DARK MATTER

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Homework DUE next time

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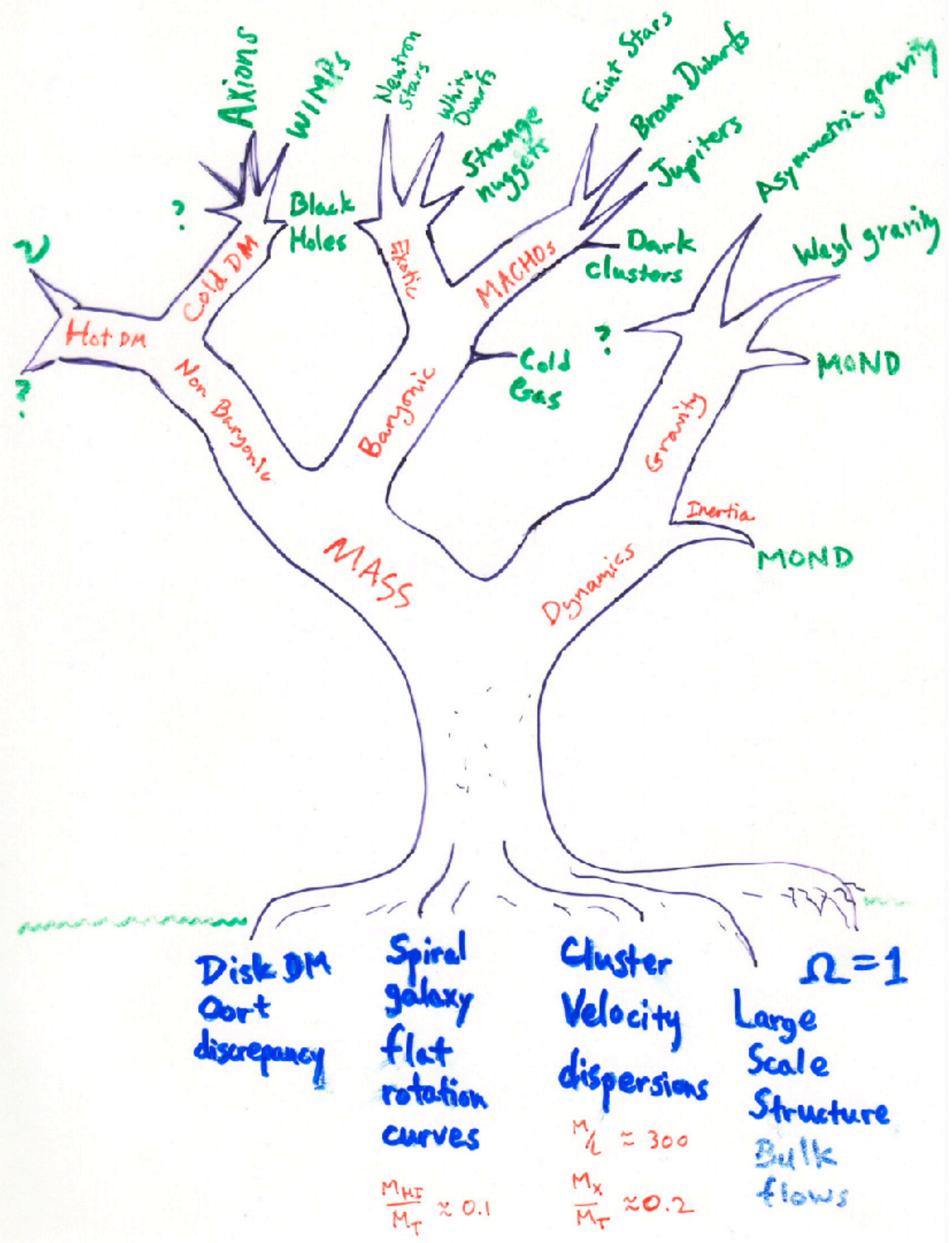
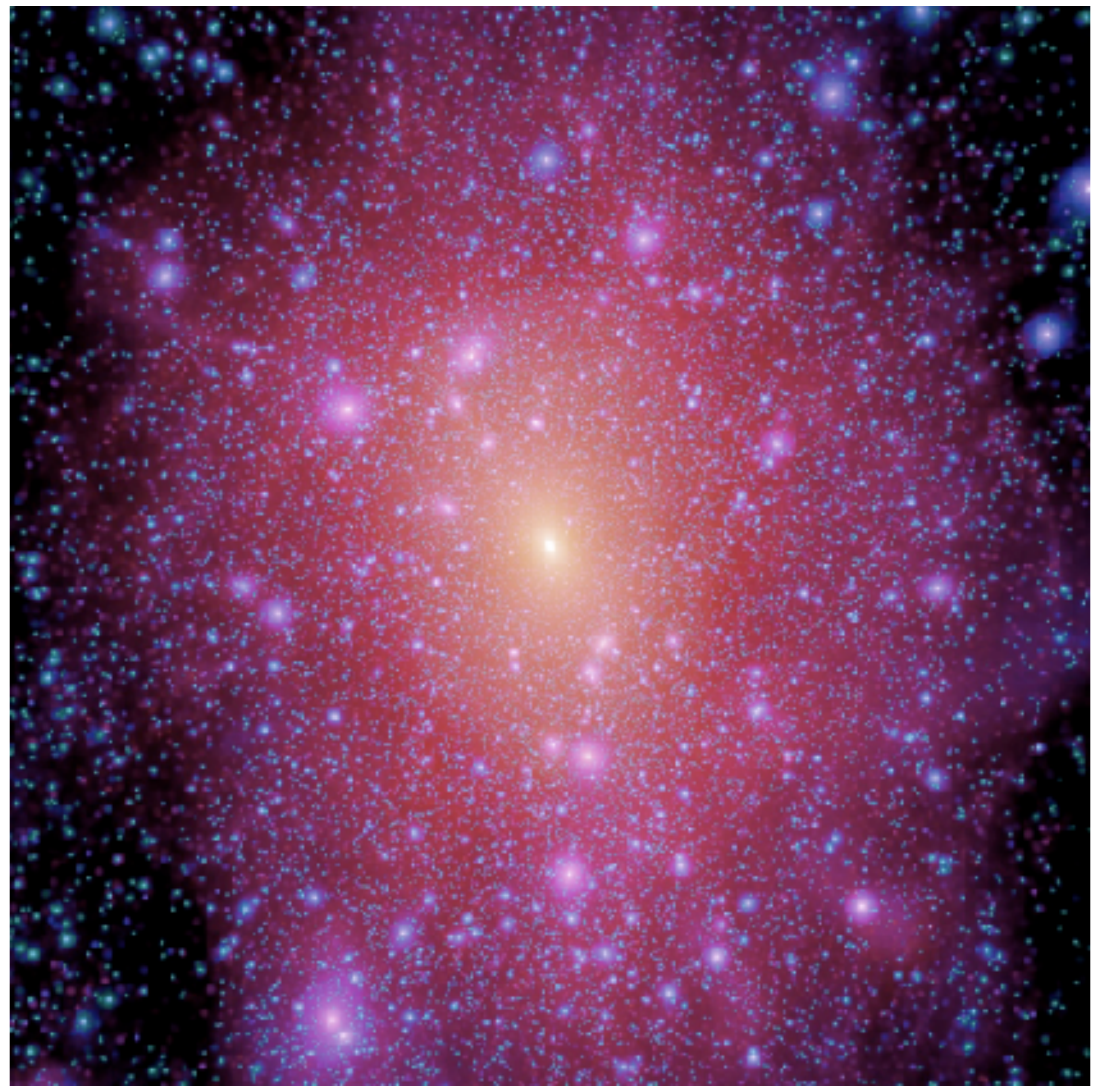


Sequence of events in galaxy formation

1. Dark matter halos form; merge into ever larger masses
2. Baryons fall into the potential wells of DM halos
3. Gas cools & 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
    - might rearrange dark matter
5. Mergers transform some disks into ellipticals
    - star formation enhanced then truncated by mergers
6. Renewed gas accretion may re-form disks around spheroids
    - thus becoming the bulges of S0s and early type (Sa, Sb) spirals
7. Merging slows; more gradual accretion of dark matter and gas may continue
8. Galaxies



