DARK MATTER

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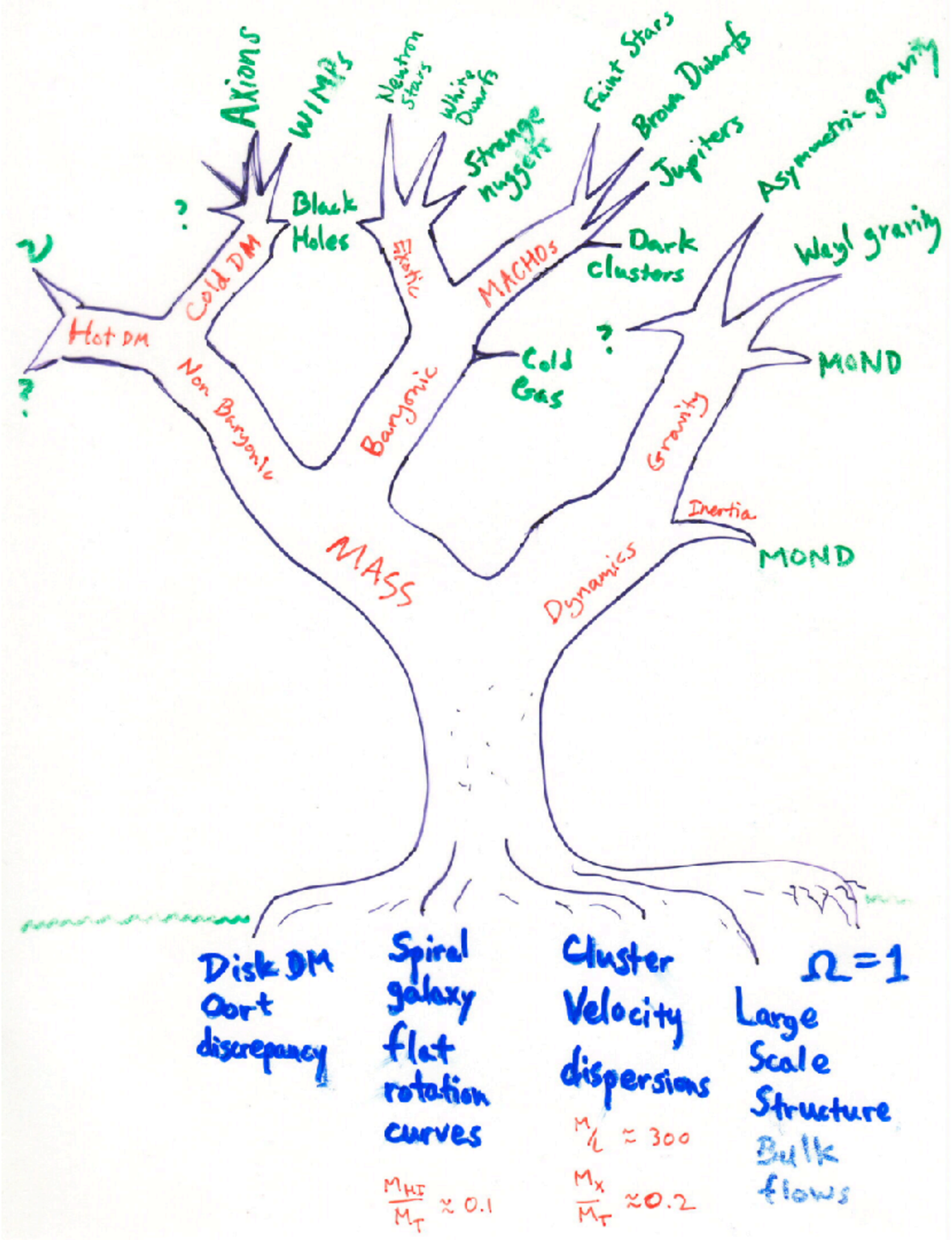

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Dark Matter Halos

Many models; none entirely appropriate

- Pseudo-isothermal
- NFW
- Burkert
- Einasto
- DC14
- coreNFW
- etc. - see Li et al. (2020, ApJS, 247, 31 ; arXiv:2001.10538)

$$V_{\rm iso}(R) = V_\infty \sqrt{1 - \frac{R_C}{R} \arctan\left(\frac{R}{R_C}\right)} \qquad V_\infty = \sqrt{4\pi G \rho_0 R_C^2}$$

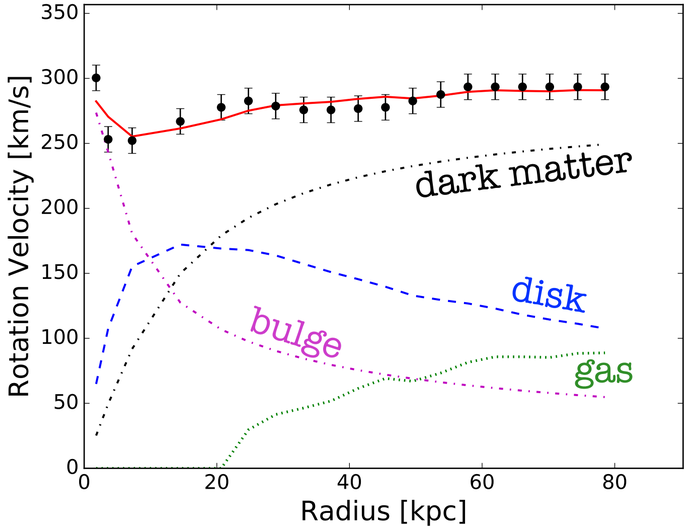
$$V_{\rm NFW}(R) = V_{200} \sqrt{\frac{\ln(1+cx) - cx/(1+cx)}{x[\ln(1+c) - c/(1+c)}} \qquad x = \frac{R}{R_{200}} \qquad c = \frac{R_{200}}{R_s}$$

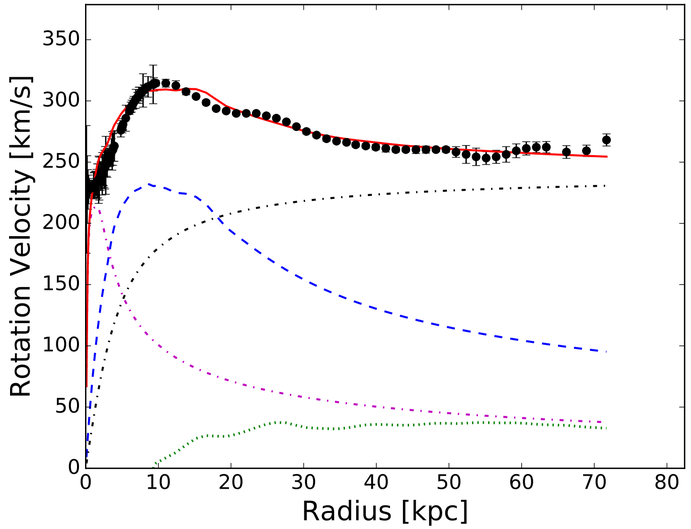
sometimes refer to halos by their “virial” temperature $kT_{vir} \propto \sigma^2$ $\qquad \sigma = \frac{1}{\sqrt{3}} V_{200}$

