
- Then use galaxy positions from DESI DR1 only

ACT DR6 tSZ cluster redshift distribution
(ACT/DES/HSC 2025, arXiv:2507.21459)



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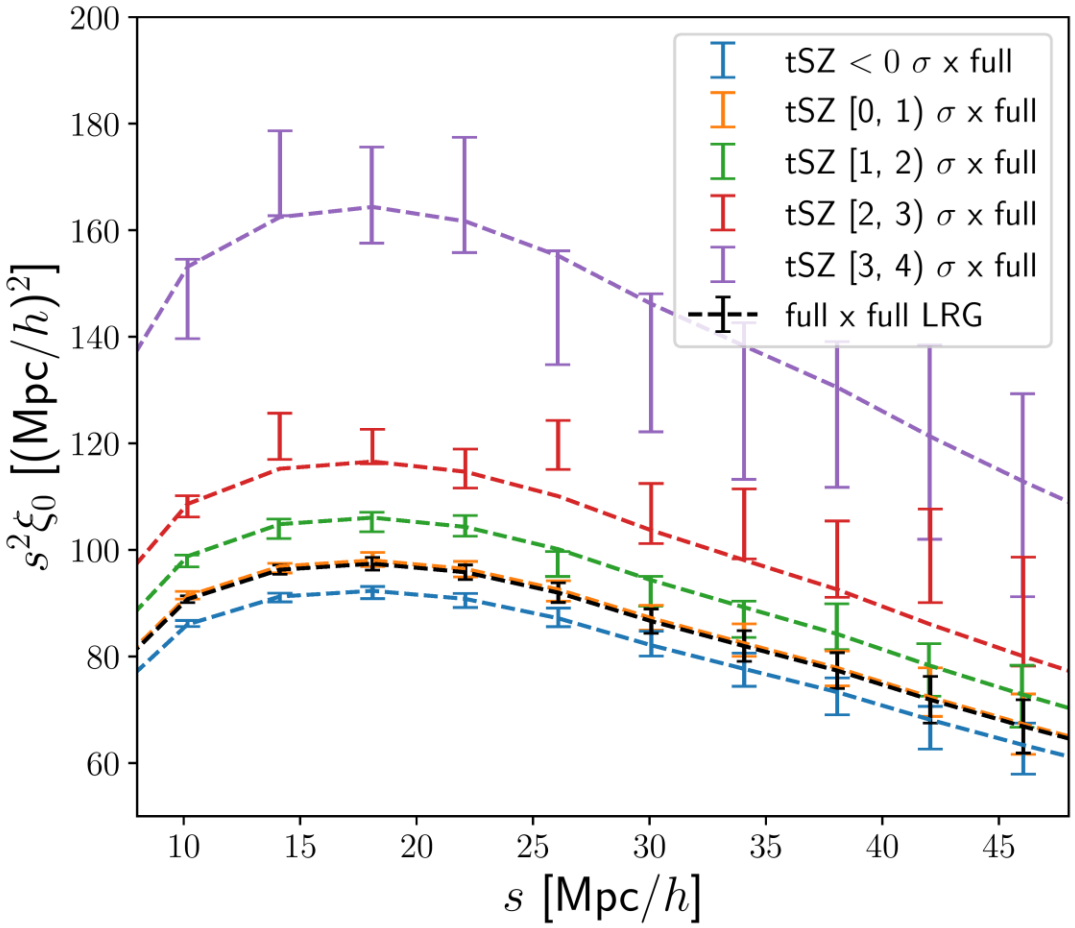
Medium-scale 2PCF enhancement

- Cross-correlation of SNR “bins” with the full LRG sample
  - (counting any LRGs around LRGs belonging to a ”bin”)
- Isotropic, intermediate scales
- Significant increase in clustering (galaxy bias) below tSZ cluster candidate threshold (4σ)
- Dashed lines — optimal scaling of full-sample clustering



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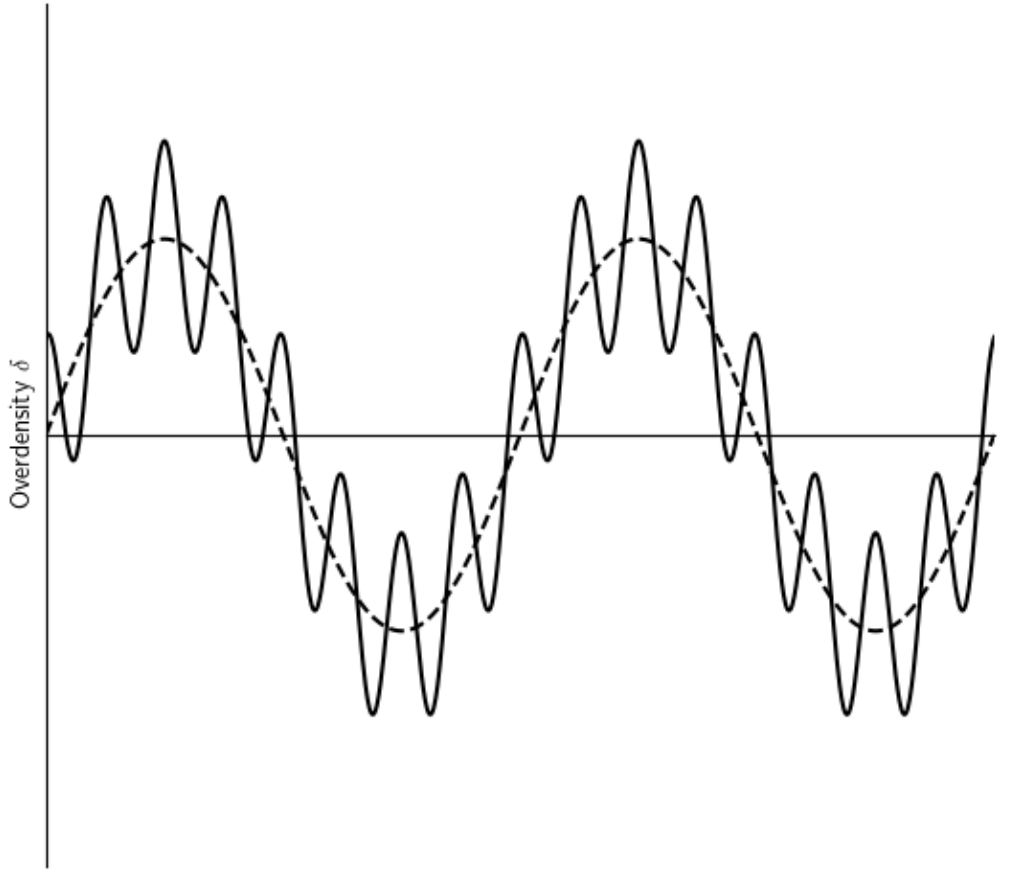
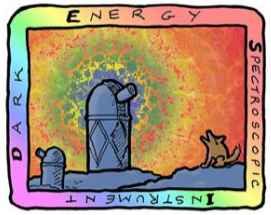
Brief explanation of bias

- Matter overdensity in solid black
- Peak-background separation: small and large-scale modes
  - Large-scale background in dashed black
  - *less clear in reality*





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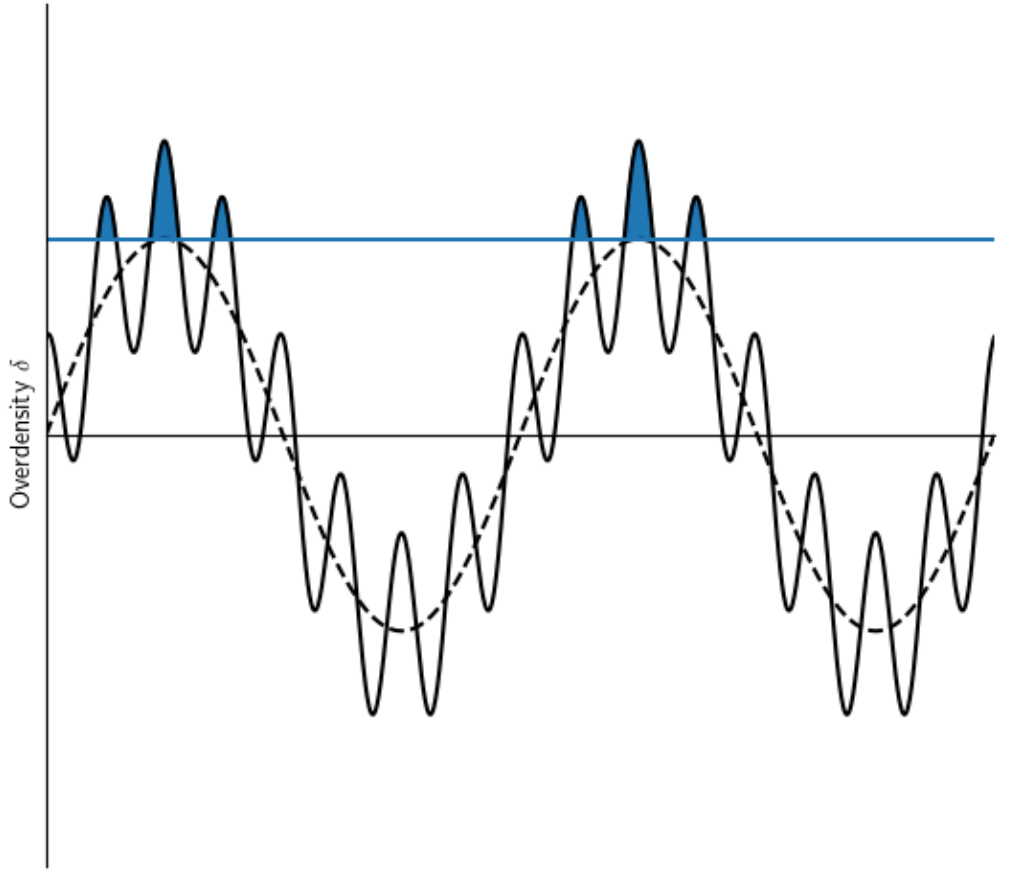
Brief explanation of bias

- Halos and then galaxies form after a certain threshold in total matter overdensity
  - *approximately*
- Peaks exceeding the threshold highlighted in blue



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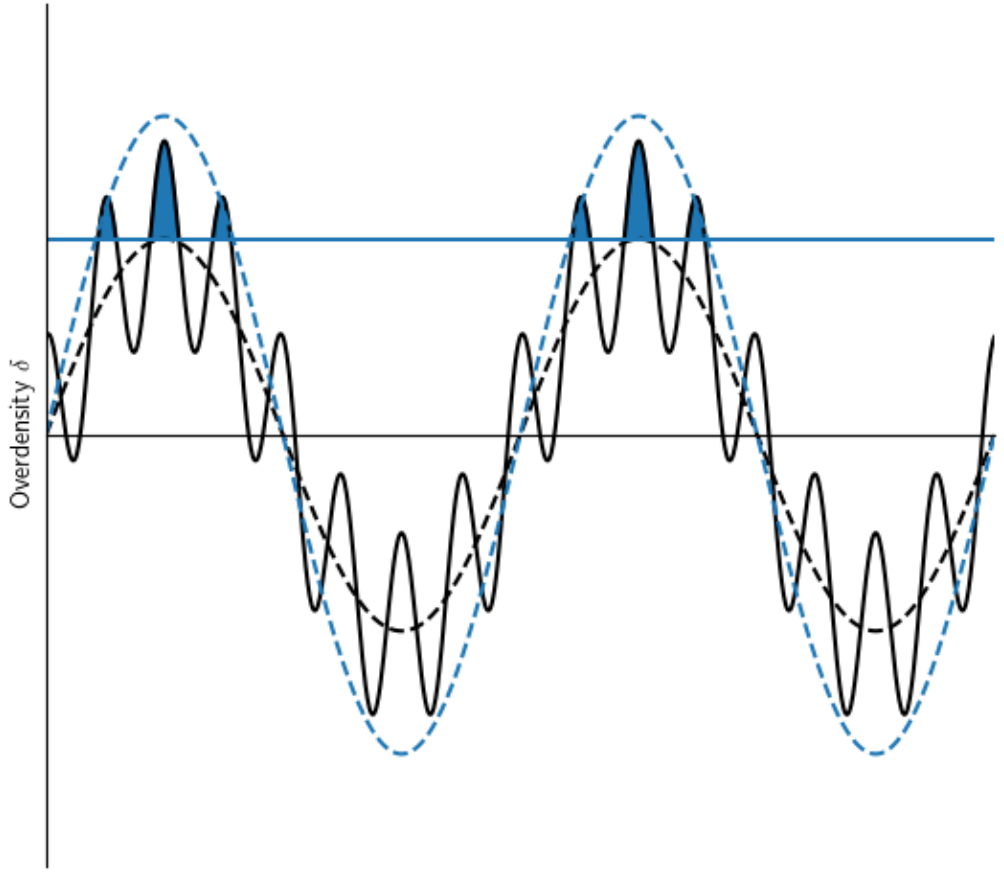
Brief explanation of bias