dark matter from simulation

spiral galaxy

Sequence of events in galaxy formation

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

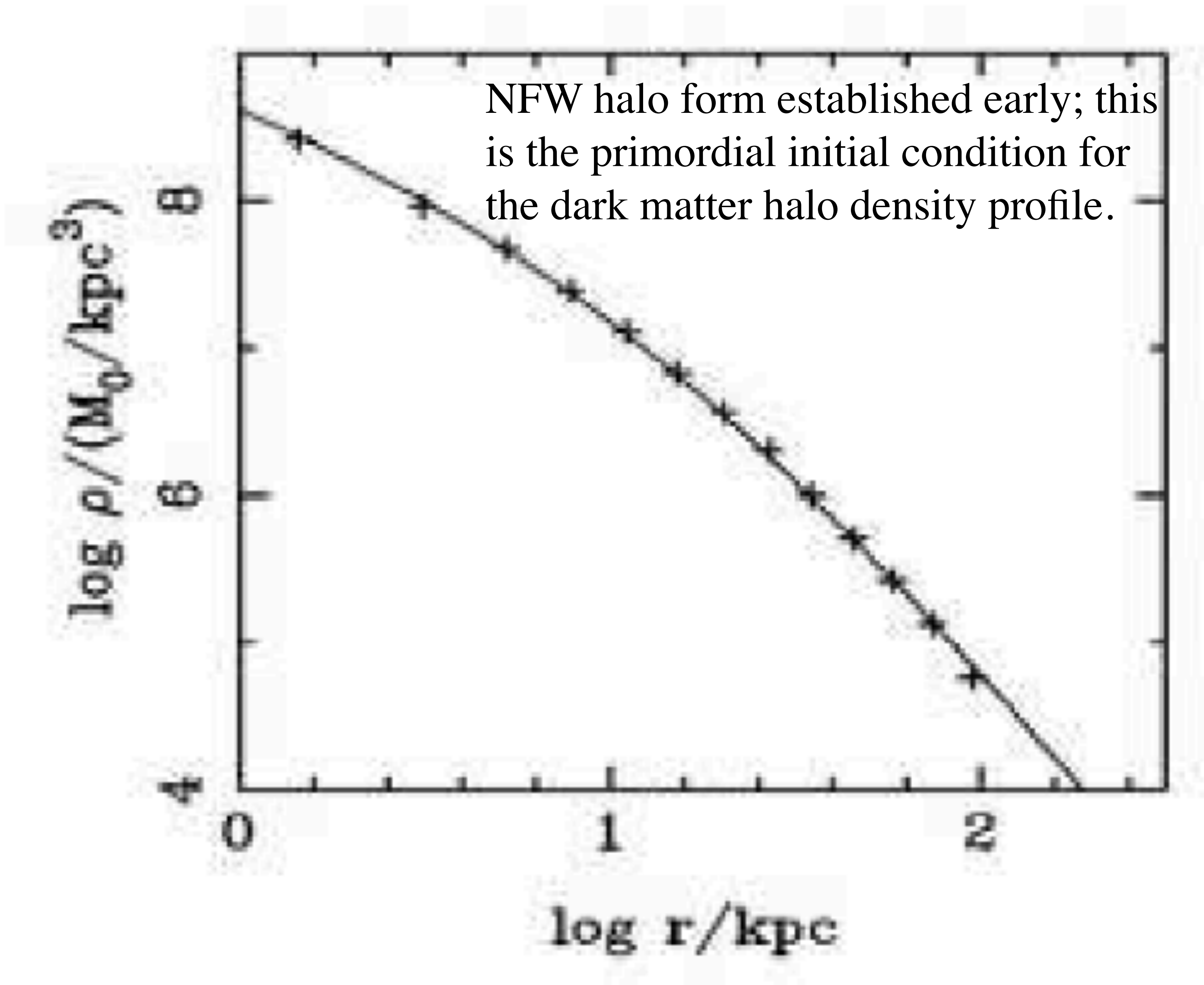


FIG. 1: Density profile of the million particle dark matter halo simulation of Dubinski & Carlberg 1990 (crosses). The solid line shows the best fit NFW profile (Eqn. 1) to the original data. This Figure was adapted from[22] by John Dubinski and it is reproduced here with his permission.

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 $\Delta = 200$

$$V_{200} = \sqrt{\frac{G\,M_{200}}{R_{200}}} = R_{200}\,h$$

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

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

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

to relate halo properties to observable quantities

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2. Baryons fall into the potential wells of DM halos

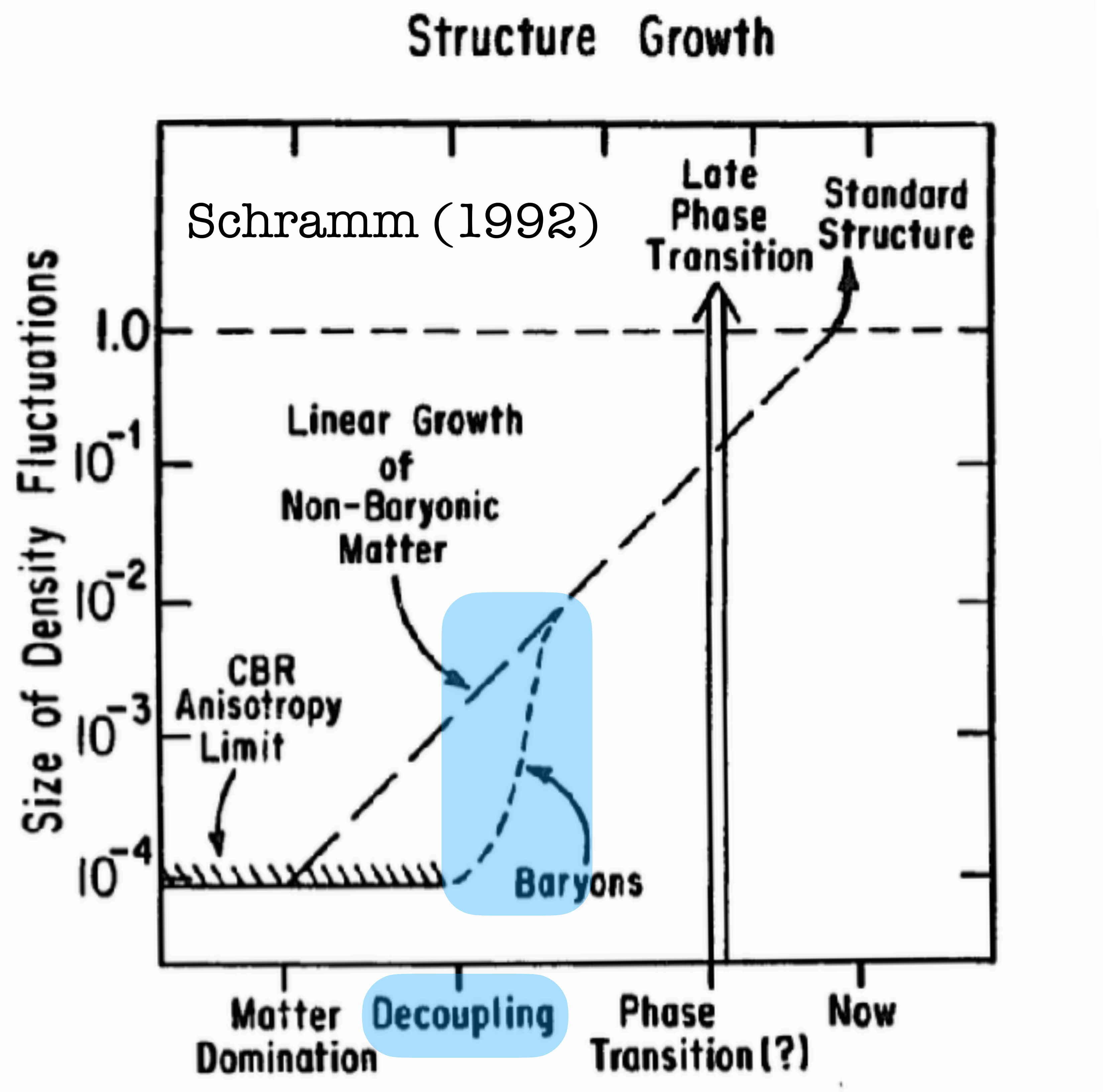
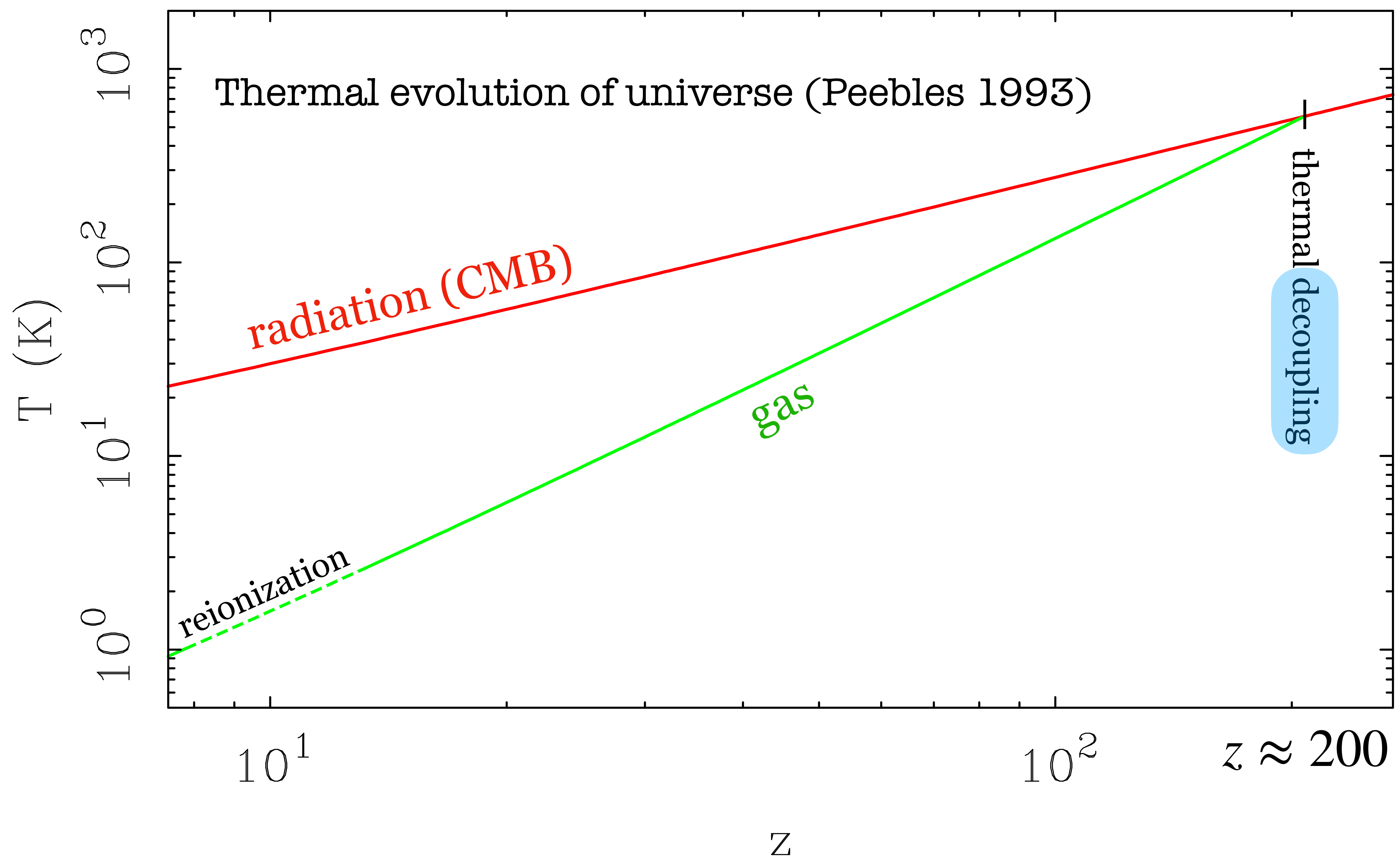


