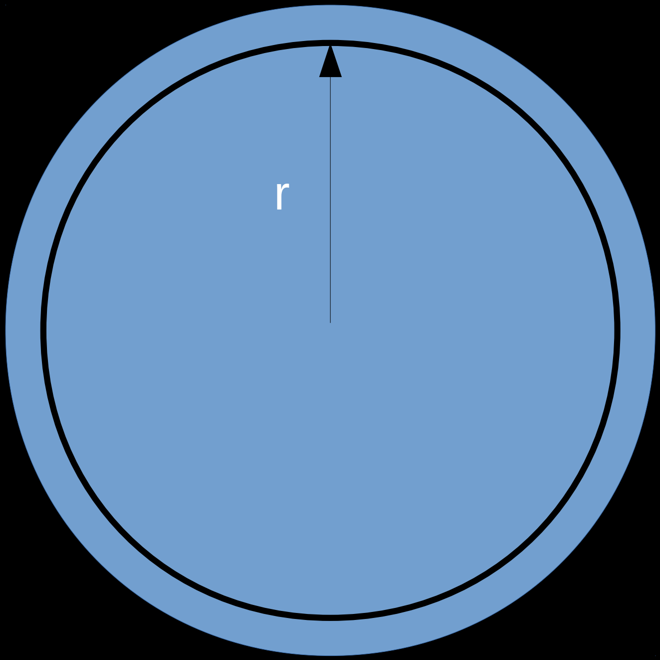
Azadeh (Azi) Fattahi
Institute for Computational Cosmology
Durham University

Top-hat Spherical Collapose Model

Spherical density perturbation with constant over density



The equation of motion is very simple:

$$\frac{d^2 r}{dt^2} = -G M(<r)/r^2$$

$$M(<r) = \frac{4}{3}\pi r^3(t)\rho(t)[1+\delta(t)]$$

Solutions:

$$r = a(1 - \cos\chi),$$

$$t = \left(\frac{a^3}{GM}\right)^{1/2}(\chi - \sin\chi),$$

Top-hat Spherical Collapose Model

$$r = a(1 - \cos\chi),$$

$$t = \left(\frac{a^3}{GM}\right)^{1/2} (\chi - \sin\chi),$$

(i) expansion $0 < \chi < \pi$

(ii) reaching maximum (trun-around, t_{ta}) , r_{max} , at $\chi=\pi$

(iii) collapsing back between $\pi < \chi < 2\pi$

(iv) final stage at $\chi=2\pi$ ($t_{col} = 2\, t_{ta}$)

In EdS universe:

$\delta_{ta} \sim 5.55$ and δ_{col} = infinity

Top-hat Spherical Collapose Model

More-realistic: system virializes

Virial theorem :

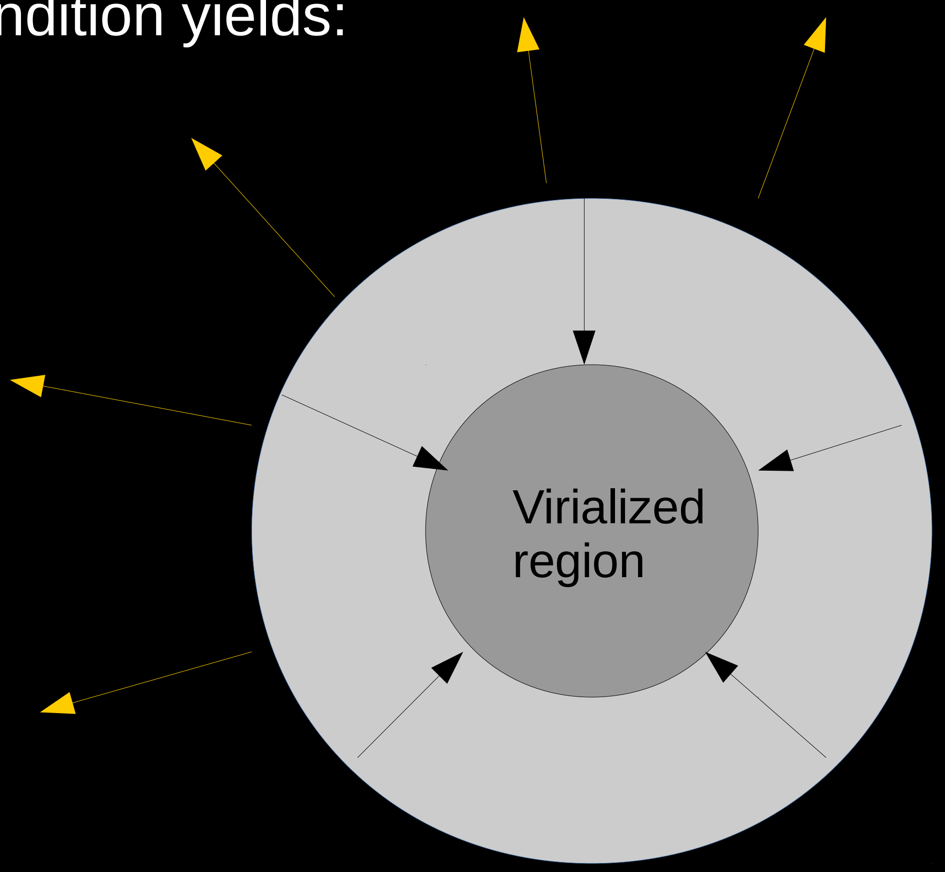
$$r_{vir} = r_{ta} / 2$$

In EdS universe system the above condition yields:
$1+\delta_{vir} \approx 178$ (note: $\delta_{vir} = \Delta_{vir}$)

