IAU Symposium
#254, Copenhagen
June 2008

Simulations of disk galaxy formation in their cosmological context

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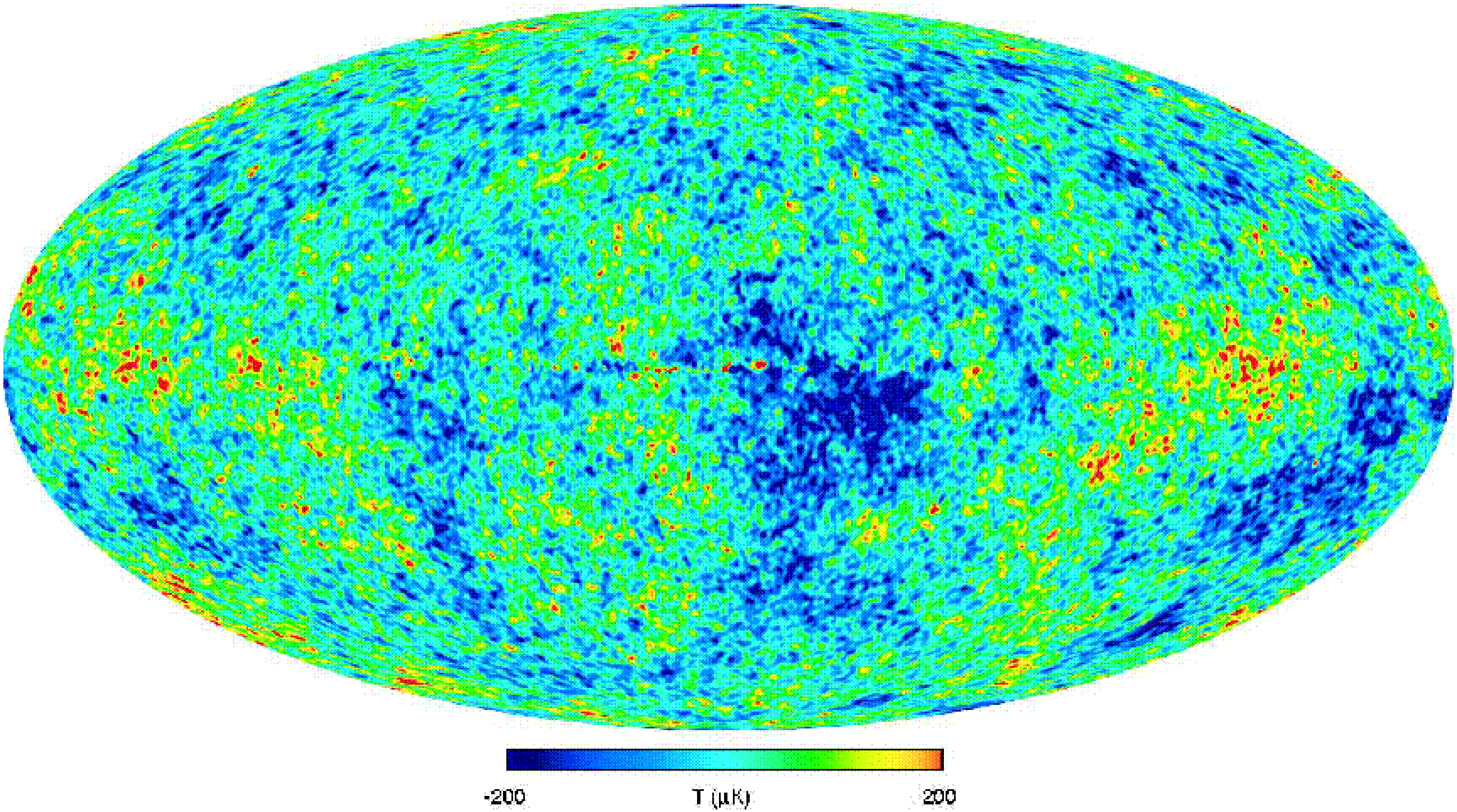
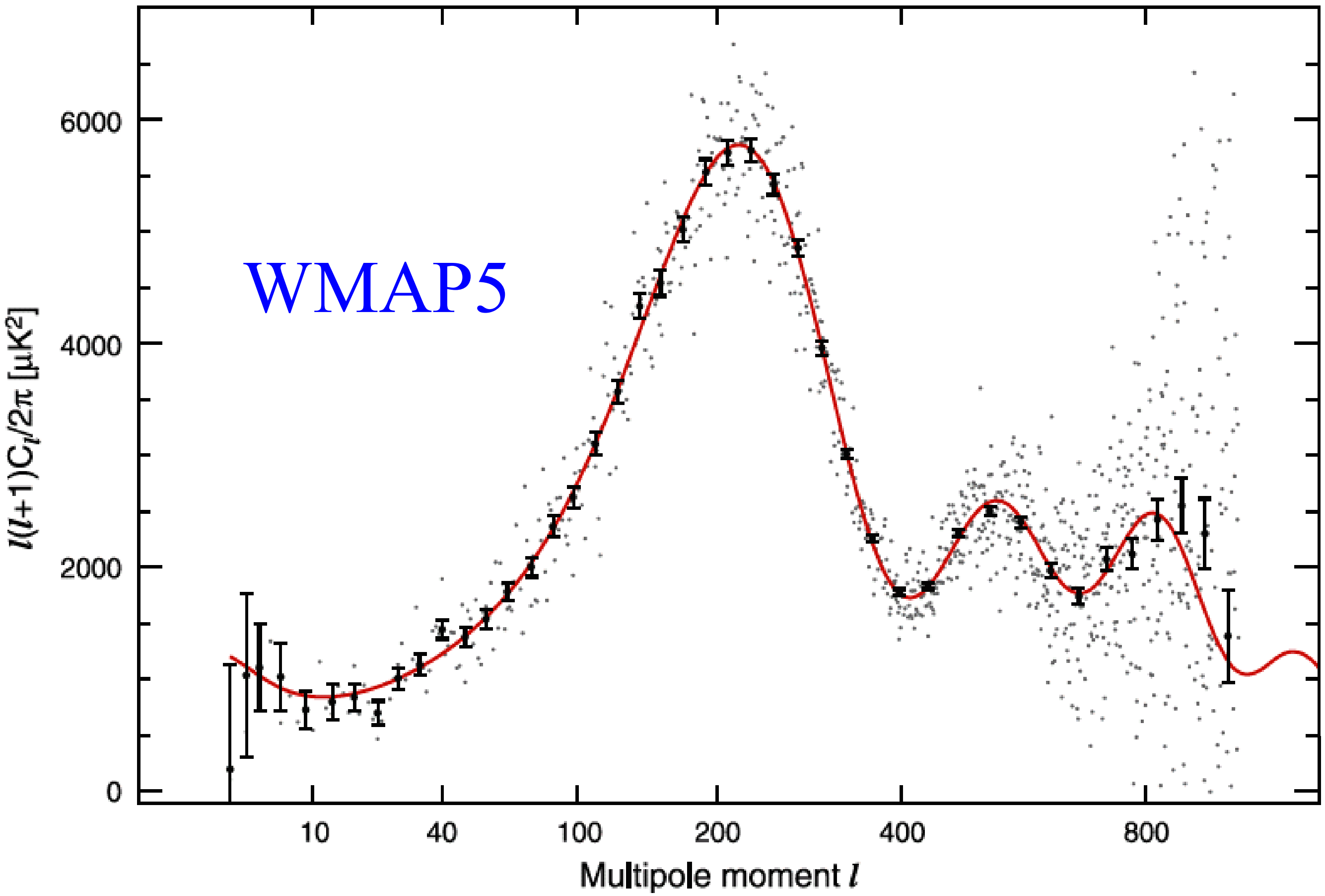
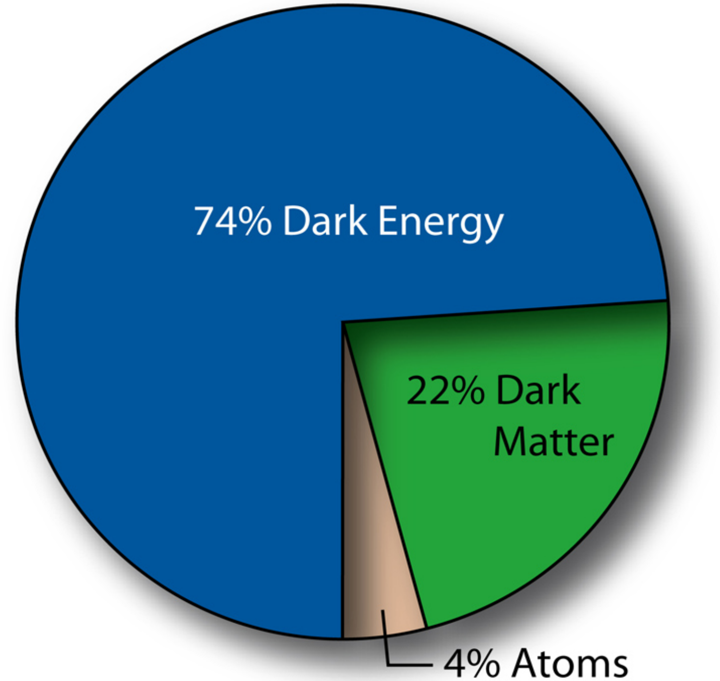
Max Planck Institute for Astrophysics

