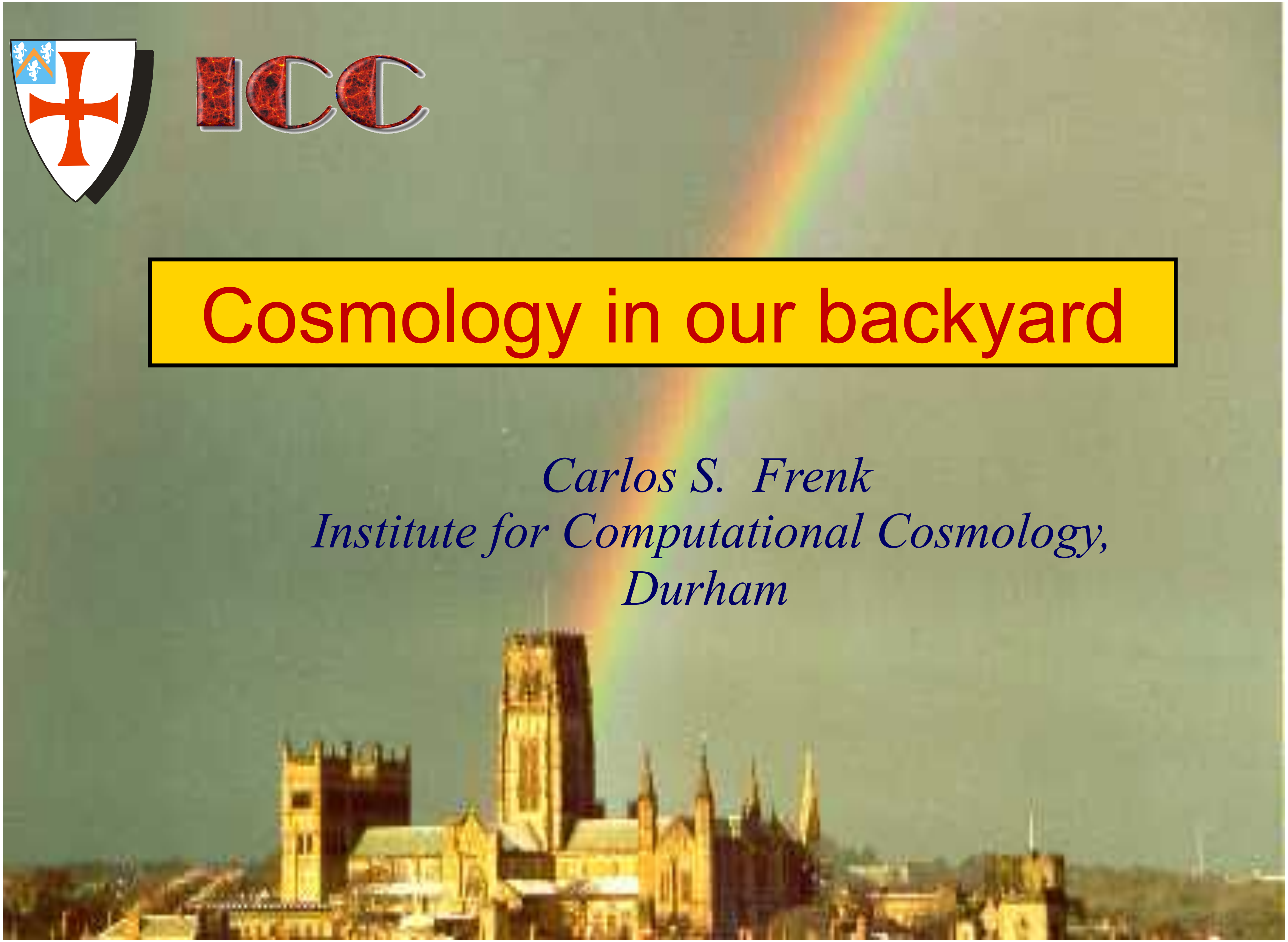
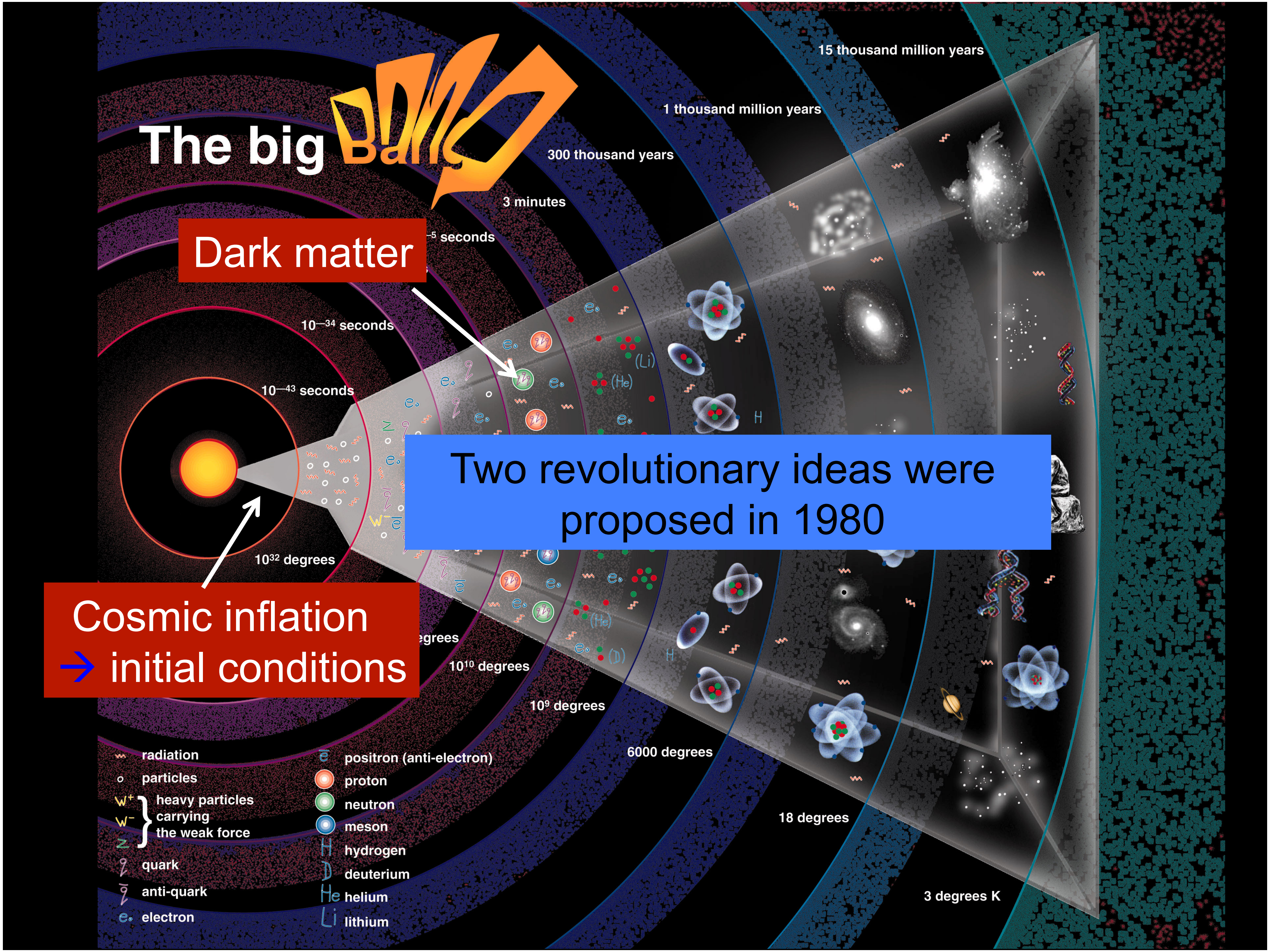


Cosmology in our backyard

Carlos S. Frenk
Institute for Computational Cosmology,
Durham

ΛCDM: the standard model of cosmology



The big Bang
Dark matter
Two revolutionary ideas were proposed in 1980
Cosmic inflation
→ initial conditions
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
–5 seconds
10–34 seconds
10–43 seconds
10^32 degrees
egrees
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	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

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The dark matter power spectrum

Free streaming →

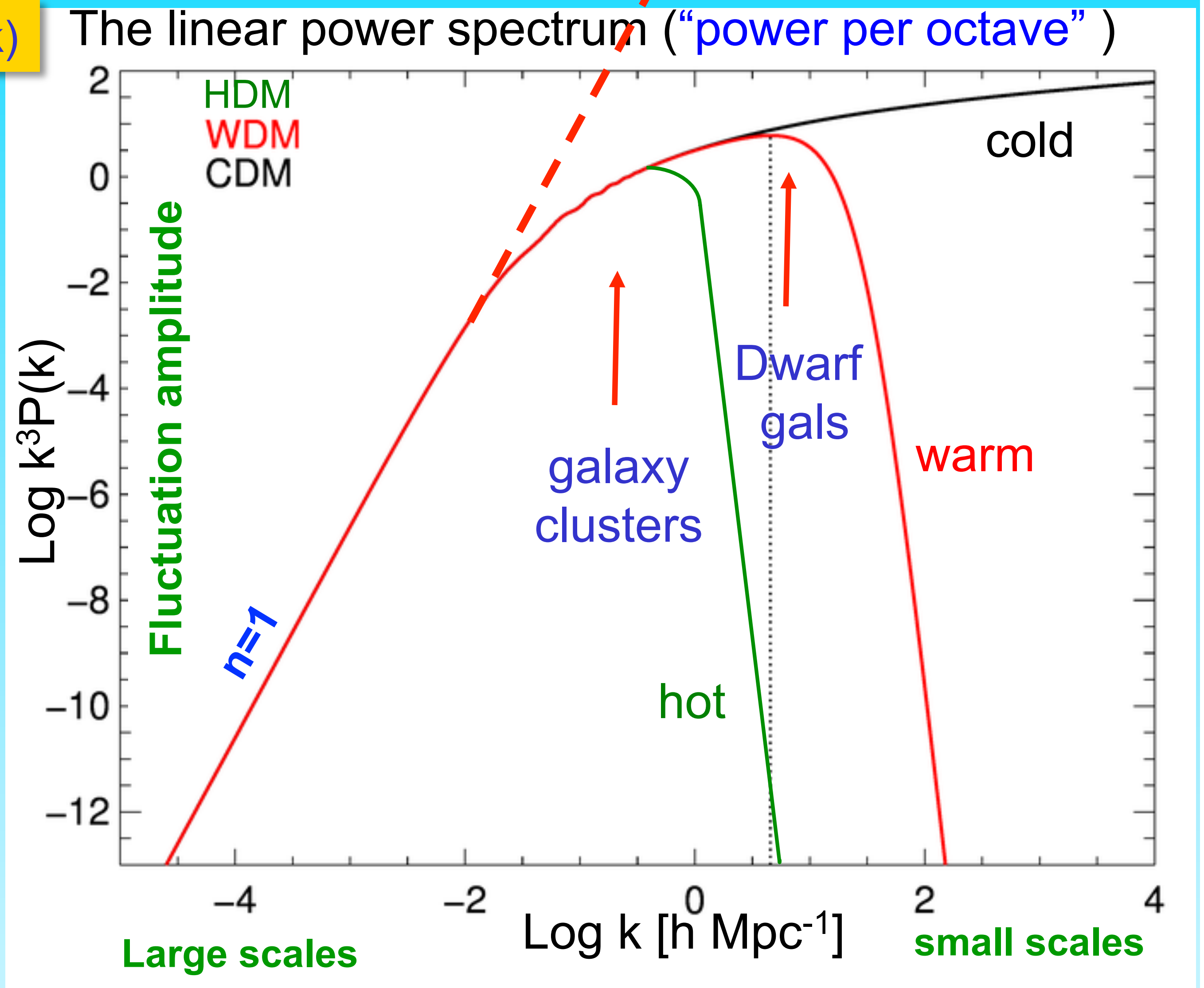
$\lambda_{cut} \propto m_x^{-1}$
for thermal relic

$m_{CDM} \sim$ 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; $M_{cut} \sim 10^{15}\ M_o$

$k^3\,P(k)$



The formation of cosmic structure

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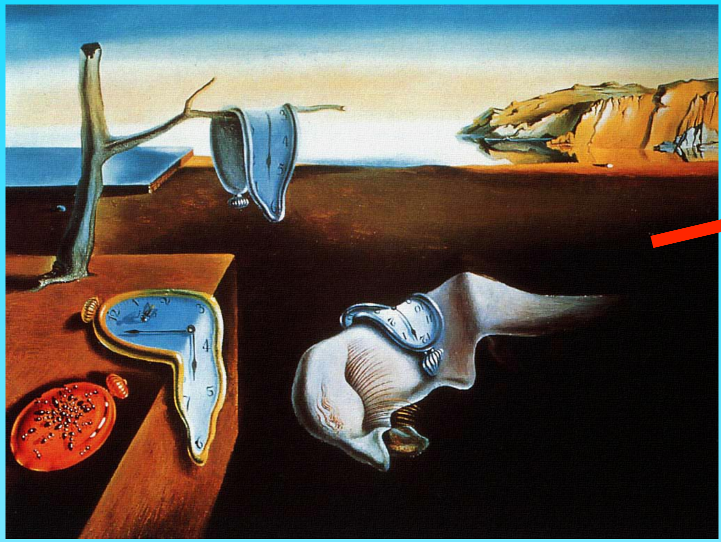
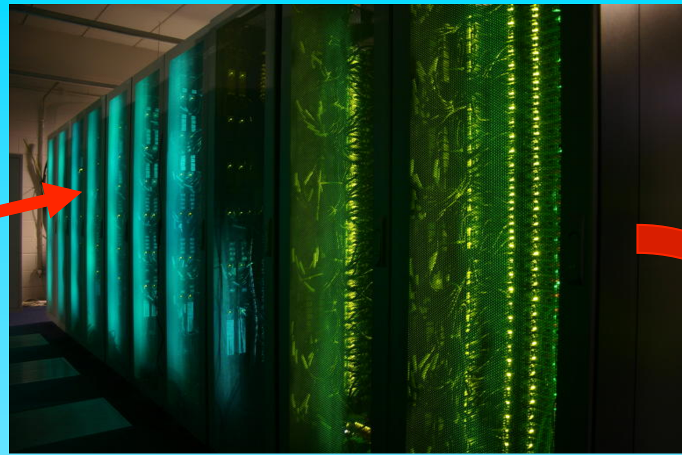
t=10^{-35} seconds



"Cosmology machine"



t=380,000 yrs

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

Simulations

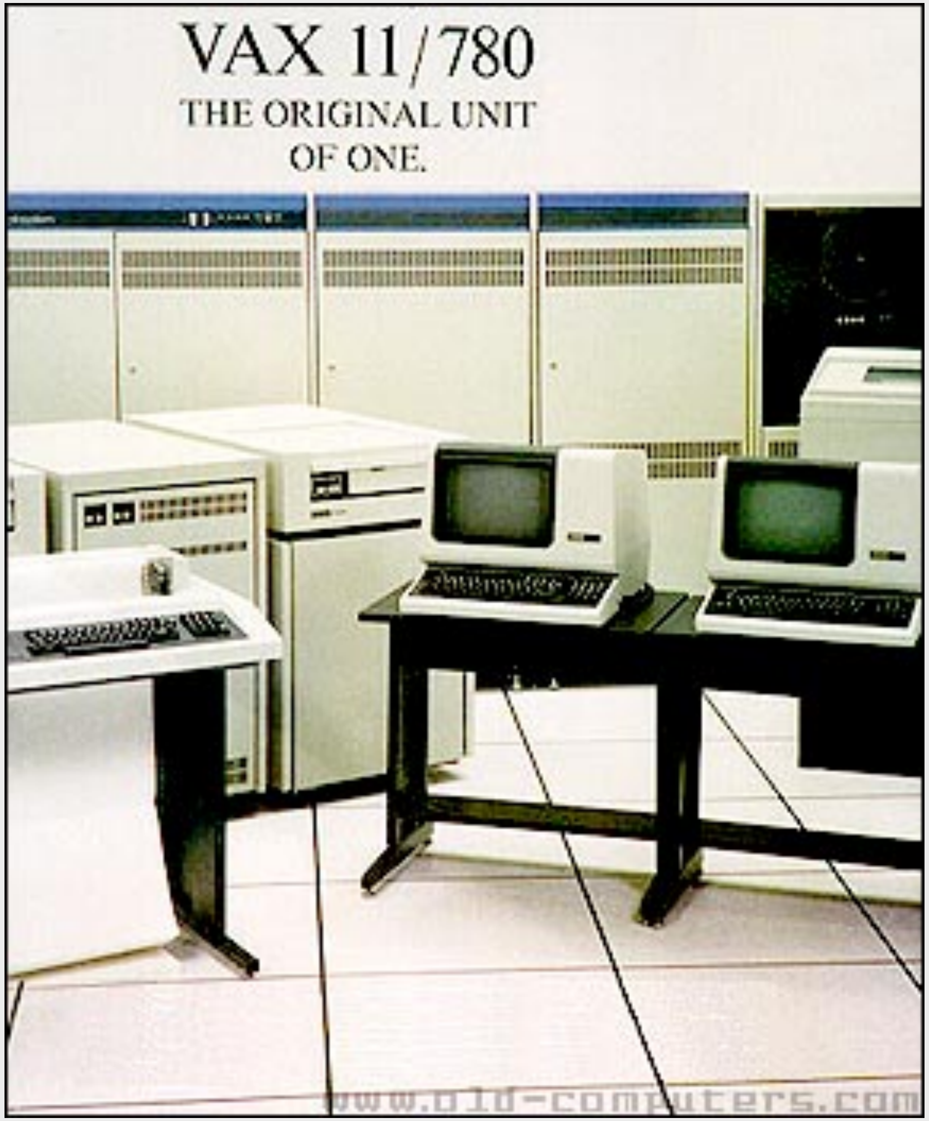
Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

t=13.8 billion yrs

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

Institute for Computational Cosmology

The universe in a computer



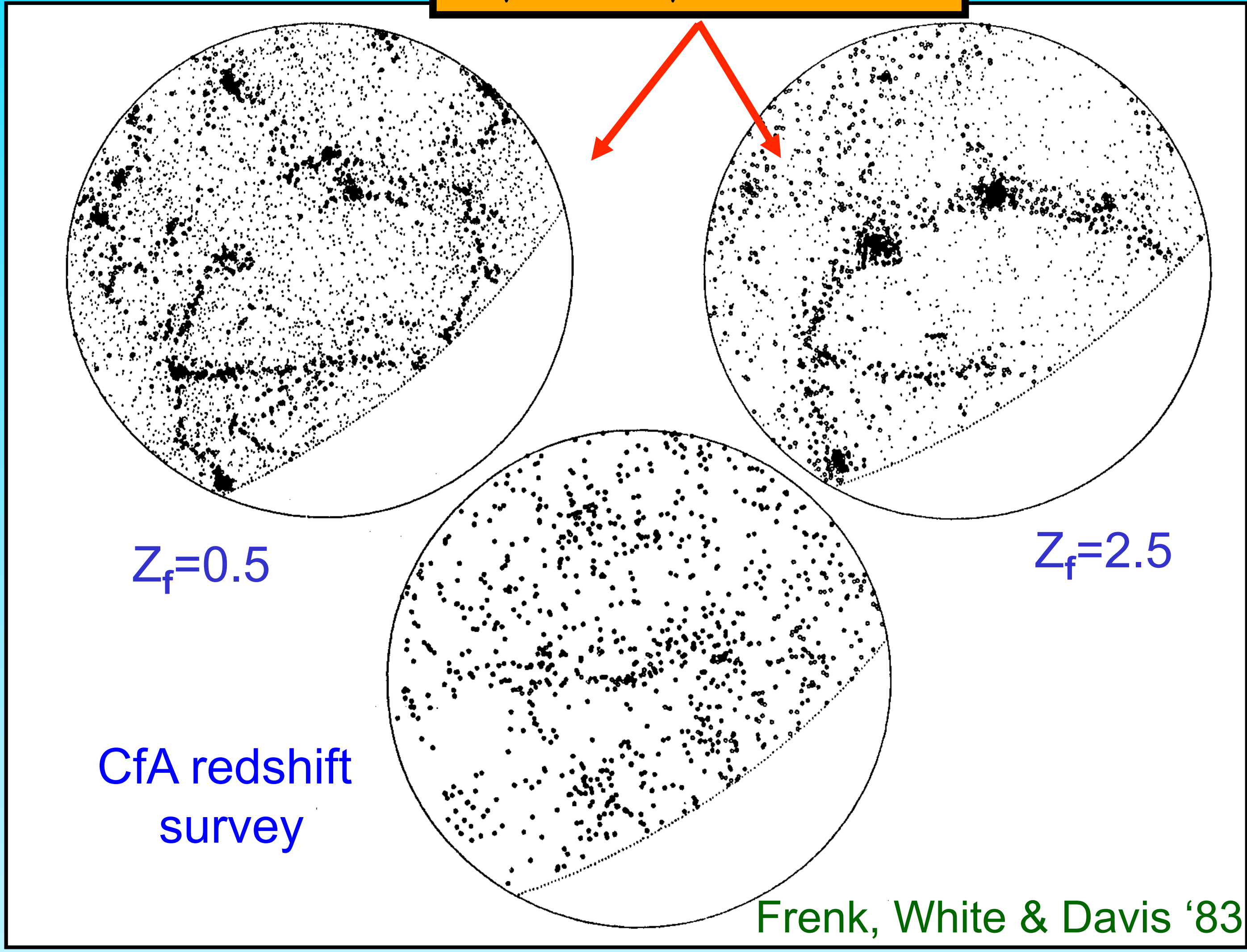
December 1981

Speed = 500,000 FLOPS
RAM = 4 Mbytes

ICC University of Durham

Neutrino (hot) dark matter

$\Omega_\nu = 1$ (m_ν = 30 ev)