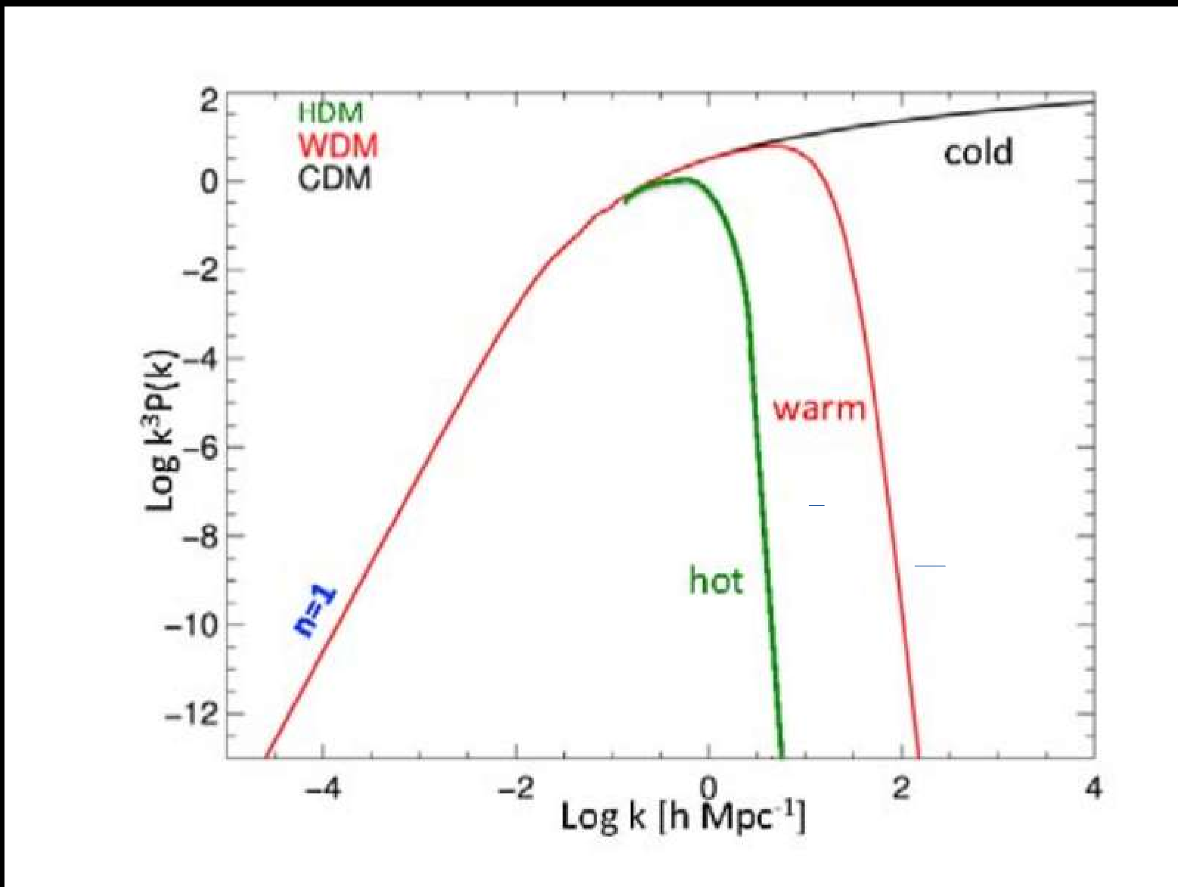
In non EdS universe with Lamda:

$1 + \delta_{vir} \approx 360$

Another common adopted vallue:
$1 + \delta_{vir} = \rho/\rho_{crit} =200$



Power spectrum



Damping scale (λ) ~ m_p^{-1}

Hot dark matter :

Relativistic at early times

m_p ~ 10 ev (neutrinos)

$\lambda \sim 10^{15}\ M_{sol}$ (galaxy clusters)

Cold dark matter:

Non-relativistic at early times

m_p ~ 1 Gev

λ ~ earth mass

warm dark matter:

m_p ~ 1 kev

λ ~ massive galaxies

Hot dark matter (HDM)

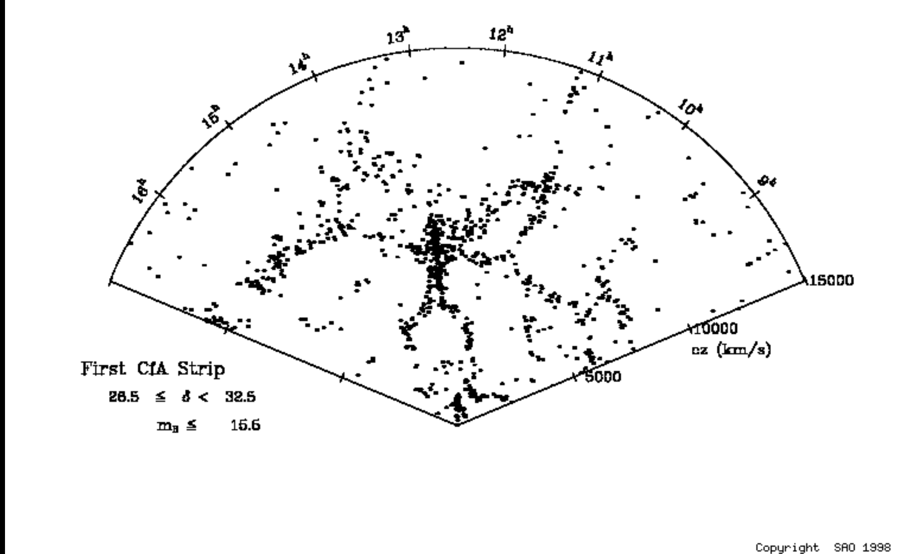
Clusters collapse first: top-down formation of structure

Cold dark matter (CDM)

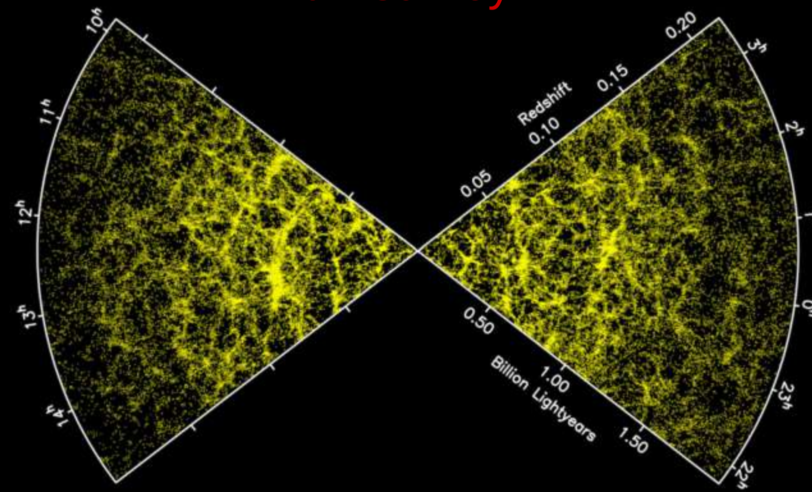
Dwarf galaxies collapse first: bottom-up (hierarchical) formatio

