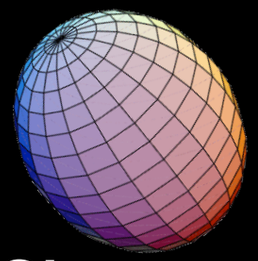
Outer Halos and Satellite Galaxies

James Bullock

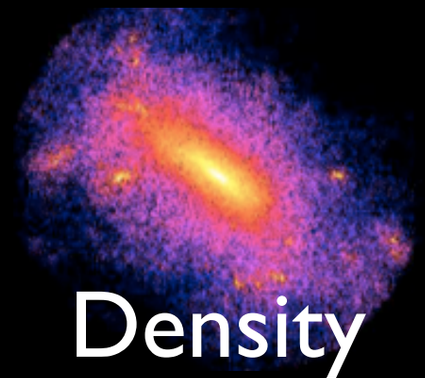
CENTER FOR COSMOLOGY

UNIVERSITY OF CALIFORNIA, IRVINE

Outline/ Matrix



Shapes



Density

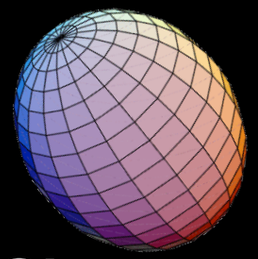
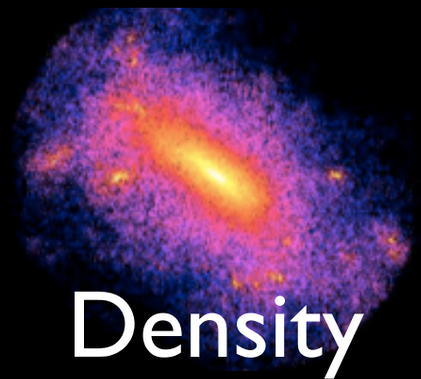
Substructure

Dwarfs

Galaxies

Clusters

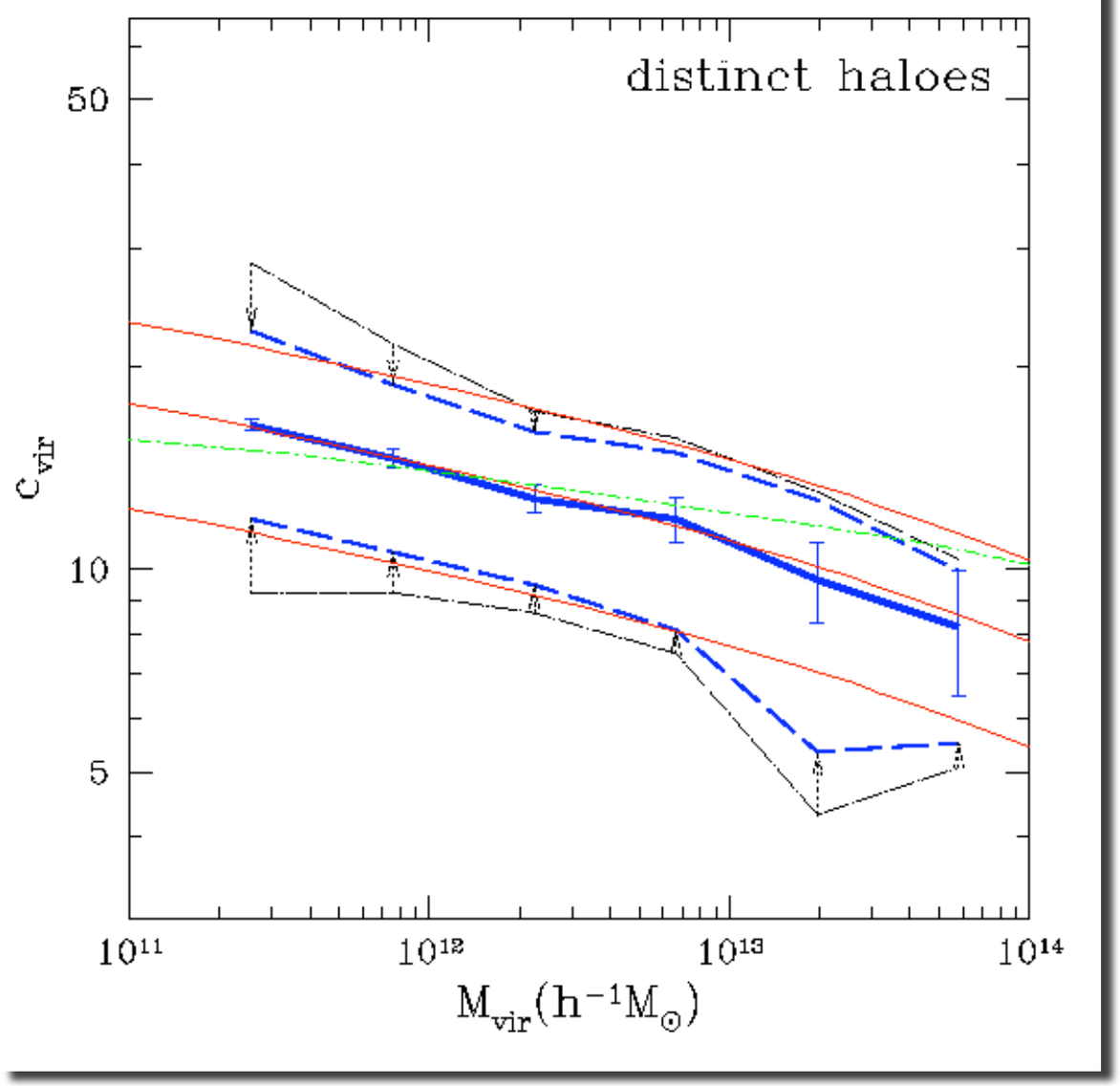
What is the outline

Outline/ Matrix	 Shapes	 Density	 Substructure
 Dwarfs			
 Galaxies			
 Clusters			

Halo Densities: JSB et al. 2001

Profiles of dark haloes: evolution, scatter, and environment

J. S. Bullock[1,2], T. S. Kolatt[1,3], Y. Sigad[3], R.S. Somerville[3,4], A. V. Kravtsov[2,5⋆], A. A. Klypin[5], J. R. Primack[1], and A. Dekel[3]



$$c \simeq \frac{8}{1+z}\left(\frac{M}{M_*}\right)^{-0.1}$$

$c = R_{vir}/r_{-2}$

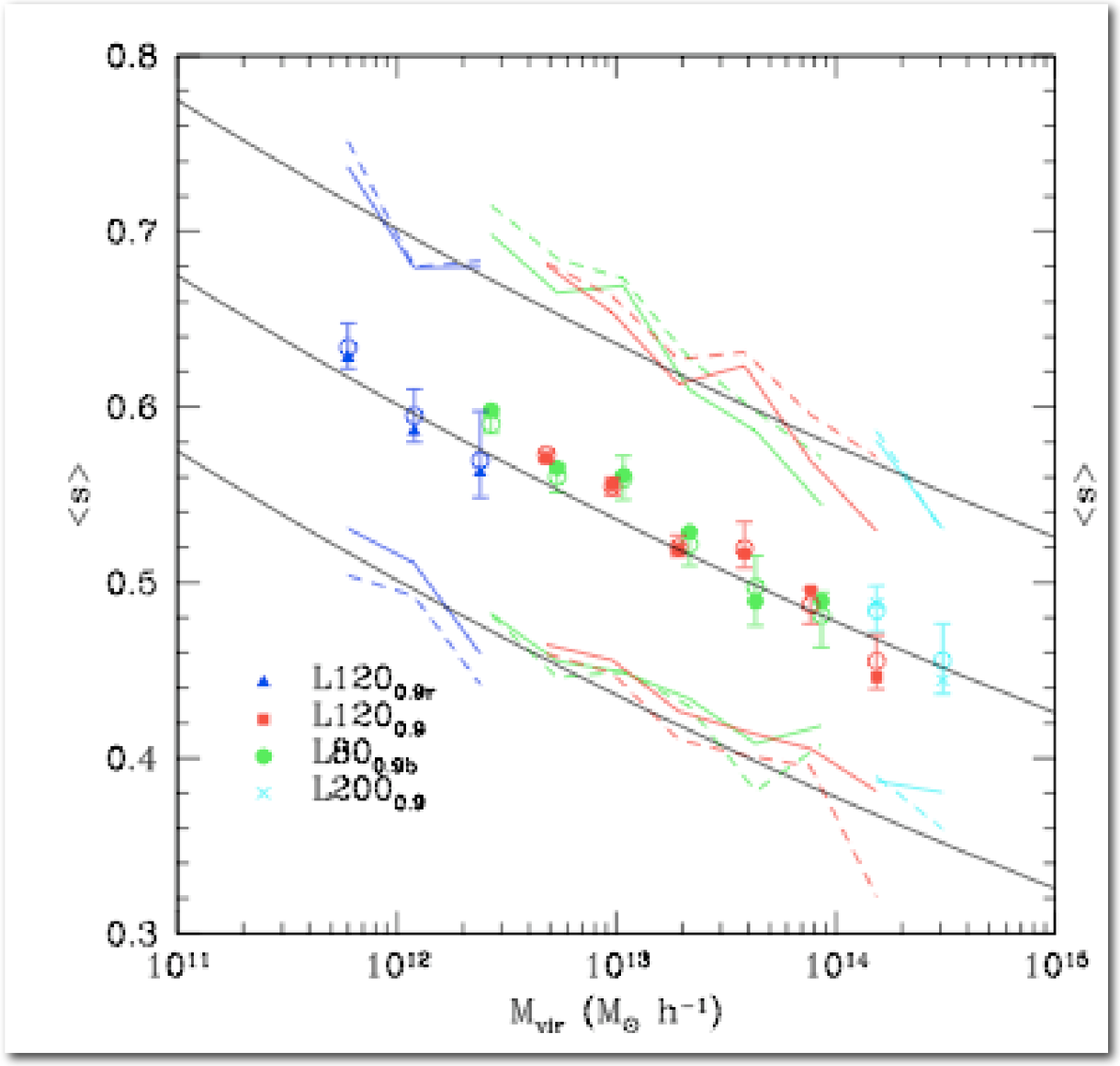
1. c decreases with mass (e.g. NFW97)
2. Large scatter at fixed M (e.g. Jing00)
3. Halos less concentrated @ z>0

NFW97, Jing 00, Eke et al. 01, ... **Maccio et al. 06**

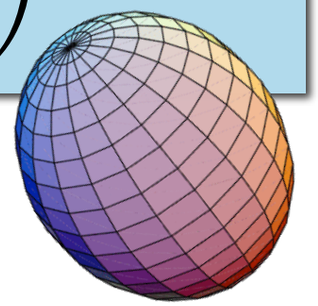
Halo Shapes: Allgood et al. 2005

The Shape of Dark Matter Halos: Dependence on Mass, Redshift, Radius, and Formation

Brandon Allgood[1], Ricardo A. Flores[2], Joel R. Primack[1], Andrey V. Kravtsov[3], Risa H. Wechsler[3,4], Andreas Faltenbacher[5], and James S. Bullock[6]



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



s = short/long axis

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

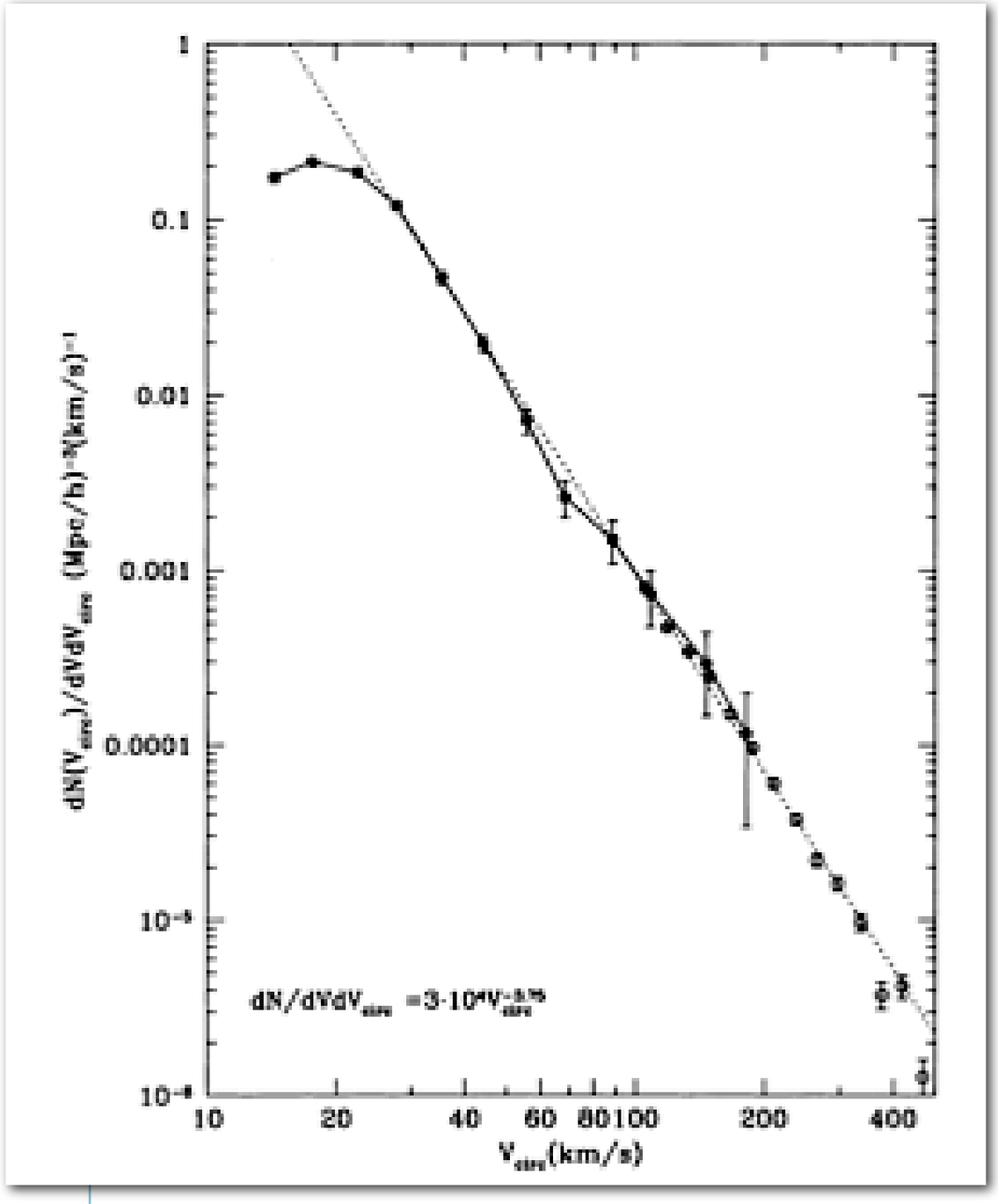
(e.g. JSB 02)

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

Halo Substructure
Klypin et al. 99

WHERE ARE THE MISSING GALACTIC SATELLITES?

