The Galaxy-Dark Matter Connection

Constraints from Clustering, Satellite kinematics & Lensing

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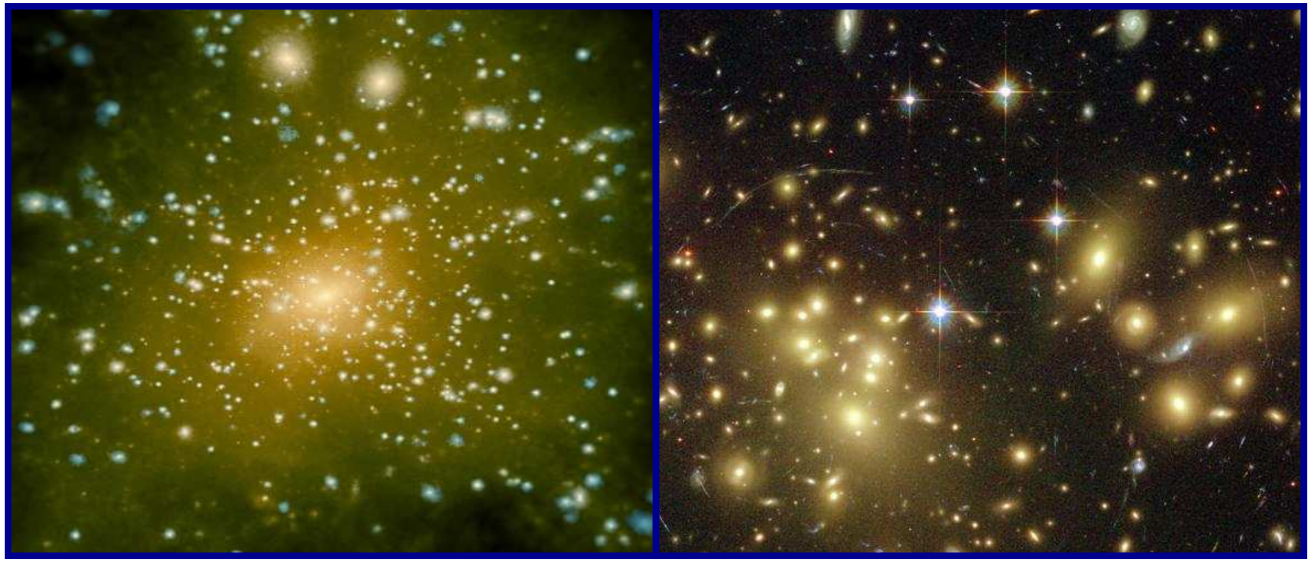
Motivation and Techniques

Why study the Galaxy-Dark Matter Connection?

- To constrain the physics of Galaxy Formation
- To constrain Galaxy Bias and Cosmological Parameters



How to Constrain the Galaxy-Dark Matter Connection?

- Luminosity Dependent Clustering
- Galaxy Group Catalogues
- Galaxy-Galaxy Lensing
- Satellite Kinematics

Introduction

Conditional Luminosity Function
- The Conditional Luminosity Function
- Luminosity & Correlation Functions
- The CLF Model
- Best-Fit Models
- The Galaxy-Dark Matter Connection
- Galaxy-Galaxy Lensing: Theory
- The Cross-Correlation Coefficient
- Galaxy-Galaxy Lensing: Comparison with CLF

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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 $\Phi(L)$:

