Constraining Cosmology & Galaxy Formation with Large Scale Structure Data

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Cosmology in a Nutshell

COSMOLOGICAL PRINCIPLE: Universe is homogeneous & isotropic

- **Robertson-Walker Metric:**

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\left[\frac{\mathrm{d}r^2}{1-Kr^2} + r^2(\mathrm{d}\vartheta^2 + \sin^2\vartheta\,\mathrm{d}\varphi^2)\right]$$

- **Friedmann Equation:**

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_K a^{-2} + \Omega_\Lambda\right]$$

HOT BIG BANG: Particle Physics $\longrightarrow \Omega_m, \Omega_r, \Omega_\Lambda$ (in principle...)

INFLATION:
- $\Omega_K \simeq 0$; Universe is (approximately) flat
- Quantum fluctuations $\longrightarrow$ adiabatic perturbations

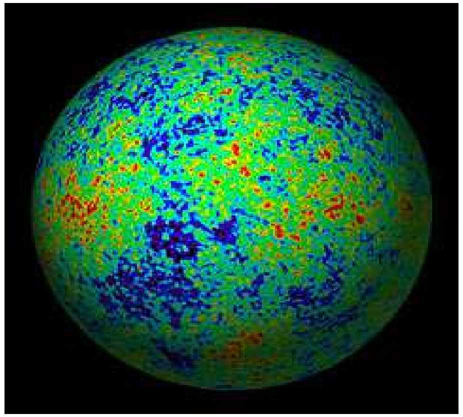
GRAVITATIONAL INSTABILITY: $\longrightarrow$ growth of fluctuations

Linear Growth ($\delta \ll 1$) $\longrightarrow$ Non-Linear Collapse $\longrightarrow$ CDM Halos

Baryons are shock-heated to virial temperature: Cooling $\longrightarrow$ Galaxies

Cosmological Parameters

The Cosmic Microwave Background and Supernova Ia have given us precise measurements of most cosmological parameters



$\Omega_m = 0.27$
$\Omega_\Lambda = 0.73$
$\Omega_b = 0.04$
$H_0 = 72$ km/s/Mpc
$n_s = 0.95$
$\sigma_8 = 0.77$

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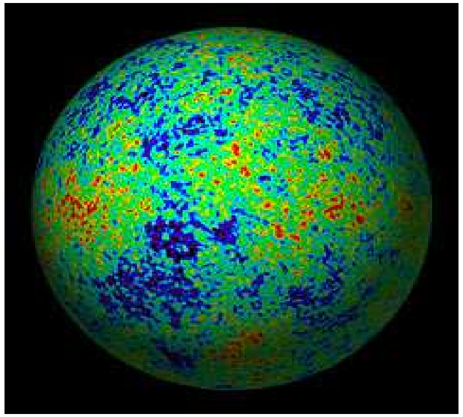

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Open Questions:

- **What is the nature of dark matter; i.e., CDM *vs.* WDM?**
- **What is the nature of dark energy i.e., what is $w = P/\rho$?**
- **What is the mass of neutrinos; i.e., what is Ω_ν?**
- **What are the properties of the inflaton; i.e., what is $V(\phi)$?**

All these fundamental questions can be addressed by probing the matter perturbation field as function of redshift.

How do we parameterize the matter field?

Define the density perturbation field: $$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

To statistically specify $\delta(\vec{x})$ we use the two-point correlation function

$$\xi(r) = \langle \delta(\vec{x}) \delta(\vec{x} + \vec{r}) \rangle$$

Since most matter is dark, we can't measure $\xi(r)$ directly

Instead, we use galaxies as a tracer population, and measure

$$\xi_{\rm gg}(r) = \langle \delta_{\rm g}(\vec{x}) \delta_{\rm g}(\vec{x} + \vec{r}) \rangle \quad \textbf{with} \quad \delta_{\rm g}(x) = \frac{n_{\rm gal}(x) - \bar{n}_{\rm gal}}{\bar{n}_{\rm gal}}$$

Danger: galaxies account for only $\sim 3\%$ of all matter...

The Issue of Galaxy Bias

There is no good reason why galaxies should trace mass.

$\Rightarrow$ **Define galaxy bias as** $b_{\rm g} = \langle \delta_{\rm g}/\delta \rangle$

This allows us to relate observable $\xi_{\rm gg}(r)$ **to quantity of interest** $\xi(r)$**.**

$$\xi_{\rm gg}(r) = b_g^2\, \xi(r)$$

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Bias is an imprint of galaxy formation, which is poorly understood.