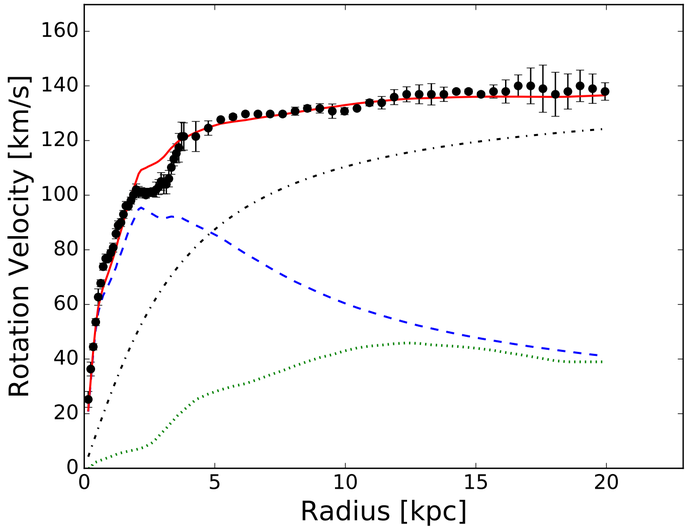
Rotation curve fits: two halo models fit to three galaxies

UGC 2885 | UGC 2953 | NGC 2403

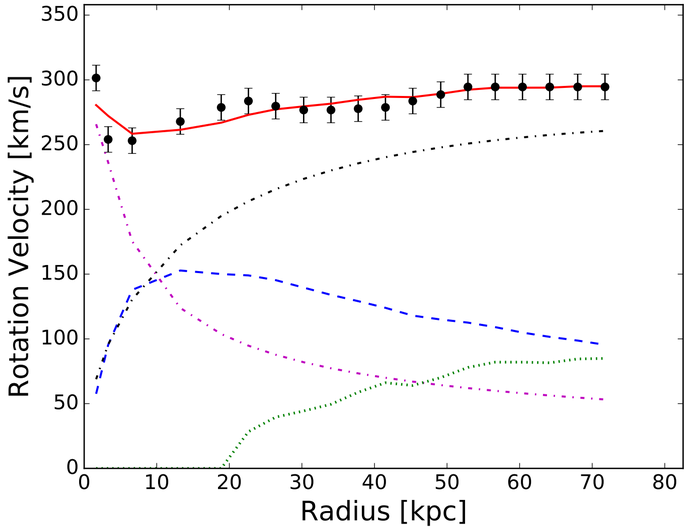
ISO

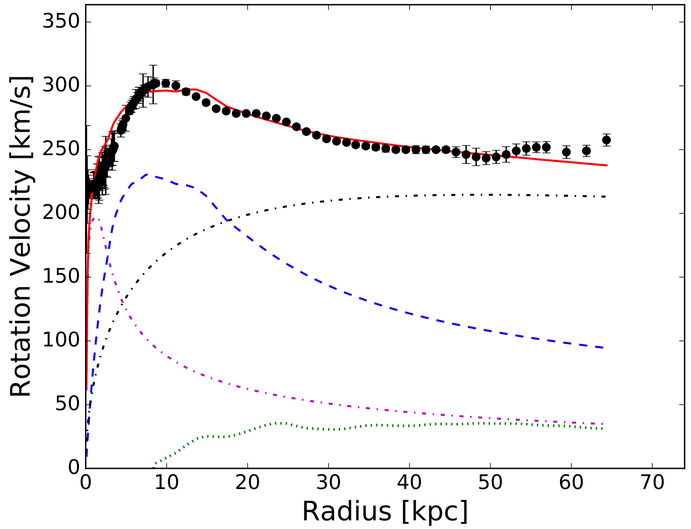


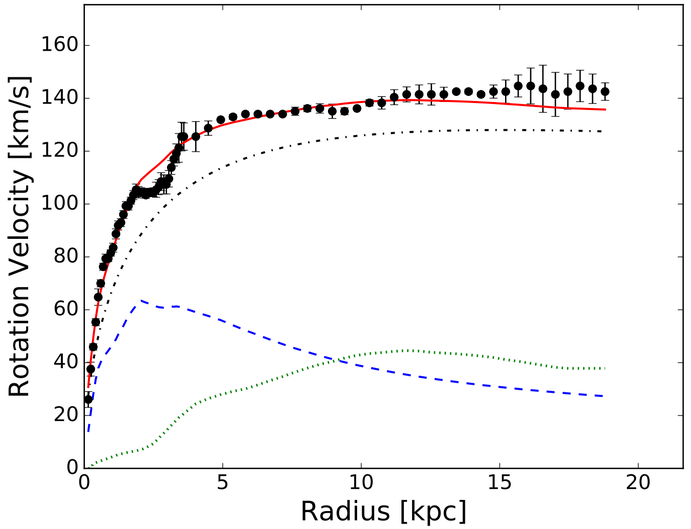




NFW







Cumulative distribution of χ^2_ν for dark matter halo fits with different Bayesian priors

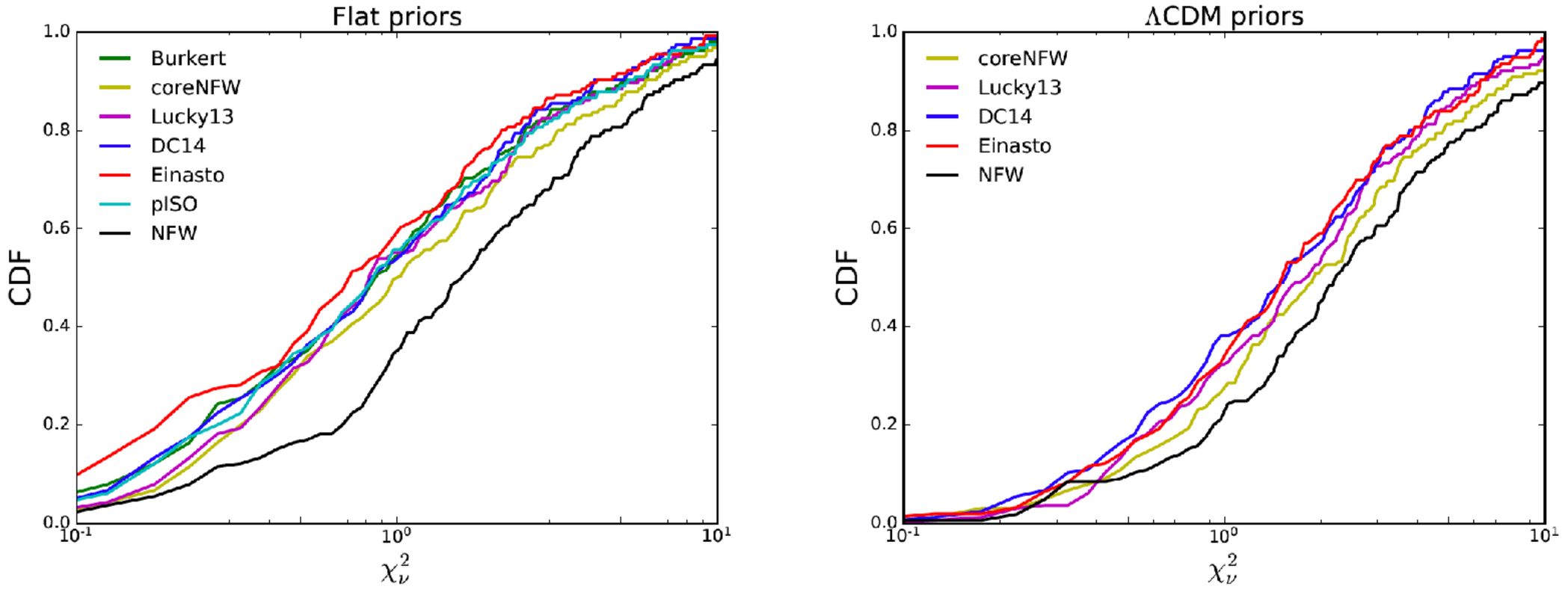


Figure 1. Cumulative distributions of the reduced χ^2_ν for seven halo profiles with flat (left) and ΛCDM priors (right).

