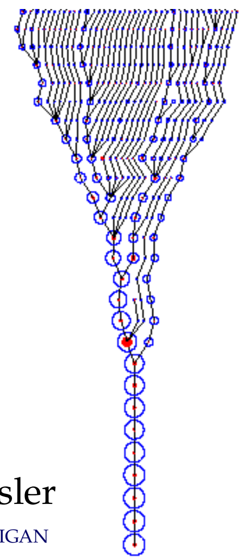
mass assembly, halo structure, and galaxy formation



Risa H. Wechsler

UNIVERSITY OF MICHIGAN
physics department
michigan center for theoretical physics

collaborators:

James Bullock (Ohio State→CfA)
Joel Primack (Santa Cruz)
Andrey Kravtsov (Chicago)
Avishai Dekel (Jerusalem)
Rachel Somerville (Michigan)
Anatoly Klypin (NMSU)
Maya Vitvitska (NMSU)

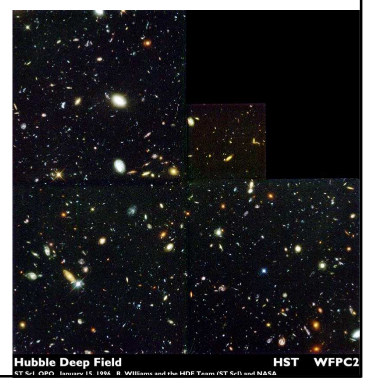
- What determines galaxy properties and their evolution?

  why do they look like they do??

  (size, morphology, color, luminosity, etc…)

- What physical processes are responsible for galaxy scaling relations?
  - Tully-Fisher/Fundamental Plane relation
  - Morphology-density relation
  - Color-magnitude relation
  - etc.

- What determines variation in galaxy properties with environment?



- What determines variation and evolution of dark matter halo properties?

halo mass assembly

accretion merging

?

galaxy observables:

