Cosmology in our backyard

Carlos S. Frenk
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cold dark matter

ΛCDM: the standard model of cosmology

cosmological constant

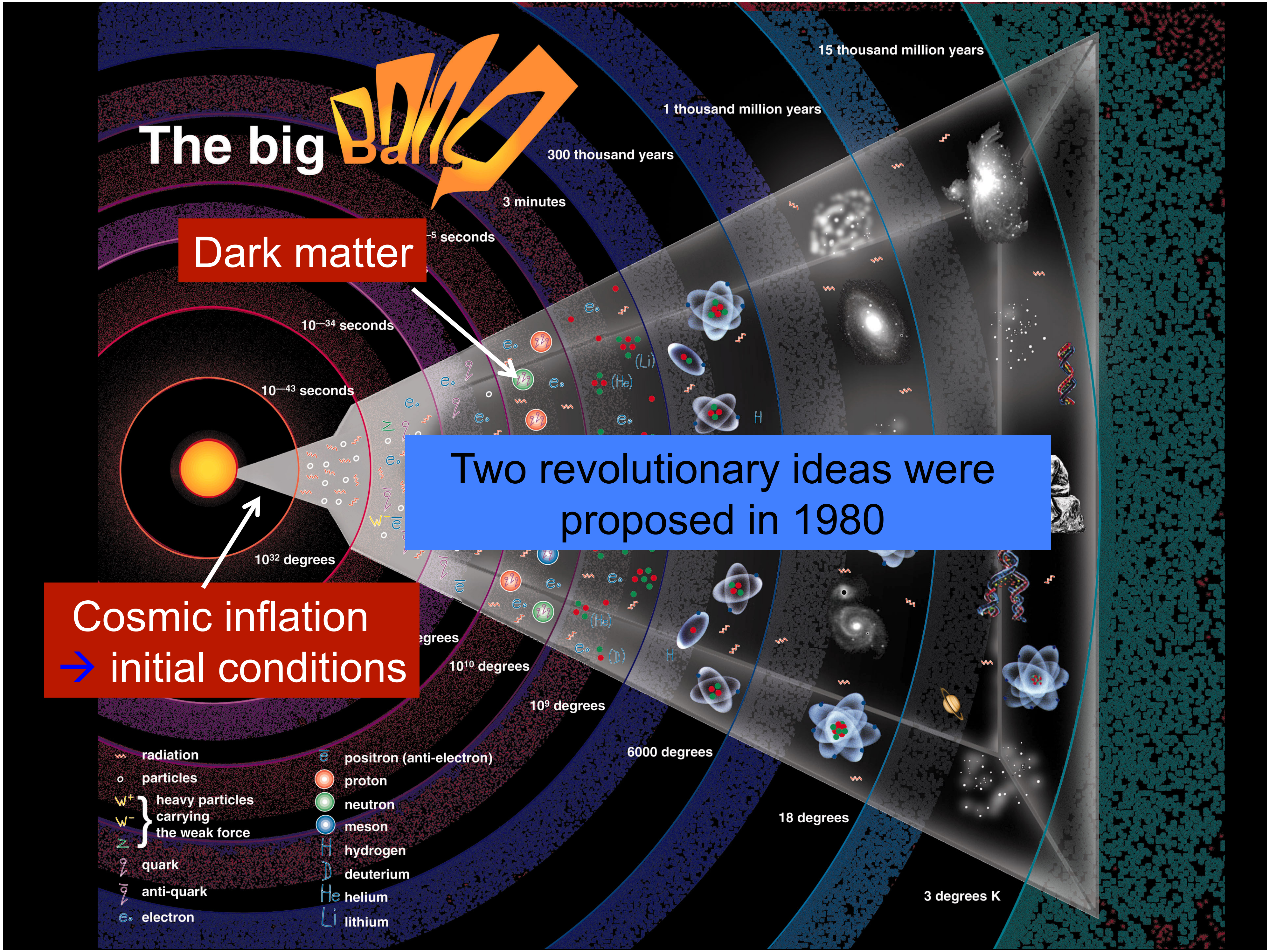
Why is this the standard model?

New tests and possible problems

Two revolutionary ideas were proposed in 1980

Dark matter

Cosmic inflation
→ initial conditions



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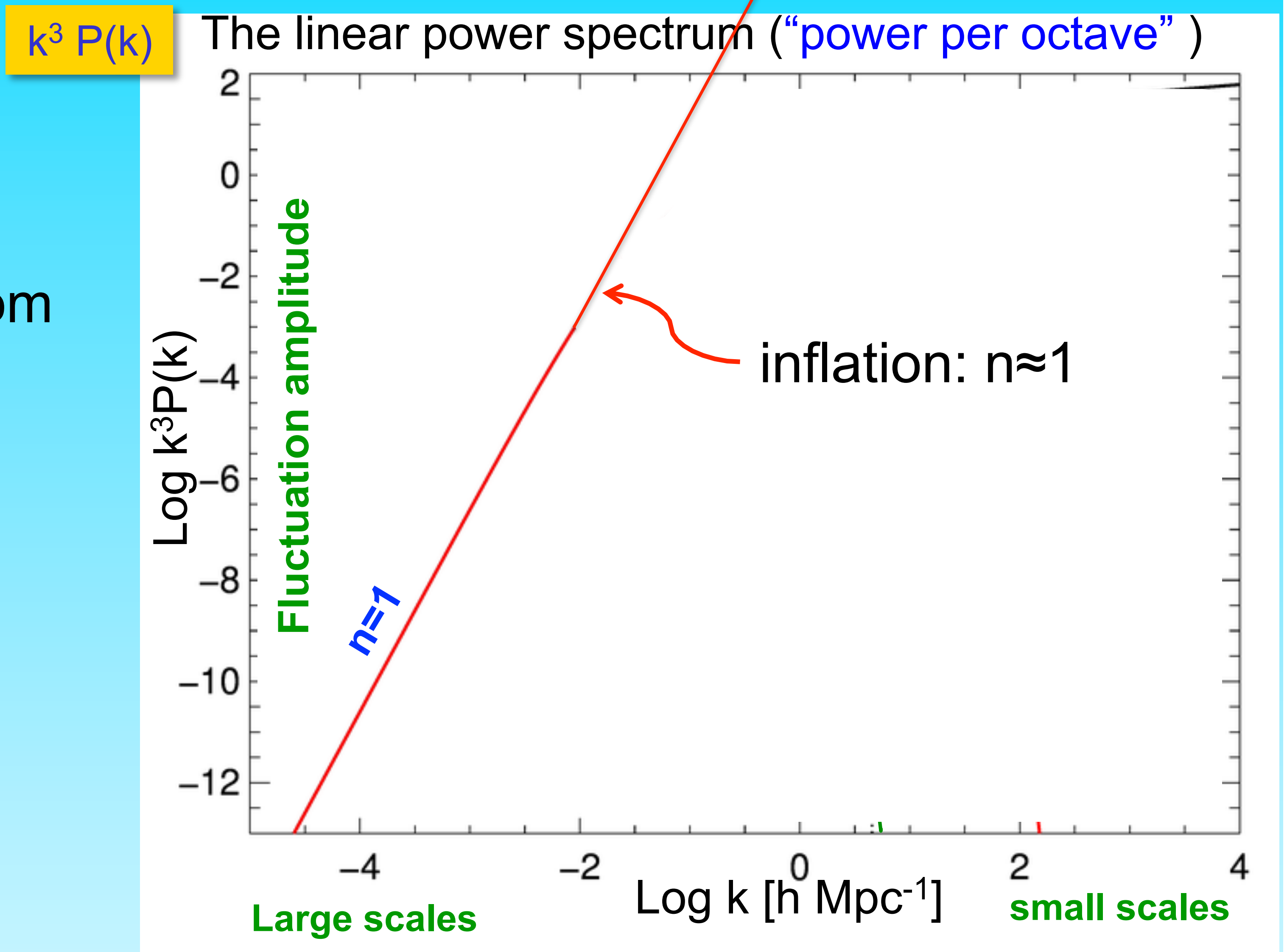
Non-baryonic dark matter candidates

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

Prediction from inflation



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The dark matter power spectrum

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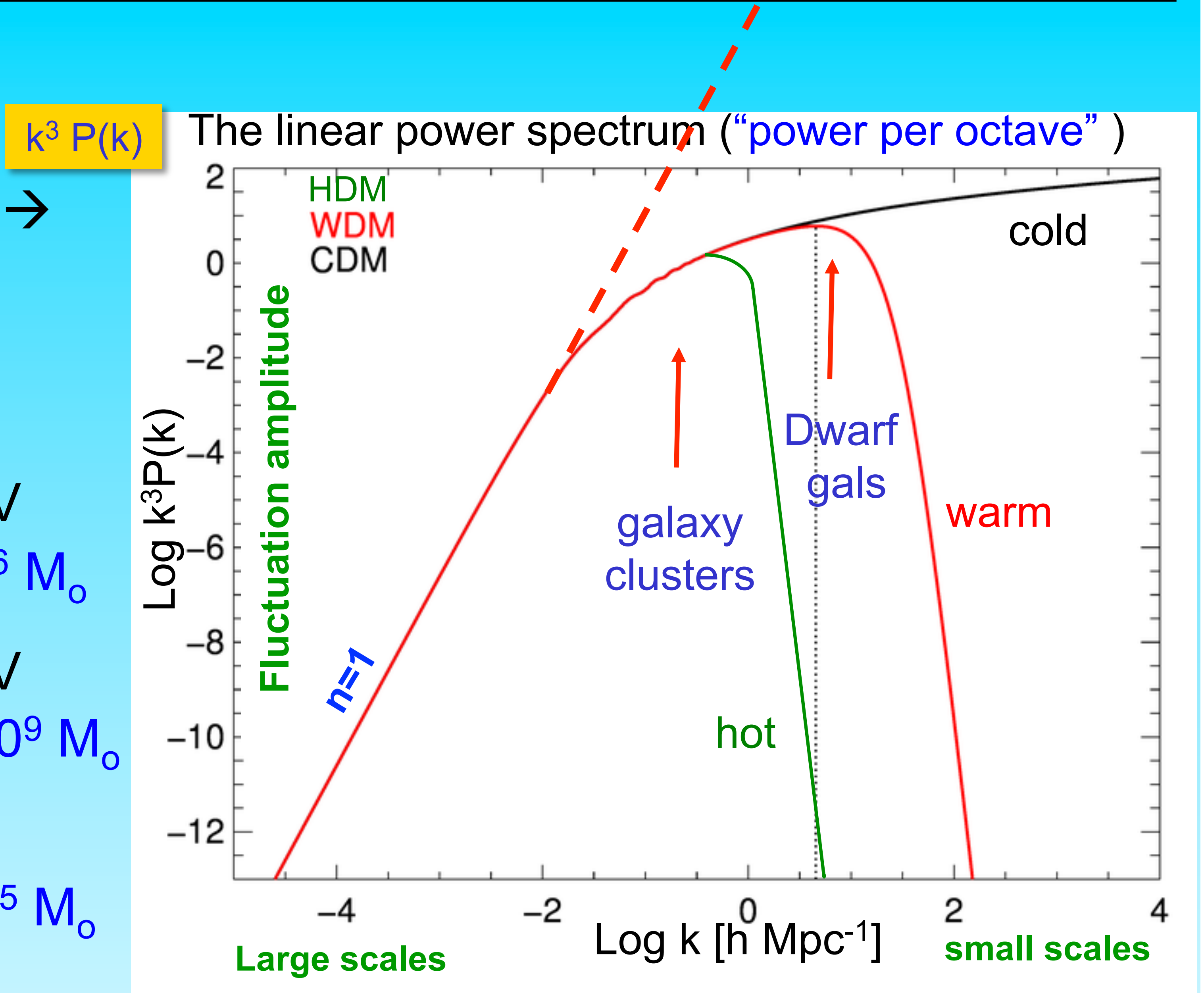
Free streaming →

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



The formation of cosmic structure

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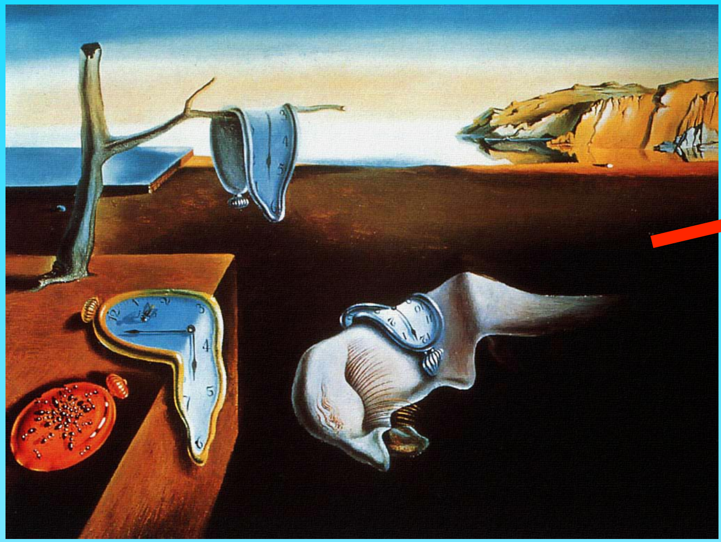
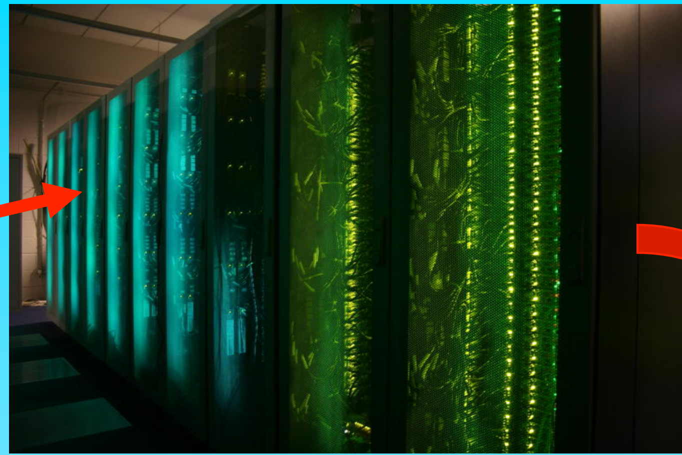
t=10^{-35} seconds



"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

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

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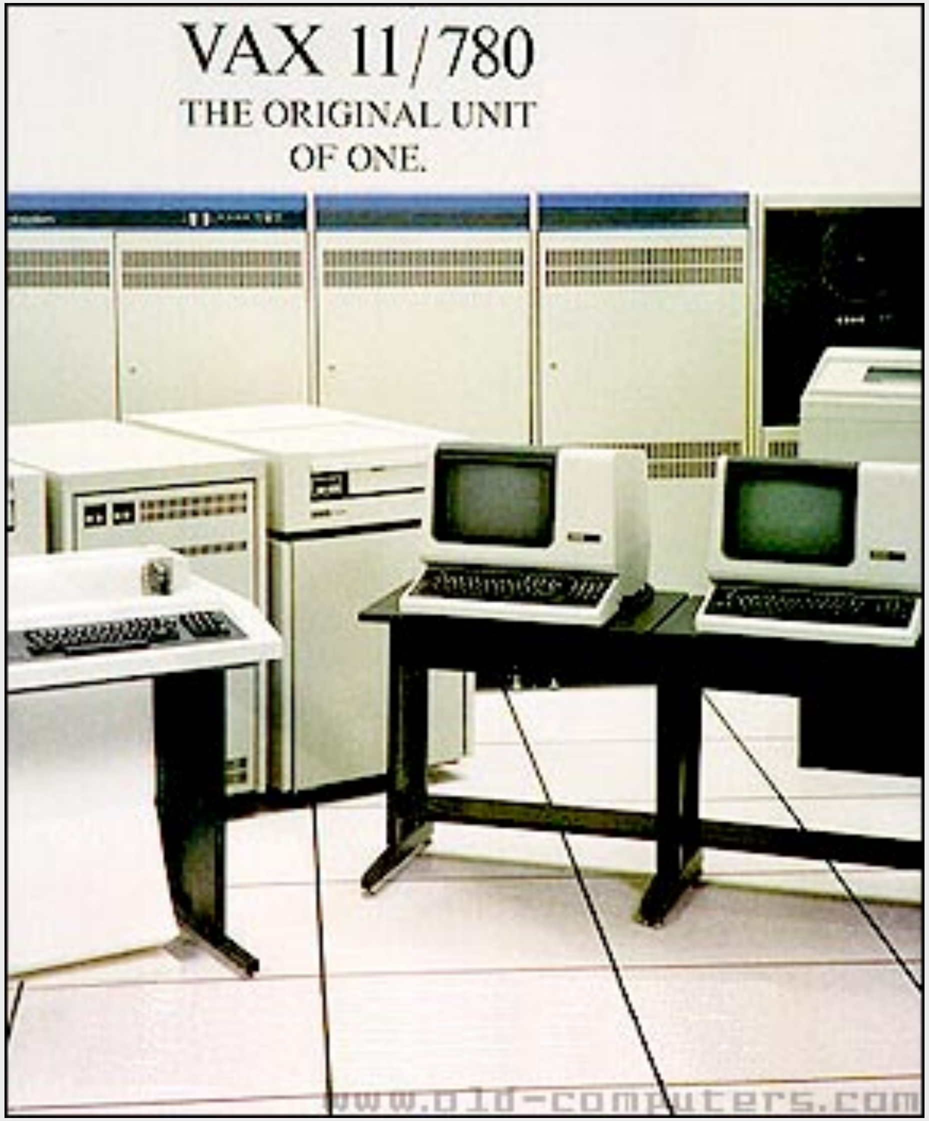
The universe in a computer



December 1981

Speed = 500,000 FLOPS
RAM = 4 Mbytes

Non-baryonic dark matter cosmologies

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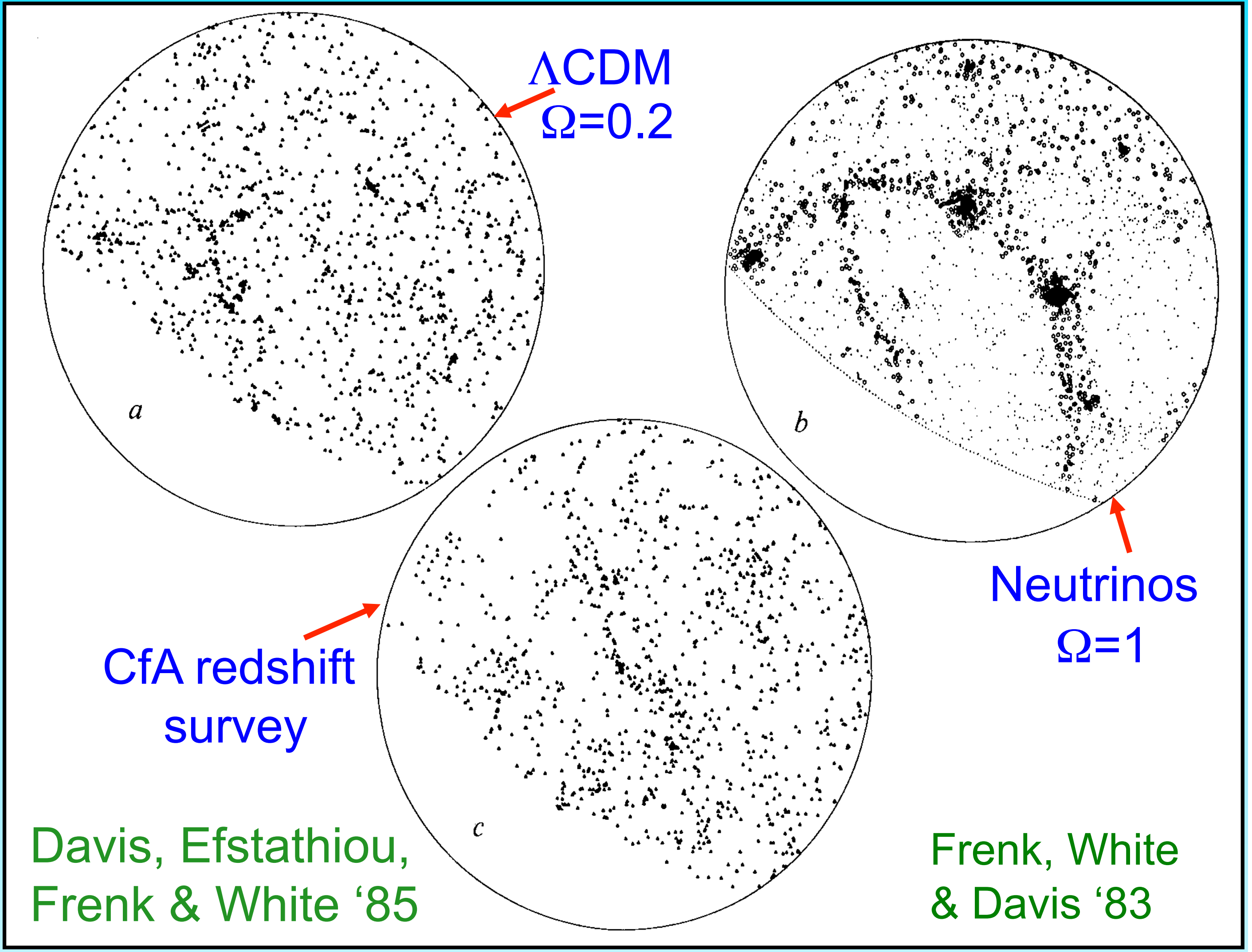
Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 10$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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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

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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