ANATOLY KLYPIN, ANDREY V. KRAVTSOV, AND OCTAVIO VALENZUELA
Astronomy Department, New Mexico State University, Box 30001, Department 4500, Las Cruces, NM 88003-0001
AND
FRANCISCO PRADA
Instituto de Astronomia, Apartado Postal 877, 22900 Ensenada, Mexico
Received 1999 January 18; accepted 1999 April 15



$$\frac{dN}{dV_{\rm max}} \sim V_{\rm max}^{-3.5}$$

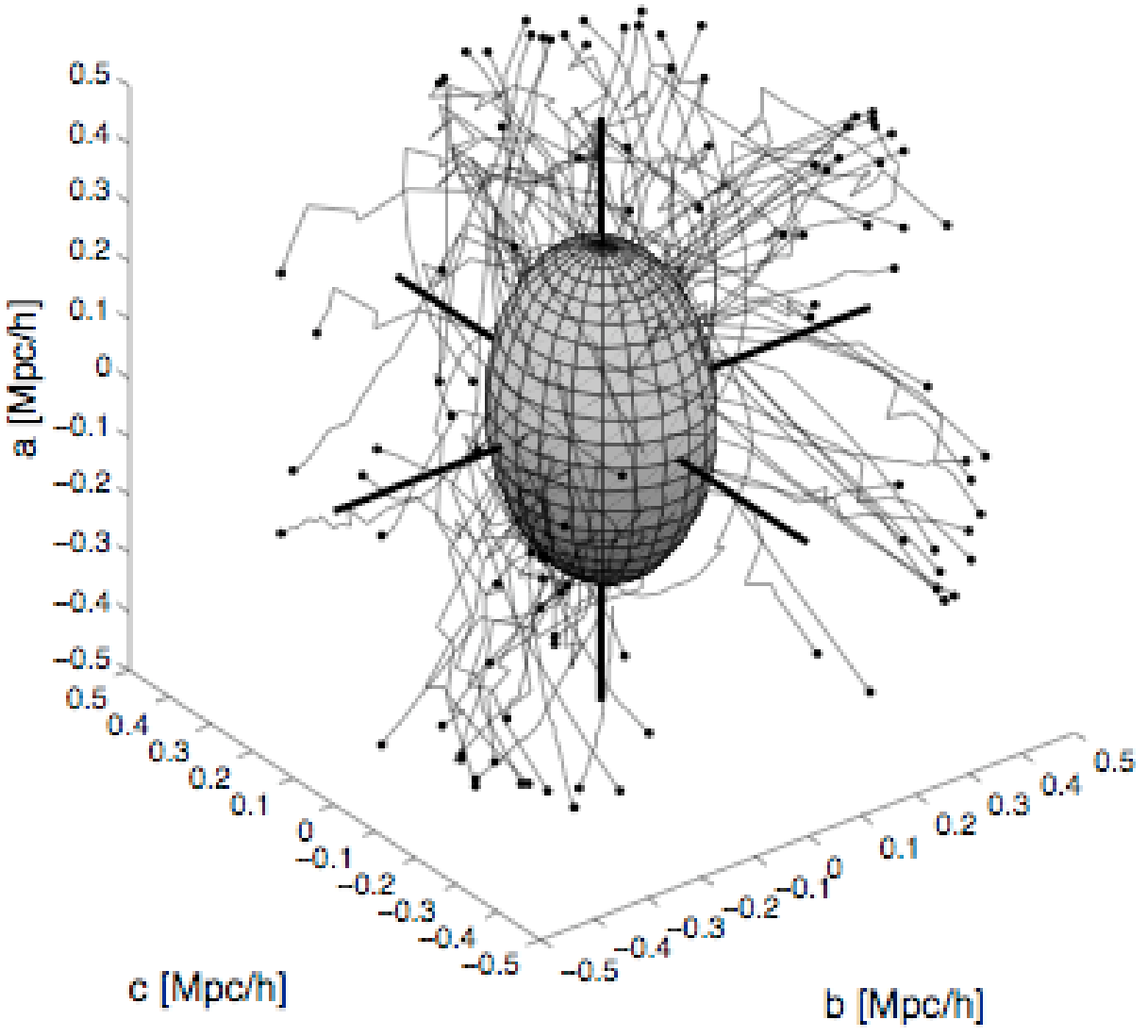
Vmax = (GM/r)^1/2

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

Moore et al. 99 Font et al. 01...
Diemand et al. 06; Kuhlen et al. 06

More Halo Substructure

Subhalos follow DM halo orientation

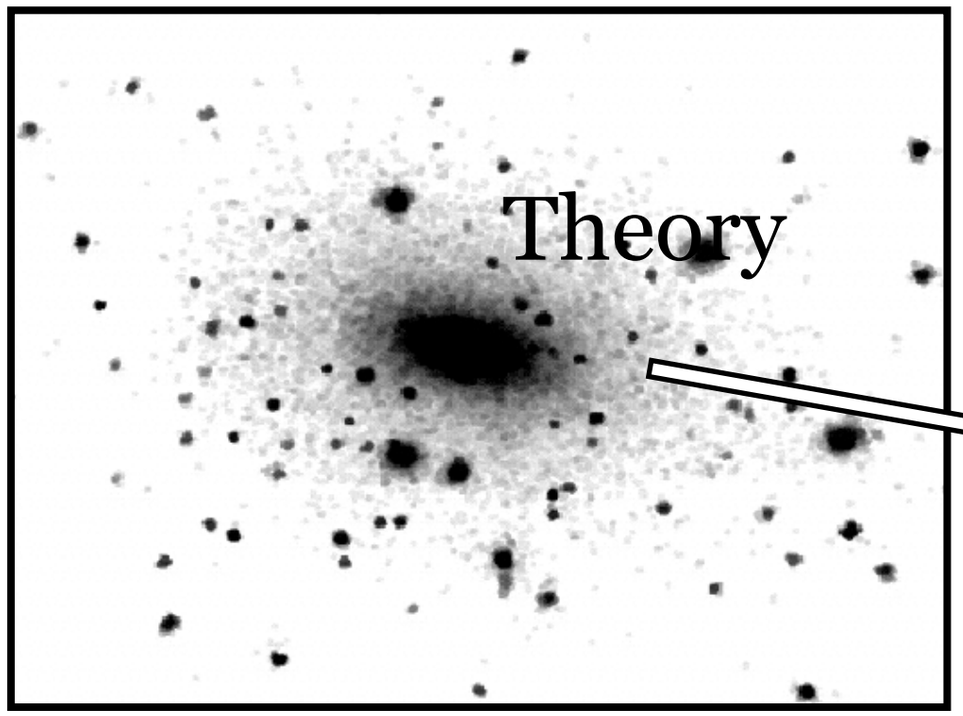


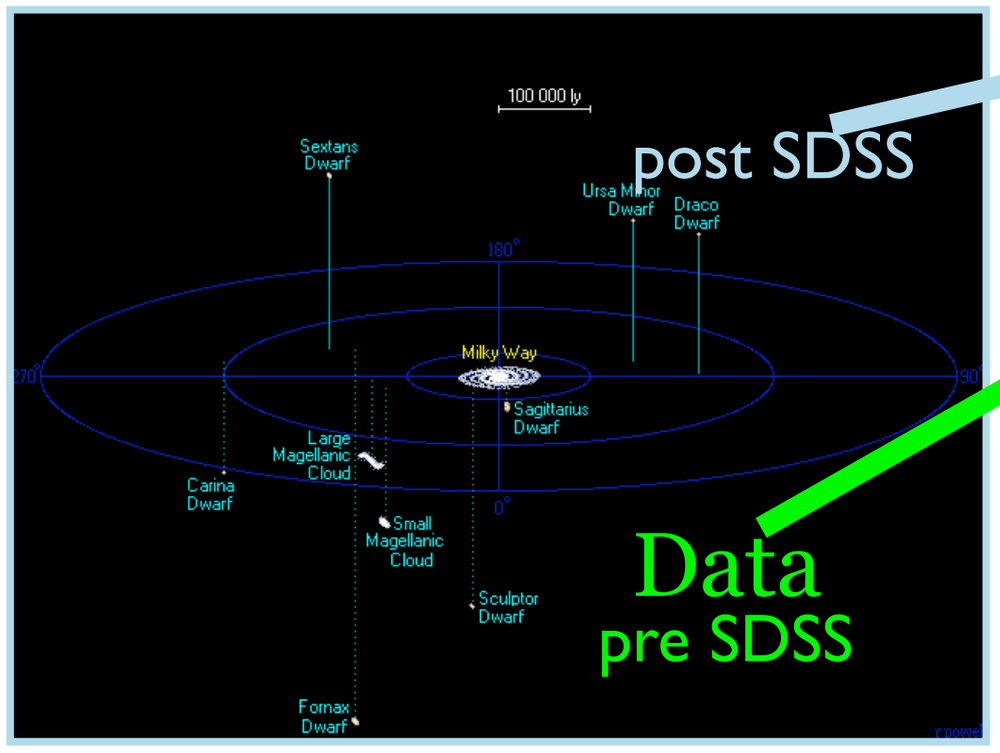
Zentner et al. 05
(N-body + hydro clusters)
=> subhalos align with MAJOR axis of DM halo (direction of last major merger...)

