Probing Dark Matter Halos with Satellite Kinematics & Weak Lensing

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Galaxy Formation in a Nutshell

- Perturbations grow due to gravitational instability and collapse to produce (virialized) dark matter halos
- Baryons cool, accumulate at center, and form stars $\Rightarrow$ galaxy
- Dark matter halos merge, causing hierarchical growth
- Halo mergers create satellite galaxies that orbit halo
**Twin Perspectives**

**Theory**

Given the mass of a DM halo, what is the luminosity of the central galaxy?

\[ \langle L \rangle (M) \]

First moment of \( P(L|M) \)

**Observations**

Given the luminosity of a central galaxy, what is the mass of its DM halo?

\[ \langle M \rangle (L) \]

First moment of \( P(M|L) \)
Twin Perspectives

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First moment of \( P(M|L) \)

\[
P(L|M) \, n(M) = P(M|L) \, \Phi(L)
\]

\[
n(M) = \text{Halo mass function}
\]

\[
\Phi(L) = \text{Galaxy Luminosity Function}
\]
Twin Perspectives

- **Theory**
  - Given the mass of a DM halo, what is the luminosity of the central galaxy?
  - First moment of $P(L|M)$
  - $\langle L \rangle (M)$

- **Observations**
  - Given the luminosity of a central galaxy, what is the mass of its DM halo?
  - First moment of $P(M|L)$
  - $\langle M \rangle (L)$

**Probabilistic Connection**

$$P(L|M) \cdot n(M) = P(M|L) \cdot \Phi(L)$$

- $n(M) = \text{Halo mass function}$
- $\Phi(L) = \text{Galaxy Luminosity Function}$

**Ab Initio Modeling**

- semi-analytical models
- numerical simulations

**Observational Data**

- rotation curves & X-ray data
- satellite kinematics
- gravitational lensing
- clustering

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Introduction
- Galaxy Formation in a Nutshell
- Twin Perspectives

Clustering
- Conditional Luminosity Function
- Satellite Kinematics
- Galaxy-Galaxy Lensing

Conclusions

Extra Material
Occupation Statistics from Clustering

- Galaxies occupy dark matter halos.
- CDM: more massive halos are more strongly clustered.
- Clustering strength of given population of galaxies indicates the characteristic halo mass

Clustering strength measured by correlation length $r_0$
Occupation Statistics from Clustering

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Clustering strength measured by correlation length $r_0$

![Graph showing correlation length $r_0$ vs. logarithm of halo mass $M$](image)

**WMAP1**
- $\Omega_m = 0.30$
- $\Omega_\Lambda = 0.70$
- $\sigma_8 = 0.90$

**WMAP3**
- $\Omega_m = 0.24$
- $\Omega_\Lambda = 0.76$
- $\sigma_8 = 0.74$
Halo Mass Functions and Occupation Numbers

Using the halo mass inferred from clustering strength the corresponding number density from the halo mass function, and the observed number density of the galaxies, one obtains the **average occupation numbers**.
The Conditional Luminosity Function

In order to parameterize the Halo Occupation Statistics we introduce the Conditional Luminosity Function (CLF), \( \Phi(L|M) \), which is the direct link between the 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 wealth of information, such as:

- The average relation between light and mass:

\[
\langle L \rangle(M) = \int_0^\infty \Phi(L|M) L \, dL
\]

- The occupation numbers of galaxies:

\[
\langle N \rangle(M) = \int_{L_{\text{min}}}^{\infty} \Phi(L|M) \, dL
\]

We constrain the CLF using the luminosity function, \( \Phi(L) \), and the correlation lengths as function of luminosity, \( r_0(L) \), from SDSS.
DATA: 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 $\xi(r_0) = 1$
Mass-to-Light ratios tightly constrained, but with strong dependence on cosmology

(Cacciato, vdB et al. 2008)
Select **centrals** and their **satellites** from a redshift survey

Using redshifts, determine \( \Delta V = V_{\text{sat}} - V_{\text{cen}} \) as function of \( L_c \)
Satellite Kinematics: Methodology

