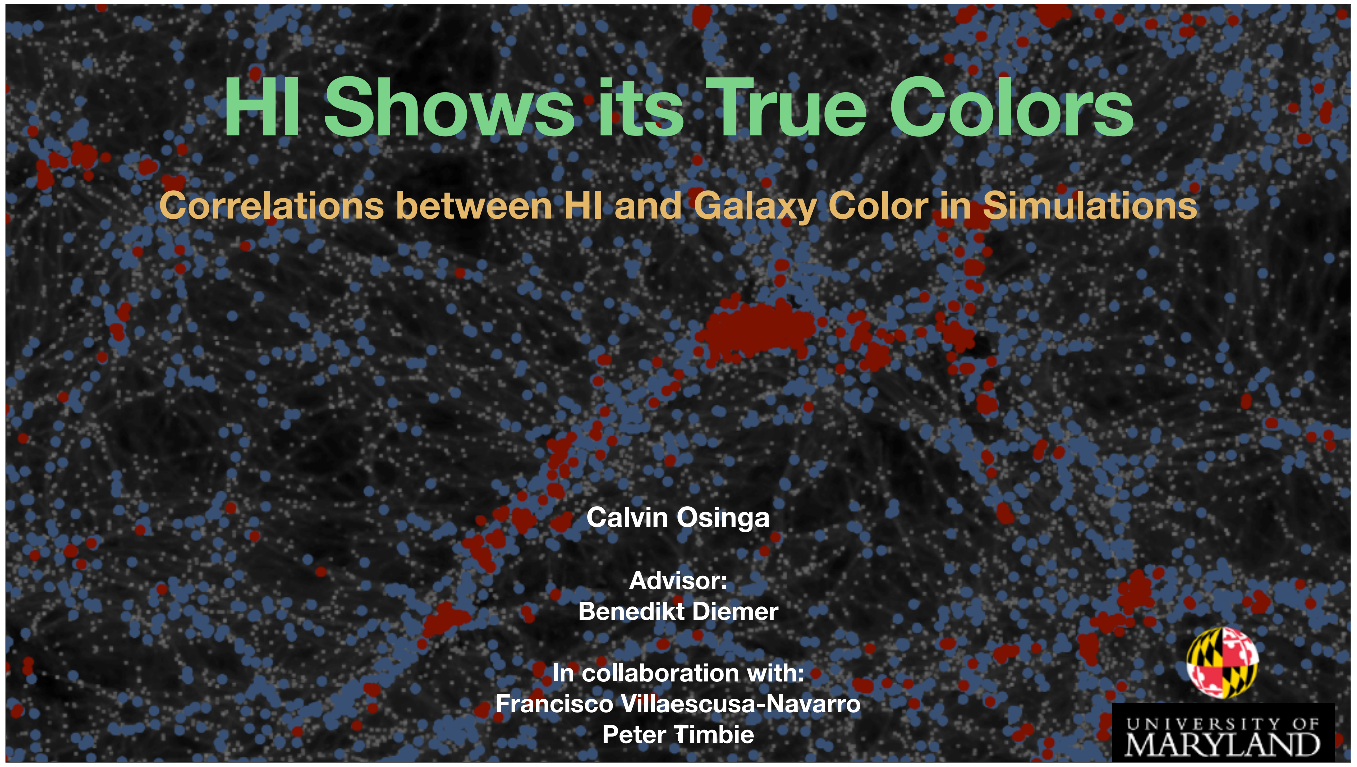

HI Shows its True Colors

Correlations between HI and Galaxy Color in Simulations

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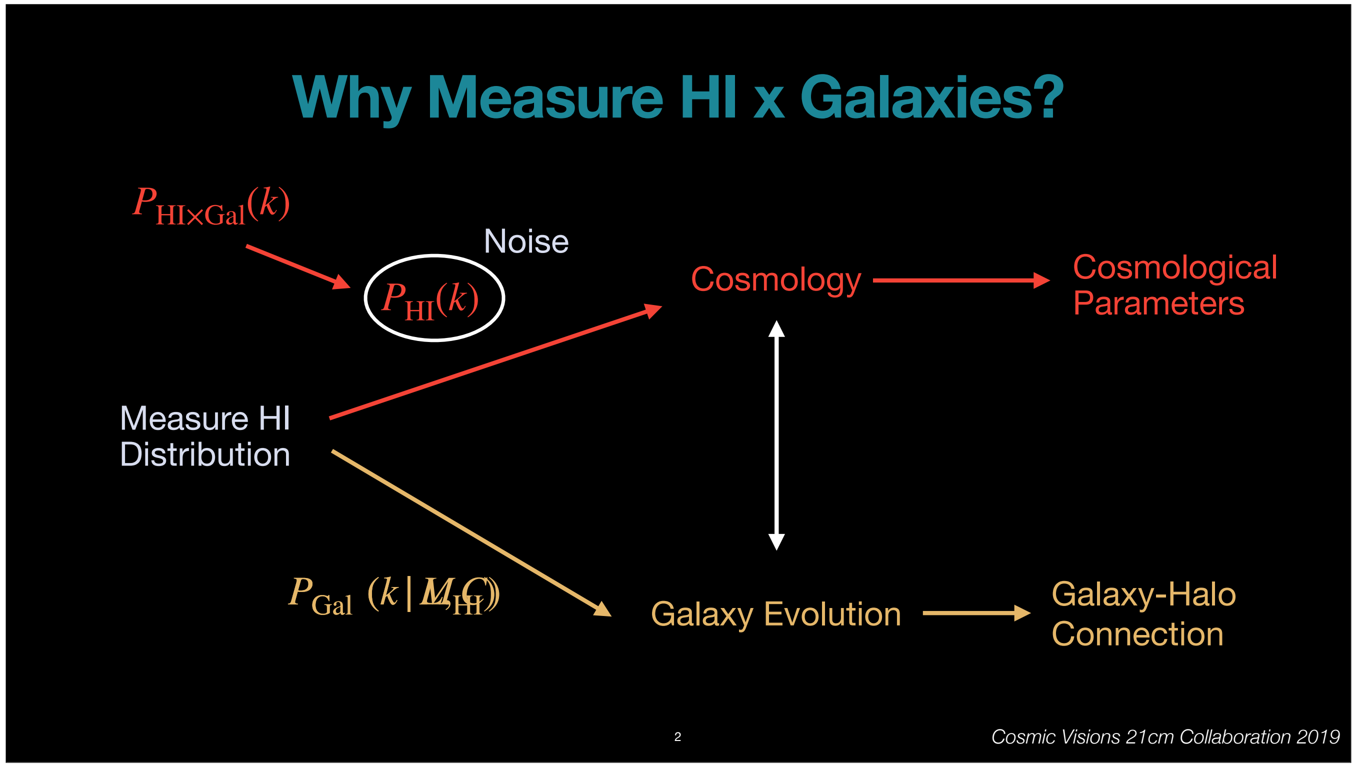
Advisor:
Benedikt Diemer

In collaboration with:
Francisco Villaescusa-Navarro
Peter Timbie

UNIVERSITY OF MARYLAND

- Introduction: Names, Location
- Today I will be talking to you about my project computing the cross-power spectra between HI and red and blue galaxies in cosmological simulations.



Why Measure HI x Galaxies?

$P_{\mathrm{HI}\times\mathrm{Gal}}(k)$

Noise

$P_{\mathrm{HI}}(k)$

Measure HI
Distribution

Cosmology

Cosmological
Parameters

$P_{\mathrm{Gal}}(k \mid L, C)$

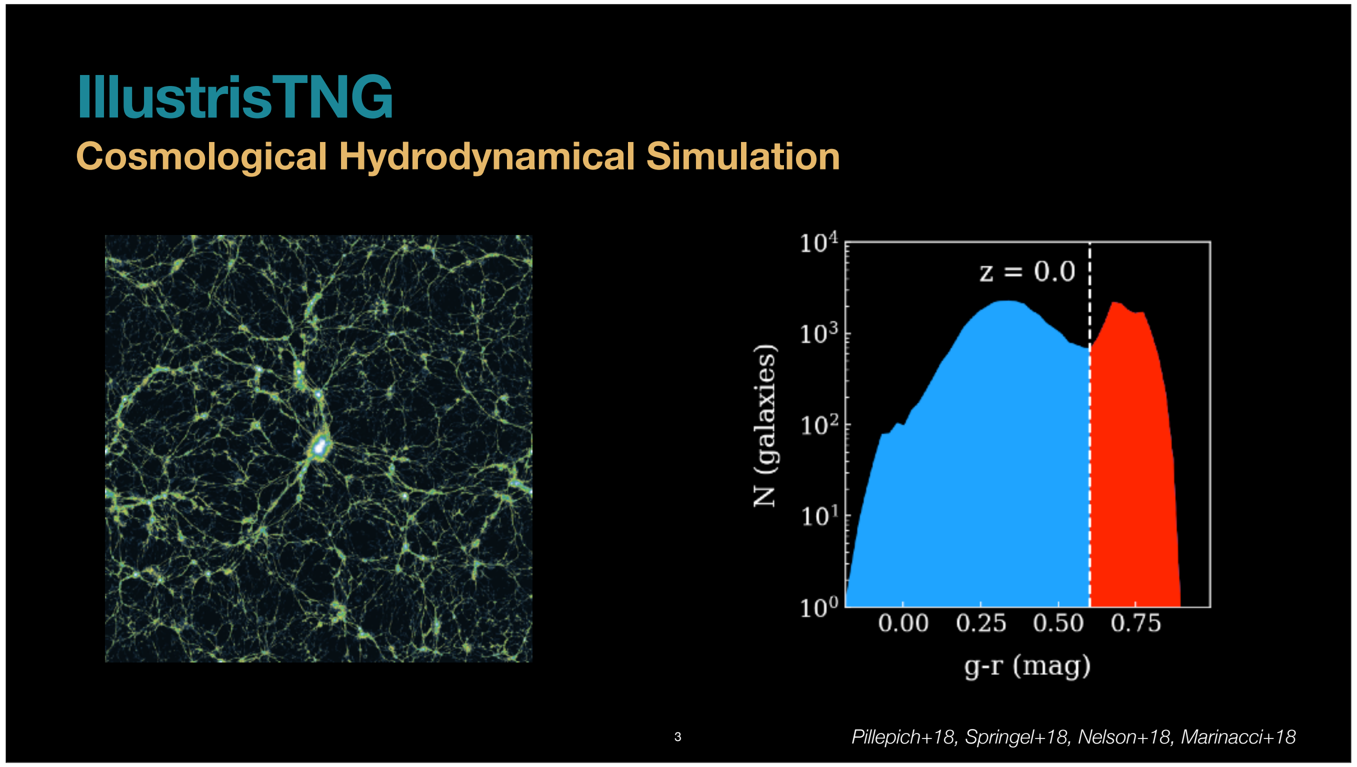
$P_{\mathrm{Gal}}(k \mid M_{\mathrm{HI}})$

Galaxy Evolution

Galaxy-Halo
Connection

Cosmic Visions 21cm Collaboration 2019

- We'll begin our discussion by motivating why we want to measure the HI-galaxy cross-power spectra in the first place.
- > One of the overarching goals of HI intensity mapping is to measure the distribution of HI throughout the universe via the HI power spectrum, > and use that to constrain cosmological parameters.
- However, the > strong noise present in HI measurements at redshifts beyond 0.5 remains a challenge.
- Fortunately, we can mitigate the noise and systematics > by crossing HI maps with galaxy surveys, since the systematics in HI maps are uncorrelated with optical surveys.
- However, these cross-power spectra have applications outside of cosmology.
- Many studies seeking insight on > galaxy evolution measure the clustering of galaxies > in order to probe the galaxy-halo connection. Basically, by studying how the clustering of galaxies changes as a function of various properties such as luminosity or color, we gain insight on how a galaxy's host halo influences that property.
- These cross-power spectra provide the unique opportunity to examine how the galaxy-halo connection shapes a galaxy's > gas properties.
- Furthermore, both cosmology and galaxy evolution work in tandem to shape the spatial distribution of HI and galaxies, so developments in one improves our ability to measure the other.
- The central task for this project is to use cosmological simulations to gain deeper knowledge on using cross-power spectra to accomplish these goals.
- I split the project into two papers, one with a focus on galaxy evolution and the second focusing on cosmology, and I'll be sharing results from both. I'll indicate when the results I'm sharing are preliminary.

