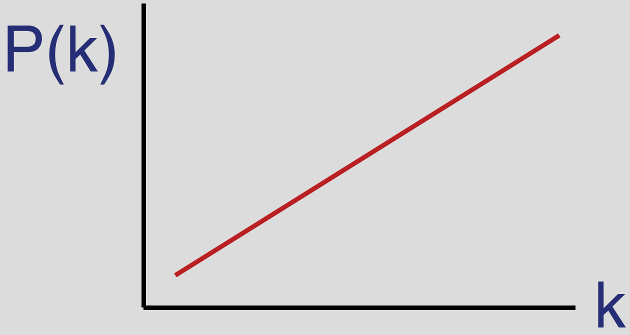
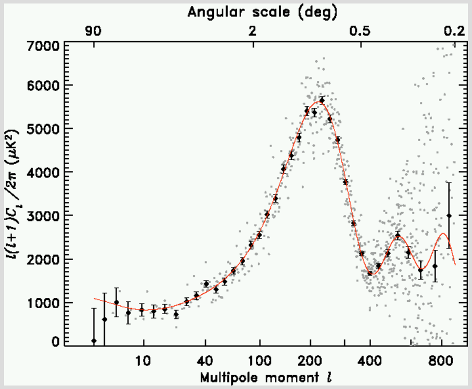
# Open questions in ΛCDM cosmology

Current cosmological paradigm is based upon:



(1) Calculation of the primordial spectrum of fluctuations from homogeneity from theory of **inflation**.



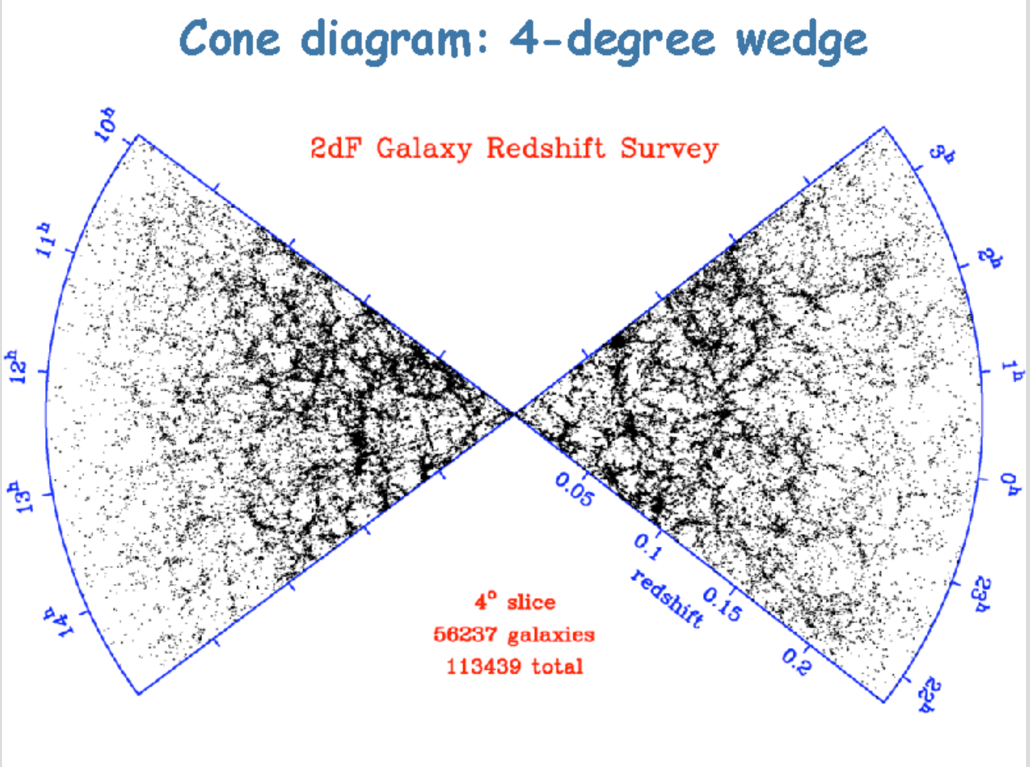
(2) Observe these fluctuations directly at large scales in the CMB, and after modification by interaction with matter and radiation at smaller scales.

(3) Observed structure (galaxies, clusters etc) forms from overdense regions due to **gravitational instability**.

Best defined predictions and clearest comparison to data involve:

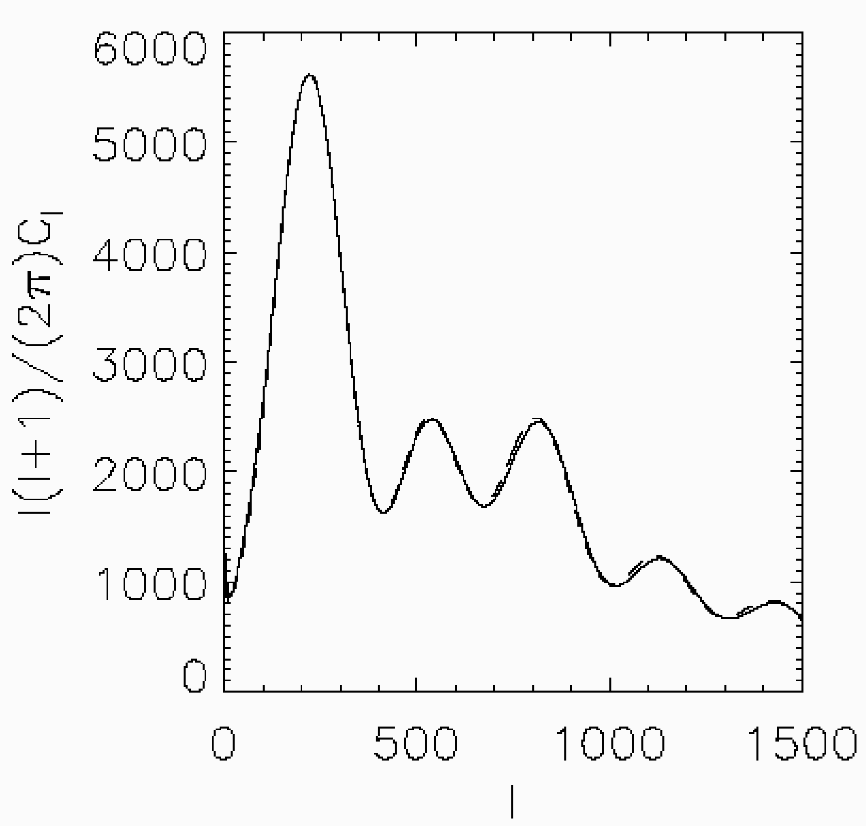
- Distribution of the **dark matter** rather than gas or stars
- **Large scales** where departures from homogeneity are relatively small

➡ Microwave background + galaxy clustering

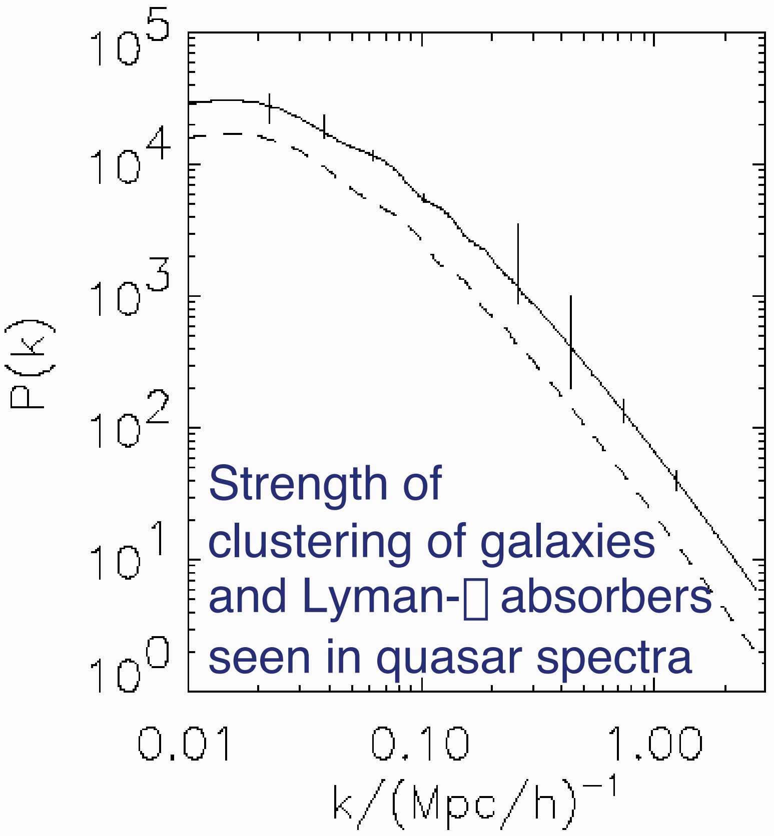


Galaxies might not trace the dark matter distribution well - they might be *biased*… but for bright galaxies this doesn't seem to be too strong an effect.

## CMB anisotropy



## Galaxies + Lyman-α



Strength of clustering of galaxies and Lyman-α absorbers seen in quasar spectra

Λ-CDM models can fit this data very well.

On smaller galactic and sub-galactic scales, situation is much less clear - several observations that *may* indicate fundamental problems with ΛCDM or missing astrophysics…

# Problem 1: Rotation curves at small radii

Numerical simulations of the formation of dark matter halos in ΛCDM predict how the dark matter density should vary with distance from the center of the halo.

