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

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University of Durham

The satellites of the MW and the nature of the dark matter

MW satellites can reveal nature of dark matter for two reasons:

- The spectrum of primordial fluctuations on small scales depends strongly on the nature of the dark matter

- Satellites have large M/L → mostly dark matter

The dark matter power spectrum

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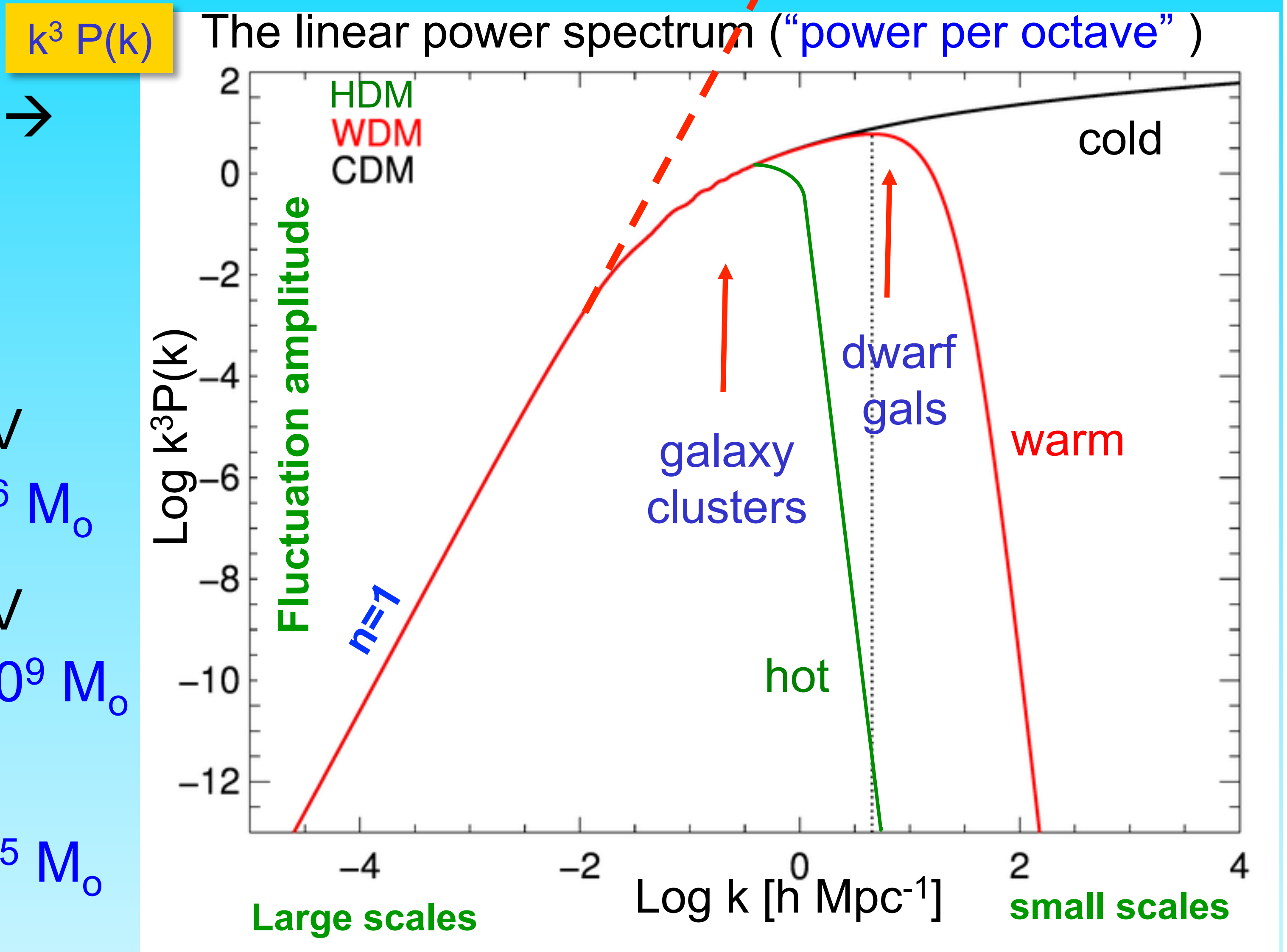
Free streaming →

$\lambda_{cut} \propto m_x^{-1}$
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
light ν; $M_{cut} \sim 10^{15}\ M_o$



The dark matter power spectrum

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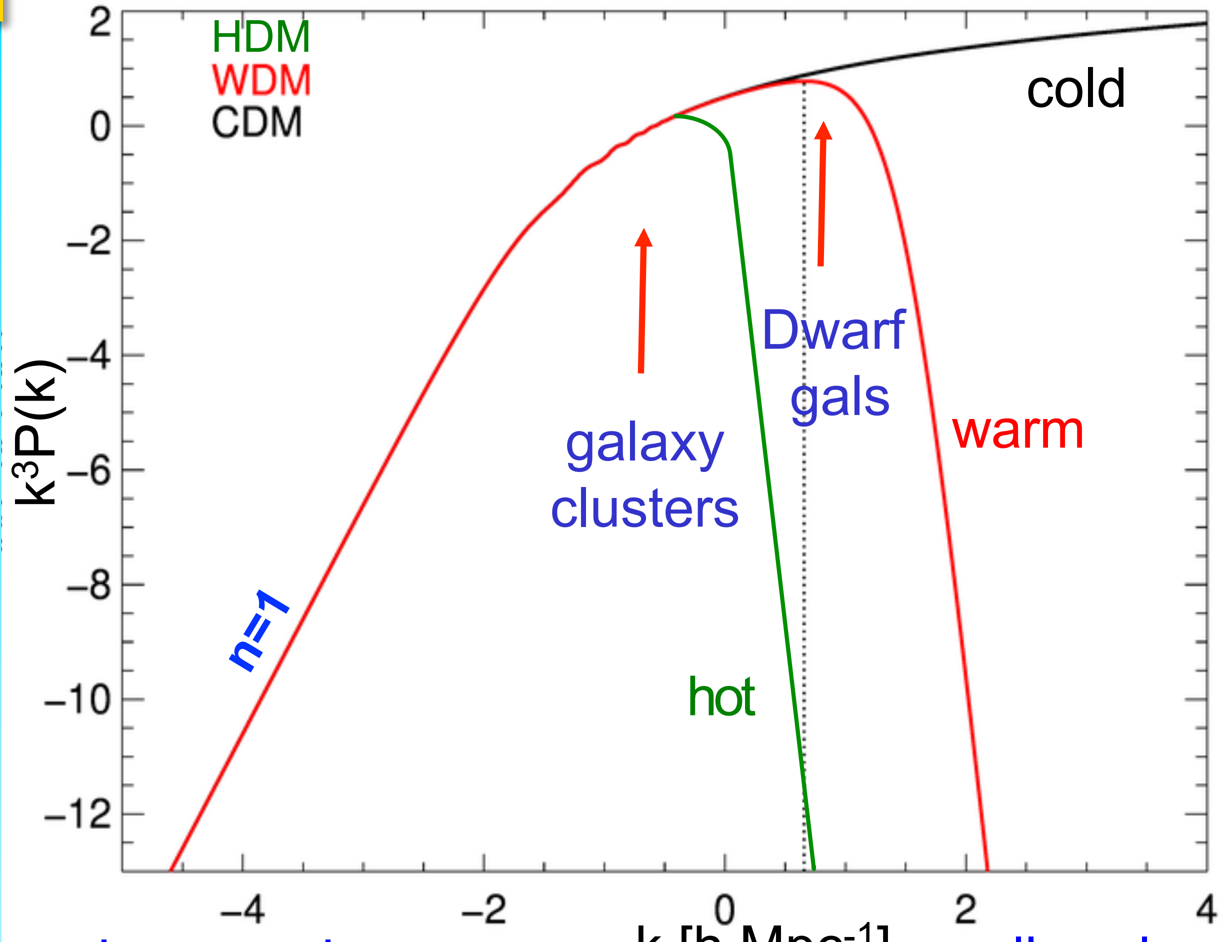
$k^3\,P(k)$

The linear power spectrum ("power per octave")



λ_{cut} α m_x^{-1}

CDM:

10^{-6} M_o for100 GeV wimp

WDM:

Ly-α forest (z~2-3) ➔

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

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

(Viel etal '08; Boyarsky etal '09)

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

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A galactic halo (~10^{12} M_0)

cold dark matter

Springel, Wang1, Vogelsberger, Ludlow, Jenkins, Helmi,

Navarro, Frenk, White

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A galactic halo (~10^{12} M_0)

cold dark matter

warm dark matter

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

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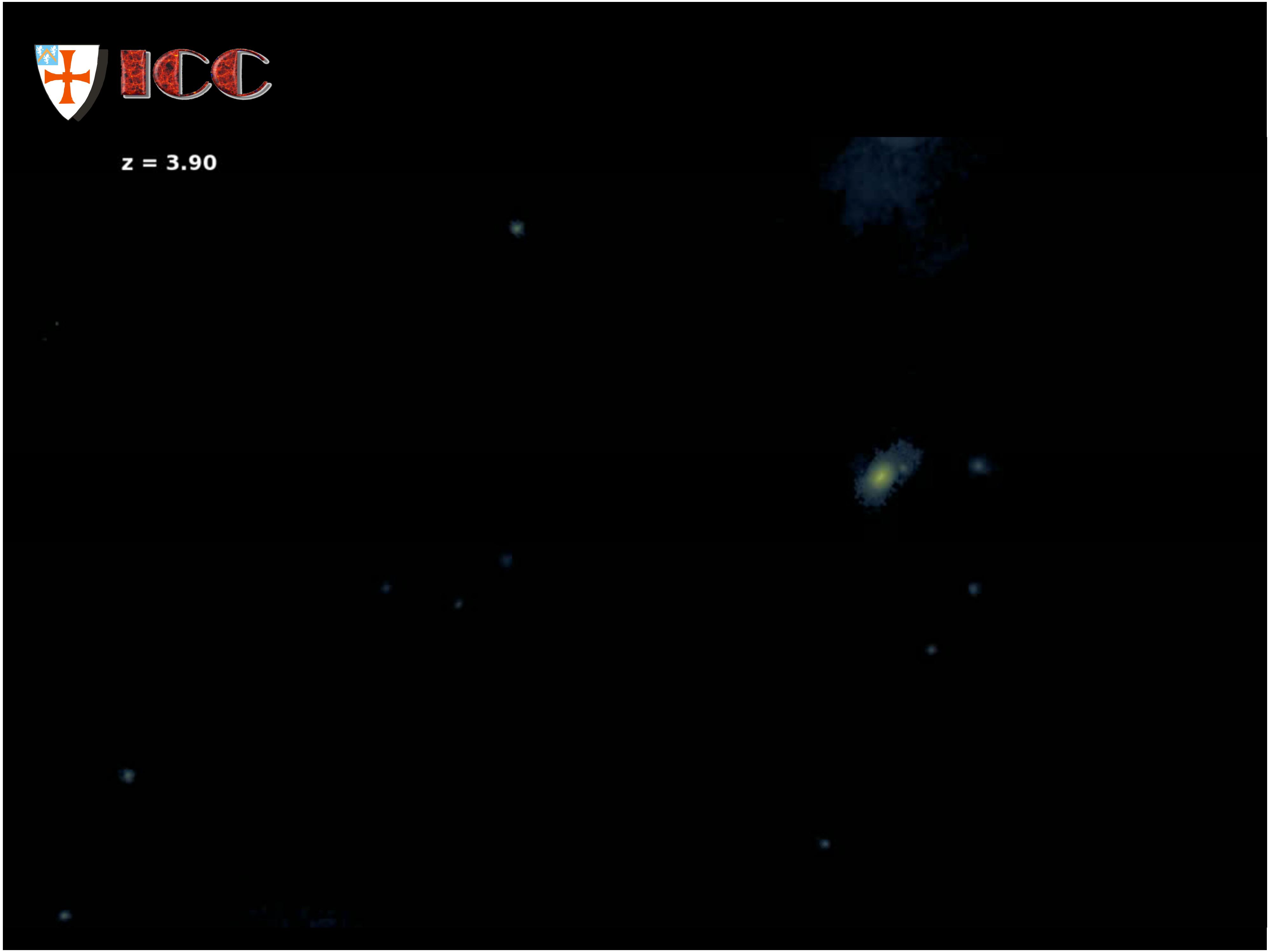
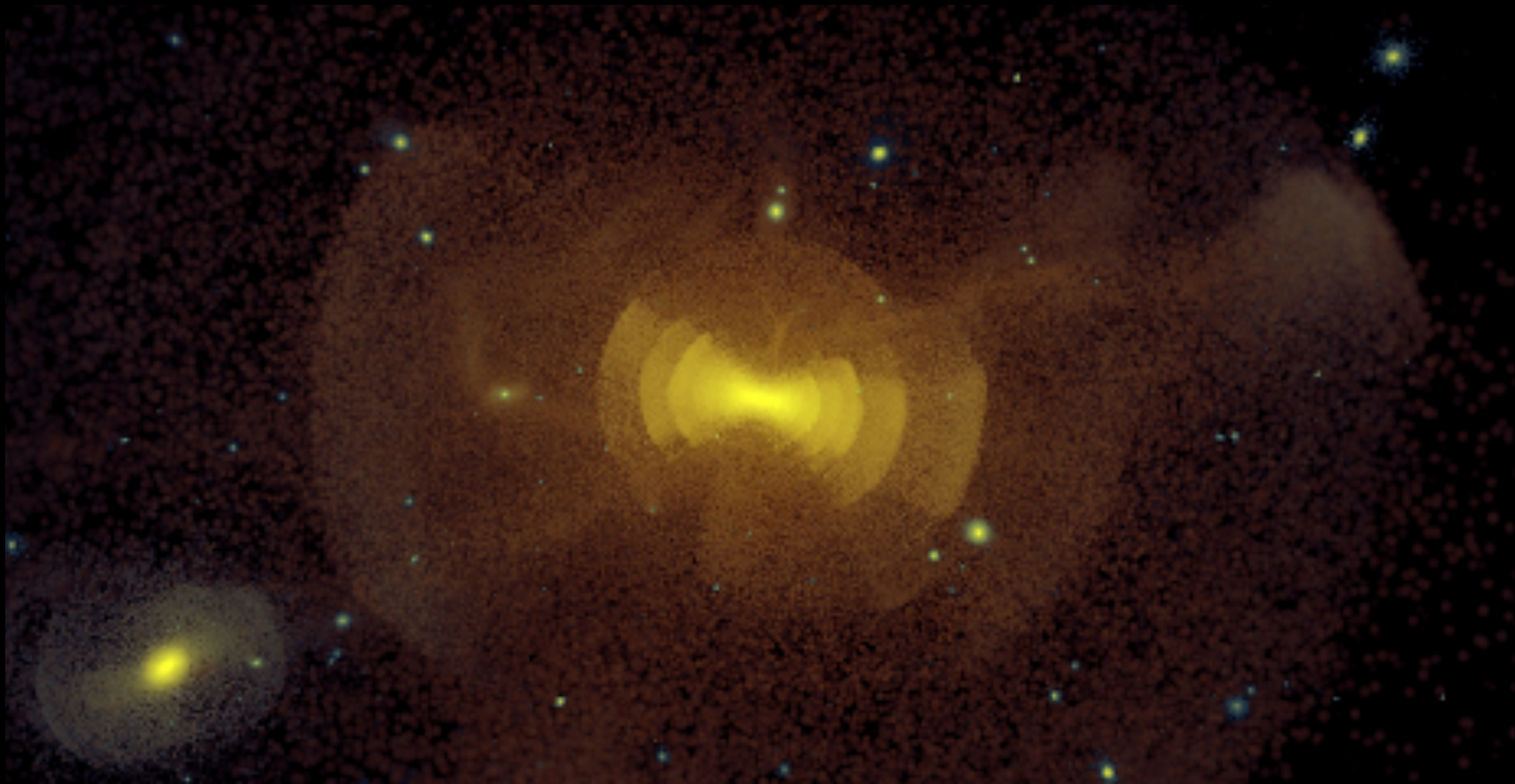

z = 3.90



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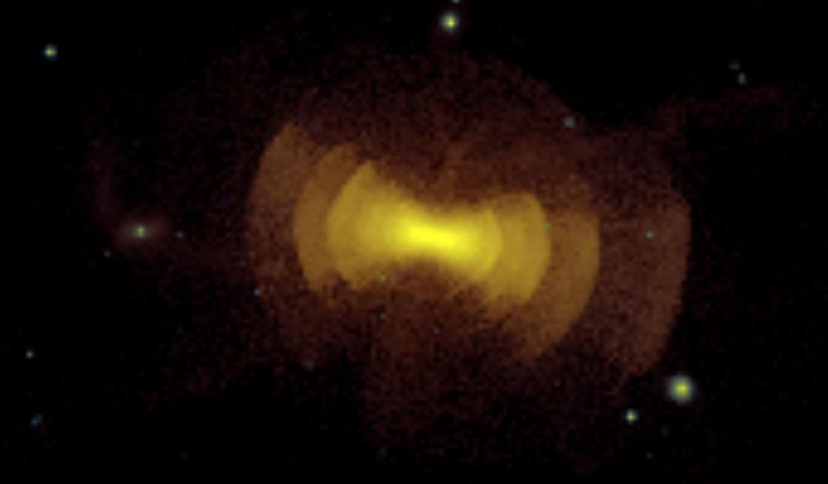
NGC 7600