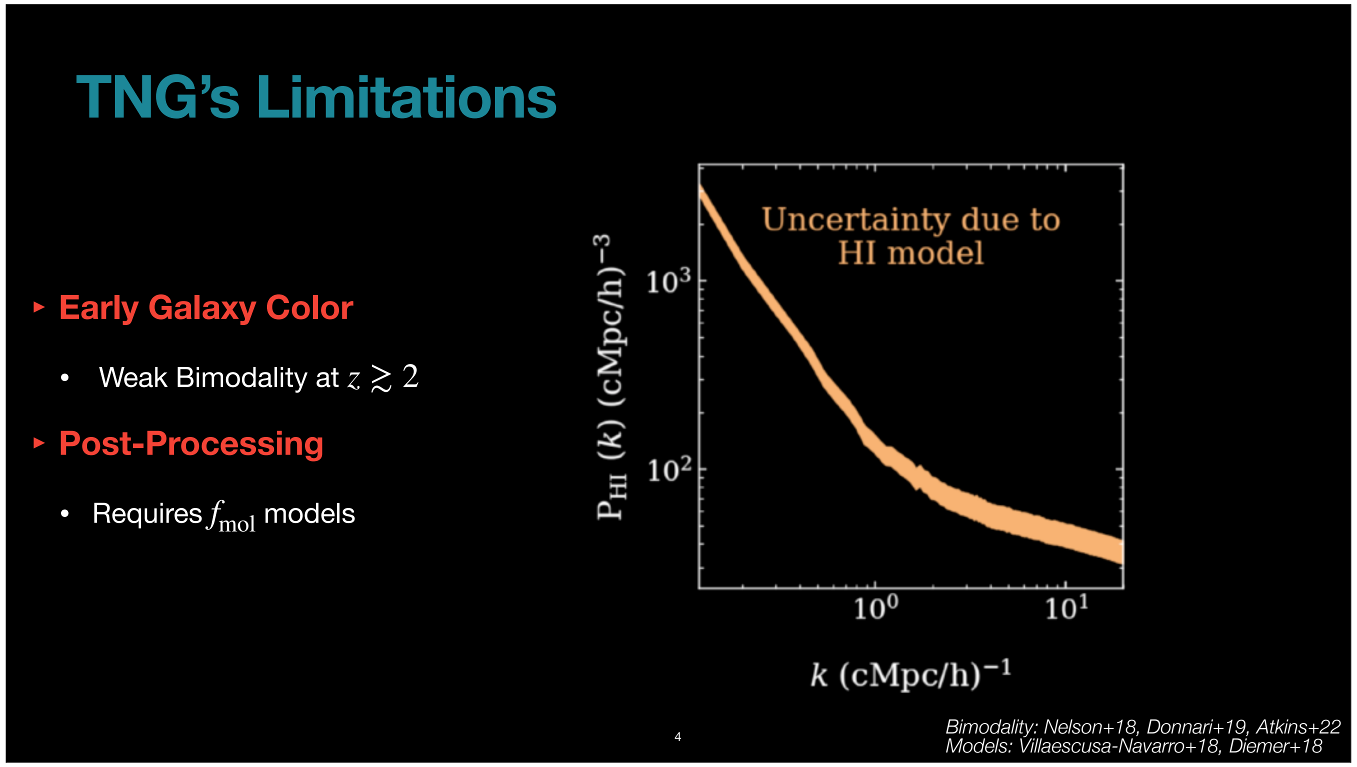


IllustrisTNG

Cosmological Hydrodynamical Simulation

Pillepich+18, Springel+18, Nelson+18, Marinacci+18

- We use the simulation IllustrisTNG, a state-of-the-art cosmological hydrodynamical simulation.
- Hydrodynamical simulations like TNG track baryons, like the gas plotted here, and dark matter over large volumes
- Improves over N-body sims by self-consistently including baryons at the expense of resolution.
- The model is tuned to match a few well-established relationships in order to produce a realistic galaxy population.
- One such relationship is the presence of the galaxy color bimodality.
- >Plotted here is the color histogram at z = 0, where a galaxy’s color is quantified as the difference between the red and green bands from SDSS.
- We then chose the minimum bin between the blue and red modes as the threshold to separate blue and red galaxies. We do this for each redshift independently.

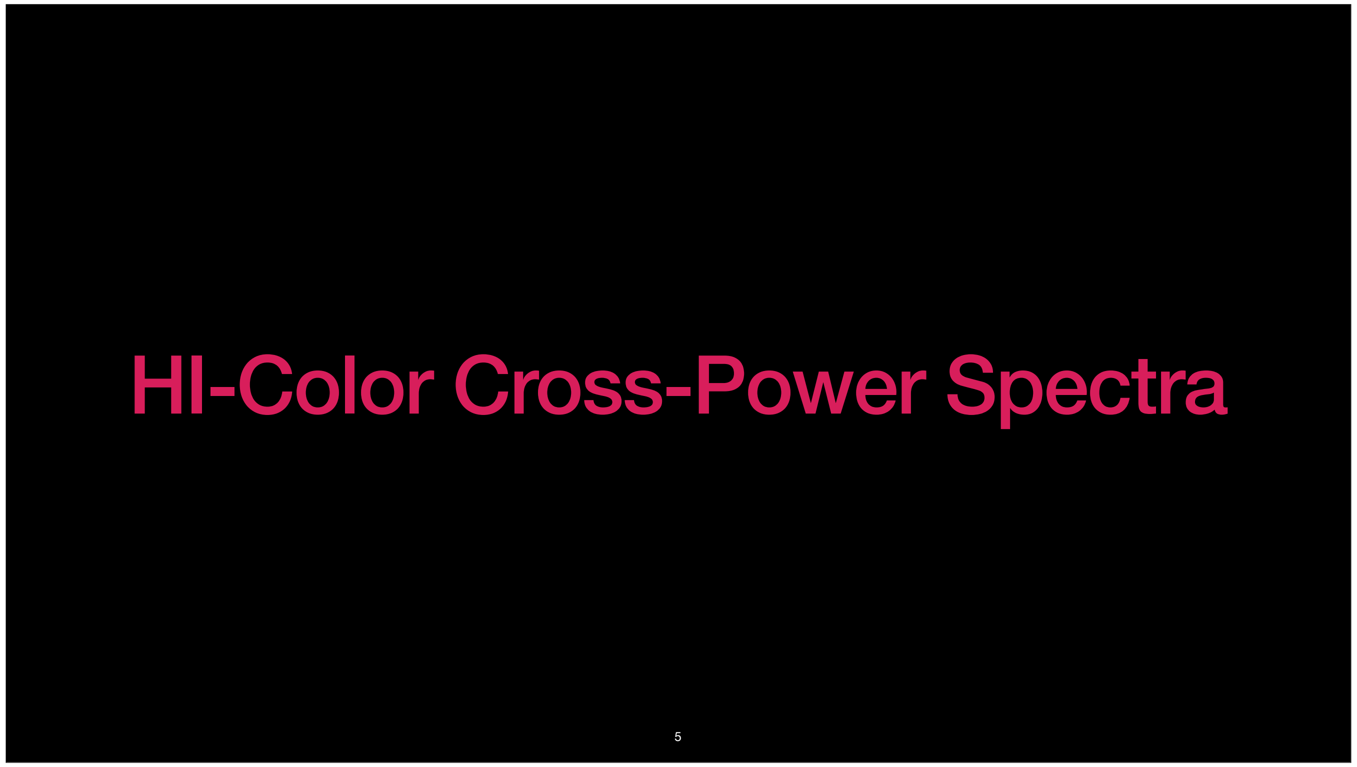


TNG's Limitations

- **Early Galaxy Color**
  - Weak Bimodality at $z \gtrsim 2$
- **Post-Processing**
  - Requires $f_{\rm mol}$ models

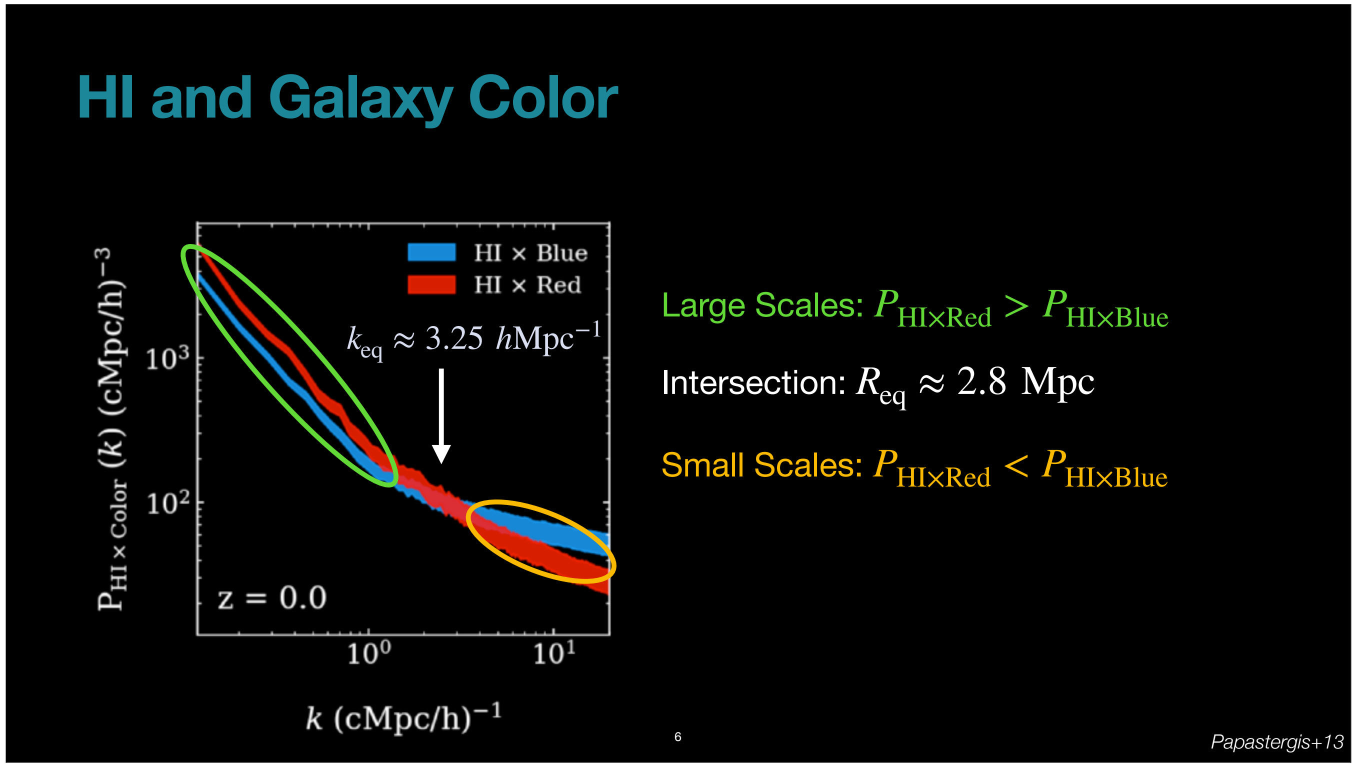
Bimodality: Nelson+18, Donnari+19, Atkins+22
Models: Villaescusa-Navarro+18, Diemer+18

- However, no simulation is perfect, and as such we should address some relevant issues before proceeding to results.
- >First, TNG is missing many red galaxies at earlier redshifts, and does not possess a strong color bimodality beyond a redshift of 2. Common issue in cosmological simulations. As such, we limit our analysis to z = 1, 0.5, 0.
- >Second, TNG does not track HI explicitly, instead tracking neutral hydrogen.
- We post-process TNG to separate the neutral hydrogen into atomic and molecular components.
- For the sake of brevity, I won't go into the details of the post-processing, but we used six different models with a variety of methodologies.
- >Shown here is the HI auto power spectrum computed from each of those models, with the wavenumber in co-moving units across the x-axis.
- >Instead of showing each model individually, we will present our results as a contour encompassing all of the models. We treat this as an "uncertainty due to HI model".
- In any case, HI clustering is fairly insensitive to the model used, especially at large scales where the model changes the power spectrum only by a factor of 1.05 or so.
- Now that I've introduced the topic and TNG, I'll proceed to the results



HI-Color Cross-Power Spectra

- The first result I’ll discuss is comparing the HI-Blue and HI-Red cross-power spectra.