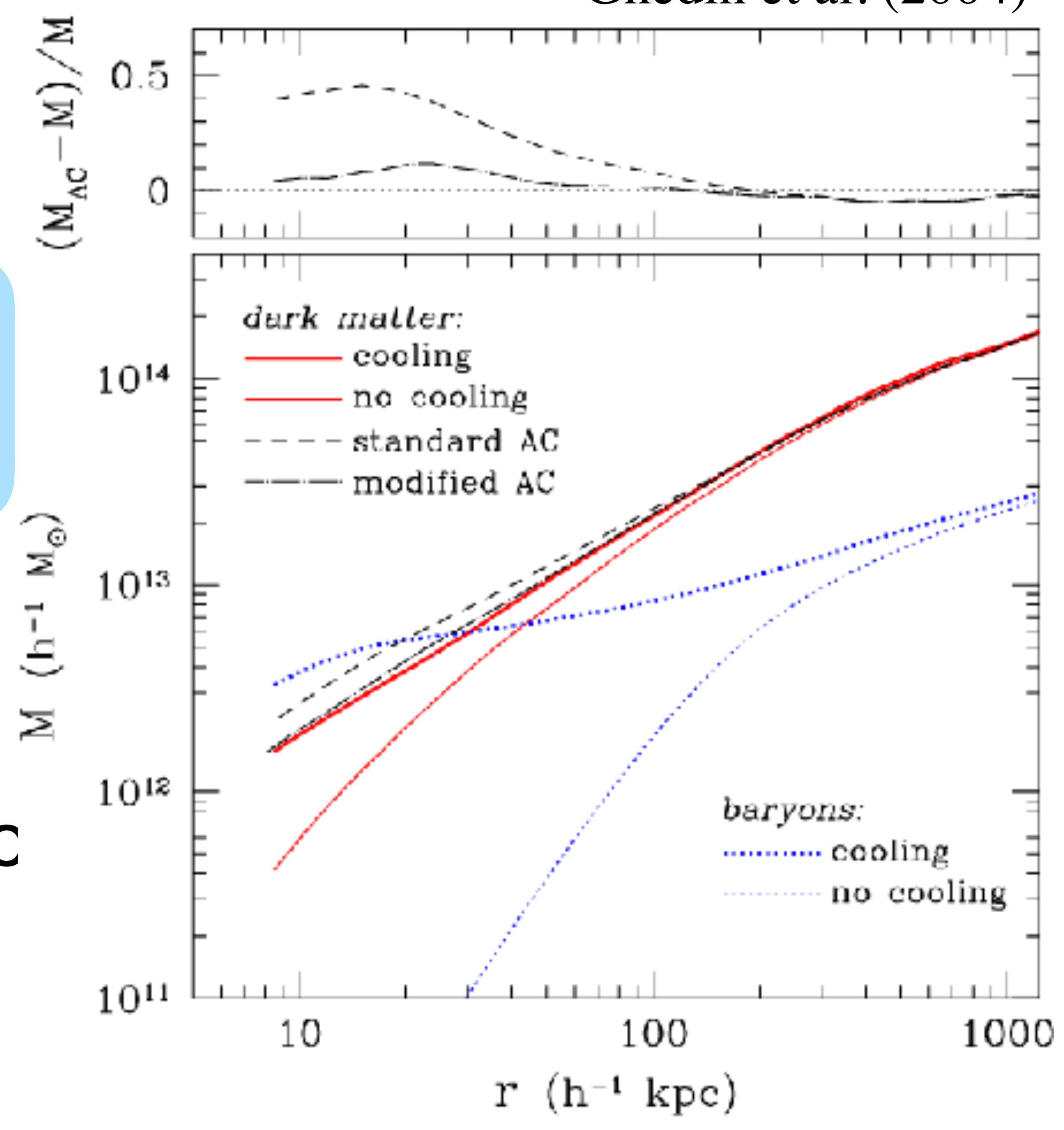
Figure 5. Linear growth of $\delta\rho/\rho$ versus inverse temperature with epochs noted.



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 accretic
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

Gnedin et al. (2004)

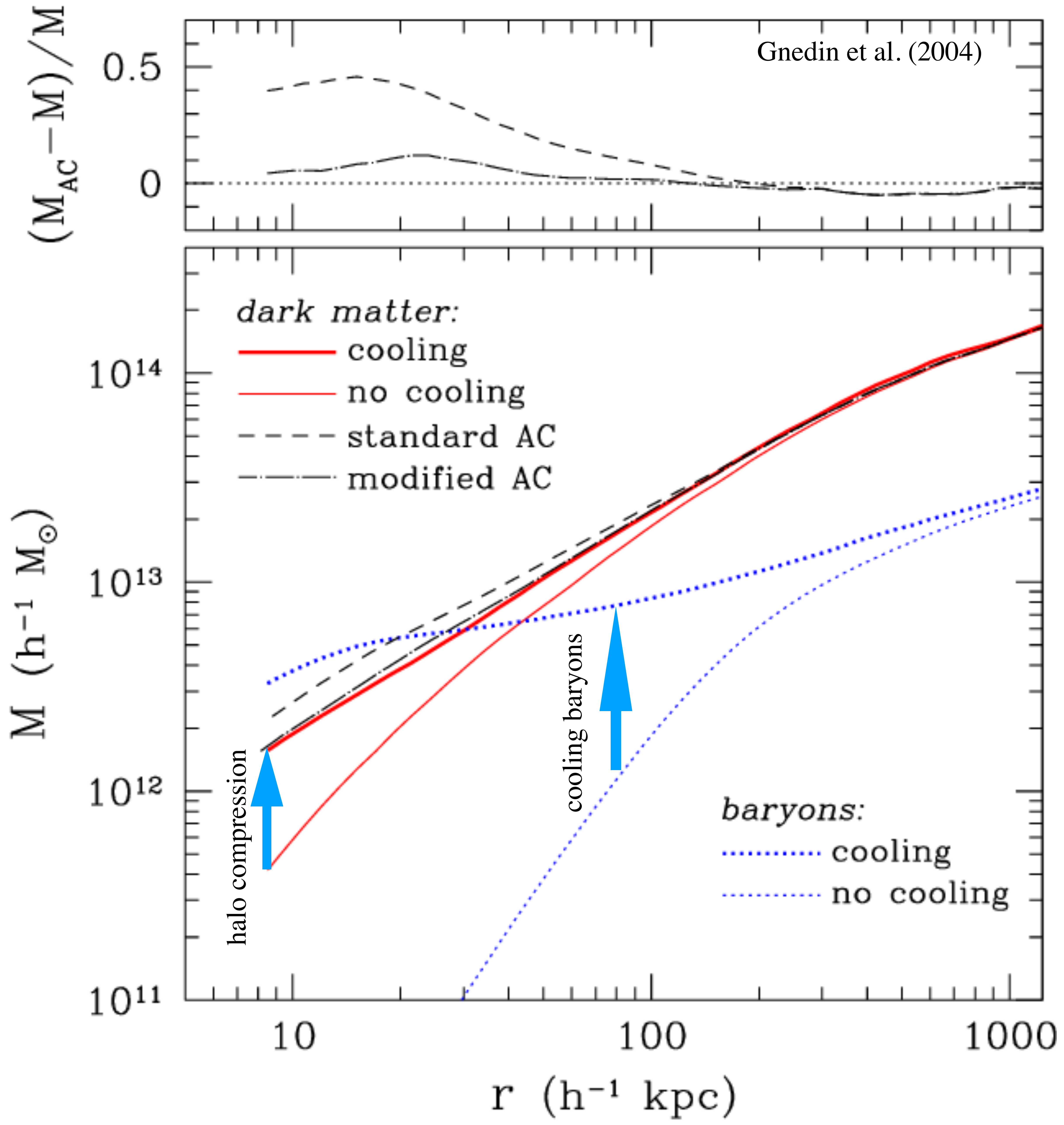


Adiabatic compression

In the absence of cooling, baryons basically follow the NFW profile of the dark matter halo.