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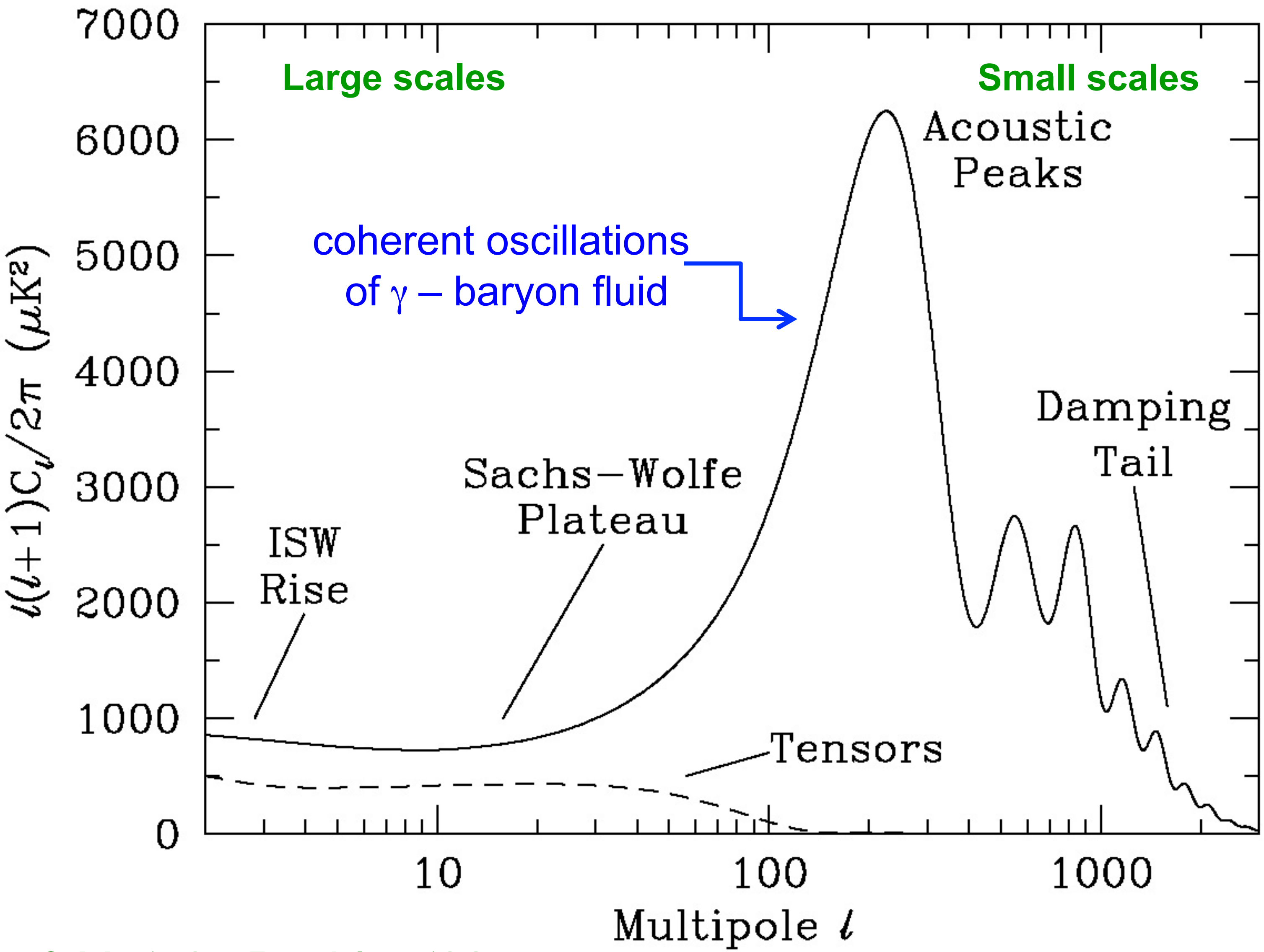
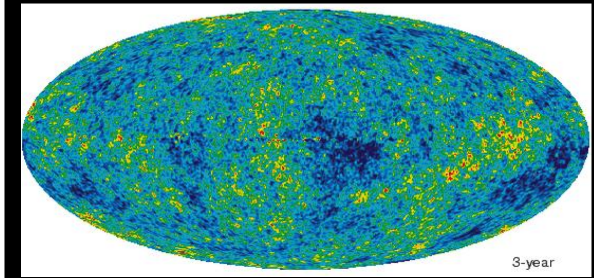
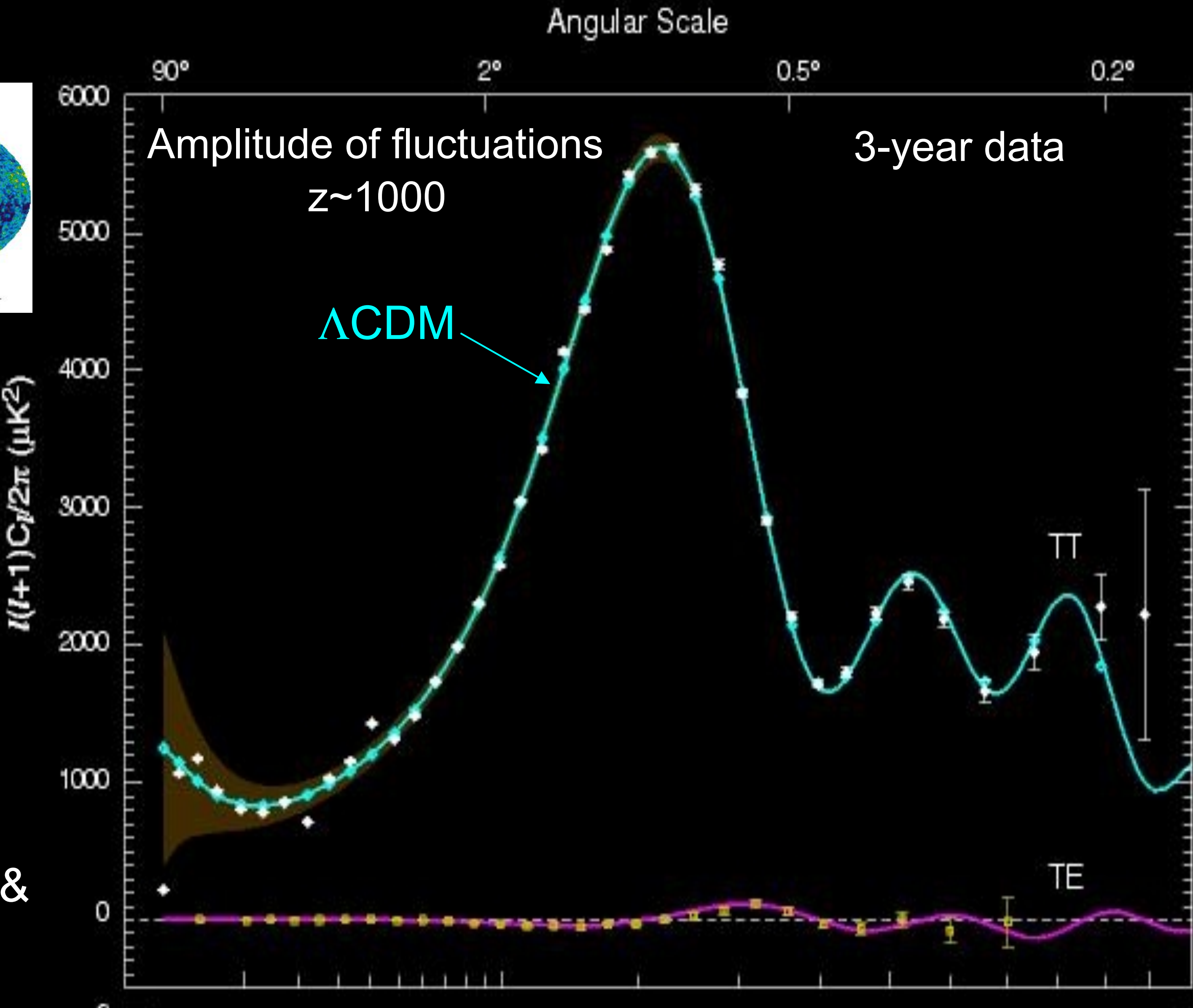


After Peebles & Yu ‘70; Peebles ‘82

WMAP temp anisotropies in CMB





The data confirm the theoretical predictions (linear theory)

Peebles '82; Bond & Efstathiou '80s

Hinshaw etal '06

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Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

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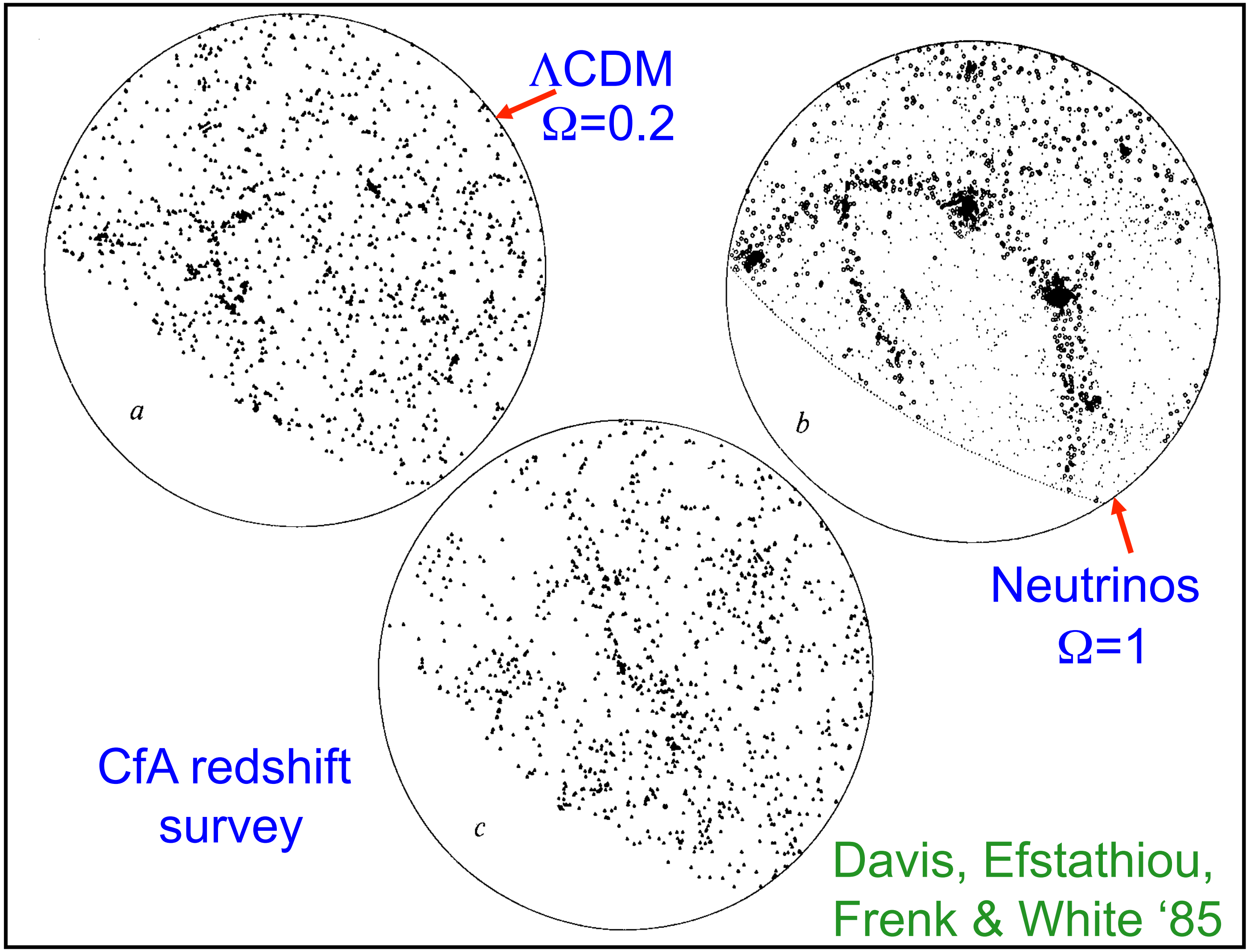

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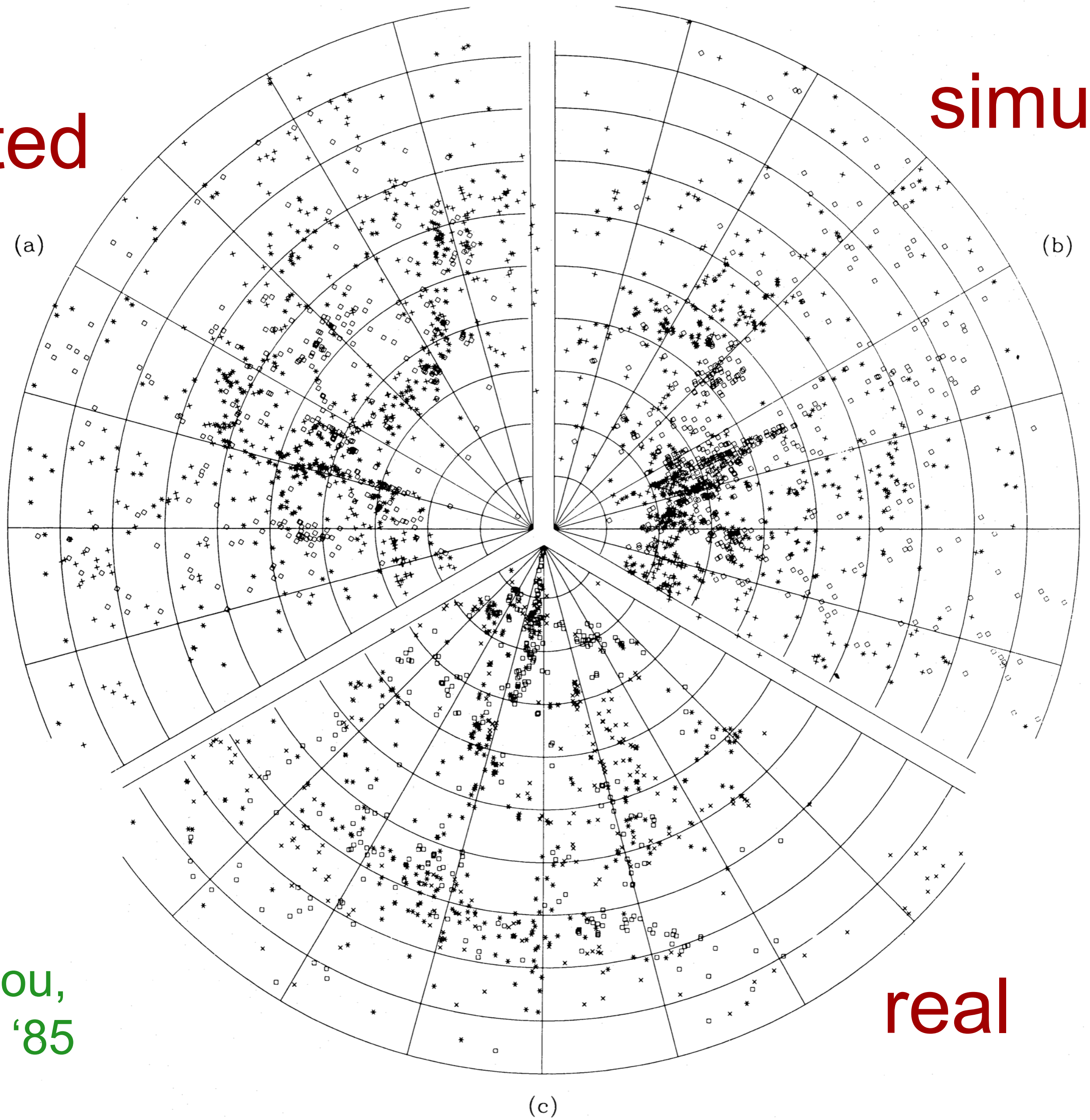
Early simulations of ΛCDM

