The satellites of the Milky Way and the nature of the dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

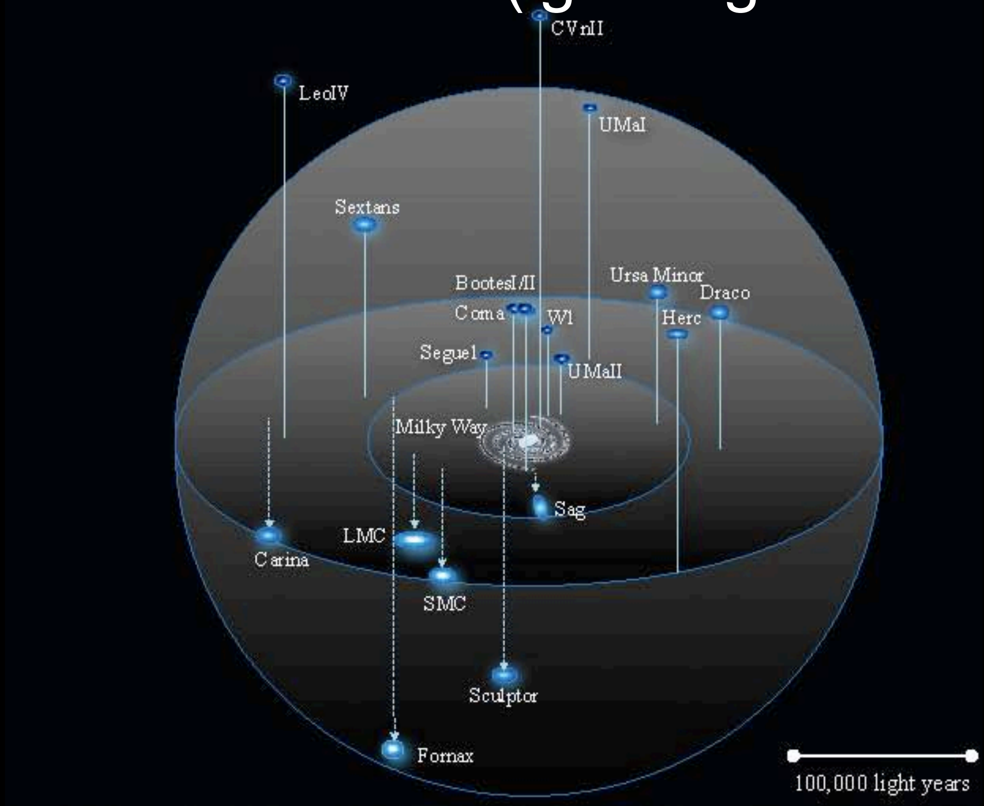
Dwarf galaxies around the Milky Way

Fornax

The satellites of the Milky Way”

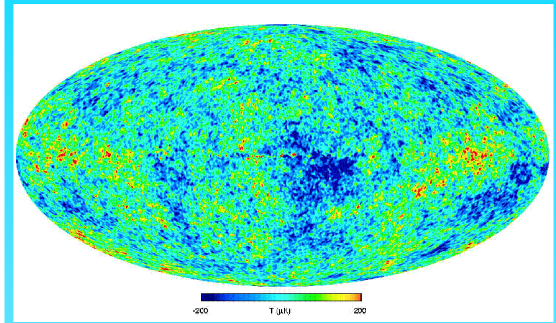
~ 25 satellites known in MW

contain ~3% of star mass in MW (ignoring LMC which has ~7%)



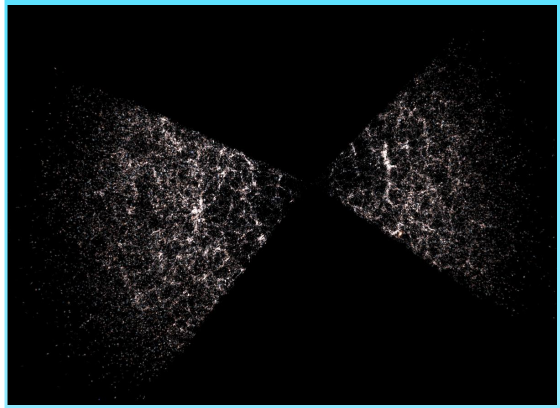
… so why bother…?

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



z~1000

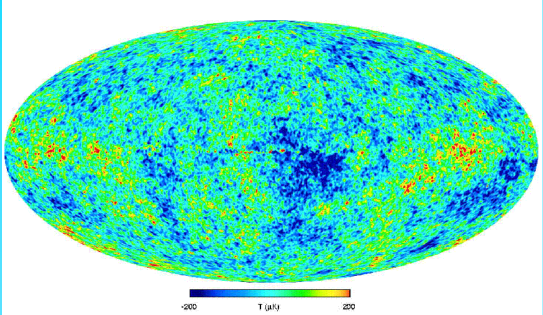
ΛCDM
- quantum fluctuations from inflation
- cold dark matter



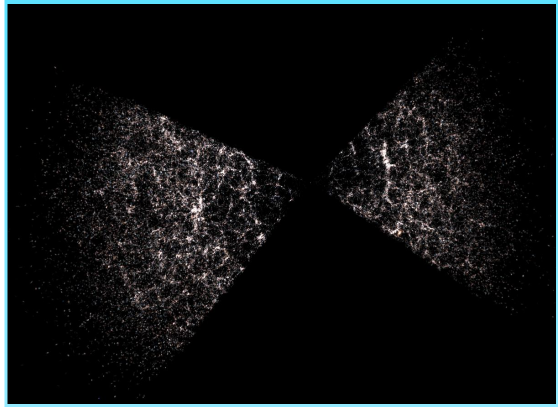
z~0

University of Durham

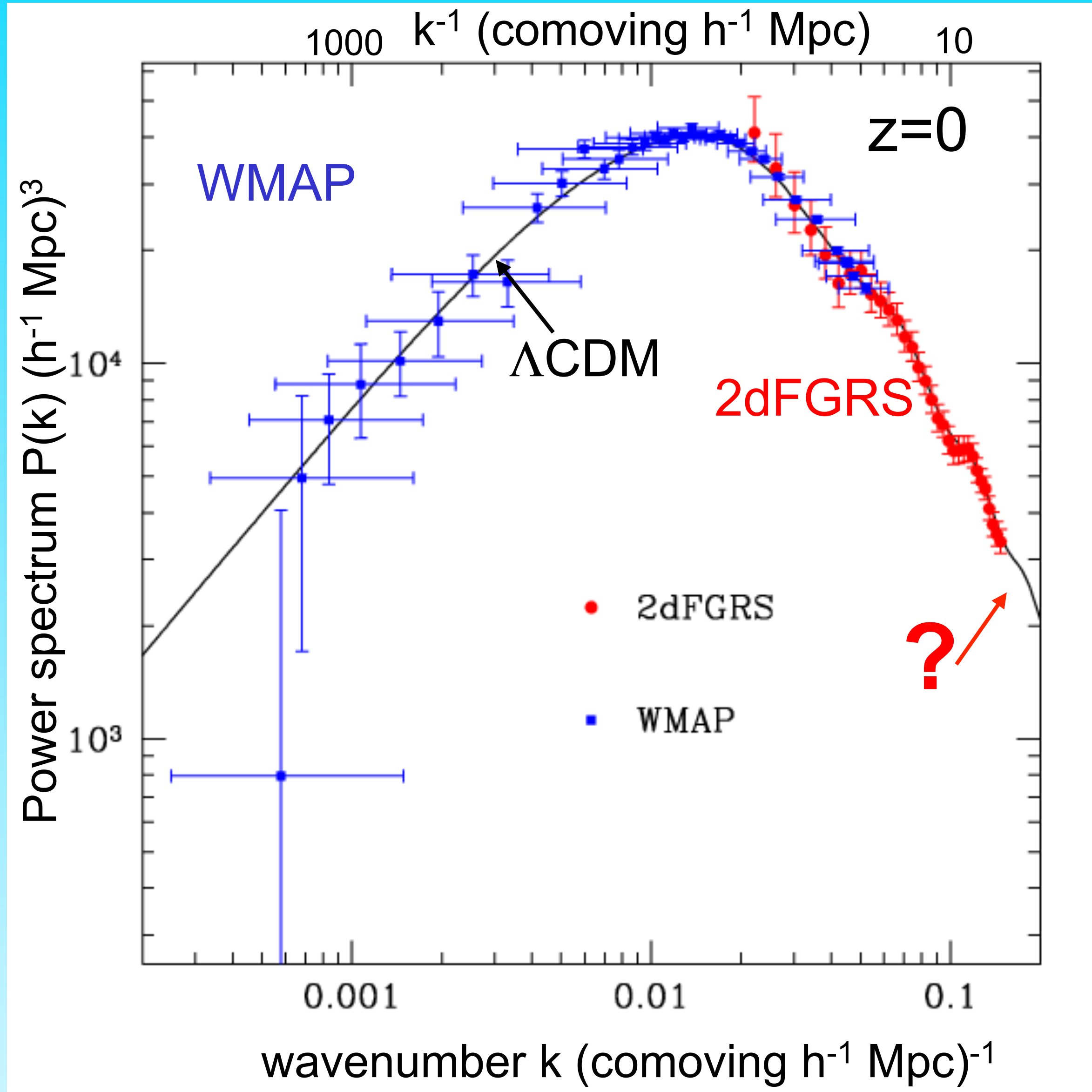
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

The small-scale structure depends sensitively on the nature of the dark matter

University of Durham

The dark matter power spectrum

$\lambda_{cut} \propto m_x^{-1}$

CDM:

10^{-6} M_o for 100 GeV wimp

WDM:

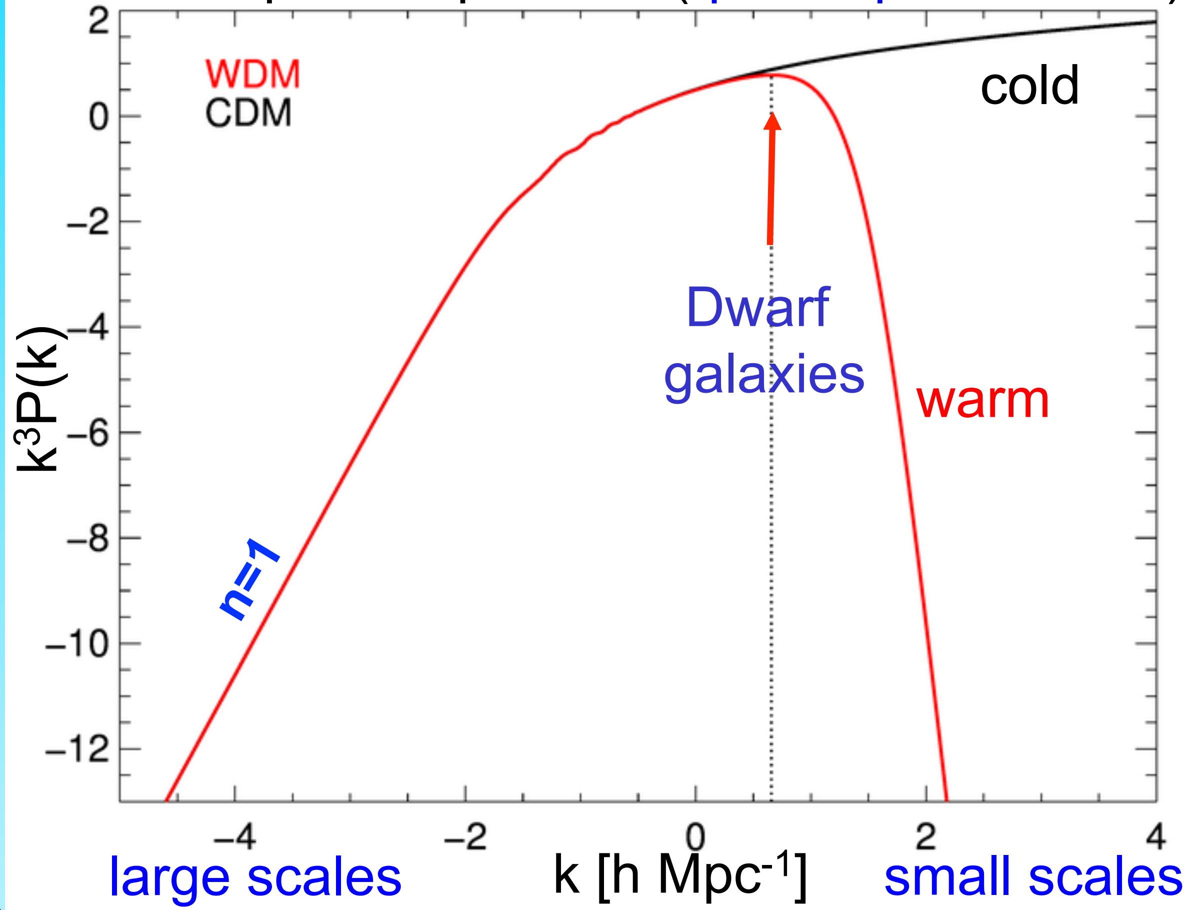
Ly-α forest (z~2-3) ➔

$m_{WDM} \gtrsim 4$keV (2σ) for thermal relic

$m_{WDM} \gtrsim 2$ keV (2σ) for sterile neutrinos

(Viel etal '08; Boyarsky etal '09)

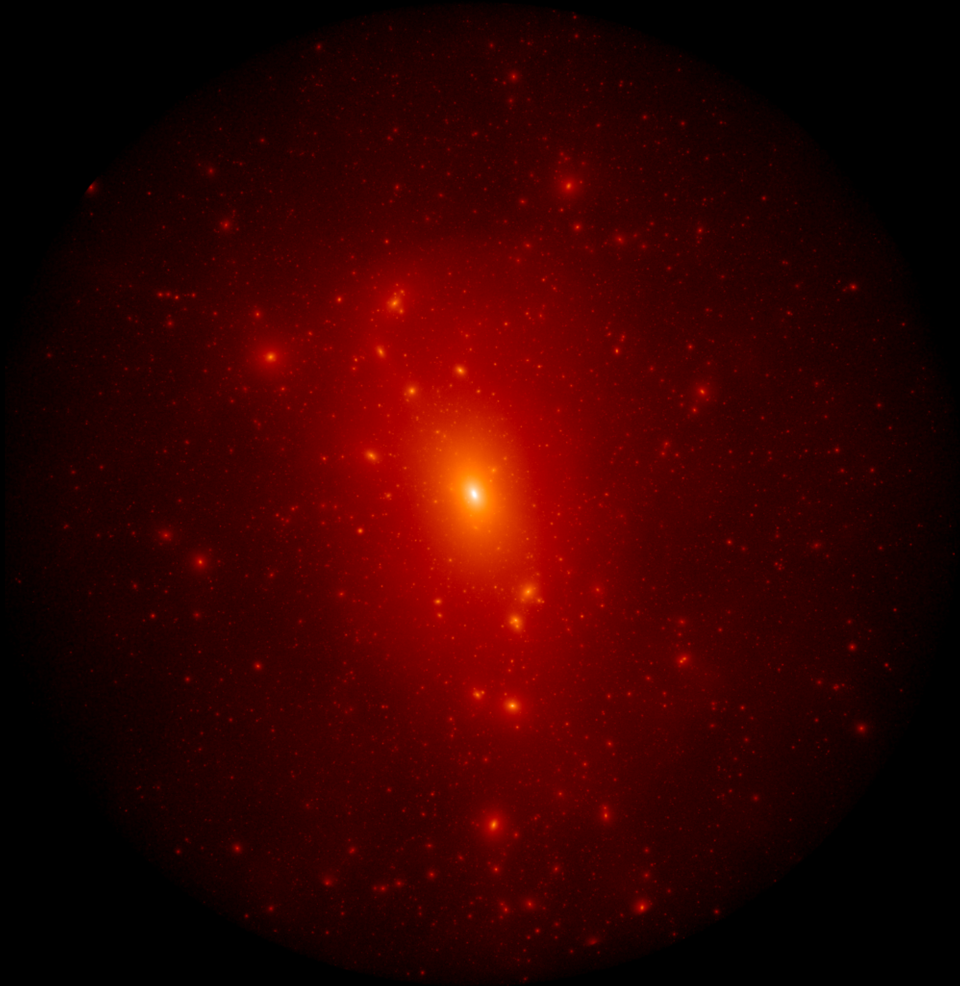
The linear power spectrum ("power per octave")



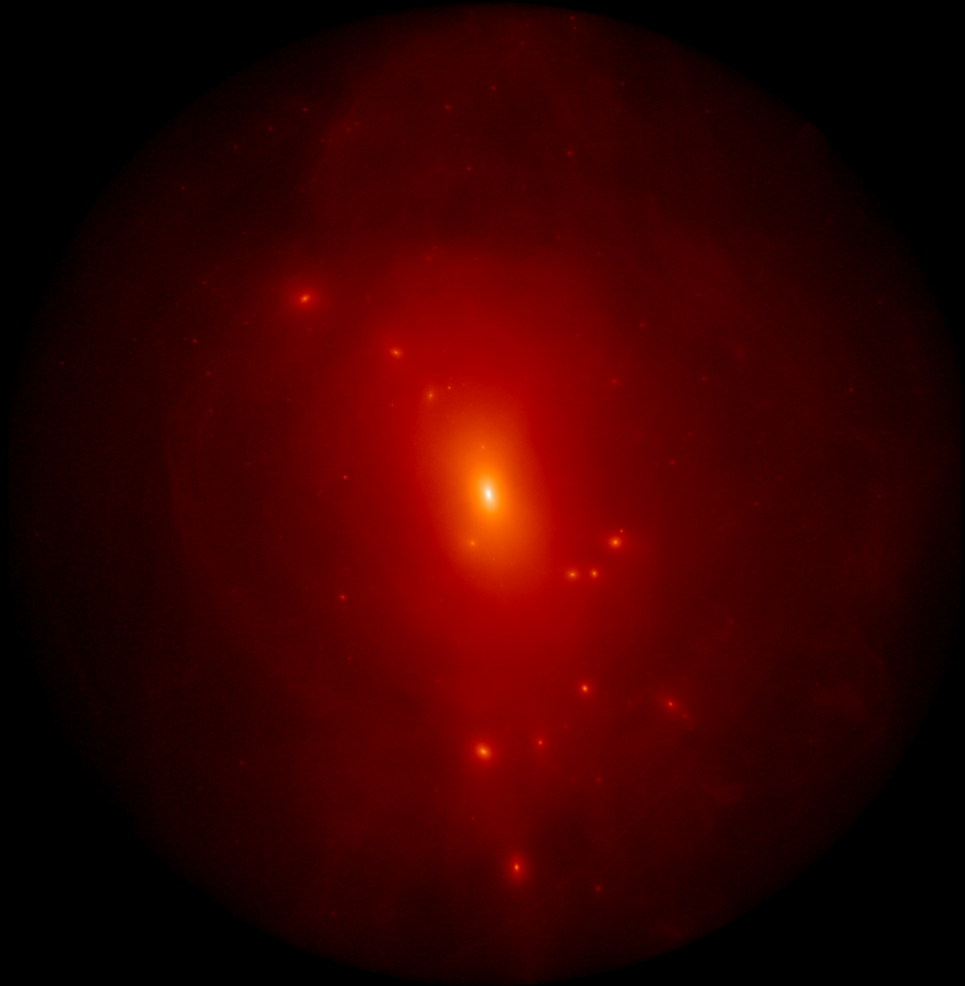
$M_{cut} \sim 10^{10}$ $(\Omega/0.3)^{1.45}$ $(h/0.65)^{3.9}$ $(keV/m_{wdm})^{3.45}$ h^{-1} M_o

