The formation of cosmic structure

Carlos S. Frenk

Institute for Computational Cosmology, Durham

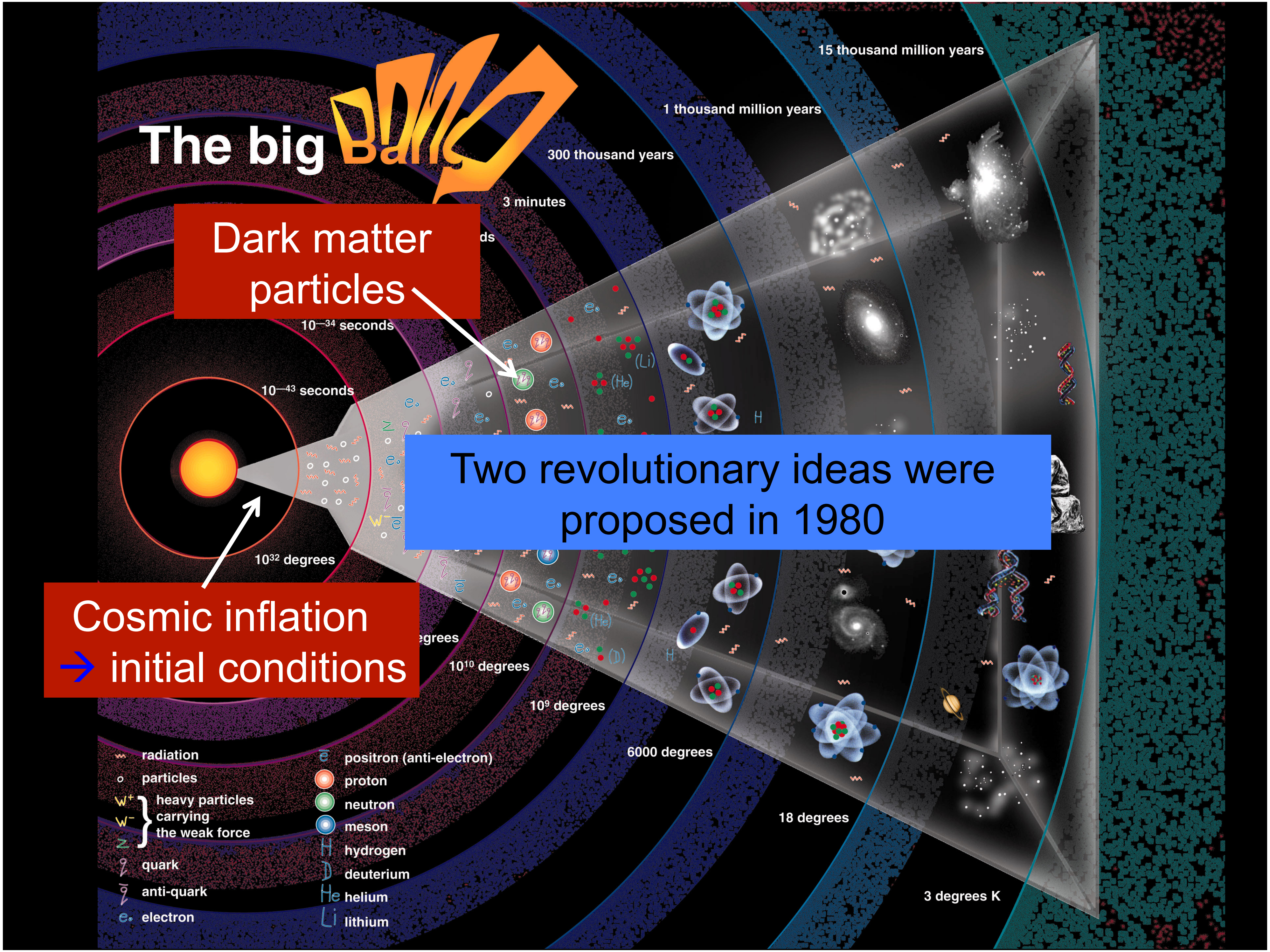
cold dark matter

ΛCDM: the standard model of cosmology

cosmological constant

Why is this the standard model?

New tests and possible problems



The big Bang
Dark matter particles
Two revolutionary ideas were proposed in 1980
Cosmic inflation
→ initial conditions
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

University of Durham ICC

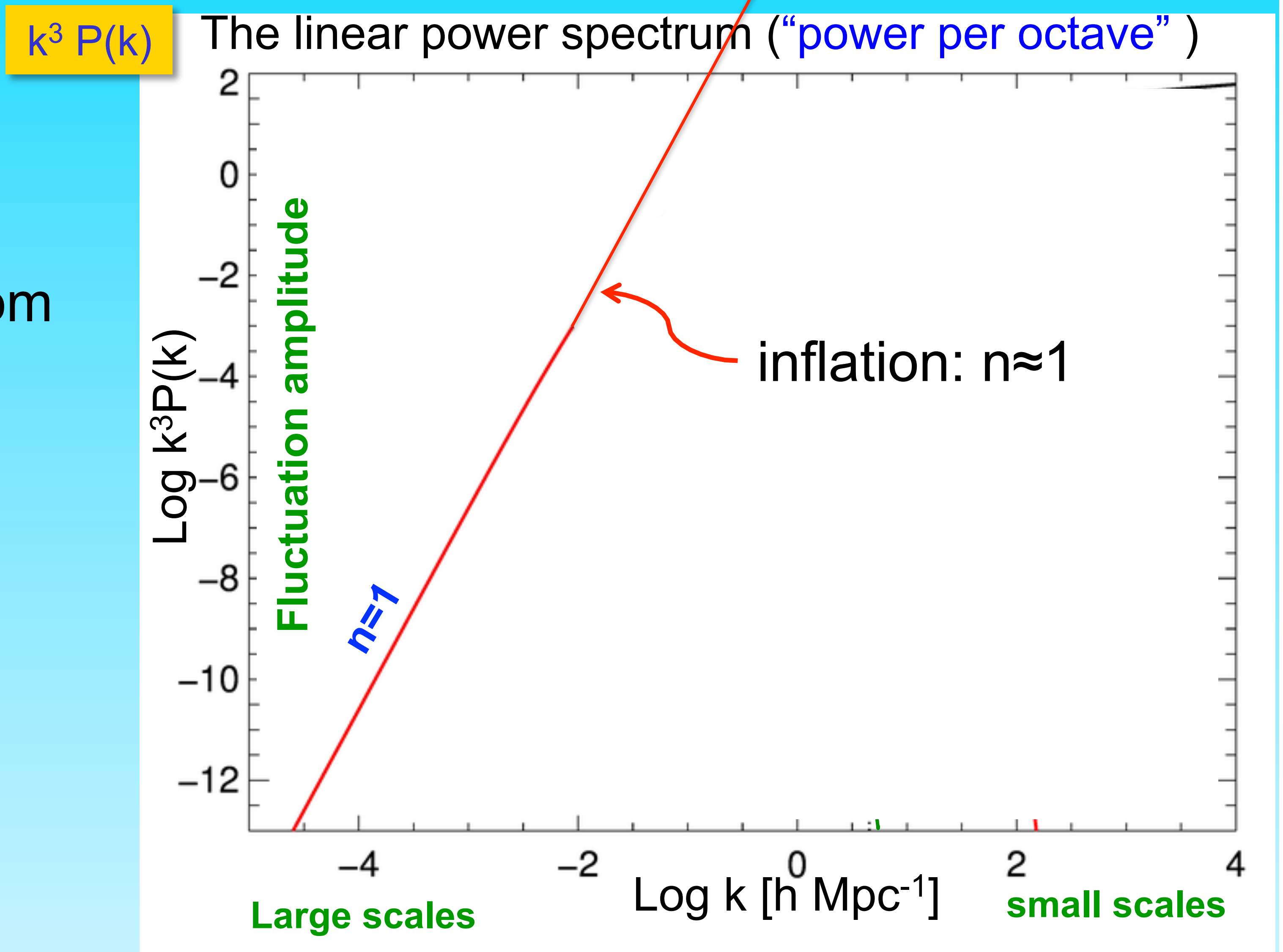
Non-baryonic dark matter candidates

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

The dark matter power spectrum

University of Durham

Prediction from inflation



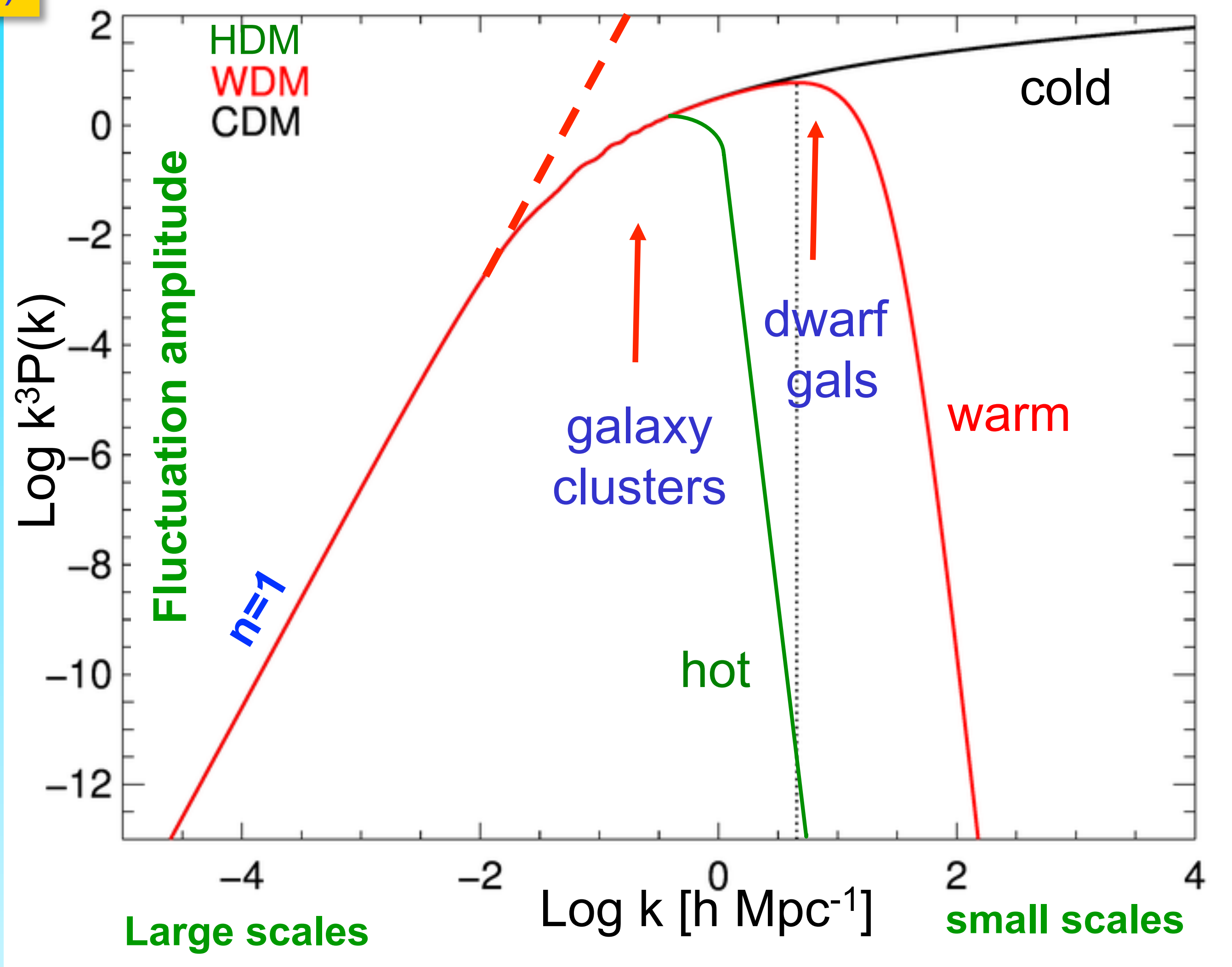
Institute for Computational Cosmology

University of Durham

The dark matter power spectrum

k³ P(k)

The linear power spectrum (“power per octave”)



Free streaming →

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

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

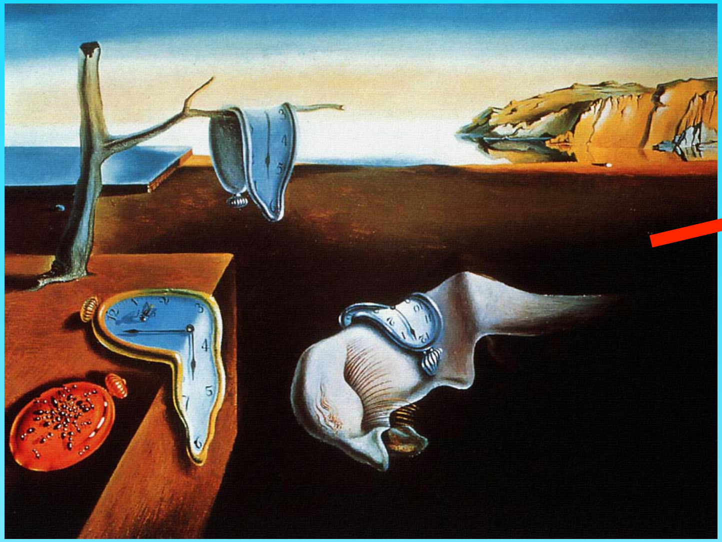
$m_{WDM} \sim$ few keV
sterile ν; $M_{cut} \sim 10^{9}\ M_o$

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

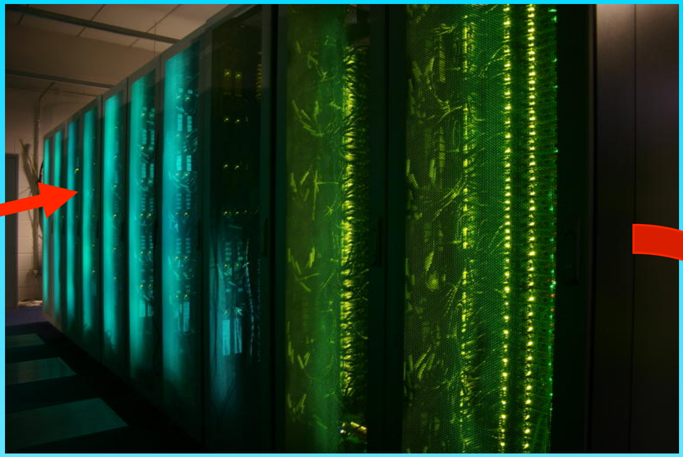
ICC
University of Durham

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

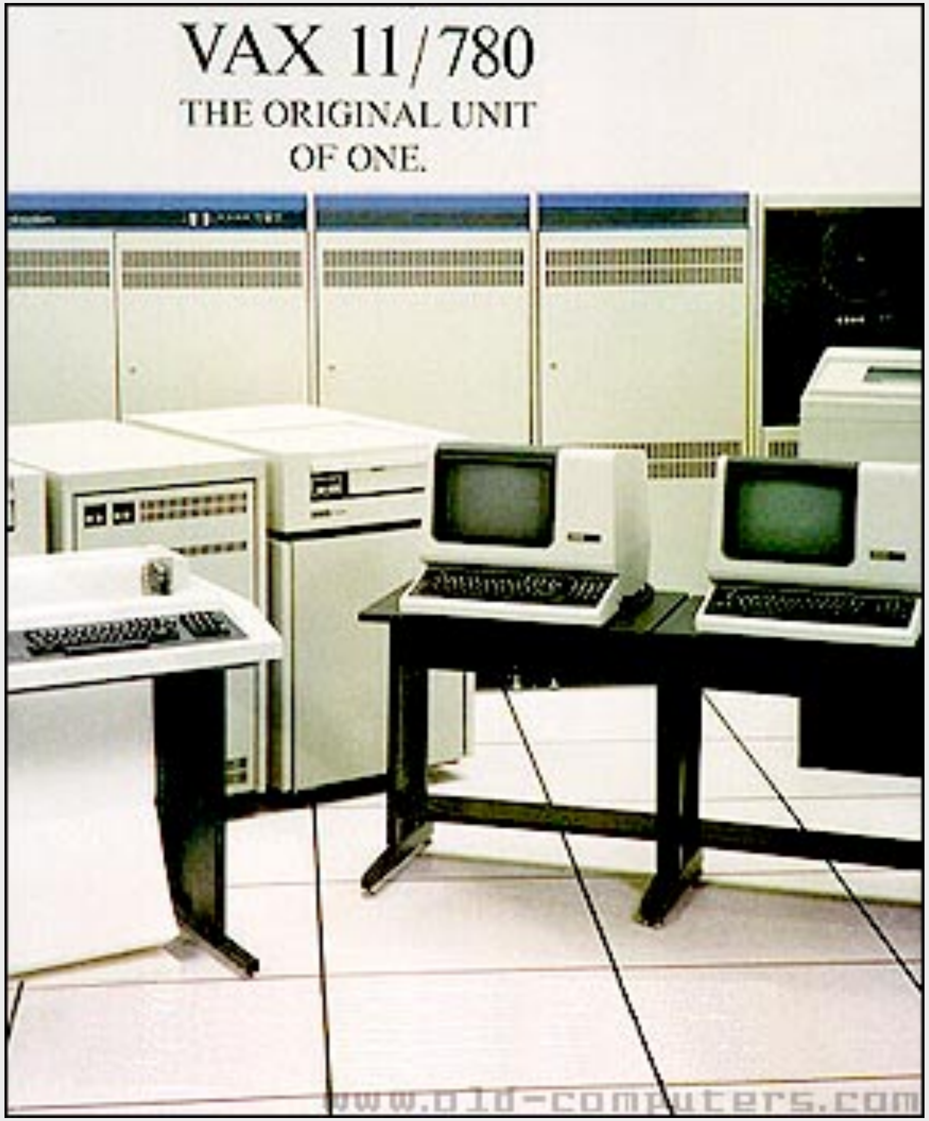
t=13.8 billion yrs

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

University of Durham

ICC

The universe in a computer

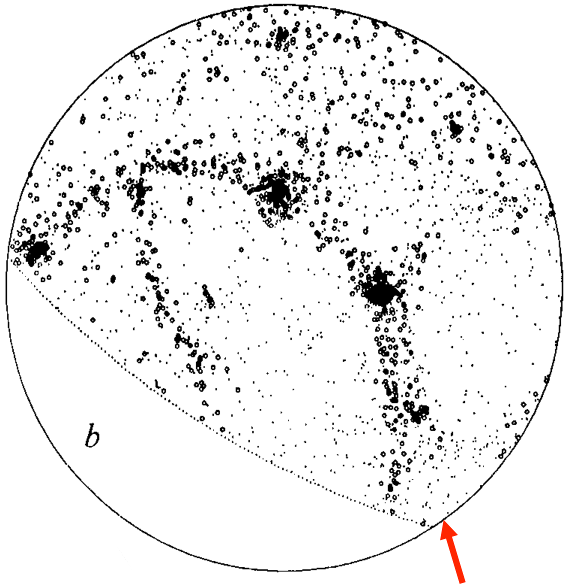


December 1981

Speed = 500,000 FLOPS
RAM = 4 Mbytes

University of Durham

Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

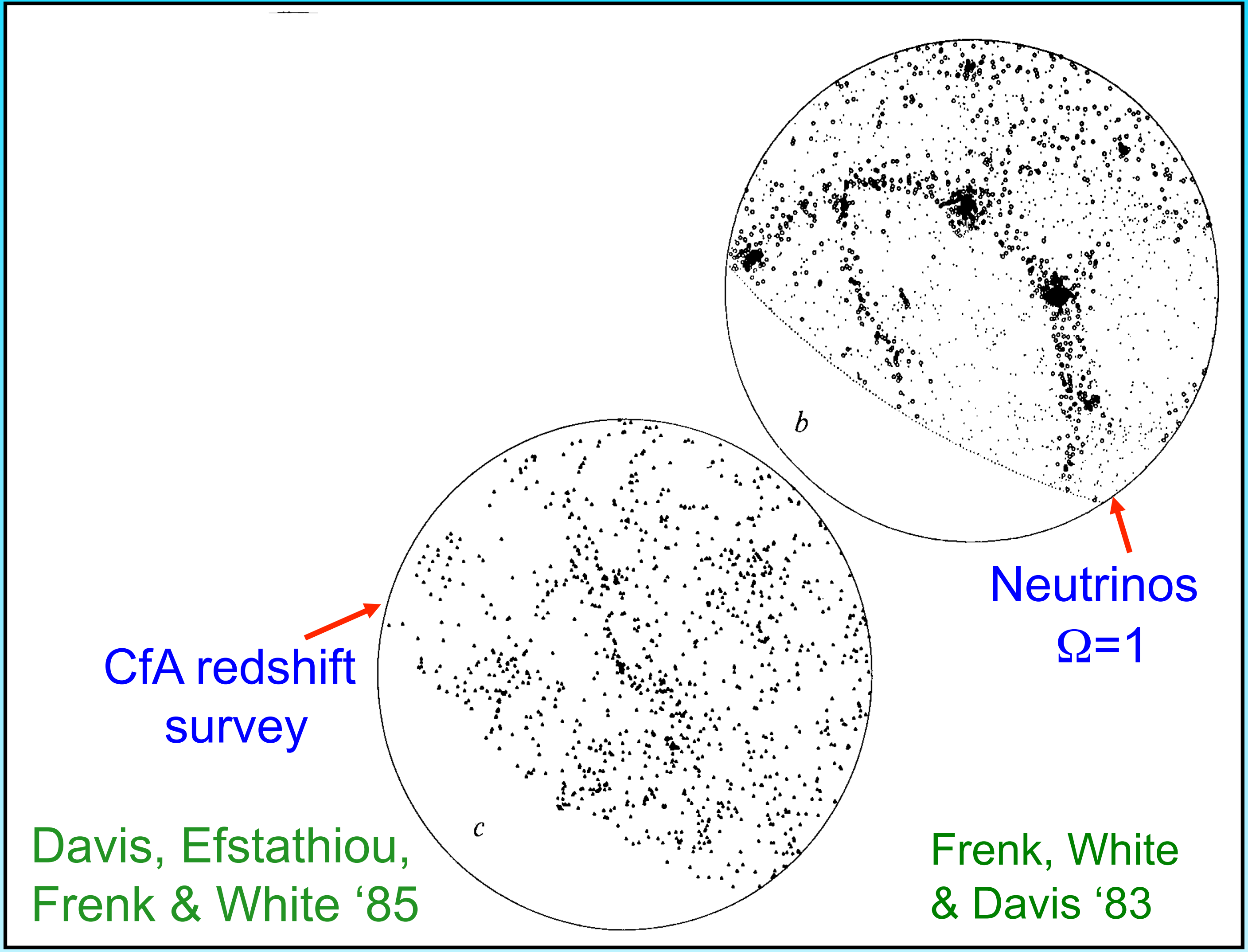
Frenk, White
& Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 10$ ev



