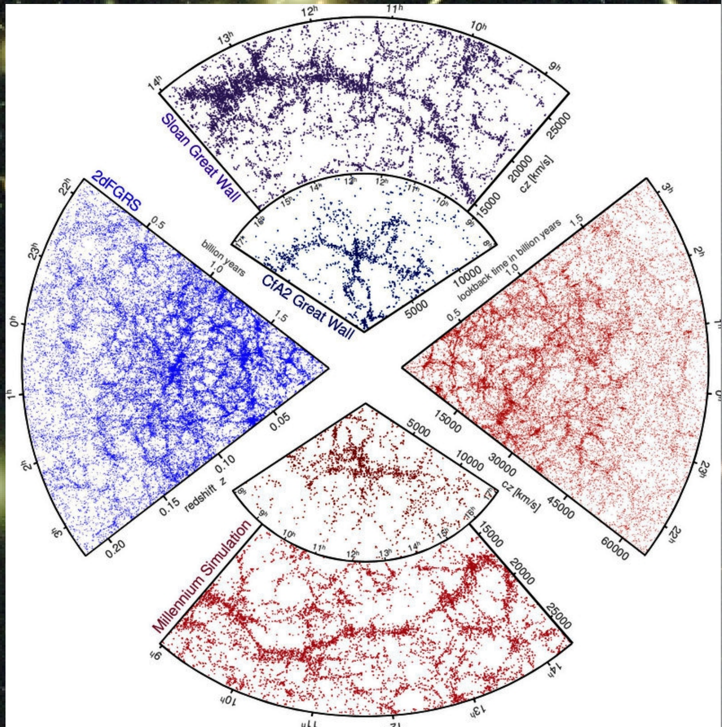
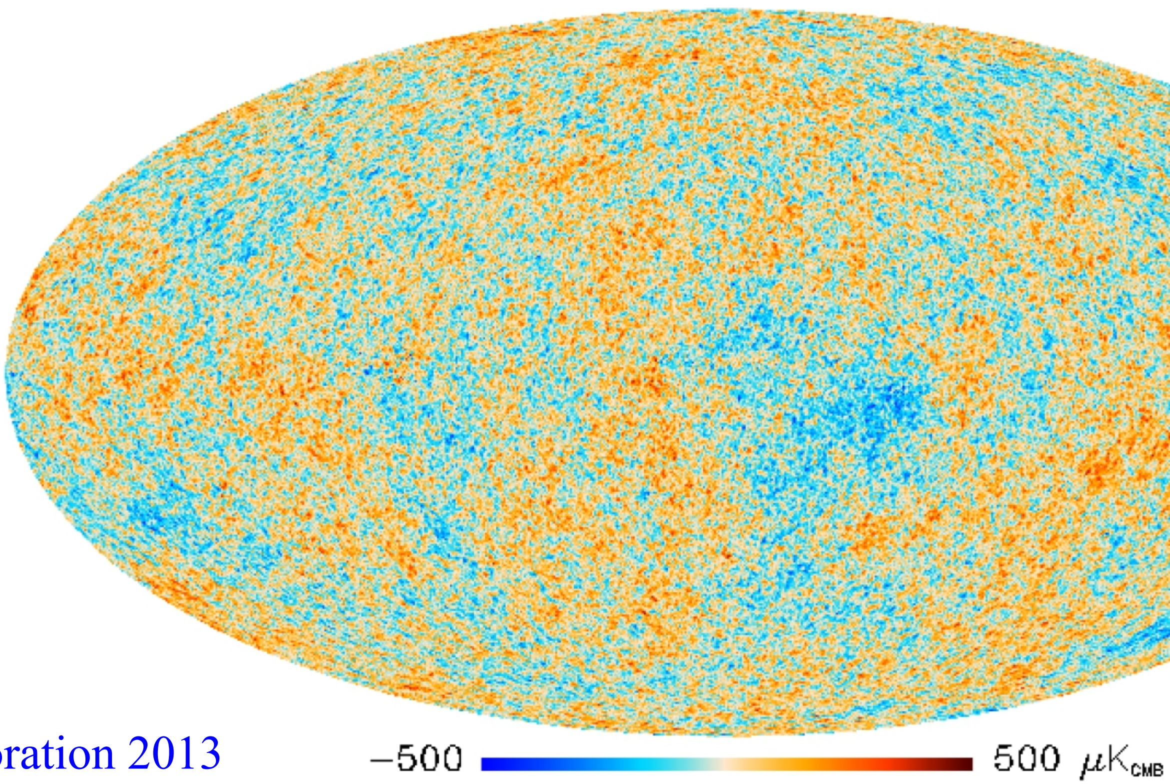
IMPRS lectures 2013

Galaxy formation

Simon White



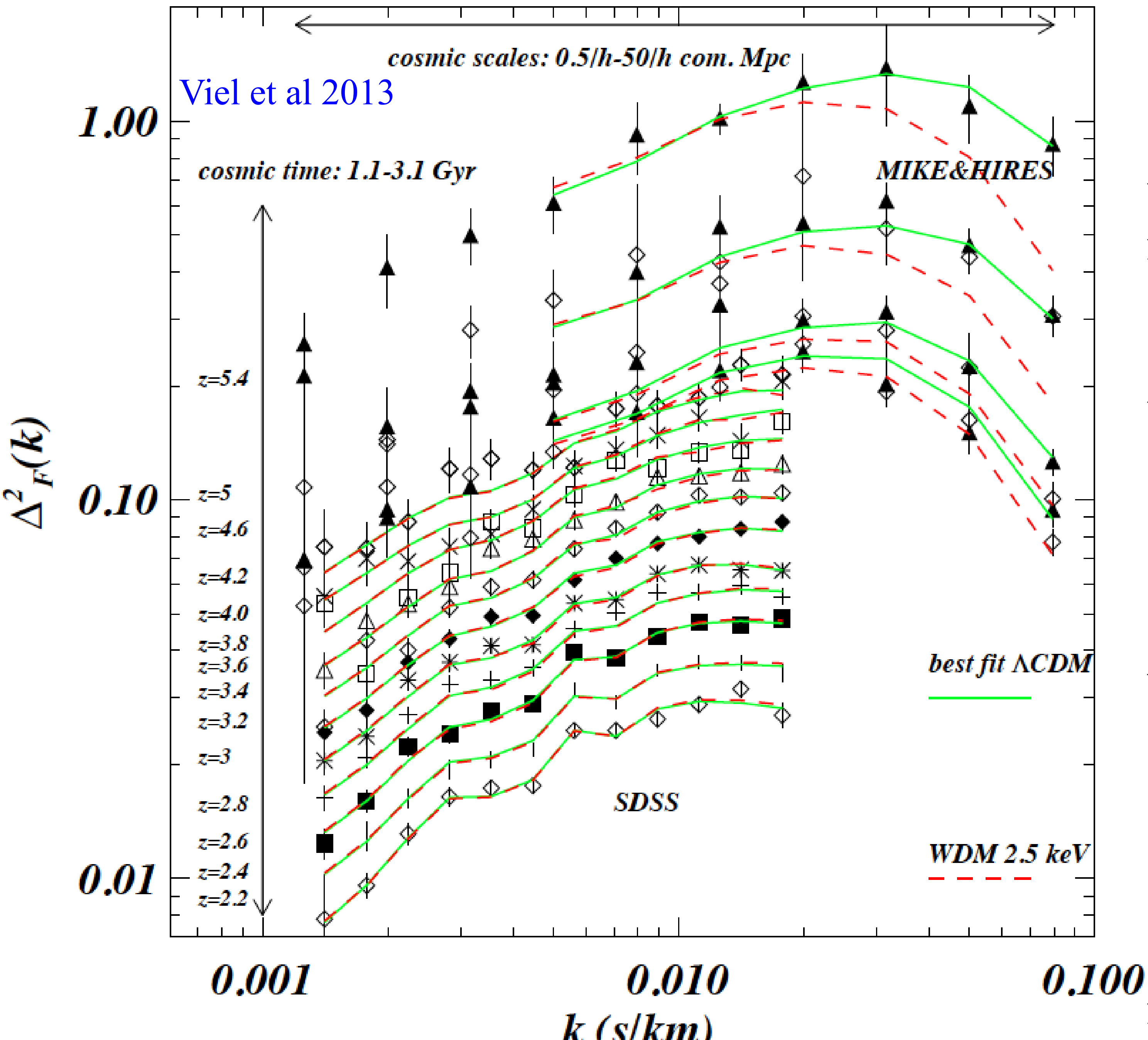
Cosmological context and initial conditions for galaxy formation



Planck Collaboration 2013

A direct image of the pregalactic Universe: $z \sim 1100$, $t = 380{,}000$ years
Appears to be an (almost) perfect gaussian random field
Power spectrum an excellent fit to the concordance ΛCDM model
At that time ~65% dark matter, ~10% baryons, ~25% radiation (γ's and ν's)
No nonlinear structure, no elements heavier than Li
Structure directly imaged down to scales corresponding to galaxy clusters.

Small-scale pregalactic structure is visible in Ly α forest



The ΛCDM model continues to provide an excellent fit down to the smallest scales measurable through absorption of distant quasar light by H in the (non-uniform) intergalactic medium.

These scales are smaller than those which collapse to form even dwarf galaxies

Thus. IC's are fully characterised on *all* scales relevant for making galaxies

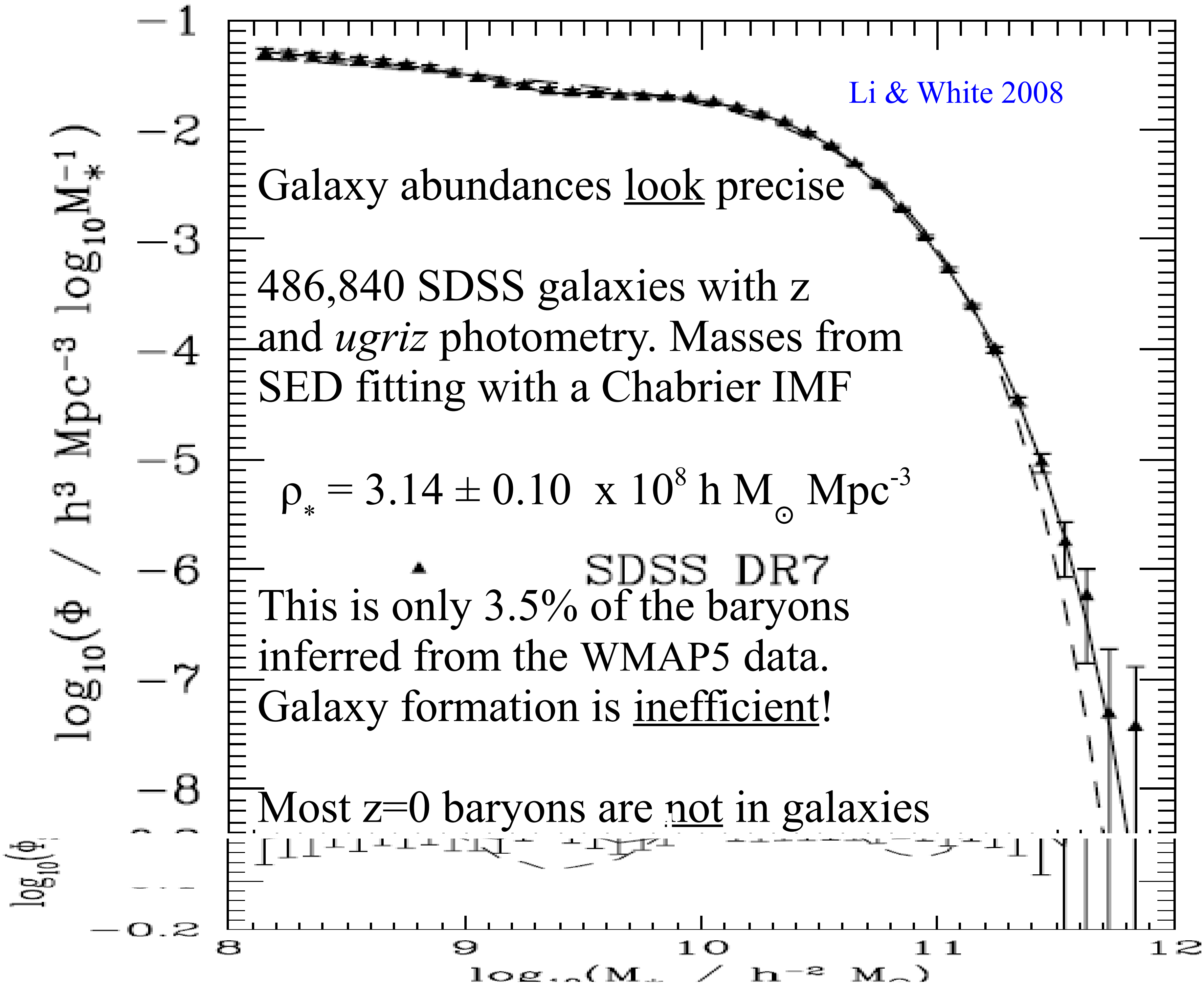
Structure growth in the DM distribution is well understood

- Growth of DM structure in a representative cosmic slice
- DM structure today -- a pattern across many scales
- DM structure today -- a flight through the Millennium Simulation
- Growth of the DM structure in a "Milky Way" dark halo

This provides detailed quantitative information on the abundance, internal structure, assembly history and spatial distribution of dark matter halos/subhalos

Baryonic evolution is more complex and so less well understood

- Formation of a rich cluster (shocks, but no cooling, star formation...)
- Formation of a disk galaxy (Eris + cooling, star formation, SN feedback..)
- A collision of disk galaxies (+ black holes and BH feedback..)



Galaxy abundances <u>look</u> precise

486,840 SDSS galaxies with z and *ugriz* photometry. Masses from SED fitting with a Chabrier IMF

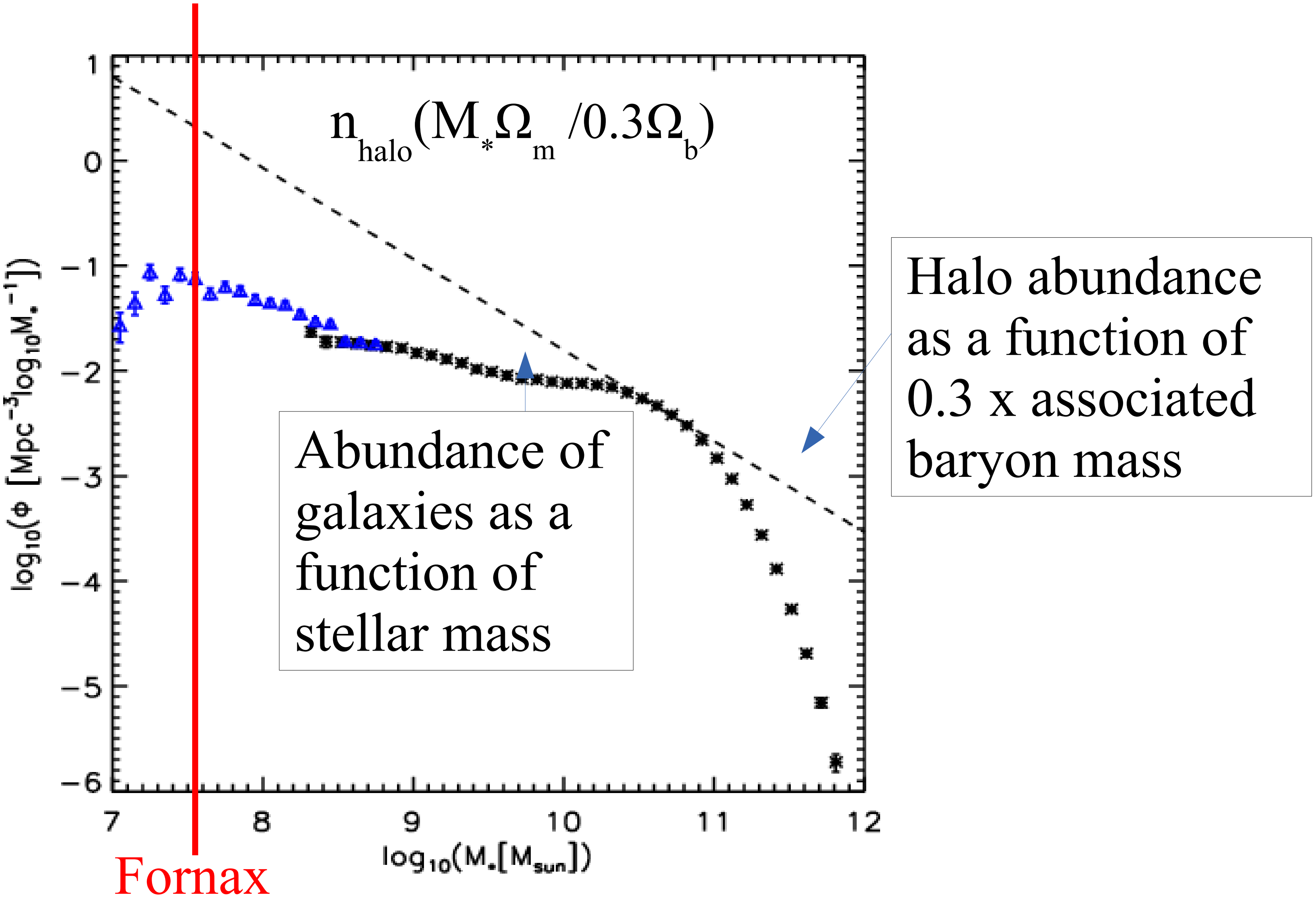
$$\rho_* = 3.14 \pm 0.10 \ \times 10^8 \ h \ M_\odot \ \mathrm{Mpc}^{-3}$$

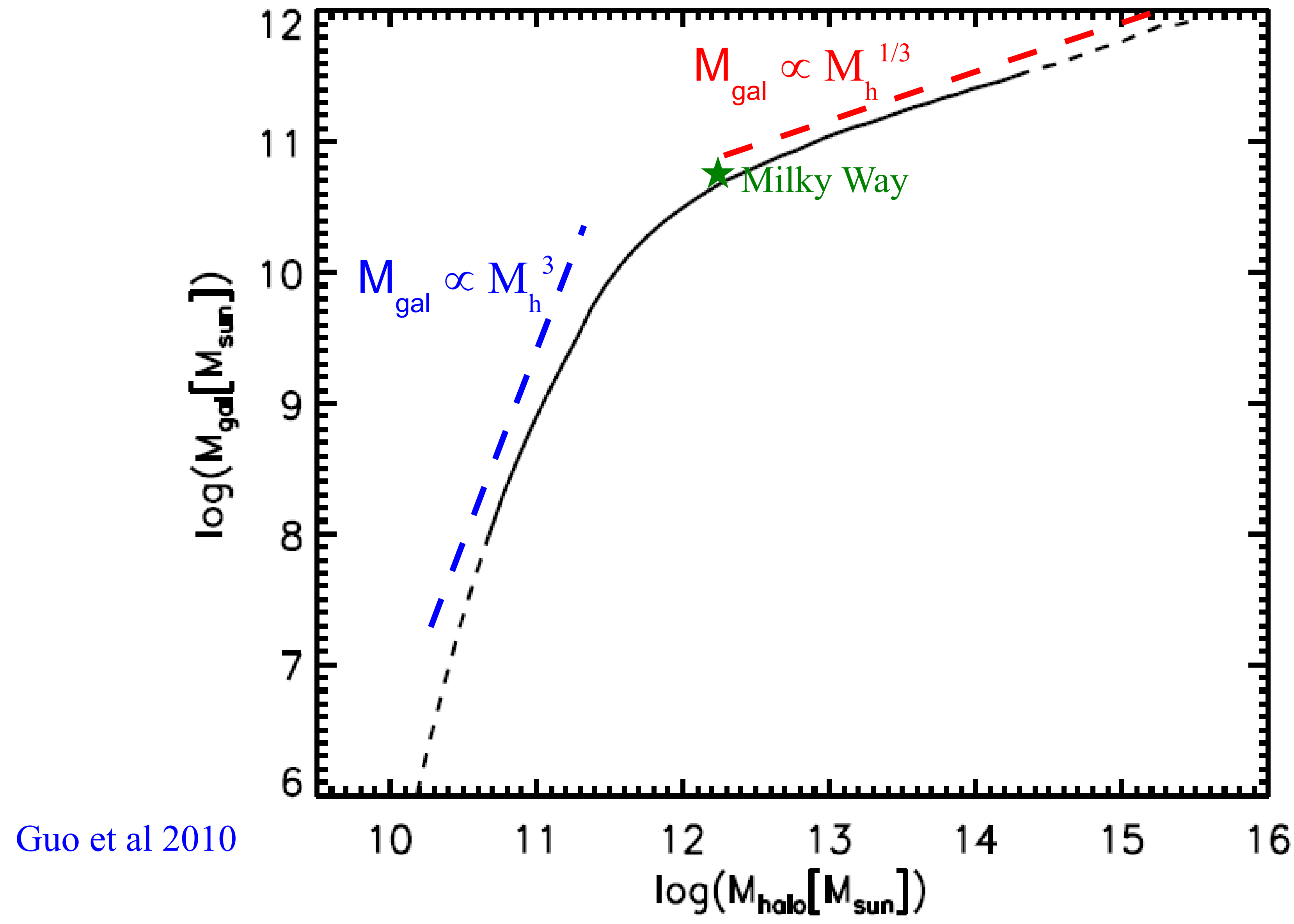
This is only 3.5% of the baryons inferred from the WMAP5 data. Galaxy formation is <u>inefficient</u>!

Most z=0 baryons are <u>not</u> in galaxies

Galaxy and halo abundances have different shapes

A formation efficiency which matches abundance of “Milky Ways” overproduces the number of “Fornax's” by a factor of 30!

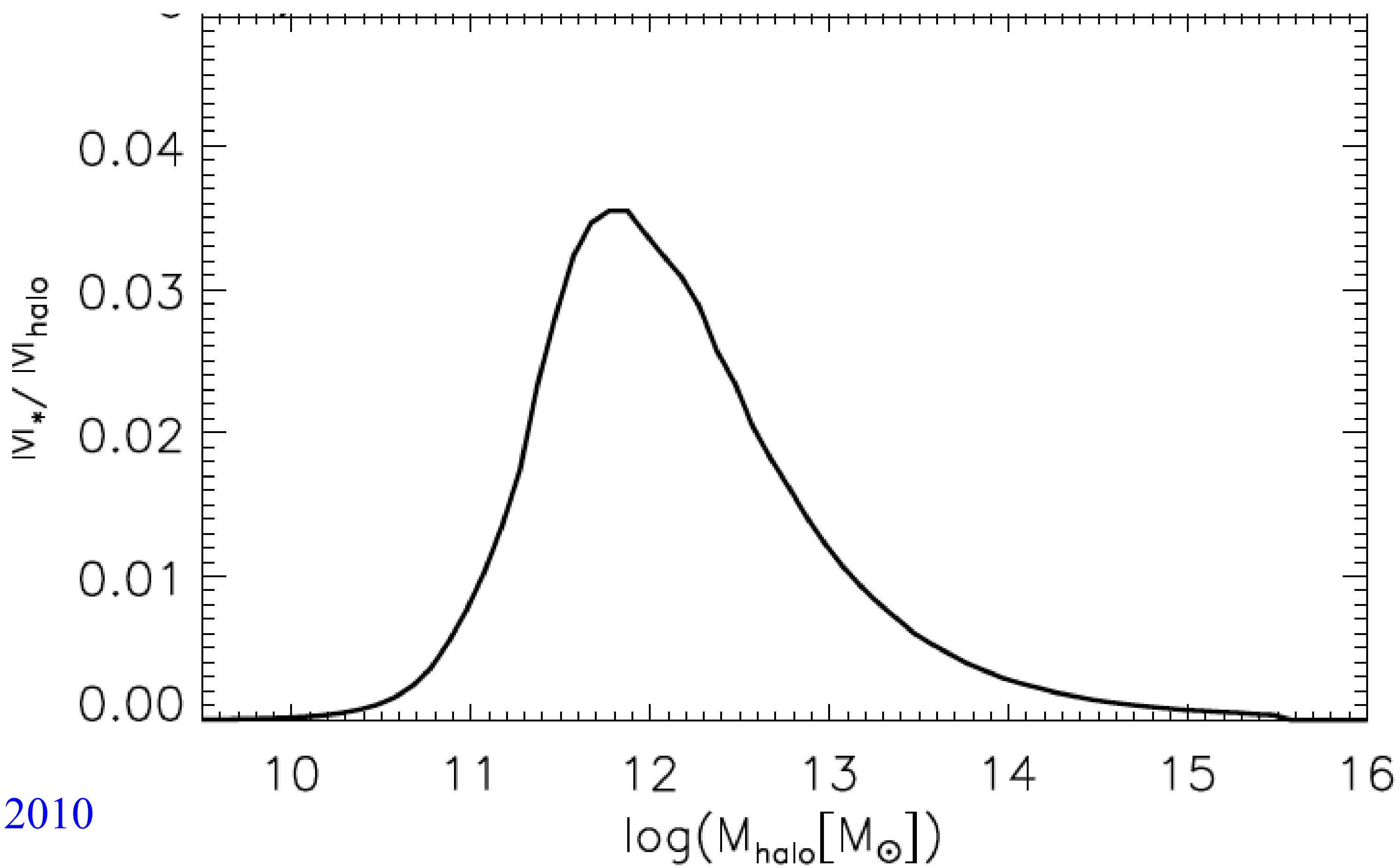




The stellar mass of the central galaxy increases rapidly with halo mass at small halo mass, but slowly at large halo mass

The characteristic halo mass at the bend is $5 \times 10^{11}\ M_\odot$

The efficiency of galaxy formation is low!



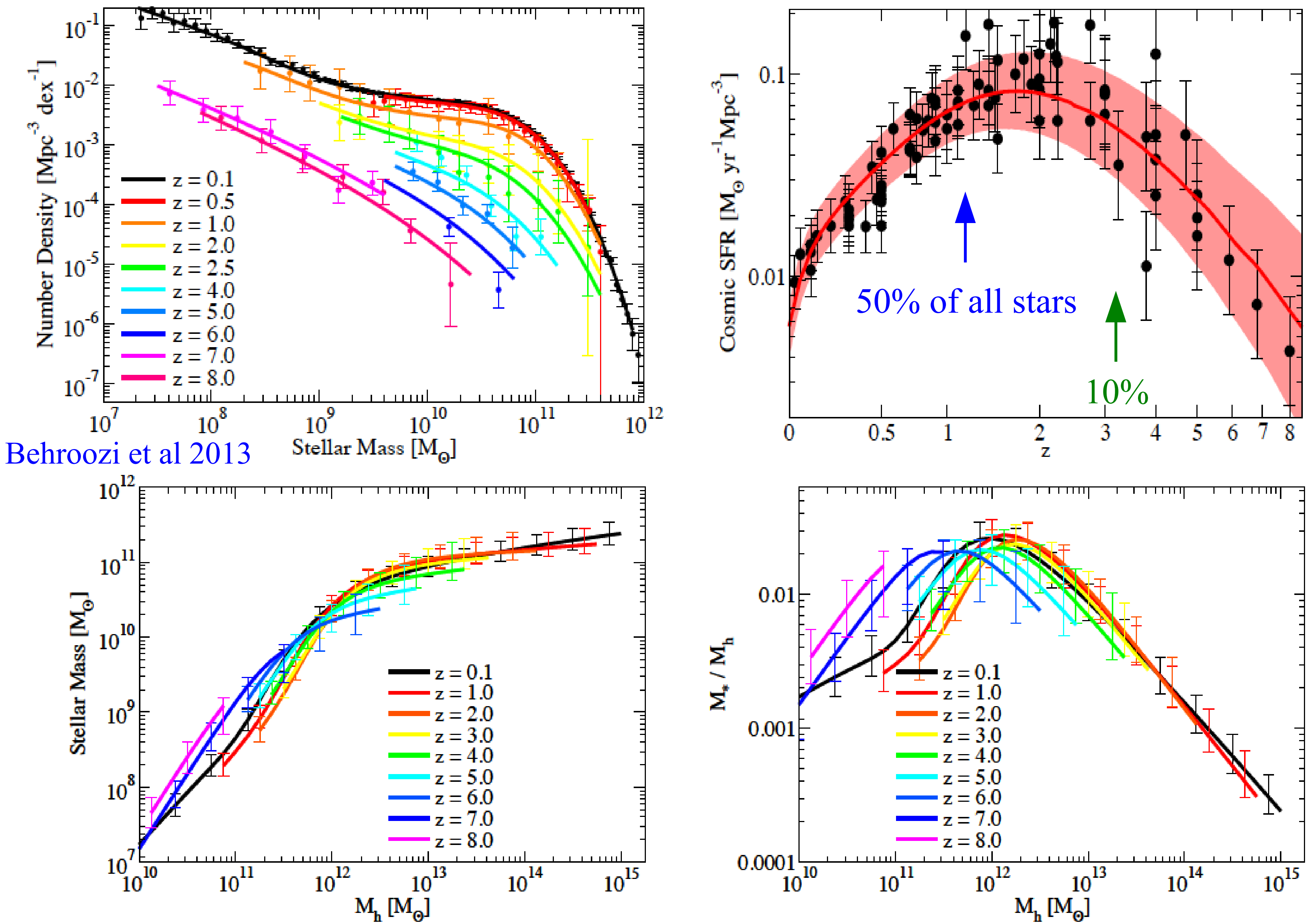
Guo et al 2010

M_*/M_{halo} *maximises* at 3.5% at halo masses of $\sim 10^{12}\, M_\odot$

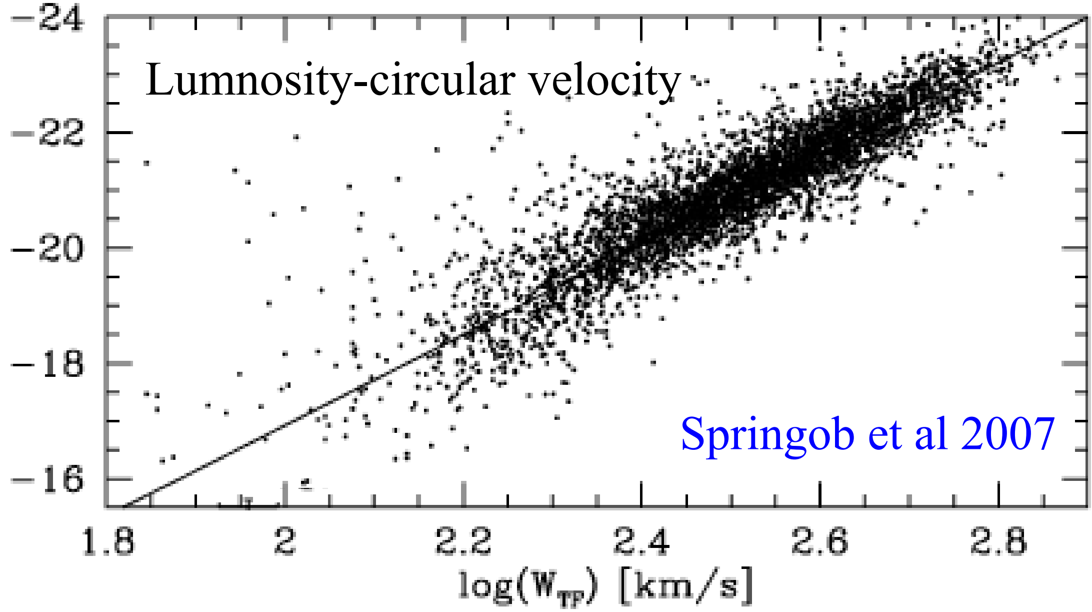
This is *much* less than the global baryon fraction ~ 17%

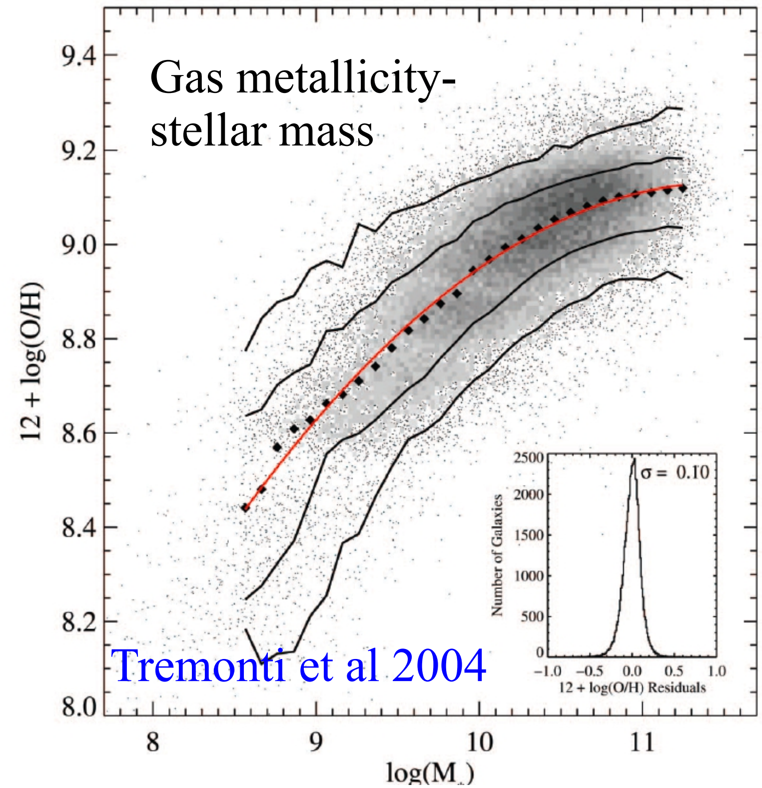
Conversion of halo baryons to stars has maximum efficiency ~20 to 30% and is much smaller at higher and lower halo mass

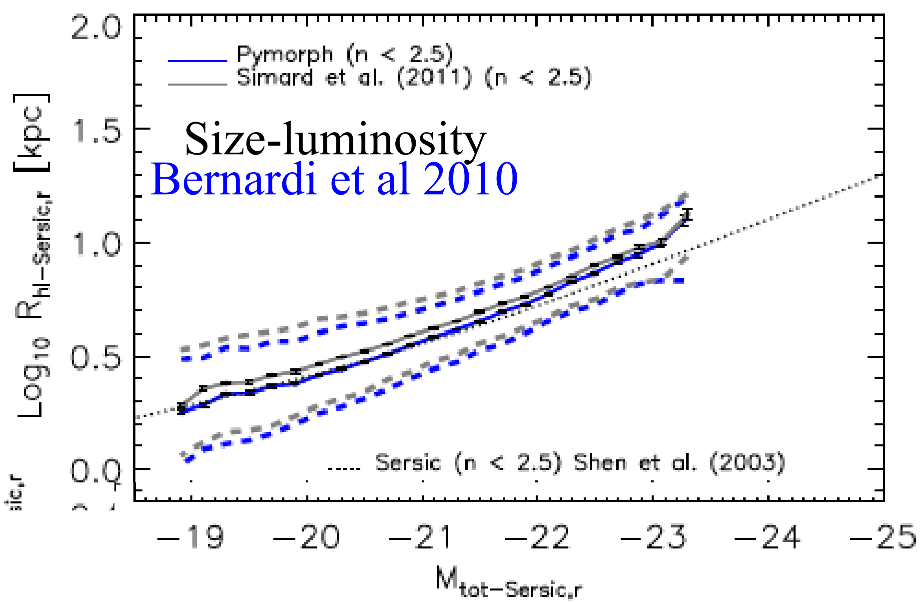
Observations of abundances now available back to z ~ 8, covering >95% of all galaxy formation



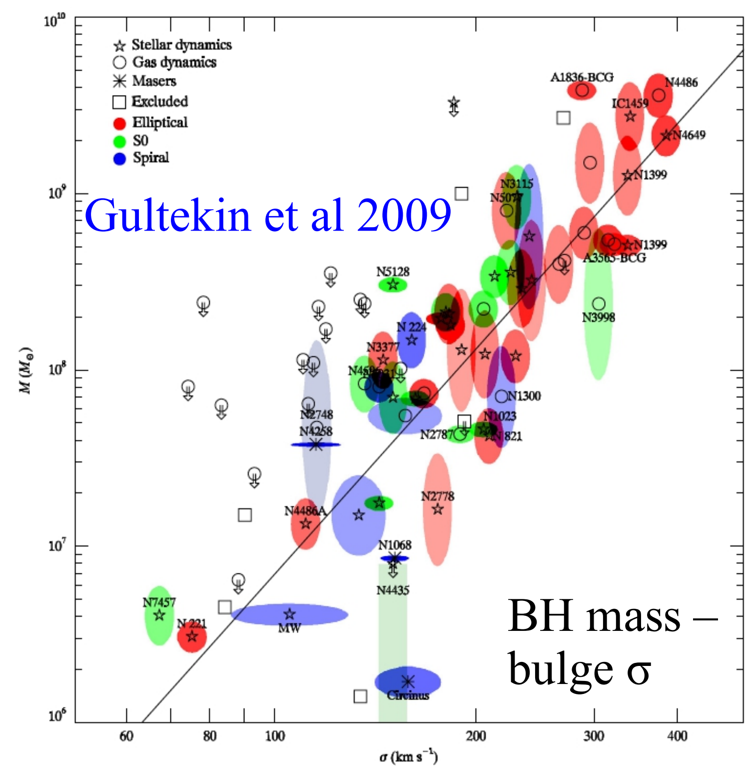
Scaling relations between global properties are well characterised at z ~ 0





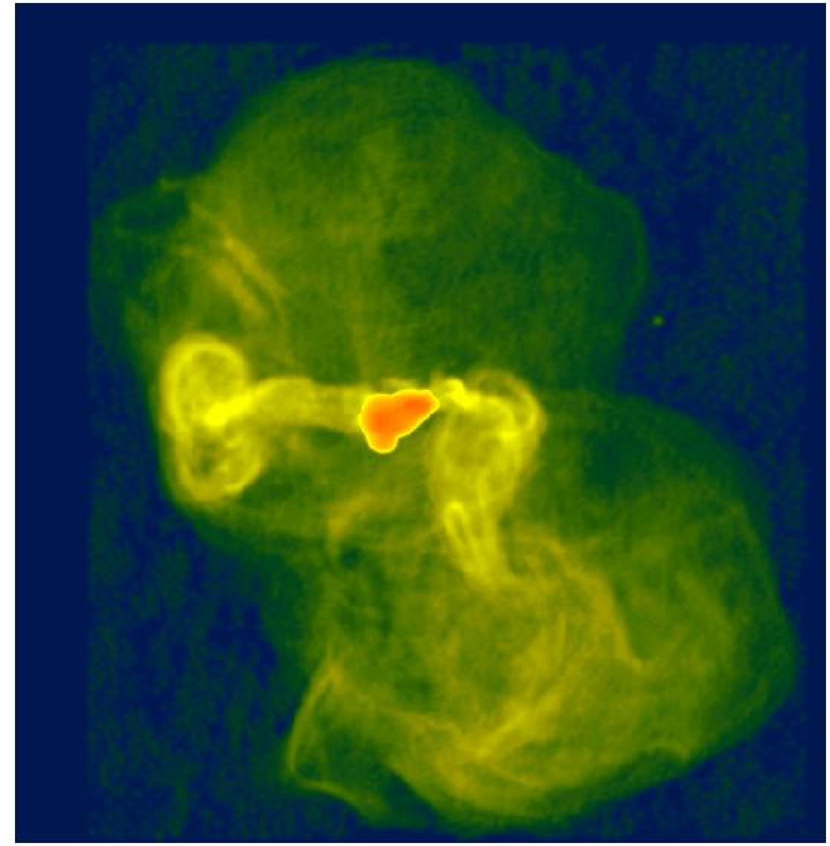


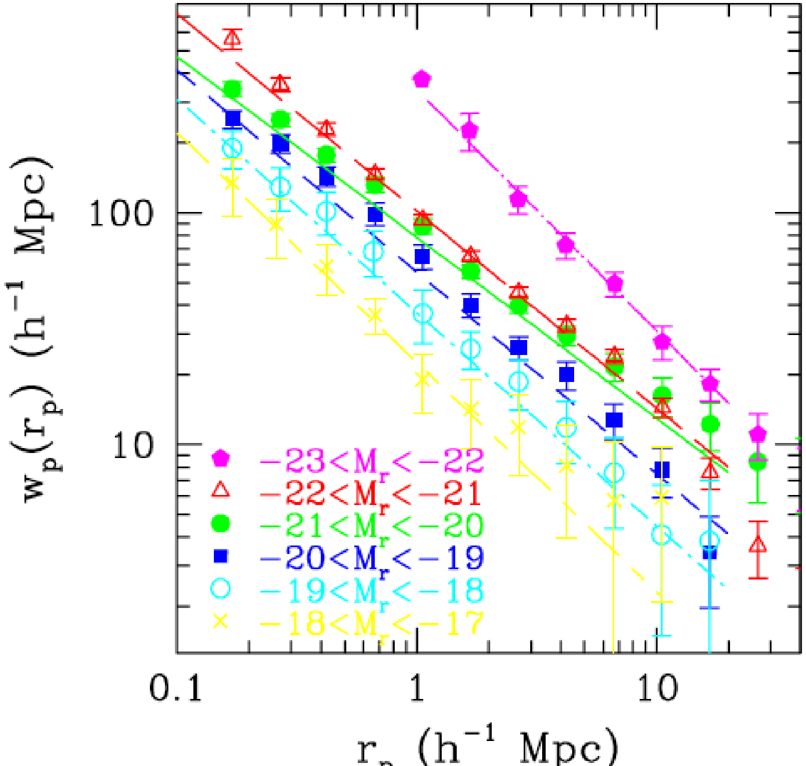
...some are also measured at higher redshift



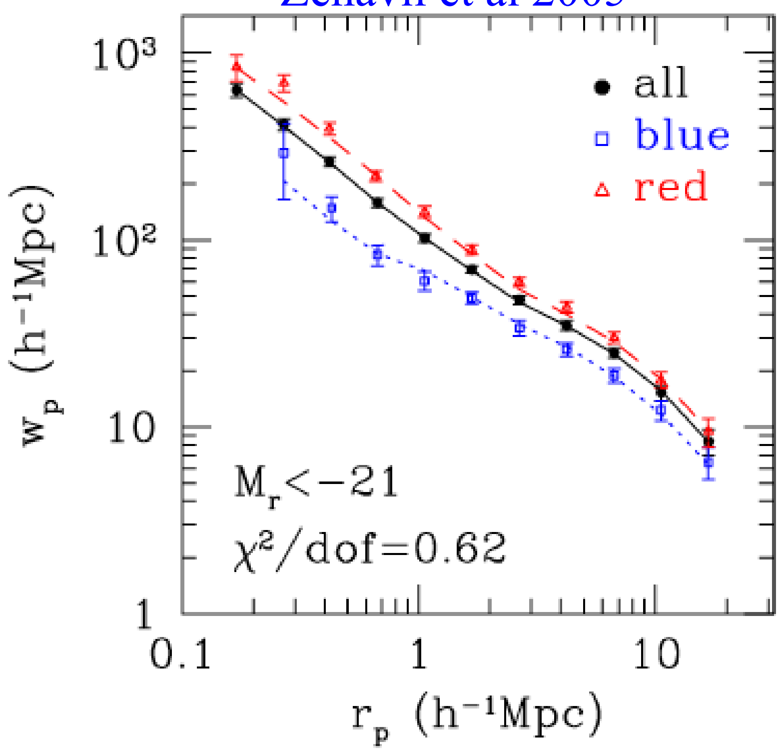
Galaxy internal structure is observed in great detail and in many components (stars, gas, B-field, cosmic rays, dark halos (via lensing)....)

Galaxy interiors are more heterogenous but also more observationally accessible than, for example, stellar interiors.





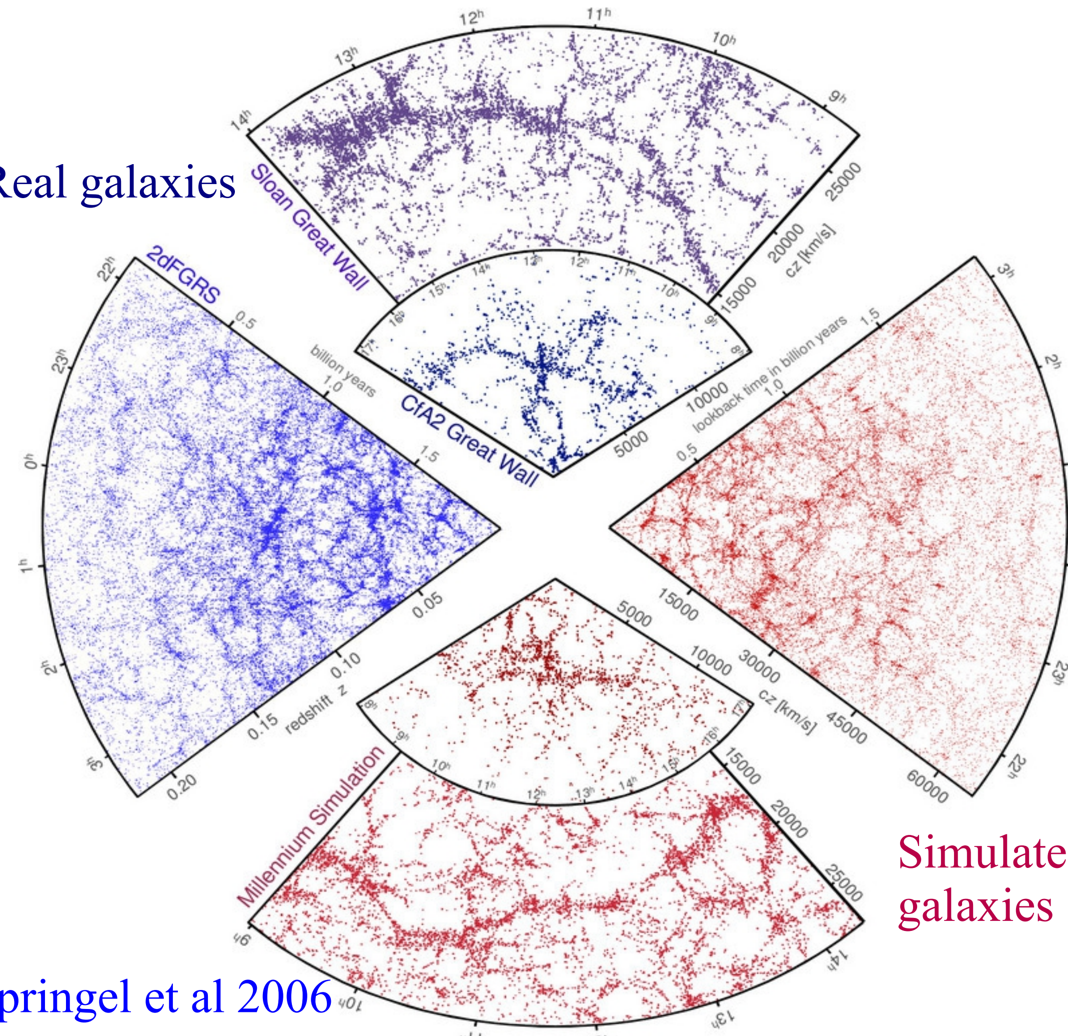
Zehavil et al 2005



The clustering of galaxies depends on their luminosity, colour, morphology, SFR, AGN status...

Galaxies are influenced by (and influence) their environment

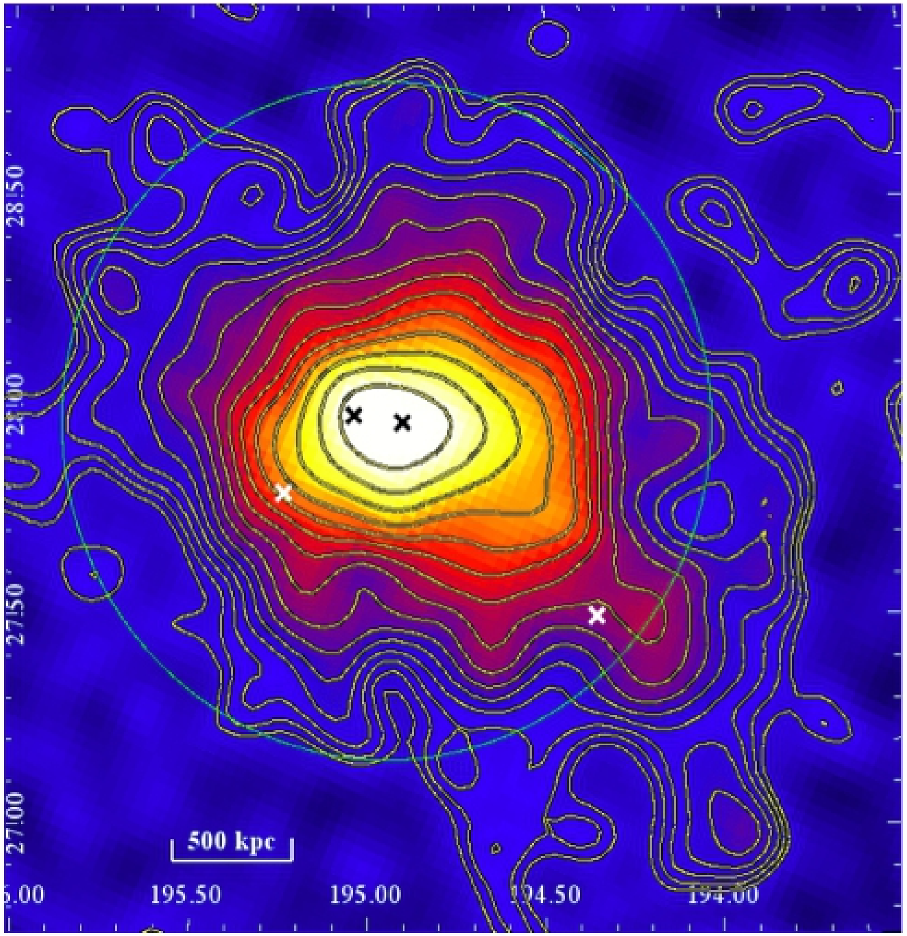
Real galaxies



Simulated galaxies

Springel et al 2006

Galaxy formation processes directly observed

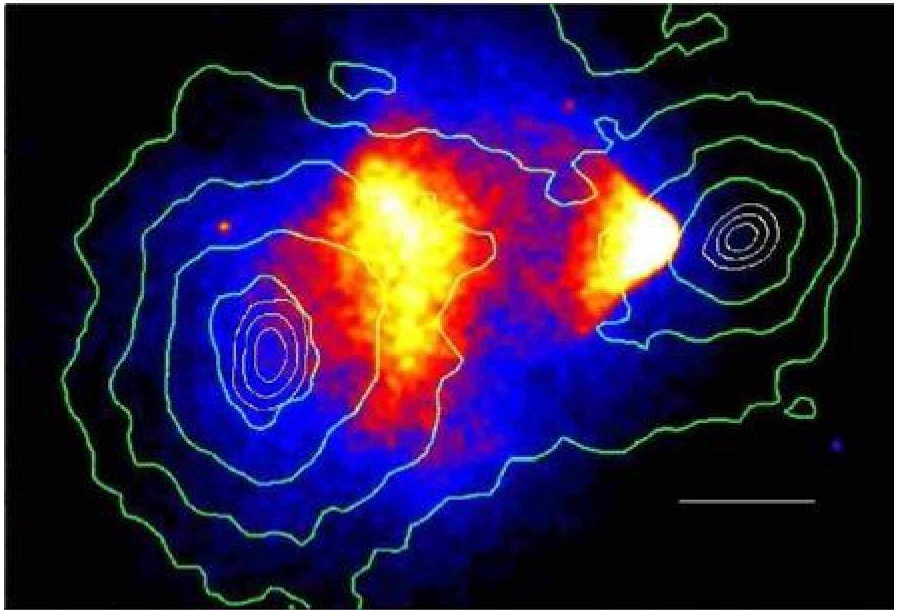


Planck Collaboration 2013

Shock Heating

In galaxy groups and clusters, the shock heated gas is directly visible through X-rays and the SZ effect

In the nearest and brightest systems the shocks are directly visible

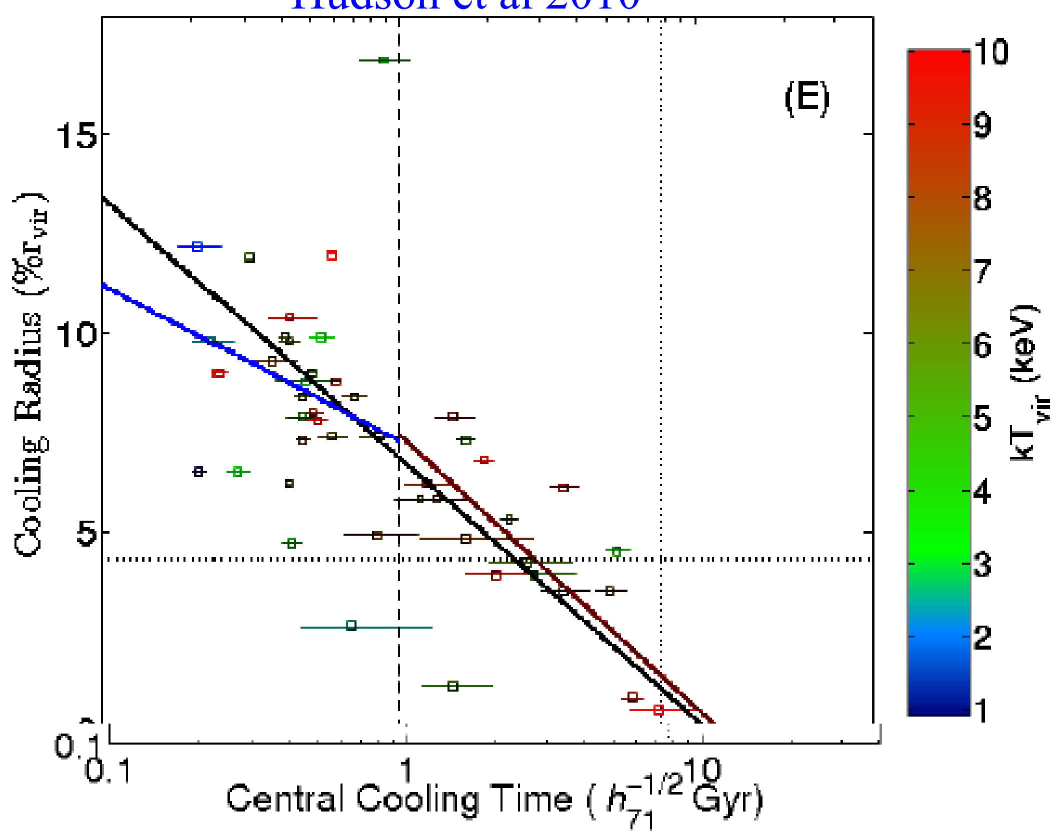


Galaxy formation processes directly observed

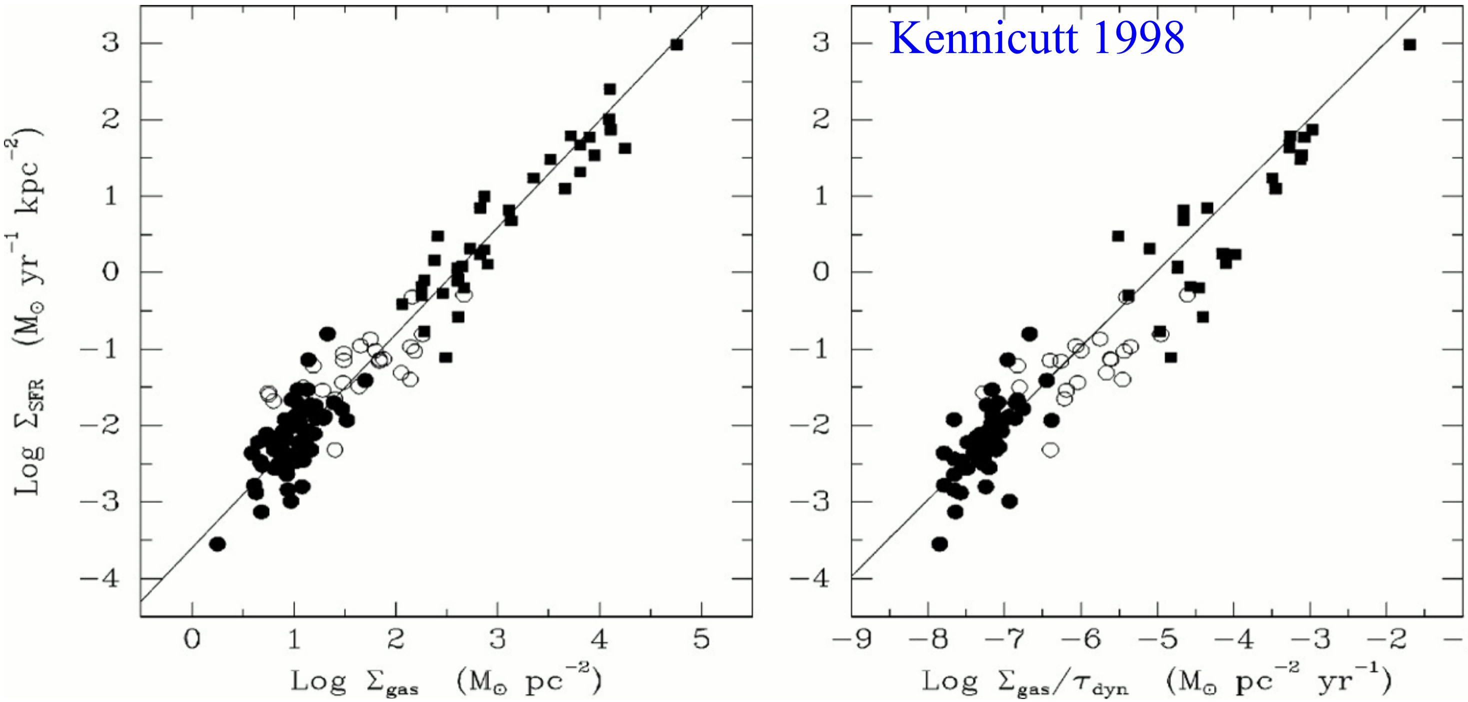
Gas cooling and condensation

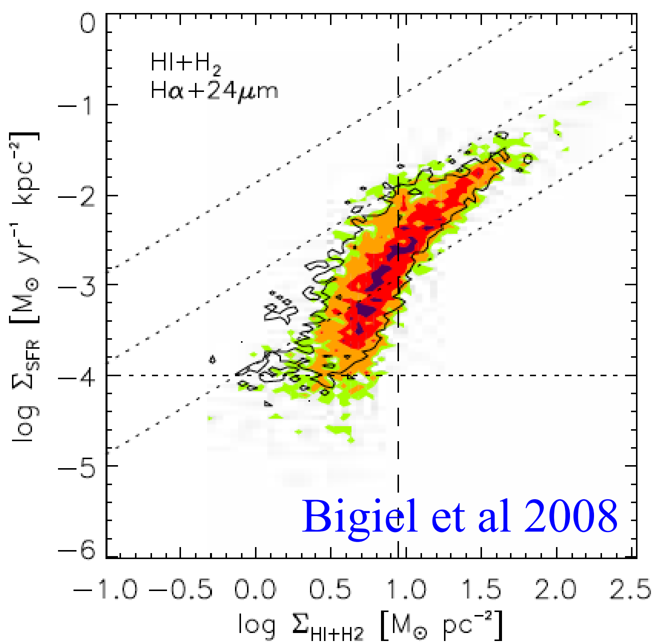
Is seen in cooling flows in clusters and groups but is not yet clearly identified on galaxy scale

Hudson et al 2010



Galaxy formation processes directly observed



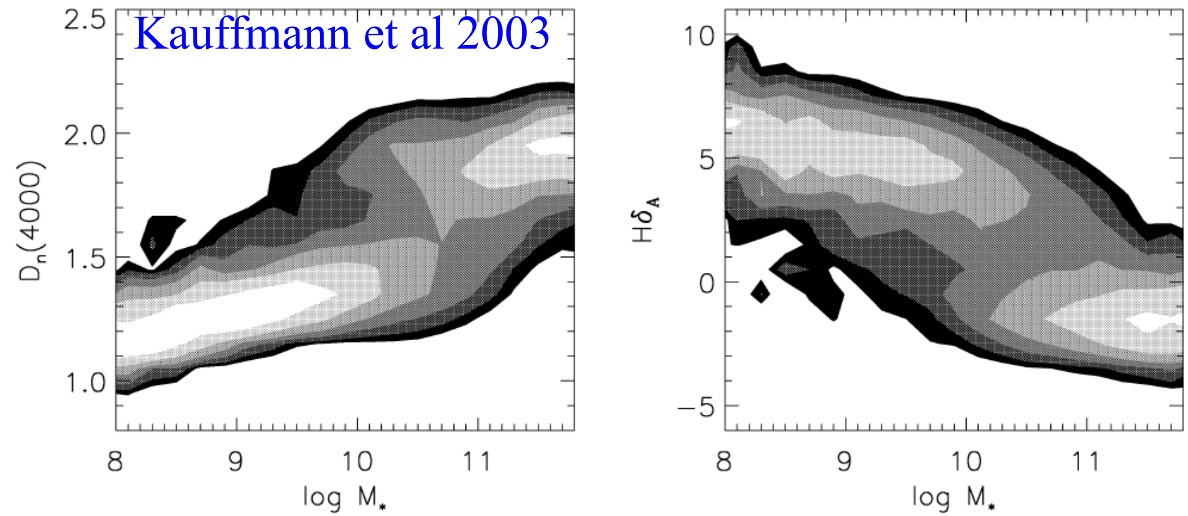


Star formation

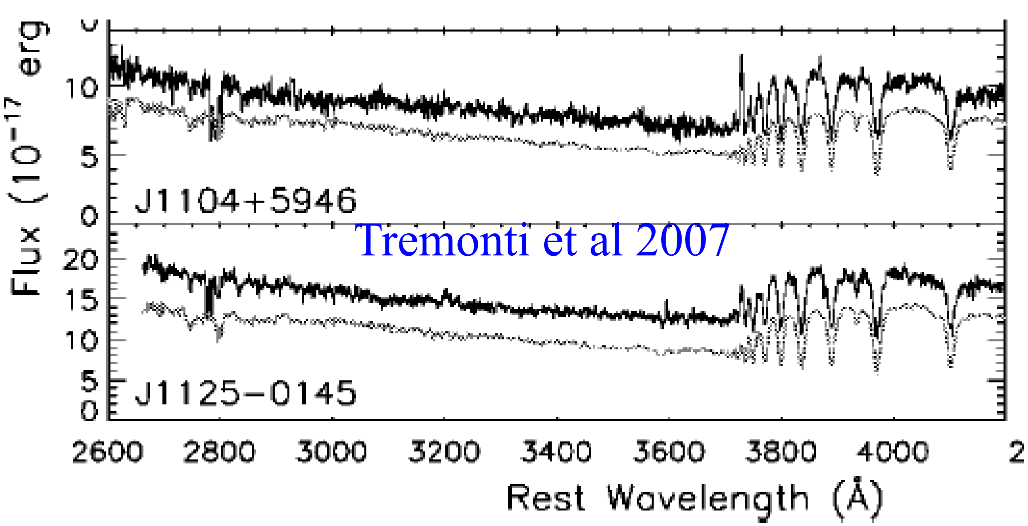
Empirical relations fit local observations averaged on kpc scales and appear to fit some high redshift data

These are understood at a heuristic rather than a fundamental level

Galaxy formation processes directly observed



Starbursts

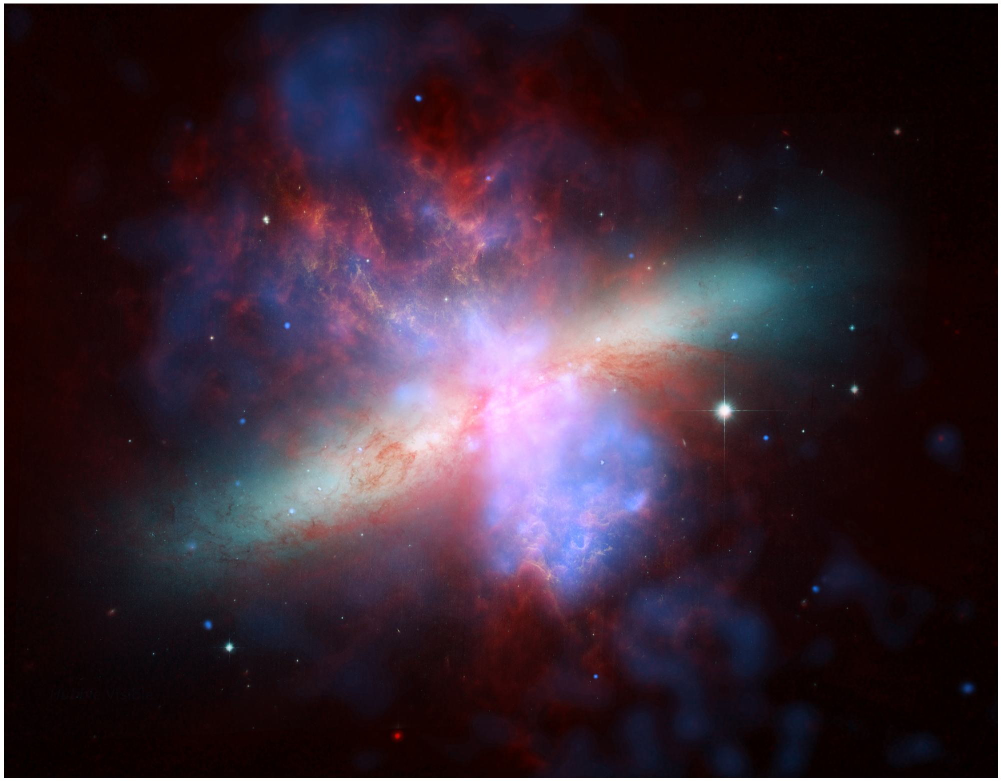


Are triggered by mergers, interactions + ?, and are visible when active through strong line and IR emission, and when complete through large fractions of intermediate age stars

Stellar evolution

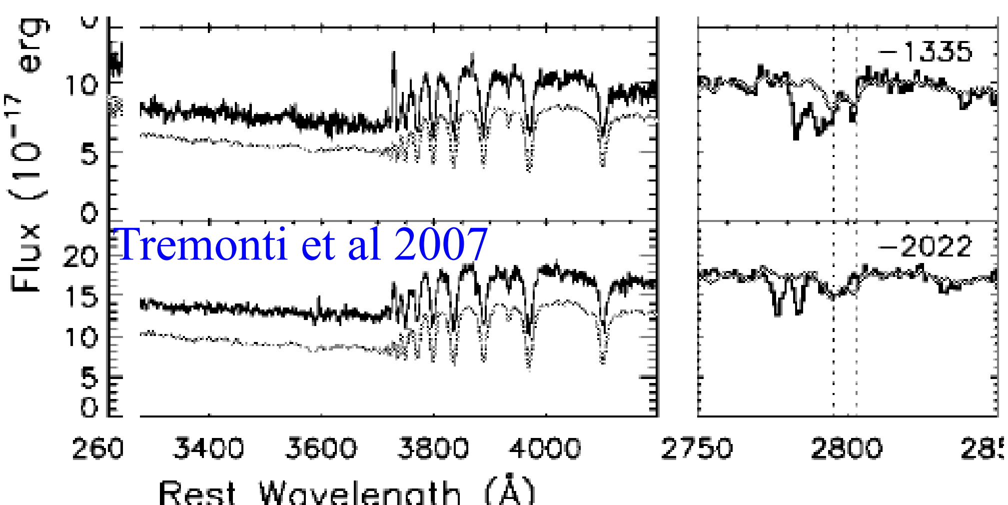
is also visible through colour and spectral evolution of populations

Galaxy formation processes directly observed

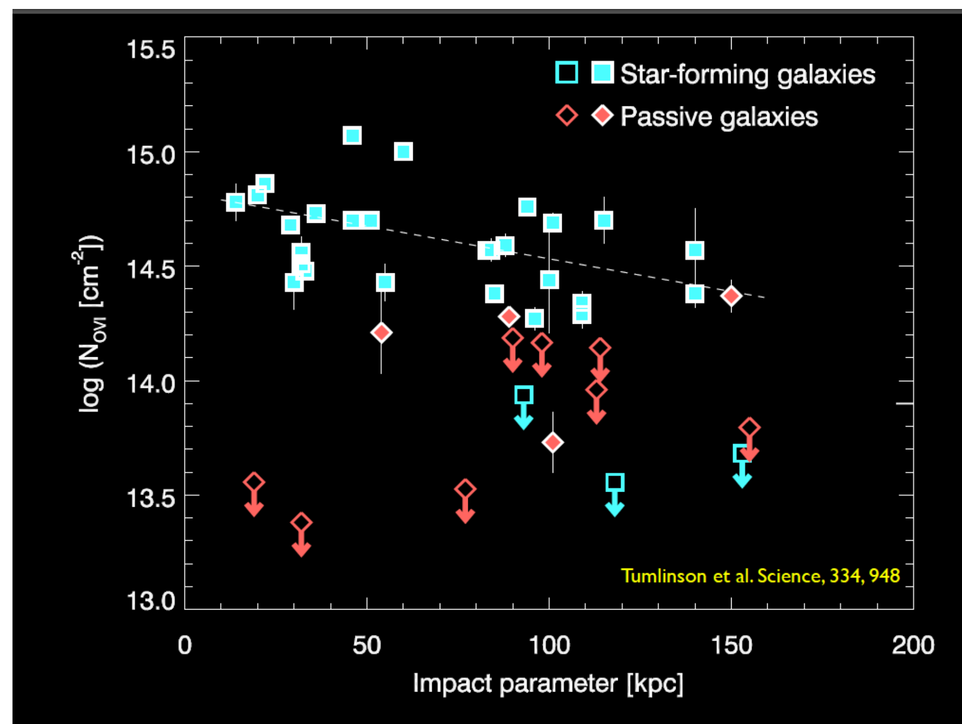


Galactic winds

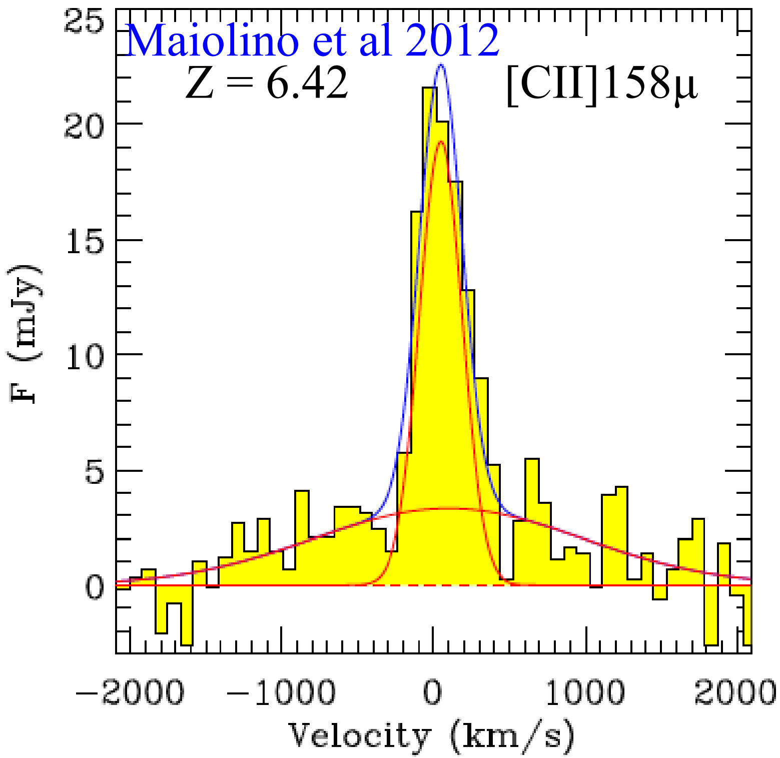
are seen in emission in nearby starburst galaxies, in absorption in distant star-forming and post-starburst galaxies, and through the heavy elements they deposit at large galactocentric radius



Tremonti et al 2007

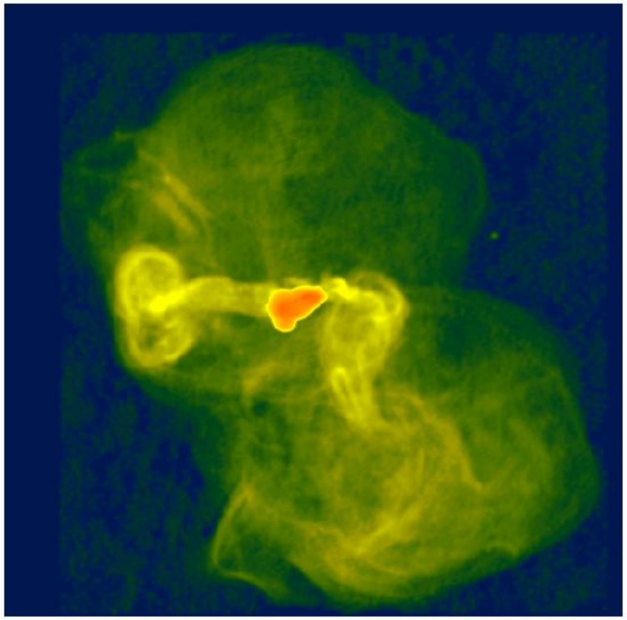


Galaxy formation processes directly observed

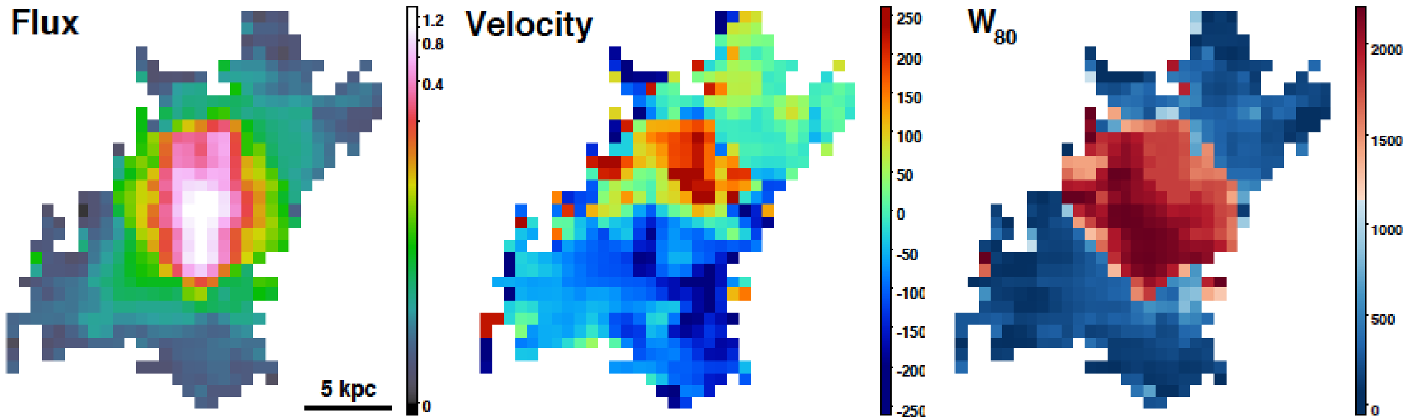


AGN Feedback

Substantial effects of feedback on the large-scale environment are seen both for quasars and for radio galaxies

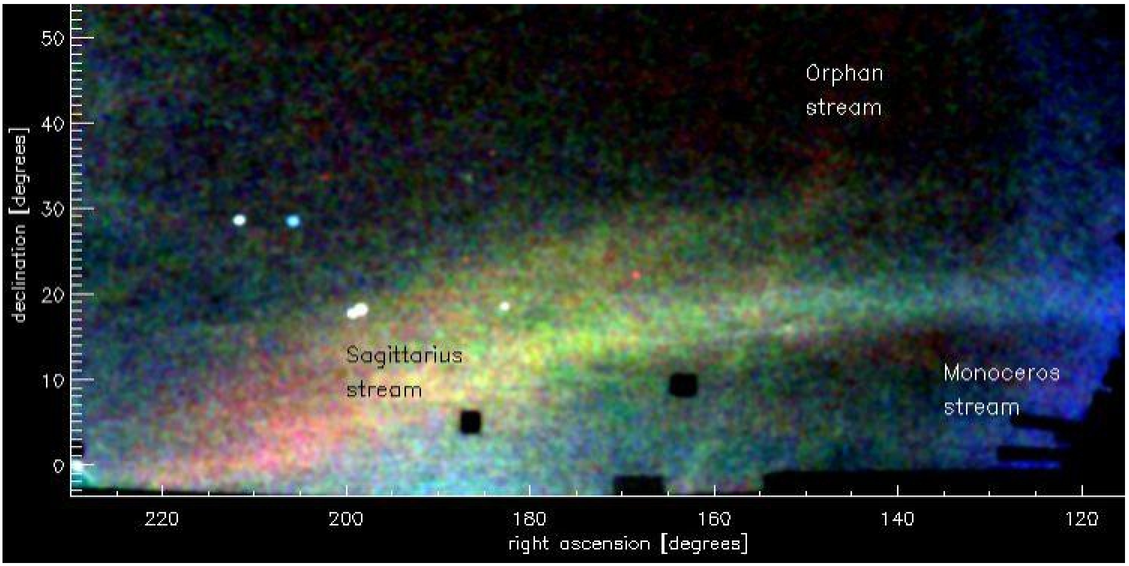


Greene et al 2011



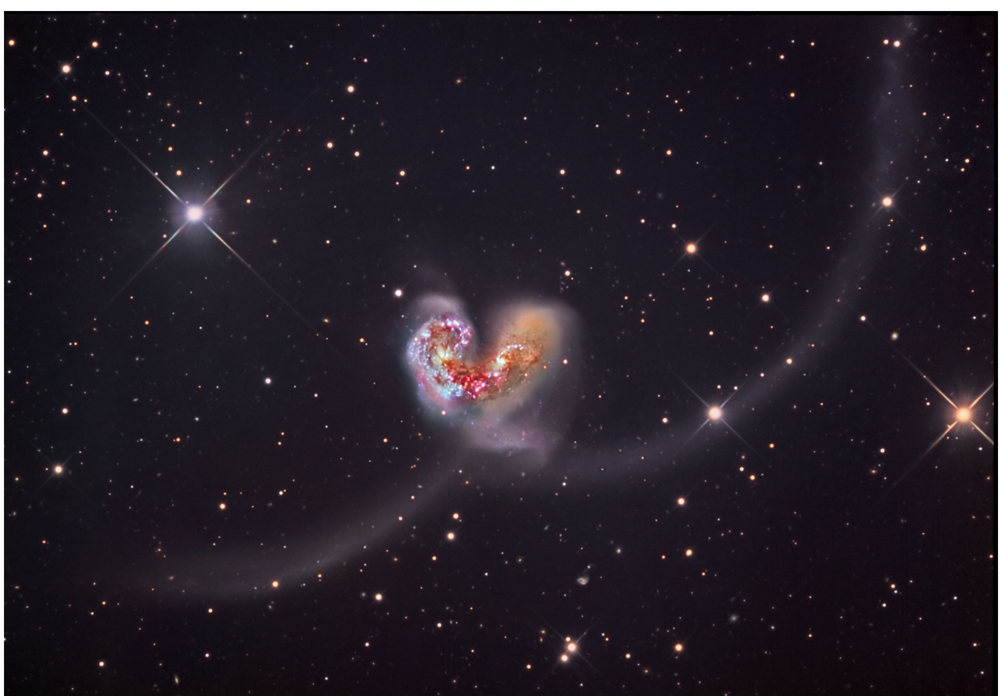
Z = 0.64 [OIII]λ5007

Galaxy formation processes directly observed

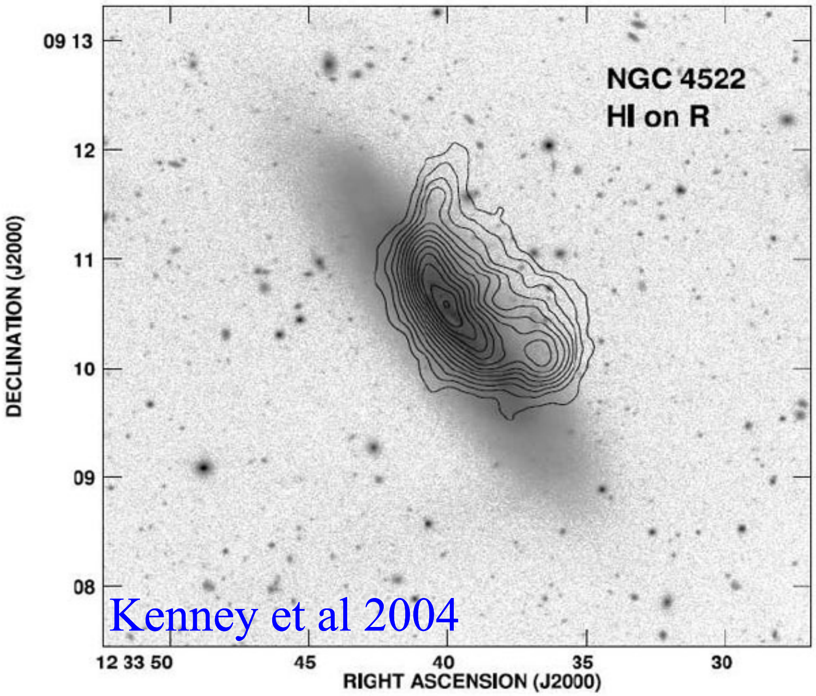


Mergers

Are observed in the field, at the centres of rich clusters and in the Milky Way's archeological record



