GALAXIES IN THE DARK

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Introducing the Jargon

Elliptical Galaxy
No longer forming many stars
“passive” or “red” or “quenched”

Spiral Galaxy
Actively forming stars
“star-forming” or “blue”
Introducing the Jargon

Weight of a galaxy
How many stars are formed
\( M^* = \text{“stellar mass”} \)
(In units of solar masses, typical value \( M^* = 10^{10} \) Msun)
Introducing the Jargon

Dark matter “Halo”
Typical mass $M_{\text{halo}} = 10^{12} \text{ M}_\odot$
Forms the Cosmic Web
Introducing the Jargon

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Typical mass $M_{\text{halo}} = 10^{12} \text{ M}_\odot$
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Hydrogen Gas
Fuel from which stars are created
Introducing the Jargon

Dark matter “Halo”
Typical mass $M_{\text{halo}} = 10^{12} \text{ M}_\odot$
Forms the Cosmic Web

“Feedback”
A mechanism that heats gas and prevents it from forming stars

Hydrogen Gas
Fuel from which stars are created
Galaxy mass, color, SFR, ...

Dark Matter density field

Key ingredient for broad range of topics.

Mechanisms that regulate galaxy growth may vary with galaxy mass, redshift, but also with the dark matter environment.
Internal / Secular

- Heating/winds from stars
- Heating from active galactic nuclei (AGN)
- Disk / bar instabilities
- Morphological quenching
- Major mergers
- Halo quenching

Dark matter environment

- “Starvation” (removes extended hot gas in sub-halo)
- Ram-pressure stripping
- Gravitational interactions with other sub-halos
- Gravitational heating

(non exhaustive list ...)
Distinct Signatures: Halos mass v.s Galaxy Mass

Simple cartoon diagram: central galaxies

Hopkins et al. 2008
Observables

- Luminosity Functions
- Galaxy Mass Function
- SFRD vs Z
- Clustering
- .....
Observables

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- .....
Observables
• Luminosity Functions
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• SFRD vs Z
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• ......

Semi-Analytic Models
Analytic prescriptions for cooling, star-formation, feedback, ...
• e.g. Kauffmann et al. 99 Somerville et al. 08, Croton et al. 06, Benson et al. 2012

Direct Simulation
Hydrodynamic Simulations.
• e.g. Katz et al. 96, Schaye et al. 2012

Phenomenological Models
Simplified quenching recipes
• e.g. Peng et al. 2010, Cattaneo et al. 2011

Statistical Approach
Parametric description of galaxy-dark matter connection.
• HOD / CLF / SHAM
• e.g Stellar-Halo-Mass Relation (SHMR)
GOAL

Robust measurement of stellar-to-halo mass relation as a function of redshift.
Distinguish centrals/satellites.

1. Integrated growth \((M_{\text{stellar}} \text{ v.s. } M_{\text{halo}})\)
2. Instantaneous growth (active/passive)

... a powerful tool to do this statistically
**Clustering + Galaxy-Galaxy Lensing**

**Galaxy correlation function**: Excess probability above random of finding two galaxies with a separation \( R \).

\[
dP = n (1 + \xi(r)) dV
\]

**But also unexploited potential**:
Marked correlation functions.
Redshift-space distortions (wedges, multipoles).
Galaxy mass correlation from magnification.
Cluster-galaxy cross-correlations.

\[
\Delta \Sigma(r) = \Sigma(\leq r) - \Sigma(r) = \Sigma_{\text{crit}} \times \gamma_t(r)
\]

\[
\Sigma_{\text{crit}} = \frac{c^2}{4\pi G_N} \frac{D_{OS}}{D_{OL} D_{LS}}
\]
Why are these statistical probes sensitive to:

halo mass
+
central / satellite fractions?
The Galaxy-Galaxy Lensing Signal

Delta Sigma: surface mass density contrast.

Stellar mass: $M_\ast = 10^{10} M_\odot$

- Point source ($\Delta \Sigma_{\text{stellar}}$)
- One halo central
- One halo satellite
- Two halo ($\Delta \Sigma_{2h}$)
- Combined signal ($\Delta \Sigma_{\text{tot}}$)

Central

Satellite
Ten Parameter Model

Leauthaud et al. 2011

Parametric form for the stellar-to-halo mass relation \((M_1, M_{*0}, \beta, \delta, \gamma)\)

\[
\log_{10}(f_{\text{shmr}}^{-1}(M_*)) = \log_{10}(M_h) = \\
\log_{10}(M_1) + \beta \log_{10} \left( \frac{M_*}{M_{*,0}} \right) + \frac{\left( \frac{M_*}{M_{*,0}} \right) \delta}{1 + \left( \frac{M_*}{M_{*,0}} \right)^{-\gamma}} - \frac{1}{2}
\]

