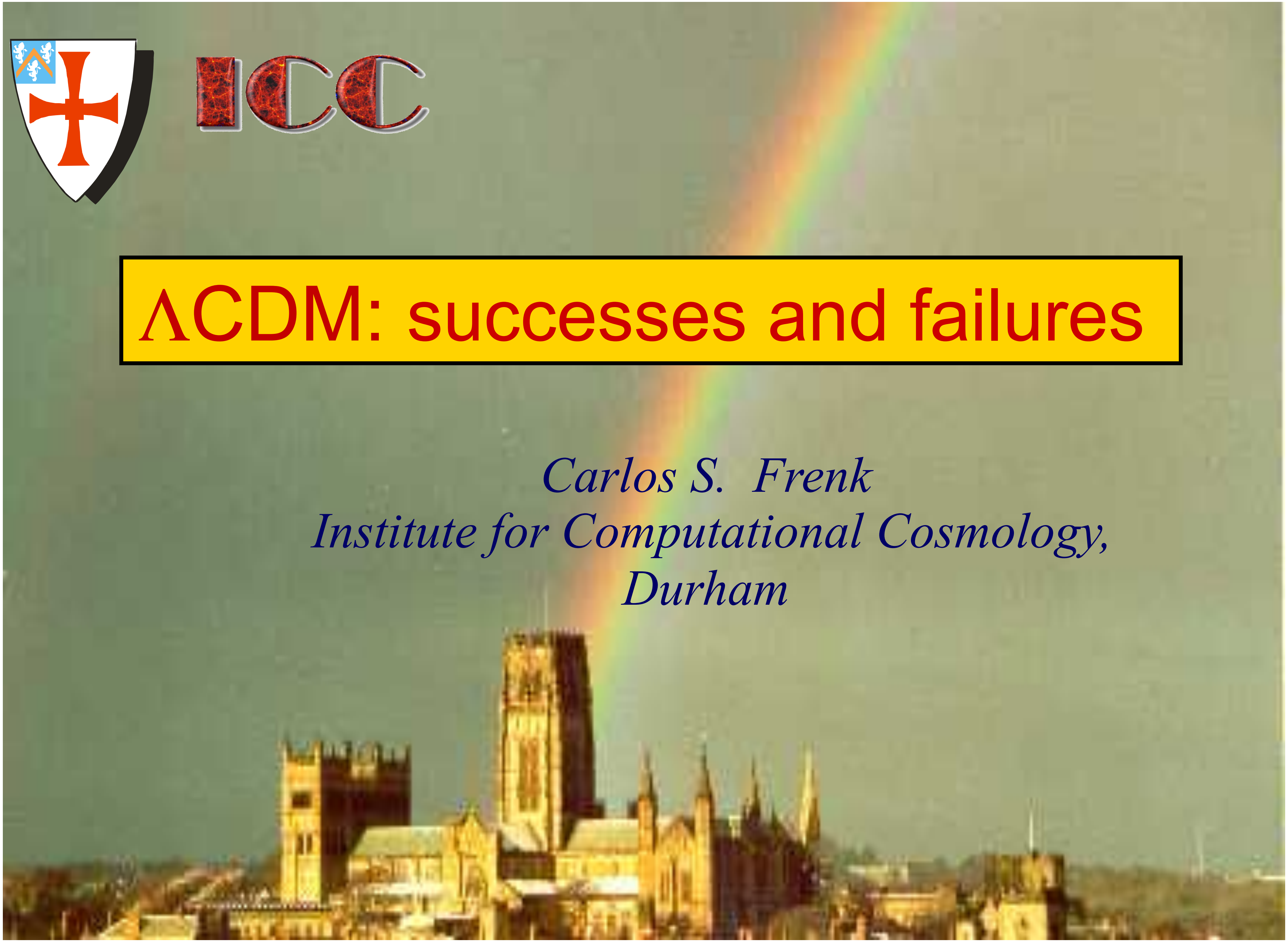
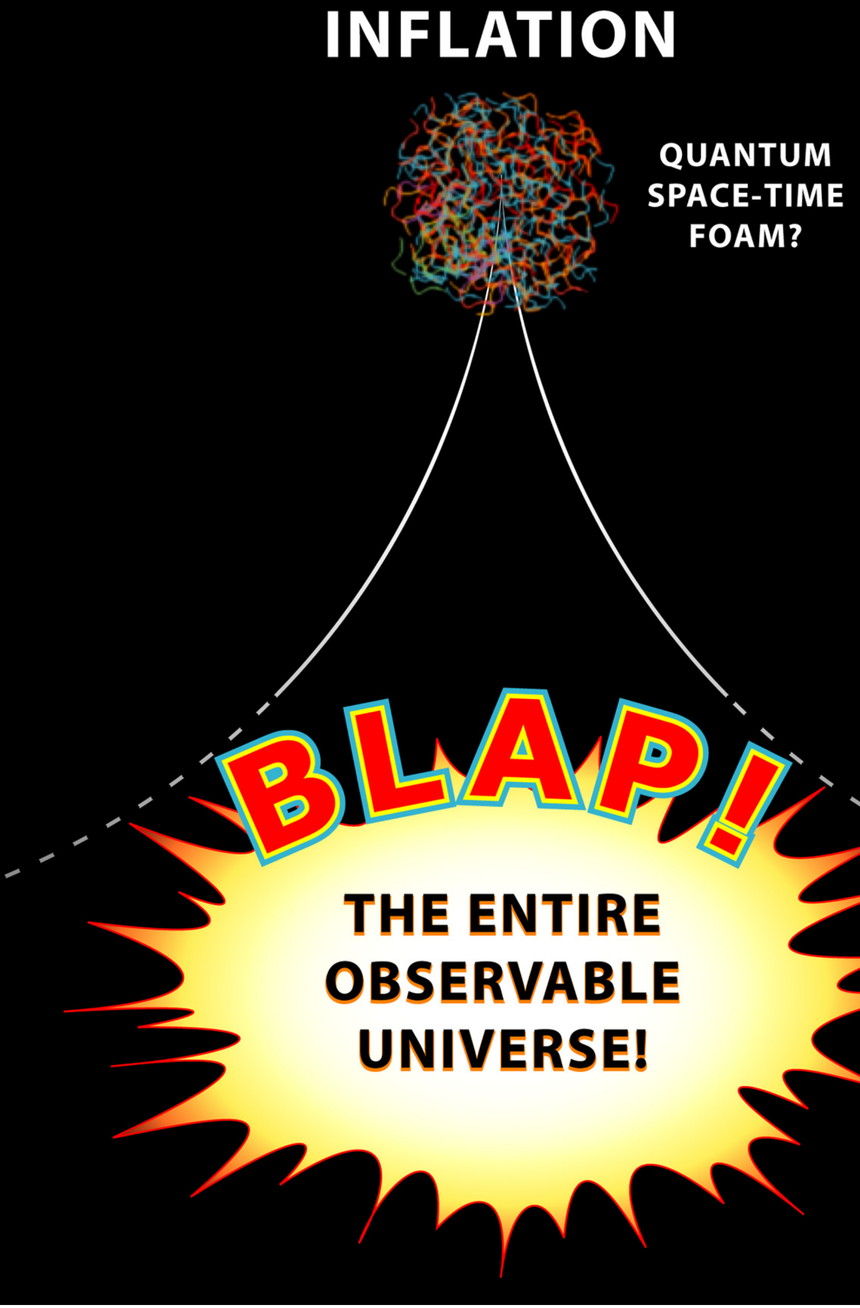


ΛCDM: successes and failures

Carlos S. Frenk
Institute for Computational Cosmology,
Durham

The initial conditions



$t=10^{-35}$ sec

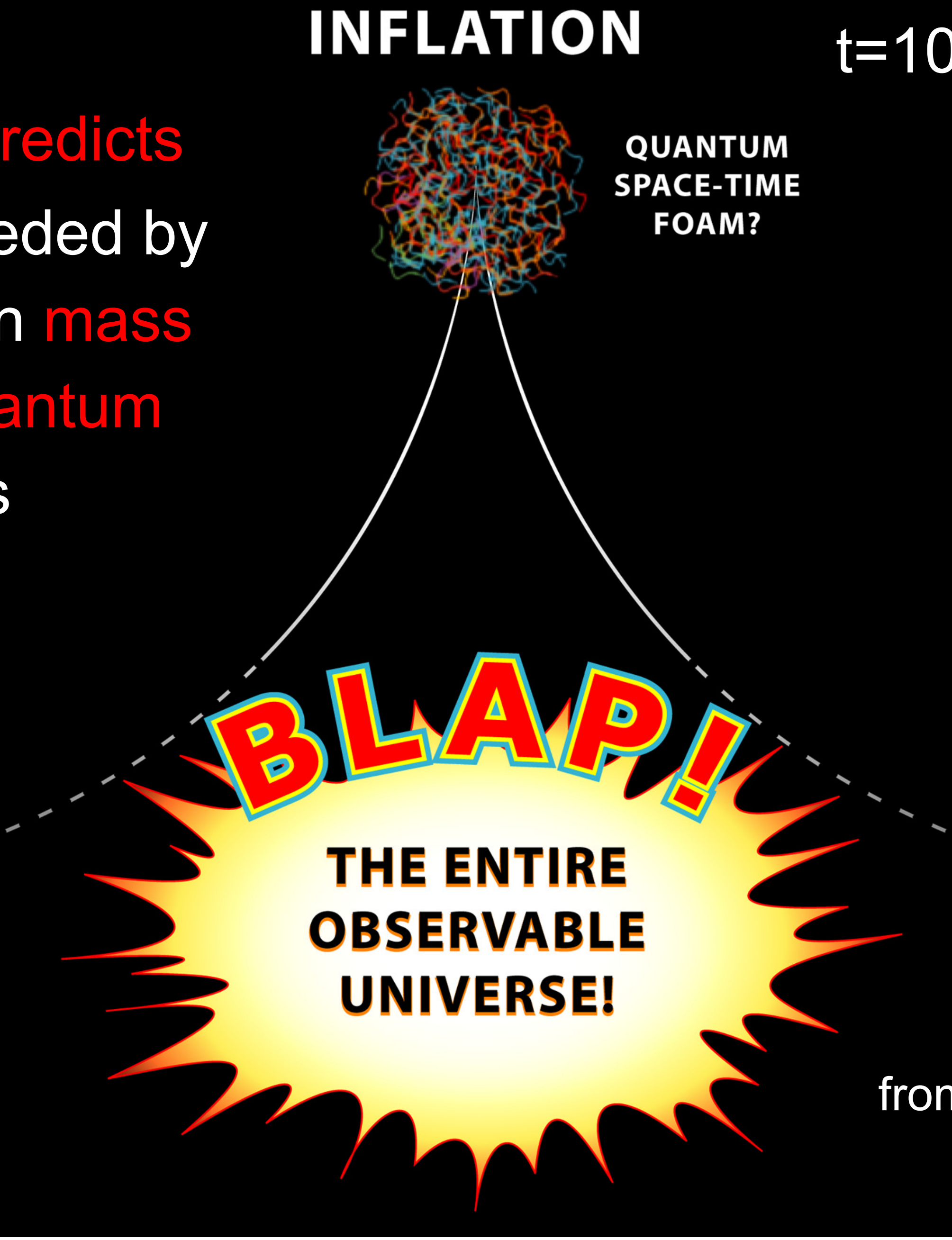
$$p = - \rho$$

from G. Efstathiou

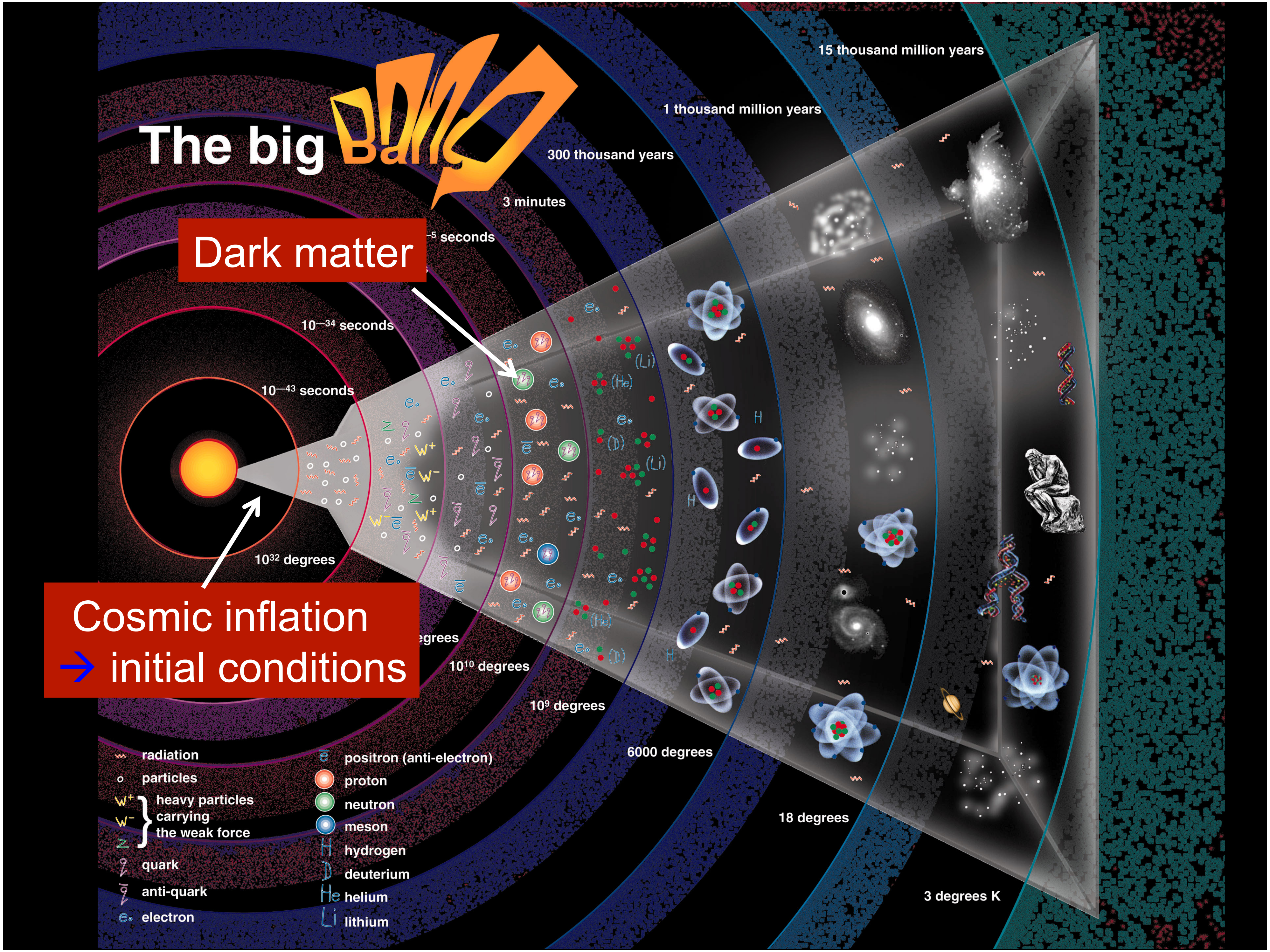
The initial conditions

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

$t=10^{-35}$ sec



from G. Efstathiou



Dark matter

Cosmic inflation

→ initial conditions

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 GeV

University of Durham

The dark matter power spectrum

Free streaming →

λ_{cut} α m_x^{-1}
for thermal relic

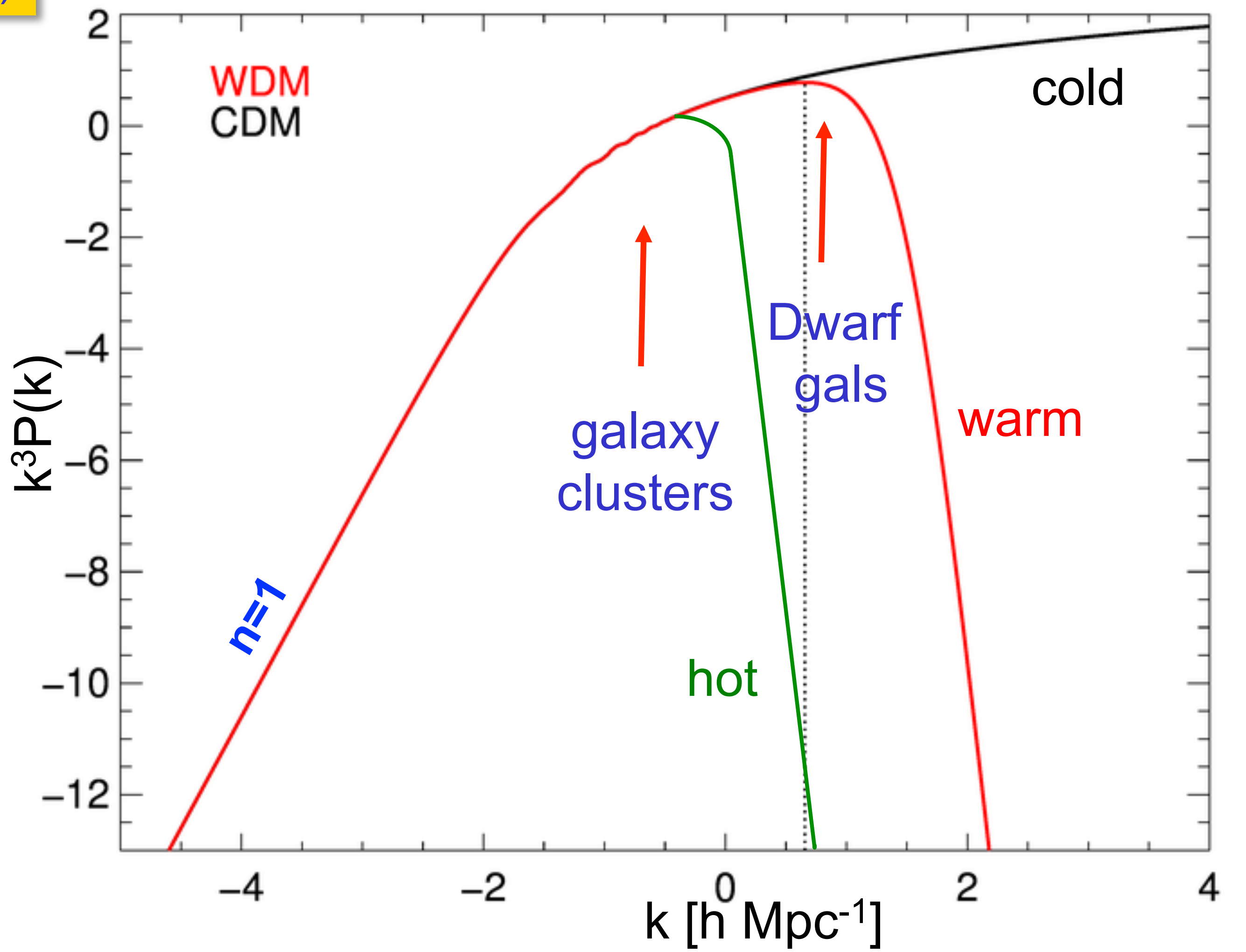
m_{CDM} ~ 100GeV
susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV
sterile ν; M_{cut}~10^9 M_o

m_{HDM} ~ few eV
light ν; M_{cut}~10^{15} M_o

k^3 P(k)

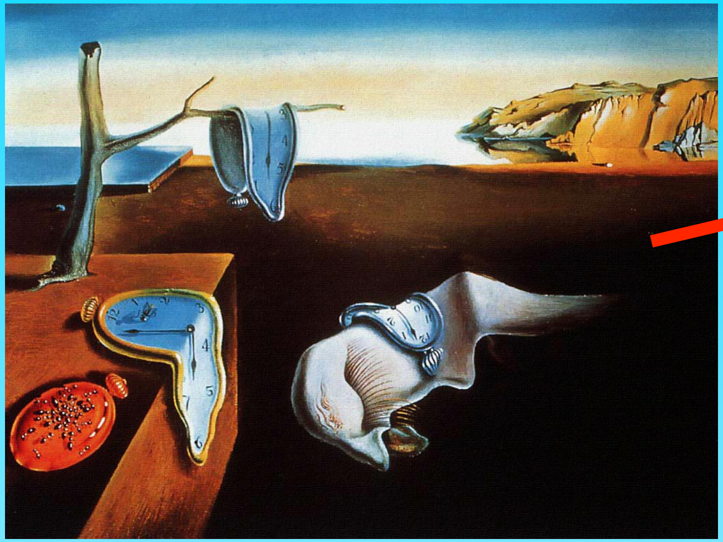
The linear power spectrum ("power per octave")



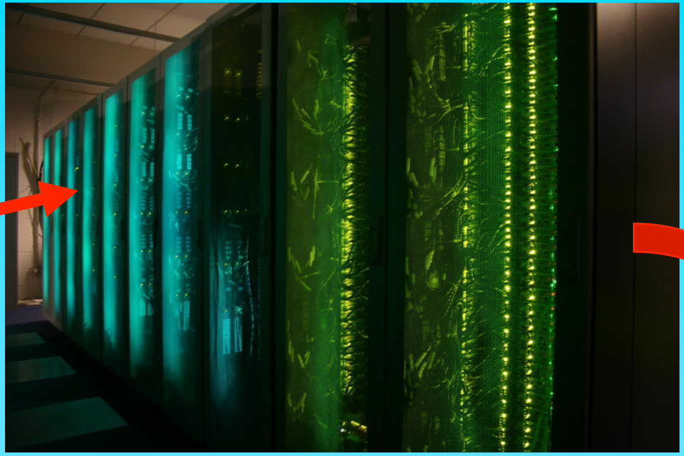
University of Durham

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

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

Institute for Computational Cosmology

University of Durham

Neutrino (hot) dark matter

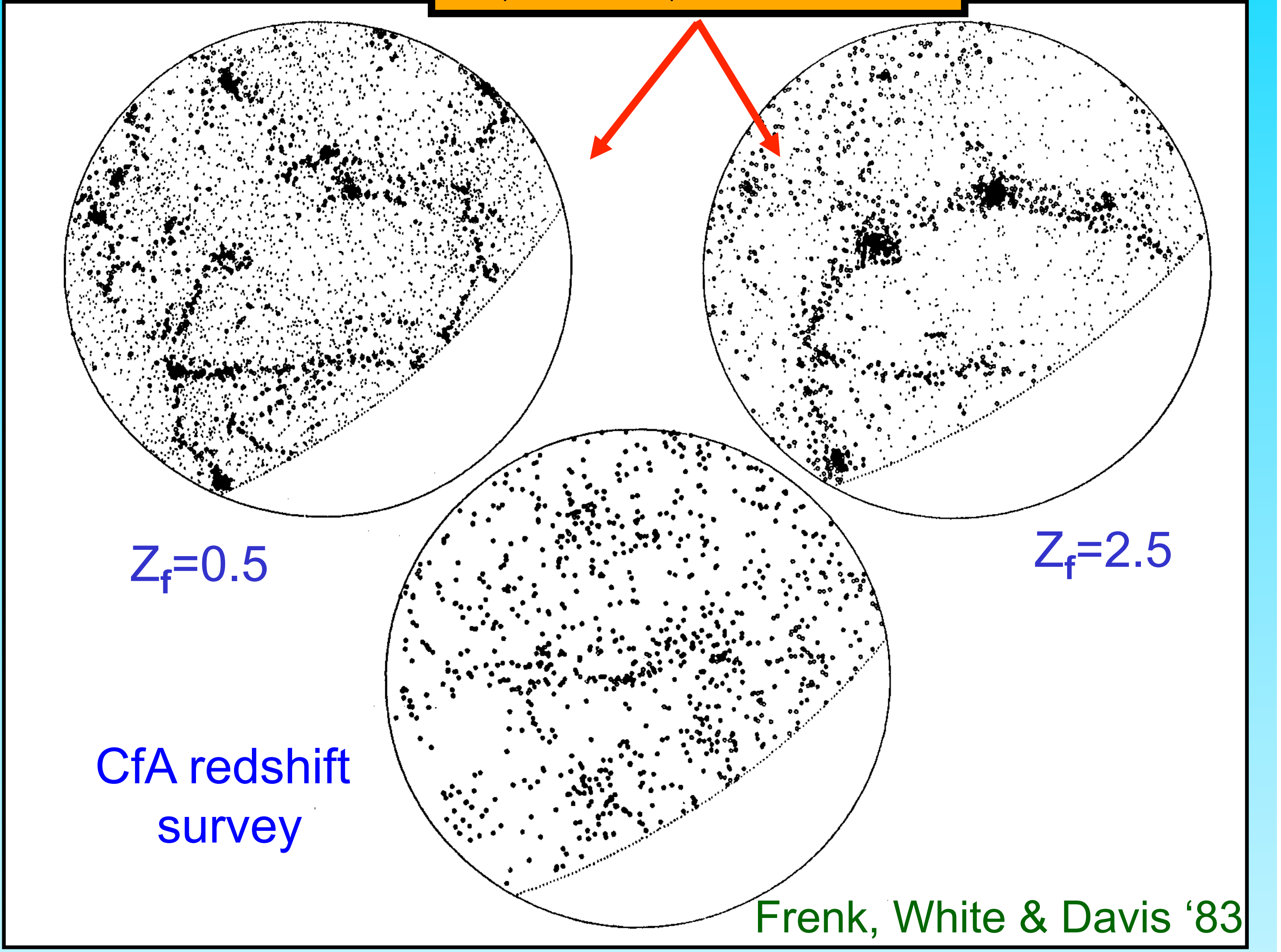
Free-streaming length so large that superclusters form first and galaxies are too young

⇨

Neutrinos cannot make an appreciable contribution to Ω

→ $m_\nu << 10$ ev

$\Omega_\nu = 1$ (m_ν = 30 ev)