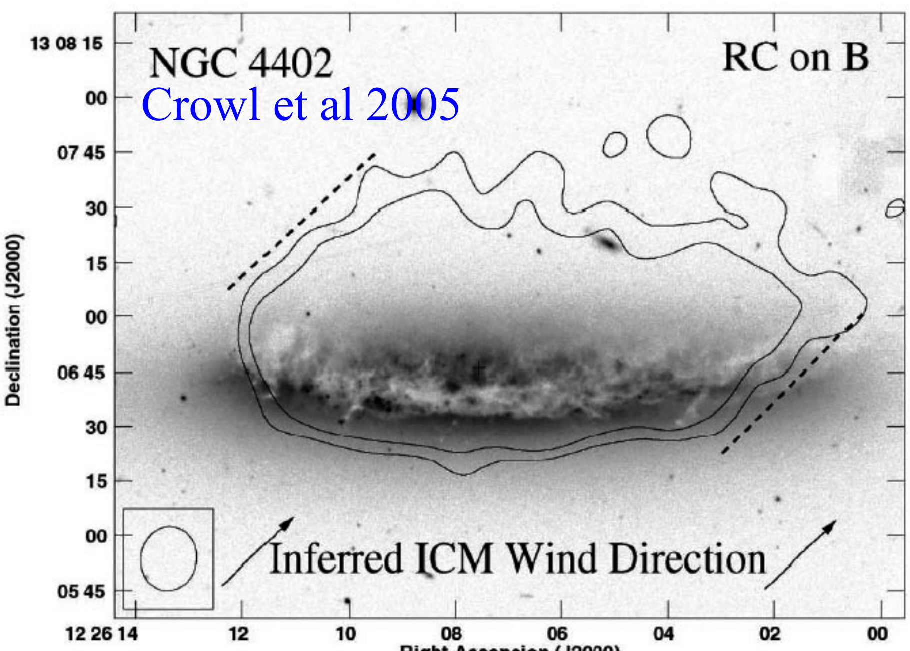
Galaxy formation processes directly observed



Kenney et al 2004

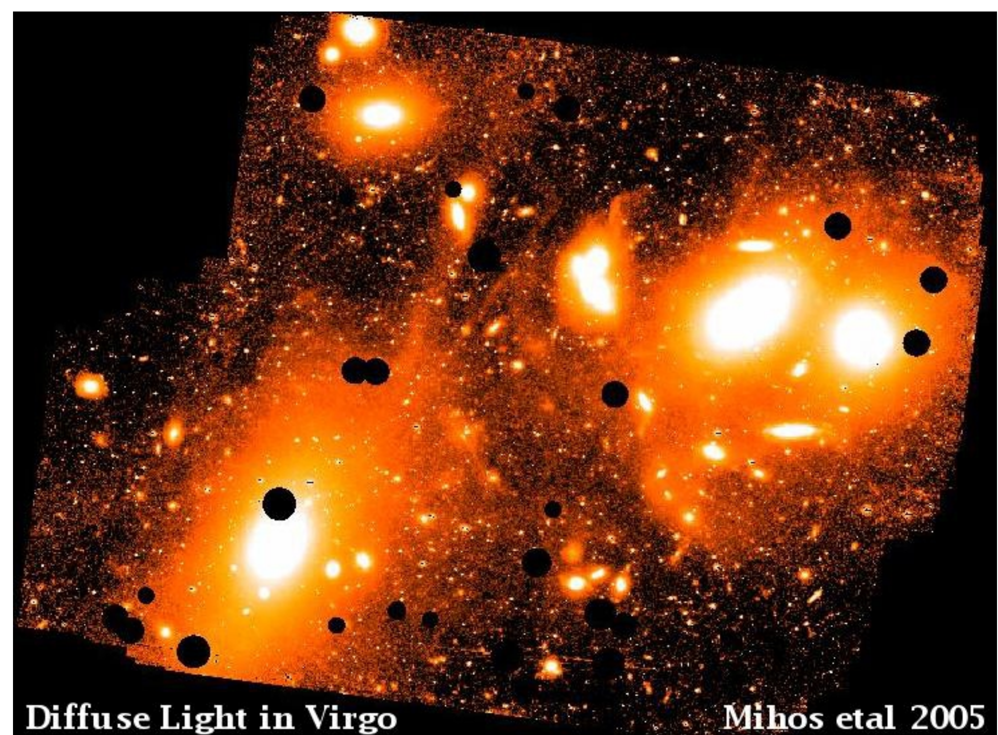
Tidal and ram-pressure stripping

are seen to be removing gas and stars from galaxies in the Virgo cluster



Crowl et al 2005

Mihos et al 2005



Galaxy Formation

- The initial/boundary conditions are precisely known
  - ---material and radiation content
  - ---structure (initially linear on all scales)
  - ---cosmological context (ΛCDM)

- The nonlinear evolution of the dominant DM component can be characterised precisely and in detail

- Population statistics available over the entire formation period
  - ---abundances
  - ---scaling relations (M, SFR, size, kinematics, Z, gas content..)
  - ---internal structure (morphology, concentration...)
  - ---clustering

- Almost all the processes driving formation/evolution have now been observed directly in individual systems

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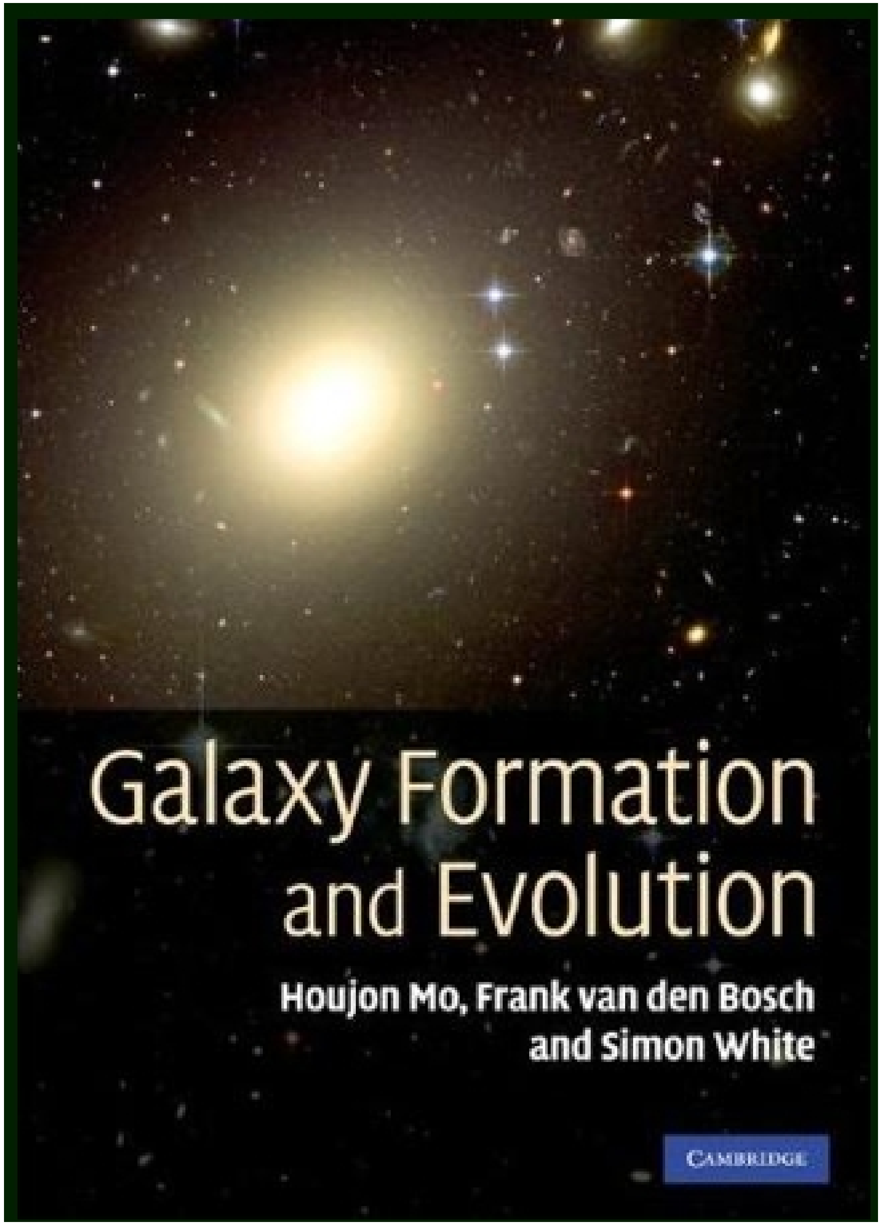
Galaxy formation is <u>inherently</u> complex, but very highly constrained

Textbook published in 2010



Contents

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840 pages
160 figures

$85 from Amazon or Barnes & Noble

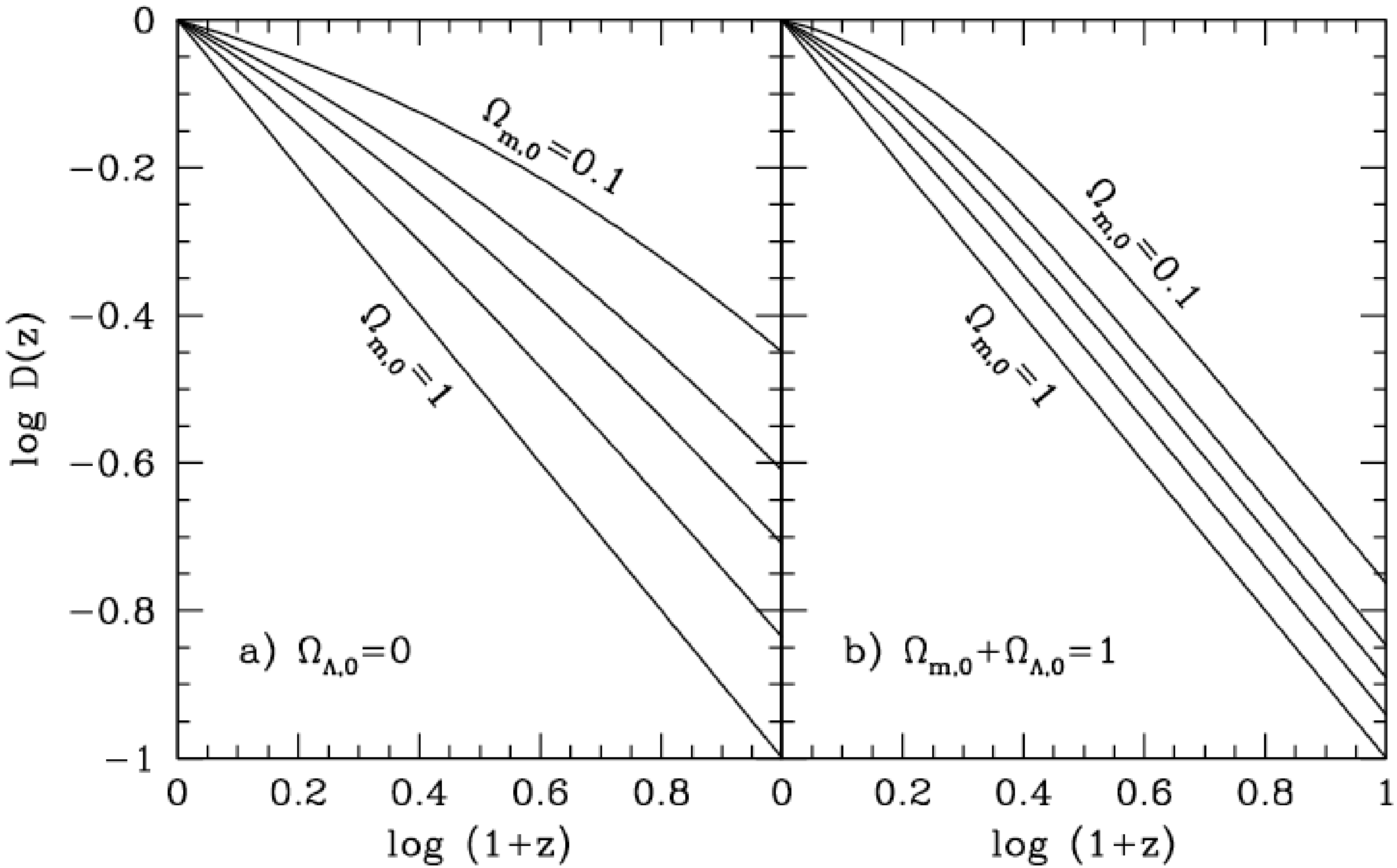
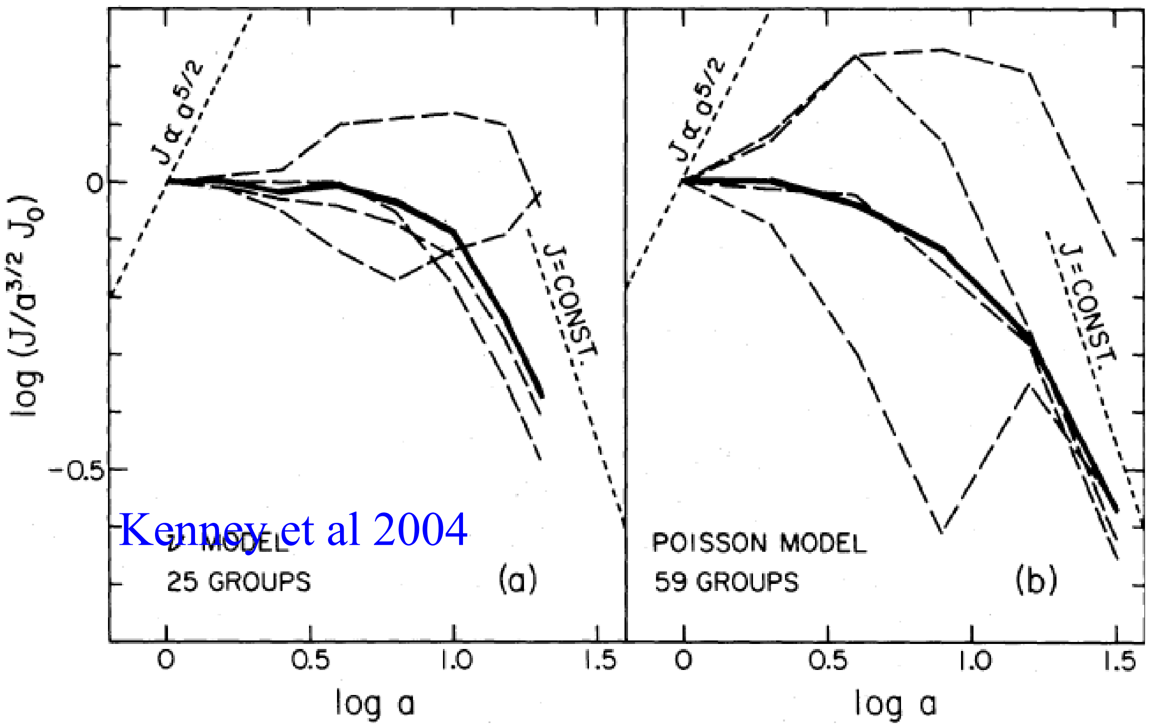


Fig. 4.1. The linear growth rates in cosmological models with $\Omega_{m,0} = 0.1$, 0.2, 0.3 0.5 and 1. The left panel assumes $\Omega_{\Lambda,0} = 0$ while the right panel assumes $\Omega_{m,0} + \Omega_{\Lambda,0} = 1$. The rates are all normalized so that $D(z=0) = 1$.

White 1984



White 1996

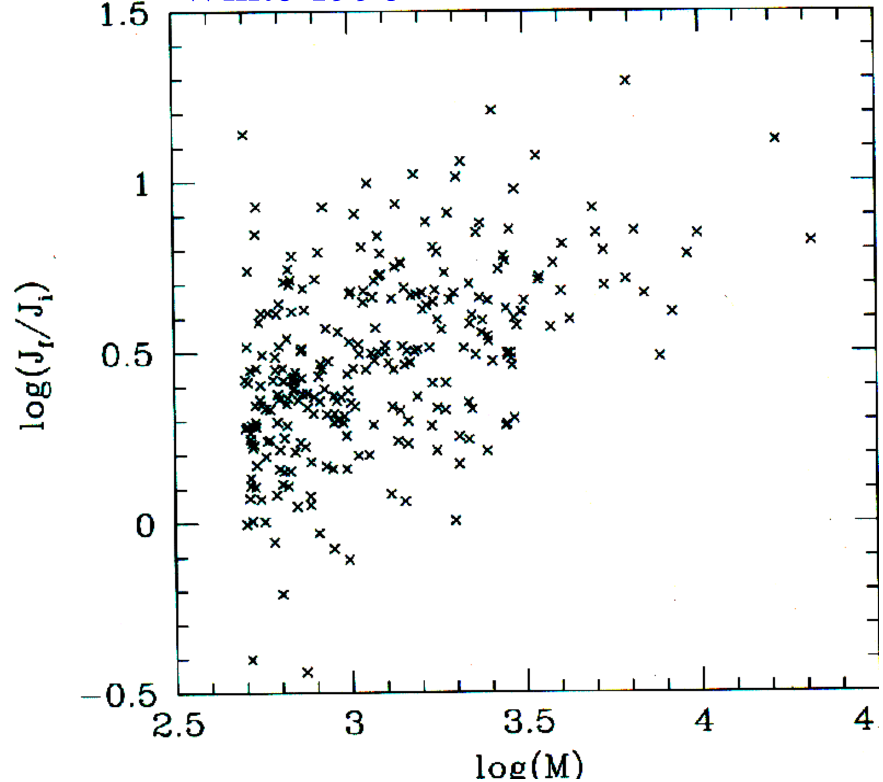


FIG. 1.—Angular momentum normalized to the value predicted by linear theory is shown as a function of expansion factor for the particles which end up in groups of more than 100 members in two N-body experiments. Fig. 1a is a simulation of a neutrino-dominated universe, while in Fig. 1b the particles were initially distributed uniformly at random. Solid lines show the mean for all rich groups in each model while dashed lines show the behavior of "typical" individual groups. The dotted lines show the relationships $J \propto a^{5/2}$ which would be obeyed if angular momentum grew at second order in perturbation theory, and J = const which is expected at late times.

Bond & Szalay 1983

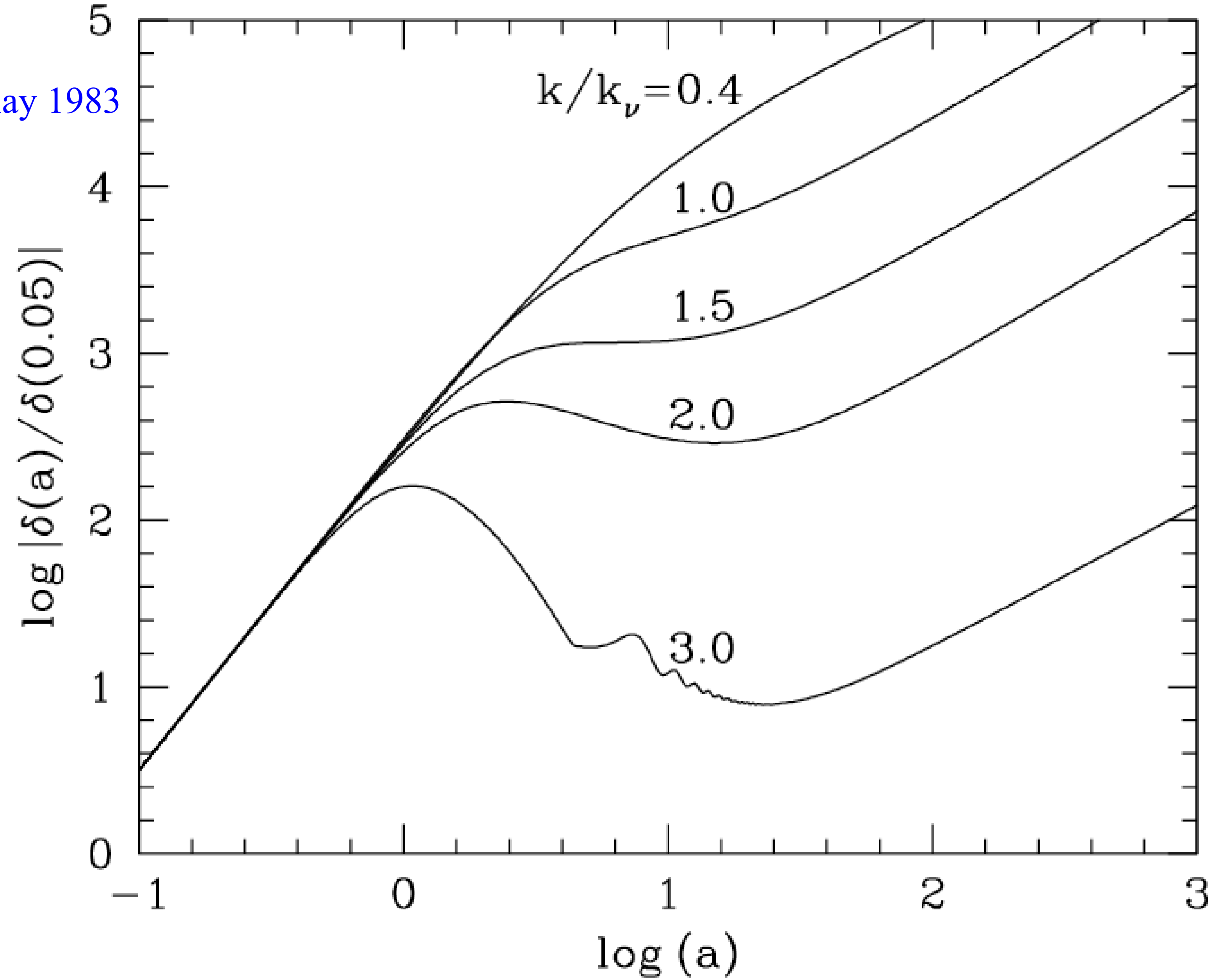
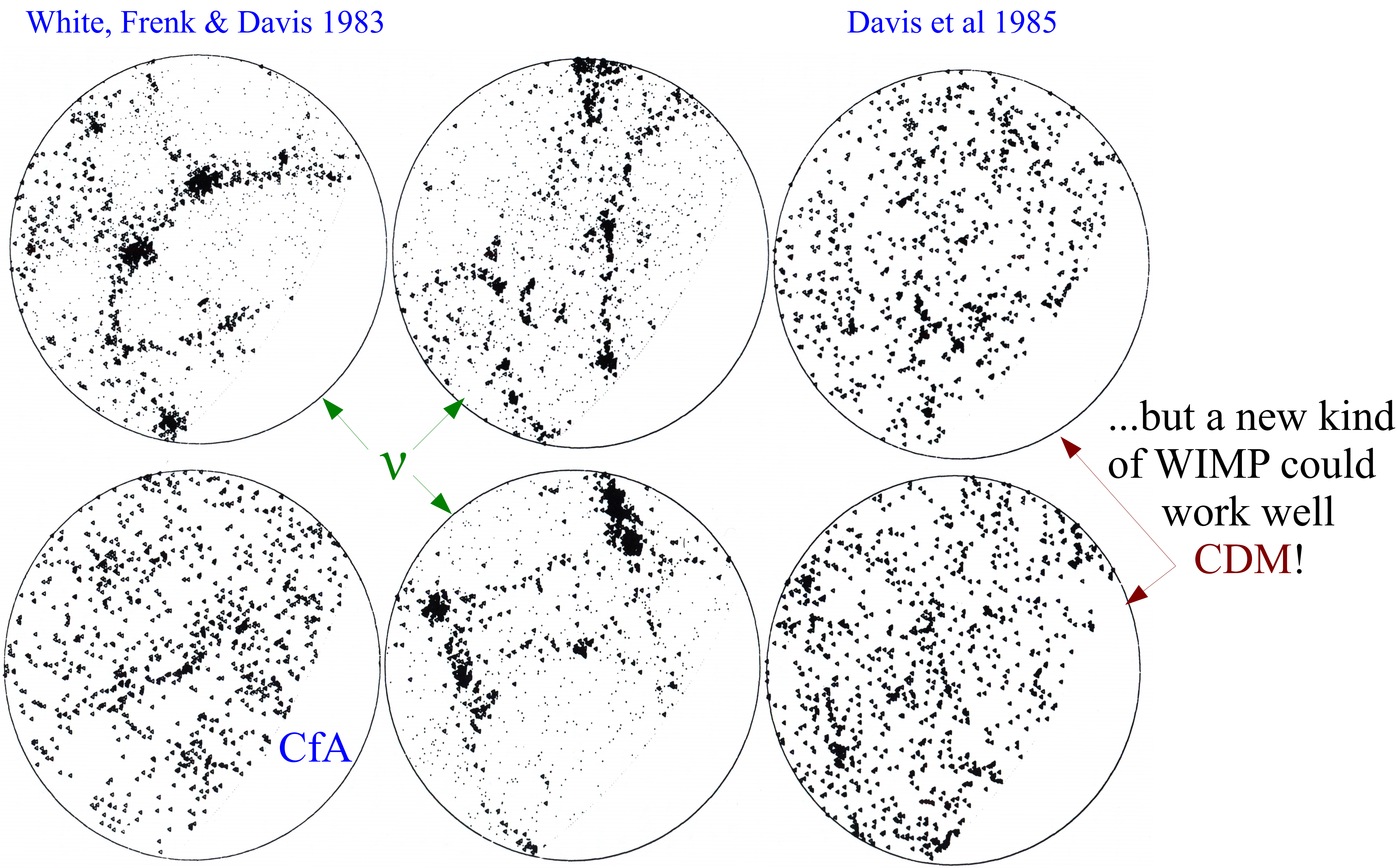
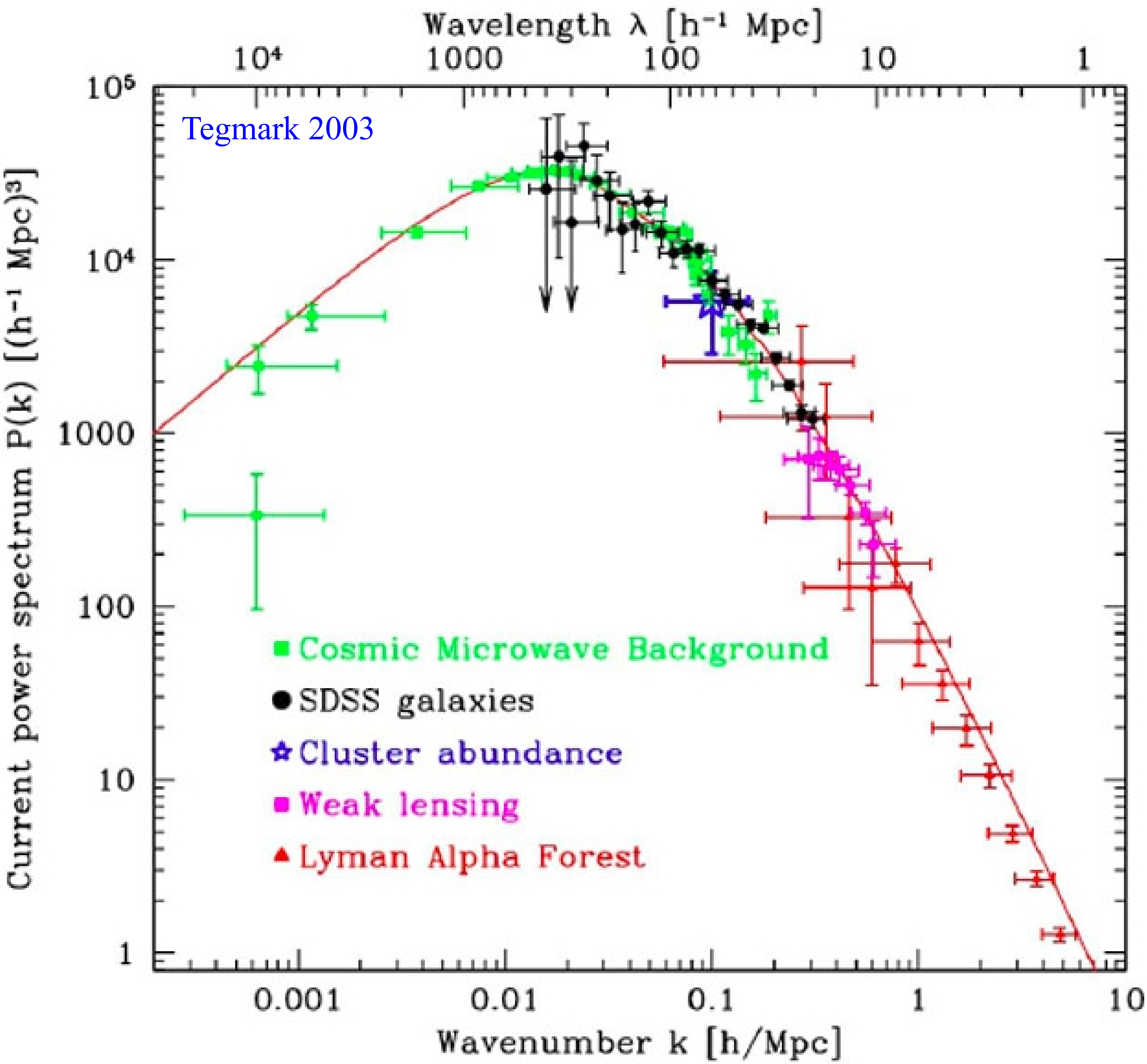


Fig. 4.3. The evolution for adiabatic neutrino perturbations with various k/k_ν. The scale factor is normalized to be unity at a redshift $z = z_{\rm nr} = 57300(m_\nu/30\,{\rm eV})$. [Adapted from Bond & Szalay (1983) by permission of AAS]

The exclusion of neutrinos as a DM candidate





Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
Tegmark 2003
Current power spectrum P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
1000
100
10
1
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Dark matter halos are the basic units of nonlinear structure

Is all dark matter part of some halo?

Was this always the case?

How do halos grow? accretion? merging?

How are they distributed?

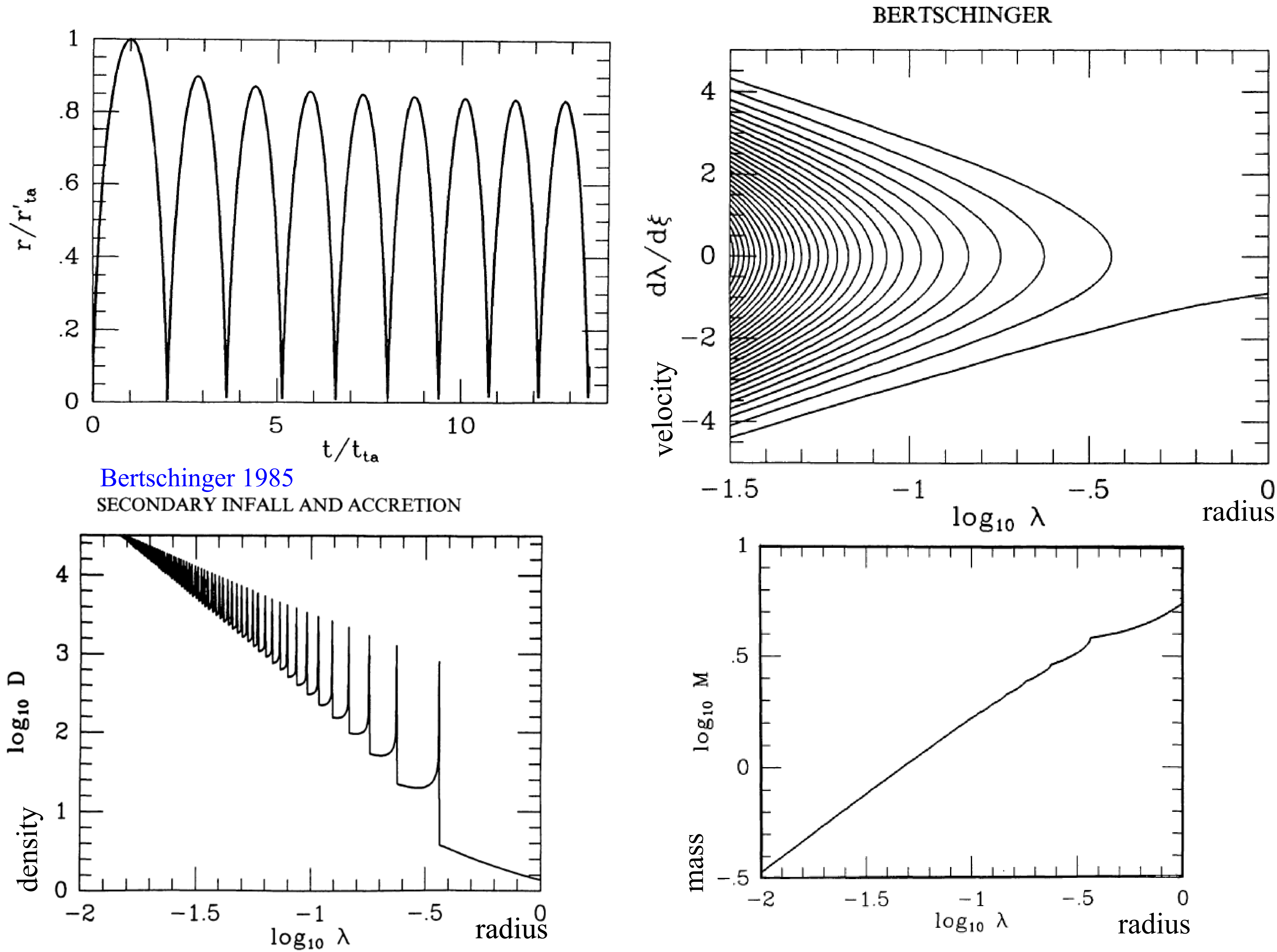
What is their internal structure?

- -- density profile
- -- shape
- -- subhalo population – mass/radial distributions, evolution
- -- caustics

How do these properties affect DM detection experiments?

How can they be used to test the standard paradigm?

How do they affect/are they affected by the baryonic matter


BERTSCHINGER
Bertschinger 1985
SECONDARY INFALL AND ACCRETION
r/r'_{ta}
t/t_{ta}
velocity
$d\lambda/d\xi$
$\log_{10}\lambda$
radius
density
$\log_{10} D$
mass
$\log_{10} M$

Bertschinger 1985

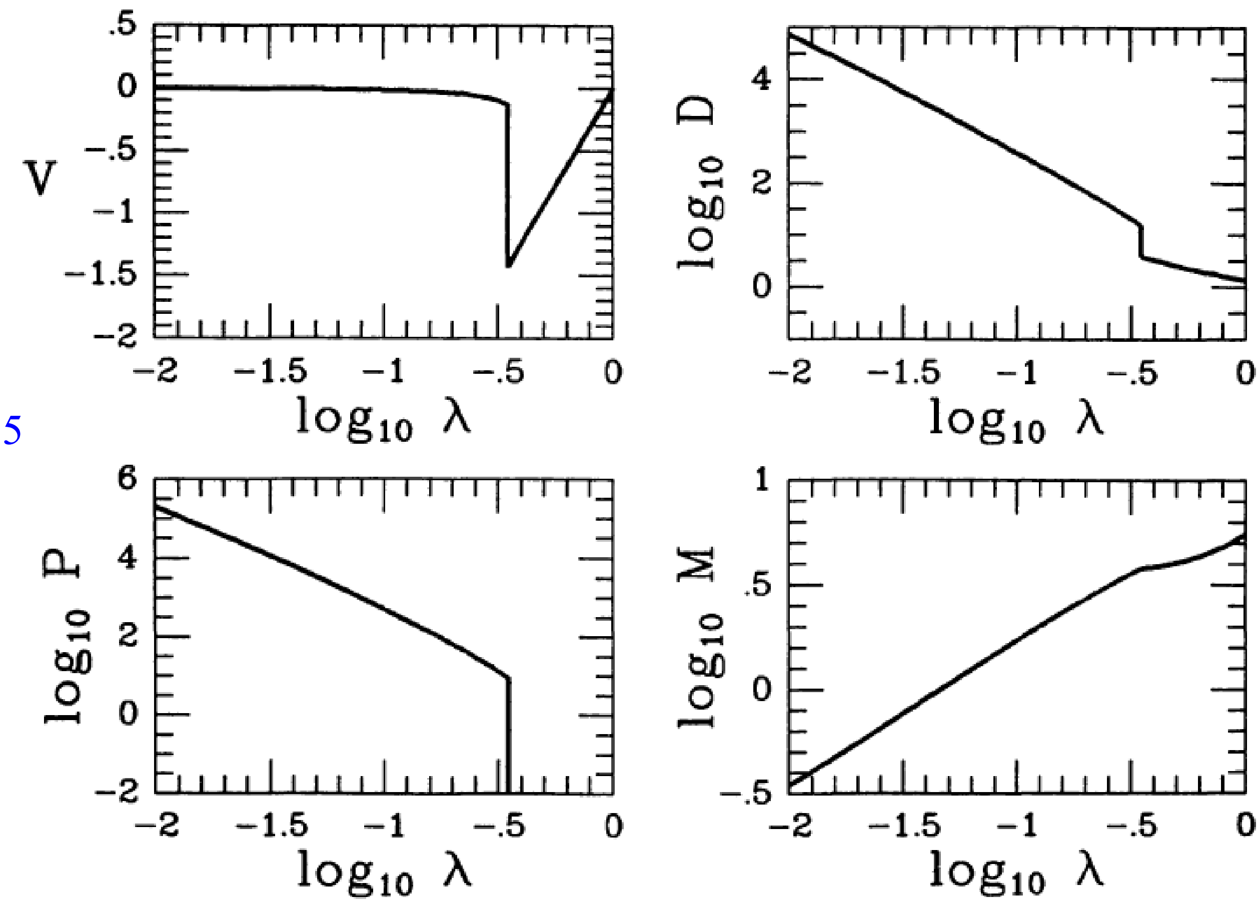


FIG. 11.—Self-similar accretion of a $\gamma = 5/3$, $\Omega_b \ll 1$ collisional gas moving in the potential of the $\Omega = 1$ collisionless solution. The velocity V, density D, pressure P, and mass M are plotted vs. radius λ, with units given by eqs. (2.9) and (3.2), with ρ_H reduced by a factor of Ω_b.

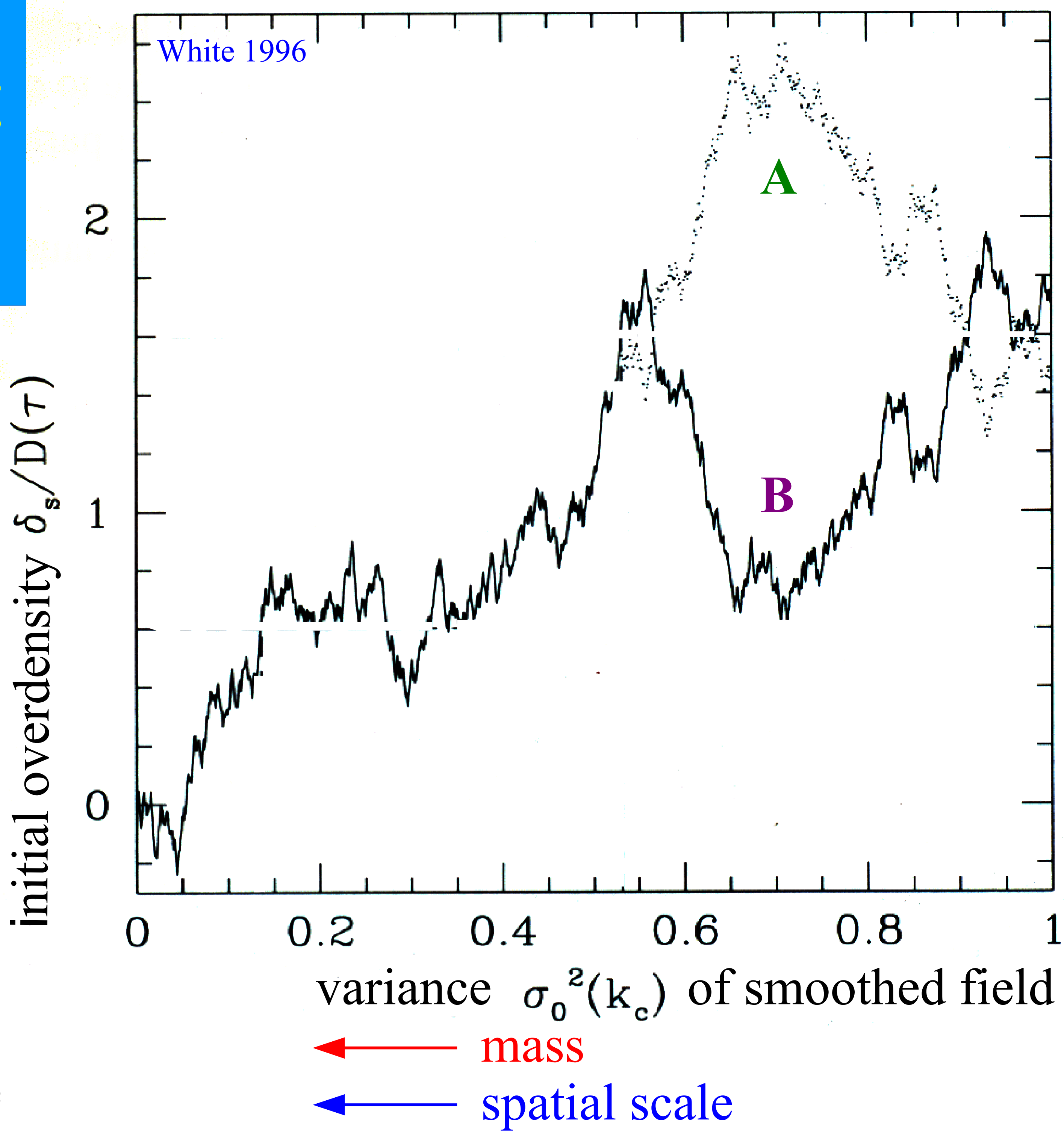
Gas hits an infall shock very close to the outermost caustic, and is static inside it with a density profile siilar to that of the DM

Overdensity vs smoothing at a given position

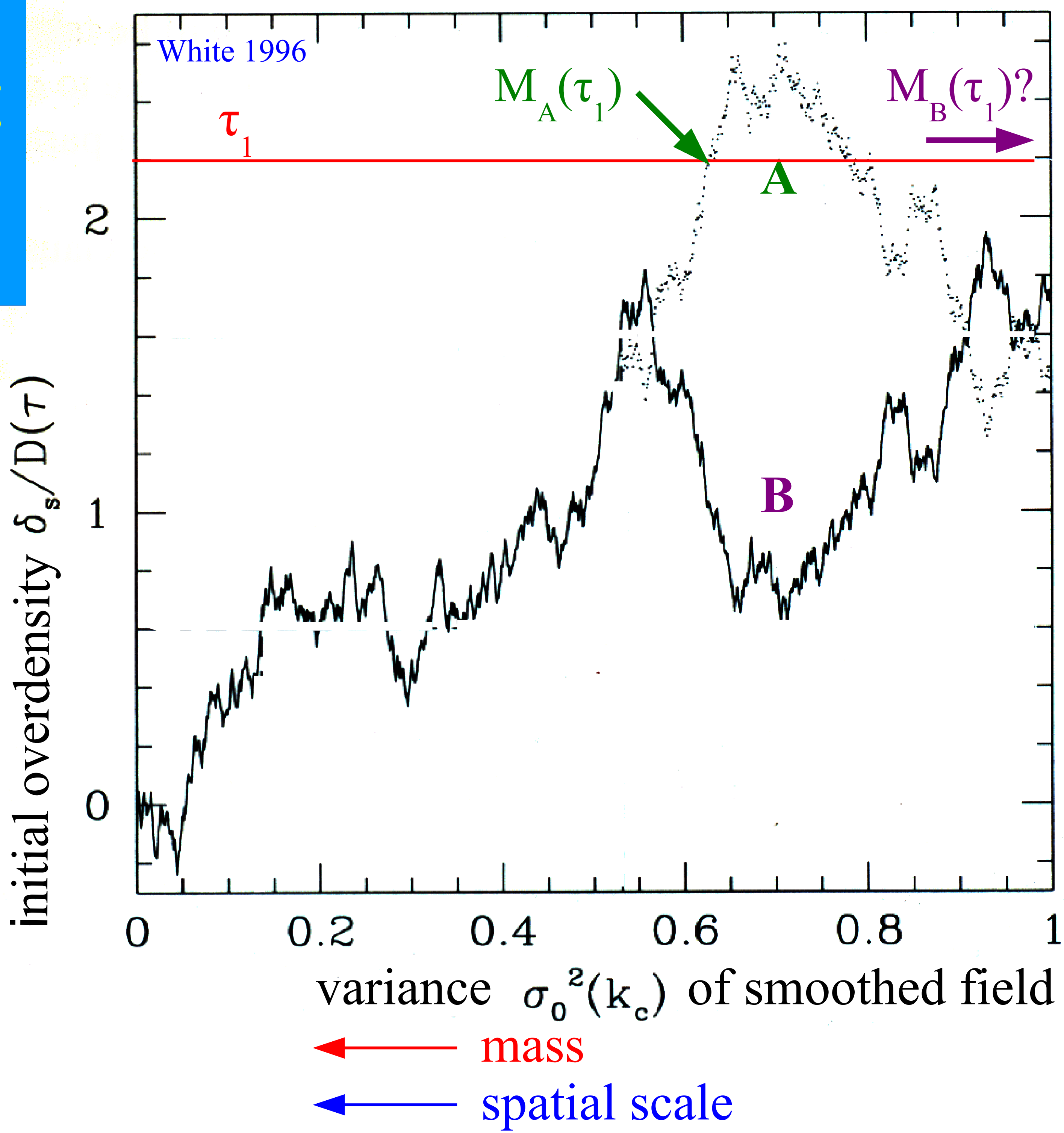
If the density field is smoothed using a sharp filter in k-space, then each step in the random walk is independent of all earlier steps

A Markov process

The walks shown at positions A and B are equally probable



Overdensity vs smoothing at a given position

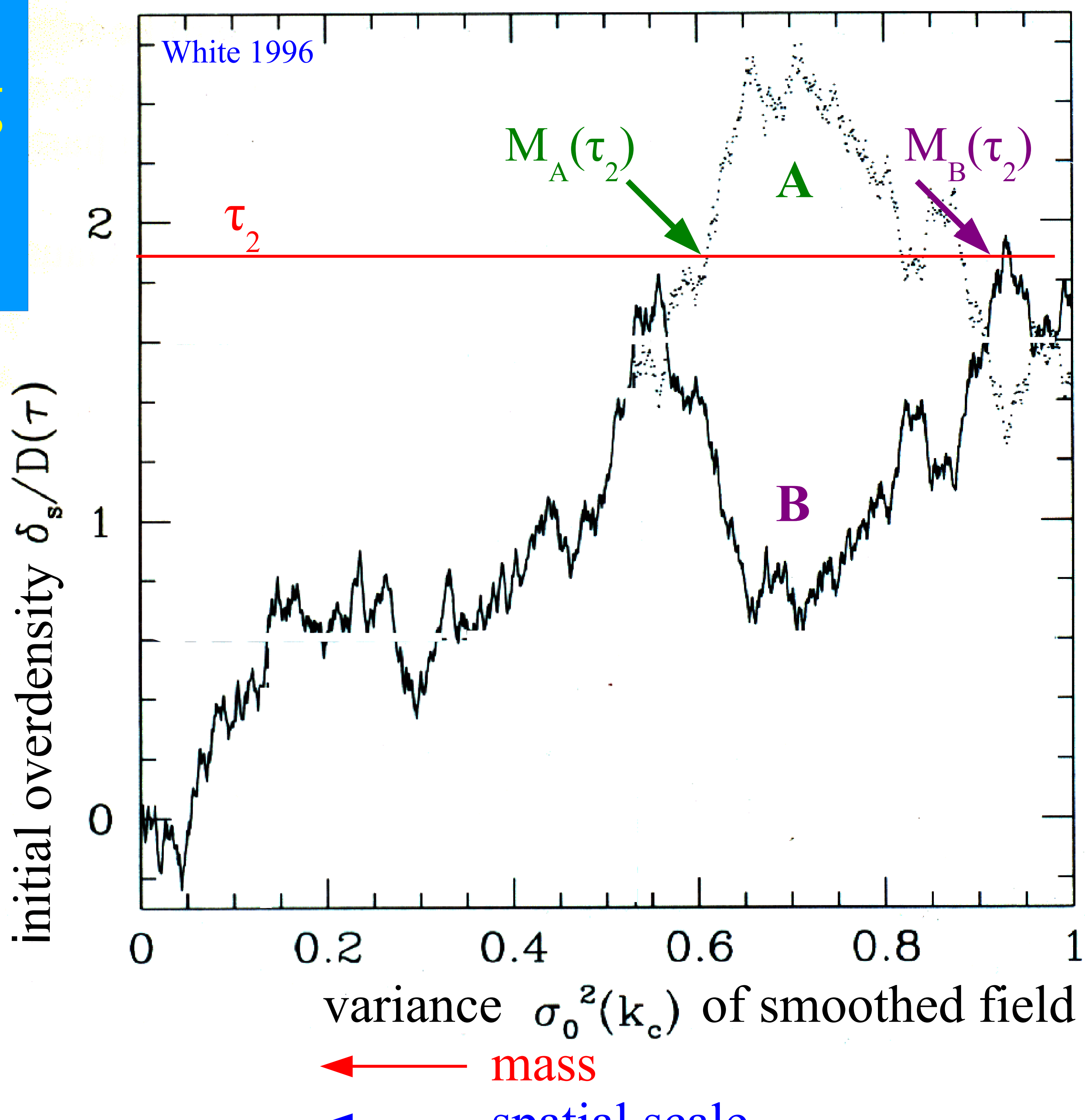


At an early time τ_1

A is part of a quite massive halo

B is part of a very low mass halo or no halo at all

Overdensity vs smoothing at a given position



Later, at time τ_2

A's halo has grown slightly by accretion

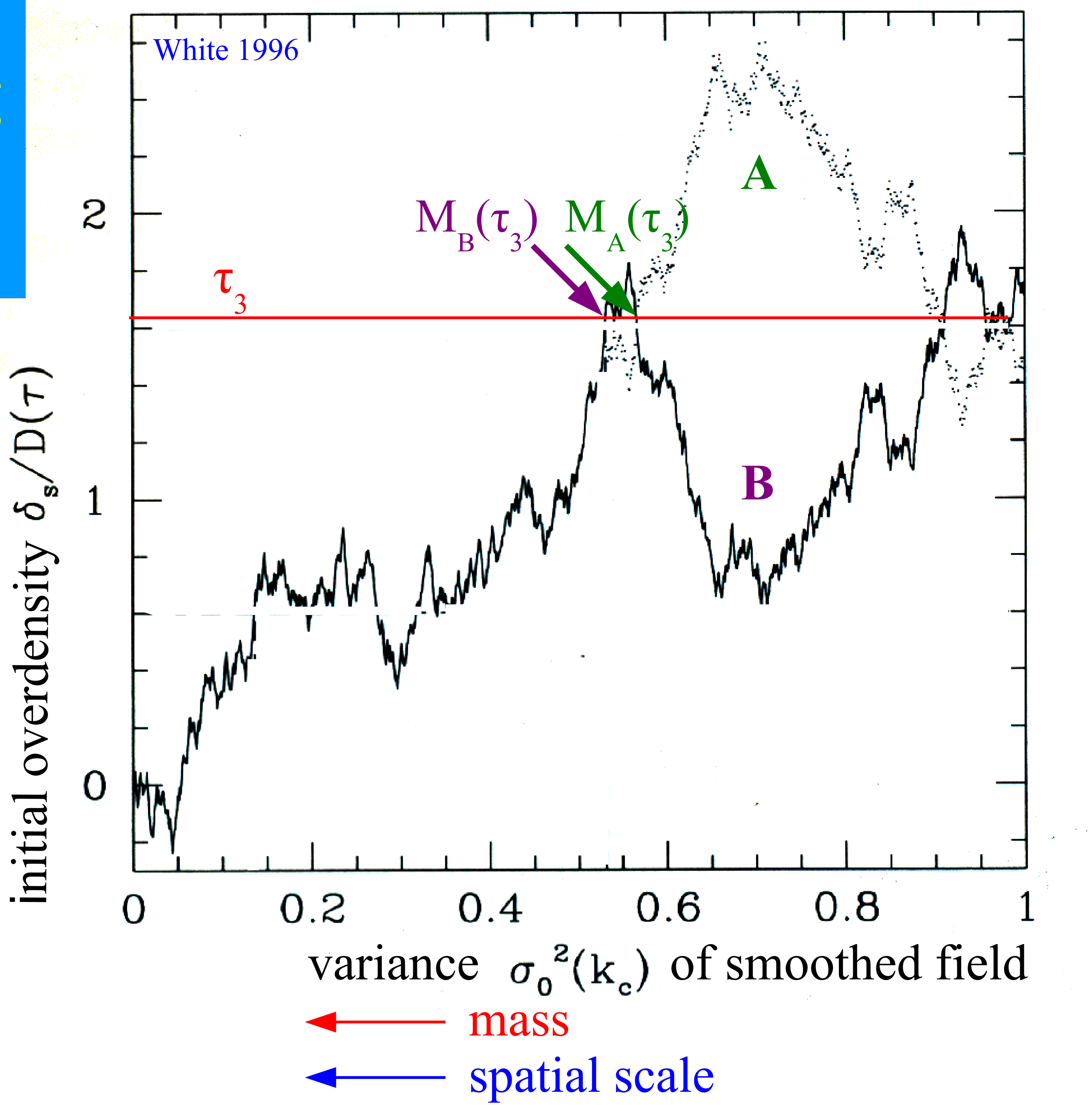
B is now part of a moderately massive halo

Overdensity vs smoothing at a given position

A bit later, time τ_3

A's halo has grown further by accretion

B's halo has merged again and is now more massive than **A**'s halo

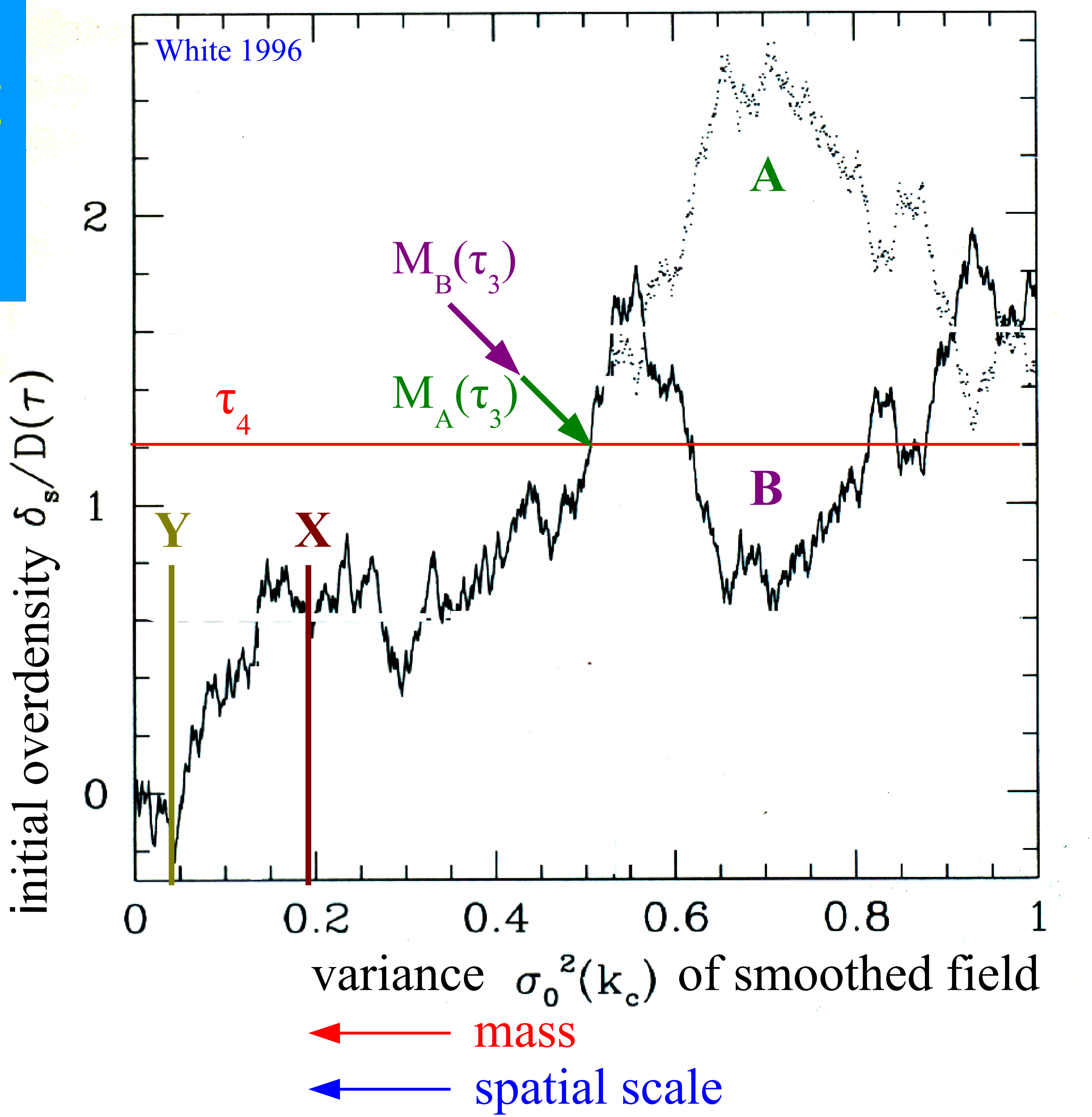


Overdensity vs smoothing at a given position

Still later, e.g. τ_4

A and **B** are part of halos which follow identical merging/ accretion histories

On scale **X** they are embedded in a high density region.
On larger scale **Y** in a low density region



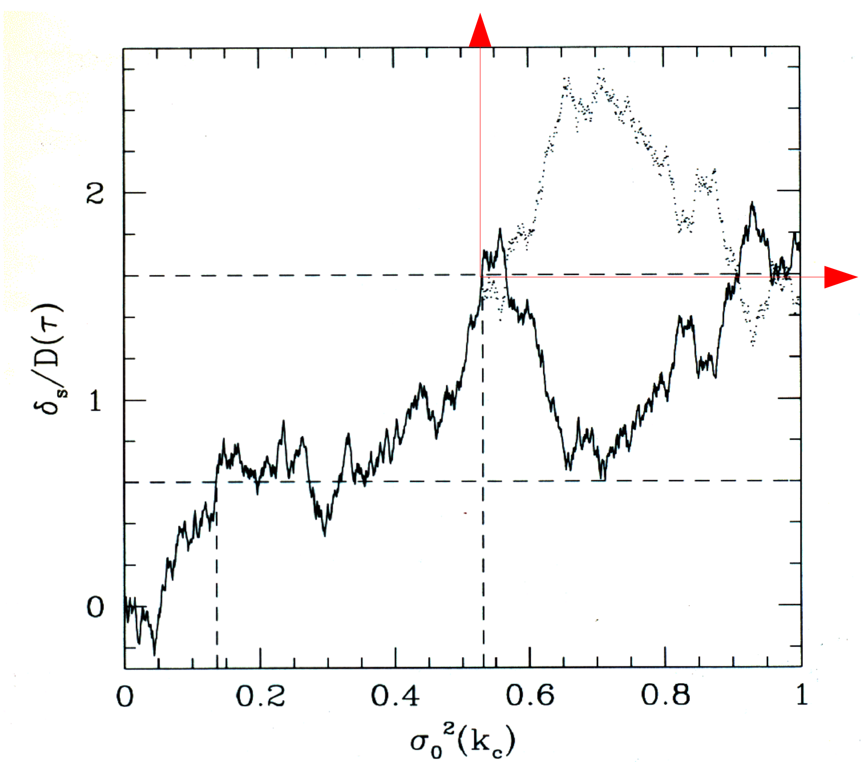
Consequences of the Markov nature of EPS walks

The assembly history of a halo is <u>independent</u> of its future

The assembly history of a halo is <u>independent</u> of its environment

The internal structure of a halo is <u>independent</u> of its environment

The mass distribution of progenitors of a halo of given M and z is obtained simply by changing the origin to $\sigma_o^2(M)$ and $\delta_c/D(z)$

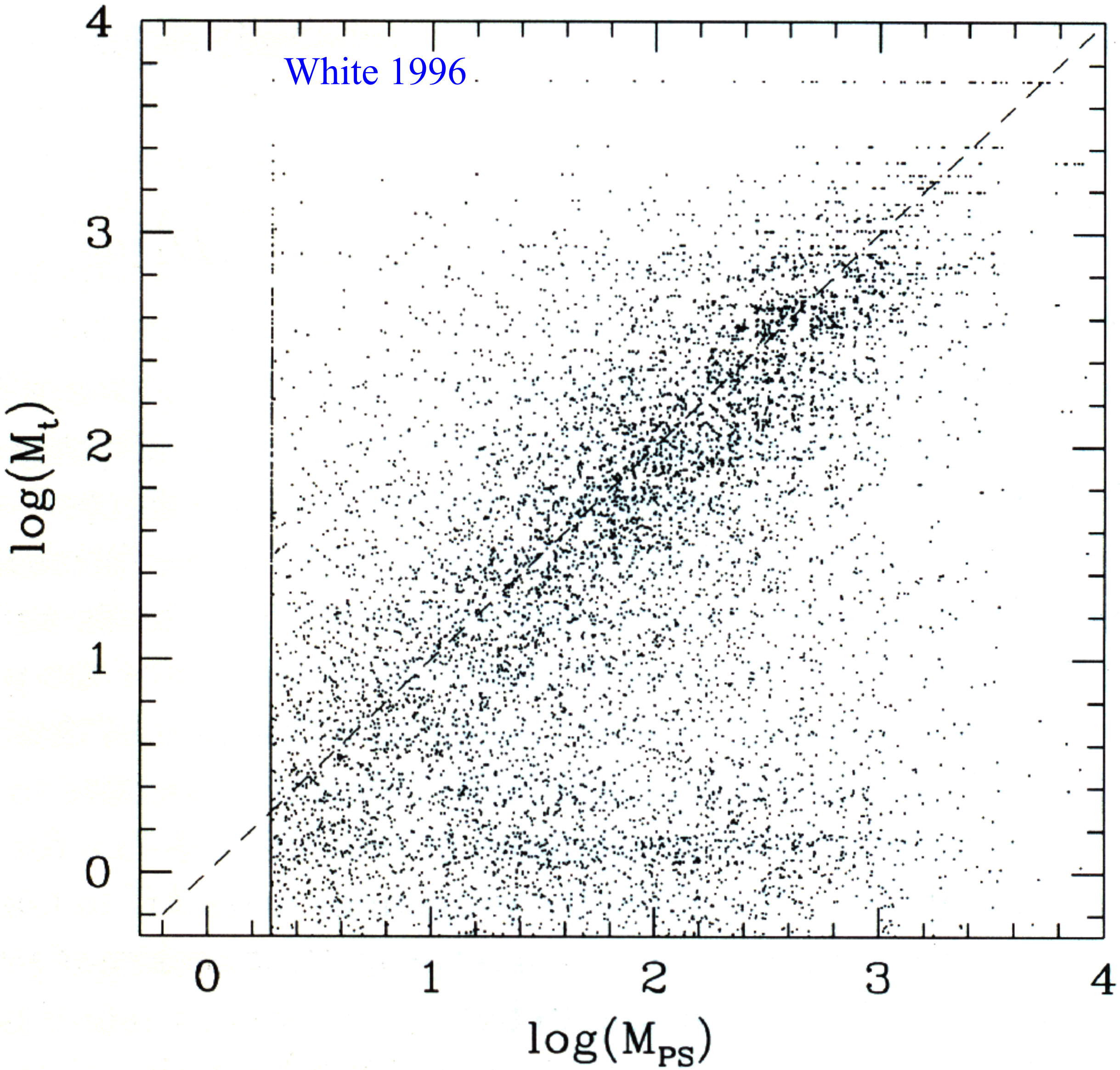


The resulting formulae can be used to obtain descendant distributions and merger rates

A similar argument gives formulae for the clustering bias of halos

Does it work point by point?

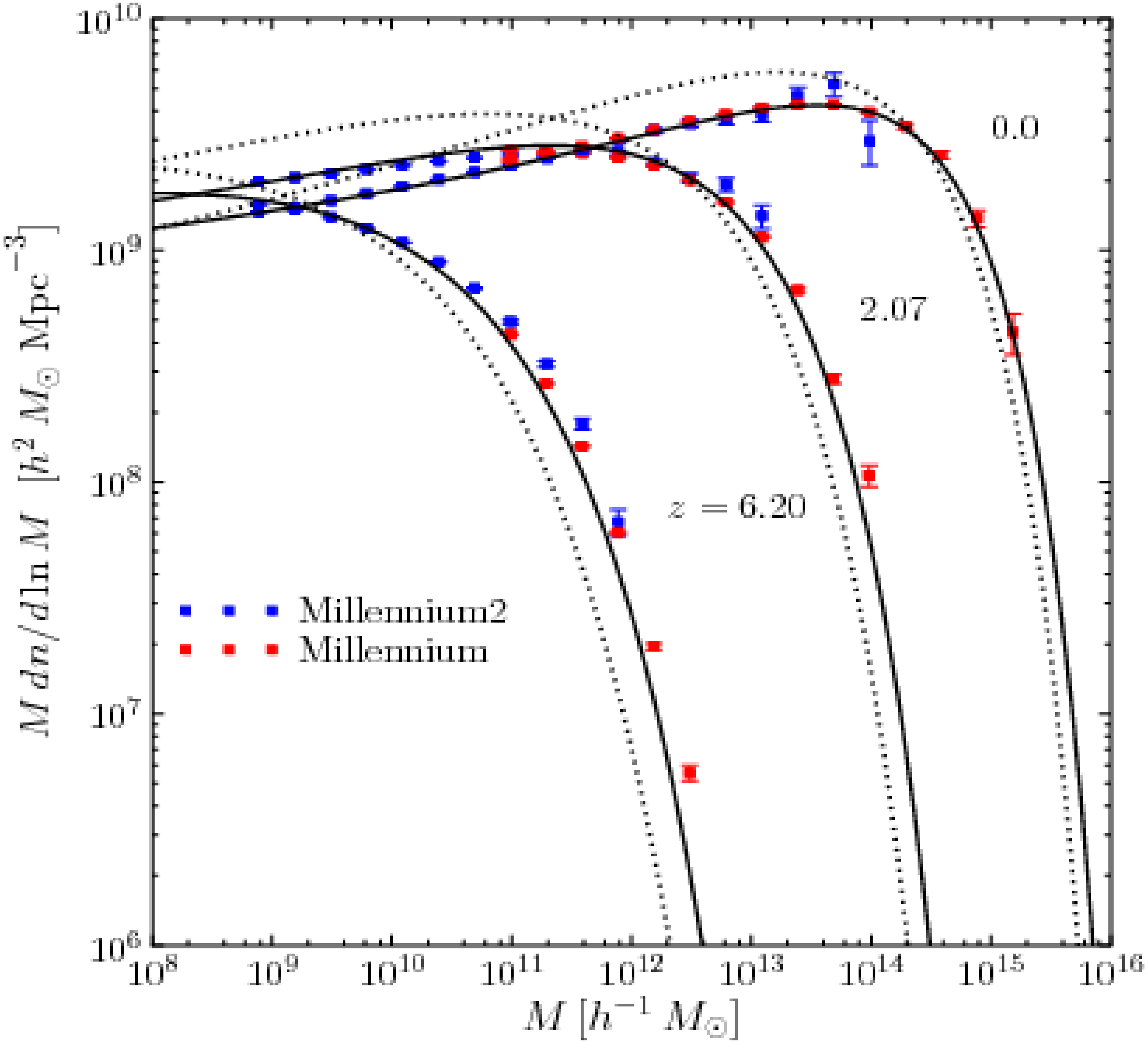
Mass of the halo in which the particle is actually found

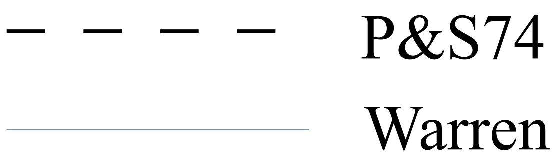


Halo mass predicted for each particle by its own sharp k-space random walk

Does it work statistically?