Central occupation function \((\sigma_{\log(M_*)})\)

\[
\langle N_{\text{cen}}(M_h|M_{*1}) \rangle = \\
\frac{1}{2} \left[ 1 - \text{erf} \left( \frac{\log_{10}(M_{*1}) - \log_{10}(f_{\text{shmr}}(M_h))}{\sqrt{2} \sigma_{\log M_*}} \right) \right]
\]

Satellite occupation function \((B_{\text{cut}}, B_{\text{sat}}, \beta_{\text{cut}}, \beta_{\text{sat}})\)

\[
\langle N_{\text{sat}}(M_h|M_{*1}) \rangle = \langle N_{\text{cen}}(M_h|M_{*1}) \rangle \left( \frac{M_h}{M_{\text{sat}}} \right)^{\alpha_{\text{sat}}} \exp \left( -\frac{M_{\text{cut}}}{M_h} \right)
\]

\[
\frac{M_{\text{sat}}}{10^{12} M_\odot} = B_{\text{sat}} \left( \frac{f_{\text{shmr}}^{-1}(M_{*1})}{10^{12} M_\odot} \right)^{\beta_{\text{sat}}}
\]

\[
\frac{M_{\text{cut}}}{10^{12} M_\odot} = B_{\text{cut}} \left( \frac{f_{\text{shmr}}^{-1}(M_{*1})}{10^{12} M_\odot} \right)^{\beta_{\text{cut}}}
\]

+ Tinker et al. 2008 halo mass function
+ Tinker et al. 2010 bias function
+ Halo exclusion
The global Stellar-to-Halo Mass Relation (SHMR) from the COSMOS Survey

Integrated

Galaxy Growth v.s Halo growth
Clustering

\[ w(\theta) \]

\[ \theta \text{ [arcseconds]} \]

Stellar mass function

\[ \log (M^* [M_{\odot}]) \]

Galaxy-galaxy lensing

\[ \Delta\Sigma \text{ [M}_{\odot}/\text{pc}^2] \]

\[ R \text{ [Mpc]} \]
Clustering

Galaxy-galaxy lensing

Stellar mass function

Leauthaud et al. 2012a

Physical transverse distance $R$ [Mpc $h_{72}^{-1}$]

$Z = [0.48, 0.74]$
Stellar mass vs Halo mass

Typical systematic error in stellar masses (between different surveys)

Z~0, centrals

Leauthaud et al. 2012a
Matching the SHMR with simulations

Z=0, centrals

No feedback
Too many stars
Low radio mode
“pivot” point
Stellar + AGN feedback
“fast” stellar winds
Not enough stars
Low mass end
Stellar feedback

\( \log \left[ \frac{M_\star}{M_\odot} \right] \)

\( \log \left[ \frac{M_{200,\text{crit}}}{M_\odot} \right] \)

(Vogelsberger et al. 2014)
Matching the SHMR with simulations

Z=0, centrals

Stellar feedback
Low radio mode
“pivot” point
Stellar + AGN feedback
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Not enough stars
Low mass end
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No feedback
Too many stars

Vogelsberger et al. 2014
Pivot masses: location of the minimum of $M_{200b}/M^*$ marks the halo mass in which accumulated stellar growth of the central galaxy has been the most efficient. Constrains transition (“pivot”) point between competing feedback mechanisms.

Leauthaud et al. 2012a
( Short detour from the main trail )
X-ray Detected AGN in COSMOS

- Deep XMM and Chandra Imaging
- 380 moderate luminosity X-ray AGN at $z<1$
- $41.5<\log(L_X)<43.5$

Method: use host stellar mass to predict halo occupation

Weak Lensing Signal
HODs for X-ray AGN at $z<1$

$\log_{10}(M_{200b})$

$\log_{10}(M^*) > 10.5$ selection cut

$\sim 4\%$
Compared to previous results from clustering

- Cut-off at $\log(M_{\text{halo}}) > 12$ due to AGN host selection of $\log(M^*) > 10.5$
- Roughly designed to mimic selections used for clustering studies ($I<22$)
Stellar-to-Halo Mass Relation
active/passive

*Instantaneous growth*
Evolution in quiescent fractions

Build up in quiescent population at low stellar masses $M_* \sim 10^{10}$ Msun
Star-forming / Passive

Same redshift bins as previous work $0.2 < z < 1$

Star-forming / passive selection, NUV-R & R-J selection

For model details, see AL 2012, & Tinker AL et al 2013

Distinguish central and satellite populations
Evolution of Stellar-Mass Functions

