Looking for the identity of the dark matter … in our backyard

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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

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The dark matter power spectrum

Free streaming →

λ_{cut} α k_{cut}^{-1} α m_x^{-1}

for thermal relic

m_{CDM} ~ 100GeV

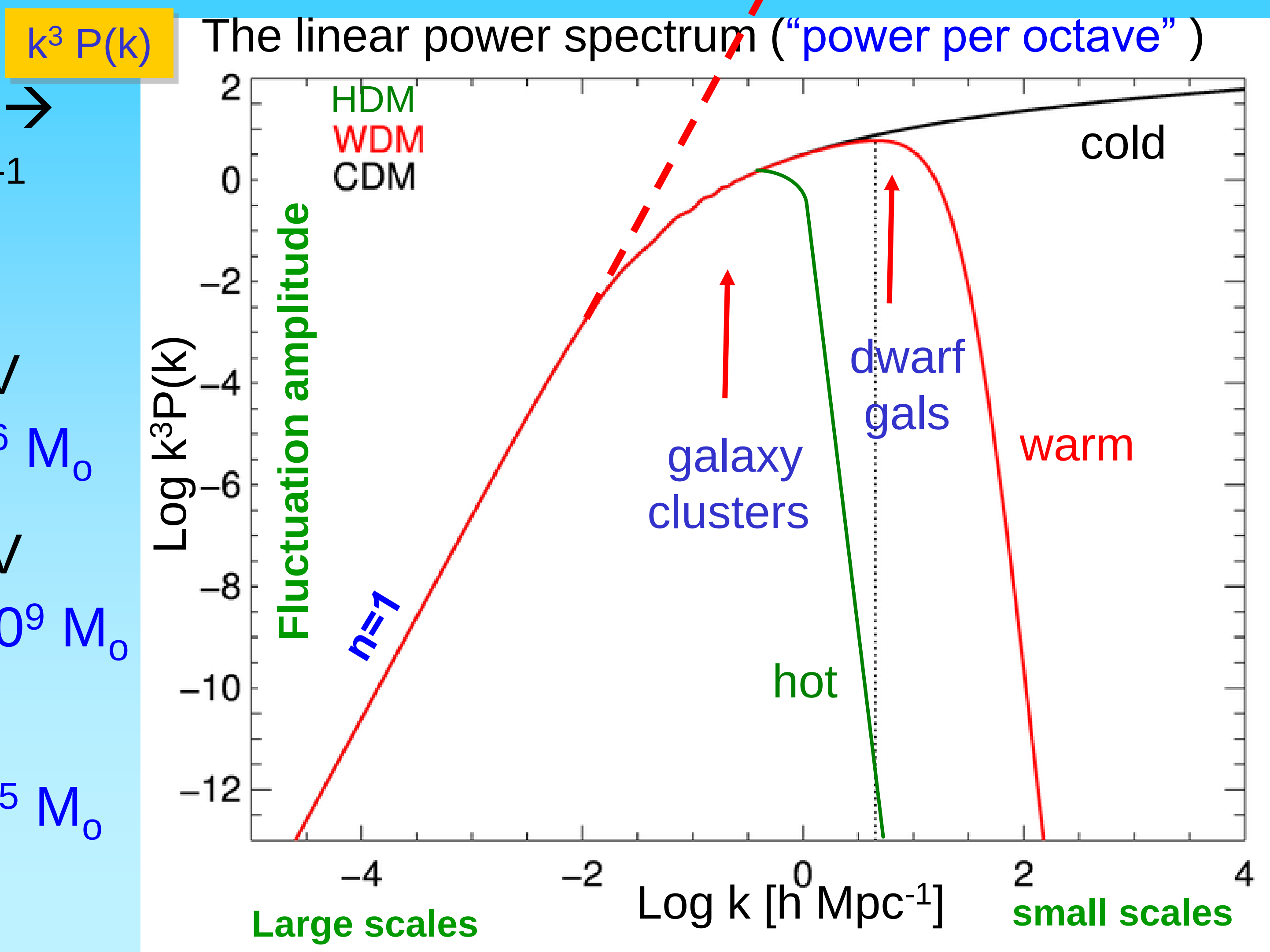
susy; M_{cut} ~ 10^{-6} M_o

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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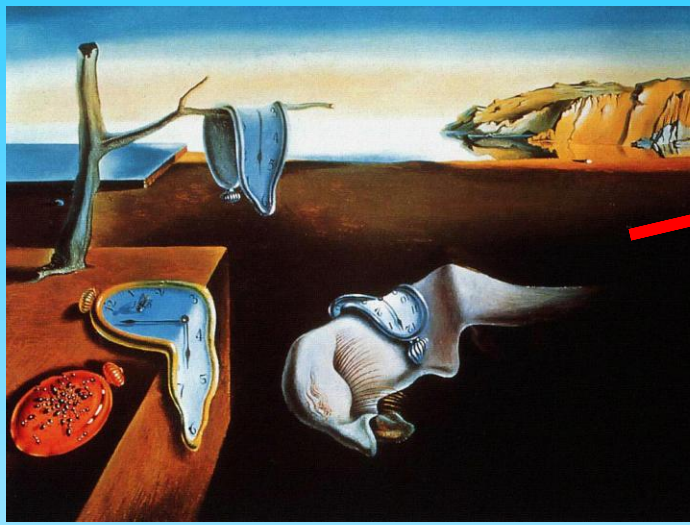
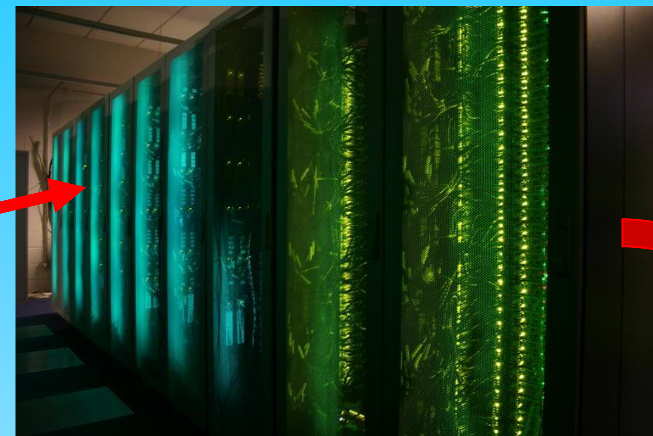
“Cosmology machine”

$t=10^{-35}$ seconds





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

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

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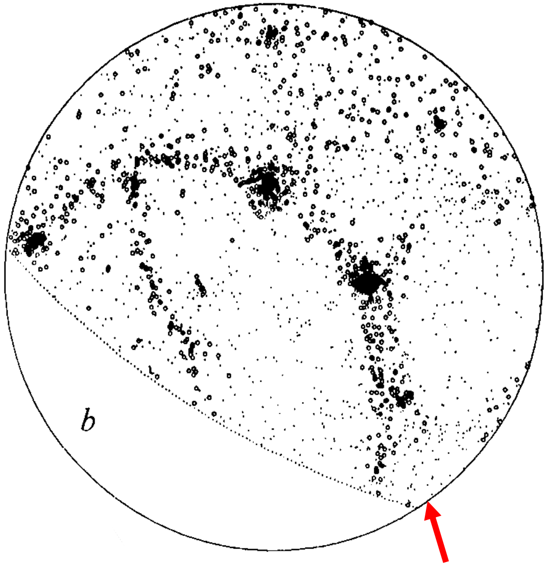
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

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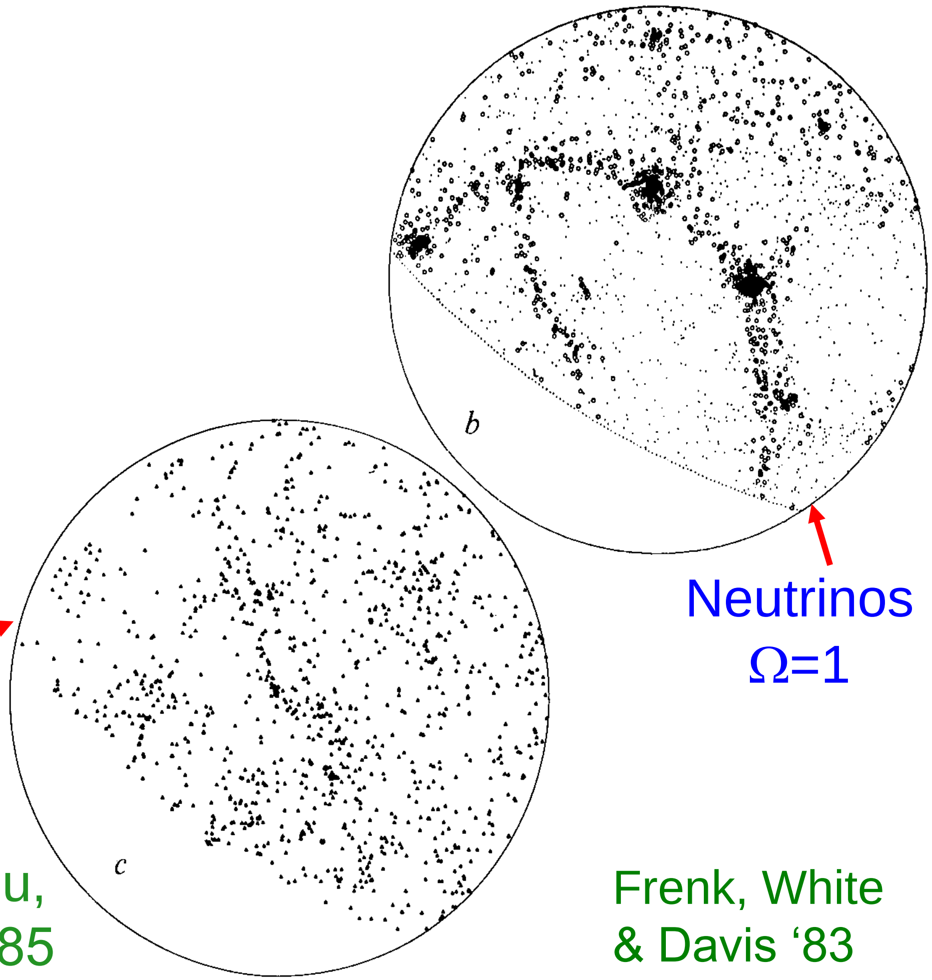
Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 10 ev



CfA redshift survey

Neutrinos
Ω=1

Davis, Efstathiou, Frenk & White '85

Frenk, White & Davis '83

University of Durham

Non-baryonic dark matter cosmologies

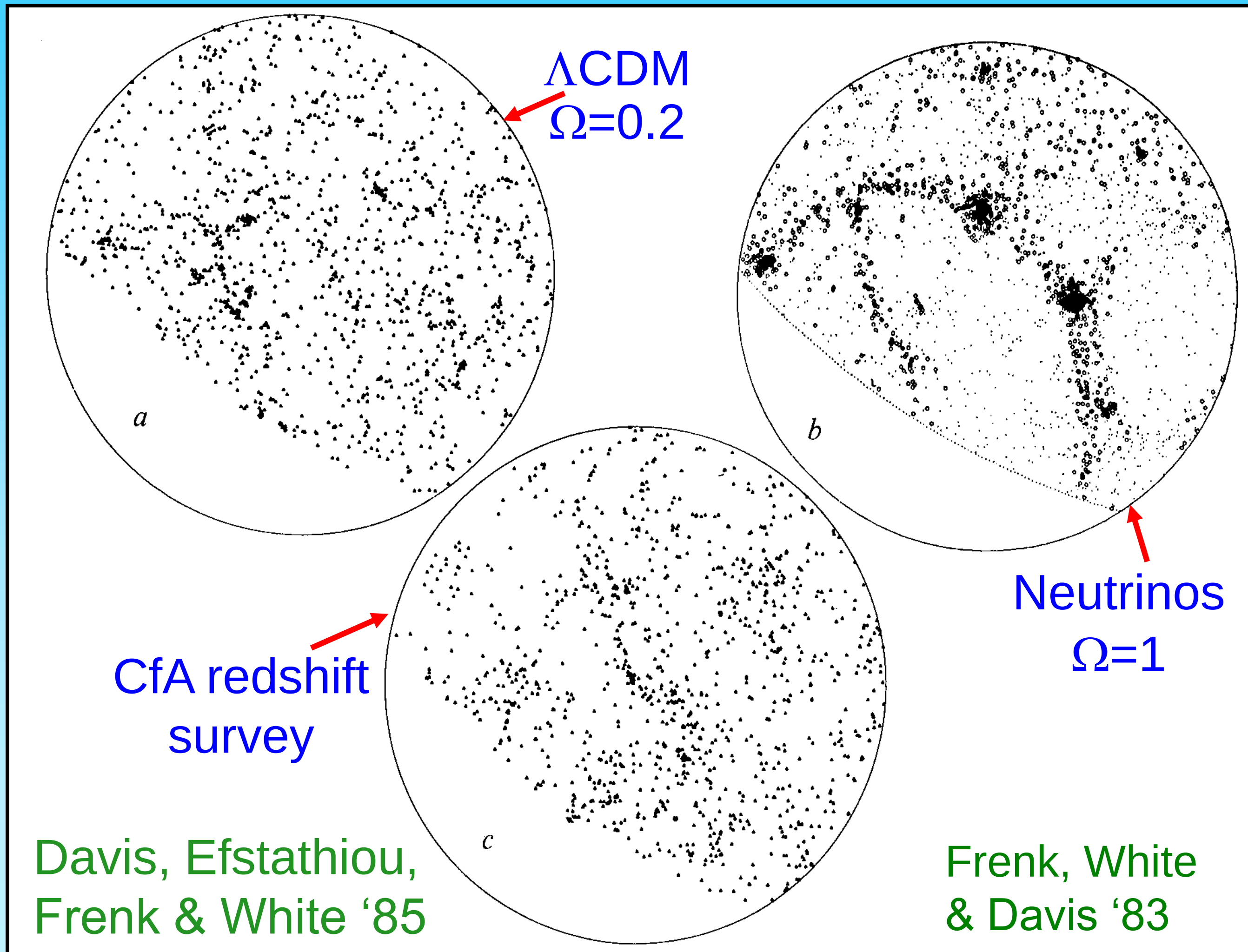
Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to **Ω**

→ m_ν<< 10 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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The dark matter power spectrum

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k^3 P(k)