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

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

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

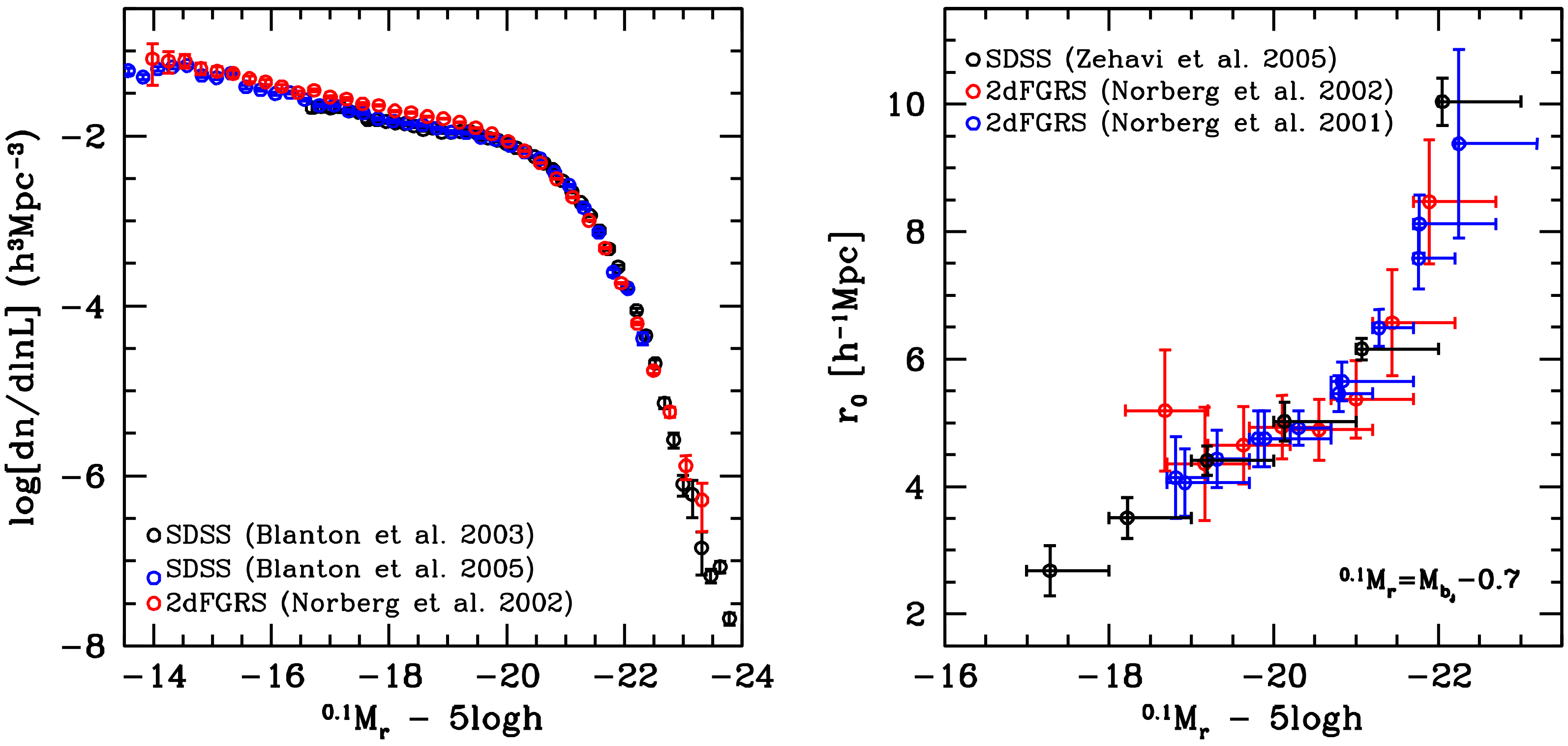
$$\boxed{\langle L\rangle(M) = \int_0^\infty \Phi(L|M)\, L\, \mathrm{d}L}$$

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

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

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

Luminosity & Correlation Functions



- **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 $\xi(r_0) = 1$

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The CLF Model

For 2dFGRS we assume that CLF has Schechter form:

$$\Phi(L|M)\mathrm{d}L = \frac{\Phi^*}{L^*}\left(\frac{L}{L^*}\right)^{\alpha}\exp[-(L/L^*)]\,\mathrm{d}L$$

Here Φ^*, L^* and α all depend on M.

(e.g., Yang et al. 2003; vdB et al. 2003, 2005)

For SDSS we split CLF in central and satellite components:

$$\begin{aligned}
\Phi(L|M)\mathrm{d}L &= \Phi_c(L|M)\mathrm{d}L + \Phi_s(L|M)\mathrm{d}L \\
\Phi_c(L|M)\mathrm{d}L &= \frac{1}{\sqrt{2\pi}\,\ln(10)\,\sigma_c}\exp\left[-\left(\frac{\log(L/L_c)}{\sqrt{2}\sigma_c}\right)^2\right]\frac{\mathrm{d}L}{L} \\
\Phi_s(L|M)\mathrm{d}L &= \frac{\Phi_s}{L_s}\left(\frac{L}{L_s}\right)^{\alpha_s}\exp[-(L/L_s)^2]\,\mathrm{d}L
\end{aligned}$$

Here L_c, L_s, σ_c, ϕ_s and α_s all depend on M

(e.g., Cooray & Milosavljevic 2005; Cooray 2005, 2006; vdB et al. 2007)

Use Monte-Carlo Markov Chain to constrain free parameters by fitting to $\Phi(L)$ and $r_0(L)$.

