Disk Galaxy Formation in a Cold Dark Matter Universe: A Test of the Paradigm

UVic

The Canadian Institute for Advanced Research
L'Institut canadien de recherches avancées

ALFRED P. SLOAN FOUNDATION
1934

Julio F. Navarro

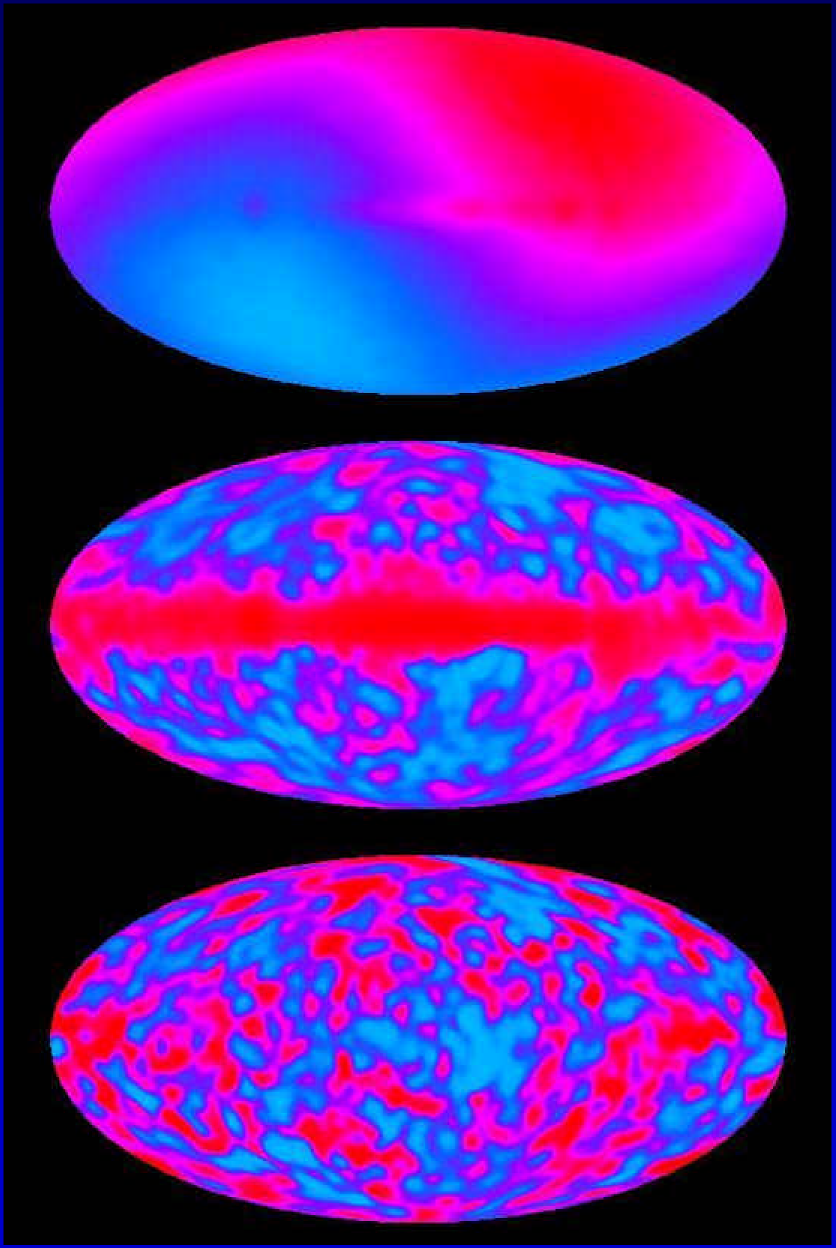
NASA

NSERC
CRSNG

The Paradigm

- Structure in the Universe originates from quantum fluctuations in the early universe that grew through a period of inflation and were subsequently amplified by gravity.

COBE Maps

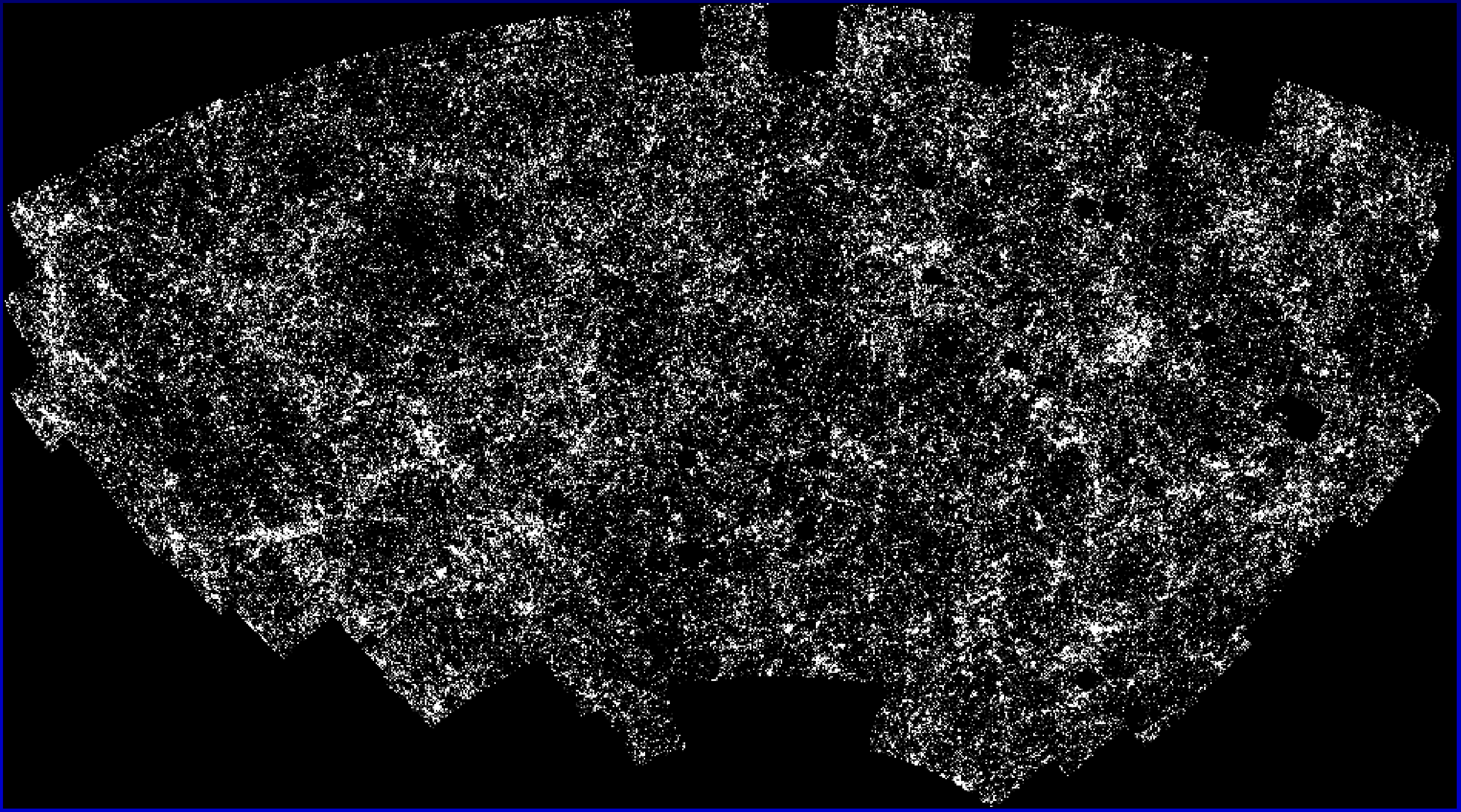


Our motion
through the universe

Dust in our own
Galaxy

Fluctuations in the
photon-baryon fluid
at z~1000
(1-part in 10^5)

The Large Scale Structure of the Universe



The APM galaxy survey

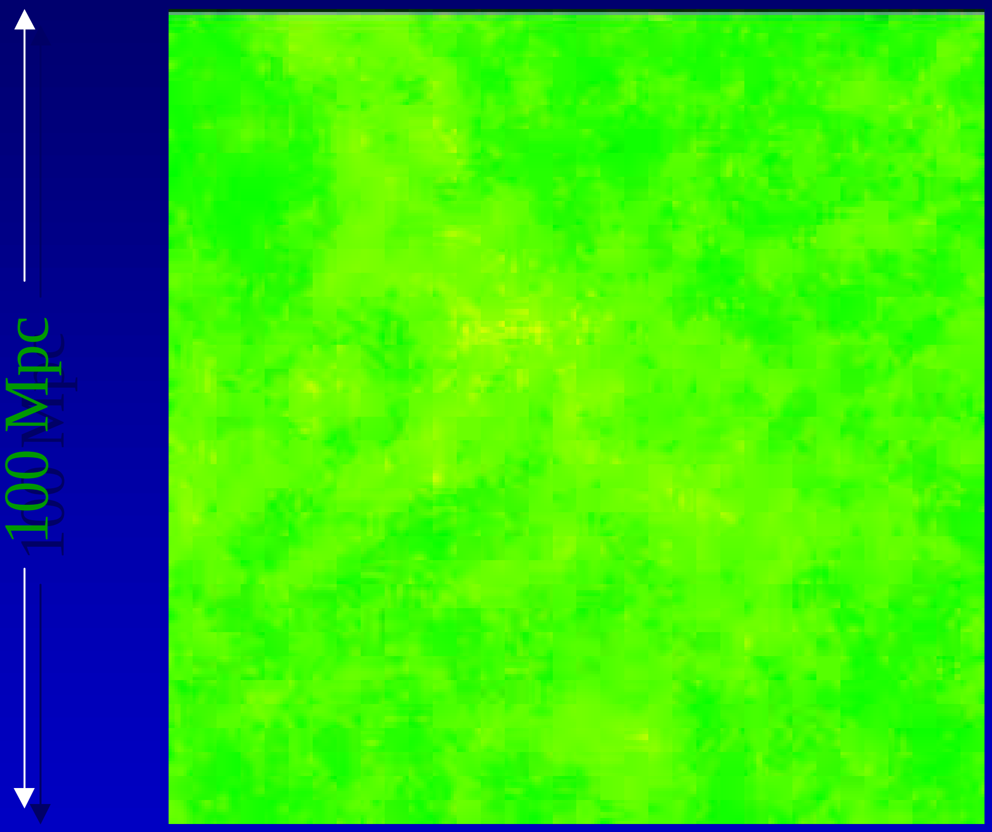
How do we get from the smooth universe of yesteryear to the highly structured universe of today?

Answer: Gravitational Instability

- Overdense regions get more and more overdense as the universe expands.
- Underdense regions get more and more underdense as the universe expands.

We can try and simulate this...

Hierarchical Structure Formation



Need
(non-baryonic)
dark matter!

Courtesy of The Virgo Collaboration

The “Concordance” Model

- The geometry of the Universe is flat (W_{tot}**=1**).
- Ordinary matter (baryons) contribute less than about 4% (W_{b}**~0.04**) of the energy density required for this. (Big Bang nucleosynthesis)
- ‘Dark’ matter contributes about 30% (W_{M}**~0.3**). This dark matter is contributed by some WIMP, and behaves as a **cold, collisionless** fluid.
- The other 70% (W_{L}**~0.7**) comes from a cosmological constant-like contribution. (SNIa)
- The universal expansion rate is

  ~ 65 (±10) km/s/Mpc

Successes of the Concordance Model

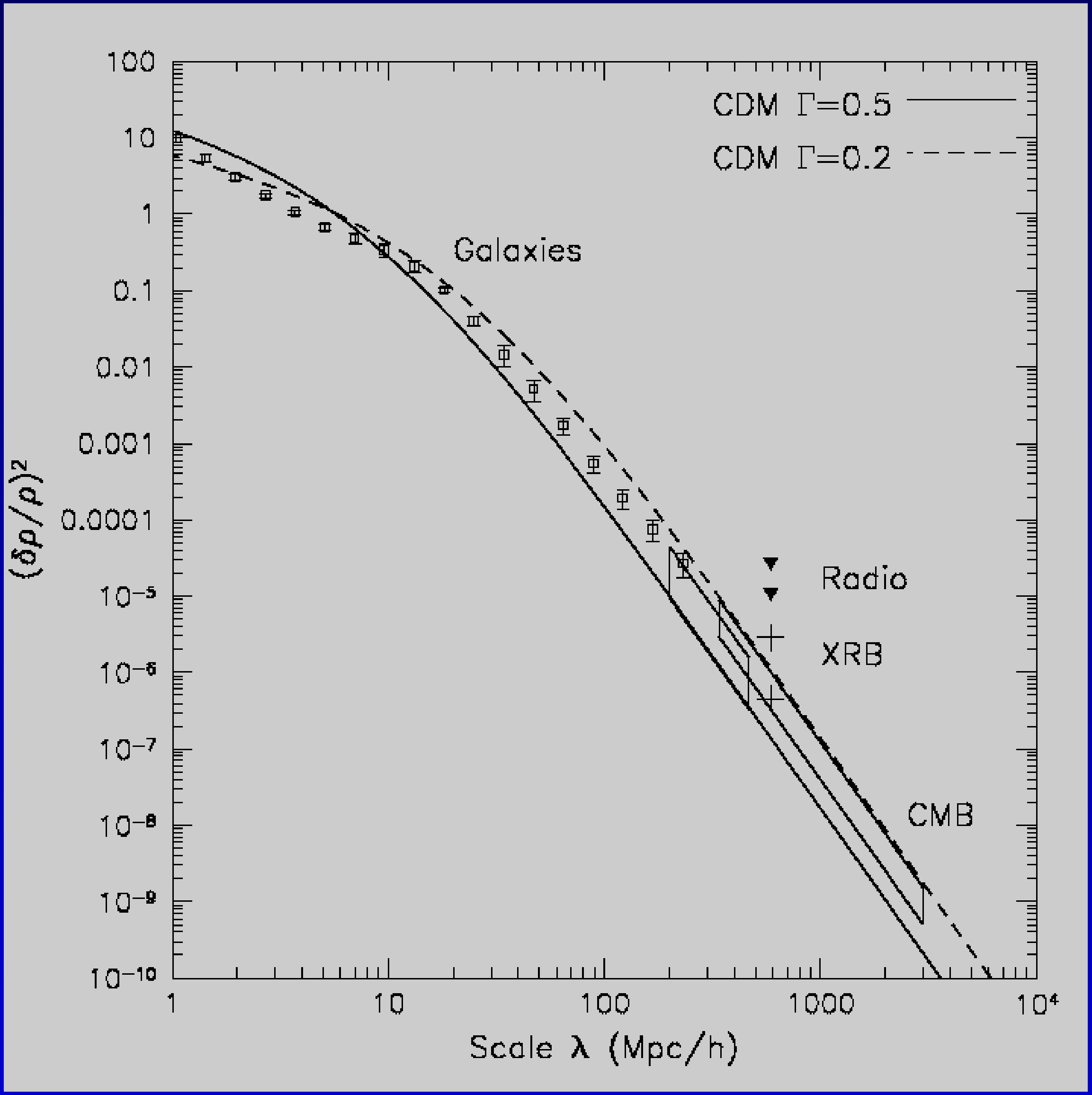
By matching these observations to the model…

- The world geometry inferred from SNIa and CMB measurements
- The extragalactic distance scale
- The primordial abundance of the light elements
- The amplitude of the CMB fluctuations

We can understand all this...

