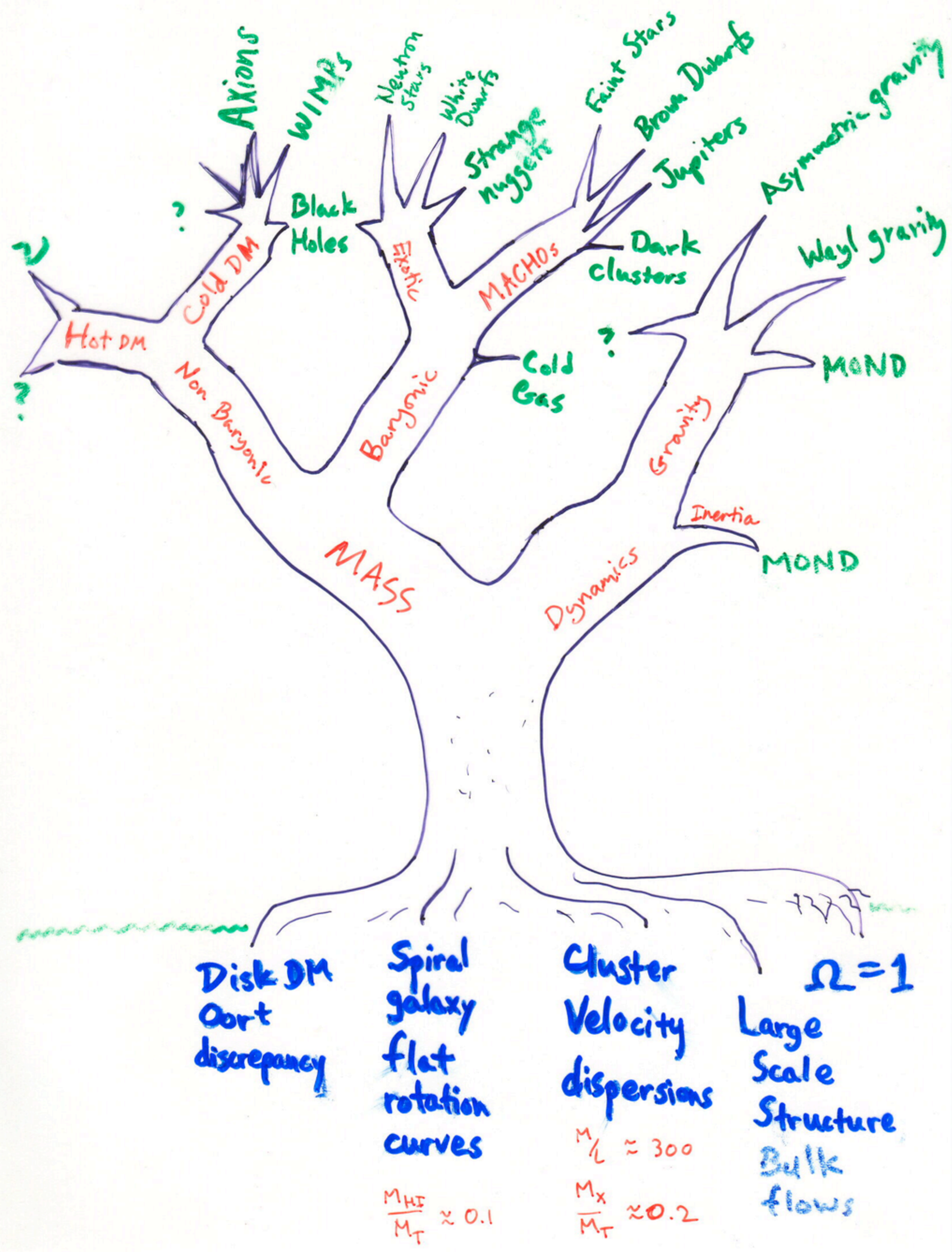
Dark Matter

ASTR 333/433

TODAY

Galaxy Formation
start to finish (?)
Adiabatic Contraction
Feedback



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
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6. Renewed gas accretion may re-form disks around ellipticals
    - thus becoming the bulges of S0s and early type spirals
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8. Galaxies