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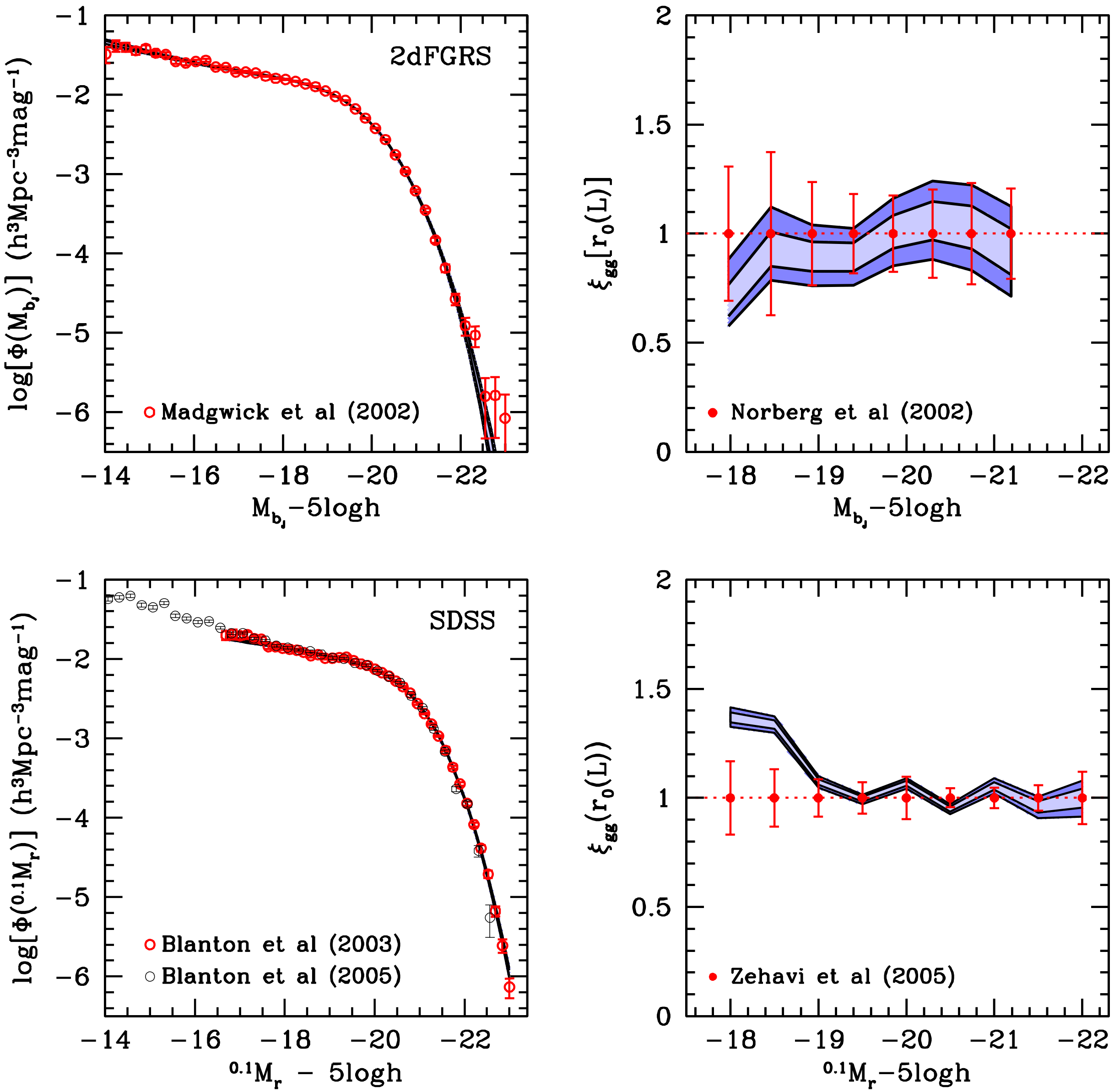
Best-Fit Models



2dFGRS: vdB et al. 2006 (astro-ph/0610686)

SDSS: vdB et al. 2007 (in preparation)