- We can count halos/galaxies, compute their number density and overdensity, and compute its long-wavelength mode
- The large-scale overdensity of the halos/galaxies (dashed blue) is typically enhanced relative to the large-scale clustering of matter (dashed black)

$$\delta_h \approx b\delta_m, \;\; b > 1$$

- *Galaxy formation introduces additional galaxy bias*



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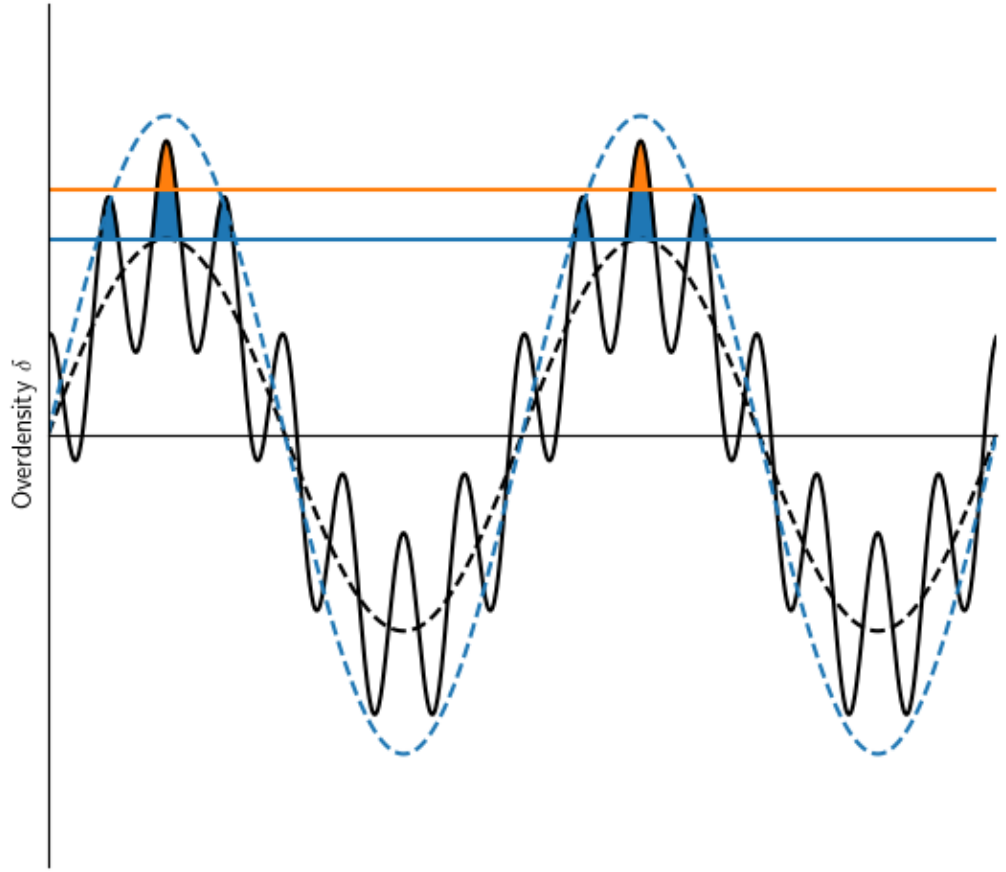
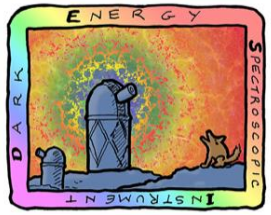
Brief explanation of bias

- Larger halos/galaxies/galaxy clusters typically require a higher threshold in total matter overdensity
- Peaks exceeding the new threshold highlighted in orange





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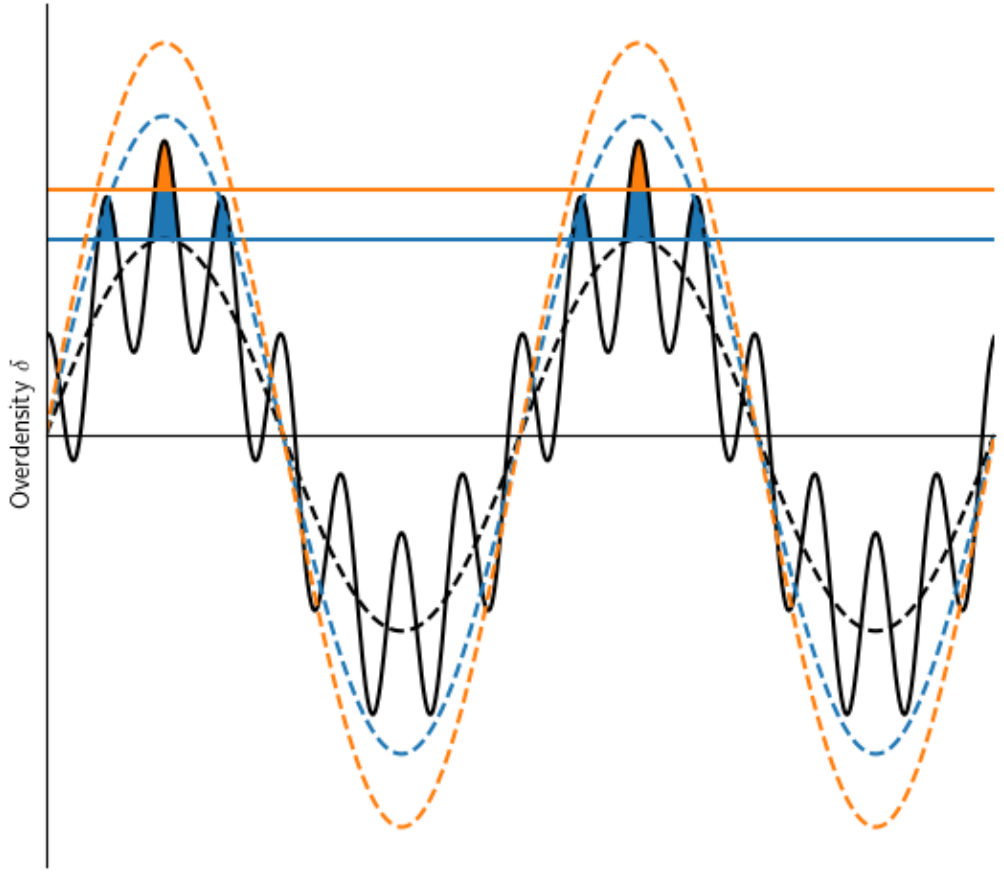
Brief explanation of bias

- Compute long-wavelength mode of number overdensity of larger halos/galaxies/galaxy clusters
- The large-scale clustering of more extreme objects (dashed orange) is typically enhanced even stronger than smaller galaxies/halos/ clusters (dashed blue)

$$\delta_h \approx b\delta_m, \quad b > 1$$

$$\delta'_h \approx b'\delta_m, \quad b' > b$$



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Medium-scale 2PCF enhancement

- Cross-correlation of SNR “bins” with the full LRG sample
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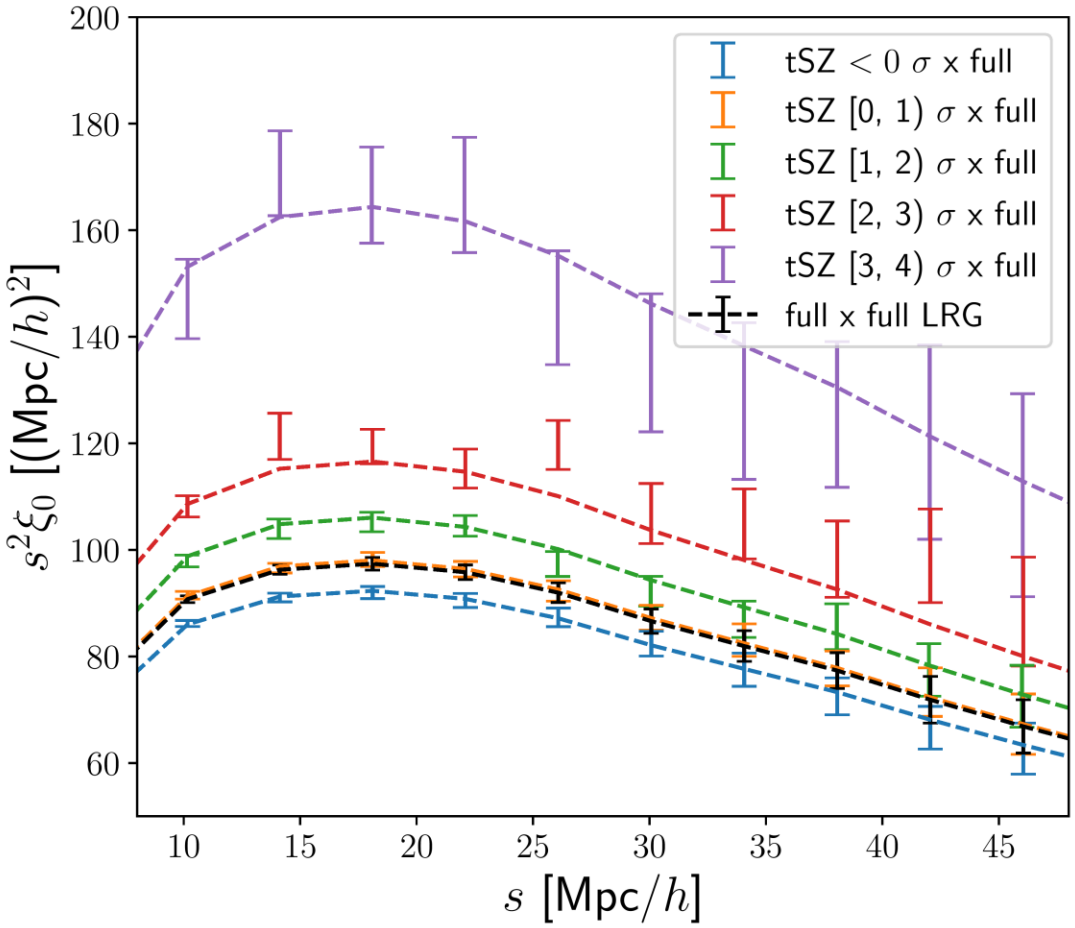

