



# My Adventures in a WDM Universe

Mark Lovell

Adrian Jenkins, Carlos Frenk, Vince Eke, Liang Gao,  
Tom Theuns, Jie Wang, Simon White, Alexey Boyarsky,  
Oleg Ruchayskiy

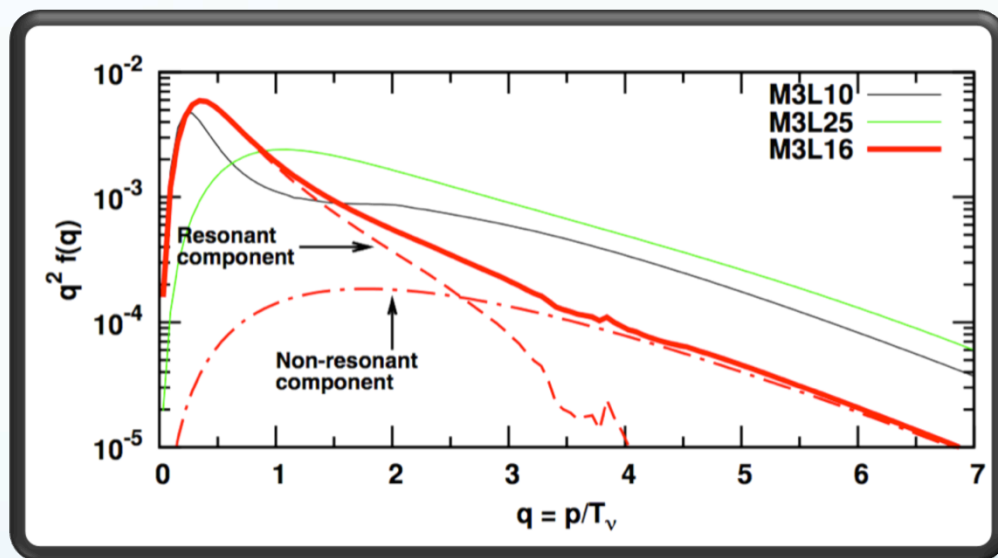
# Outline

- Motivation – particle physics
- Our approach (simulations – discussion of particle velocities)
- Removal of spurious haloes
- The massive satellite problem
- Introduce different WDM models
- Examine variation of halo properties with temperature.

# Motivation: $\nu$ MSM

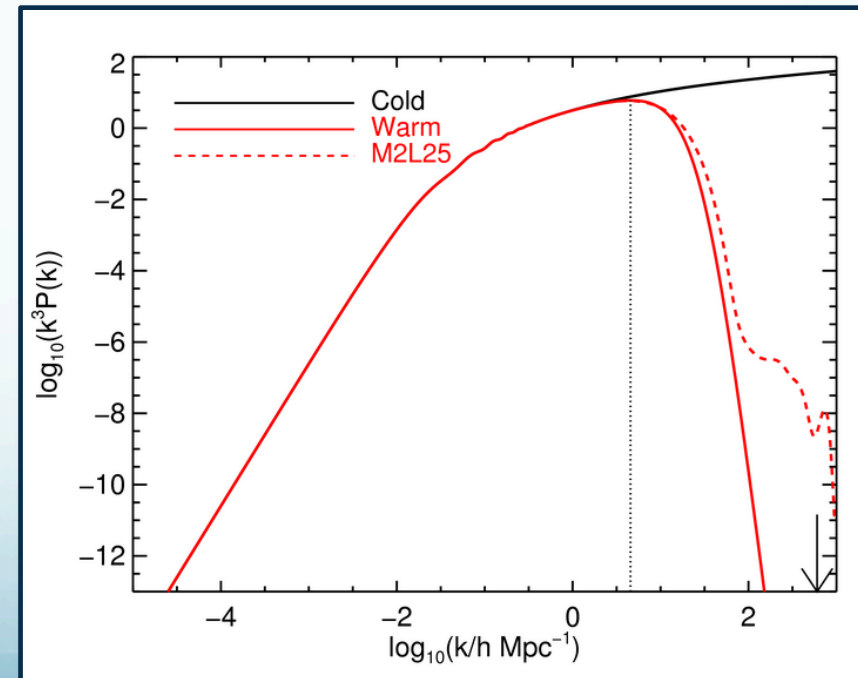
- Standard model of particle physics + three right-handed, sterile neutrinos.
- May address issues with baryogenesis and neutrino oscillations.
- ‘Cooler’ power spectrum than standard sterile neutrino due to resonant production channel.
- Modeled by some as CDM+WDM mixture. We approximate to WDM only.

Boyarsky et al. 2009



# So this is what we did:

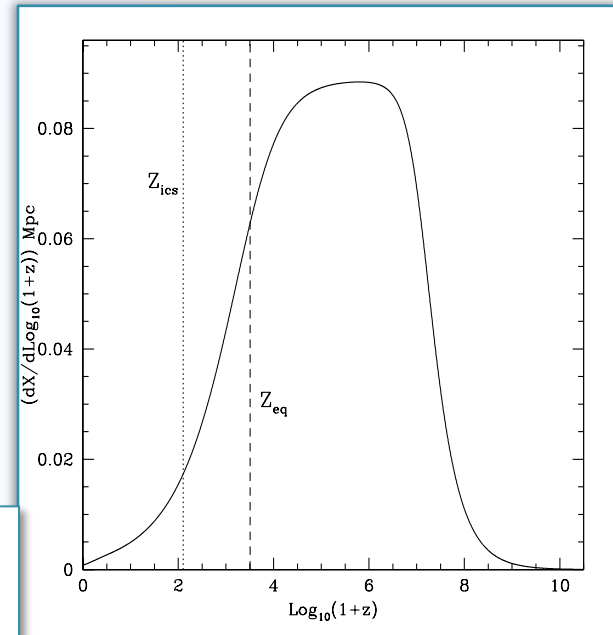
- Resimulate Aquarius Aq-A halo (Springel et al. 2008) with a WDM model
- WDM power spectrum picked to approximate M2L25 model of Boyarsky et al. 2009.
- WMAP1 cosmology
- $M_{\text{particle}} = 10^4 M_{\text{sun}}$
- $M_{200} = 1.8 \times 10^{12} M_{\text{sun}}$
- $r_{200} = 246 \text{ kpc}$
- $\alpha = 0.03399 h^{-1} \text{ Mpc}$



$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

# How important are thermal velocities?

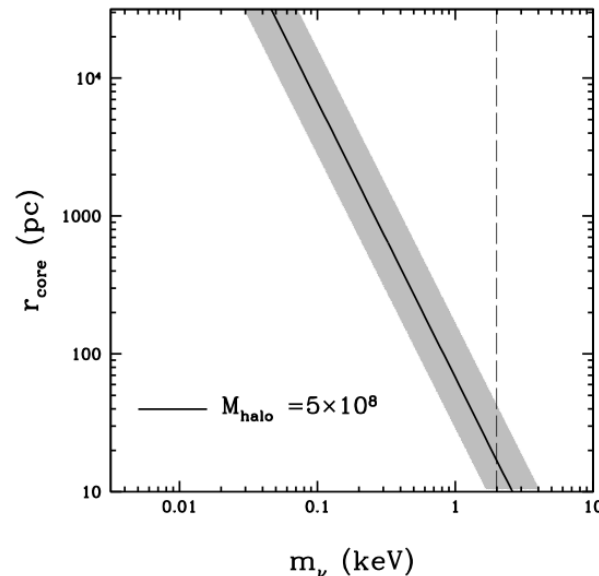
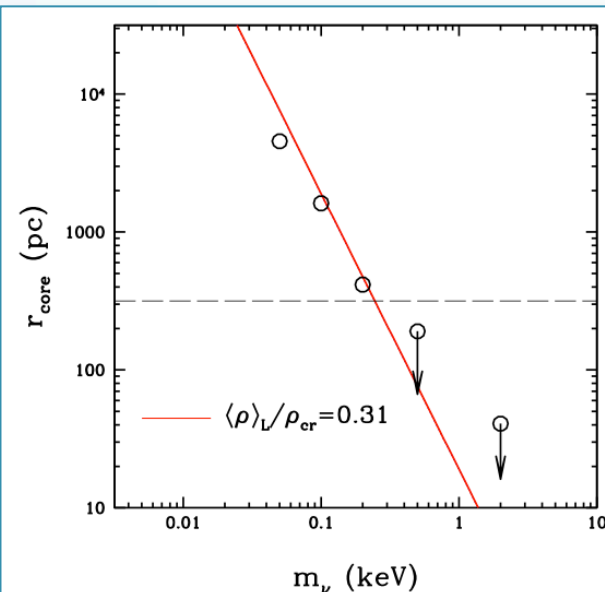
- WDM introduces a cutoff in the power spectrum and non-negligible thermal velocities.
- Mean distance travelled since the start of the simulation is 14kpc, of order the inter-particle separation.
- For realistic dark matter masses, the core is only a few parsec across.



Lovell et al. 2012

Maccio et al. 2012

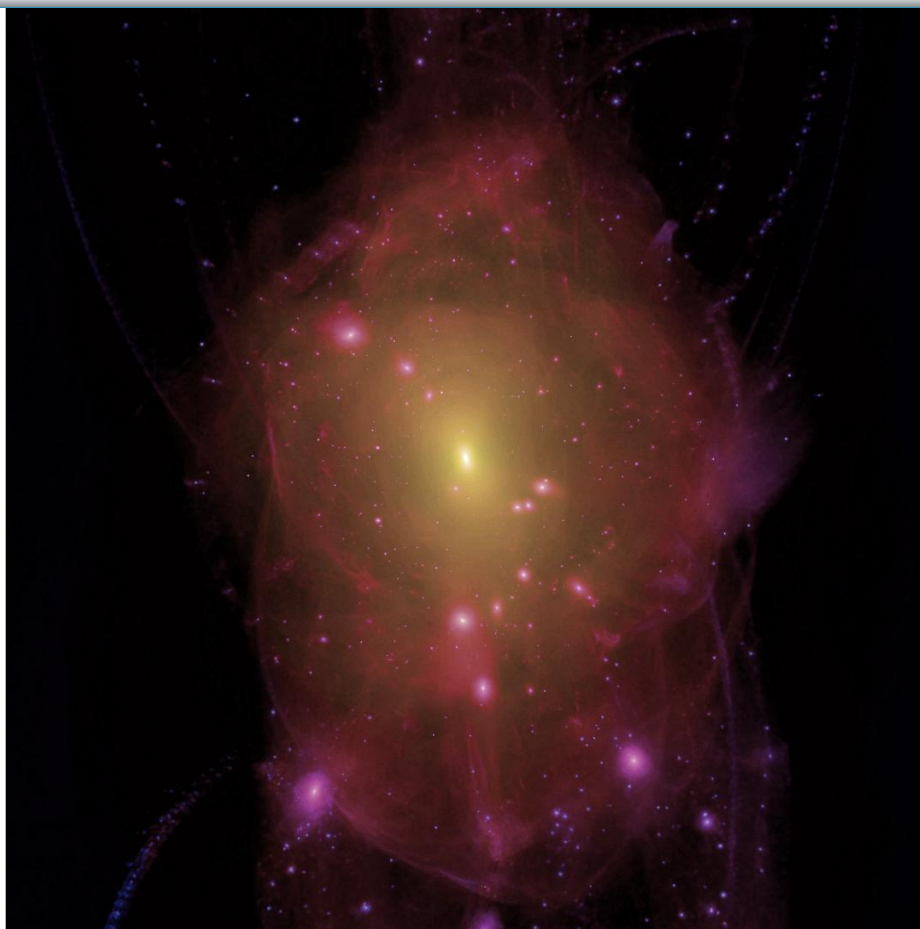
M Lovell, Durham University, Meudon 2012