The Galaxy-Dark Matter Connection

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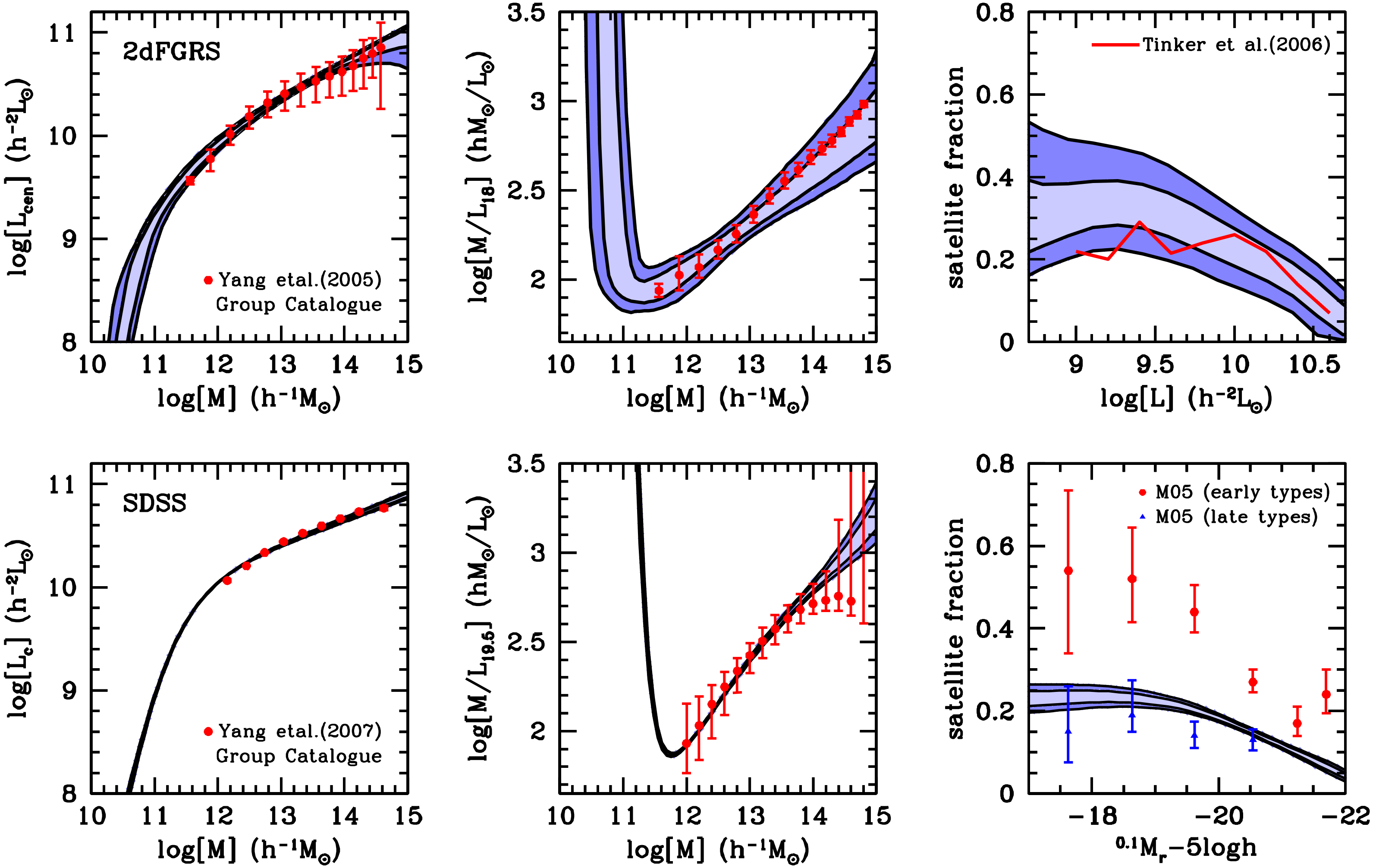

Excellent agreement between CLF and Group results

2dFGRS: vdB et al. 2006 (astro-ph/0610686)

SDSS: vdB et al. 2007 (in preparation)

Galaxy-Galaxy Lensing: Theory

G-G lensing measures tangential shear distortions of background sources, which holds information on galaxy-matter cross correlation

$$\gamma_t = \frac{\Delta\Sigma(R)}{\Sigma_{\rm crit}} \qquad \Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_{\rm s}}{D_{\rm l} D_{\rm ls}(1+z_{\rm l})^2}$$

$$\Delta\Sigma(R) = \overline{\Sigma}(< R) - \Sigma(R) \qquad \Sigma(R) = \overline{\rho}\int[1+\xi_{\rm gm}(r)]\,{\rm d}\chi$$

In order to boost signal-to-noise one needs to stack lenses

$$\begin{aligned}\langle\Delta\Sigma\rangle(R|L) &= \int P(M|L)\,\Delta\Sigma(R|M)\,{\rm d}M \\ P(M|L) &= [1-f_{\rm sat}(L)]\;P_{\rm cen}(M|L) + f_{\rm sat}(L)\,P_{\rm sat}(M|L)\end{aligned}$$

Previous studies typically had to make various assumptions:

- $f_{\rm sat}(L)$ **treated as free parameter(s)**
- $P_{\rm cen}(M|L) = \delta^D(M - \langle M\rangle_L)$ **(ignore stochasticity)**
- $P_{\rm sat}(M|L) \propto M\,n(M)\,\Theta_{\rm H}[M - M_{\rm min}(L)]$

(e.g., Mandelbaum et al. 2005, 2006; Seljak et al. 2005)

With CLF $f_{\rm sat}(L)$, $P_{\rm cen}(M|L)$ and $P_{\rm sat}(M|L)$ are all known.