Free streaming →

λ_{cut} α m_x^{-1} fo

thermal relic

m_{CDM} ~ 100GeV

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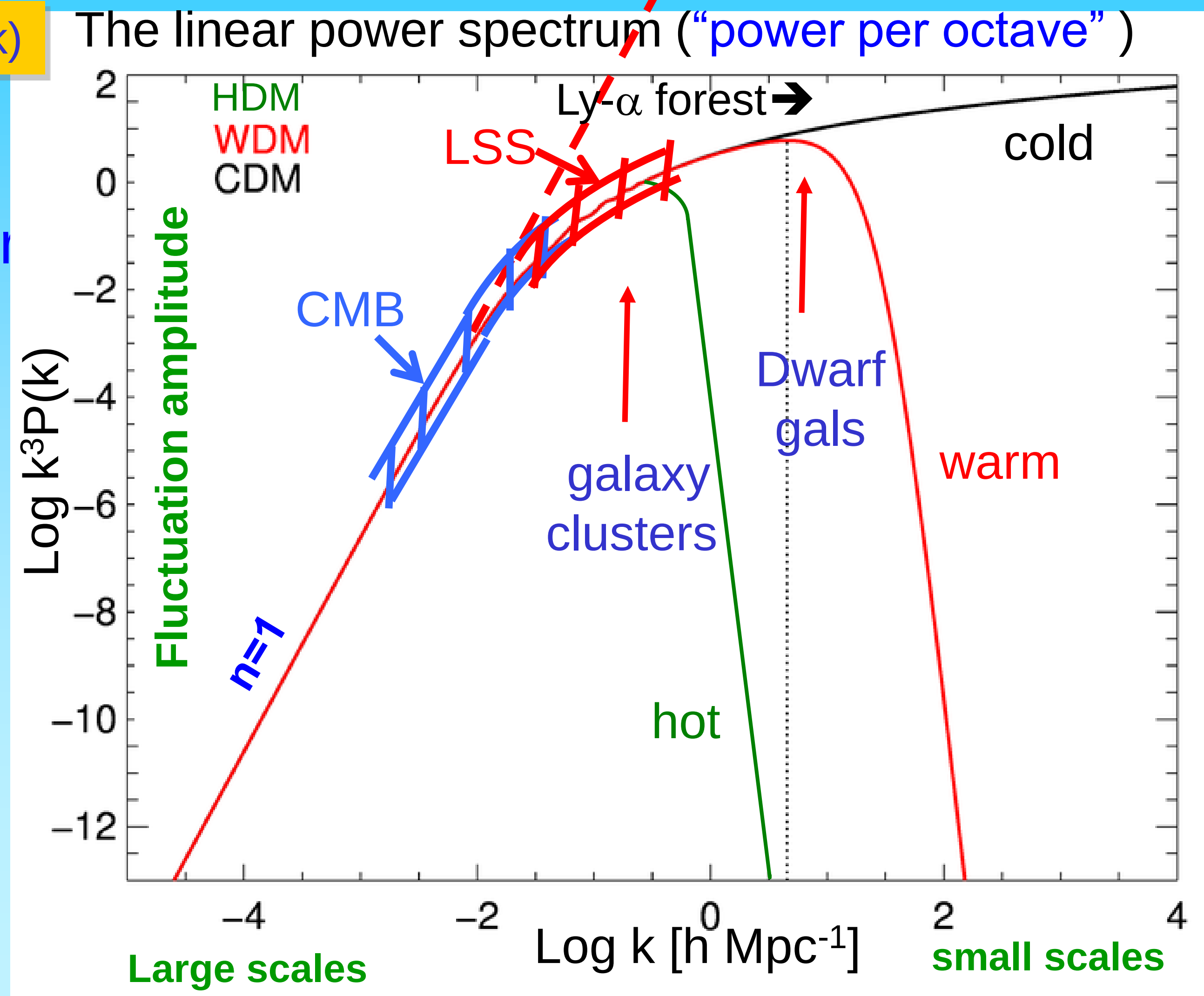


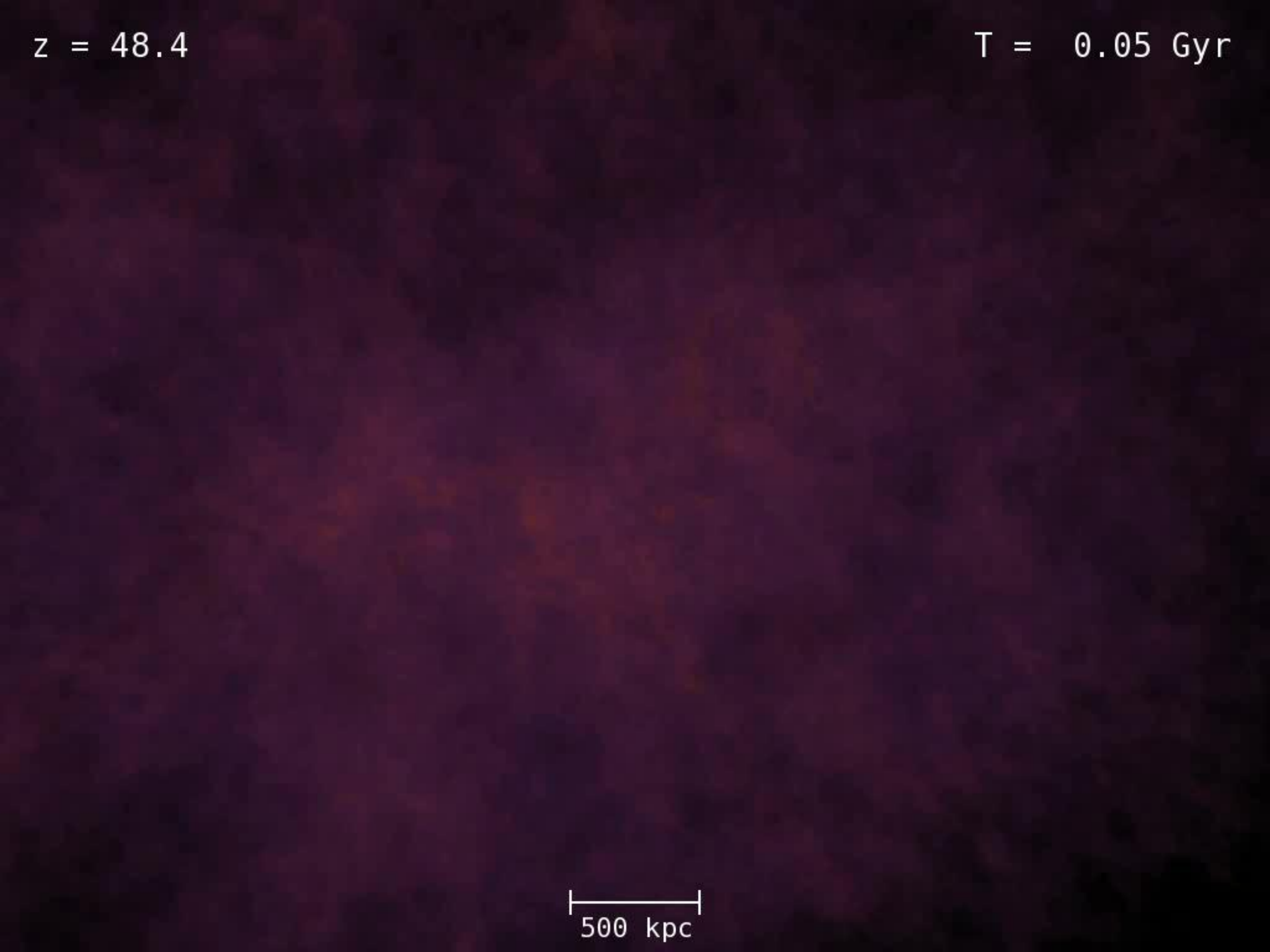
Cosmology on small – strongly non-linear – scales

→ key to the identity of the dark matter

cold dark matter

warm dark matter

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


z = 48.4
T = 0.05 Gyr
500 kpc

z = 48.73

cold dark matter

warm dark matter

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

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N-body simulations: CDM *vs* WDM

Simulations make 2 important predictions on galactic scales:

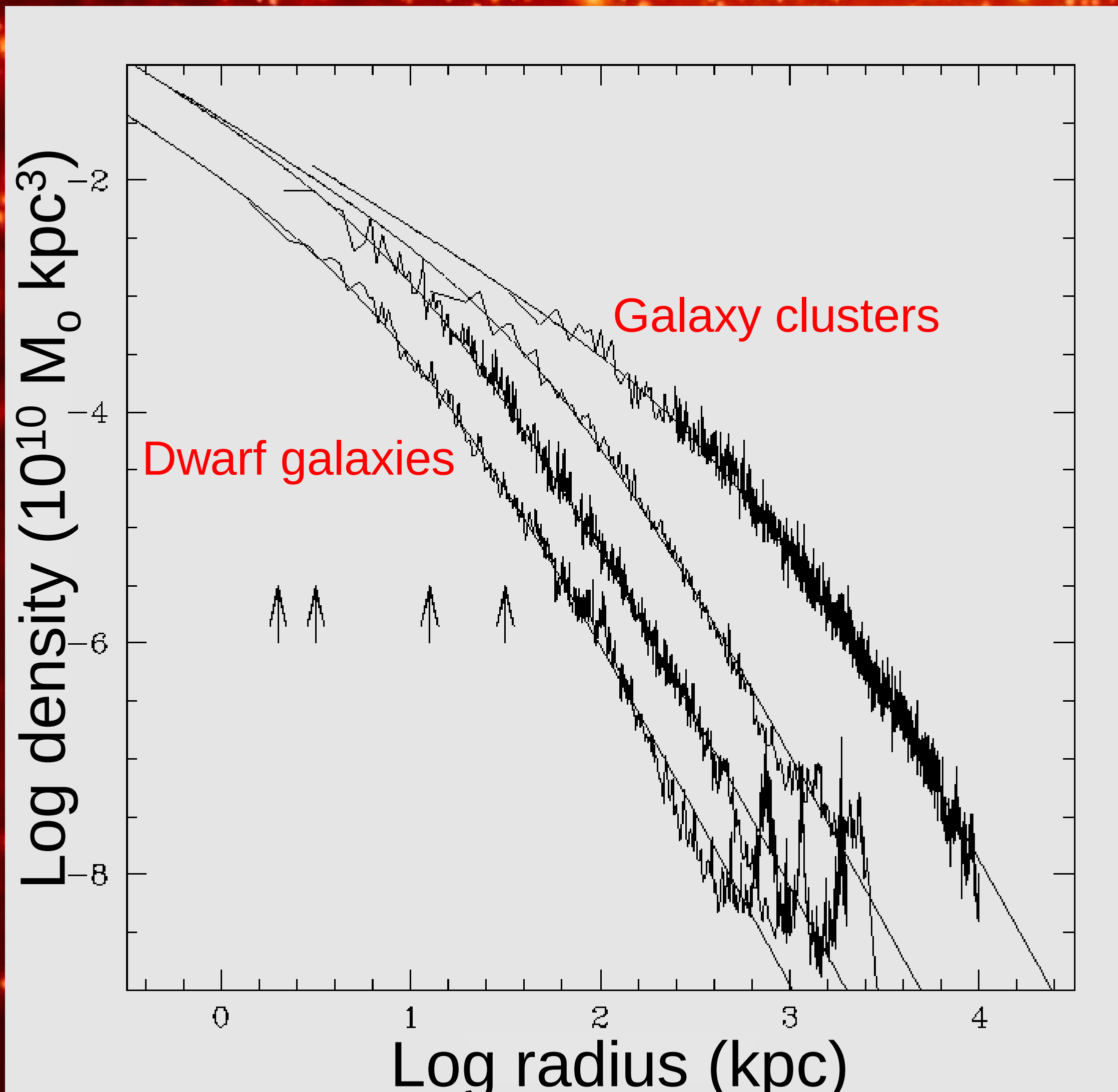
Cold dark matter

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

Warm dark matter

- Main halo profile identical to CDM; subhalos still "cuspy" but less concentrated than in CDM
- Far fewer self-bound substructures (3% of mass) survive

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

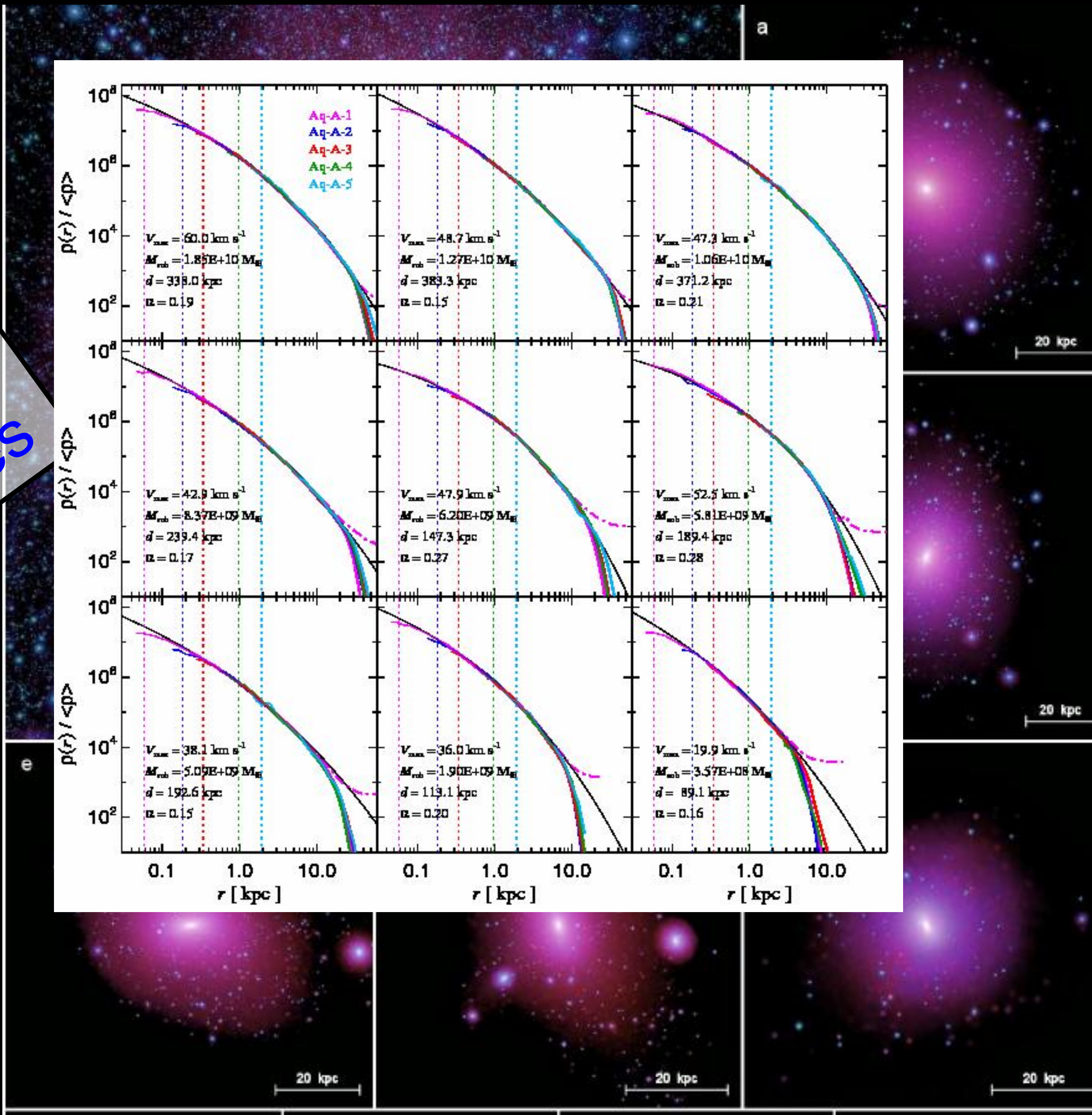
There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

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

Halos that form earlier have higher densities (bigger δ)