# Our Simulations: First View

CDM - WDM

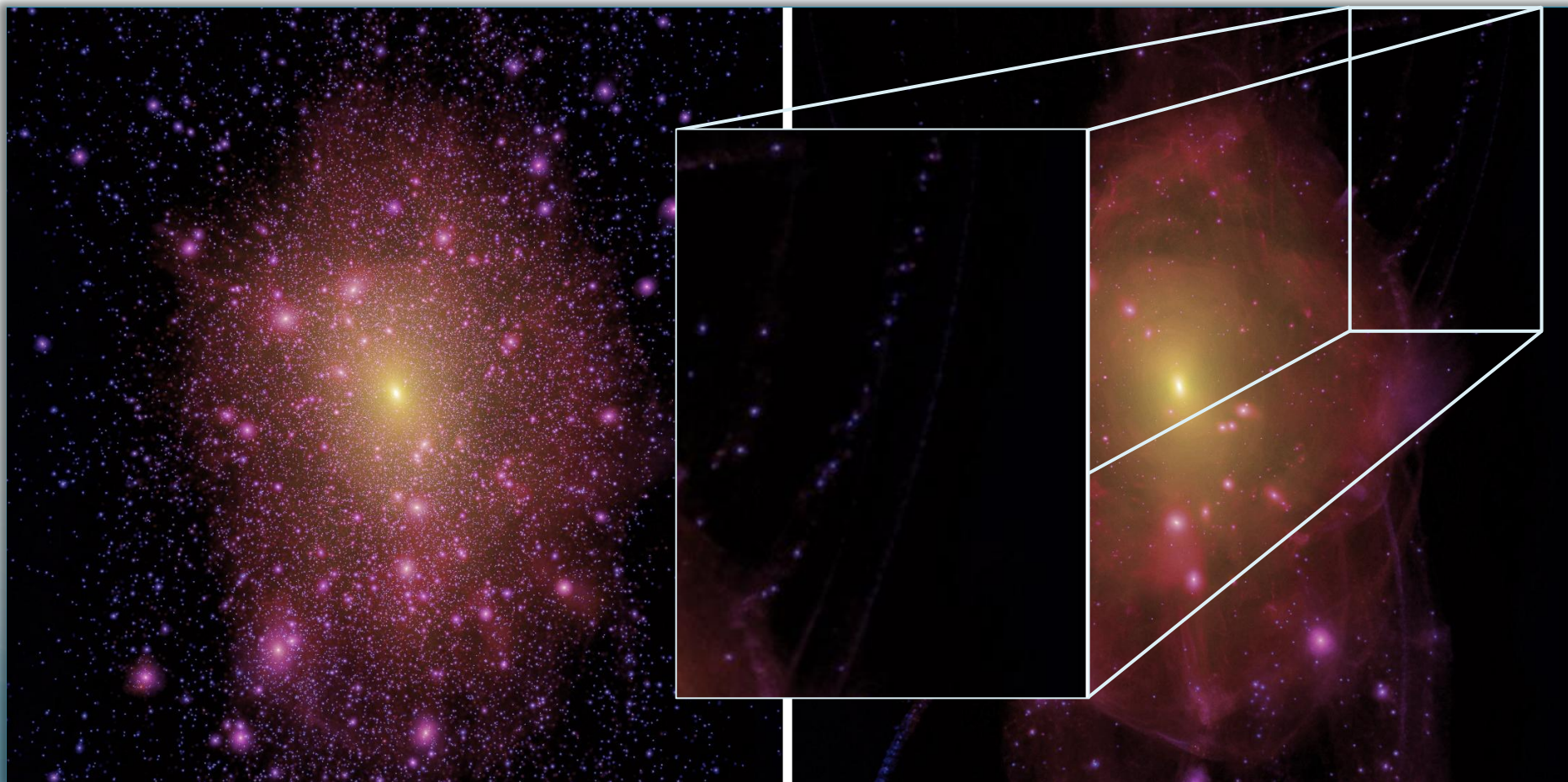
$z=0$



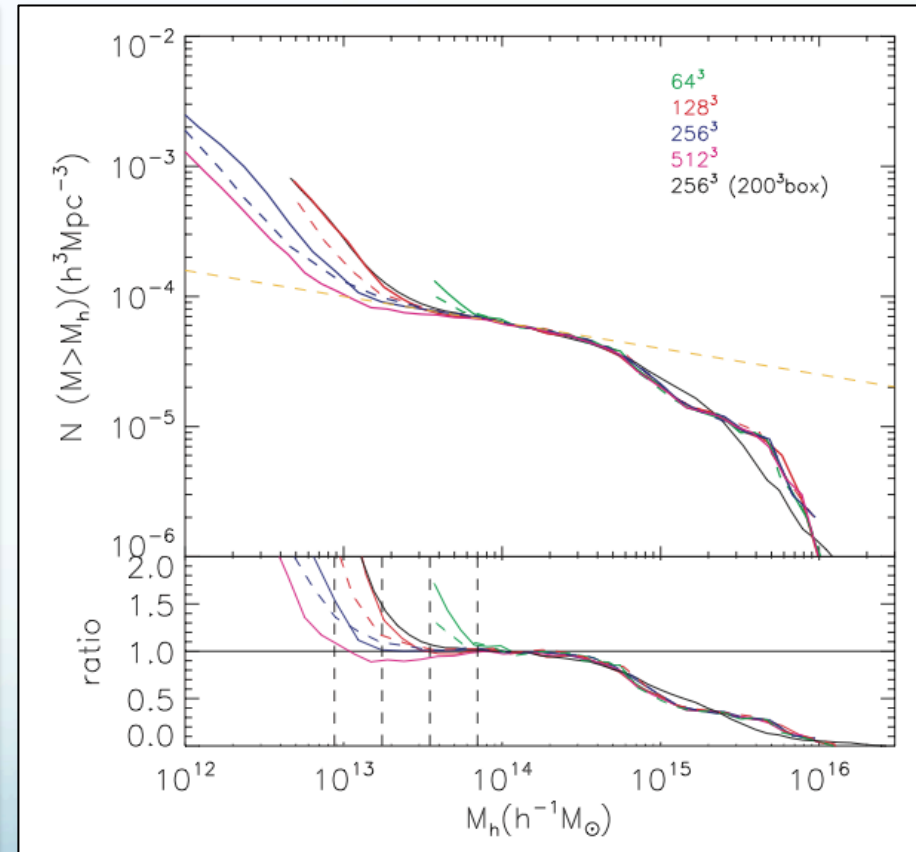
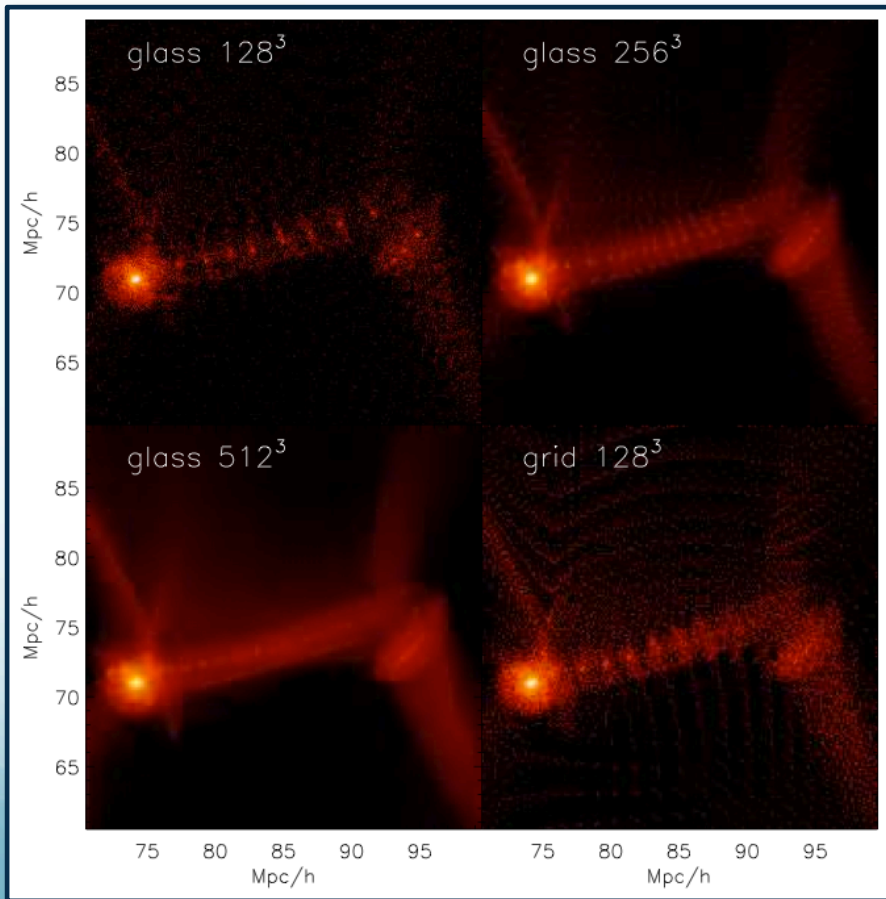
# Our Simulations: First View

