Dark matter simulations

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Dark matter annihilation in galaxy clusters

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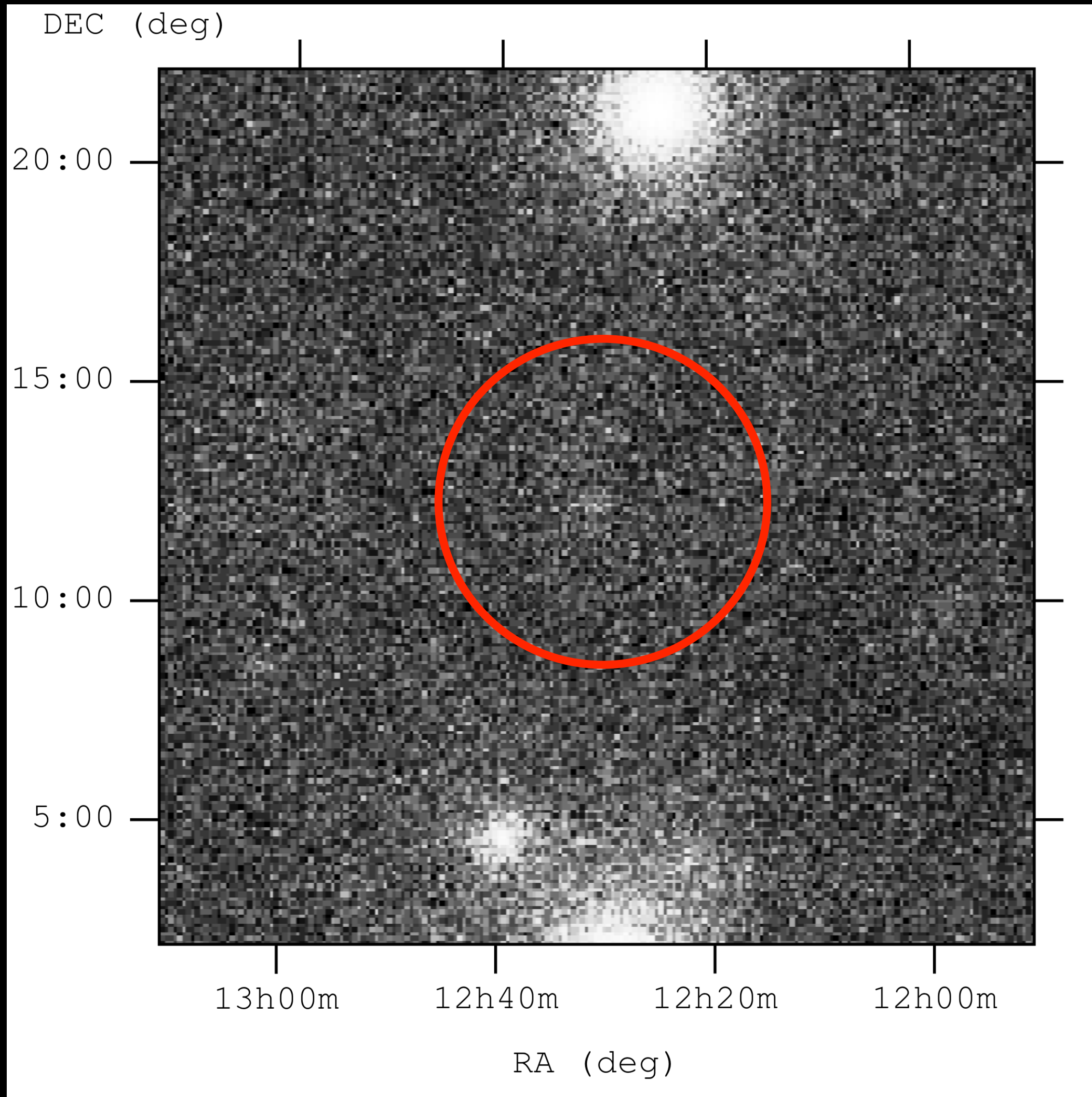
The Virgo cluster in Fermi

Fermi-LAT image

100MeV – 100 GeV

2-year data

(Also Coma and Fornax)



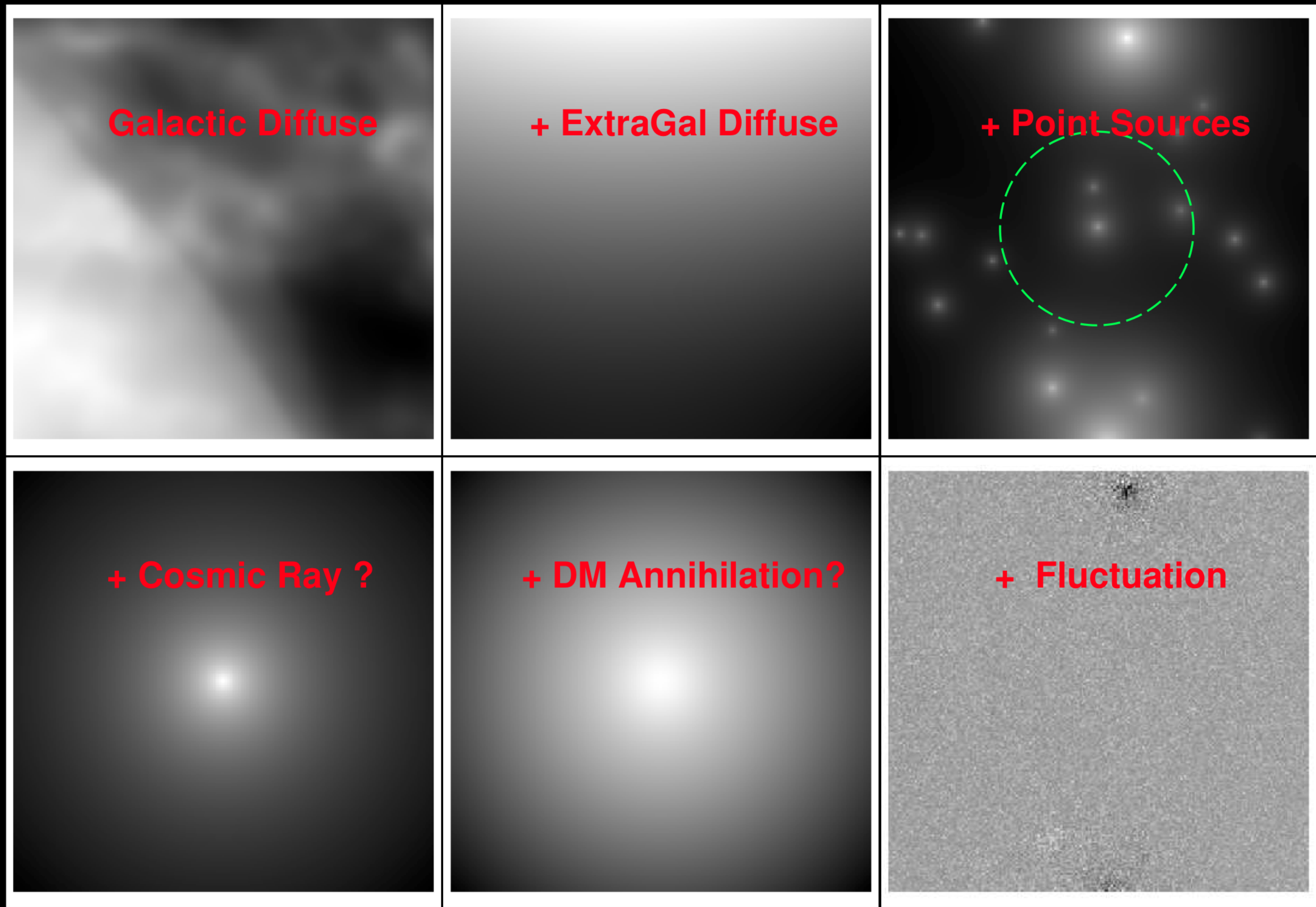
Han, Frenk, Eke, Gao, White arXiv:1201.1003

Modelling γ-ray emission in clusters

Virgo best-fit model

Diffuse bckgs:
Fermi templates

Point sources:
2FGL catalogue



Han, Frenk, Eke, Gao, White '12

Maximum likelihood analysis

$b\bar{b}$ channel

$$TS = -2\ln(L_0/L)$$

L= likelihood full model

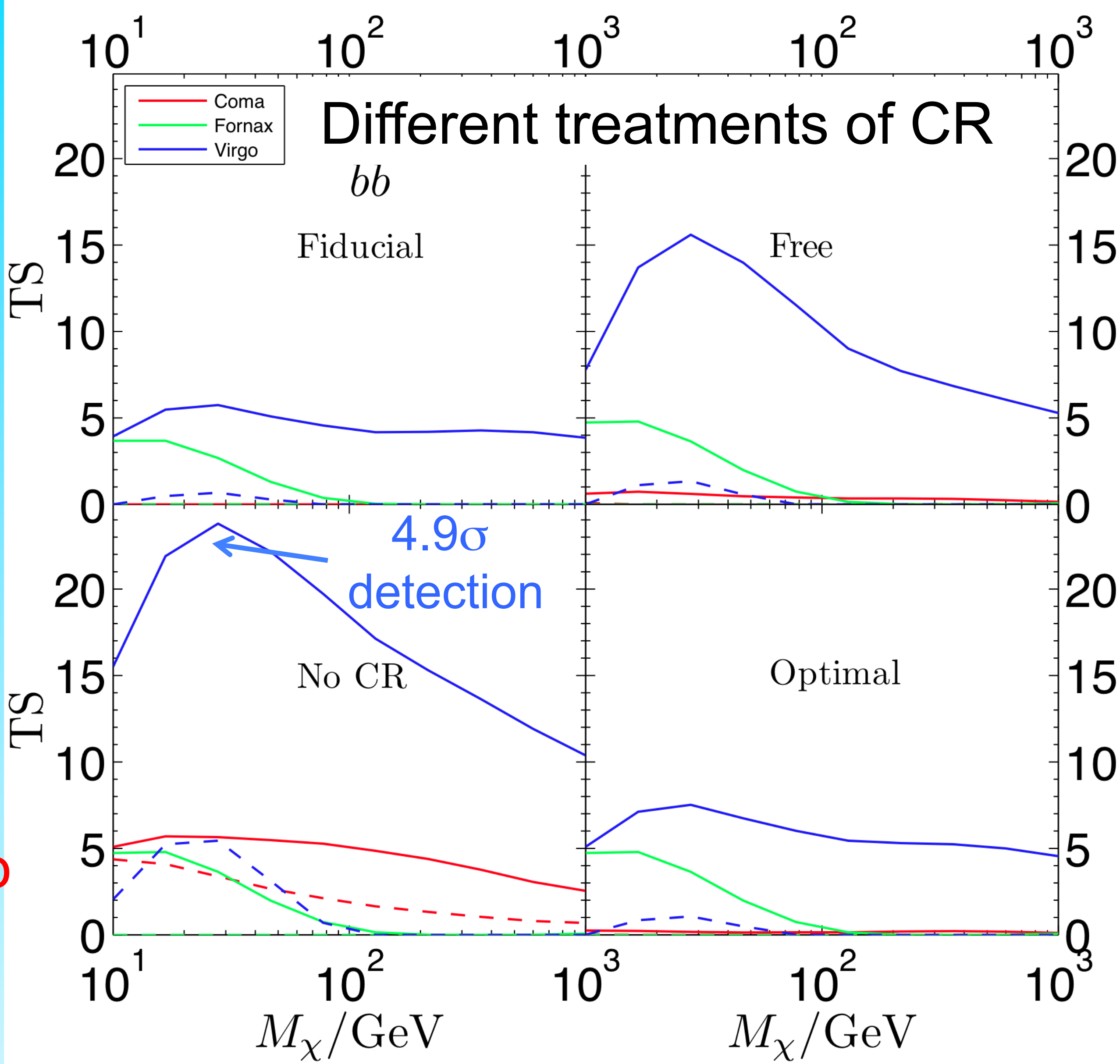
L_0= likelihood for null hypothesis (i.e. no DM)

TS follows a χ^2 distr

Significance is $\sqrt{TS}\ \sigma$

4.9σ detection of Virgo (for no CR)!

M_χ~ 30 GeV



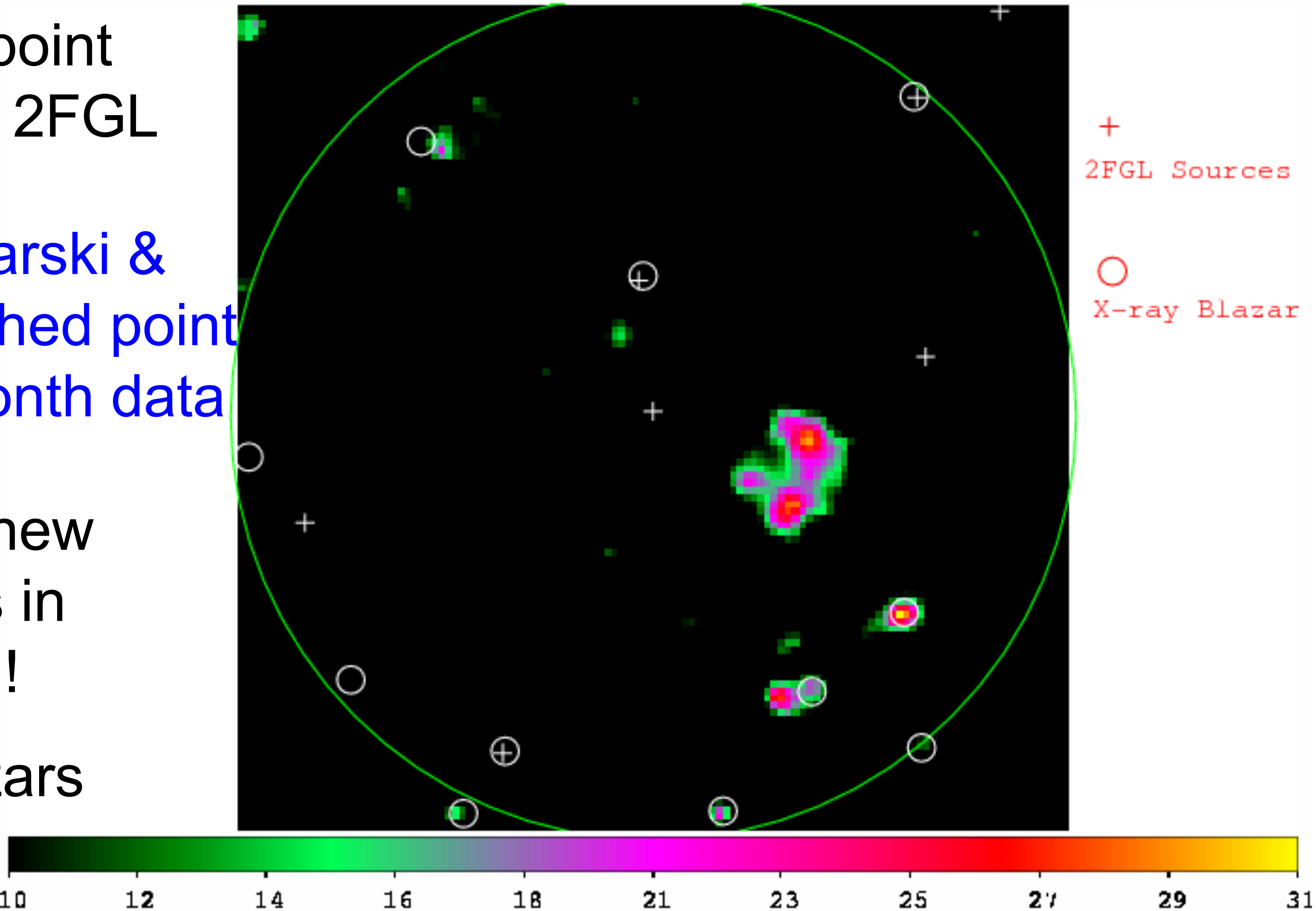
The Virgo cluster in Fermi

Analysis used published 2-yr point source catalogue 2FGL

Alerted by Boyarski & Ruchayskiy searched point sources in 45-month data

Found several new points sources in Virgo region!

