Dark matter halos of disk galaxies: constraints from the Tully-Fisher relation

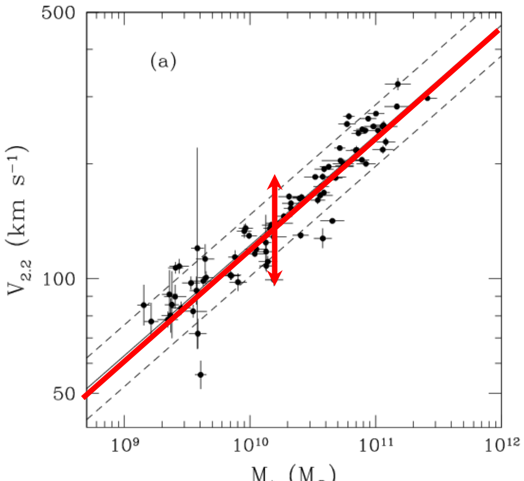
Oleg Gnedin (University of Michigan)

David Weinberg, James Pizagno (Ohio State)

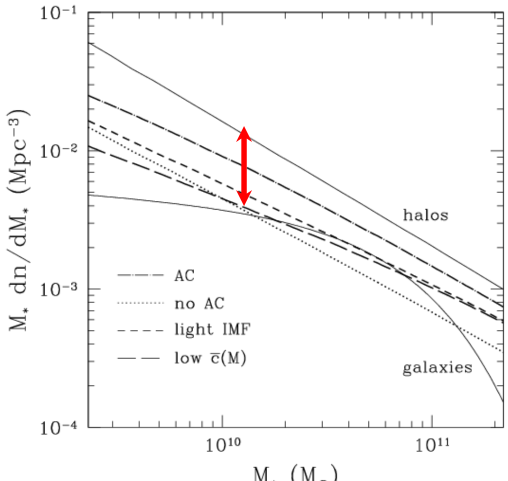
Francisco Prada (Granada)

Hans-Walter Rix (MPIA)