CDM - WDM

$z=0$

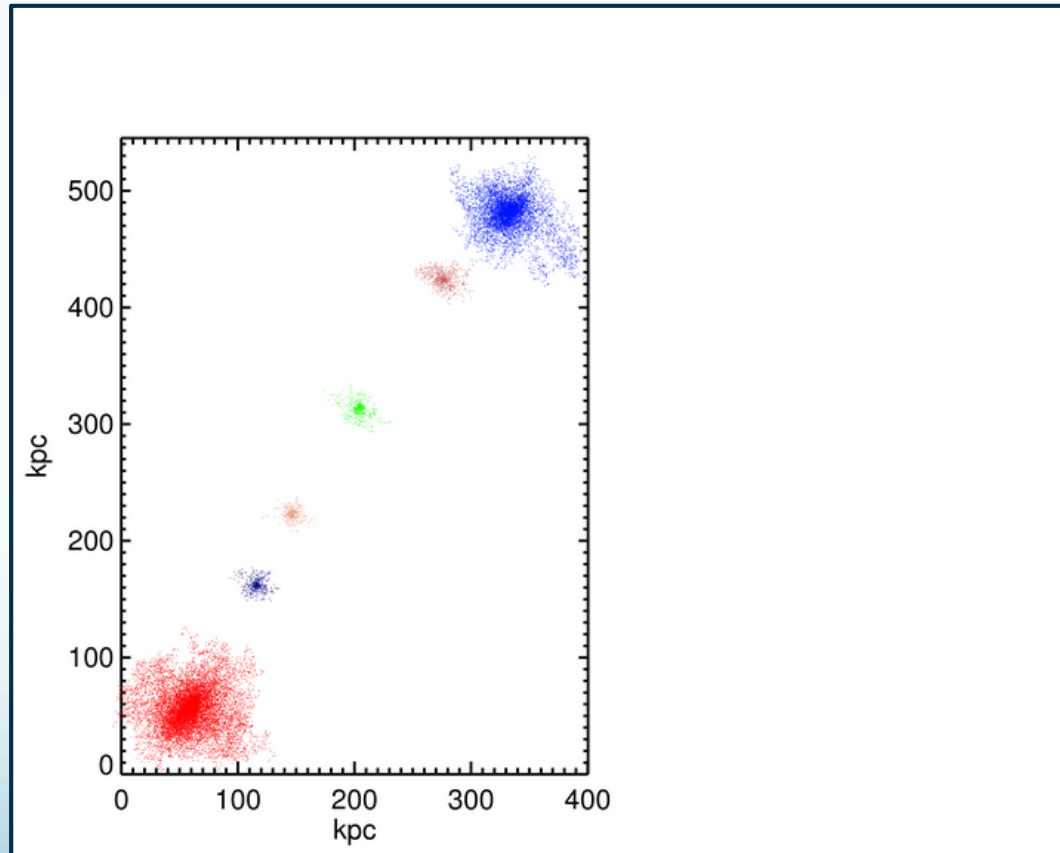


# Spurious haloes

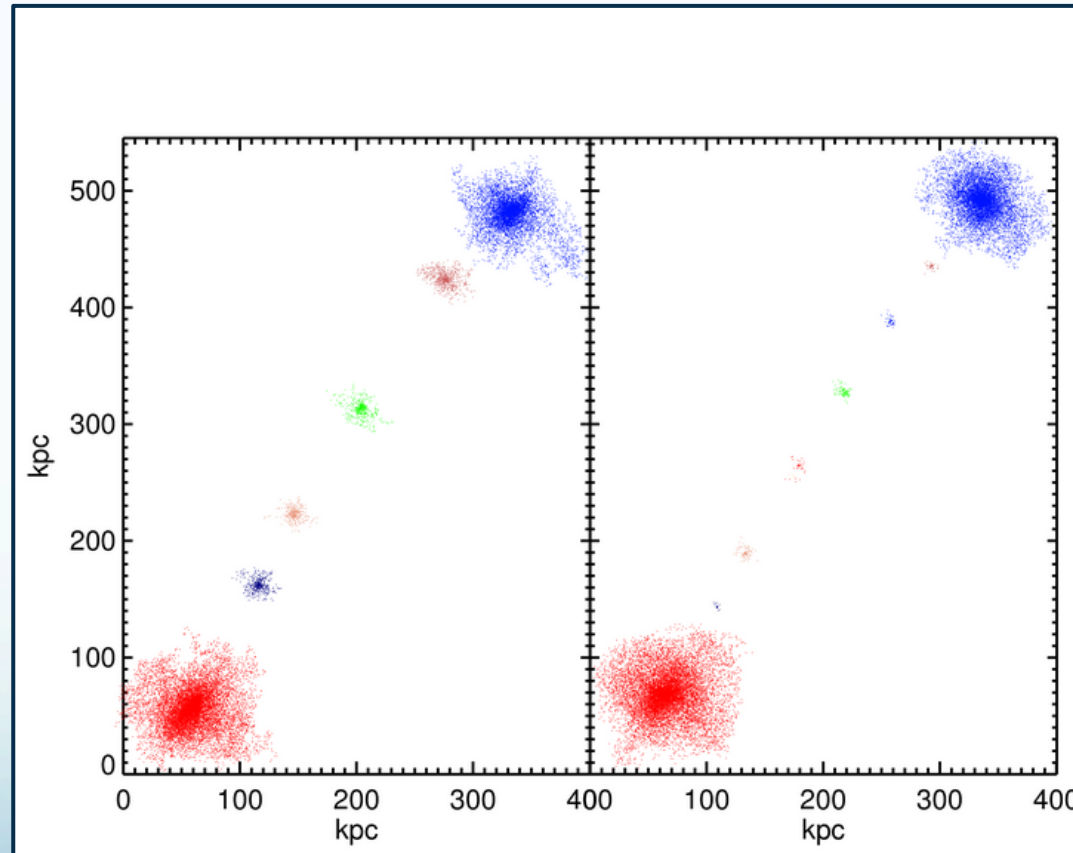




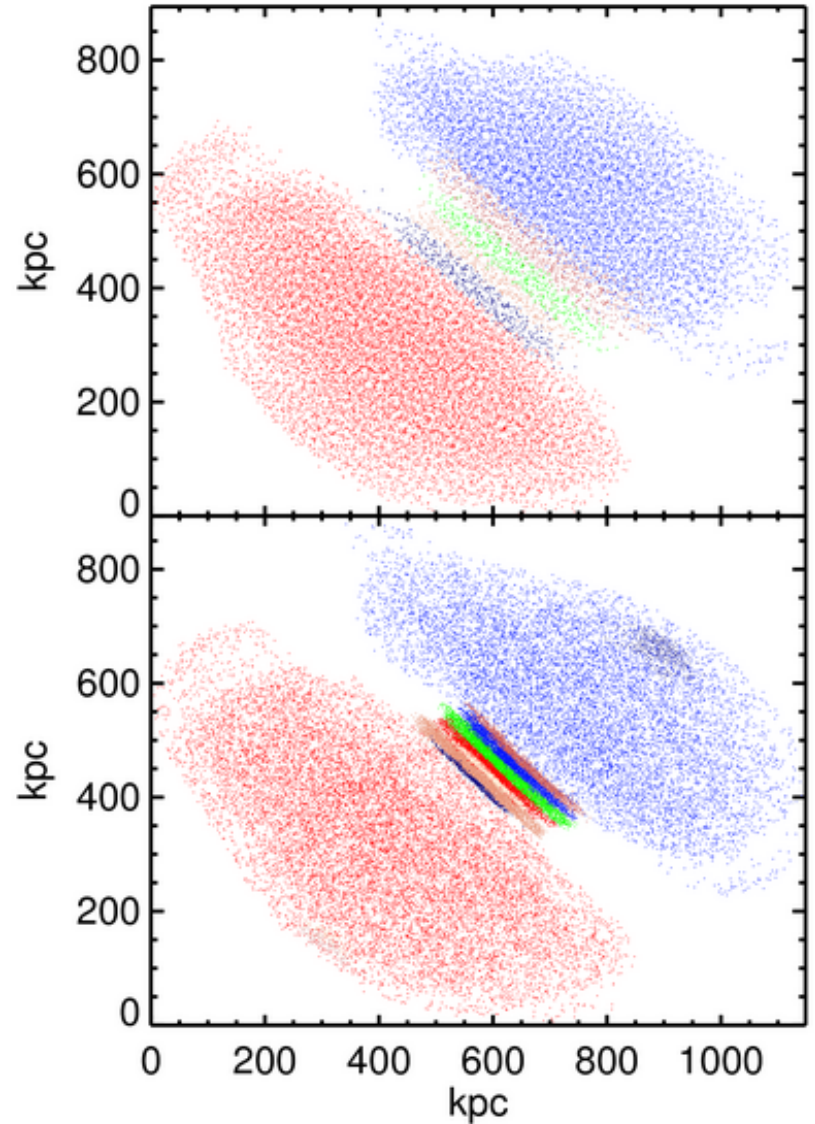
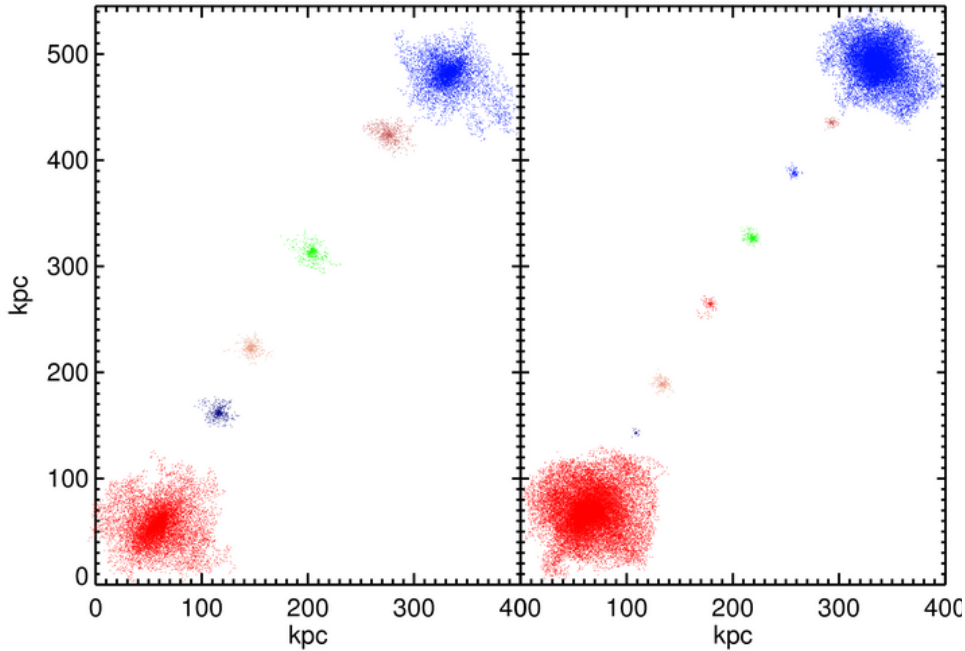
# Example