HI and Galaxy Color

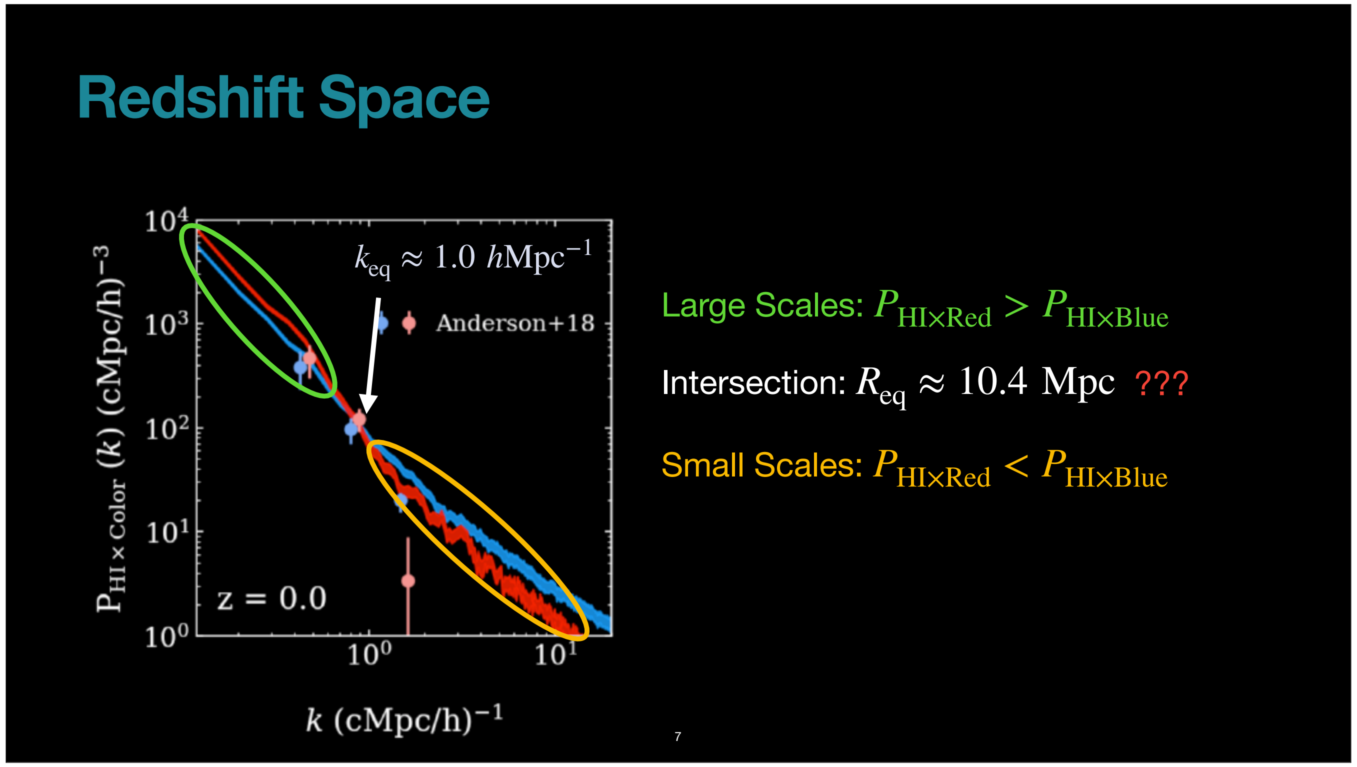
Large Scales: $P_{\mathrm{HI\times Red}} > P_{\mathrm{HI\times Blue}}$

Intersection: $R_{\mathrm{eq}} \approx 2.8\ \mathrm{Mpc}$

Small Scales: $P_{\mathrm{HI\times Red}} < P_{\mathrm{HI\times Blue}}$

Papastergis+13

- This is the real-space cross-power spectrum for HI-red and HI-blue at z = 0.
- Comparing the power spectra, we can see that two regimes emerge. > At large scales, HI-red is greater than HI-blue.
- > Then we have HI-red and HI-blue intersect at k ~ 3.25, or an equivalent distance of about 2.8 Mpc.
- > After the intersection, HI-blue is greater than HI-red on small scales.
- These regimes indicate the scales at which HI is dependent on environment. Red galaxies are more clustered than blue galaxies on all scales, so when at large scales where HI is not affected by environment, HI-red is greater than HI-blue
- HI-red dipping below HI-blue indicates HI tends to be depleted within ~2.8 Mpc of a red galaxy, a quantity that agrees very nicely with redshift zero observations from Papastergis et al. 2013, who found an avoidance region of 3 Mpc.



Redshift Space

Large Scales: $P_{\mathrm{HI\times Red}} > P_{\mathrm{HI\times Blue}}$

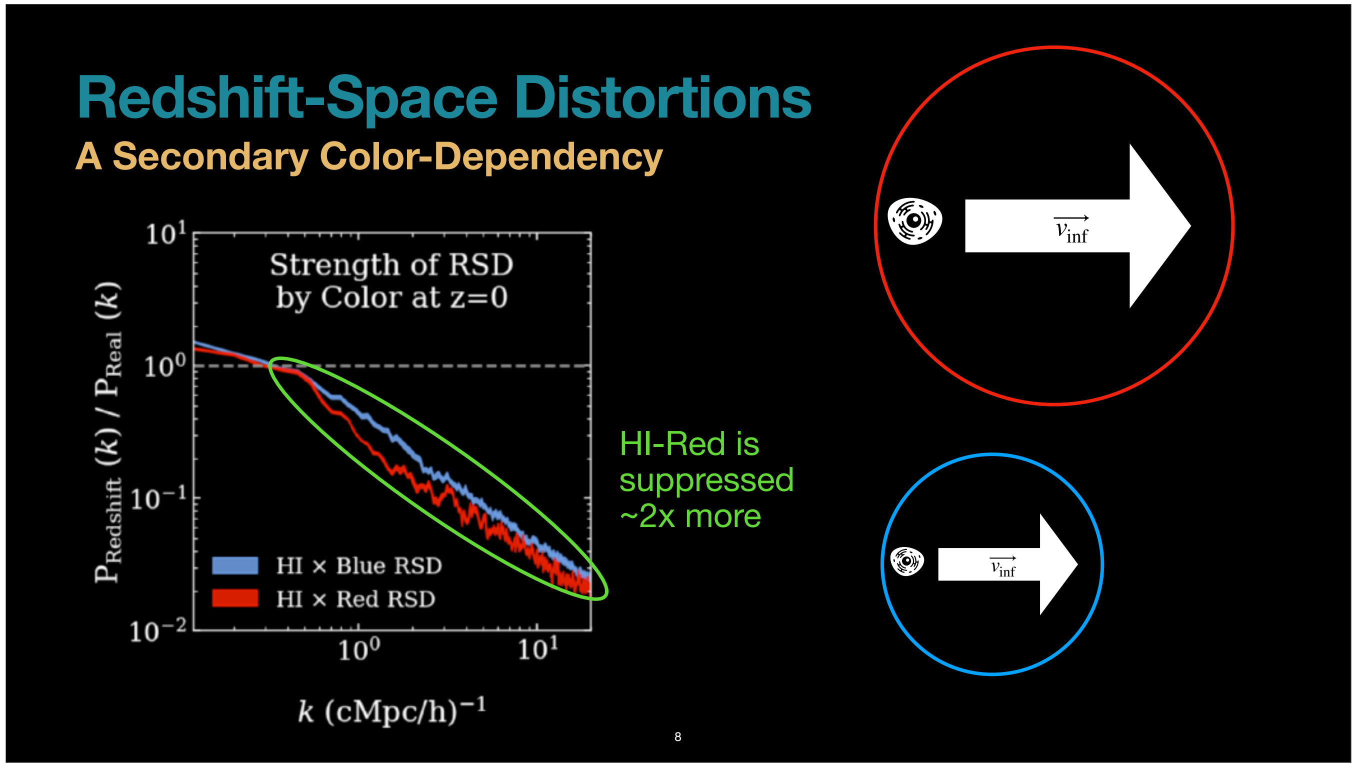
Intersection: $R_{\mathrm{eq}} \approx 10.4\ \mathrm{Mpc}$???

Small Scales: $P_{\mathrm{HI\times Red}} < P_{\mathrm{HI\times Blue}}$

- However, HI intensity mapping observations occur in redshift-space.
- Here we make the same comparison, instead measuring redshift-space clustering.
- We overplot results from Anderson et al. 2018, and find fairly good agreement until the smallest scales they probed.
- We find similar trends as the real-space cross-powers, with > HI-red greater than HI-blue, > then they intersect and > HI-blue becomes larger than HI-red.
- > but the intersection between HI-red and HI-blue occurs at a *much* larger scale than in real space, further than 10 Mpc.
- Why does the intersection grow five-fold in redshift space?

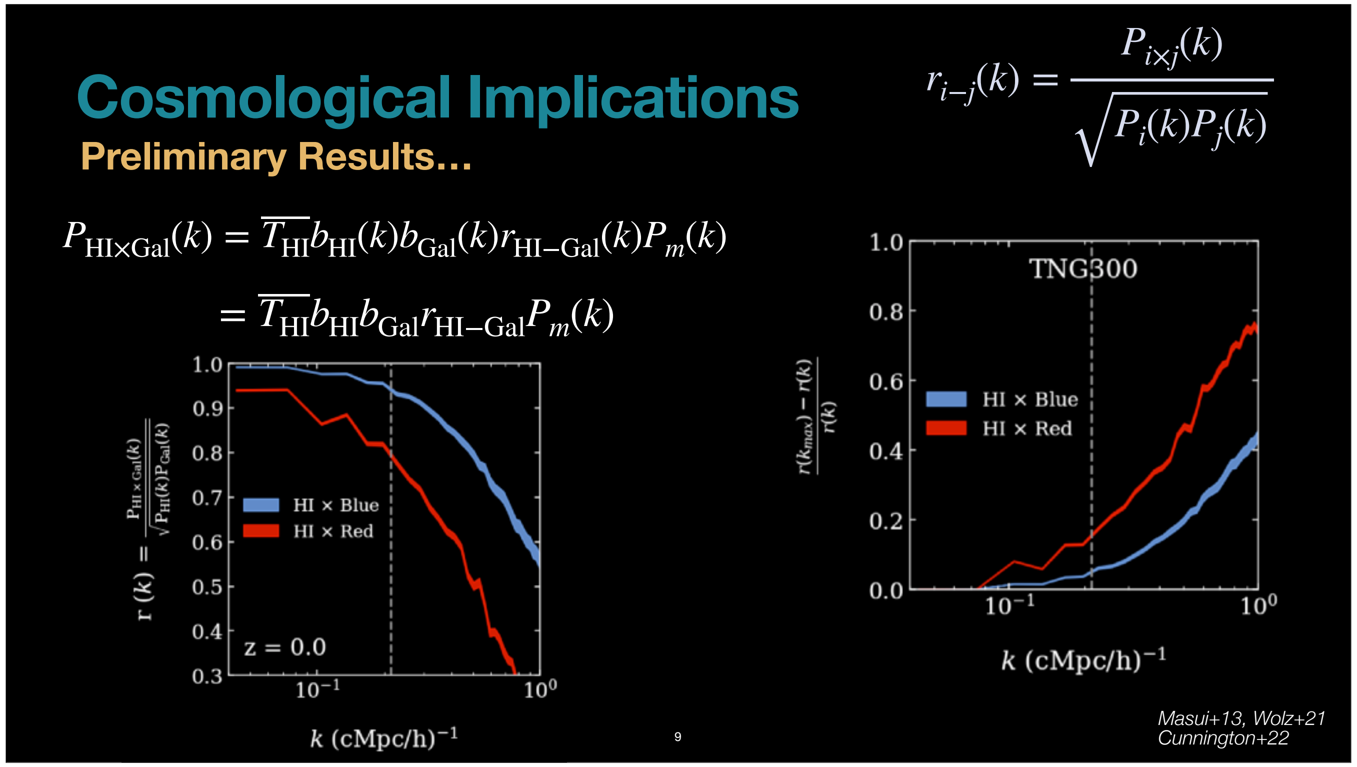
Redshift-Space Distortions

A Secondary Color-Dependency



HI-Red is suppressed ~2x more

- We can see this when we compare redshift-space distortions, which we quantify using the ratio of the redshift space over real space power spectrum.
- >At scales smaller than k ~ 0.7, HI-red is suppressed ~ 2x more than HI-blue, causing it to fall below HI-blue at larger scales.
- The color-dependence of the redshift-space distortions arises from the kinds of halos blue and red galaxies occupy.
- > Red galaxies occupy massive halos which tend to be HI-poor, whereas blue galaxies occupy smaller HI-rich halos.
- > The deeper potential wells of the massive galaxies permit larger velocity dispersions in their member galaxies, leading to a stronger Fingers-of-God effect in red galaxies than in blue/HI-rich galaxies.
- Does this affect our ability to use cross-powers to constrain cosmological parameters?