The *WMAP* of the whole CMB sky

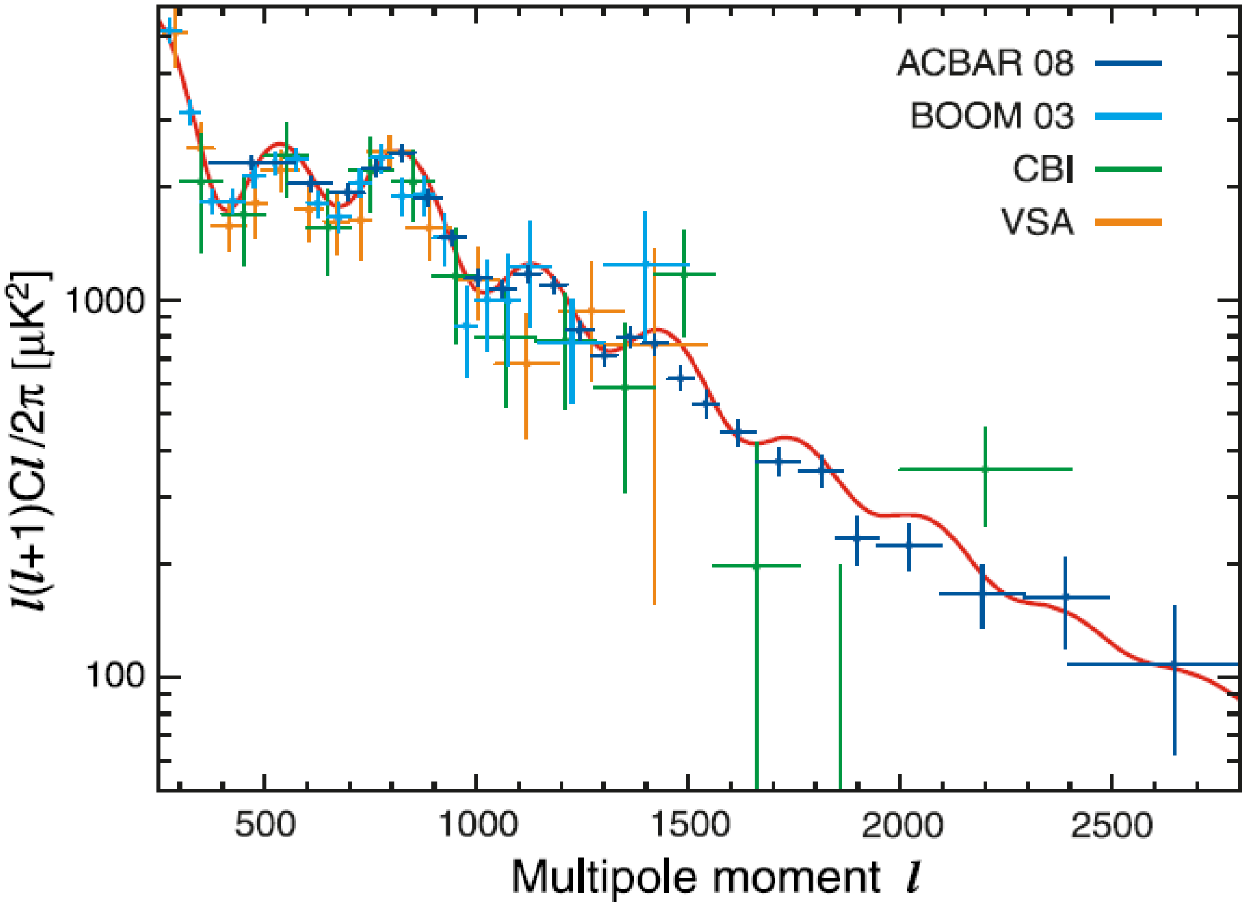


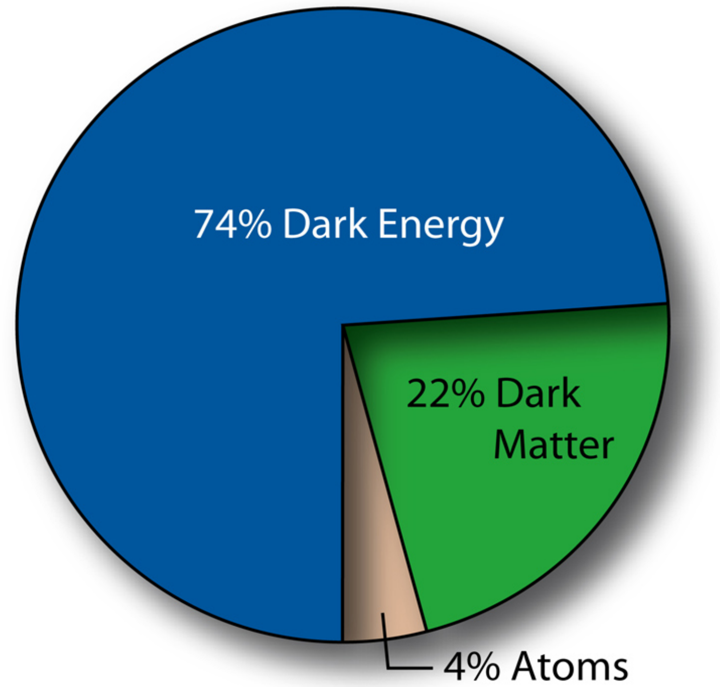
Bennett et al 2003





parameter	symbol	WMAP-5 alone	WMAP-5 + BAO + SNe	comment
CMB temperature	$T_{\rm CMB}$	2.728 ± 0.004 K	–	from (Fixsen *et al.* 1996)
total matter density	$\Omega_{\rm tot}$	$1.099^{+0.100}_{-0.085}$	1.0052 ± 0.0064	
matter density	$\Omega_{\rm m0}$	0.258 ± 0.03	0.279 ± 0.015	assuming spatial flatness
baryon density	$\Omega_{\rm b0}$	0.0441 ± 0.0030	0.0462 ± 0.0015	here and below
cosmological constant	$\Omega_{\Lambda 0}$	0.742 ± 0.03	0.721 ± 0.015	
Hubble constant	h	$0.719^{+0.026}_{-0.027}$	0.701 ± 0.013	
power-spectrum normalisation	σ_8	0.796 ± 0.036	0.817 ± 0.026	
age of the Universe in Gyr	t_0	13.69 ± 0.13	13.73 ± 0.12	
decoupling redshift	$z_{\rm dec}$	1087.9 ± 1.2	1088.2 ± 1.1	
reionisation optical depth	τ	0.087 ± 0.017	0.084 ± 0.016	
spectral index	$n_{\rm s}$	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$	





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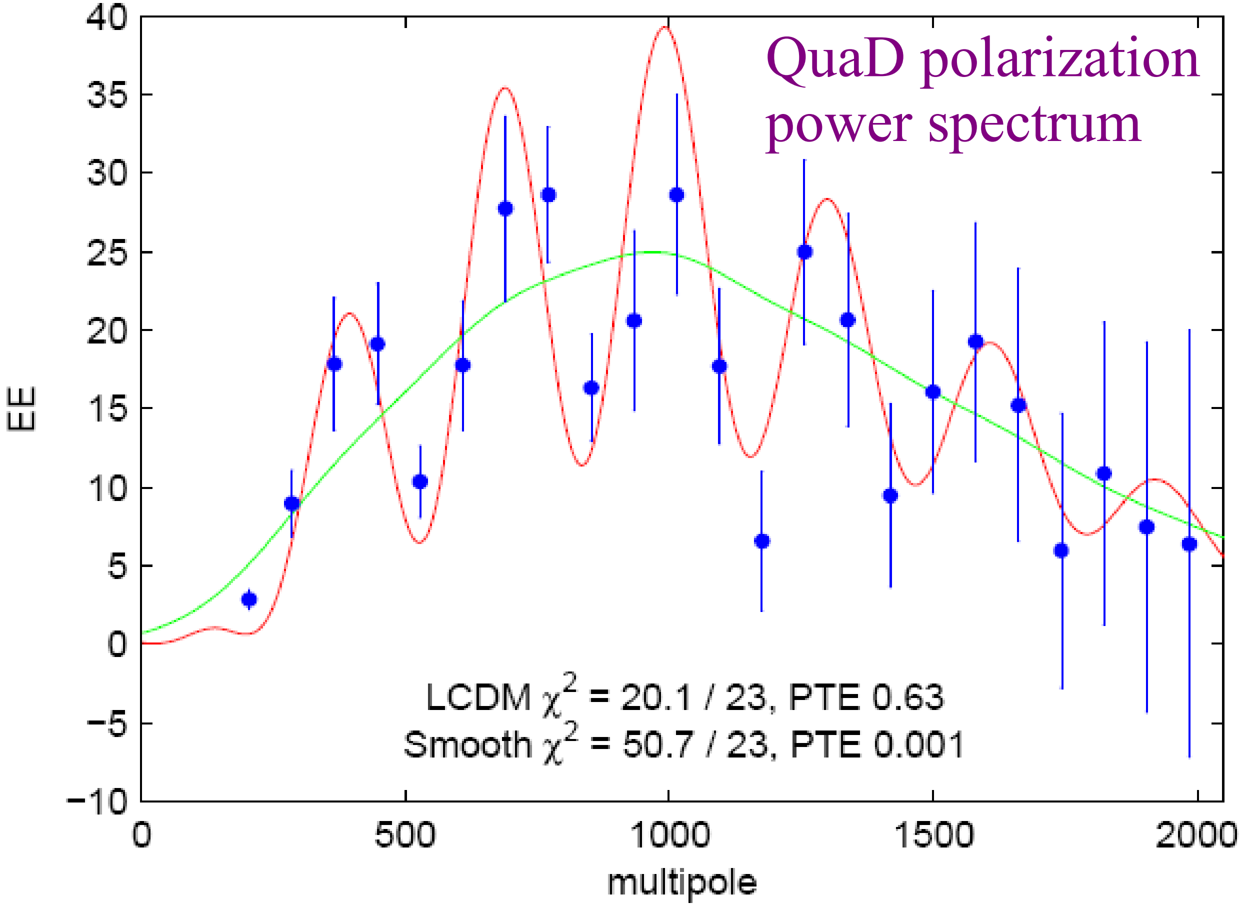

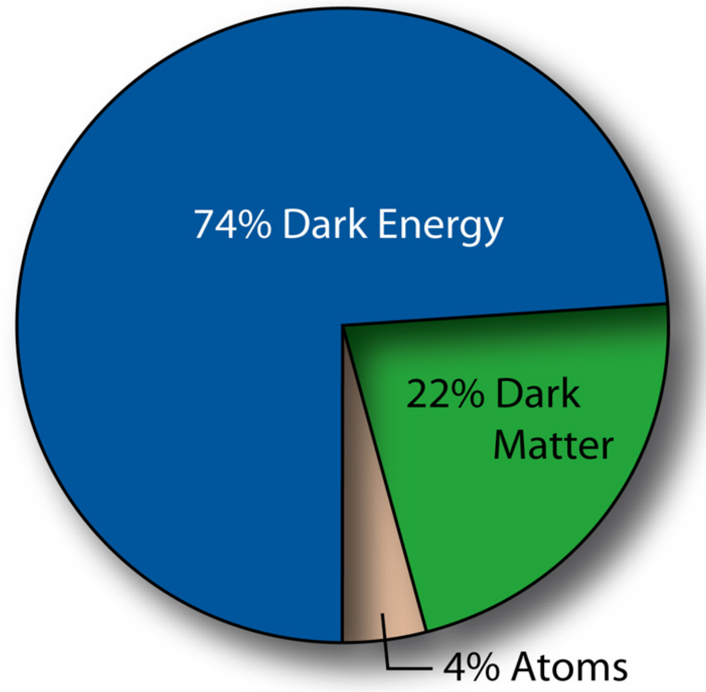

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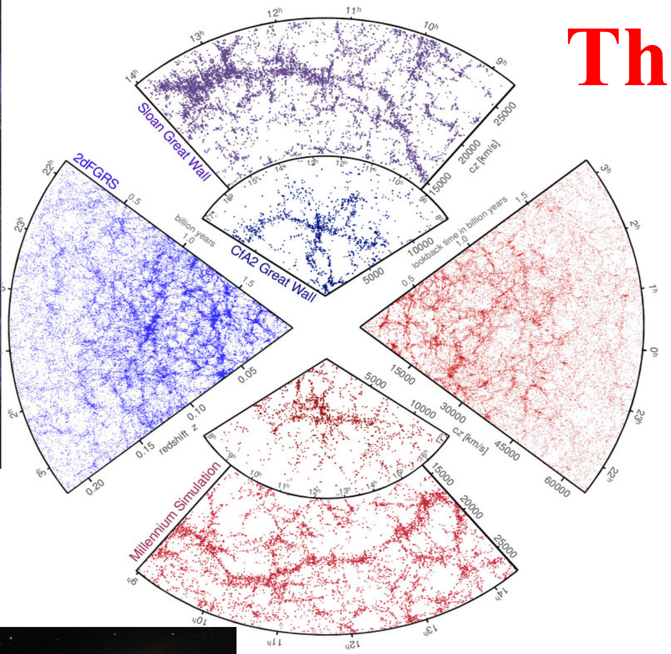
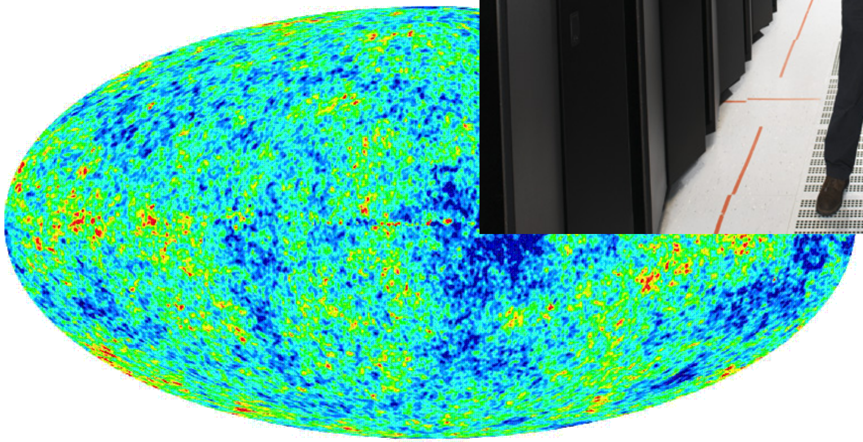
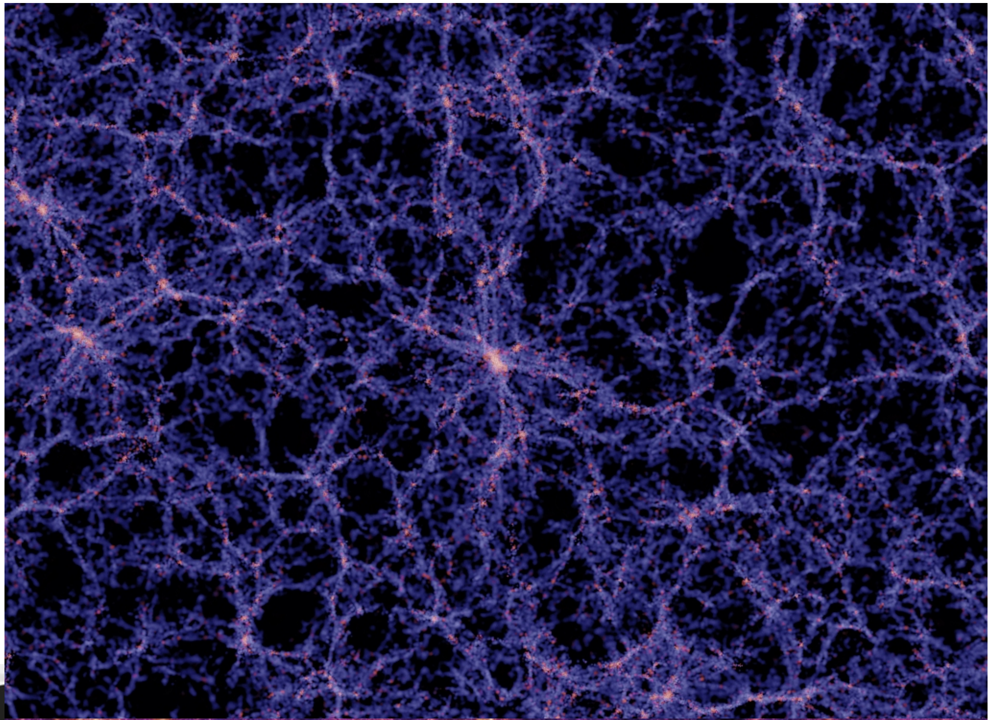
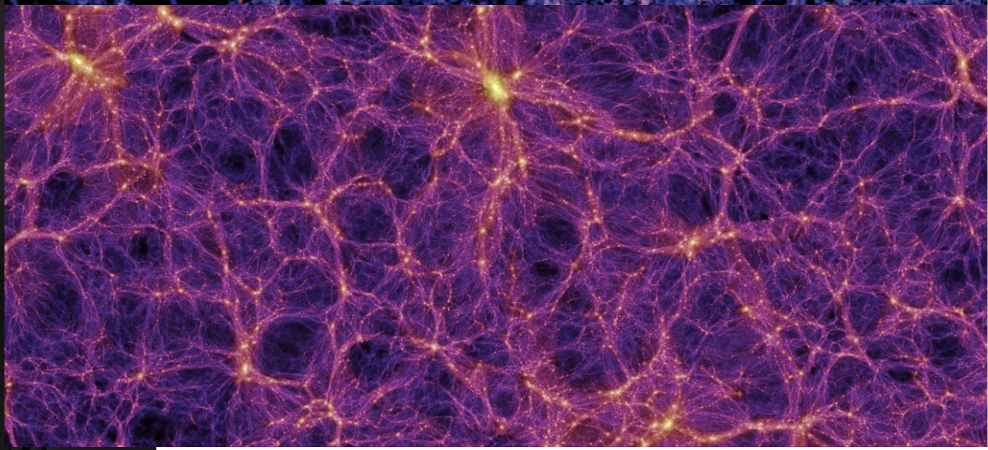
The disk formation problem