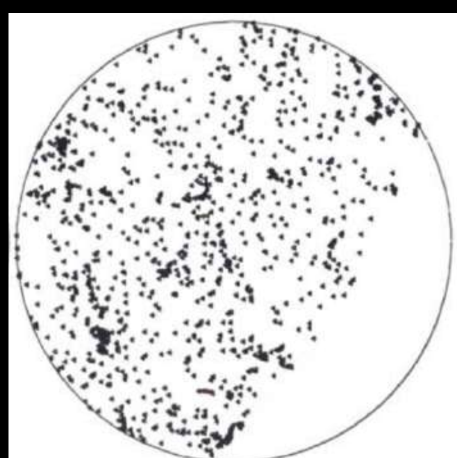
Numerical simulations and large scales

CfA redshift survey



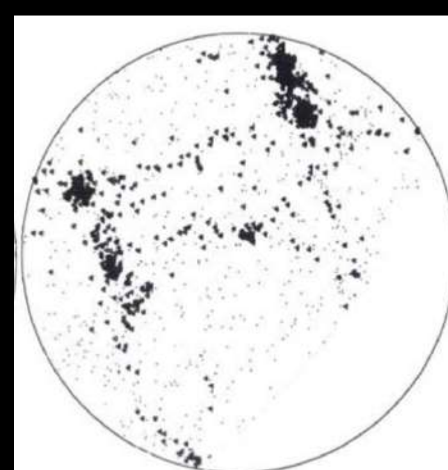
2dF survey

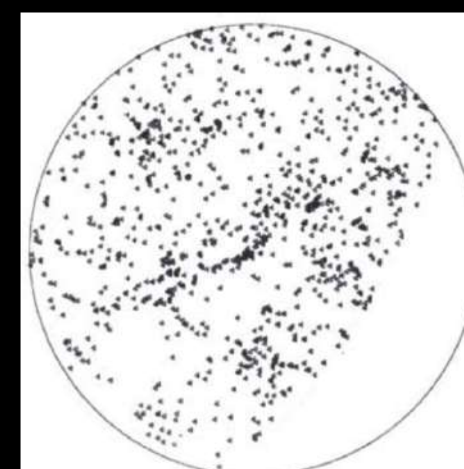




CfA redshift Survey
sky projection

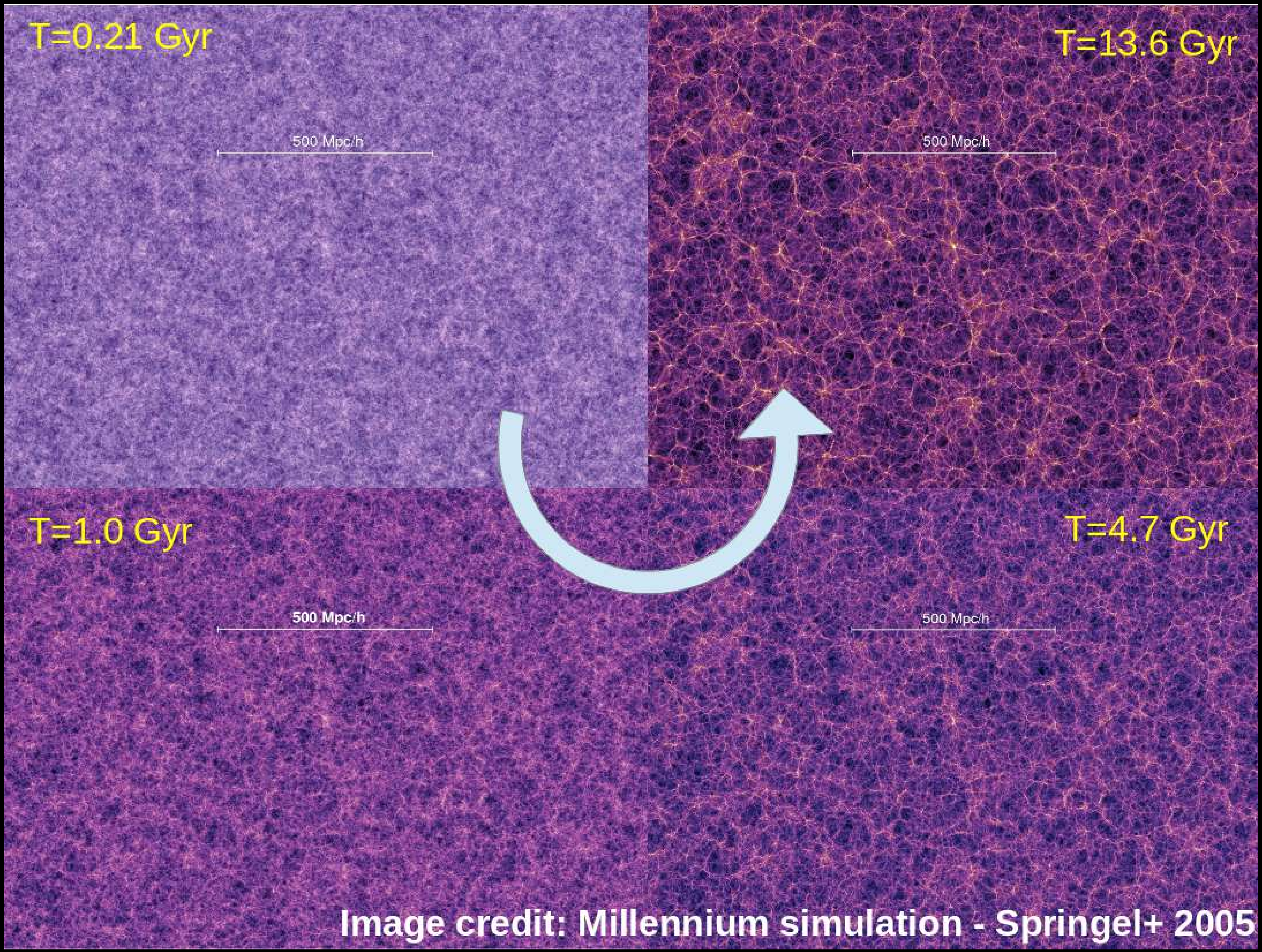
HDM sims.





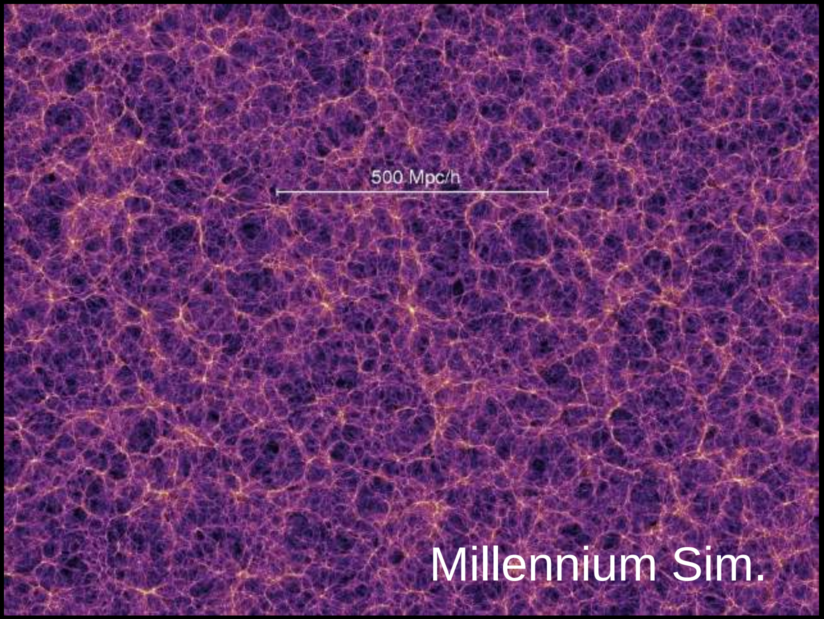
CDM sims.