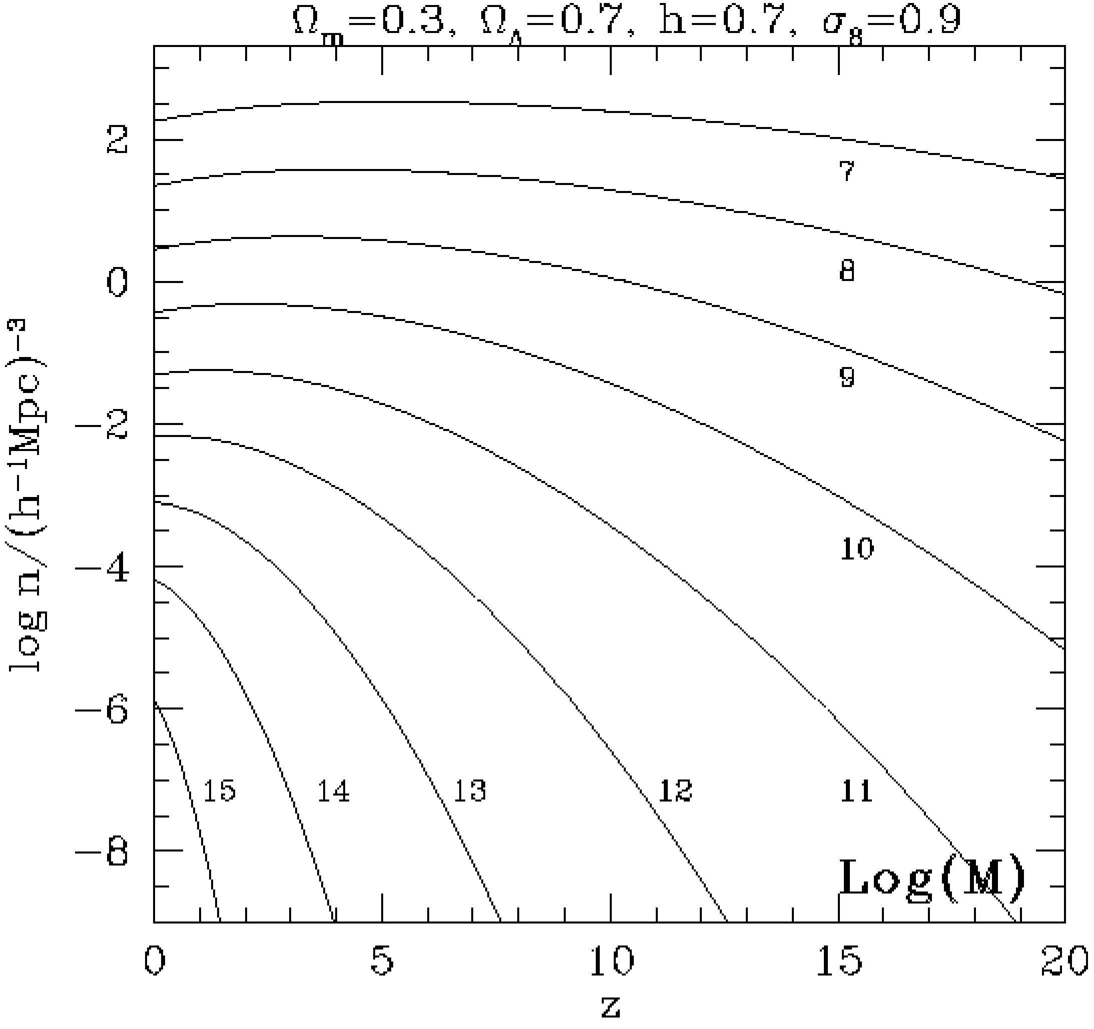
Boylan-Kolchin et al 2009





Evolution of halo abundance in ΛCDM

Mo & White 2002



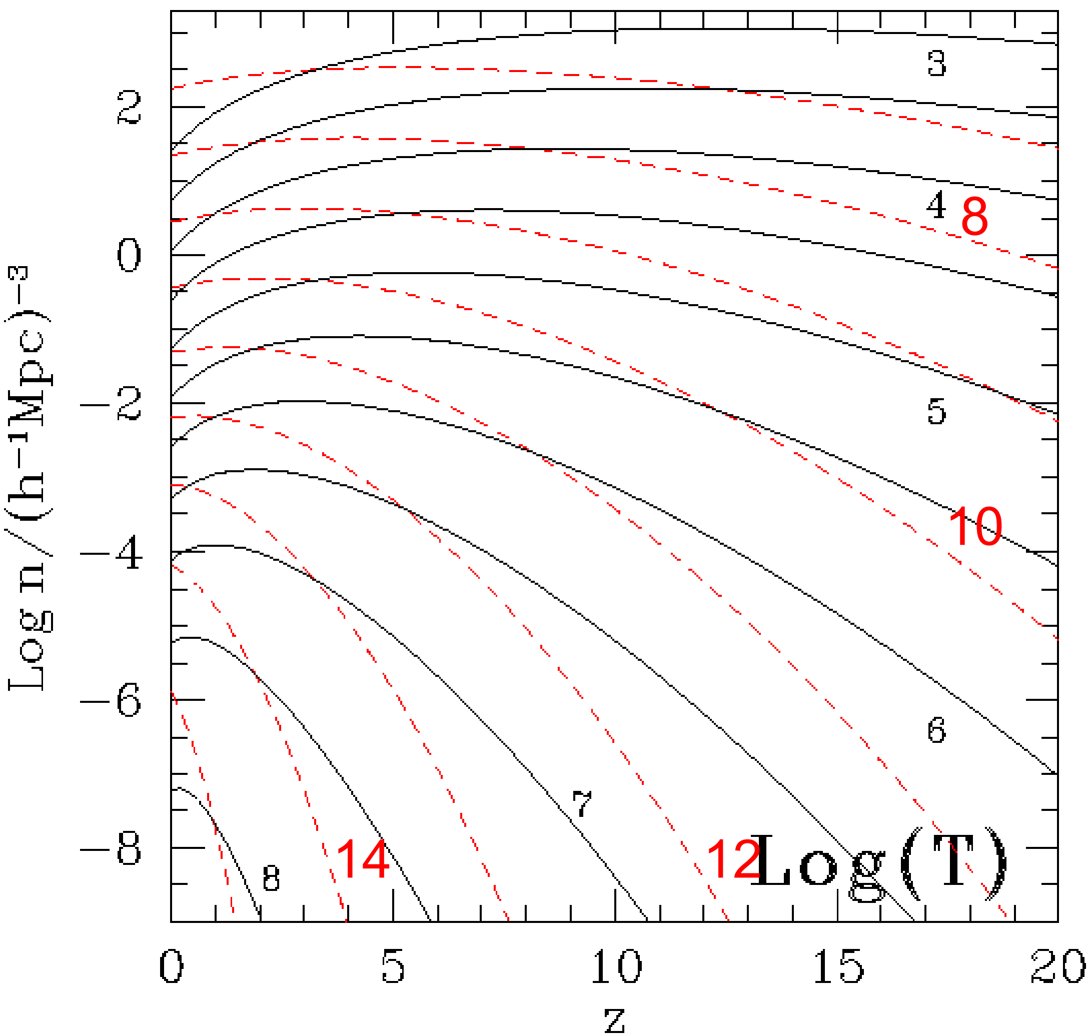
Abundance of rich cluster halos drops rapidly with z

Abundance of Milky Way mass halos drops by less than a factor of 10 to z=5

$10^9 M_\odot$ halos are almost as common at z=10 as at z=0

Evolution of halo abundance in ΛCDM

Mo & White 2002



Temperature increases with both mass and redshift

$$T \propto M^{2/3} (1 + z)$$

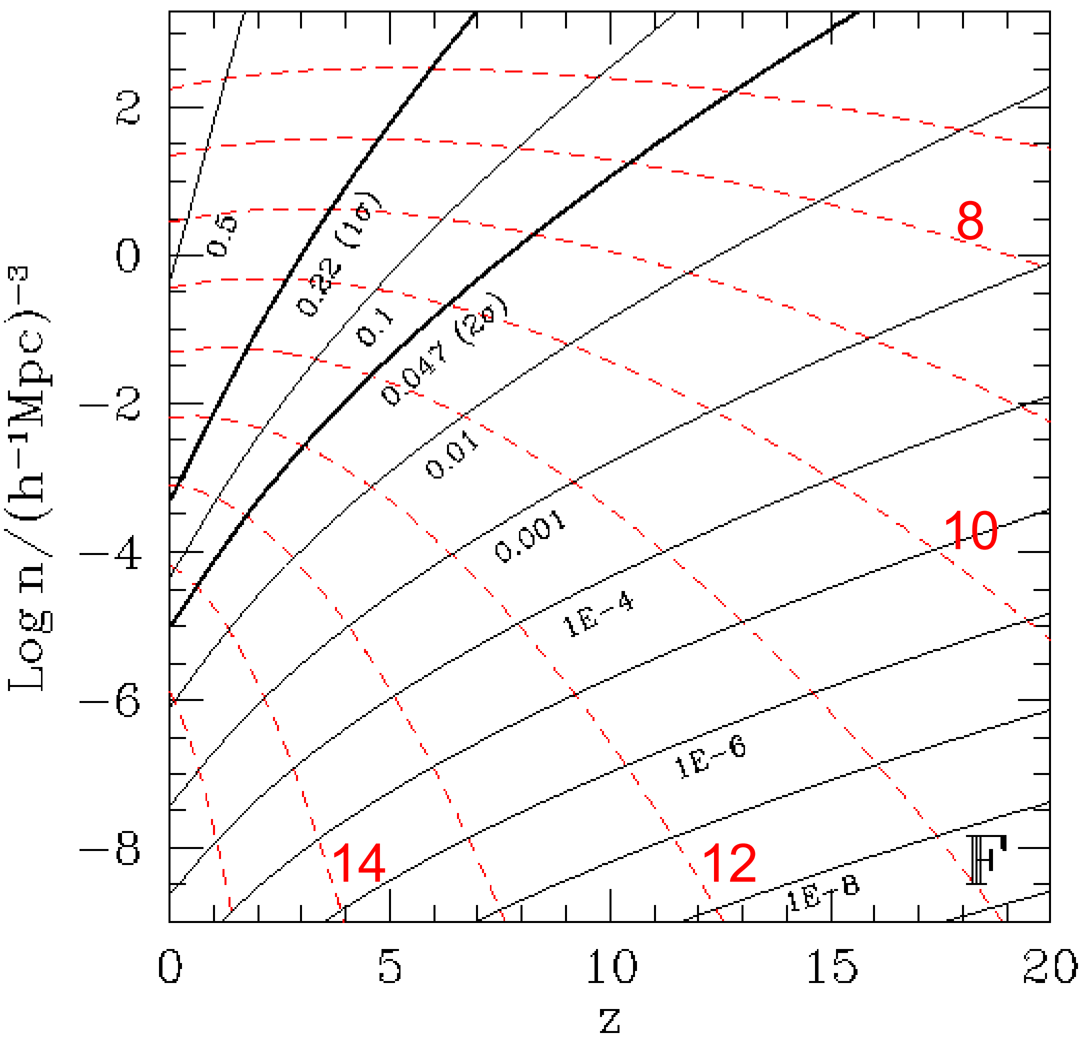
Halos with virial temperature $T = 10^7$ K are as abundant at $z = 2$ as at $z=0$

Halos with virial temperature $T = 10^6$ K are as abundant at $z = 8$ as at $z=0$

Halos of mass $>10^{7.5} M_\odot$ have $T > 10^4$ K at $z=20$ and so can cool by H line emission

Evolution of halo abundance in ΛCDM

Mo & White 2002



Half of all mass is in halos more massive than $10^{10}M_\odot$ at z=0, but only 10% at z=5, 1% at z=9 and 10^{-6} at z=20

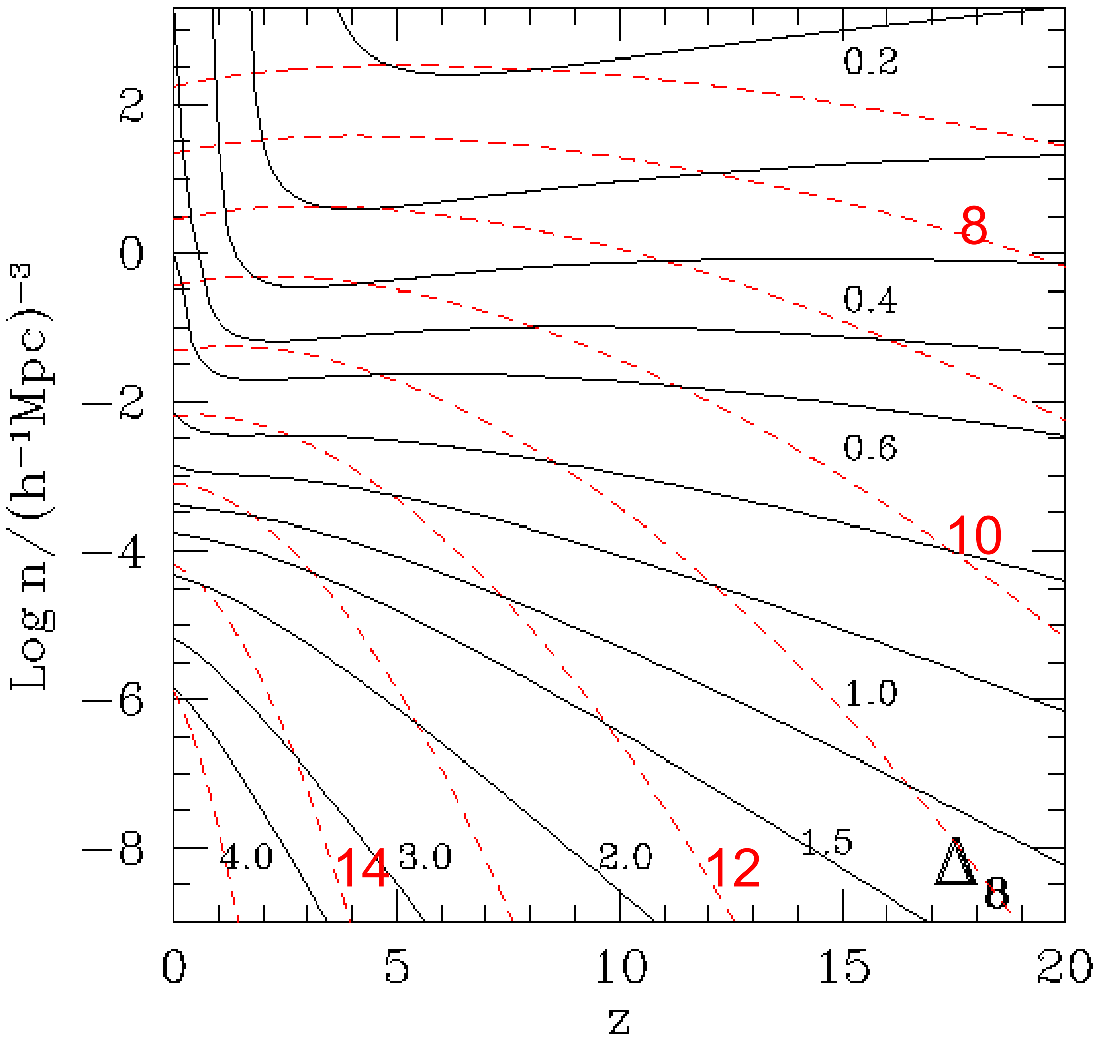
1% of all mass is in halos more massive than $10^{15}M_\odot$ at z=0

40% of all mass at z=0 is in halos which cannot confine photoionised gas

1% of all mass at z=15 is in halos hot enough to cool by H line emission

Evolution of halo abundance in ΛCDM

Mo & White 2002

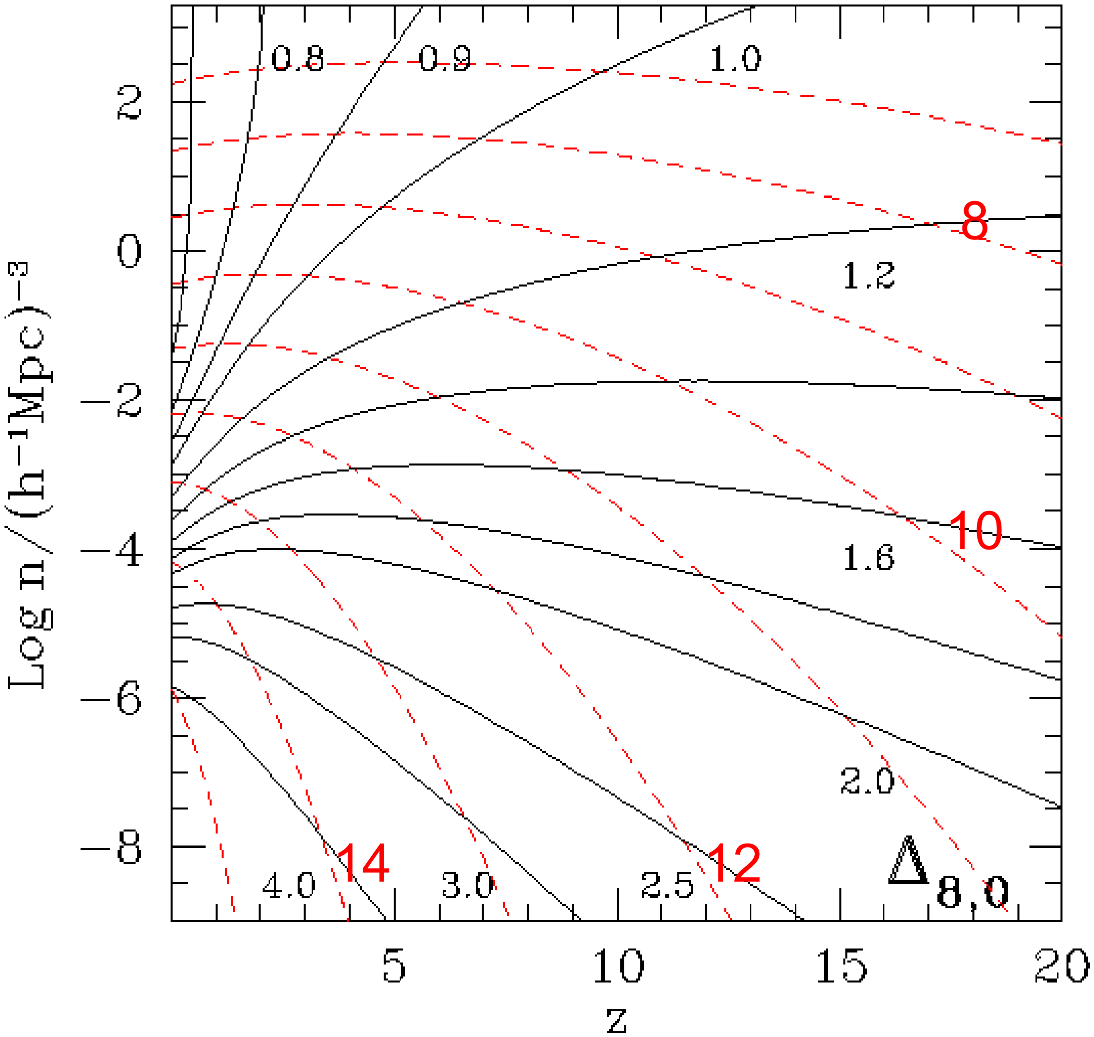


Halos with the abundance of L_* galaxies at z=0 are equally strongly clustered at all z < 20

Halos of given mass or virial temperature are more clustered at *higher* z

Evolution of halo abundance in ΛCDM

Mo & White 2002

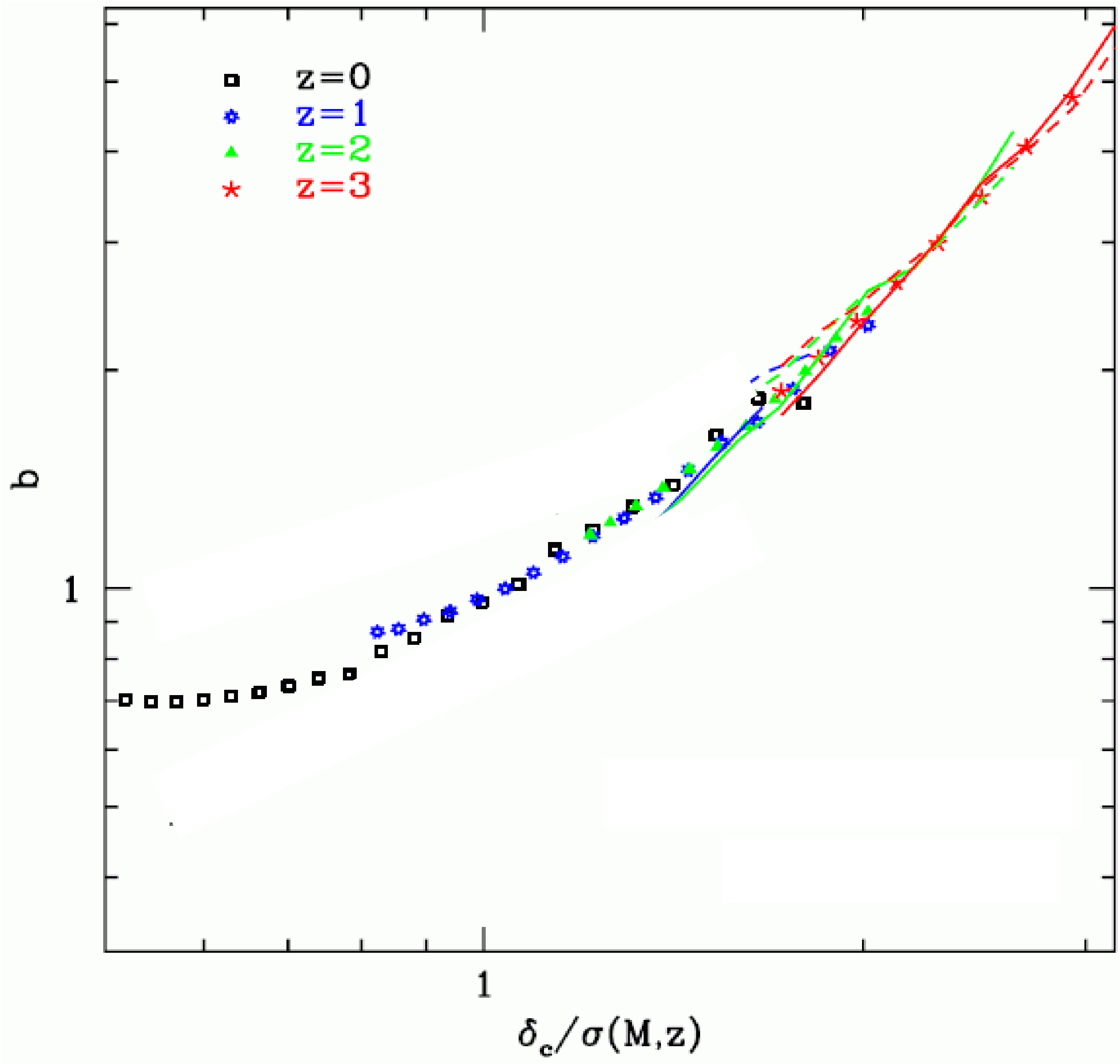


The remnants (stars and heavy elements) from all star-forming systems at z>6 are today more clustered than L_* galaxies

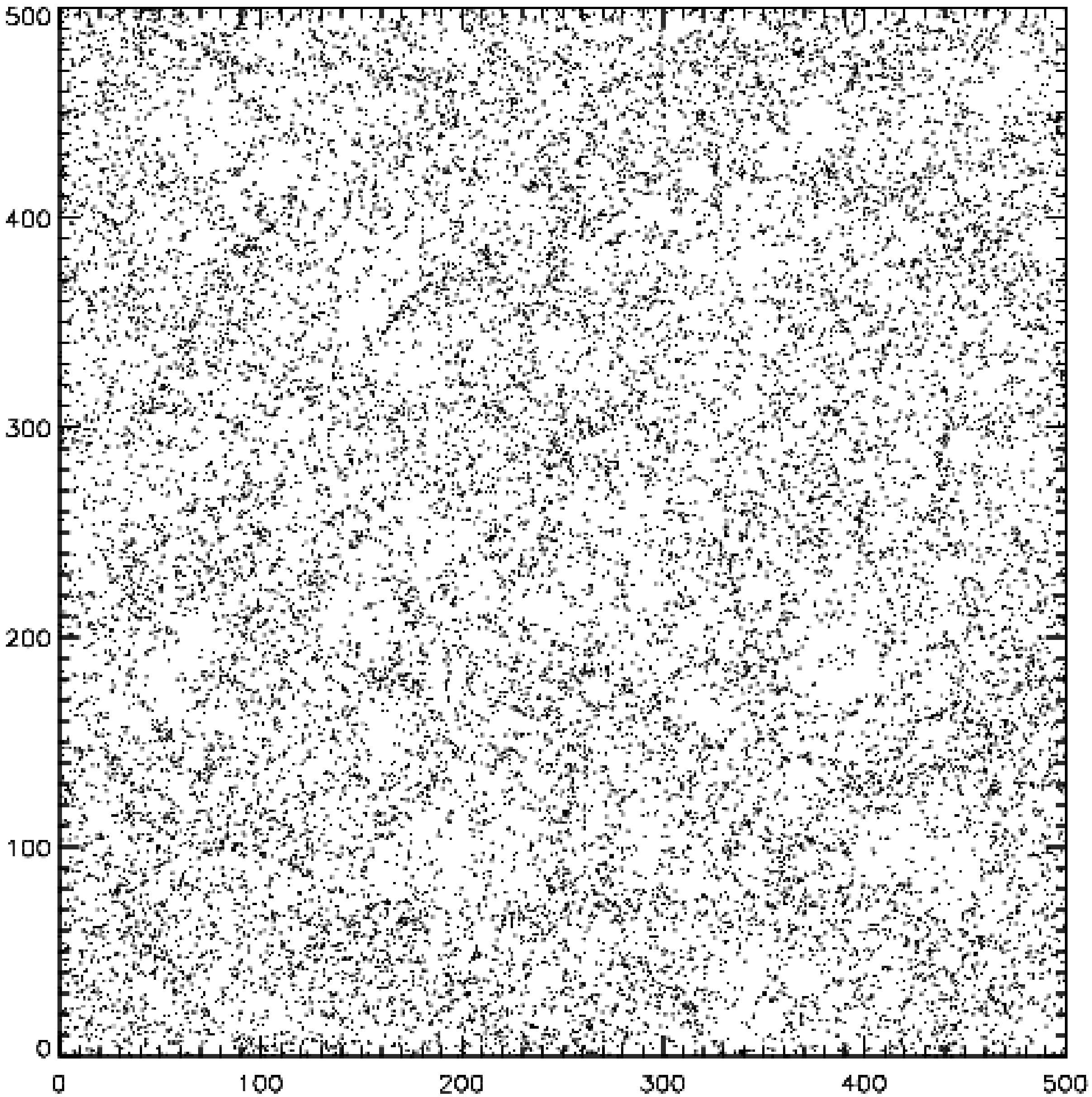
The remnants of objects which at any z > 2 had an abundance similar to that of present-day L_* galaxies are today more clustered than L_* galaxies

Bias as a function of ν

Gao & White 2007



Halo clustering depends on formation history!

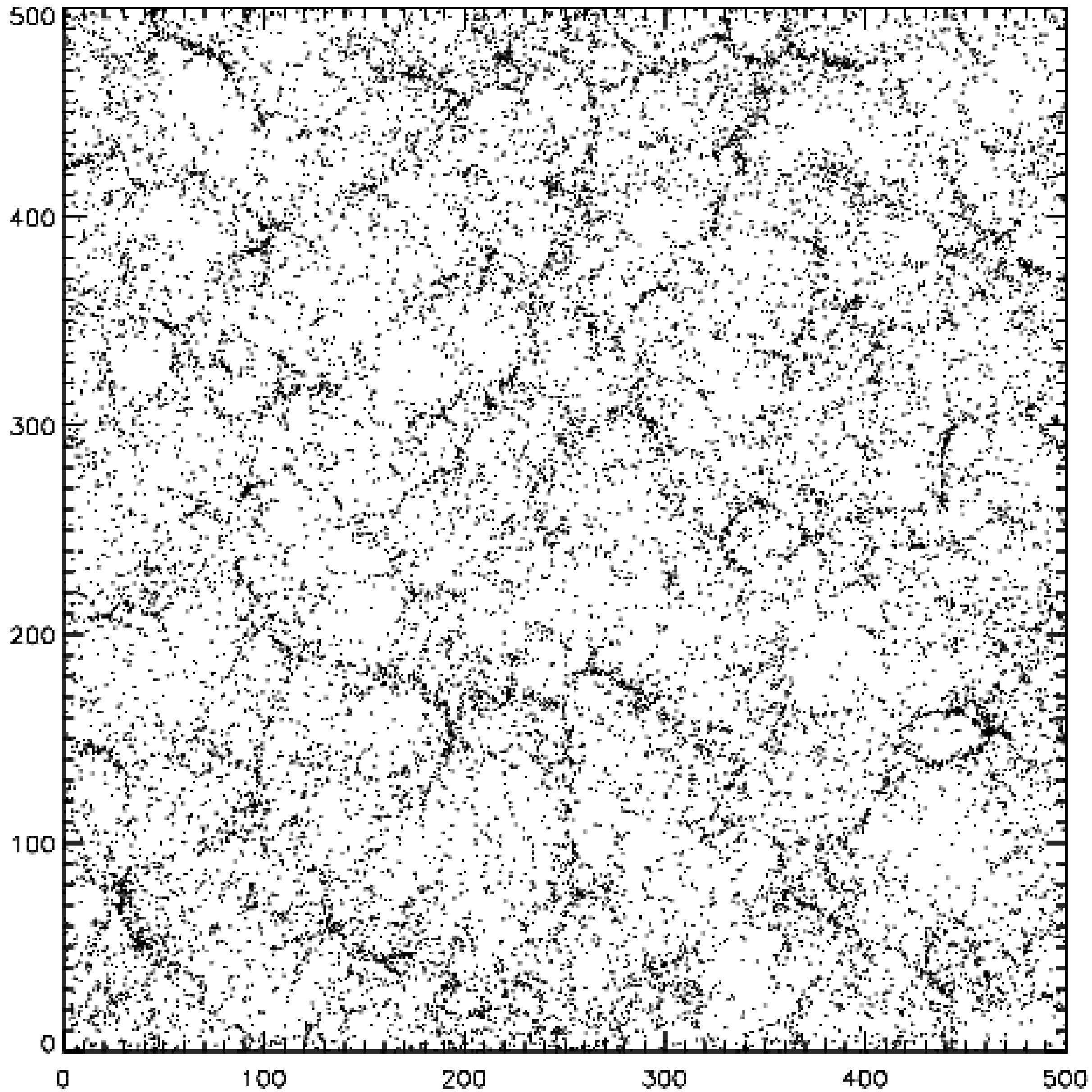


Gao, Springel & White 2005

The 20% of halos with the *lowest* formation redshifts in a 30 Mpc/h thick slice

$$M_{halo} \sim 10^{11} M_{\odot}$$

Halo clustering depends on formation history!



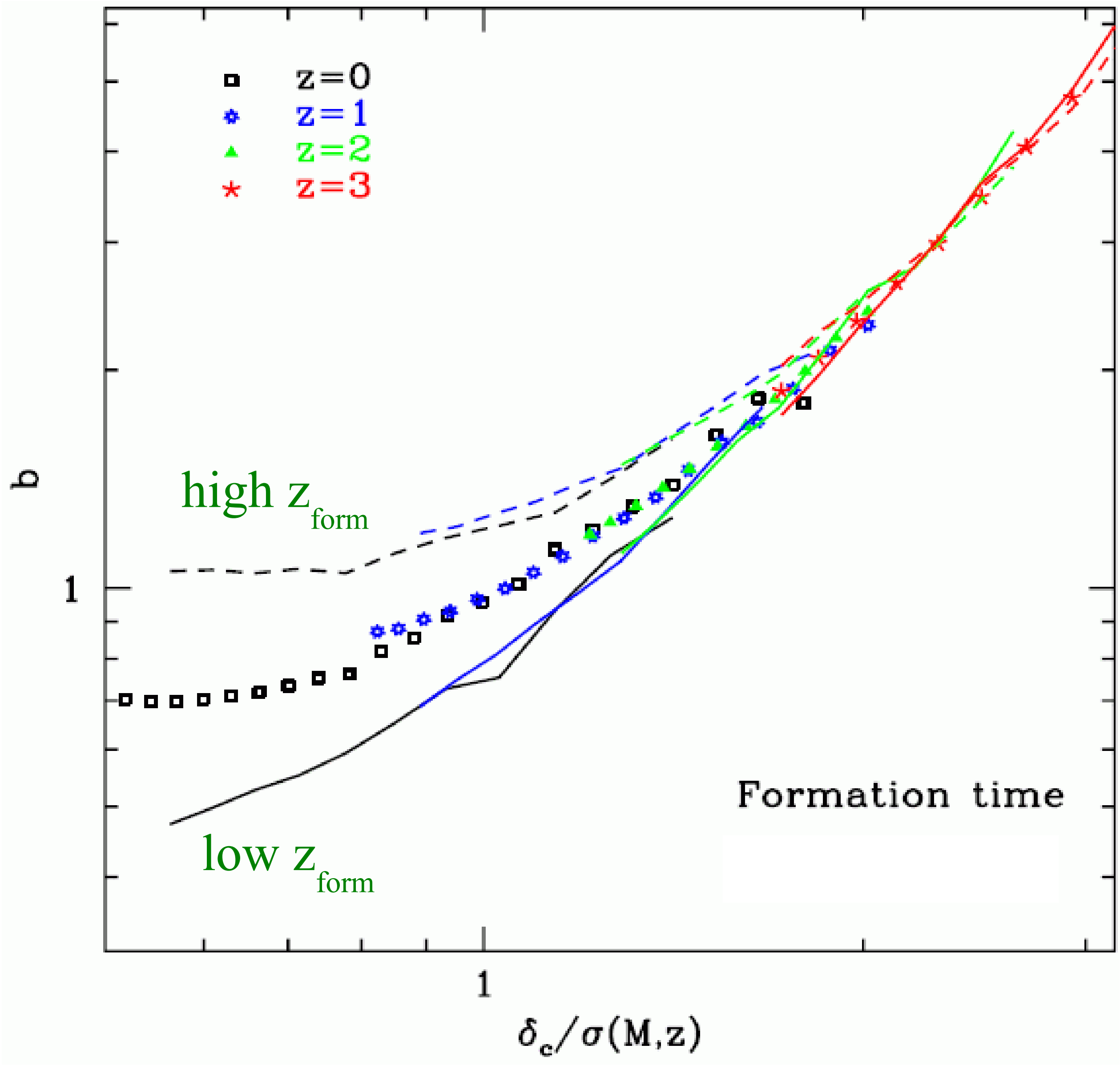
Gao, Springel & White 2005

The 20% of halos with the ***highest*** formation redshifts in a 30 Mpc/h thick slice

$$M_{halo} \sim 10^{11} M_{\odot}$$

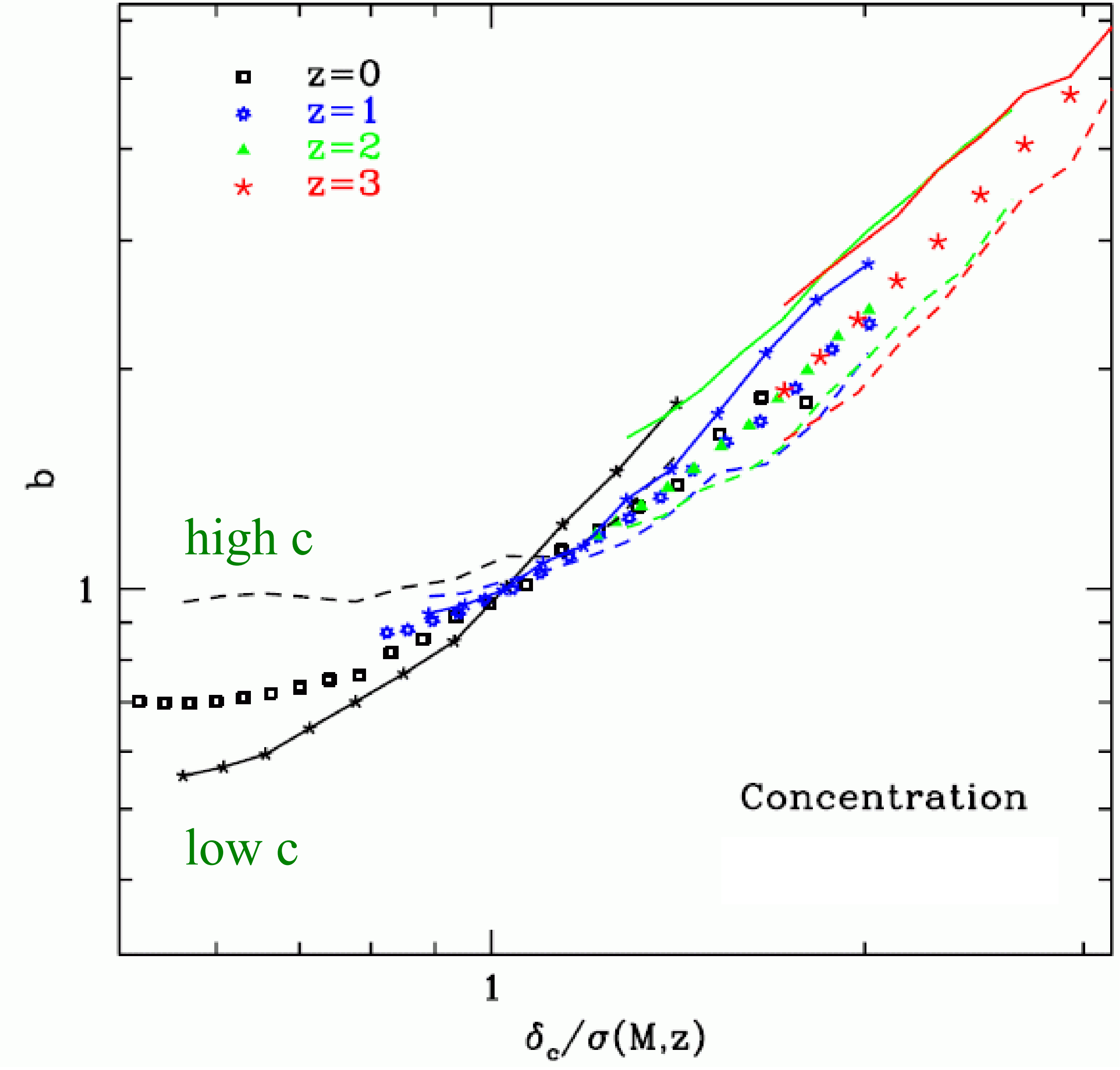
Bias as a function of ν and formation time

Gao & White 2007



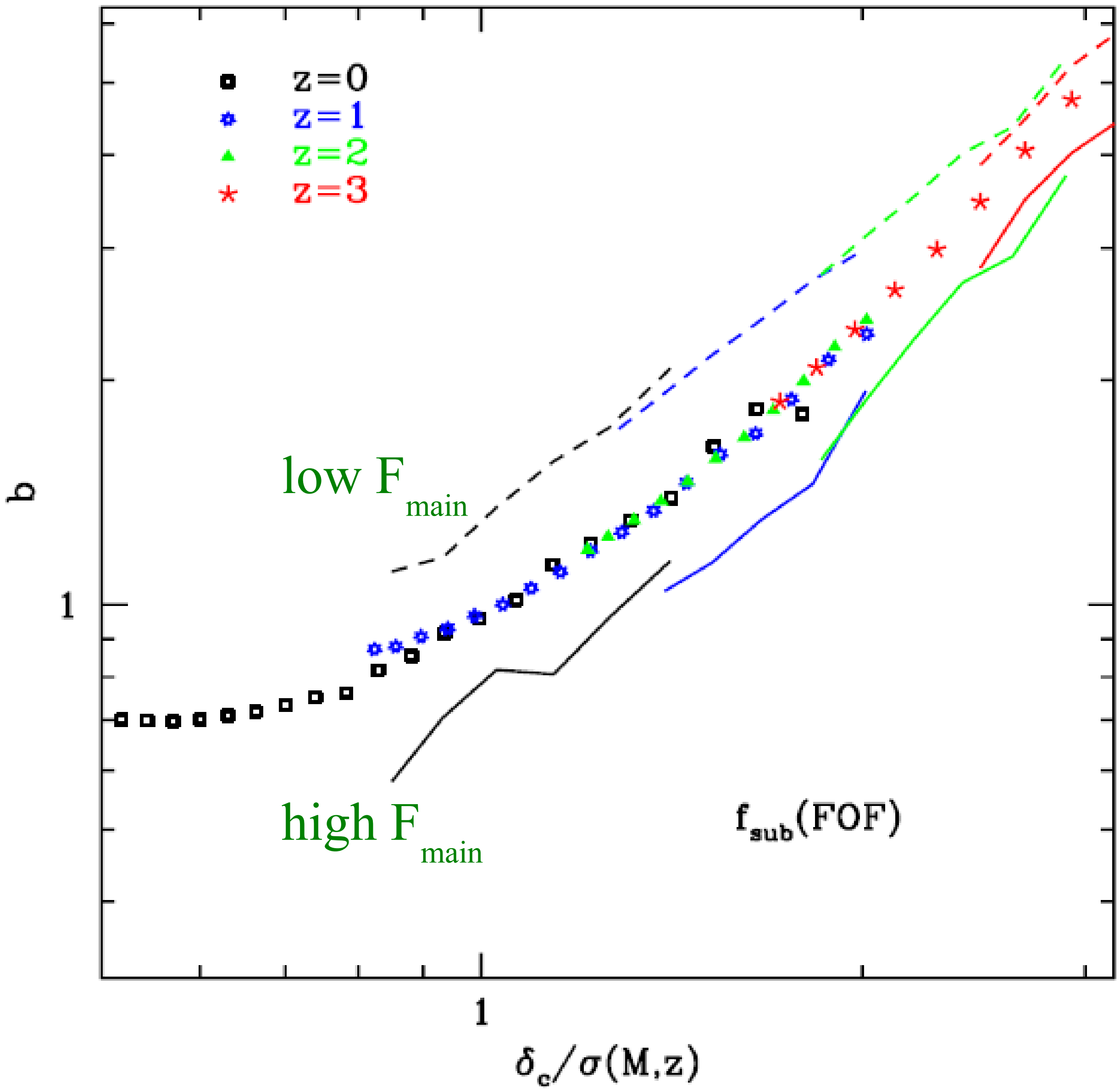
Bias as a function of ν and concentration

Gao & White 2007



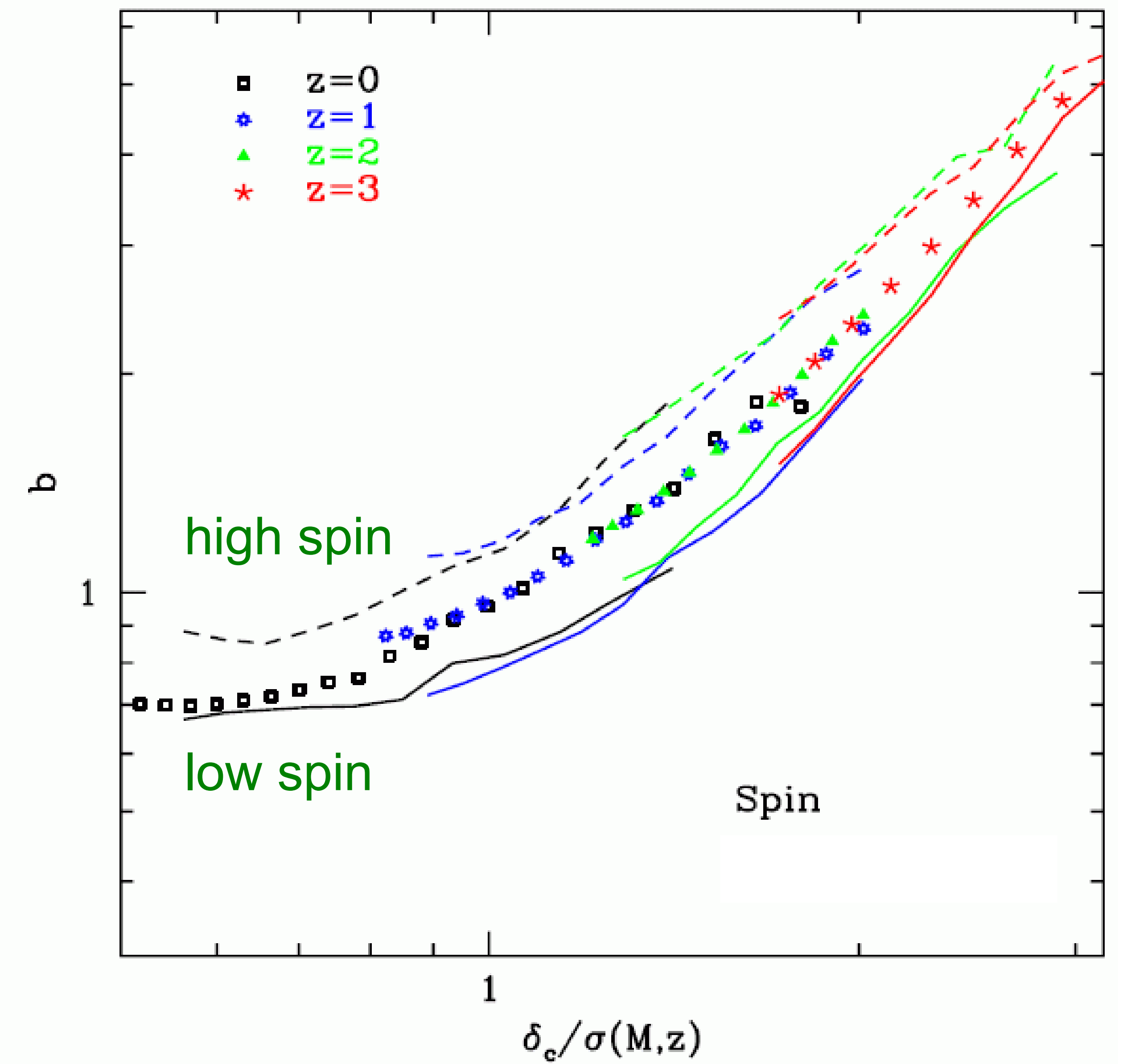
Bias as a function of ν and main halo mass fraction

Gao & White 2007



Bias as a function of ν and spin

Gao & White 2007



Halo assembly bias: conclusions

The large-scale bias of halo clustering relative to the dark matter depends on halo mass through $\nu = \delta_c / D(z)\, \sigma_o(M)$ and also on

- -- formation time
- -- concentration
- -- substructure content
- -- spin

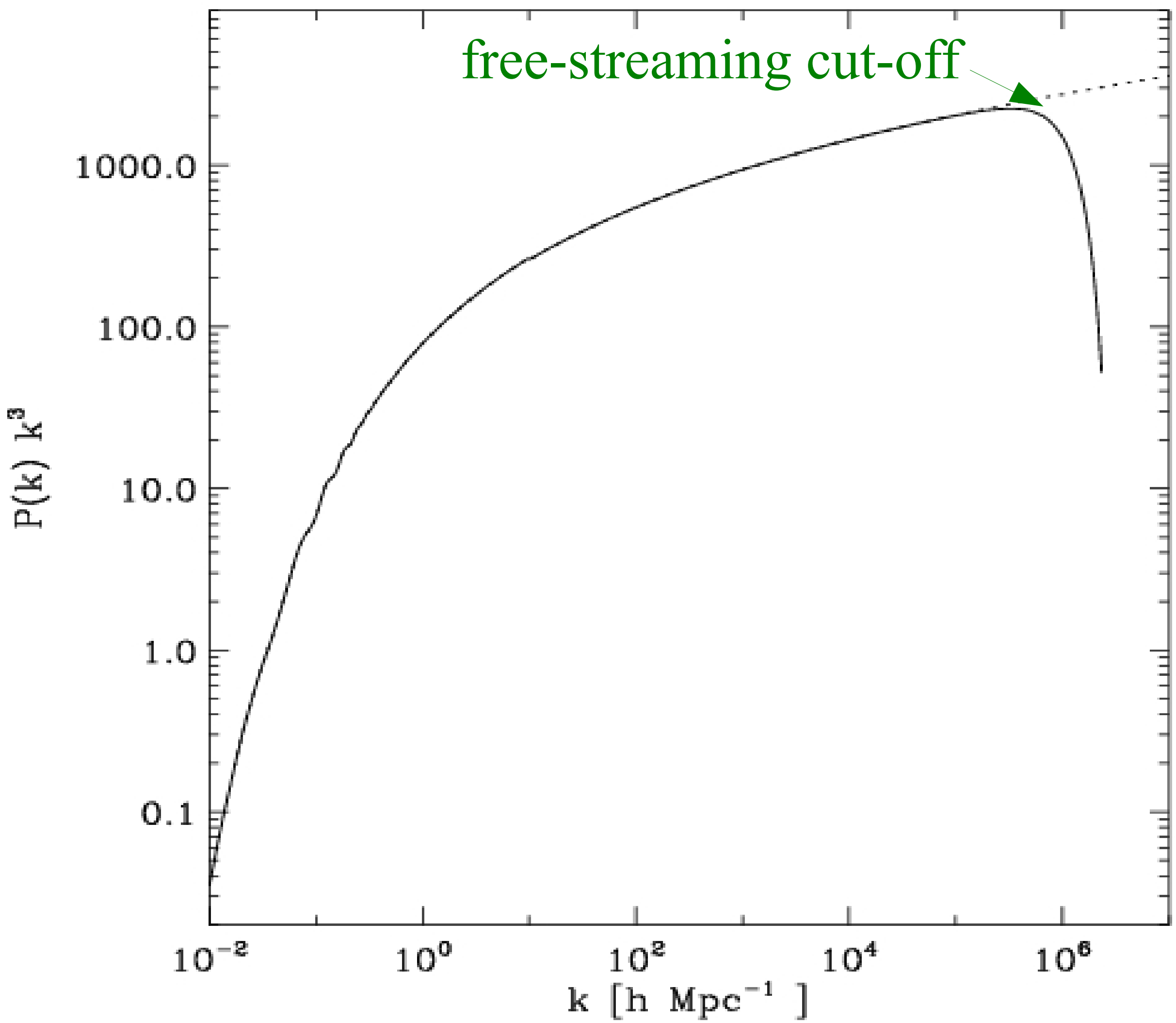
The dependences on these assembly variables are different and <u>cannot</u> be derived from each other, e.g. more concentrated halos are more strongly clustered at low mass but less strongly clustered at high mass; rapidly spinning halos are more strongly clustered by equal amounts at all masses.

These dependences are likely to be reflected in <u>galaxy</u> bias

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2010



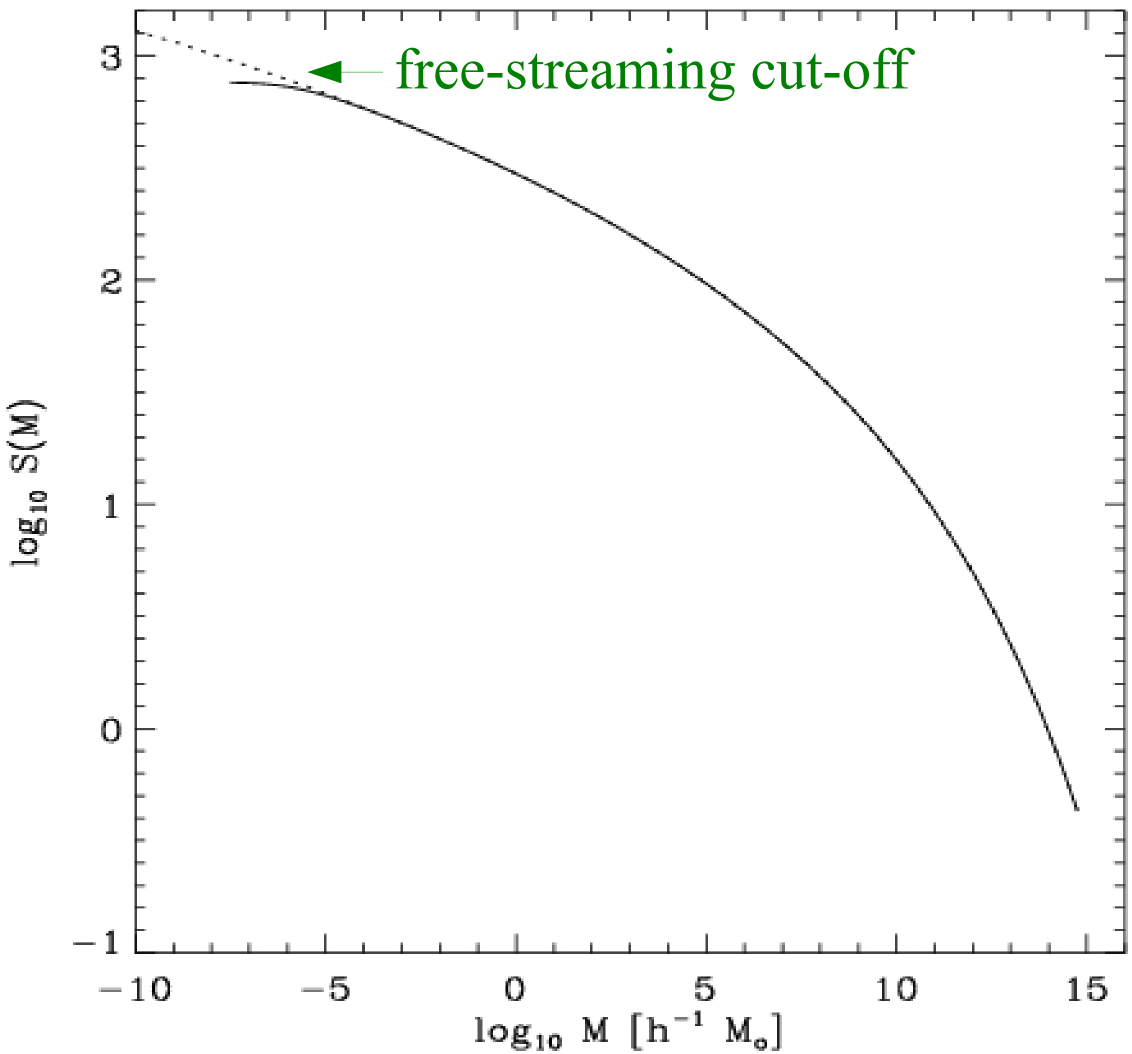
The linear power spectrum in "power per octave" form

Assumes a 100GeV wimp following Green et al (2004)

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo & White 2010

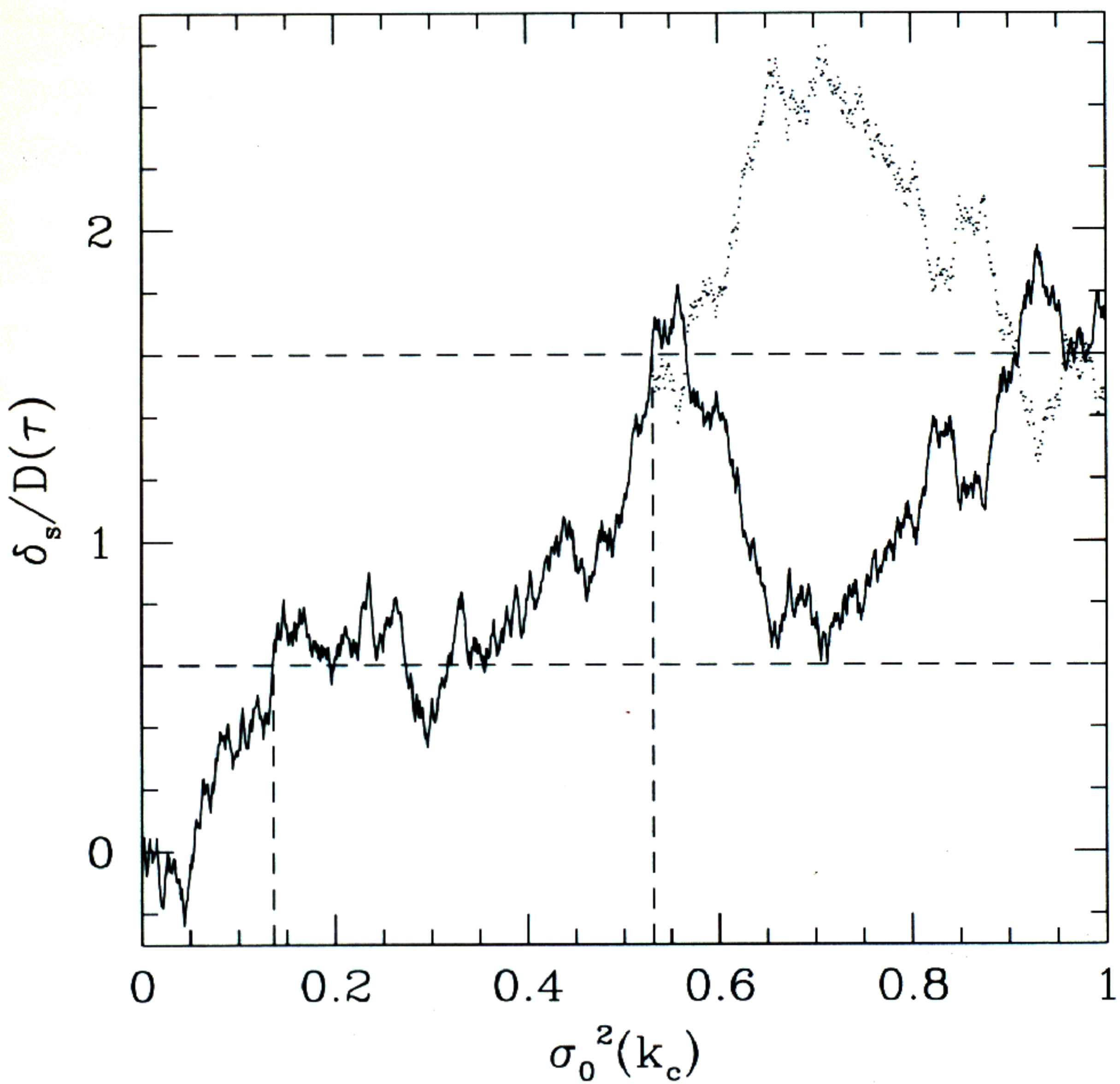


Variance of linear density fluctuation within spheres containing mass M, extrapolated to z = 0

As M → 0, S(M) → 720

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$



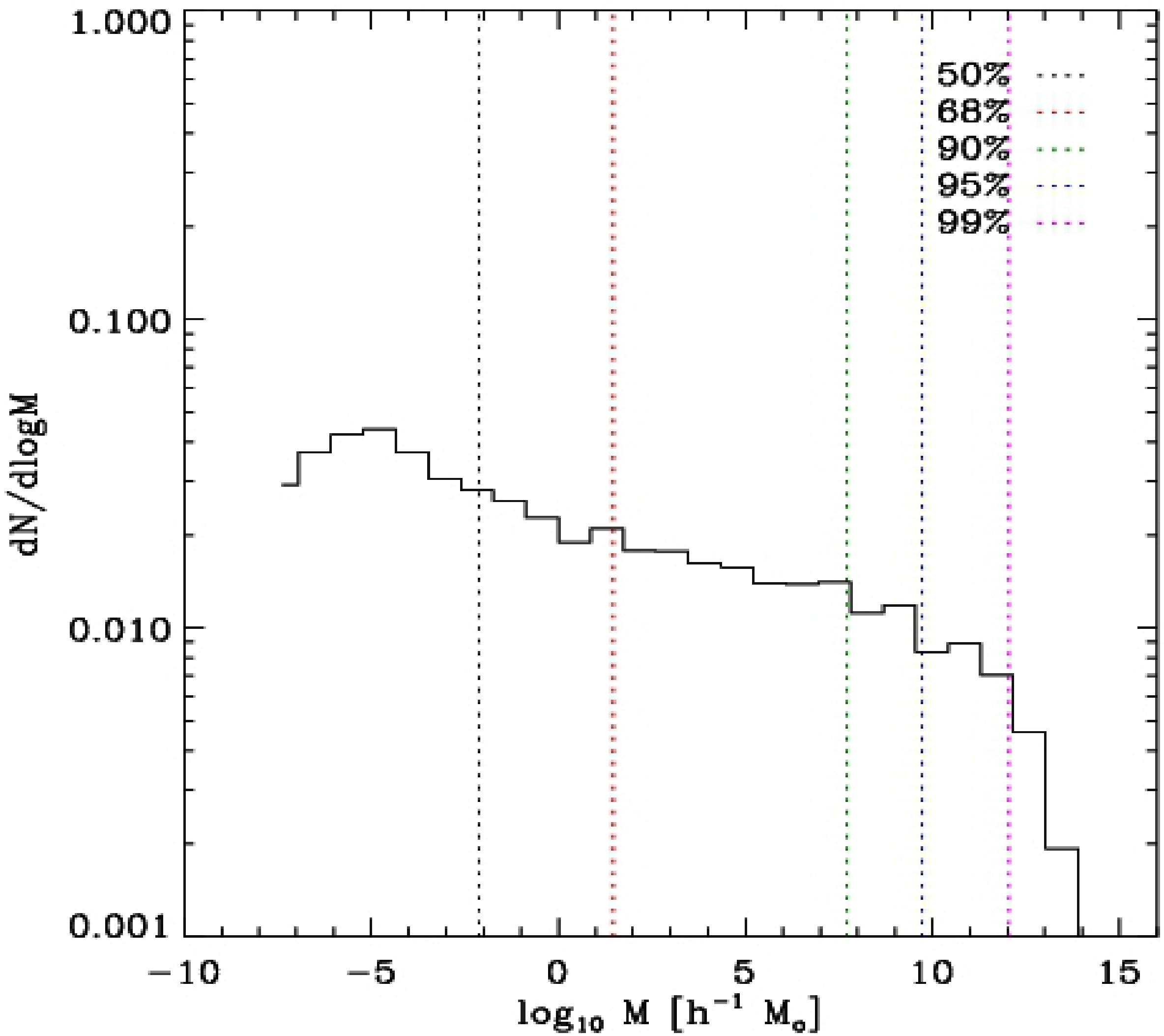
If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by √720, then they represent complete halo assembly histories for random CDM particles.

An ensemble of walks thus represents the probability distribution of assembly histories

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo & White 2010



Distribution of the masses of the first halos for a random set of dark matter particles

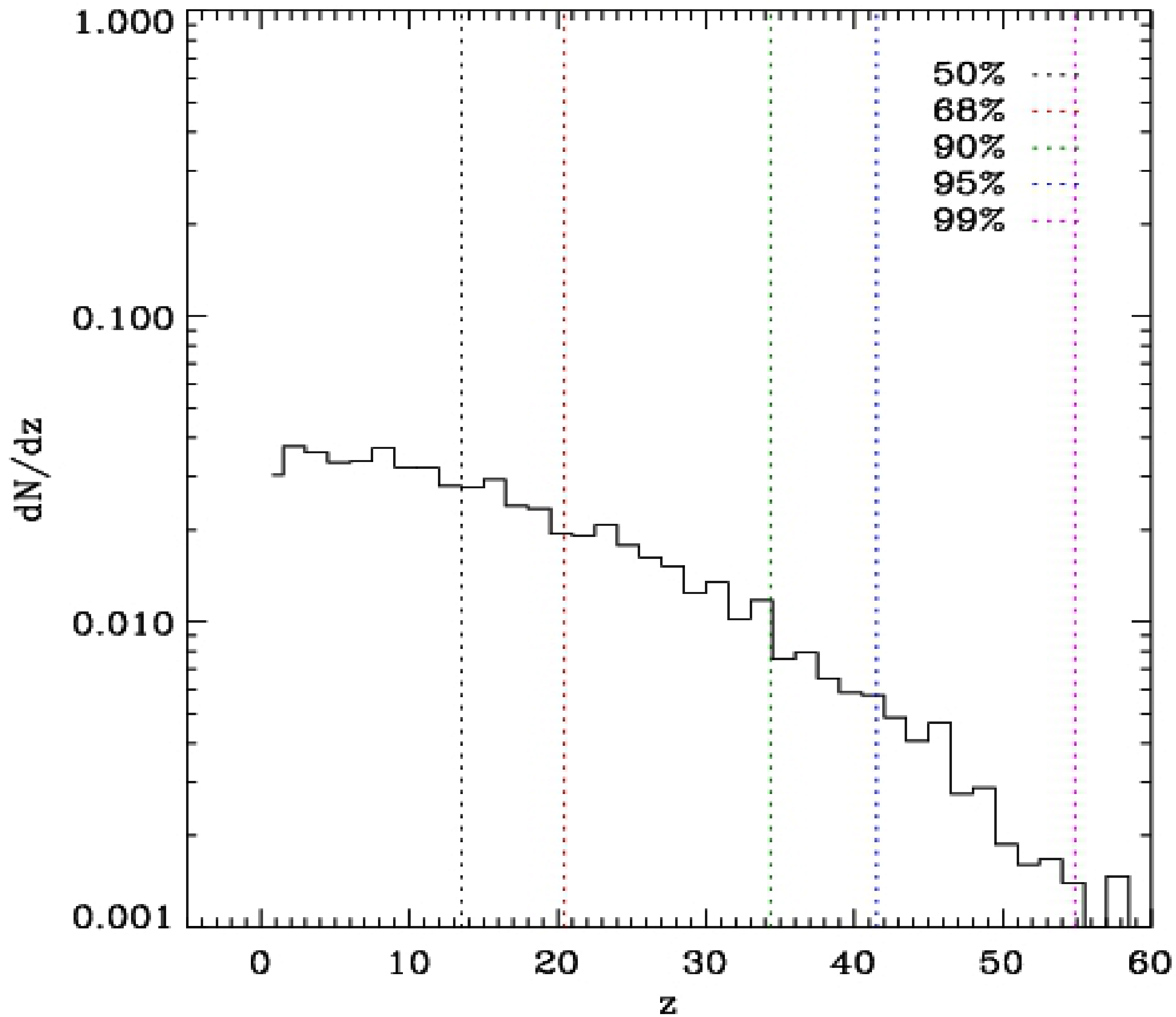
The median is $10^{-2}M_\odot$

For 10% of the mass the first halo has $M > 10^7 M_\odot$

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2010



Distribution of the collapse redshifts of the first halos for a random set of dark matter particles

The median is z = 13

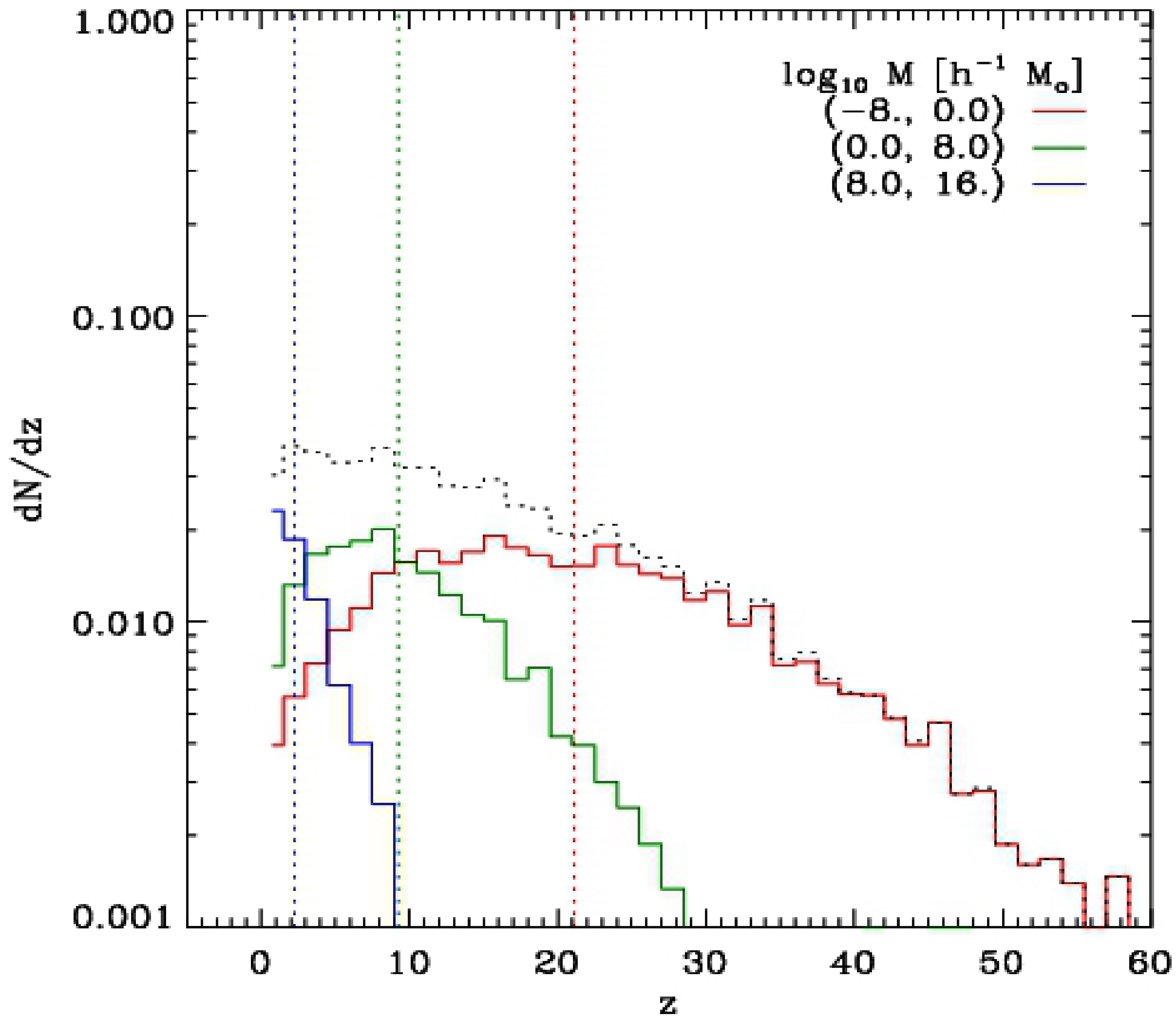
For 10% of the mass the first halo collapses at z > 34

For 1% at z > 55

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo & White 2010



Distribution of the collapse redshifts of the <u>first</u> halos for dark matter particles split by the mass of the first object

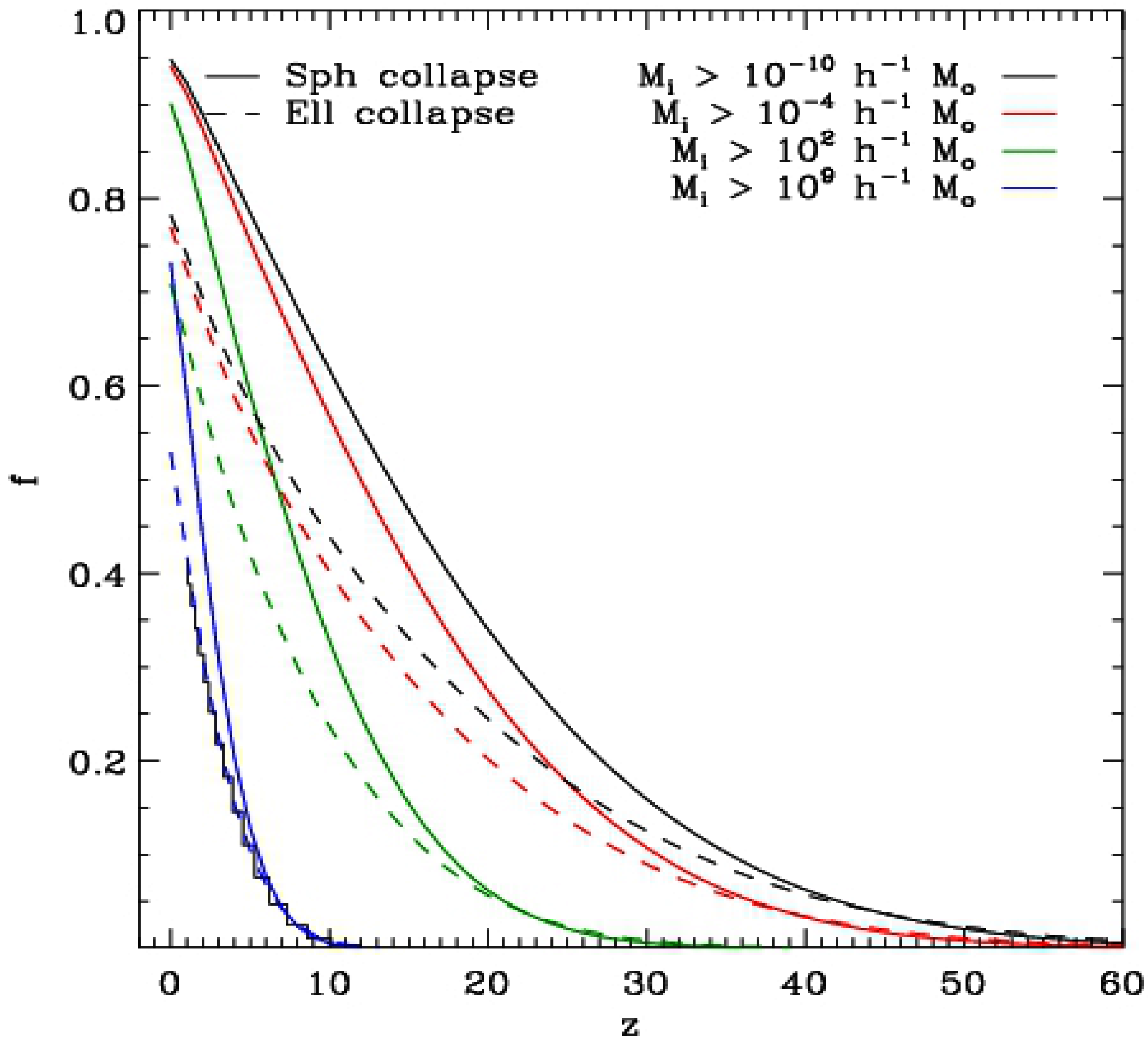
The high redshift tail is entirely due to matter in small first halos

For first halo masses below a solar mass, the median collapse redshift is z = 21

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo & White 2010



Total mass fraction in halos

At z = 0 about 5% (Sph) or 20% (Ell) of the mass is still diffuse

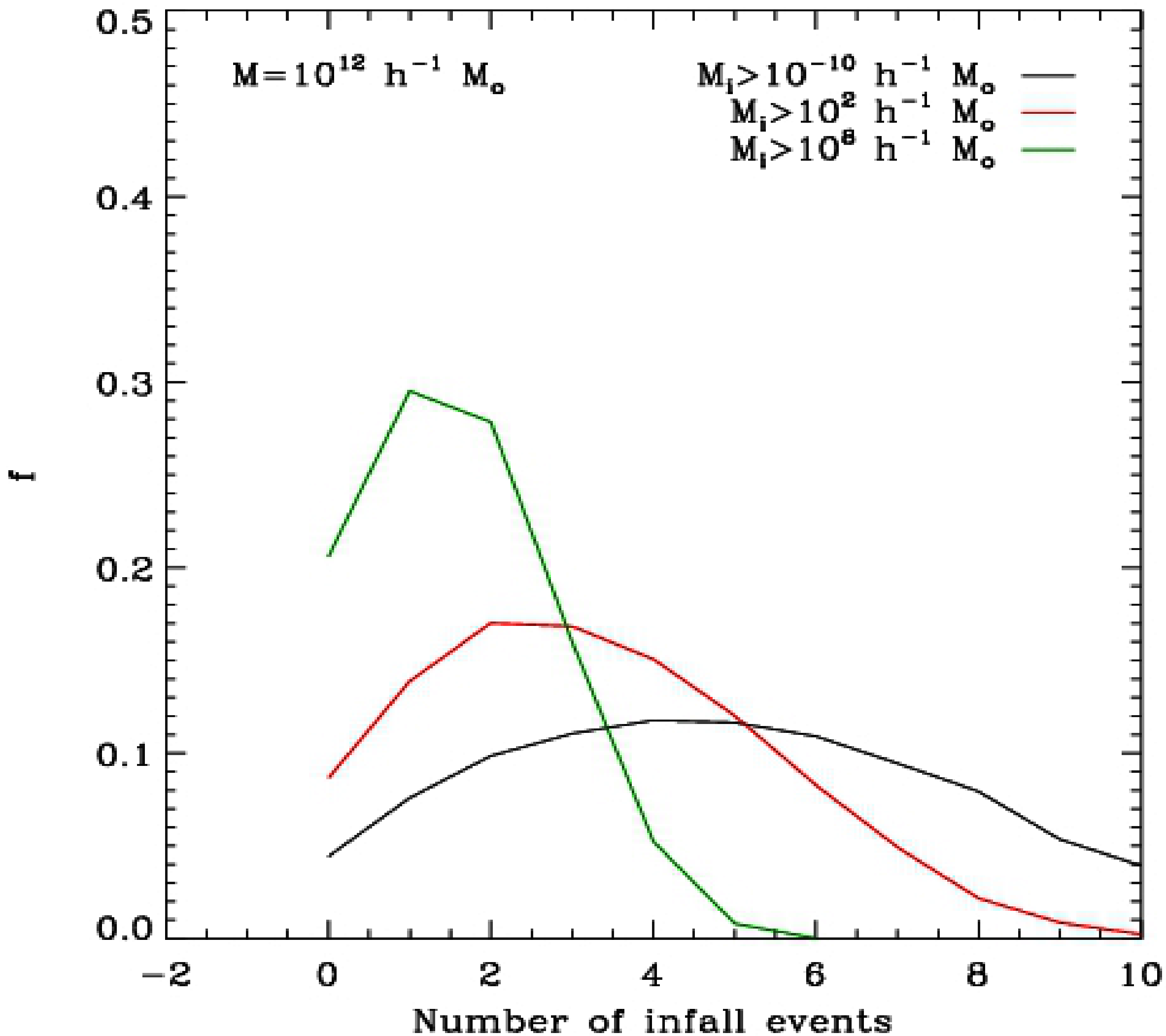
Beyond z = 50 almost all the mass is diffuse

Only at z < 2 (Sph) or z<0.5 (Ell) is most mass in halos with $M > 10^8 M_\odot$ The "Ell" curve agrees with simulations

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2010



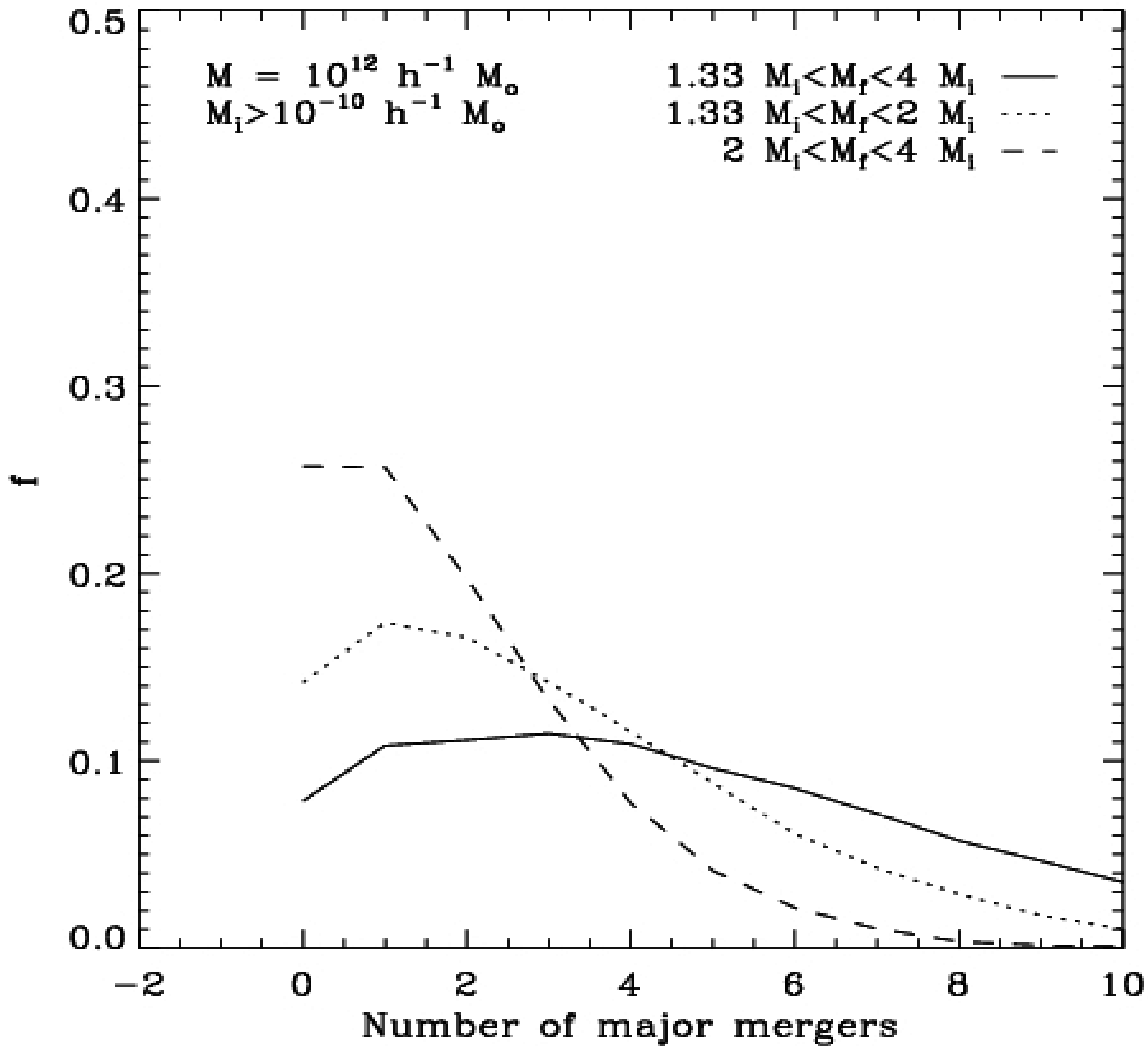
The typical mass element in a "Milky Way" halo goes through ~5 "infall events" where its halo falls into a halo bigger than itself.

Typically only one of these is as part of a halo with $M > 10^8 M_\odot$

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo & White 2010



The typical mass element in a "Milky Way" halo goes through ~3 "major mergers" where the two halos are within a factor of 3 in mass

The majority of these occur when the element is part of the larger halo

EPS halo assembly: conclusions

The typical first halo is much more massive than the free streaming mass

First halos typically collapse quite late $z \sim 13$

Halo growth occurs mainly by accretion of much smaller halos

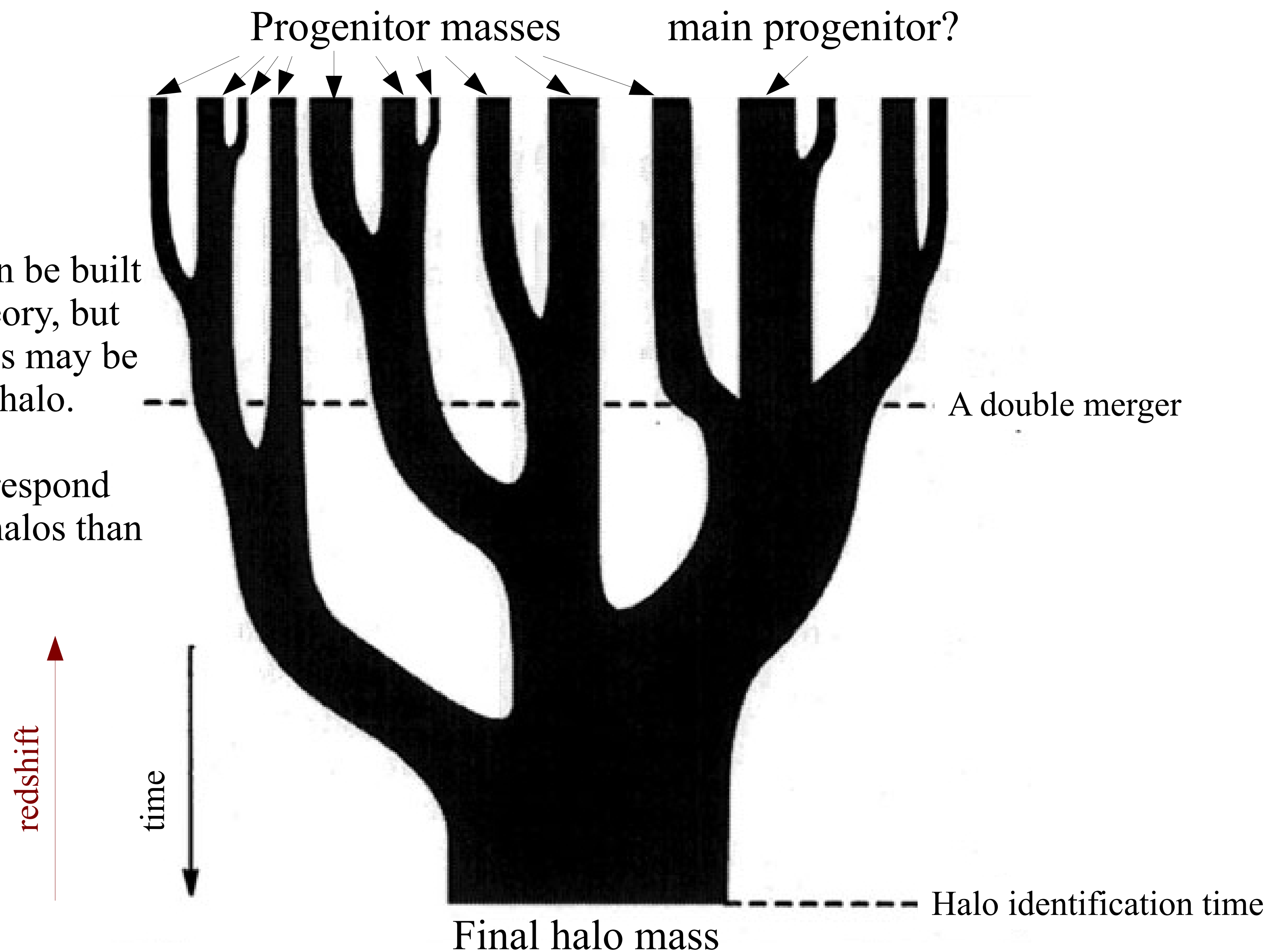
There are rather few “generations” of accretion/merger events

Major mergers are not a major part of the growth of many halos

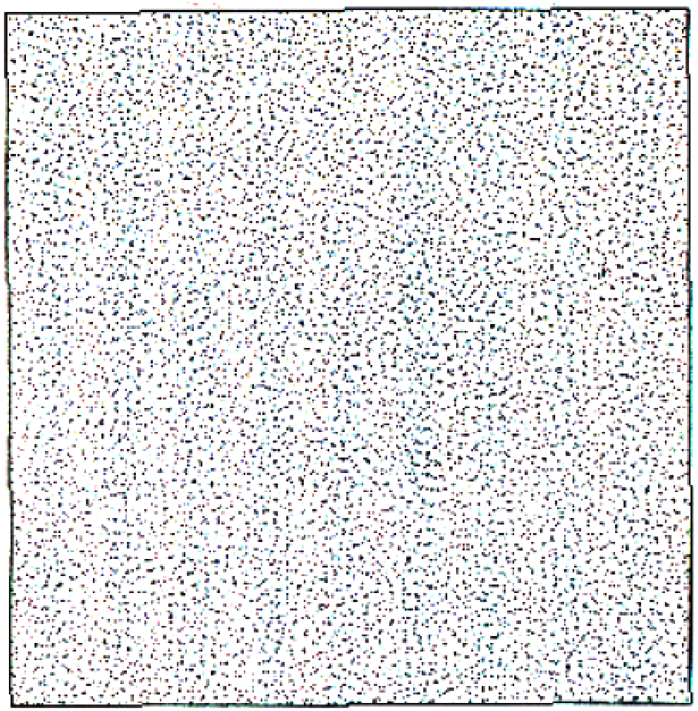
A Halo Merger Tree

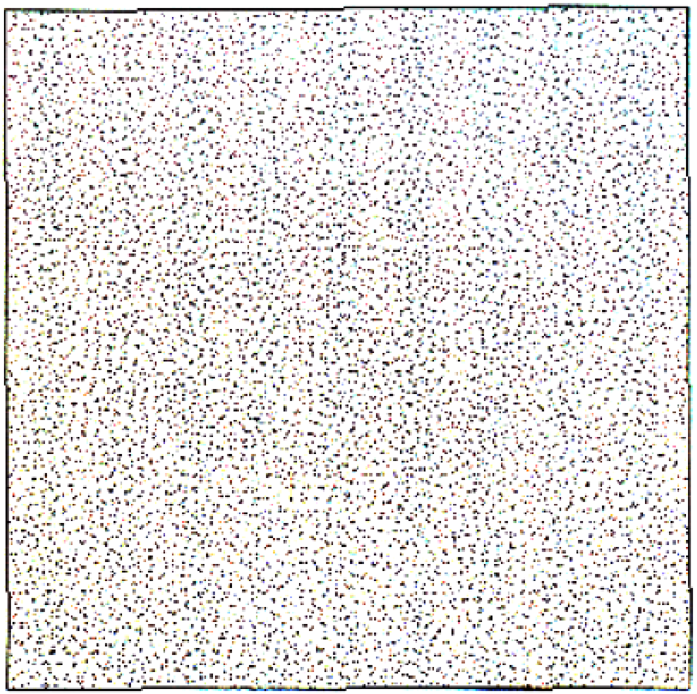
Halo trees can be built from EPS theory, but many galaxies may be in a (cluster) halo.