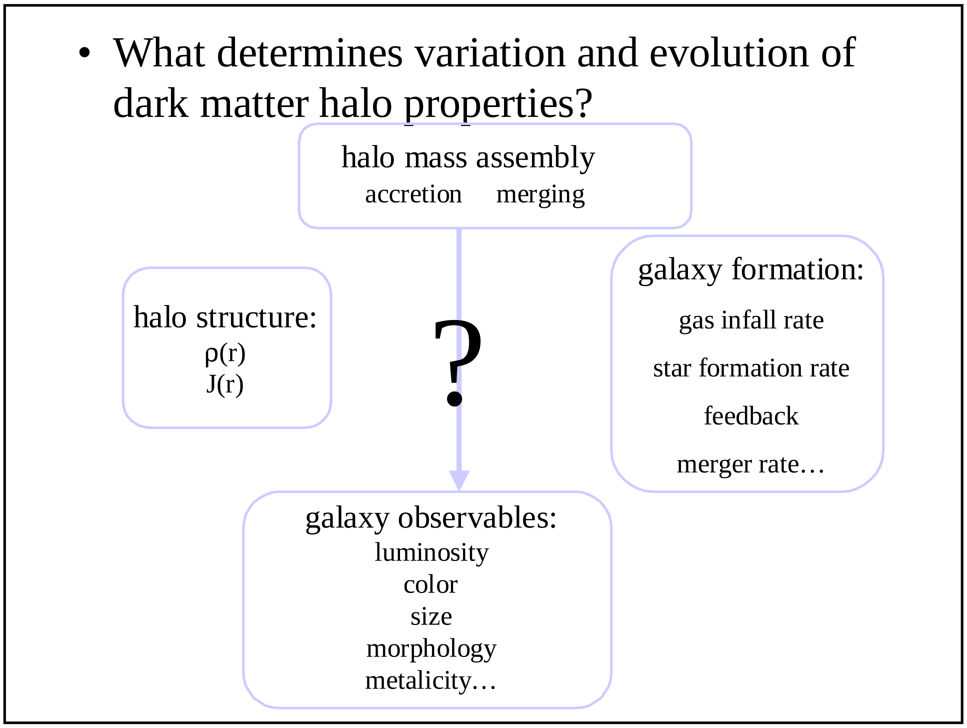
luminosity

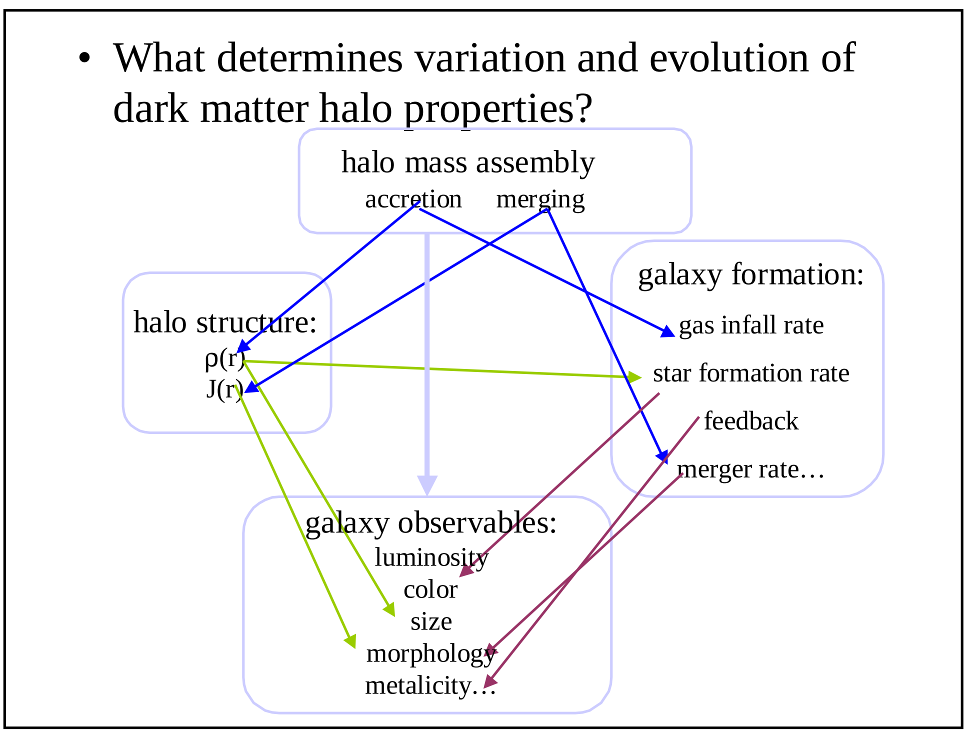
color

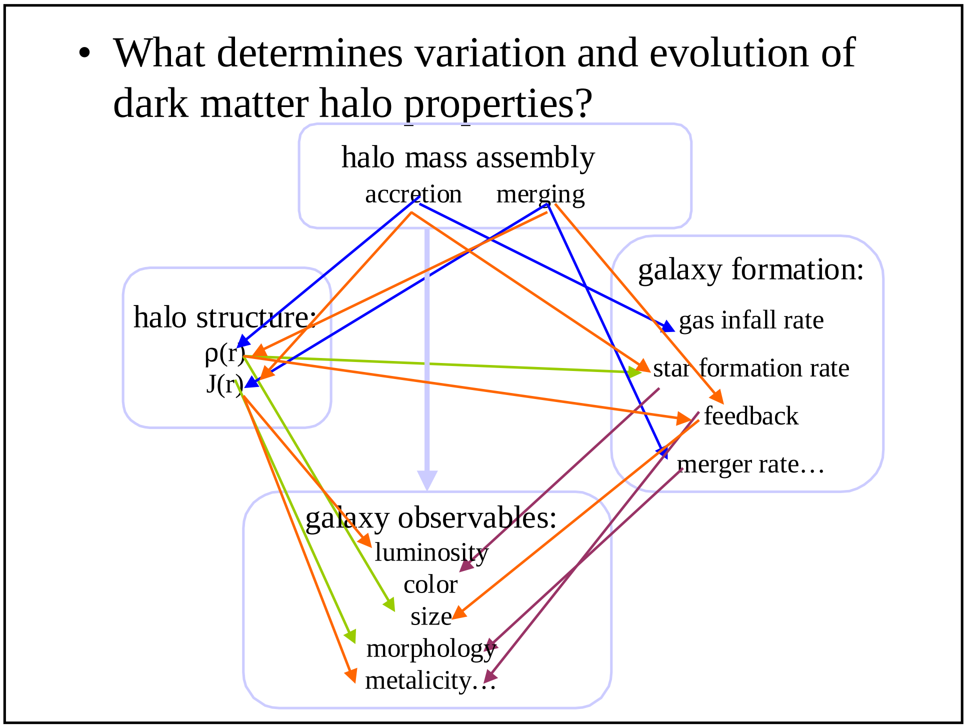
size

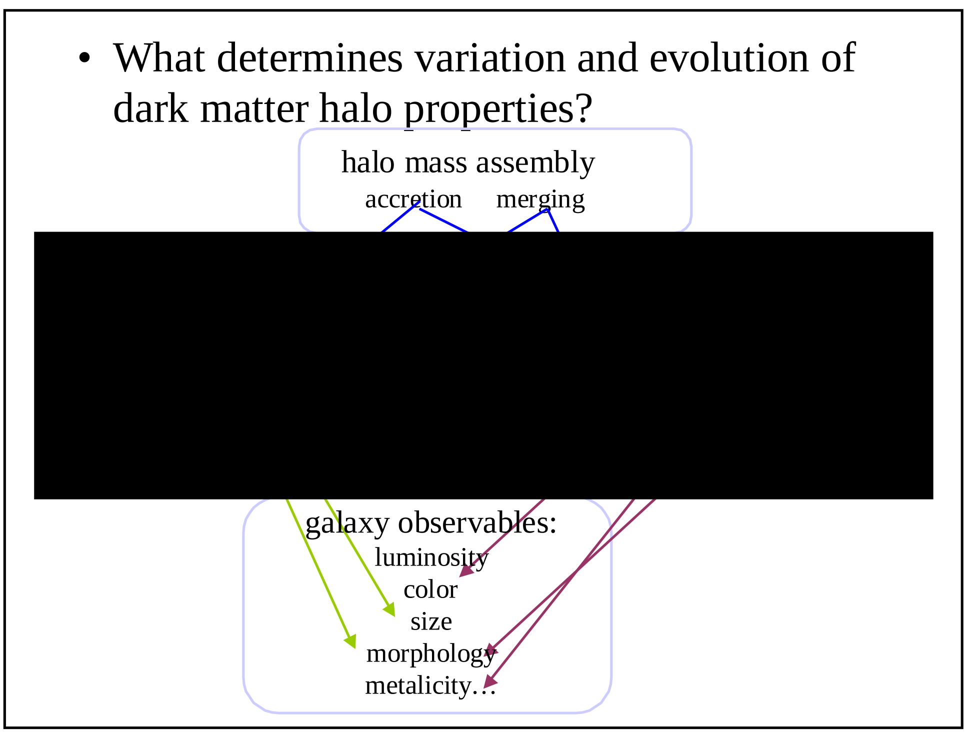
morphology

metalicity…


• What determines variation and evolution of dark matter halo properties?
halo mass assembly
accretion merging
halo structure:
ρ(r)
J(r)
?
galaxy formation:
gas infall rate
star formation rate
feedback
merger rate…
galaxy observables:
luminosity
color
size
morphology
metalicity…


• What determines variation and evolution of dark matter halo properties?
halo mass assembly
accretion merging
halo structure:
ρ(r)
J(r)
galaxy formation:
gas infall rate
star formation rate
feedback
merger rate…
galaxy observables:
luminosity
color
size
morphology
metalicity…


• What determines variation and evolution of dark matter halo properties?
halo mass assembly
accretion merging
halo structure:
ρ(r)
J(r)
galaxy formation:
gas infall rate
star formation rate
feedback
merger rate…
galaxy observables:
luminosity
color
size
morphology
metalicity…


• What determines variation and evolution of dark matter halo properties?
halo mass assembly
accretion merging
[redacted]
galaxy observables:
luminosity
color
size
morphology
metalicity…

small-scale power & cdm

is there a problem?