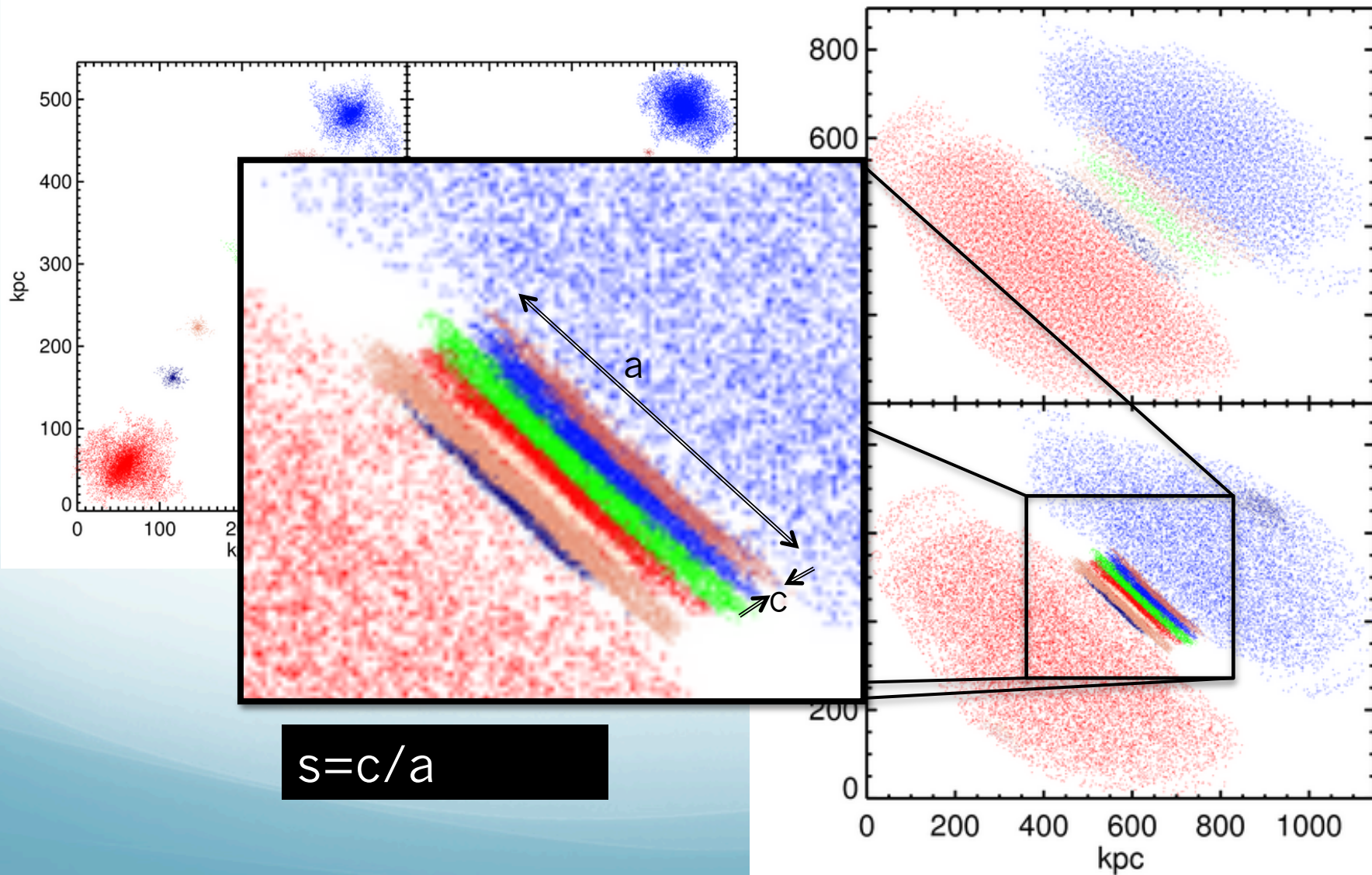
# Example



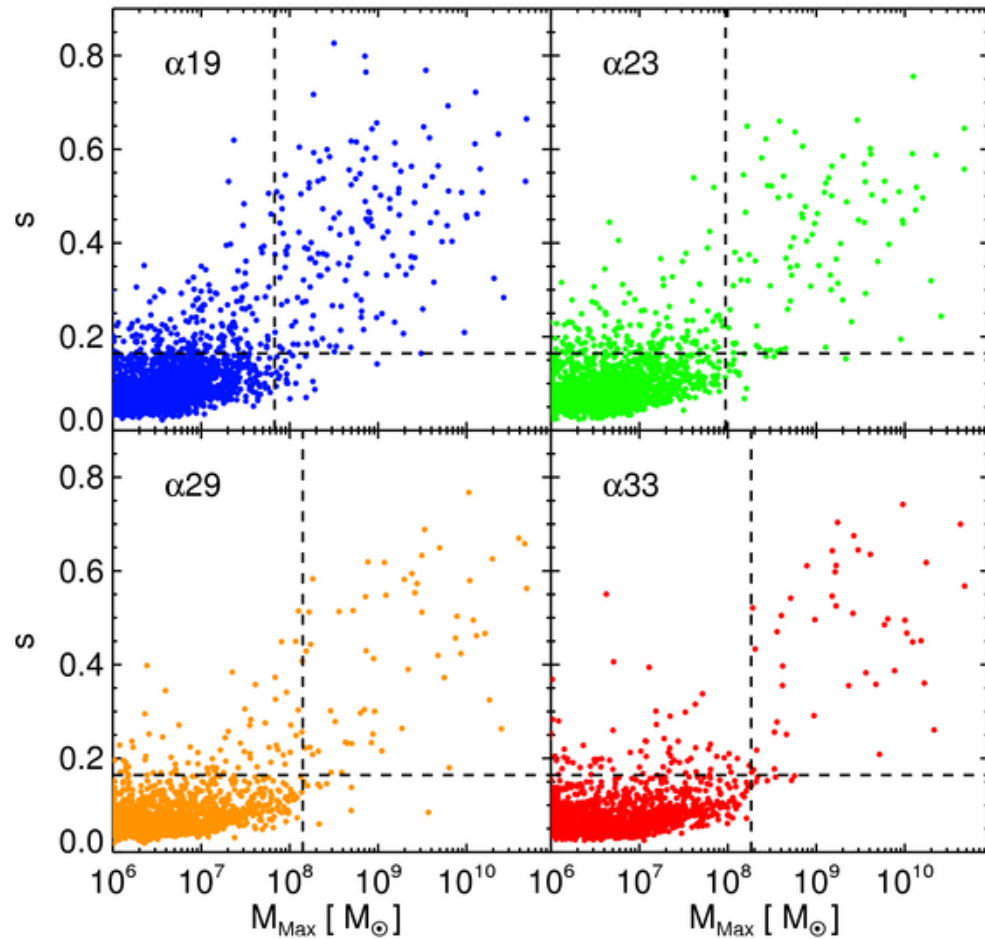
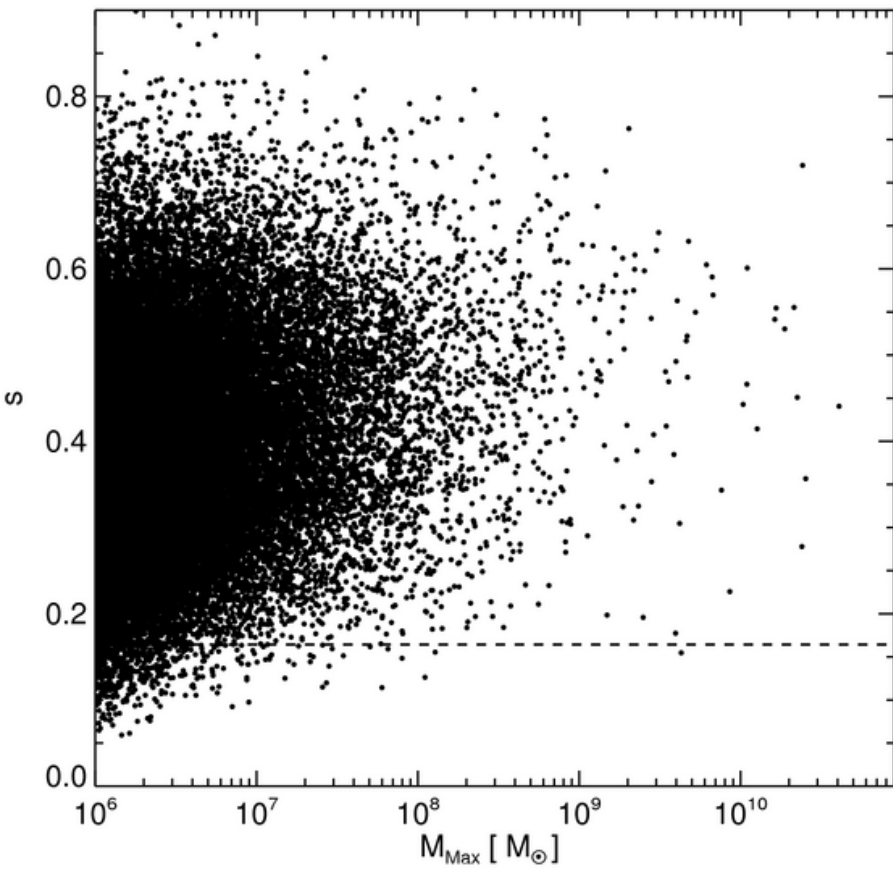
# Example (cont)



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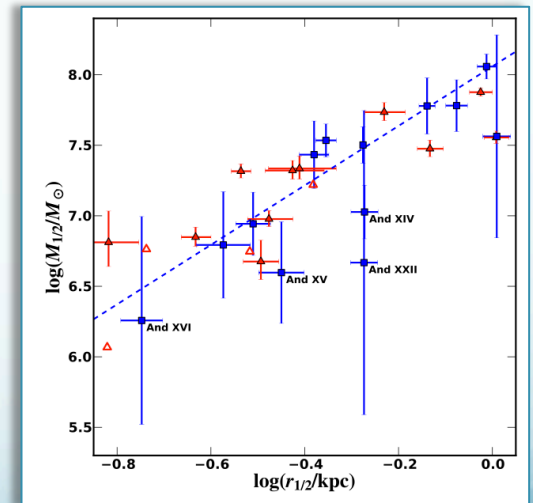
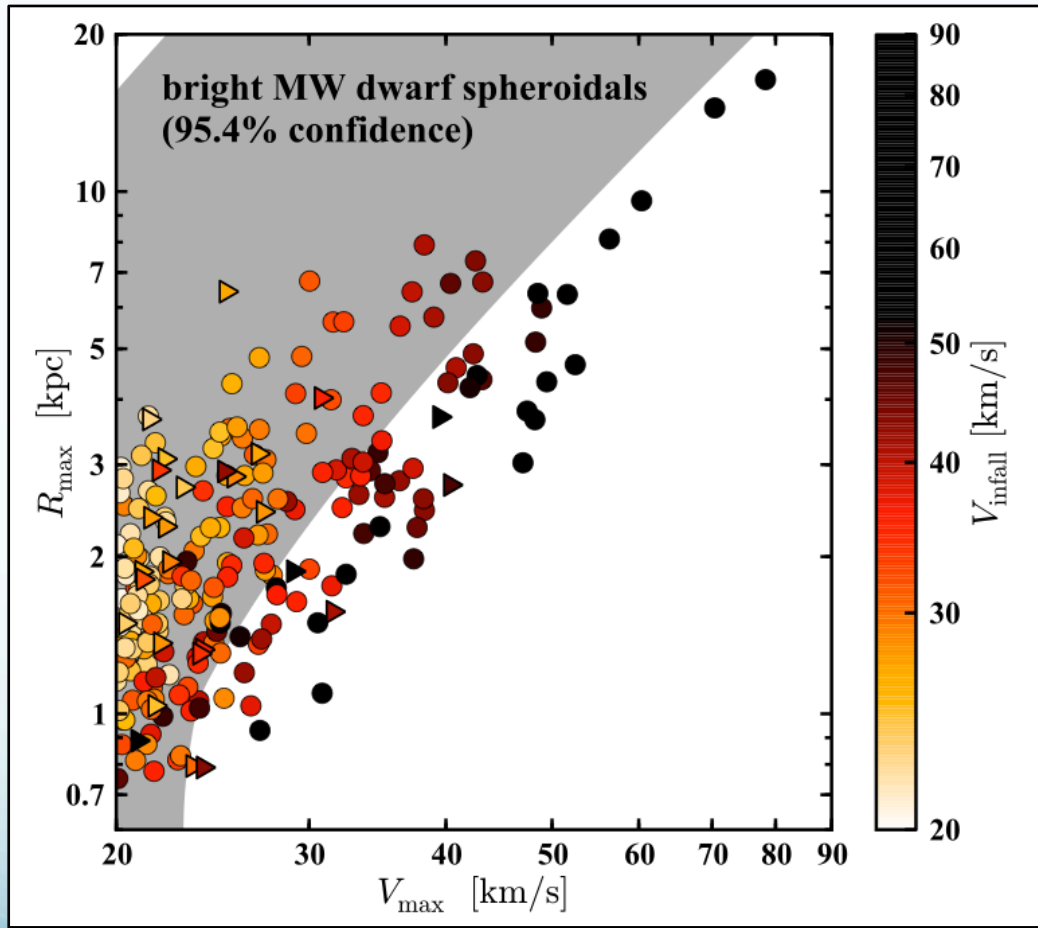
# Proto-halo sphericities



# Implementation

Insert Movie here...