For a spherically symmetric distribution of dark matter, this is equivalent to a prediction of the rotation curve, since:

$$\frac{v_c^2}{R} = \frac{GM(<R)}{R^2}$$

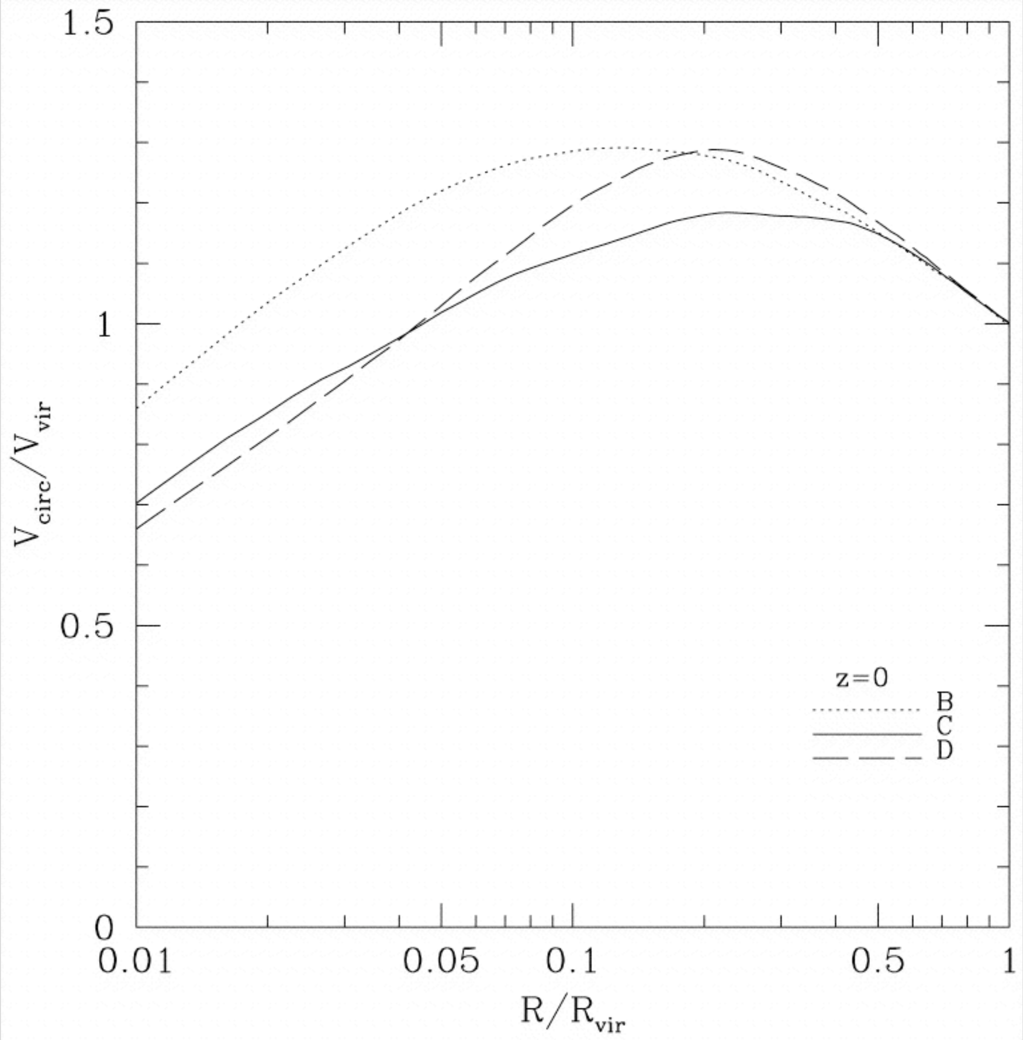
Theoretical prediction is the **Navarro-Frenk-White profile**:

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

…which tends to $\propto r^{-1}$ at small radii. More recent work suggests a slightly steeper slope, perhaps $\propto r^{-1.5}$

Recall that a density profile of $\square \quad r^{\square 2}$

flat rotation curve ($v_c$ independent of radius)