NGC 7600

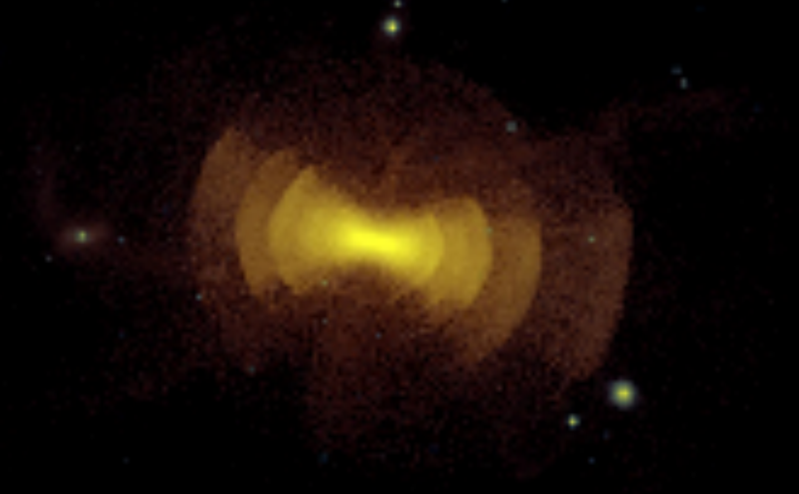
Aquarius



Cooper et al arxiv1111.2864

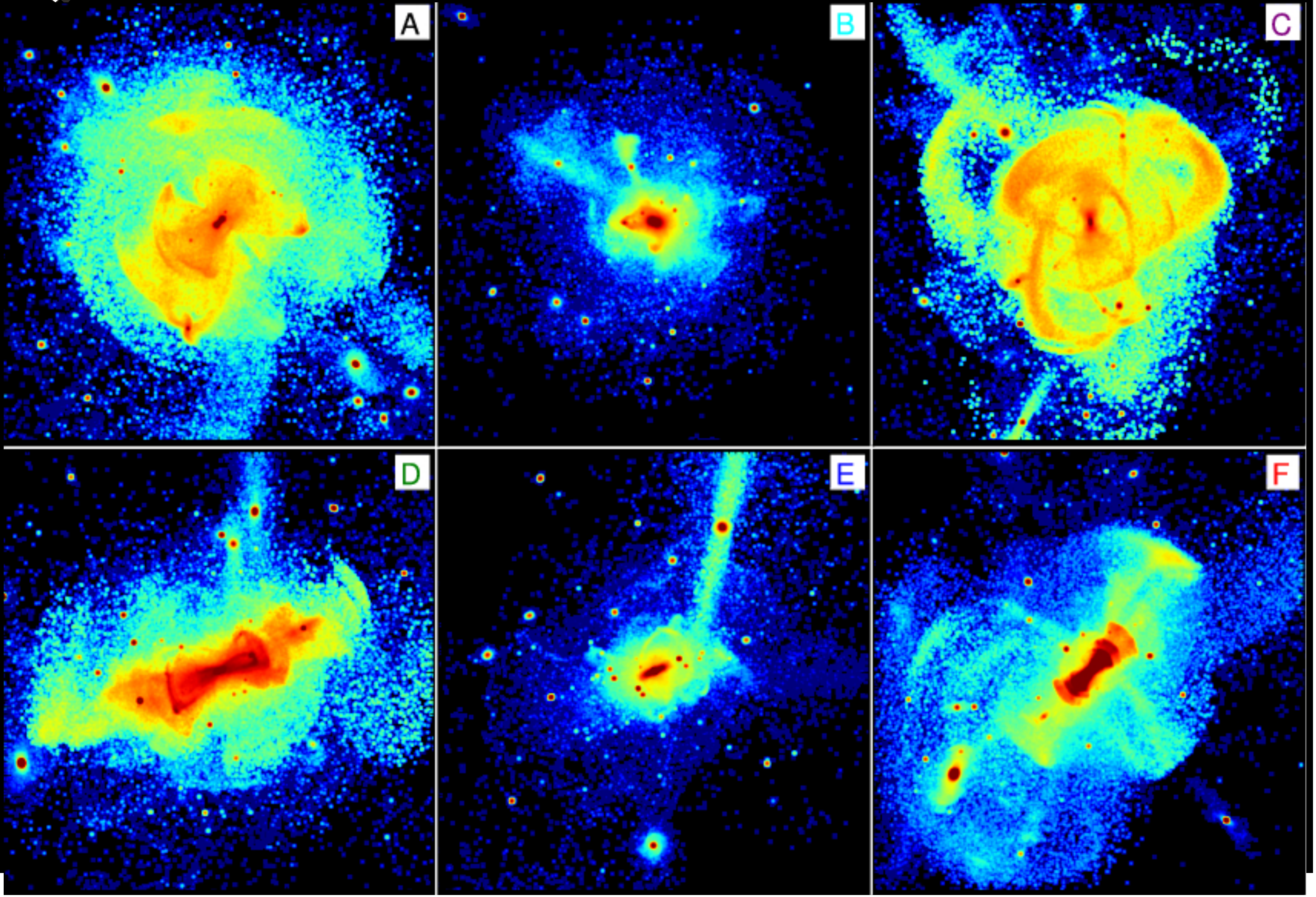
NGC 7600

Aquarius



(http://www.virgo.dur.ac.uk/shell-galaxies)

Cooper et al 2010



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A cold dark matter universe

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

- Halos of all masses and subhalos have “cuspy” density profiles
- Large number of self-bound substructures (10% of mass) survive

→Can test for identity of the dark matter!

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

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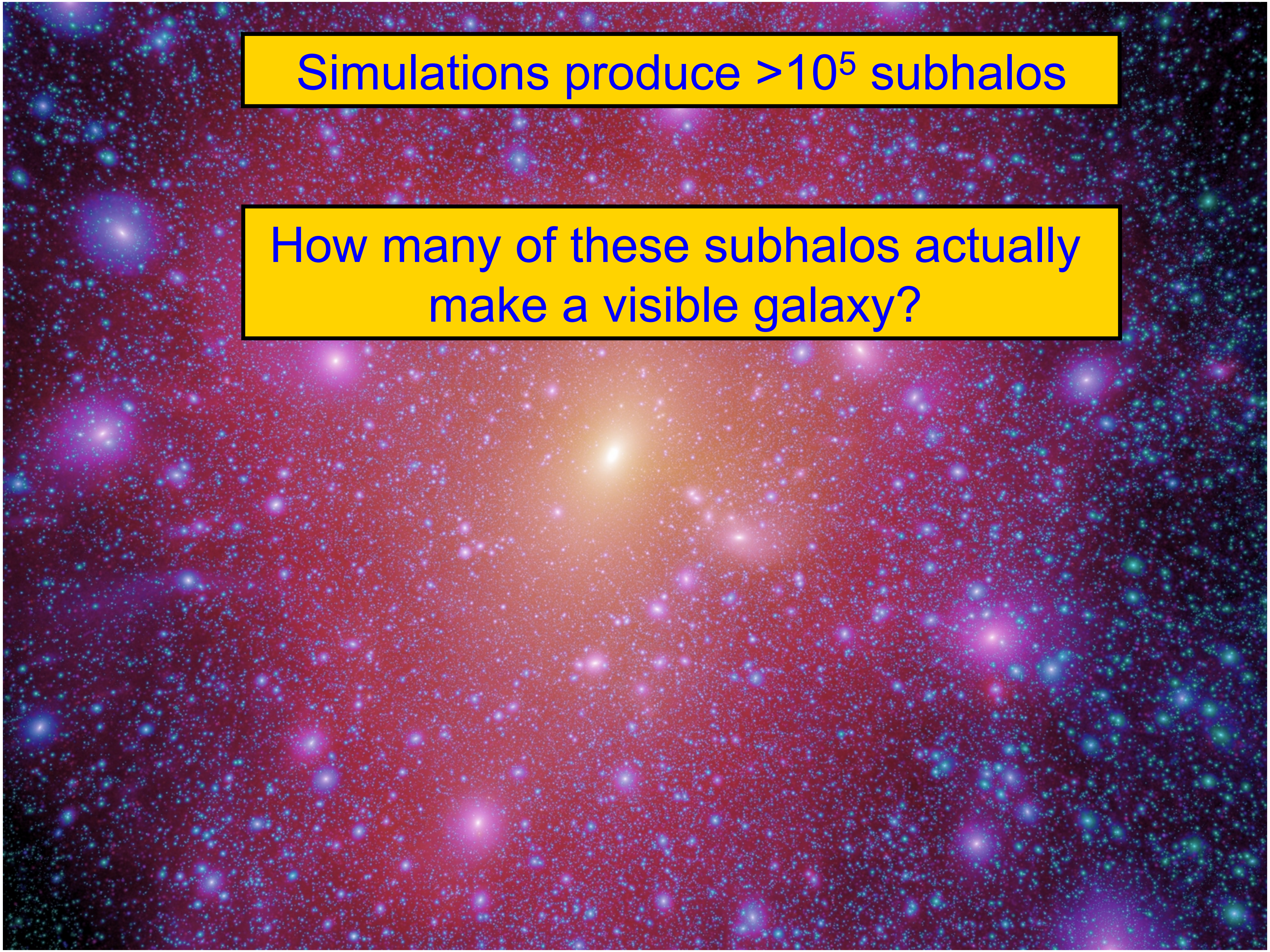
Simulations produce >10^5 subhalos
How many of these subhalos actually make a visible galaxy?

The galaxy luminosity function

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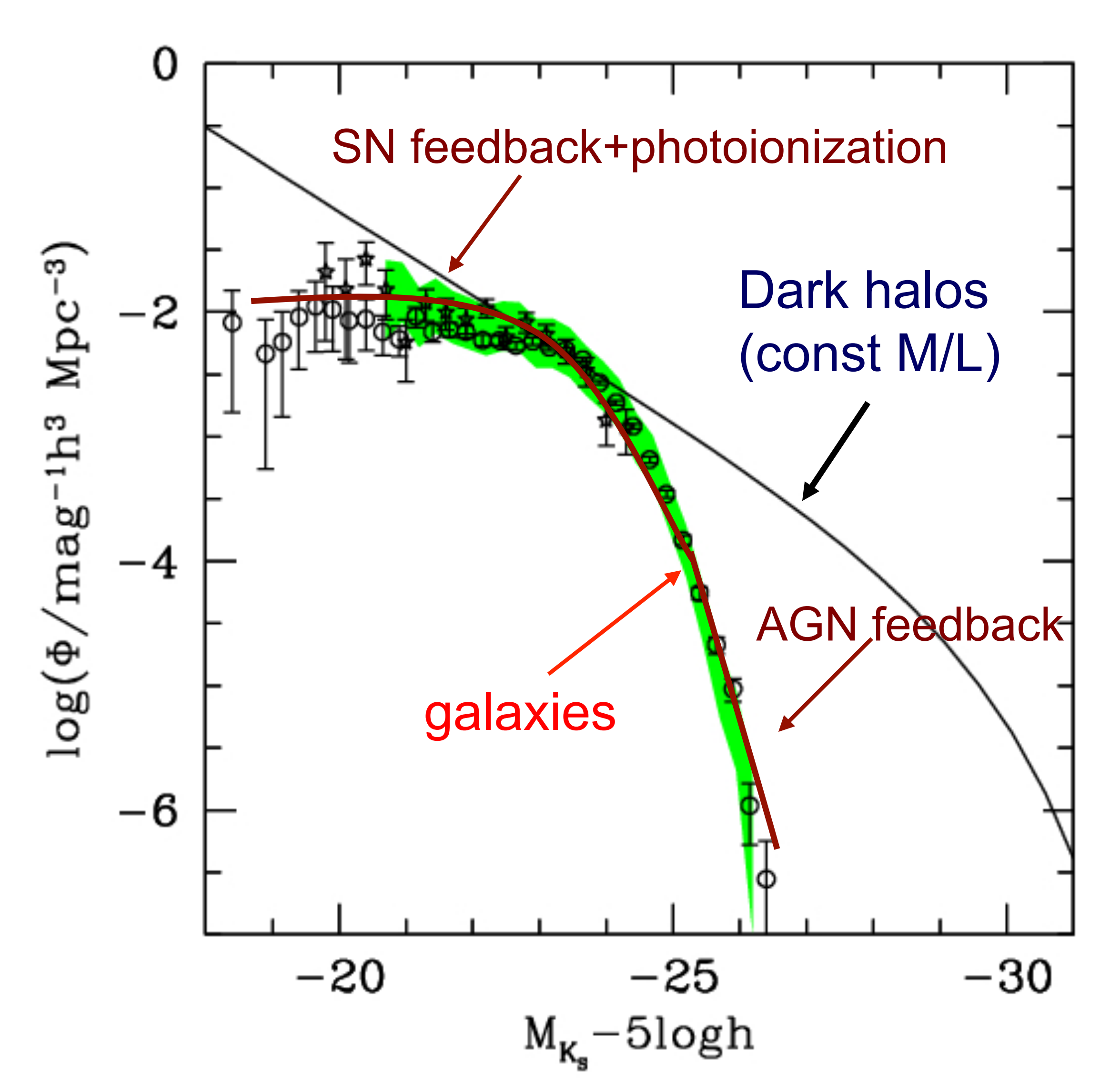
The halo mass function and the galaxy luminosity function have different shapes

⇨

Complicated variation of M/L with halo mass



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

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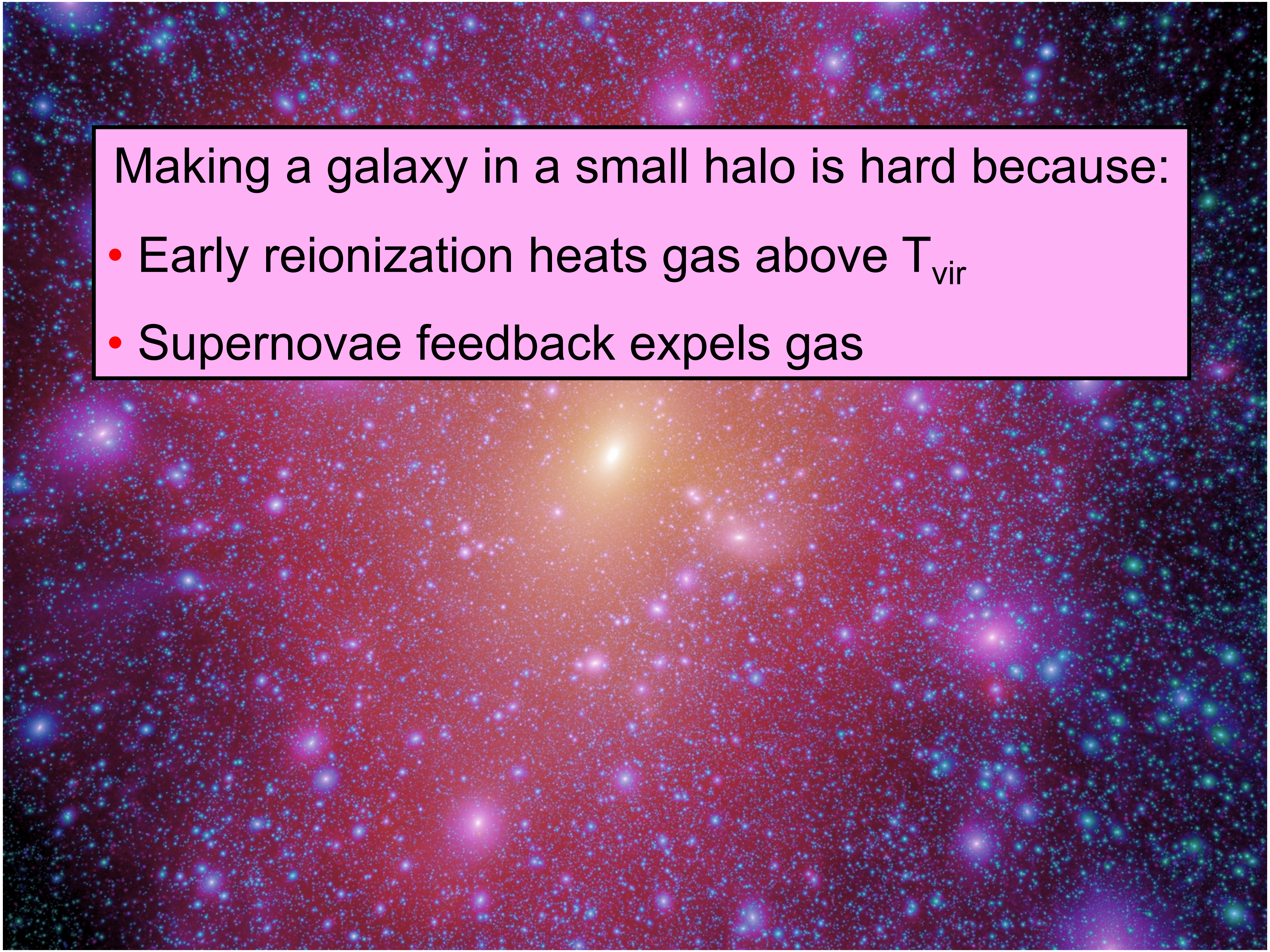
Making a galaxy in a small halo is hard because:

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



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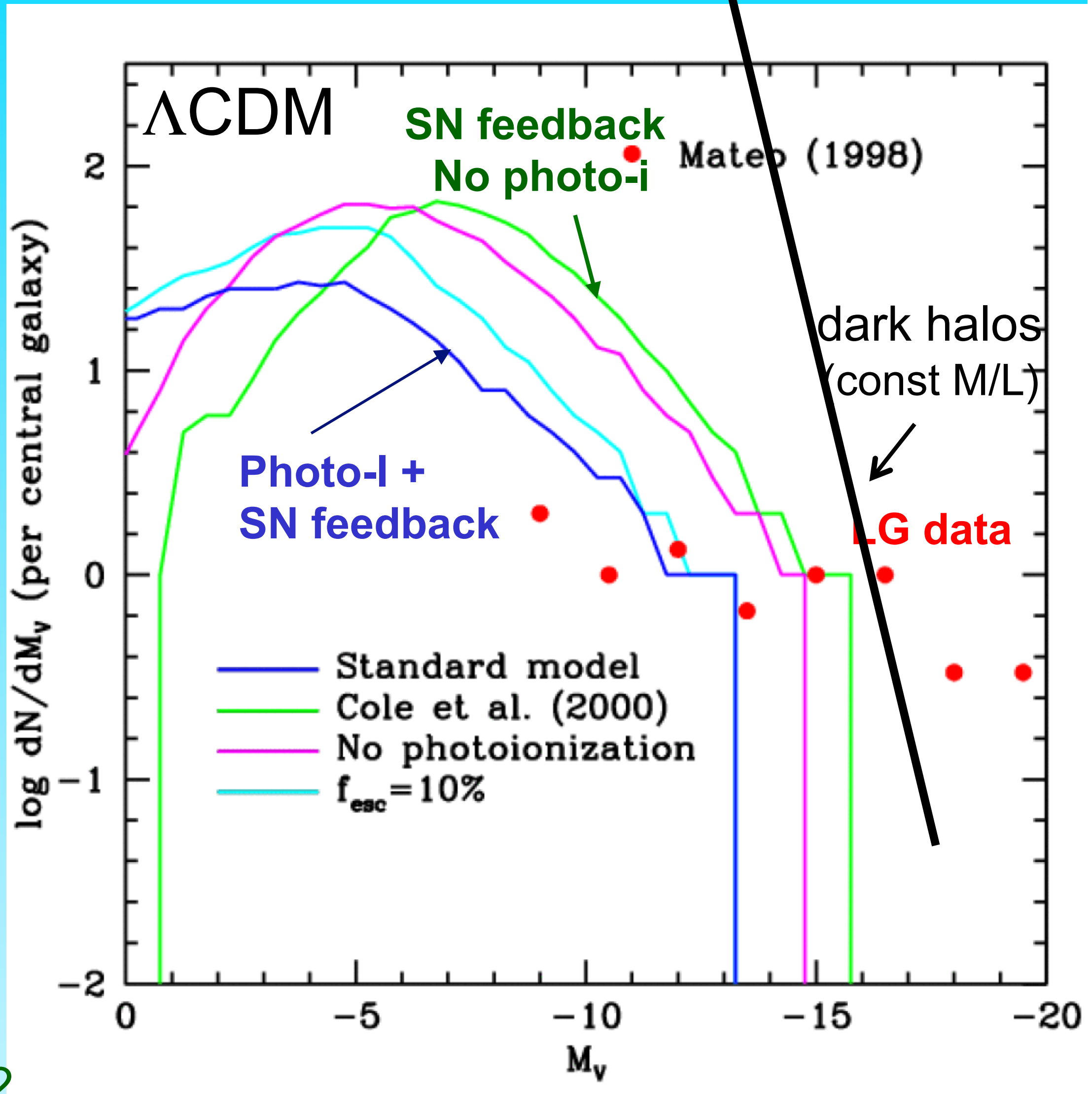
Luminosity Function of Local Group Satellites

