The Galaxy-Dark Matter Connection

...Shedding Light on the Dark...

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In collaboration with:
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The Standard Paradigm

Inflation

Hot Big Bang

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Tuesday, April 27, 2010
The Standard Paradigm

Quantum fluctuations

Inflation

Hot Big Bang

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- Hot Big Bang
- Initial perturbations
- Quantum fluctuations
- Inflation

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Initial perturbations

Quantum fluctuations

Inflation

Hot Big Bang

Dark Energy 73%

Cold Dark Matter 23%

Atoms 4%

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The Standard Paradigm

- **Gravitational Instability**
- **Initial Perturbations**
- **Quantum Fluctuations**
- **Inflation**

**Hot Big Bang**

- **Core:** Core of the early universe
- **Expansion:** Expansion of the universe

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The Standard Paradigm

- **Initial perturbations**
- **Quantum fluctuations**
- **Gravitational instability**
- **Halo collapse**

**Inflation**

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The Standard Paradigm

- Initial perturbations
- Quantum fluctuations
- Gravitational instability
- Halo collapse
- Angular momentum conservation
- Gas cooling

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The Standard Paradigm

initial perturbations → gravitational instability → halo collapse → angular momentum conservation

galaxy merging → gas cooling
The Standard Paradigm

- gravitational instability
- elliptical formation
- halo collapse
- galaxy merging
- gas cooling
- angular momentum conservation
Our main goal is to study the Galaxy-Dark Matter connection; i.e., what galaxy lives in what halo?

To constrain the physics of Galaxy Formation
To constrain cosmological parameters

Four Methods to Constrain Galaxy-Dark Matter Connection:

- Large Scale Structure
- Satellite Kinematics
- Galaxy-Galaxy Lensing
- Abundance Matching
The Conditional Luminosity Function

The CLF $\Phi(L|M)$ describes the average number of galaxies of luminosity $L$ that reside in a halo of mass $M$.

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

- Describes occupation statistics of dark matter haloes
- Links galaxy luminosity function to halo mass function
- Holds information on average relation between light and mass

see Yang, Mo & vdBosch 2003
The Conditional Luminosity Function

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see Yang, Mo & vdBosch 2003

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The CLF Model

We split the CLF in a **central** and a **satellite** term:

\[
\Phi(L|M) = \Phi_c(L|M) + \Phi_s(L|M)
\]

For **centrals** we adopt a log-normal distribution:

\[
\Phi_c(L|M)dL = \frac{1}{\sqrt{2\pi}\sigma_c} \exp \left[ - \left( \frac{\ln(L/L_c)}{\sqrt{2}\sigma_c} \right)^2 \right] \frac{dL}{L}
\]

For **satellites** we adopt a modified Schechter function:

\[
\Phi_s(L|M)dL = \frac{\phi_s}{L_s} \left( \frac{L}{L_s} \right)^{\alpha_s} \exp \left[ -(L/L_s)^2 \right] dL
\]

**Note:** \(\{L_c, L_s, \sigma_c, \phi_s, \alpha_s\}\) all depend on halo mass

Free parameters are constrained by fitting data.
Galaxy Group Catalogues
We have developed a new, iterative group finder which uses an adaptive filter modeled after halo virial properties.

- Calibrated & optimized using mock galaxy redshift surveys
- Low interloper fraction (<15%) & high completeness of members (>90%)
- Halo masses estimated from total group luminosity/stellar mass using abundance matching (...cosmology dependent....)
- Can also detect `groups' with single member; large dynamic mass range

For details see Yang et al. (2005) and Yang et al. (2007).
CLF Constraints from Group Catalogue

Yang, Mo & vdB (2008)
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

Cluster strength measured by correlation length $r_0$

![Graph showing correlation lengths and halo mass function]
Occupation Statistics from Clustering

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Clustering strength measured by correlation length $r_0$

**CAUTION**: results depend on cosmology

\[ \begin{align*}
\Omega_m &= 0.30 \\
\Omega_{\Lambda} &= 0.70 \\
\sigma_8 &= 0.90
\end{align*} \]

\[ \begin{align*}
\Omega_m &= 0.24 \\
\Omega_{\Lambda} &= 0.76 \\
\sigma_8 &= 0.74
\end{align*} \]
Galaxy Clustering: The Data

More luminous galaxies are more strongly clustered.