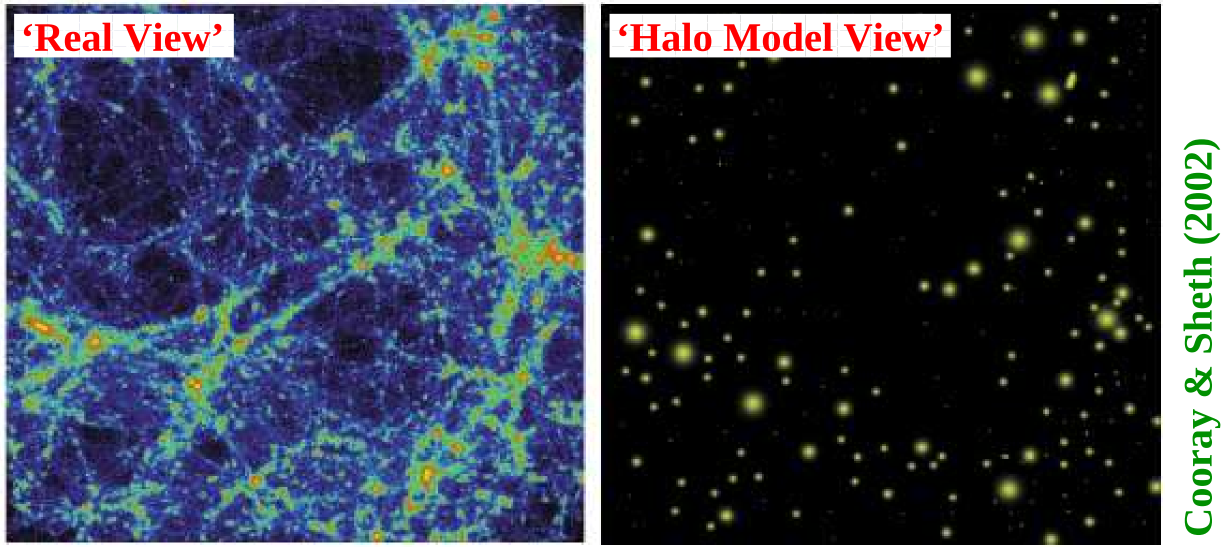
Since $\xi_{\rm gg}(r)$ depends on galaxy properties, galaxy bias $b_{\rm g}$ also depends on galaxy properties.

Consequently, little progress has been made constraining cosmology with Large-Scale Structure, despite several large redshift surveys.

How to constrain and quantify galaxy bias in a convenient way?

How to Handle Bias?

Halo Model: Describe CDM distribution in terms of halo building blocks, assuming that every CDM particle resides in virialized halo



Halo Bias: Dark Matter haloes are biased tracer of mass distribution.
More massive haloes are more strongly biased.

Halo Occupation Statistics: A statistical description of how galaxies are distributed over dark matter halos

Galaxy Bias = Halo Bias + Halo Occupation Statistics

The Conditional Luminosity Function

To specify Halo Occupation Statistics we introduce Conditional Luminosity Function, $\Phi(L|M)$, which is the direct link between halo mass function $n(M)$ and the galaxy luminosity function $\Phi(L)$:

$$\Phi(L) = \int_0^\infty \Phi(L|M)\, n(M)\, \mathrm{d}M$$

The CLF contains a lot of important information, such as:

- **The average relation between light and mass:**

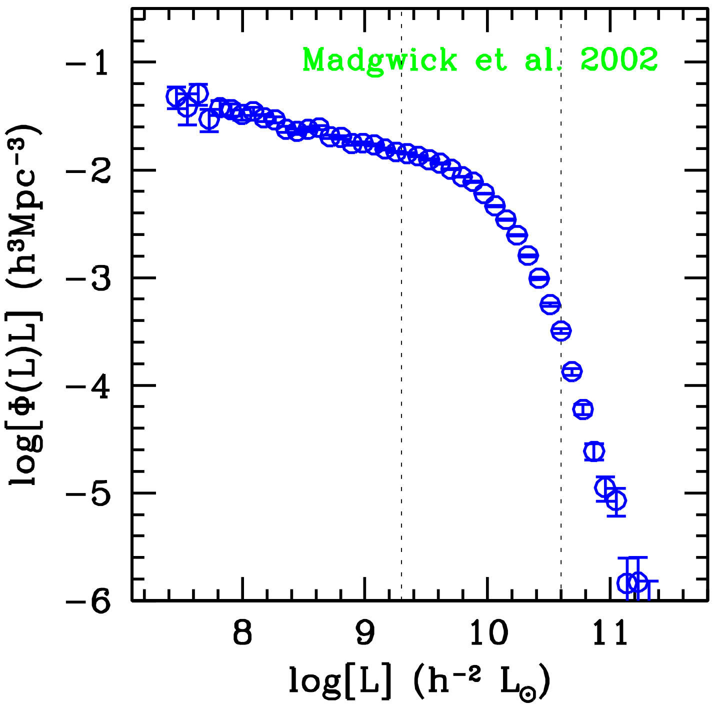
$$\langle L \rangle (M) = \int_0^\infty \Phi(L|M)\, L\, \mathrm{d}L$$