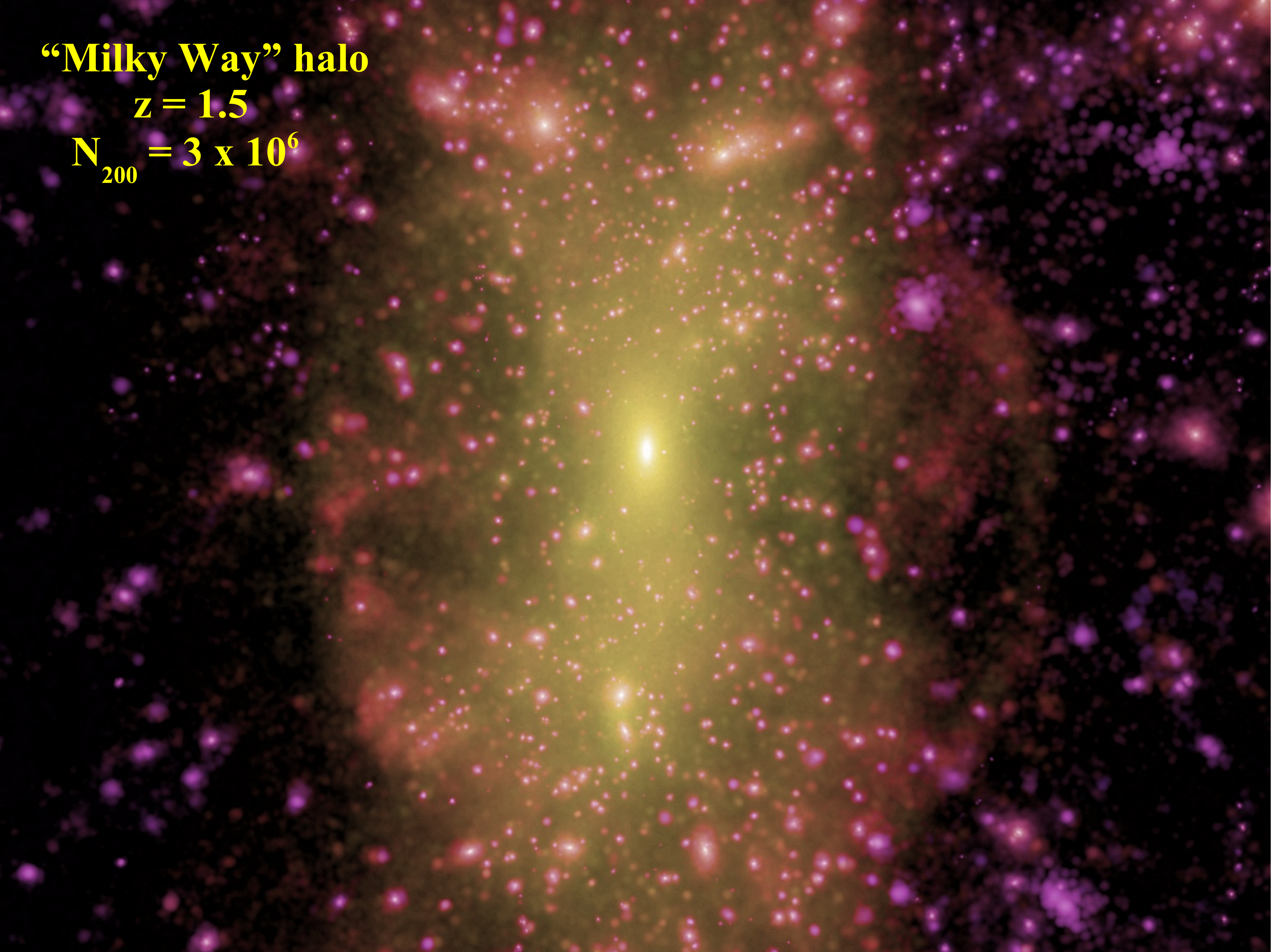




Structure formation in the Dark Matter

- Structure growth on large scales

- The formation of a “Milky Way” halo

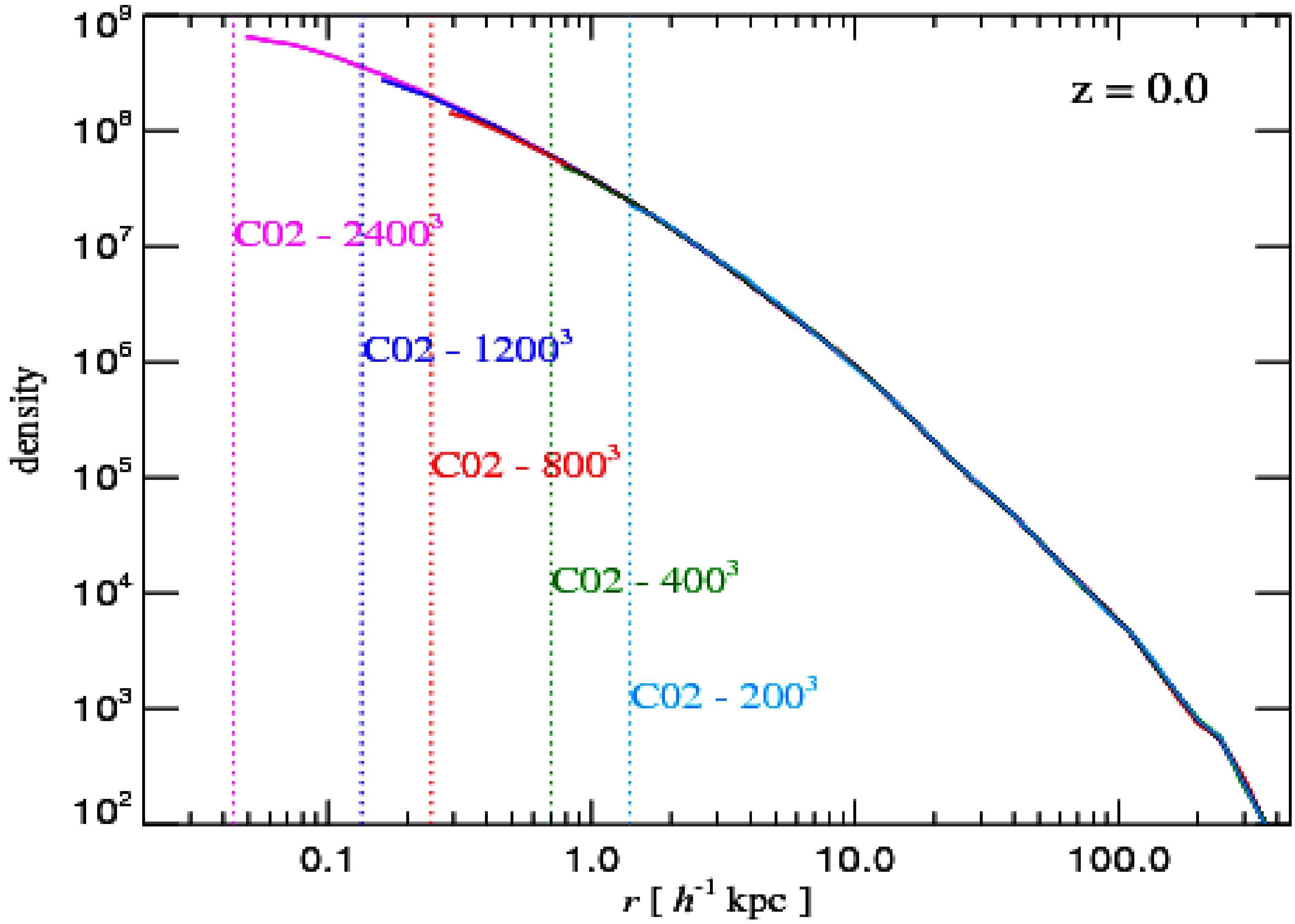

"Milky Way" halo
z = 1.5
$N_{200} = 3 \times 10^6$


"Milky Way" halo
z = 1.5
N200 = 94 x 10^6


"Milky Way" halo
z = 1.5
N_{200} = 750 x 10^6

Density profiles have converged!

