Decoding the identity of the dark matter from Milky Way data

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Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm		keV-MeV
cold	axion neutralino	10^{-5}eV - 100 GeV

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The dark matter power spectrum

Free streaming →

$\lambda_{cut} \; \alpha \; m_x^{-1}$

for thermal relic

$m_{CDM} \sim 100GeV$

susy; $M_{cut} \sim 10^{-6} M_o$

$m_{WDM} \sim$ few keV

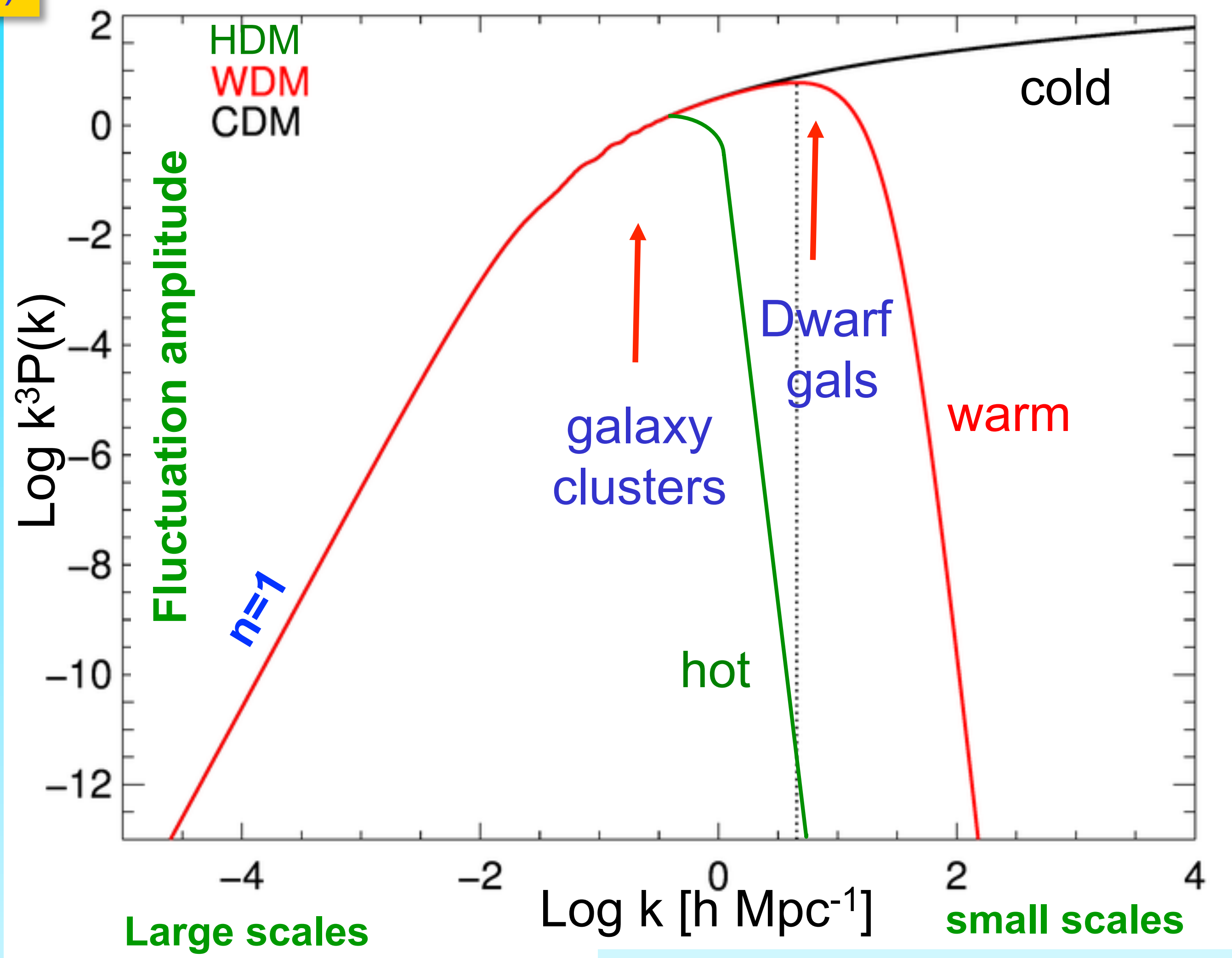
sterile ν; $M_{cut} \sim 10^9 M_o$

$m_{HDM} \sim$ few eV

light ν; $M_{cut} \sim 10^{15} M_o$

$k^3 P(k)$

The linear power spectrum ("power per octave")



The formation of cosmic structure

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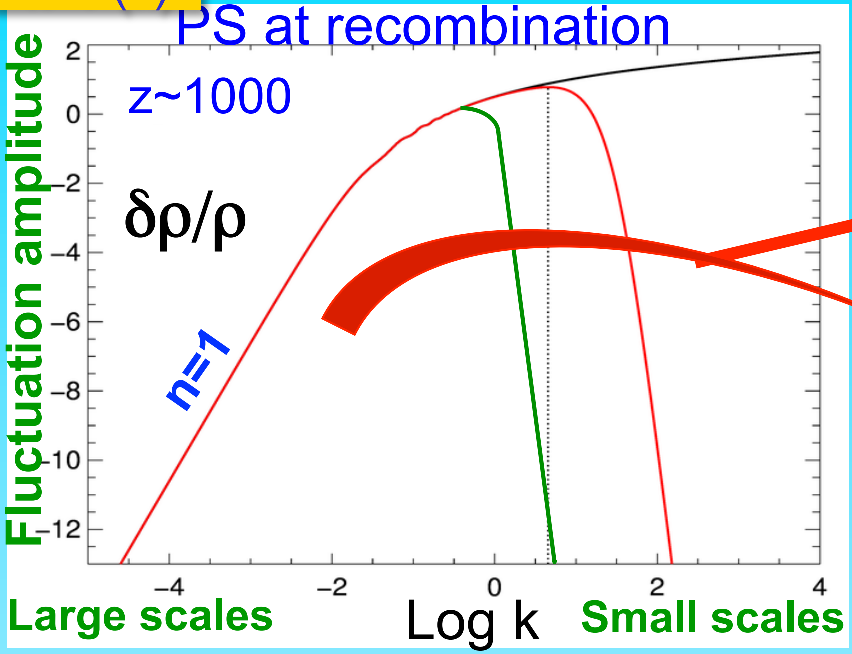
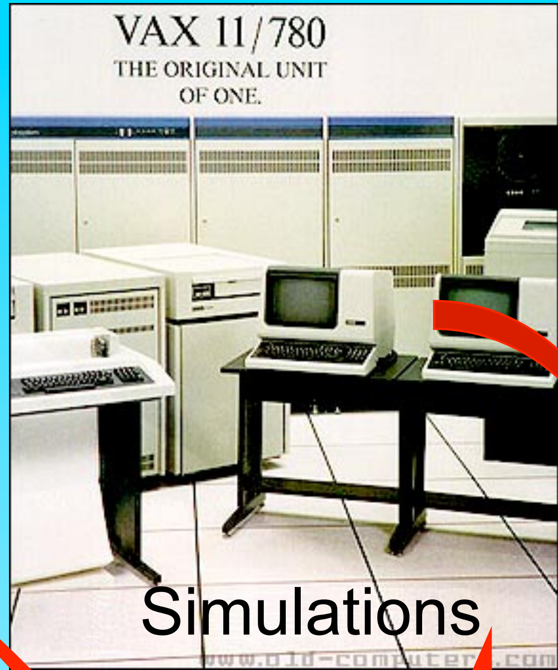
$k^3 P(k)$





t=380,000 yrs

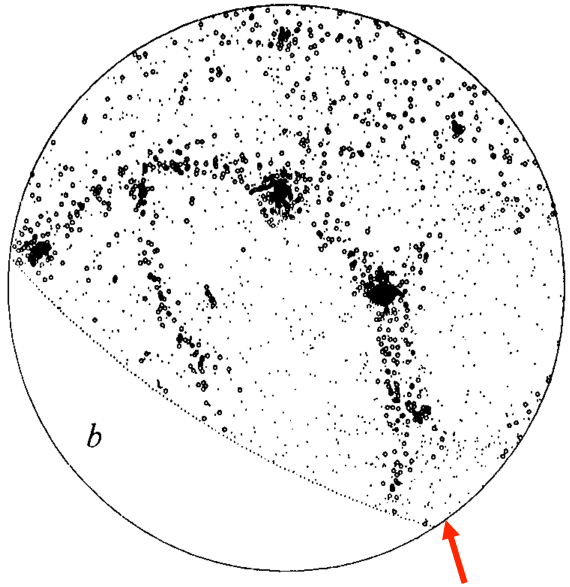
$\delta\rho/\rho \sim 10^{-5}$

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

t=14.1billion yrs

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

Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

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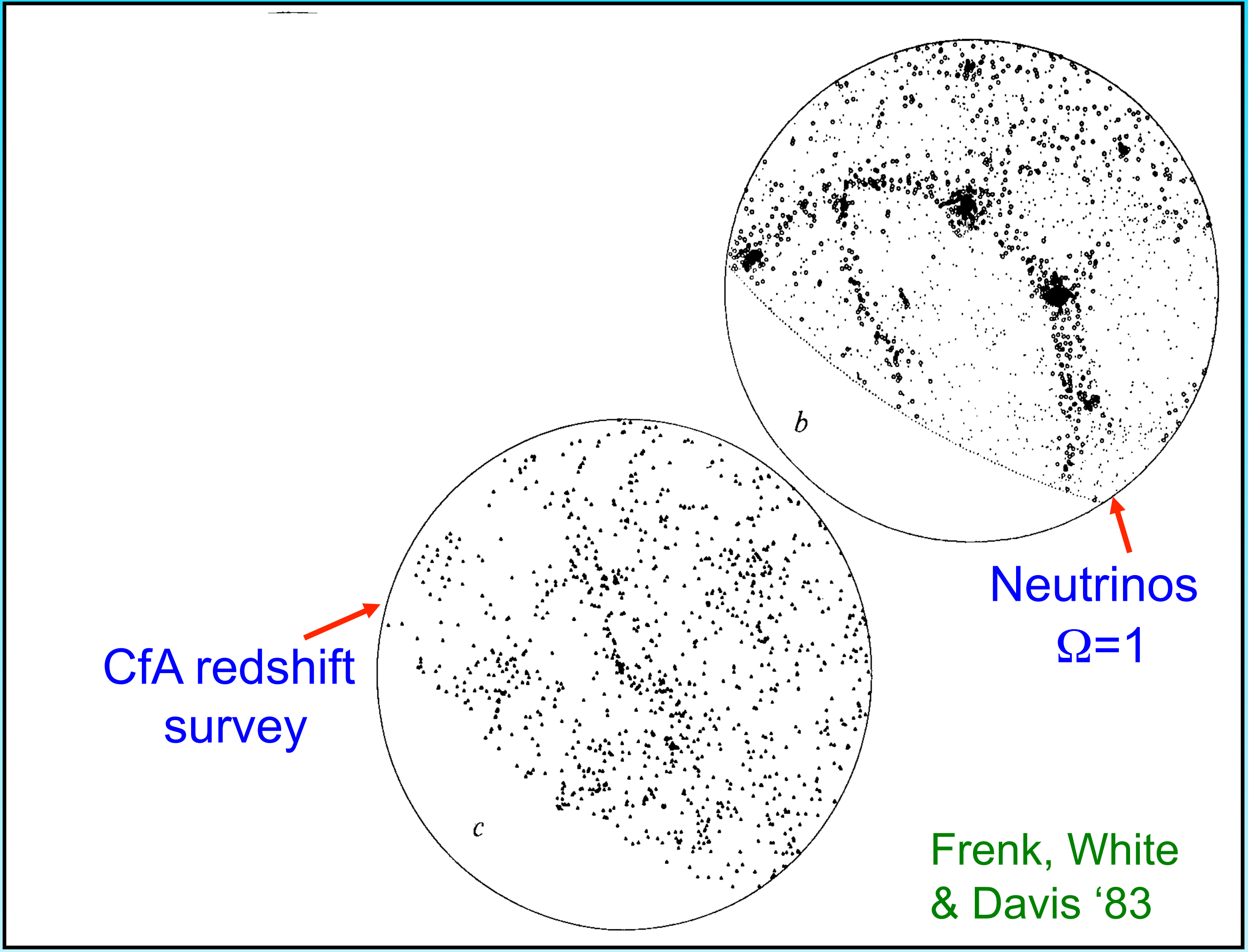
Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 10$ ev



