



Λ CDM: successes and failures

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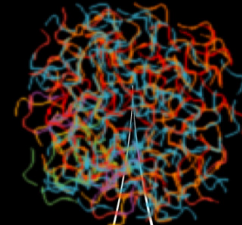




The initial conditions

INFLATION

$t=10^{-35}$ sec



QUANTUM
SPACE-TIME
FOAM?



$$p = -\rho$$

BLAP!

**THE ENTIRE
OBSERVABLE
UNIVERSE!**

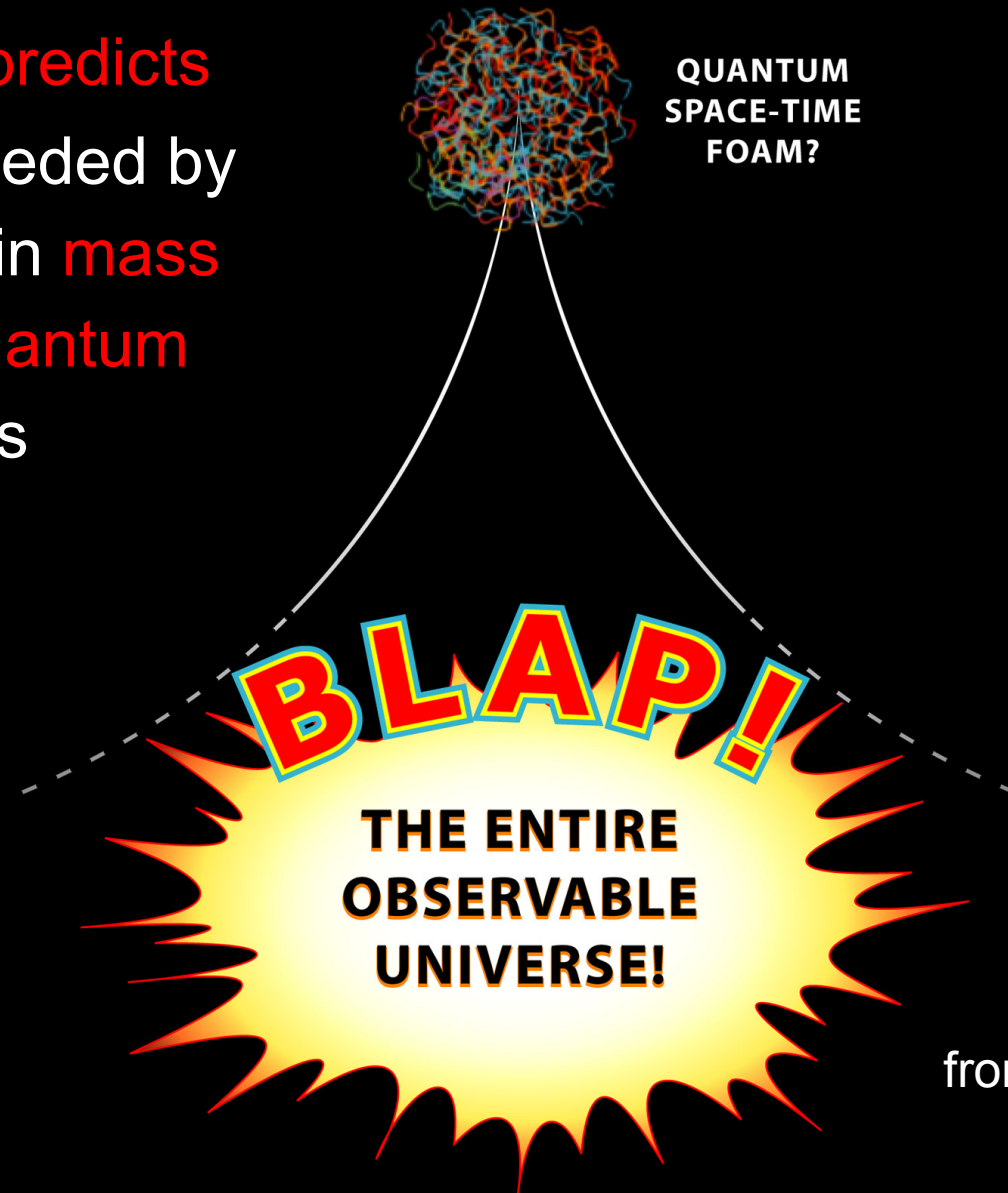
from G. Efstathiou

The initial conditions

INFLATION

$t=10^{-35}$ sec

Inflation theory **predicts**
early universe seeded by
tiny **fluctuations** in **mass**
produced by **quantum**
processes

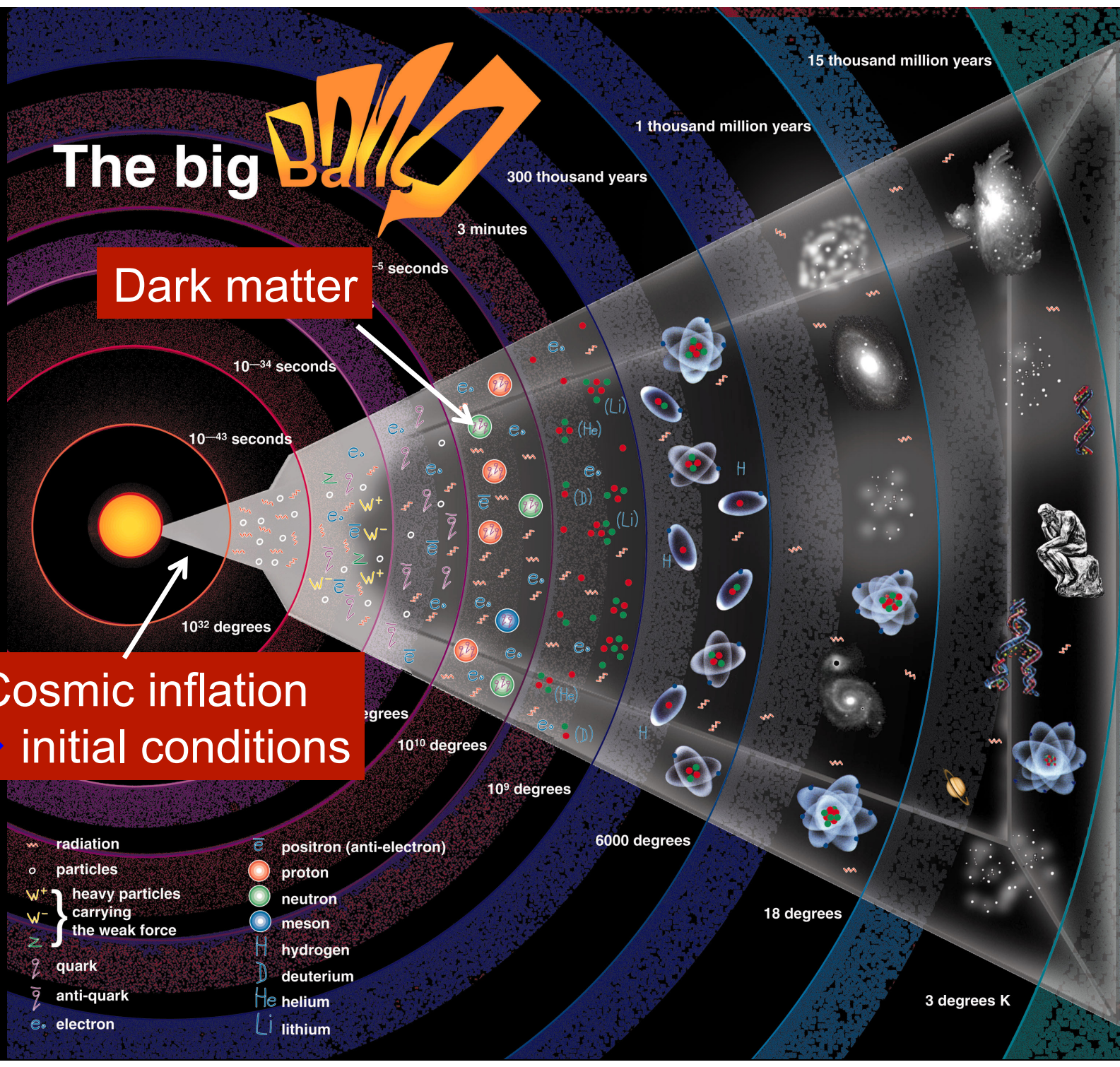


from G. Efstathiou

The big Bang

Dark matter

Cosmic inflation
→ initial conditions



- radiation
- particles
- heavy particles carrying the weak force
- quark
- anti-quark
- electron
- positron (anti-electron)
- proton
- neutron
- meson
- hydrogen
- deuterium
- helium
- lithium

Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm	sterile ν majoron	keV-MeV
cold	axion neutralino	10^{-5}eV- $>100\text{ GeV}$

The dark matter power spectrum

$k^3 P(k)$

Free streaming →

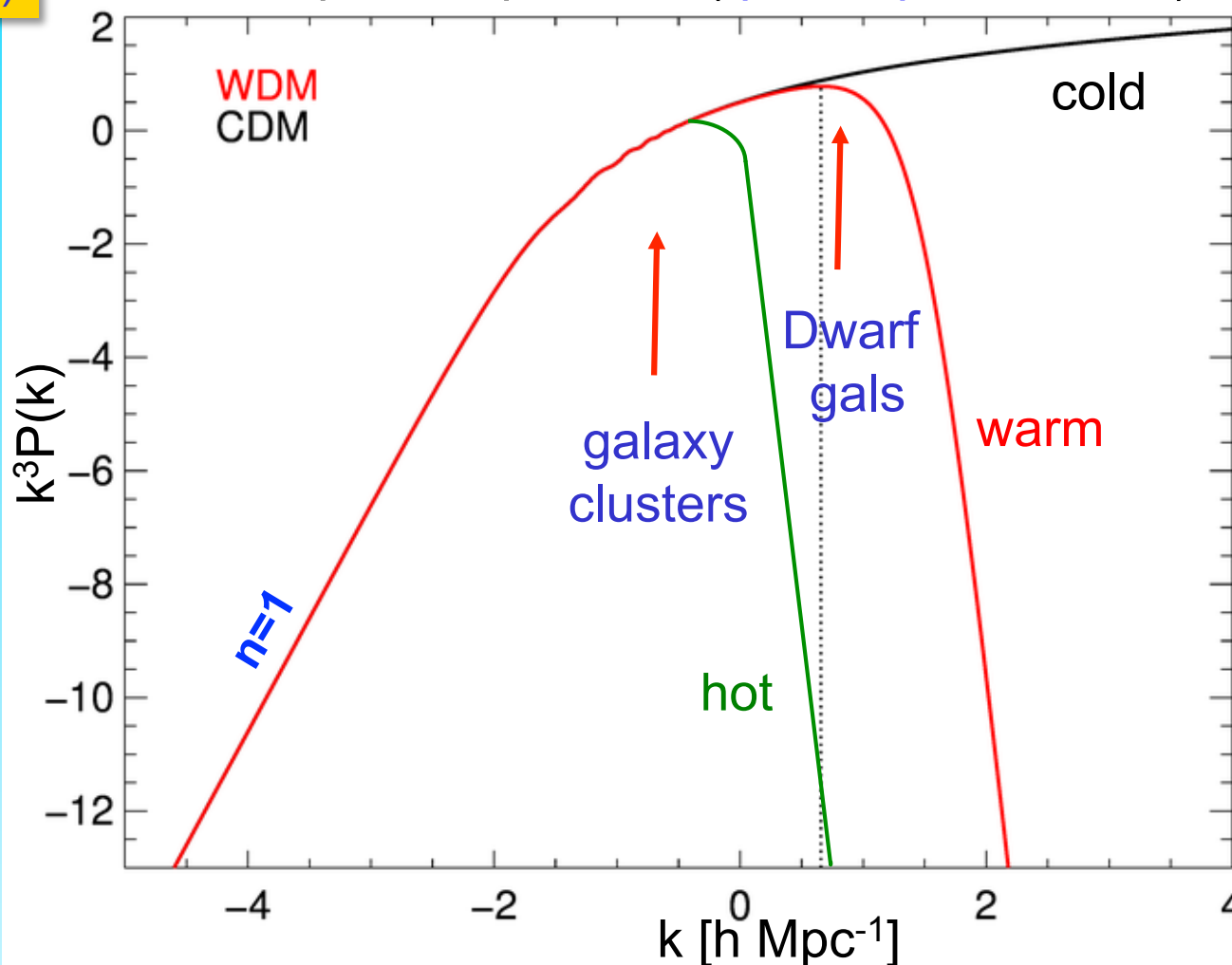
$\lambda_{\text{cut}} \propto m_x^{-1}$
for thermal relic

$m_{\text{CDM}} \sim 100 \text{ GeV}$
susy; $M_{\text{cut}} \sim 10^{-6} M_{\odot}$

$m_{\text{WDM}} \sim \text{few keV}$
sterile ν ; $M_{\text{cut}} \sim 10^9 M_{\odot}$

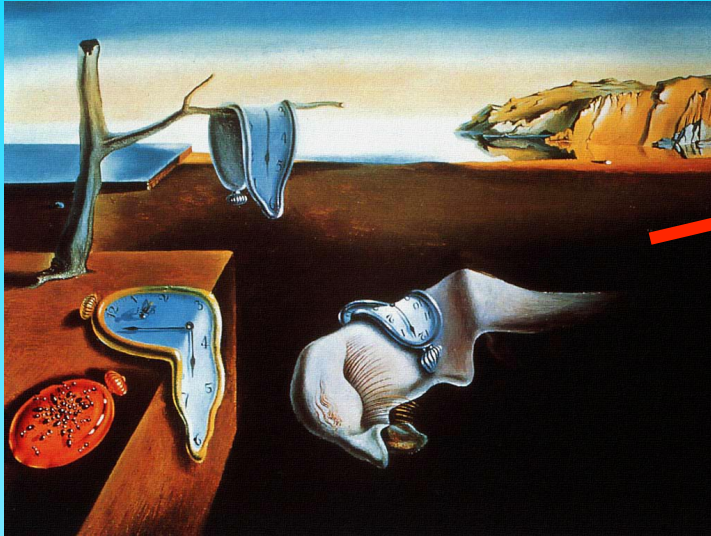
$m_{\text{HDM}} \sim \text{few eV}$
light ν ; $M_{\text{cut}} \sim 10^{15} M_{\odot}$

The linear power spectrum (“power per octave”)

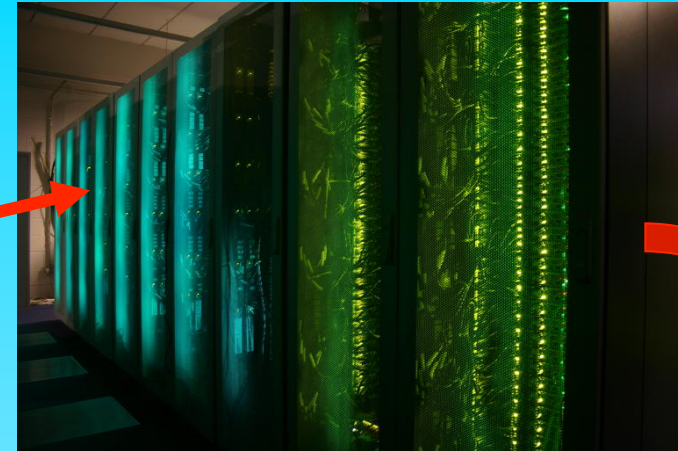


The formation of cosmic structure

$t=10^{-35}$ seconds



“Cosmology machine”



$t=380,000$ yrs

$\delta\rho/\rho \sim 10^{-5}$

Simulations

Supercomputer **simulations** are the best technique for calculating how small primordial **perturbations** grow into **galaxies** today



$t=13.8$ billion yrs

$\delta\rho/\rho \sim 1-10^6$

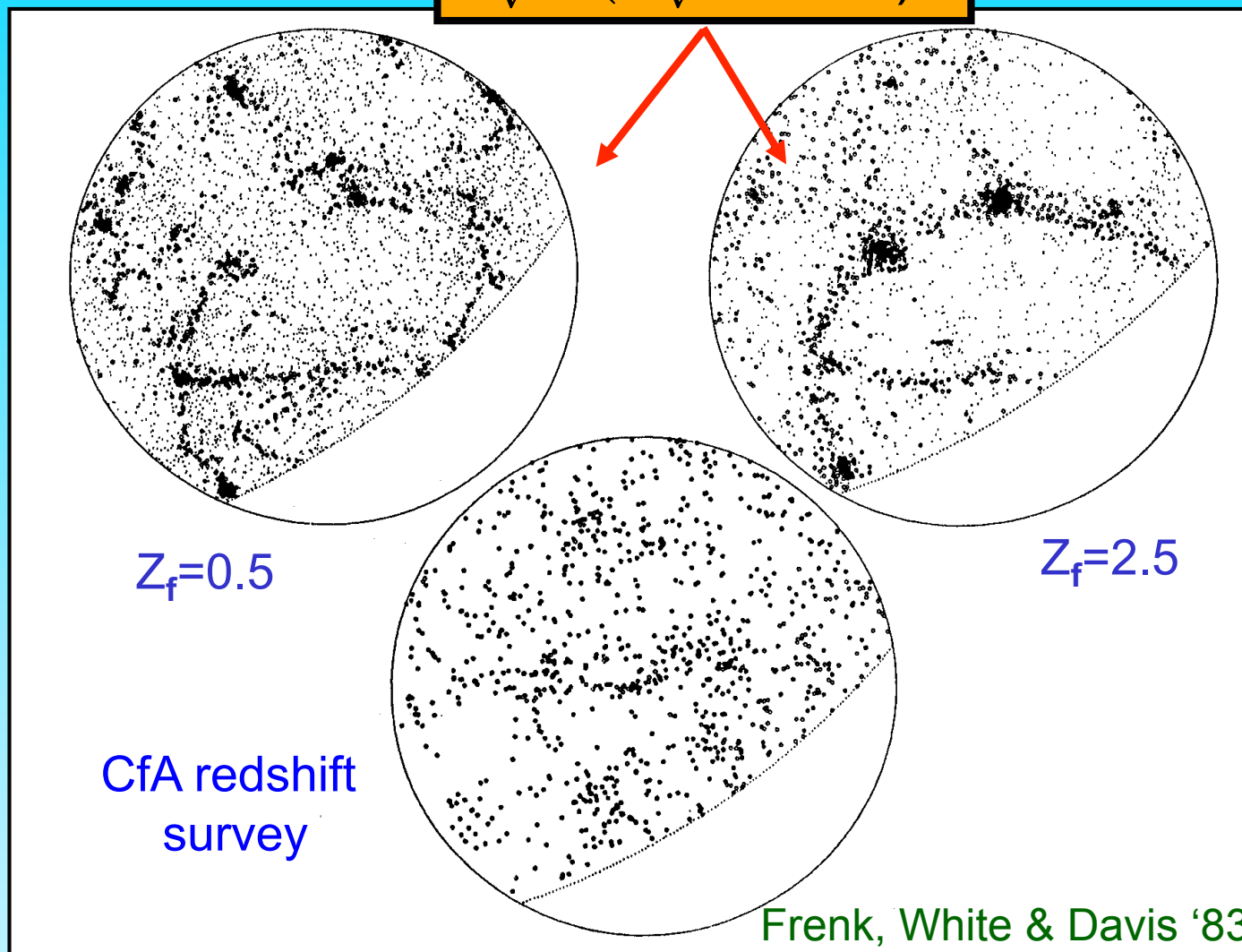
Neutrino (hot) dark matter

$$\Omega_{\nu}=1 \ (m_{\nu} = 30 \text{ eV})$$

Free-streaming length so large that superclusters form first and galaxies are too young



Neutrinos cannot make an appreciable contribution to Ω
 $\rightarrow m_{\nu} \ll 10 \text{ eV}$

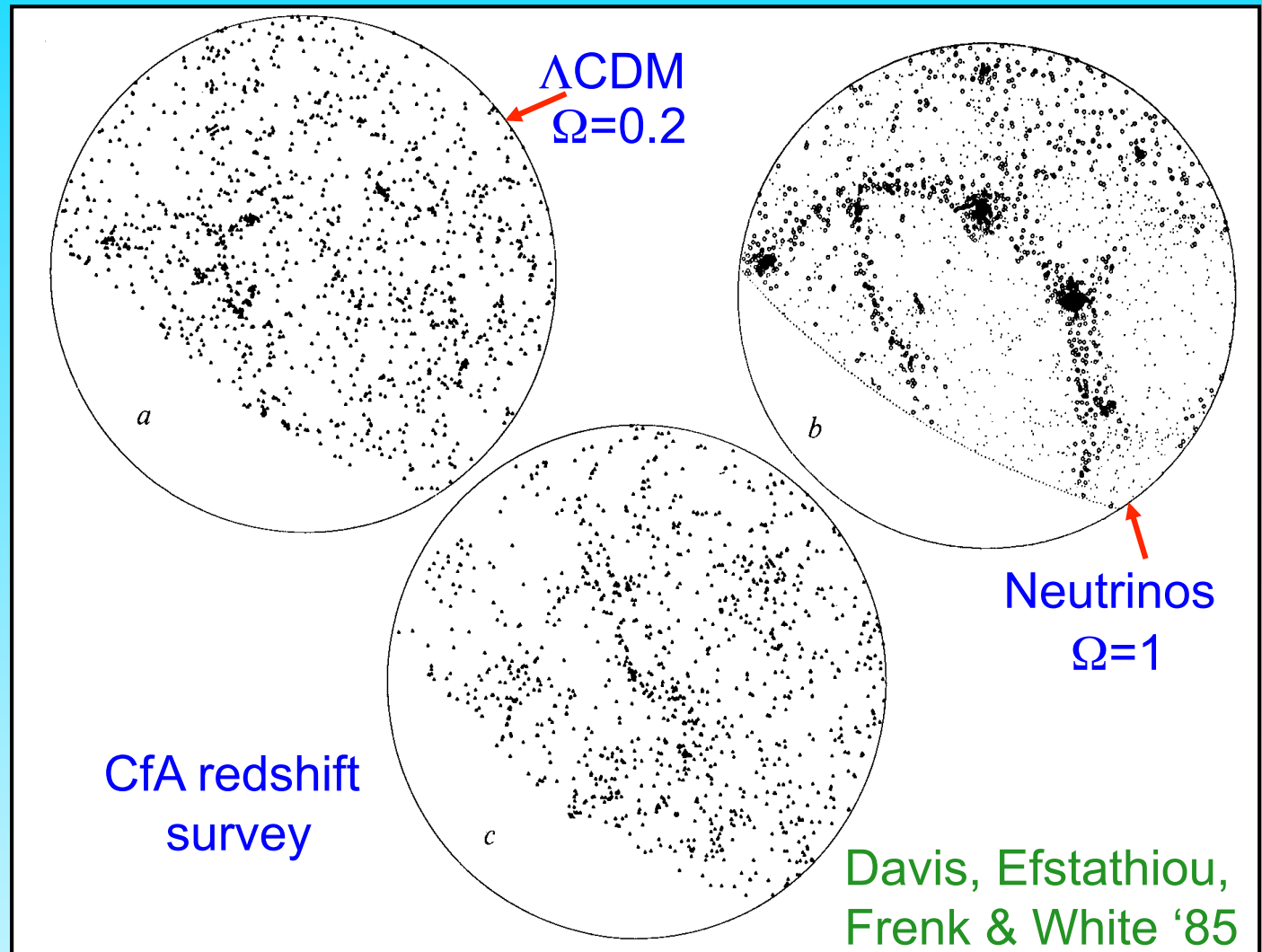


Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



Davis, Efstathiou,
Frenk & White '85

Non-baryonic dark matter candidates

Type example mass

hot	neutrino	a few eV
warm	sterile ν majoron	keV-MeV
cold	axion neutralino	10^{-5}eV- $>100\text{ GeV}$



The cold dark matter cosmogony

THE ASTROPHYSICAL JOURNAL, 263:L1-L5, 1982 December 1
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Peebles '82

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES

Joseph Henry Laboratories, Physics Department, Princeton University
Received 1982 July 2; accepted 1982 August 13

THE ASTROPHYSICAL JOURNAL, 292:371-394, 1985 May 15
© 1985. The American Astronomical Society. All rights reserved. Printed in U.S.A.

