# Detection of anisotropic assembly bias in BOSS galaxies

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Cosmology from Home, 2020

arXiv:1906.11823

arXiv:2004.07240

# Outline

- Introduction
- Halo anisotropic assembly bias (AB) in simulations
- Galaxy AB in BOSS sample
- Consequences & Summary

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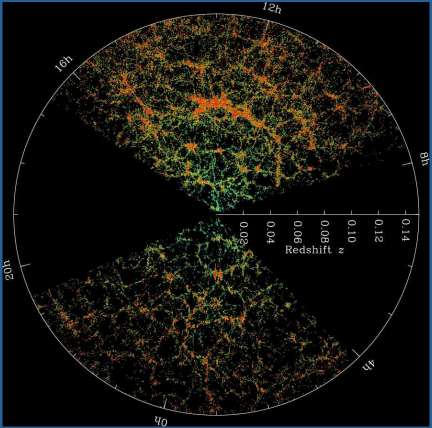
- Inhomogenities dominant source of information, mainly through 2-point statistics of fluctuations
- CMB measurements still dominate the constraints on cosmological parameters
- But Large-scale Structure is 3D – expected to ultimately have more constraining power
- Upcoming galaxy redshift surveys (DESI, Euclid) will reach unprecedented precision

# Large-scale structure

- Overdensity field:
  $\delta_m(\mathbf{x}) = \rho_m(\mathbf{x})/\bar{\rho}_m - 1$
- Power spectrum:
  $P_m(\mathbf{k_1}, \mathbf{k_2}) \propto \langle \delta_m(\mathbf{k_1}) \delta_m(\mathbf{k_2}) \rangle$




SDSS

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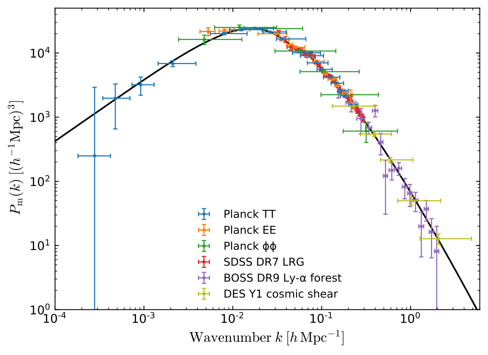


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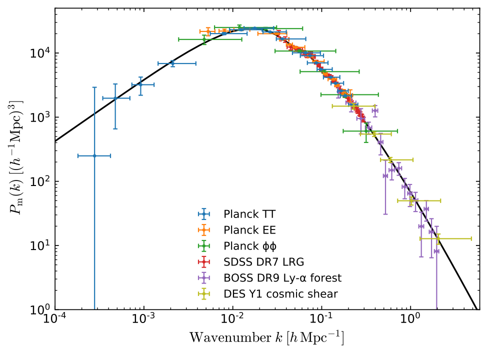
- However we neither observe dark matter nor real-space positions $\mathbf{x}$

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# Linear bias and redshift-space distortions

Galaxies, halos, voids, 21cm, Ly$\alpha$ forest ... all biased tracers of matter in real space, observed in redshift-space

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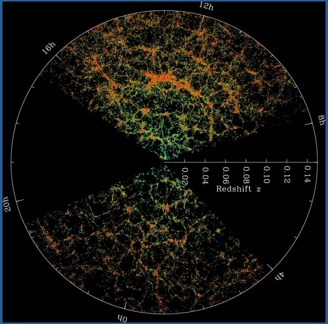


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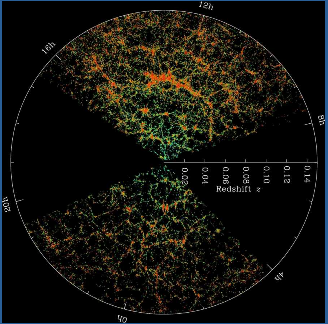


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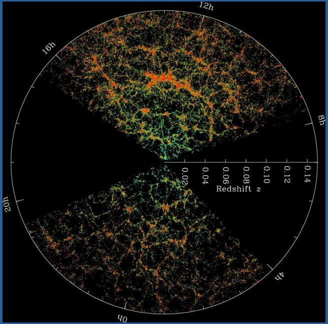