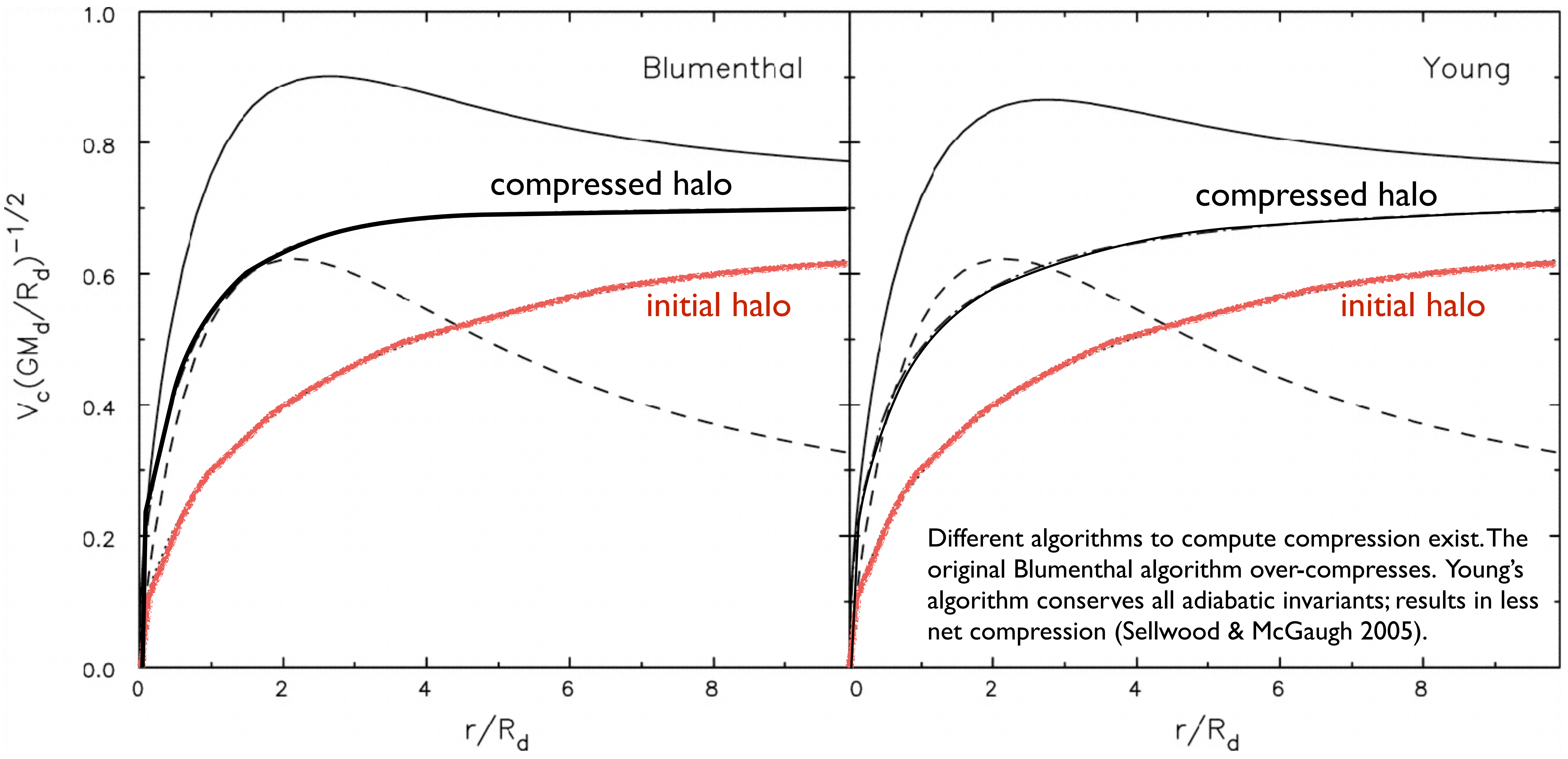
The cooling baryons fall inwards, during which time the gravitational potential is not stationary: the time derivative of the moment of inertia is non-zero as the mass is rearranged. Consequently, the virial theorem does not apply at this time.

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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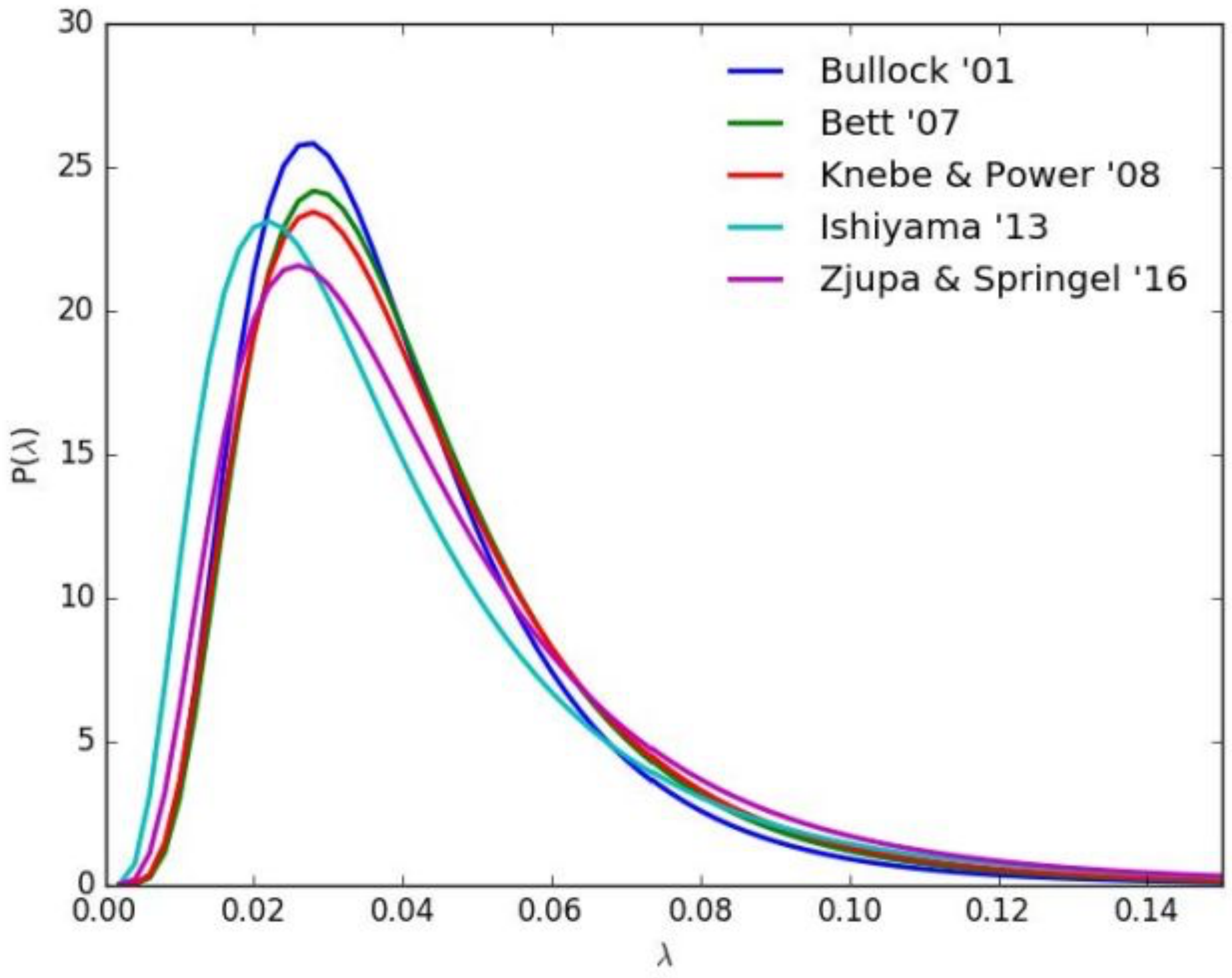
   - Halos compressed by sinking baryons
   - gas forms rotating disks at centers of DM halos