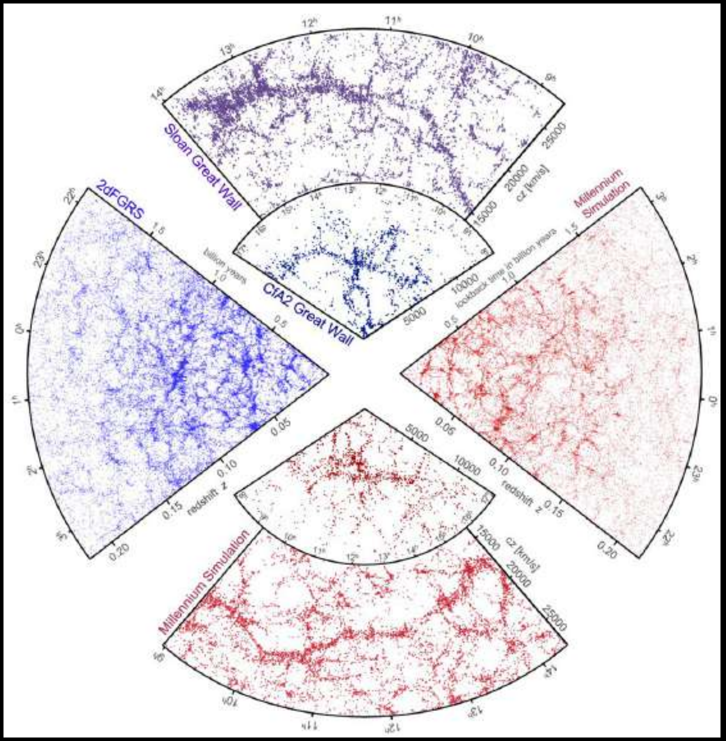
Millennium simulation



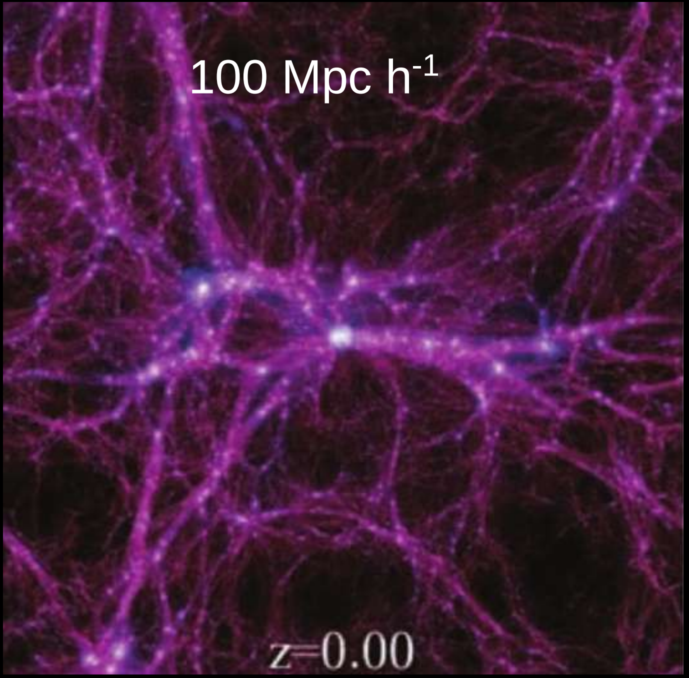
Virgo Consortium

Millennium simulation series





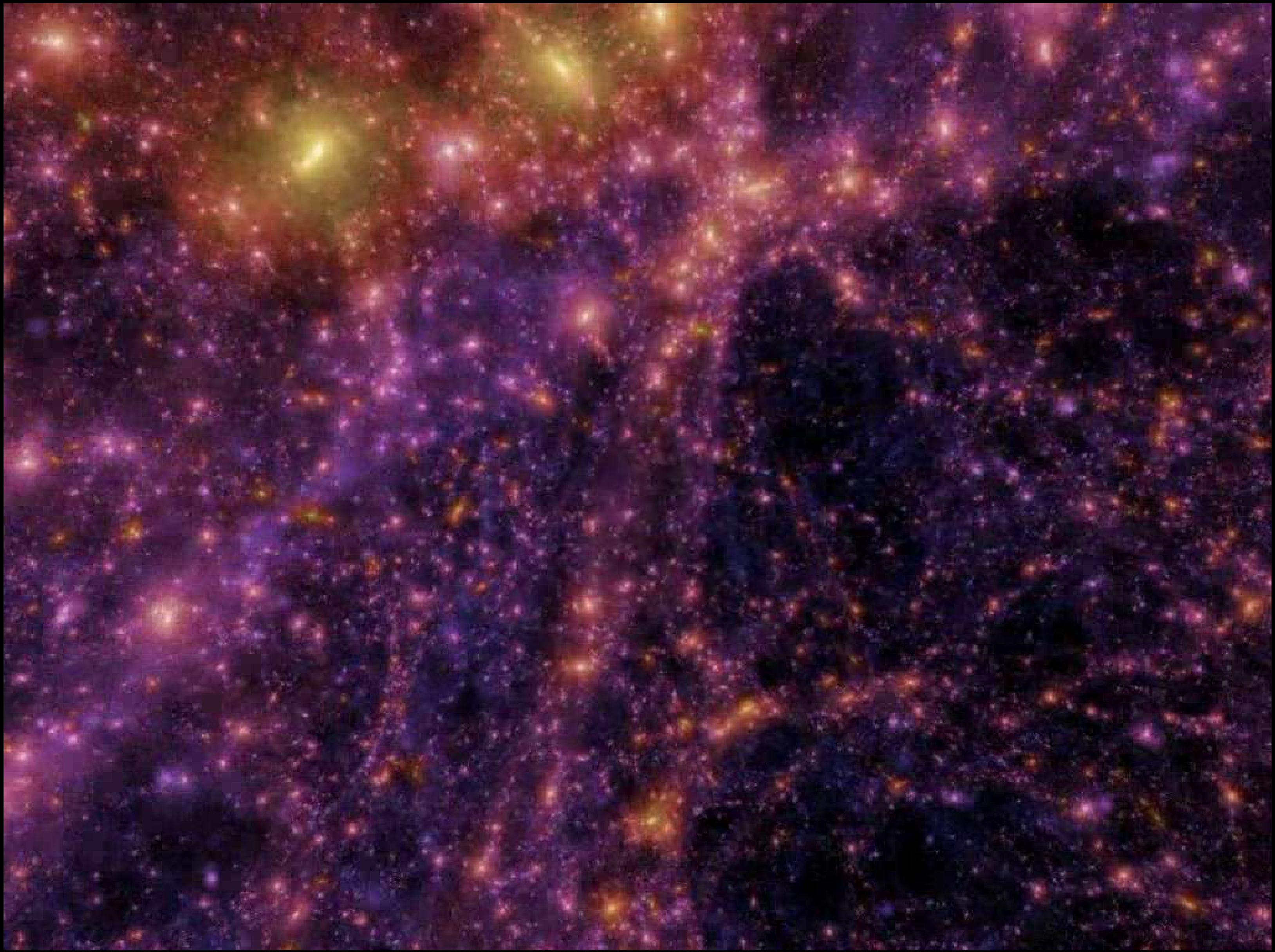
Assigning galaxies to dark matter halos based on semi-analytic models