Some are blazars

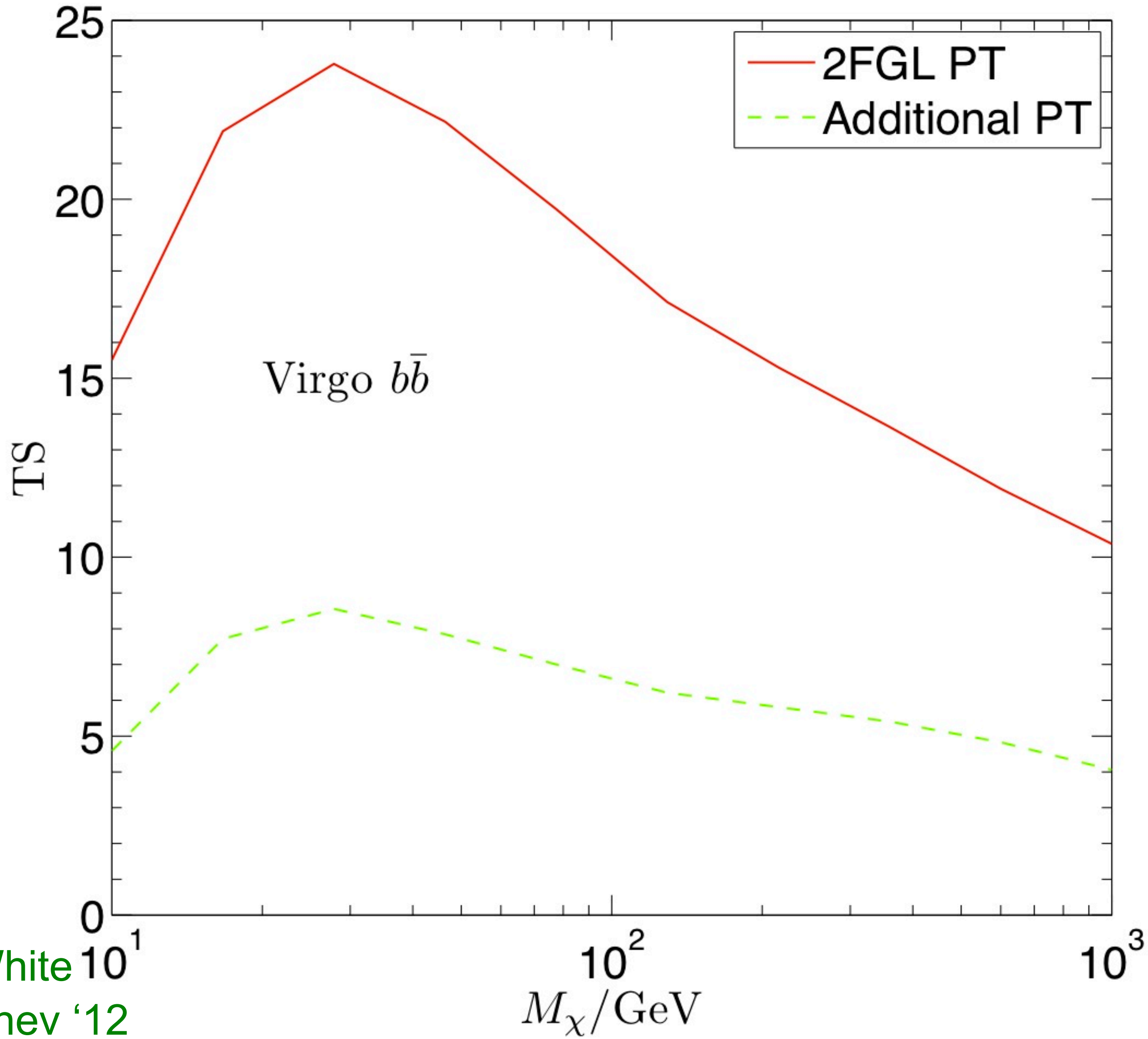


Han, Frenk, Eke, Gao, White
Boyarski, Ruchayskiy, Malyshev '12

The Virgo cluster in Fermi

University of Durham

Significance of DM detection reduced from 4.9σ to 2.9σ



Han, Frenk, Eke, Gao, White
Boyarski, Ruchayskiy, Malyshev '12

Upper limits on x-section

University of Durham

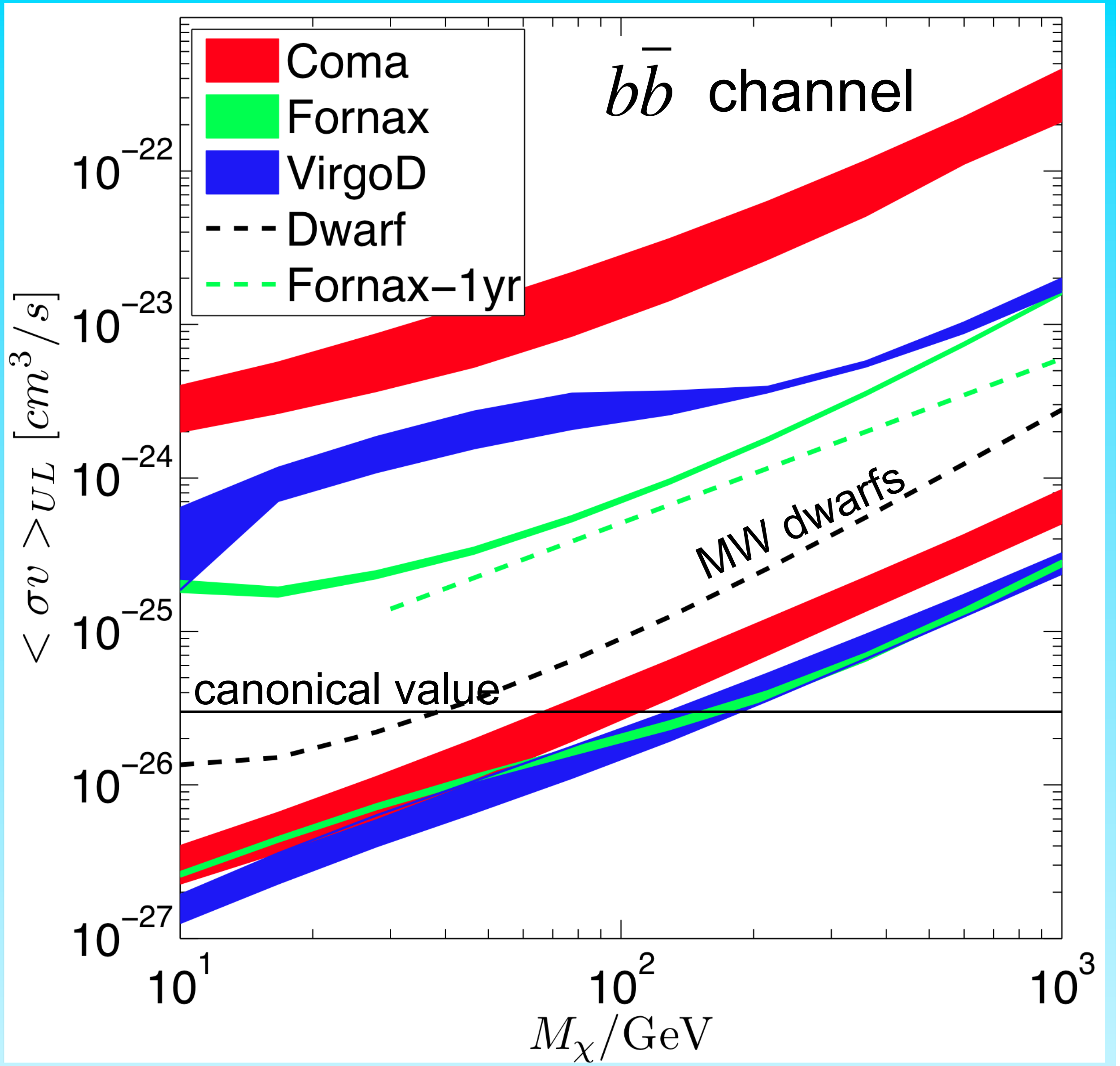
Bands = uncertainty in CR

Canonical x-section:

$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$$

excluded for M<100 GeV

(for $M_{cut} = 10^{-6} M_o$)



Han, Frenk, Eke, Gao, White
Boyarski, Ruchayskiy, Malyshev ‘12

Institute for Computational Cosmology

Upper limits on x-section

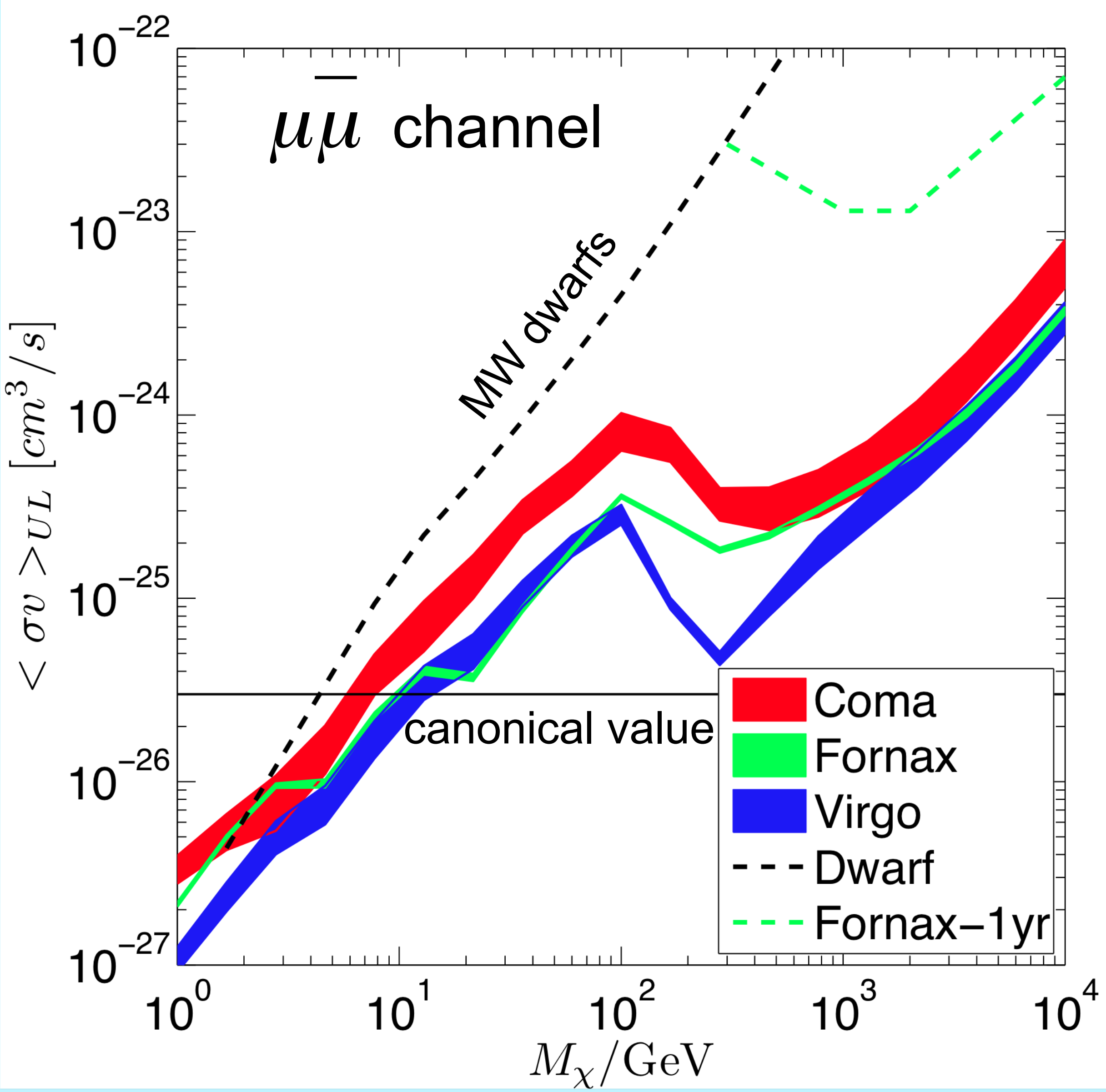
Bands = uncertainty in CR

Canonical x-section:

$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$$

excluded for M<10 GeV

(for $M_{cut} = 10^{-6} M_o$)



Han et al '12

Upper limits on x-section

University of Durham

Bands = uncertainty in CR

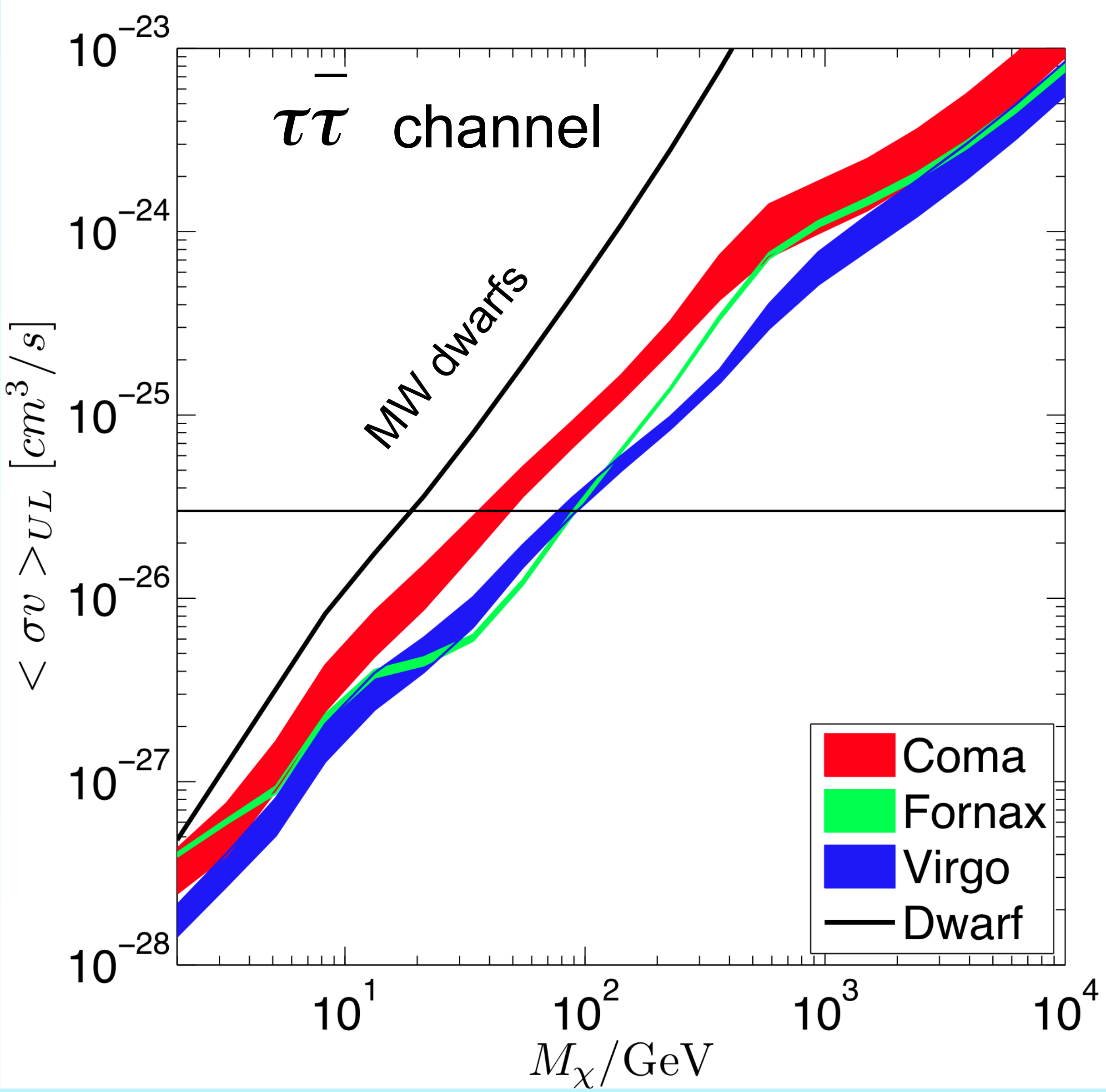
Canonical x-section:

$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$$

excluded for M<50 GeV

(for $M_{cut} = 10^{-6} M_o$)

Han et al '12



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University of Durham ICC

Conclusions: analysis of Fermi data

Using 2-year data and point source catalogue →

- 4.9σ detection of DM annihilation in Virgo
- marginal detections in Coma and Fornax

But, 45 month data find new point sources, some are blazars

→ Significance of DM detection in Virgo drops to 2.9σ

Upper limits

	M_χ	Channel
Thermal x-section excluded for M_χ	<100GeV	$b\bar{b}$
	<10 GeV and 50 GeV	$\mu^+\mu^-$ and $\tau^+\tau^-$

Dark matter simulations

Carlos S. Frenk
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Durham

University of Durham

Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm	sterile ν majoron; KeVin	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

The dark matter power spectrum

University of Durham

Free streaming →

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

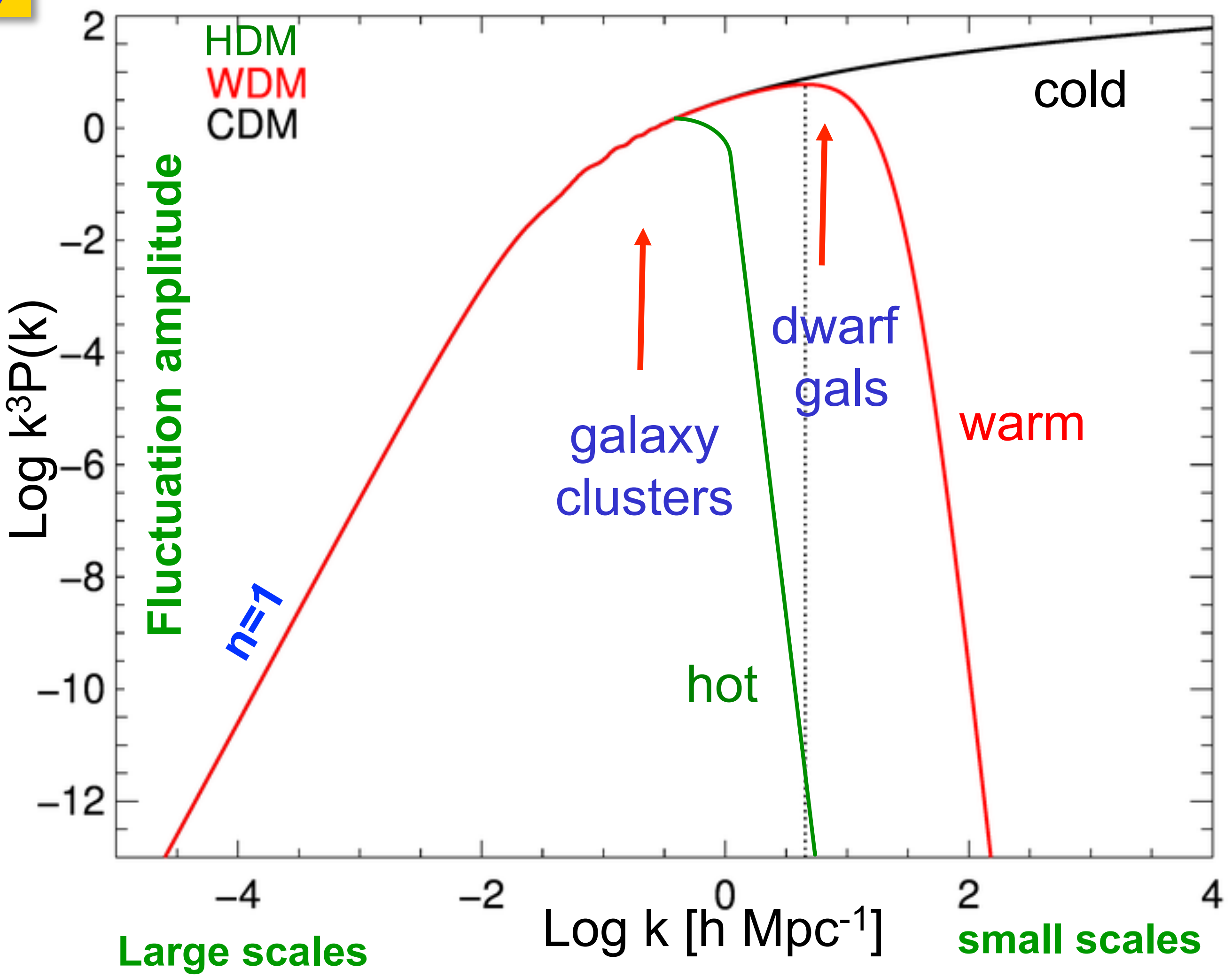
$m_{CDM} \sim 100GeV$
susy; $M_{cut} \sim 10^{-6}\ M_o$

$m_{WDM} \sim$ few keV
sterile ν; $M_{cut} \sim 10^9\ M_o$

$m_{HDM} \sim$ few eV
light ν; $M_{cut} \sim 10^{15}\ M_o$

$k^3\ P(k)$

The linear power spectrum ("power per octave")



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The formation of cosmic structure