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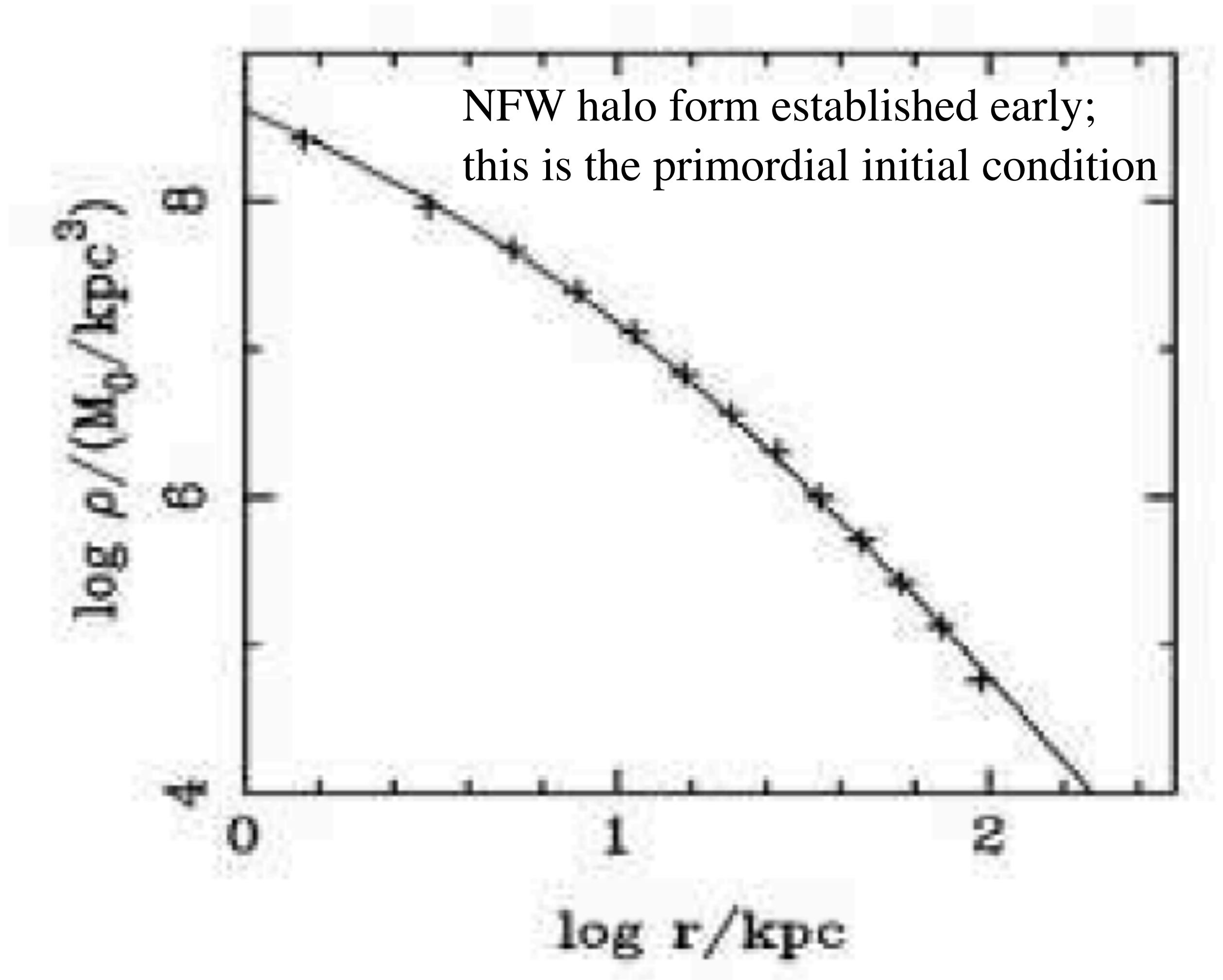
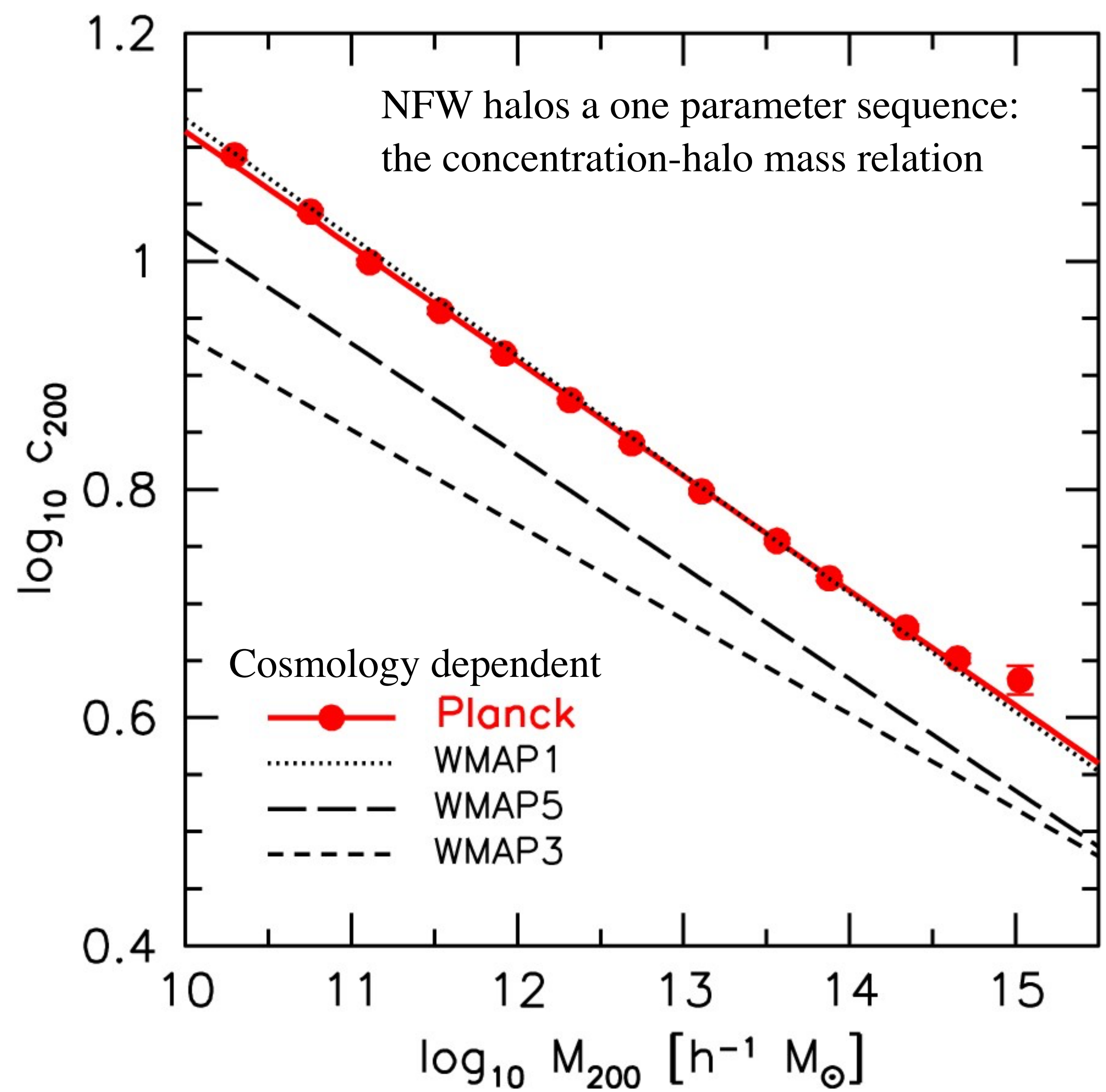


FIG. 1: Density profile of the million particle dark matter halo simulation of Dubinski & Carlberg 1990 (crosses). The solid line shows the best fit NFW profile (Eqn. 1) to the original data. This Figure was adapted from[22] by John Dubinski and it is reproduced here with his permission.



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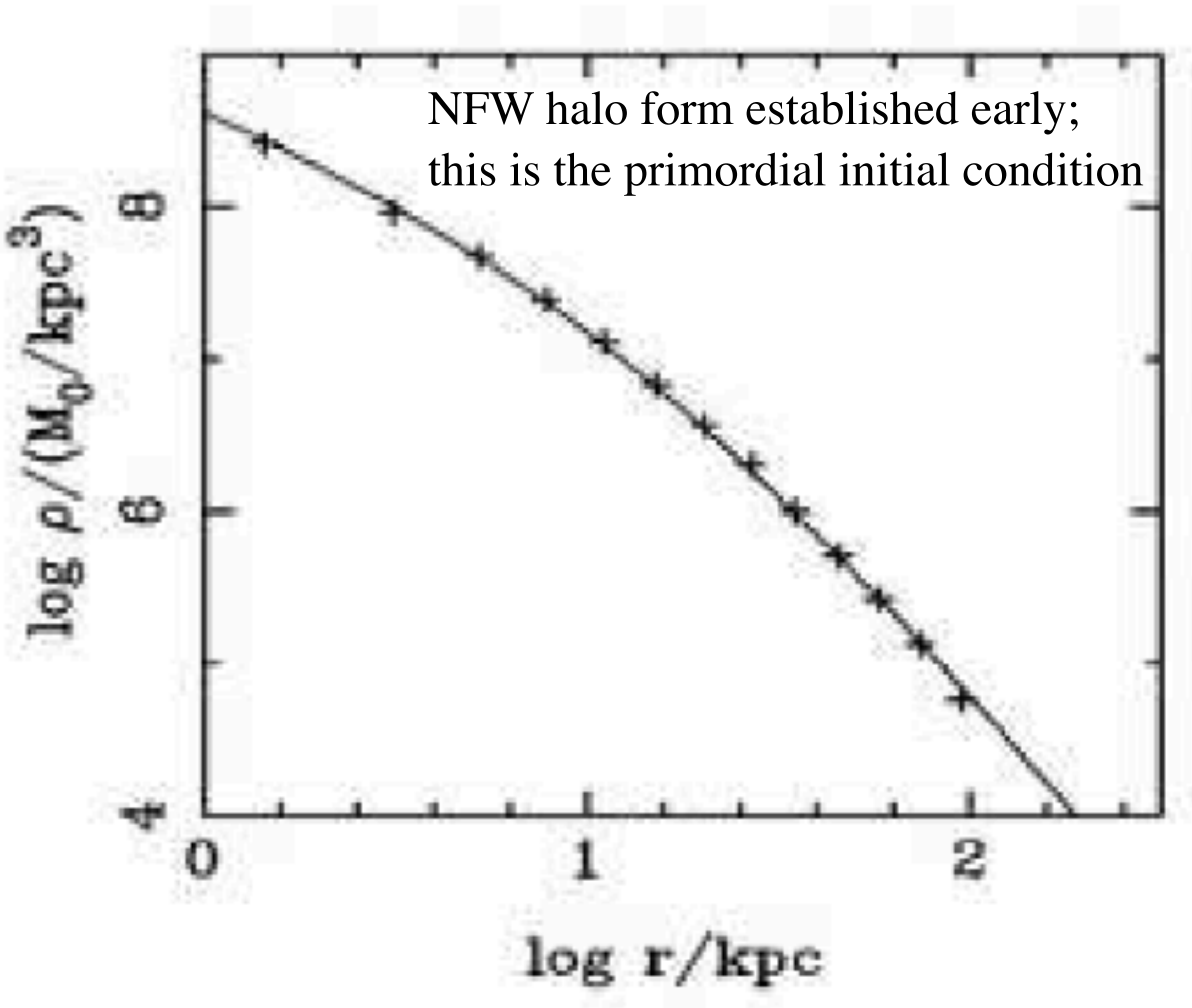
NFW halo form established early;
this is the primordial initial condition