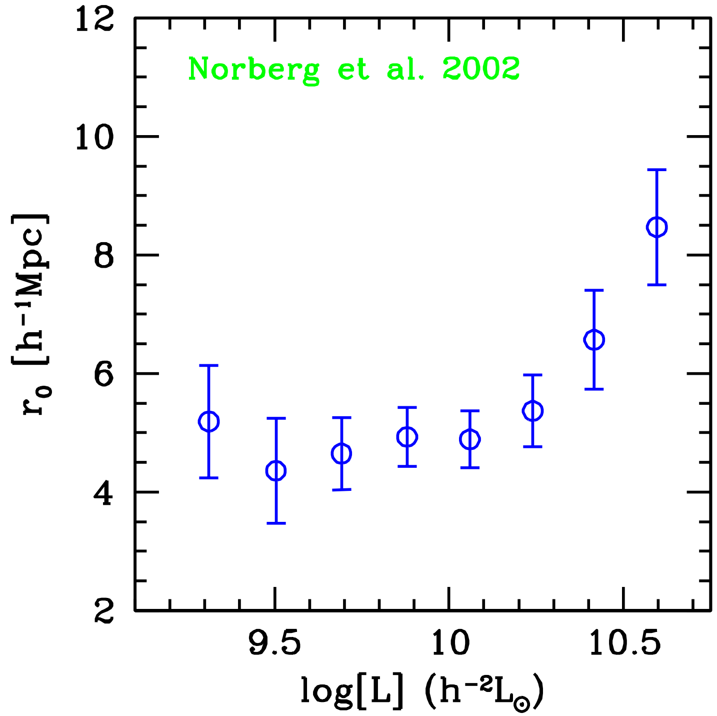
- **The bias of galaxies as function of luminosity:**

$$b_g(L) = \frac{1}{\Phi(L)} \int_0^\infty \Phi(L|M)\, b_h(M)\, n(M)\, \mathrm{d}M$$

