Cluster Reading Group:
Dark Matter Halos

The halo mass function, origins of the NFW profile, and the impact of baryonic physics

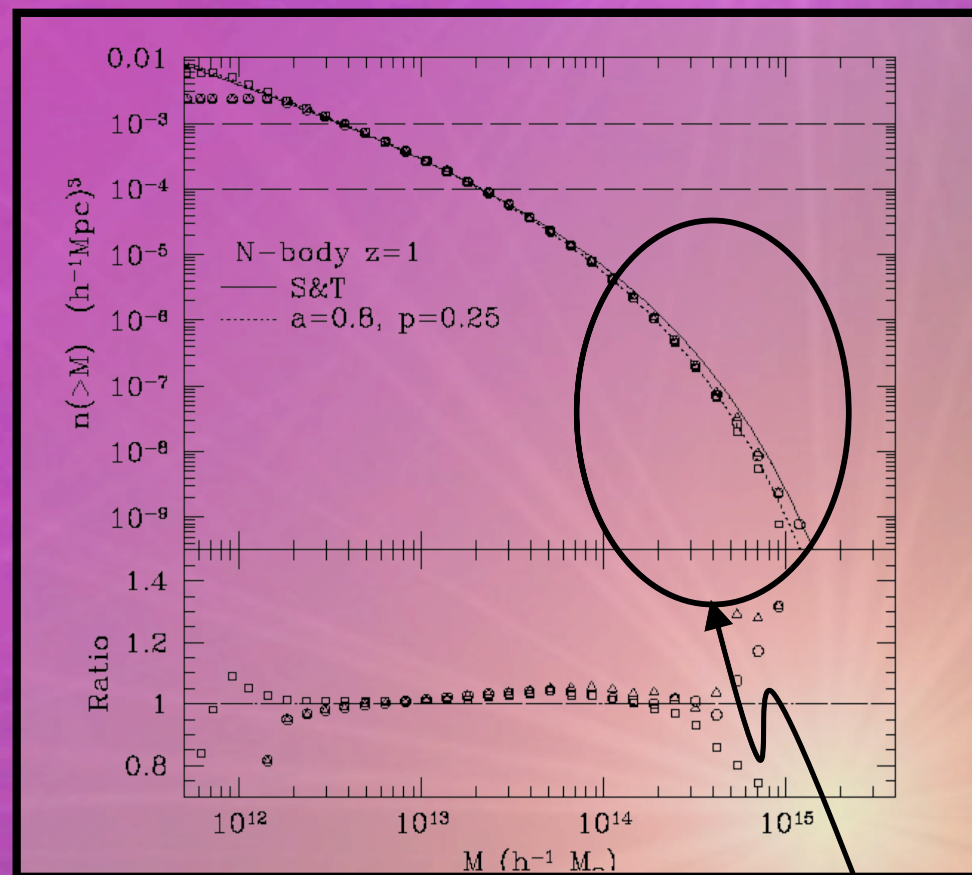
Overview

- The halo mass function
  - What it is and why we care about it
  - Press-Schechter and the peak/background split
  - Calibrations from N-body simulations
- The NFW “universal” profile
  - What is it?
  - Why is it universal?
  - Trends with age
  - The role of mass accretion history
- The influence of baryons
  - Changes in shape of dark matter halo
  - Changes in profile of dark matter halo
  - Changes in the dark matter power spectrum
  - implications

The halo mass function

- How does the dark matter organize itself in the universe?
- Dark matter lives in halos
- Mass function - breakdown of halo masses
- Big halos are rare
- Little halos are common
- Mass function evolves with z
  - Moves to the left as z increases

Number of halos of mass >M



Clusters

What use is the mass function?