CDM subhalos also have cuspy profiles



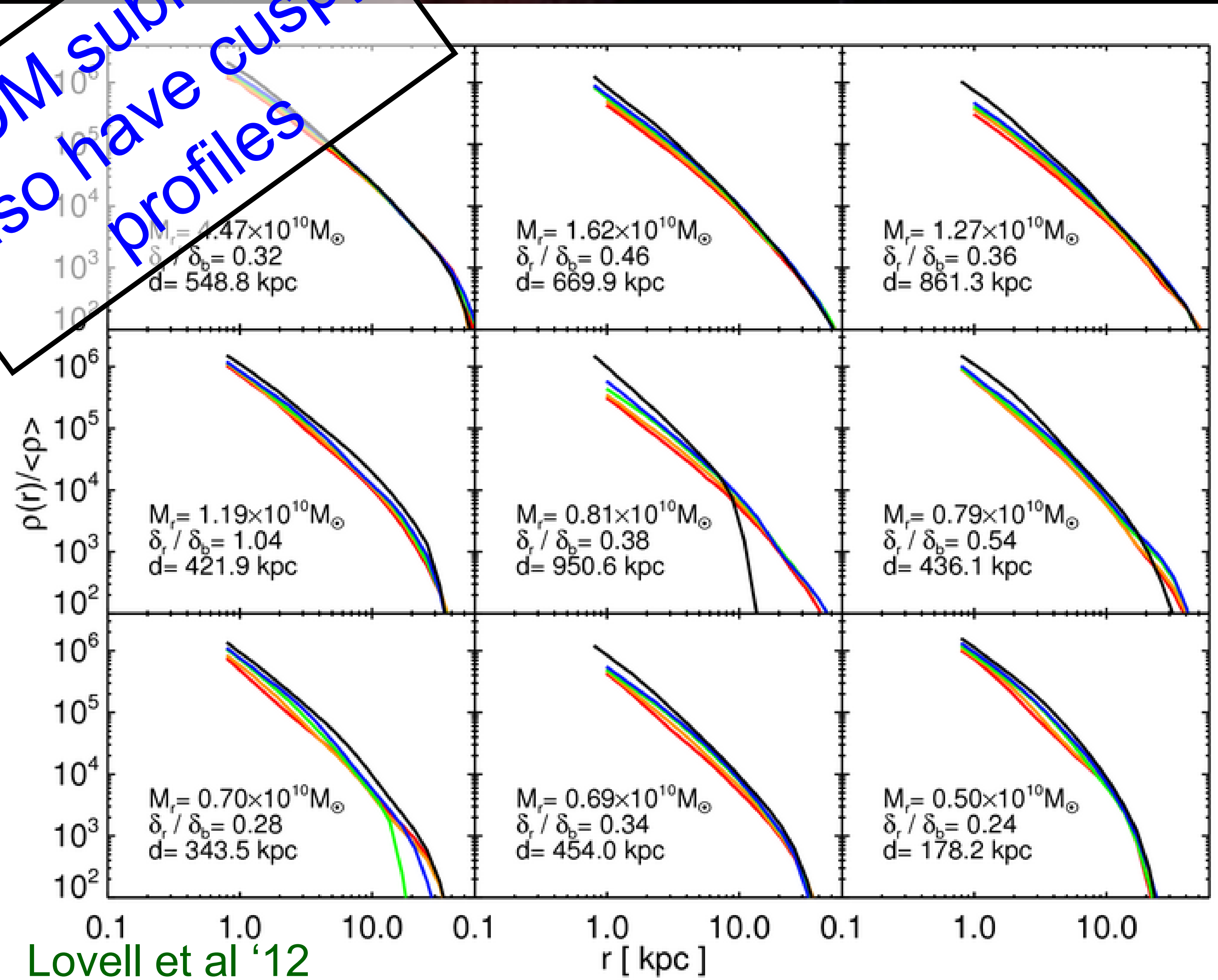
Aquarius

Springel et al ‘08

A warm dark matter universe

WDM subhalos also have cuspy profiles

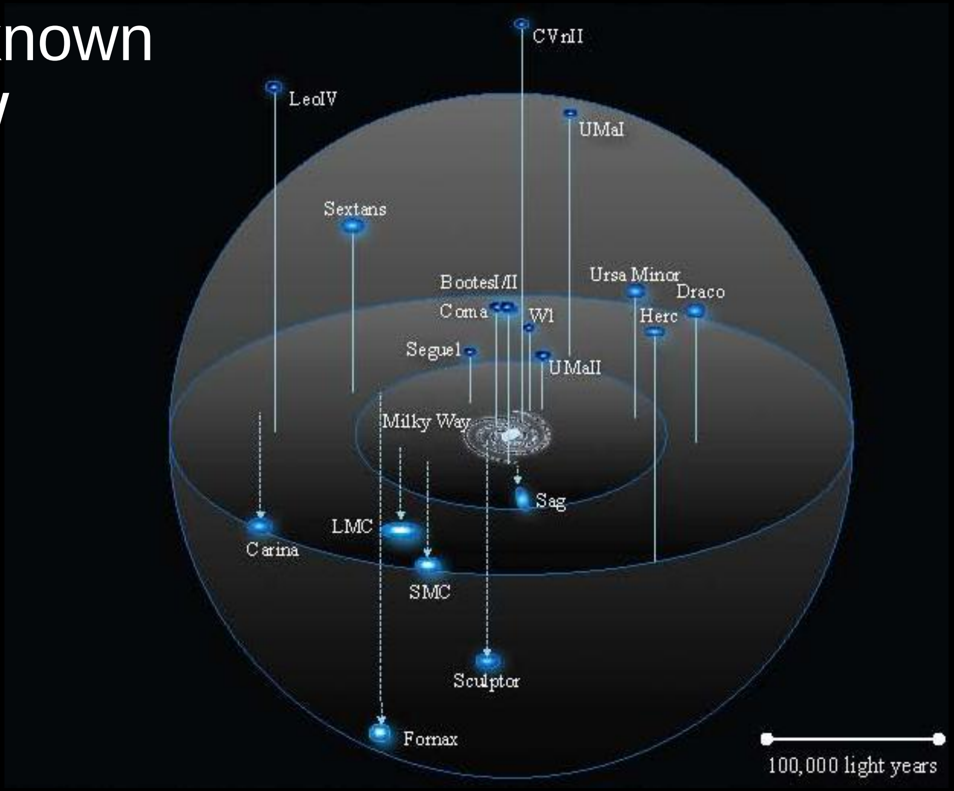
CDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV



Lovell et al ‘12

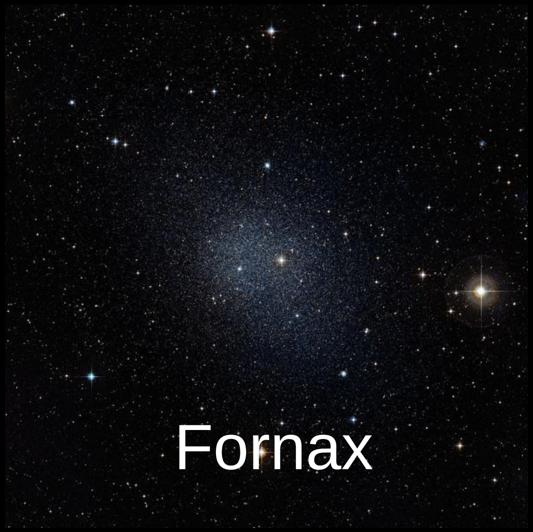
The satellites of the Milky Way

~25 satellites known
in the MW



J. Bullock

Dwarf galaxies around the Milky Way




Sextans

Carina


Sagittarius

Tests of the nature of the DM

Test 1: Do satellite subhalos have the predicted cuspy profiles?

The structure of dark matter halos

Dwarf sphs: cores or cusps?

Jeans eqn:

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

- stellar density profile → ρ_*
- radial velocity dispersion → σ_r^2
- from Aquarius sim → $M(r)$
- vel. anisotropy → β

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 '10

Dwarf sphs: cores or cusps?

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Jeans eqn:

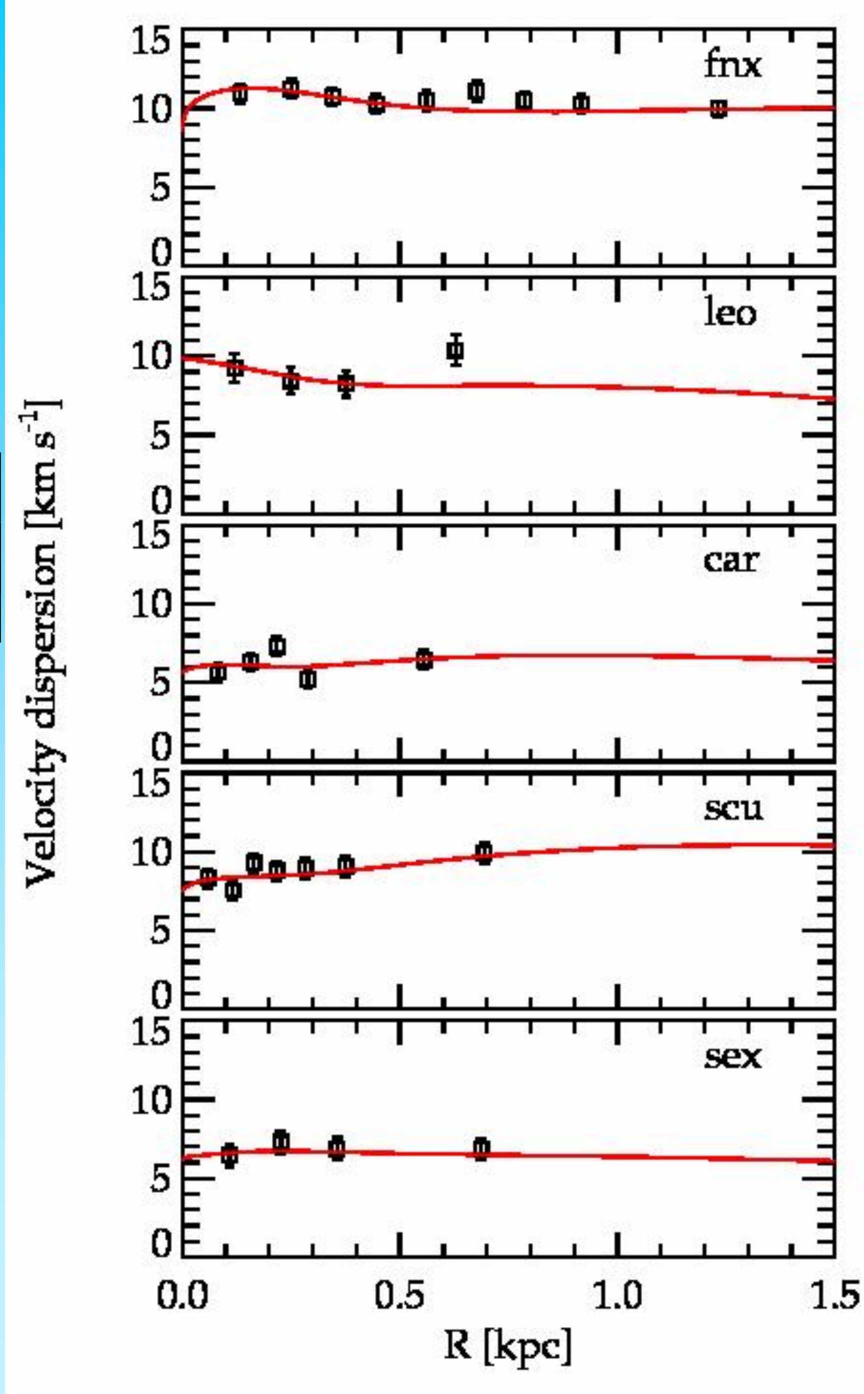
$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

vel. anisotropy

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

Strigari, Frenk & White 2010



Dwarf sphs: cores or cusps?

University of Durham

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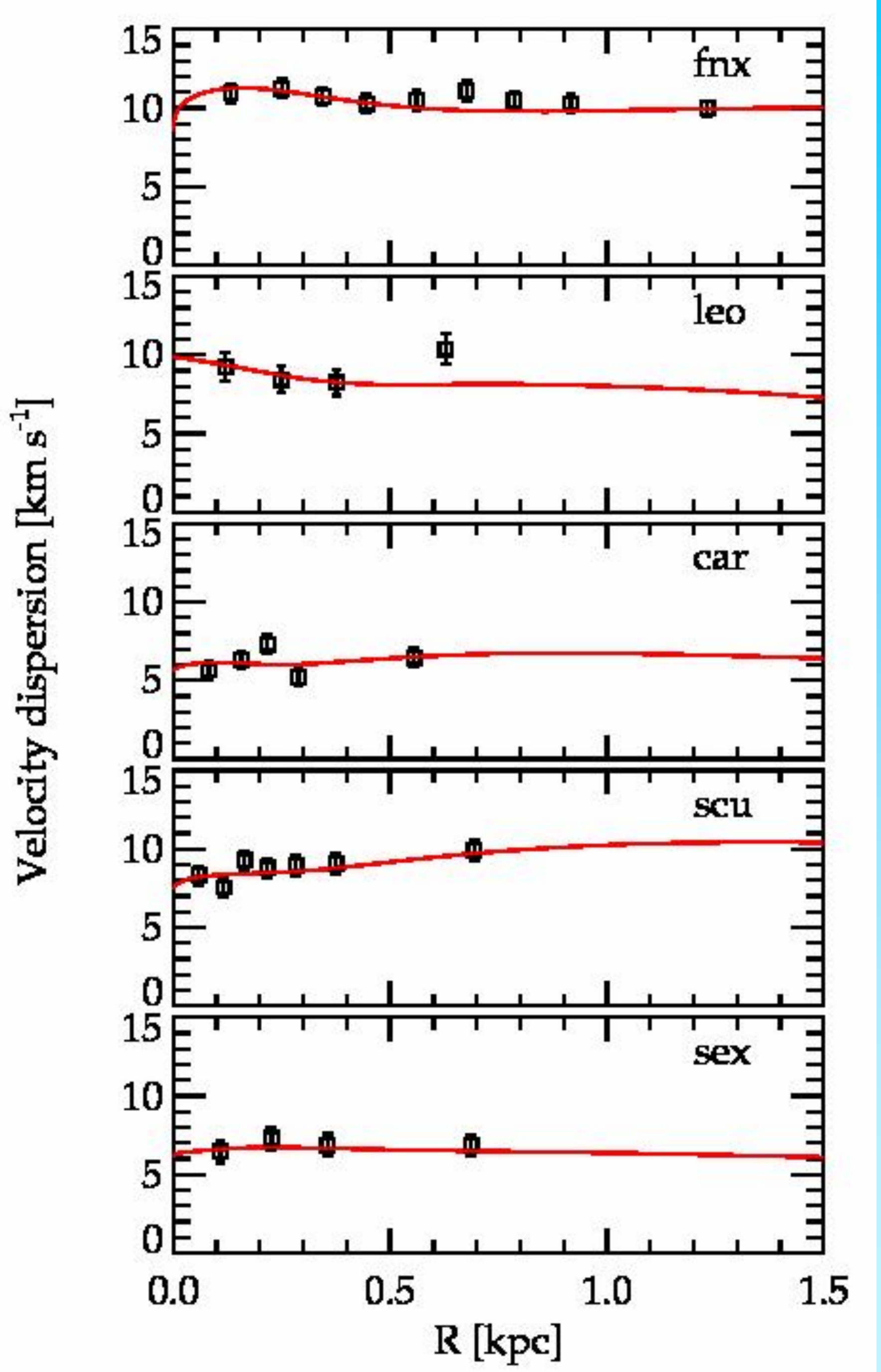
from Aquarius sim

vel. anisotropy

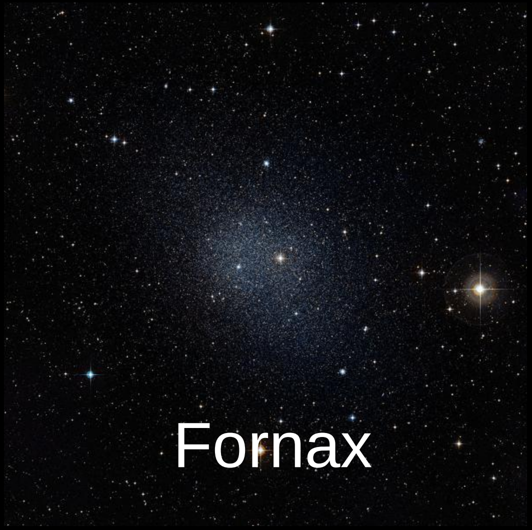
1-p= prob. that "best fit" can be rejected (β=0)