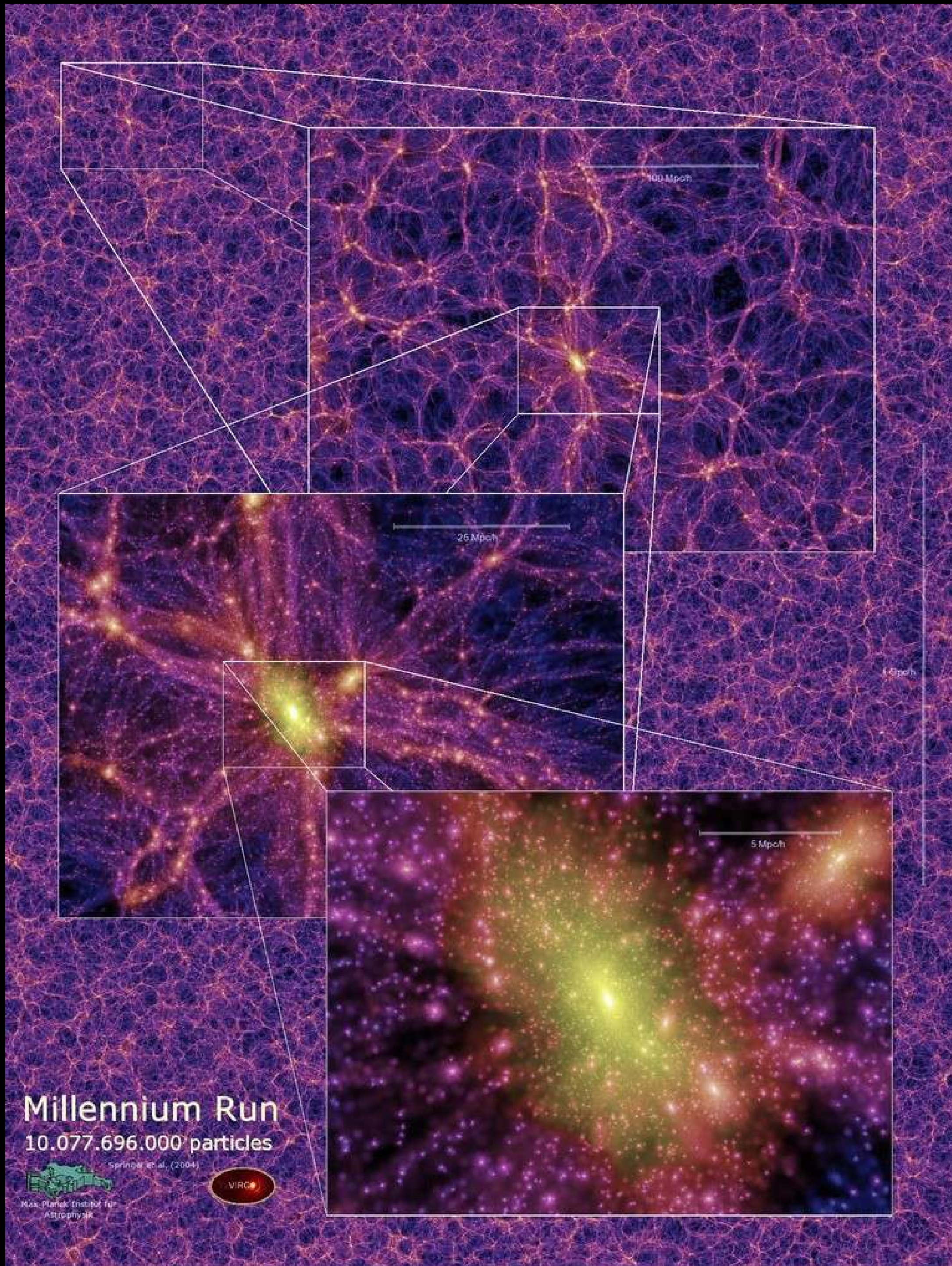


Millennium Sim. II

Virgo Consortium
Springel+2005
Boylan-Kolchin+2009

Millennium simulation fly-through





- cosmic web structure
  - Voids
  - Fillaments
  - Sheets

- Bigger objects form at the intersection of fillaments

- Clumpiness

- Hierarchical growth …

- Self-similarity ...

CDM Hierarchical Growth

Aquarius project: simulations of Milky Way like halos

Springel et al. 2008 – Virgo Consortium

CDM Hierarchical Growth

CDM Hierarchical Growth

CDM Hierarchical Growth

CDM Hierarchical Growth

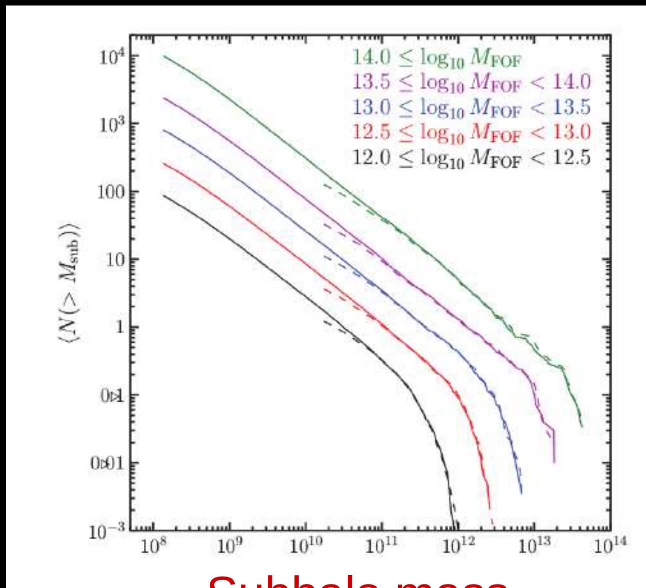
CDM self-similarity

One is a Milky-Way size halo (mass~10^{12} M_{sol});
another a galaxy cluster halo (mass ~10^{14} M_{sol})