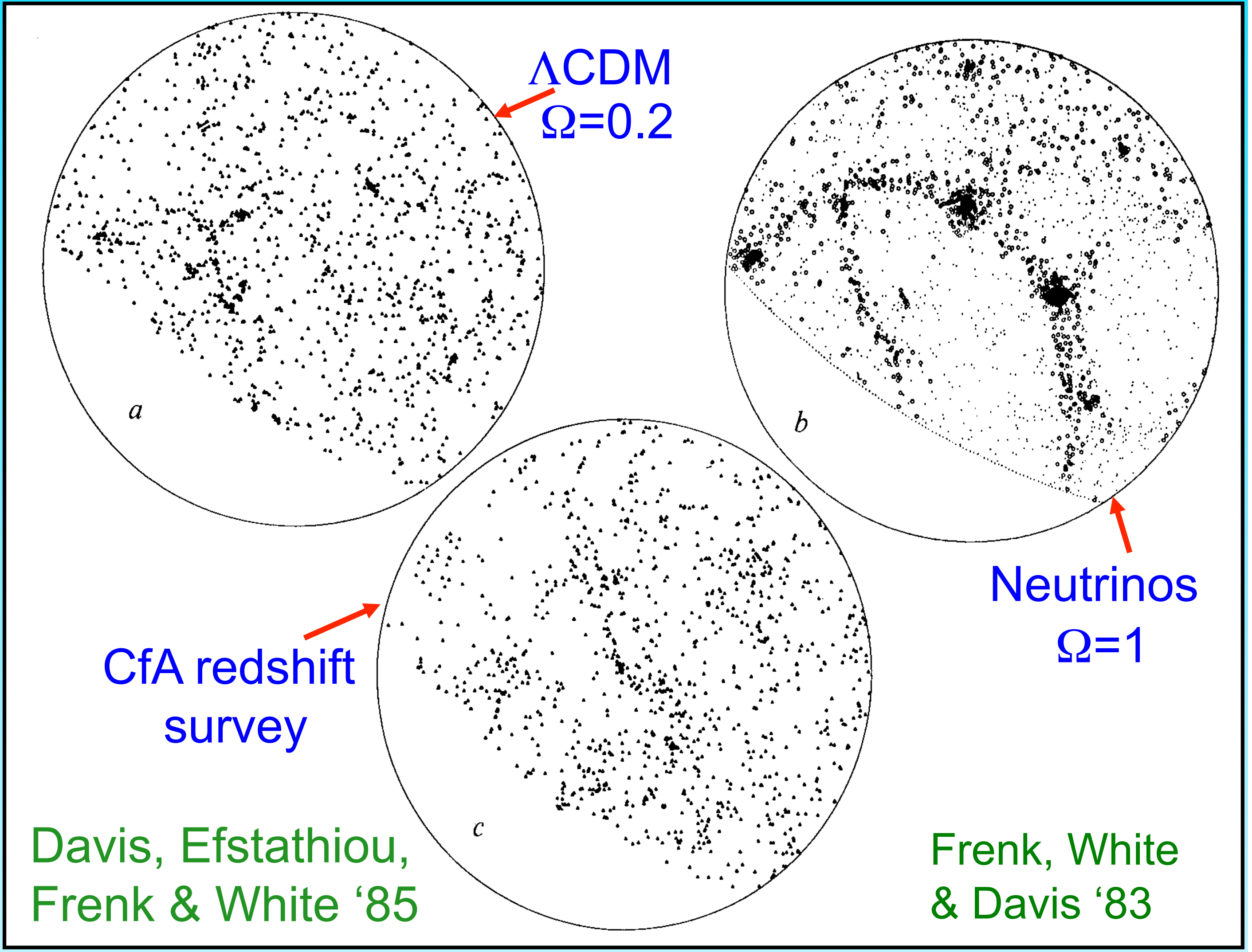
Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω → $m_\nu << 10$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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

ΛCDM model is an *a priori* implausible model!

… but makes definite predictions and is therefore testable

The cold dark matter cosmogony

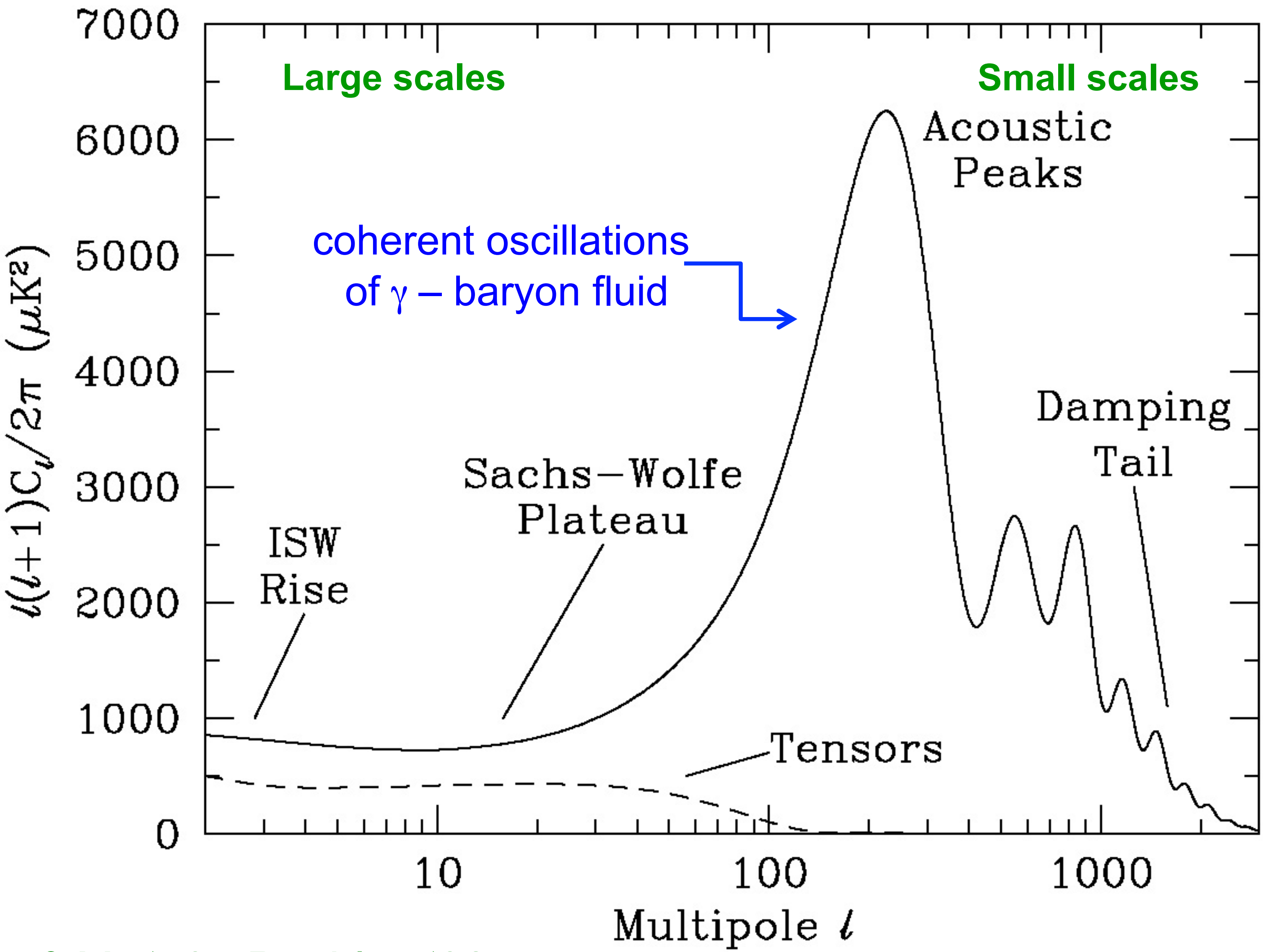
University of Durham

Main successes of the CDM cosmogony:

1. CMB temp. anisotropies: predicted in 1981, discovered in 1993
2. Spatial distribution of gals (1990- QDOT, APM, 2dFGRS, SDSS)
3. General features of galaxy luminosity function (1991 -)
4. Evolution of the galaxy population (2000 -)

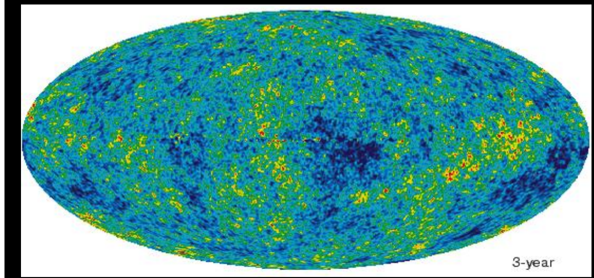
Temperature anisotropies in CMB

University of Durham

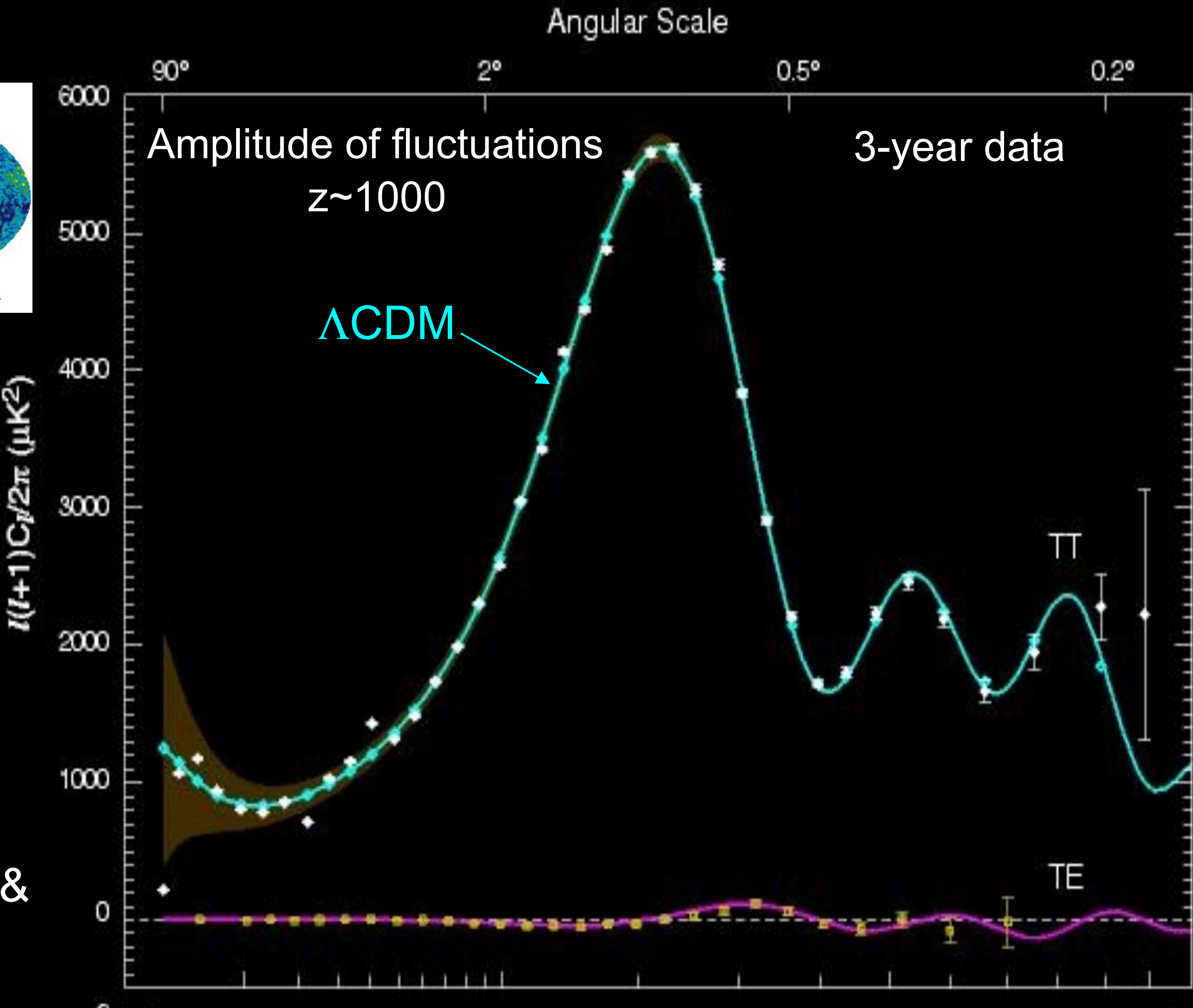


After Peebles & Yu '70; Peebles '82

WMAP temp anisotropies in CMB



The data confirm the theoretical predictions (linear theory)



Peebles '82; Bond & Efstathiou '80s

Hinshaw etal '06

University of Durham

The cold dark matter cosmogony

Main successes of the CDM cosmogony:

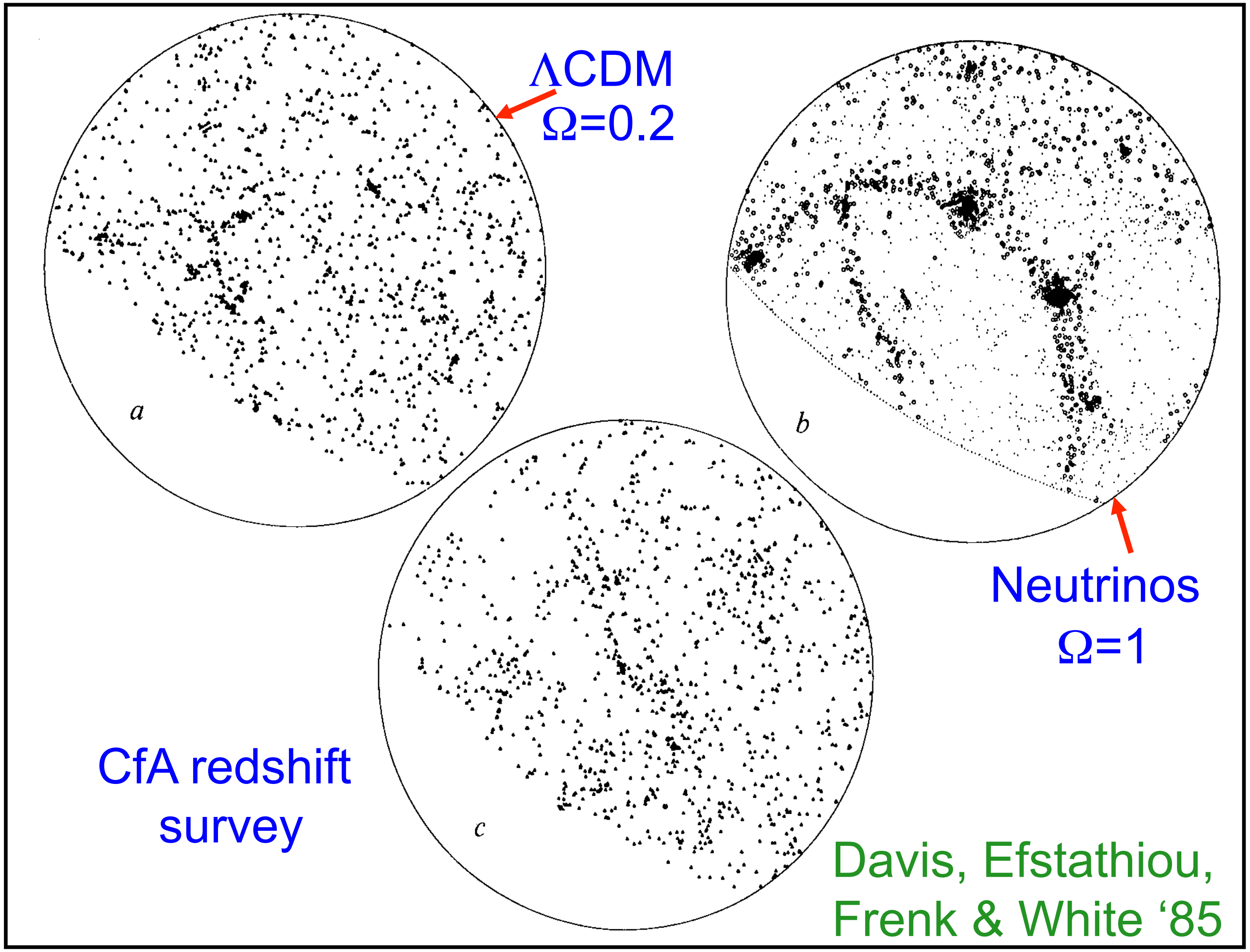
1. CMB temp. anisotropies: predicted in 1981, discovered in 1993
2. Spatial distribution of gals (1990- QDOT, APM, 2dFGRS, SDSS)
3. General features of gal luminosity function (1991 -)
4. Evolution of the galaxy population (2000 -)

Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically

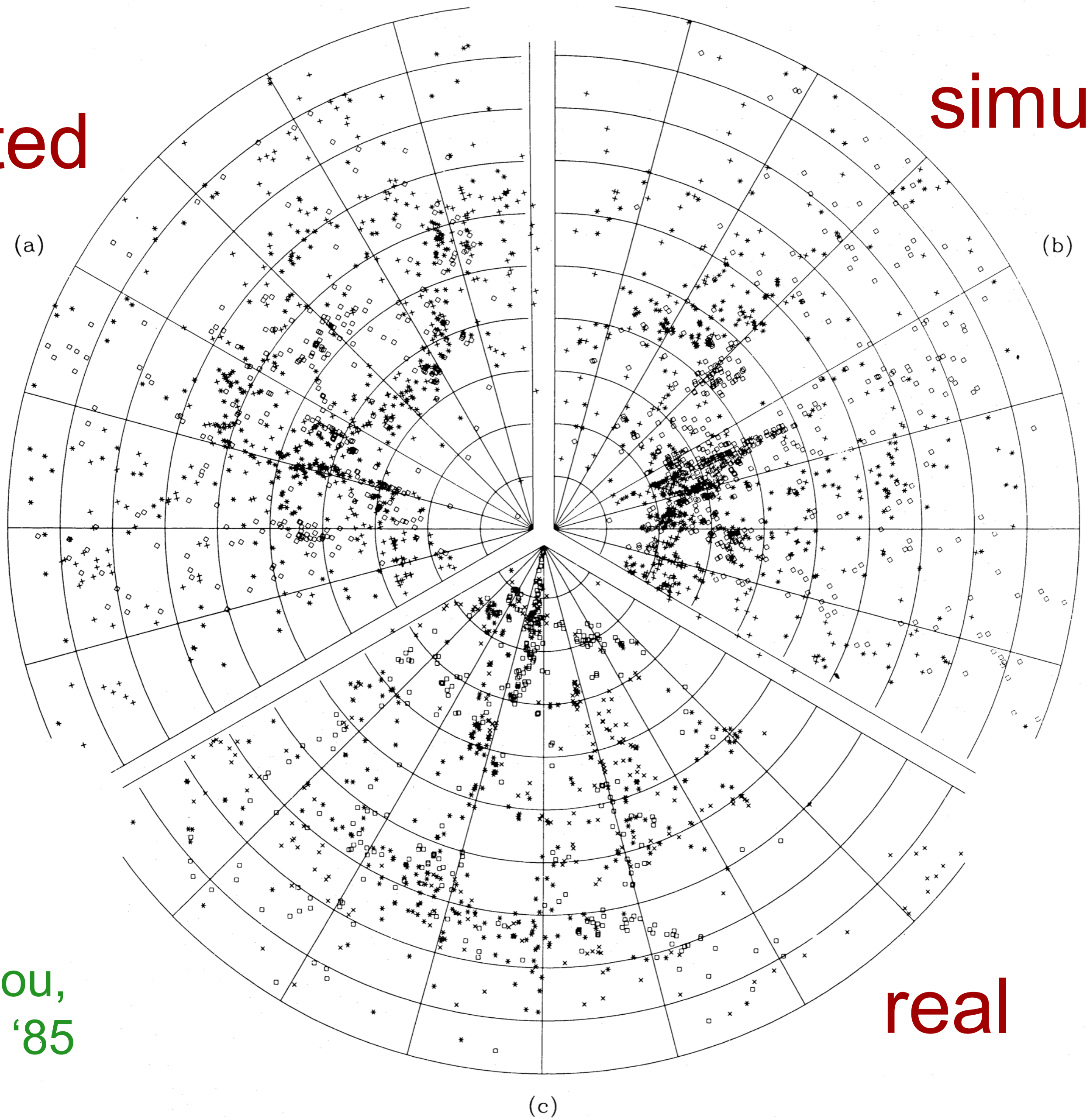


University of Durham

Early simulations of ΛCDM

simulated

simulated



real

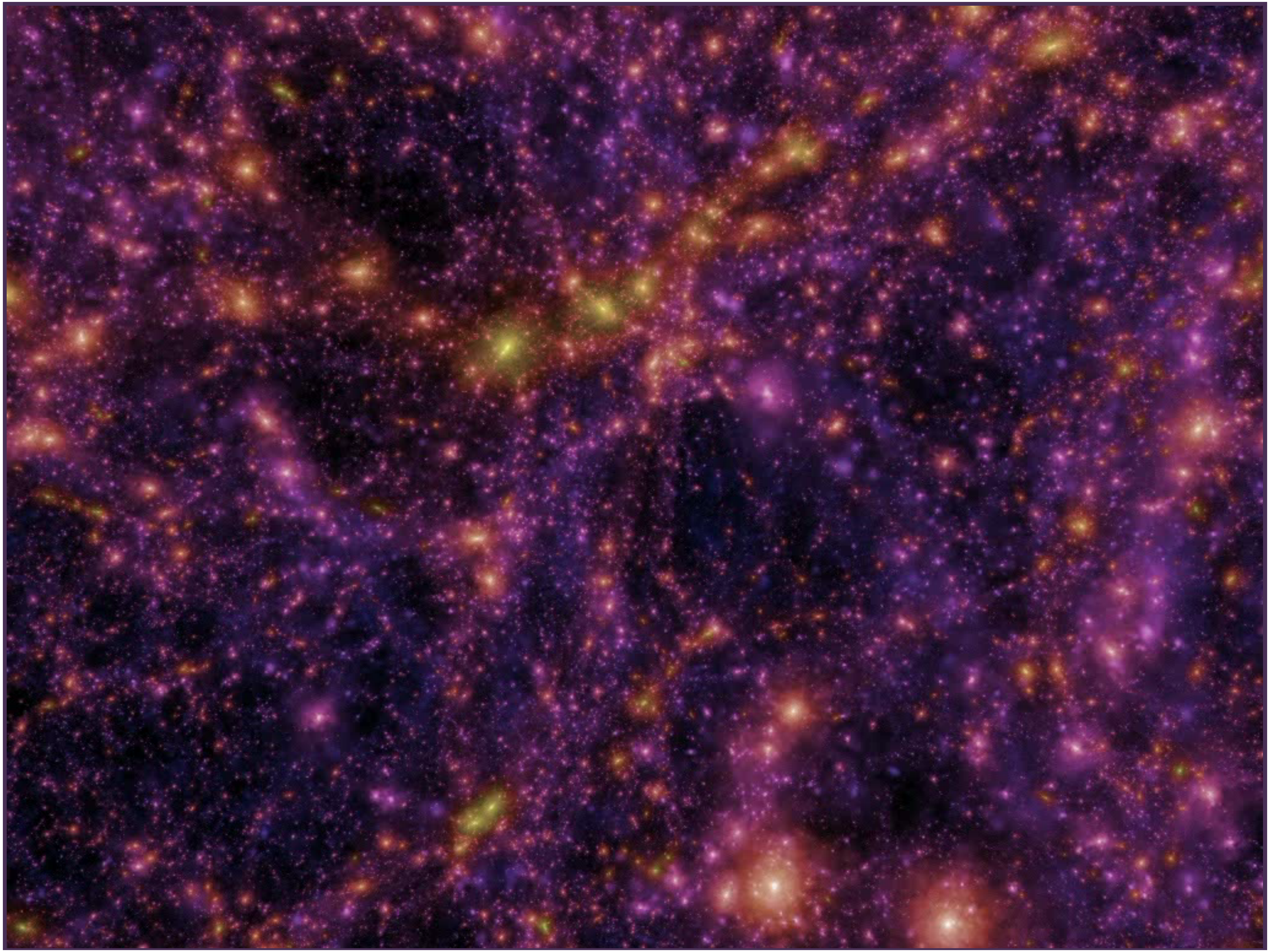
Davis, Efstathiou, Frenk & White ‘85

The 2dF Galaxy Redshift Survey

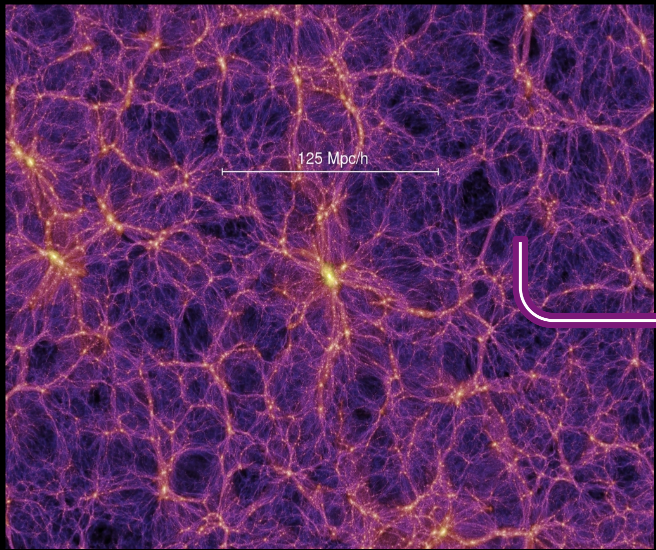
221,000 redshifts

z~0

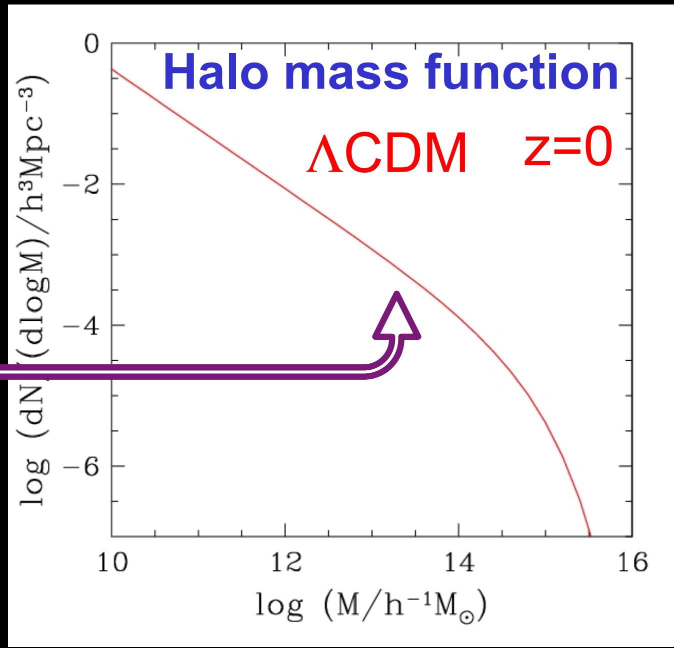
2005

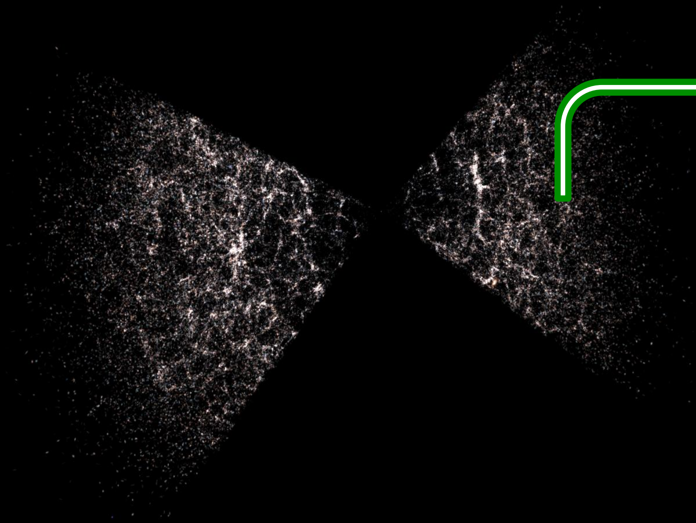


Abundance of gals & dark halos

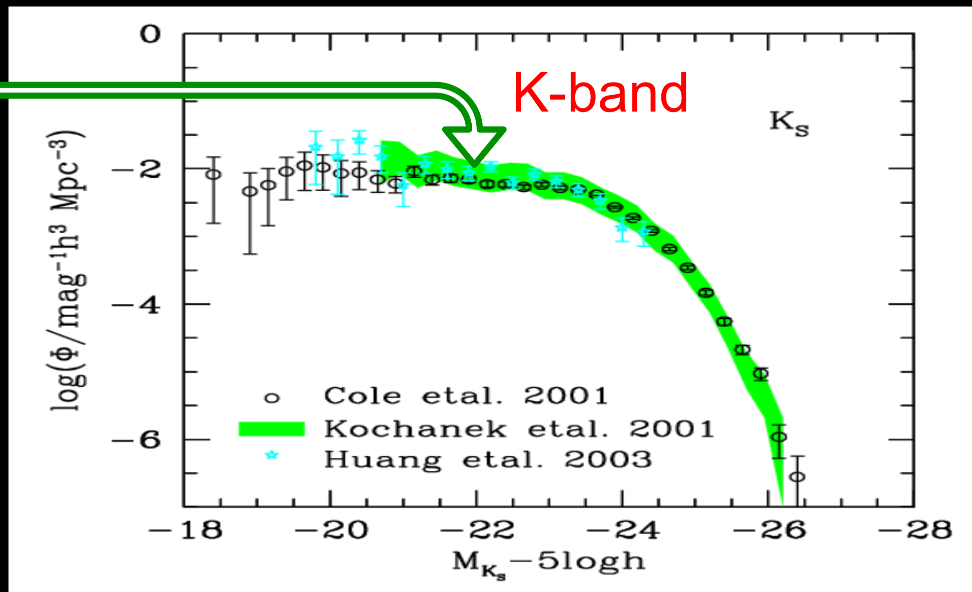


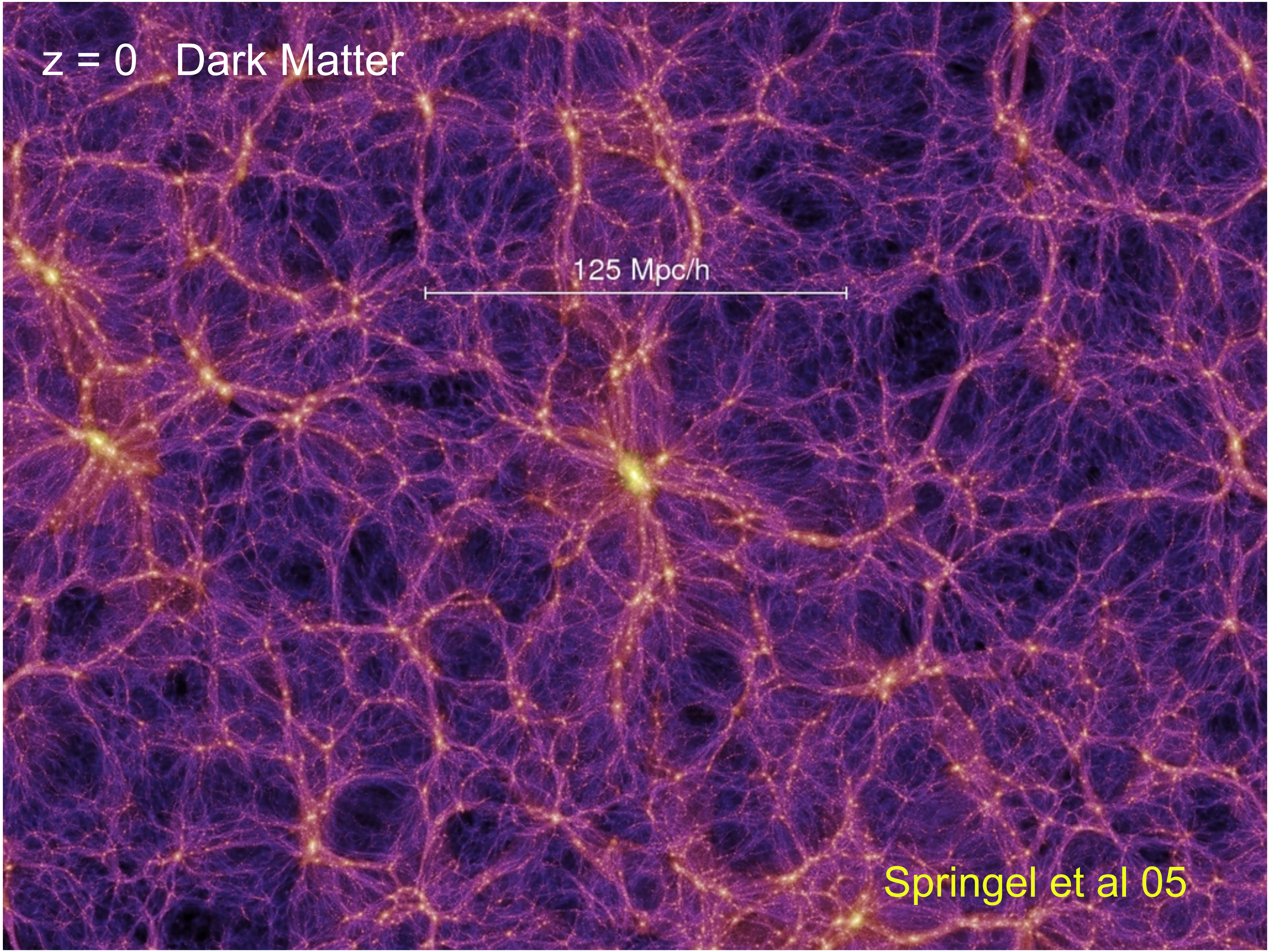
Millennium run





2dFGRS




z = 0 Dark Matter
125 Mpc/h
Springel et al 05

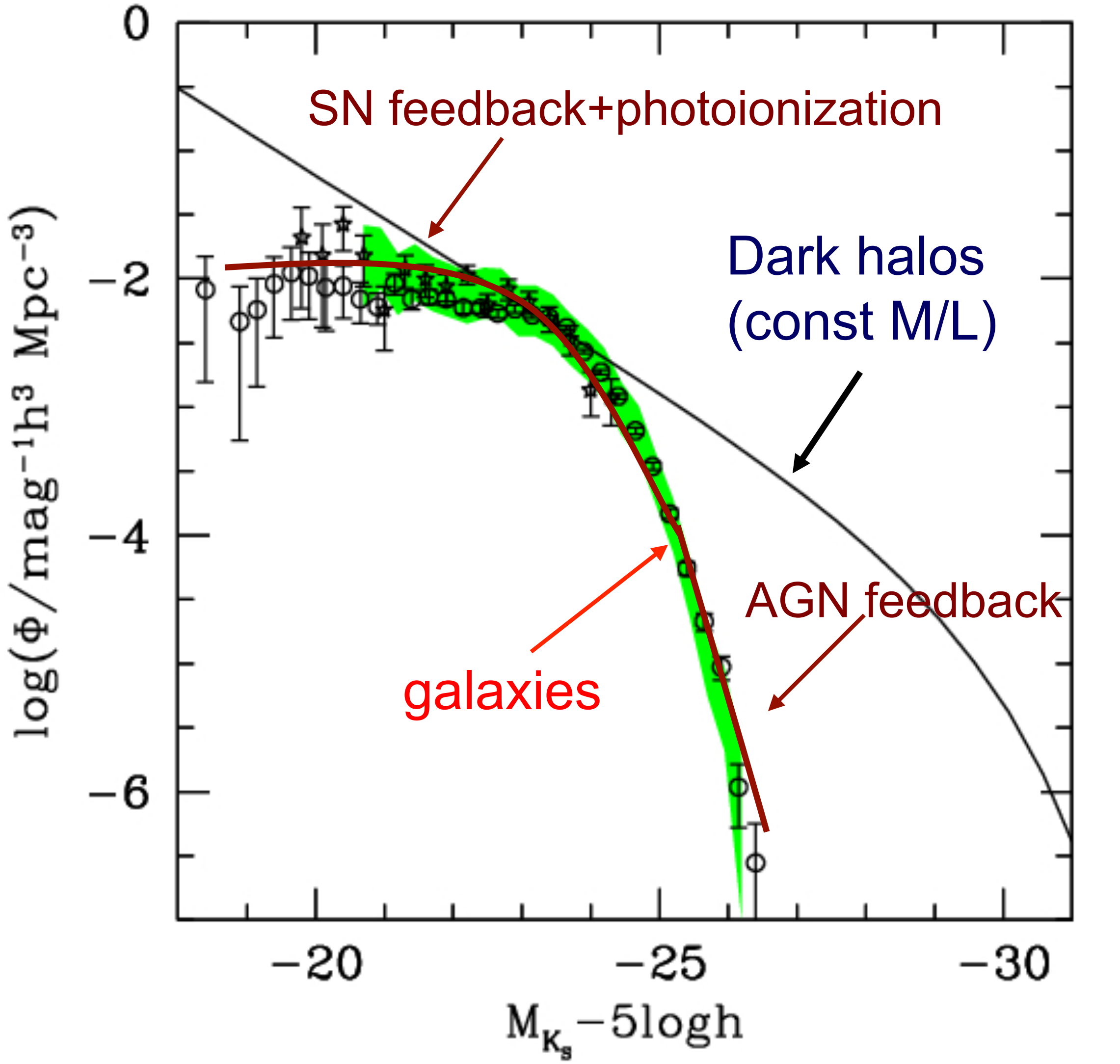
The galaxy luminosity function

University of Durham

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

⇨

Complicated variation of M/L with halo mass

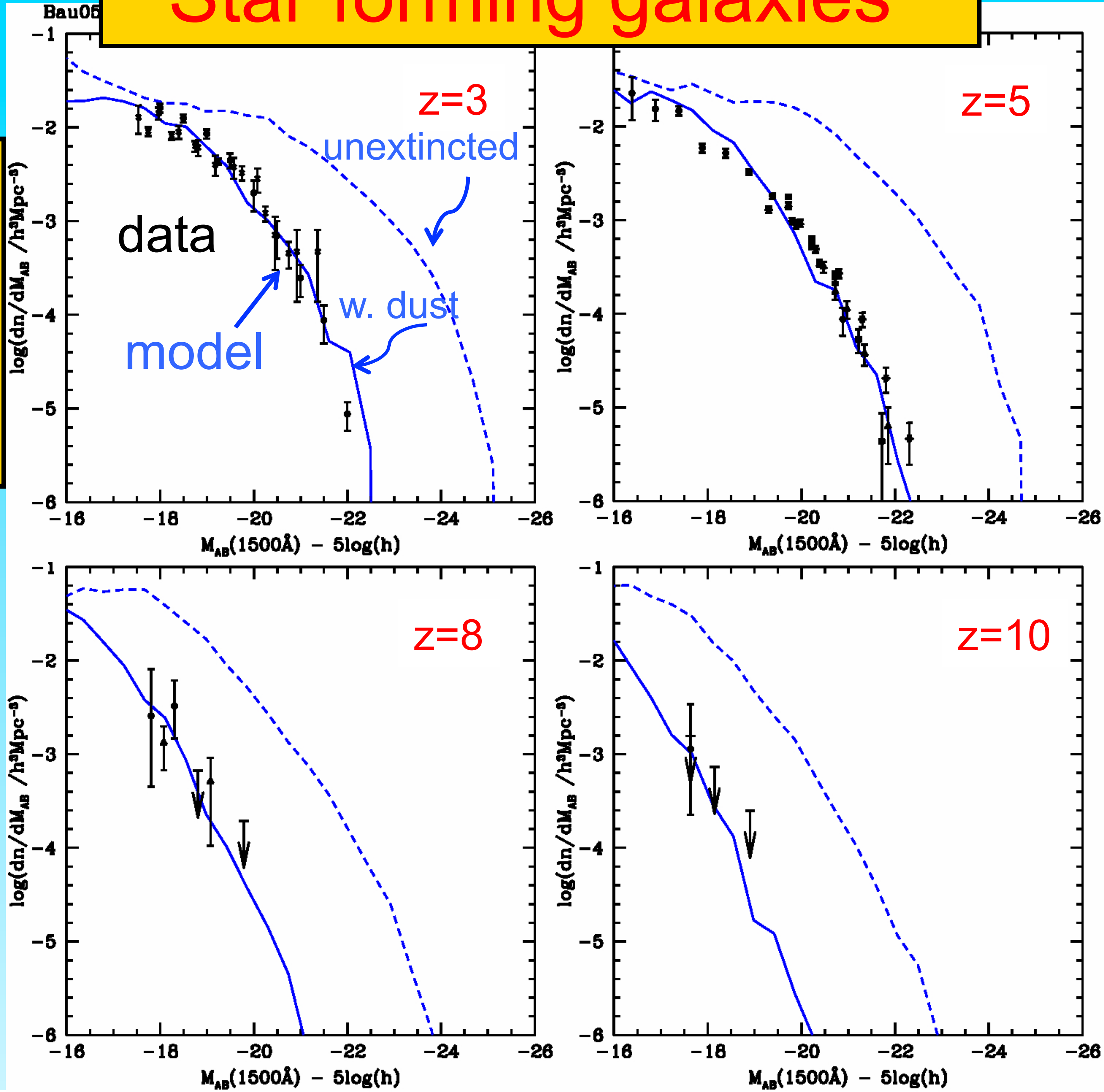


White & Frenk ‘91; Kauffmann et al ‘93; Benson et al ’03; Croton et al ‘05; Bower et al. ’06