Satellite	1-p
Fornax	0.4
Leo I	0.5
Carina	0.4
Sculptor	0.8
Sextans	0.2

Strigari, Frenk & White 2010



Dwarf galaxies around the Milky Way



Sculptor

Sextans

Carina

Sagittarius

Cuspy NFW profiles consistent with MW satellite kinematic data

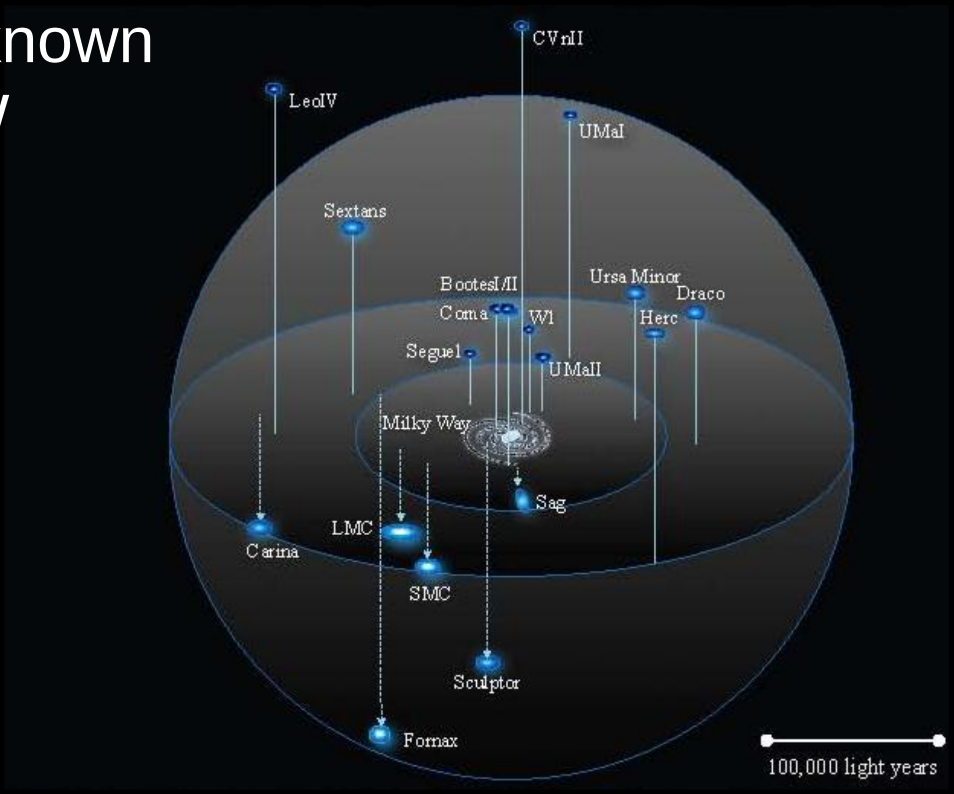
Tests of the nature of the DM

cold dark matter | warm dark matter

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

The satellites of the Milky Way

~25 satellites known
in the MW



Institute for Computational Cosmology

Spot the difference!

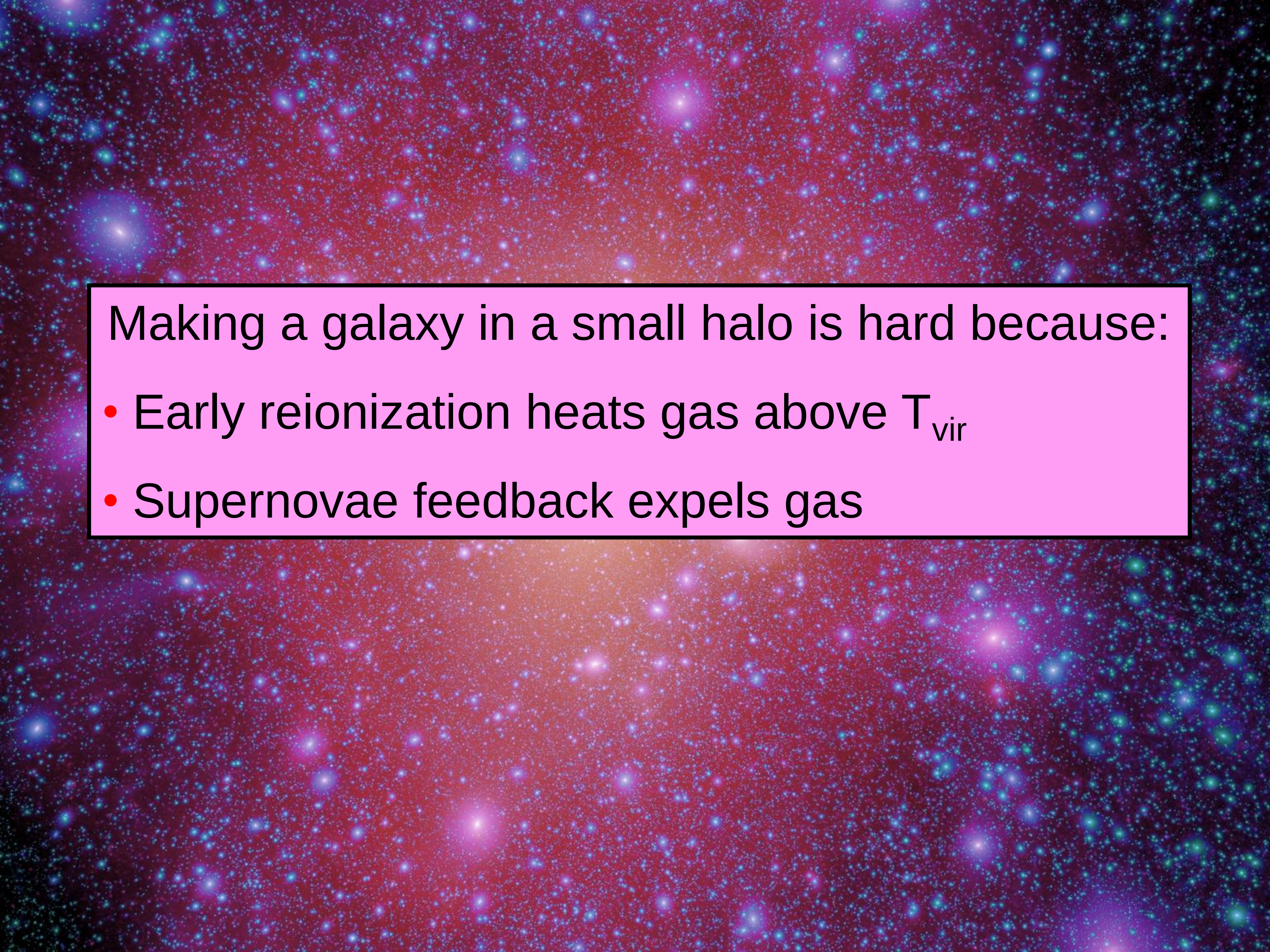
cold dark matter

warm dark matter

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

CDM simulations produce >10^5 subhalos

Most of these subhalos never manage to make a visible galaxy



Making a galaxy in a small halo is hard because:

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

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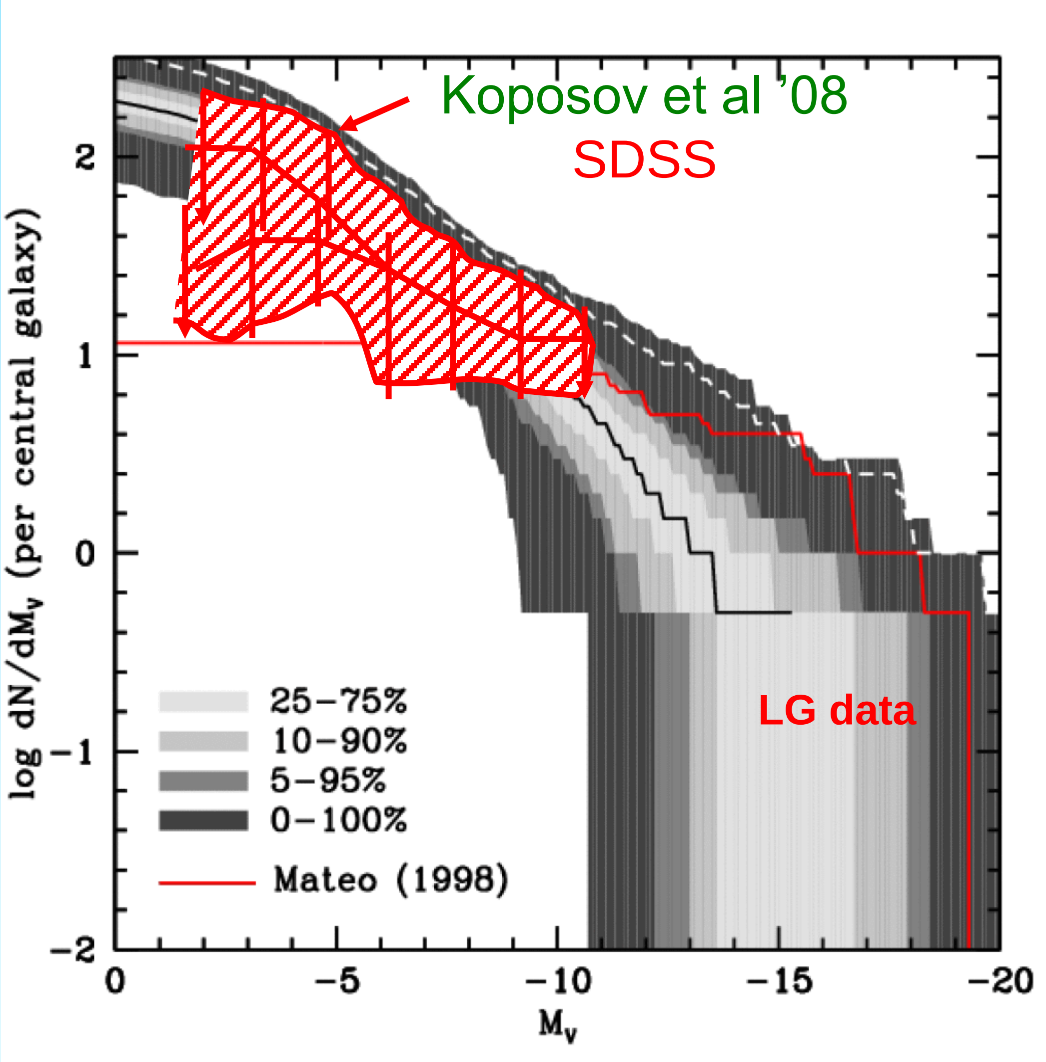
Luminosity Function of Local Group Satellites

- 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

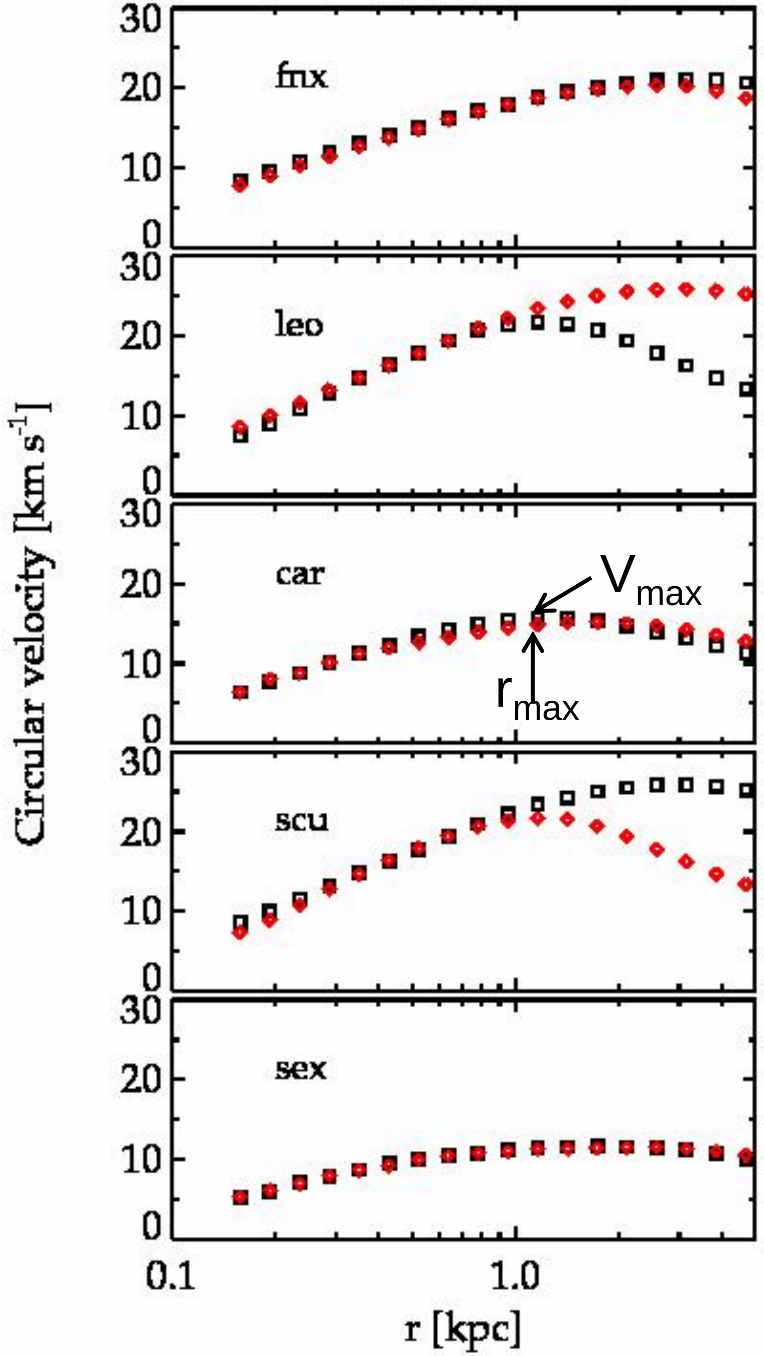
warm dark matter

Counting satellites cannot distinguish CDM from WDM!