Institute for Computational Cosmology

cold dark matter



warm dark matter



Lovell, Frenk, Gao et al 2011

Dwarf galaxies may encode the identity of the dark matter

Testing CDM with satellite data

University of Durham

A Cold dark matter universe

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

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

Three challenges to CDM :

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

The Aquarius programme

Adrian Jenkins

Aaron Ludlow

Julio Navarro

Volker Springel,

Mark Vogelsberger

Jie Wang

Carlos Frenk

Simon White

Aquarius ++

Shaun Cole

Andrew Cooper

Amina Helmi

Gao Liang

Gabriella de Lucia

UK, Germany, Netherlands, Canada, Japan, China collaboration

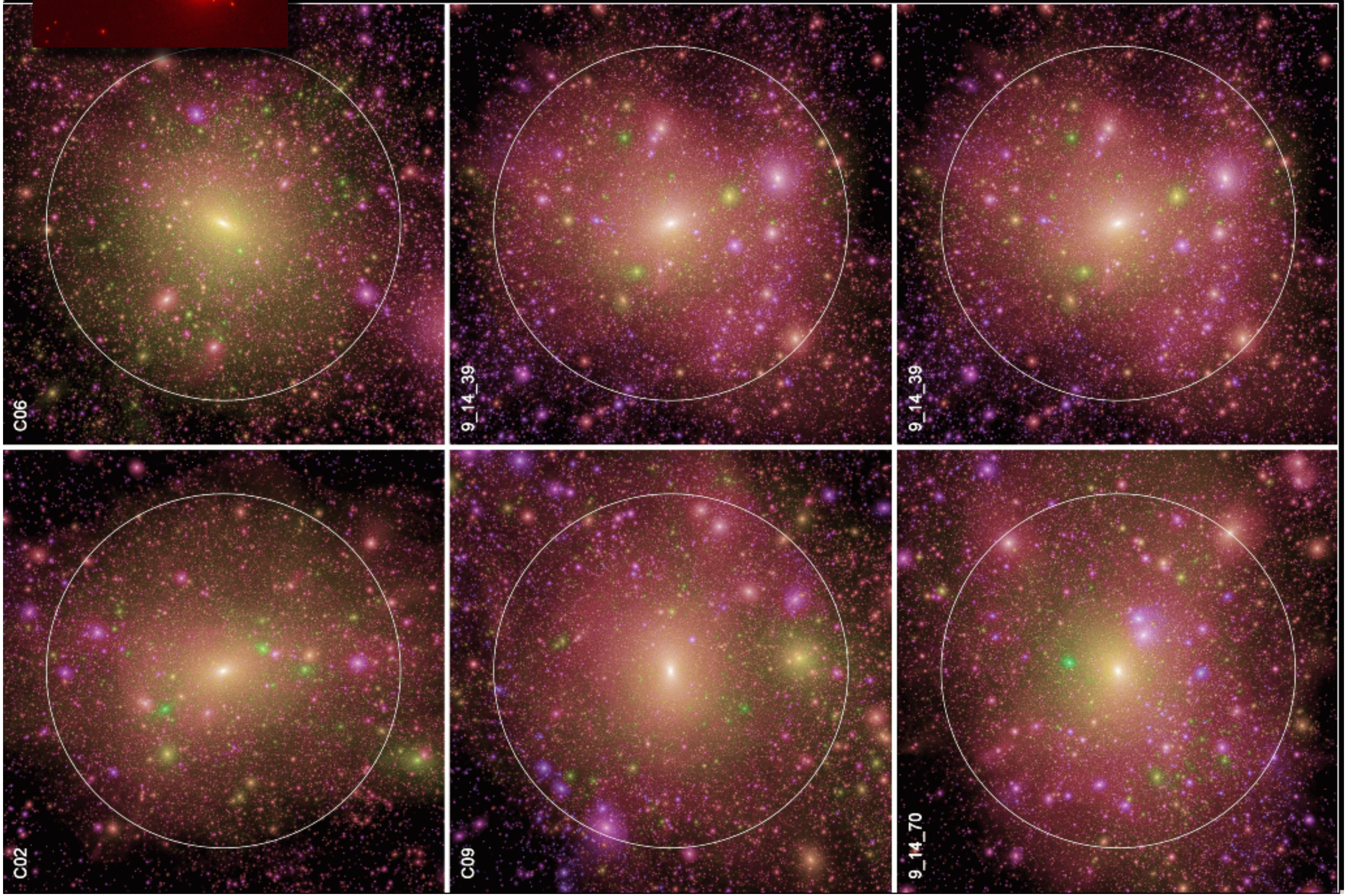
Pictures, movies and simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

www.durham.ac.uk/virgo


z = 48.4
T = 0.05 Gyr
500 kpc

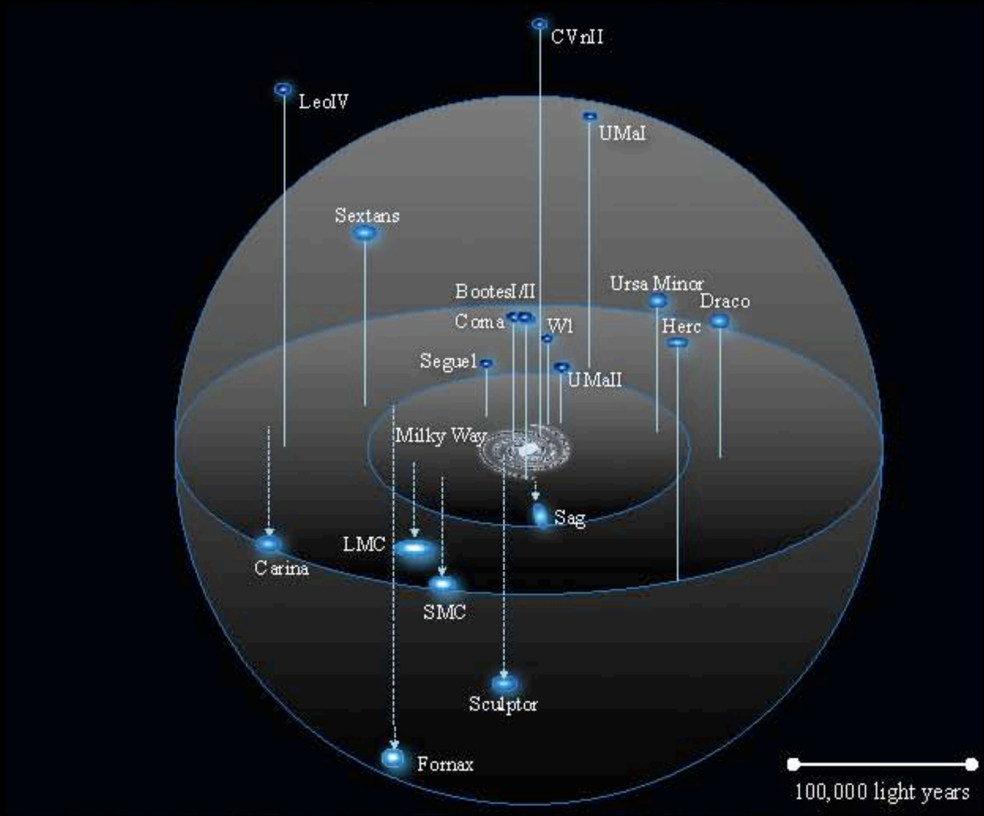
Images of all Aquarius halos (level-2)

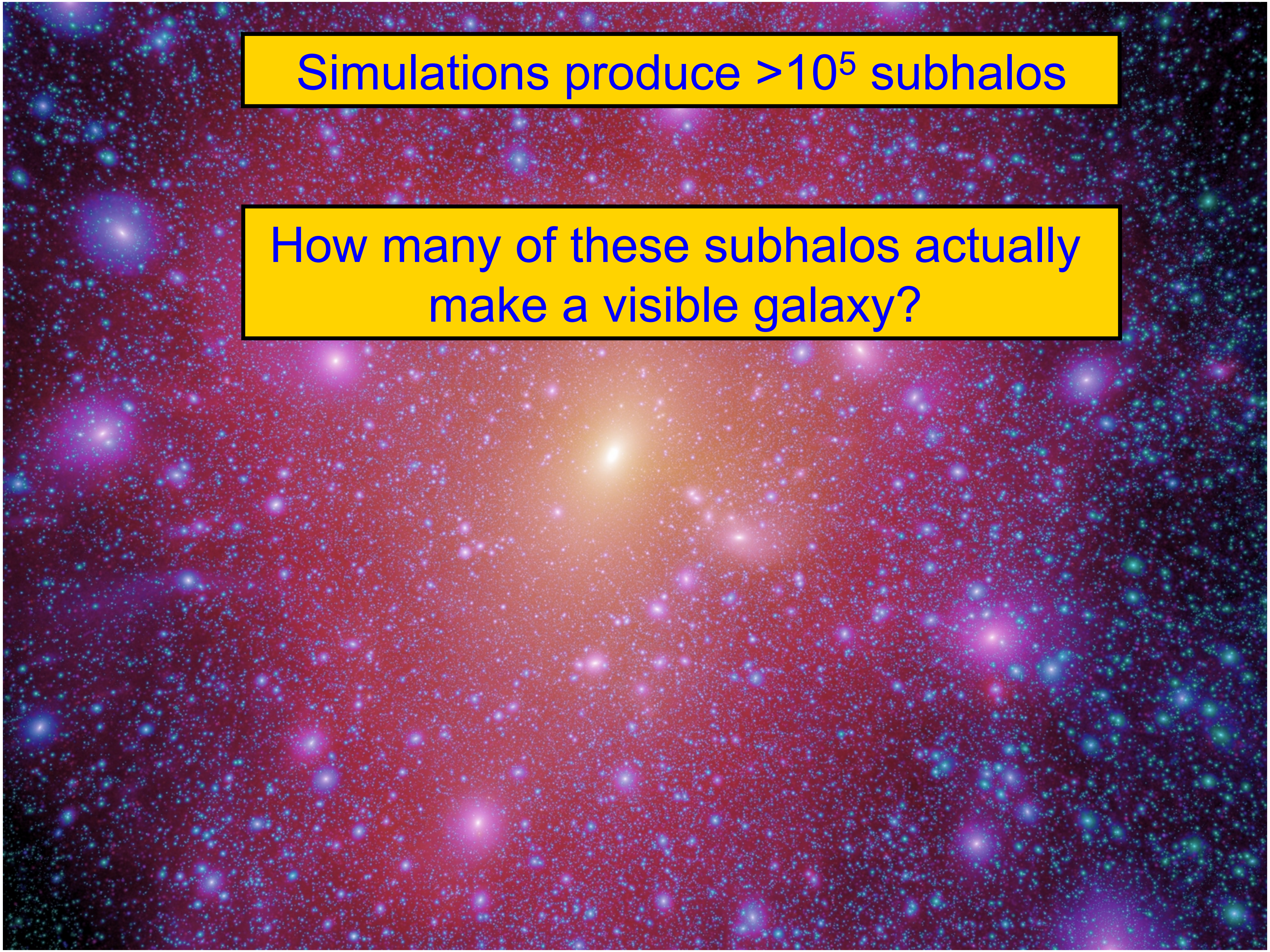


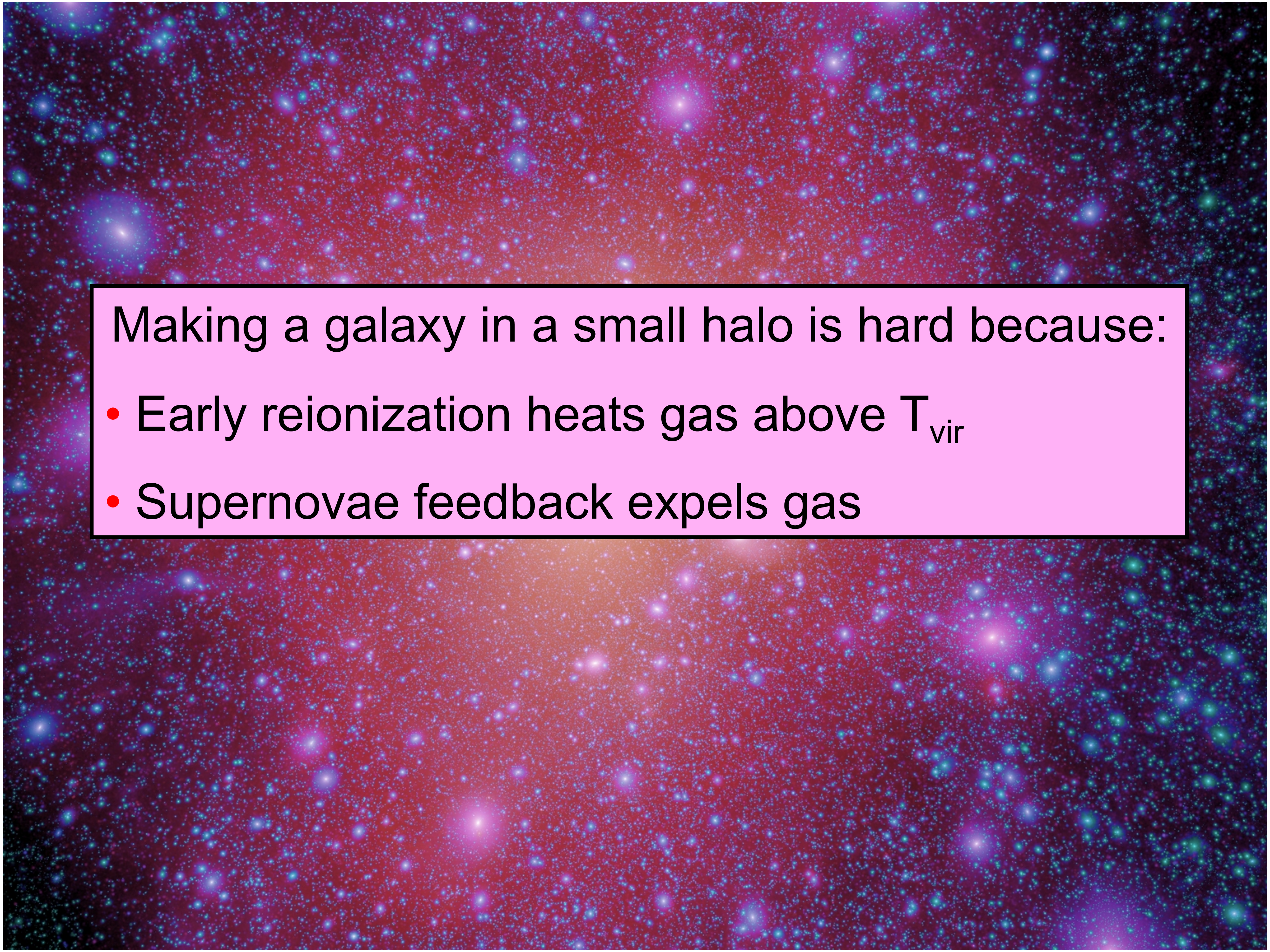
Three challenges for CDM on galactic scales:

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?

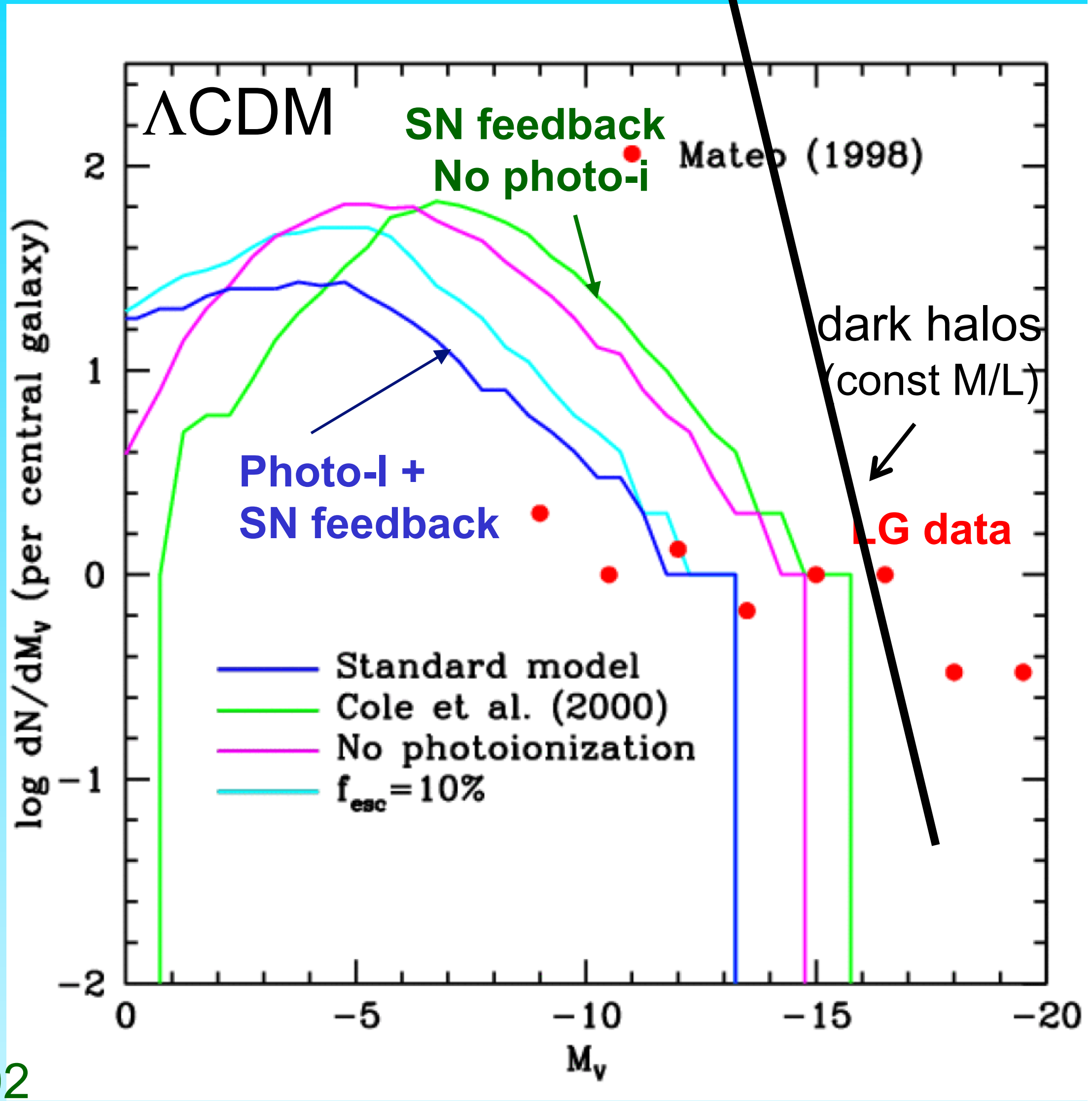


Making a galaxy in a small halo is hard because:

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

Luminosity Function of Local Group Satellites

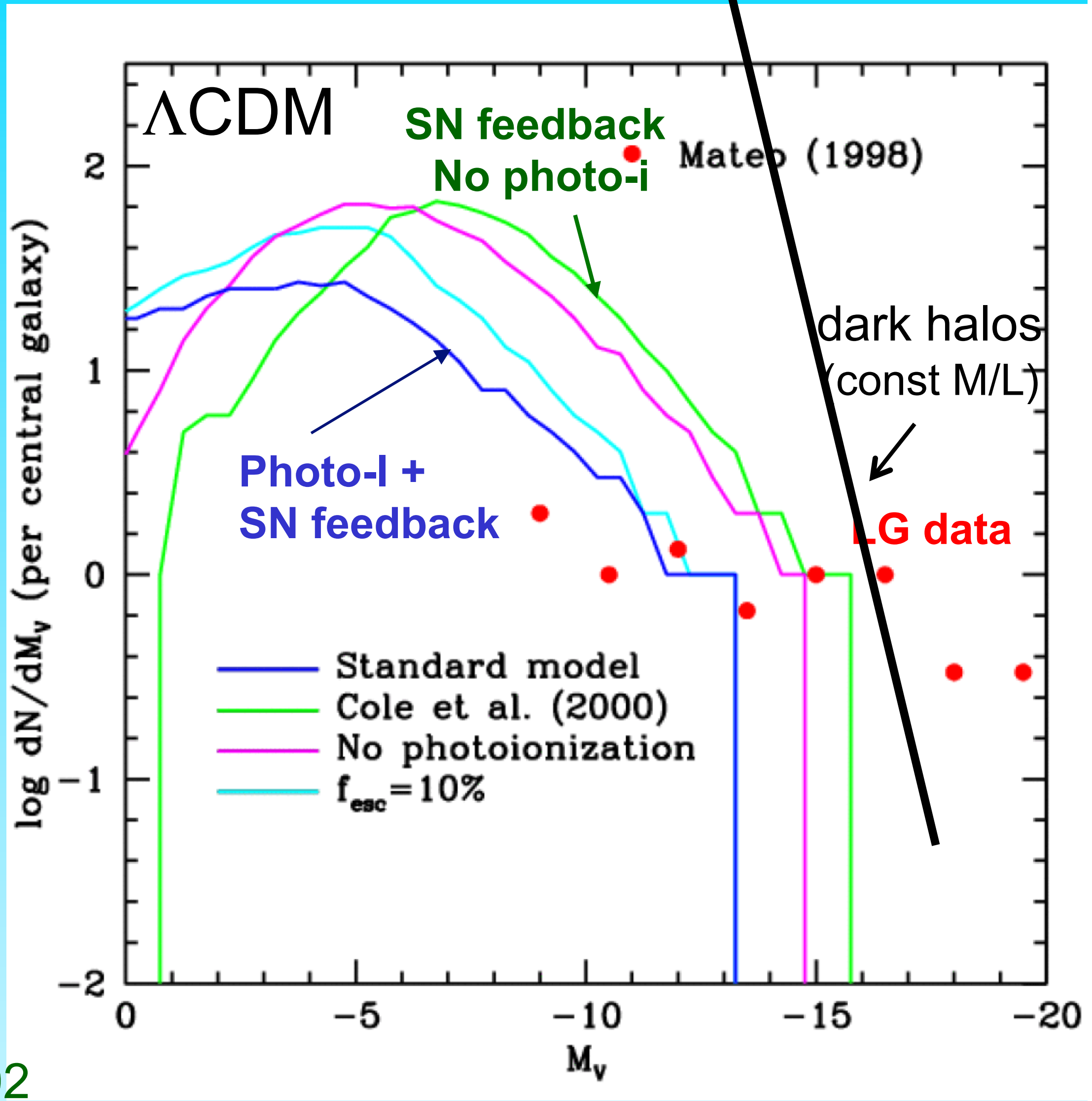
- Photoionization inhibits the formation of satellites
- Abundance of satellies reduced by large factor!
- Median model gives correct abundance of sats brighter than M_V=-9, V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites



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

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

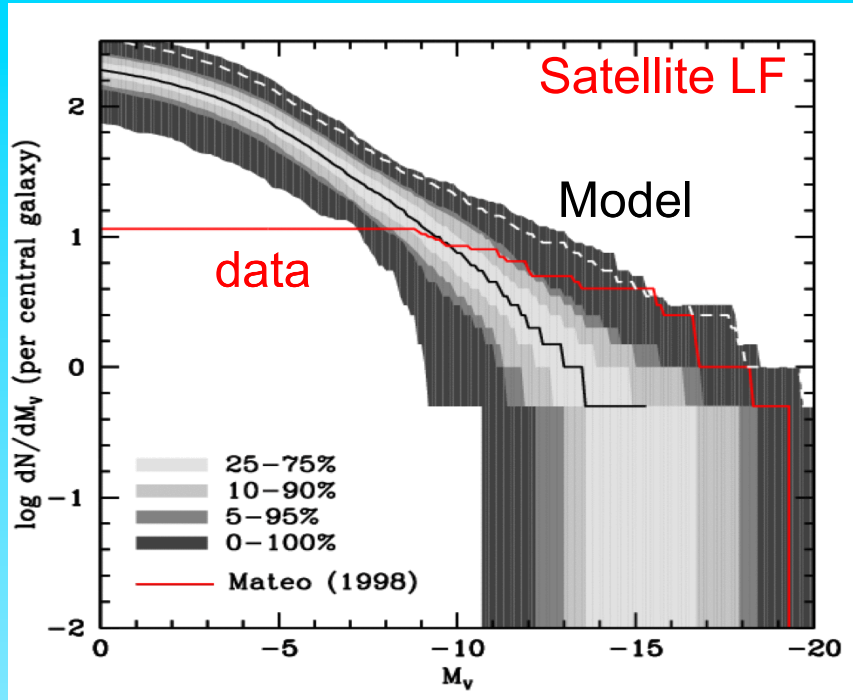


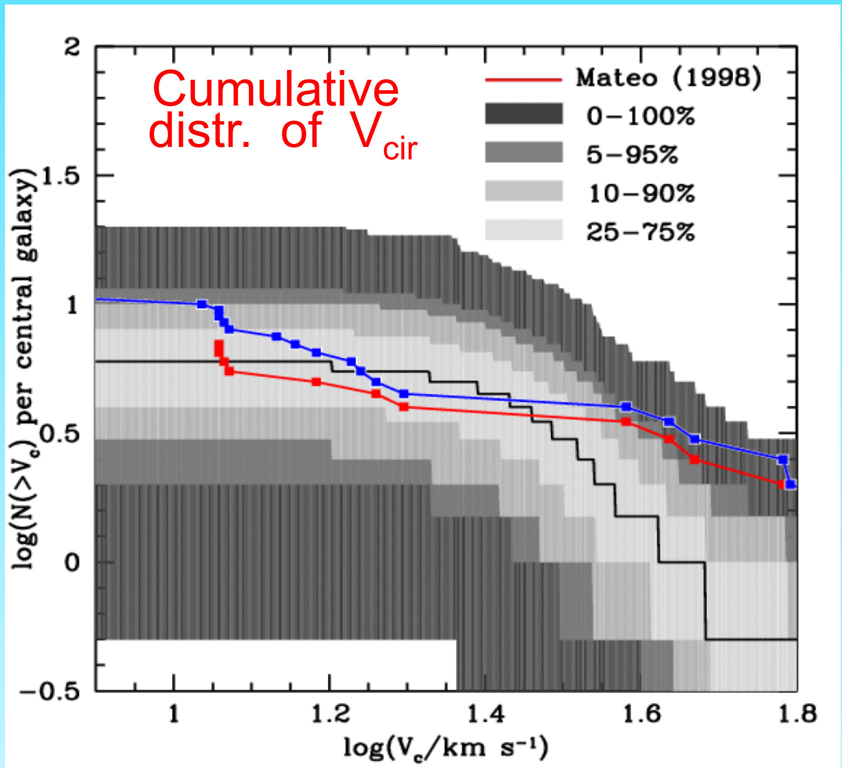
Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

The satellites of the Local Group

University of Durham

- LF of satellites within the virial radii of MW and M31
- Photoionization inhibits the formation of satellites

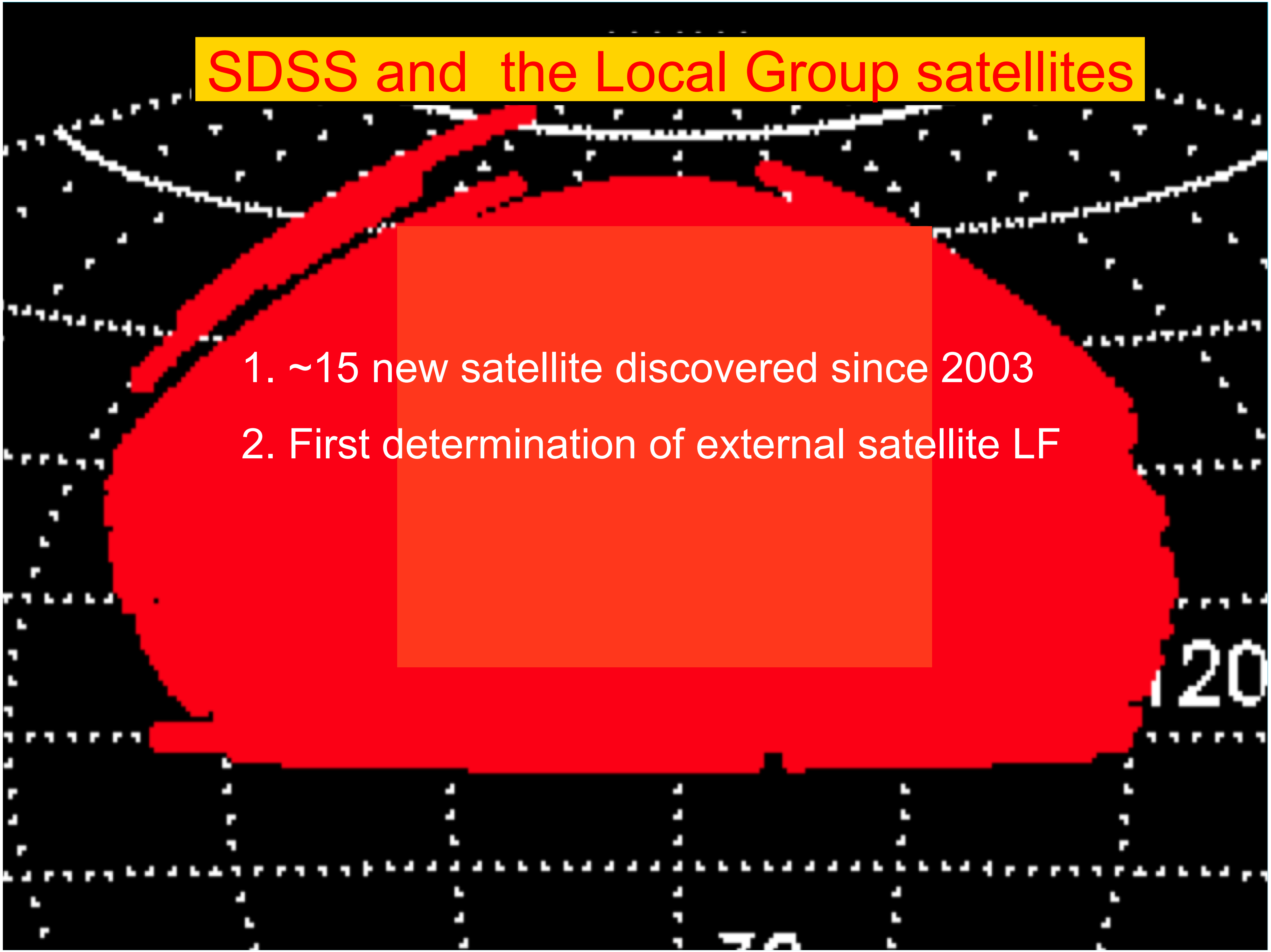




Benson, Frenk, Lacey, Baugh & Cole '02

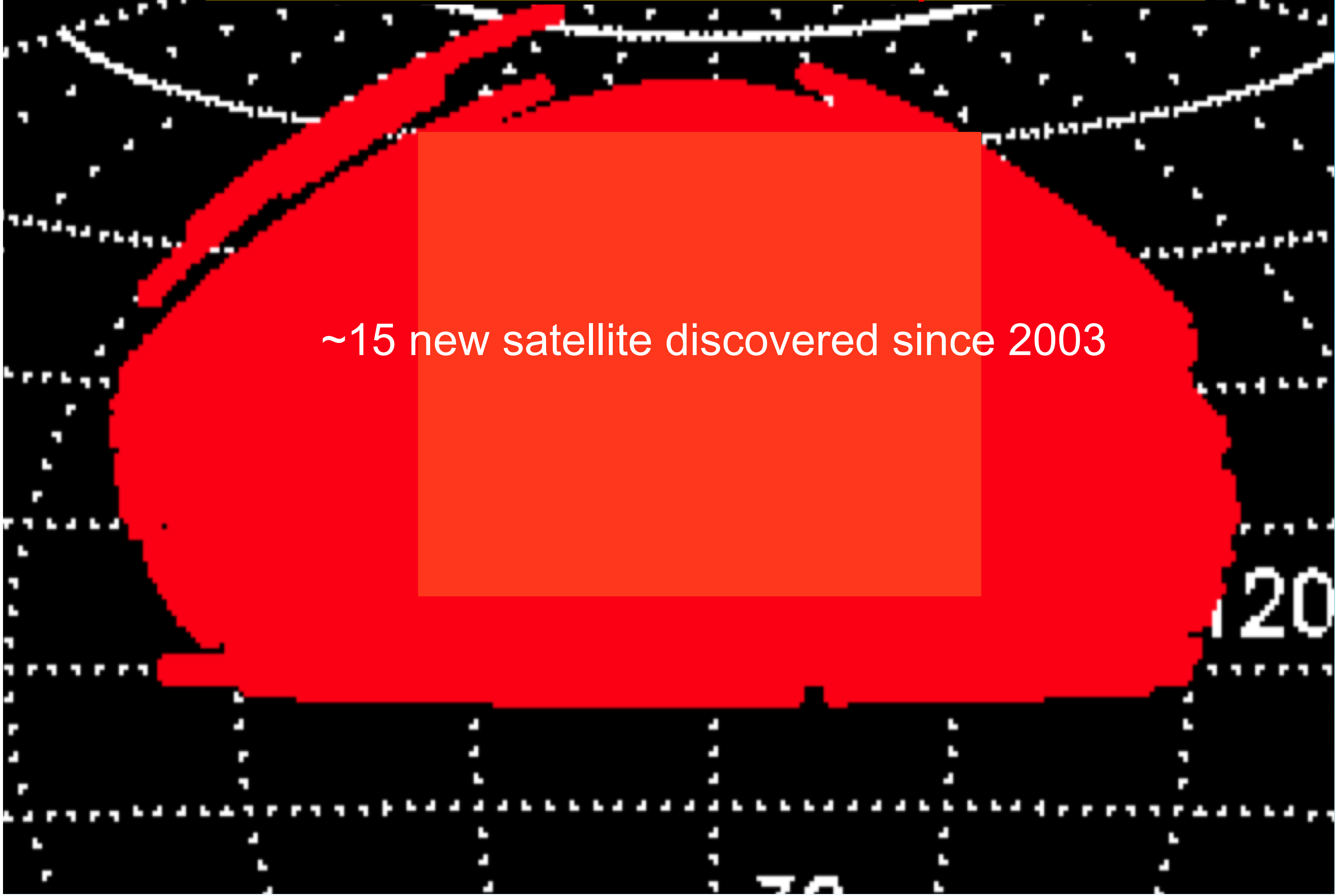
- Median model gives correct abundance of satellites brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)

SDSS and the Local Group satellites



1. ~15 new satellite discovered since 2003
2. First determination of external satellite LF