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

⇨

Neutrinos cannot make an appreciable contribution to Ω

→ m_ν<< 10 ev

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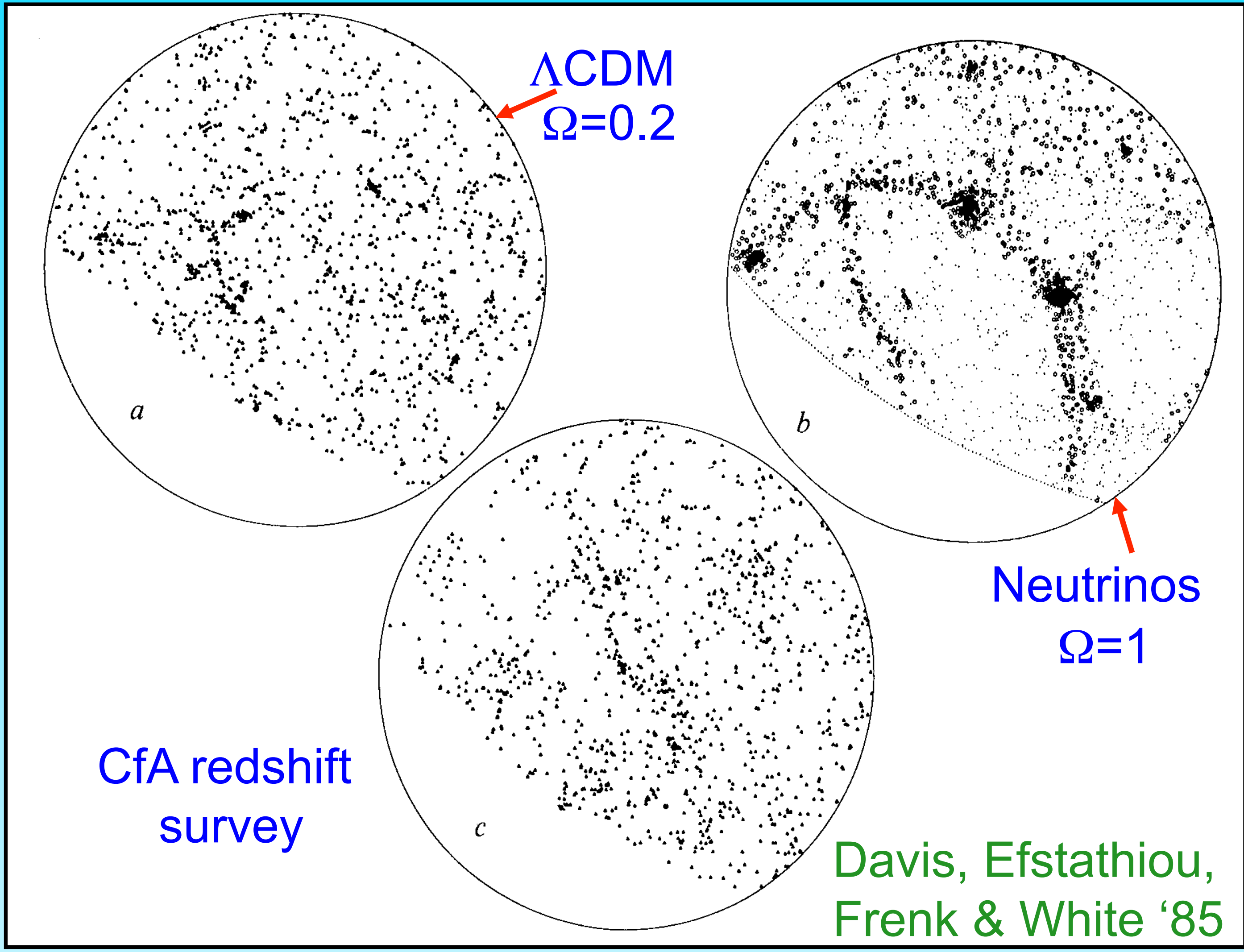
Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

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

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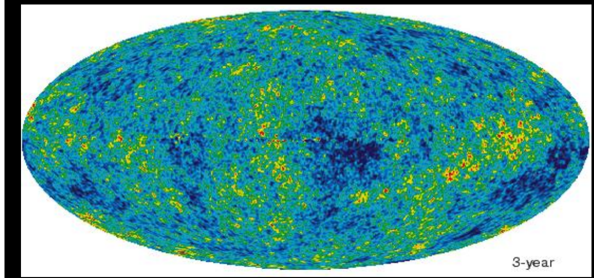
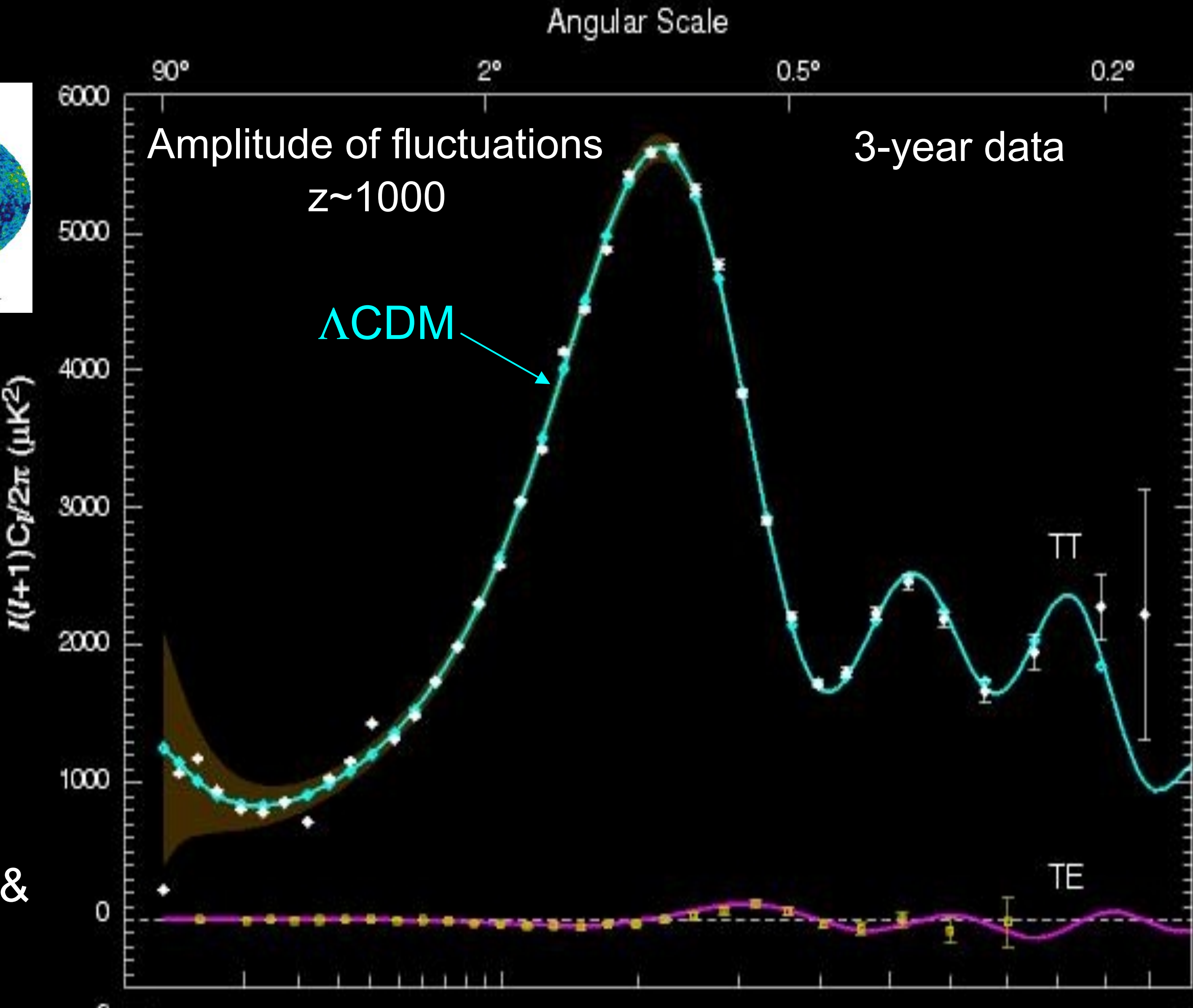
The cold dark matter cosmogony

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 -)

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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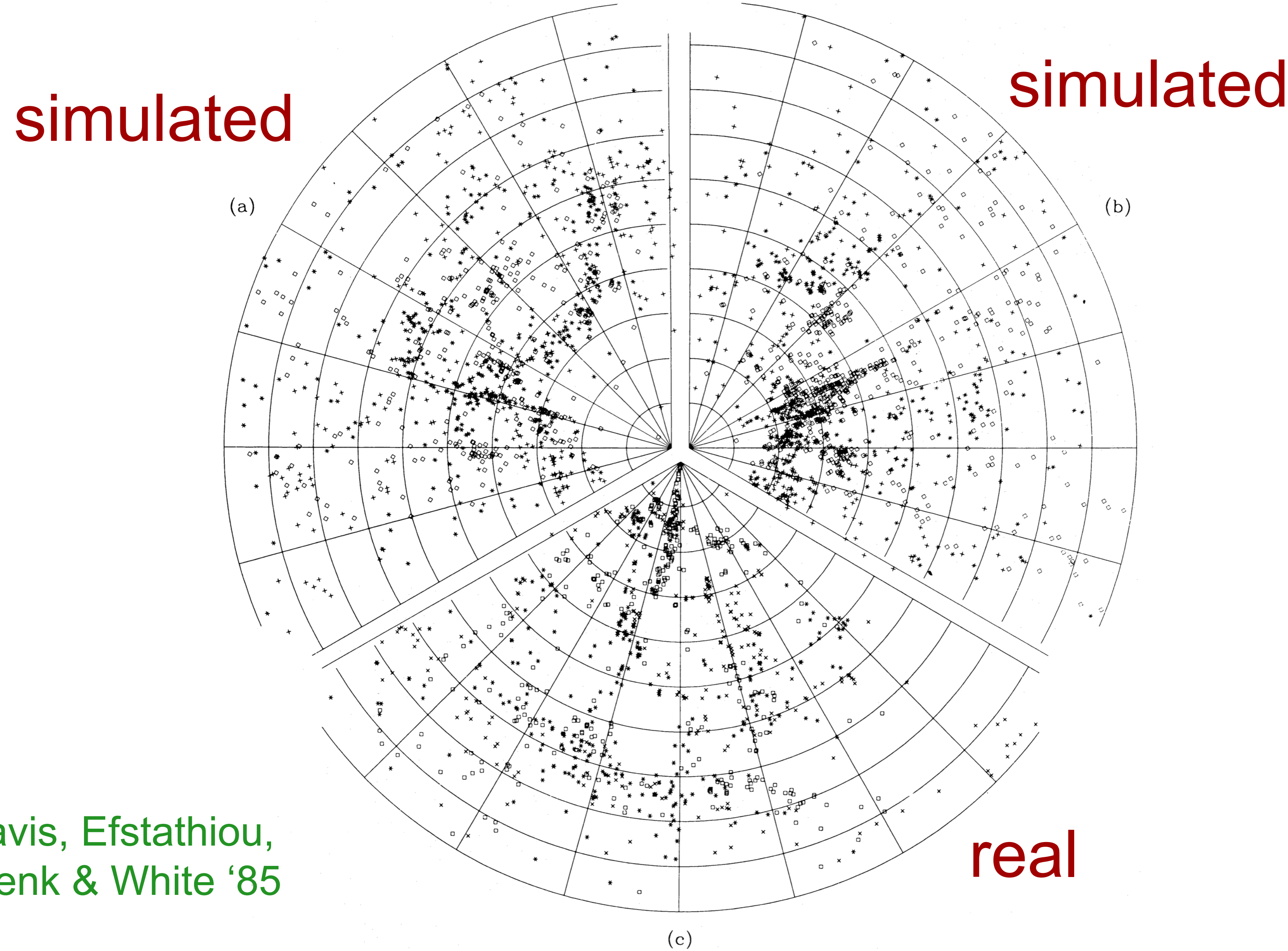
Early simulations of ΛCDM