Frenk, White & Davis ‘83

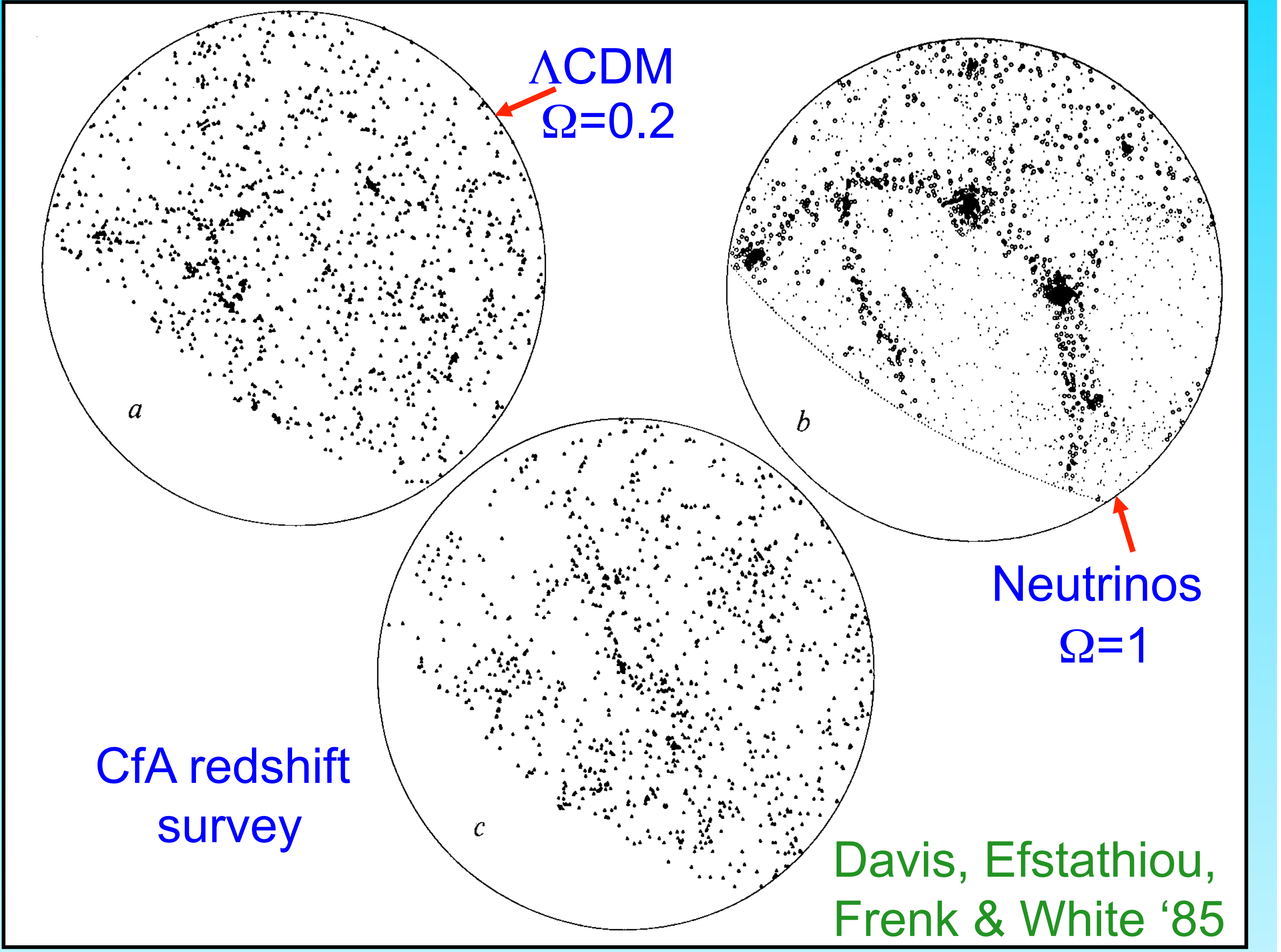
University of Durham

Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically

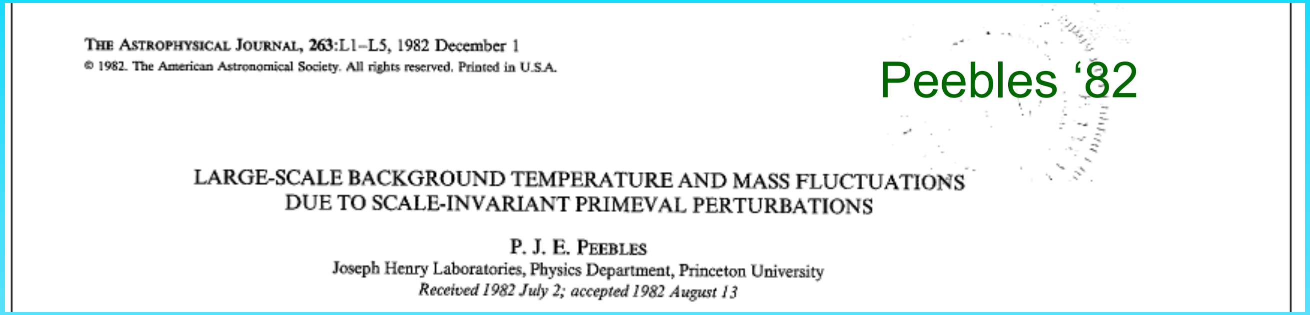


Davis, Efstathiou, Frenk & White ‘85

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 GeV

The cold dark matter cosmogony



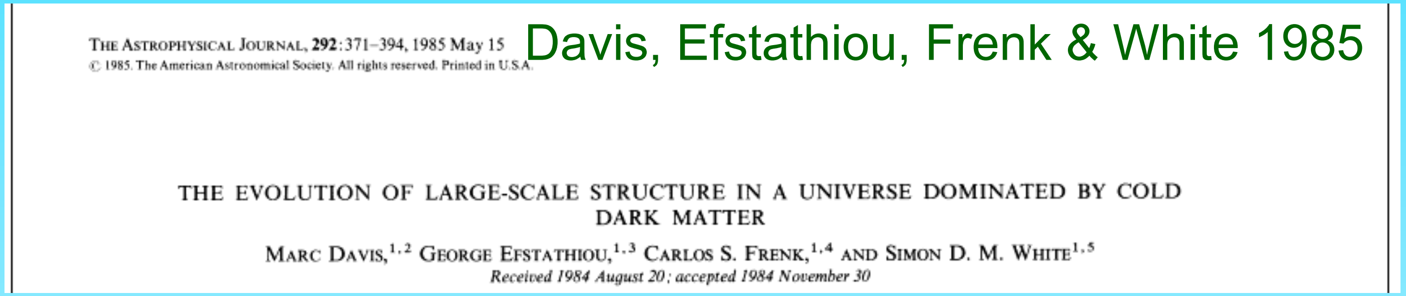
Peebles '82

THE ASTROPHYSICAL JOURNAL, 263:L1–L5, 1982 December 1

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



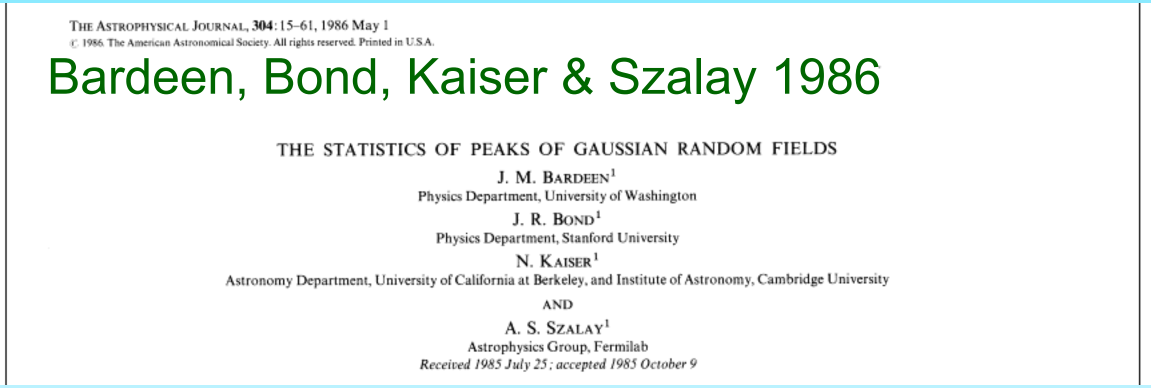
Davis, Efstathiou, Frenk & White 1985

THE ASTROPHYSICAL JOURNAL, 292:371–394, 1985 May 15

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

Bardeen, Bond, Kaiser & Szalay 1986

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

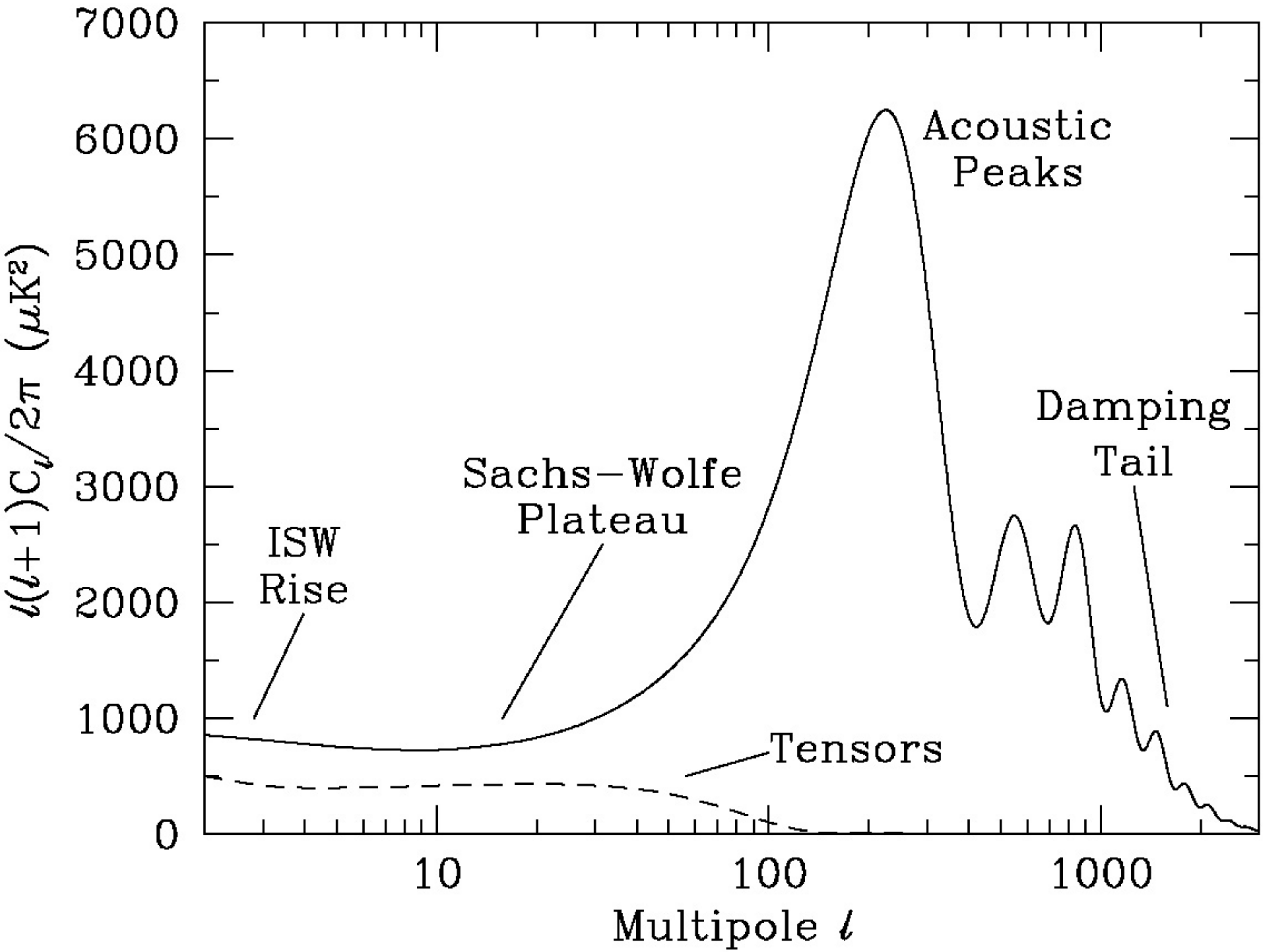
J. M. BARDEEN[1]
Physics Department, University of Washington
J. R. BOND[1]
Physics Department, Stanford University
N. KAISER[1]
Astronomy Department, University of California at Berkeley, and Institute of Astronomy, Cambridge University
AND
A. S. SZALAY[1]
Astrophysics Group, Fermilab

Received 1985 July 25; accepted 1985 October 9

ΛCDM model is an *a priori* implausible model!

… but makes definite predictions and is therefore testable

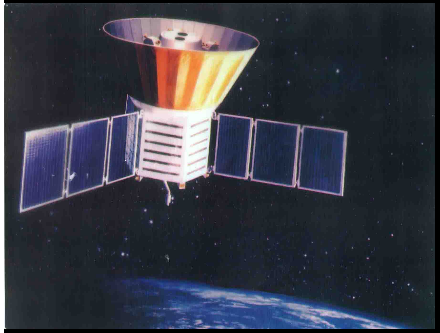
Temperature anisotropies in CMB

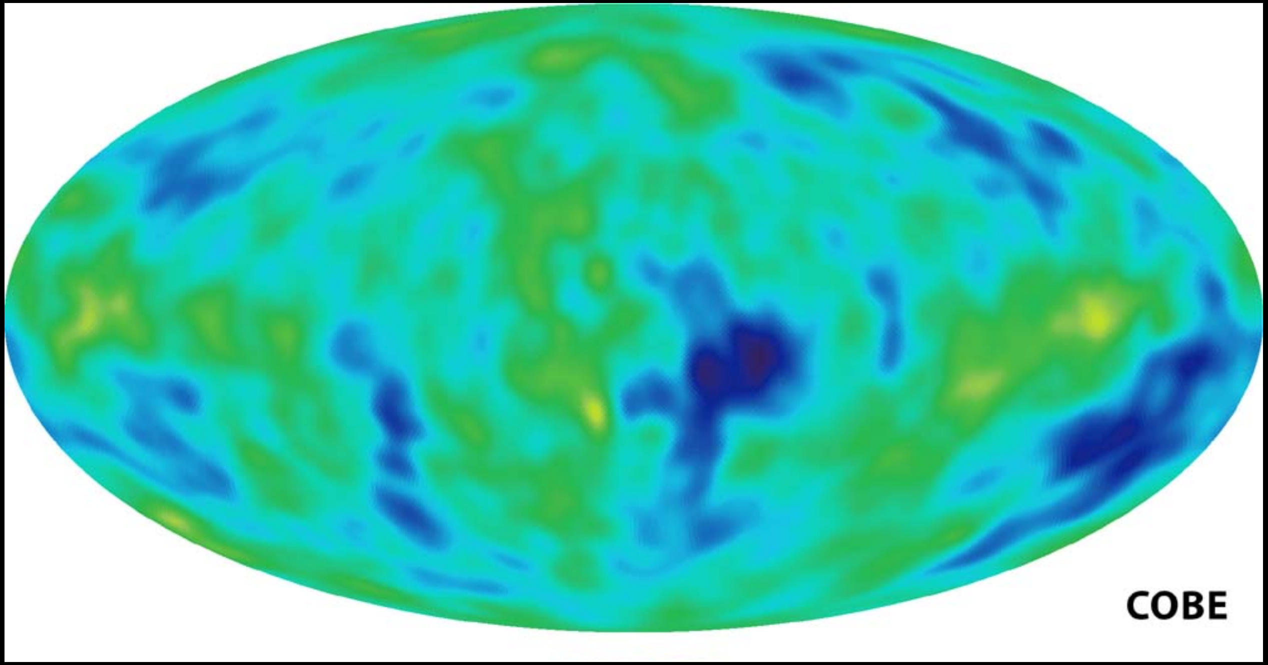


First calculated by Peebles '82

The CMB

1992



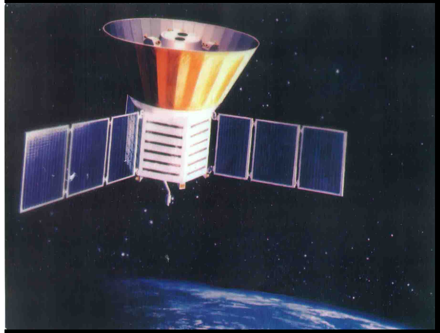


The cosmic microwave background radiation (CMB) provides a window to the universe at t~3x10^5 yrs

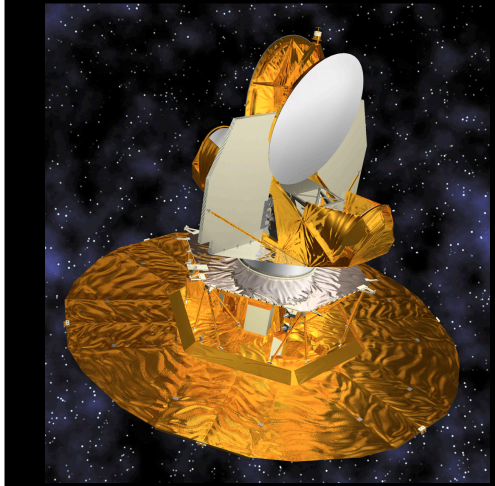
In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions

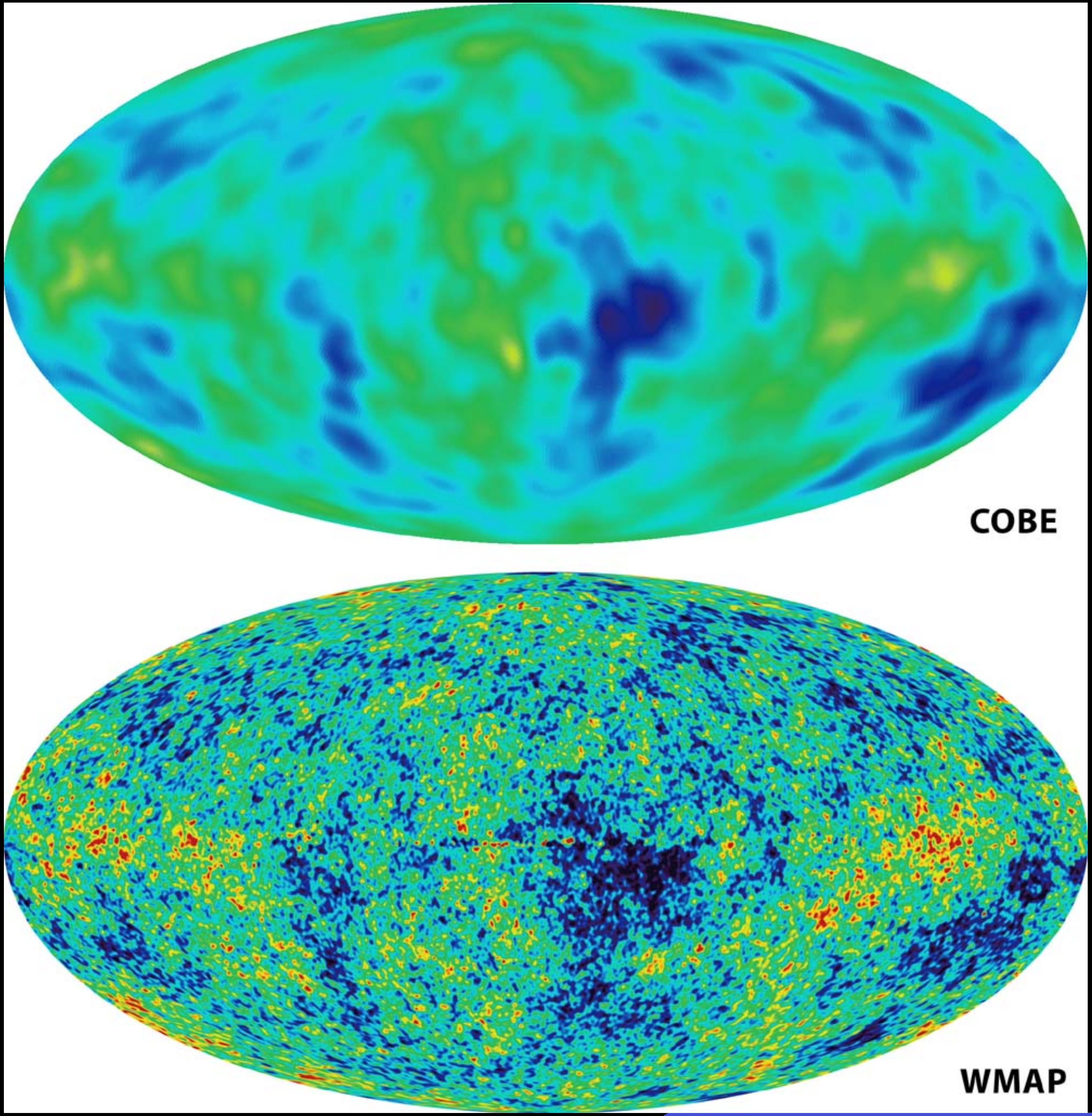
The CMB

1992

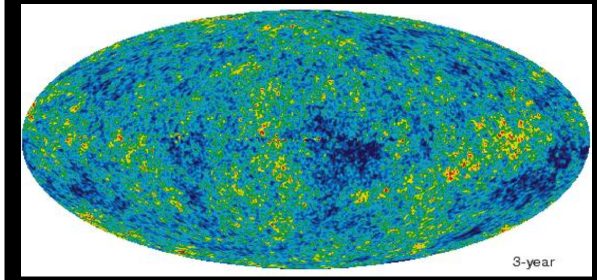


2003

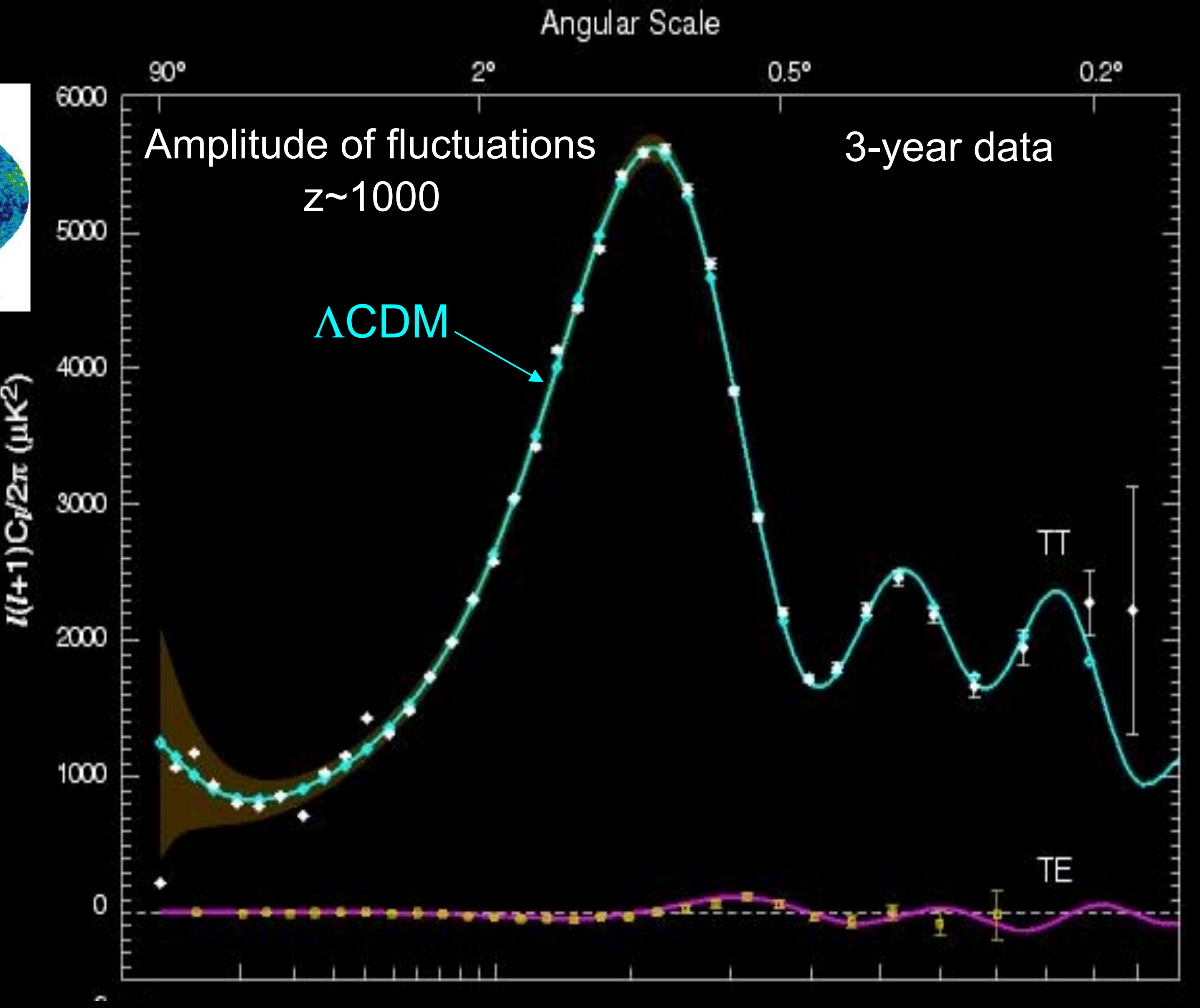




WMAP temp anisotropies in CMB



The data confirm the theoretical predictions



Amplitude of fluctuations
z~1000

3-year data

ΛCDM

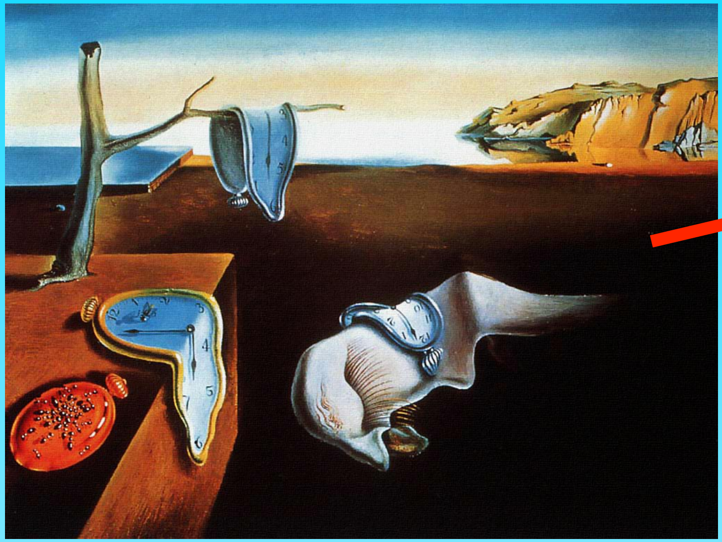
Hinshaw etal ‘06

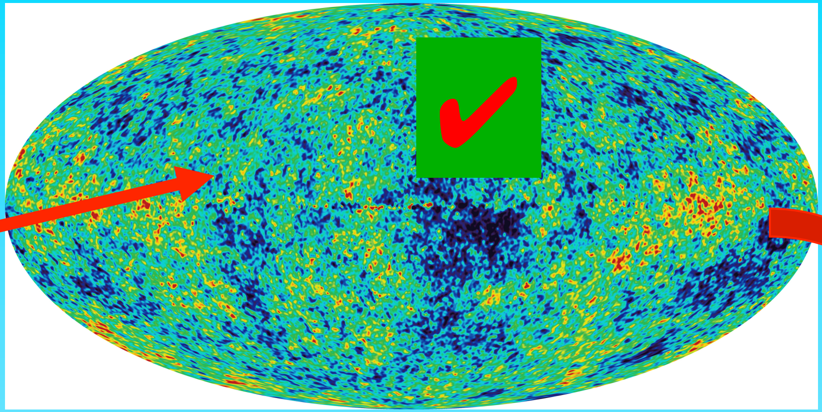
ICC

University of Durham

The formation of cosmic structure

$t=10^{-35}$ seconds





t=380,000 yrs

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

Simulations

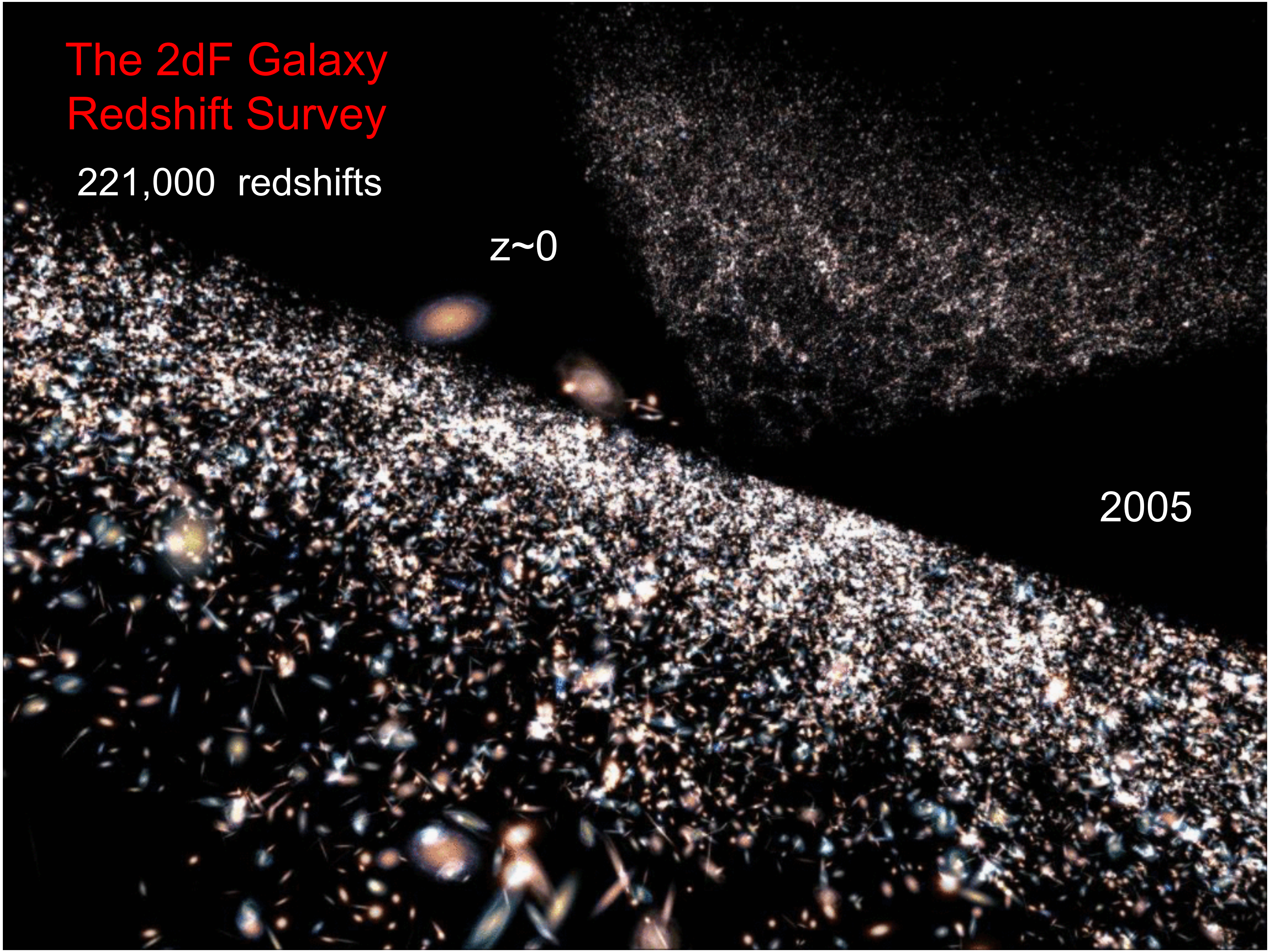
Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

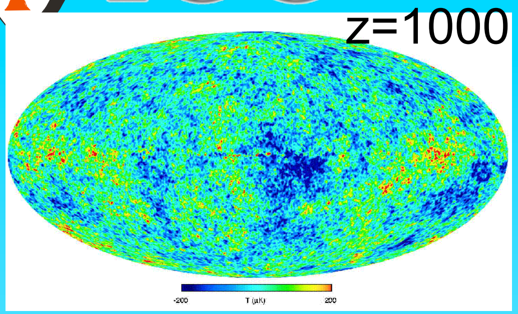
t=13.8 billion yrs

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

The 2dF Galaxy Redshift Survey

221,000 redshifts





Cosmological model

(Ω_m, Ω_Λ, h); dark matter

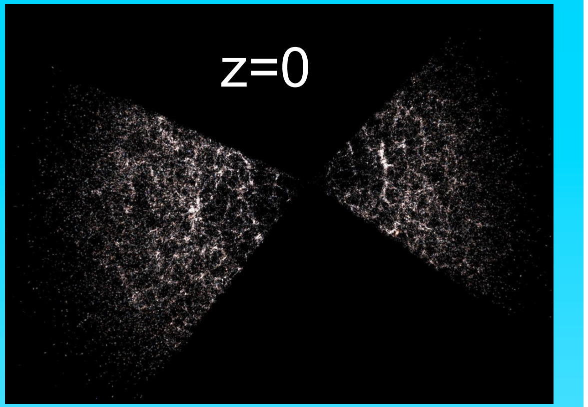
↓

Primordial fluctuations

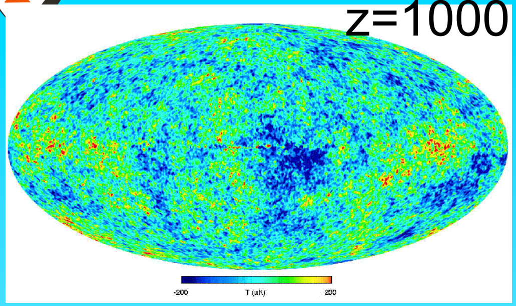
$\delta\rho/\rho$(M, t)

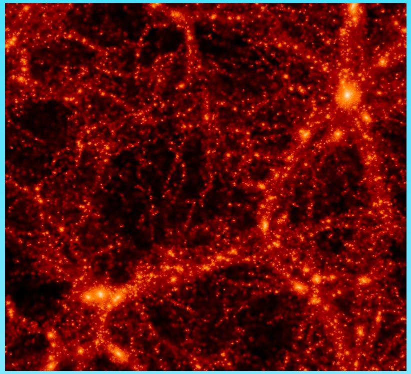
↓

?