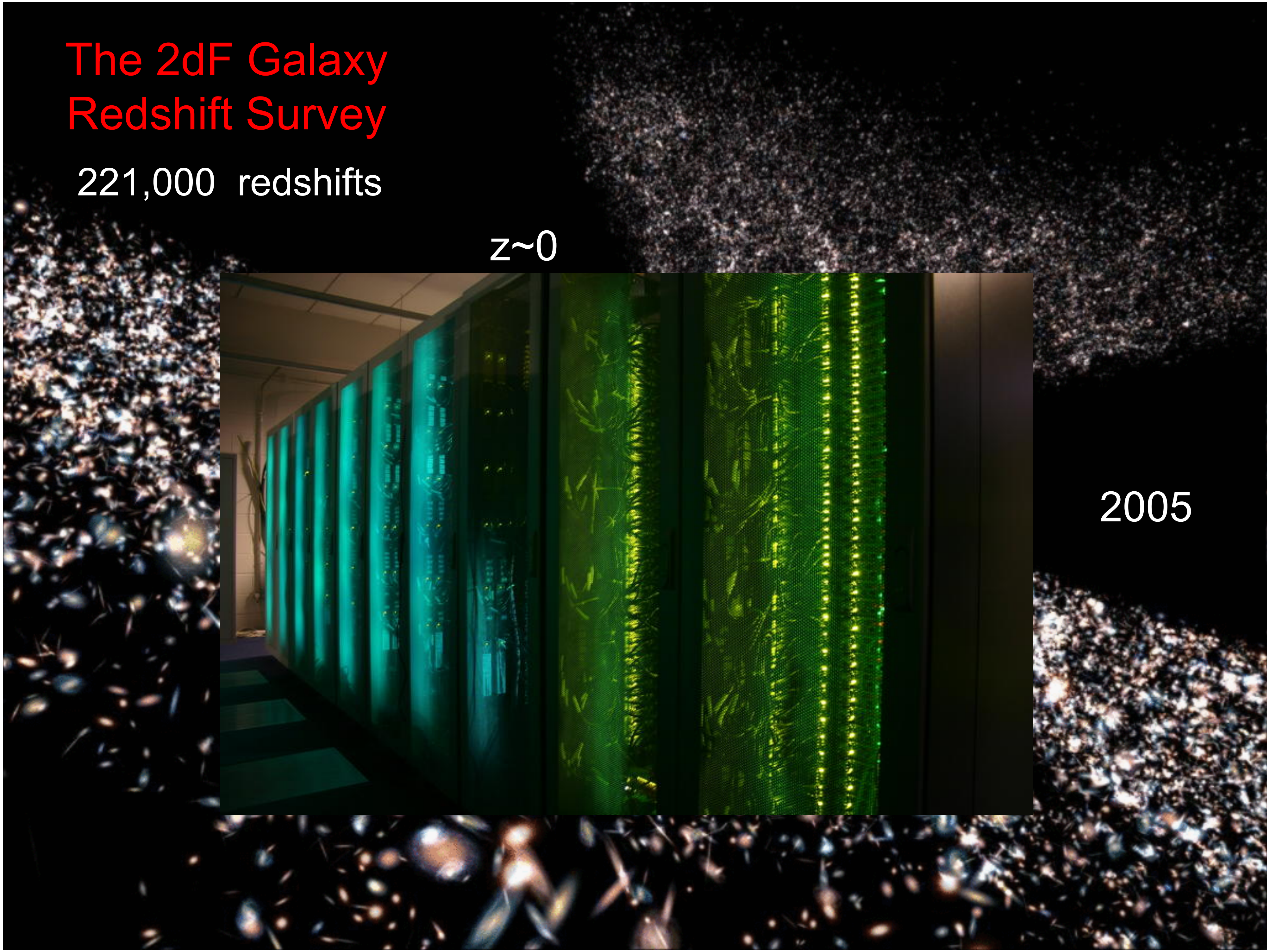
simulated

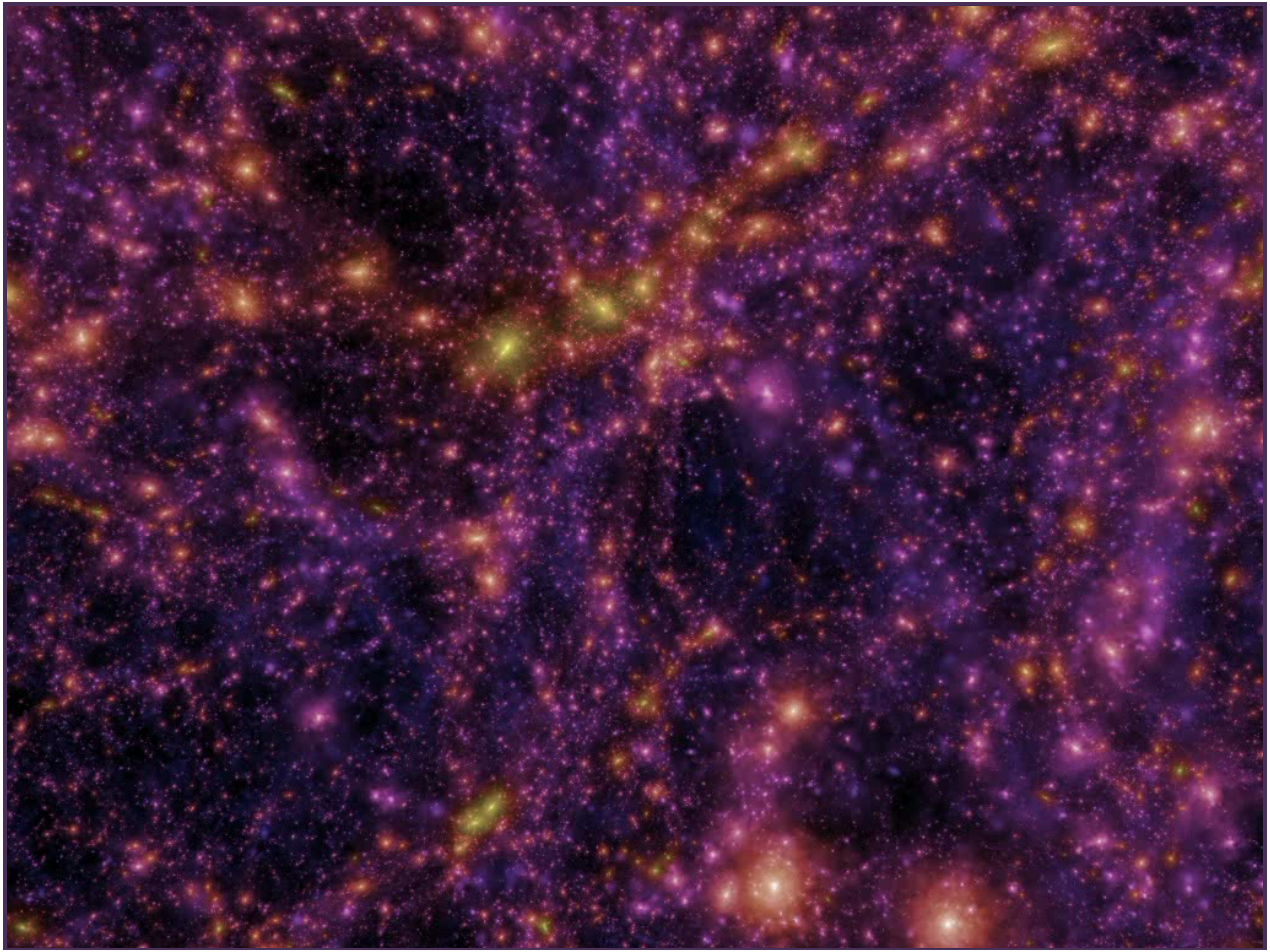


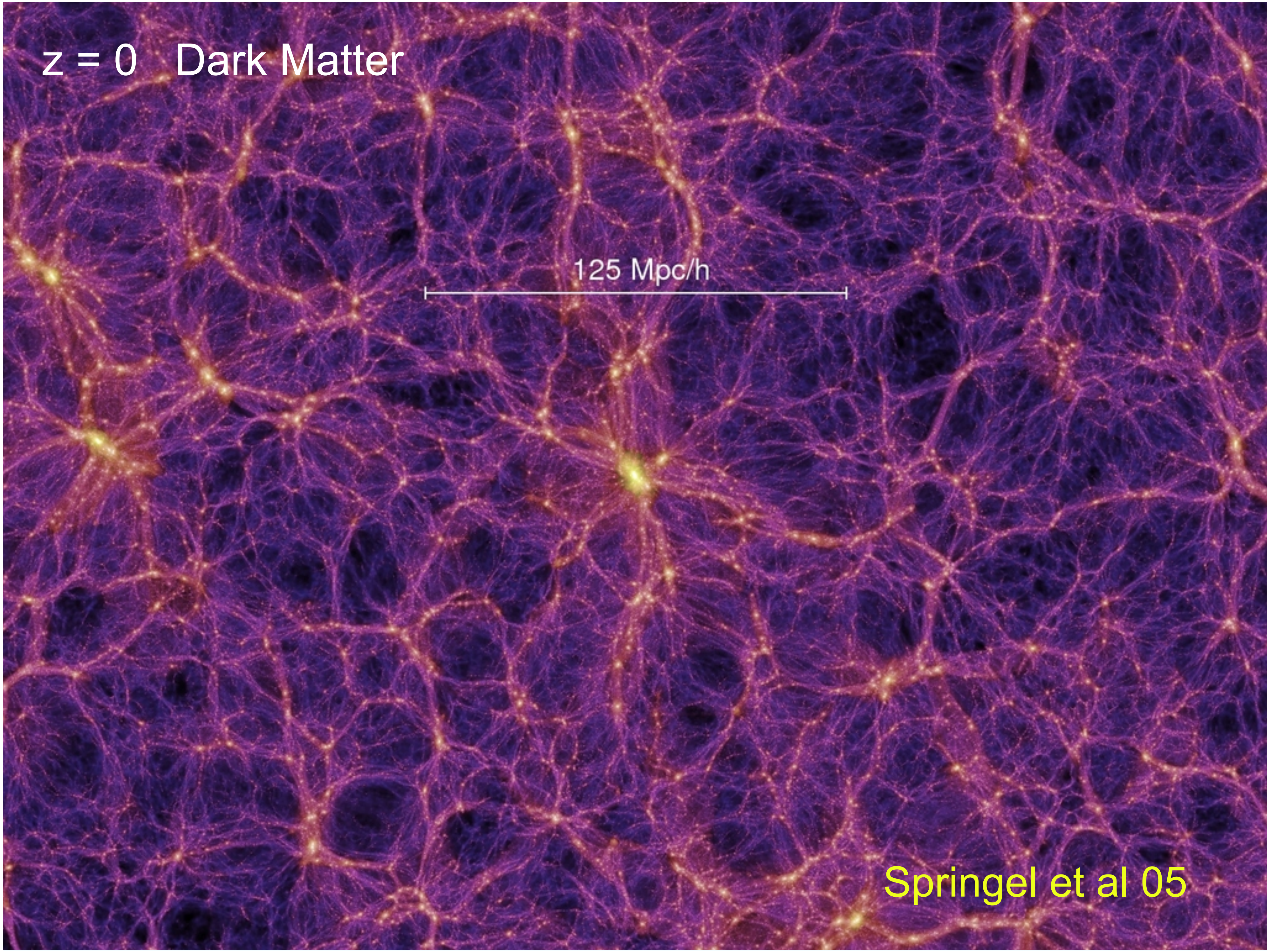
simulated

real

Davis, Efstathiou, Frenk & White ‘85

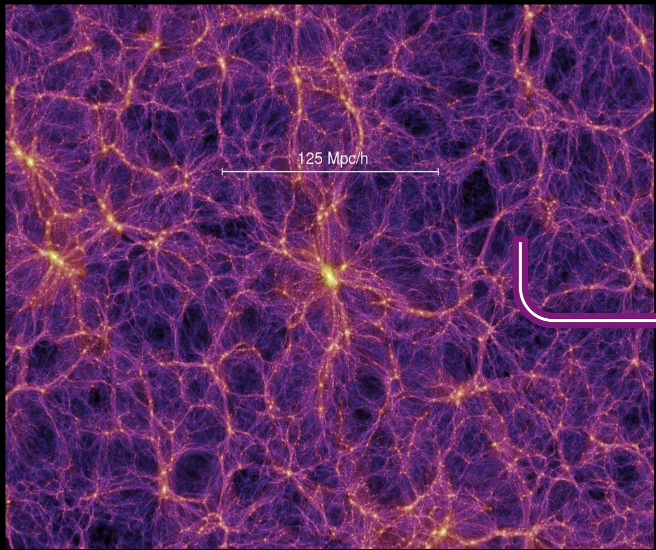

The 2dF Galaxy Redshift Survey
221,000 redshifts
z~0
2005



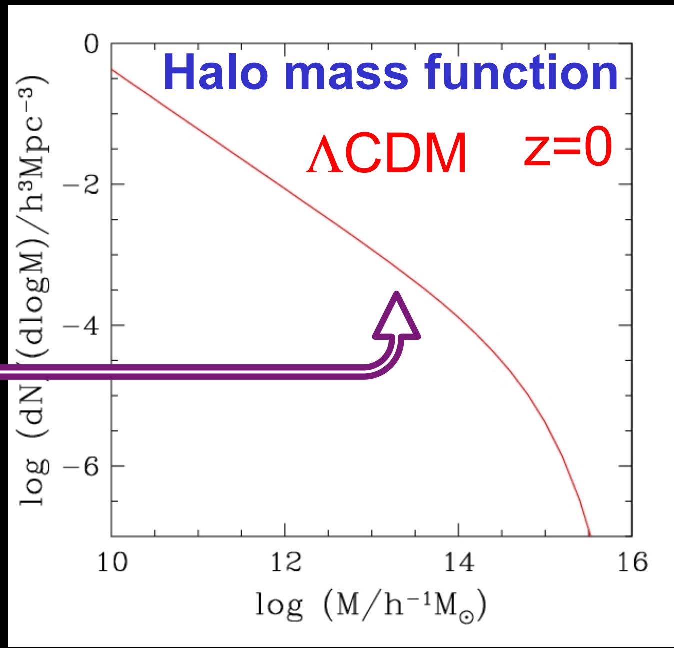


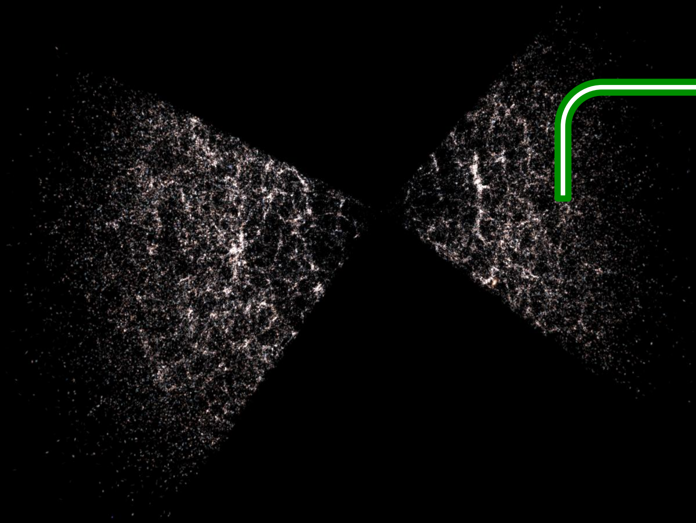
z = 0 Dark Matter
125 Mpc/h
Springel et al 05

Abundance of gals & dark halos

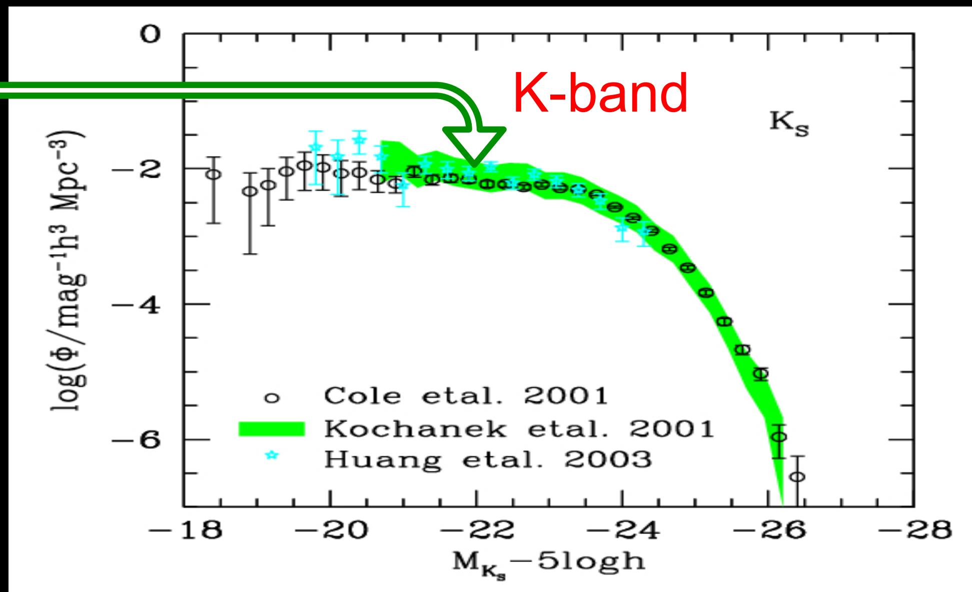


Millennium run





2dFGRS



The galaxy luminosity function

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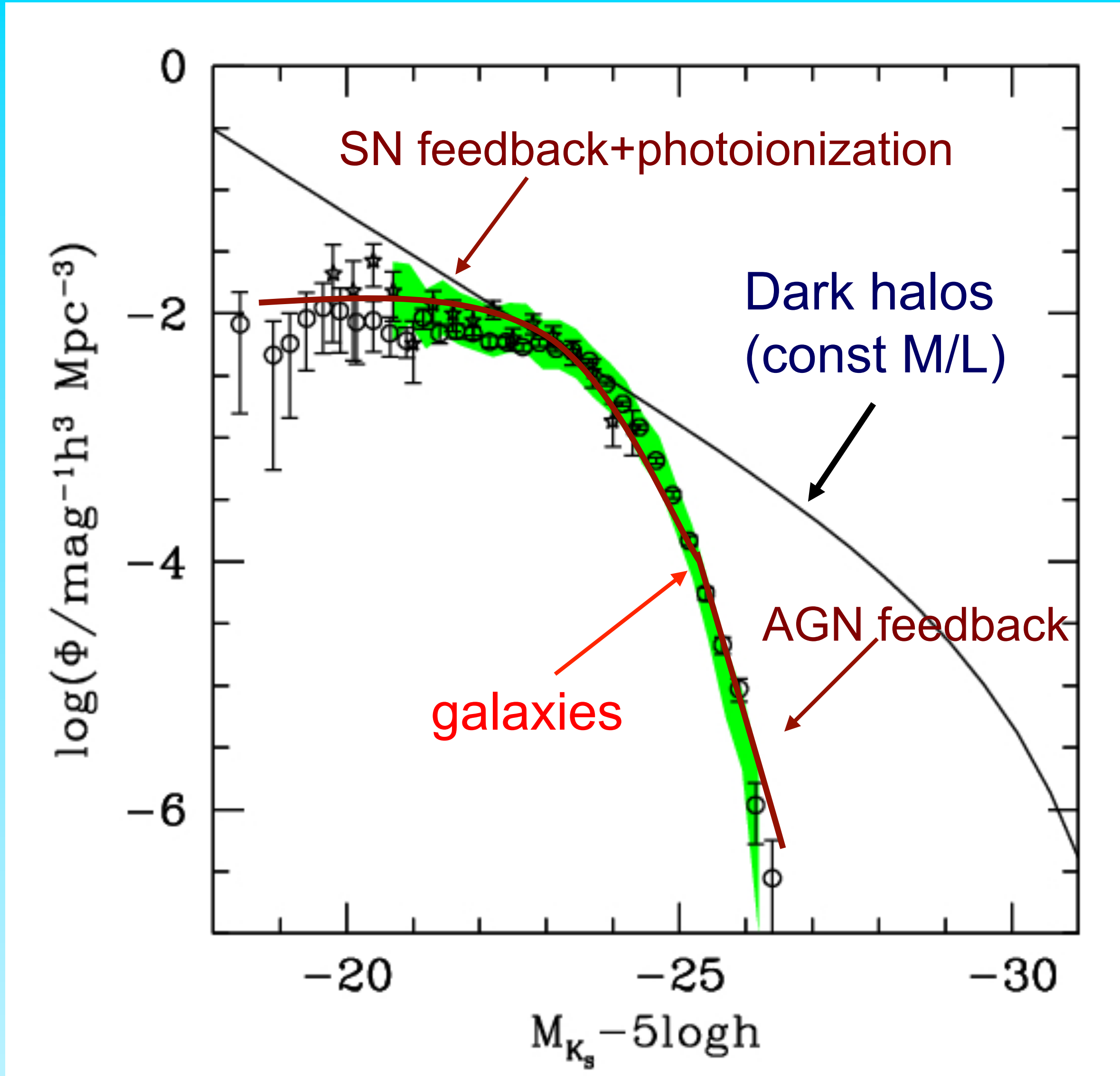
The halo mass function and the galaxy luminosity function have different shapes

⇨

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

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The cold dark matter cosmogony

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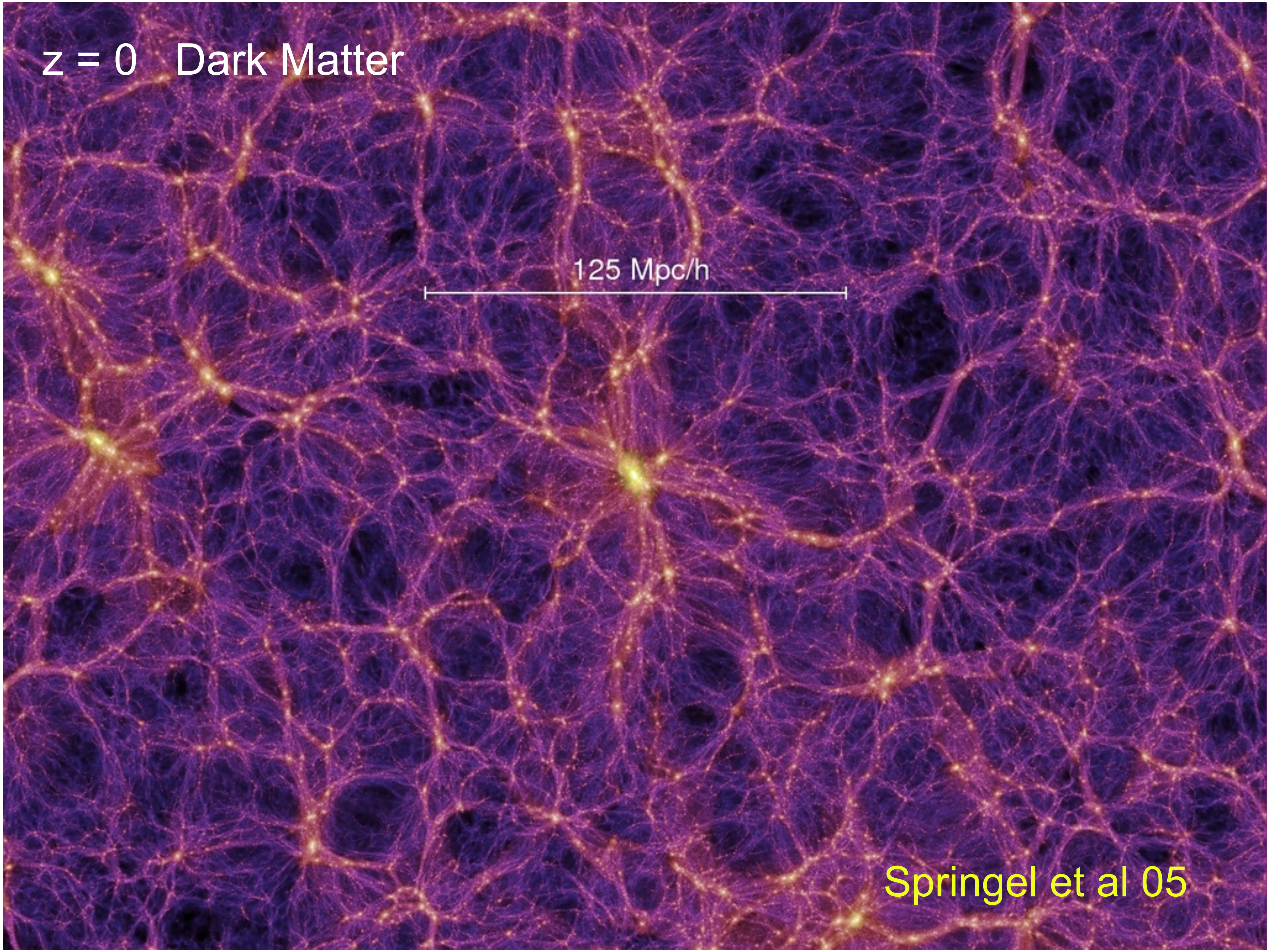
z = 0 Dark Matter
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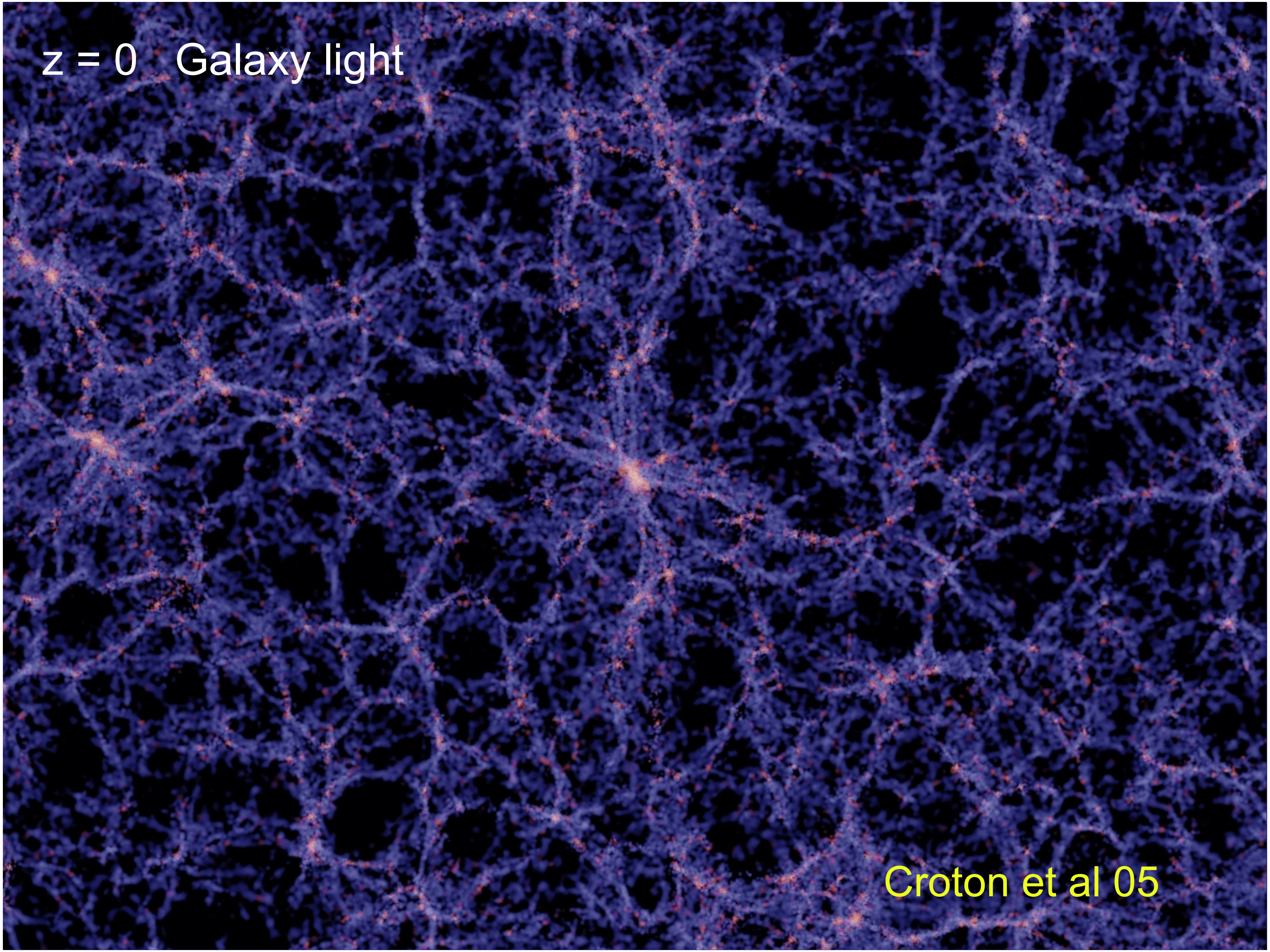
z = 0 Galaxy light
Croton et al 05