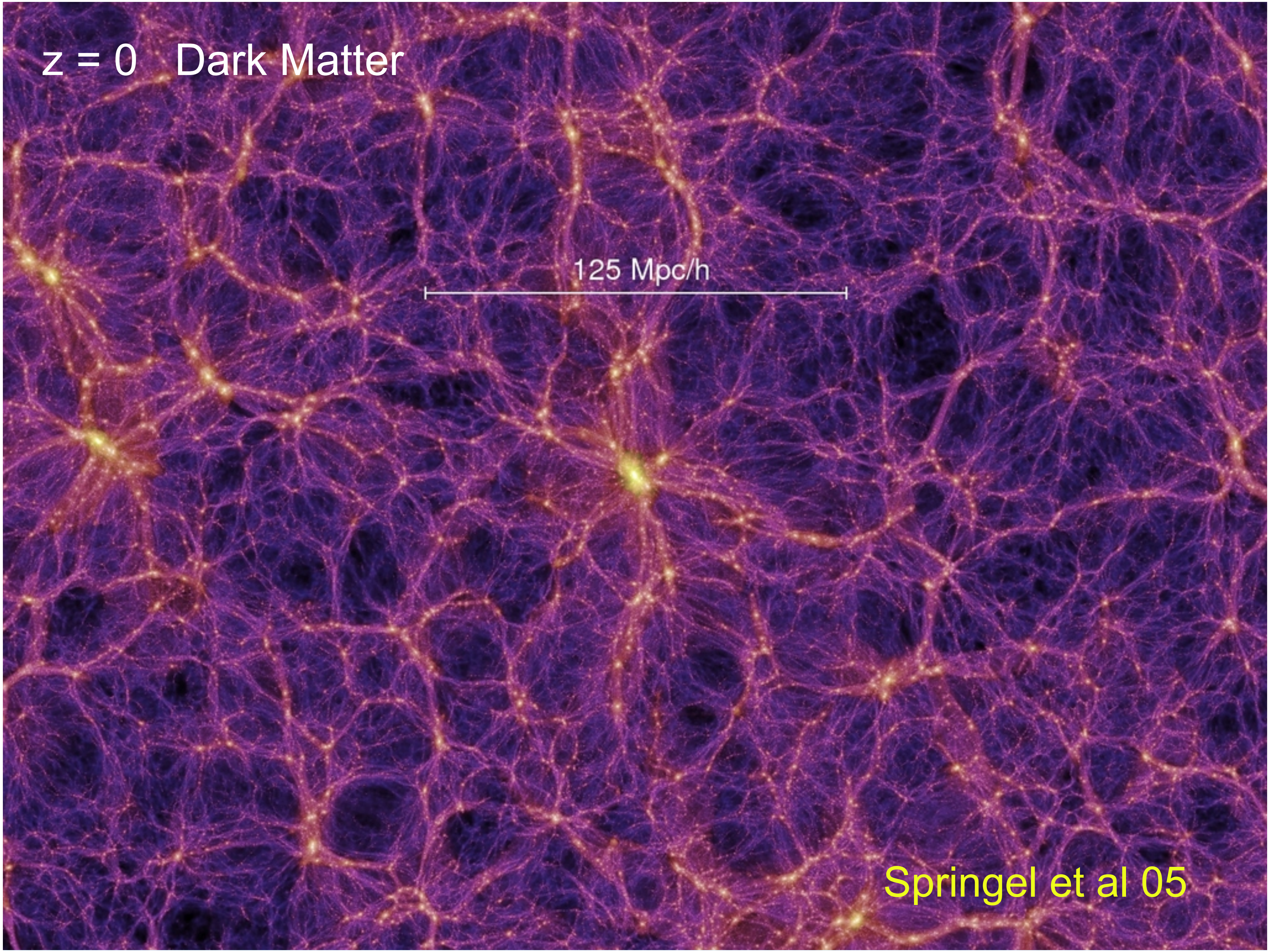
Davis, Efstathiou, Frenk & White '85

The 2dF Galaxy Redshift Survey

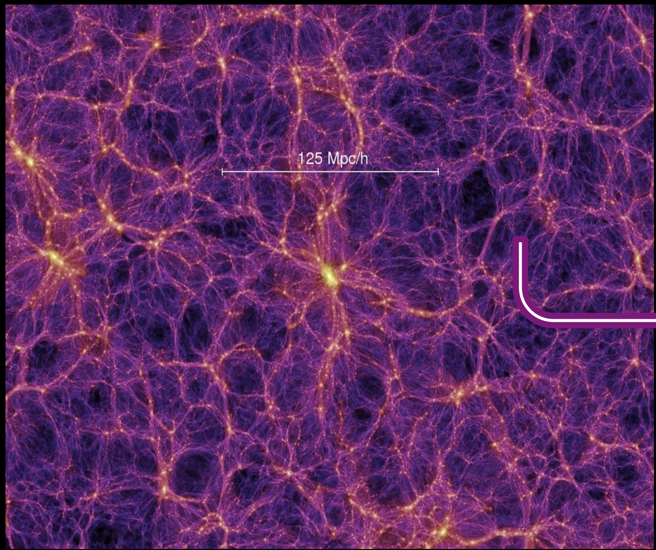
221,000 redshifts

z~0

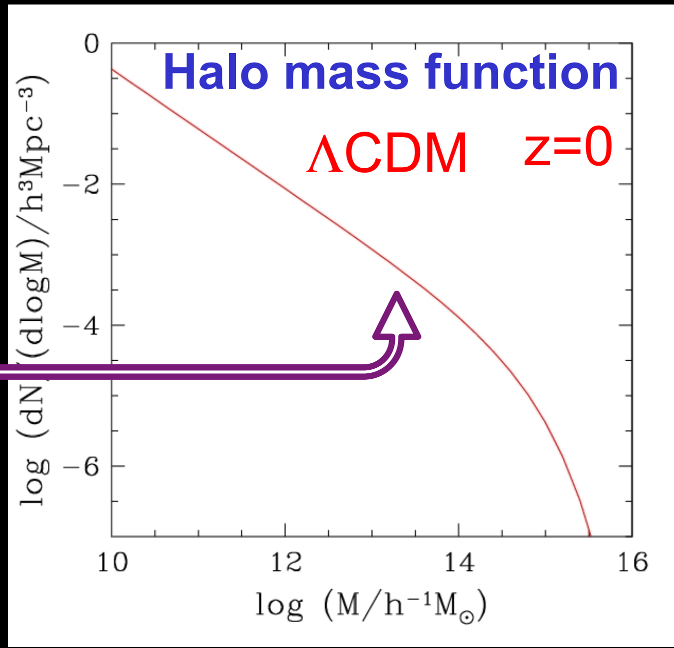
2005

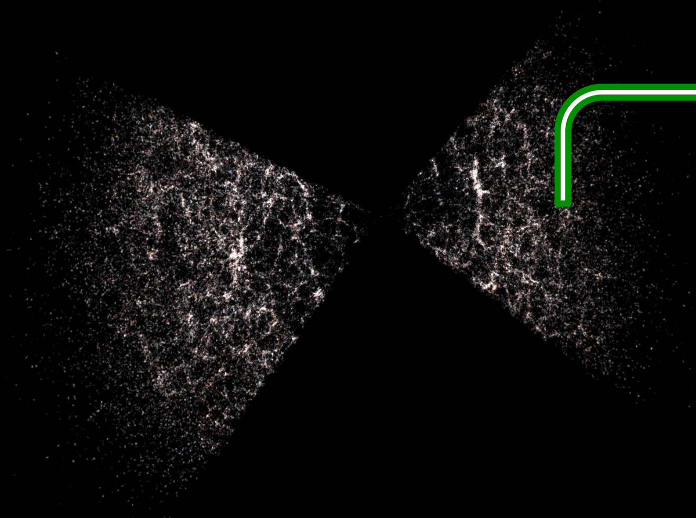

z = 0 Dark Matter
125 Mpc/h
Springel et al 05

Abundance of gals & dark halos

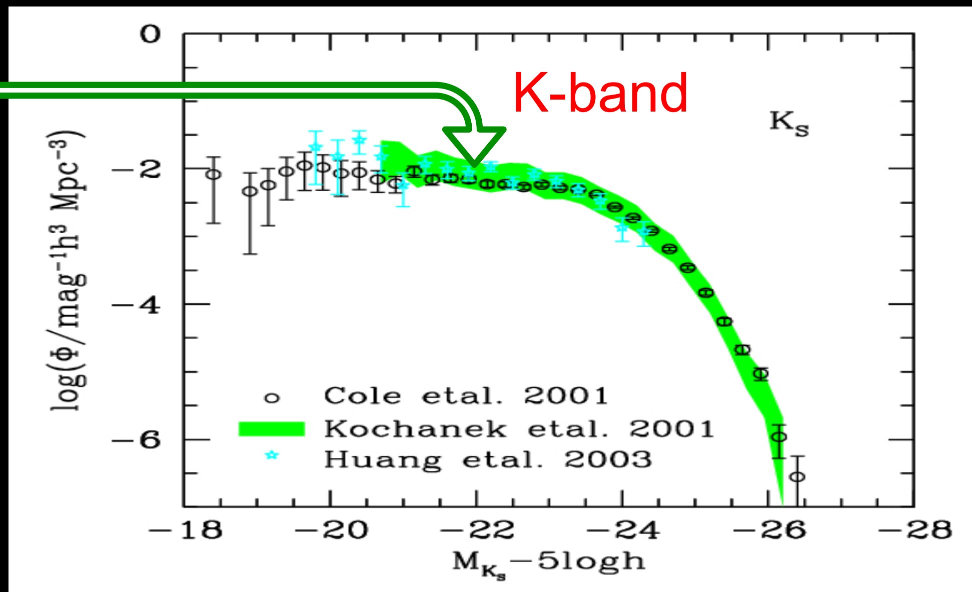


Millennium run





2dFGRS



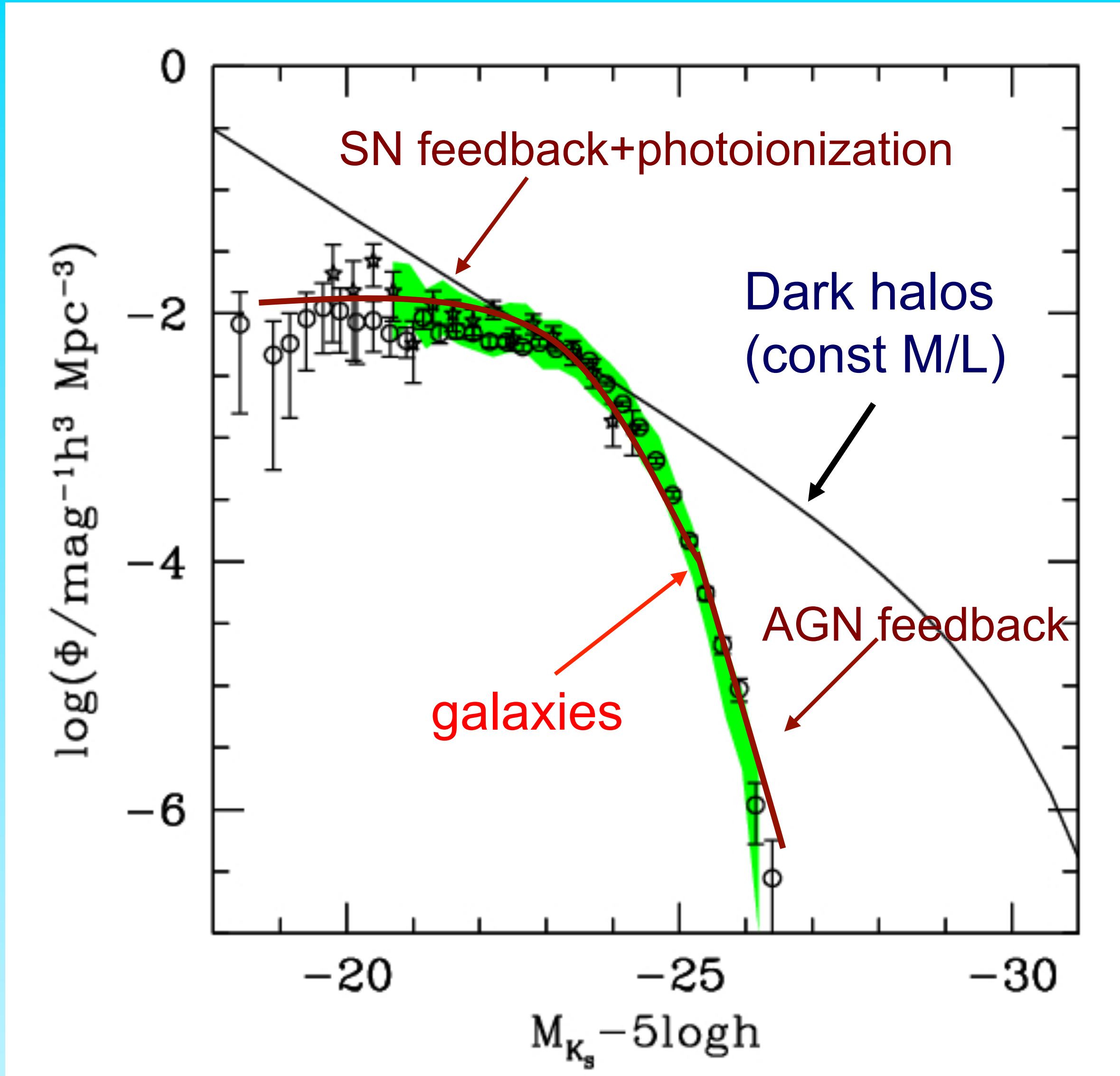
The galaxy luminosity function

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

The cold dark matter cosmogony

University of Durham

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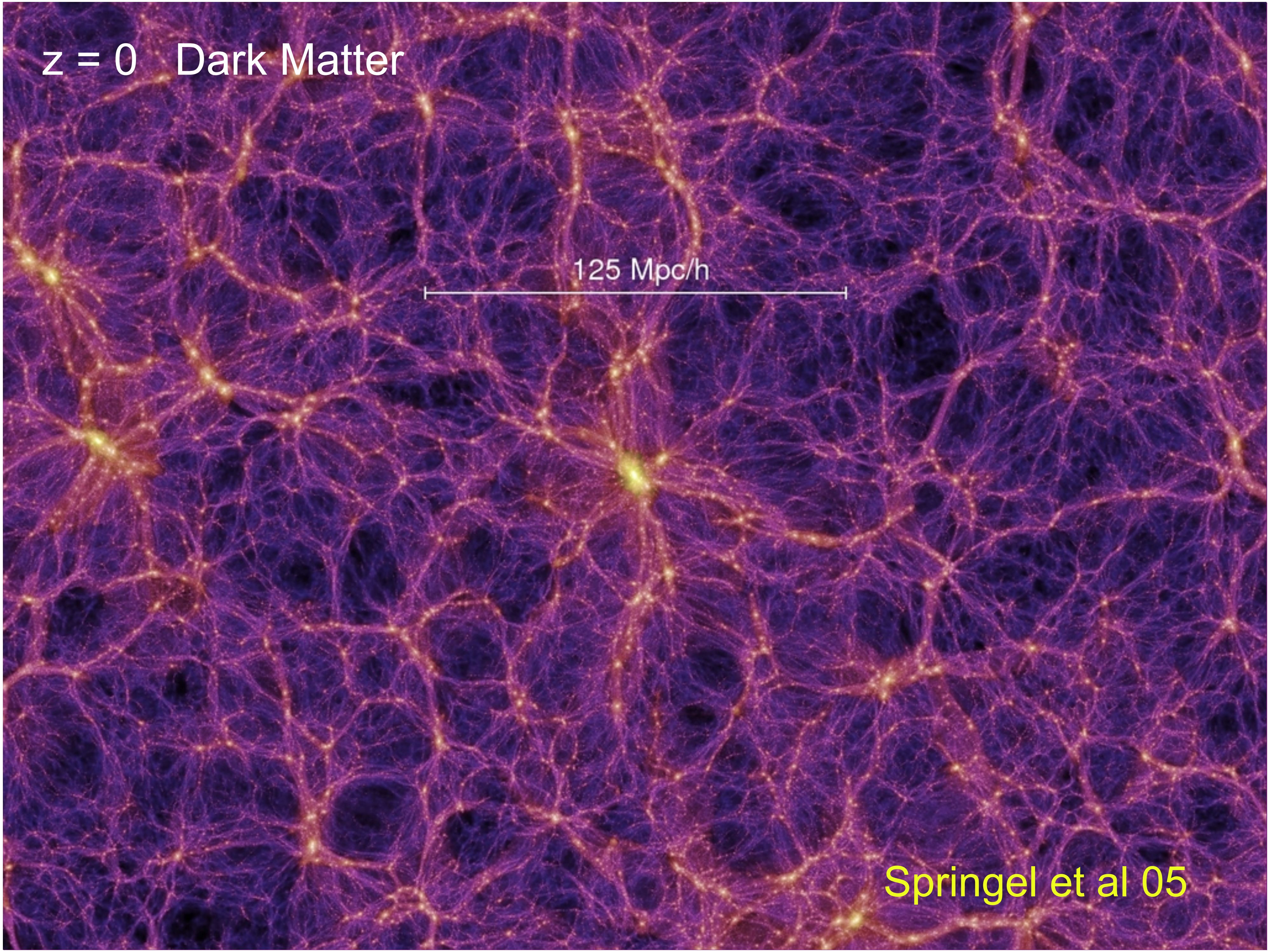
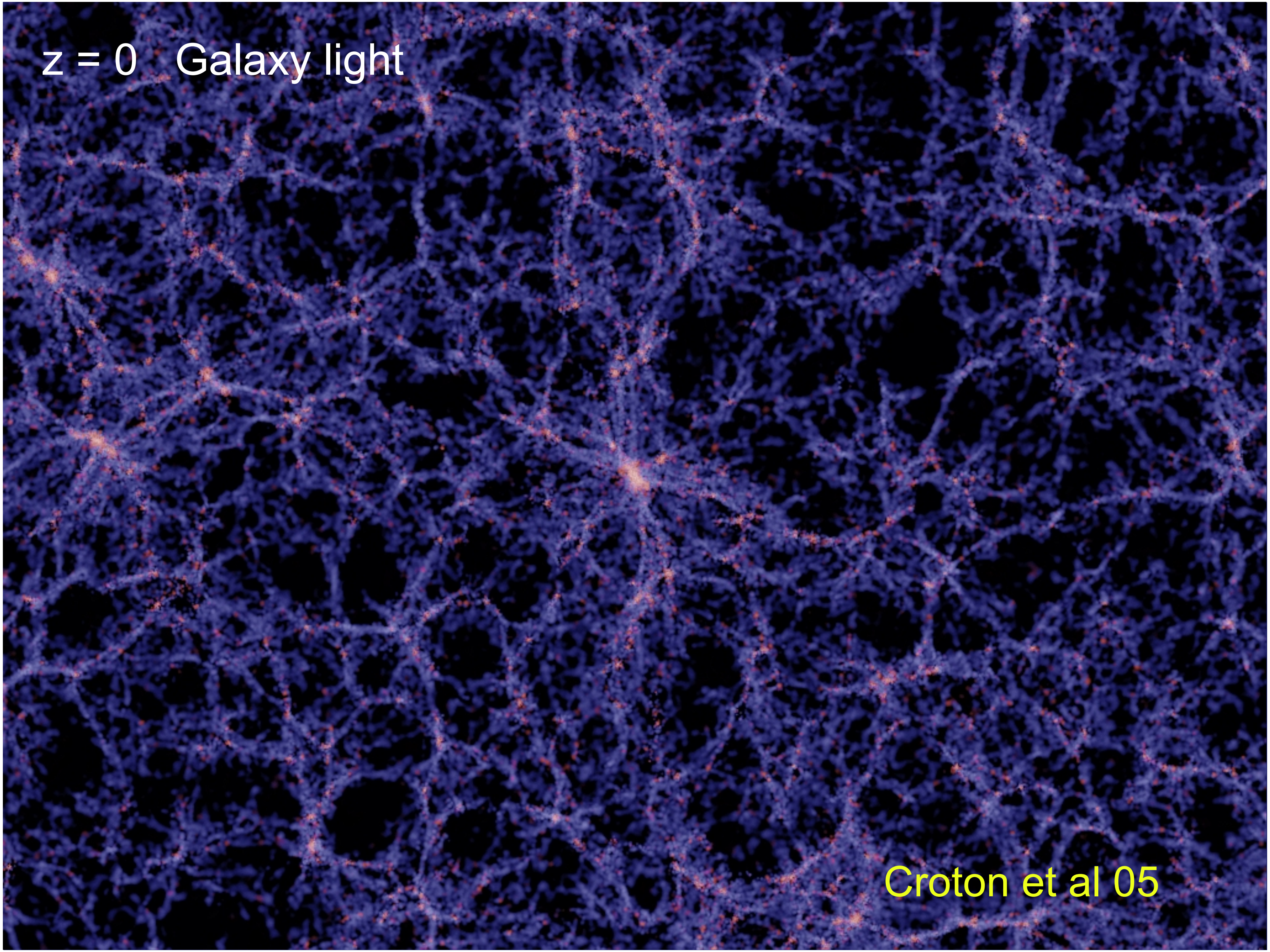

z = 0 Dark Matter
125 Mpc/h
Springel et al 05


z = 0   Galaxy light
Croton et al 05

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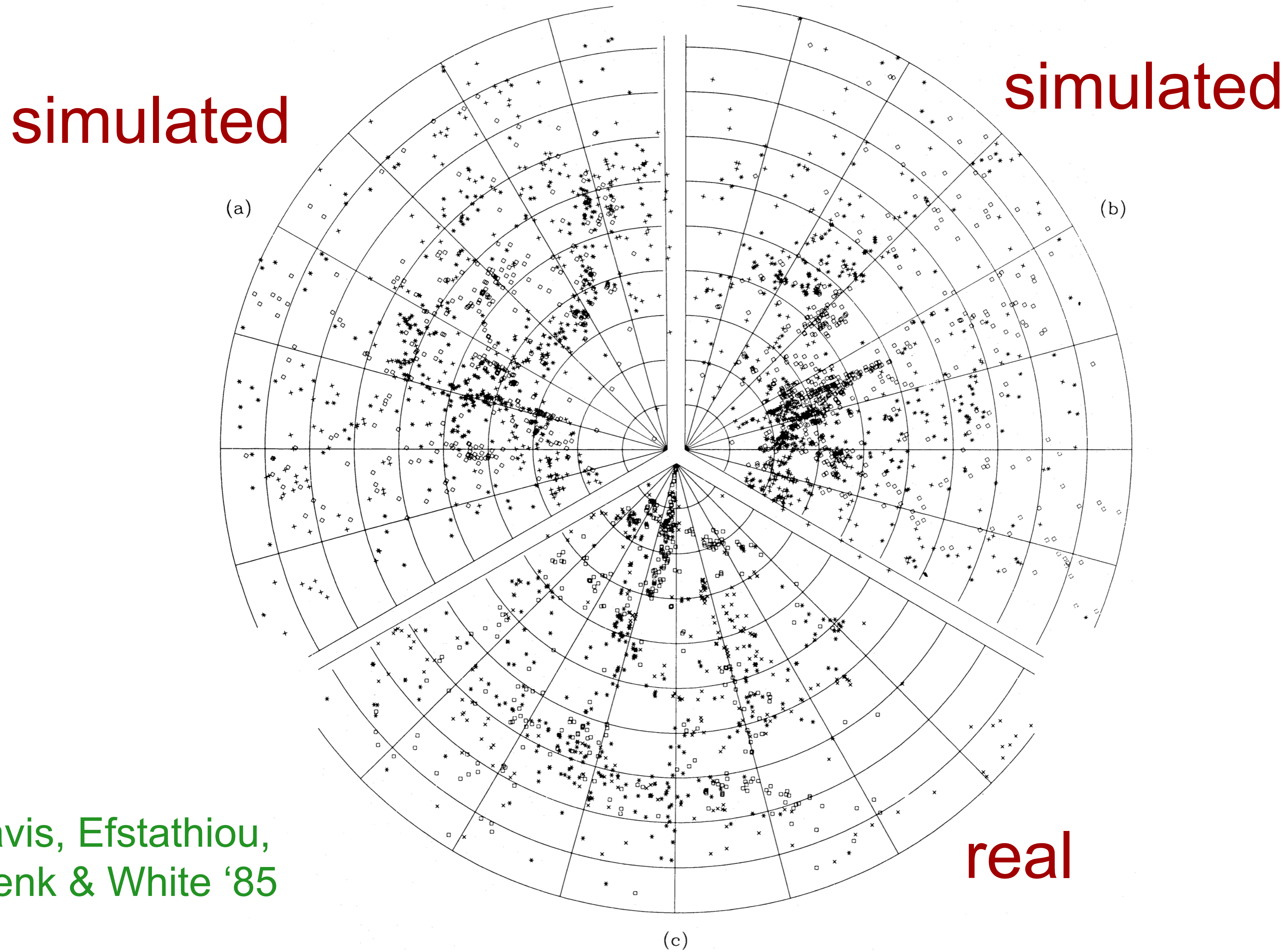
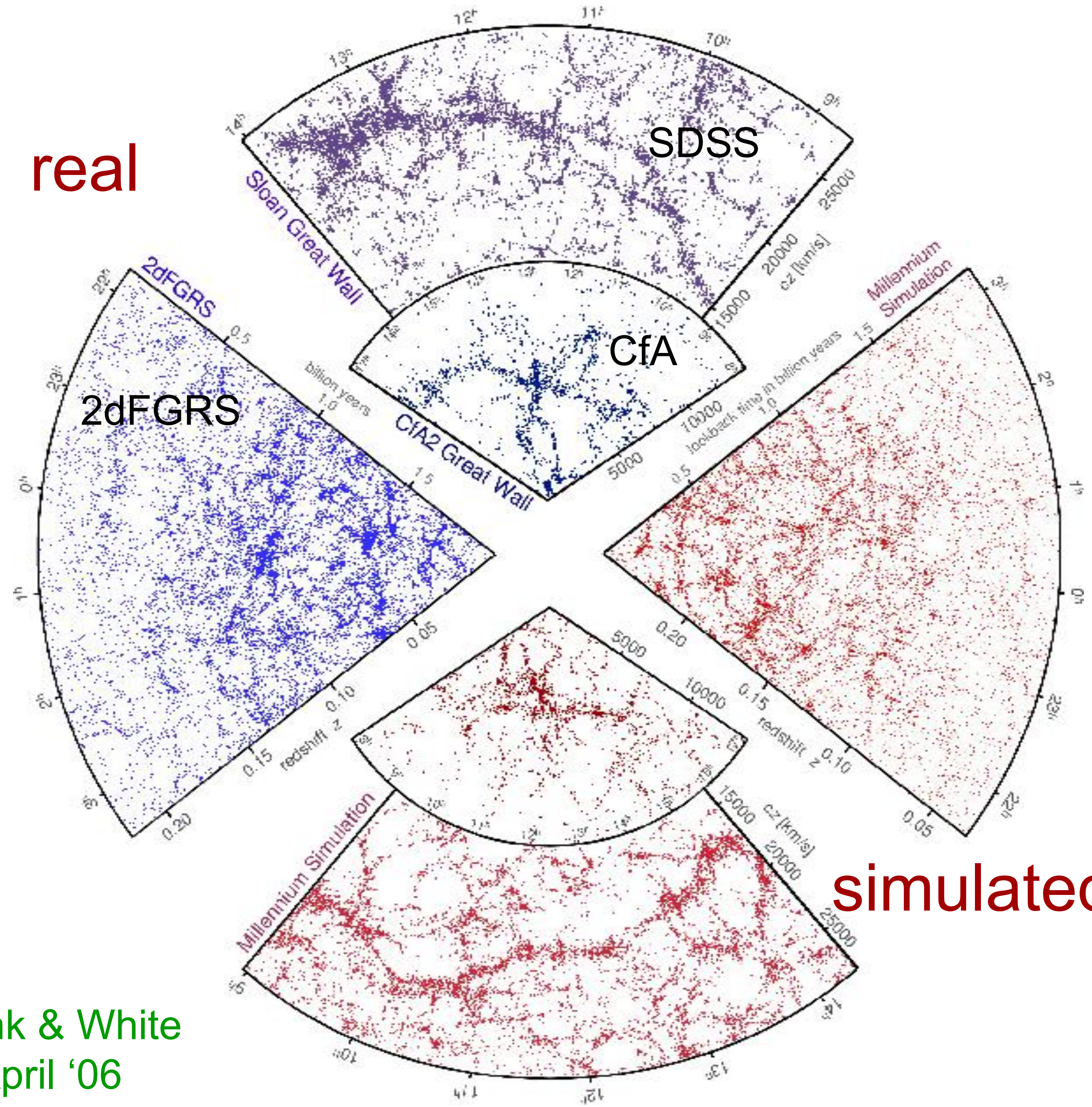
Early simulations of ΛCDM



Davis, Efstathiou, Frenk & White ‘85



Springel, Frenk & White
Nature, April ‘06

The cold dark matter cosmogony

University of Durham

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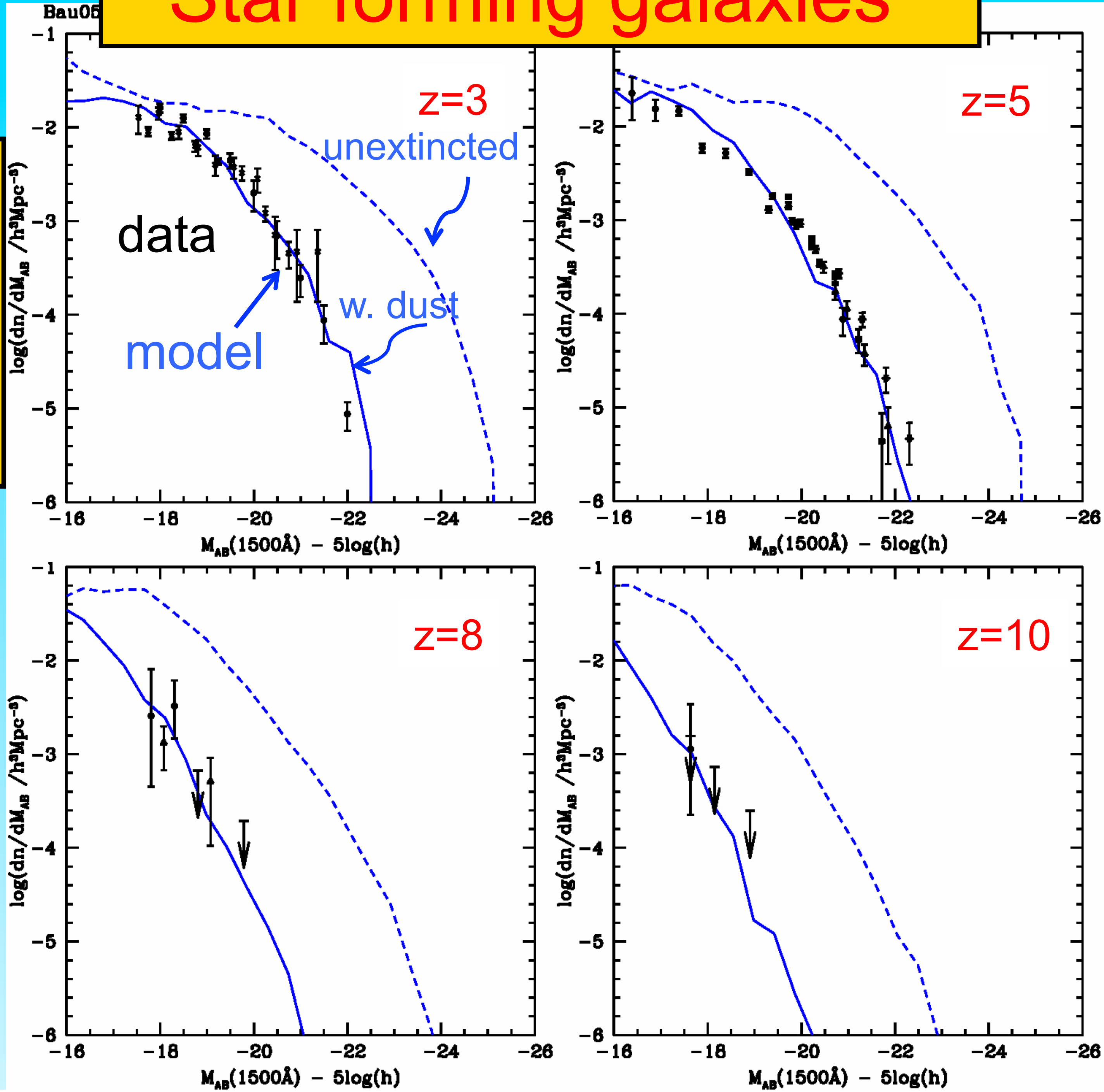
Star forming galaxies

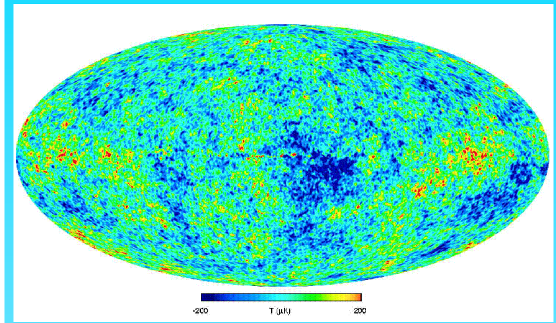
Evolution of Lyman-break galaxy lum. function