- The age of the universe
- The baryonic mass fraction of galaxy clusters
- The present-day abundance of massive galaxy clusters
- The shape and amplitude of galaxy clustering patterns
- The magnitude of large-scale coherent motions of galaxies
- Etc..

One example...



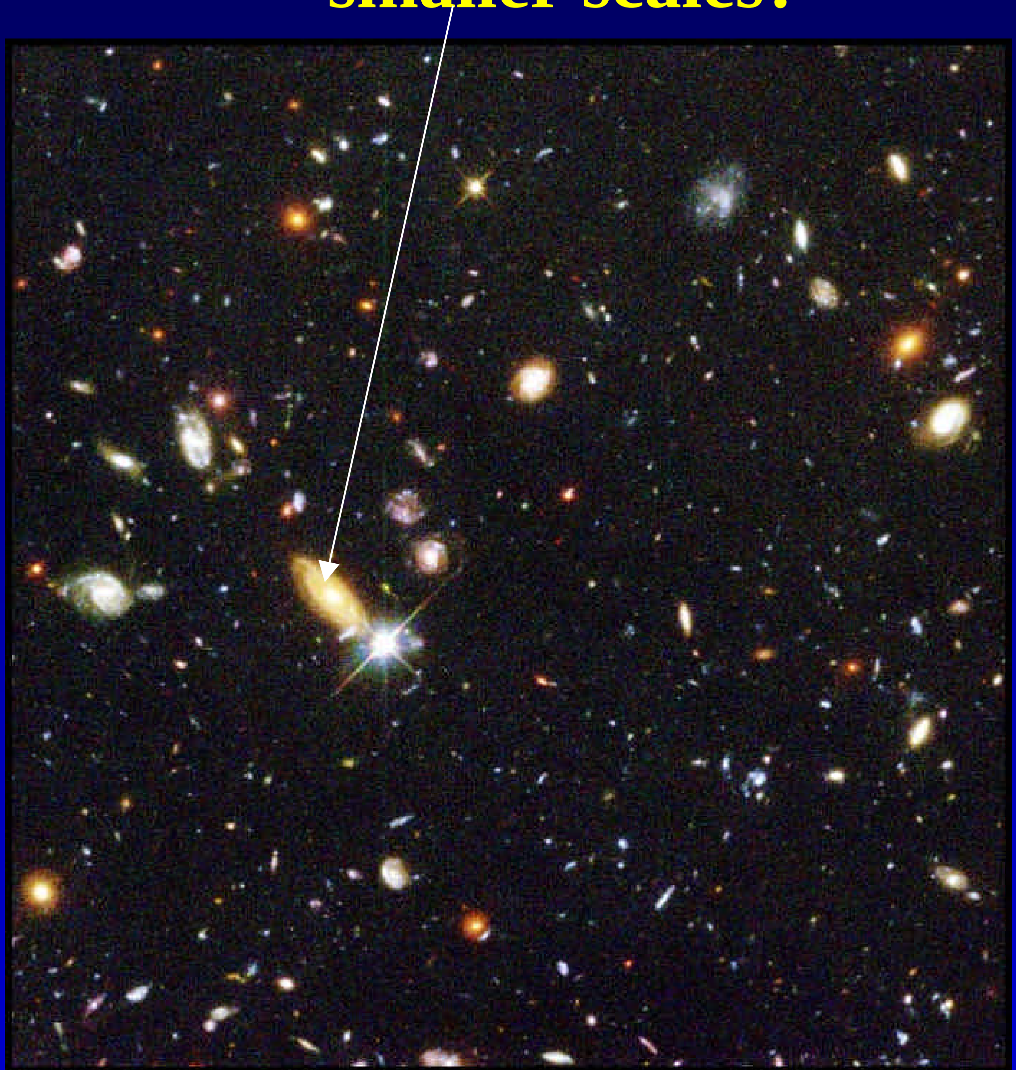
Density Fluctuations

Length Scale

Note that
the successes
of the model
are on scales
> 1 Mpc or so!

Wu, Lahav & Rees 1999

So the large scale structure seems OK, how about smaller scales?



Hubble Deep Field HST · WFPC2

PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

Disk galaxies: probes of the small scale structure of the Universe

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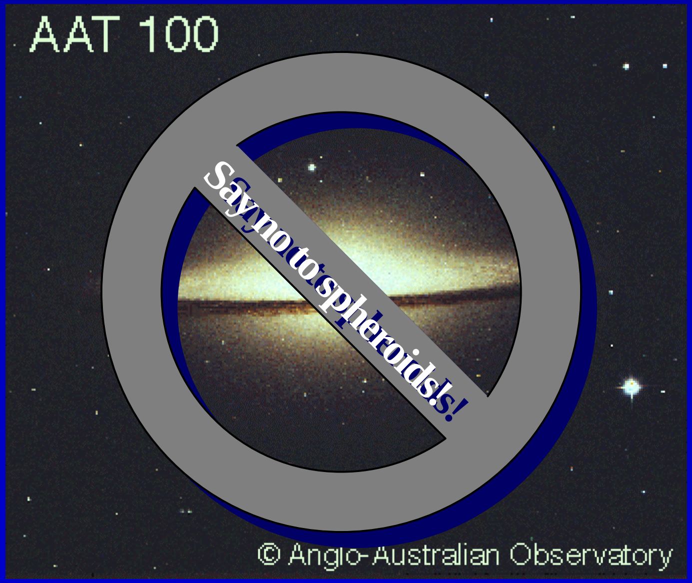
- Disk galaxies are thin, dynamically cold (fragile!) stellar systems supported by rotational motions.
- They are the most common type of galaxy in the Universe

© IAC/RGO/Malin



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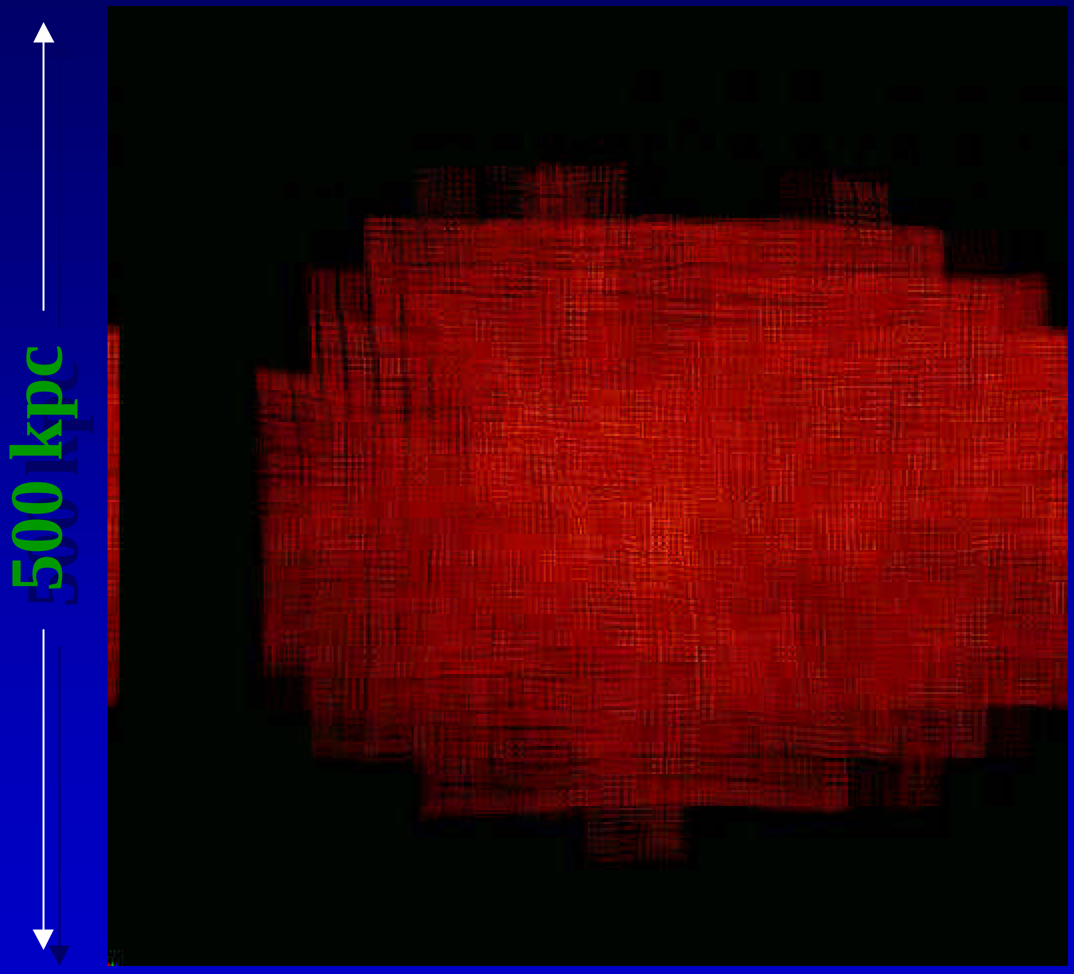
The formation of a galaxy-sized CDM halo

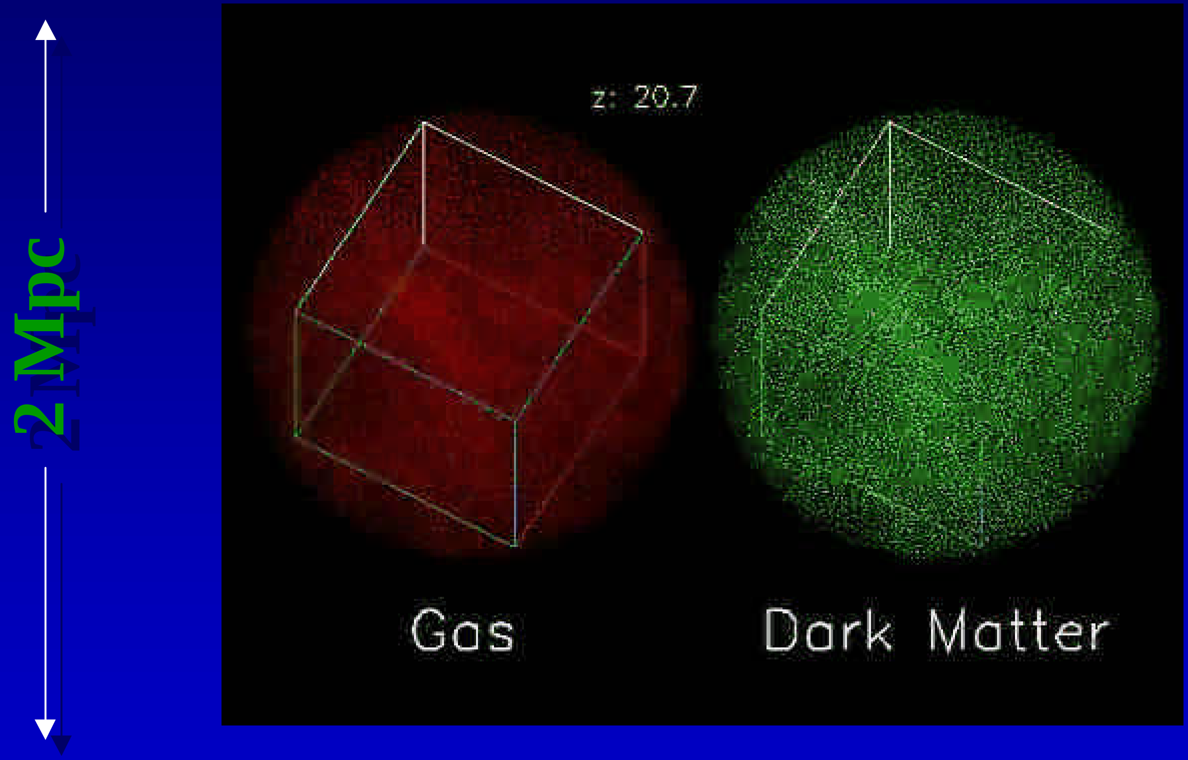


Dark Matter only

- A substantial fraction of the mass is accreted through mergers.
- Lots of satellites (“substructure”) remain at the present day
- Not a easy environment for the formation of disk galaxies!

Steinmetz & Navarro 2000

Hierarchical Galaxy Formation

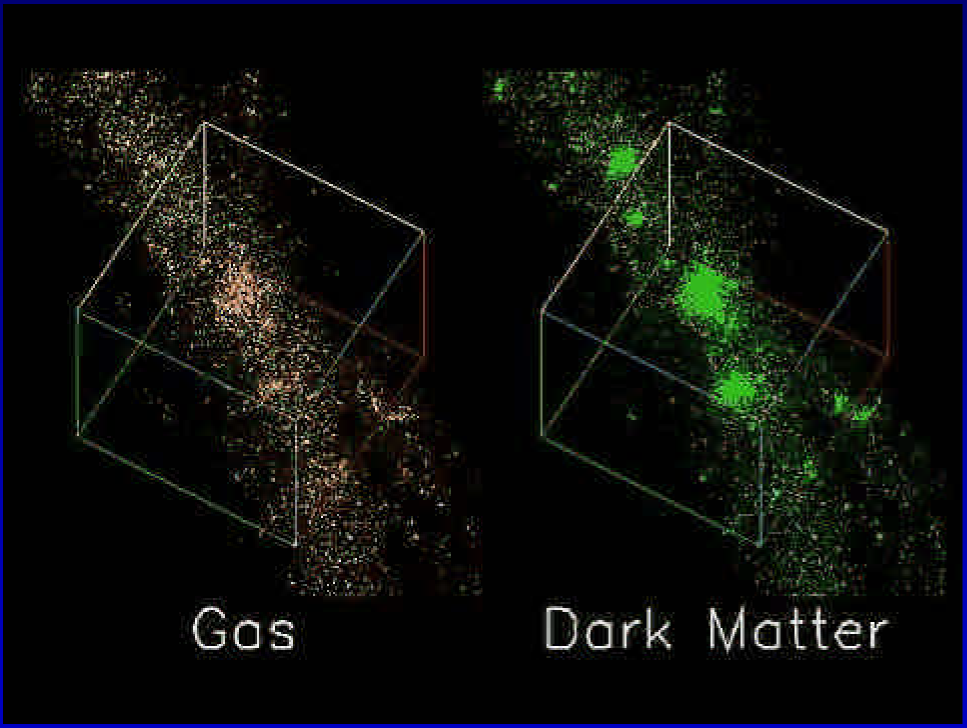


Galaxies form
by the collapse of
baryons within dark
halos.