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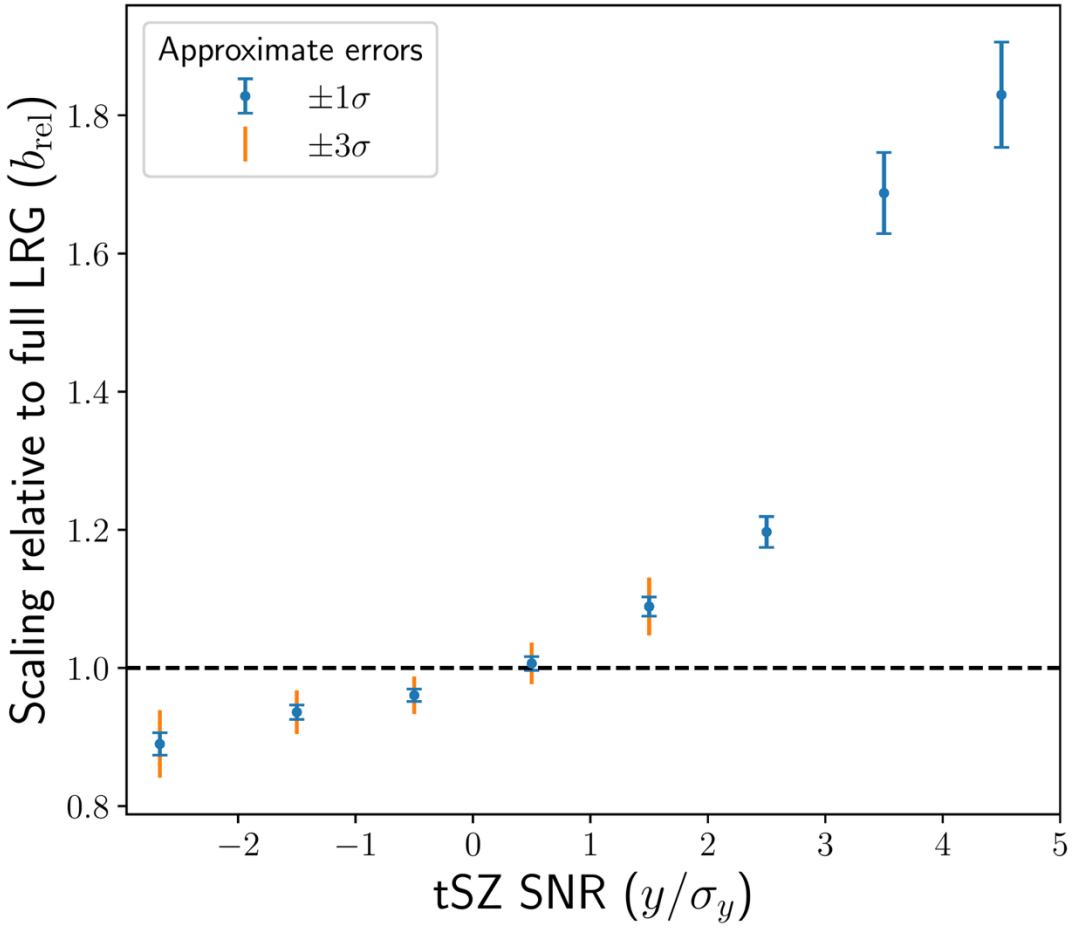
Medium-scale 2PCF scaling

- Collapsed each line from the previous plot into a single number
  - Scaling of the full-sample correlation function (~ratio of galaxy biases)
- Increasing trend, especially for positive tSZ signal
- Consistent with higher tSZ -> larger halos, but even at low significance
- Distinct galaxy subsamples allow more accurate modeling and cross-validation



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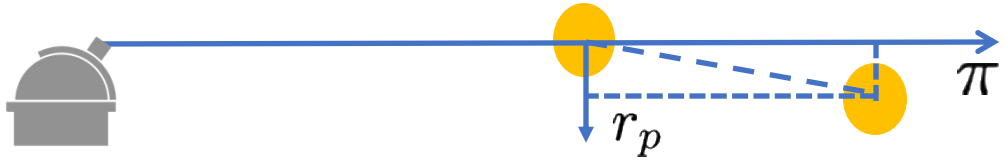
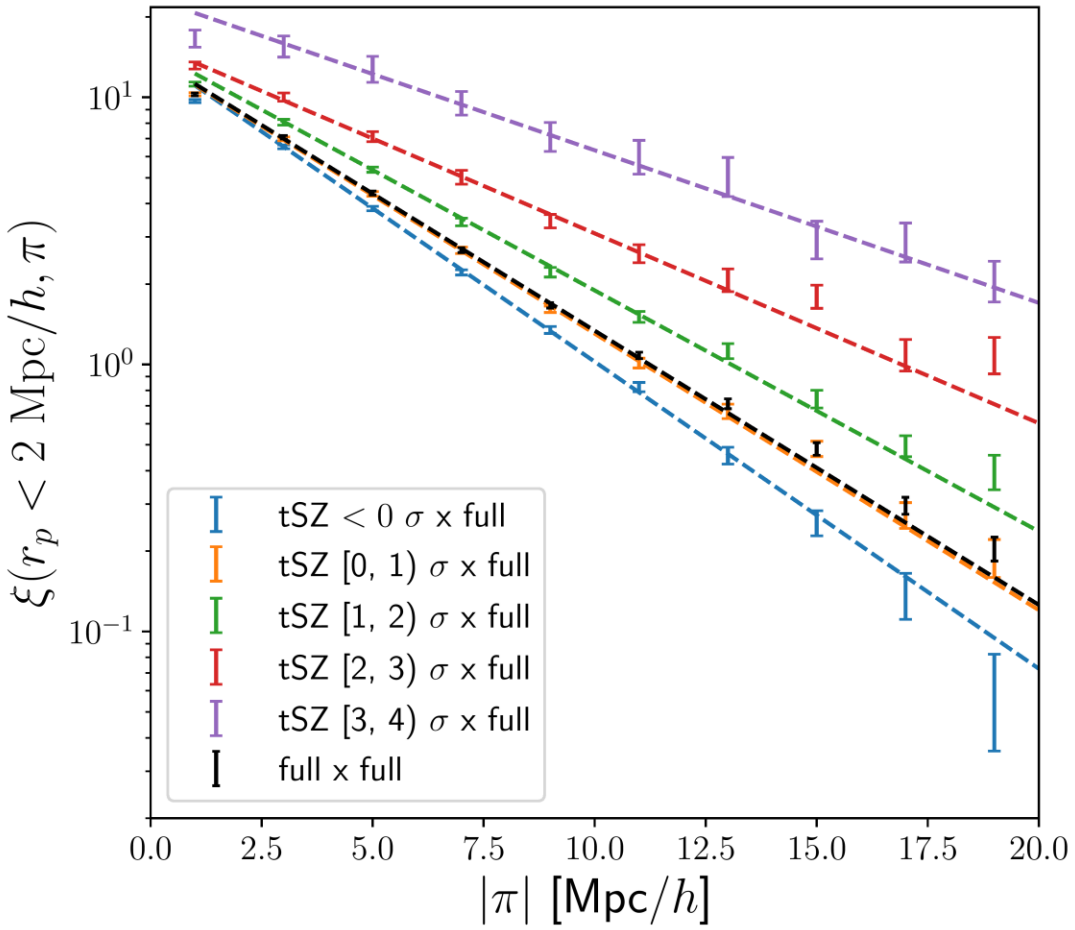
Small-scale line-of-sight clustering



- Same data and tSZ SNR “binning”
- Correlation function in a narrow (r_p=2 Mpc/h) cylinder along the line of sight (π coordinate)
  - Increasing amplitude
- Dashed lines are exponential fits
- Decreasing slope => larger velocity dispersion (before cluster candidate detection)



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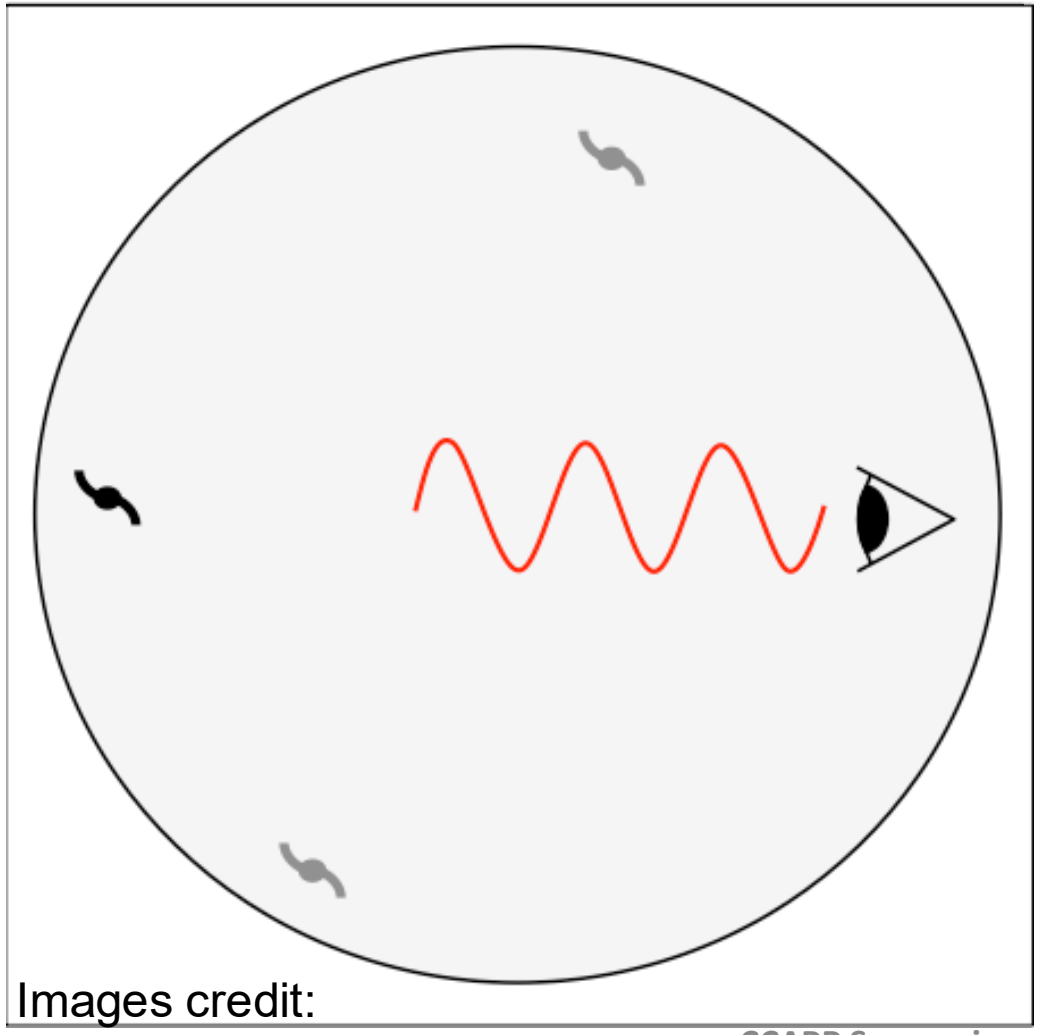
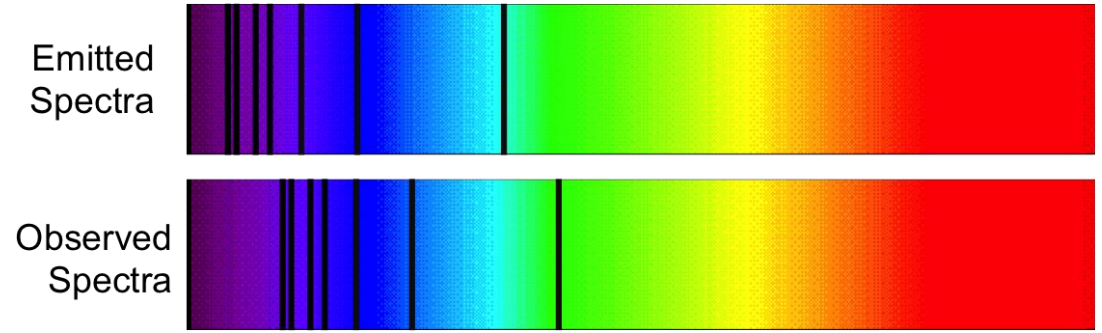
Cosmological redshift



Images credit:
SDSS Voyages



- Spectral lines shift to red
- Light waves stretch with the Universe as it expands
- Proxy for time (higher redshift = farther back in time)
- And distance because light has limited speed

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Doppler effect and Doppler redshift