- 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, Somerville '02)

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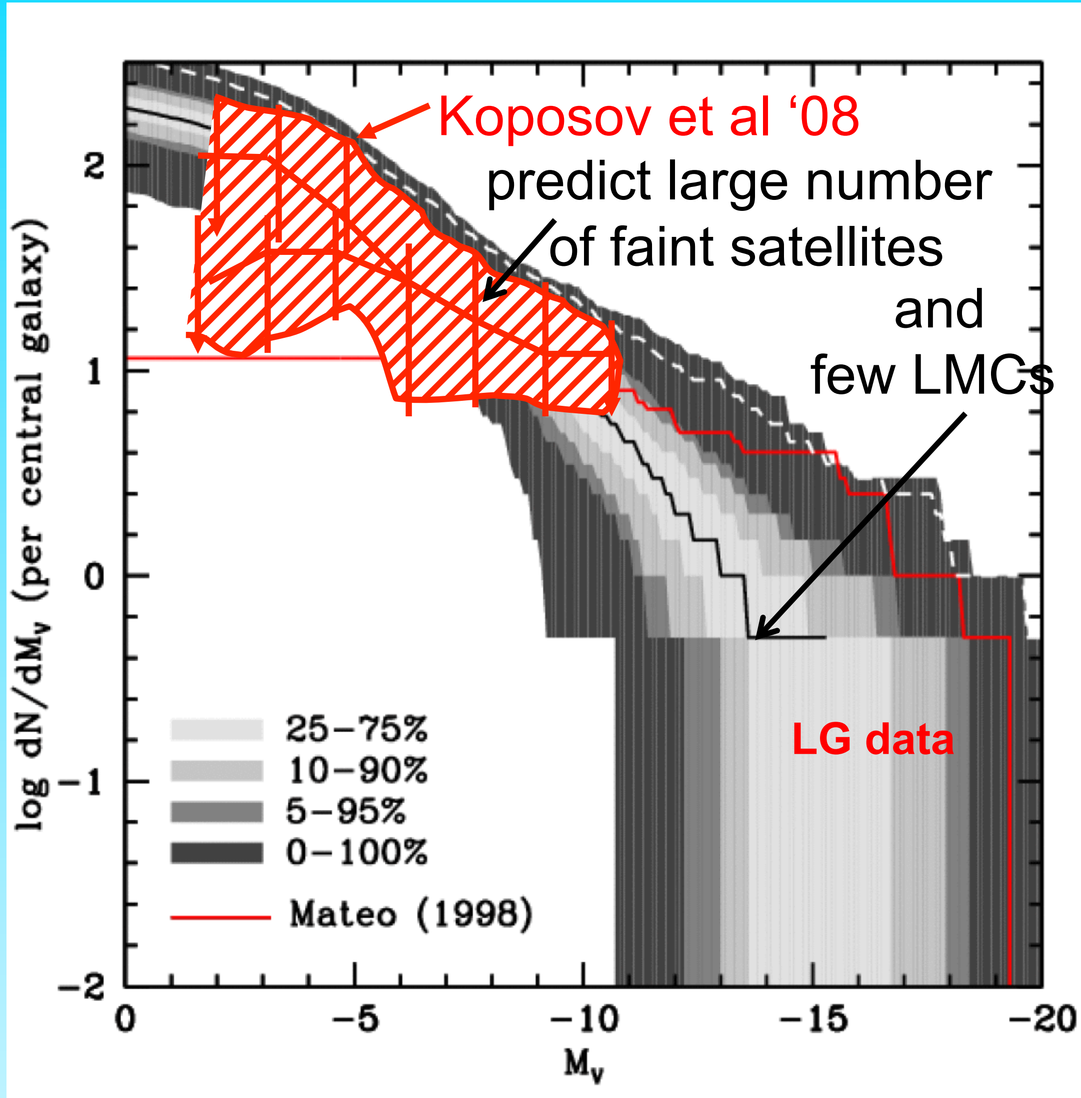
Luminosity Function of Local Group Satellites

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

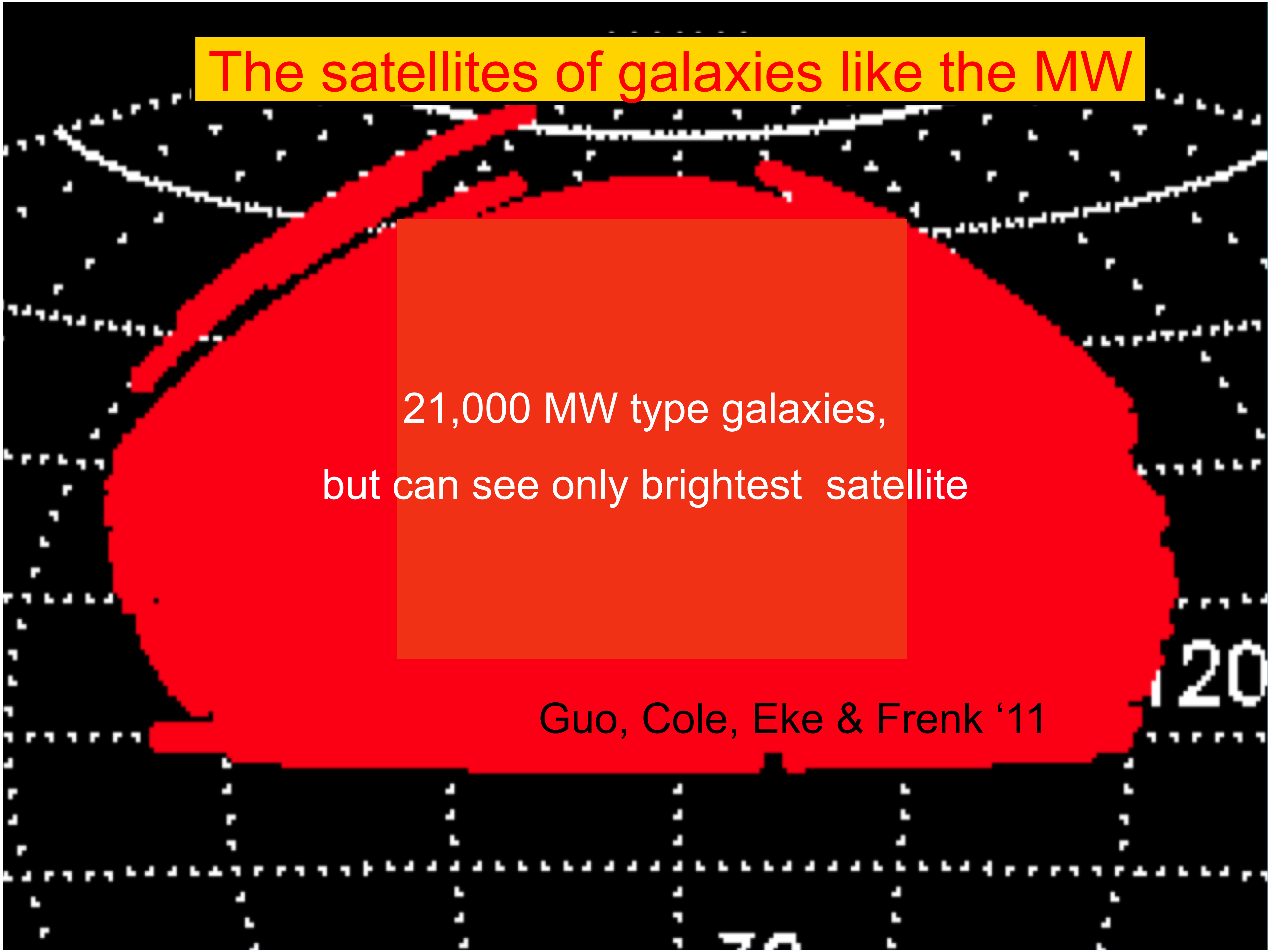
- Model predicts many, as yet undiscovered, faint satellites

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



Benson, Frenk, Lacey, Baugh & Cole '02

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?

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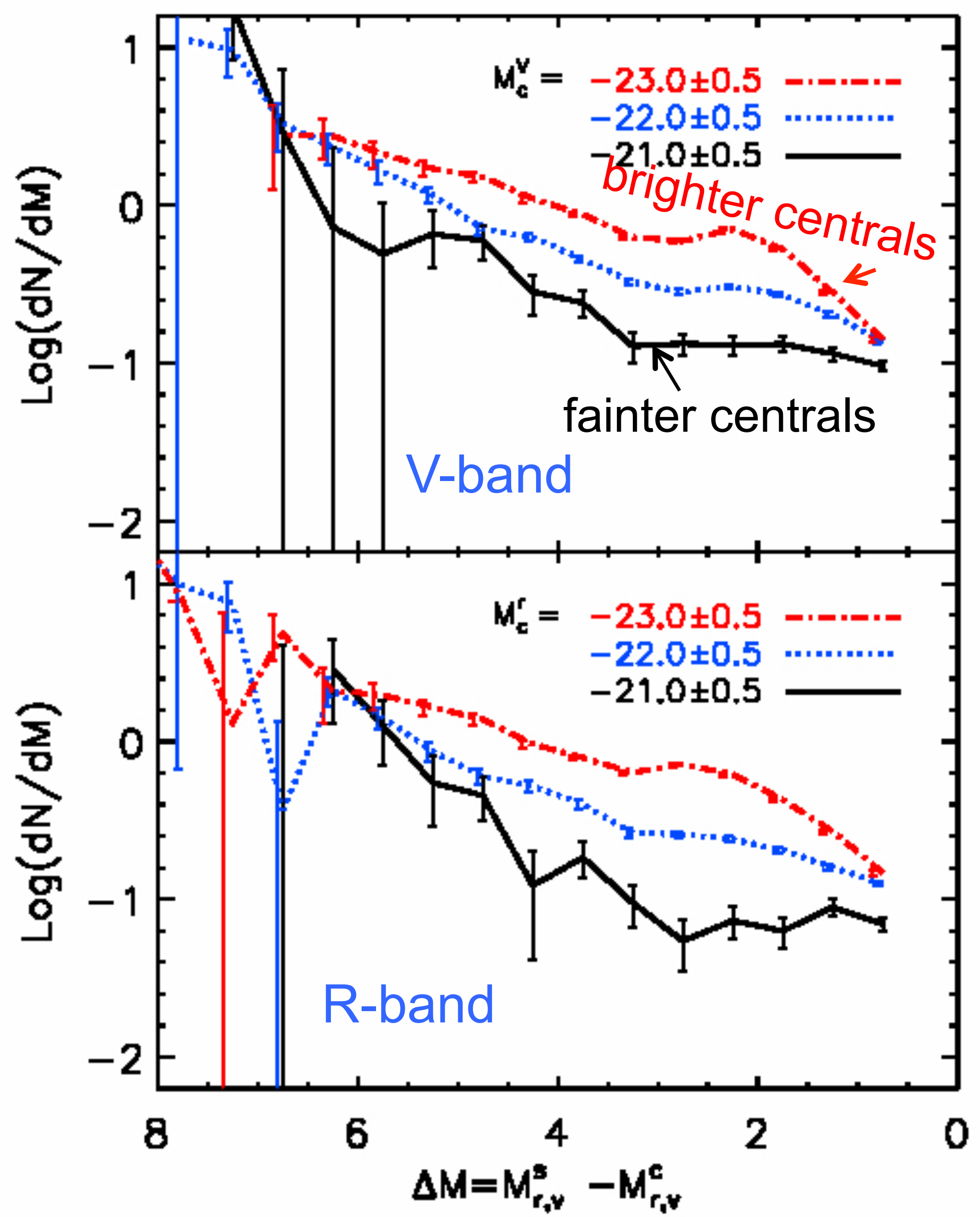
Find Milky Way analogues (eg isolated spirals) in SDSS

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?

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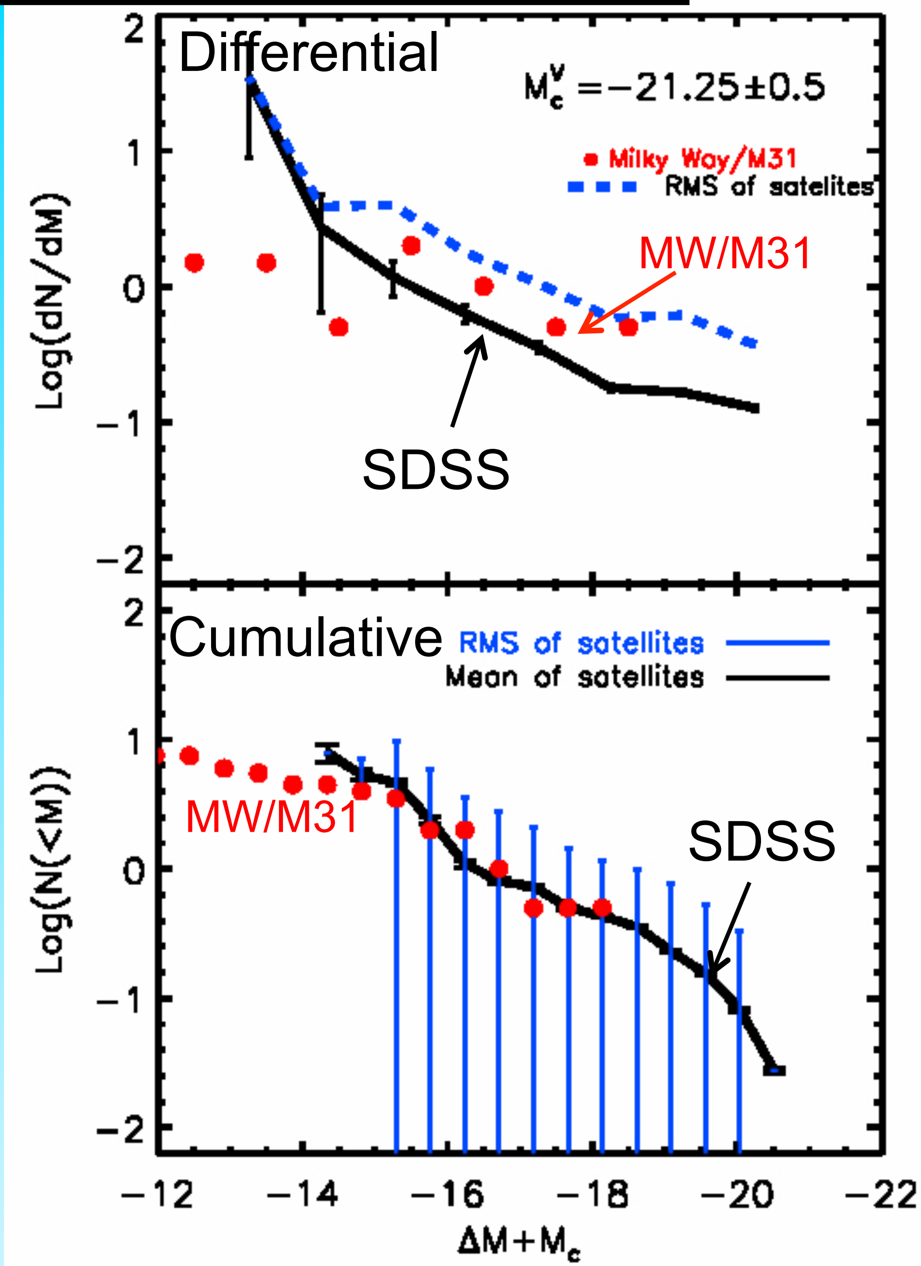
Satellite LF of MW analogues