Star forming galaxies

University of Durham

Evolution of Lyman-break galaxy lum. function



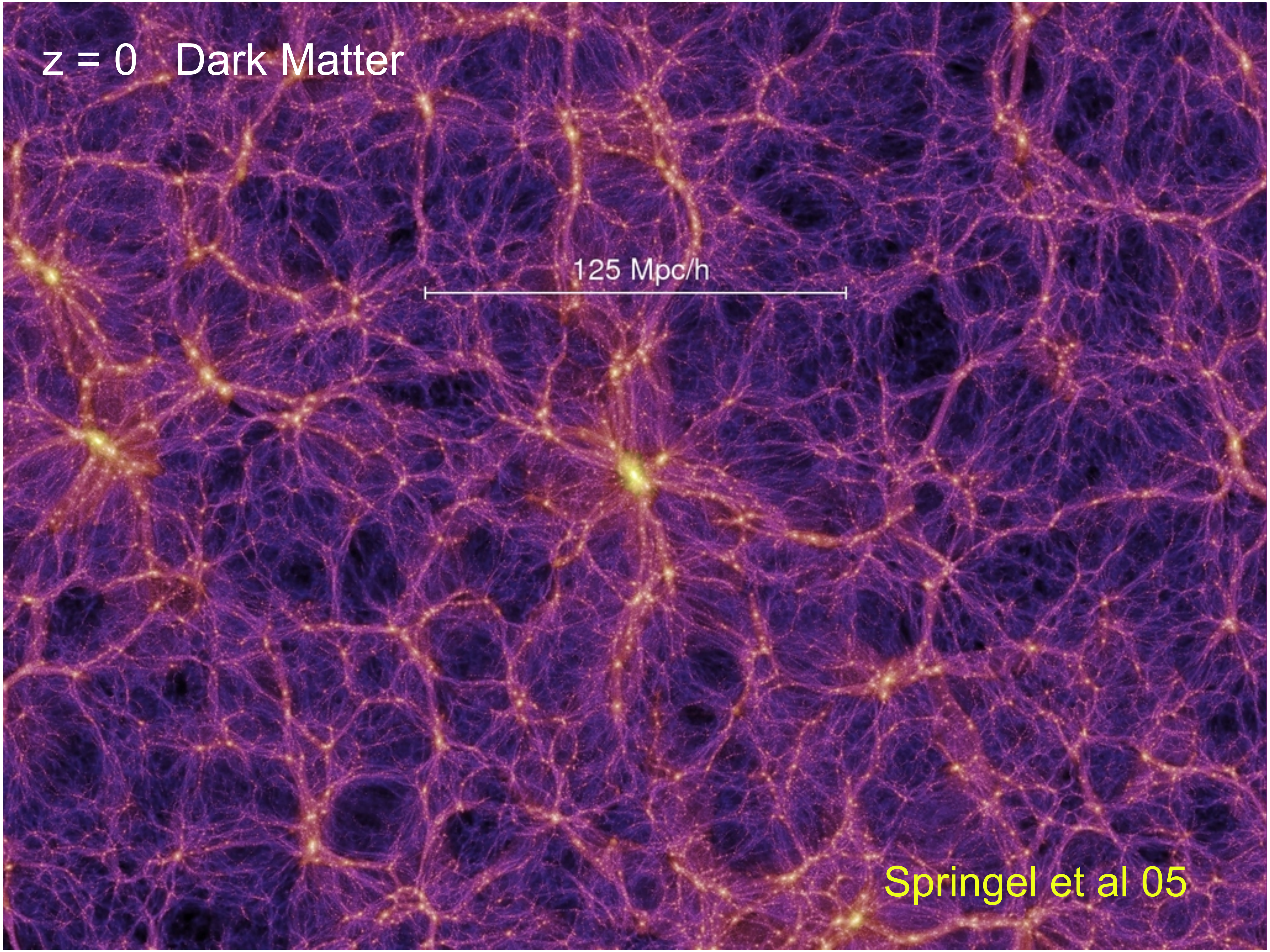
Lacey, Baugh, Frenk, Benson '11

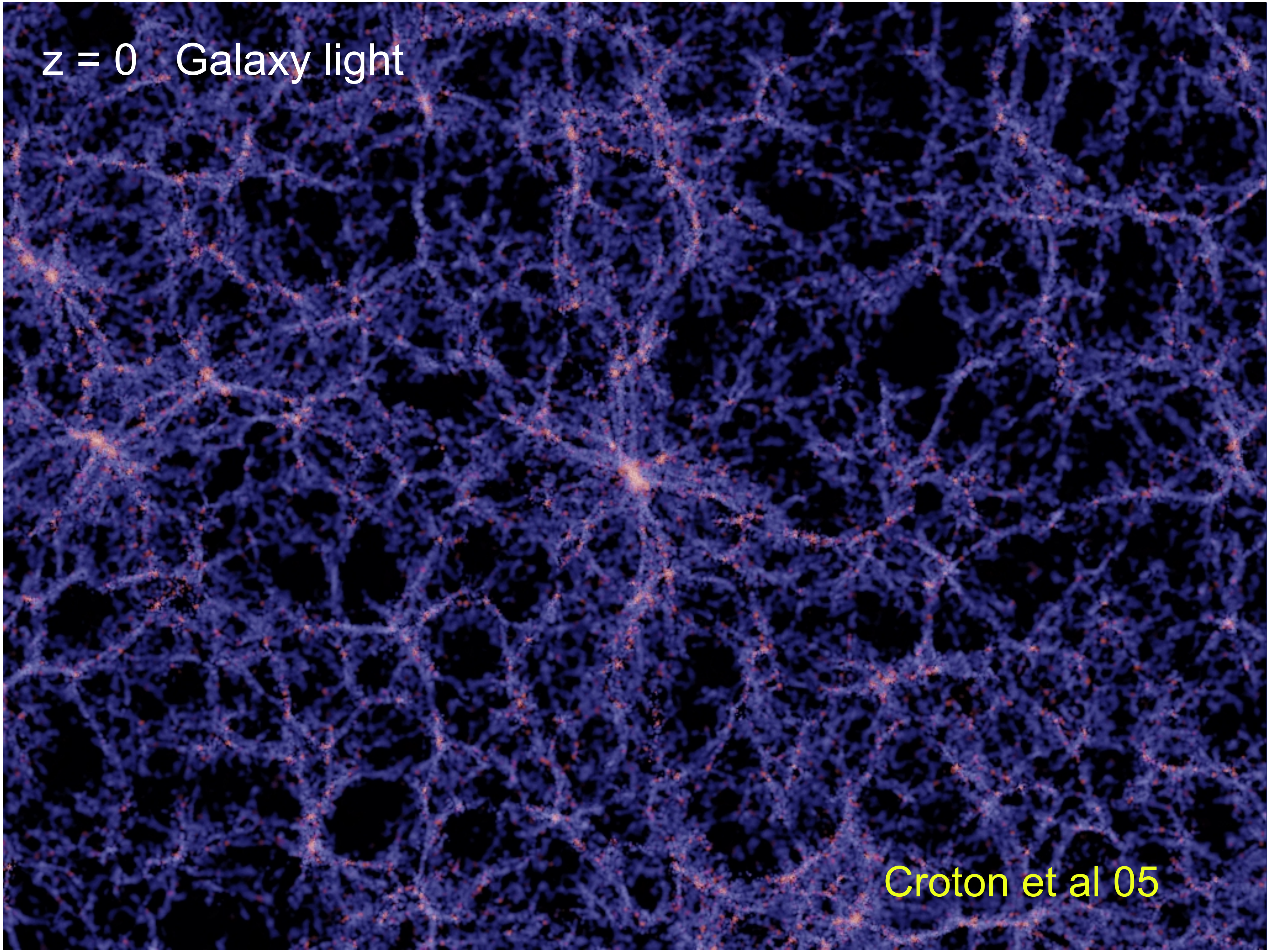
University of Durham

The cold dark matter cosmogony

Main successes of the CDM cosmogony:

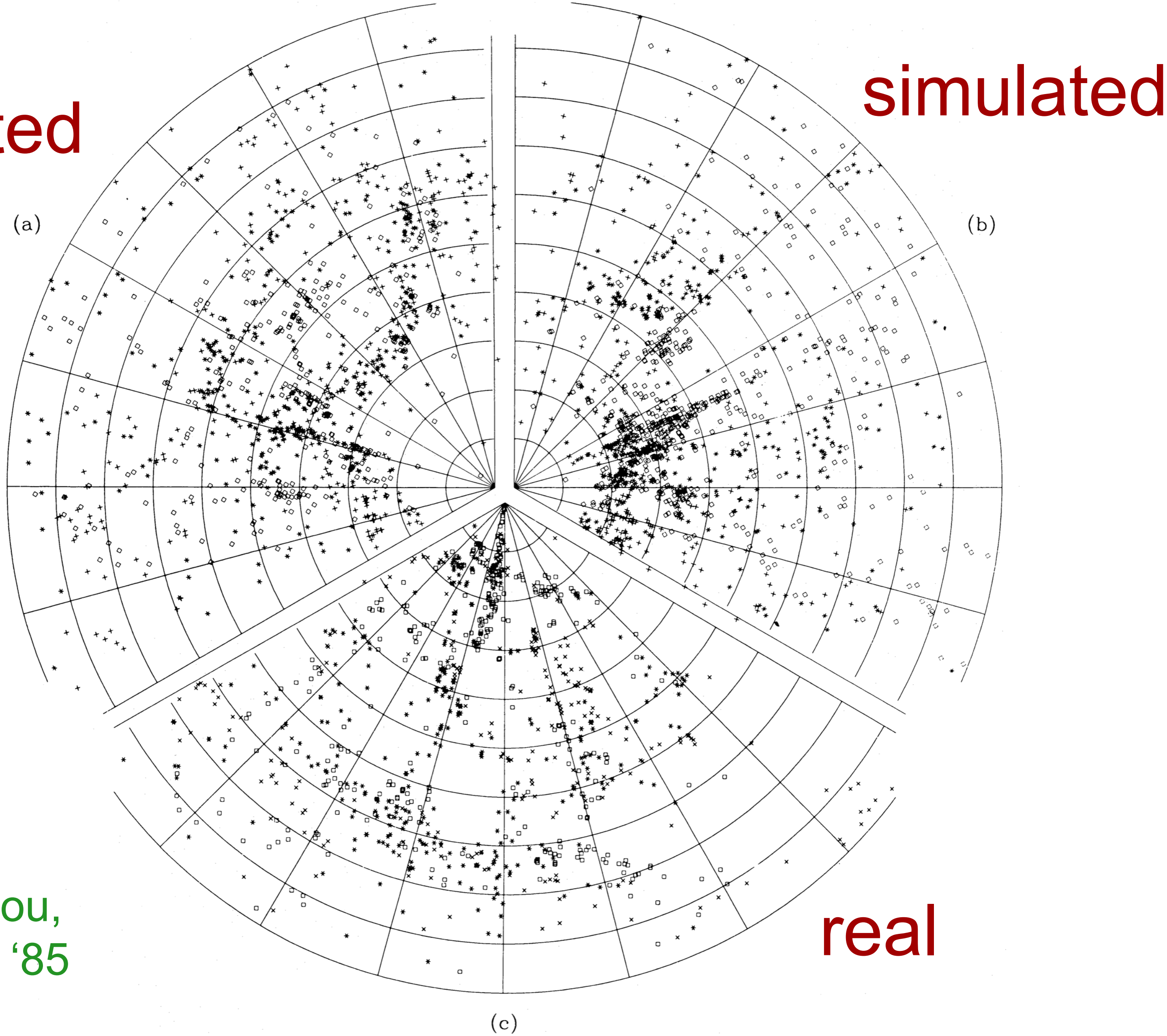
1. CMB temp. anisotropies: predicted in 1981, discovered in 1993
2. Spatial distribution of gals (1990- QDOT, APM, 2dFGRS, SDSS)
3. General features of galaxy luminosity function (1991 -)
4. Evolution of the galaxy population (2000 -)


z = 0 Dark Matter
125 Mpc/h
Springel et al 05


z = 0 Galaxy light
Croton et al 05

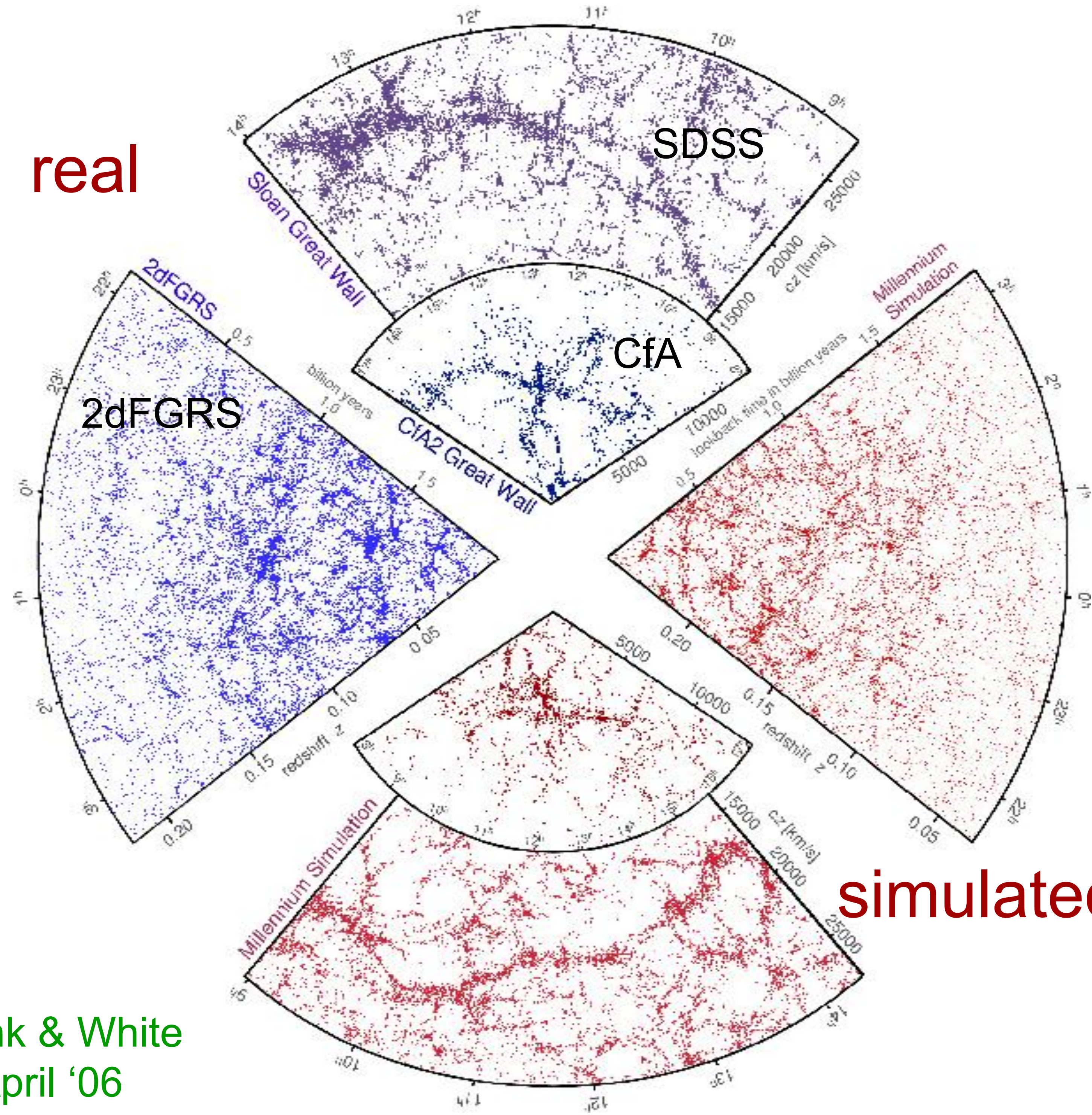
Early simulations of ΛCDM

University of Durham



Davis, Efstathiou, Frenk & White '85

real



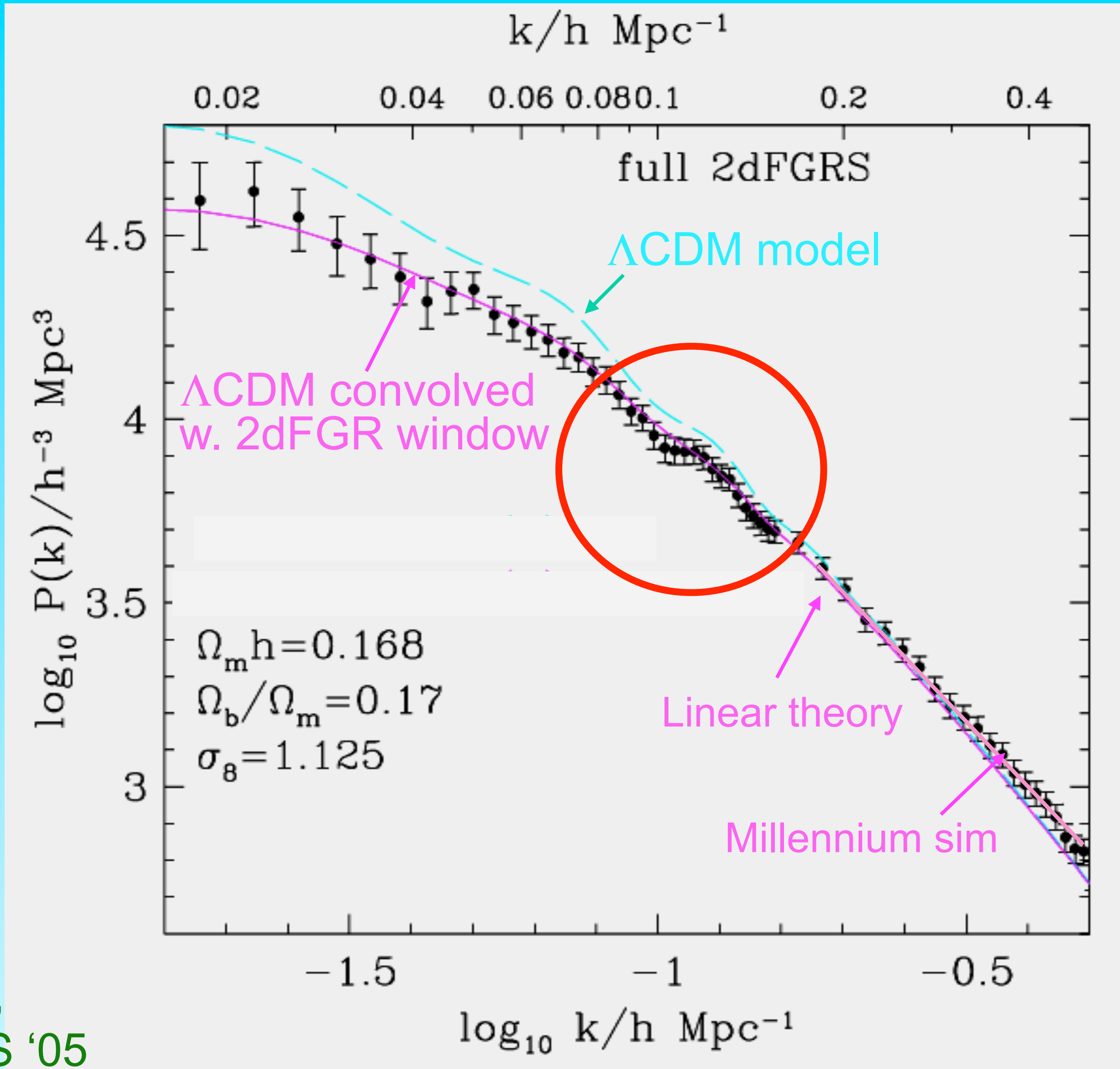
simulated

Springel, Frenk & White
Nature, April ‘06

The final 2dFGRS power spectrum

University of Durham

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



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

The final 2dFGRS power spectrum

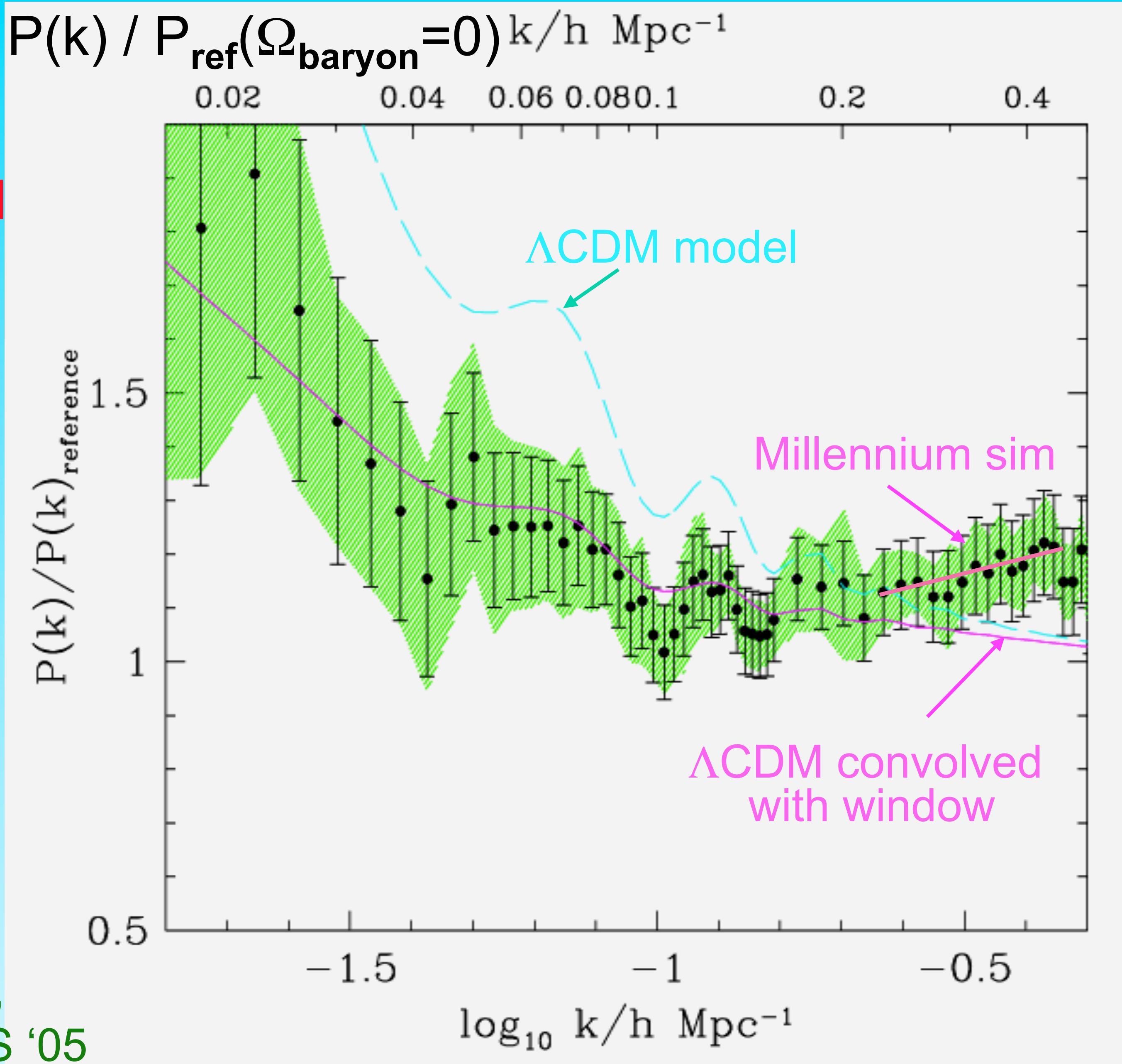
University of Durham

Baryon oscillations conclusively detected in 2dFGRS!!!