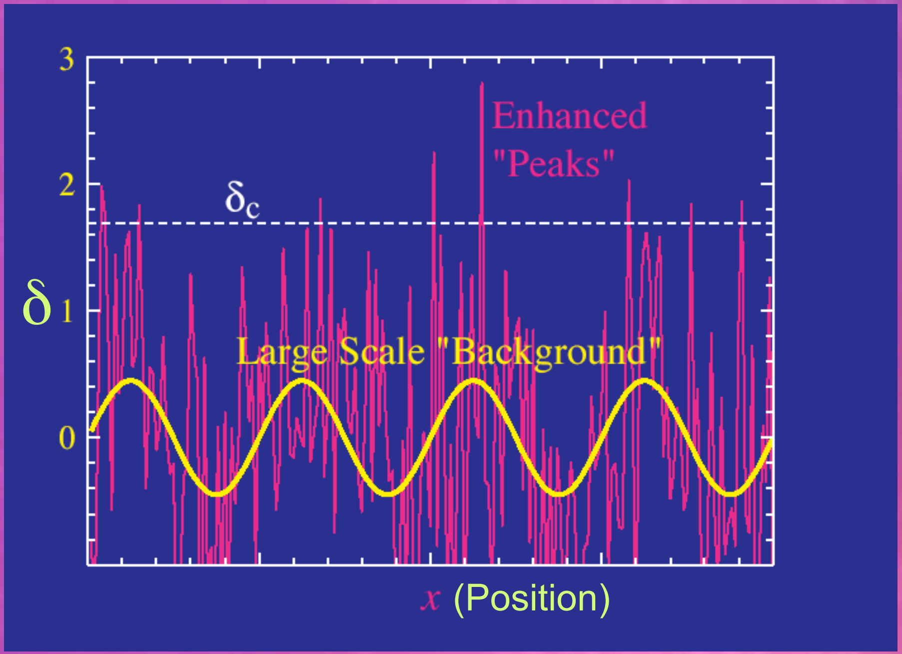
- Cosmology
  - Number density of halos is sensitive to the rate of structure formation
  - The growth function is sensitive to several important cosmological parameters
    - Matter density Ω_m
    - Normalization of power spectrum σ_8
    - Dark Energy parameters and evolution
  - Observations of the evolution of the mass function help constrain cosmological parameters
- Applications non-cosmological
  - Important for determining abundances and observational rates of extragalactic phenomena that trace the dark matter, as a function of redshift

Where does the mass function come from?

- Analytic arguments made by Press and Schechter
  - Fraction of volume collapsed

$$f_{\rm coll}(M(R),z) = \frac{2}{\sqrt{2\pi}\sigma(R,z)}\int_{\delta_c}^{\infty} d\delta e^{-\delta^2/2\sigma^2(R,z)}$$

- Assumptions
  - Overdensity fluctuations are Gaussian on all scales
  - Cheat in normalization
  - Non-linear effects ignored in computation of the rms of the smoothed density field



Number density given by

$$dn(M,z) = -\frac{\rho_m}{M}\frac{df_{\rm coll}(M(R),z)}{dM}dM$$

Mass Functions with N-body Simulations

- Press Schechter theory is based on a number of flawed assumptions
  - Numerical simulations confirm that it is pretty accurate (White, Efstathiou & Frenk 1993)
- Not immediately clear why it works
  - Some theoretical justifications exist (Peacock & Heavens 1990; Bond *et al*. 1991)
- Some N-body calibrations of the threshold δ_c for spherical collapse exist
  - Results so close to δ_c=1.686, the value for SCDM cosmology, that most people just use that value (Eke, Cole & Frenk 1996)
- Very important extensions to Press Schechter theory exits
  - Mass functions calibrated with N-body simulations have been widely used, most notably (Sheth & Tormen 1999) but also a more modern fit with larger simulations (Warren et al. 2005)

Meet the NFW profile!

- Dark matter lives in halos, but where in the halo?

$$\rho_{\rm NFW}(r) = \frac{\delta_{\rm ch}\rho_{\rm crit}}{(cr/r_{\rm vir})\,(1 + cr/r_{\rm vir})^2}$$

- Two parameter family with a normalization δ_{ch} and a concentration c
- The "mass" of the halo is given by

$$M = 4\pi \int_0^{r_{\rm vir}} \rho(r)\, r^2 dr$$

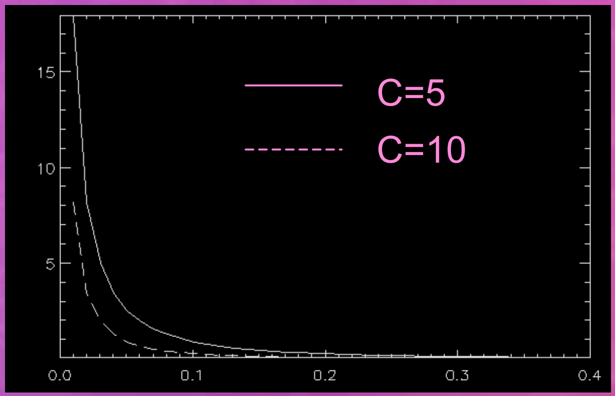
- N-body simulations: the virial radius corresponds to an enclosed overdensity of approximately 200
- Reduce the number of free parameters to get δ_{ch} in terms of c

$$\delta_{\rm ch} = \frac{200}{3}\,\frac{c^3}{[\ln(1+c) - c/(1+c)]}$$

What's concentration?