Non-baryonic dark matter cosmologies

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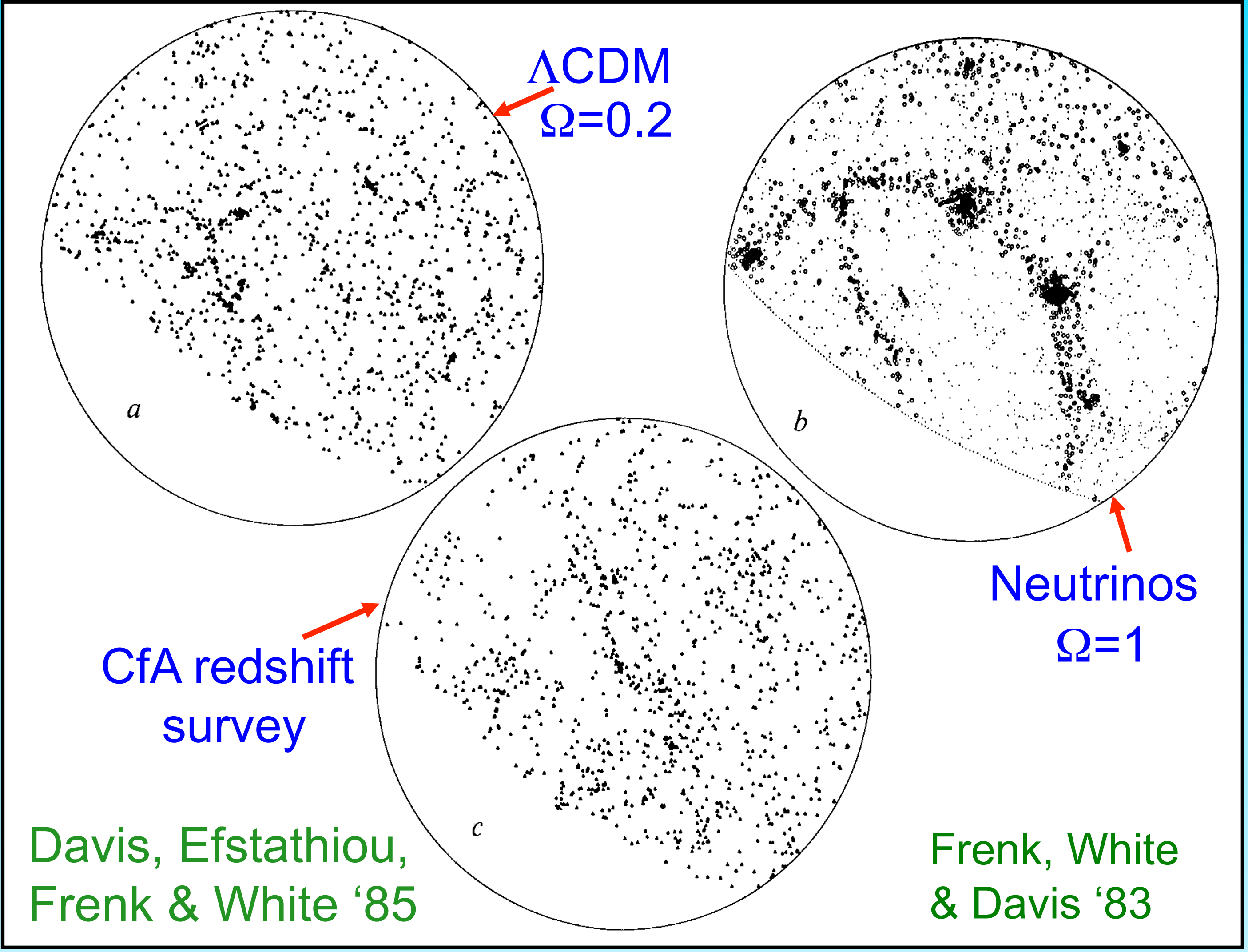
Neutrino DM → unrealistic clust'ing

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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Non-baryonic dark matter candidates

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

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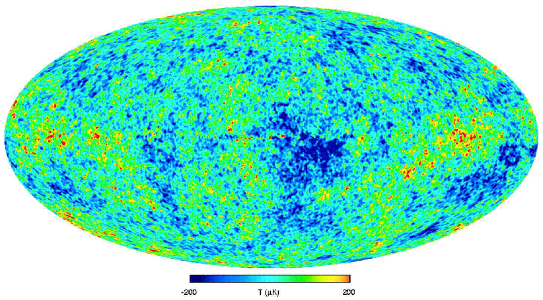
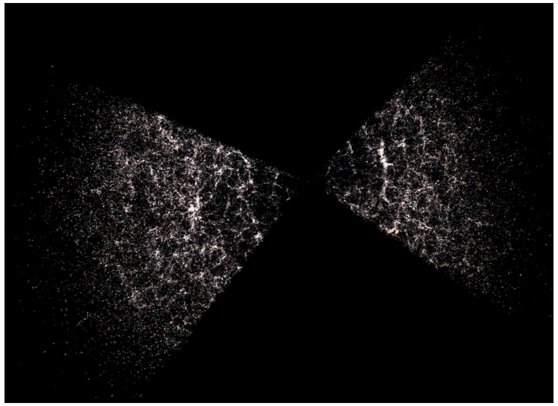
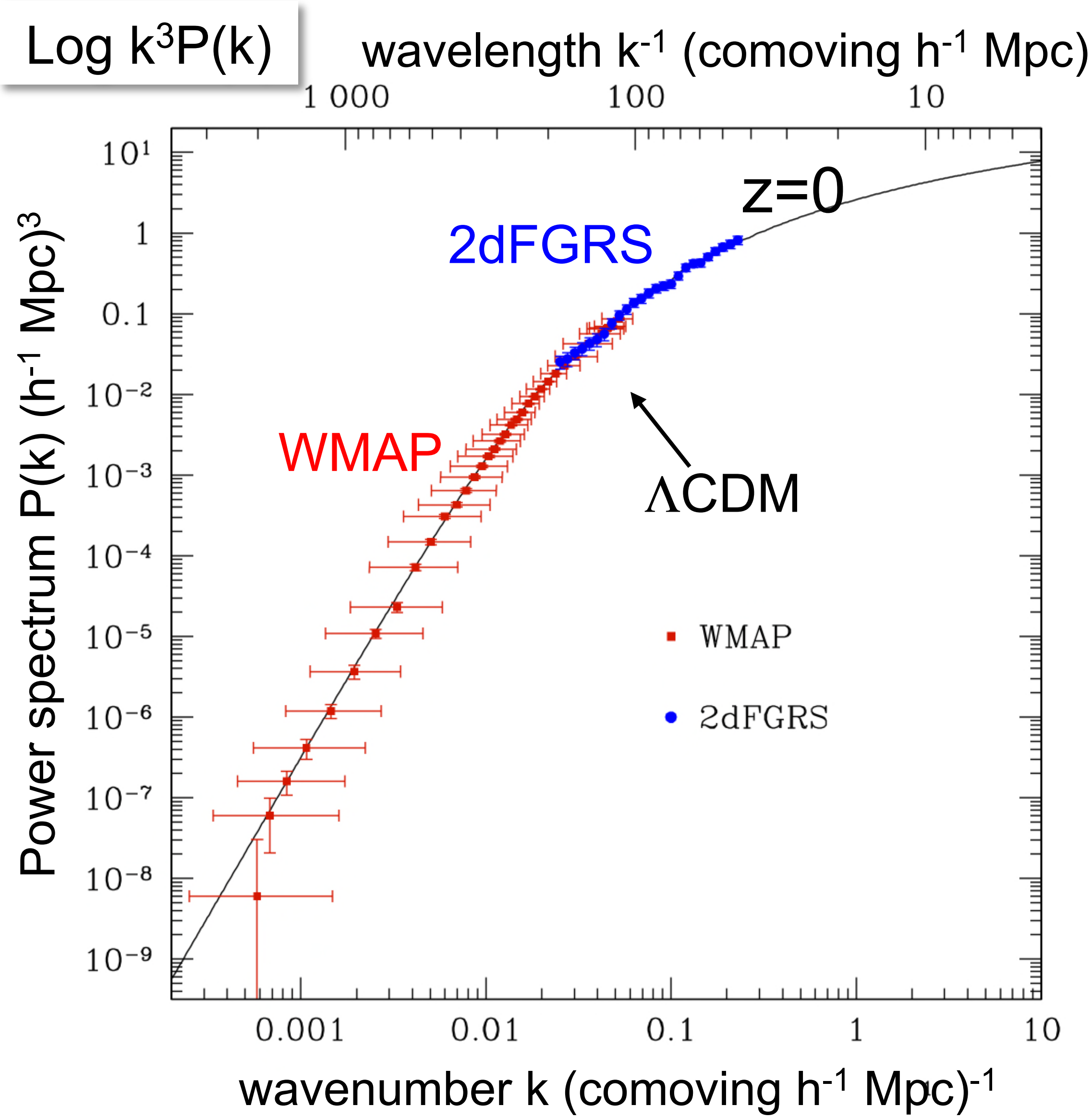
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

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

Free streaming →

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

for thermal relic

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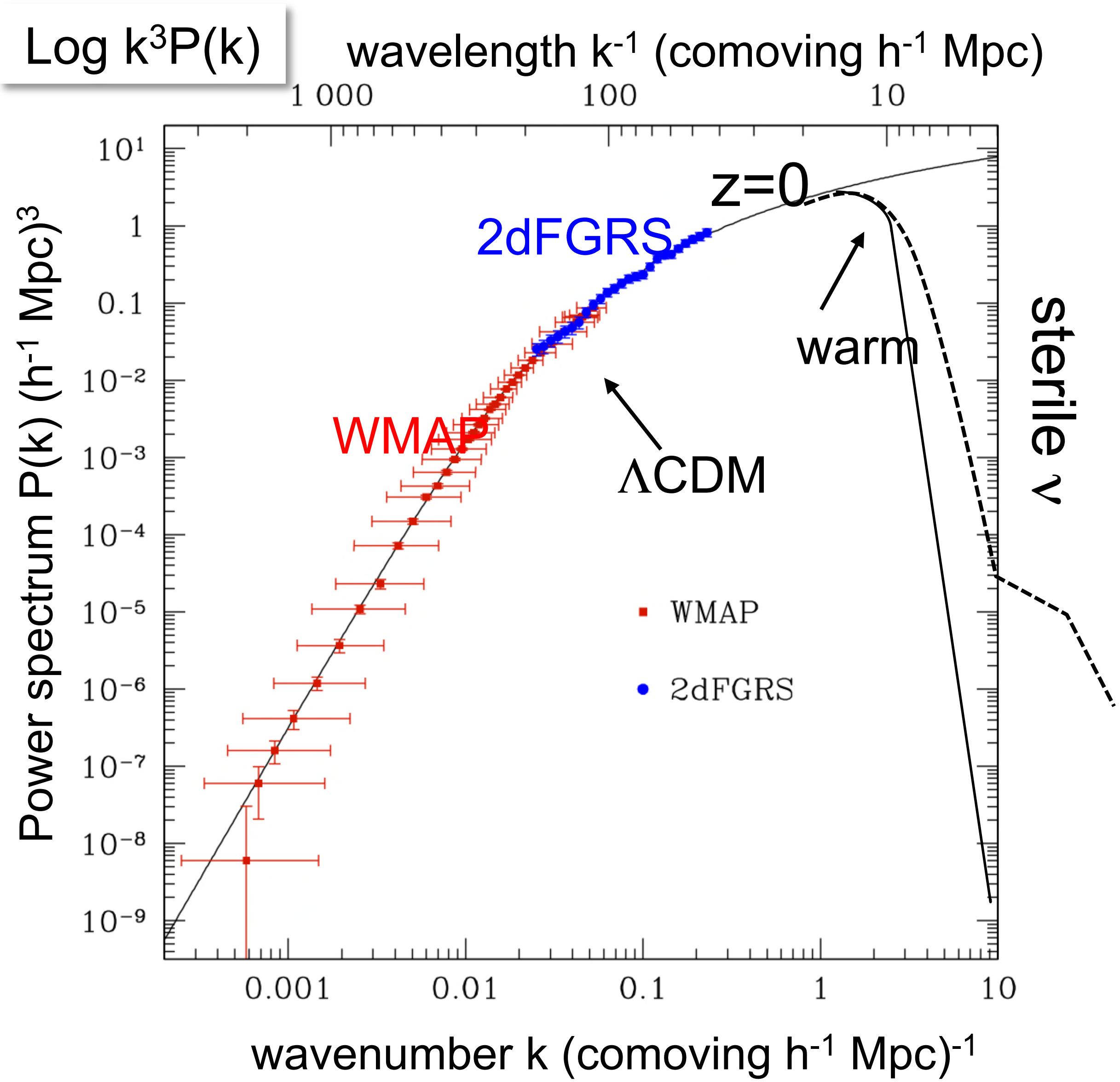

Astrophysical key to identity of dark matter:

→Subgalactic scales

(strongly non-linear)


z = 48.4
T = 0.05 Gyr
500 kpc

Cold Dark Matter Warm Dark Matter

13.4 billion years ago

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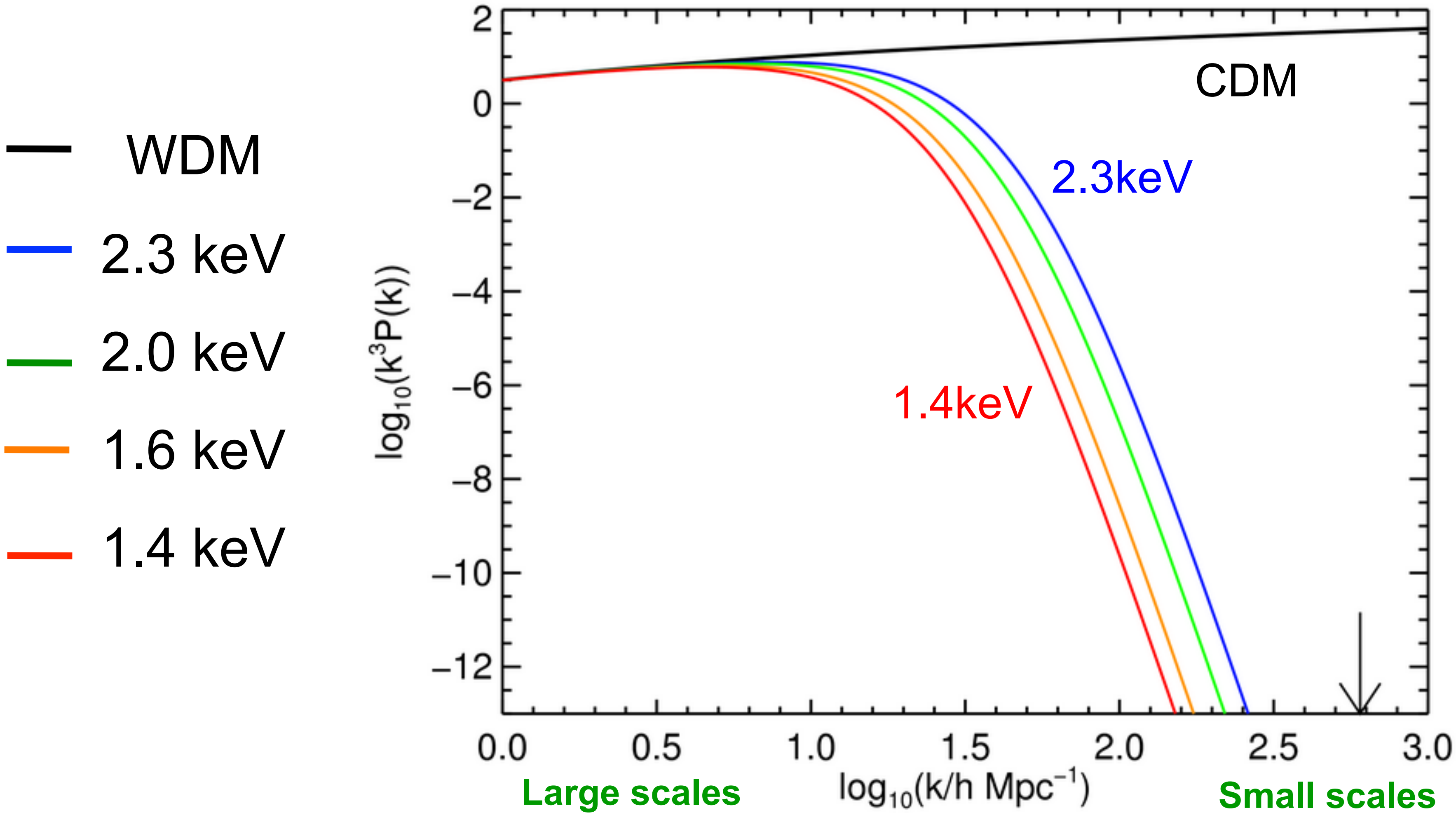
cold dark matter | warm dark matter

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

Warm DM: different ν mass

The linear power spectrum ("power per octave")

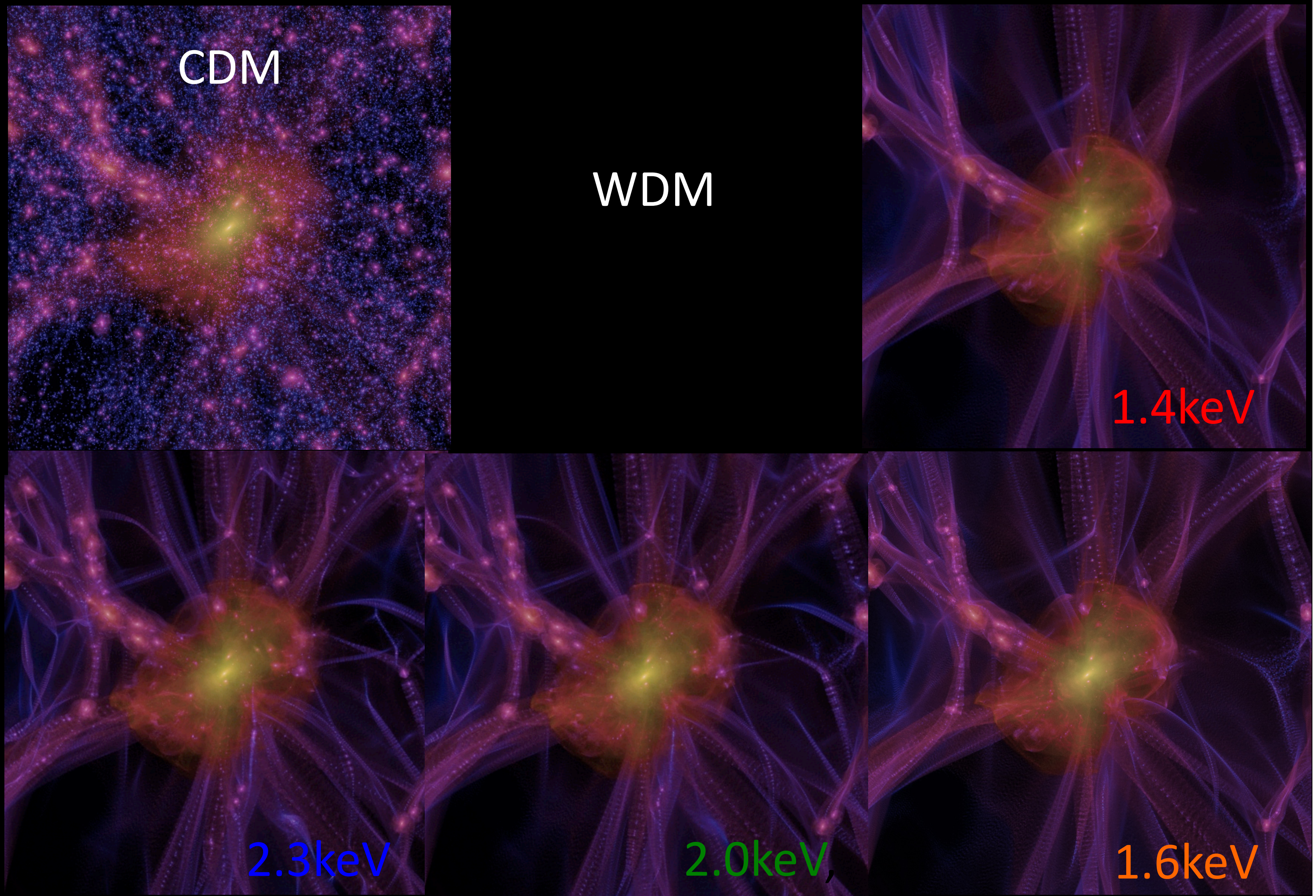


Lovell et al '13

Warm DM: different ν mass

z=3

WDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV



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N-body simulations: CDM *vs* WDM

Simulations make 2 important predictions on galactic scales:

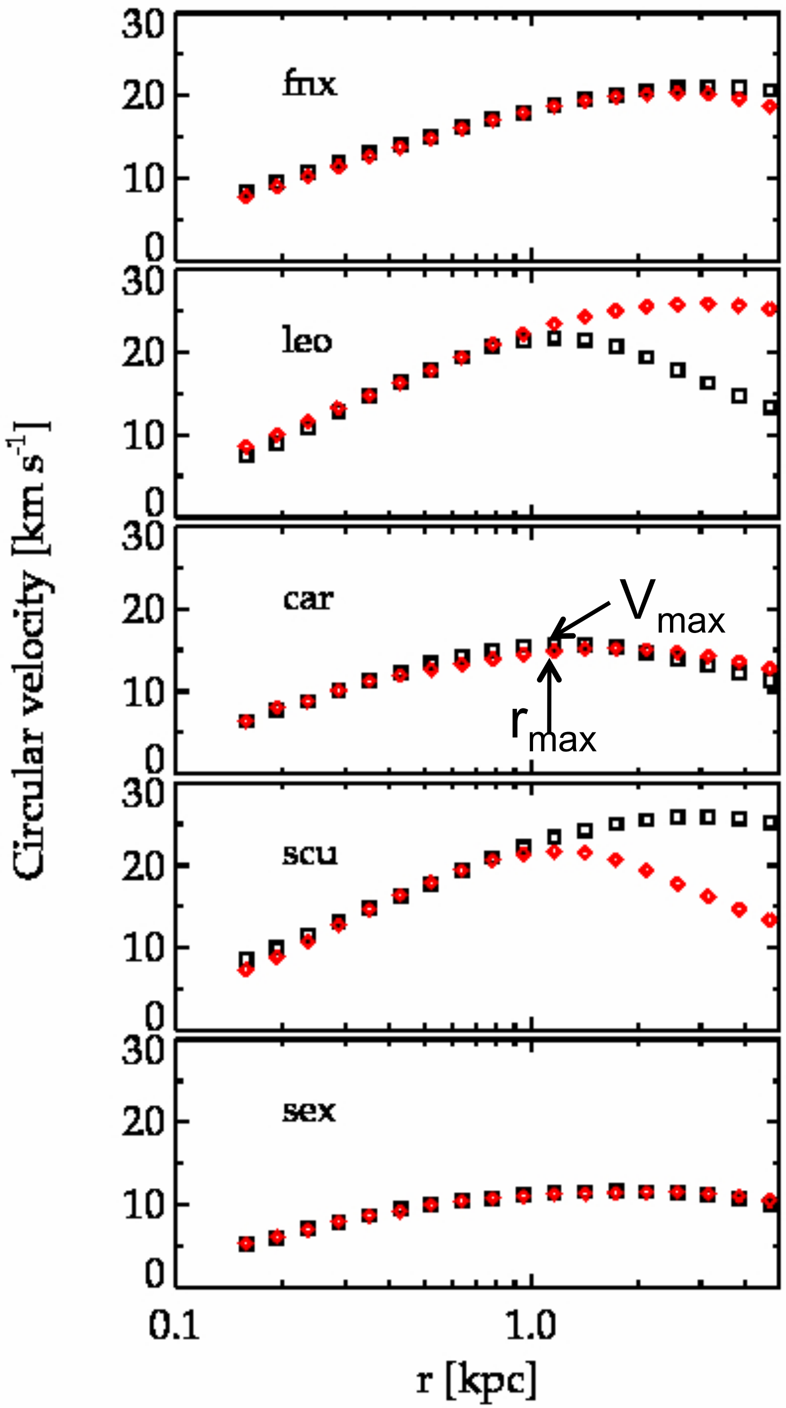
Cold dark matter

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

Warm dark matter

- Far fewer self-bound substructures (5% of mass) survive
- Main halo profile identical to CDM; subhalos still "cuspy" but less concentrated than in CDM

The structure of the Milky Way satellites



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

Strigari, Frenk & White 2010

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The mass function of substructures

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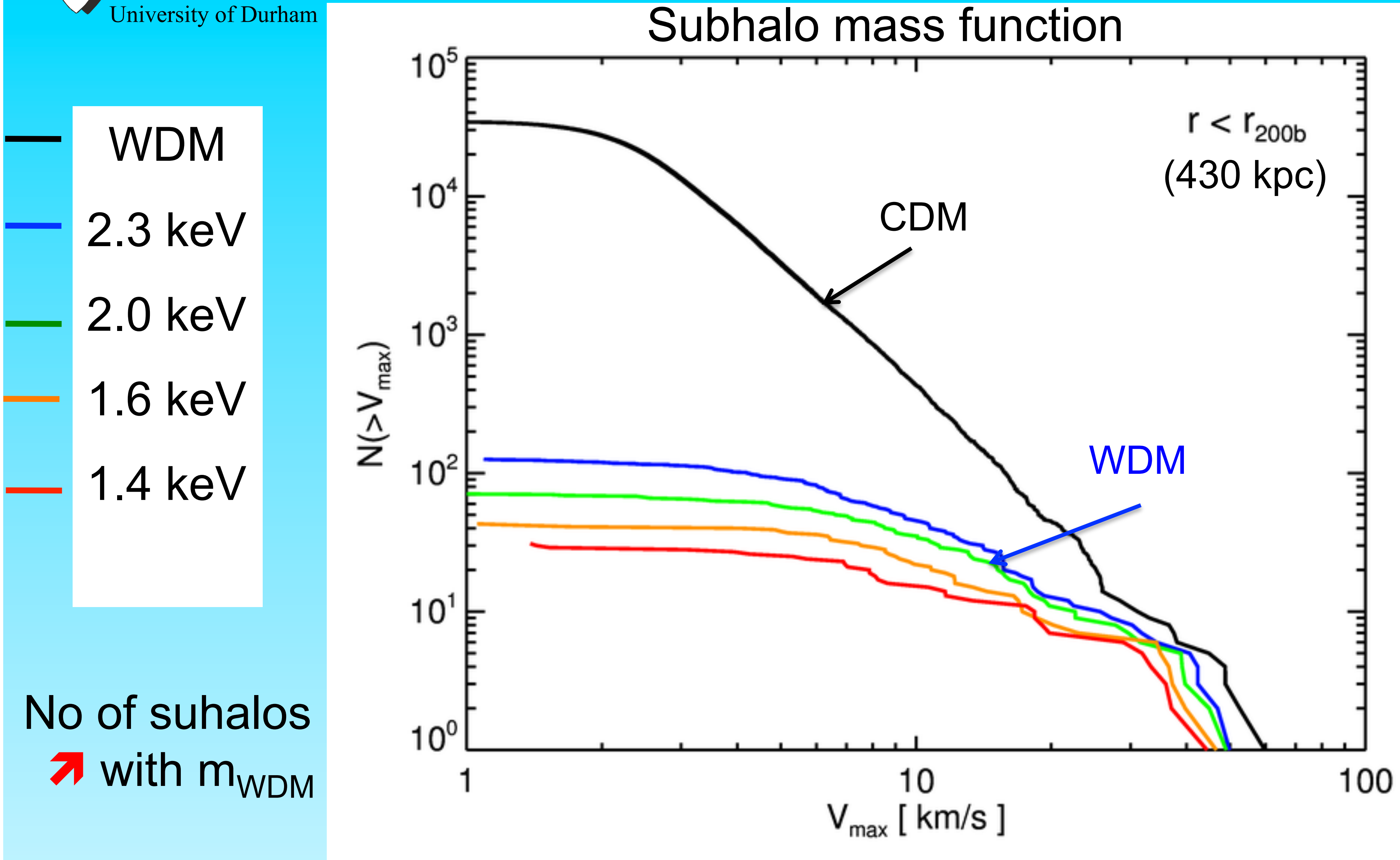