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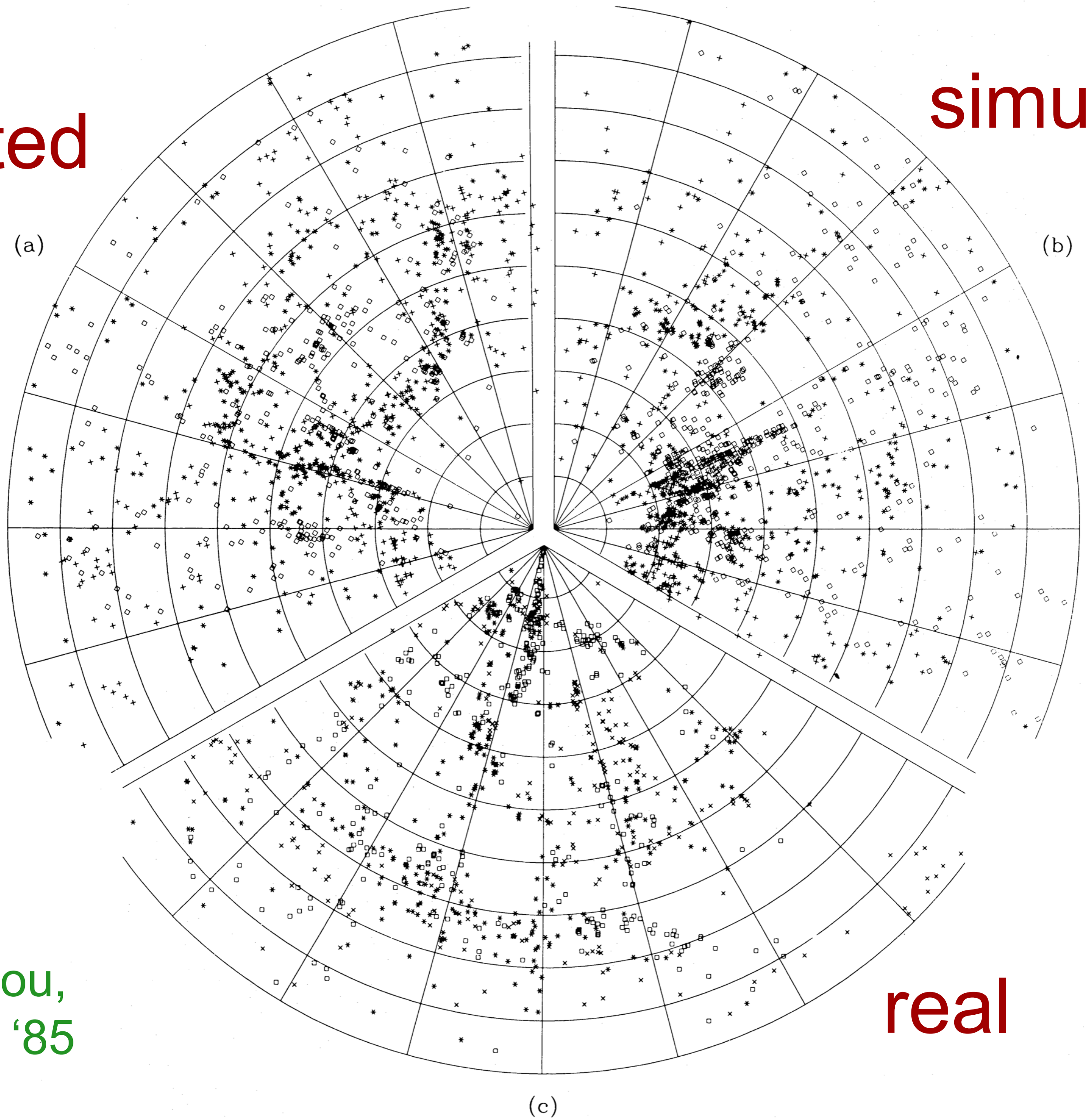
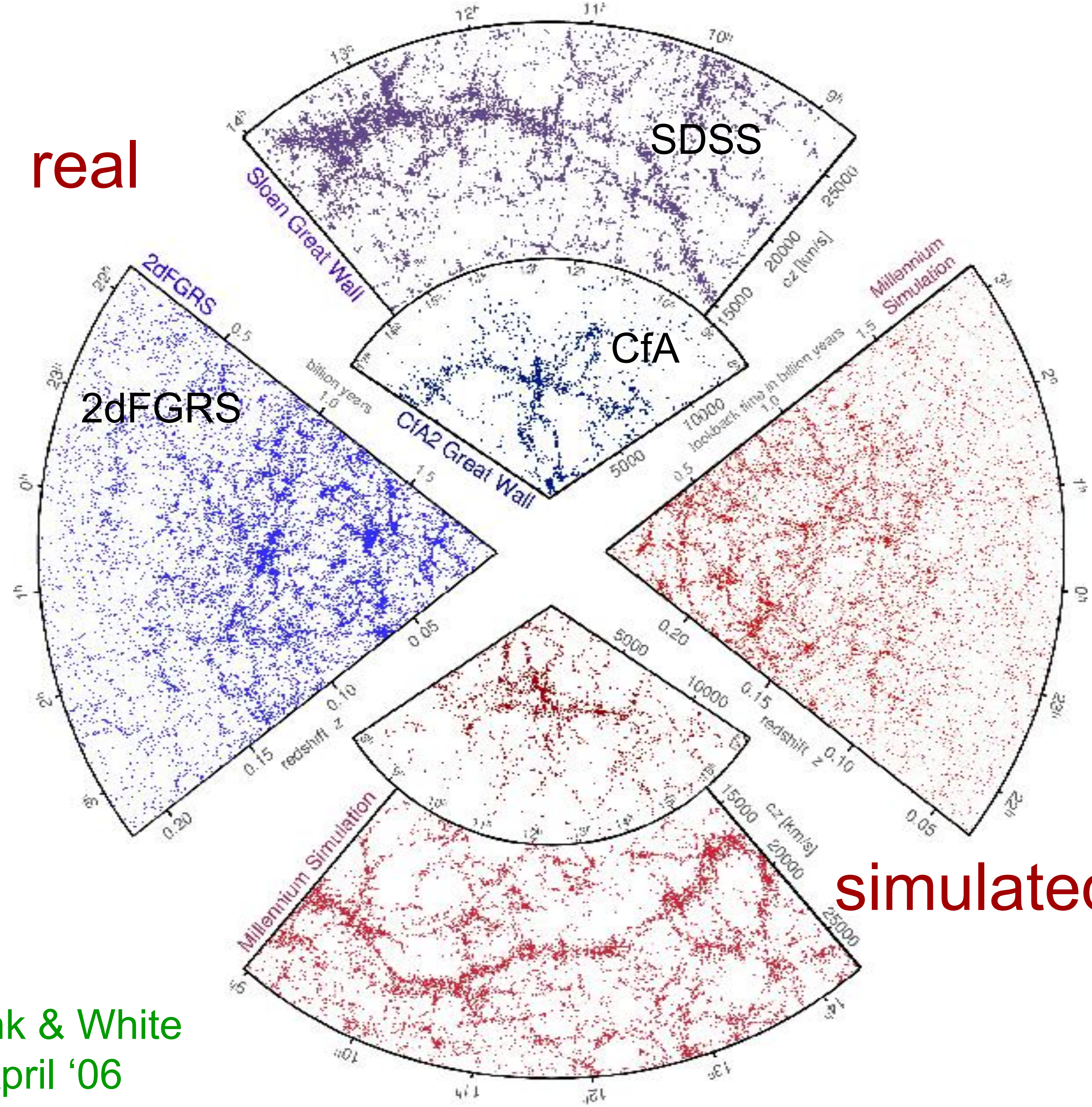
Early simulations of ΛCDM



Davis, Efstathiou, Frenk & White ‘85

real

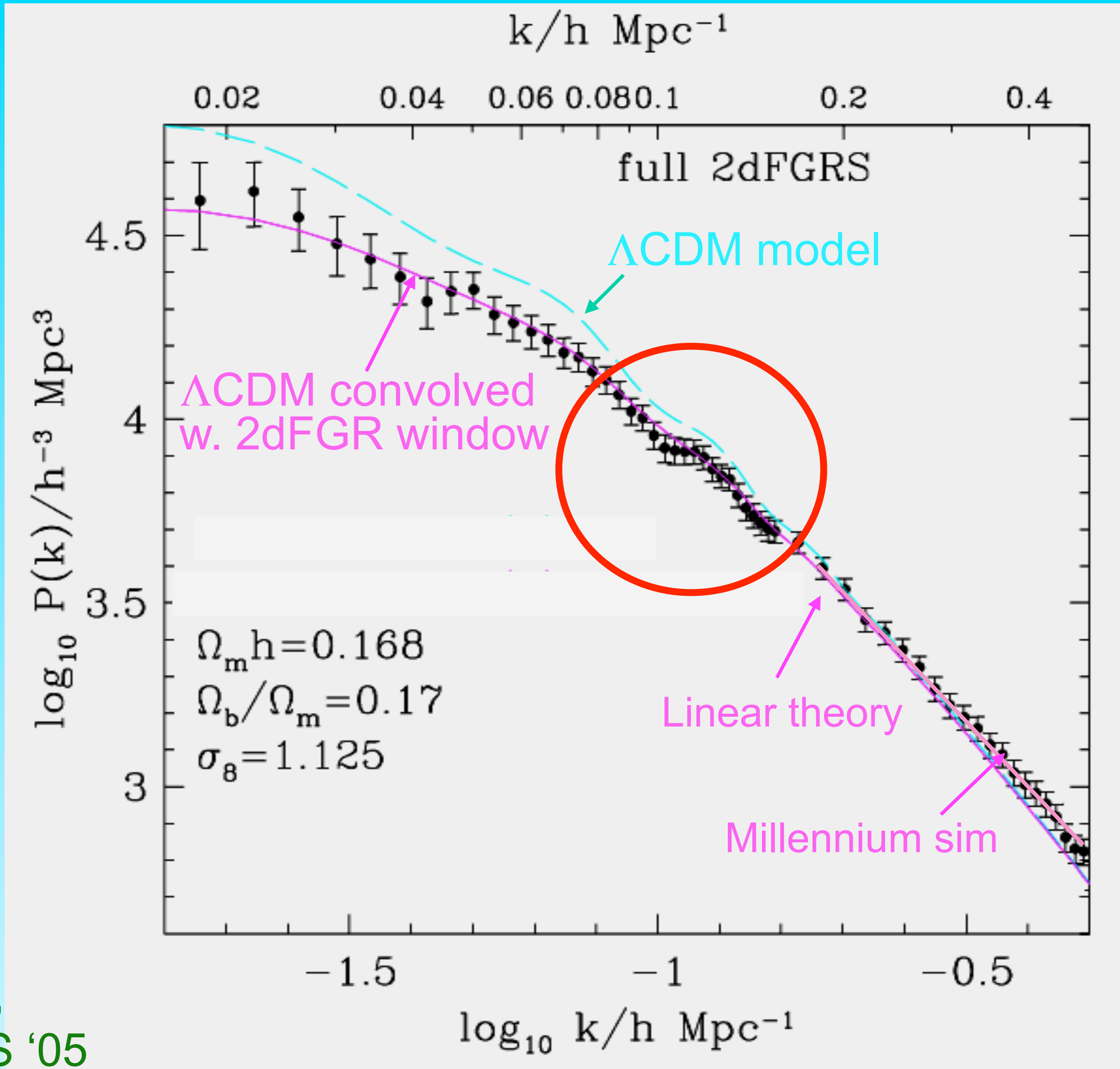


simulated

Springel, Frenk & White
Nature, April '06

The final 2dFGRS power spectrum

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



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

The final 2dFGRS power spectrum

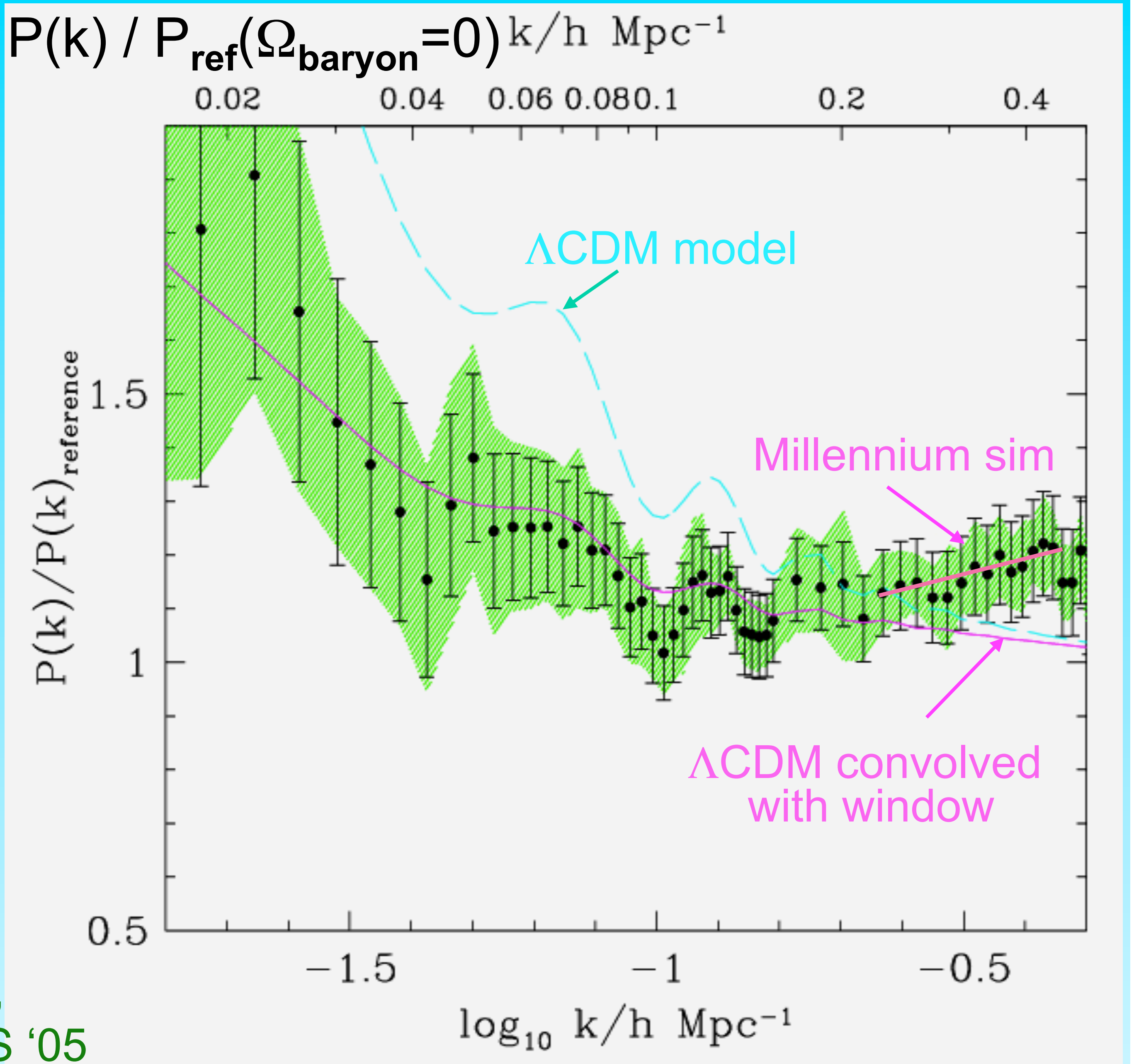
University of Durham

Baryon oscillations conclusively detected in 2dFGRS!!!

Demonstrates that structure grew by gravitational instability in ΛCDM universe

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

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



The cold dark matter cosmogony

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Star forming galaxies

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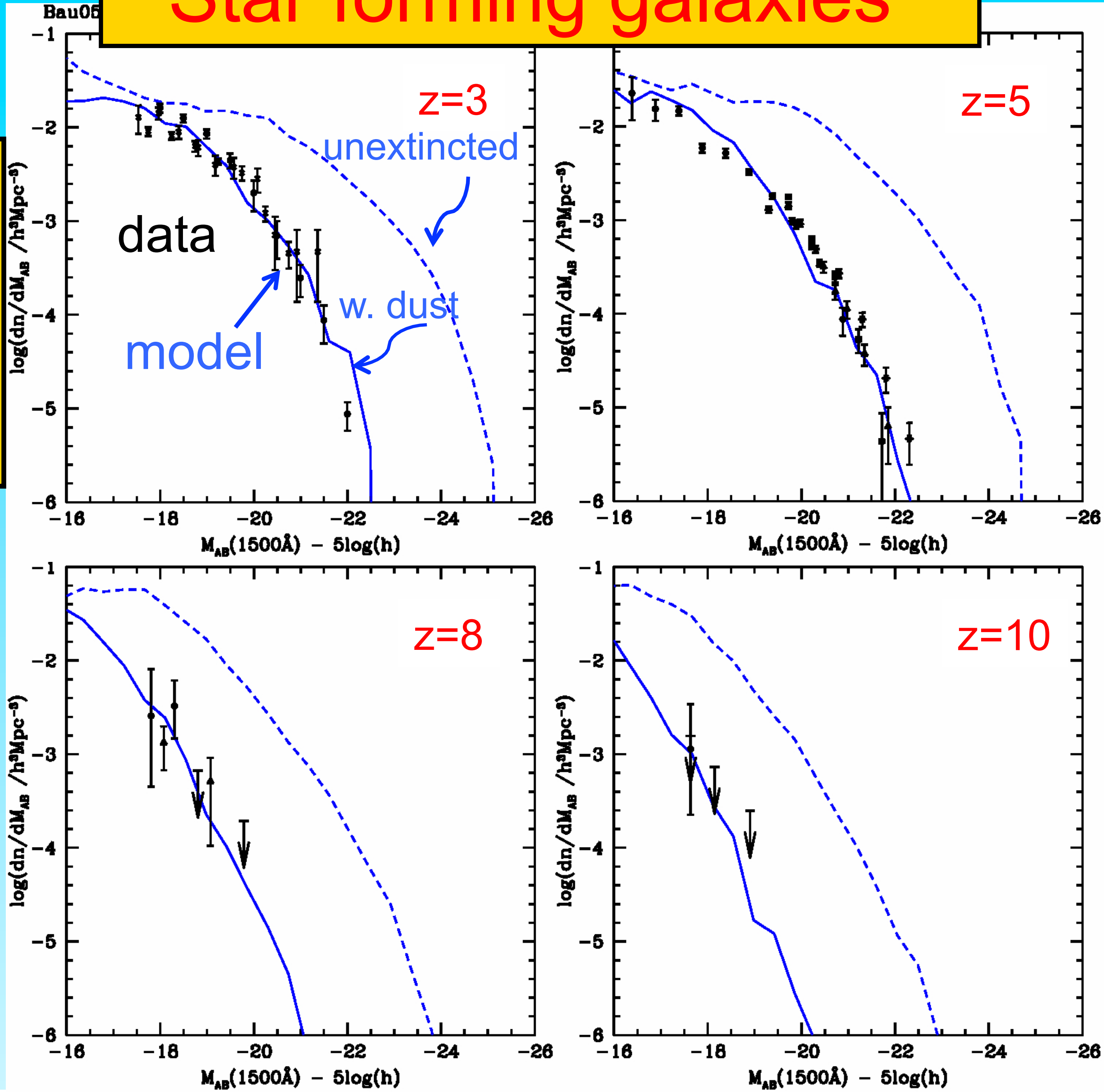
Evolution of Lyman-break galaxy lum. function



Lacey, Baugh, Frenk, Benson '11

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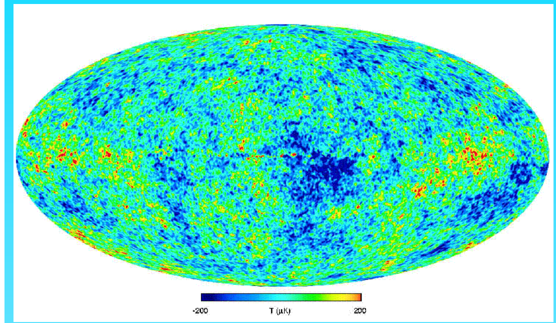
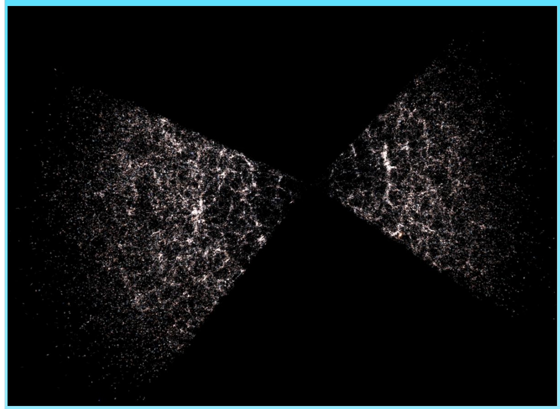
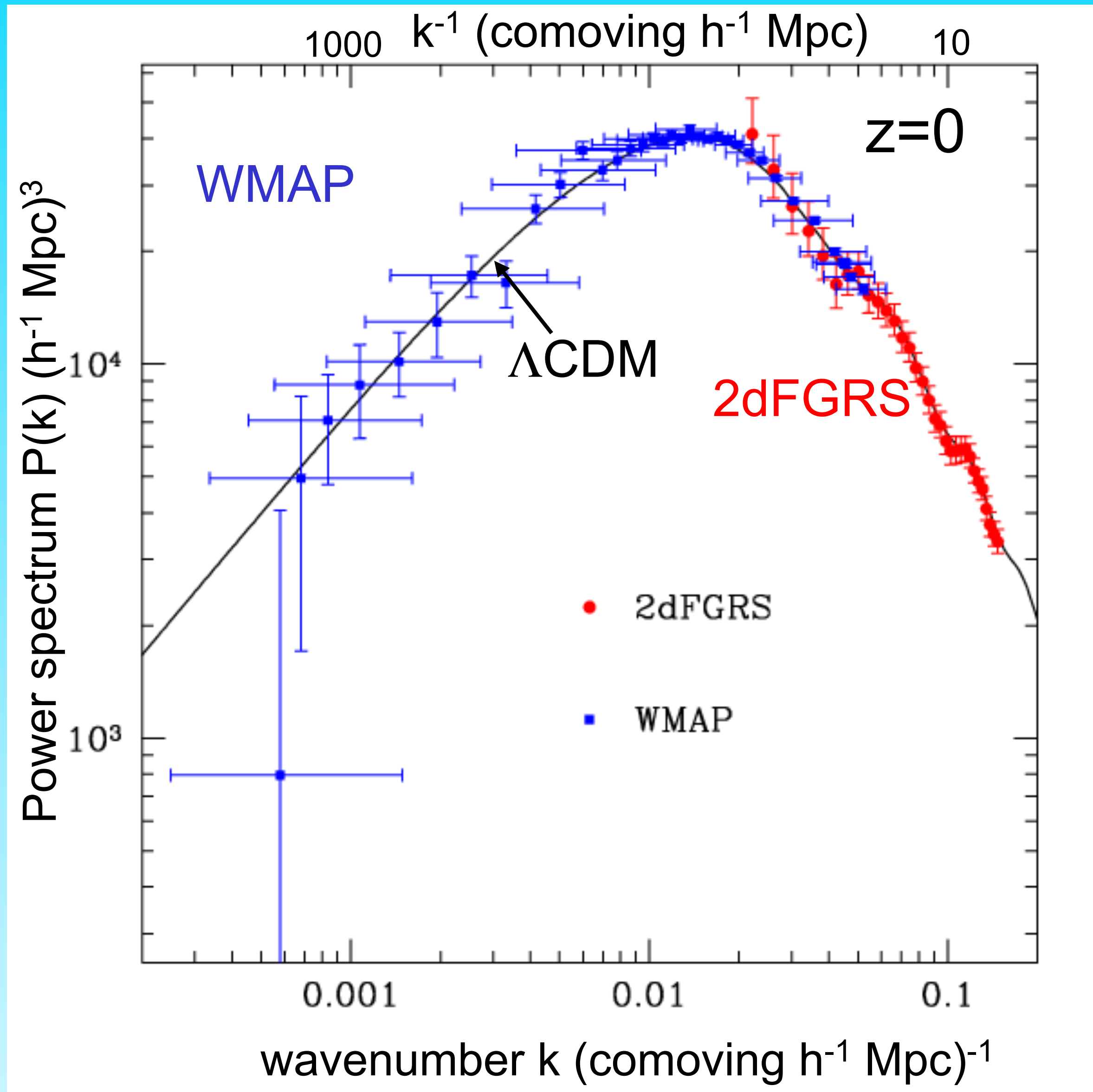
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

The dark matter power spectrum

University of Durham

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; $M_{cut} \sim 10^{9}\ M_o$