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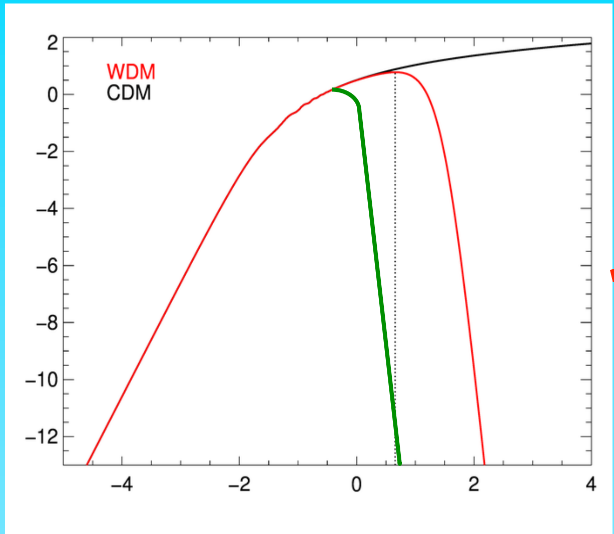
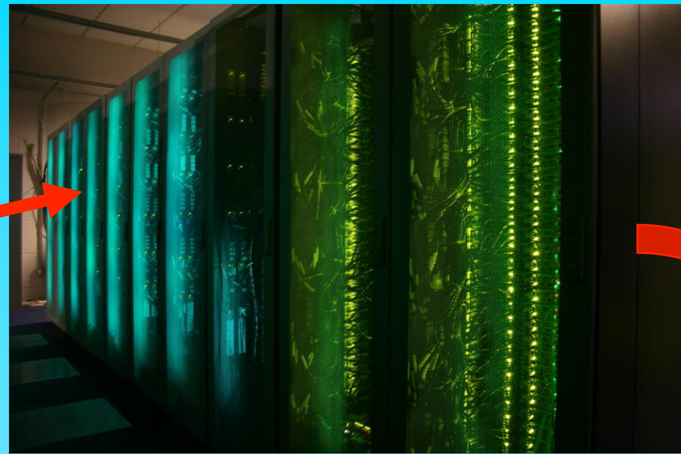
"Cosmology machine"





t=380,000 yrs

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

Simulations

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

t=13.8 billion yrs

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

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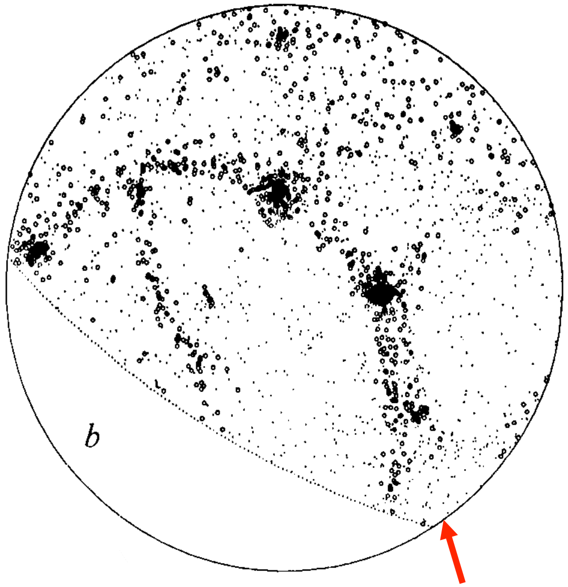
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

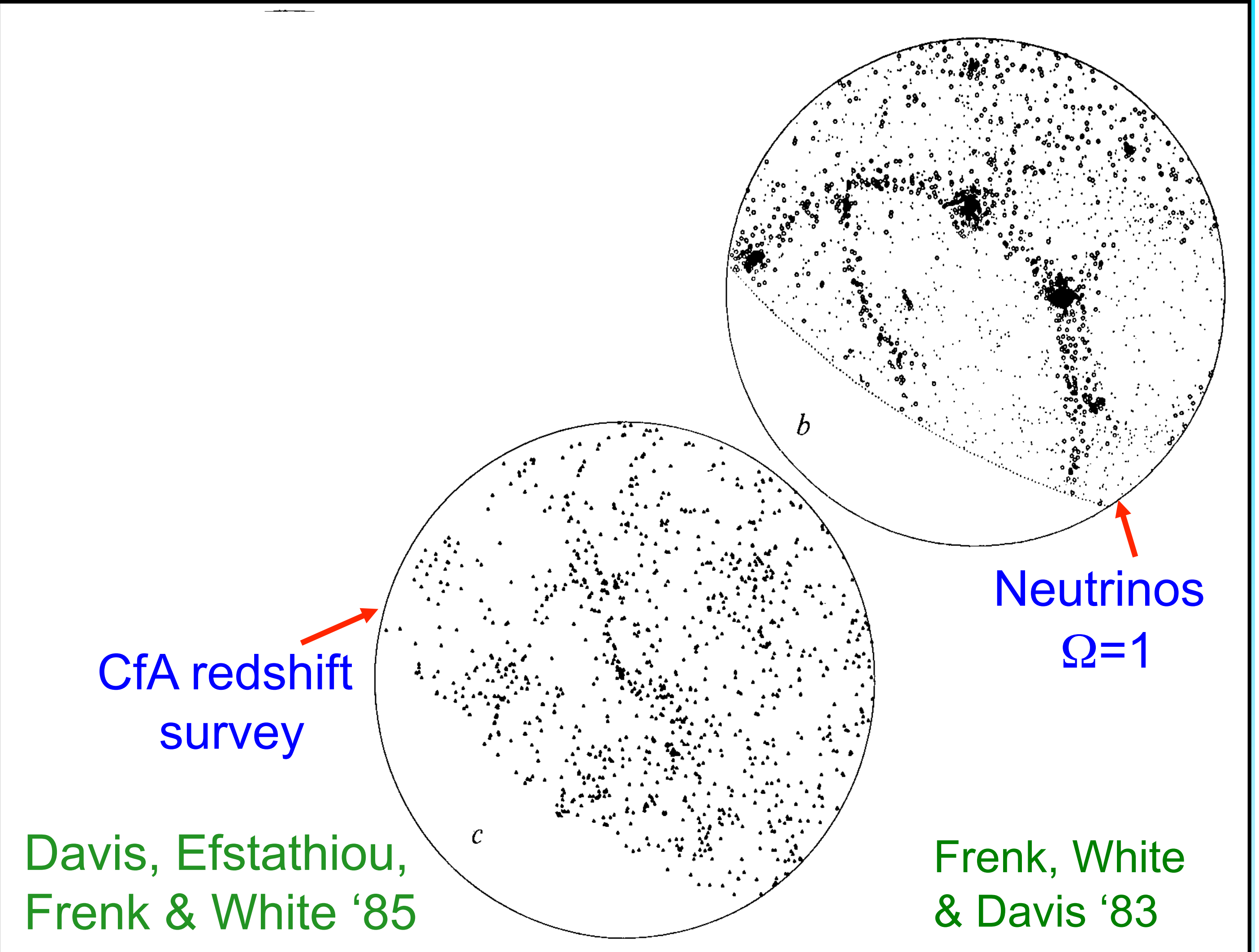
Frenk, White
& Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω

→ m_ν << 10 ev



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Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

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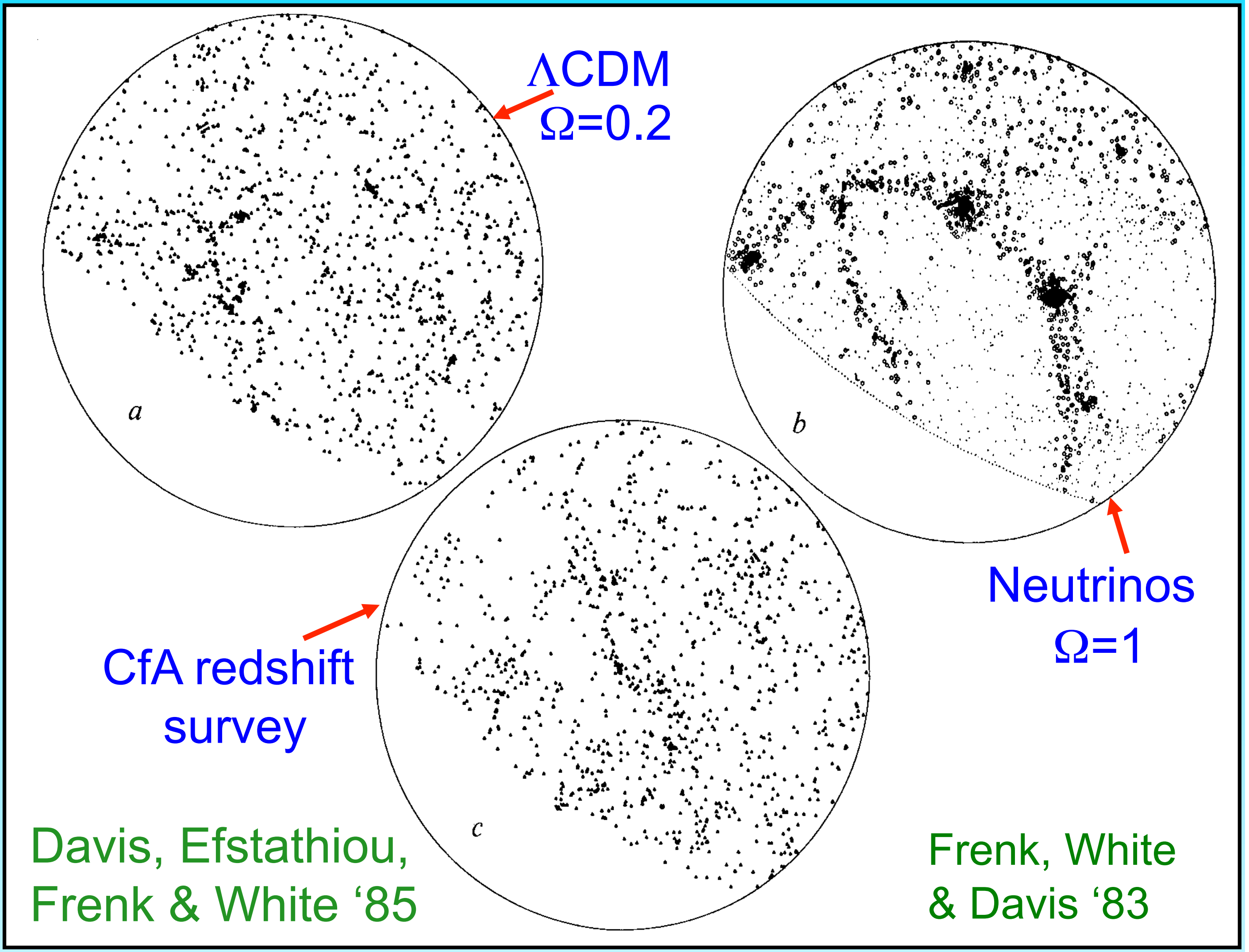
Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



The dark matter power spectrum

Free streaming →

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m_{CDM} ~ 100GeV
susy; $M_{cut} \sim 10^{-6} M_o$

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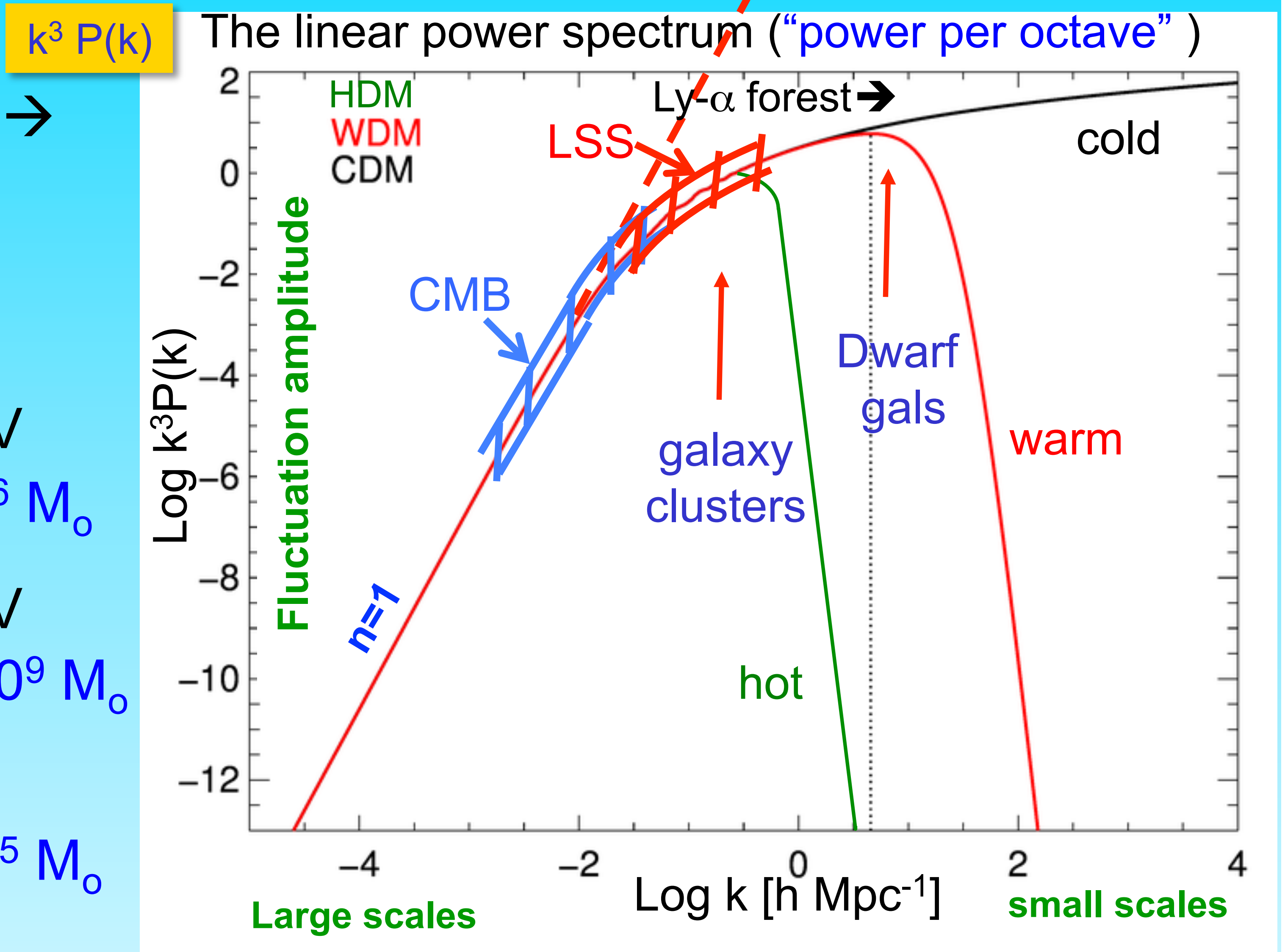

Cosmology on small – strongly non-linear – scales

→ 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

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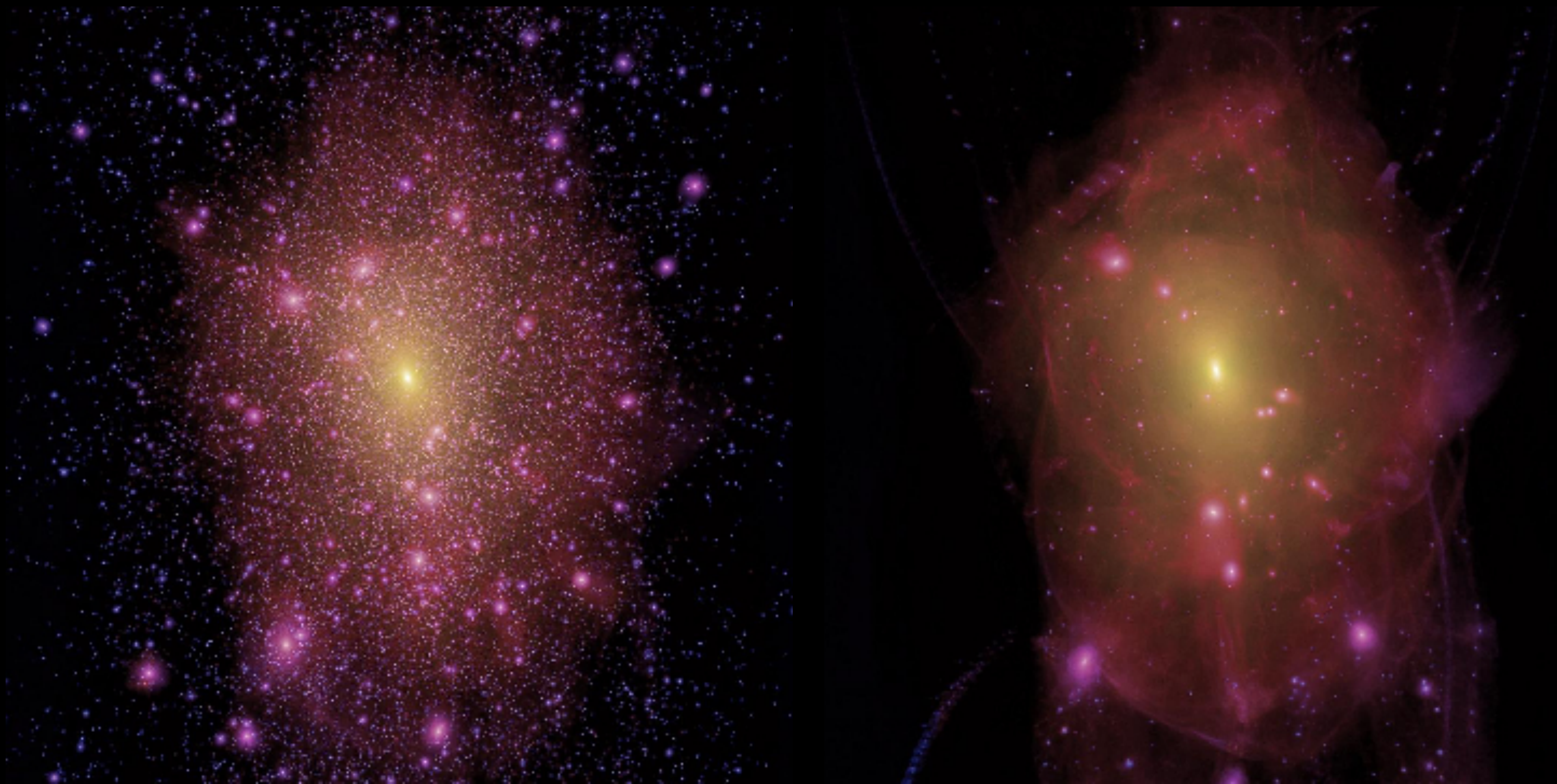
z = 48.4
T = 0.05 Gyr
500 kpc

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:

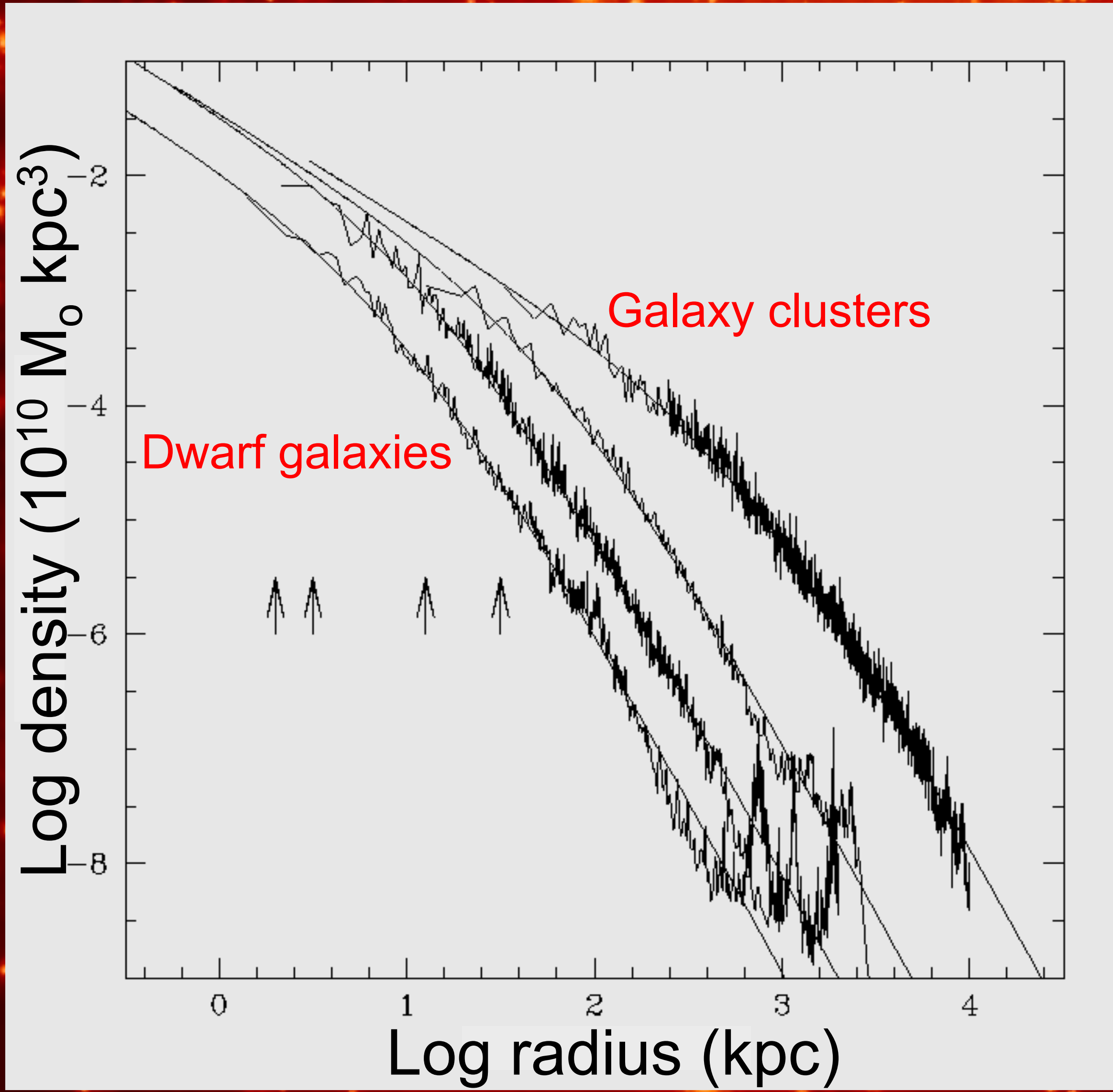
Cold dark matter

- 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

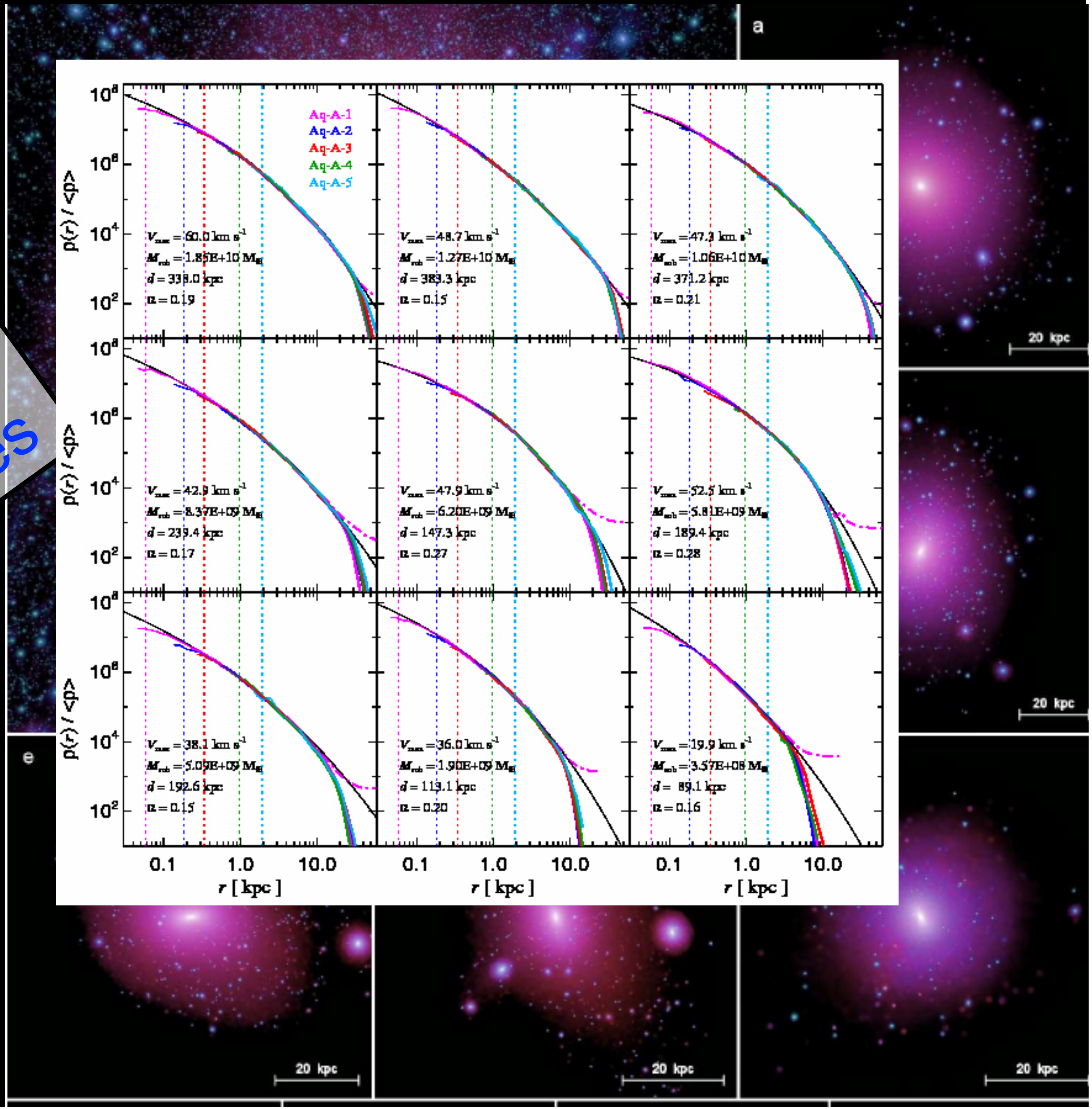
There is no obvious density plateau or `core' near the centre.

(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)

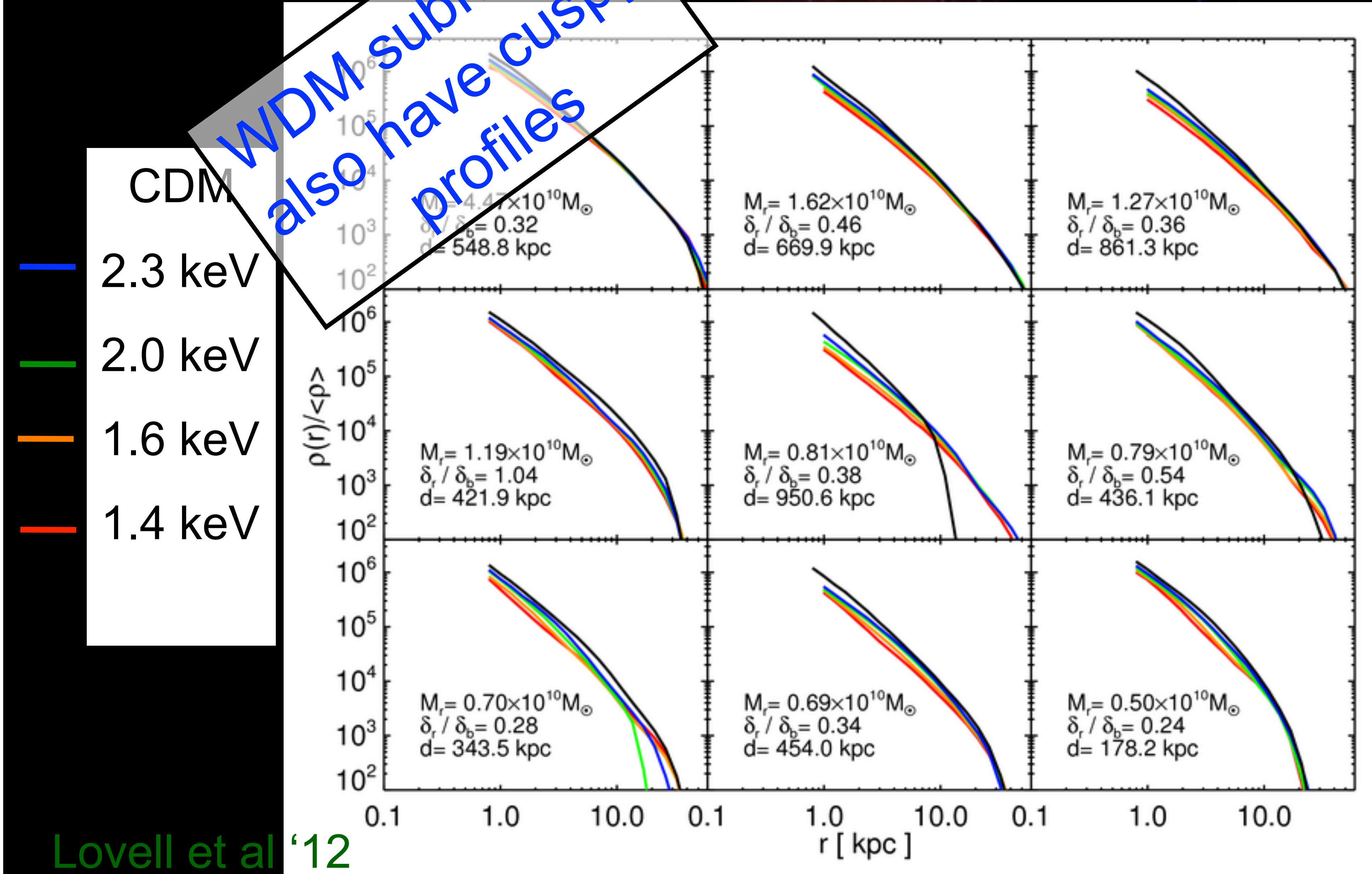
CDM subhalos also have cuspy profiles



Aquarius

Springel et al ‘08

A warm dark matter universe

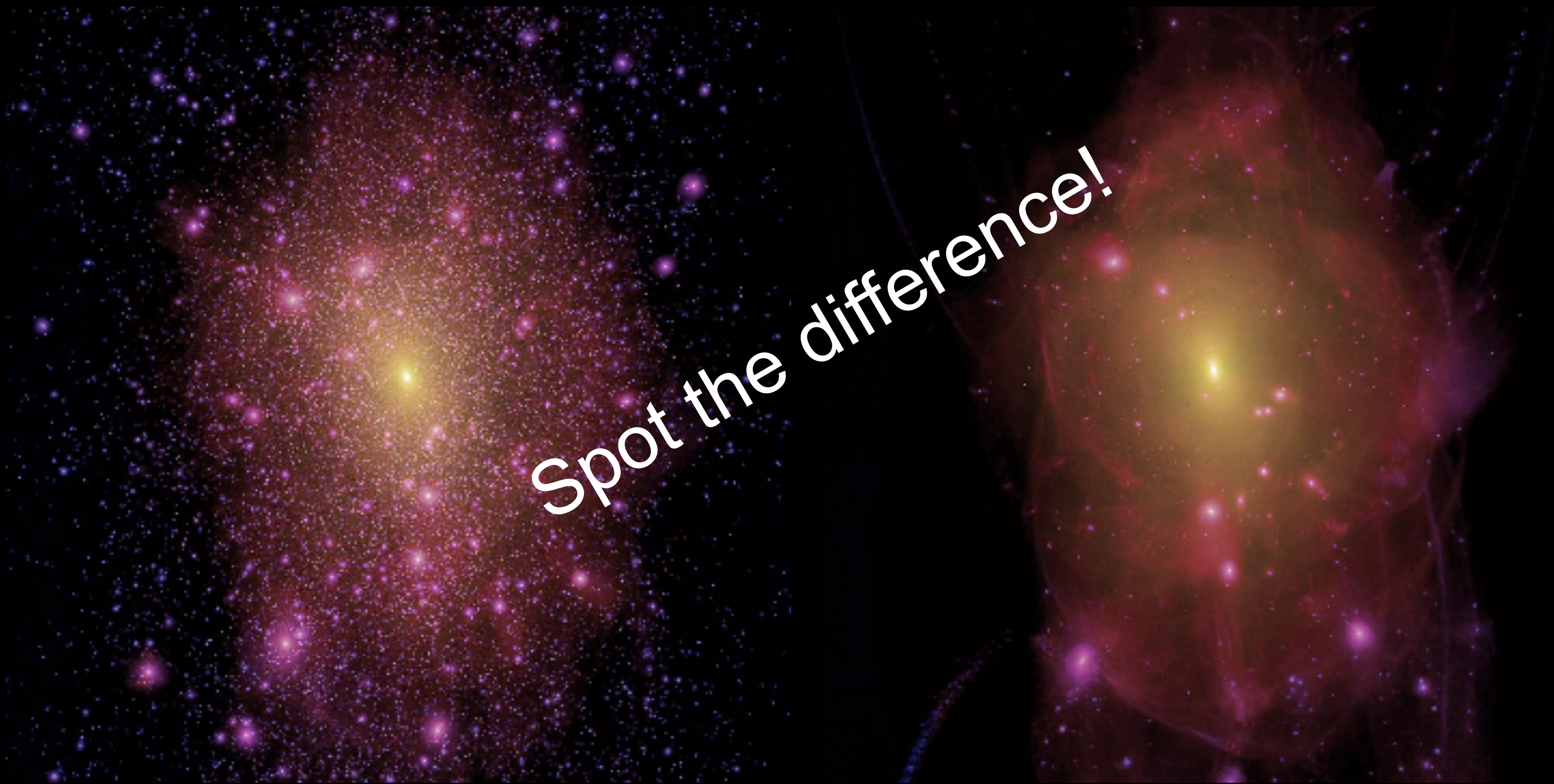


Lovell et al '12

Tests of the nature of the DM

cold dark matter

warm dark matter



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

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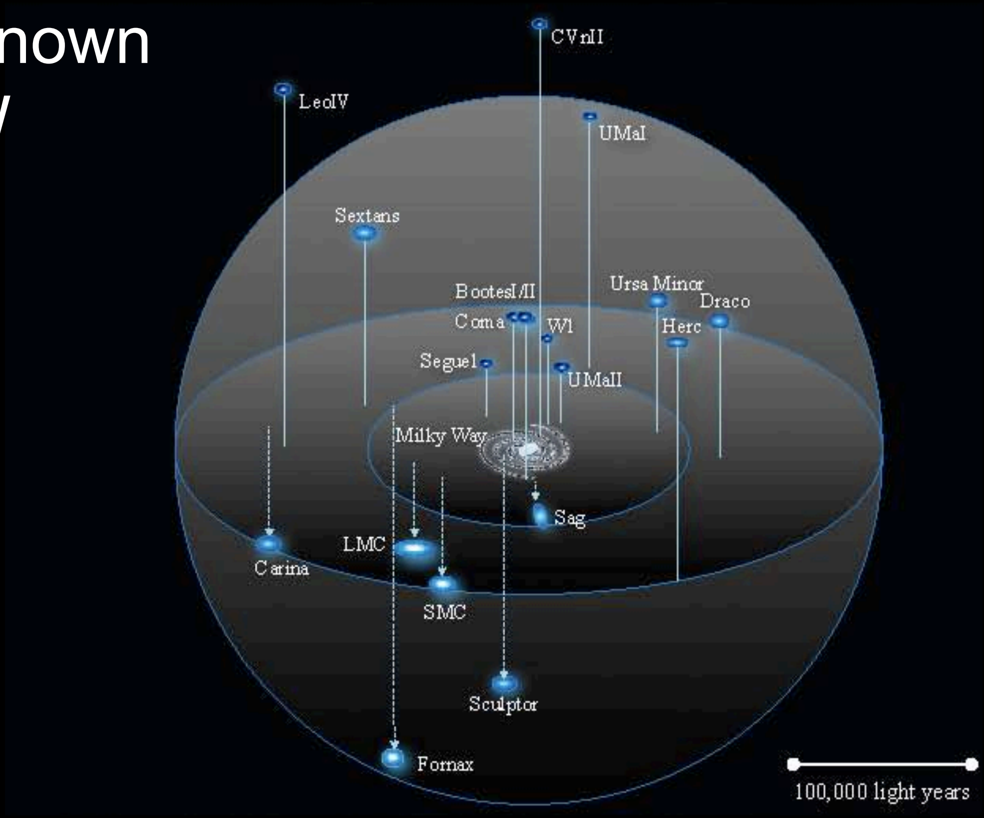
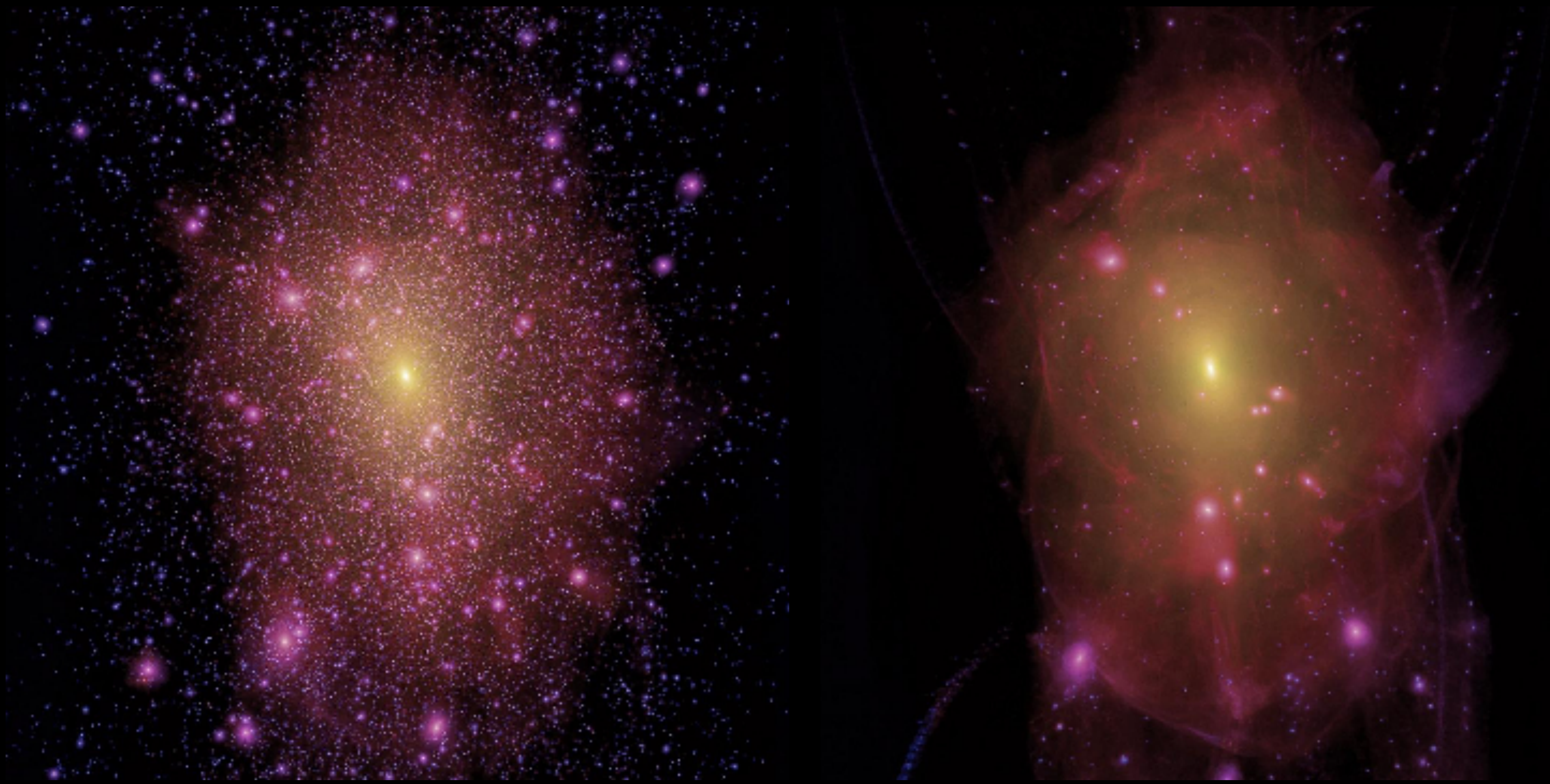
The satellites of the Milky Way