No of suhalos ↗ with m_{WDM}

Lovell et al '13

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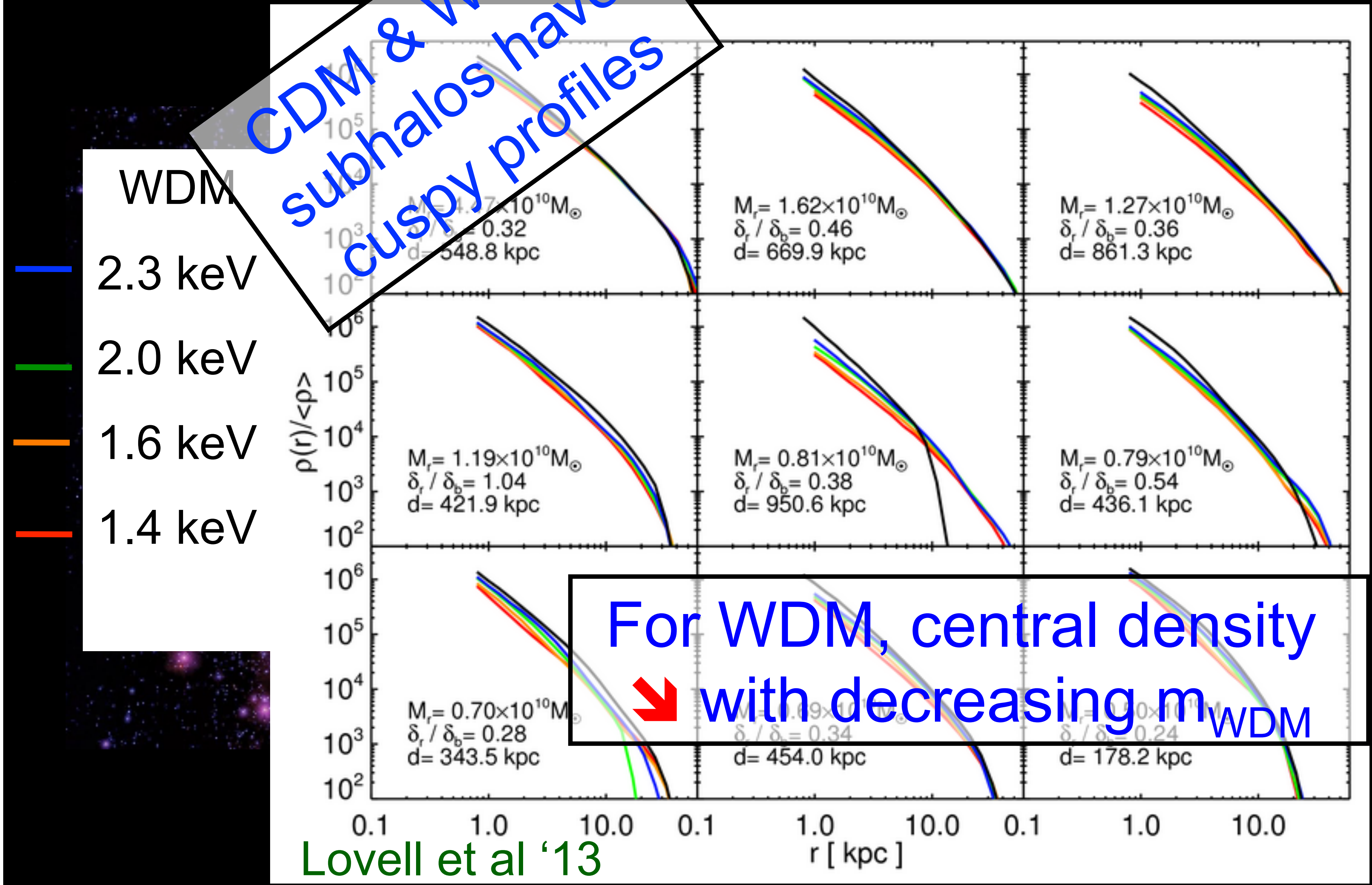
Subhalo density profiles

CDM & WDM subhalos have cuspy profiles



For WDM, central density ↘ with decreasing m_{WDM}

Lovell et al ‘13

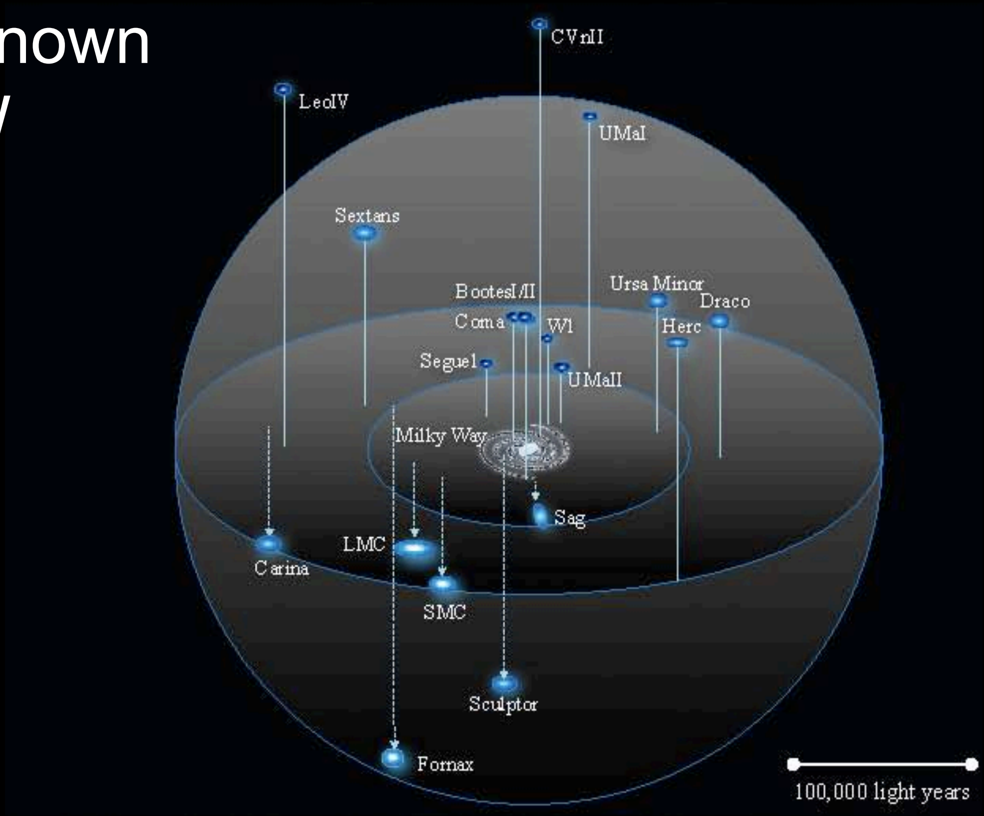
How can we distinguish between CDM & WDM ?

Cosmology on small scales

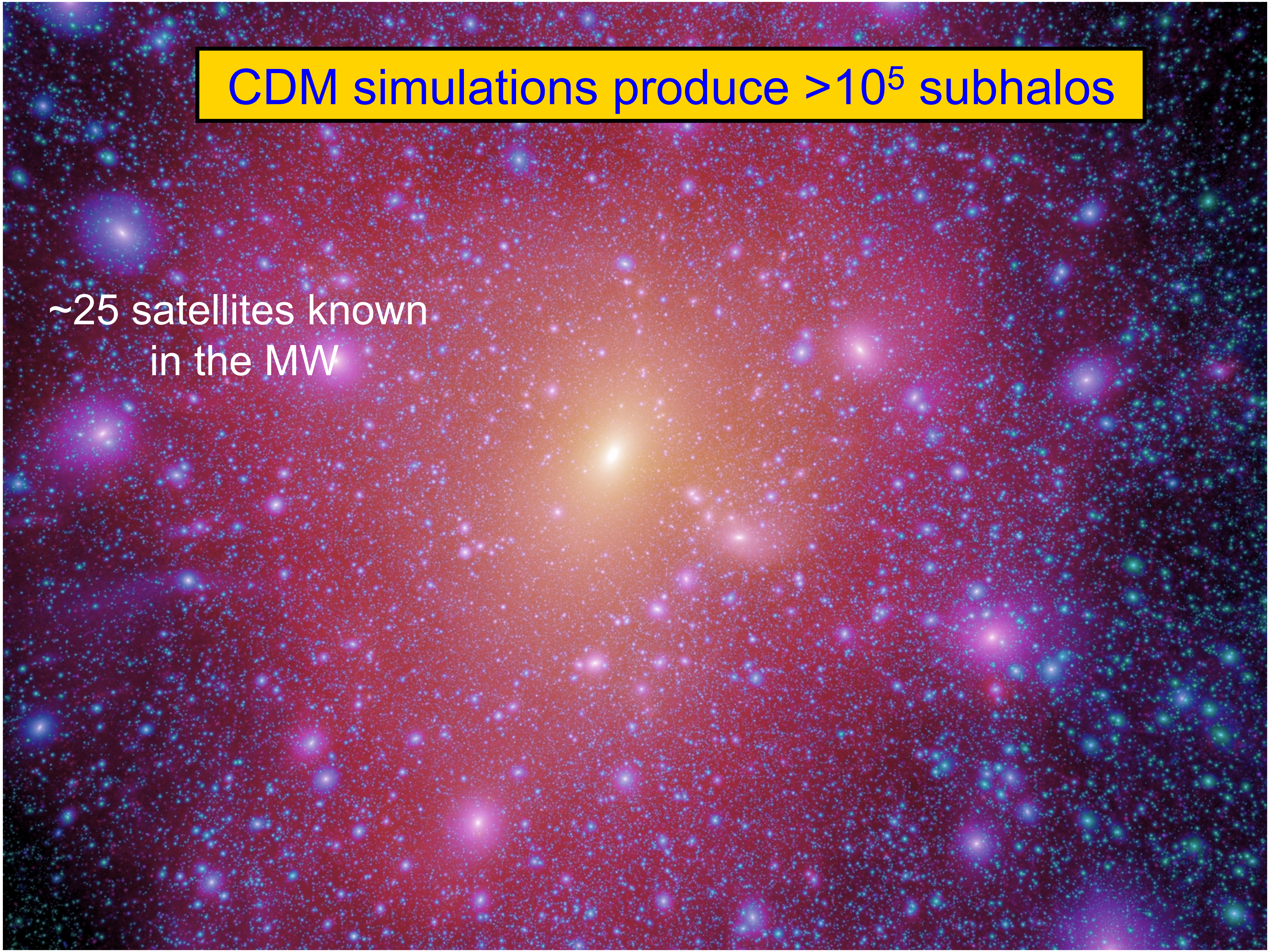
- The number of satellites (the “satellite problem”)
- The structure of satellites (the “too-big-to-fail” problem)