- Halos of differing masses have different concentrations
  - Small galaxy sized halos very concentrated with c~10
  - Large cluster sized halos are much less concentrated with c~5 for most clusters
- Concentration governs how centralized the mass distribution is

ρ / ρ_s

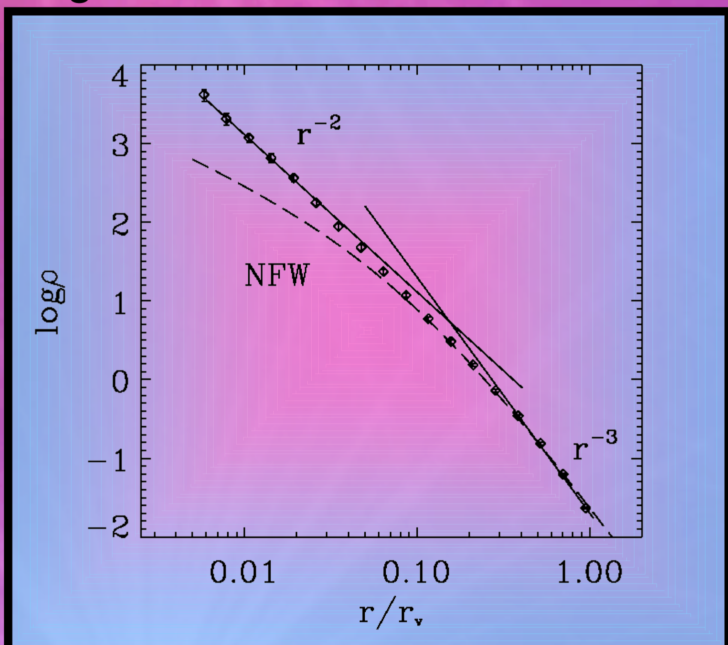


r/r_{vir}

Why is it universal?

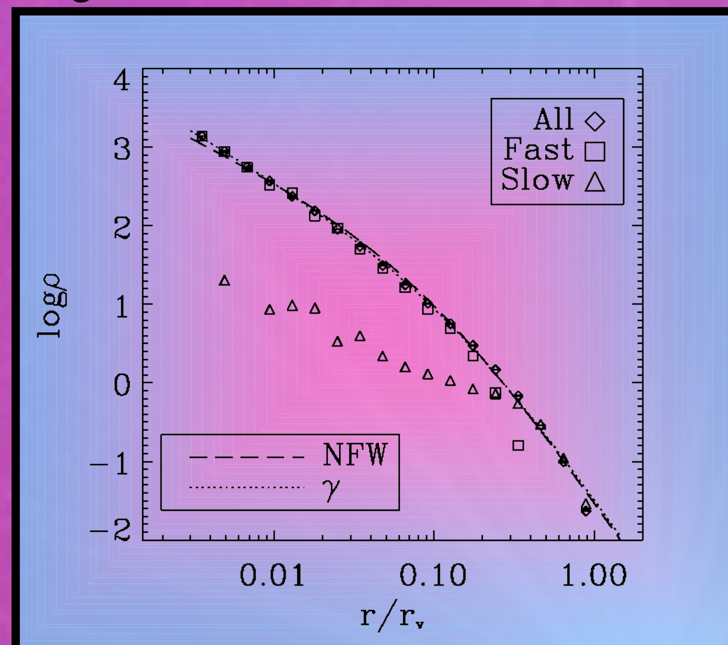
- Paper I (Lu *et al*. 0508624) starts to address this question
- Postulate all halos form in a two stage process