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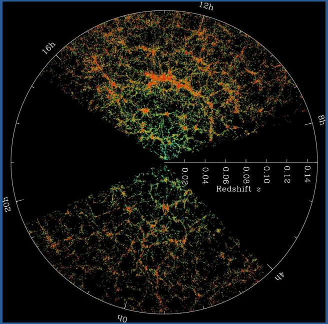


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- Equivalence principle $\implies$ no velocity bias

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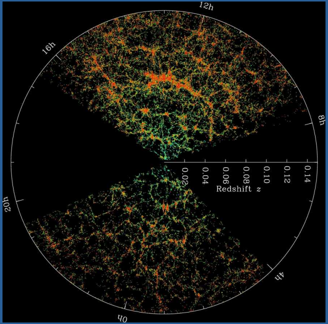


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# Galaxy power spectrum in redshift-space

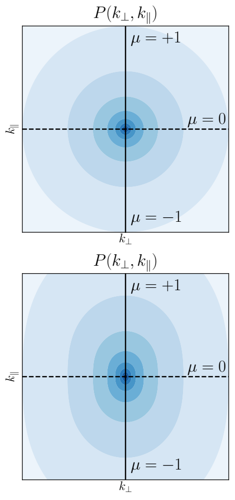
- Linear theory: $P_g^s(k, \mu) = (b_g + f\mu^2)^2 P_m(k)$
- Use Legendre expansion into multipoles:

$$P_\ell(k) = \frac{2\ell + 1}{2} \int_{-1}^{1} P_g^s(k, \mu) \mathcal{L}_\ell(\mu) \, d\mu$$

$$P_0(k) = \left( b_g^2 + \frac{2}{3} f \, b_g + \frac{1}{5} f^{\,2} \right) P_m(k)$$

$$P_2(k) = \left( \frac{4}{3} b_g \, f + \frac{4}{7} f^{\,2} \right) P_m(k)$$

- Measuring $P_0$ & $P_2$ gives $b_g$ & $f$
- Note quadrupole $P_2 \propto f$
- In real-space $P_2 = 0$



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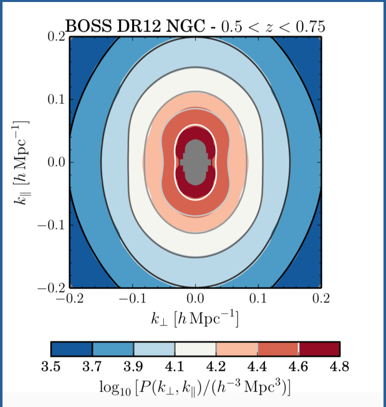
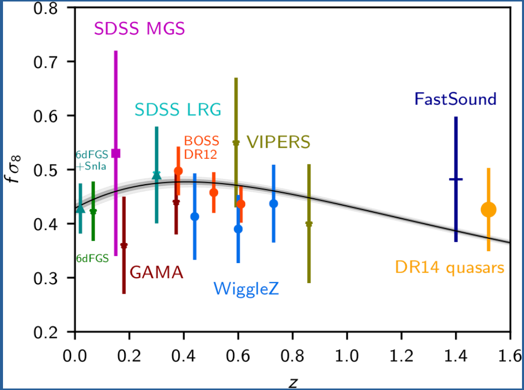



Alam+2016

# Growth rate $f$

One of the key parameters

- $f \equiv \frac{d \ln D(a)}{d \ln a}$
- GR prediction: $f = \Omega_{\rm m}(z)^{0.55}$
- Important for:
  - Testing Gravity
  - Constraining neutrino masses
  - Testing dark energy models
  - ...
- Currently $\sim 5 - 10\%$
- Future surveys (DESI, Euclid) expected to reach $\sim 1 - 5\%$ precision

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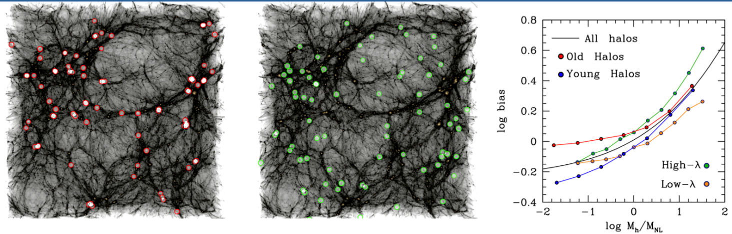
# Assembly bias

Bias depends on other *scalar* properties, for fixed halo mass and redshift

- Assembly history
- Age
- Spin
- Concentration
- Shape ...