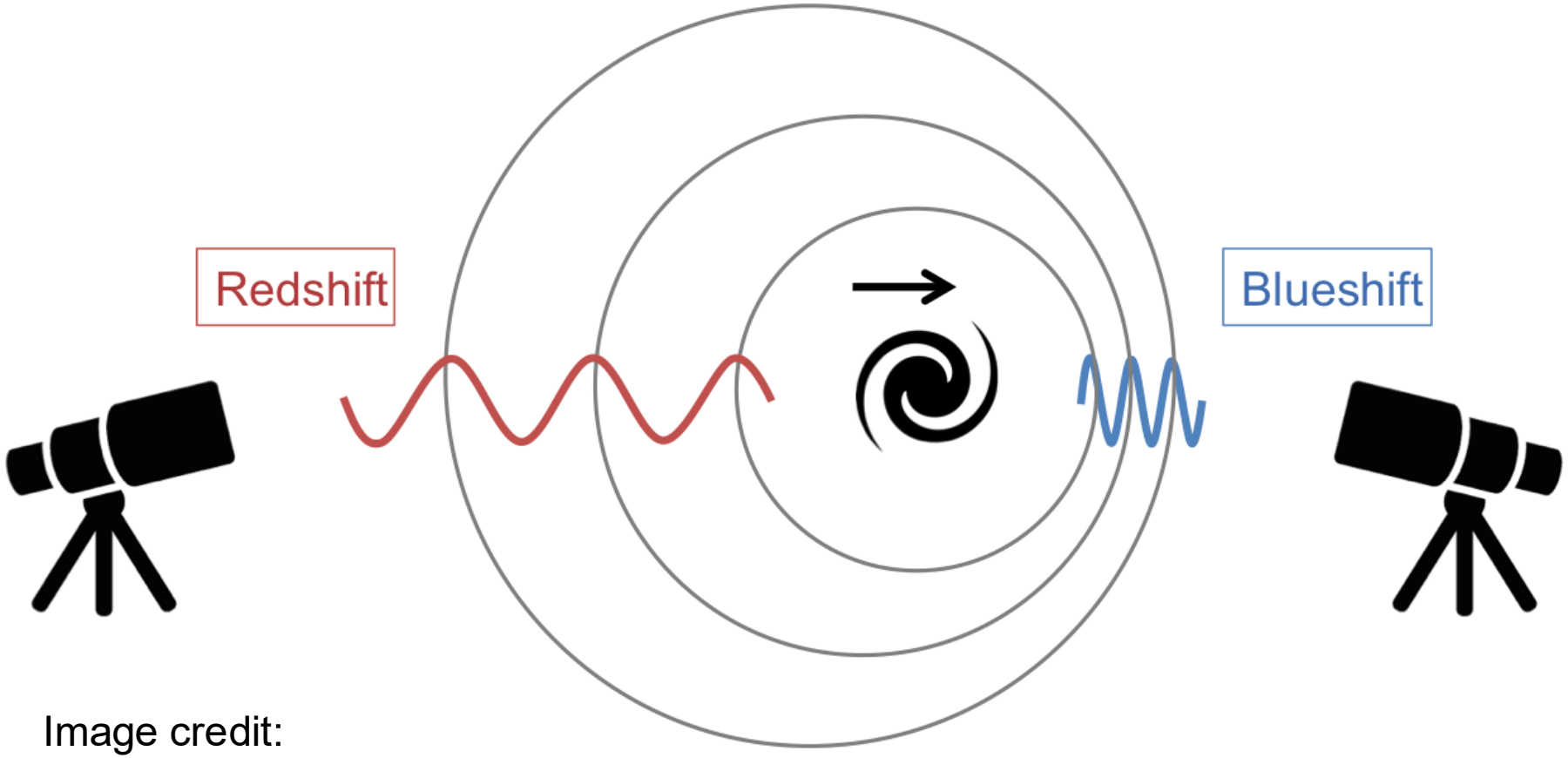

Image credit:
SDSS Voyages

- Galaxies have peculiar velocities (move besides Universe expanding uniformly)

⇒additional redshift

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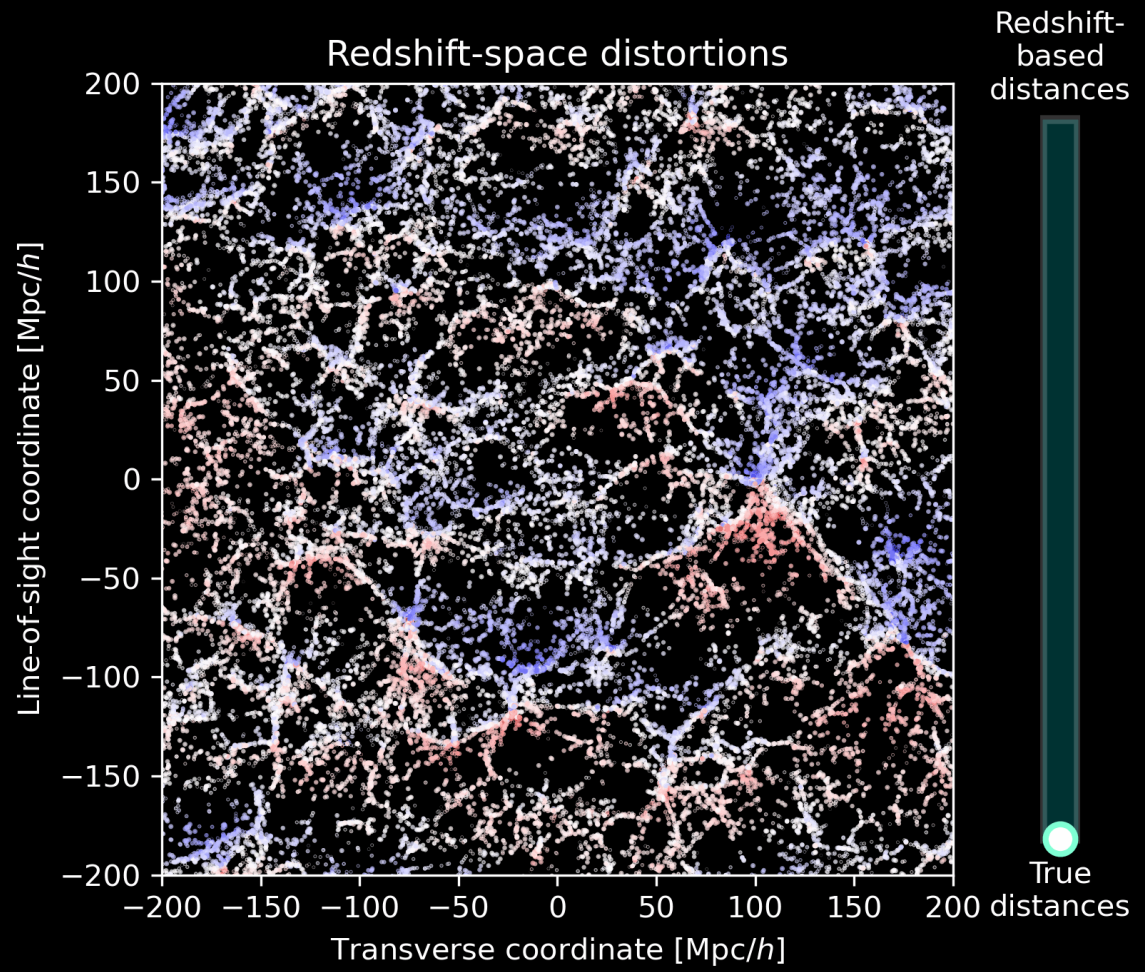
Redshift-space distortions (RSD)

- Redshift-based distances (redshift-space coordinates) are biased (distorted) by Doppler redshift
- Larger-scale squishing — Kaiser effect (“pancakes of God”)
  - Cosmological probe
- Smaller-scale elongation along the line of sight — Fingers of God
  - Motions in galaxy clusters
  - Hard to model, often nuisance
- Much of the apparent small-scale separation is velocity



Animation: MR, C. Lamman, D. Eisenstein, C. Miller

See https://rashkovetsky.im/outreach for more

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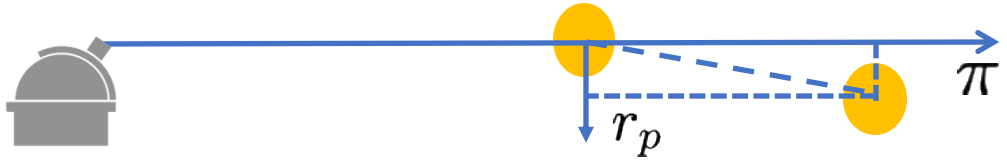
Small-scale line-of-sight clustering



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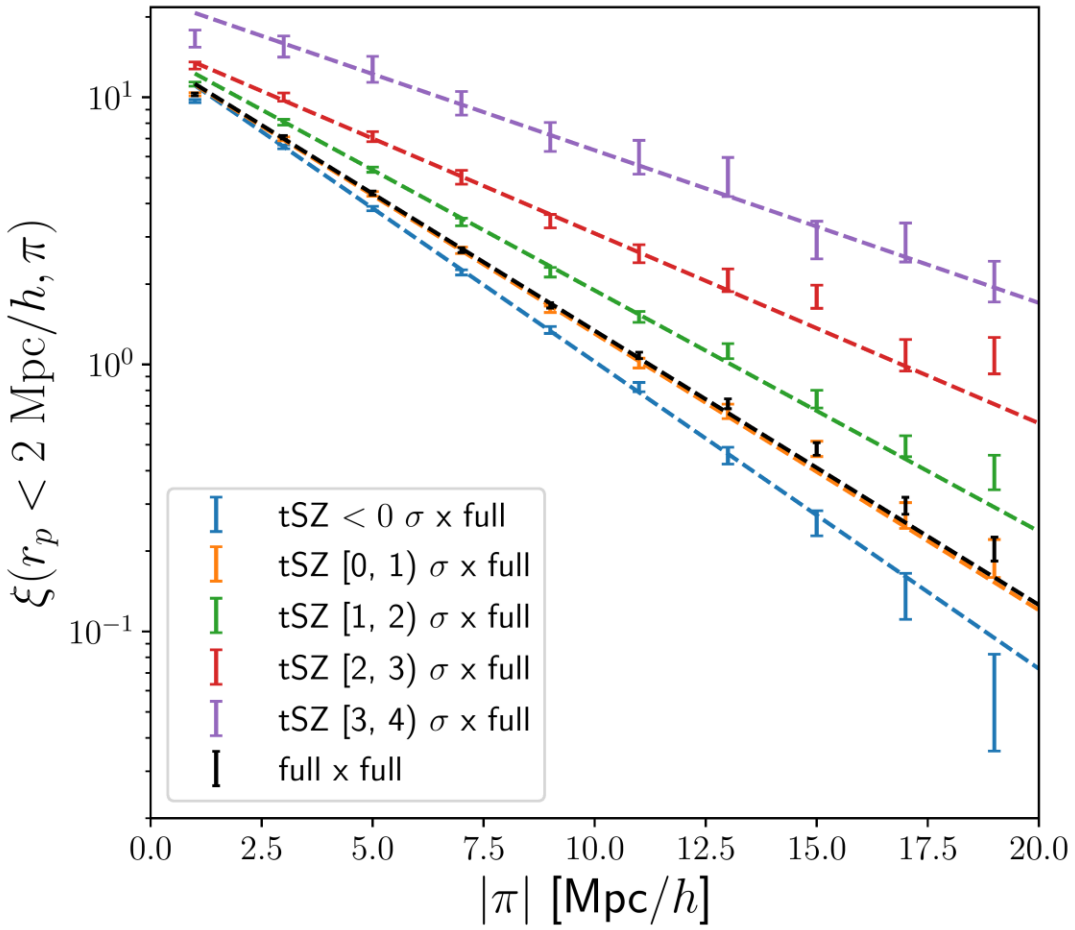