Davis, Efstathiou, Frenk & White 1985

THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

MARC DAVIS,^{1,2} GEORGE EFSTATHIOU,^{1,3} CARLOS S. FRENK,^{1,4} AND SIMON D. M. WHITE^{1,5}
Received 1984 August 20; accepted 1984 November 30

THE ASTROPHYSICAL JOURNAL, 304:15-61, 1986 May 1
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Bardeen, Bond, Kaiser & Szalay 1986

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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Physics Department, University of Washington

J. R. BOND¹

Physics Department, Stanford University

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Astronomy Department, University of California at Berkeley, and Institute of Astronomy, Cambridge University

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Astrophysics Group, Fermilab

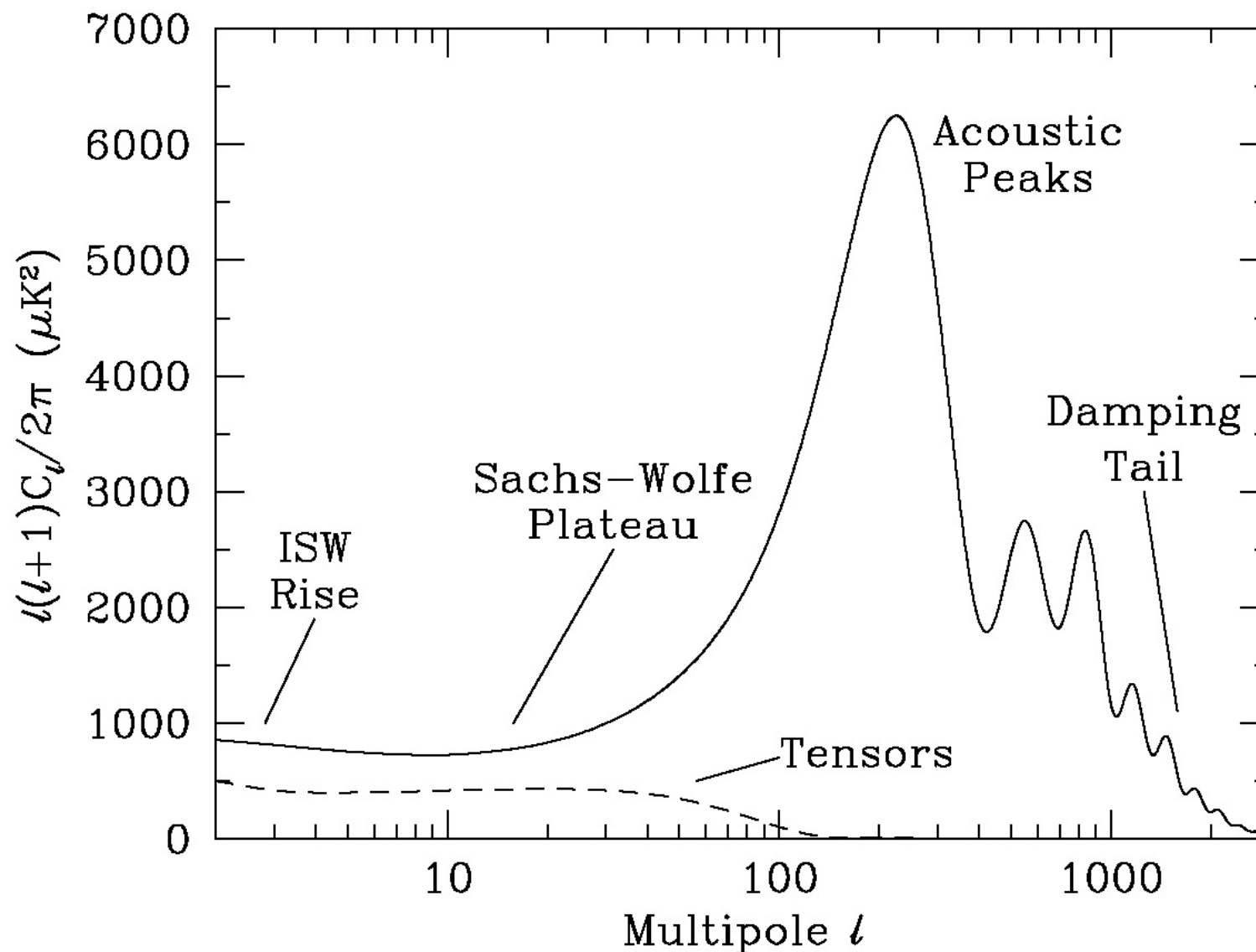
Received 1985 July 25; accepted 1985 October 9



Λ CDM model is an *a priori*
implausible model!

... but makes definite predictions and is therefore testable

Temperature anisotropies in CMB

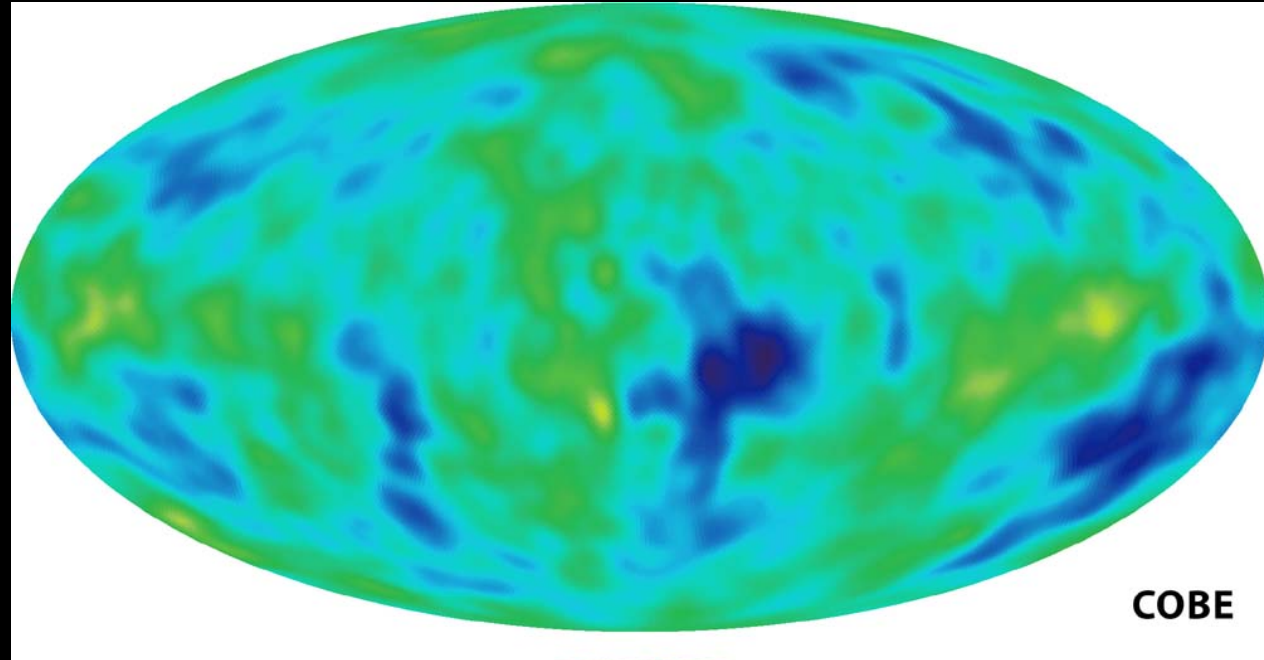


First calculated by Peebles '82



The CMB

1992



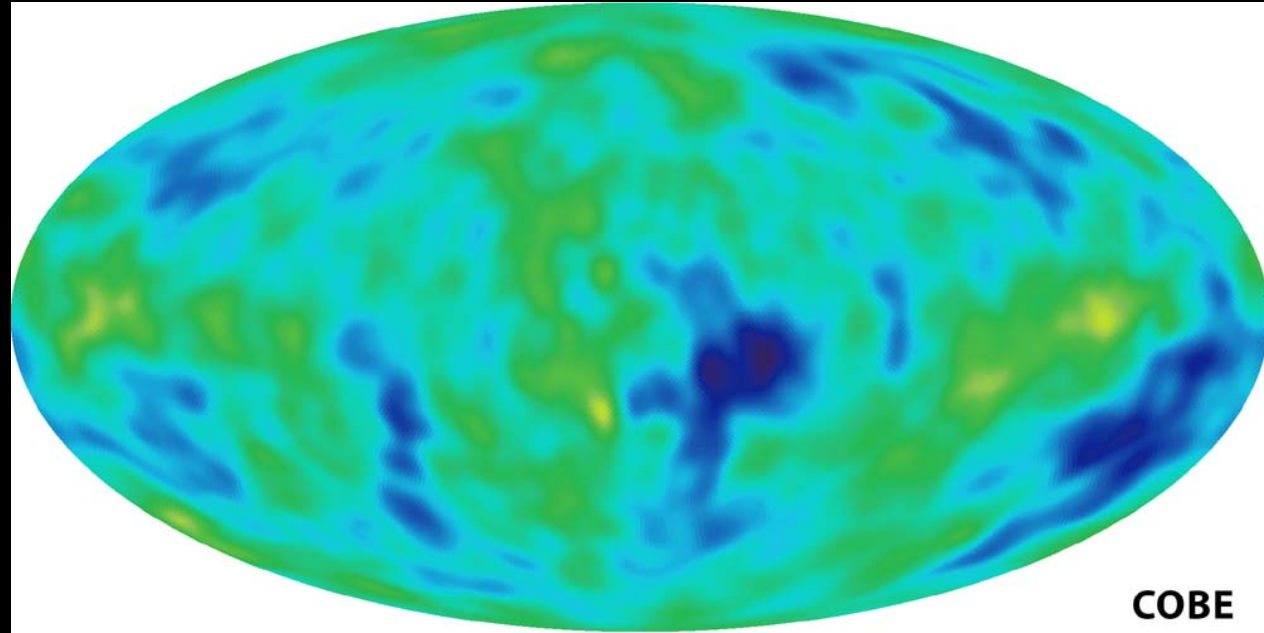
The cosmic microwave background radiation (CMB) provides a window to the universe at $t \sim 3 \times 10^5$ yrs

In 1992 COBE discovered temperature fluctuations ($\Delta T / T \sim 10^{-5}$) consistent with inflation predictions



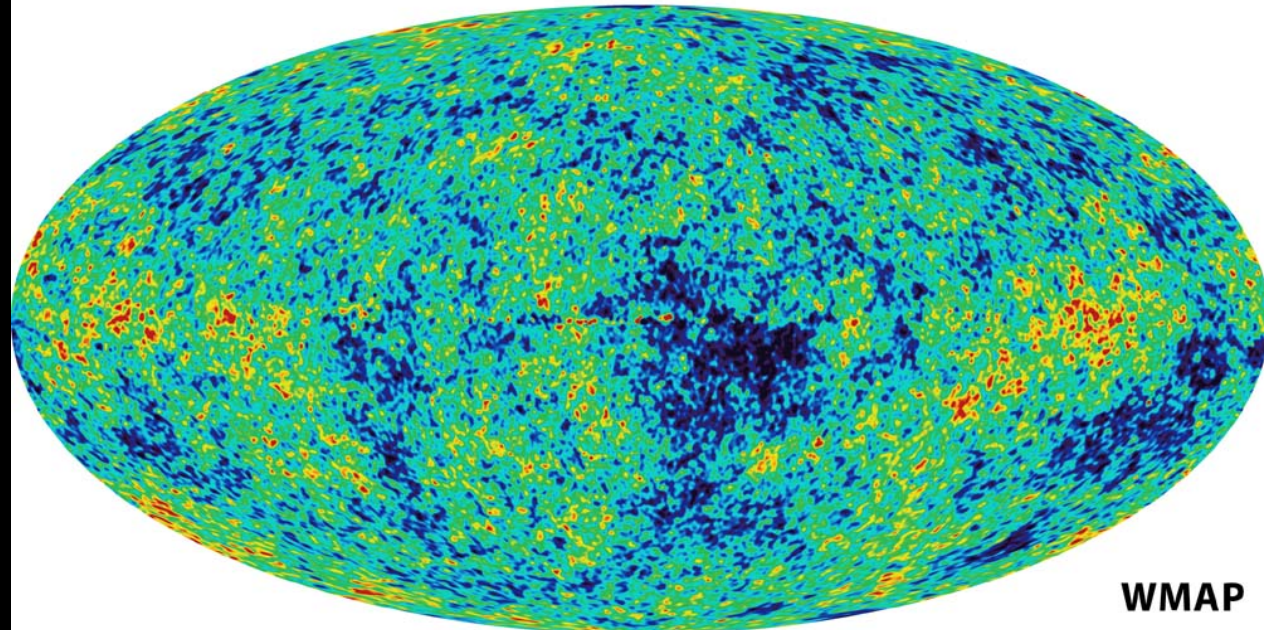
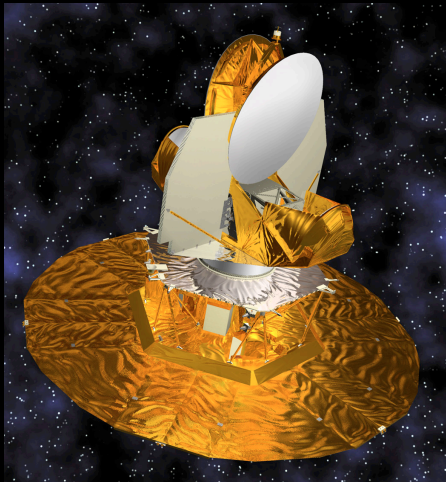
The CMB

1992



COBE

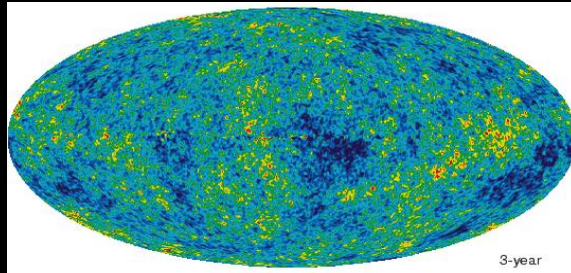
2003



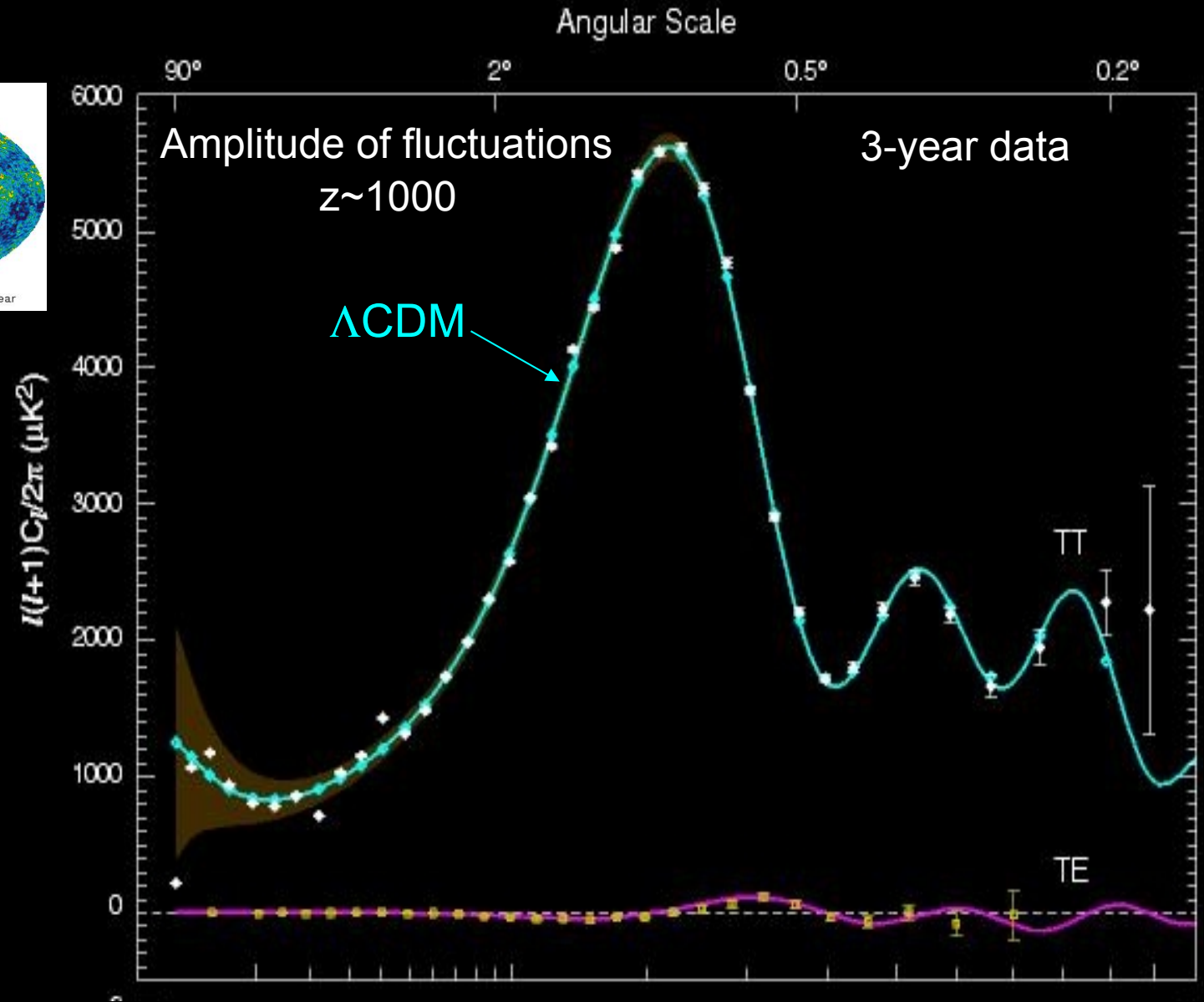
WMAP



WMAP temp anisotropies in CMB



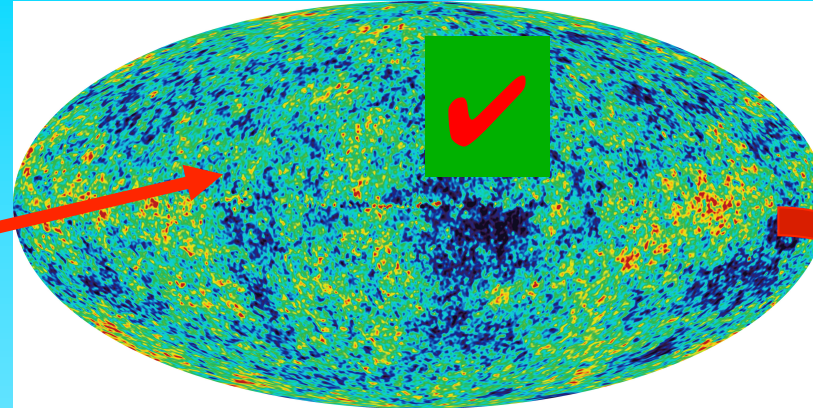
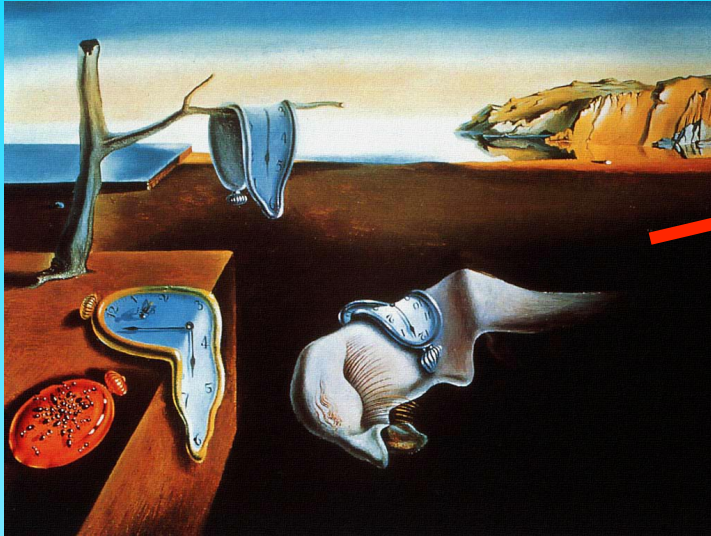
The data confirm
the theoretical
predictions



Hinshaw et al '06

The formation of cosmic structure

$t=10^{-35}$ seconds



$t=380,000$ yrs

$\delta\rho/\rho \sim 10^{-5}$

Simulations

Supercomputer **simulations** are the best technique for calculating how small primordial **perturbations** grow into **galaxies** today