Li et al. (2020)

ΛCDM priors

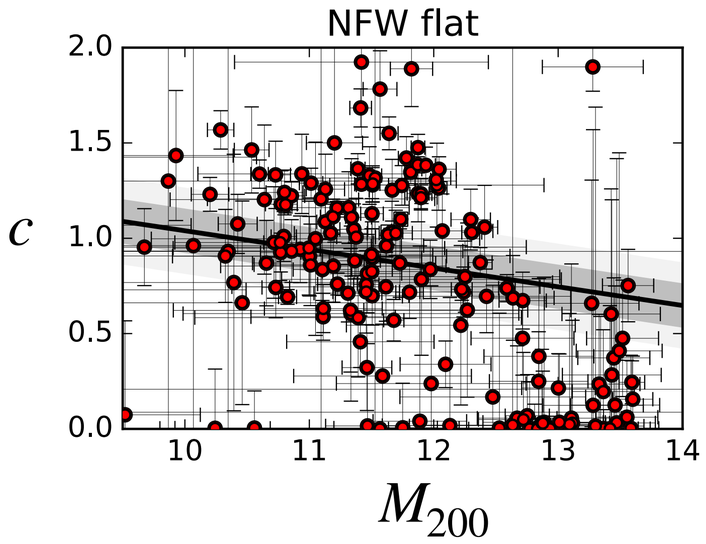
halo mass-concentration relation

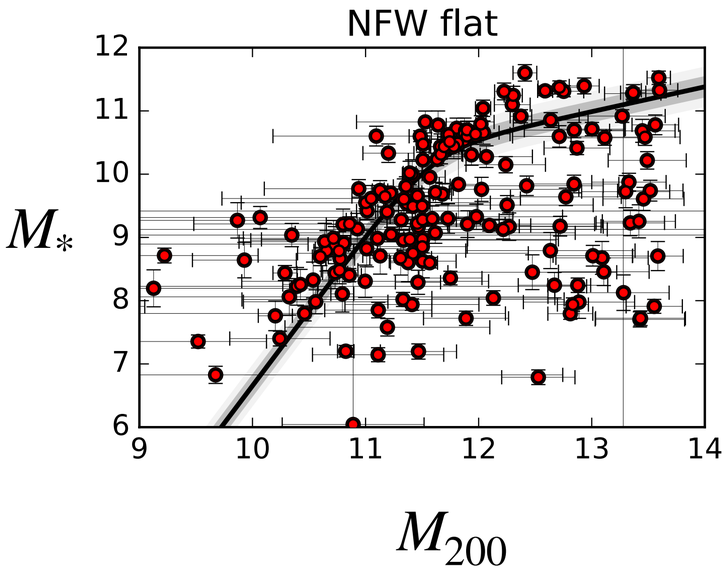
$c - M_{200}$

stellar mass-halo mass relation

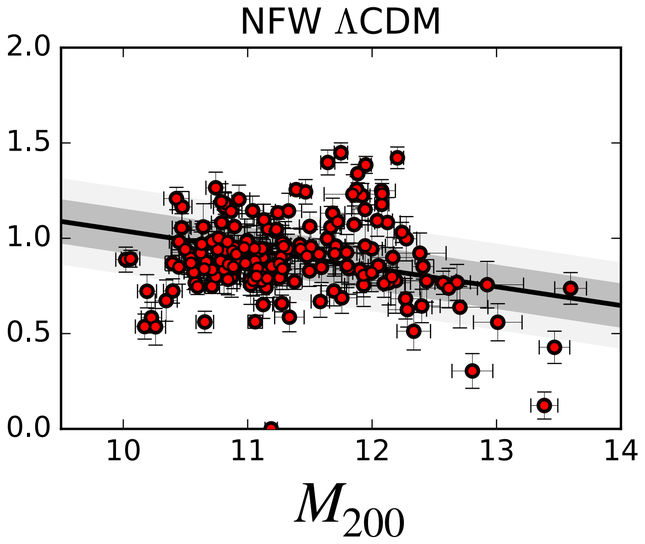
$M_* - M_{200}$

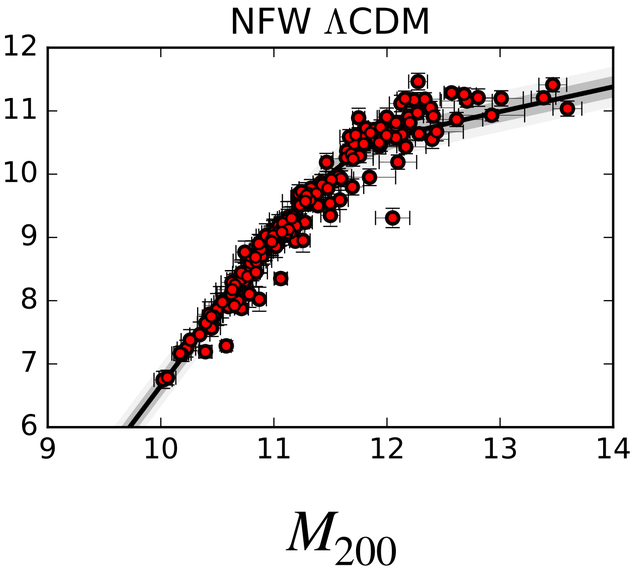
flat priors





LCDM priors





Radial Acceleration Relation

The observed acceleration correlates with that predicted by the baryons

The data are well fit by

$$g_{obs} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_\dagger}}}$$

$$g_\dagger = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

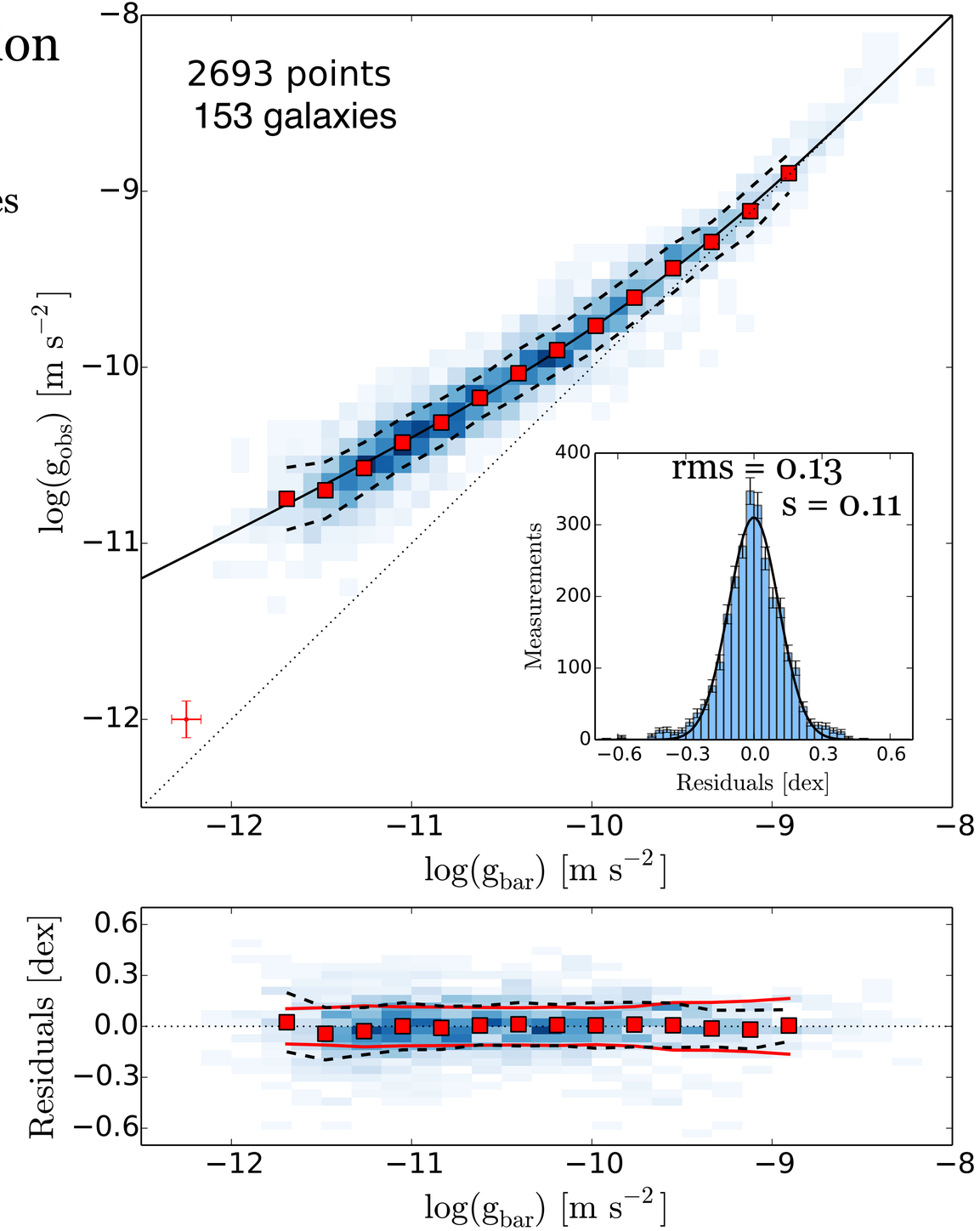
$$\pm 0.02\ (\mathrm{random}) \pm 0.24\ (\mathrm{systematic})$$