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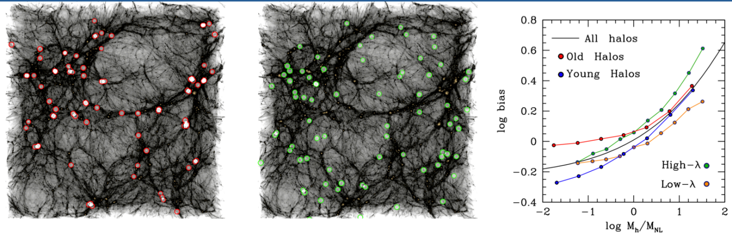


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Detected in simulations, no convincing evidence in data

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$$s_{ij}(\mathbf{x}) = (\nabla_i\nabla_j\nabla^{-2} - \delta_{ij}/3)\,\delta_m(\mathbf{x}) \iff s_{ij}(\mathbf{k}) = (k_ik_j/k^2 - \delta_{ij}/3)\,\delta_m(\mathbf{k})$$

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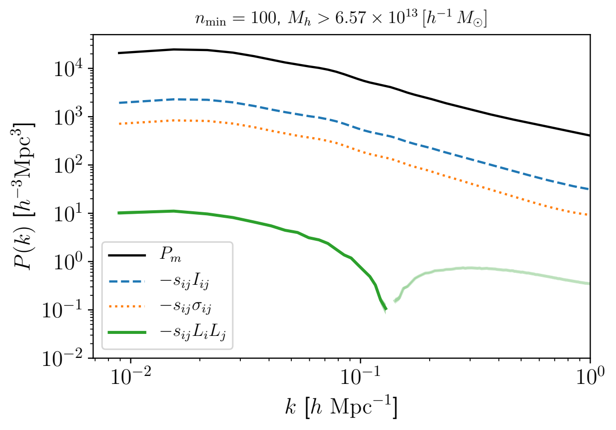
  - projected sizes, velocity dispersion & angular momentum

# How correlated are halos & tidal field?

We use 1000 Quijote N-body sims (Villaescusa-Navarro+, 2019) to measure cross-correlations

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- Azimuthal symmetry & $b_q \equiv b_{zz}$

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- First pointed out by Hirata (2009)

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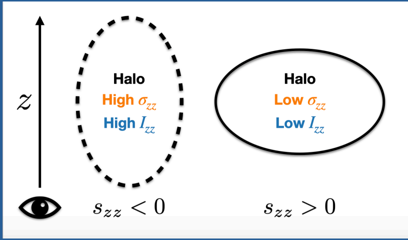
- Note $b_q$ is perfectly degenerate with $f$ !
- $b_q = 0$ if:
  - Selection independent of halo orientation,
    e.g. projected size, velocity dispersion, angular momentum
  - *or* if observed tracer and host halo randomly misaligned

# Halo selection based on tensor properties

Selection on radial halo extent & velocity dispersion $\sigma_{\rm 1D}$ in **real space**



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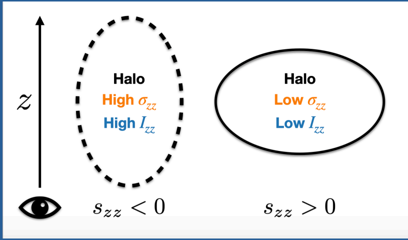


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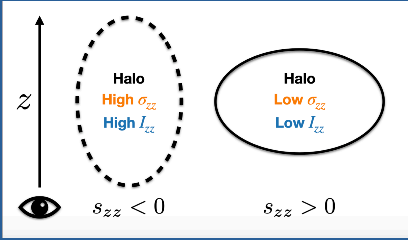


