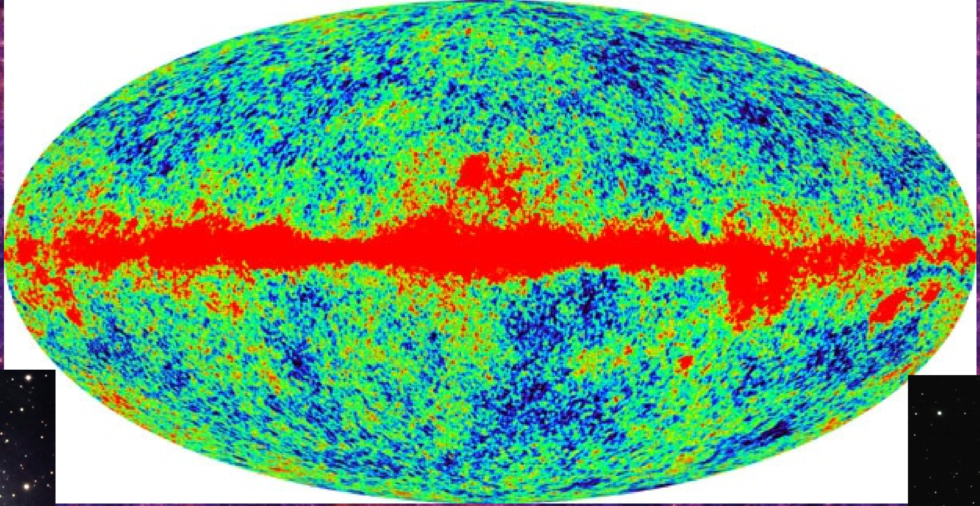

The influence of halo evolution on galaxy structure

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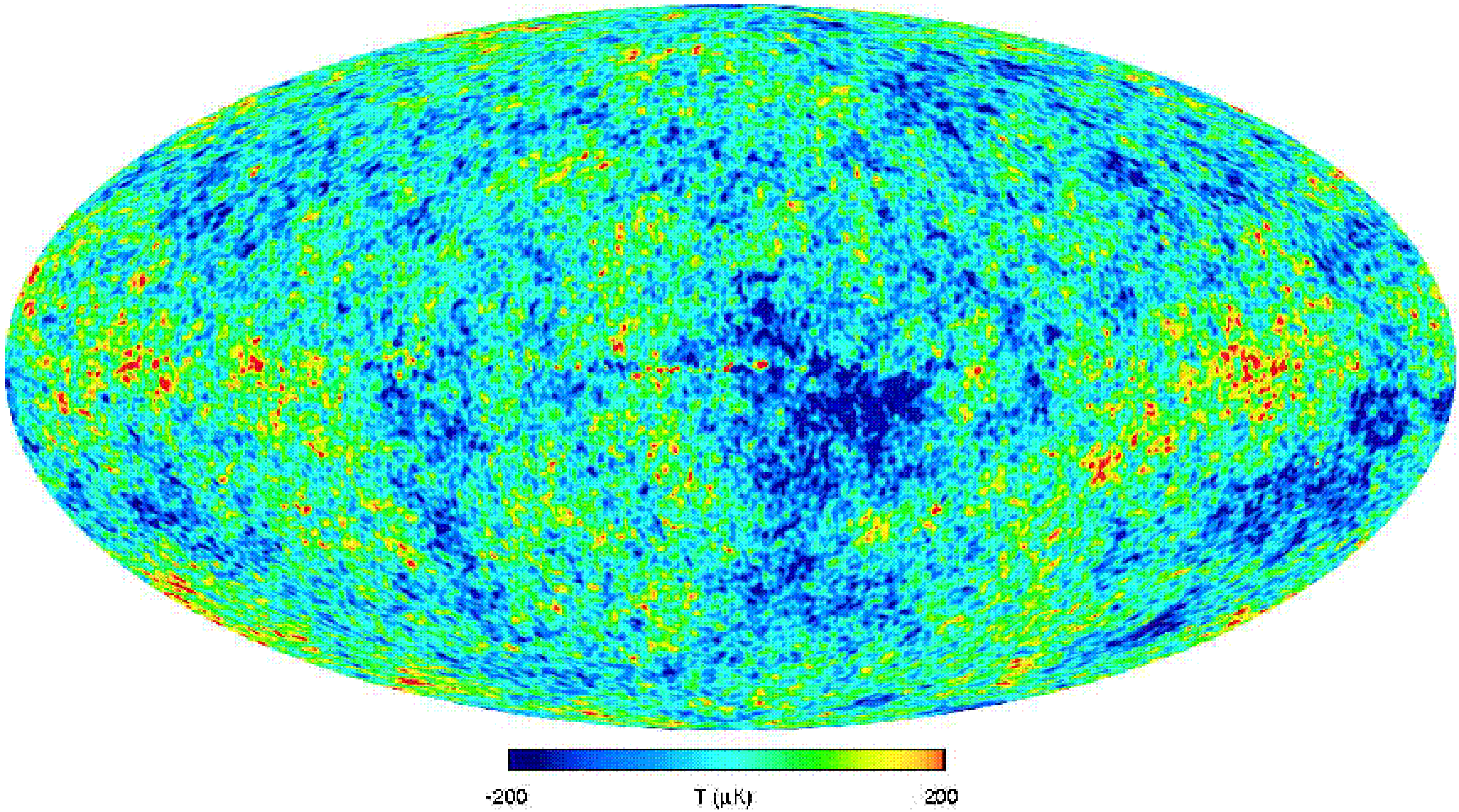
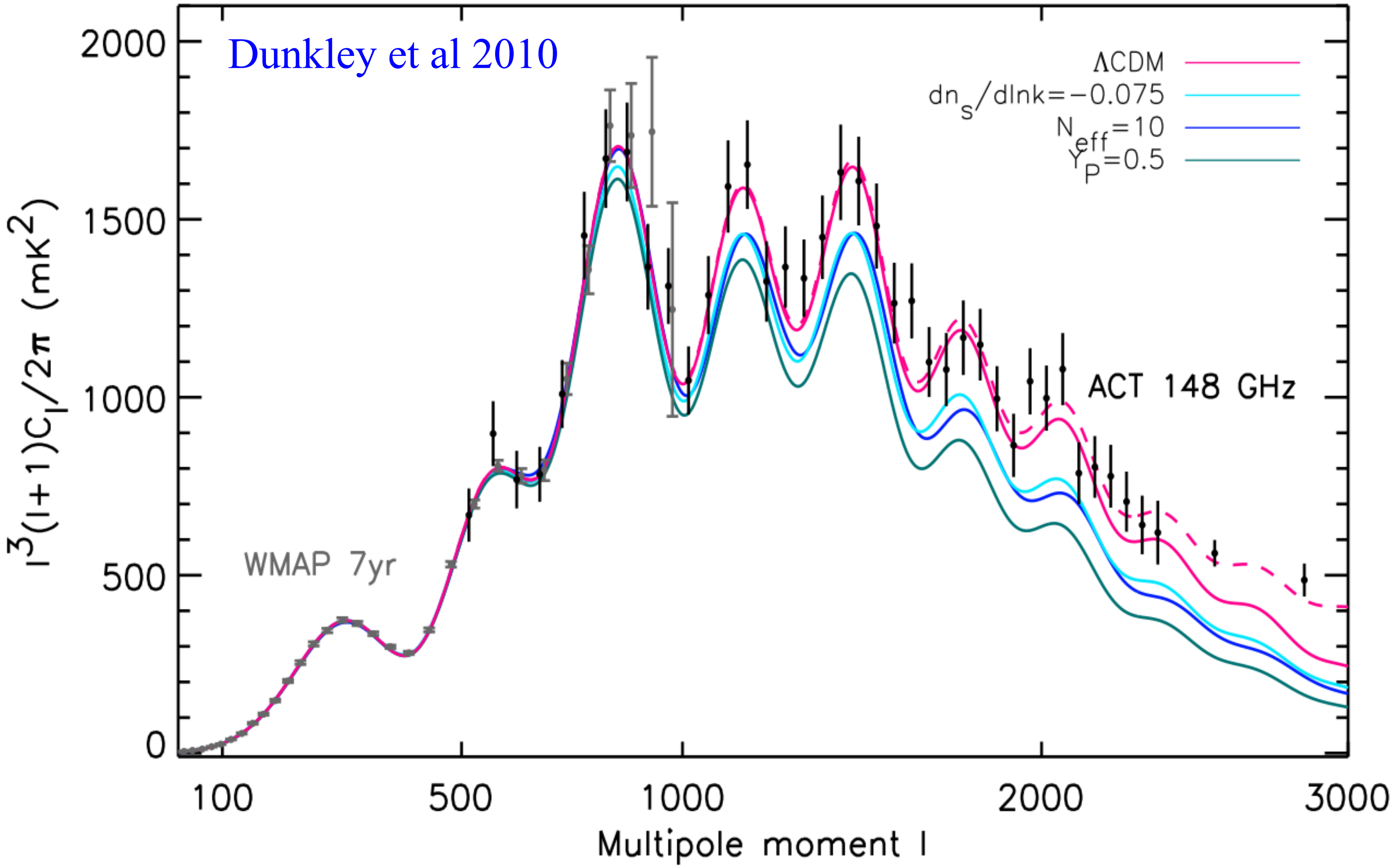
The *WMAP* of the whole CMB sky



Bennett et al 2003



Primary	$100\Omega_b h^2$	2.214 ± 0.050
ΛCDM	$\Omega_c h^2$	0.1127 ± 0.0054
	Ω_Λ	0.721 ± 0.030
	n_s	0.962 ± 0.013
	τ	0.087 ± 0.014
	$10^9 \Delta^2_{\mathcal{R}}$	2.47 ± 0.11
Derived	σ_8	0.813 ± 0.028
	Ω_m	0.279 ± 0.030
	H_0	69.7 ± 2.5

a 20σ detection of DM!