~25 satellites known
in the MW



Spot the difference!

cold dark matter warm dark matter



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

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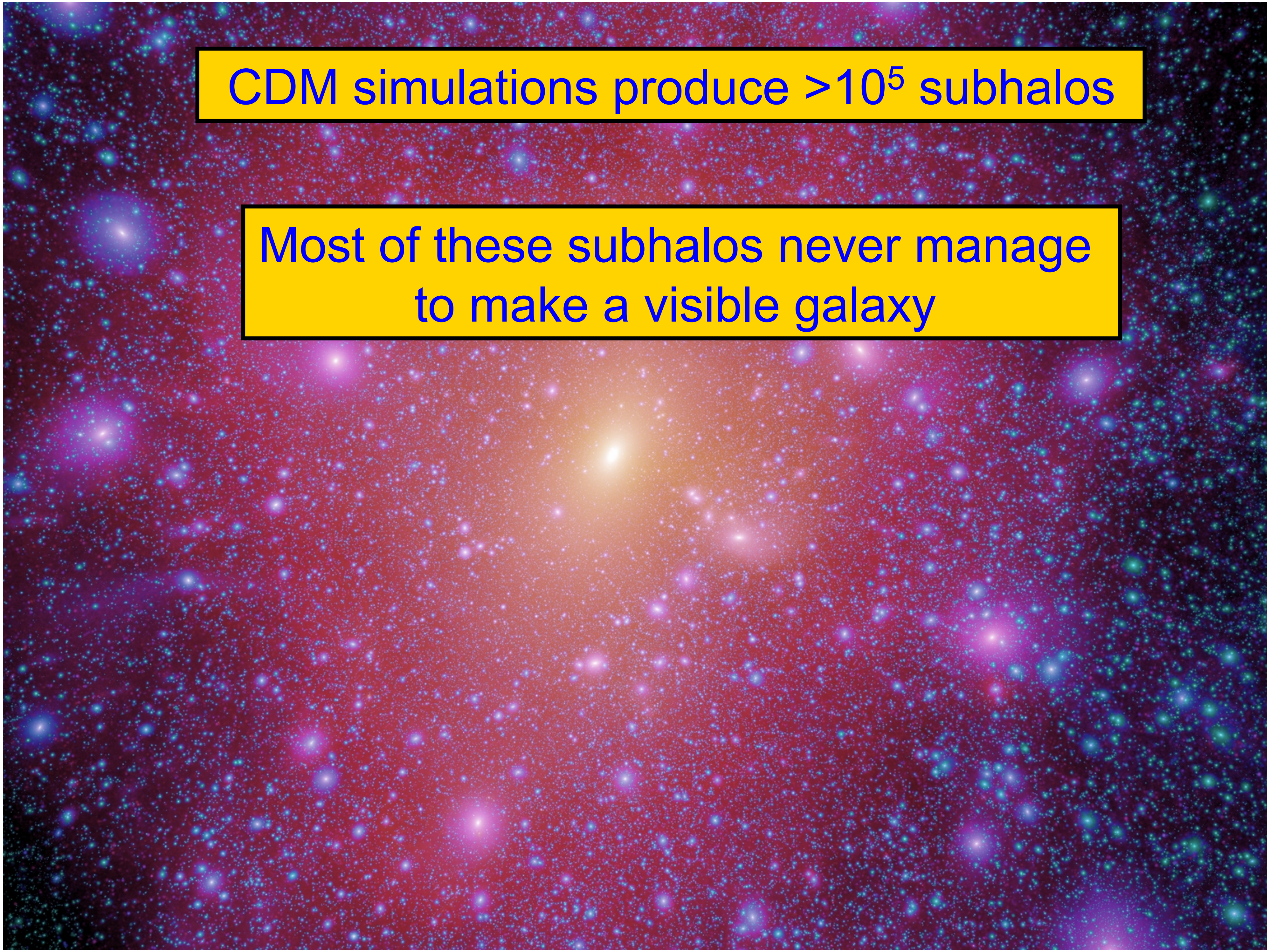
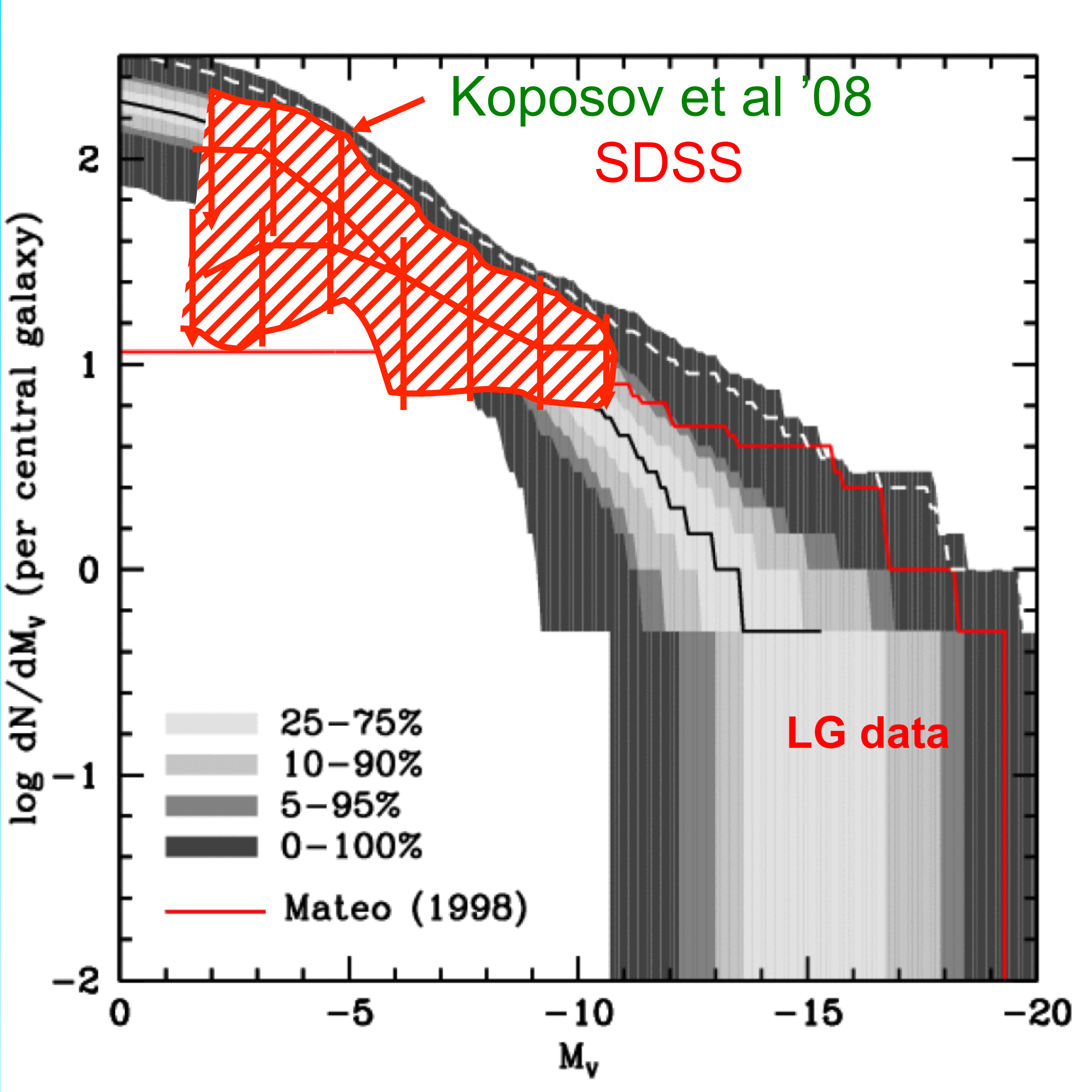

CDM simulations produce >10^5 subhalos
Most of these subhalos never manage to make a visible galaxy

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

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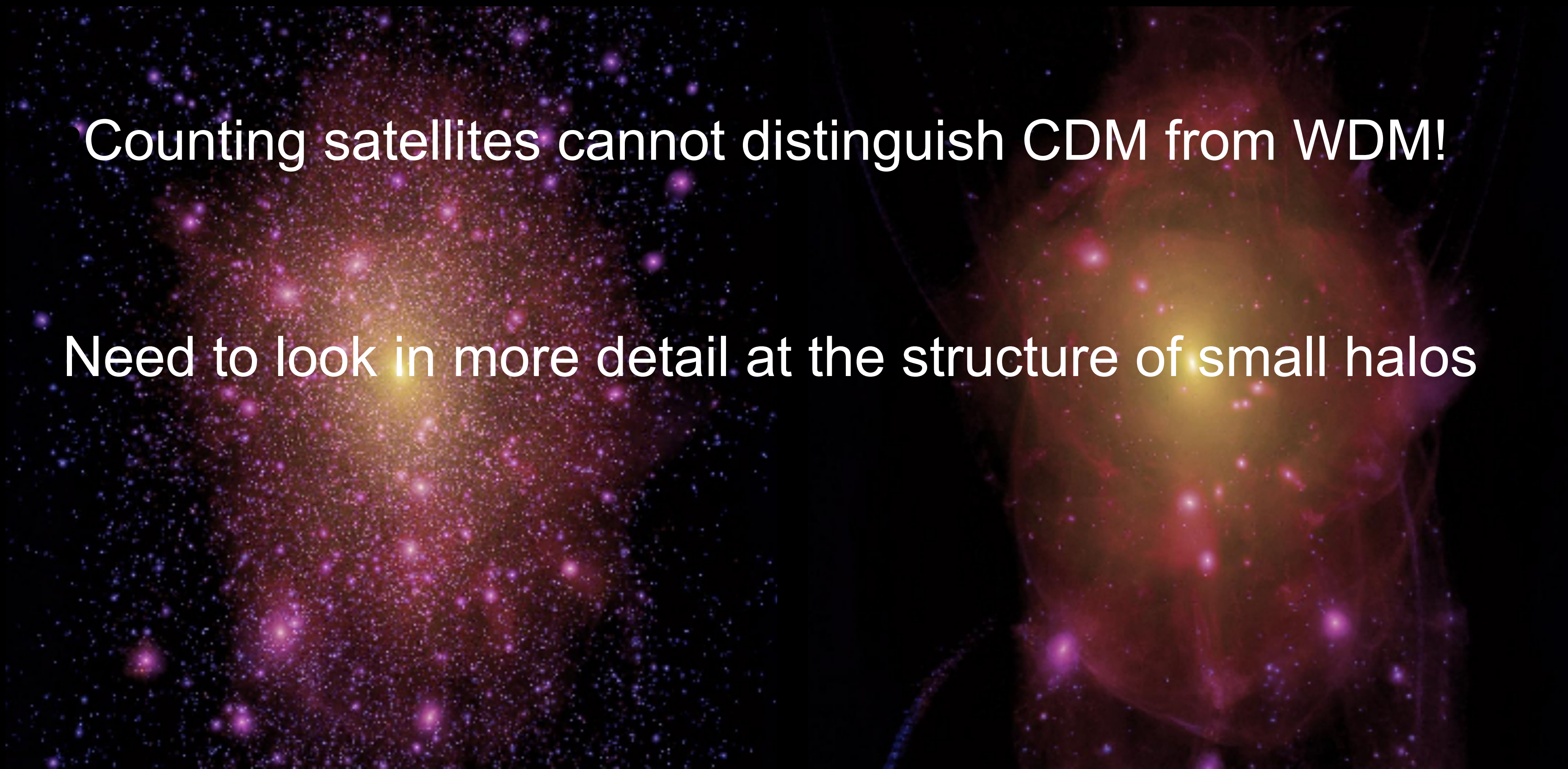
cold dark matter

warm dark matter

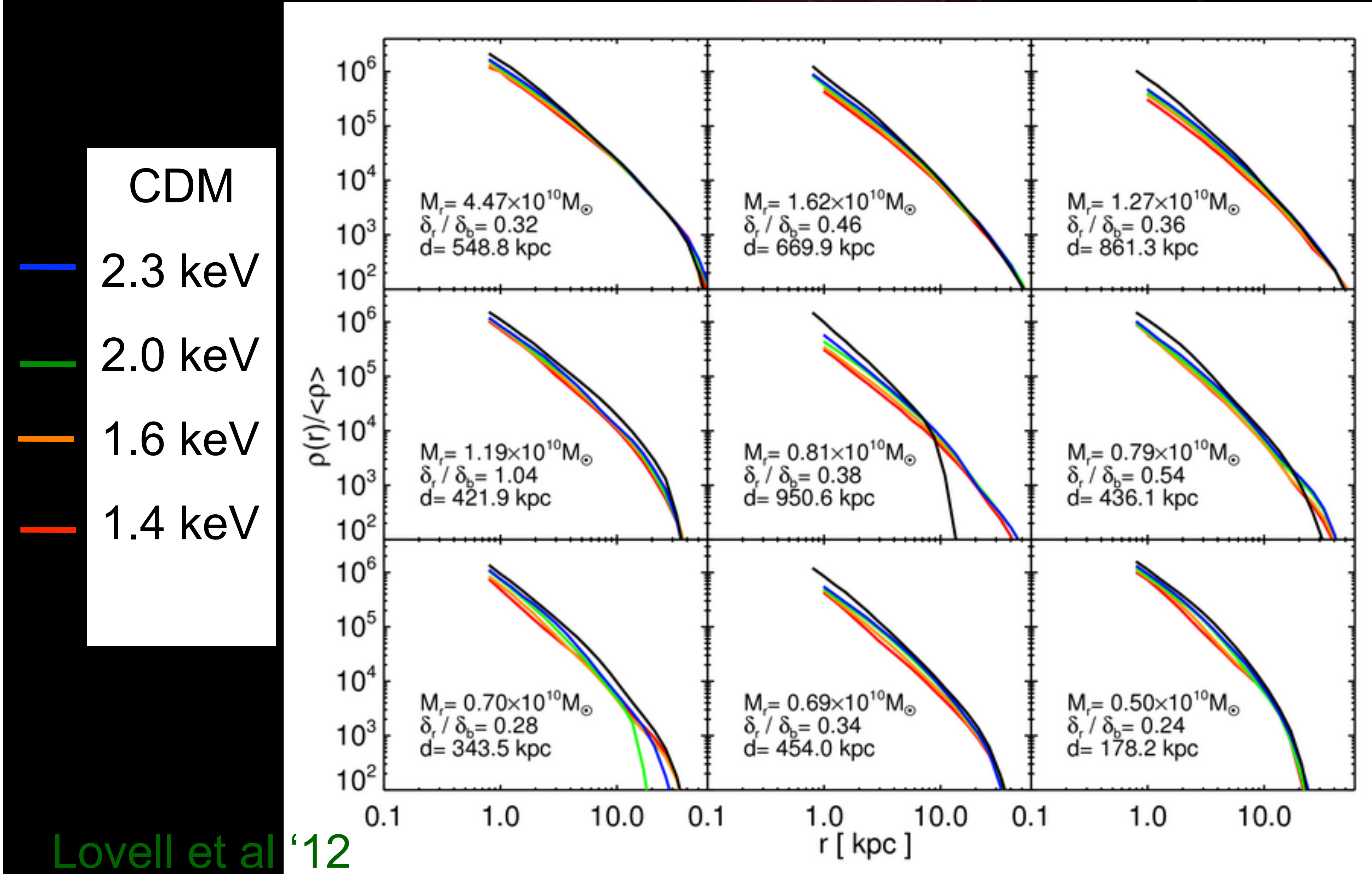


Counting satellites cannot distinguish CDM from WDM!