Cosmological Implications

Preliminary Results…

$$r_{i-j}(k) = \frac{P_{i\times j}(k)}{\sqrt{P_i(k)P_j(k)}}$$

$$P_{\mathrm{HI\times Gal}}(k) = \overline{T_{\mathrm{HI}}}\, b_{\mathrm{HI}}(k)\, b_{\mathrm{Gal}}(k)\, r_{\mathrm{HI-Gal}}(k)\, P_m(k)$$

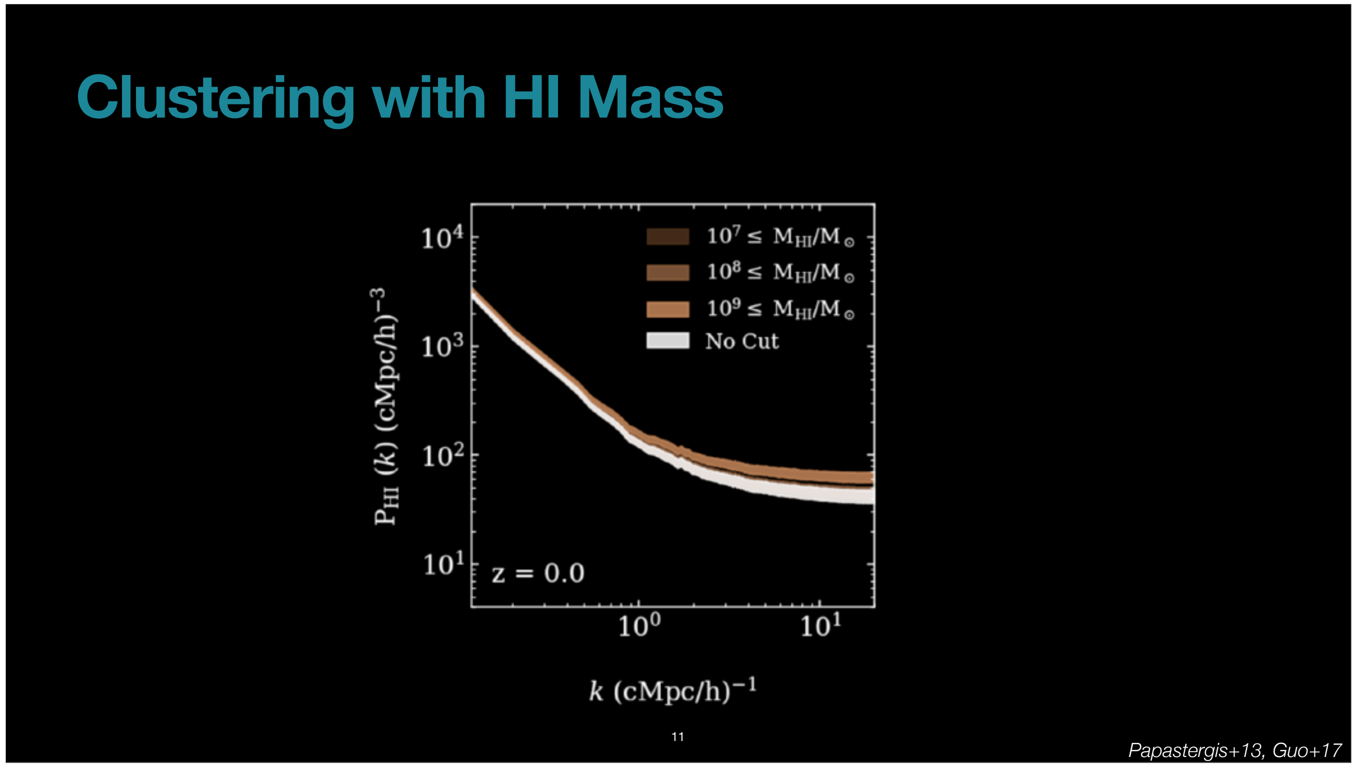
$$= \overline{T_{\mathrm{HI}}}\, b_{\mathrm{HI}}\, b_{\mathrm{Gal}}\, r_{\mathrm{HI-Gal}}\, P_m(k)$$

Masui+13, Wolz+21
Cunnington+22

- To understand what I mean by this, let's first look at how cross-power spectra are used to constrain the cosmic HI density, Omega HI.
- > This equation is true by definition - we can use the matter power spectrum, HI bias, the galaxy bias for whatever survey we use, and the correlation coefficient between HI and the galaxies to constrain Omega_HI via T_HI.
- > For those unfamiliar, I added the definition of the correlation coefficient in the top right corner
- > If we assume that the HI and galaxy biases and R are scale-independent, then the equation takes this form
- We can take the galaxy bias from the optical survey, and then treat T_HI, b_HI and r_HI-gal as a degenerate parameter.
- We can then fit this equation over a range of wavenumbers and constrain omega, bias, and the correlation coefficient that way.
- Let's test the assumption of scale-independence in TNG
- > This is the correlation coefficient for HI and red galaxies and HI and blue galaxies, with a gray dashed line used to indicate the scales probed by observations where this scale-independent assumption is made.
- The correlation coefficients approach 1 towards large scales, but fall rapidly before the gray line
- >To give an idea of the induced error that TNG predicts, I've taken the r value at the largest scale and calculated the % error from the actual correlation coefficient at that wavenumber.
- From this, we can see that within the scales probed HI-red can differ by around 10-15% whereas HI-blue stays pretty reasonably within 5%
- This doesn't necessarily mean that these fits err by that amount, but from this we may conclude that if future work will require sophisticated models to account for scale-dependencies in order to improve accuracy and go to smaller scales.

Stellar and HI Mass

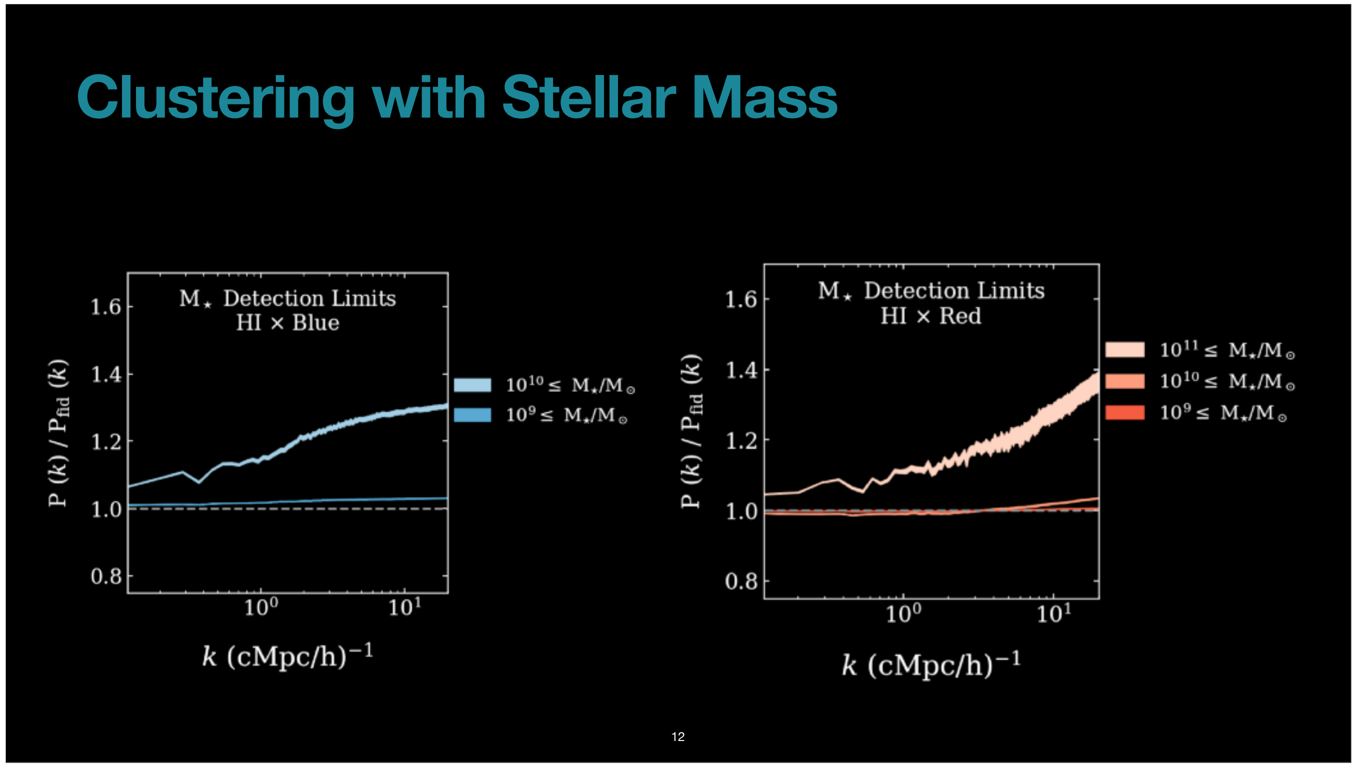
- In addition to examining the color-dependency, we also examine clustering as a function of HI and stellar mass.
- I’ve kept this section of the presentation brief, but more details will be available in the paper



Clustering with HI Mass

Papastergis+13, Guo+17

- For our first test, we used HI mass limits, with brighter colors corresponding to greater mass bins, as a rough analog for detection limits and compared the HI auto power spectrum between each sample and the fiducial power spectrum with no mass cut.
- We found that HI clustering is nearly identical in each mass-limited sample all the way out to 10^9 solar masses. Even there, at large scales, the clustering is very similar. We repeated this analysis up until a redshift of 1, and the conclusion is the same at each redshift.
- This shows that instruments that can measure galaxies with HI masses of 10^9 solar masses will find power spectra that is not substantially different from a perfect instrument.

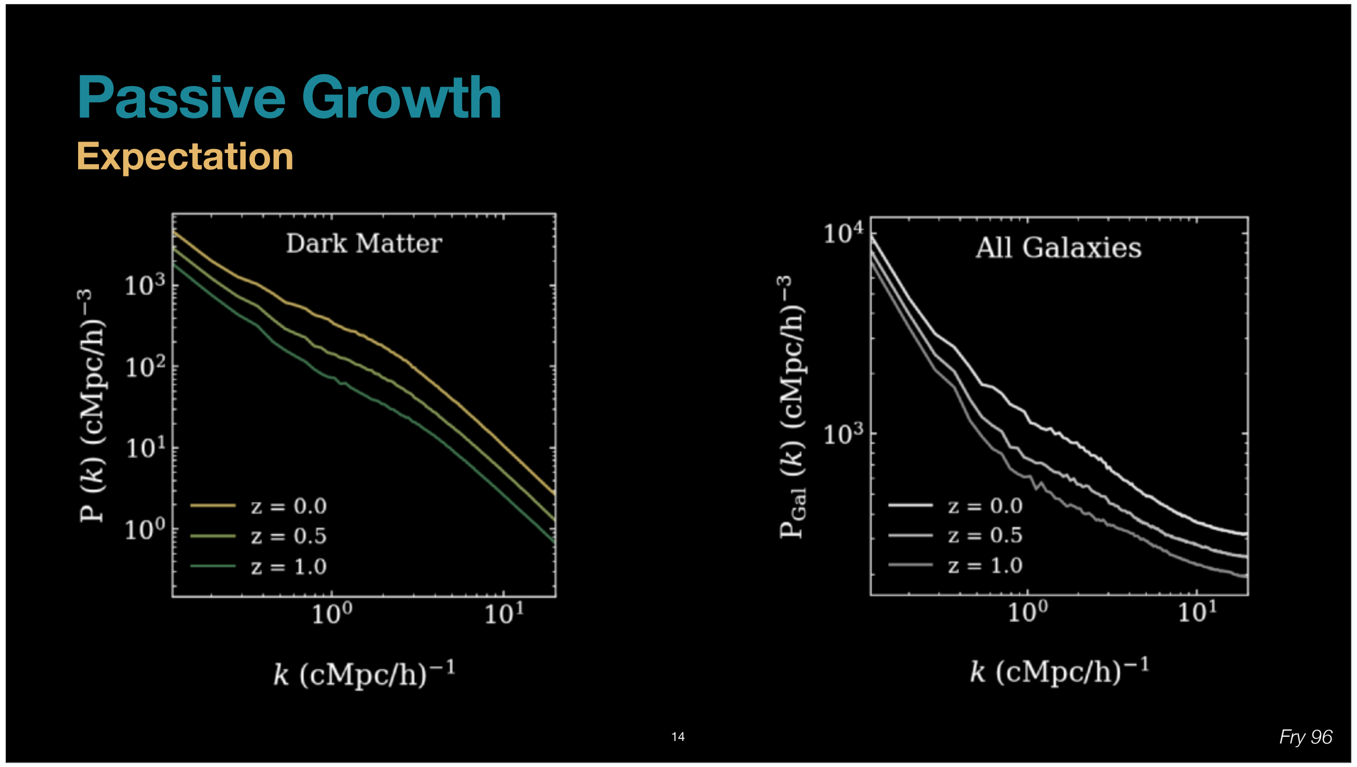


Clustering with Stellar Mass

- We complete a similar analysis with galaxy surveys, using stellar mass limits as a rough analog for optical detection limits.
- These are plots that show the ratio of the cross-power spectrum with a mass-limited galaxy sample over the fiducial cross-power with no mass cut, with lighter colors corresponding to larger mass cuts.
- The idea is that if the ratio is close to unity, then we can conclude that the measured clustering of a survey complete to that stellar mass would be about the same as that of a perfect instrument.
- On the left, we have a plot that tests the sensitivity of HI-blue, finding that a galaxy sample complete up to 10^9 solar masses would not incur significant errors.
- On the right, we have a similar plot for HI-red, although this time the limit is 10^10 solar masses.
- This could be considered a trade-off between using HI-blue and HI-red: HI-blue is easier to model (as seen in previous slides) but requires more completeness in measurements.

Redshift Evolution

- Now that we have established a few relationships, let’s look at how they evolve with redshift.