Consistent with structure growth by gravitational instability in a ΛCDM universe

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

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



University of Durham

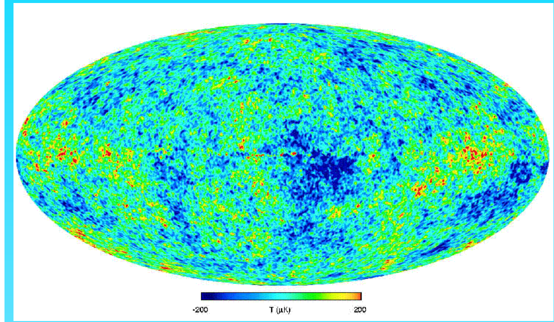
The cold dark matter cosmogony

Main successes of the CDM cosmogony:

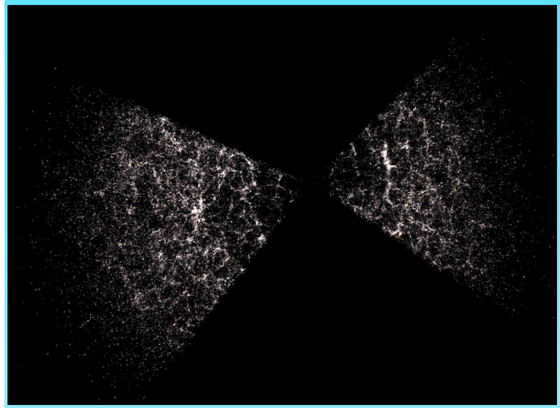
1. CMB temp. anisotropies: predicted in 1981, discovered in 1993
2. Spatial distribution of gals (1990- QDOT, APM, 2dFGRS, SDSS)
3. General features of gal luminosity function (1991 -)
4. Evolution of the galaxy population (2000 -)

University of Durham

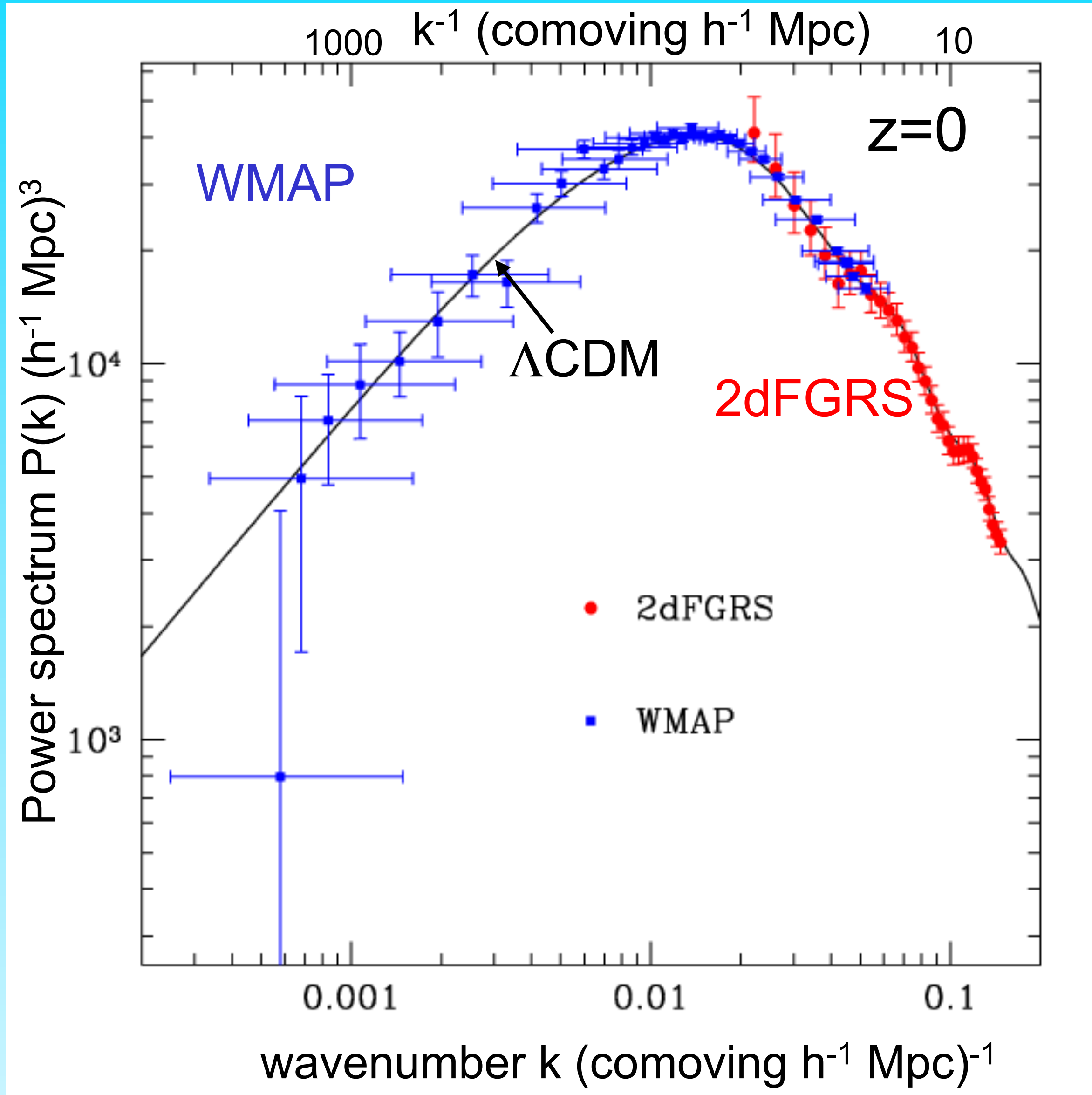
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

The dark matter power spectrum

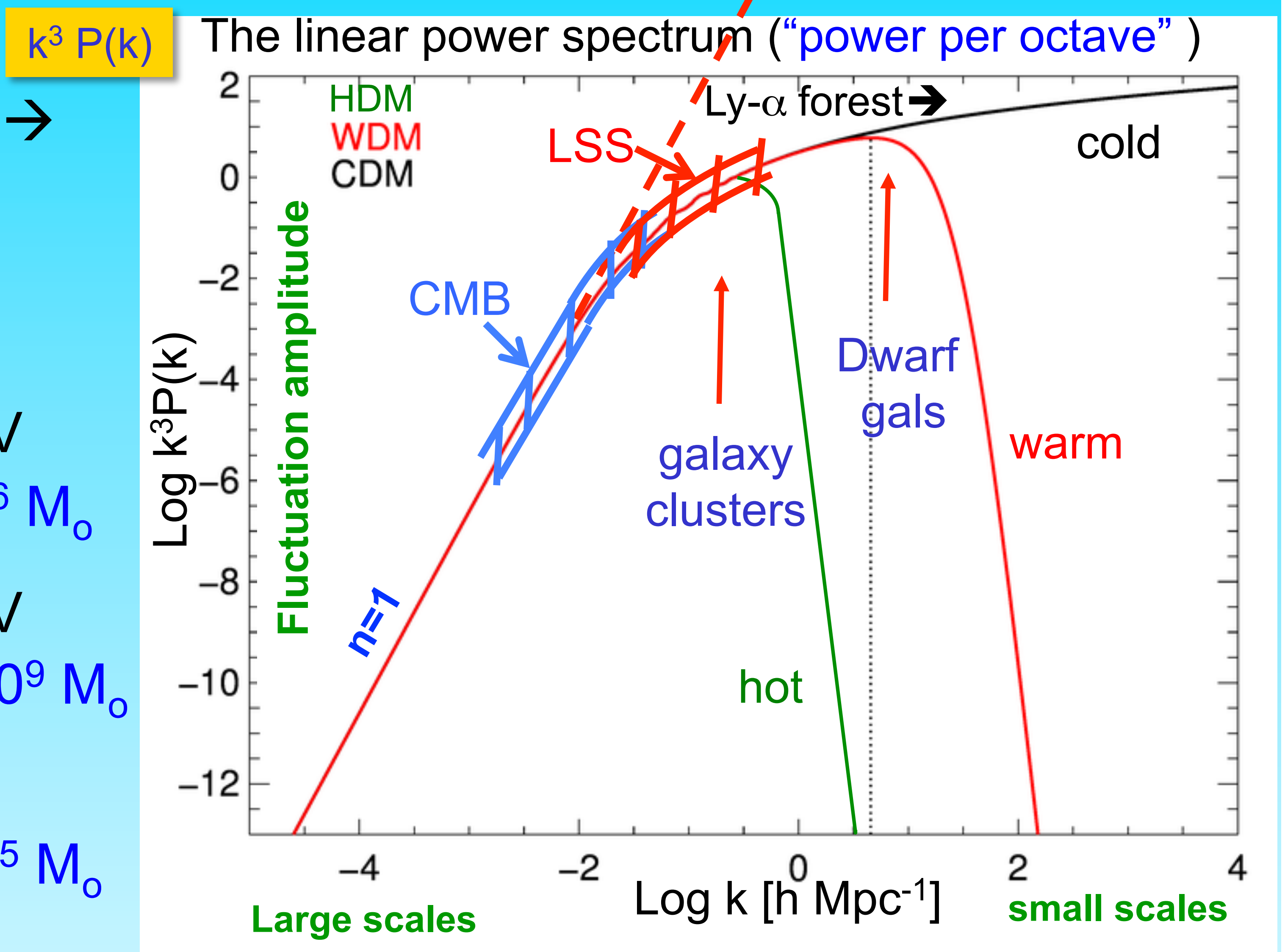
Free streaming →

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

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

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

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



Cosmology on small – strongly non-linear – scales

→ key to the identity of the dark matter

z = 48.4
T = 0.05 Gyr
500 kpc

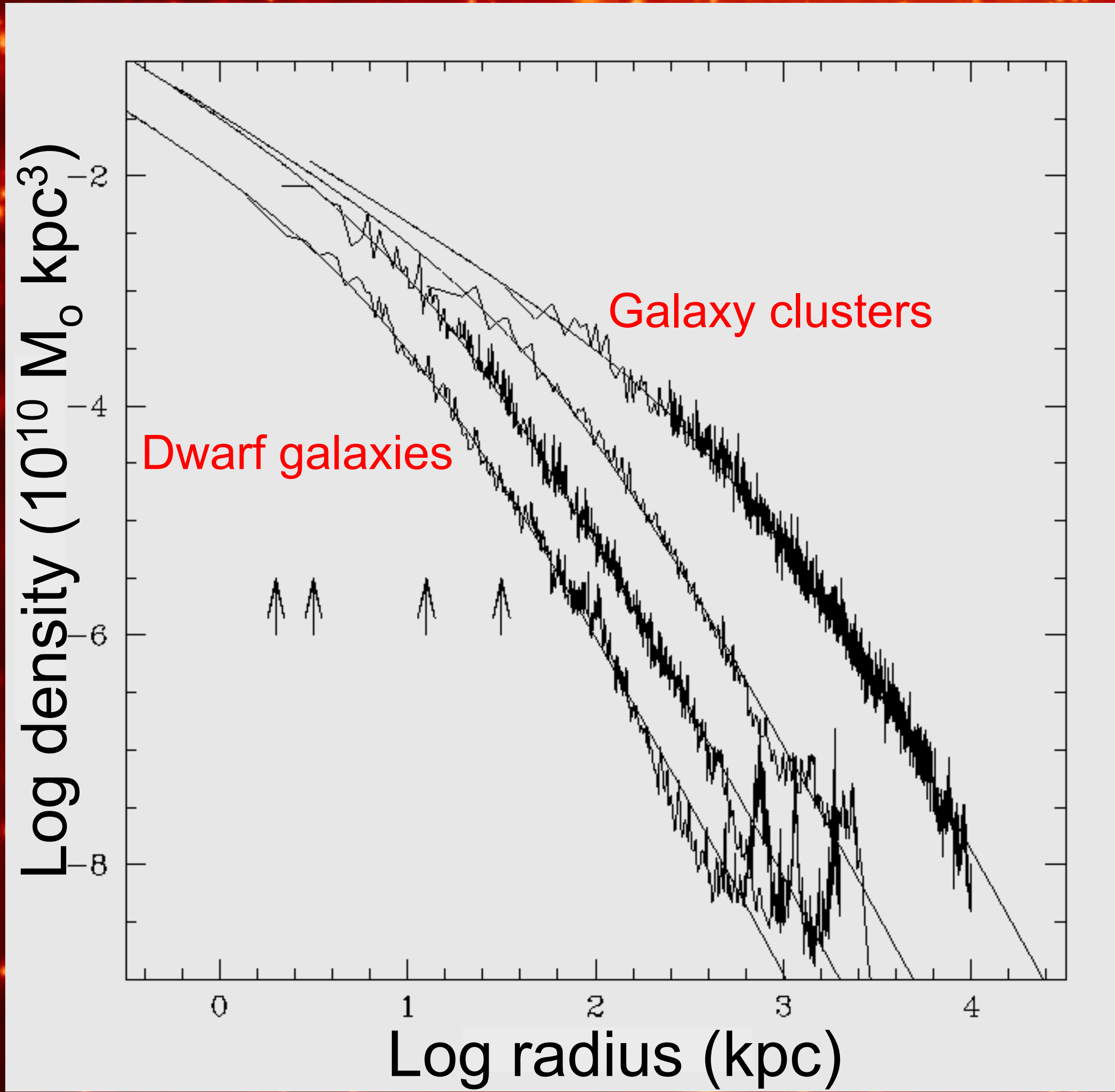
University of Durham

A cold dark matter universe

CDM N-body simulations make two important predictions on non-linear (halo) scales:

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

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

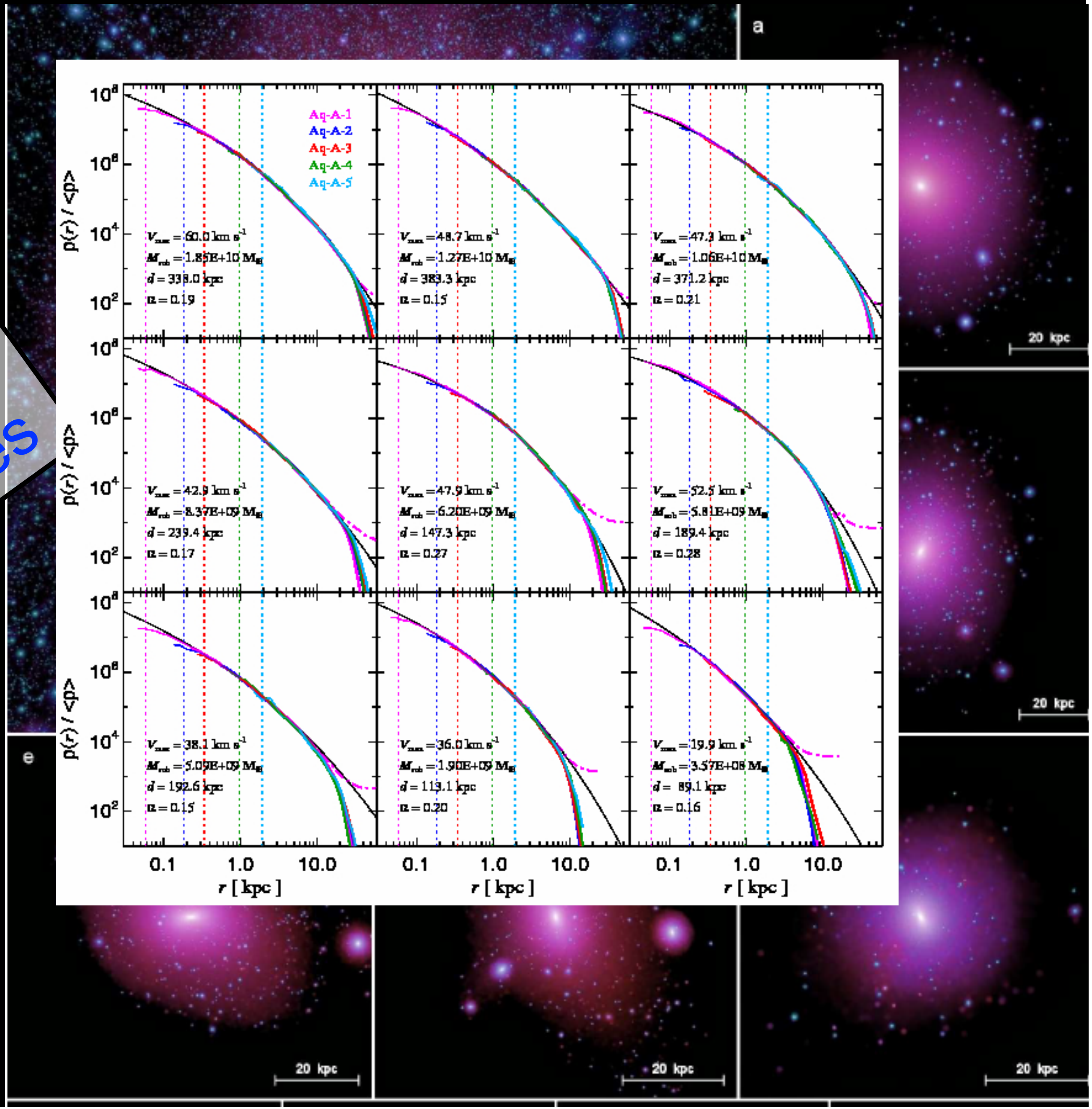
There is no obvious density plateau or `core' near the centre.

(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)

CDM subhalos also have cuspy profiles



Aquarius

Springel et al ‘08

cold dark matter — warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy ‘12

A warm dark matter universe

For viable WDM particle masses, there is little difference between CDM and WDM on scales larger than galaxies.

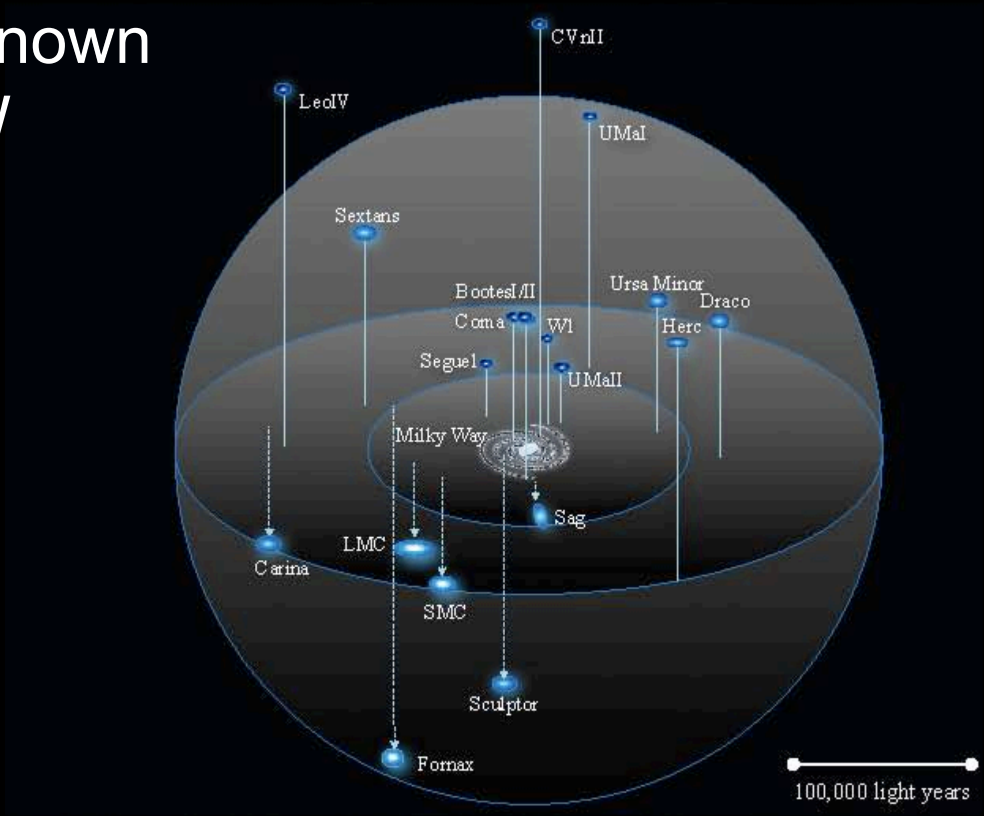
On subgalactic scales:

- Subhalos still “cuspy” but less concentrated than in CDM
- Far fewer self-bound substructures (3% of mass) survive

➔Can test for identity of the dark matter!

The satellites of the Milky Way

~25 satellites known
in the MW



J. Bullock

Dwarf galaxies around the Milky Way


Sextans

Carina


Sagittarius

University of Durham

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

University of Durham

Dwarf sphs: cores or cusps?

Jeans eqn:

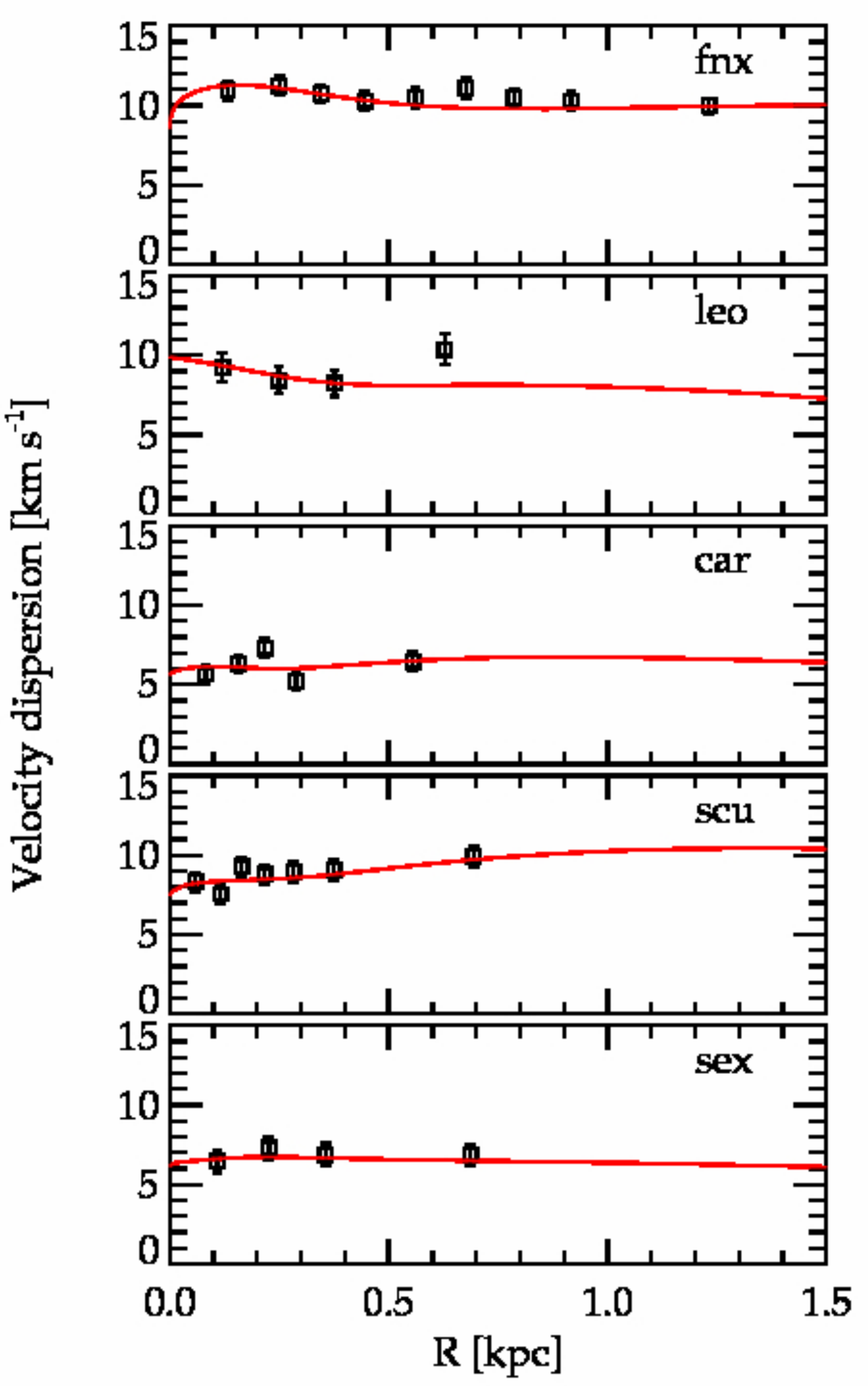
$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

vel. anisotropy

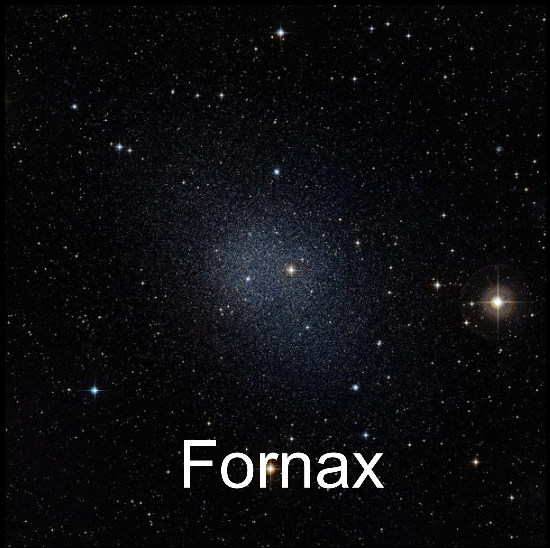
- Assume isotropic orbits
- Solve for σ_r (r)
- Compare with observed σ_r (r)
- Find "best fit" subhalo