- too cuspy?

  CDM halos indicate steep central density profiles, dwarf/LSB galaxies have slowly rising rotation curves

- too concentrated?

  dwarf/LSB rotation curves

  Tully-Fisher offset

  fast rotating bars

- too much substructure?

  more subhalos in CDM than satellites in the local group

cusp/core problem?

$$\rho(\mathrm{r}) = \frac{\rho_s}{r/R_s(1+r/R_s)^2}$$

- CDM halos are ~NFW $\rho \sim r^{-1}$

  (or steeper? Moore 99;

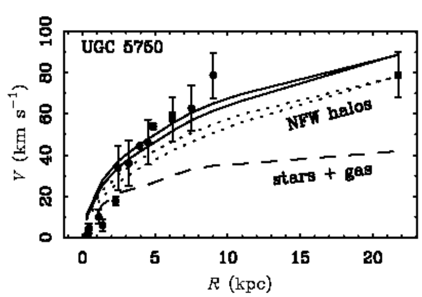
  shallower? Taylor & Navarro 01)

  rotation curves of dark matter dominated galaxies are slowly rising in center

- but:
  - inner ~kpc
  - hard to measure both rotation curves and density profiles
  - observational issues
  - ways to erase the inner structure?

    (e.g. Weinberg & Katz 2001)

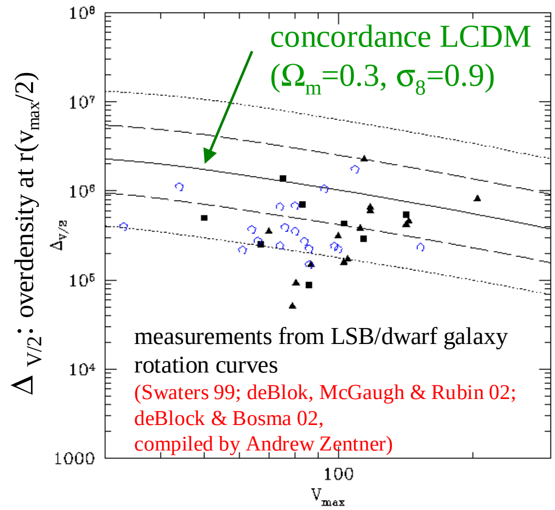
- Swaters et al 2002: ¾ of sample consistent with NFW halos, remaining quarter non-circular motions



McGaugh 2001

central density problem

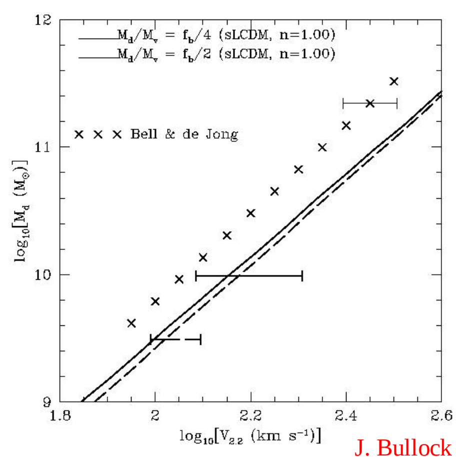
$$\Delta_{v/2} \equiv \frac{\overline{\rho}(r_{v/2})}{\rho_{crit}} = \frac{1}{2}\left(\frac{V_{\max}}{H_0 r_{v/2}}\right)^2$$



central density problem: TF

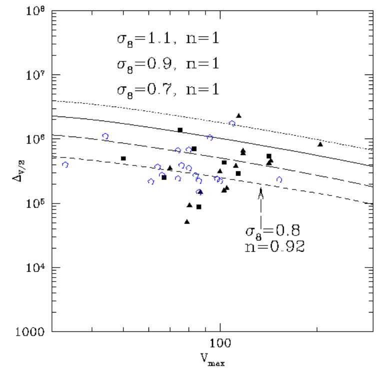
halos rotate too fast
for a given luminosity

problems matching
TF & LF simultaneously



proposed solutions:

- modify gravity
- cosmology:
  - modify the nature of dark matter (WDM, SIDM)
  - modify the power spectrum (e.g., Zentner & Bullock 2002)
- astrophysics:
  - baryon-dm coupling
  - angular momentum transfer
  - black holes… etc.



are these problems generic?

- do they apply to *all* galaxy size halos?
- do they apply for all *mass* scales?

are these problems generic?

- do they apply to *all* galaxy size halos?
- do they apply for all *mass* scales?

another possible solution:

halo structure is a function of history

→ introduces selection effects

are these problems generic?

- do they apply to *all* galaxy size halos?
- do they apply for all *mass* scales?

proposed solutions have degenerate predictions as a function of mass scale and halo/galaxy formation history

want to understand what sets halo density profiles!

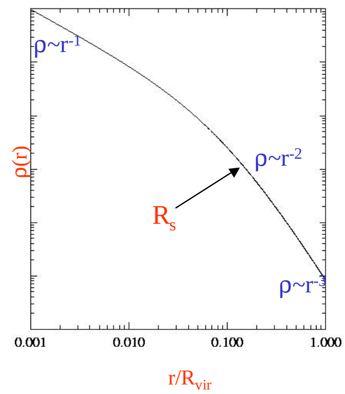
halo density profiles

- universal form: Navarro, Frenk & White 1996, 1997(NFW)

$$\rho(\mathrm{r}) = \frac{\rho_s}{r/R_s(1+r/R_s)^2}$$

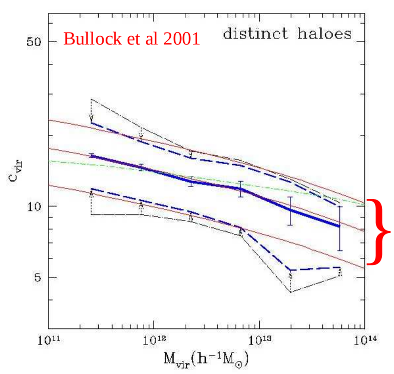
- concentration parameter:

$$c_{vir} \equiv \frac{R_{vir}^{*}}{R_s}$$



* virial radius with respect to the background density; Δ_{vir}=337 at z=0

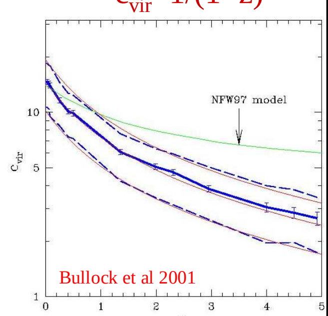
halo concentrations



68% intrinsic scatter in halo population

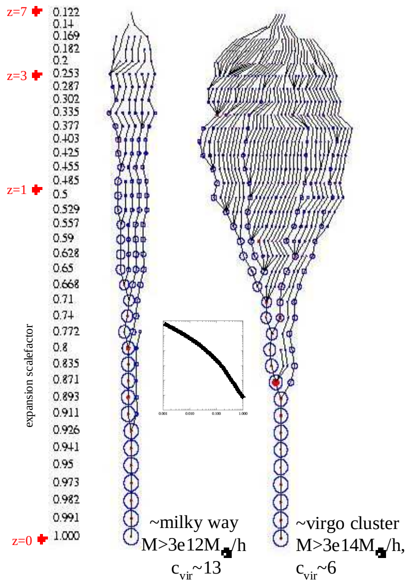
B01:
measured in LCDM for thousands of halos
2×10^{11}<M<few x 10^{14} 0<z<5

c_{vir}~1/(1+z)



- large scatter – what determines c_{vir} for *individual* halos?
- what is responsible M,z trends? (formation time?)
- correlated with galaxy properties?

a structural merger tree



- high resolution simulation allows for identification of substructure and measurement of halo density profiles

  flat ΛCDM: Ω_m=0.3, h=0.7, σ_8=1.0

  ART code (Kravtsov & Klypin)

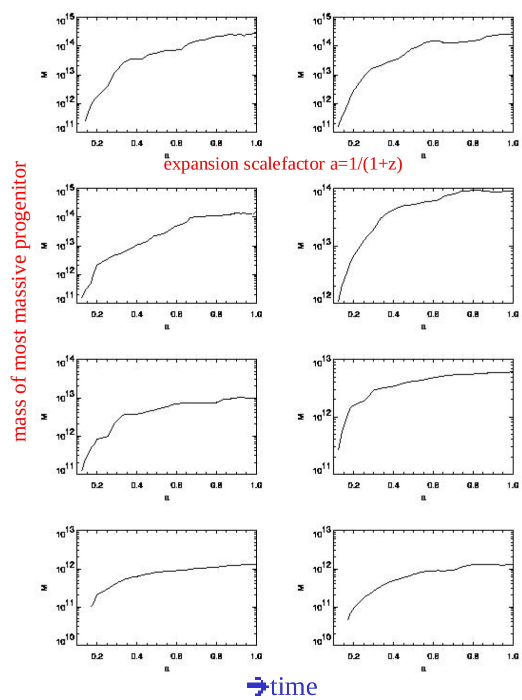
  60 Mpc/h box, 256^3 particles, M_p=1.1x10^9 $M_\odot$/h

  2 kpc/h force resolution

- tracks full merging and accretion history for ~15,000 halos from z=7➔0
- fits NFW density profiles to ~3000 halos, tracks evolution of concentration and angular momentum

Wechsler 2001; RW, Bullock, Primack, Kravtsov & Dekel et al 2002 (ApJ 568, 52)

selected mass accretion histories

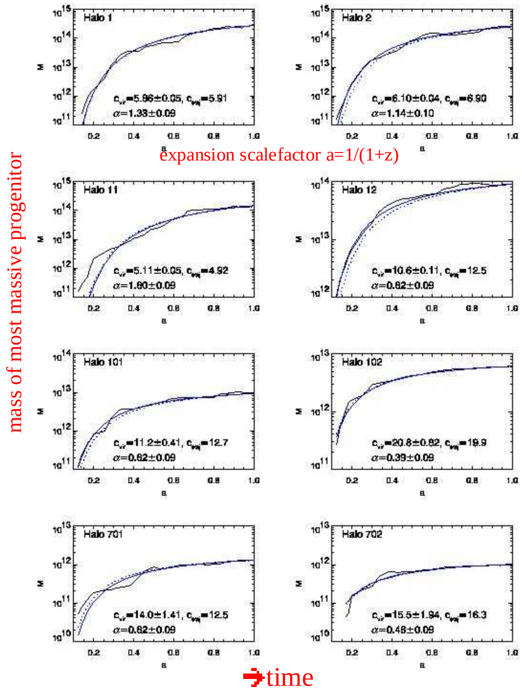


a universal mass accretion history

MAH well fit by:

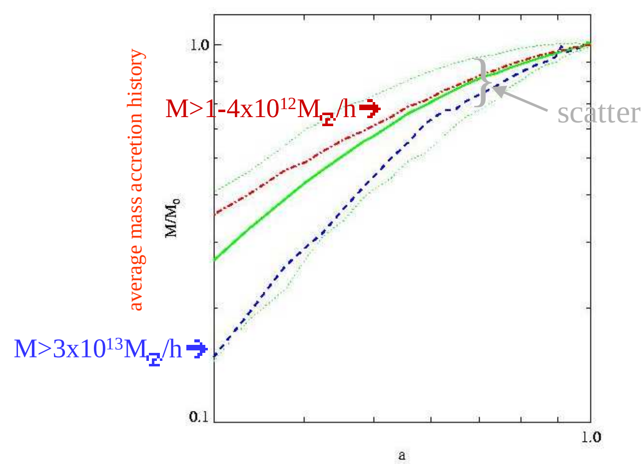
$M(z)=M_0 e^{-S a_c z}$

where a_c is scalefactor
where dlogM/dloga=S

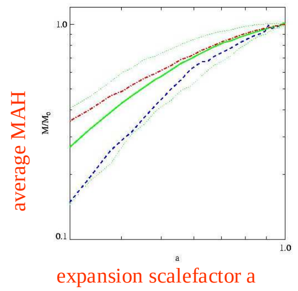


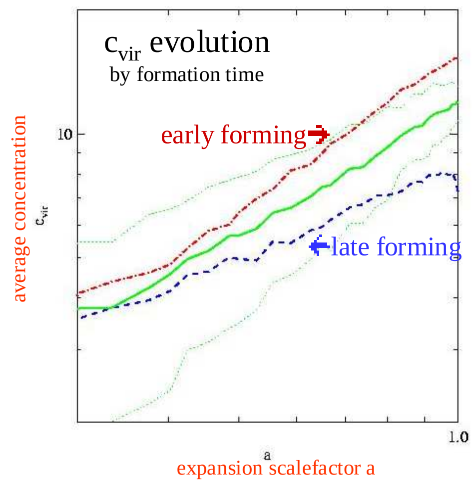
WBPKD02 (c.f. van den Bosch 2002)