$t=13.8$ billion yrs

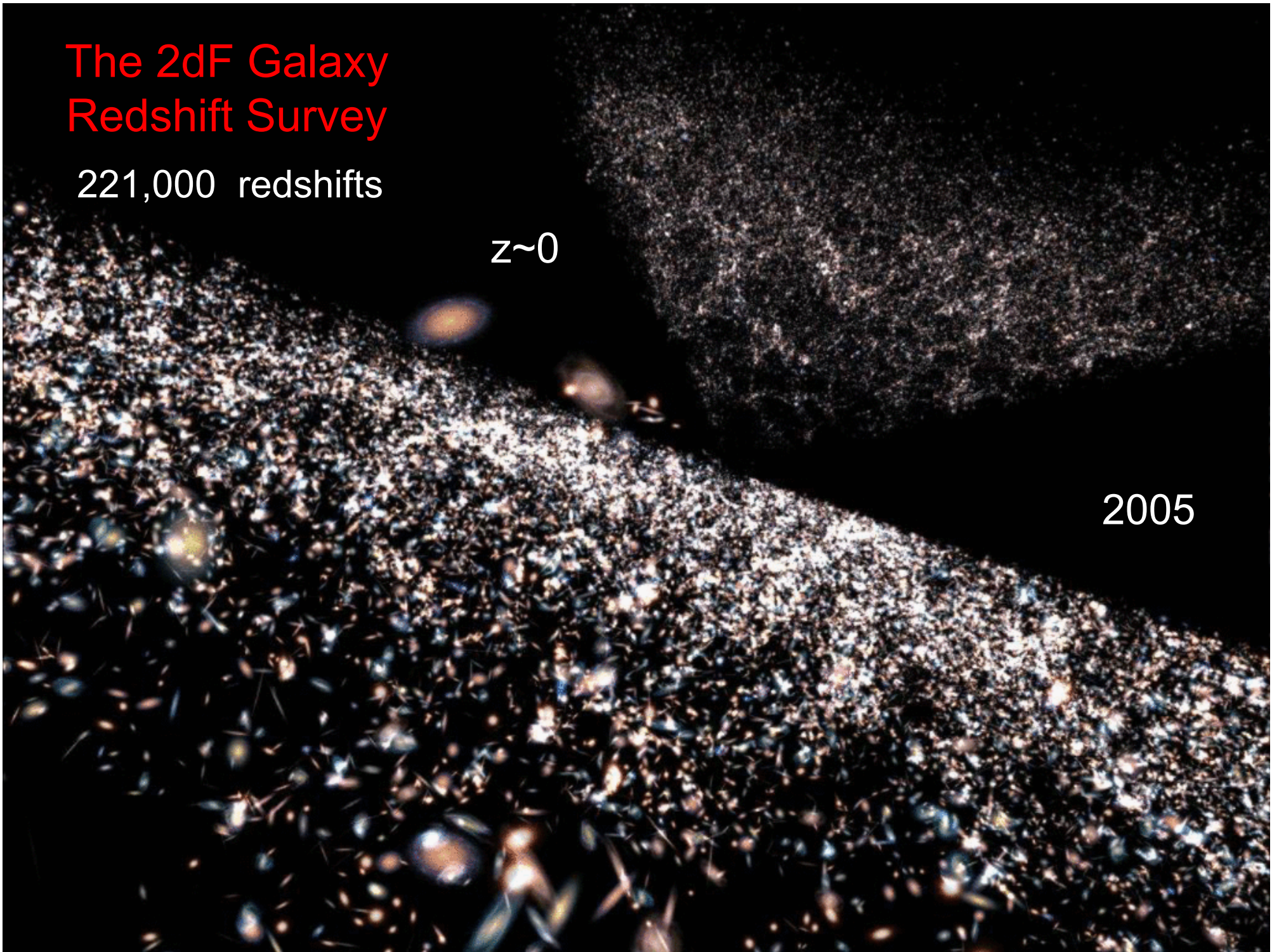
$\delta\rho/\rho \sim 1-10^6$

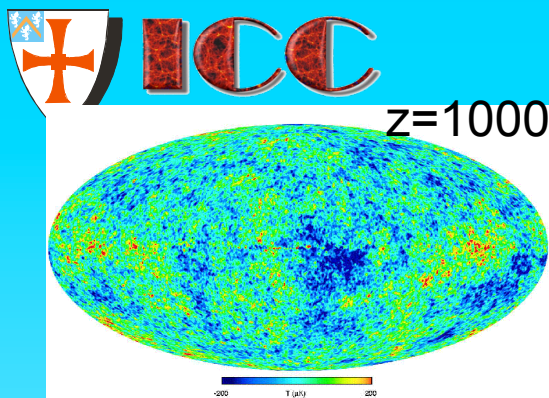
The 2dF Galaxy Redshift Survey

221,000 redshifts

$z \sim 0$

2005





Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter

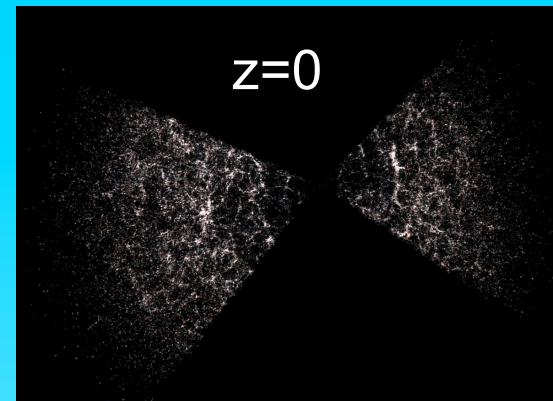


Primordial fluctuations

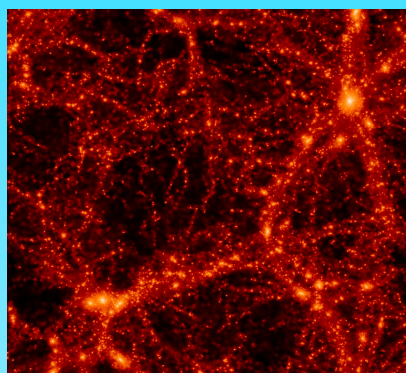
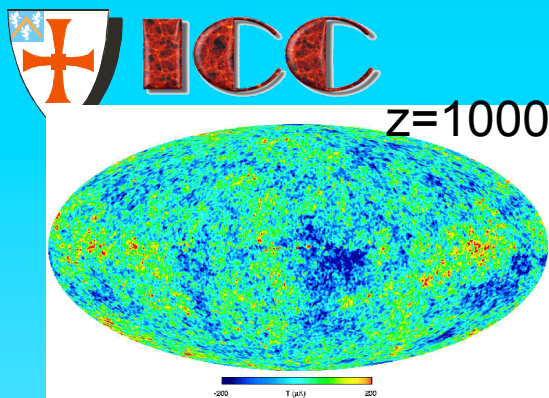
$\delta\rho/\rho(M, t)$



?



Formation and evolution of galaxies



Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter

Primordial fluctuations

$$\delta\rho/\rho(M, t)$$

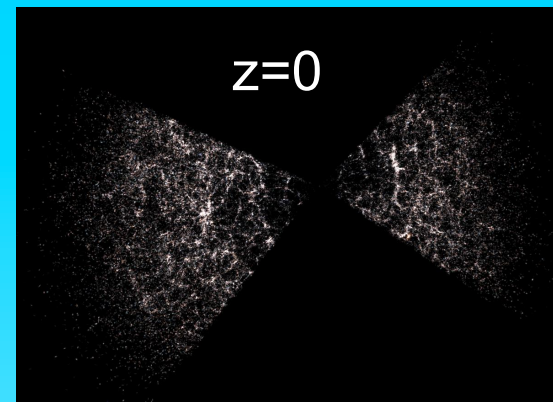
Dark matter halos
(N-body simulations)

Gas processes
(cooling, star formation, feedback)

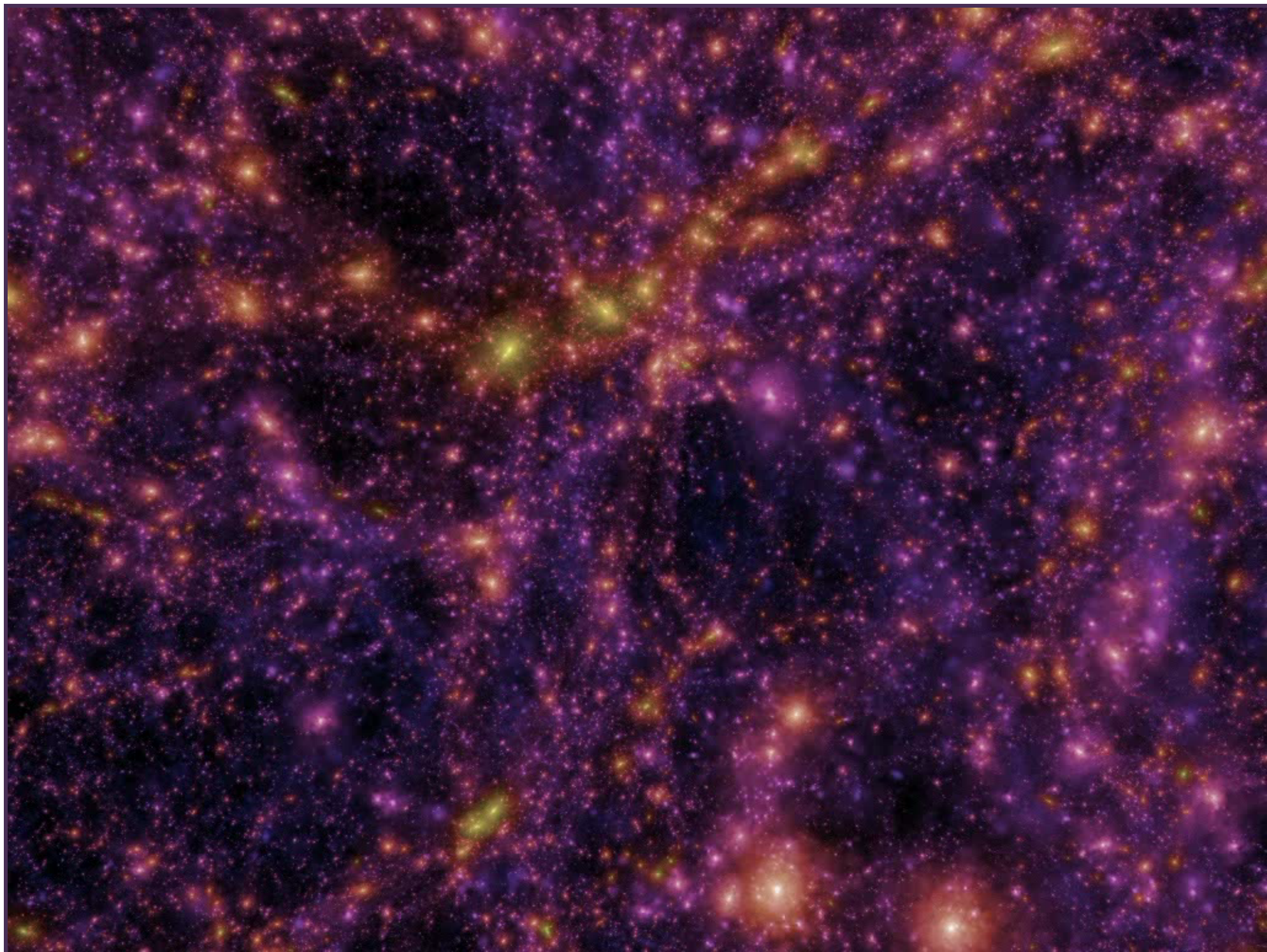
Gasdynamic simulations

Semi-analytics

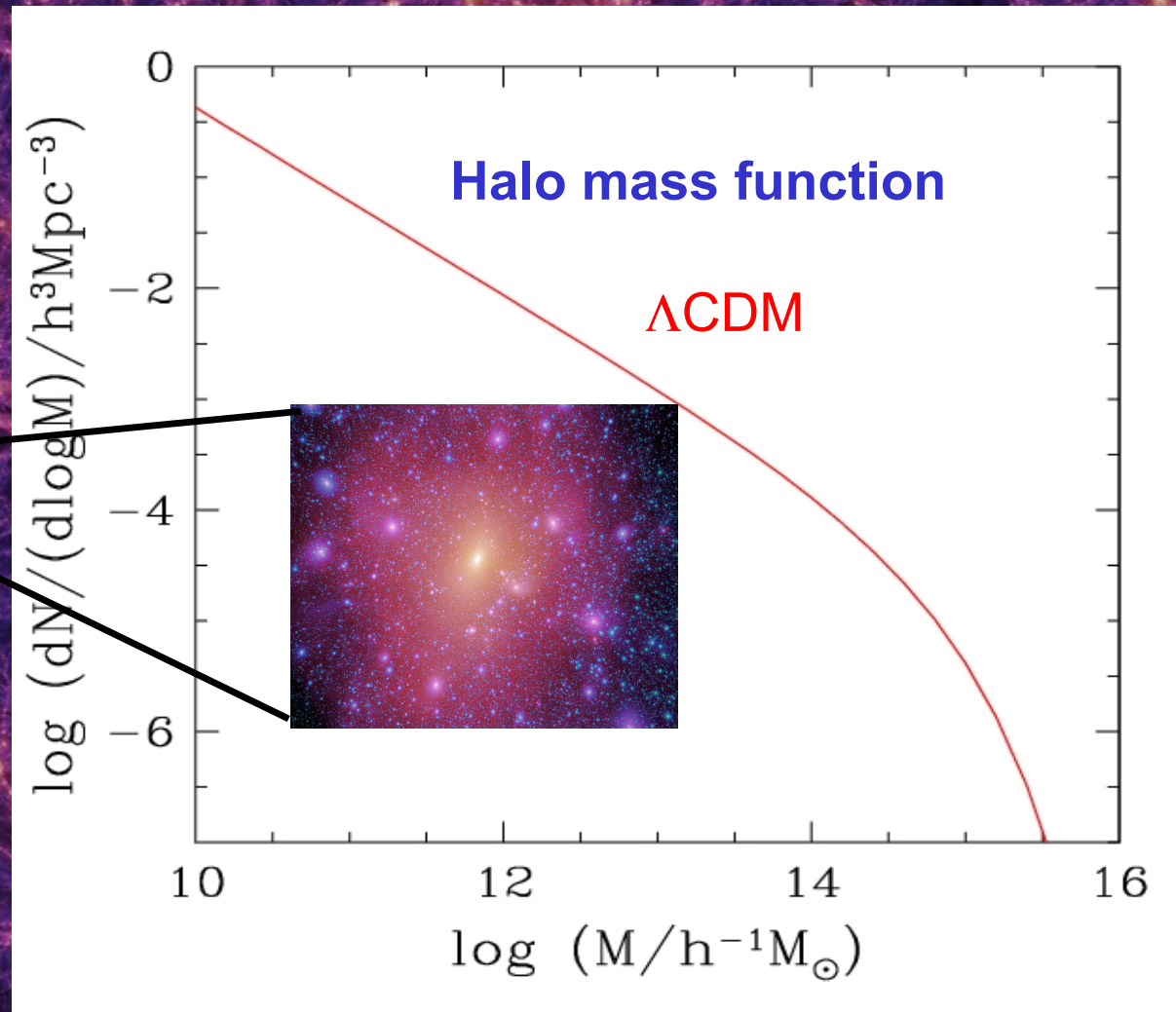
Formation and evolution of galaxies



Well understood



$z = 0$ Dark Matter



Springel et al 05



Modelling galaxy formation

Aim: follow history of galaxy formation *ab initio*, i.e starting from a cosmological model for structure formation so as to predict observables

Main baryonic processes:

- Shock-heating and radiative cooling of gas within halos

- Star formation and SN feedback

- Reionization

- Production & mixing of metals

- Evolution of stellar populations

- Dust obscuration

- AGN feedback

Need to use
phenomenological
models

$z = 0$ Dark Matter

Populating the MS with galaxies

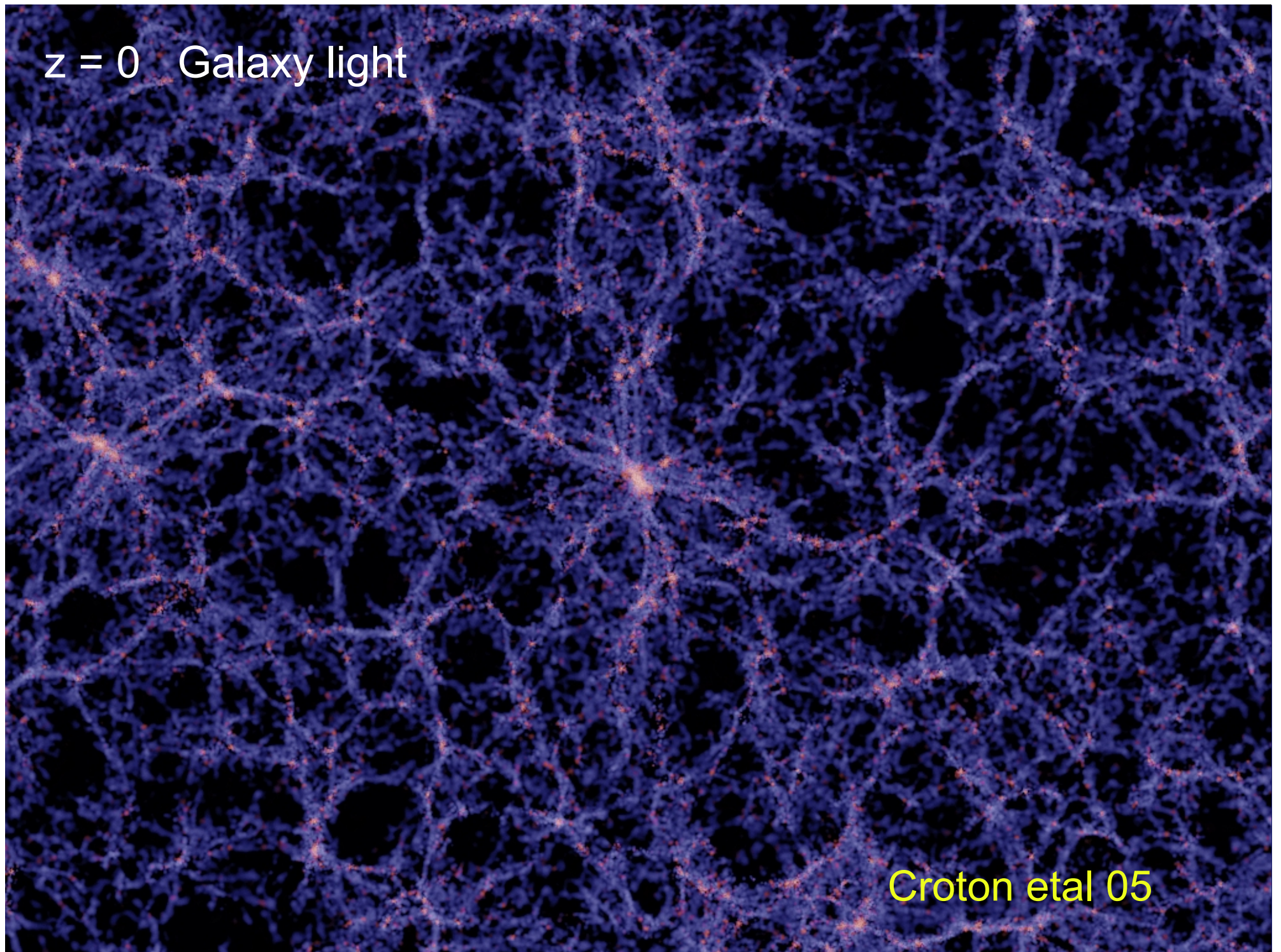
125 Mpc/h

Semi-analytic modelling

- Find dark matter halos
- Construct halo merger trees
- Apply SA model (gas cooling, star formation, feedback)

Springel et al 04

$z = 0$ Galaxy light



Croton et al 05

The 2dF Galaxy Redshift Survey

221,000 redshifts

$z \sim 0$

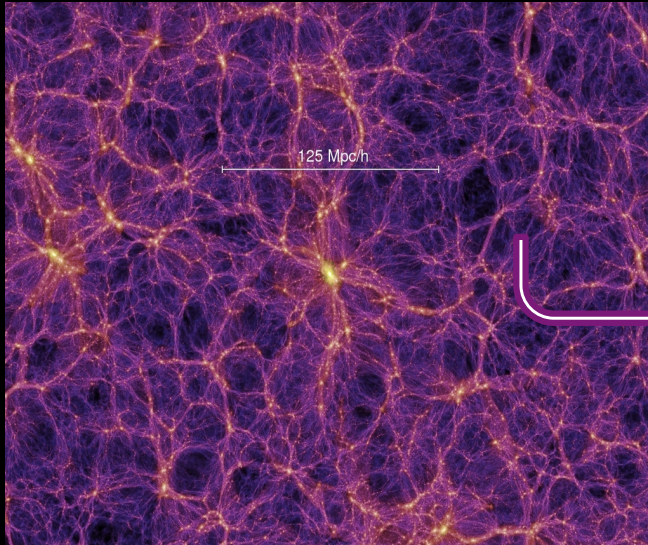
Three key tests:

- The galaxy luminosity function at $z=0$
- The evolution of the galaxy population
- The spatial distribution of galaxies

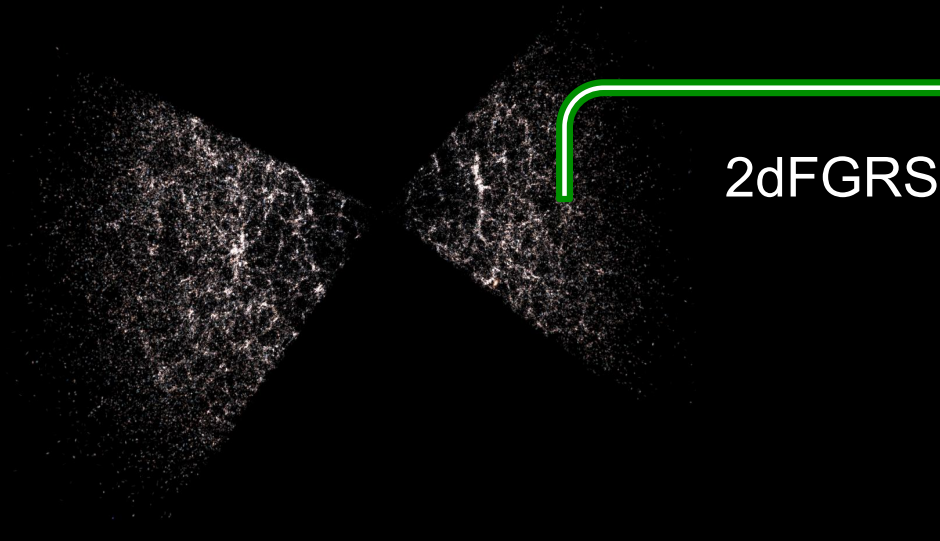
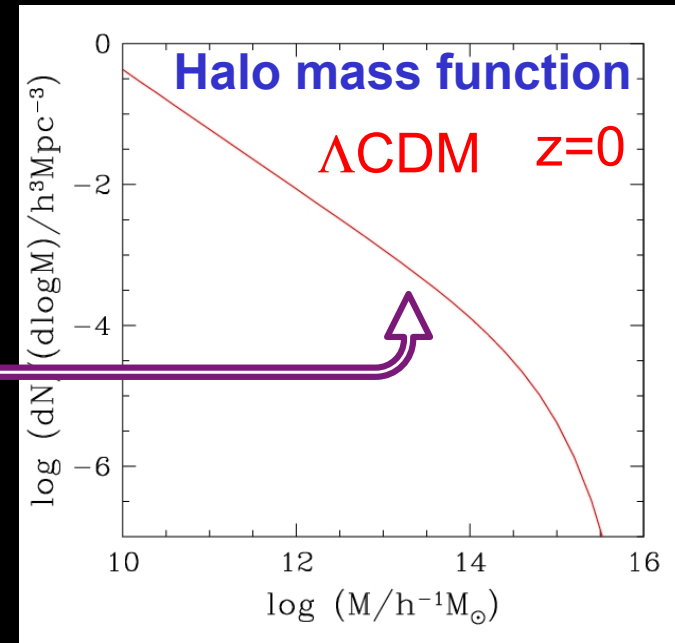
2005