Baryons dissipate
energy through
radiation and settle
into centrifugally
supported disks.

Steinmetz & Navarro 1997

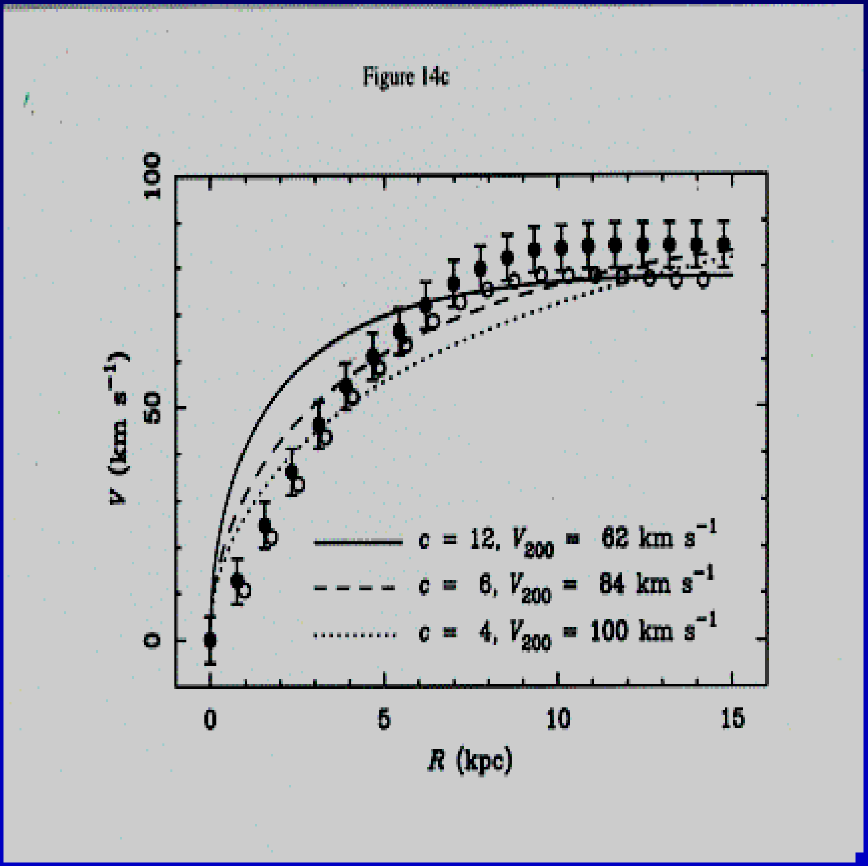
Disk Galaxies within Dark Halos



Steinmetz & Navarro 1997

Potential Problems for CDM (I):

- Cold Dark Matter halos are “cuspy”: i.e. the density increases monotonically towards the center. (At odds with rotation curves of low surface brightness galaxies?)

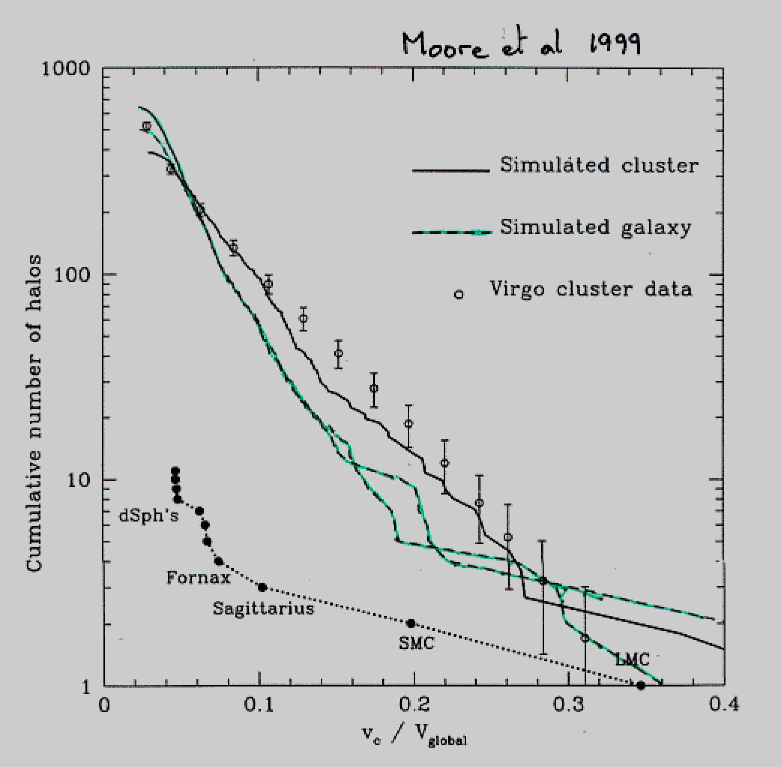


McGaugh & de Block 1998

Navarro, Frenk & White 1996
see also Moore 1994
Flores & Primack 1994

Potential Problems for CDM (II):

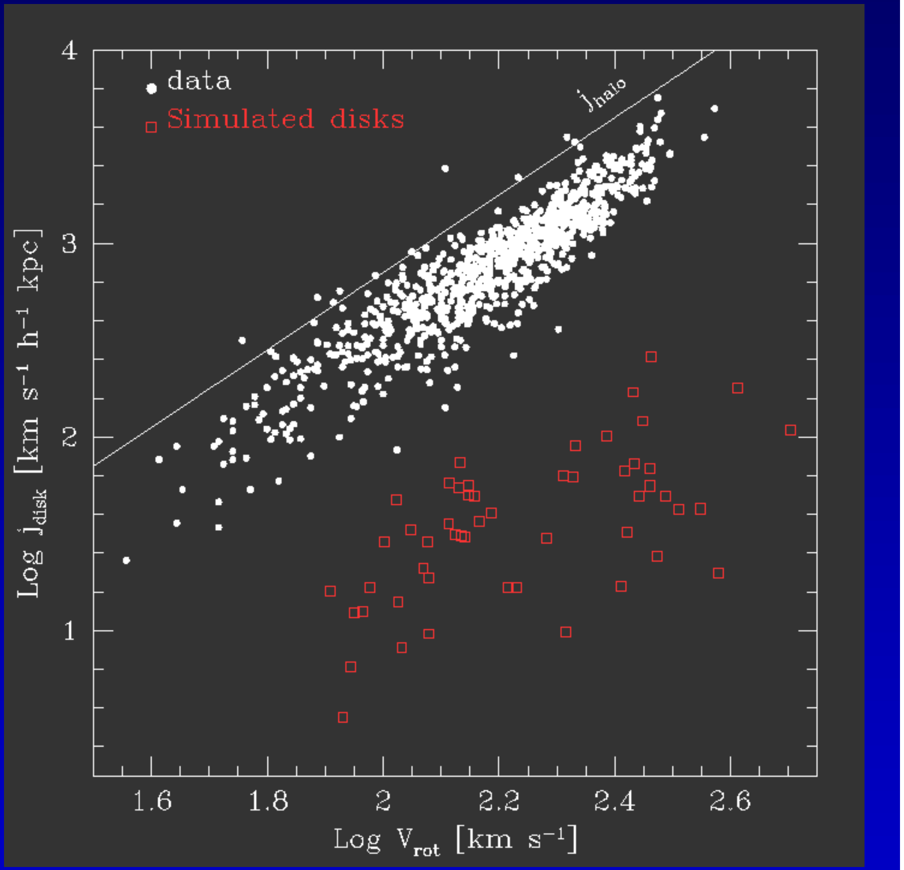
- CDM galaxy halos possess large amounts of “substructure”; several hundred satellites with circular velocities > 10 km/s. (At odds with the relatively few known satellite companions of the Milky Way?)



Moore et al 1999
Klypin et al 1999

Potential Problems for CDM (III):

- Cold Dark Matter halos are assembled through a sequence of merger events. (At odds with the angular momentum and thinness of stellar disks?)



Steinmetz & Navarro 1999

Steinmetz & Navarro 1999

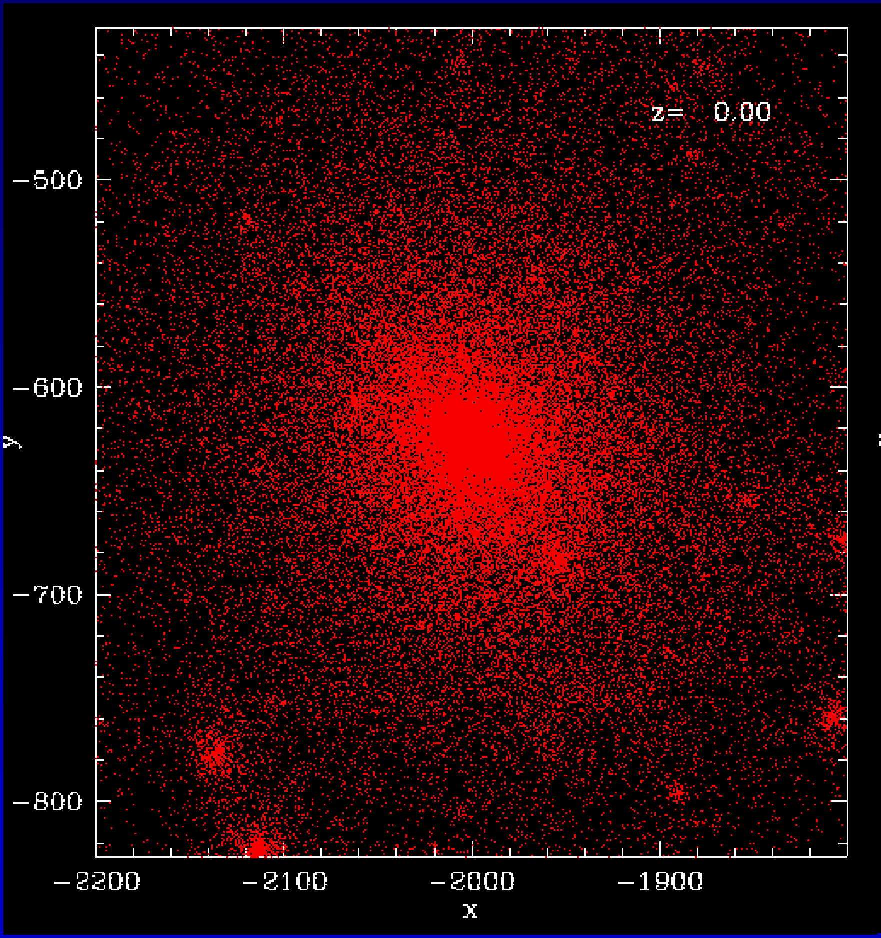
Are these fatal problems for CDM?

At least some theorists seem to think so. This has led to some radical proposals:

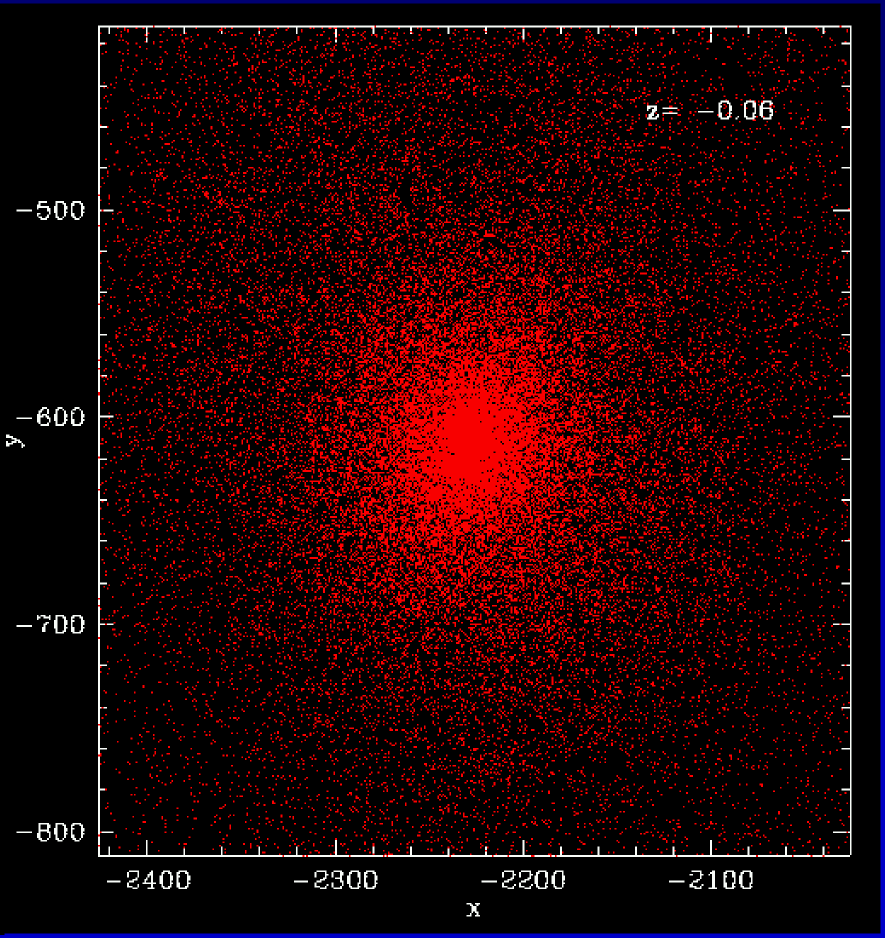
- Self-interacting dark matter
- Warm dark matter
- Self-interacting warm dark matter
- ‘Fuzzy’ dark matter
- Other combinations of the above…

How does this help? For example...