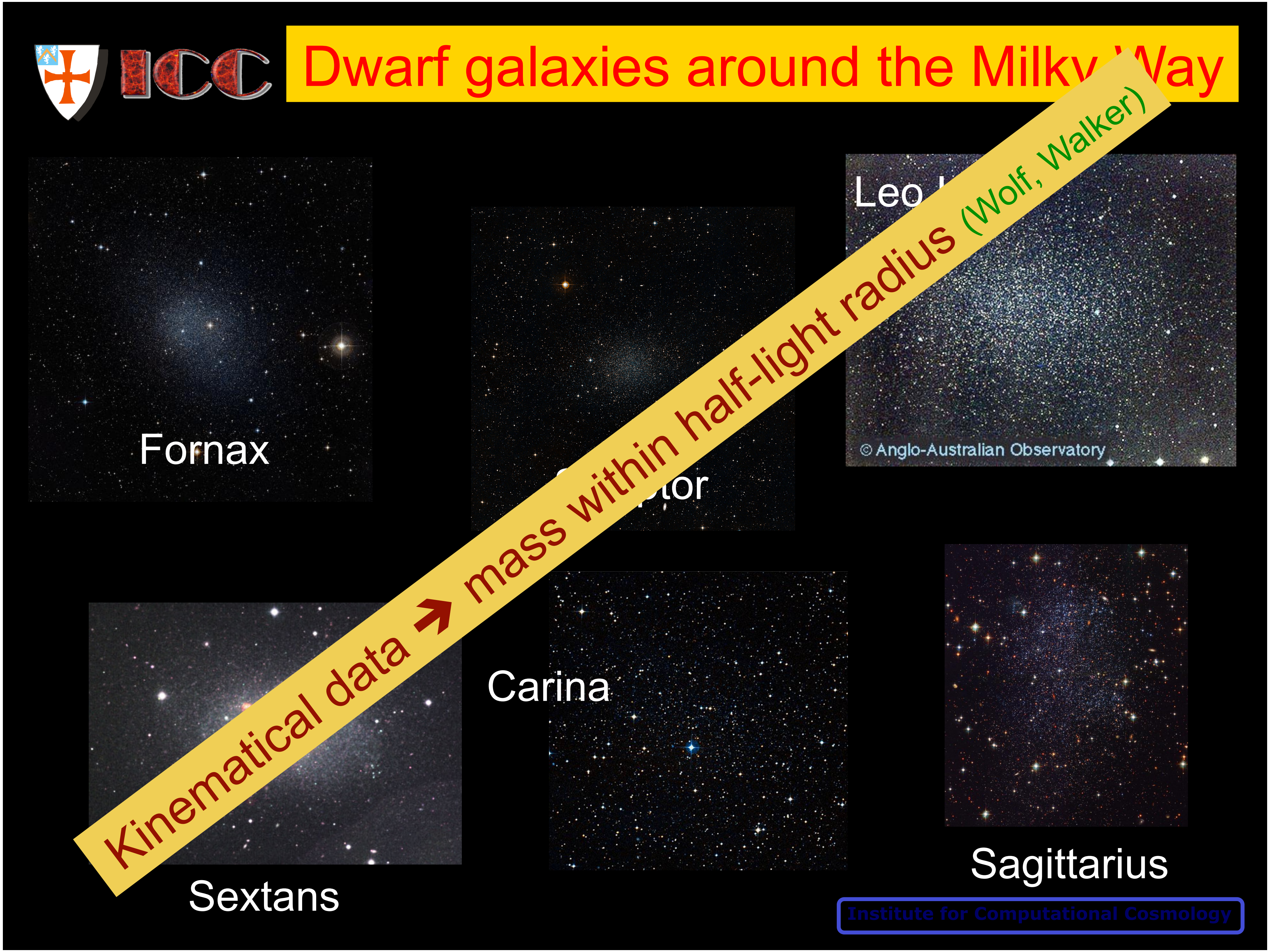
Need to look in more detail at the structure of small halos

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

A warm dark matter universe



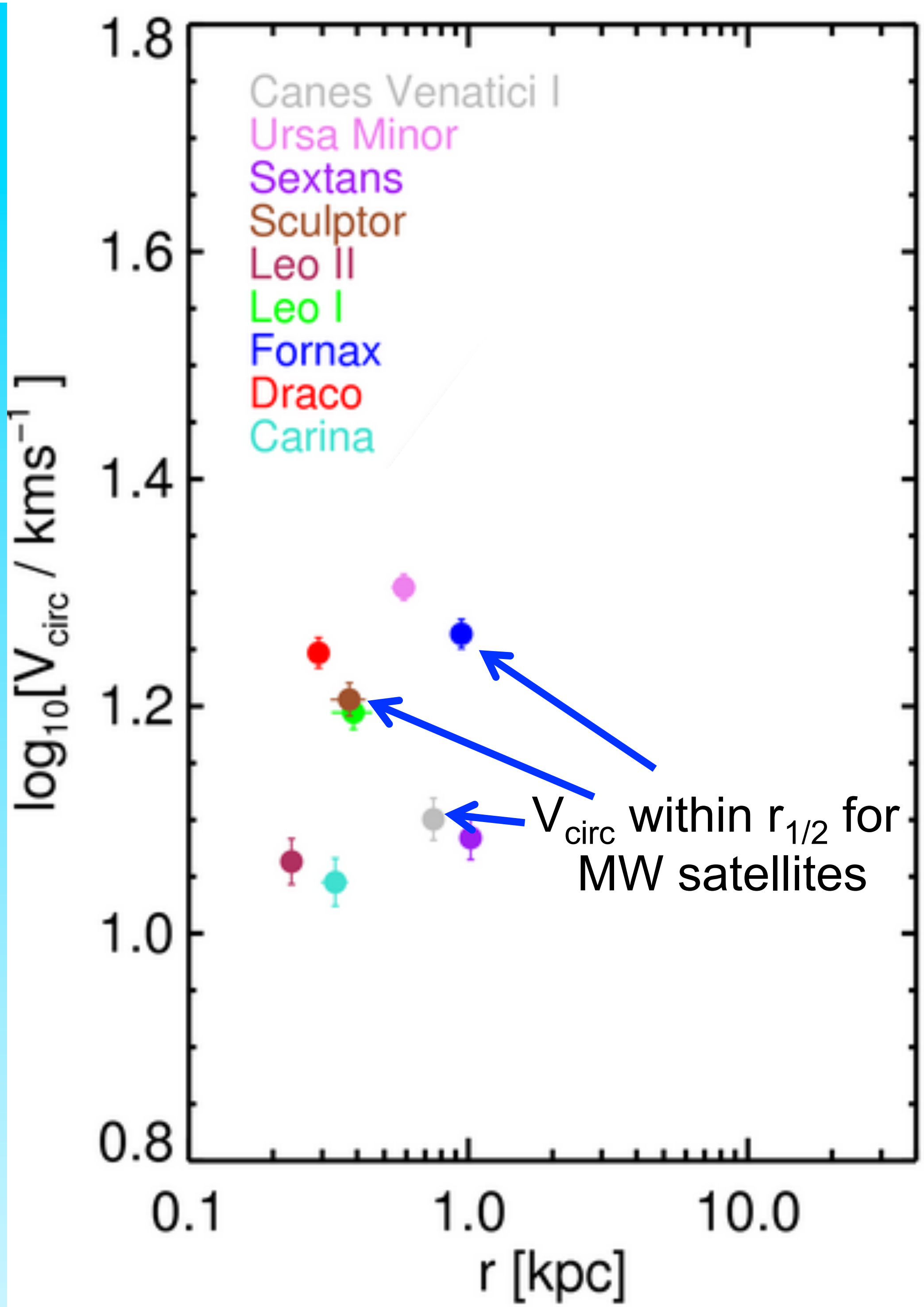
Lovell et al '12


Dwarf galaxies around the Milky Way
Kinematical data → mass within half-light radius (Wolf, Walker)
Fornax
Leo
© Anglo-Australian Observatory
Carina
Sextans
Sagittarius
Institute for Computational Cosmology

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

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

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



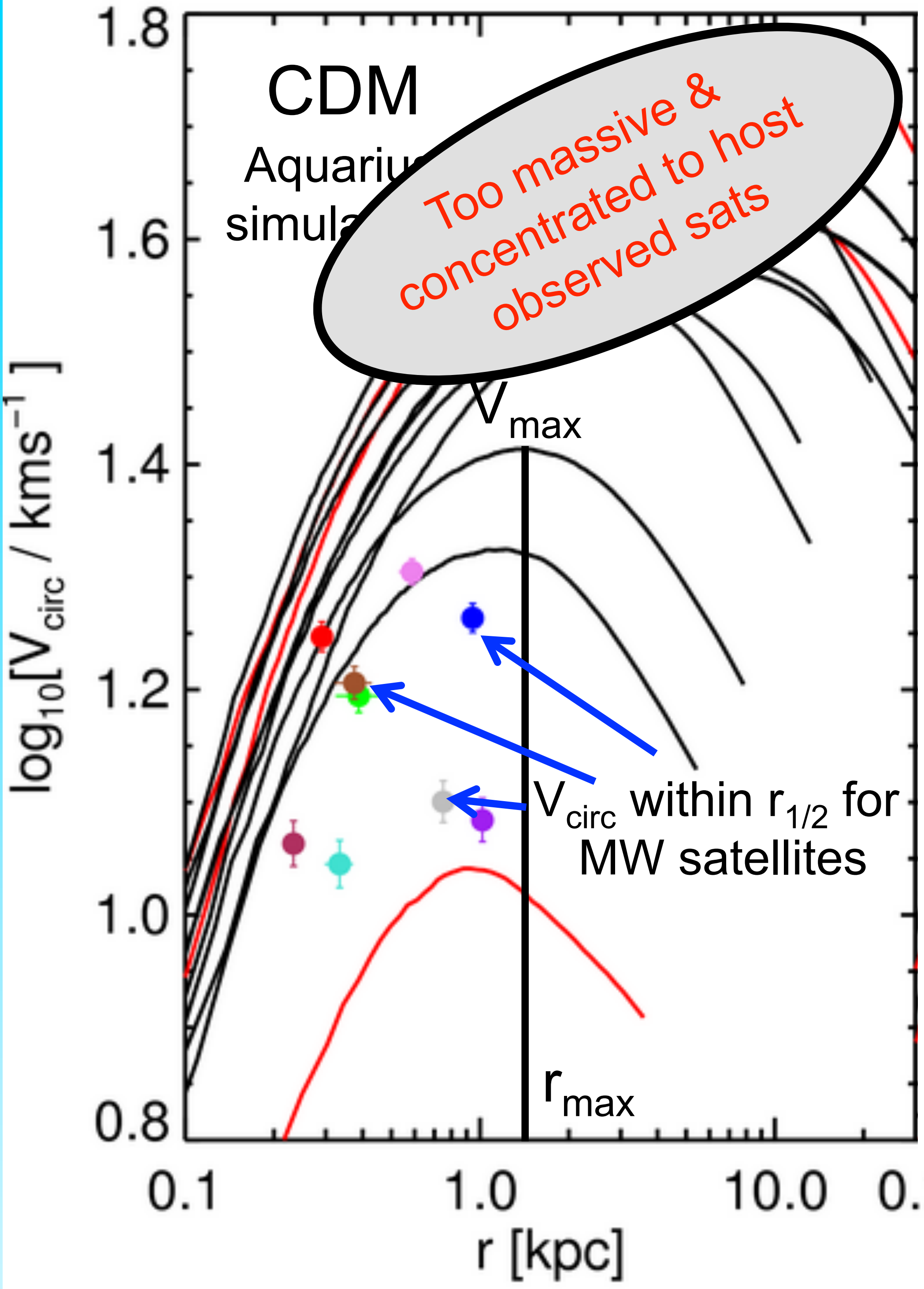
Is CDM compatible w. luminosity & structure of observed satellites?

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

Rotation curves of 12 subhalos with most massive progenitors

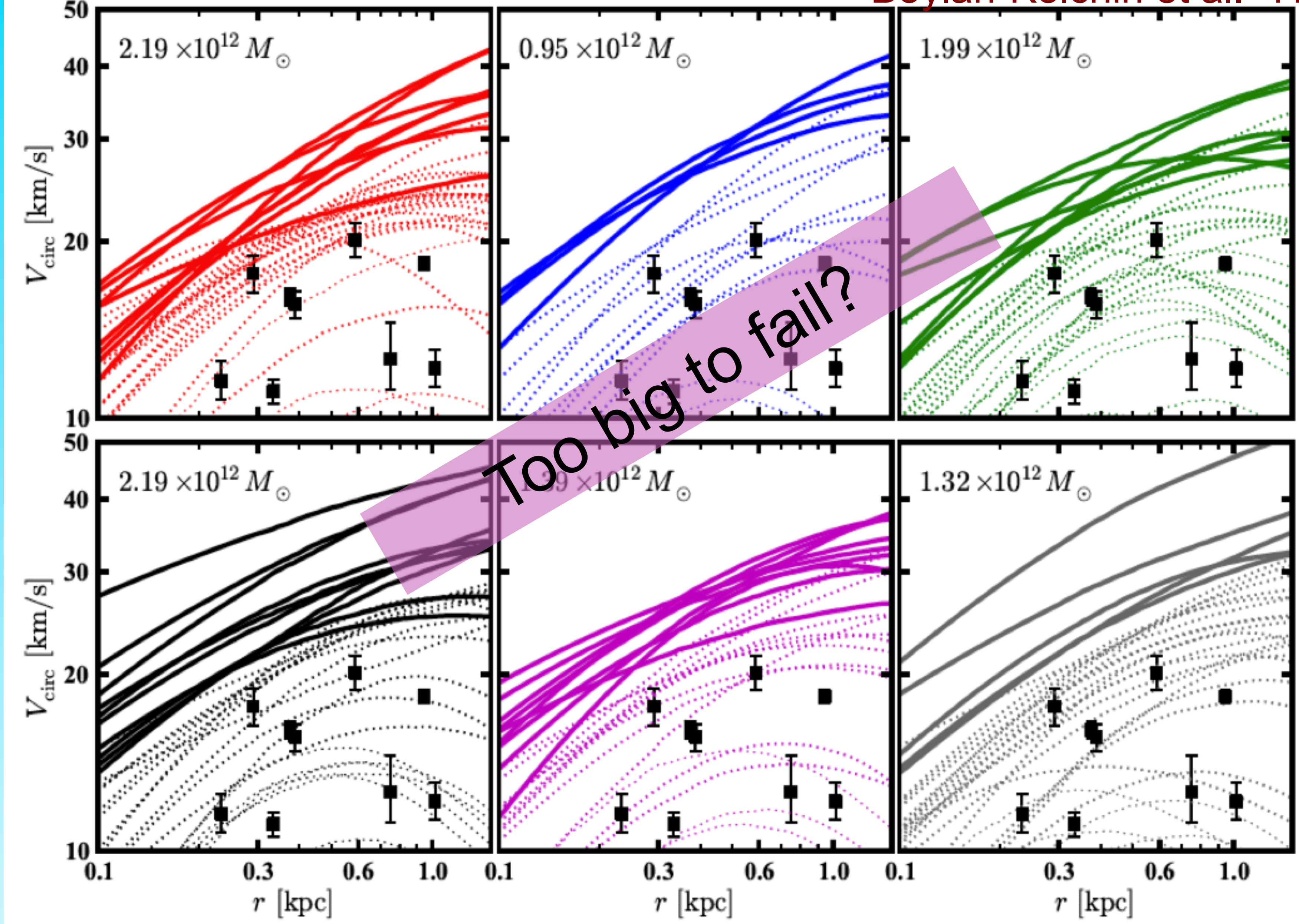
Red → 3 halos with most massive progenitors (LMC, SMC, Sagittarius?)