Aquarius Project: Virgo Consortium 2008



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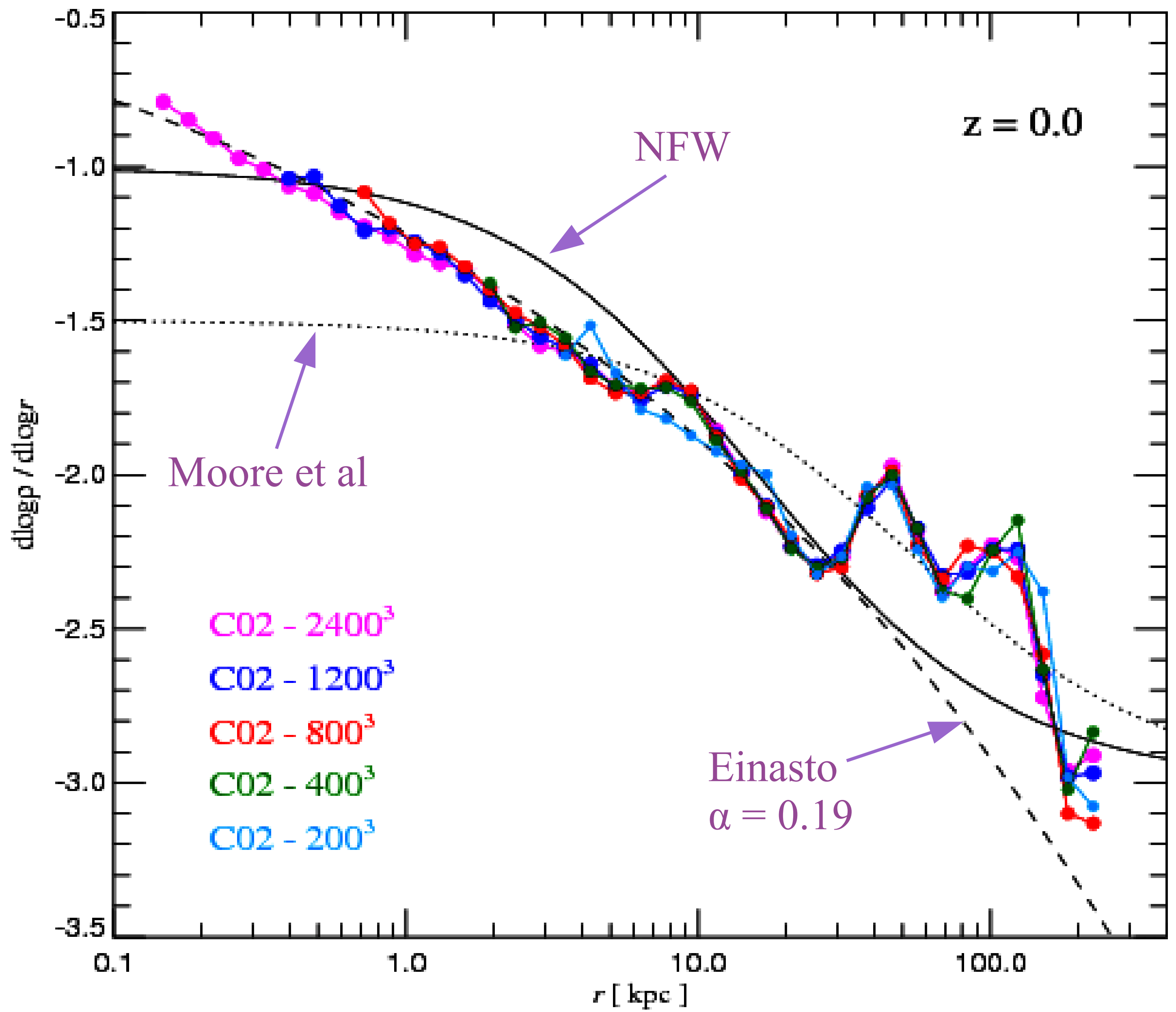
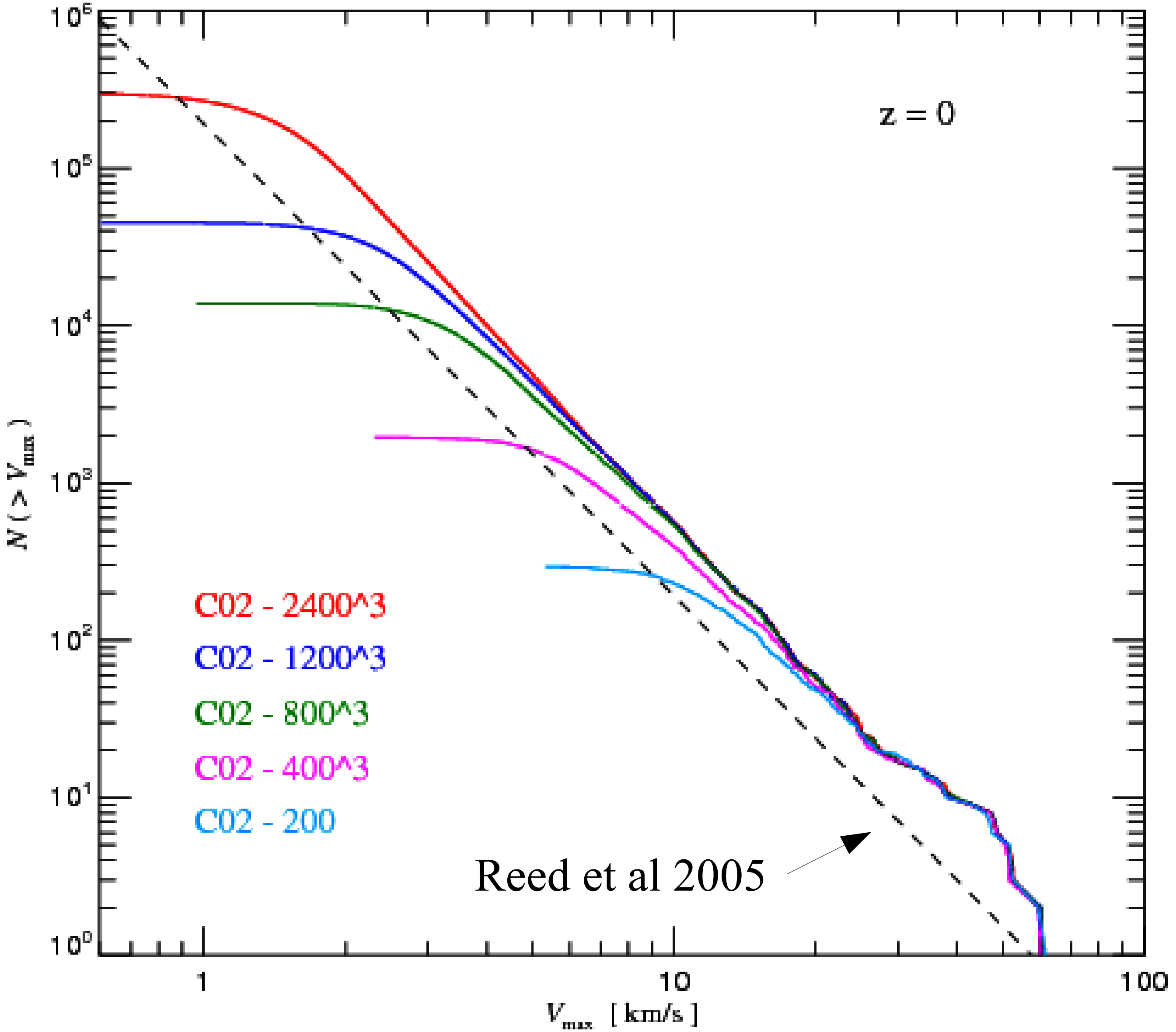


Substructure has also converged!

Aquarius Project: Virgo Consortium 2008



Substructure has also converged!

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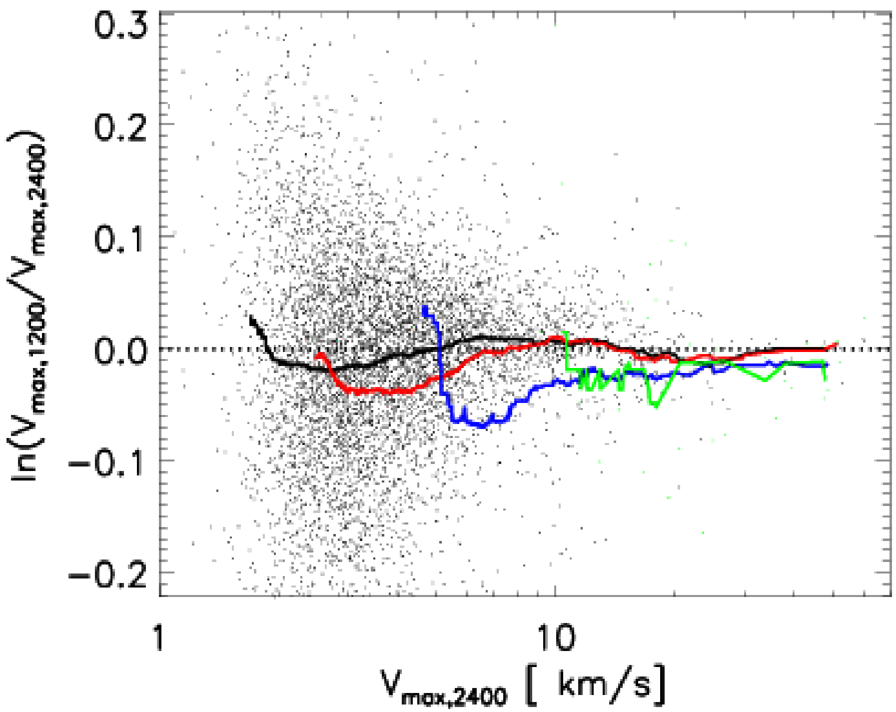
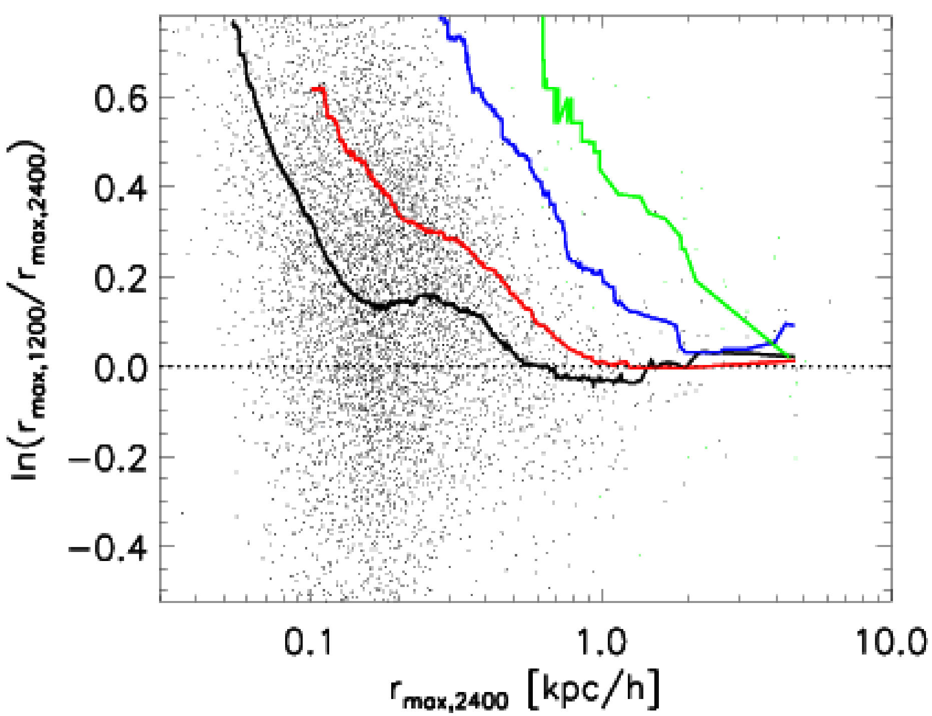


Convergence in the size and maximum circular velocity for individual subhalos cross-matched between simulation pairs.



Biggest simulation gives convergent results for

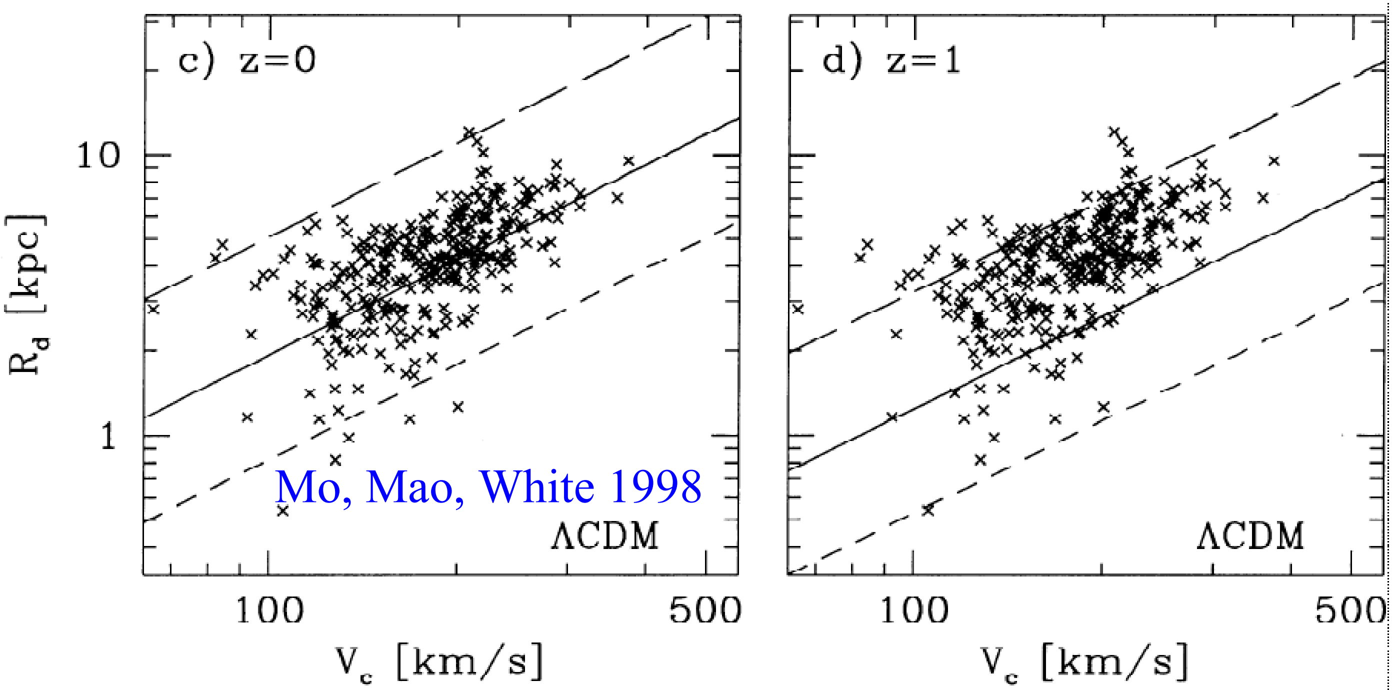
$$V_{max} > 1.5 \text{ km/s}$$

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

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

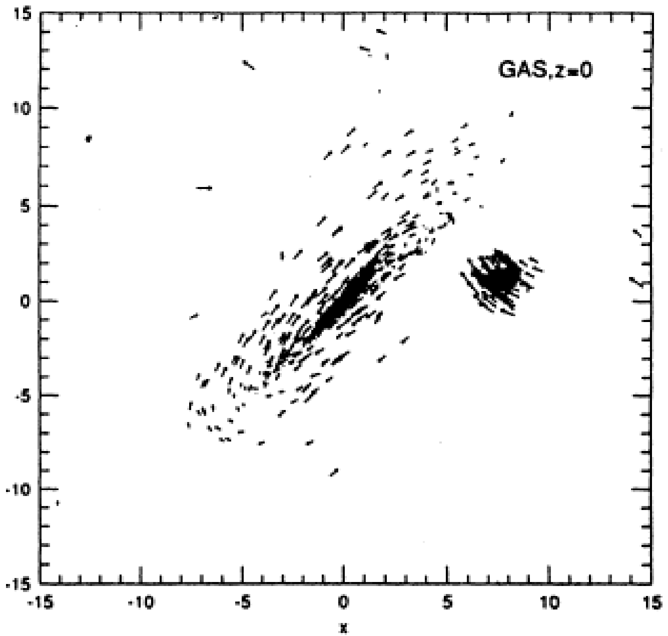
The simple model for disk formation

- Disk is a modest (~1/3) fraction of the available baryons, $f_b M_{halo}$
- The disk baryons have the same mean J/M as the halo DM
- The disk is exponential, stable and in equilibrium
- An NFW halo is adiabatically compressed by disk formation