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



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A cold dark matter universe

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

- Halos of all masses and subhalos have “cuspy” density profiles
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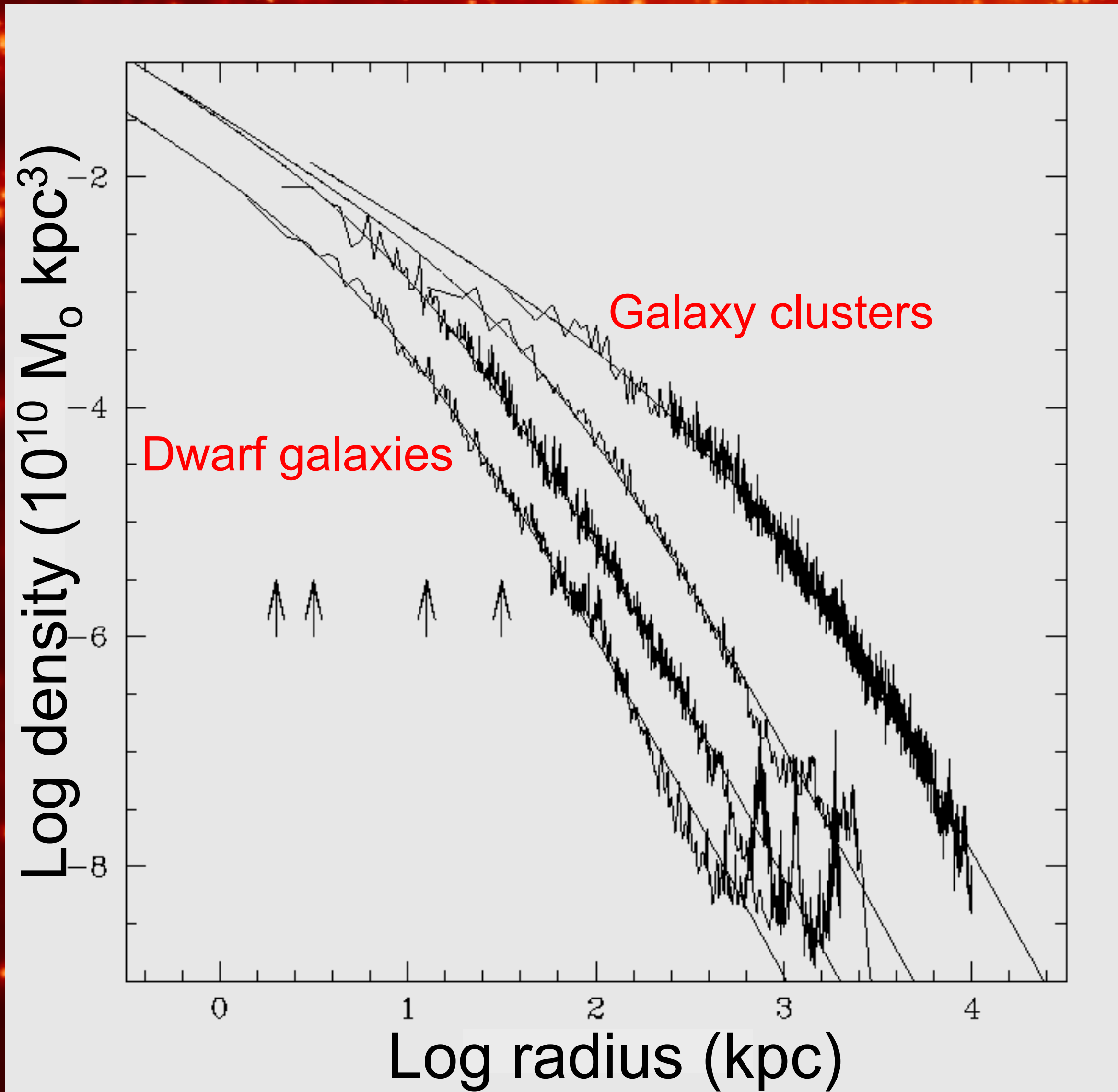
Three challenges to CDM on galactic scales

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

The structure of dark matter halos

The "NFW" profile

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)

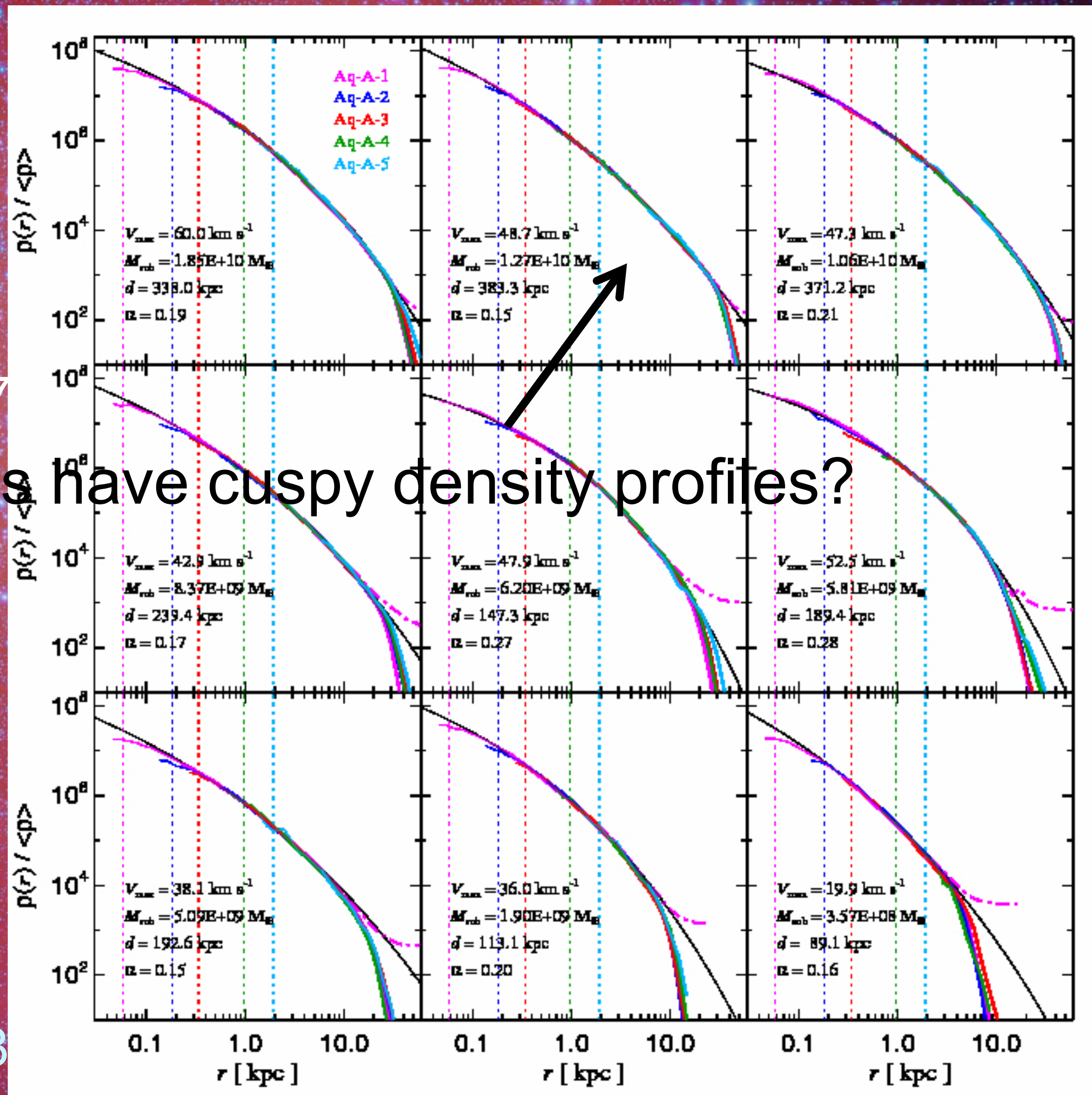
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

Halos that form earlier have higher densities (bigger δ)

CDM predicts 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



Do subhalos have cuspy density profiles?

Springel et al '08

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A Cold dark matter universe

N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

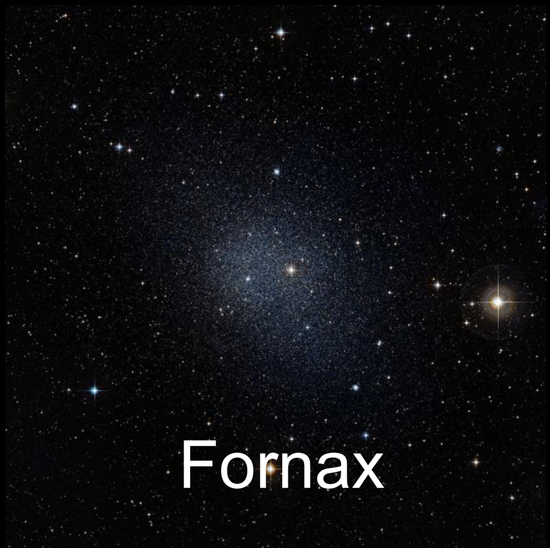
“Cuspy” density profiles

Does nature have them?

Satellites have large M/L and their halos may be relatively unaffected by baryonic effects

Satellite halo profiles can be probed with stellar kinematics

Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

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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 β =0)
- Compare with the observed dispersion profile
- Compute χ^2

Strigari, Frenk & White '10

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Dwarf sphs: cores or cusps?

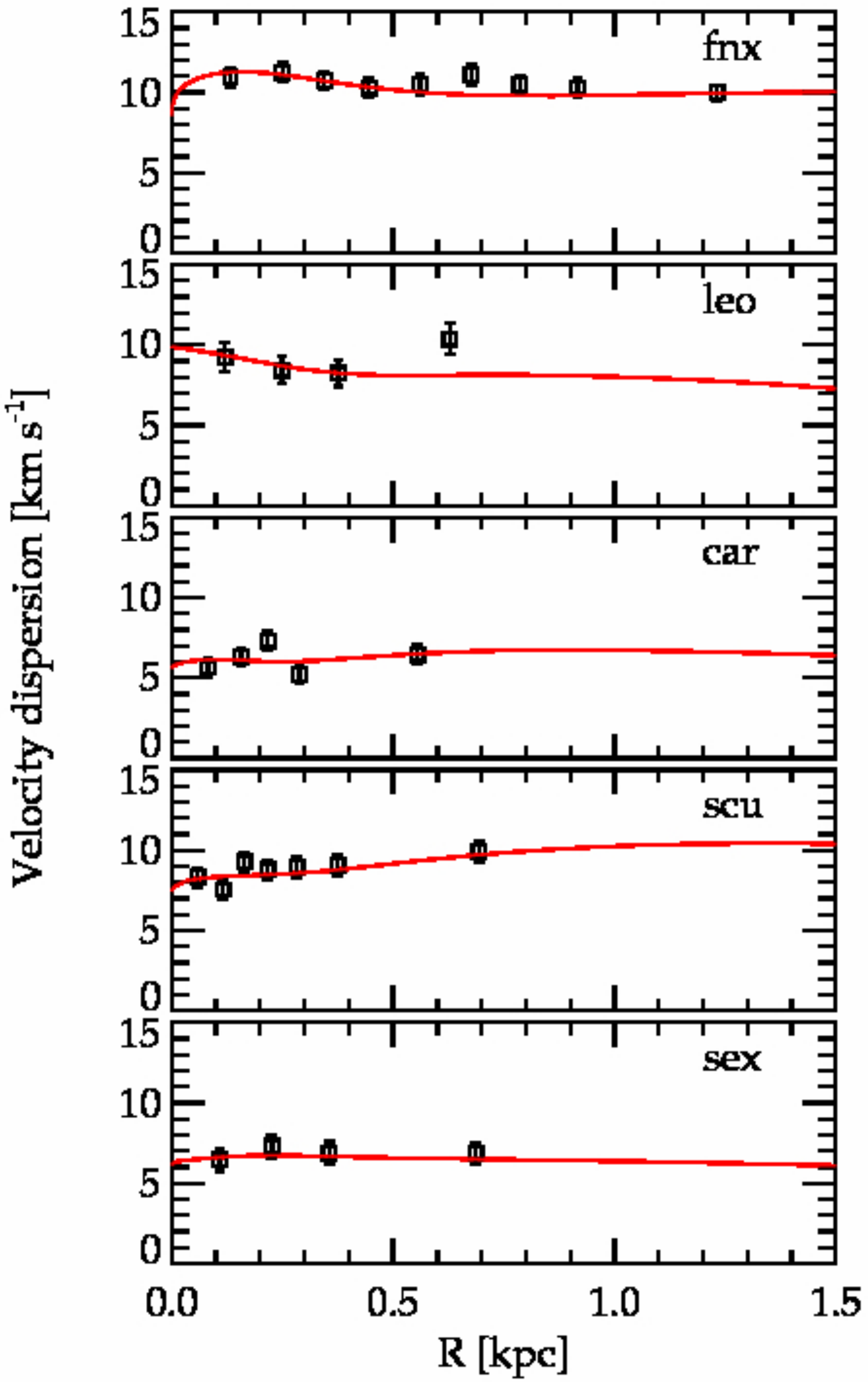
Jeans eqn:

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

from Aquarius sim

vel. anisotropy

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



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Dwarf sphs: cores or cusps?

Jeans eqn:

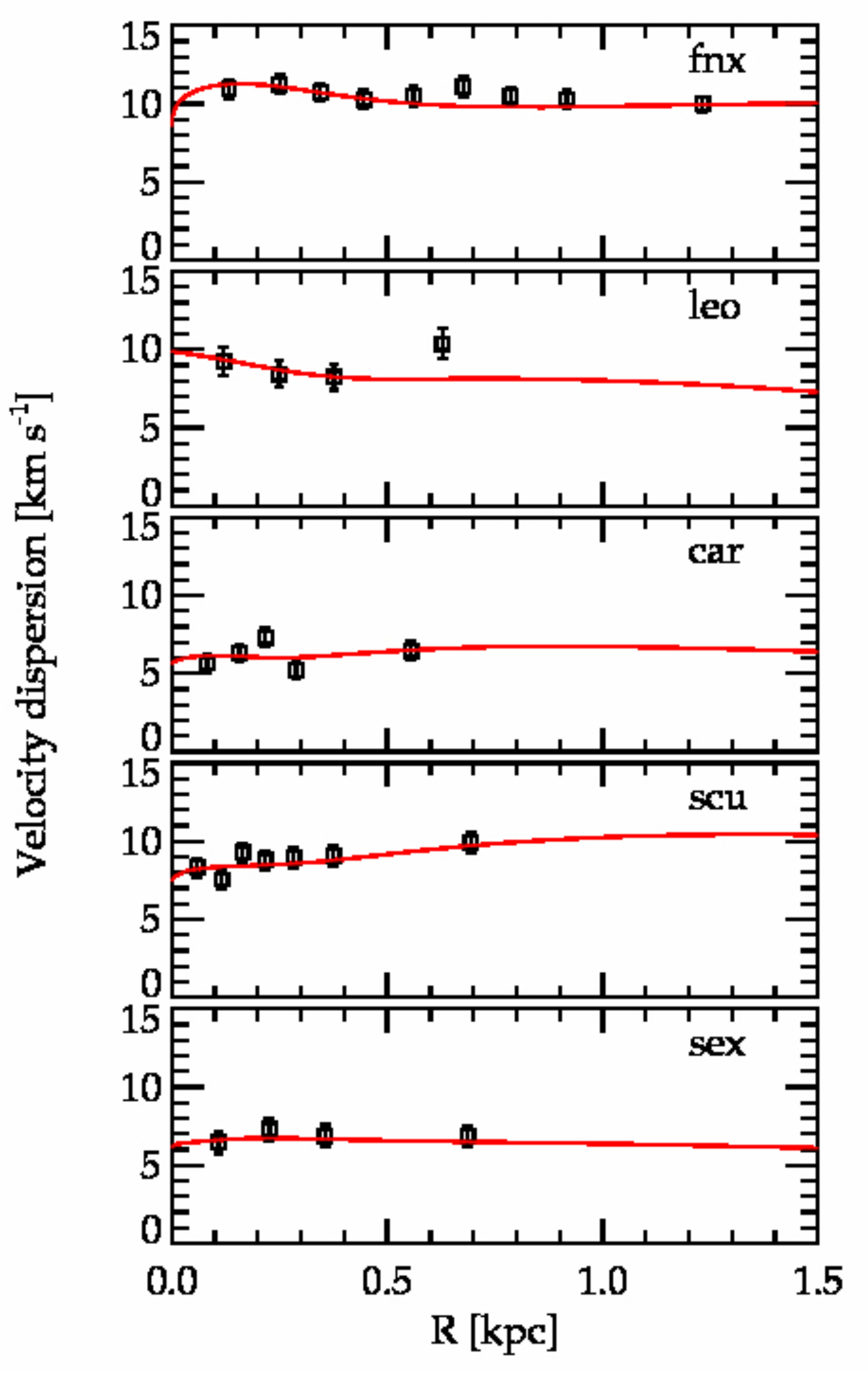
$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

vel. anisotropy

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

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3. 1 and 2 combined

Three challenges for CDM on galactic scales:

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2. The structure of satellite halos ✓
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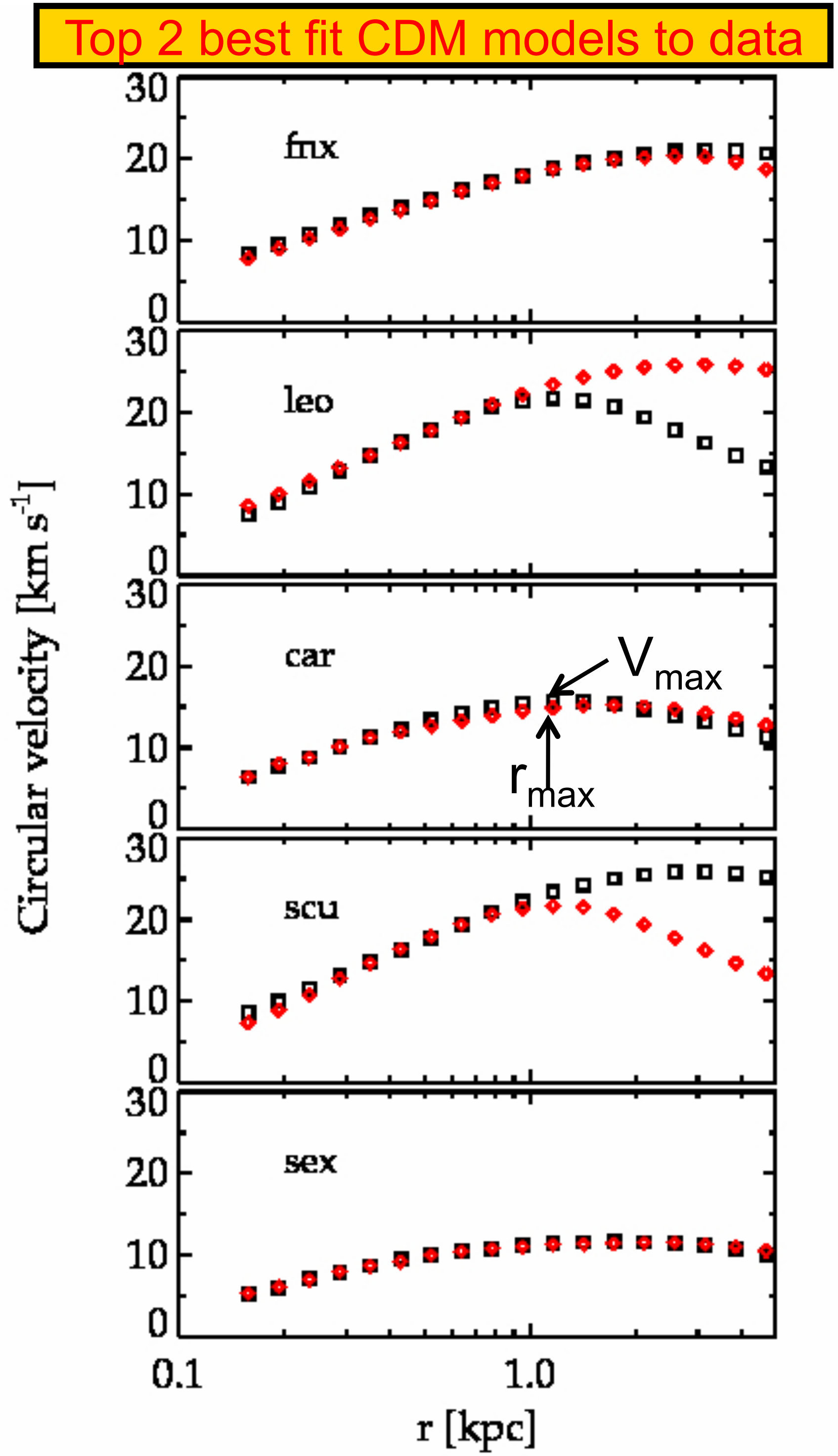
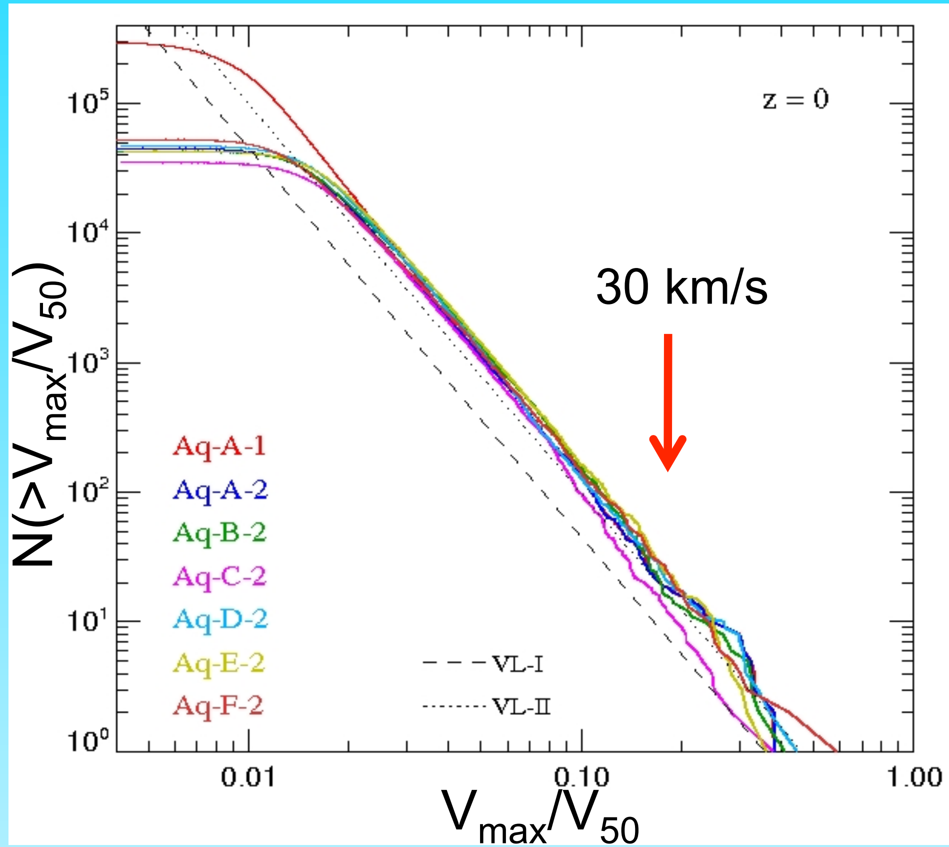
Does CDM theory put satellites of a given luminosity in halos with the right structure?