The stellar mass functions of passive and SF cosmos galaxies broken down into the contributions from central and satellite galaxies. Panels (a) and (b) show results for quenched satellite and central galaxies, respectively. Panels (c) and (d) show results for star-forming satellite and central galaxies, respectively. The shaded regions represent the 68% range of values within the MCMC chains. For all four subsamples, there is little evolution at the high-mass end ($M^* \gtrsim 10^{11} M_\odot$). There is a dearth of high-mass quenched satellites at $z=0.36$, but this is likely a statistical outlier. At low masses, the only subsample that shows significant evolution is passive central galaxies; at $M^*=10^{10} M_\odot$, the abundance of passive central increases by an order of magnitude across our redshift baseline. Figure 11 shows that this growth in the fraction of quenched central galaxies continues to increases to $z=0$. The rise in low mass red central galaxies.

Previous studies have also detected an acceleration of the migration rate onto the red sequence with cosmic time. Both the PRIMUS results and results from zCOSMOS of Pozzetti et al. (2010) find that growth rate, in number and mass density, for objects on the red sequence is increasing with decreasing redshift at $M^* \lesssim 10^{10.6} M_\odot$. These studies find significantly less evolution in the growth rate than in this work, which is a natural consequence of analyzing the overall galaxy population as opposed to focusing on central galaxies.

The results here make strong predictions for the minimum $M^*$ that can be quenched in the field. Geha et al. (2012) find that there are no isolated field galaxies below $10^9 M_\odot$ that are passively evolving in the low-redshift NASA-Sloan Atlas. Our models predict that the $q(\text{cen})$ drops below 1% at $M^*=3 \times 10^9 M_\odot$ at $z=0$. Extending this search for the minimum quenched field galaxy can confirm and strengthen the constraints from the SHMR analysis.

The quenching timescale for satellite galaxies.
Evolution of Quenched Fraction

**Panel (a)**: Evolution of quenched fraction for all galaxies. The quenched fraction decreases with increasing redshift, and the decrease is more pronounced for lower host halo masses. The lines represent different host halo masses, with red circles for log M = 11.2, orange triangles for log M = 10.8, green squares for log M = 10.5, blue diamonds for log M = 10.1, and purple pentagons for log M = 9.7.

**Panel (b)**: Evolution of quenched fraction for satellites. The quenched fraction decreases with increasing redshift, and the decrease is more pronounced for lower host halo masses. The lines represent different host halo masses, with red circles for log M = 11.2, orange triangles for log M = 10.8, green squares for log M = 10.5, blue diamonds for log M = 10.1, and purple pentagons for log M = 9.7.

**Panel (c)**: Evolution of quenched fraction for centrals. The quenched fraction decreases with increasing redshift, and the decrease is more pronounced for lower host halo masses. The lines represent different host halo masses, with red circles for log M = 11.2, orange triangles for log M = 10.8, green squares for log M = 10.5, blue diamonds for log M = 10.1, and purple pentagons for log M = 9.7.
$z = 0.88$
(6.4 Gyr)

$z = 0.6$
(7.6 Gyr)

$z = 0.3$
(10 Gyr)

$z = 0.1$
(12.3 Gyr)

**Time**

**Halo Mass**

**Stellar Mass**

**COSMOS**

Tinker, AL et al. 2013

**SDSS**

Mandelbaum et al. 2006
Quenched Fraction: Central Versus Satellite?

Panel (a) shows $f_{\text{sat}}$ for all galaxies. Panel (b) shows $f_{\text{sat}}$ for red galaxies. Panel (c) shows $f_{\text{sat}}$ for star-forming galaxies. Error bars on the COSMOS measurements represent the 68% range within the MCMC chains. Data points at $z=0.05$ are from the SDSS groups catalog of Tinker et al. (2011). The SDSS stellar masses have been modified to allow for comparison to COSMOS stellar masses, but these changes yield little to no change in the value on the y-axis. See text for details.

Panel (a) shows the SMF from $z=0.36$ along with the original best fit (dotted curve, taken from Figure 3). The solid curve shows the results where all parameters are fixed to the best-fit values except for $f_q(M_h)$, which is taken from the $z=0.88$ fit. In this model, $f_q(M_h)$ has a cutoff at $M_h=10^{12} M_{\odot}$, thus suppressing the abundance of red central galaxies and lowering the overall SMF. The right panels show the effect on the clustering of passive galaxies. Reducing the abundance of quenched central galaxies increases the fraction of quenched galaxies that are satellites. The increased $f_{\text{sat}}$ enhances the clustering at all scales.

Assume $z=0.88$ red central fraction is constant.