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Using redshifts, determine $\Delta V = V_{\text{sat}} - V_{\text{cen}}$ as function of $L_c$

**Brighter centrals reside in more massive haloes.**

(More, vdB et al. 2008)
Satellite Kinematics: Mass Estimates

Using \textit{virial equilibrium} and \textit{spherical collapse model}:

\[ \sigma^2 \propto \frac{GM}{R} \quad M \propto R^3 \quad \sigma \propto M^{1/3} \]
Satellite Kinematics: Mass Estimates

Using *virial equilibrium* and *spherical collapse model*:

\[
\sigma^2 \propto \frac{GM}{R}, \quad M \propto R^3, \quad \sigma \propto M^{1/3}
\]

On average only \( \sim 2 \) satellites per central \( \rightarrow \) *stacking*

Unless \( P(M|L_c) \) is a Dirac delta function, stacking means combining halos of different masses

Consequently, one has to distinguish two different weighting schemes:

**Satellite Weighting**: each satellite receives weight of one

\[
\sigma_{sw}^2 = \frac{\int P(M|L_c) \langle N_{sat} \rangle_M \sigma_{sat}^2(M) \ dM}{\int P(M|L_c) \langle N_{sat} \rangle_M \ dM}
\]

**Host Weighting**: each host receives weight of one

\[
\sigma_{hw}^2 = \frac{\int P(M|L_c) \sigma_{sat}^2(M) \ dM}{\int P(M|L_c) \ dM}
\]
Satellite Weighting or Host Weighting?

![Graph showing comparisons between satellite weighted and host-weighted models.](image-url)
The combination of $\sigma_{sw}$ and $\sigma_{sw}$ allows one to determine mean and scatter of $P(M|L_c)$.
Satellite Kinematics in the SDSS

Based on SDSS volume-limited sample with 3863 centrals & 6101 satellites

Note that $\sigma_{sw} \neq \sigma_{hw} \Rightarrow$ non-zero scatter in $P(M|L_c)$
Recall:

\[
\sigma_{sw}^2 = \frac{\int P(M|L_c) \langle N_{sat} \rangle_M \sigma_{sat}^2(M) \, dM}{\int P(M|L_c) \langle N_{sat} \rangle_M \, dM}
\]

\[
\sigma_{hw}^2 = \frac{\int P(M|L_c) \sigma_{sat}^2(M) \, dM}{\int P(M|L_c) \, dM}
\]

- Jeans equations yield $\sigma_{sat}^2(M)$ for NFW halos
- Use parametric model for $P(M|L_c)$ and $\langle N_{sat} \rangle_M$
- Constrain model parameters by fitting the observed $\sigma_{sw}(L_c)$ and $\sigma_{hw}(L_c)$
Modeling Methodology & Results

Recall:

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The 68 and 95 percent confidence levels from MCMC
Modeling Methodology & Results

Recall:

\[
\begin{align*}
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Good agreement with CLF clustering results
Modeling Methodology & Results

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\[ \sigma_{sw}^2 = \frac{\int P(M|L_c) \langle N_{sat} \rangle_M \sigma_{sat}(M) \, dM}{\int P(M|L_c) \, dM} \]
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- Use parametric model for \( P(M|L_c) \) and \( \langle N_{sat} \rangle_M \)
- Constrain model parameters by fitting the observed \( \sigma_{sw}(L_c) \) and \( \sigma_{hw}(L_c) \)

and with the SAM predictions of Croton et al. (2006)
The scatter in $P(L_{cen}|M)$ is independent of $M$. 
Implications for Galaxy Formation Stochasticity

- The scatter in $P(L_{\text{cen}}|M)$ is independent of $M$.
- The scatter in $P(M|L_{\text{cen}})$ increases strongly with $L_{\text{cen}}$. 

\[ \text{log } M \]
\[ \text{log } L \]
Our results on satellite kinematics imply that
\[ \sigma_{\log L}(M) = 0.16 \pm 0.04 \]
with no significant dependence on halo mass.