Lelli et al. (2017)
McGaugh et al. (2016)

observed rms scatter

scatter expected from observational errors

The data are consistent with zero intrinsic scatter



The Radial Acceleration Relation can be used to infer the dark matter distribution just by looking at a galaxy.

total $\quad g_{obs} = \mathcal{F}(g_{bar})$

$$\mathcal{F} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_\dagger}}}$$

dark matter $\quad g_{DM} = g_{obs} - g_{bar}$

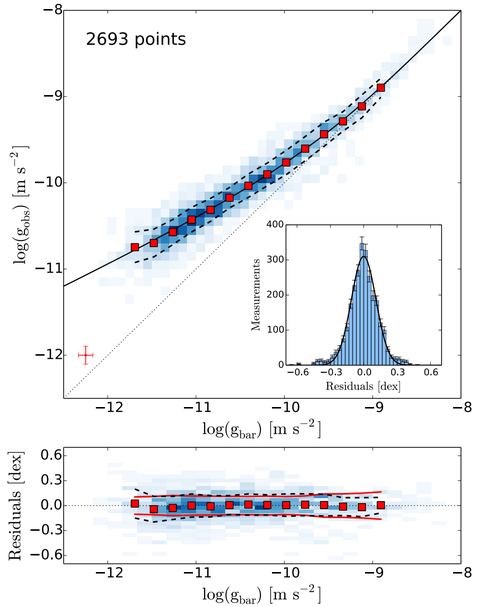
$$g_\dagger = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

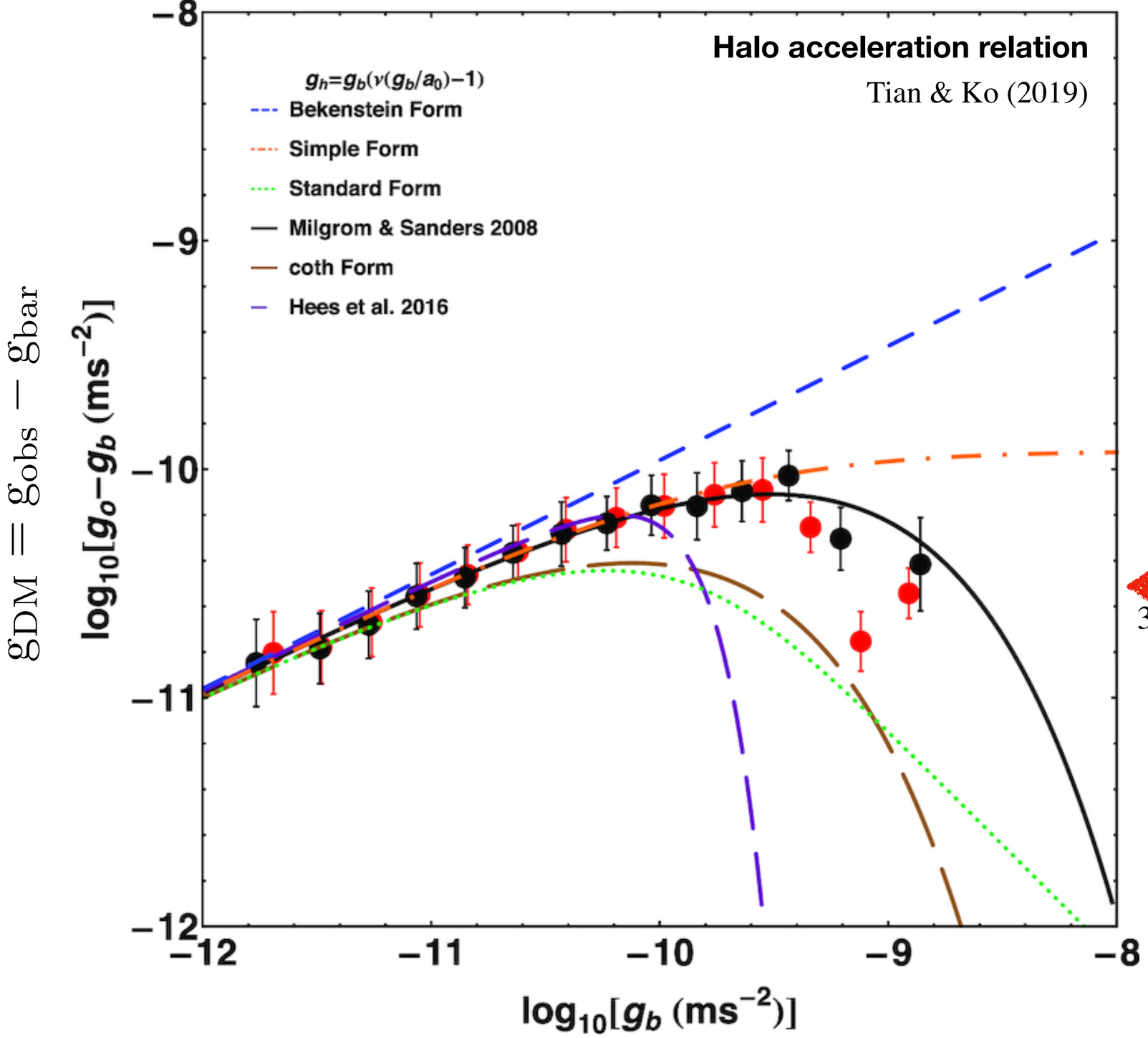
$$\pm 0.02\ (\mathrm{random}) \pm 0.24\ (\mathrm{systematic})$$