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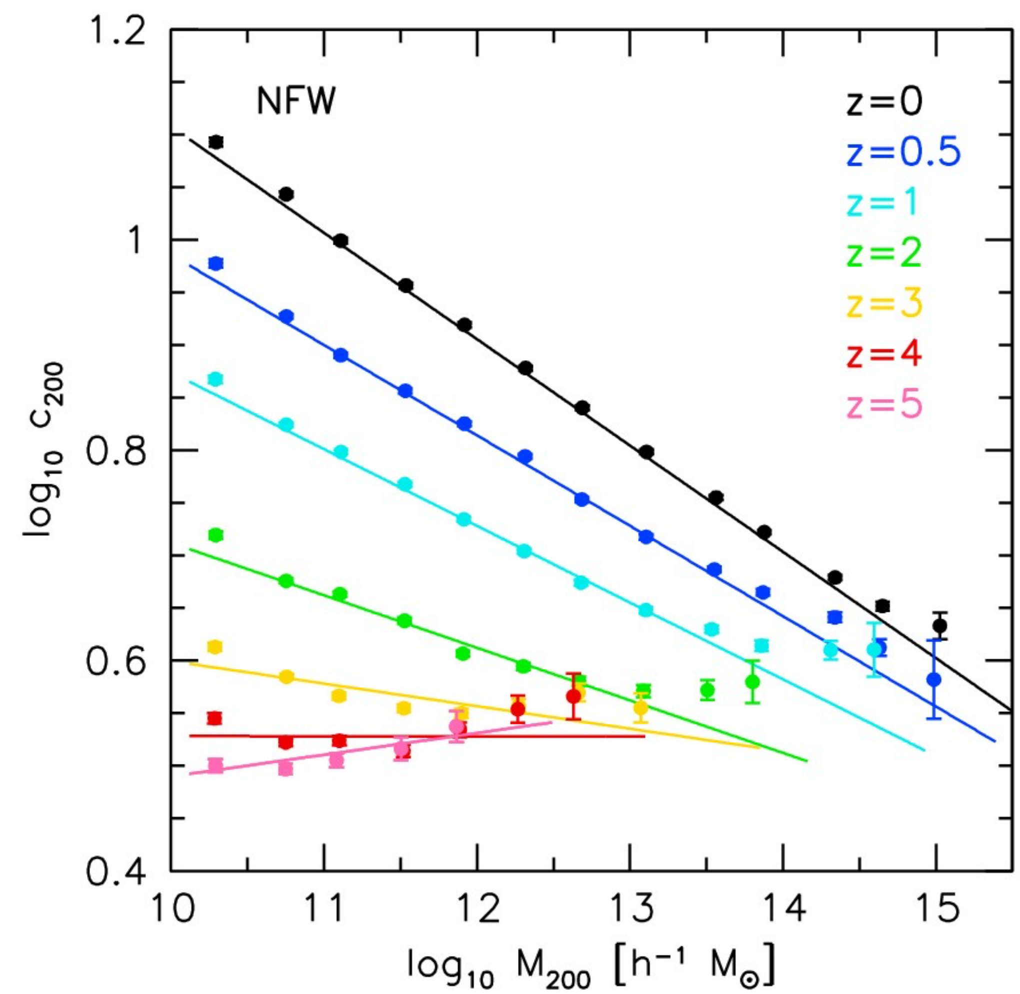
The concentration increases over time as dark matter accretes, increasing R_{200}



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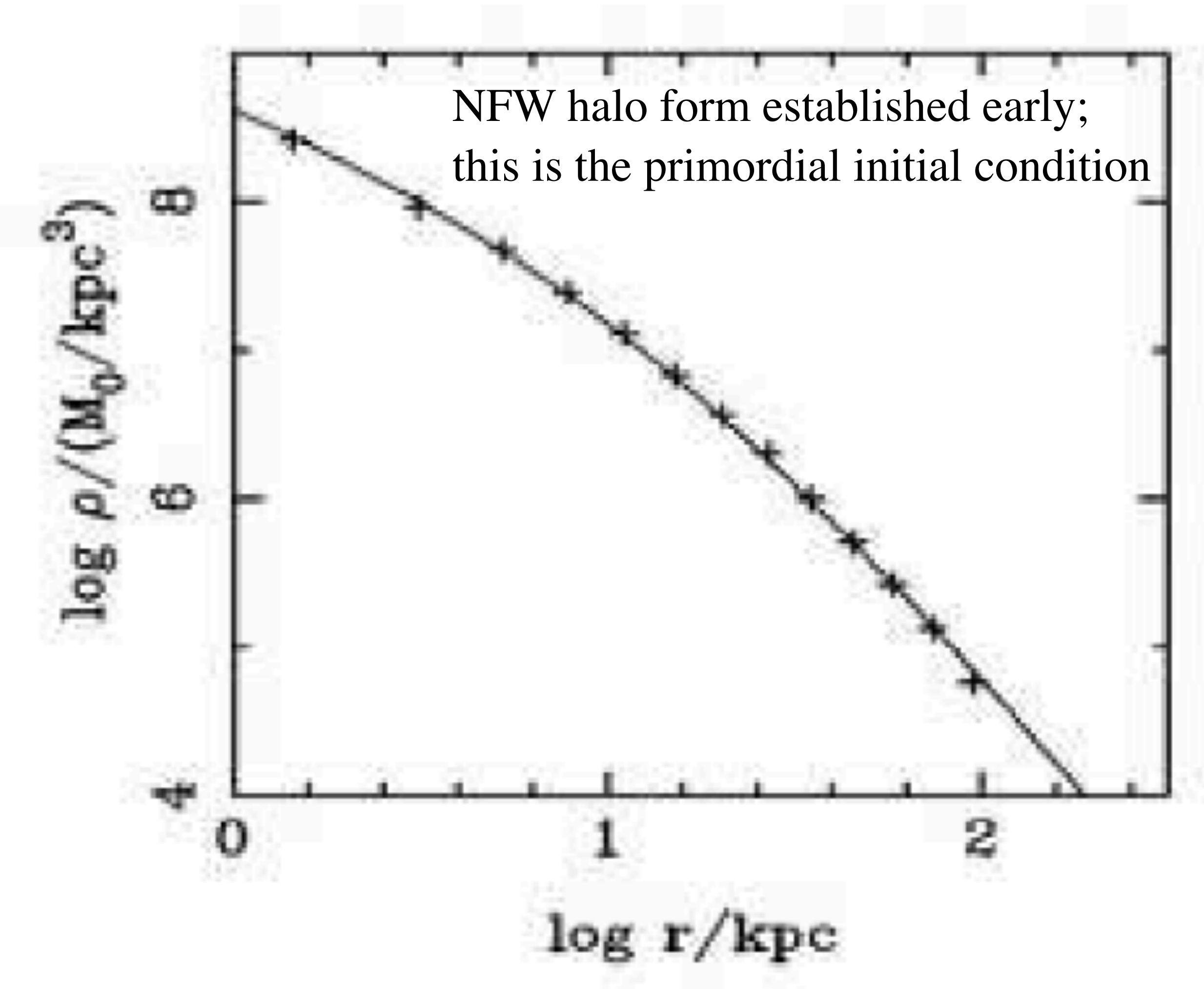