At an age of 400,000 years, the mass-energy content of the Universe was dominated by a nonrelativistic, nonuniform component which interacts purely gravitationally with the baryon-photon fluid.

This could not consist of neutrinos or any other known elementary particle

The structure seen in the CMB agrees with that predicted by the concordance ΛCDM model down to scales corresponding to today's groups and clusters of galaxies

Structure in pregalactic gas at high redshift

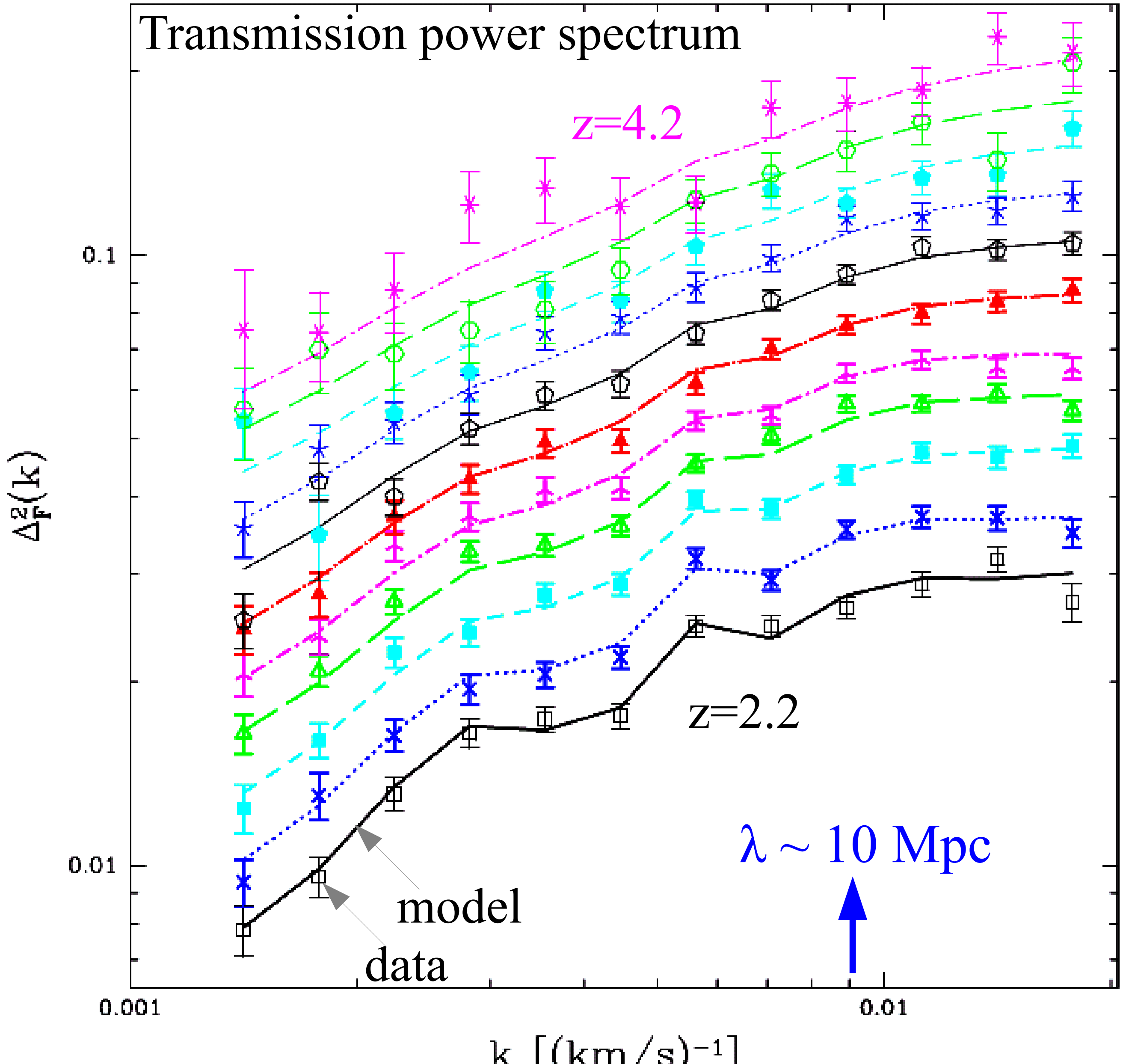
McDonald et al 2005

Diffuse intergalactic gas at "high" redshift can be observed through its Ly α absorption in QSO spectra

Structure in the absorption is due to fluctuations in the density and gravitationally induced velocities

Data - 3300 SDSS quasars

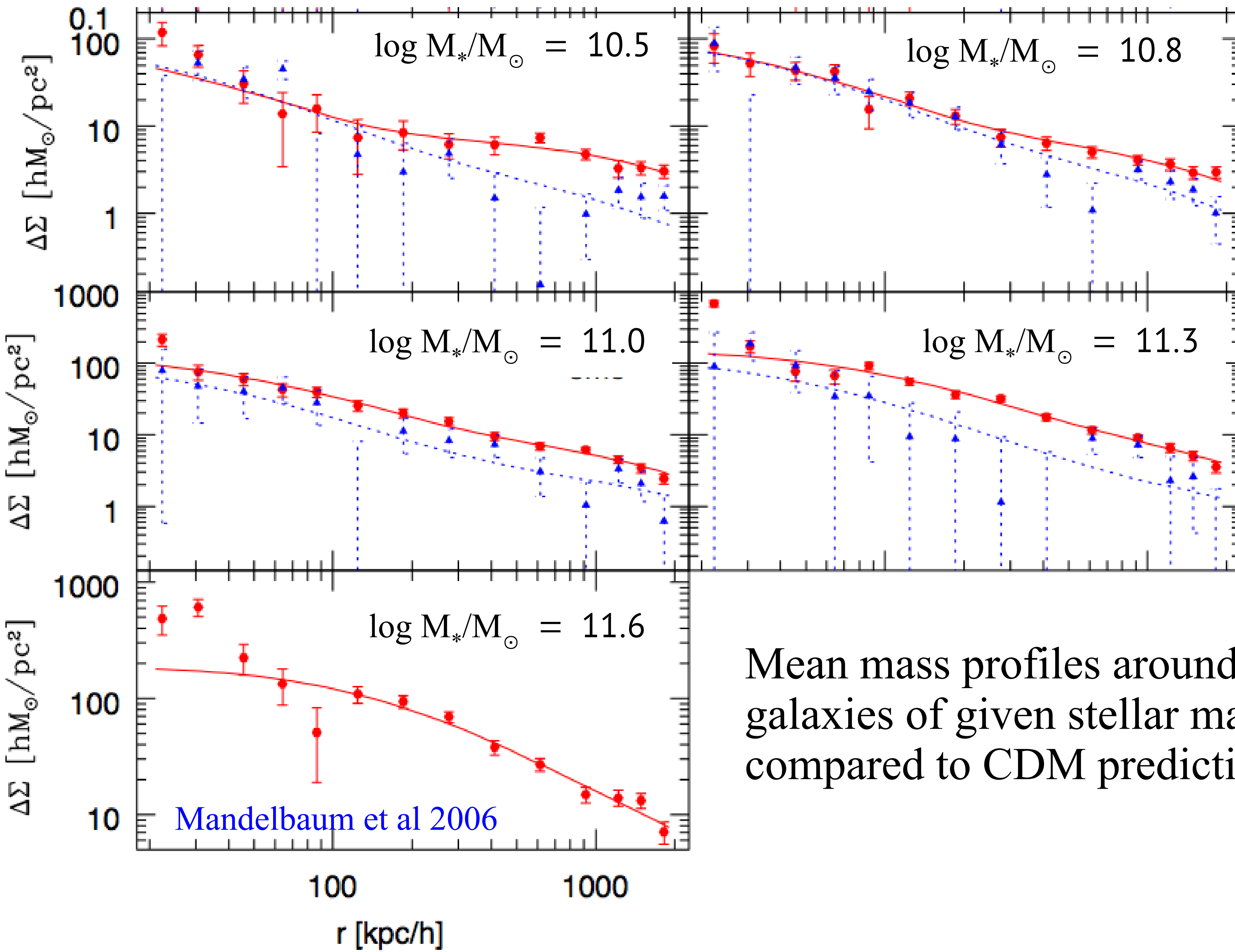
Model - ΛCDM



At redshifts between 4 and 2 the density and velocity perturbations in the diffuse pregalactic baryons are a close match to those expected for Dark-Matter-driven quasilinear growth from the structure seen at $z=1000$

This structure in the Ly-α forest agrees with the predictions of the concordance model down to scales corresponding to the masses of small dwarf galaxies.