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:

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

Gas shrinks until centrifugally supported, i.e., when $\lambda \rightarrow 1$

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

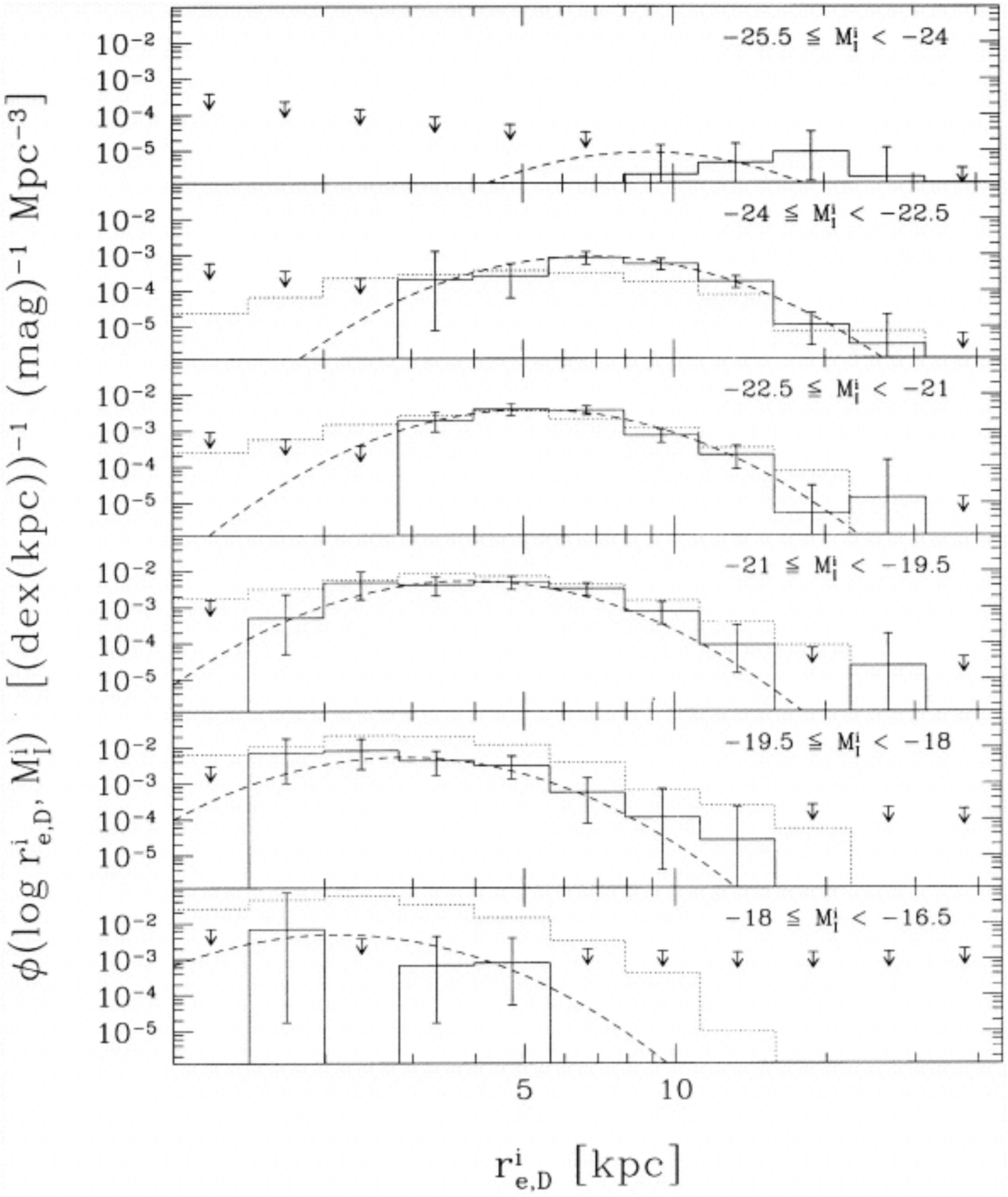
low surface brightness

<u>Low spin</u>

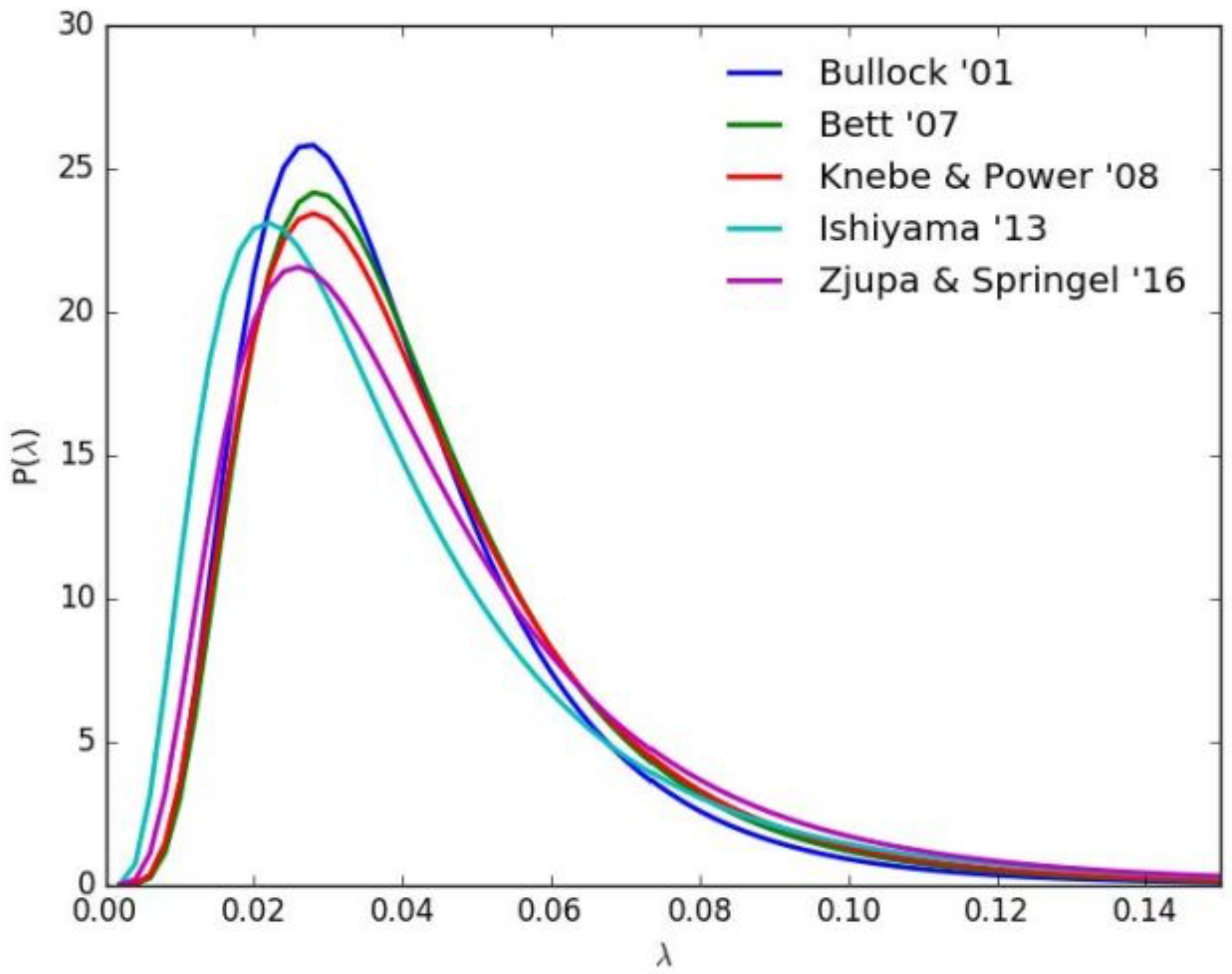
small scale length

high surface brightness

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

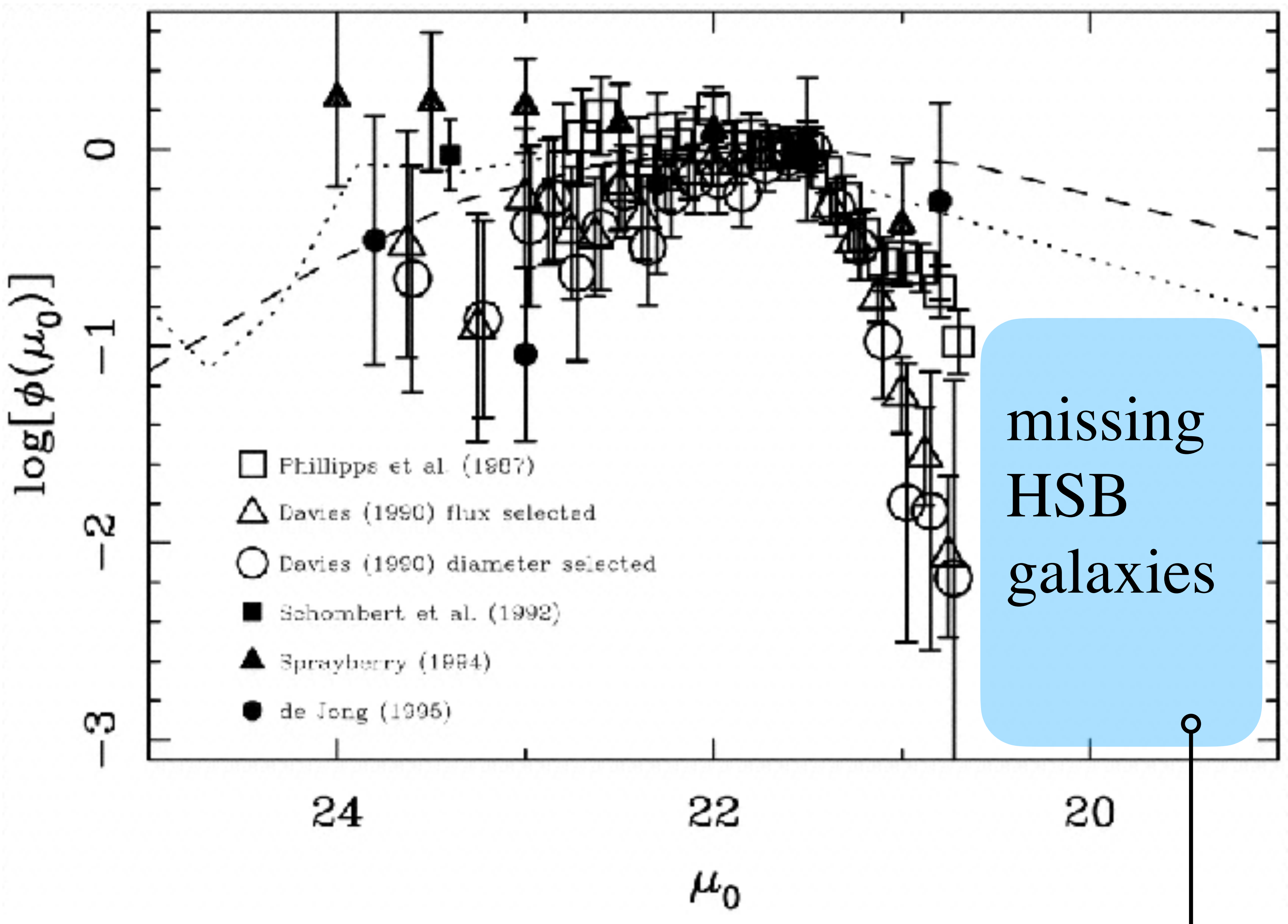


The primordial spin of the halo maps to the size of the resident galaxy in this picture



<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)

High surface density objects perhaps become elliptical galaxies. Makes intuitive sense, but have to put in a disk stability threshold by hand.