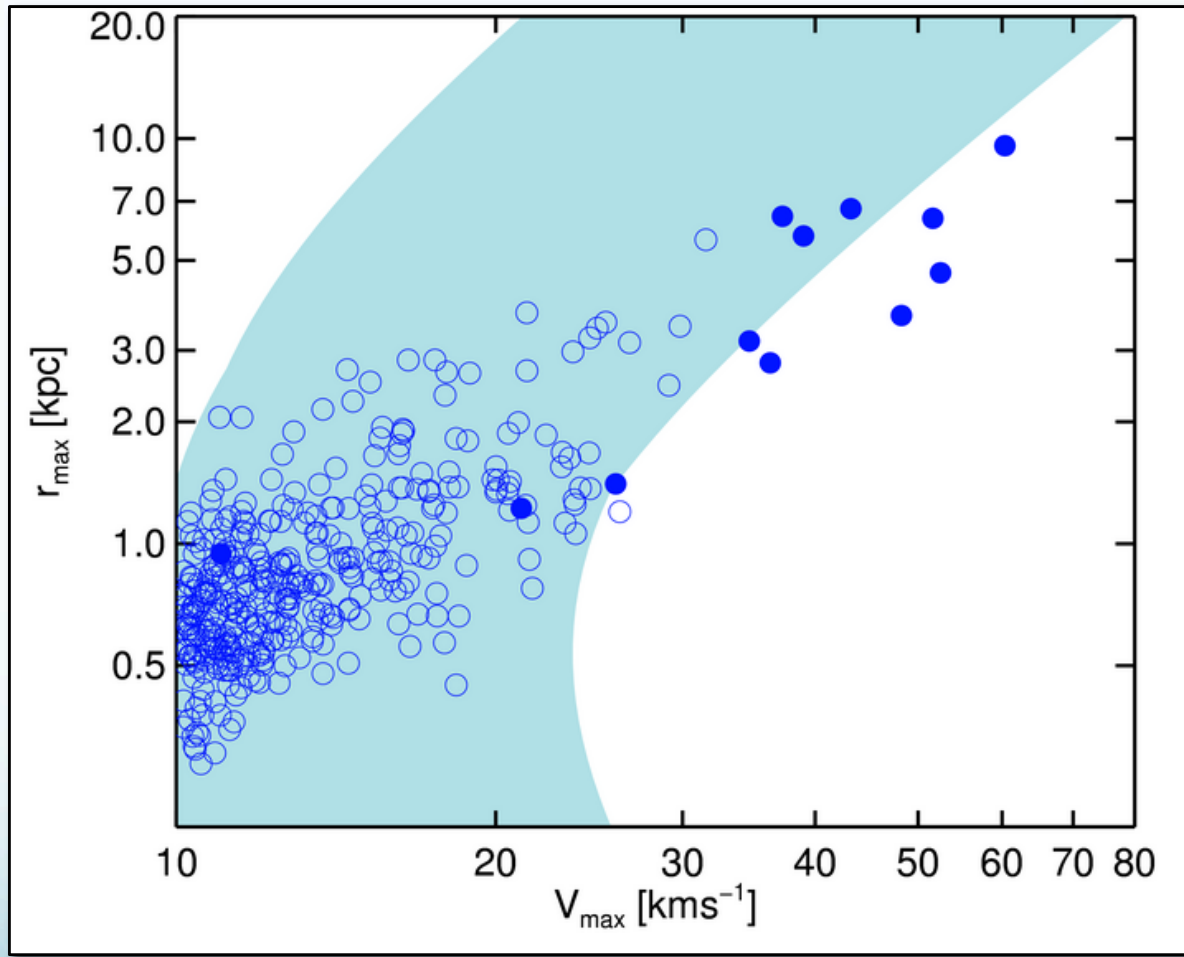
# The Problem



Boylan-Kolchin et al. 2011

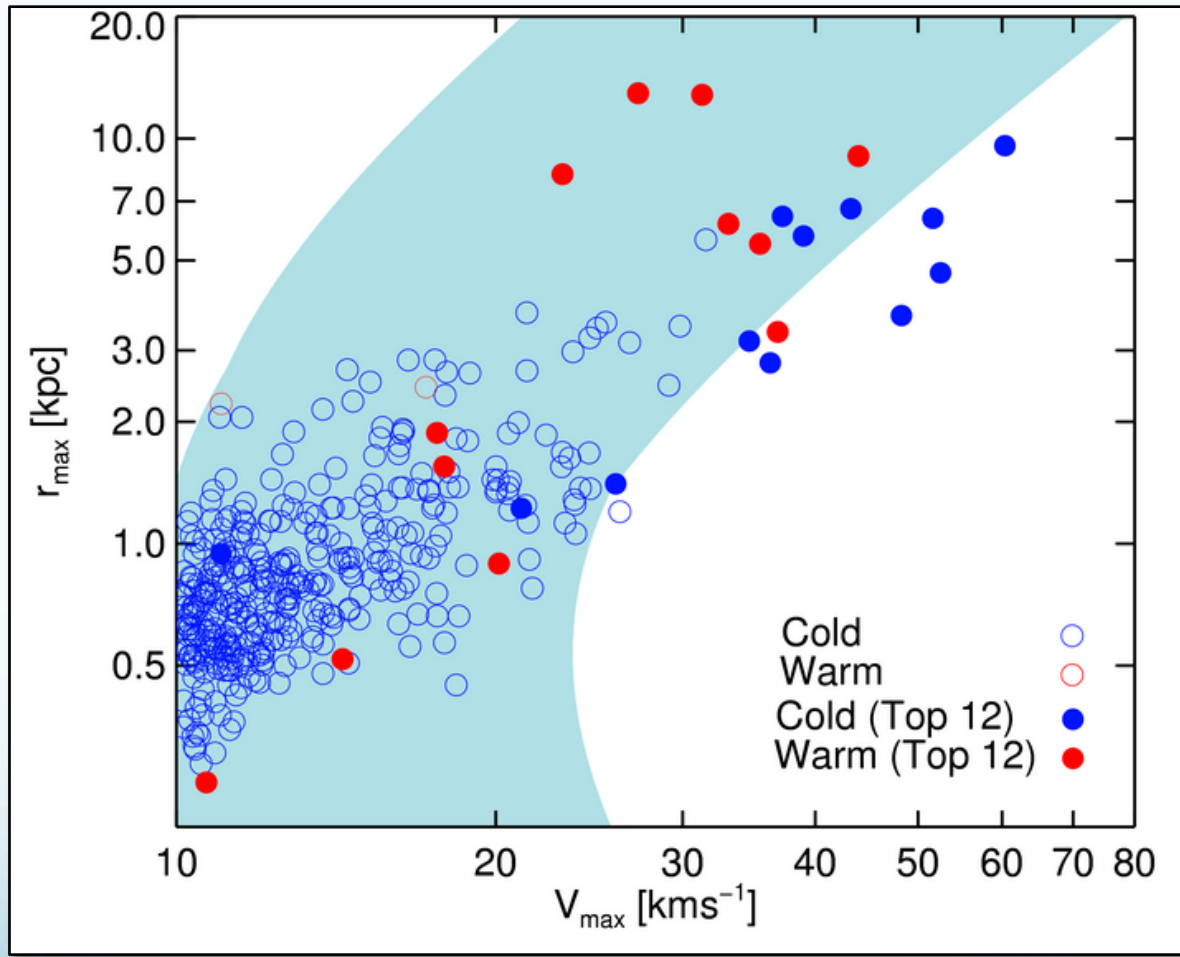
Tollerud et al. 2011

# WDM and satellites



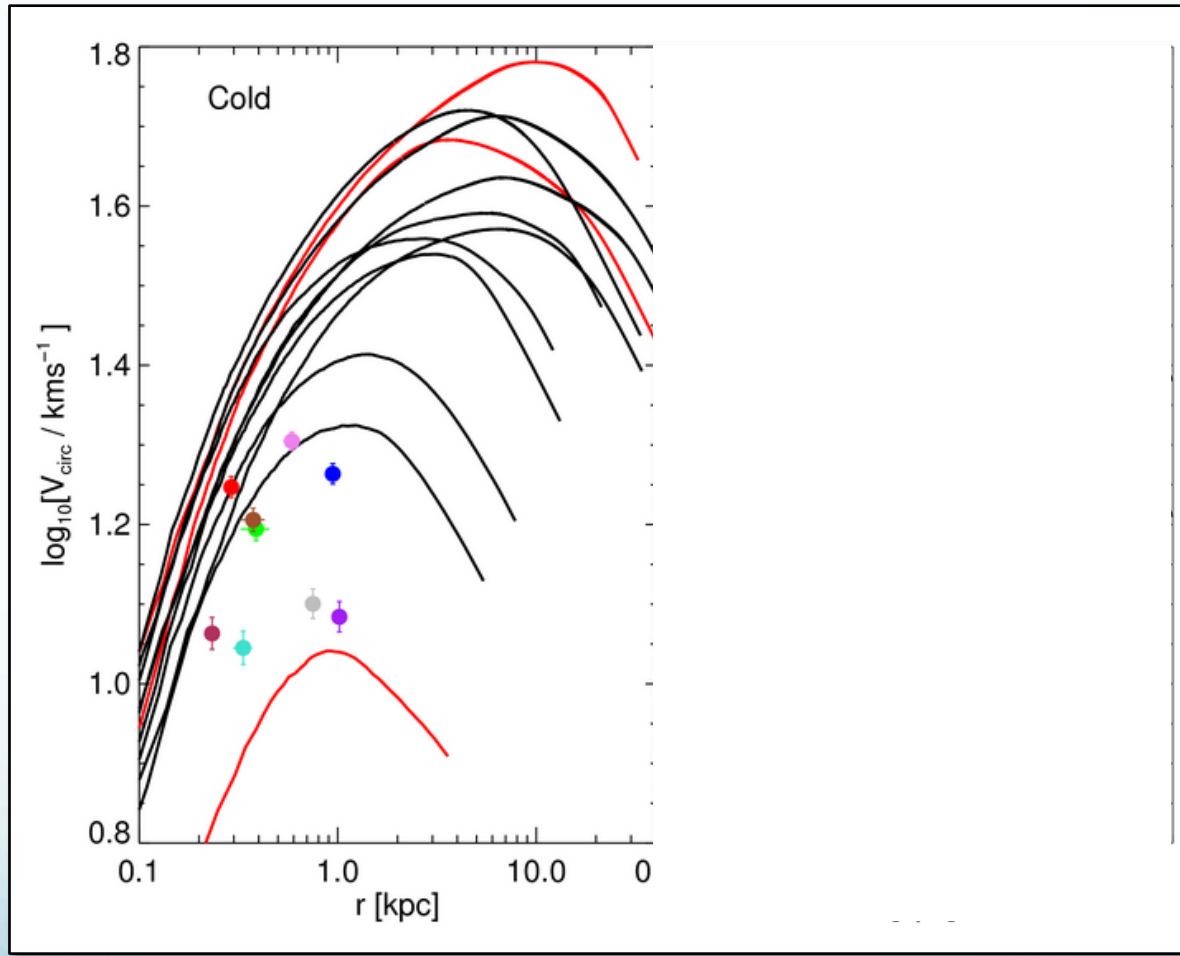


# WDM and satellites



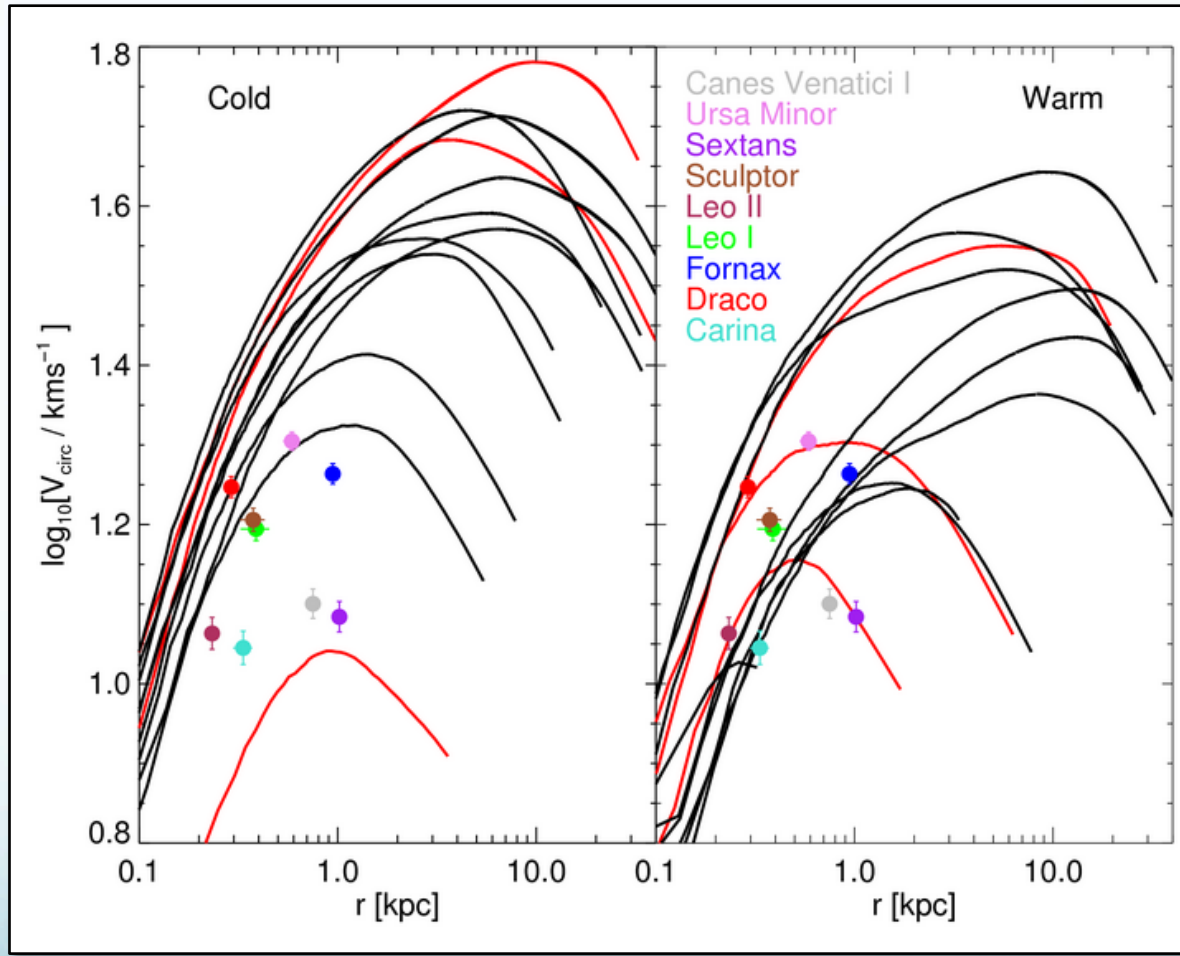
# WDM and satellites (2)