Warm vs Cold Dark Matter

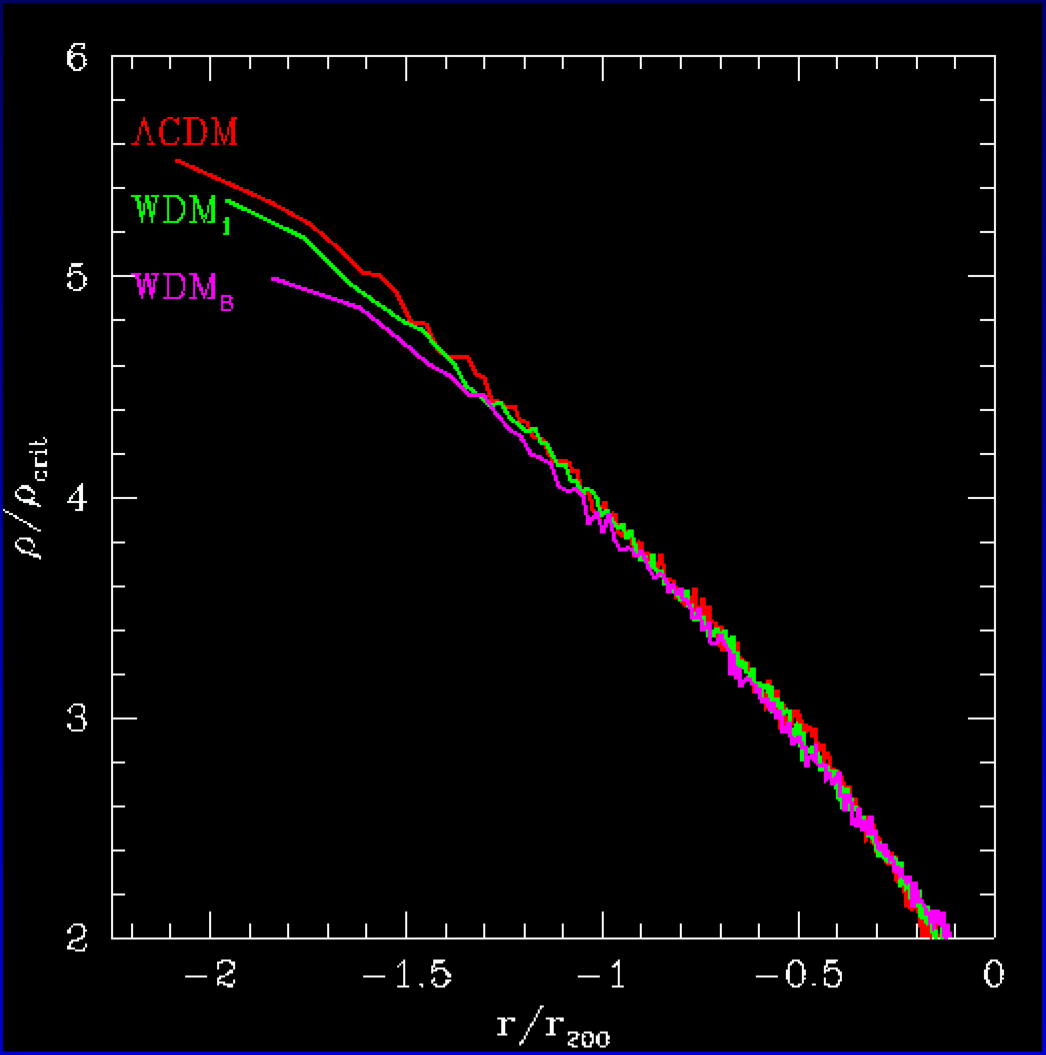


Cold



Warm

Density Profiles: Cold vs Warm Dark Matter



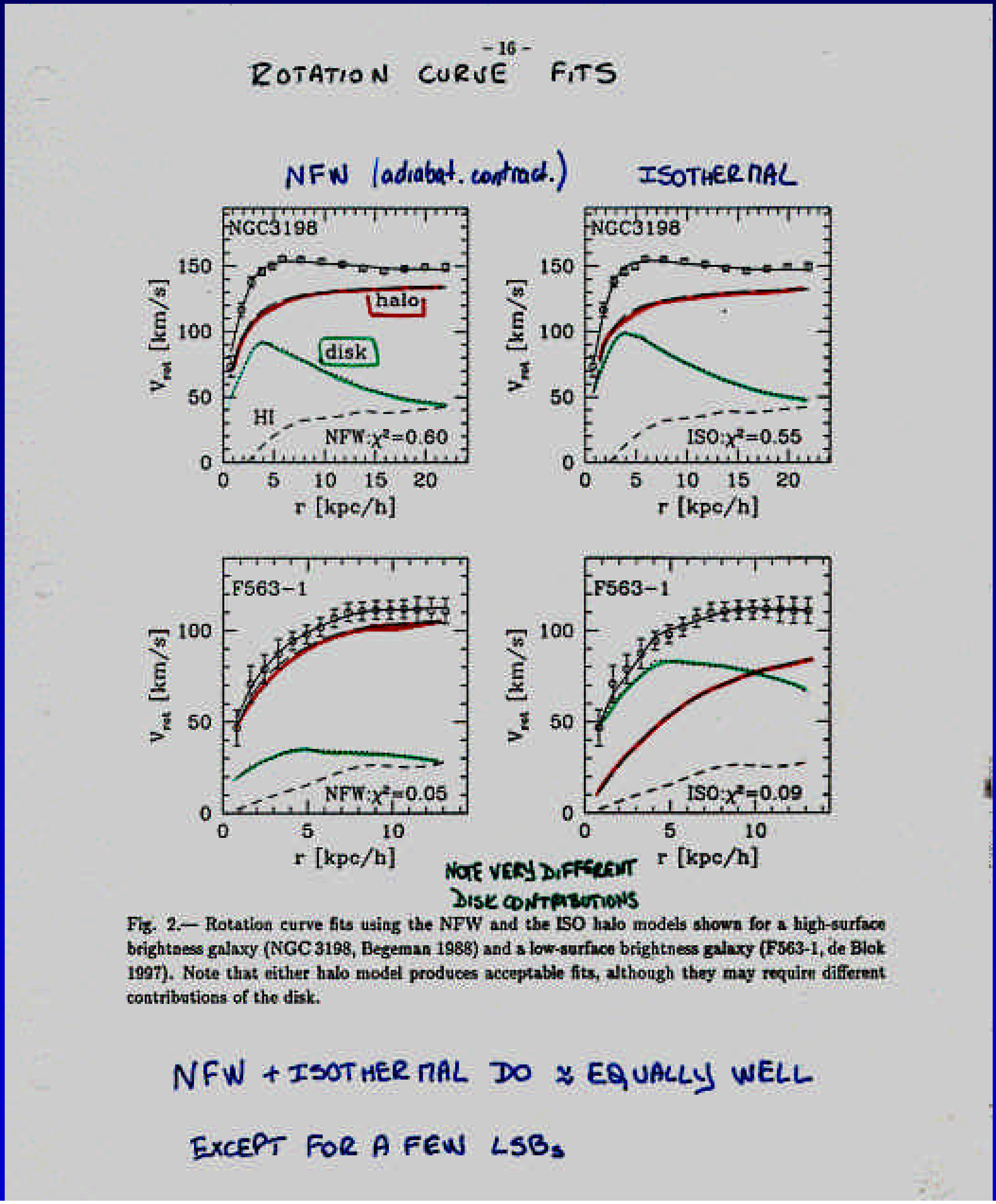
The end of the paradigm?

- Before abandoning the paradigm, it seems appropriate to scrutinize the problems in more detail...

Cold Dark Matter and the rotation curves of low surface brightness galaxies

- Simulations and analytical arguments show that the dark matter density increases systematically towards the center (the halo has a ‘cusp’).
- Rotation curves of low surface brightness galaxies seem to show that the dark halo has a constant density ‘core’ rather than a ‘cusp’ at the center.

Most disk galaxy rotation curves are consistent with “cuspy” CDM halos



ROTATION CURVE FITS

NFW (adiabat. contract.)

ISOTHERMAL

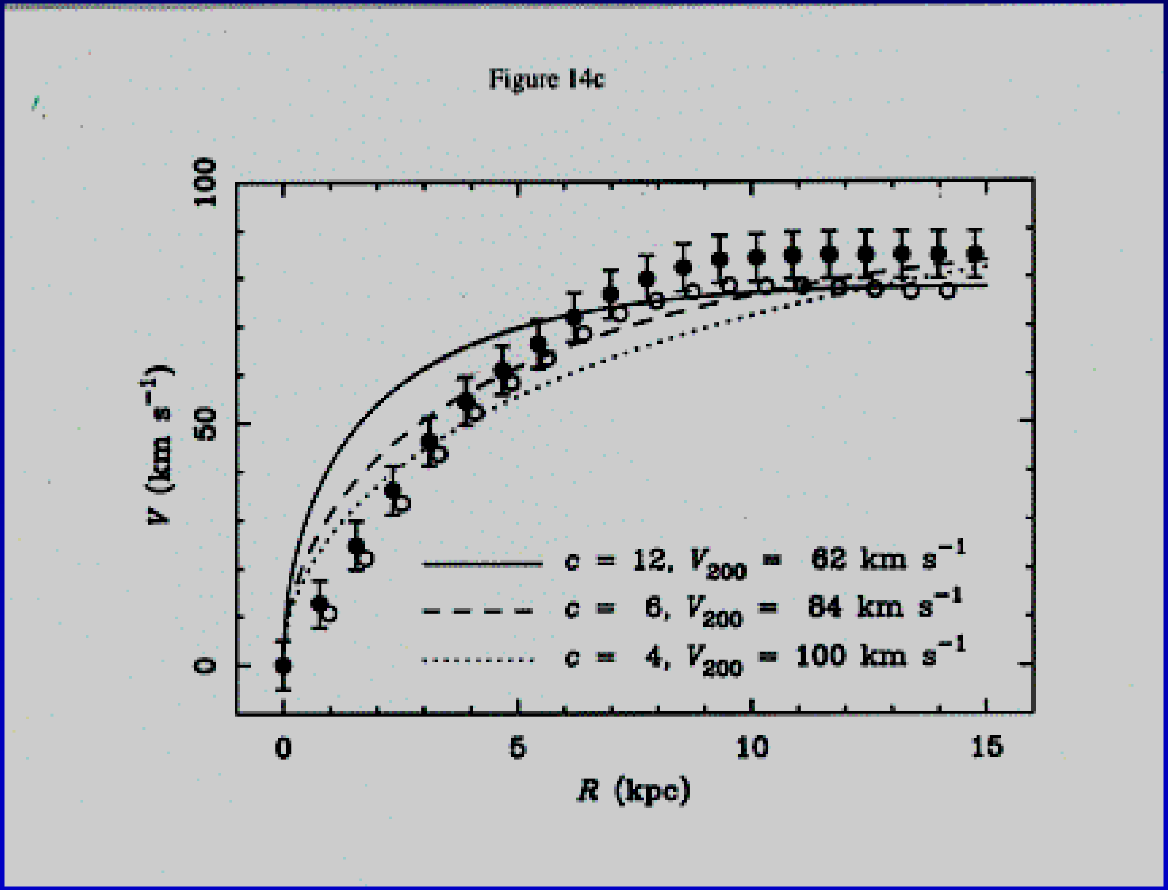
NOTE VERY DIFFERENT DISK CONTRIBUTIONS

Fig. 2.— Rotation curve fits using the NFW and the ISO halo models shown for a high-surface brightness galaxy (NGC 3198, Begeman 1988) and a low-surface brightness galaxy (F563-1, de Blok 1997). Note that either halo model produces acceptable fits, although they may require different contributions of the disk.

NFW + ISOTHERMAL DO ≈ EQUALLY WELL

EXCEPT FOR A FEW LSBs

Rotation curve vs CDM predictions for a Low Surface Brightness (LSB) galaxy

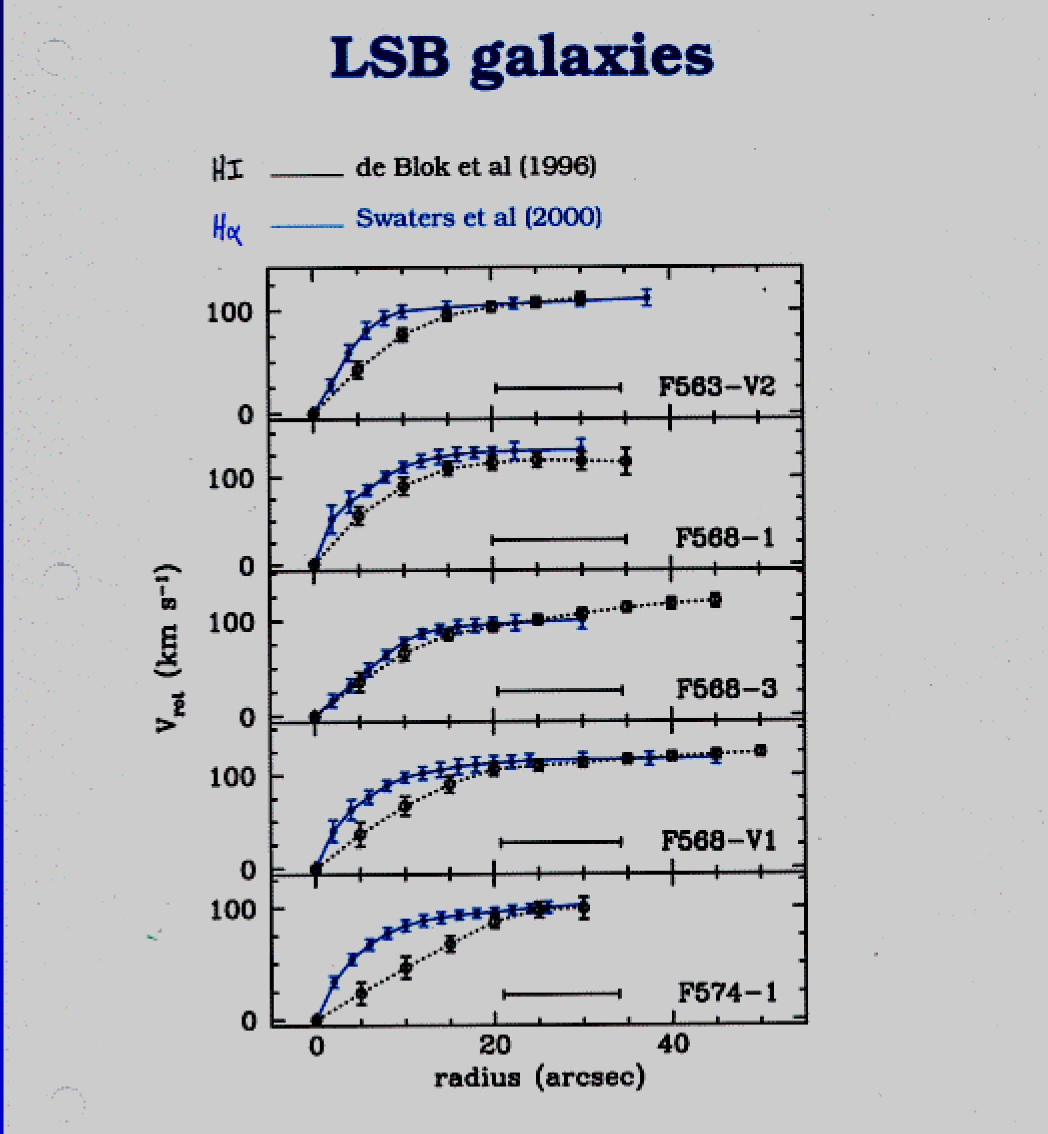


LSB galaxies
are dominated
by dark matter

McGaugh & de Block 1998
see also Moore 1994
Flores & Primack 1994

Beam smearing?