Fig. 1



Slow accretion phase only: pure radial infall

Fig. 2



Slow and fast accretion phases: radial infall plus a merger dominated part

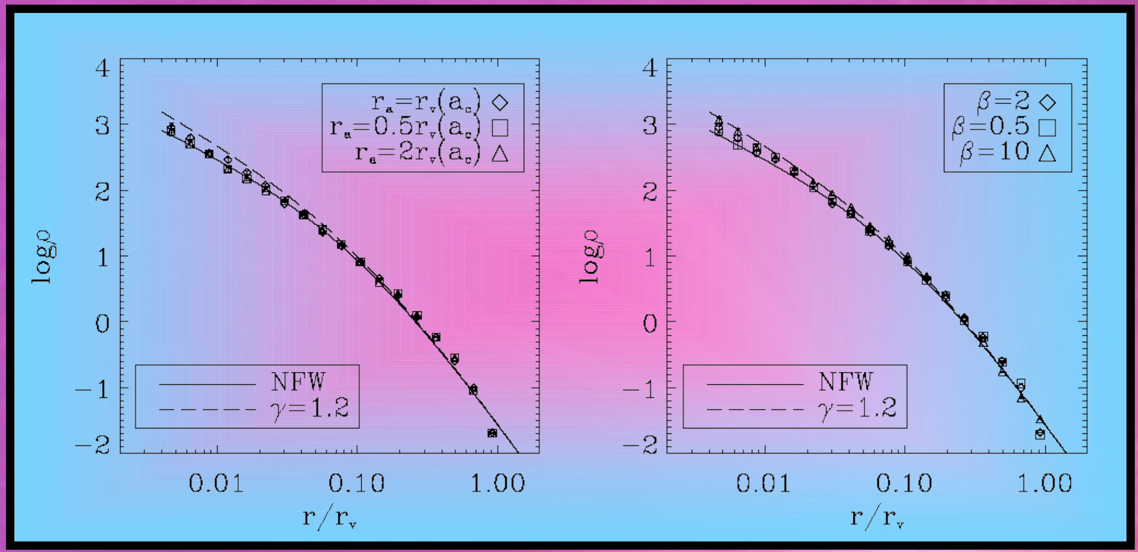
Why is it universal?

- Fast accretion phase dominates inner profile and slow accretion dominates the outer part
- Modify the NFW to accommodate a varying inner slope, and test sensitivity to parameters of the fast accretion

$$\rho(r) = \frac{\delta_{\rm ch}\rho_{\rm crit}}{(cr/r_{\rm vir})^{\gamma}\ (1 + cr/r_{\rm vir})^{(3-\gamma)}}$$

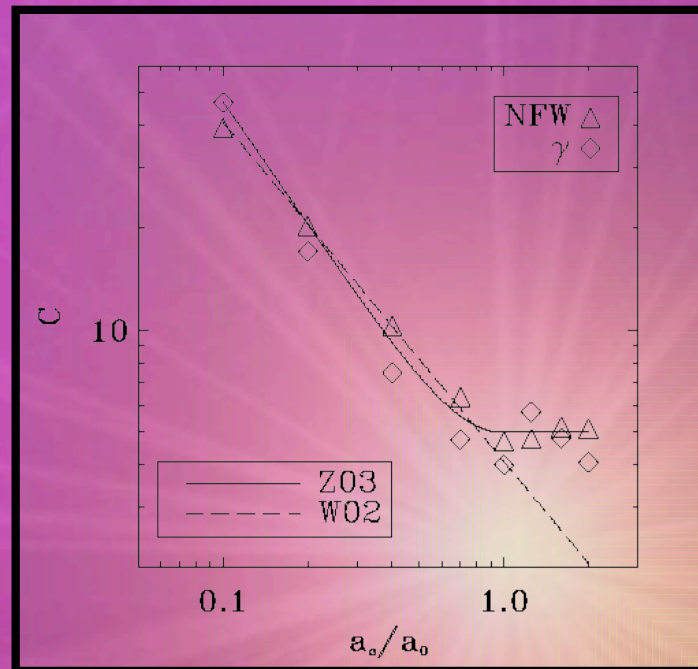
Inner slope

- Vast changes in the fast accretion parameters lead to minimal variation of the inner slope: γ~1 seems to be a generic result