rotation velocity



luminosity

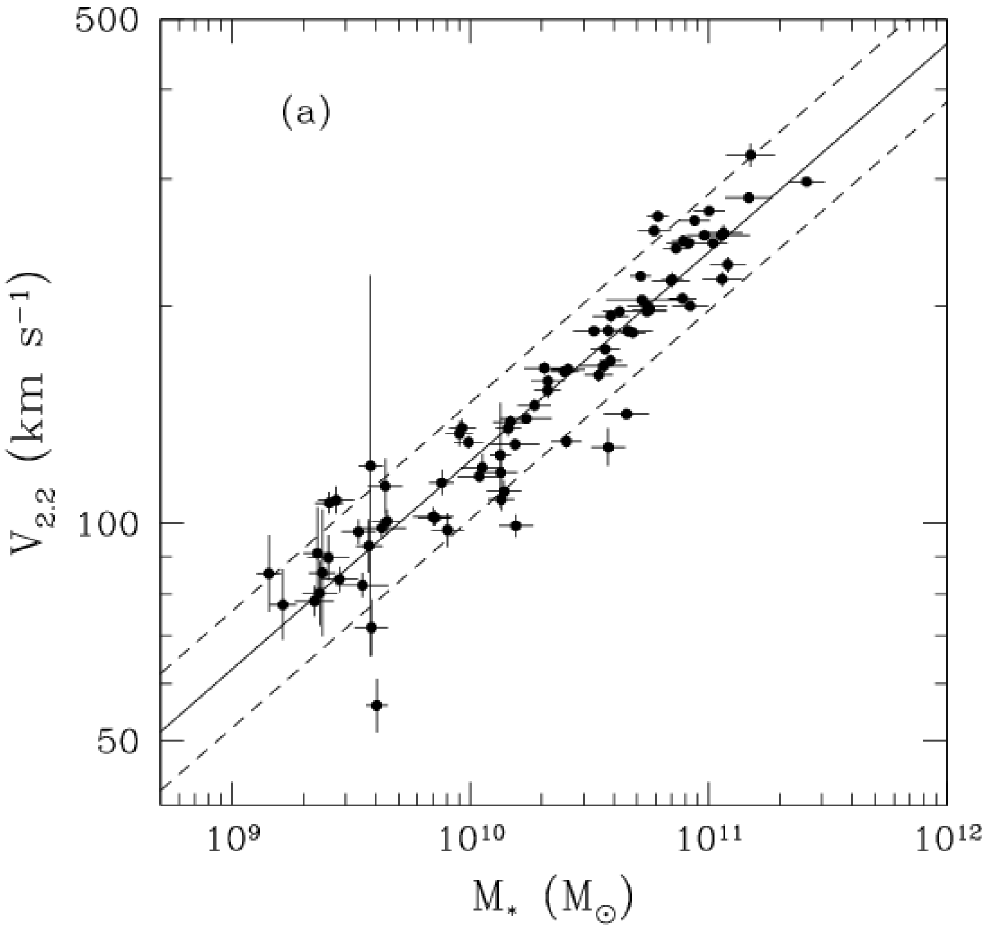


number

luminosity

Stellar Mass – Velocity relation

rotation velocity at 2.2 scale lengths



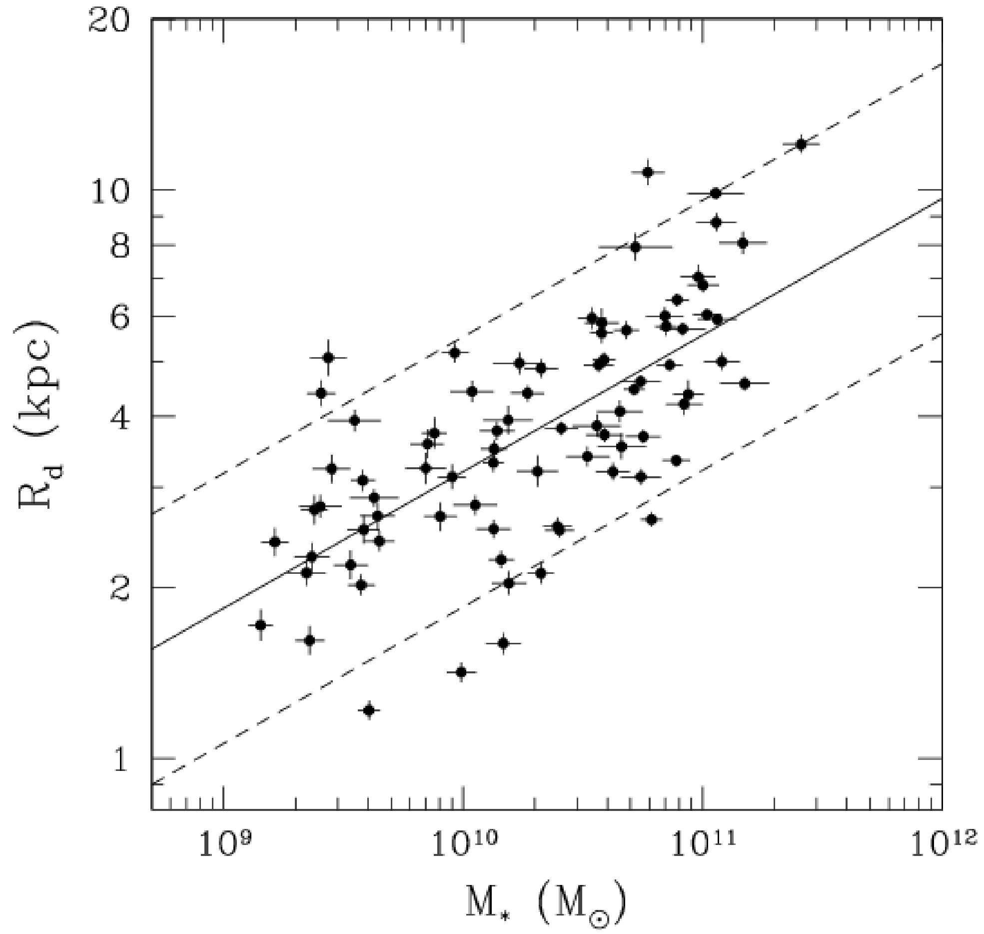
__goals:__

model mean relation

understand intrinsic scatter, beyond observational errors

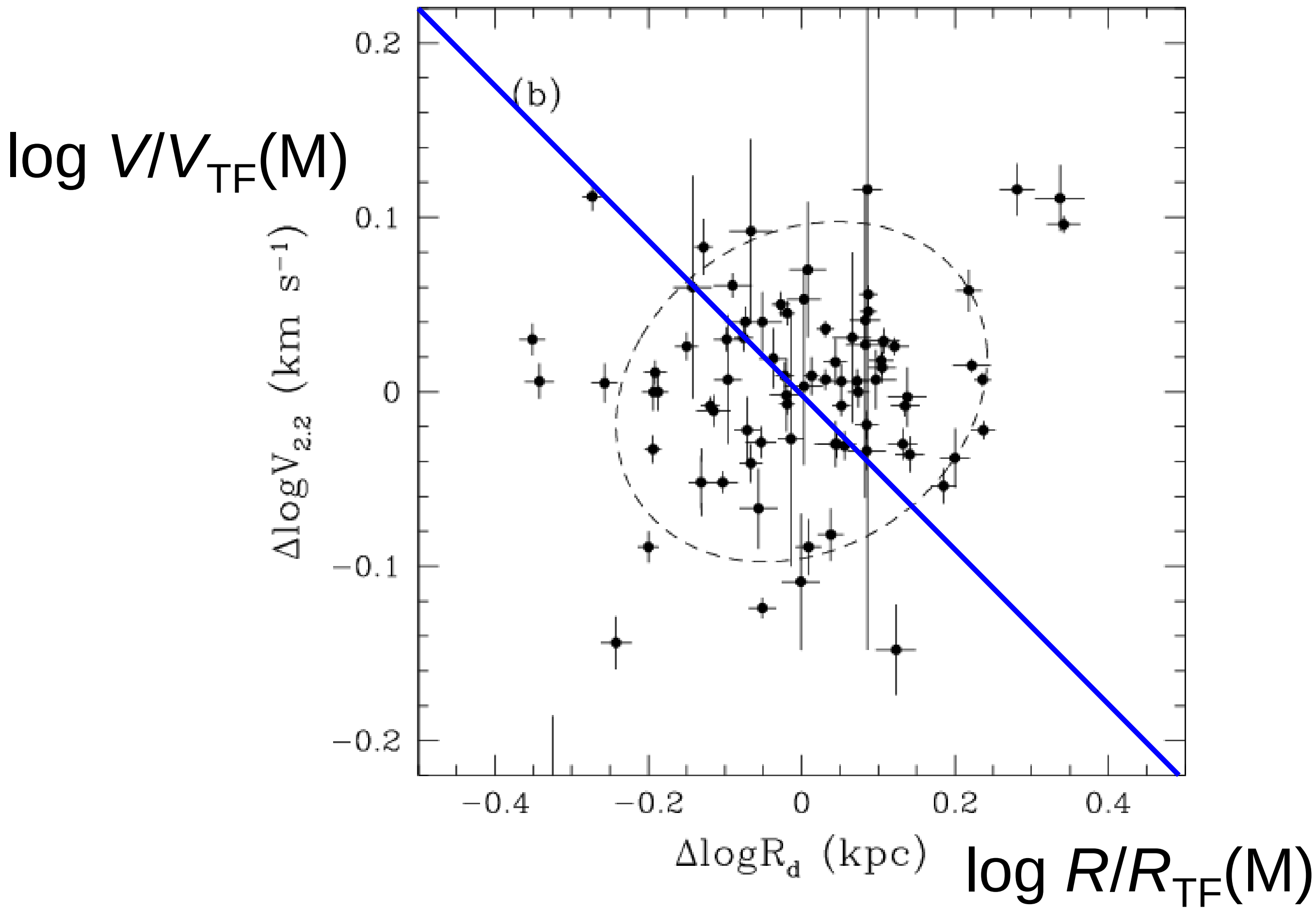
Homogeneous sample of 81 disk-dominated galaxies from SDSS, flat distribution of abs. magnitudes between -18.5 > M_r > -23.2

Stellar Mass – Radius relation



The mean mass-radius relation can be removed to study the residual scatter of TF relation

Residuals of the Tully-Fisher relation



Absence of residual correlation argues against maximal disk models, where $V \propto R^{-1/2}$ (Courteau & Rix 1999) – DARK MATTER HALO

What does the Tully-Fisher relation tell us?

Convert $L \rightarrow M^*$ using Kroupa stellar IMF, fit for $\{M_{vir}, R_{vir}\}$:

Determine stellar mass fraction $m_d = M_* / M_{vir}$
angular momentum parameter $\lambda_d = R_d / R_{vir}$

Method: fit the slope (***a***), zero-point (***b***), intrinsic scatter (σ), correlation coefficient of the residuals (***r***) for the galaxy sample

Galaxy model: stellar disk + dark matter halo $V^2 \approx GM_*/R_d + V_h^2$

Disk: exponential surface density with the observed $\boldsymbol{M_*}$ and $\boldsymbol{R_d}$ including observational uncertainties

Halo: NFW profile with mass $\mathbf{M_{vir}}$ and concentration **c** (log-normal PDF given by cosmological simulations)

An important ingredient: halo contraction

CONTRACTION OF DARK MATTER GALACTIC HALOS DUE TO BARYONIC INFALL[1]

GEORGE R. BLUMENTHAL AND S. M. FABER
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz

RICARDO FLORES
Department of Physics, Brandeis University, Waltham, Massachusetts

AND

JOEL R. PRIMACK
Board of Studies in Physics, University of California, Santa Cruz

Received 1985 June 14; accepted 1985 July 9

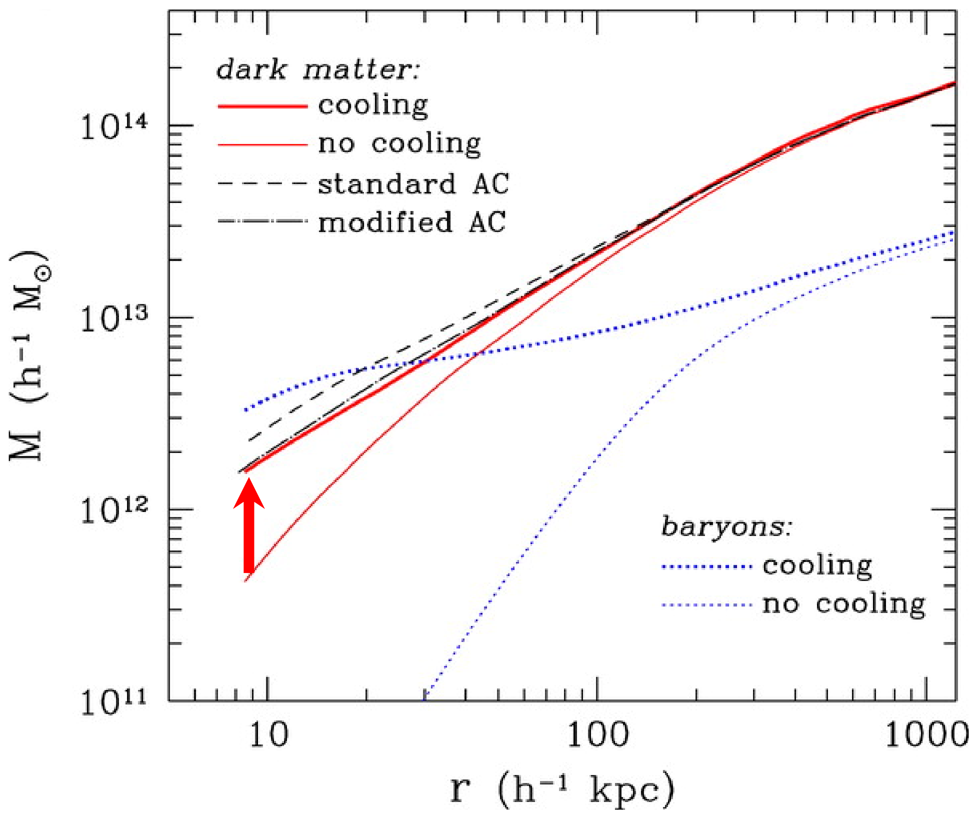
ABSTRACT

Varied evidence suggests that galaxies consist of roughly 10% baryonic matter by mass and that baryons sink dissipatively by about a factor of 10 in radius during galaxy formation. We show that such infall strongly perturbs the underlying dark matter distribution, pulling it inward and creating cores that are considerably smaller and denser than would have evolved without dissipation. Any discontinuity between the baryonic and dark matter mass distributions is smoothed out by the coupled motions of the two components. If dark halos have large core radii in the absence of dissipation, the above infall scenario yields rotation curves that are flat over large distances, in agreement with observations of spiral galaxies. Such large dissipationless cores may plausibly result from large internal kinetic energy in protogalaxies at maximum expansion, perhaps as a result of subclustering, tidal effects, or anisotropic collapse.

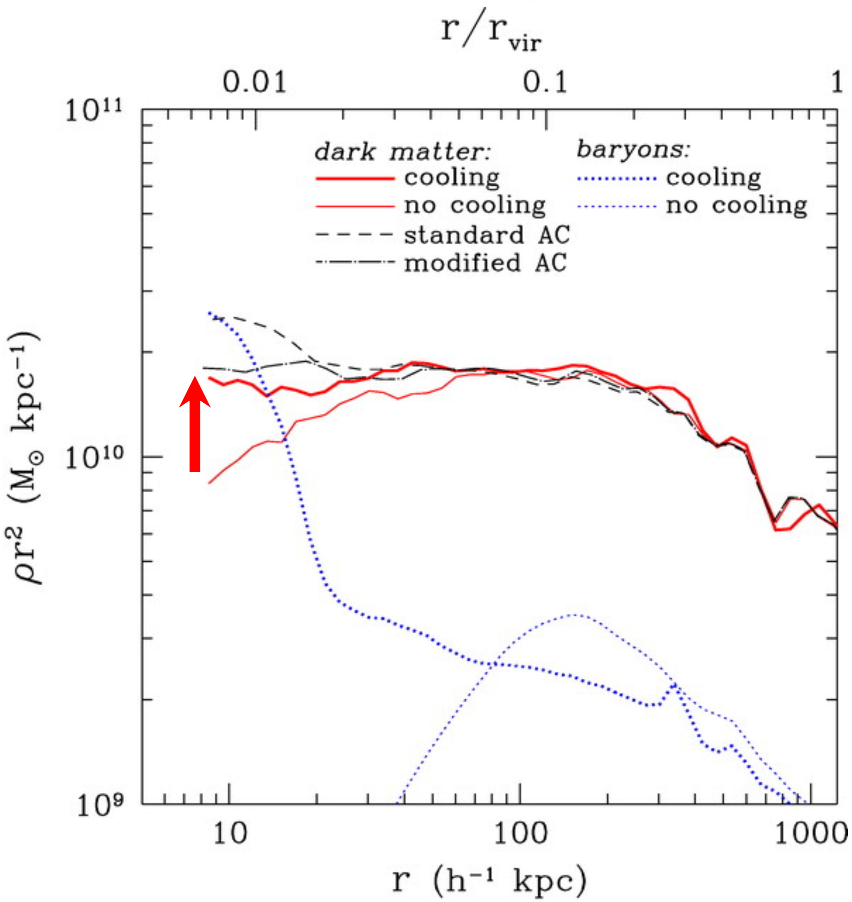
Subject headings: galaxies: evolution — galaxies: internal motions — galaxies: structure — interstellar: matter