For $z=0.36$, the graph shows a significant decrease in the abundance of red central galaxies, which is reflected in the lower overall SMF. The clustering of passive galaxies also decreases, indicating a lower quenched central fraction. For $z=0.88$, the red central fraction remains constant; thus, the clustering of passive galaxies remains consistent with previous data.
Comparison with Models? Red Central Mass Functions

Phenomenological Models

Simplified quenching recipes
**Birrer et al. 2014**

Semi-Analytic Models

Analytic prescriptions for baryonic processes
**Benson et al. 2012**

Figure Adapted from Birrer et al. 2014
The stellar mass functions of passive and star-forming galaxies broken down into the contributions from central and satellite galaxies. Panels (a) and (b) show results for quenched satellite and central galaxies, respectively. Panels (c) and (d) show results for star-forming satellite and central galaxies, respectively. The shaded regions represent the 68% range of values within the MCMC chains. For all four subsamples, there is a dearth of high-mass quenched satellites at $z=0$, but this is likely a statistical outlier. At low masses, the only subsample that shows significant evolution is passive central galaxies; at $M_\ast=10^{10} M_\odot$, the abundance of passive central increases by more than an order of magnitude across our redshift baseline. Figure 11 shows that this growth in the fraction of quenched central galaxies continues to increase to $z=0$.

Baseline within the SDSS Main galaxy sample is small, the overall number of galaxies is very large and it is possible to detect changes in the abundance of red central galaxies with in the volume-limited group catalogs of Tinker et al. (2011) (see their Table 1). As discussed earlier, direct comparison of the SDSS stellar masses with COSMOS stellar masses is not possible, but given the lack of significant slope of the migration rate with stellar mass, the difference in $M_\ast$ estimator is less relevant. The SDSS results yield a migration rate nearly an order of magnitude higher than the $z=0.66$ COSMOS results. Previous studies have also detected an acceleration of the migration rate onto the red sequence with cosmic time. Both the PRIMUS results and results from zCOSMOS of Pozzetti et al. (2010) find that growth rate, in number and mass density, for objects on the red sequence is increasing with decreasing redshift at $M_\ast\lesssim10^{10} M_\odot$. These studies find significantly less evolution in the growth rate than in this work, which is a natural consequence of analyzing the overall galaxy population as opposed to focusing on central galaxies. The results here make strong predictions for the minimum $M_\ast$ that can be quenched in the field. Geha et al. (2012) find that there no isolated field galaxies below $10^{9} M_\odot$ that are passively evolving in the low-redshift NASA-Sloan Atlas. Our models predict that the $q_{\text{cen}}$ drops below 1% at $M_\ast=3\times10^{9} M_\odot$ at $z=0.66$ and $M_\ast=6\times10^{9} M_\odot$ at $z=0.88$. Extending this search for the minimum quenched field galaxy can confirm and strengthen the constraints from the SHMR analysis.
Build up in red sequence due to rise in low mass red central population.

How about the high mass end? ...
\[ z = 0.88 \quad (6.4 \text{ Gyr}) \]
\[ z = 0.6 \quad (7.6 \text{ Gyr}) \]
\[ z = 0.3 \quad (10 \text{ Gyr}) \]
\[ z = 0.1 \quad (12.3 \text{ Gyr}) \]

**COSMOS**

**Tinker, AL et al. 2013**

**SDSS**

**Mandelbaum et al. 2006**
Evolution of SHMR for Massive Galaxies

\( z = 1 \)

\( z = 0 \)

Stochastic Star formation
Evolution of SHMR for Massive Galaxies

- Stochastic Star formation

$z = 1$

$z = 0$

$time$

Fixed $M_{\text{halo}}$

Blue central now has larger $M^*$

Blue turn onto red sequence

stops growing
Evolution of SHMR for Massive Galaxies

Distinct evolutionary tracks. “Inherited Evolution”? 

- Larger $M^*$ ahead of curve
- Fixed $M_{\text{halo}}$

$t = 1$

$t = 0$

overtakes red counterpart

Larger $M^*$

Ahead of curve
Evolution of SHMR for Massive Galaxies

Distinct evolutionary tracks. “Inherited Evolution”? 

Halo growth $x 1.8$

Star formation $x 1.6$

Gas accretion? Black hole masses? (speculative)
Future is Glorious ... and Hellish
Future is Glorious ... and Hellish
Future is Glorious ….. and Hellish
(tremendous S/N) (and now the details I swept under the rug will really start to matter)

1400 deg² Hyper Suprime Cam Lensing Survey
Japan. Princeton. Taiwan.
Dark matter matters!

SHMR to $z = 1$

Gravitational Lensing

HSC

Active / Passive
- Rise in low mass red centrals
- Switch over at high masses