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

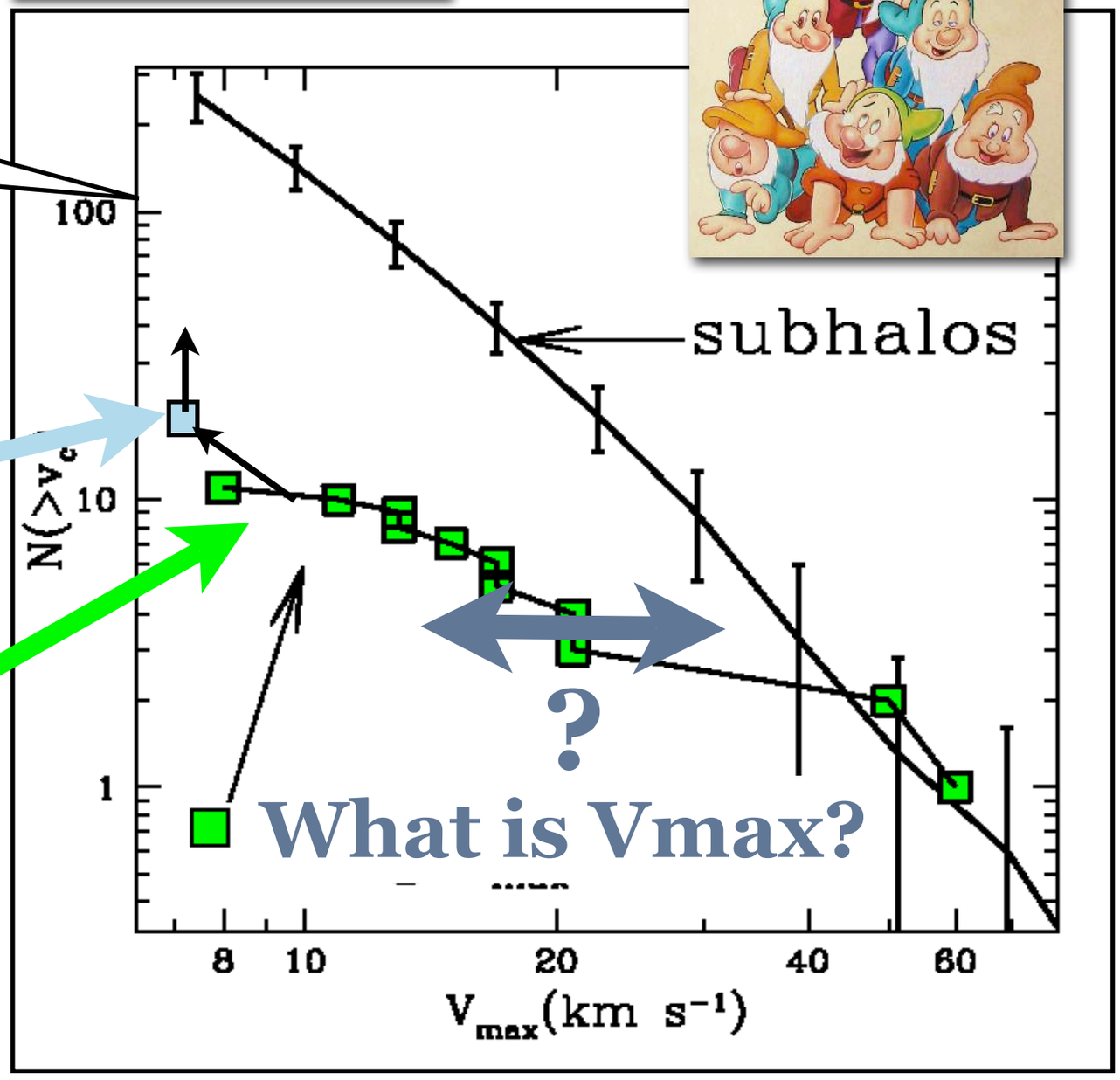
Halo Substructure

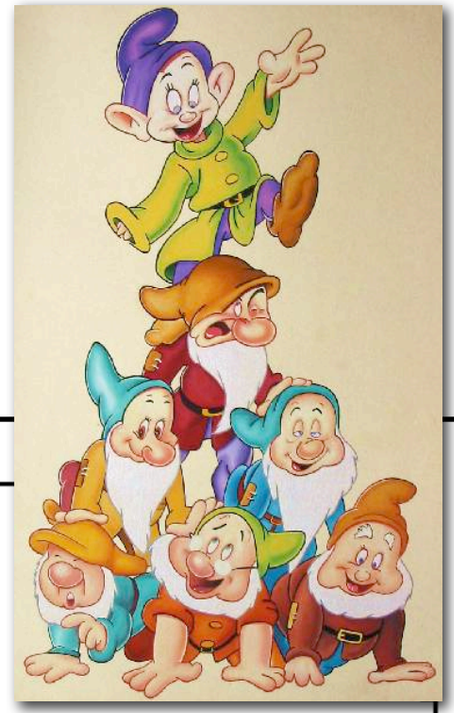
The Dwarf Problem





Zentner & JSB 03





Stoehr et al. 02, Hayashi et al. 03, Kazantzidis et al. 04

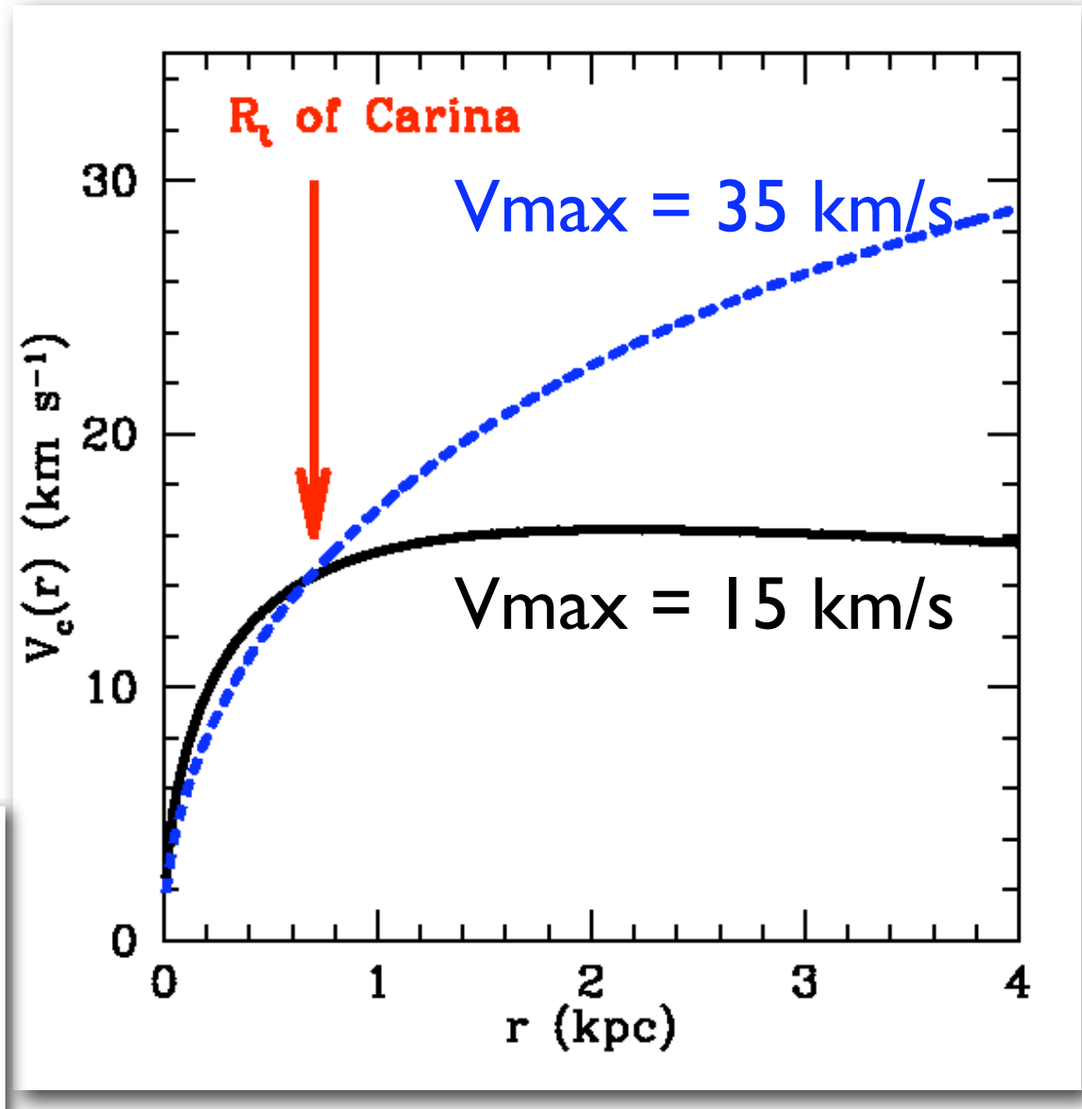
Counting Dwarfs: What is the Vmax of a dSph?

Answer: it's very hard to tell

Simple example:

Given: **2 observed constraints**:

1. A central velocity dispersion, σ_*
2. A galaxy size, r_*



Both V(r) profiles work.

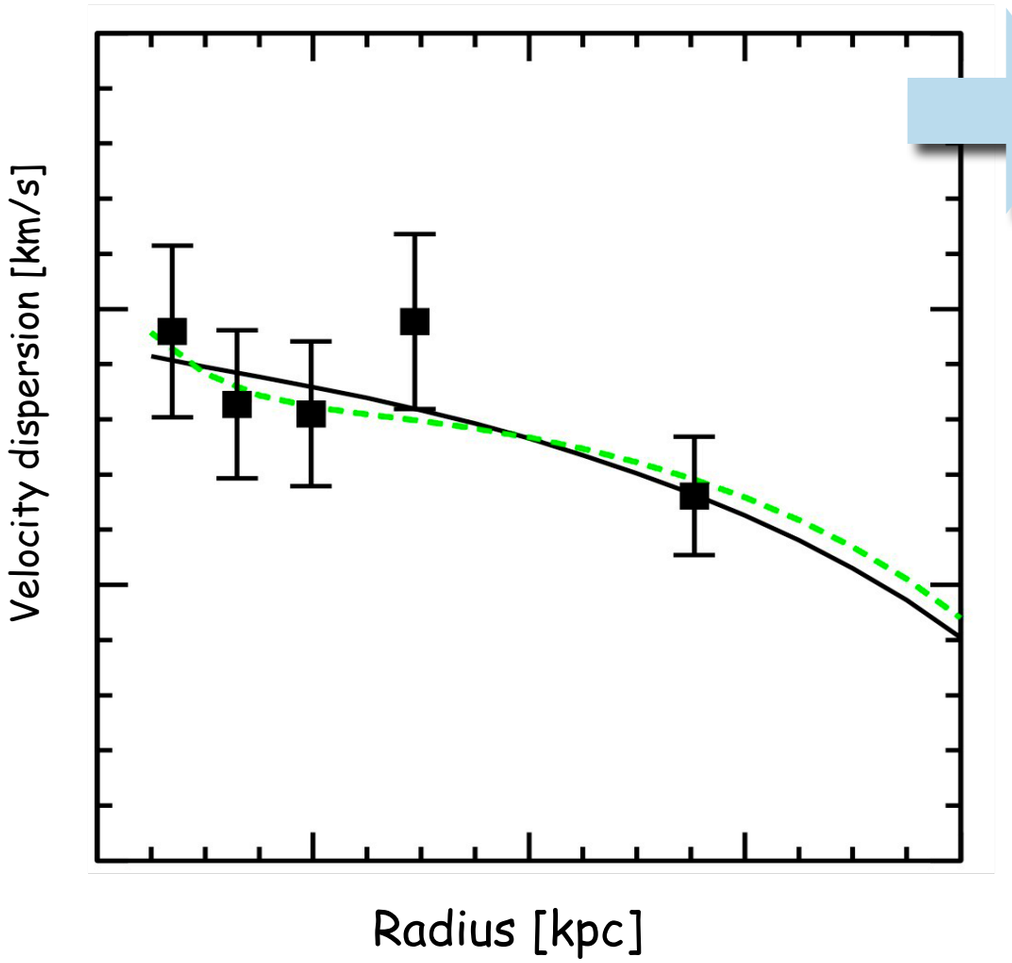
Infinite pairs of DM halo parameters can fit data...

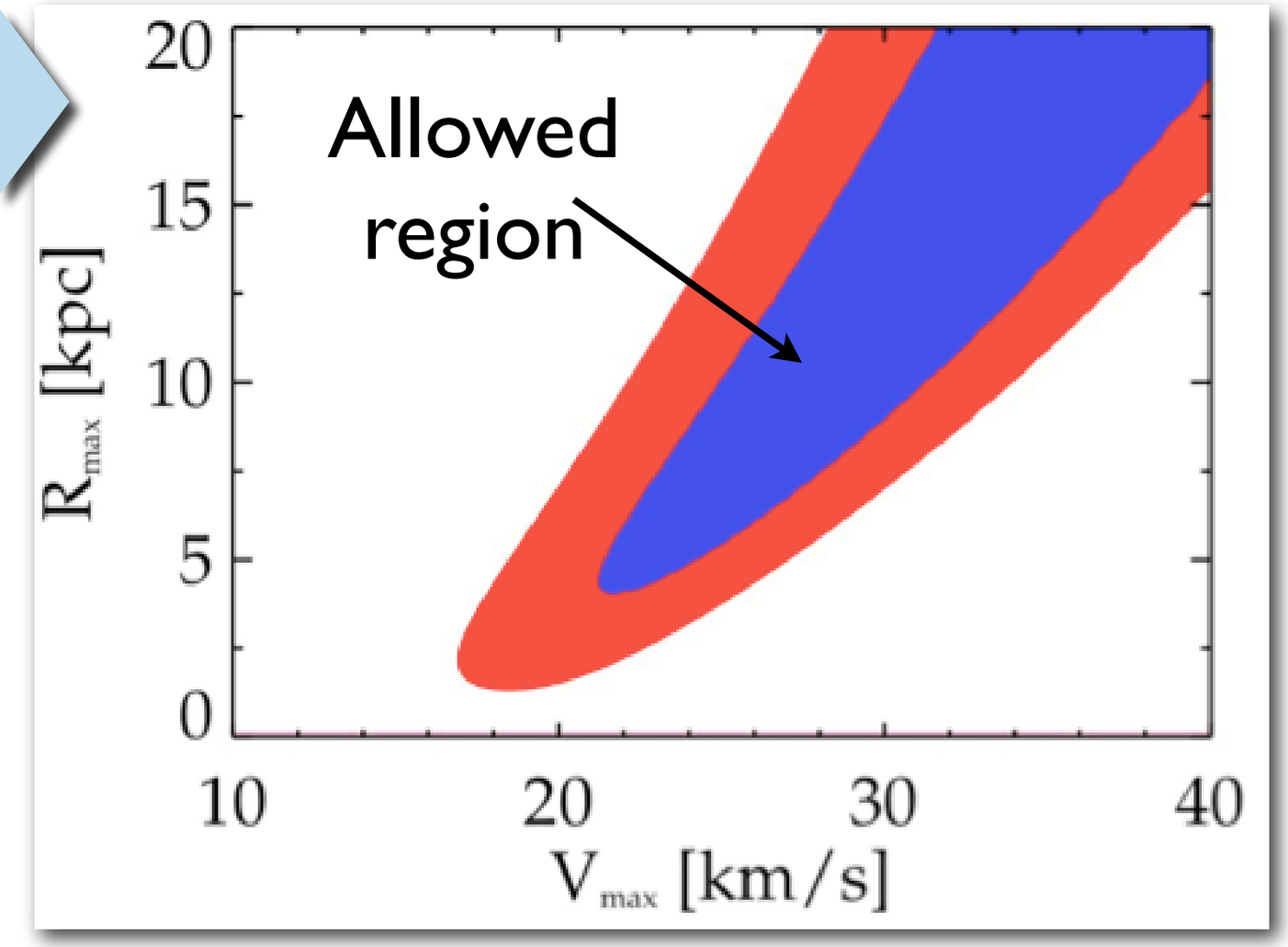
1. Maximum circular velocity, V_{max}
2. Radius of maximum velocity, R_{max}

Real situation is even worse -- Velocity anisotropy β of stars is unknown.

Counting Dwarfs: What is the Vmax of a dSph?

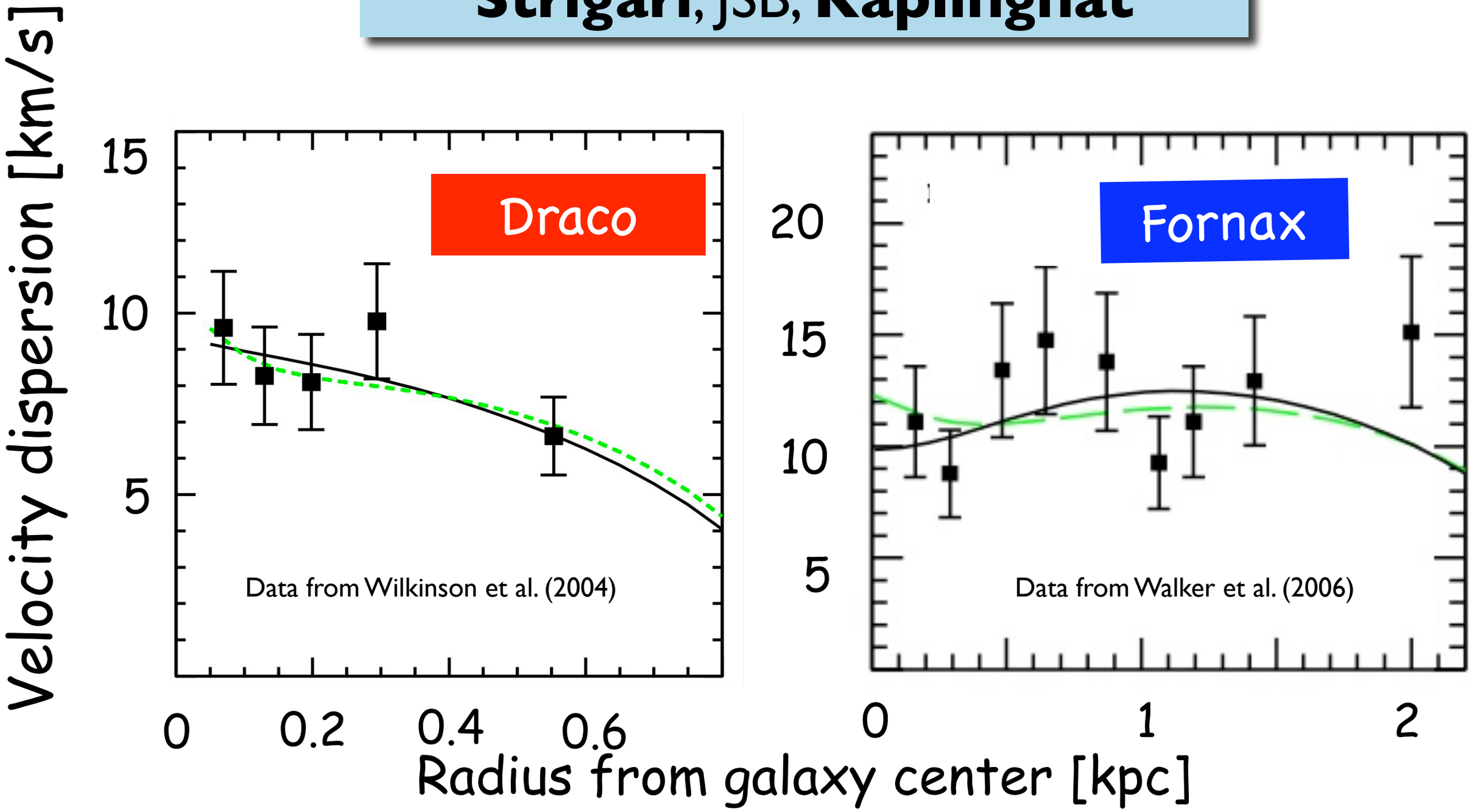
Fit a Line Of Sight (LOS) stellar velocities to DM halo parameters.