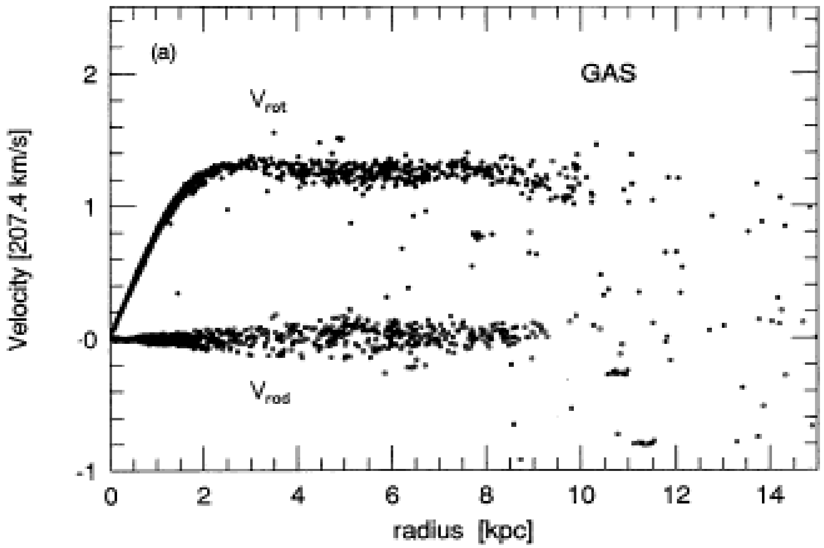


This results in disks of the right size if scaled to z=0, but in disks which are too small if they must form by z=1

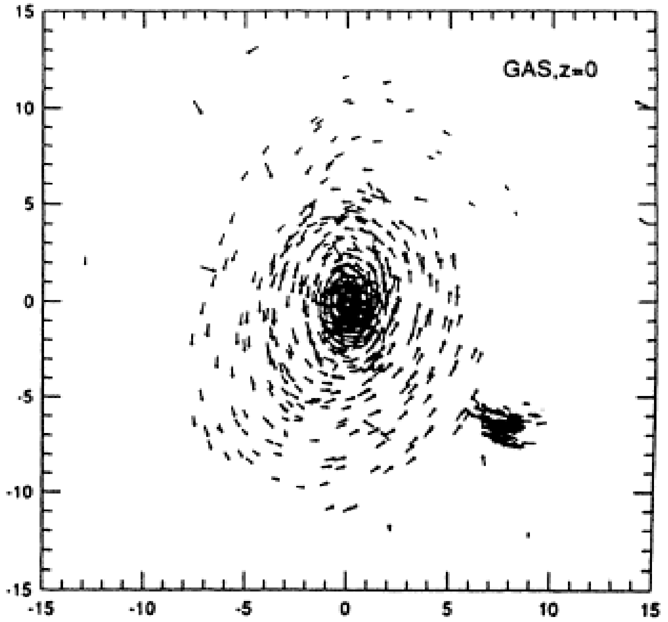
Simulations of cosmological disk formation



Cooling but no star formation or feedback

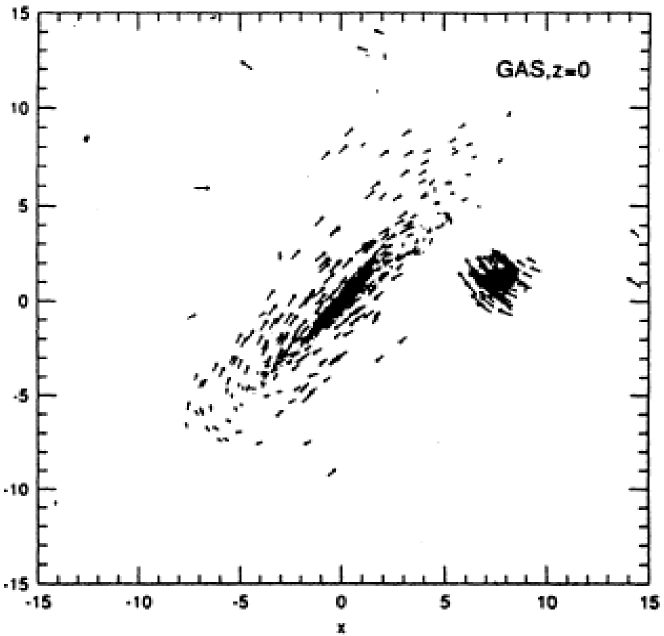


Navarro & White 1994



- Cold gas accumulates in a flat disk...

Simulations of cosmological disk formation



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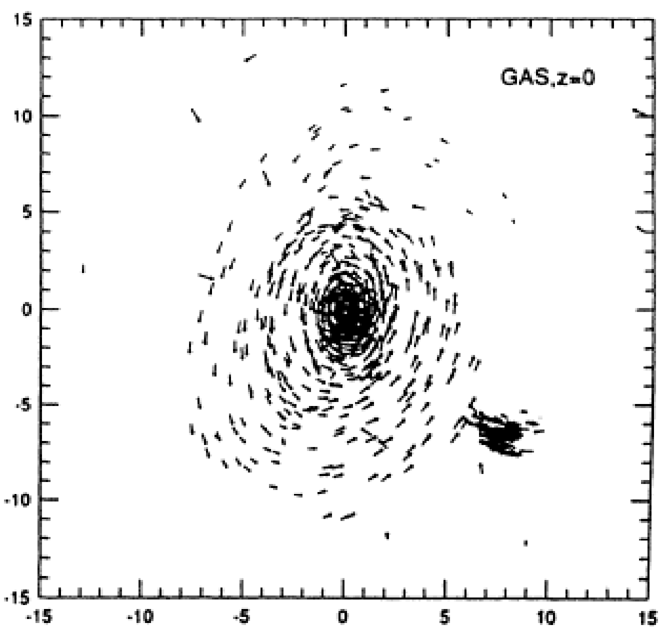

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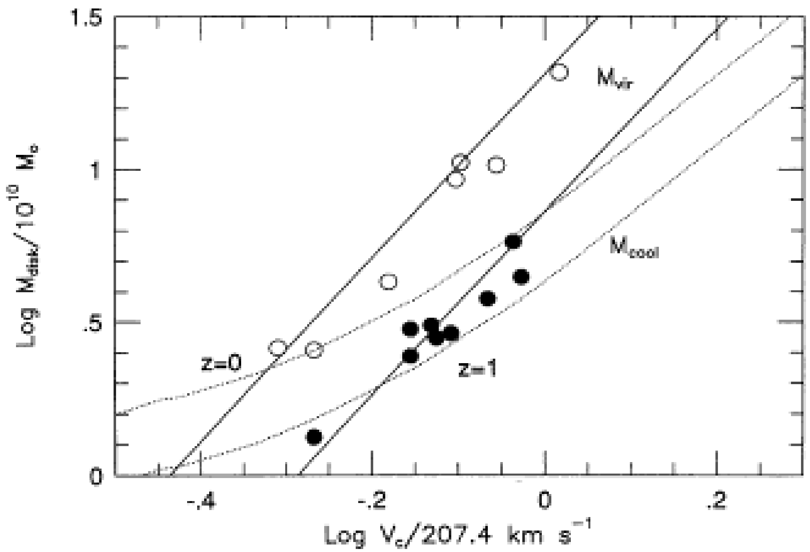
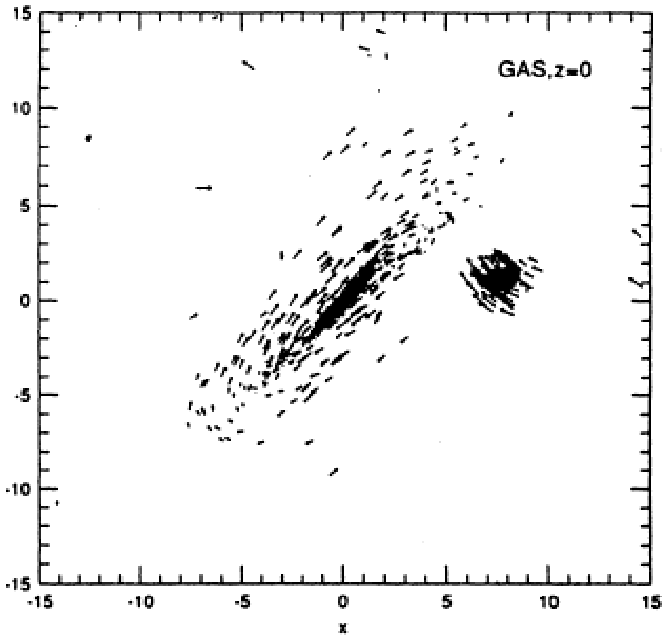


- Cold gas accumulates in a flat disk...
- ...made of most of the available baryons...

Simulations of cosmological disk formation



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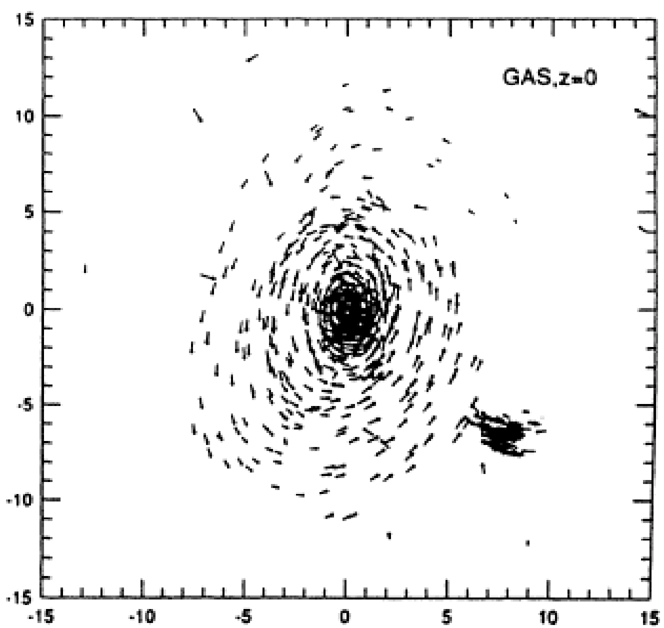

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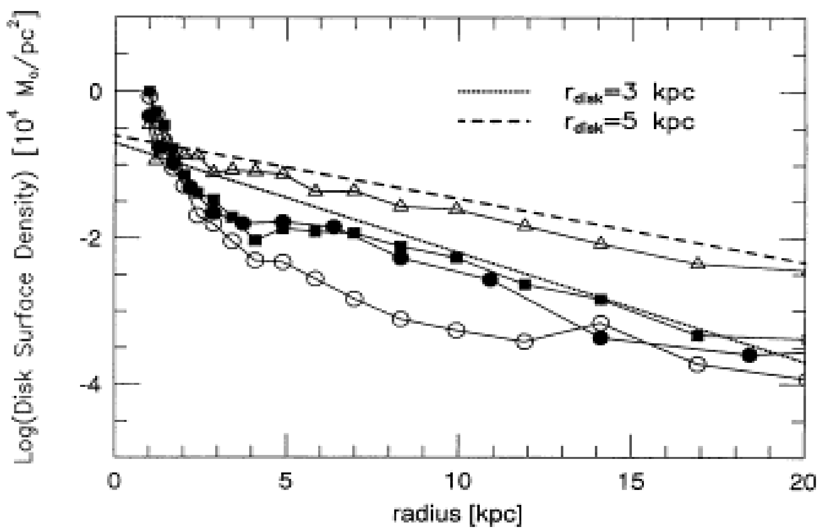
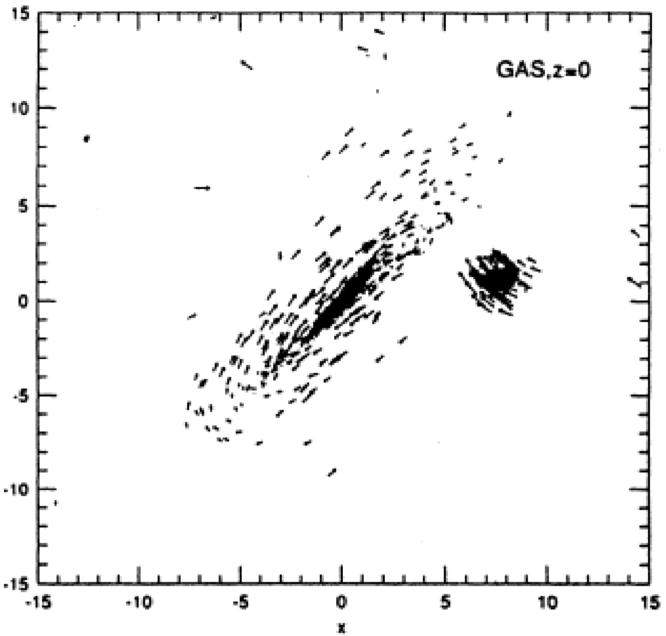


- Cold gas accumulates in a flat disk...
- ...made of most of the available baryons...
- ...with an "exponential" density profile...