Mean halo profiles from gravitational lensing



Mean mass profiles around galaxies of given stellar mass compared to CDM predictions

The mean $z = 0$ mass profiles of galaxies of given stellar mass are a good match to the ΛCDM predictions for evolution from the linear initial conditions observed in the CMB at $z = 1000$ and in the Ly α forest at $z = 2.5$

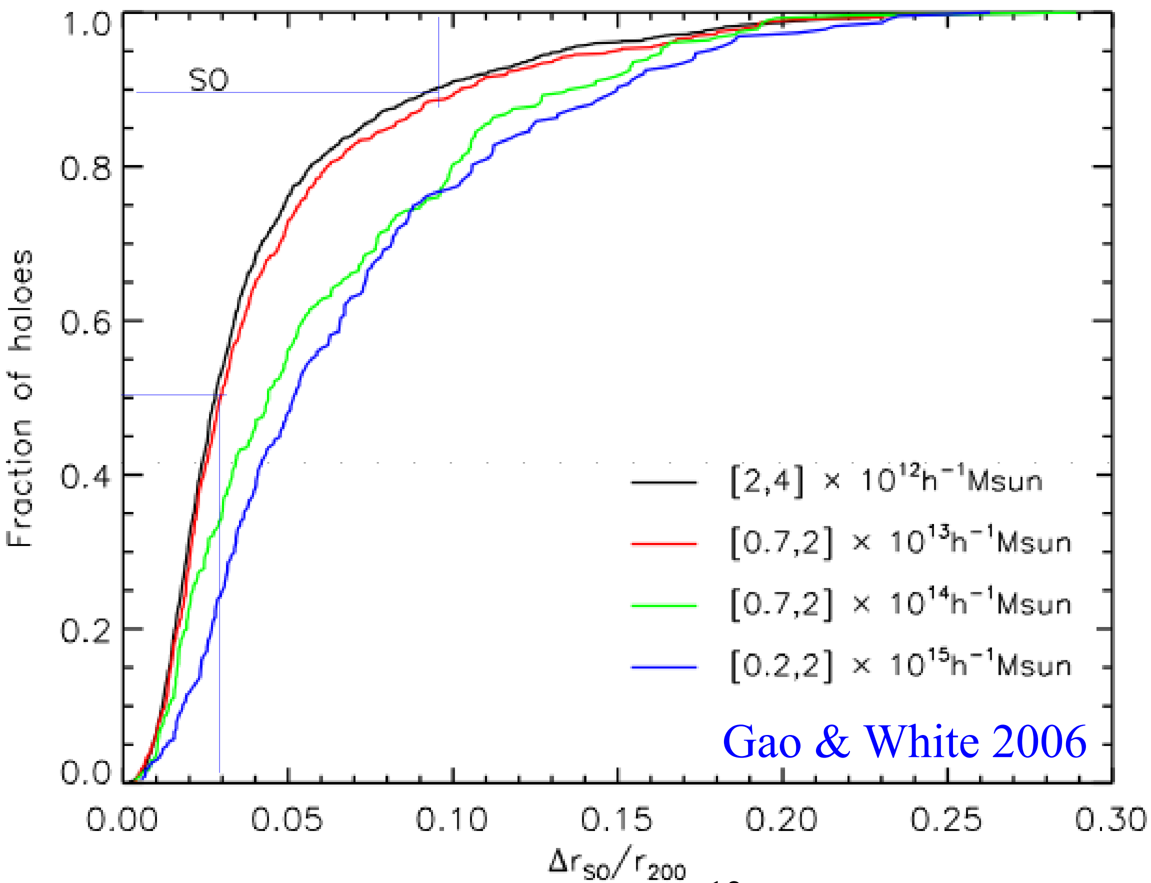
This comparison has, in essence, *no* free parameters because the assignment of galaxies to model halos can be made by matching the observed abundance of galaxies, without reference to the lensing results.

Overall, dark matter is thus the dominant component of galaxies, and is comparable in mass to the stars in the inner visible regions.

DM is likely to be a significant repository of energy and angular momentum during secular evolution, which may also be forced by evolution and non-steady behaviour of the DM halo.

The fine-scale structure of a dark matter halo

Offset of potential minimum from barycentre

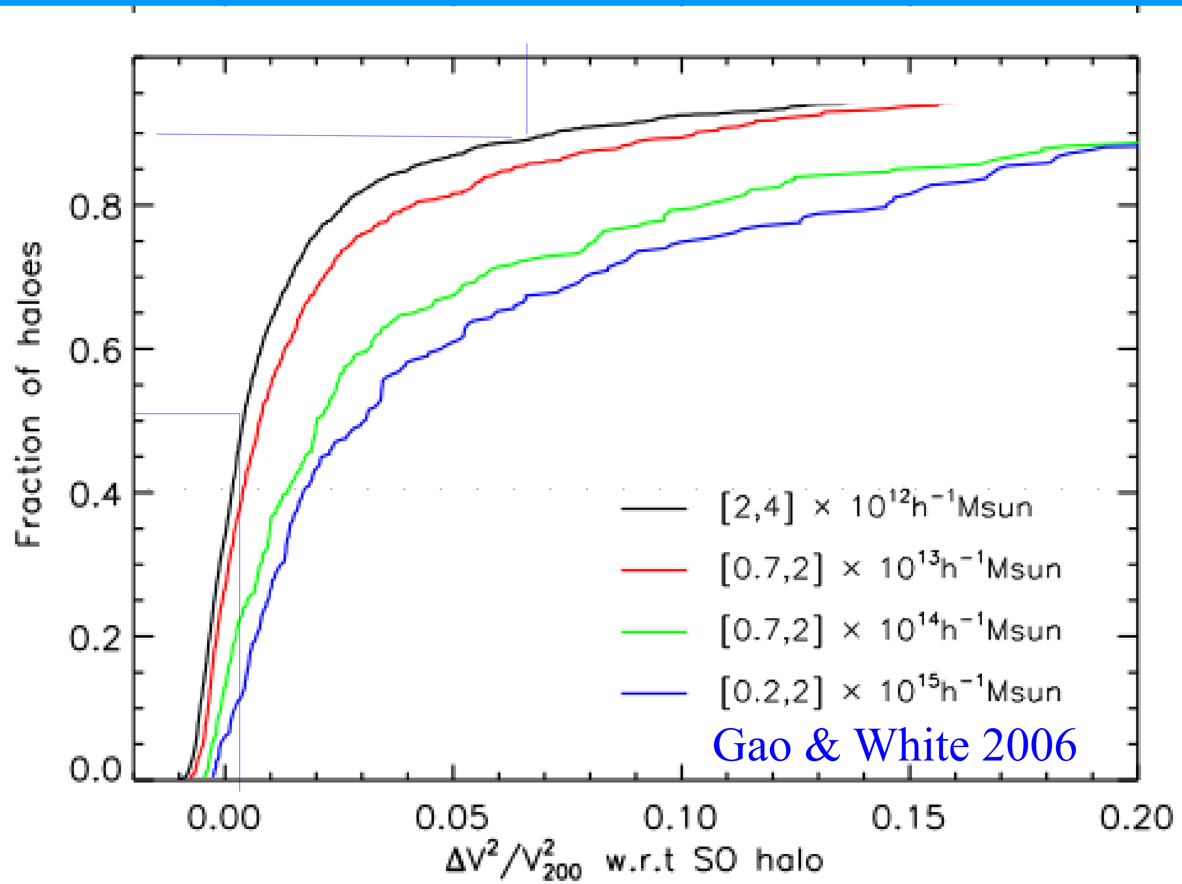


For halos with virial mass $M_{200} \sim 4 \times 10^{12} M_\odot$ the typical offset between potential minimum and barycentre is $0.03\ r_{200} \sim 10$ kpc