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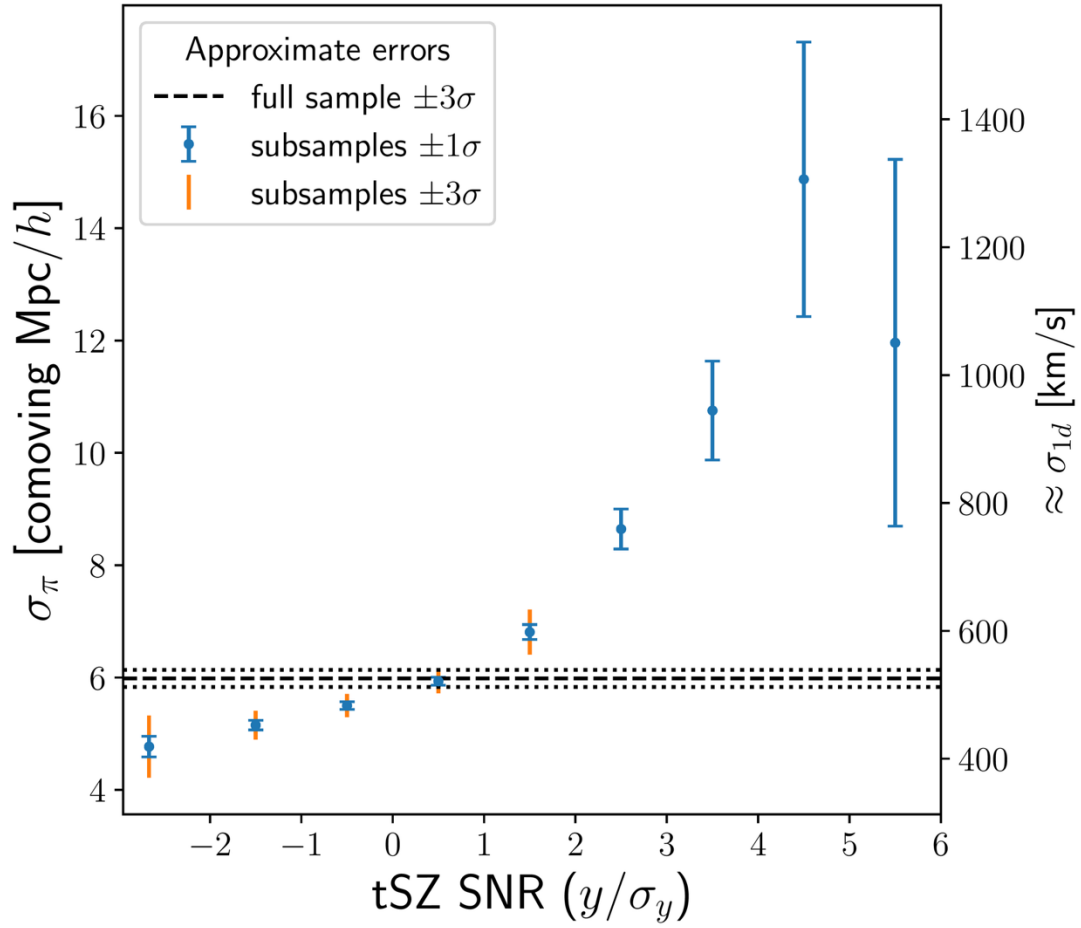
Increasing velocity dispersions

- Extracted coordinate dispersions using the exponential fits

$$\xi(\pi) \approx C \exp\left(-\sqrt{2}\frac{|\pi|}{\sigma_\pi}\right)$$

(sigma = 1D dispersion)

- Significant increase with SNR (except in the last noisy bin)
- Consistent with larger halos having stronger tSZ and higher velocity dispersions



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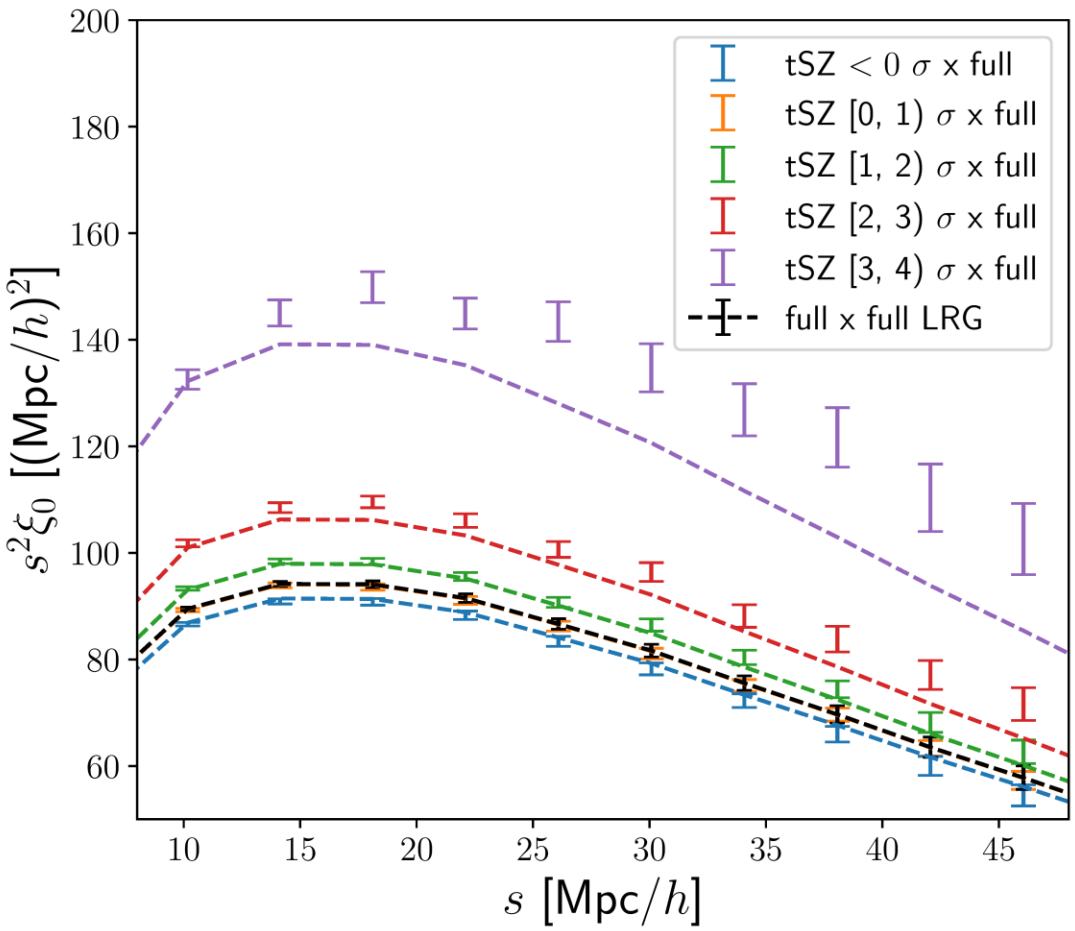
Steps towards (forward) modeling

- Combination of different probes is (also) hard to model analytically
- Need to consistently model or simulate SZ and galaxies
- Made our own simple y map from Abacus dark matter-only simulations in cubic boxes to use with galaxy catalogs
- After refinement steps, see similar trends to data —>
- (but not a perfect match)



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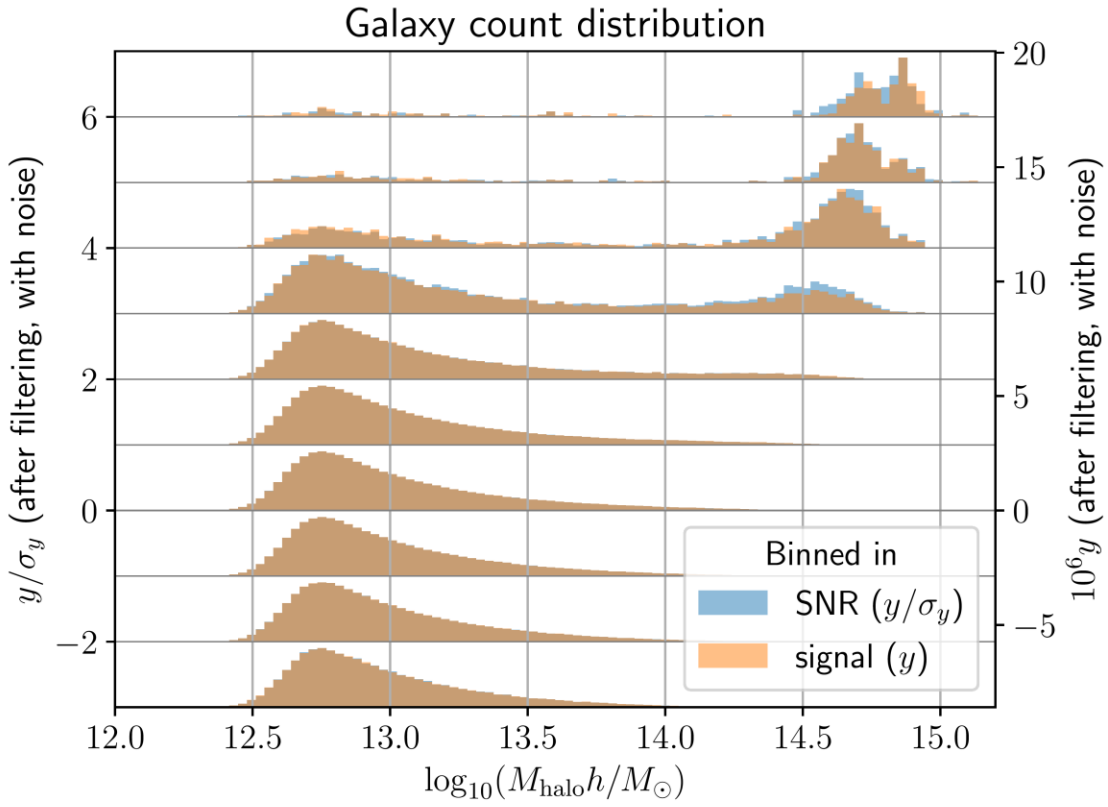
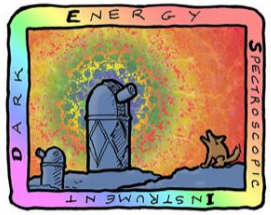
Relation to halo mass

Halo mass for mock galaxies vs tSZ in corresponding map pixels

- 1-dimensional halo mass histograms in tSZ SNR “bins”
- Binning in the signal may seem easier to model but gives little difference (with comparable bin width)
- At low SNR, primary peak at low masses, high-mass tail thickens and extends
- At 3-4 sigma, secondary peak at high masses emerges, and becomes dominant at higher SNR





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Conclusions and further plans

- There is valuable information in modern tSZ maps in the lower-SNR regions far beyond the individual clusters
- Promising combination
  - DESI taking galaxy spectra at an unprecedented rate
  - Next CMB (SO, CMB-S4) great for SZ
- Potential to test consistency and discover new tensions
- Hope to calibrate the halo mass–Compton-y relation and build semi-analytical models for cosmological inference
  - Promising similarity of data to mocks without systematics
  - Promising indications of weak sensitivity to galaxy-halo connection
- Study in simulations with different cosmologies

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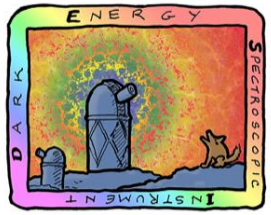
Backup slides



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Motivation

- Leverage clustering information from different-density environments
  - ~ Density-split clustering (split regions by smoothed density)
  - ~ Density-marked (weighted) clustering
- Tighter constraints on Ω_m, σ_8, etc.
- Reduce nonlinearities for more robust theoretical modeling
- Modified gravity — less constrained in low-density regime
- Environmental effects on galaxy formation, assembly bias
- tSZ as density indicator with non-DESI/LS spectro/imaging systematics
  - However, integrated along the line of sight + blurred by the beam