Galaxies correspond better to subhalos than to halos



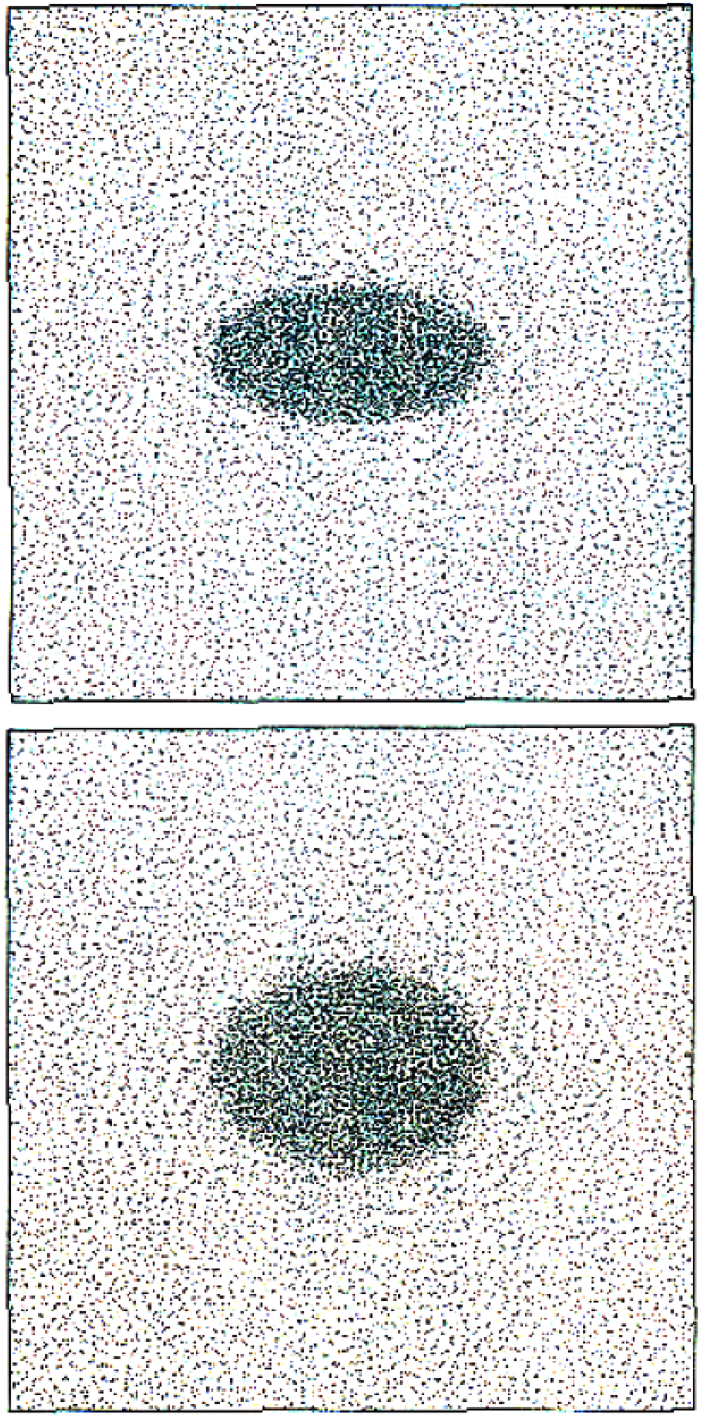
Total progenitor mass is not conserved because of diffuse (unresolved) infall onto halos





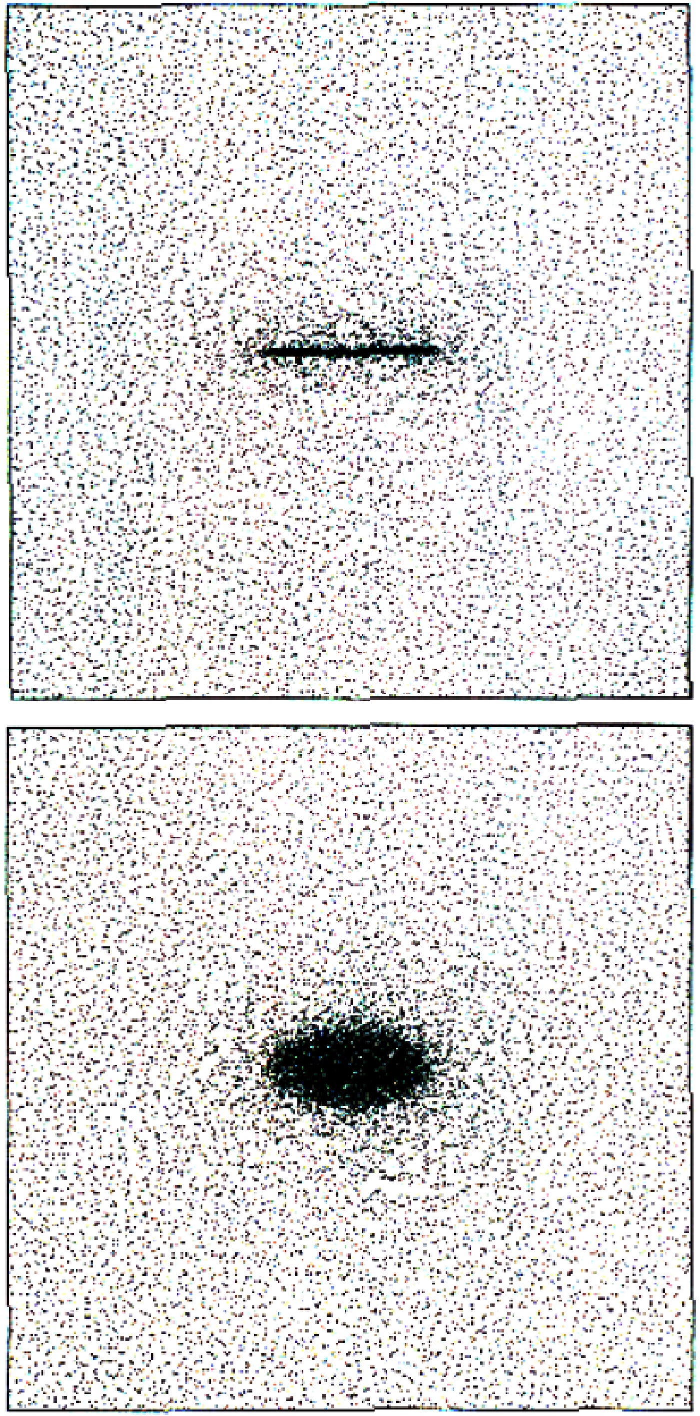
Two orthogonal slices through a 10% growing mode density perturbation imposed on a glass initial load in an EdS cosmology

Initial conditions a = 1



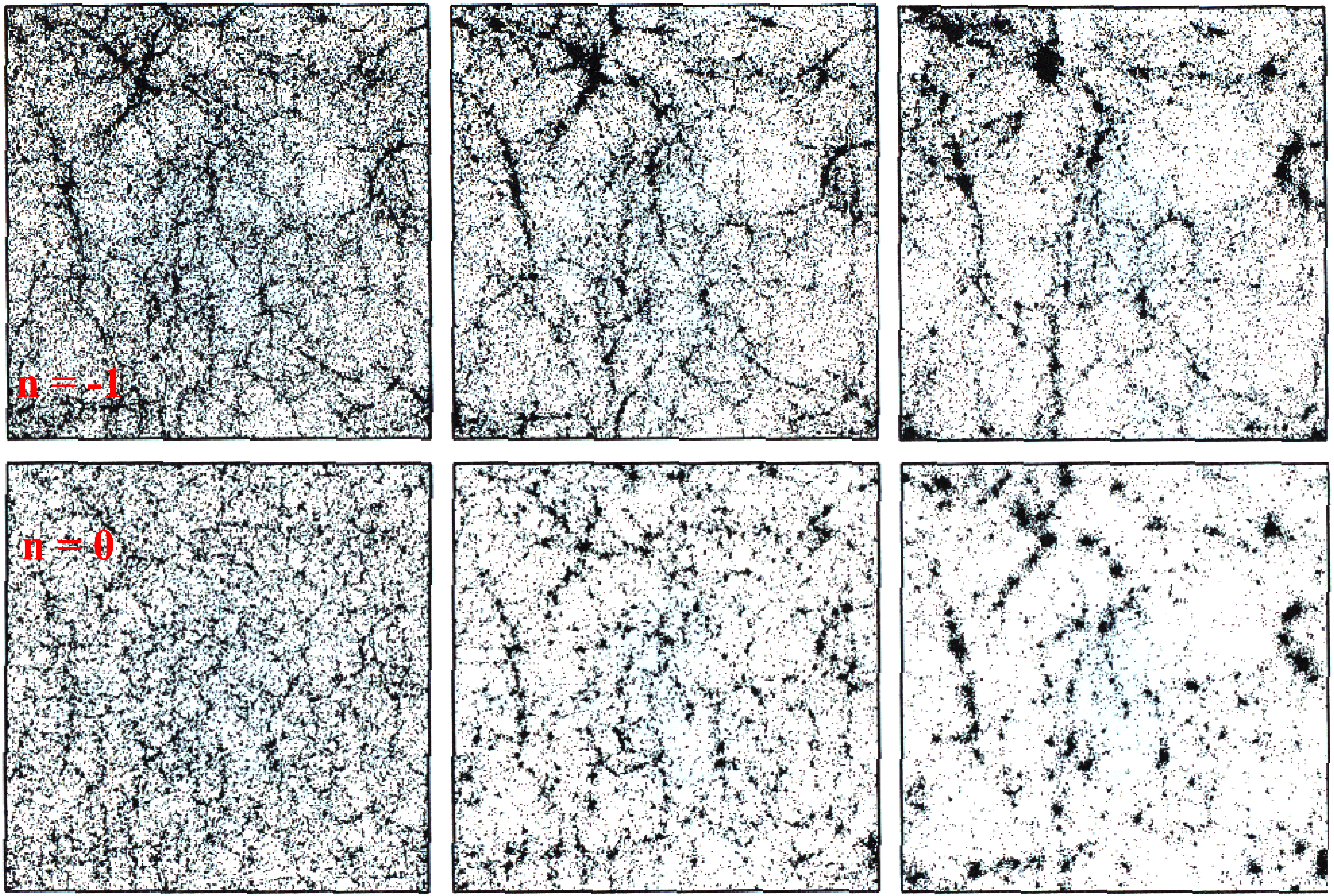
Two orthogonal slices through a 10% growing mode density perturbation imposed on a glass initial load in an EdS cosmology

$a = 10$



Two orthogonal slices through a 10% growing mode density perturbation imposed on a glass initial load in an EdS cosmology

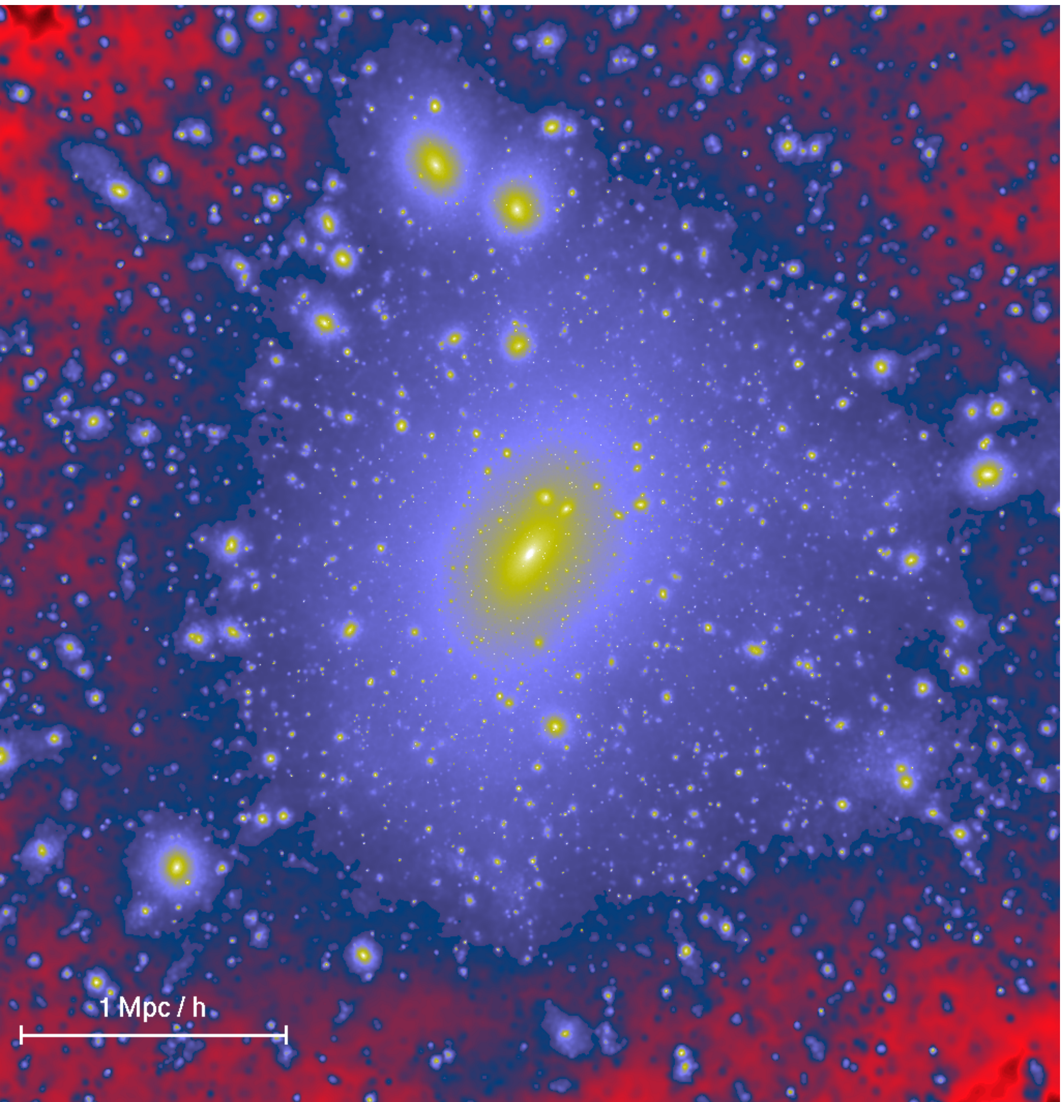
$a = 16$



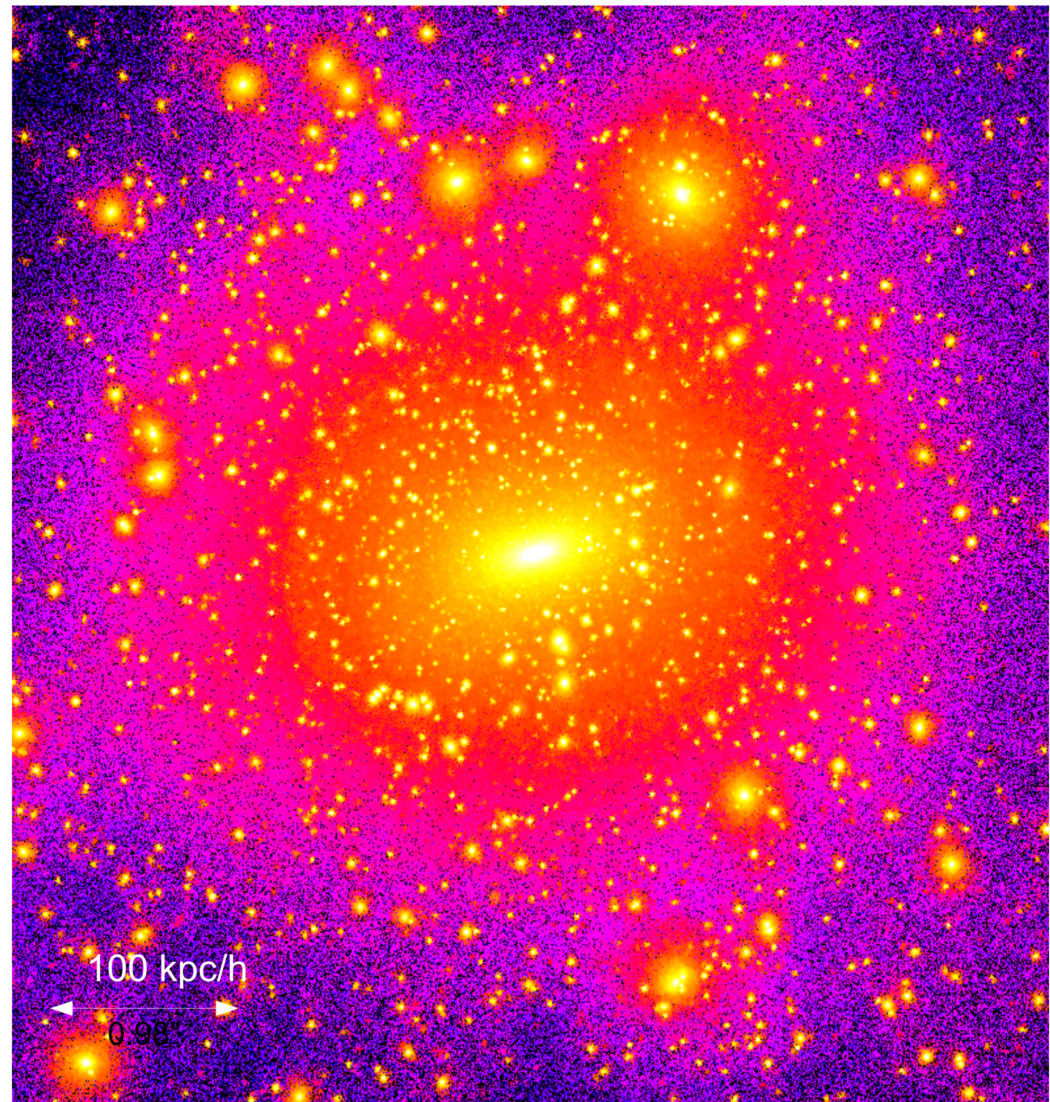
Self-similar evolution from scale-free ICs in EdS: matched nonlinear masses M_*

The dark matter structure of ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001



A 'Milky Way' halo
Power et al 2002



ΛCDM galaxy halos (without galaxies!)

Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions

Halos are not spherical but approximate triaxial ellipsoids

-- more prolate than oblate

-- axial ratios greater than two are common

"Cuspy" density profiles with outwardly increasing slopes

-- $d\ ln\ \varrho\ /\ d\ ln\ r = \gamma$ with $\gamma <$ -2.5 at large r

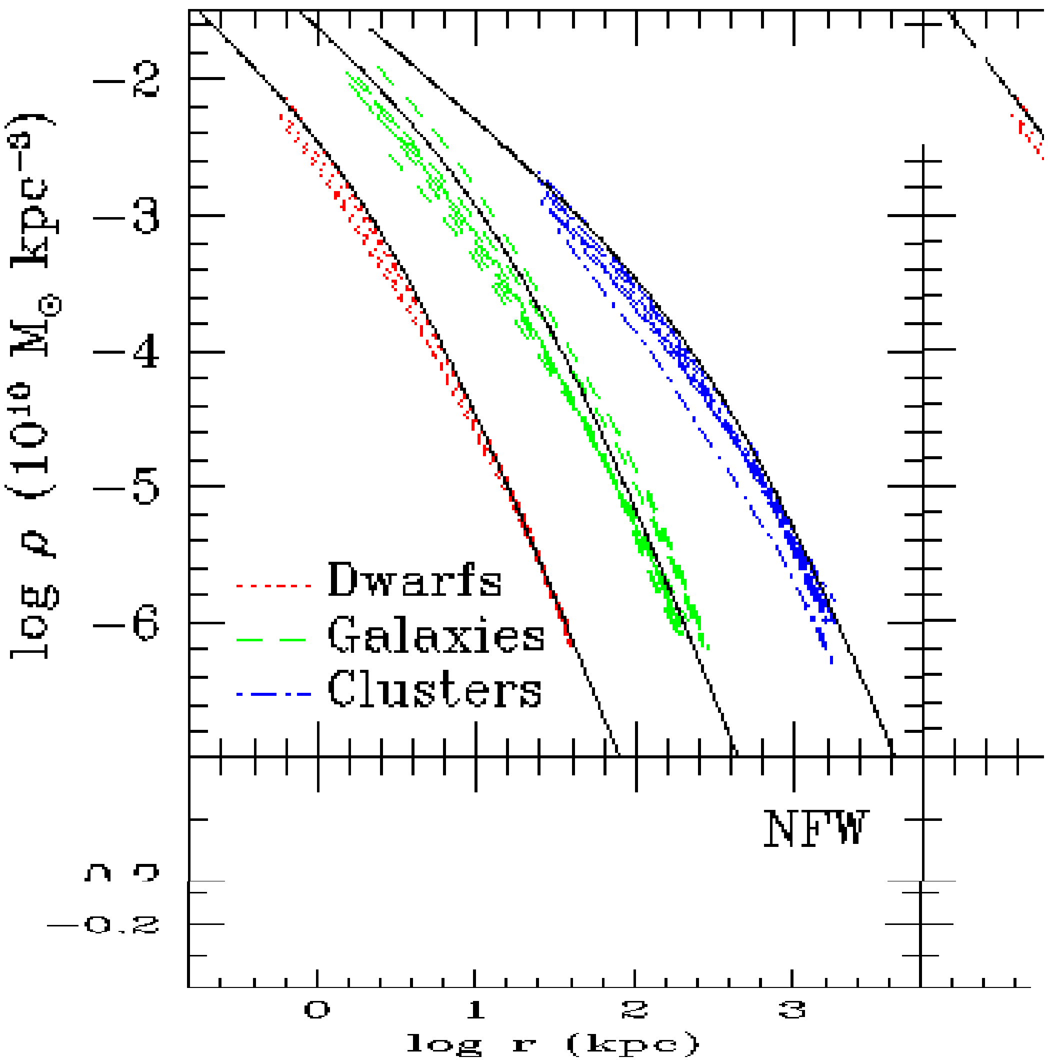
$\gamma >$ -1.2 at small r

Substantial numbers of self-bound subhalos contain ~10% of the halo's mass and have $d\,N\,/\,d\,M \sim M^{-1.8}$

→ Most substructure mass is in most massive subhalos

Density profiles of dark matter halos

Navarro, Frenk & White 1996



The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times

-- a universal profile shape --

$$\rho(r)/\rho_{crit} \approx \delta \; r_s / r(1 + r/r_s)^2$$

Less massive halos and halos that form earlier have higher densities (bigger δ)

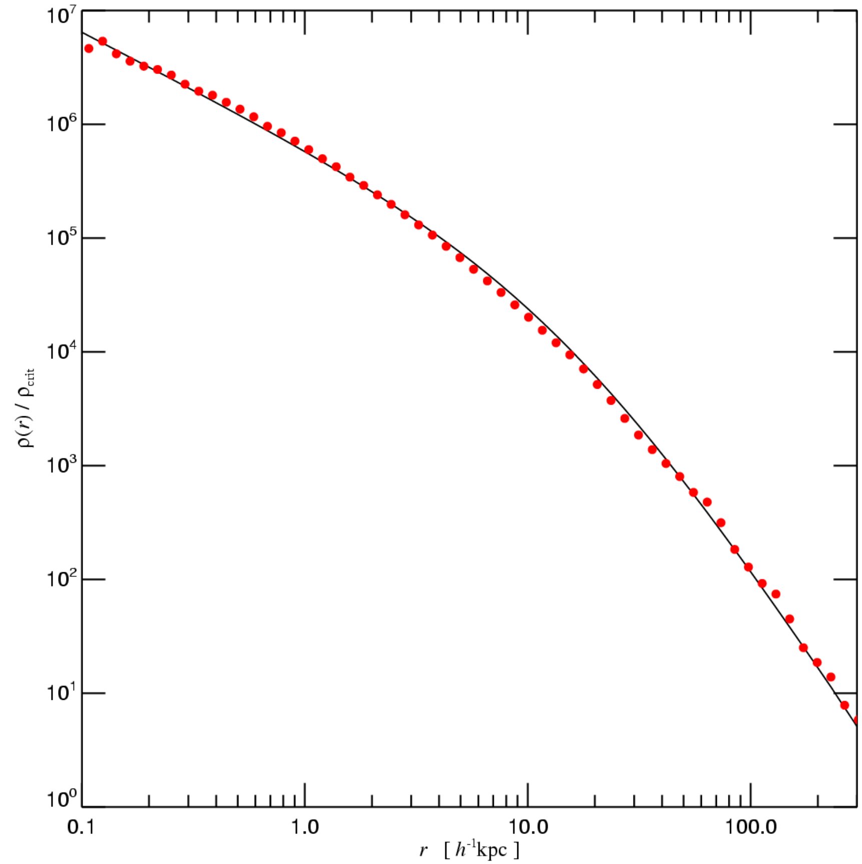
Concentration $c = r_{200} / r_s$ is an alternative density measure

Beware variety of definitions!

NFW profiles may not be pretty....

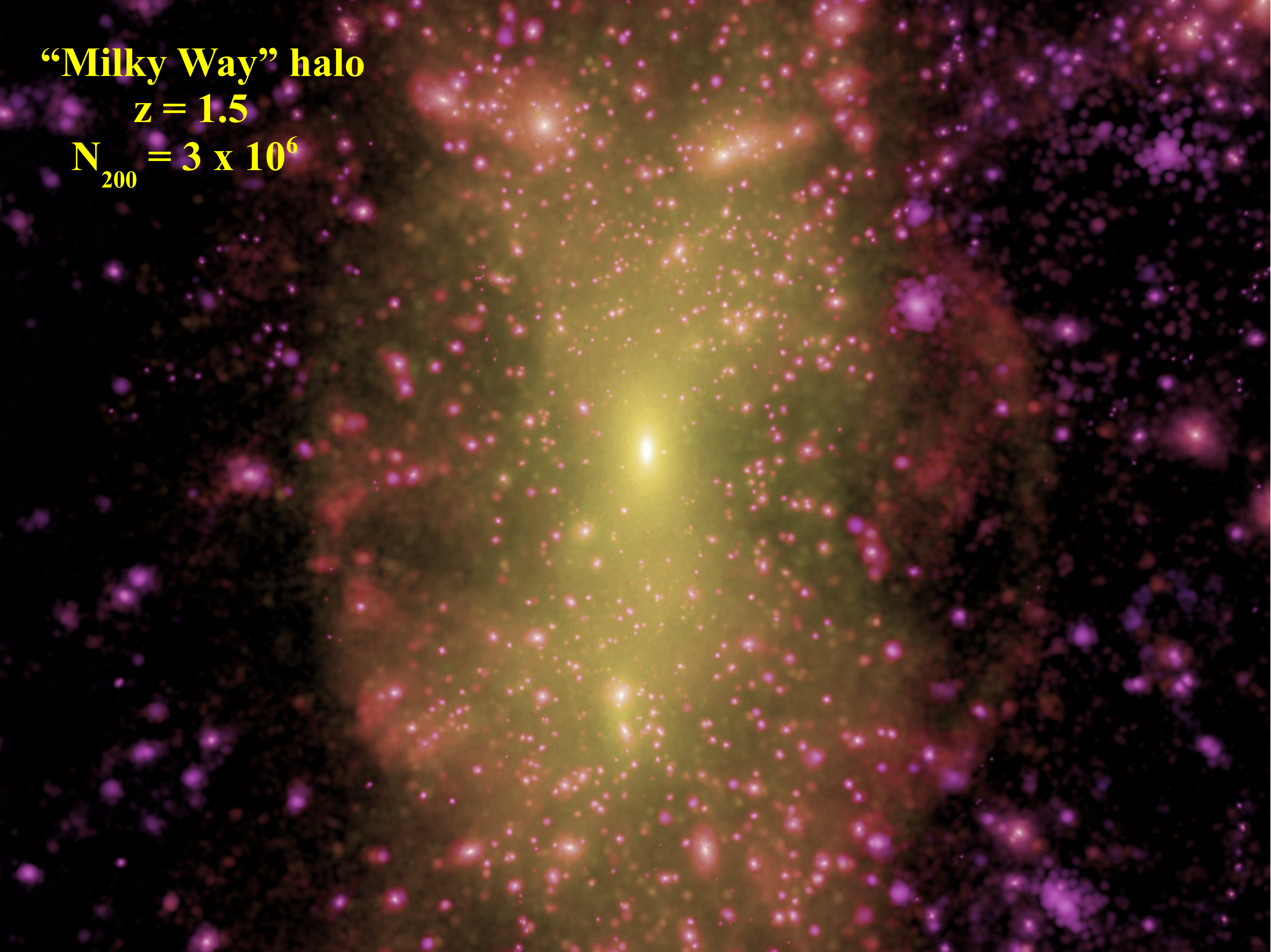
...but they work surprisingly well

600 kpc



$N_{200} \sim 3 \times 10^7$

Navarro et al 2006

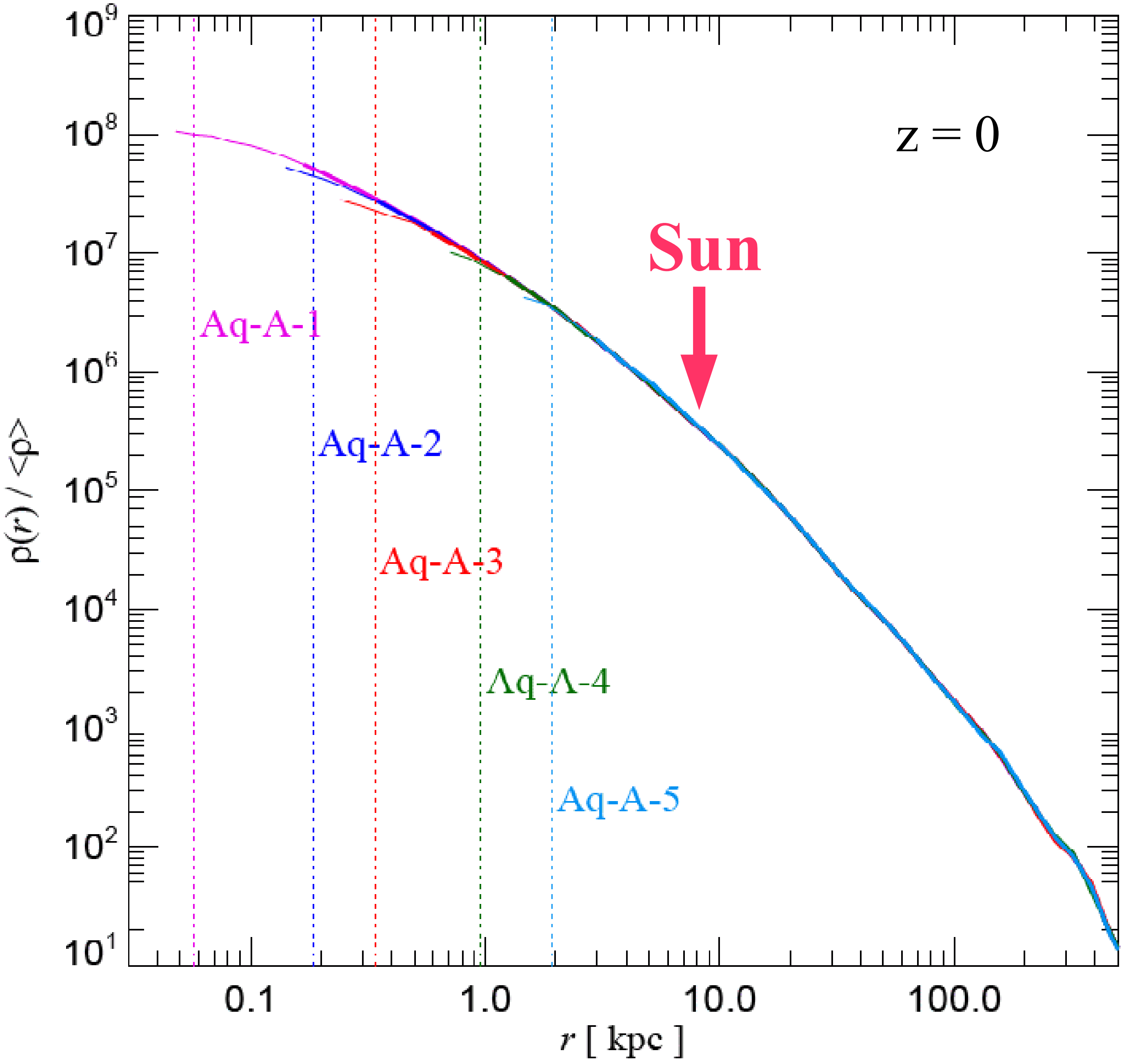

"Milky Way" halo
z = 1.5
N200 = 3 x 10^6


"Milky Way" halo
z = 1.5
$N_{200} = 94 \times 10^6$


"Milky Way" halo
z = 1.5
N200 = 750 x 10^6

How well do density profiles converge?

Aquarius Project: Springel et al 2008



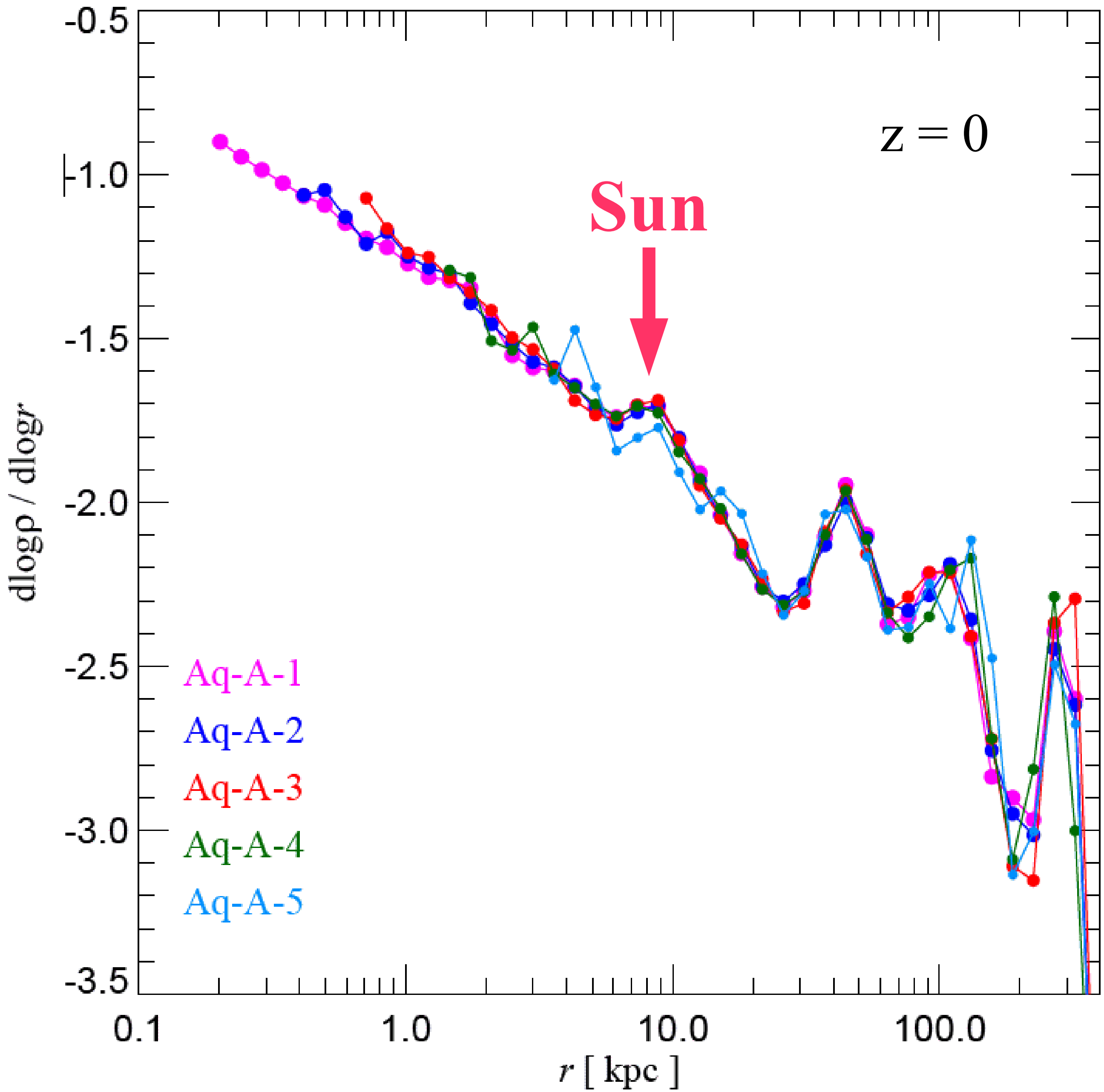
Mass and length resolution vary by factors of 2000 and 35

Convergence excellent to radii well below that of the Sun's orbit

Real DM profile will be modified by growth of the visible Galaxy

How well do density profiles converge?

Aquarius Project: Springel et al 2008



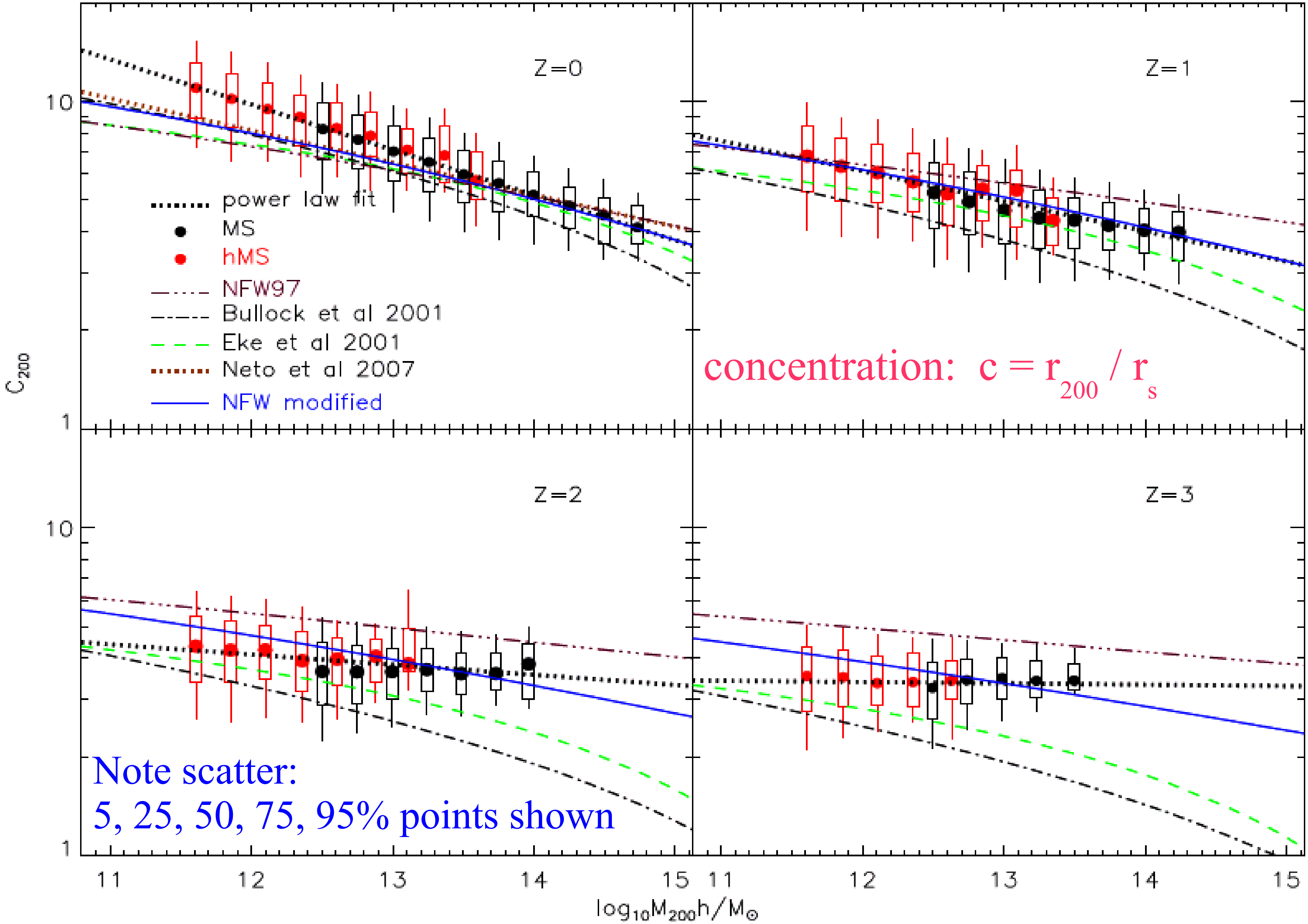
Mass and length resolution vary by factors of 2000 and 35

Convergence excellent to radii well below that of the Sun's orbit

Real DM profile will be modified by growth of the visible Galaxy

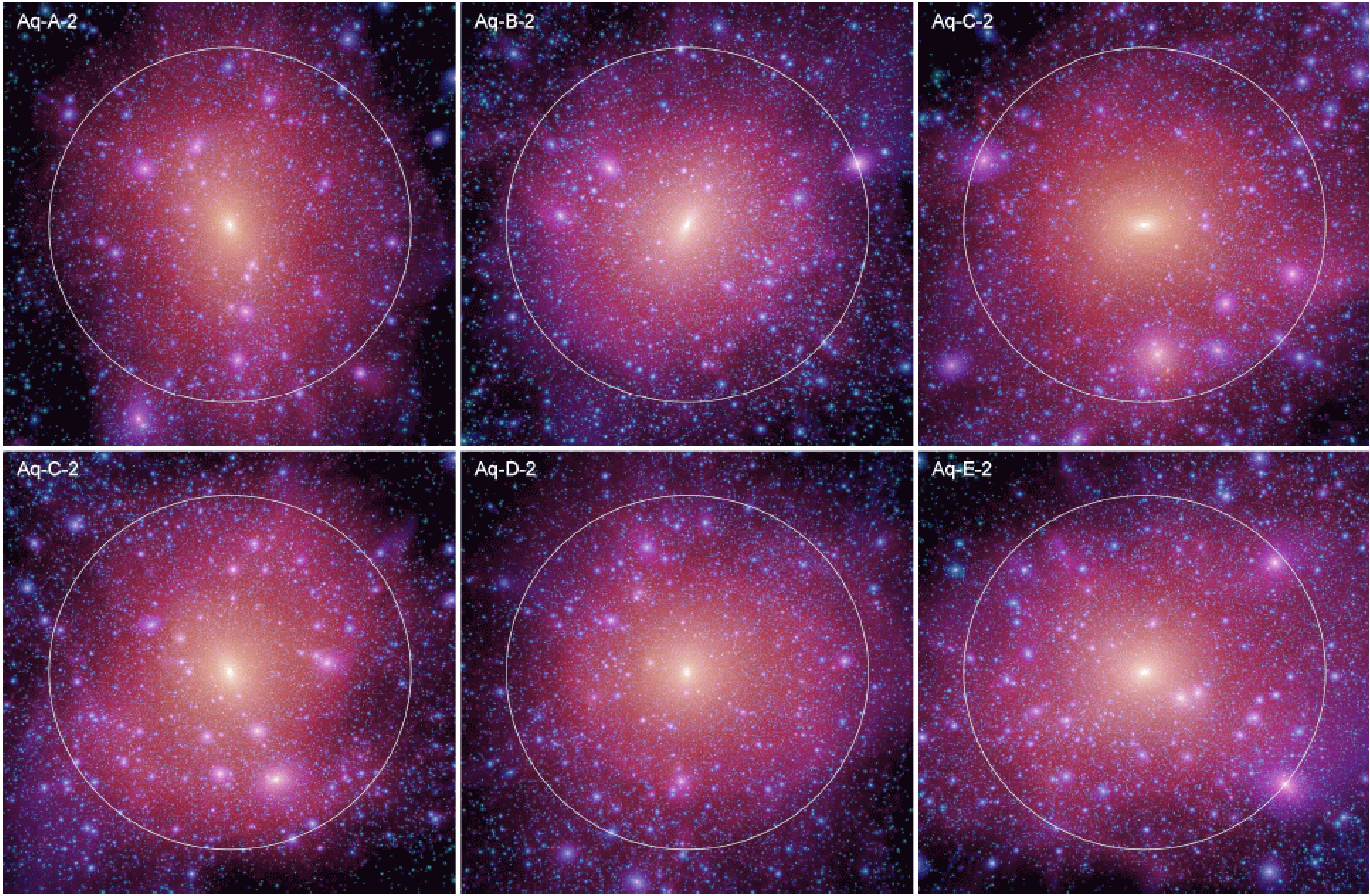
Concentration scatter and trend with M and z

Gao et al 2008



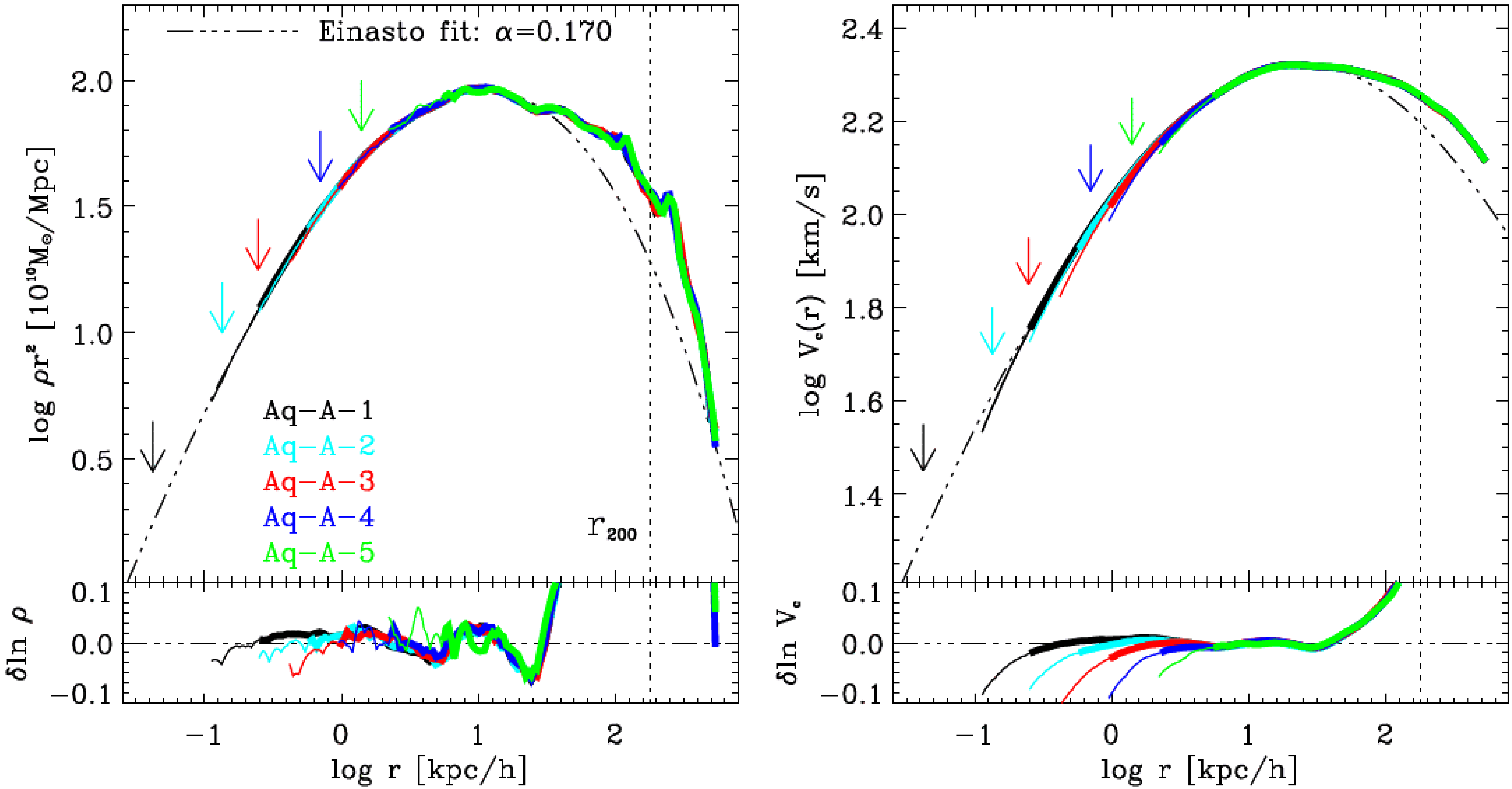
The Aquarius halos

Springel et al 2008



The Einasto profile fits the inner cusps

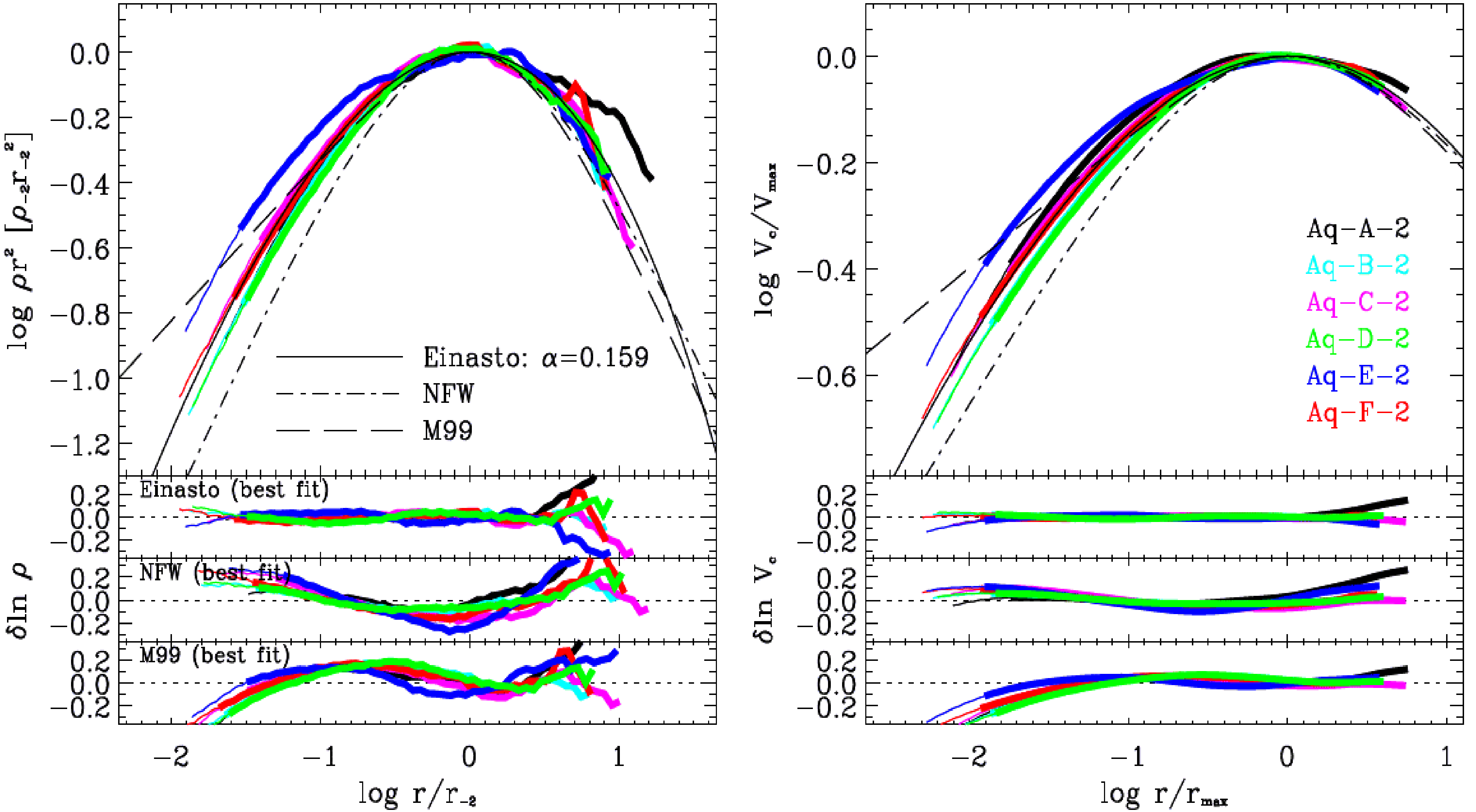
Navarro et al 2009



Einasto's (1965) profile: $\ln \rho(r)/\rho_{-2} = -2/\alpha \; [(r/r_{-2})^{\alpha} - 1]$

The Einasto profile fits the inner cusps

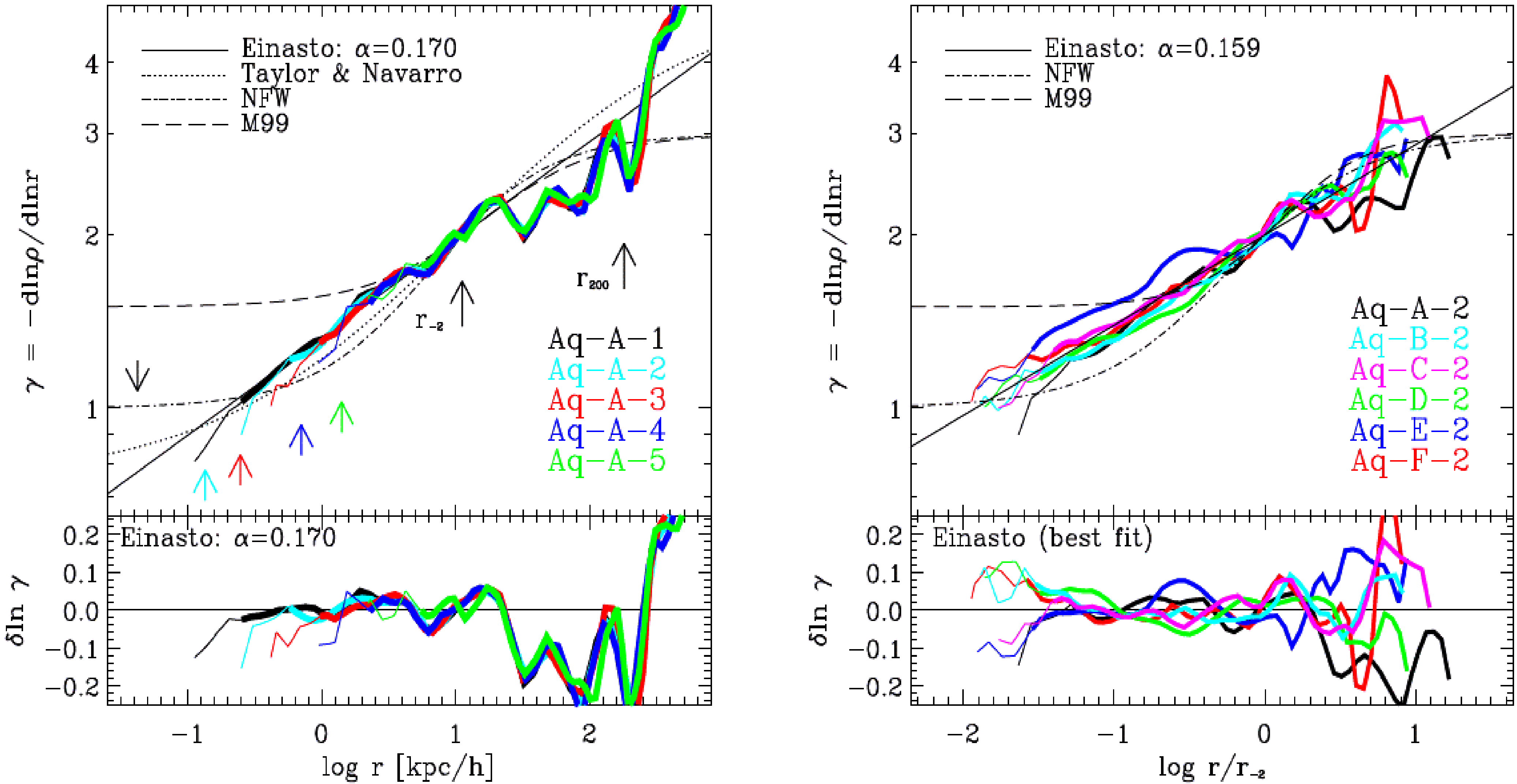
Navarro et al 2009



Einasto's (1965) profile: $\ln \rho(r)/\rho_{-2} = -2/\alpha \left\lfloor (r/r_{-2})^{\alpha} - 1 \right\rfloor$

The Einasto profile fits the inner cusps

Navarro et al 2009

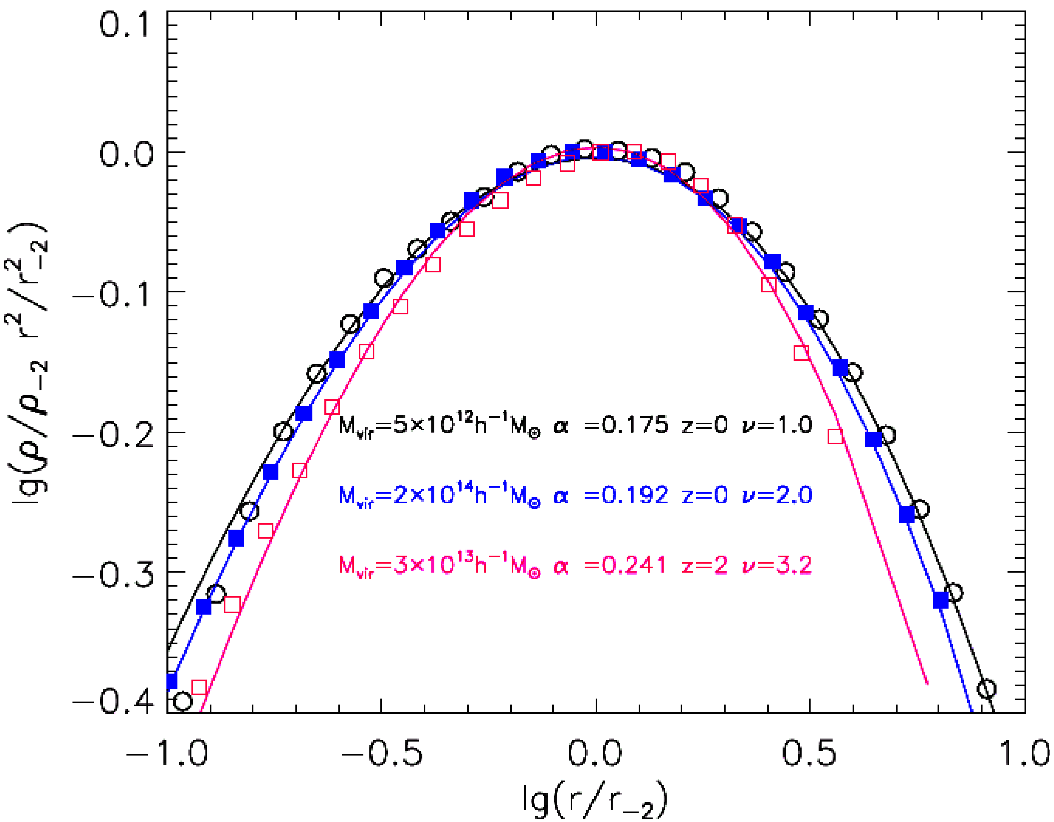


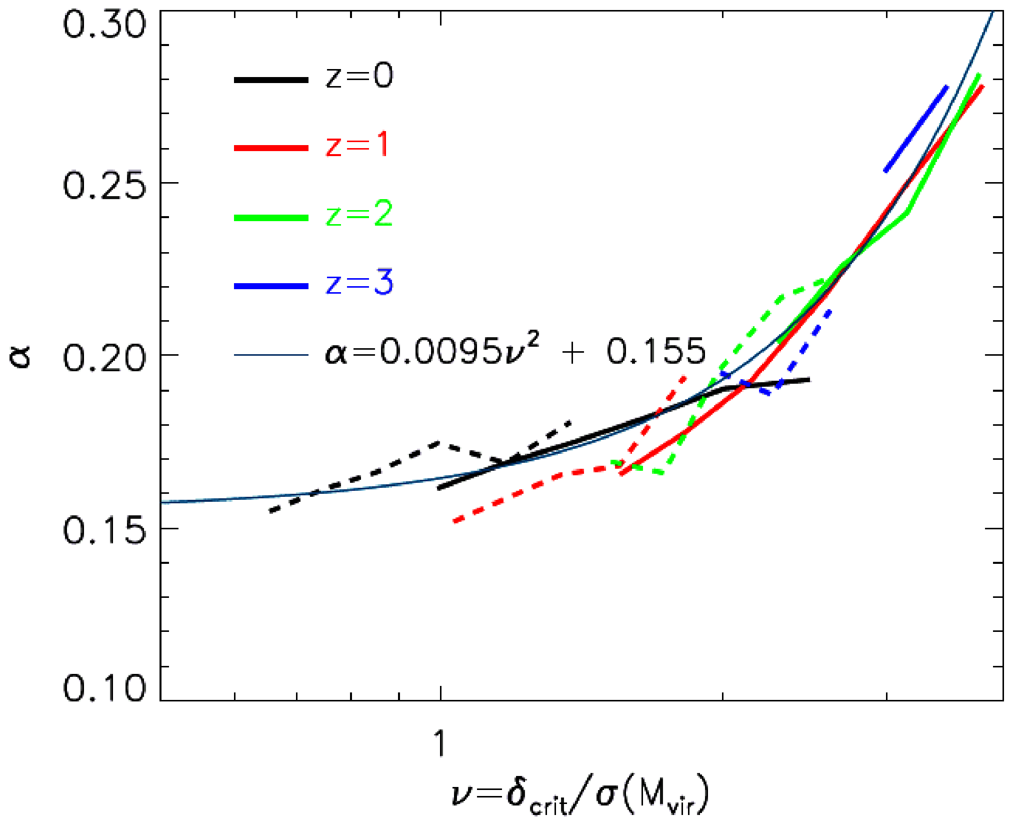
Einasto's (1965) profile: $\ln \rho(r)/\rho_{-2} = -2/\alpha \left[(r/r_{-2})^{\alpha} - 1\right]$

The Einasto α varies with mass

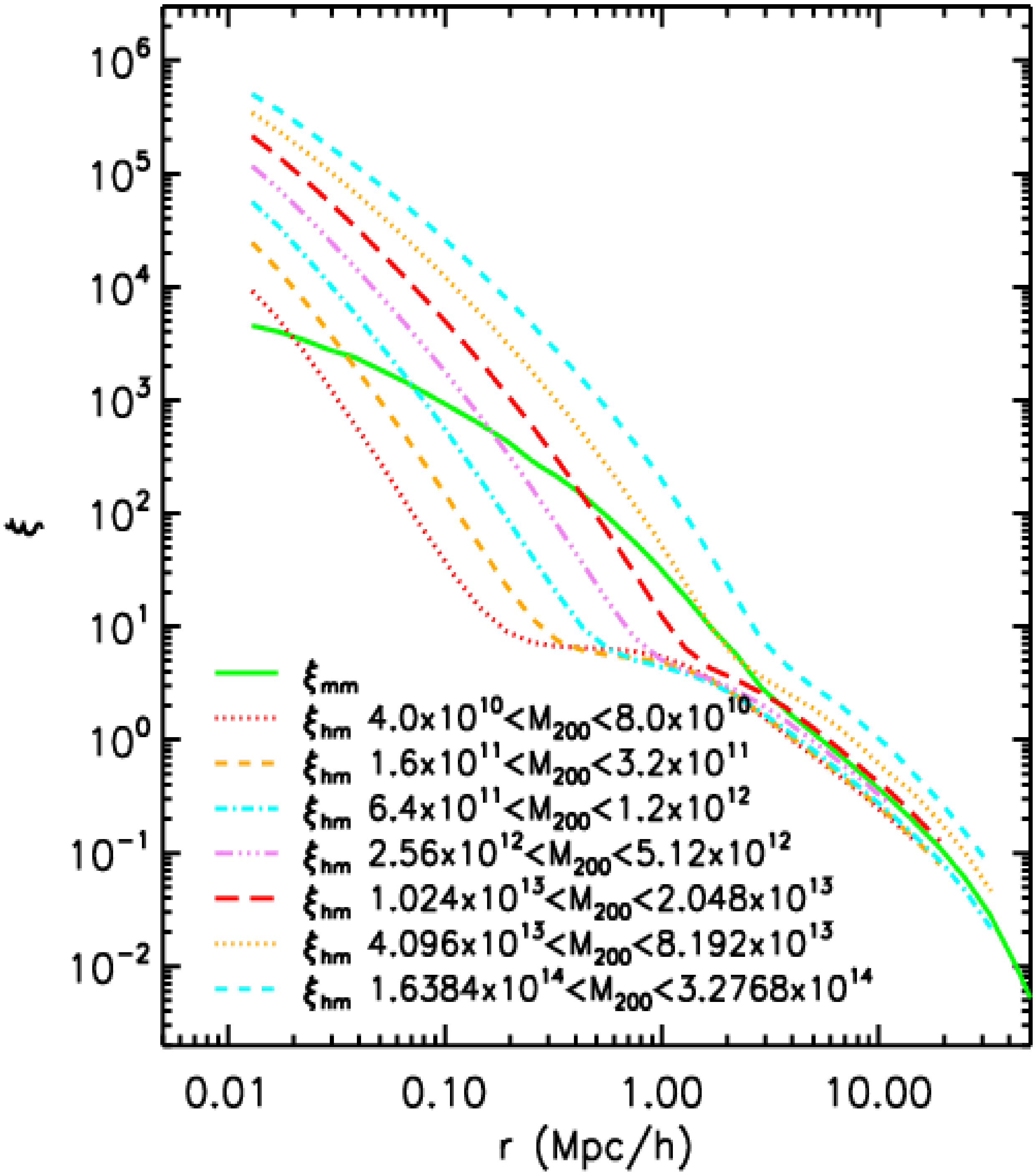
Gao et al 2008

Results for stacked halos in the Millennium Simulation





Einasto's (1965) profile: $\ln\ \rho(r)/\rho_{-2} = -2/\alpha\ [(r/r_{-2})^{\alpha} - 1]$



Mean profiles to much larger radii

Hayashi & White 2008

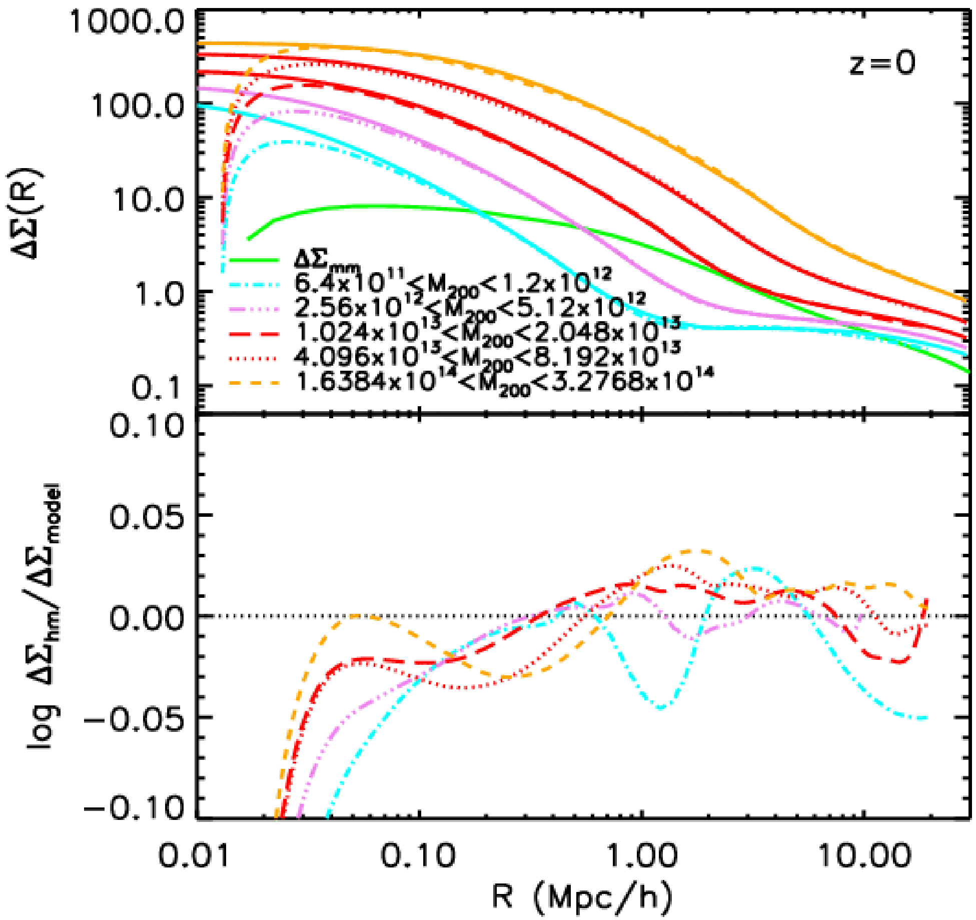
At large radii, the mean density profile $\bar{\rho}(r) \propto \xi_{lin}(r)$, the *linear* mass correlation function

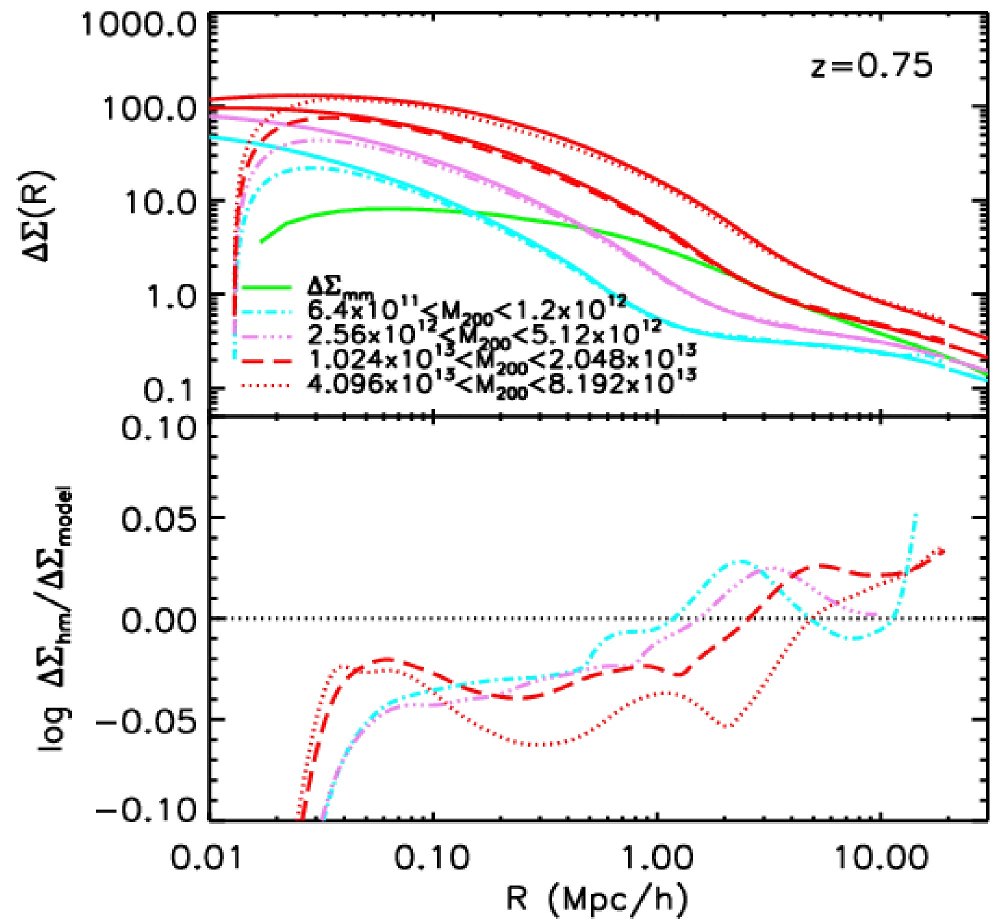
To a good approximation

$$\bar{\rho}(r) = \max[\ \rho_{Ein}(r),\ b\ \xi_{lin}(r)\ ]$$

A lensing test of the DM paradigm?

Hayashi & White 2008

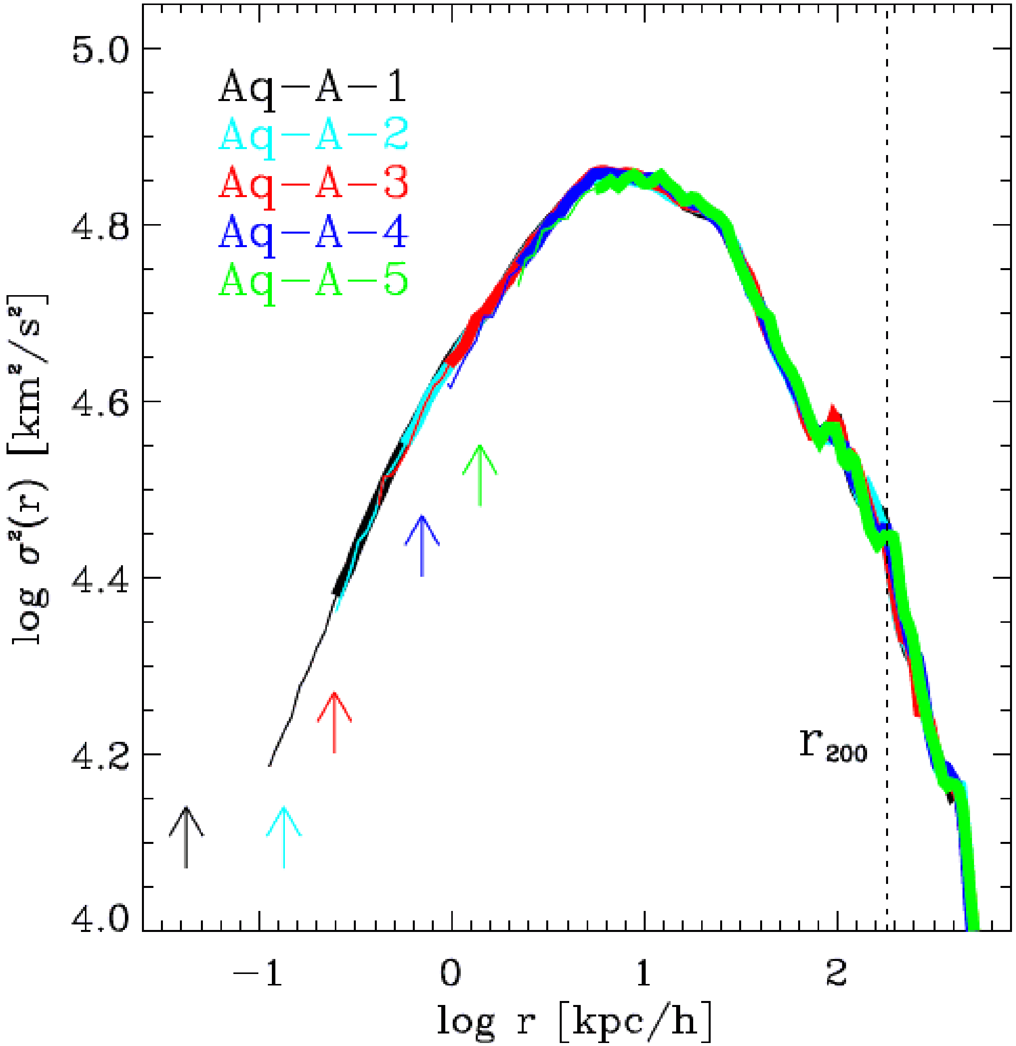


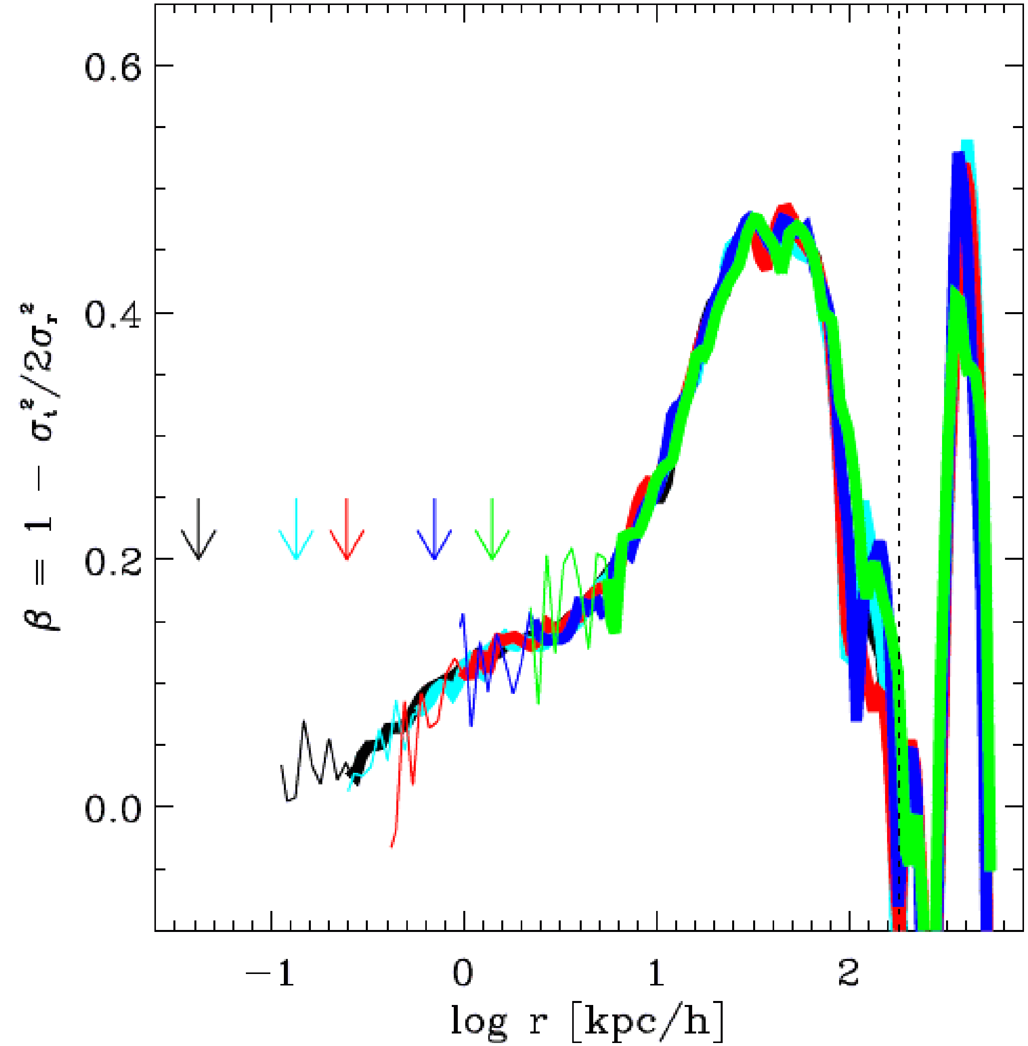


Gravitational lensing allows *measurement* of these mean profiles
The characteristic shape is a direct test of the DM paradigm

Velocity dispersion profiles

Navarro et al 2009



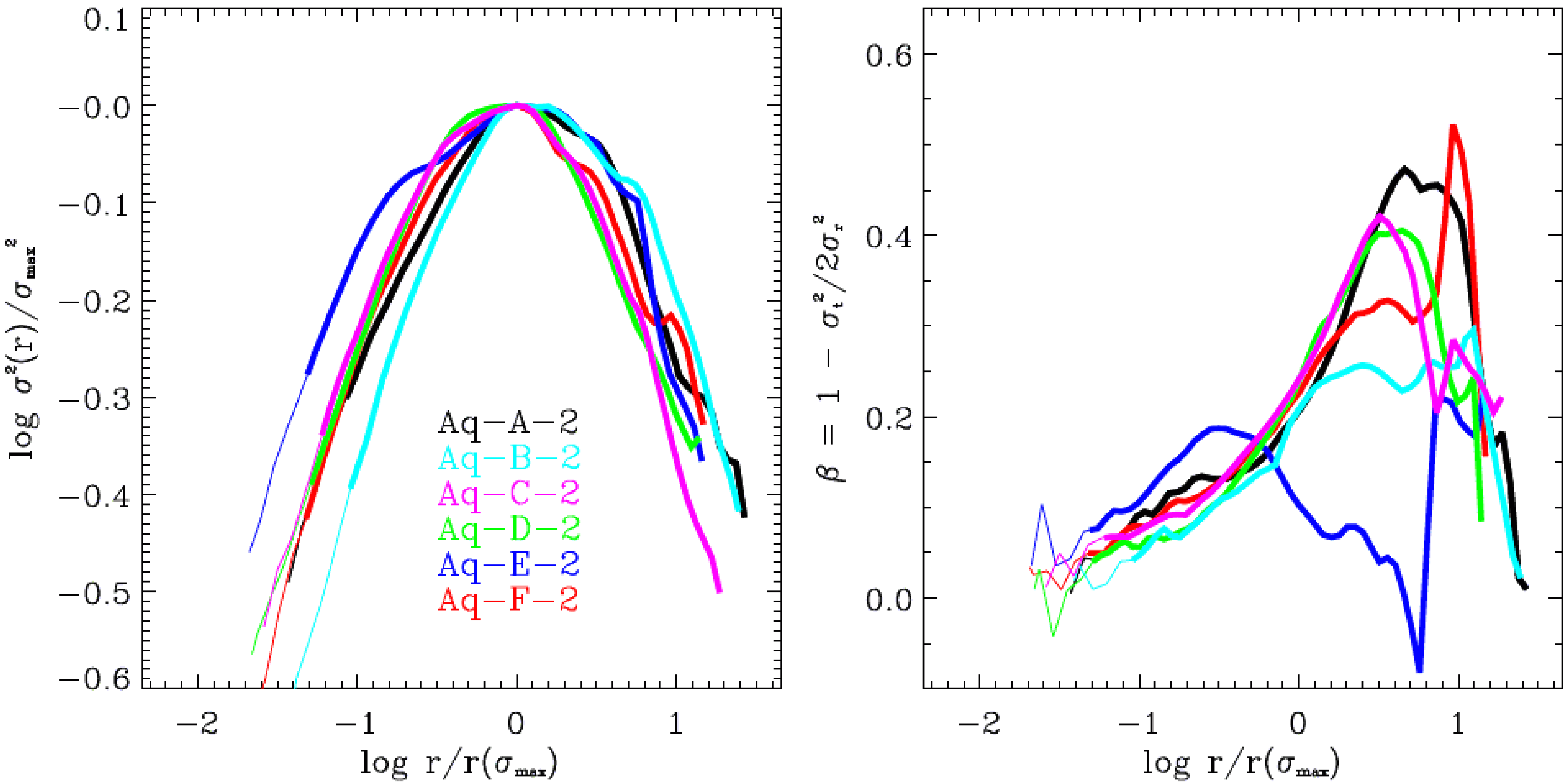


Results are well converged

Velocity dispersion and anisotropy peak at intermediate radii

Velocity dispersion profiles

Navarro et al 2009



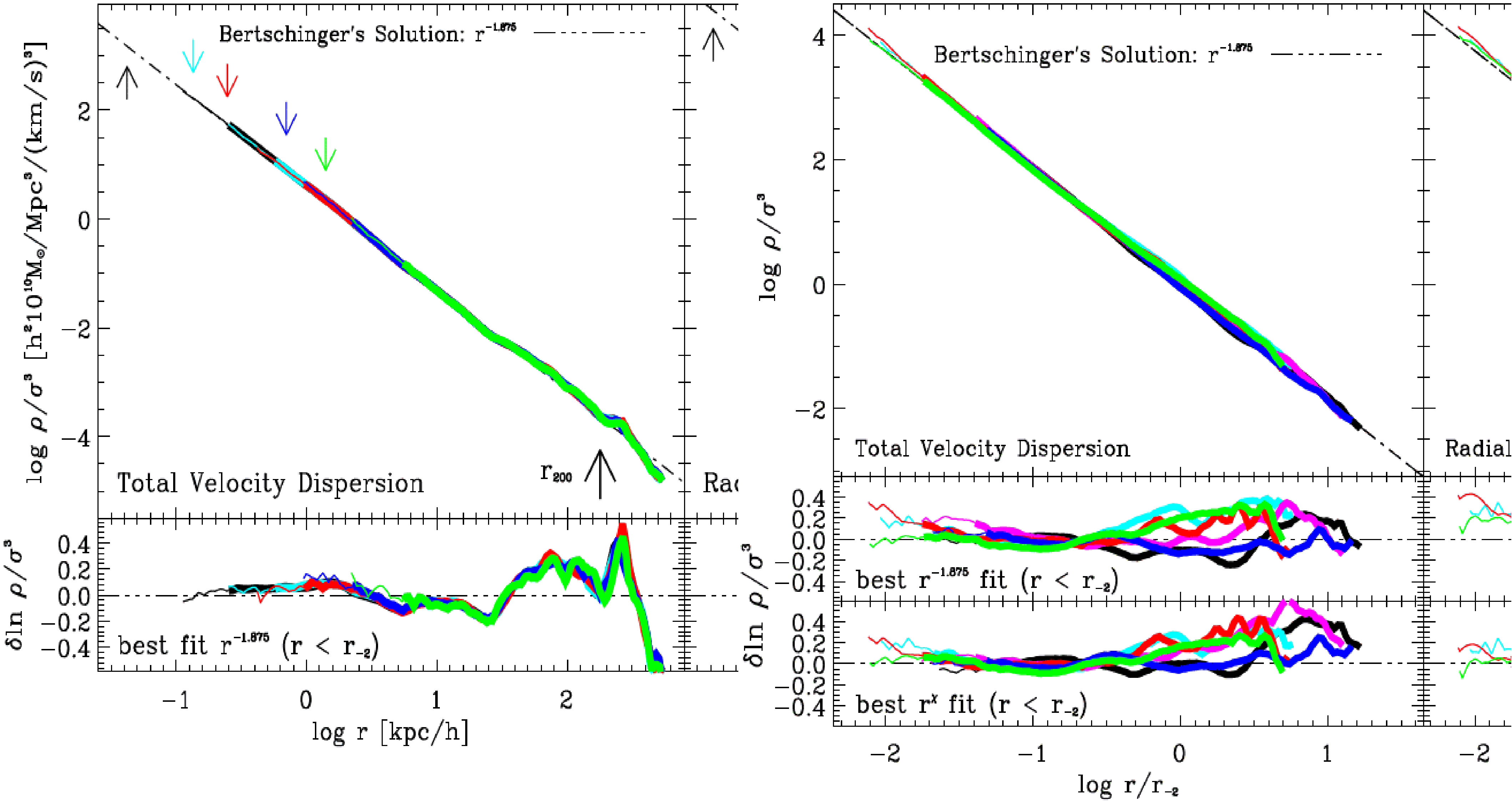
Results are well converged

Velocity dispersion and anisotropy peak at intermediate radii

Profiles vary significantly between halos

Pseudo-phase-space density profiles

Navarro et al 2009



Shape variations in the density and velocity dispersion profiles compensate to make $\rho(r)/\sigma(r)^3$ an almost universal power law