SDSS and the Local Group satellites

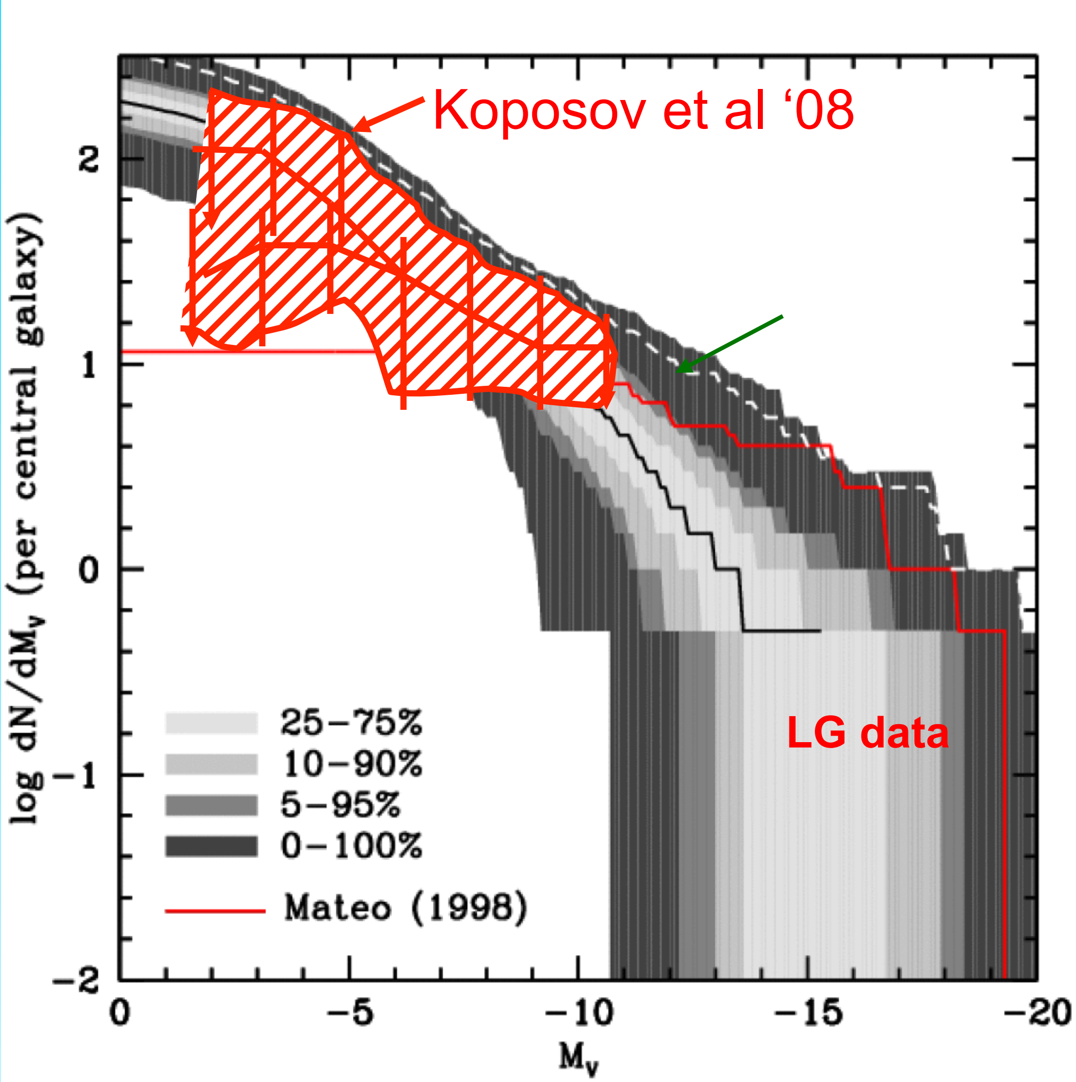


Luminosity Function of Local Group Satellites

- 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

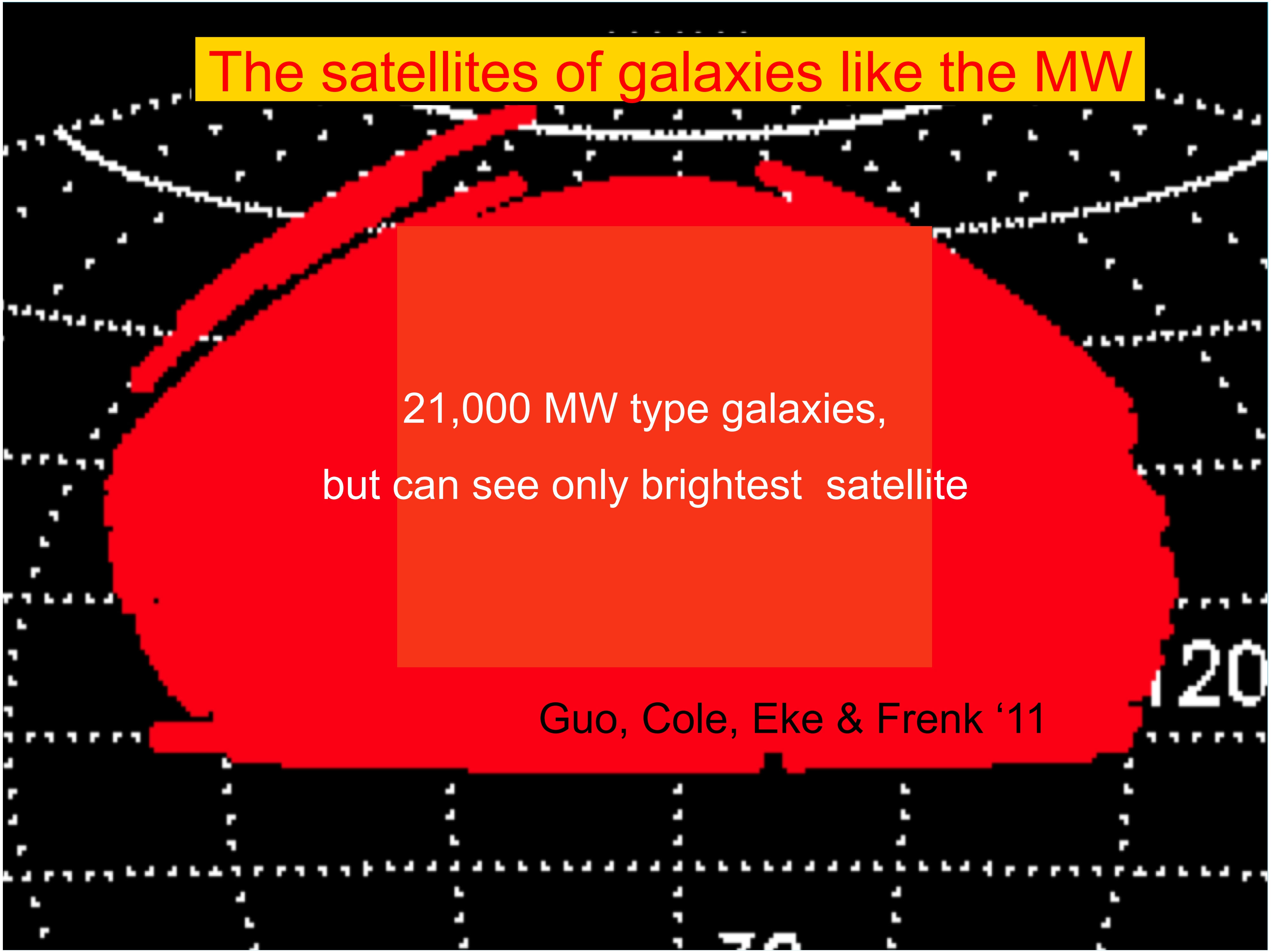
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02

The satellite luminosity function in galaxies similar to the Milky Way

The satellites of galaxies like the MW



21,000 MW type galaxies,

but can see only brightest satellite

Guo, Cole, Eke & Frenk '11

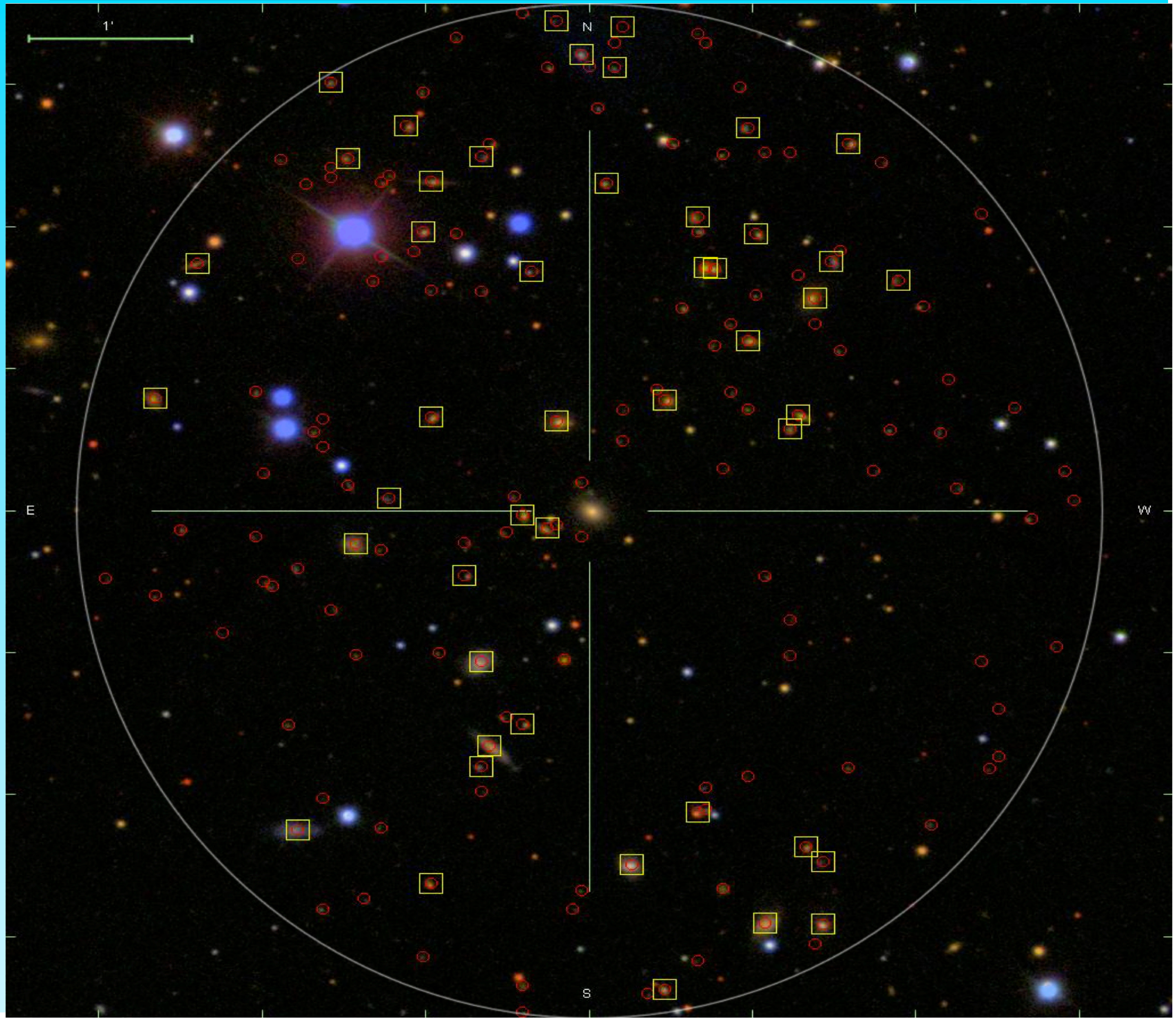
How typical is the MW satellite system?

Find Milky Way analogues (eg isolated spirals) in SDSS

103,000 galaxies, 21,000 with MW luminosity

Use photo-z to help remove bck

Guo, Cole, Eke & Frenk ‘11



How typical is the MW satellite system?

University of Durham

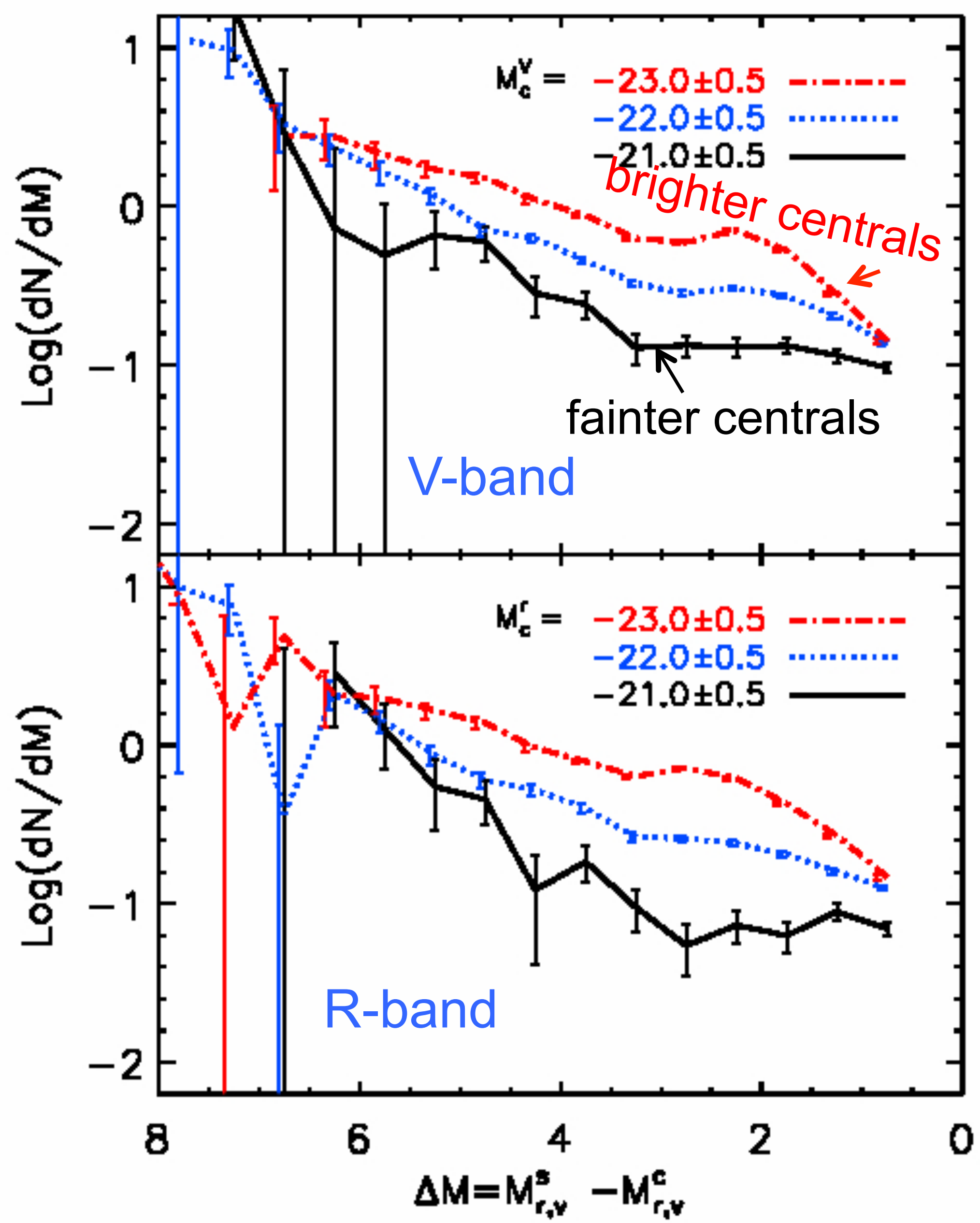
Find Milky Way analogues (eg isolated spirals) in SDSS

103,000 galaxies, 21,000 with MW luminosity

No. of satellites depends on luminosity of primary

Changes by ~x10 $\Delta M=2$

Guo, Cole, Eke & Frenk '11



How typical is the MW satellite system?

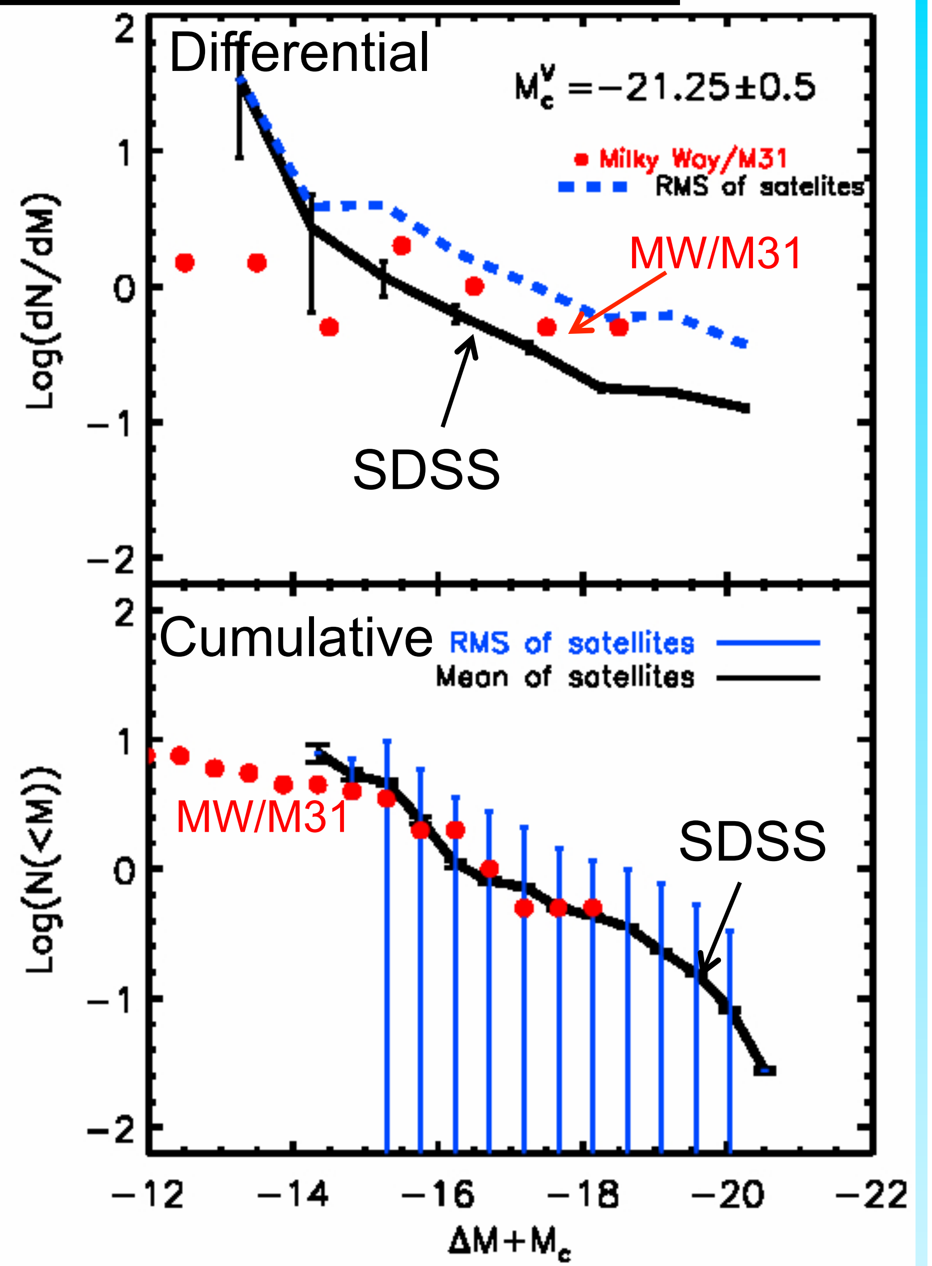
Satellite LF of MW analogues

The MW and M31 contain (2-3)x more bright ($-18.5 < M_V < -14$) satellites than other isolated galaxies of similar luminosity

The LMC/SMC system occurs only once in every 30 gals

(see Liu et al '11, Lares et al '11)

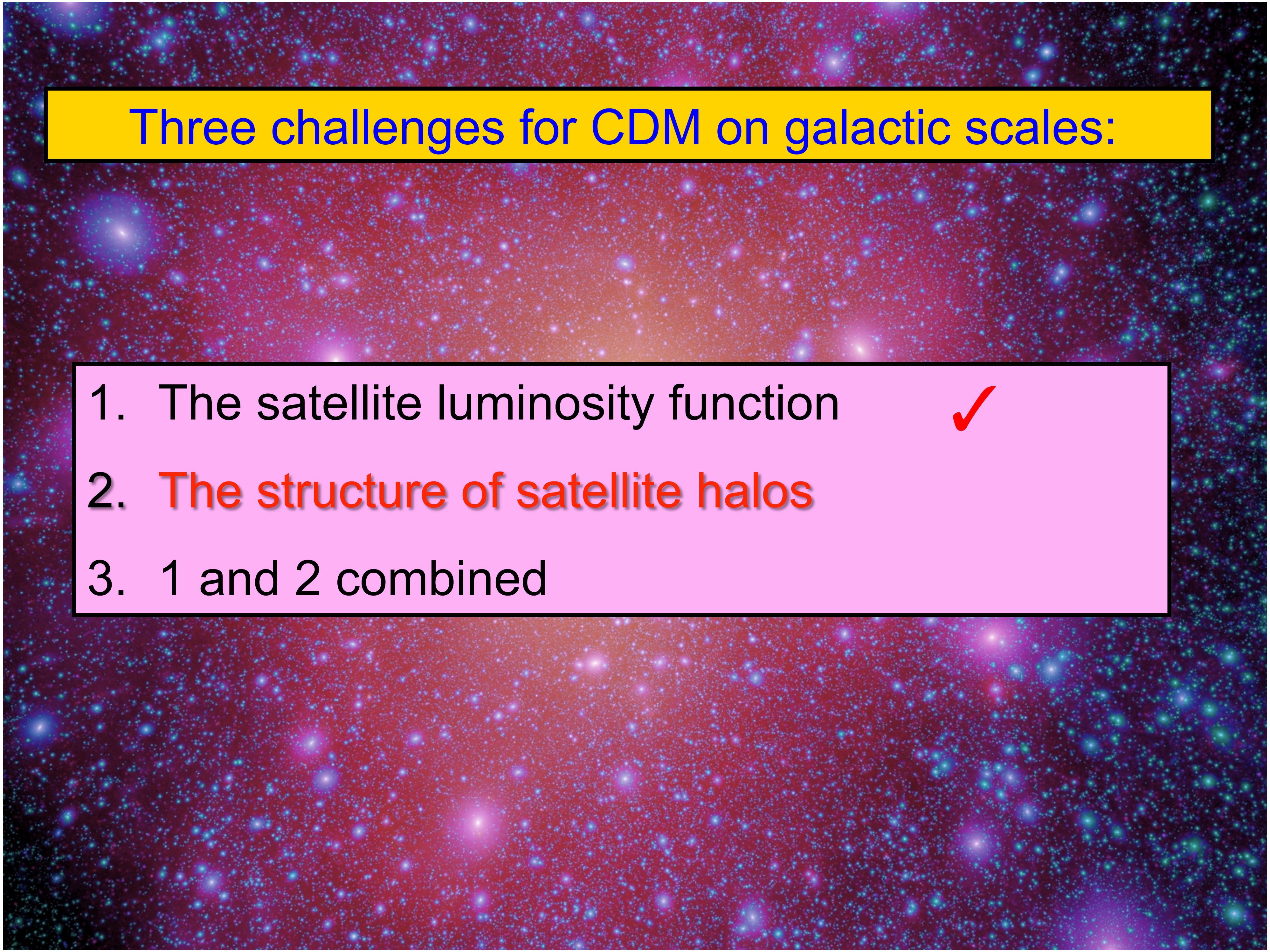
Guo, Cole, Eke & Frenk '11



Must be careful when interpreting MW/M31 satellite data!