CDM self-similarity

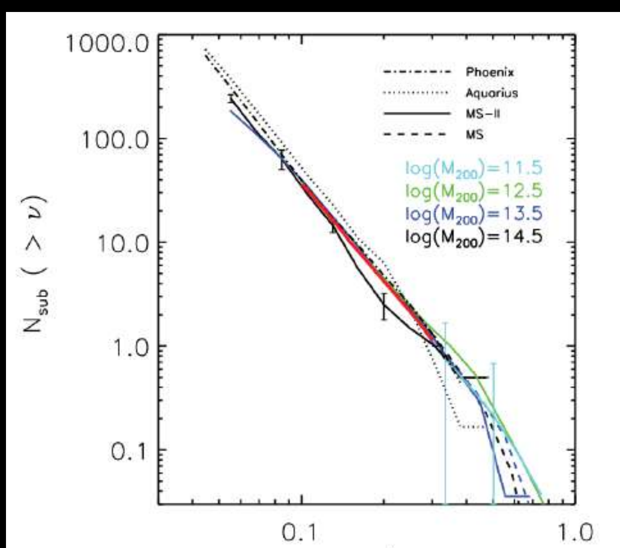
Substructures mass function

Boylan-Kolchin+2009



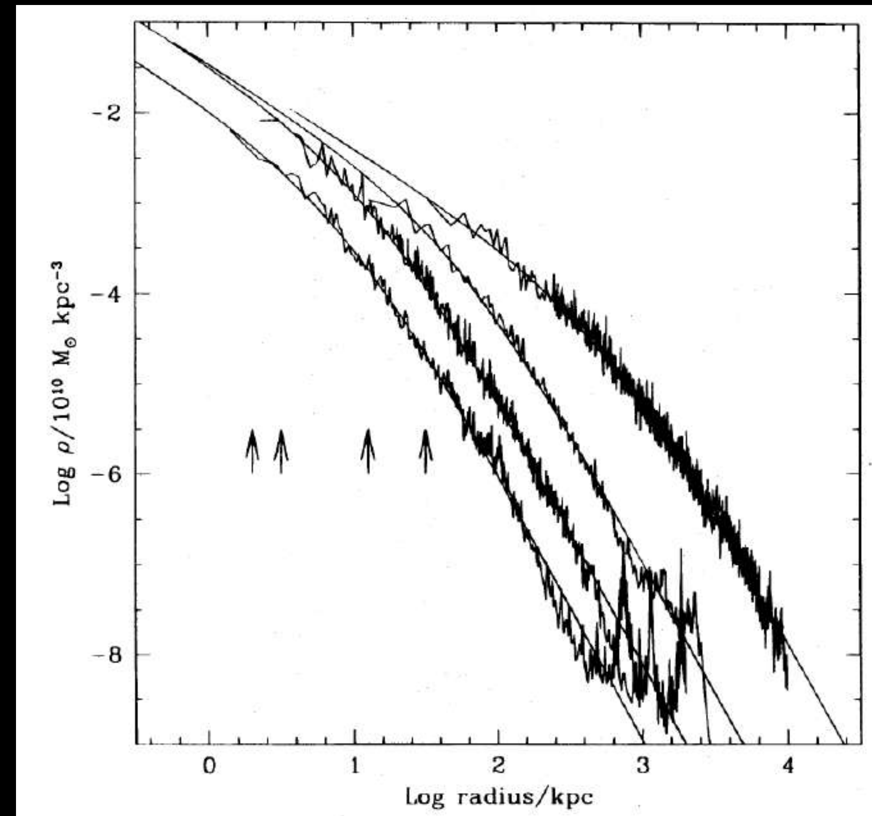
Subhalo mass

Wang+2012



Subhalo mass/host mass

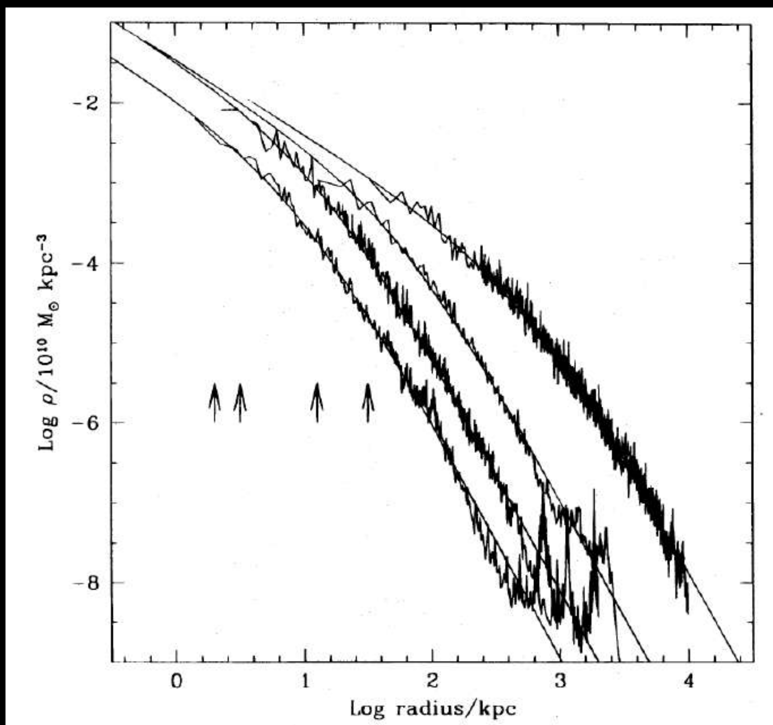
density profile (mass profile)



Navarro, Frenk, White 1996, 1997

Dark matter halo density profile in CDM

Density profiles of halos spanning 4 orders of magnitude in mass



Navarro, Frenk, White (NFW) 1996, 1997

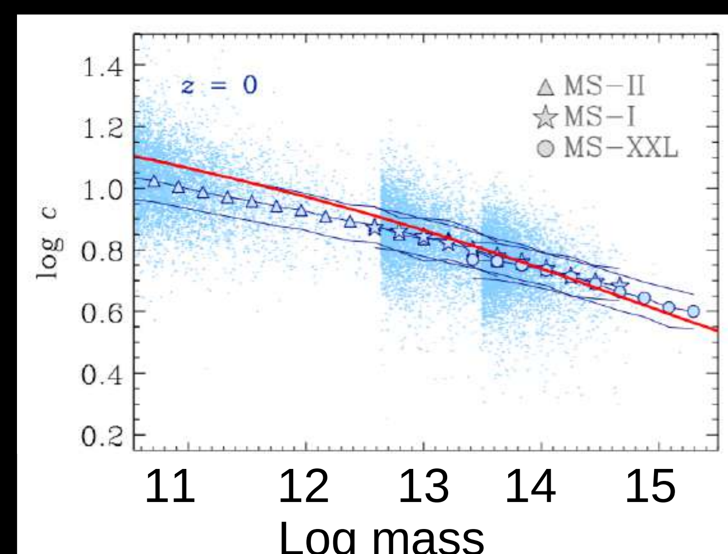
NFW profile

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

Two-parmeters profile:

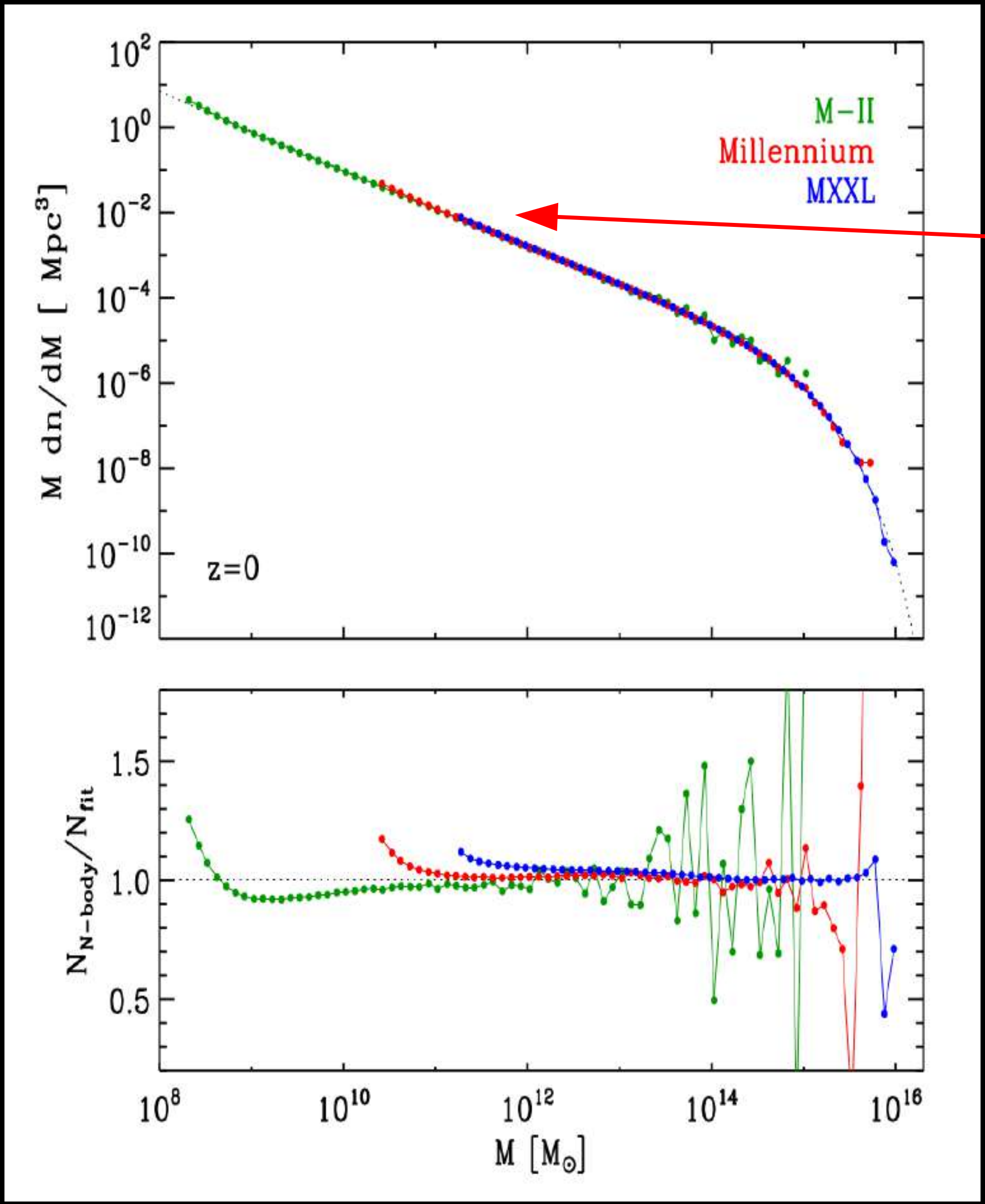
- r_s, ρ_s
- M_{200}, c

Mass-concentration relation:



Neto+2007, Maccio+2008, Ludlow+2014, Ludlow+2017

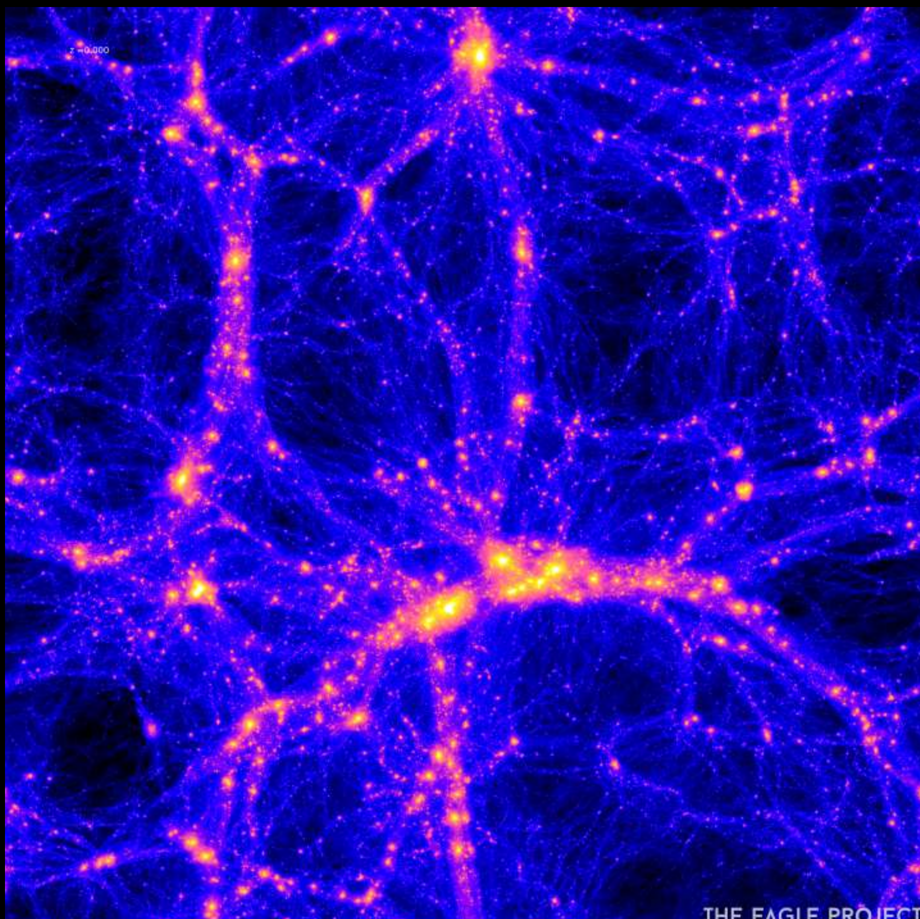
Halo mass function in LCDM



Increasing number of small structures

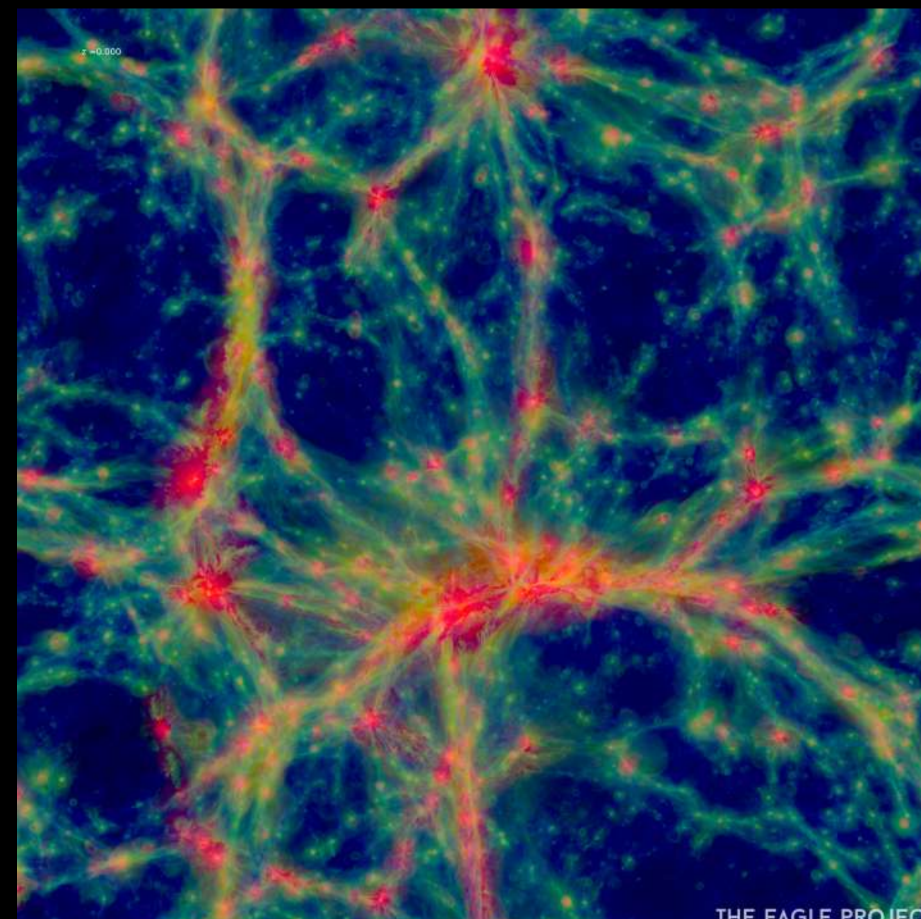
Baryons and Galaxy formation within LCDM