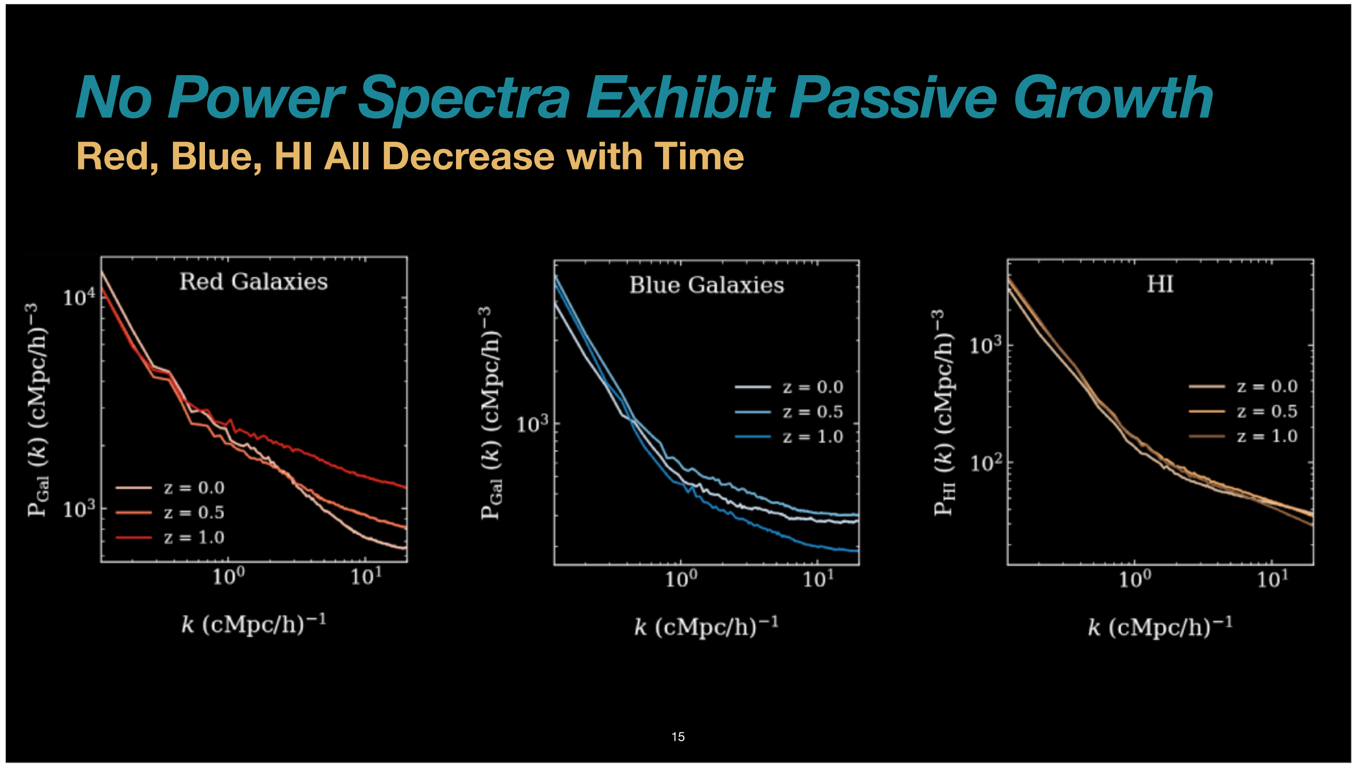


Passive Growth

Expectation

Fry 96

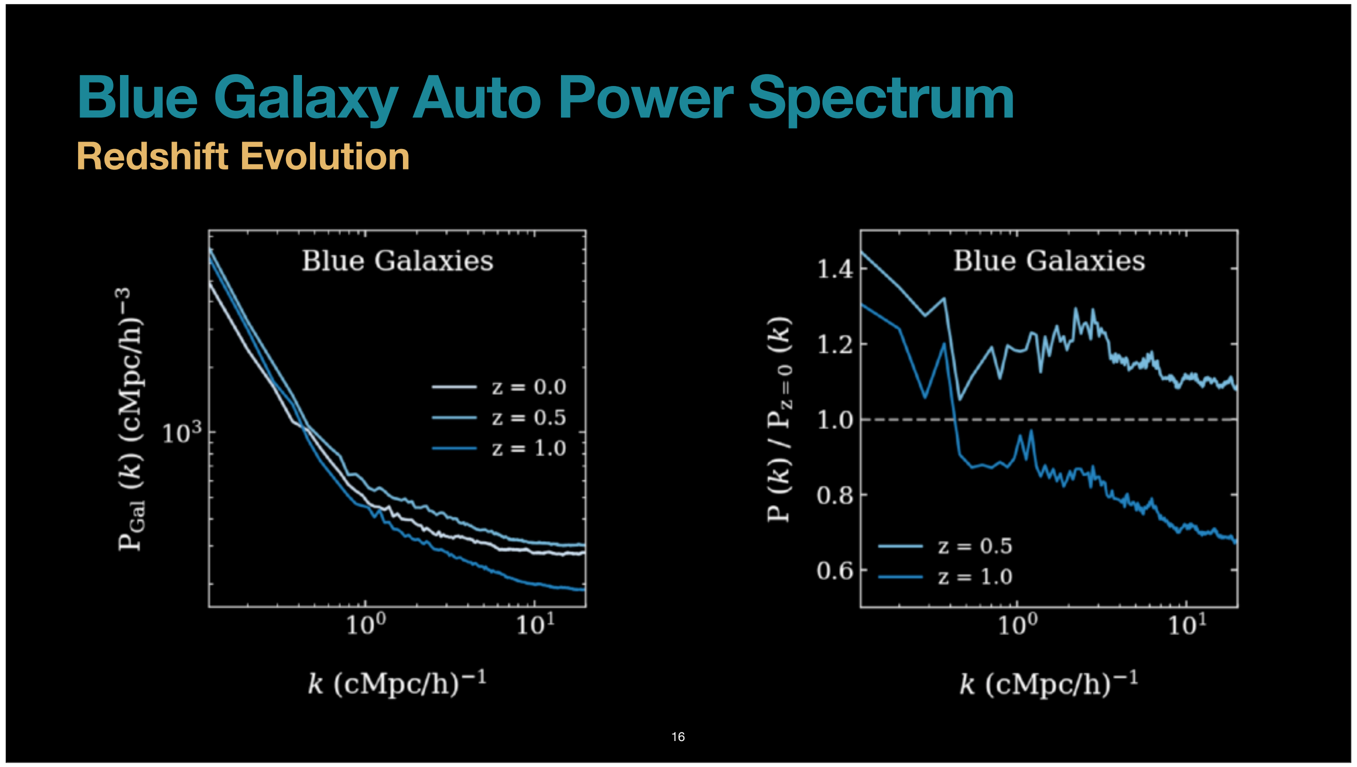
- How would we expect power spectra to evolve with time?
- A population exempt from forces other than gravity, like dark matter, should increase monotonically with time on all scales, since gravity will attract mass together and increase their clustering. It’ll do so at different rates at different scales, but overall we would expect a population to increase with time.
- > This plot includes the power spectrum for dark matter, with brighter colors representing more recent redshifts.
- Clearly, dark matter increases in clustering with time on all scales.
- > Looking at a similar plot for all galaxies in TNG, we find a similar trend. The growth is different from dark matter by itself because galaxies are subject to changes in star-formation rate and mergers, which may change how the clustering increase manifests, but we would probably conclude from this that gravity largely governs the growth of galaxies.



No Power Spectra Exhibit Passive Growth

Red, Blue, HI All Decrease with Time

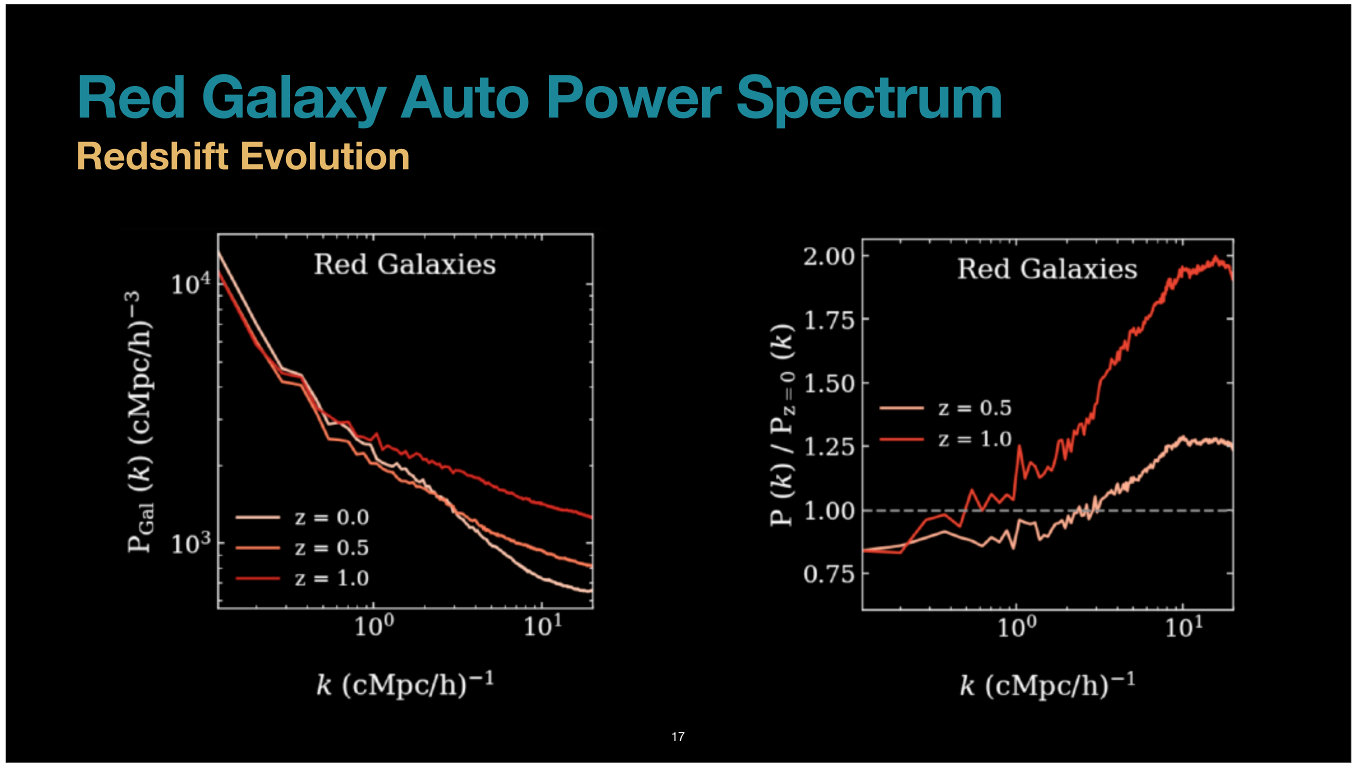
- However, when we look at the evolution of the HI, blue and red galaxy auto and cross-power spectra, NOT a single one exhibits passive growth.
- And this is not just a small-scale effect, this is true even to the largest scales probed by TNG.
- I'll go through each of the auto power spectra shown here one-by-one to explain why this is the case.