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The Cross-Correlation Coefficient

From large-scale structure we obtain galaxy power spectrum

$$P_{\rm gg}(k) = b^2(k)\, P_{\rm mm}(k) \qquad\qquad b^2(k) = \frac{P^2_{\rm gg}(k)}{P_{\rm mm}(k)}$$

From G-G lensing we obtain galaxy-matter cross-power spectrum

$$P_{\rm gm}(k) = r(k)\, b(k)\, P_{\rm mm}(k) \qquad\qquad r^2(k) = \frac{P^2_{\rm gm}(k)}{P_{\rm gg}(k)\, P_{\rm mm}(k)}$$

- $P_{\rm mm}(k)$ **is the dark matter power spectrum**
- $b(k)$ **is the (scale-dependent) galaxy bias**
- $r(k)$ **is the galaxy-matter cross-correlation coefficient**

With large (redshift) surveys we can measure both $P_{\rm gg}(k)$ **and** $P_{\rm gm}(k)$

Not enough to solve for three unknowns: $b(k), r(k)$ **and** $P_{\rm mm}(k)$

However, when $r(k) = 1$ **then**

$$P_{\rm mm}(k) = P^2_{\rm gm}(k)/P_{\rm gg}(k) \qquad\qquad b(k) = P_{\rm gg}(k)/P_{\rm gm}(k)$$

Galaxy-Galaxy Lensing: Comparison with CLF

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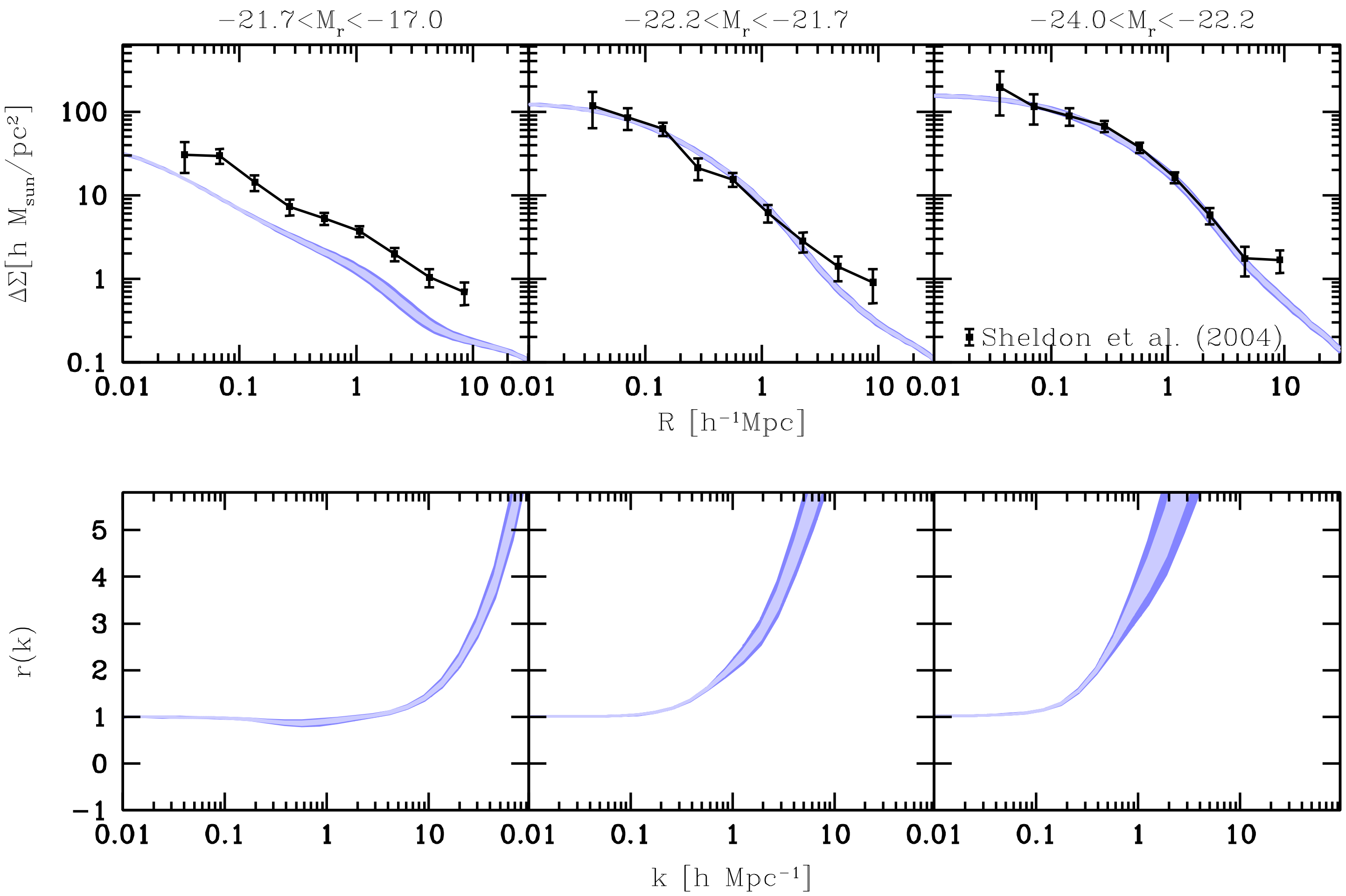