!0% are offset by $0.09\ r_{200} \sim 30$ kpc

More massive halos are proportionately more asymmetric

Velocity offset of "centre" from barycentre

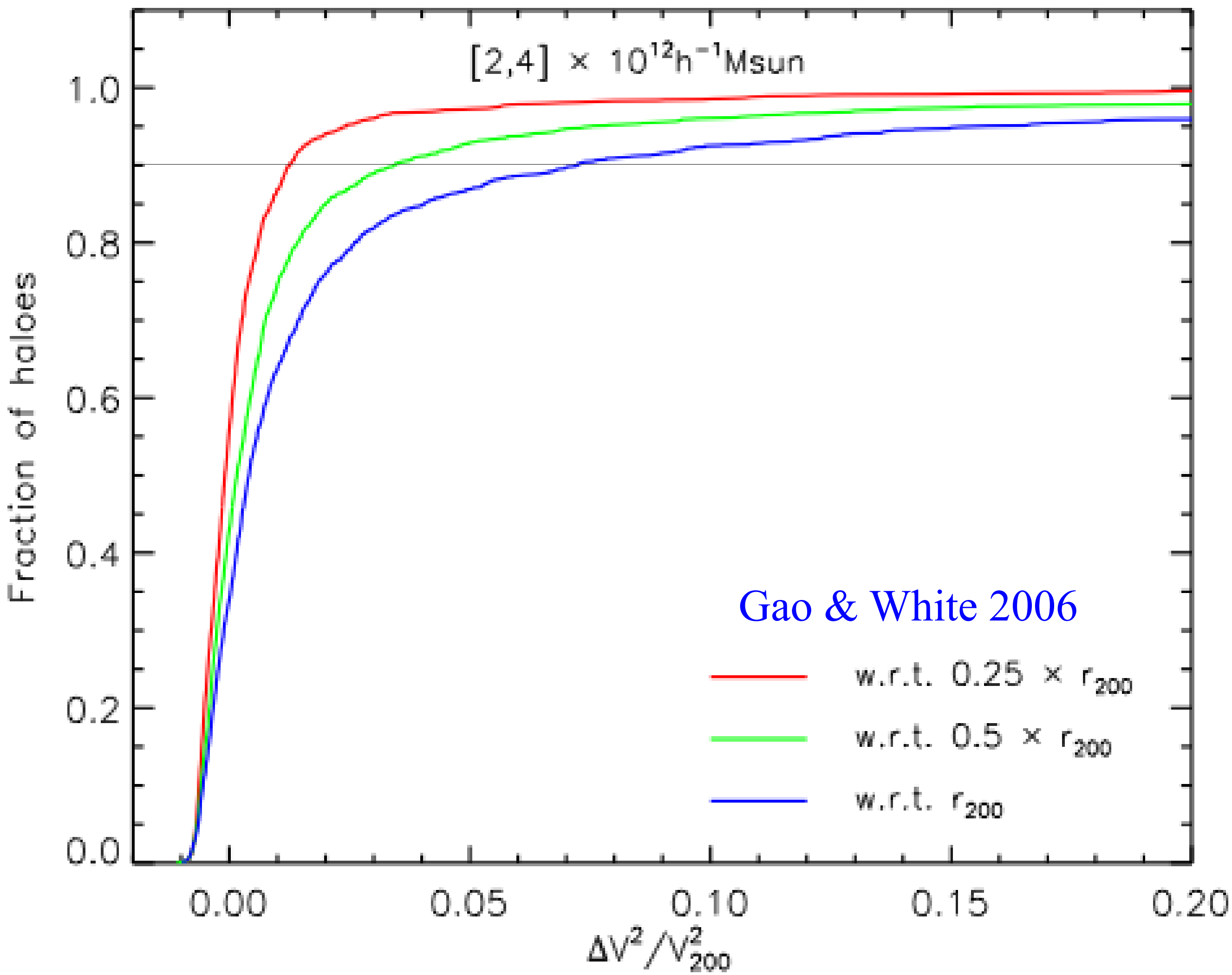


For halos with virial mass $M_{200} \sim 4 \times 10^{12}\, M_\odot$ the typical velocity offset between potential minimum and barycentre is ~15 km/s

!0% are offset by $0.25\, V_{200} \sim 60$ km/s

More massive halos are proportionately more asymmetric

Velocity offset of "centre" from barycentre



10% velocity offsets are 60 km/s w.r.t. mass within 300 kpc
40 km/s w.r.t. mass within 150 kpc
23 km/s w.r.t. mass within 75 kpc

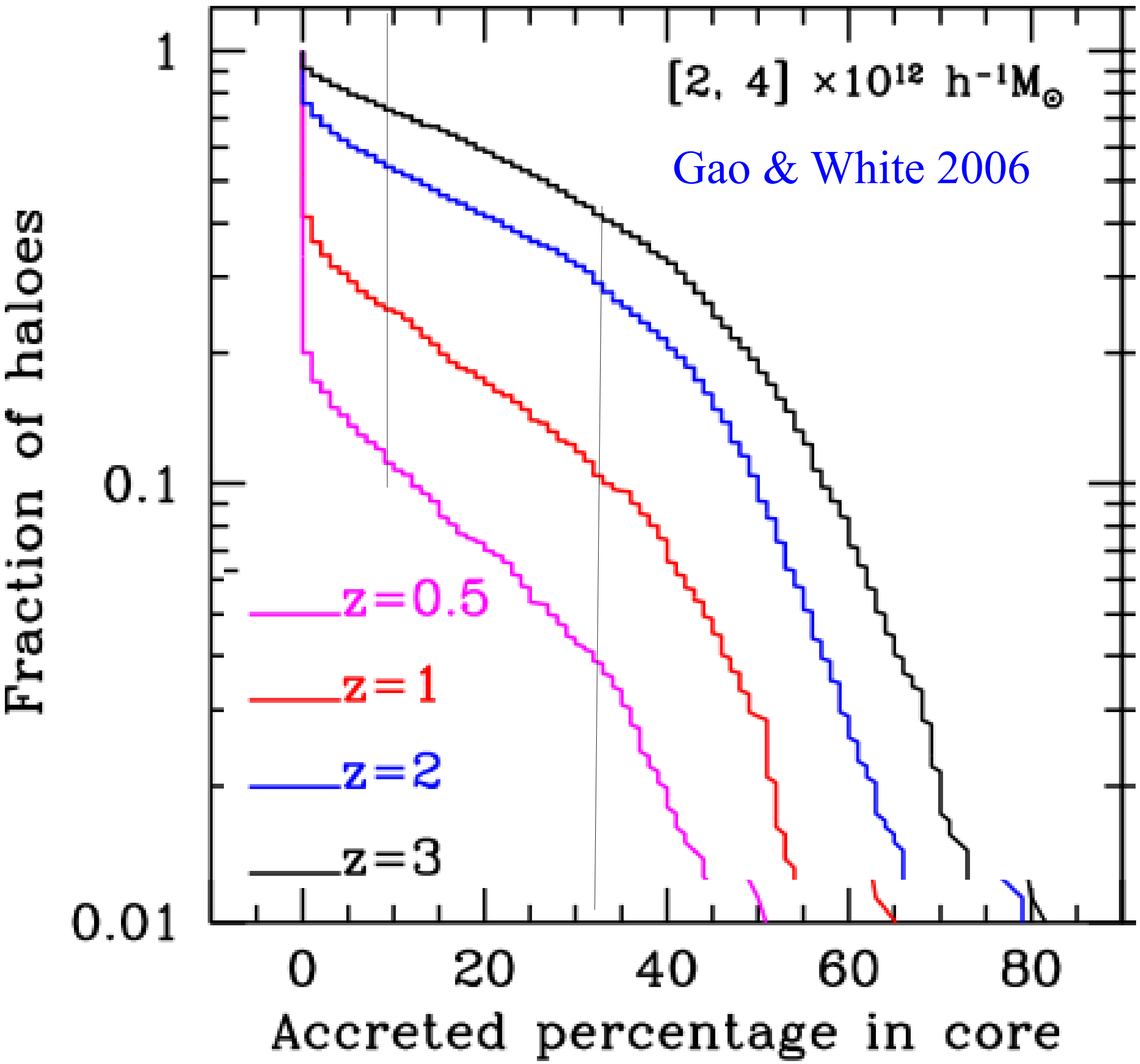
The inner regions tend to move together

The cores of dark halos where galaxies reside are relatively symmetrically located and move quite slowly with respect to the bulk of the halo mass in the majority of objects.

Asymmetries tend to be concentrated in the outer regions

Oscillations forced purely by the DM halo are of modest amplitude in most objects and so do not seem likely, of themselves, to explain lop-sidedness statistics or warps.

Mass growth in the inner halo



The inner halo (defined as the most bound 10^{11} $M_\odot$) has accreted at least 10% of its final mass since z=3 in 80% of all halos

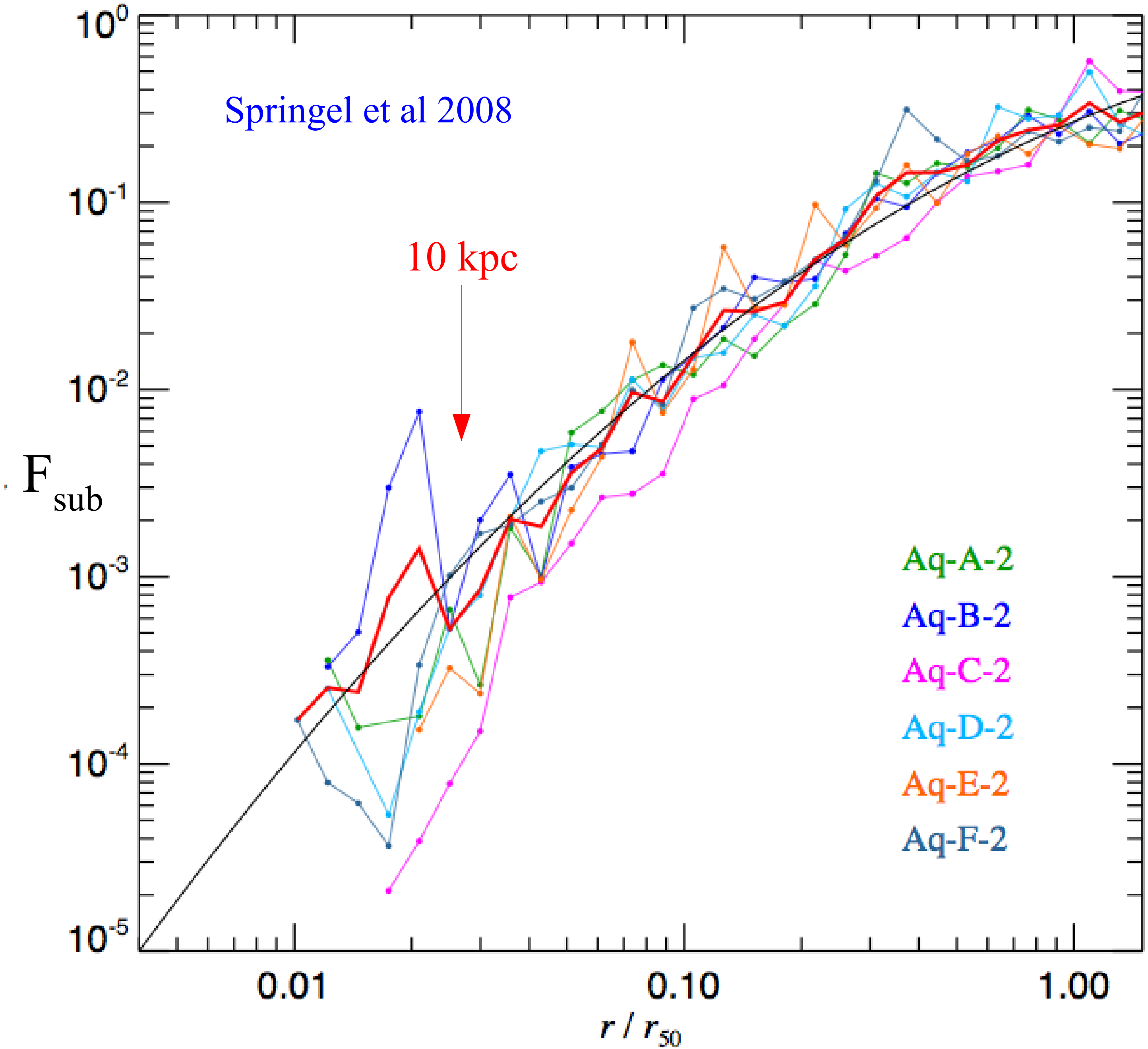
Since z=0.5, only 12% of inner halos have gained this much mass

About half of all halos have gained a third of their inner mass since z=3, but only 4% since z=0.5

In the great majority of galaxy halos, most of the DM mass in the inner regions has been in place since high redshift.