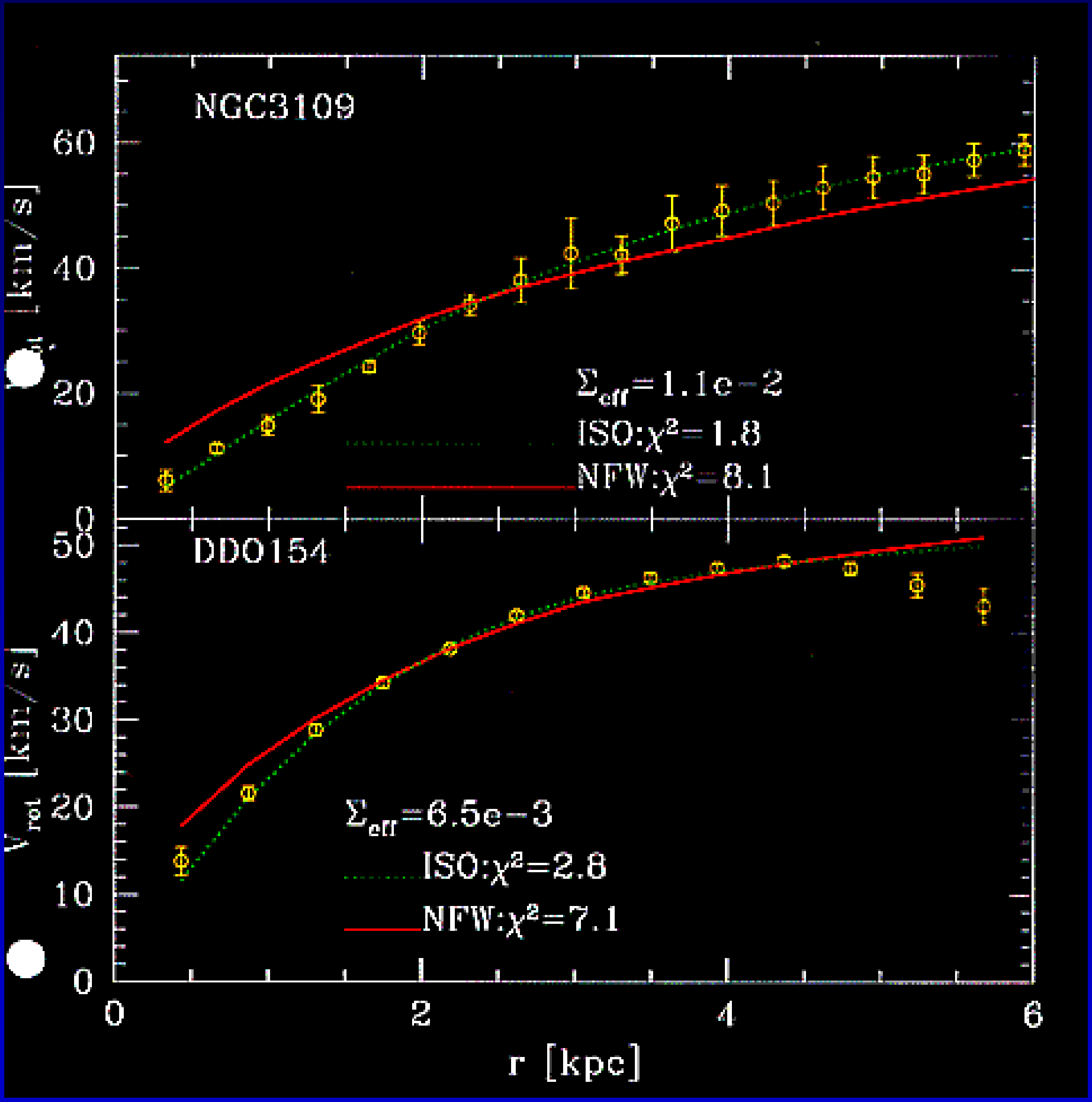
Rotation Speed in km/s



Radius in arcsec

See also
van den Bosch
et al 2000

Dwarf LSBs also show the same problem...

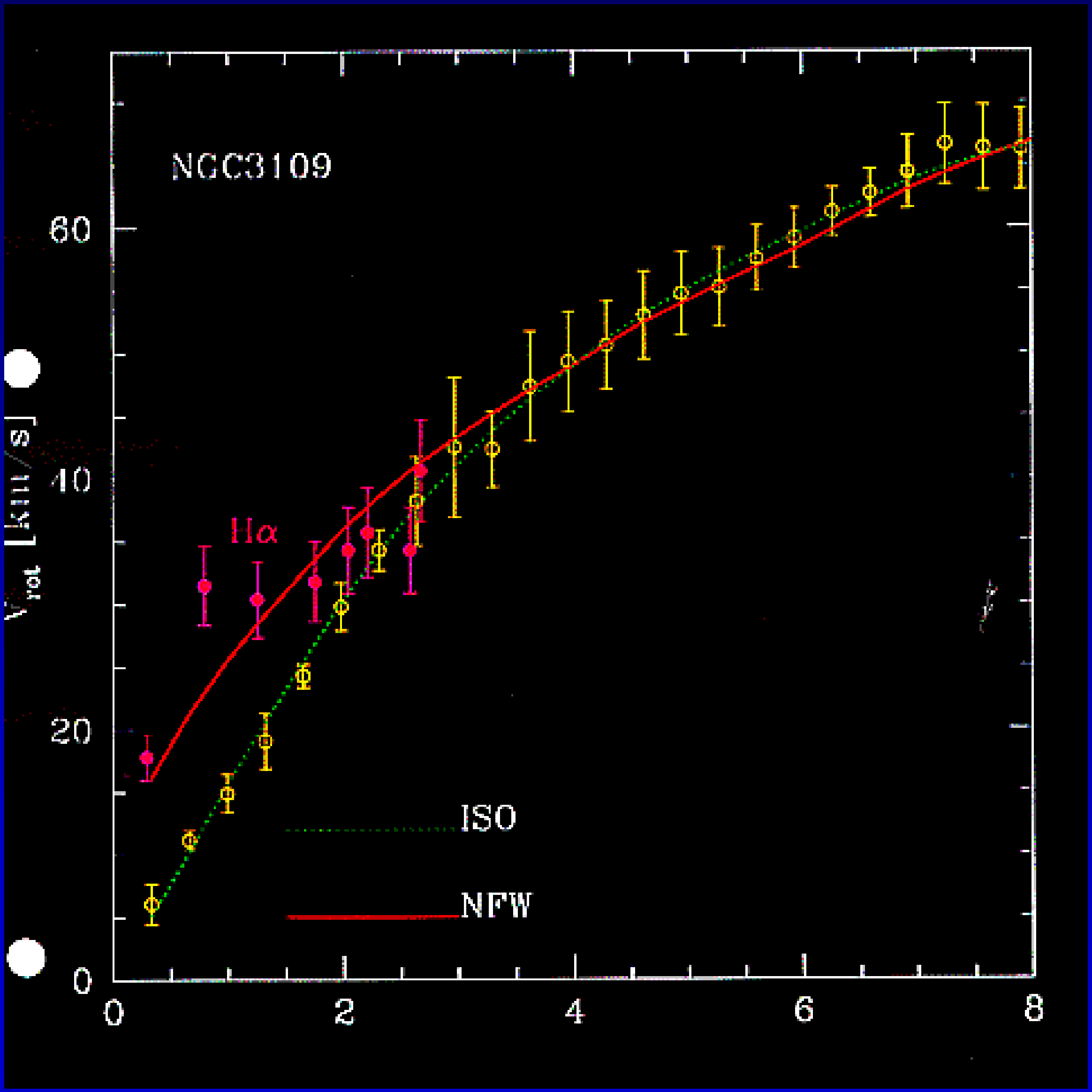


Rotation Speed in km/s

Radius in kpc

The end of
Cold Dark Matter
or just a few
rogue galaxies?

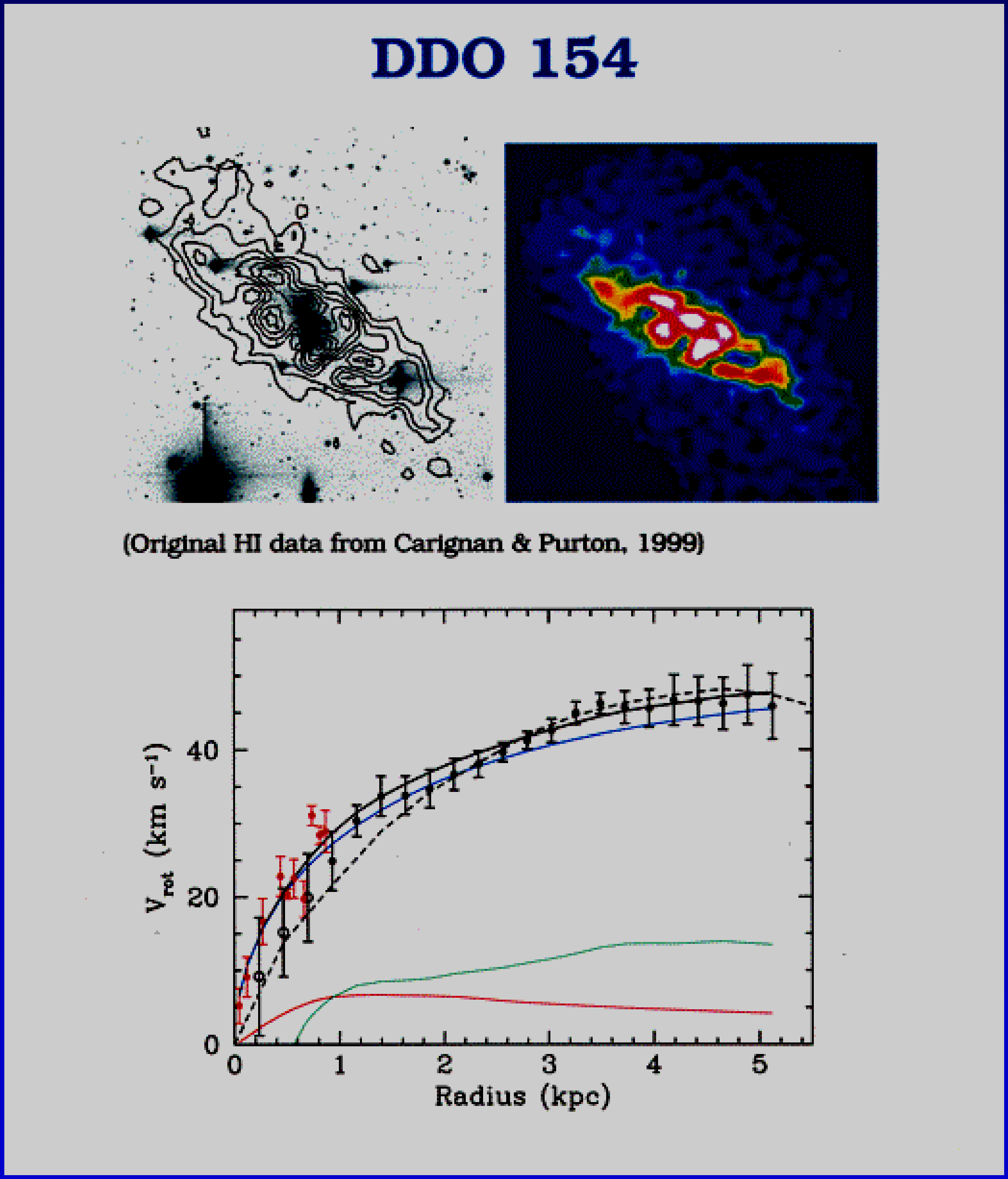
A rogue?



Rotation Speed in km/s

Radius in kpc

The cuspy dark halo of DDO154



DDO 154

(Original HI data from Carignan & Purton, 1999)

Swaters and Navarro 2000

Summary and Conclusions

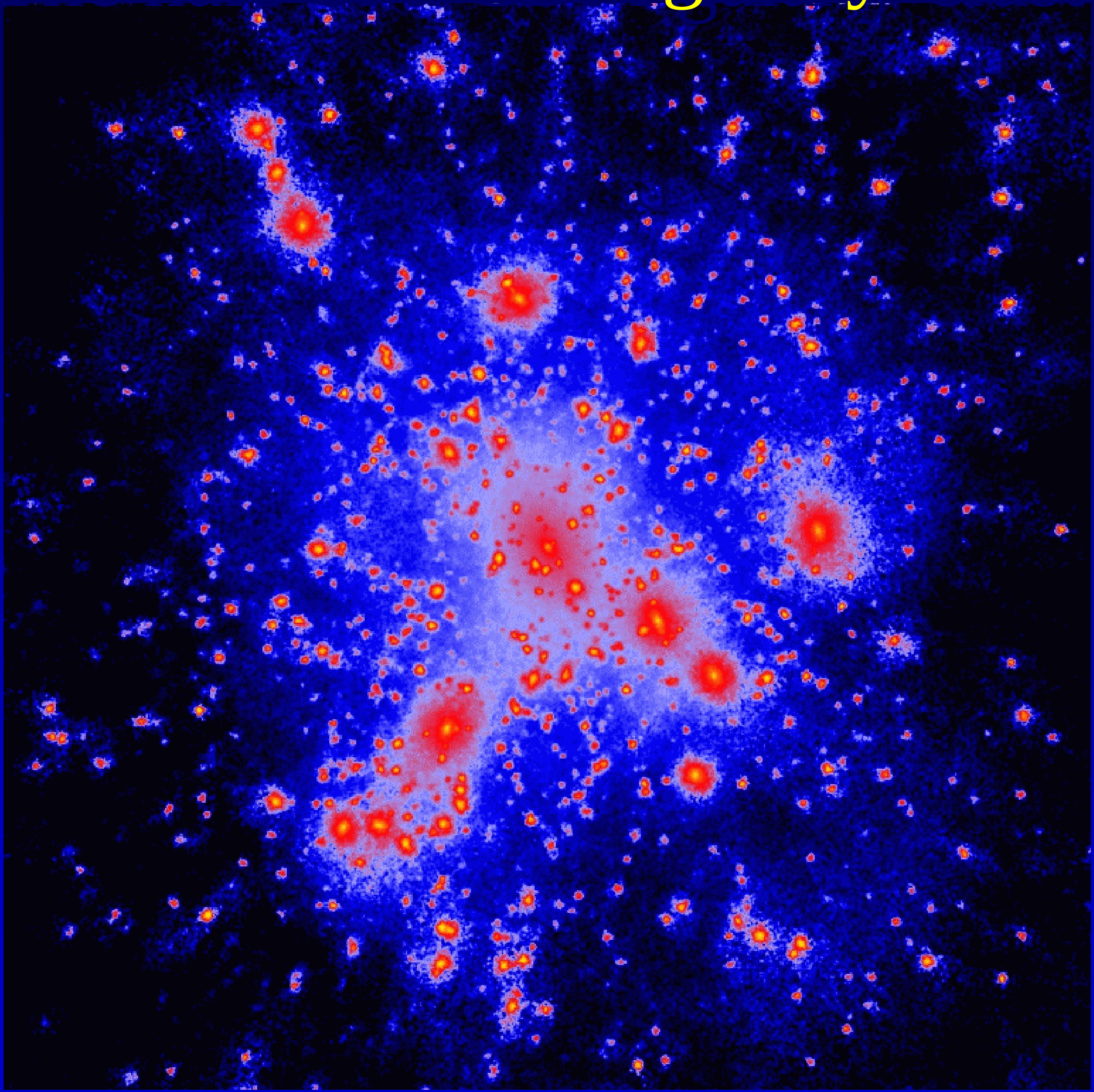
- Gaseous disks generally resembling spiral galaxies are produced through dissipative infall of baryons within dark matter halos.
- Disk galaxy rotation curves, including those of LSBs and dwarf galaxies, are consistent with the “cuspy” dark halos predicted in CDM scenarios.