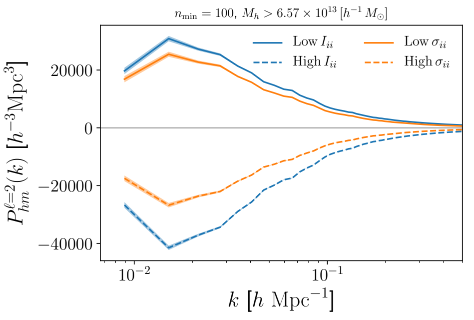


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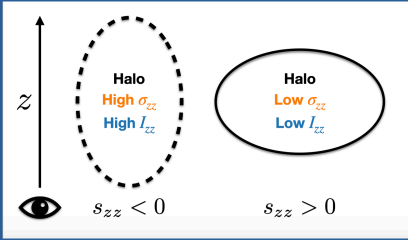


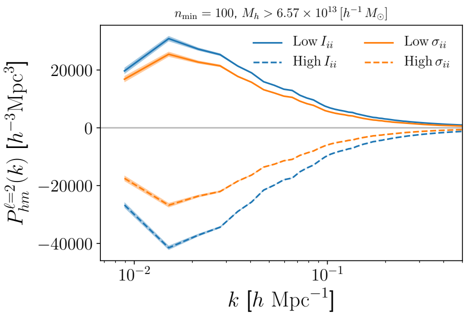


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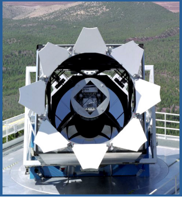
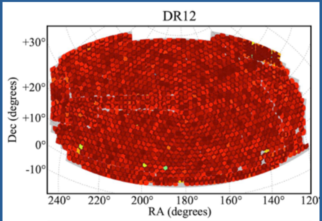
- Halos: $\Delta b_q \approx 1 - 2$
- Redshift-space $f \approx 0.7$

# What about real galaxies?

When split on orientation dependent quantities, do galaxies show different clustering strength?

- Baryon Oscillation Spectroscopic Survey **BOSS** DR12 galaxy sample
- $\sim 10^6$ galaxy redshifts
- $0.15 < z < 0.7$
- Luminous red galaxies, $b_g \sim 2$
- Ellipticals, $M_h \sim 10^{13} M_\odot/h$
- Galaxy samples
  - LOWZ $(0.15 < z < 0.43)$
  - CMASS $(0.43 < z < 0.7)$



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- Our null hypothesis is $\Delta b_q = 0$

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- Mismatch $P_2$ $\rightarrow$ evidence $\Delta b_q \neq 0$

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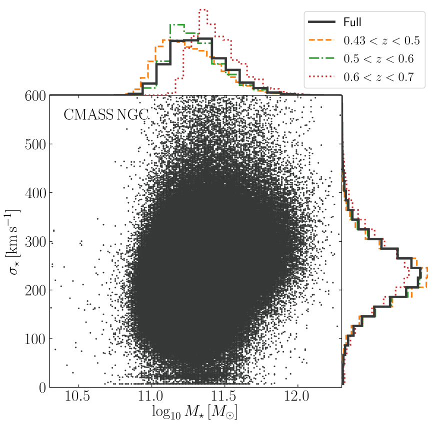

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Main idea – split on orientation $(\sigma_\star) \to$ look for differences in anisotropy $(\Delta b_q)$

- Subsamples matching $n(z)$ have matching $f$
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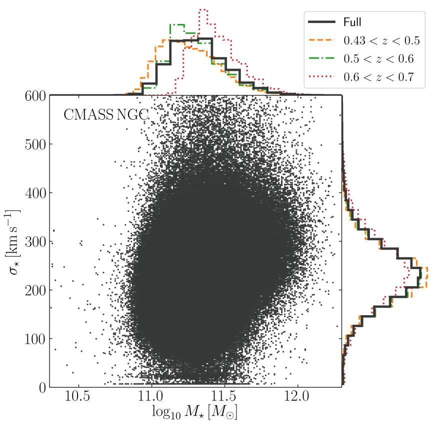