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Halo mass correlates with halo size and the circular speed at the virial radius:

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

for $\Delta = 200$

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

$$M_{200} = (3.3 \times 10^5\,\mathrm{M_\odot}\,\mathrm{km}^{-3}\,\mathrm{s}^3)\ V_{200}^3$$

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

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

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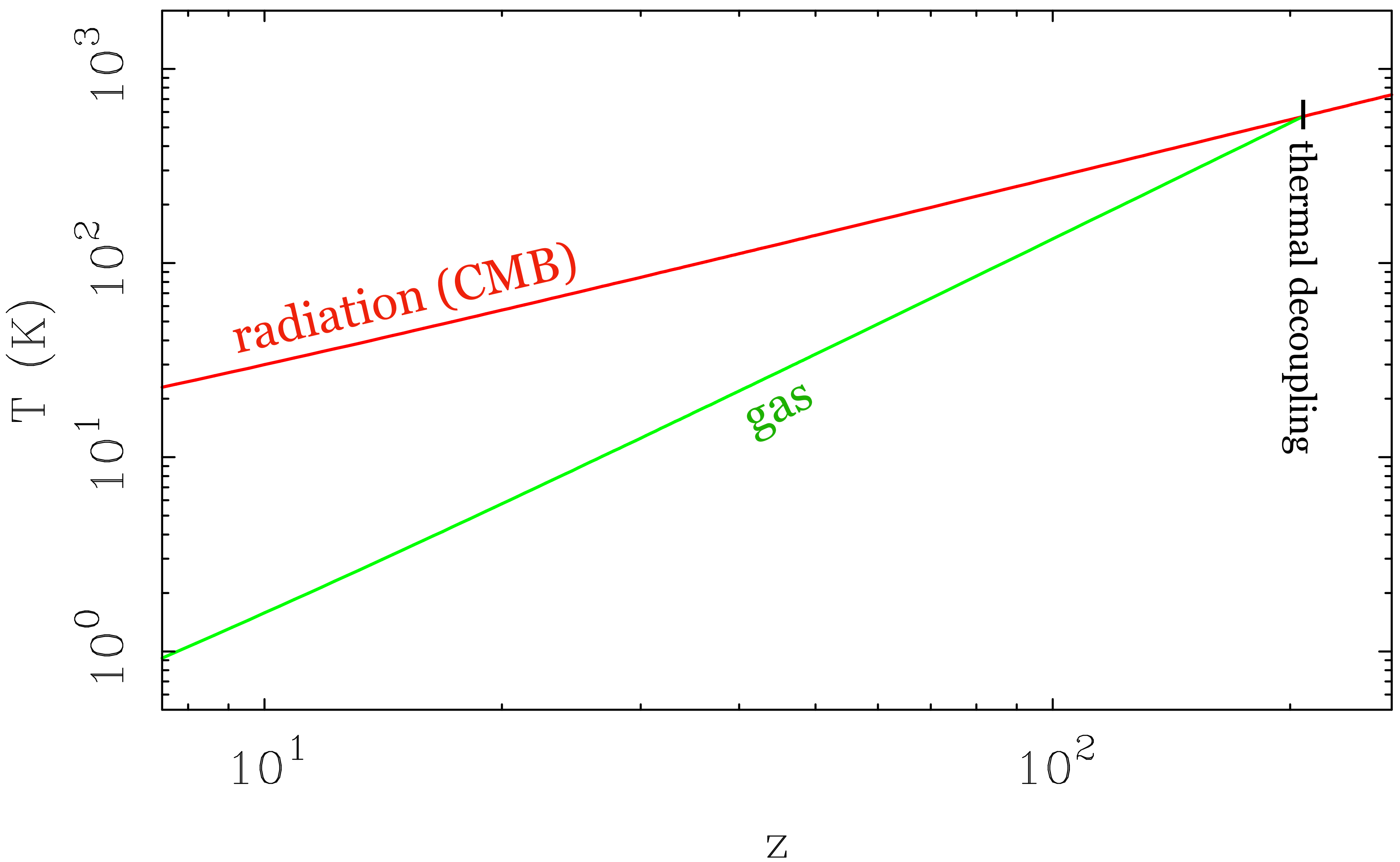

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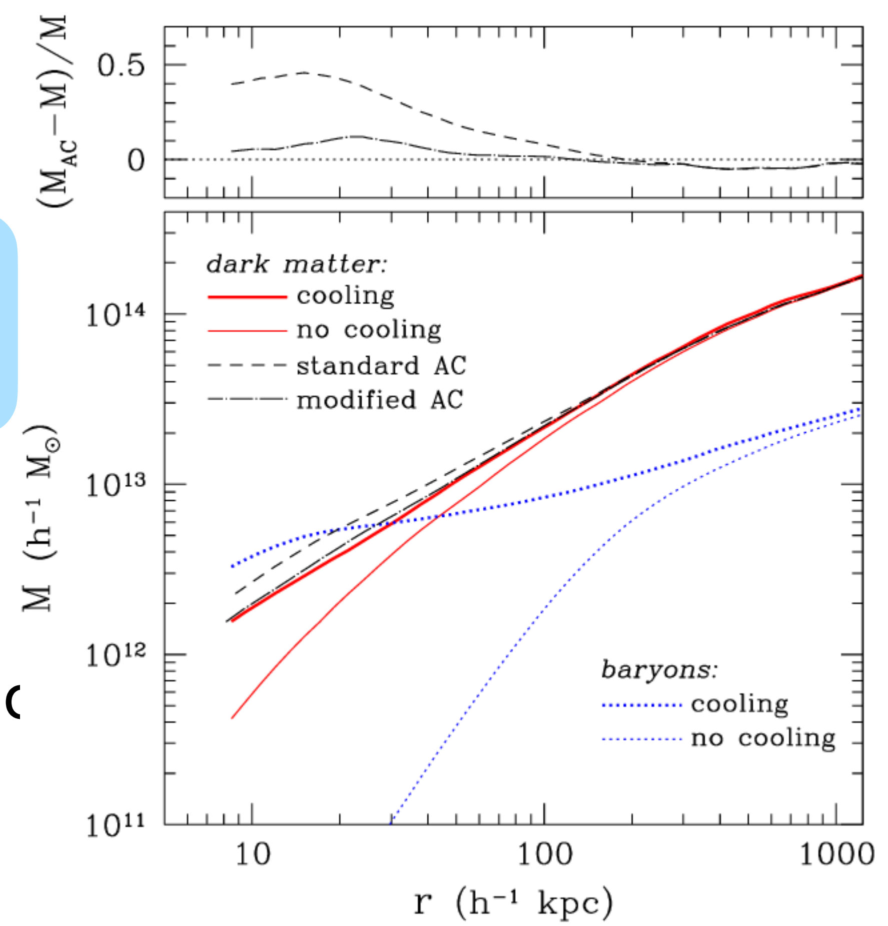