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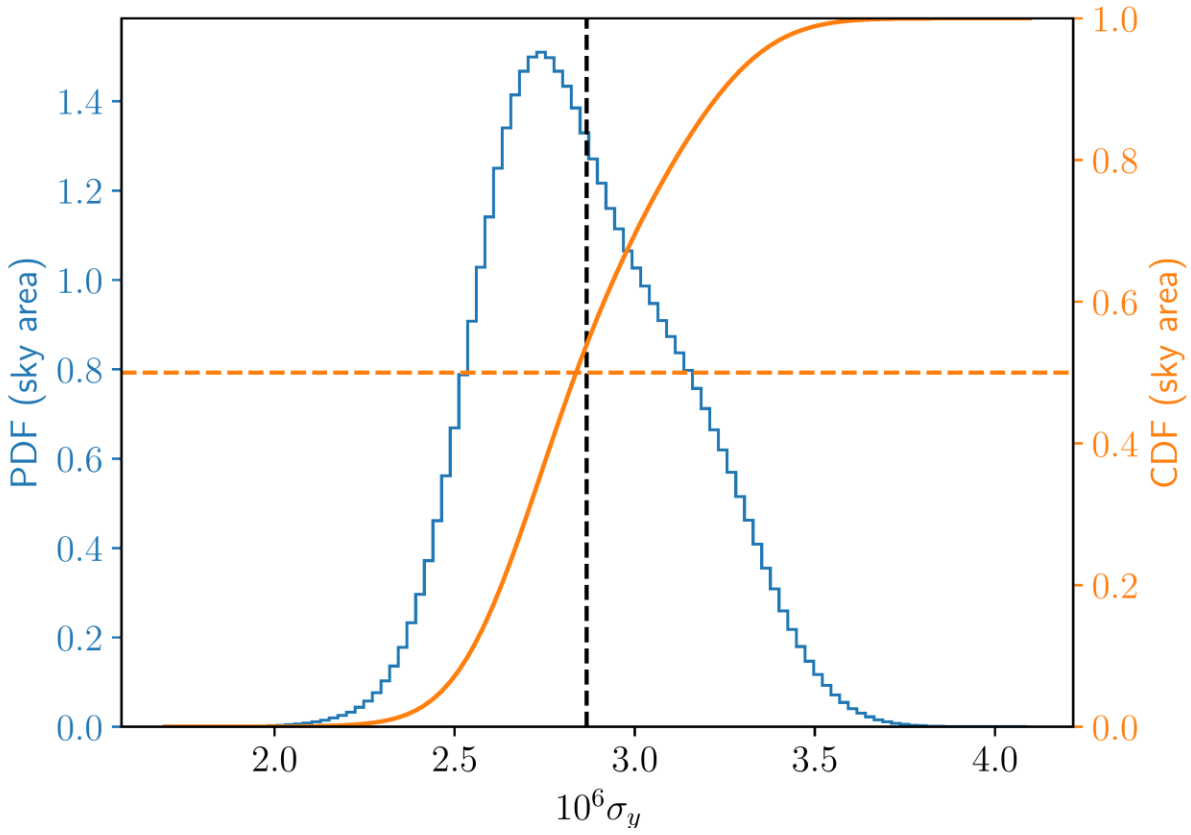
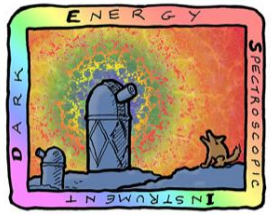
Pixel-level noise std distribution





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Methodology details

- Filter the ACT+Planck tSZ y map with a 2.4’ FWHM Gaussian filter
  - Estimate pixel std with 304 noise maps (same filter) to obtain SNR
- Match DESI luminous red galaxies (LRG, z=0.4-0.85) to the map
- Look at different SNR ranges, lower than CMB SZ cluster detection (4σ)
- Tricky geometry, hard to make randoms and estimate errorbars
- Avoid randoms by cross-correlation with all LRG + Davis-Peebles CF estimator not requiring all pair counts unlike Landy-Szalay

$$\hat{\xi}^{\rm DP}_{12} = \frac{D_1 D_2}{D_1 R_2} - 1$$

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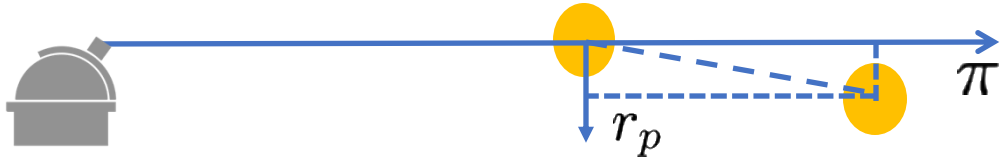
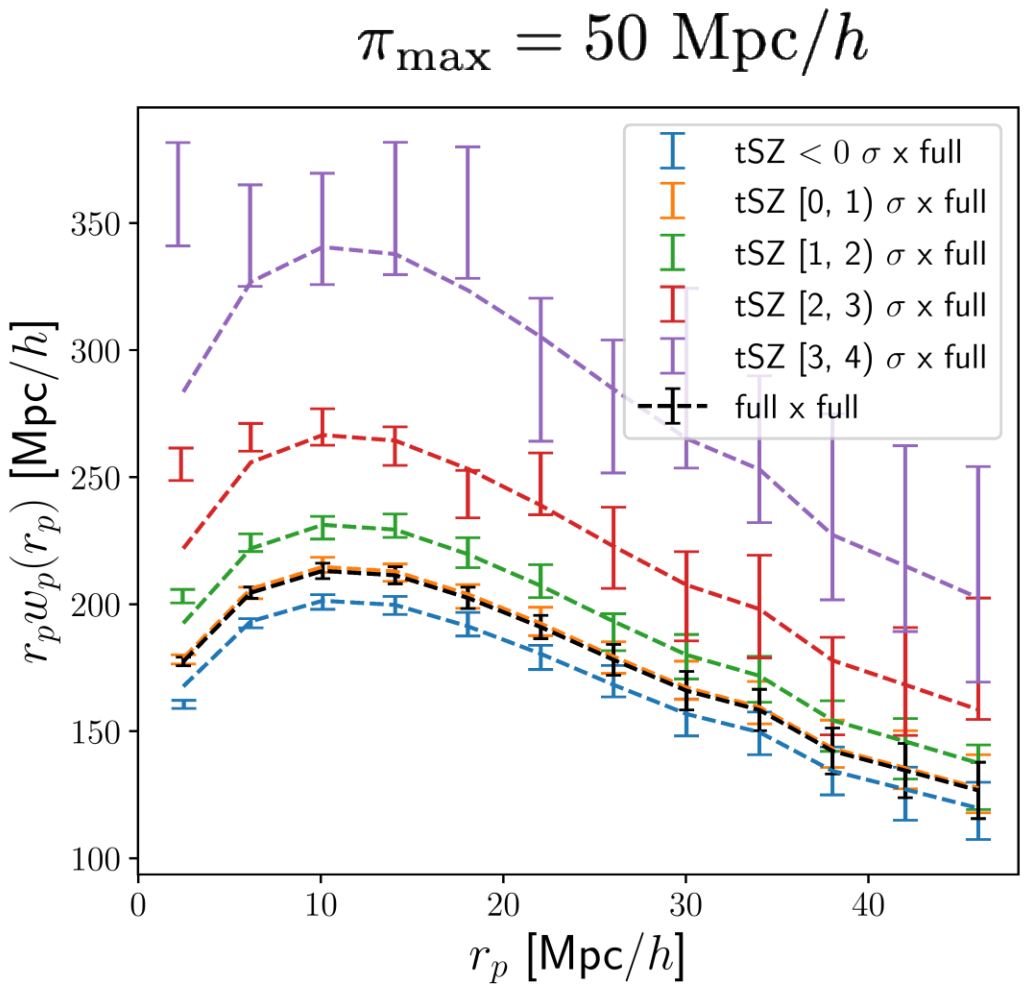
Projected correlation function



- Same data and binning
- Very similar relative biases (fit r_p between 8 and 48 Mpc/h) with slightly larger errorbars
- Less demanding on redshift precision
- Can be used with larger photometric samples, like DESI Extended LRG from Legacy Imaging (Zhou et al 2023)



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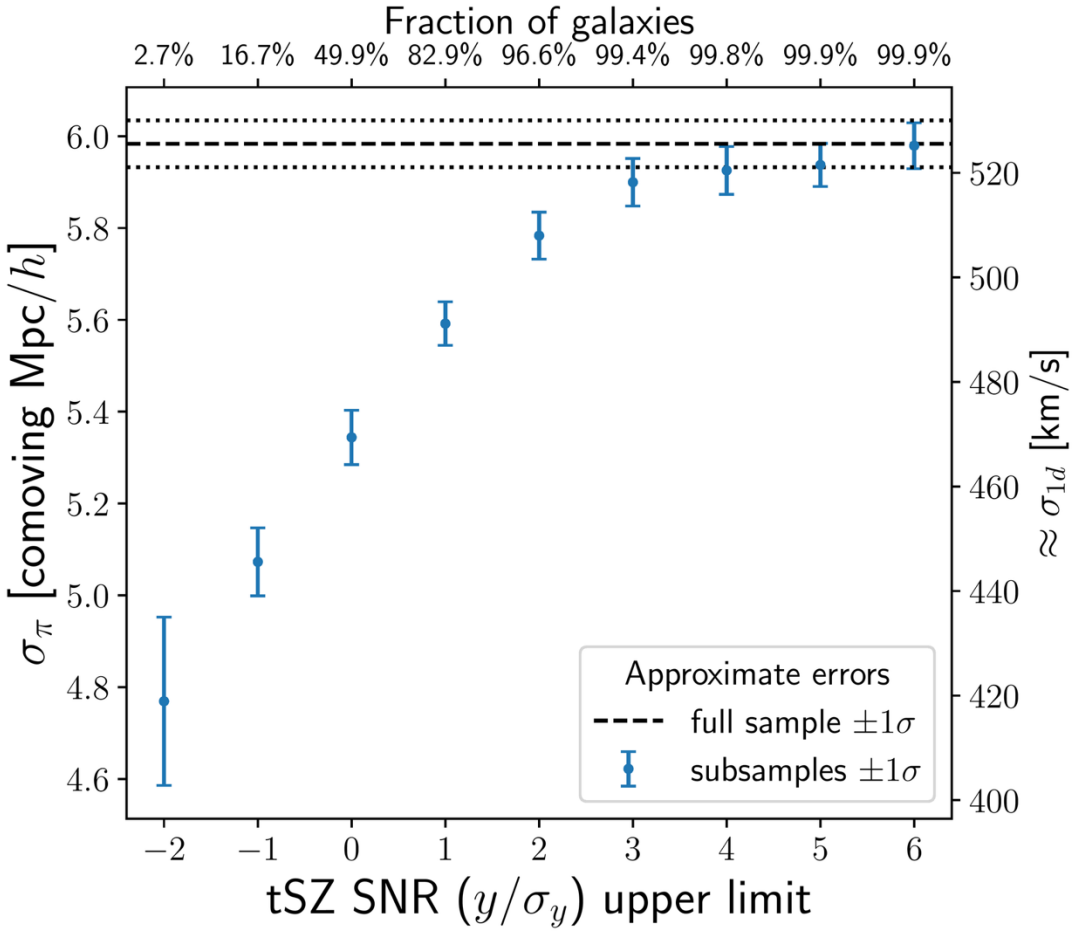
Reducing Fingers of God (FoG)

- Baleato Lizancos et al 2025: cleaning galaxy samples from the strongest FoG to help LSS theory models. Use local indicators: colors and tSZ
- We test tSZ cutoffs (upper limits) with real data
- Reduction of velocity dispersions not big but significant
- Can look for the optimum between fraction of galaxies vs FoG removal