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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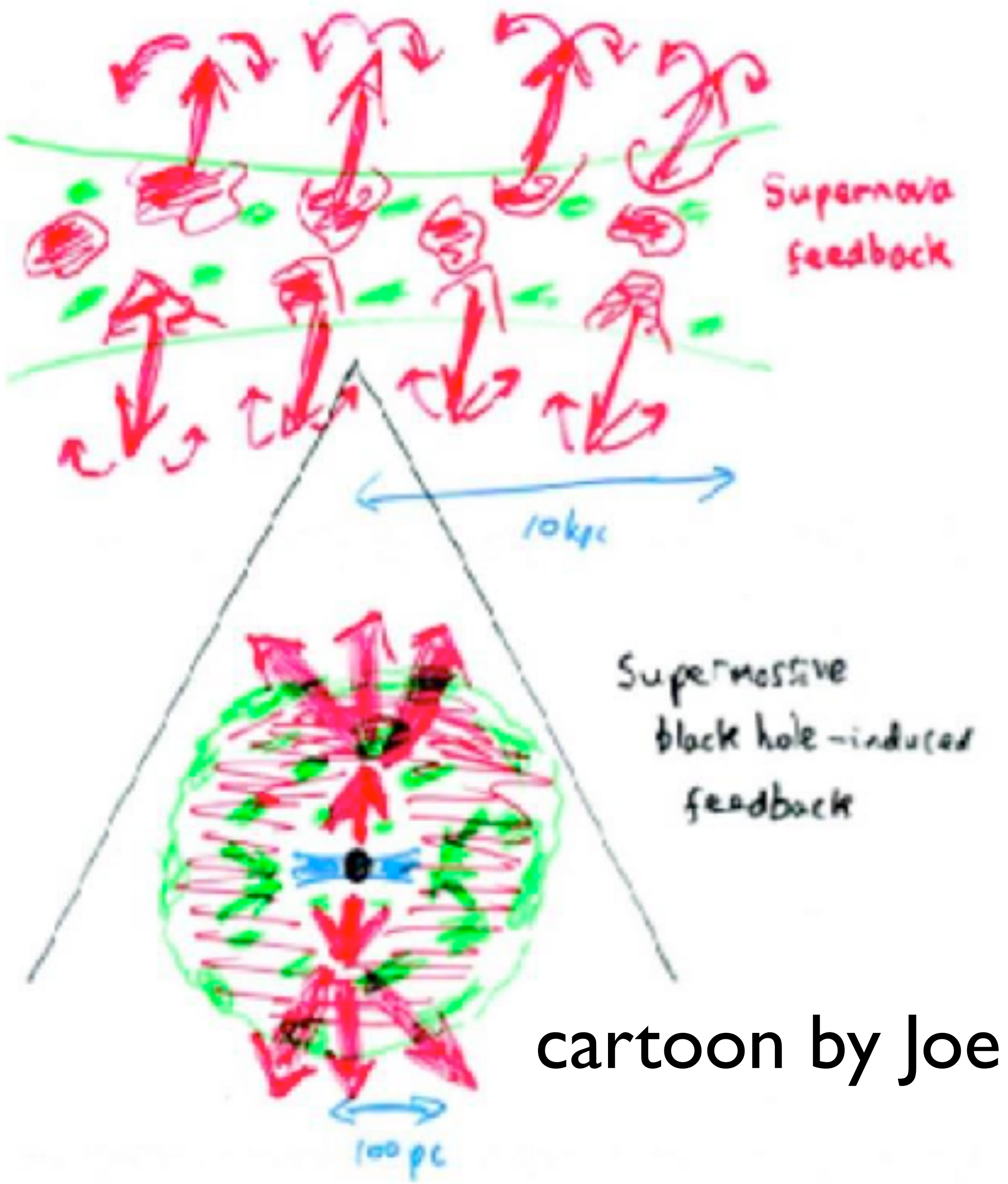
   - Feedback heats gas, dissuading further gas accretion

Types of feedback
AGN (Active Galactic Nuclei)
jets from supermassive black holes
Star formation
Supernovae
Stellar winds
Ionizing radiation / Radiation pressure
Exotic
X-ray binaries



cartoon by Joe Silk

"Feedback" is used to mean basically any process that produces energy and returns *some* of it to the interstellar medium.

FEEDBACK

<u>Types of feedback</u>
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  jets from supermassive black holes
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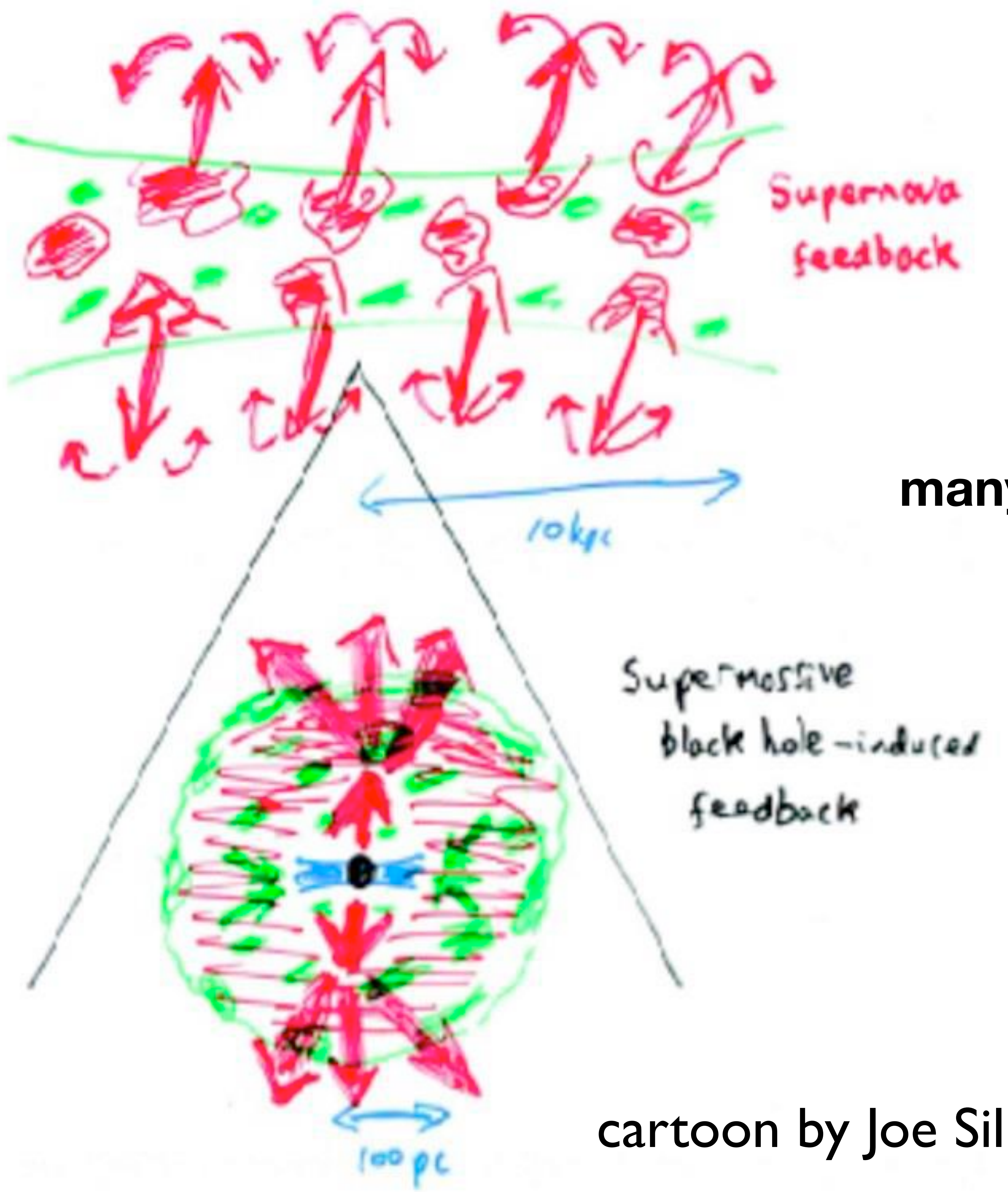