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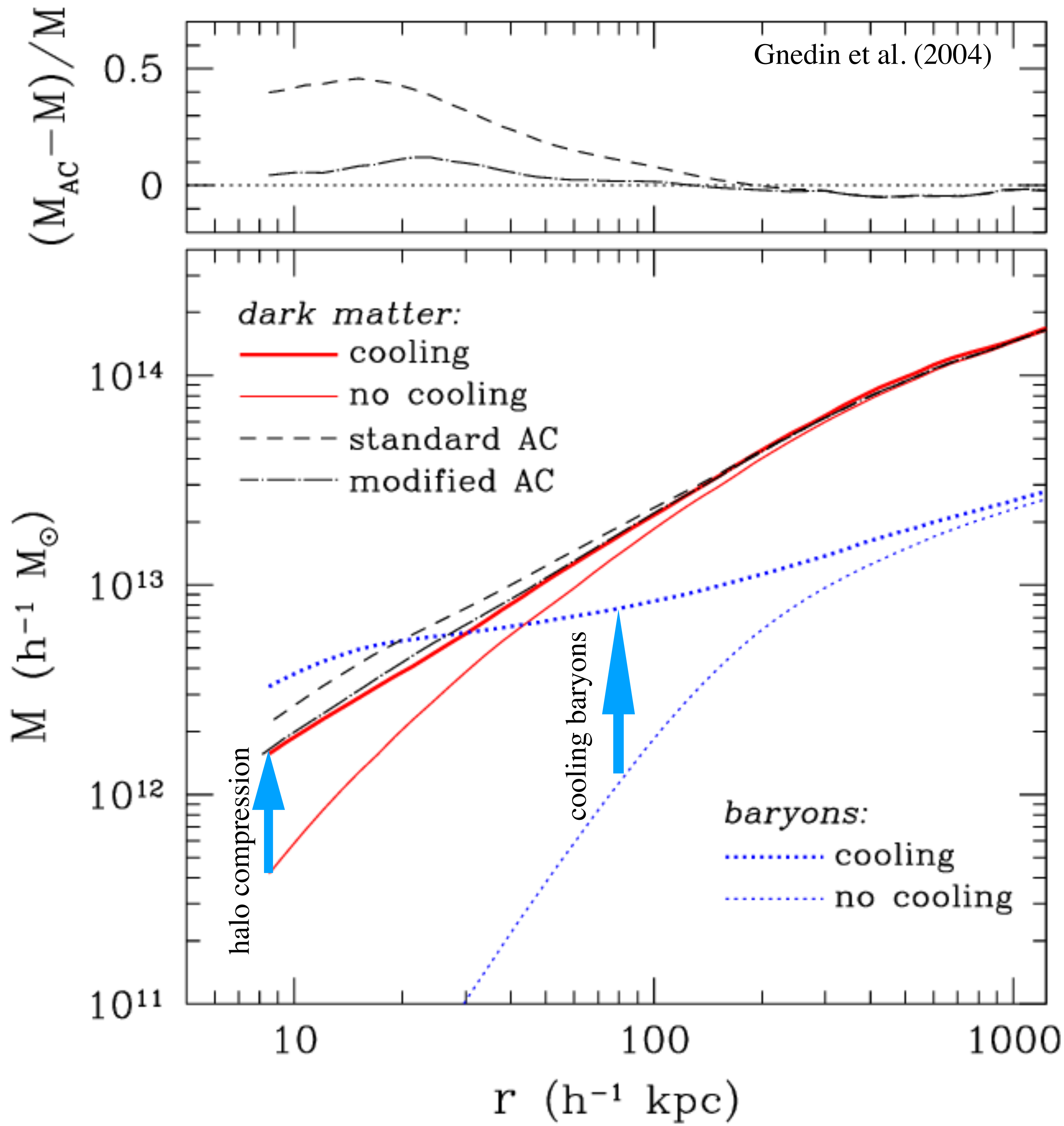
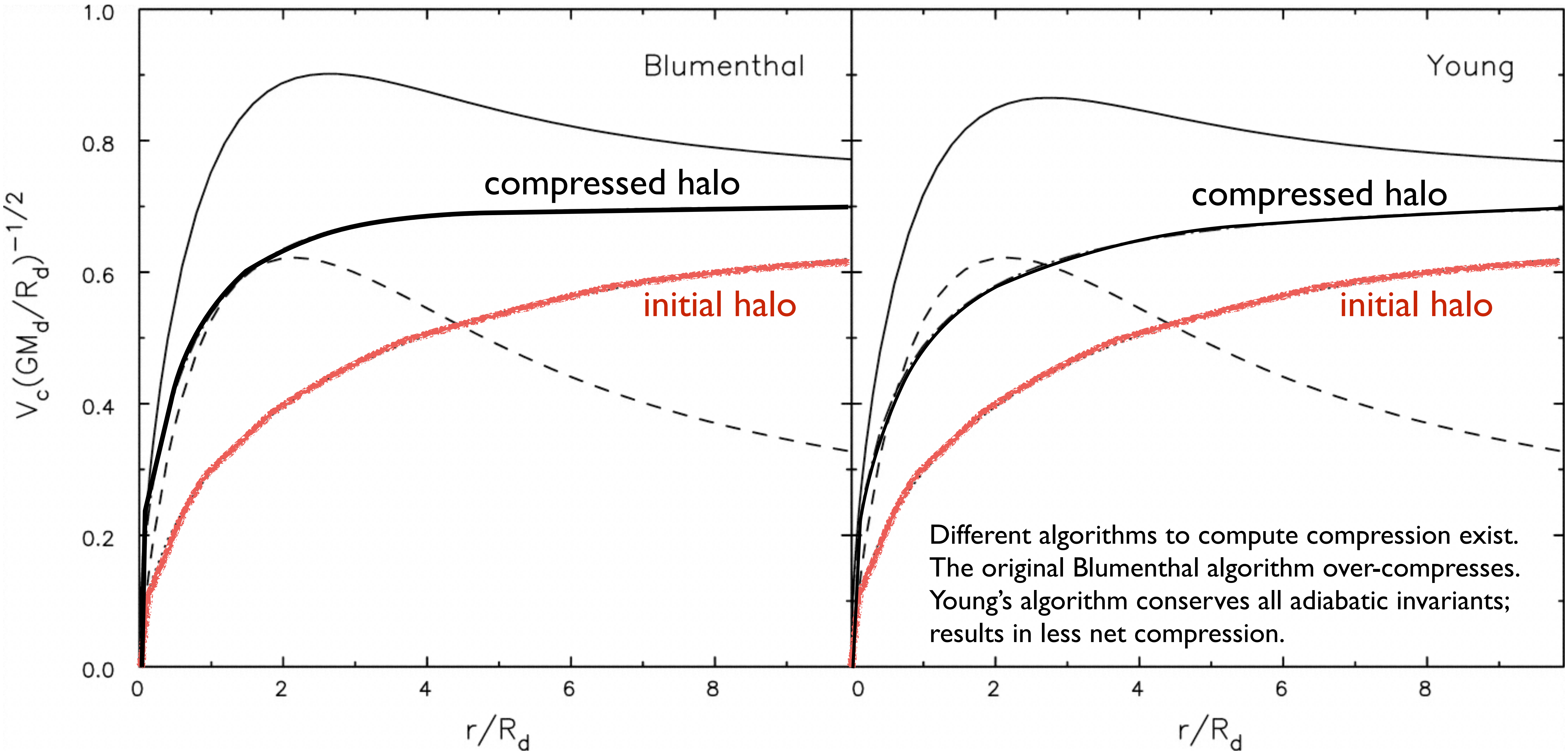
Adiabatic compression

The cooling baryons fall in, causing a non-zero time derivative of the moment of inertia. The gravitational potential has to respond to this redistribution of mass. The net effect is that the baryons drag some of the dark matter along with them, compressing the central regions of the DM halo



Adiabatic compression

Pure CDM halos start with the NFW form. The dissipative infall of baryons drags some dark matter along with it, compressing the initial halo.