Zeldovich et al. (1980), Barnes & White (1984),
Ryden & Gunn (1987), Flores et al. (1993),
Dalcanton et al. (1997), Mo et al. (1998), …

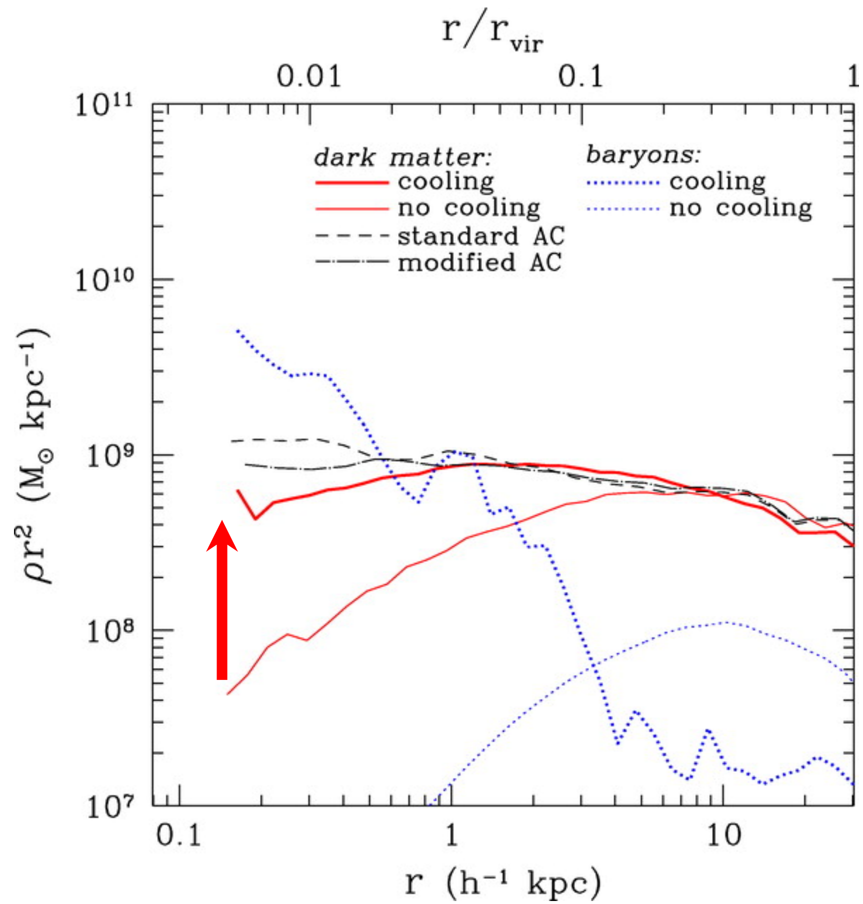
Dark matter density is increased by baryonic infall



Cosmological simulations of 8 galaxy clusters at z=0 and one galaxy at z=4: compare runs *with* and *without* gas cooling, for the same initial conditions (OG, Kravtsov, Klypin & Nagai 2004) cluster of galaxies



galaxy



Both galaxy- and cluster-sized dark matter halos contract, but the standard model overestimates the effect

noticed previously by Barnes, Sellwood, and others

Modified model of halo contraction

Standard model is based on conservation of angular momentum for circular orbits *or* radial action for purely radial orbits.

Orbits in real halos have a wide distribution of eccentricities.

Circular orbit: $J^2 = J_{max}(E)^2 = GM(r)r$

Radial orbit, self-similar potential: $I_r^2 \propto M(r_a)r_a$

General case: $I_r^2 \propto M(\langle r \rangle)\langle r \rangle$ or $M(\langle r \rangle)r$

$$\text{modified invariant} = M(\langle r \rangle)r$$

(*approximately correct but maintains the simplicity of the method)*

Contra: a code for halo contraction

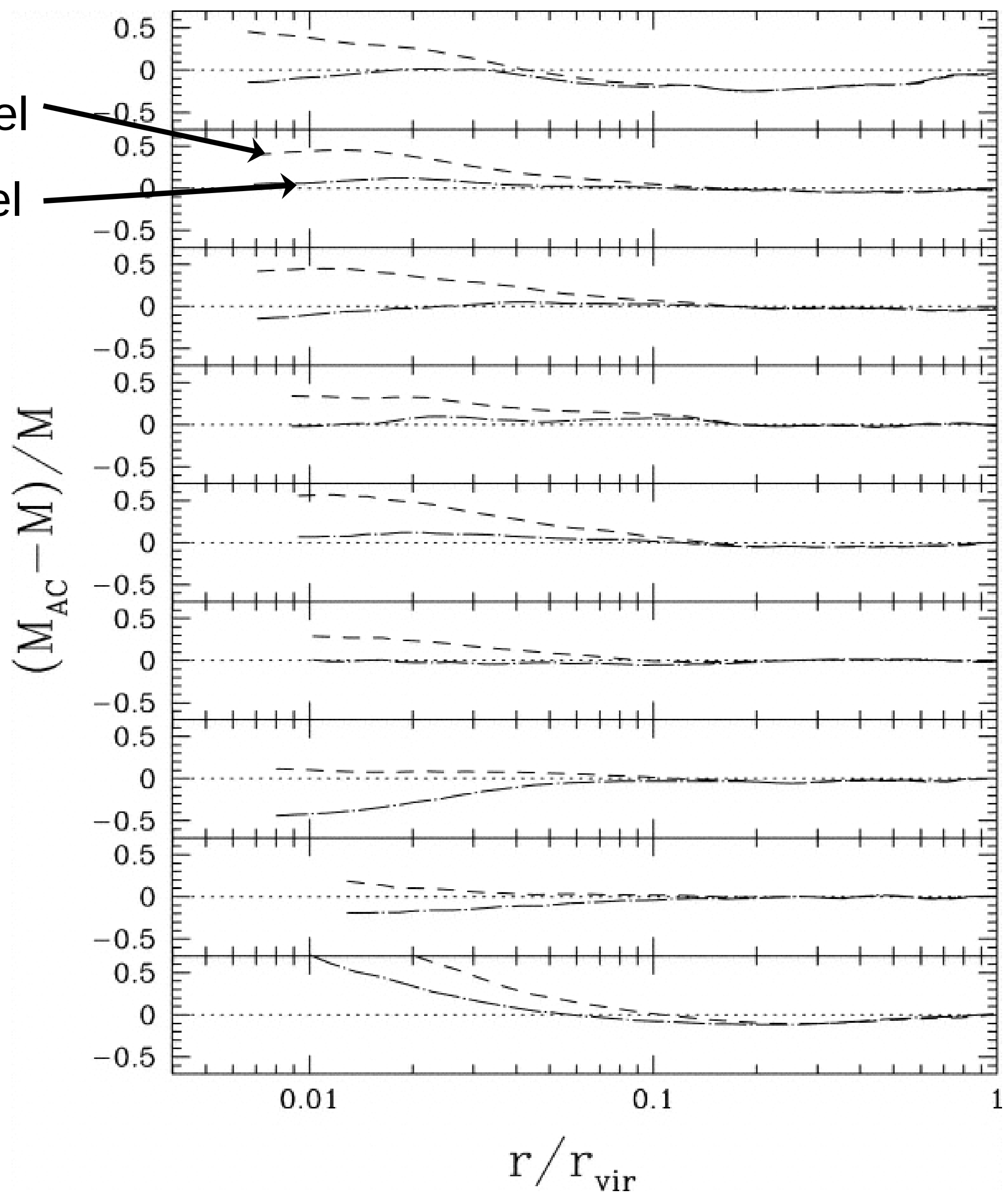
http://www.astro.lsa.umich.edu/~ognedin/contra/