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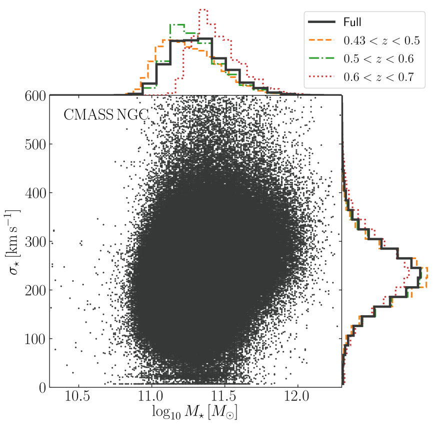

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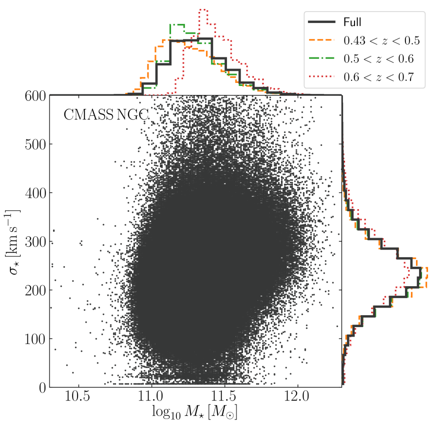

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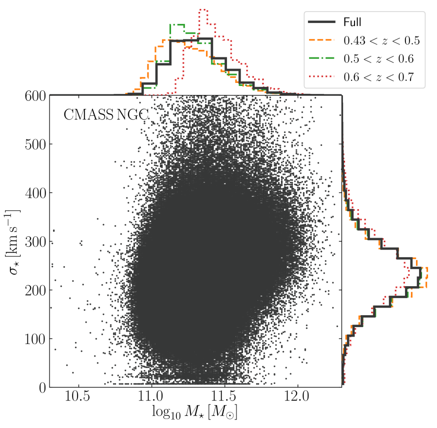

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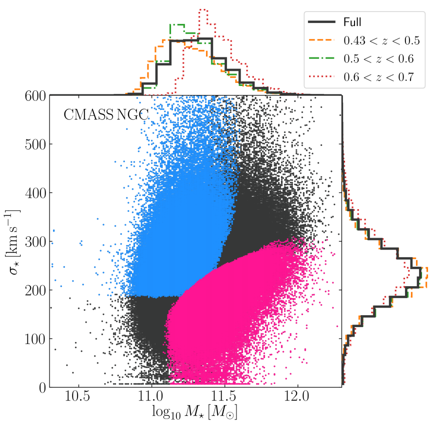
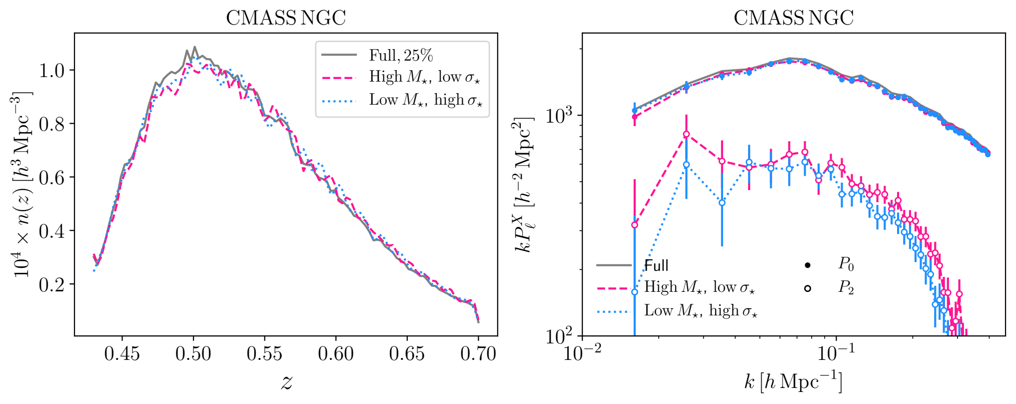