Three challenges for CDM on galactic scales:

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

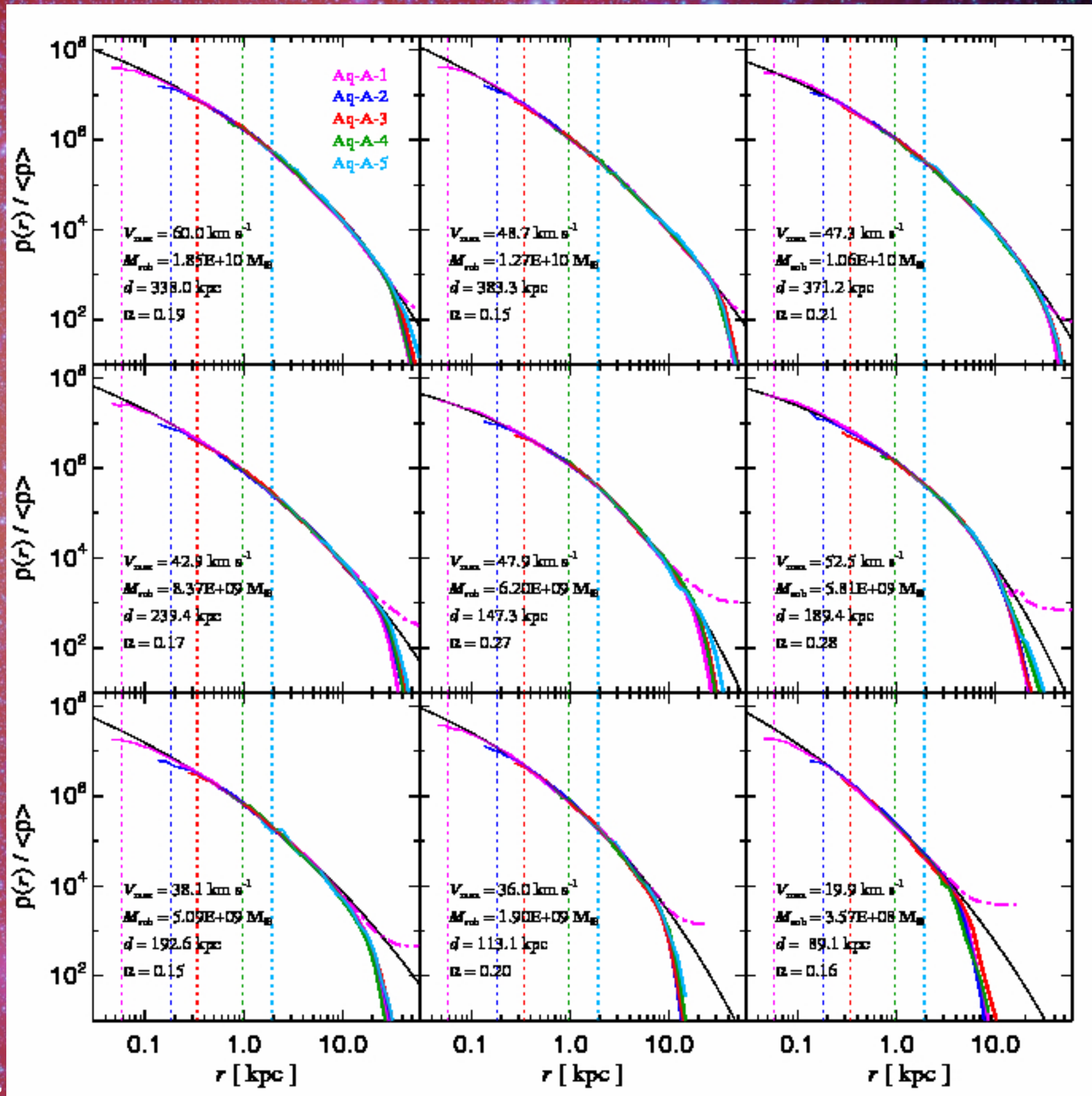


Three challenges for CDM on galactic scales:

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

In CDM predict: cuspy density profiles in halos and subhalos

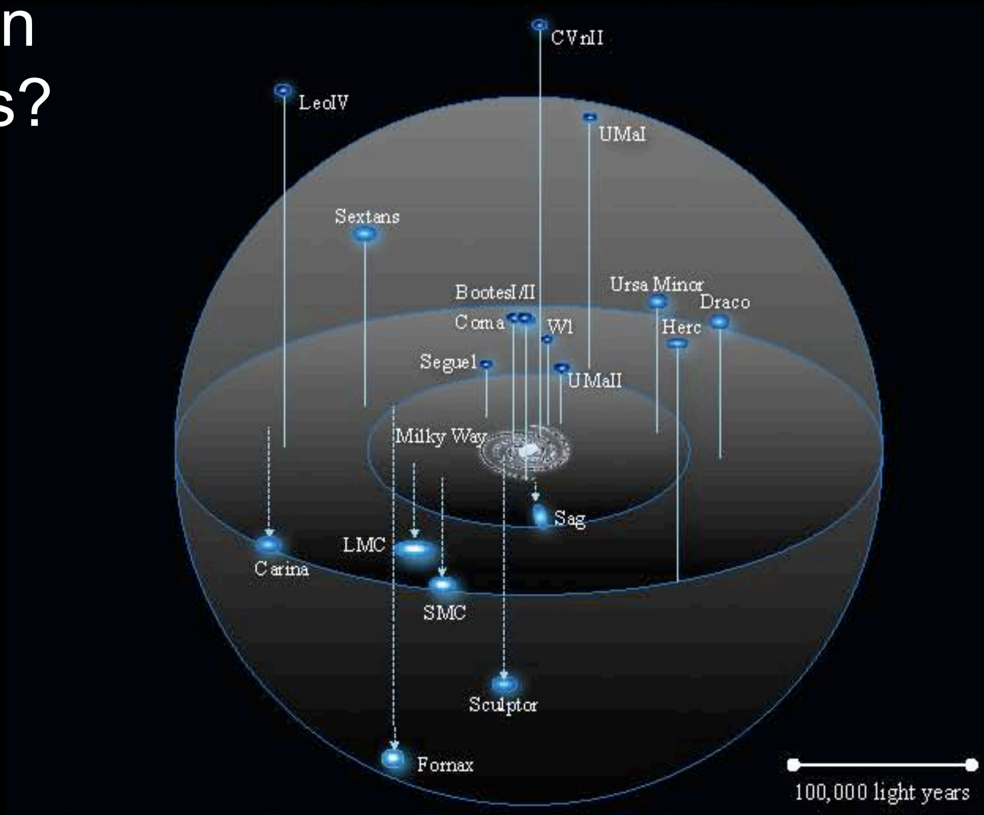
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$



Navarro, Frenk & White '96, '97

The satellites of the Milky Way”

Do they live in
“cuspy” halos?



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

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 2010

University of Durham

Dwarf sphs: cores or cusps?

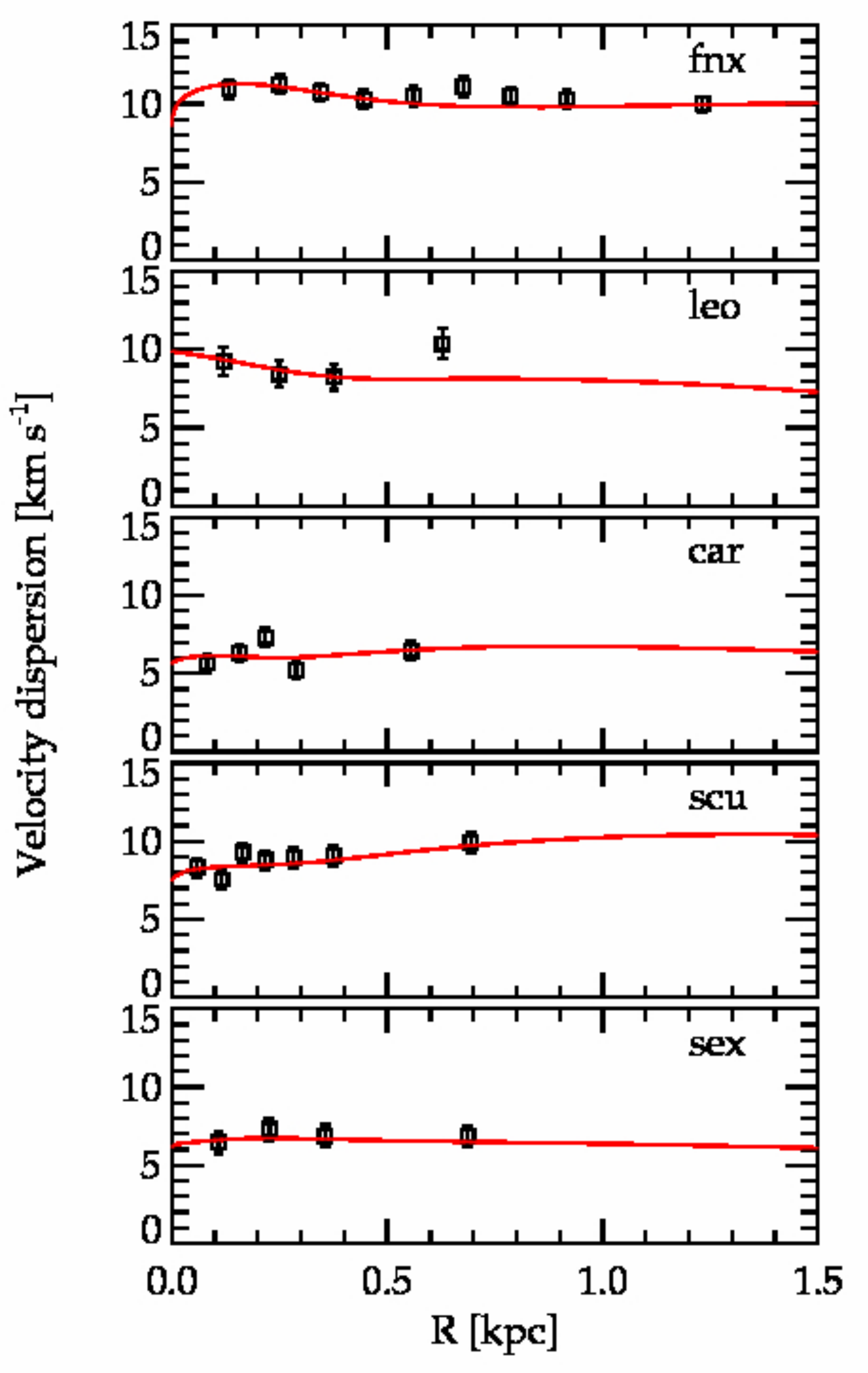
Jeans eqn:

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

from Aquarius sim

vel. anisotropy

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



University of Durham

Dwarf sphs: cores or cusps?

Jeans eqn:

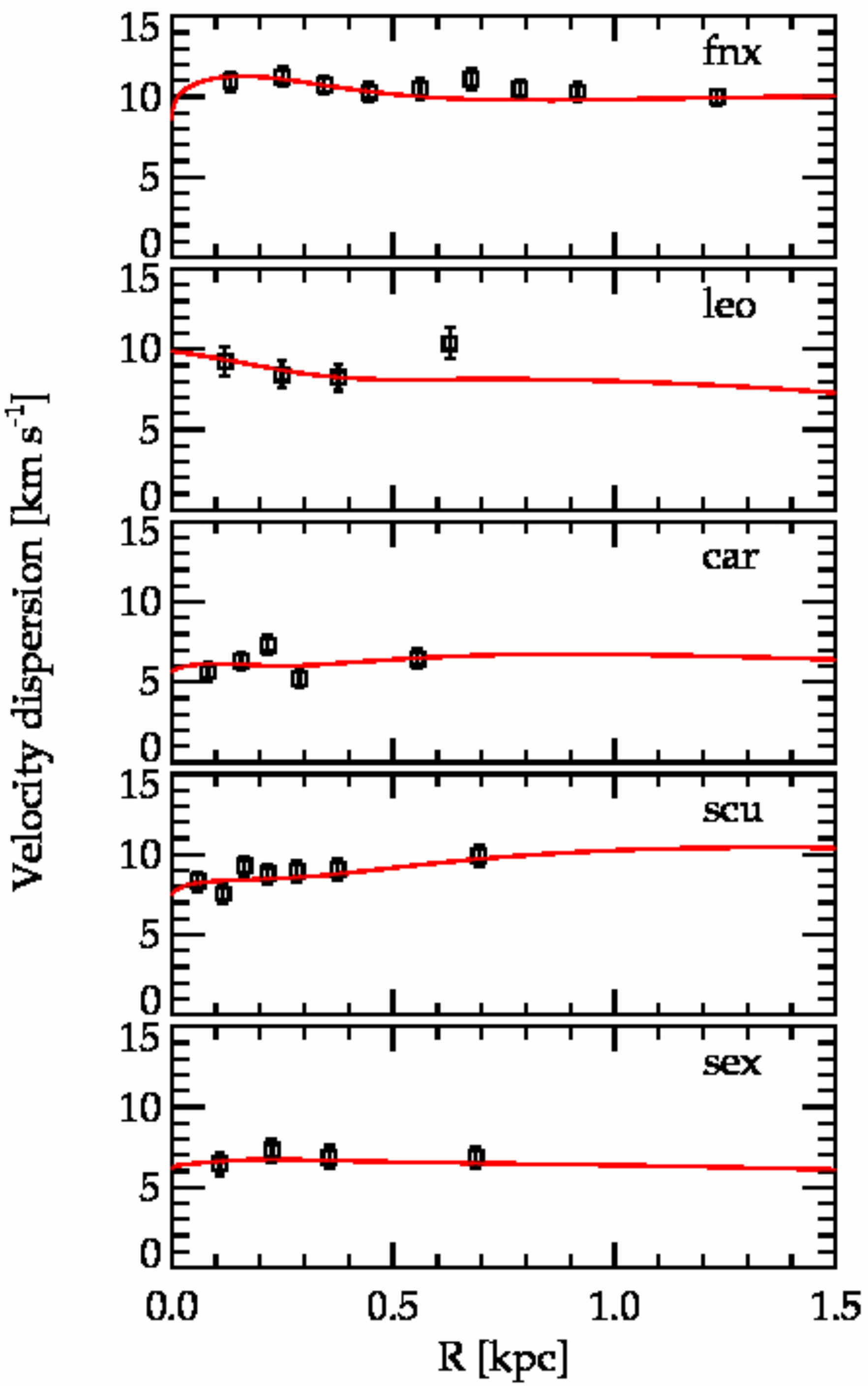
$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta \right]$$

from Aquarius sim

vel. anisotropy

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

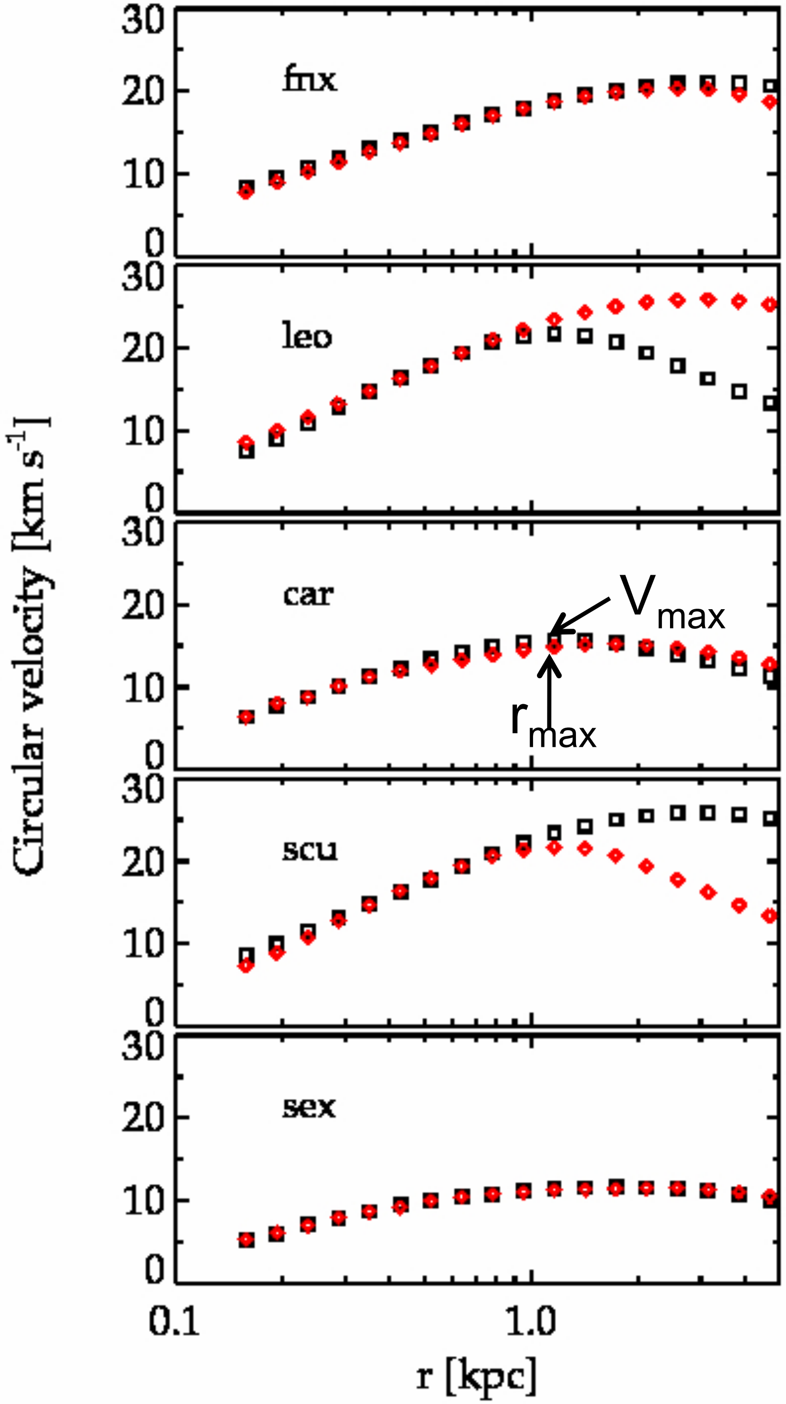
Three challenges for CDM on galactic scales:

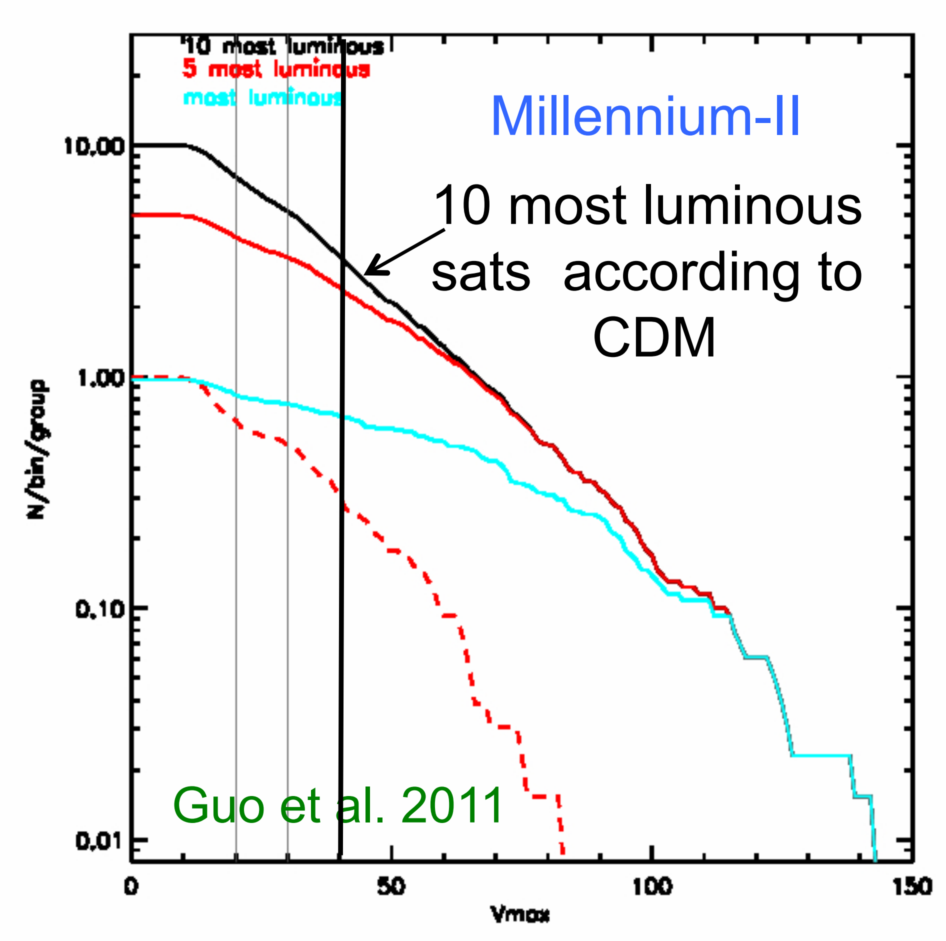
1. The satellite luminosity function ✓
2. The structure of satellite halos ✓
3. 1 and 2 combined

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

The satellites of the Milky Way

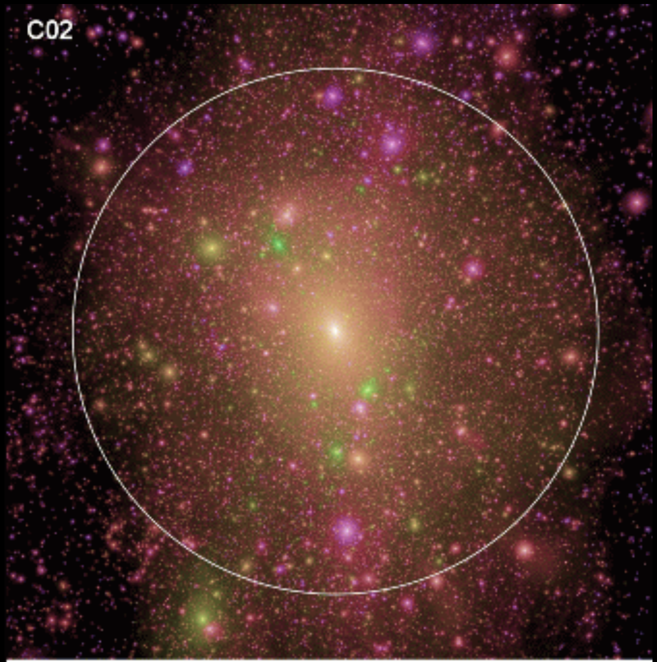
Top 2 best fit CDM models to data

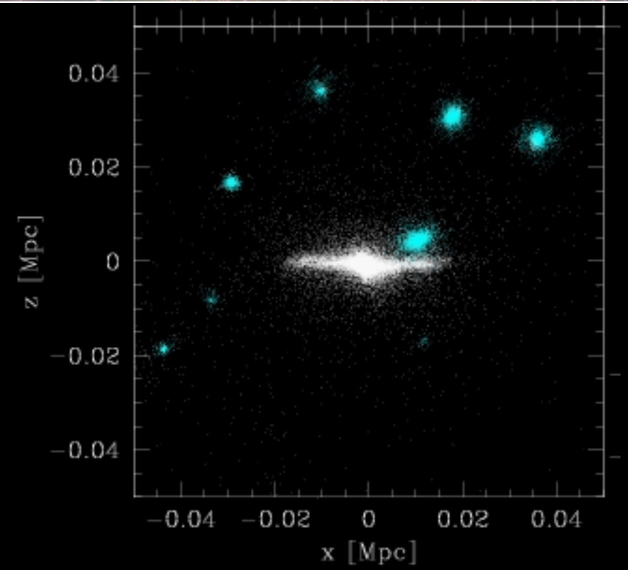




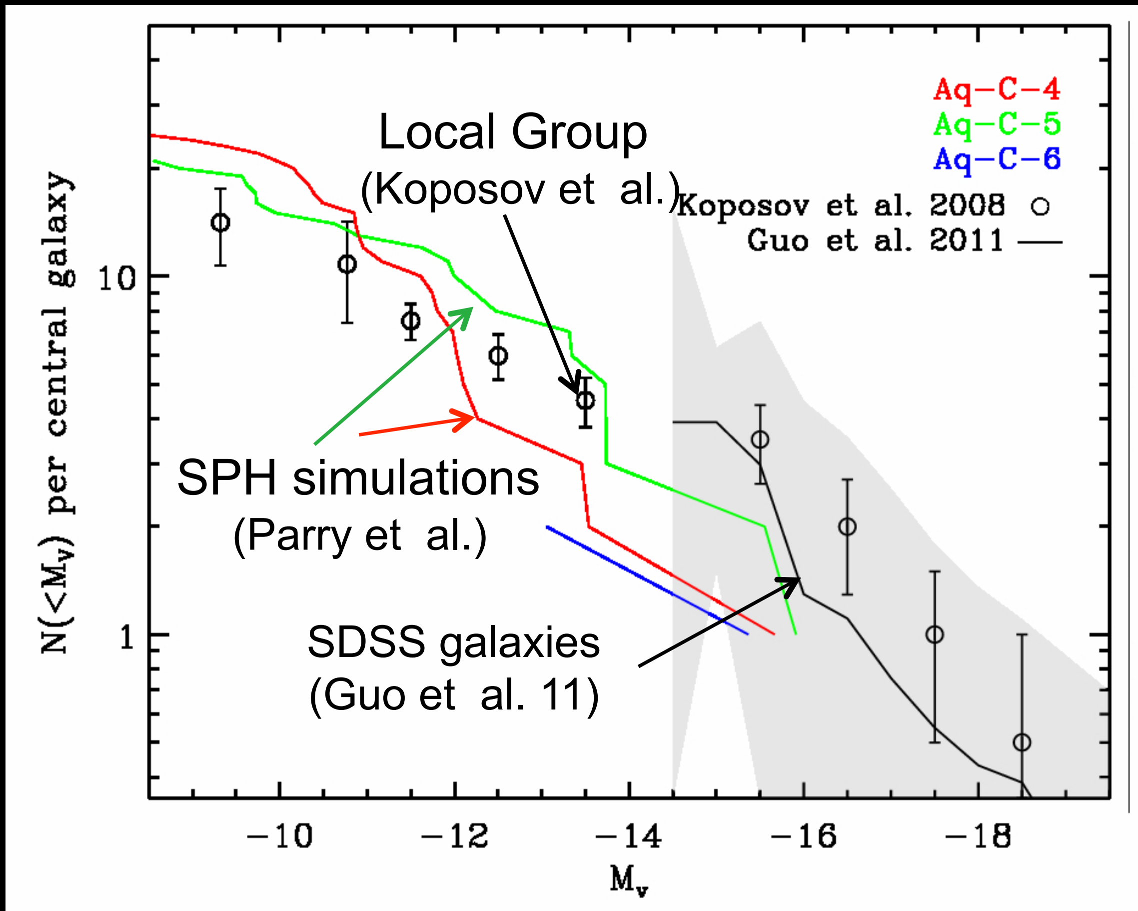
Strigari, Frenk & White 2010

The satellites of the Milky Way





SPH simulations of galaxy formation in one of the Aquarius halos

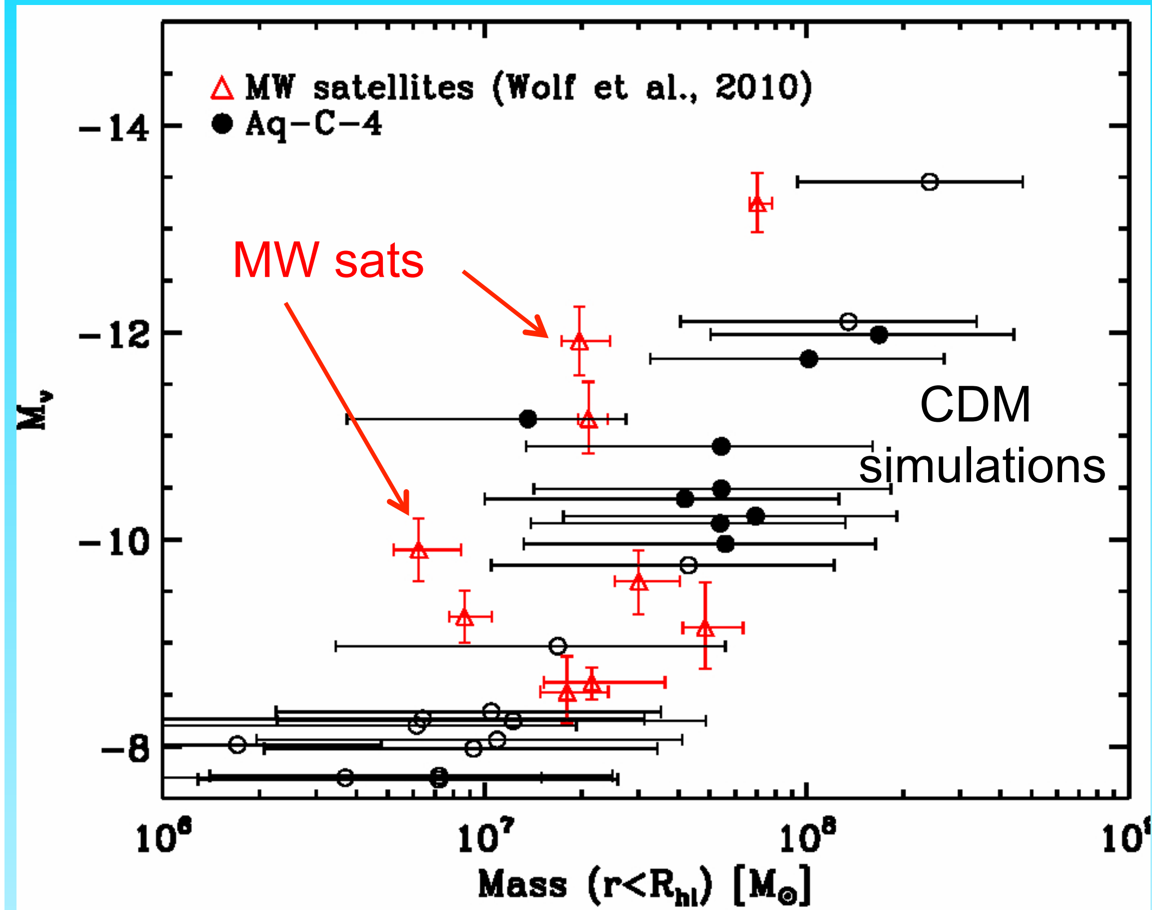


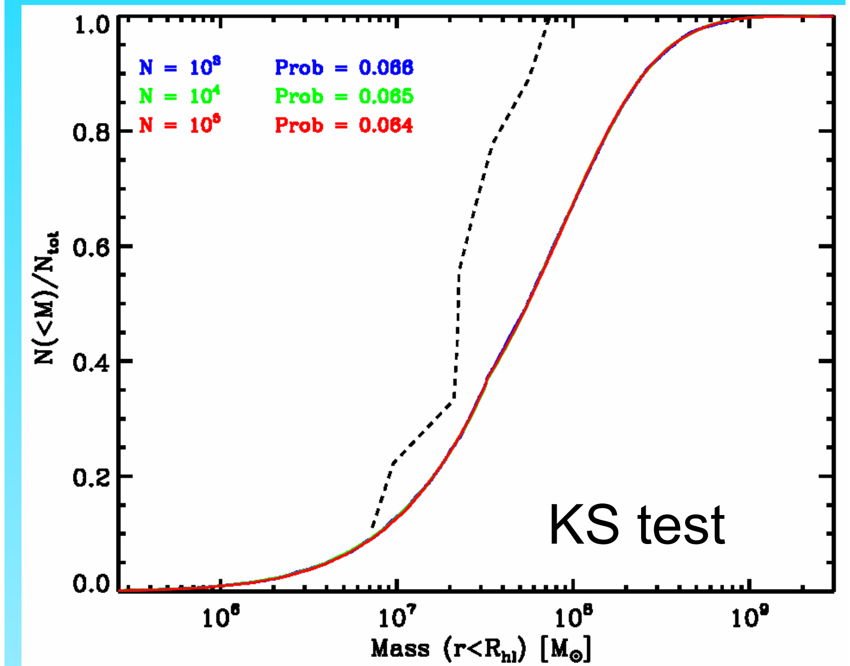
Parry, Eke, Frenk & Okamoto '11

The satellites of the Milky Way

University of Durham

Mass within half-light rad. (spectroscopy)





CDM rejected at 93.6% confidence level

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

Parry, Eke & Frenk '11

Institute for Computational Cosmology

University of Durham

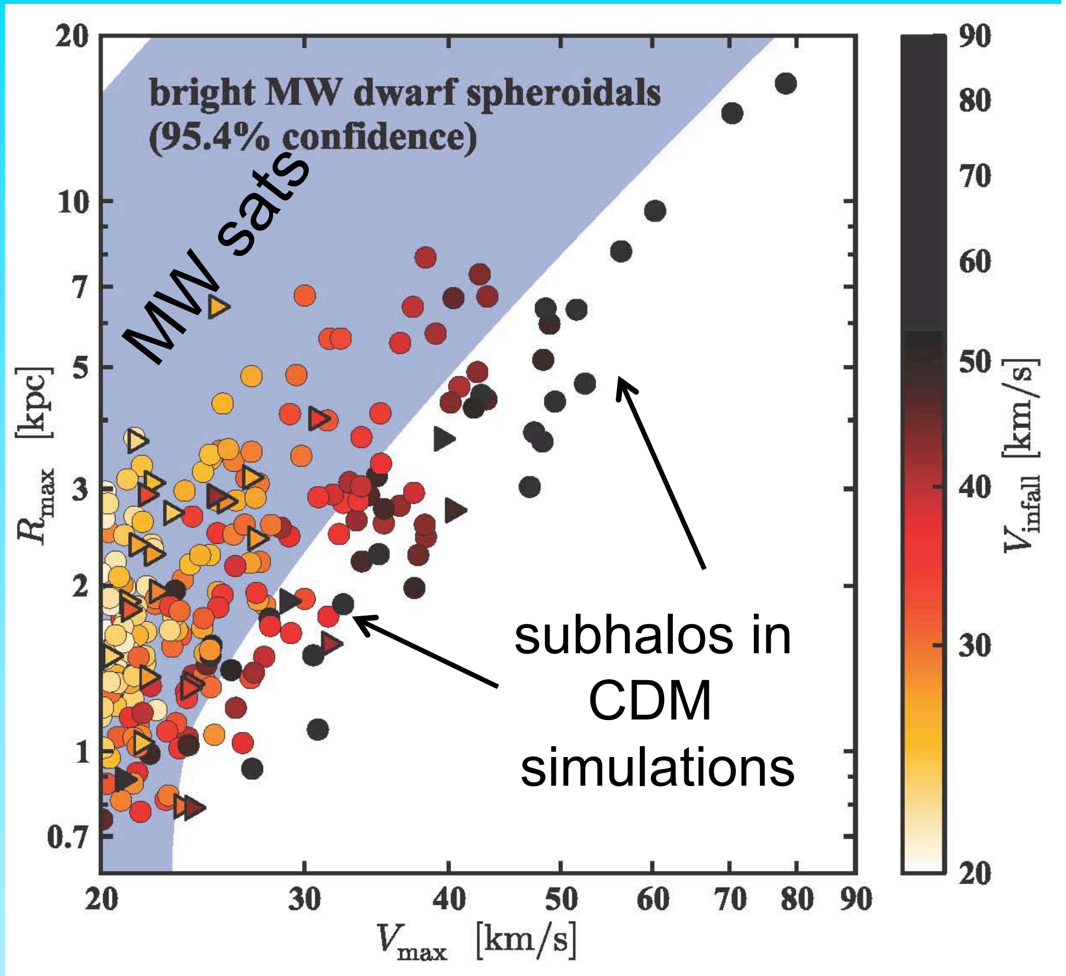
The satellites of the Milky Way

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 dense to host any of the bright MW sats.