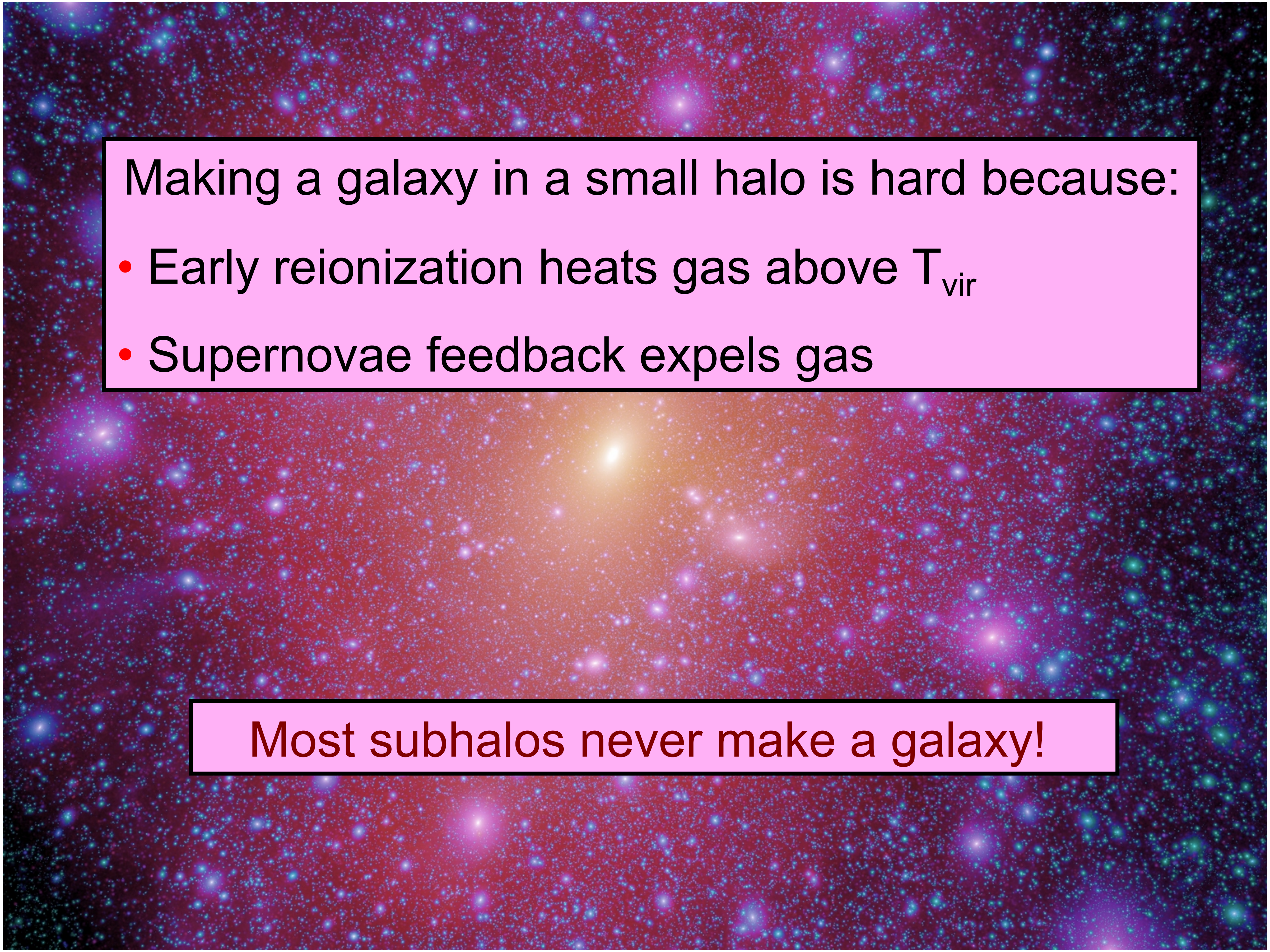
The satellites of the Milky Way

~25 satellites known
in the MW



CDM simulations produce >10^5 subhalos





Making a galaxy in a small halo is hard because:

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

Most subhalos never make a galaxy!

Luminosity Function of Local Group Satellites

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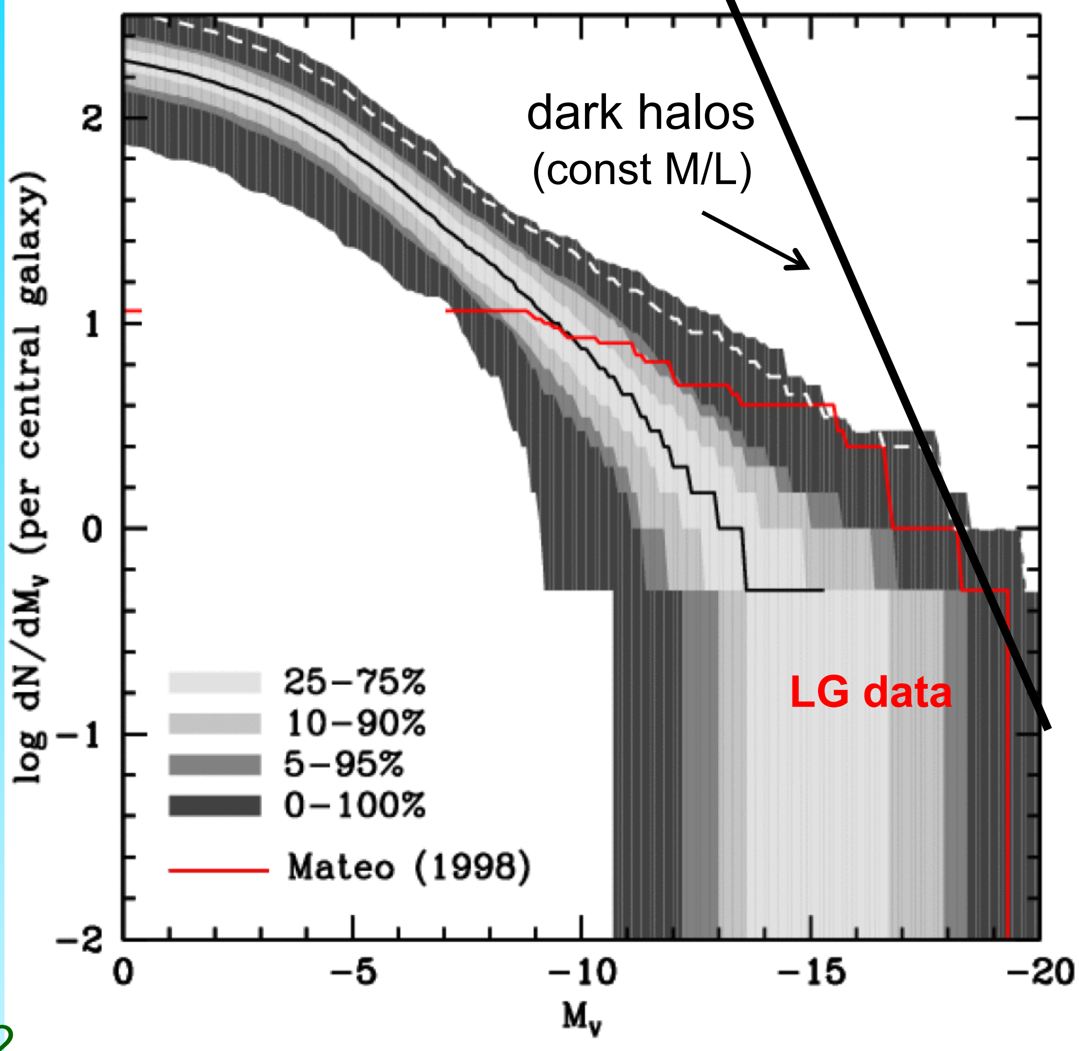
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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

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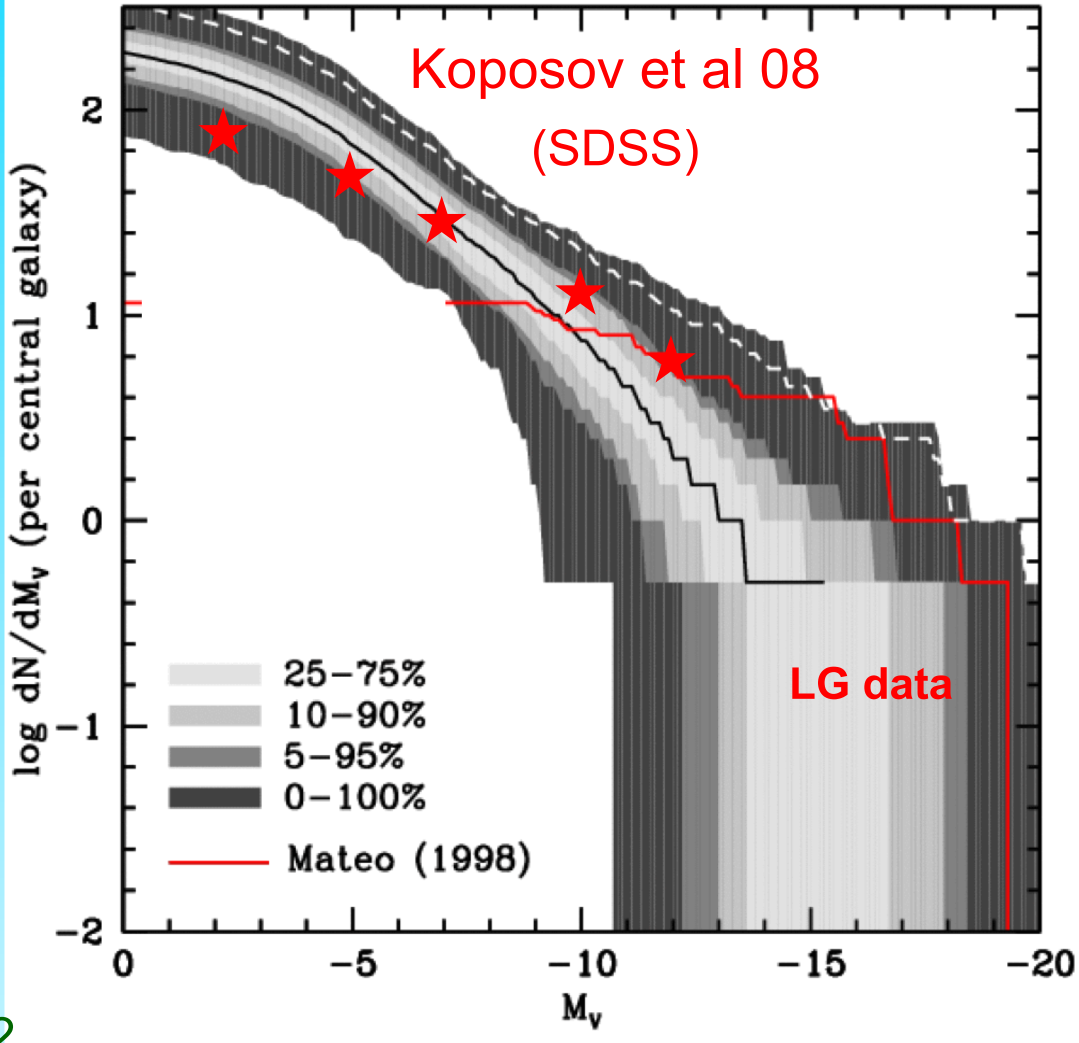

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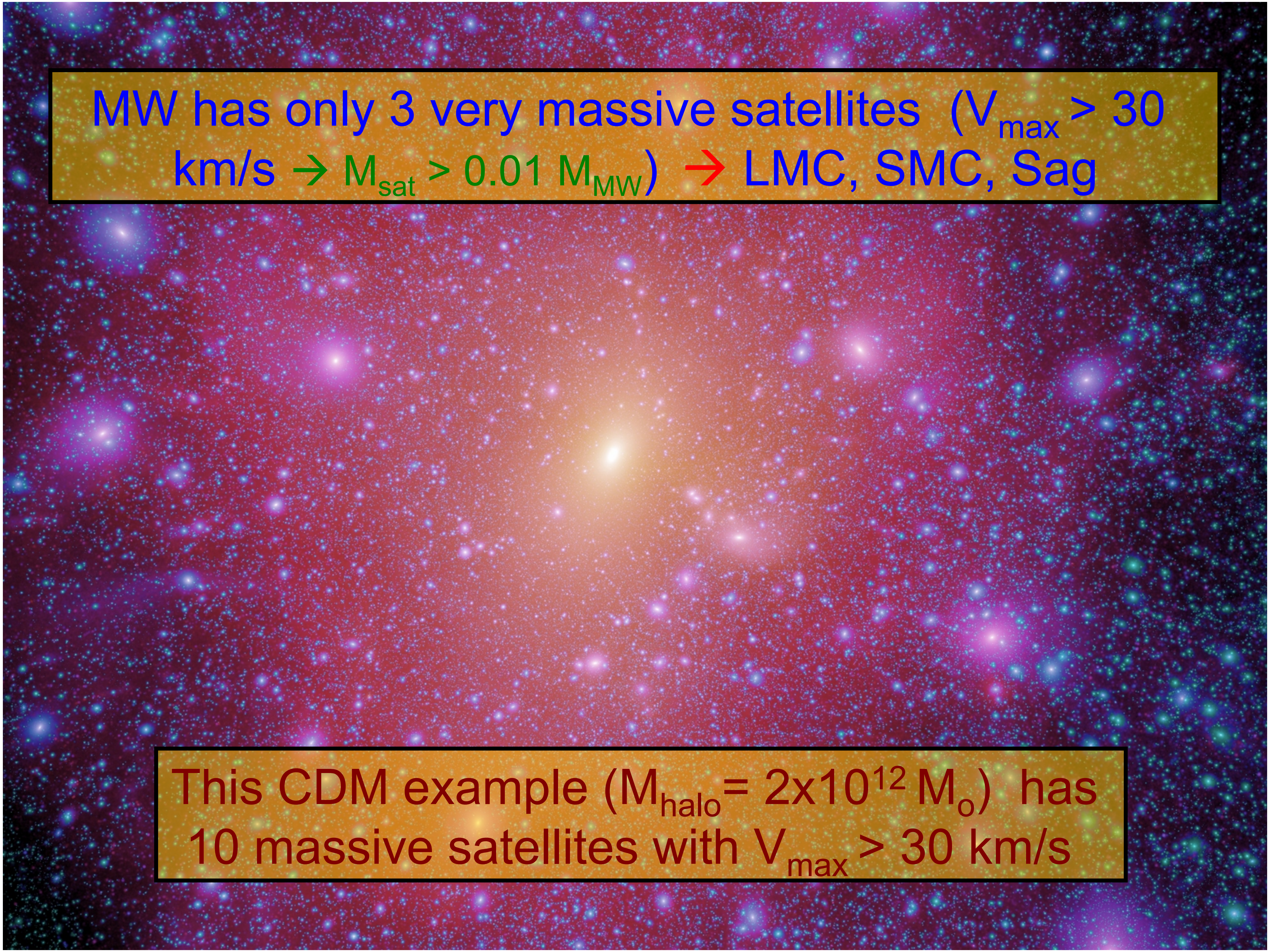