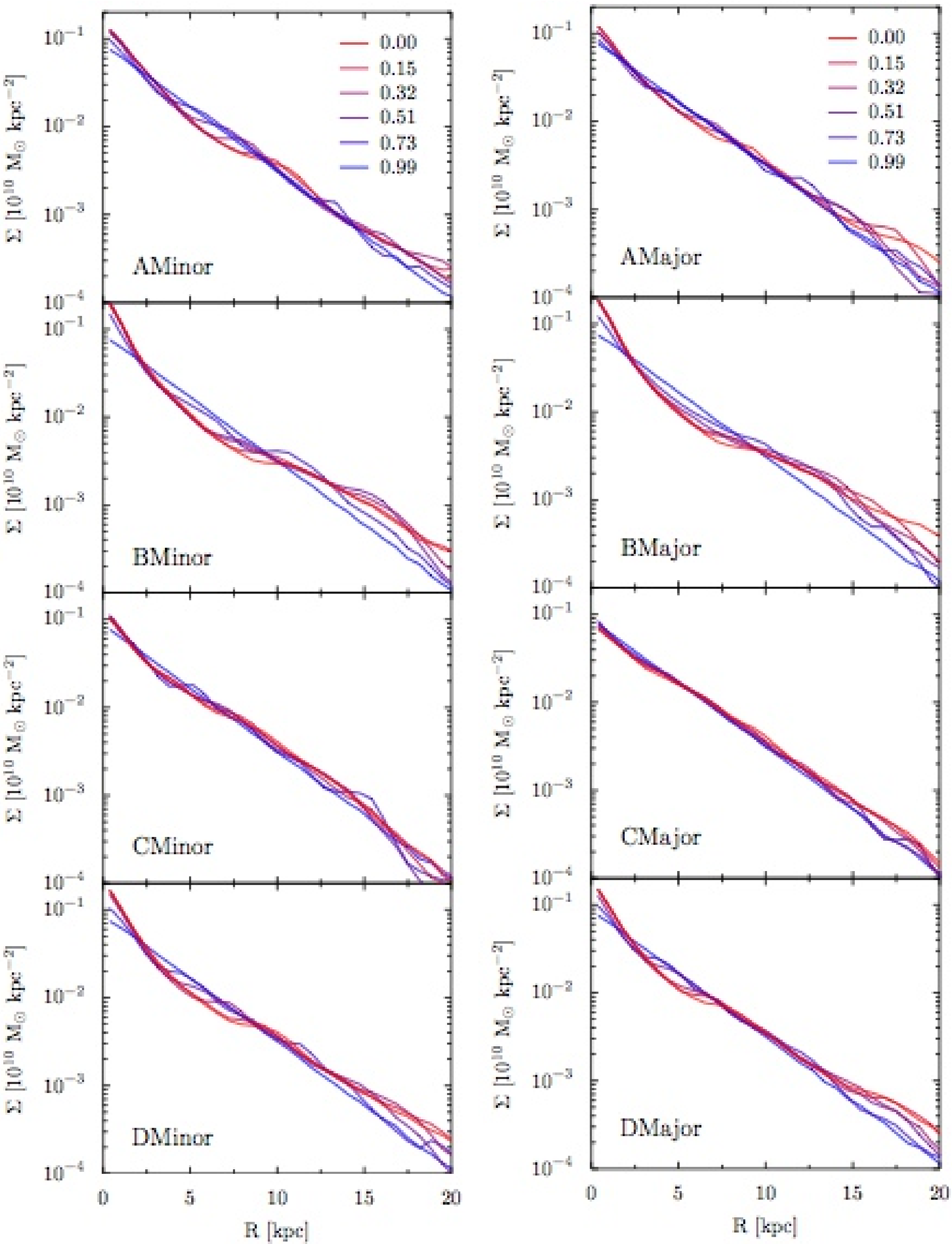
Mergers which substantially affect the mass in the regions where galaxies lie are quite uncommon and affect a small fraction of present-day objects.

Substructure in the inner halo



Although the mass fraction in subhalos is ~10% for galaxy halos as a whole, at r=10 kpc subhalos account for only ~10^{-3} of the *local* dark matter density.

DM subhalos have only a weak effect on the stellar dynamics of galaxies



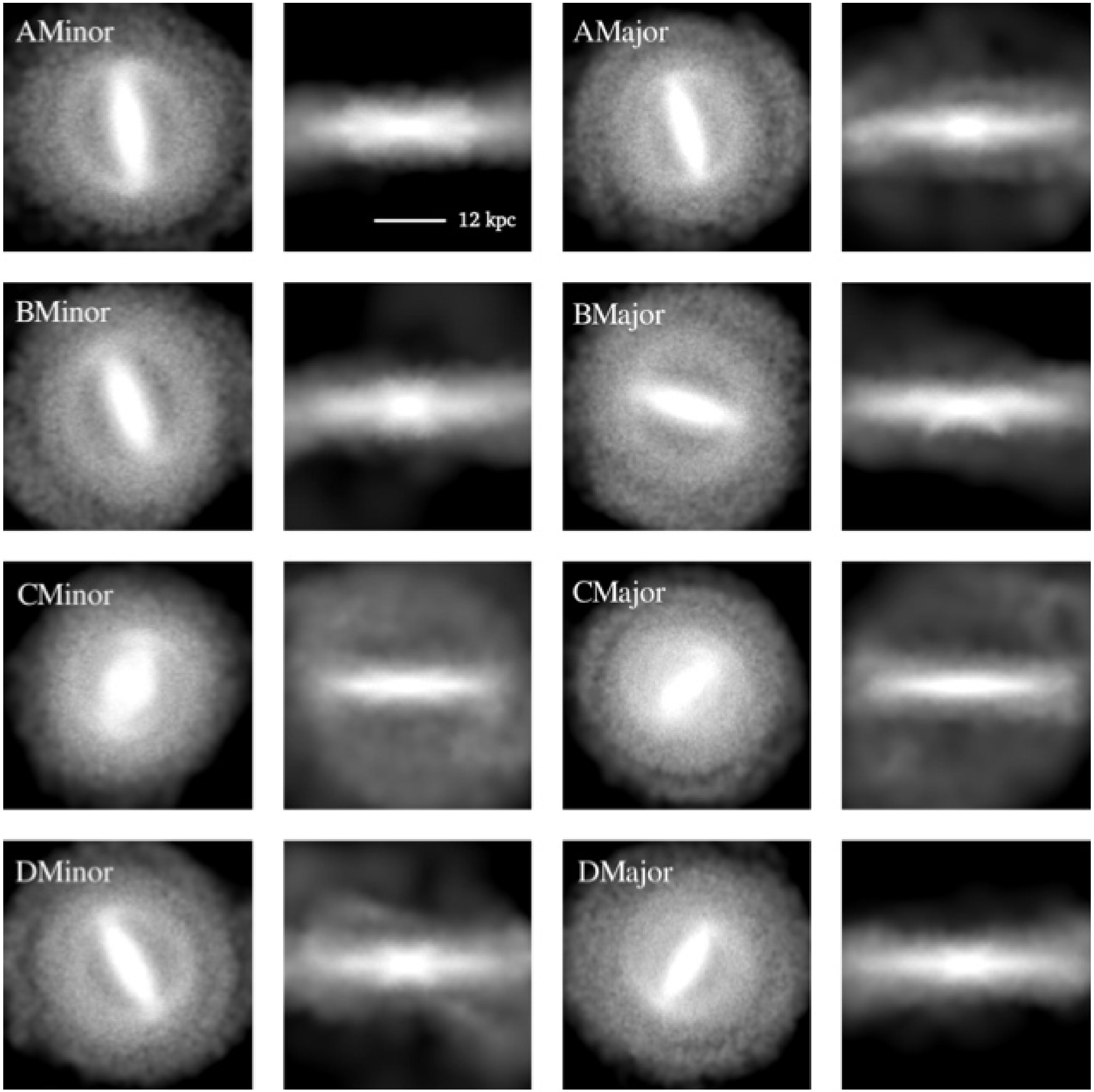
Stellar disks evolving in ΛCDM halos

DeBuehr, Ma & White 2012

Equilibrium exponential disks are inserted adiabatically into 4 Aquarius halos (with J parallel to inner major or minor axis) and allowed to evolve from z=1 to z=0

Radial surface density profiles remain fairly stable...