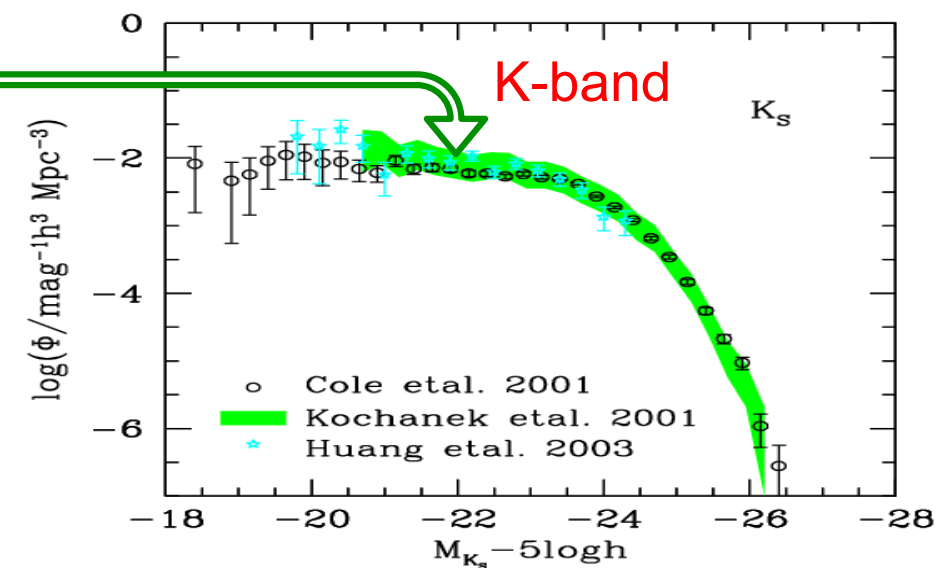
Abundance of gals & dark halos



Millennium run



2dFGRS

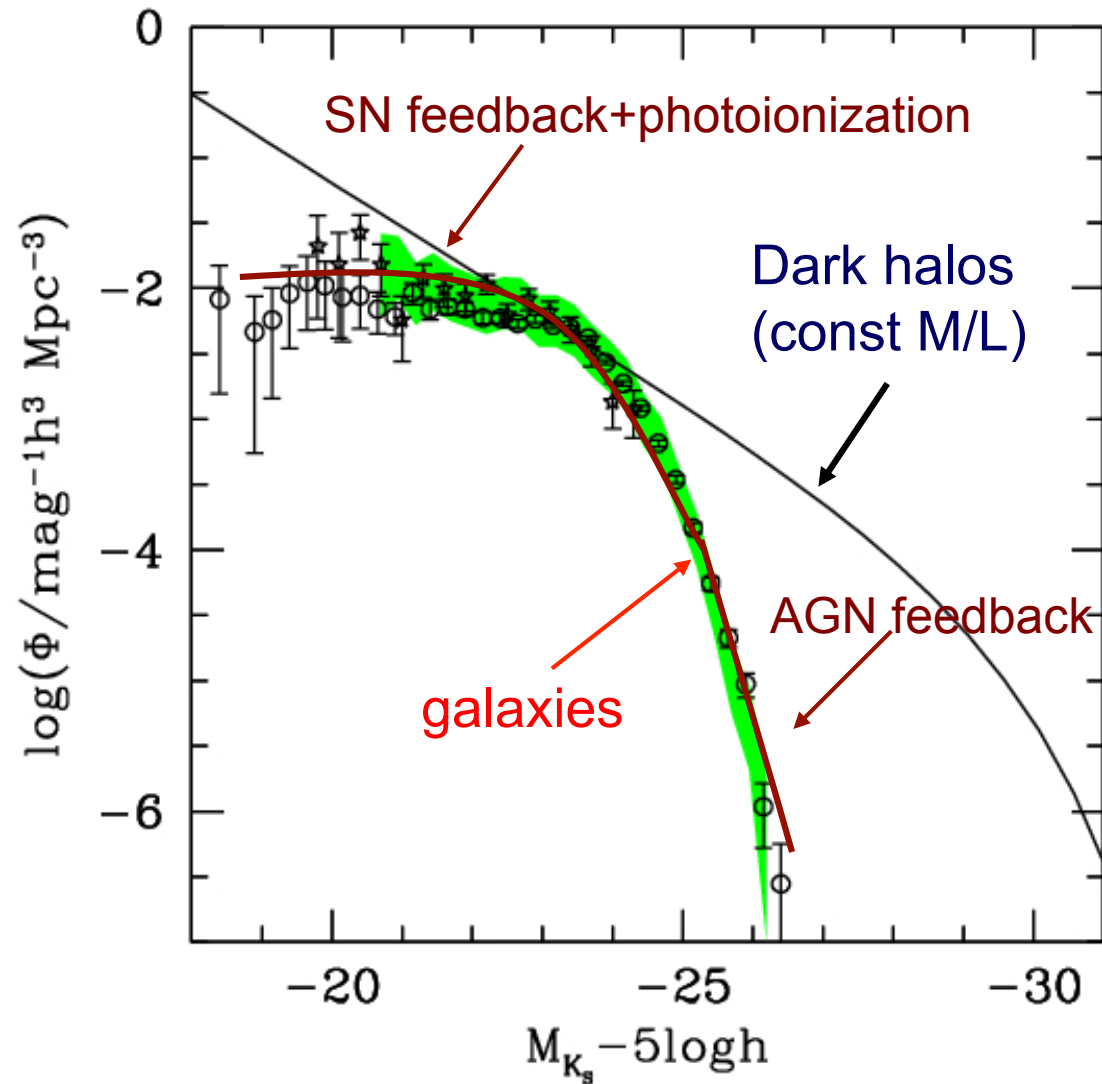


The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes



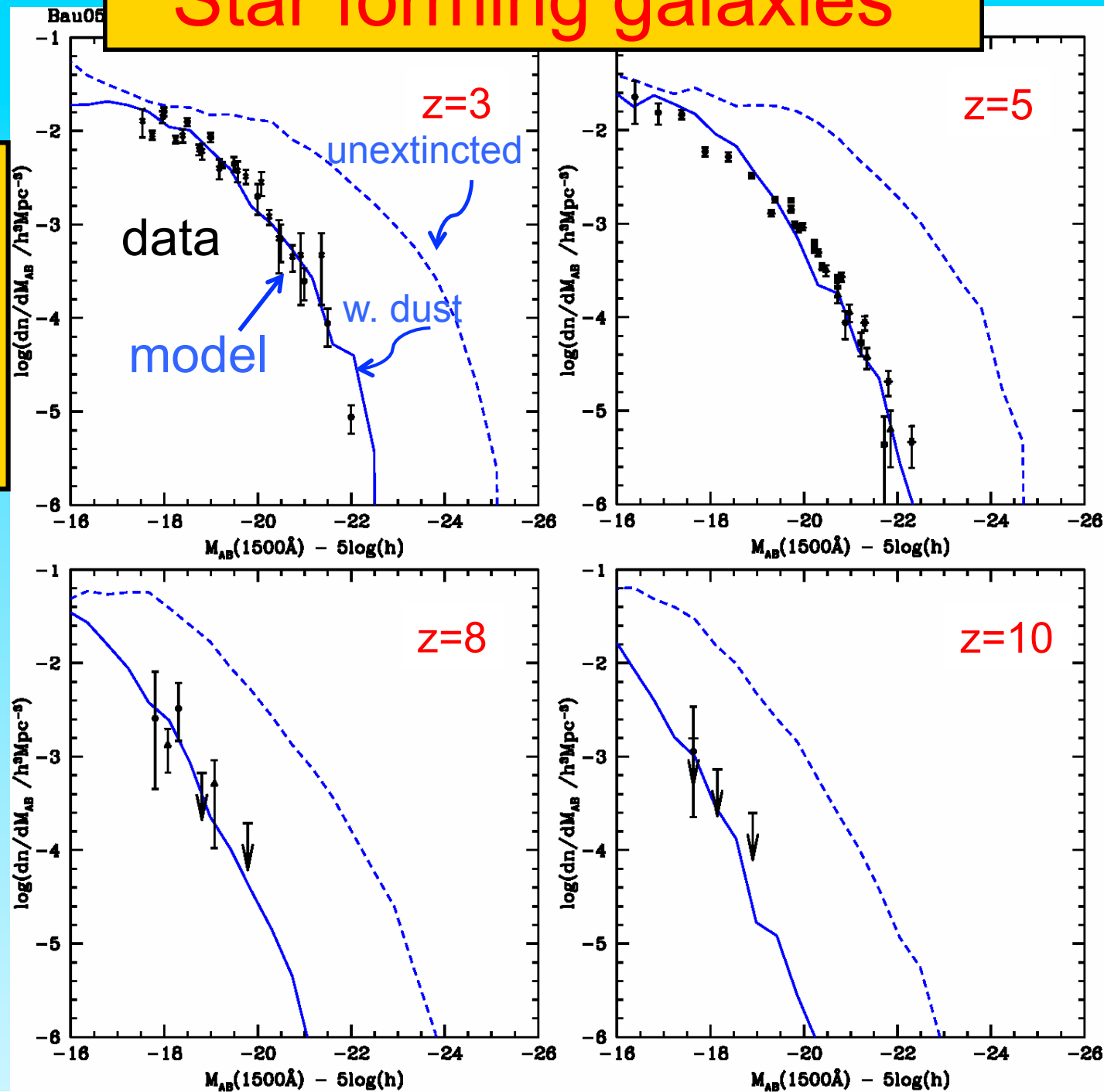
Complicated variation of M/L with halo mass



Star forming galaxies

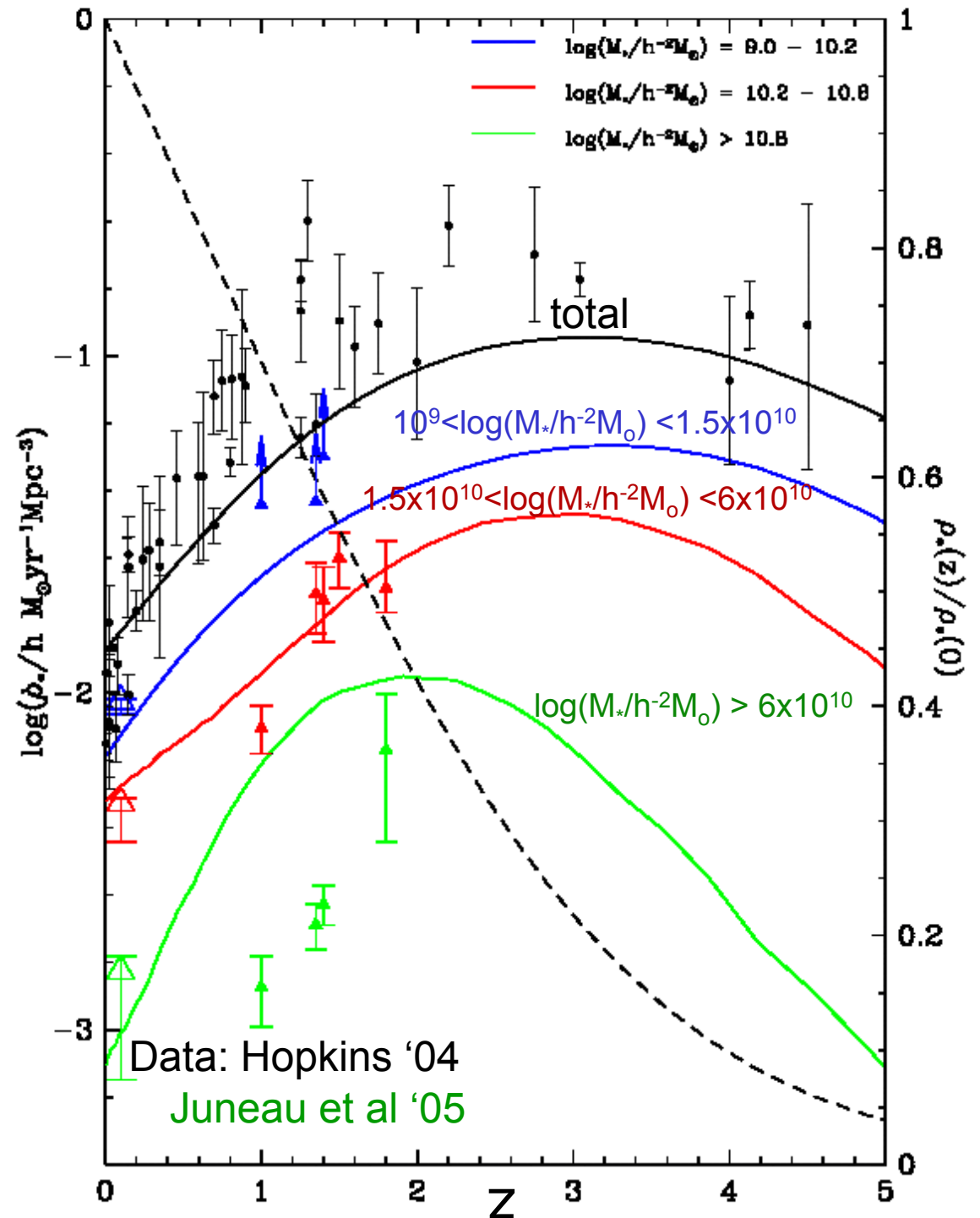
Evolution of Lyman-break galaxy lum. function

Lacey, Baugh, Frenk, Benson '11



History of cosmic star formation

Bower et al 06



2003: The 2dF Galaxy Redshift Survey

221,000 redshifts

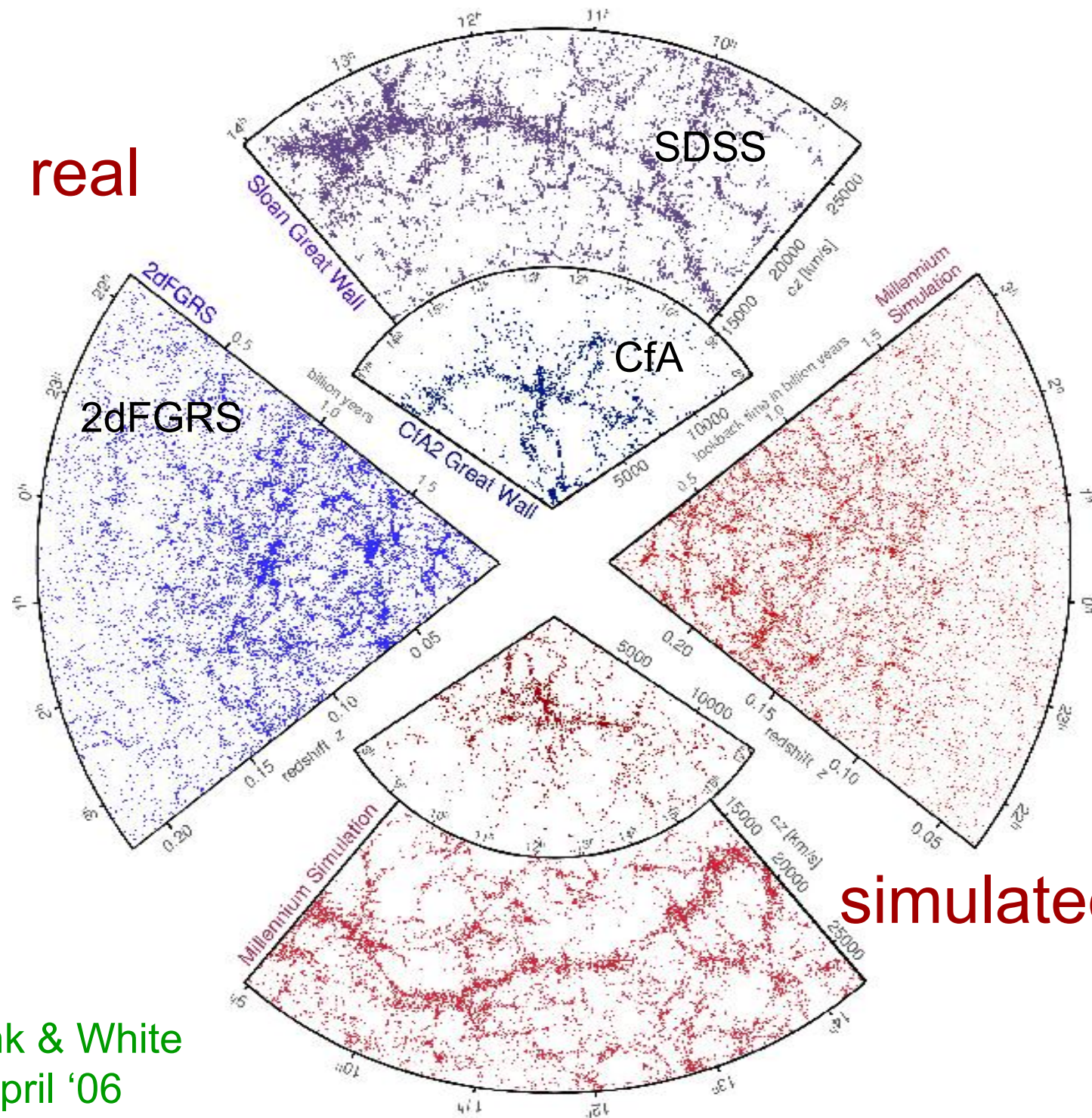
$z \sim 0$

Three key tests:

- The galaxy luminosity function at $z=0$ ✓
- The evolution of the galaxy population ✓
- The spatial distribution of galaxies

2005

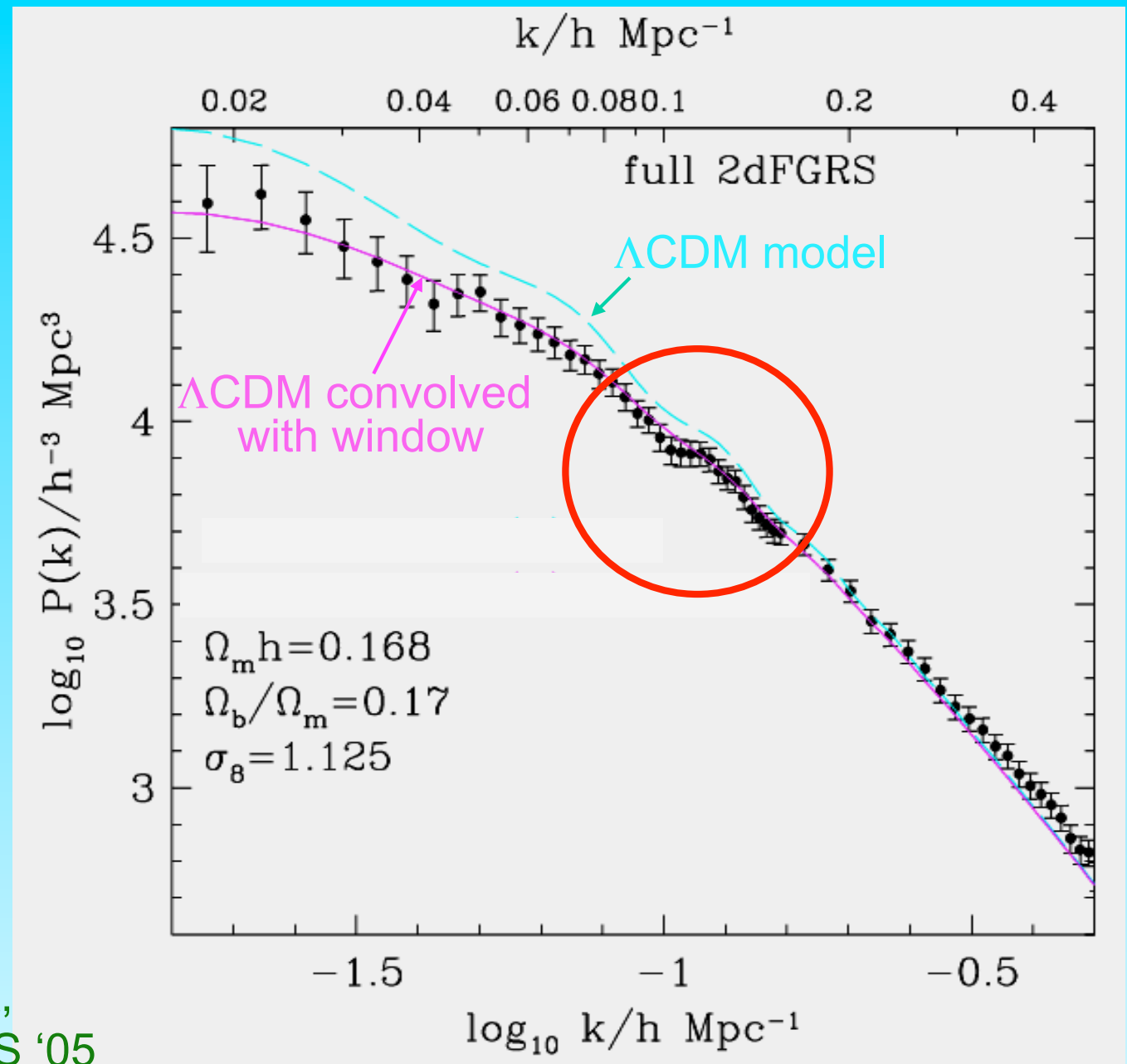
real



Springel, Frenk & White
Nature, April '06

The final 2dFGRS power spectrum

2dFGRS $P(k)$
well fit by Λ CDM
model convolved
with window
function



Cole, Percival, Peacock,
Baugh, Frenk + 2dFGRS '05

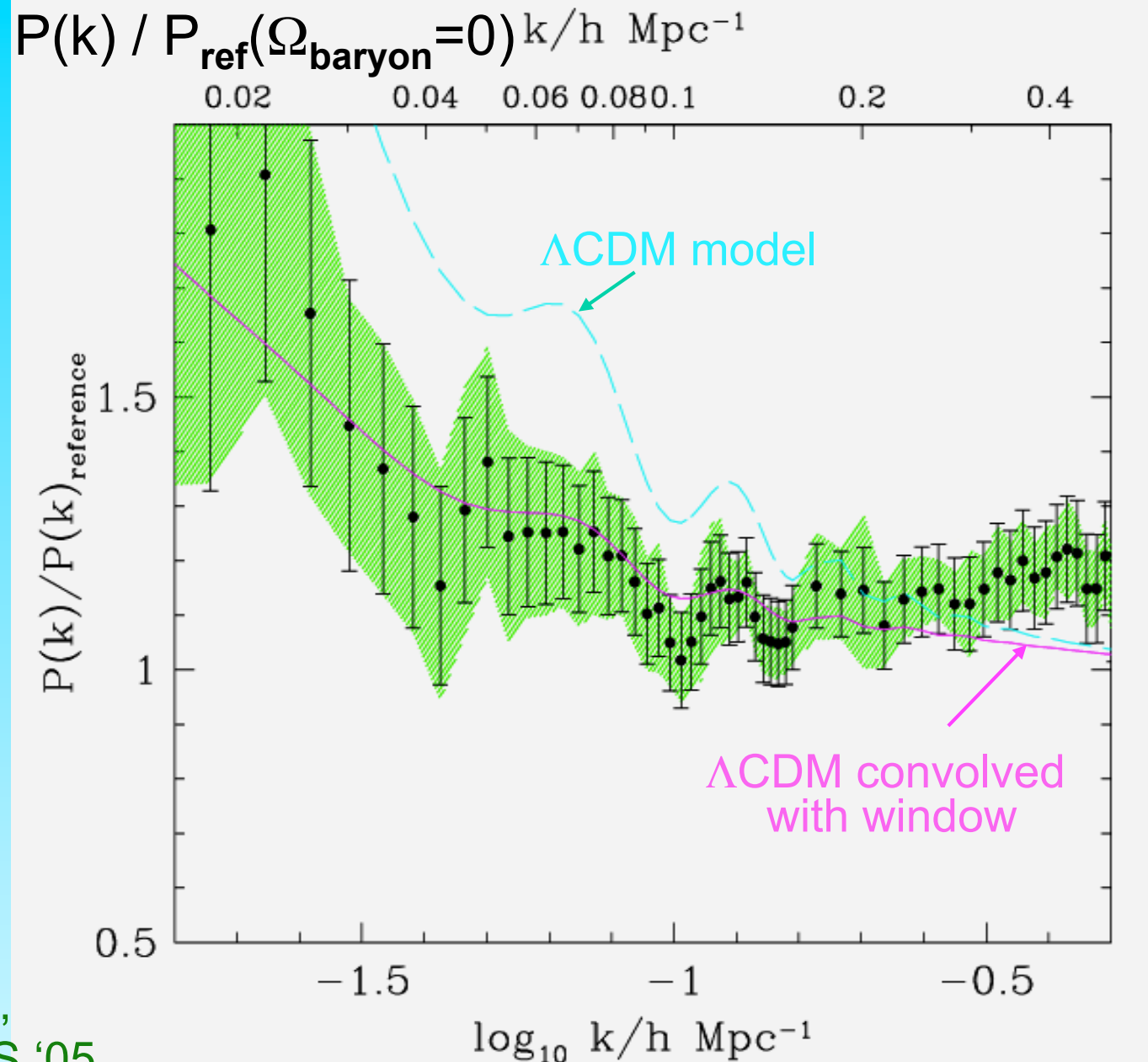
The final 2dFGRS power spectrum

Baryon oscillations
conclusively
detected in
2dFGRS!!!