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many devils in the details

Feedback as a physical process occurs on sub-pc scales that are never resolved in cosmological simulations, which must rely on semi-empirical prescriptions for such "sub-grid physics."

<u>Types of feedback</u>

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jets from supermassive black holes

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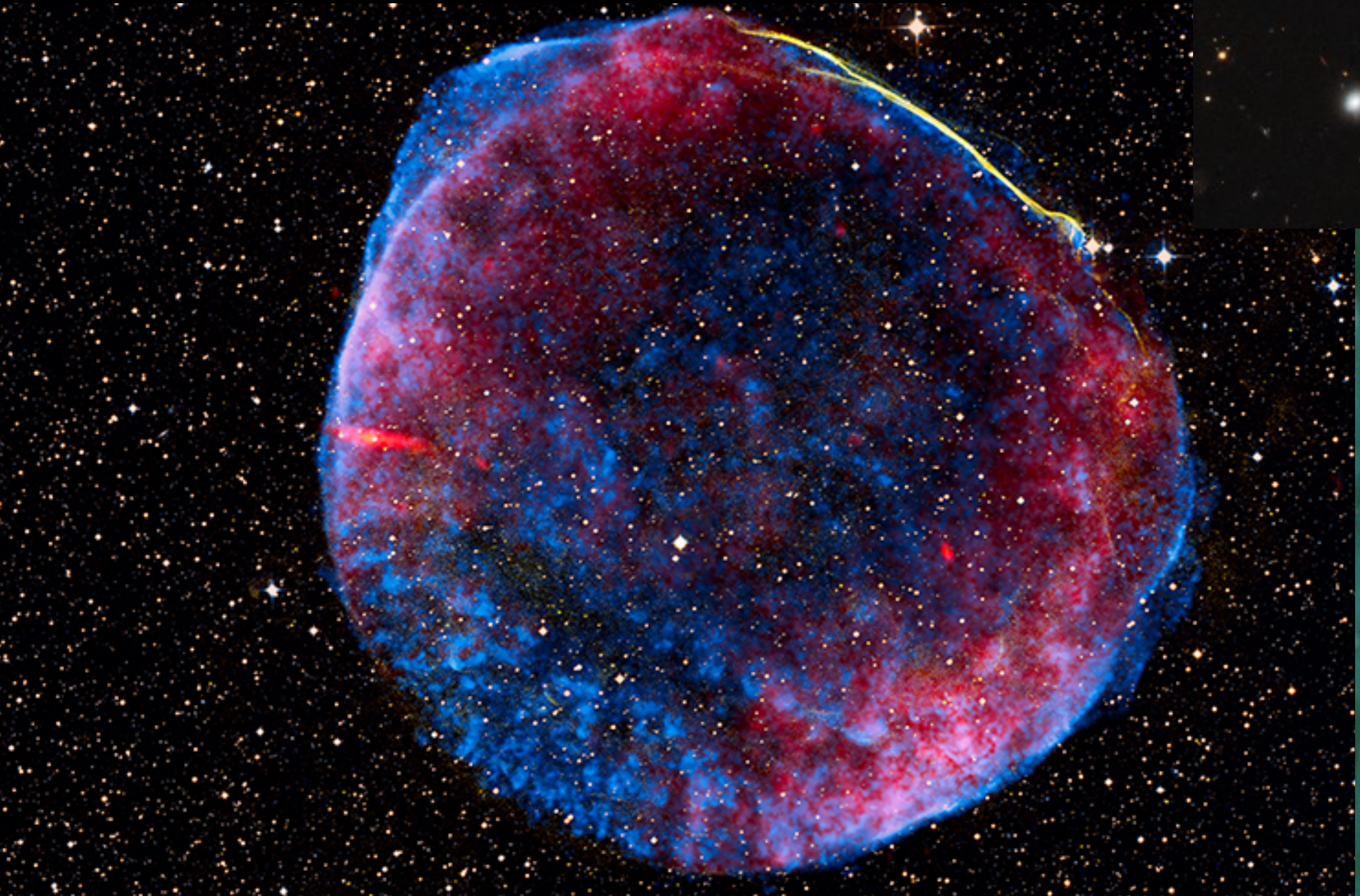
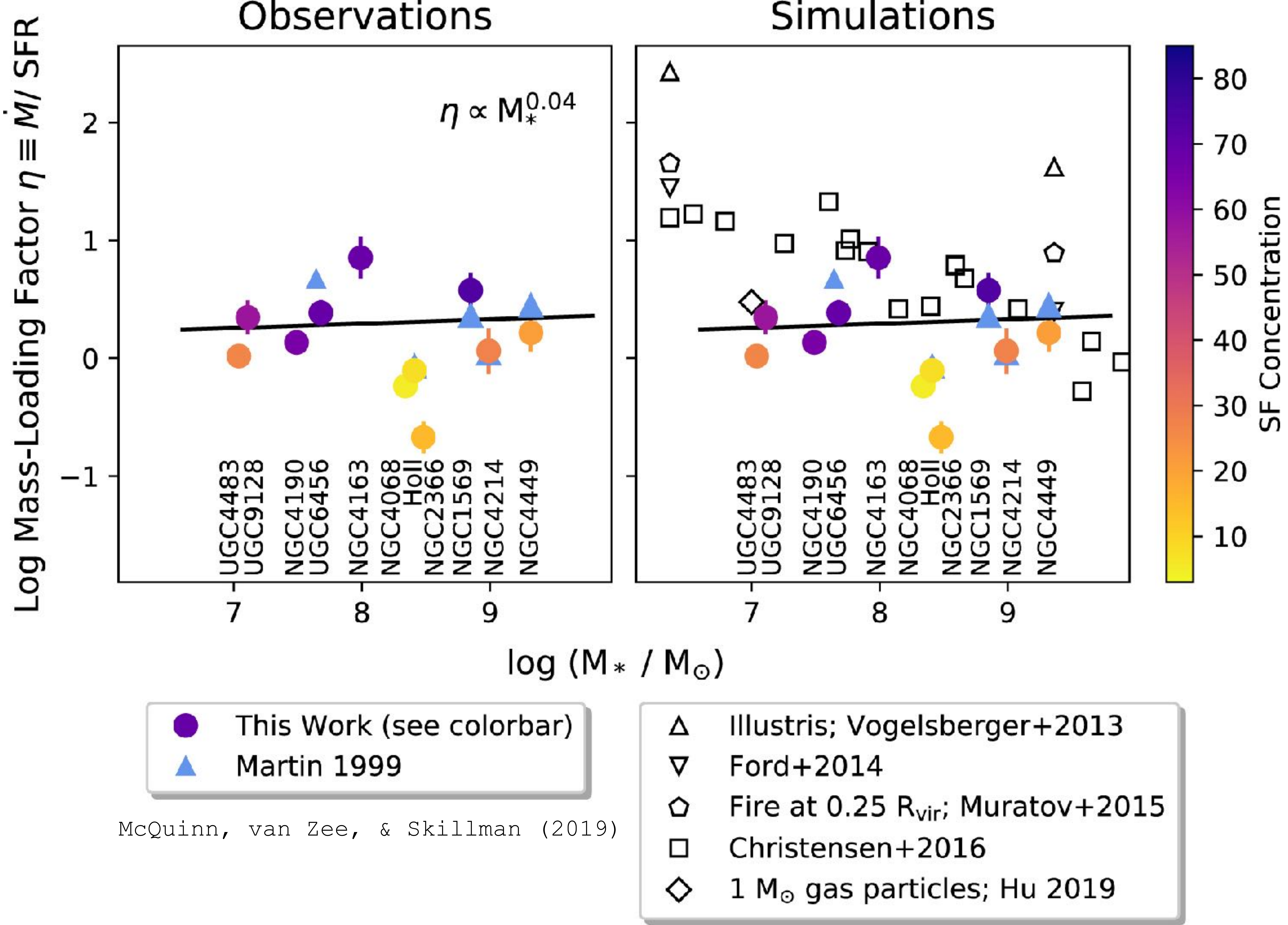


many devils in the details

The mass-loading factor η compares the mass-loss rate from outflows ($\dot{M}$) to the SFR