Stellar disks evolving in ΛCDM halos



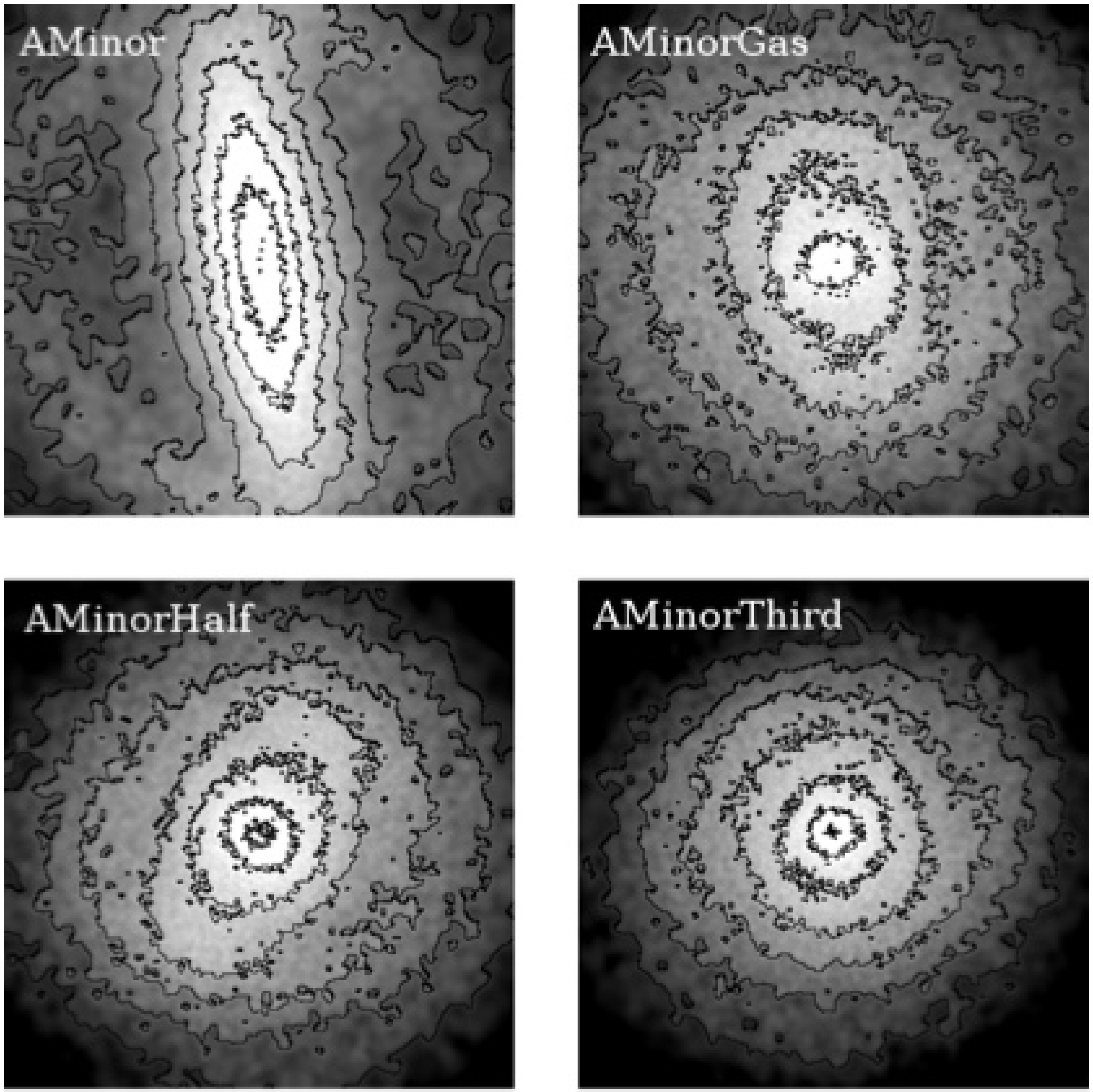
DeBuehr, Ma & White 2012

..but the disks all form bars which are strong enough in 6 cases for buckling to produce an X-shape bulge

Notice the substantial out-of-plane material in many of the cases

Stellar disks evolving in ΛCDM halos

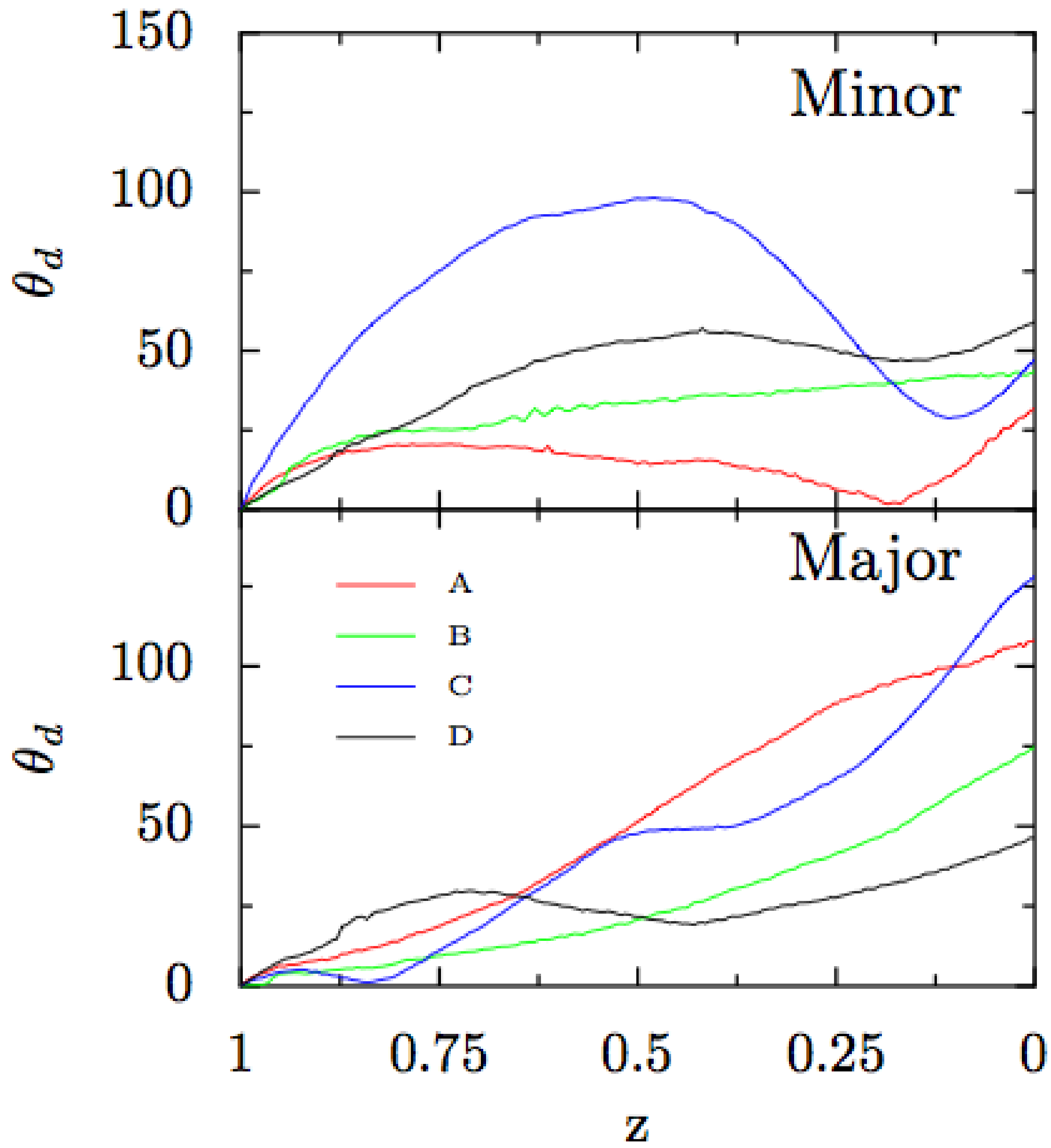
DeBuehr, Ma & White 2012



The bar instability can be removed by replacing 40% of the stars by non-radiative gas or by reducing the disk mass

The stellar disks satisfy the ELN82 criterion for stability quite well $V_{max}/(G\ M_d\ /\ R_d)^{0.5} > 1.1$