average MAH



M and c_{vir} evolution



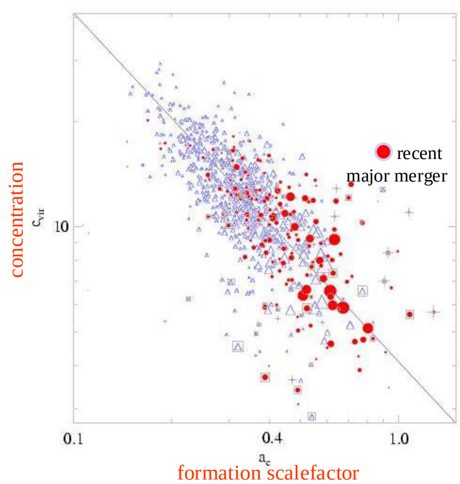


concentration vs. formation time

- fit to density profiles and mass accretion histories of z=0 halos

$c_{vir} \sim 1+z_c$

- details of merger history relatively unimportant



WBPKD02

concentration vs. formation time

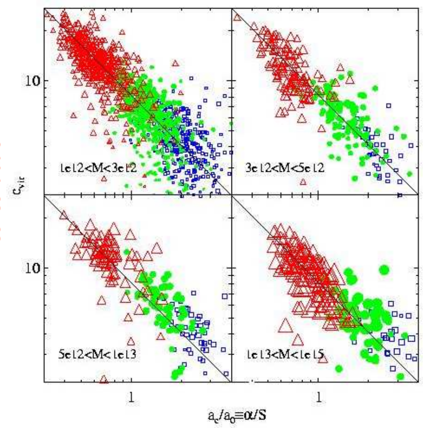
$c_{vir} = c_1 a_{obs} / a_c$

for all masses and redshifts!

scatter at a given mass
and redshift caused by scatter
in mass accretion histories

➔ correlated with galaxy type?

concentration

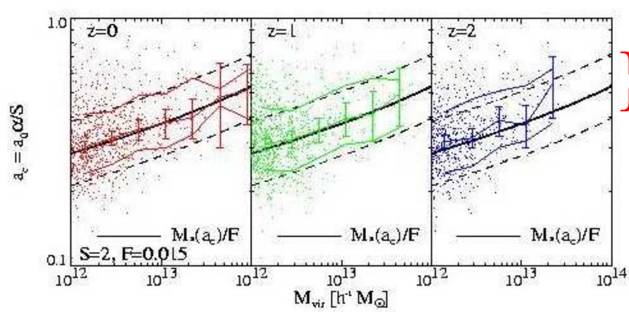


scaled formation scalefactor

△ z=0
● z=1
□ z=2

WBPKD02

$a_c(M,z)$



} scatter in c_{vir}

- formation time set by mass, independent of z

  for a halo of mass M, the average time that dlogM/dloga=S is equal to the time that $M=M_*/F$ ➔ equivalent to Bullock et al model for c_{vir}

  (typical definition of formation time $M(z_f)=fM$ changes with z in a non self-similar way)

- large scatter for a given mass: ~0.13 in $\log(a_c)$

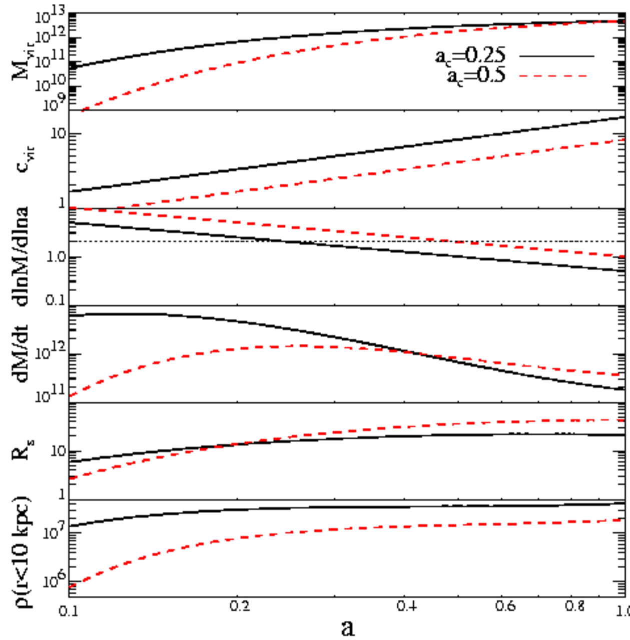
  ➔ accounts for scatter in cvir,
  explains c(M,z)

WBPKD02

M(a) predicts ρ(r)

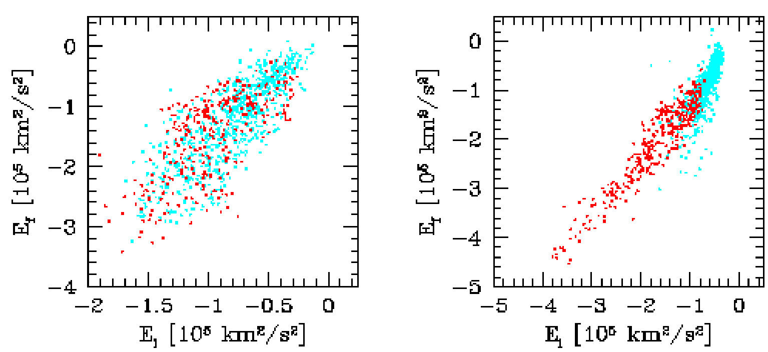
assuming:

1. NFW ρ(r)
2. $M \sim e^{-2a_c z}$
3. $c_{vir} \sim a/a_c$



fast accretion phase

slow accretion phase



Zhao et al 2002

can the MAH be predicted from EPS?