Demonstrates that
structure grew by
gravitational
instability in Λ CDM
universe

Also detected in
SDSS LRG sample
(Eisenstein et al 05)

Cole, Percival, Peacock,
Baugh, Frenk + 2dFGRS '05

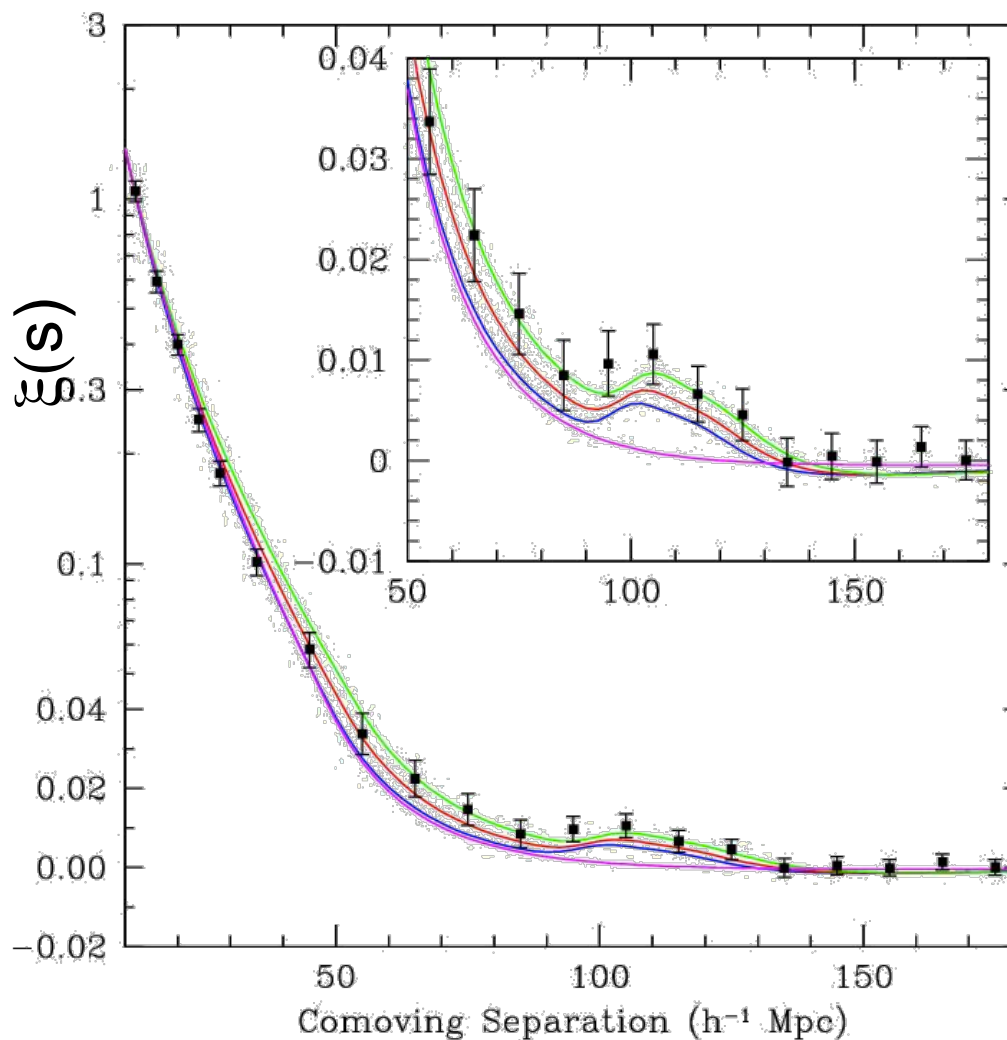


Again, CDM models fit the correlation function adequately well (although peak height is slightly too large; assuming $n_s=1$, $h=0.72$)

$$\Omega_b h^2 = 0.024,$$

$$\Omega_m h^2 = 0.133 \pm 0.011,$$

$$\Rightarrow \Omega_b / \Omega_m = 0.18$$



Eisenstein et al. 05

2003: The 2dF Galaxy Redshift Survey

221,000 redshifts

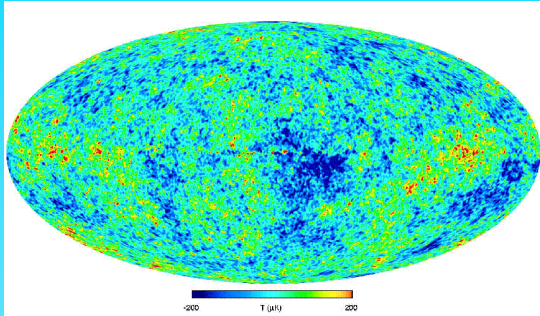
$z \sim 0$

Three key tests:

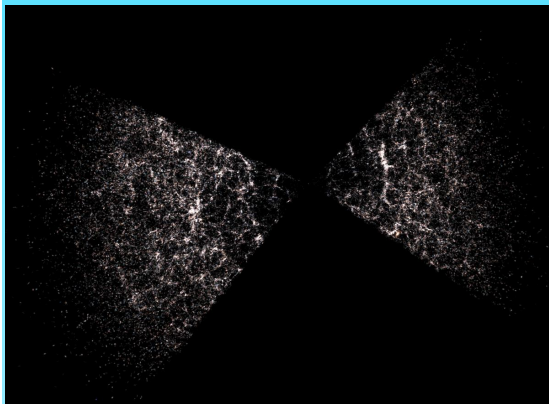
- The galaxy luminosity function at $z=0$ ✓
- The evolution of the galaxy population ✓
- The spatial distribution of galaxies ✓

2005

The cosmic power spectrum: from the CMB to the 2dFGRS



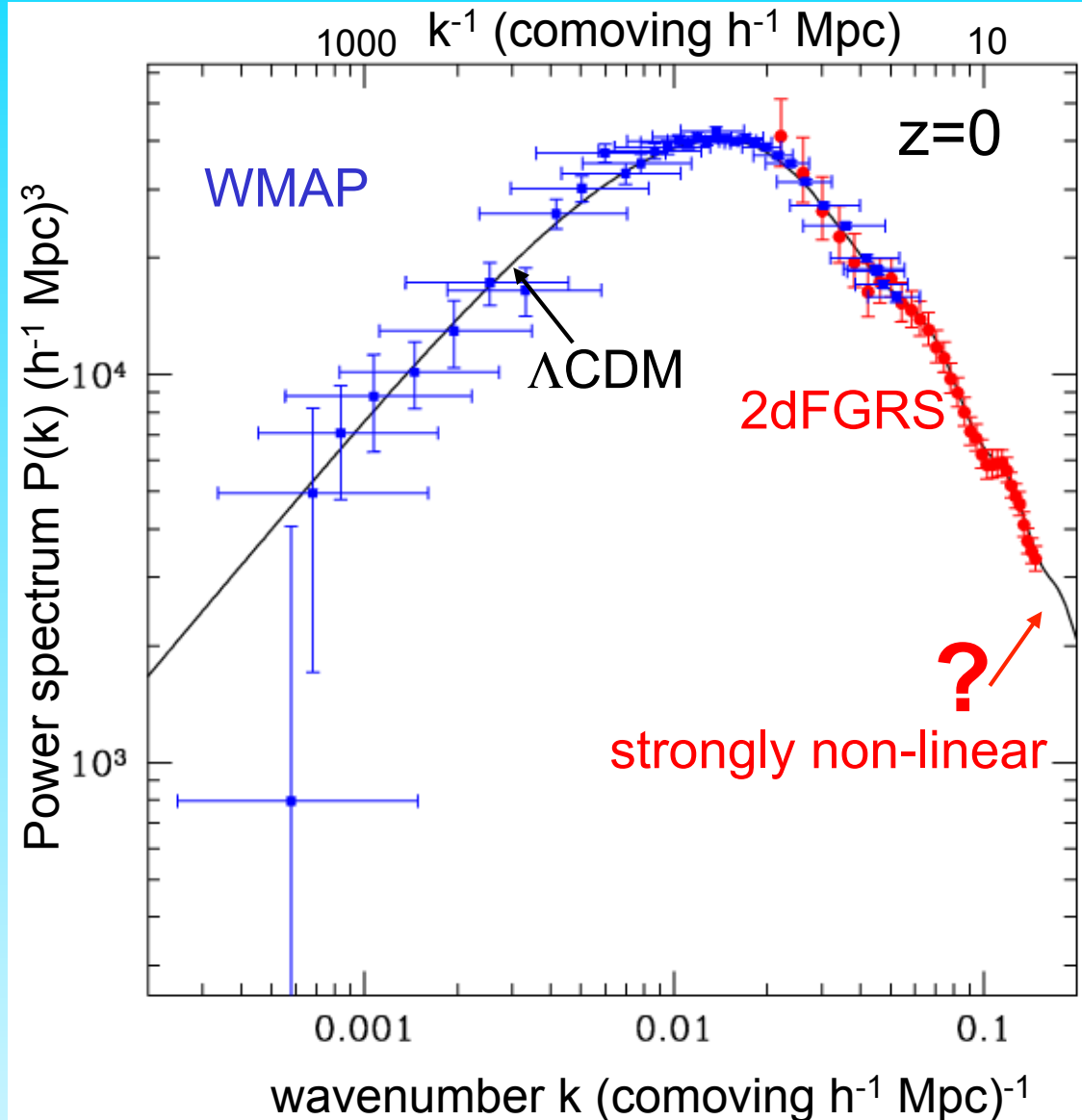
$z \sim 1000$



$z \sim 0$

⇒ Λ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

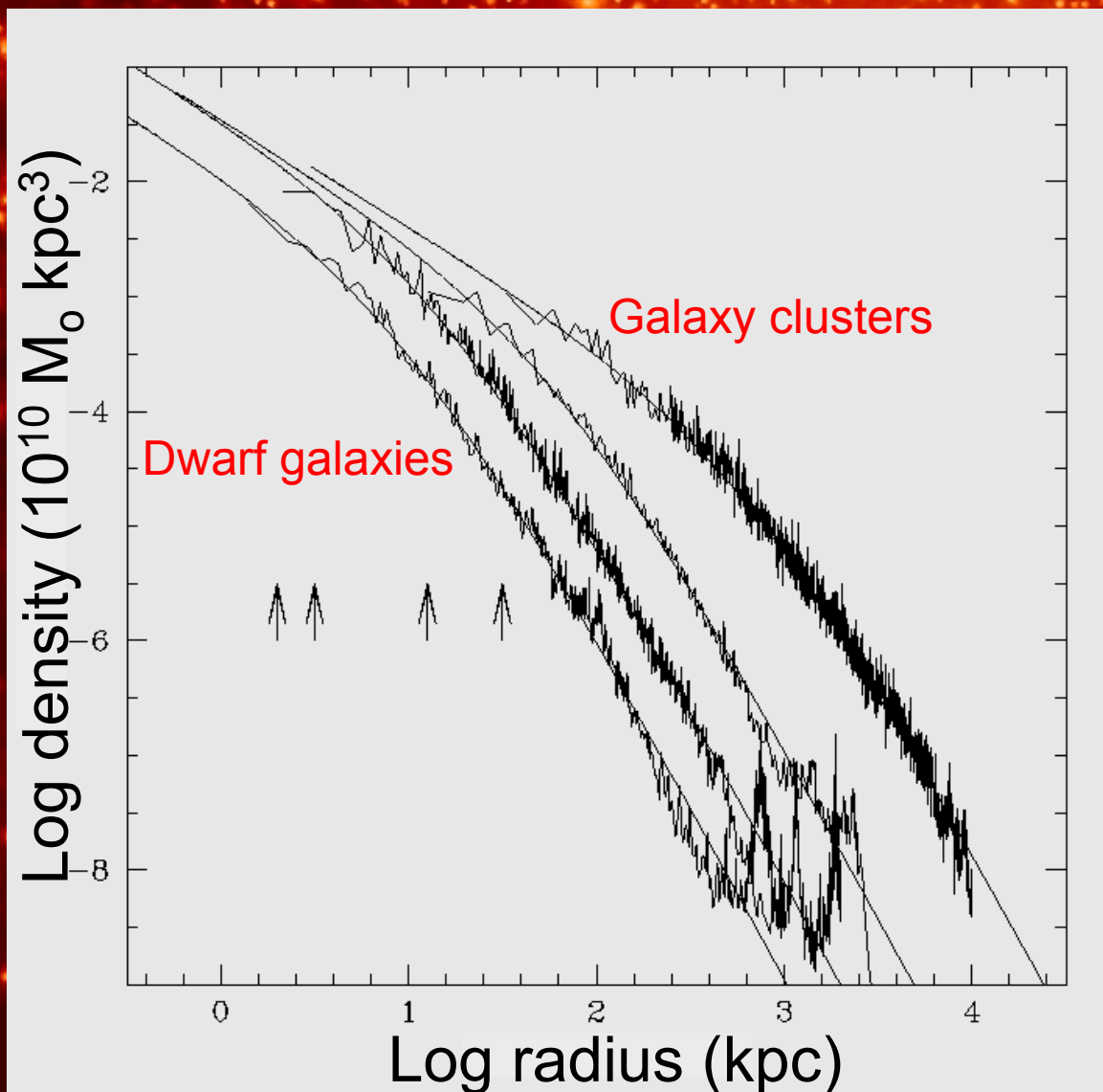
Sanchez et al 06





The structure of dark matter halos

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or 'core' near the centre.

(Navarro, Frenk & White '97)

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

Halos that form earlier have higher densities (bigger δ)



The “NFW” profile



© BT - musicolor.wordpress.com

A Cold dark matter universe

N-body simulations show that cold dark matter halos
(from galaxies to clusters) have:

“Cuspy” density profiles

Does nature have them?

Look in galaxies and clusters



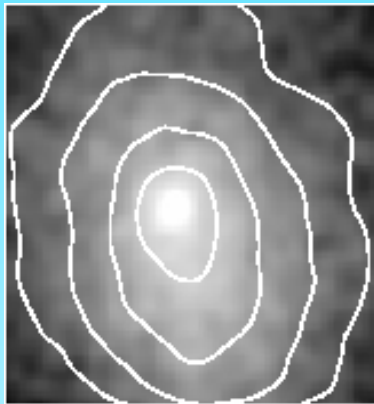
Galaxy halo structure strongly modified by baryons?

Cluster profiles can be probed with:

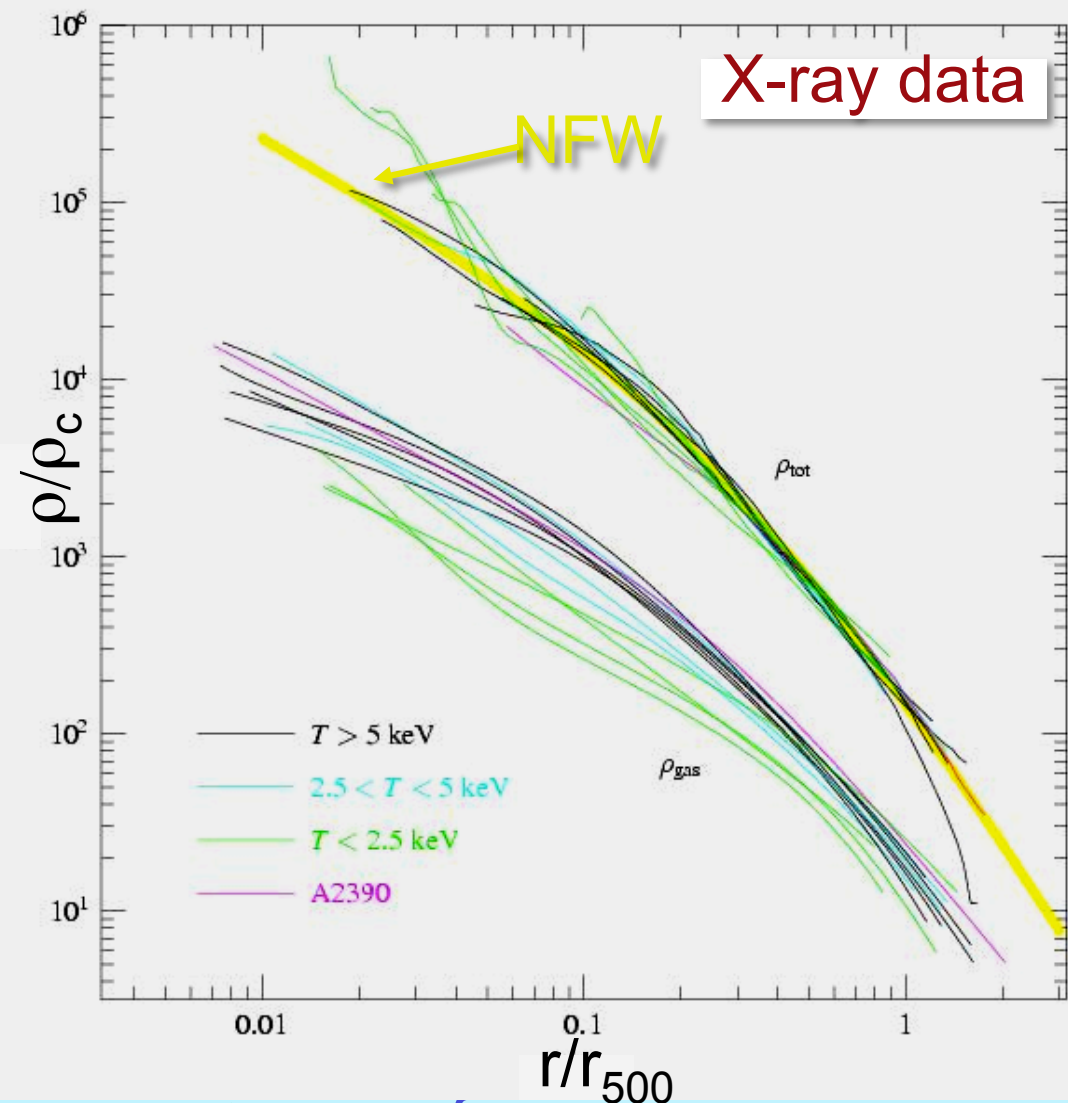
- X-ray emission
- Gravitational lensing

The central density profile of galaxy cluster dark halos

Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium

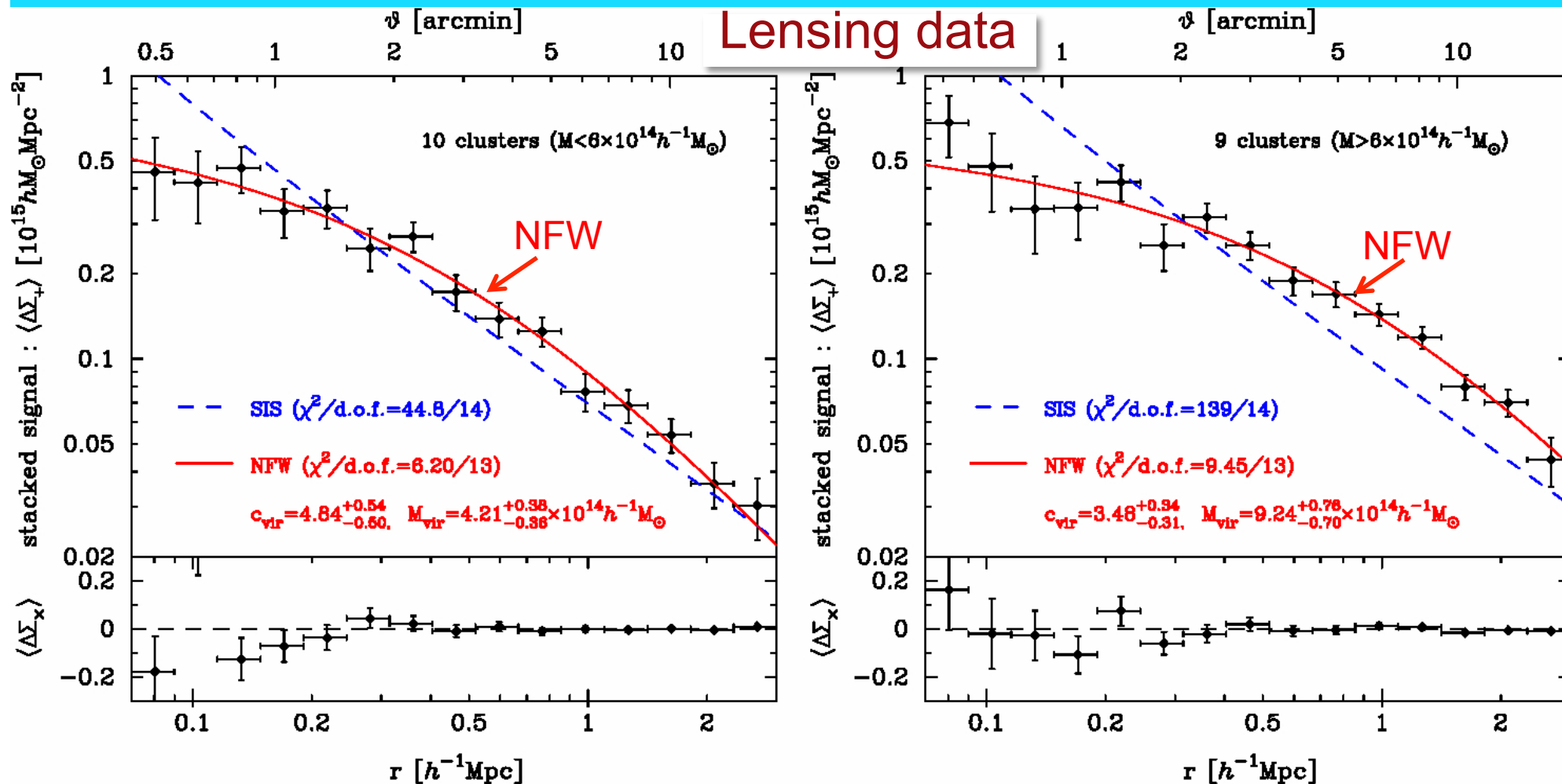


Excellent agreement with CDM halo predictions



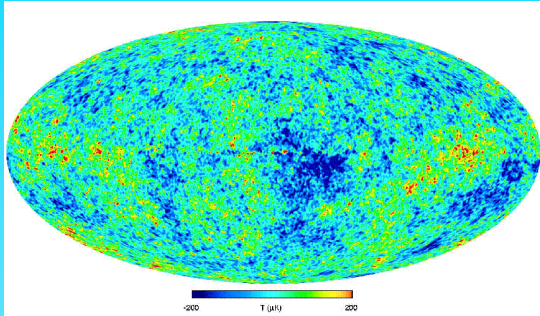
The density profile of galaxy cluster dark halos