$$V(r) = \sqrt{GM(<r)/r}$$

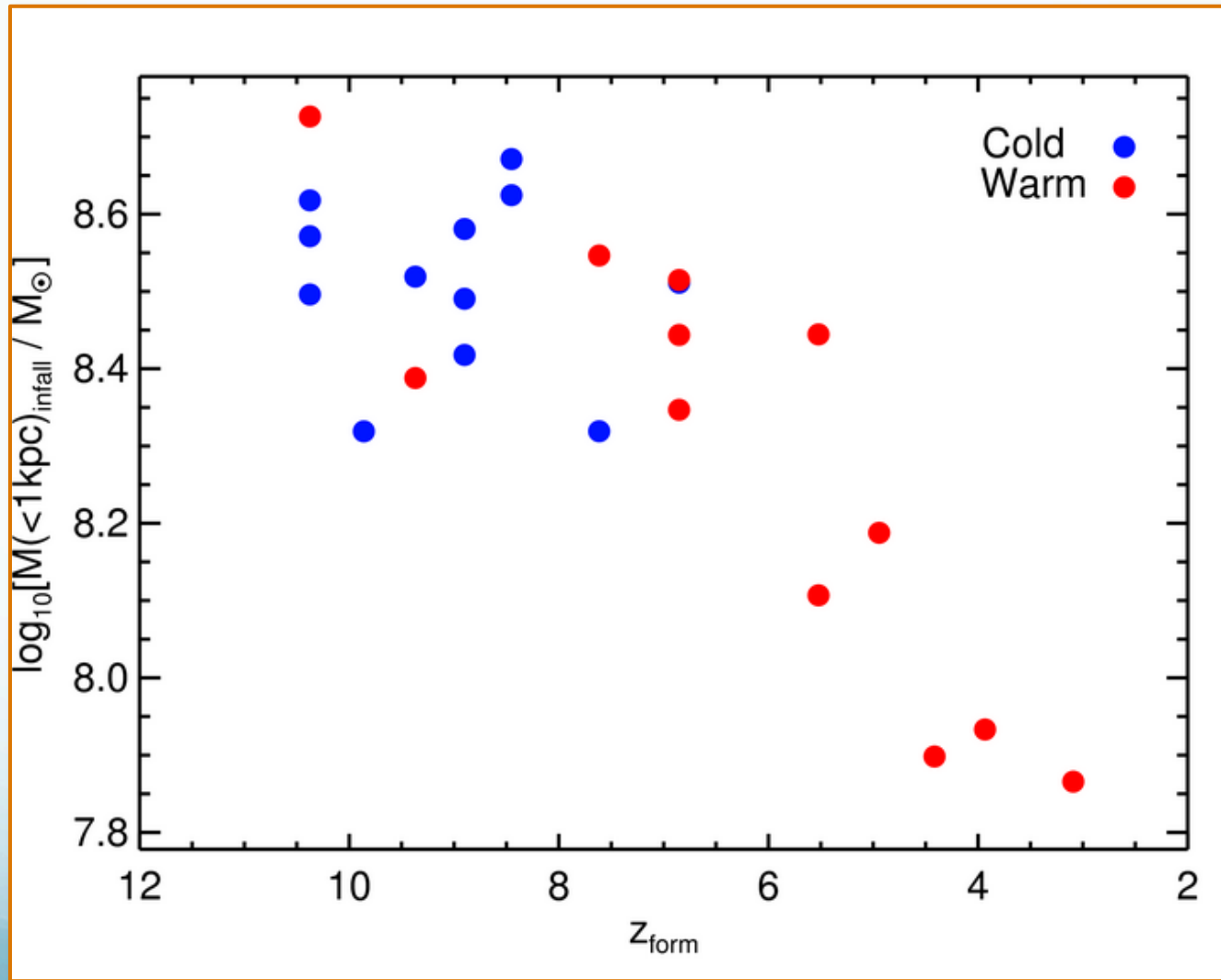


# WDM and satellites (2)

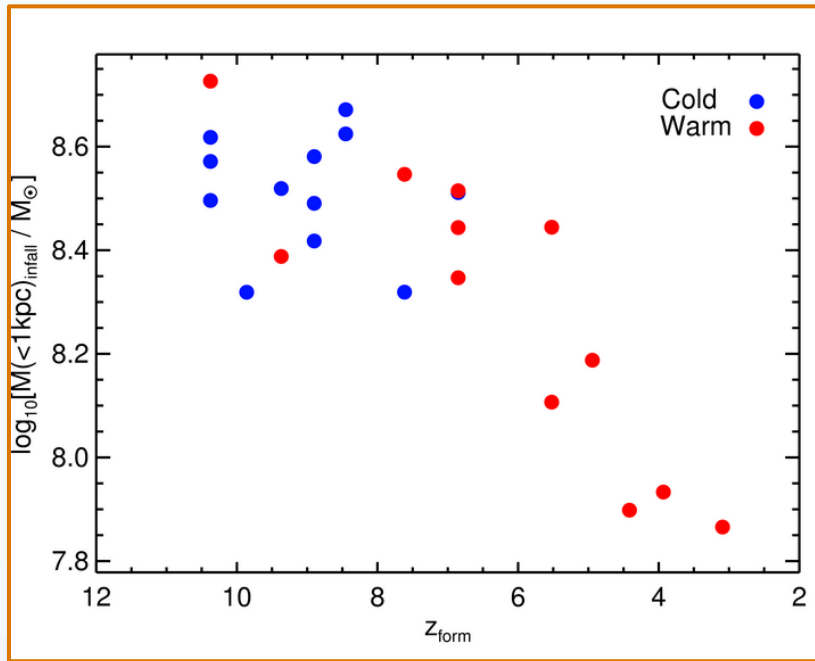
$$V(r) = \sqrt{GM(<r)/r}$$



# WDM Formation Times



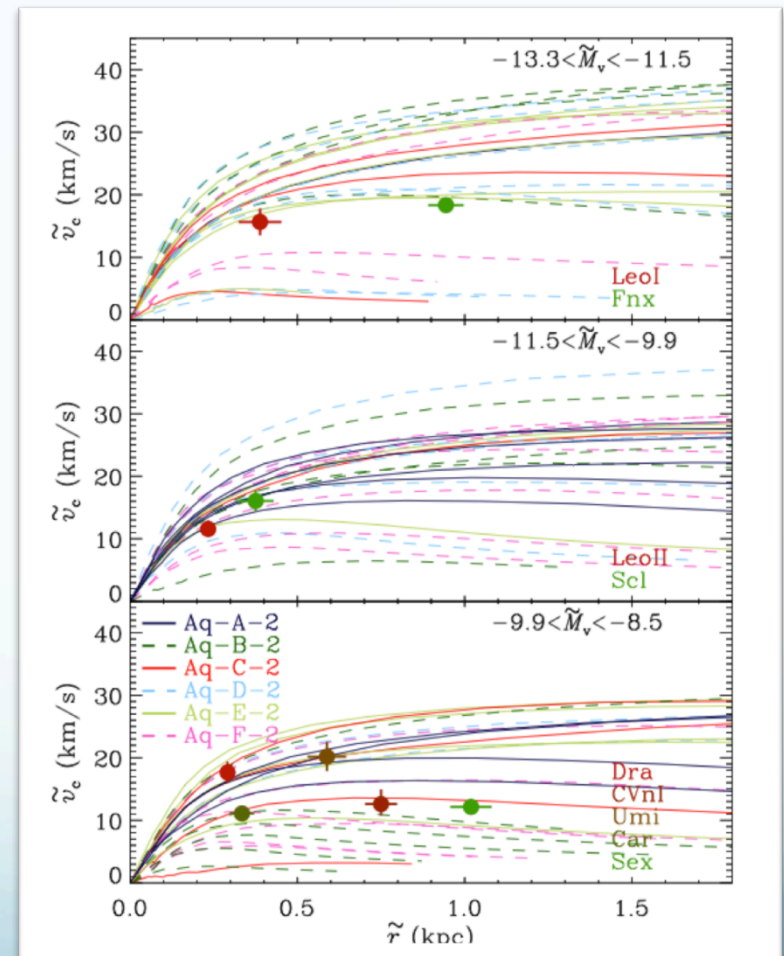
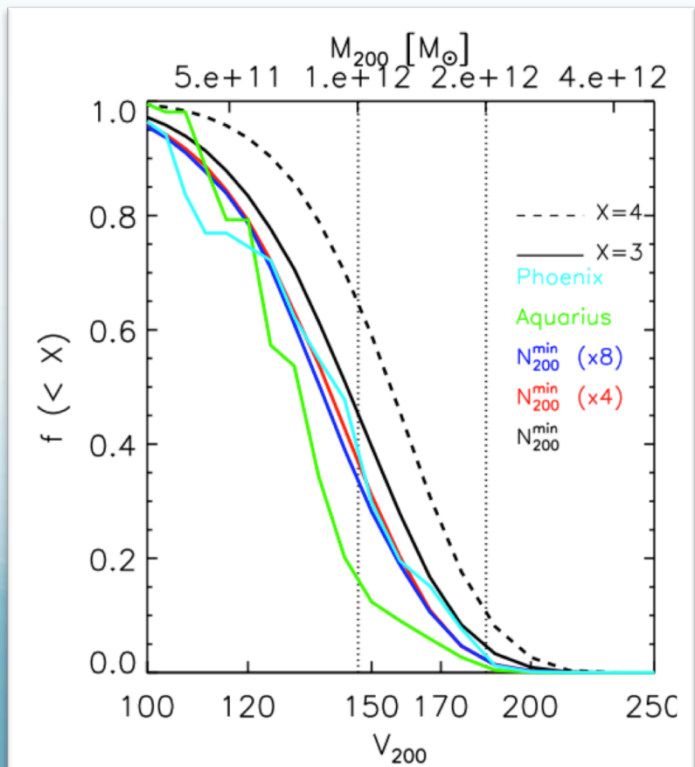
# WDM Formation Times



We only find  $\sim 18$  satellite galaxies.  
Too warm!

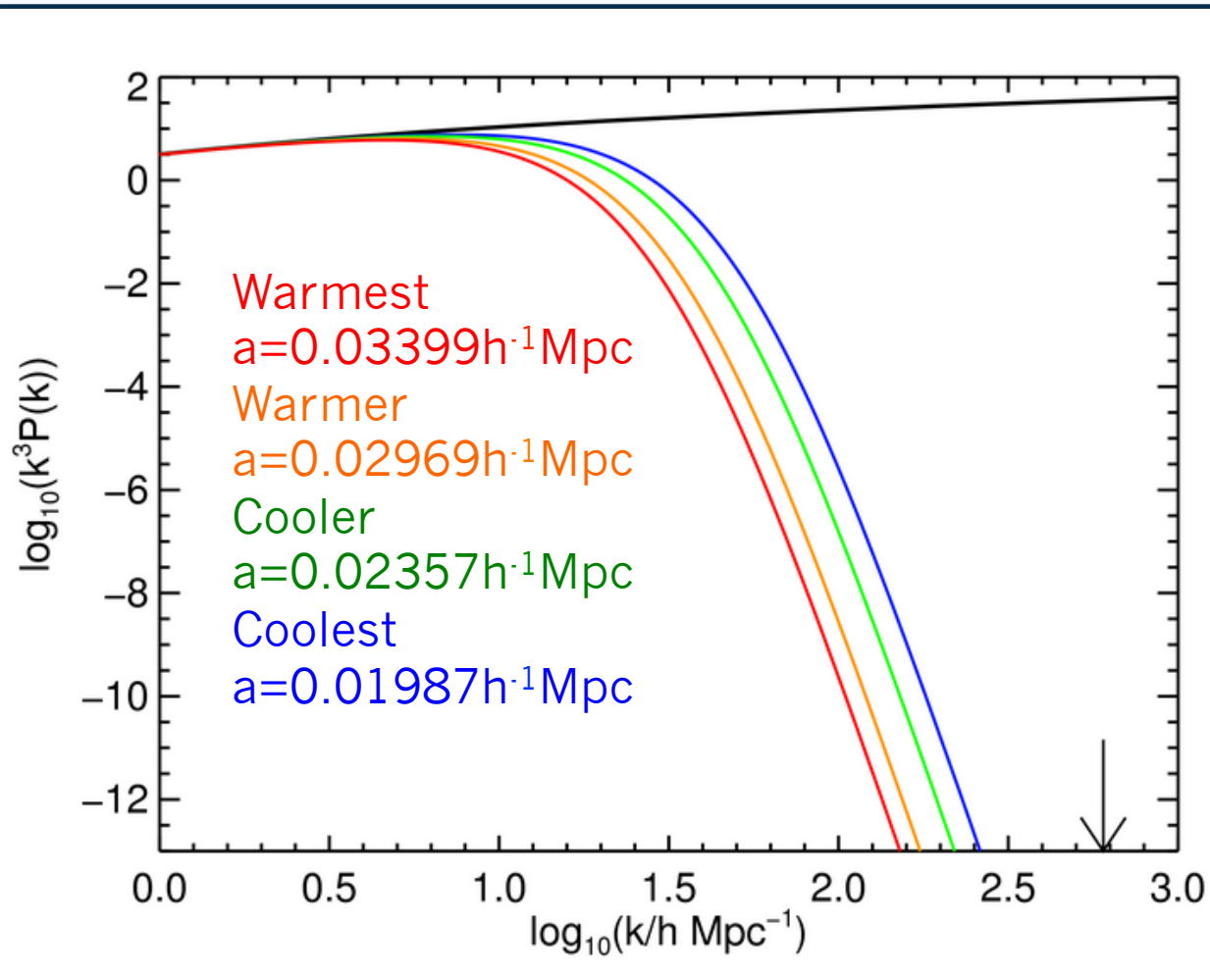
# Postscript: one problem, many solutions

- Di Cintio et al. 2012
- Vera-Ciro et al. 2012
- Vogelsberger et al. 2012
- Wang et al. 2012