The satellites of the Milky Way





Strigari, Frenk & White 2010

Warm vs cold dark matter subhalos

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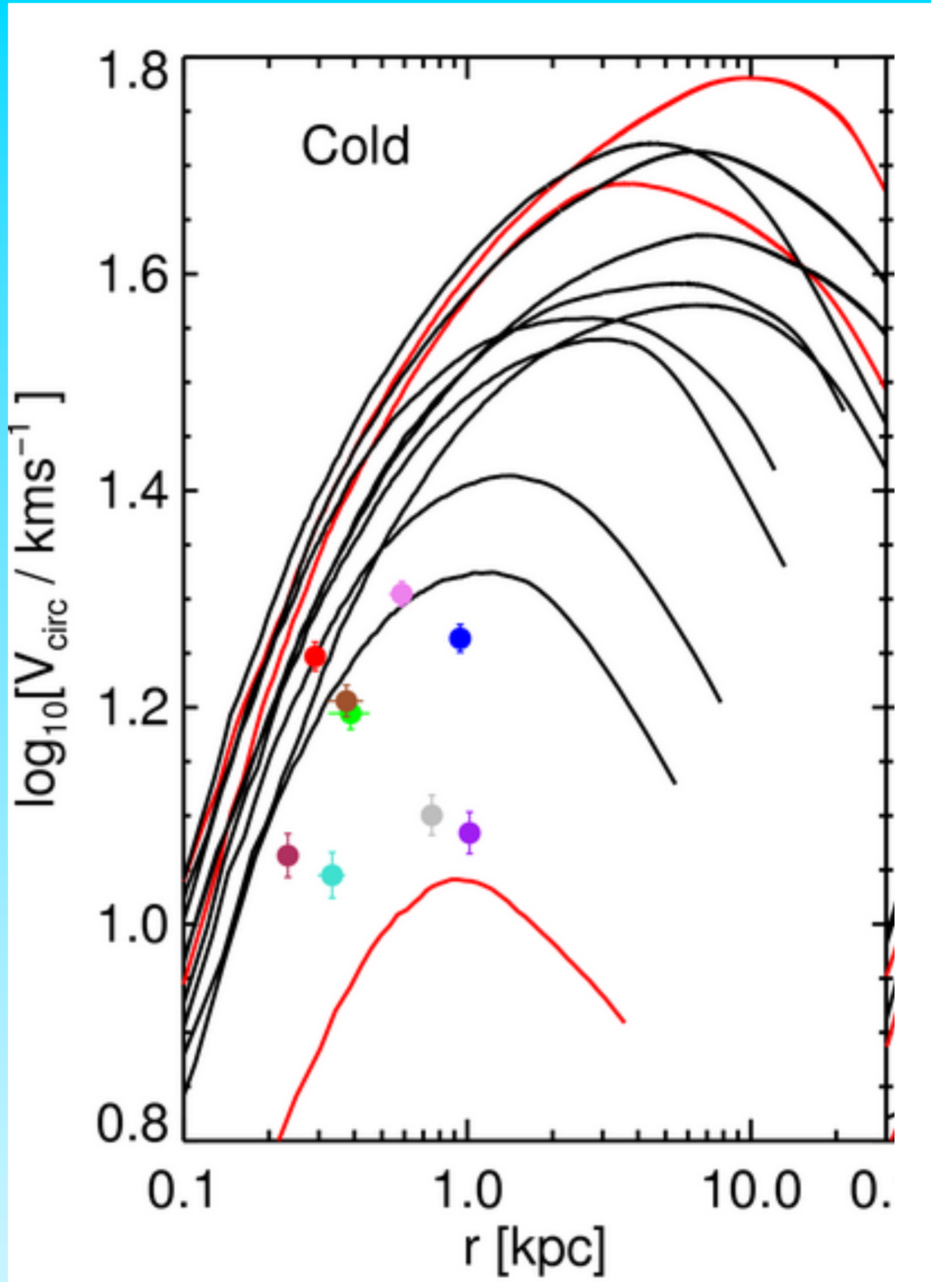
How about the masses?

Density profiles 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 halos of the MW satellites

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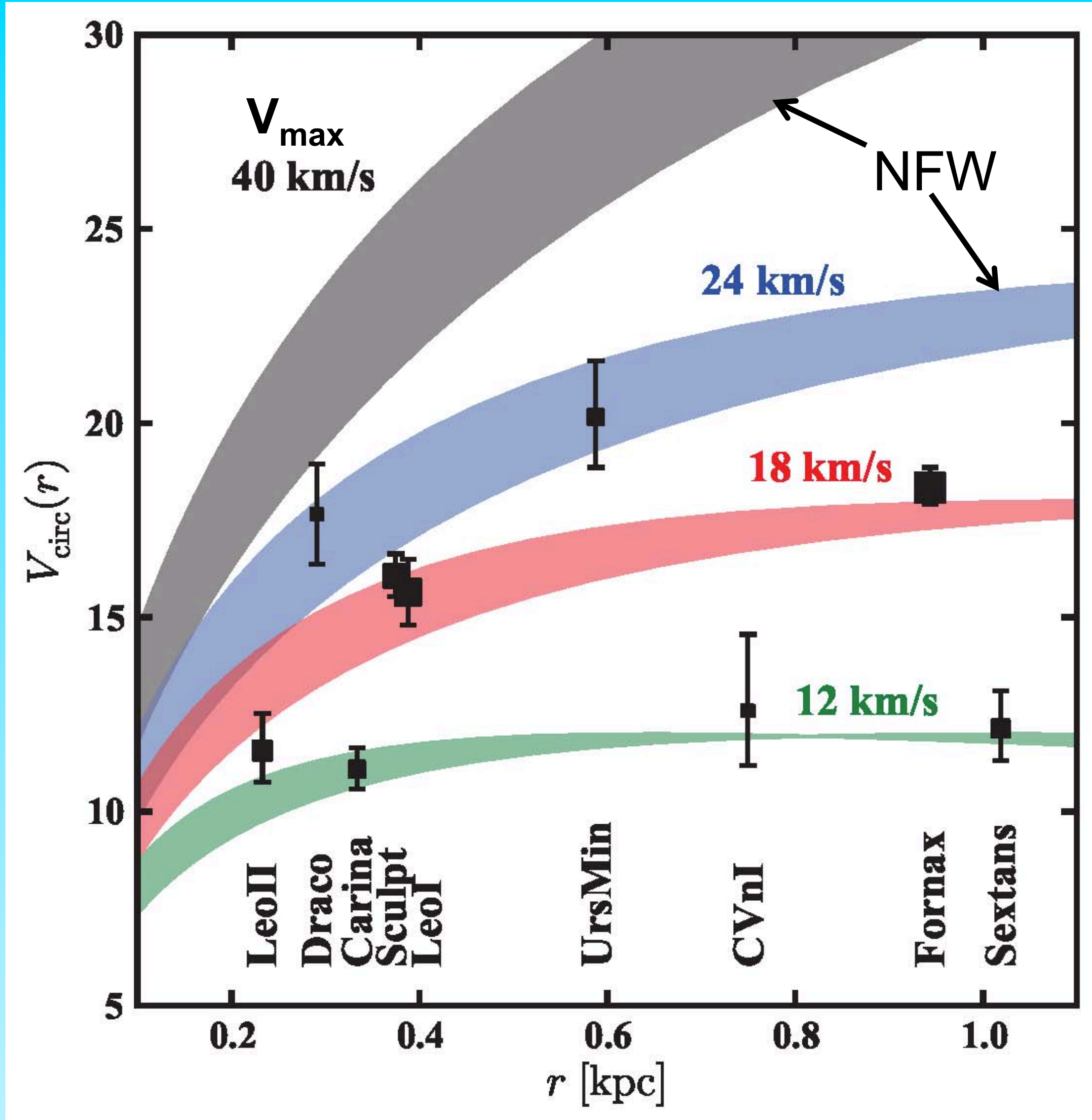
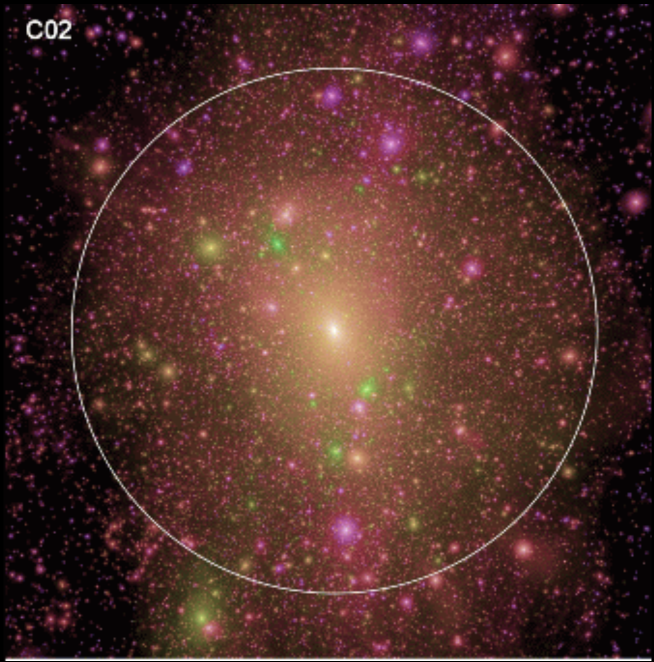
MW dwarf spheroidals are in halos with V_{max} < 25 km/s

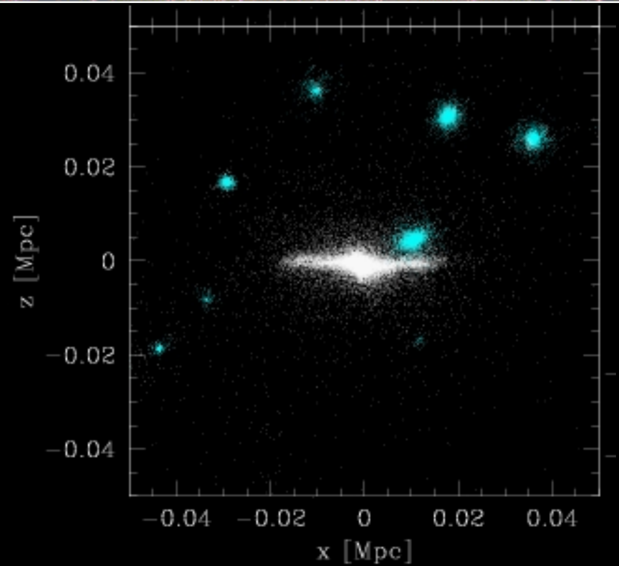
(with possible exception of Draco for which V_{max} < 40 km/s)