CLF is ideal statistical tool to specify Galaxy-Dark Matter Connection

Luminosity & Correlation Functions



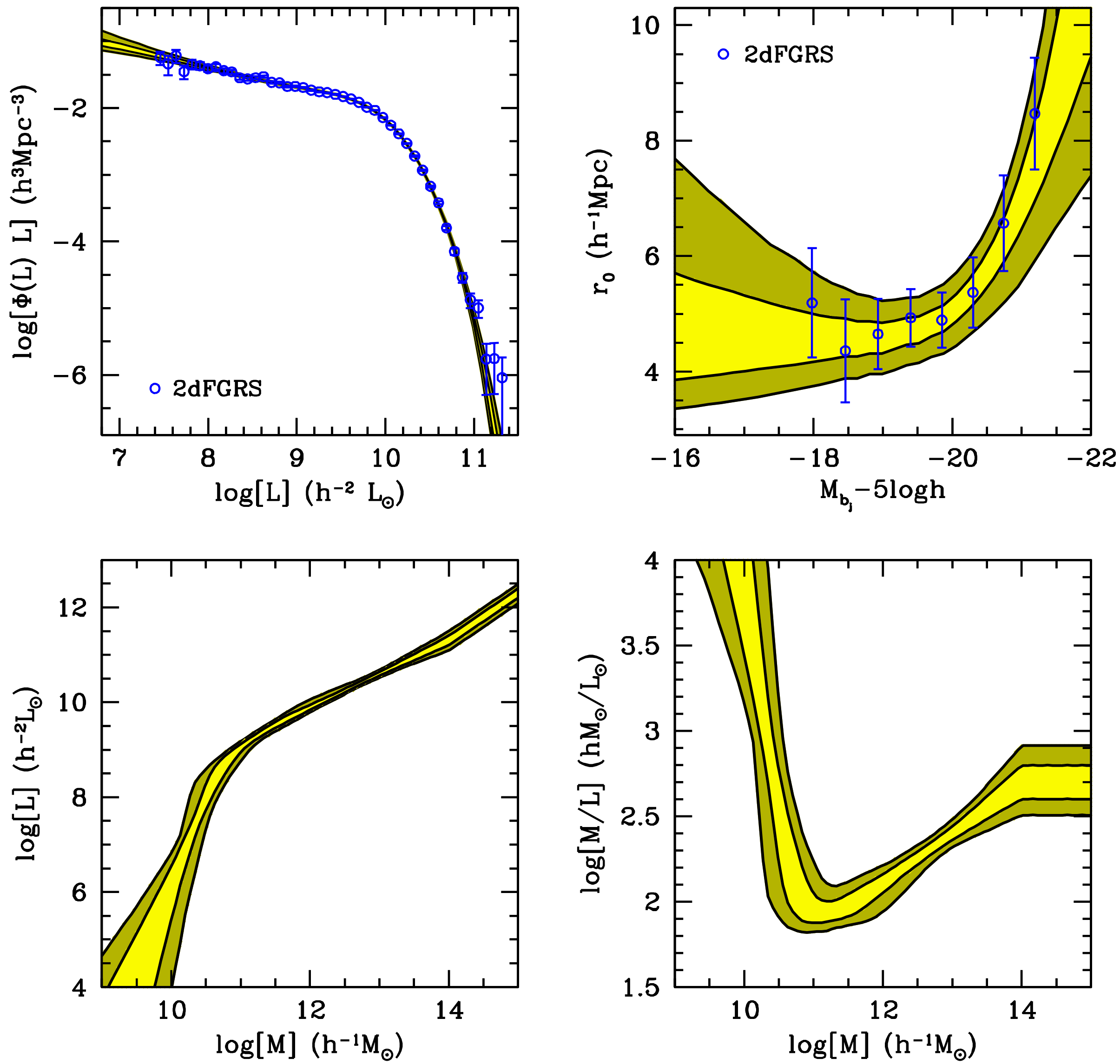


- **2dFGRS:** More luminous galaxies are more strongly clustered.
- **ΛCDM:** More massive haloes are more strongly clustered.