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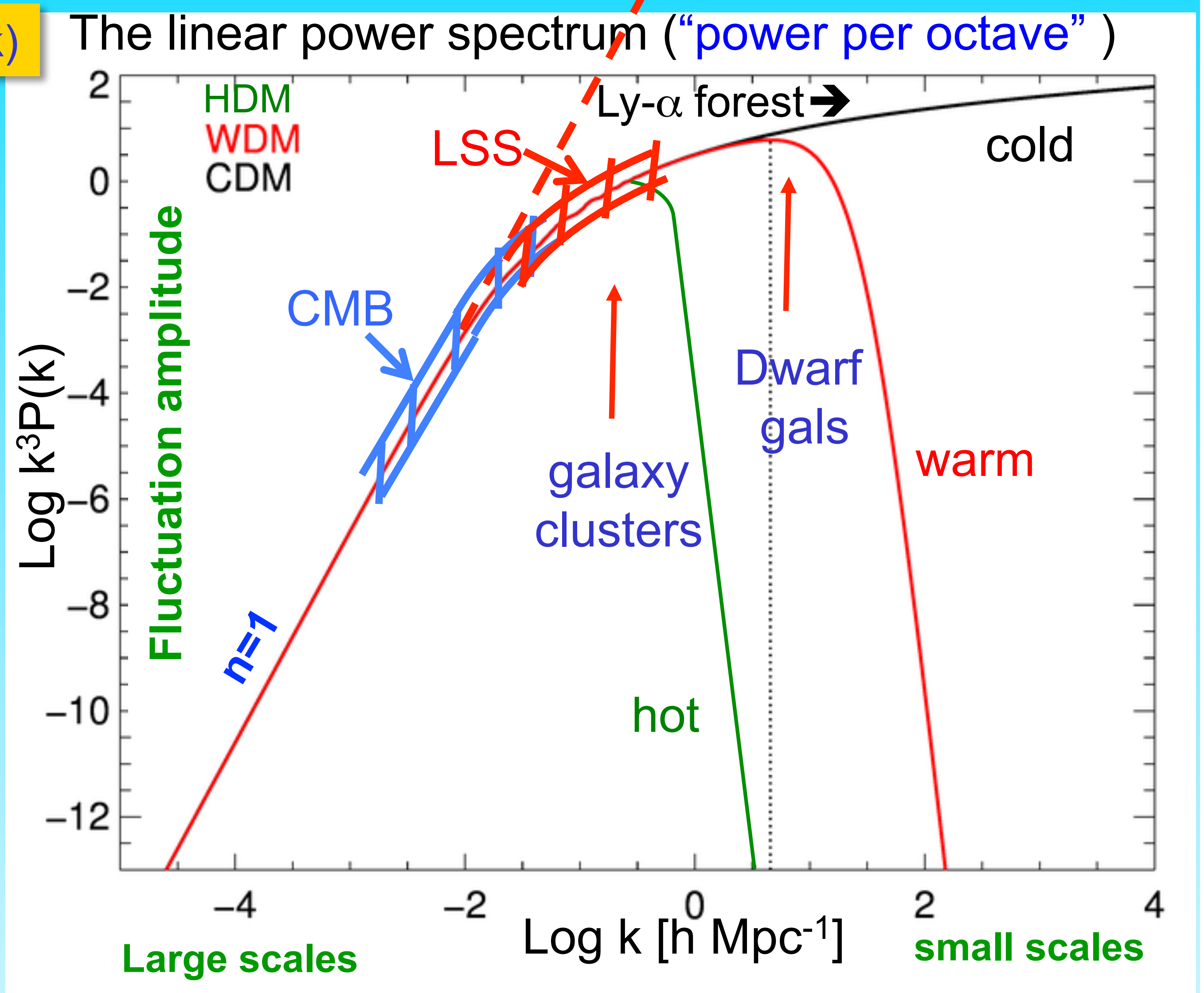
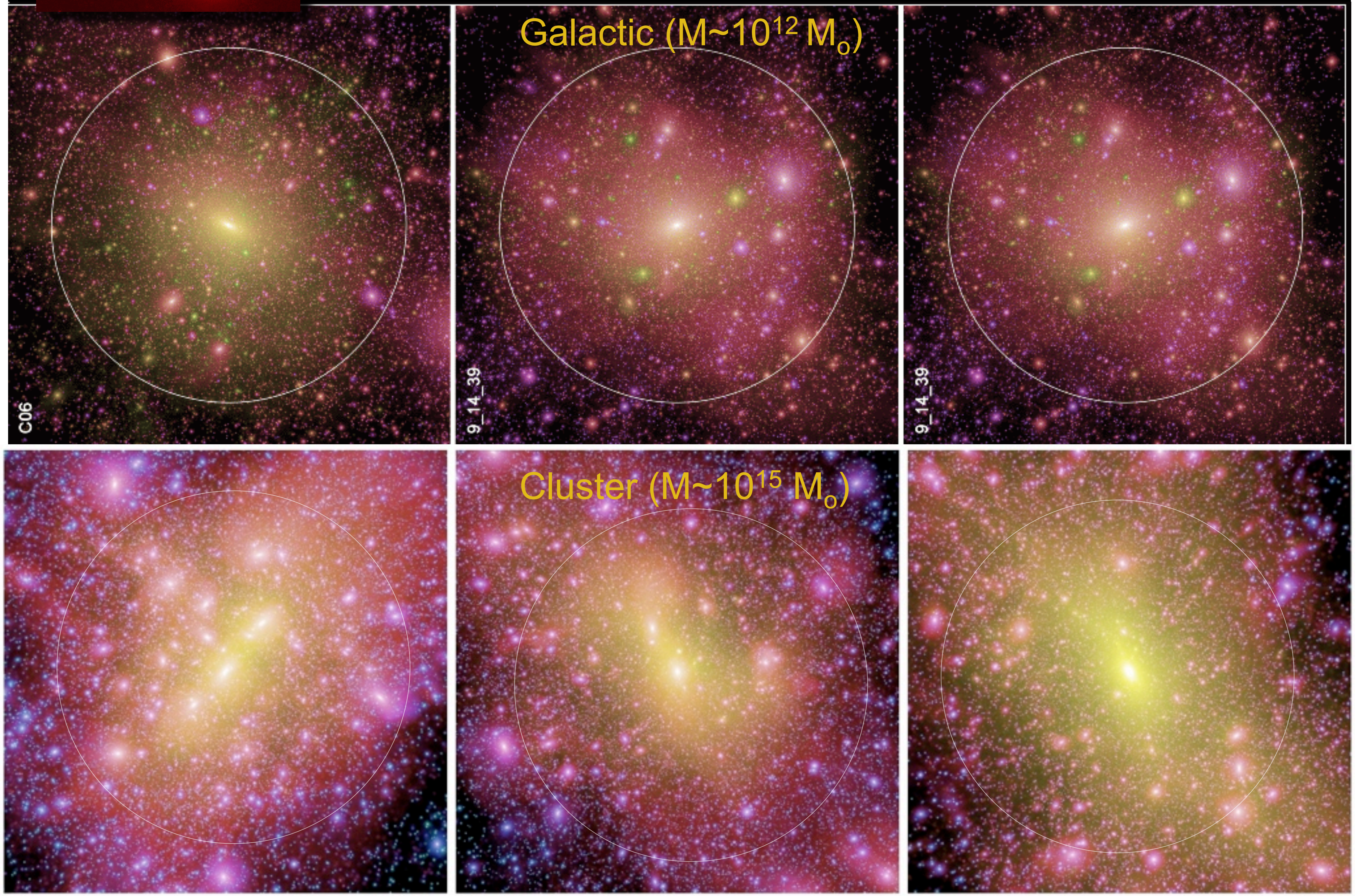


Cosmology on small – strongly non-linear – scales

→ key to the identity of the dark matter


z = 48.4
T = 0.05 Gyr
500 kpc

Aquarius and Phoenix halos (level-2)



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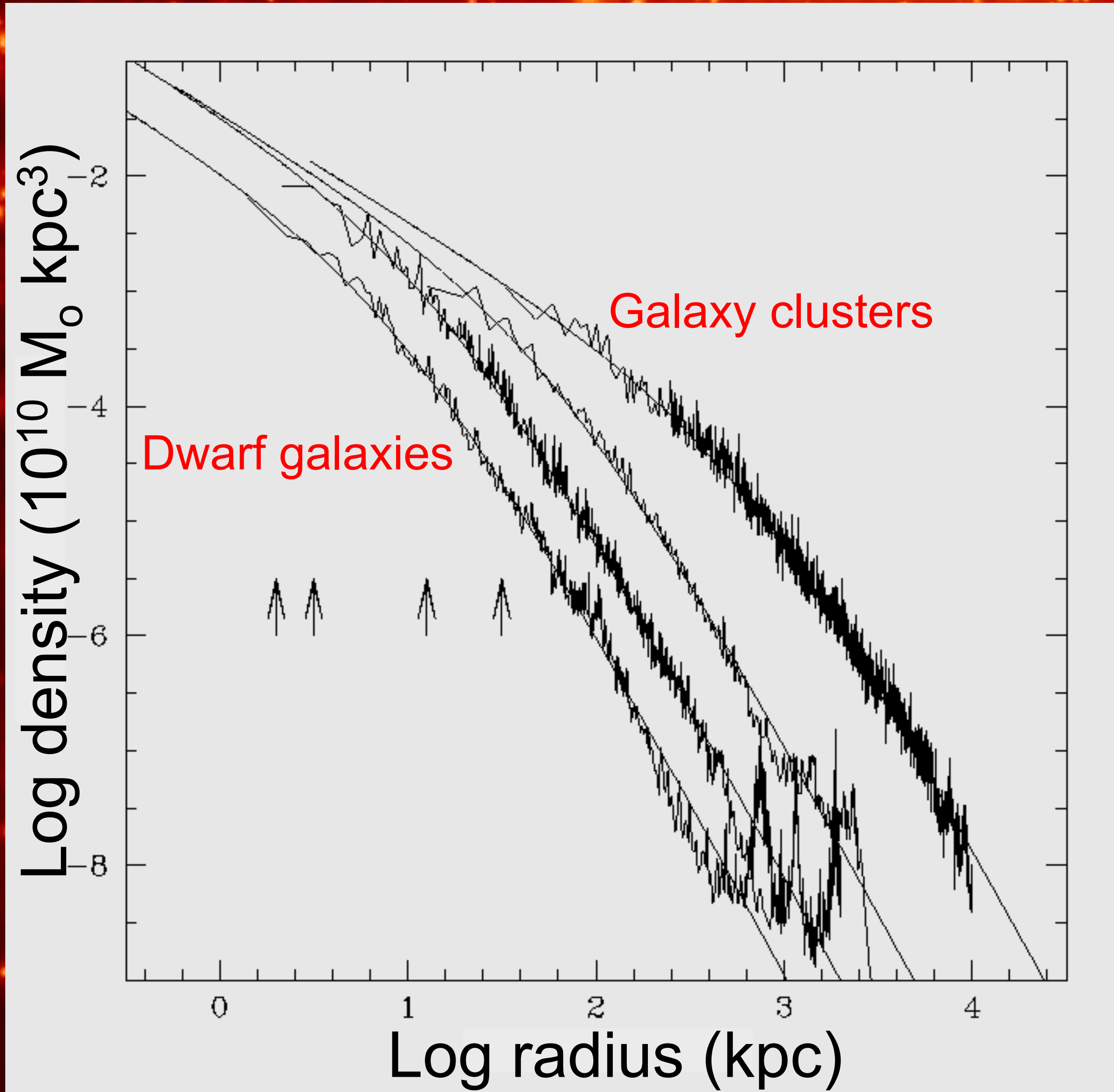
A cold dark matter universe

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)

ICC

cold dark matter | warm dark matter

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

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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 structure of dark matter halos

(Both CDM and WDM predict cuspy density profiles)

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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

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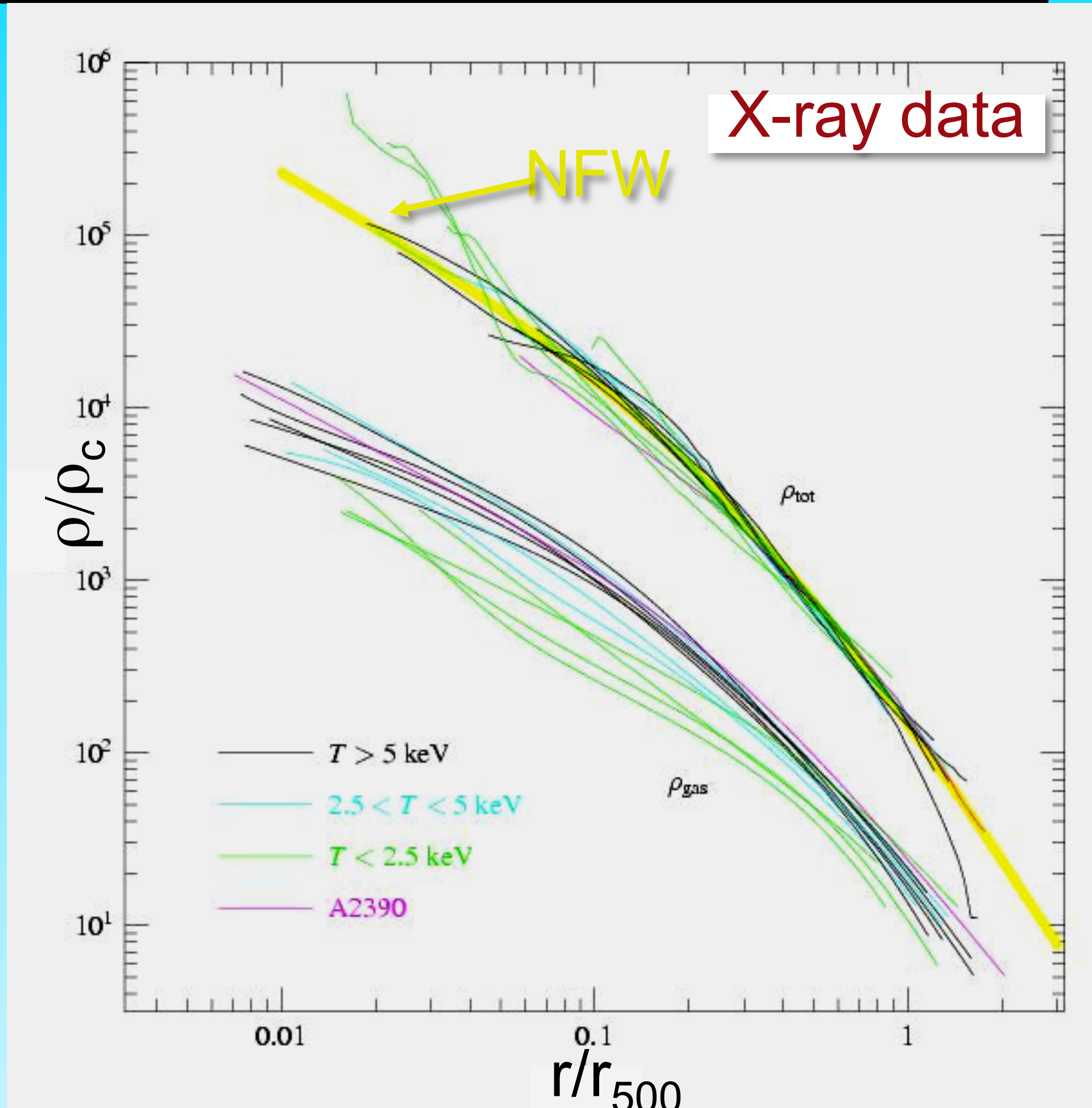
The central density profile of galaxy cluster dark halos

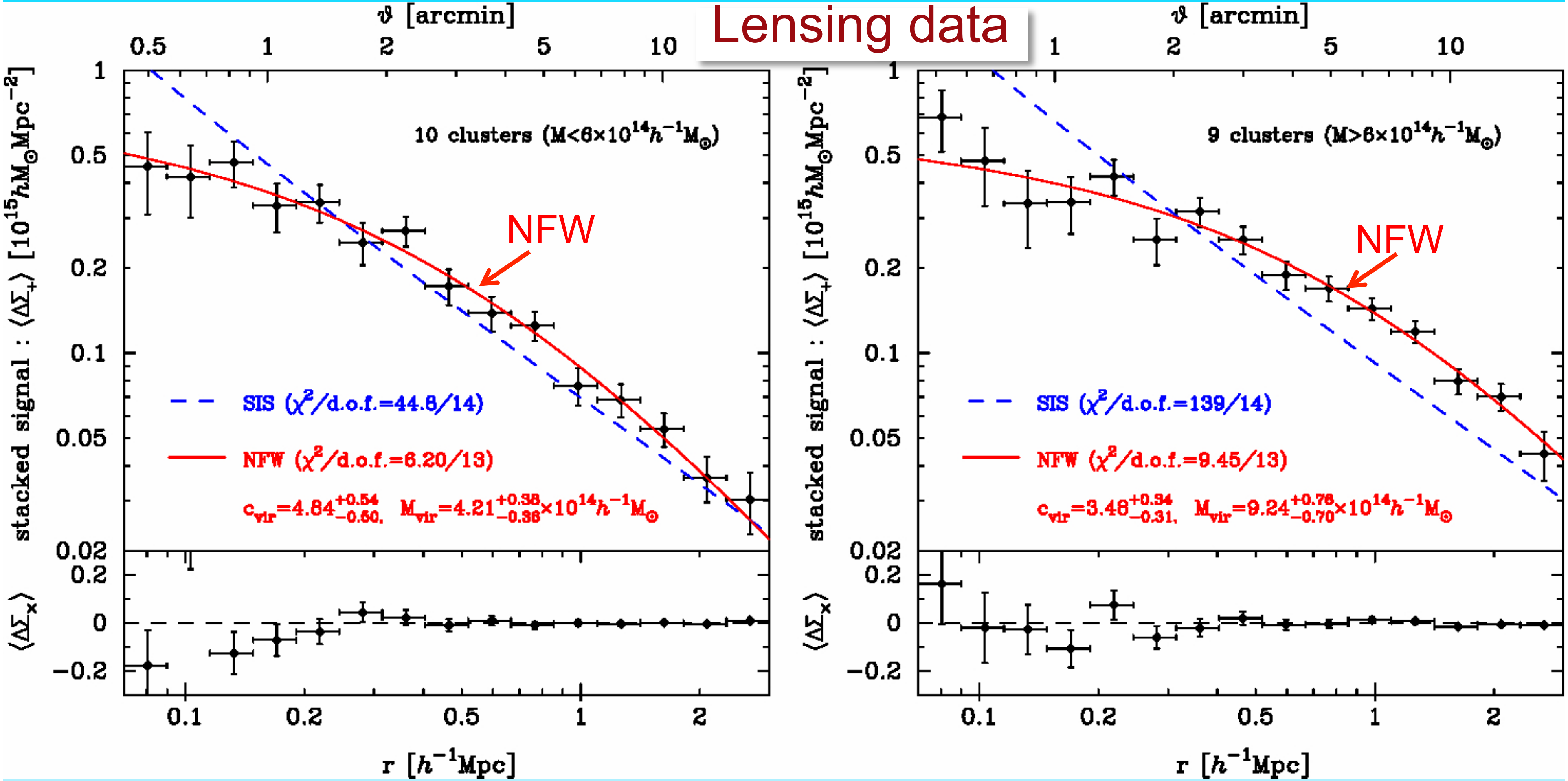
Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium

Excellent agreement with CDM halo predictions



Vikhlinin et al ‘06

The density profile of galaxy cluster dark halos



Okabe et al '10

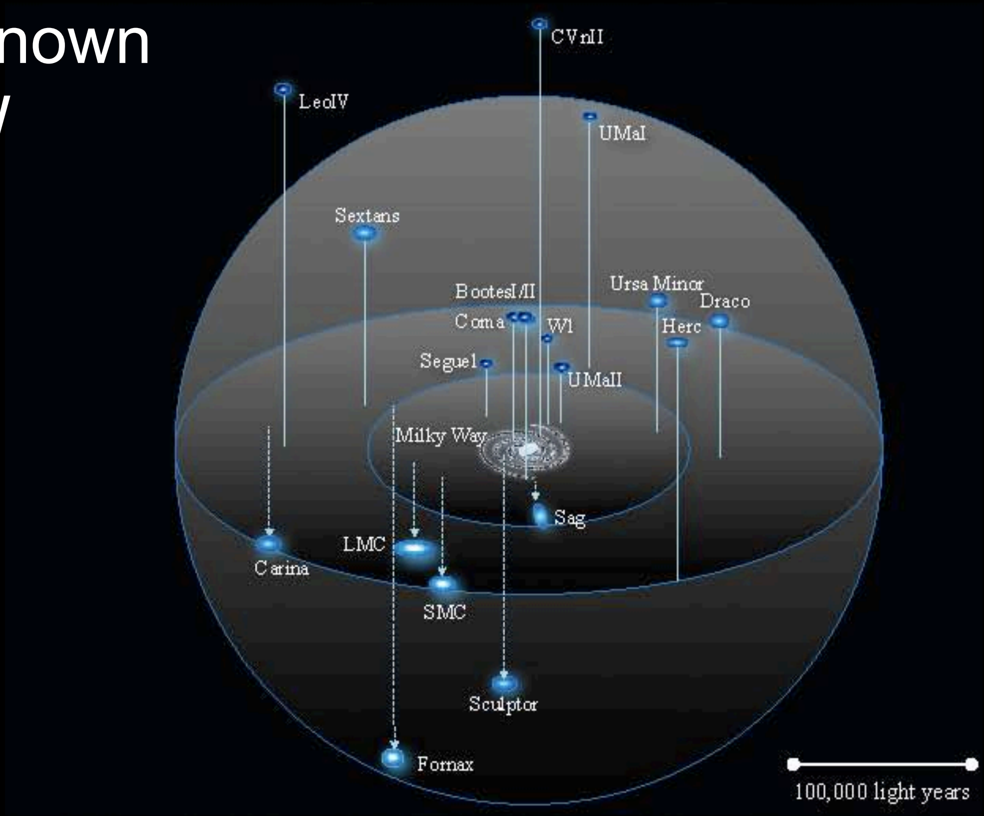
ΛCDM and WDM → OK on scales of galaxy clusters and larger

How about on smaller scales?

(again, expect cusps in both CDM and WDM)

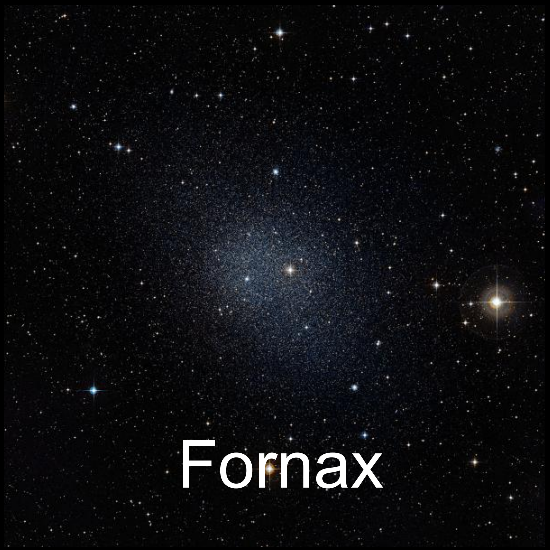
The satellites of the Milky Way

~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?