The dark matter halos we observe today have been modified from the initial (NFW) conditions.

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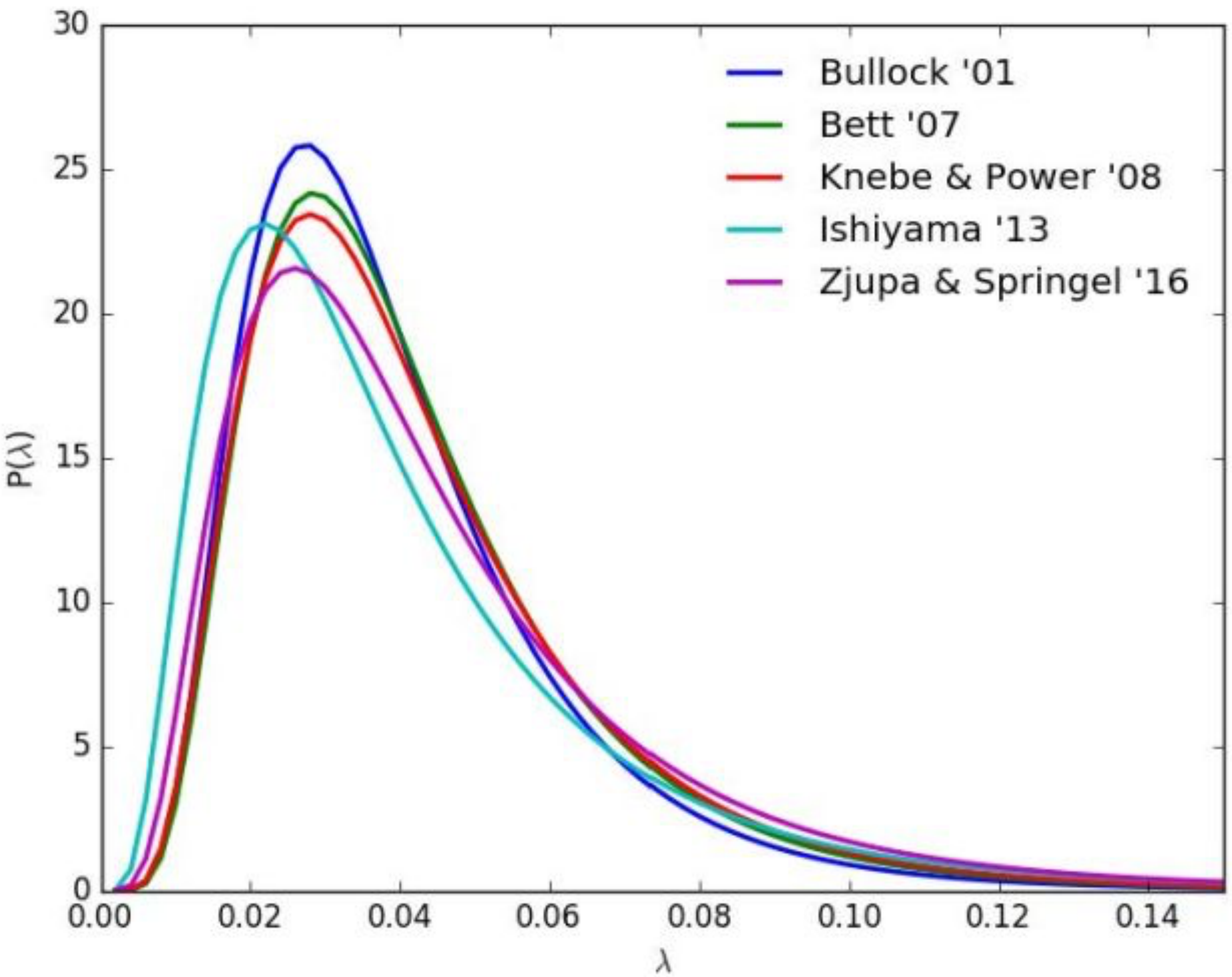


Spin parameter

$$\lambda_P = \frac{J|E|^{1/2}}{GM^{5/2}}$$

Peebles (1971)

Bullock et al. (2001)

$$\lambda = \frac{J/M}{\sqrt{2}V_{vir}R_{vir}}$$

Spins caused by primordial tidal torques
Distribution of spins well-described by a lognormal distribution:

$$P(\lambda) = \frac{1}{\sqrt{2\pi}\lambda\sigma}e^{-\frac{\ln^2(\lambda/\lambda_0)}{2\sigma^2}}$$

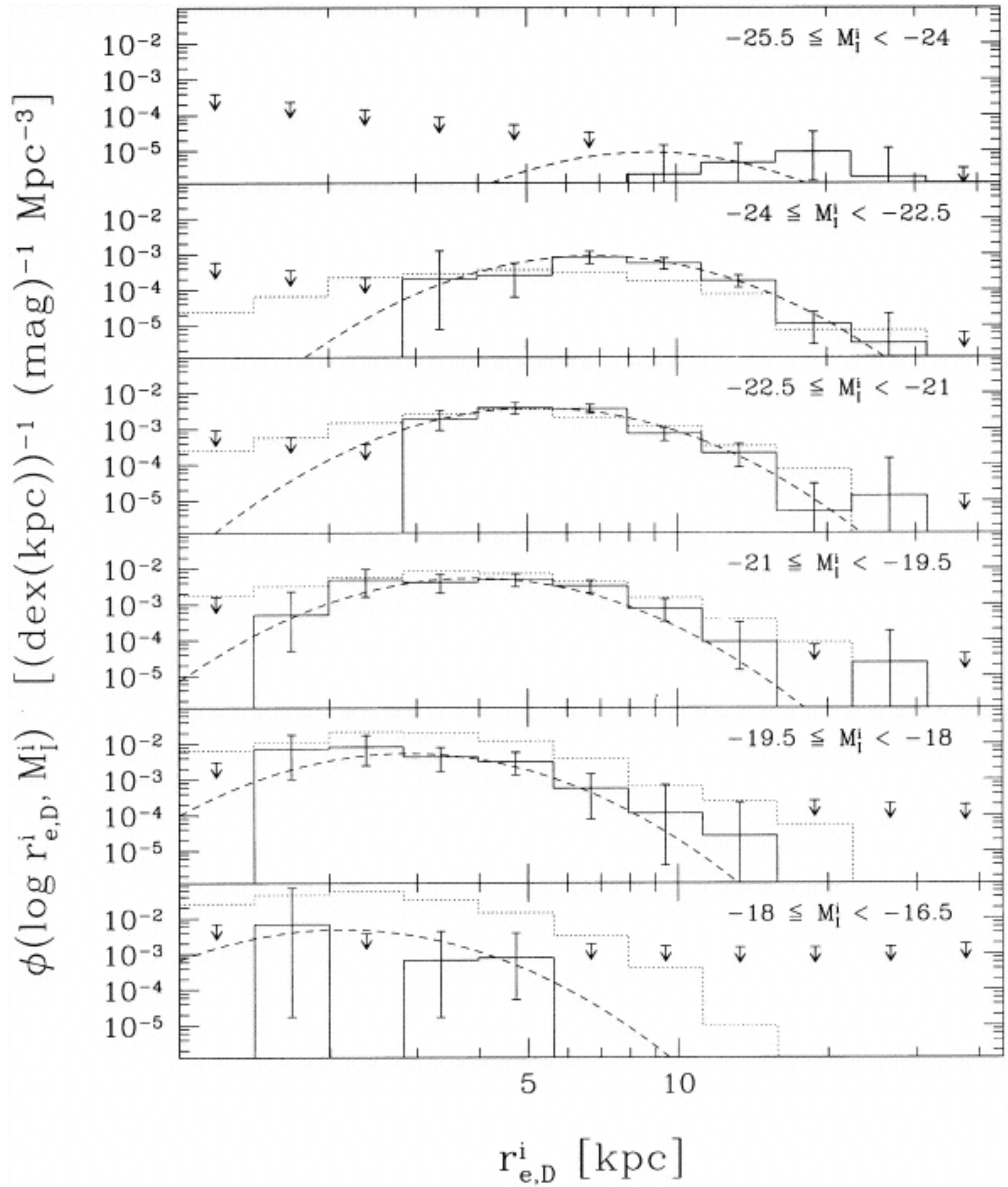
Bivariate distribution of luminosity and size (de Jong & Lacey 2000)