# Varying the sterile neutrino mass

$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$



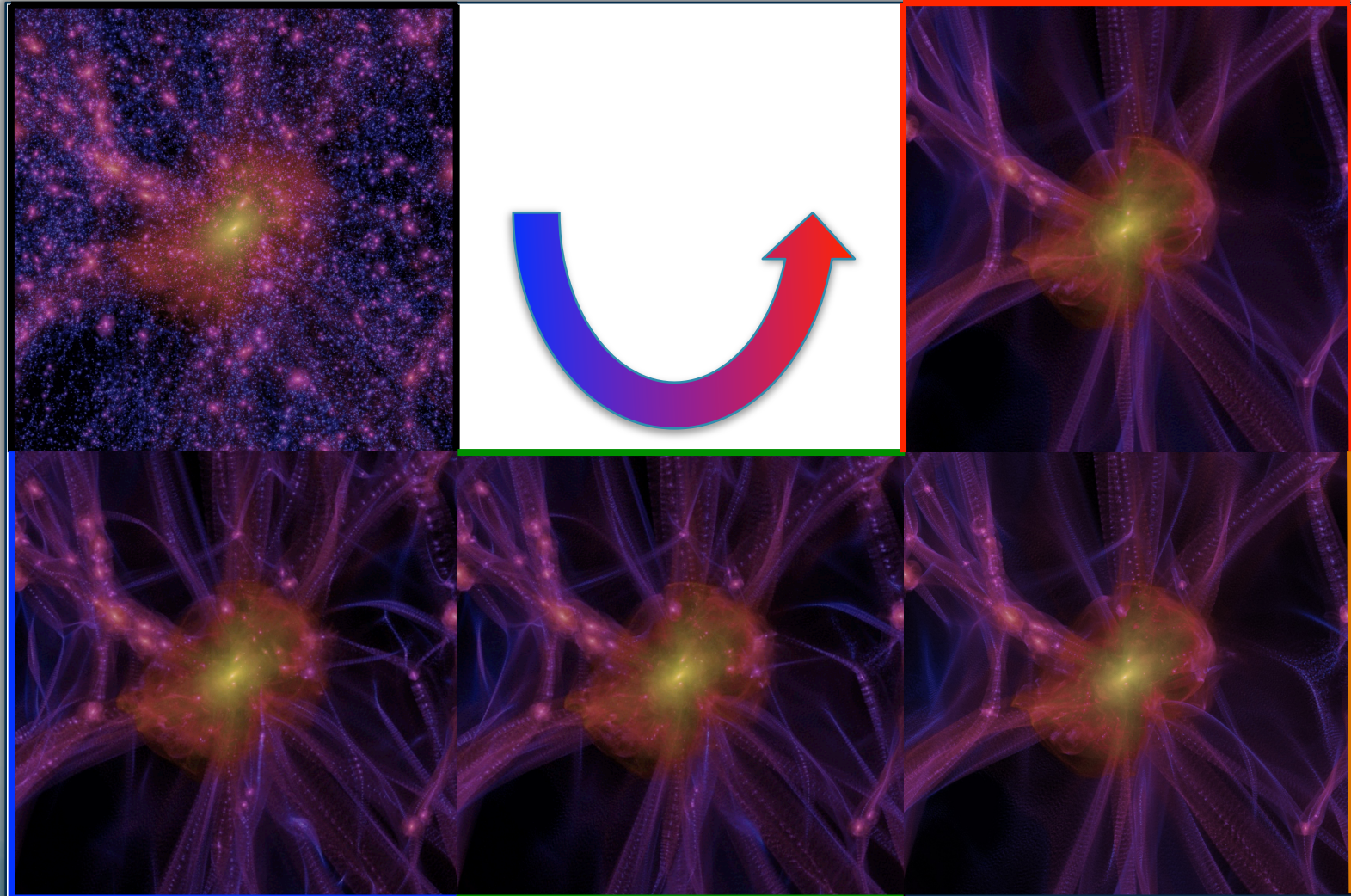
- Introduce WMAP7
- Resimulate CDM and 4 WDM models