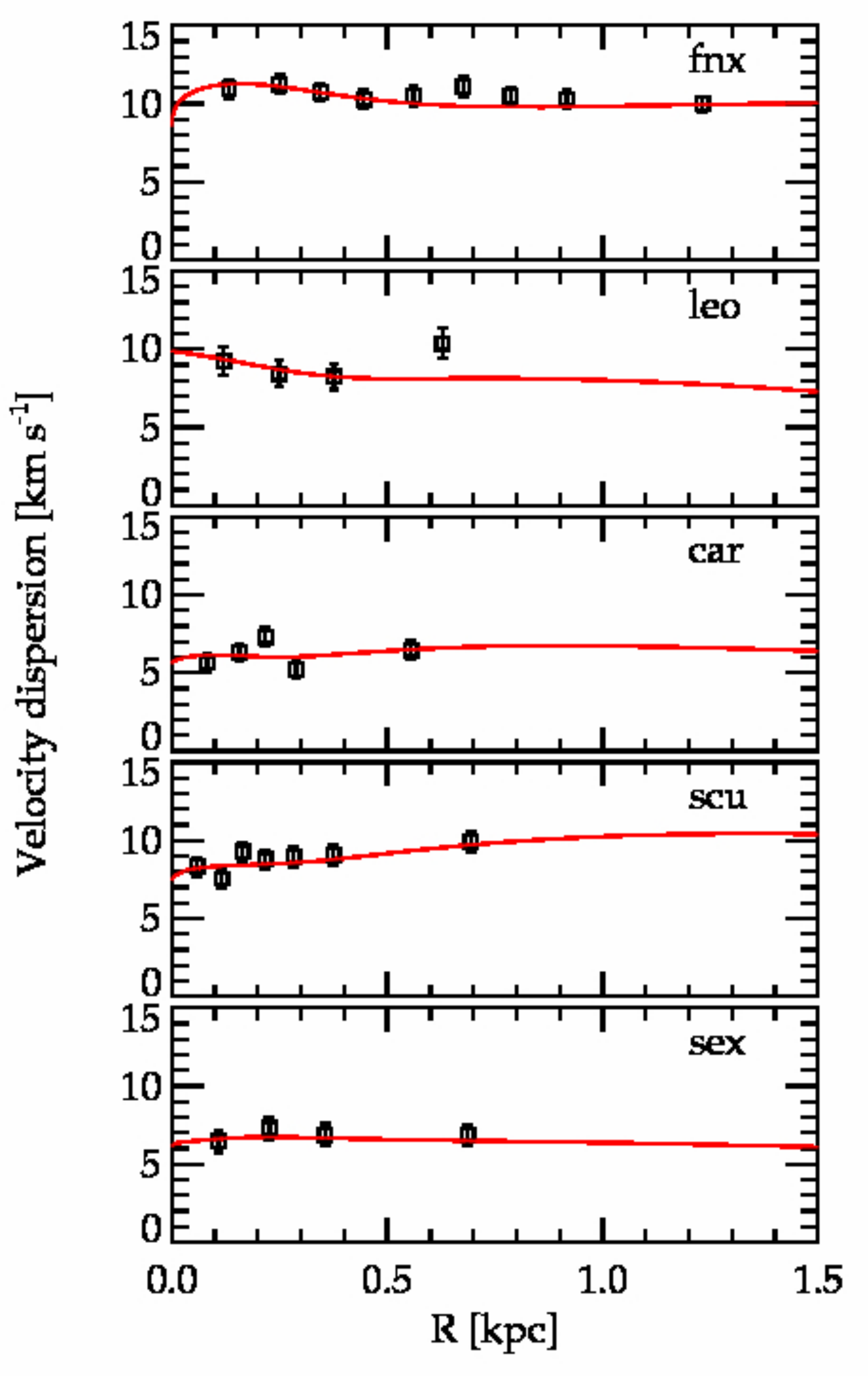
Jeans eqn:

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

from Aquarius sim

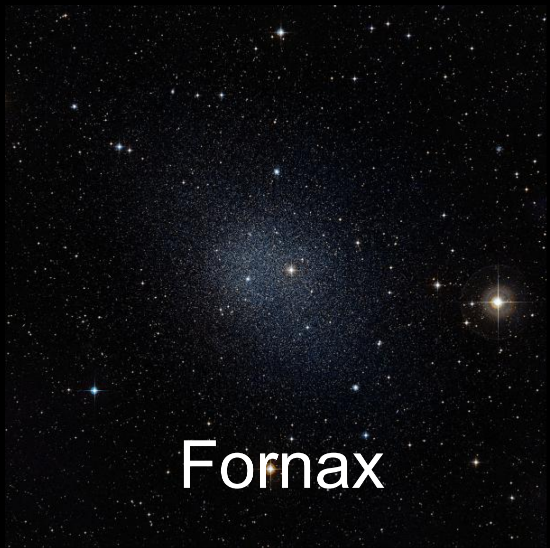
vel. anisotropy

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



Dwarf galaxies around the Milky Way

Cuspy NFW profiles consistent with MW satellite kinematic data



Sculptor

Sextans

Carina

Sagittarius

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Halo structure, from galaxy clusters to dwarf satellites seems OK in both ΛCDM and WDM

How can we distinguish between CDM & WDM ?

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Galactic halos

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

CDM:

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

WDM:

- The main halo and its subhalos have "cuspy" density profiles, but the subhalos are less concentrated
- Small number of self-bound substructures (3% of mass) survive

cold dark matter

warm dark matter

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

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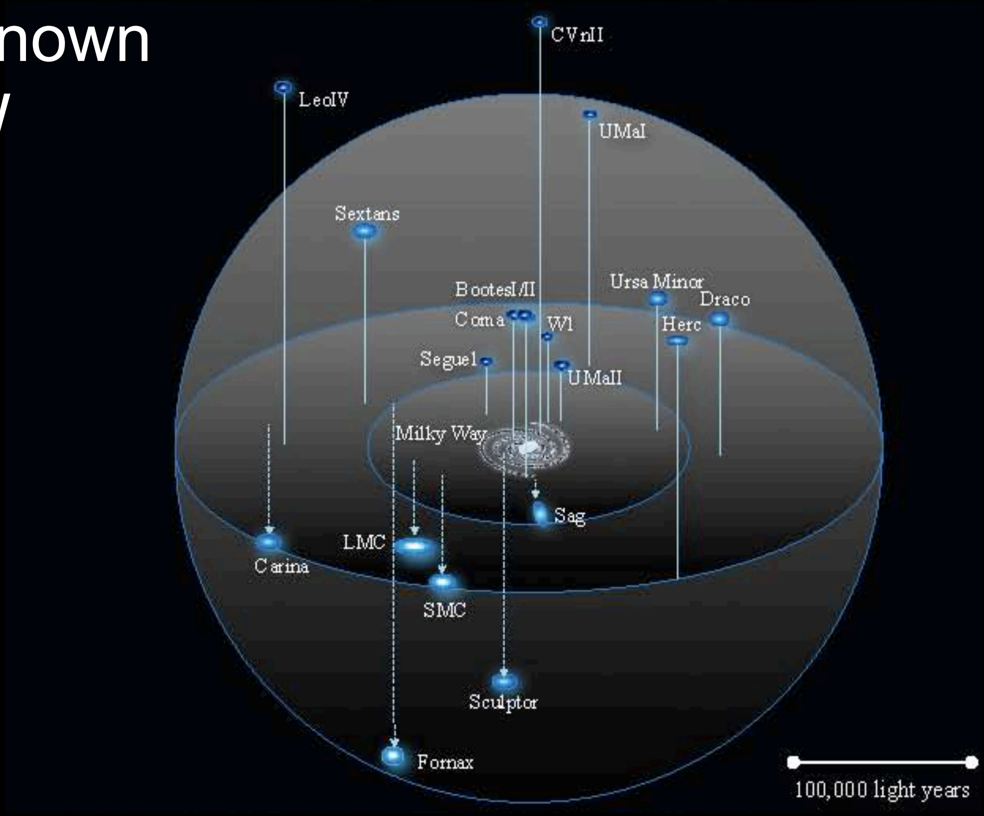
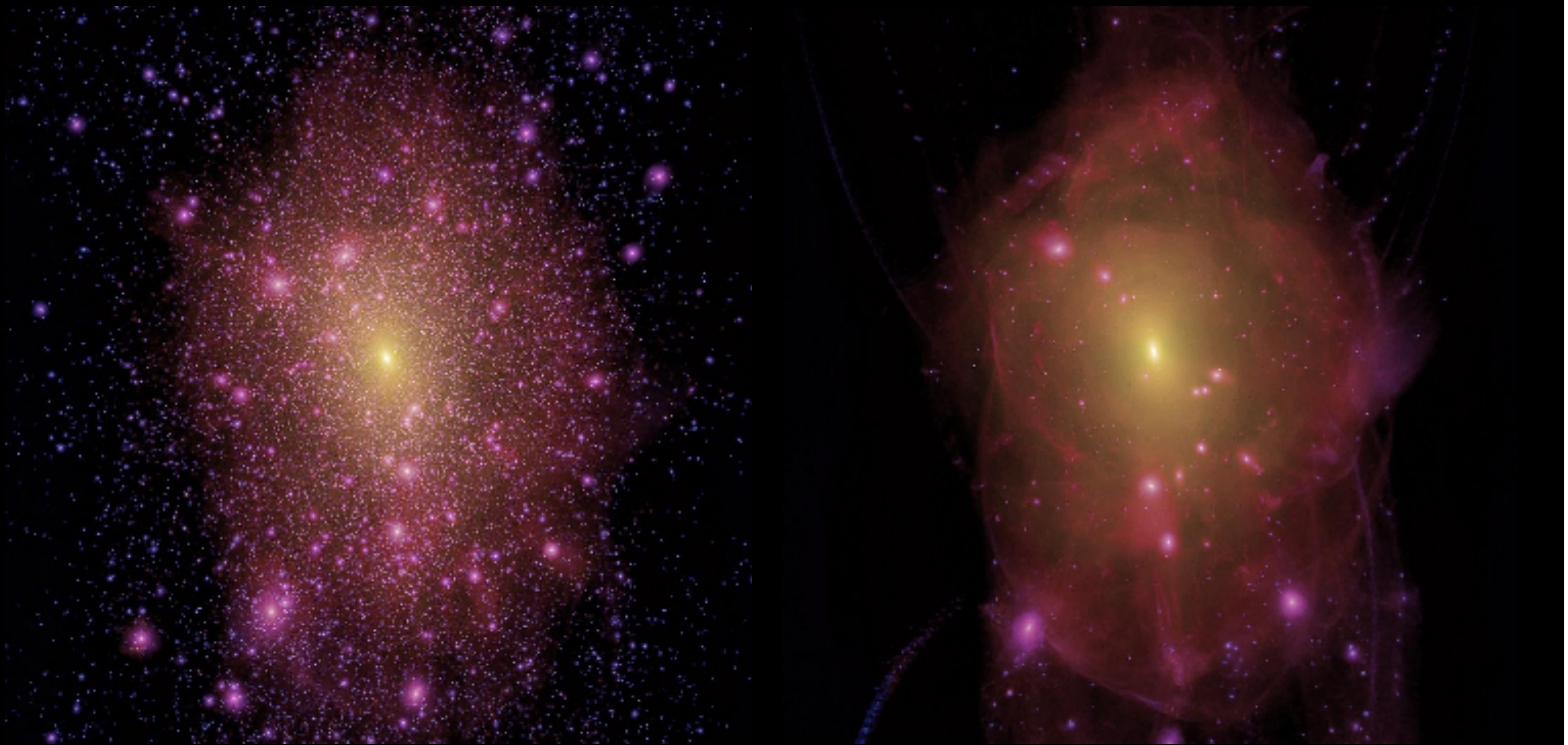
The satellites of the Milky Way

~25 satellites known
in the MW



Spot the difference!

cold dark matter warm dark matter



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

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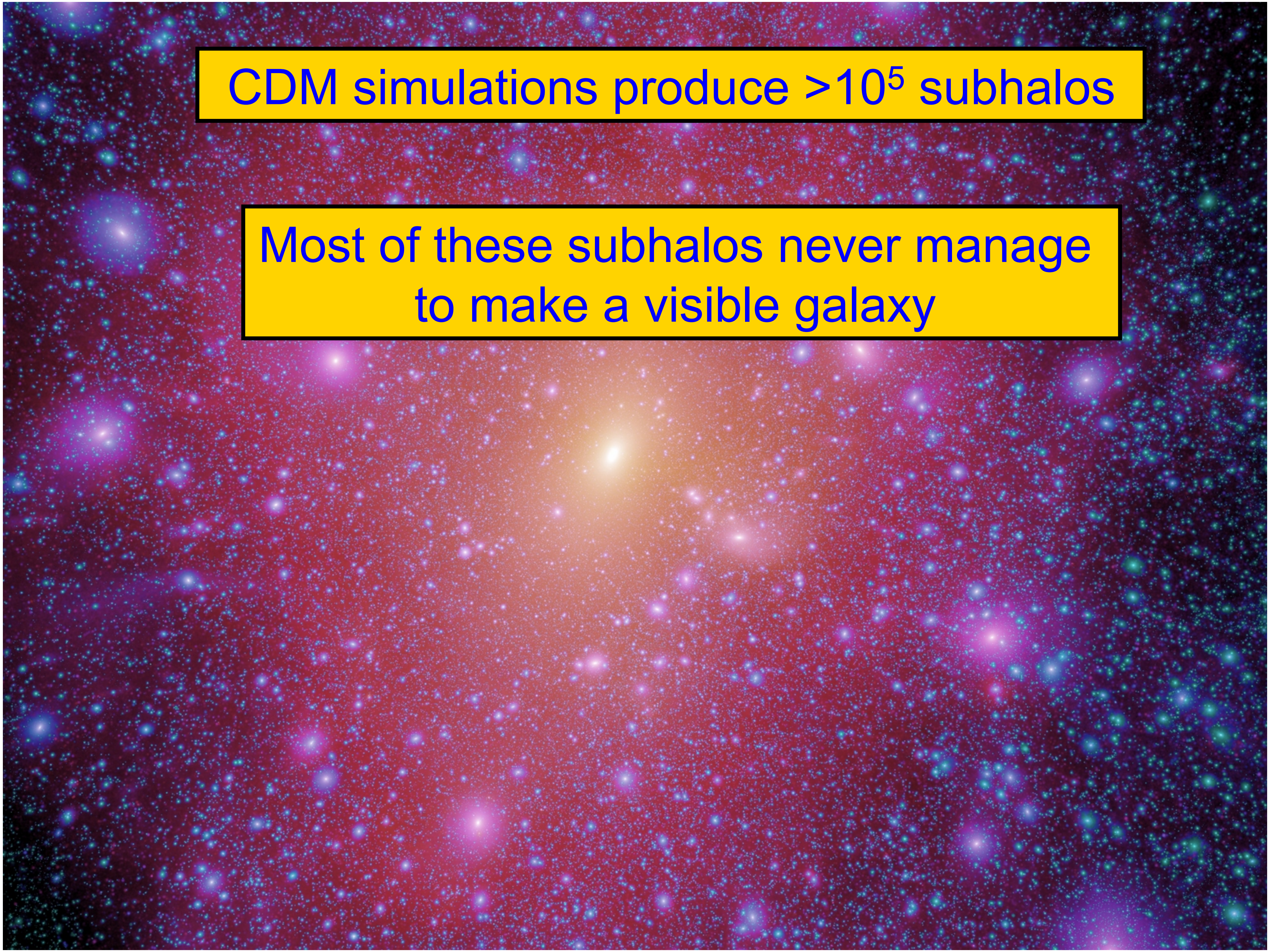
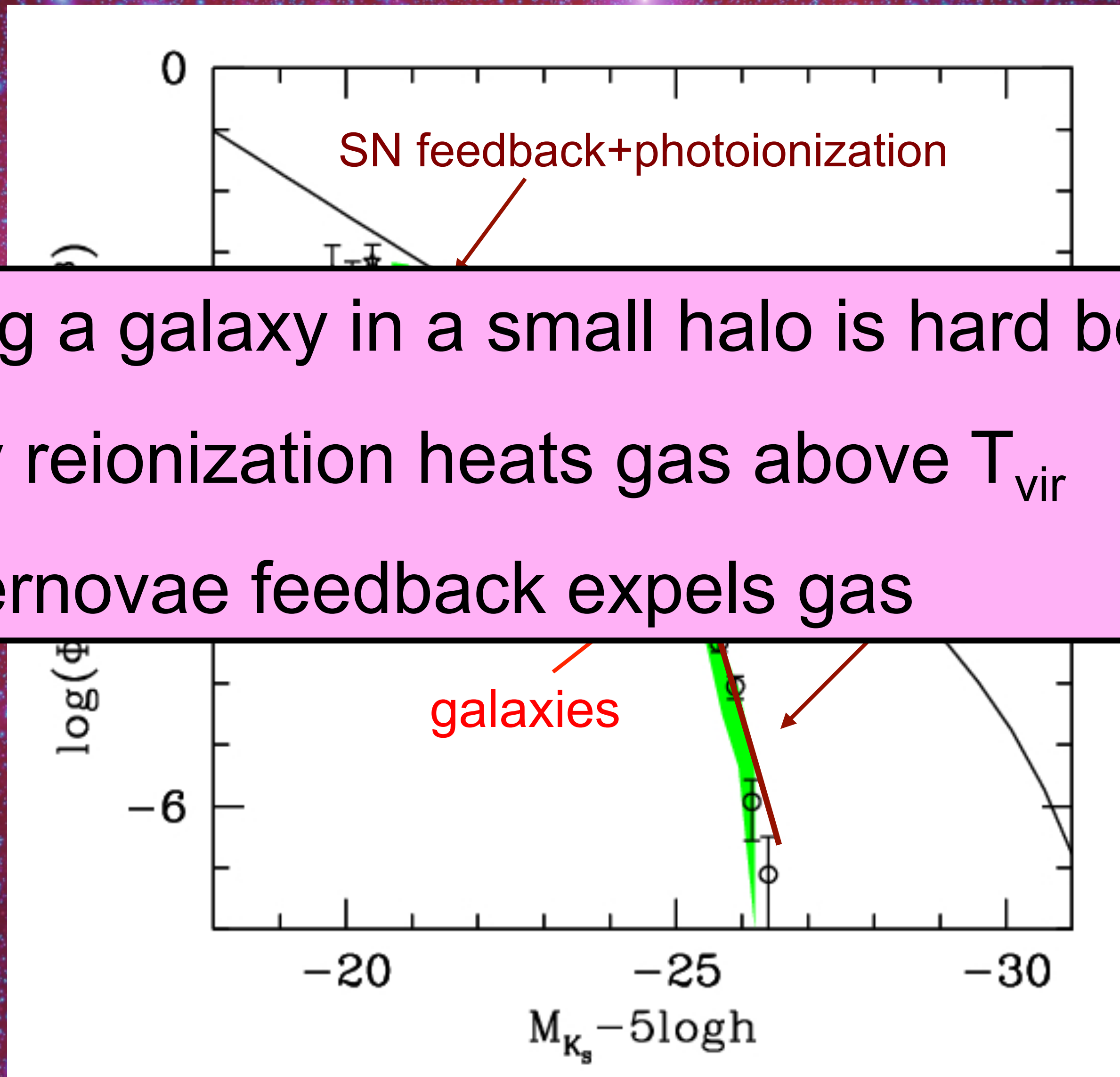

CDM simulations produce >10^5 subhalos
Most of these subhalos never manage to make a visible galaxy

Making a galaxy in a small halo is hard because:

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

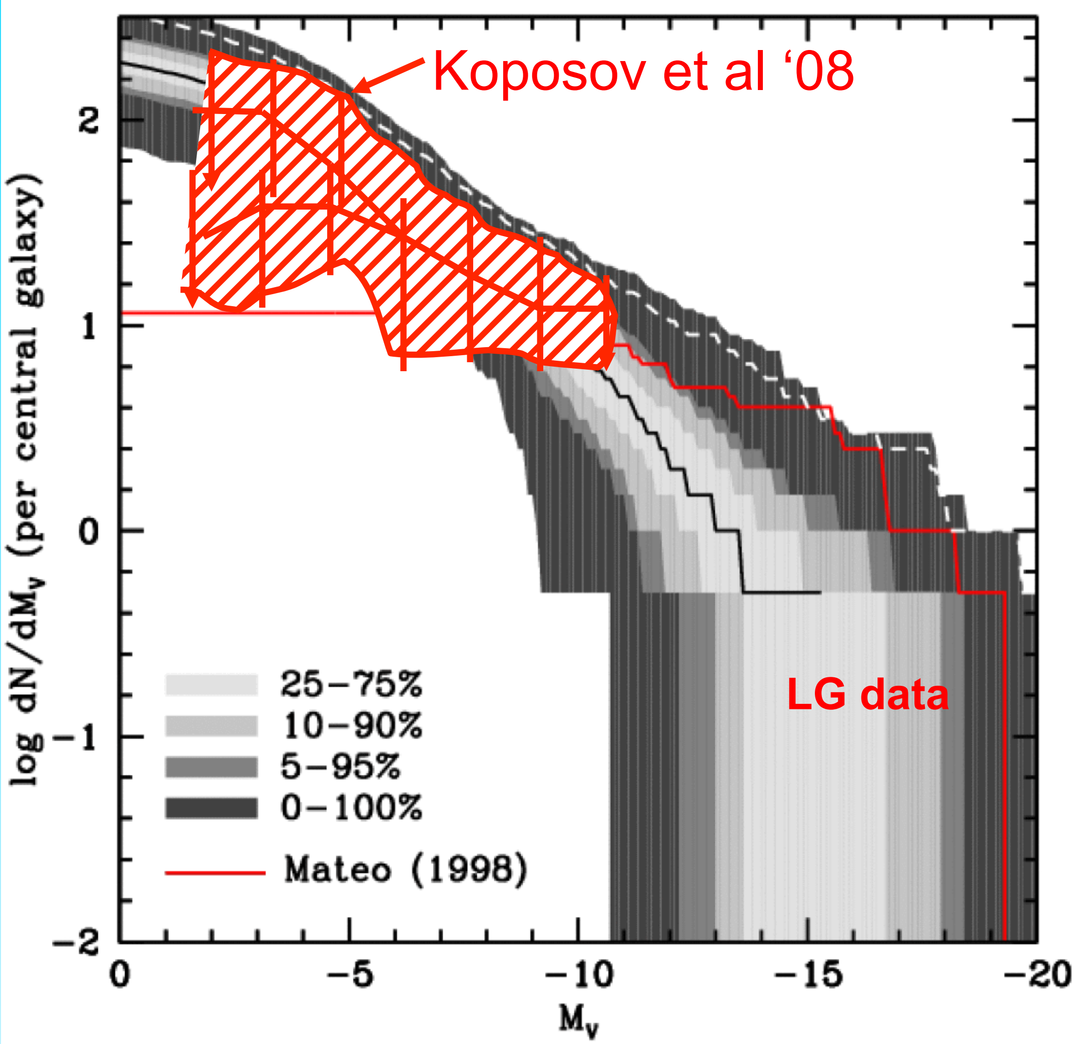


Luminosity Function of Local Group Satellites

- 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

cold dark matter

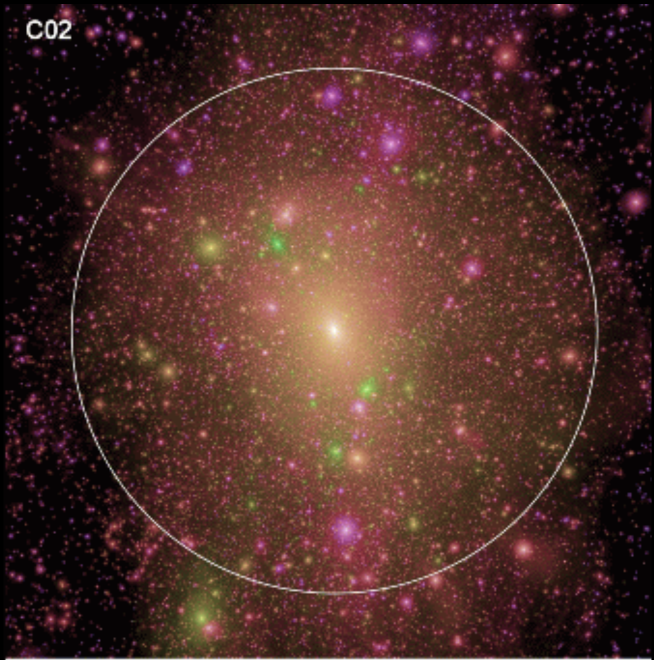
warm dark matter

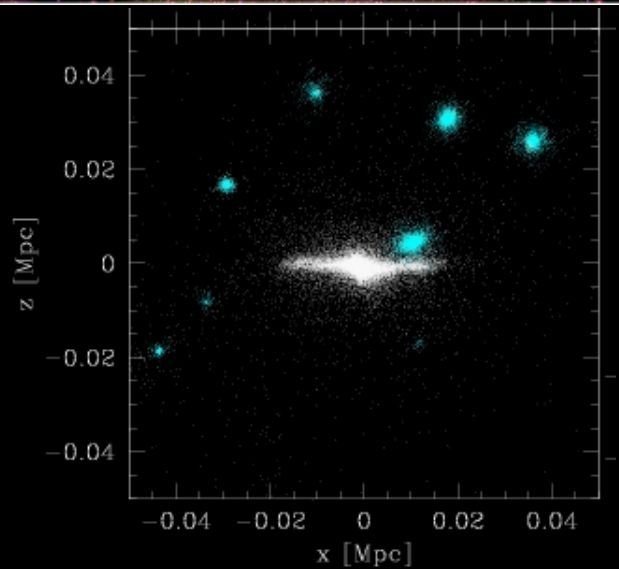
Counting satellites cannot distinguish CDM from WDM!

