Outer Halos and Satellite Galaxies

James Bullock
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- Dwarf galaxies: $\sim 10^{14} M_\odot$; $\sim 10^{11} M_\odot$; $\sim 10^{8} M_\odot$

- Galaxy clusters: $\sim 10^{10} M_\odot$; $\sim 10^{9} M_\odot$; $\sim 10^{8} M_\odot$
Halo Densities: JSB et al. 2001

\[ c \approx \frac{8}{1 + z} \left( \frac{M}{M_*} \right)^{-0.1} \]

\( c = \frac{R_{\text{vir}}}{r_2} \)

1. \( c \) decreases with mass (e.g. NFW97)
2. Large scatter at fixed \( M \) (e.g. Jing00)
3. Halos less concentrated @ \( z>0 \)

NFW97, Jing 00, Eke et al. 01, ... Maccio et al. 06
Halo Shapes: Allgood et al. 2005

\[ s(M, z) \simeq 0.54 \left( \frac{M}{M_*(z)} \right)^{-0.05} \]

\( s = \) short/long axis

1. Galaxy halos rounder than clusters
2. Halos get rounder with time

(e.g. JSB 02)

Jing & Suto 02, Springel et al. 04, Bailin & Steinmetz 05, Kasun & Evrard 05, Hopkins et al. 05.
Halo Substructure
Klypin et al. 99

\[ \frac{dN}{dV_{\text{max}}} \sim V^{-3.5} \]

V_{\text{max}} = (GM/r)^{1/2}

1. Rising subhalo velocity function
2. Mass fraction \( f_{\text{sub}} \lesssim 10\% \)

Moore et al. 99 Font et al. 01...
Diemand et al. 06; Kuhlen et al. 06
J. Bullock, UC Irvine

More Halo Substructure

Subhalos follow DM halo orientation

Zentner et al. 05
(N-body + hydro clusters)
=> subhalos align with MAJOR axis of DM halo (direction of last major merger...)

Bailin et al. 05; Libeskind et al. 05
(Hydro)
=> outer halo uncorrelated with disk. Halos (& sat distribution) flattened.
Halo Substructure

The Dwarf Problem

What is $V_{\text{max}}$?

Stoehr et al. 02, Hayashi et al. 03, Kazantzidis et al. 04
Counting Dwarfs: What is the Vmax of a dSph?

Answer: it’s very hard to tell

Simple example:
Given: 2 observed constraints:
1. A central velocity dispersion, $\sigma_*$
2. A galaxy size, $r_*$

Infinite pairs of DM halo parameters can fit data...
1. Maximum circular velocity, $V_{\text{max}}$
2. Radius of maximum velocity, $R_{\text{max}}$

Real situation is even worse -- Velocity anisotropy $\beta$ of stars is unknown.

Both V(r) profiles work.

$V_{\text{max}} = 35 \text{ km/s}$

$V_{\text{max}} = 15 \text{ km/s}$
Counting Dwarfs: What is the $V_{\text{max}}$ of a dSph?

Fit a Line Of Sight (LOS) stellar velocities to DM halo parameters.

![Graph showing velocity dispersion vs. radius and allowed region in $R_{\text{max}}$ vs. $V_{\text{max}}$ space.](image)
A more detailed comparison

Strigari, JSB, Kaplinghat

Data from Wilkinson et al. (2004)

Data from Walker et al. (2006)
Use CDM “Prior” to estimate $V_{\text{max}}$

1. Assume cuspy (stripped) profiles and derive 2-sigma allowed parameter range:

2. Impose slightly theory prior for the $R_{\text{max}}$ vs. $V_{\text{max}}$ relation

---

**Draco**

**Fornax**

LCDM expectation

“field halos”

“subhalos”
Without some kind of theory prior, $V_{\text{max}}$ of every dwarf is unconstrained!

- Fornax: $V_{\text{max}} \sim 20\text{km/s}$
- Draco: $V_{\text{max}} \sim 20\text{km/s}$
- Carina: $V_{\text{max}} \sim 12\text{km/s}$
- Sculptor: $V_{\text{max}} \sim 15\text{km/s}$
Will it ever be possible to measure $V_{\text{max}}$?

Today: state of the art:
~500 LOS velocities.

Future?
1000 LOS velocities
500 proper motions (SIM)

Strigari et al.
Satellites & Random Velocities (External Galaxies)

Satellite kinematics => outer halos fall as expected for NFW (Prada et al. 06)

Satellite orientations -- Sats oriented along MAJOR axis of red galaxies.
(Zaritzky et al.; Yang et al.; Brainerd et al.; Sales & Lambas)

-- Sats around disks? -- no strong preference (Azarro et al.)

Stellar velocity dispersions -- Big degeneracy, hard to probe halo (Dekel et al. 05)

Satellites & Random Velocities (Milky Way)

Satellite Orientation -- Sats sit towards Galactic poles?

Stellar streams (Sgr) -- Halo quite round, s>0.9 (e.g. Johnston et al. 05)

Stellar halo velocities -- Big degeneracy, hard to probe halo (Dehnen et al. 05)
Should get better in the future, e.g. LSST
Galaxy Scales

Mass to (Central Galaxy) Light Ratios

Here be baryons!