Formation and evolution of galaxies





Cosmological model

(Ω_m, Ω_Λ, h); dark matter

Primordial fluctuations

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

Dark matter halos
(N-body simulations)

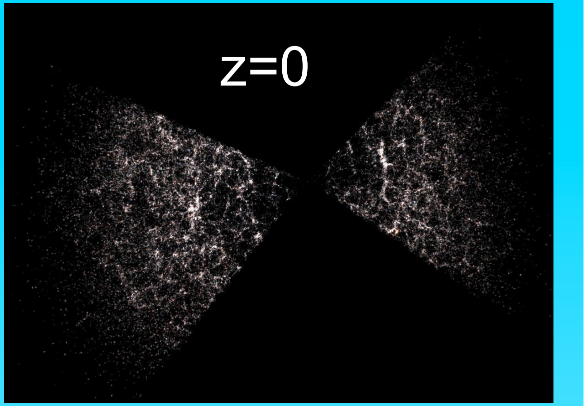
Well understood

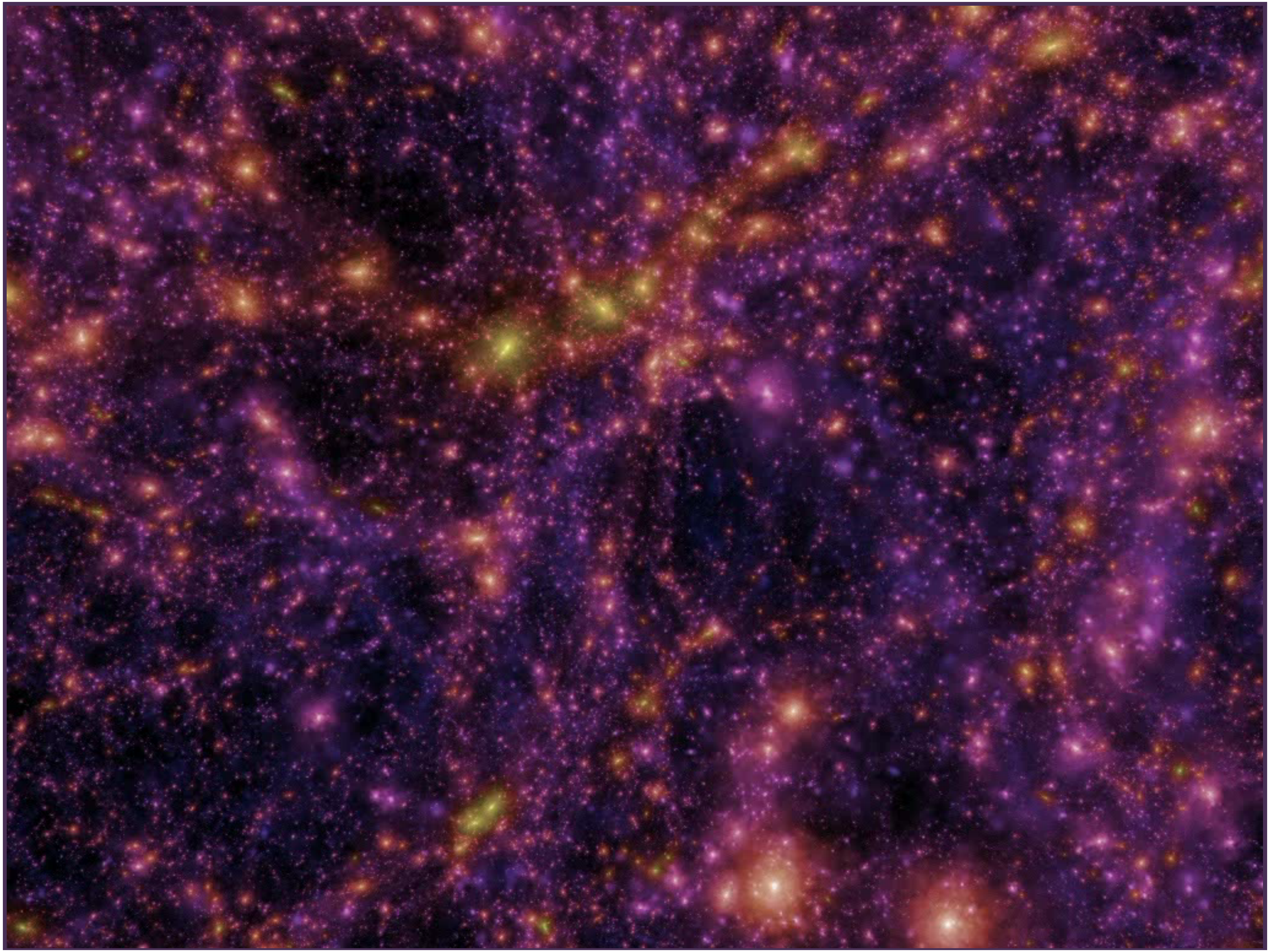
Gas processes
(cooling, star formation, feedback)

Gasdynamic simulations

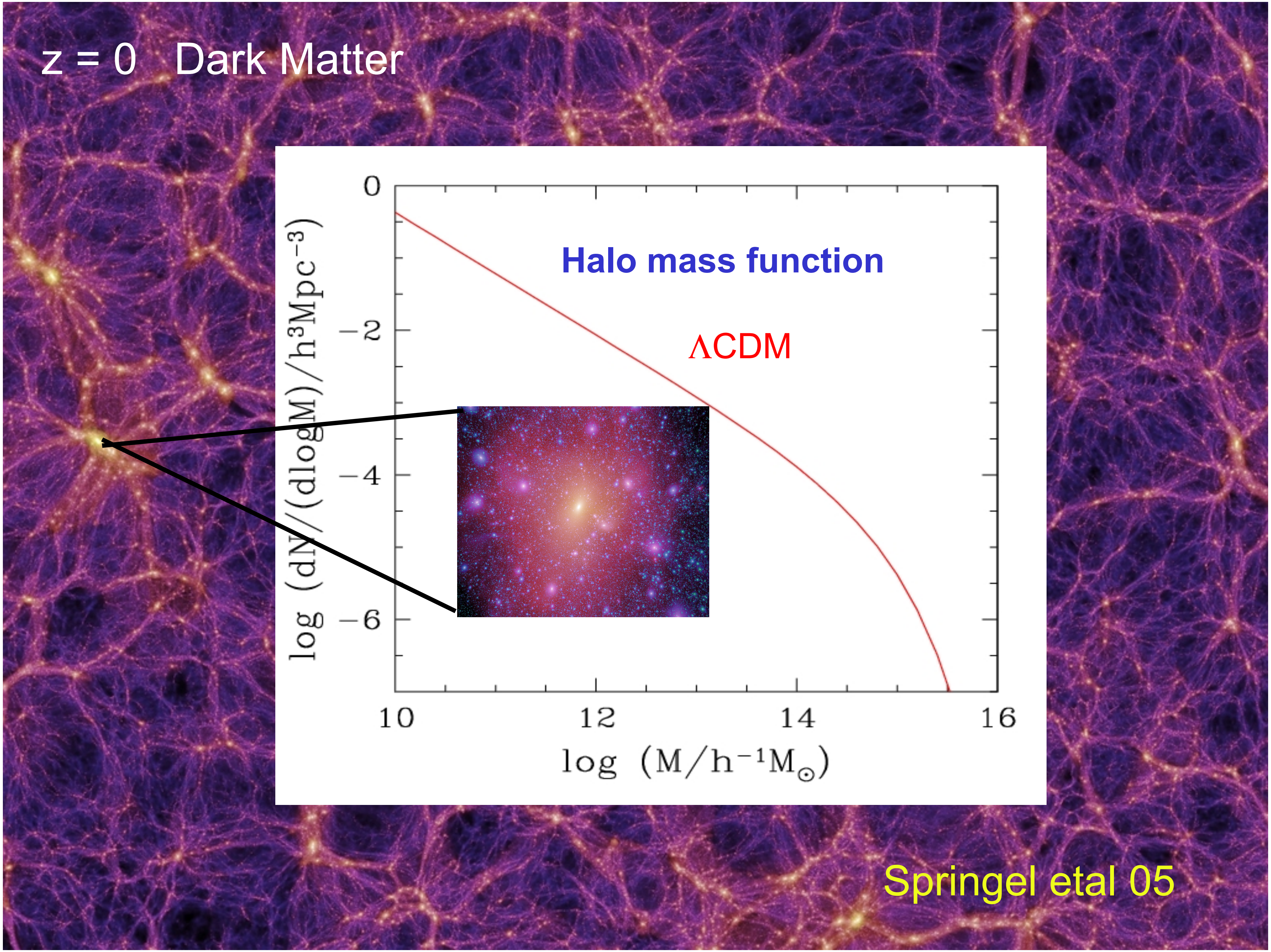
Semi-analytics

Formation and evolution of galaxies





z = 0 Dark Matter



Springel etal 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

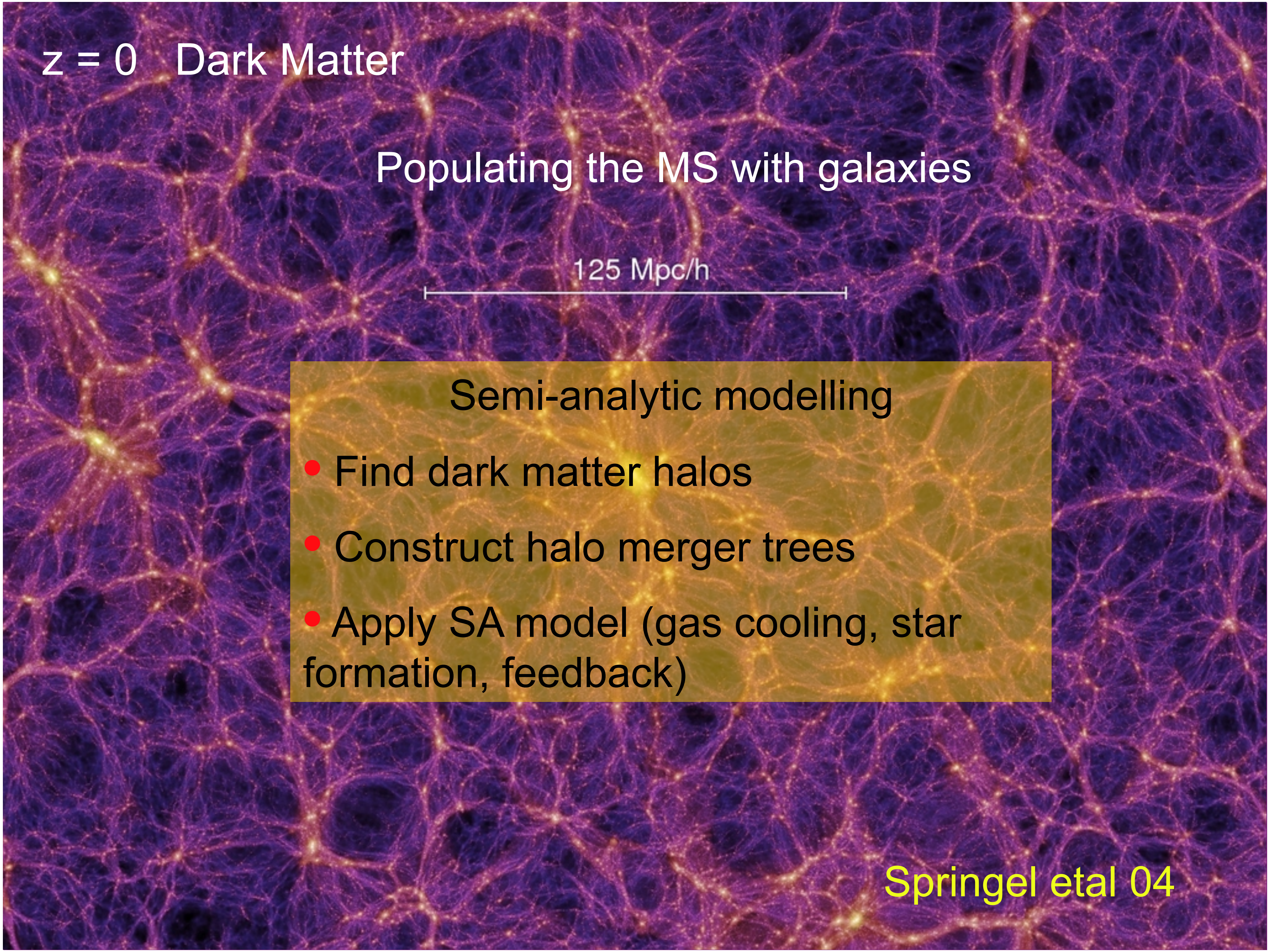
Main baryonic processes:

- Shock-heating and radiative cooling of gas within halos

Sub-grid physics

- Star formation and SN feedback
- Reionization
- Production & mixing of metals
- Evolution of stellar populations
- Dust obscuration
- AGN feedback

Need to use phenomenological models

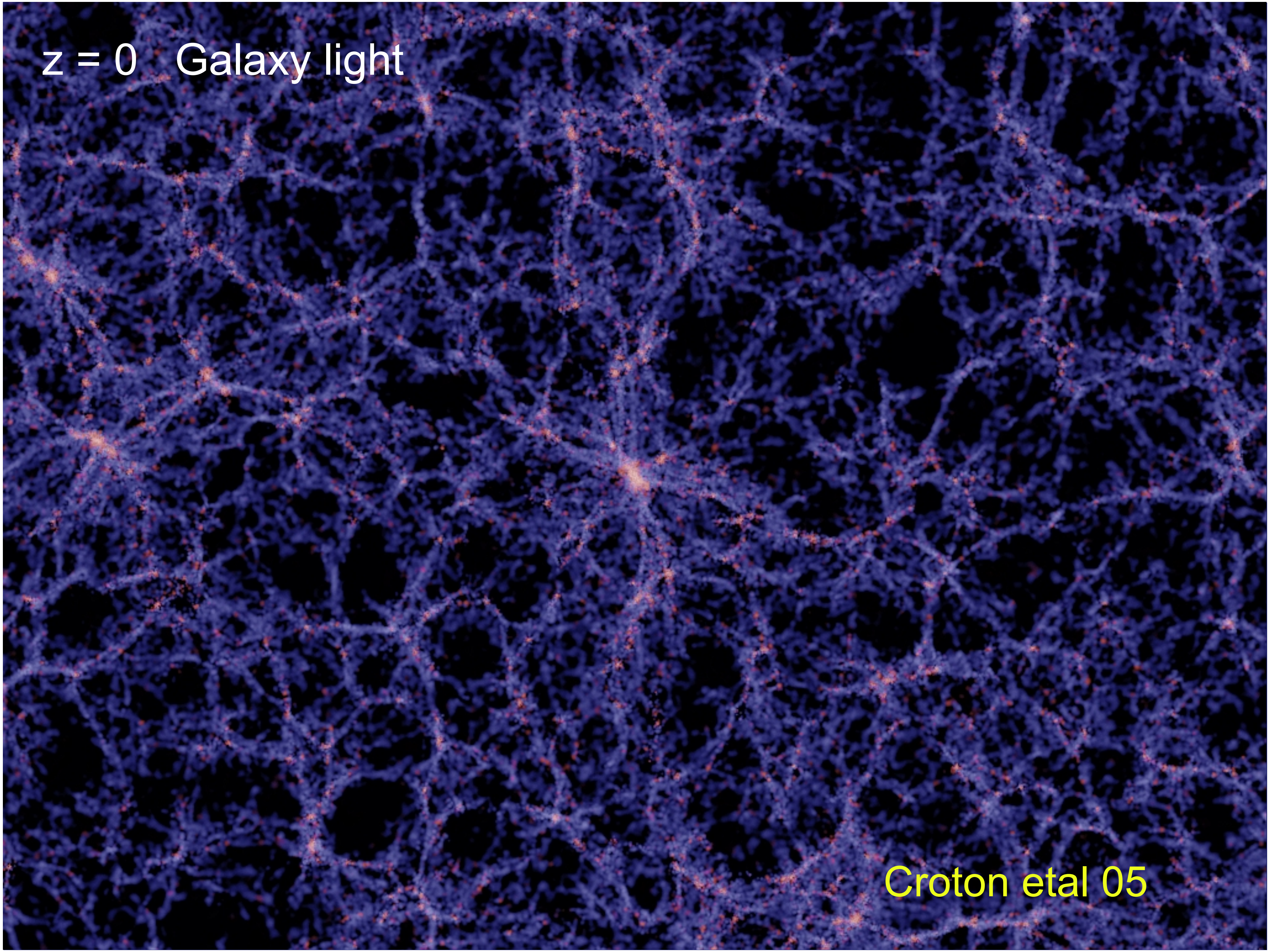


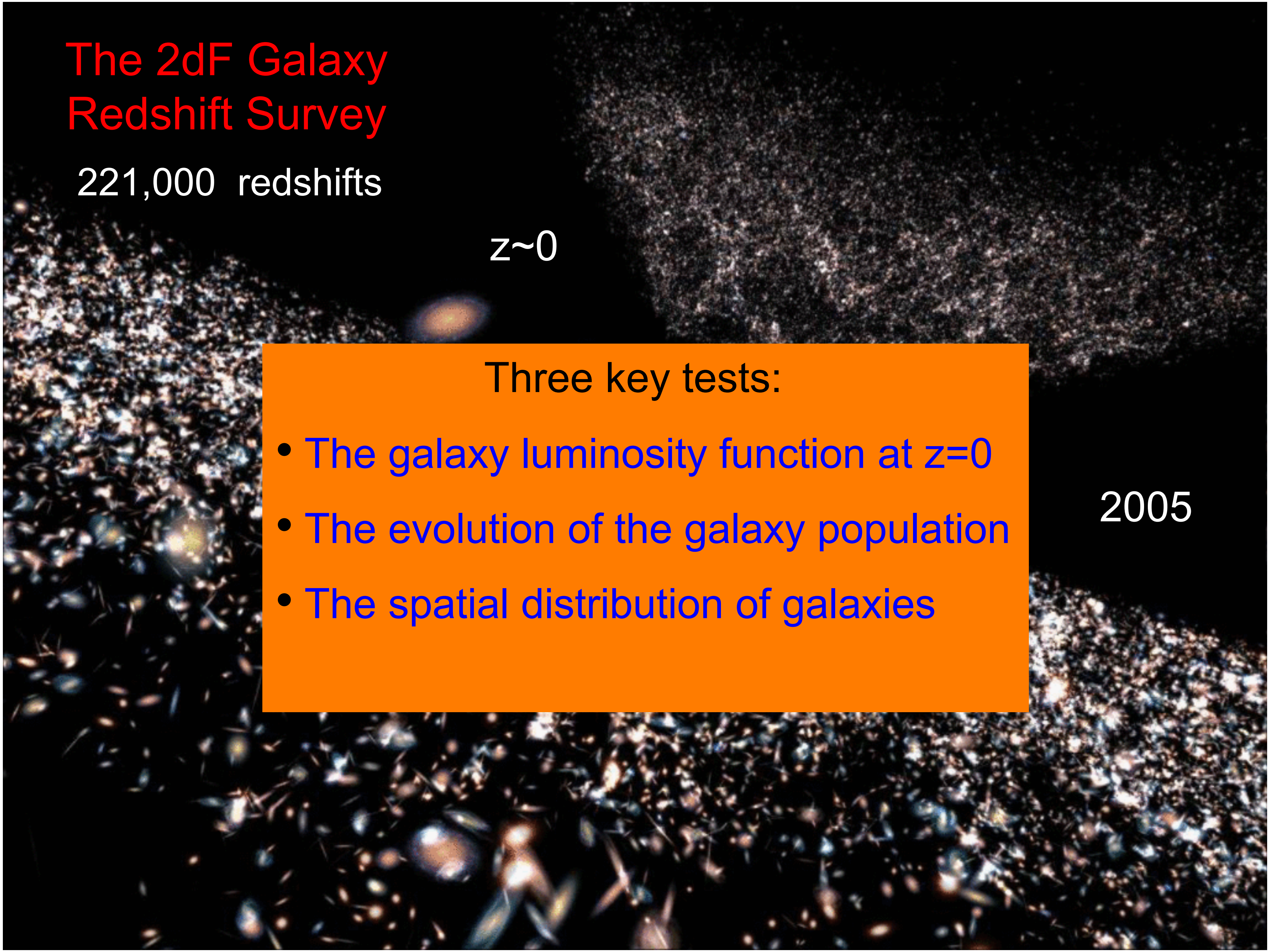
Populating the MS with galaxies

Semi-analytic modelling

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

Springel etal 04


z = 0 Galaxy light
Croton etal 05



The 2dF Galaxy Redshift Survey

221,000 redshifts

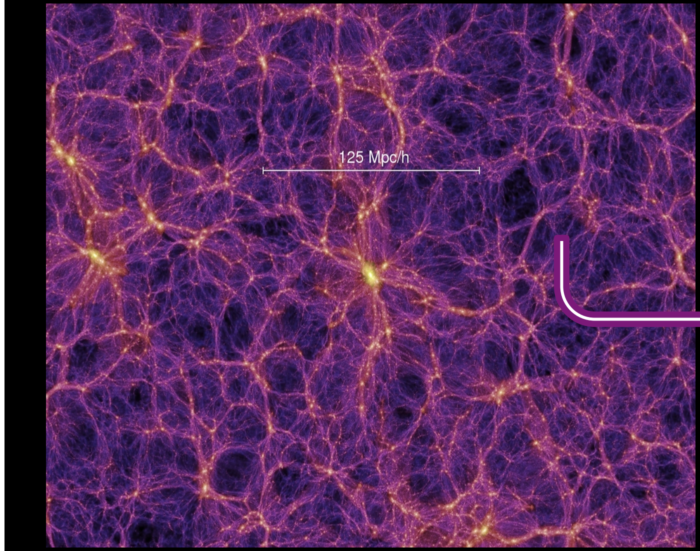
z~0

Three key tests:

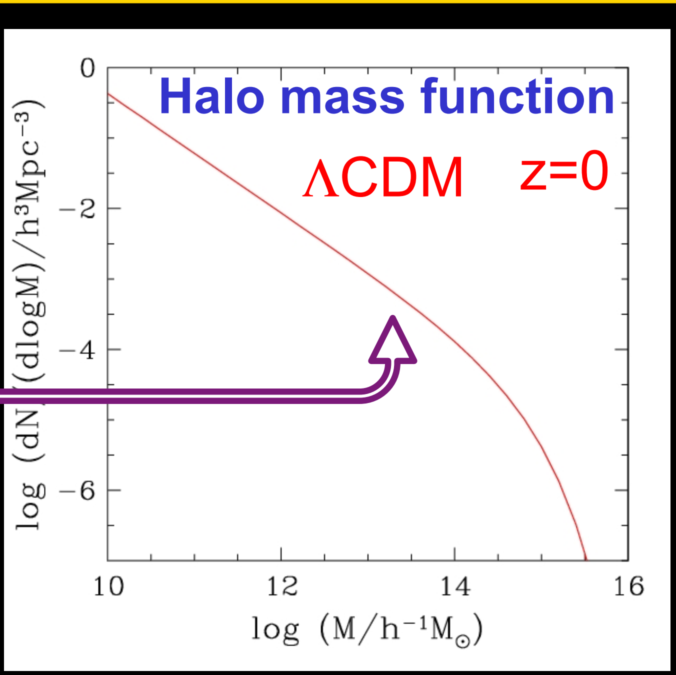
- The galaxy luminosity function at z=0
- The evolution of the galaxy population
- The spatial distribution of galaxies