$$g_{DM} = \mathcal{F}(g_{bar}) - g_{bar}$$

The dark matter distribution is specified by the baryon distribution

That's weird





Dark Matter halos
provide an approximately constant added acceleration.

Walker et al. (2010)

3×10^{-11}

More generally, lower surface brightness means slightly less acceleration from dark matter.

Galaxy Formation

A many faceted problem

(sort of like Cthulhu being a multi-tentacled nightmare cult god)

Competition between gas accretion (to form disks) and lumpy fragments (forms spheroids, substructure)

Monolithic galaxy formation

collapse of one big gas cloud

(e.g., Eggen, Lynden-Bell, & Sandage 1962)

Hierarchical galaxy formation

"bottom up" formation from sequence of mergers

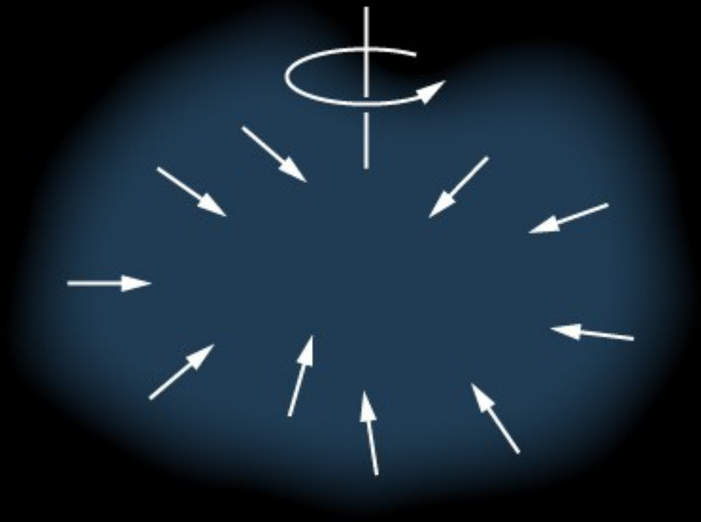
(big galaxies are built up with small galaxies - modern picture with CDM)

Searle-Zinn (1978) fragments:

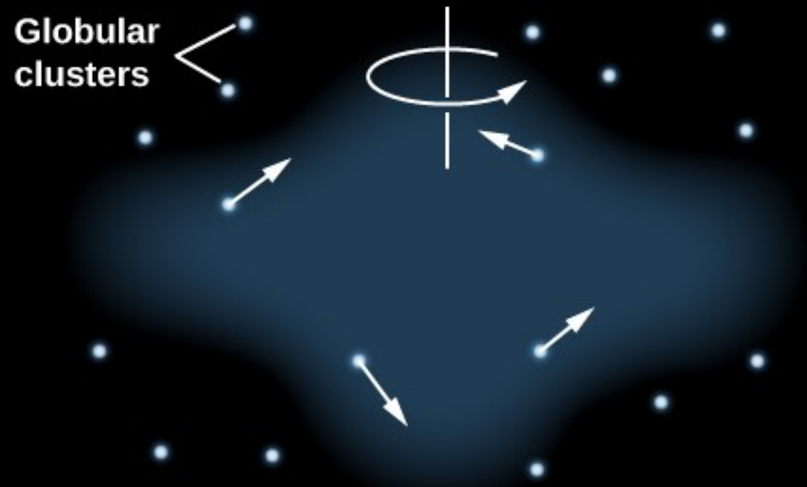
"…halo [globular] clusters originated within transient protogalactic fragments that gradually lost gas while undergoing chemical evolution and continued to fall into the Galaxy after the collapse of its central regions had been completed."

Monolithic galaxy formation

1 gas starts to collapse

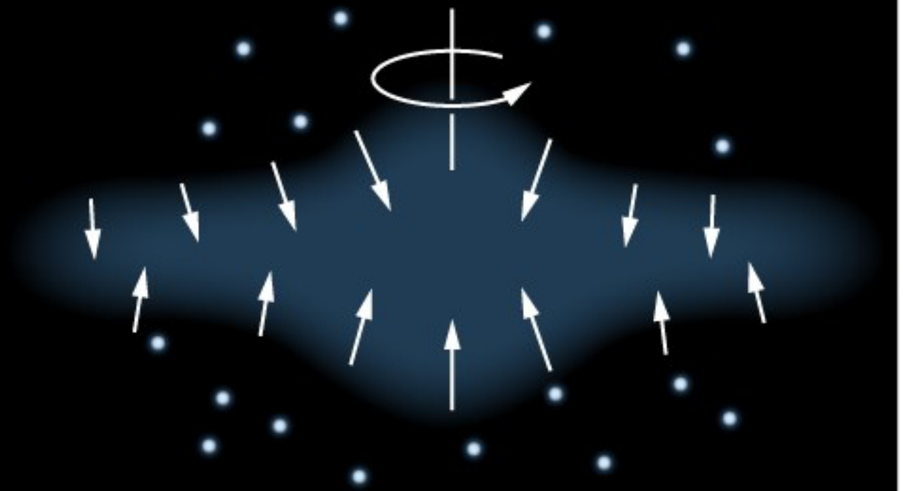


2 first stars form during collapse



retain memory of infall in their radial orbits

3 gas settles into disk



plane of disk specified by initial angular momentum

4 stars form in disk

Good at forming spiral galaxies

Hierarchical galaxy formation
(bottom up - *not* monolithic)

Small objects conglomerate to make big ones

Gas dissipates and cools to form thin disks.

Stars cannot cool: if hot coming in, stay hot.