Blue Galaxy Auto Power Spectrum

Redshift Evolution

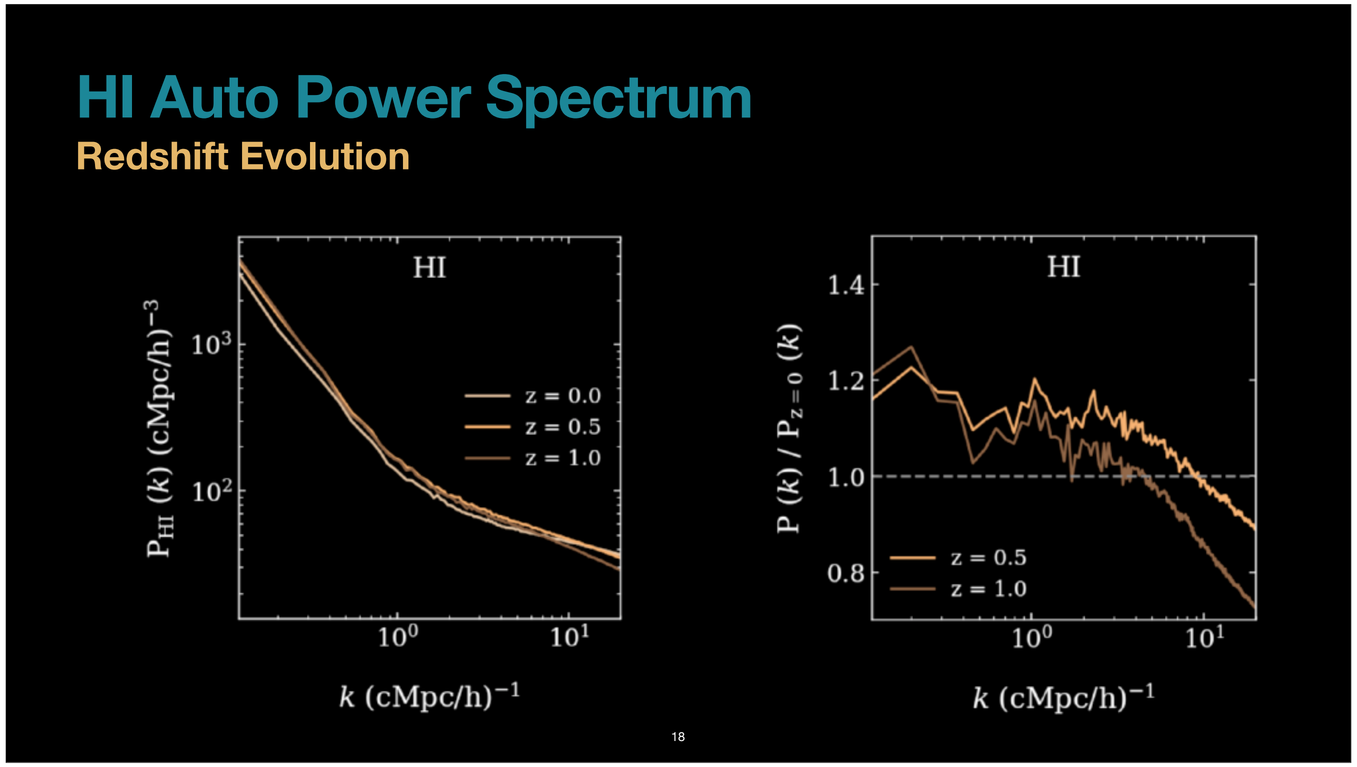
- This is the blue galaxy auto power spectrum, with later redshifts corresponding to lighter colors.
- On the right, I’m showing the ratio of the power spectra at each redshift over the z = 0 power spectrum, in order to better see changes with time.
- If we expect the power spectra to always be increasing, we would therefore expect that the z = 0 power spectrum would be the greatest, so the ratios in that case would be below unity.
- However, the ratios are not below unity, especially at the largest scales.
- This would seem to imply that, even at the largest scales probed by TNG, gravity is not the primary factor governing the clustering growth of blue galaxies.
- The process that accounts for the inverted evolution is color transitions.
- The oldest, most massive and clustered blue galaxies are the closest to becoming red at any given redshift.
- At the next redshift, these galaxies transition and join the red galaxies.
- Upon losing their most clustered component, the average clustering of blue galaxies goes down.
- This is effectively an extension of assembly bias, which explains why this occurs to such large scales.



Red Galaxy Auto Power Spectrum

Redshift Evolution

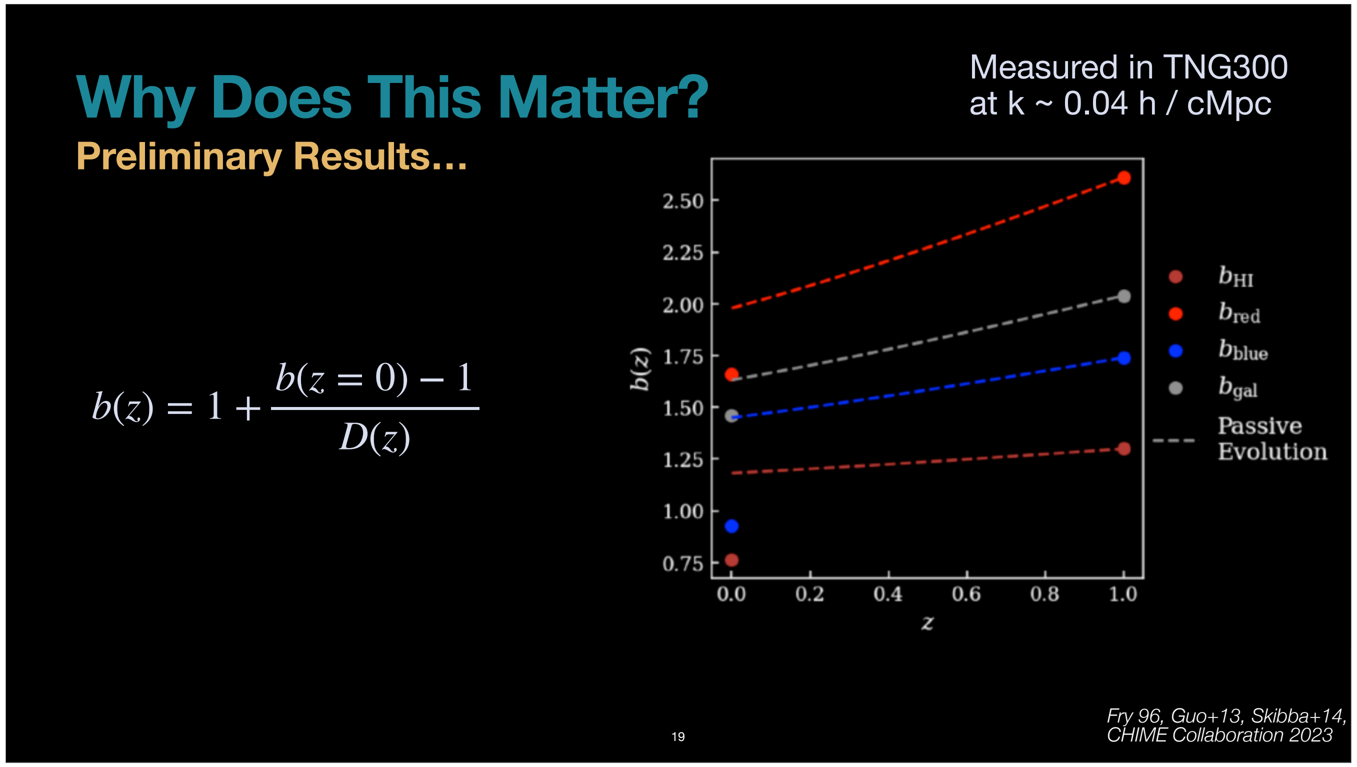
- Here we have similar plots for the red galaxy auto power spectrum. The effect manifests a little differently than in blue galaxies.
- The clustering at small scales drops like a rock, while at large scales the clustering is still growing albeit relatively slowly.
- The transitioning population that just left blue galaxies at the previous redshift, joins red galaxies as their youngest, least massive and clustered component.
- This, in effect, reduces the average clustering of red galaxies.



HI Auto Power Spectrum

Redshift Evolution

The effect in HI is very reminiscent of the evolution of blue galaxies, albeit somewhat muted.
Because of this, I'm only showing the center of the contours so that there's less overlap in the lines.
Ok, so we've established that blue, red, and HI all decrease with time, contrary to what would be expected from passive growth. So what?



Why Does This Matter?

Preliminary Results…

Measured in TNG300
at k ~ 0.04 h / cMpc

$$b(z) = 1 + \frac{b(z=0) - 1}{D(z)}$$

Fry 96, Guo+13, Skibba+14,
CHIME Collaboration 2023

- Well, it has implications for how we model HI and galaxy bias.
- The redshift evolution of constant bias for any population is given by this equation

Why Does This Matter?

Speculation…

Lagrangian Perturbation Theory

$$\mathbf{x} = \mathbf{q_1} + \mathbf{\Psi}(z, \mathbf{q_1})$$

~~Conservation~~ of Mass implies

$$\delta(z, \mathbf{x}) = \int d^3 q_1 \delta_D(\mathbf{x} - \mathbf{q_1} - \mathbf{\Psi}(z, \mathbf{q_1})) - 1$$

Leads to power spectrum model…

$$P(z, k) = \cancel{D^2} P_{\mathrm{lin}}(k) + D^4 P_{1-\mathrm{loop}}(k) + \ldots$$

Gas Loss dominates structure growth, implying that mass is not conserved

HI power spectrum does not increase with growth rate

Zel'dovich 70, Sugiyama 14

Conclusions

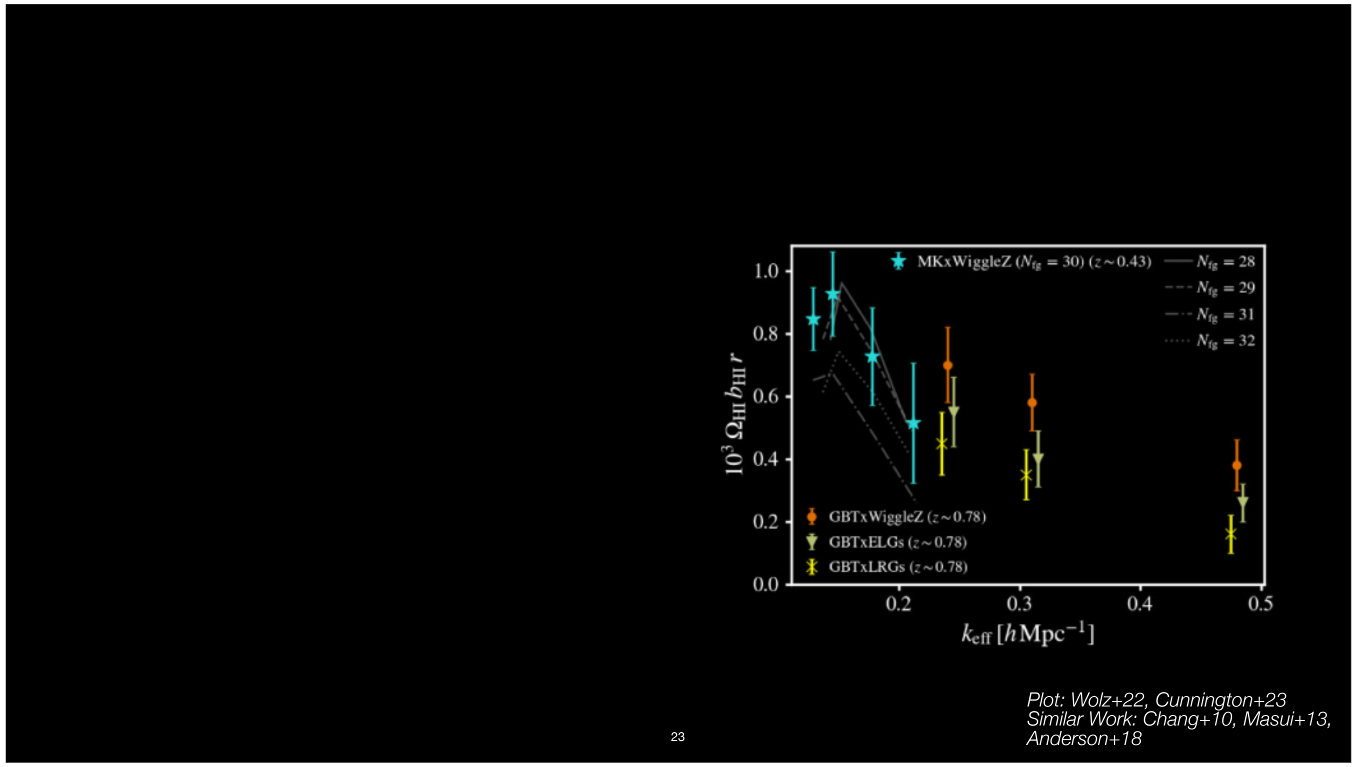
Summary

Osinga+23 (ETA September)

1. Cross-powers agree with observations
2. HI starts to become dependent on local effects at ~ 3 Mpc in real space, ~10 Mpc in redshift space
3. RSDs introduce a secondary color-dependency, and suggest HI-Blue may be easier to model
4. Cross-powers are relatively insensitive to detection limits
5. HI, blue, and red galaxies do not exhibit passive growth at z <= 1

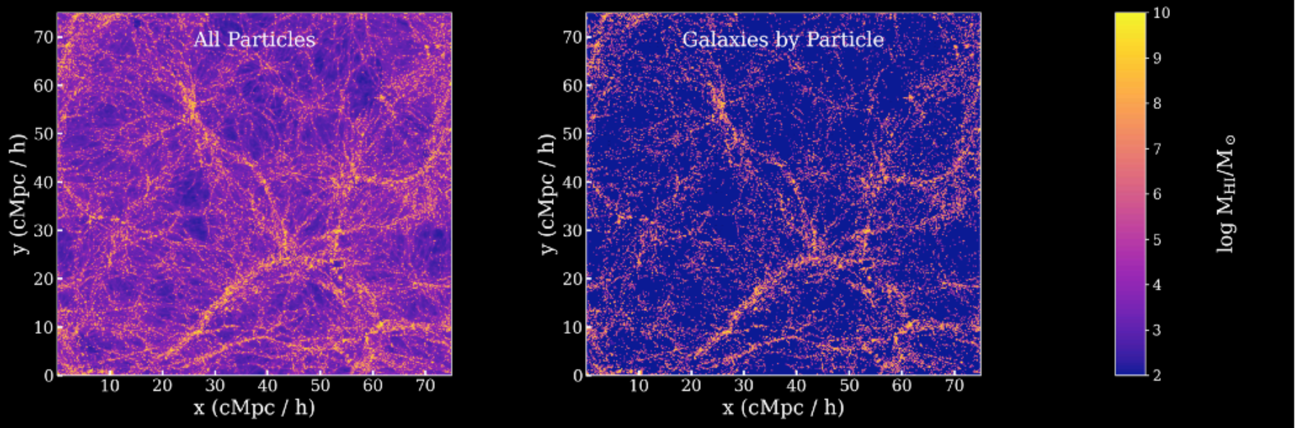
Osinga+24 (ETA January)

1. Despite agreement in cross-powers, derived cosmological constraints disagree significantly.
2. HI and galaxy bias and correlation coefficients are scale-dependent even to “linear” scales
3. LPT may not be a suitable model for HI bias at z <= 1, HOD preferable
4. Can 2D power spectra break degeneracies?