Simulations of cosmological disk formation



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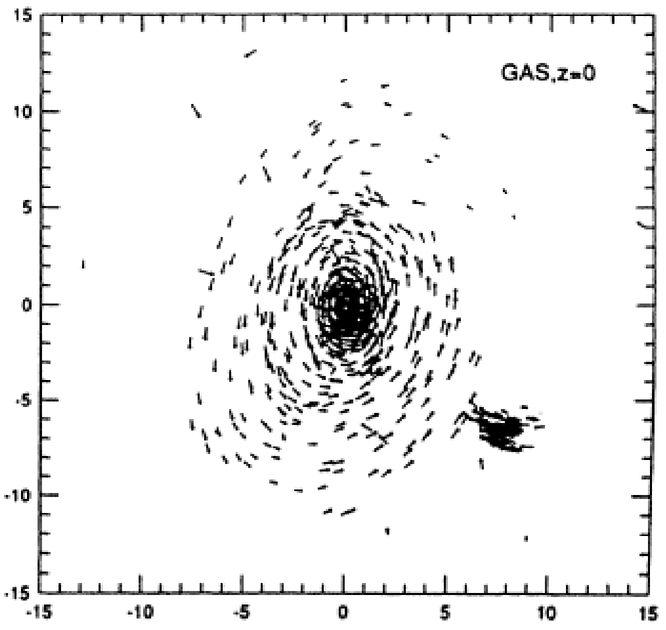

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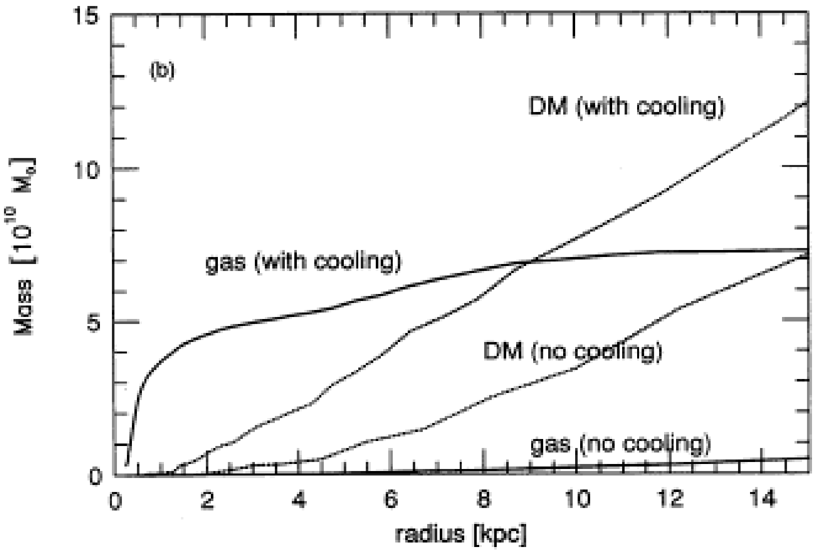
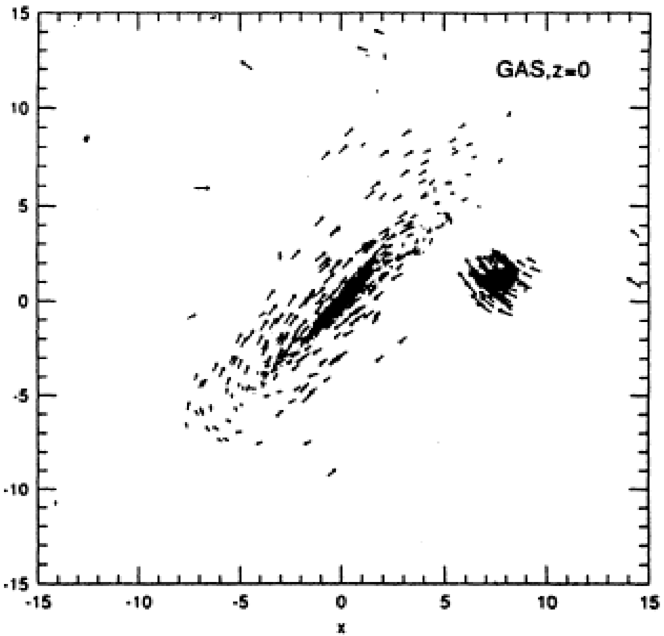


- Cold gas accumulates in a flat disk...
- ...made of most of the available baryons...
- ...with an "exponential" density profile...
- ...dominating the central potential...

Simulations of cosmological disk formation



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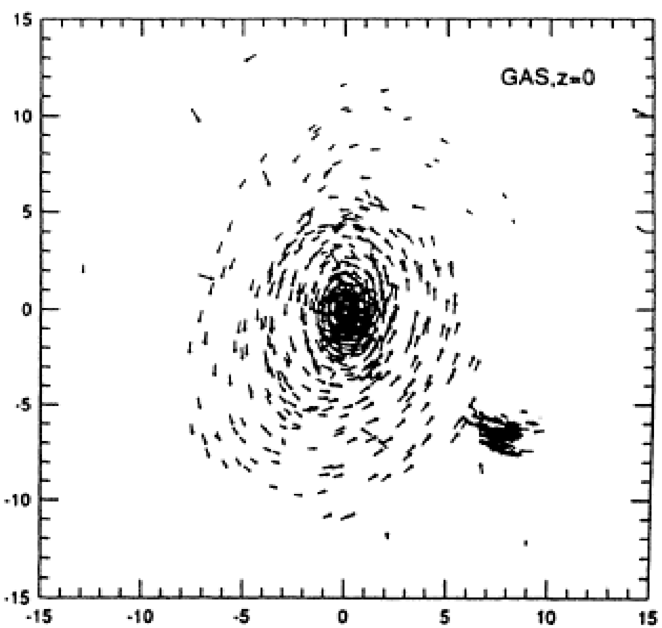

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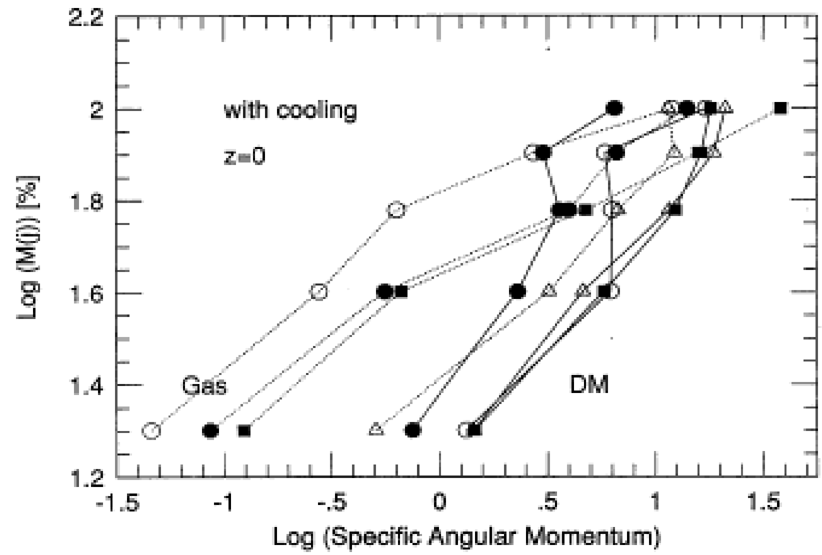


- Cold gas accumulates in a flat disk...
- ...made of most of the available baryons...
- ...with an “exponential” density profile...
- ...dominating the central potential...
- ...but with little angular momentum

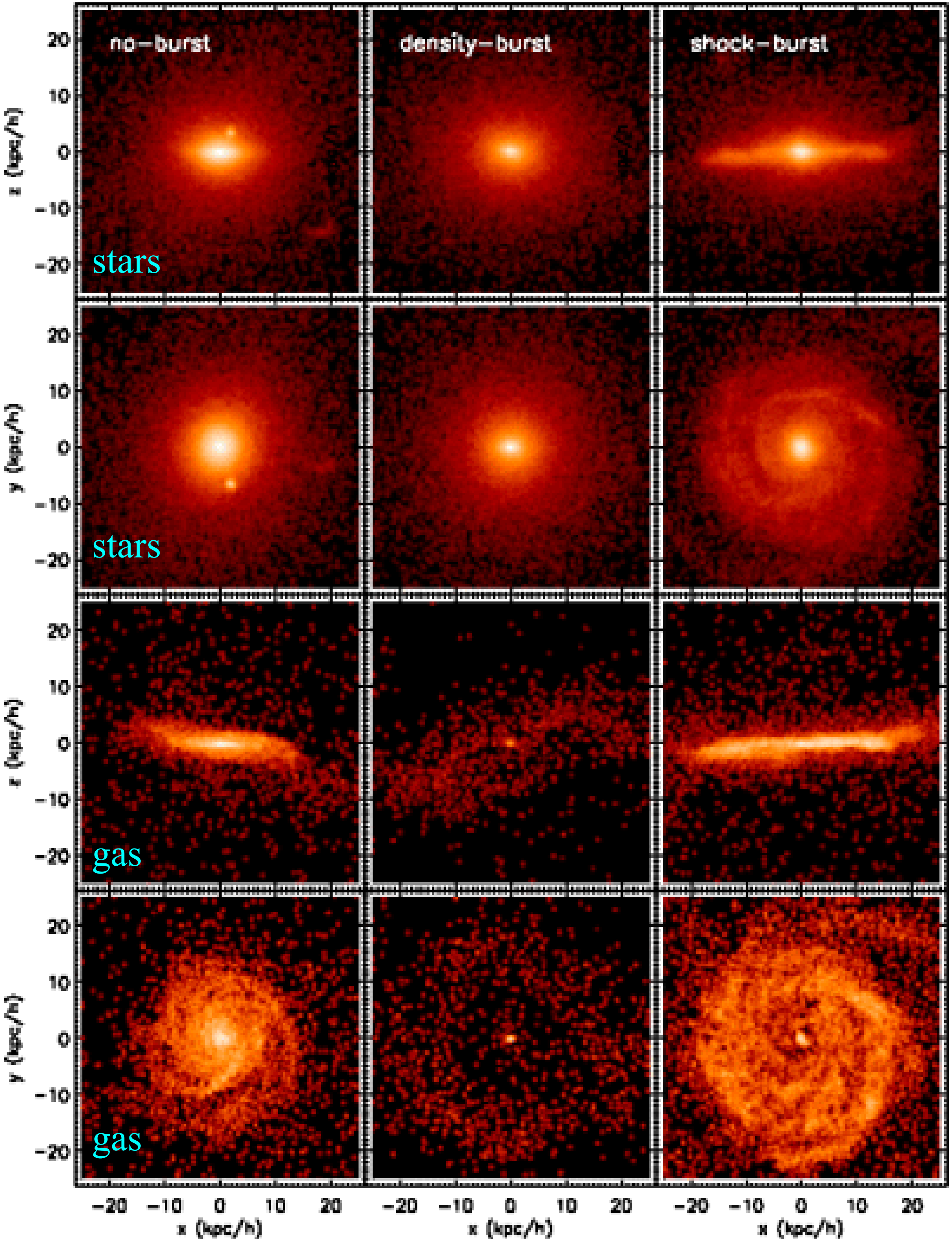
→ Feedback needed to reduce M and boost J