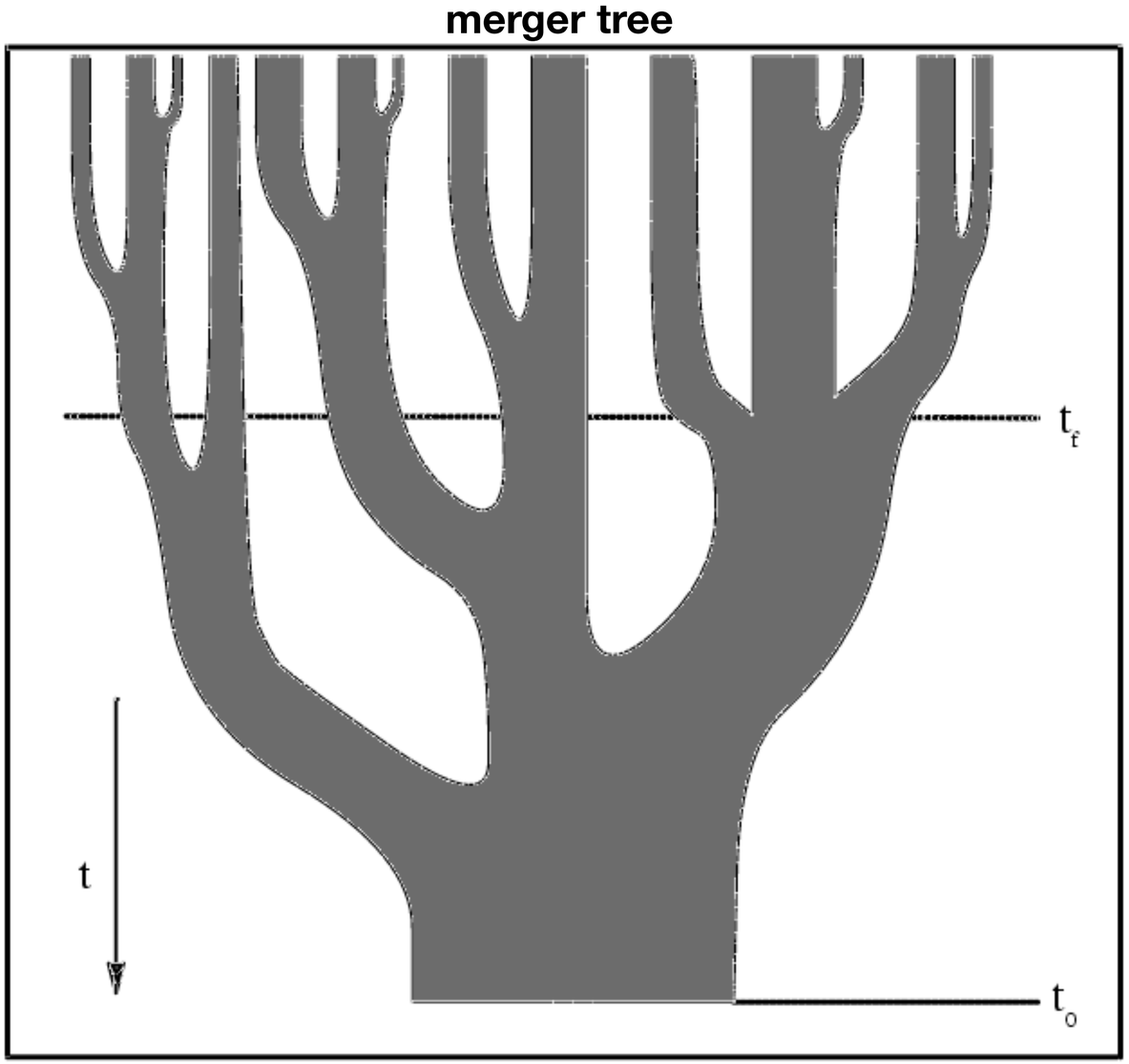
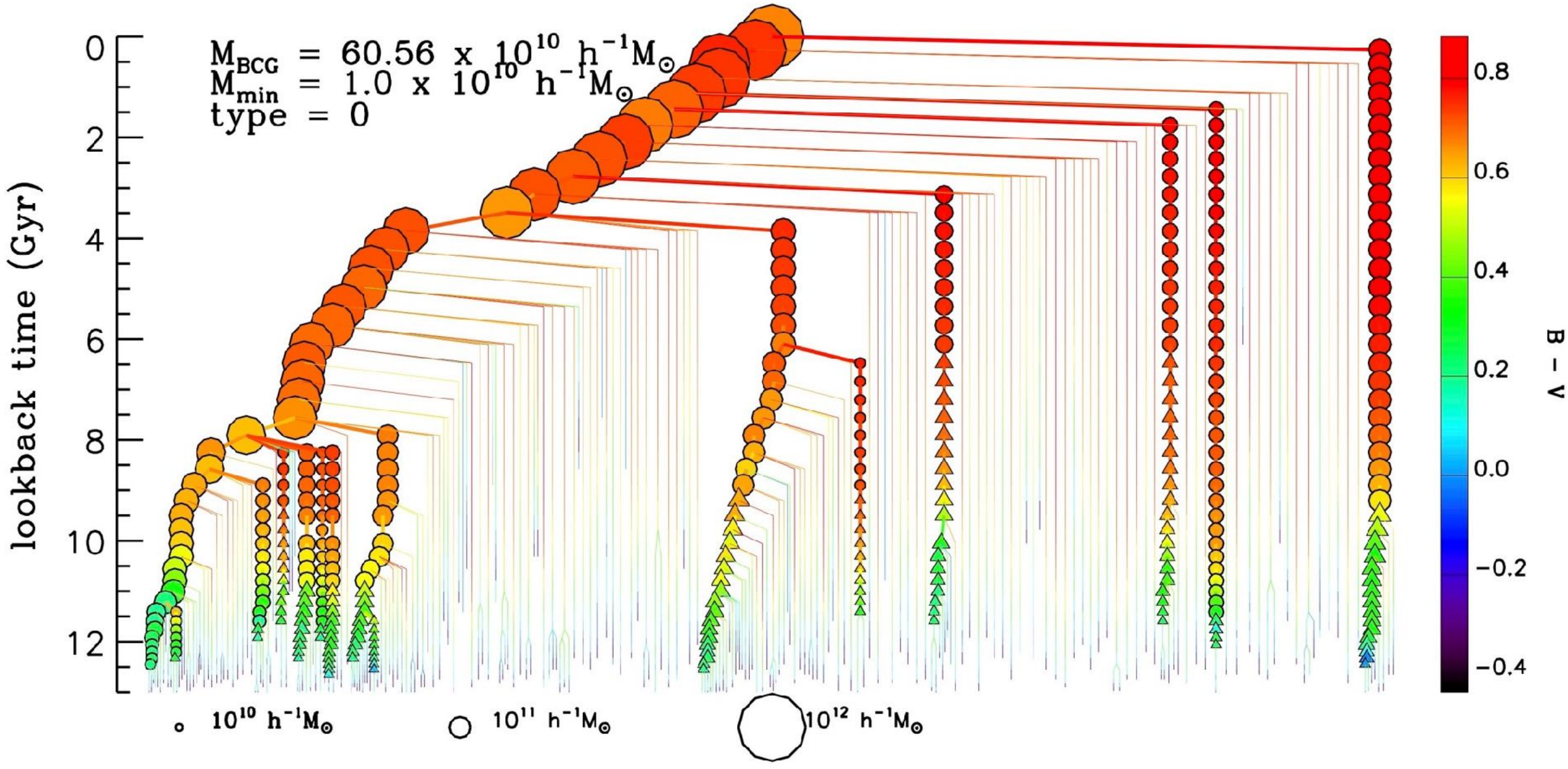


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.