McQuinn, van Zee, & Skillman (2019)

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4. Stars form in disks
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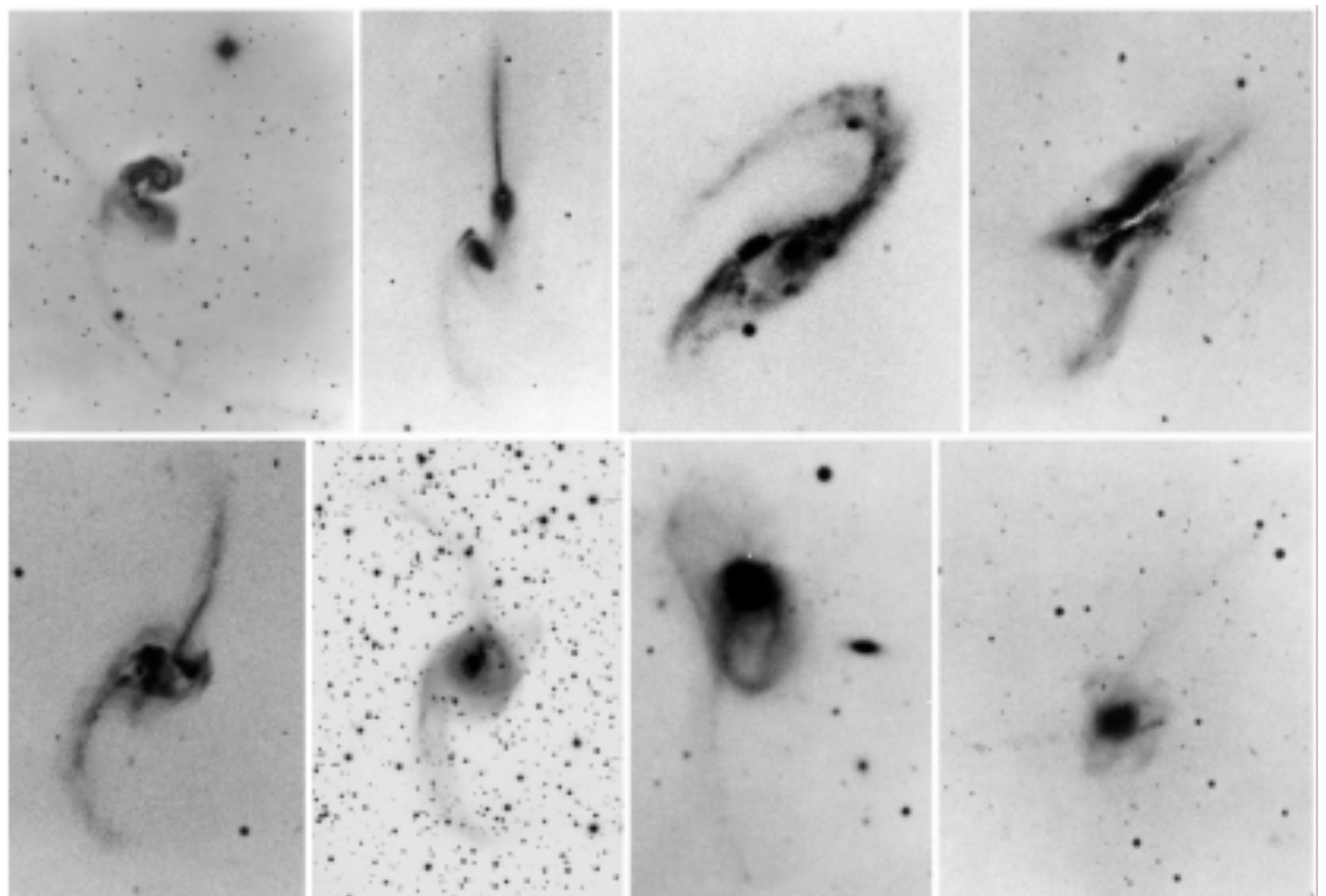
5. Mergers transform some disks into ellipticals
   - star formation enhanced during merger; truncated post-merger

wet vs. dry mergers:

galaxies in

- wet mergers start with gas
  - burst of star formation
- dry mergers lack gas
  - no new star formation



Toomre merger sequence (courtesy of John Hibbard)

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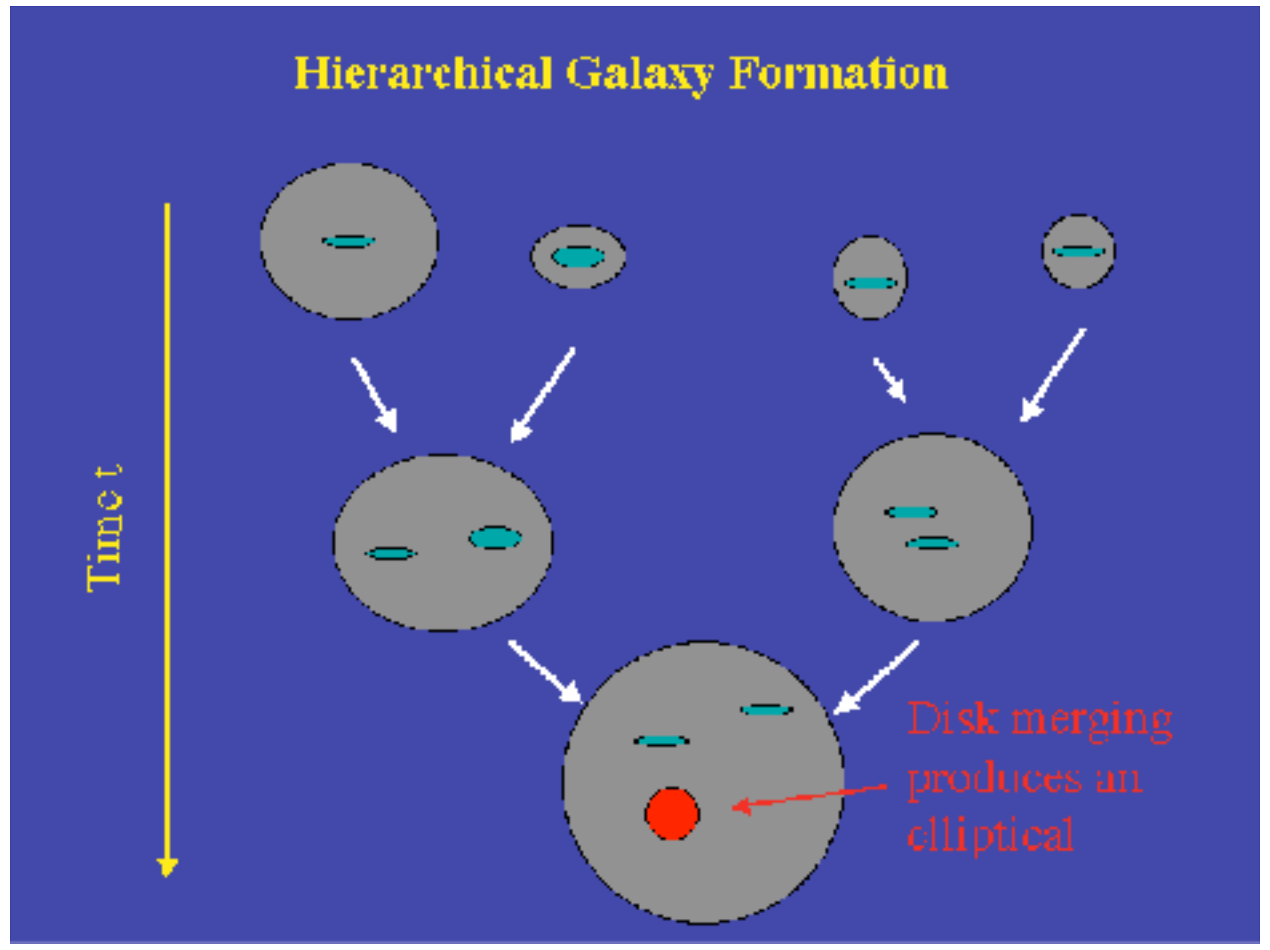

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Structure formation moderates at $z \approx \frac{1}{\Omega_m} - 1$ as the expansion of the universe outstrips gravitational collapse.

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