Summary and Conclusions (II)

- The currently favourite cosmological model (ΛCDM), however, fails to reproduce:
  - angular momentum (or size) of observed disks
    - Feedback from stellar evolution or active nuclei?
  - substructure and satellite numbers (?).
    - Lack of correspondence between stellar and halo velocities?
- Although options are certainly being considered, the evidence for a failure of the paradigm on galactic scales is less than overwhelming.

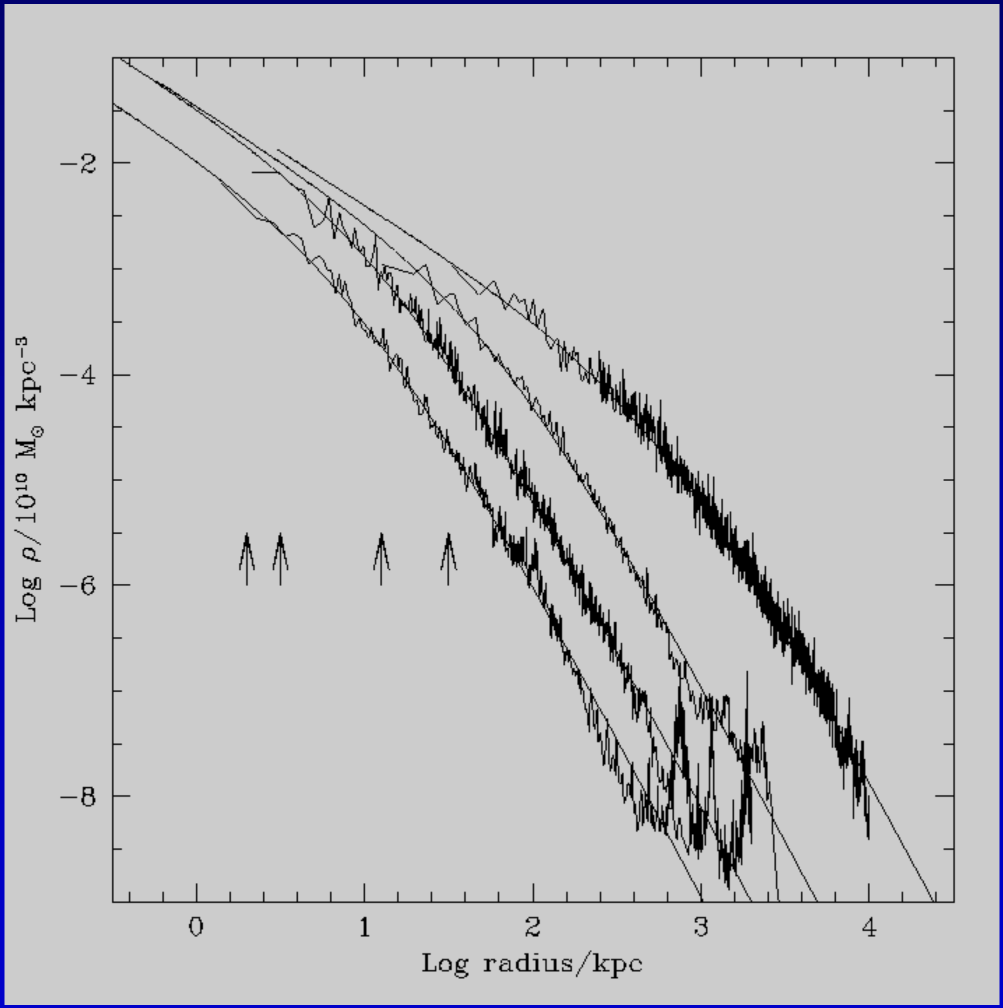
The End

The halo of a CDM galaxy cluster



Moore et al 1999

Cuspy Cold Dark Matter halos



Density

Radius

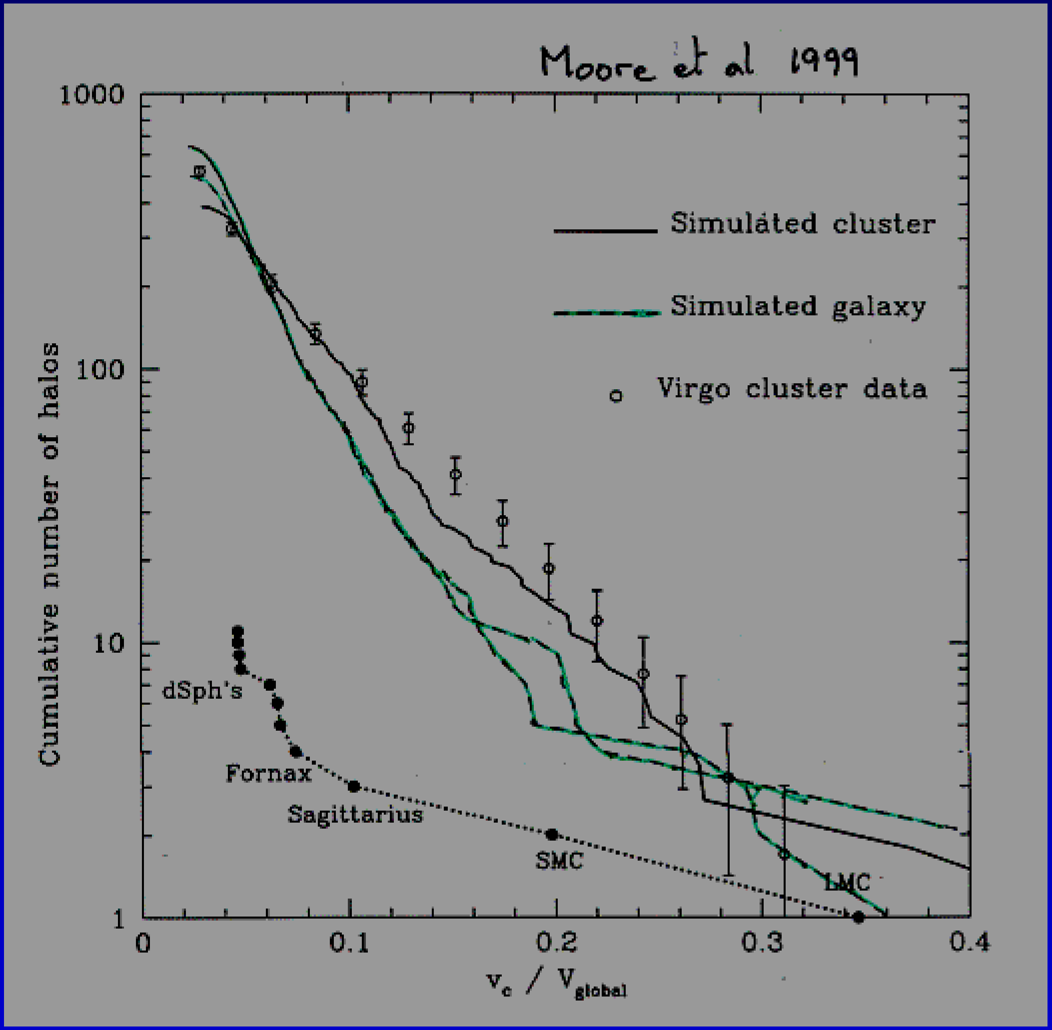
- Mass profiles of dark halos are independent of halo mass and cosmological parameters (Navarro, Frenk & White 1997)