Strigari, Frenk & White 2010



Dwarf galaxies around the Milky Way

Cuspy NFW profiles consistent with MW satellite kinematic data


Fornax


Sculptor

Leo I


Sextans


Carina


Sagittarius

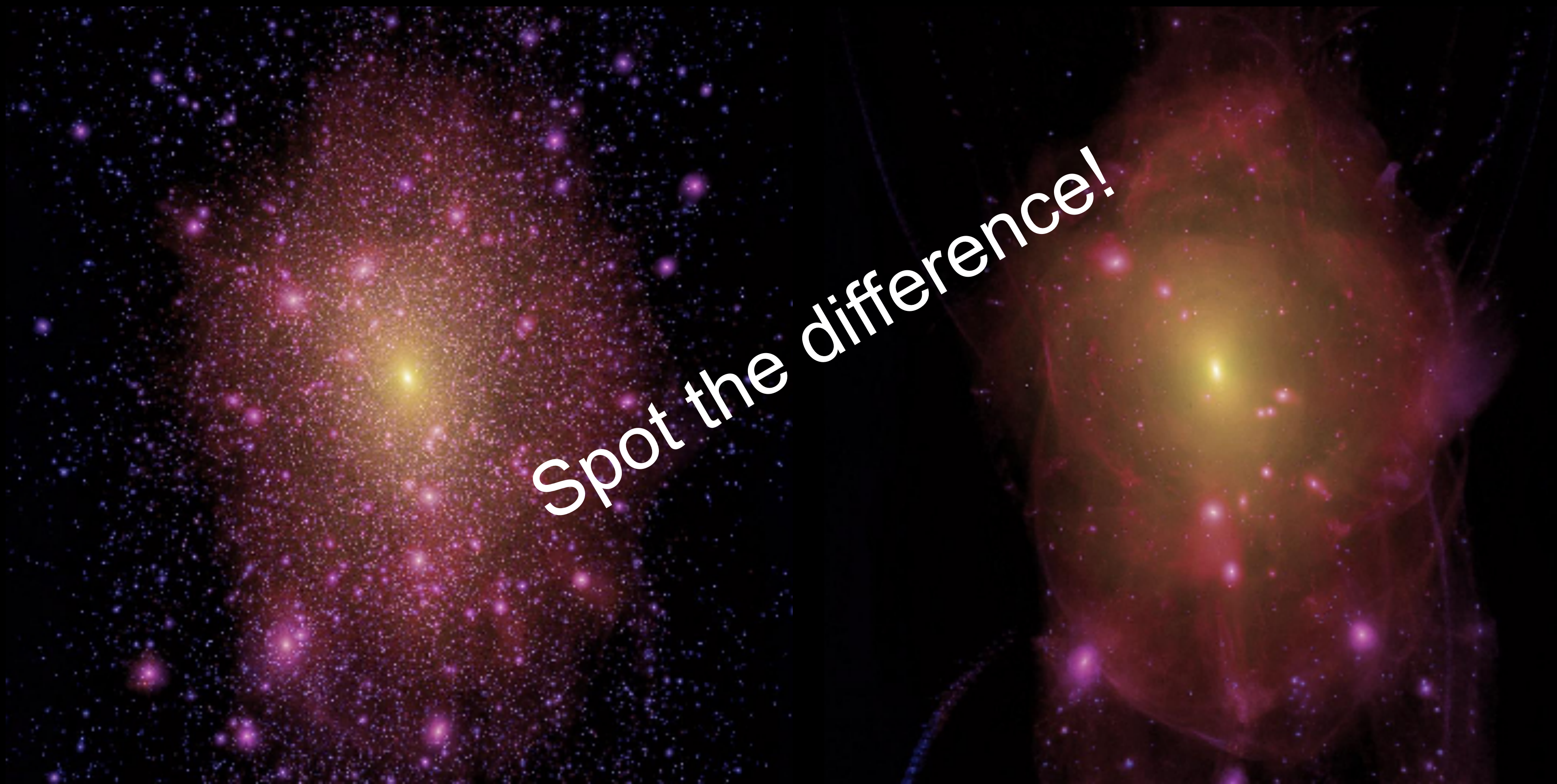
Halo structure of dwarf satellites seems OK in both ΛCDM and WDM

How can we distinguish between CDM & WDM ?

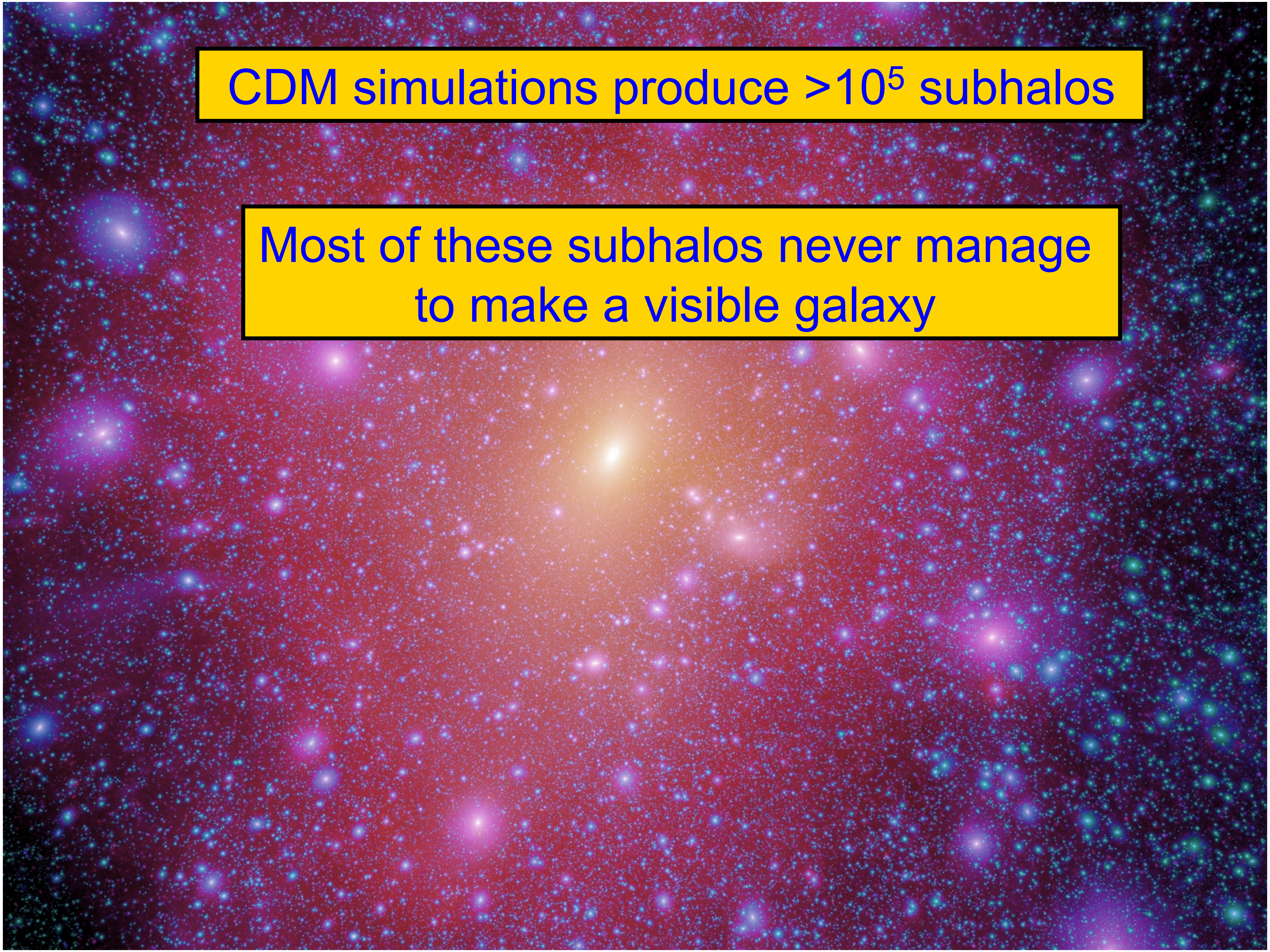
ICC

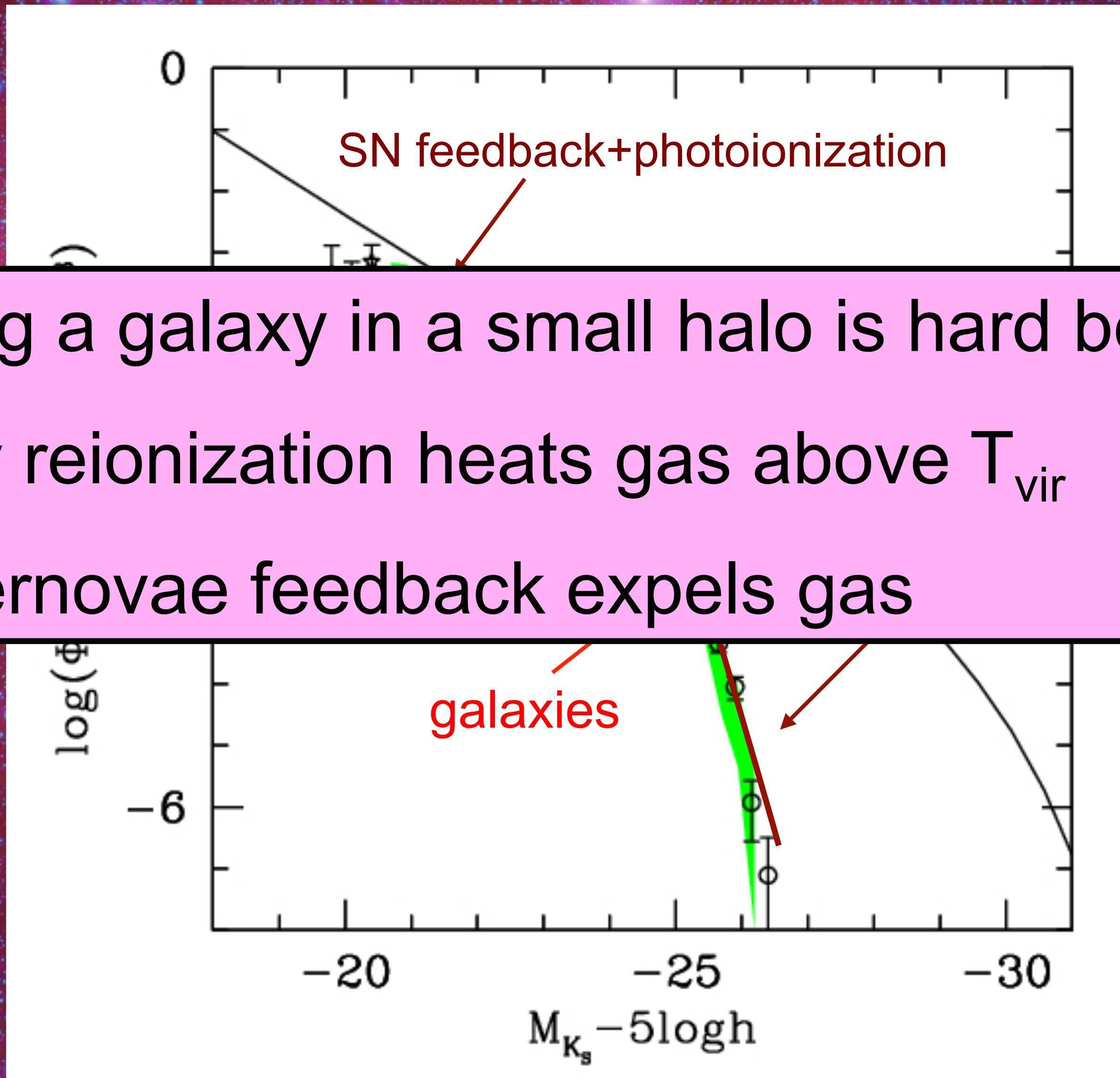
cold dark matter

warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12


CDM simulations produce >10^5 subhalos
Most of these subhalos never manage to make a visible galaxy



Making a galaxy in a small halo is hard because:

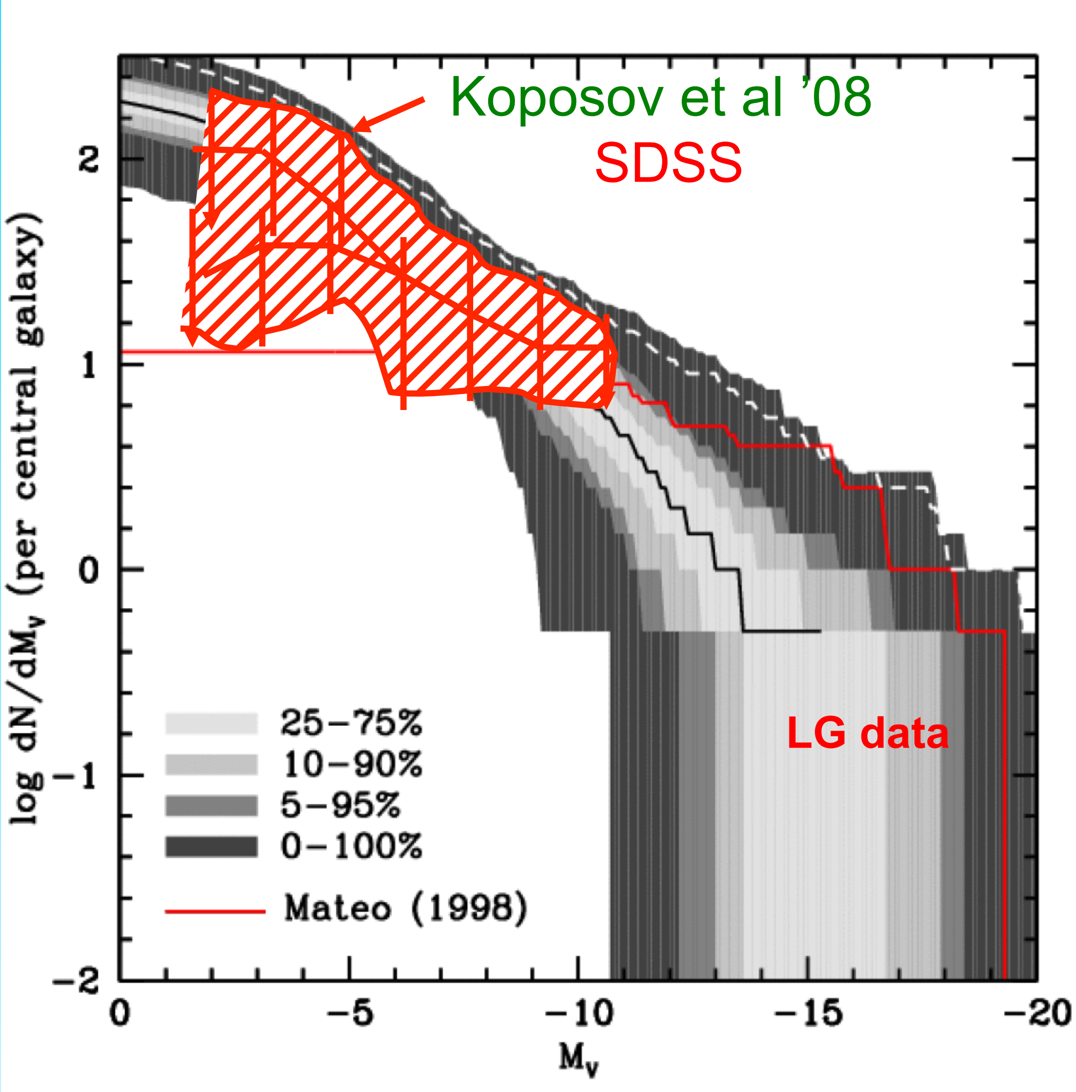
- Early reionization heats gas above T_{vir}
- Supernovae feedback expels gas

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

University of Durham
Institute for Computational Cosmology

cold dark matter

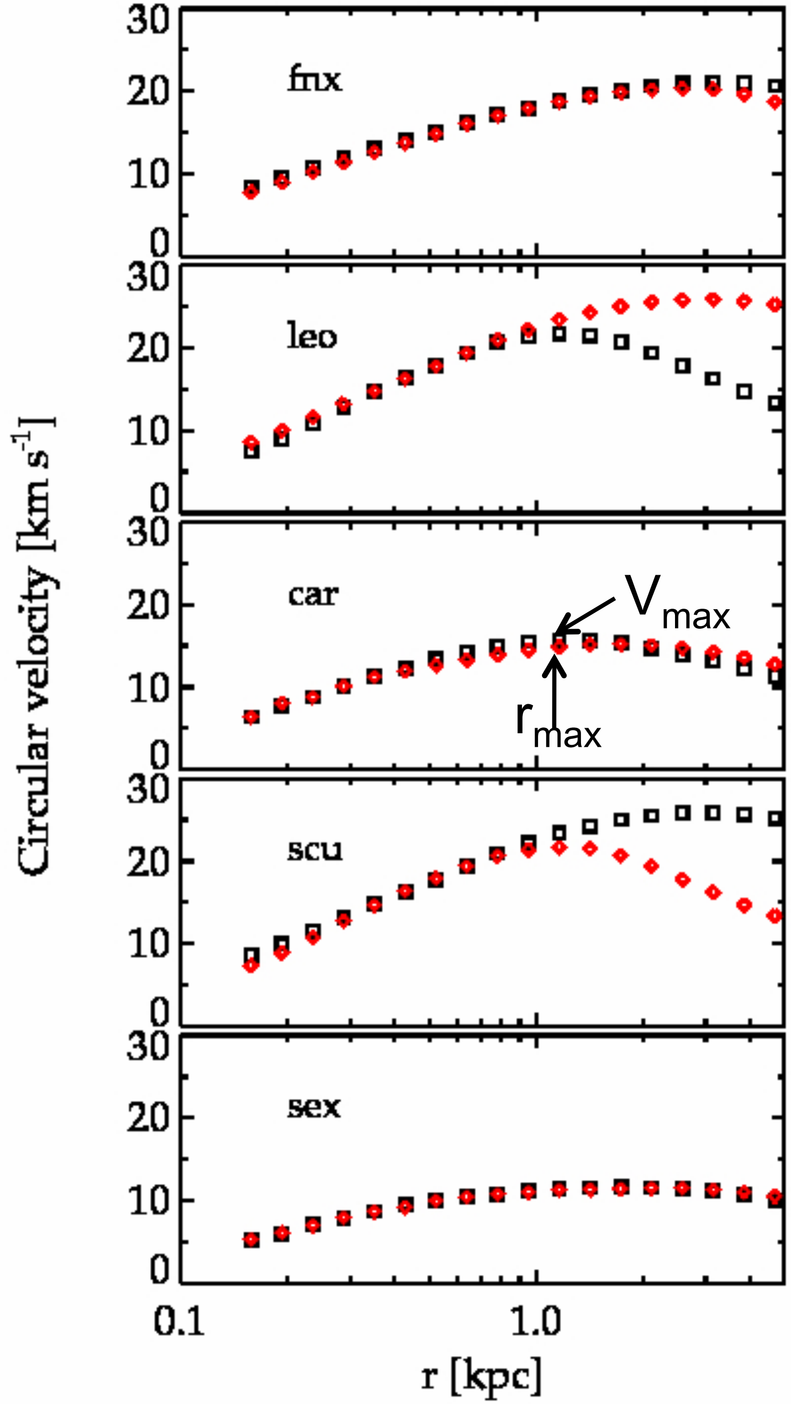
warm dark matter

Counting satellites cannot distinguish CDM from WDM!