Halo profiles: conclusions

The NFW formula fits spherically averaged profiles of most objects to within 10% out to at least 2 r_s

The characteristic density (or concentration) varies with mass, redshift and cosmology

The Einasto formula fits better – its additional shape parameter varies systematically with mass

There is no indication of *any* "asymptotic inner power law"

The scatter among halos is larger than the Einasto-NFW difference

Mean profiles change shape dramatically at large radius ($\delta < 10$)

Velocity dispersion profiles show considerable variation

Variations in $\rho(r)$ and $\sigma(r)$ compensate to give power law ρ/σ^3

Halo profiles: observational issues

ΛCDM halos agree well with the observed structure of

Galaxy halos (10 to 200 kpc: lensing, satellite motions)

Cluster halos (30 to 2000 kpc: lensing, X-ray data on gas)

They appear to disagree with data in the inner parts of galaxies

Milky Way $M_{200} = 1(2)\ \mathrm{x}10^{12} M_\odot \longrightarrow M(R_\odot) = 3.3(4.5)\mathrm{x}10^{10} M_\odot$

to compare with $M_*(R_\odot) = 5\mathrm{x}10^{10} M_\odot$

LSB/dwarf galaxies Rotation curves rise slower than expected

The “Cusp Problem”

Baryonic physics complicates this comparison

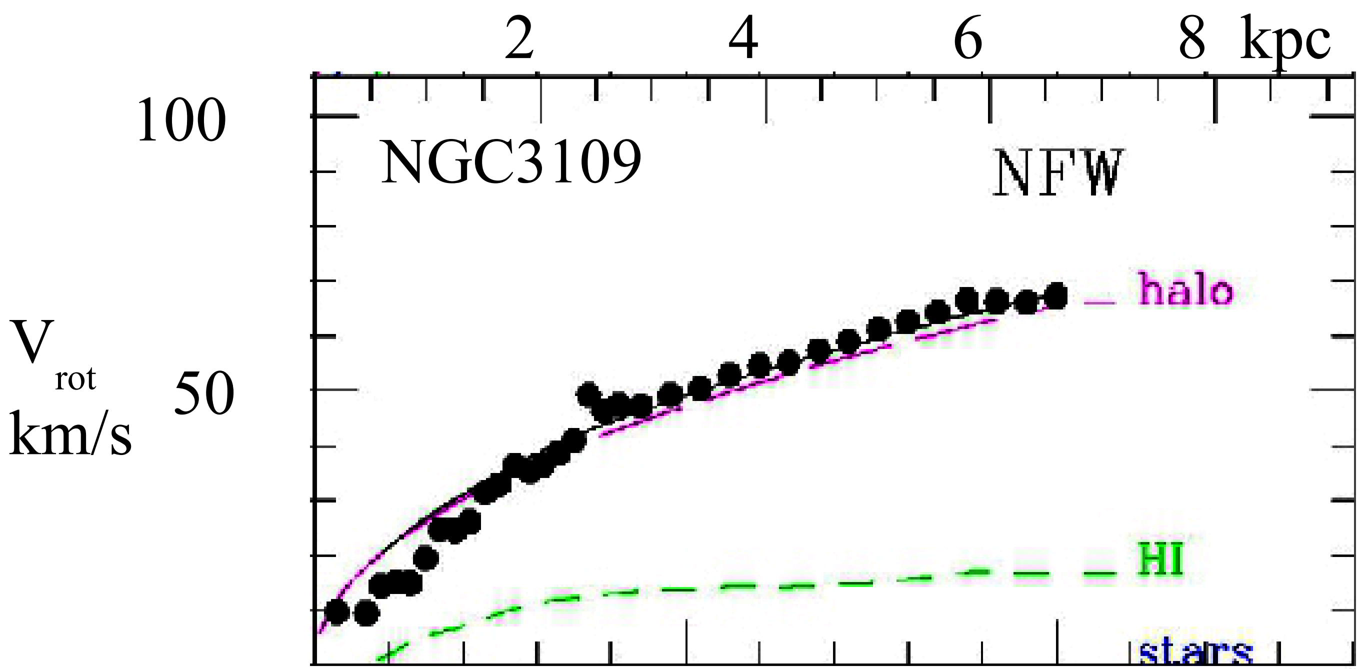
Adiabatic compression increase may central DM densities

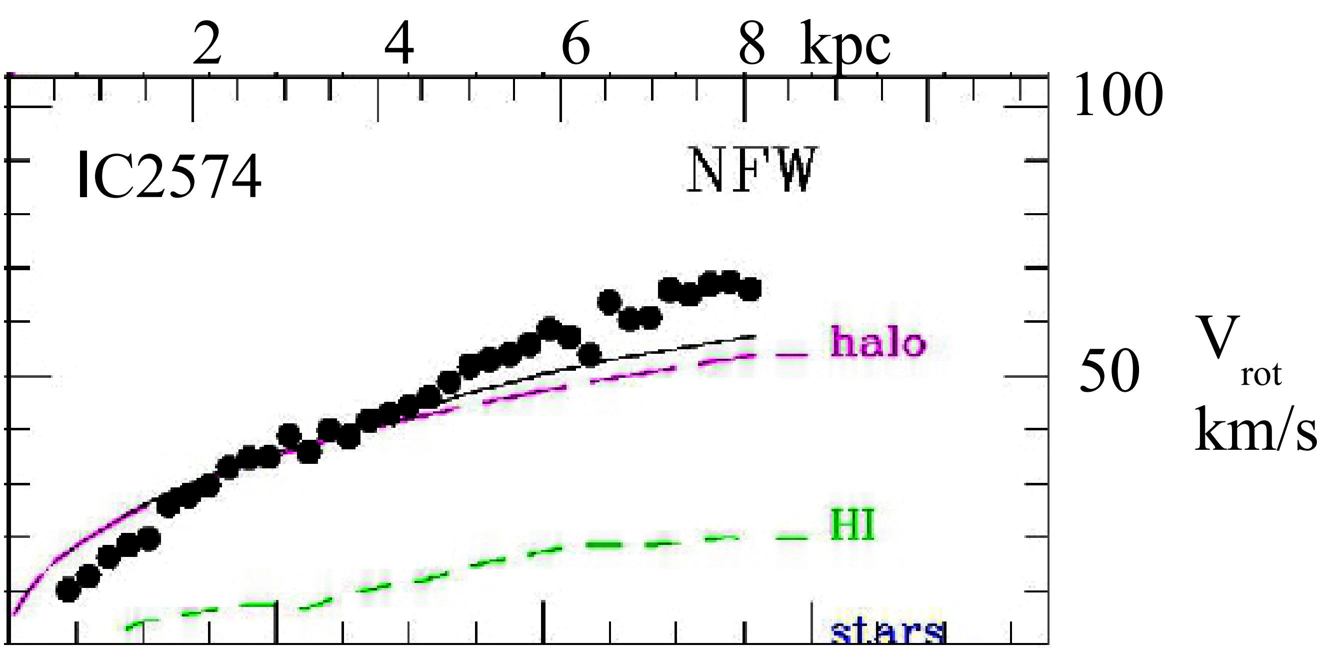
Sudden expulsion of gas may decrease central DM densities

both are quite uncertain

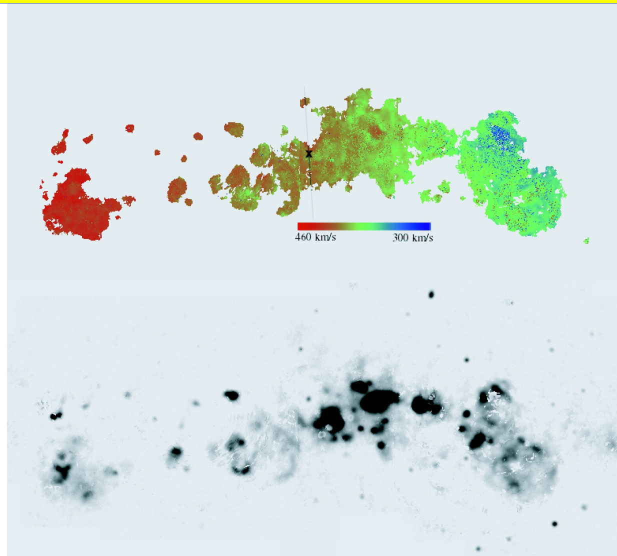
High quality rotation curves for nearby dwarfs: I

Blais-Ouellette, Amram & Carignan 2001



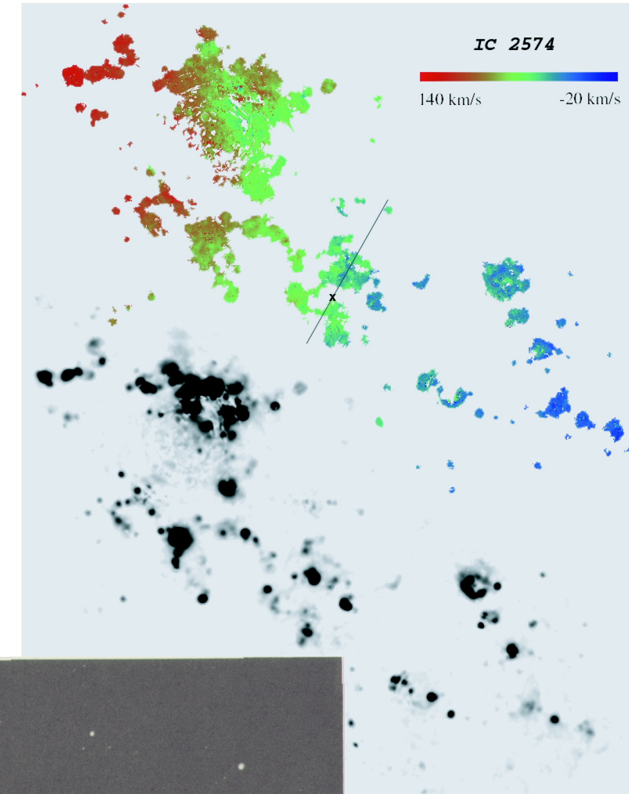


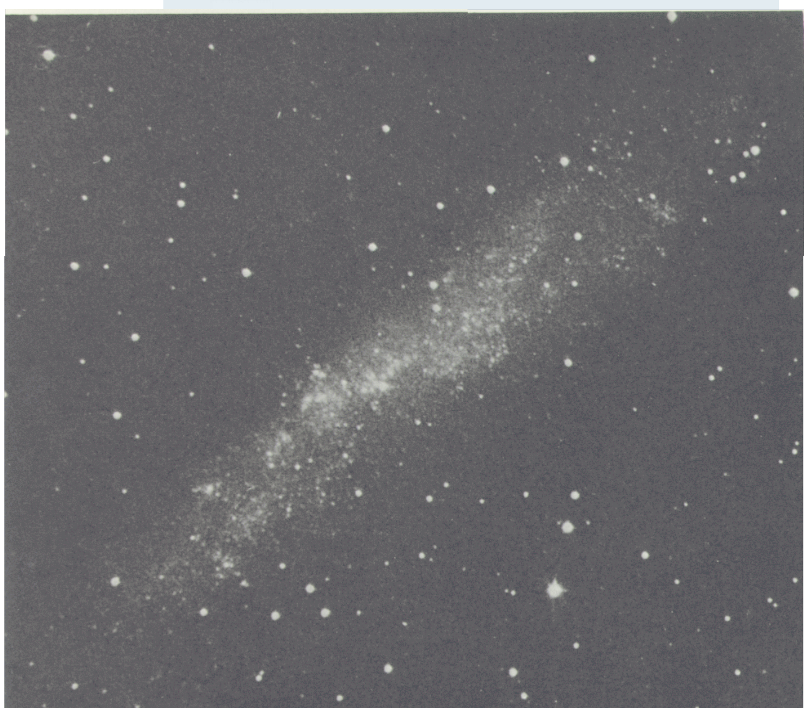
High quality rotation curves for nearby dwarfs: II

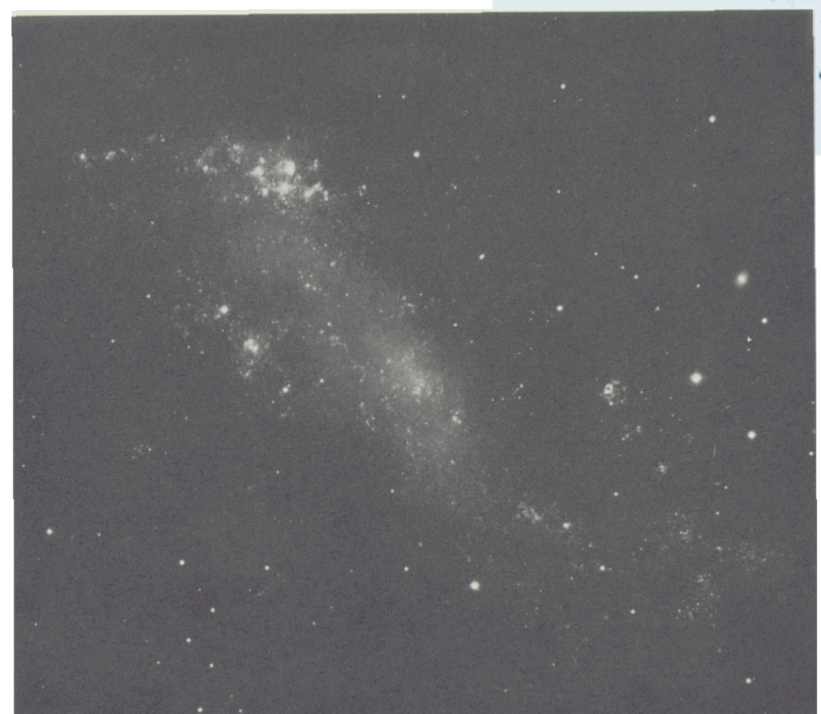


NGC3109

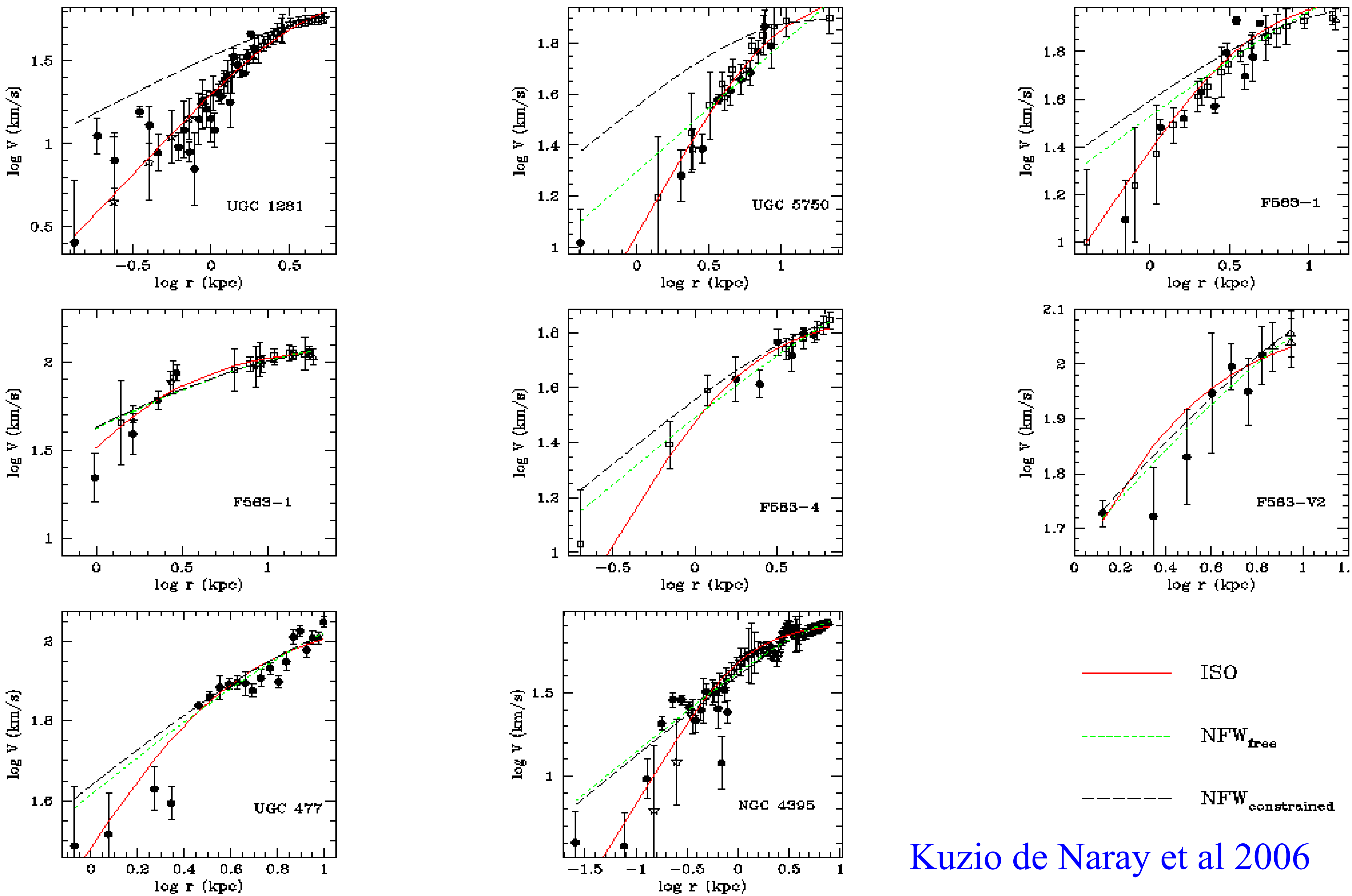
IC2574



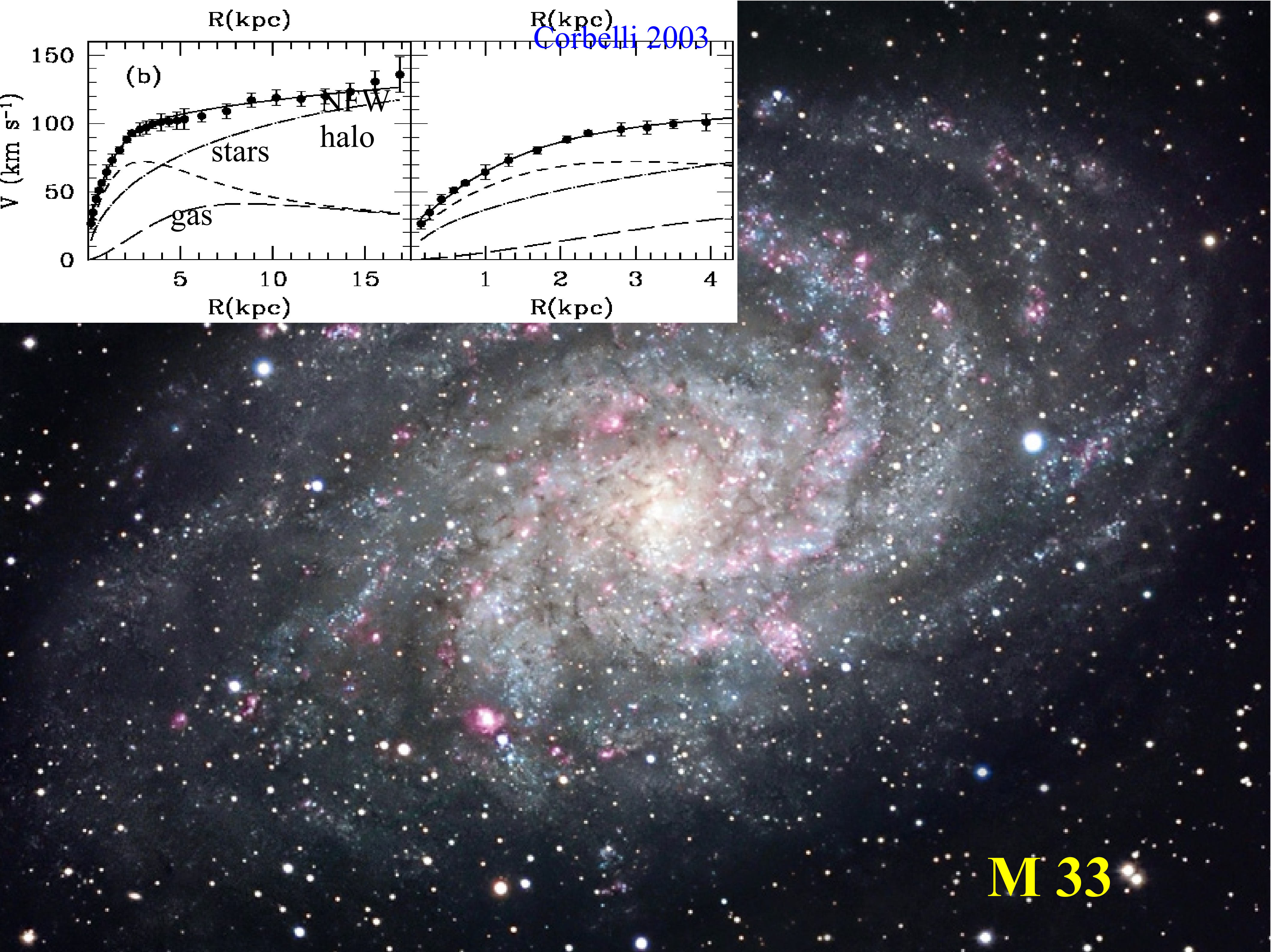




Inner rotation curves of low SB galaxies

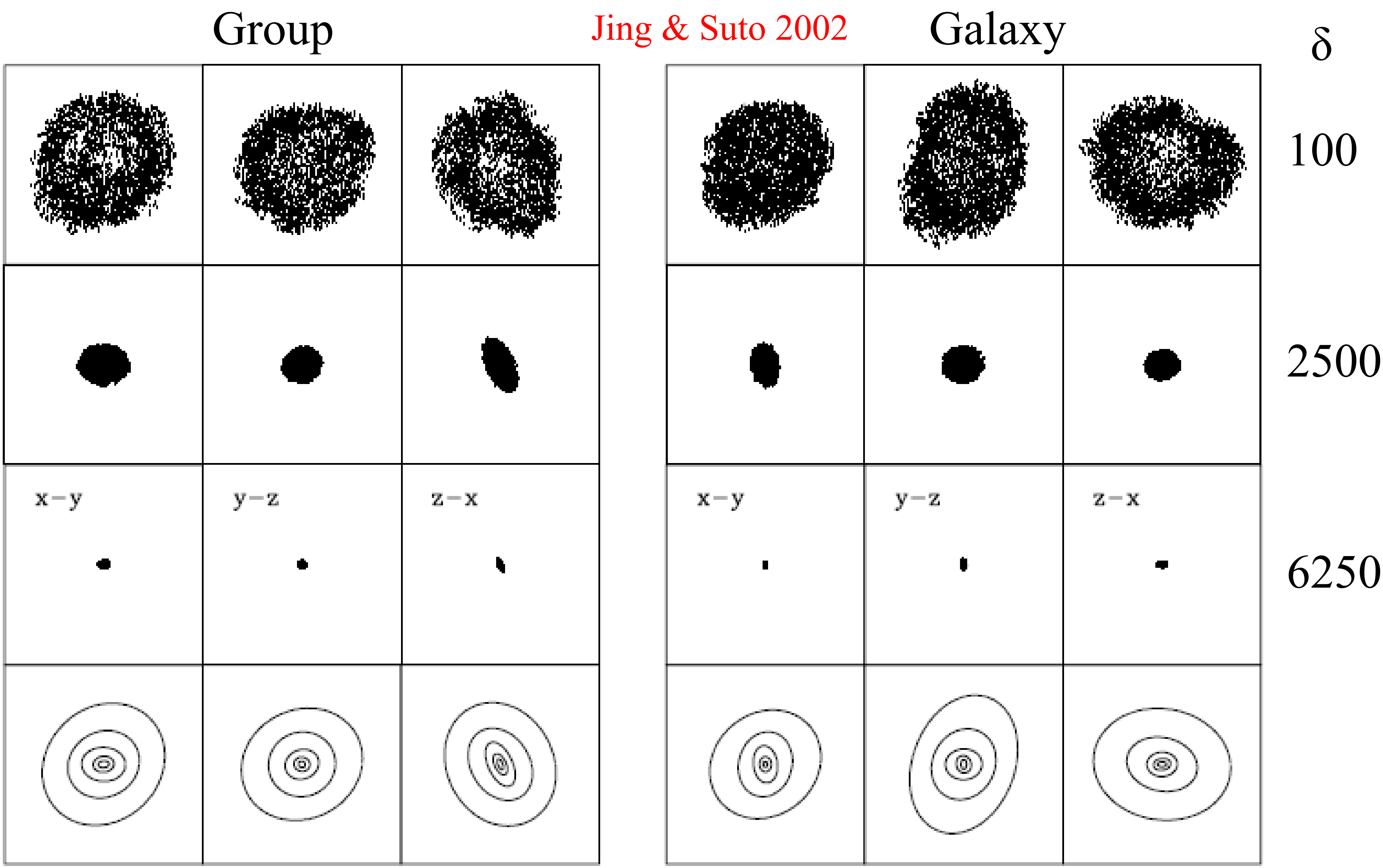


Kuzio de Naray et al 2006



Corbelli 2003
R(kpc)
R(kpc)
V (km s-1)
150
100
50
0
(b)
NFW
halo
stars
gas
5
10
15
1
2
3
4
R(kpc)
R(kpc)
M 33

Shapes of halo equidensity surfaces



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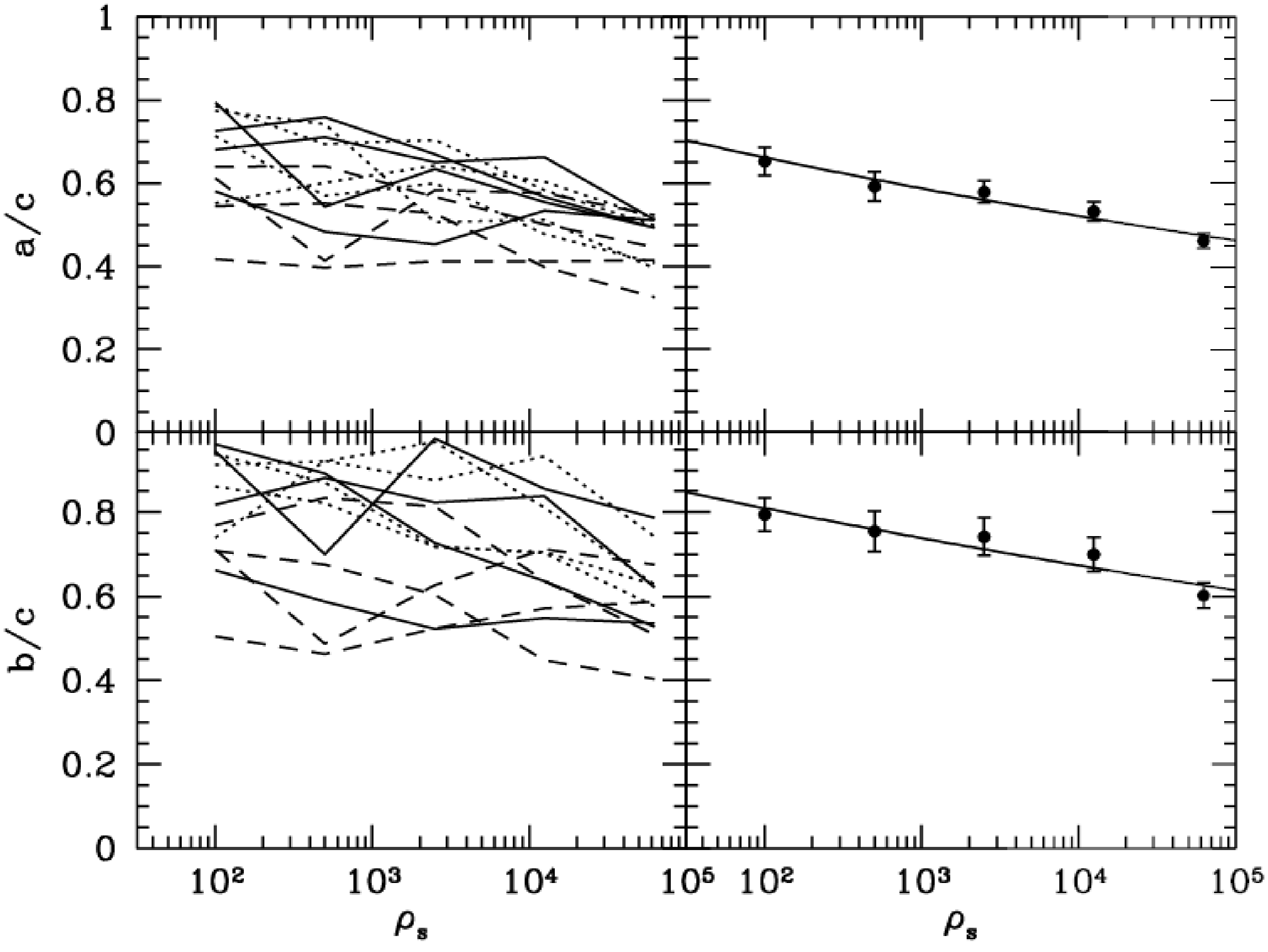


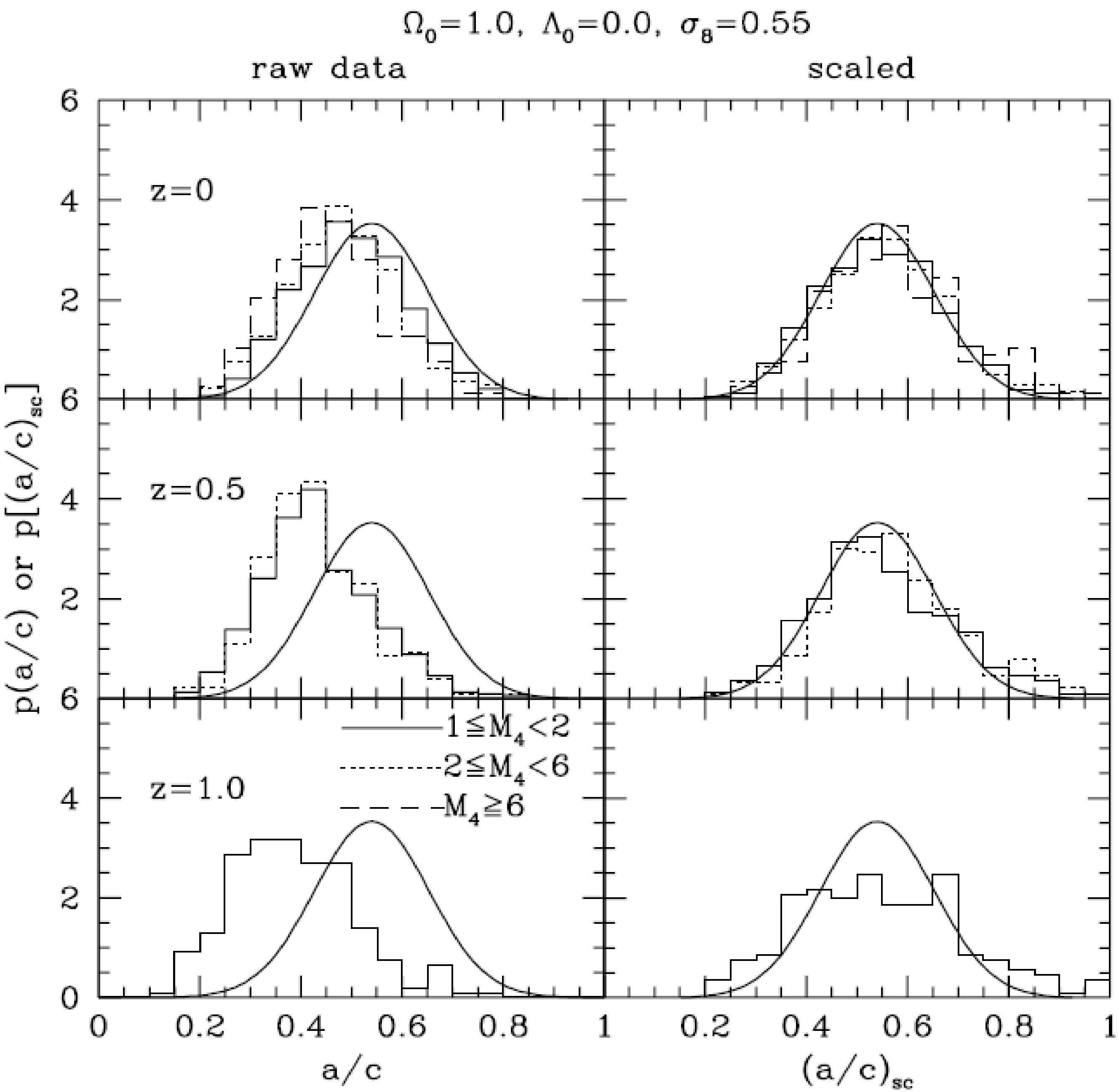
Jing & Suto 2002

Shapes become systematically less spherical with decreasing radius

There is a lot of scatter between halos

Principal axes may change direction

Shapes of halo equidensity surfaces



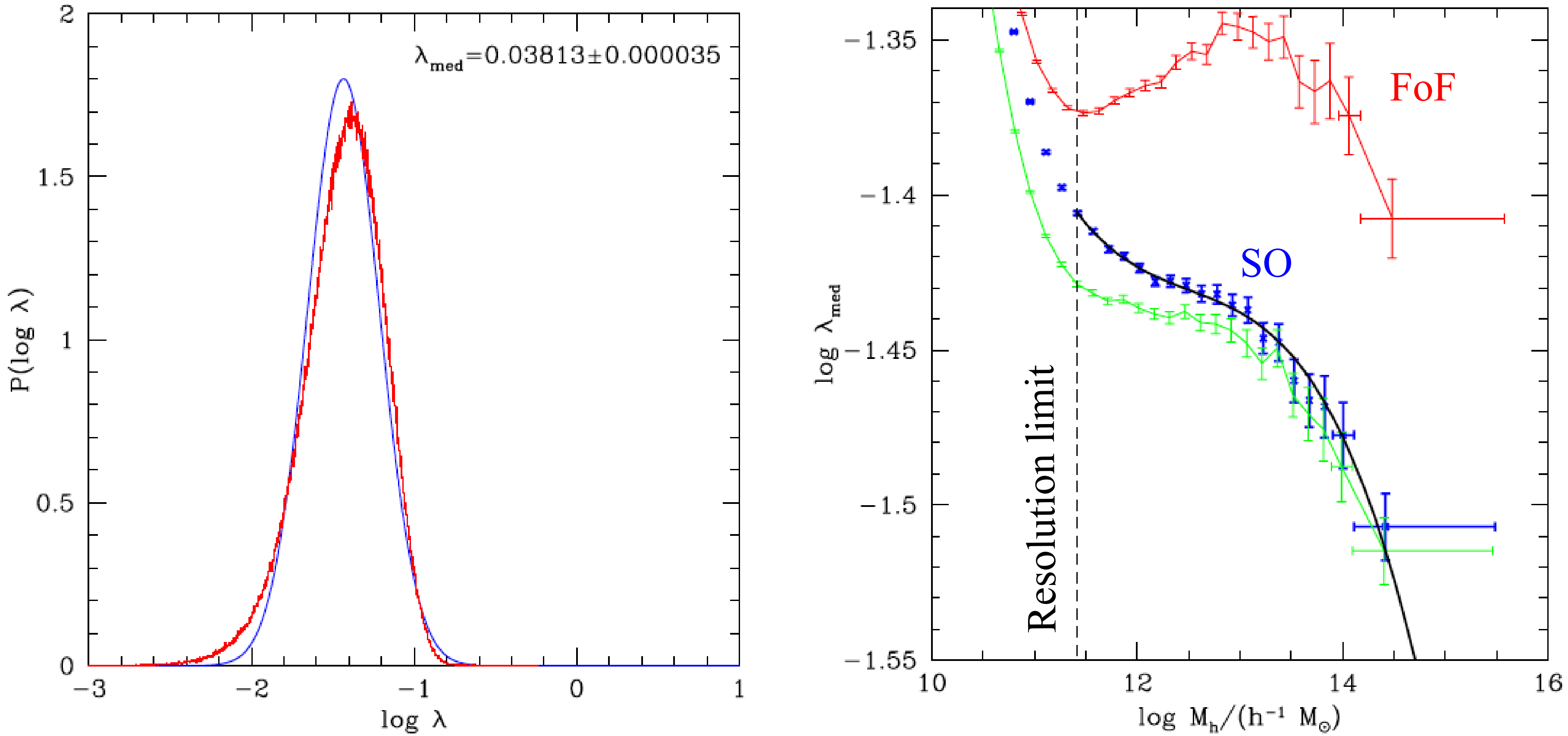
Jing & Suto 2002

Shapes become systematically less spherical with increasing mass

A simple scaling leaves a "universal" result for the axis ratio distributions

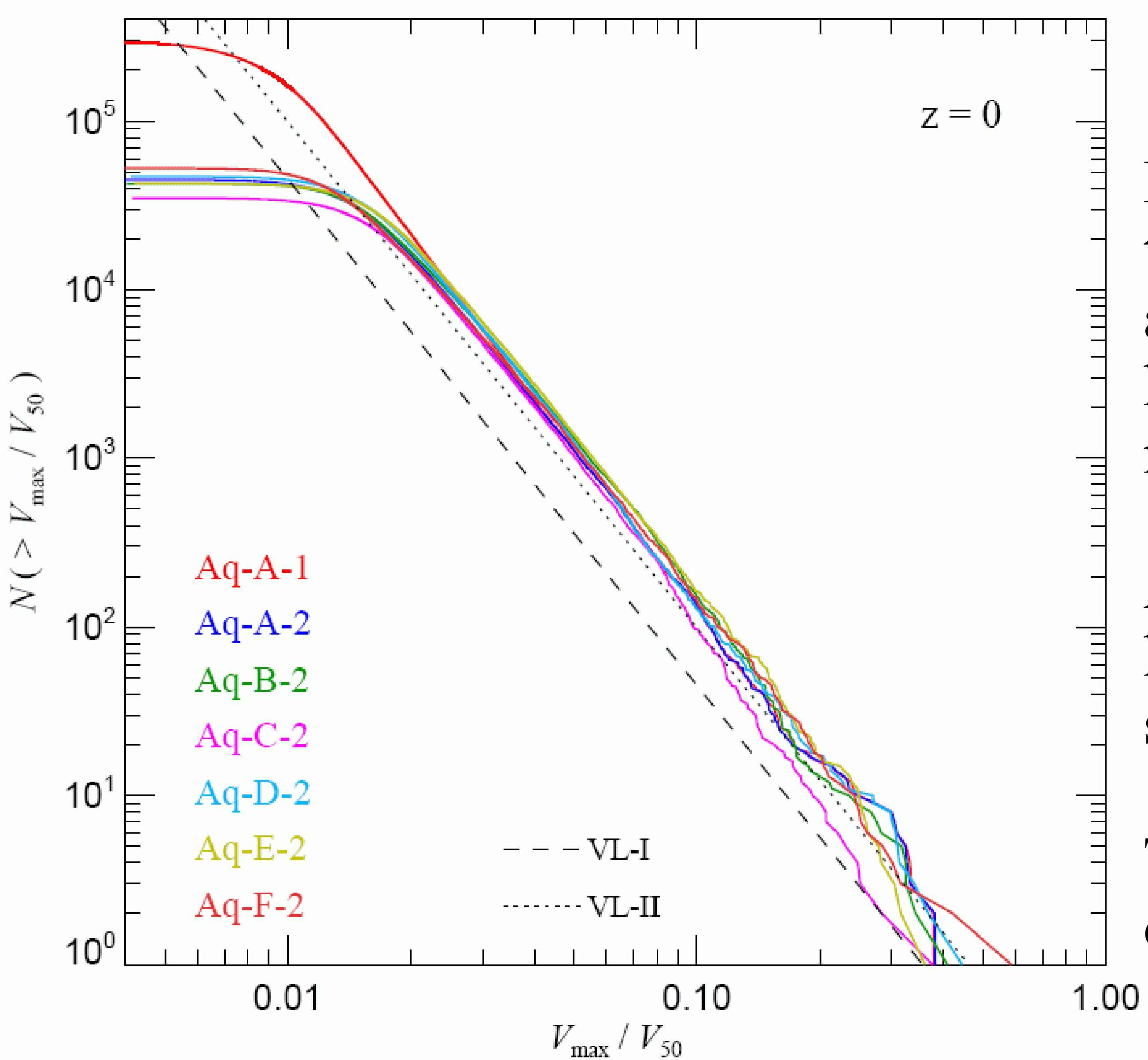
Halo spin distributions

Bett et al 2007



The distribution of spin parameter λ is approximately lognormal.
It depends little on mass, but significantly on halo definition.

How uniform are subhalo populations?



Springel et al 2008

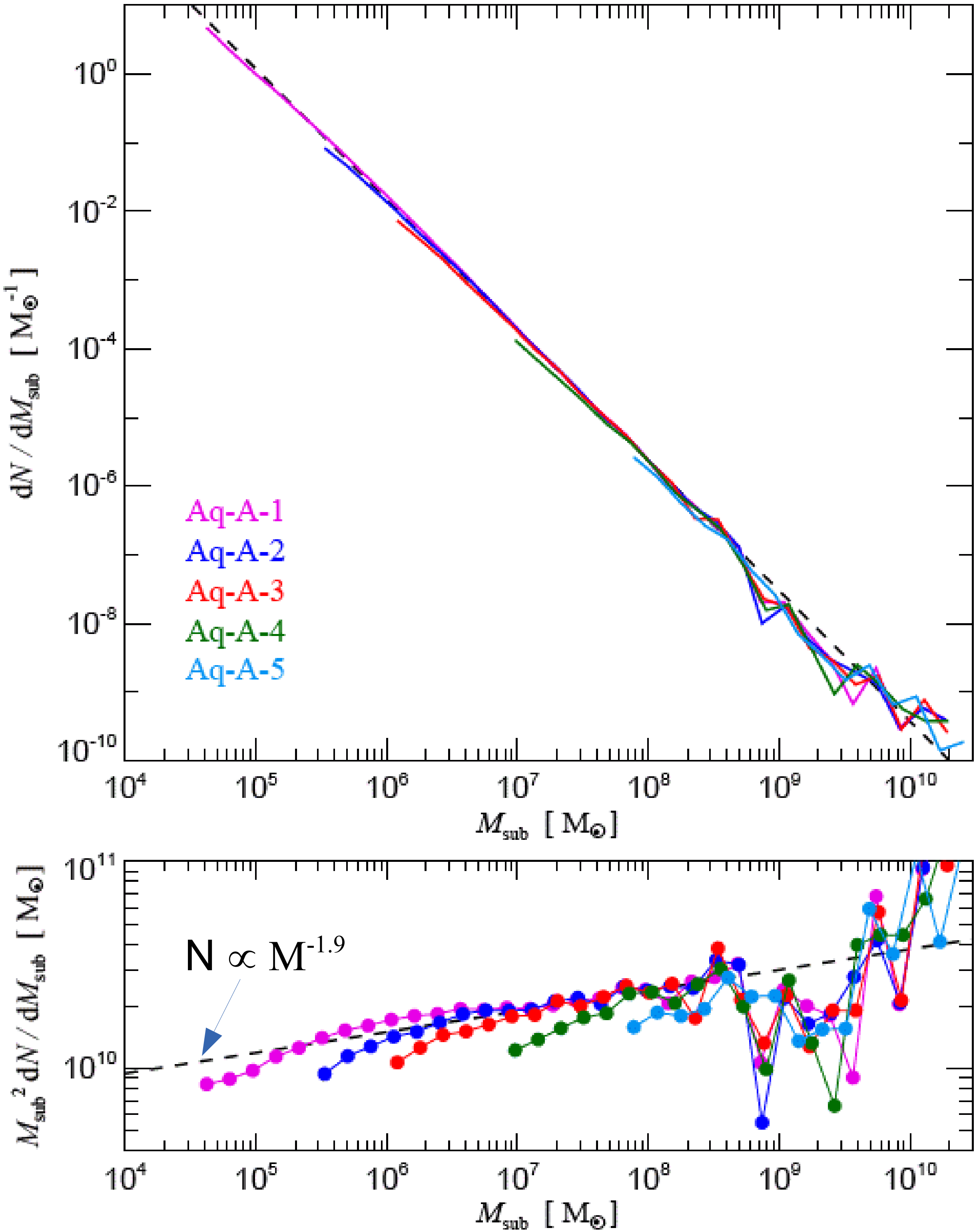
For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and ~20% at low mass

All "Milky Way" halos have similar amounts of substructure

The Via Lactea simulations differ significantly

How well does substructure converge?

Springel et al 2008



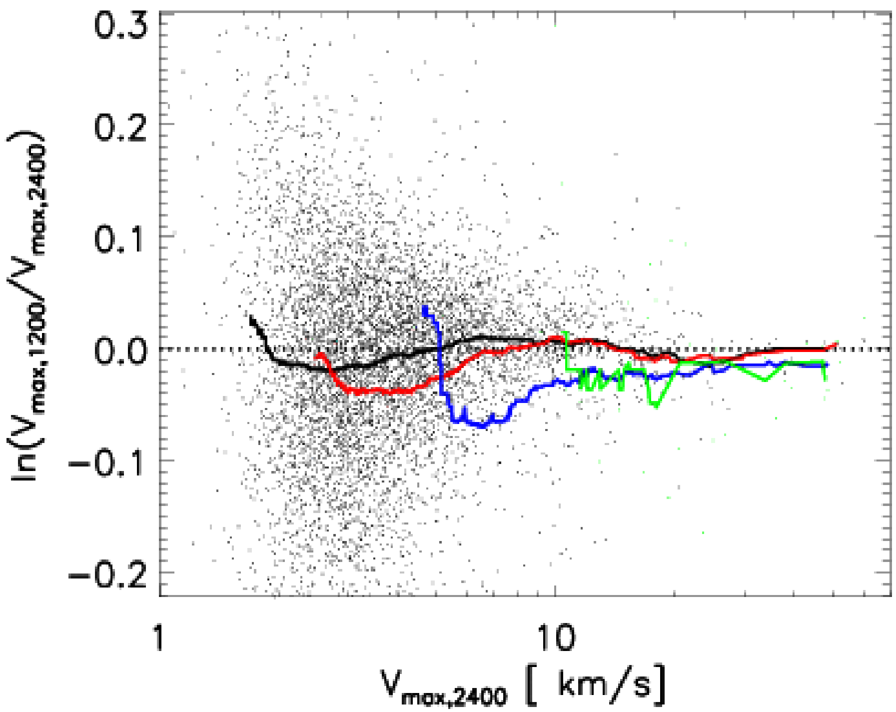
Differential number count of subhalos with r < 400 kpc

Convergence is excellent

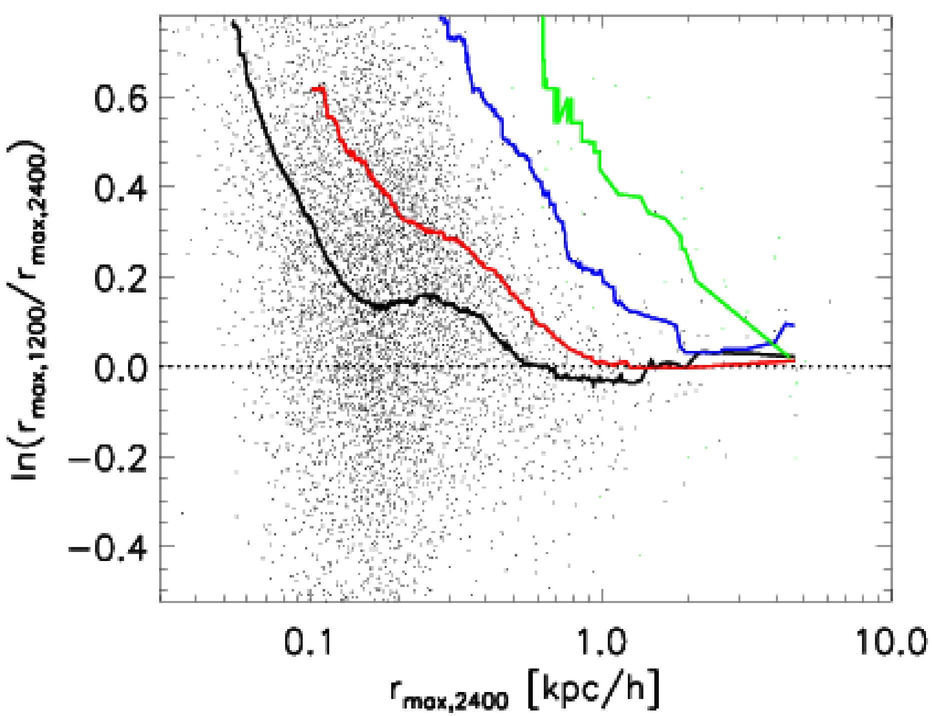
Slope is slightly shallower than −2 → most subhalo mass is in the biggest objects

How well does substructure converge?

Aquarius Project: Springel et al 2008



Convergence in the size and maximum circular velocity for individual subhalos cross-matched between simulation pairs.



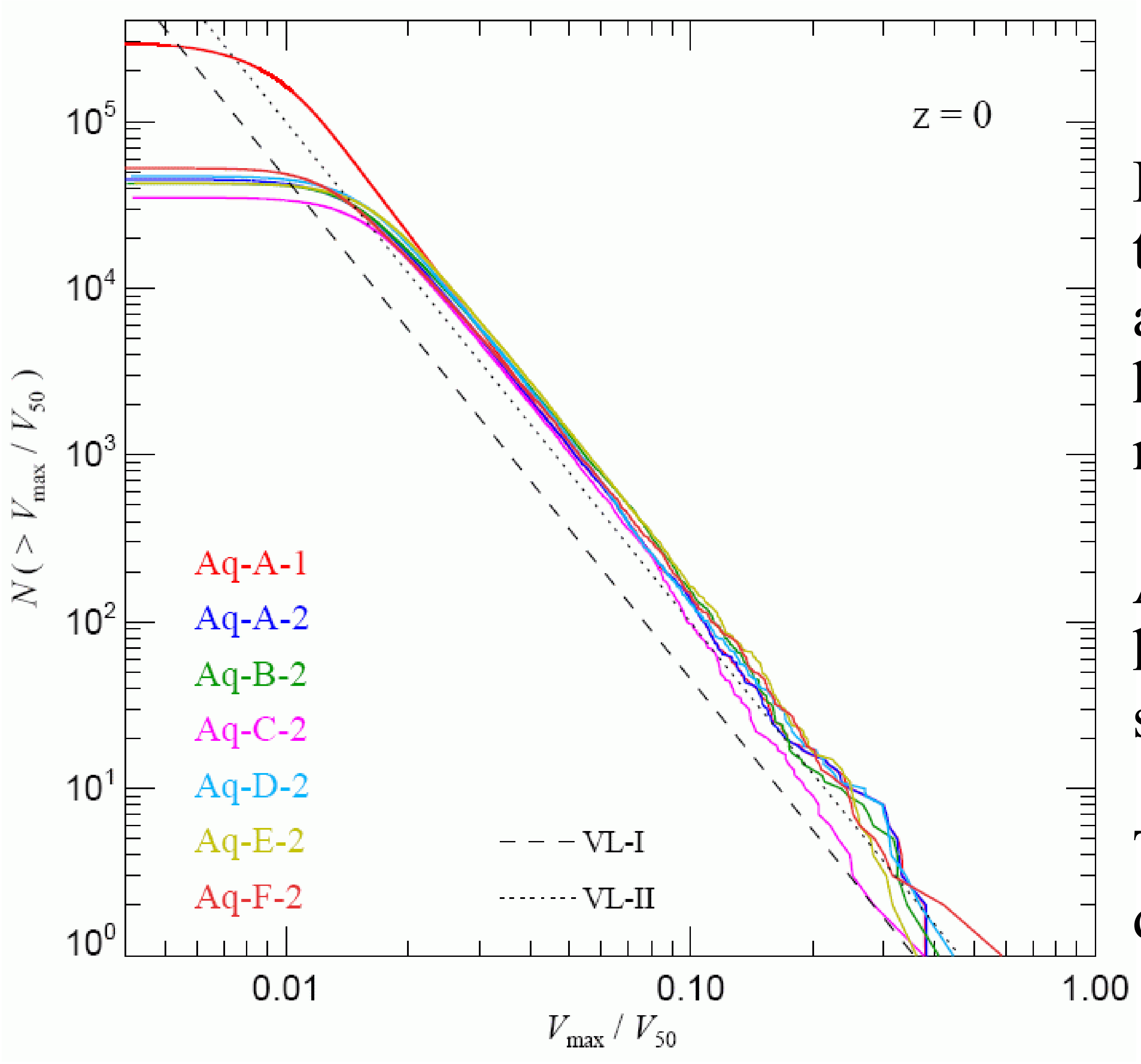
Biggest simulation gives convergent results for

$$V_{max} > 1.5 \text{ km/s}$$

$$r_{max} > 165 \text{ pc}$$

Much smaller than the halos inferred for even the faintest dwarf galaxies

How uniform are subhalo populations?



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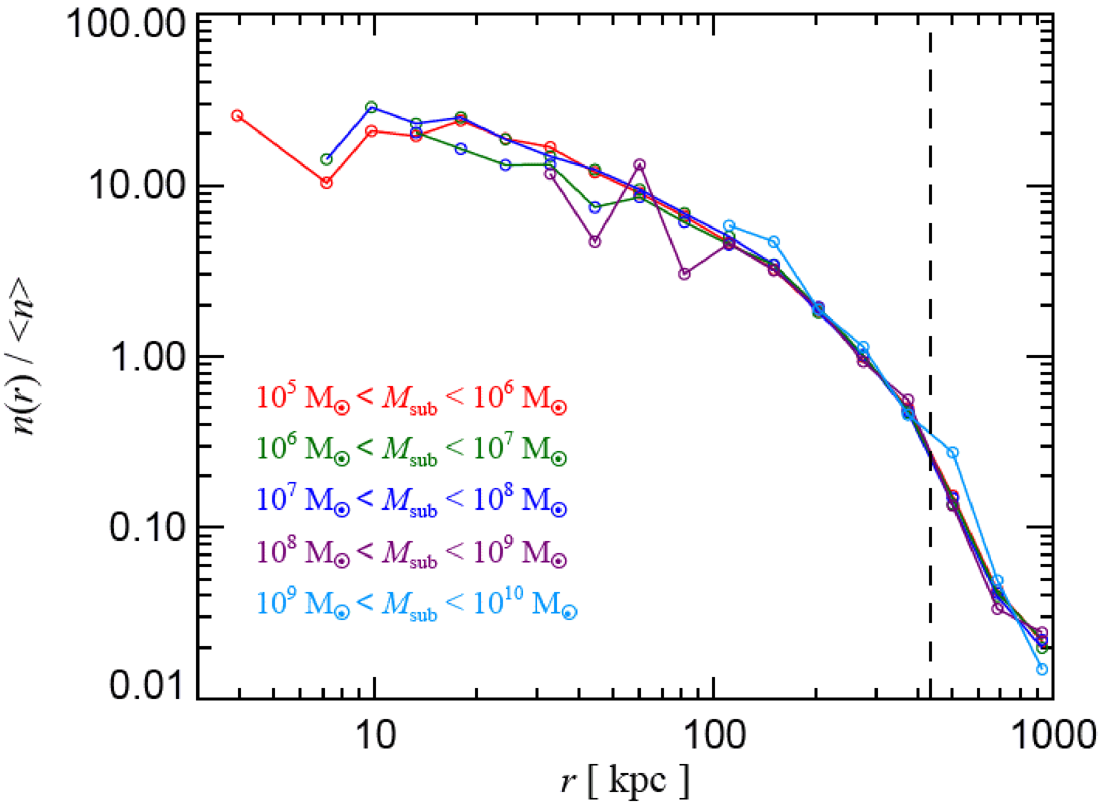
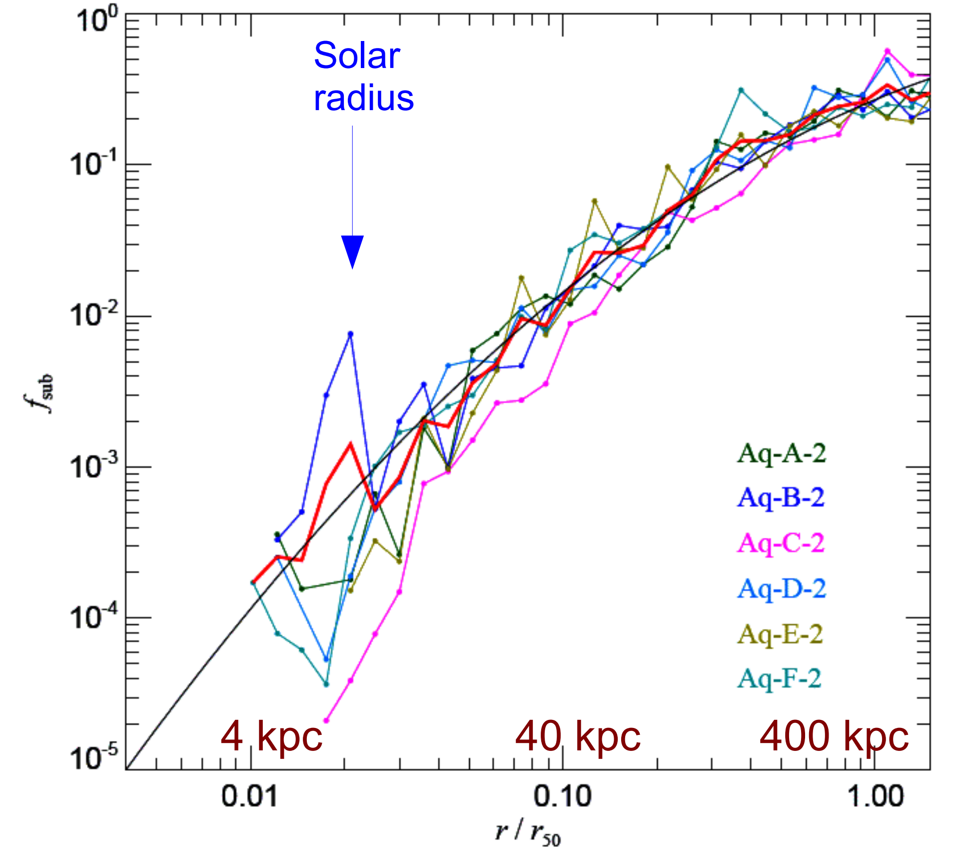
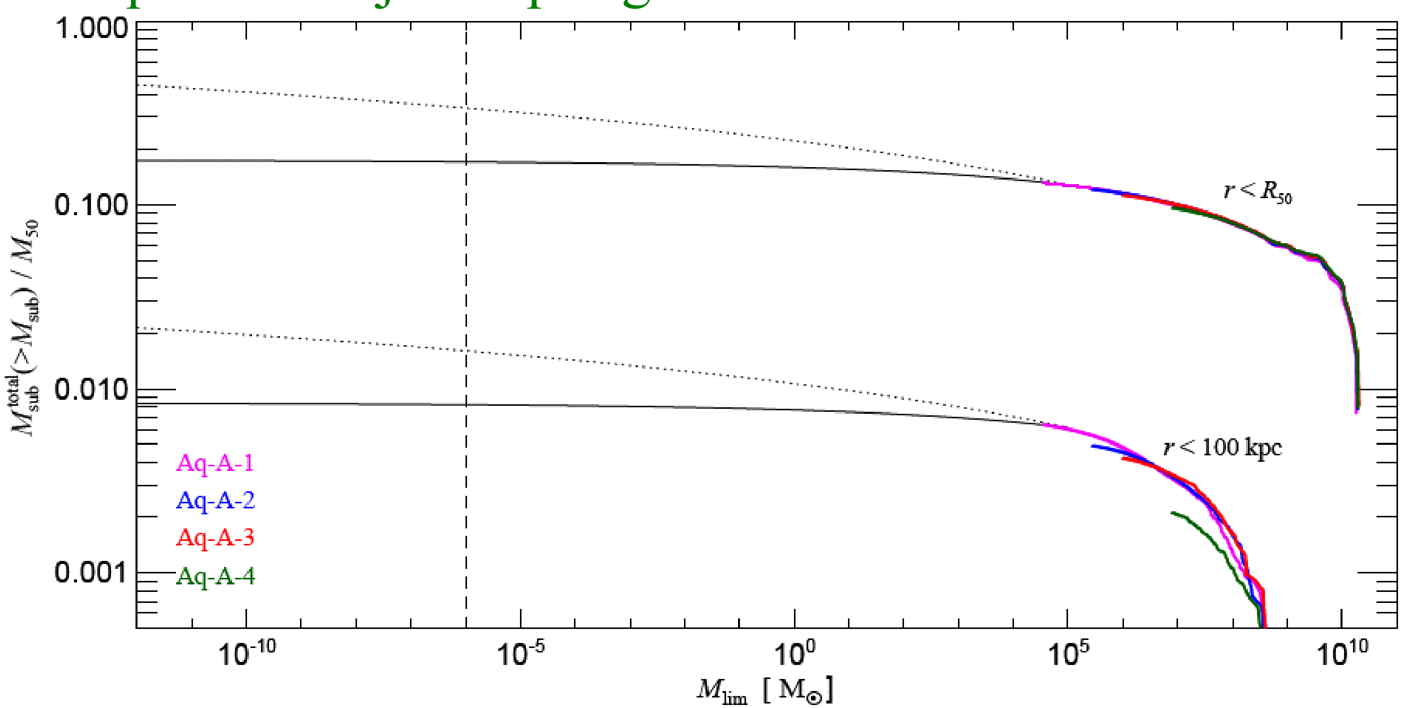




Aquarius Project: Springel et al 2008



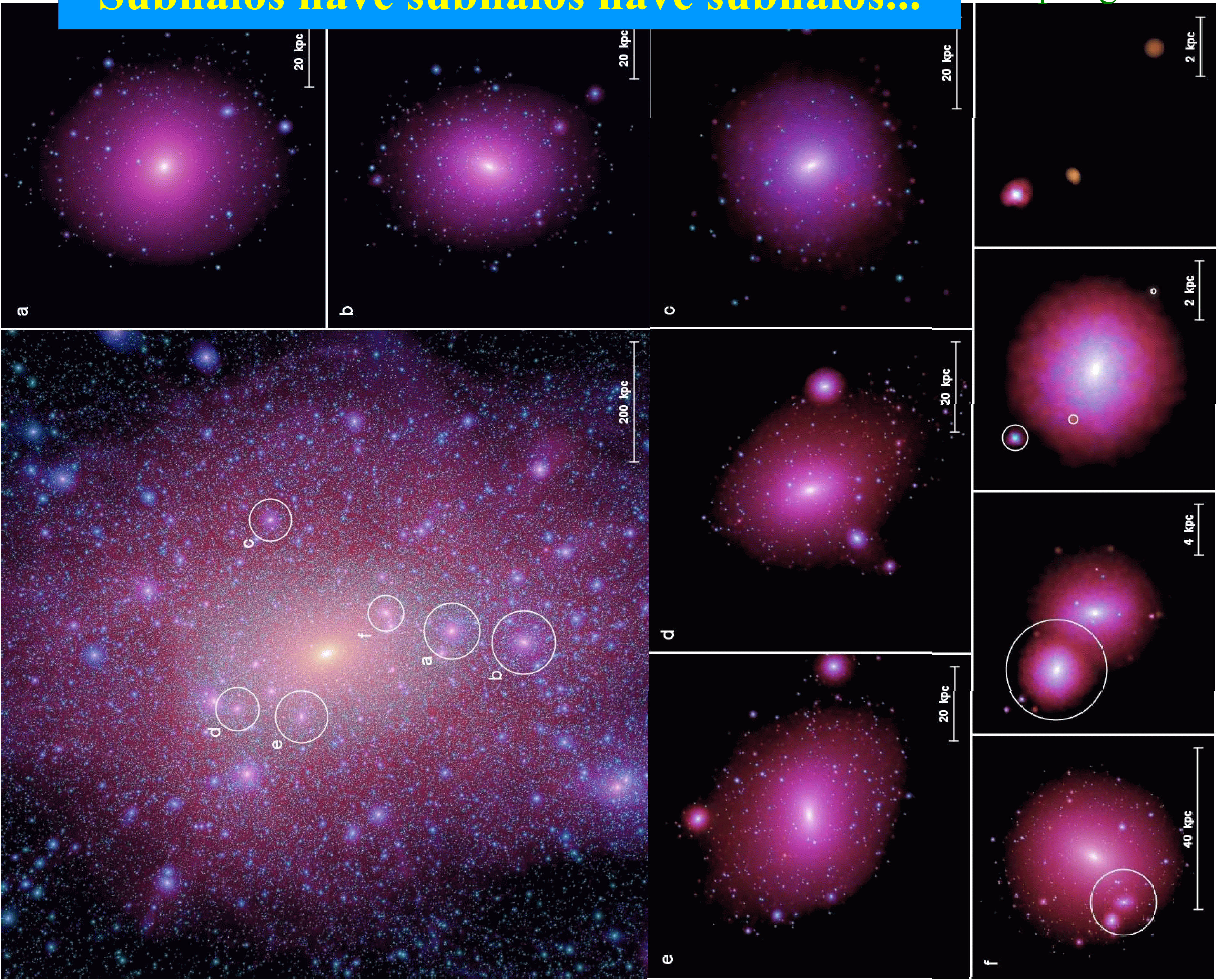
All mass subhalos are similarly distributed

A small fraction of the inner mass in subhalos

<<1% of the mass near the Sun is in subhalos

Subhalos have subhalos have subhalos...

Springel et al 2008



Substructure: conclusions

Substructure is primarily in the outermost parts of halos

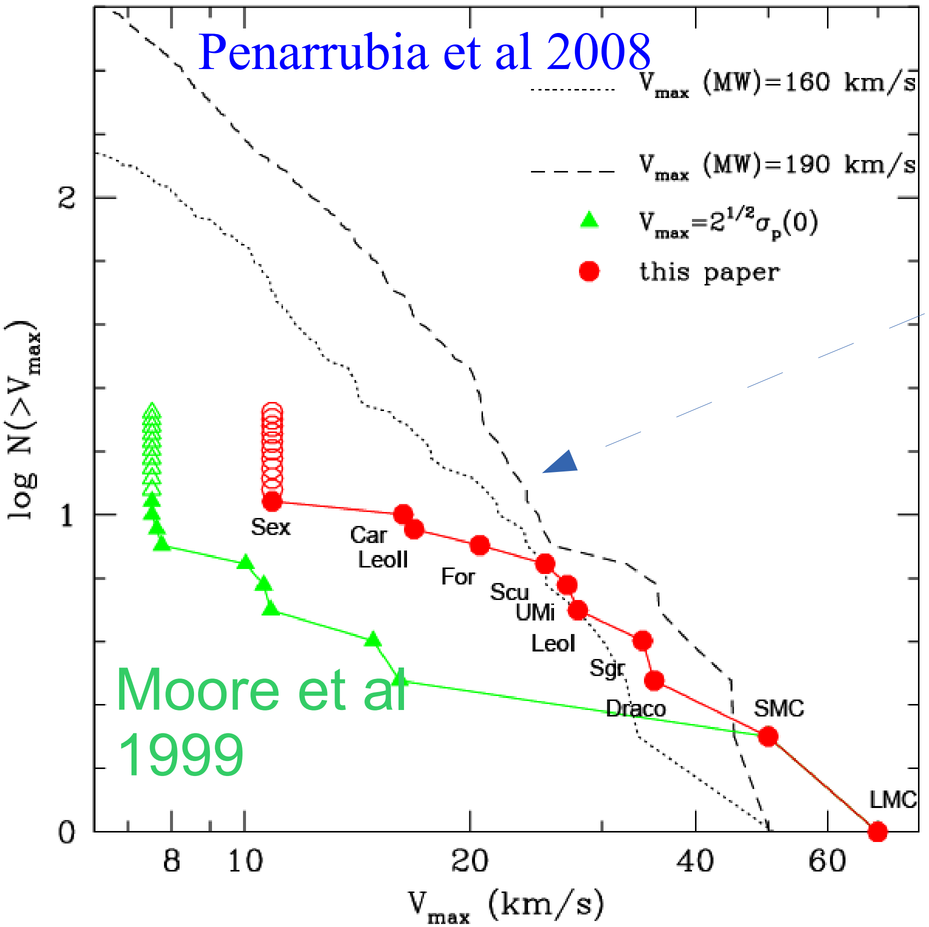
The radial distribution of subhalos is almost mass-independent

Subhalo populations scale (almost) with the mass of the host

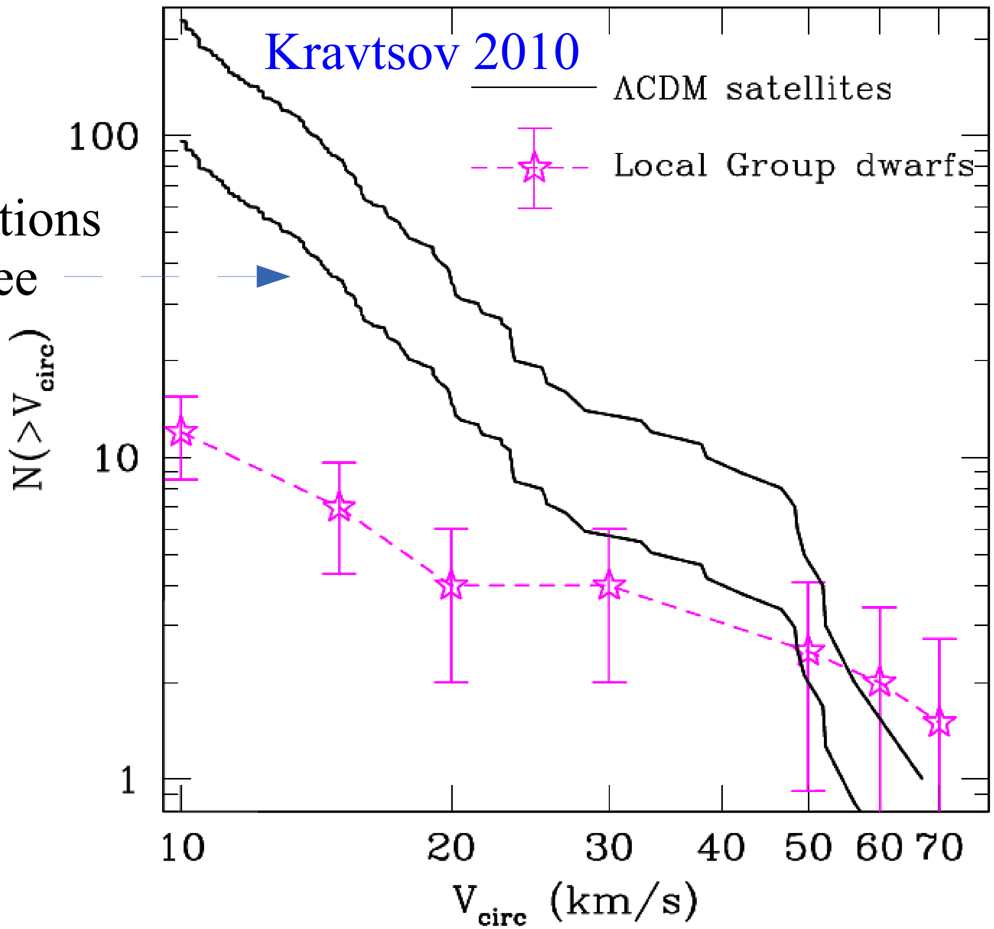
The subhalo mass distribution converges only weakly at small m

Subhalos contain a small fraction of the mass in the inner halo

A Milky Way satellite problem?



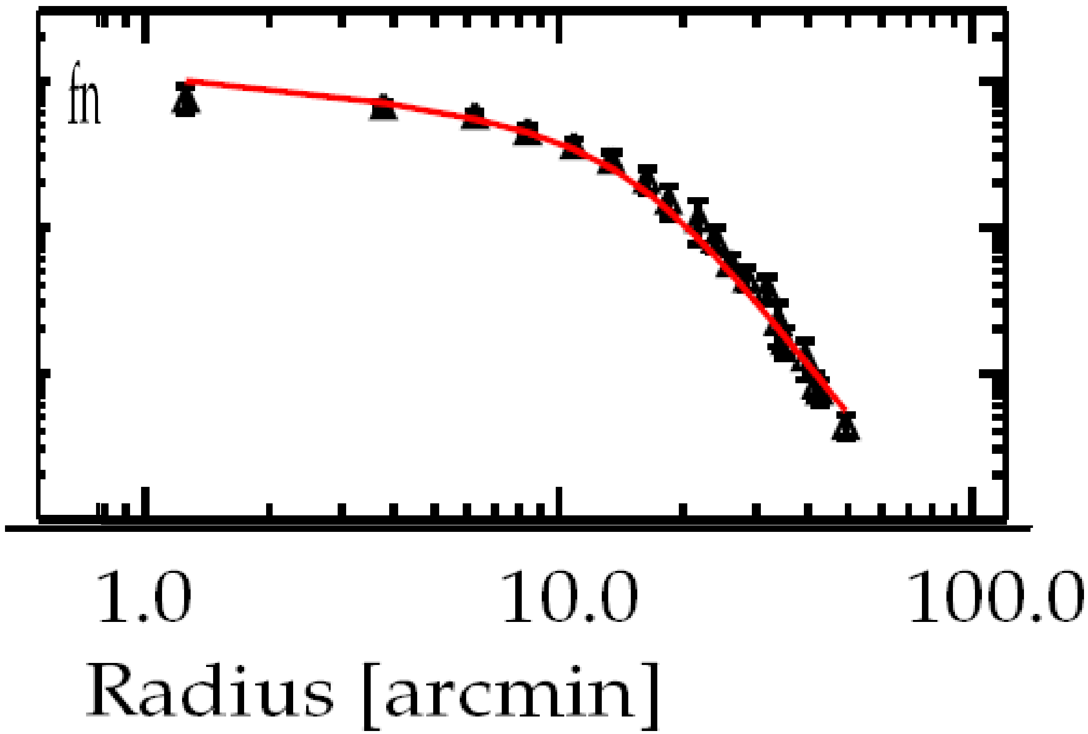
simulations agree



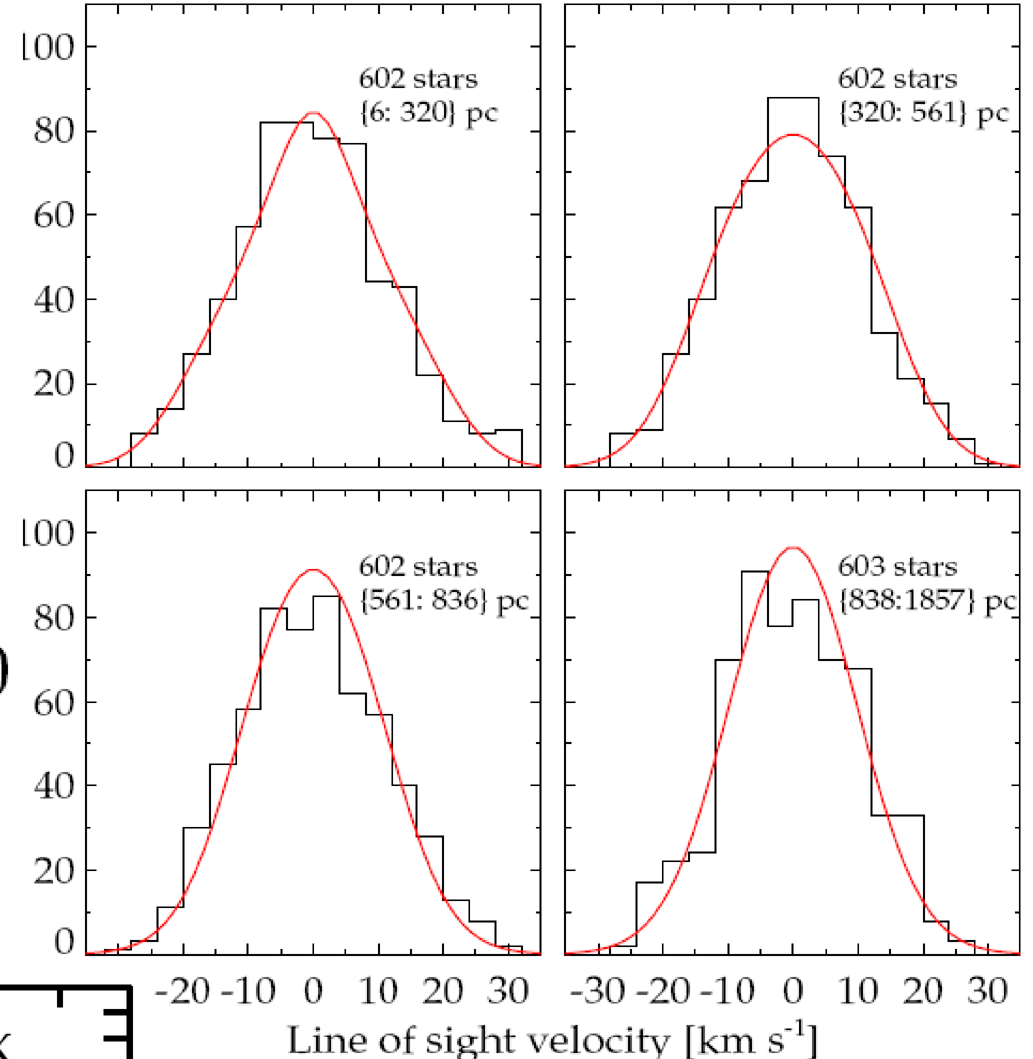
# of small subhalos in ΛCDM halos ≫ # of MW satellites

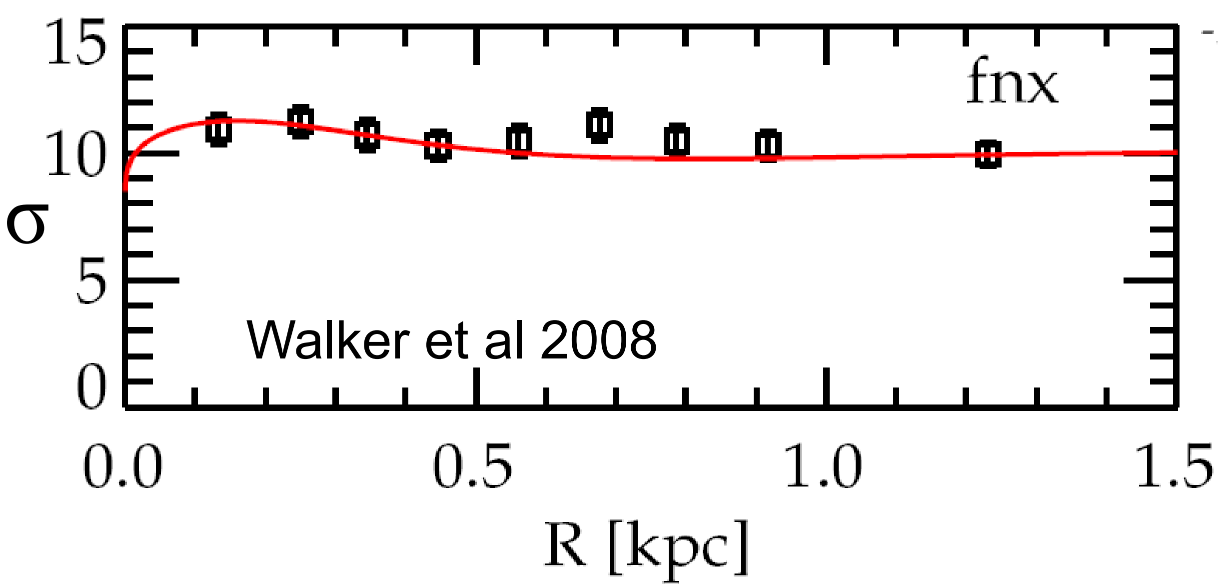
Maybe most of them just didn't make stars?