# Results – CMASS NGC




AO+2020

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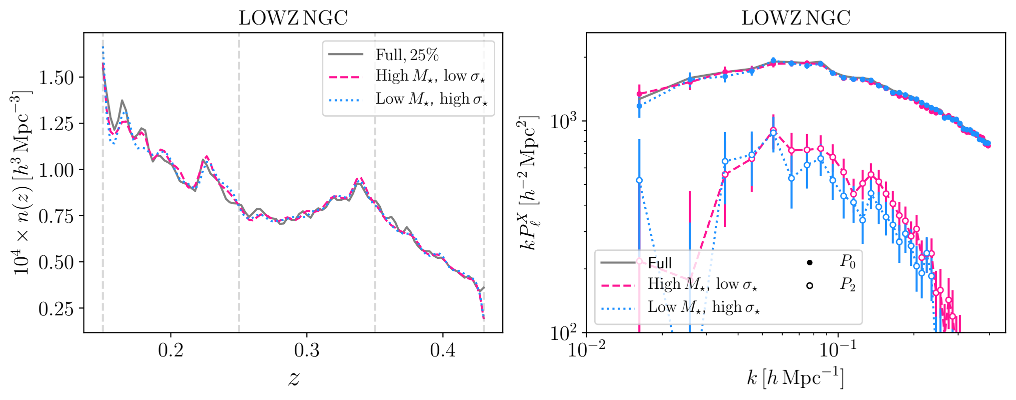


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# Detection significance

- Use mock galaxy catalogs
- Split each mock in two random subsamples
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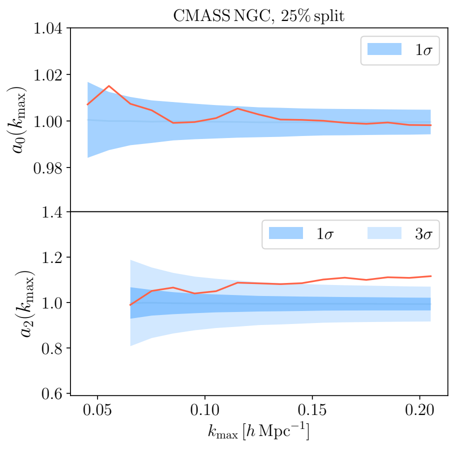

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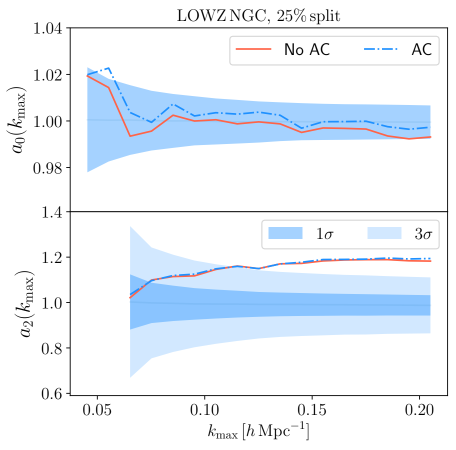
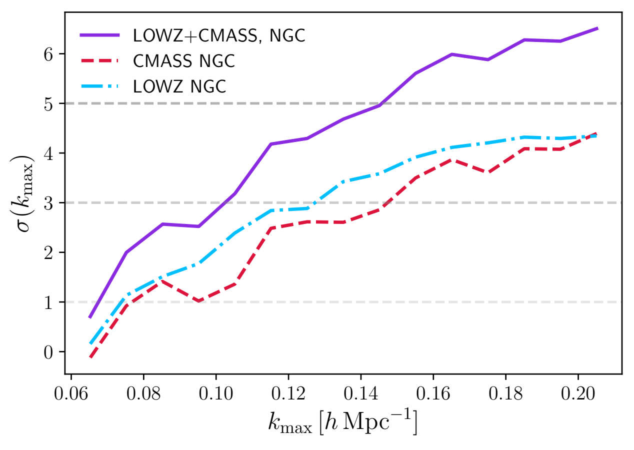


# Combined detection significance

$5\sigma$ using $k_{\rm max} \sim 0.15\, h\,{\rm Mpc}^{-1}$

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