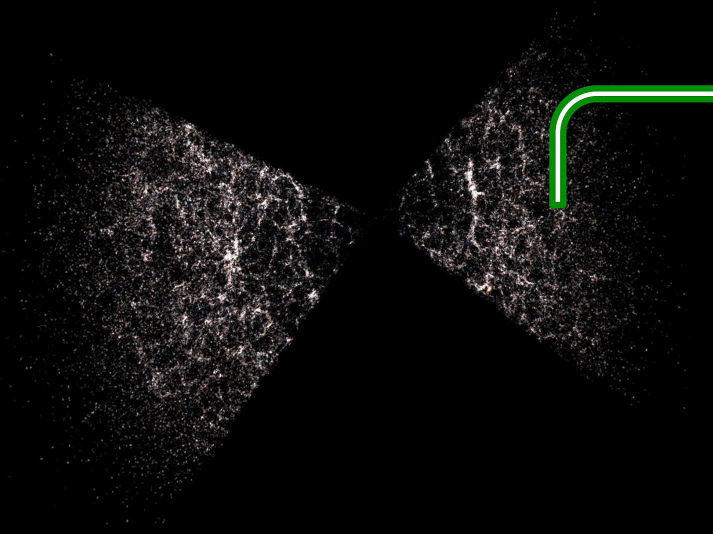
2005

Abundance of gals & dark halos

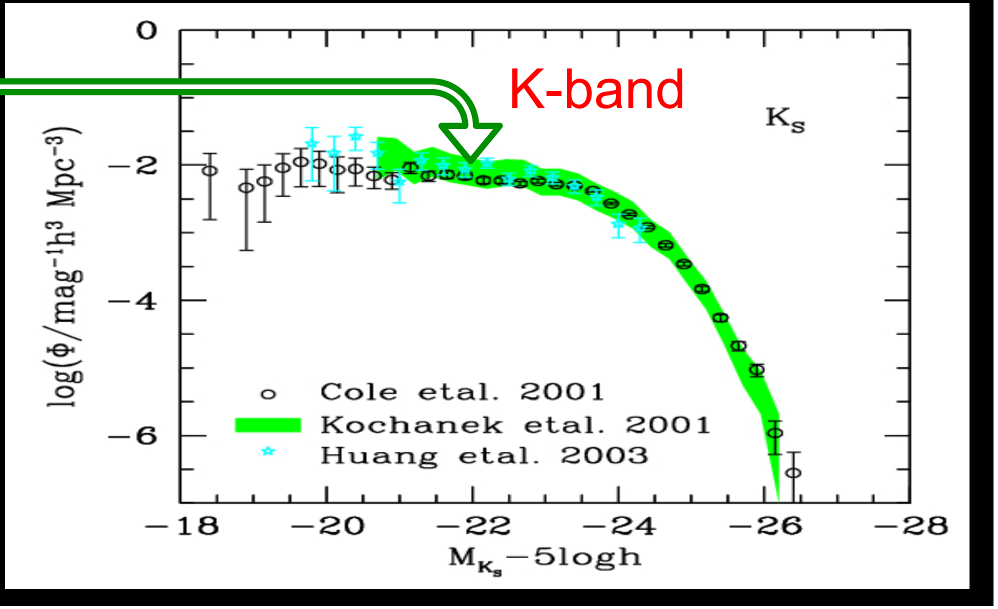


Millennium run





2dFGRS

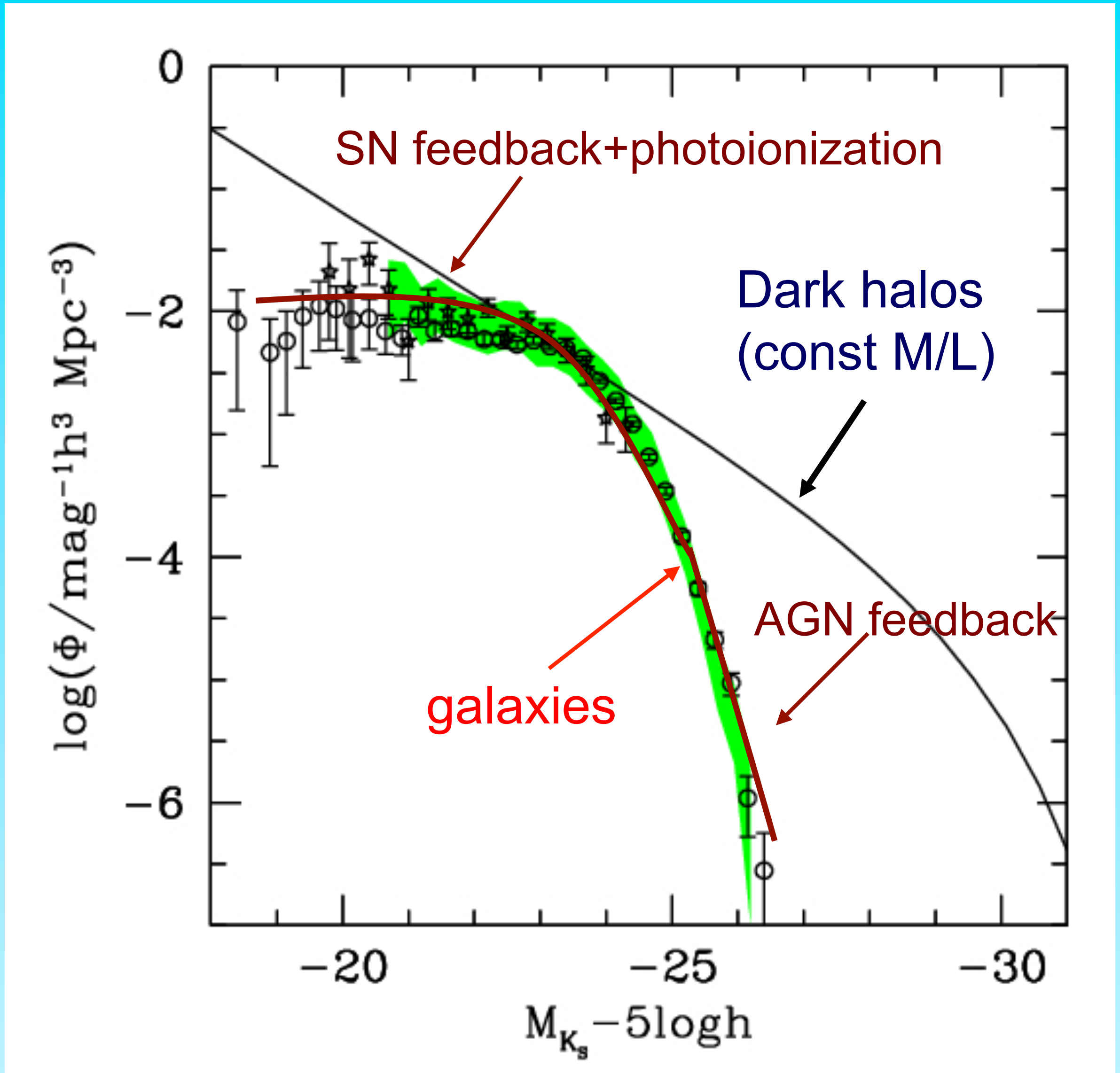


The galaxy luminosity function

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

⇨

Complicated variation of M/L with halo mass

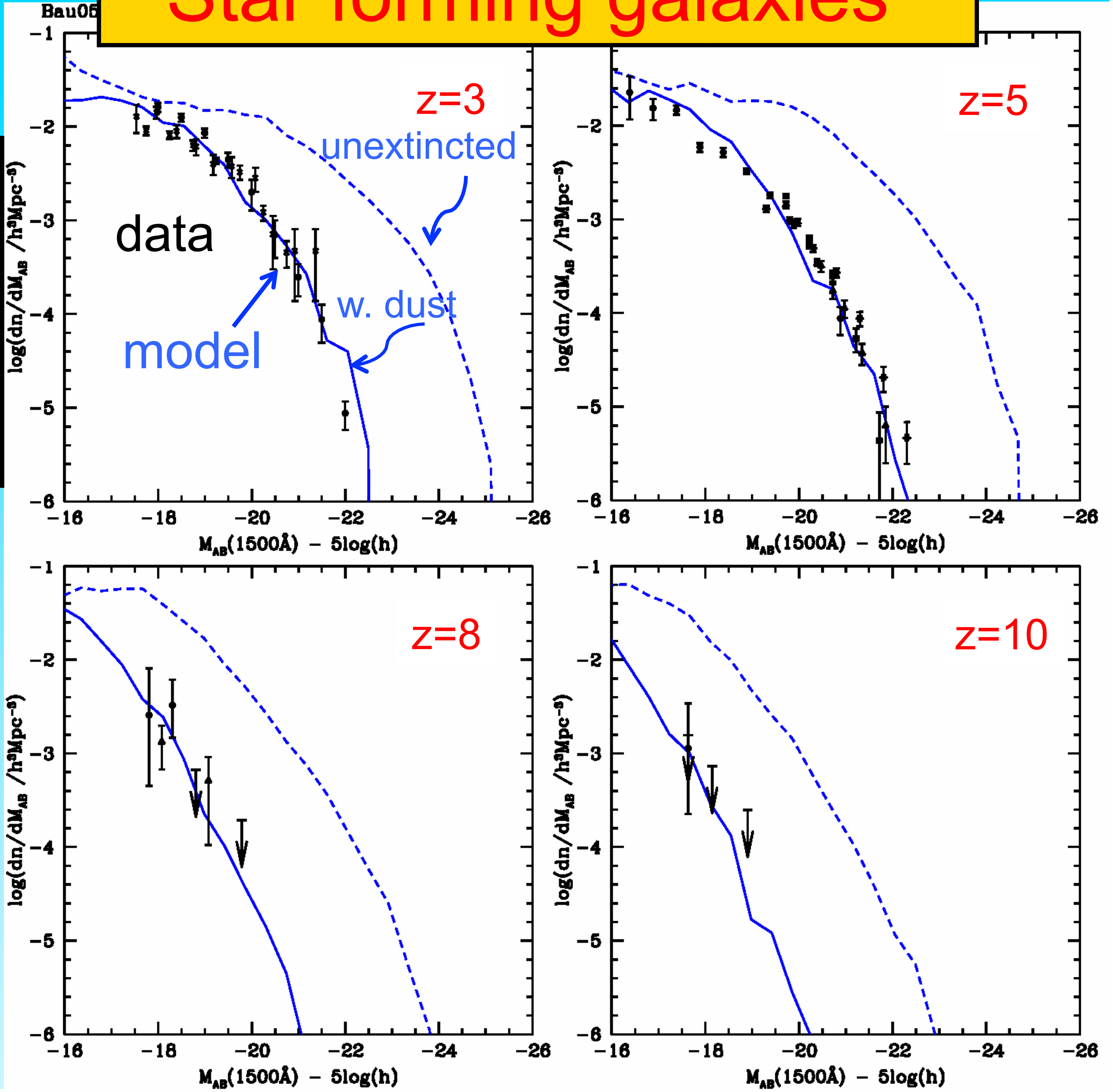


Benson, Bower, Frenk, Lacey, Baugh & Cole ‘03

University of Durham

Star forming galaxies

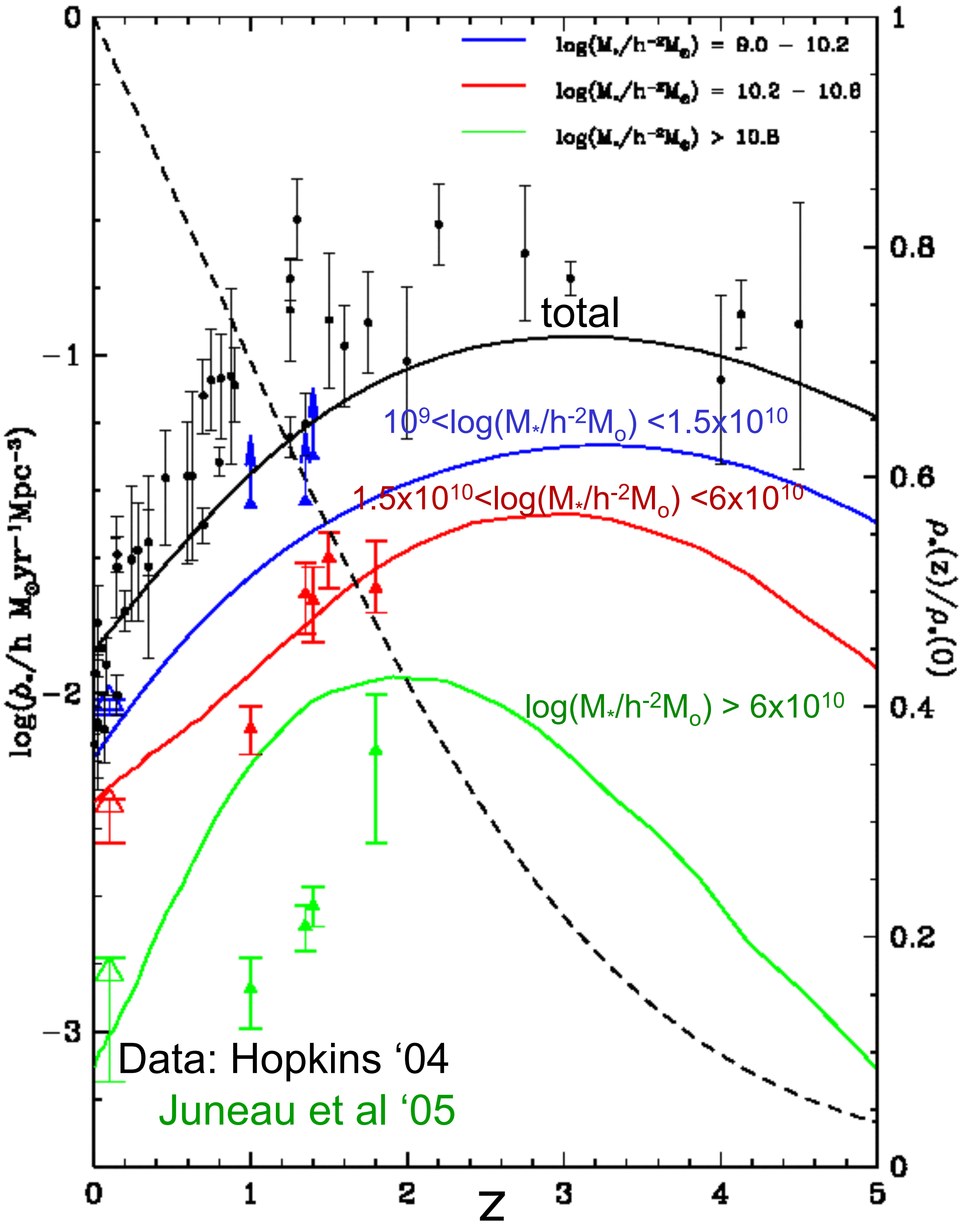
Evolution of Lyman-break galaxy lum. function



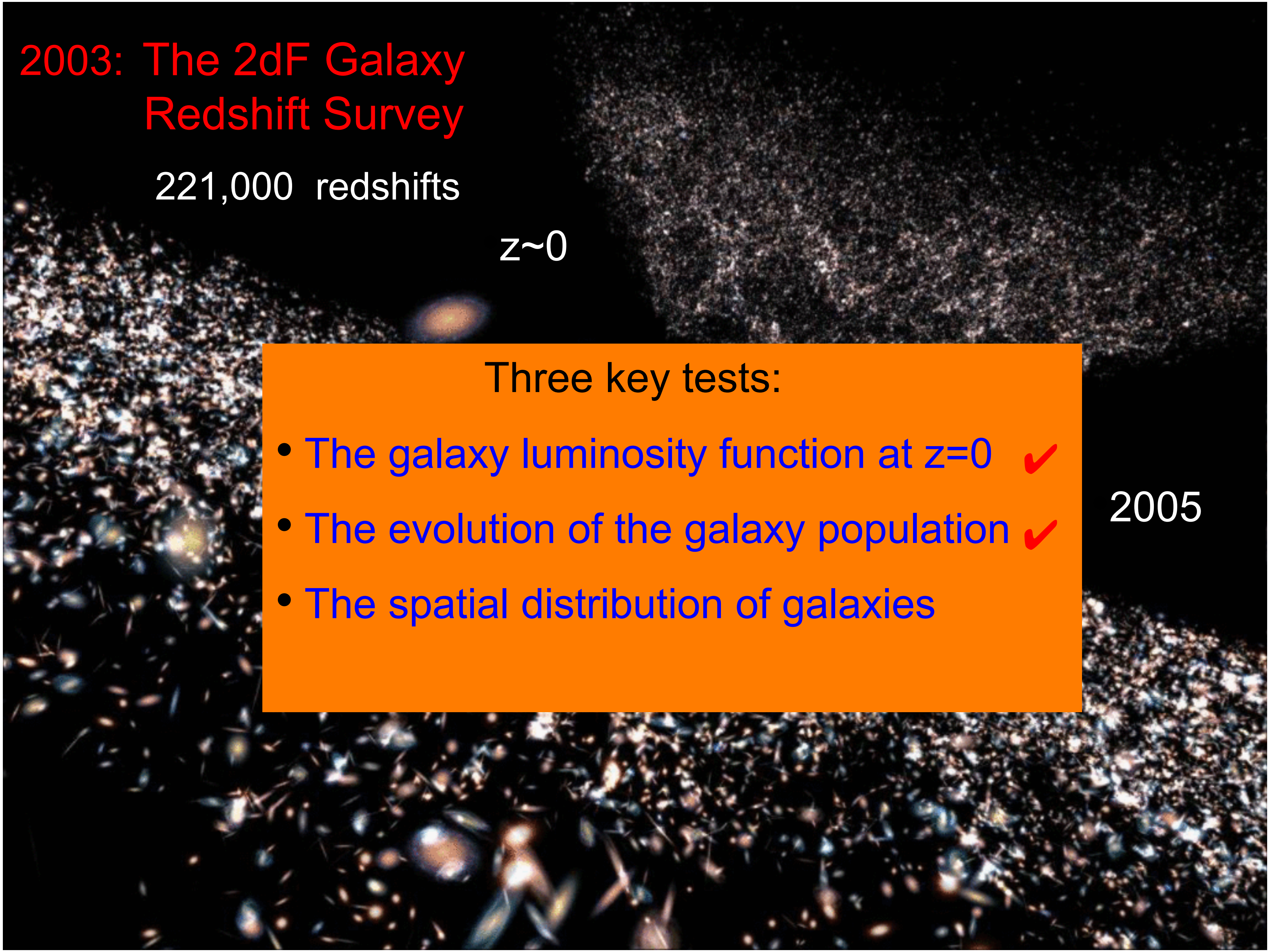
Lacey, Baugh, Frenk, Benson '11

ICC
University of Durham

History of cosmic star formation



Bower et al 06



2003: The 2dF Galaxy Redshift Survey

221,000 redshifts

z~0

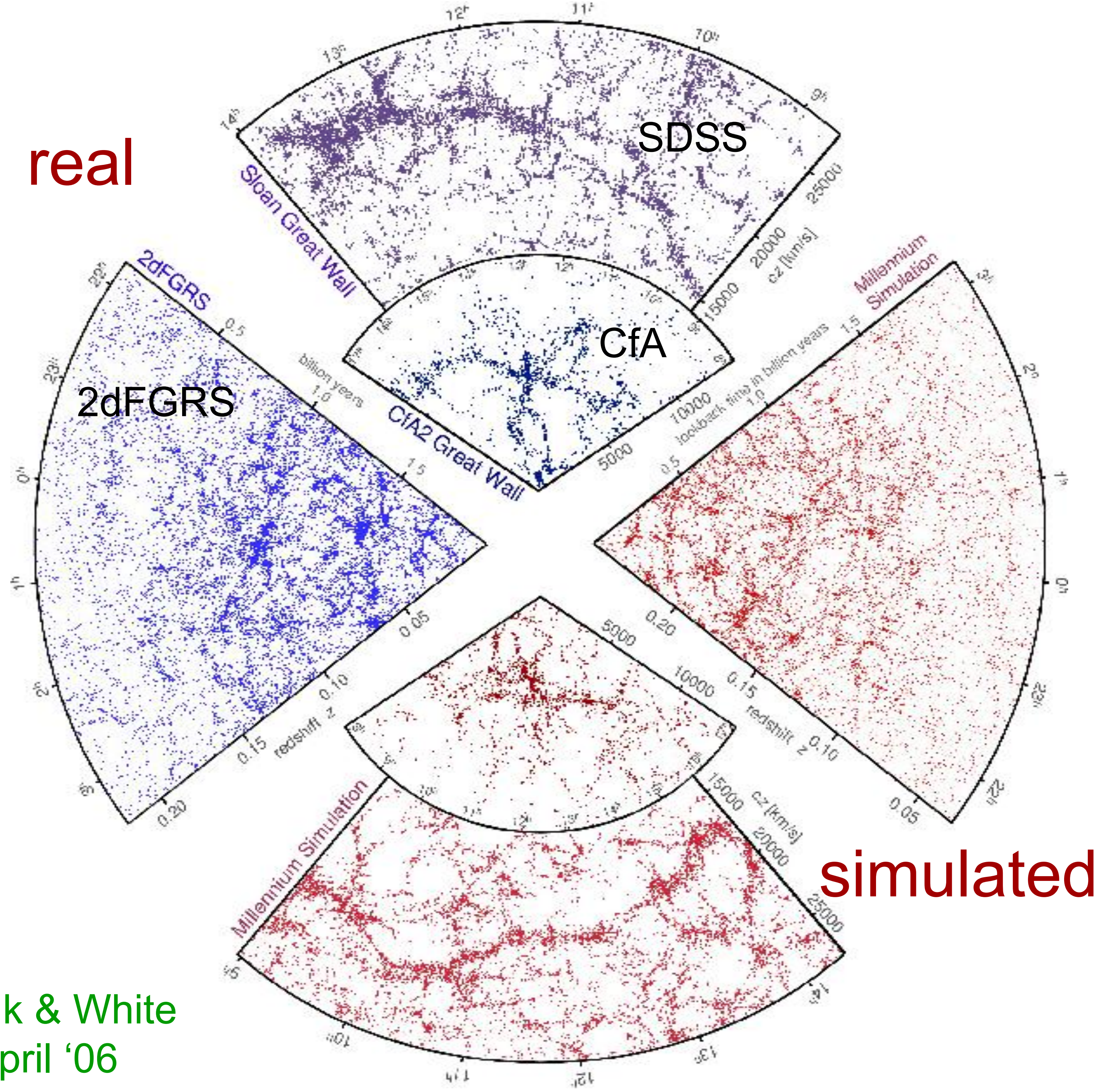
Three key tests:

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

2005

real

simulated

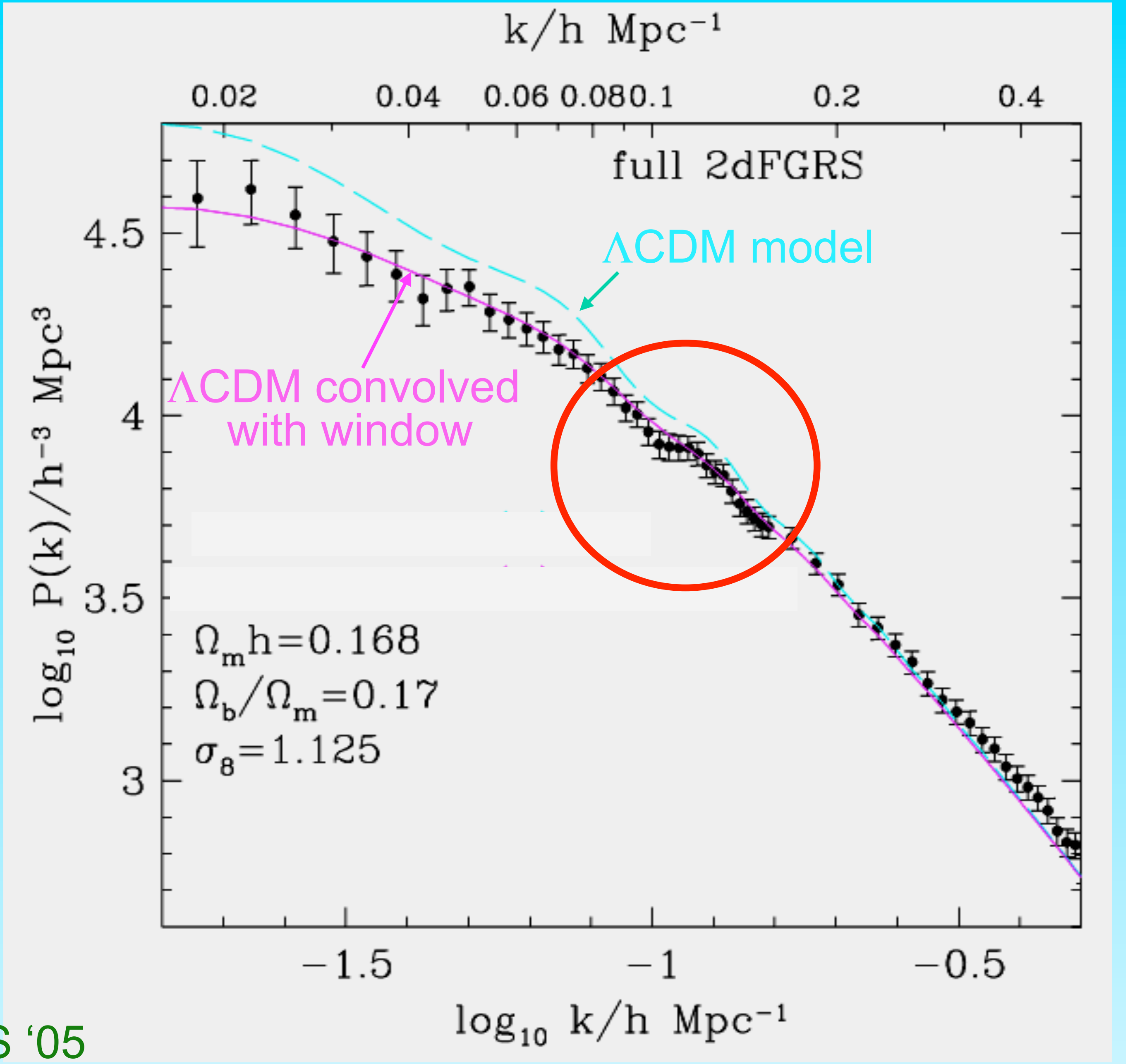


Springel, Frenk & White
Nature, April ‘06

University of Durham

The final 2dFGRS power spectrum

2dFGRS P(k) well fit by ΛCDM model convolved with window function



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

University of Durham

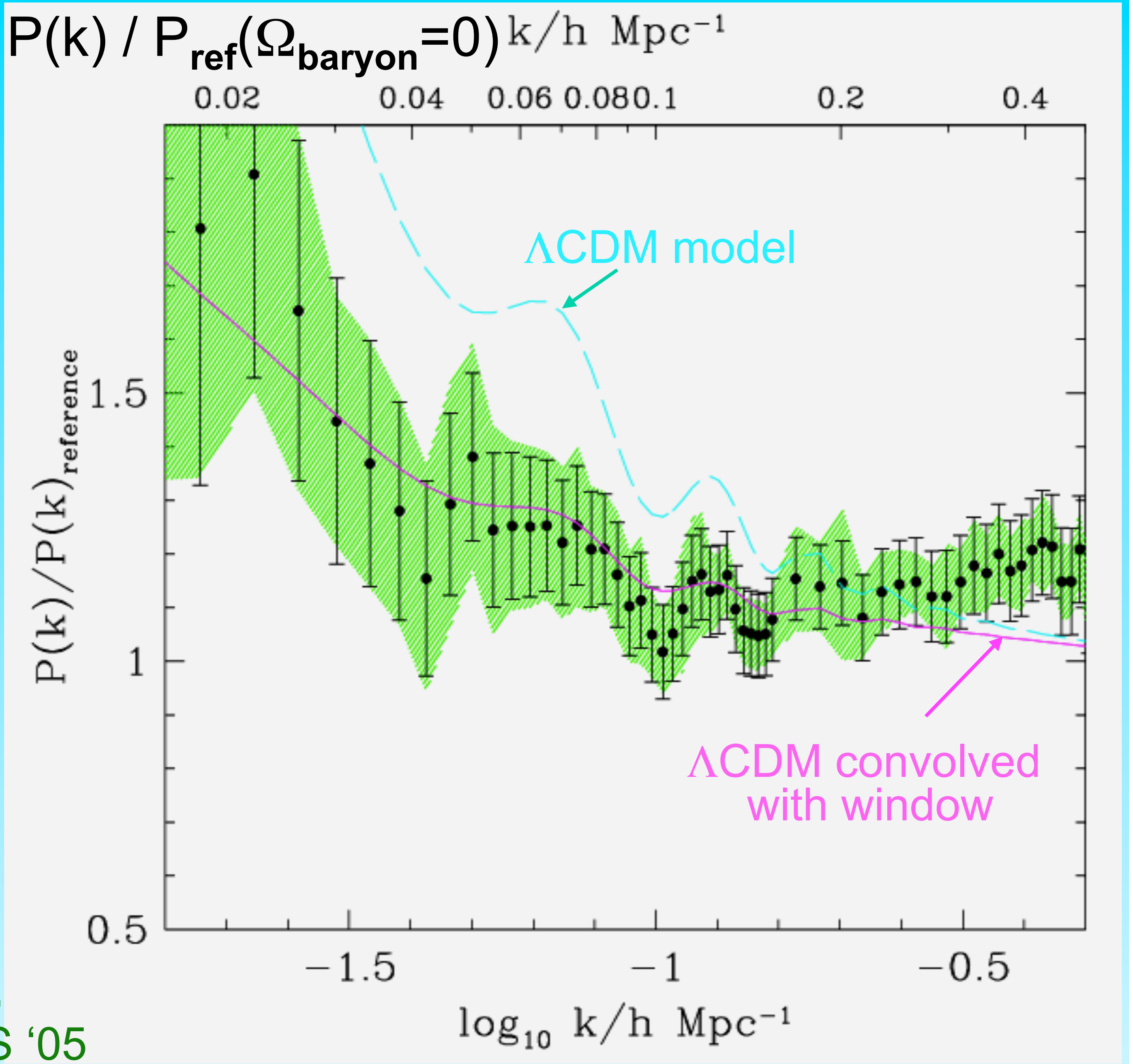
The final 2dFGRS power spectrum

Baryon oscillations conclusively detected in 2dFGRS!!!