M_{BCG} = 60.56 x 10^{10} $h^{-1}M_\odot$
M_{min} = 1.0 x 10^{10} $h^{-1}M_\odot$
type = 0
lookback time (Gyr)
0
2
4
6
8
10
12
B - V
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
10^{10} $h^{-1}M_\odot$
10^{11} $h^{-1}M_\odot$
10^{12} $h^{-1}M_\odot$

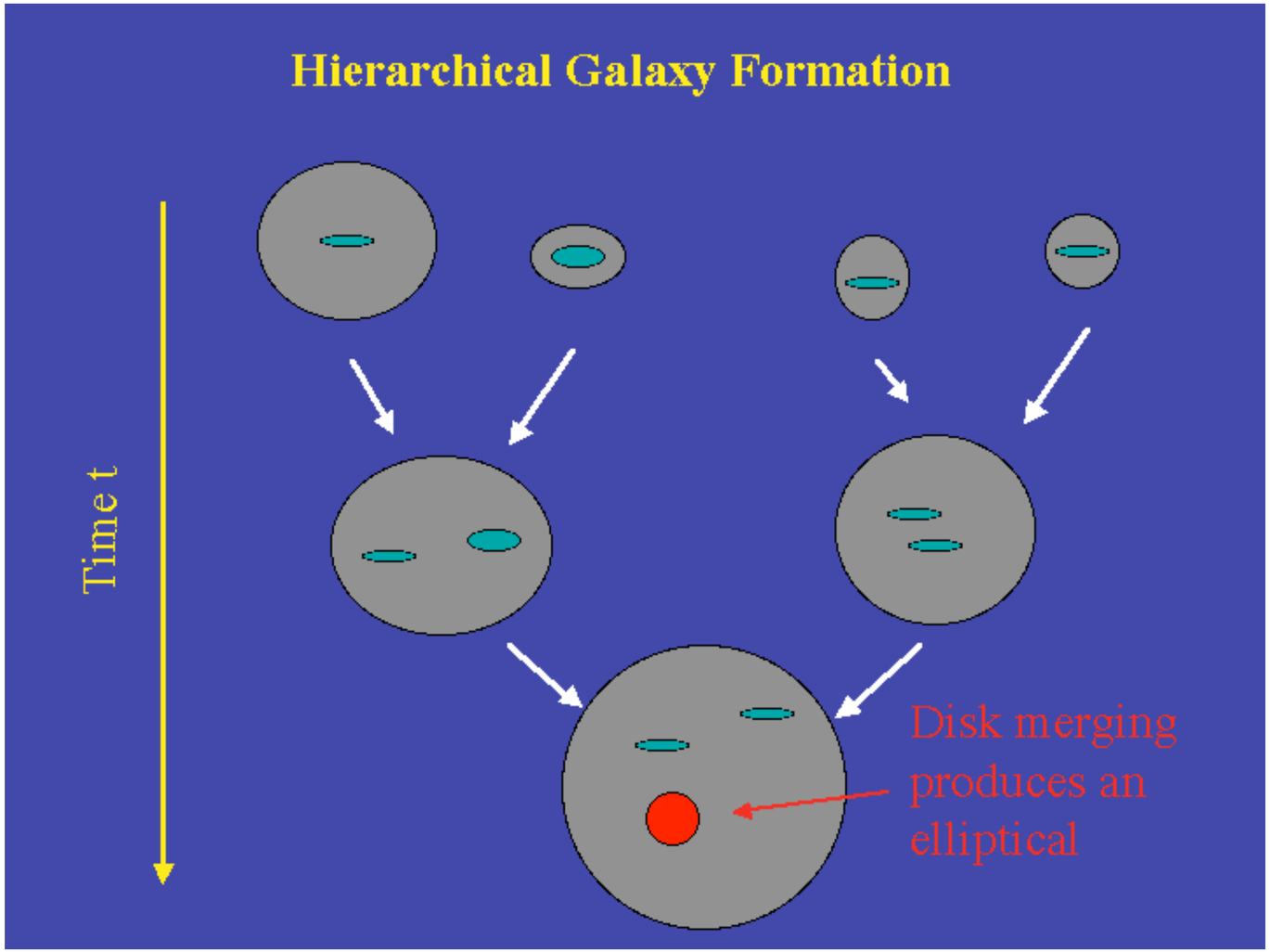
merging subhalos containing protogalaxies

Gray:
dark matter halos

Blue:
gas rich disks

Red:
elliptical merger remnant

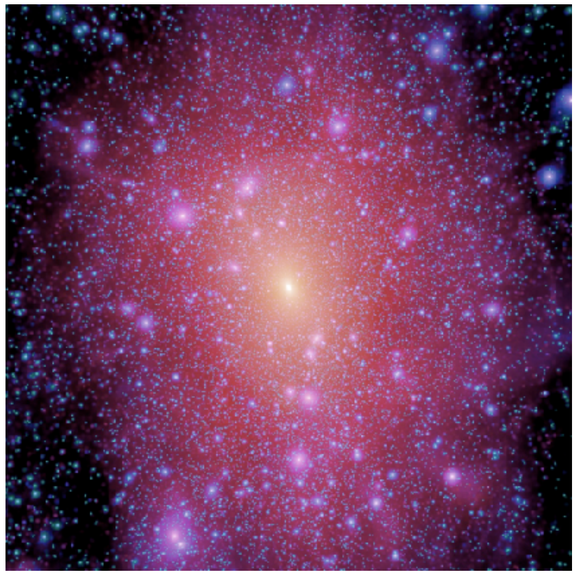
sometimes it is imagined that a disk re-forms around an elliptical to form a bulge+disk system like and Sa galaxy



Good at forming elliptical galaxies

Sequence of events in galaxy formation

1. Dark matter halos form; merge into ever larger masses
2. Baryons fall into the potential wells of DM halos
3. Gas dissipates, sinks to centers of DM halos
    - Halos compressed by sinking baryons
    - gas forms rotating disks at centers of DM halos
4. Stars form in disks
    - Feedback heats gas, dissuading further gas accretion
5. Mergers transform some disks into ellipticals
    - star formation truncated
6. Renewed gas accretion may re-form disks around ellipticals
    - thus becoming the bulges of S0s and early type spirals
7. Merging lessens; more gradual accretion of dark matter and gas may continue
8. Galaxies