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

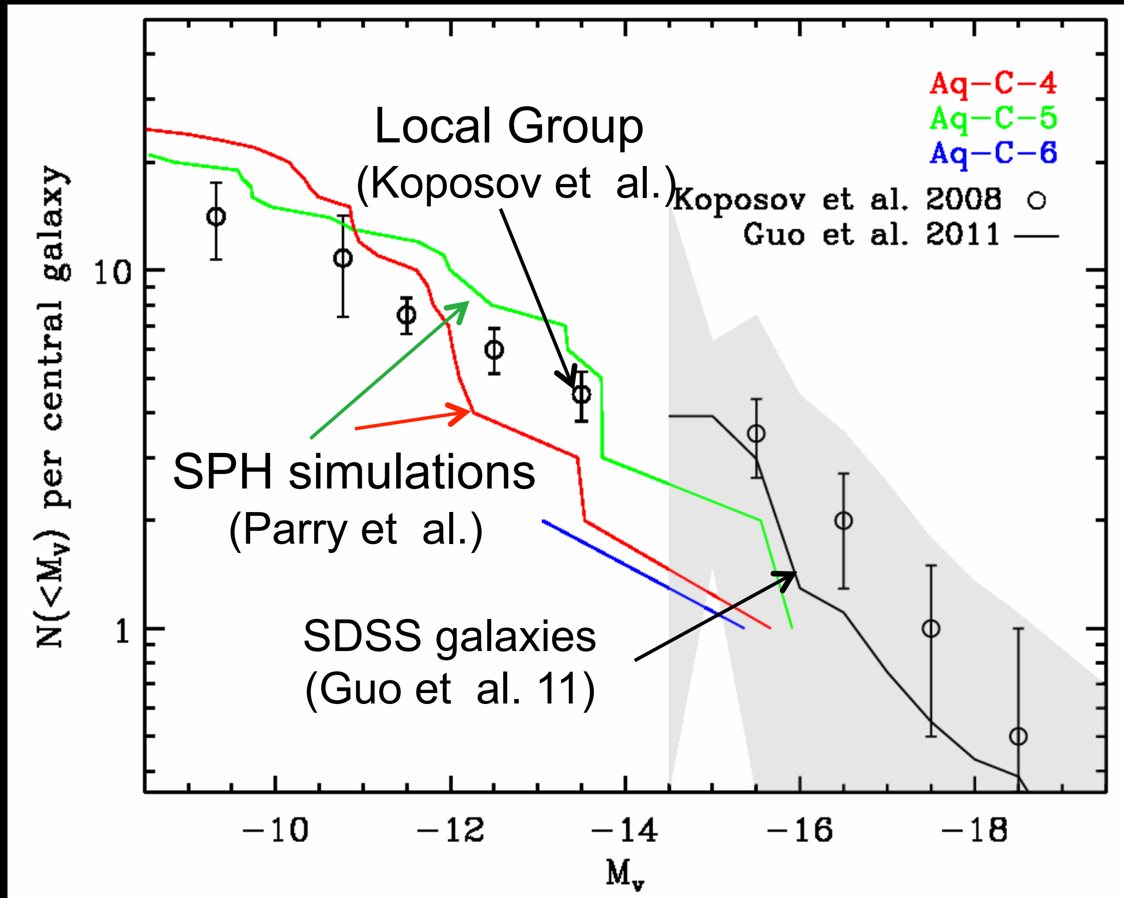
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

The satellites of the Milky Way





SPH simulations of galaxy formation in one of the Aquarius halos

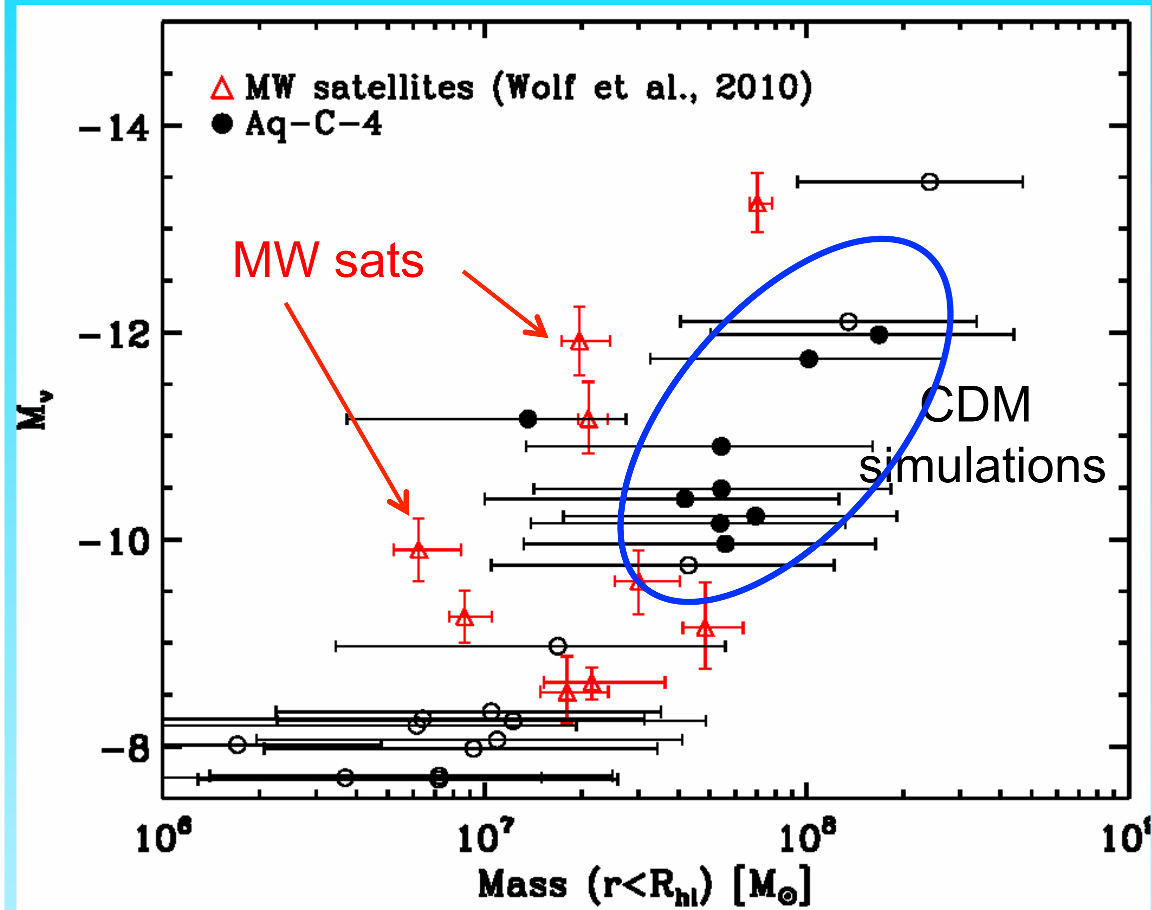


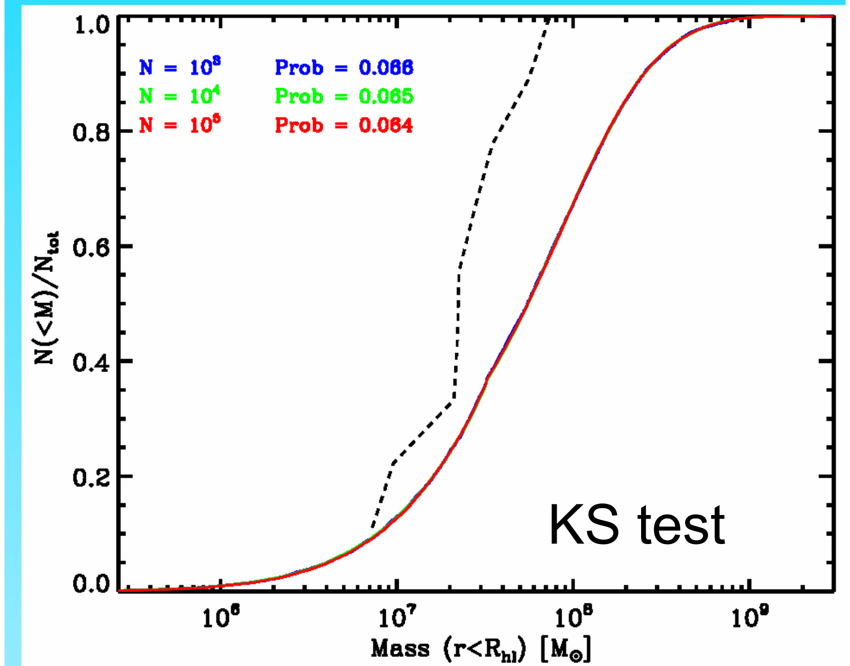
Parry, Eke, Frenk & Okamoto '11

The satellites of the Milky Way

University of Durham

Mass within half-light rad. (spectroscopy)





CDM puts the brightest sats in the biggest halos, but these are more massive than those indicated by the real data

CDM rejected at 93.6% confidence level

Parry, Eke & Frenk & Okamoto'11

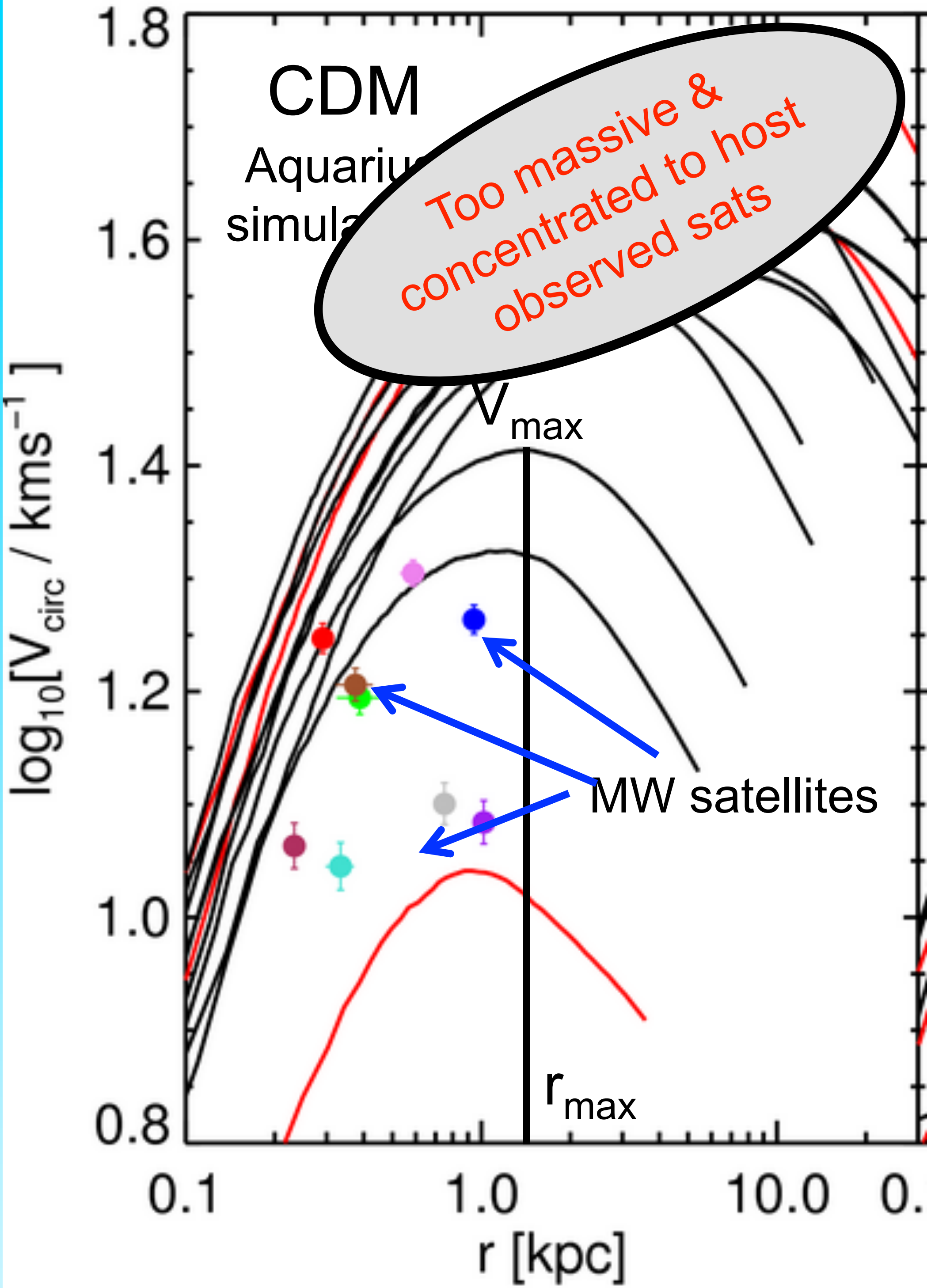
Institute for Computational Cosmology

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

cold dark matter

warm dark matter

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

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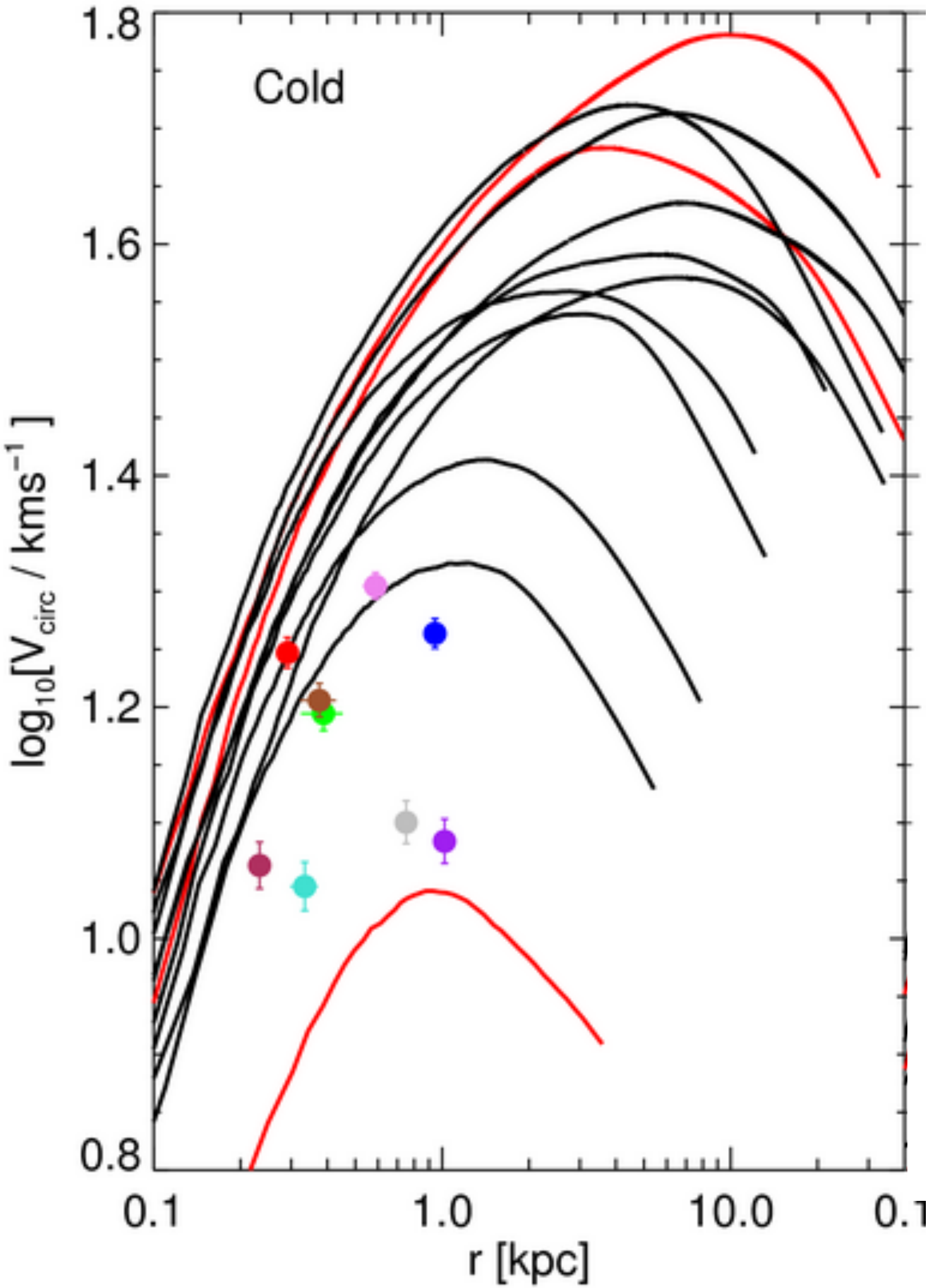
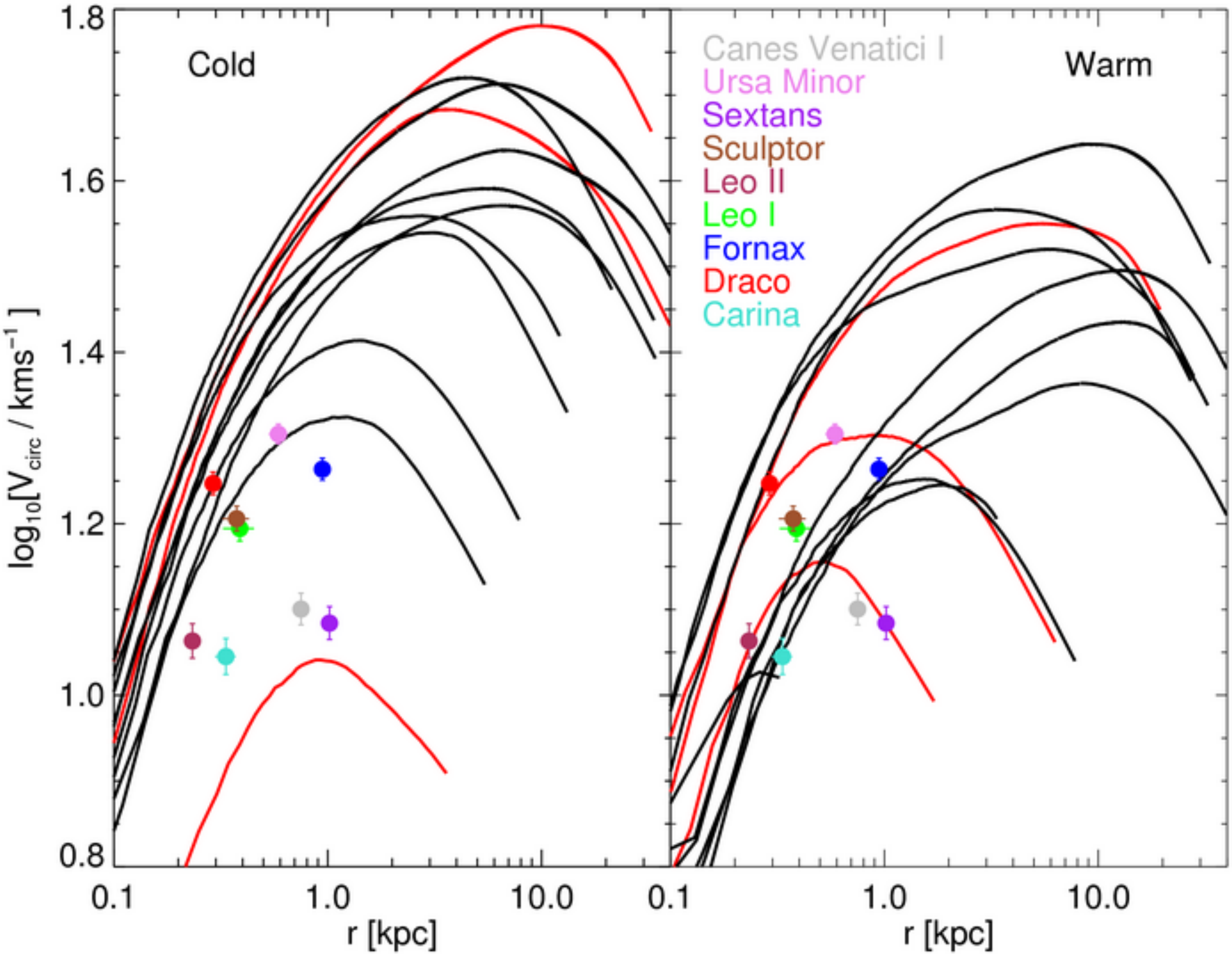


Lovell, Eke, Frenk, Gao,
Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '11