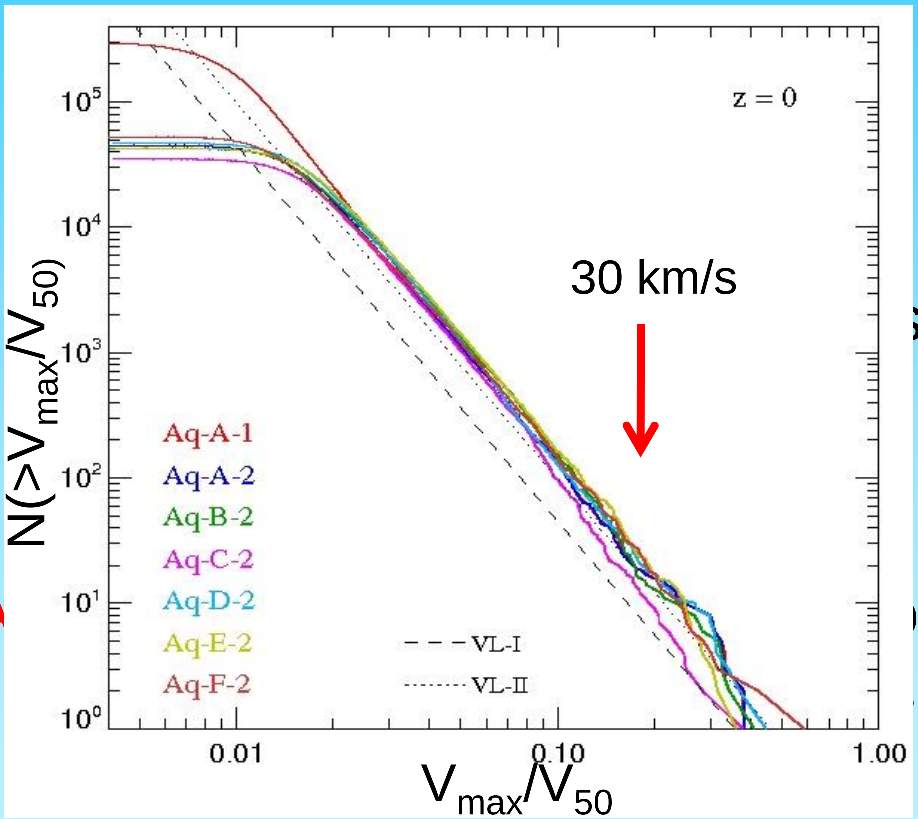
Need to look in more detail at the structure of small halos

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

Top 2 best fit CDM models to data

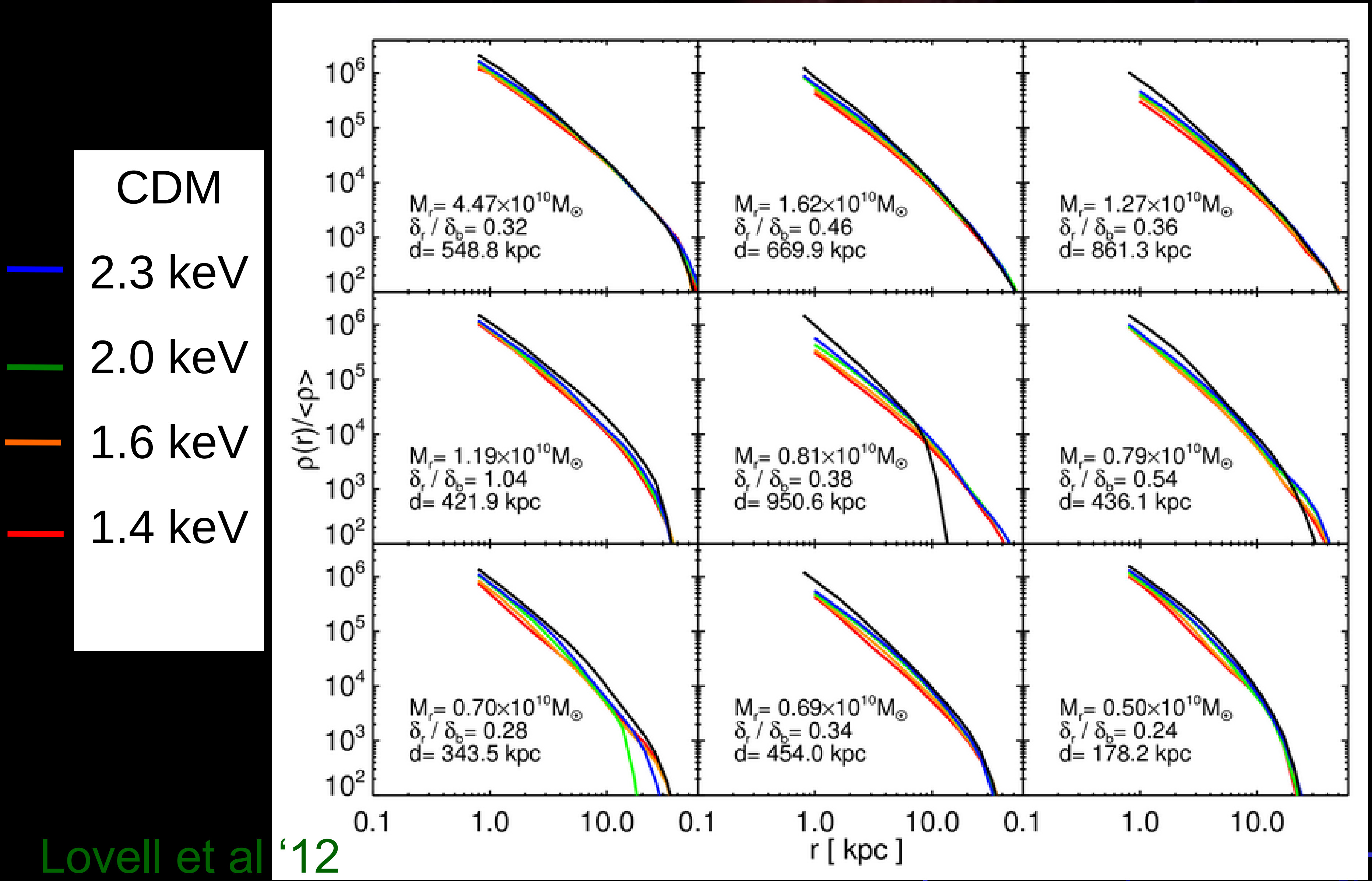


The Aquarius subhalos and the satellites of the Milky Way



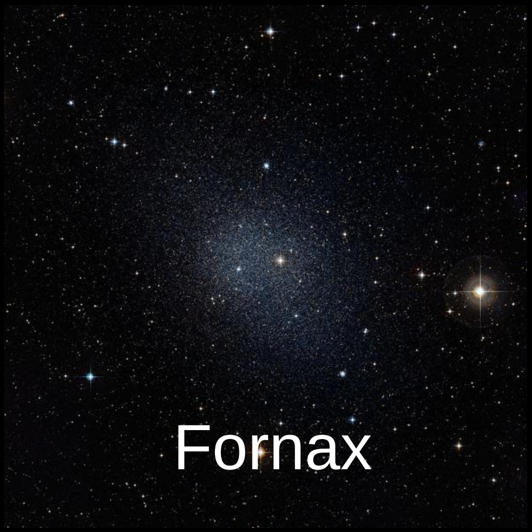
Strigari, Frenk & White 2010

A warm dark matter universe



Lovell et al '12

Dwarf galaxies around the Milky Way


Fornax


Sculptor

Leo I

Kinematical data → mass within half-light radius (Wolf, Walker)


Sextans

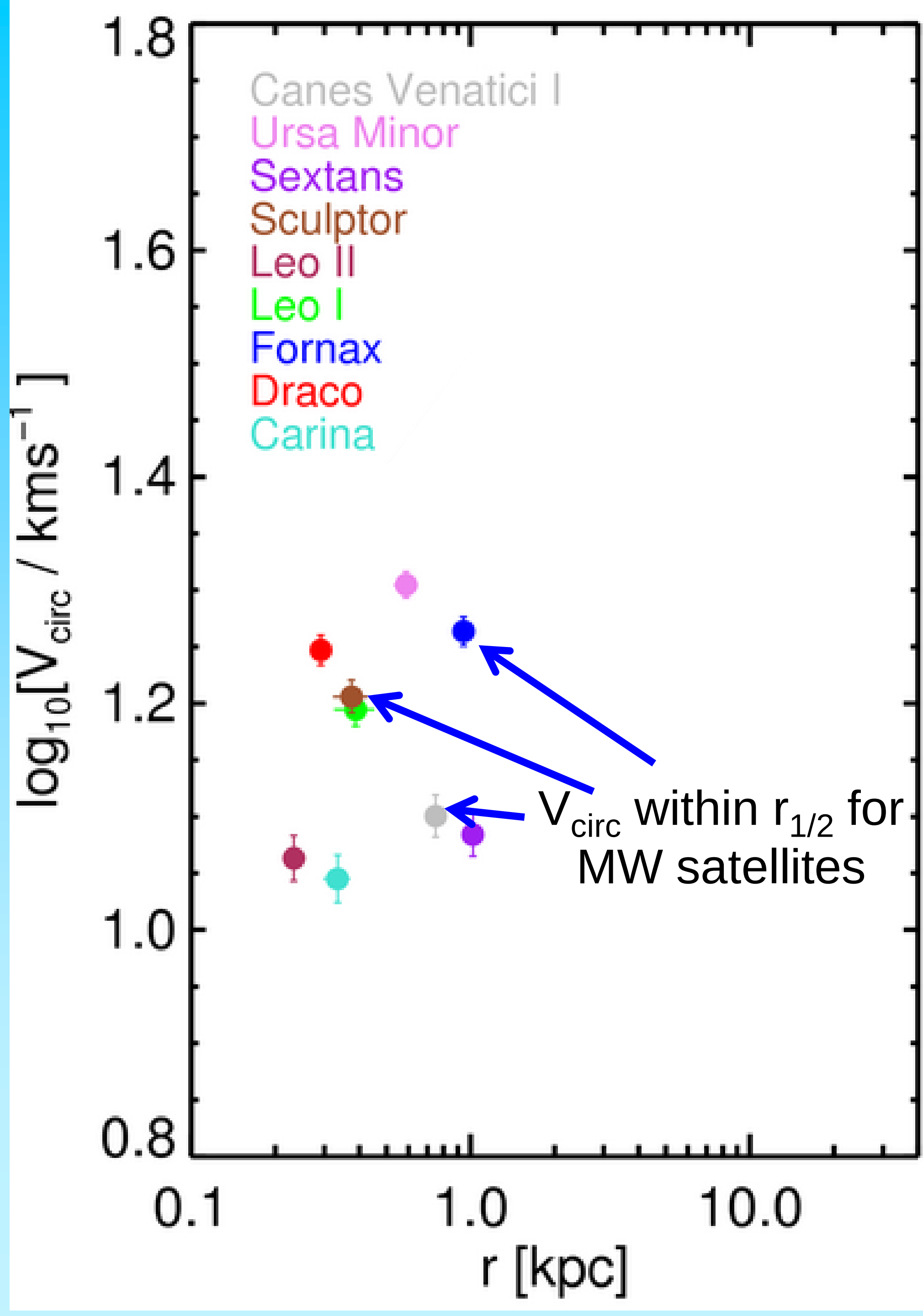

Carina


Sagittarius

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

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

Mass within half-light radius for 9 dwarf satellites of the Milky Way



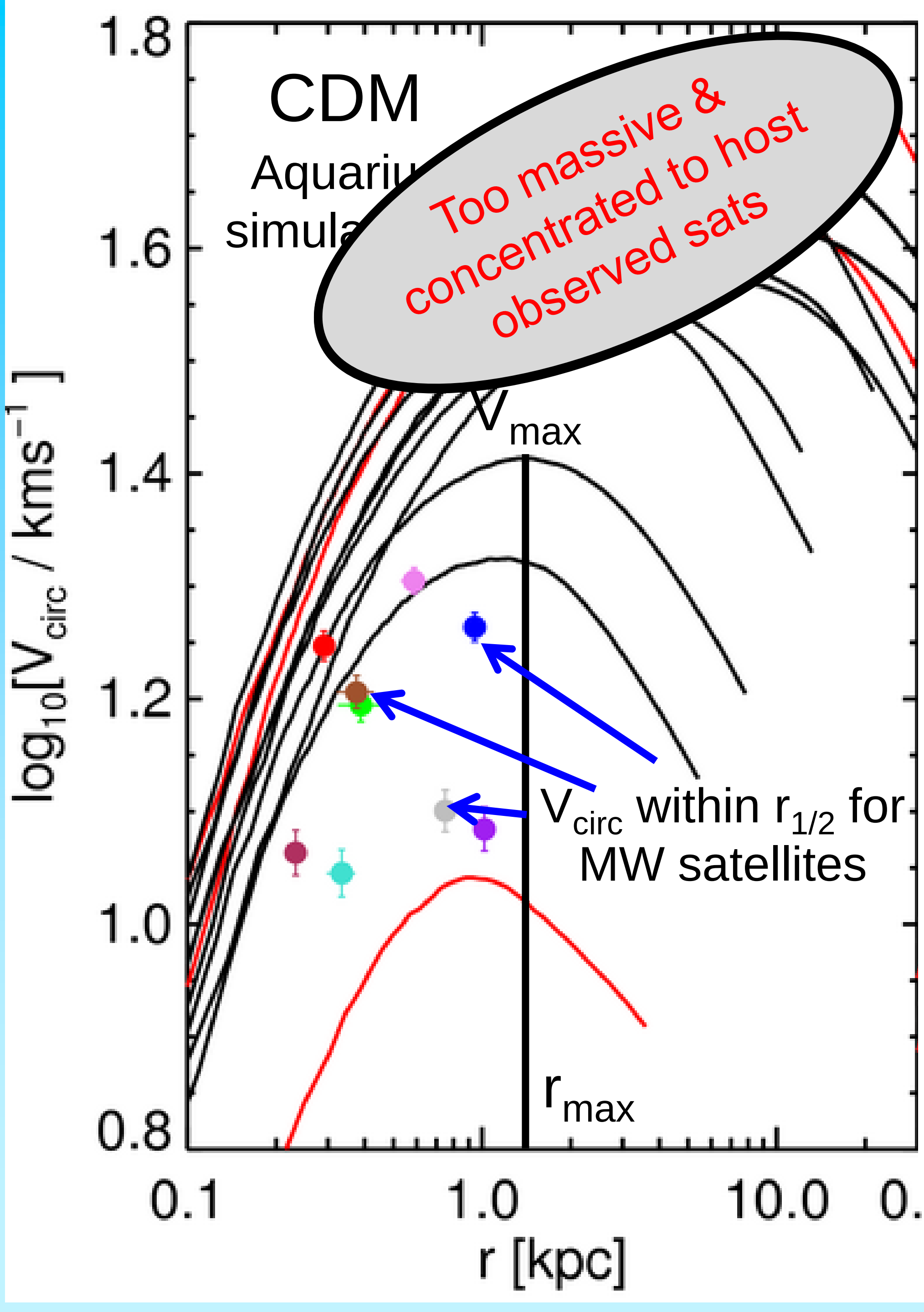
Is CDM compatible w. luminosity & structure of observed satellites?