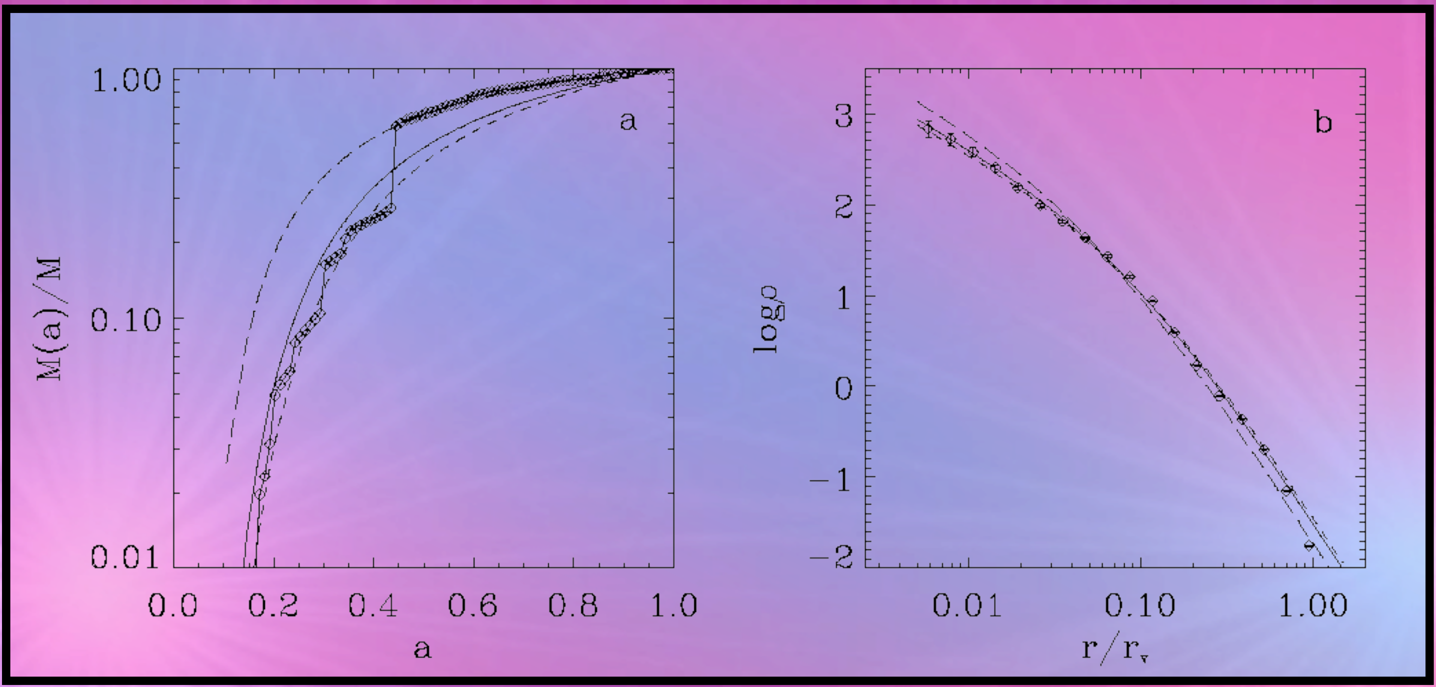
Trends with age (concentration)

- Older halos are, in general, more concentrated
- Smaller halos are older (form earlier) than large ones ⇒ galaxy sized halos more concentrated than cluster sized halos
- Andreas Berlind quote: “The concentration of the halo reflects the density of the universe at the time that it formed”
- The trend of concentration with age seems to be dominated by the slow radial infall accretion phase
- The trend flattens out at late times -- halos in the fast accretion phase have concentration independent of age