Modified model better describes the simulation results

Standard model

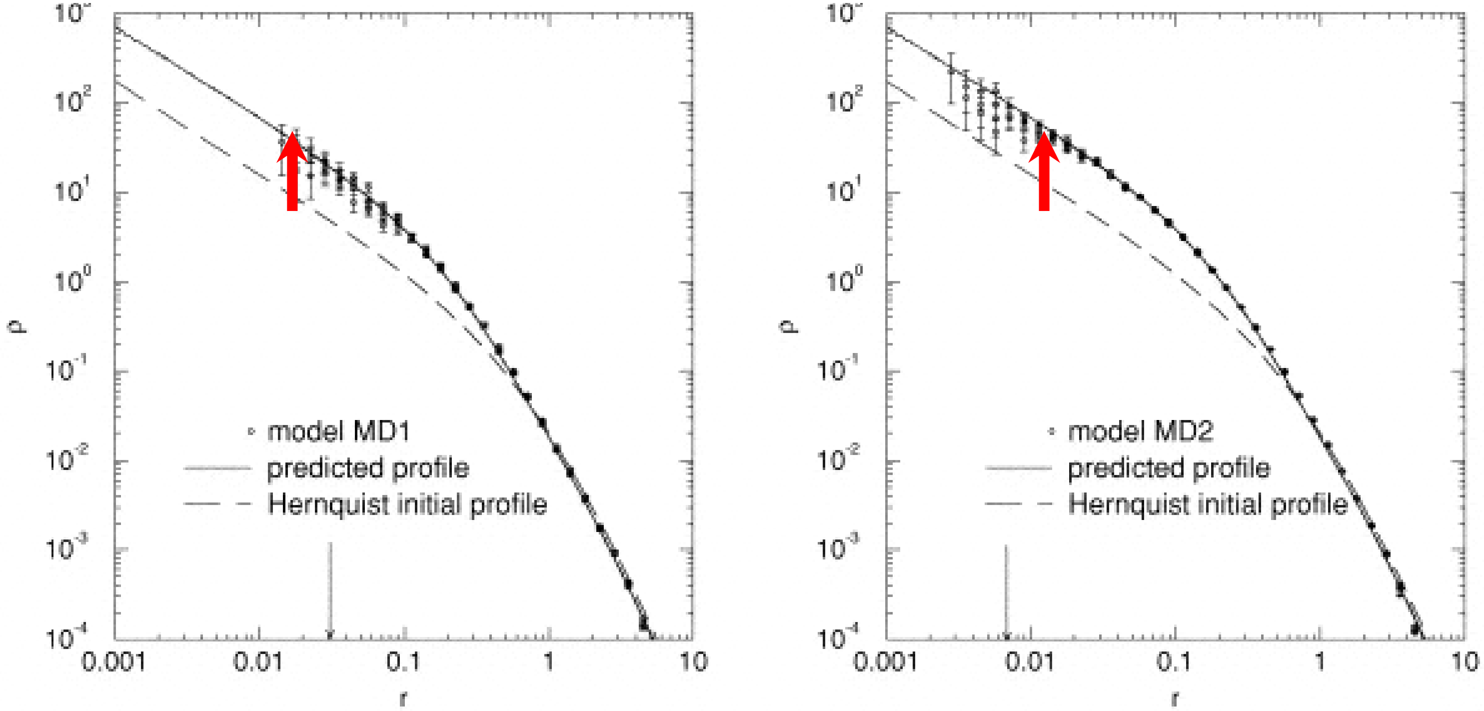
Modified model

Relative error compared to the simulations



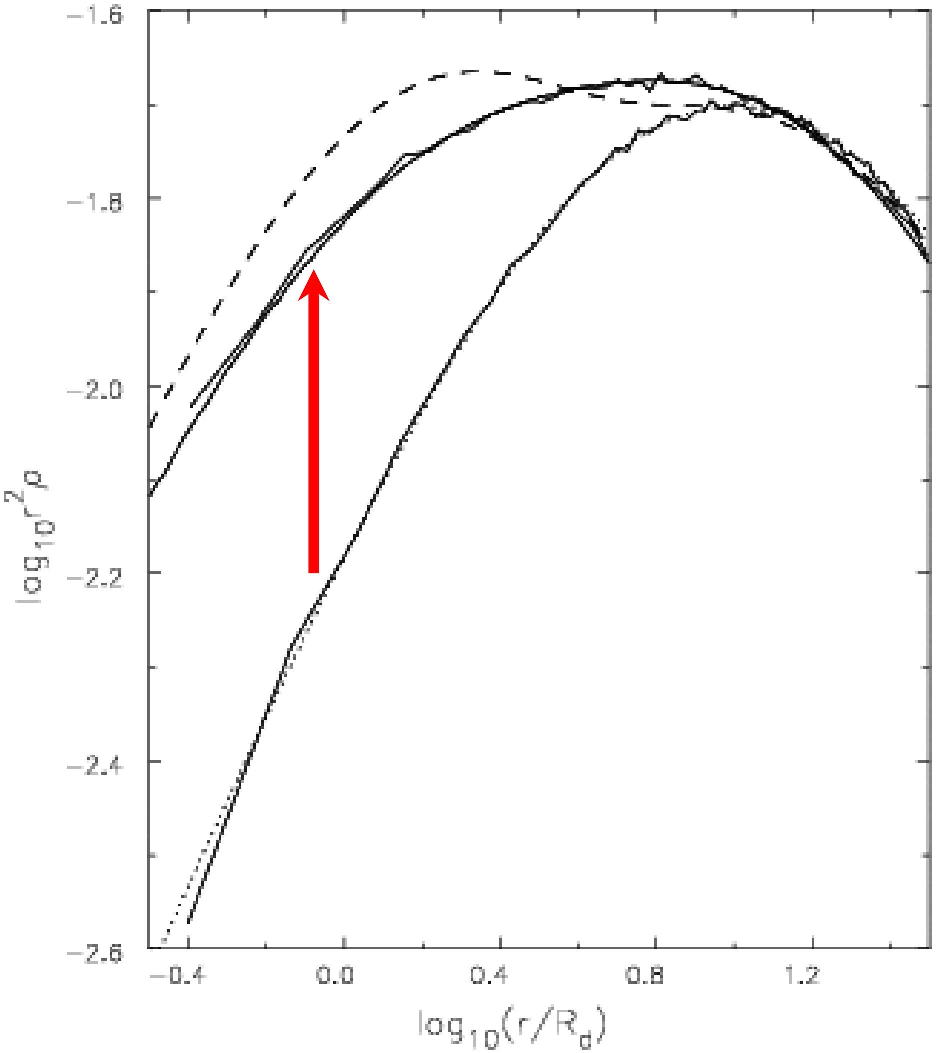
Jesseit, Naab & Burkert (2002)

N-body simulation, 10^6 particles



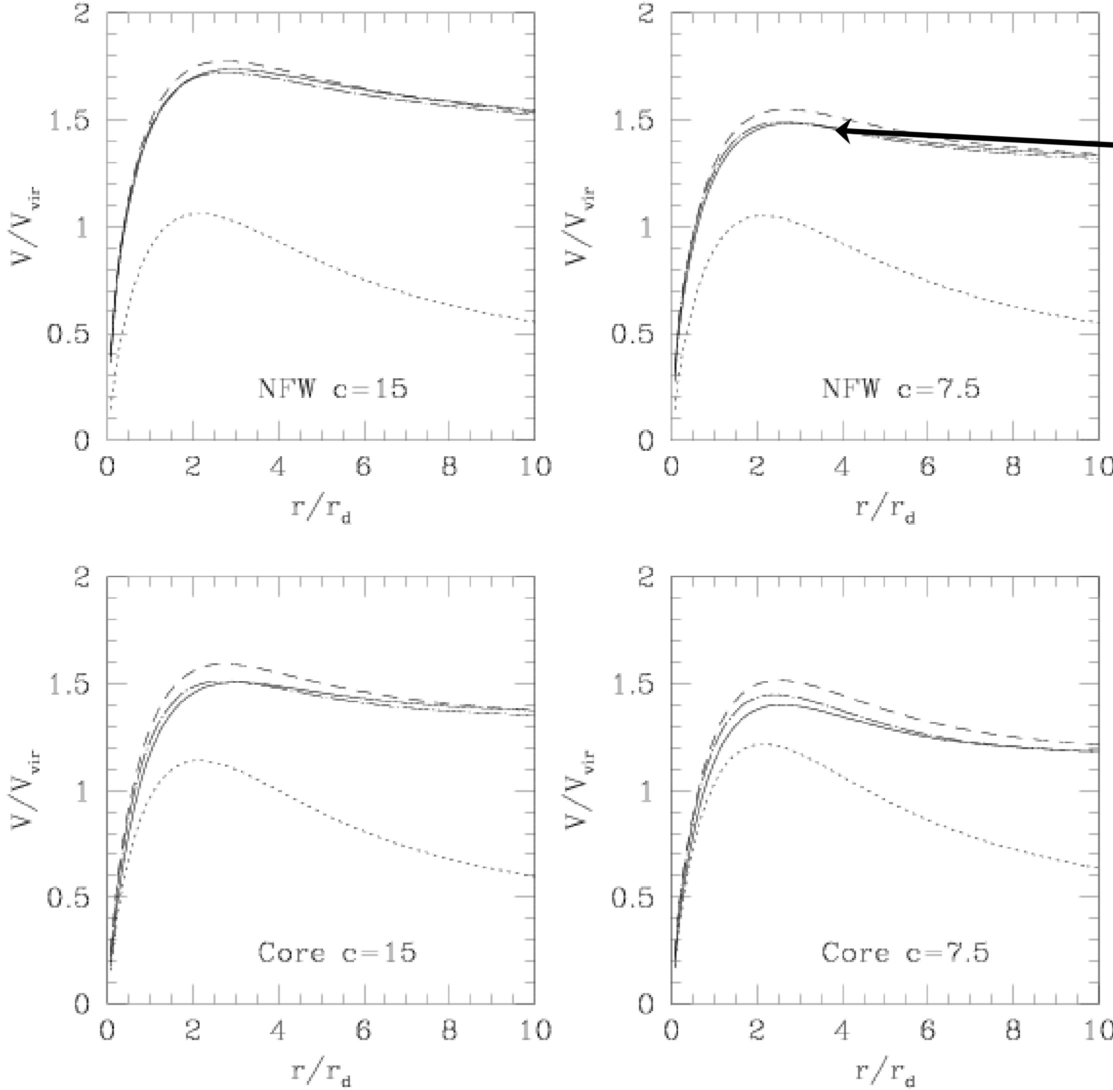
Sellwood & McGaugh (2005)