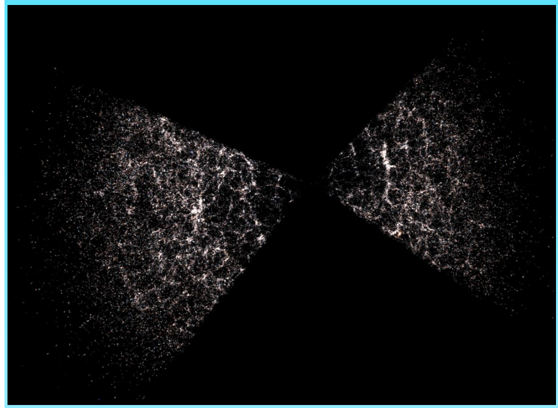
Lacey, Baugh, Frenk, Benson '11

University of Durham

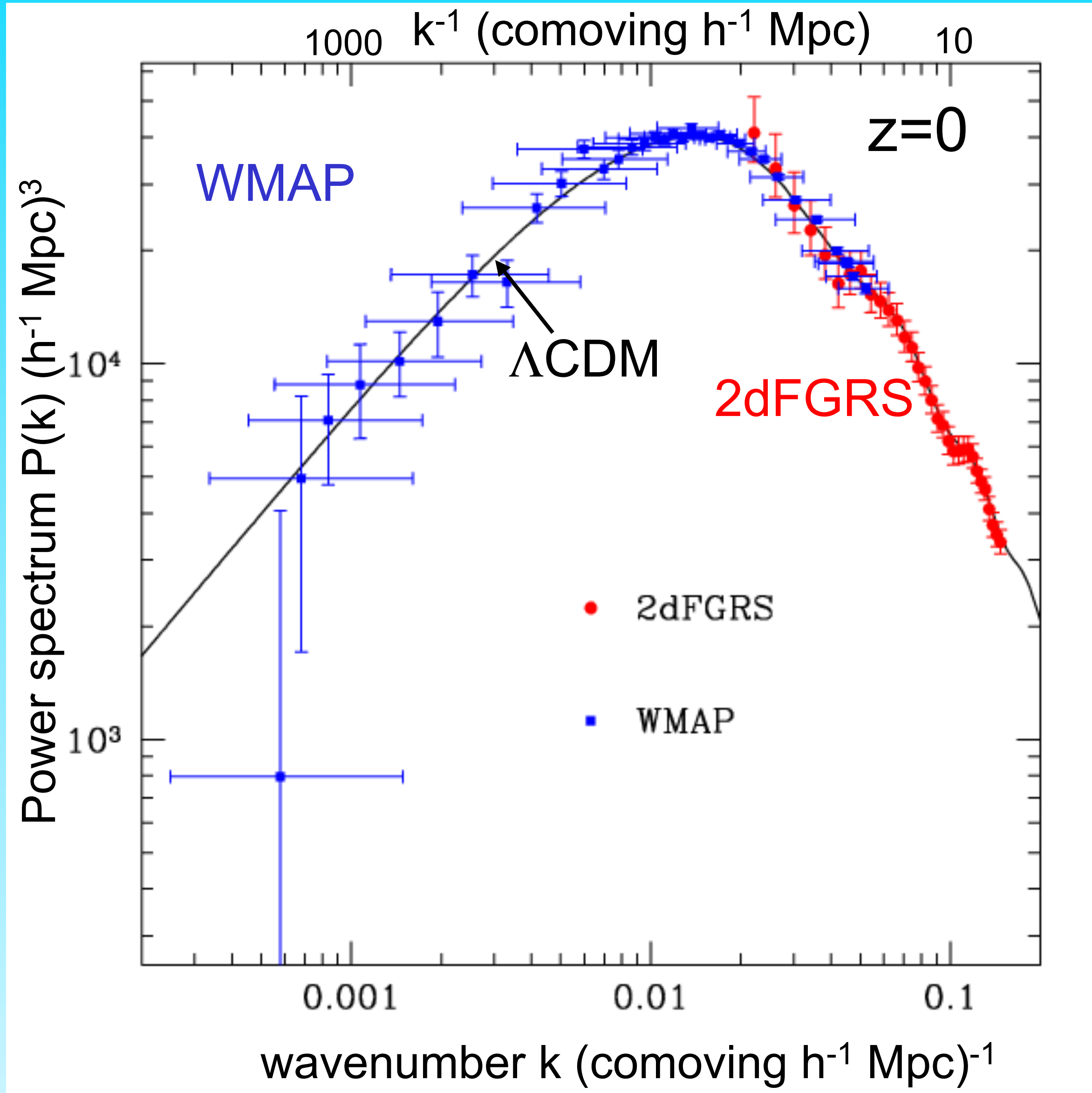
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

The dark matter power spectrum

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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
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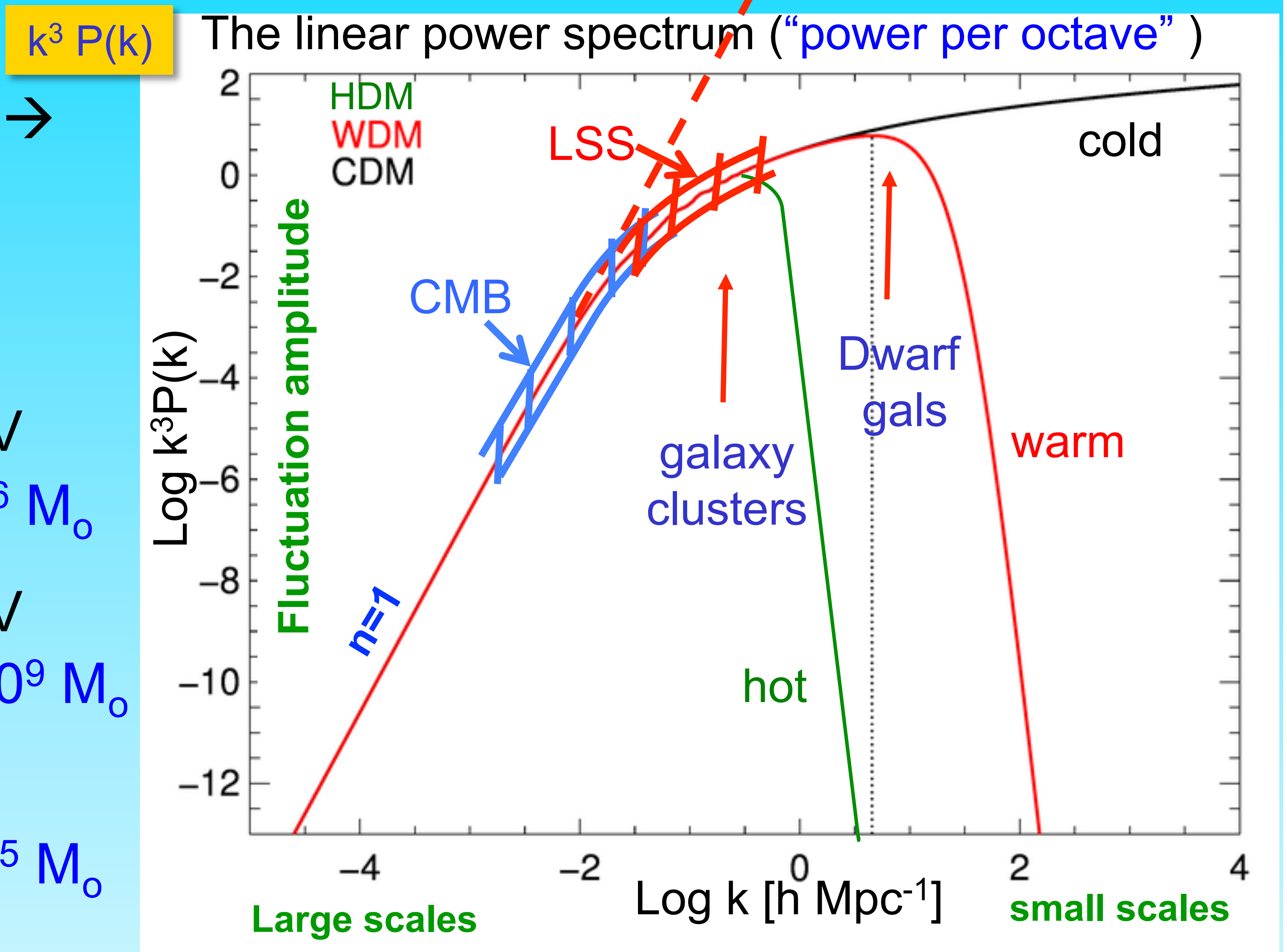

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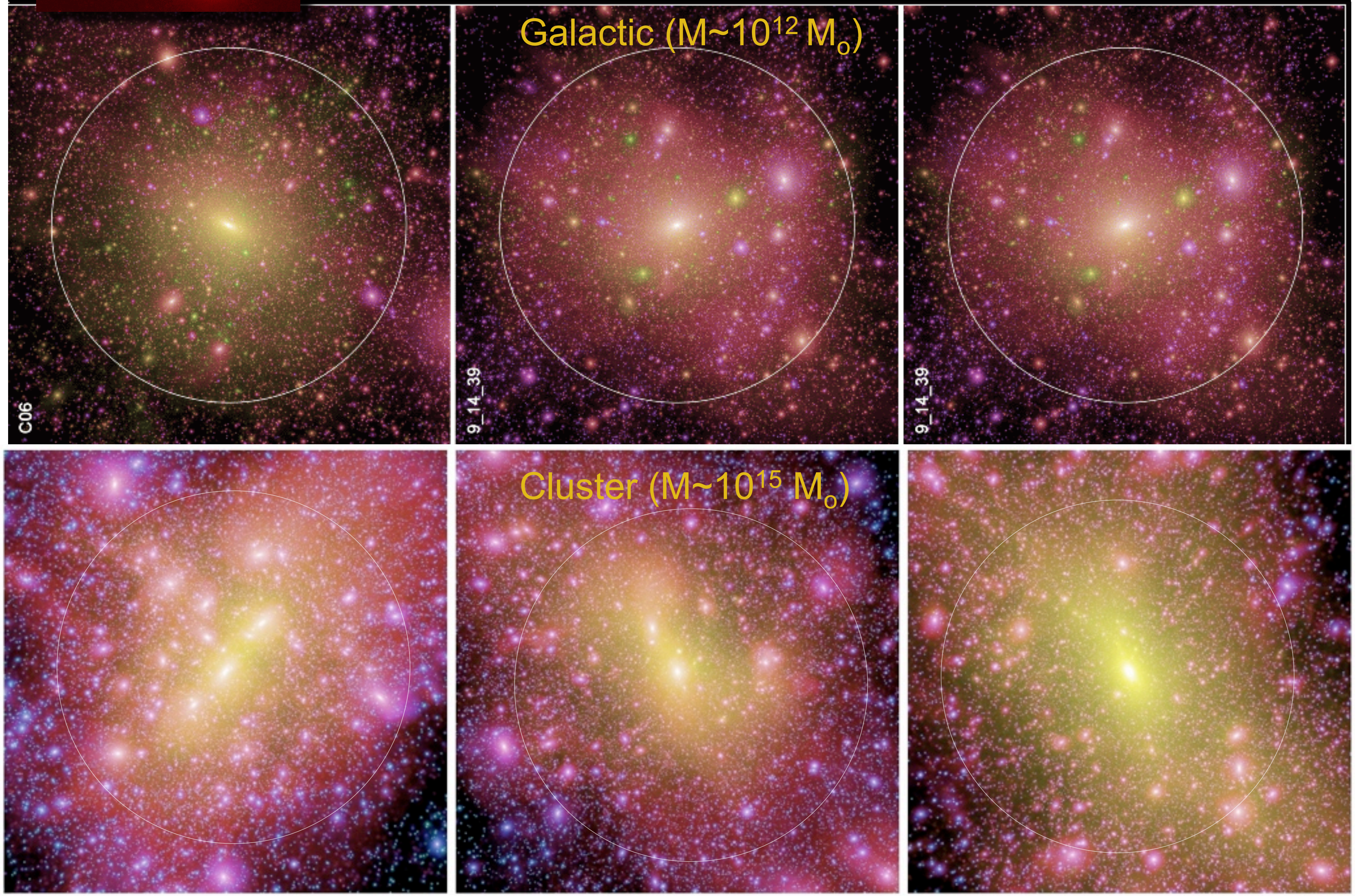
Cosmology on small – strongly non-linear – scales

→ 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

cold dark matter

warm dark matter

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

Institute for Computational Cosmology

A warm dark matter universe

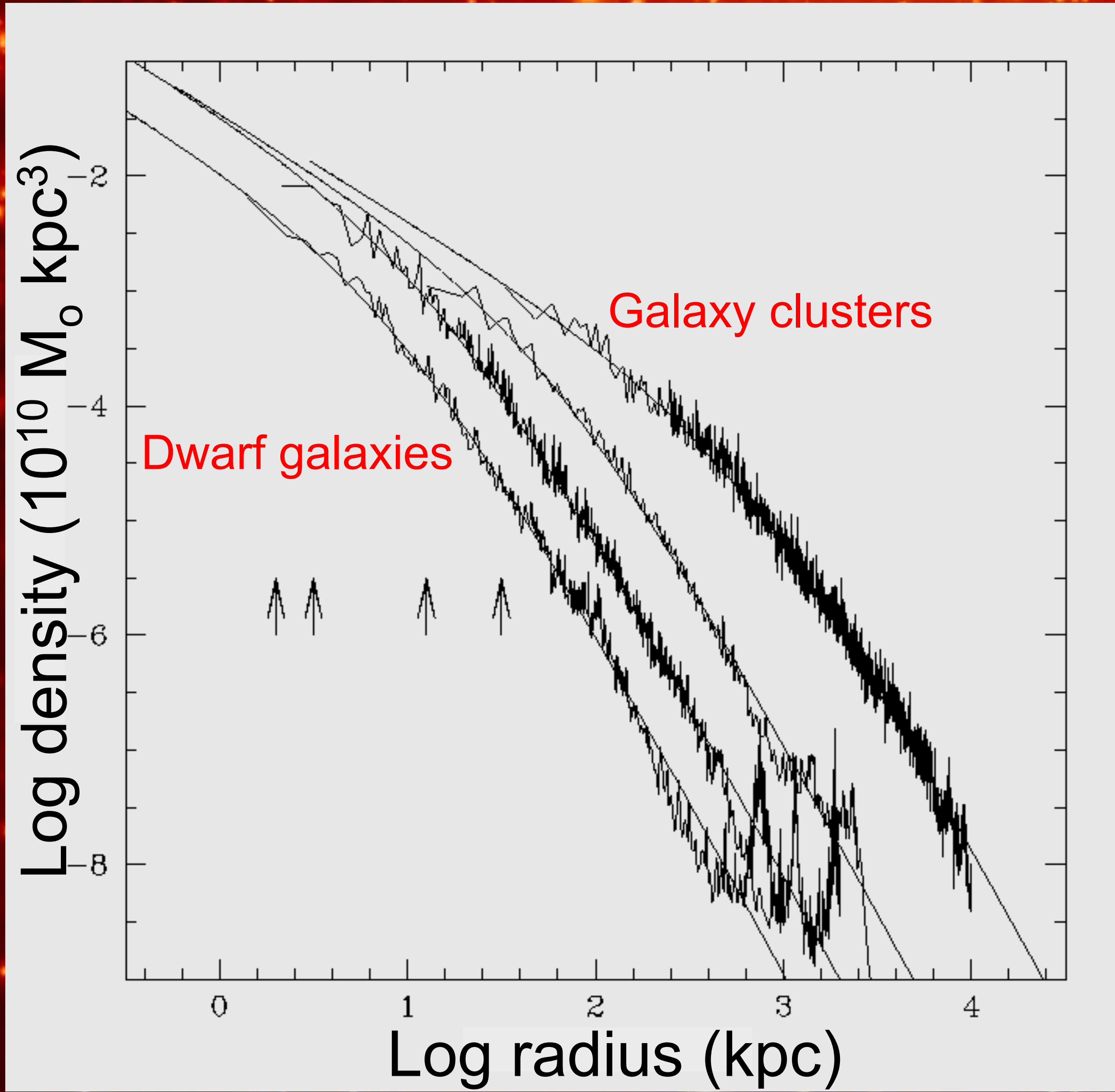
For viable WDM particle masses, there is little difference between CDM and WDM on scales larger than galaxies.

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 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)

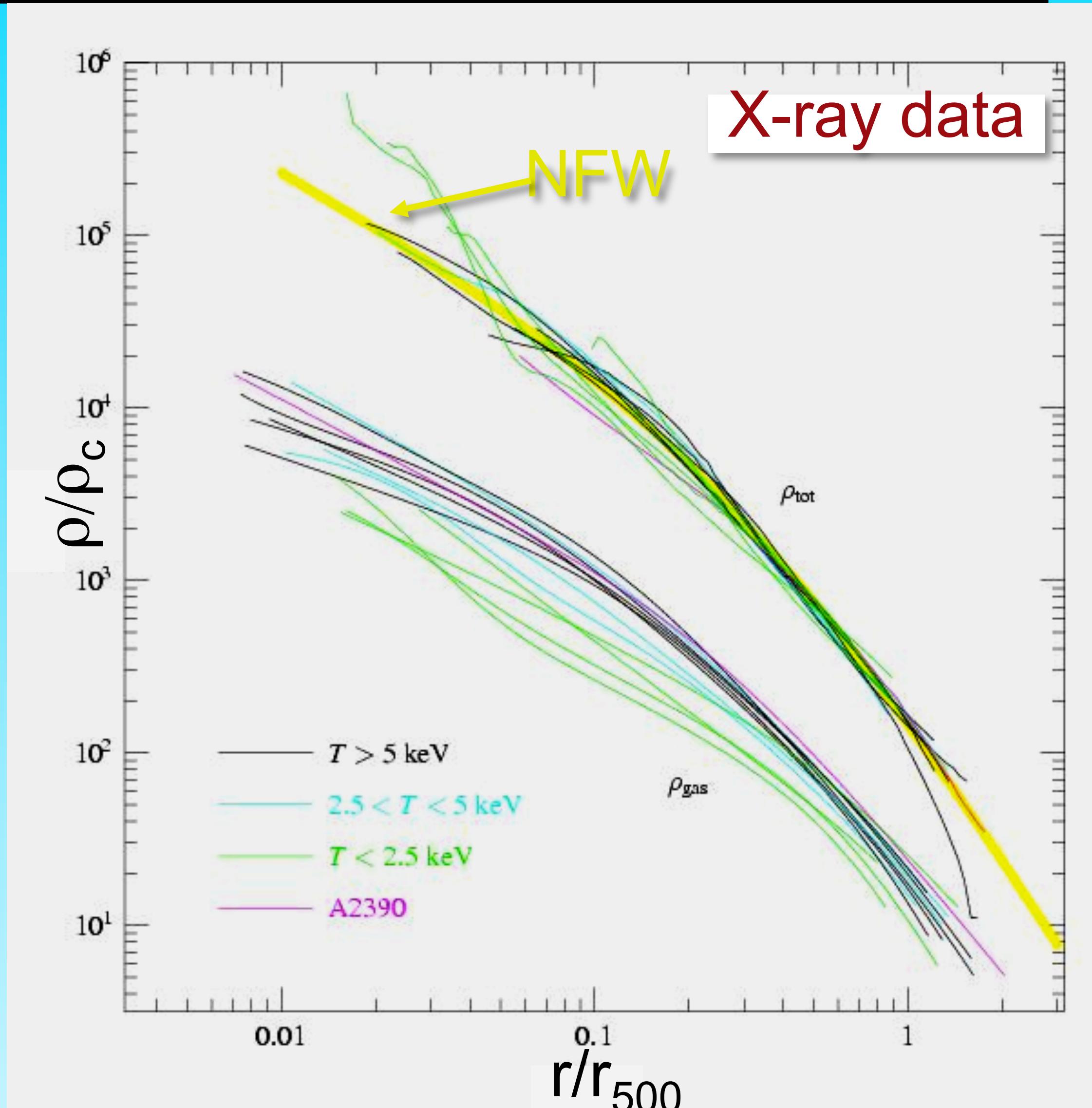
The structure of dark matter halos

University of Durham

The central density profile of galaxy cluster dark halos

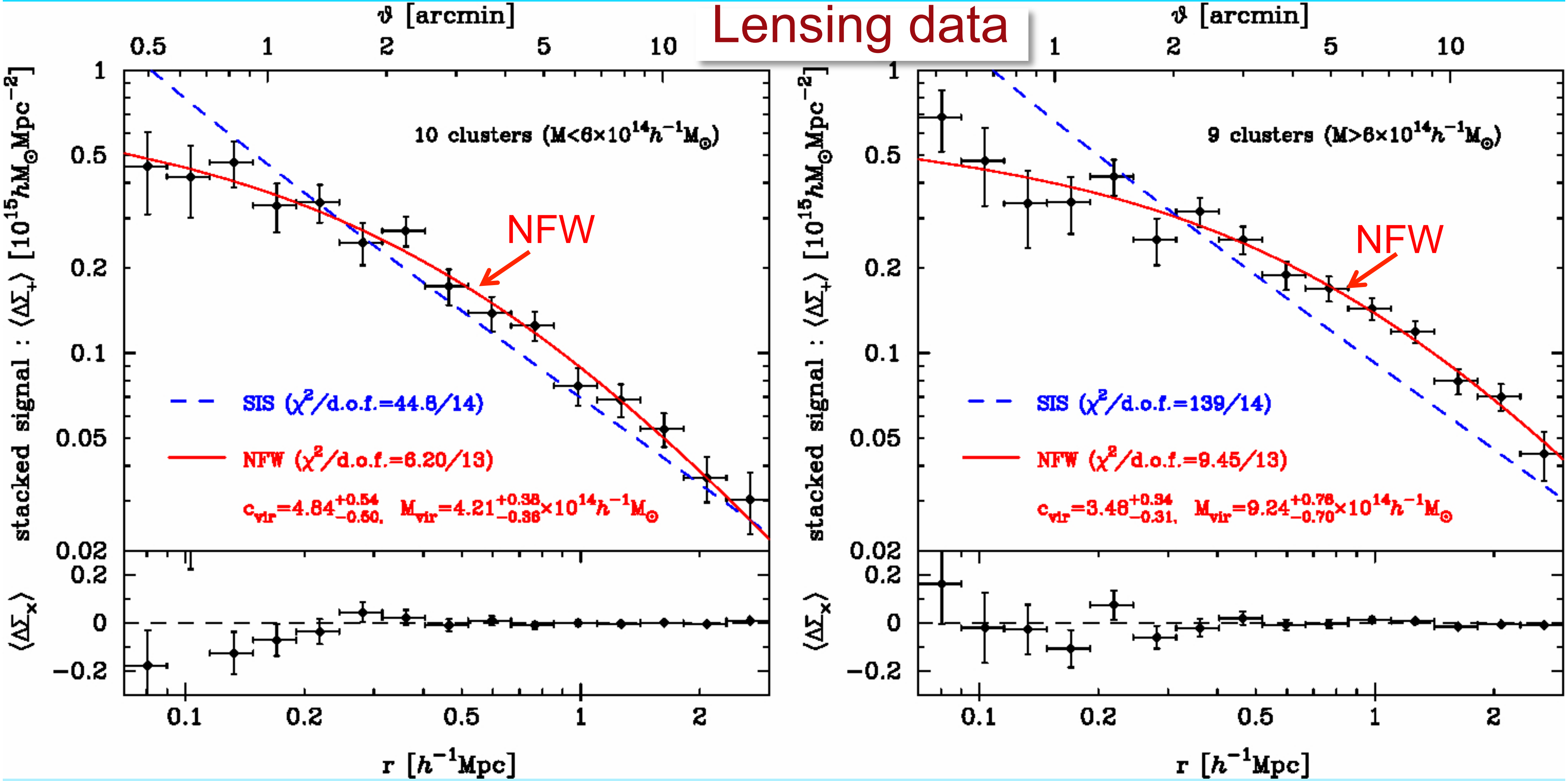
Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium

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?