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

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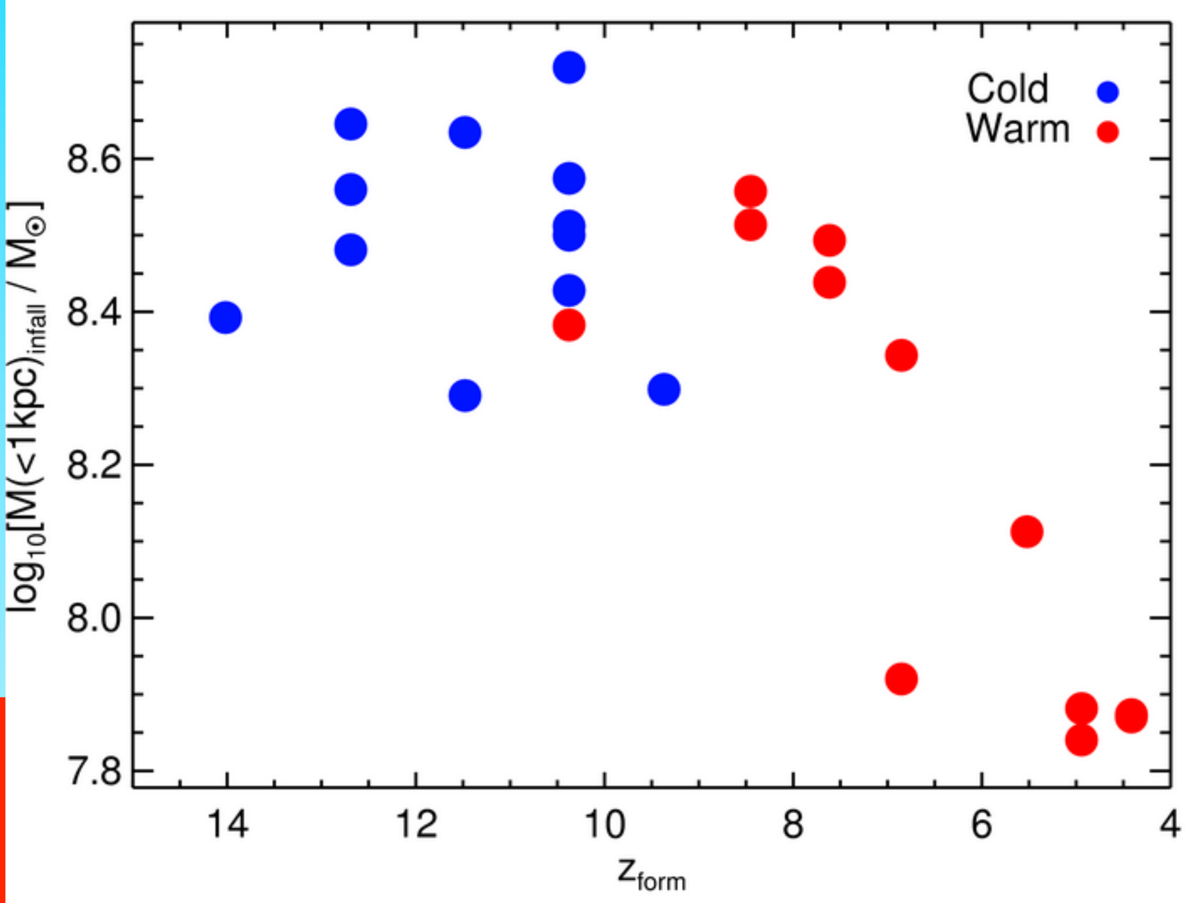
Warm vs cold dark matter subhalos

"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

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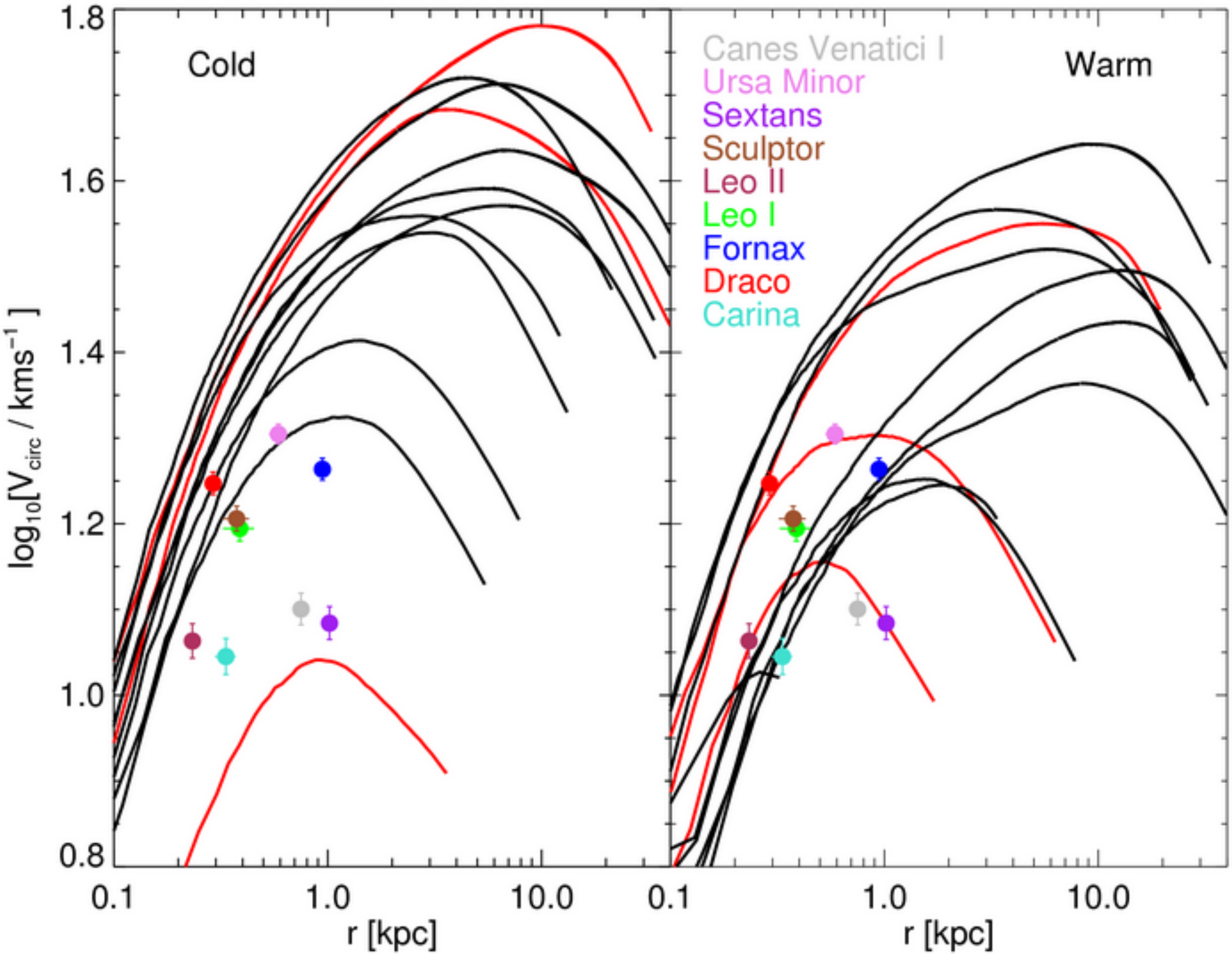

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r [kpc]
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1.6
1.4
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1.0
0.8
0.1
1.0
10.0

Is this the end of CDM?

1. Baryon effects
2. The mass of the MW

Baryon effects in the MW satellites

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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

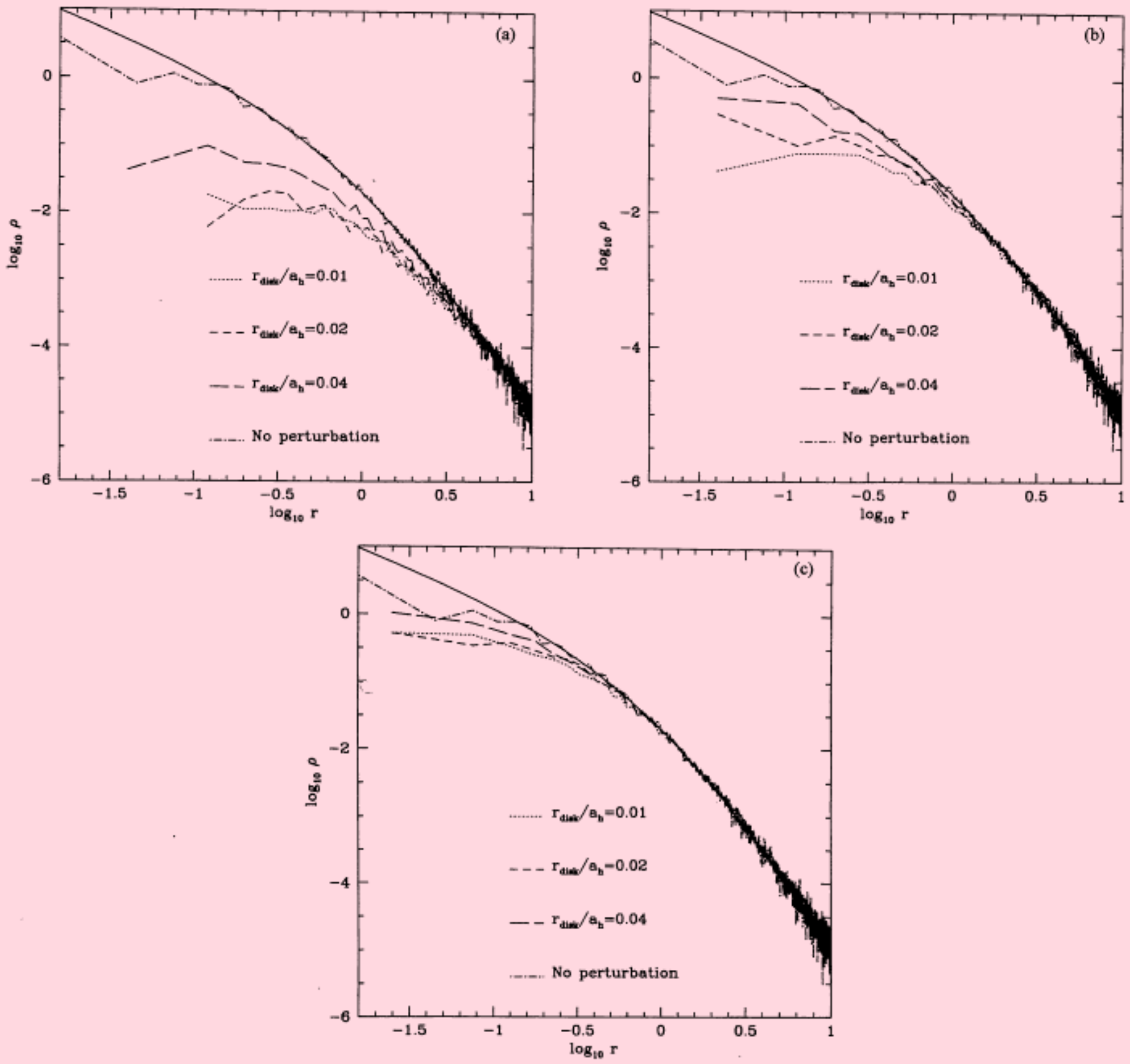
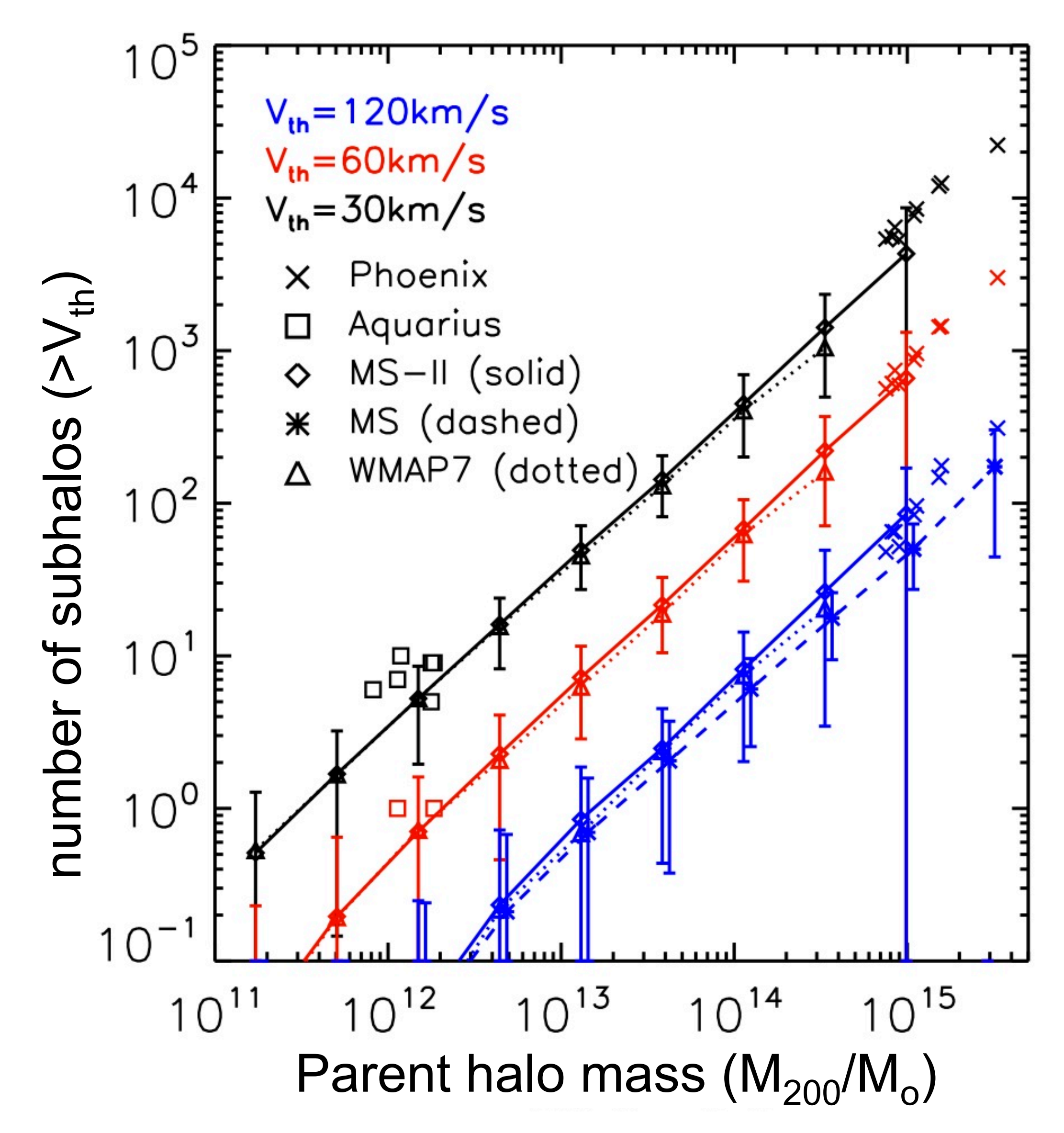


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

Number of massive subhalos

Number of subhalos increases rapidly with halo mass



Probability of massive subhalos

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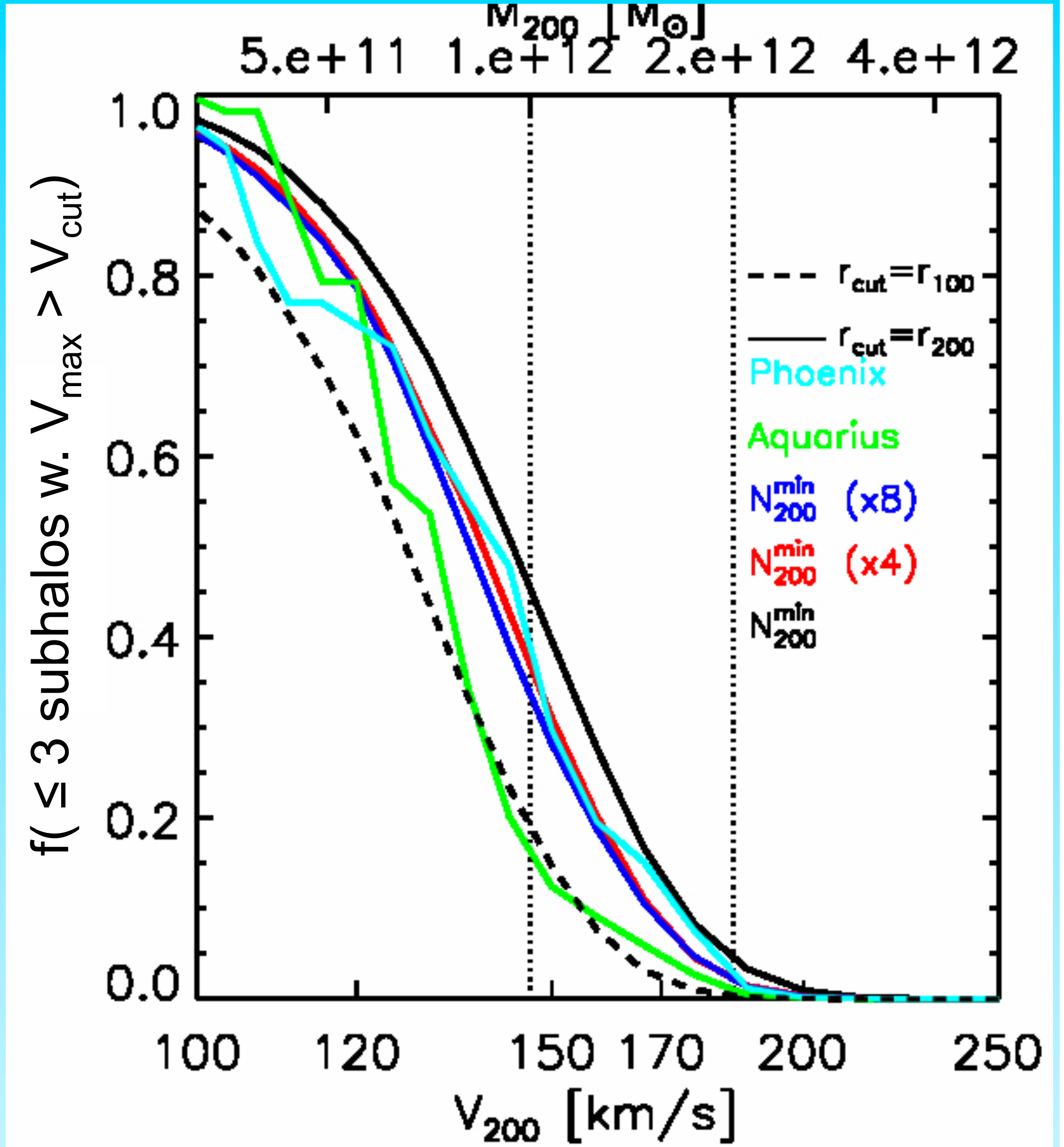
Probability of having no more than 3 subhalos with $V_{max} > V_{cut}$



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

If mass of MW ~$1x10^{12}M_o$, CDM may be OK!

Wang, Frenk, Navarro, Gao '12

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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

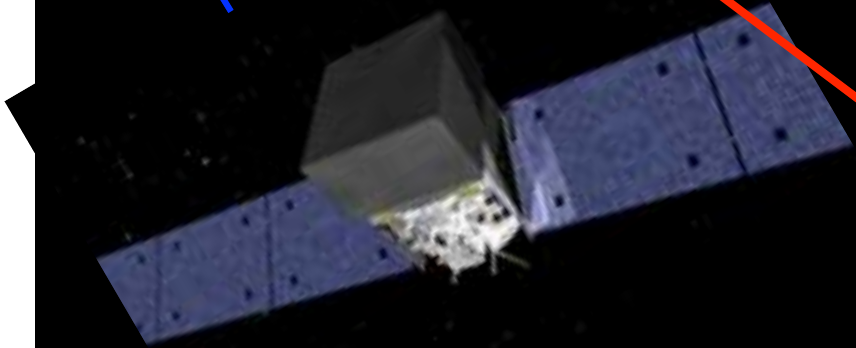
Possible solutions:

- Warm dark matter
- Baryon effects that make large CDM subhalos less concentrated
- Sat. pop. in the MW is atypical or V_{cut}>25 km/s or $M_{halo} \leq 10^{12} M_o$

Cold dark matter ?

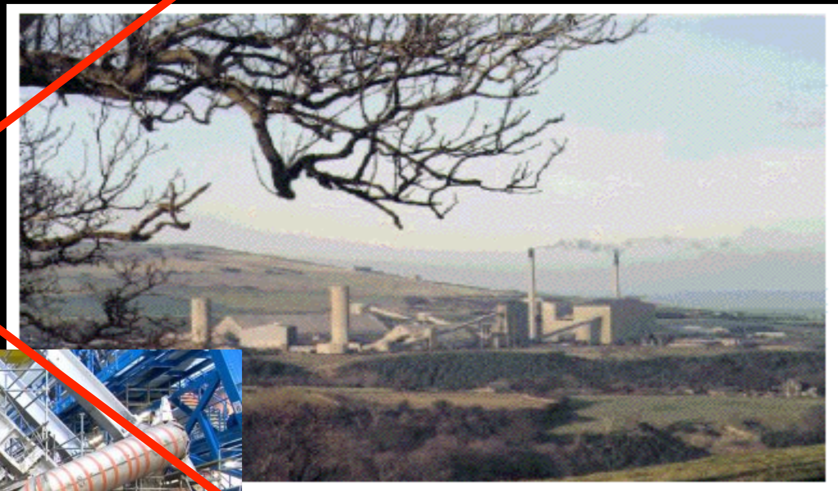
Dark matter discovery possible in several ways

Fermi

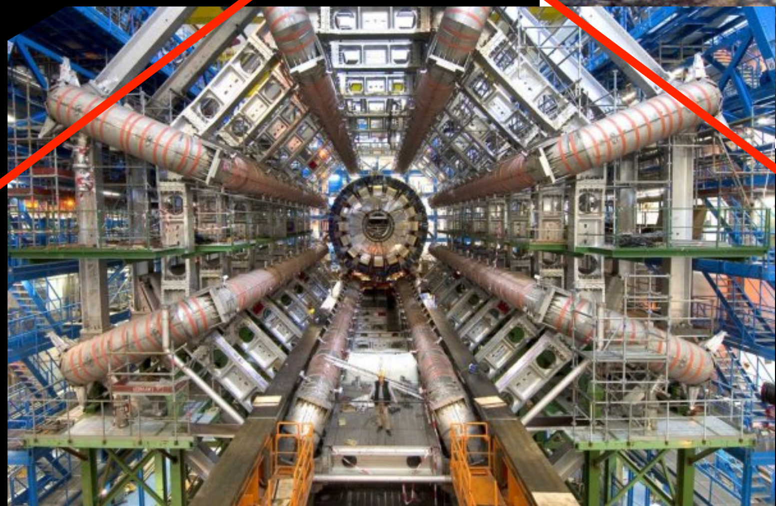


Annihilation radiation

Direct detection



UK DM search
(Boulby mine)



Evidence for SUSY

Institute for Computational Cosmology

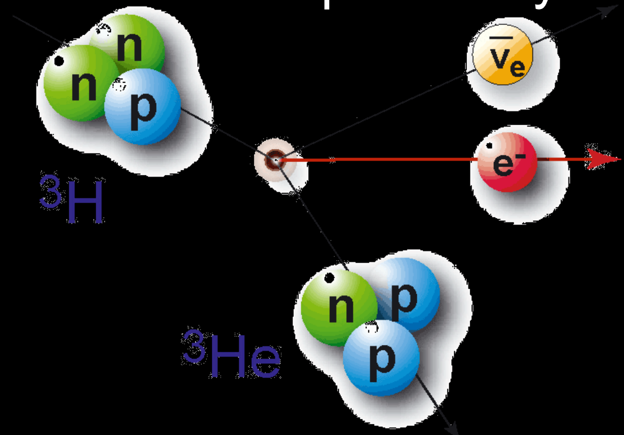
Warm dark matter ?

Sterile neutrino detection possible

Decay line in X-rays

Constellation X

Tritium β - decay



KATRIN
Karlsruhe Tritium Neutrino Experiment