More luminous galaxies reside in more massive haloes

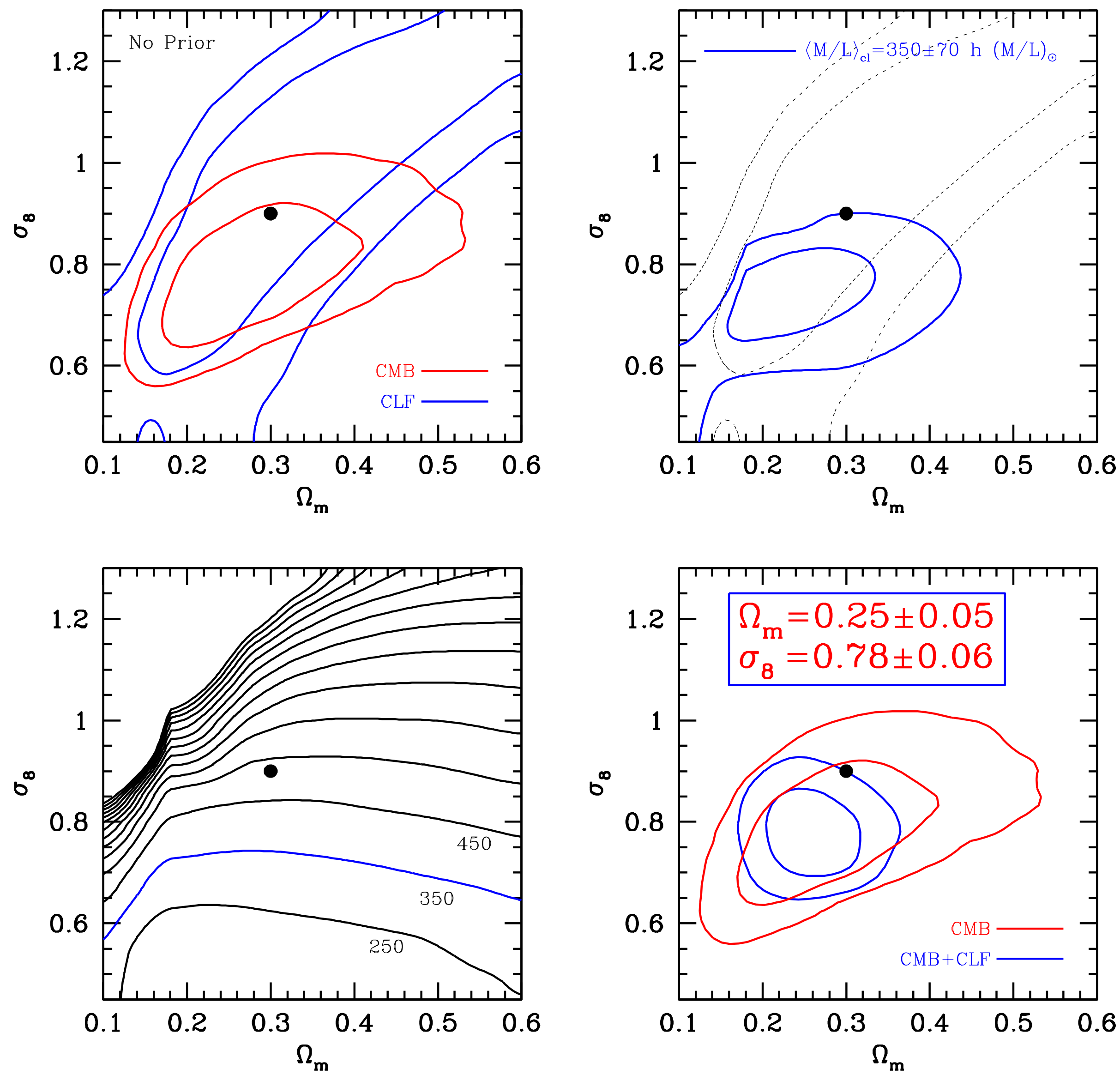
REMINDER: Correlation length r_0 defined by $\xi(r_0) = 1$

The Galaxy-Dark Matter Connection



vdB, Yang, Mo & Norberg, 2005, MNRAS, 356, 1233

Cosmological Constraints



vdB, Mo & Yang, 2003, MNRAS, 345, 923

Conclusions

Measurements of the cosmological matter field as function of red-shift can constrain fundamental physics

Large redshift surveys probe distribution of galaxies, which are a biased tracer of mass distribution

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We have developed a powerful statistical tool to quantify and con-strain galaxy bias, which is essential for relating galaxies to the underlying matter field