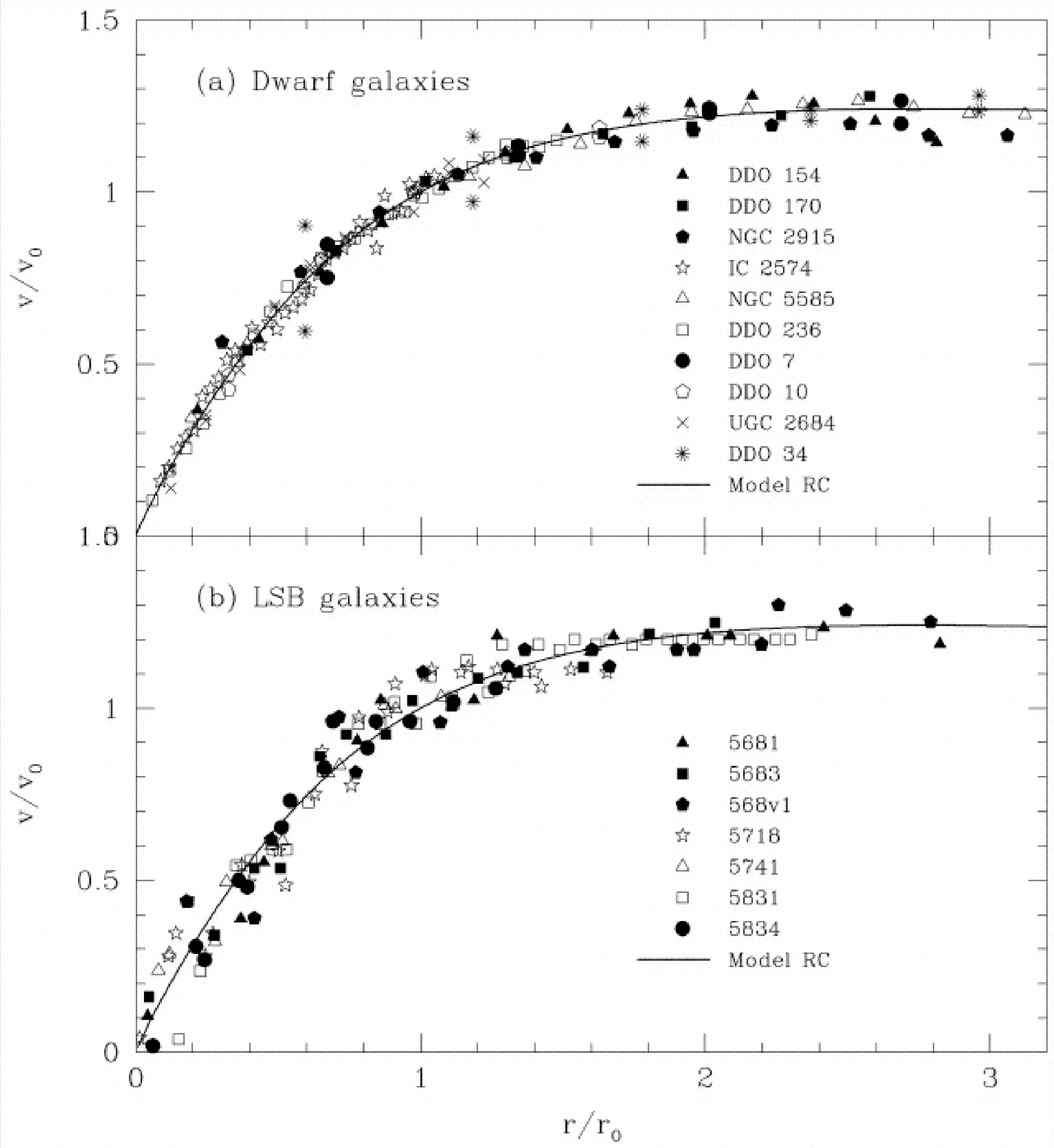


Theoretical prediction is that galaxies should have:

- Dense dark matter **cusps** at small r
- Rotation curves that decline only fairly modestly towards the center…

Example rotation curves from simulations by Klypin et al.

# In real galaxies, the rotation velocity declines more rapidly toward the center of the galaxy…



Compilation of data by Kratsov et al.

Effect seems particularly pronounced in dwarf and low surface brightness galaxies where dark matter might be expected to dominate…

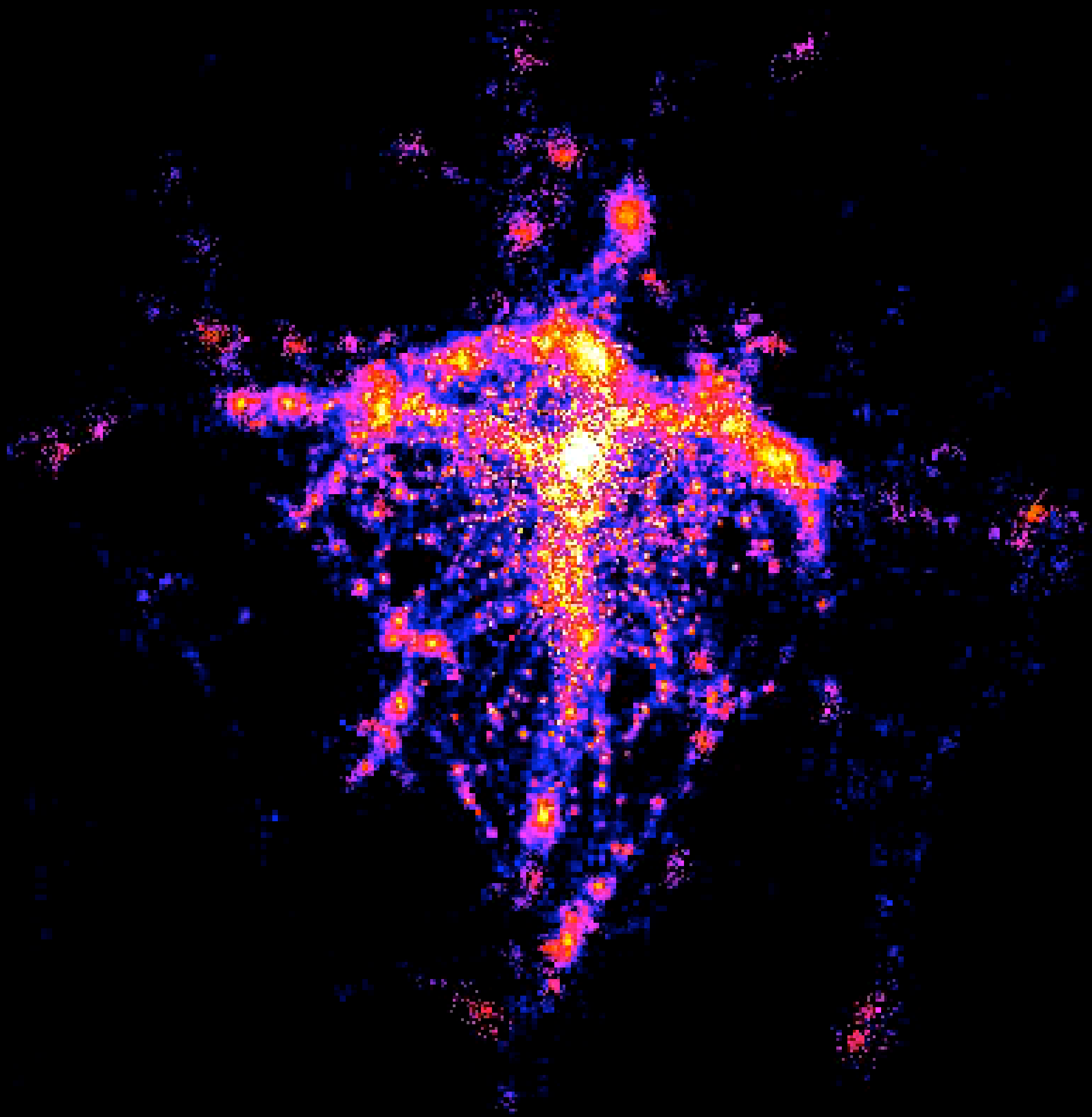
Observations suggest a density that can be described as a power-law near the center - perhaps $\rho \propto r^{-(0.2-0.4)}$