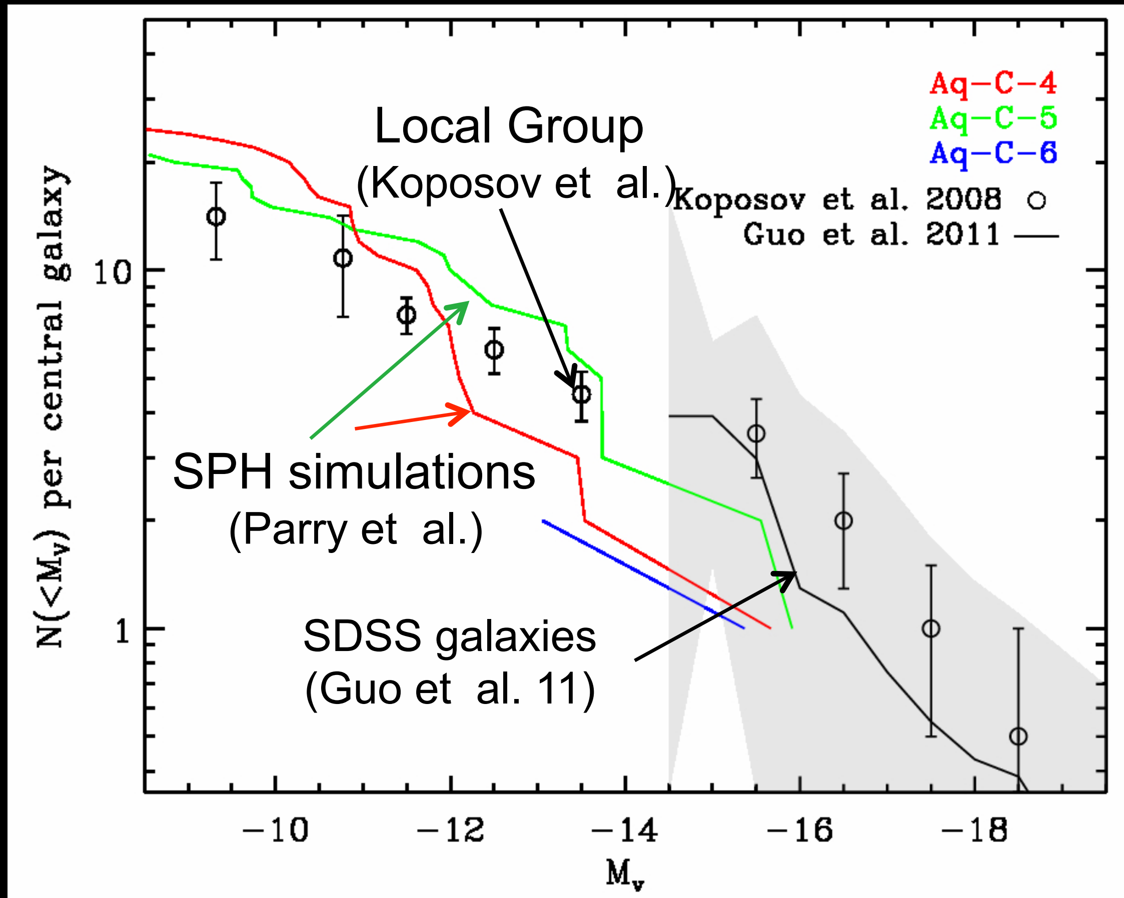
Boylan-Kolchin et al ‘12

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

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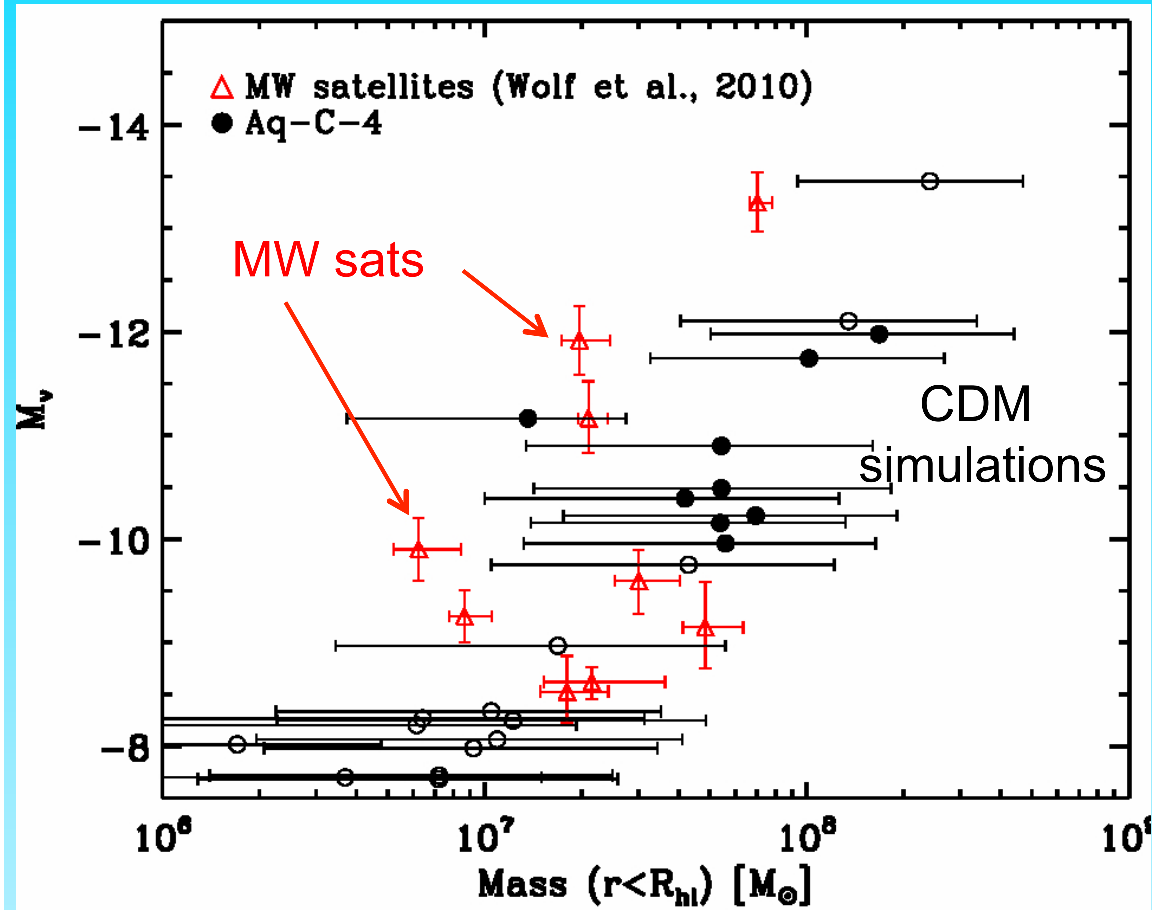
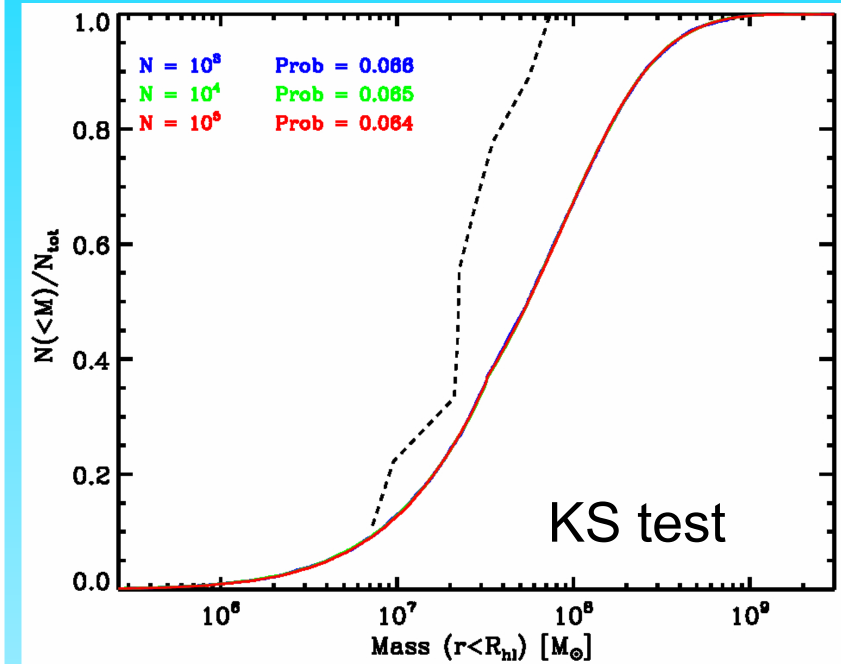
Mass within half-light rad. (spectroscopy)





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

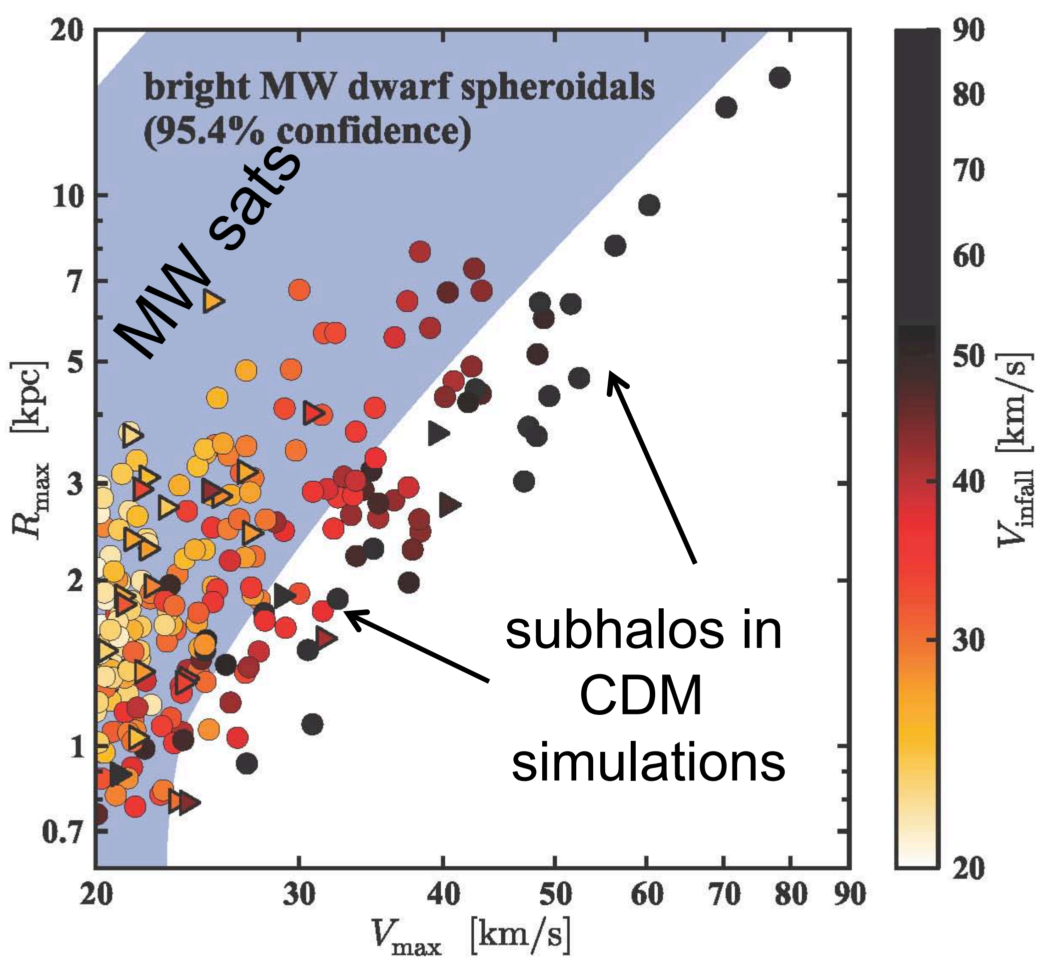
The satellites of the Milky Way

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.

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 seem to be more massive/concentrated than indicated by Local Group data.

Note: this has nothing to do with "core radii"

Possible solutions?

Solution 1: Warm dark matter

cold dark matter

warm dark matter

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

Warm vs cold dark matter subhalos

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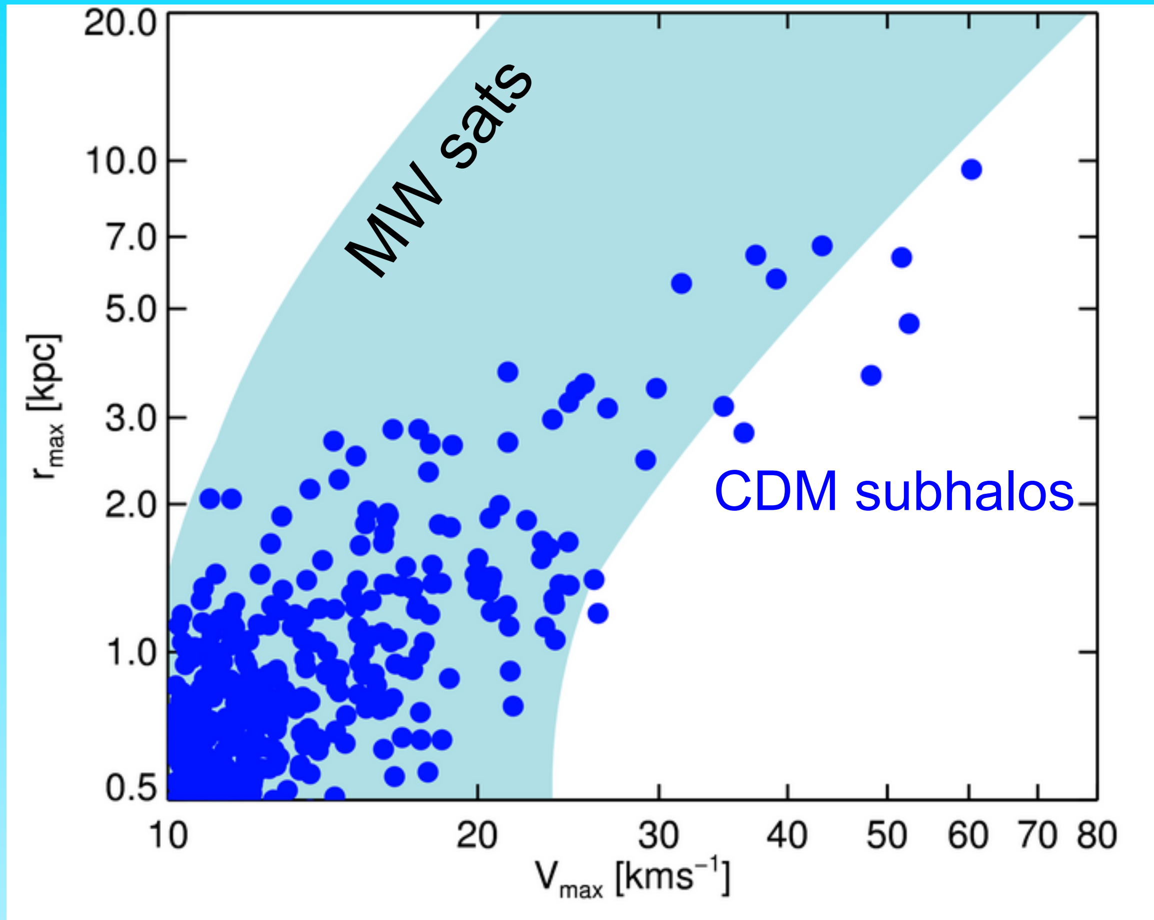
Majority of most massive CDM subhalos too dense to host any of the bright MW sats.



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

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Warm vs cold dark matter subhalos

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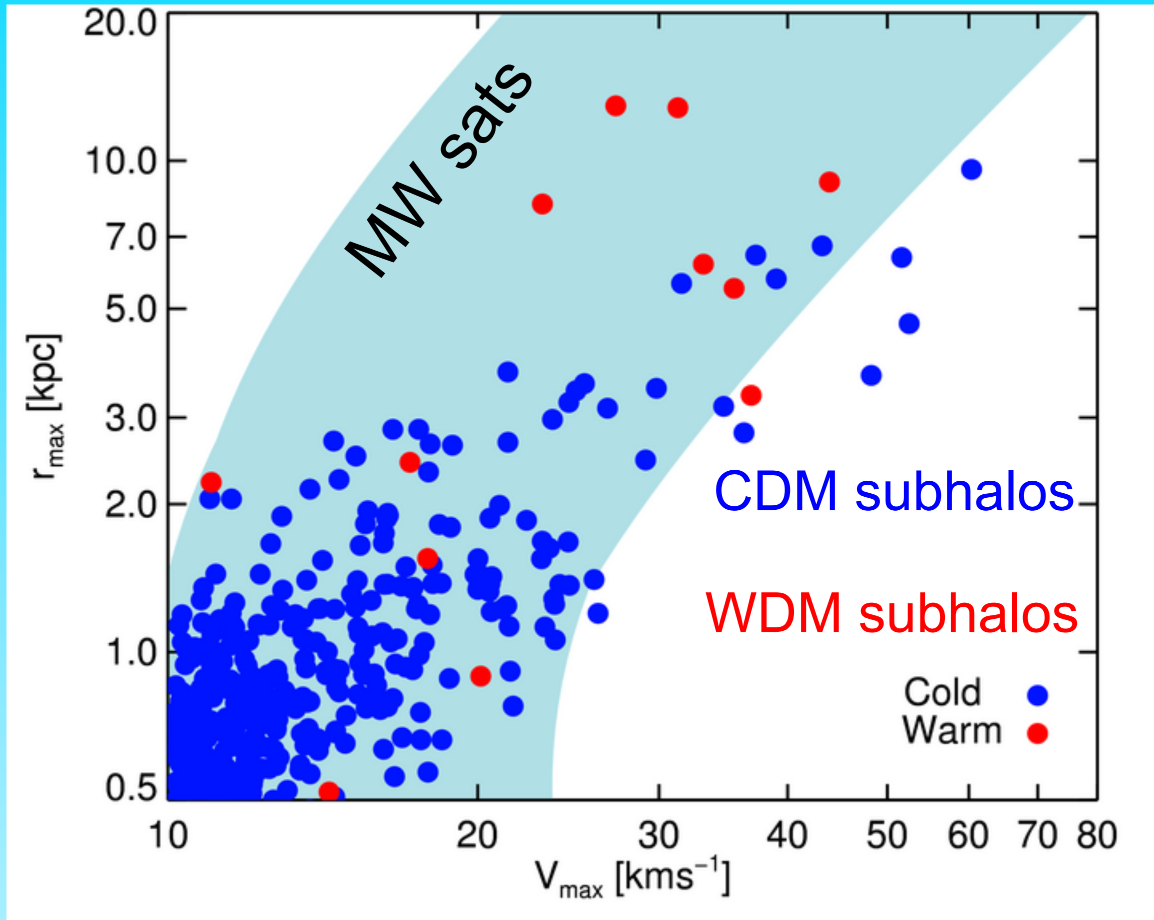
WDM subhalos have the right concentration to host the bright MW satellites



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

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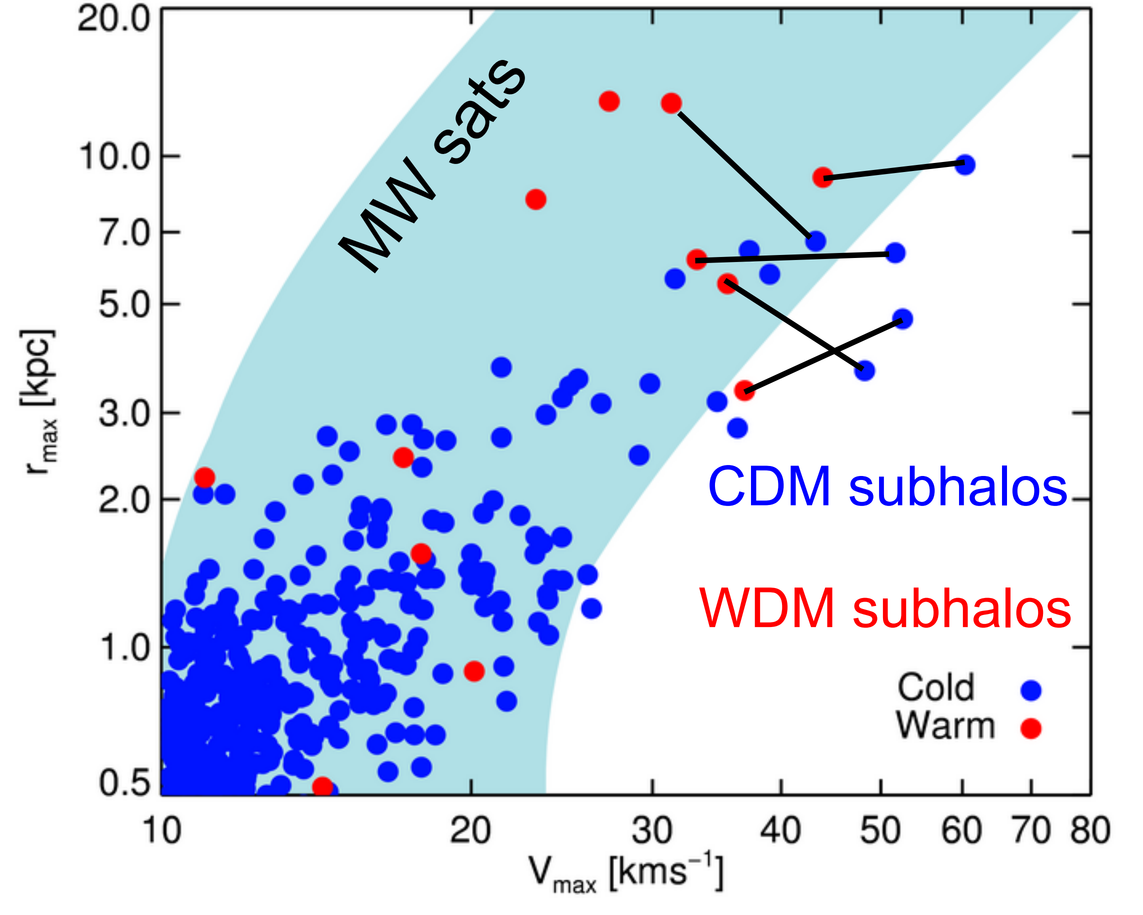

Lovell, Eke, Frenk, Gao, Jenkins et al '11

Warm vs cold dark matter subhalos

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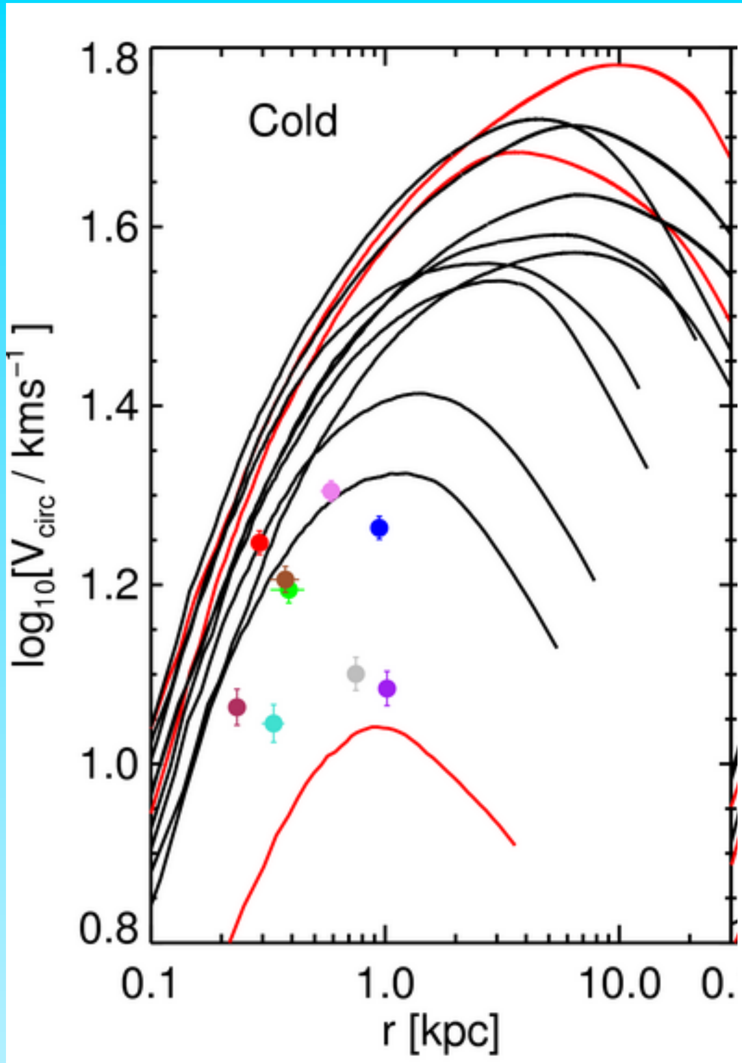
How about the masses?