Wang et al. (2007)
DATA: more luminous galaxies are more strongly clustered

LCDM: more massive halos are more strongly clustered

CONCLUSION: more luminous galaxies reside in more massive halos
Results from MCMC Analysis

Cacciato, vdB et al. (2009)

- Model fits data extremely well with
- Same model in excellent agreement with results from SDSS galaxy group catalogue

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Cosmology Dependence

![Graph showing cosmology dependence](image.png)
Satellite Kinematics
Select **centrals** and their **satellites** from a redshift survey. Using redshifts, determine $\Delta V = V_{sat} - V_{cen}$ as function of $L_c$.
Satellite Kinematics: Methodology

Select **centrals** and their **satellites** from a redshift survey. Using redshifts, determine $\Delta V = V_{\text{sat}} - V_{\text{cen}}$ as function of $L_c$. 

![Diagram showing scatter plot and histogram]

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Satellite Kinematics: Methodology

Select **centrals** and their **satellites** from a redshift survey. Using redshifts, determine $\Delta V = V_{\text{sat}} - V_{\text{cen}}$ as function of $L_c$.

Brighter centrals reside in more massive haloes.
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 stacking

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

Consequently, one has to distinguish two weighting schemes:

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

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

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

\[
\sigma_{hw}^2 = \frac{\int P(M|L_c) \mathcal{P}_1(M) \sigma^2_{sat}(M) \, dM}{\int P(M|L_c) \mathcal{P}_1(M) \, dM}
\]
Combination of satellite- and host-weighted velocity dispersions holds information on both the mean and scatter of $P(M|L)$.

Methodology

Jeans Equations yield $\sigma^2_{\text{sat}}(M)$ for NFW halos $P(M|L_c)$ and $\langle N_{\text{sat}} \rangle_M$ follow from CLF

Constrain CLF model parameters by fitting the observed $\sigma_{\text{sw}}(L_c)$ and $\sigma_{\text{hw}}(L_c)$

More, vdB et al. (2009)
Combination of satellite- and host-weighted velocity dispersions holds information on both the mean and scatter of $P(M|L)$

**Results**

More, vdB et al. (2009)
Combination of satellite- and host-weighted velocity dispersions holds information on both the mean and scatter of $P(M|L)$.

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**Results**

Excellent agreement with results from clustering analysis, but statistical errors too large to break degeneracy with cosmology...
Galaxy-Galaxy Lensing
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

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

$\Delta \Sigma$ is line-of-sight projection of galaxy-matter cross correlation

$$\Sigma(R) = \bar{\rho} \int_0^{D_s} [1 + \xi_{g,\text{dm}}(r)] d\chi$$
Galaxy-Galaxy Lensing: The Data

- Number of background sources per lens is limited
- Measuring shear 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. (2006), using different bins in lens-luminosity

Mandelbaum et al. (2006)
How to interpret the signal?

Because of *stacking* the lensing signal is difficult to interpret.

In order to model the data, what is required is:

\[
P_{\text{cen}}(M|L) \quad P_{\text{sat}}(M|L) \quad f_{\text{sat}}(L)
\]

These can all be computed from the CLF...

For a given \( \Phi(L|M) \) we can *predict* the lensing signal \( \Delta \Sigma(R|L_1, L_2) \).
Galaxy-Galaxy Lensing: Results

NOTE: this is not a fit, but a prediction based on CLF

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Galaxy-Galaxy Lensing: Results

Combination of clustering & lensing can constrain cosmology!!!
Constraining Cosmology
Fiducial Model

- Total of 13 free parameters:
  - 11 parameters to describe CLF
  - 2 cosmological parameters; $\Omega_m$ and $\sigma_8$

- Total of 172 data points.

- All other cosmological parameters kept fixed at the best-fit WMAP5 values.

- Dark matter haloes follow NFW profile.

- Radial number density distribution of satellites follows that of dark matter particles.

- Halo mass function and halo bias function of Sheth & Tormen (1999).
Results: Clustering Data

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Results: Lensing Data

\[ \Delta \Sigma (h M_\odot / \text{pc}^2) \]

\[ R (h^{-1}\text{Mpc}) \]

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Luminosity Function & Satellite Fractions

Luminosity Function

Satellite Fractions

fit to data

Model Prediction

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Cosmological Constraints

WARNING: preliminary results!!
Conclusions

- Recent years have seen enormous progress in establishing galaxy-dark matter connection.

- Different methods (group catalogues, satellite kinematics, galaxy-galaxy lensing, clustering & abundance matching) now all yield results in good mutual agreement.

- Combination of galaxy clustering and galaxy-galaxy lensing can constrain cosmological parameters.
  - This method is complementary to and competitive with BAO, cosmic shear, SNIa & cluster abundances.
  - Preliminary results are in excellent agreement with CMB constraints from WMAP5.
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