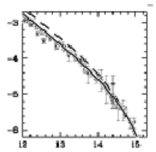
- PS ➔ mass function

  based on spherical collapse
- Well-known problem:

  overpredicts halos with M<<M* (e.g. Gross et al 1998)
- fix:

  Sheth & Tormen 1999, Sheth, Mo & Tormen 2000, Jenkins et al 2001

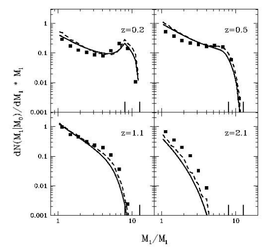
  ellipsoidal collapse



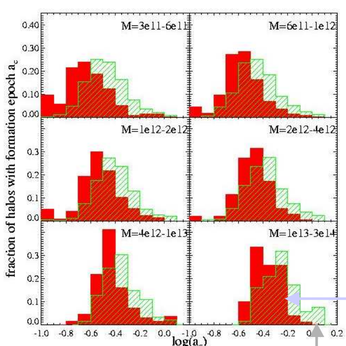
- But EPS is based on PS…

  ➔ problems translate to conditional mass function

  (Somerville et al 2000)



can the MAH be predicted from EPS?

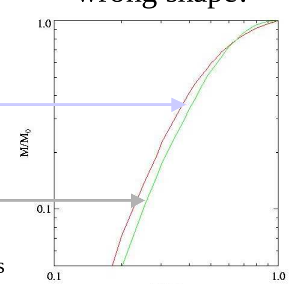


EPS: late formation times

simulated halos

EPS halos

wrong shape!

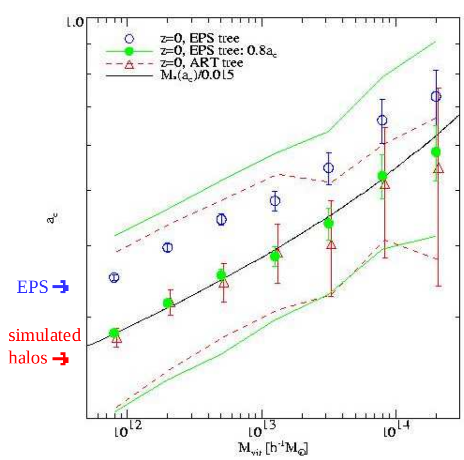


progenitor masses too big at small look back times
too small at large look back times

ways to improve:

- adjust threshold for collapse
  e.g. Benson et al 2001: $\delta_c^{eff}=[1+0.14[\log(M/h^{-1}\,M_\odot)-15.64]]\delta_c$ (ΛCDM)
  empirical fix for specific cosmology, doesn't fix shape
- incorporate ellipsoidal collapse into EPS
  e.g., Sheth & Tormen 2001; Lin, Chiueh & Lee 2001
  so far, unsuccessful/insufficiently accurate for merger histories
- PINOCCHIO (PINpointing Orbit-Crossing Collapsed HIerarchical Objects)
  Monaco et al 2001, based on Lagrangian Perturbation Theory
  works well in limited mass range, fix with free parameters?
- use simulated histories

an empirical fix

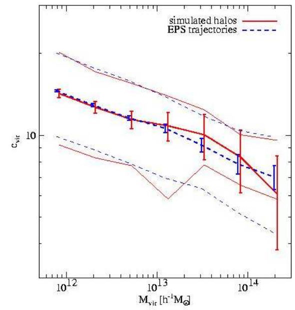


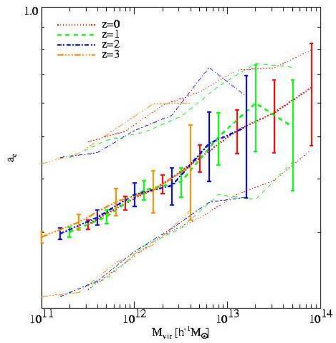
←constant offset

matches mass dependence and scatter

concentrations from EPS

- can predict $c_{vir}(M,z)$ & scatter
  with $c_{vir}=c_1 a_{obs}/a_c$
  using EPS + correction factor





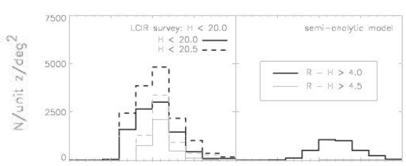
- $a_c(M)$ constant with redshift …
  average value set by M, scatter const.

➔ $c_{vir}\sim 1/(1+z)$
  for fixed M & on average for individual halos

consequences for galaxies?

- Most gf models (e.g. Somerville) use EPS to construct merging histories…
- too much late star formation? MAH➔SFH
  (e.g., Avila-Reese & Firmani 2001)
  ➔more red galaxies with correct mass accretion history
- too much late merging?

Firth, Somerville et al 2001



not enough EROs

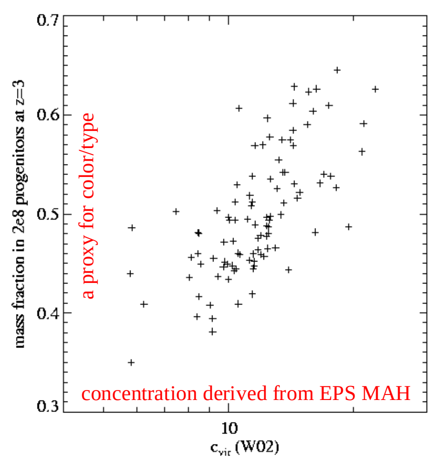
caution interpreting results of models with uncorrected EPS histories

effects of a c-history correlation for galaxies:

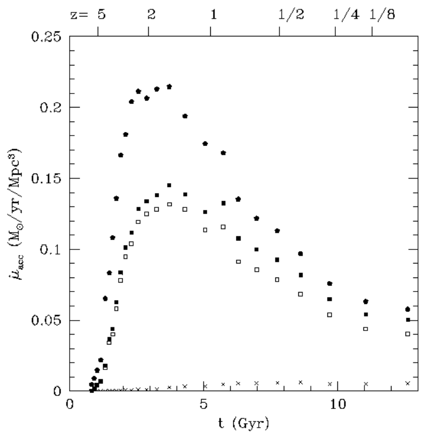
early forming halos	late forming halos
↓	↓
high concentration	low concentration
↓	↓
more clustered	less clustered
↓	↓
steep rotation curves	slowly rising rotation curves
↓	↓
early star formation (red)	late star formation (blue)
↓	↓
higher surface brightness	lower surface brightness
↓	↓
metal rich	metal poor

a toy model for galaxy type

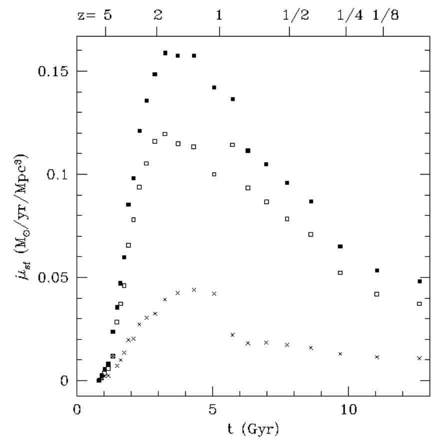
assume old/bulge stars are formed in progenitor halos more massive than M_b at $z=z_b$



→the most concentrated halos host red/early type galaxies baryonic mass accretion rate



star formation rate



Murali et al 2002

including halo structure in gf models

semi-analytic galaxy formation models:

(e.g., Somerville & Primack 1999, Cole et al 2000, Kauffmann et al 2000)

halo merging history
+
gas cooling and reheating
+
star formation & feedback
+
stellar evolution & chemical enrichment
+
dust absorption and emission
+
disk & spheroid formation

current generation of semi-analytic models:

typically,

$c = c_{ave}(M,z)$ (from simulations)

spin parameter λ: (sets disk scale length)

lognormal distribution from simulations,

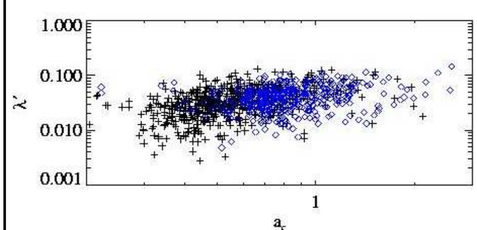
chosen at random and kept fixed

→no relation between halo structure and galaxy properties

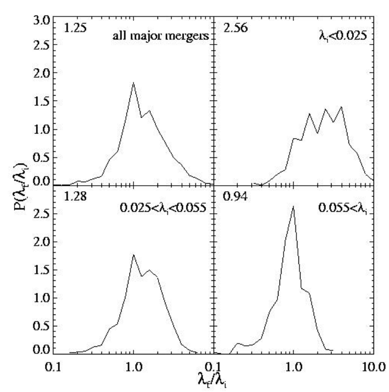
c.f. disk formation models (w/o merging history)
(e.g., Firmani & Avila-Reese 2000; van den Bosch 2000; Buchalter, Jimenez & Kamionkowski 2001)

spin and merger history

Wechsler 2001



$$\lambda' = \frac{J}{\sqrt{2} M_{vir} V_c R_{vir}}$$



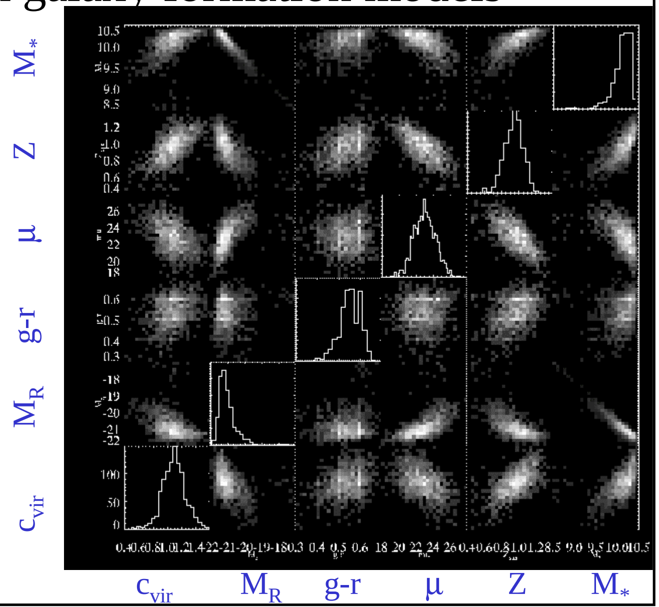
spin determined by merger history

built up by orbital angular momentum of randomly accreted satellites

Vitvitska, Klypin, Kravtsov, RW, Primack, Bullock 2002

effect of a c-history correlation on properties from galaxy formation models

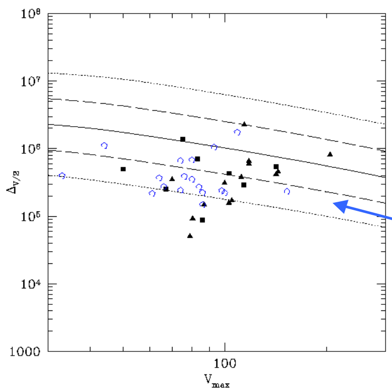
concentration set by mass accretion history



w/ r. somerville

implications for the "small scale crisis"?