Density profiles of 12 subhalos with most massive progenitors

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



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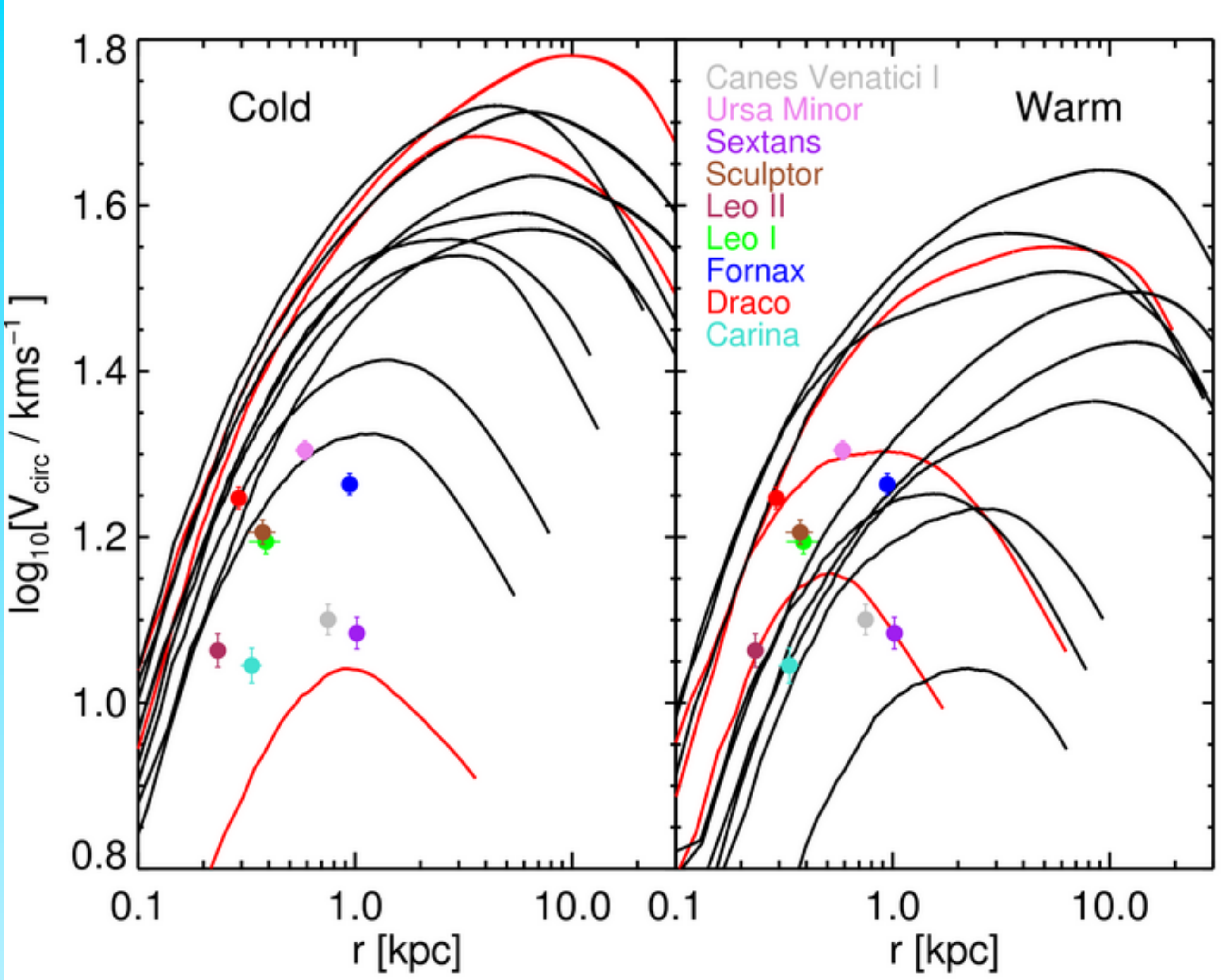

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Warm vs cold dark matter subhalos

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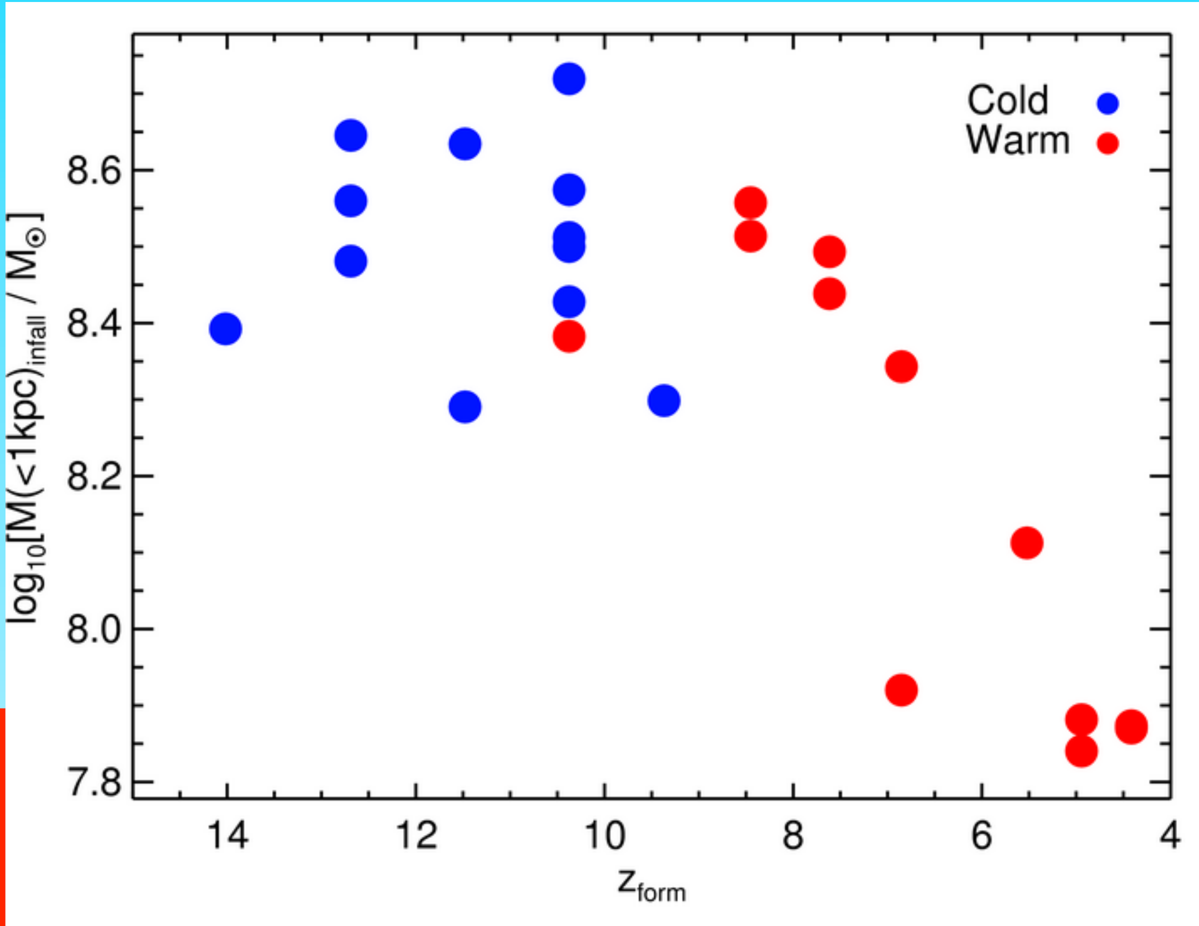
"Formation redshift" →
z at which M_{halo} first exceeded $M_{infall}(<1kpc)$

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

Possible solutions?

Solution 1: Warm dark matter

Solution 2: Baryon effects

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

The cores of dwarf galaxy haloes

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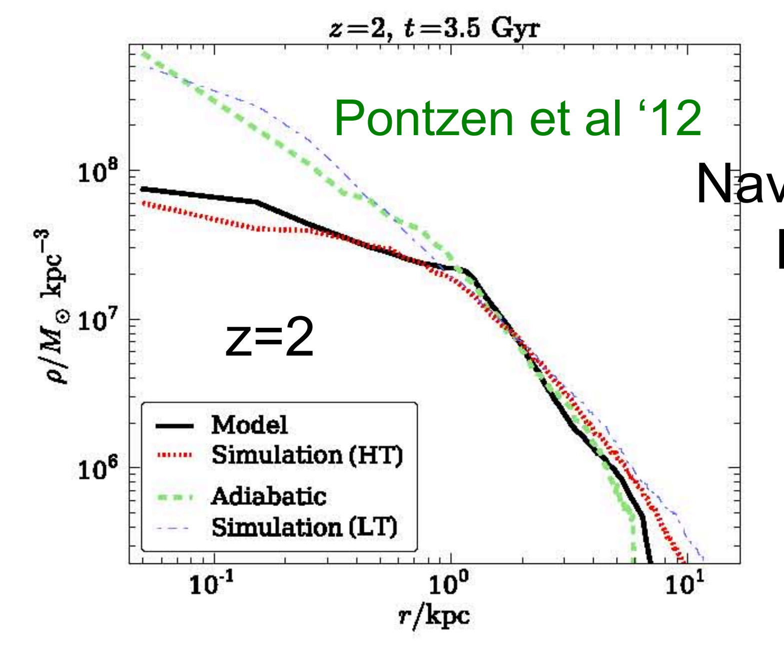
ABSTRACT