Demonstrates that structure grew by gravitational instability in ΛCDM universe

Also detected in SDSS LRG sample (Eisenstein etal 05)

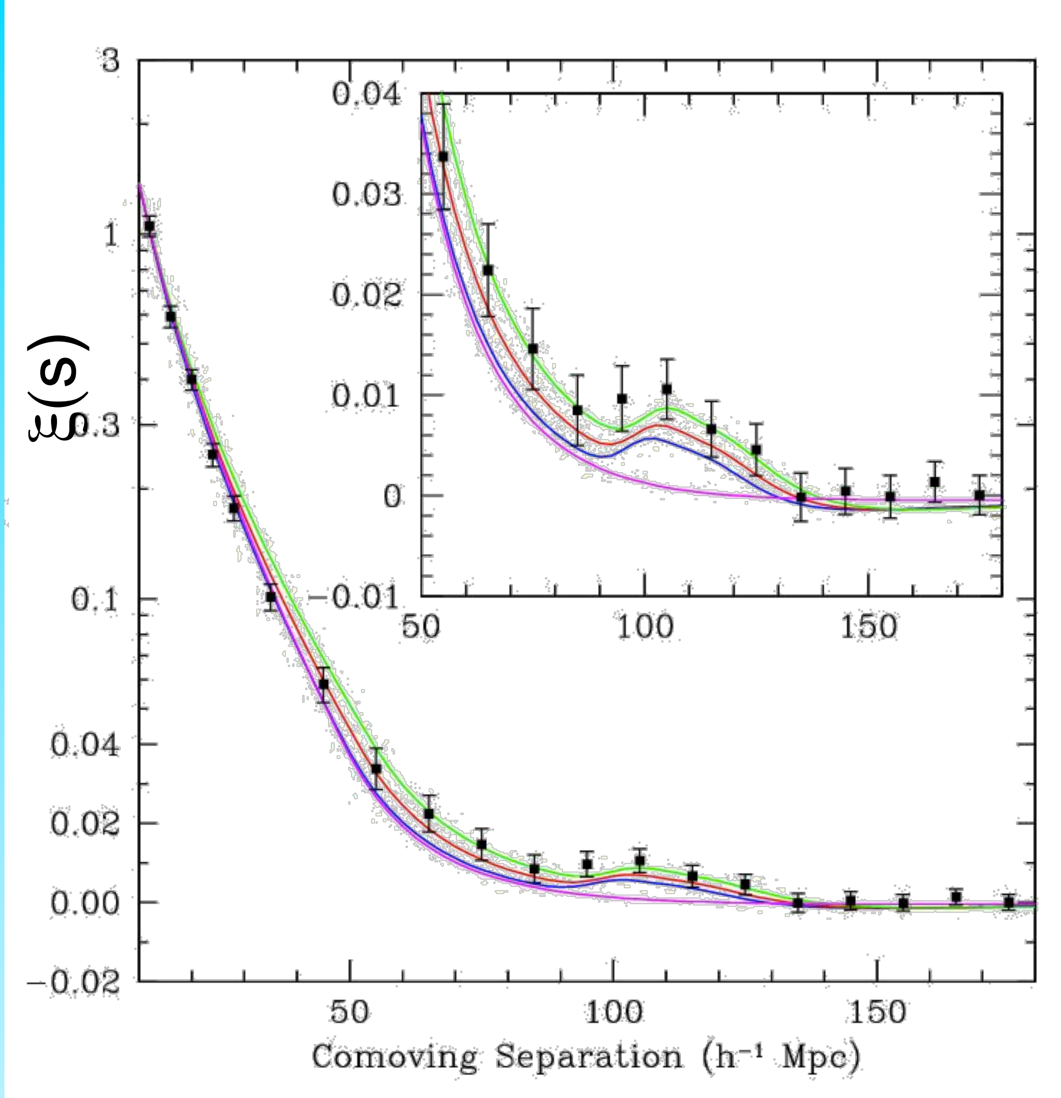
Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05



SDSS LRG correlation function

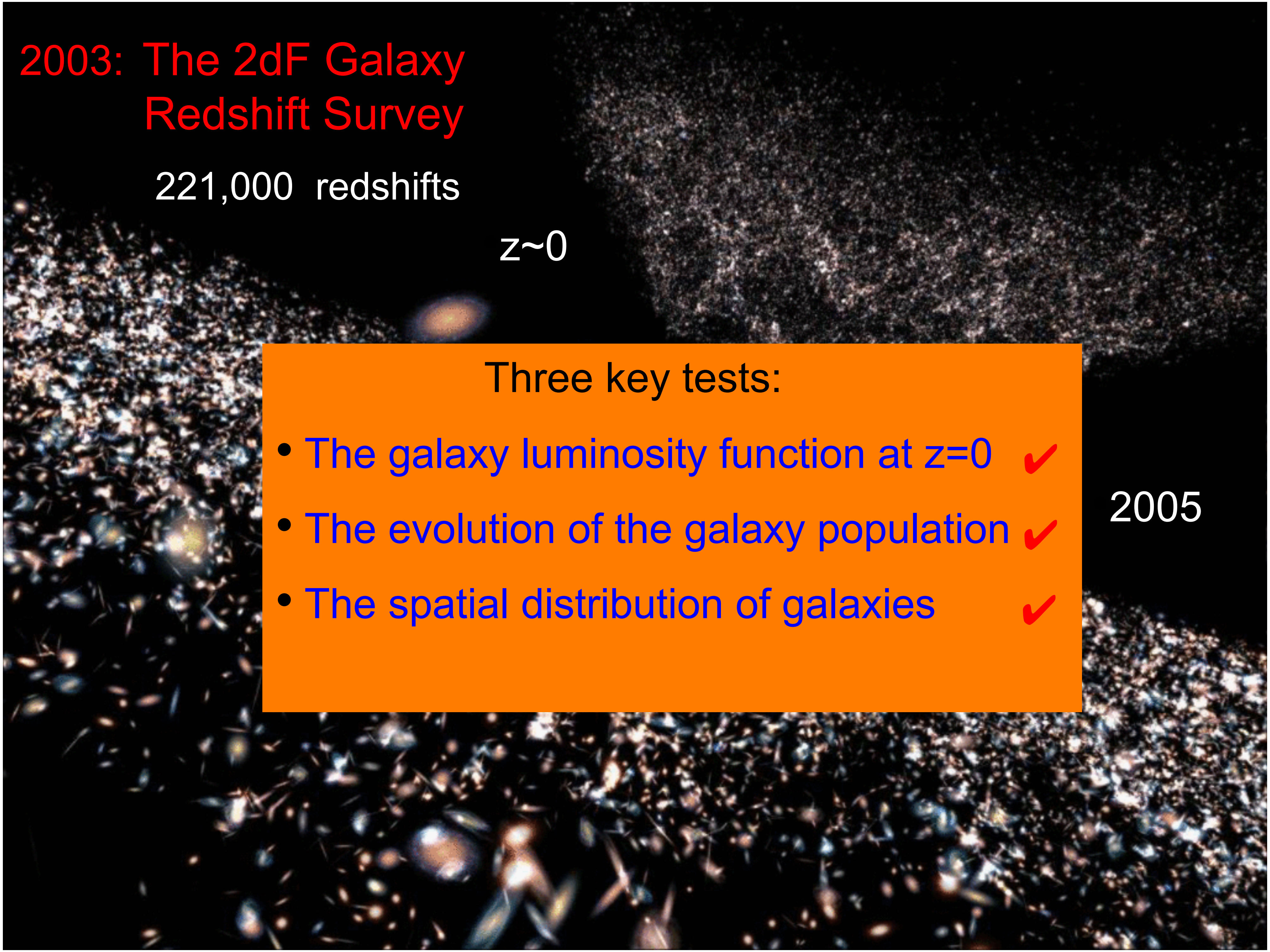
Again, CDM models fit the correlation function adequately well (although peak height is slightly too large; assuming n_s=1, h=0.72)

$\Omega_b h^2$ =0.024,
$\Omega_m h^2$ =0.133±0.011,
$\Rightarrow$ Ω_b/Ω_m= 0.18



Eisenstein et al. 05

2003: The 2dF Galaxy Redshift Survey



221,000 redshifts

z~0

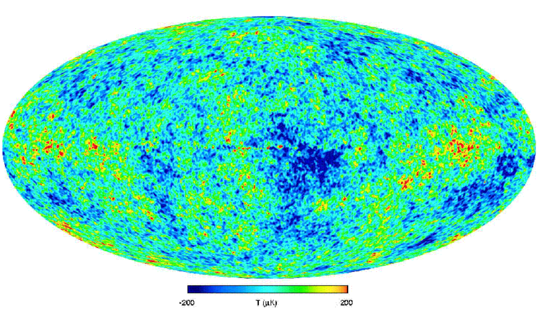
Three key tests:

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

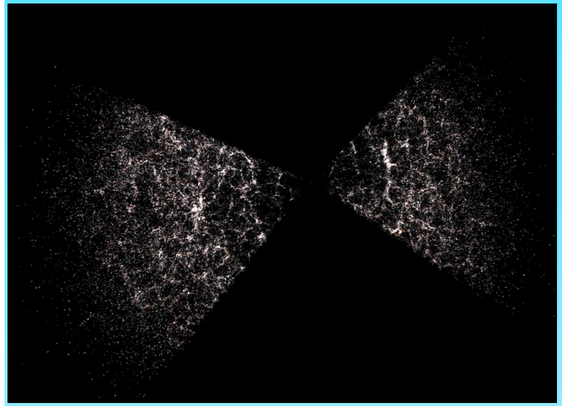
2005

ICC University of Durham

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



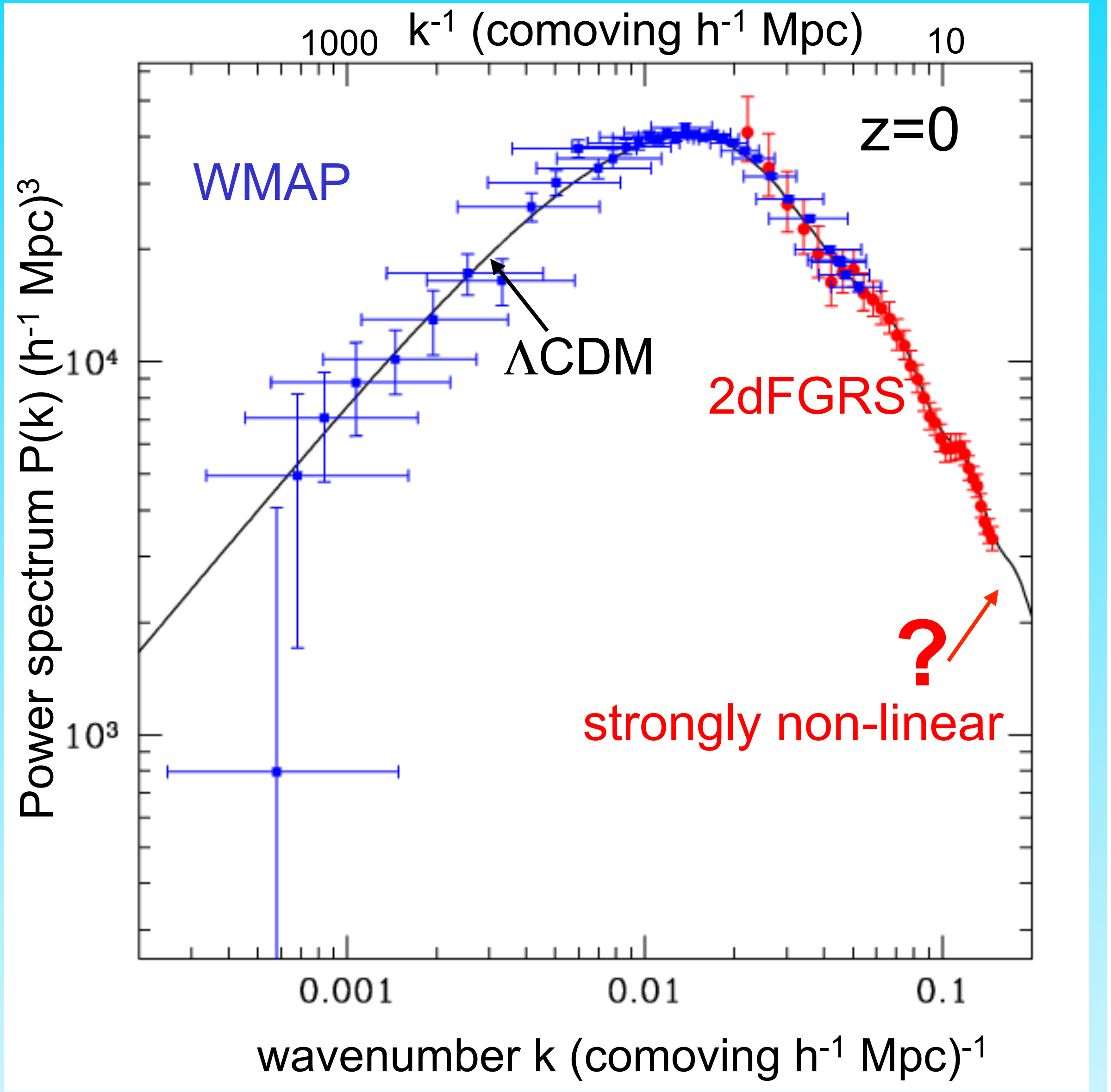
z~1000



z~0

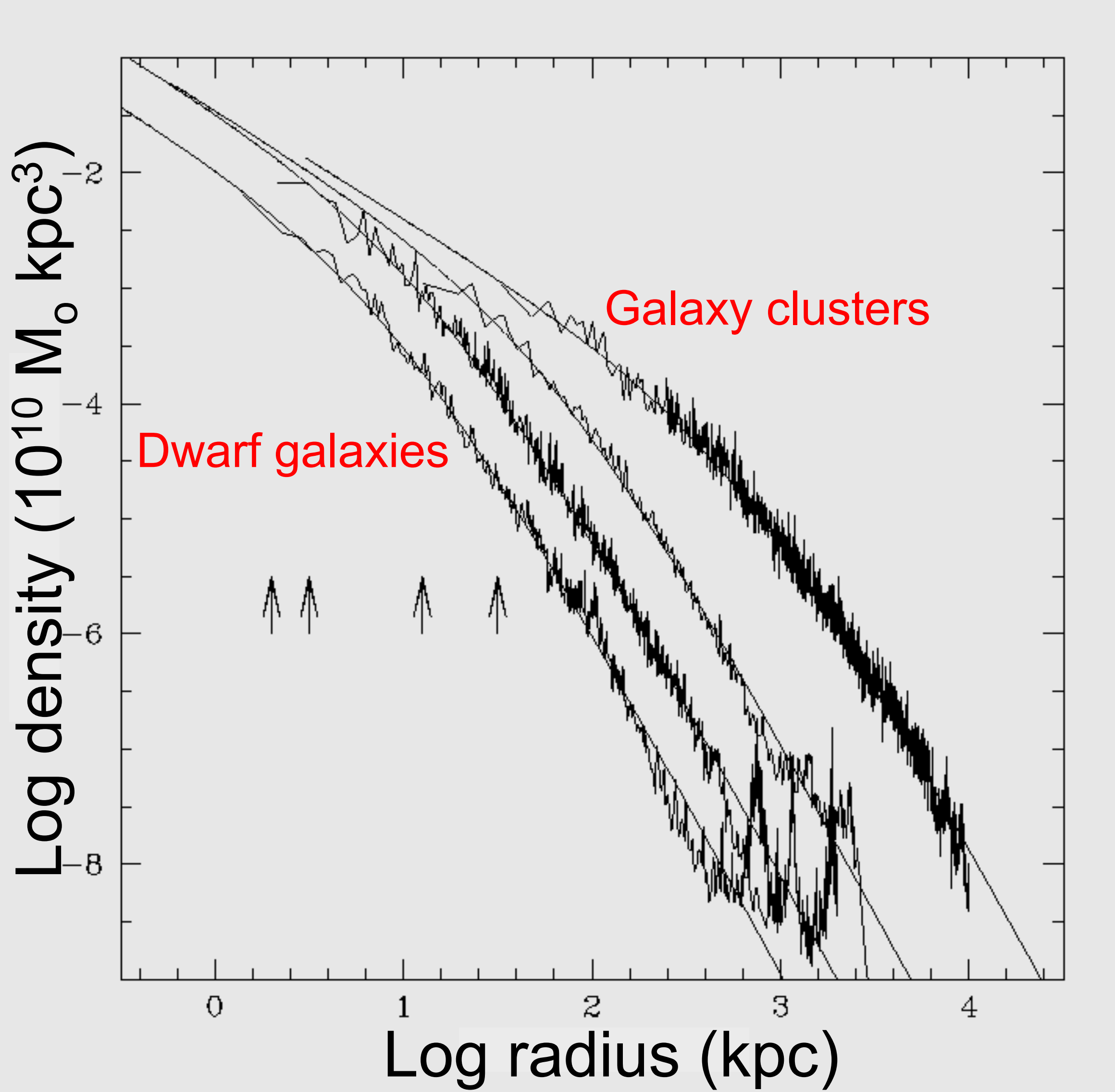
⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

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:

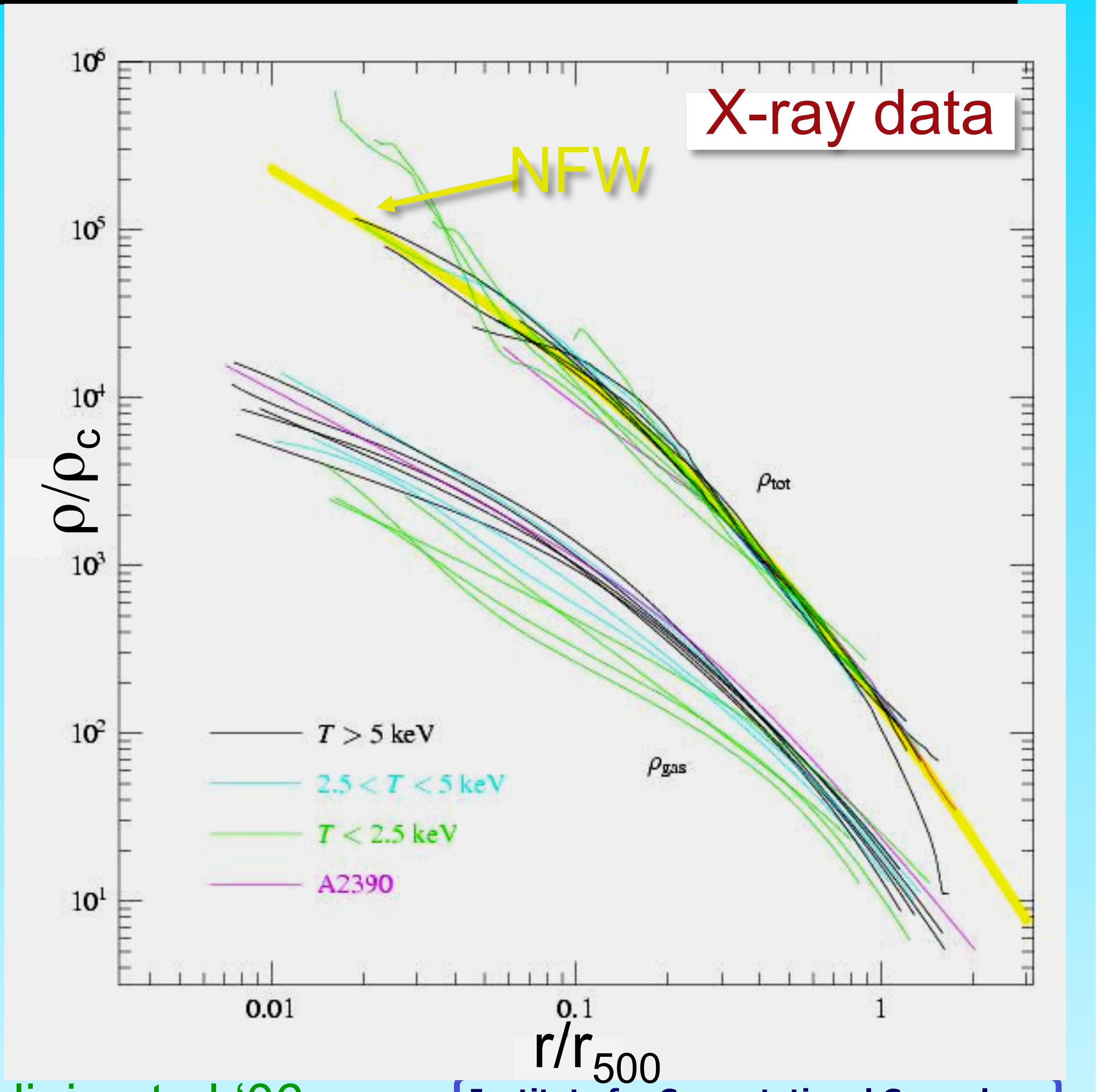
- X-ray emission
- Gravitational lensing

The central density profile of galaxy cluster dark halos

University of Durham

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

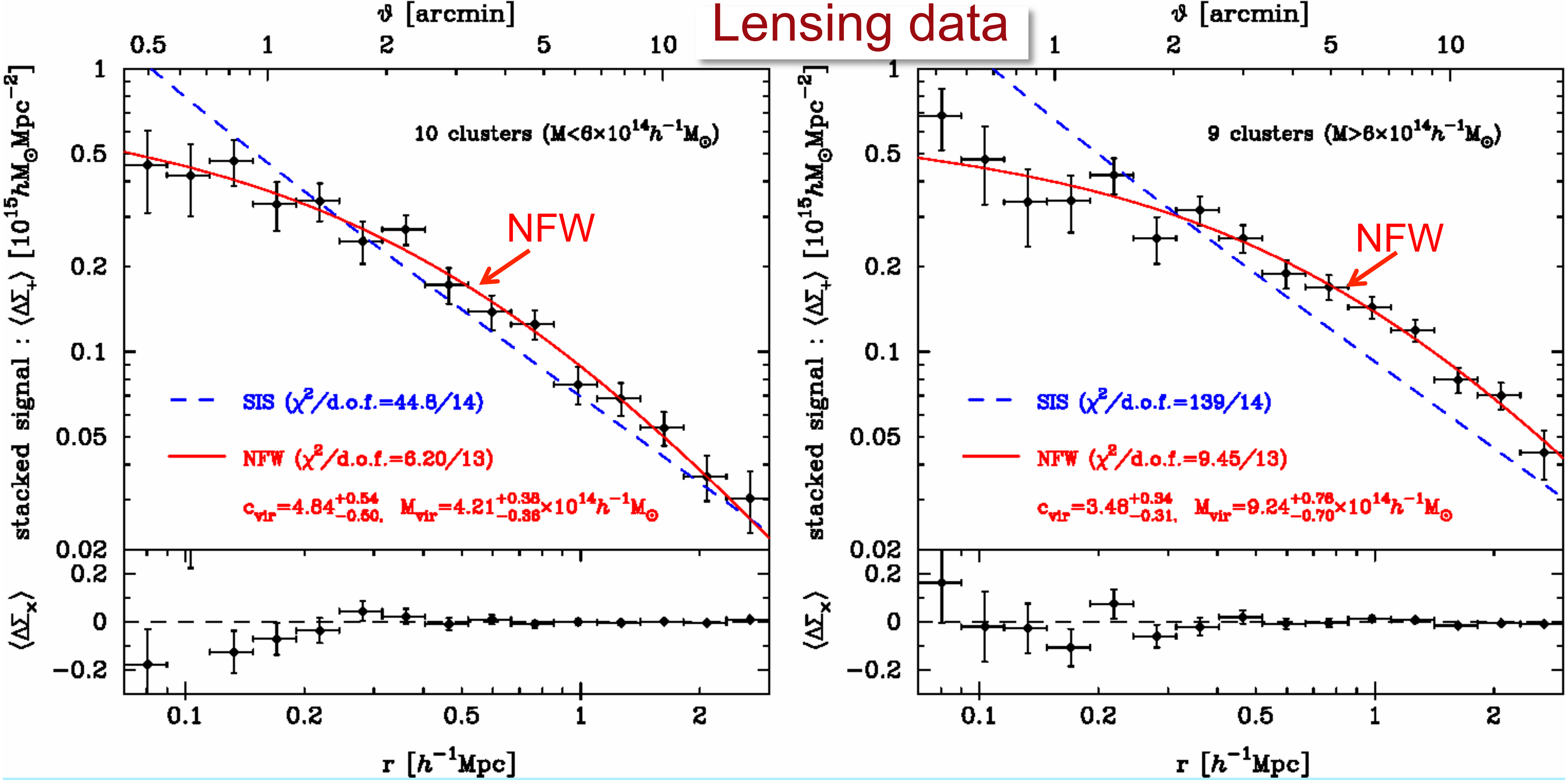
Excellent agreement with CDM halo predictions



Vikhlinin et al ‘06

University of Durham

The density profile of galaxy cluster dark halos


Lensing data

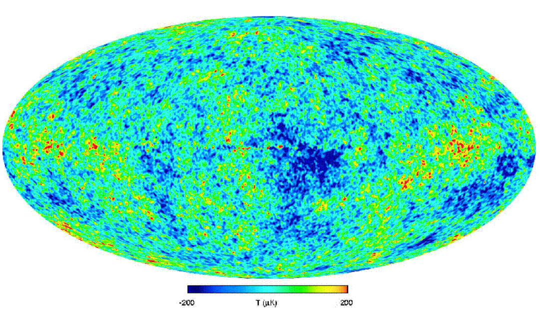
NFW

NFW

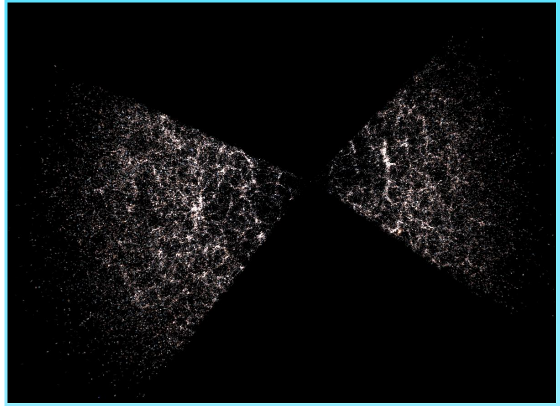
Okabe et al ‘10

University of Durham

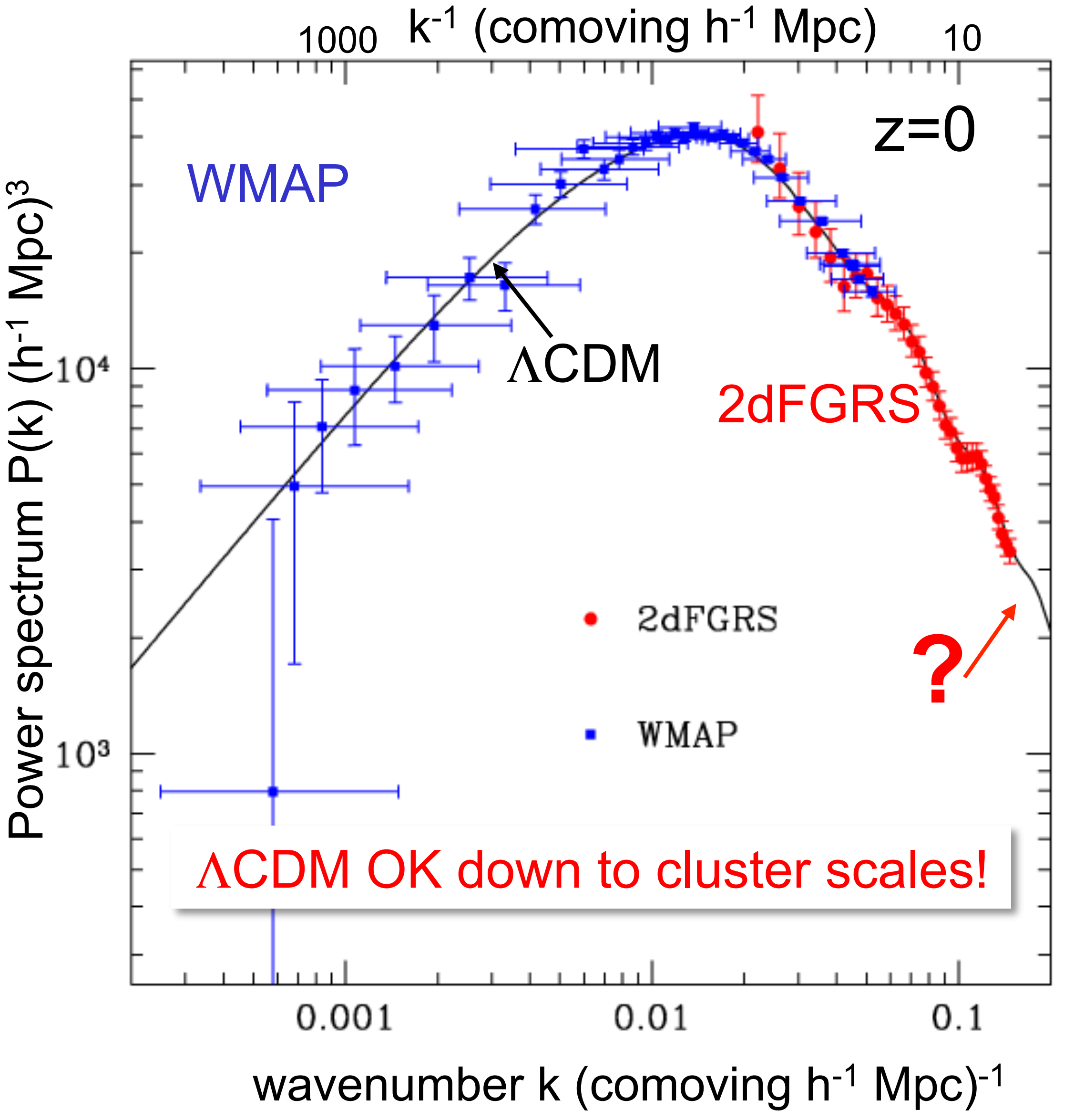
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