Sequence of events in galaxy formation

1. Dark matter halos form; merge into ever larger masses

$$c_{200} = \frac{R_{200}}{r_s}$$

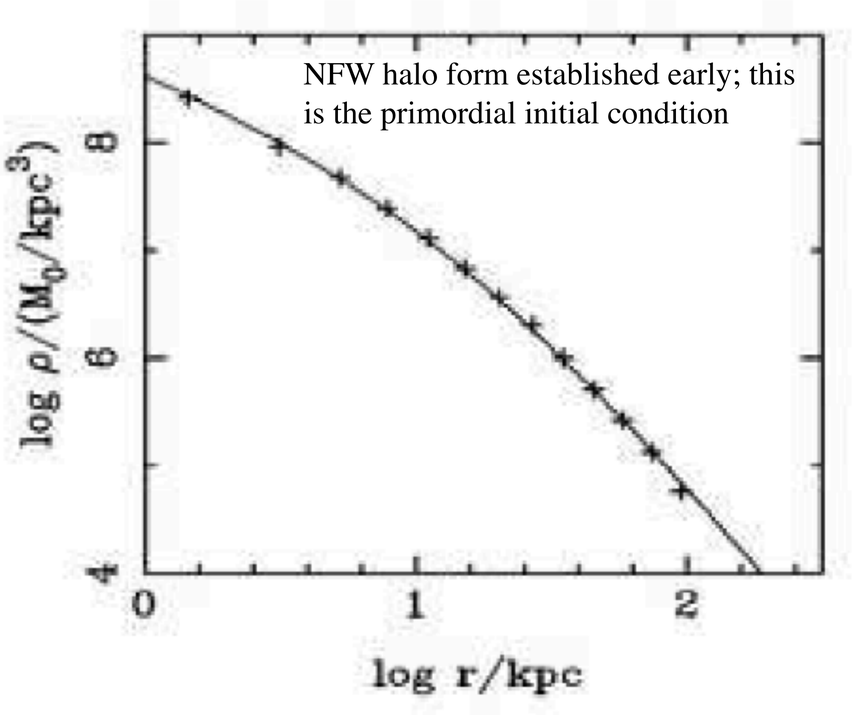
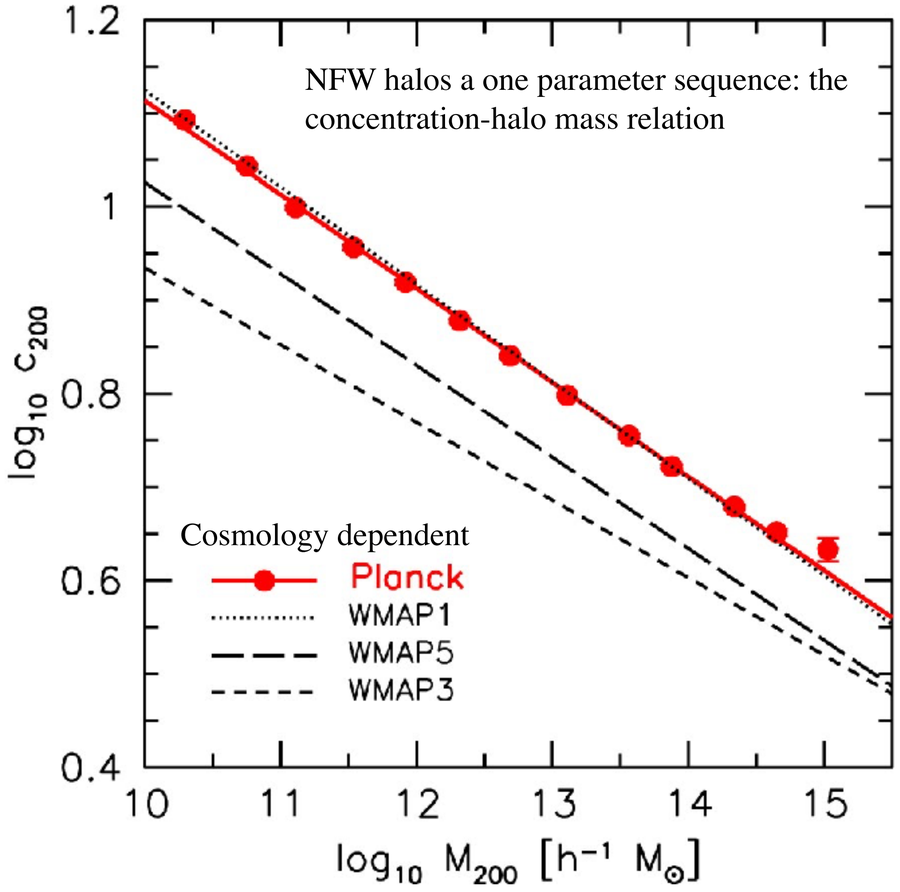
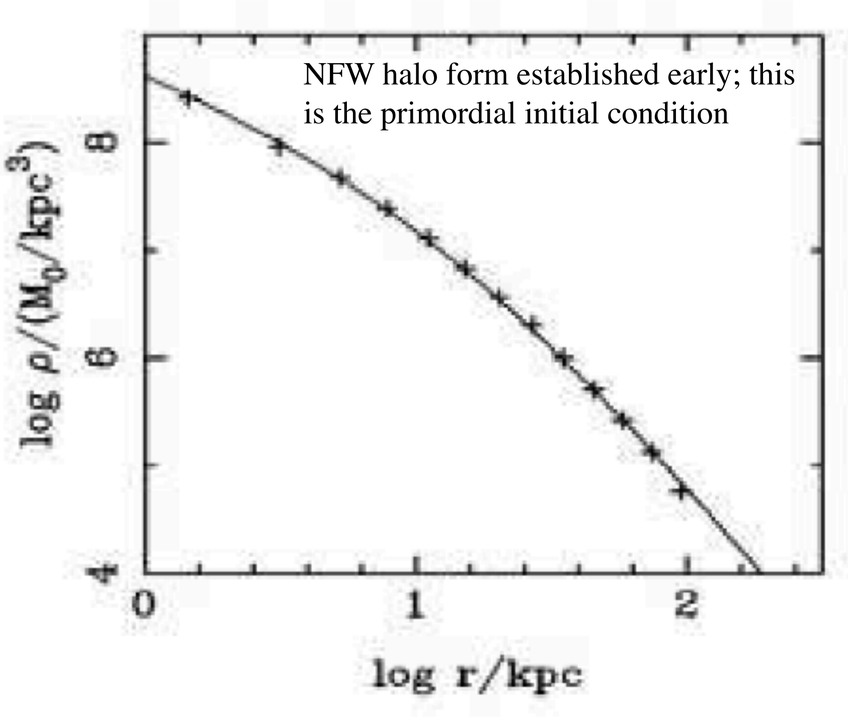


FIG. 1: Density profile of the million particle dark matter halo simulation of Dubinski & Carlberg 1990 (crosses). The solid line shows the best fit NFW profile (Eqn. 1) to the original data. This Figure was adapted from[22] by John Dubinski and it is reproduced here with his permission.



Sequence of events in galaxy formation

1. Dark matter halos form; merge into ever larger masses



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Halo mass correlates with halo size and the circular speed at the virial radius:

$$M_\Delta = \frac{4\pi}{3}\Delta\rho_{crit}R_\Delta^3$$

for $\Delta = 200$

$$V_{200} = R_{200}\,h$$

$$M_{200} = (3.3\times10^5\,\mathrm{M_\odot\,km^{-3}\,s^3})\;V_{200}^3$$

This is often cited as the cosmic origin of the Tully-Fisher relation, but must include fudge factors

$$M_* = m_*\,M_{200} \qquad V_f = f_V\,V_{200}$$