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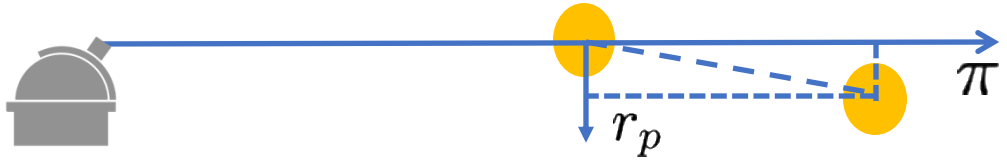
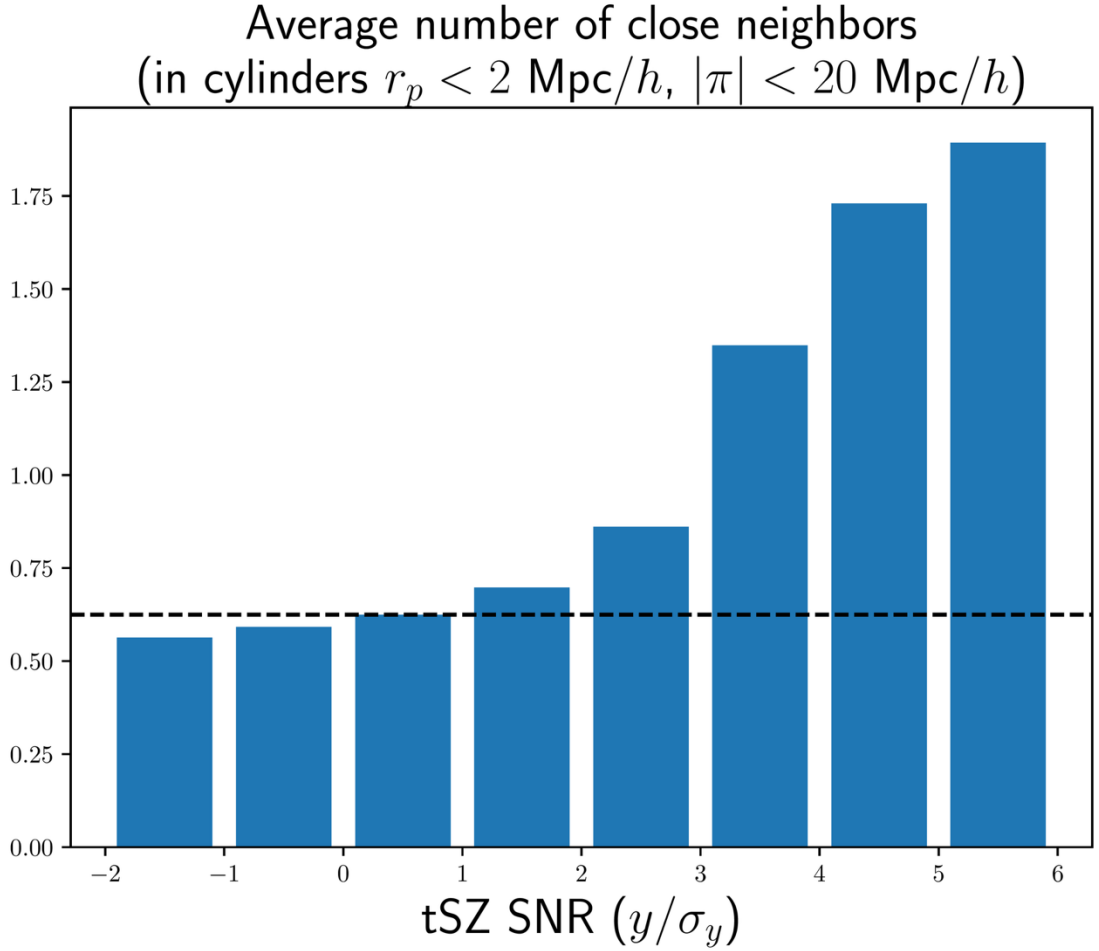
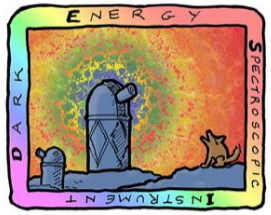
More close neighbors



- Related to clustering amplitude (integral of the line-of-sight correlation functions)
- tSZ hints at larger groups and can be used to inform galaxy multiplet studies (Claire, H. Wang) in low-completeness samples
  - Although tSZ probably can't hint at their orientation





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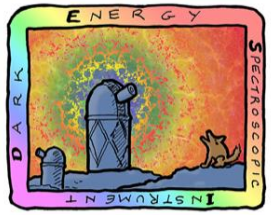
tSZ mocks consistent with LRG

- Make approximate y maps from Abacus halo catalogs

$$y \sim \int \frac{k_B T_e}{m_e c^2} \sigma_T n_e dl$$

- Electron density ~ mass density
  - 85% baryons in hot gas
- Temperature ~ halo velocity dispersion
  - KE per mass in hot gas ~ same as in DM
- 1.6 arcmin (FWHM) Gaussian beam
- 0.5 arcmin final pixels as in ACT+Planck map



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Further refinement of mocks

- Realistic spatial correlations of the noise
  - Taken power spectrum from noise simulations
- Recreated pattern of noise std across ACT+Planck footprint
- Calibration of signal/noise scale
  - Matching the 3D density of >4σ detections after Gaussian filtering
  - Need to do this after adding noise!

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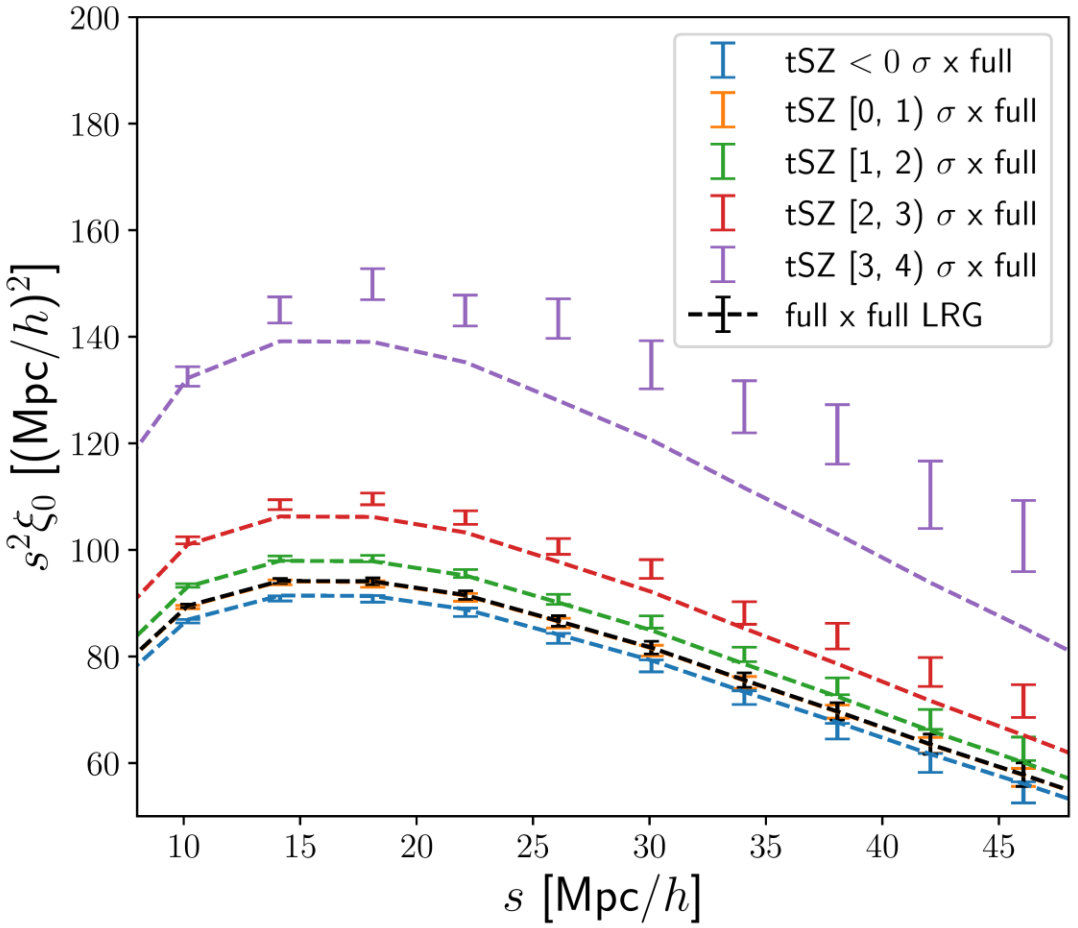
Simulation toy model & validation

- Made simple Compton-y maps from Abacus DM-only simulations in cubic boxes
- Used (AbacusHOD) galaxy catalog made from the same simulation
- Obtain similar clustering enhancement —>
- Dashed lines: fit optimal scaling of the full-sample clustering (counterintuitive with correlated points)



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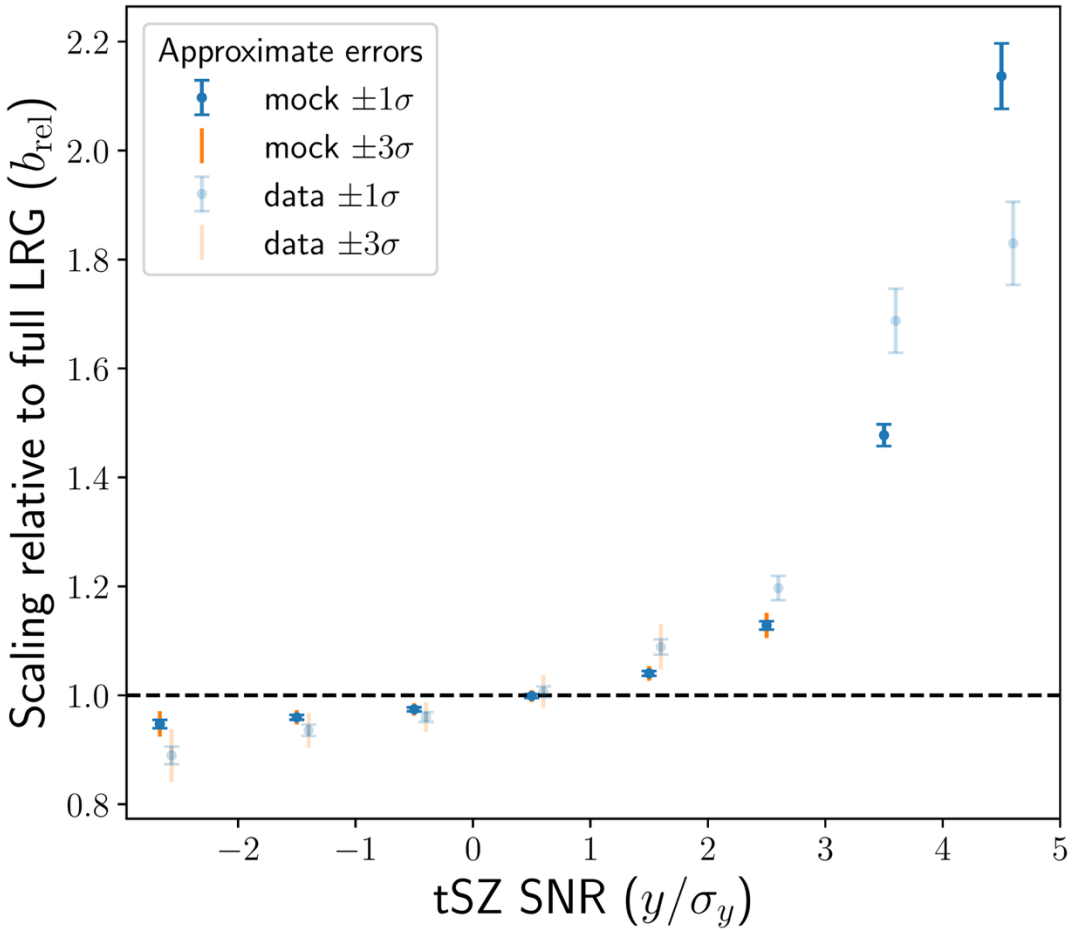
Similar relative bias pattern

- Collapsed each line from the previous plot into a single number
  - Scaling of the full-sample correlation function (~ratio of galaxy biases)
- Similar increasing trend, but slower near 0 and faster at high SNR
- 0-1σ group similar to the full sample as before
- Mocks with no systematics (like cosmic infrared background or fiber assignment incompleteness)