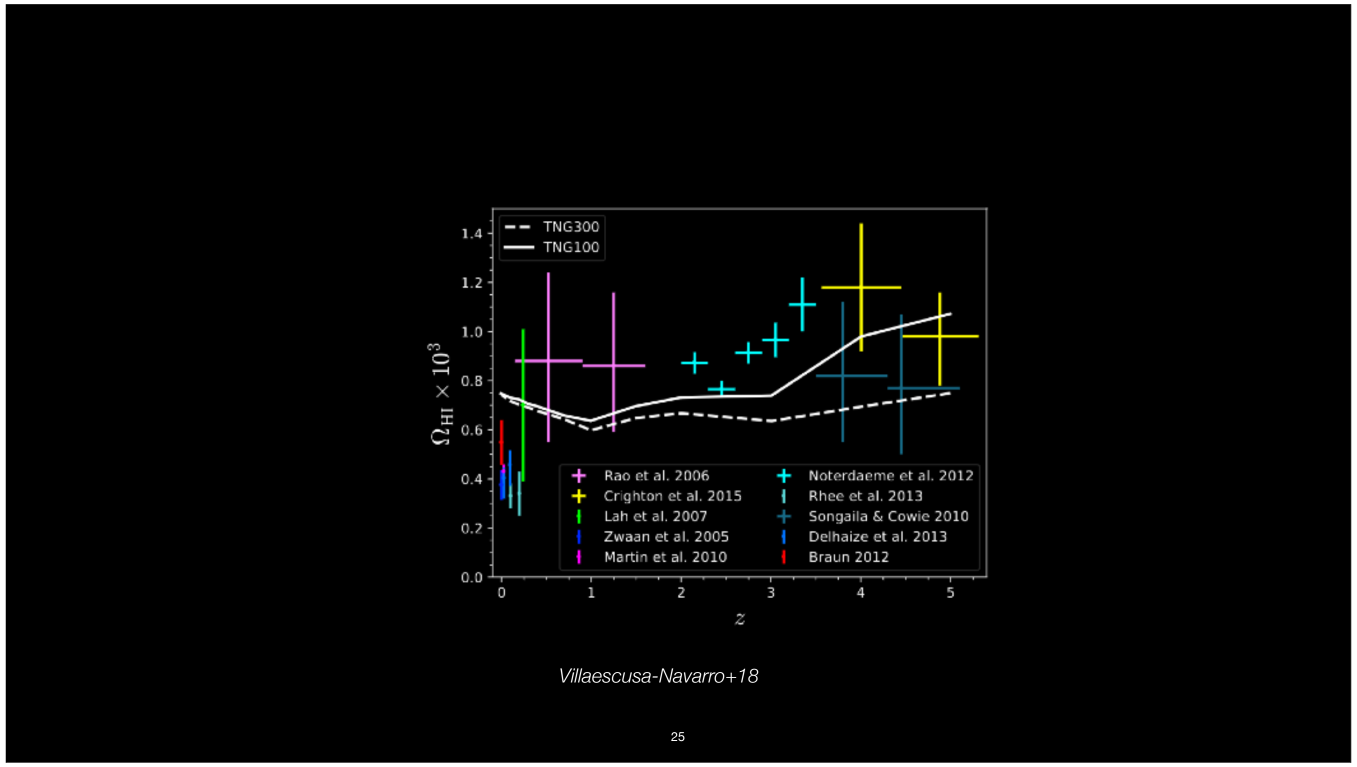


Plot: Wolz+22, Cunnington+23
Similar Work: Chang+10, Masui+13, Anderson+18

- First, we need to address why this study would be interesting in the first place
- Cross-power spectra between galaxies and HI have many uses, but I'll just highlight a few that have been used in the past
- Measurements of HI clustering can constrain cosmological parameters, such as HI bias with respect to matter or the cosmological abundance of HI, Omega HI.
- This was recently done in the HI auto power spectrum in Paul+23 - I'll skip the details on how the constraints are done
- One obstacle for auto power spectra however is noise. Systematics within HI signal are compounded in auto, mitigated in cross
- The plot shown here shows some recent constraints, using cross-correlations between GBT and Meerkat and various galaxy surveys.
- Note that the measurements directly constrain the degenerate parameter obr, but this degeneracy can be broken later in 2D power spectra (citation needed)

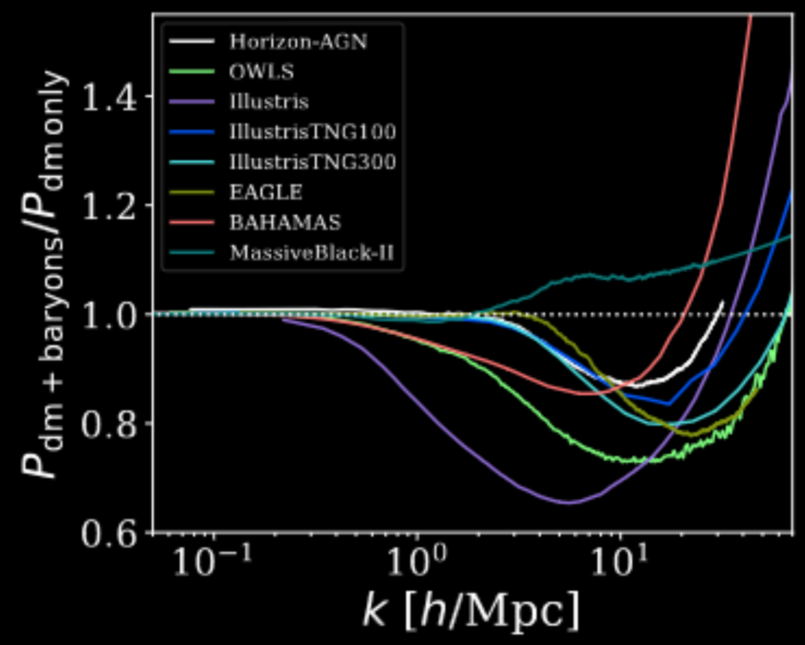


Left: Villaescusa-Navarro+18
Right: Diemer+18

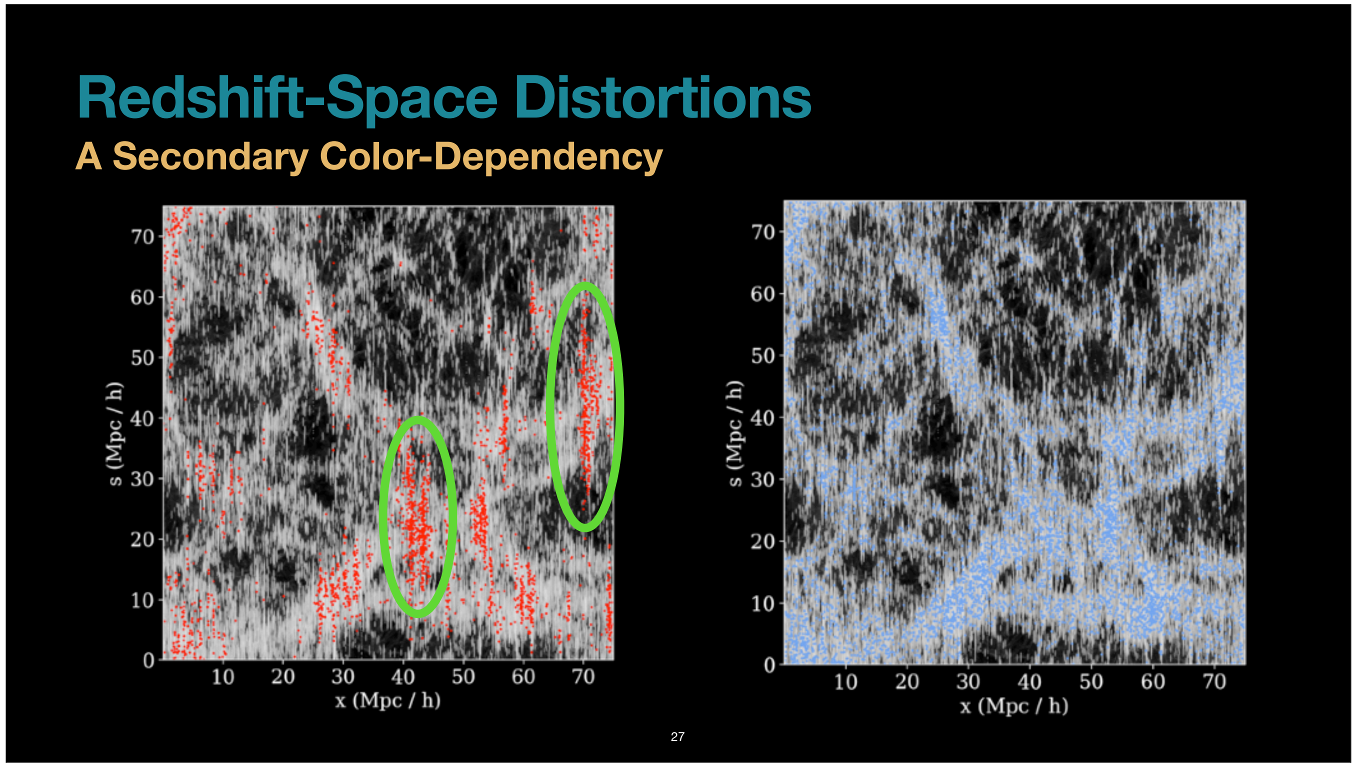


Villaescusa-Navarro+18

- Before we proceed to results, we should discuss some of the issues with TNG, which is worth keeping in mind as we progress through the results
- First, TNG does not possess a strong bimodality beyond z = 2, and is missing many red galaxies. Common issue in cosmological simulations. As such, we limit our analysis to z = 1, 0.5, 0.
- Second, TNG does not track HI explicitly, and instead tracks neutral hydrogen.
- In order to separate neutral hydrogen into molecular and atomic, we to use post-processing methods.
- For the sake of brevity, I won’t go into the details of the post-processing, but we used six different models with a variety of methodologies. We present our results as contours that encompass all of the models, as I’ll show in a bit.
- Thirdly, TNG seems to have an overabundance of HI at z ~ 0.