Three challenges for CDM on galactic scales:

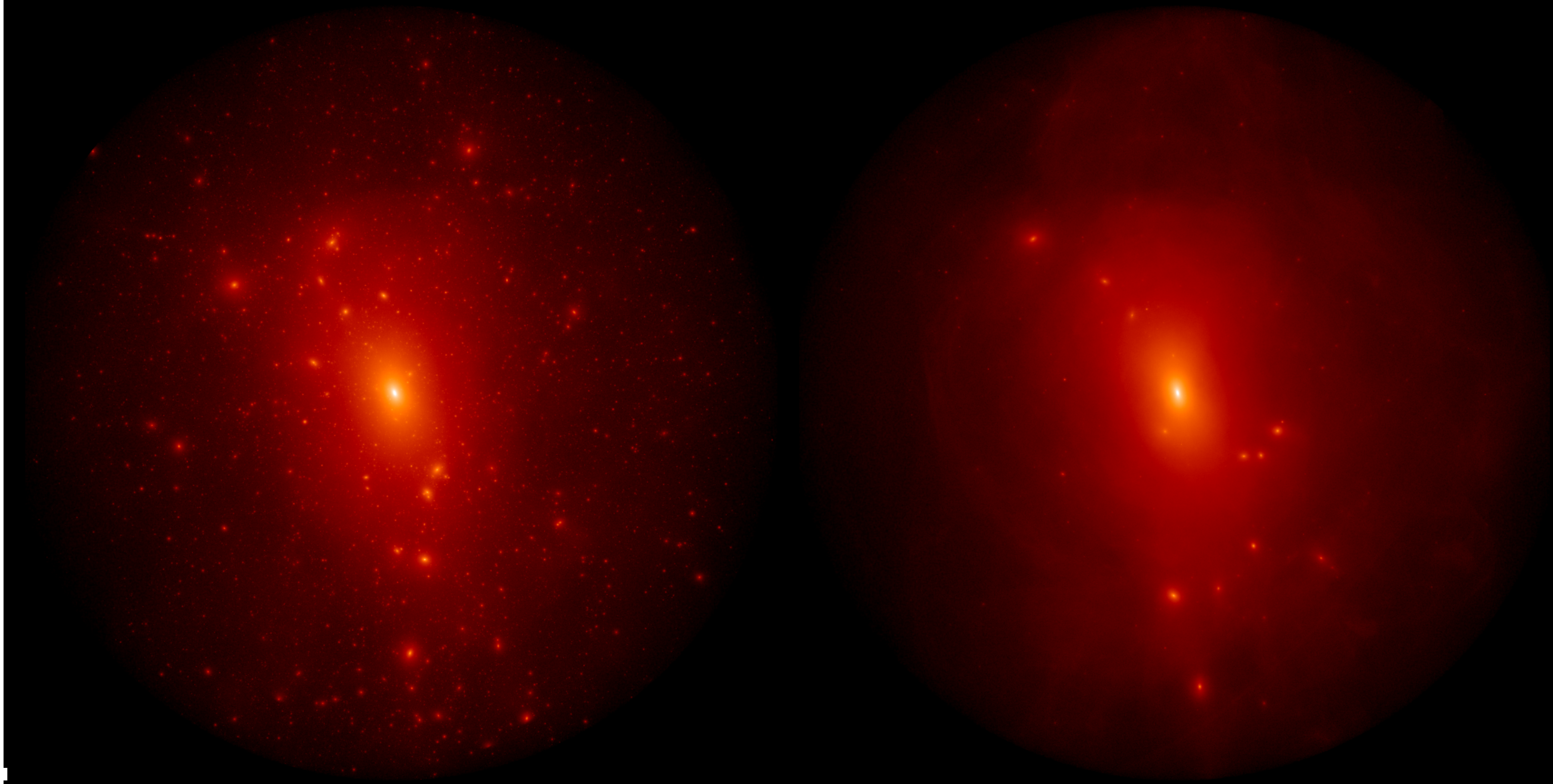
1. The satellite luminosity function ✓
2. The structure of satellite halos ✓
3. 1 and 2 combined ✗

CDM galaxy formation theory (semi-analytics and SPH) puts brightest sats in the biggest halos, but these are more massive/concentrated than indicated by real Local Group data

Possible solutions?

cold dark matter

warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins et al 2011

Warm vs cold dark matter subhalos

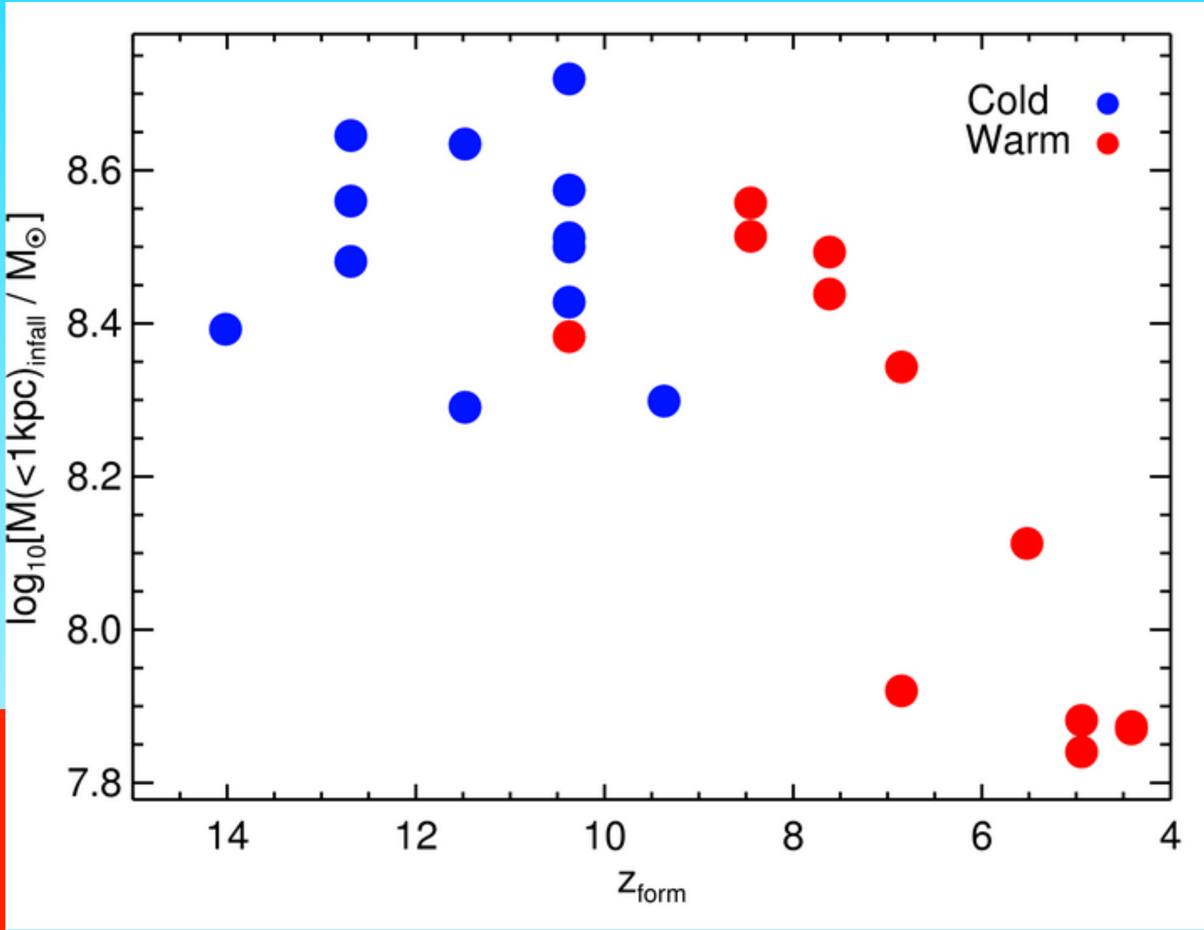
University of Durham

"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 less concentrated than CDM subhalos



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

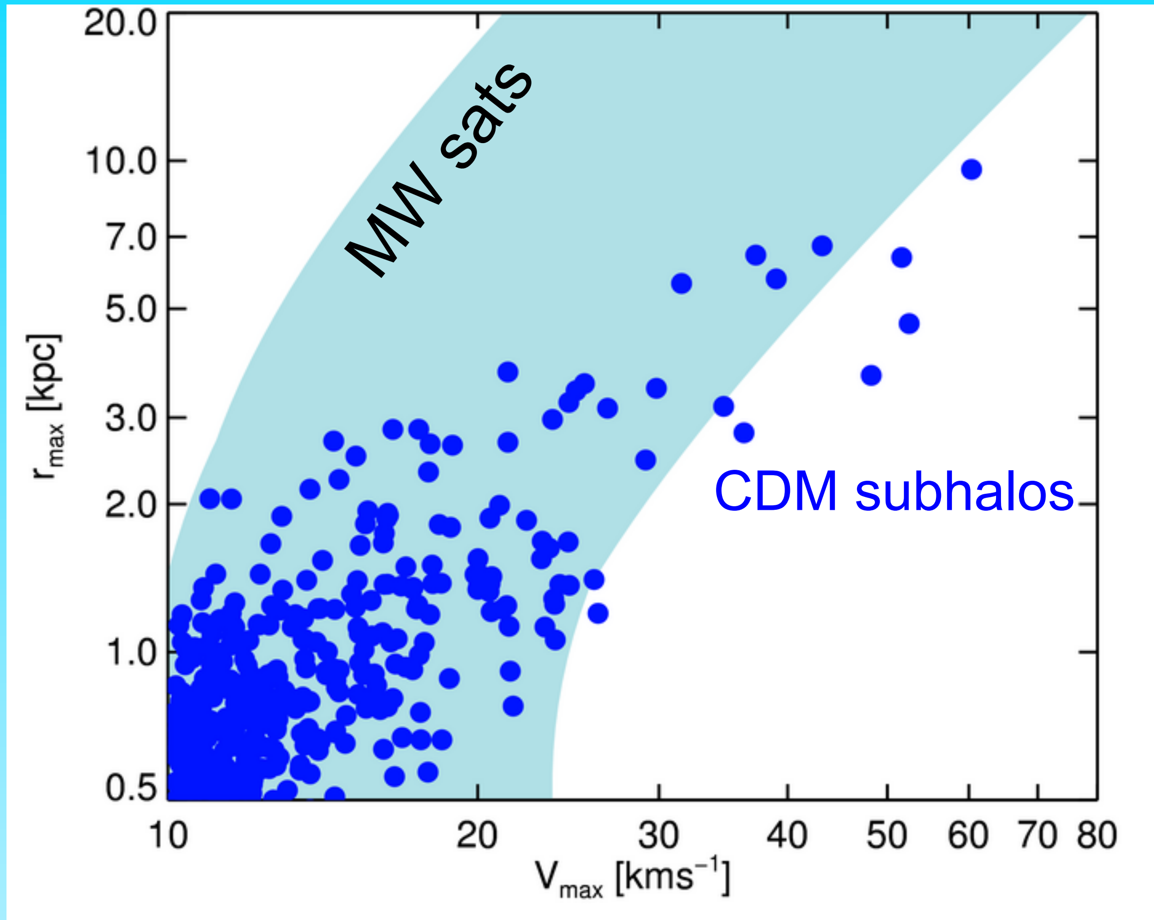
Institute for Computational Cosmology

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.



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

Institute for Computational Cosmology

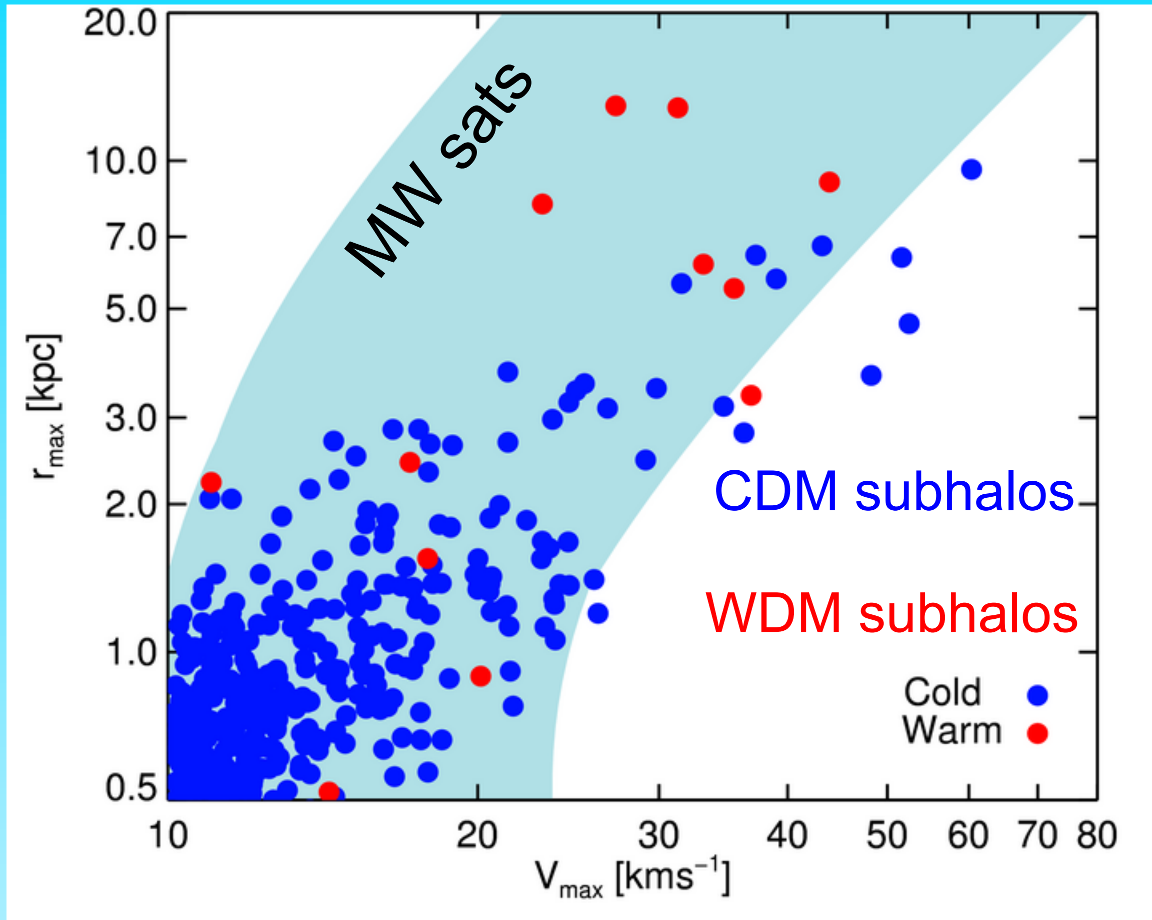
Warm vs cold dark matter subhalos

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

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

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

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

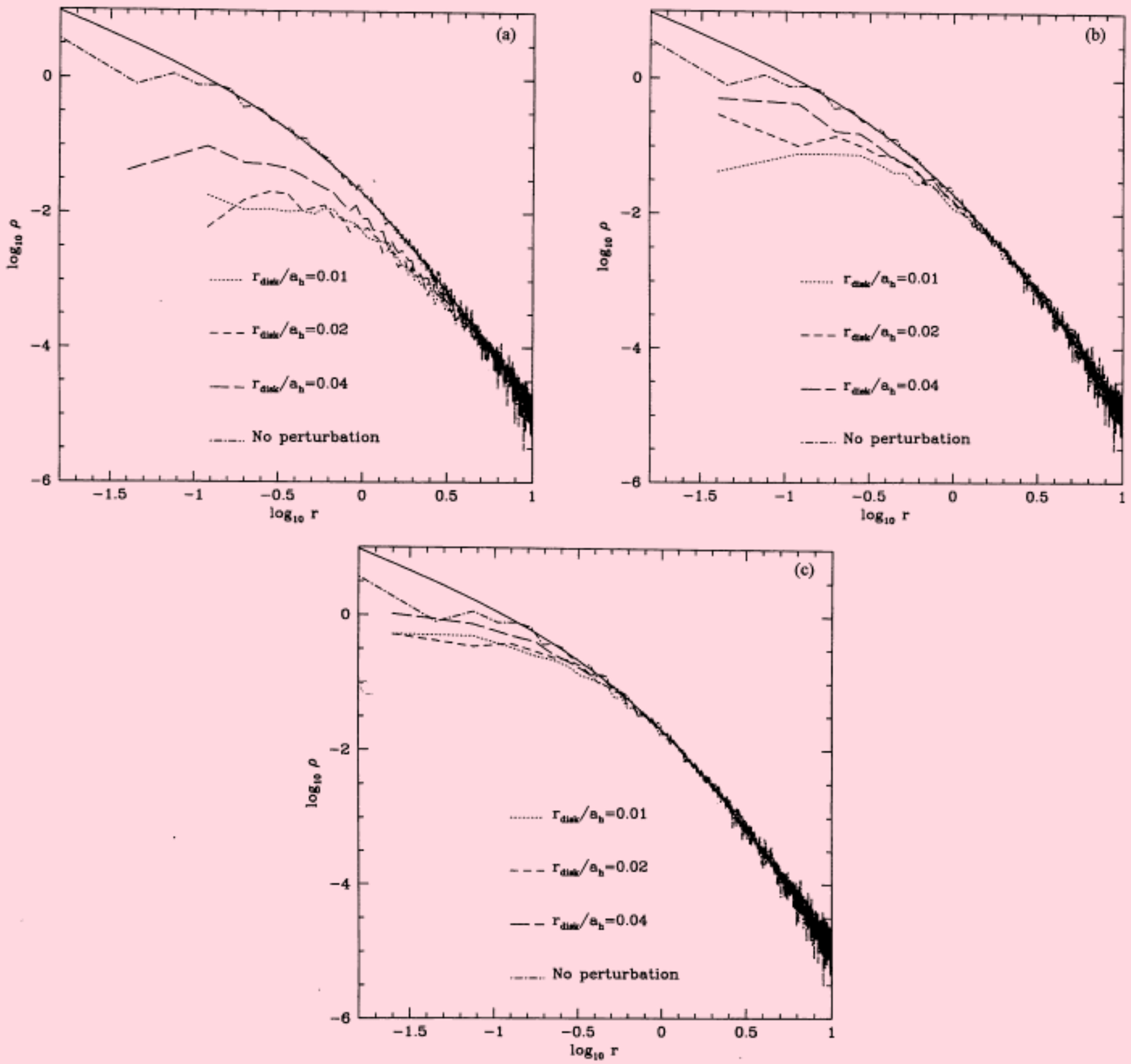
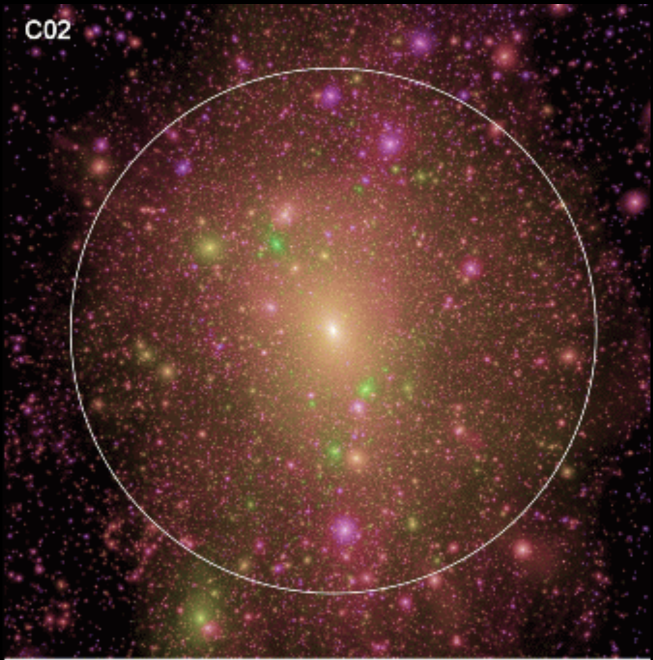
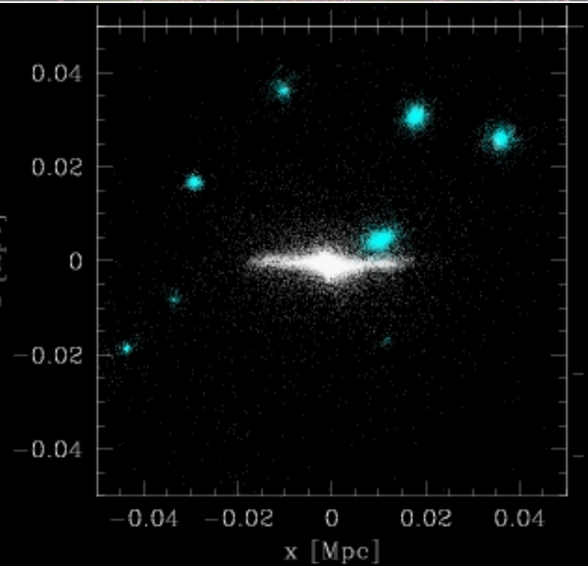


