the galaxy-halo connection from abundance matching: simplicity and complications

with Peter Behroozi, Michael Busha, Rachel Reddick (KIPAC/Stanford) & Charlie Conroy (Harvard/CfA)
subHalo abundance matching

- The basic idea:
  - Galaxies live in halos (including subhalos)
  - There is a property of halos (e.g. mass) that is tightly correlated with some property of galaxies (e.g. stellar mass, luminosity)

- Some details matter:
  - which property, what is the scatter?
  - proper treatment of satellite galaxies: stripping, star formation once halos become substructures

- Very powerful idea:
  - the mass of a dark matter halo is the primary determinant of its properties.
  - detailed tests of the model can test both LCDM and galaxy formation physics

- Results to date:
  - matching stellar mass/or luminosity to the maximum mass/$v_{\text{max}}$ its halo ever had (current mass/$v_{\text{max}}$ for central galaxies; mass at accretion for satellites), with a small amount of scatter, works very well.
  - excellent agreement with a wide range of galaxy statistics, including two-point clustering, three-point clustering, lensing, etc.
  - data are getting good enough to test the details, and infer some physics.
Some interesting questions

- How much scatter is there in the galaxy-halo connection?
- What is it due to?
- How does the halo occupation evolve?
- Does the model extend to low masses?
abundance matching technique

assign galaxies to halos velocities by matching \( n(>M^*) \) to \( n(>M) \) (assume the most massive galaxy lives in the most massive halo)

key assumptions: one galaxy per dark matter clump; galaxy mass/luminosity tightly correlated with halo mass/velocity required high-res cosmological simulations to properly test

Distinct Halo Evolution

Subhalo Evolution

Accretion epoch

Wechsler et al 2002 hypothesis: maximum/accretion mass/velocity is tightly correlated with stellar mass/total luminosity

$h_{\text{max}}$, $\text{mass}^{1/3}$

Constant increase

$V_{\text{max}}$, $\text{mass}^{1/3}$

increase
decrease

Time

Time
The scale & luminosity dependence of galaxy clustering at high z are very well explained by this simple approach!

Conroy, Wechsler, & Kravtsov 2006
The galaxy-halo connection at z=0

This work, $< M_\star / M_h | M_h >$

This work, $M_\star / < M_\star | M_h >$

Moster et al. 2009 (AM)

Guo et al. 2009 (AM)

Wang & Jing 2009 (AM+CC)

Zheng et al. 2007 (HOD)

Mandelbaum et al. 2006 (WL)

Klypin et al. in prep. (SD)

Gavazzi et al. 2007 (SL)

Yang et al. 2009a (CL)

Hansen et al. 2009 (CL)

Lin & Mohr 2004 (CL)

constraints from abundance & clustering

mass measurements from lensing/dynamics

galaxy content of clusters

Behroozi, Conroy & RW 2010
How well is the galaxy-halo connection constrained?

consider errors in: mass function, stellar mass function, scatter, cosmology, matching algorithm

statistical errors only

systematic errors

Behroozi, Conroy & RW 2010

includes poisson and sample variance errors, uncertainty due to scatter in \( M^* - M \)

includes random errors in stellar masses, possible systematic errors in the stellar mass function

current uncertainty due to cosmological model is smaller than systematic errors in stellar mass function
Uncertainty due to scatter in $M^*-M$

...but this can be constrained by clustering
Distinguishing scatter between mass and luminosity with clustering statistics

scatter values: 0.0, 0.2, 0.4

-21.5

-20.5

-19.5

data: Zehavi et al 2010 SDSS DR7
model: Bolshoi simulation, merger trees created by Peter Behroozi
assign L-v_{max} for centrals; L-v_{acc} for satellites
Distinguishing scatter between mass and luminosity with clustering statistics

\[ L-v_{\text{max}} \] for centrals; \[ L-v_{\text{acc}} \] for satellites

scatter values: 0.0, 0.2, 0.4

-21.5 -20.5 -19.5

for a one parameter (scatter) model, already very strong constraints, even for one magnitude below \( L^* \)

scatter is small: ~0.15-0.2 dex in \( L \) at a given \( M \)
Distinguishing scatter between mass and luminosity with clustering statistics

$L - v_{\text{max}}$ for centrals; $L - v_{\text{acc}}$ for satellites

scatter values: 0.0, 0.2, 0.4

what controls the clustering:

- scatter in the mass-luminosity relation
- satellite fraction (what does the sat luminosity do after accretion?)
- cosmological model

data is so good that conclusions are sensitive to simulation details inc halo finding and merger trees
Consistent picture with other measurements

HOD constraints from 2 point clustering

constraints from satellite dynamics

Zheng, Coil & Zehavi 07

constraints from BCGs

Hansen, Sheldon, RW & Koester 09

More et al 09

+ T-F relation
(Trujillo-Gomez talk)

0.15-0.2 dex scatter
How much scatter just from accretion histories?

- a simple model: assume SFR(M,z) with no scatter. (Conroy & Wechsler 09)
- follow star formation history along merger trees in a cosmological box.
- what is the resulting scatter in stellar mass at a given halo mass?

result: ~ 0.1 dex scatter

given measurement errors in SM and HM, this is consistent with 50-100% of scatter in M*-M due to differences in mass accretion histories
evolution of halo occupation

Reddick et al in prep
based on Bolshoi sim + Behroozi merger trees

halo occupation for galaxies (subhalos) with a fixed number density:
nearly constant from $z \sim 1$ to $z \sim 0$

in very good agreement with recent observational estimates (e.g. Ross et al 2010), but conclusions are sensitive to photo-z errors
under the assumption of LCDM, all galaxies should live in halos and subhalos.

this means that fitting to a standard HOD model does not use all of the available information
Can we extend this to lower masses?
How many Magellanic Cloud like galaxies do we expect around MW like halos in LCDM?

Busha et al in prep based on Bolshoi simulation

statistics of satellites 2-4 mags dimmer than hosts

only ~10% of halos have 2 or more satellites!
How many Magellanic Cloud like galaxies do we observe around MW like halos?

Liu, Gerke, RW et al in prep

four example MW-like halos with exactly two satellites

investigate the statistics of photometrically selected satellite galaxies around spectroscopically selected host galaxies using SDSS data
How many Magellanic Cloud like galaxies do we observe around MW like halos?

Busha et al in prep
halos from Bolshoi simulation

Liu et al in prep
(see Gerke talk for details)
observational results based on
SDSS: spectroscopically selected host galaxies, photometrically selected satellite galaxies 2-4 mags fainter

- most MW like halos have no satellites; the MW has more MC-like satellites than ~90% of galaxies of its luminosity.

- the *statistics* of the distribution of satellite number match almost perfectly between LCDM prediction & SDSS, as long as the scatter in L-v is relatively small (<0.3 dex)
Highlights

- Scatter between galaxy luminosity & halo mass is small: ~0.15-0.2dex
- Good agreement between several approaches: 2-point clustering, Tully-Fisher relation, measuring luminosities for central galaxies, satellite dynamics
- ~50-100% of the scatter comes from halo mass accretion histories

- HOD of galaxies of a given number density is predicted to be roughly constant from z=0-1. Good agreement with observations but more robust tests are necessary.

- Simple L-M correspondence with low scatter appears to hold down to ~SMC masses
- MW has more MC-like satellites than ~90% of galaxies of its luminosity.
- \( P(N_{\text{sat}}) \) predicted from LCDM agrees with new measurements from SDSS

Simple model works very well.
But data & sims are now good enough to test the details.