The 'NFW' profile

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

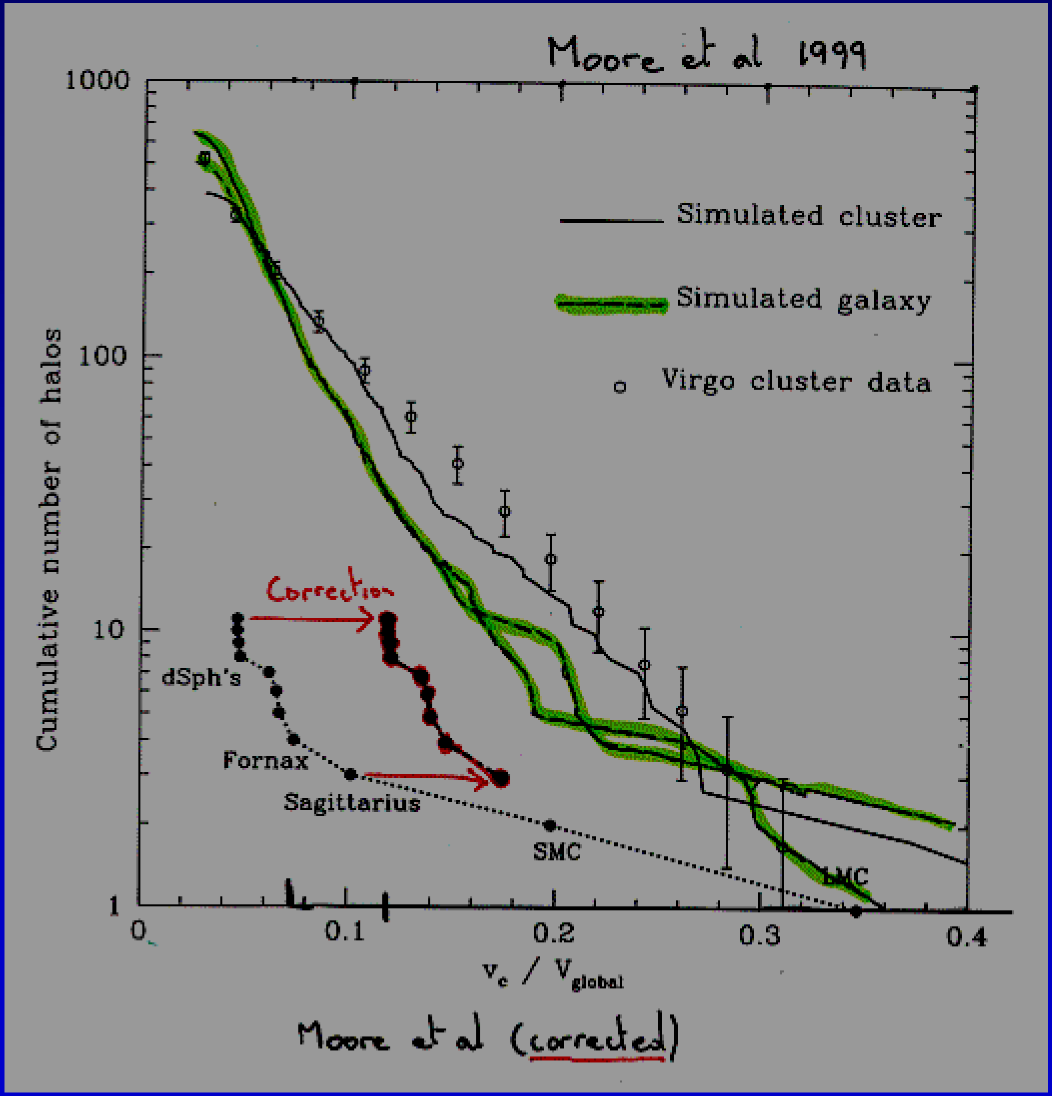
The abundance of Milky Way satellites

Cumulative Number



Circular Velocity

The (corrected) abundance of Milky Way satellites

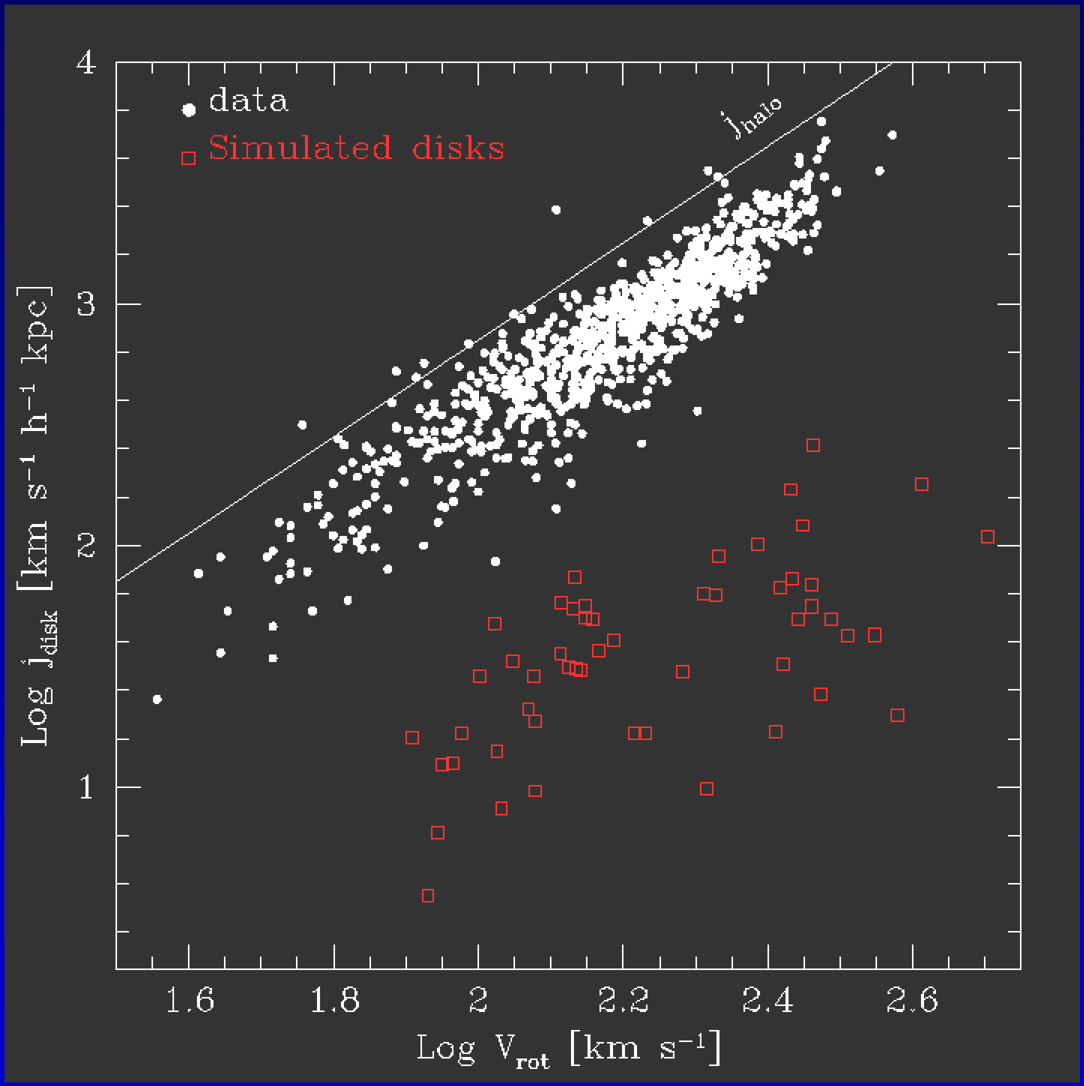


From Simon White

From Simon White

The angular momentum of observed and simulated disks

Specific
Angular
Momentum



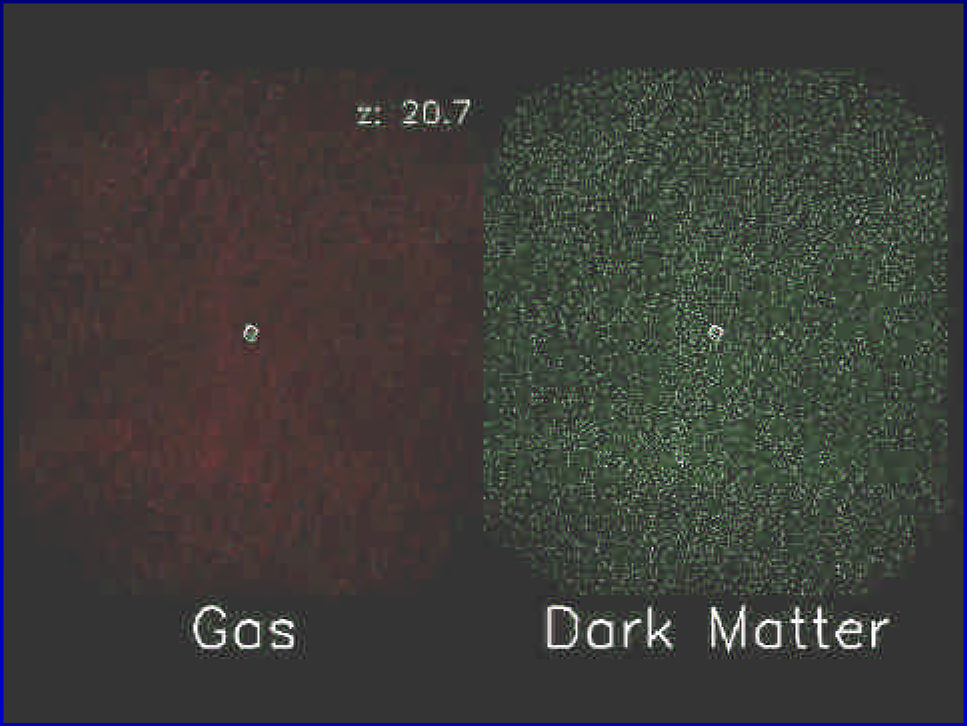
Angular momentum is transferred from the baryons to the dark matter during mergers.

It is not easy to form disks that resemble observed spirals in CDM models!

Disk Rotation Speed

Steinmetz & Navarro 1999

Mergers and Disk Angular Momentum

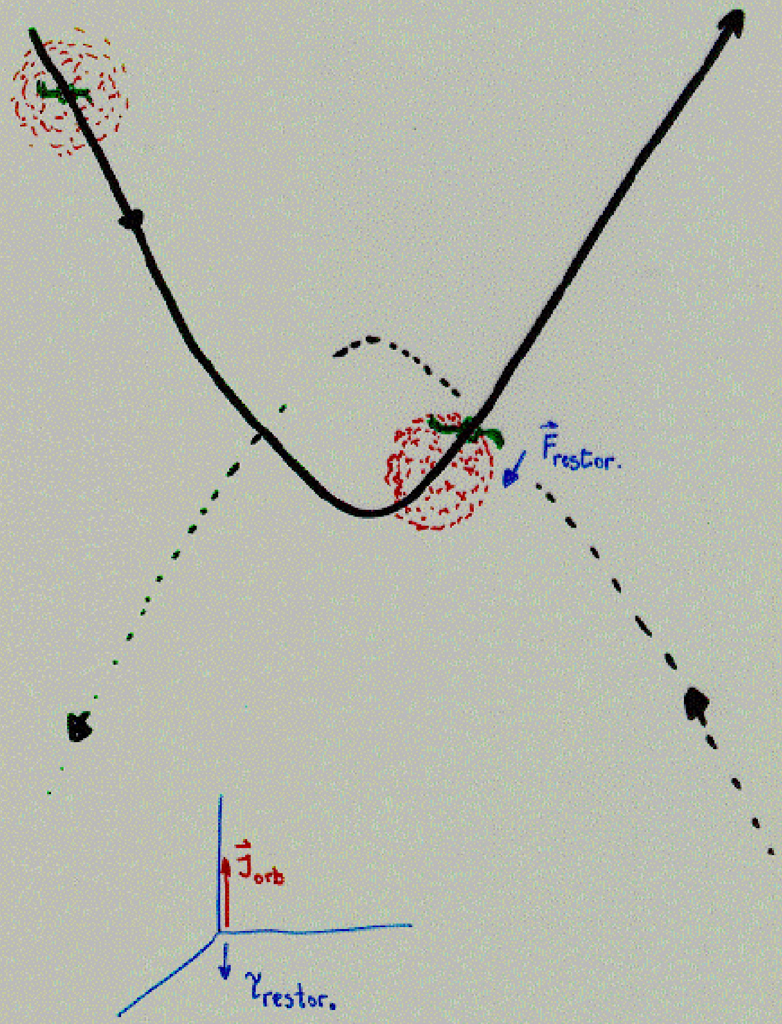


Most of the angular
momentum
is in the orbit
of the merging system.

Final disk
angular momentum
is much lower than
that of the halo.

Steinmetz & Navarro 1997

ANGULAR MOMENTUM TRANSFER DURING MERGERS



Cold Dark Matter and Substructure

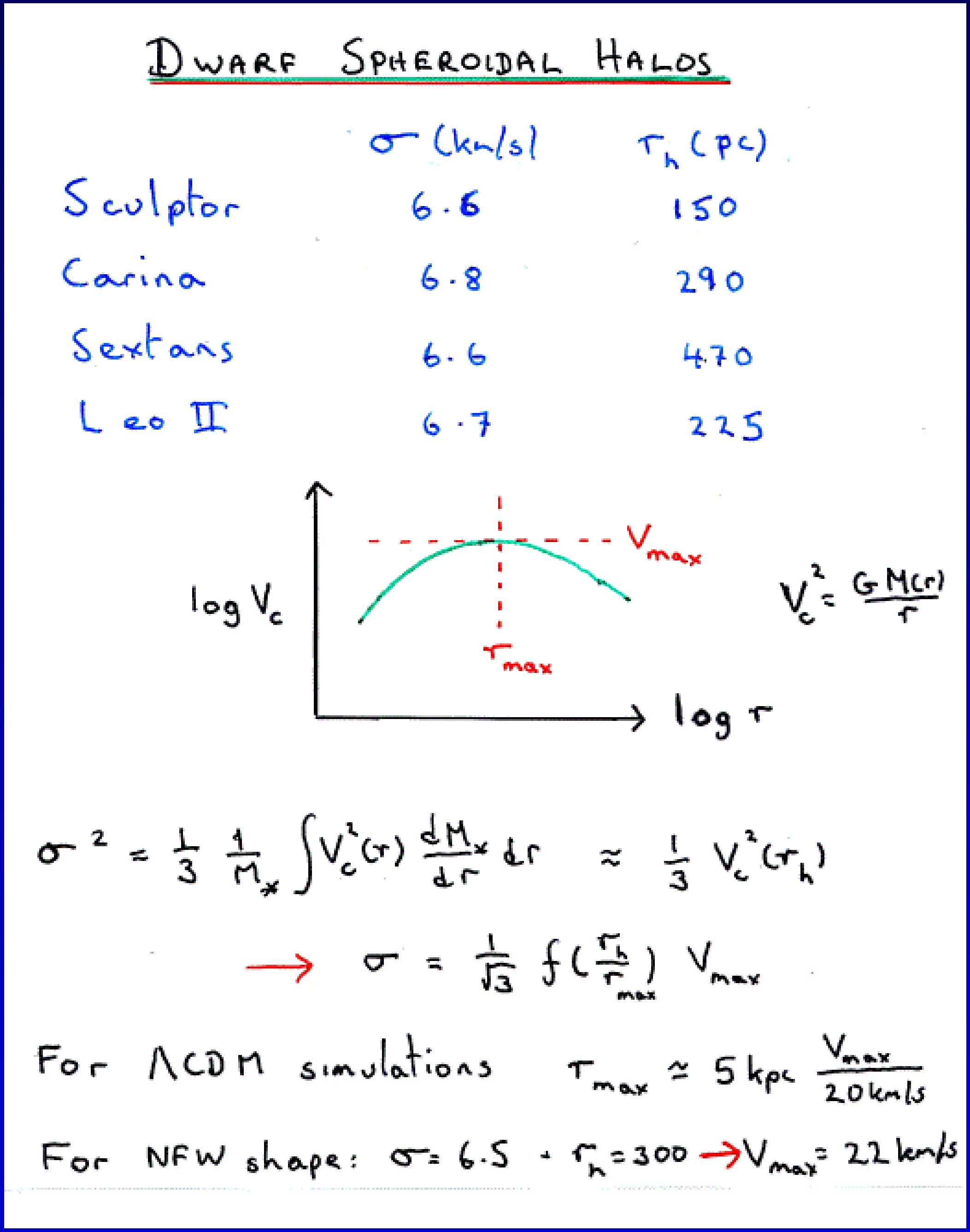
- Simulations show that a significant fraction of low mass halos accreted within larger structures are not fully destroyed but remain as ‘sub-halos’ or ‘substructure’ within the larger system
- At face value, this presents two problems:
  - – Dark satellites are far more numerous than known satellites of the Milky Way.
  - – Milky Way disk heating by tidal encounters with substructure halos.

CDM halos on different scales

OBSERVED STRUCTURES

DARK HALOS

Moore 2000



DWARF SPHEROIDAL HALOS

	σ (km/s)	r_h (pc)
Sculptor	6.6	150
Carina	6.8	290
Sextans	6.6	470
Leo II	6.7	225

V_{max}

$\log V_c$

r_{max}

$\log r$

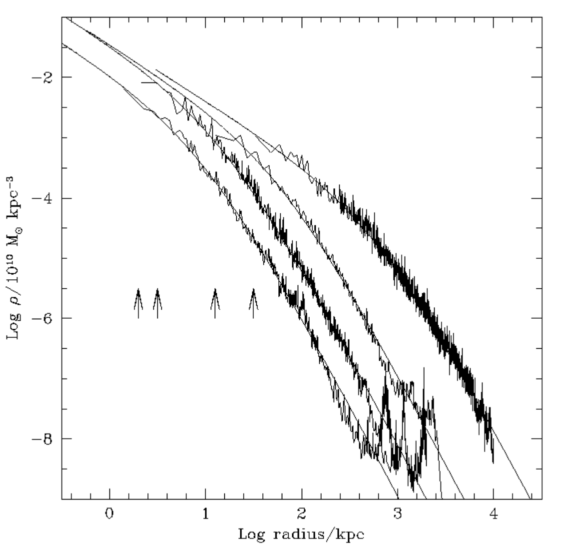
$$V_c^2 = \frac{G M(r)}{r}$$

$$\sigma^2 = \frac{1}{3} \frac{1}{M_*} \int V_c^2(r) \frac{dM_*}{dr} dr \approx \frac{1}{3} V_c^2(r_h)$$

$$\rightarrow \sigma = \frac{1}{\sqrt{3}} f\left(\frac{r_h}{r_{max}}\right) V_{max}$$

For ΛCDM simulations $r_{max} \simeq 5\,\mathrm{kpc} \frac{V_{max}}{20\,\mathrm{km/s}}$