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

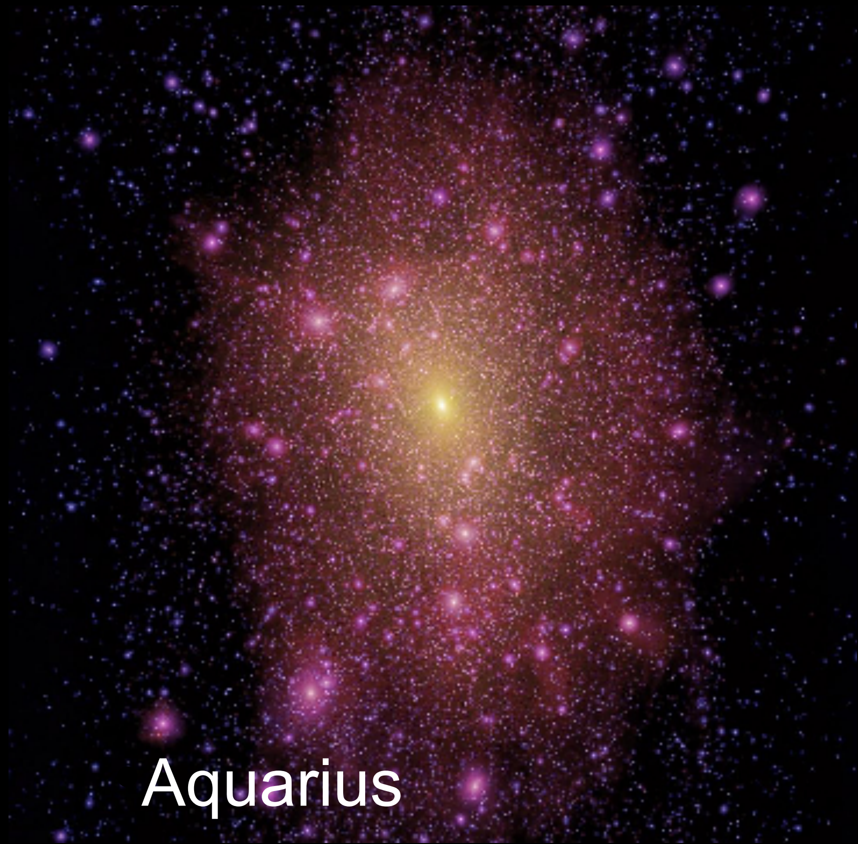


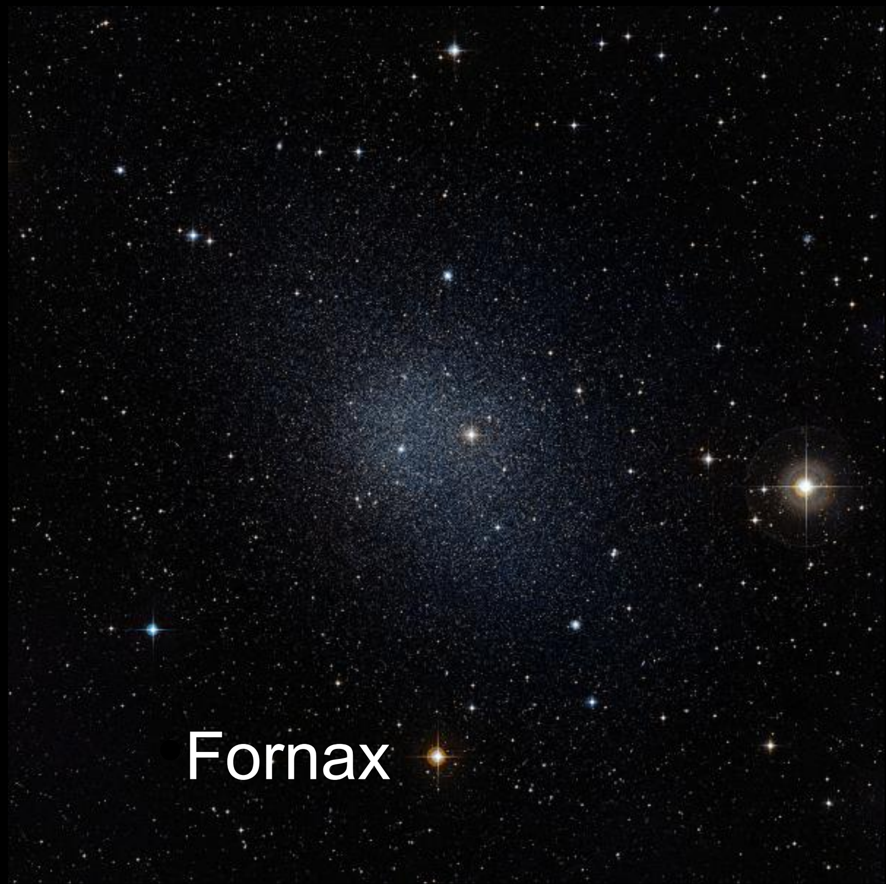
Rotation curves of Aquarius subhalos

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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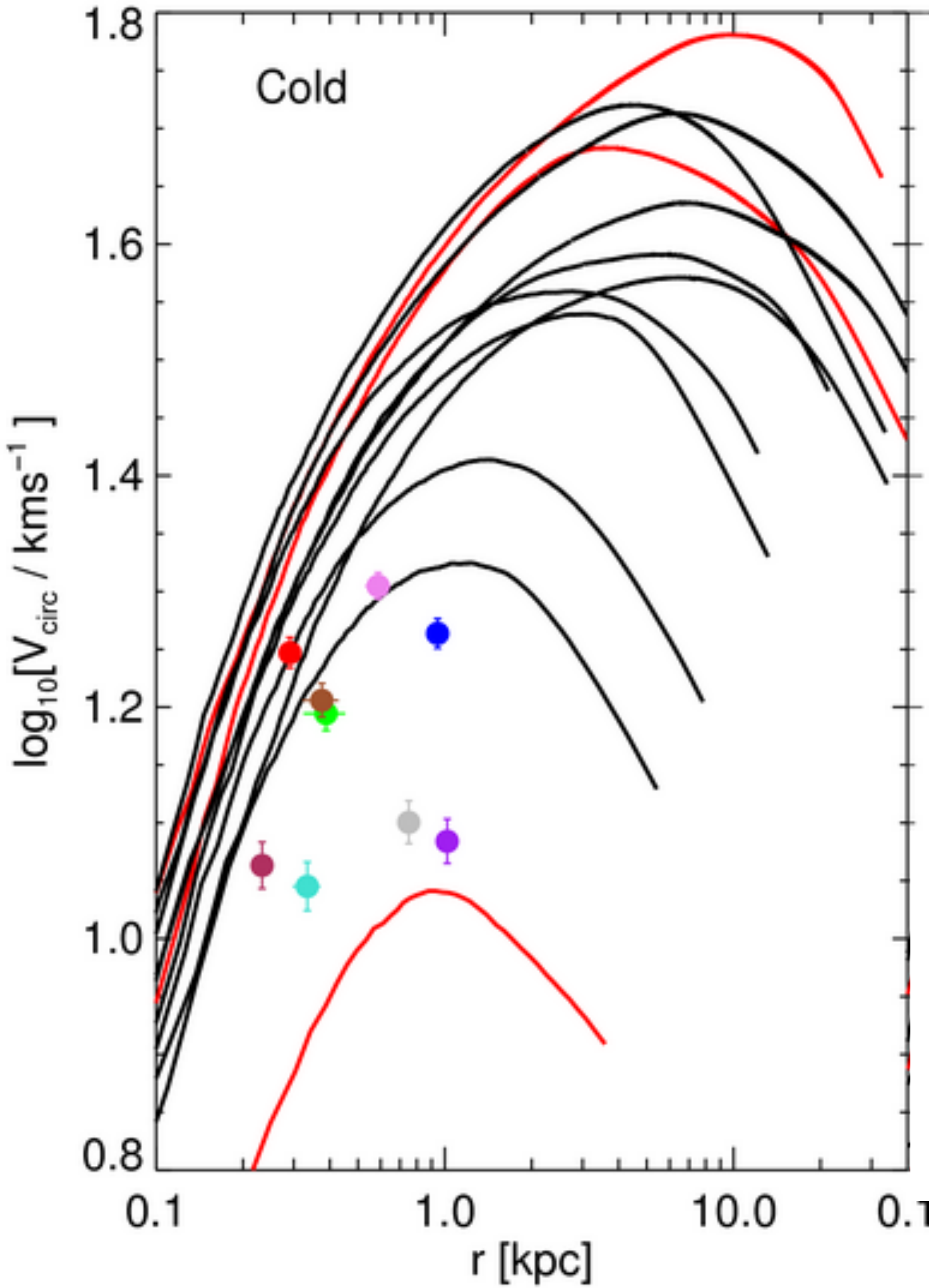

Lovell, Eke, Frenk, Gao,
Jenkins, Wang, White, Theuns,
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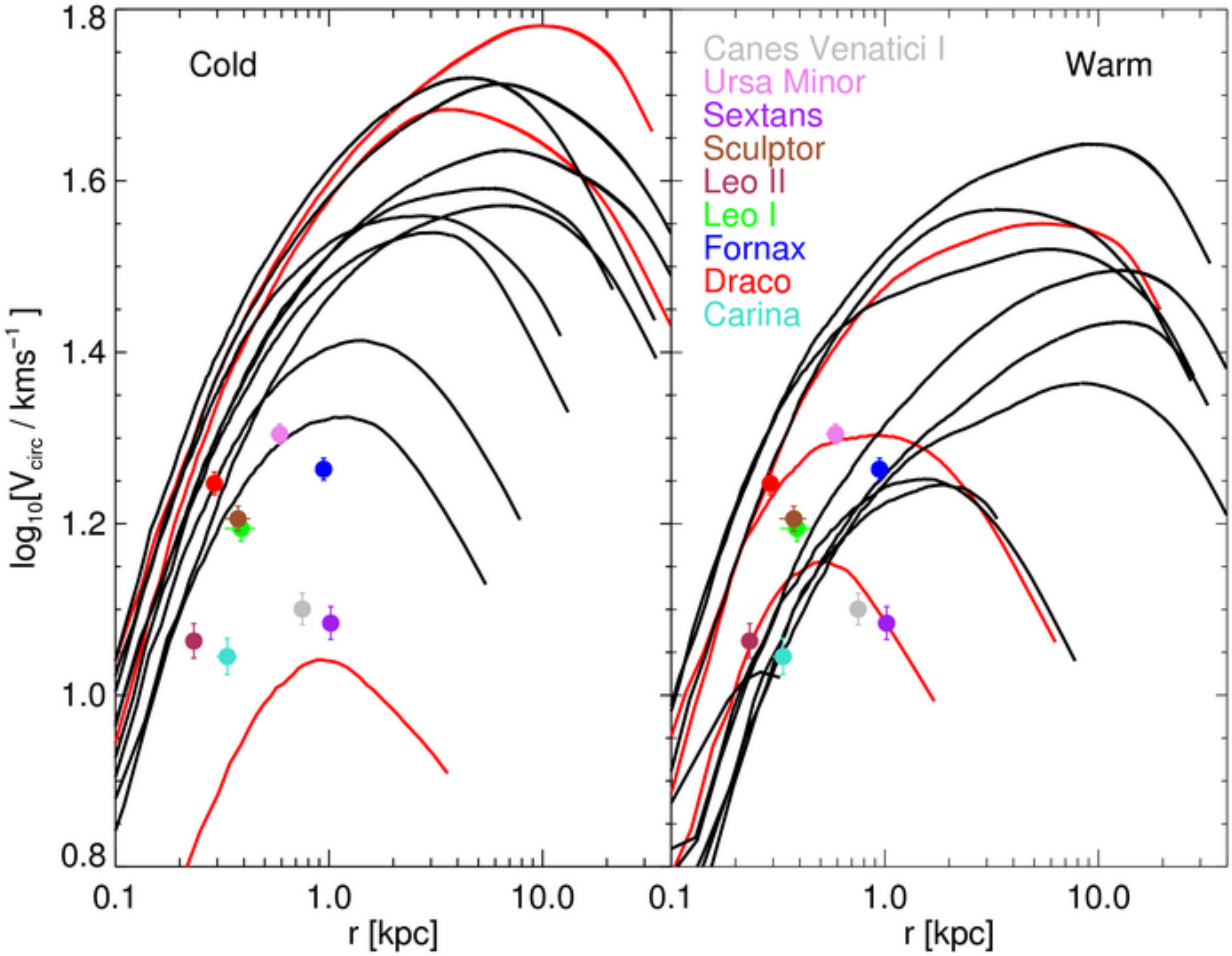


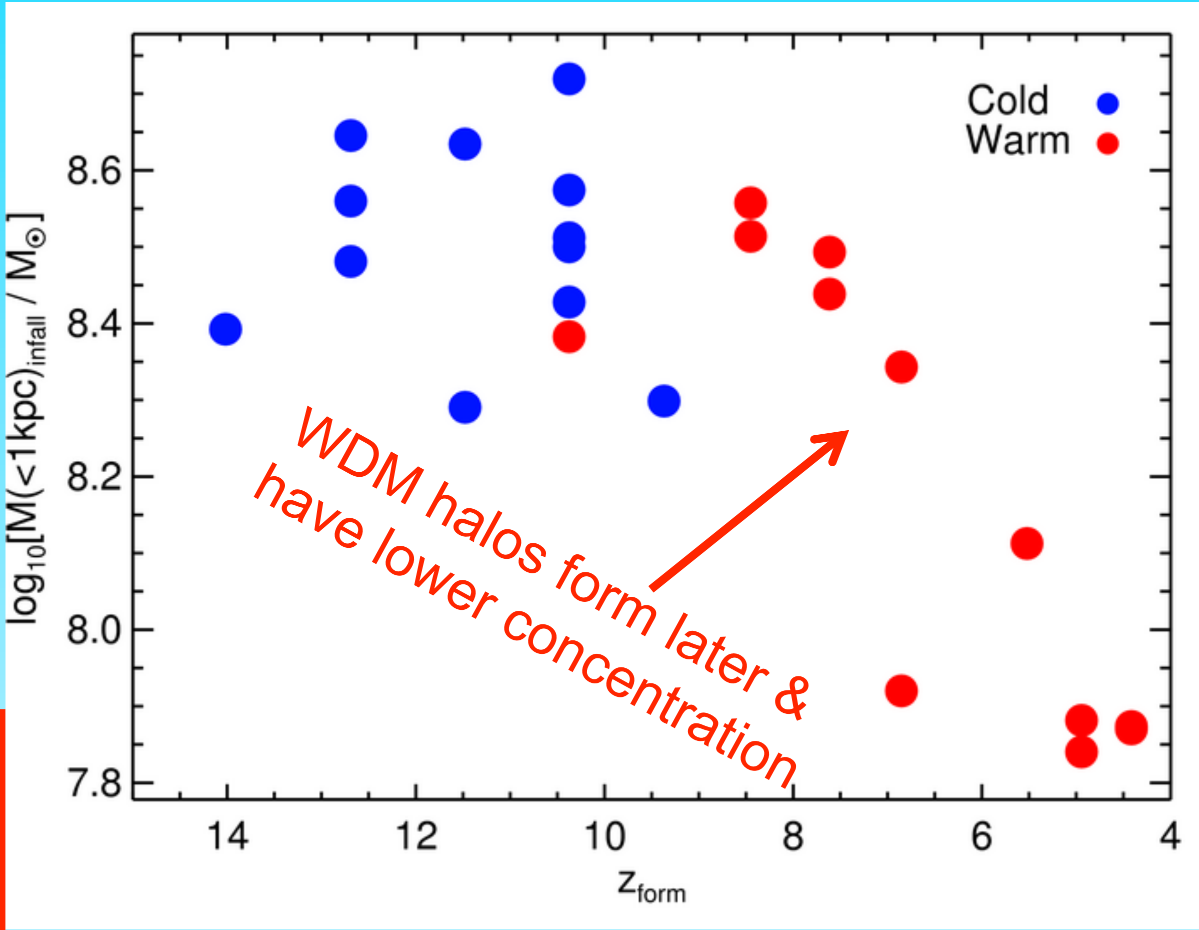
Cold
Warm
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
log10[Vcirc / kms-1]
r [kpc]
1.8
1.6
1.4
1.2
1.0
0.8
0.1
1.0
10.0

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

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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

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*
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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

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

Pontzen & Governato '12

Brooke et al. '12

The cores of dwarf galaxy haloes L75

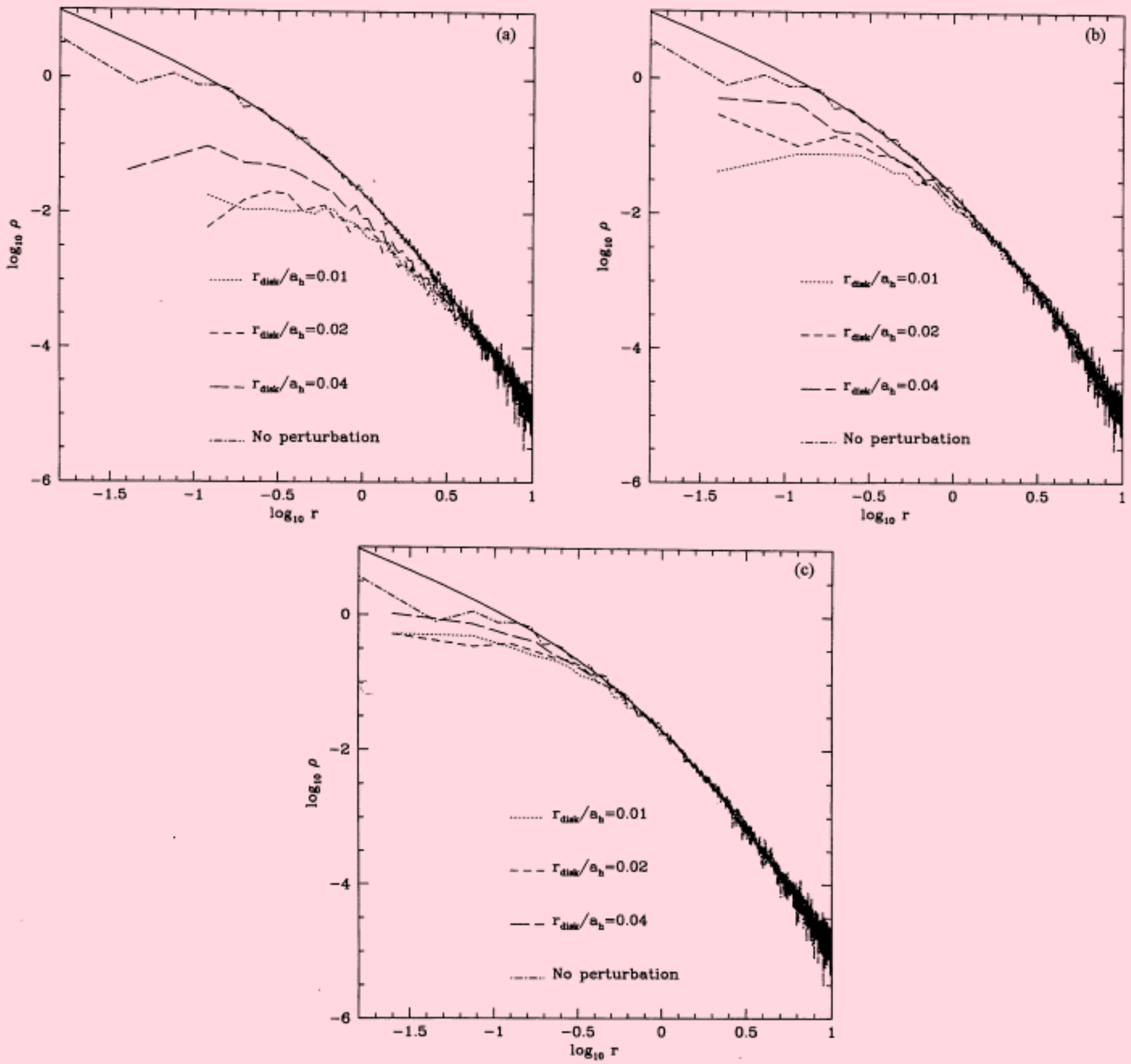
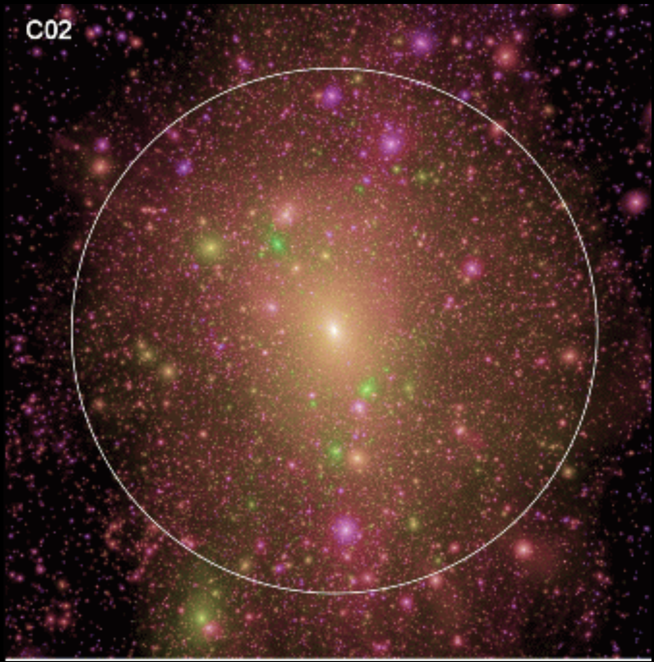
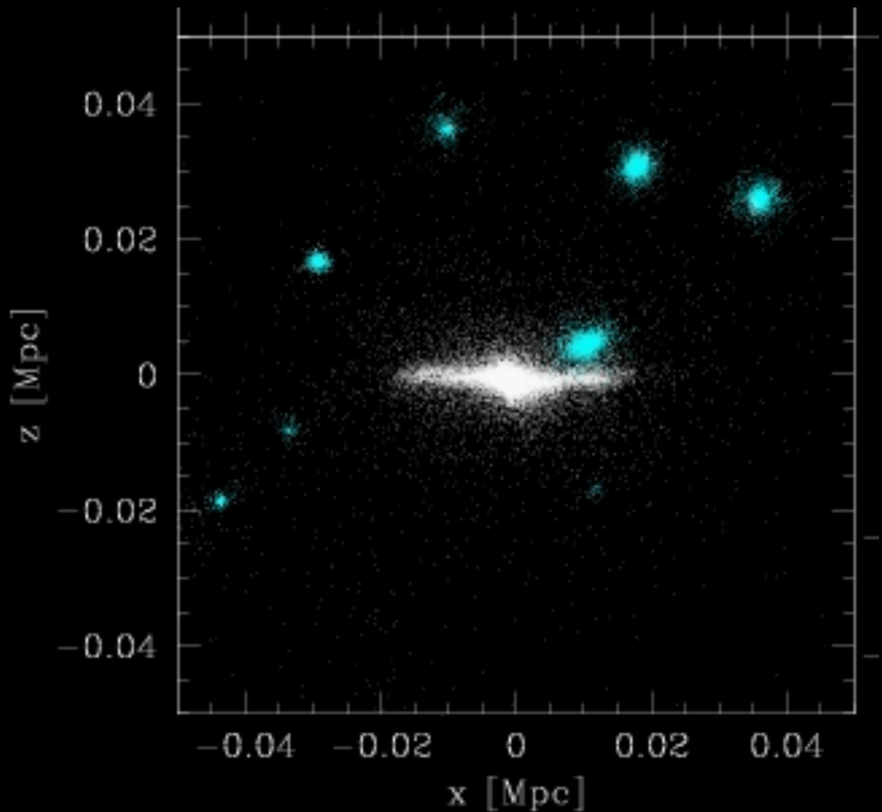