MW has only 3 very massive satellites (V_{max} > 30 km/s → M_{sat} > 0.01 M_{MW}) → LMC, SMC, Sag
This CDM example (M_{halo}= $2x10^{12}$ M_o) has 10 massive satellites with V_{max} > 30 km/s

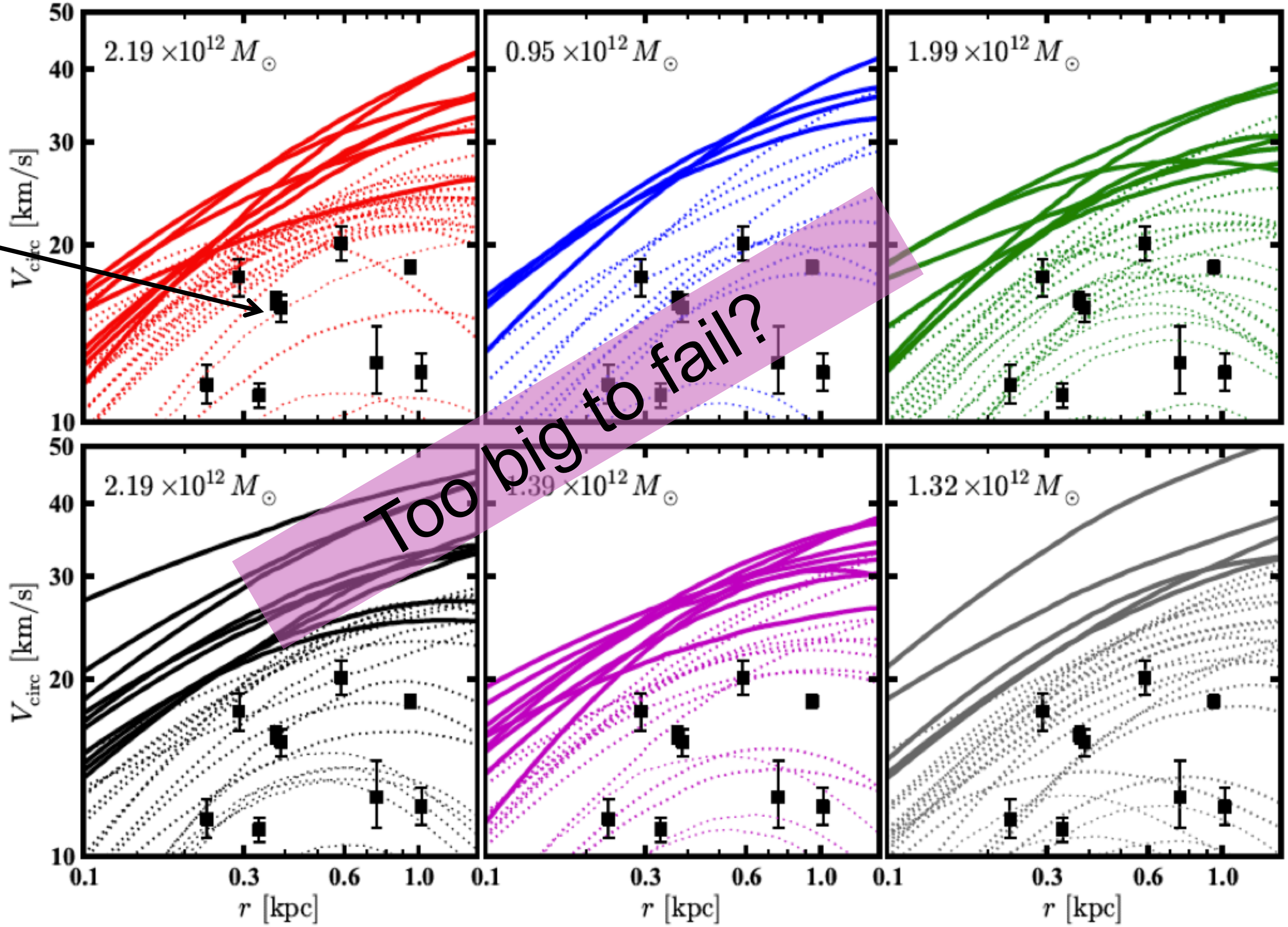
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11

$$V_c = \sqrt{\frac{GM}{r}}$$

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

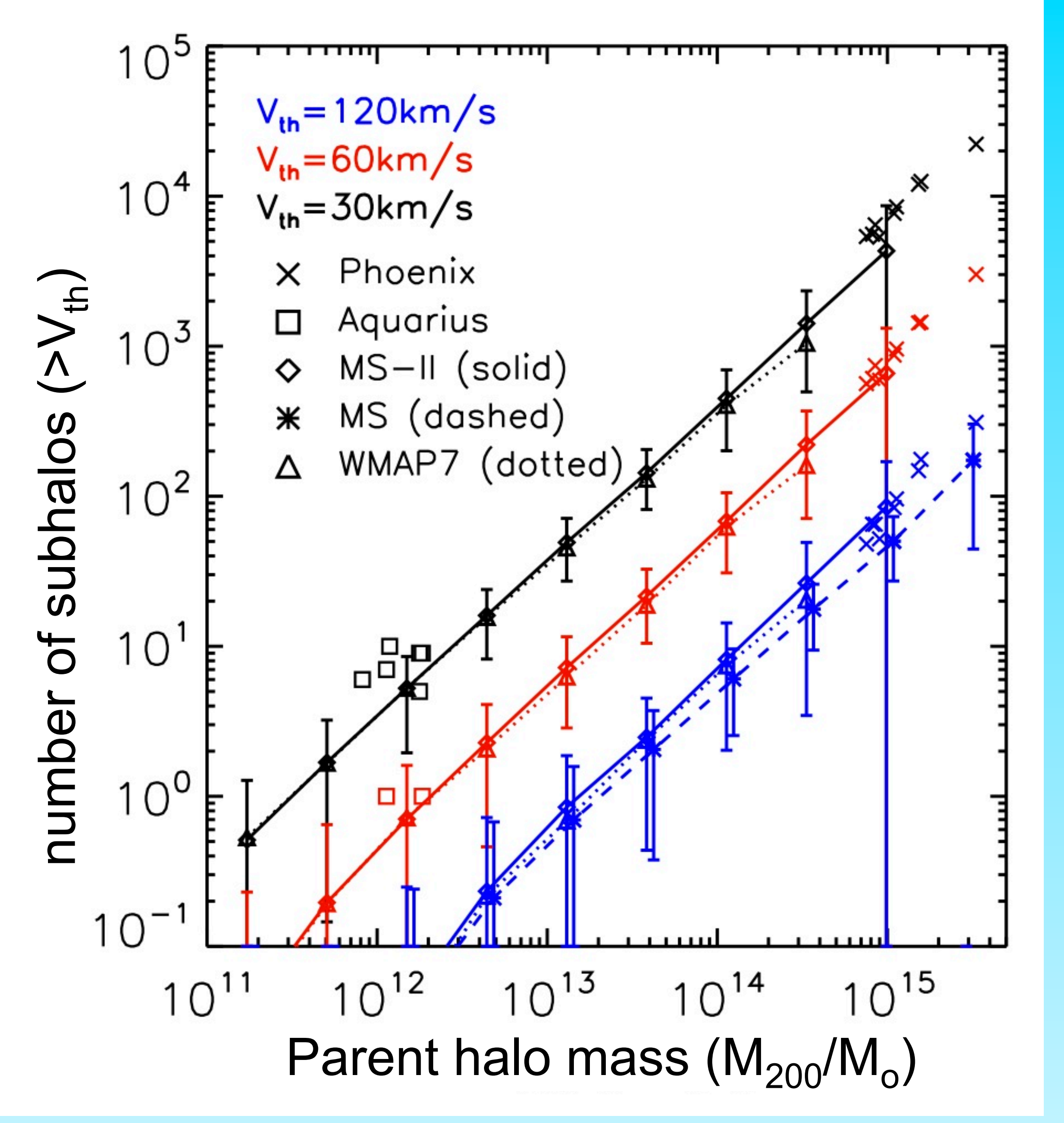
Excludes LMC, SMC, Sagittarius



Number of massive subhalos

Number of massive subhalos increases rapidly with halo mass

→ Milky Way halo mass cannot be too large if CDM is right!



Wang, Frenk, Navarro, Gao '12

Probability of massive subhalos

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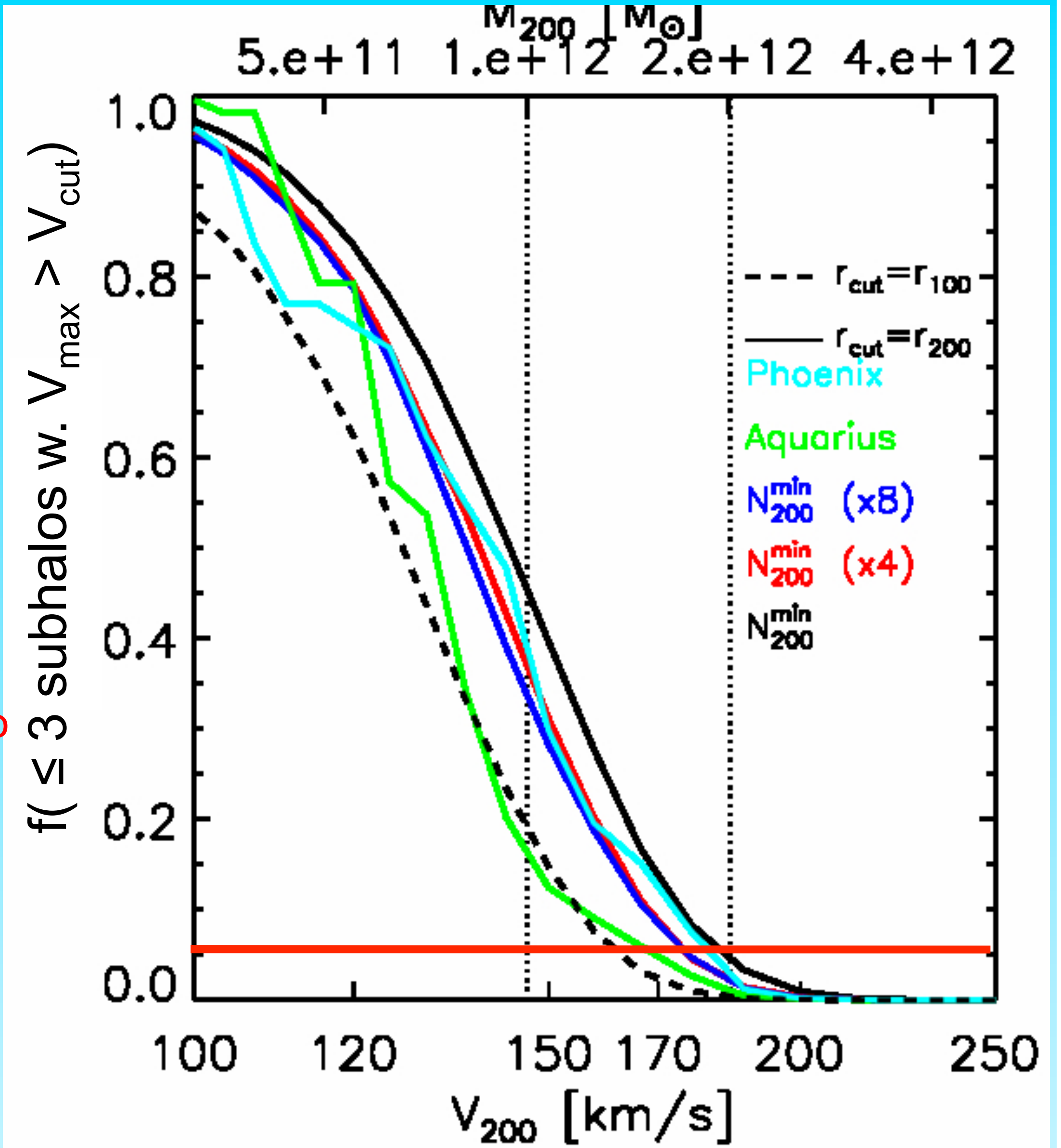
Probability of having no more than 3 subhalos with V_{max}> 30 km/s