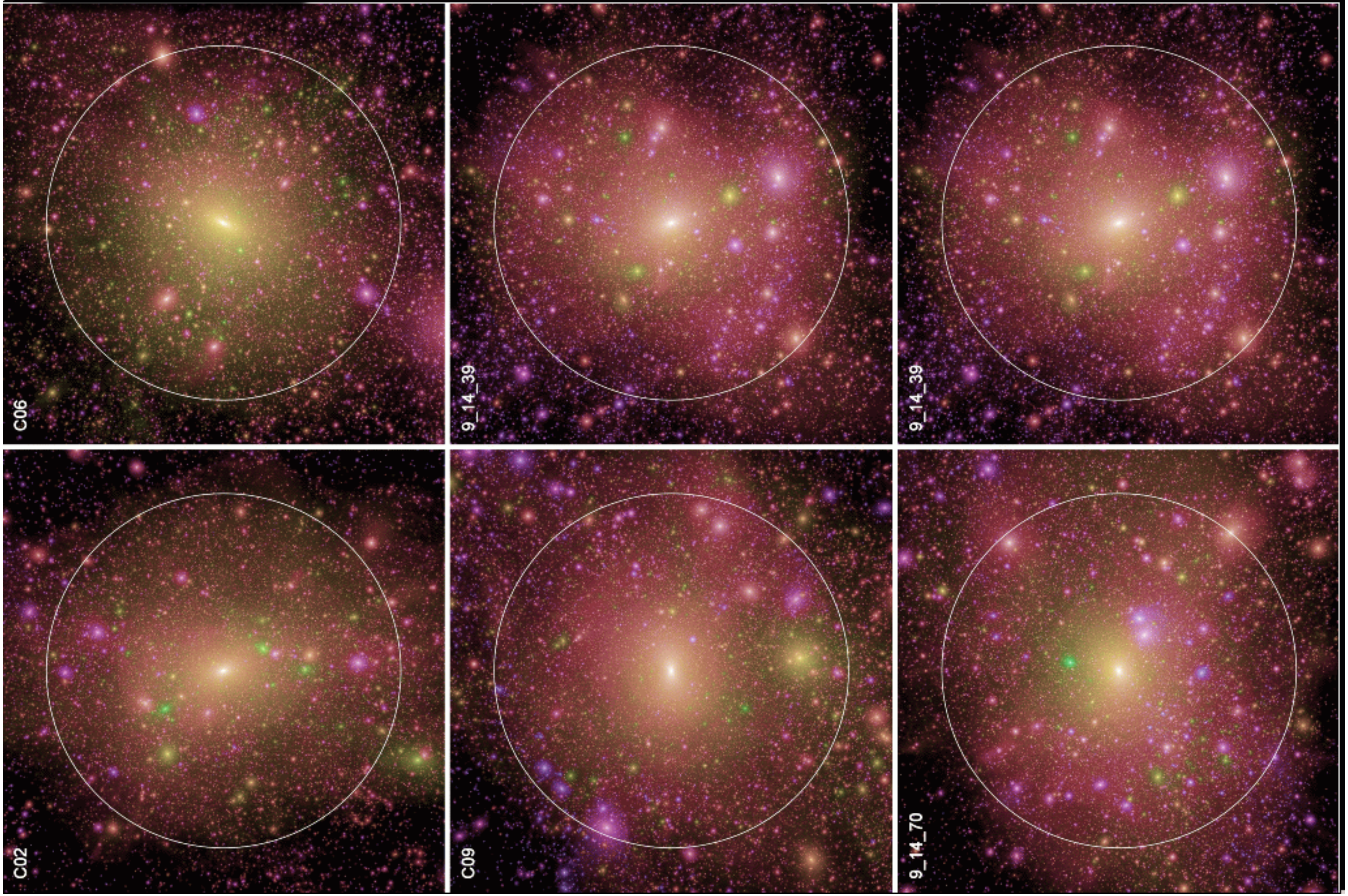
ΛCDM OK down to cluster scales!

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

Sanchez et al 06


z = 48.4
T = 0.05 Gyr
500 kpc

Images of all Aquarius halos (level-2)



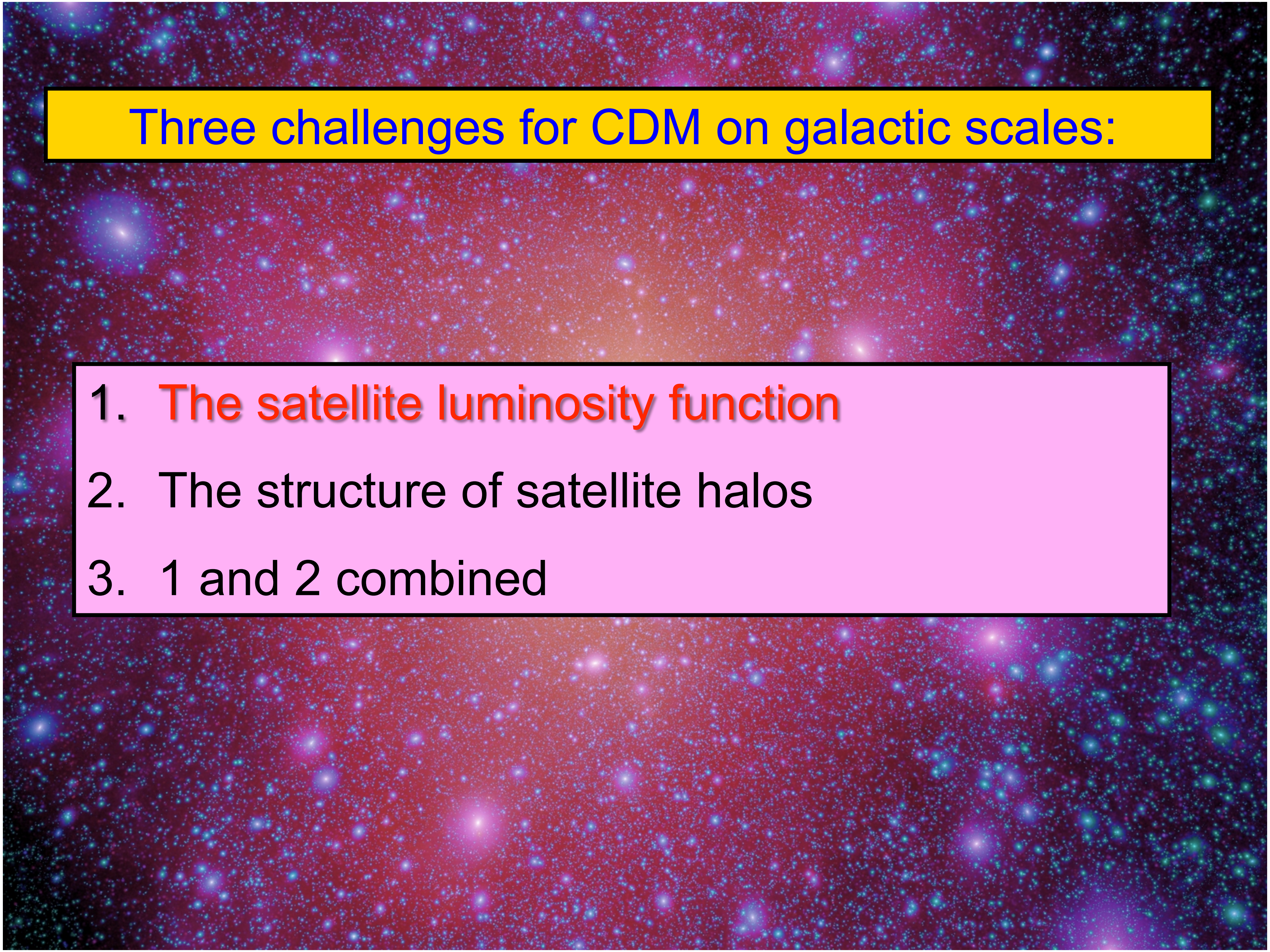
A Cold dark matter universe

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 :

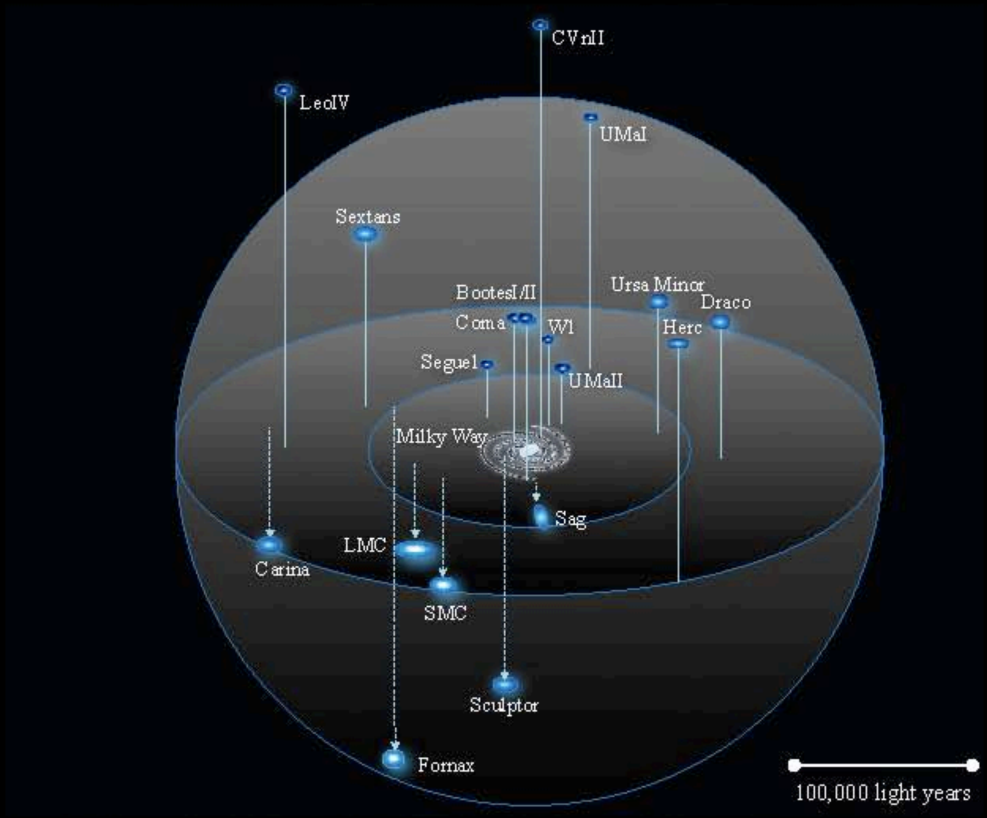
1. The satellite luminosity function
2. The structure of satellite halos
3. 1 and 2 combined

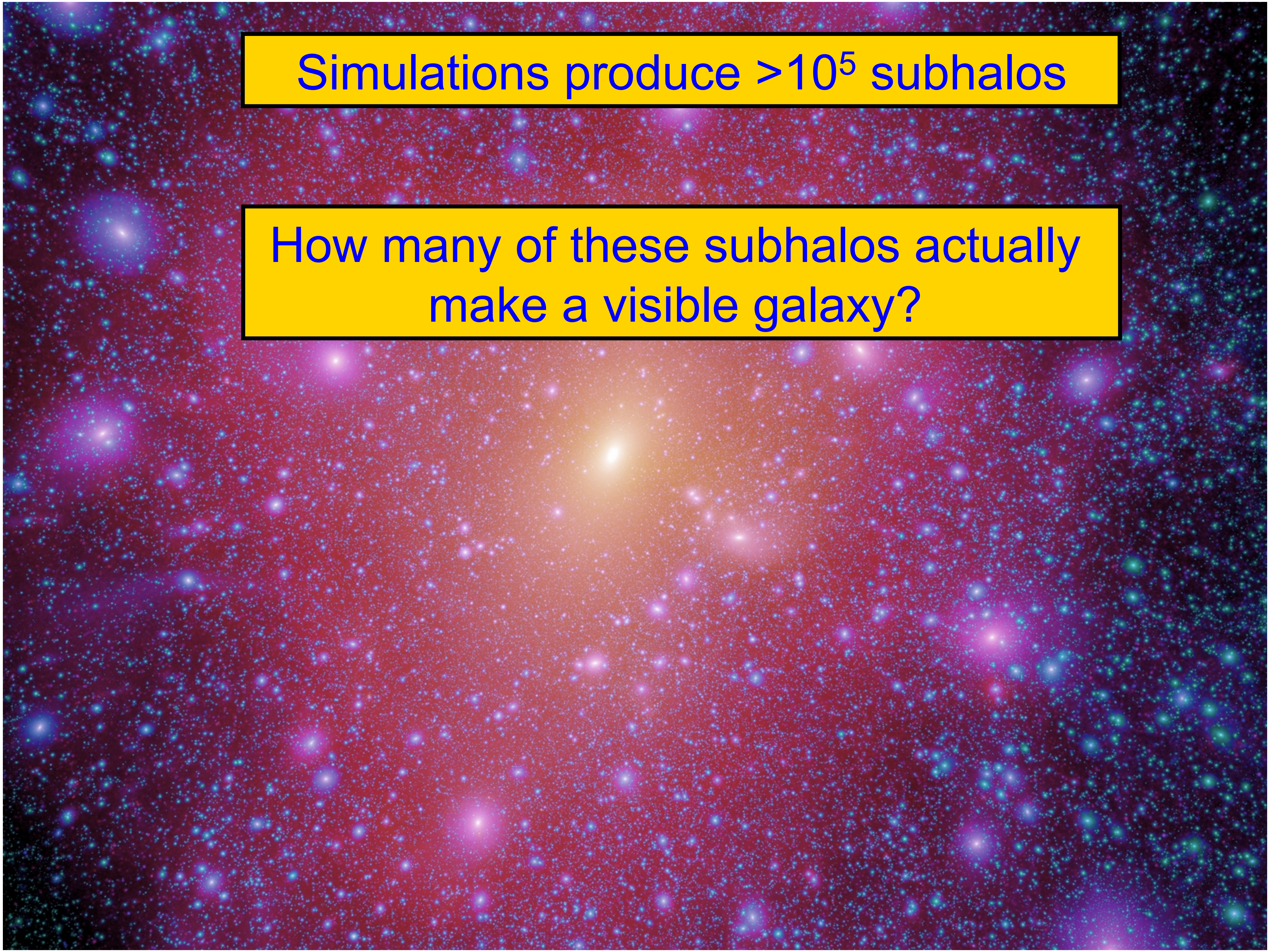


Three challenges for CDM on galactic scales:

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

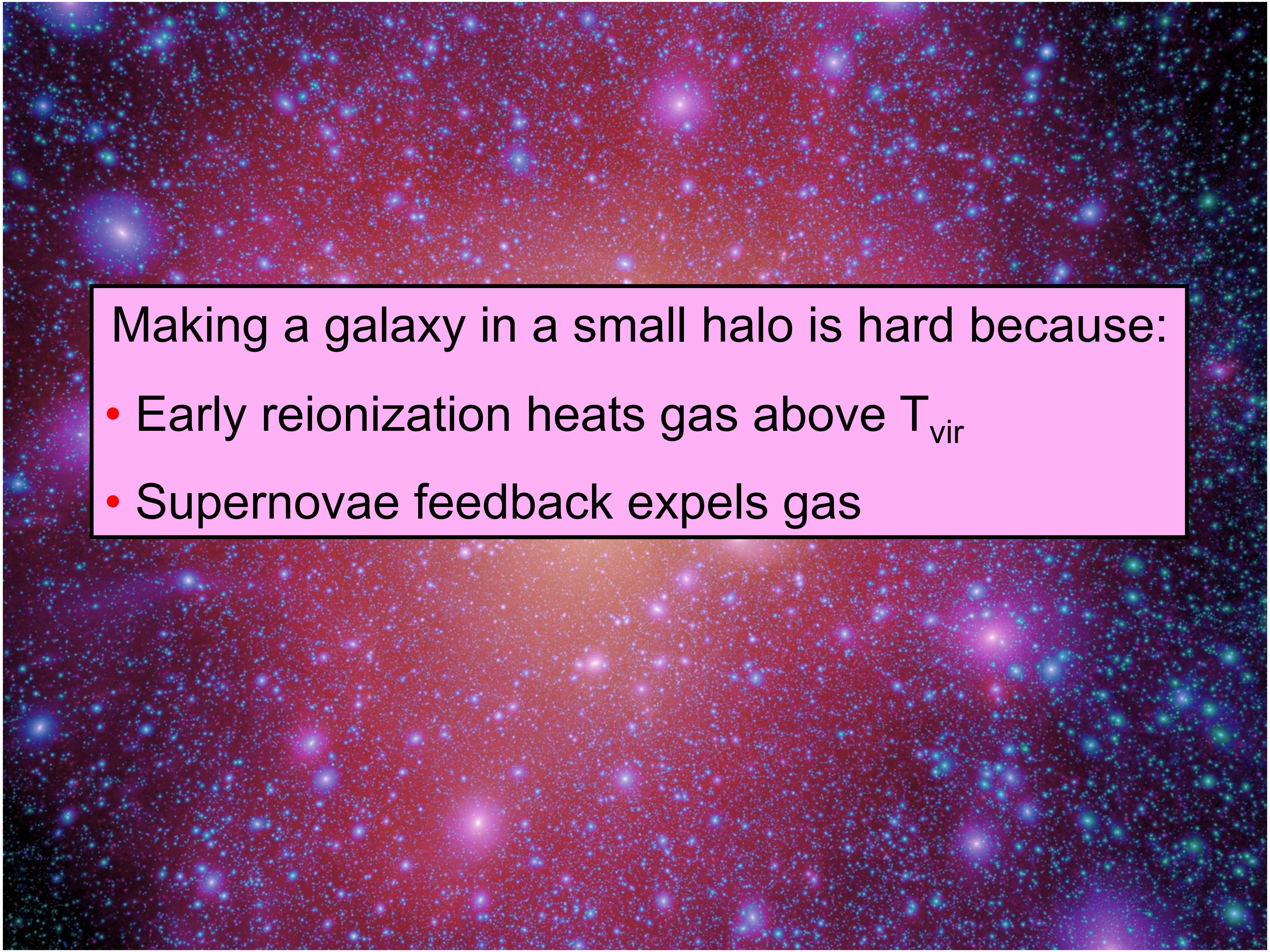
Does CDM predict the right number of satellites?





Simulations produce >10^5 subhalos

How many of these subhalos actually make a visible galaxy?



Making a galaxy in a small halo is hard because:

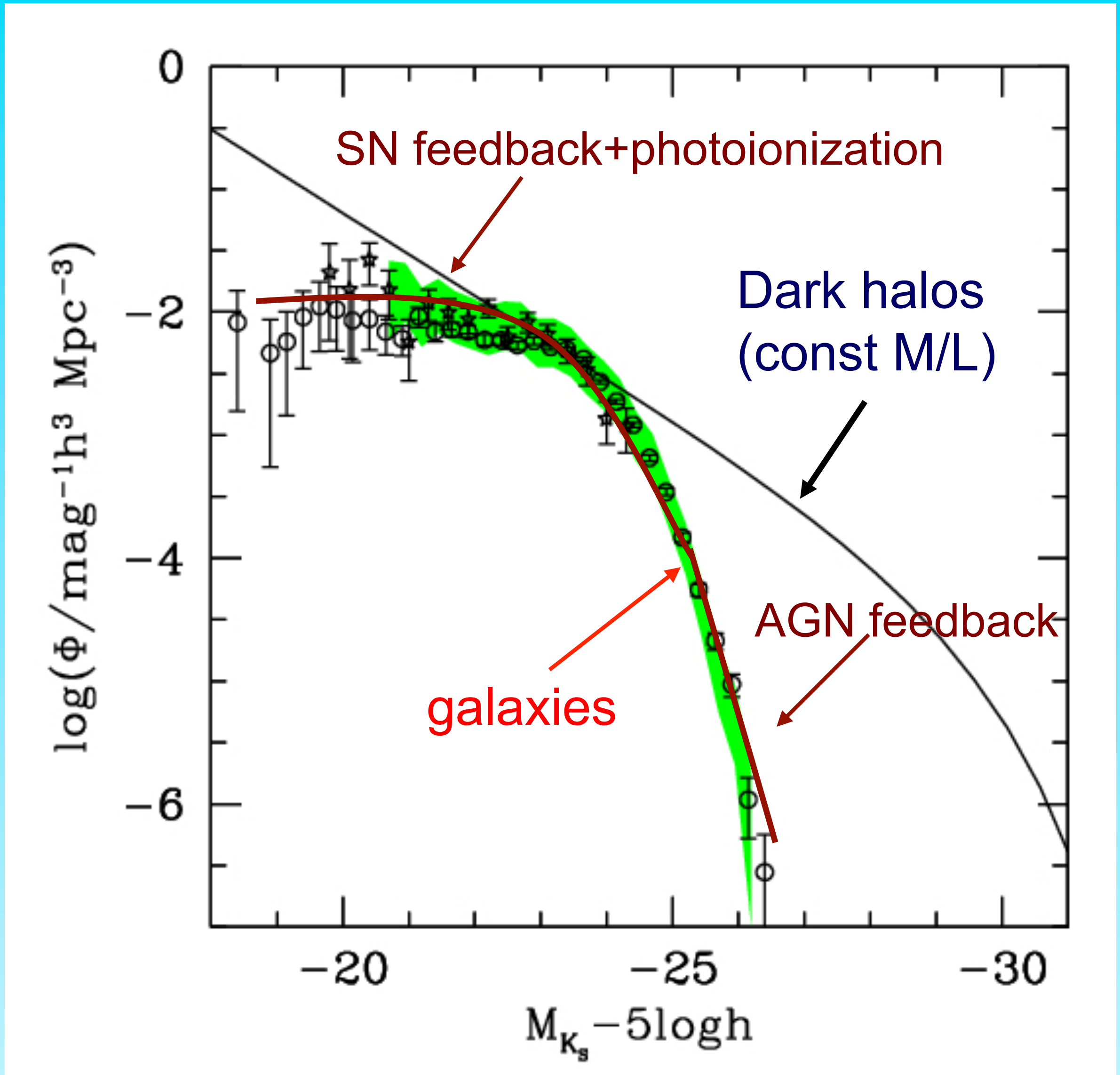
- Early reionization heats gas above T_{vir}
- Supernovae feedback expels gas

The galaxy luminosity function

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

⇨

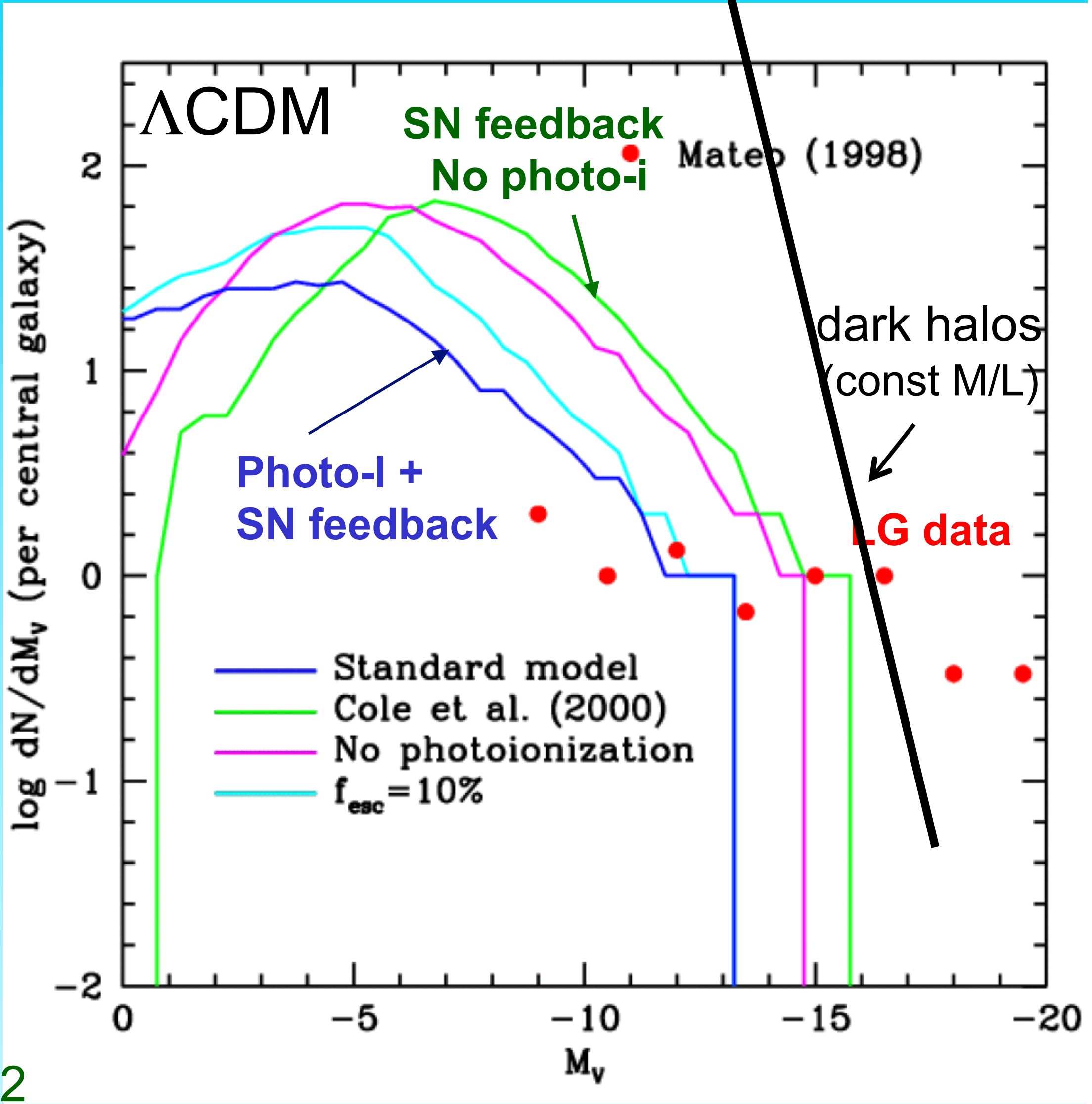
Complicated variation of M/L with halo mass



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

Luminosity Function of Local Group Satellites

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



SN feedback
No photo-i

dark halos
(const M/L)