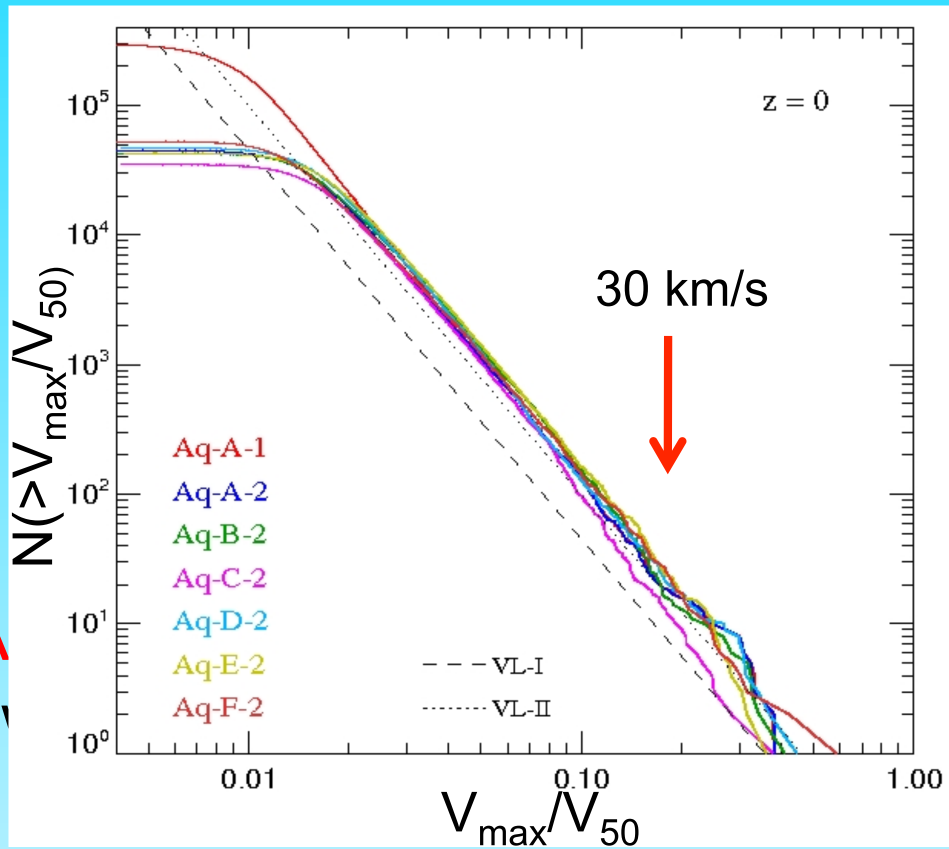
Need to look in more detail at the structure of small halos

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

Top 2 best fit CDM models to data



The Aquarius subhalos and the satellites of the Milky Way



Strigari, Frenk & White 2010

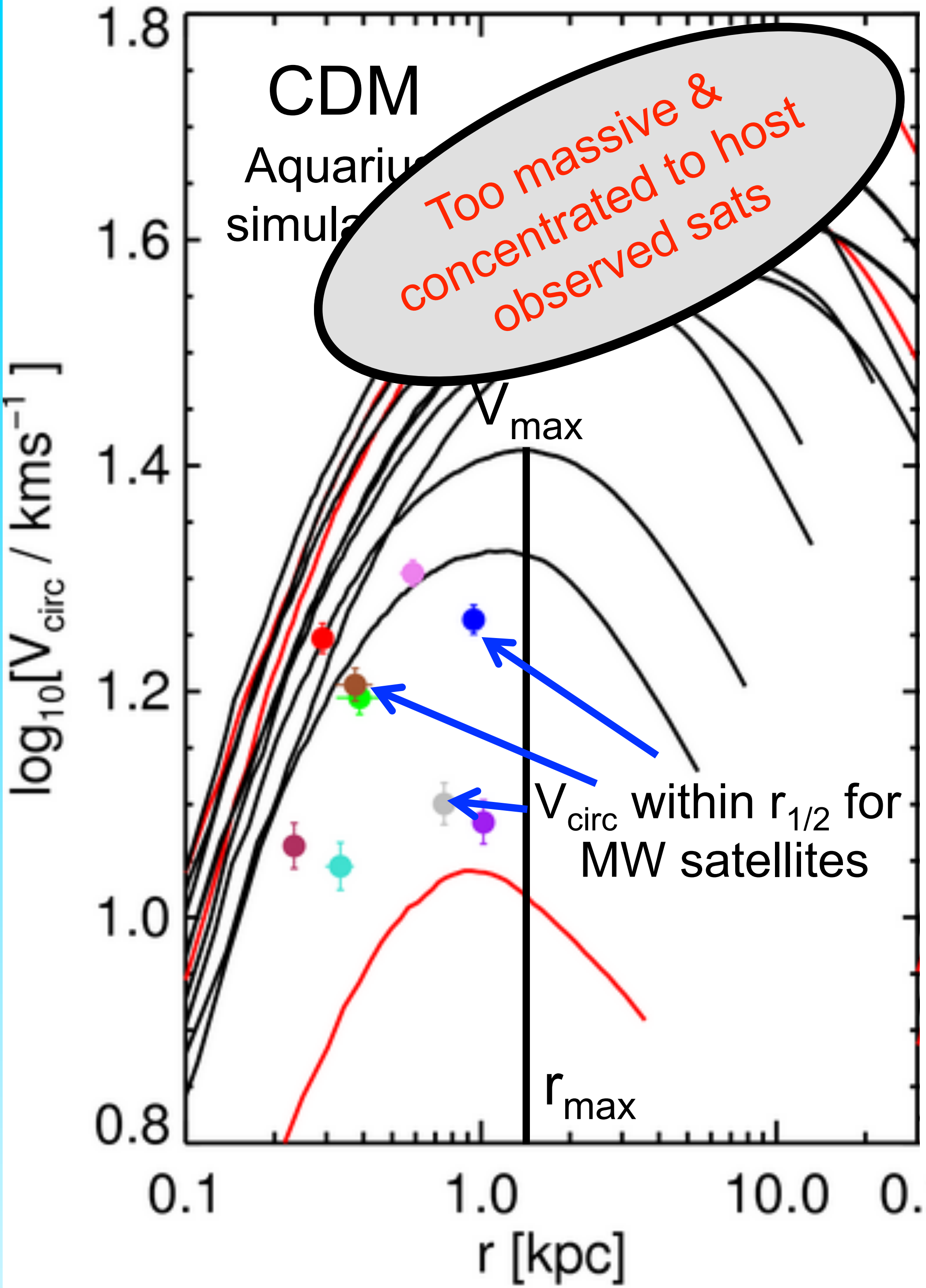
Is CDM compatible w. luminosity & structure of observed satellites?

$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$

Rotation curves of 12 subhalos with most massive progenitors

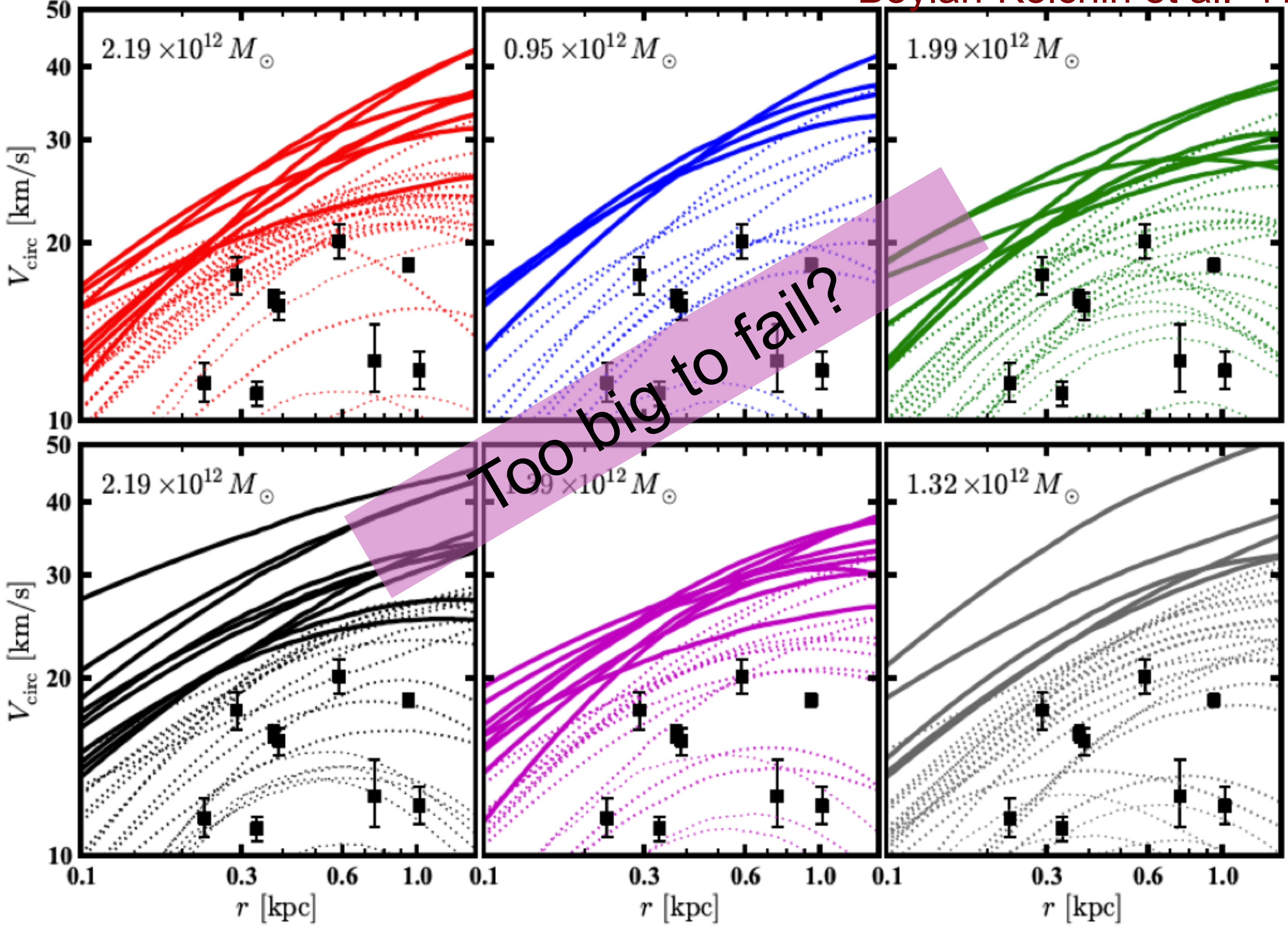
Red → 3 halos with most massive progenitors (LMC, SMC, Sagittarius?)

Lovell, Eke, Frenk, Gao et al '11; see also Boylan-Kolchin et al '11a,b

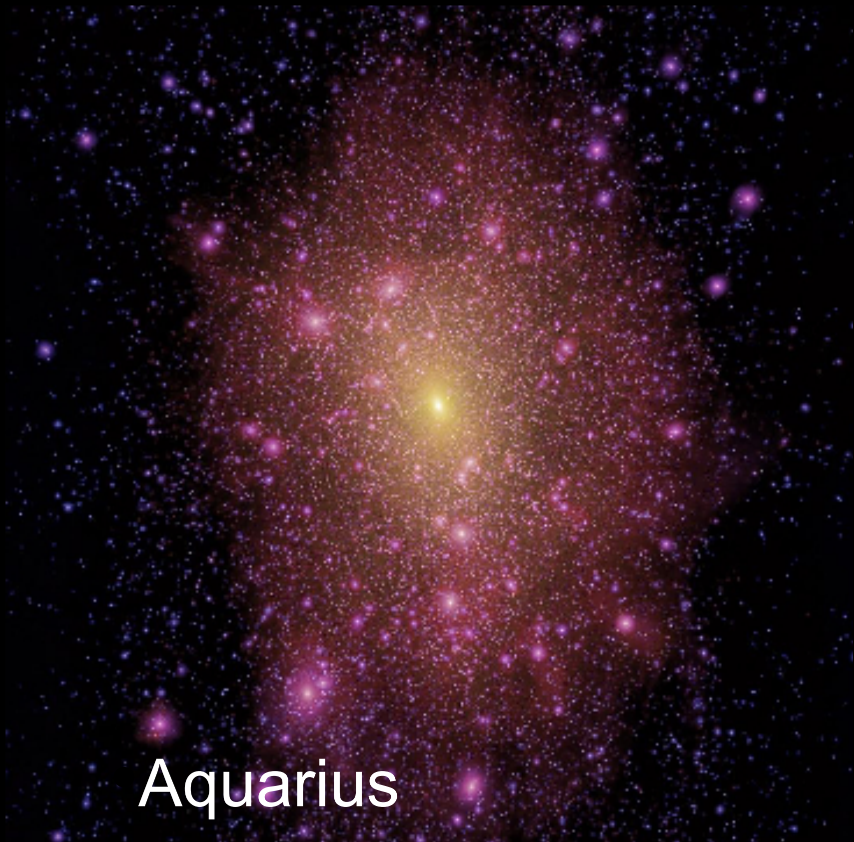


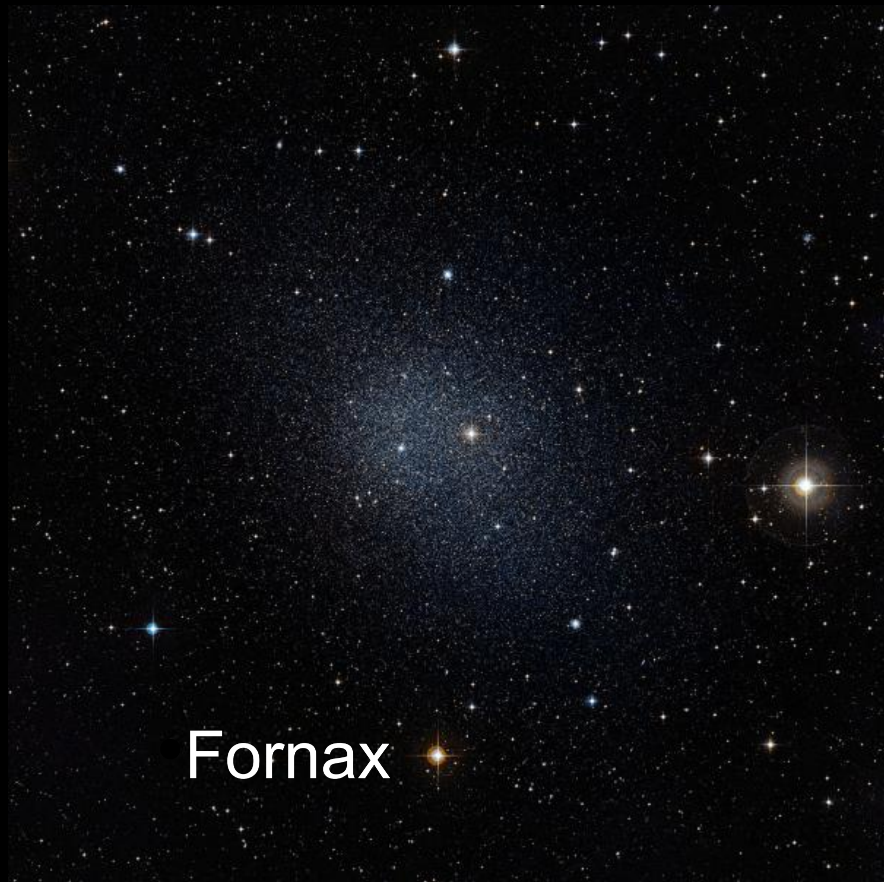
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11



The Aquarius halos have ~10 subhalos with too large a V_{max} (i.e. much too concentrated) to be compatible with observed kinematics of MW dwarfs



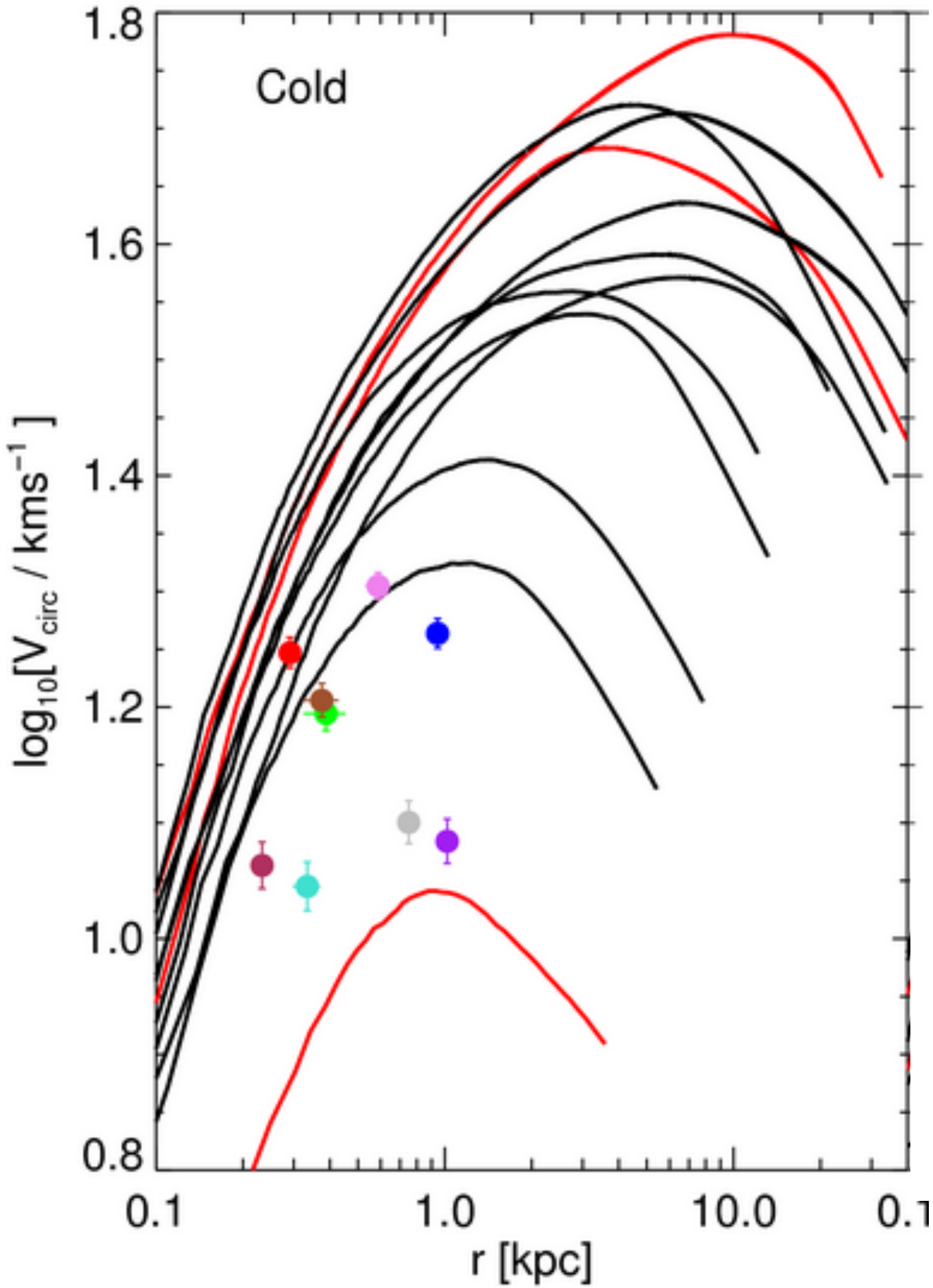


cold dark matter

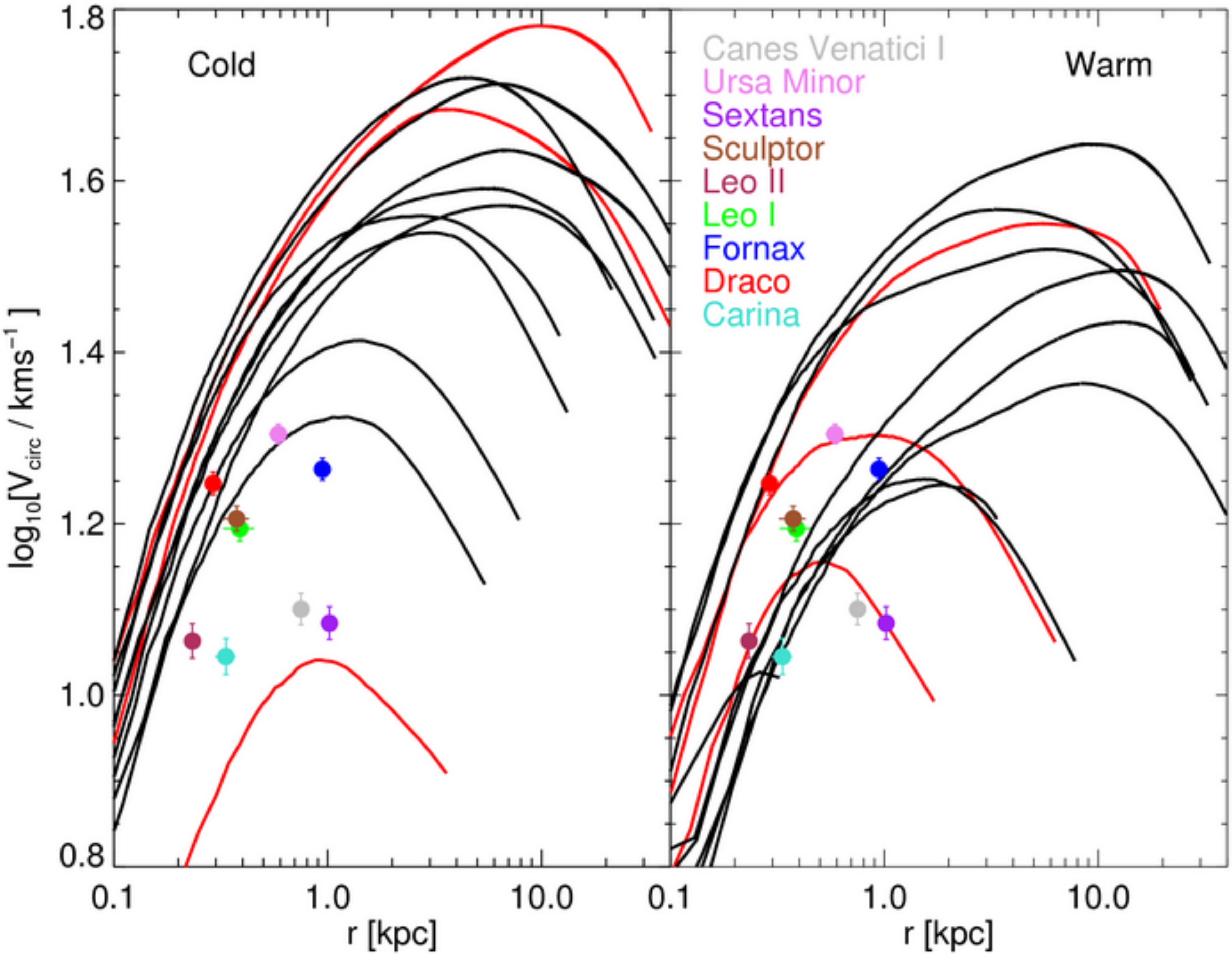
warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '11

Institute for Computational Cosmology



Lovell, Eke, Frenk, Gao,
Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '11



Cold
Warm
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
$\log_{10}[V_{circ} / kms^{-1}]$
r [kpc]
r [kpc]
1.8
1.6
1.4
1.2
1.0
0.8
0.1
1.0
10.0
0.1
1.0
10.0

Warm vs cold dark matter subhalos

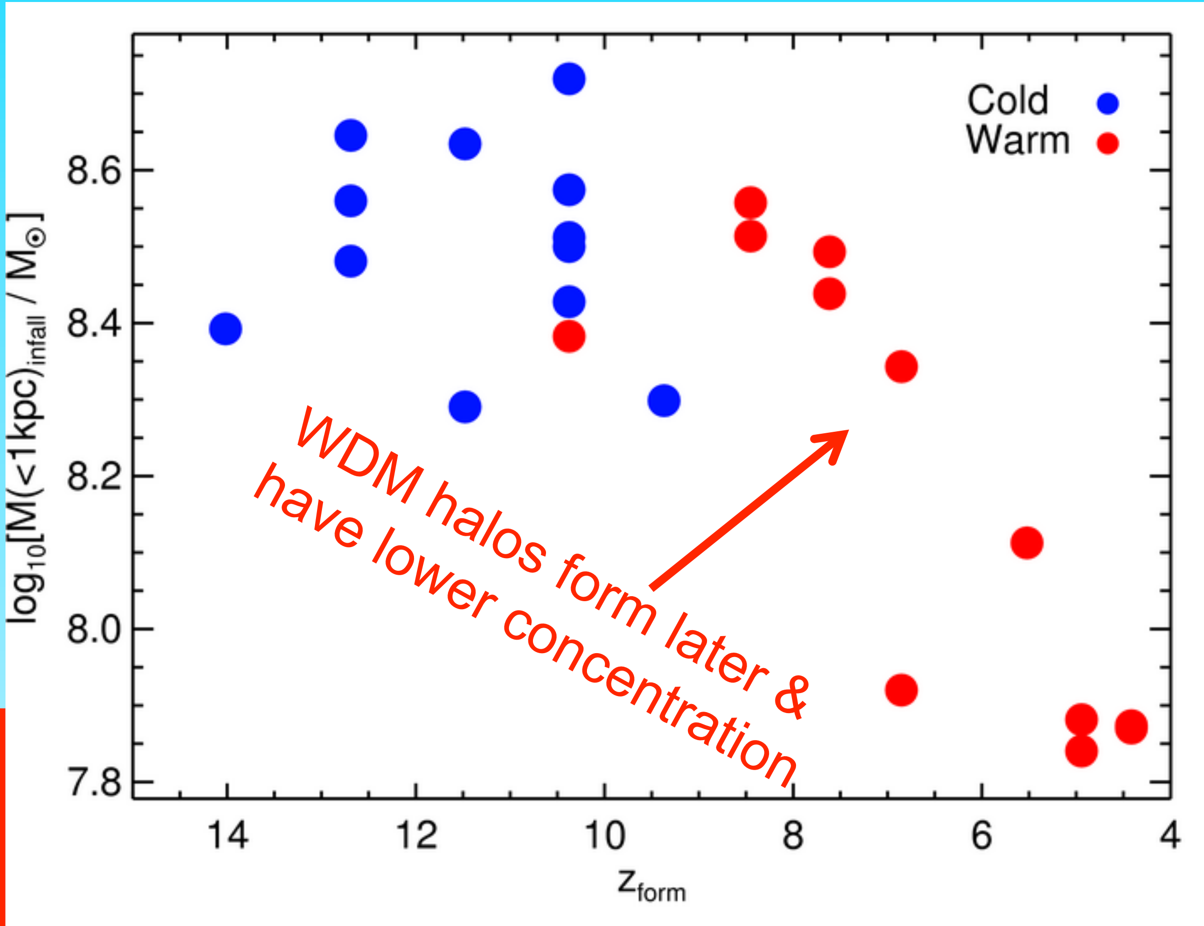
University of Durham

"Formation redshift" → z at which M_{halo} first exceeded $M_{infall}(<1kpc)$

WDM halos form later & have lower central masses than their CDM counterparts!