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

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

CDM requires

$M_{halo}< 1.5x10^{12}M_o$ (95% confidence)



Wang, Frenk, Navarro, Gao '12

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Cosmology on small scales

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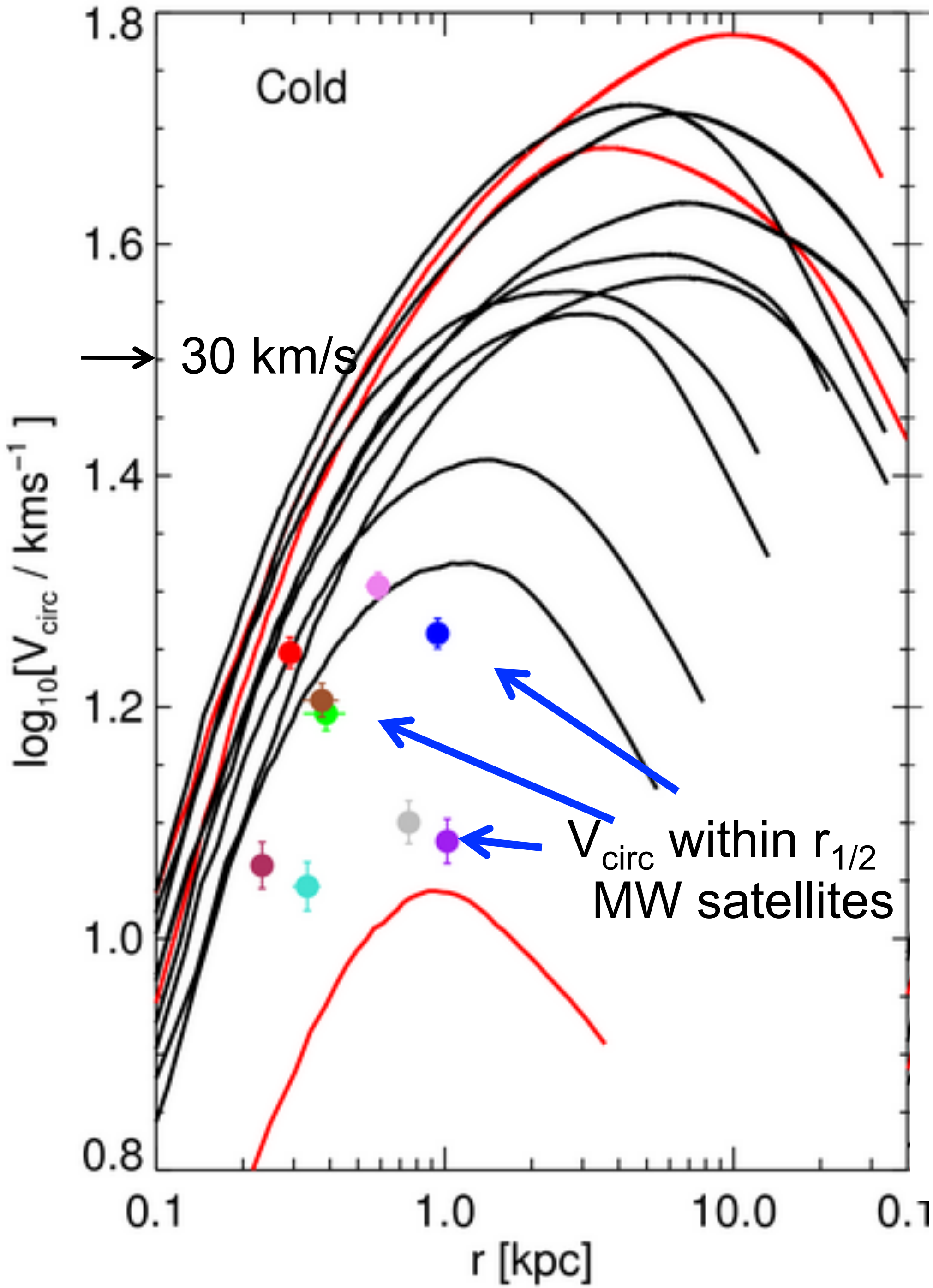
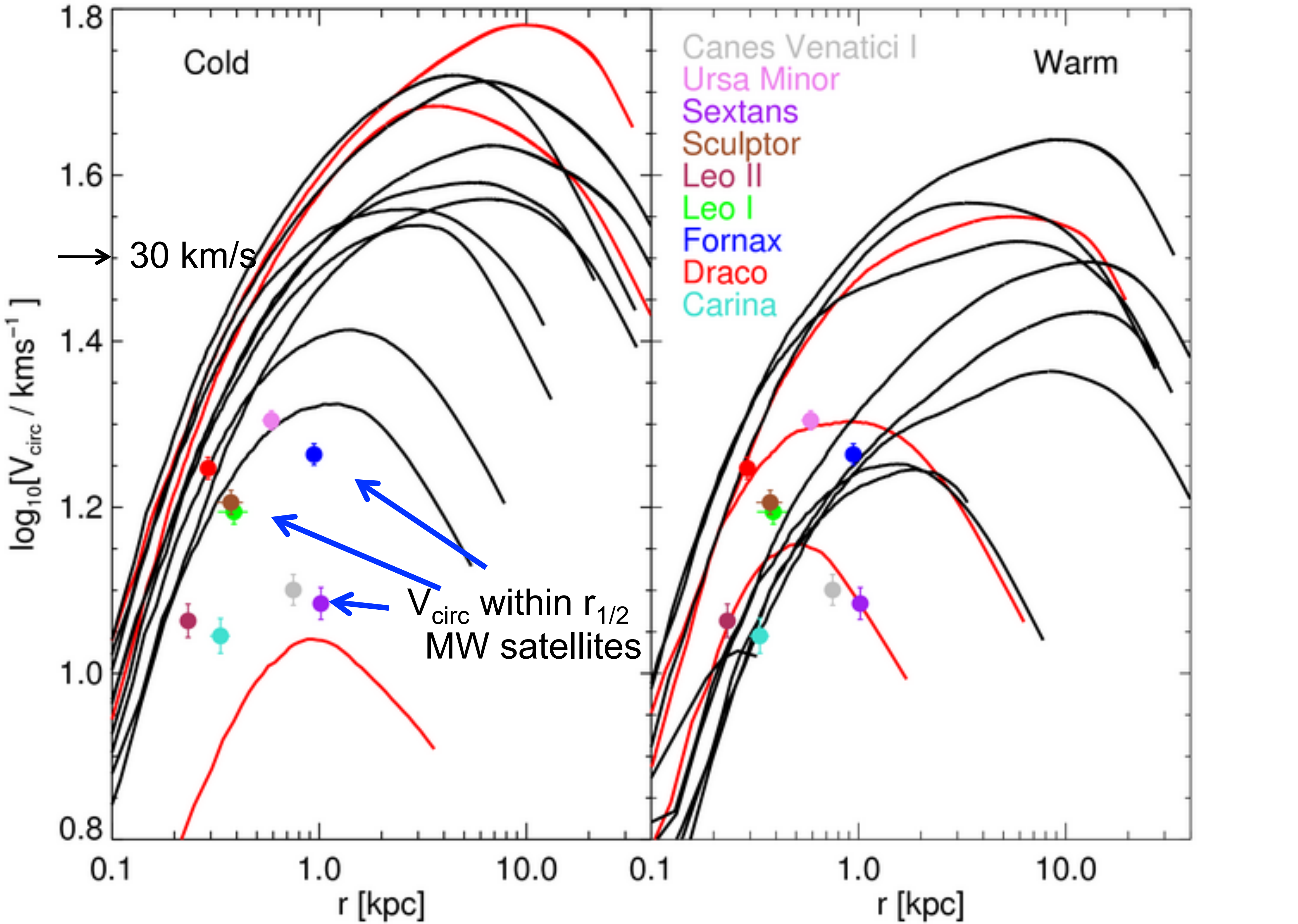
How about WDM?



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


Cold
Warm
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
30 km/s
V_{circ} within $r_{1/2}$
MW satellites
$\log_{10}[V_{circ} / kms^{-1}]$
r [kpc]
1.8
1.6
1.4
1.2
1.0
0.8
0.1
1.0
10.0

Cosmology on small scales

- The number of satellites (the "satellite problem")
- The structure of satellites (the "too-big-to-fail" problem)

How about WDM?

Tests of the nature of the DM

cold dark matter

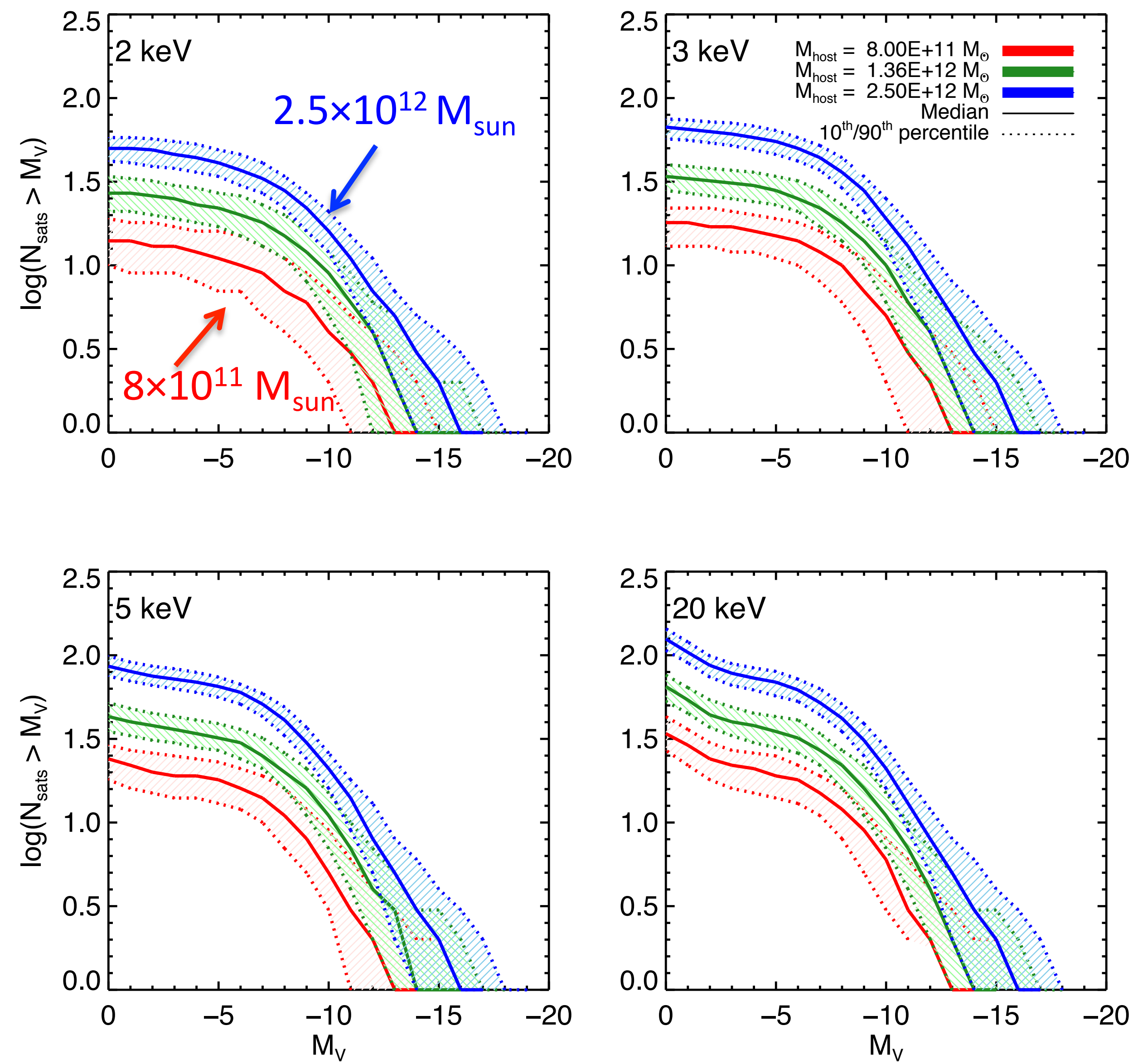
warm dark matter

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

Luminosity Function of Local Group Satellites in WDM

No of sats ↗ with:

- host halo mass
- WDM particle mass



Kennedy, Cole & Frenk '13

Luminosity Function of Local Group Satellites in WDM

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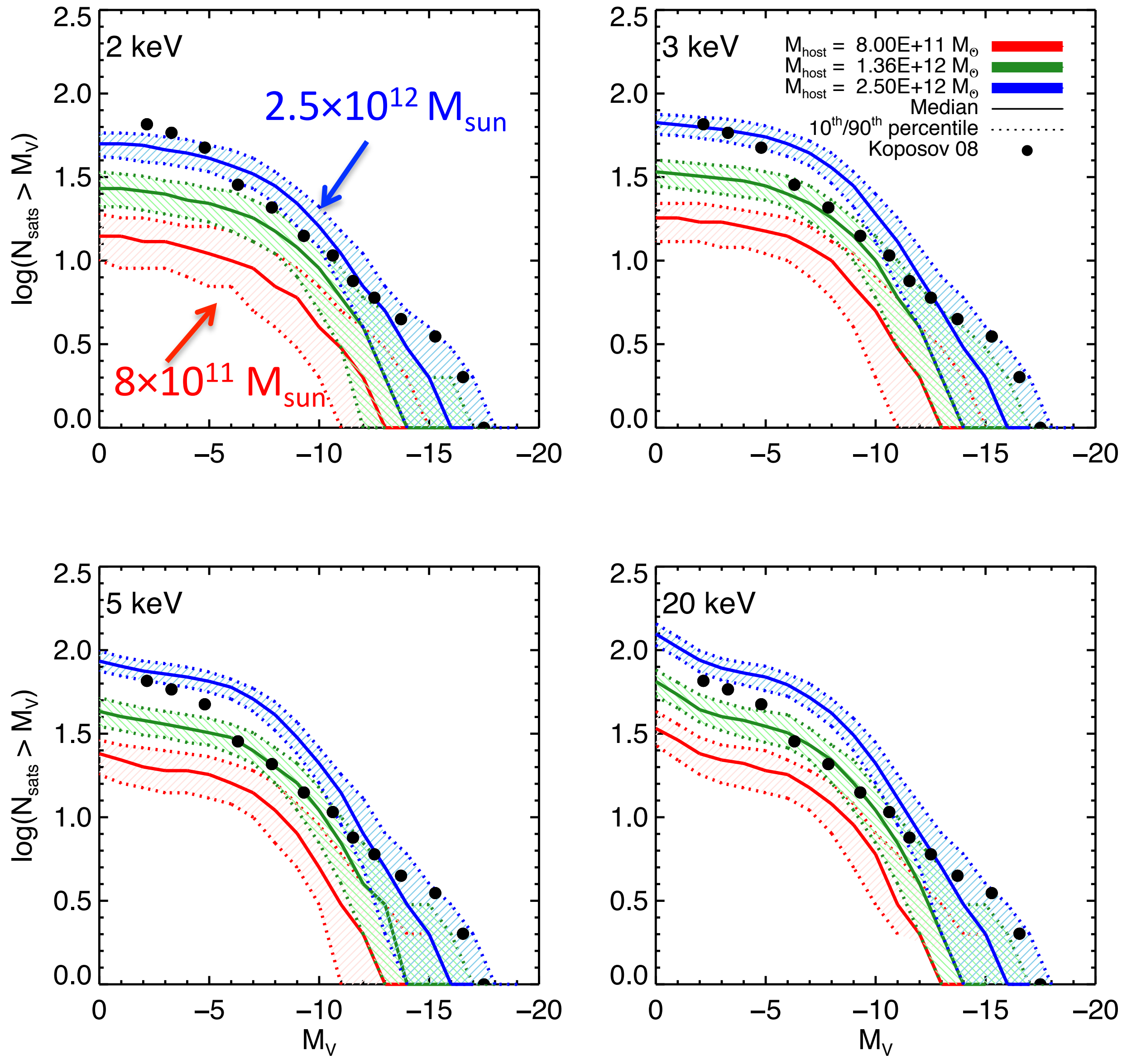


Kennedy, Cole & Frenk '13

Limits on WDM particle mass

For given m_{wdm} model must predict at least observed no of sats

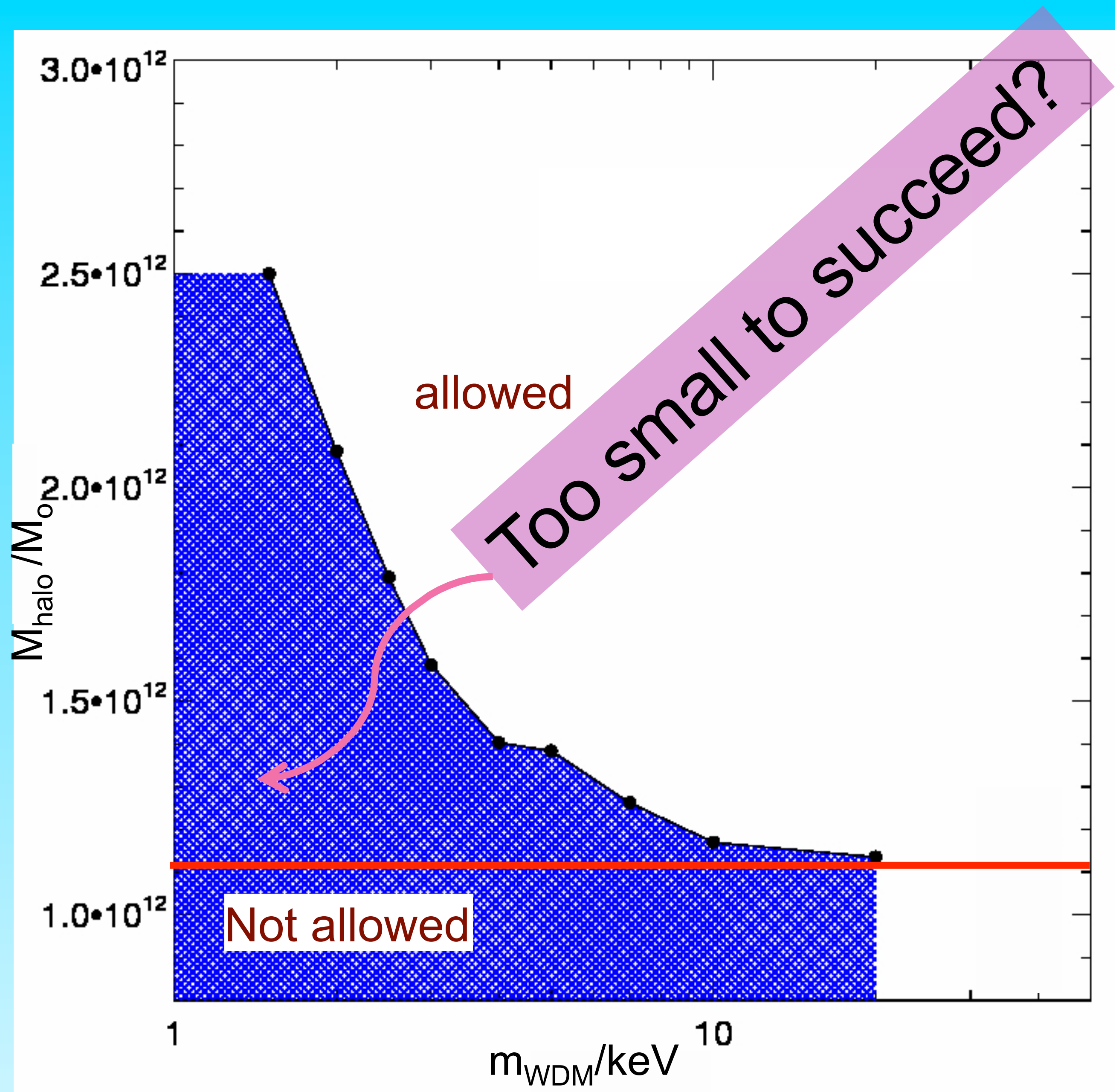
➔ lower limit on m_{wdm}

Limits on WDM particle mass

Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

For standard galaxy formation model, WDM ruled out if $M_{halo}<1.1\times10^{12}\ M_o$

Kennedy, Cole & Frenk '13



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Estimates of the MW halo mass

- Li & White → $M_{200} = 2.4\times10^{12}\,M_o$; $M_{200} > 8\times10^{11}\,M_o$ at 95% CL
- Guo et al → $8\times10^{11}\,M_o < M_{200} < 4.7\times10^{12}\,M_o$
- Deason et al → $5\times10^{11}\,M_o < M_{150kpc} < 1\times10^{12}\,M_o$
- Xue et al → $8\times10^{11}\,M_o < M_{100} < 1.3\times10^{12}\,M_o$
- Battaglia et al → $6\times10^{11}\,M_o < M_{100} < 3\times10^{12}\,M_o$

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Constraints on CDM & WDM from the Milky Way satellites

With our standard assumptions: at 95% confidence

Cold dark matter :

Unless baryon effects are important

Ruled out unless $M_{halo} < 1.5 \times 10^{12} M_o$

(from abundance of massive satellites)

Warm dark matter :

Ruled out unless $M_{halo} > 1.2 \times 10^{12} M_o$

(from abundance of satellites)

From X-ray decay limit, for resonantly produced sterile νs

→ need $m_{WDM} < 5$keV and $M_{halo} > 1.4 \times 10^{12} M_o$

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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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

Governato et al. '12
Pontzen & Governato '12
Brooks et al. '12

The cores of dwarf galaxy haloes L75

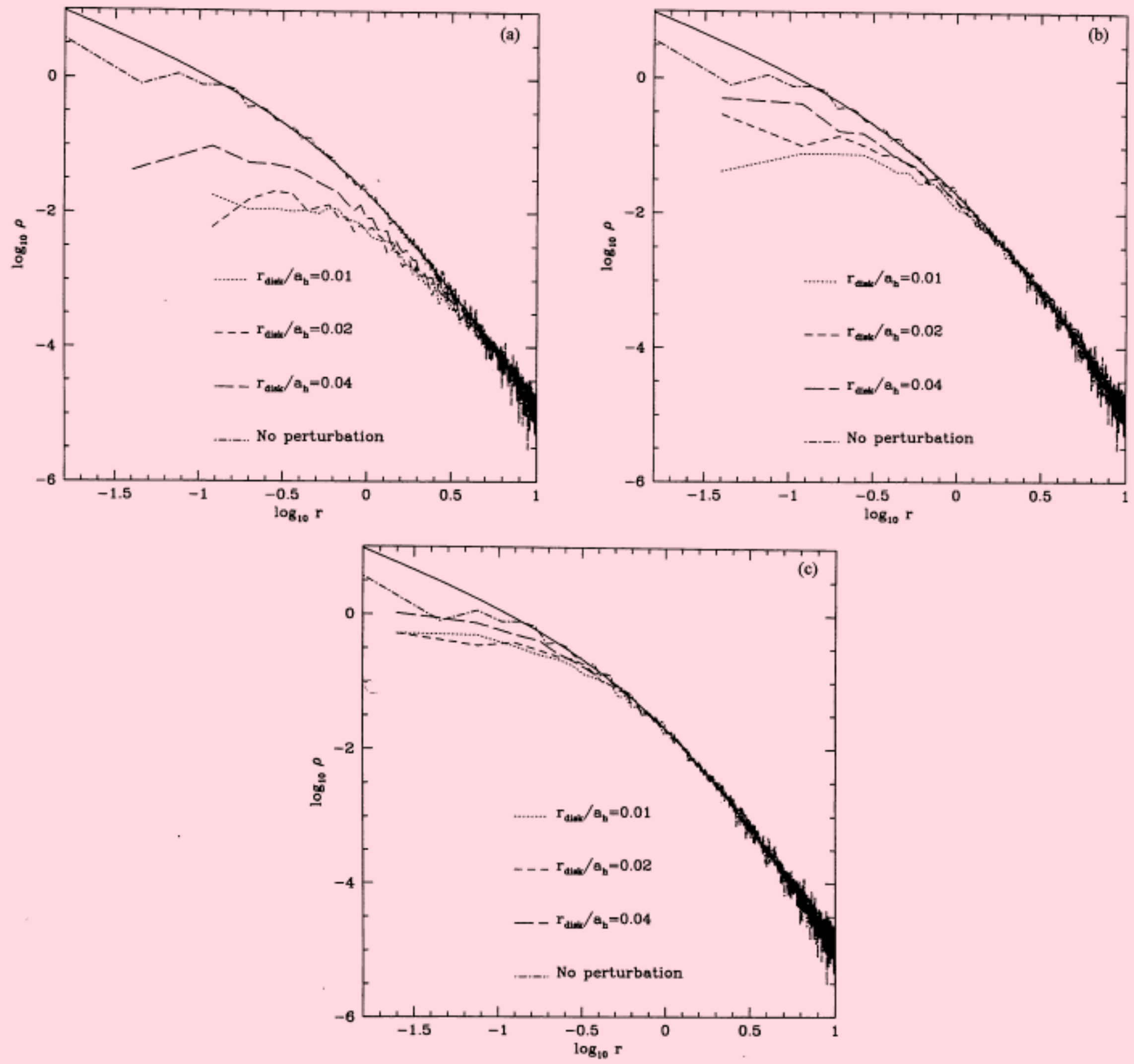

Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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DM & sats of the MW: conclusions

Abundance and kinematics of MW sats set strong constraints on nature of dark matter

Key properties of sat system:
- Luminosity function
- Abundance of most massive sats

Model	Sat Lum Fn	Massive sats	Comments
CDM	OK	$M_{halo} < 1.5\times10^{12}\ M_o$	Unless baryon effects reduce central density
WDM	$M_{halo} > 1.2\times10^{12}\ M_o$	OK	+ X-ray constraint $M_{halo} > 1.5\times10^{12}\ M_o$ $m_x < 5$keV