A more detailed comparison

Strigari, JSB, **Kaplinghat**

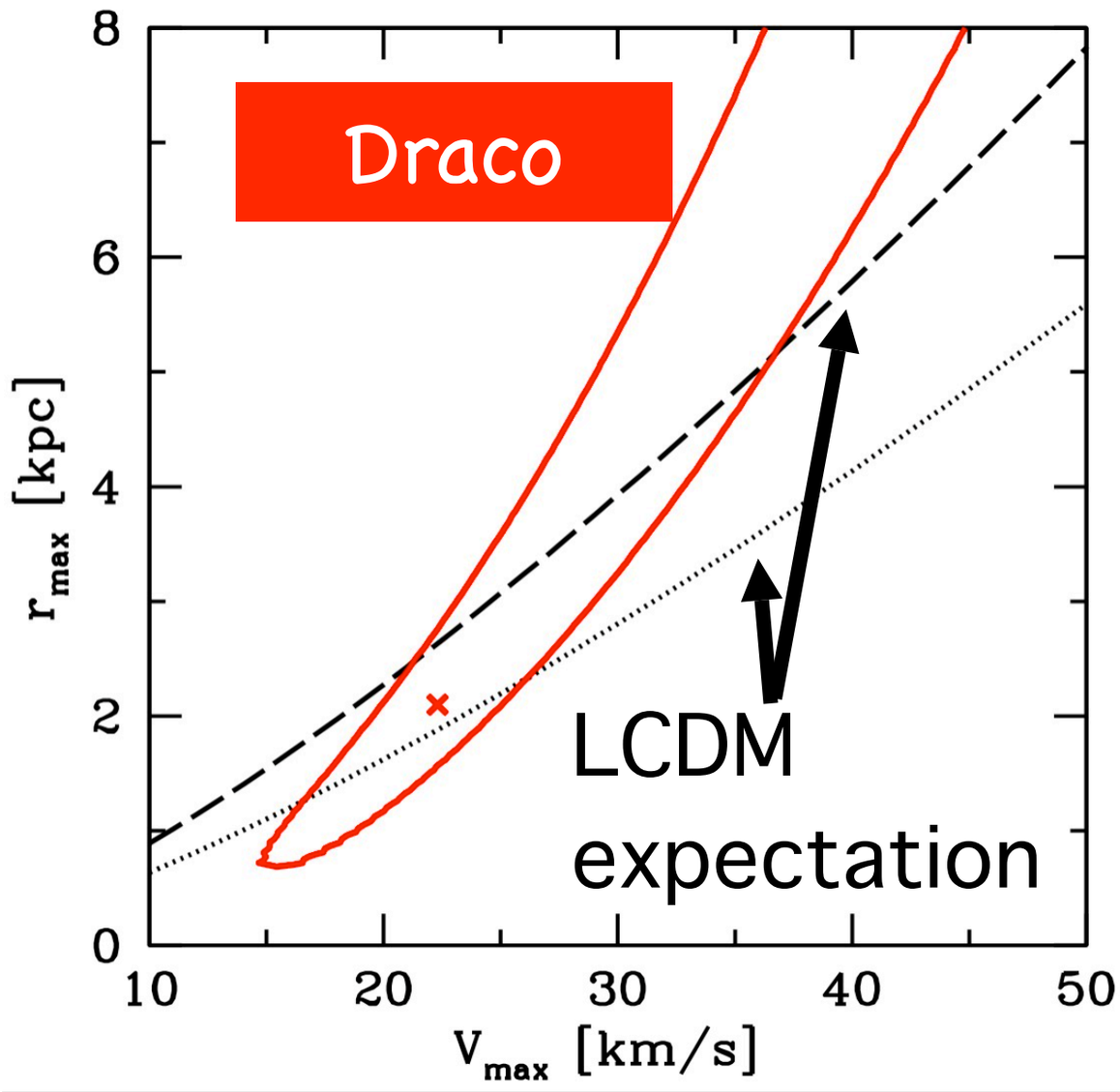


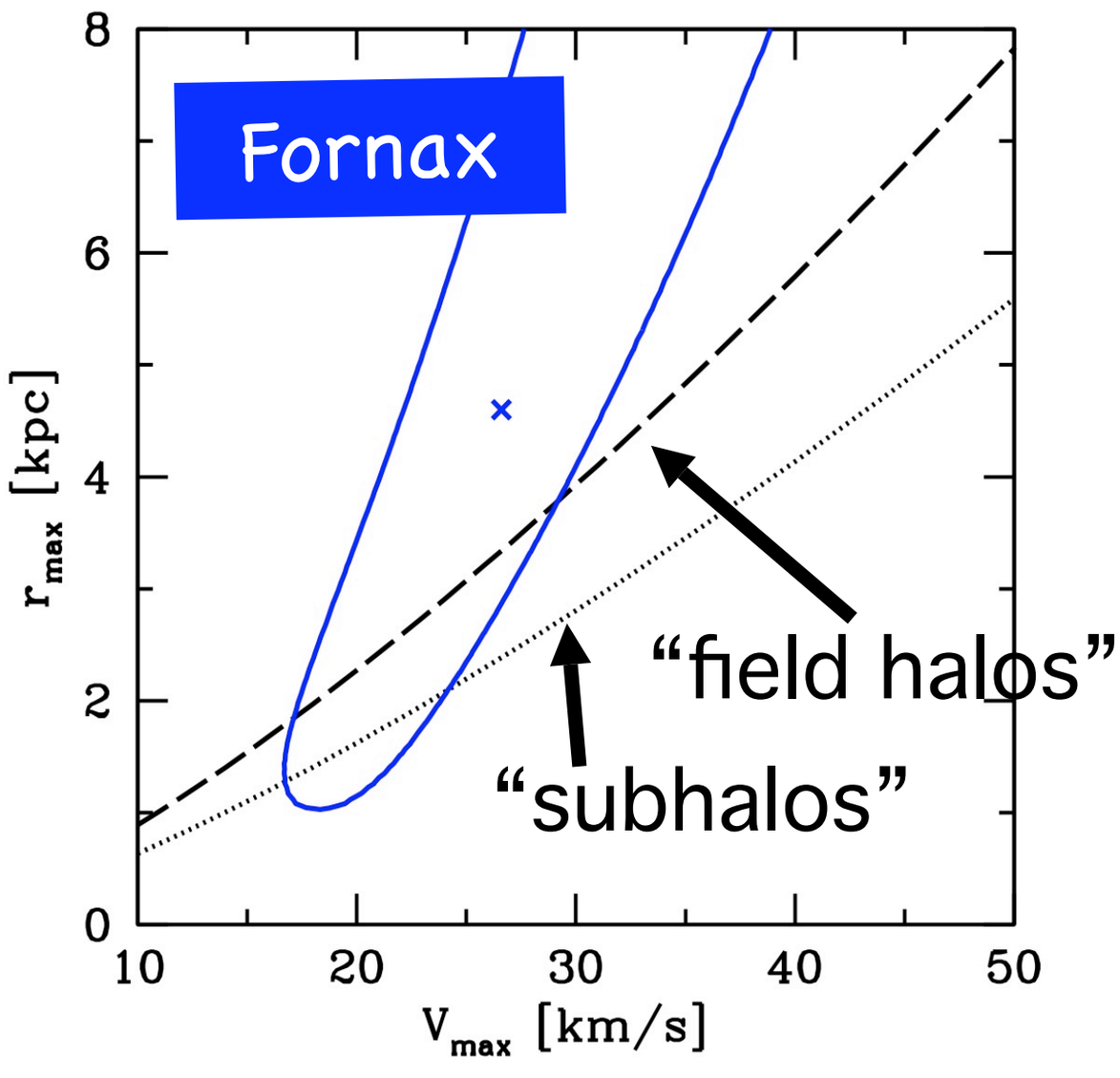
Strigari et al.

Use CDM "Prior" to estimate Vmax

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

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

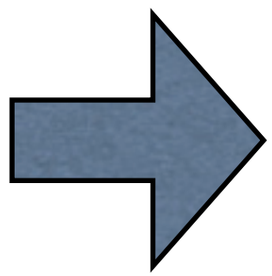




Strigari et al.

Best Guess for LCDM Halos:

Without some kind of theory prior, Vmax of every dwarfs is unconstrained!

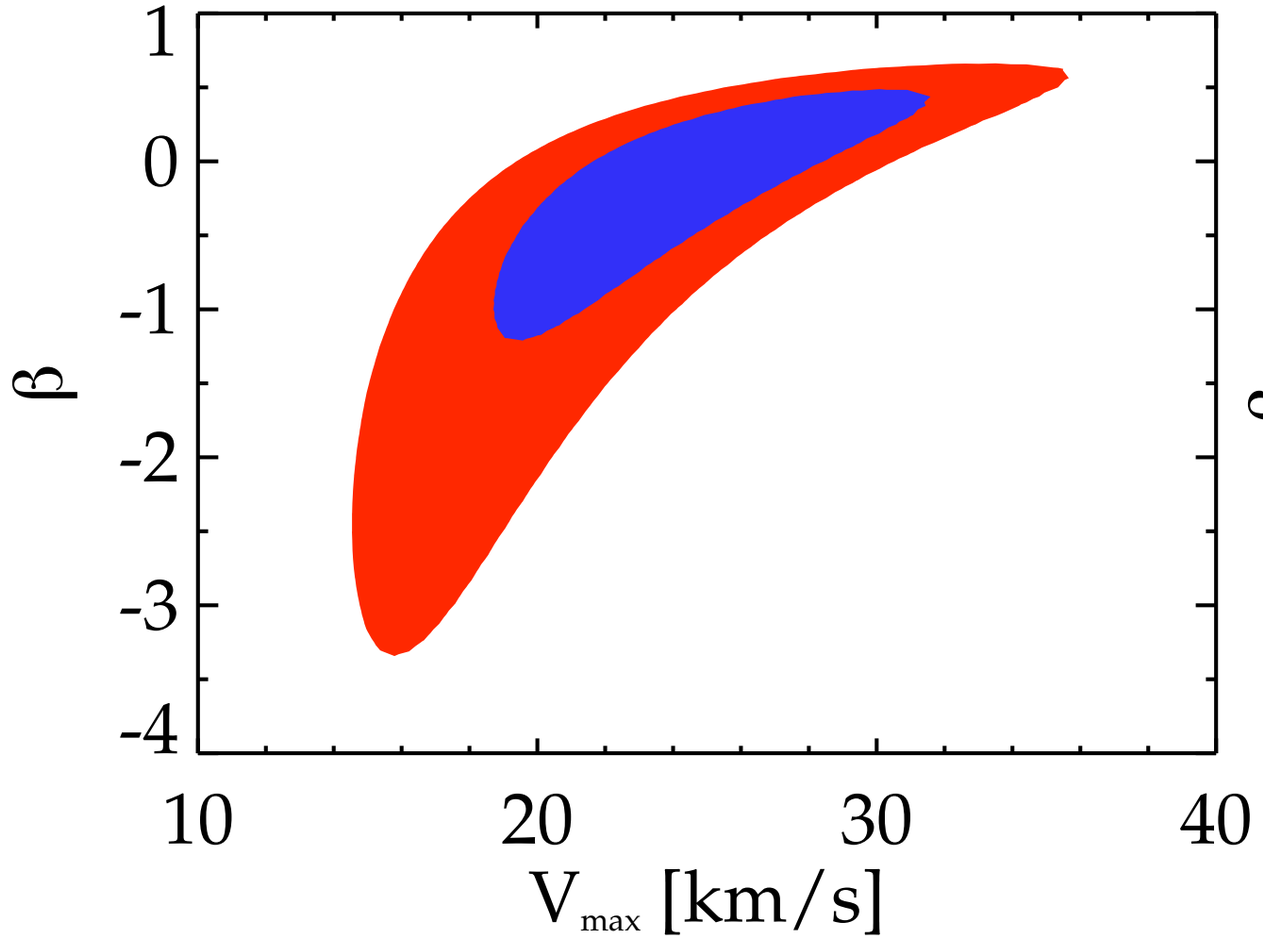


- Fornax: V_{max}~20km/s
- Draco: V_{max}~20km/s
- Carina: V_{max}~12km/s
- Sculptor: V_{max}~15km/s

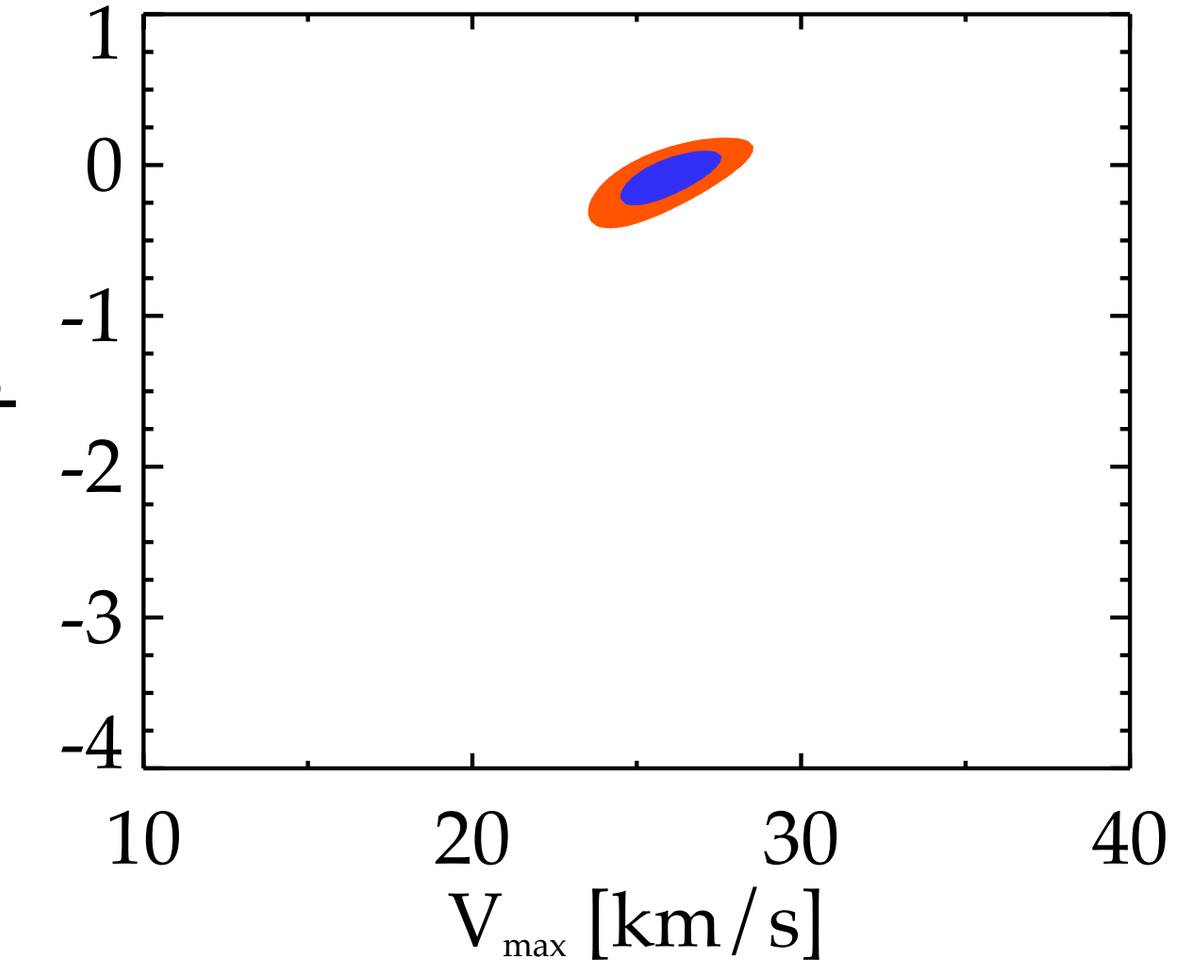
Will it ever be possible to measure Vmax?