N-body simulation 10^6 particles



Choi, Lu, Mo & Weinberg (2006)

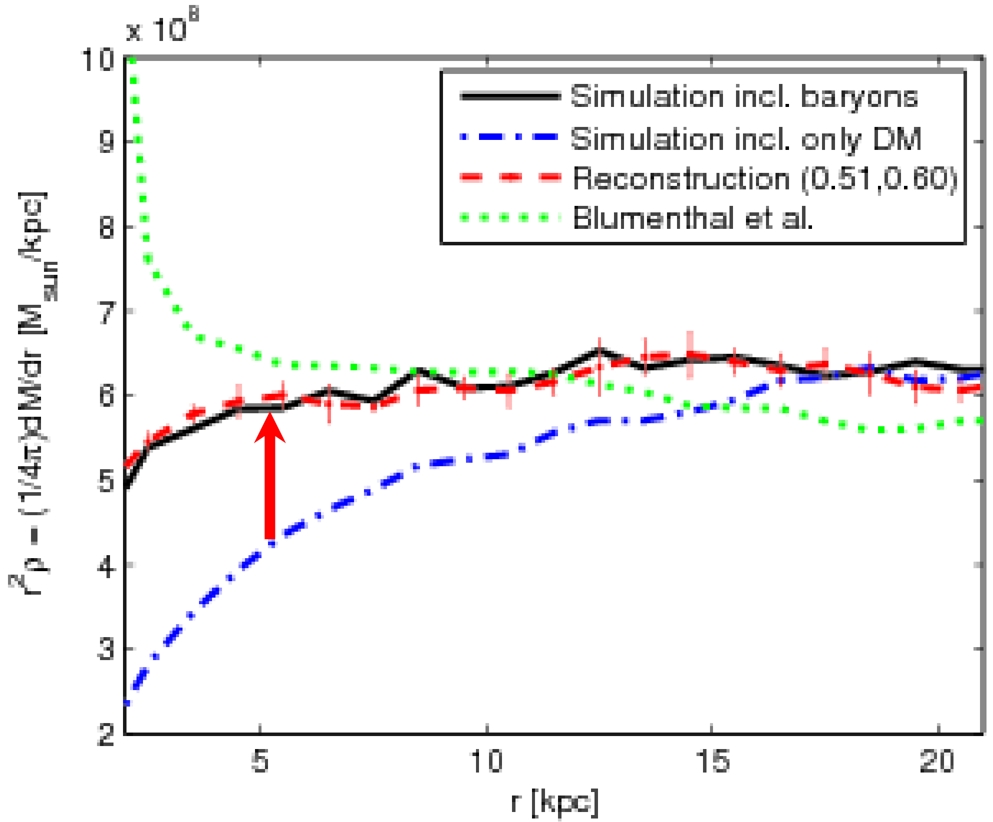
1D spherical shell simulation

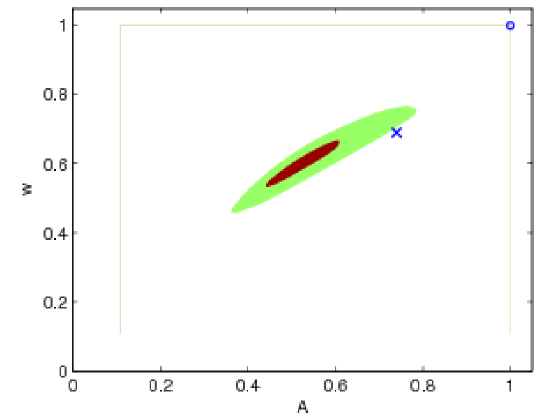


Simulation
Mod. model

Gustafsson, Fairbairn & Sommer-Larsen (2006)