Suggests dark matter in real galaxies is both:

- Less centrally concentrated
- Less cuspy

…than is predicted by standard ΛCDM models.

# Problem 2: Substructure in galactic halos



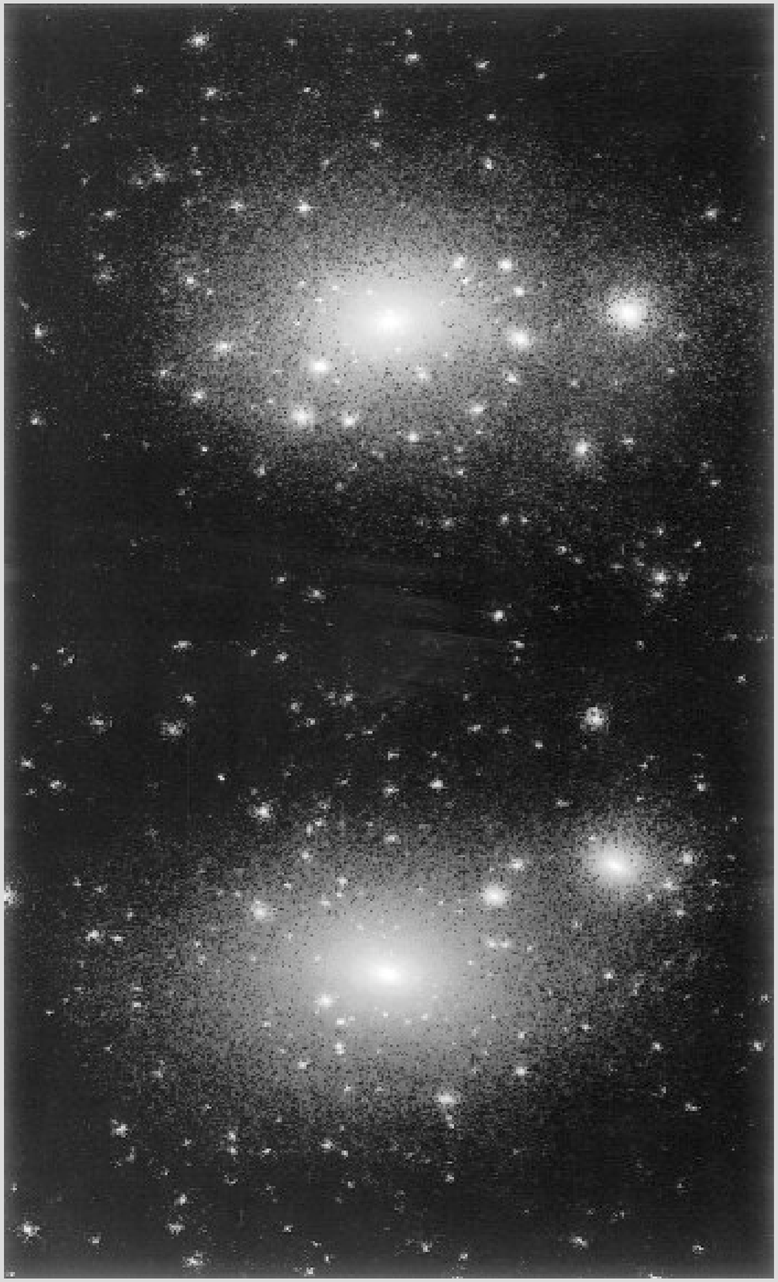
Numerical simulations of structure formation in all CDM models find that dark matter halos possess lots of **substructure** - smaller halos that have fallen in but which preserve their identity.