Strigari et al.

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



Future?
1000 LOS velocities
500 poper motions (SIM)



Galaxy Scales ⇒ Probes of Galaxy Halos

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) (as would be expected if formed in merger.)

-- 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?

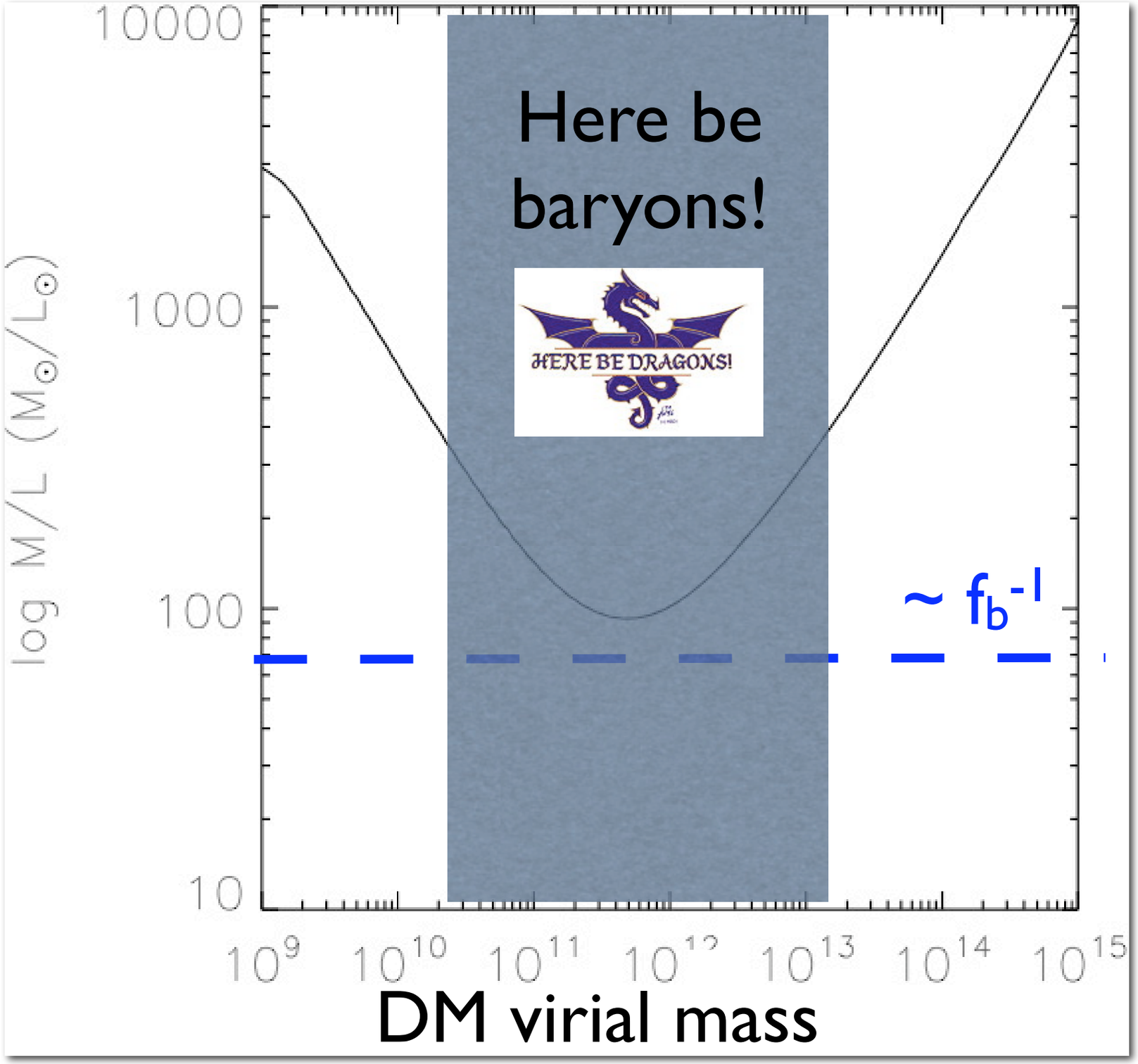
Stellar streams (Sgr) -- Halo quite round, s>0.9 (e.g. Johnston et al. 05)

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



Purcell, JSB, & Zentner (adopted from **Yang et al. 2003**)

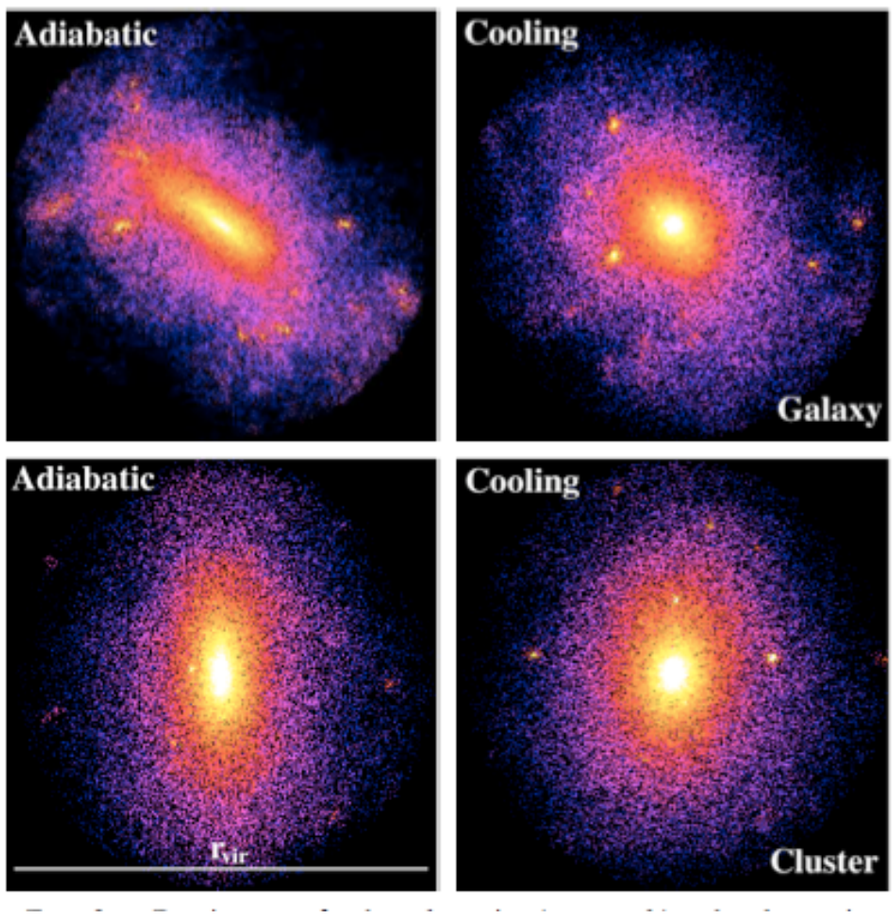
Galaxy Scales

Baryons affect halo shapes:

Kazantzidis et al. 05 (Theory):

Baryon Cooling => rounder halos.

Effect may be less in clusters (overcooling?)



"Evidence Against":

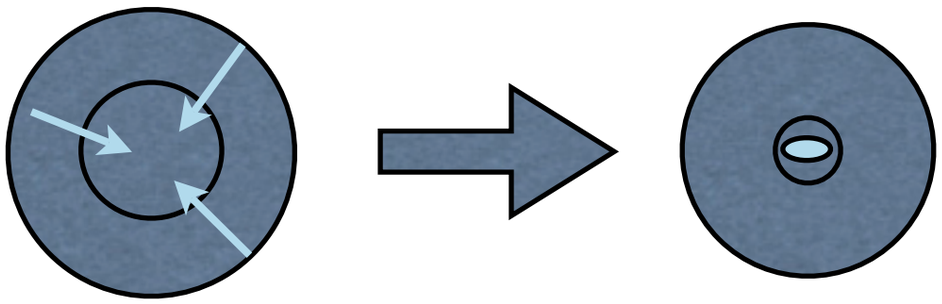
- X-ray cluster isophote shapes match (uncontracted) LCDM halo expectations well. (Flores et al. 2006)

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)

Galaxy Scales

Baryons affect halo concentration:



Gnedin et al. 05: (Theory)

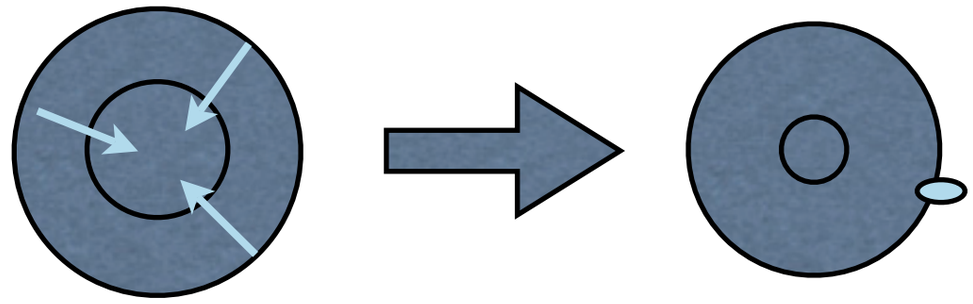
DM halo adiabatically contract (AC) in reaction to infall of baryons. "Expected" for smooth slow infall, but seems to happen even in cosmological simulations.

Evidence 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)

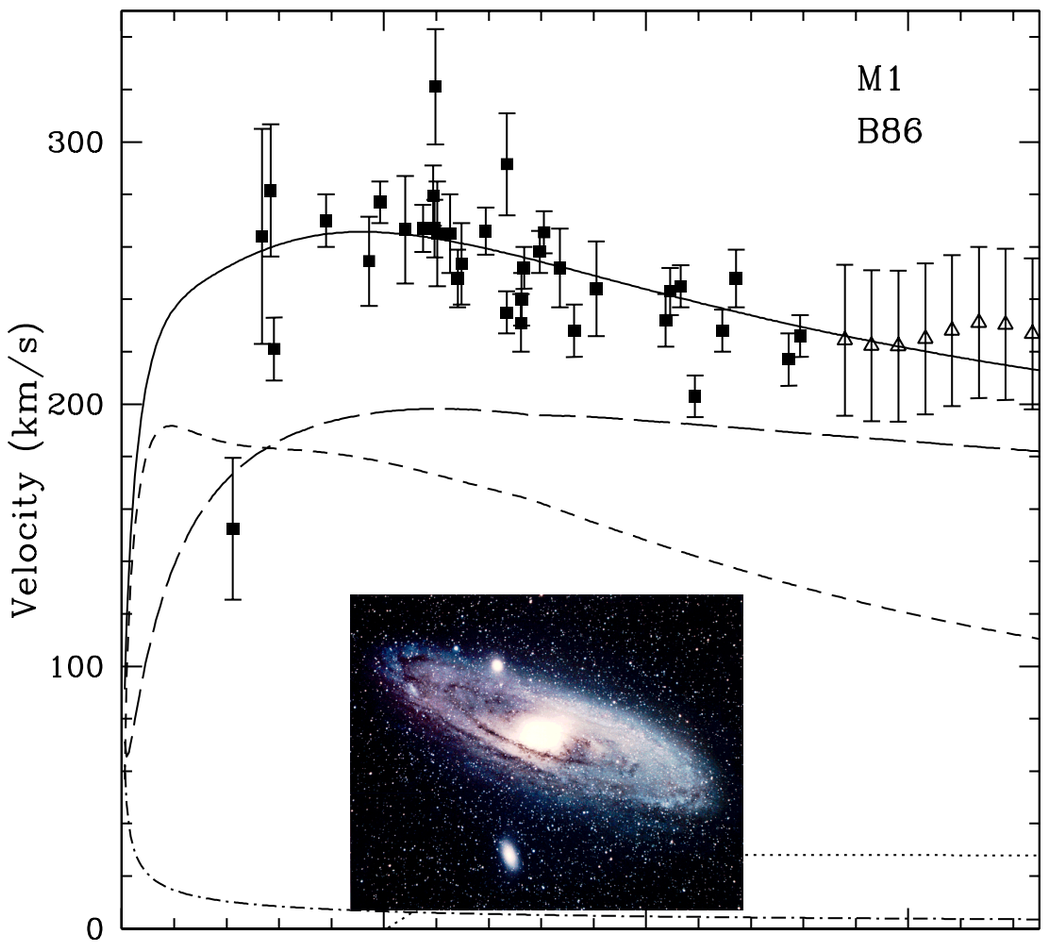
Galaxy Scales Baryons affect halo concentration:

Gnedin et al. 05: (Theory)
DM halo adiabatically contract (AC).