SPH simulations 10^6 particles per halo





calibration of the parameters of the modified model

The overall effect of gas dissipation, including

non-sphericity

non-adiabaticity

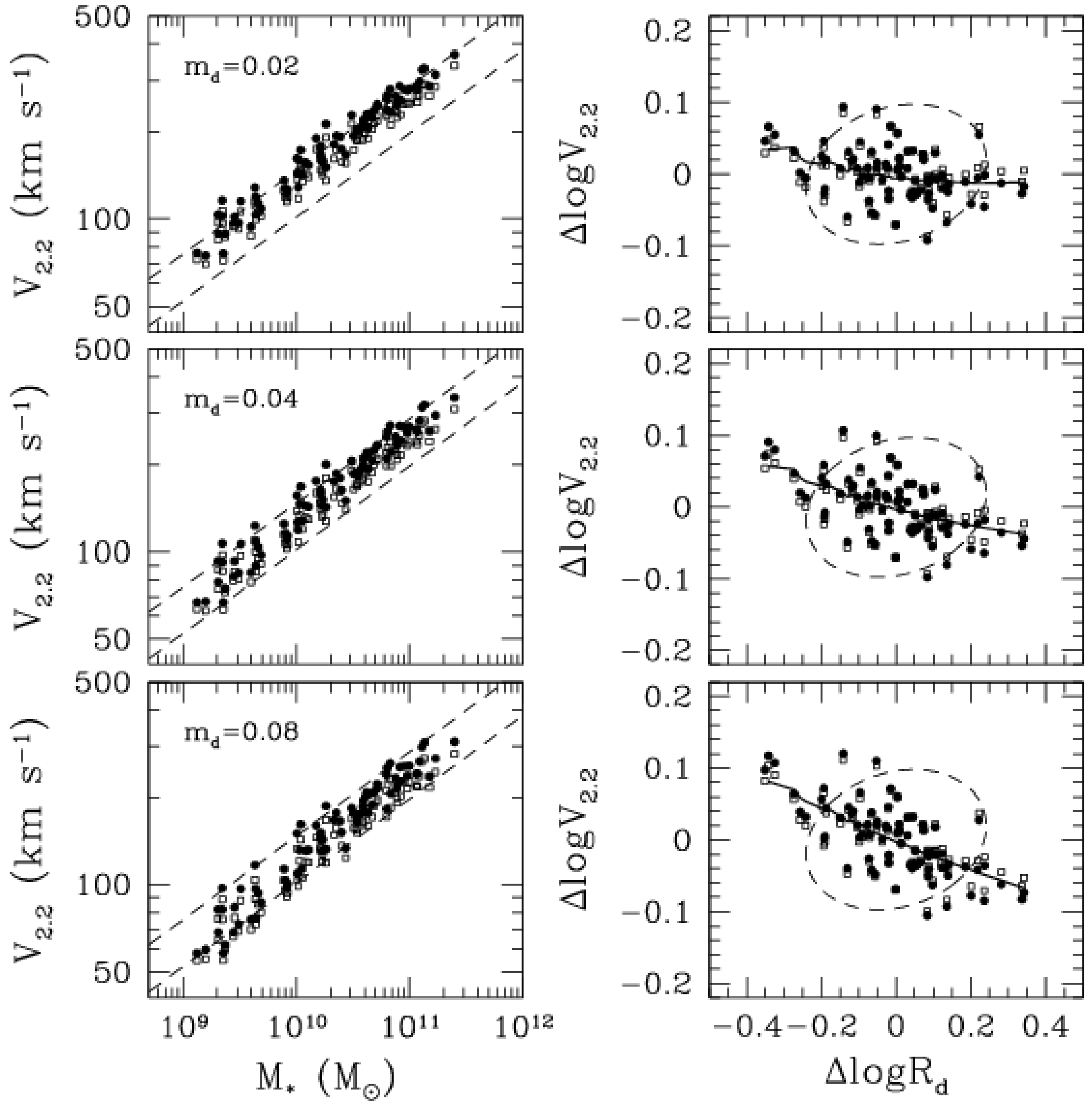
dynamical friction

galaxy mergers, etc.,

is

halo contraction

Constant m_d : too little scatter, residual correlation

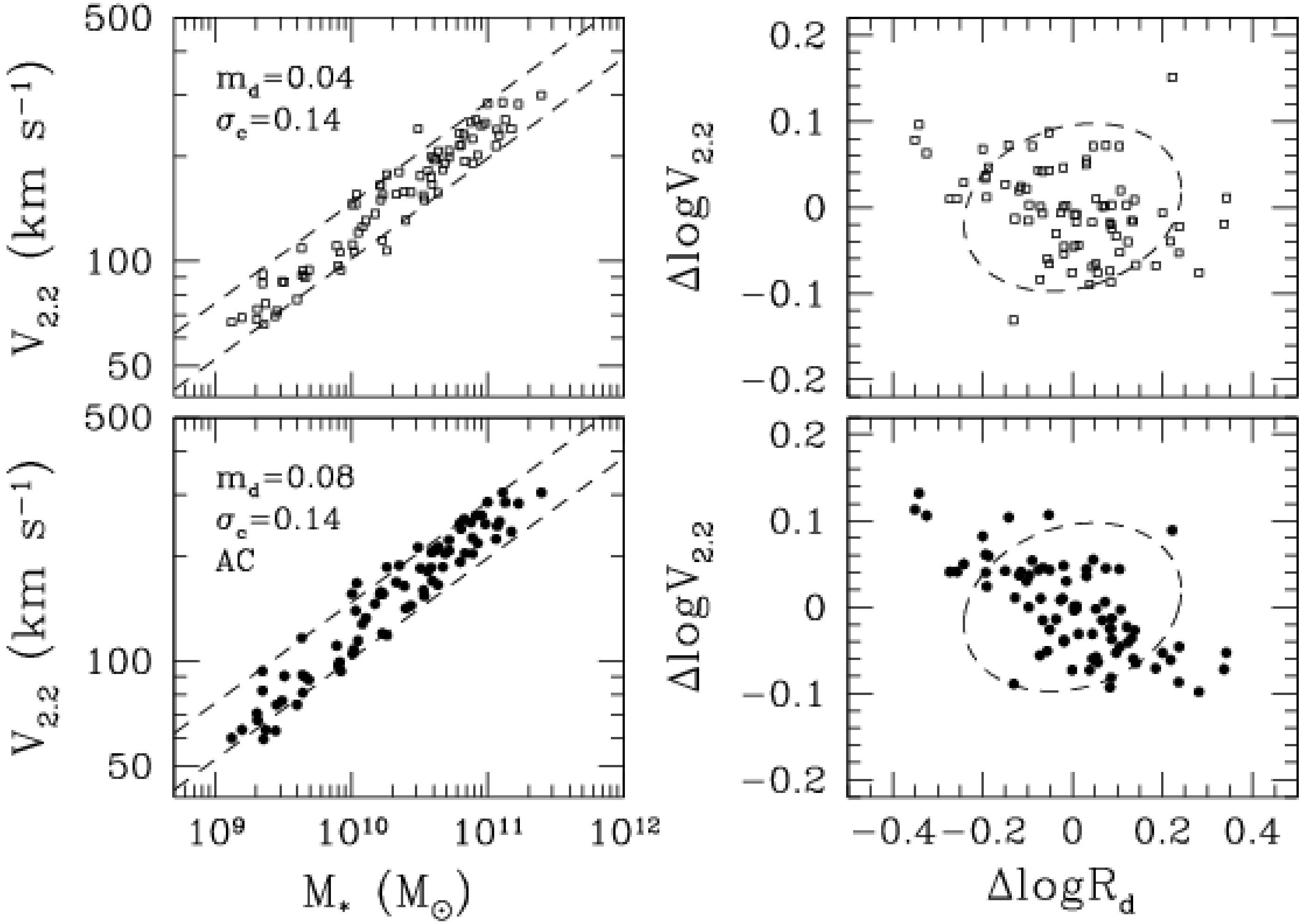


solid points – model with AC

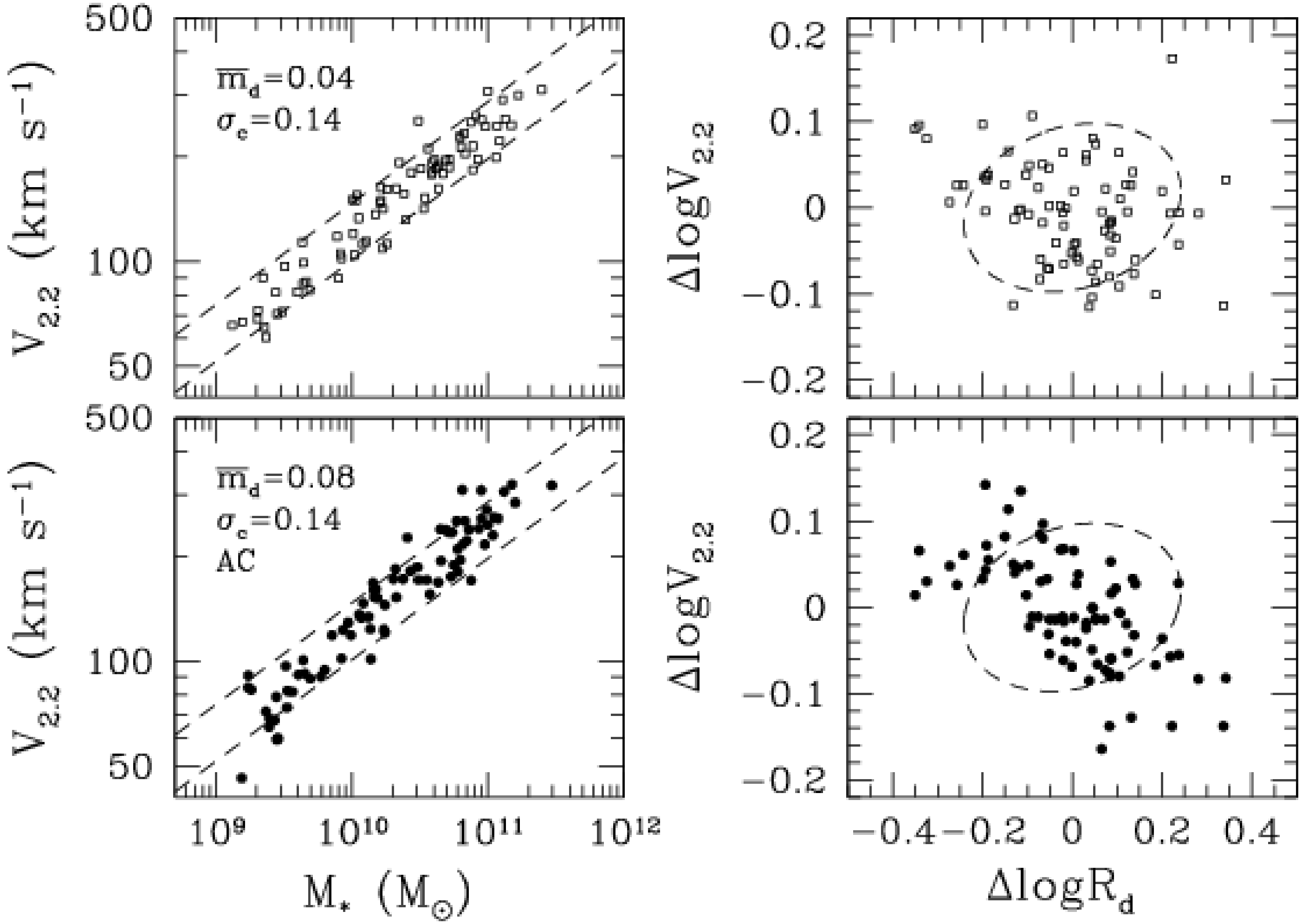
open points – no AC

---- 90% data contours

Scatter of halo concentrations is not enough to account for the observed TF intrinsic scatter



Scatter of disk mass fractions is not enough to account for the lack of TF residual correlation