Stellar disks evolving in ΛCDM halos



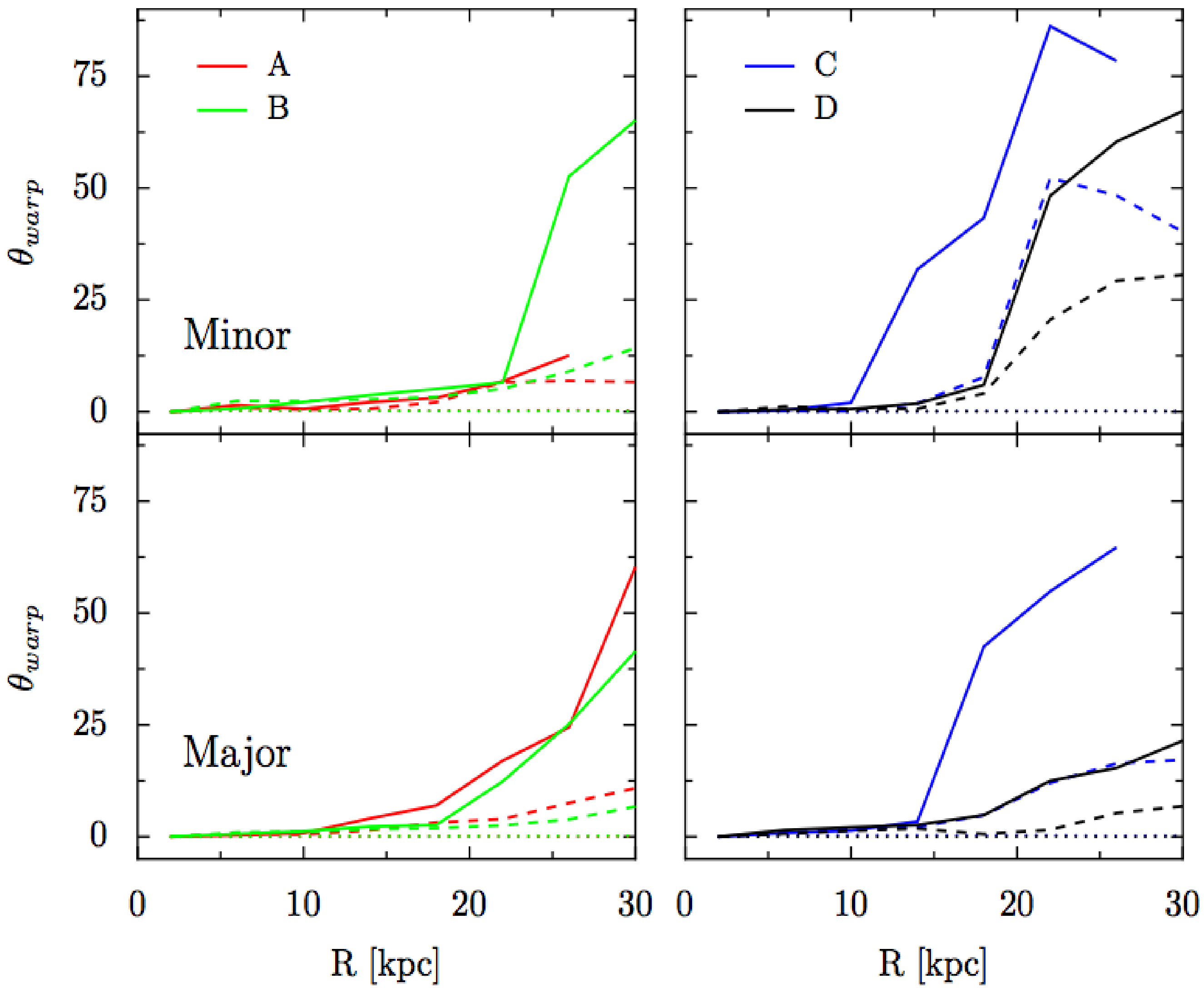
DeBuehr, Ma & White 2012

In almost all cases the inner disk (r < 5 kpc) changes orientation by large angles between z=0 and z=1

During these shifts it remains aligned with the principal axes of the inner dark halo.

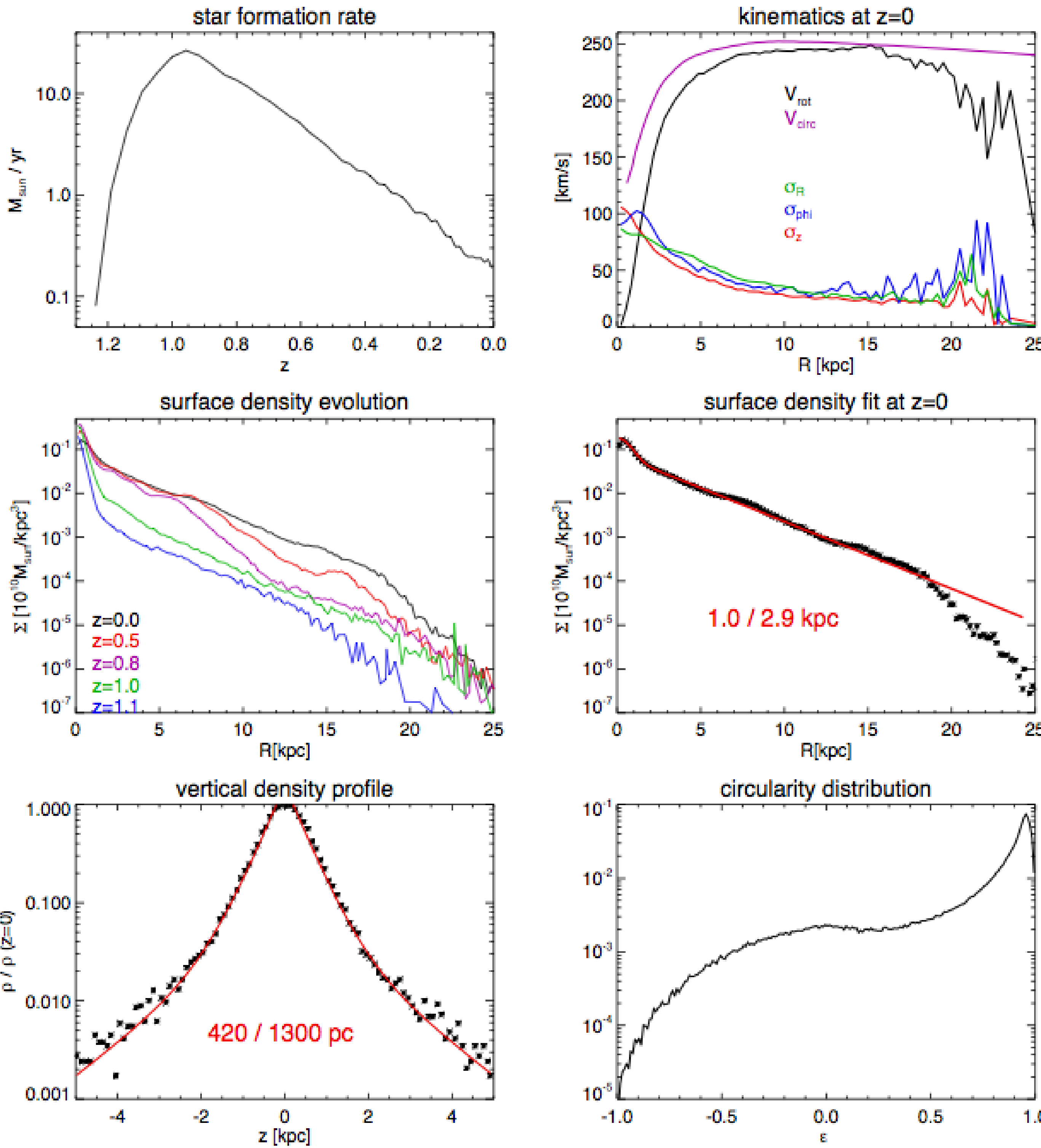
Stellar disks evolving in ΛCDM halos

DeBuehr, Ma & White 2012



.The outer disks do not follow these shifts but are "left behind" leading to strong "fossil" warps.

Note that these are *not* formed by late infall or by satellite perturbation



Disks forming in ΛCDM halos from cooling gas

Aumer & White 2012

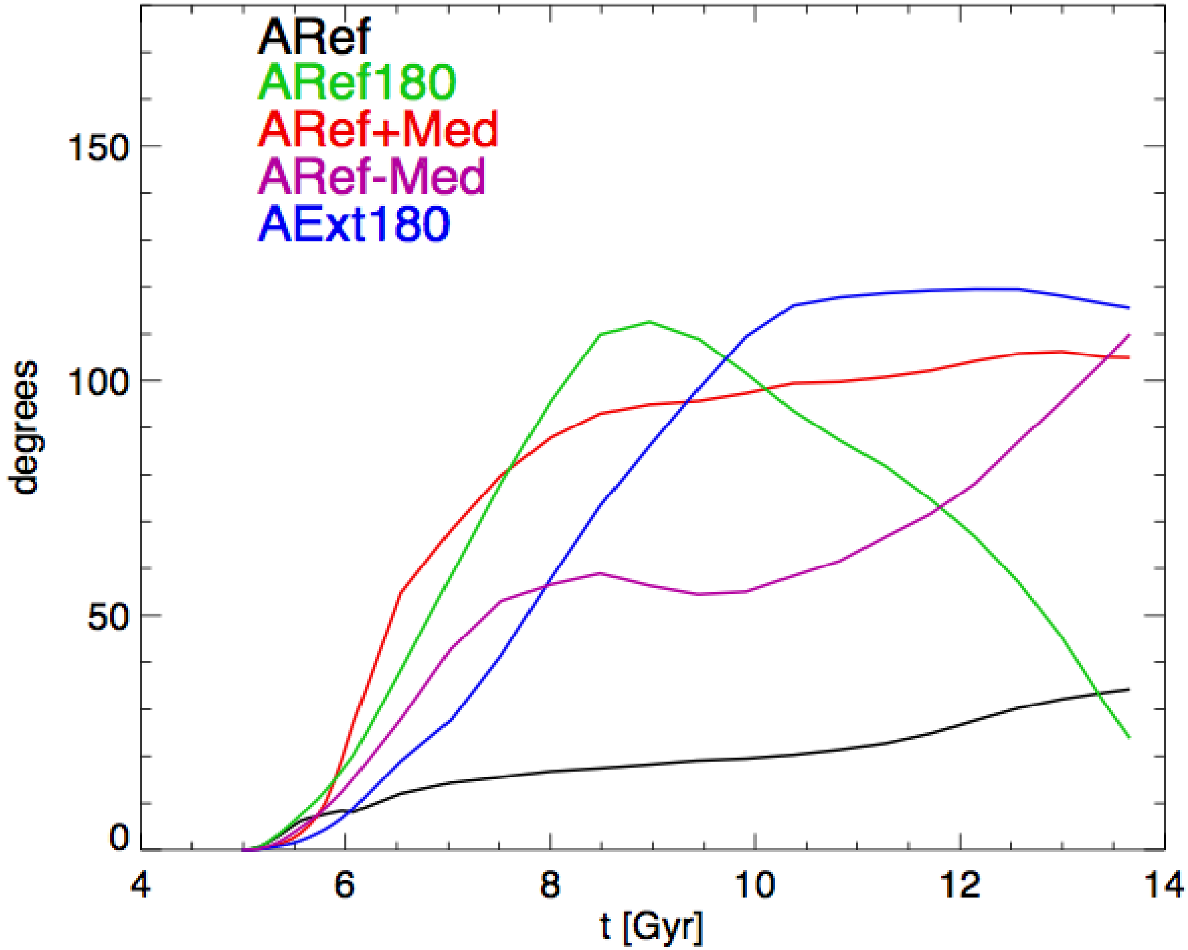
Simulate disk formation in Aquarius halos starting at z=1.3 with a smooth, <u>spherical</u>, equilibrium gas distribution with $\rho \propto 1/r$ rotating at constant V

Vary cooling law and orientation of J vector

Here, the reference model, with J parallel to J_{DM} (close to the minor axis).