Evidence For:

Seigar, Barth, & JSB, submitted



New mass model for M31:
(Improved baryonic model)
=>

$M_{vir} = 9 \times 10^{11}$ Msun
$c_{vir} = 12$ (initial)
$f_{gal}/f_b = 0.7$

~typical for LCDM

model without AC cannot produce fall-off in rotation curve

see also Klypin et al. 02

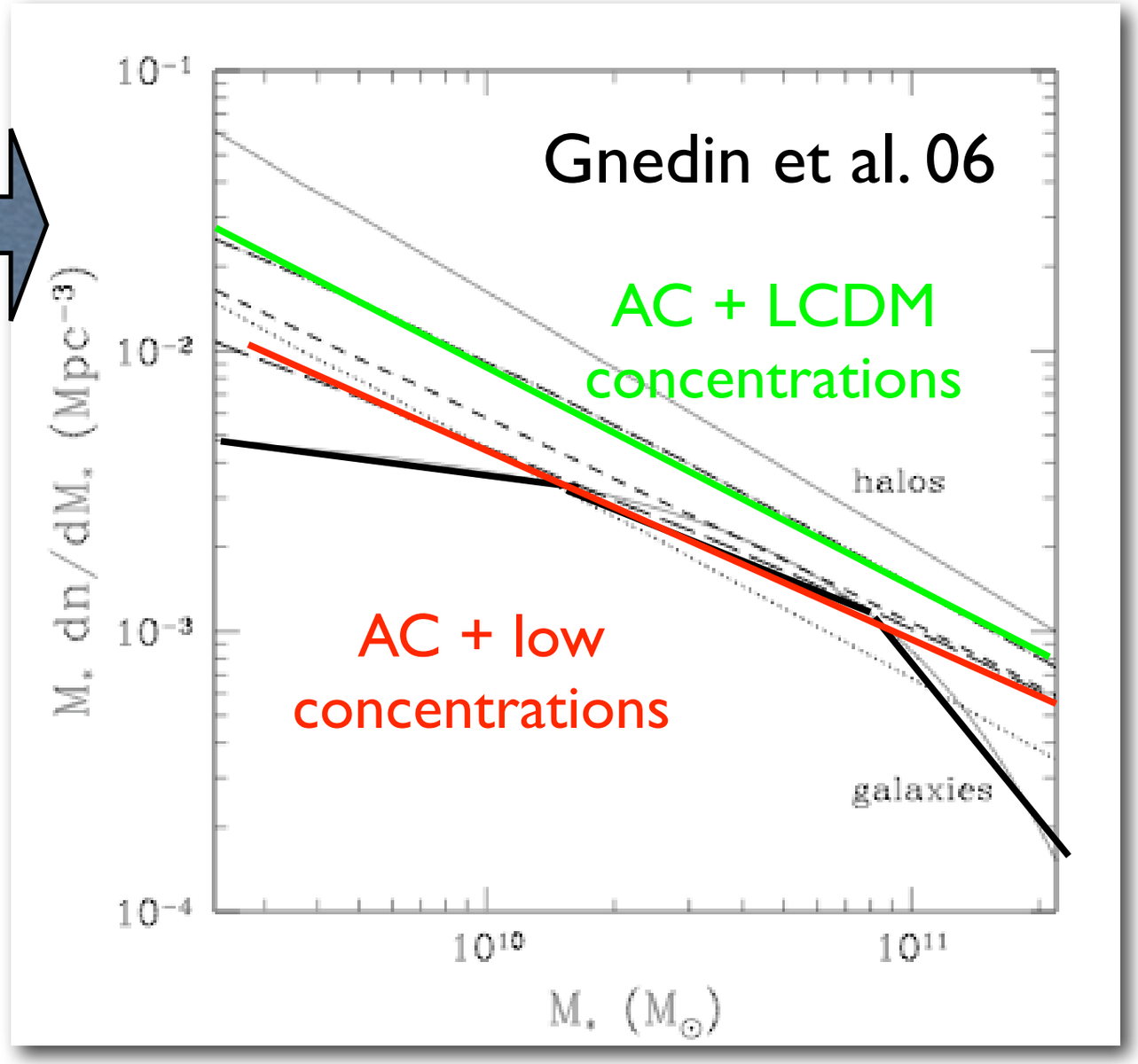
Galaxy Scales

Dutton et al. 06, Gnedin et al. 06

More on Adiabatic Contraction

TF relation constraints on Halo Densities...

EITHER
lower concentrations
OR
no Adiabatic Contraction

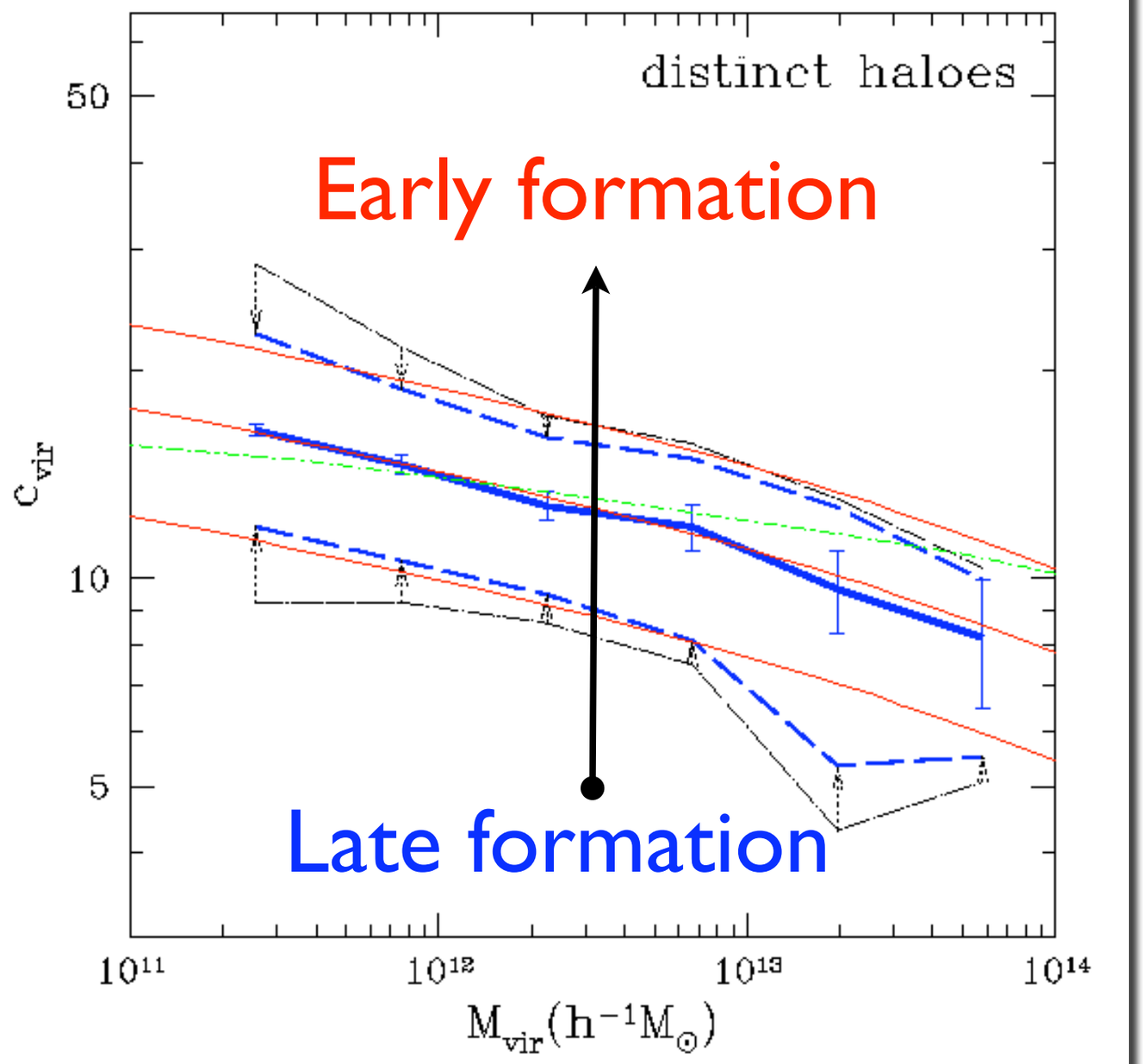


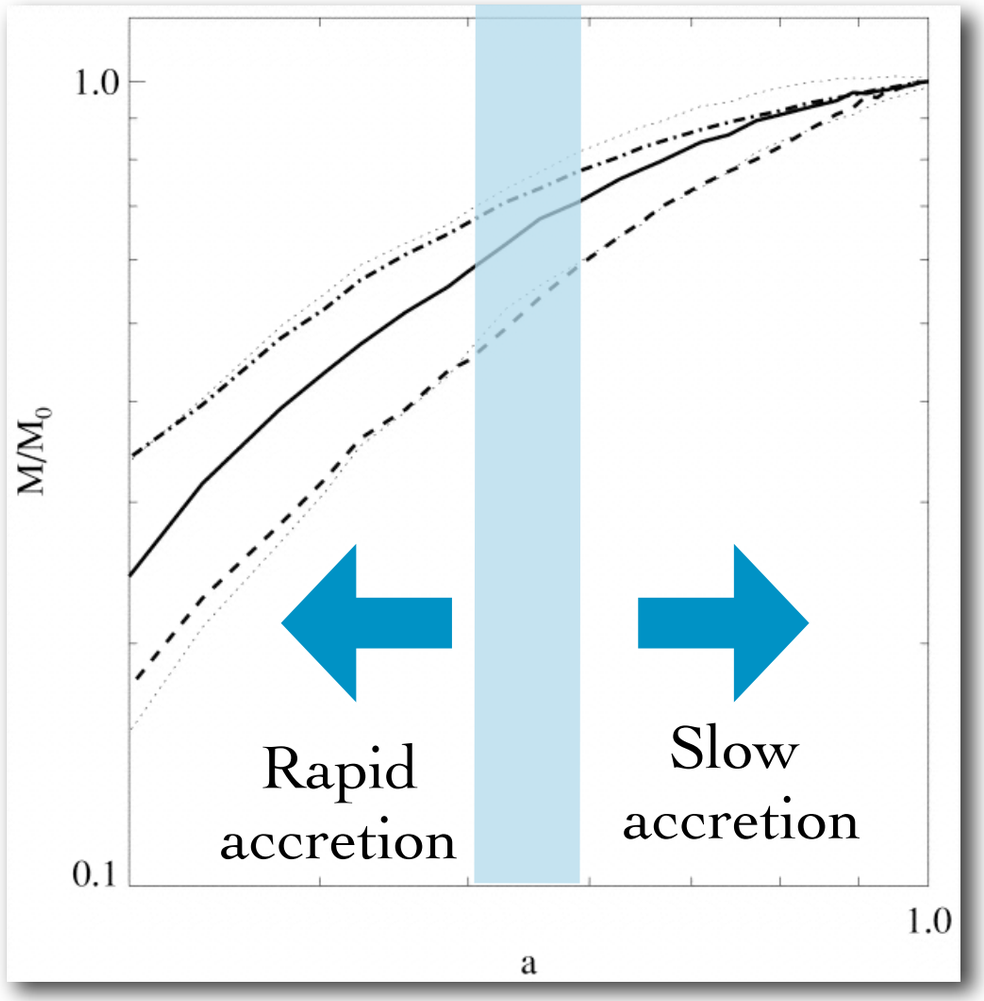
More Density Profiles...