- **Only good agreement with data for very bright galaxies**
- **Small scale increase of $r(k)$ reflects that f_{sat} is small**
- **WARNING: results very preliminary**

Cacciato, vdB et al. 2007 (in preparation)

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- Satellite Kinematics
- Results: The First Two Moments
- Why scatter increases with luminosity

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Stochasticity and Stacking

To measure satelite kinematics or the weak lensing shear around galaxies, one needs to stack the signal of many galaxies.

Typically one stacks (central) galaxies in a narrow luminosity bin.

Unless $P(M|L_{\rm cen})$ is very narrow, this means stacking haloes of different masses, and signal does not reflect $\langle M\rangle(L_{\rm cen})$.

Proper interpretation of satelite kinematics and galaxy-galaxy lensing requires knowledge of $\sigma_{\rm logM}$.

How can we constrain the scatter in $P(M|L_{\rm cen})$?

- Use ‘predictions’ from semi-analytical models for galaxy formation
- Compute from **CLF**: $P(M|L_{\rm cen}) = \frac{\Phi_c(L|M)\,n(M)}{\Phi_c(L)}$ *(Bayes Theorem)*
- Use satellite kinematics; host-weighting *vs.* satellite weighting

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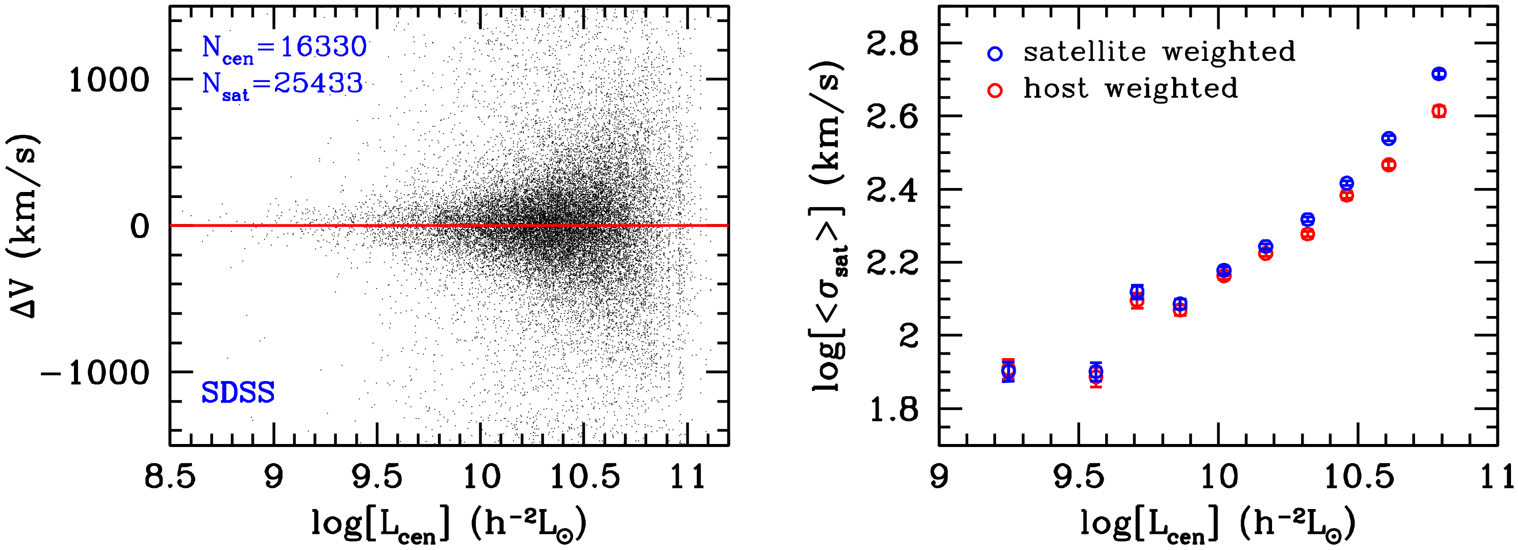
Satellite Kinematics

Select centrals and satellites and determine $\sigma_{\rm sat}(L_{\rm cen})$, describing the width of $P(\Delta V)$ with $\Delta V = V_{\rm sat} - V_{\rm cen}$ **(More, vdB, et al. 2007, in prep.)**