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

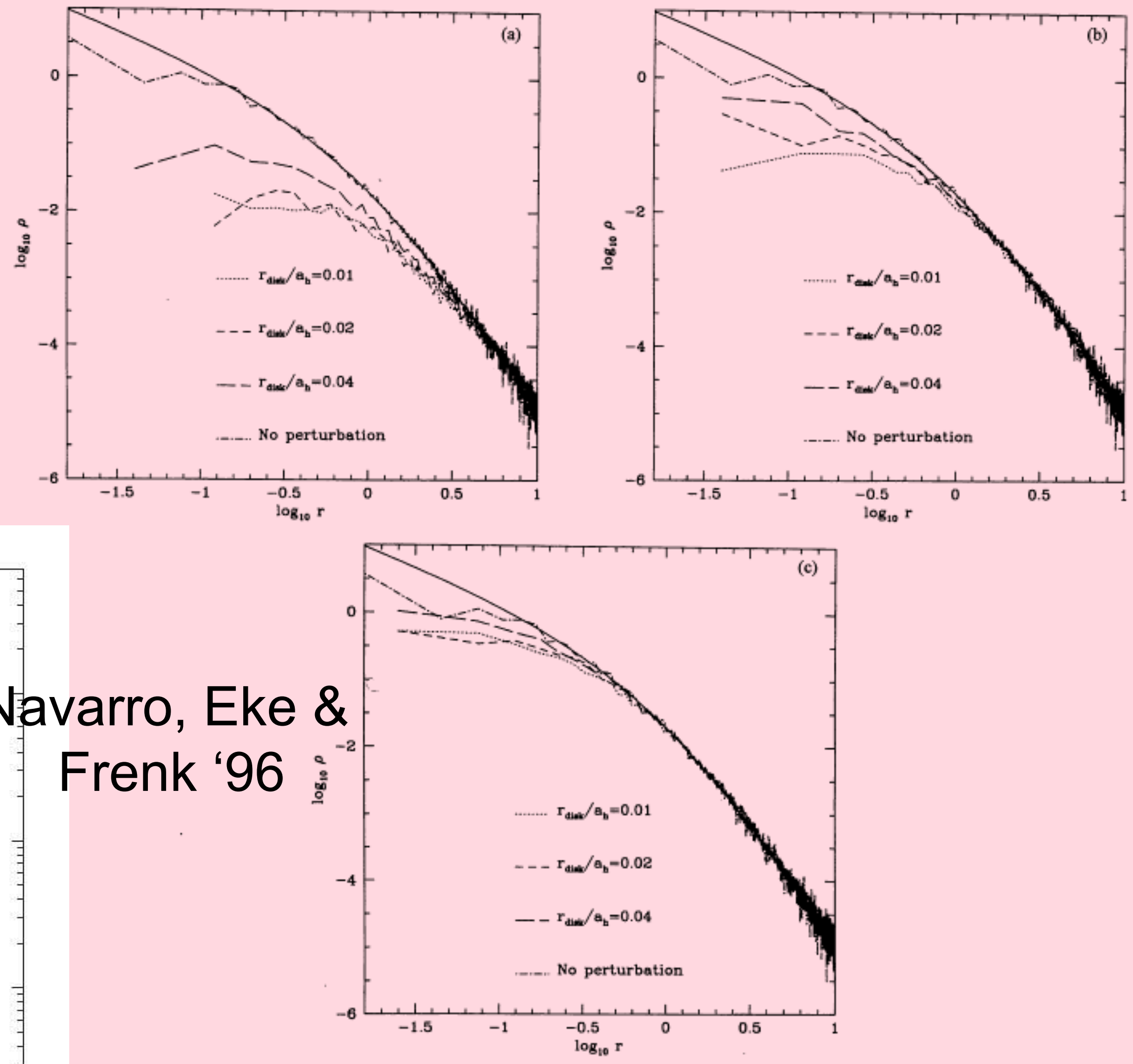
University of Durham

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



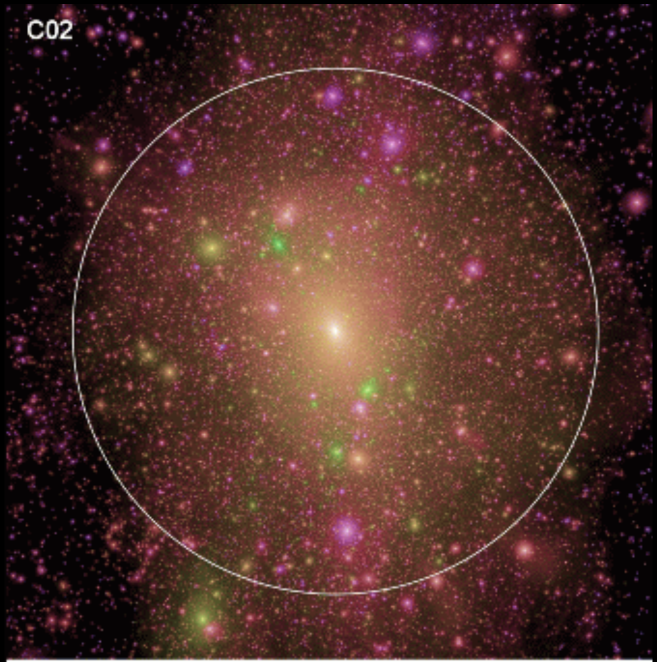
Navarro, Eke & Frenk ‘96

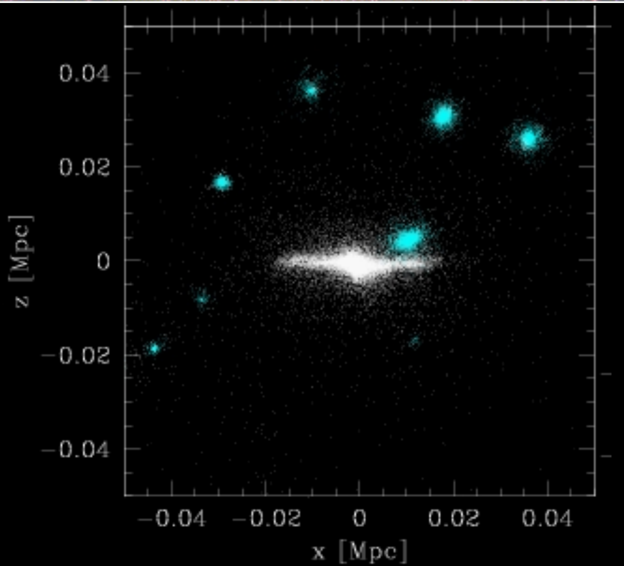
The cores of dwarf galaxy haloes L75



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

The satellites of the Milky Way

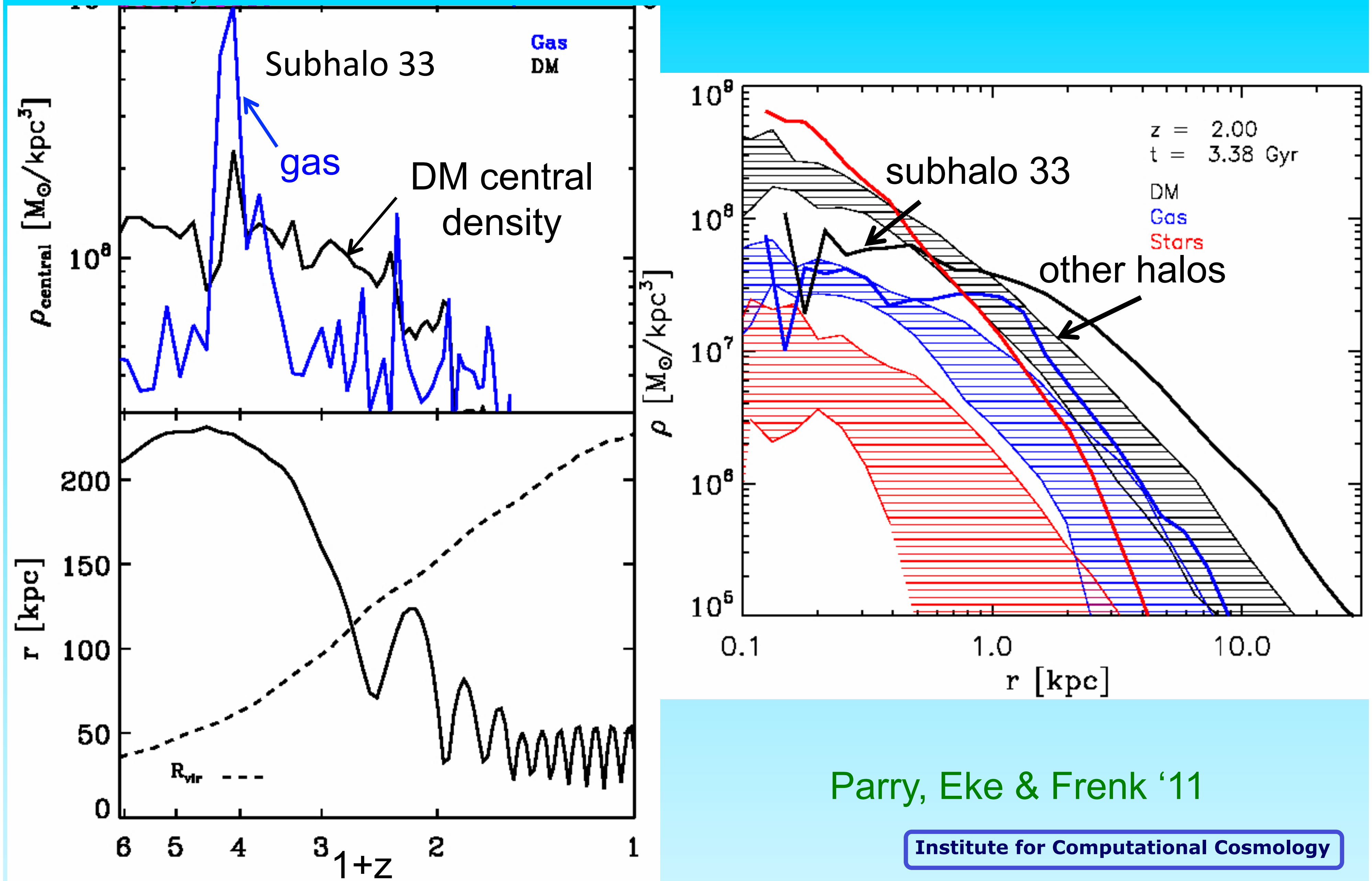




SPH simulations of galaxy formation in one of the Aquarius halos

Parry, Eke, Frenk & Okamoto '11

Baryon effects in the MW satellites



Parry, Eke & Frenk '11

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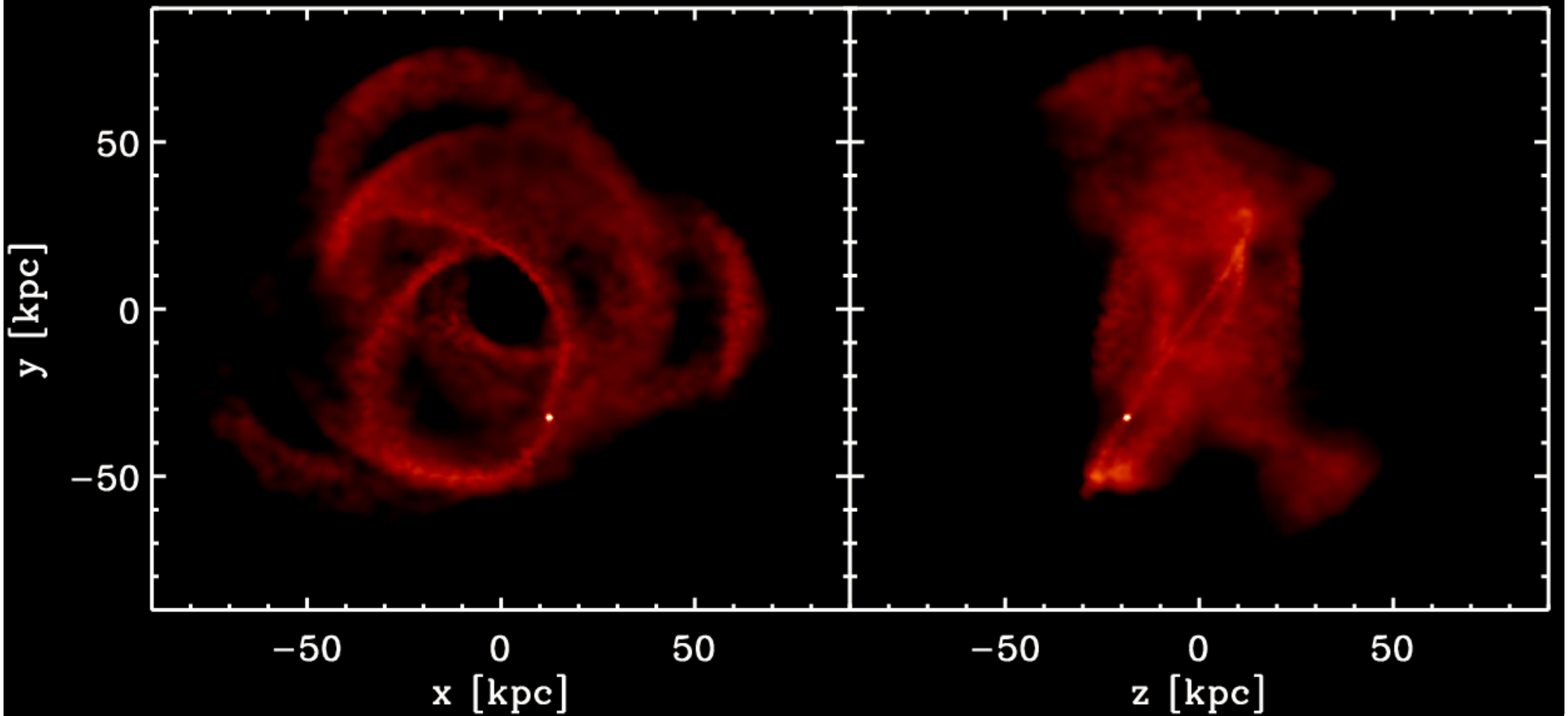
Baryon effects in the MW satellites

Subhalo 33



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Possible solutions?

Solution 1: Warm dark matter

Solution 2: Baryon effects

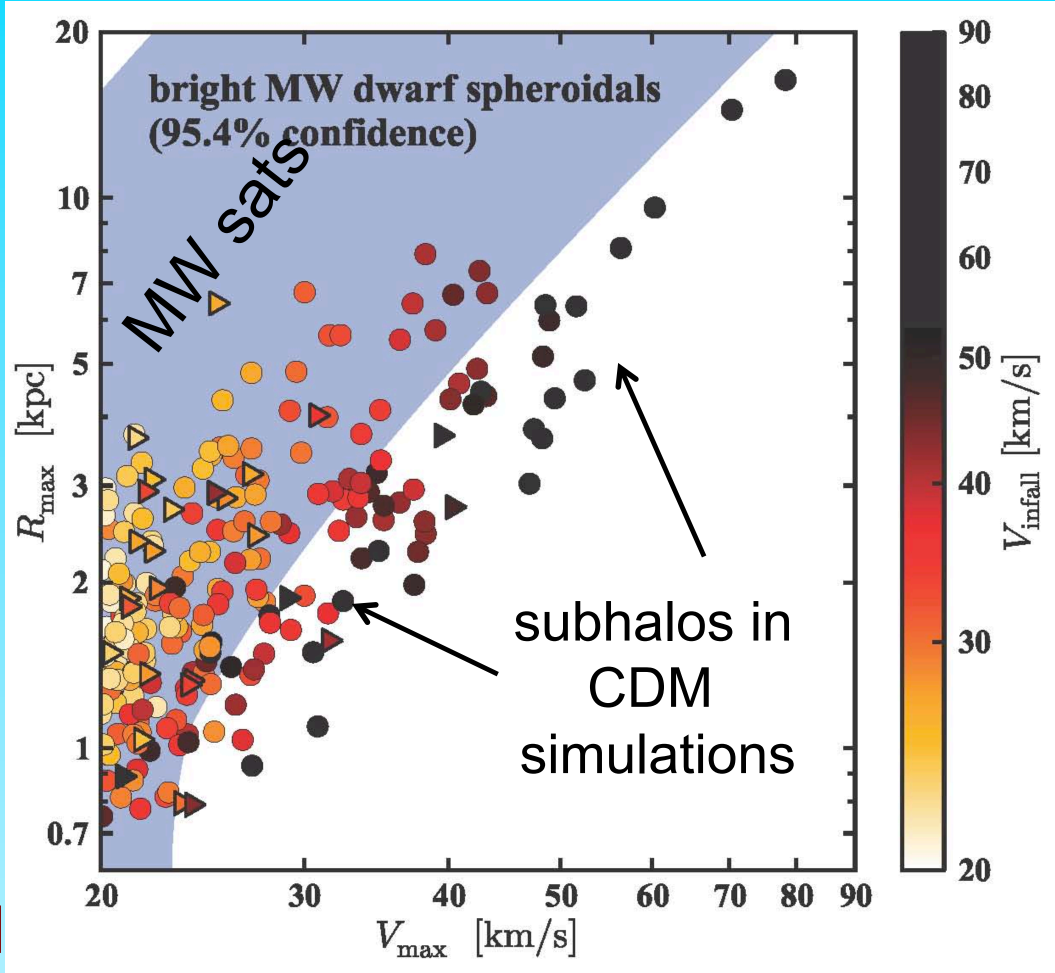
Solution 3: The MW is atypical or its halo is less massive than $1.5\times10^{12}M_{o}$

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.

Solution 3

Apart from the LMC, SMC and Sagittarius, Milky Way satellites seem to live in subhalos with $V_{max} < 25$ km/s

All 6 Aquarius halos have several massive ($V_{max} > 25$ km/s) subhalos where bright satellites should have formed

What is the probability of a halo having no more than 3 (LMC, SMC, Sag) massive, e.g. $V_{max} > 25$ km/s, subhalos?

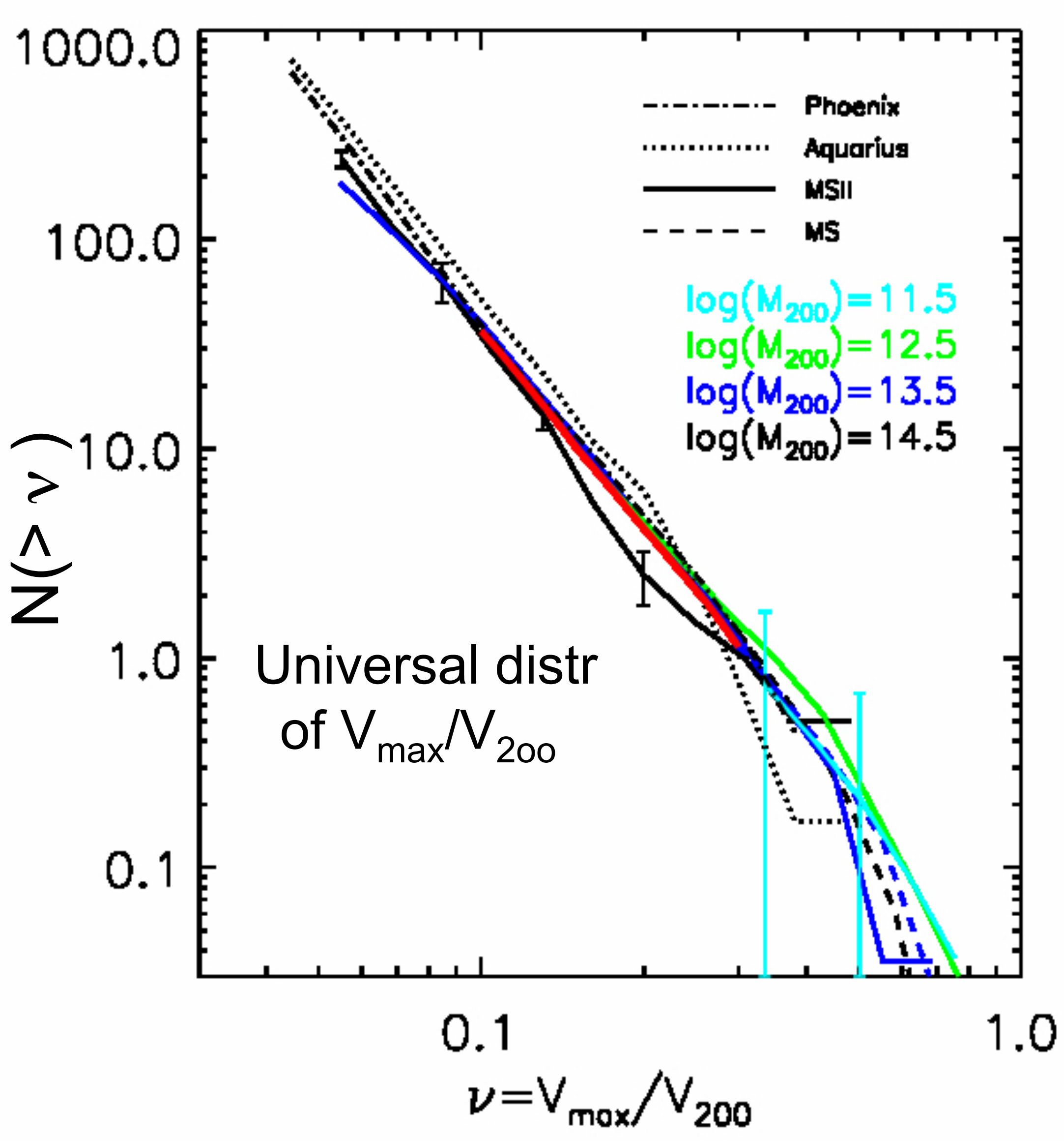
Subhalo abundance in ΛCDM

Millennium II resolves subhalos with V_{max} > 30 km/s in 10^{12} M_o halos

However, the distribution of V_{max}/V_{200} is nearly universal (independent of halo mass)

→ can use resolved subhalos in other simulations like MI, MII, etc

Wang, Frenk, Navarro '12



Probability of massive subhalos

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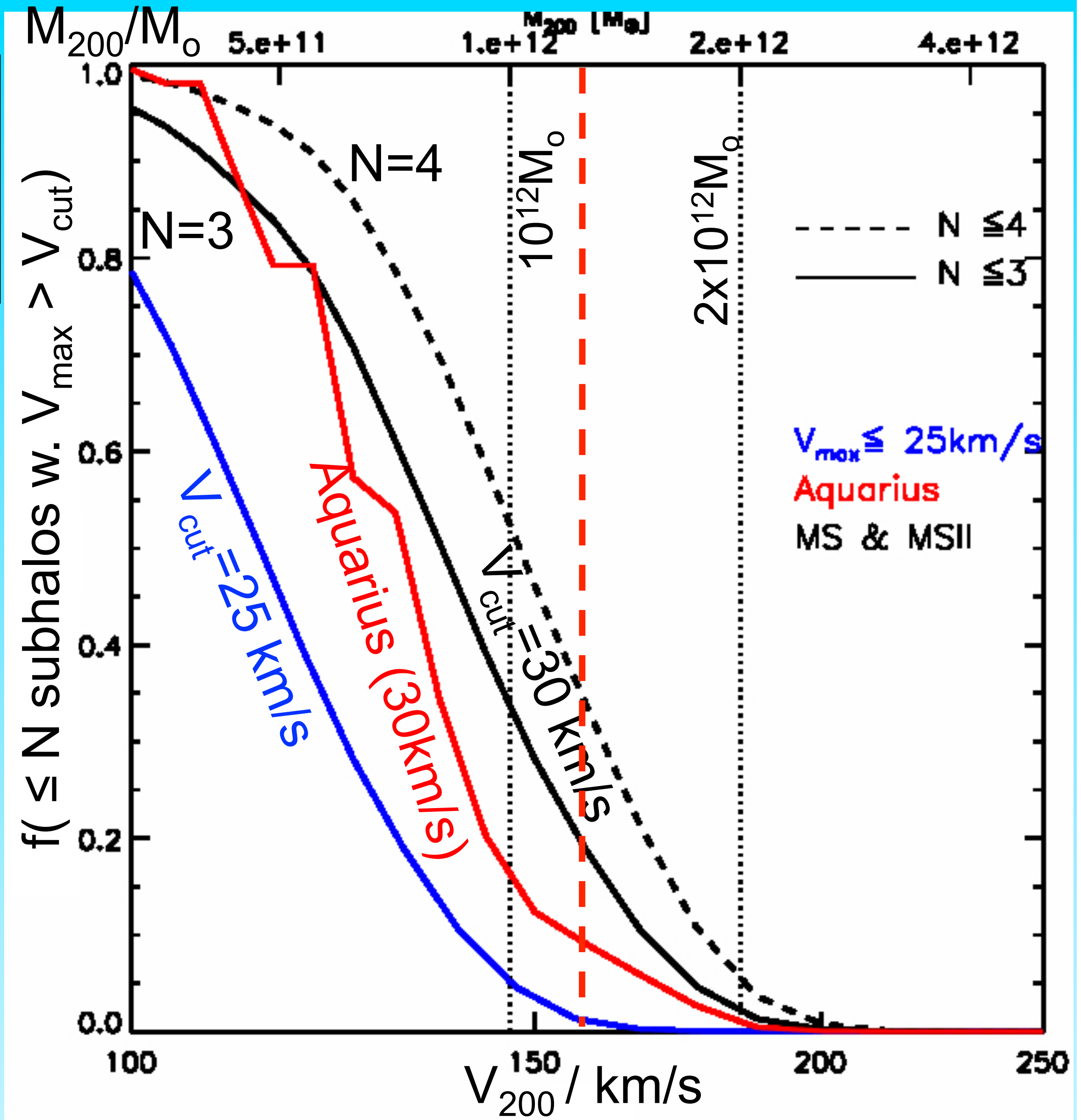
Probability of having no more than N subhalos with $V_{max} > V_{cut}$

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

If $M_{halo} = 1 \times 10^{12} M_o$, probability of having no more than 3 subhalos with $V_{max} > 30$ km/s is ~40%

If $M_{halo} = 1 \times 10^{12} M_o$, probability of having no more than 3 subhalos with $V_{max} > 25$ km/s is ~5%



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ΛCDM: problems/possible solutions

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- 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 $M_{halo} \leq 10^{12} M_o$