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Dwarf sphs: cores or cusps?

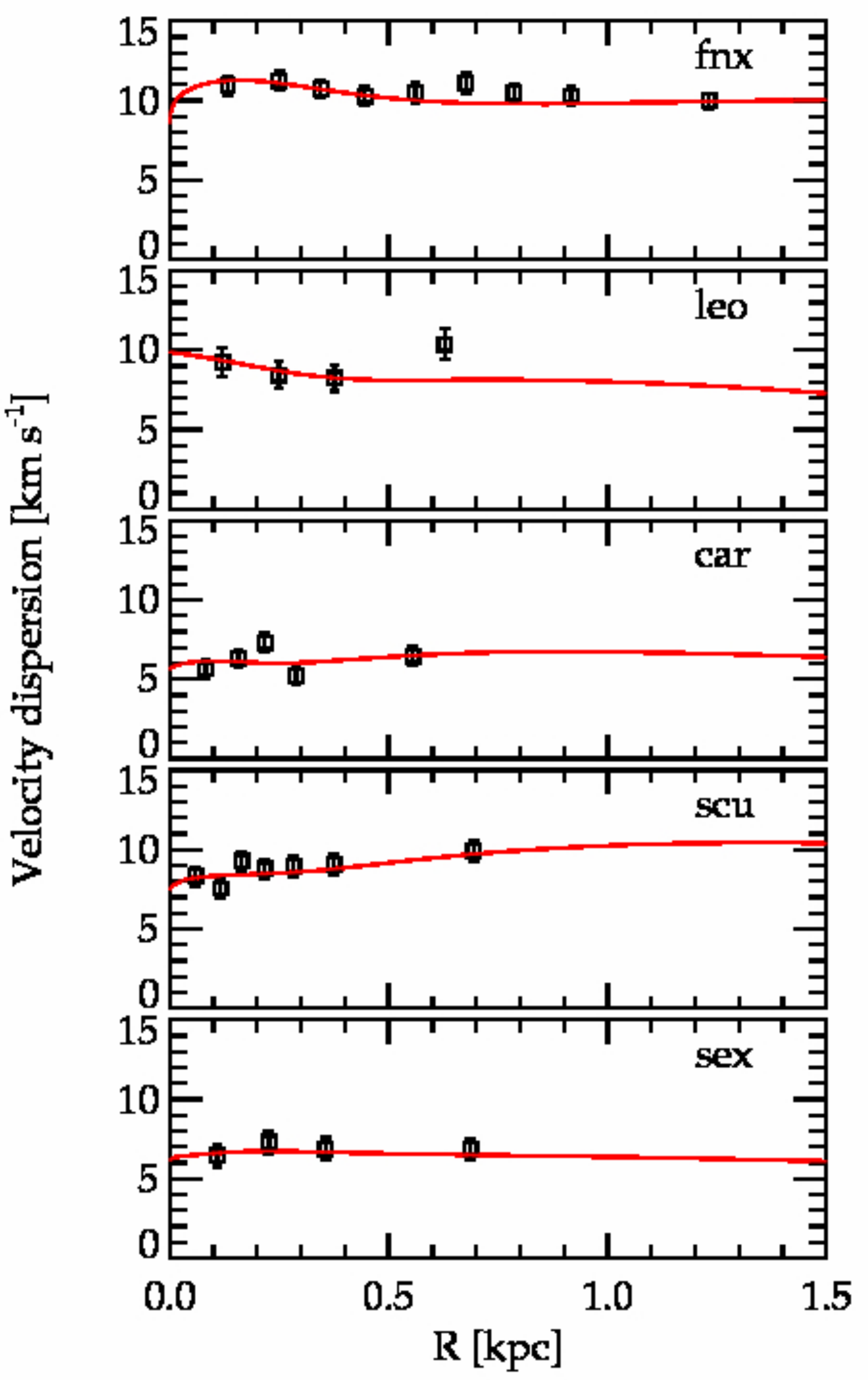
Jeans eqn:

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

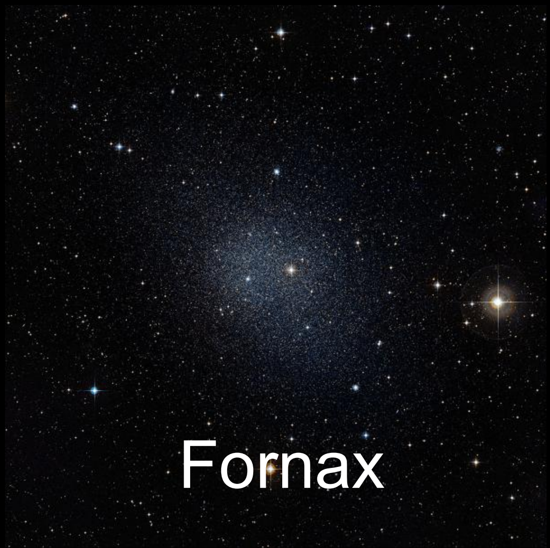
from Aquarius sim

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


Fornax


Sculptor

Leo I


Sextans

Carina

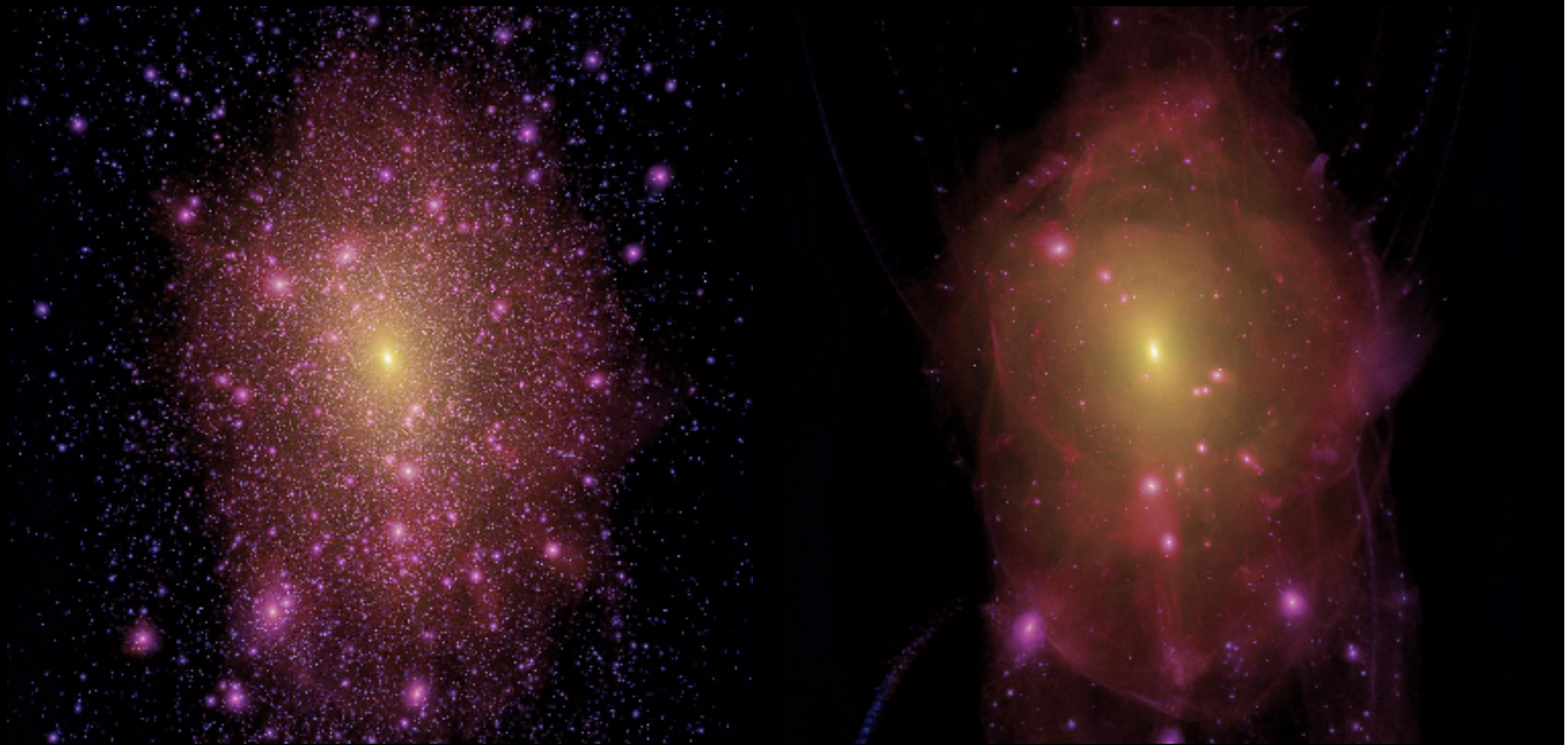


Sagittarius

Cuspy NFW profiles consistent with MW satellite kinematic data

cold dark matter

warm dark matter



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

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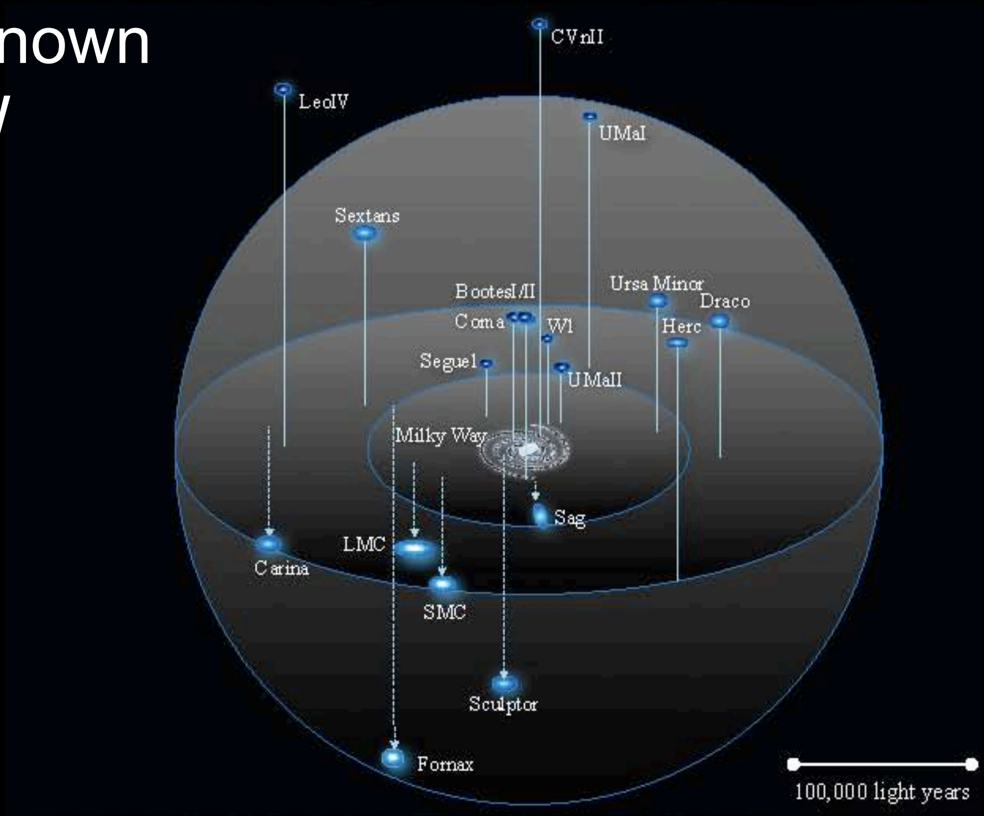
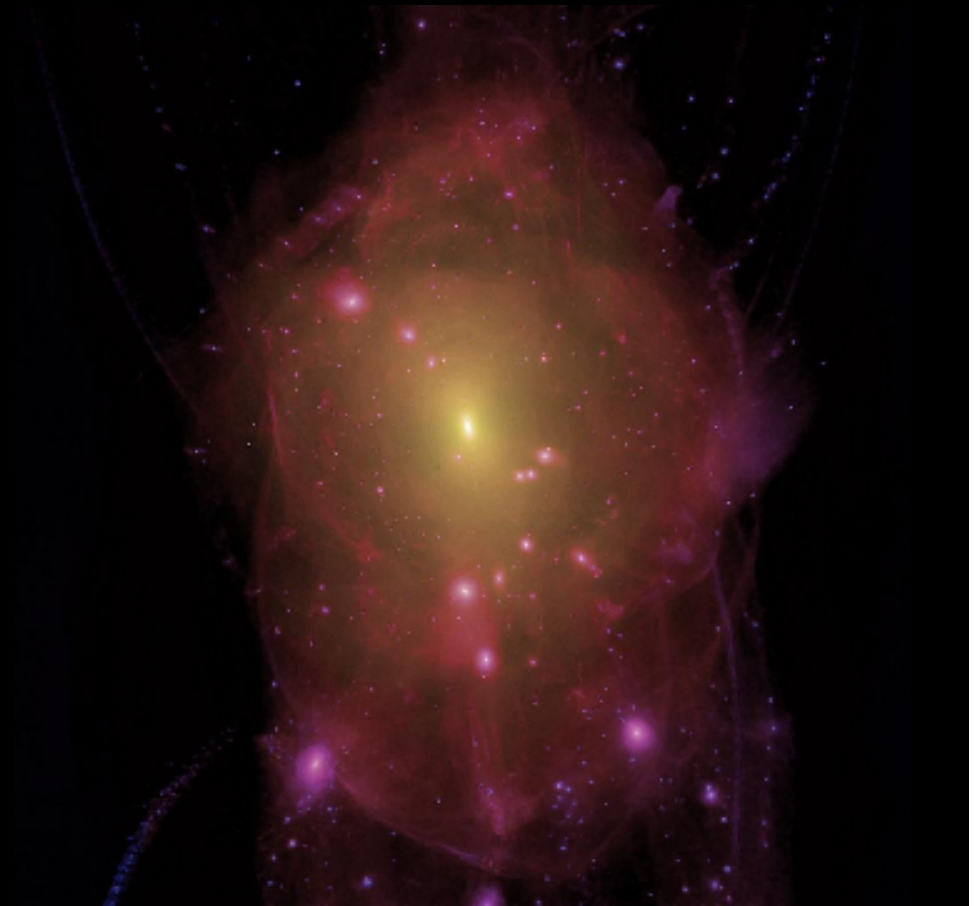
The satellites of the Milky Way

~25 satellites known
in the MW



cold dark matter

warm dark matter



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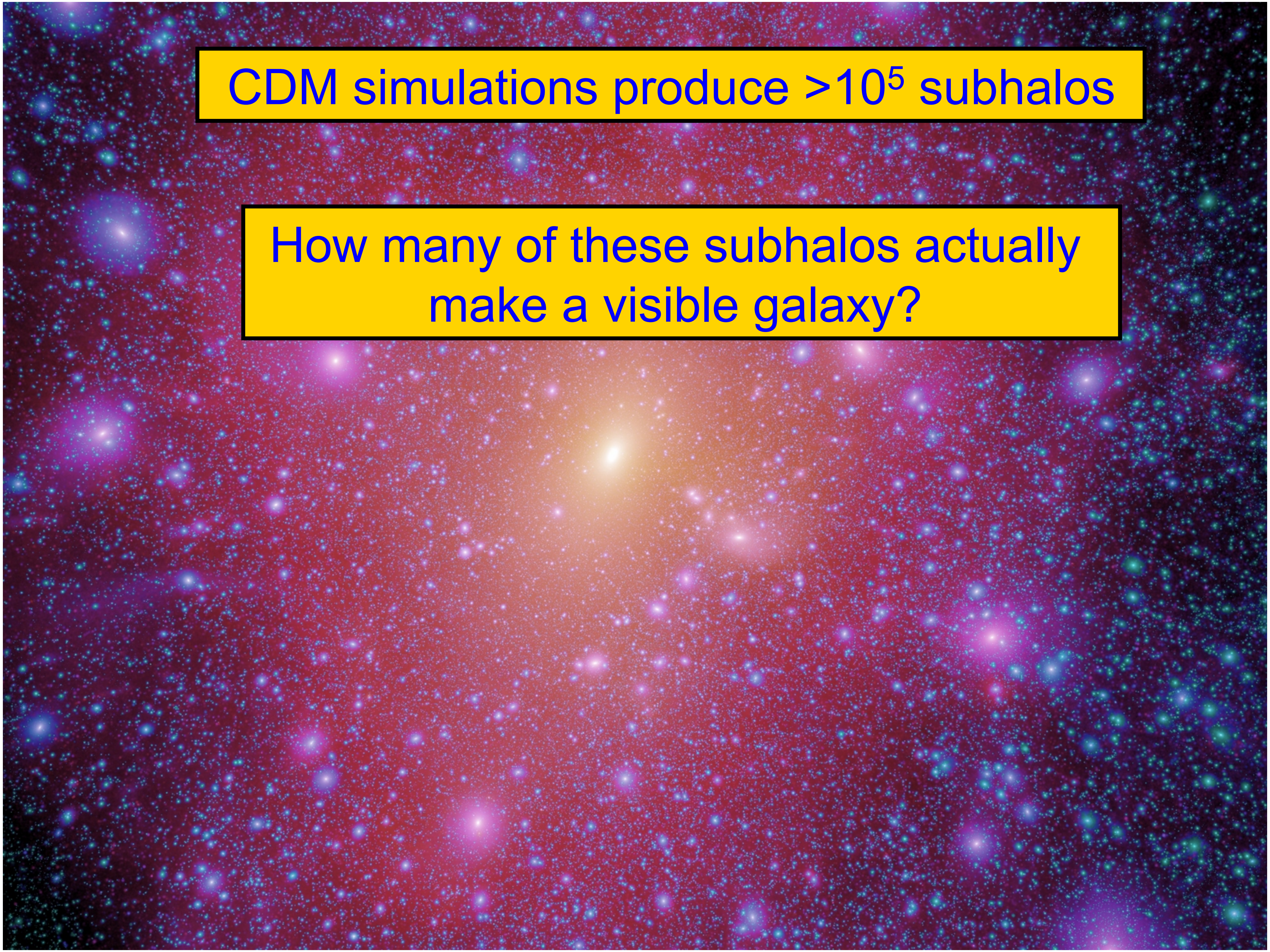
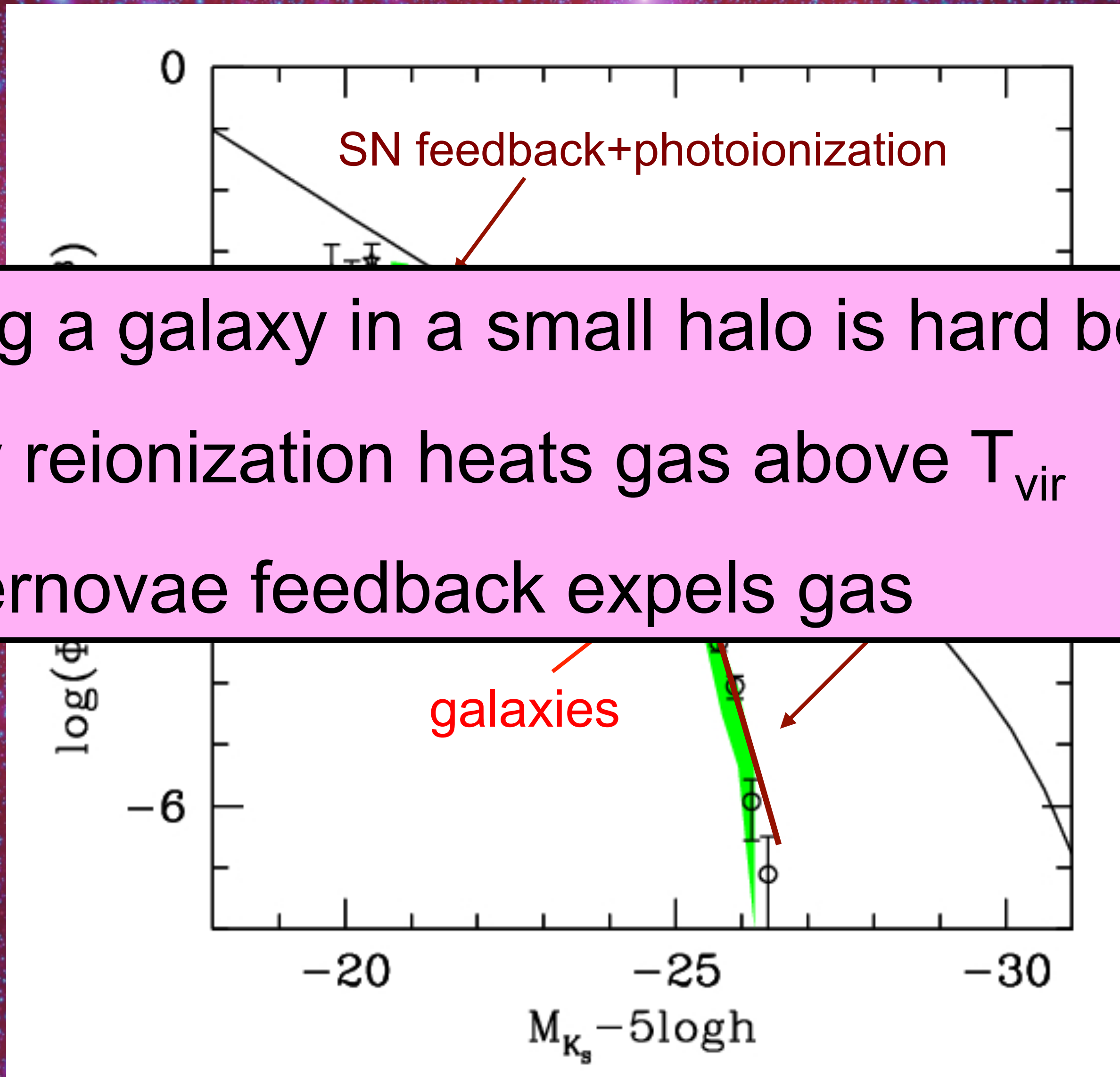
Institute for Computational Cosmology