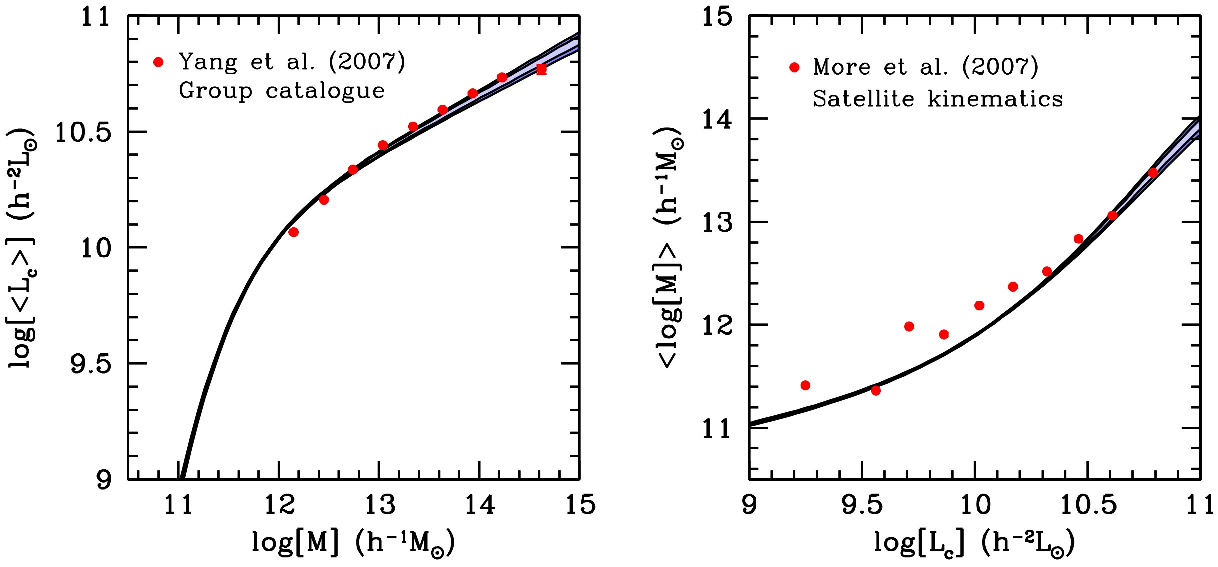
$$\langle\sigma_{\rm sat}\rangle(L_{\rm cen}) = \frac{\int P(M|L_{\rm cen})\ \langle N_{\rm sat}\rangle_M^p\ \langle\sigma_{\rm sat}\rangle_M\ {\rm d}M}{\int P(M|L_{\rm cen})\ \langle N_{\rm sat}\rangle_M^p\ {\rm d}M}$$

- $p = 1$: **satellite-weighted mean** $\langle\sigma_{\rm sat}\rangle_{\rm sw}$
- $p = 0$: **host-weighted mean** $\langle\sigma_{\rm sat}\rangle_{\rm hw}$

Unless $P(M|L_{\rm cen}) = \delta(M - \langle M\rangle)$ one has that $\langle\sigma_{\rm sat}\rangle_{\rm sw} > \langle\sigma_{\rm sat}\rangle_{\rm hw}$

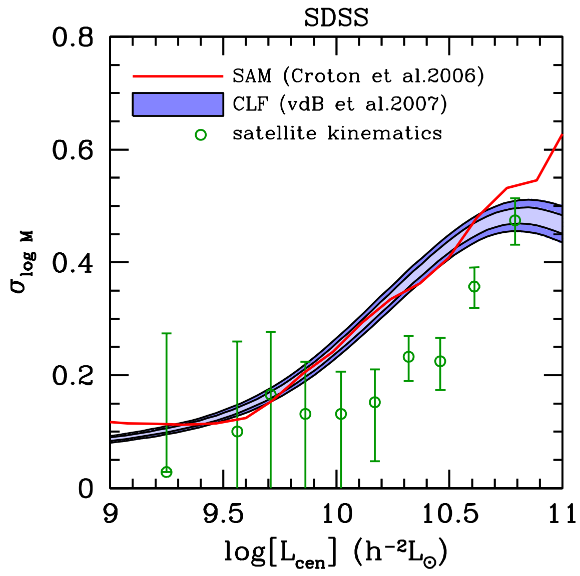
Both $\langle\sigma_{\rm sat}\rangle_{\rm sw}$ and $\langle\sigma_{\rm sat}\rangle_{\rm hw}$ can be determined from data.