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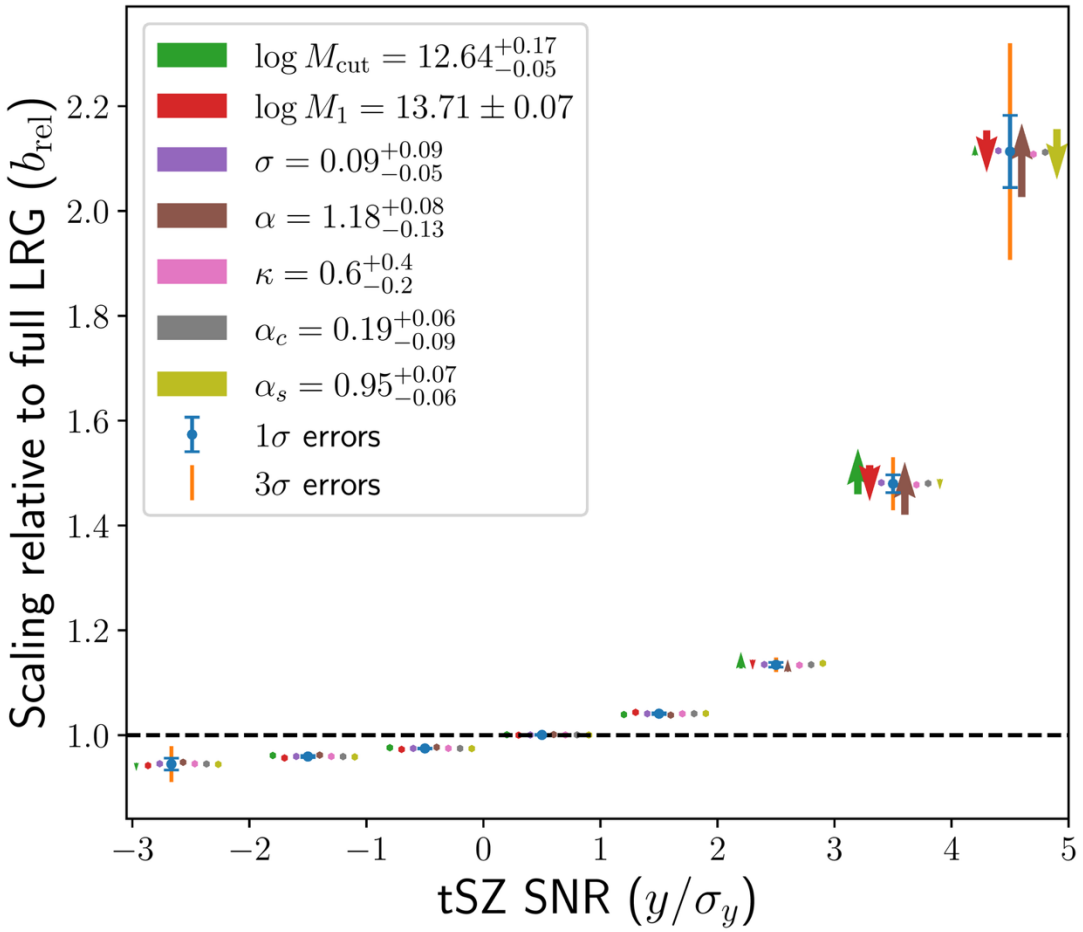
Sensitivity to galaxy-halo connection

- Shifted each halo occupation distribution (HOD) parameter individually up and down by marginalized 1 sigma for simplicity
- Best fit and errorbars from DESI EDR LRG z=0.6-0.8 HOD analysis (Yuan et al 2024)

⇒Effect must be exaggerated

- Not very significant changes in relative biases (but big density variations)
- Bad for constraining HOD, but good for cosmological inference



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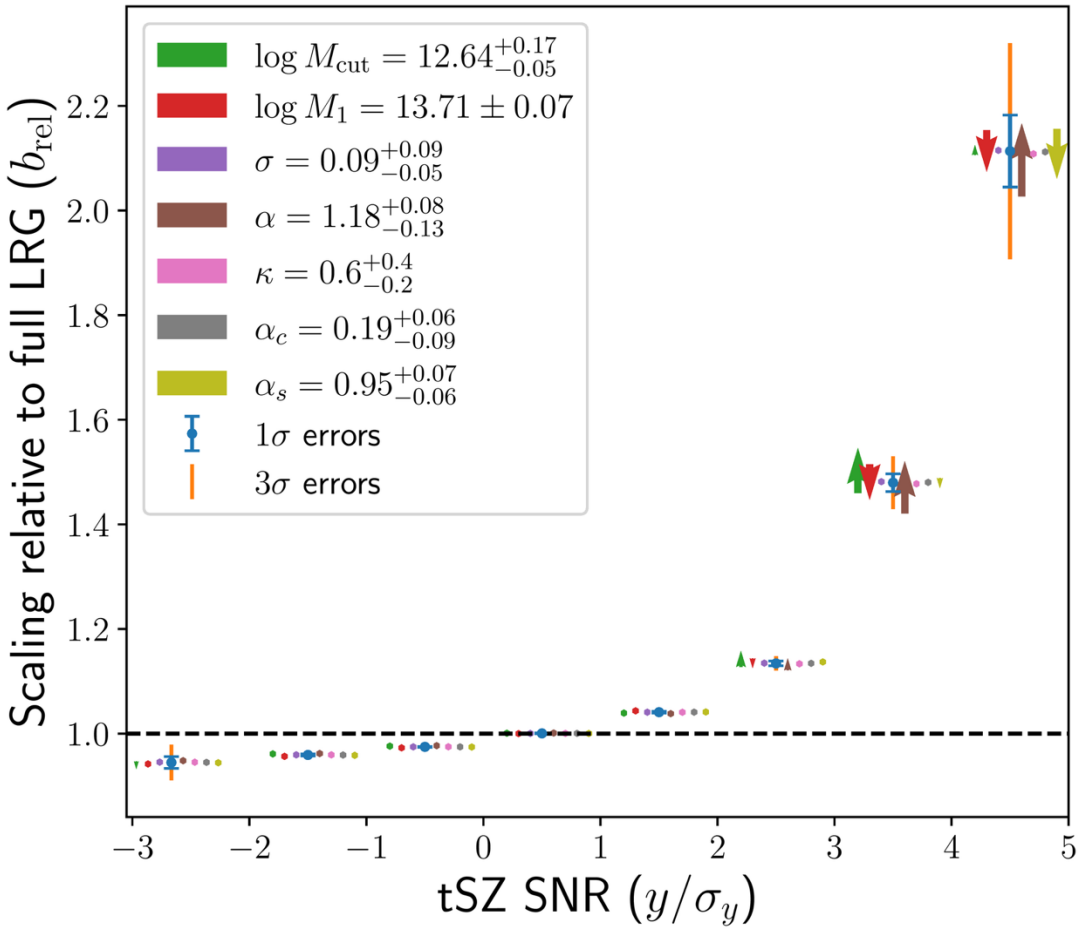
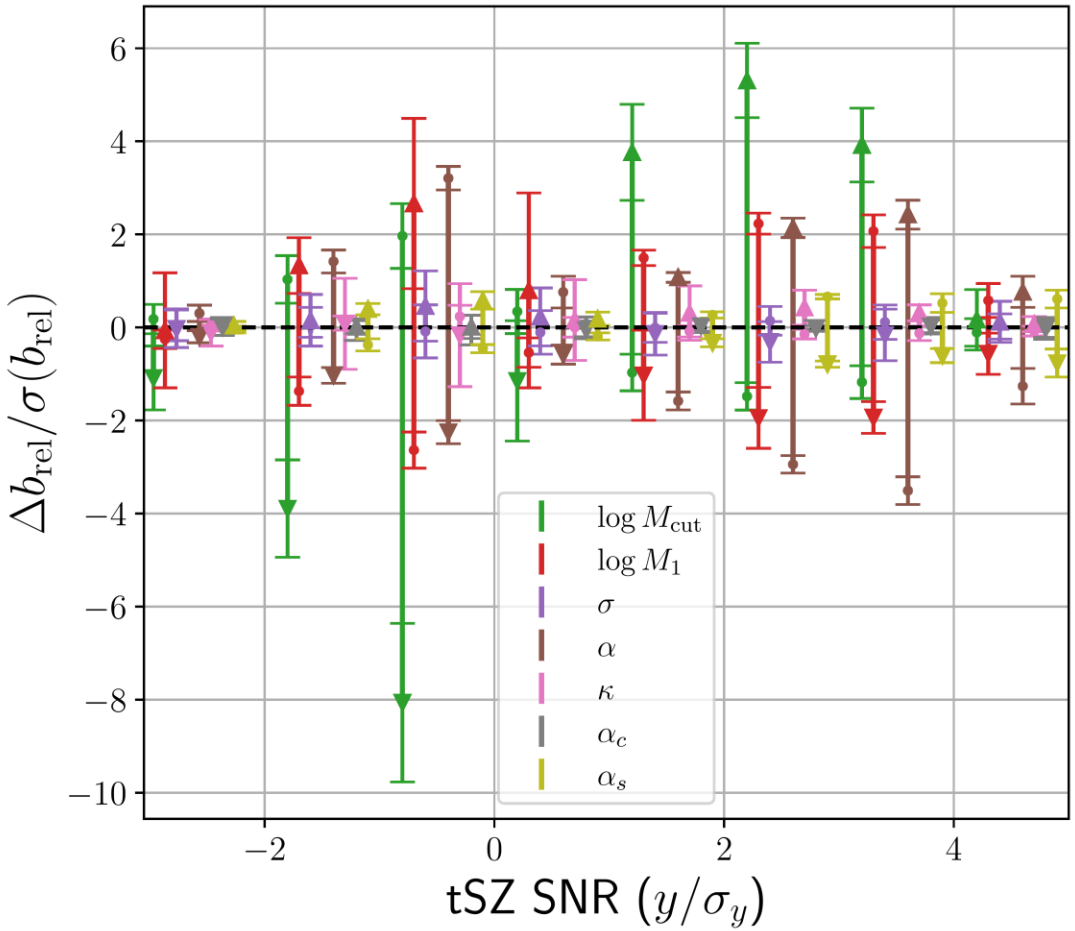
Details on HOD variations





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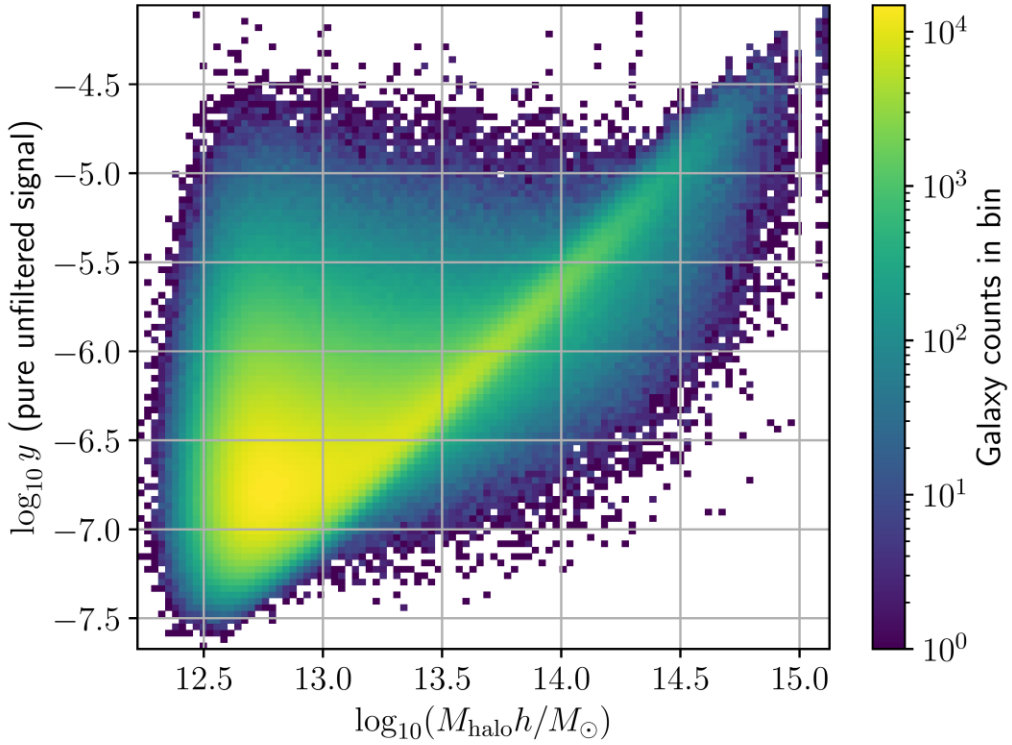
tSZ vs halo mass in simulations

Halo mass for galaxies from best-fit HOD catalog vs tSZ in corresponding map pixels

W/o noise: power-law with index slightly larger than 1 (as in literature) + smearing due to unrelated galaxies in the same line of sight



With noise: unit Gaussian smearing at low halo masses, increase at the high end