McGaugh & de Blok (1998):

This [λ] parameterizes the angular momentum acquired by protogalaxies from tidal torques. The details of this process are uncertain, but all that matters here is that *within this framework* dissipative baryonic collapse is halted by angular momentum. Collapse of the protogalaxy stops when $\lambda_s^{\rm disk} \rightarrow 1$. Objects with high primordial spin will collapse less than low spin objects.

Presuming that spin is the underlying reason for variations in the scale length give the mapping from spin to surface brightness:

$$\mu_0 = 5 \log \left(\frac{\lambda_s}{\lambda_s^*} \right) + \mu_0^* \, .$$



<u>High spin</u>

large scale length

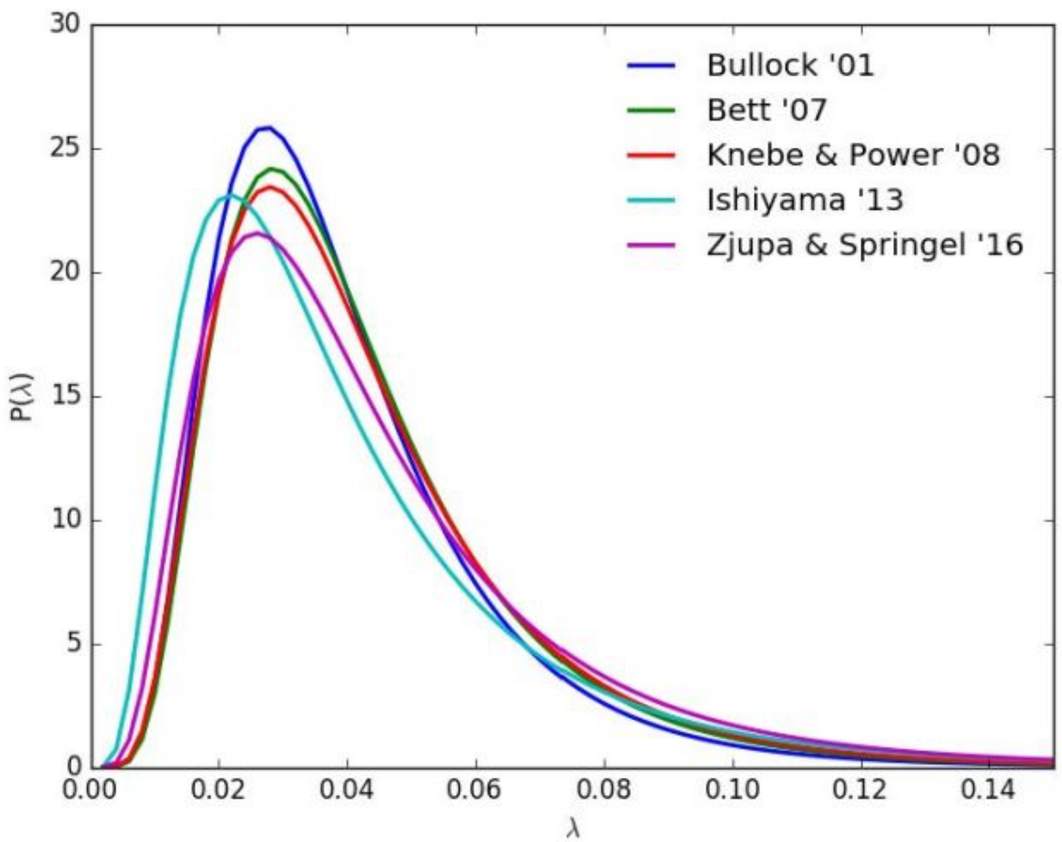
low surface brightness

<u>Low spin</u>

small scale length

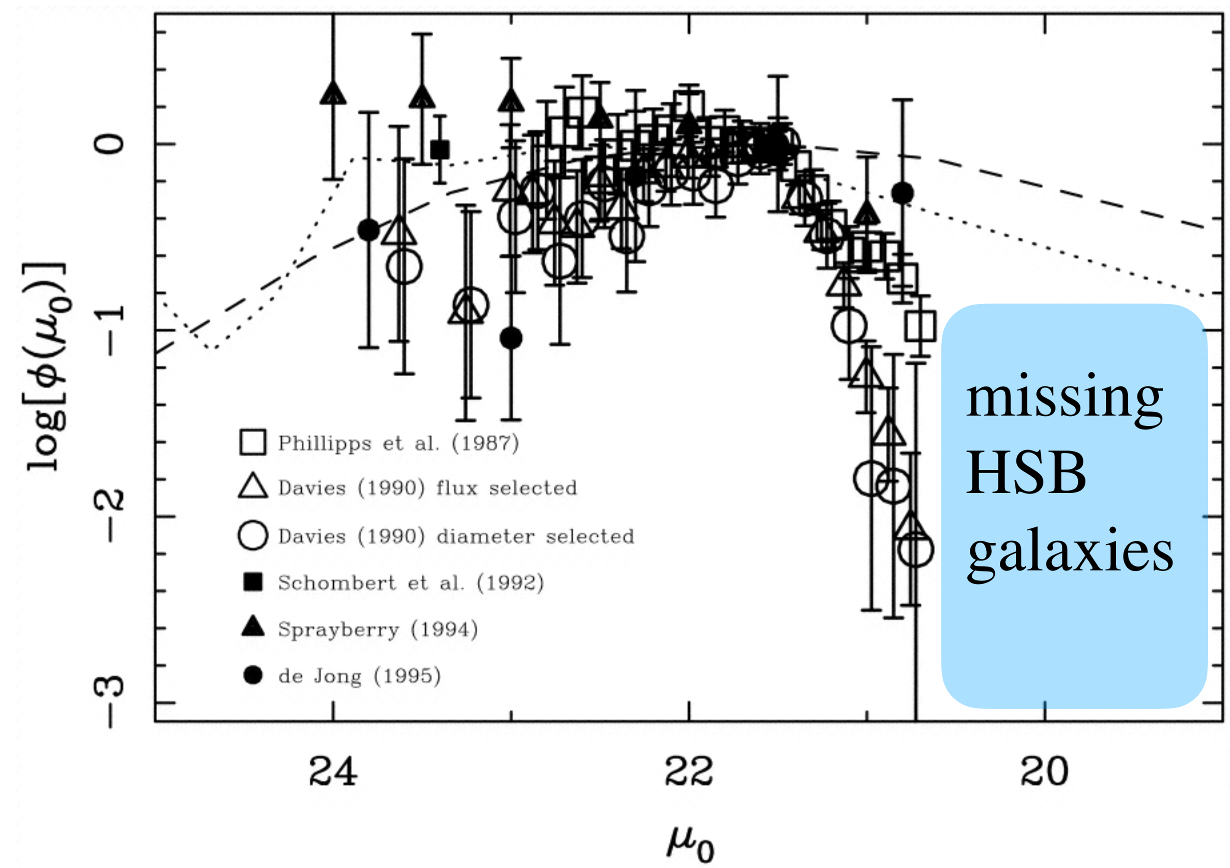
high surface brightness

The primordial spin of the halo maps to the size of the resident galaxy in this picture



<u>Low spin</u>
small scale length
high surface brightness

<u>High spin</u>
large scale length
low surface brightness



McGaugh & de Blok (1998); see also Mo, Mao, & White (1998)