CDM 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

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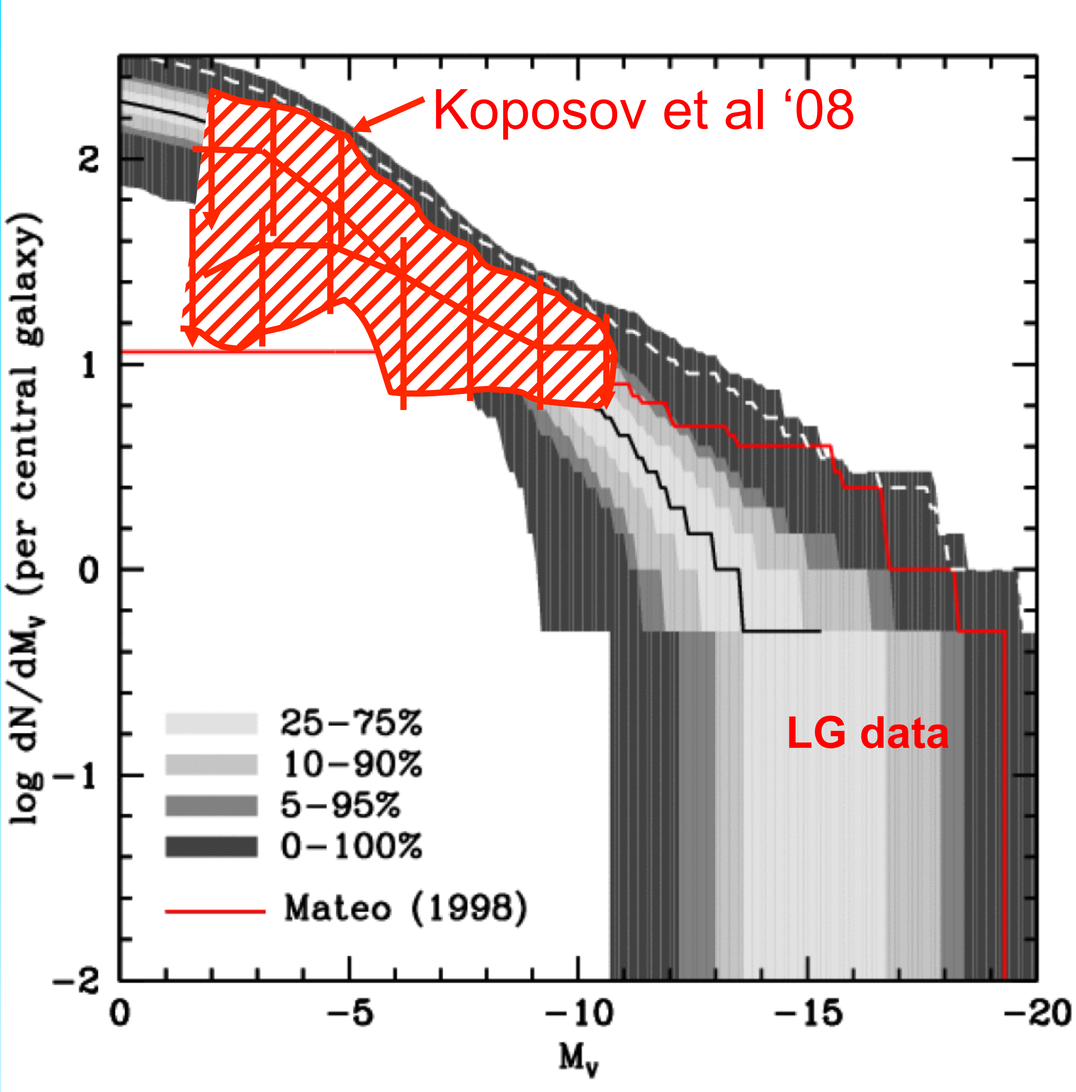
Luminosity Function of Local Group Satellites

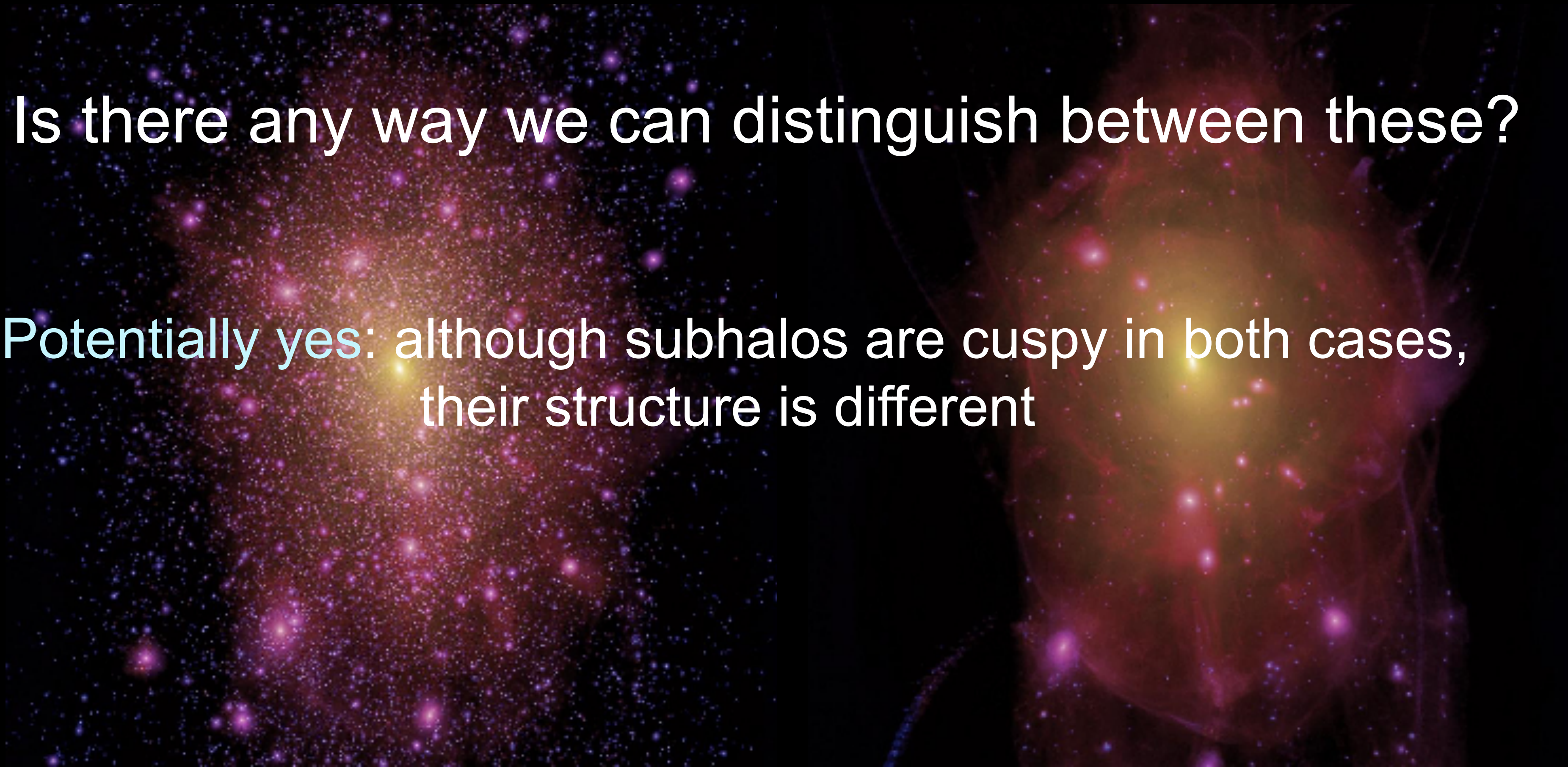
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02

cold dark matter

warm dark matter



Is there any way we can distinguish between these?

Potentially yes: although subhalos are cuspy in both cases, their structure is different

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

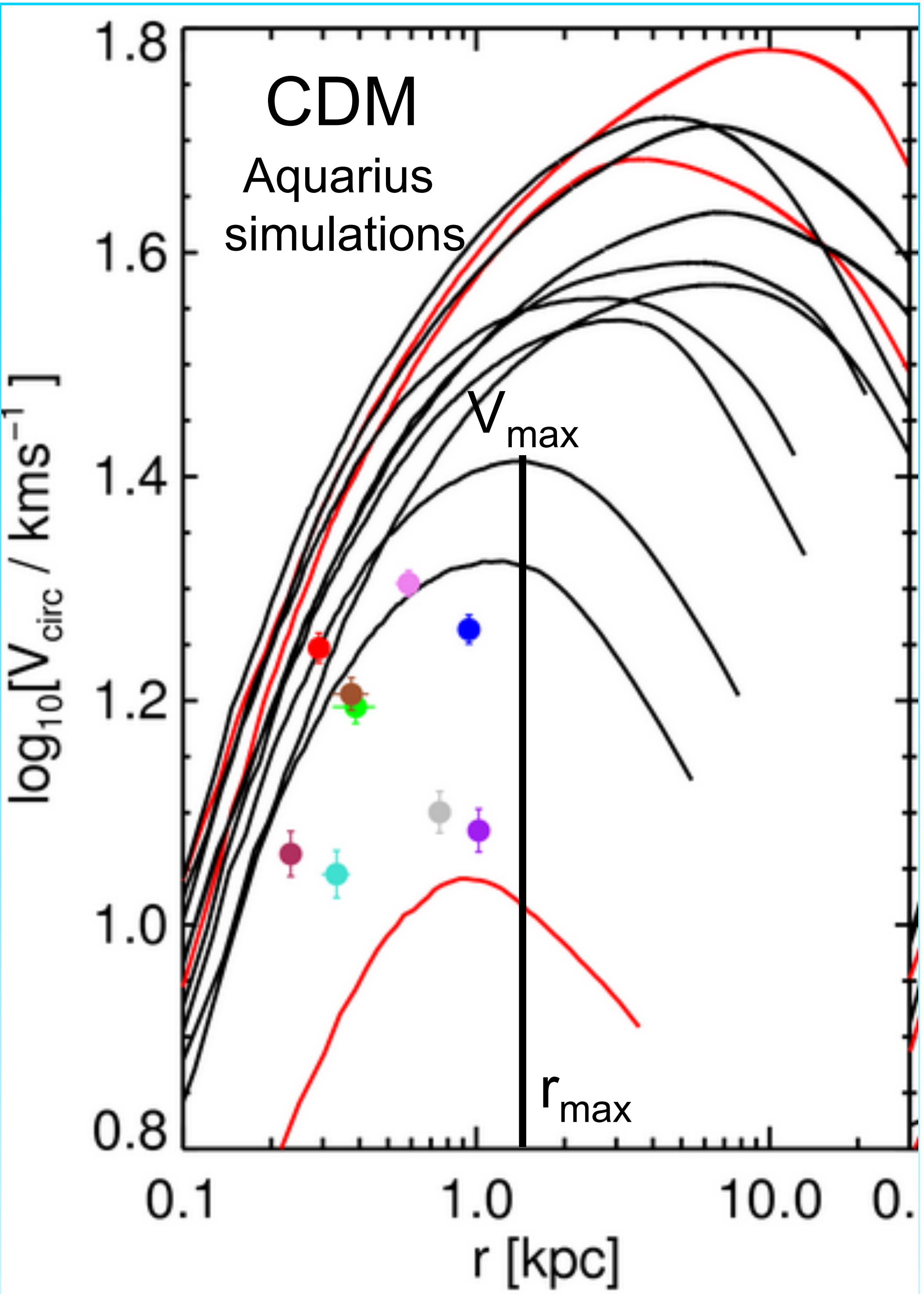
University of Durham

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

Rotation curves of 12 subhalos with most massive progenitors

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

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



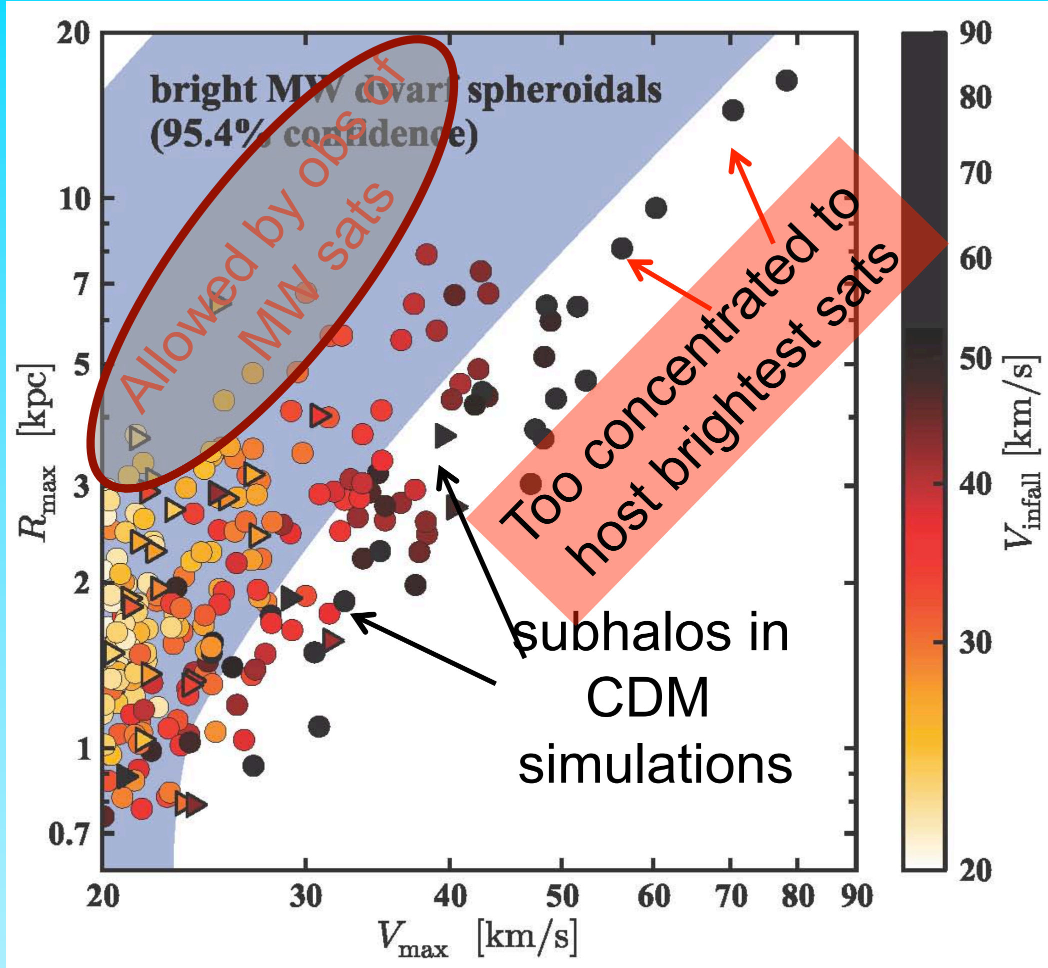
The satellites of the Milky Way

University of Durham

Boylan-Kolchin et al '11

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

Allowed range of (V_{max}, R_{max}) inferred for each MW sat from $M(r<r_{hl})$ assuming NFW



Majority of most massive CDM subhalos are too concentrated to host any of the bright MW sats.

cold dark matter

warm dark matter

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

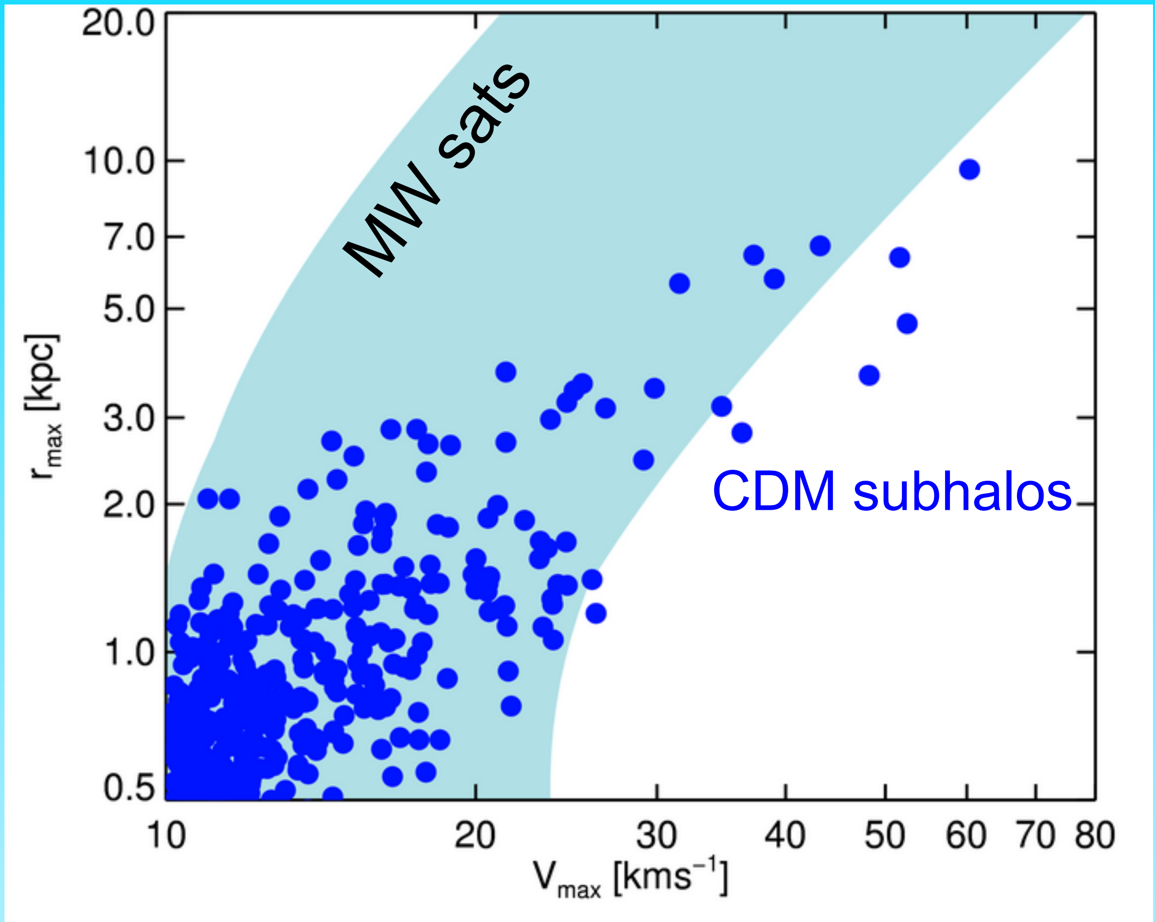
Institute for Computational Cosmology

University of Durham

Warm vs cold dark matter subhalos

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

Majority of most massive CDM subhalos too dense to host any of the bright MW sats.



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

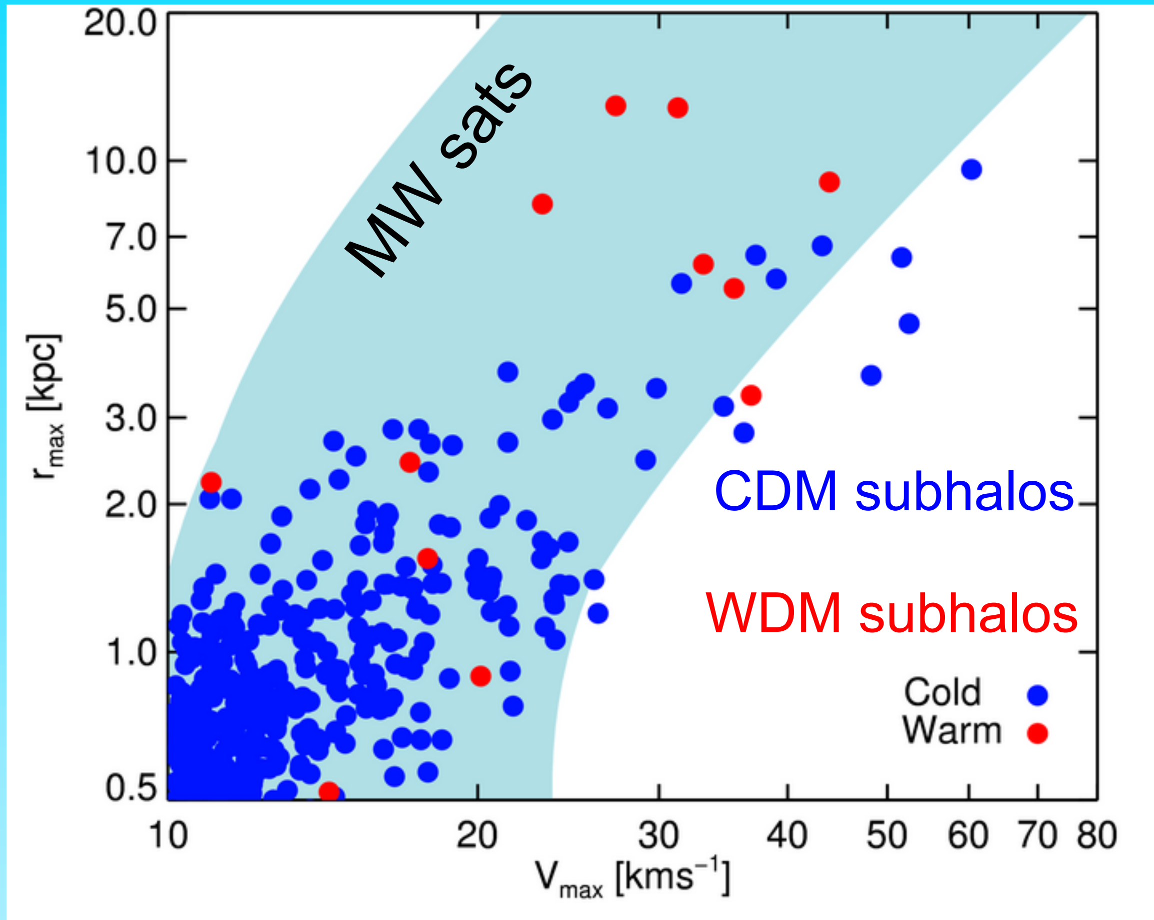
Warm vs cold dark matter subhalos

University of Durham

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

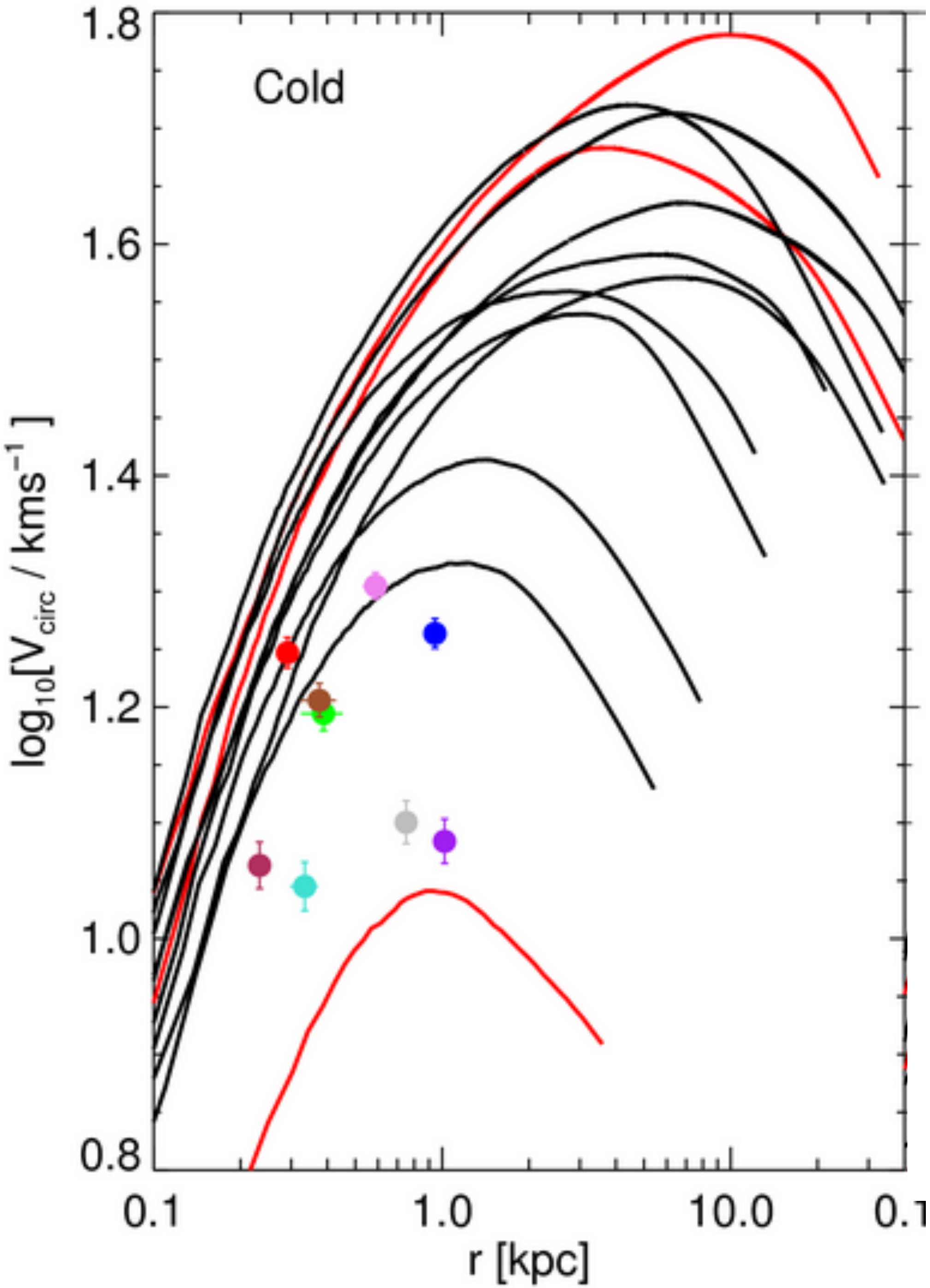
Majority of most massive CDM subhalos too dense to host any of the bright MW sats.