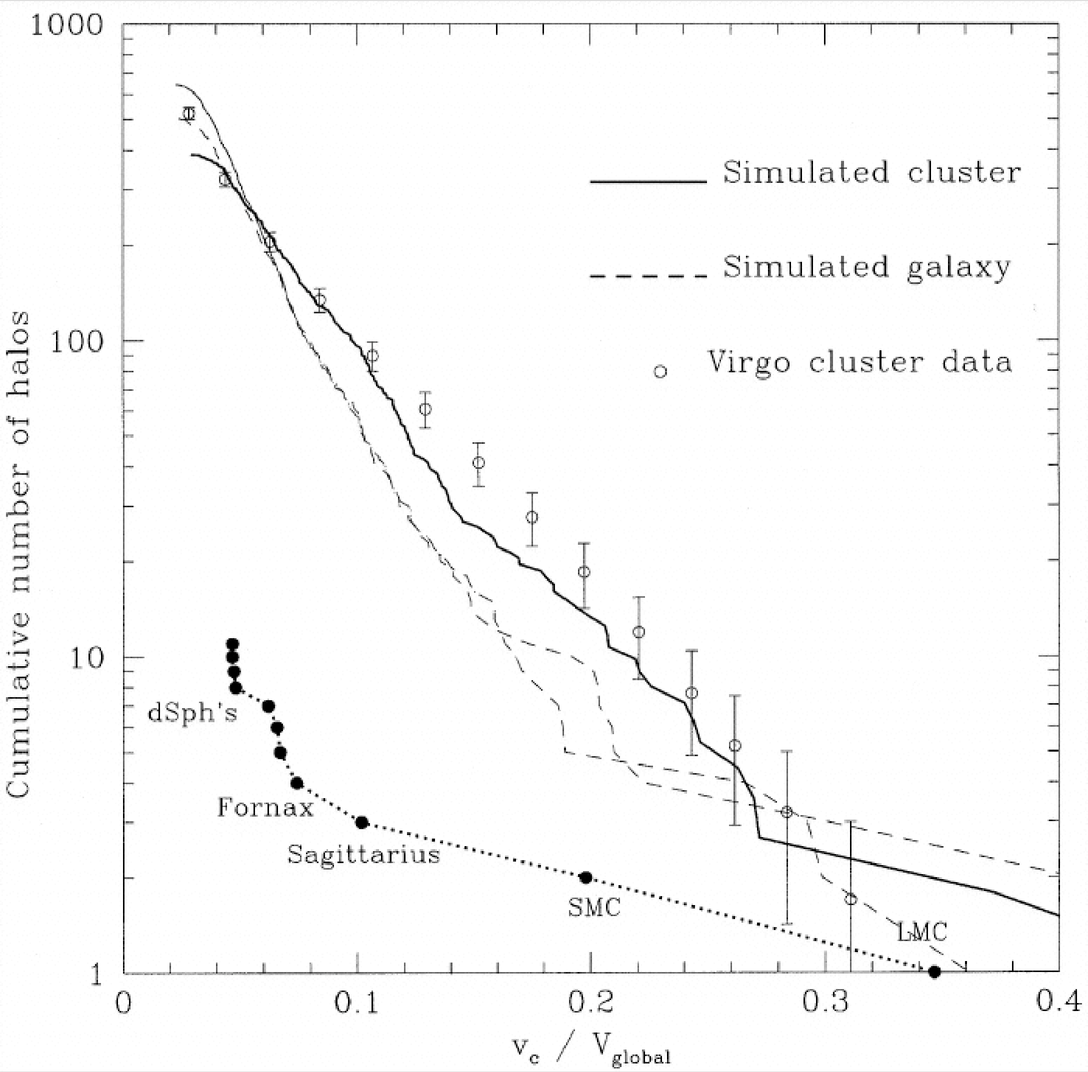
Simulation by Ben Moore (again!)

Cluster scales - lots of substructure is OK - galaxy clusters contain lots of individual galaxies.

Abell 2218

Problem is that $\Lambda$CDM predicts a similar amount of small scale structure within **galactic scale** dark matter halos. If each halo hosts a small galaxy, would expect very large number of galactic satellites.





Predict several hundred satellites
Observe approximately 10

Simulated halos

Both problems involve:

- Similar sub-galactic scales - of the order of kpc
- Systems that have (or would have had) gas and stars

Suggests that either:

- Something is wrong with ΛCDM on these small scales
- We don’t understand galaxy formation well enough to make reliable predictions on these scales.

Either possibility is very interesting.