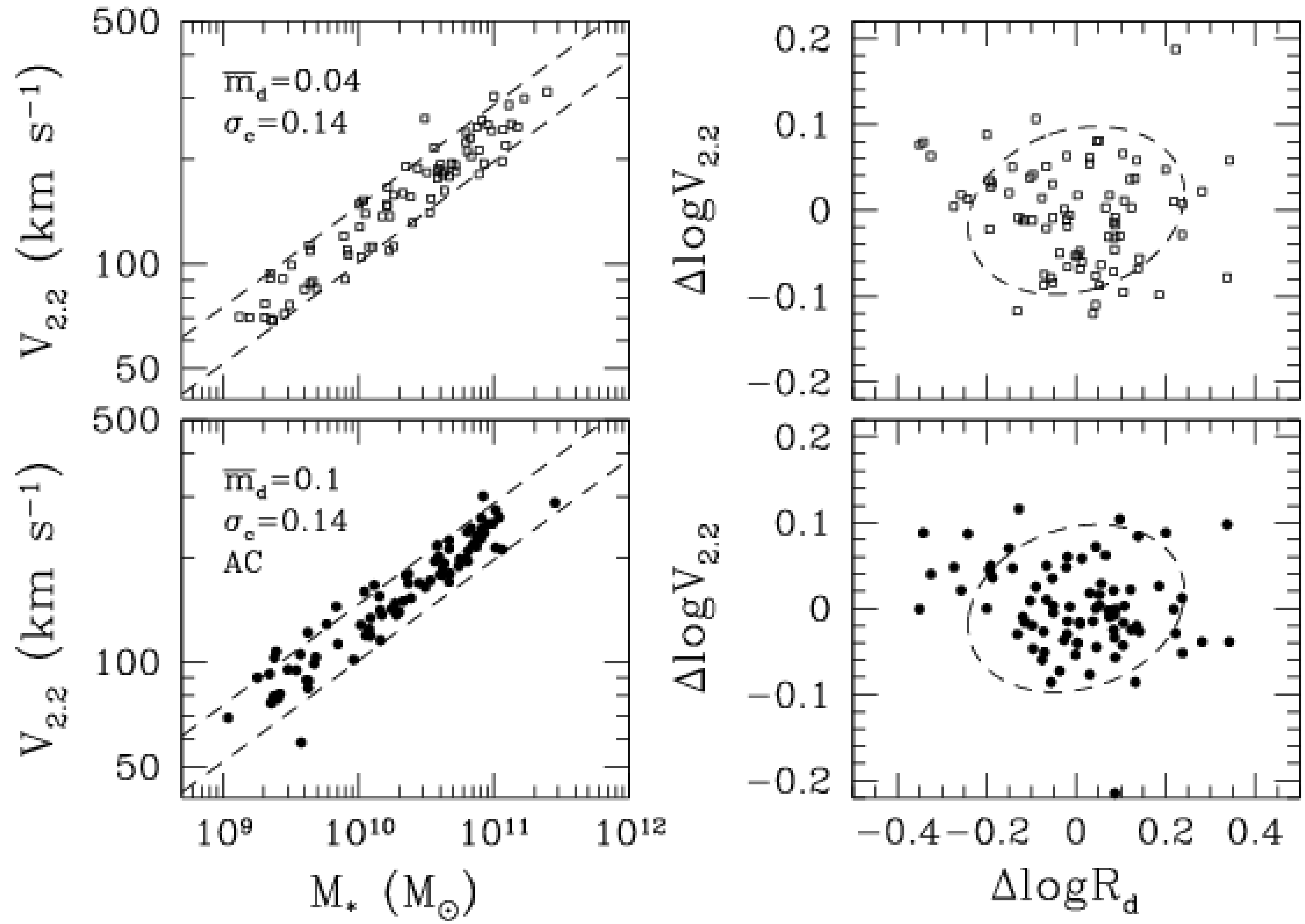


BEST ML FIT

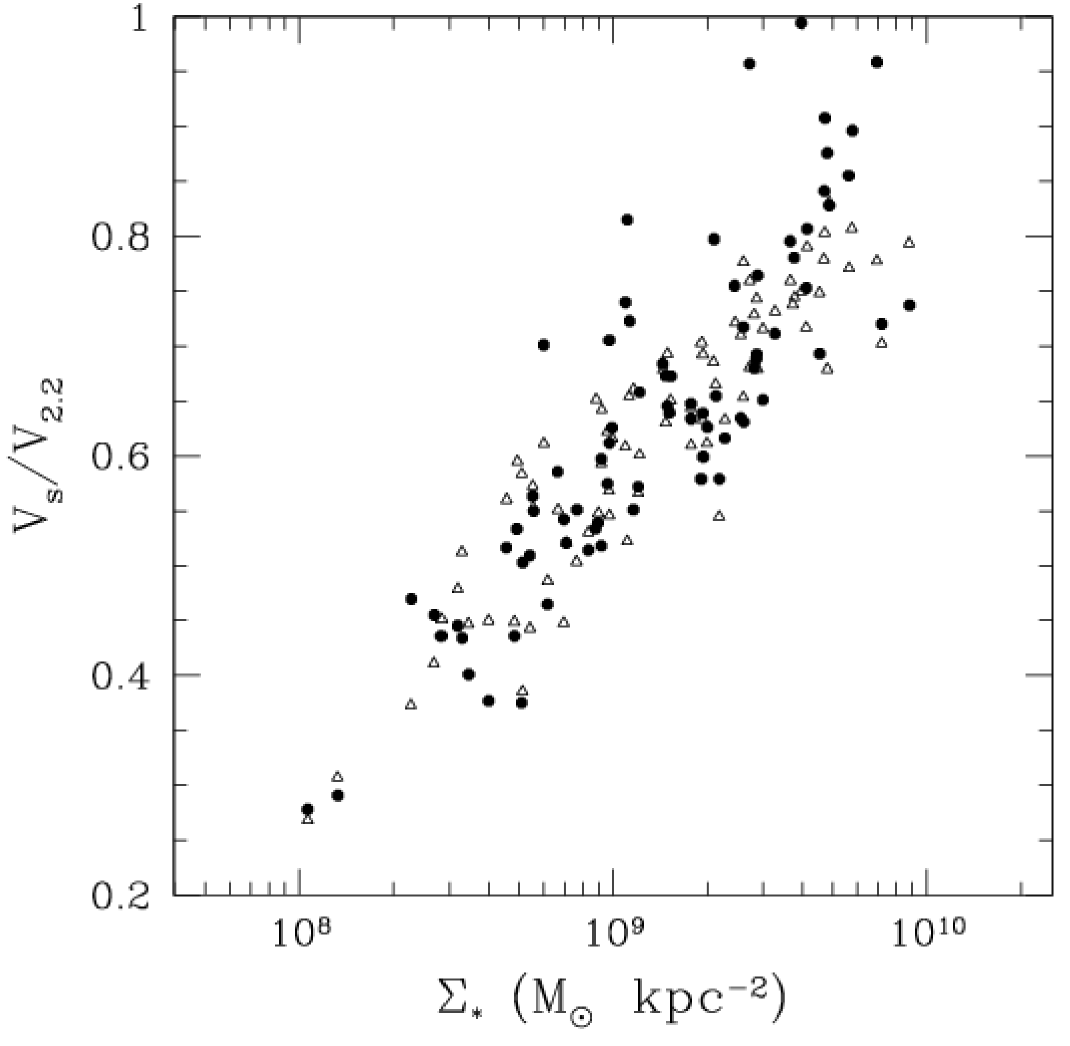
no AC: $m_d = 0.04\ (\Sigma_* / 10^{9.2}\, M_\odot\ \mathrm{kpc}^{-2})^{0.2}$