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

Rotation curves of 12 subhalos with most massive progenitors

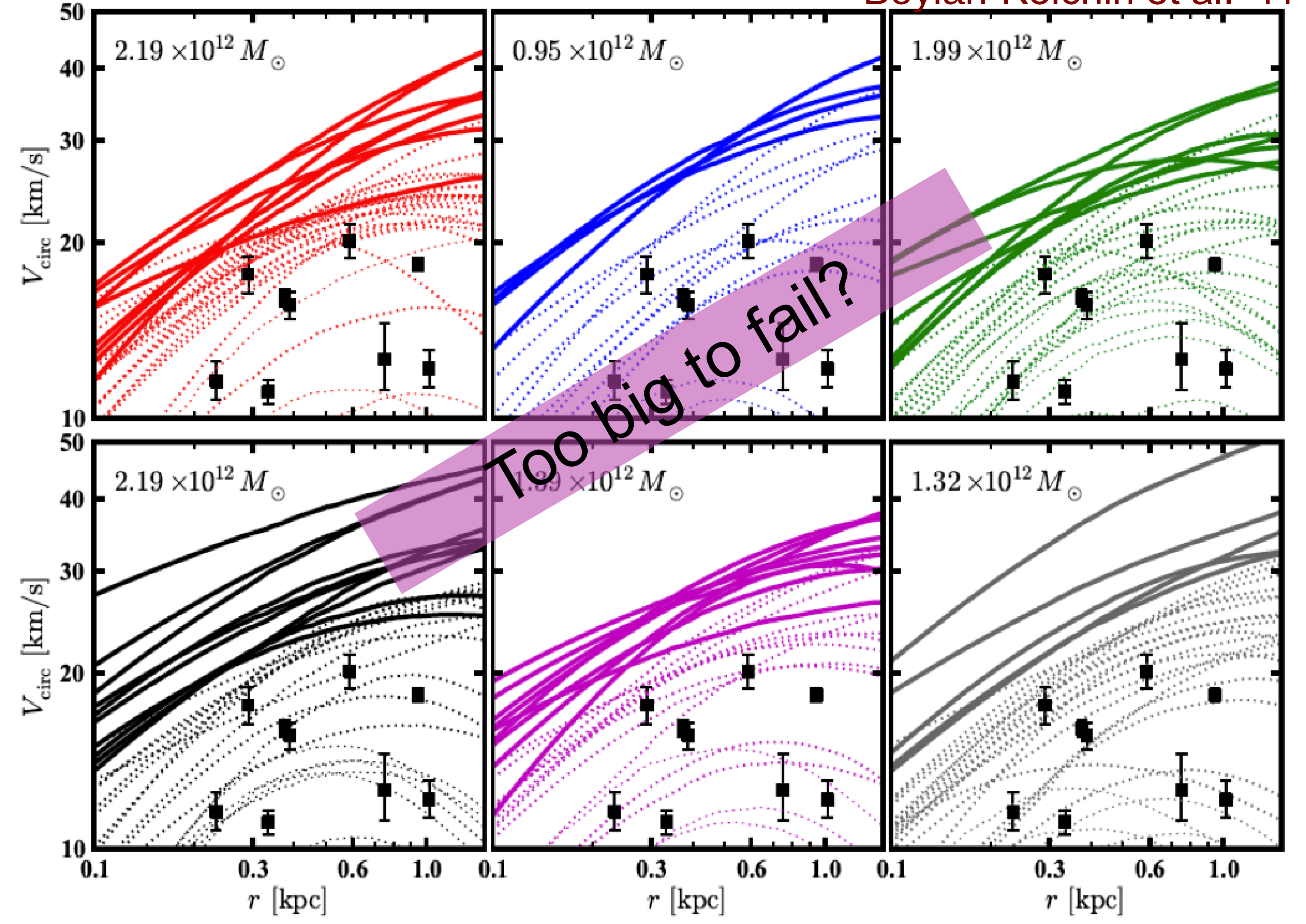
Red → 3 halos with most massive progenitors (LMC, SMC, Sagittarius?)

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

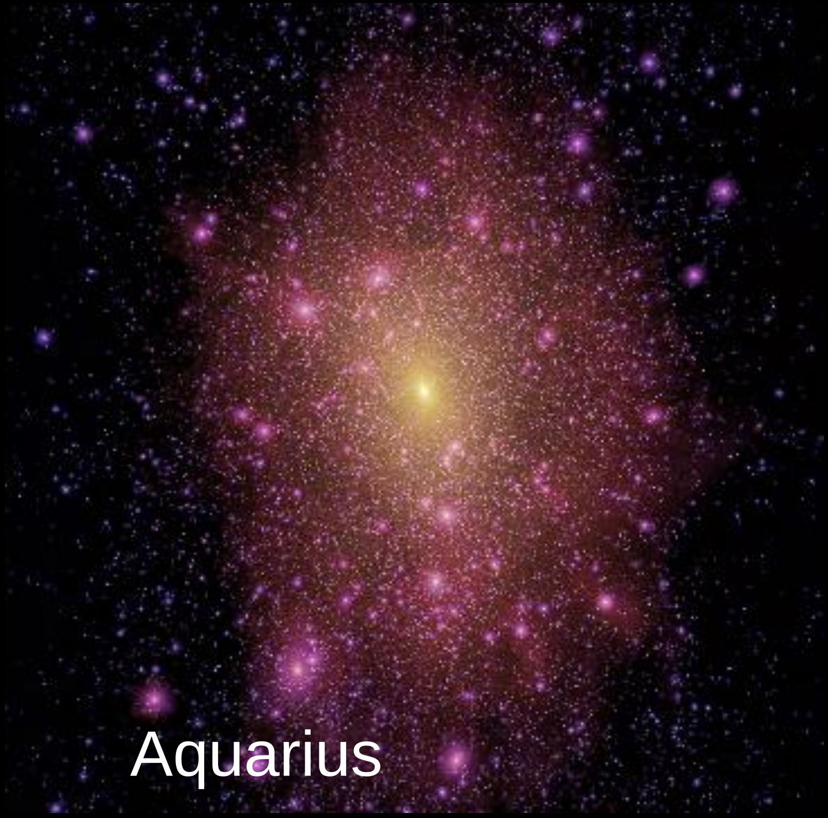


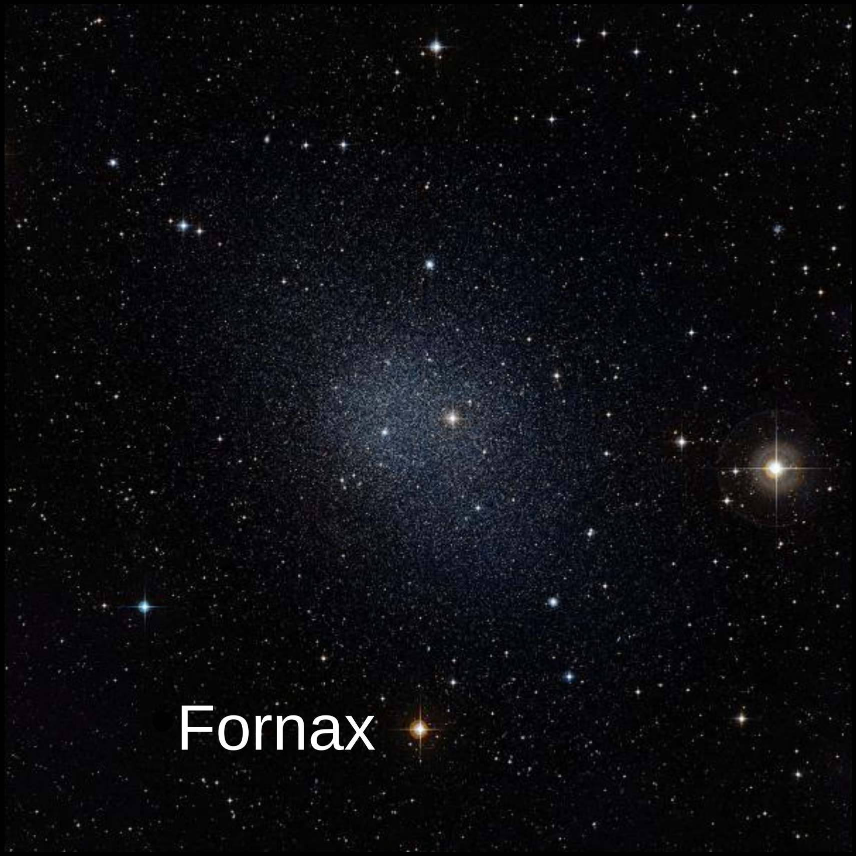
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11



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

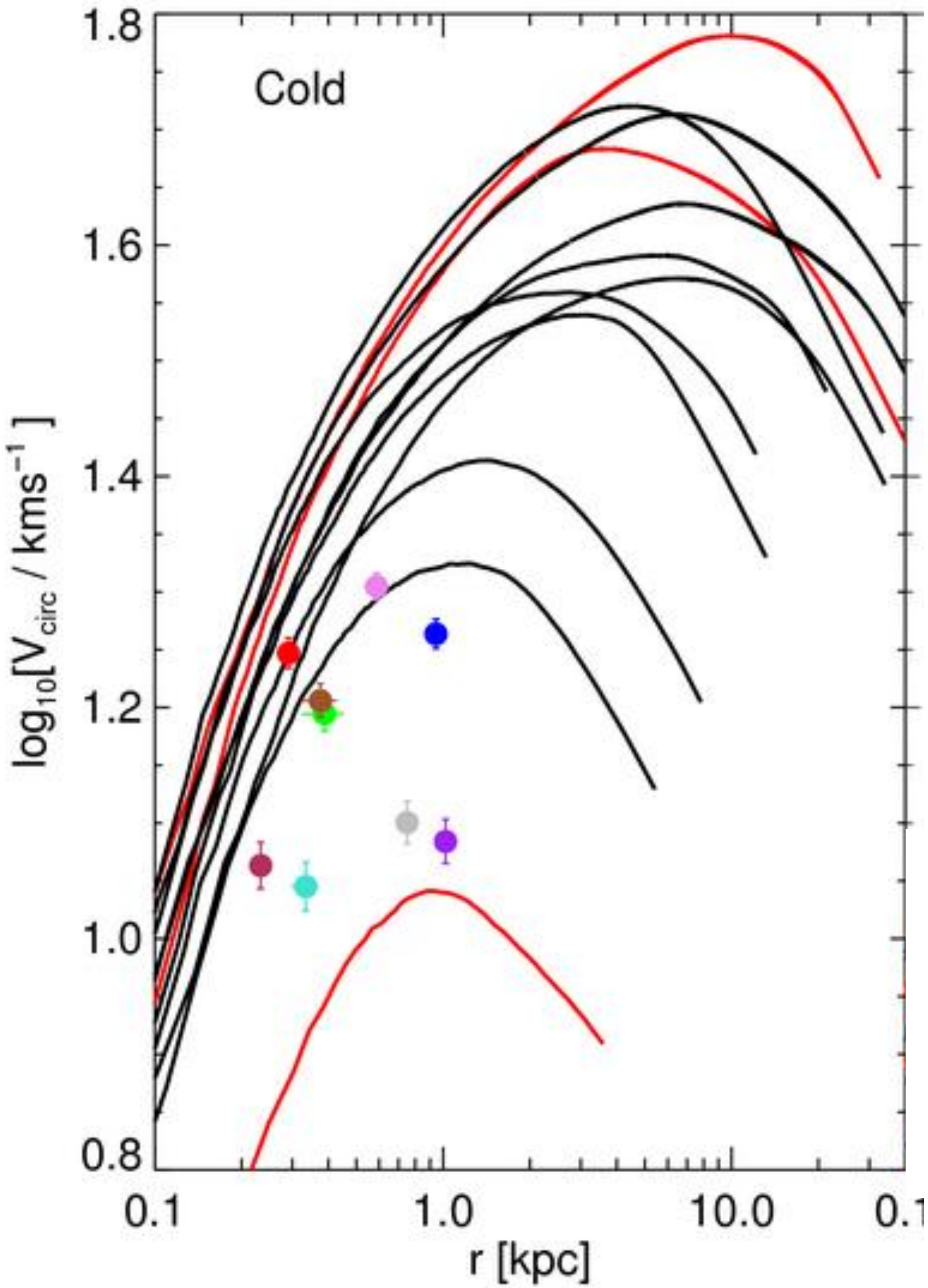




cold dark matter

warm dark matter

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



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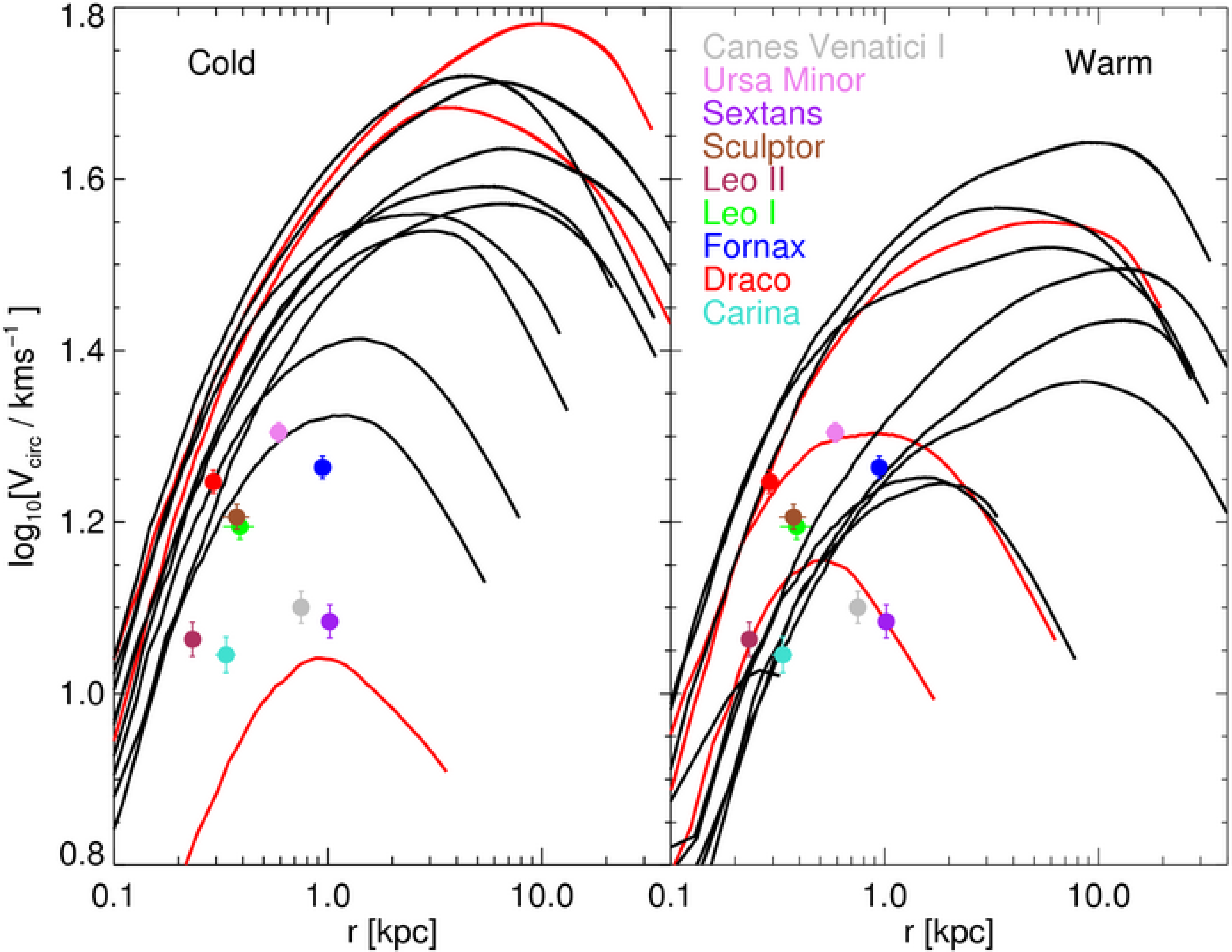

Cold
Warm
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
$\log_{10}[V_{circ}$ / kms^{-1}]
r [kpc]
1.8
1.6
1.4
1.2
1.0
0.8
0.1
1.0
10.0

ICC

Is this the end of CDM?