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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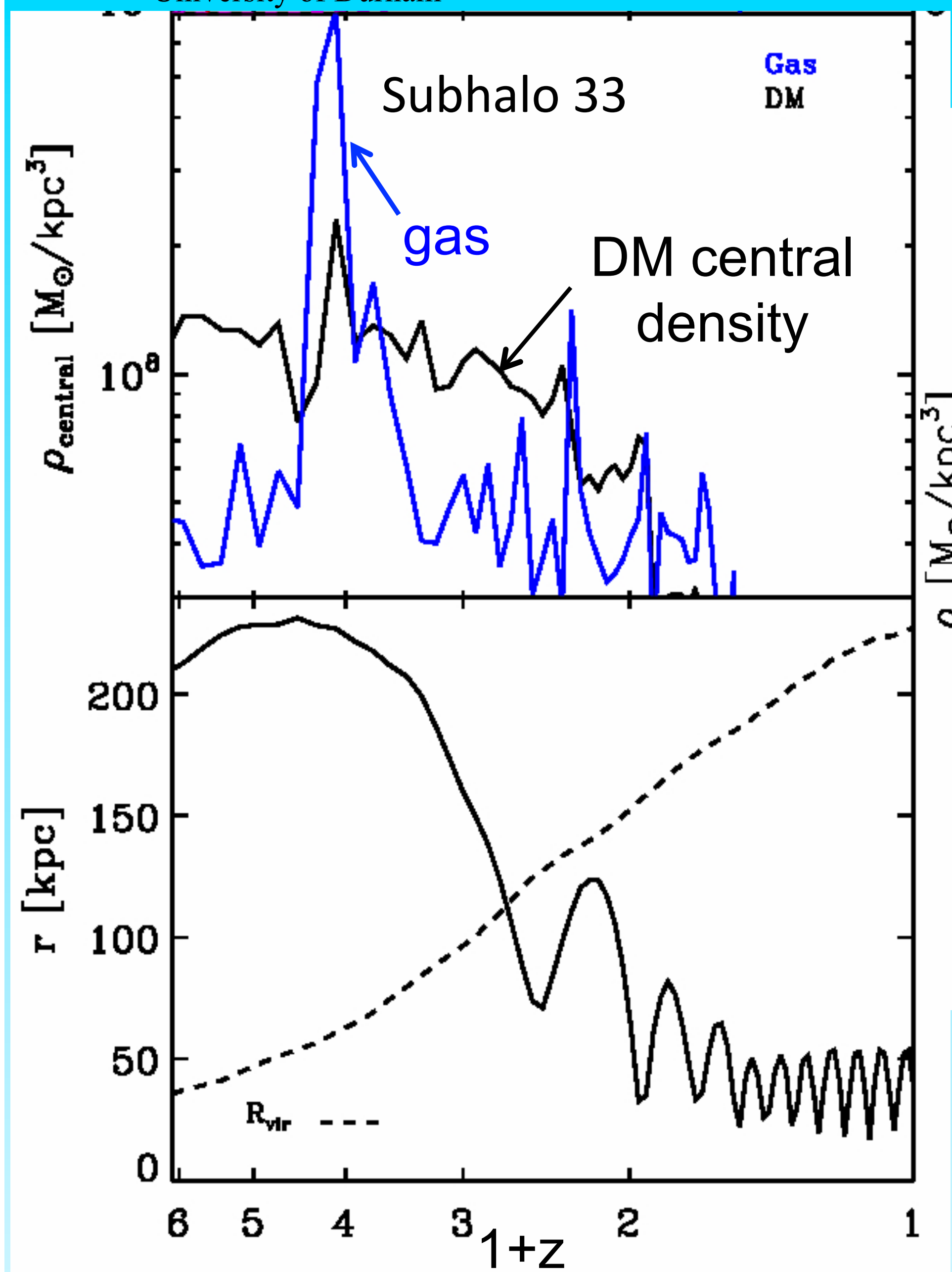

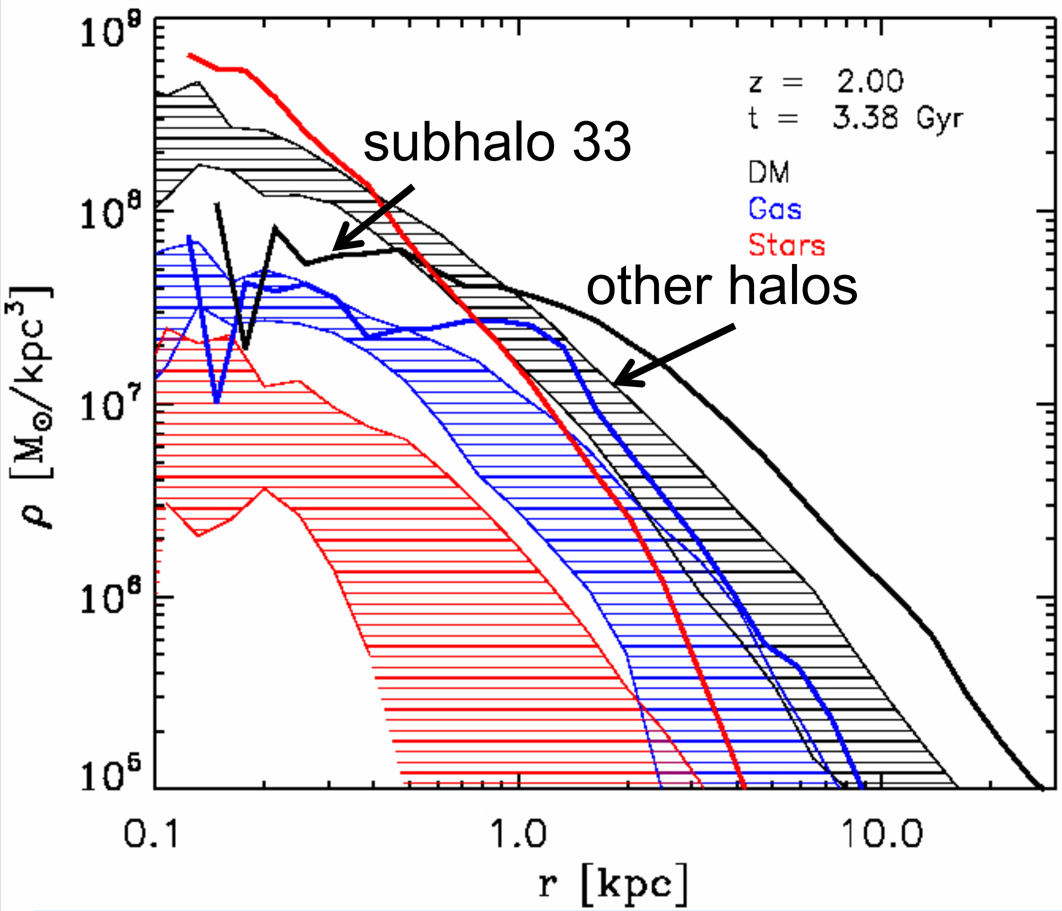

Parry, Eke & Frenk '11

Institute for Computational Cosmology

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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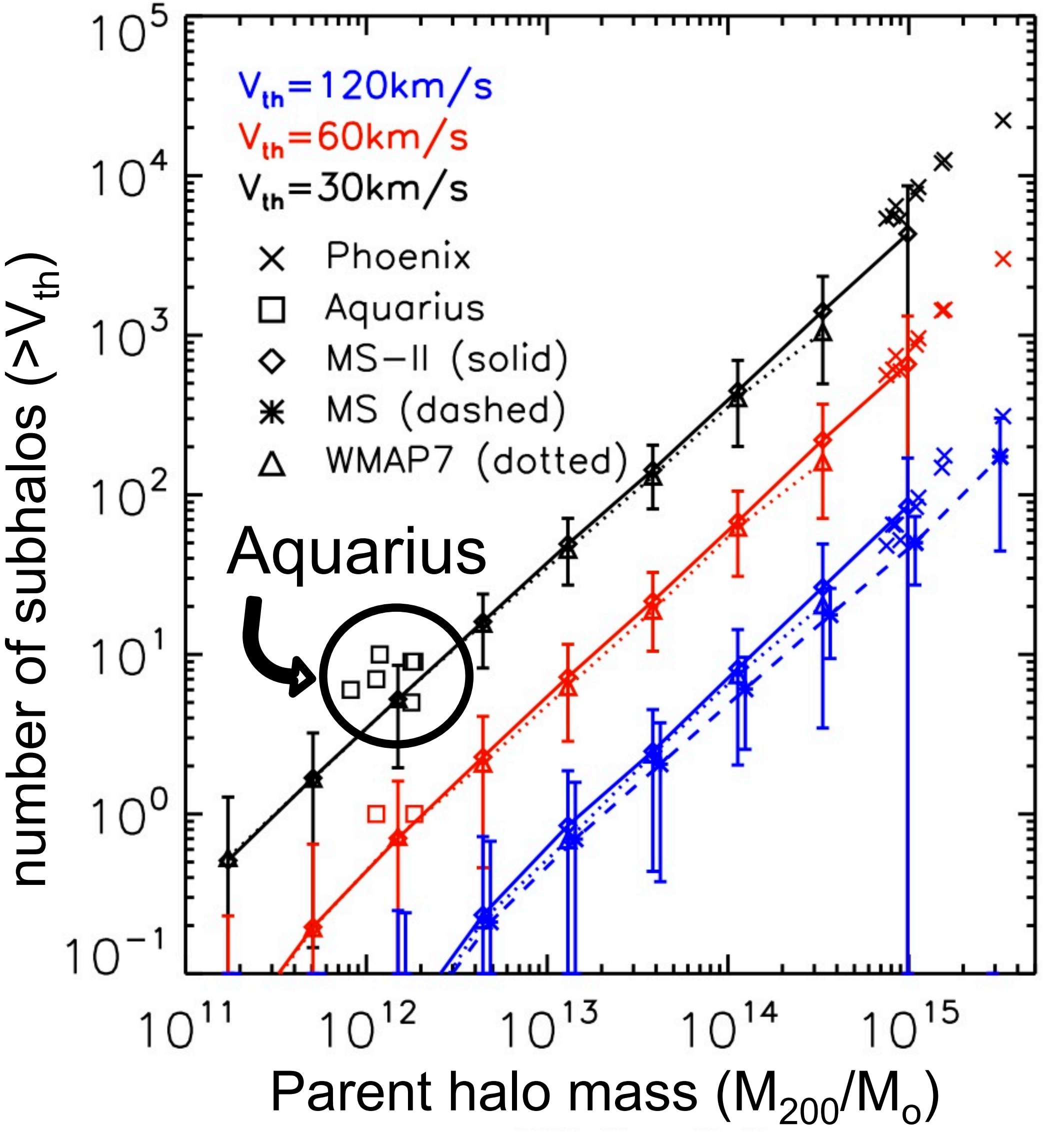
Number of massive subhalos

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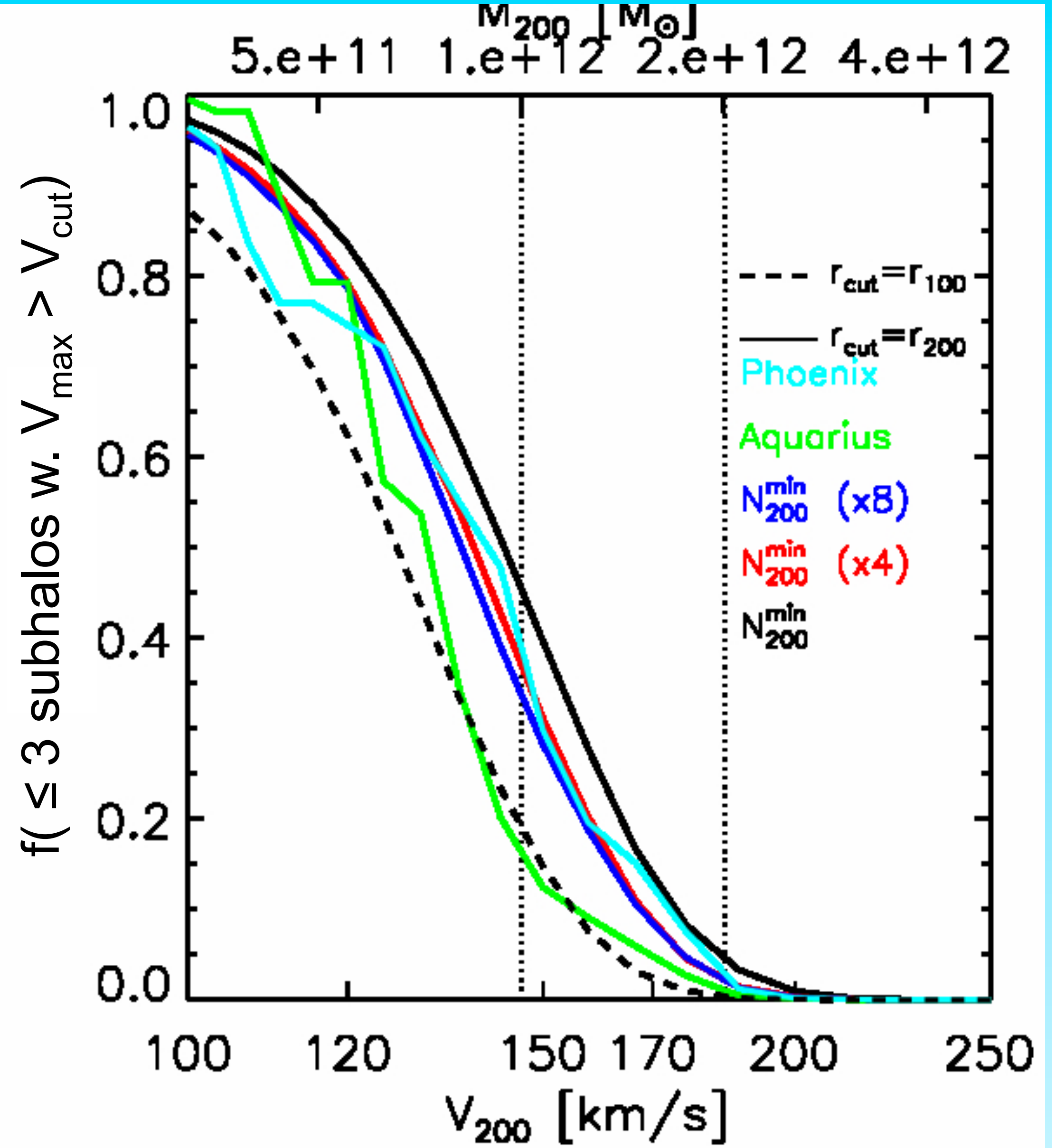
Probability of having no more than 3 subhalos with V_{max}> 30 km/s

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

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

If mass of MW ~1x10^{12}M$_o$, CDM is OK



Wang, Frenk, Navarro, Gao '12

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University of Durham

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

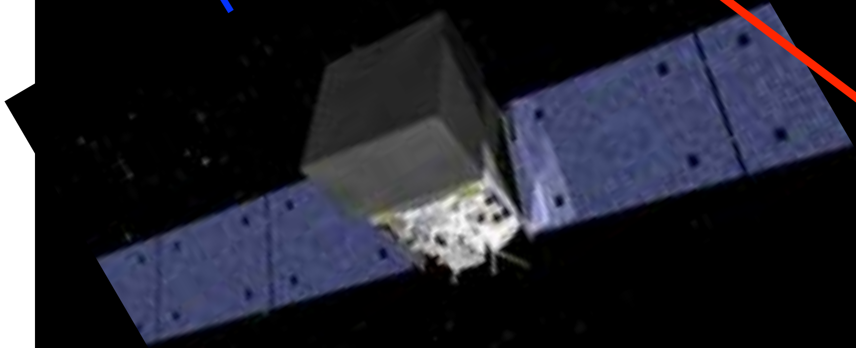
Possible solutions:

- Warm dark matter
- Baryon effects that make large CDM subhalos less concentrated
- $M_{MW\text{-}halo} \leq 10^{12} M_o$ rather than $2\times10^{12} M_o$

Cold dark matter ?

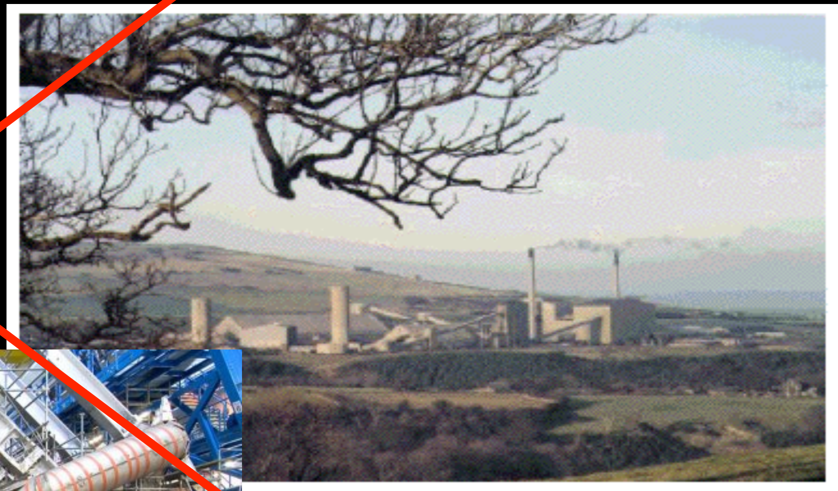
If mass of MW halo $>2 \times 10^{12} M_{\odot}$

Fermi

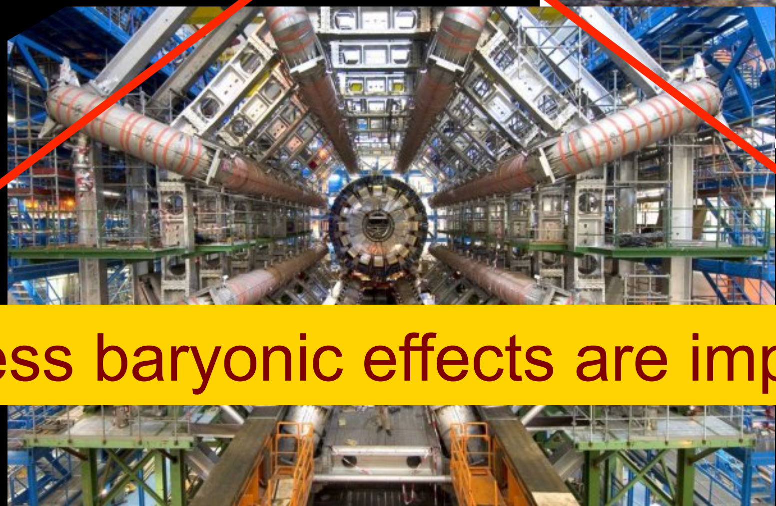


Annihilation radiation

Direct detection



UK DM search
(Boulby mine)



Unless baryonic effects are important

Evidence for SUSY

Warm dark matter ?

Sterile neutrino detection possible

Decay line in X-rays

Constellation X

Tritium β - decay