AC: $m_d = 0.1\ (\Sigma_* / 10^{9.2}\, M_\odot\ \mathrm{kpc}^{-2})^{0.65}$

+ log-normal scatter

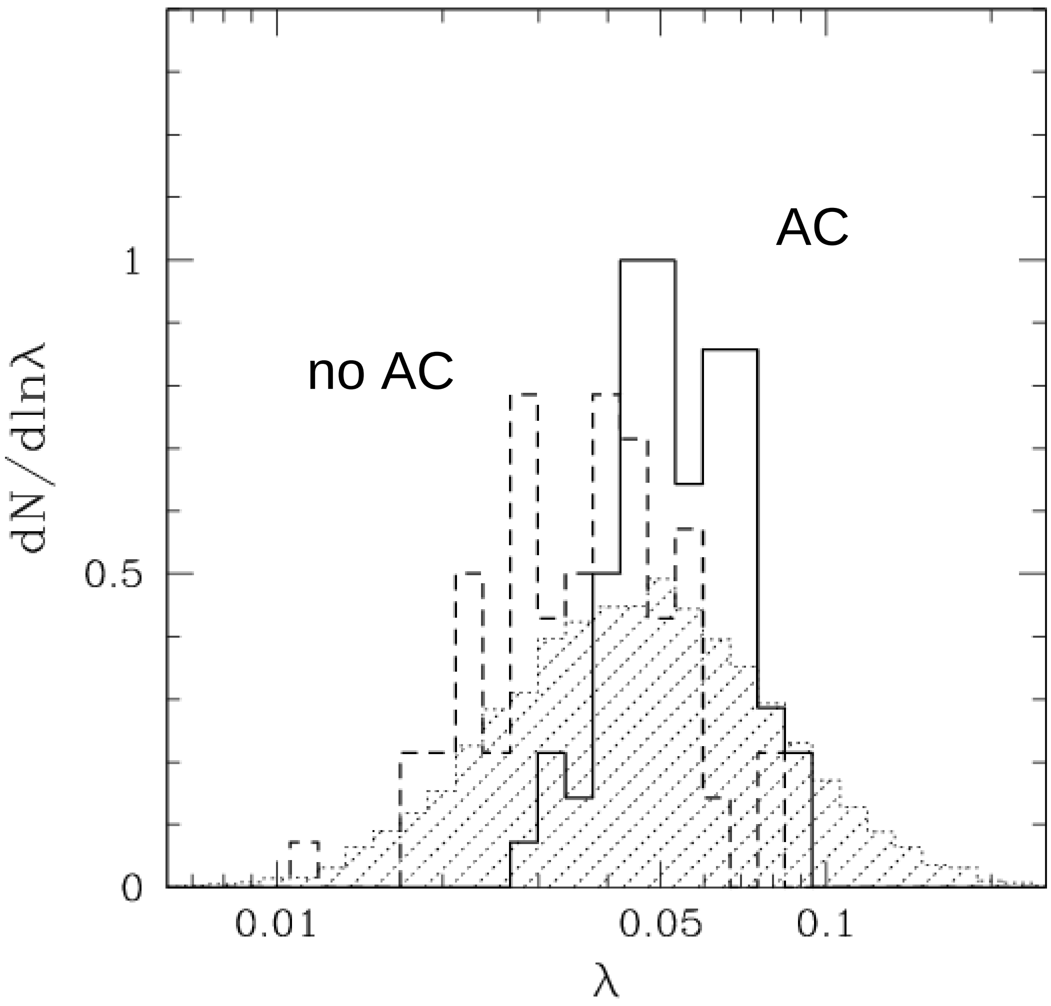


Stars dominate in high surface density galaxies

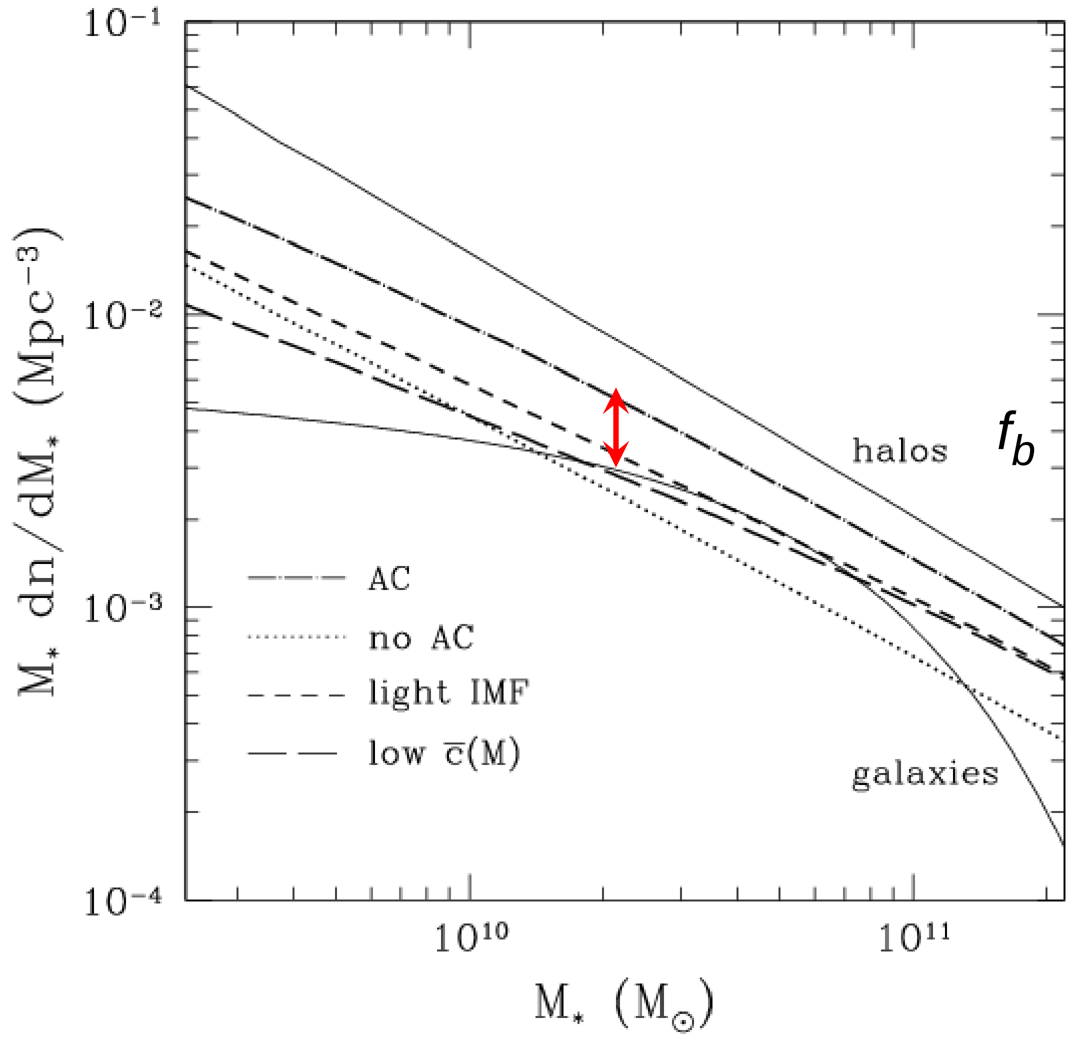


Circles – data, triangles - model

Disk angular momentum: less broad distribution than DM



Stellar mass function



high m_d –

means small halos –

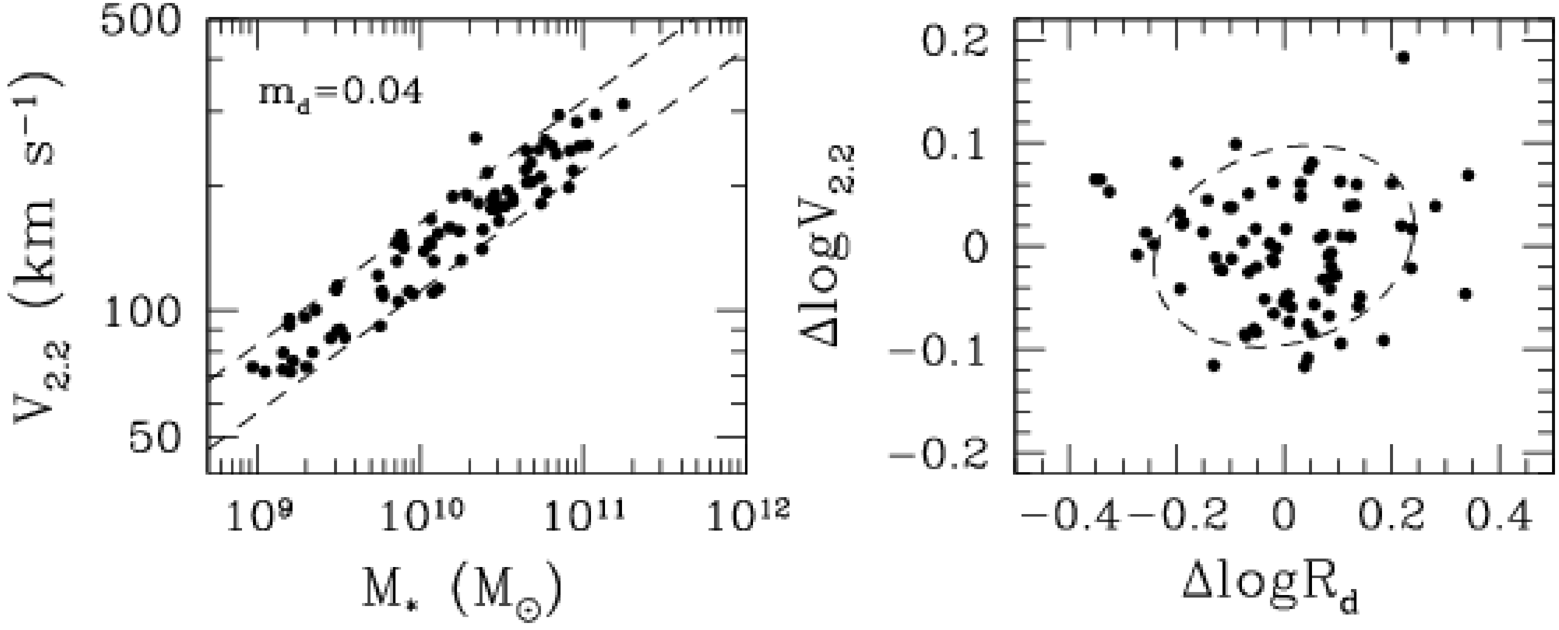
means many galaxies

Data: SDSS + 2MASS (Bell et al. 2003)

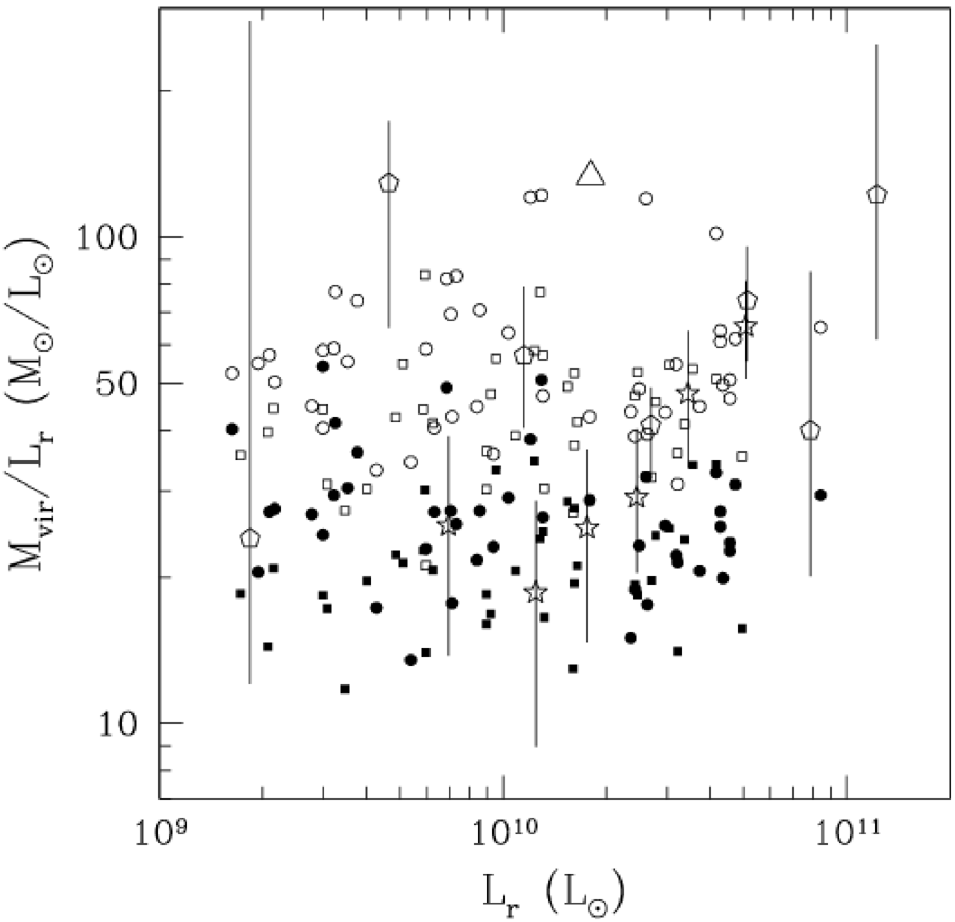
Three Possible Solutions

- Ignore halo contraction
  (*against tested physics*)
- Assume stellar IMF lighter than Kroupa
  by ~ 0.15 dex
  (*plausible)*
- Reduce halo concentrations, as expected
  for low σ_8 from WMAP3
  (*likely*)

Light stellar IMF (Kroupa – 0.15 dex)



Dynamical mass-to-light ratio



filled: Kroupa IMF
open: light IMF

squares: compact
circles: extended

Stars and pentagons – weak lensing (Hoekstra et al. 2005, Mandelbaum et al. 2005), triangle – satellite dynamics (Prada et al. 2006)

Summary

Gas cooling and dissipation lead to the contraction of dark matter halos (compared to the collisionless case) and can significantly increase the central concentration of dark matter in galaxies and clusters of galaxies.

Structural properties of disk galaxies (Tully-Fisher relation) can be fit by CDM models, for both high- and low surface brightness galaxies, with and without halo contraction.

Tully-Fisher relation and stellar mass function can be reconciled if:

- We ignore halo contraction (against tested physics)
- Stellar IMF is lighter than Kroupa by ~ 0.15 dex
- Halo concentrations are lower, as expected for WMAP3 results