LG data

Photo-I +
SN feedback

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

Luminosity Function of Local Group Satellites

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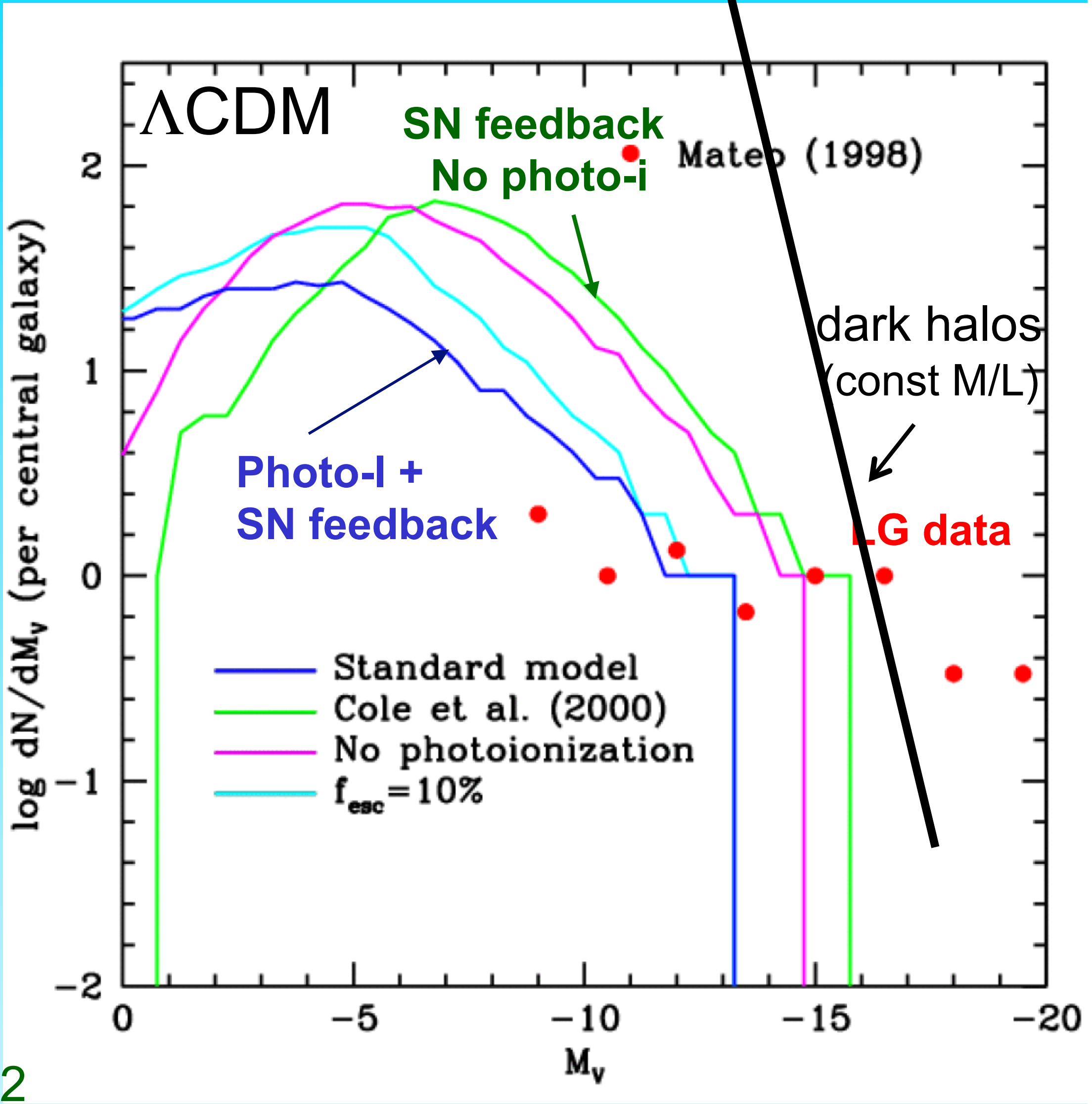


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman etal ’93, Bullock etal ’01)

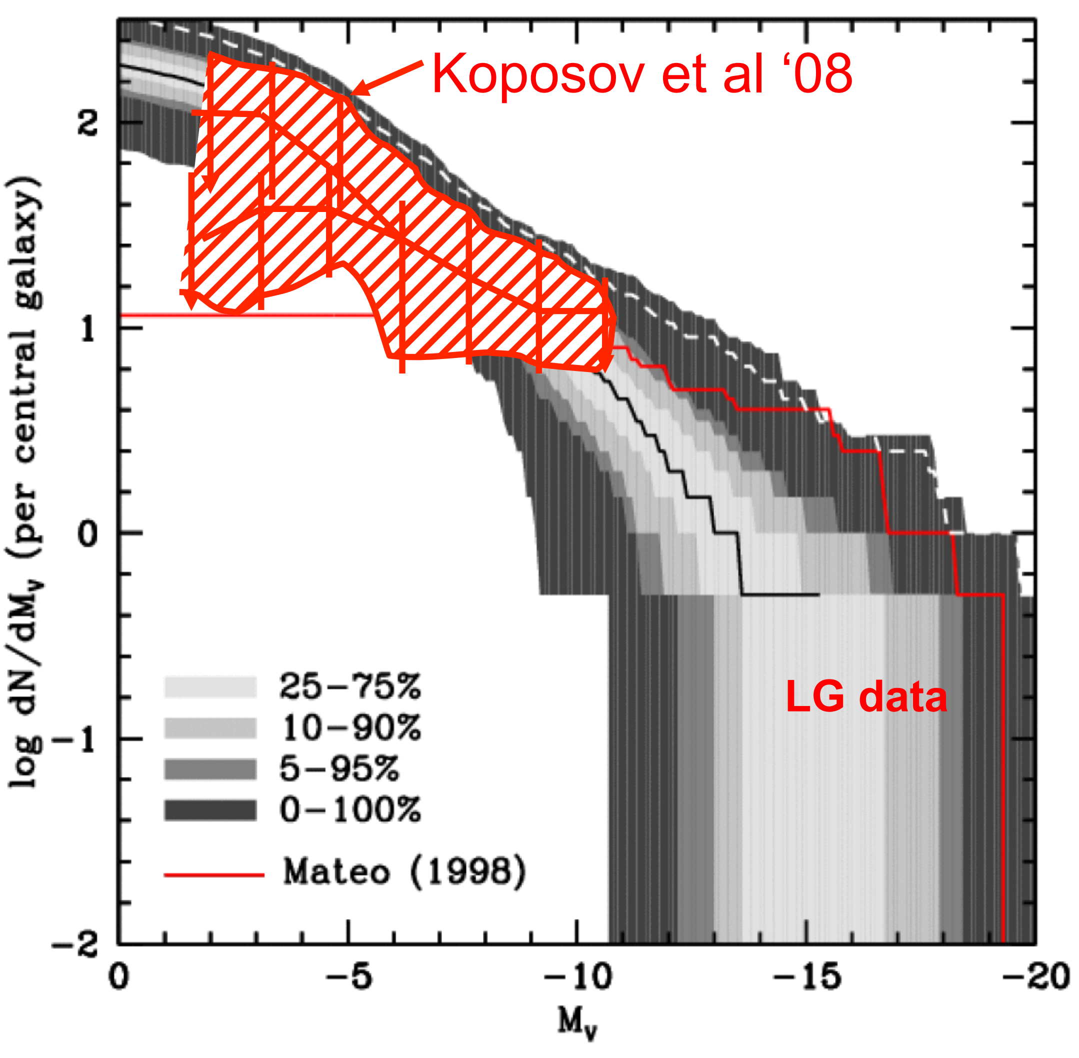
University of Durham

Luminosity Function of Local Group Satellites

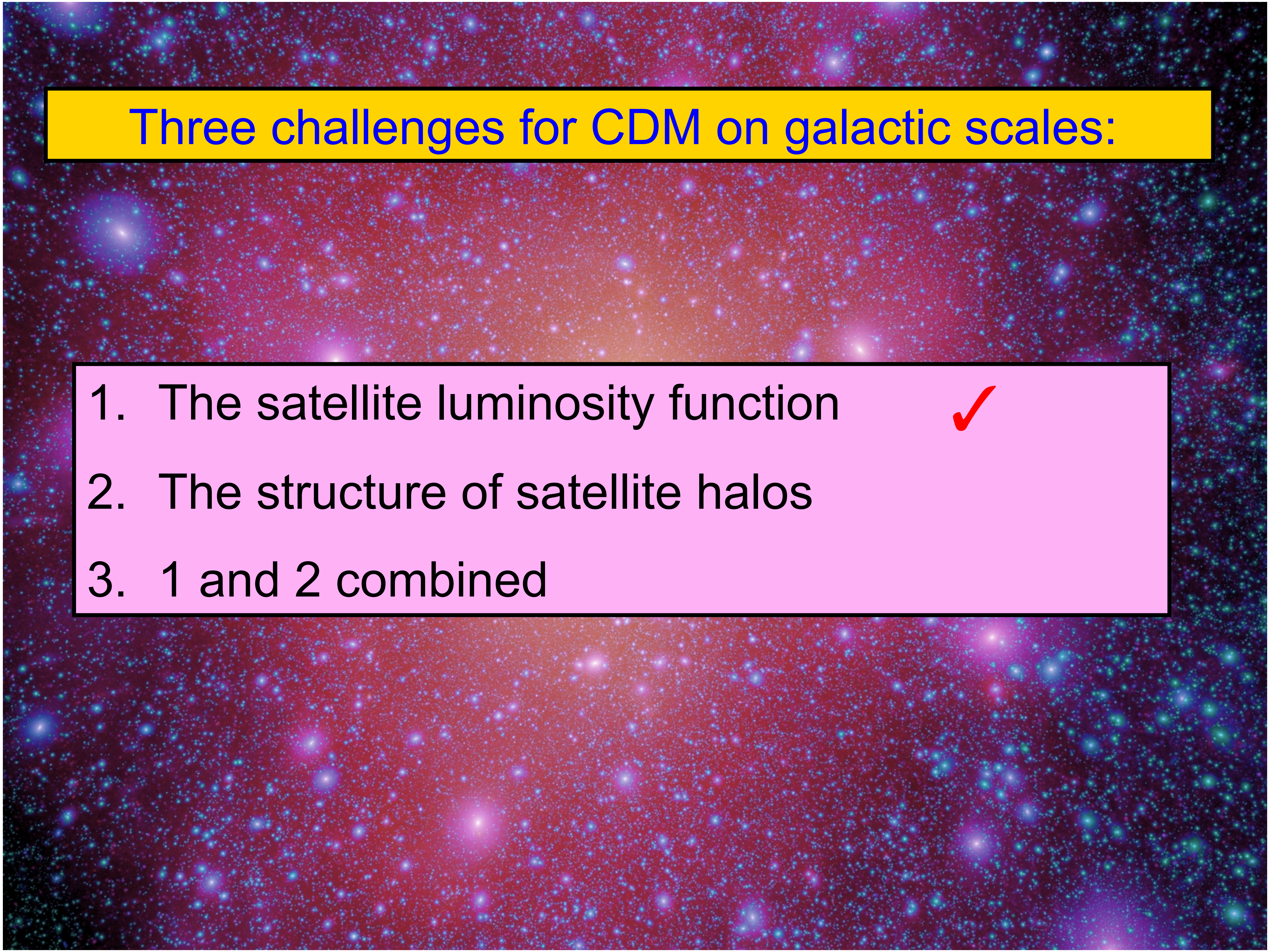
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s

- Model predicts many, as yet undiscovered, faint satellites

- LMC/SMC should be rare (~2% of cases)

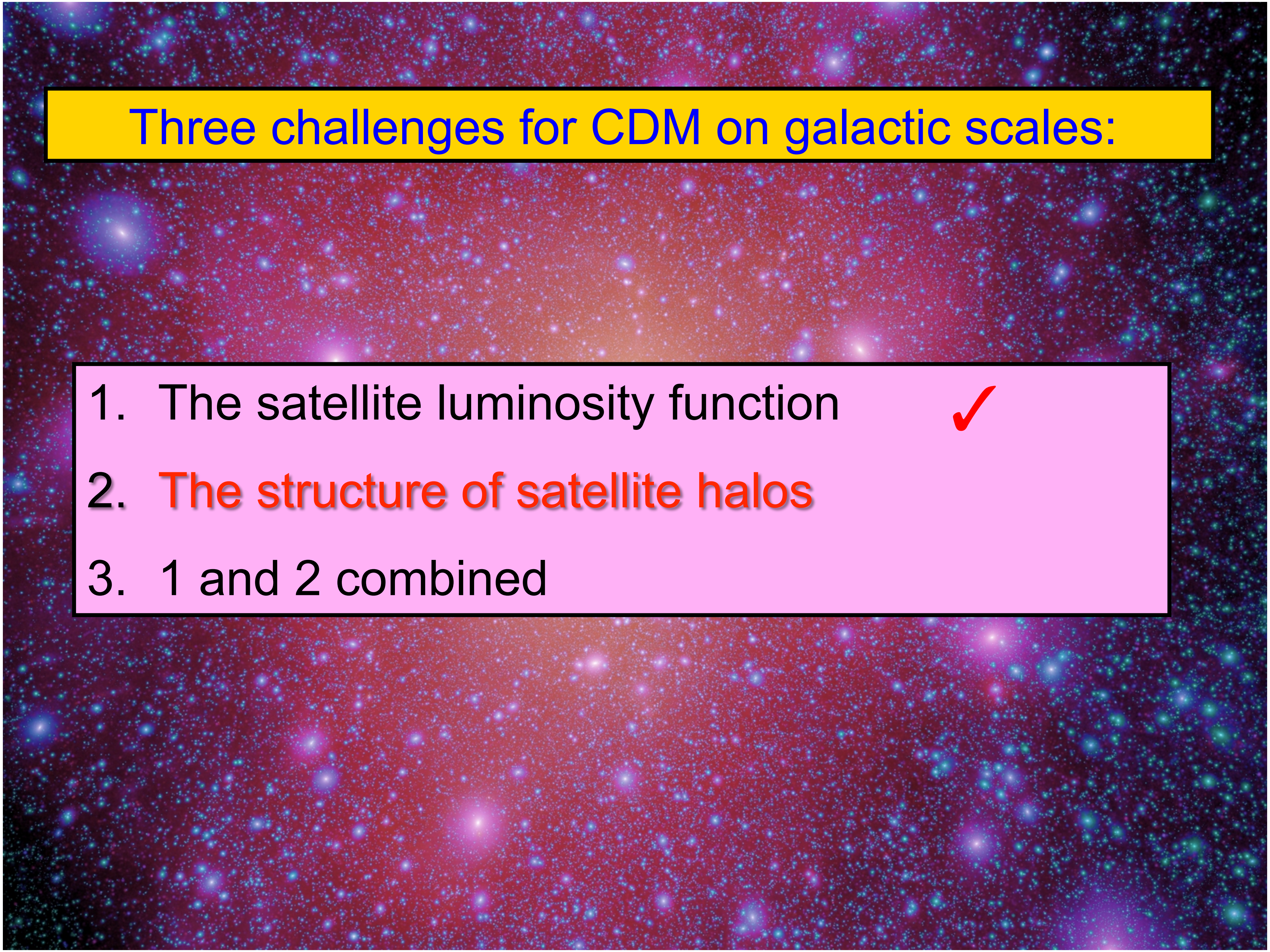


Benson, Frenk, Lacey, Baugh & Cole ’02



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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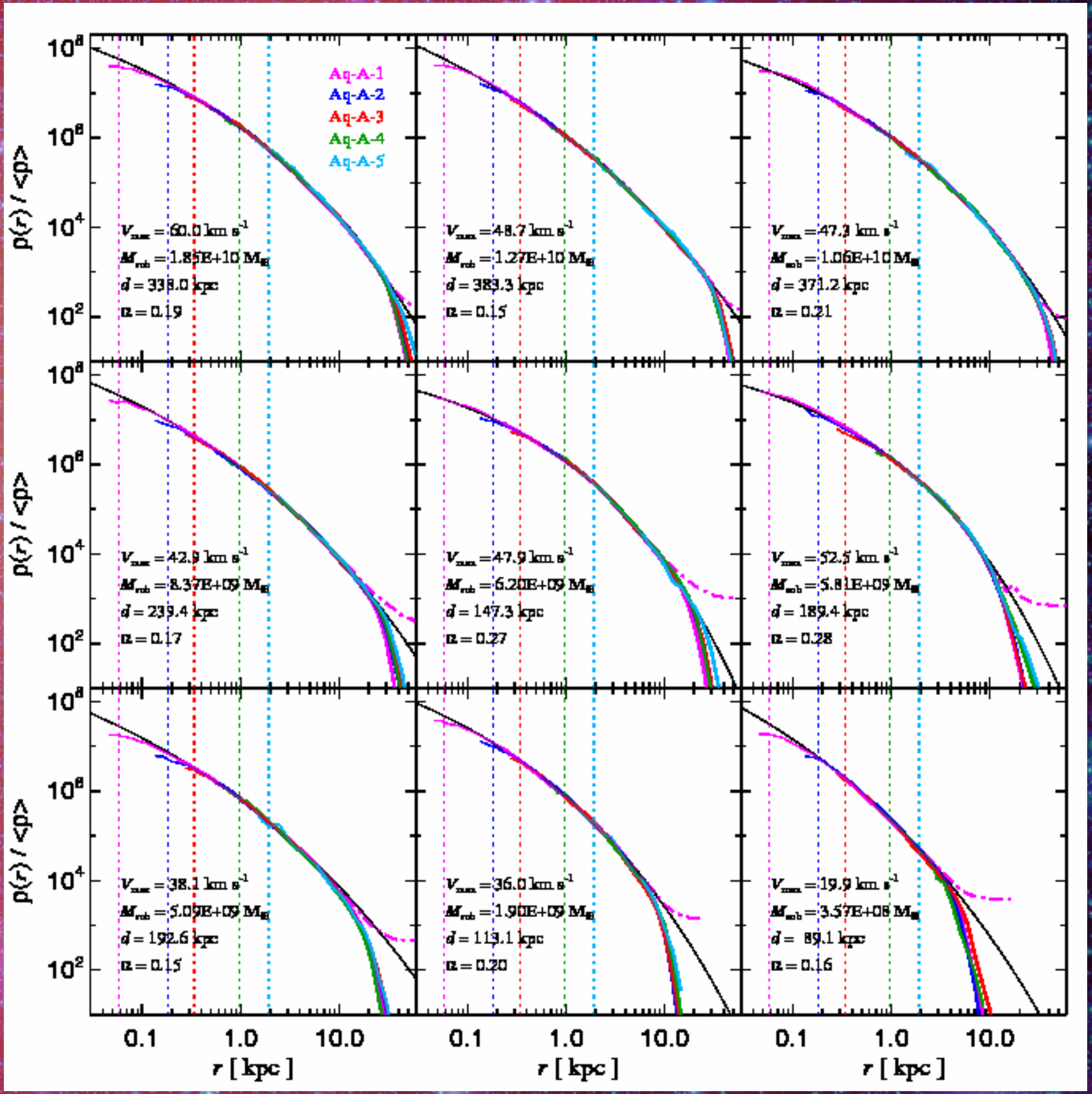
3. 1 and 2 combined

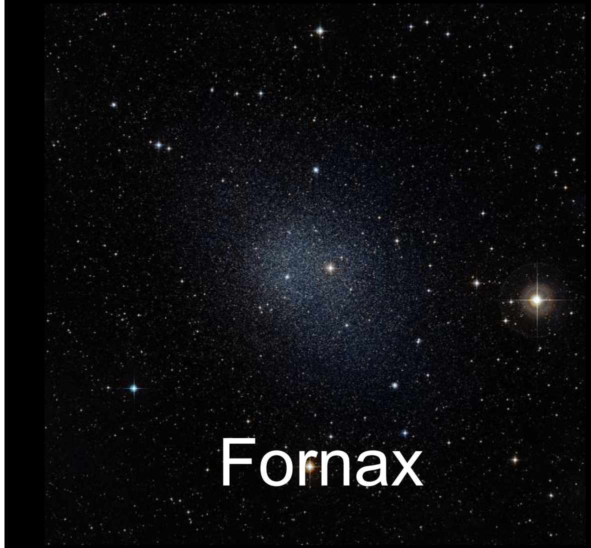
In CDM predict: cuspy density profiles in halos and subhalos

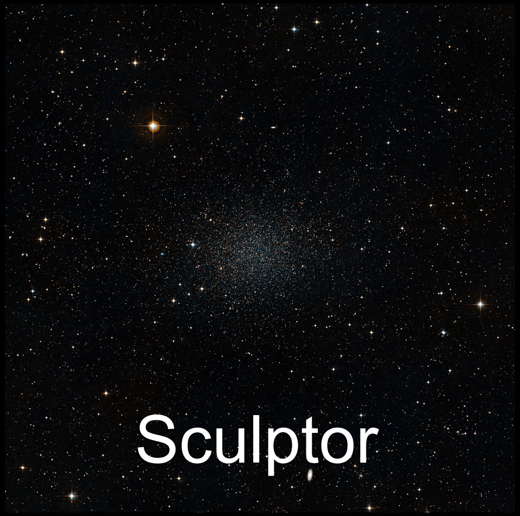
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$



Navarro, Frenk & White ‘96, ‘97

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:

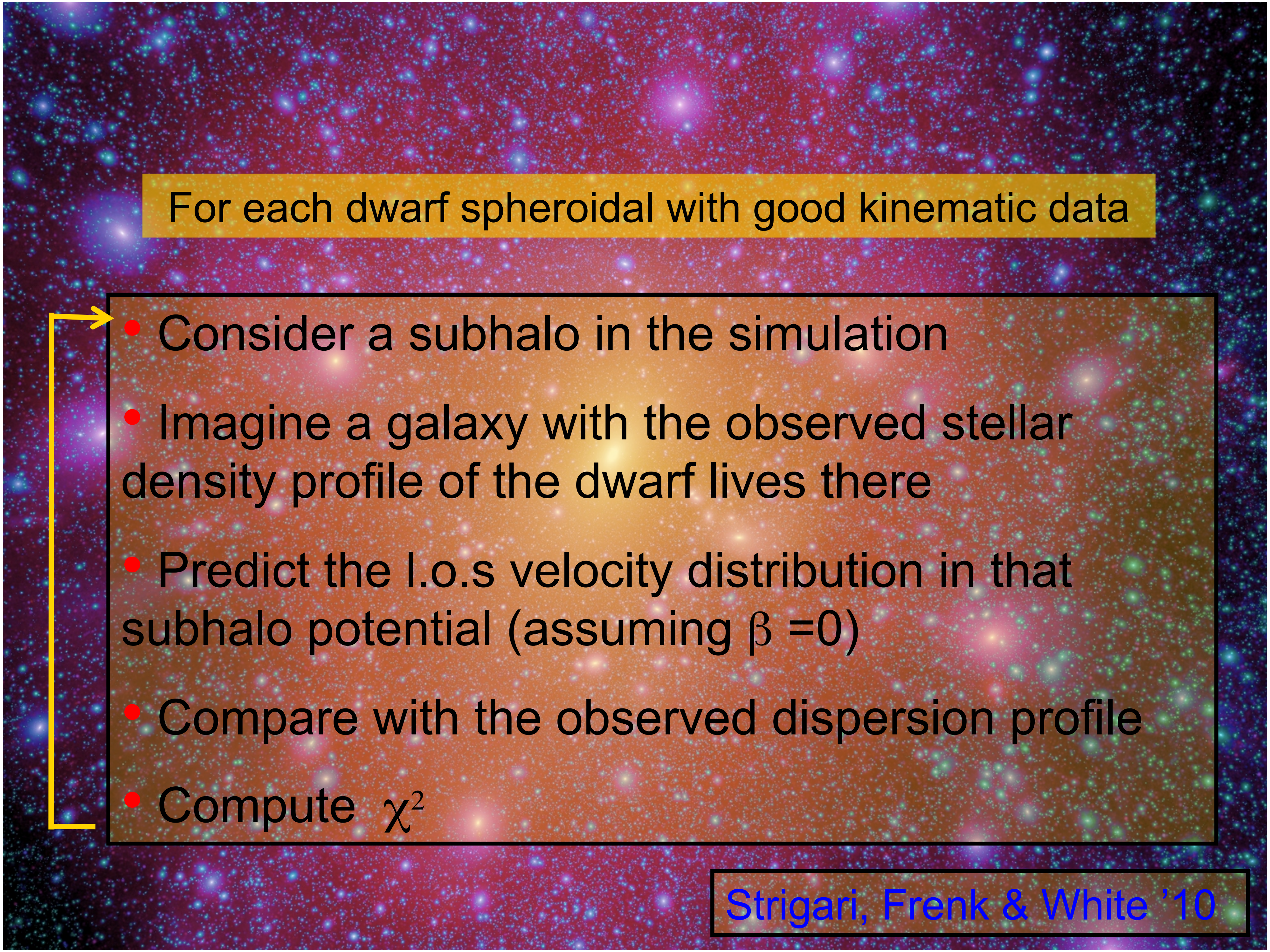
stellar density profile

radial velocity dispersion

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

from Aquarius sim

vel. anisotropy



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

Strigari, Frenk & White ’10

University of Durham

Dwarf sphs: cores or cusps?

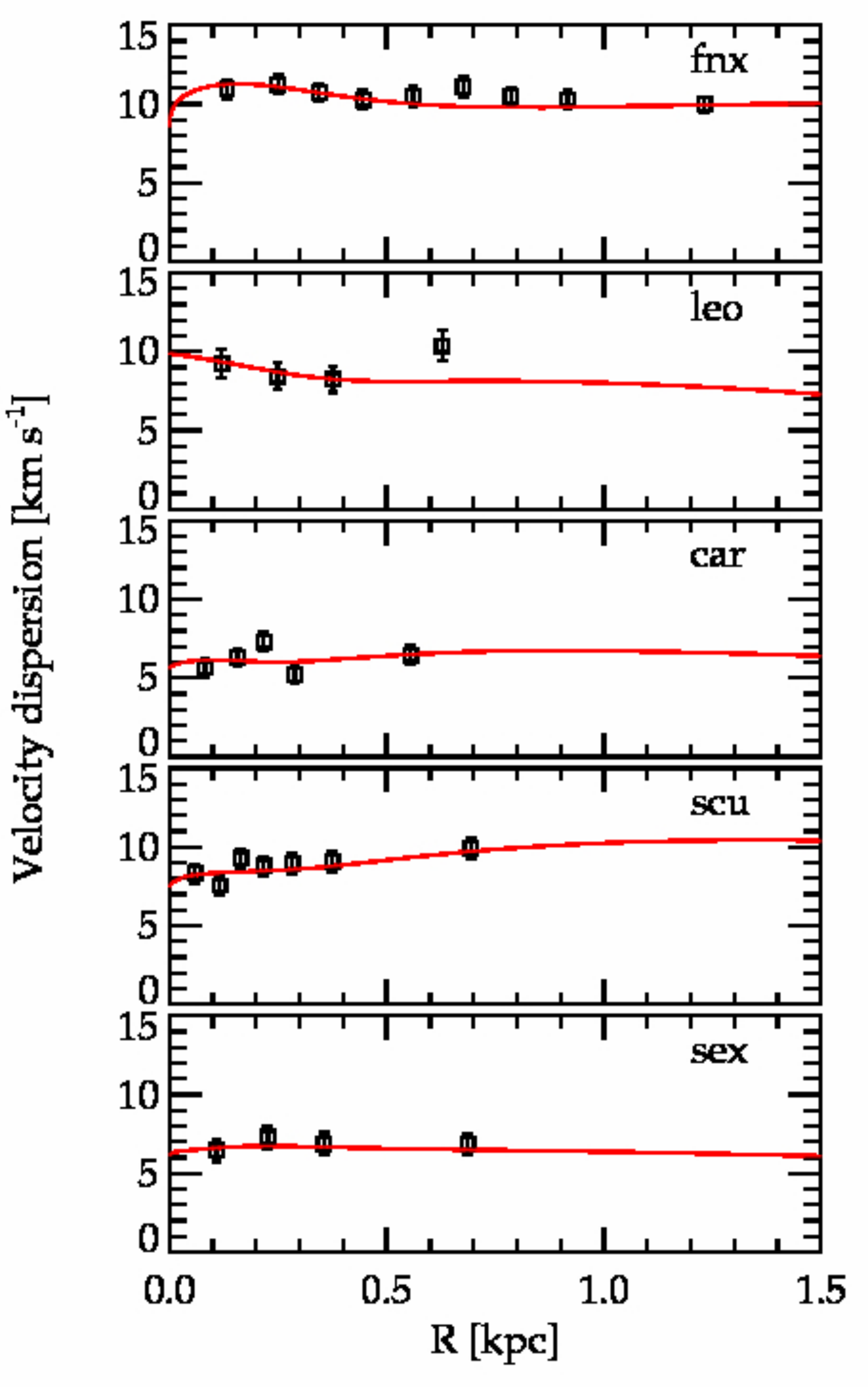
Jeans eqn:

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

from Aquarius sim

vel. anisotropy

- Assume isotropic orbits
- Solve for σ_r (r)
- Compare with observed σ_r (r)
- Find "best fit" subhalo



Dwarf sphs: cores or cusps?