Simulations of cosmological disk formation

- Simulation of the Aquarius halo with strong feedback
  (Okamoto et al 2008)

- Simulation of the Aquarius halo with "N-body shop" feedback
  (Okamoto et al 2008)

- Simulation of another halo by the N-body shop themselves
  (Governato et al 2007)



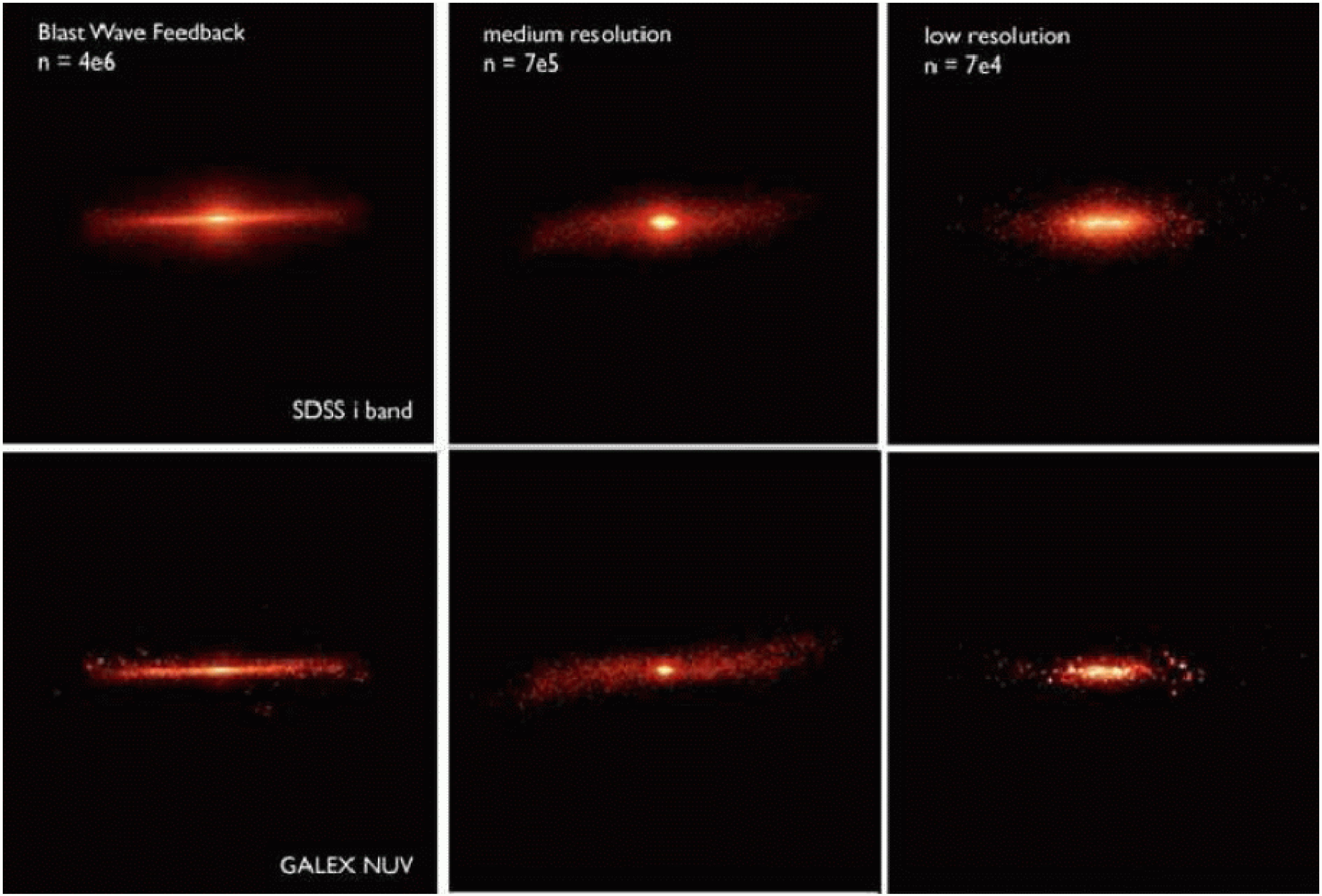
Varying feedback can change E → Sb!

Okamoto et al 2005

Changing the amount of feedback and where it occurs can completely alter the z=0 morphology

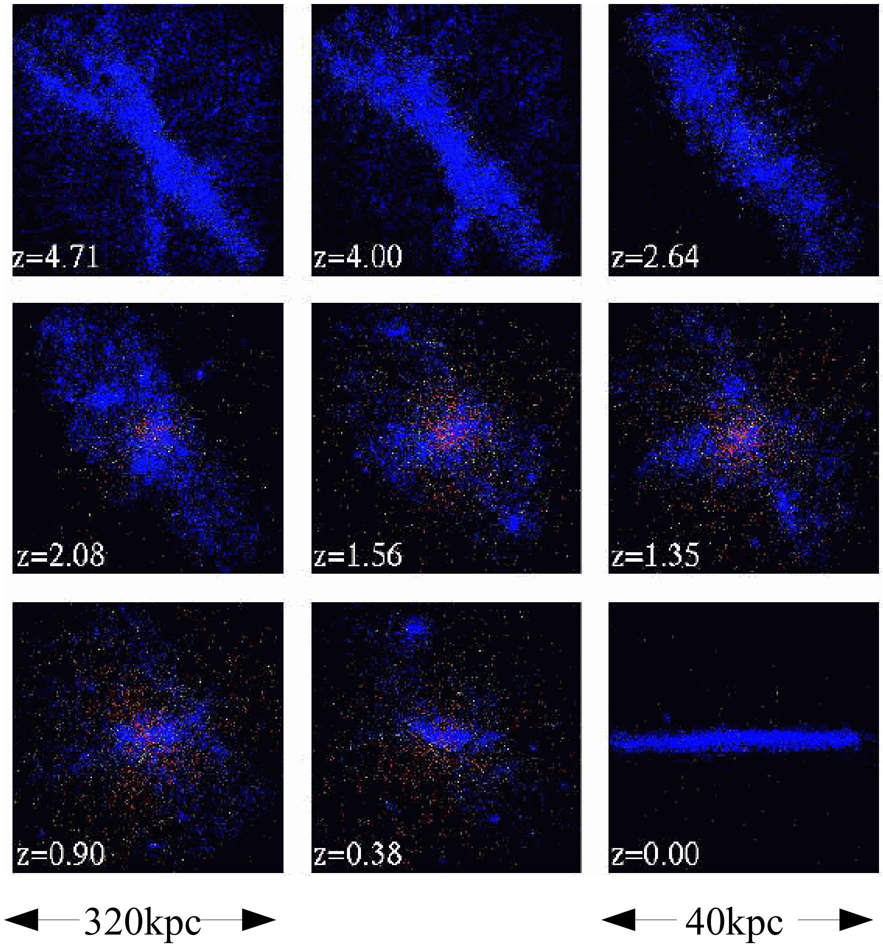
Varying resolution also changes B/T!

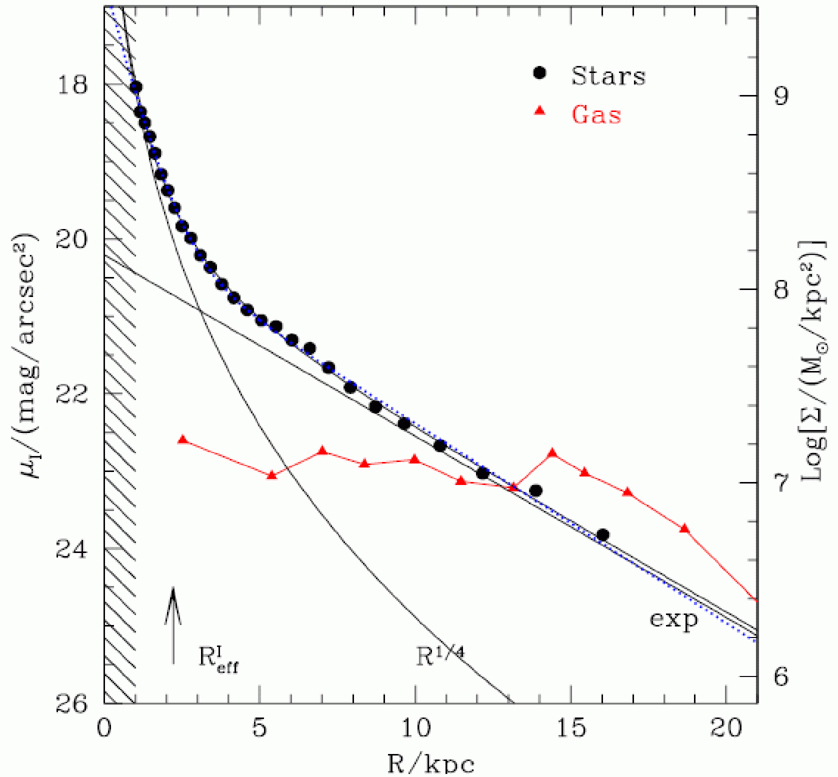
Governato et al 2007

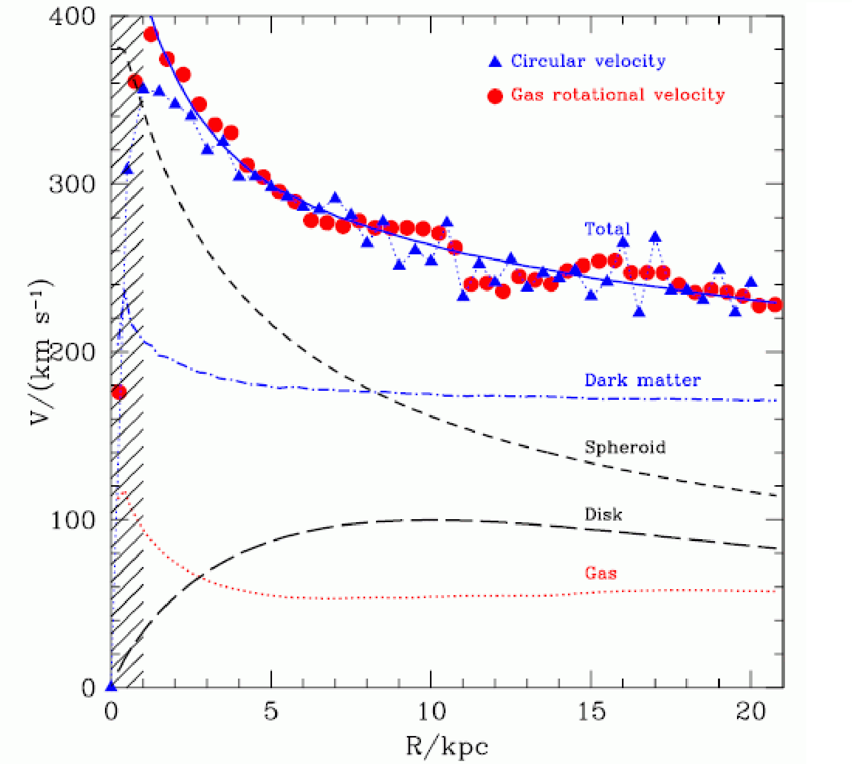


A careful look at a "spiral"