Disks forming in ΛCDM halos from cooling gas

Aumer & White 2012



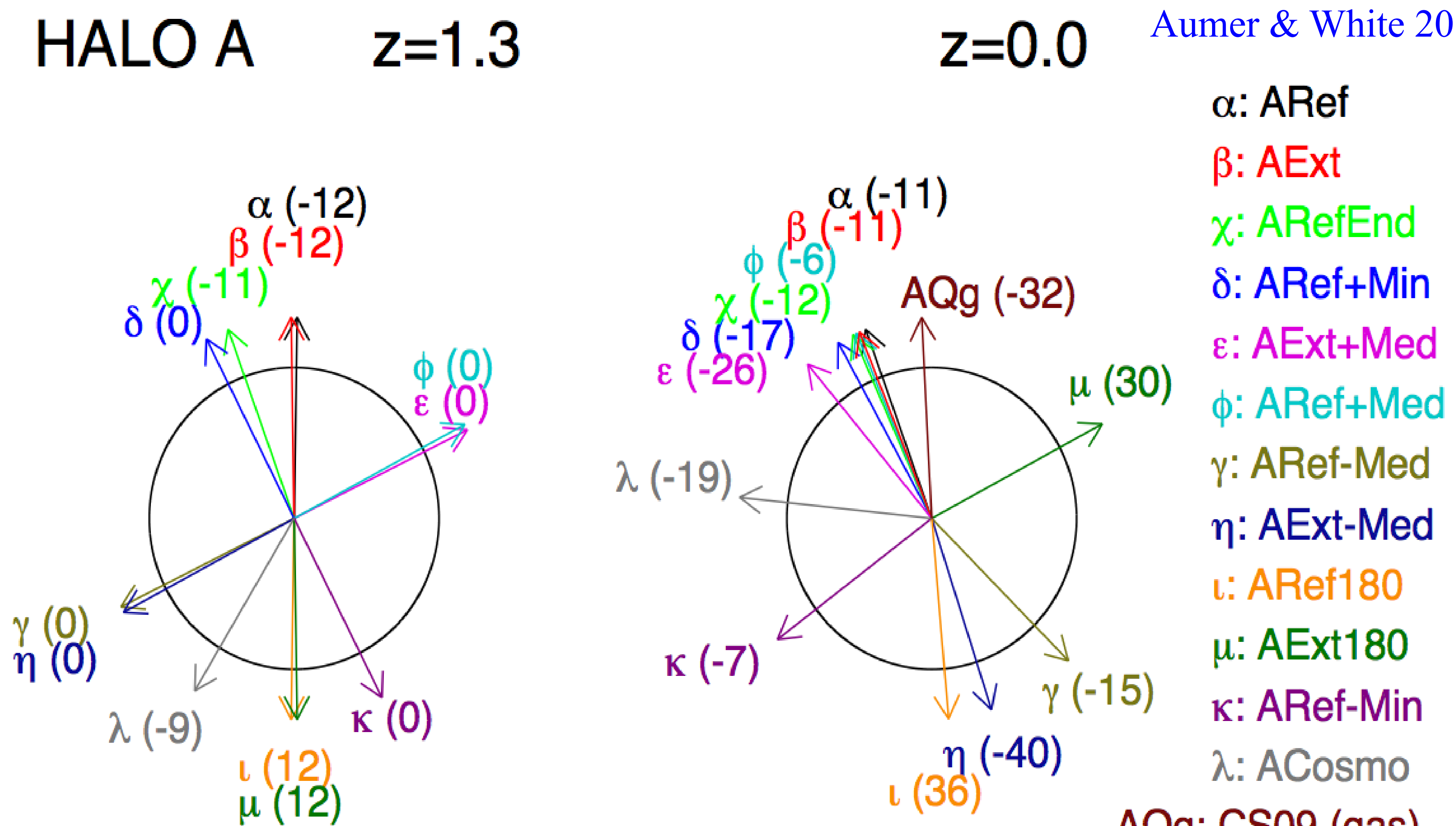
The orientation of J for the baryons (stars+gas) changes with time in a way which depends on its initial orientation

The change is small when the initial J is aligned with J_{DM} (in this particular halo)

The change depends on the *sign* of the initial J

Disks forming in ΛCDM halos from cooling gas

Aumer & White 2012



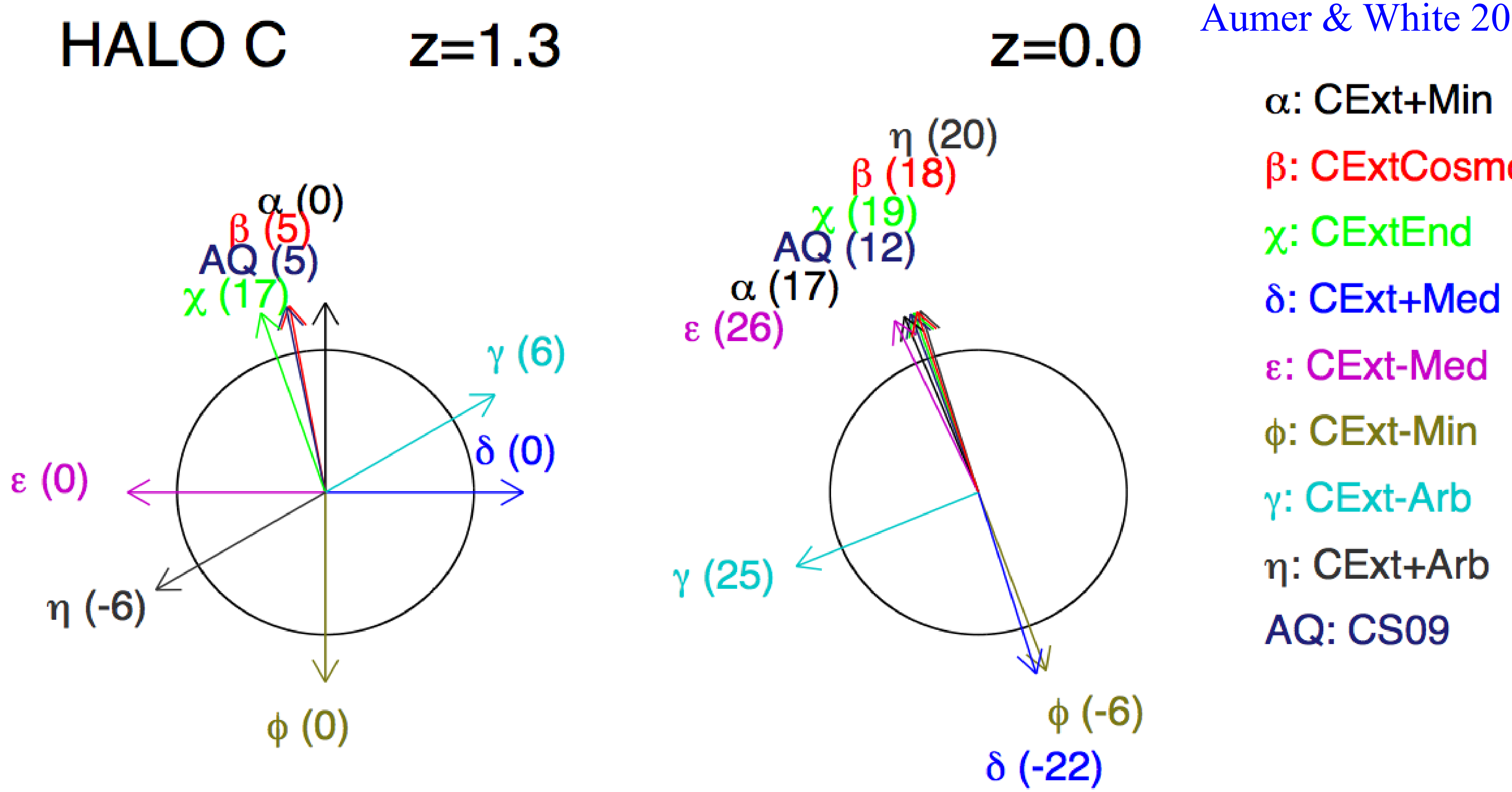
A variety of final orientations are possible

Most are close to that found for a realistic cosmological gas treatment

Final orientation does not depend *only* on initial orientation

Disks forming in ΛCDM halos from cooling gas

Aumer & White 2012



Different halos behave differently

Here most end up close to the cosmological case

Live ΛCDM halos affect visible galaxies through

(i) providing a sink for energy and angular momentum, thus affecting disk and bar evolution

(ii) bombardment by substructures (relatively weak - only 0.1% of inner halo mass is in substructure)

(iii) addition of mass through infall/merging (also weak – most of the mass added at late times stays at large radius)

(iv) variation of shape and orientation of the potential, leading to substantial orientation changes in the disk and causing “fossil warps” and disk heating