Lensing data

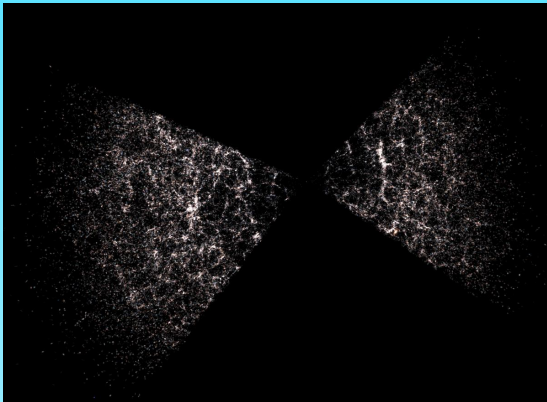


Okabe et al '10

The cosmic power spectrum: from the CMB to the 2dFGRS



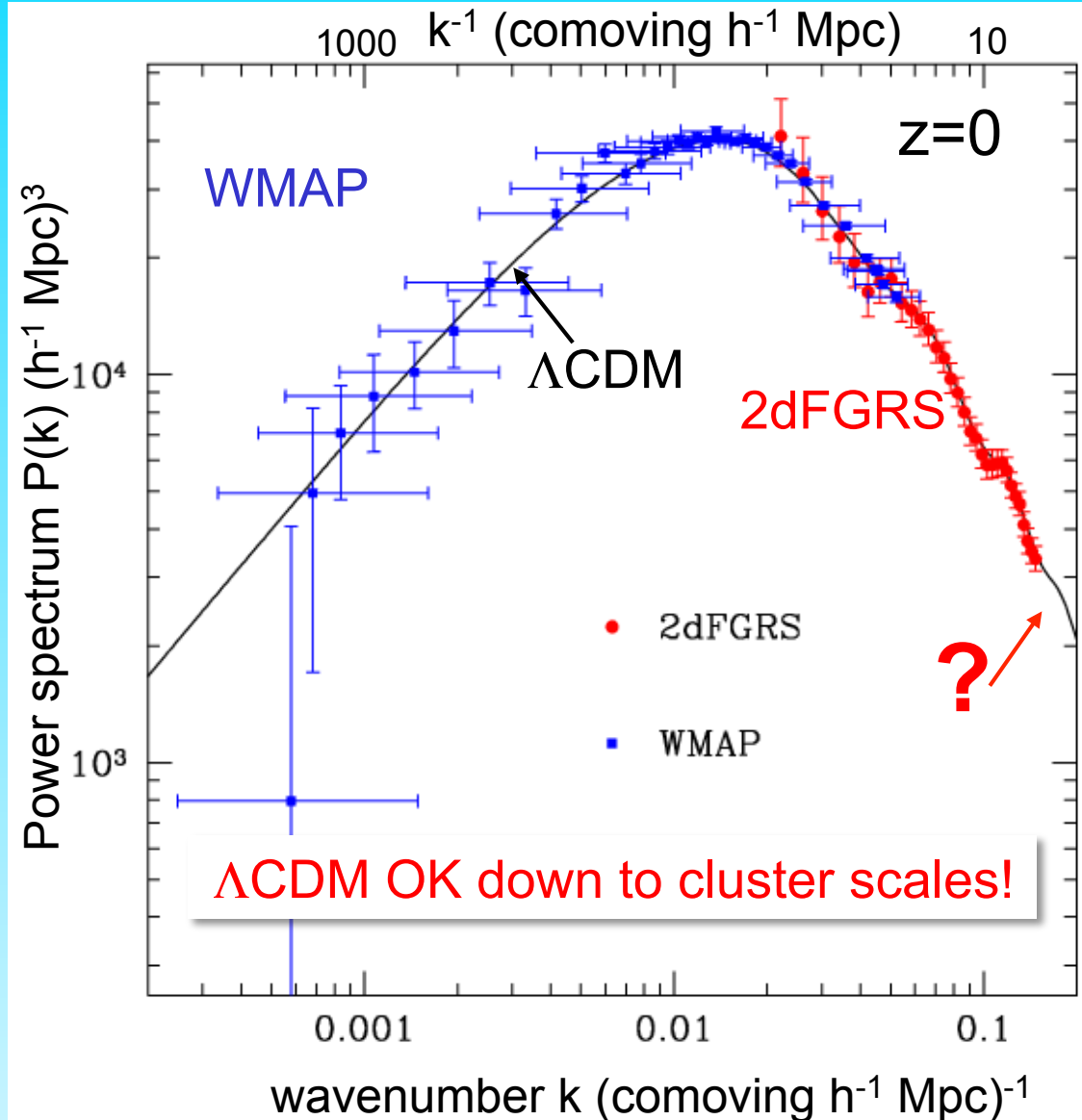
$z \sim 1000$



$z \sim 0$

$\Rightarrow \Lambda$ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06



$z = 48.4$

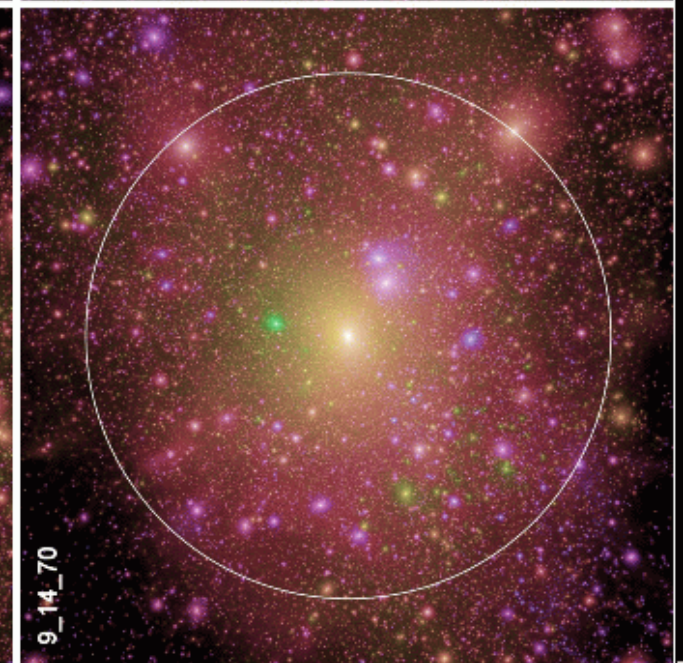
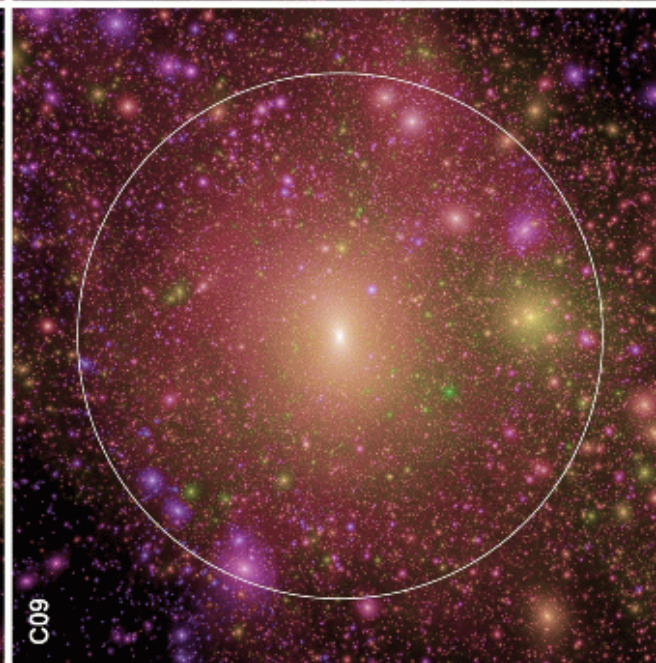
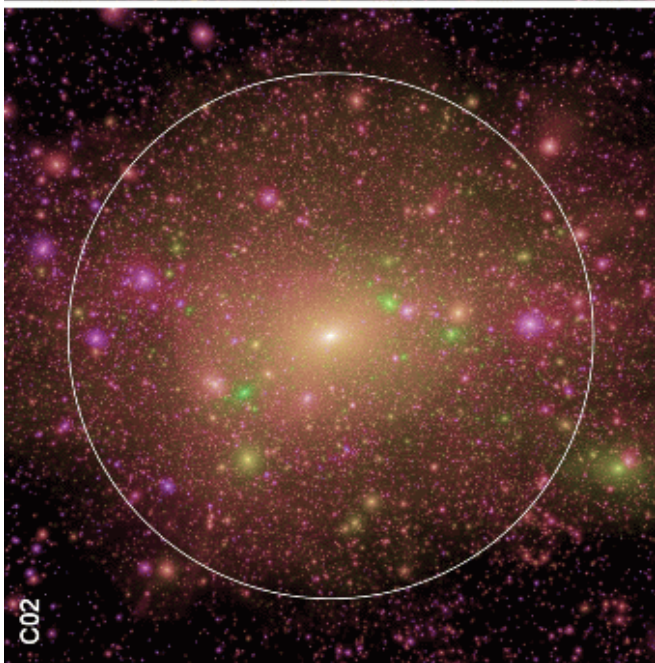
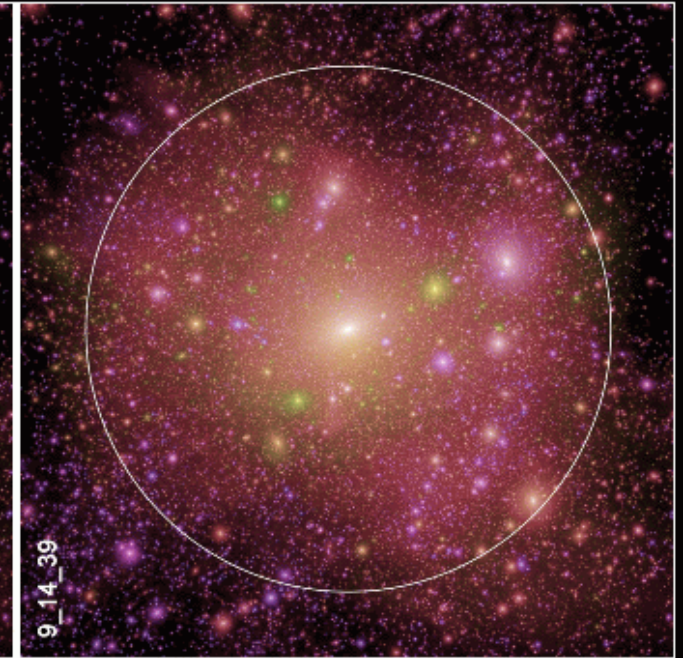
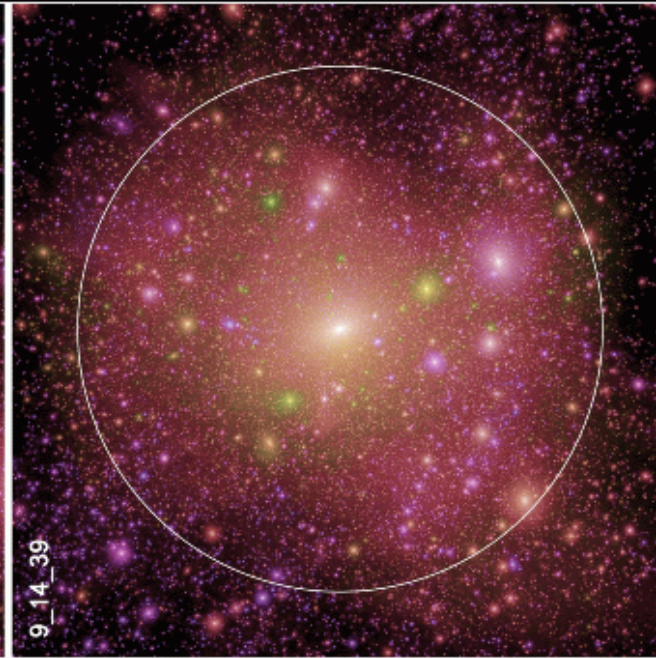
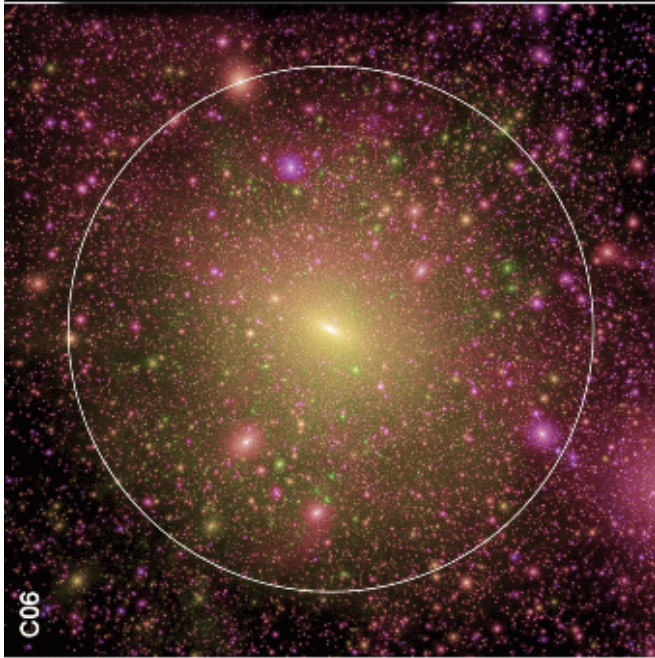
$T = 0.05 \text{ Gyr}$

500 kpc

The image shows a dark, textured field of purple and black, representing a simulated galaxy at a very early stage. The texture is grainy and noisy, with some faint, irregular patterns of slightly lighter purple. In the top left corner, the text 'z = 48.4' is displayed. In the top right corner, the text 'T = 0.05 Gyr' is displayed. At the bottom center, there is a horizontal scale bar with vertical end caps, and the text '500 kpc' is written below it.

VIRG

Images of all Aquarius halos (level-2)



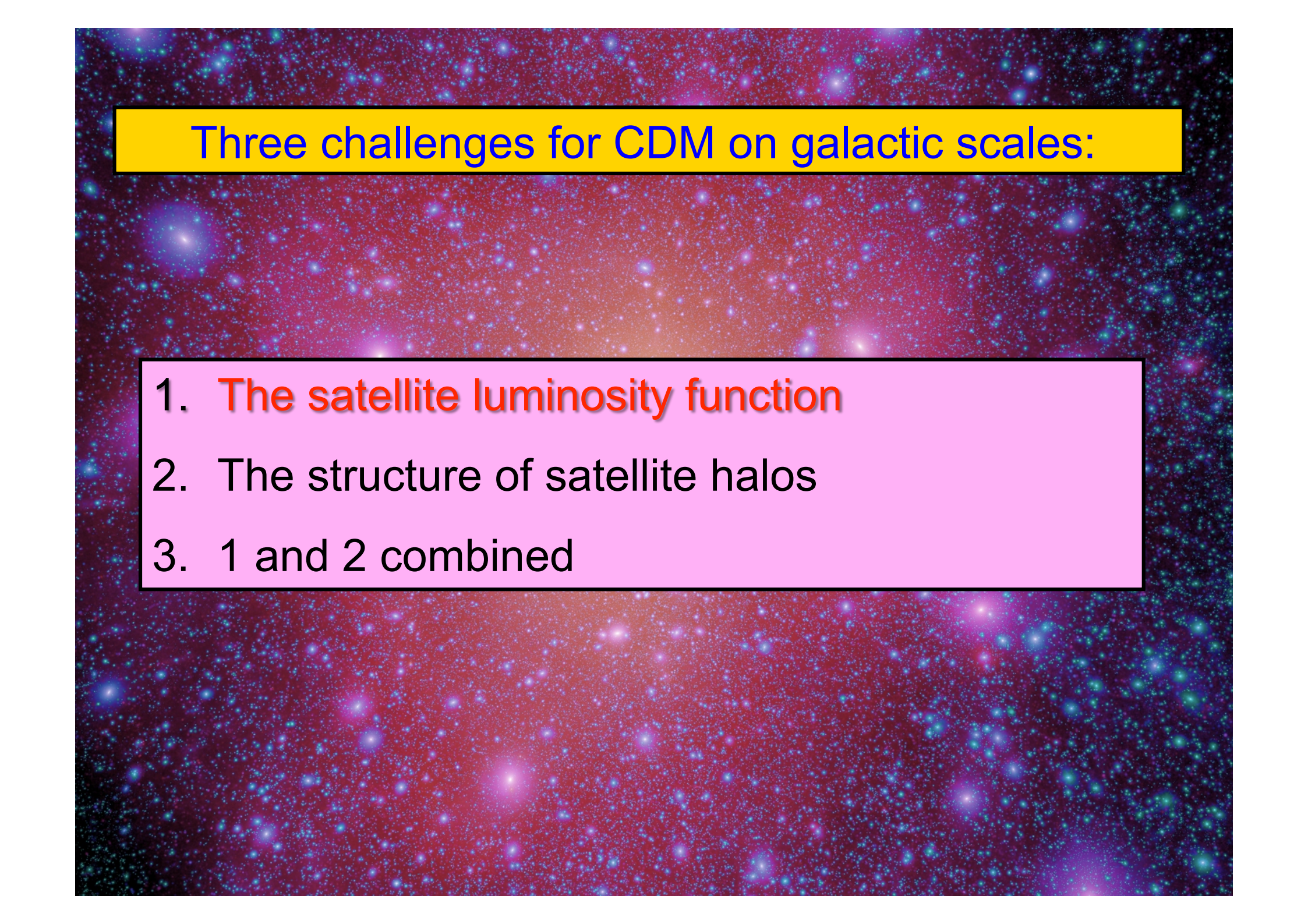
A Cold dark matter universe

CDM N-body simulations make two important predictions on galactic scales:

- Large number of self-bound substructures (**10% of mass**) survive
- The main halo and its subhalos have “cuspy” density profiles

Three challenges to CDM :

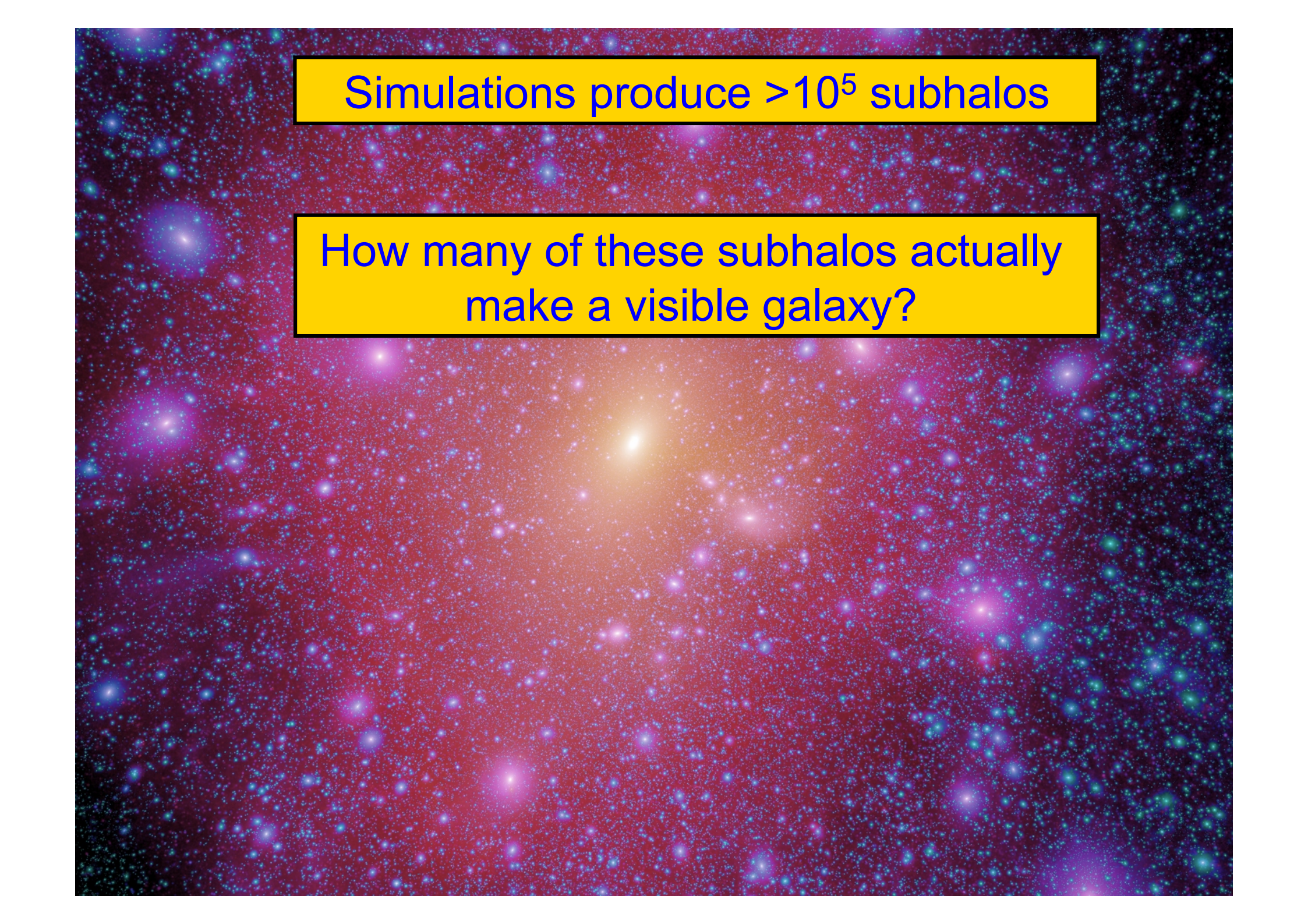
1. The satellite luminosity function
2. The structure of satellite halos
3. 1 and 2 combined

The background of the slide is a deep space image filled with numerous small, bright blue and white speckles, resembling distant stars or galaxies, set against a dark blue and purple gradient.

Three challenges for CDM on galactic scales:

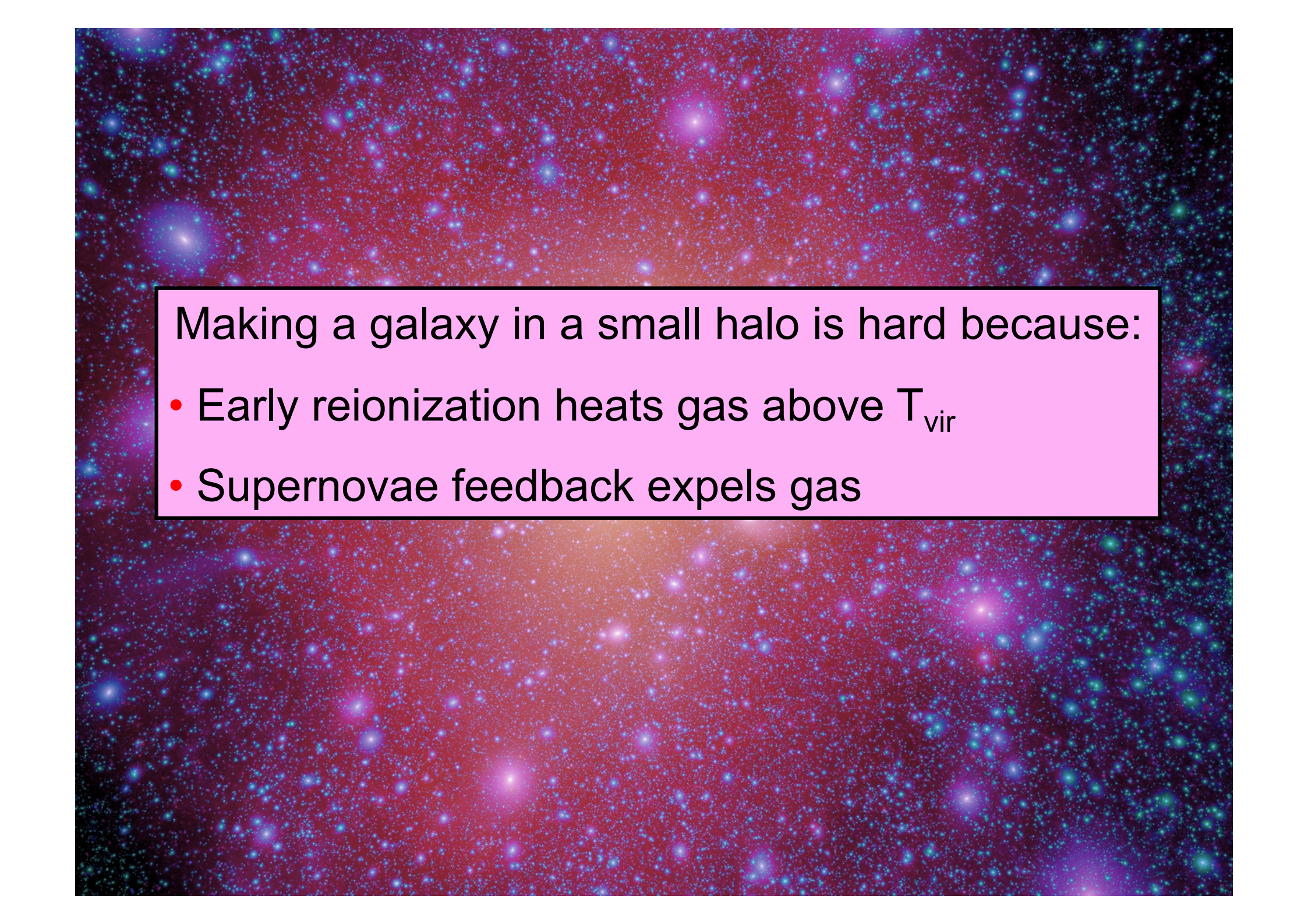
1. **The satellite luminosity function**
2. The structure of satellite halos
3. 1 and 2 combined



The background of the slide is a deep space image showing a vast field of stars and galaxies. A prominent, bright, yellowish-white galaxy is located in the center, surrounded by a dense field of smaller, distant galaxies and stars. The colors range from deep blue and purple to bright yellow and white.

Simulations produce $>10^5$ subhalos

How many of these subhalos actually
make a visible galaxy?