1. Baryon effects
2. The mass of the MW

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

The cores of dwarf galaxy haloes

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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.

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Baryon effects in the MW satellites

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

The cores of dwarf galaxy haloes L75

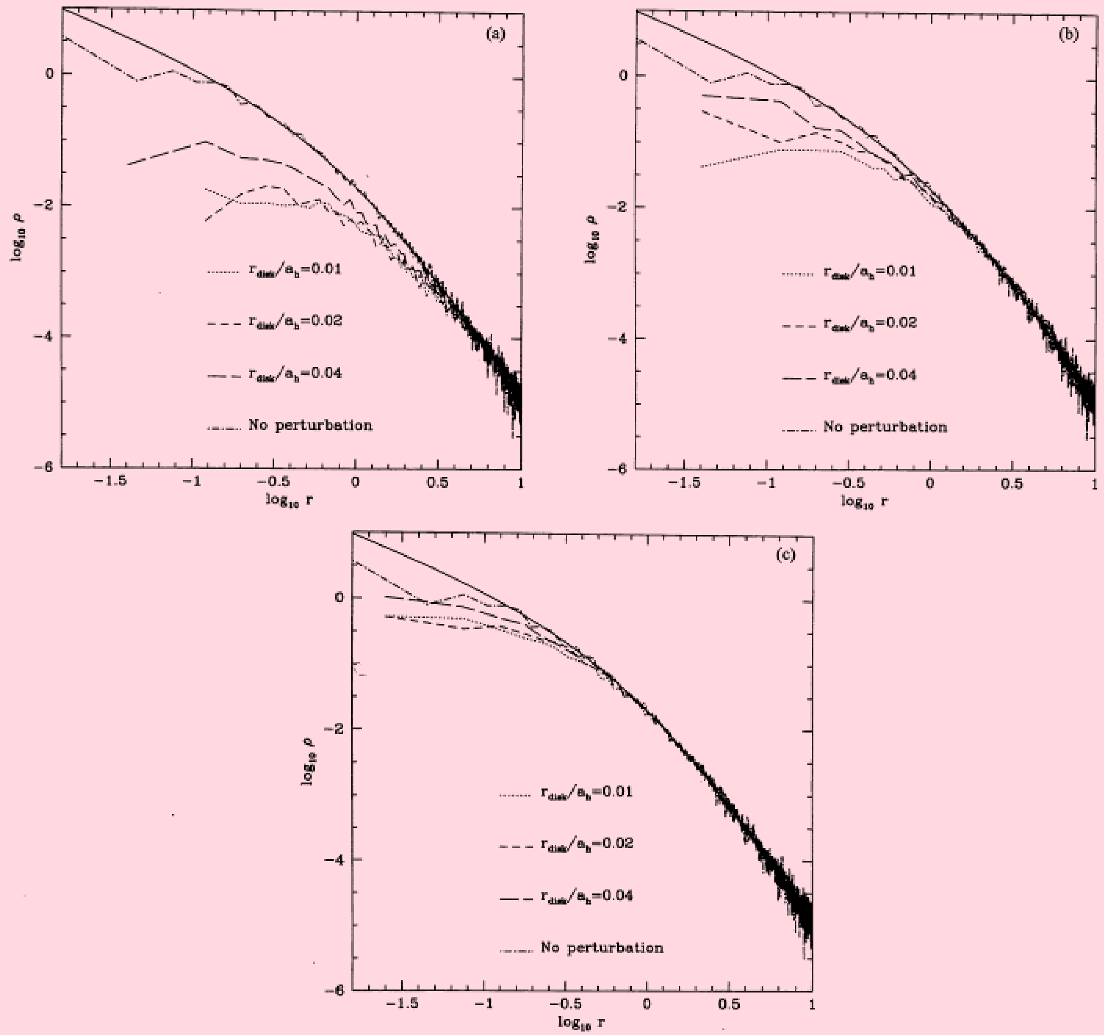
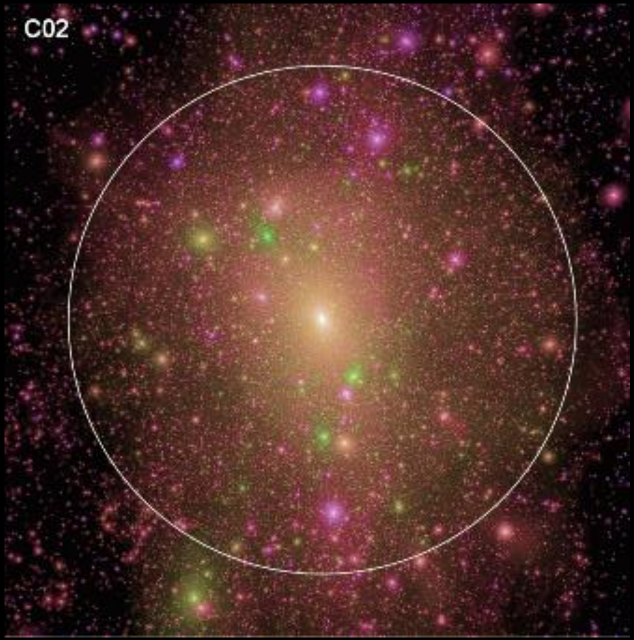


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

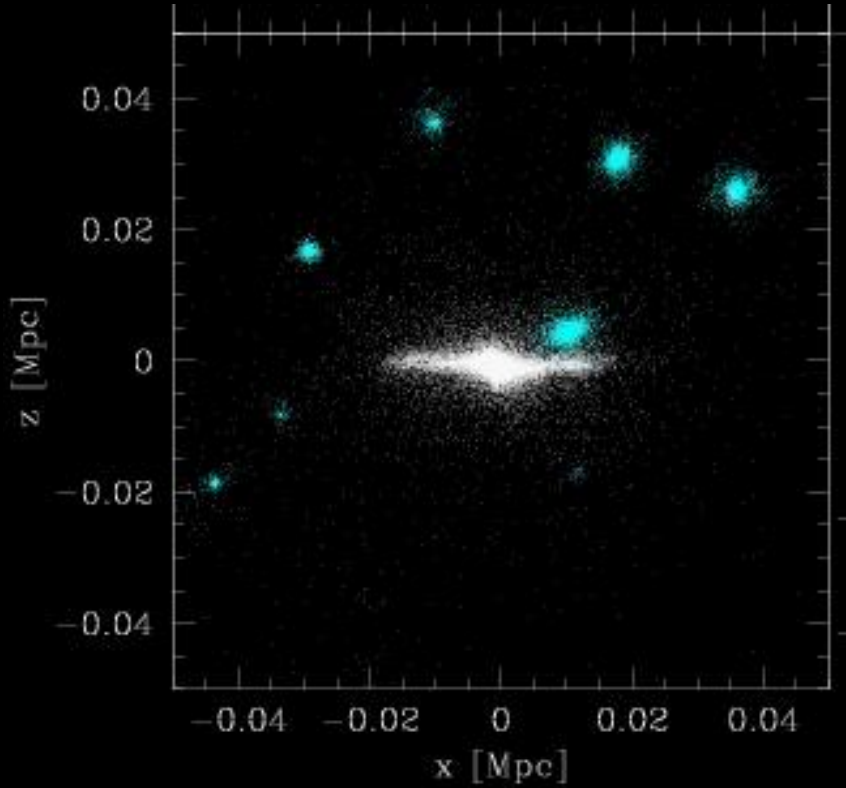
Pontzen & Governato '12

Brooke et al. '12

The satellites of the Milky Way

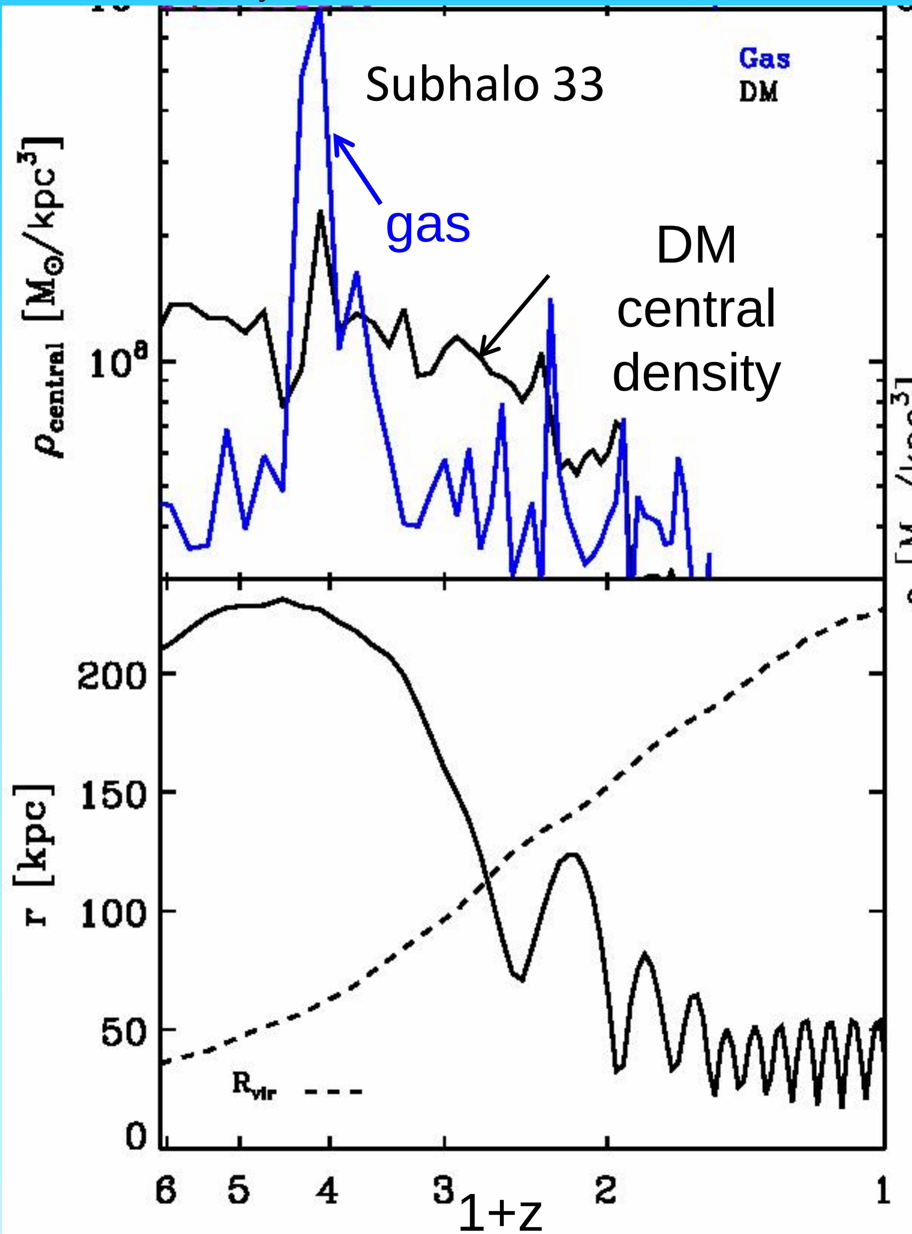


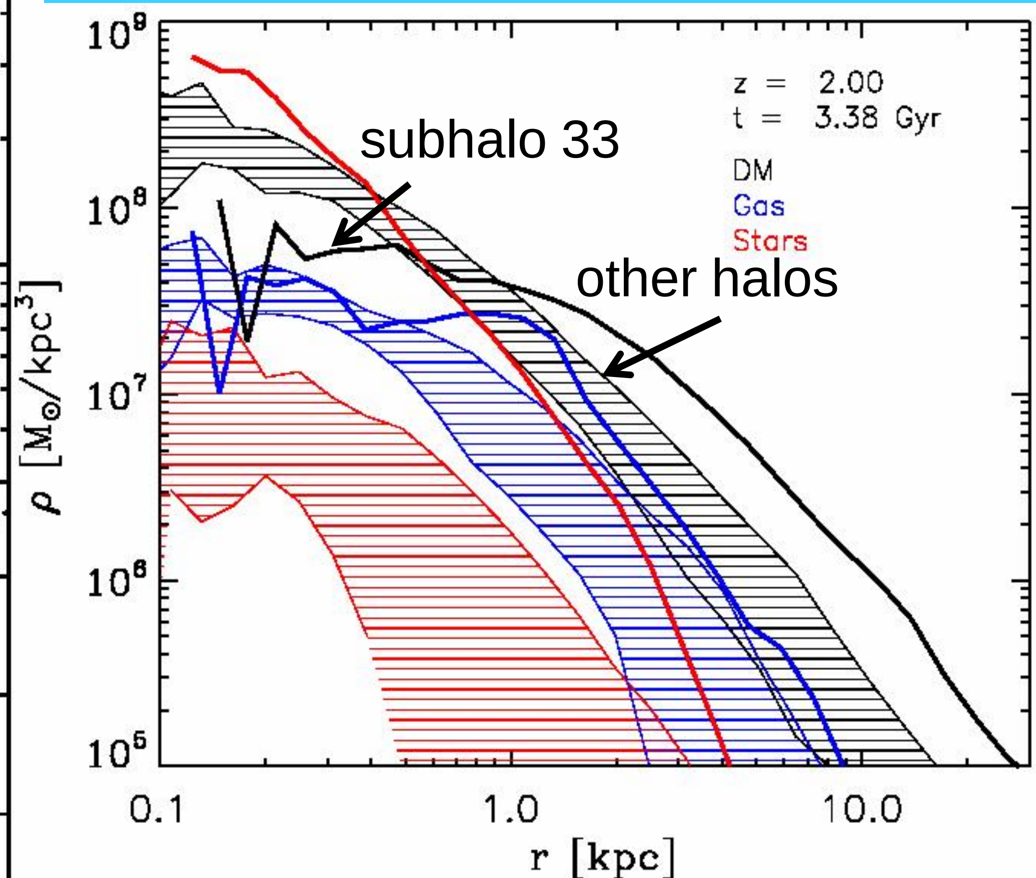
SPH simulations of galaxy formation in one of the Aquarius halos



Parry, Eke, Frenk & Okamoto '11

Baryon effects in the MW satellites





Parry, Eke & Frenk '11

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Is this the end of CDM?