Subhalos with stars must be less massive than many without stars?



Strigari, Frenk & White 2010



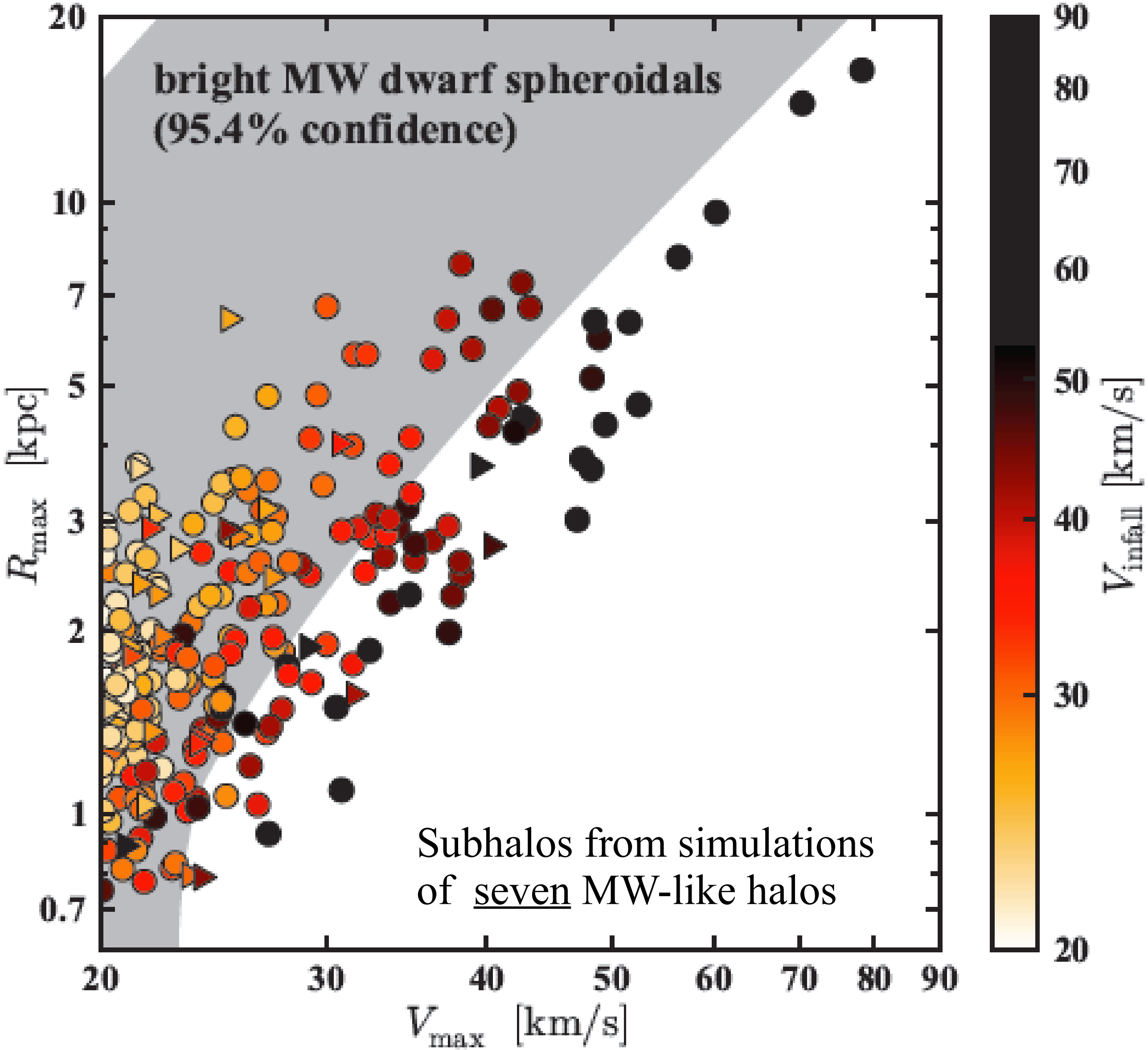


Fornax data are **consistent** with living in an Aquarius CDM subhalo with isotropic velocity dispersions

→ a cusp is not excluded

Too big to fail – another satellite problem?

Boylan-Kolchin et al2011



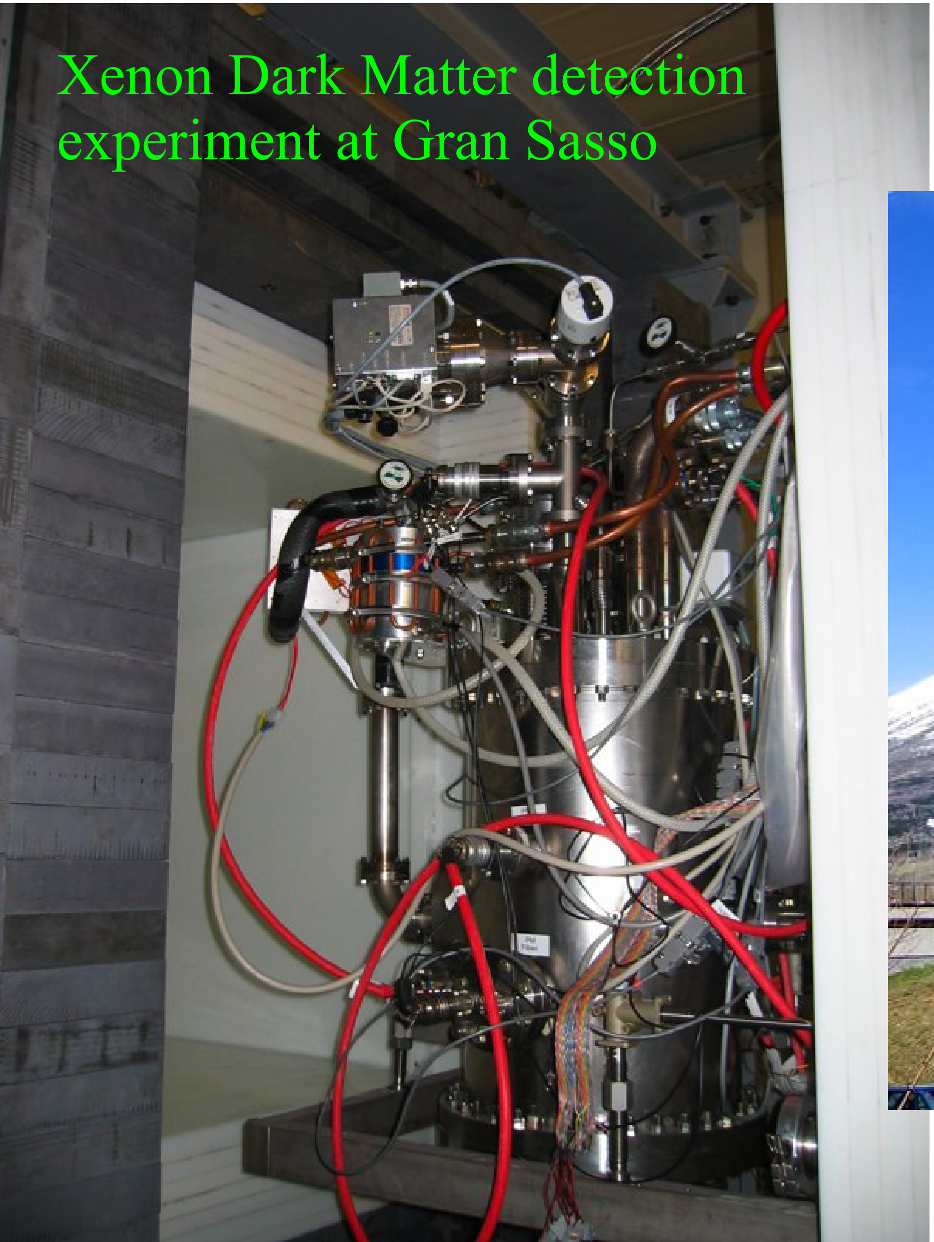
ΛCDM simulations of the formation of halos like that of the Milky find many satellite subhalos with central densities bigger than any MW dSph.

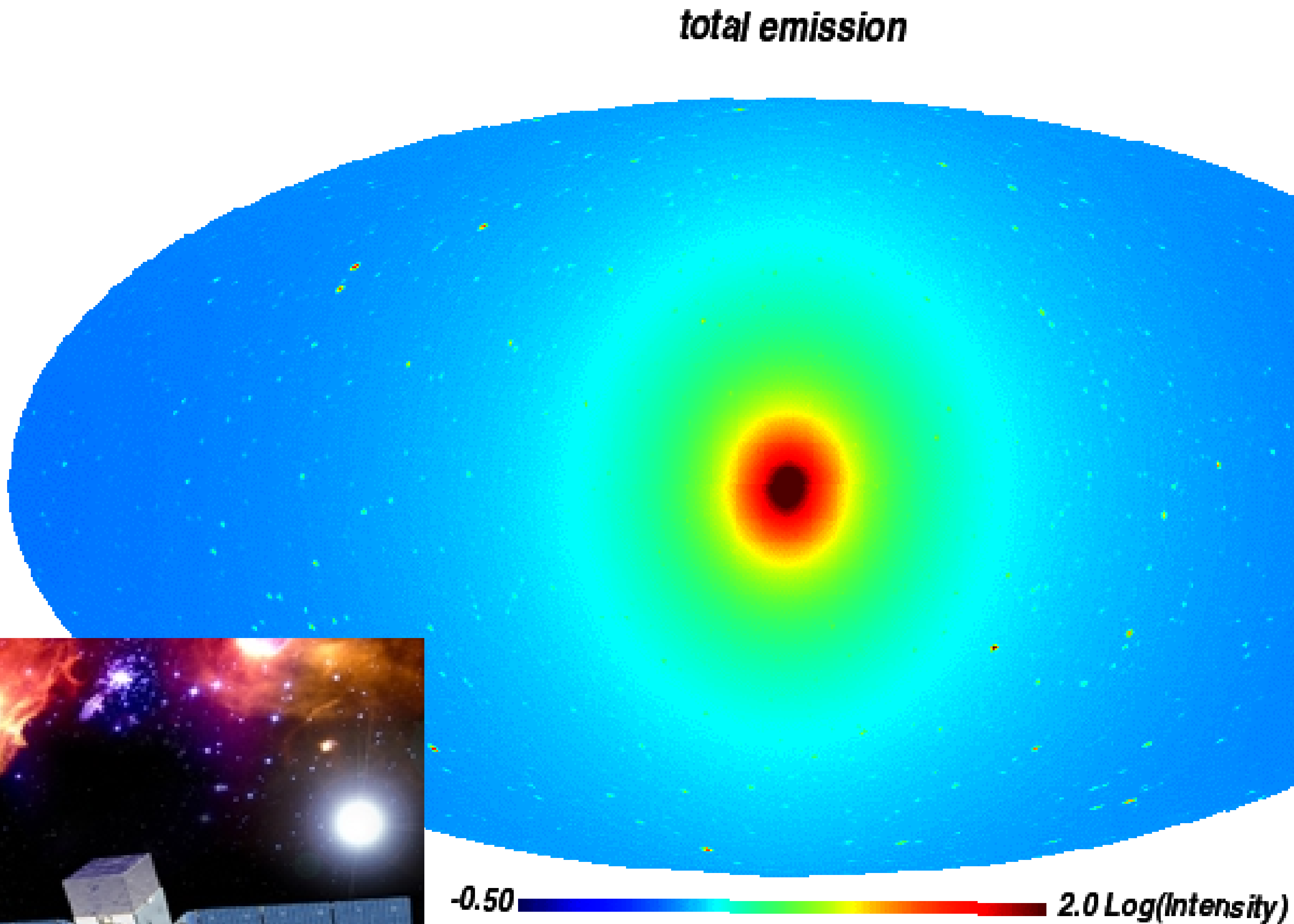
Note that LMC, SMC and the Sagittarius dwarf not included.

Resolutions?

-- Lower mass MW halo?
-- WDM?
-- Baryonic effects during star formation?

Maybe Dark Matter can be detected in a laboratory





Maybe the annihilation of Dark Matter will be seen by Fermi?

Small-scale structure and DM detection

Direct detection involves bolometers/cavities of meter scale which are sensitive to particle momentum

-- what is the density structure between m and kpc scales?

-- how many streams intersect the detector at any time?

Indirect detection involves annihilation radiation

$$L \propto \int \rho^2(\boldsymbol{x}) \langle \sigma v \rangle \, dV$$

-- what is the density distribution around individual CDM particles on the annihilation interaction scale?

Predictions for detection experiments depend on the CDM distribution on scales <u>far</u> below those accessible to simulation

→ We require a good theoretical understanding of mixing and small-scale structure

Physics for Galaxy Formation Modelling

Gas Cooling and Condensation

Sensitive to metal content, phase structure, UV background...

Star Formation

No *a priori* understanding -- efficiency? IMF?

Stellar Feedback

SF regulation, metal enrichment, galactic winds

Stellar Aging

Population synthesis → luminosities, colours, spectra, (dust?)

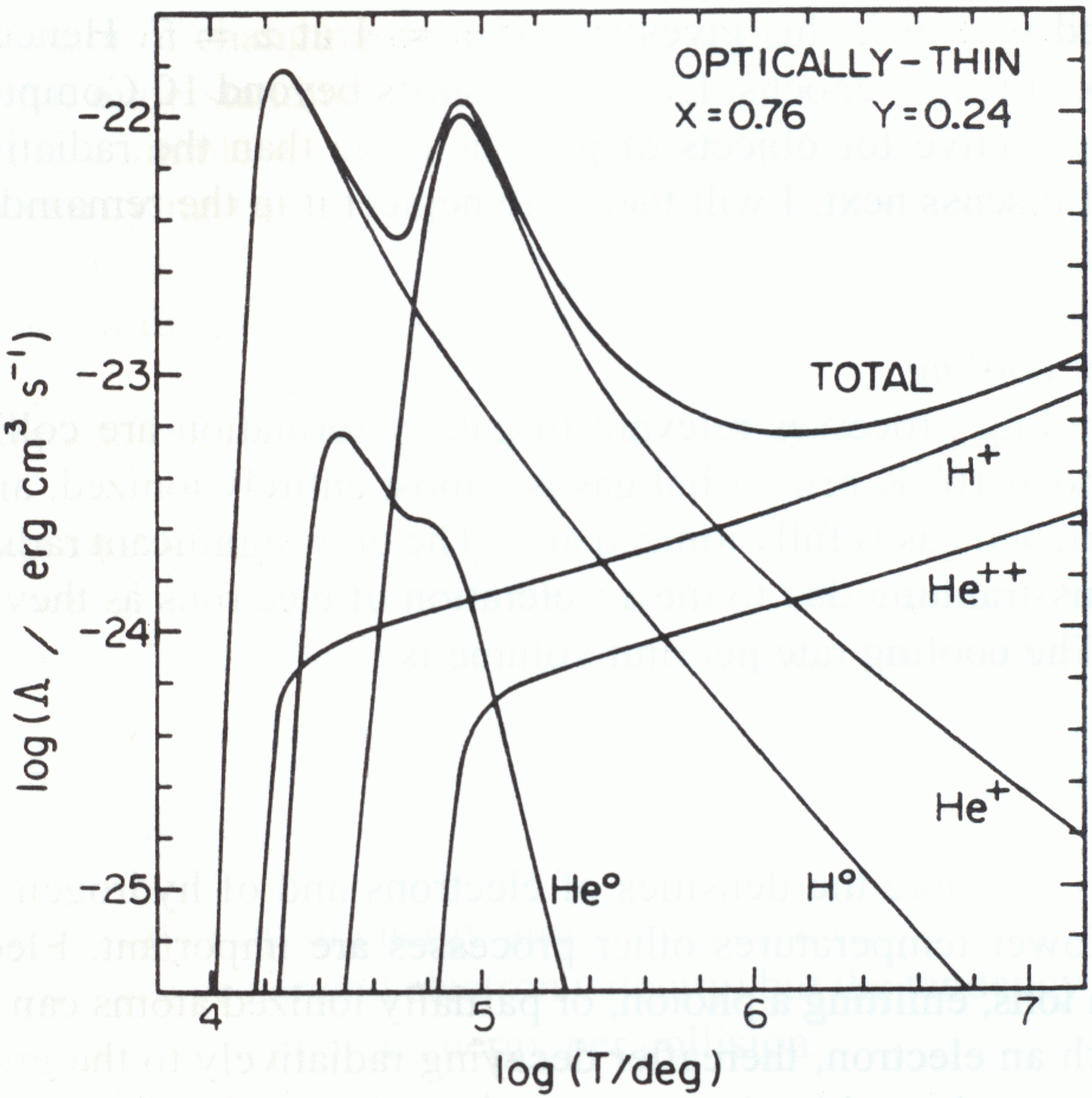
AGN physics

Black hole formation, feeding, AGN phenomenology, feedback

Environment interactions

Galaxy mergers, tidal effects, ram pressure effects

Cooling curve for metal-free, optically thin gas in collisional ionisation equ.



Luminosity/unit volume is

$$L = n_e^{\,2}\,\Lambda(T)$$

No cooling occurs below 10^4K unless H_2 can form

→ Optically thin cooling time $t_{cool} \propto n_e T / L \propto T / n_e \Lambda(T)$

c.f. gravitational collapse time $t_{dyn} \propto (G\,\rho)^{-1/2} \propto n_e^{-1/2}$

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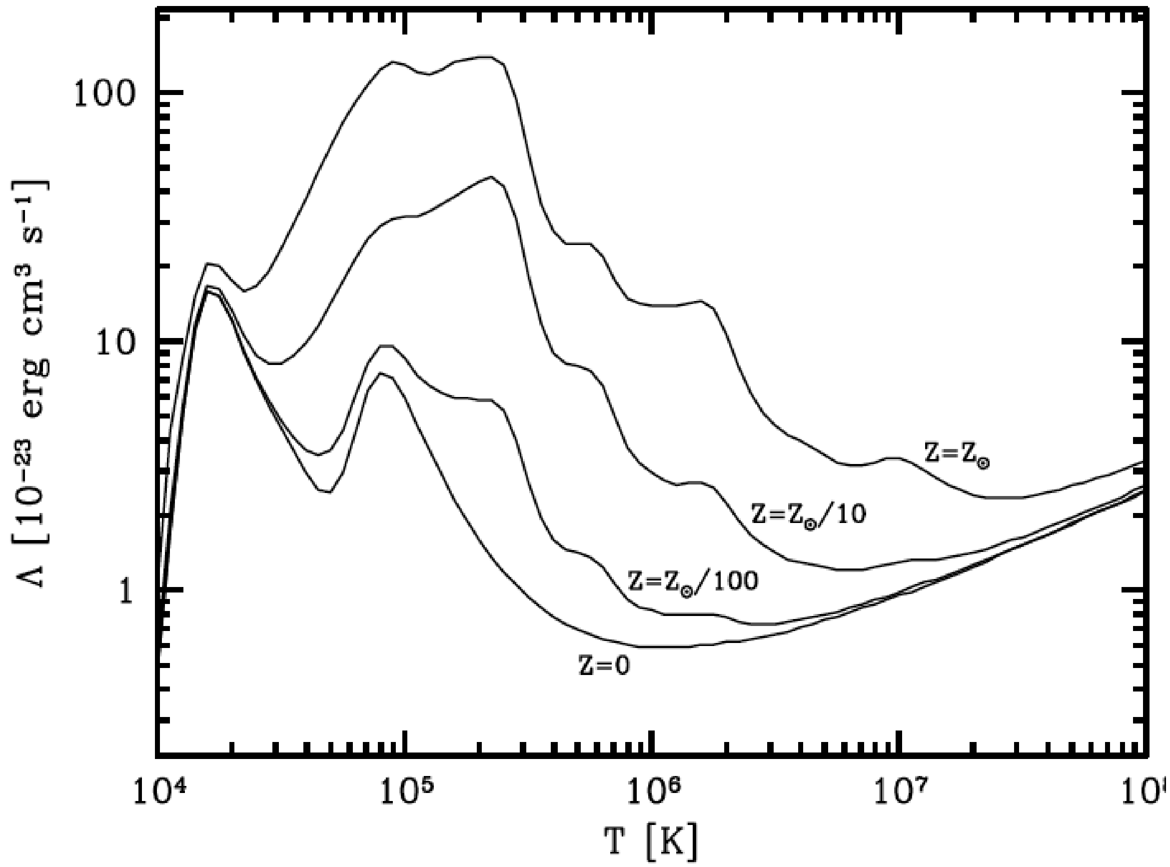

Luminosity/unit volume is

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Addition of heavy elements increases cooling in the range 10^5K to 10^7K

Optically thin cooling time $t_{cool} \propto n_e T / L \propto T / n_e \Lambda(T)$

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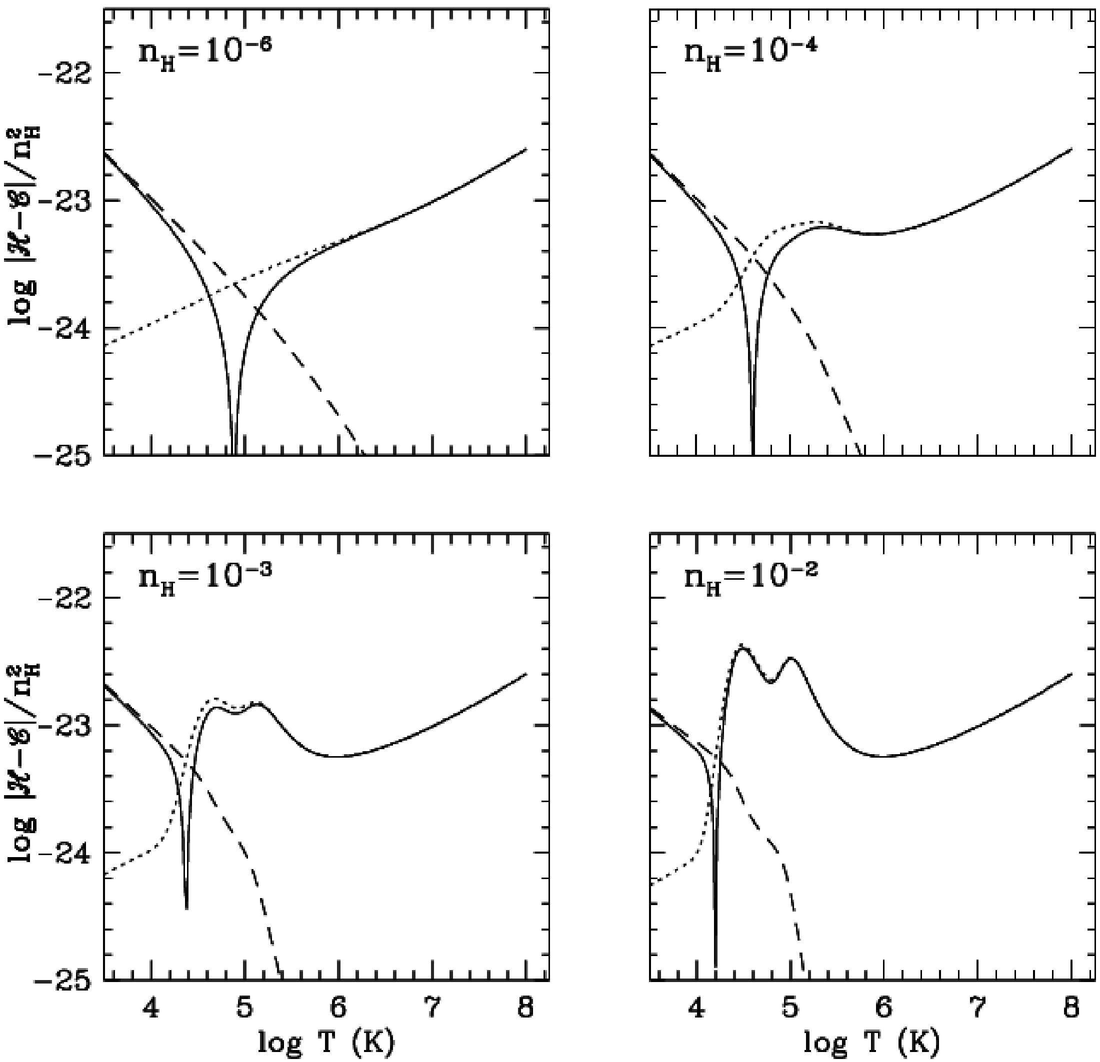

Luminosity/unit volume is

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No cooling occurs below 10^4K unless H_2 can form

Addition of UV background suppresses line cooling → density-dependent heating

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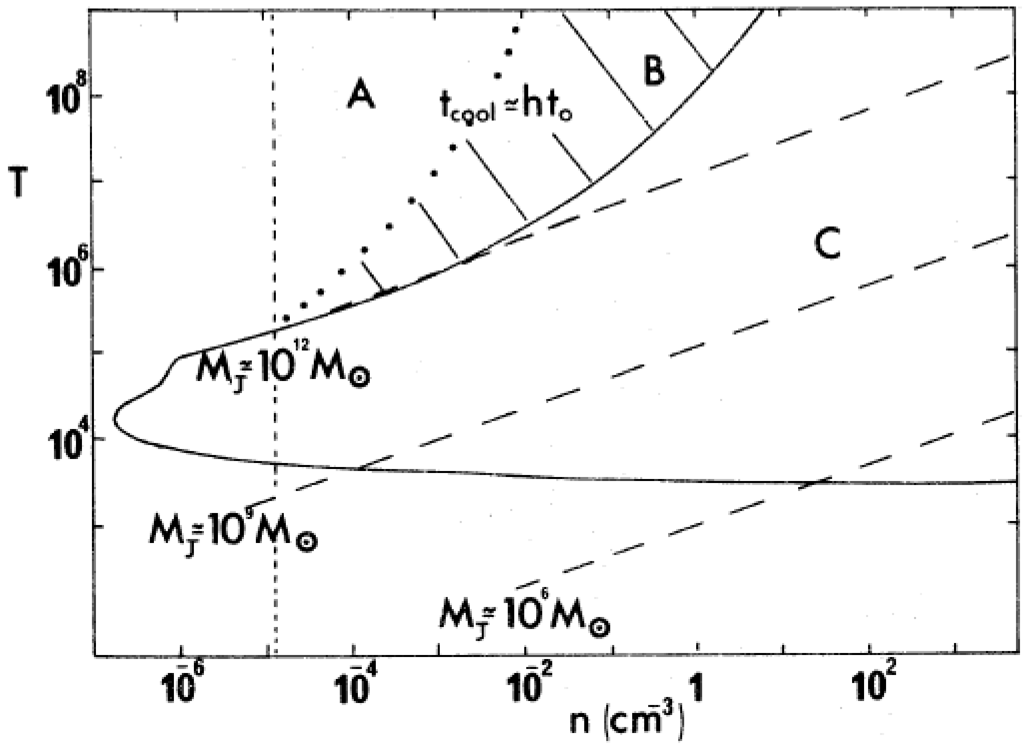
Radiative processes in galaxy formation



Rees & Ostriker 1977
Silk 1977
Binney 1977

When gas clouds of galactic mass collapse:

(i) shocks are radiative and collapse unimpeded, when $t_{cool} < t_{dyn}$

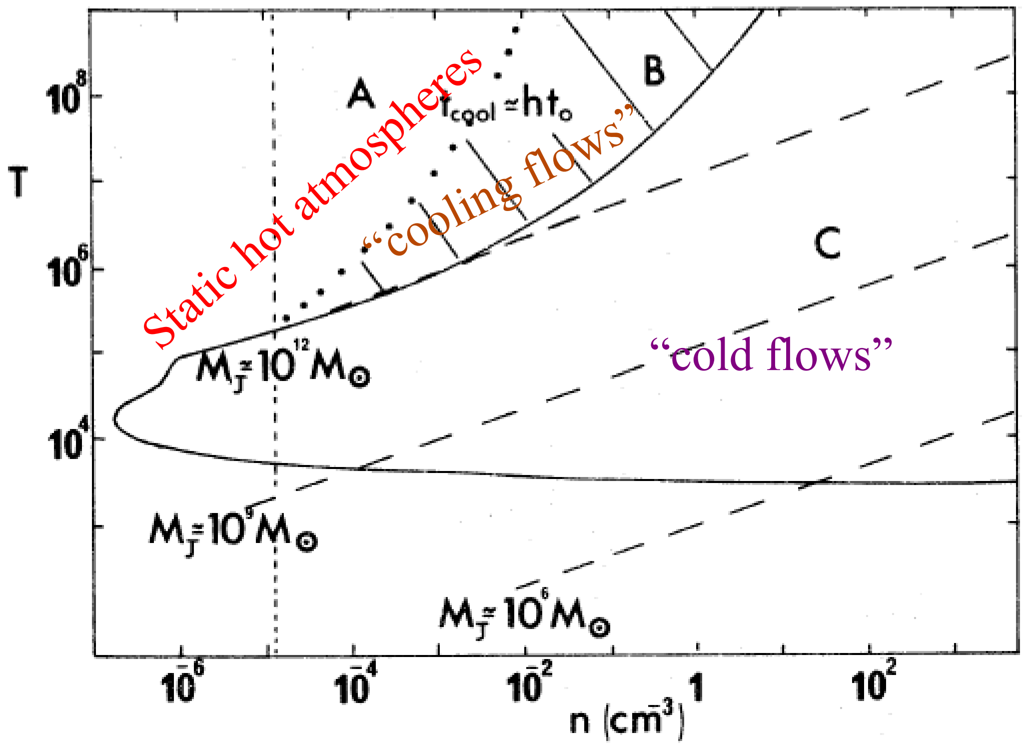
(ii) shocks are non-radiative and collapse arrested, when $t_{cool} > t_{dyn}$

where quantities are estimated at virial equilibrium

Galaxies form in case (i) since fragmentation is possible

Primordial cooling curve → characteristic mass $10^{12}\,M_\odot$

Radiative processes in galaxy formation



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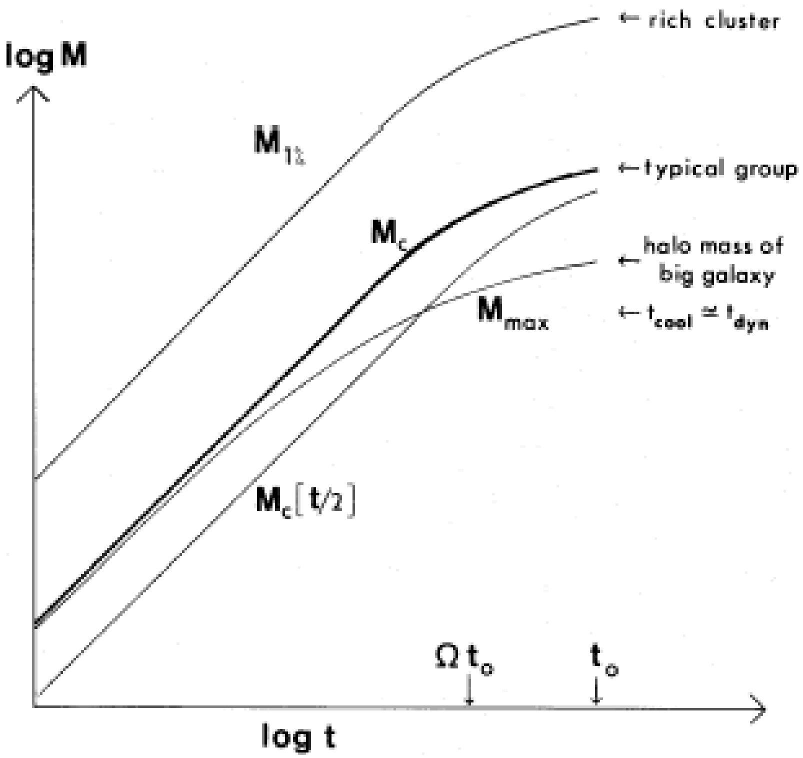
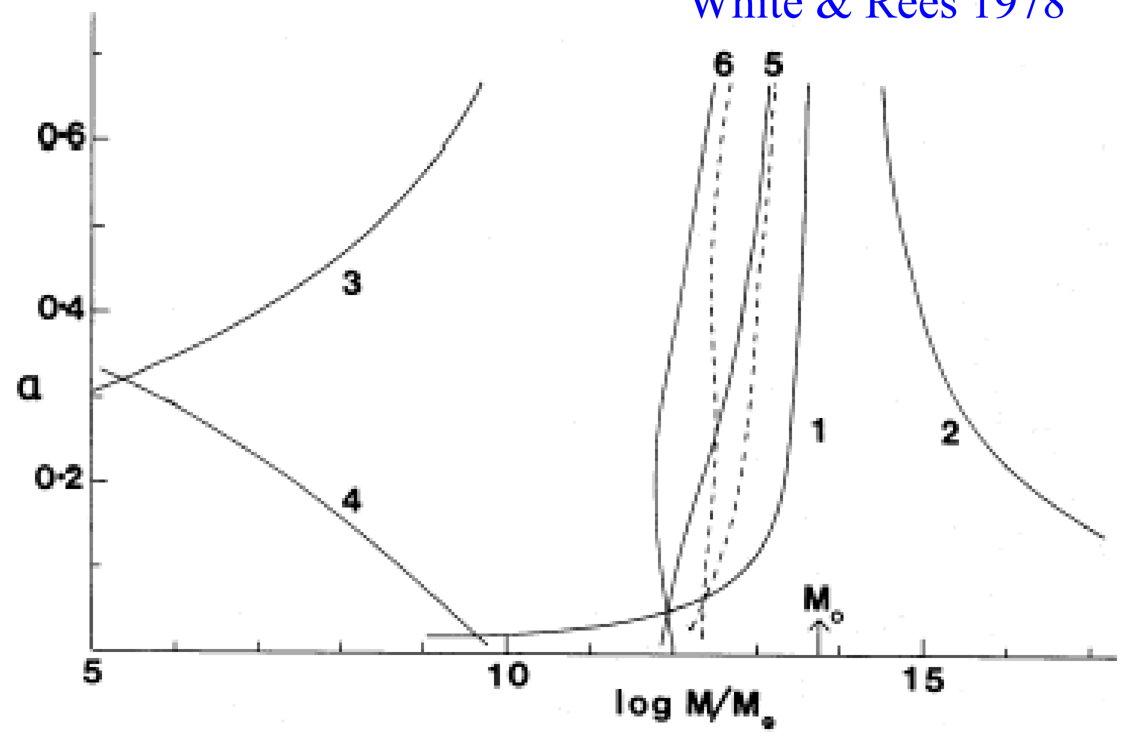
Primordial cooling curve $\longrightarrow$ characteristic mass $10^{12} M_\odot$

Towards a “modern” theory



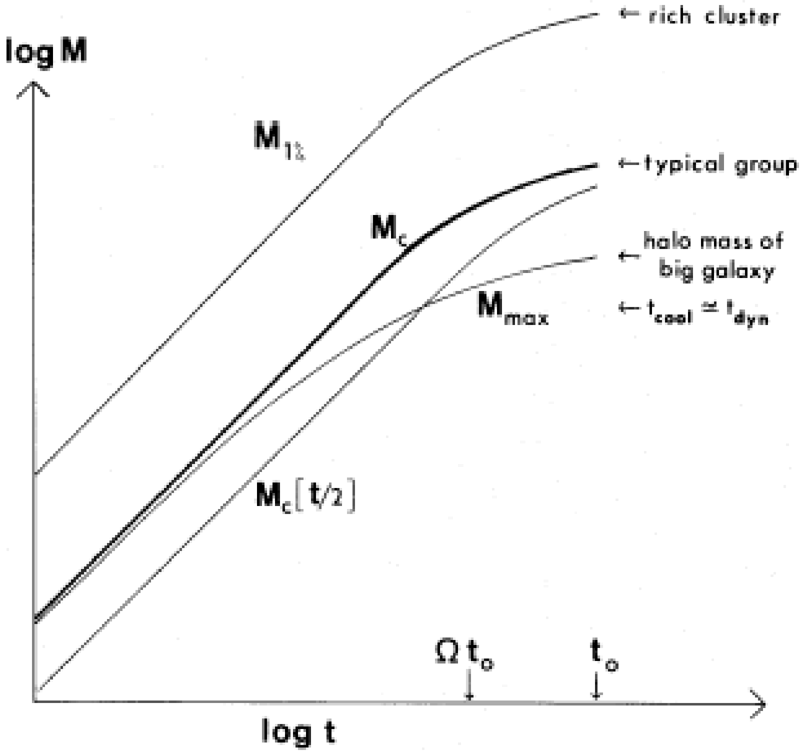
White & Rees 1978



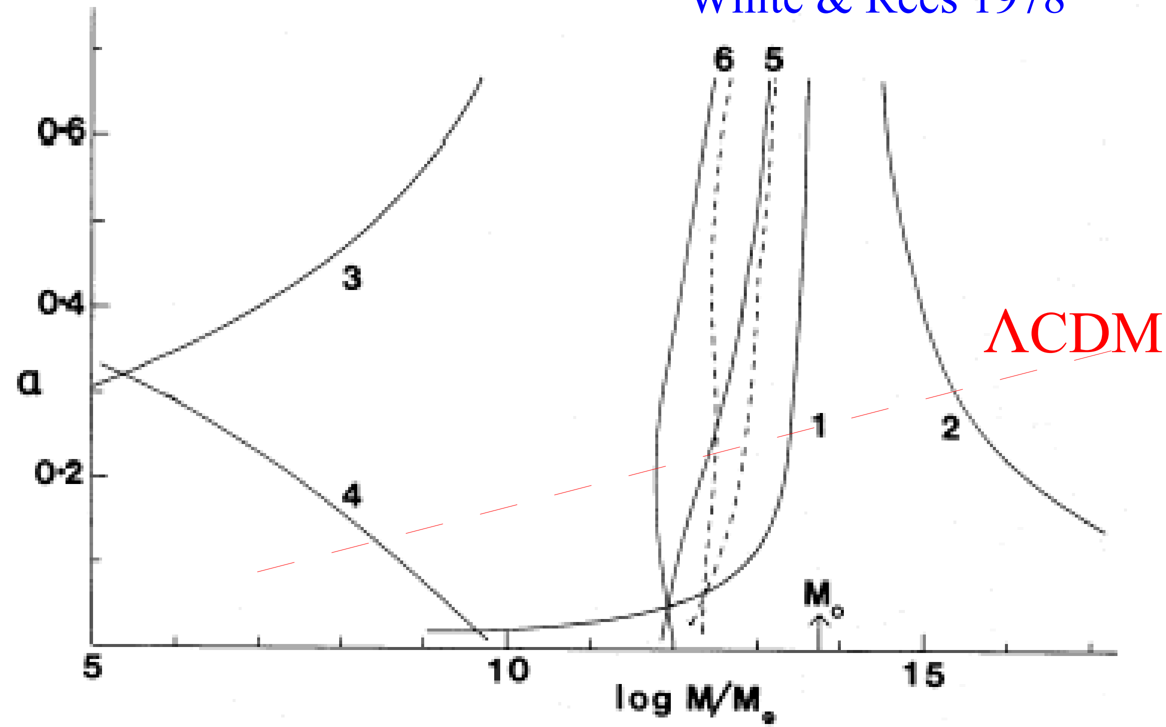
Adding : (i) dark matter, (ii) hierarchical clustering, (iii) feedback
- -- cooling always rapid for small masses and early times
- -- only biggest galaxies sit in cooling flows
- -- feedback *à la* Larson (1974) needed to suppress small galaxies

A good model: $\Omega_m = 0.20$, $\Omega_{gas} / \Omega_{DM} = 0.20$, $\alpha = 1/3$ (n = -1)

Towards a “modern” theory



White & Rees 1978



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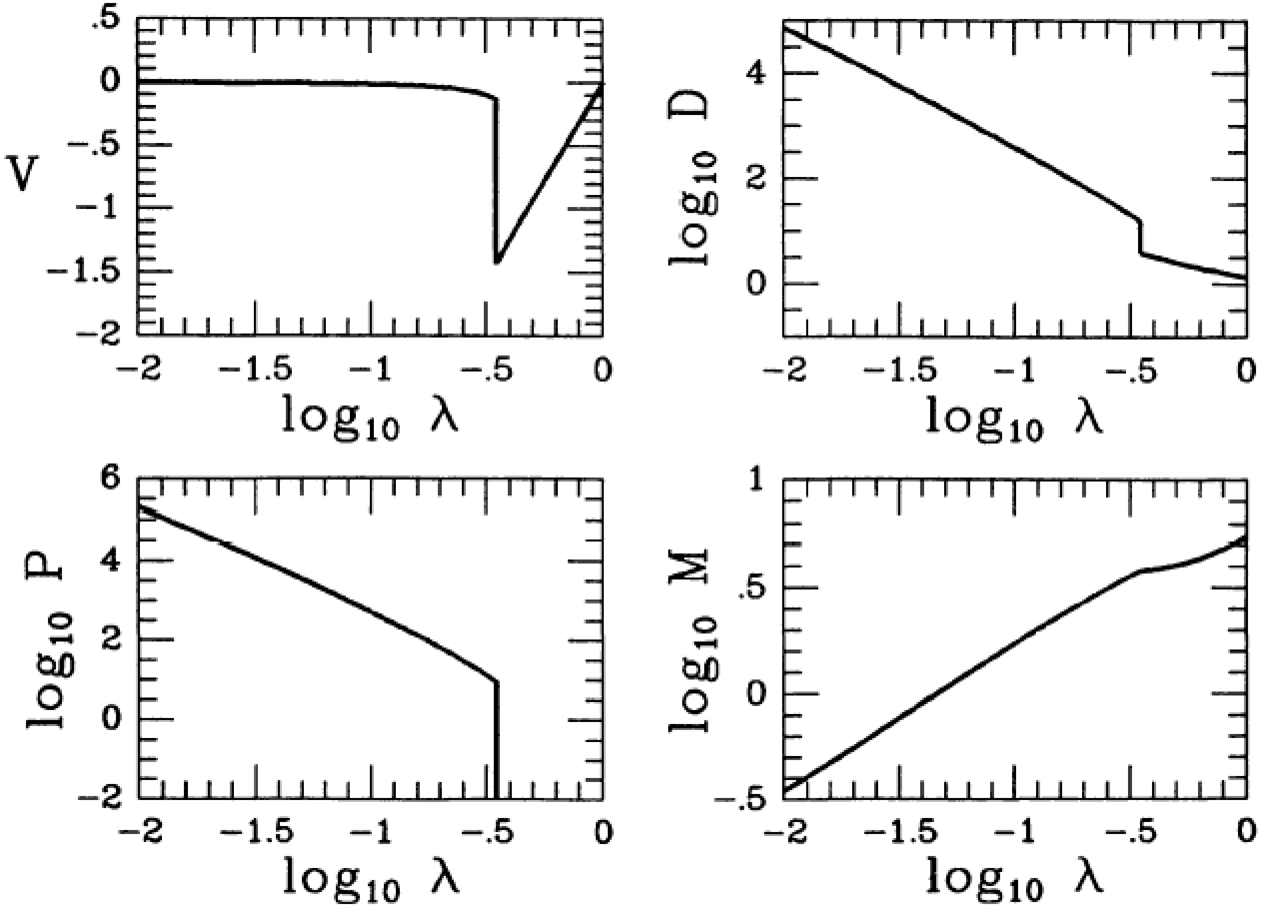
Spherical similarity solutions for infall



Bertschinger 1985

No cooling

Infall of DM + $\gamma = 5/3$ gas onto a point mass in an EdS universe

-- accretion shock at ~1/3 of turn-round radius

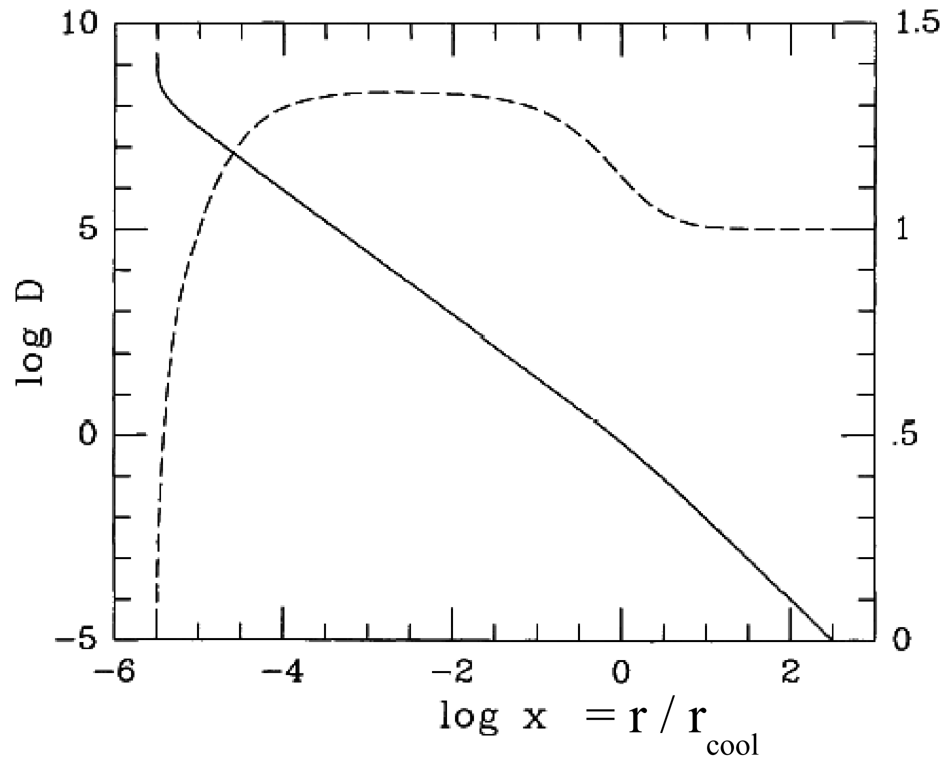
-- gas almost static inside shock

-- pre-shock gas has density about 4 times the cosmic mean

-- $kT(r) / \mu \sim GM(r) / r = V_c^{\,2}$; $R \sim V_c t$, $M \sim V_c^{\,3}\ t / G$

Spherical similarity solutions for cooling

Bertschinger 1989



$V_c^2 \propto T \propto$ const.

$M = r V_c^2 / G \propto r$

$\rho \propto r^{-2}$

Cooling wave in equilibrium gas in an isothermal DM potential

-- $\rho \propto r^{-2}$ at large radius $r > r_{cool}$ where $t_{cool}(r_{cool}) = t$

-- $\rho \propto r^{-1.5}$ and $T = 1.33\, T_\infty$ at $r_{sonic} < r < r_{cool}$

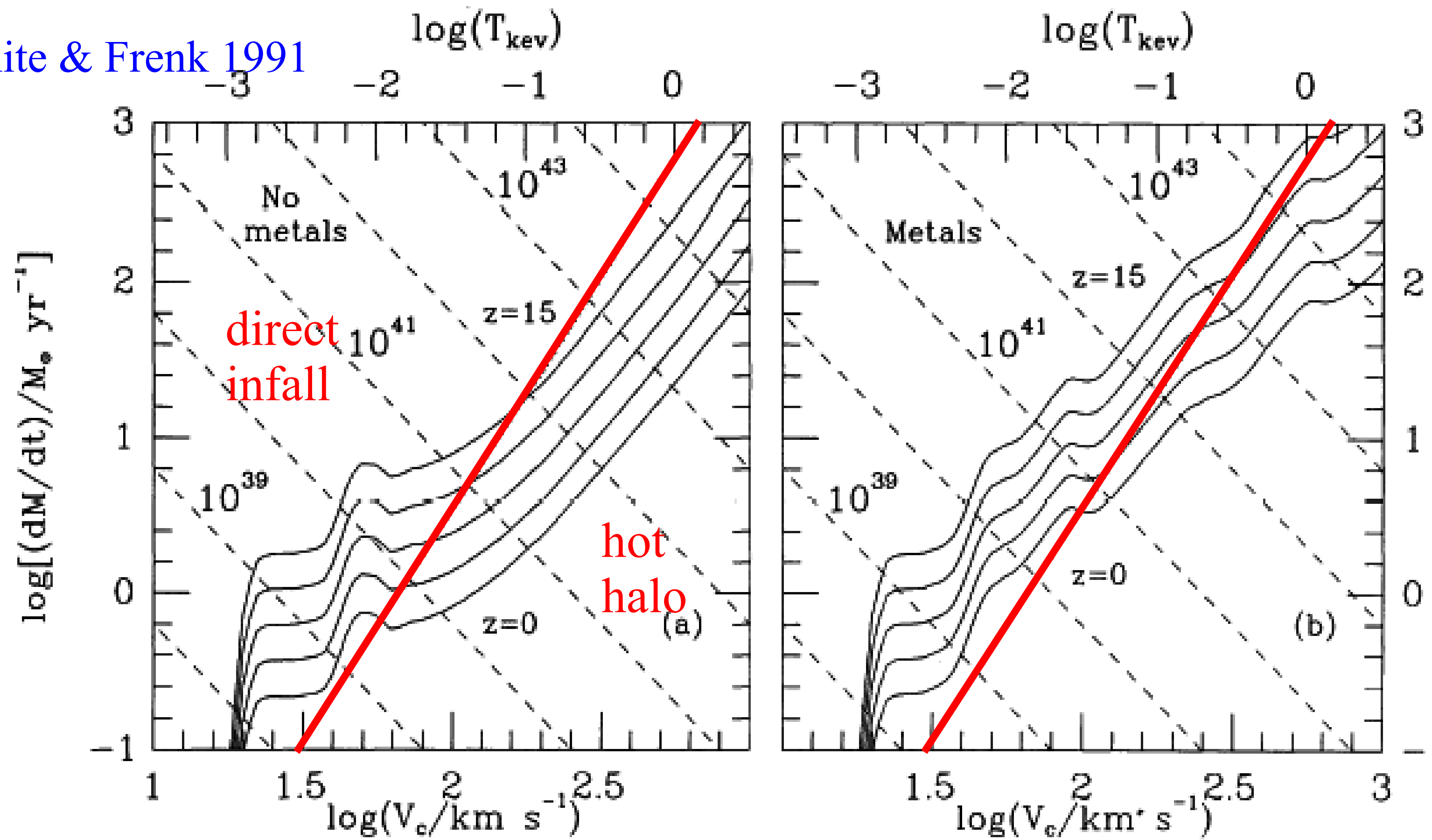
-- $\rho \propto r^{-1.5}$, flow is supersonic free-fall, and $T \rightarrow 0$ at $r < r_{sonic}$

Inflow rate $\propto t^{-1/2}$, cooling radius and cold mass $\propto t^{+1/2}$

$r_{sonic} \sim r_{cool} \sim r_{shock}$ in protogalaxies ⟶ no static atmosphere?

Putting it together in a sCDM universe

White & Frenk 1991



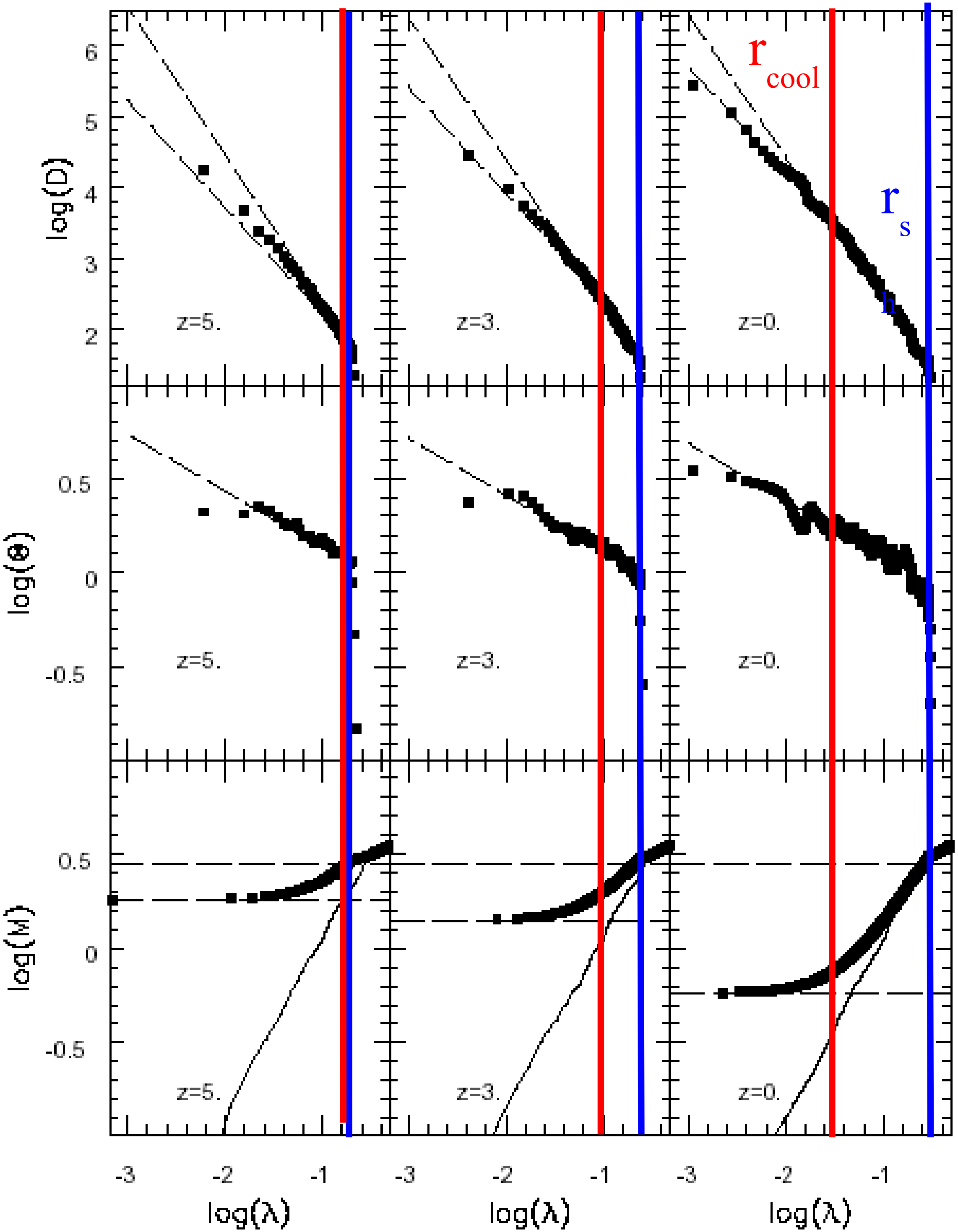
Assuming $r_{cool} < r_{shock}$ for a hot atmosphere and taking $f_{baryon} = 0.1$

→ direct infall (i.e. no hot atmosphere – a "cold flow")

for $V_{circ} <$ 80 km/s at z=3 when there is no chemical mixing,

and for $V_{circ} <$ 250 km/s at z=3 when efficient mixing is assumed

Radiative cooling in spherical infall models



Forcada-Miró & White 1997
astro-ph/9712204

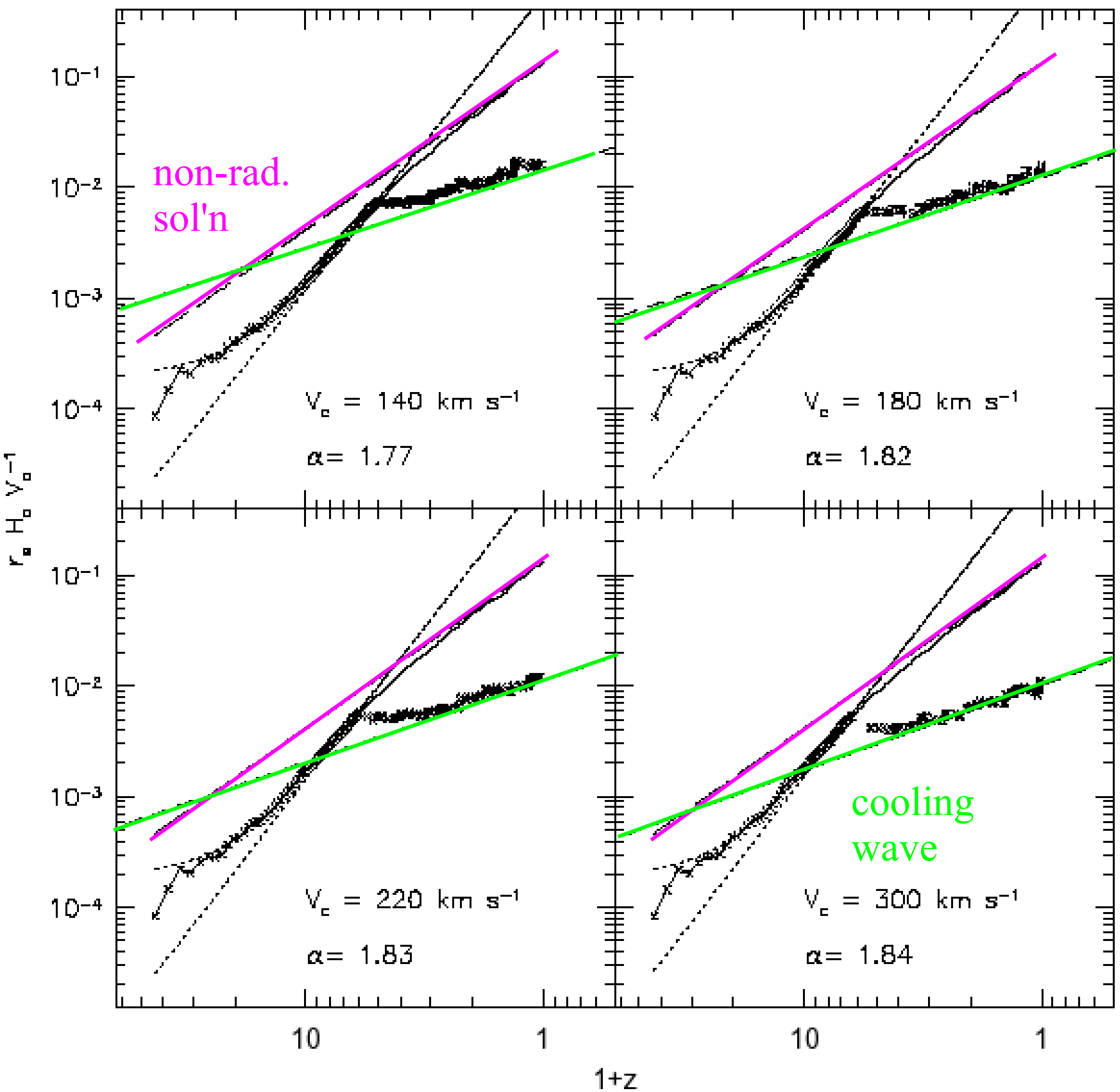
Spherical, isothermal infall model with V_{circ} = 220 km/s and f_{gas} = 0.05

Non-equilibrium H and He ionization and radiation

At early times r_{cool} and r_{shock} coincide; interior dynamic cooling flow has $\rho \propto r^{-1.5}$

At later times r_{cool} and r_{shock} separate, enclosing a near static region: $\rho \propto r^{-2.0}$

Shock and cooling radius evolution in isothermal models



Forcada-Miró & White 1997

At early times shock and cooling radii are determined by $t_{cool} \approx t_{free\text{-}fall}$

$$\rightarrow \quad r_{cool} \approx r_{shock} \propto t^{1.8}$$

Cooling radius breaks away from shock as both near similarity shock radius

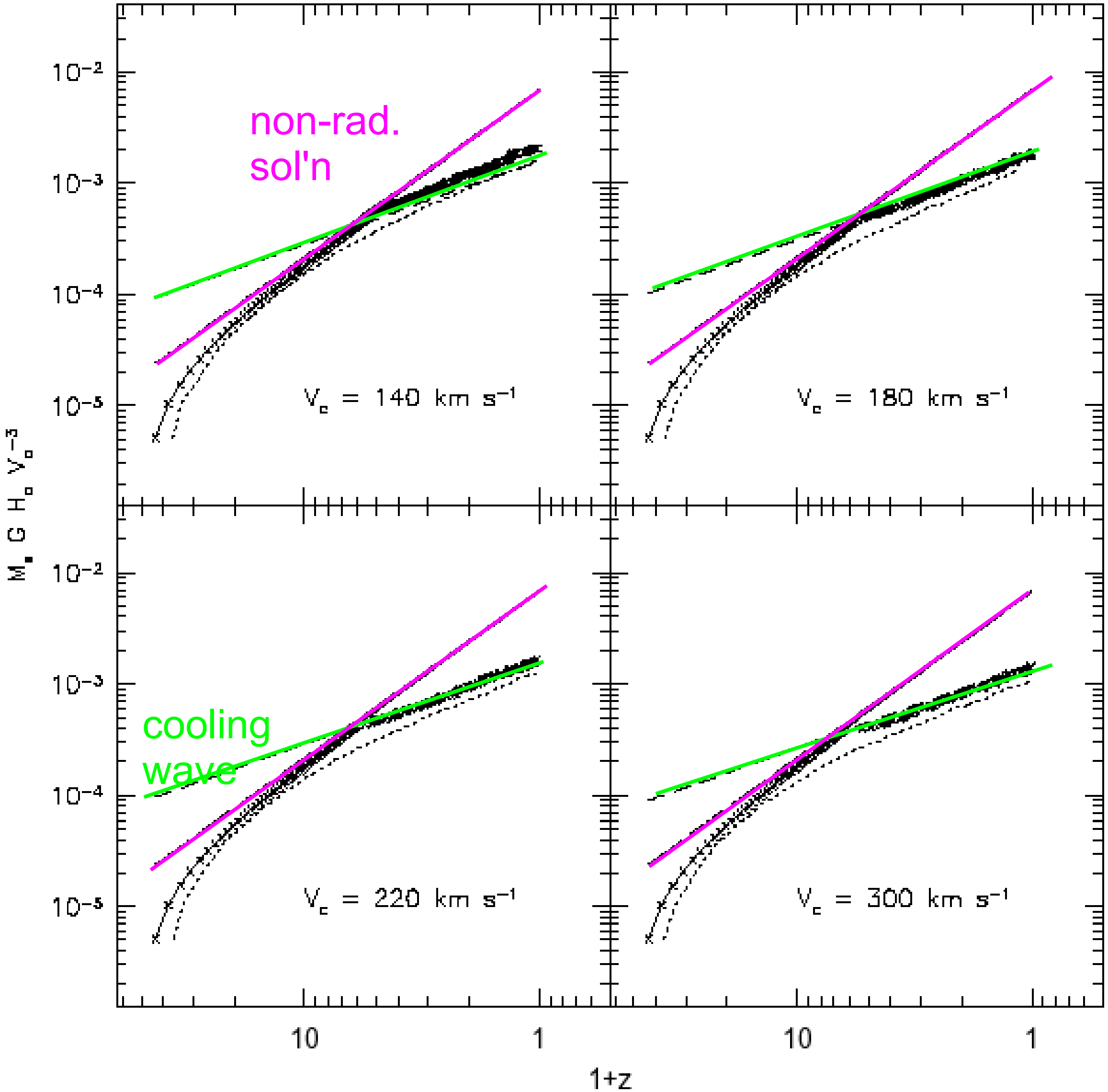
Cooling radius then follows the Bertschinger solution

$$r_{cool} \propto t^{0.5}$$

Shock asymptotes to the non-radiative sim. solution

$$r_{shock} \propto t$$

Cold and shocked mass evolution in isothermal models



Forcada-Miró & White 1997

At early times cold mass and shocked mass grow as

$$M_{cold} \approx M_{shock} \propto t$$

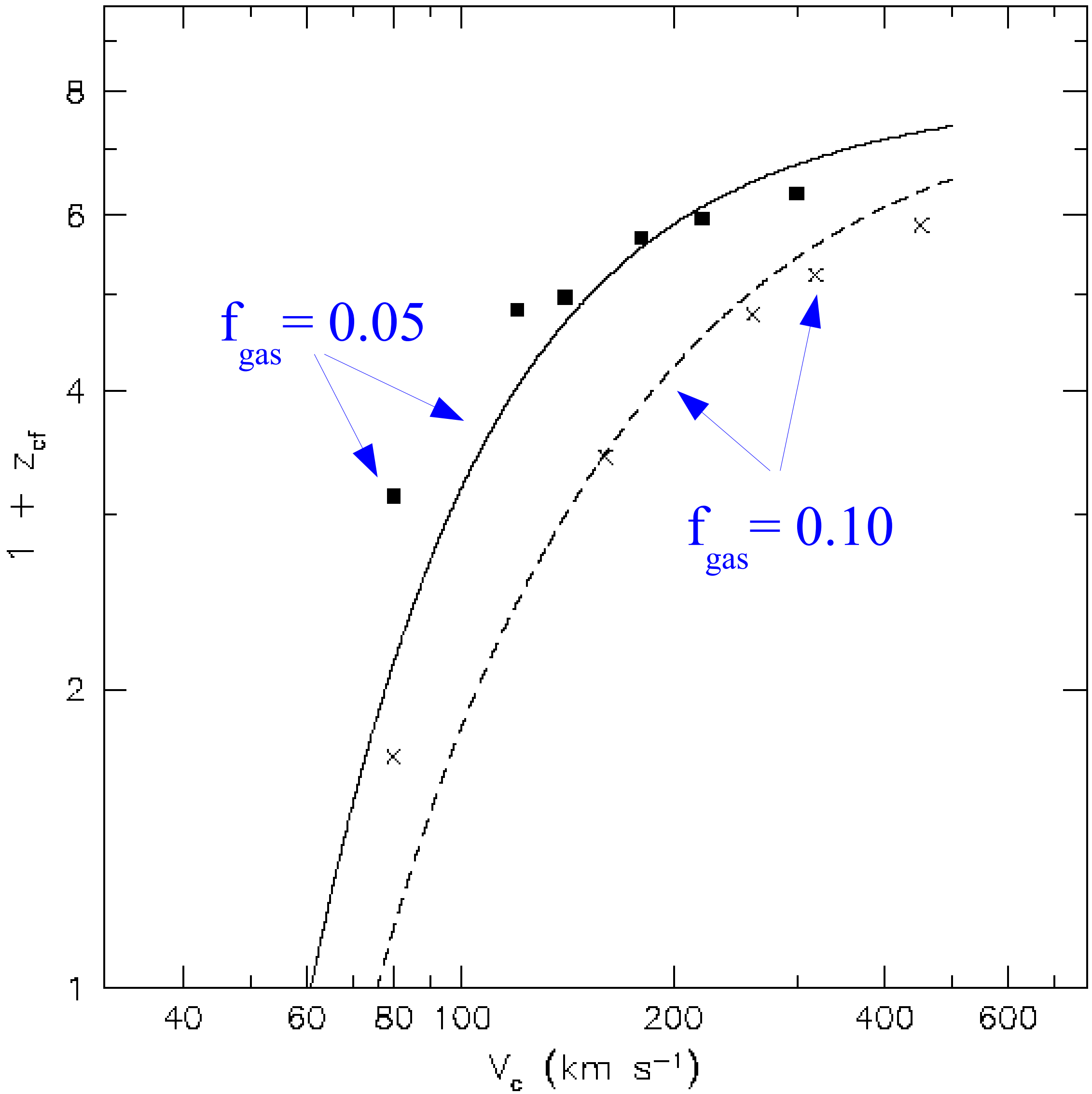
At late times shocked mass continues this behaviour

$$M_{shock} \propto t$$

..but cold mass follows the cooling wave solution

$$M_{cool} \propto t^{0.5}$$

Transition from infall- to cooling-dominated flow



Forcada-Miró & White 1997

Infall dominated flow switches to cooling from static atmosph.

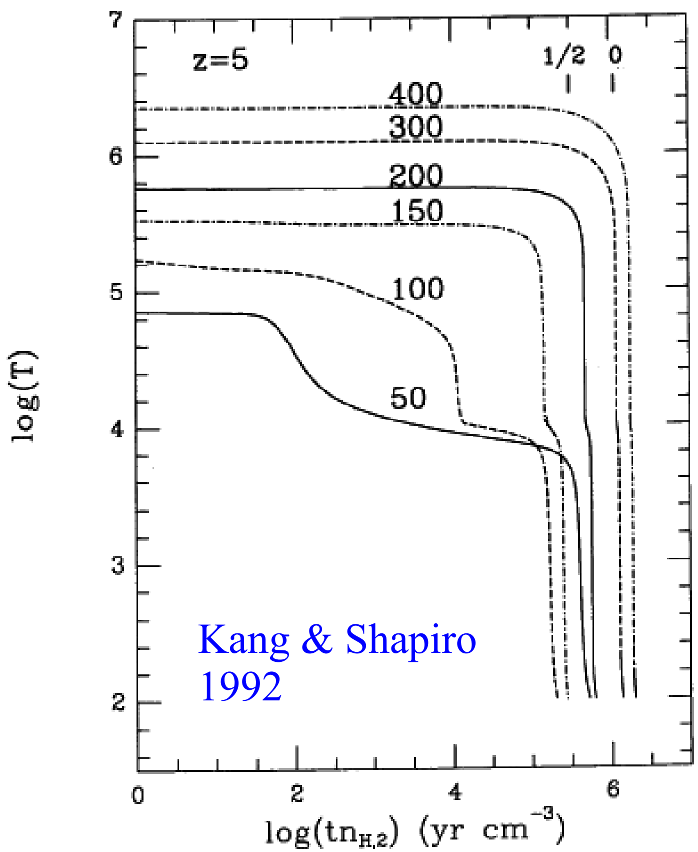
$r_{cool} \approx r_{shock} \longrightarrow r_{cool} < r_{shock}$

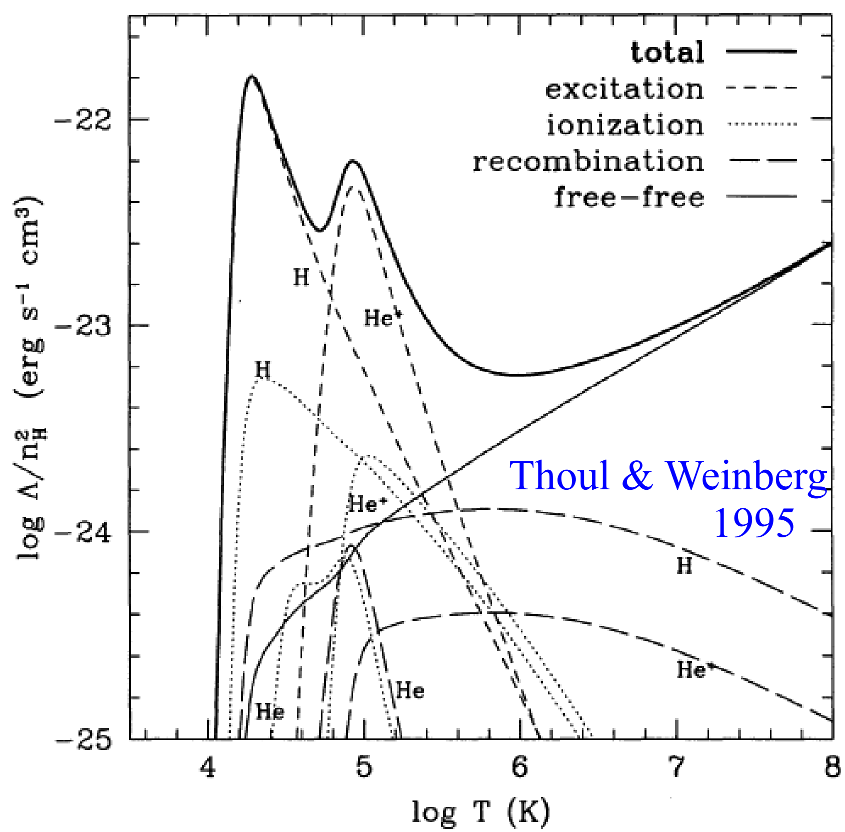
when the cooling time for gas at the post-shock temperature and density in the *non-radiative* solution is equal to the age of the system

This is the "semi-analytic" criterion suggested by White & Frenk (1991) and is equivalent to the shock stability criterion of Birnboim & Dekel (2003)

Radiation from shocks

For collisional ionisation equilibrium, the radiation from shocks would be dominated by He II 304 for 70 km/s < V_{sh} < 270 km/s

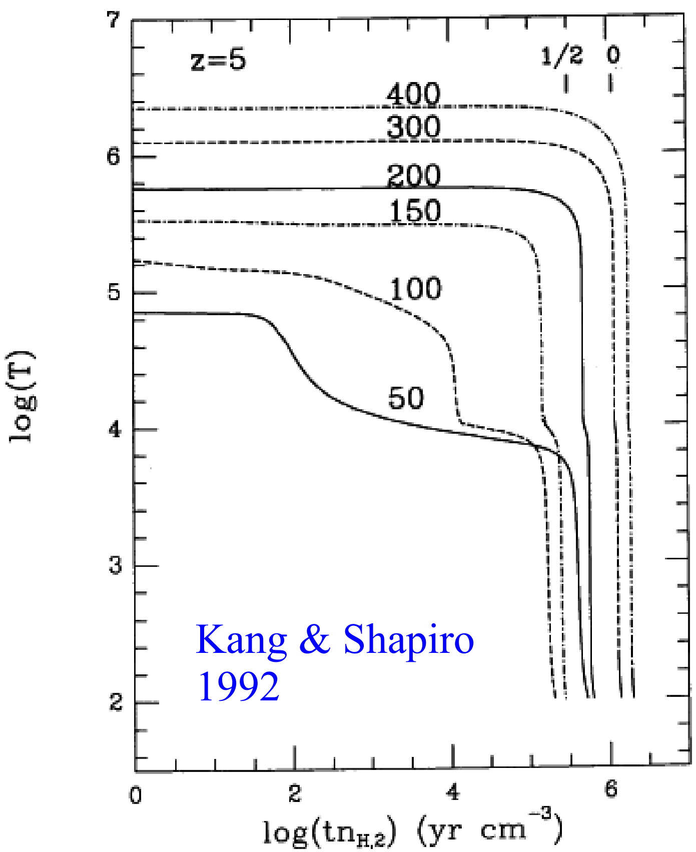


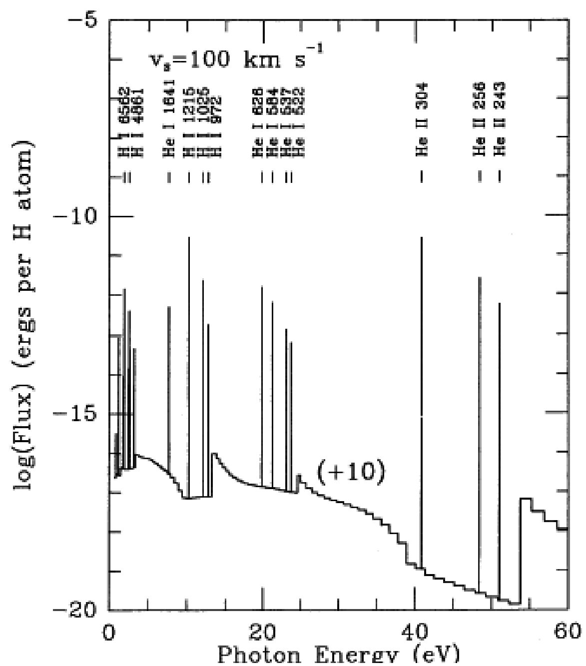


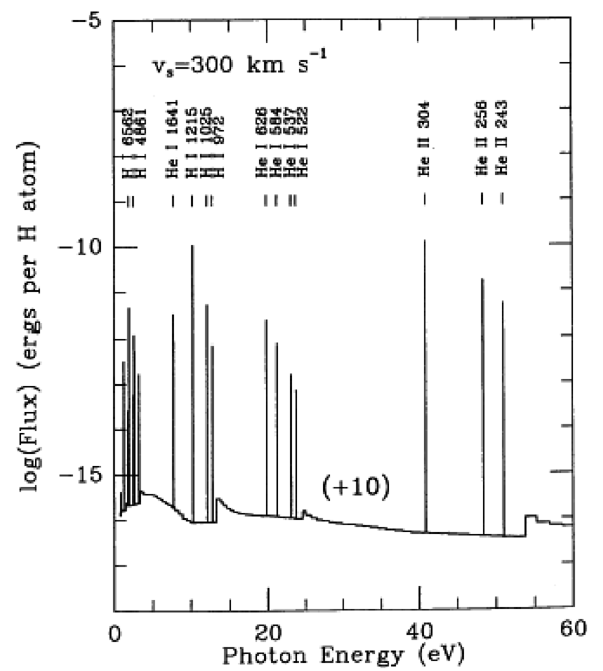
Radiation from shocks

For collisional ionisation equilibrium, the radiation from shocks would be dominated by He II 304 for 70 km/s < V_{sh} < 270 km/s

...but, in fact, non-equilibrium processes affect line emission strongly, particularly enhancing H I 1216 (Ly α)

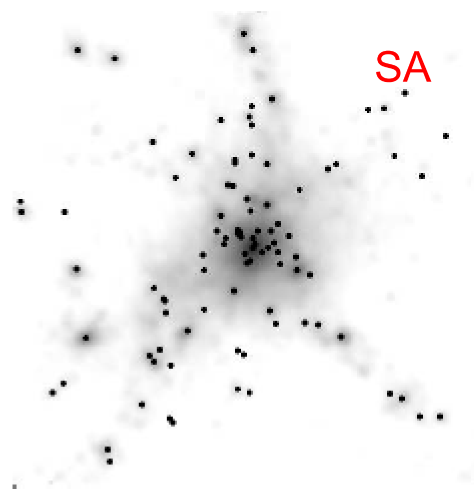




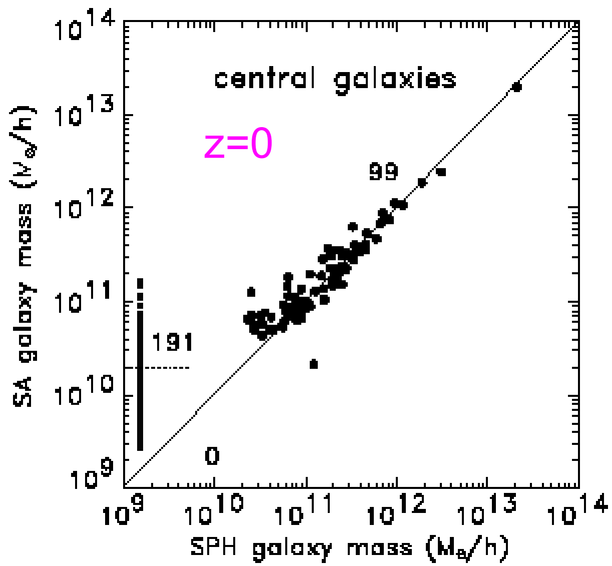


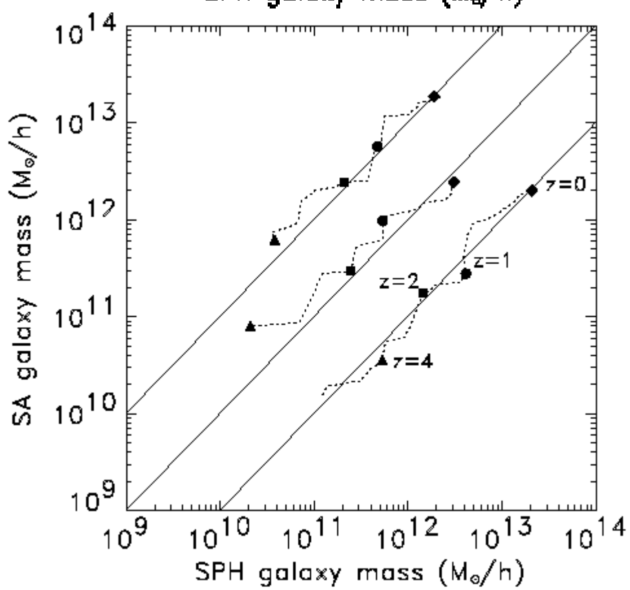
Cooling in SPH compared to a SA model

Yoshida et al 2002



$M_g > 6 \times 10^{10} h^{-1} M_\odot$





Comparison of implementation in the *same* N-body ΛCDM cluster formation simulation of cooling

(a) with SPH

(b) with a standard SA model

Masses of central objects in halos agree well once above the SPH resolution limit (~ 50 particles)

Range checked includes transition from efficient to inefficient cooling

Different SPH implementations give different results

Other physical complications

Radiative mixing layers (Begelman & Fabian 1990) on the interface between cold clouds and a hot phase may radiate much of the cooling energy at an intermediate temperature

Cosmic ray populations (e.g. Miniati et al 2001) from large-scale shocks or radio galaxies may add pressure support and also provide additional heating and energy transport

Metal enhanced cooling instability may occur in differentially enriched regions. The more metal-rich regions cool and condense faster, dropping preferentially out of the hot phase

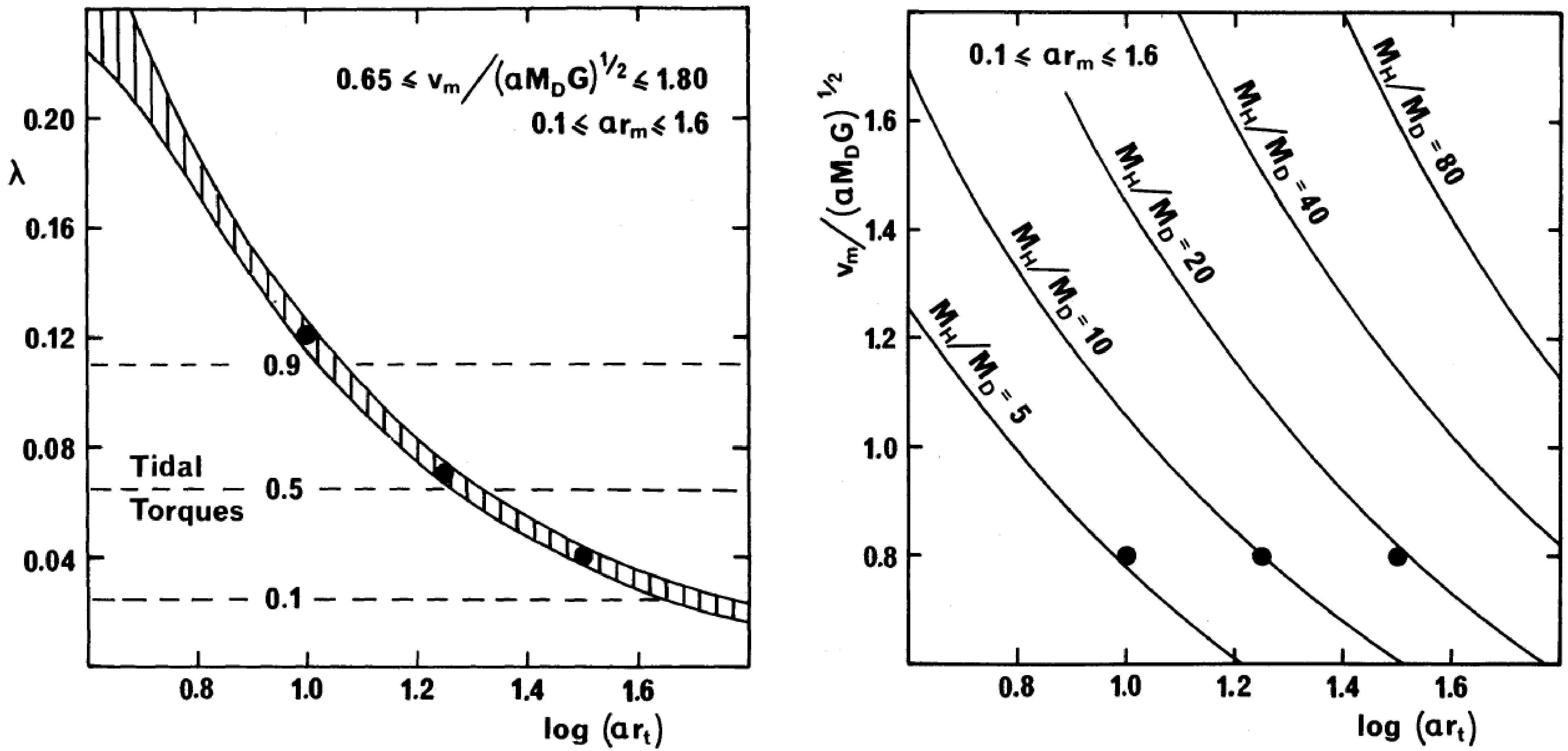
Winds/outflows from AGN and from star-forming regions interact with infalling gas – driven by gas/radiation pressure, CR's..