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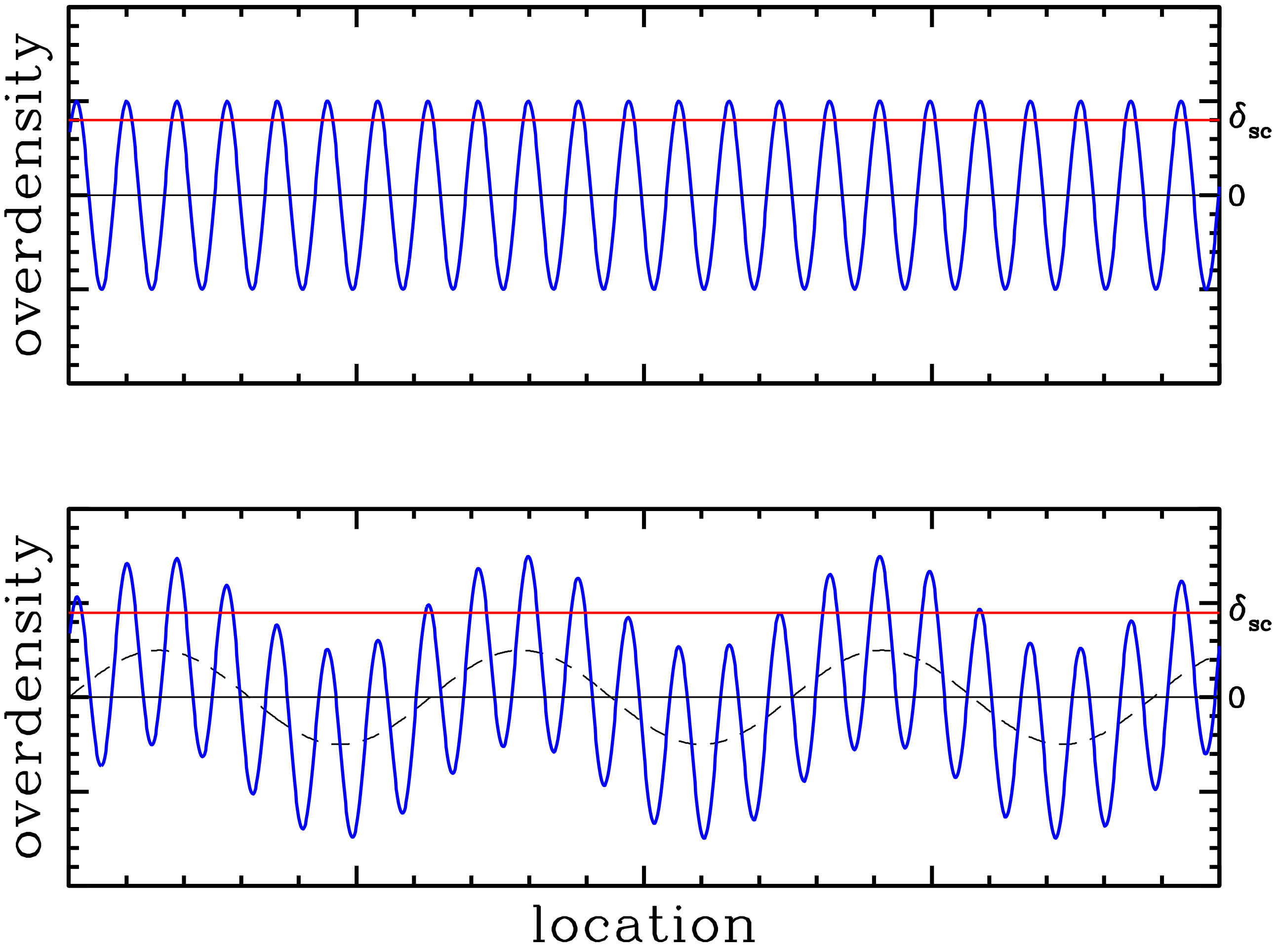
Large redshift surveys probe distribution of **galaxies**, which are a **biased tracer** of mass distribution

We have developed a powerful **statistical tool** to quantify and constrain **galaxy bias**, which is essential for relating galaxies to the underlying matter field

The **galaxy-dark matter connection** thus quantified yields stringent constraints on **galaxy formation** and on **cosmological parameters**

Future galaxy surveys promise a bright future...

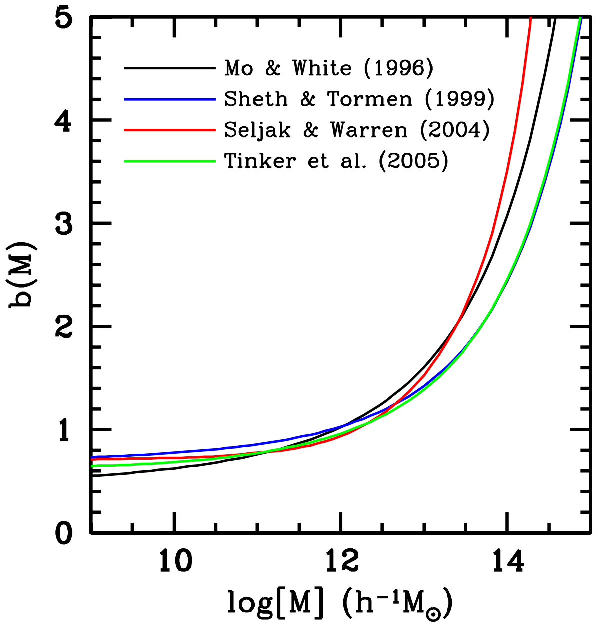
The Origin of Halo Bias



Modulation causes statistical bias of peaks (haloes)

Modulation growth causes dynamical enhancement of bias

Analytical Description of Halo Bias



Define **halo bias** as $b(m) = \langle \delta_h(m)/\delta \rangle$

Then the halo-halo correlation function for haloes of mass m can be written as

$$\xi_{\rm hh}(r) \equiv \langle \delta_{h_1} \delta_{h_2} \rangle = b^2(m)\xi(r)$$

More massive dark matter haloes are more strongly clustered

Clustering strength of galaxies is a measure of the mass of the haloes in which they reside

Halo Occupation Statistics completely specifies Halo Bias

Halo Occupation Statistics also constrain **Galaxy Formation**

The Relation between Light & Mass