WDM subhalos have the right concentration to host the bright MW satellites

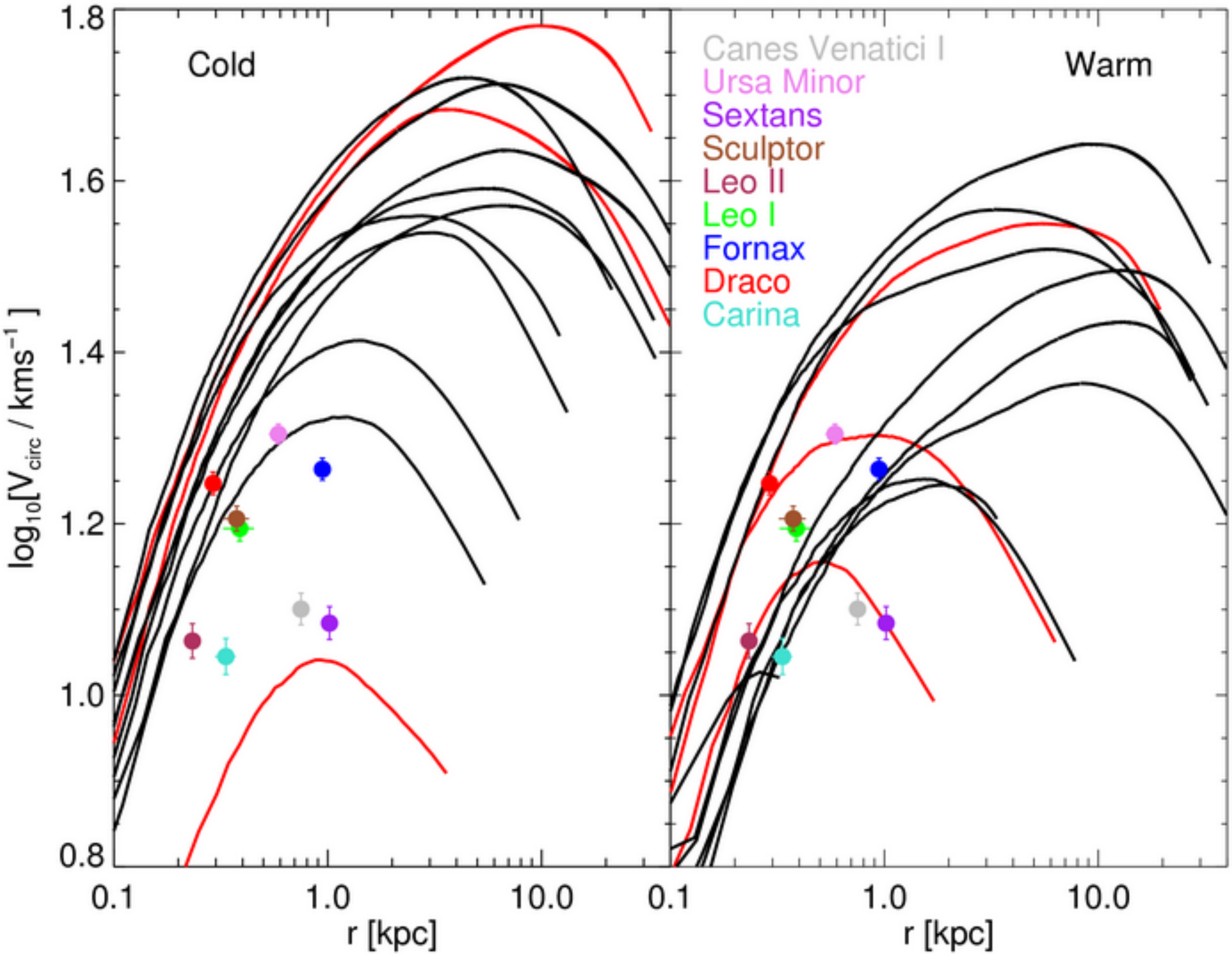


Lovell, Eke, Frenk, Gao, Jenkins et al '11

Institute for Computational Cosmology



Cold
1.8
1.6
1.4
1.2
1.0
0.8
log10[Vcirc / kms-1]
0.1
1.0
10.0
0.1
r [kpc]



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

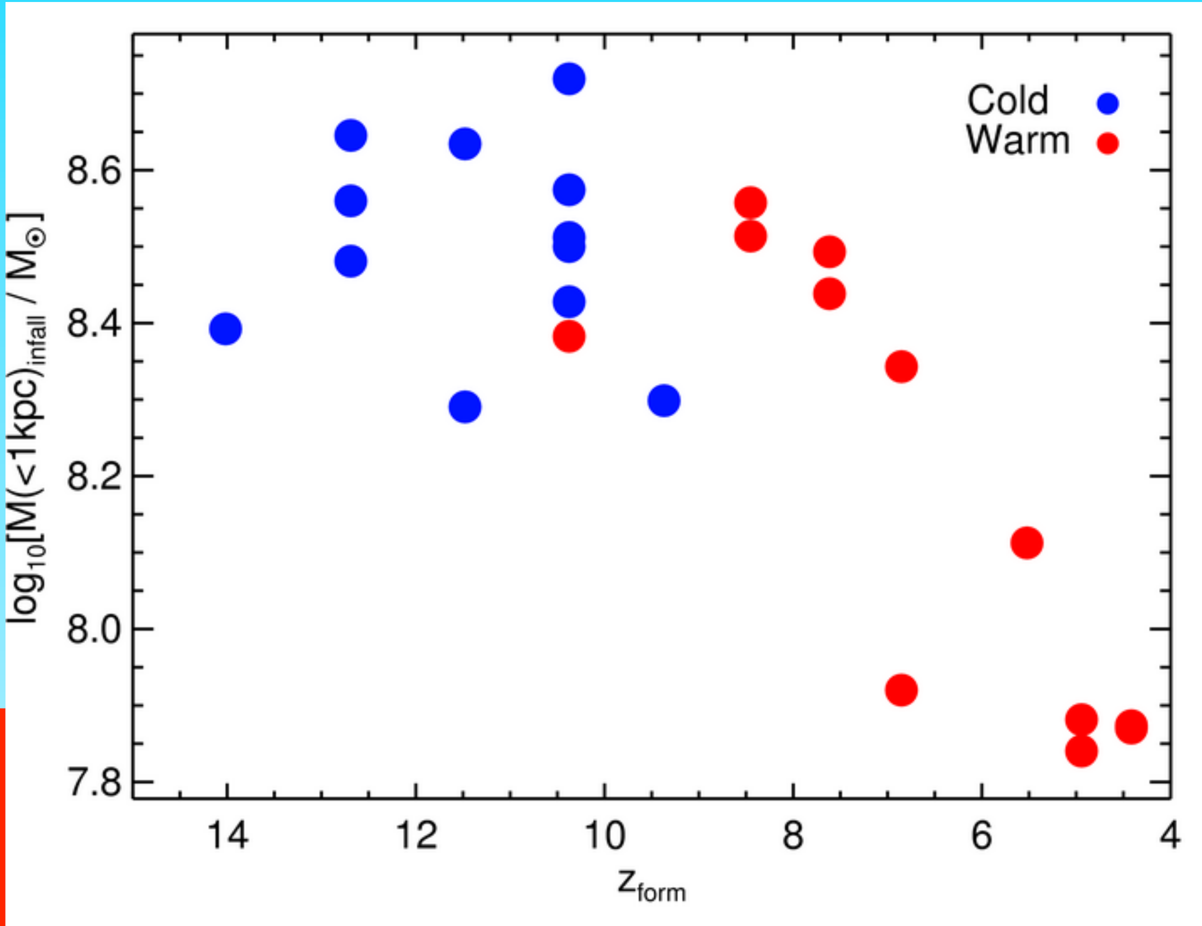
University of Durham

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

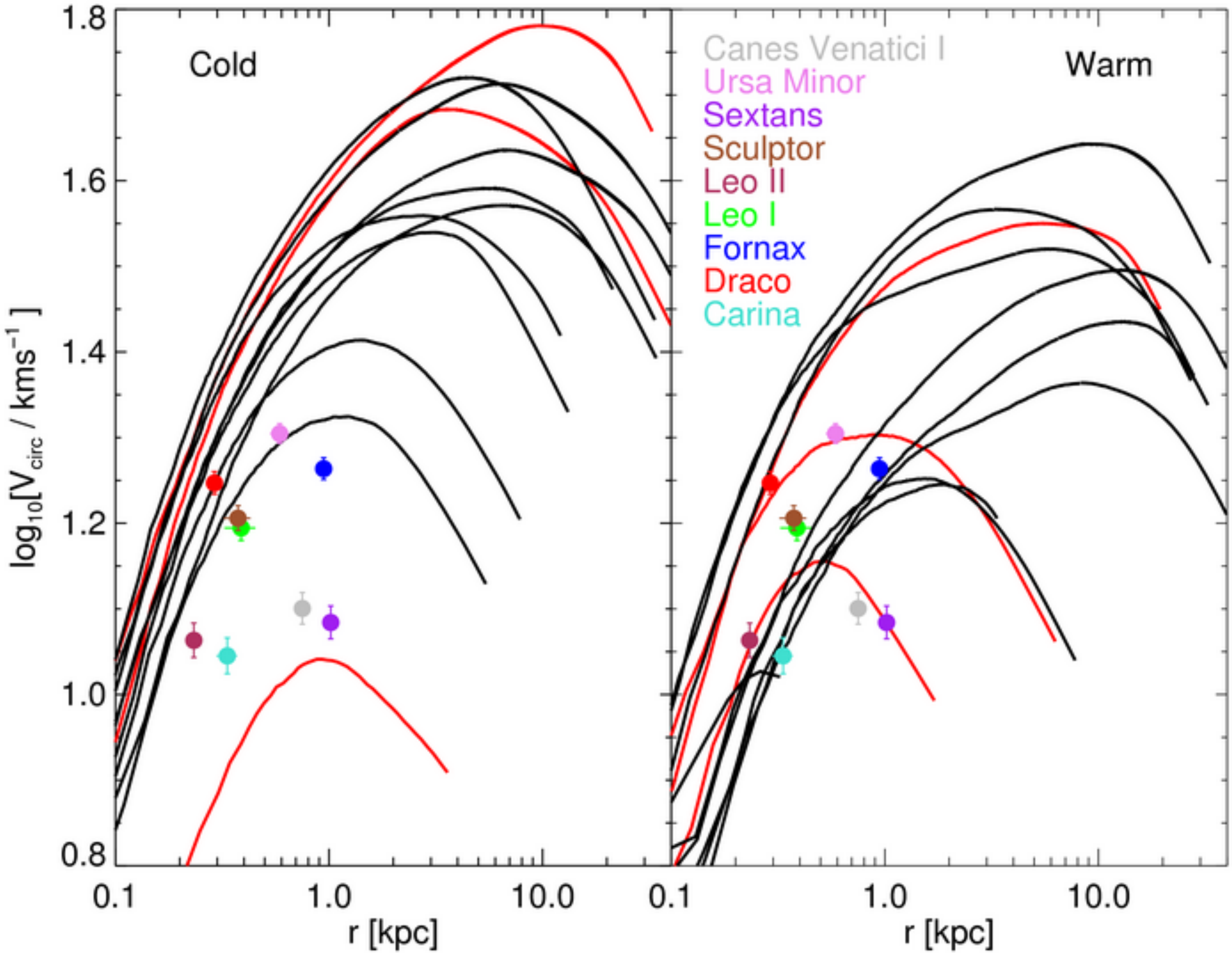
WDM halos form later & have lower central masses than their CDM counterparts!

→

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



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



Cold
Warm
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
log10[Vcirc / 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

Is this the end of CDM?

Could baryon effects reduce the central halo concentration?

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

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.

Baryon effects in the MW satellites

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

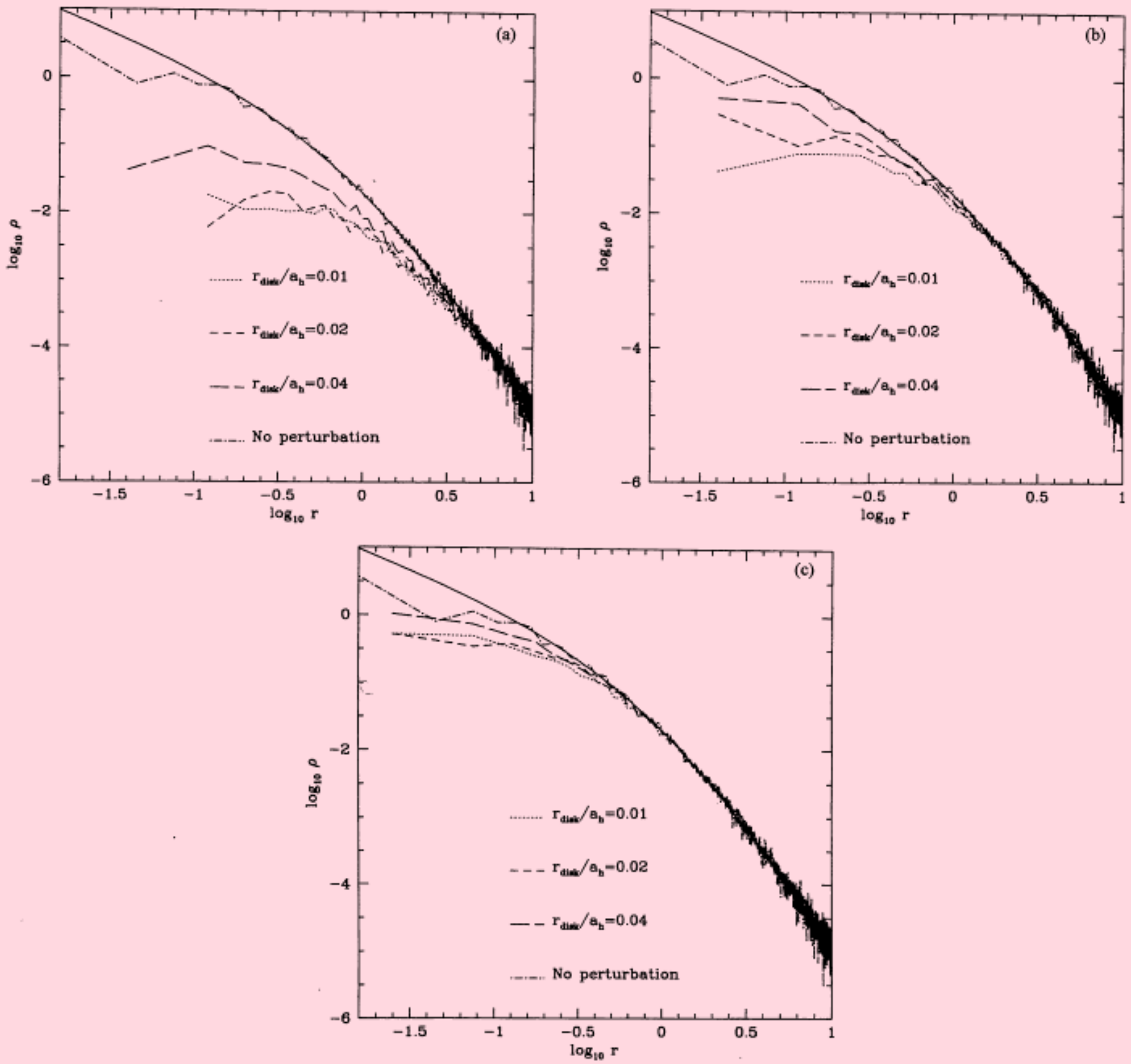

Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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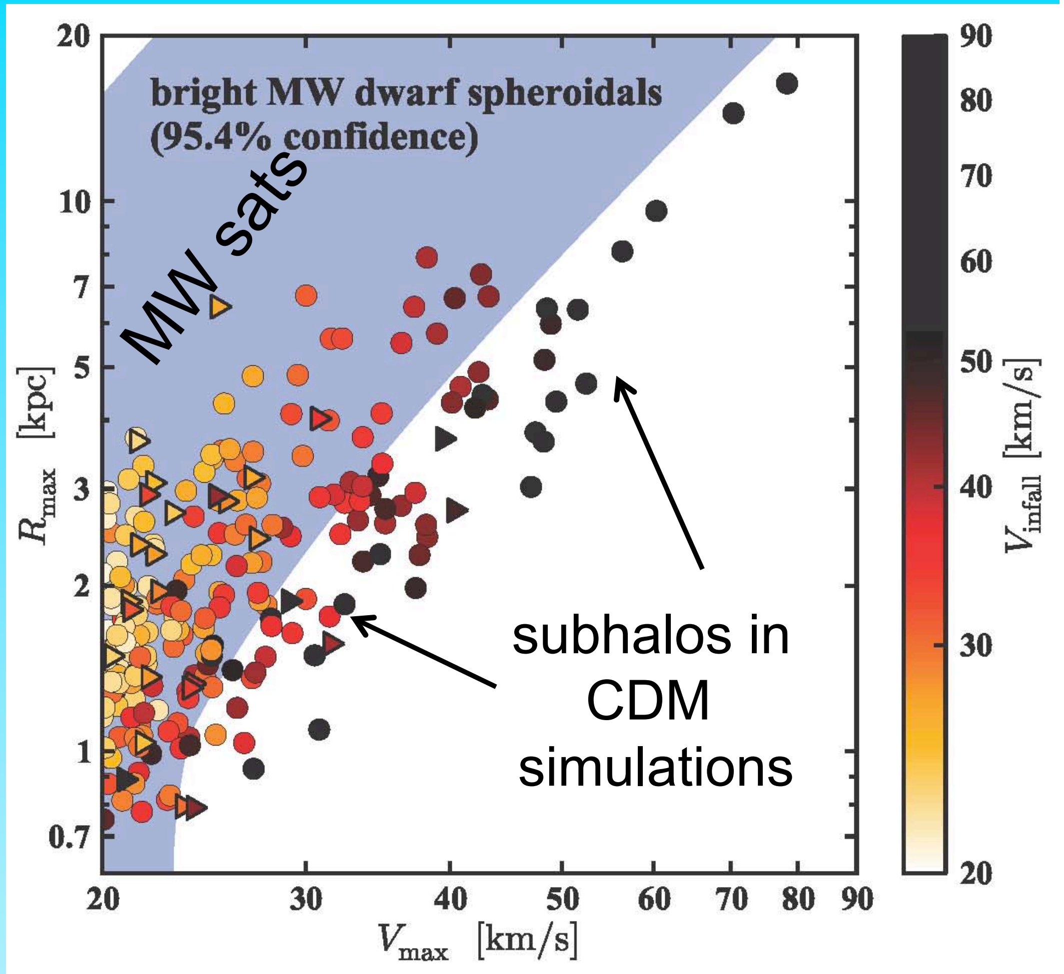
The satellites of the Milky Way

Boylan-Kolchin et al '11

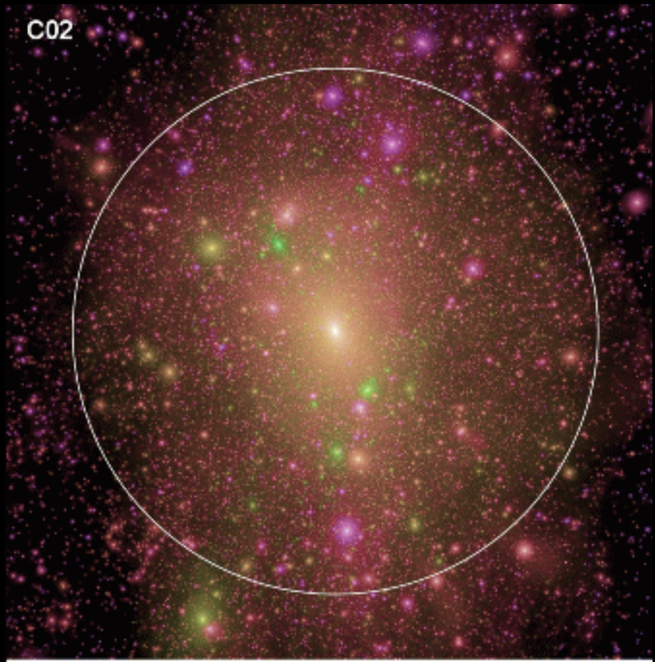
$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$