Radiative transfer effects modify shock structure and emitted spectral energy distribution

Magnetic fields as always...

Formation of galaxy disks

Fall & Efstathiou 1980



For $\lambda \sim 0.05$, the " collapse factor" $\alpha r_t = r_t / r_d$ is about 20.

For $V_{max}^2\, r_d / G\, M_d \sim 0.7$ (e.g. The Milky Way) → $M_{halo} / M_d \sim 15$.

Massive and extended dark halos are needed if tidal torques are to produce the angular momentum of galaxy disks (conclusion predates ΛCDM).

Formation of galaxy disks

Mo, Mao & White 1998

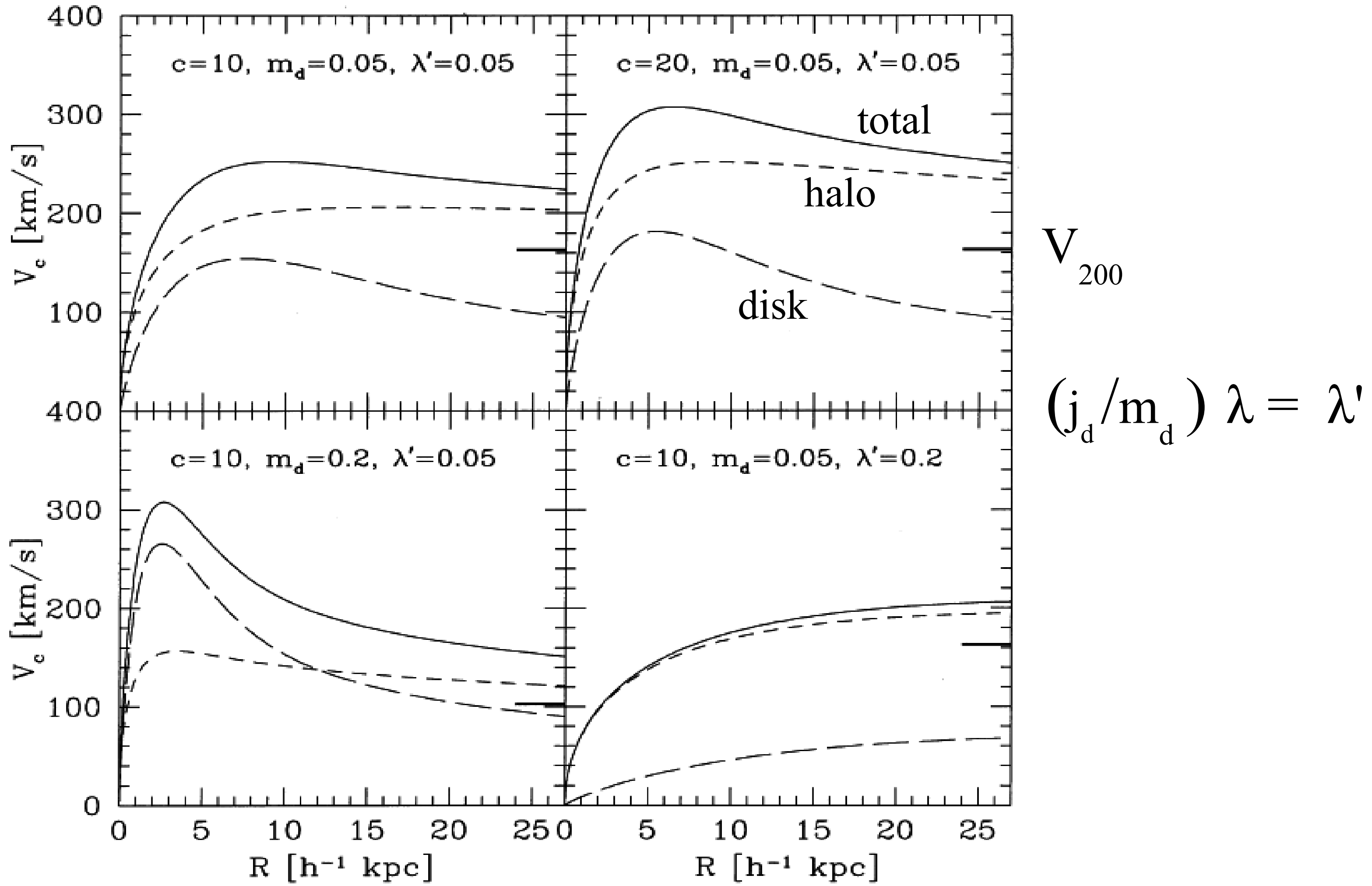


Figure 2. Rotation curves for disc galaxies formed in haloes with an initial density distribution described by the NFW profile. The shape of the rotation curves depends only on the concentration parameter, c, the fraction of mass in the disc, m_d, and the spin parameter, $\lambda' \equiv (j_d/m_d)\lambda$. The total mass of a halo determines both the disc scalelength and the amplitude of the rotation curve. Four panels are shown for different sets of c, m_d and λ'. The disc mass is assumed to be $M_d = 5\times10^{10}h^{-1}\,M_\odot$. The rotation velocities induced by the disc and the dark matter are shown using long-dashed and short-dashed lines, respectively, while the total rotation velocity is shown by a solid line. The rotation velocity induced by the disc reaches a peak at about two disc scalelengths. The rotation velocity at r_{200} is indicated by thick horizontal bars and is identical to the rotation velocity at all radii for a singular isothermal sphere with the same mass. The upper left panel should be viewed as the reference panel. Only one parameter is varied between this panel and any other. Notice how both the prominence and amplitude of the peak in the rotation curve change between panels.

Formation of galaxy disks

Mo, Mao & White 1998

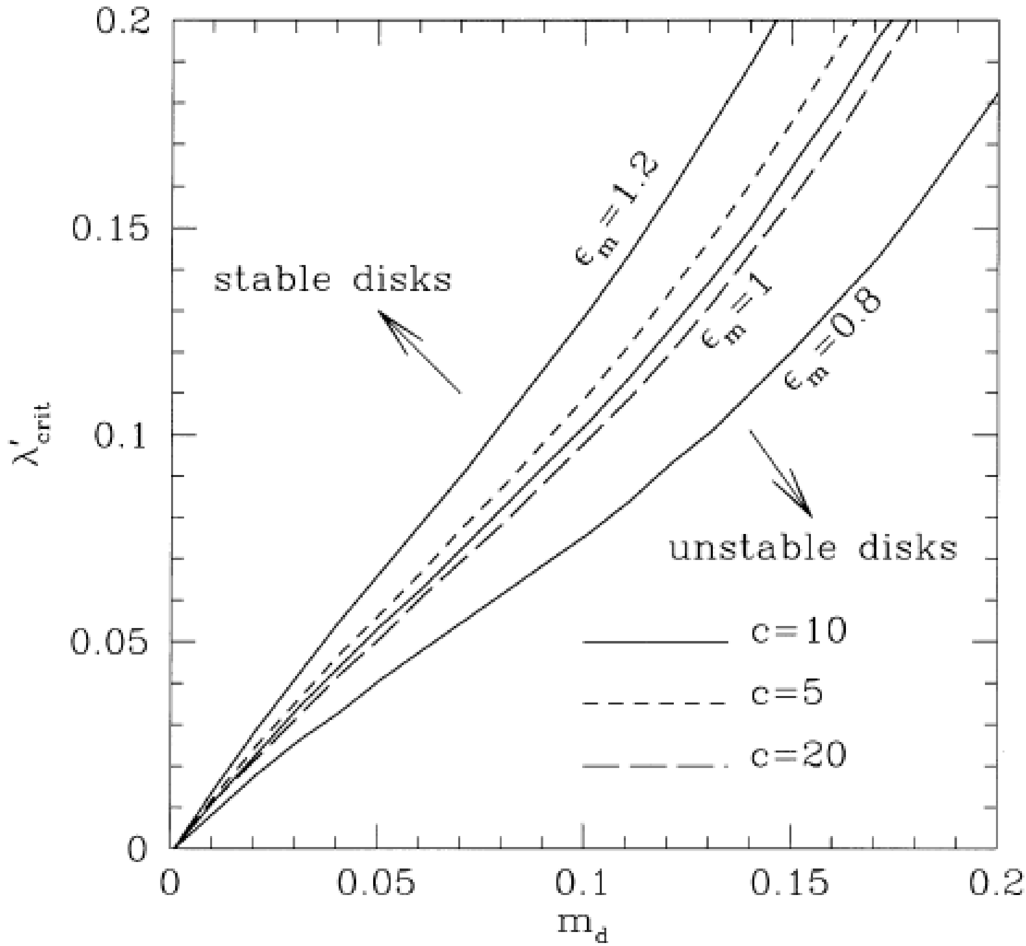


Figure 3. Critical values of λ' ($\equiv \lambda j_d/m_d$) for disc instability as a function of m_d. Results are shown for three choices of ϵ_m. For a given m_d, discs are stable if $\lambda' > \lambda'_{crit}$. The dependence on halo concentration, c, is weak, and is shown only for $\epsilon_m = 1$.

For $(j_d/m_d)\,\lambda < \lambda'_{crit}$, the disk is predicted to be unstable to bar formation → a bulge?

Since typically $\lambda \sim 0.05$ or less, the formation of stable disks requires:

(i) $m_d < 0.05$

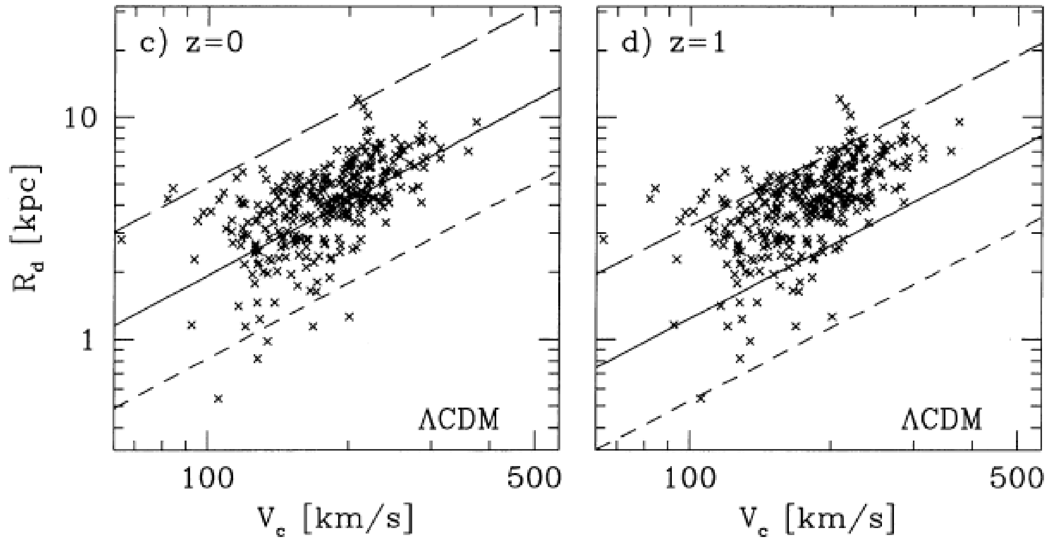
(ii) $j_d \sim m_d$

The first requires disk formation to be inefficient

The second favours cold flows over settling through cooling

Formation of galaxy disks

Mo, Mao & White 1998



$m_d = j_d$, $\lambda = 0.1$

stable: $m_d = 0.05$

stable: $m_d = 0.025$

Figure 4. Model predictions for R_d as a function of V_c for stable discs assembled at $z = 0$ and at $z = 1$ in the SCDM and ΛCDM models. The solid lines give the relations for critical discs when $m_d = 0.05$, while short-dashed lines give the corresponding relations for $m_d = 0.025$. Stable discs must lie above the line for the relevant value of m_d. The long-dashed lines correspond to $m_d = j_d$ and $\lambda = 0.1$; at most 10 per cent of discs should lie above these lines. The data points are the observational results of Courteau (1996, 1997) for a sample of nearby normal spirals.

Observed disks follow the expectations for moderately stable disks with $m_d = j_d$ and $m_d < 0.05$.

Modest evolution towards smaller sizes is predicted to $z \sim 1$

Formation of galaxy disks

Mo, Mao & White 1998

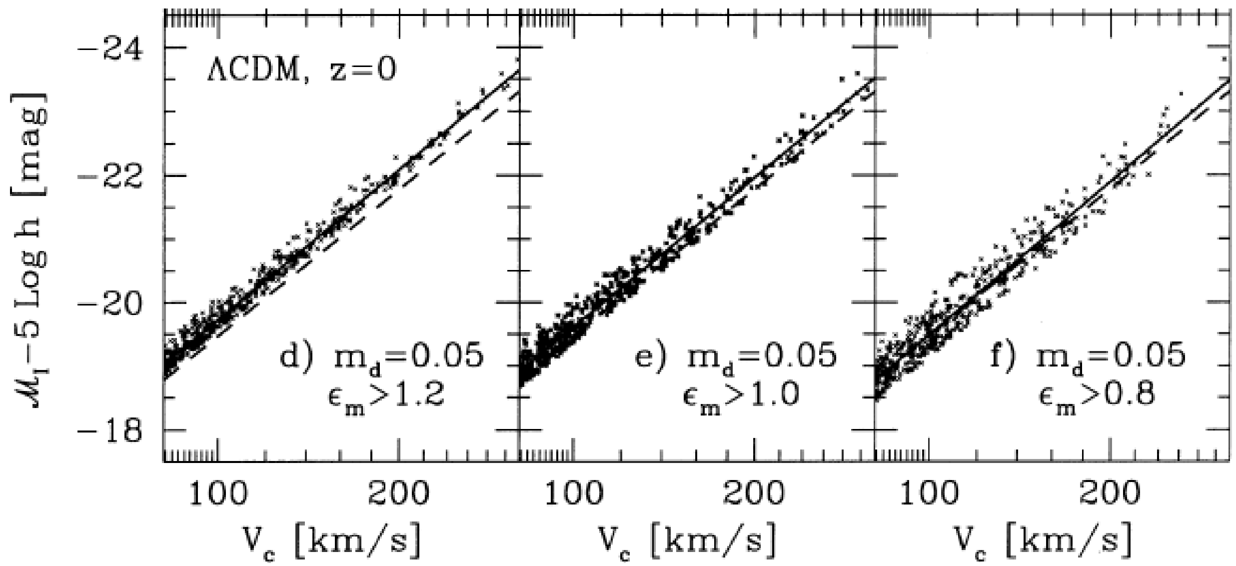
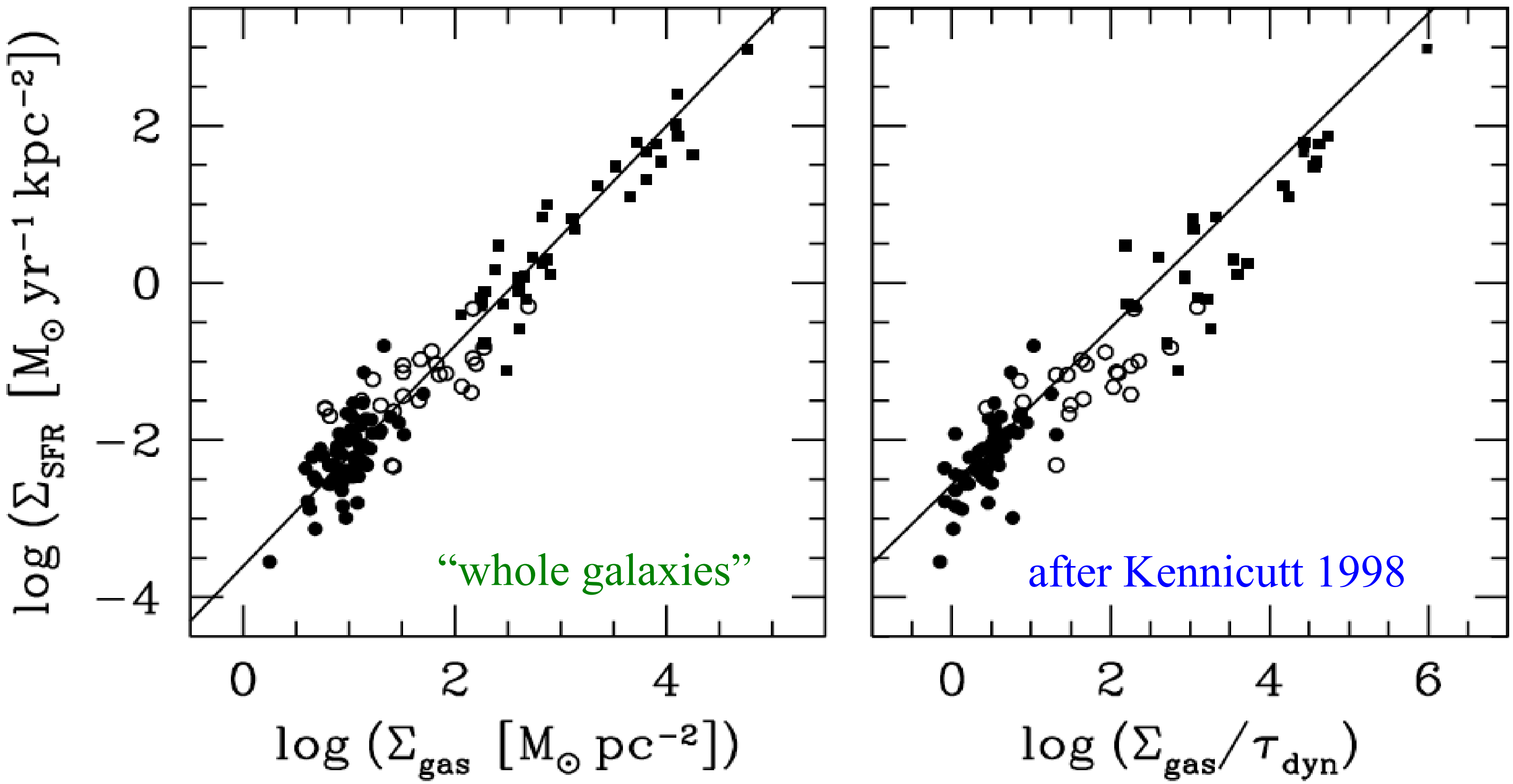


Figure 6. Tully–Fisher (TF) relations for stable discs at $z = 0$ in the SCDM and ΛCDM cosmogonies. Monte Carlo samples of the predicted luminosity–rotation velocity distribution are shown for three choices of ϵ_m. We have converted stellar mass (in the model) into I-band luminosity using $\Upsilon = 1.7h$ (Bottema 1997). The solid lines give the linear regressions of absolute magnitude against log V_c. The dashed lines show the observed TF relation as given by Giovanelli et al. (1997).

Predicted Tully-Fisher relations for *stable* disks with *constant* m_d are compared with the observed relation for three stability criterion choices.

...but why is $m_d = j_d$ = constant appropriate?

Empirical star formation "laws"



Kennicutt-Schmidt "laws" are actually observational scaling relations between mean gas surface density and mean SFR surface density:

$$M_* \propto M_{gas}^{1.4} \qquad \text{or} \qquad M_* \propto M_{gas} \,/\, t_{dyn}$$

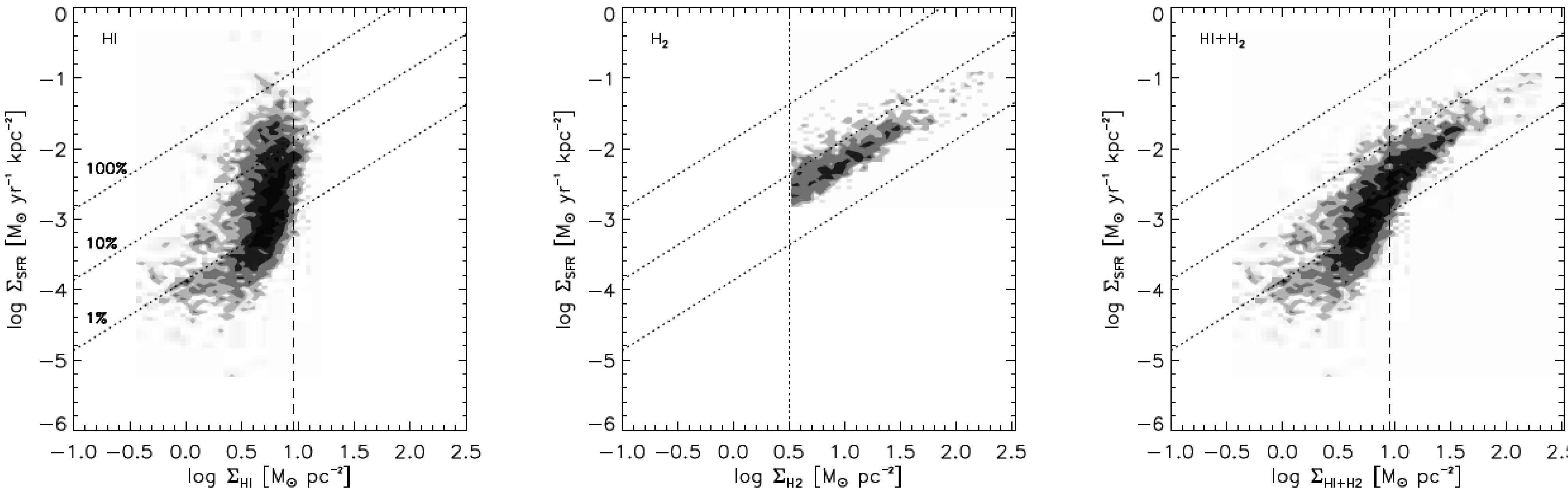
where definitions and proportionality constants are set purely empirically

-- which gas density? (atomic, molecular, , total?)

-- which averaging area?

-- thresholds?

Empirical star formation “laws”



1 kpc “pixels” within galaxies

after Bigiel et al 2008

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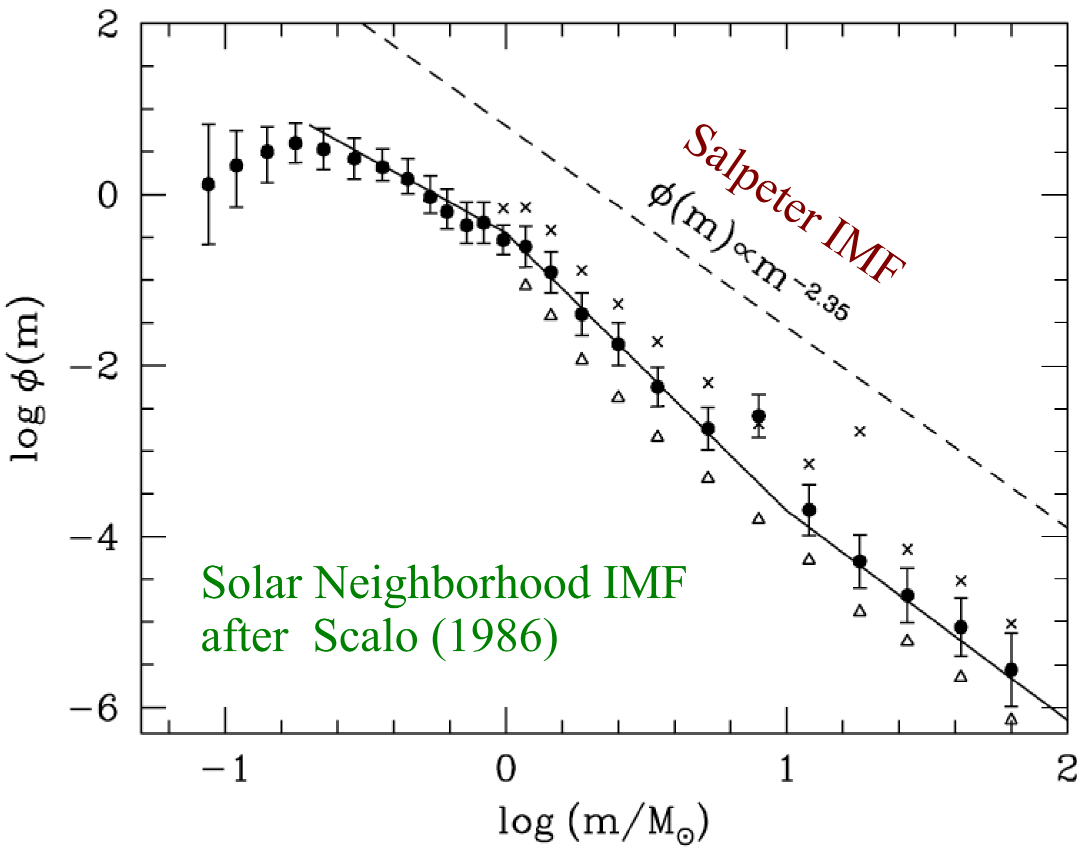
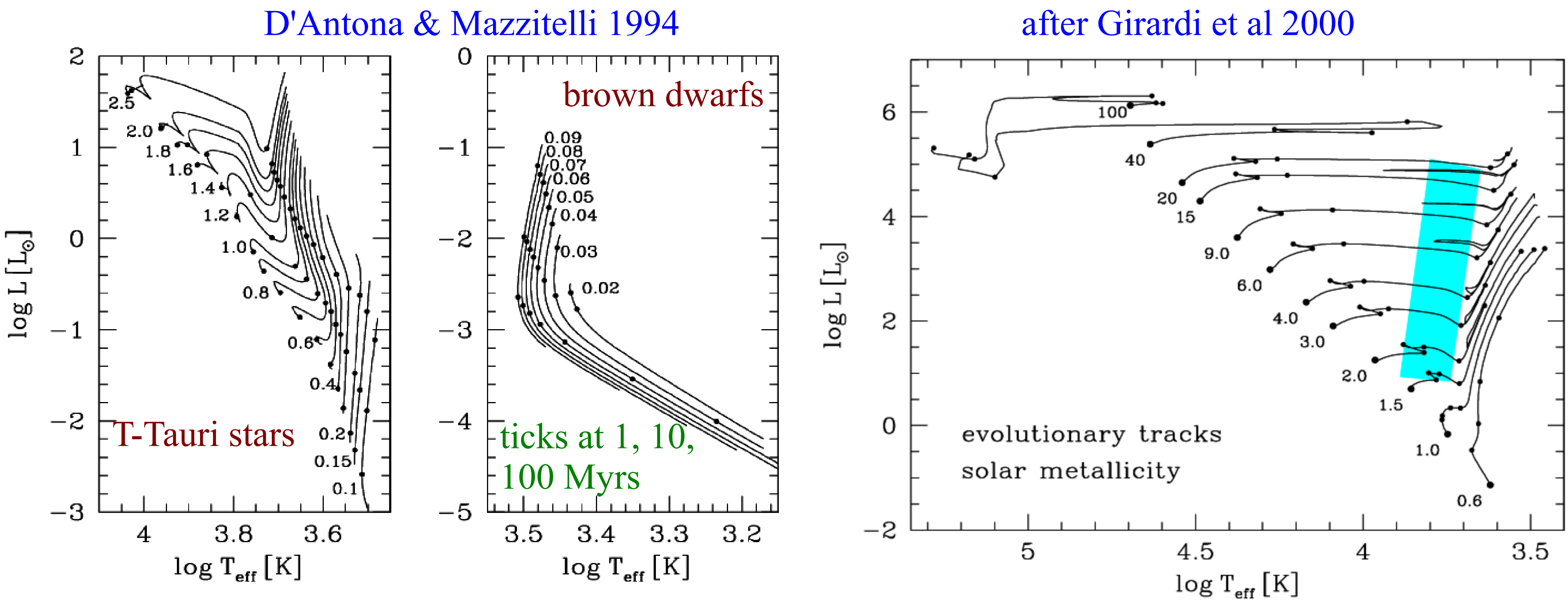
-- thresholds?

The stellar Initial Mass Function (IMF)



Total mass set by the turnover at low masses
Luminosity, ionising and mechanical feedback set by high mass tail
Usually assumed “universal” -- little theoretical/observational basis
Some indications for variations but little consensus so far
→ a <u>major</u> systematic uncertainty in galaxy formation models

Stellar Population Synthesis



Pre- and post-main sequence evolutionary tracks must be combined with

-- stellar atmosphere models (to predict colours and spectra)

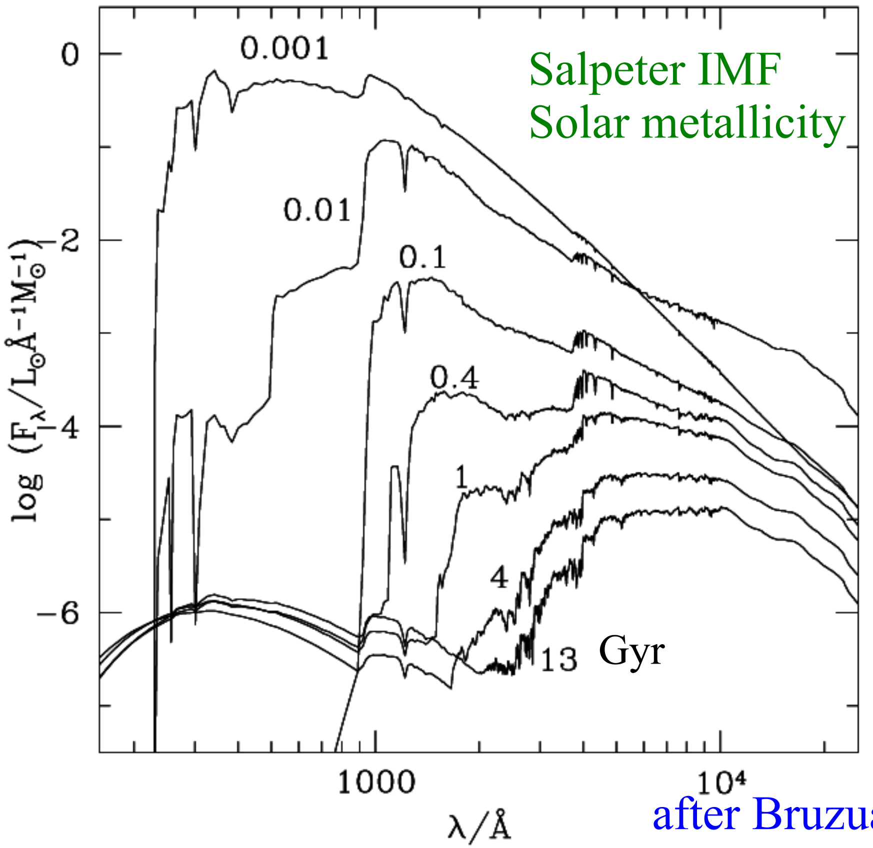
-- with stellar wind and PN models (to predict material returned to ISM)

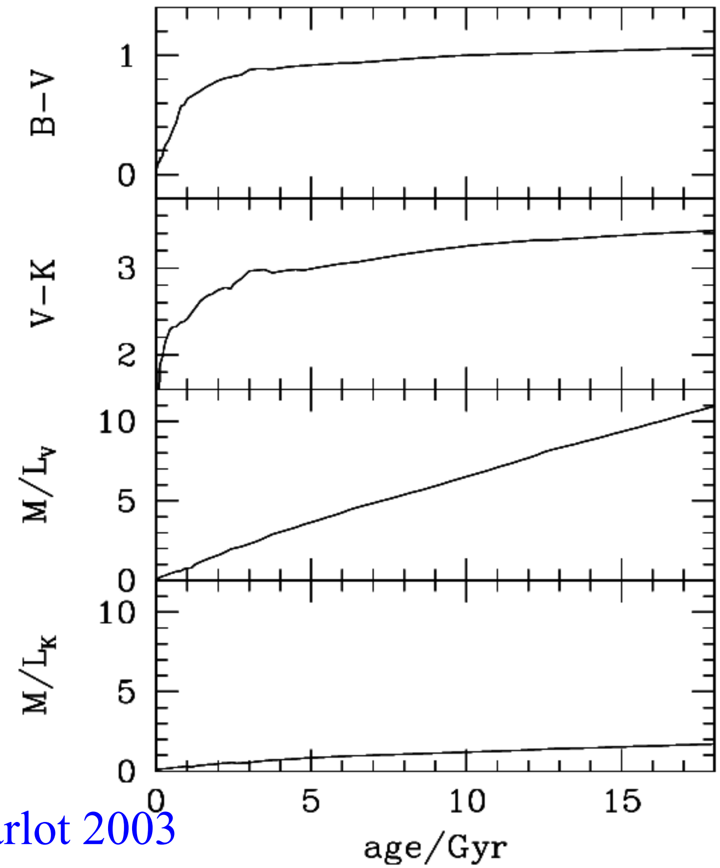
-- with nucleosynthesis modelling (to predict yields of heavy elements)

-- with supernova models (for energetic and chemical feedback)

-- with ISM modelling (to predict line emission and dust obscuration)

Stellar Population Synthesis





after Bruzual & Charlot 2003

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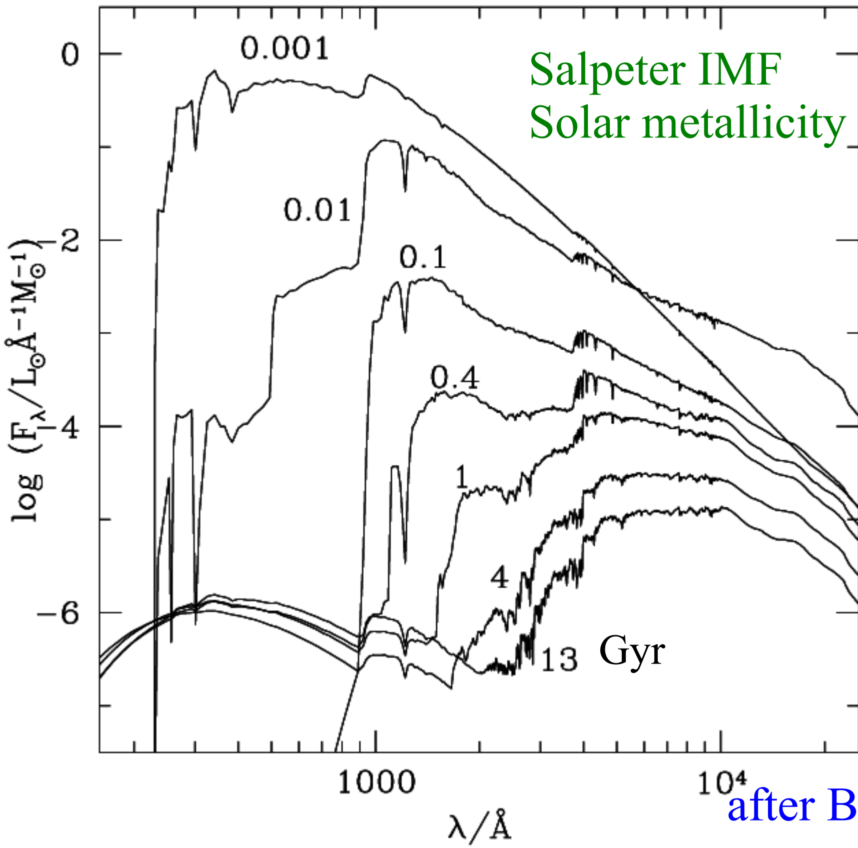
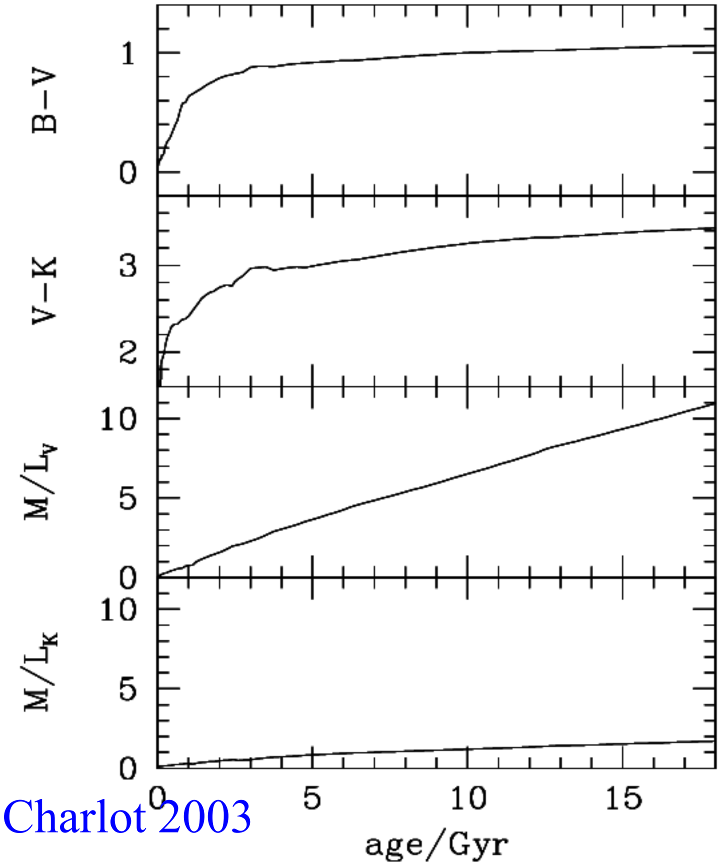




after Bruzual & Charlot 2003

For real galaxies, the colours and integrated optical/IR spectra are affected by

-- the stellar age distribution

-- the stellar metallicity distribution

-- the local and large-scale dust distributions

In practice, these three aspects are <u>strongly</u> correlated

→ Major degeneracies in inferring formation history from observation.

Even inferring colours from a specific model is hindered by dust, TP-AGB...

Adding the baryons: hydrodynamics

After recombination the baryons are in the form of a diffuse, near-uniform mixture of neutral H and He – no stars, almost no elements heavier than He, no magnetic fields (?)

Need to solve hydrodynamics equations for the gas in addition to N-body equations for the DM

$\partial\rho/\partial t + \nabla.(\rho\mathbf{u}) = 0$ Mass conservation

$\partial(\rho\mathbf{u})/\partial t + \mathbf{u}\,.\nabla(\rho\mathbf{u}) + \nabla p + \rho\nabla\Phi = 0$ Momentum cons.

+ Energy conservation

Main solution techniques

-- discretise on a regular fixed mesh (Eulerian hydro)

-- discretise on a variable, adaptive Eulerian mesh (Adaptive Mesh Refinement)

-- discretise using a finite set of fluid elements (Smoothed Particle Hydrodynamics: SPH)

-- discretise on an irregular quasi-Lagrangian mesh (e.g. a Voronoi tesselation, AREPO)

Hydrodynamics and cluster formation

Structure formation produces shocks which transform the K.E. of fluid motions into heat

Bremsstrahlung and line emission from cluster gas is observable in X-rays $S = \int dl\ \rho^2 \Lambda(T)$

Cluster "shadows" are observable against the CMB through the Sunyaev-Zeldovich effect $\Delta T \propto \int dl\ p$

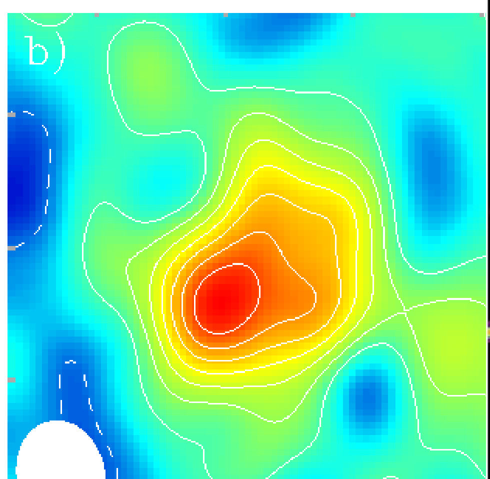
Hierarchical growth of structure produces the phenomenology observed in images of clusters

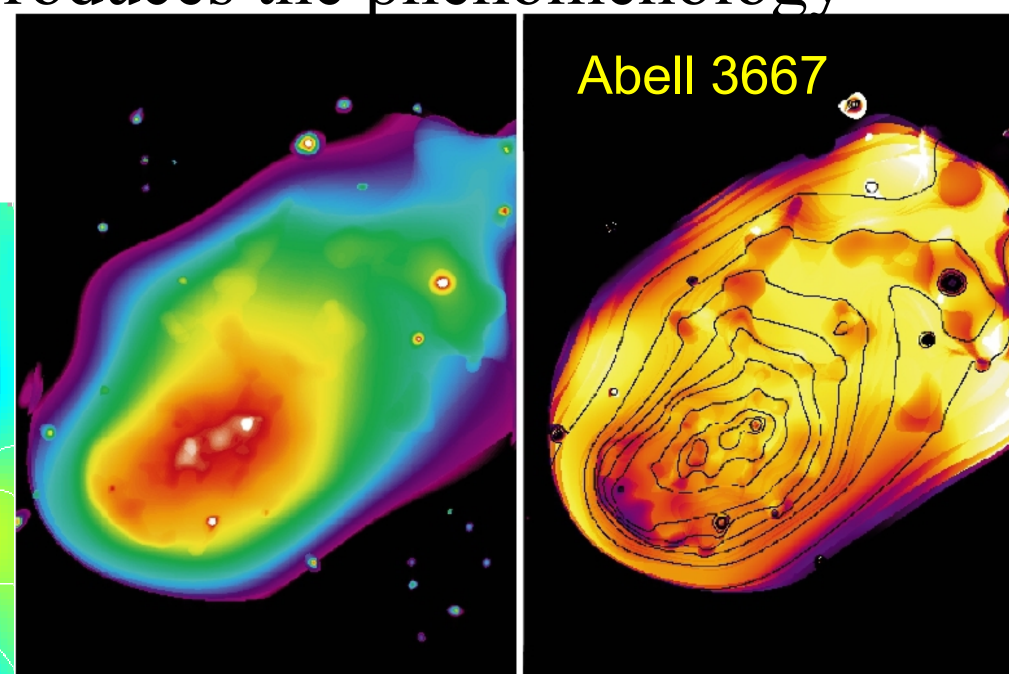
--asymmetries and sublumps

--shocks

--cold fronts

--cold cores





Gas cooling and galaxy formation

Gas cooling times due to bremsstrahlung and line emission scale as $t_{cool} \propto T / \rho\Lambda(T)$ while objects at cosmic time t have typical density $\rho \propto t^{-2}$. Hence $t_{cool} / t \propto t\, T / \Lambda(T)$

→ rapid cooling in lower mass objects and at early times

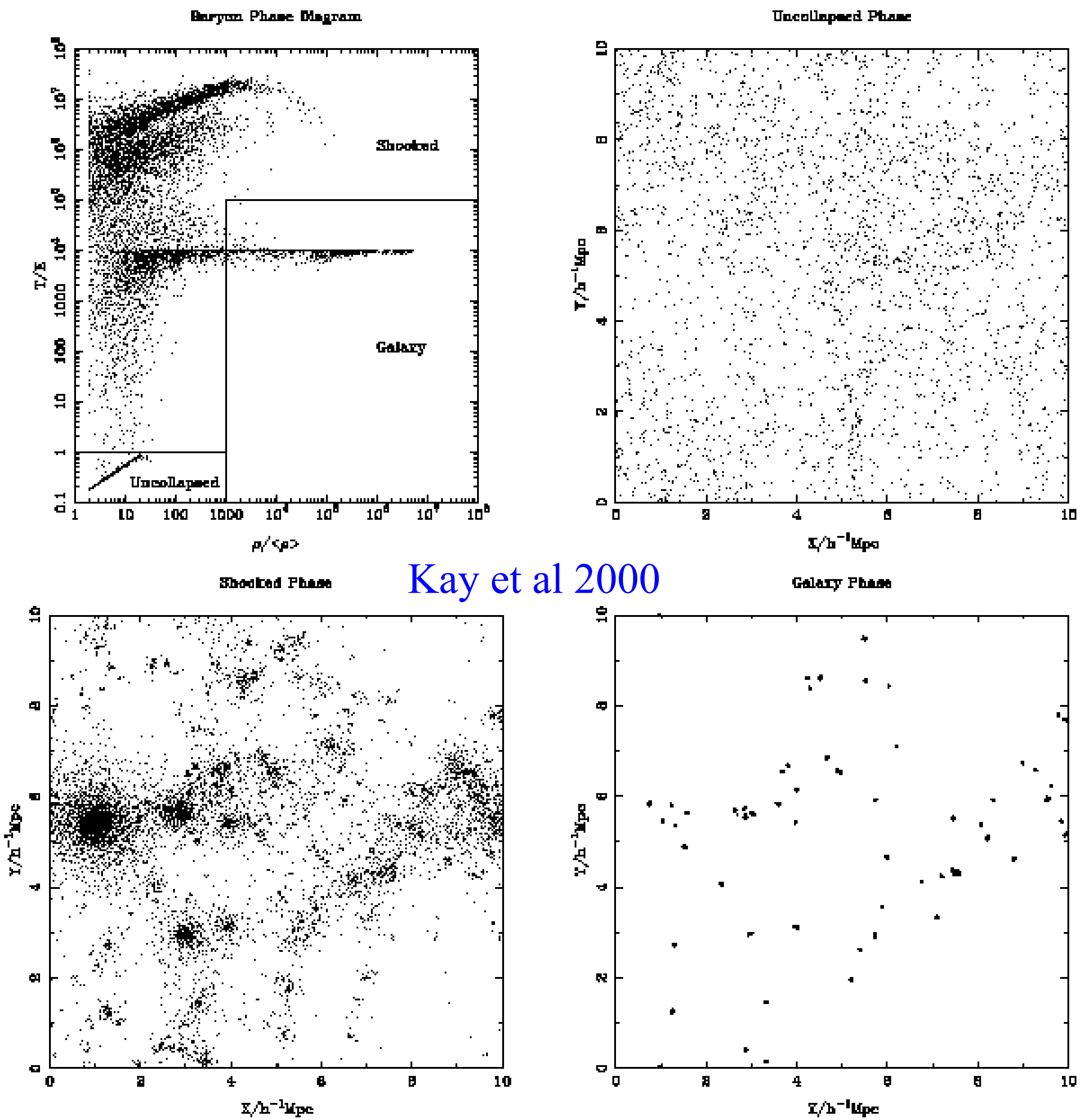
→ efficient galaxy formation with little hot halo gas.

→ strong feedback needed to offset gas condensation

When seen in cosmological simulations this was hailed as a "new paradigm" of cold flows. However, the novelty lies only in the characterisation of flow *morphology*. Low entropy gas from filaments can stream through hot halos to fuel galaxy formation.

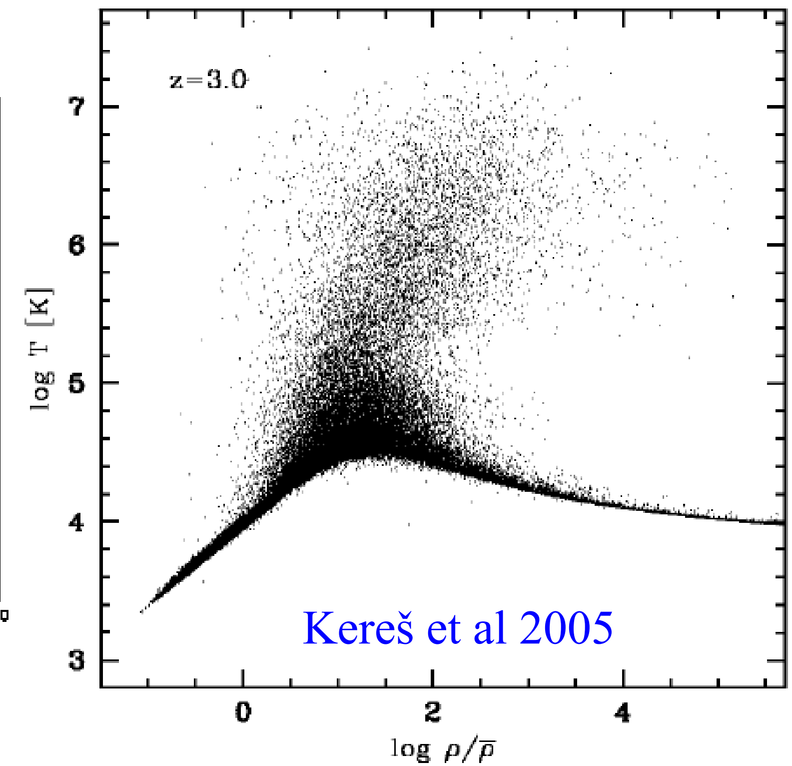
The effect is important near the transition halo mass $10^{1i\text{-}12} M_\odot$
It depends strongly on the hydrodynamics scheme used
It will be affected by interaction between inflows and winds

Gas cooling in cosmological simulations

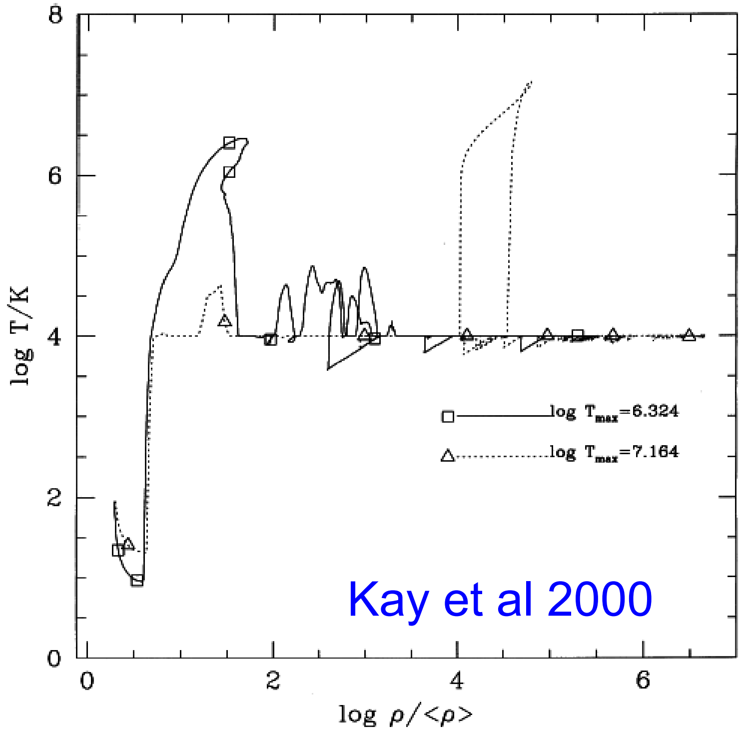


Kay et al 2000

Gas separates cleanly into three phases
- --cool, diffuse IGM
- --hot, shocked IGM
- --cold, dense ISM



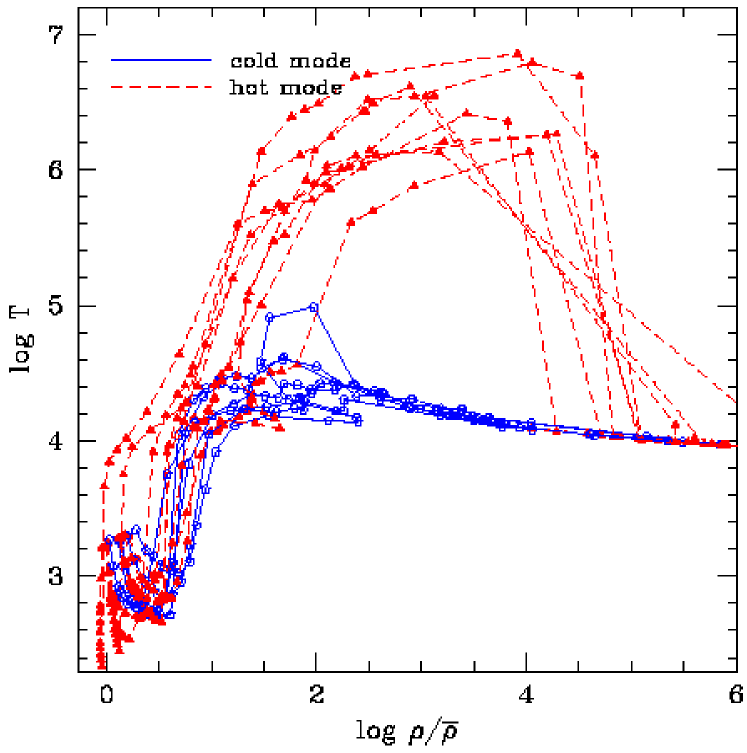
Cold and hot accretion modes

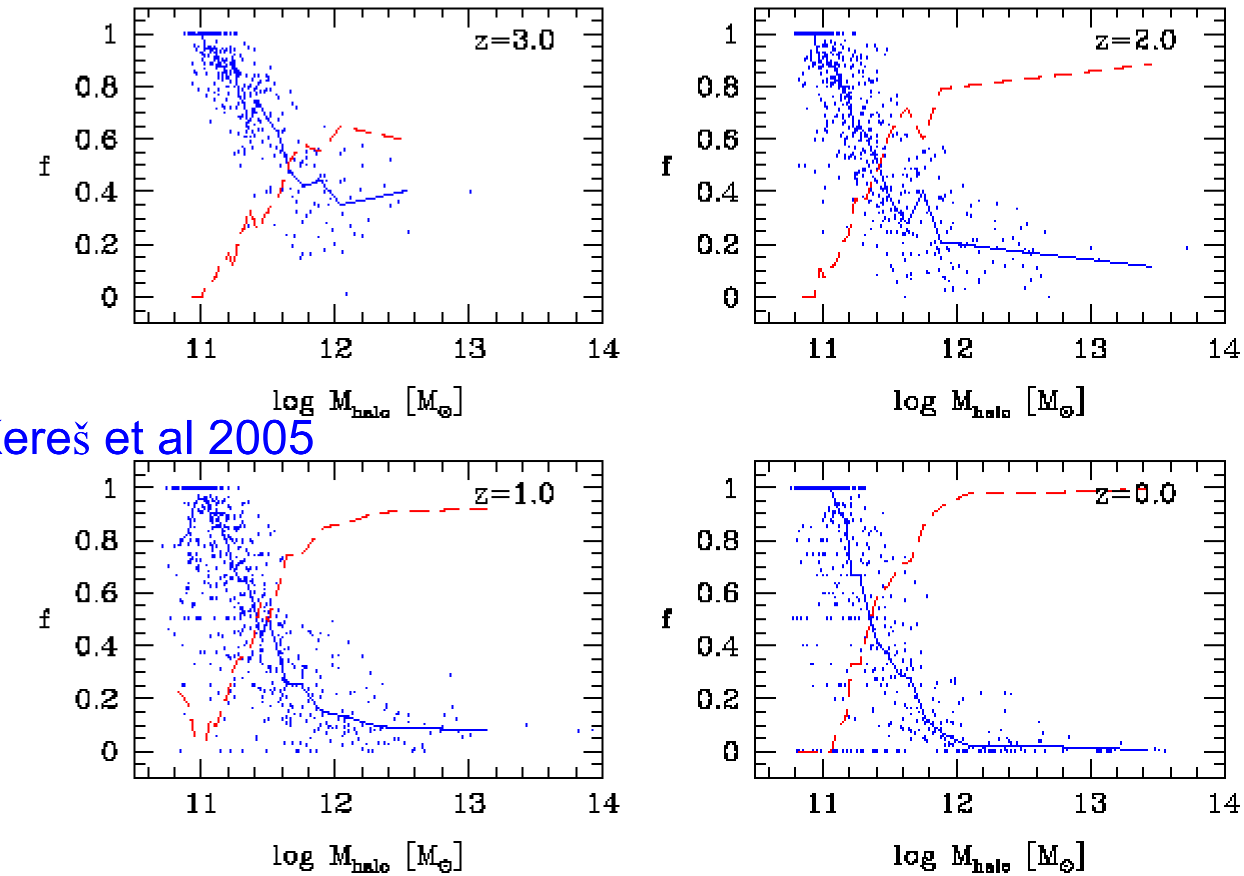


Half or more of all SPH particles accreted onto galaxies never heat above a few 10^4 K

"Cold" accretion dominates in halos with V_{circ} less than about 100 km/s

Same point as transition from infall to cooling domination in spherical models?

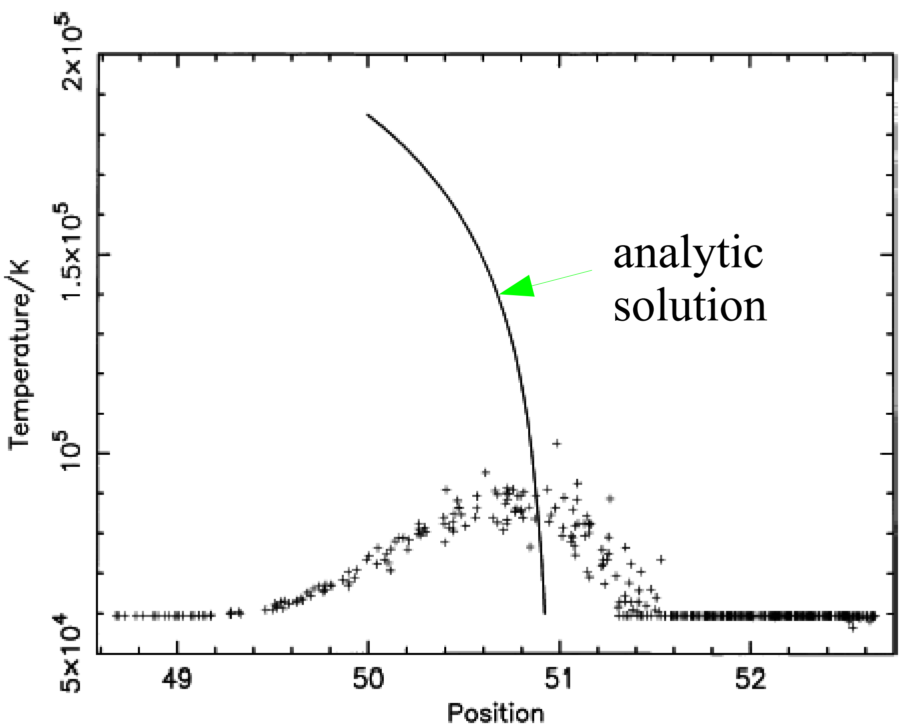




Kereš et al 2005

In-shock cooling

Hutchings & Thomas 2000



A radiative shock in a shock tube followed with SPH

$$t_{cool} \sim h / V_{sh}$$

Immediately behind a strong shock the gas heats to a temperature

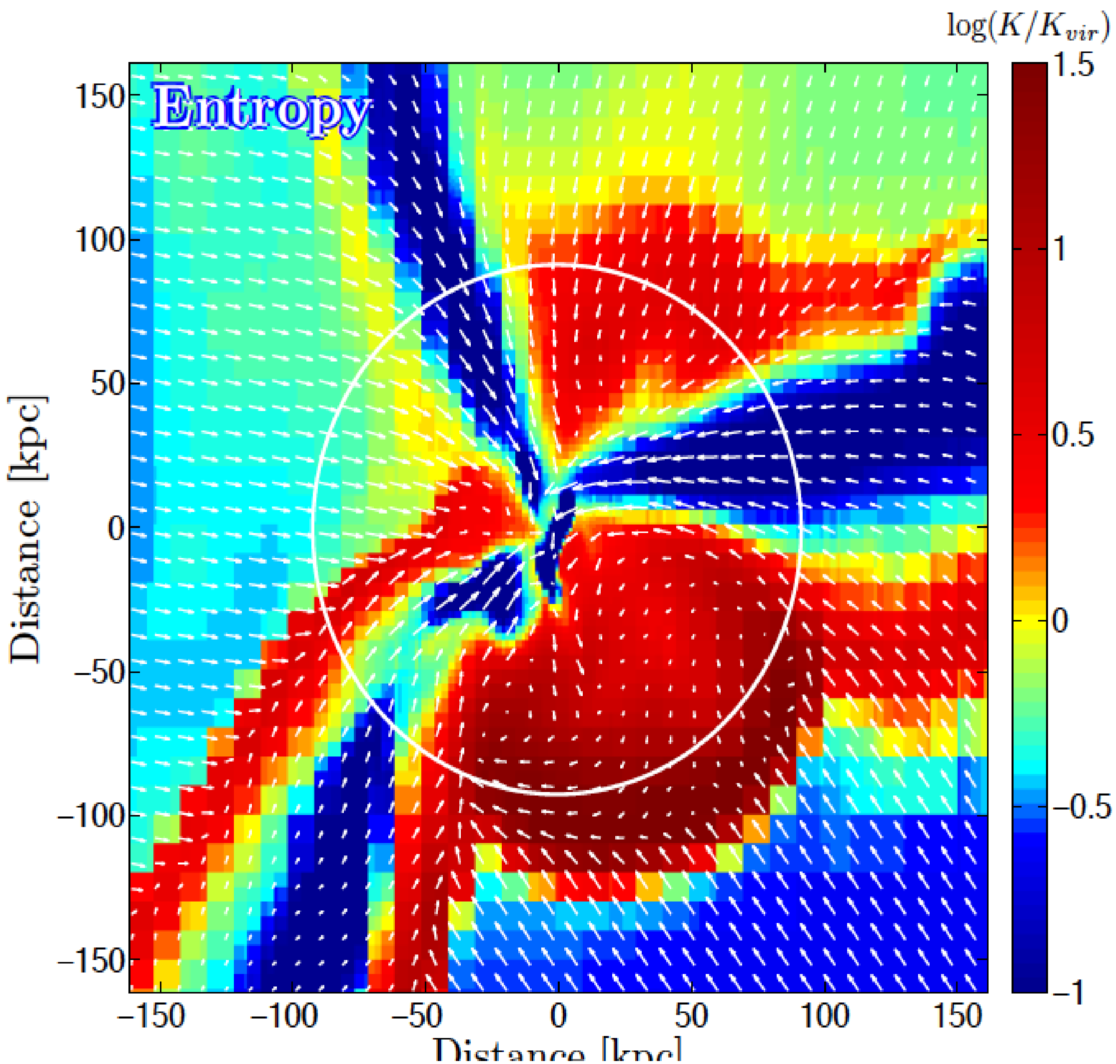
$$T = 3\mu V_{sh}^{\ 2} / 16\ k$$
$$\sim\ 1.4 \times 10^5 (V_{sh} / 100\ \mathrm{km/s})^2$$

Collisional thermalisation, ionisation and radiation processes then all occur simultaneously, often far from equilibrium

Many numerical hydrodynamics schemes broaden the shock heating region over several zones (grid) or smoothing lengths (SPH)

When post-shock cooling times are short this leads to spurious temperature evolution

Cold flows in an AMR simulation



Dekel et al 2009

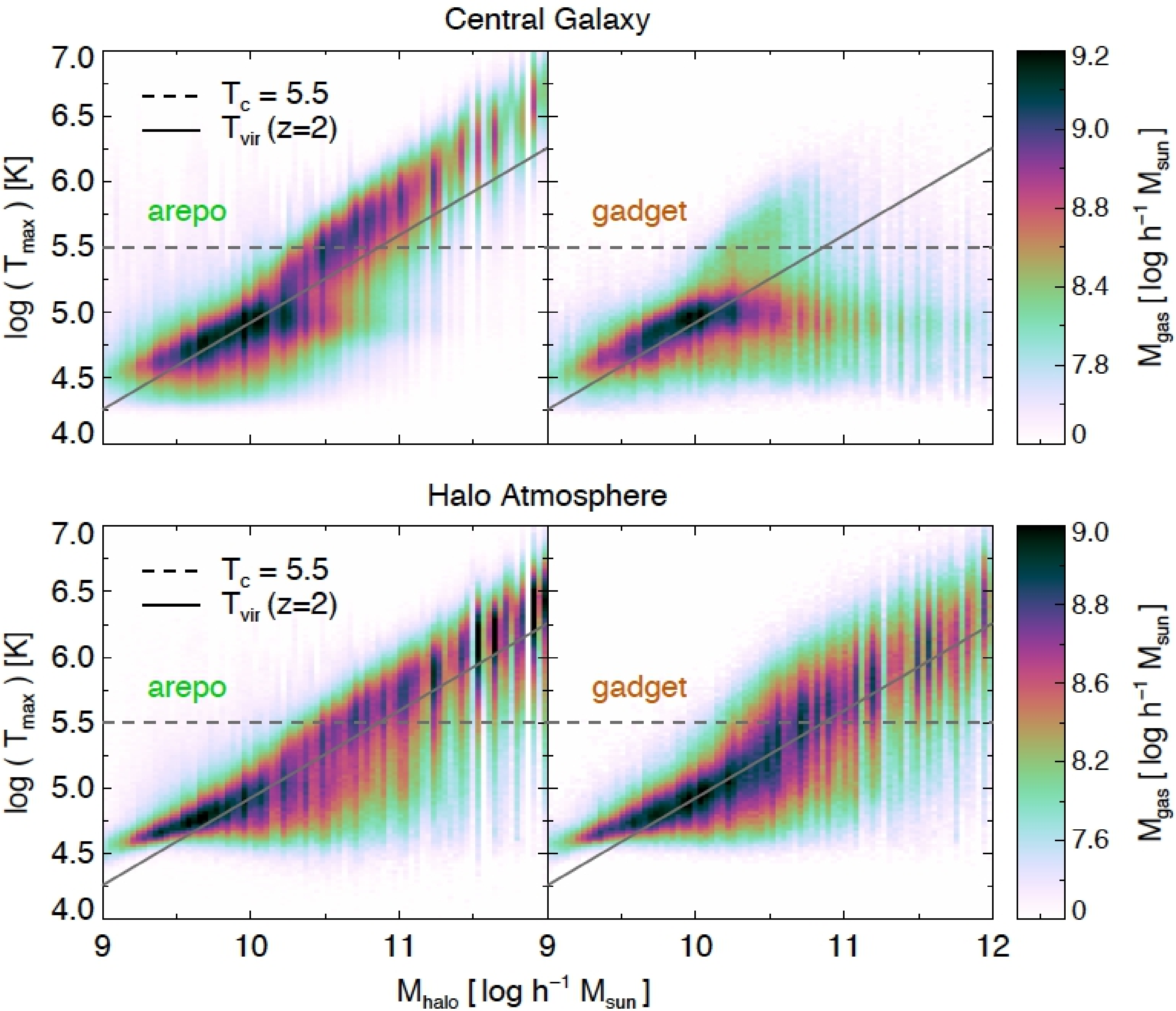
A slice at z=2.5 through a ΛCDM simulation centred on a halo of virial mass 10^{12} $M_{\odot}$

Circle is virial radius, colour scale gives entropy, arrows show flow velocity.

Note the shock just outside the virial radius and the cold streams penetrating the hot halo and apparently reaching the galaxy

Cold flow fractions in differing hydro schemes

Nelson et al 2013

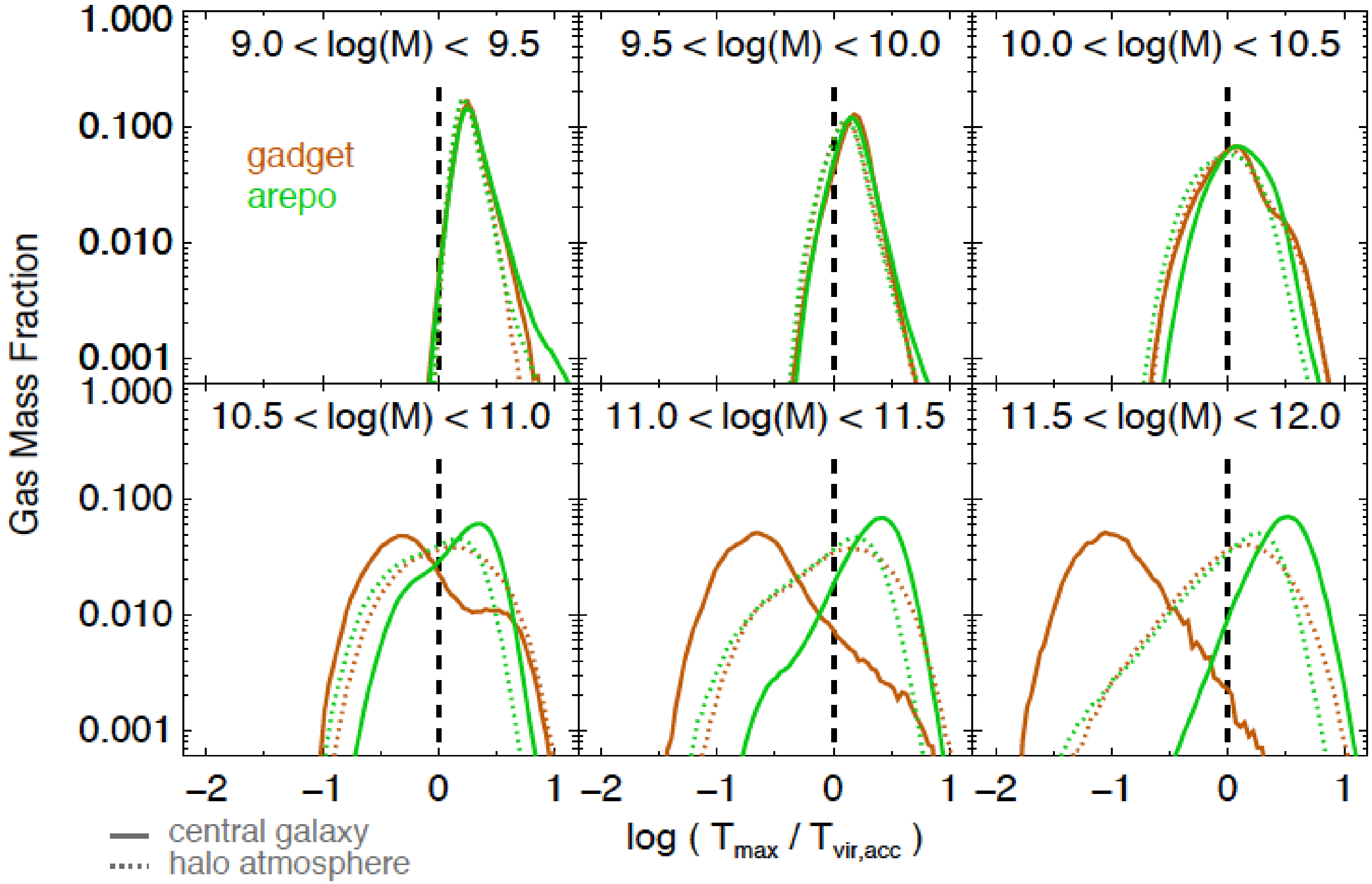


The maximum past temperature of gas elements accreted by z=2 halos (bottom) and galaxies (top) as a function of halo mass.

Note similarity/ difference for accretion onto halos/galaxies.

Cold flow fractions in differing hydro schemes

Nelson et al 2013

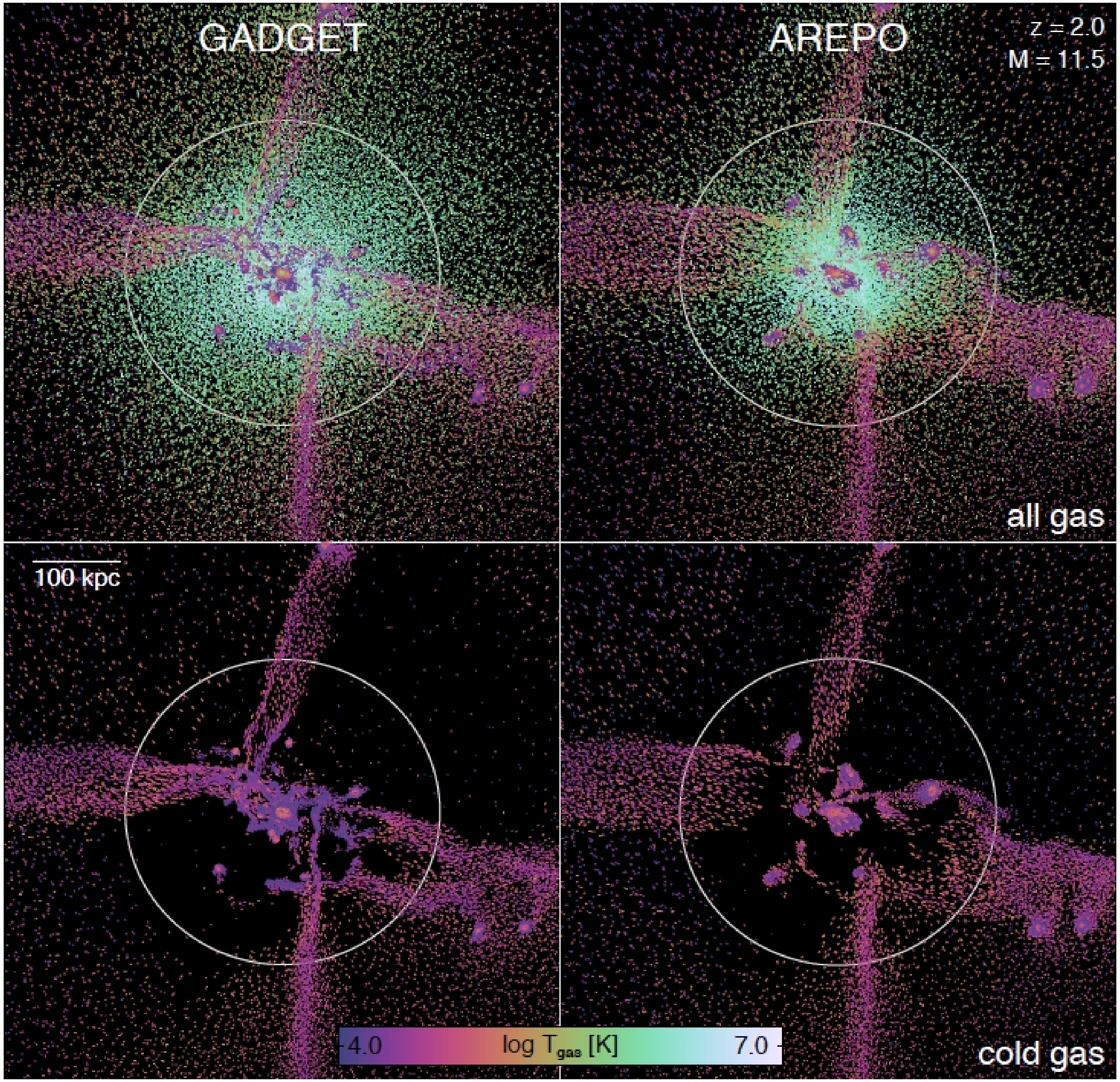


Past maximum temperatures (normalised to halo virial temperature) for gas accreted by halos (dotted) and galaxies (solid) in bins of z=2 halo mass.

For AREPO this peaks just above 1 for both components and all masses - Gas is always heated to just above the halo virial temperature.
For GADGET this is not true for gas accreted onto higher mass galaxies

Cold flow fractions in differing hydro schemes

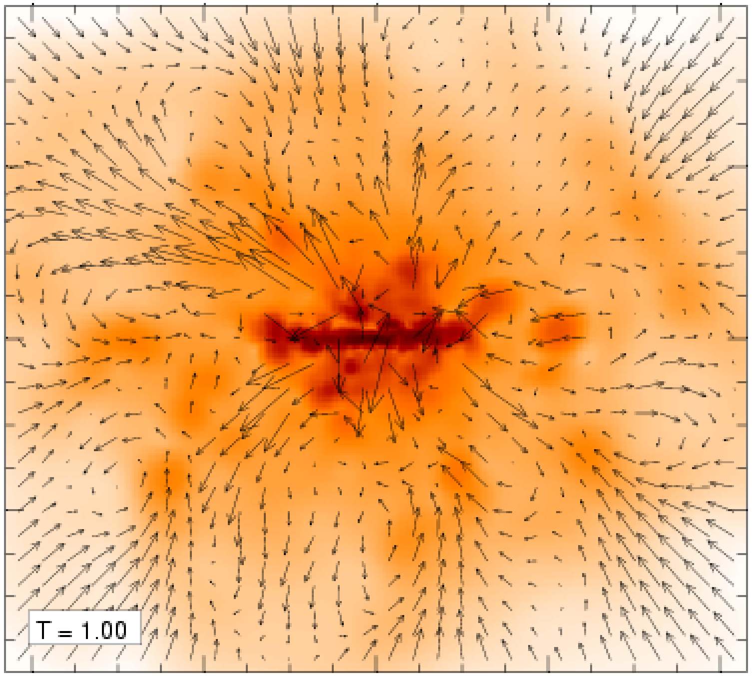
Nelson et al 2013



This is not due to differences in accretion morphology, but rather to differences in dissipative heating and mixing.

Note that these simulations still do not have sufficient feedback to produce a realistic galaxy population.

Feedback/galactic wind issues



Can supernova feedback drive galactic winds?