The background of the slide is a deep space image featuring a dense field of stars. A prominent horizontal band of reddish-pink light, likely representing the Milky Way, stretches across the middle. Above and below this band, the background is a dark blue/black space filled with numerous bright blue and white stars of varying sizes.

Making a galaxy in a small halo is hard because:

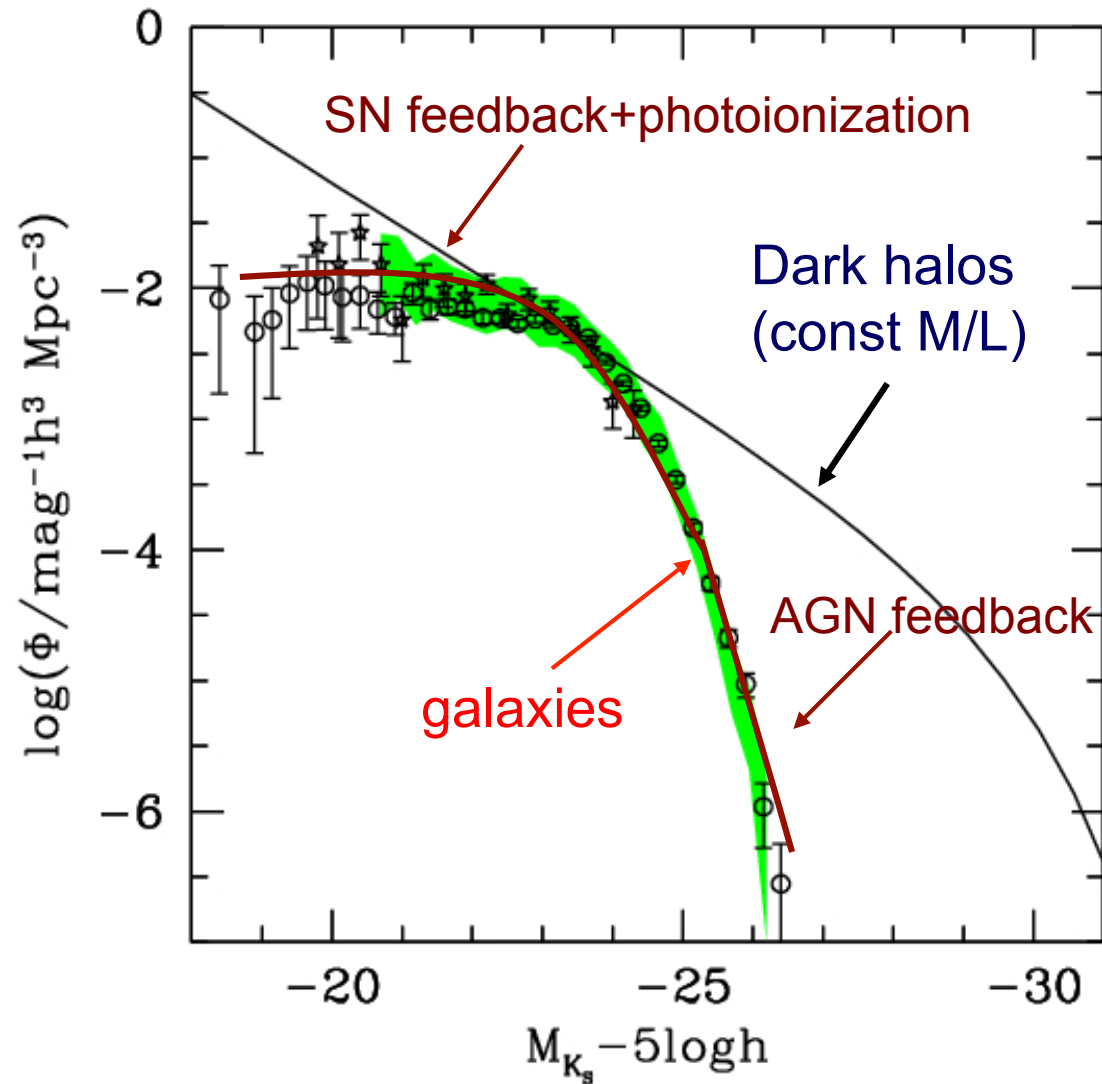
- Early reionization heats gas above T_{vir}
- Supernovae feedback expels gas

The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes

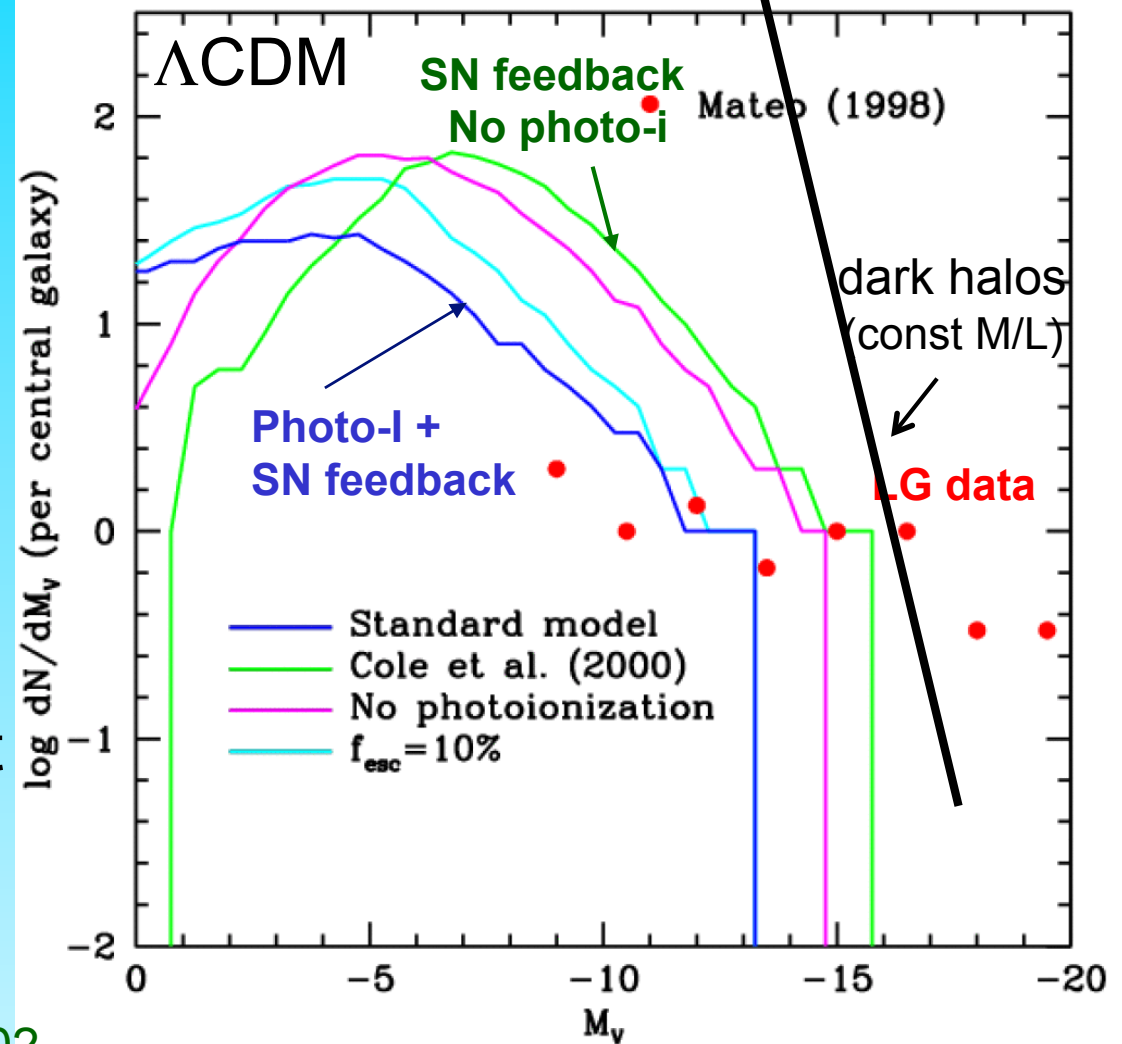


Complicated variation of M/L with halo mass



Luminosity Function of Local Group Satellites

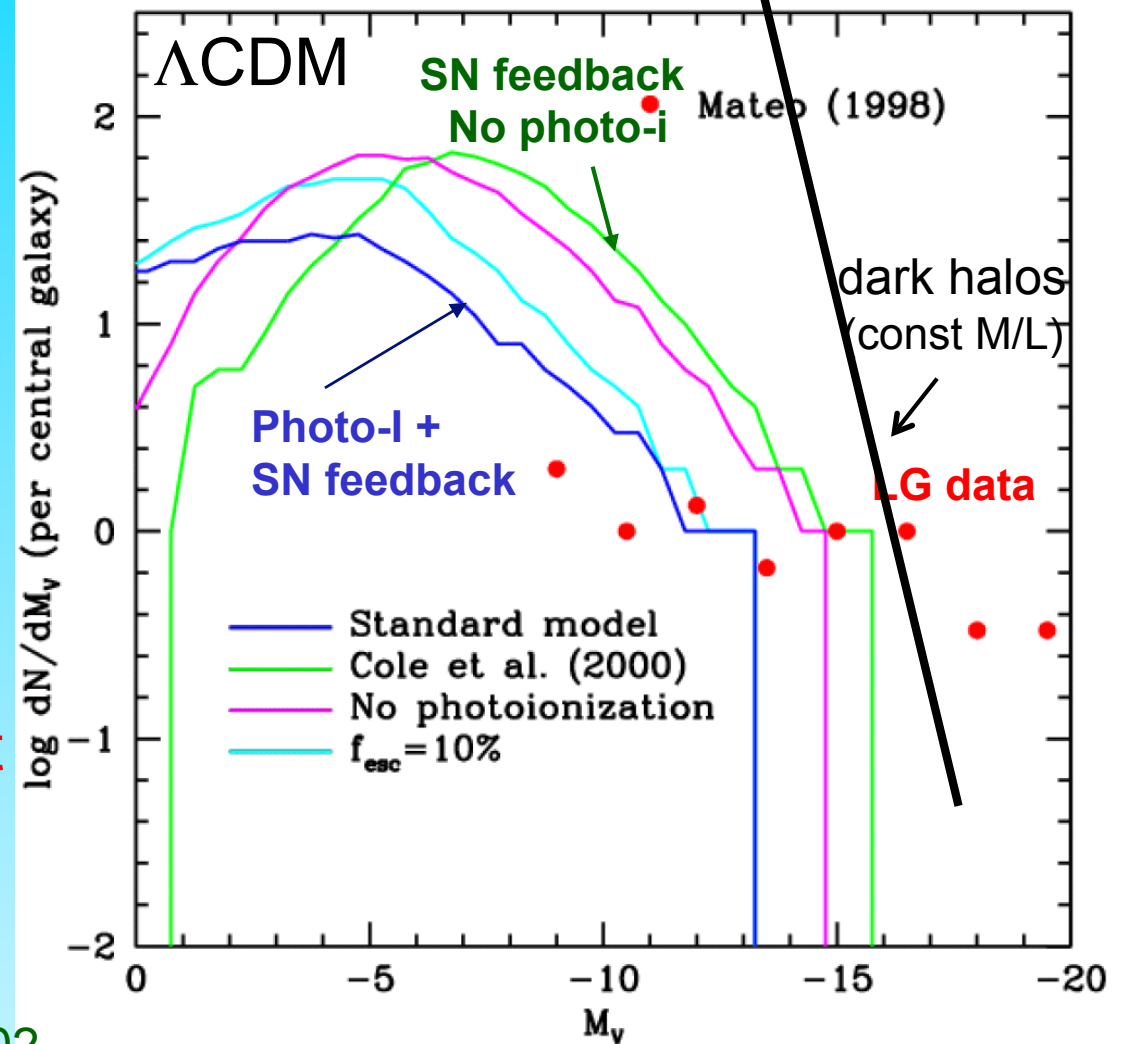
- **Photoionization** inhibits the formation of satellites
- Abundance of satellites reduced by large factor!
- Median model gives correct abundance of sats brighter than $M_V = -9$, $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

Luminosity Function of Local Group Satellites

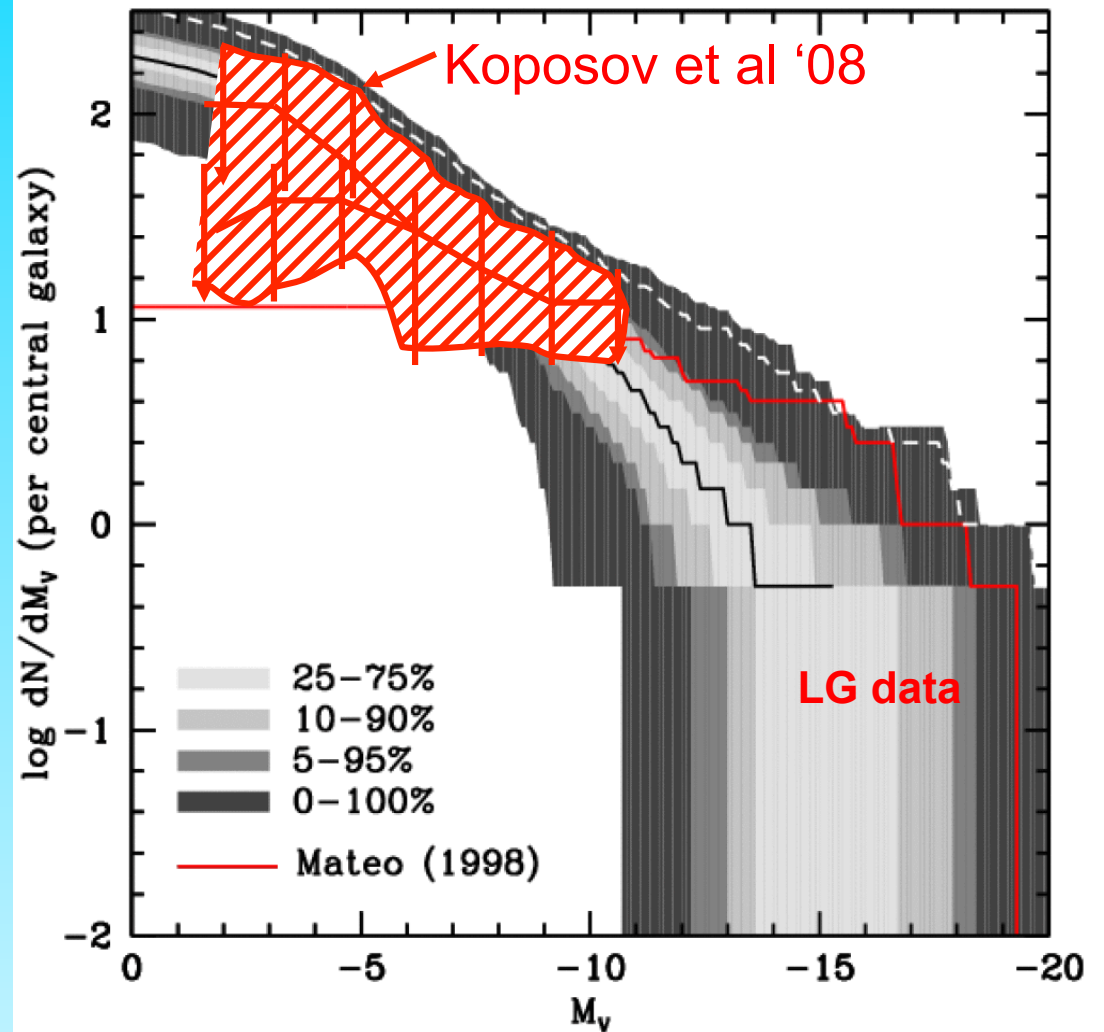
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Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Three challenges for CDM on galactic scales:

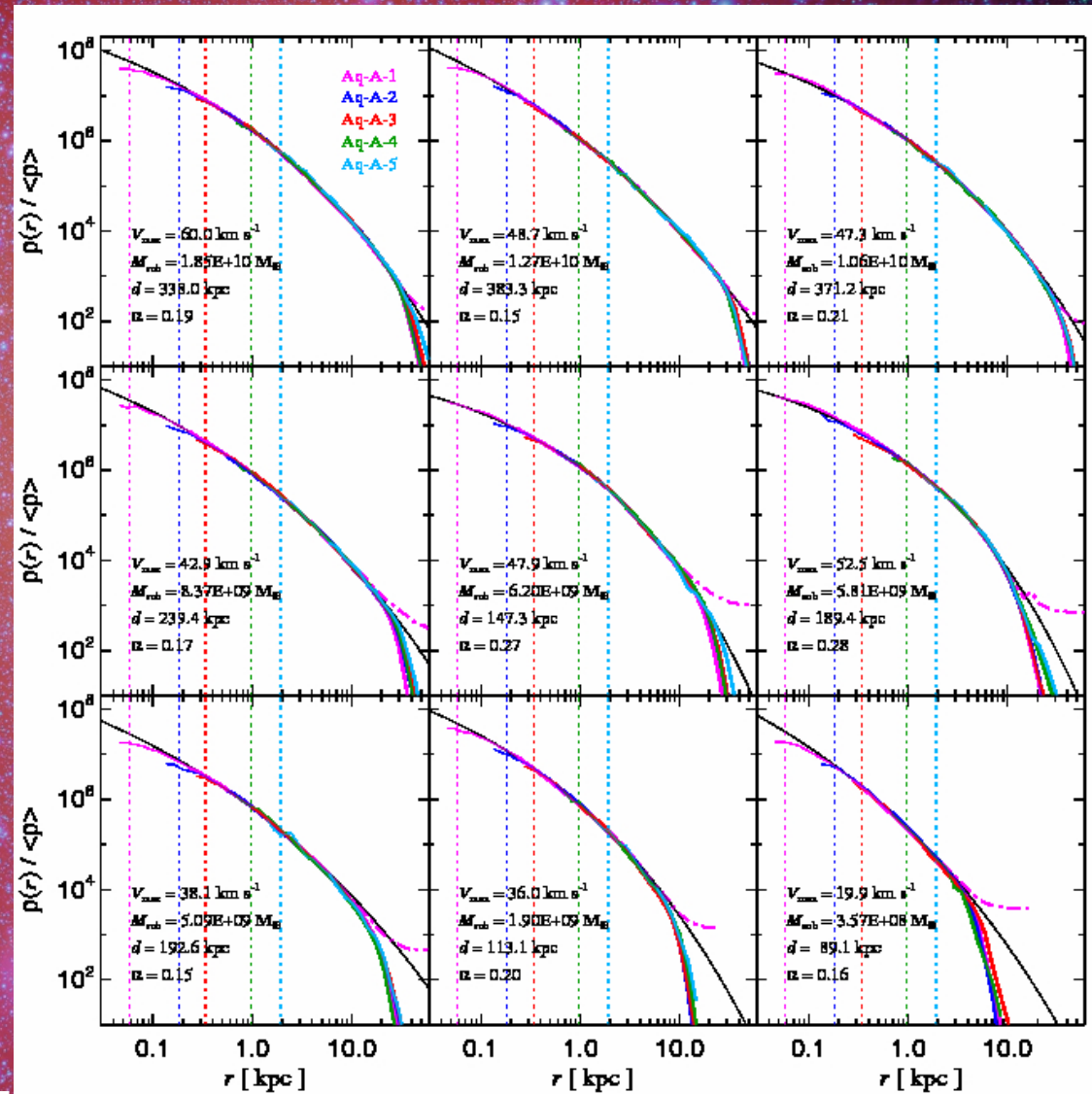
1. The satellite luminosity function ✓
2. The structure of satellite halos
3. 1 and 2 combined

Three challenges for CDM on galactic scales:

1. The satellite luminosity function ✓
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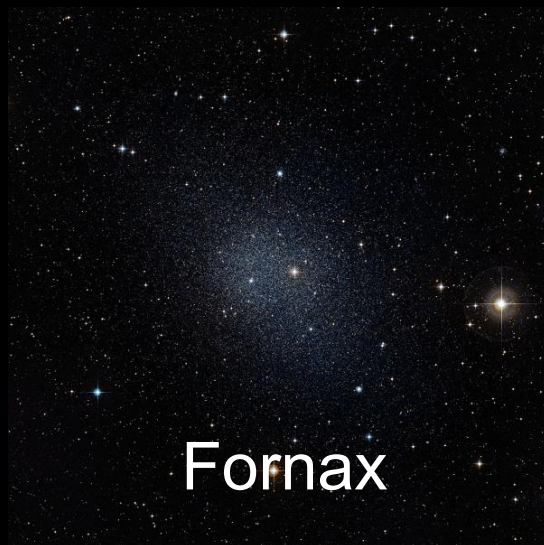
In CDM predict: cuspy density profiles in halos and subhalos

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





Dwarf galaxies around the Milky Way



Fornax



Sculptor



Leo I

© Anglo-Australian Observatory



Sextans



Carina



Sagittarius

The structure of dark matter halos

Dwarf sphs: cores or cusps?

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

stellar density profile

radial velocity dispersion

from Aquarius sim

vel. anisotropy

For each dwarf spheroidal with good kinematic data

- Consider a subhalo in the simulation
- Imagine a galaxy with the observed stellar density profile of the dwarf lives there
- Predict the l.o.s velocity distribution in that subhalo potential (assuming $\beta = 0$)
- Compare with the observed dispersion profile
- Compute χ^2

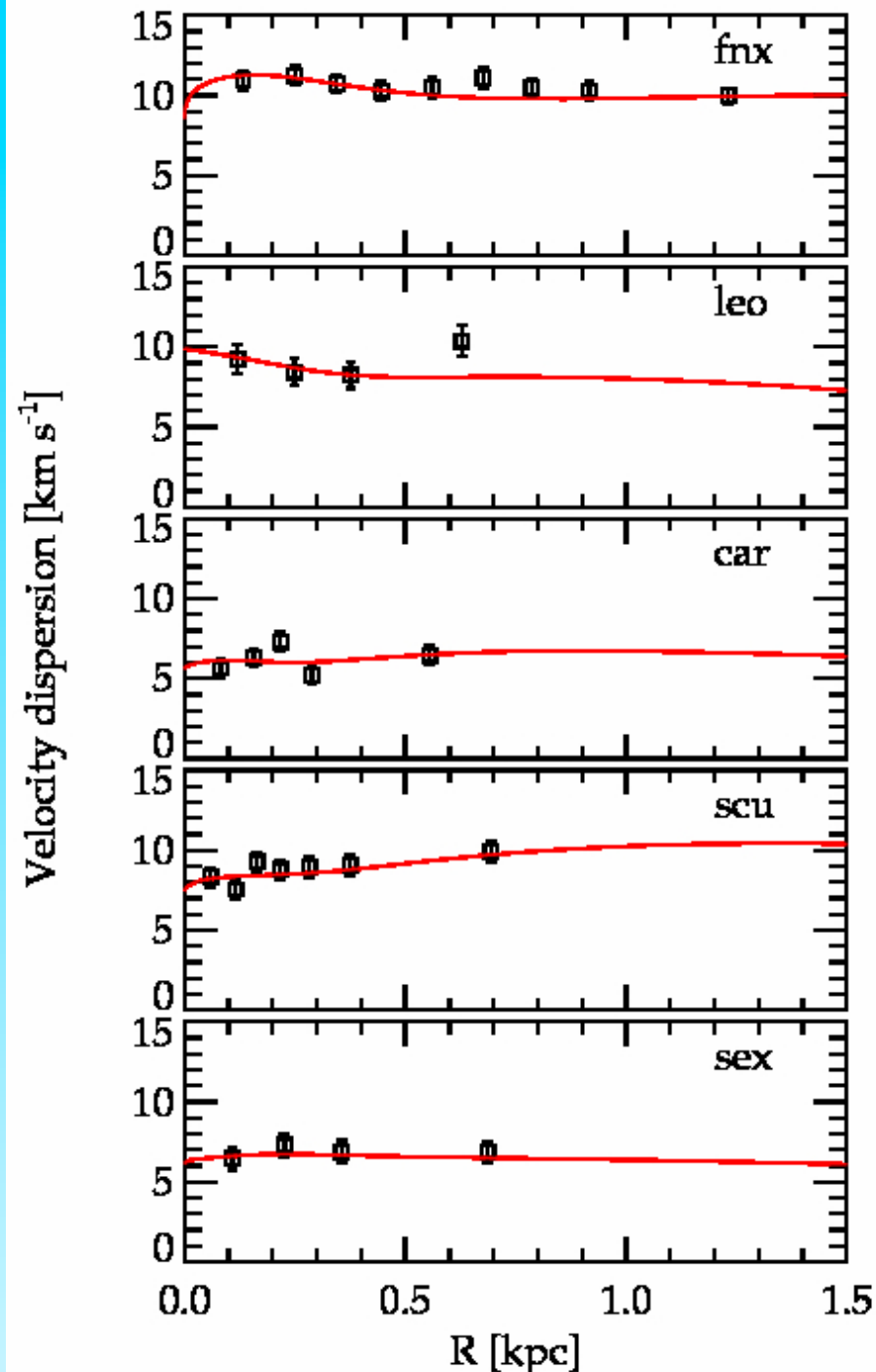
Dwarf spherical galaxies: cores or cusps?