spread at fixed M is cause by formation time

Wechsler, JSB, Primack, Kravtsov, & Dekel 02

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



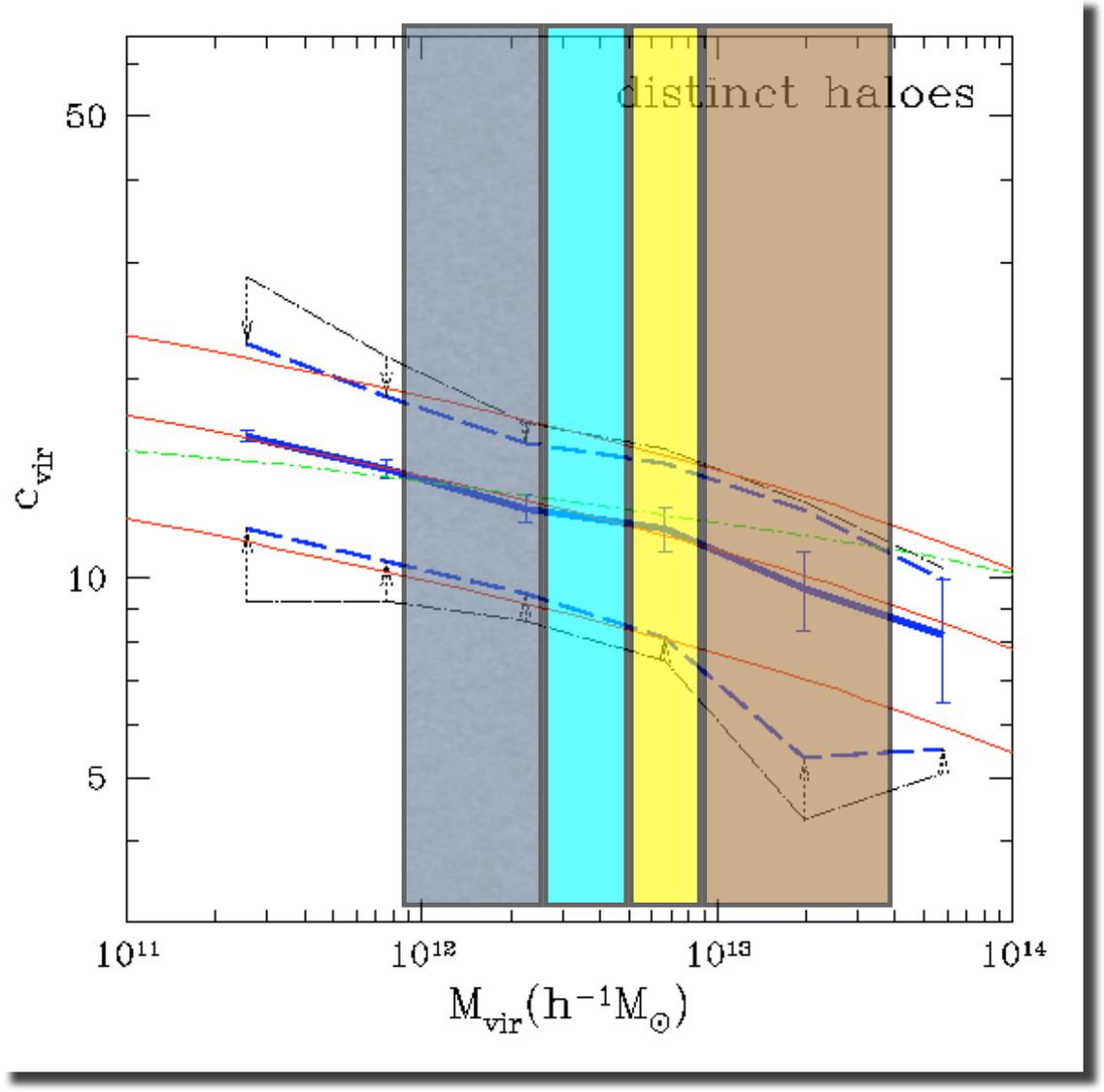


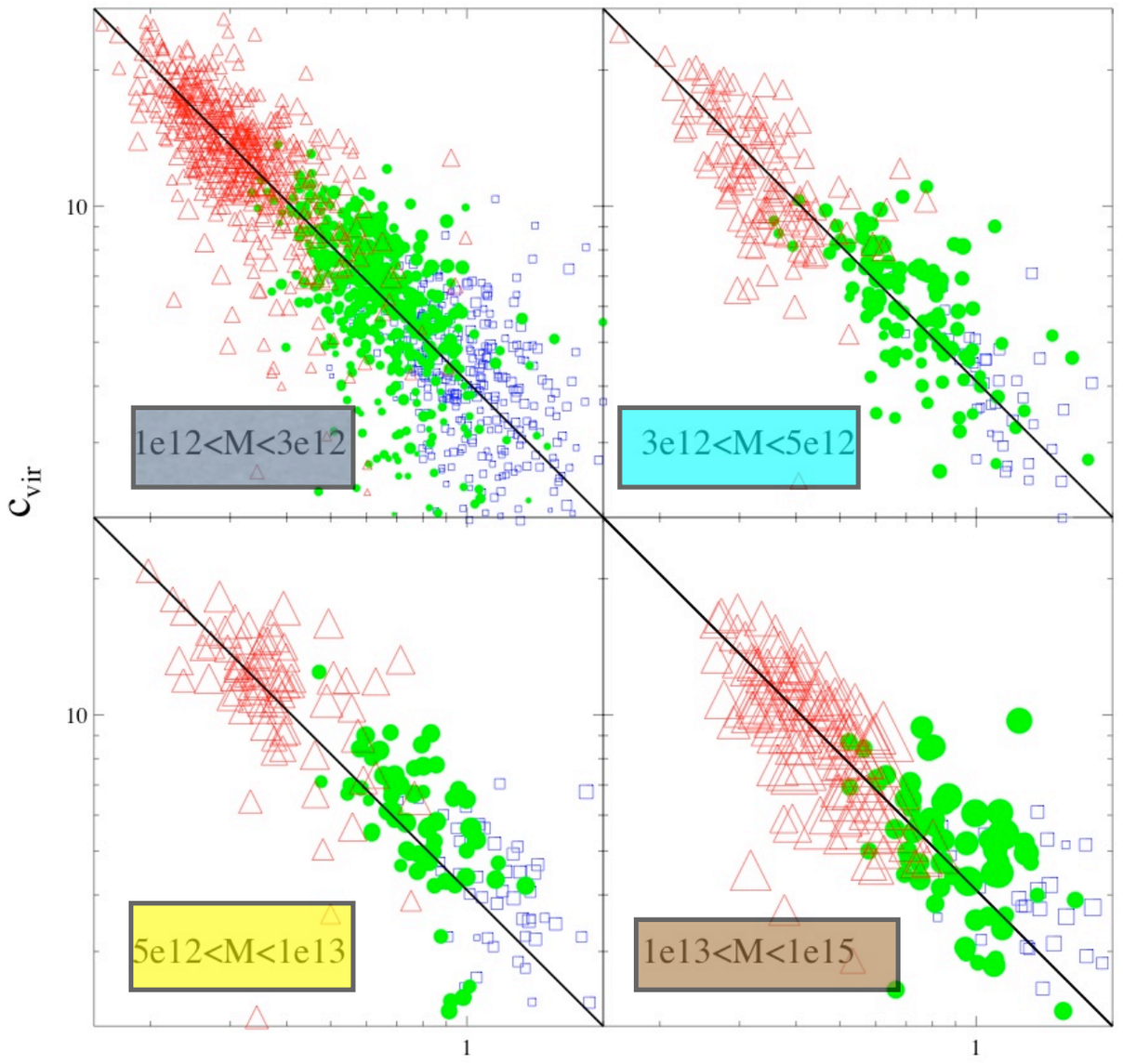
Formation epoch

$\mathbf{a_c}$

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

Formation epoch of "rapid mass accretion" governs c in nearly 1 to 1 way.



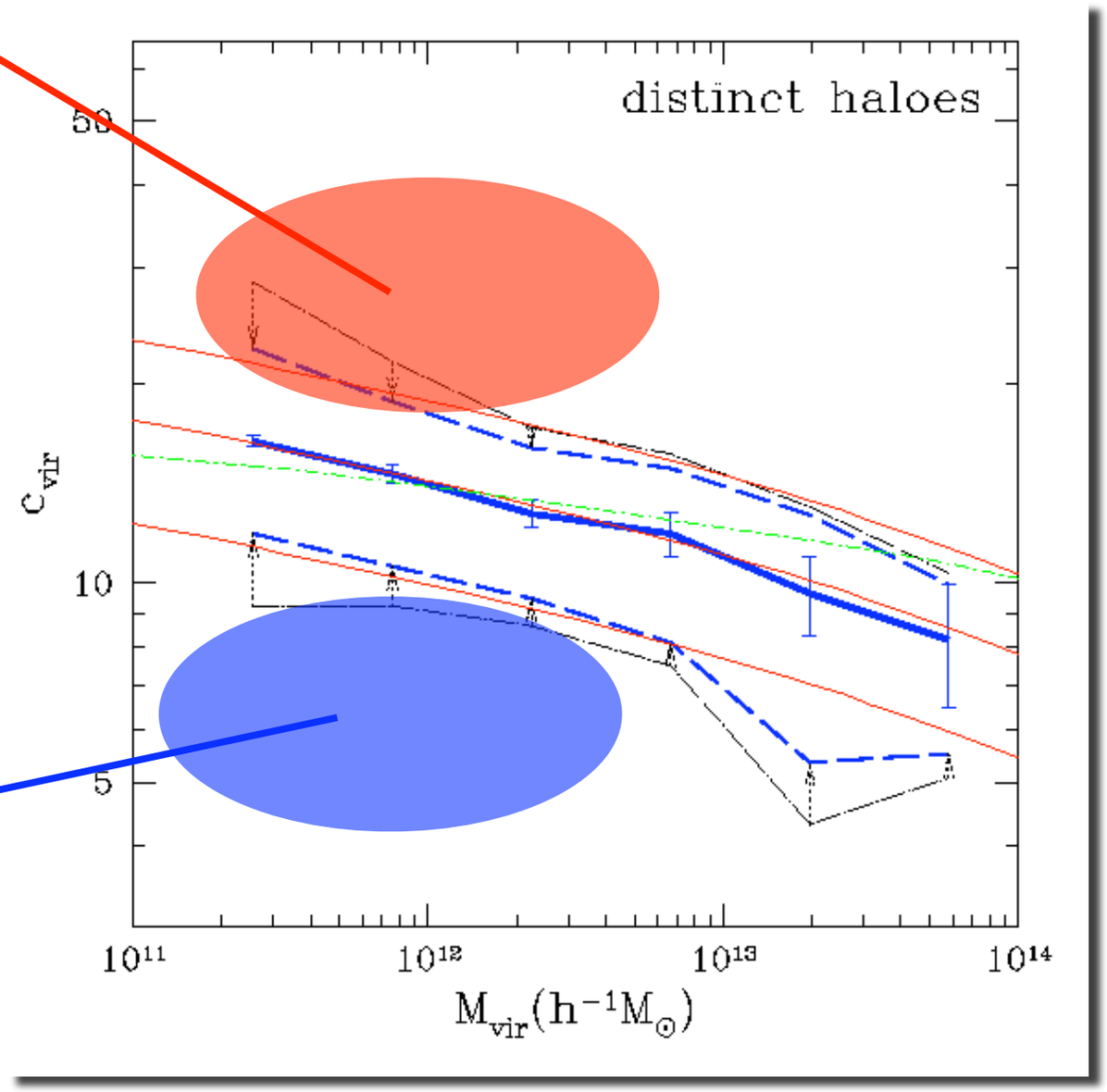


Wechsler, JSB, Primack, Kravtsov, & Dekel 02

early — late

Formation epoch

Early Type galaxies?



Late Type galaxies?

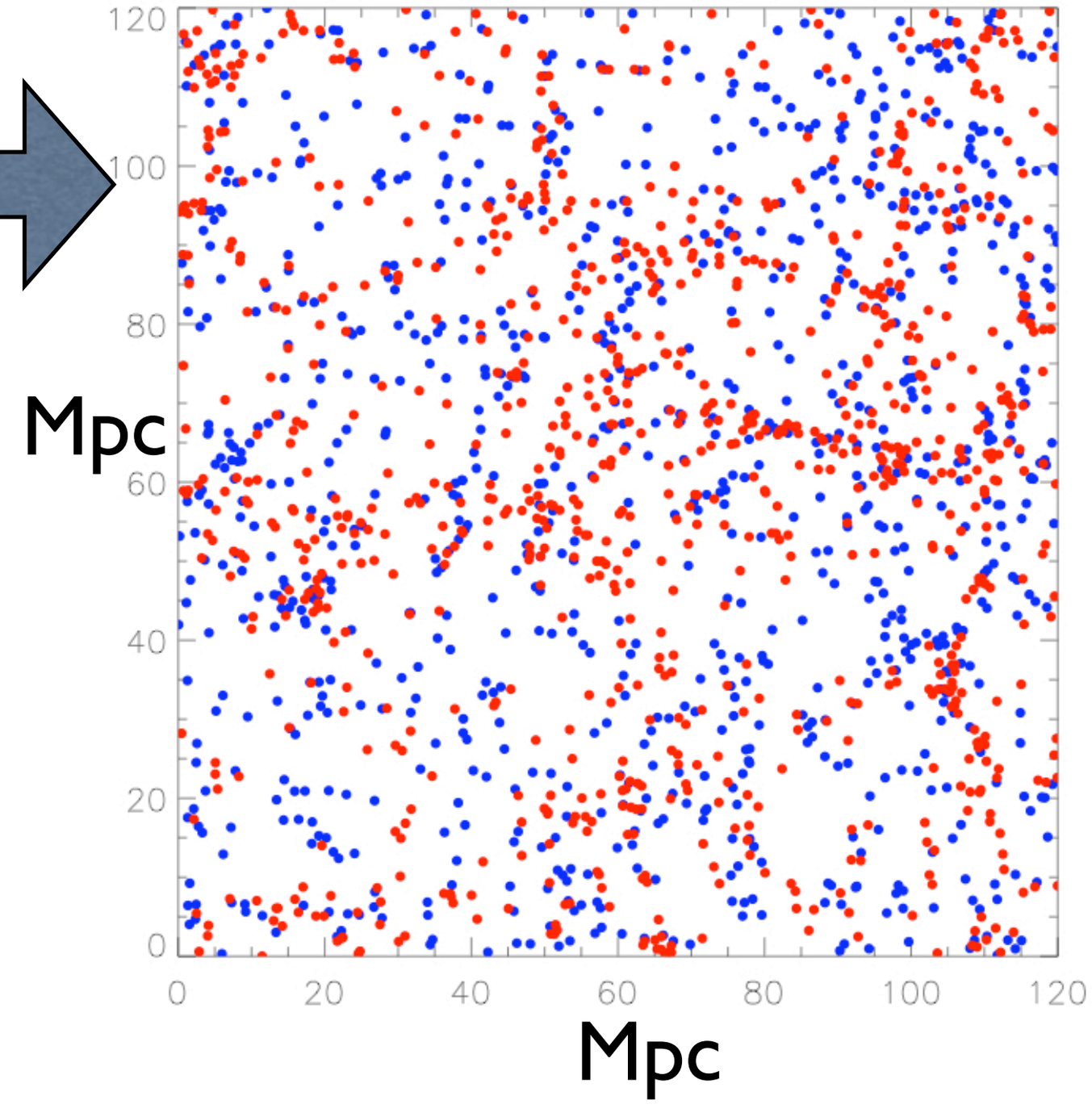
Wechsler & JSB

See also discussion in Maccio et al. 06

Low concentration galaxy halos are less clustered than high concentration halos.

Wechsler, Zentner, JSB, Kravtsov 06

120 Mpc box
LCDM simulation

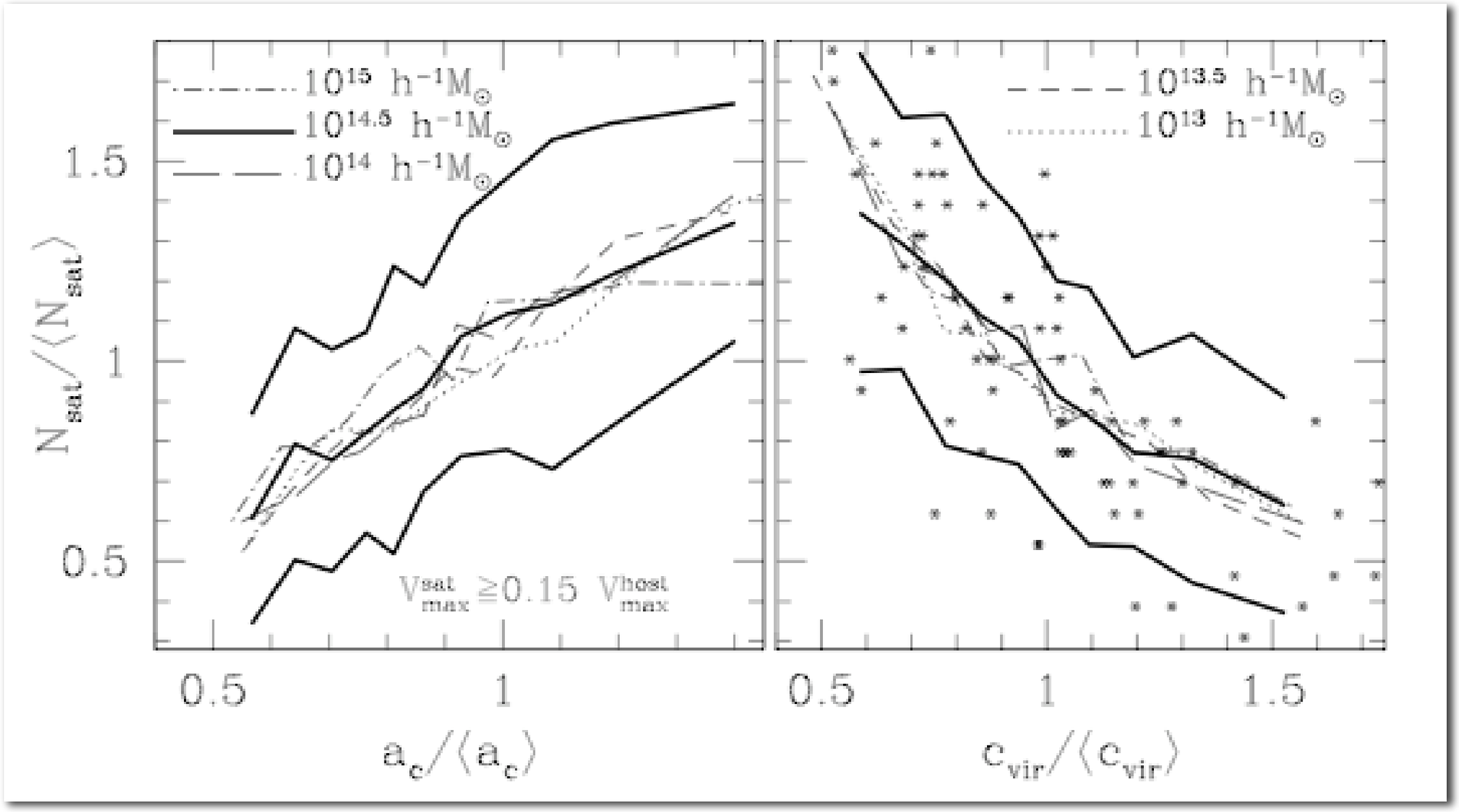


- Similar to trend seen with late type vs. early type galaxies...