# The compulsory movie(s)

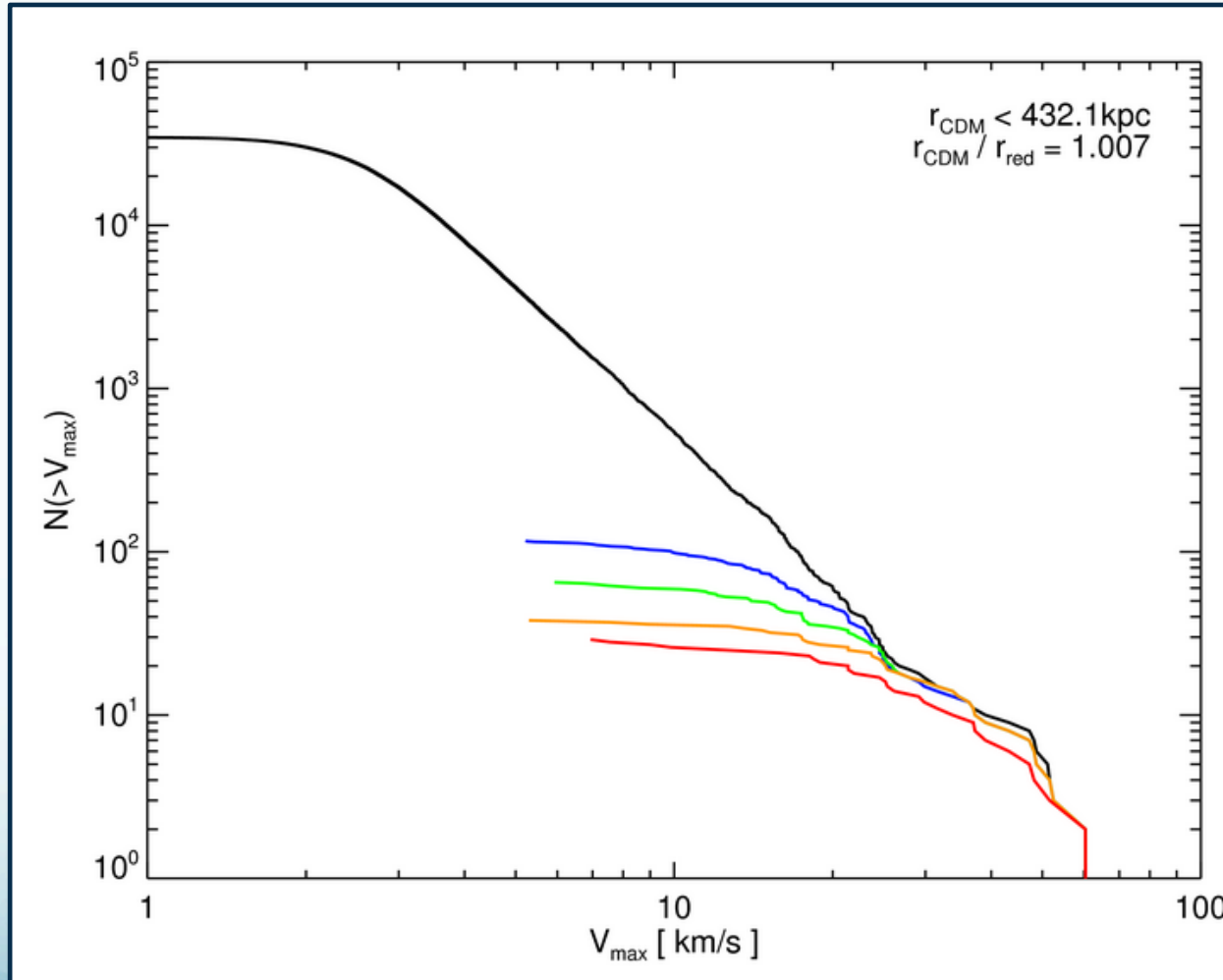
**z = 48.73**



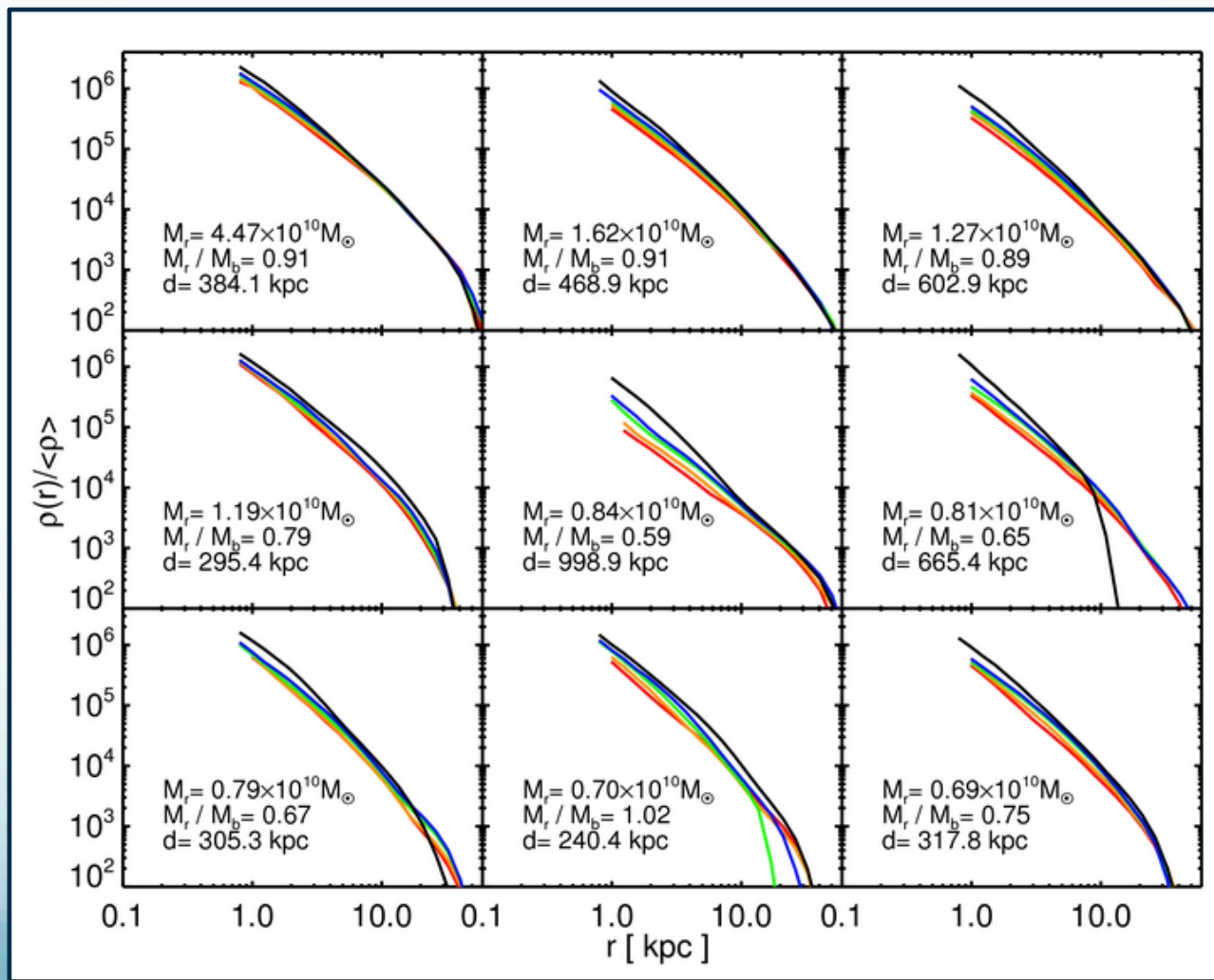
# Varying the particle mass



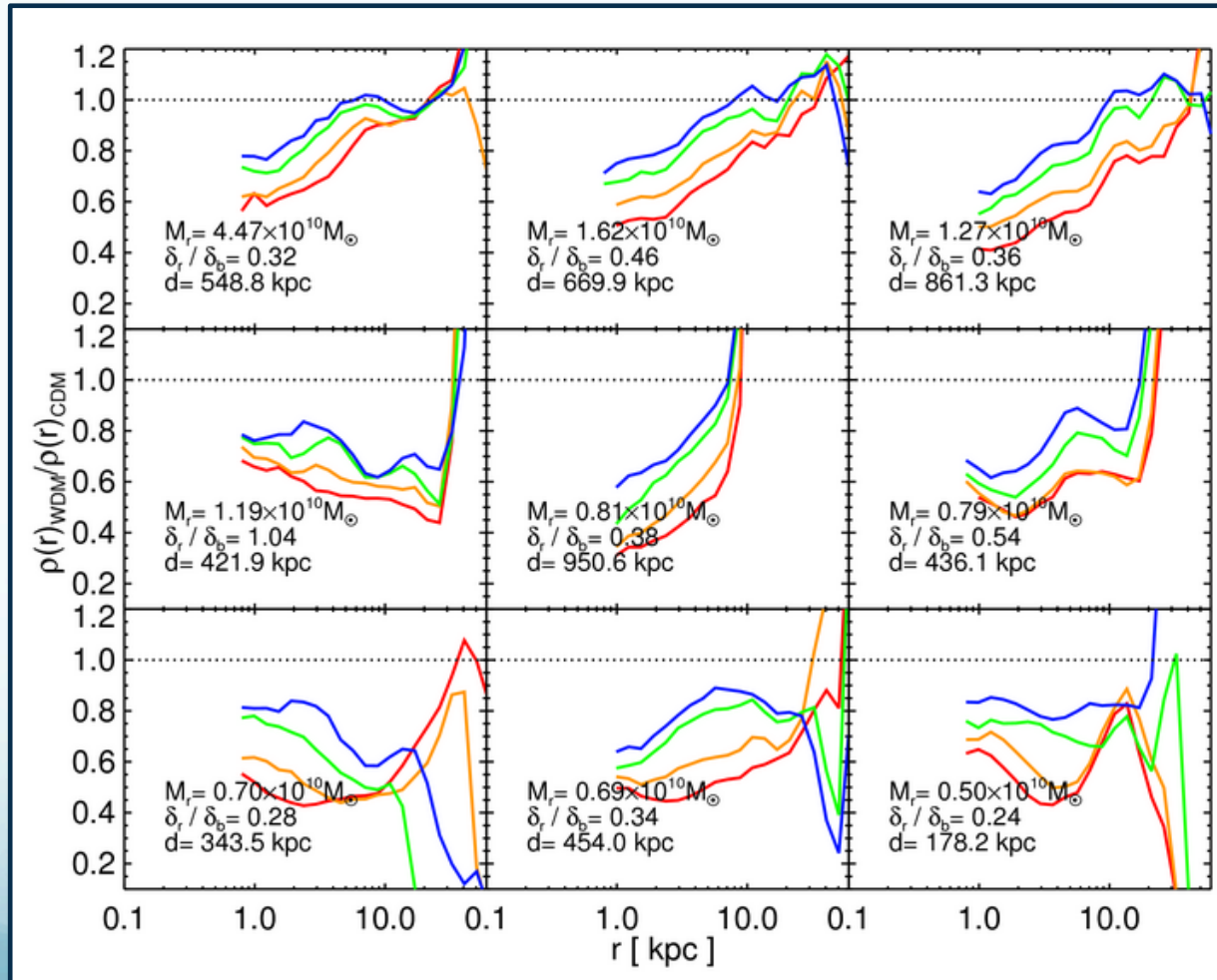
# Subhalo abundances



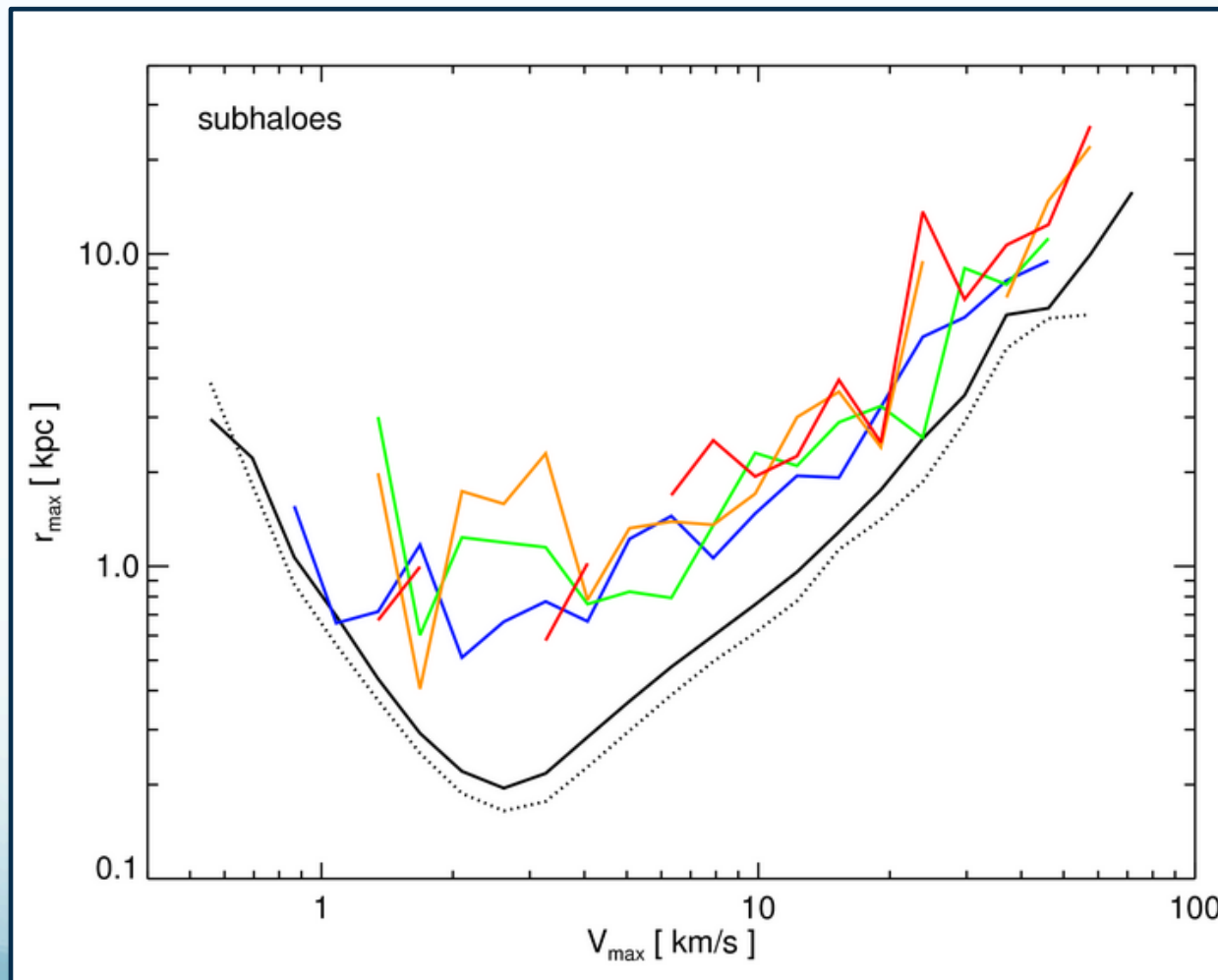
# Density Profiles



# Density Profile Ratios



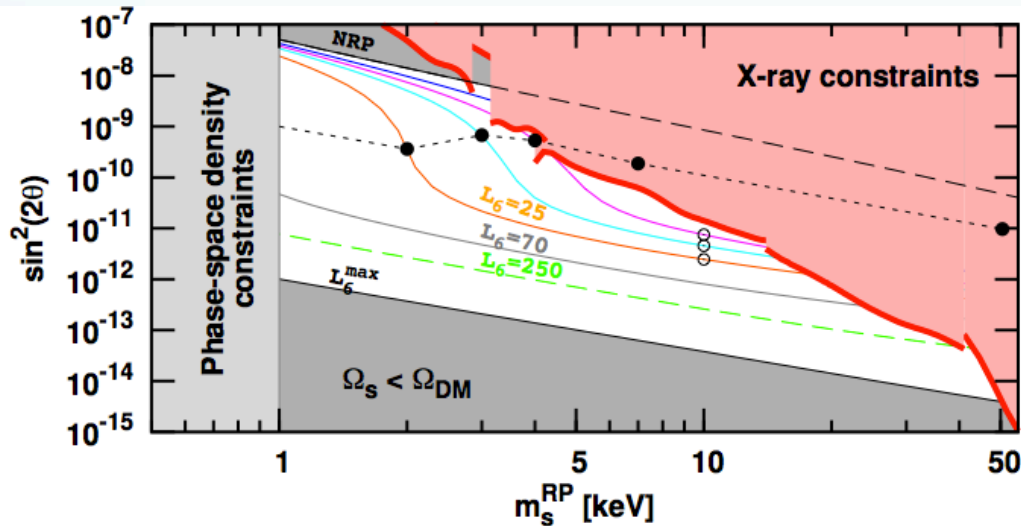
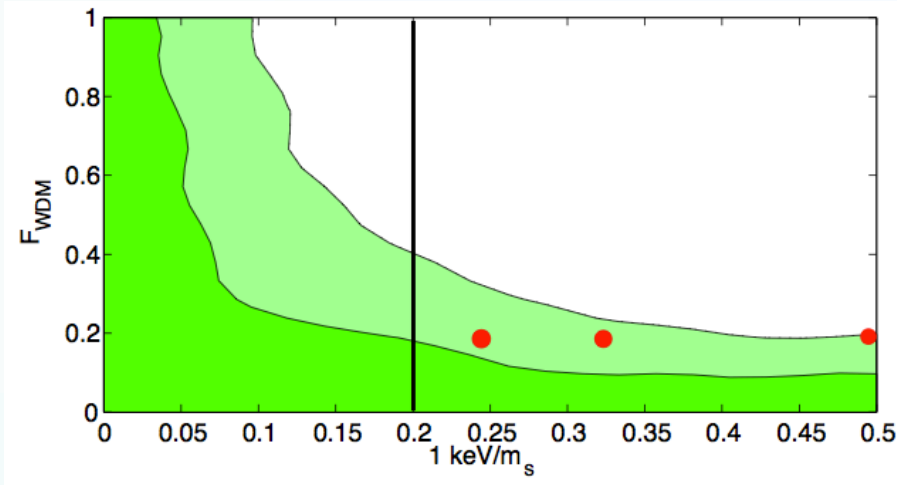
# Central densities



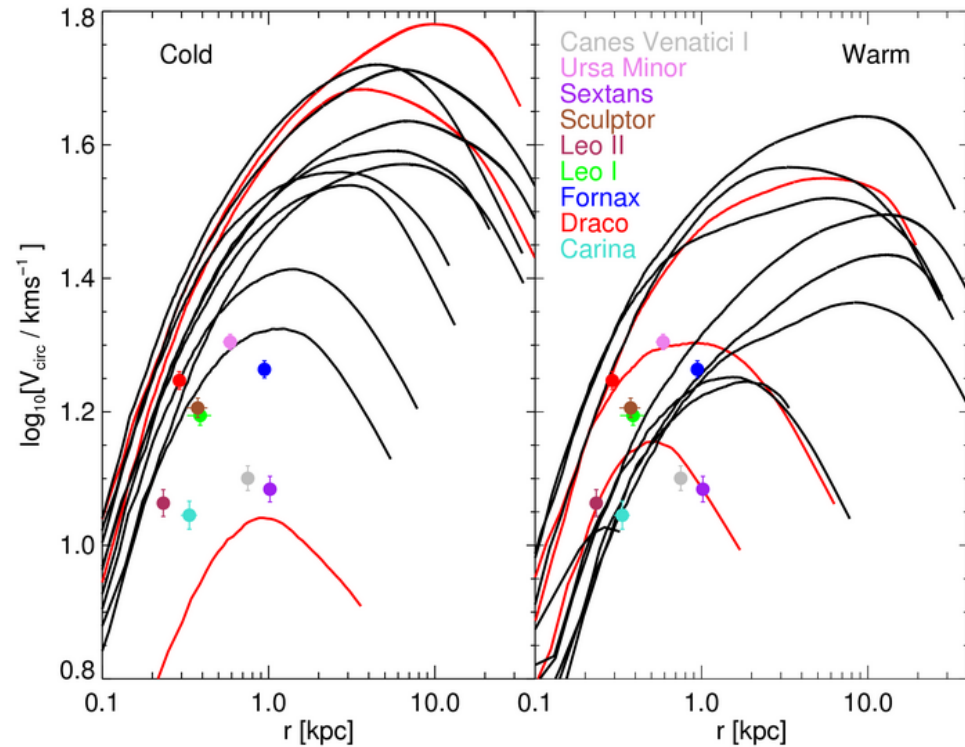
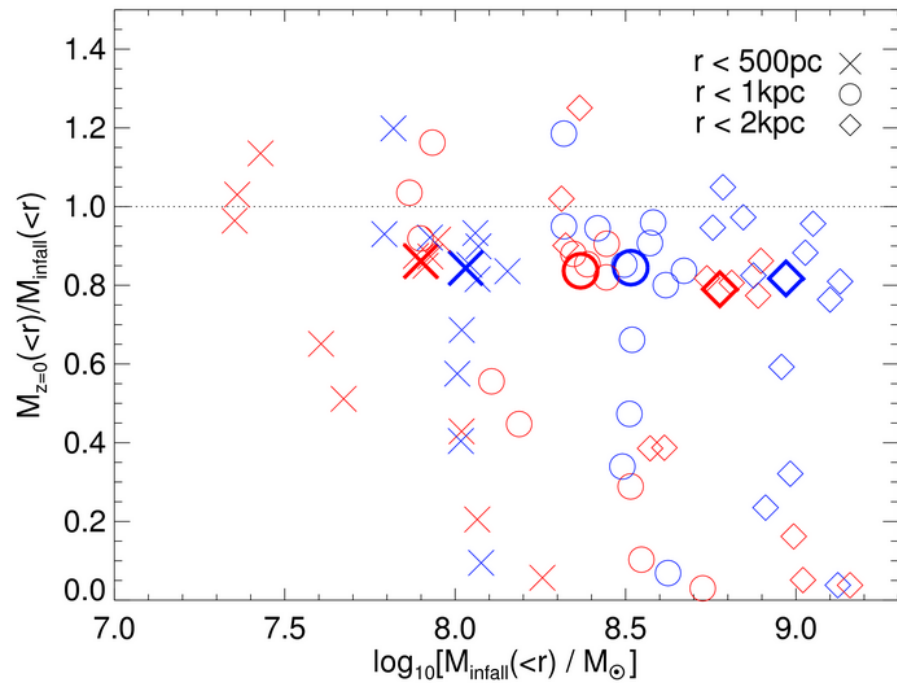
# Conclusions

- CDM predicts more dark matter in the centres of satellite galaxies than has been observed.
- Simulated Aq-A halo with WDM power spectrum (suppress power at small scales).
- Developed method for removing spurious haloes from catalogue.
- ‘Massive satellite problem’ ameliorated by late formation of WDM haloes compared to CDM.
- Now examining the effects of different sterile neutrino masses.
- Choice of cosmological parameters may be important.

# Bonus Slide 1



# Bonus Slide 2





# Bonus Slide 3