$\sim f_b^{-1}$

DM virial mass

Purcell, JSB, & Zentner
(adopted from Yang et al. 2003)
Baryons affect halo shapes:

Kazantzidis et al. 05 (Theory):
Baryon Cooling => rounder halos.
Effect may be less in clusters (overcooling?)

“Evidence Against”:
- X-ray cluster isophote shapes match (uncontracted) LCDM halo expectations well. (Flores et al. 2006)

Evidence For:
- Sag. Stream models for MW halo suggest MW halo is rounder than dissipationless LCDM halos, s>0.9. (e.g. Johnston et al. 2006)
Evidence Against:
- TF relation, late type galaxies (Dutton et al. 06; Gnedin et al. 06) unless $c(M)$ initial is lower than standard LCDM
- X-ray studies of massive early-type galaxies (Humphrey et al. 06)
- X-ray studies of galaxy clusters (e.g. Zappacosta et al. 06)

Gnedin et al. 05: (Theory)
DM halo adiabatically contract (AC) in reaction to infall of baryons. “Expected” for smooth slow infall, but seems to happen even in cosmological simulations.
Evidence For:

Seigar, Barth, & JSB, submitted

New mass model for M31:
(Improved baryonic model)

\[ M_{\text{vir}} = 9 \times 10^{11} \text{ Msun} \]
\[ c_{\text{vir}} = 12 \text{ (initial)} \]
\[ f_{\text{gal}}/f_{\text{b}} = 0.7 \]

model without AC cannot produce fall-off in rotation curve

see also Klypin et al. 02
TF relation constraints on Halo Densities...

Galaxy Scales
Dutton et al. 06, Gnedenin et al. 06
More on Adiabatic Contraction

EITHER
lower concentrations
OR
no Adiabatic Contraction

Gnedin et al. 06
AC + LCDM
concentrations

AC + low
concentrations
spread at fixed $M$ is caused by formation time

Wechsler, JSB, Primack, Kravtsov, & Dekel 02

$$M_{DM} = M_0 e^{-\alpha z}$$

Also NFW97, Jing00, Zhao et al. 03; Tasitsiomi et al. 04

**More Density Profiles...**

Distinct haloes

Early formation

Late formation

$M_{DM} = M₀ e^{-αz}$

Rapid accretion

Slow accretion

Formation epoch $a_c$
Formation epoch of “rapid mass accretion” governs c in nearly 1 to 1 way.

Wechsler, JSB, Primack, Kravtsov, & Dekel 02
Early Type galaxies?

Late Type galaxies?

Wechsler & JSB
See also discussion in Maccio et al. 06
Low concentration galaxy halos are less clustered than high concentration halos.

Similar to trend seen with late type vs. early type galaxies...

120 Mpc box LCDM simulation

Also: Wang et al. 06, Wetzel et al. 06, Croton et al. 06, Zhu et al. 06, Reed et al. 06, Gao et al. 05, Sheth et al. 04.
Zentner et al. 05

Concentration correlates with # of objects in groups/clusters

**Low c: many satellites**

=> Unrelaxed Groups & Clusters

**High c: few satellites**

“Fossil Groups” / Relaxed Clusters
Early Type galaxies?

Late Type galaxies?

Fossil Groups
Relaxed clusters

Unrelaxed groups
Disturbed clusters

Wechsler & JSB
See also discussion in Maccio et al. 06
Compilation:
39 \textit{relaxed} systems with highest quality XMM & Chandra Data

\textbf{Humphrey et al. 06} [Early type galaxies]

\textbf{Gastaldello et al. 06} [Groups + poor clusters]

\textbf{Zappacosta et al. 06} 
\textbf{Pointecouteau et al. 05} 
\textbf{Vikhlinin et al. 06} [Massive Clusters]

\textbf{Buote et al. 06}

\textit{The X-ray Concentration-Virial Mass Relation}

\textbf{David A. Buote}^{1}, \textbf{Fabio Gastaldello}^{1}, \textbf{Philip J. Humphrey}^{1}, \textbf{Luca Zappacosta}^{1}, \textbf{James S. Bullock}^{1}, \textbf{Fabrizio Brighenti}^{2,3}, \textbf{& William G. Mathews}^{2}

Submitted to The Astrophysical Journal

astro-ph/\~next week

\textbf{LCDM} $\sigma_8 \sim 0.9$
Wechsler & JSB
See also discussion in Maccio et al. 06
**Density profiles**

**TF / rotation curves** -- Late-types need lower c’s than LCDM or no adiabatic contraction

**X-ray** -- Massive E’s, Relaxed Groups, Clusters. Clear c(M) trend detected (first!). Need slightly higher c’s than LCDM.

**Substructure**

**Dwarf counts** -- ? need model prior OR next generation data.

**Sat orientation** -- with Major axis of ellipticals (good!) need more data on disks

**Shapes**

**X-ray & Milky Way** -- Generally consistent with LCDM expectations.