1. Baryon effects → could reduce central concentration of CDM subhalos

2. The mass of the MW

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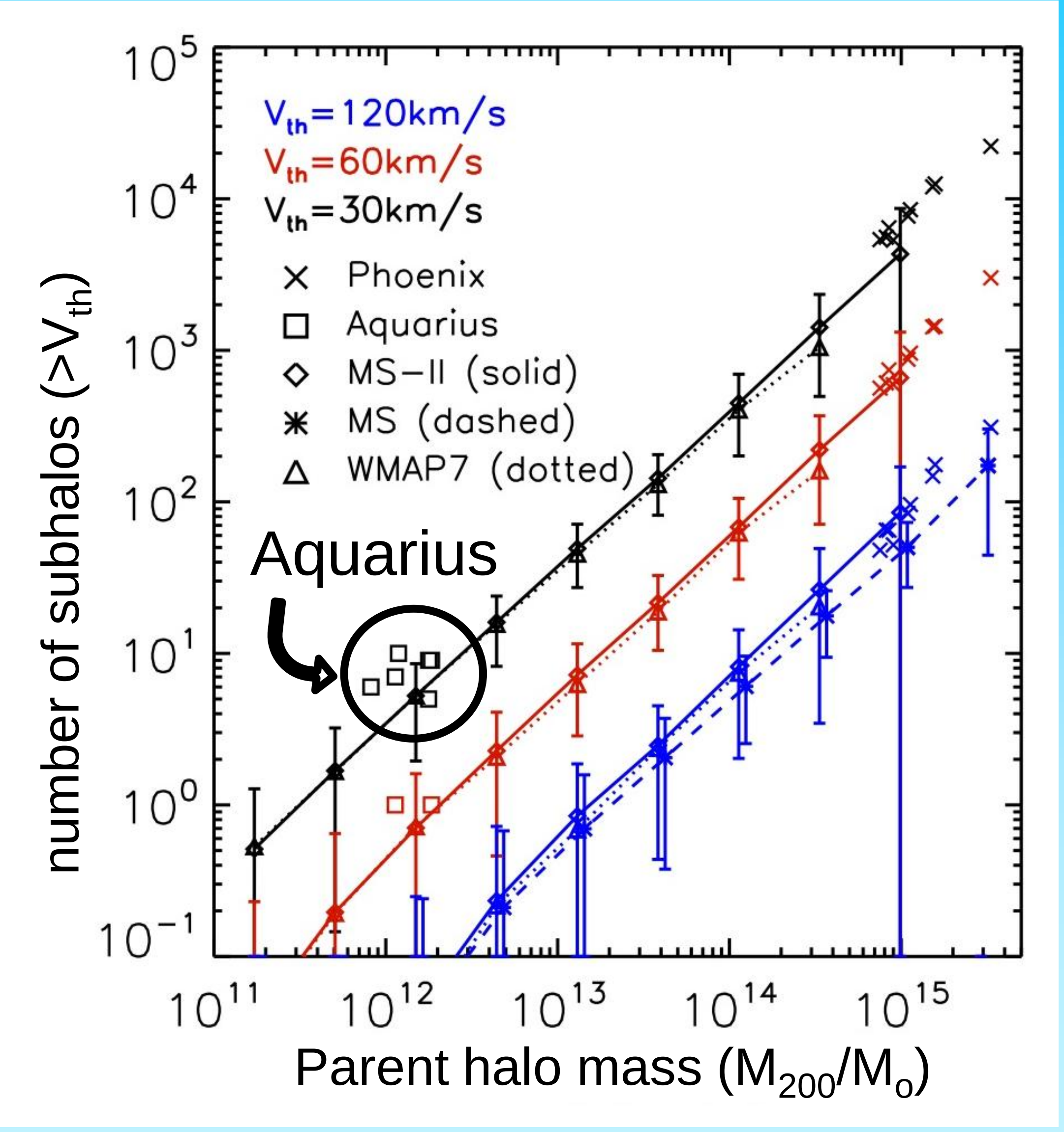
Number of massive subhalos

Number of massive subhalos increases rapidly with halo mass



Aquarius halos have $M \sim 2 \times 10^{12}\, M_o$

But: is this the mass of the MW halo?

Probability of massive subhalos

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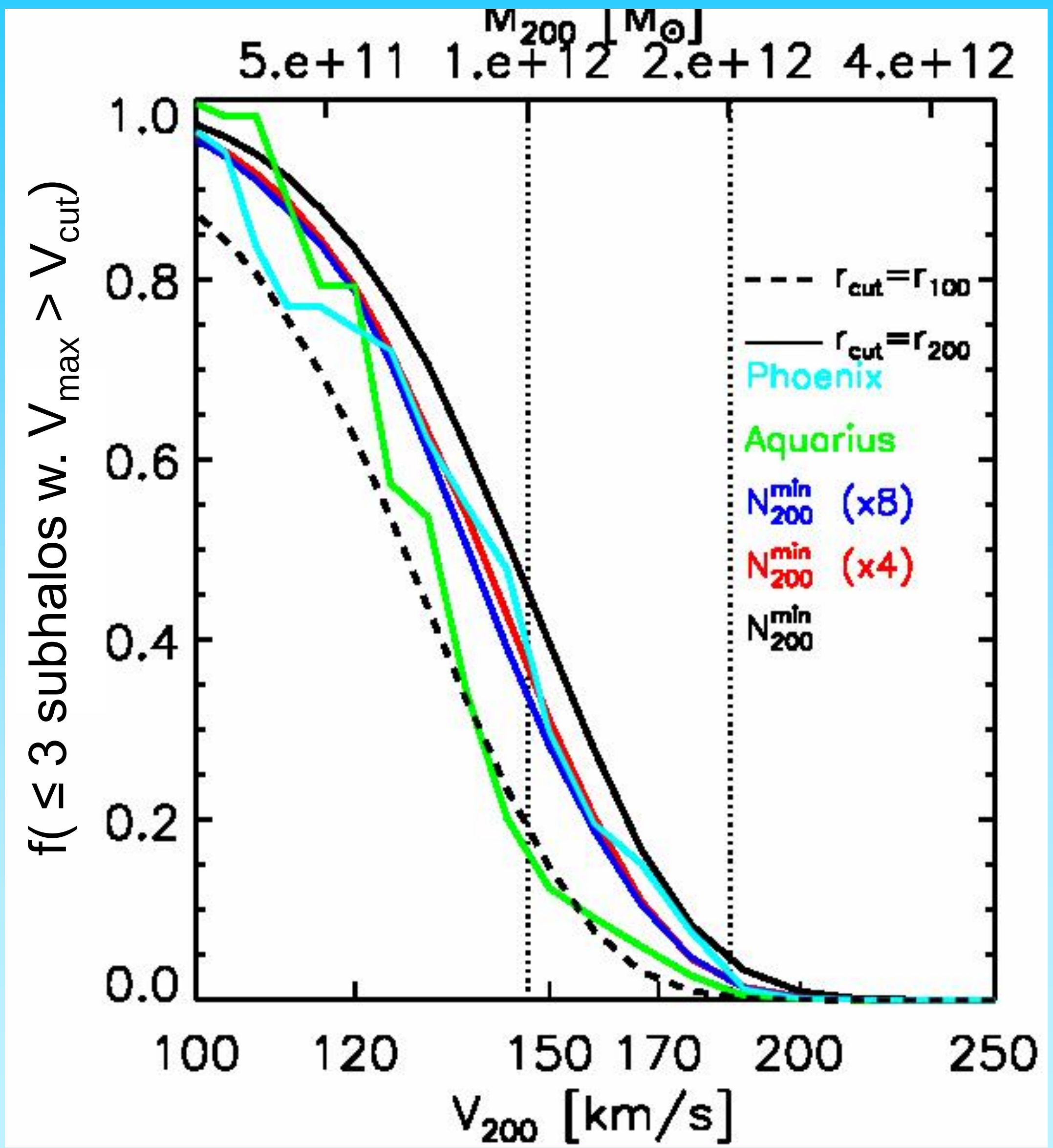
Probability of having no more than 3 subhalos with V_{max}> 30 km/s



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

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

If mass of MW $\sim1x10^{12}M_o$, CDM is 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?

NOT a problem:

The satellite LF → can be explained by galaxy formation

However:

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

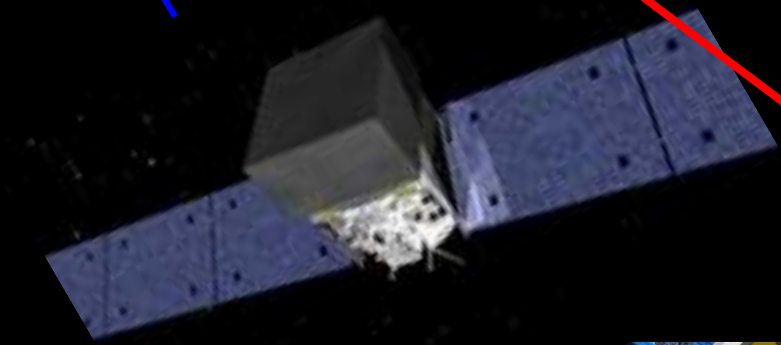
Possible solutions:

- Warm dark matter
- Baryon effects that make large CDM subhalos less concentrated
- $M_{MW-halo} \leq 10^{12} M_o$ rather than $2 \times 10^{12} M_o$

Cold dark matter ?

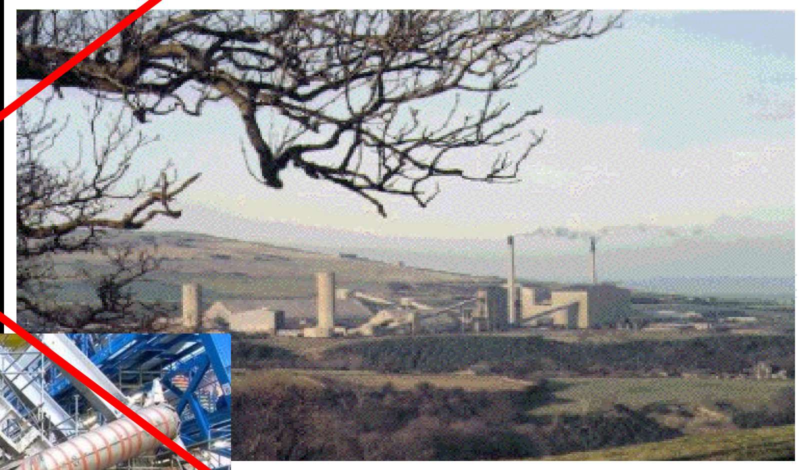
If mass of MW halo >$2\times10^{12}M_o$

Fermi

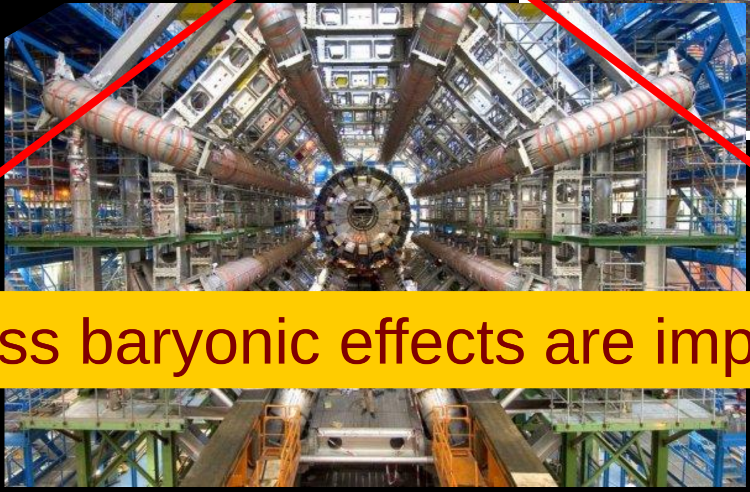


Annihilation radiation

Direct detection



UK DM search
(Boulby mine)



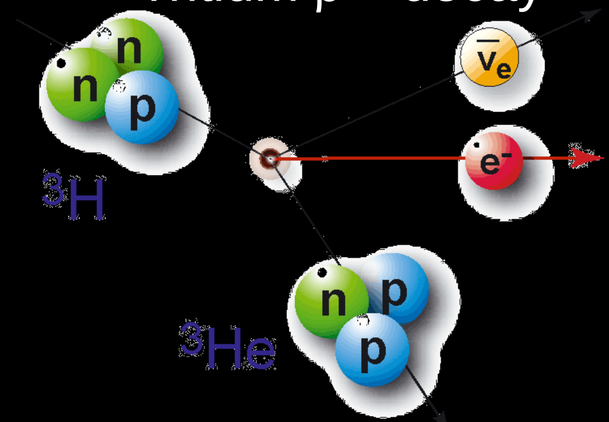
Unless baryonic effects are important

Evidence for SUSY

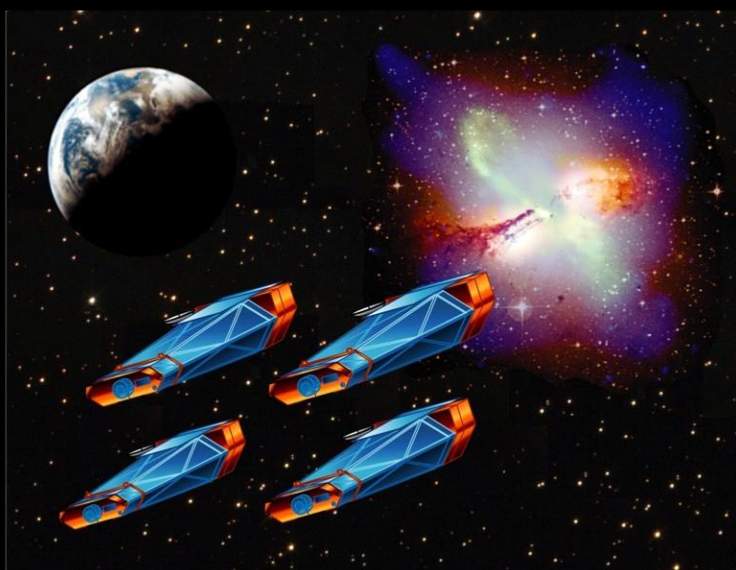
Warm dark matter ?

Sterile neutrino detection possible

Tritium β - decay



Decay line in X-rays



Constellation X

cold dark matter

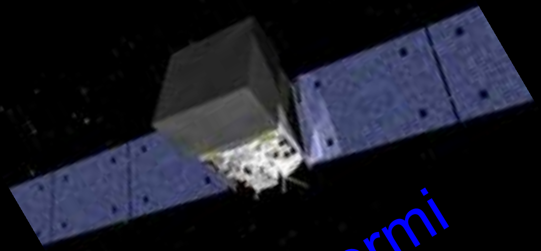
warm dark matter

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

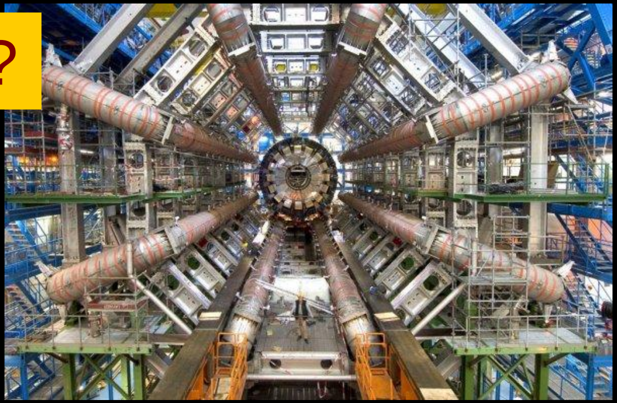
Cold dark matter ?

Theory predicts: dark matter is a particle, probably a SUSY particle

Dark matter discovery?



Fermi



LHC – will it make it?

UK DM search
(Boulby mine)