- The scatter in \( P(L_{\text{cen}}|M) \) is independent of \( M \)
- The scatter in \( P(M|L_{\text{cen}}) \) increases strongly with \( L_{\text{cen}} \)
Comparison with other Constraints

- Probability Distribution from Satellite Kinematics
  - Constraints from Galaxy Group Catalogue (Yang et al. 2008)
  - Constraints from Clustering Analysis (Cooray 2006)
  - Predictions from Semi Analytical Model (Croton et al. 2006)
Galaxy-Galaxy Lensing

The mass associated with galaxies lenses background galaxies

Lensing causes correlated ellipticities, the tangential shear, $\gamma_t$, which is related to the excess surface density, $\Delta \Sigma$, according to

$$\gamma_t(R) \Sigma_{\text{crit}} = \Delta \Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

$\Sigma(R)$ is line-of-sight projection of galaxy-matter cross correlation:

$$\Sigma(R) = \bar{\rho} \int_0^{D_S} [1 + \xi_{g, dm}(r)] \, d\chi$$
The Measurements

- Number of background sources per lens is limited.
- Measuring $\gamma_t$ with sufficient $S/N$ requires stacking of many lenses
- $\Delta \Sigma(R|L_1, L_2)$ has been measured using the SDSS by Mandelbaum et al. (2005) for different bins in lens luminosity
How to interpret the signal?

Because of stacking the lensing signal is difficult to interpret

\[
\Delta \Sigma(R|L) = [1 - f_{sat}(L)] \Delta \Sigma_{cen}(R|L) + f_{sat}(L) \Delta \Sigma_{sat}(R|L)
\]

\[
\Delta \Sigma_{cen}(R|L) = \int P_{cen}(M|L) \Delta \Sigma_{cen}(R|M) dM
\]

\[
\Delta \Sigma_{sat}(R|L) = \int P_{sat}(M|L) \Delta \Sigma_{sat}(R|M) dM
\]

\[P_{cen}(M|L) \text{ and } P_{sat}(M|L) \text{ can be computed from } \Phi_{cen}(L|M) \text{ and } \Phi_{sat}(L|M) \text{ and so can } f_{sat}(L)\]

\[\Phi(L|M) \text{ constrained from clustering data, we can predict the lensing signal } \Delta \Sigma(R|L_1, L_2)\]
Comparison with CLF Predictions

NOTE: This is not a fit, but a prediction based on CLF
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Cosmological Constraints

\[ \chi^2 = 3.1 \]

WMAP3 cosmology clearly preferred over WMAP1 cosmology.
Conclusions

Three methods to statistically constrain $P(M|L)$

- Straightforward to constrain $P(M|L)$ with CLF
- Accurate constraints from large galaxy redshift surveys
- Results are strongly cosmology-dependent
Conclusions

Three methods to statistically constrain $P(M|L)$

### Clustering
- Requires selection of **centrals** and **satellites** from redshift surveys
- Requires **stacking** and is therefore sensitive to **scatter** in $P(M|L)$
- Using **satellite weighting** and **host weighting** simultaneously constrains both mean and scatter of $P(M|L)$
- Scatter in $P(M|L)$ increases strongly with increasing $L$
- Scatter in $P(L|M)$ is independent of halo mass with $\sigma_{\log L} = 0.16 \pm 0.04$
- **Stochasticity** in galaxy formation well constrained and consistent with model predictions
- Even with large redshift surveys such as SDSS, statistics are limited
- Data not sufficient to discriminate between **WMAP1** and **WMAP3**
### Conclusions

Three methods to statistically constrain $P(M|L)$

<table>
<thead>
<tr>
<th>Clustering</th>
<th>Satellite Kinematics</th>
<th>Galaxy-Galaxy Lensing</th>
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- **Lensing probes masses directly**
- Requires **stacking** and is therefore sensitive to **scatter** in $P(M|L)$
- Very sensitive to satellite fractions $f_{\text{sat}}(L)$
- Most easily interpreted with use of **CLF $\Phi(L|M)$**
- Combination of **lensing** and **clustering** holds potential to tightly constrain cosmological parameters
- This method is complementary to cosmological constraints from **galaxy power spectrum**, which only probes linear scales
- Current data strongly favors **WMAP3** over **WMAP1** cosmology