For NFW shape: $\sigma = 6.5$ · $r_h = 300 \rightarrow V_{max} = 22$ km/s



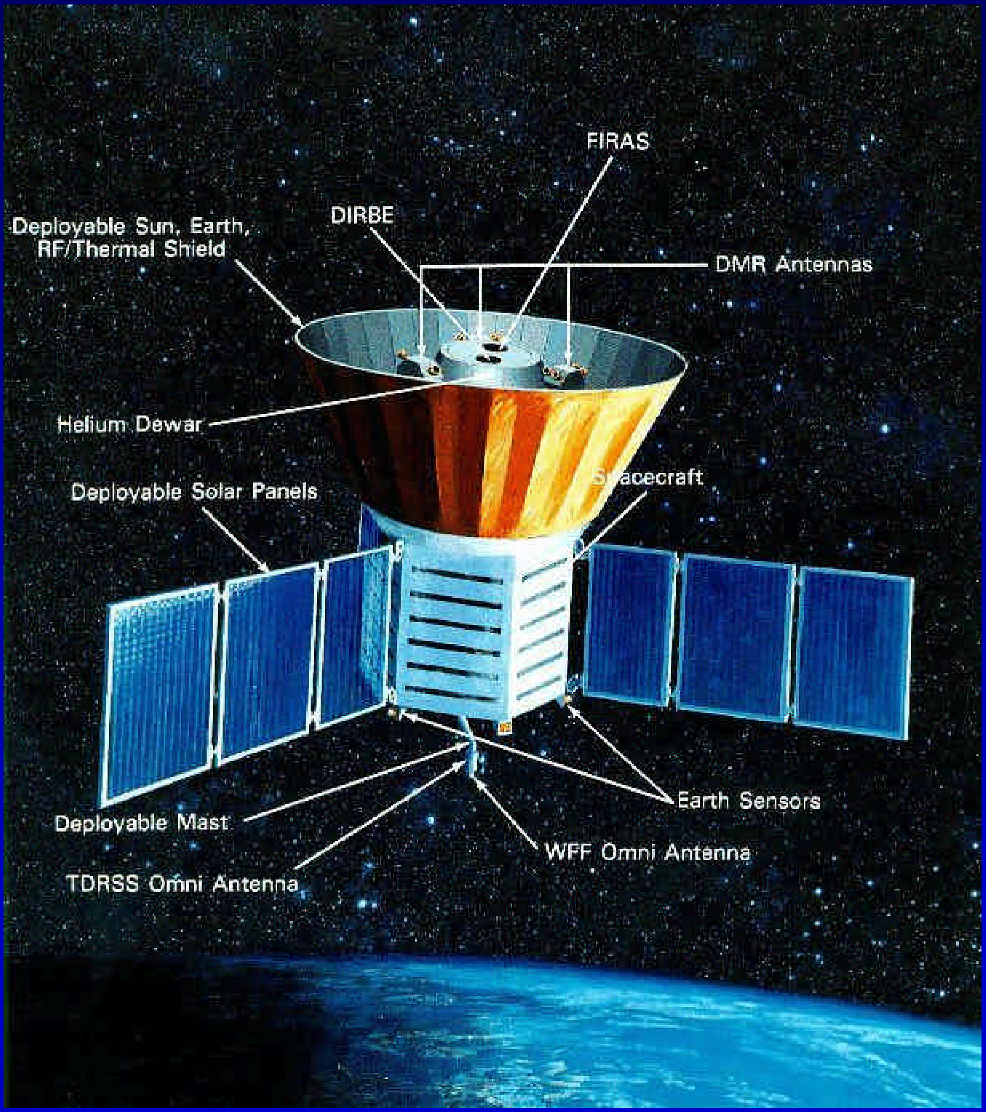
Dark Halos
are shallower than
isothermal
(logarithmic slope >-2)
near the center.

S.D.M. White 2000

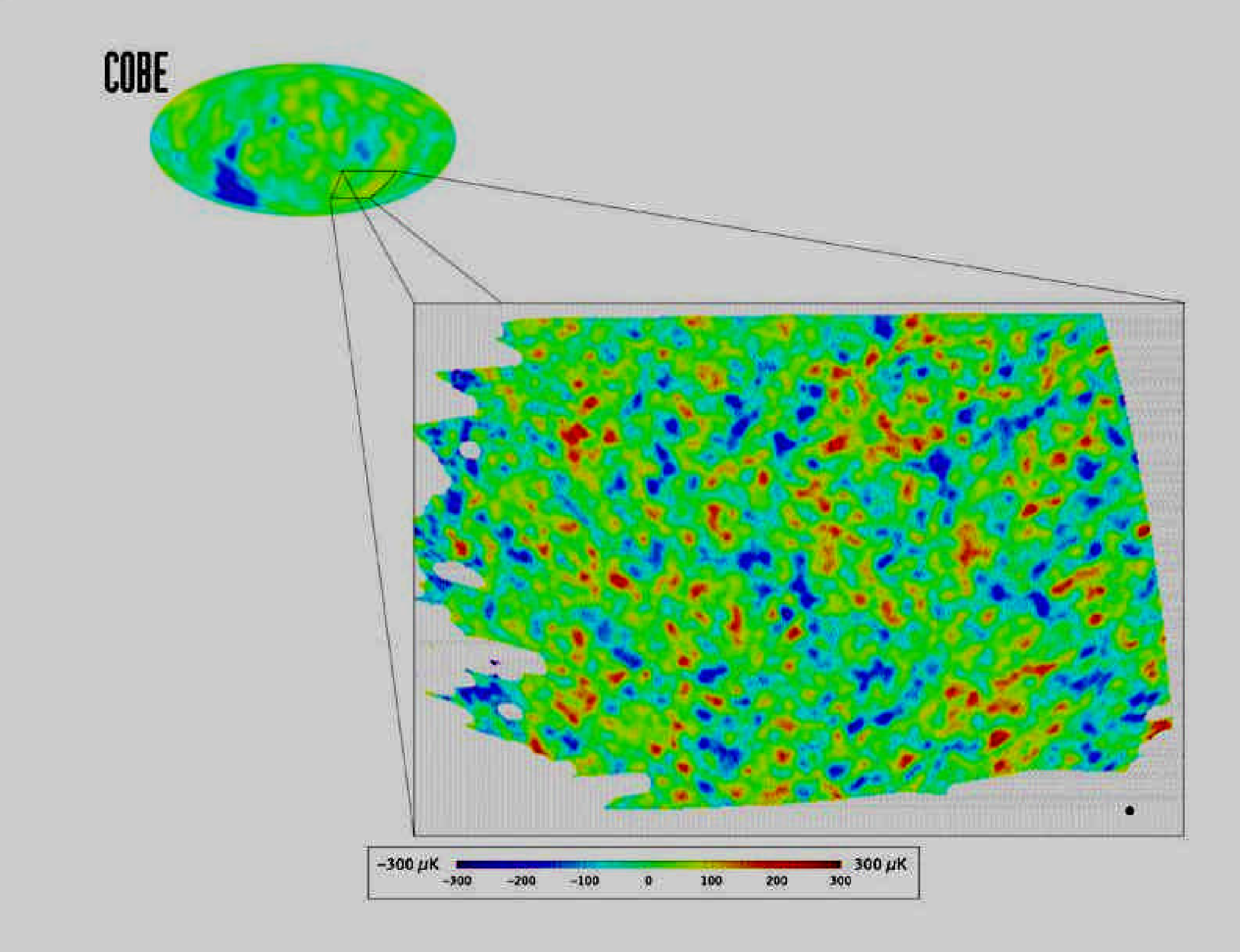
Potential Problems for CDM (IV):

- Cold Dark Matter halos are dense: about 10^{11} M_{sun} of dark matter are expected within ~8 kpc for the Milky Way. (At odds with observational estimates in our Milky Way?)

The COBE Satellite

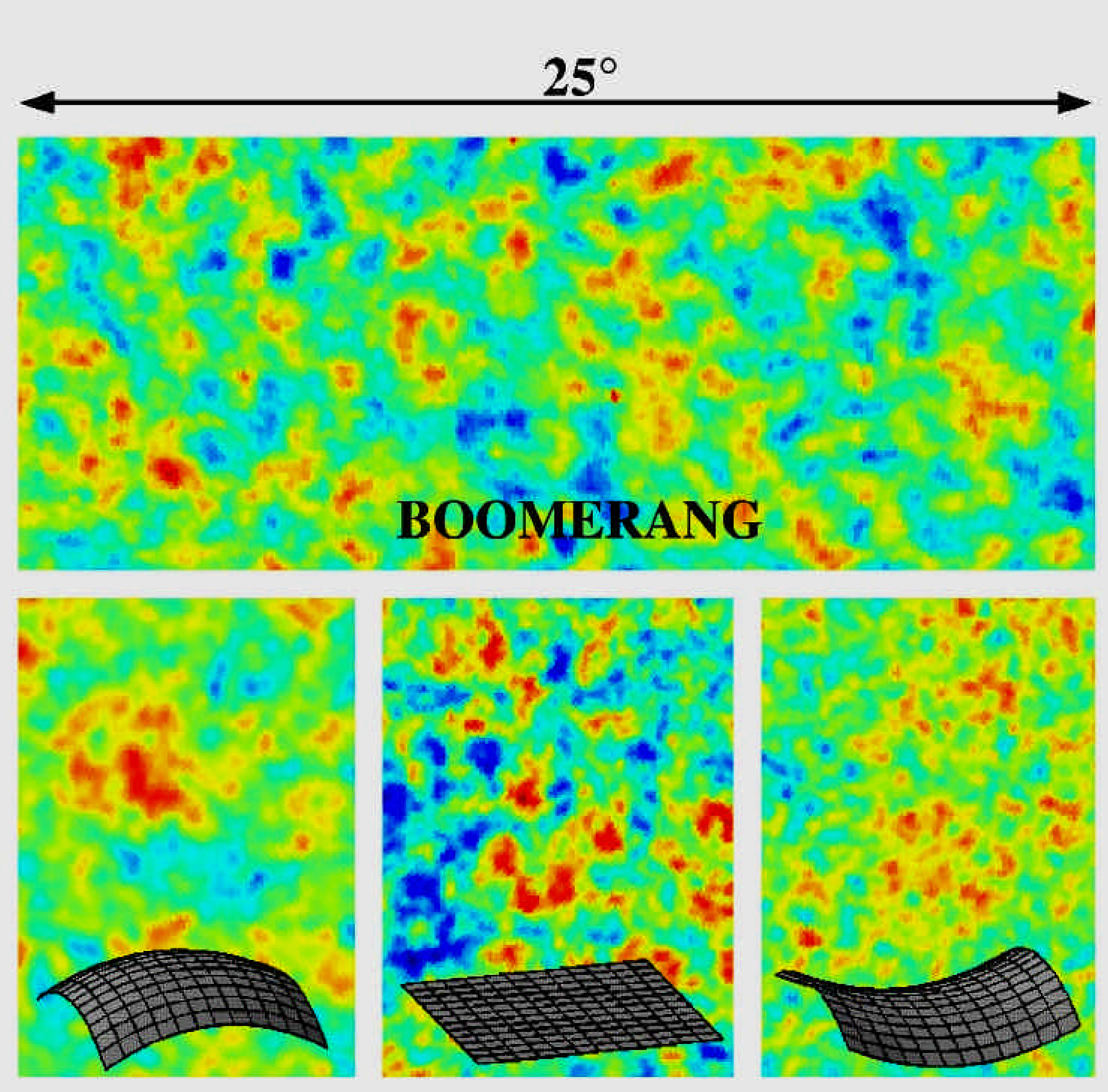


From COBE to BOOMERANG



The
seeds
of
structure
formation

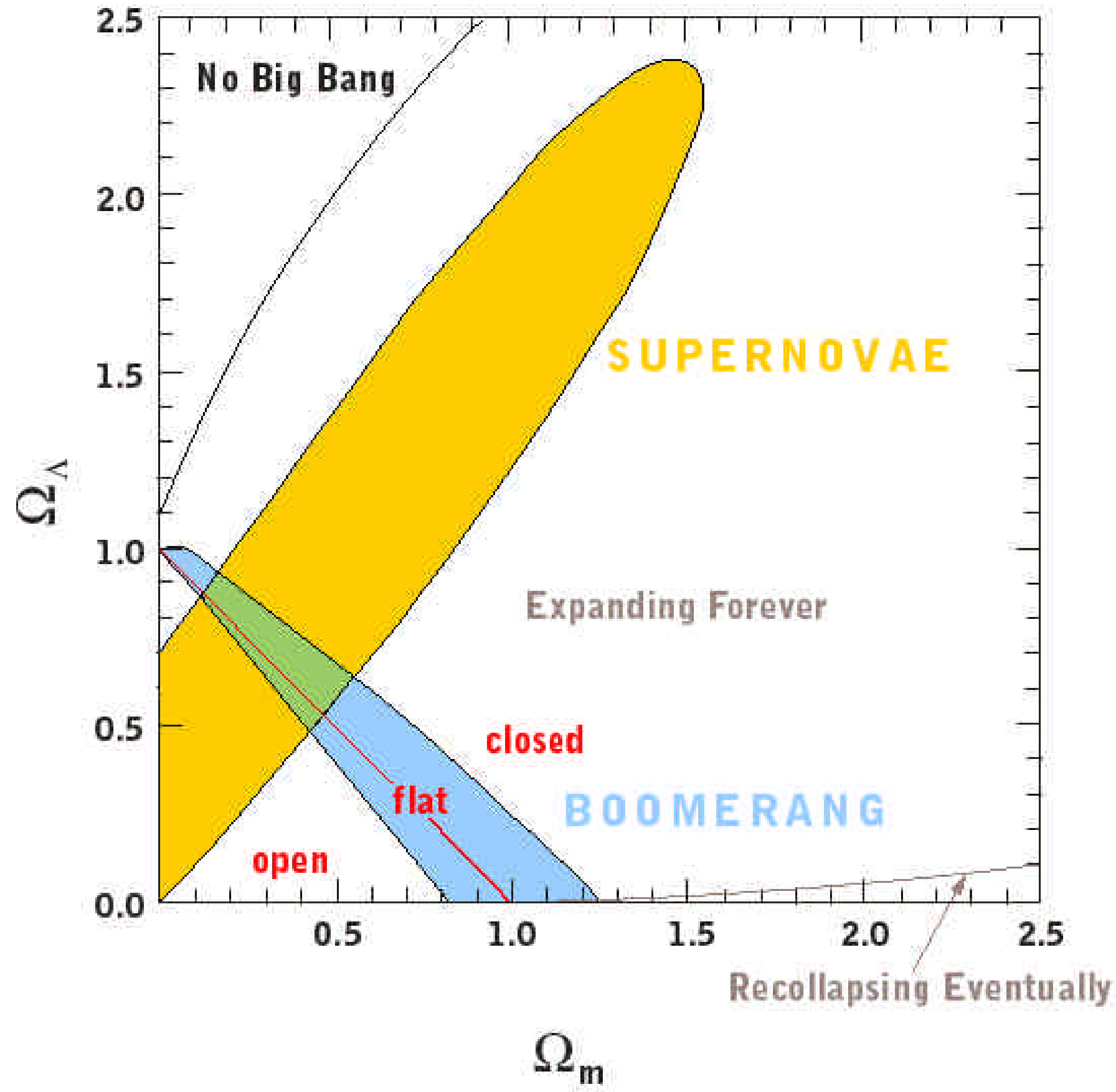
The Matter-Energy Density of the Universe: brought to you by BOOMERANG



$\Omega > 1$ $\Omega = 1$ $\Omega < 1$

BOOMERANG vs SUPERNOVAE

Cosmological Constant = Vacuum Energy



Matter Density