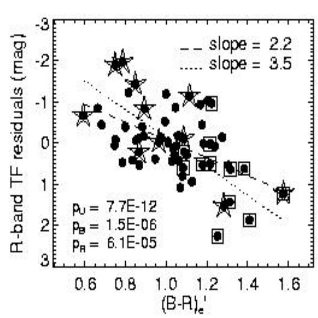
color/surface brightness selection effects



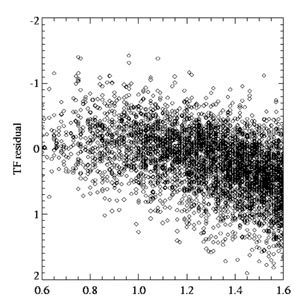
low surface brightness;
bluest half of model galaxies
of a given mass:
~40% lower concentrations

effect on tully-fisher:

correlation between Tully-Fisher residual and color
(red galaxies➔
more concentrated➔
rotate faster for a given luminosity)



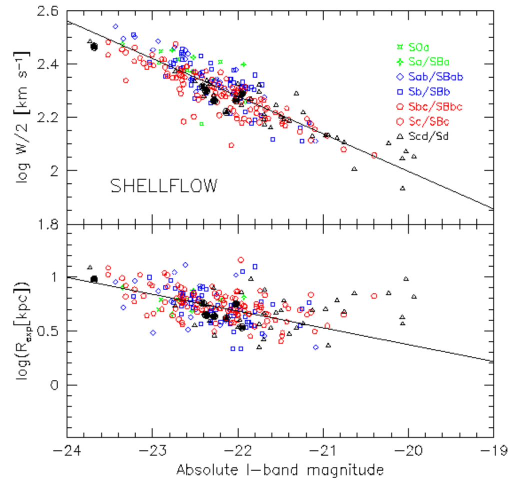
Kannappan, Fabricant & Franx 2002
(NFGS: Sa➔Sd gals)

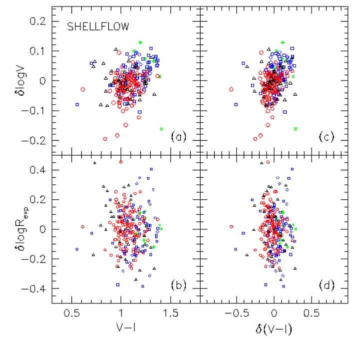


from models

halos without recent disruptions (➔disks)
have smaller scatter in c_{vir} (~25%)

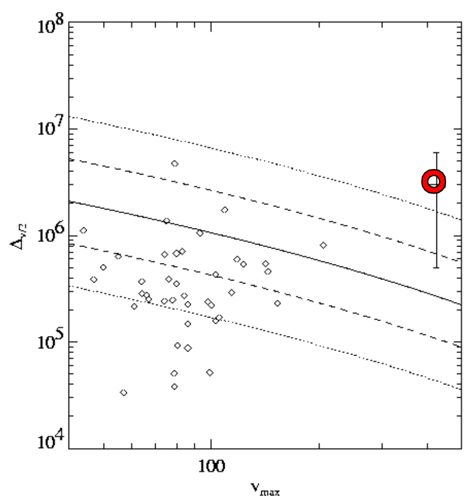
Tully-Fisher offsets





Courteau et al 2002 (in prep)

what about ellipticals?

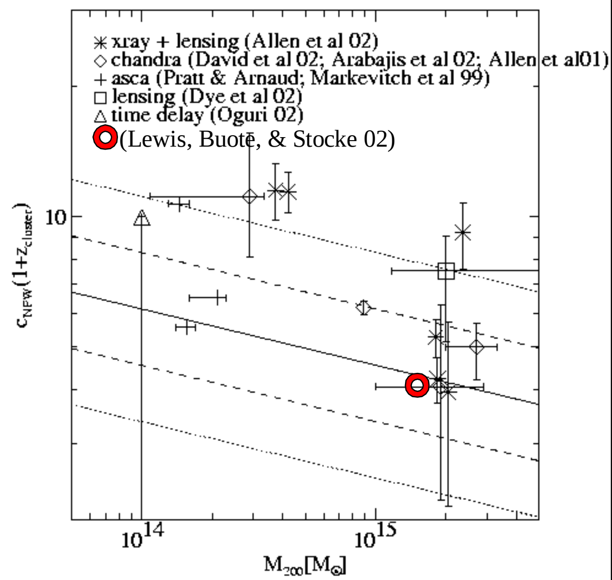


Loewenstein & Mushotsky 2002:

x-ray observation of a giant elliptical galaxy NGC 4636: high concentration!

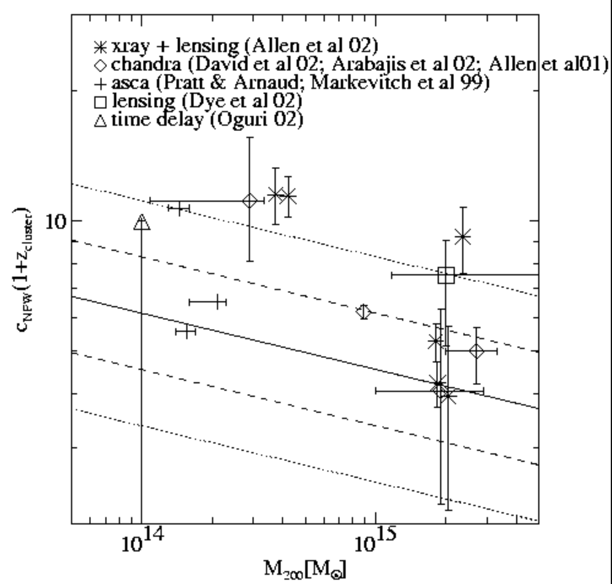
lensing: steep inner slopes?

what about cluster size halos?



what about cluster size halos?

any solution to the dwarf/LSB problem must also account for the properties of elliptical galaxies and relaxed clusters



summary

- $M(z) = f(M_{vir}, a_c)$ → $\rho(r) = f(M_{vir}, a_c)$
  → a physically-motivated and well-tested recipe
  for calculating the distribution of c(M,z)
- correlation between halo assembly and structure implies a correlation between halo structure and galaxy type.
- provides a natural explanation for the distribution of c(M) observed over a wide range of galaxy types and mass scales
- the fundamental relation is $c(a_c)$, not c(M)
  → even if this is only a partial solution to the central density problem, must consider selection effects !
- correlations between halo structure and galaxy properties are essential for a self-consistent galaxy formation theory