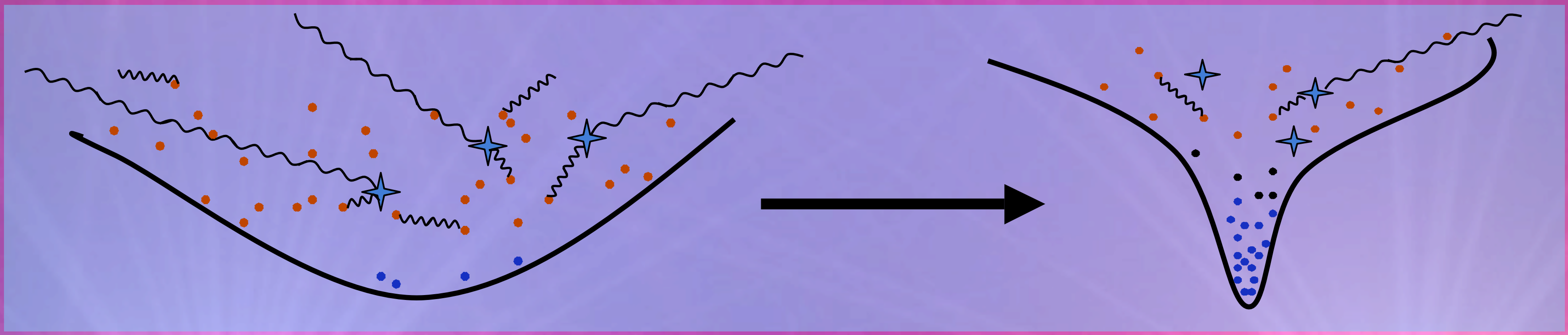
The role of mass accretion history

- In reality, cluster mass is acquired by a sequence of mergers
- Details of the mass accretion history introduce scatter in the age-concentration (or mass-concentrations) relations
- The profile can still be fit by an NFW, but in the event of a big mass jump, a compromise between the recent and past histories must be used to understand the shape



Enter: the Baryons!

- Baryons make up around %4 of the total energy density
- They differ from dark matter in that they couple to radiation
  - They cool
  - Through cooling they contract to high densities and form stars and galaxies
  - They emit photons we can observe



- The physics is more complex because there is more than just gravity
- Everything we can observe is touched by the baryons

Baryons change halo shape

- Paper II (Kazantzidis *et al*. 2005) quantifies this effect with numerical simulations
- Halos are rounder overall with baryon cooling
  - Inner radii %30-40 rounder(.1 r_{vir})
  - Outer radii %10-20 rounder(~r_{vir})

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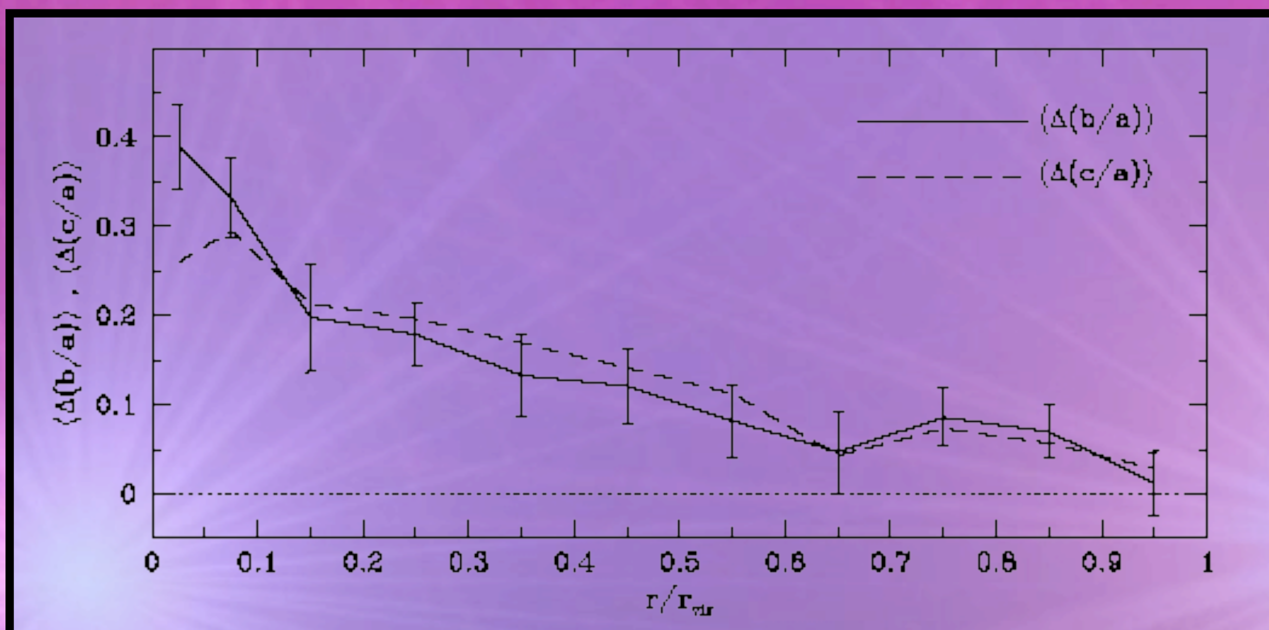
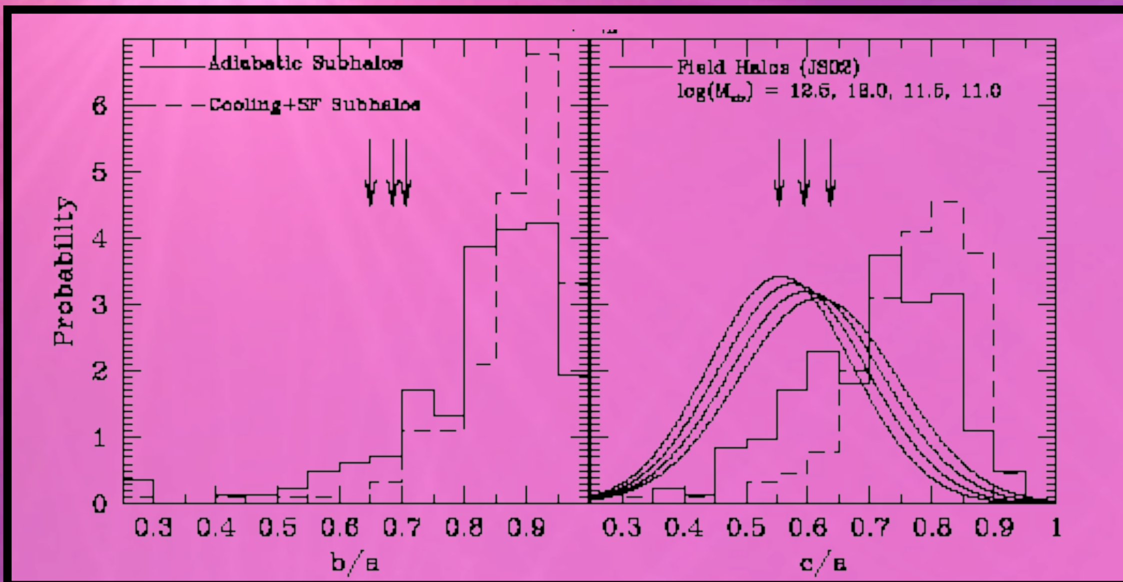