Horizon-AGN
OWLS
Illustris
IllustrisTNG100
IllustrisTNG300
EAGLE
BAHAMAS
MassiveBlack-II
$P_{\rm dm+baryons}/P_{\rm dm\,only}$
1.4
1.2
1.0
0.8
0.6
10^{-1}
10^{0}
10^{1}
k [h/Mpc]

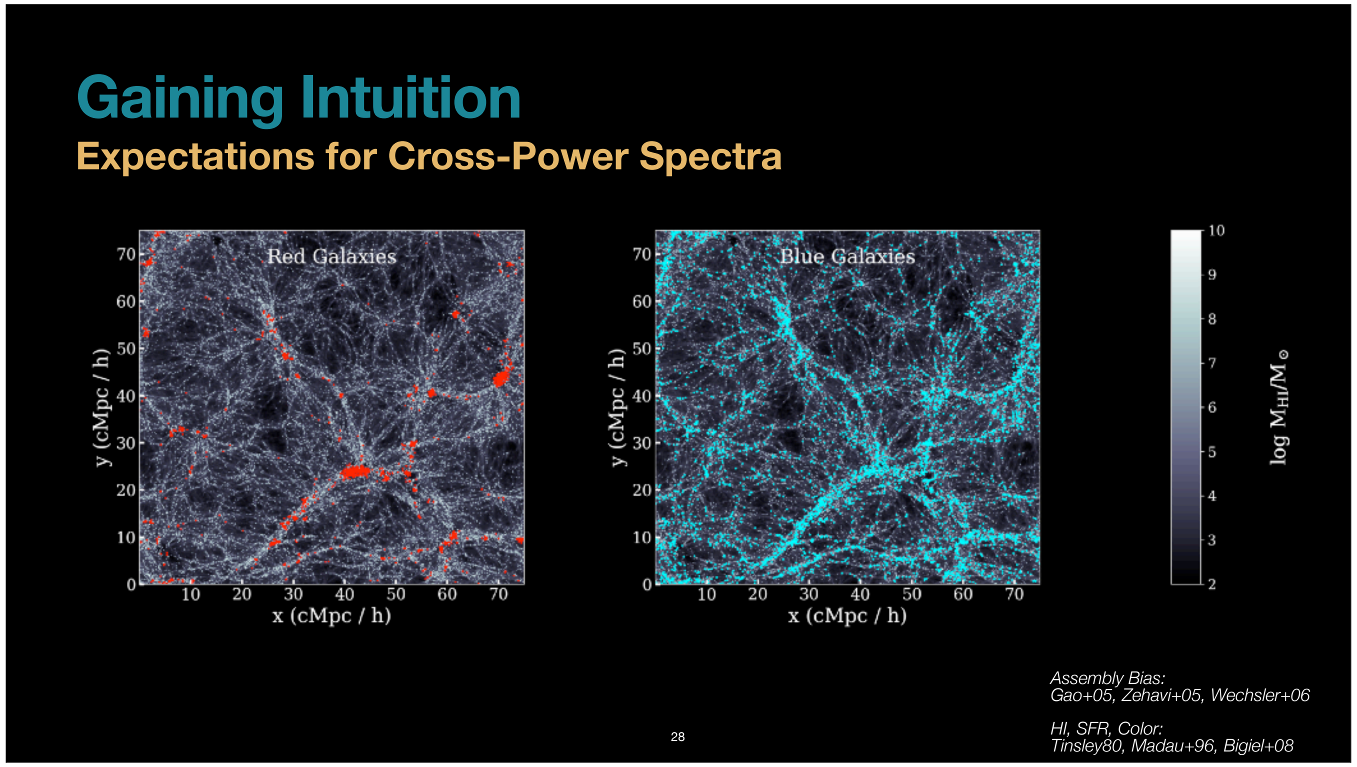
Chisari+19



Redshift-Space Distortions

A Secondary Color-Dependency

- The reason becomes clear when we re-examine the slices of the blue, red and HI distributions in redshift space. These are the same slices as I showed before, except the HI and galaxies are put into redshift space by projecting their velocities along the y-axis, which is our arbitrarily chosen line-of-sight.
- The fingers-of-god effect is very clear in these plots, however when we compare them we can clearly see that red galaxies are smeared over longer distances than blue galaxies.
- Red galaxies tend to occupy massive, HI-poor halos, whose deeper potential wells permit larger velocity dispersions and therefore longer fingers.
- The HI-rich halos that host blue galaxies tend to be less massive, and thus possess smaller fingers.
- The difference in the strength of the fingers-of-God effect serves to further sever the spatial connection between red galaxies and HI in redshift space



Gaining Intuition

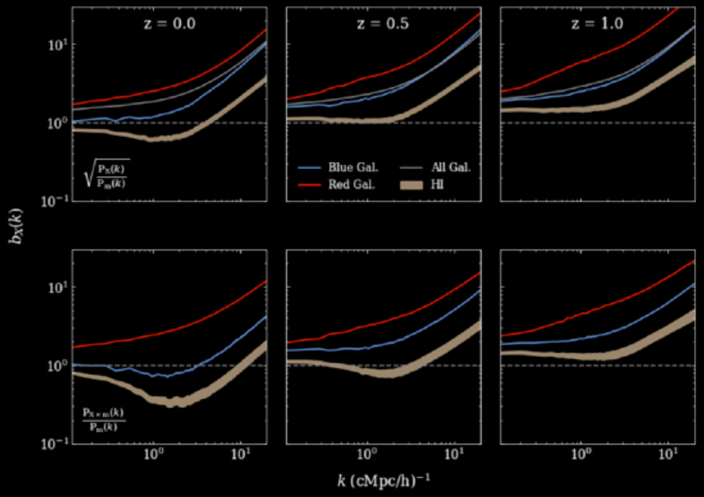
Expectations for Cross-Power Spectra

Assembly Bias:
Gao+05, Zehavi+05, Wechsler+06

HI, SFR, Color:
Tinsley80, Madau+96, Bigiel+08

- Let’s start our discussion by gaining some intuition on what we might expect the cross-power spectra to look like.
- Plotted here are slices of the HI distribution from the TNG simulation, where lighter colors indicate more HI.
- Overlaid on top of the HI distributions are points corresponding to blue and red galaxies.
- Clearly, red galaxies are clumped in the densest regions while blue galaxies are more evenly distributed across the cosmic web
- This also manifests in the power spectrum, where the red galaxy power spectrum is greater than blue on all scales.
- If we naively believe that the HI distribution is independent of color, we would then expect the HI-red cross-power to be greater than HI-blue, just because red galaxies inherently cluster more strongly.

Why Does This Matter?



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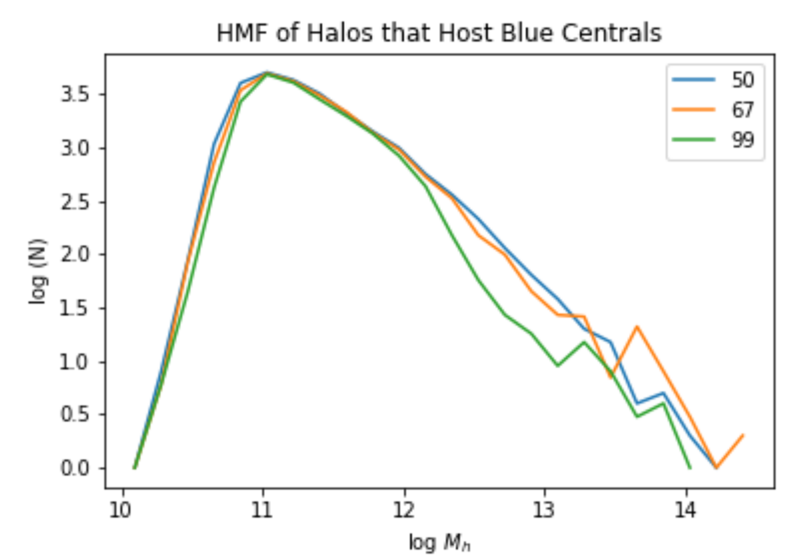
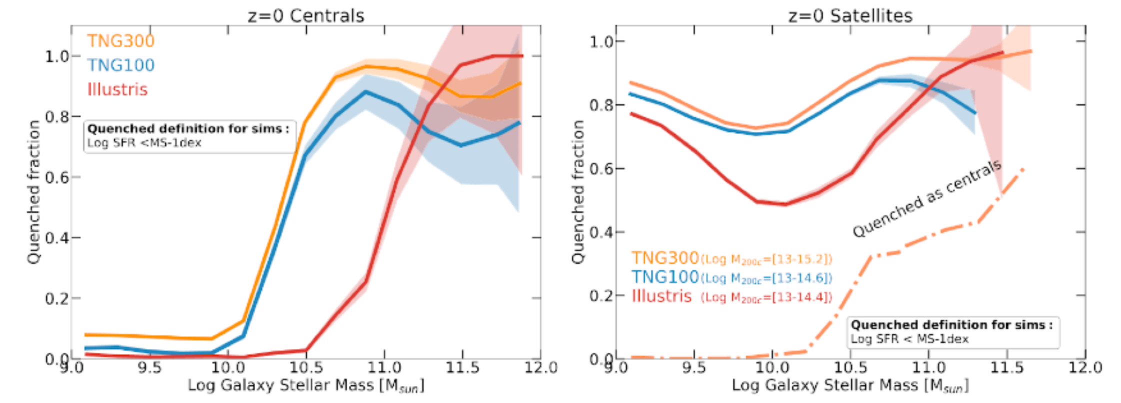

HMF of Halos that Host Blue Centrals
log (N)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
log M_h
10
11
12
13
14
50
67
99

Citations


z=0 Centrals
TNG300
TNG100
Illustris
Quenched definition for sims :
Log SFR <MS-1dex
Quenched fraction
0.0
0.2
0.4
0.6
0.8
1.0
9.0
9.5
10.0
10.5
11.0
11.5
12.0
Log Galaxy Stellar Mass [M_sun]
z=0 Satellites
Quenched as centrals
TNG300 (Log M200c=[13-15.2])
TNG100 (Log M200c=[13-14.6])
Illustris (Log M200c=[13-14.4])
Quenched definition for sims :
Log SFR < MS-1dex
Quenched fraction
Log Galaxy Stellar Mass [M_sun]

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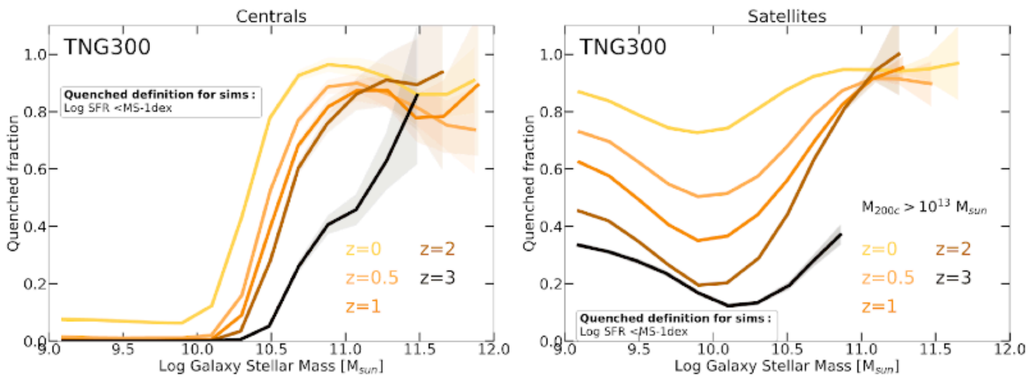

Figure 2. *Trends with redshift*. Quenched fraction versus galaxy stellar mass for TNG300 centrals (right-hand panel) and satellites (left-hand panel) at five different redshifts: $z = 0, 0.5, 1, 2$, and 3. The definition adopted to separate quenched versus star-forming galaxies is log SFR < MS − 1 dex. Shaded areas in both panels indicate the Poissonian error. For both centrals and satellites, the quenched fraction is lower at higher redshift.

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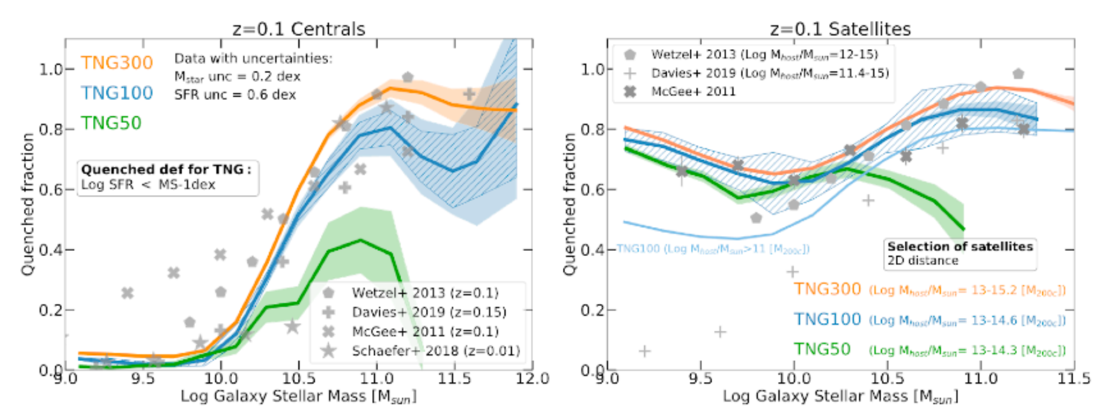
z=0.1 Centrals
TNG300
TNG100
TNG50
Data with uncertainties:
M_{star} unc = 0.2 dex
SFR unc = 0.6 dex
Quenched def for TNG :
Log SFR < MS-1dex
Wetzel+ 2013 (z=0.1)
Davies+ 2019 (z=0.15)
McGee+ 2011 (z=0.1)
Schaefer+ 2018 (z=0.01)
Quenched fraction
Log Galaxy Stellar Mass [M_{sun}]
0.0
0.2
0.4
0.6
0.8
1.0
9.0
9.5
10.0
10.5
11.0
11.5
12.0
z=0.1 Satellites
Wetzel+ 2013 (Log M_{host}/M_{sun}=12-15)
Davies+ 2019 (Log M_{host}/M_{sun}=11.4-15)
McGee+ 2011
TNG100 (Log M_{host}/M_{sun}>11 [M_{200c}])
Selection of satellites
2D distance
TNG300 (Log M_{host}/M_{sun}= 13-15.2 [M_{200c}])
TNG100 (Log M_{host}/M_{sun}= 13-14.6 [M_{200c}])
TNG50 (Log M_{host}/M_{sun}= 13-14.3 [M_{200c}])
Quenched fraction
Log Galaxy Stellar Mass [M_{sun}]
0.0
0.2
0.4
0.6
0.8
1.0
9.0
9.5
10.0
10.5
11.0
11.5

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