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:
  \[ ds^2 = dt^2 - a^2(t) \left[ \frac{dr^2}{1-Kr^2} + r^2(\,d\vartheta^2 + \sin^2 \vartheta \,d\varphi^2) \right] \]

- Friedmann Equation:
  \[ \left( \frac{\dot{a}}{a} \right)^2 = H_0^2 \left[ \Omega_\text{r}a^{-4} + \Omega_\text{m}a^{-3} + \Omega_\text{K}a^{-2} + \Omega_\Lambda \right] \]

HOT BIG BANG: Particle Physics \( \rightarrow \Omega_\text{m}, \Omega_\text{r}, \Omega_\Lambda \) (in principle...)

INFLATION: \( \Omega_\text{K} \simeq 0 \); Universe is (approximately) flat
  - Quantum fluctuations \( \rightarrow \) adiabatic perturbations

GRAVITATIONAL INSTABILITY: \( \rightarrow \) growth of fluctuations
  - Linear Growth (\( \delta \ll 1 \)) \( \rightarrow \) Non-Linear Collapse \( \rightarrow \) CDM Halos
  - Baryons are shock-heated to virial temperature: Cooling \( \rightarrow \) Galaxies
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
- $n_s = 0.95$
- $\sigma_8 = 0.77$
Cosmological Parameters

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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 \( \Omega_\nu \)?
- 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

\[ \xi_{gg}(r) = \langle \delta_g(\vec{x}) \delta_g(\vec{x} + \vec{r}) \rangle \quad \text{with} \quad \delta_g(x) = \frac{n_{gal}(x) - \bar{n}_{gal}}{\bar{n}_{gal}} \]

Danger: galaxies account for only \( \sim 3\% \) of all matter...
There is no good reason why galaxies should trace mass.

\[ b_g = \left\langle \frac{\delta_g}{\delta} \right\rangle \]

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

\[ \xi_{gg}(r) = b_g^2 \xi(r) \]
The Issue of Galaxy Bias

There is no good reason why galaxies should trace mass.

⇒ Define galaxy bias as

\[ b_g = \langle \delta_g / \delta \rangle \]

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

\[ \xi_{gg}(r) = b_g^2 \xi(r) \]

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

Since \( \xi_{gg}(r) \) depends on galaxy properties, galaxy bias \( b_g \) 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 $\Phi(L)$:

$$\Phi(L) = \int_0^\infty \Phi(L|M) n(M) \, dM$$

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

- The average relation between light and mass:
  $$\langle L \rangle(M) = \int_0^\infty \Phi(L|M) L \, dL$$

- The bias of galaxies as function of luminosity:
  $$b_g(L) = \frac{1}{\Phi(L)} \int_0^\infty \Phi(L|M) b_h(M) n(M) \, dM$$

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

- Introduction
- Galaxy Bias
- Conditional Luminosity Function
- Results
  - The Galaxy-Dark Matter Connection
  - Cosmological Constraints
- Conclusions
- Extra

Cosmological Constraints

Conclusions

Measurements of the **cosmological matter field** as function of redshift 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 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**
Conclusions

Measurements of the cosmological matter field as function of redshift can constrain fundamental physics

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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

\[ \xi_{hh}(r) \equiv \langle \delta_{h1} \delta_{h2} \rangle = b^2(m) \xi(r) \]

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 Origin of Halo Bias
Analytical Description of Halo Bias
The Relation between Light & Mass