This picture assumes that *baryonic* angular momentum is conserved. This sounds like a no-brainer, but baryons and dark matter can exchange angular momentum, so it is not obvious that the baryons keep all the angular momentum that they start with.

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<u>Types of feedback</u>

AGN (Active Galactic Nuclei)

jets from supermassive black holes

Star formation

Supernovae

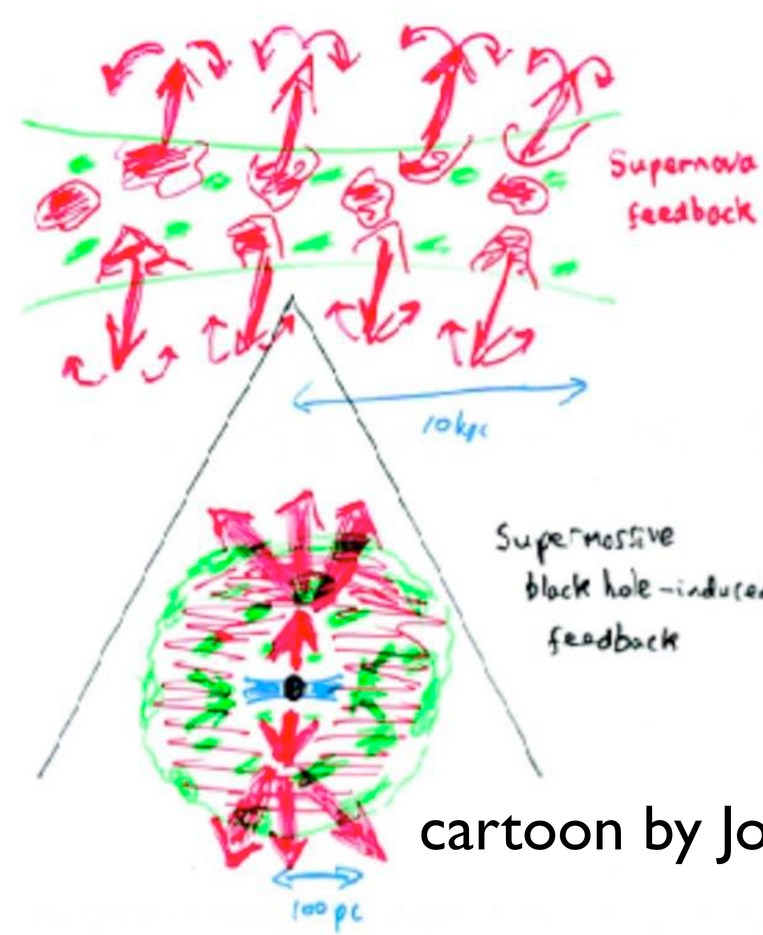
Stellar winds

Ionizing radiation / Radiation pressure

Exotic

X-ray binaries

Basically any process that produces energy and returns *some* of it to the interstellar medium



cartoon by Joe Silk

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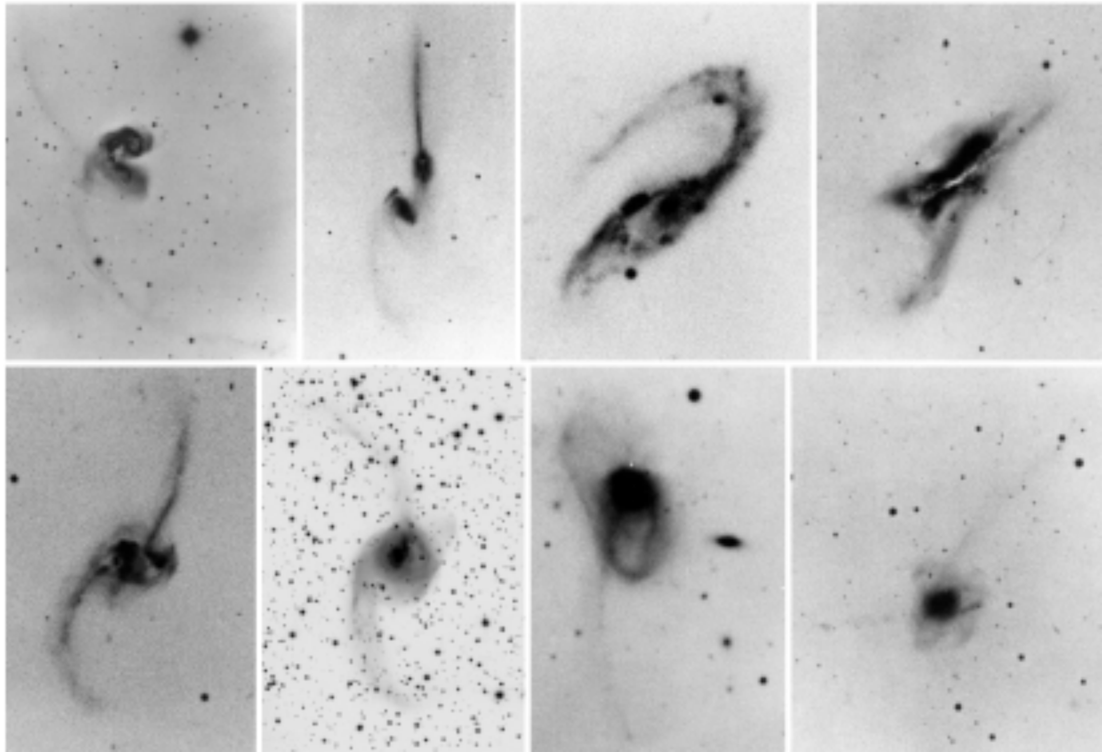

Toomre merger sequence (courtesy of John Hibbard)

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Generic CDM problems

- Too much mass at small radii
  - Cusp-core problem (esp. in dwarfs)
  - Massive bulges too common
  - Maximal disks practically impossible
- Missing Satellites
  - too few satellites around bright galaxies
  - overcooling problem in field

Generic prescription: Feedback