Jeans eqn:

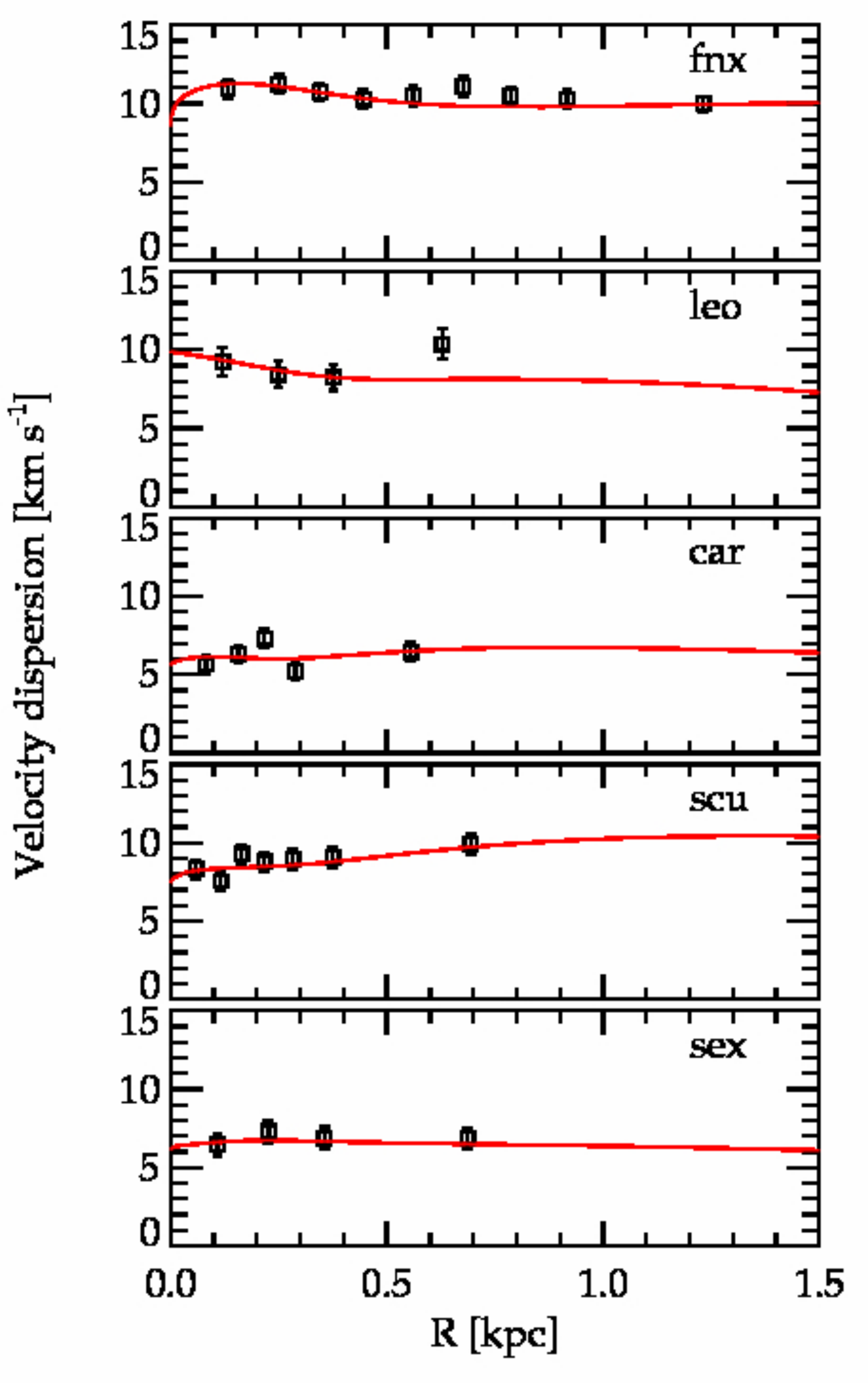
$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r}+\frac{d\ln\sigma_r^2}{d\ln r}+2\beta\right]$$

from Aquarius sim

vel. anisotropy

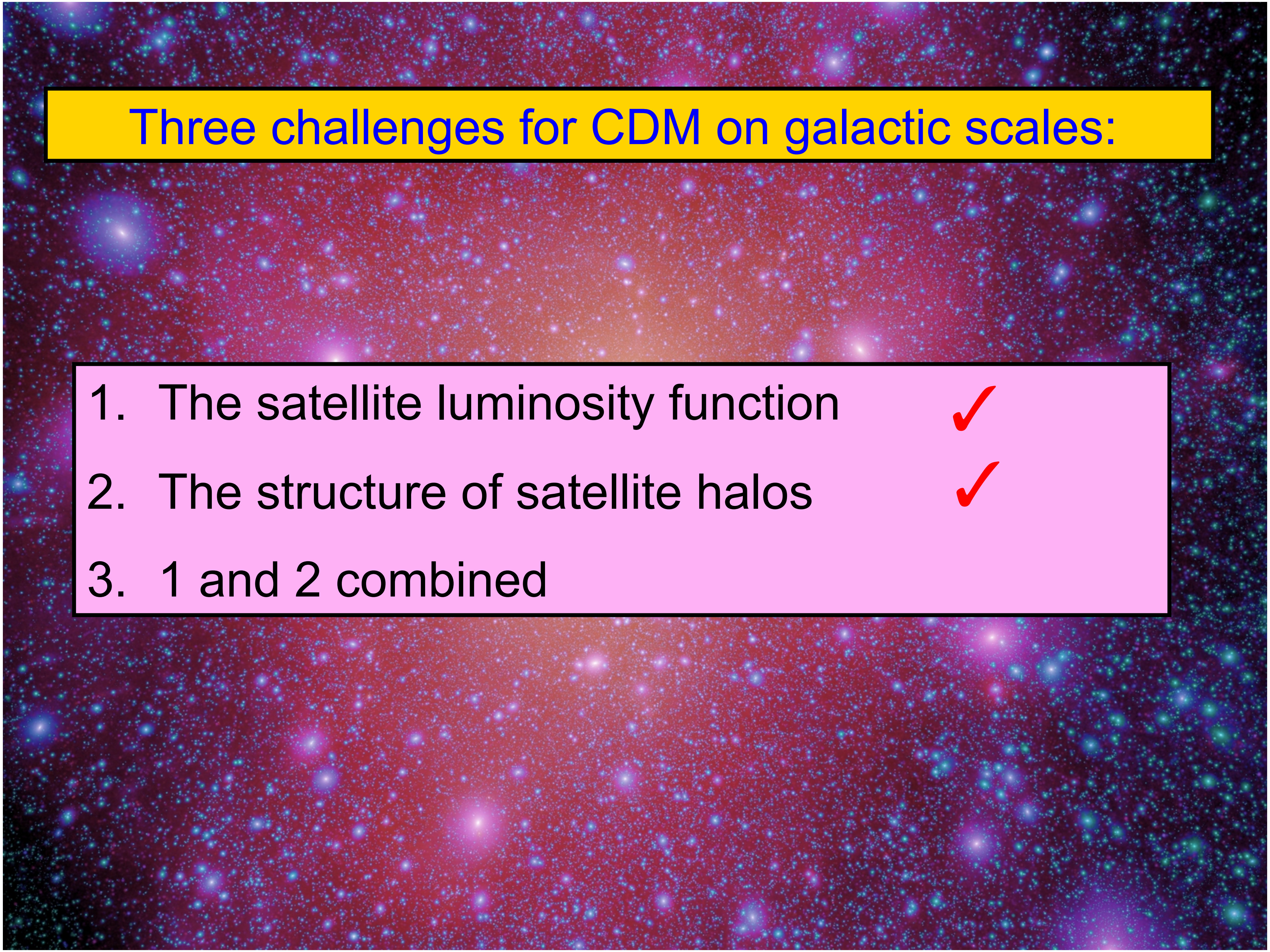
1-p= prob. that “best fit” can be rejected (β=0)

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

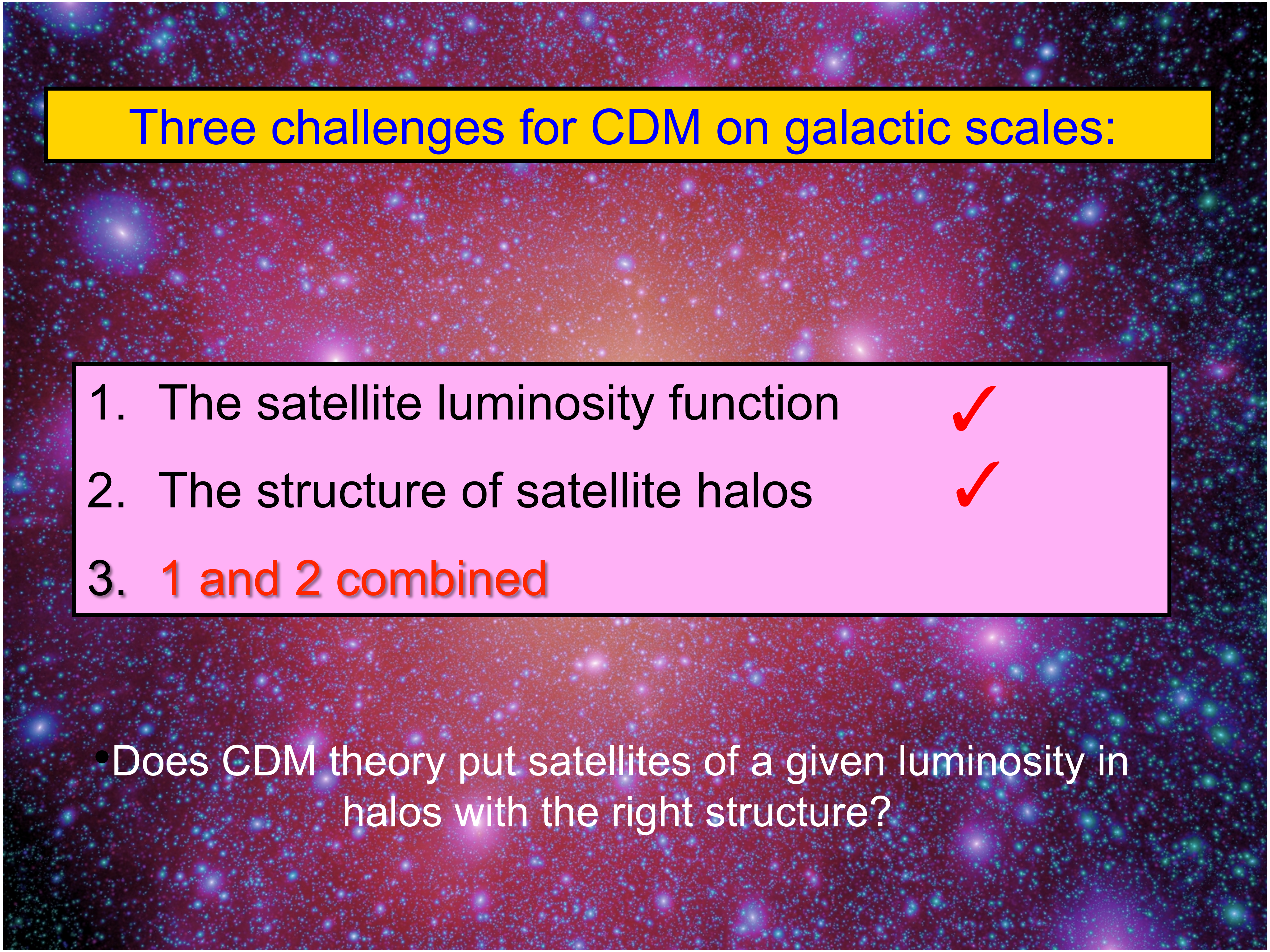


Strigari, Frenk & White 2010

Three challenges for CDM on galactic scales:



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



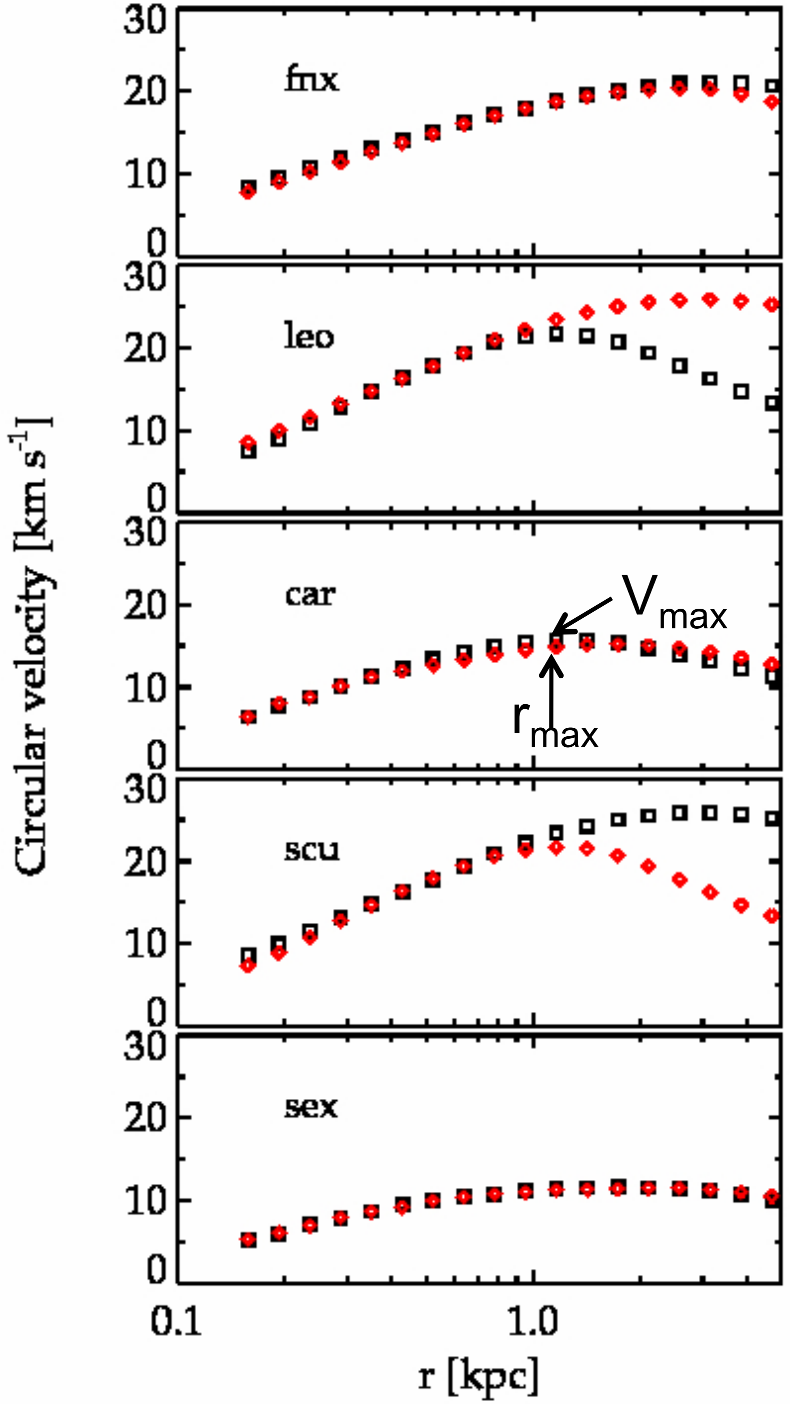
Three challenges for CDM on galactic scales:

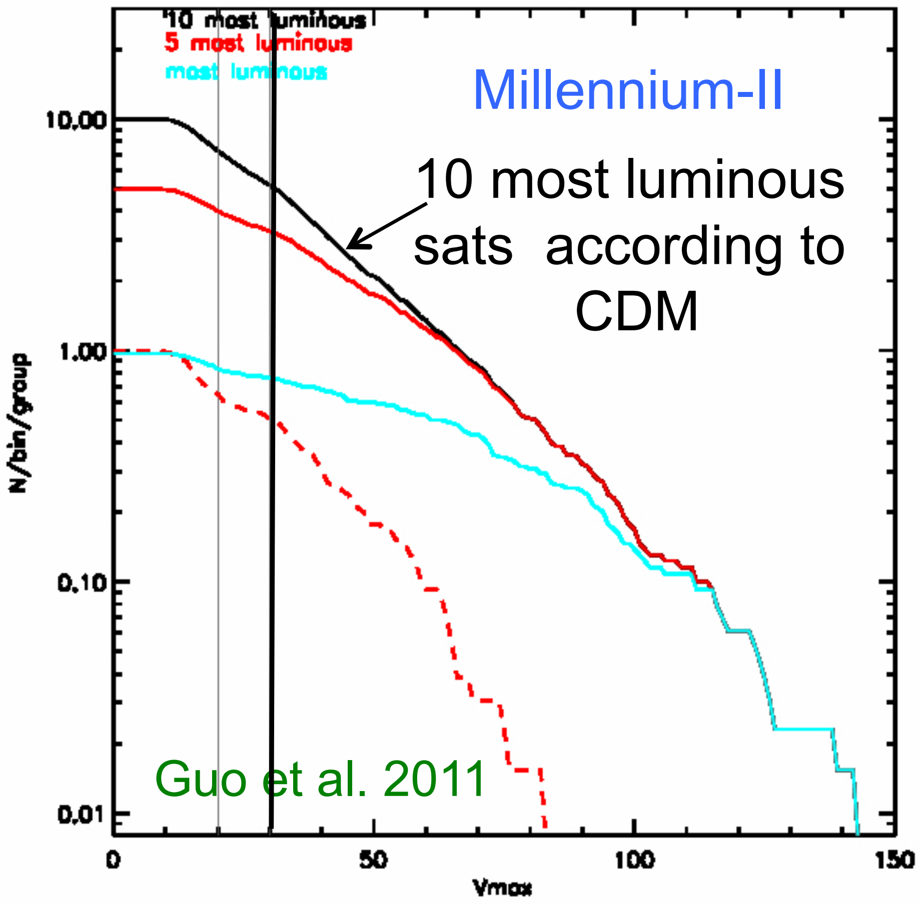
1. The satellite luminosity function ✓
2. The structure of satellite halos ✓
3. 1 and 2 combined

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

The satellites of the Milky Way

Top 2 best fit CDM models to data





Millennium-II

10 most luminous sats according to CDM

Guo et al. 2011

Strigari, Frenk & White 2010

Is this the end of CDM?

How about baryon effects?

Mon. Not. R. Astron. Soc. **283**, L72–L78 (1996)

The cores of dwarf galaxy haloes

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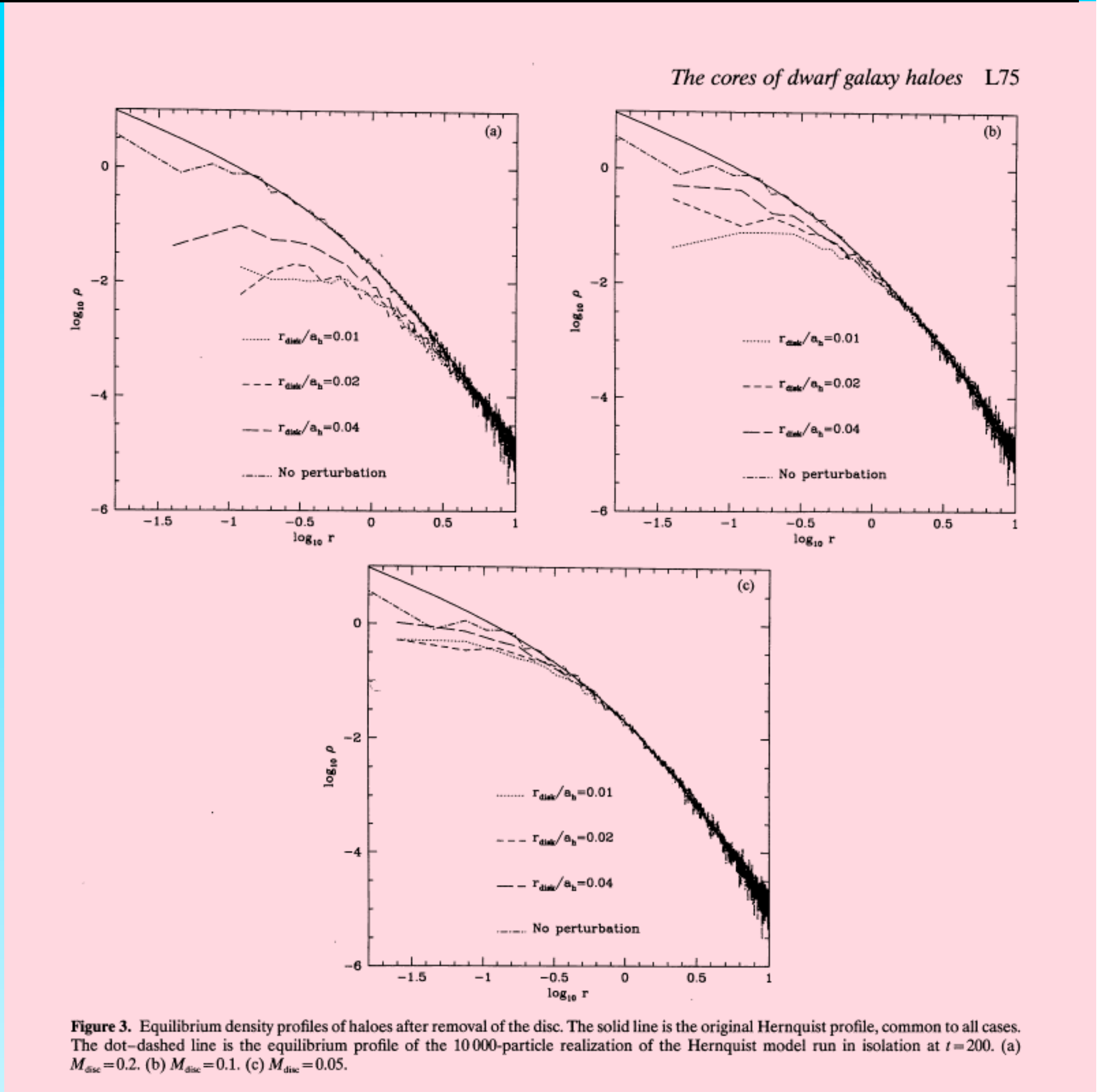
Accepted 1996 September 2. Received 1996 August 28; in original form 1996 June 26

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.

Baryon effects in the MW satellites

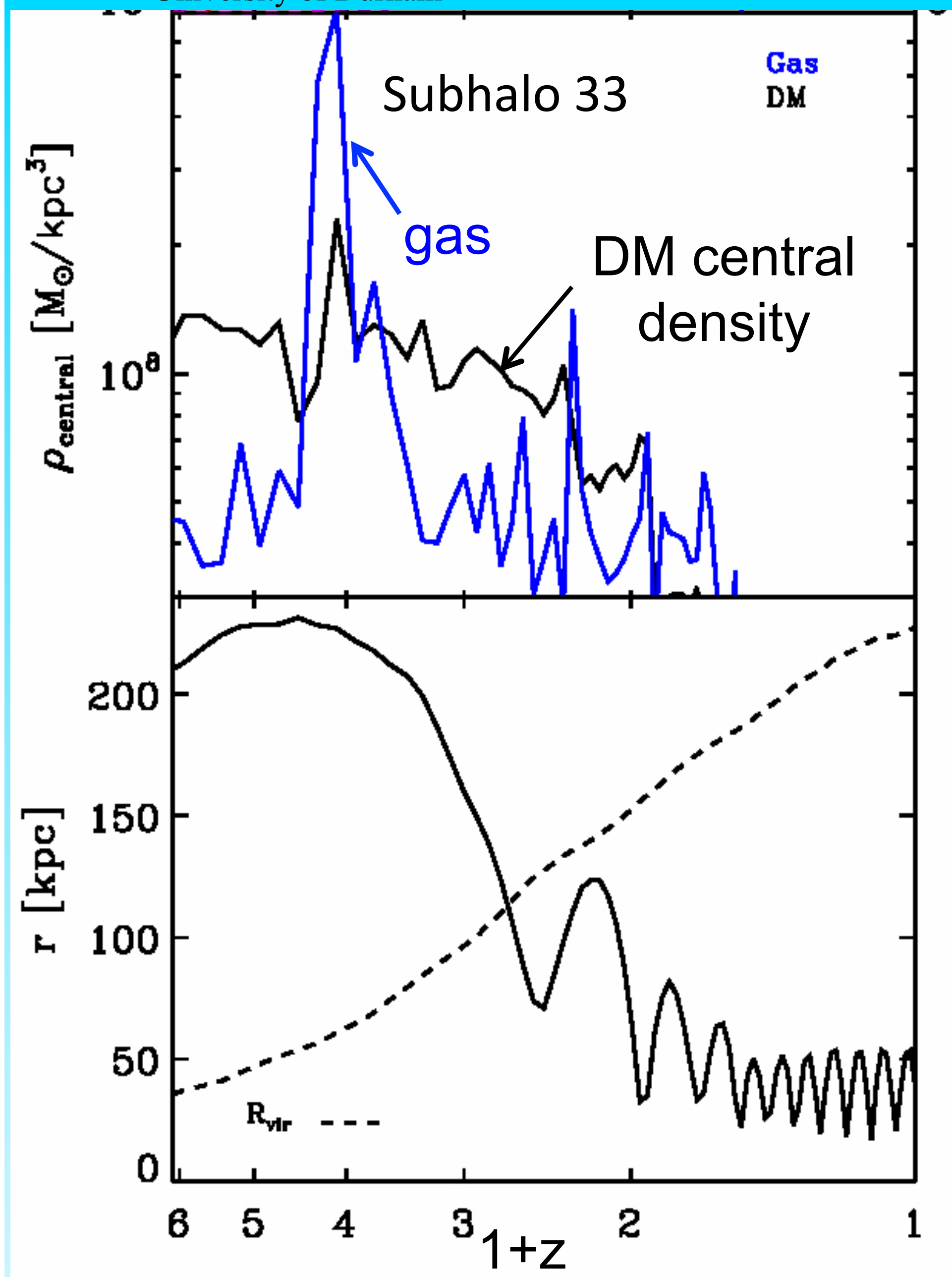
Rapid ejection of large fraction of gas during starburst can lead to a core in the halo dark matter density profile



The cores of dwarf galaxy haloes L75

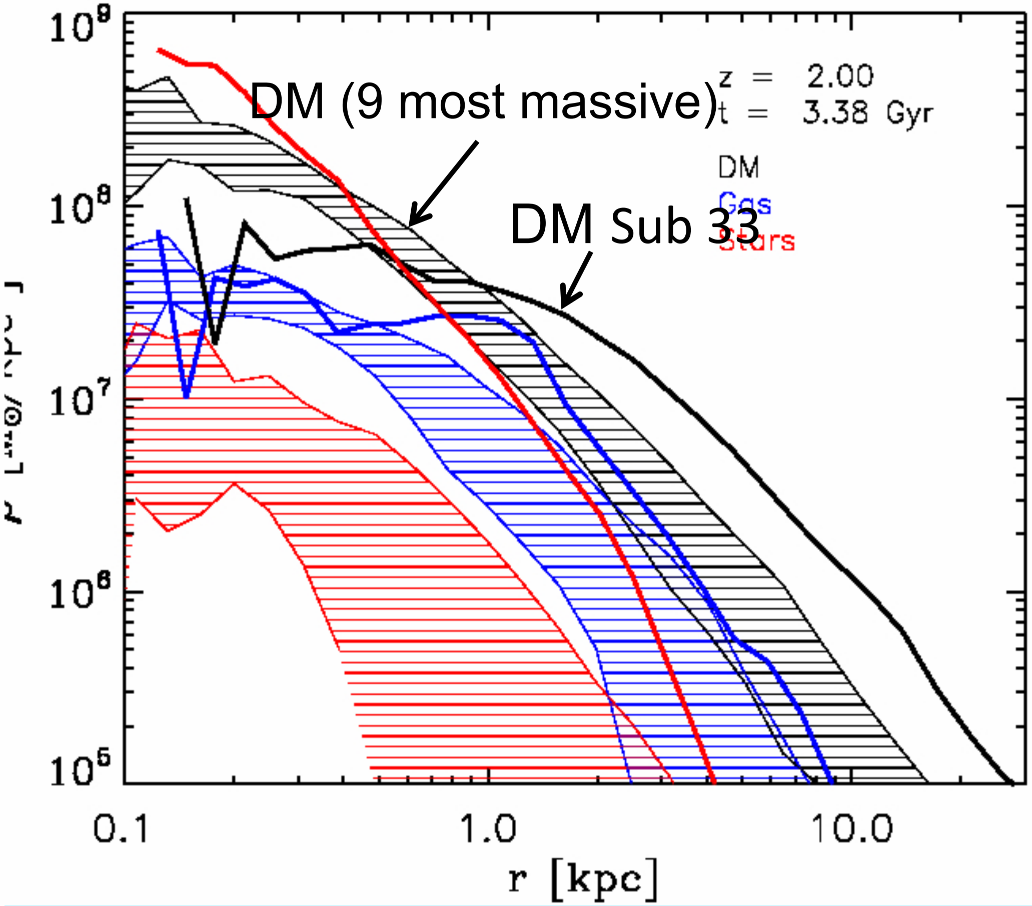
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

Baryon effects in the MW satellites


Subhalo 33

gas

DM central density


DM (9 most massive)

DM Sub 33

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: ΛCDM on small scales

- Satellite luminosity function can be understood in ΛCDM as a result of feedback effects during galaxy formation
- There exist subhalos in ΛCDM galactic halos that are consistent with the photo/kinematic data for Milky Way satellites
- But galaxy formation models in ΛCDM 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