Baryon cooling also changes shapes of substructure



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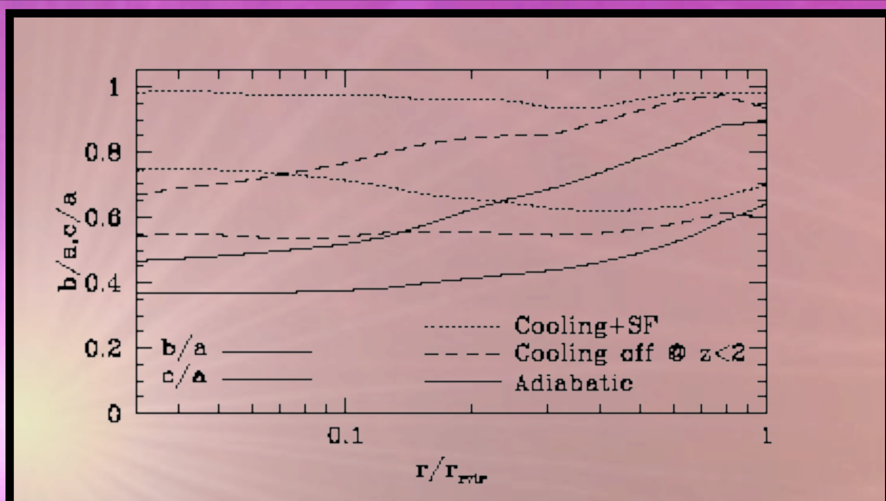
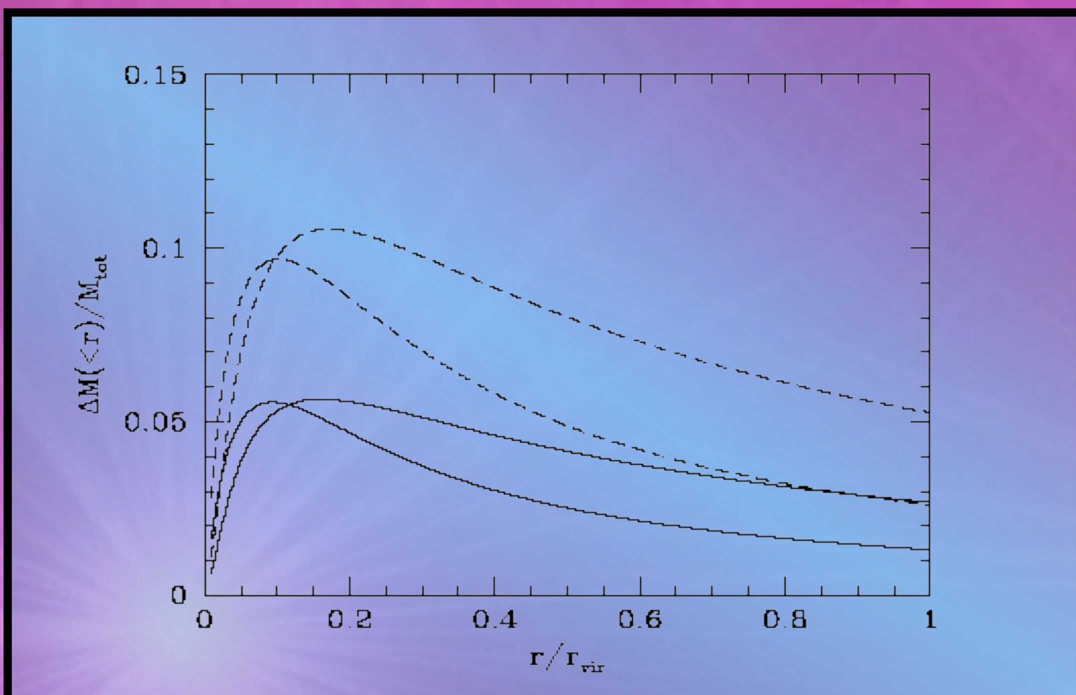