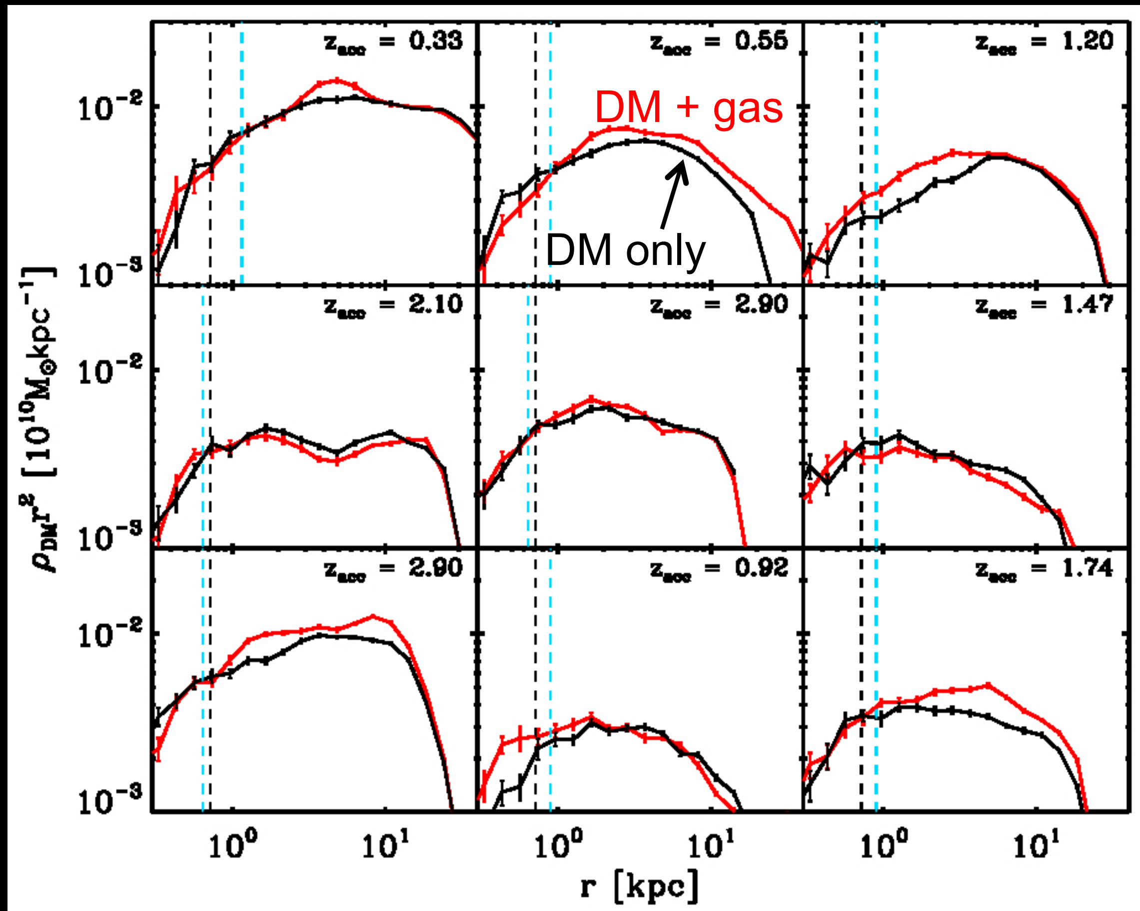
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t = 200$. (a) $M_{disc} = 0.2$.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

The satellites of the Milky Way





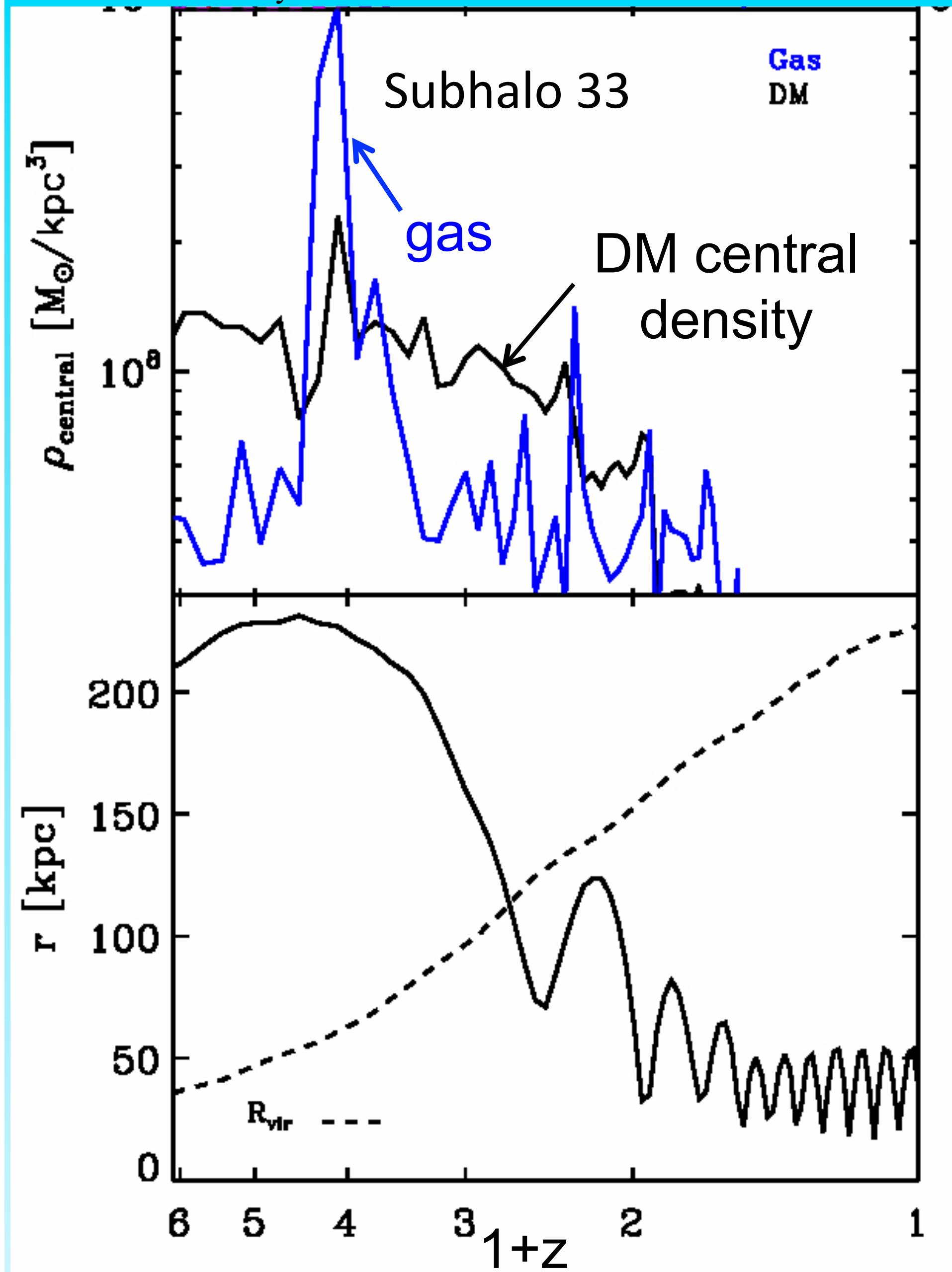
SPH simulations of galaxy formation in one of the Aquarius halos

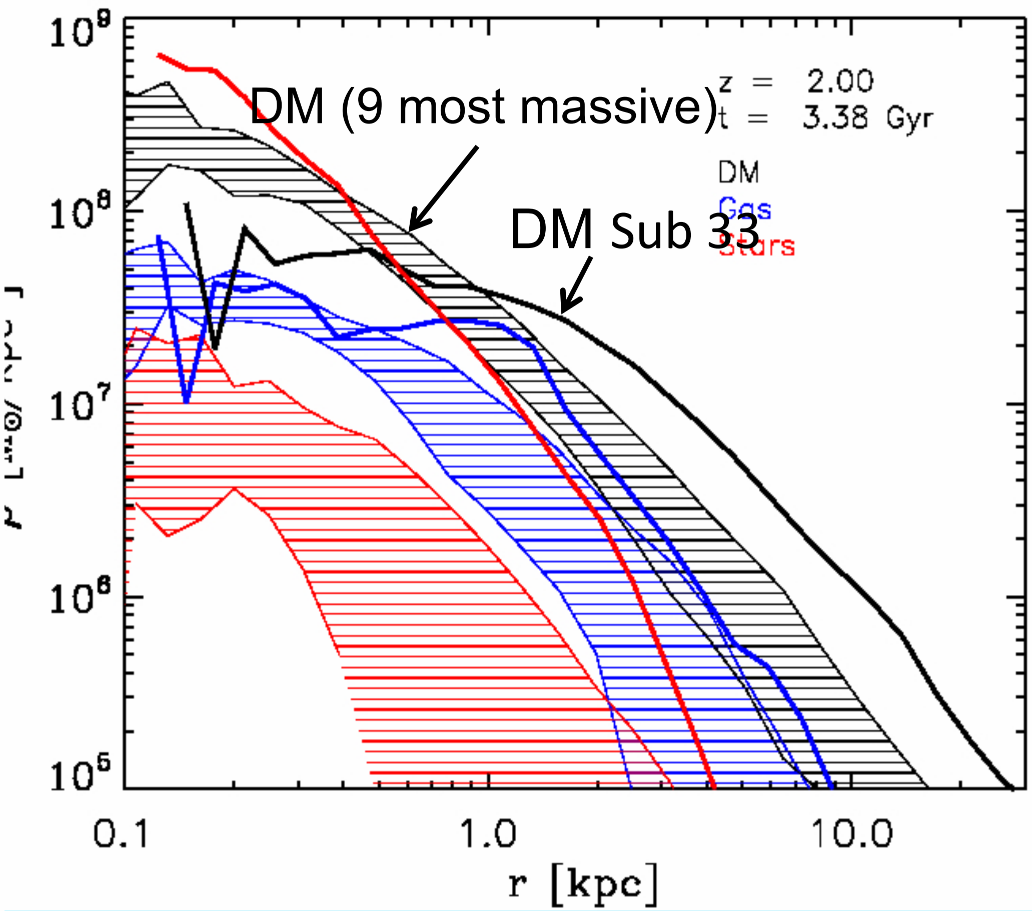


Parry, Eke, Frenk & Okamoto '11

Baryon effects in the MW satellites

University of Durham





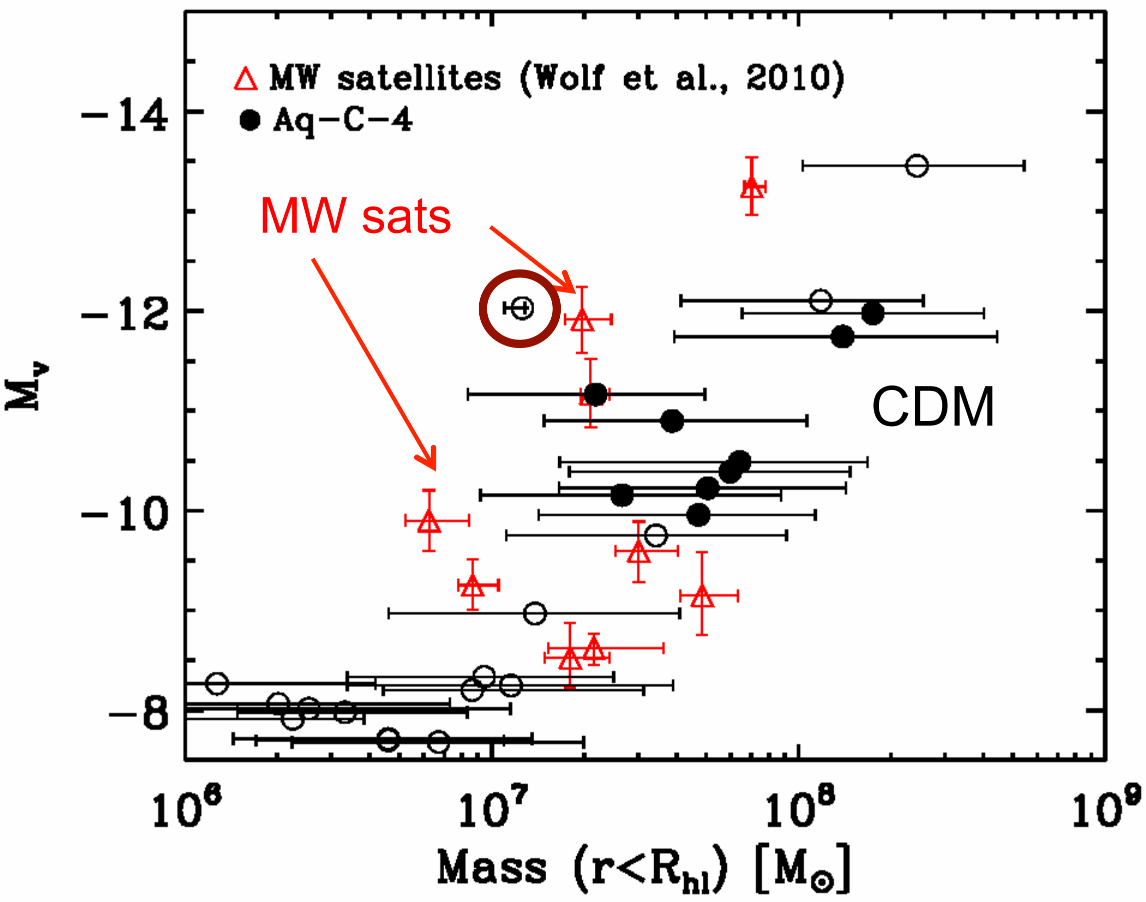
Parry, Eke & Frenk '11

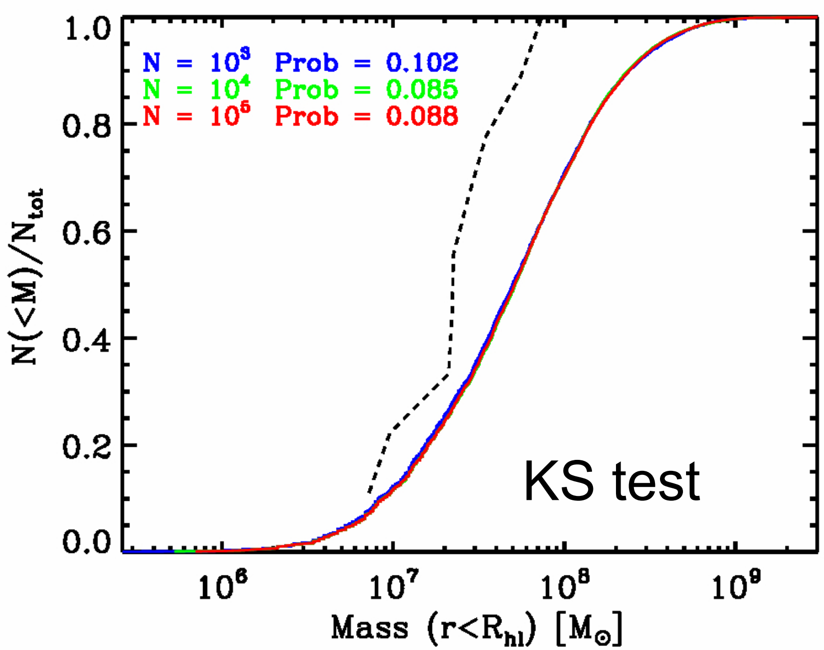
Institute for Computational Cosmology

The satellites of the Milky Way

University of Durham

Mass within half-light rad. (spectroscopy)





CDM rejected at 93.6% confidence level

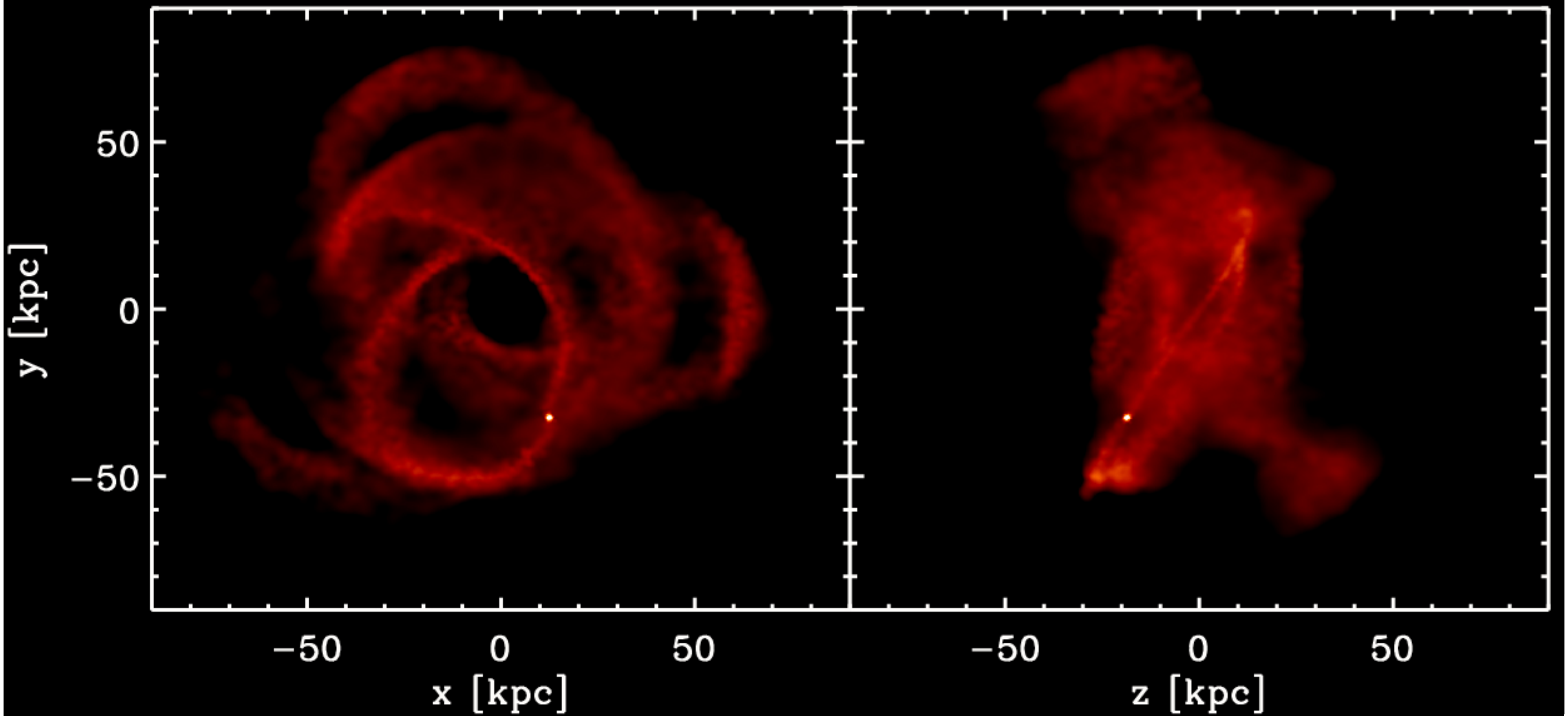
CDM puts the brightest sats in the biggest halos, but these are more massive than those indicated by the real data

Parry, Eke & Frenk '11

Institute for Computational Cosmology

Baryon effects in the MW satellites

Subhalo 33



University of Durham

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