# Solutions that alter ΛCDM

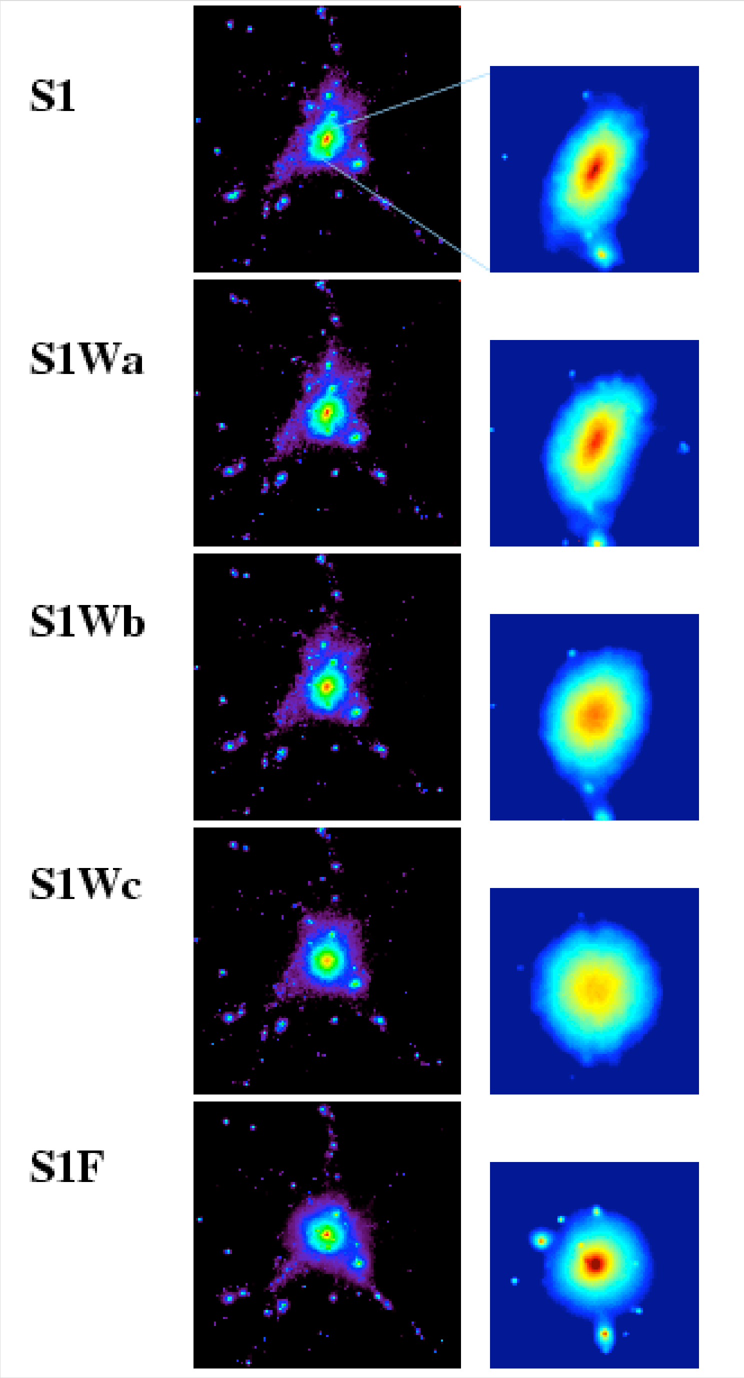
## 1) Dark matter is not collisionless

Standard model assumes that cold dark matter is made up of particles (perhaps neutralinos) which have almost no interactions with each other or with baryons apart from via gravity.

Spergel & Steinhardt (2000) proposed that dark matter might instead have a non-negligible collision cross-section - **Self-Interacting Dark Matter (SIDM)**. Specifically, they suggested that the mean free path of dark matter near the Sun should be:

$$\lambda \sim 1\ \mathrm{kpc} \rightarrow 1\ \mathrm{Mpc}$$

- At $\rho_{galaxy}$, implies 1 - 1000 collisions per Hubble time
- At $\rho_{crit}$, << 1 collision - agreement on **large scales is unaffected by collisions**



SIDM affects the properties of halo cores and substructure:

**Substructure** is reduced - small halos are heated as they move through larger ones, and tend to dissolve and merge into the larger structure

**Cores** of halos are also heated by collisions, and at least initially have lower central densities and shallower density profiles (cf stars)

Detailed studies have dampened the initial enthusiasm for SIDM. Critical constraints appear to be:

- Collisions cannot be very important on cluster scales because the gravitational potential in many clusters is not spherical. Collisional dark matter halos tend to become spherical rather rapidly.
- A single collision cross-section $\sigma_{XX}$ may fail to reproduce observations. Problems SIDM is designed to solve occur in galaxies of very different sizes and densities. A cross-section that works for small galaxies won’t fit data in large galaxies, and vice versa.

## 2) The primordial fluctuation spectrum may be tilted

Simplest models of inflation predict a Harrison-Zeldovich spectrum of perturbations - equal power on all scales. If the amplitude of perturbations was smaller on sub-galactic scales, fewer small objects would collapse, solving the substructure problem.

Initial WMAP results provided tentative evidence ($\sim 2\sigma$) for exactly this effect - a `running' spectral index.