- Substructure is rounder
- These results are not just because of the overcooling problem in simulations

Baryonic cooling alters the profile and concentration

- A very good paper I should have made you read: White 2004 (astro-ph/0405593)
- Gas cooling in the center causes the halo to become more concentrated



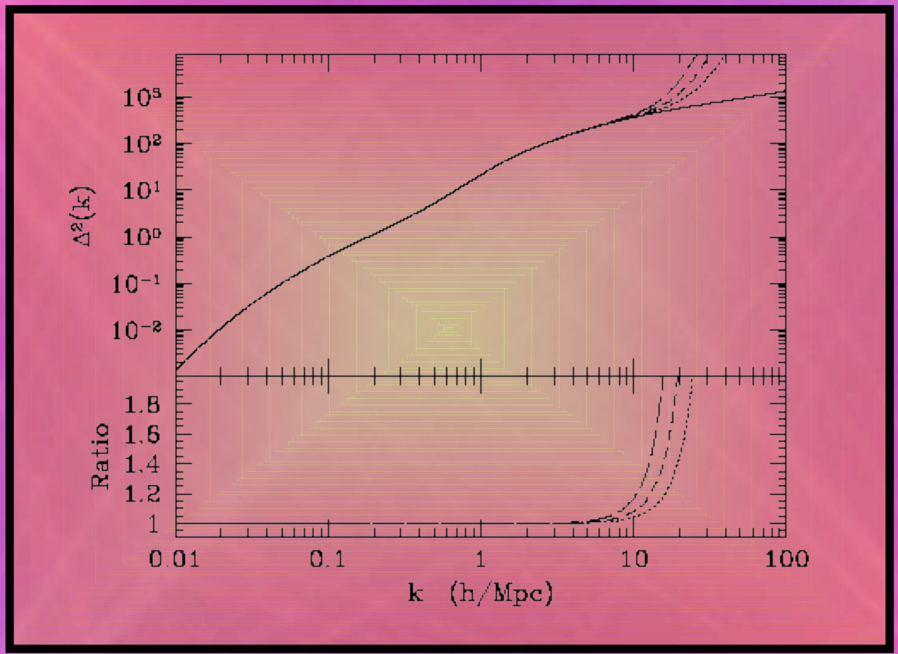
- - -   Cooled fraction %10

——   Cooled fraction %5

Upper curves have c=10 (galaxy)

Lower curves have c=5 (cluster)

Baryons change dark matter power spectrum



- Cooled dense baryon clumps drag in the dark matter, and therefore change the power spectrum on small scales

Implications

- Baryonic physics potentially plays a role in:
  - Weak lensing power spectra
  - Weak lensing cluster mass estimation
  - Cluster X-ray temperature
  - Cluster SZ decrement
  - Cluster shapes (which impacts scatter in mass observable relationships)
  - The nature of cluster substructure (more scatter)
  - Galaxy profile within large clusters
  - Hot gas profile within large clusters
  - Models of galaxy bias
- So it's a good thing we're planning to think about this and learn to model it if we can!