Results: The First Two Moments



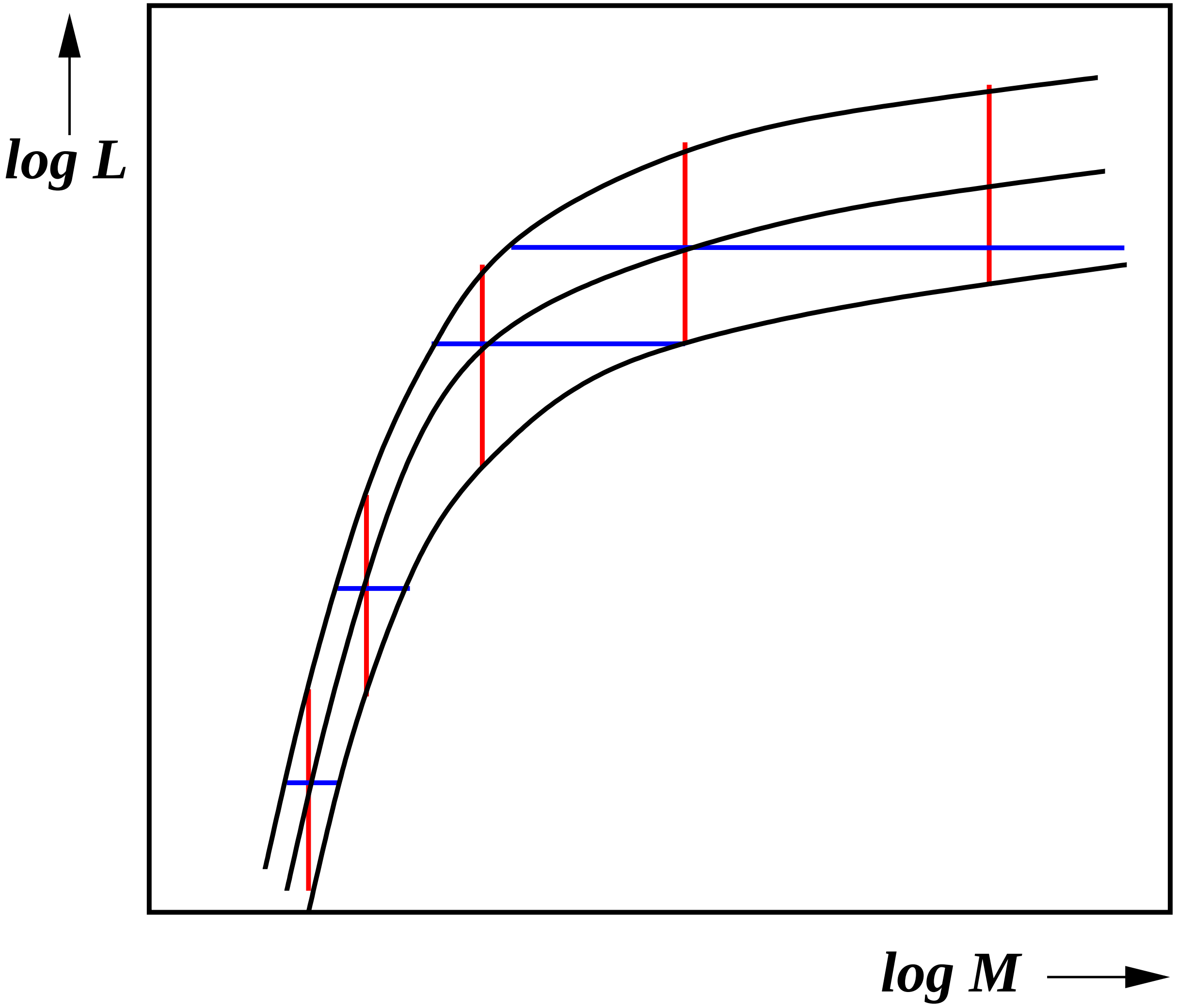
Assuming that $P(M|L_{\rm cen})$ is a log-normal, the combination of $\langle\sigma_{\rm sat}\rangle_{\rm sw}$ and $\langle\sigma_{\rm sat}\rangle_{\rm hw}$ allows one to compute both $\langle M\rangle$ and $\sigma_{\log M}$ as function of $L_{\rm cen}$.

(More, vdB et al. 2007, in prep.)



All methods agree that scatter in $P(M|L_{\rm cen})$ increases with $L_{\rm cen}$

Why scatter increases with luminosity



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

Conclusions

- The **CLF** allows a powerful and consice treatment of **galaxy bias**.
- The **CLF** also quantifies universal relation between light and mass.
- Galaxy-Dark Matter connection inferred from **luminosity dependent clustering** in excellent agreement with results obtained from **galaxy group catalogues**.
- The **CLF** predictions only match **galaxy-galaxy lensing** signal for very bright galaxies.
- Satellite kinematics can be used to probe and quantify the **stochasticity** in galaxy formation.
- Scatter in $P(M|L_{\rm cen})$ increases strongly with increasing $L_{\rm cen}$