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

from Aquarius sim
vel. anisotropy

- Assume isotropic orbits
- Solve for $\sigma_r(r)$
- Compare with observed $\sigma_r(r)$
- Find “best fit” subhalo



Dwarf sphs: cores or cusps?

Jeans eqn:

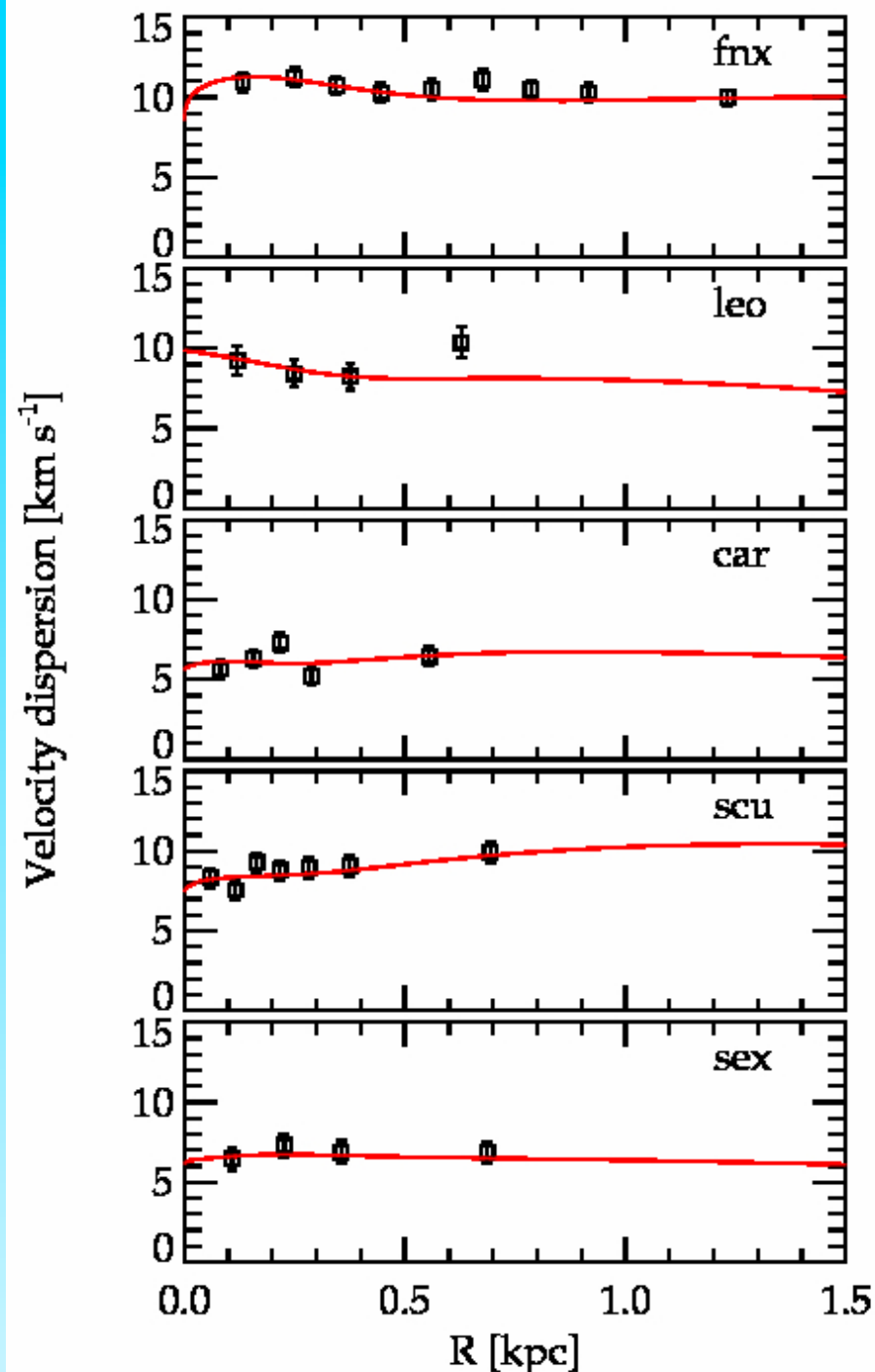
$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

from Aquarius sim
vel. anisotropy

1-p= prob. that
“best fit” can be
rejected ($\beta=0$)

Satellite	1-p
Fornax	0.4
Leo I	0.5
Carina	0.4
Sculptor	0.8
Sextans	0.2

Strigari, Frenk & White 2010



Three challenges for CDM on galactic scales:

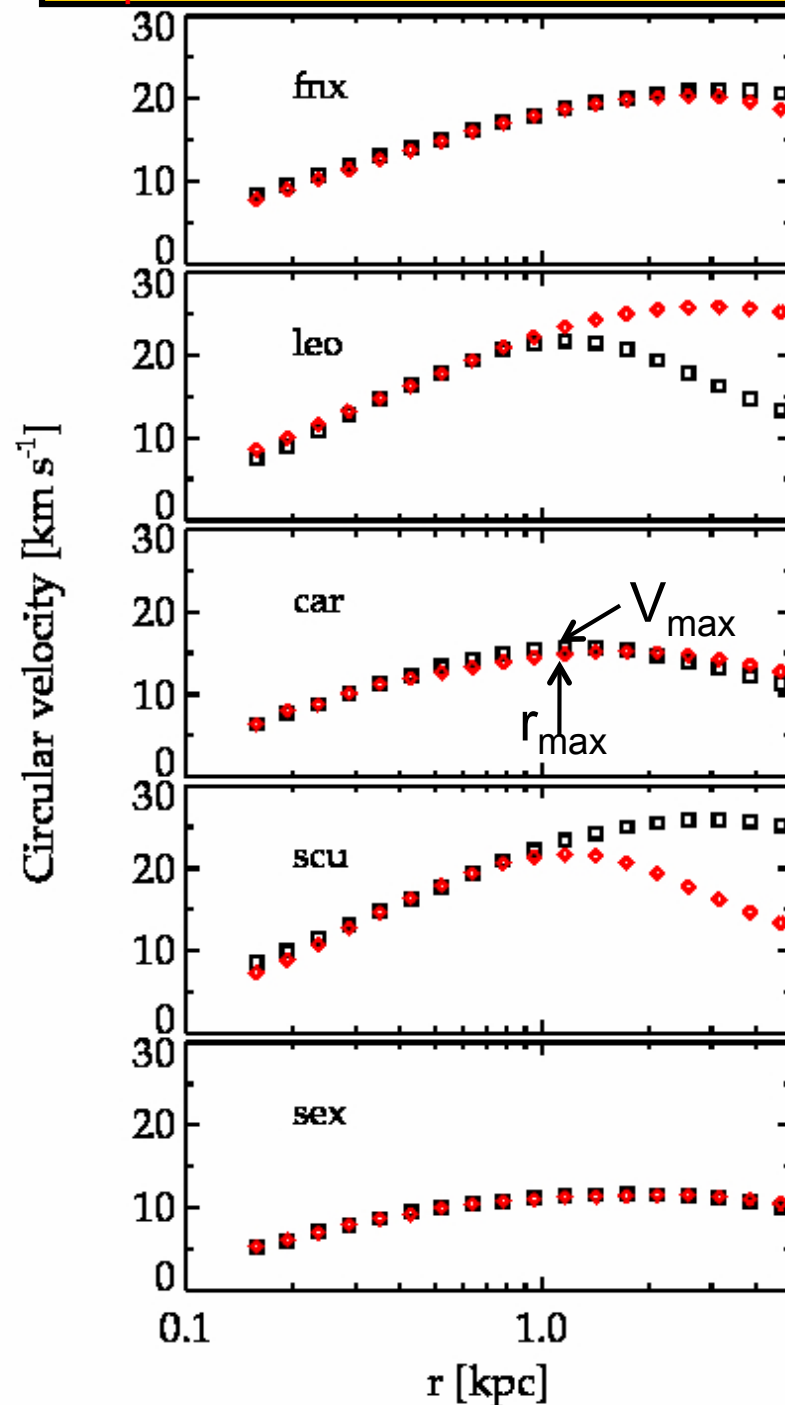
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Three challenges for CDM on galactic scales:

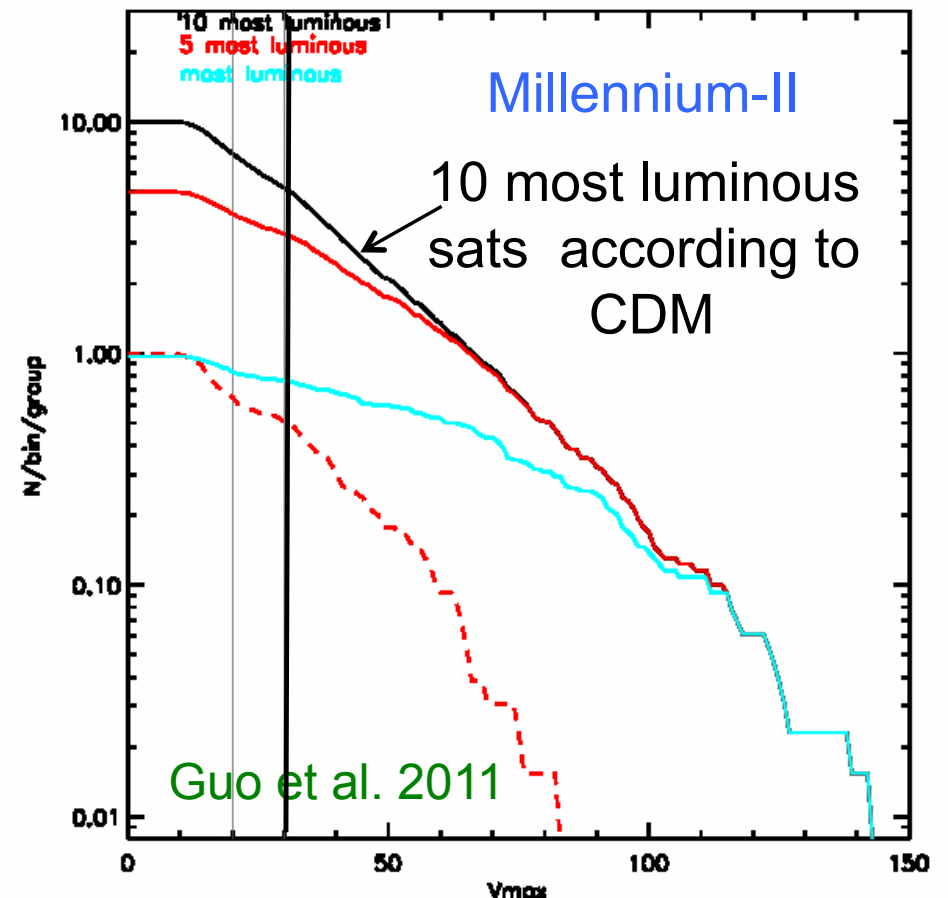
1. The satellite luminosity function ✓
2. The structure of satellite halos ✓
3. **1 and 2 combined**

- Does CDM theory put satellites of a given luminosity in halos with the right structure?

Top 2 best fit CDM models to data



The satellites of the Milky Way



Strigari, Frenk & White 2010



Is this the end of CDM?

How about baryon effects?

The cores of dwarf galaxy haloes

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ABSTRACT

We use N -body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.

Rapid ejection of large fraction of gas during starburst can lead to a core in the halo dark matter density profile

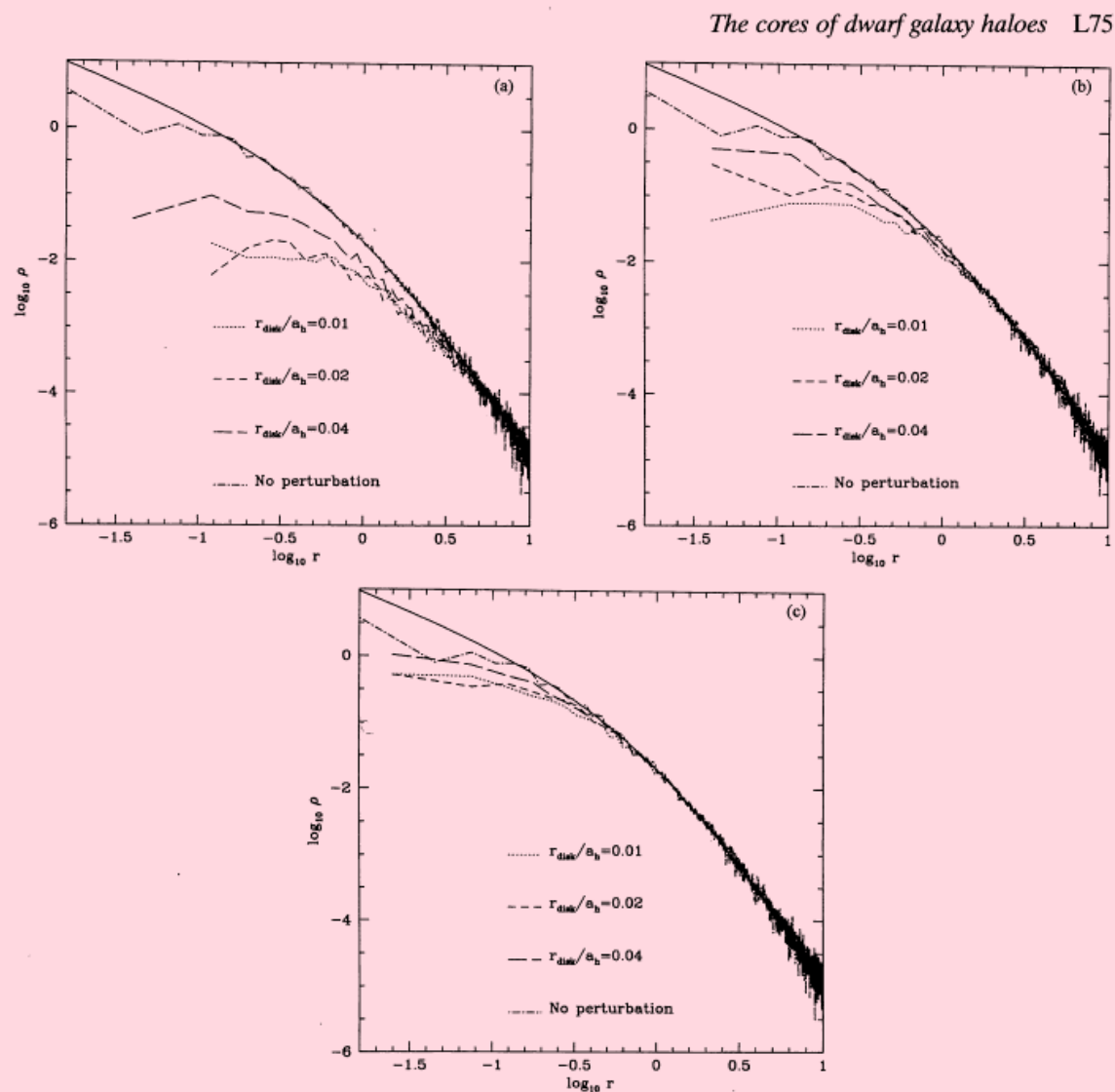
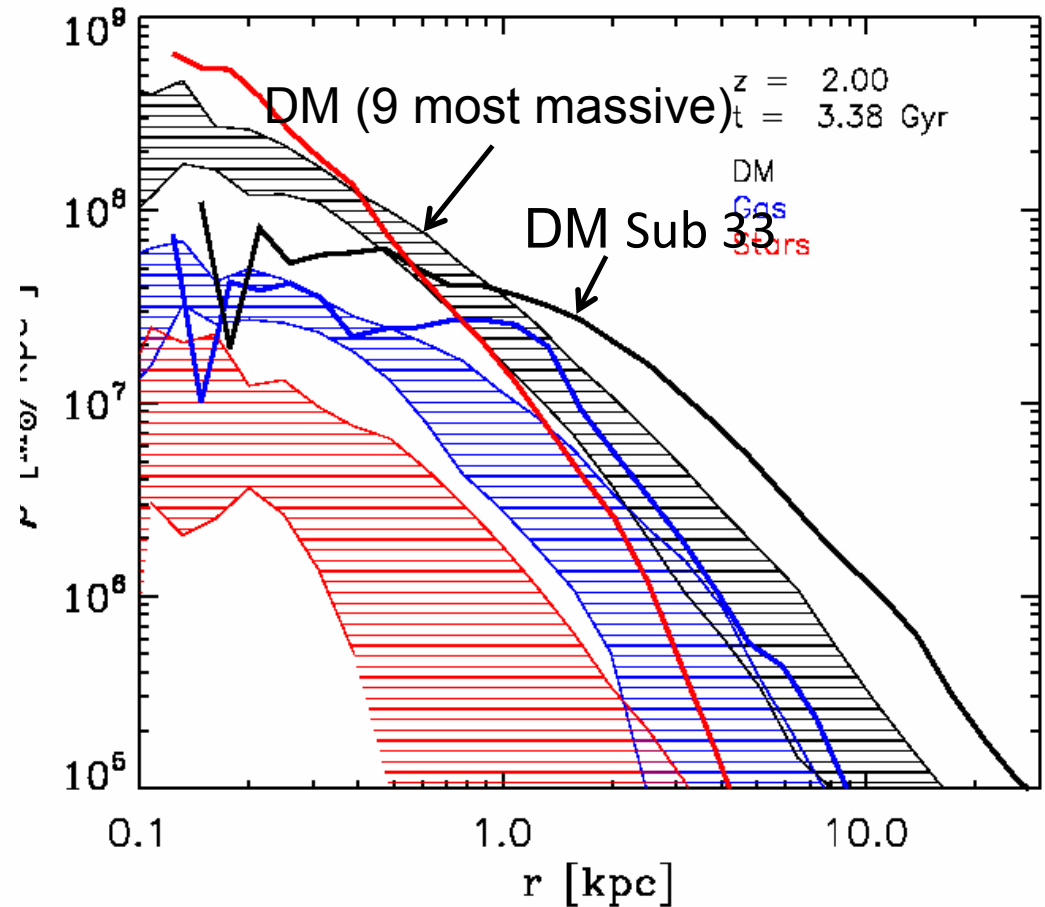
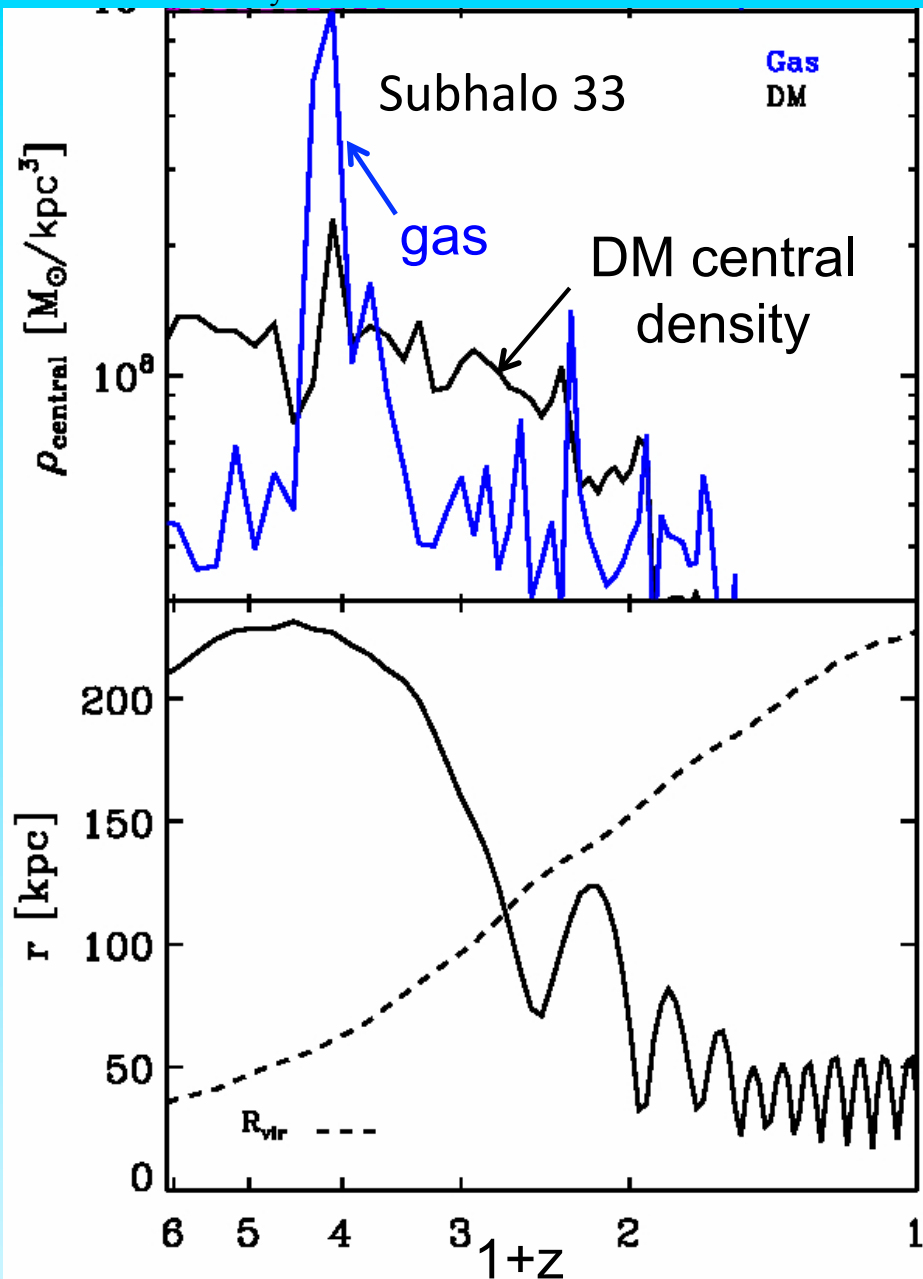


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{\text{disc}}=0.2$. (b) $M_{\text{disc}}=0.1$. (c) $M_{\text{disc}}=0.05$.

Baryon effects in the MW satellites



Parry, Eke & Frenk '11



Is this the end of CDM?

How about baryon effects?

We have one example of a low concentration subhalo , but we need ~ 5 per halo

Conclusions: Λ CDM on small scales

- Satellite luminosity function can be understood in Λ CDM as a result of feedback effects during galaxy formation
- There exist subhalos in Λ CDM galactic halos that are consistent with the photo/kinematic data for Milky Way satellites
- **But** galaxy formation models in Λ CDM make the brightest satellites in the largest subhalos which seem more massive and concentrated than in the real MW satellites

Possible solutions:

- Satellite population in the MW is atypical
- Warm dark matter
- Baryon effects that make large subhalos less concentrated