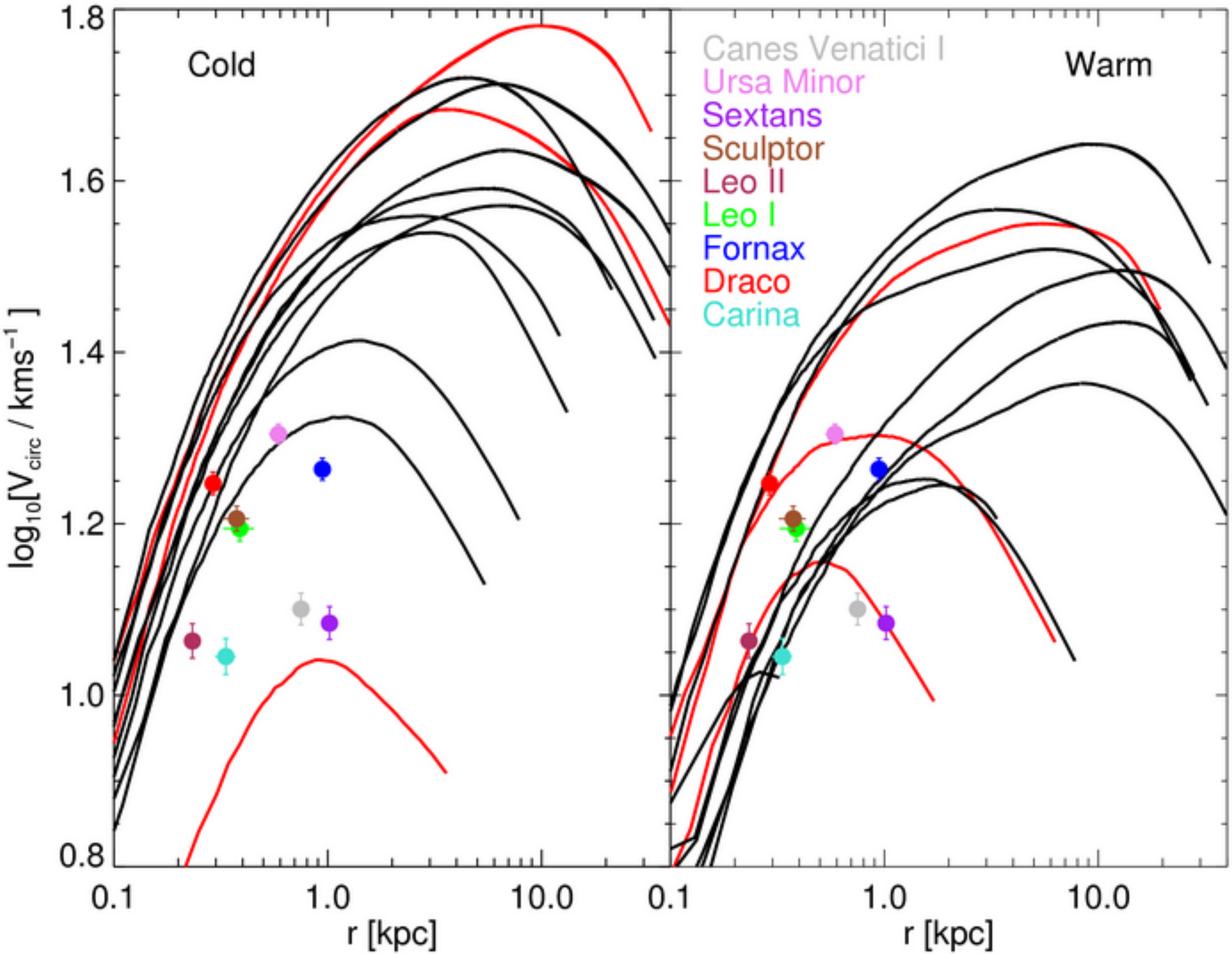
→

WDM subhalos are still cuspy but are less concentrated than CDM subhalos



Lovell, Eke, Frenk, Gao, Jenkins et al '11

Institute for Computational Cosmology



Cold
Warm
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
$\log_{10}[V_{circ} / kms^{-1}]$
r [kpc]
1.8
1.6
1.4
1.2
1.0
0.8
0.1
1.0
10.0

Is this the end of CDM?

1. Baryon effects
2. The mass of the MW

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

The cores of dwarf galaxy haloes

Julio F. Navarro,[1,2★] Vincent R. Eke[2] and Carlos S. Frenk[2]

[1]*Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA*
[2]*Physics Department, University of Durham, South Road, Durham DH1 3LE*

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

University of Durham

Let baryons cool and condense to the galactic centre

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

Navarro, Eke, Frenk '96

Ponzen & Governato '12

The cores of dwarf galaxy haloes L75

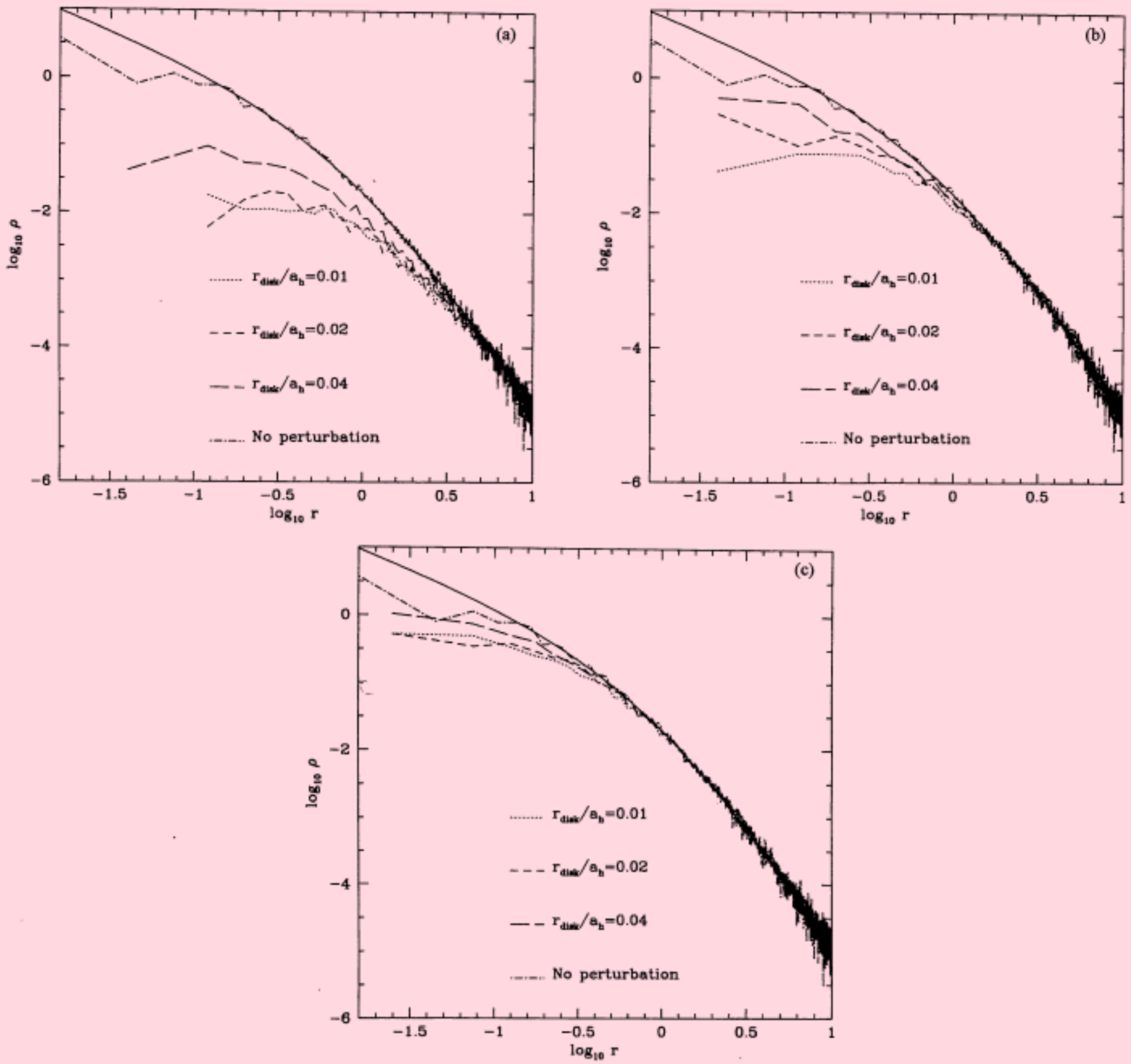
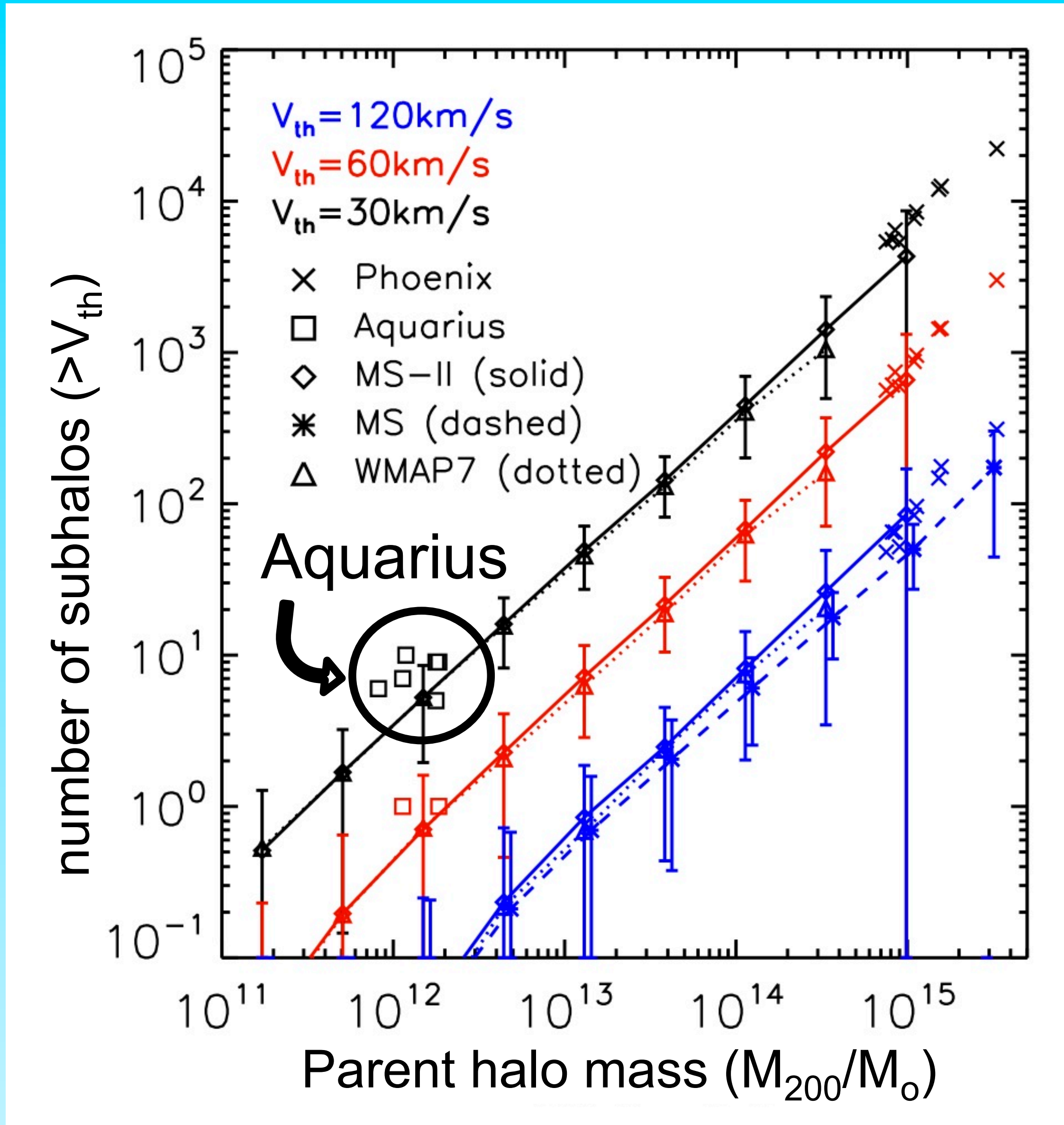


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

Number of massive subhalos

University of Durham

Number of massive subhalos increases rapidly with halo mass



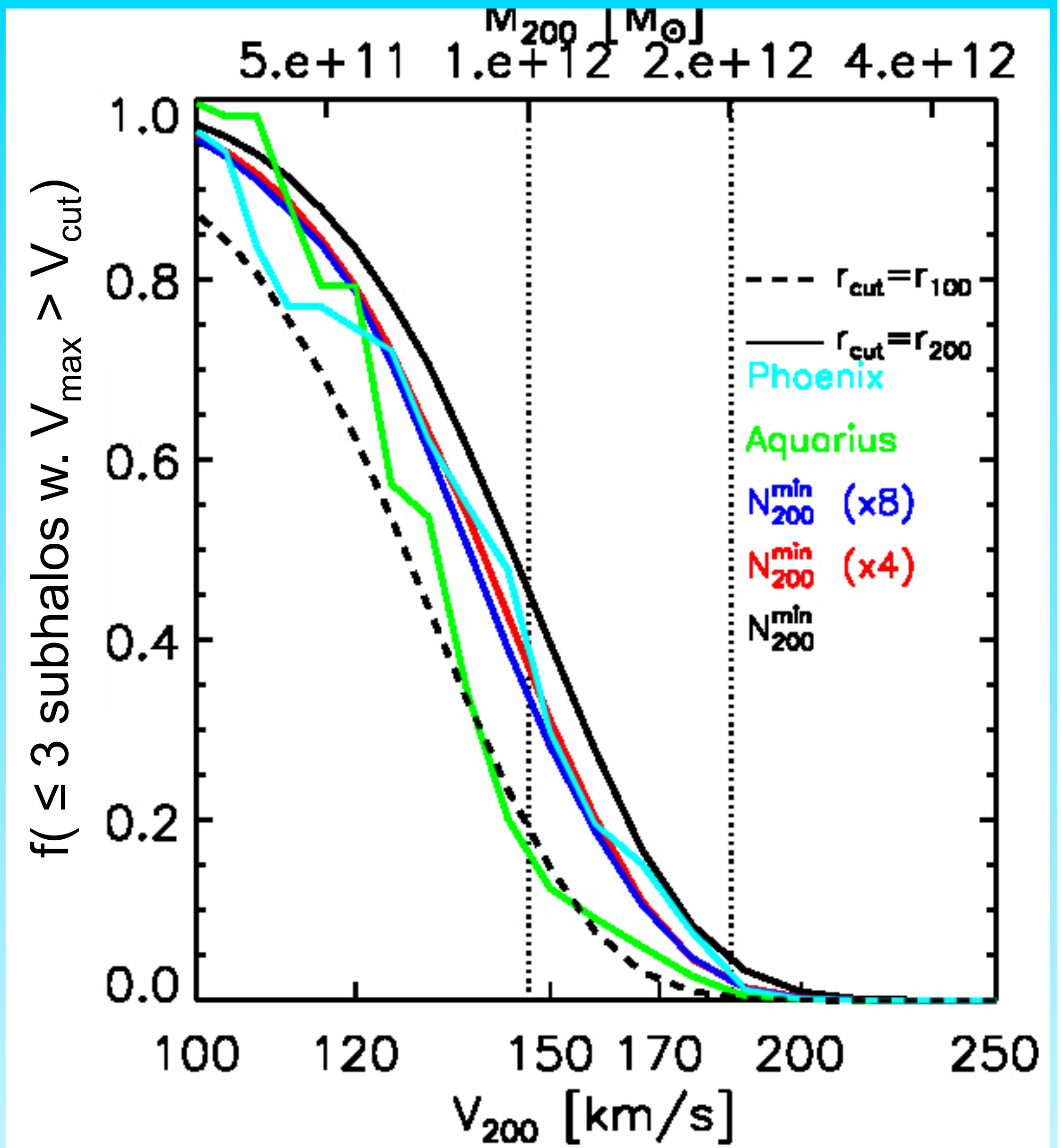
Aquarius halos have $M{\sim}2\times10^{12}\,M_o$

But: is this the mass of the MW halo?

Probability of massive subhalos

University of Durham

Probability of having no more than 3 subhalos with V_{max}> 30 km/s



Depends strongly on M_{200} (and V_{cut})

If mass of MW >2x10^{12}M$_o$, CDM is ruled out!

If mass of MW ~1x10^{12}M$_o$, CDM is OK

Wang, Frenk, Navarro, Gao '12

Institute for Computational Cosmology

University of Durham

ΛCDM: problems/possible solutions

- ΛCDM great success on scales > 1Mpc: CMB, LSS, gal evolution

A problem on subgalactic scales?

Two NO-problems:

1. The satellite LF → can be explained by galaxy formation
2. Central cores → data consistent with cusps

However:

- CDM models place brightest sats in most massive subhalos and these appear to be too concentrated to be compatible w. kinematics

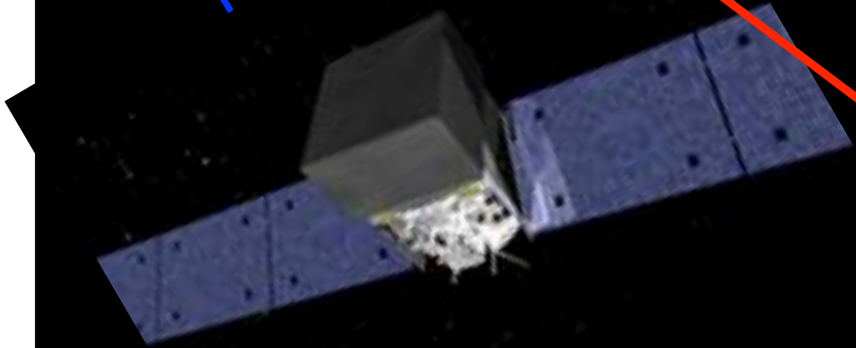
Possible solutions:

- Warm dark matter
- Baryon effects that make large CDM subhalos less concentrated
- Sat. pop. in the MW is very atypical or $M_{halo} \leq 10^{12} M_o$

Cold dark matter ?

If mass of MW halo $>2x10^{12}M_{\odot}$

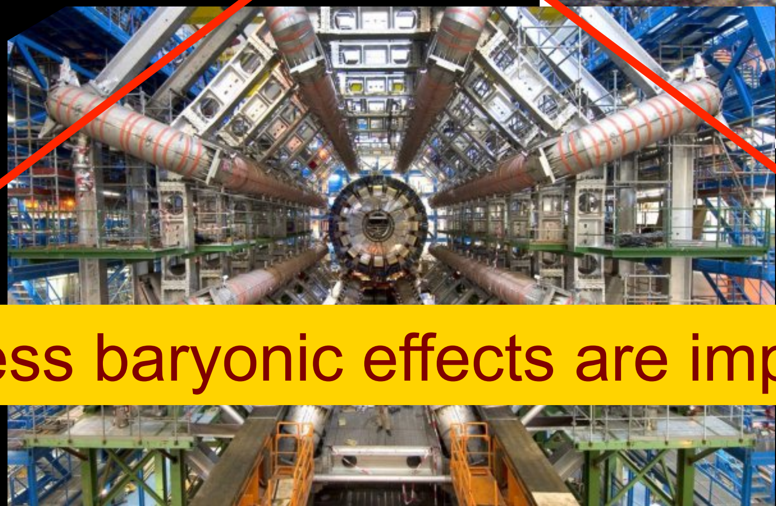
Fermi



Annihilation radiation

Direct detection

UK DM search
(Boulby mine)



Unless baryonic effects are important

Evidence for SUSY

Warm dark matter ?

Sterile neutrino detection possible

Decay line in X-rays

Constellation X

Tritium β - decay