Can these reproduce the mass-element abundance relation?

Can they enrich intergalactic gas with heavy elements?

Can these enhance formation of disks over bulges?

What about feedback from Active Galactic Nuclei?

Feedback/galactic wind issues

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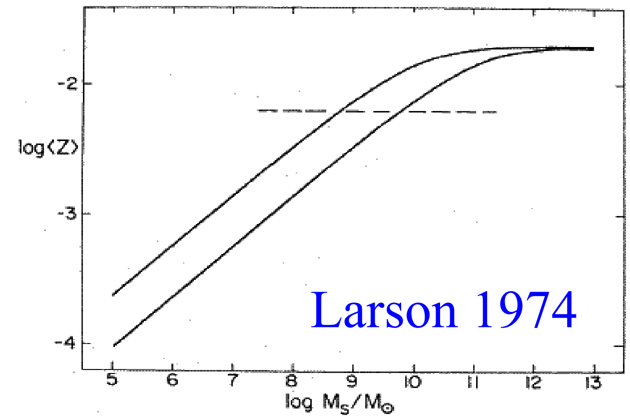

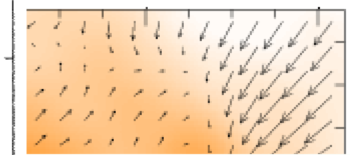

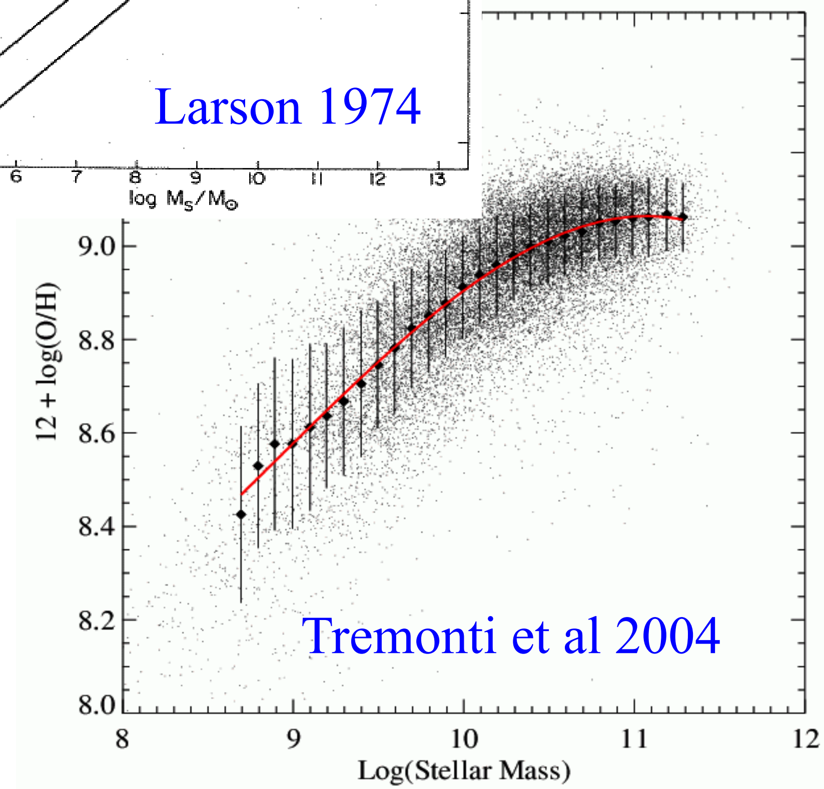

$$\dot{M}_{wind} \propto \dot{E}_{SN} / V_{esc}^2$$
$$\propto \dot{M}_* / V_c^2$$

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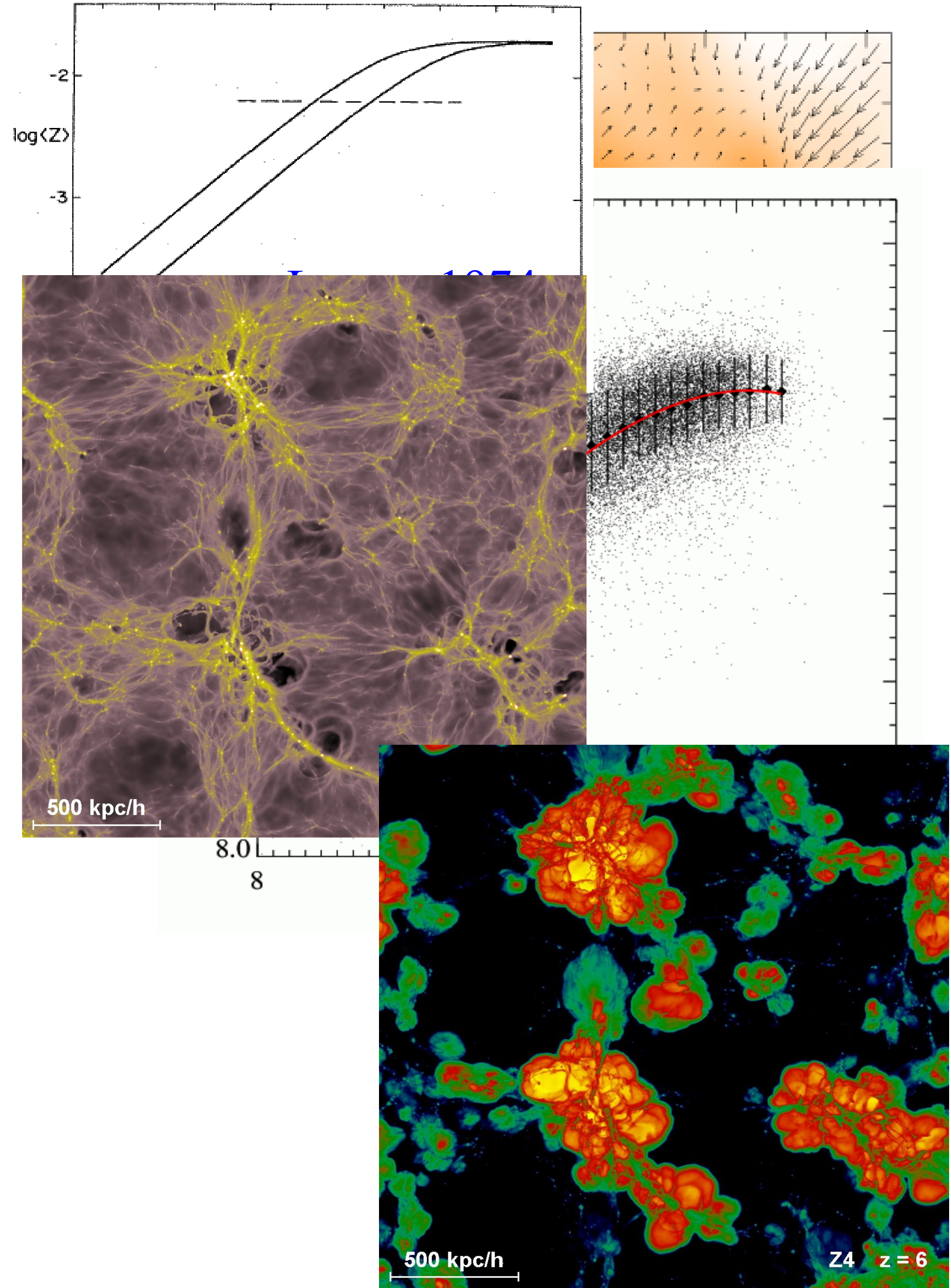
Can these enhance formation of disks over bulges?

What about feedback from Active Galactic Nuclei?



Including the formation and evolution of stars

Stars form where gas is dense, cold and self-gravititating

Star formation is *not* resolved in galaxy formation simulations
→ a simple *sub-grid* prescription is needed, for example

$$\dot{\rho}_* = \alpha \; \rho_{\mathrm{gas}} \; / \; t_{dyn}$$

Aging of stars affects their brightness and colour

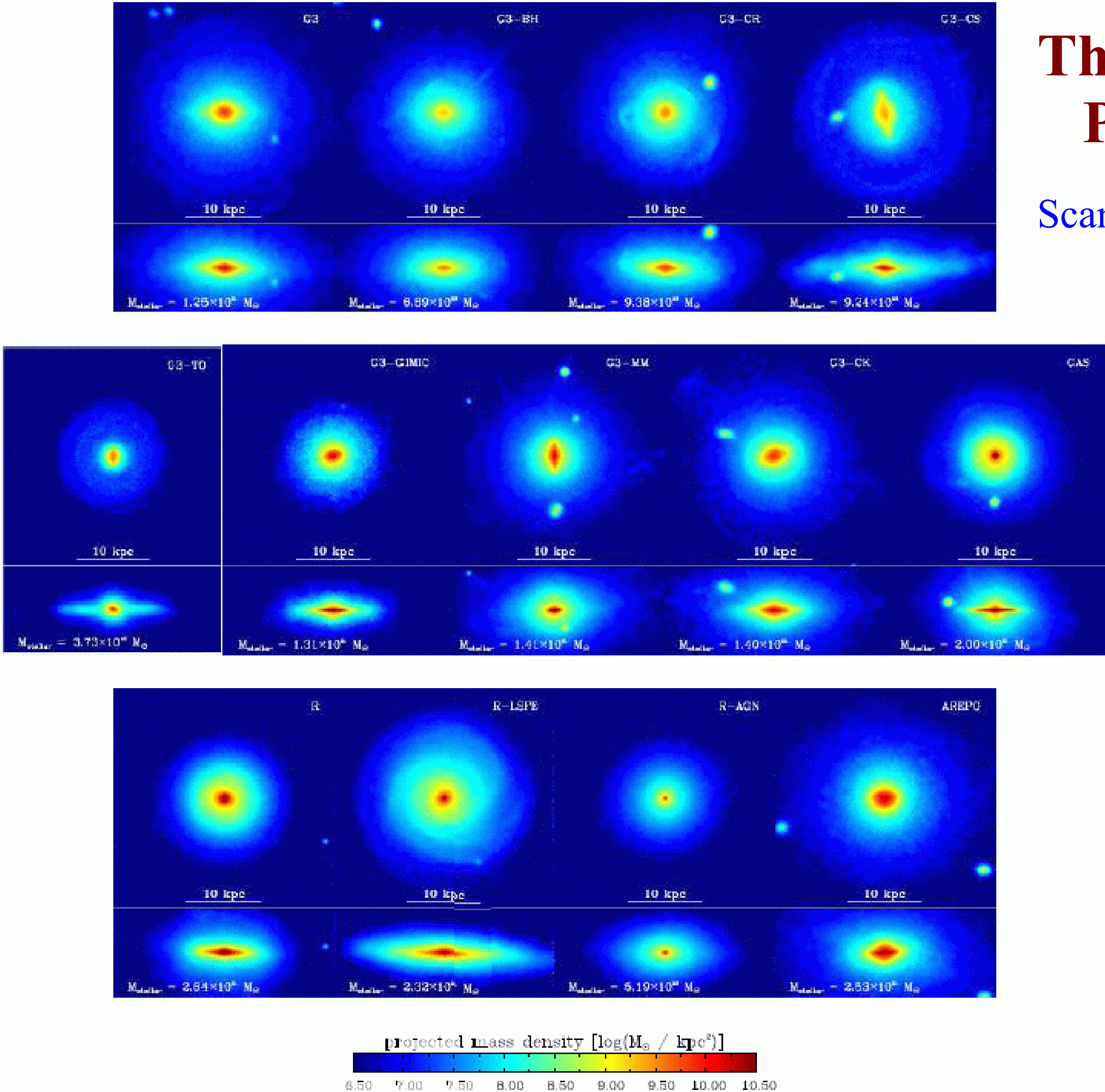
Supernovae, explosions of massive stars put energy and heavy elements into surrounding gas – *feedback, chemical enrichment*

Feedback processes are also not resolved and must also be implemented with phenomenological recipes

Implementation details *strongly* affect galaxy formation models

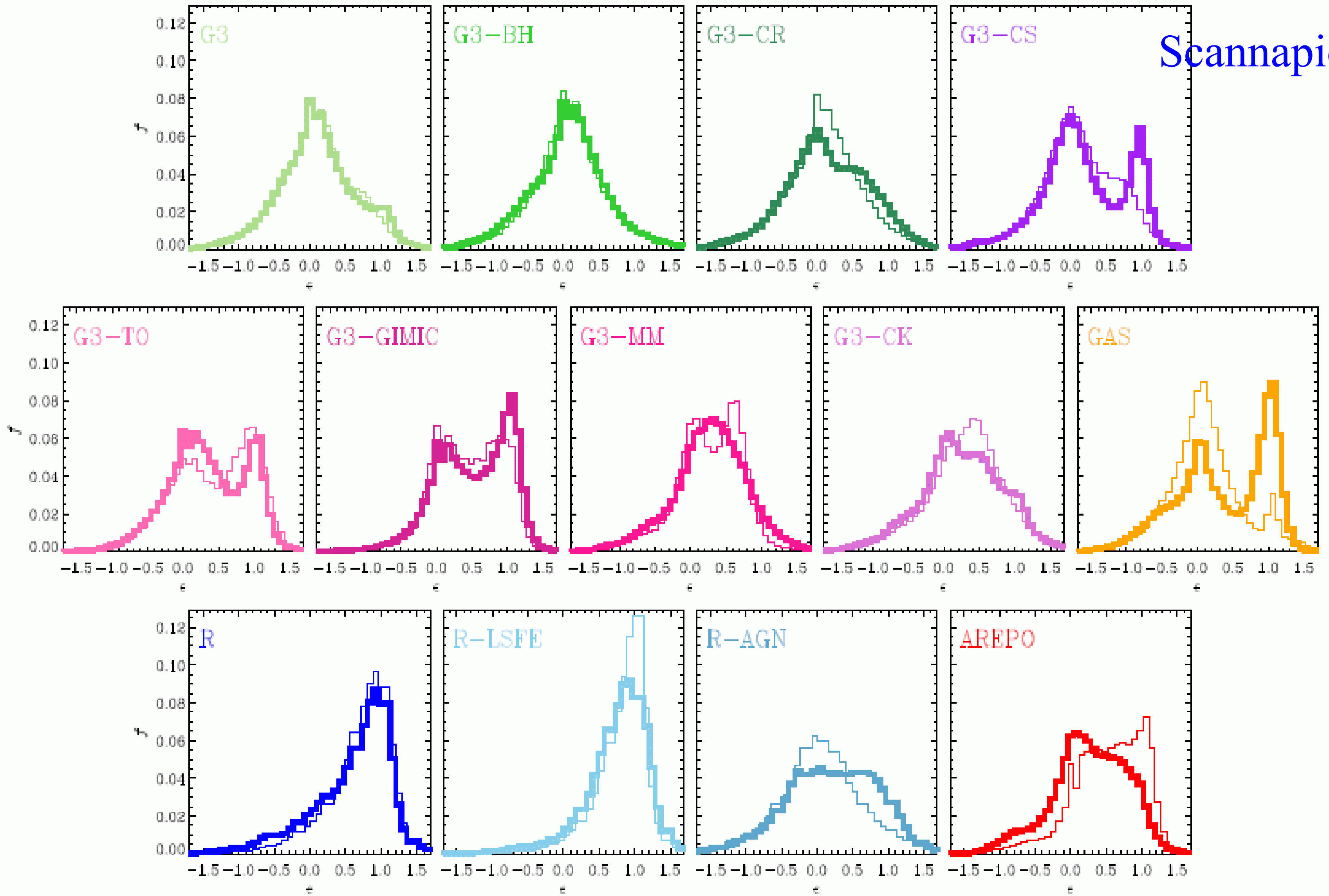
The Aquila Project

Scannapieco et al 2011



The Aquila Project

Scannapieco et al 2011



The Aquila Project

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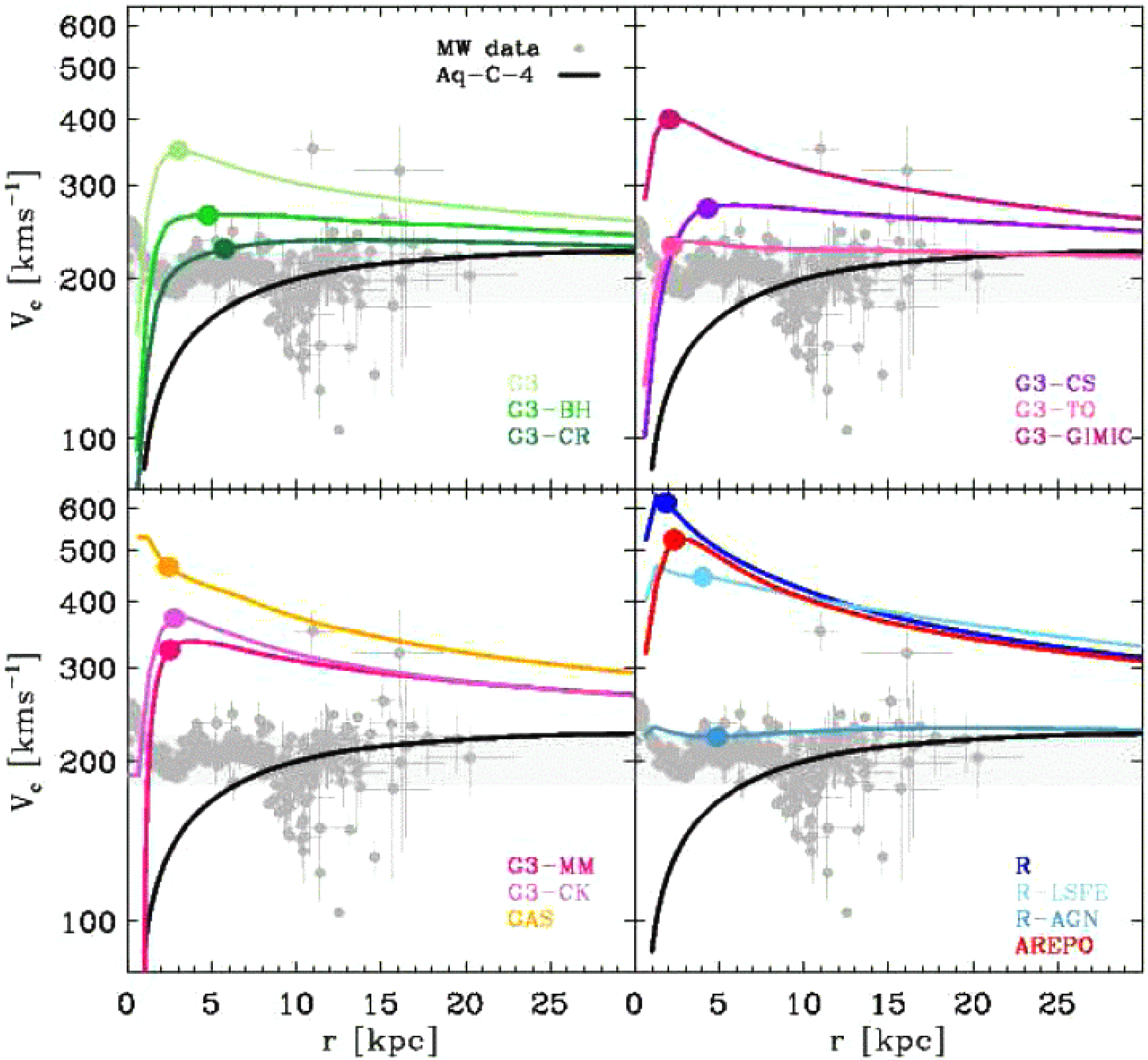

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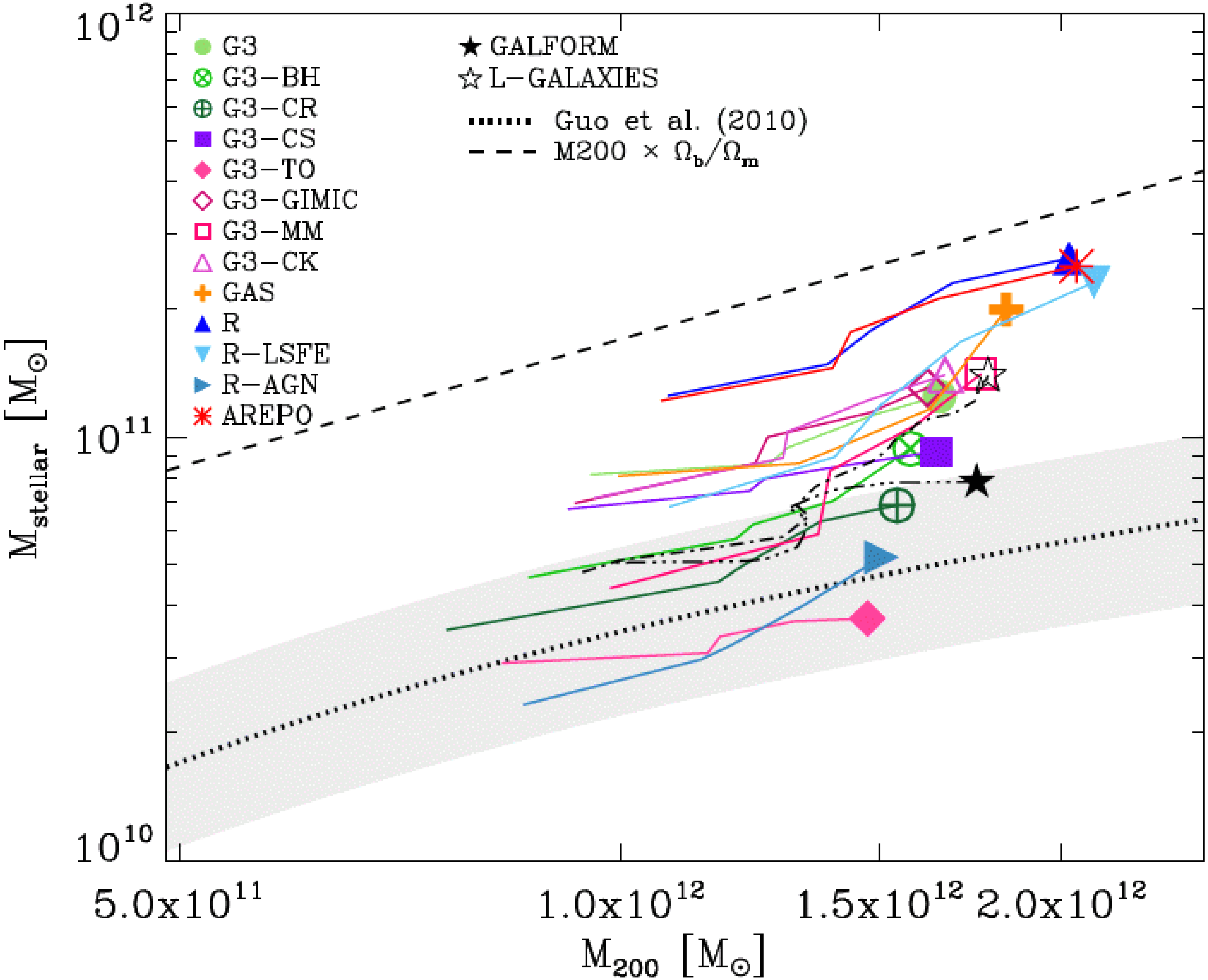


Simulating the formation of individual galaxies

Systems which have a *major merger* after most of their stars have formed end up looking like **Elliptical galaxies**

Systems which have no major merger at late times end up having a substantial disk and looking like **Spiral galaxies**
Disks grow inside-out and late,

It has proved hard to make spiral galaxies with small bulges

It's also hard to match the low formation efficiencies required by abundance matching....

. ..or to get get enough heavy elements out of galaxies

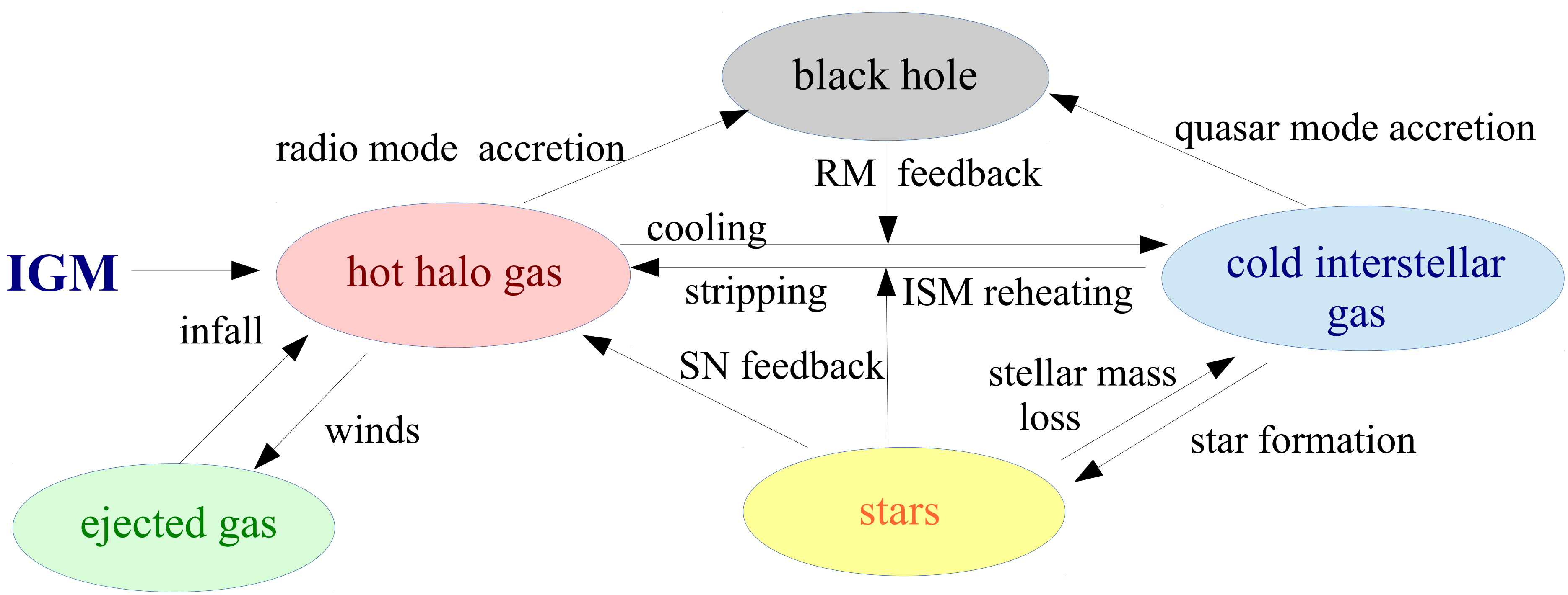
Resolution and feedback problems?

An alternative to following the gas within halos by direct hydro is to use simplified "semi-analytic" formulations of each of the major processes and integrate the resulting system of equations down the merger trees of all subhalos in a high-resolution DM simulation

→ "semi-analytic" or galaxy population simulations

For the baryonic components associated with each halo

$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$



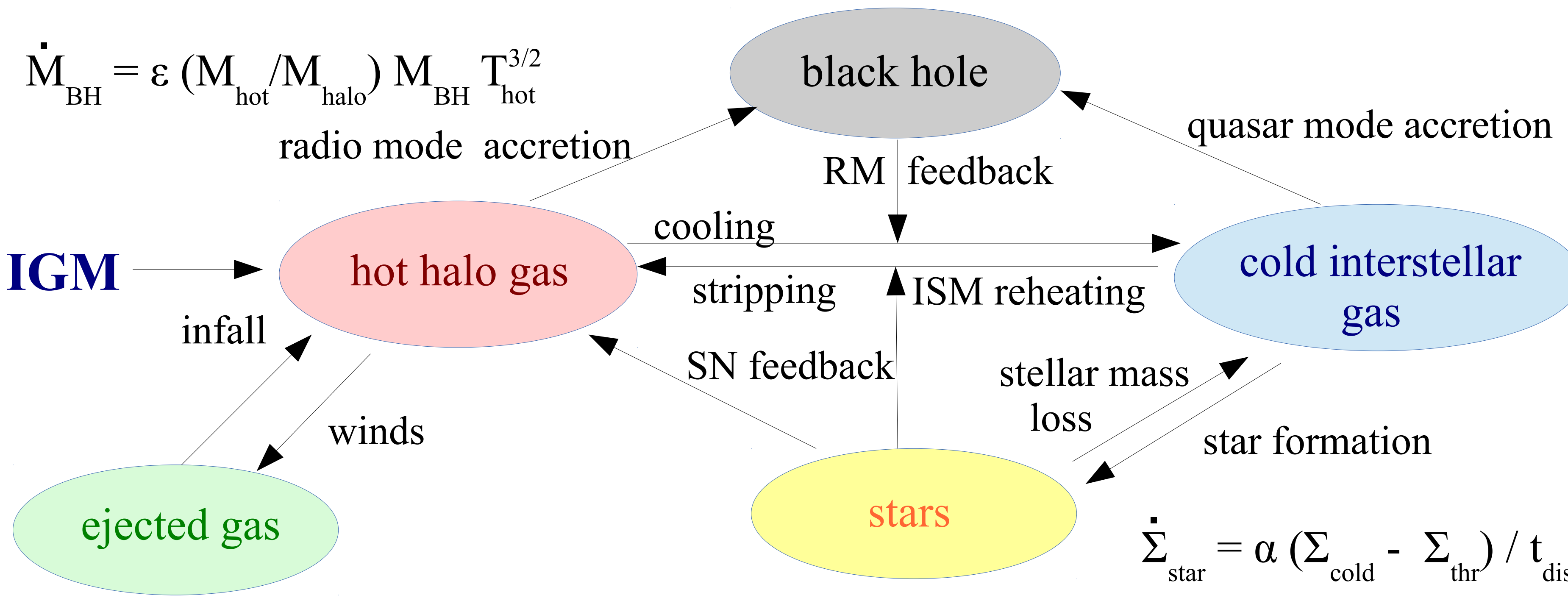
An alternative to following the gas within halos by direct hydro is to use simplified "semi-analytic" formulations of each of the major processes and integrate the resulting system of equations down the merger trees of all subhalos in a high-resolution DM simulation

→ "semi-analytic" or galaxy population simulations

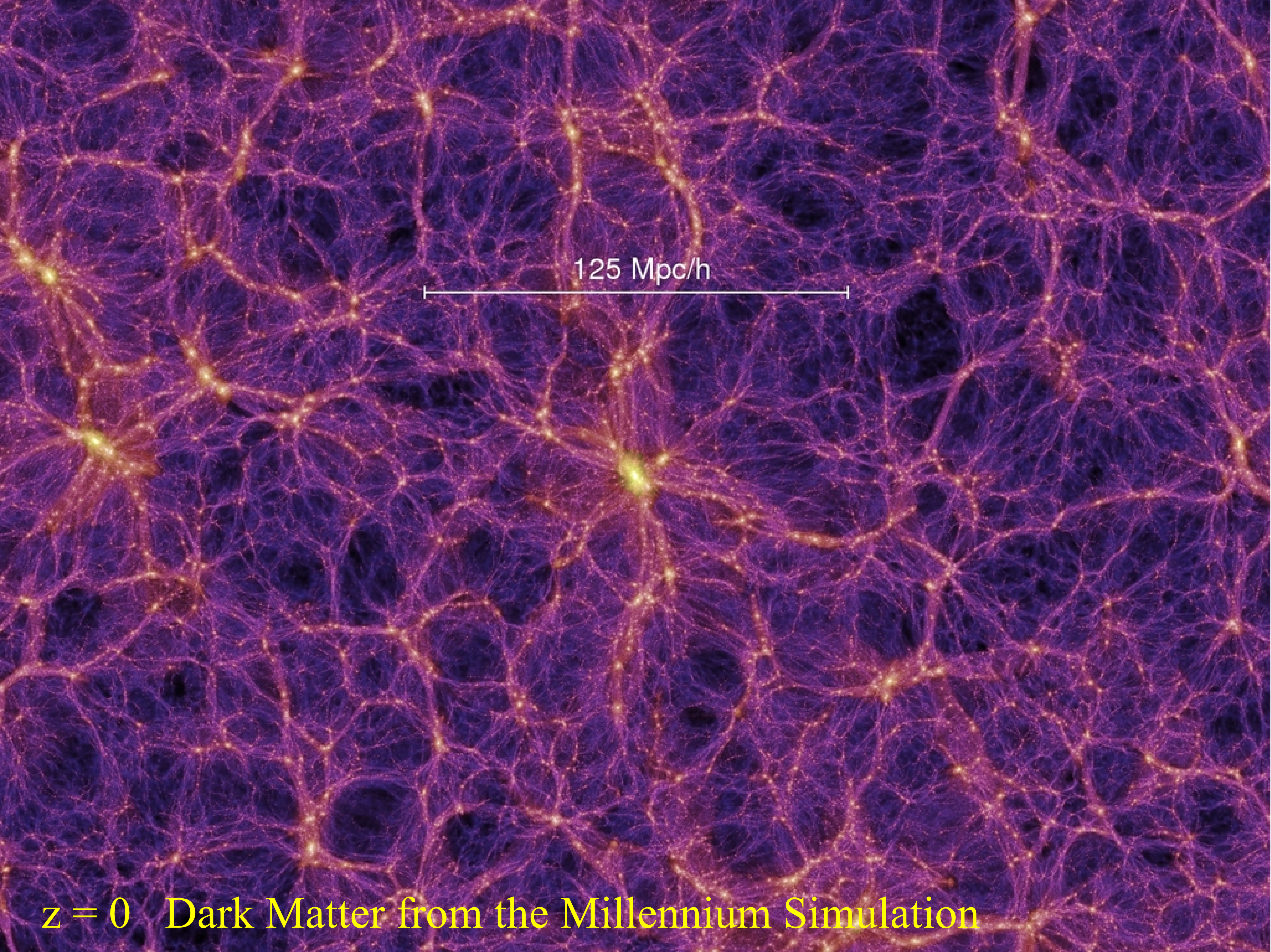
For the baryonic components associated with each halo

$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$

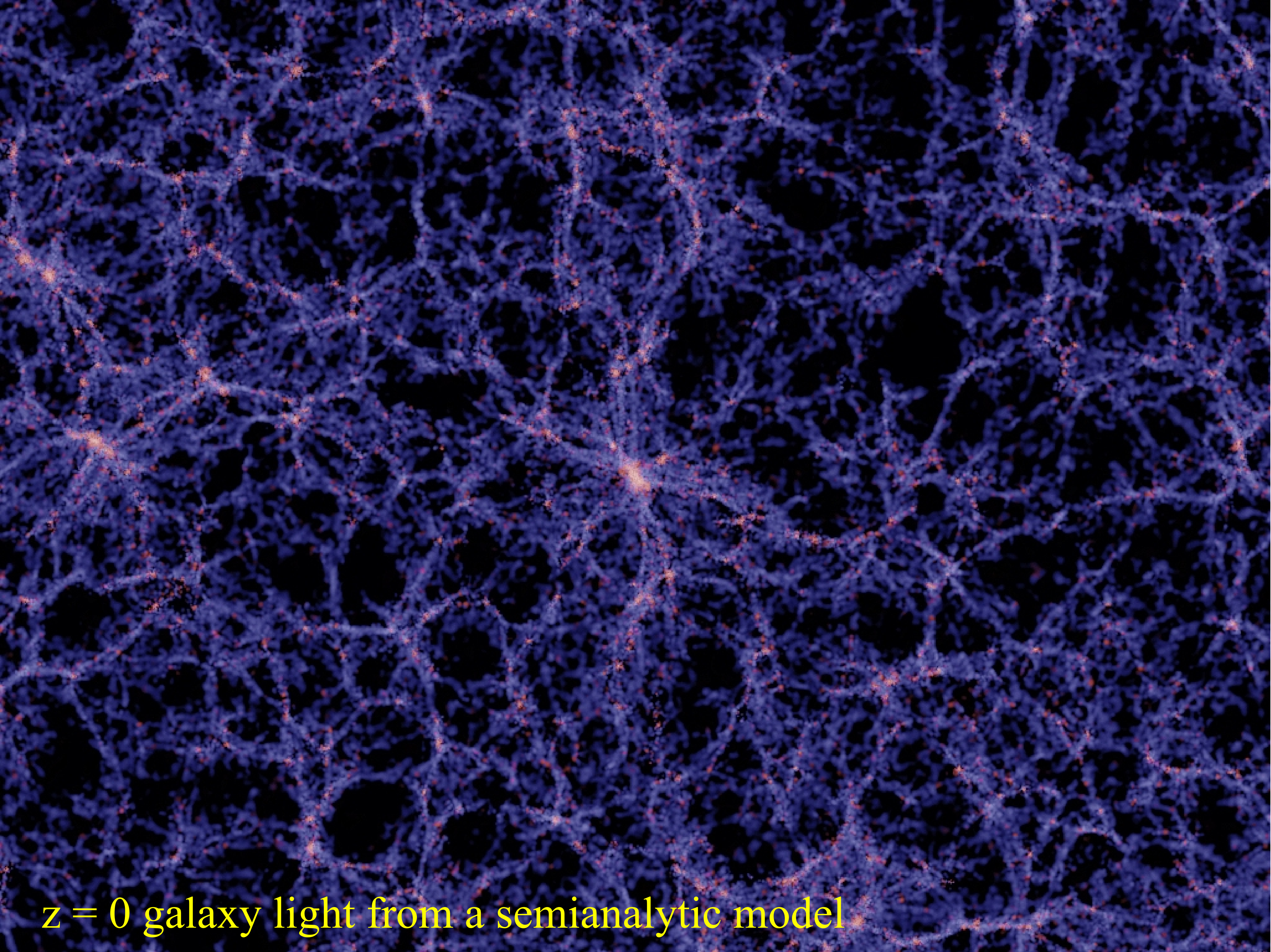
$$\dot{M}_{BH} = \varepsilon\, (M_{hot}/M_{halo})\, M_{BH}\, T_{hot}^{3/2}$$



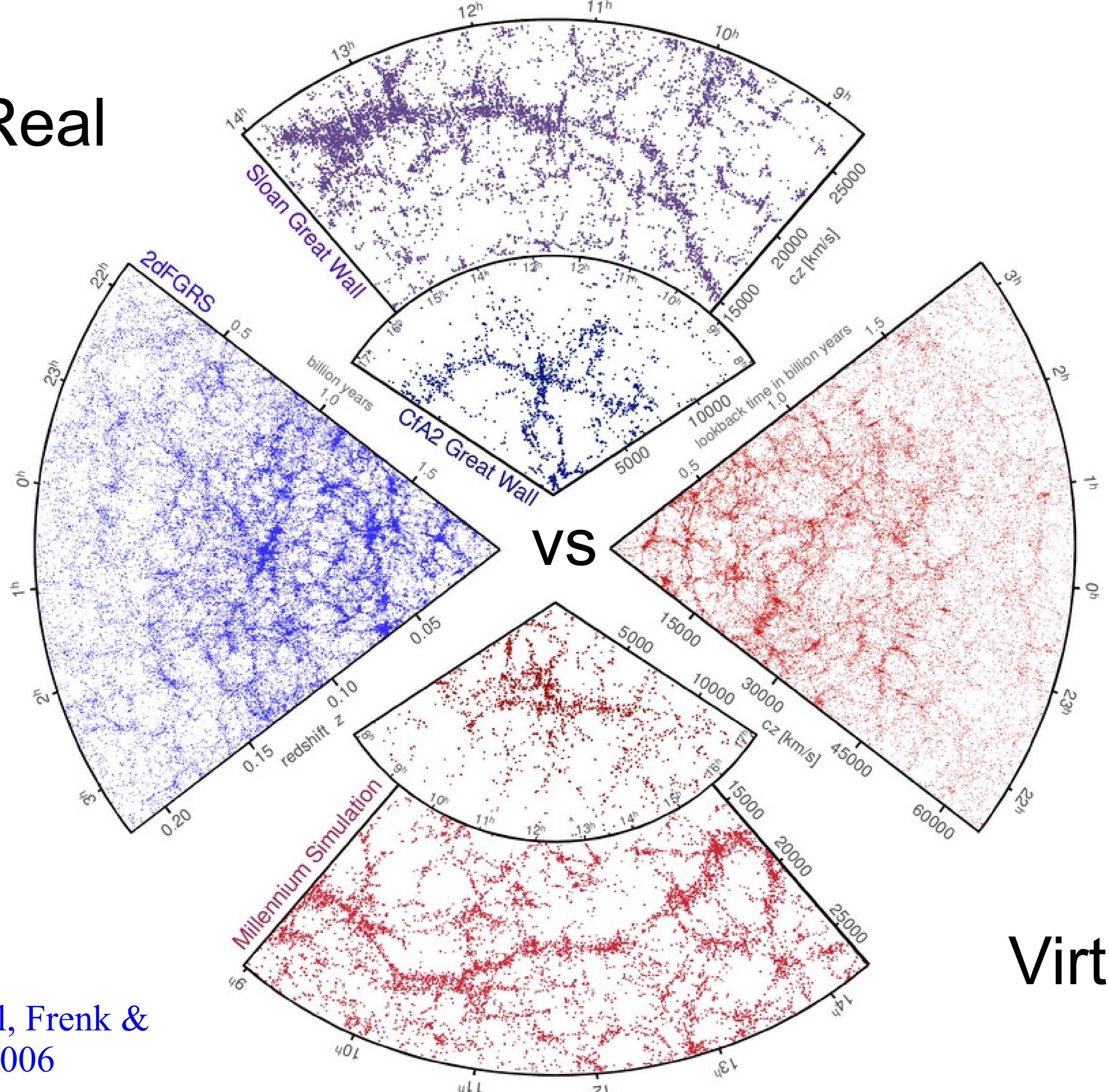
$$\dot{\Sigma}_{star} = \alpha\, (\Sigma_{cold} - \Sigma_{thr}) / t_{disk}$$



z = 0   Dark Matter from the Millennium Simulation


z = 0 galaxy light from a semianalytic model

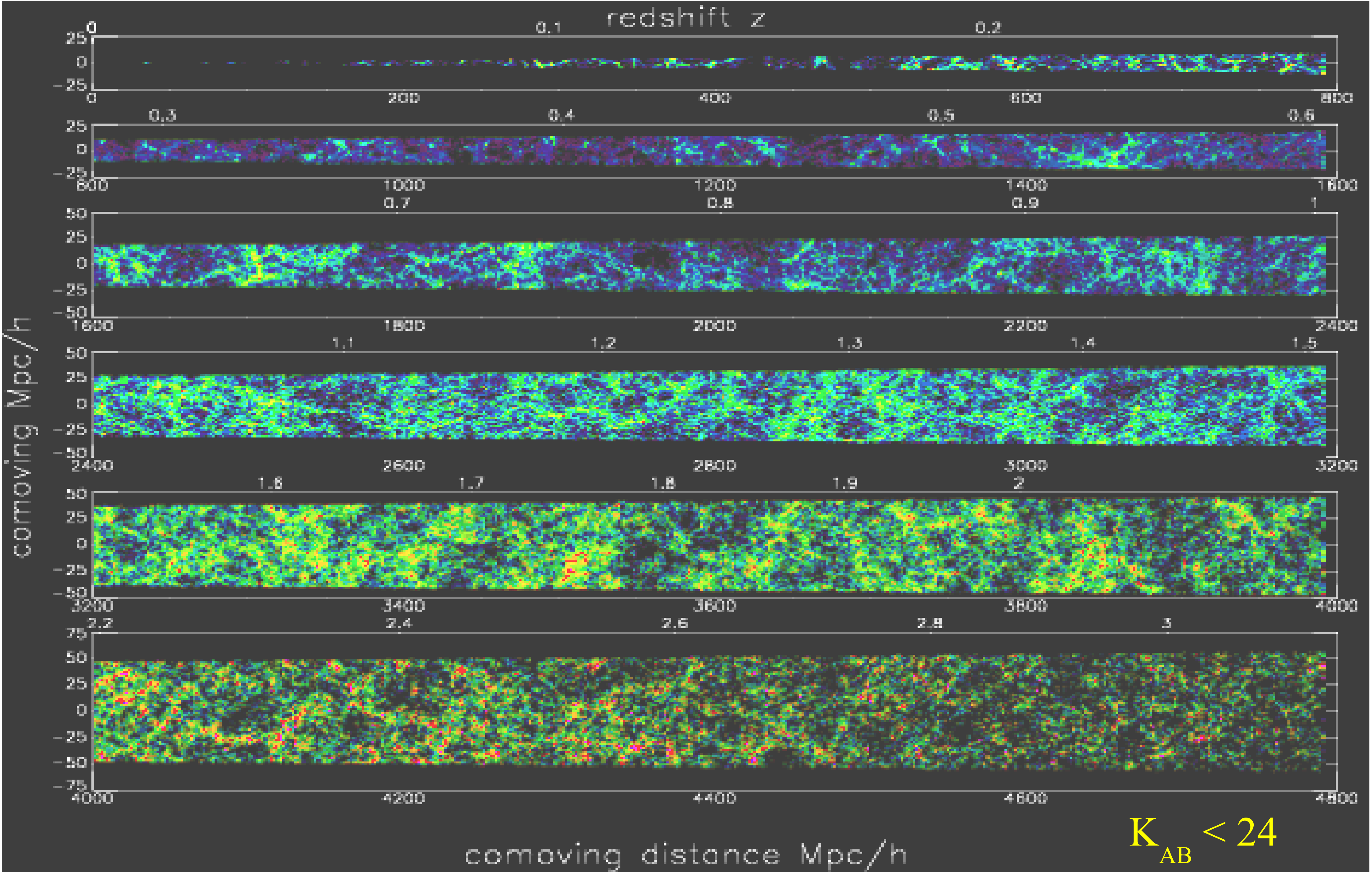
Real



vs

Virtual

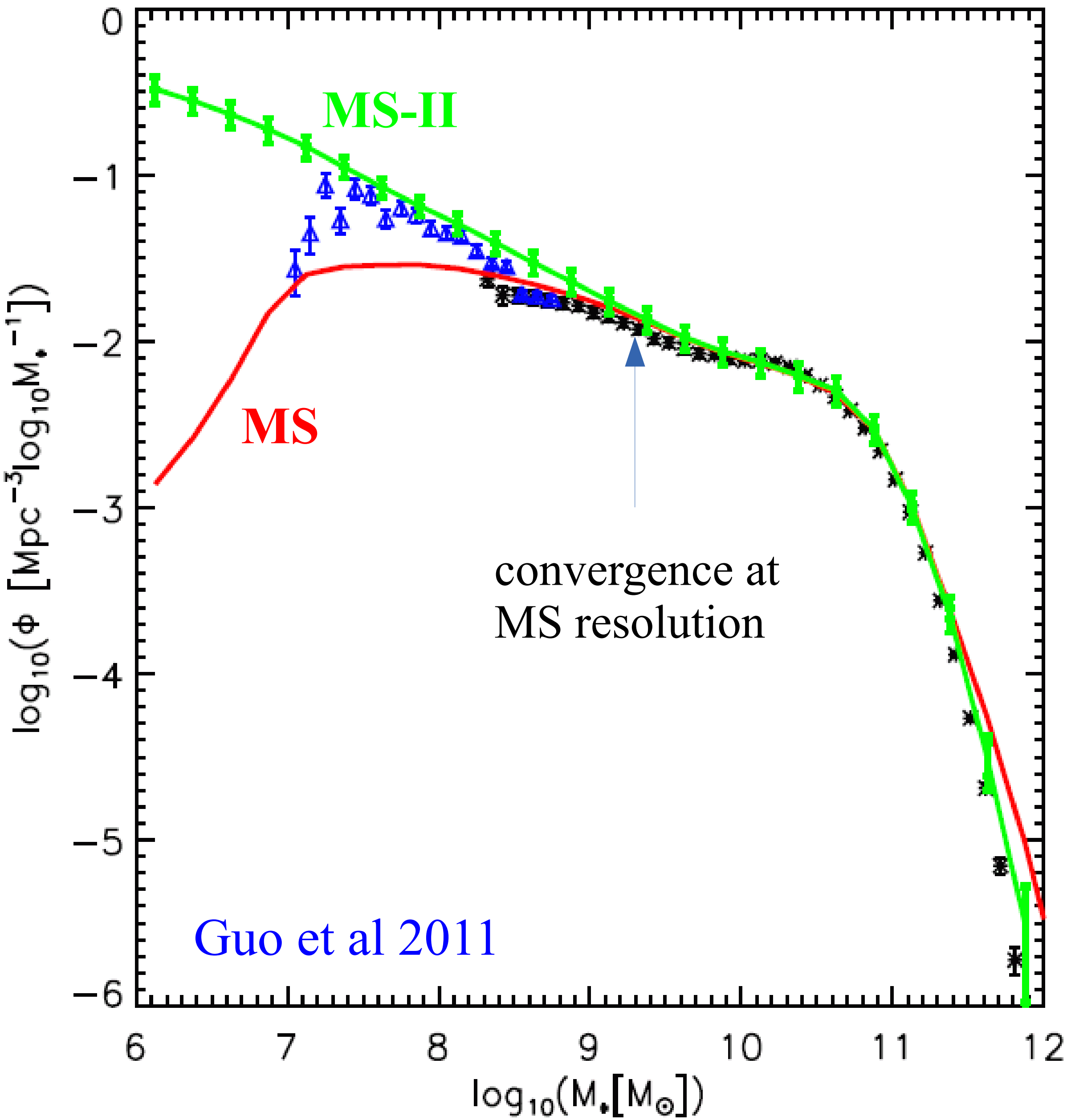
Springel, Frenk & White 2006



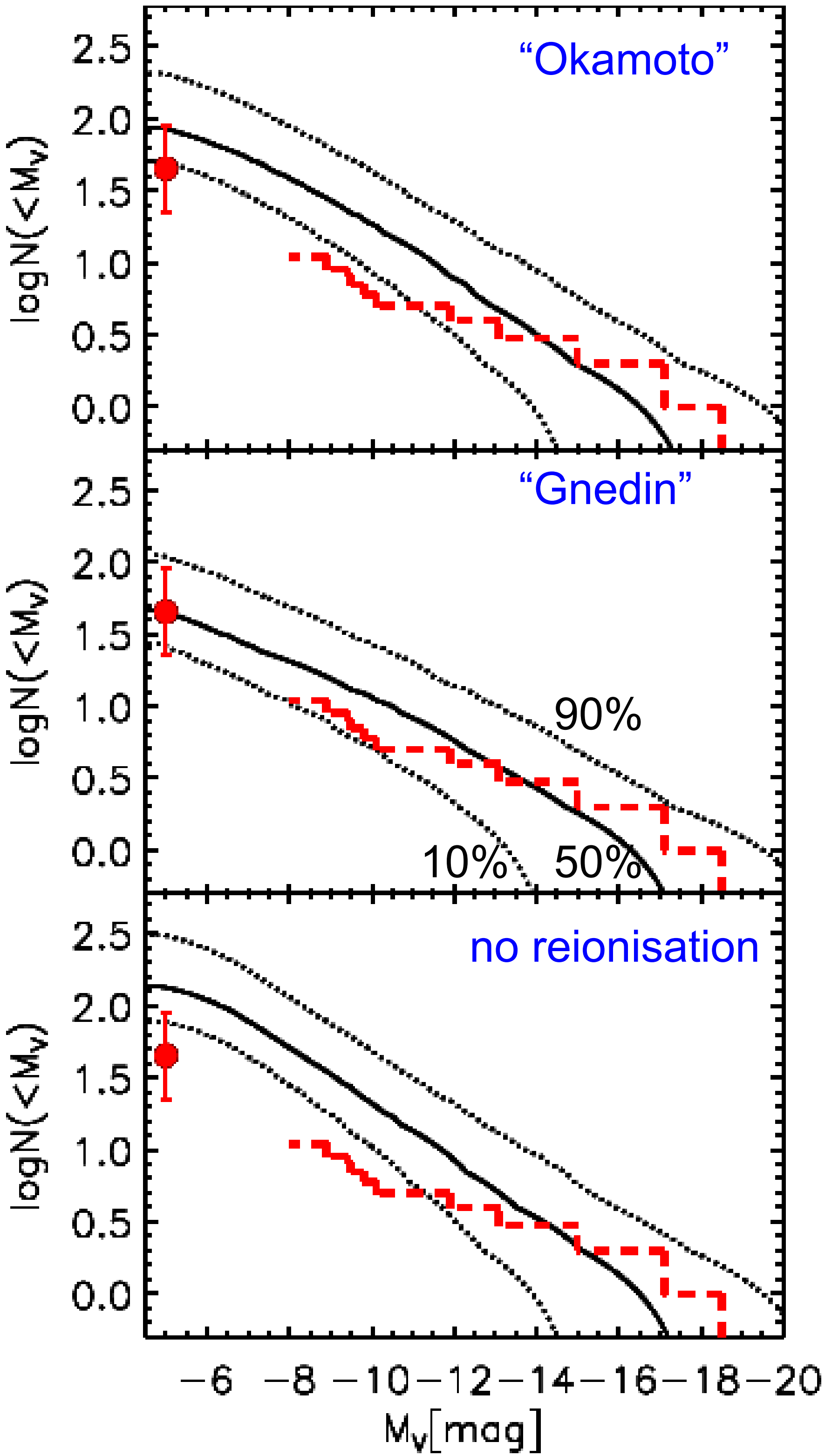
Light-cone with the simulated formation/evolution of $2x10^7$ galaxies from z = 10 to z = 0

Kitzbichler & White 2007

Population simulations predict:
(i) galaxy abundances e.g the stellar mass function



Note that the simulated mass function fits the data over 5 dex in stellar mass! This is a result of adjusting various parameters in the physical model



Population simulations predict:
(i) galaxy abundances e.g the stellar mass function

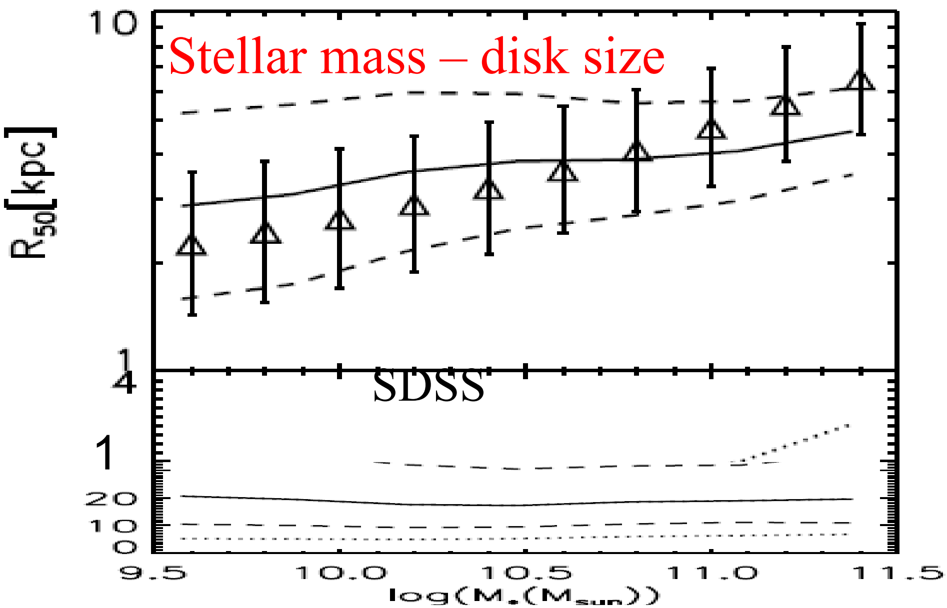
Luminosity functions of satellites around 1500 "Milky Ways" i.e. isolated disk galaxies with log $M_* = 10.8$

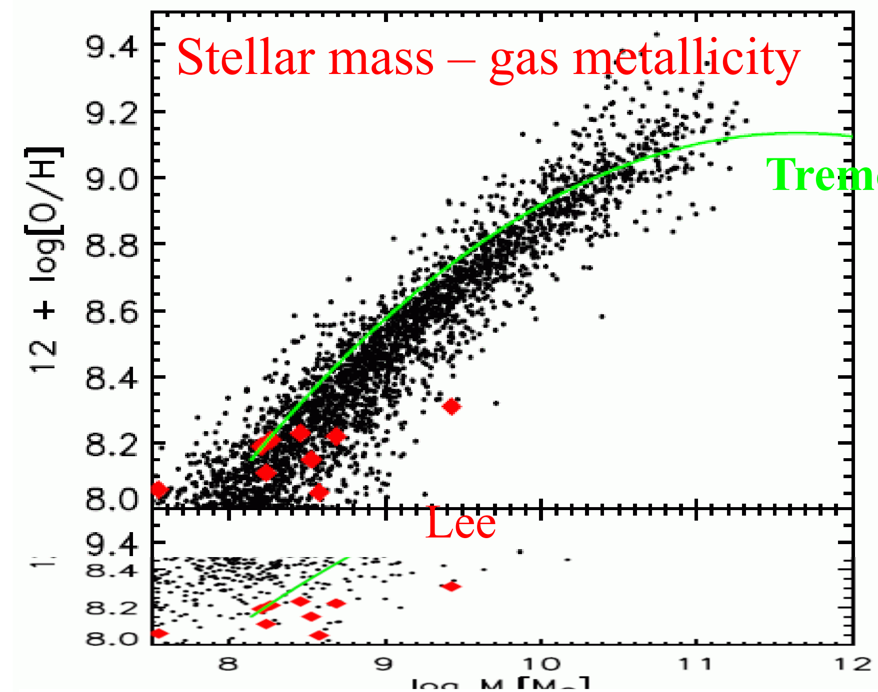
Note that the result depends on a "new" parameter describing the effectiveness of reionisation

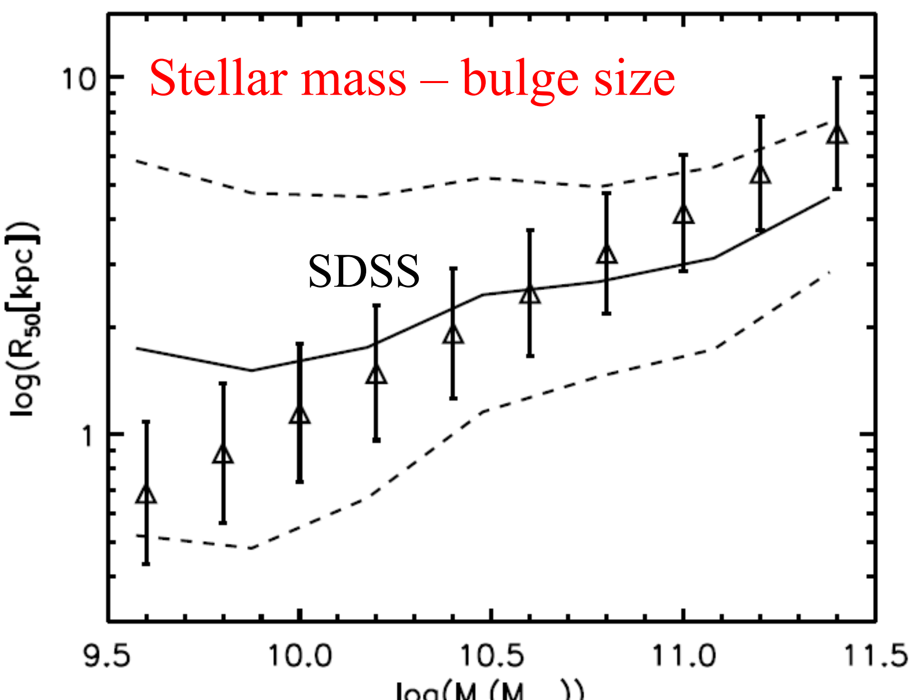
Guo et al 2011

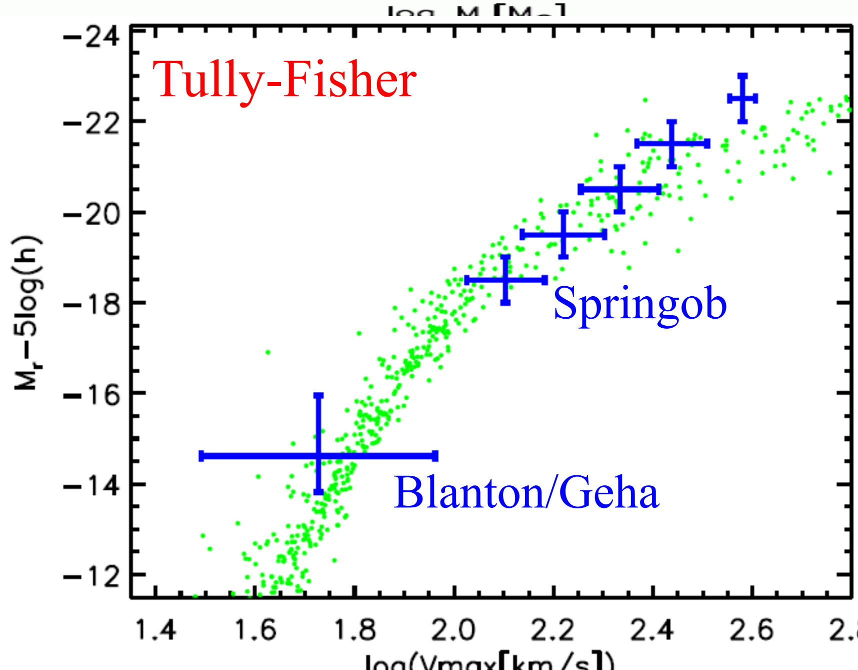
Population simulations predict:
(ii) galaxy scaling relations

Guo et al 2011



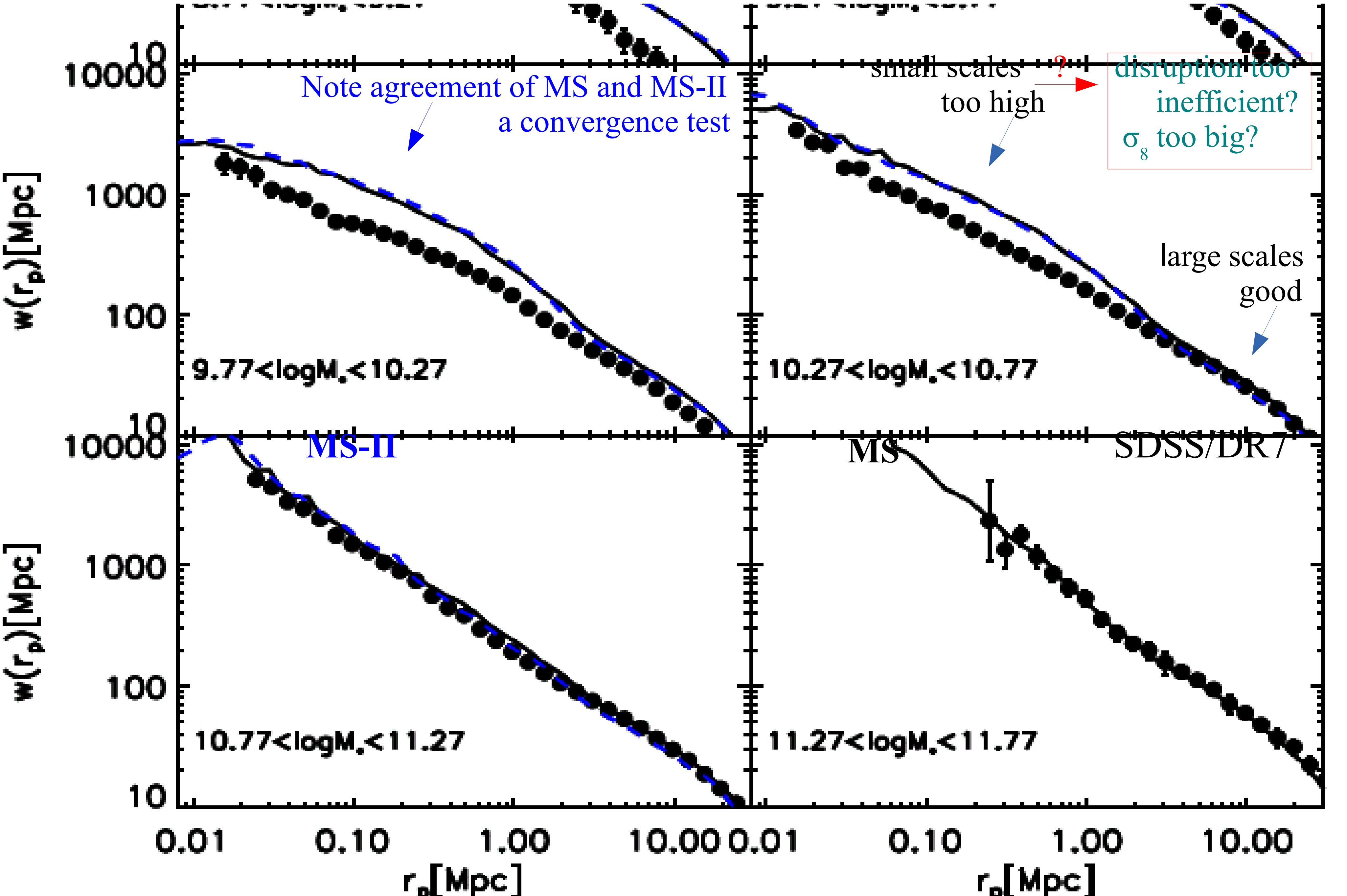


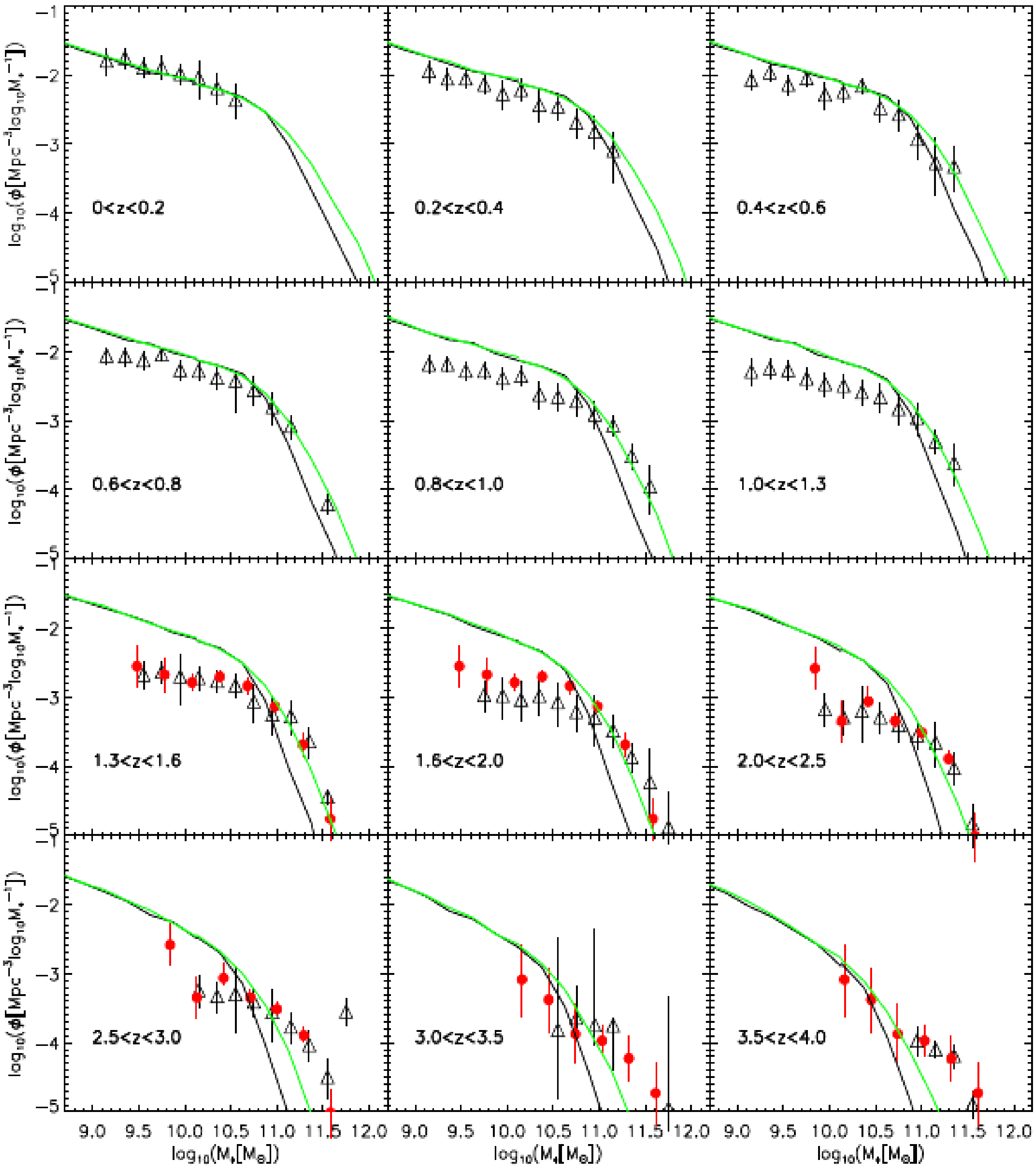




Population simulations predict:
(iii) galaxy clustering

Guo et al 2011





Population simulations predict: (iv) galaxy evolution

△ Perez-Gonzalez et al 2008

● Marchesini et al 2009

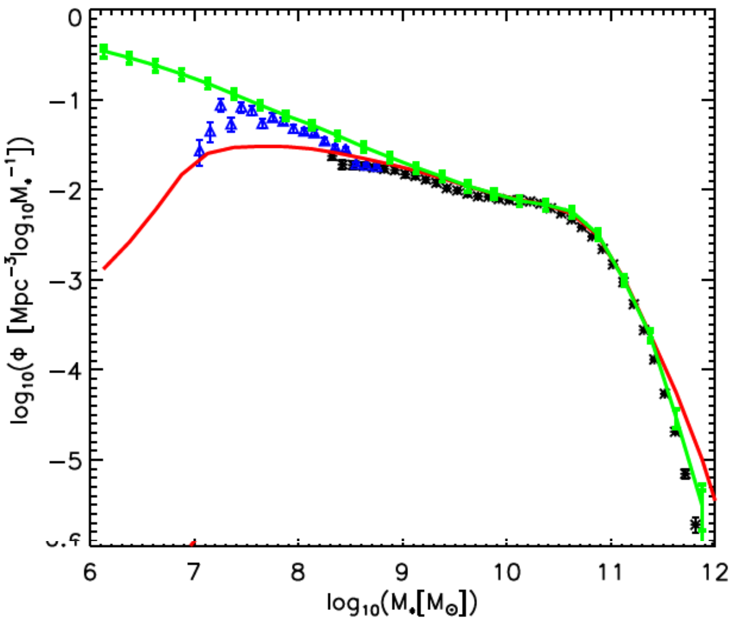
Lower mass galaxies log $M_* < 10.5$ form <u>too early</u>

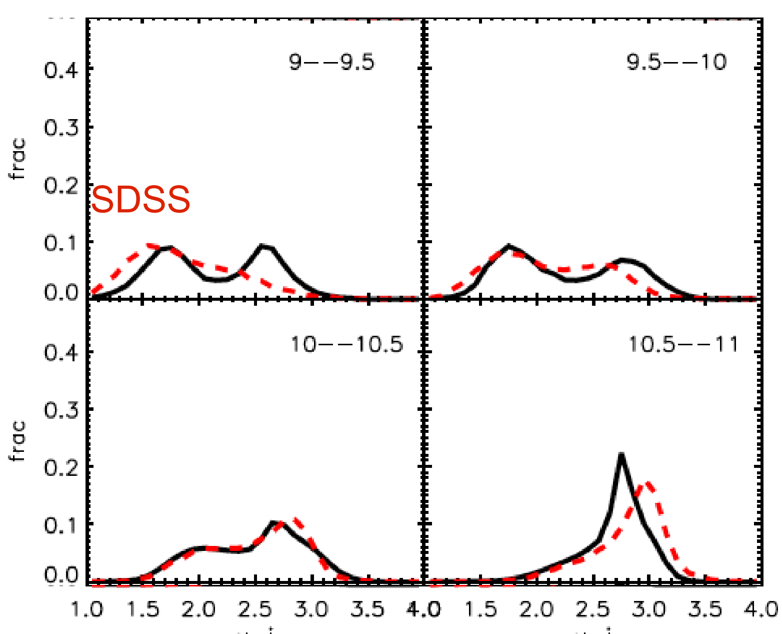
Efficiency of star-formation is too high in lower mass objects at high z?

Guo et al 2011

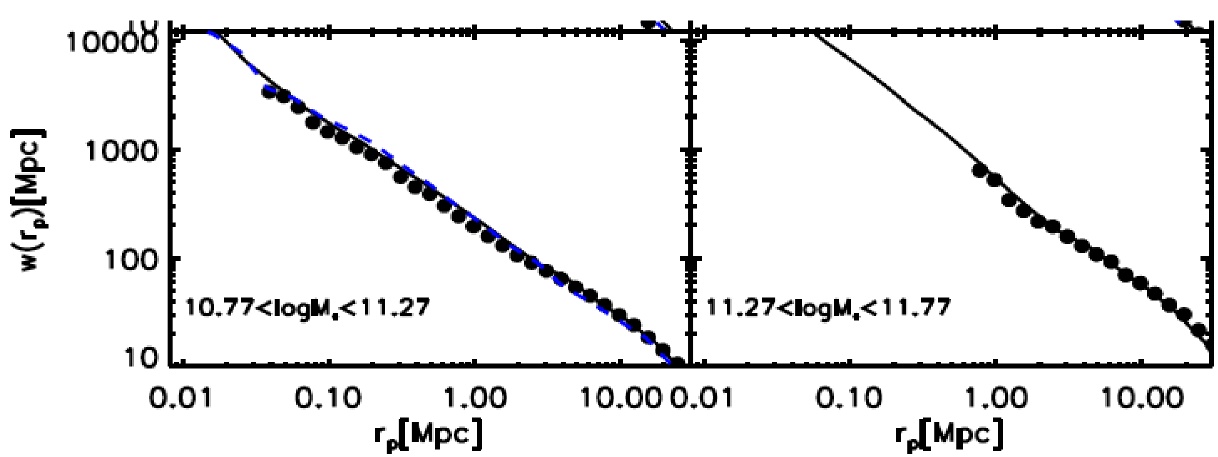
How do we learn from population simulations?

When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...





Guo et al 2011



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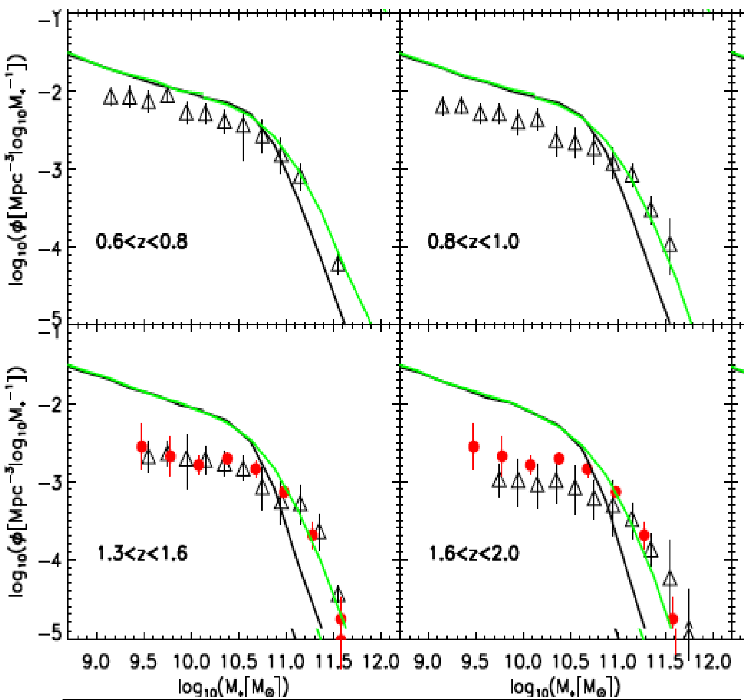
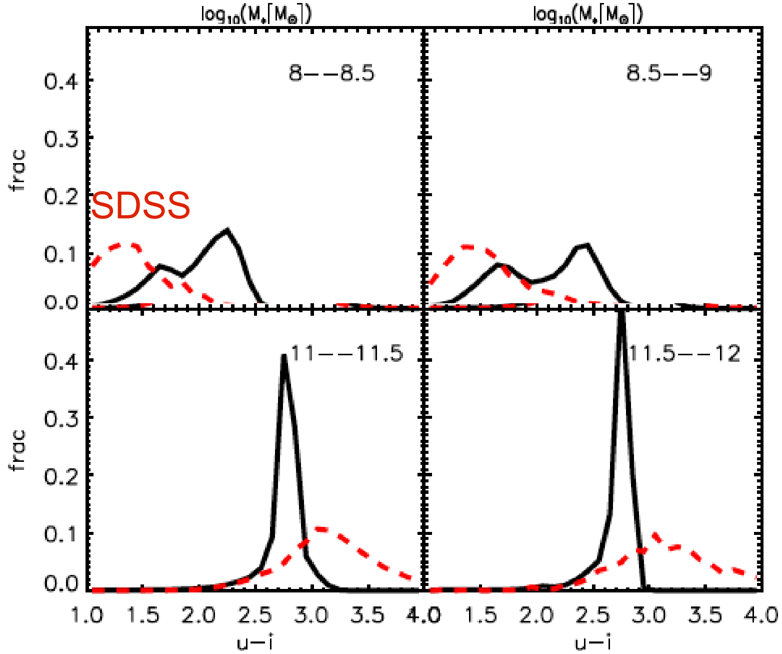


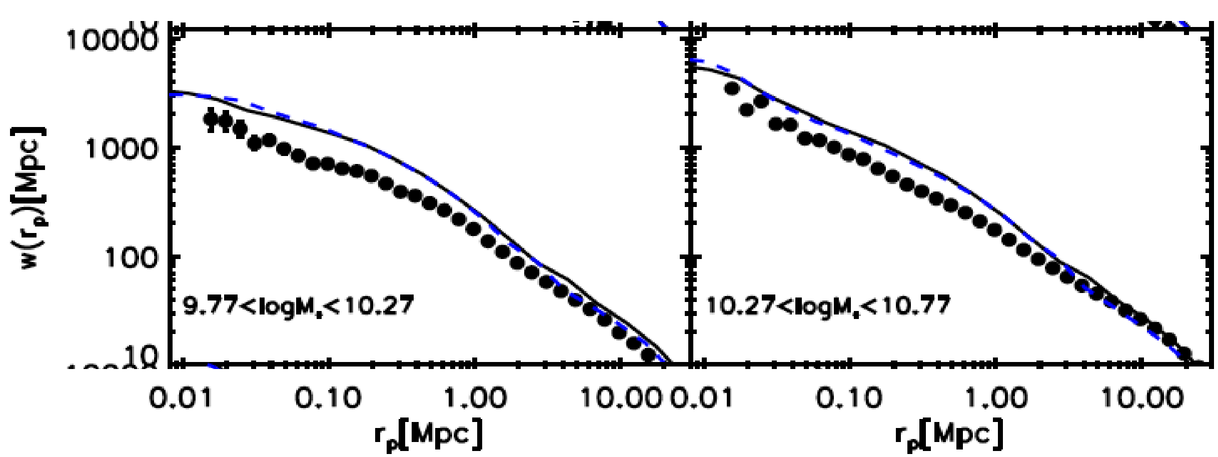
When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

...but it is the failures which show where there is missing or inadequate physics

cosmology? star formation? enrichment and feedback? environmental effects?



Guo et al 2011



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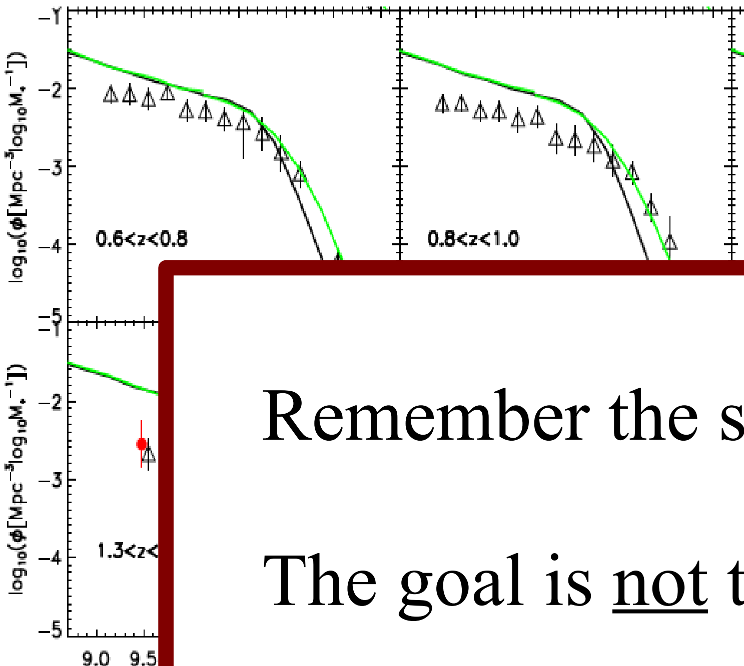

When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

re

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Remember the scientific method!

The goal is <u>not</u> to fit the observations

It is to improve understanding of the real world by framing hypotheses based on available data, and then <u>testing</u> them through acquisition of new data