GAS



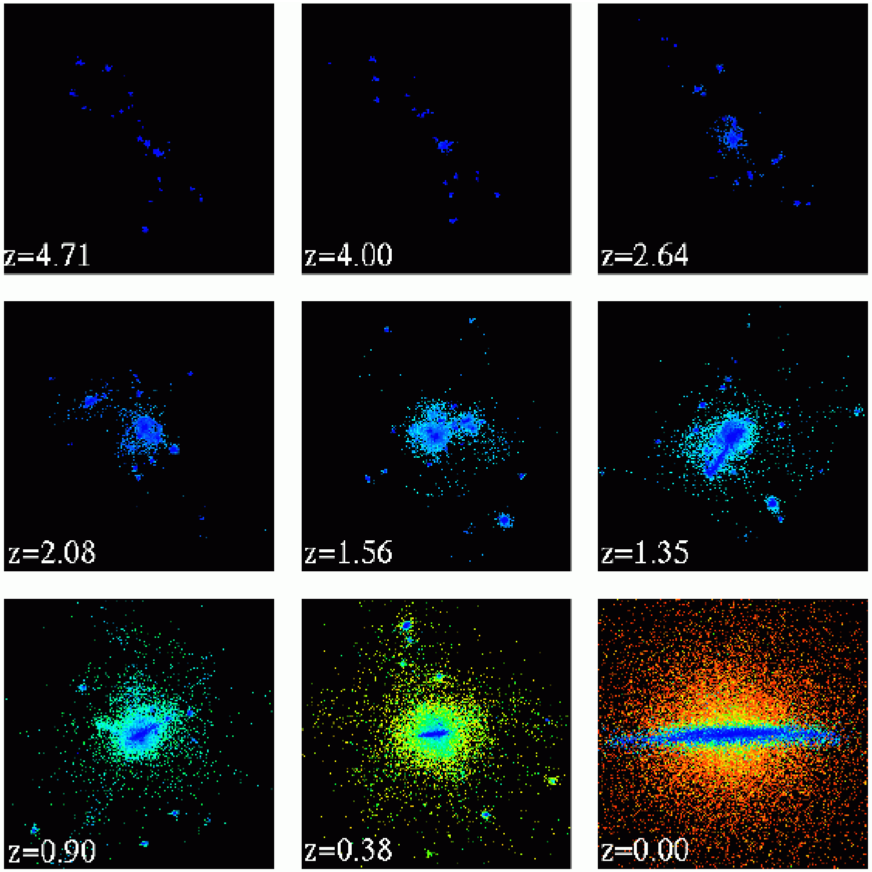




Abadi et al 2003

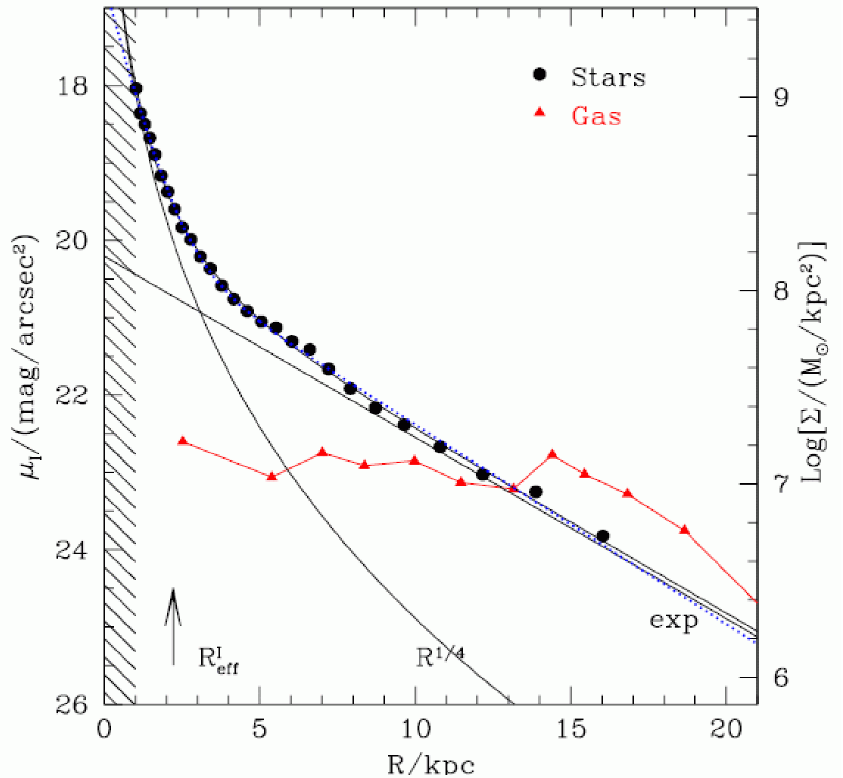
A careful look at a "spiral"

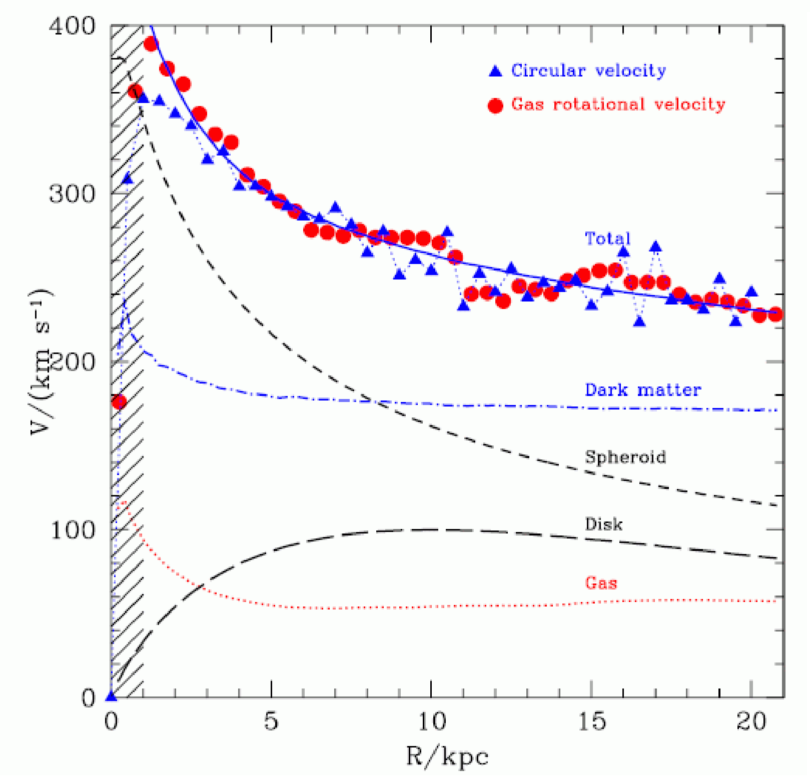
STARS



← 320kpc →

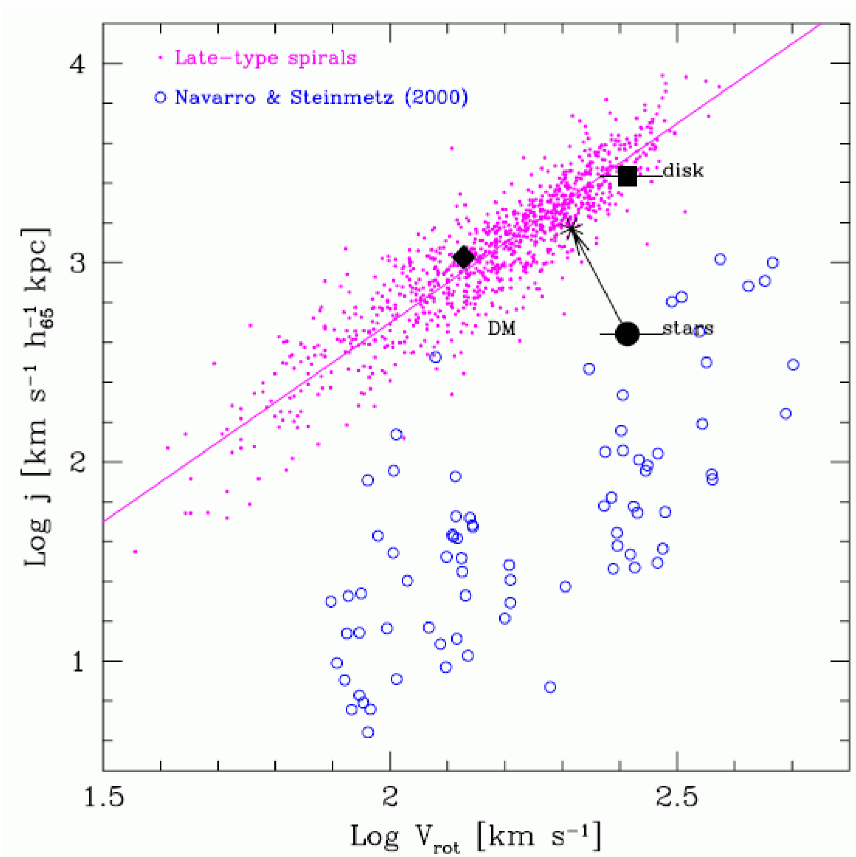
← 40kpc →



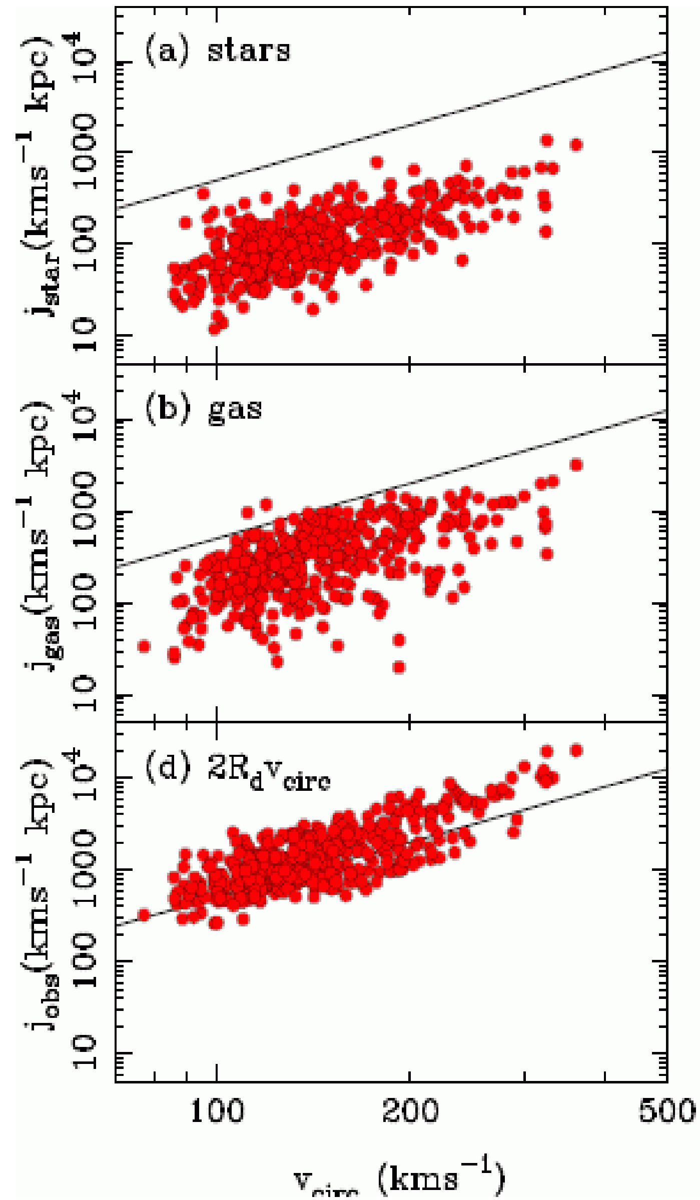


Abadi et al 2003

Too little angular momentum or too much bulge?

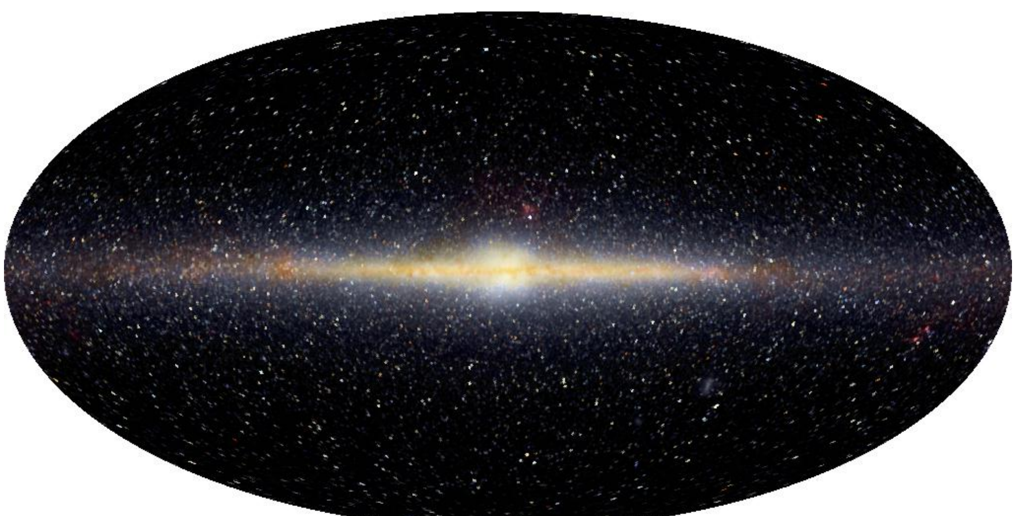


Abadi et al 2003



Croft et al 2008

Disk galaxies that ΛCDM (simulations) can't make



Disk formation issues in ΛCDM (simulations)

- Do real galaxies have (compressed) NFW halos?
- How do we make Sc and later galaxies?
- What differentiates barred and unbarred galaxies?
- Do we see secular evolution produce bulges?
- Can thin disks survive satellite bombardment?
- Are warps and lopsidedness reproduced?
- Is feedback the answer? How does it work? Does it leave chemical clues?
- What do we learn from high redshift data on disks?