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

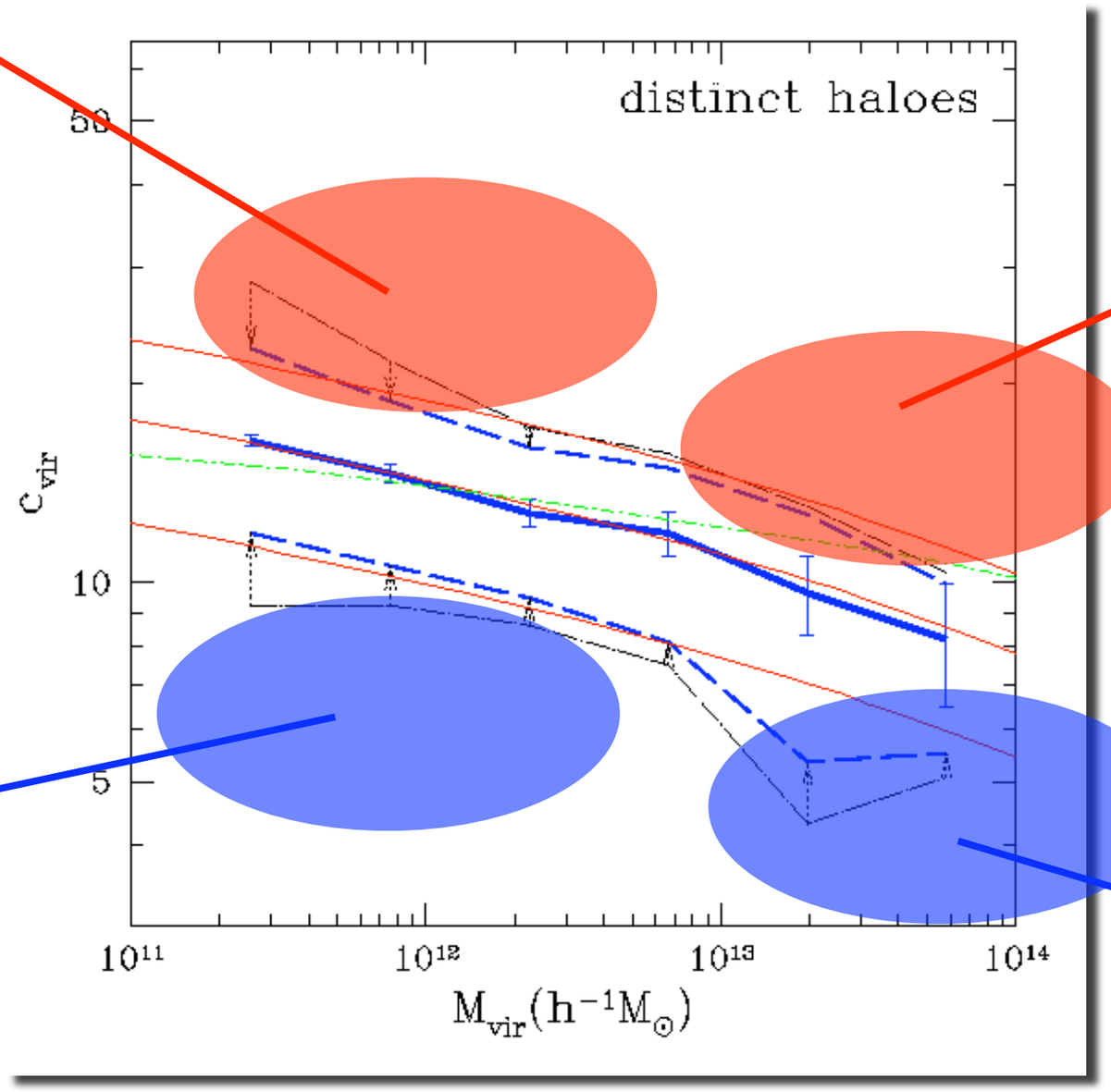
Concentration correlates with # of objects in groups/clusters



Low c: many satellites
=>Unrelaxed Groups & Clusters

High c: few satellites
"Fossil Groups" / Relaxed Clusters

Early Type galaxies?



Fossil Groups
Relaxed clusters

Late Type galaxies?

Unrelaxed groups
Disturbed clusters

Wechsler & JSB
See also discussion in Maccio et al. 06

Buote et al. 06

THE X-RAY CONCENTRATION-VIRIAL MASS RELATION

David A. Buote[1], Fabio Gastaldello[1], Philip J. Humphrey[1], Luca Zappacosta[1], James S. Bullock[1], Fabrizio Brighenti[2,3], & William G. Mathews[2]

Submitted to The Astrophysical Journal astro-ph/~next week

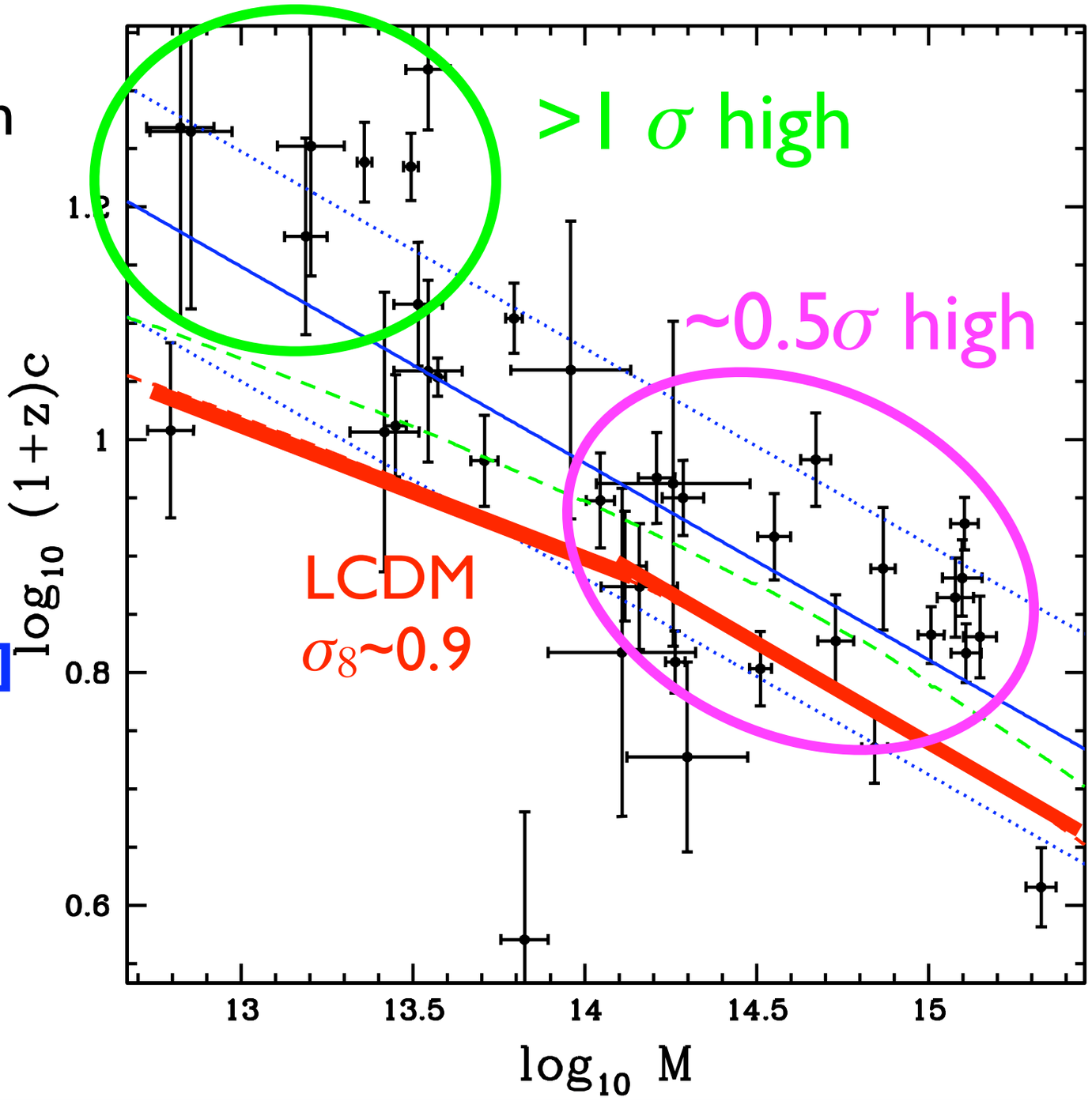
Compilation:

39 **relaxed** systems with highest quality XMM & Chandra Data

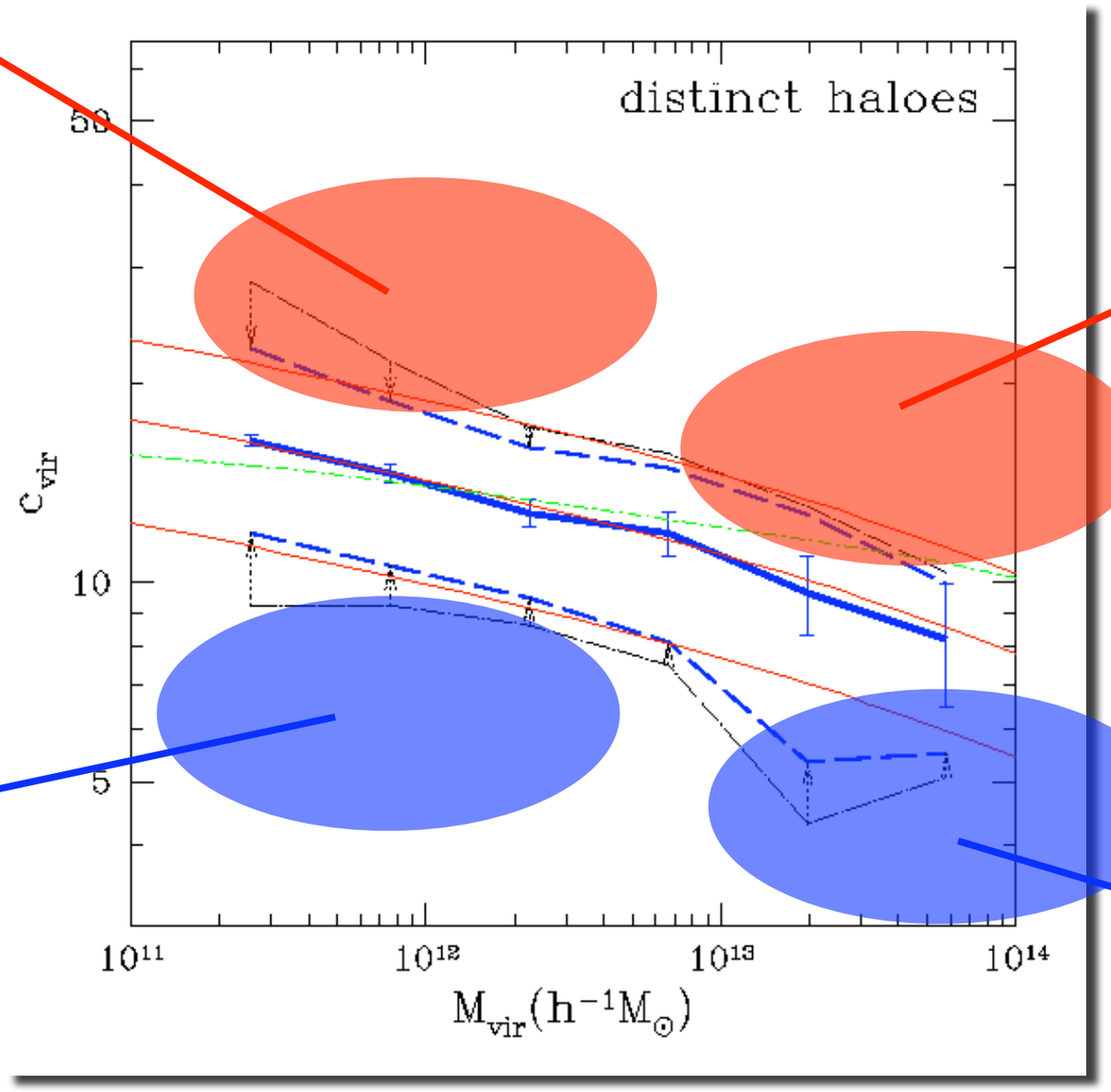
Humphrey et al. 06
[Early type galaxies]

Gastaldello et al. 06
[Groups + poor clusters]

Zappacosta et al. 06
Pointecouteau et al. 05
Vikhlinin et al. 06
[Massive Clusters]



Early Type galaxies?



Fossil Groups
Relaxed clusters

Late Type galaxies?

Unrelaxed groups
Disturbed clusters

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.