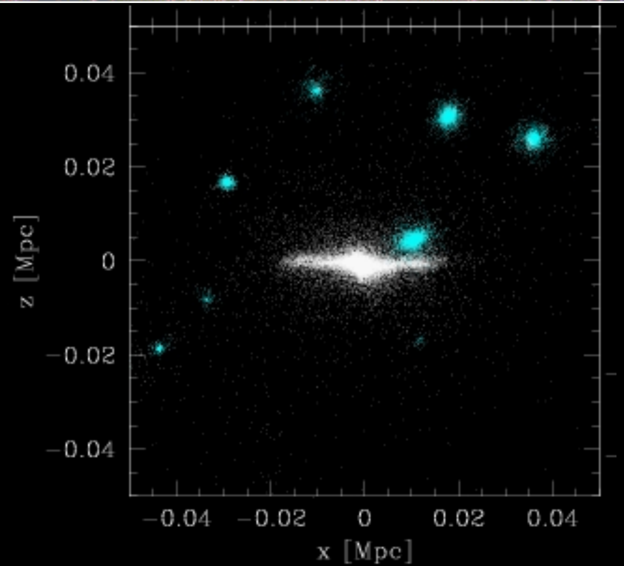
Allowed range of (V_{max}, R_{max}) inferred for each MW sat from $M(r<r_{hl})$ assuming NFW



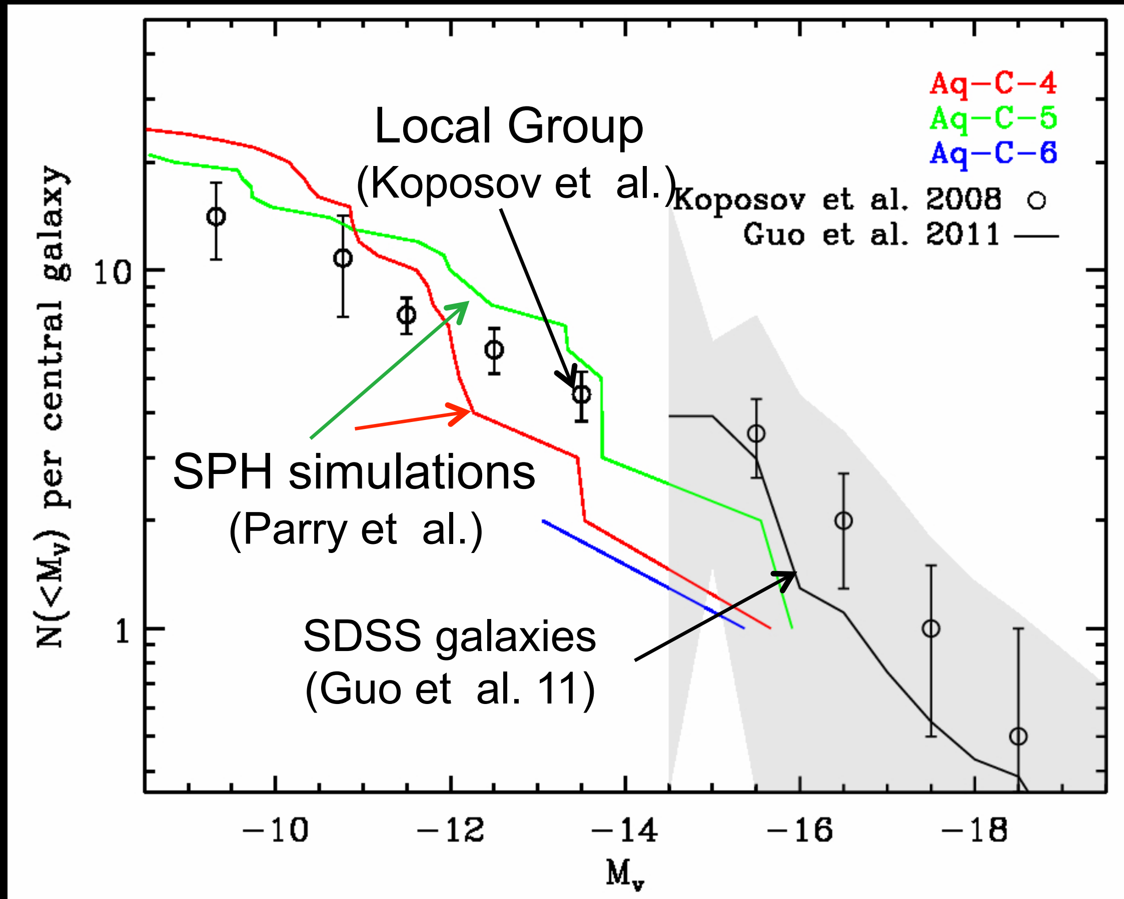
Majority of most massive CDM subhalos are too concentrated to host any of the bright MW sats.

The satellites of the Milky Way





SPH simulations of galaxy formation in one of the Aquarius halos



Parry, Eke, Frenk & Okamoto '11

Baryon effects in the MW satellites

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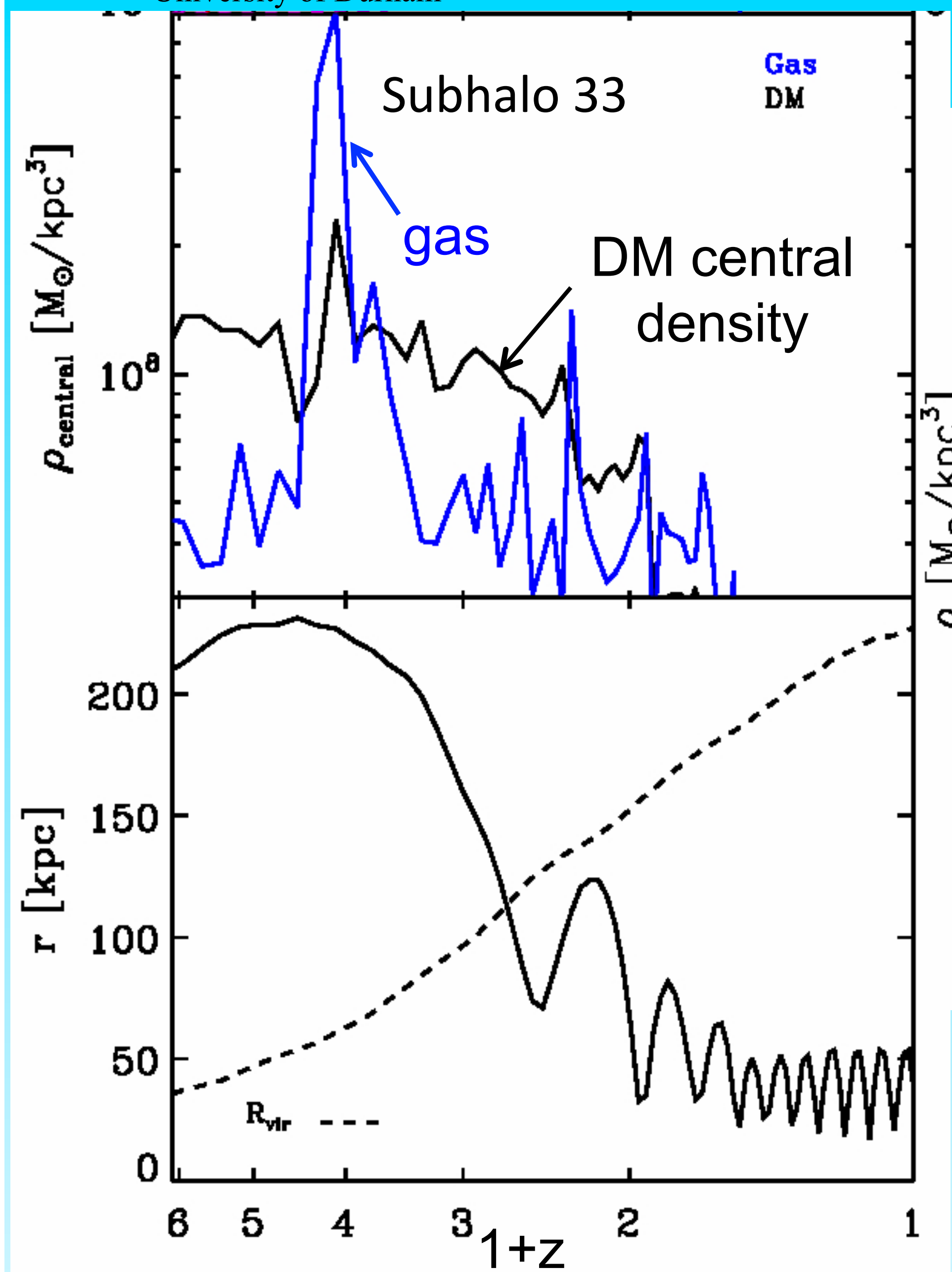

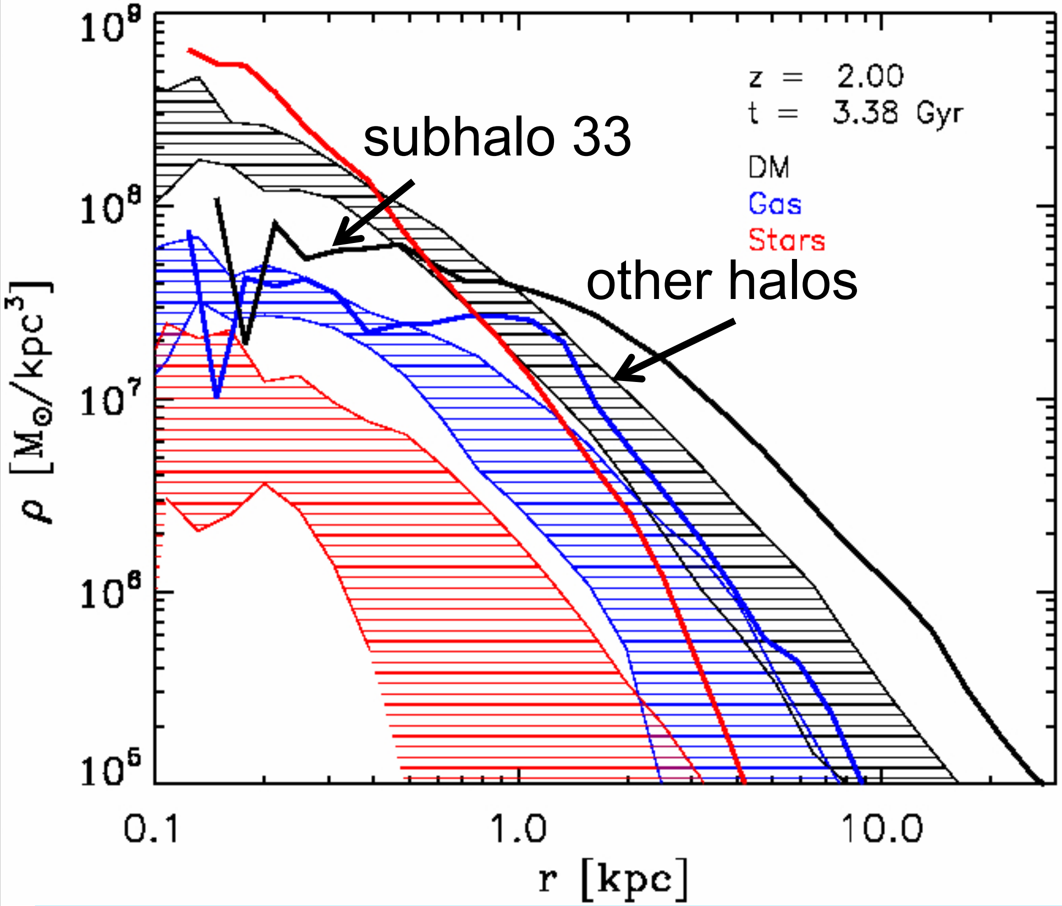

Parry, Eke & Frenk ‘11

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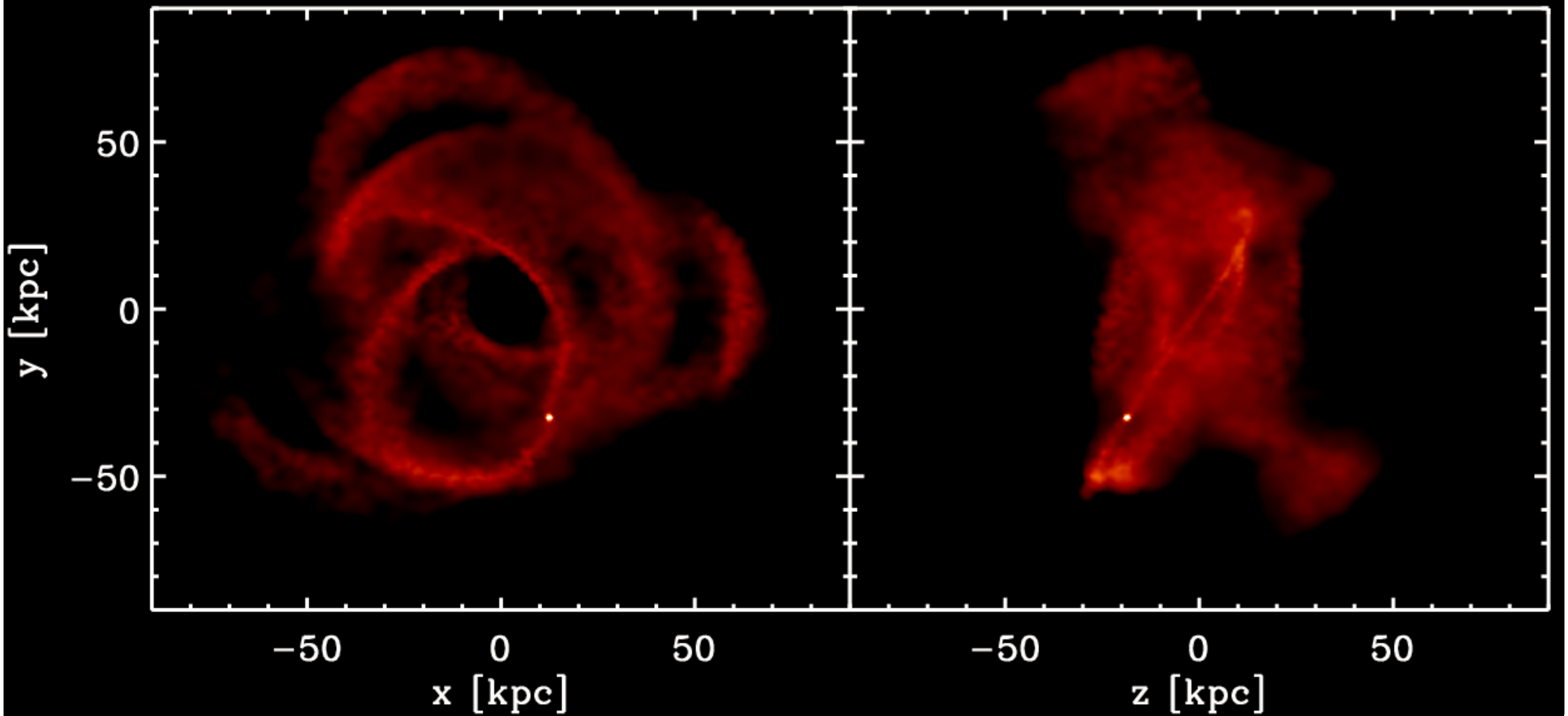
Baryon effects in the MW satellites

Subhalo 33

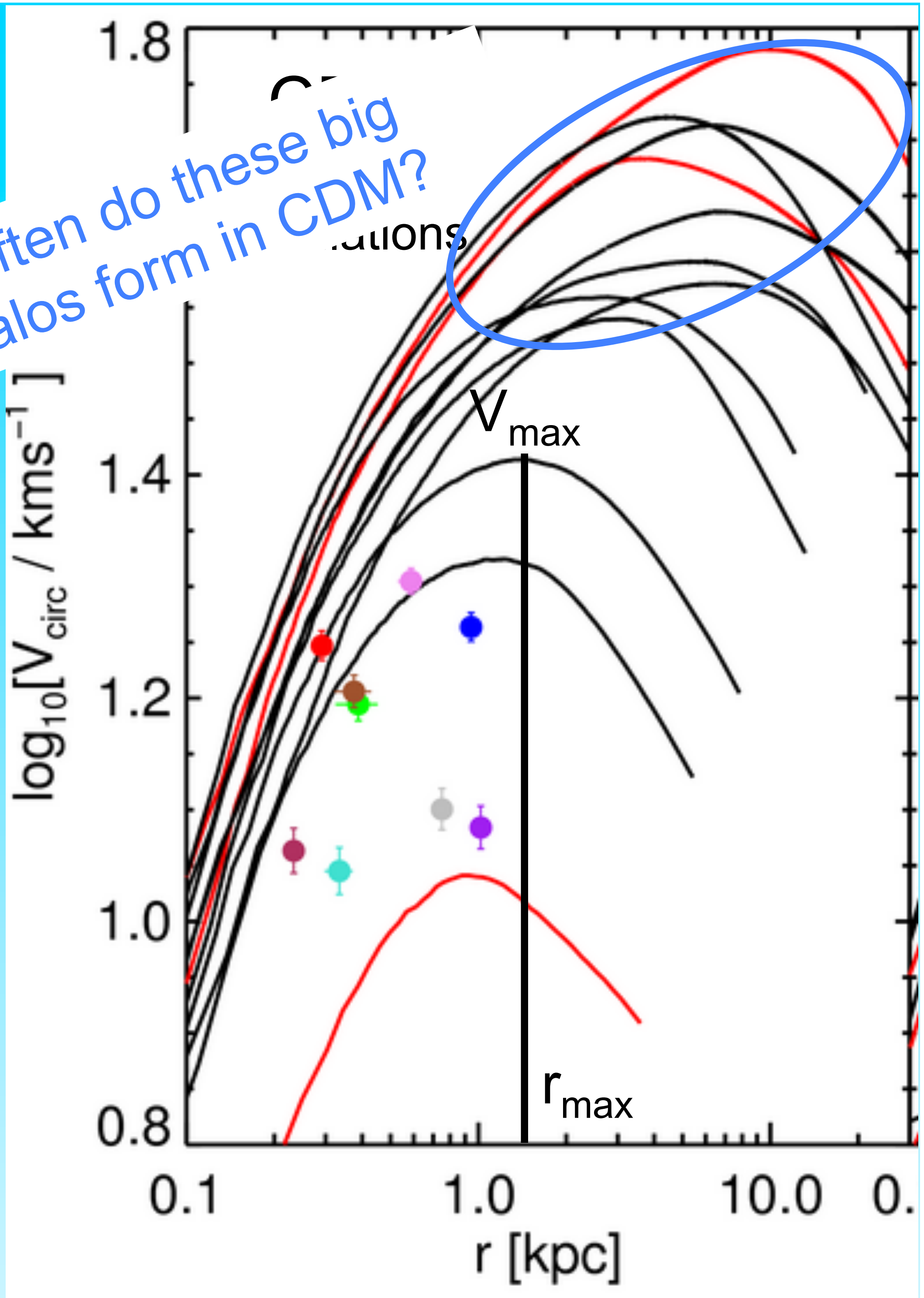


Is CDM compatible with luminosity & structure of observed satellites?

Rotation curves of 12 subhalos with most massive progenitors

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

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



Probability of massive subhalos

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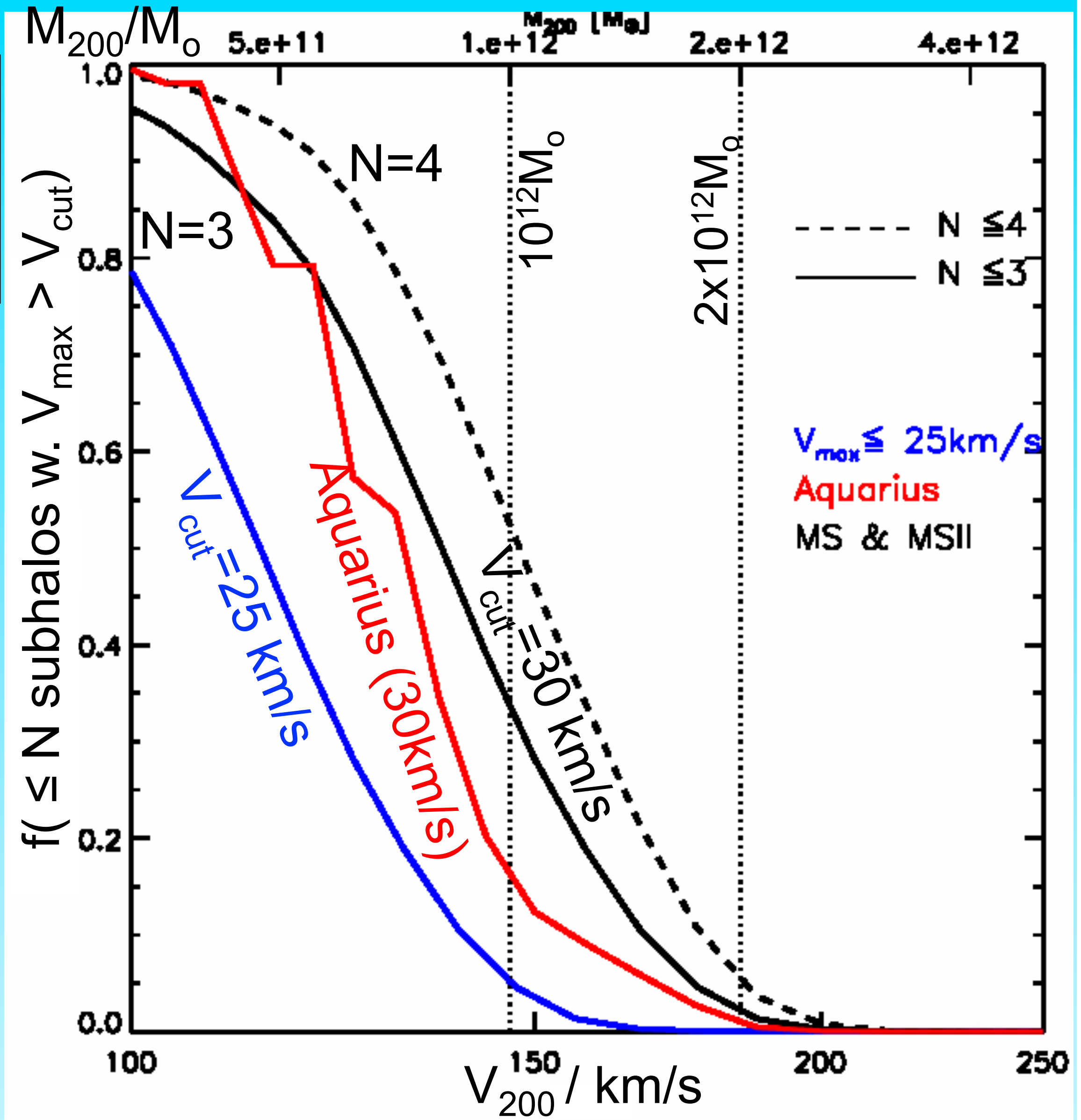
Probability of having no more than N subhalos with $V_{max} > V_{cut}$

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



Wang, Frenk, Navarro '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 subhalos less concentrated
- Sat. pop. in the MW is atypical or V_{cut}>25 km/s or $M_{halo} \leq 10^{12} M_o$