Currently controversial, but:

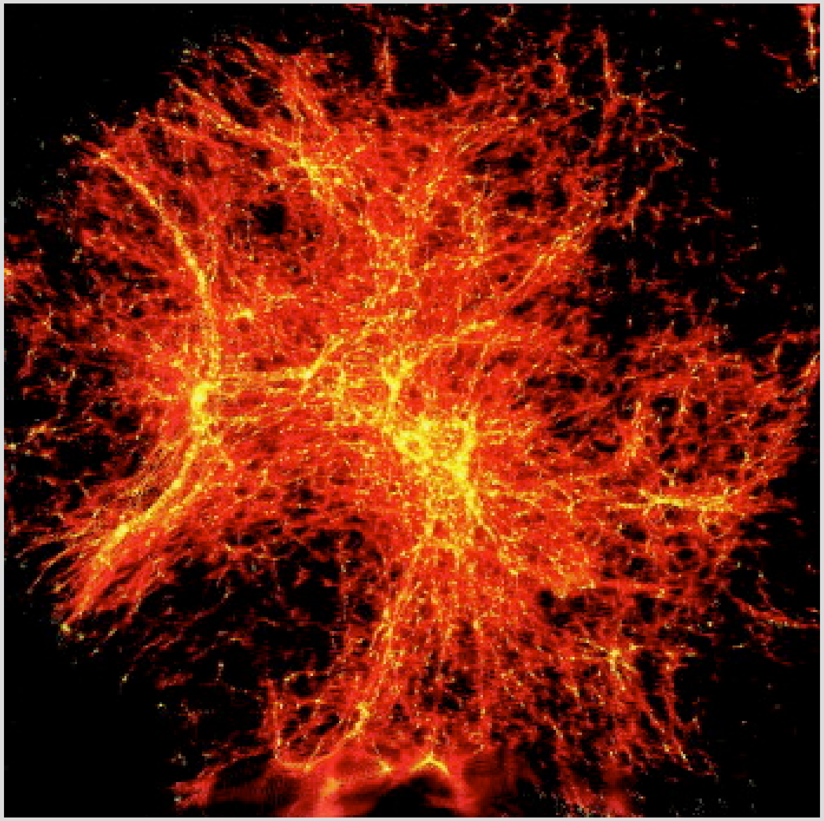
- Could be important for understanding of the very early universe
- Ought to be settled with further WMAP data

# Solutions that involve astrophysics

## 1) Small halos only rarely form galaxies

Basic idea: we don't know that the Milky Way has few satellites, only that it has few satellite *galaxies*.

- For small halos that collapsed after the Universe was reionized, potential well may not have been deep enough to capture significant amounts of gas
- An early generation of supernovae may have injected enough energy into the gas to blow it clear of the smallest halos, leaving them `dark'



Ideas seem very plausible - the dark matter that forms the Milky Way halo today was mostly distributed in many small objects at high redshift

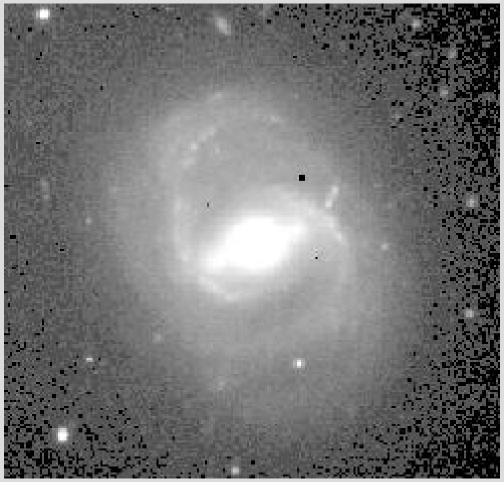
➡ vulnerable to the effects of reionization and supernovae

Ben Moore’s simulation

How could we detect a population of dark galaxies, if they exist?

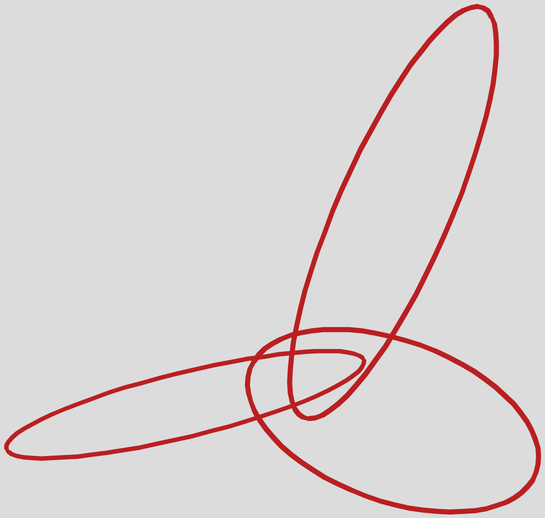
- Gravitational lensing? Problem is the low mass…
- Effects on normal galaxies - e.g. heating of the disk?

# 2) Effect of stellar bars on the dark matter density



Many galaxies today have stellar bars in their central regions.

Strong bars present when the galaxy was forming could influence the dark matter distribution at small radii.



Typical dark matter particle has a fairly eccentric orbit - additional of small amount of angular momentum transferred from the stellar bar will cause it to avoid the galaxy center

→ Reduces central density
Erases initially steep dark matter cusps