Dark matter



100 Mpc

Gas on large scales

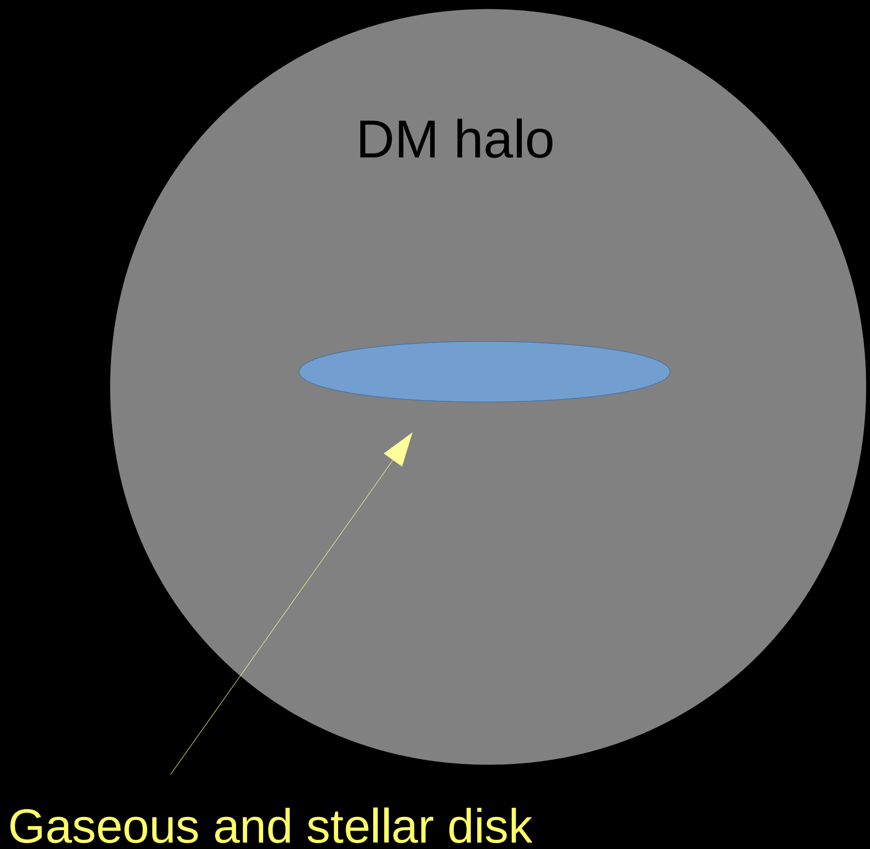


color=temperature

Eagle simulation - Schaye et al. 2016

Baryons and Galaxy formation within LCDM

Gas condensation in the centre of potential of halos
(White & Rees 1978)



Dark matter is collisionless:
Collapses into a spherical component

Gas is collisional:
loses energy due to friction, radiation, etc,
Settles into a disk due to the conservation of angular momentum

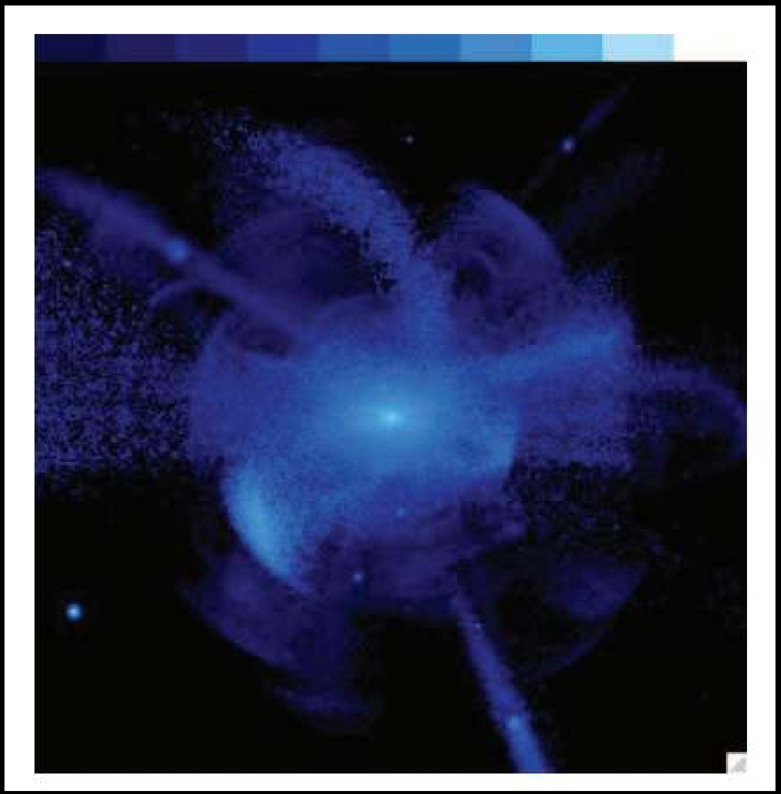
Sizes are not proportional; e.g for a Milky-Way size galaxy:
Stellar disk ~ 20 kpc; halo virial radius ~ 250kpc

Baryons and Galaxy formation within LCDM

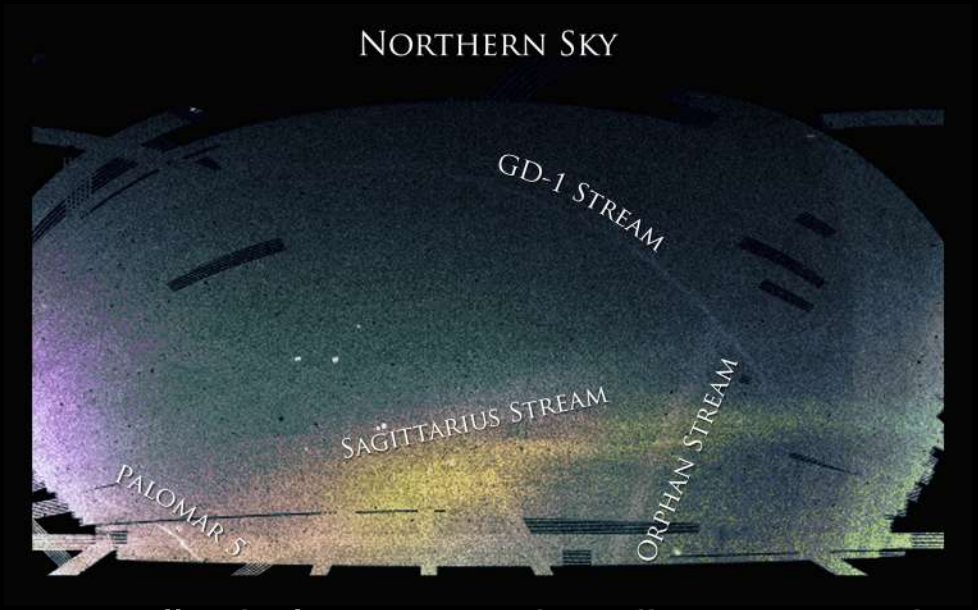
Credit: EAGLE collaboration – Virgo Consortium

Baryons and Galaxy formation within LCDM

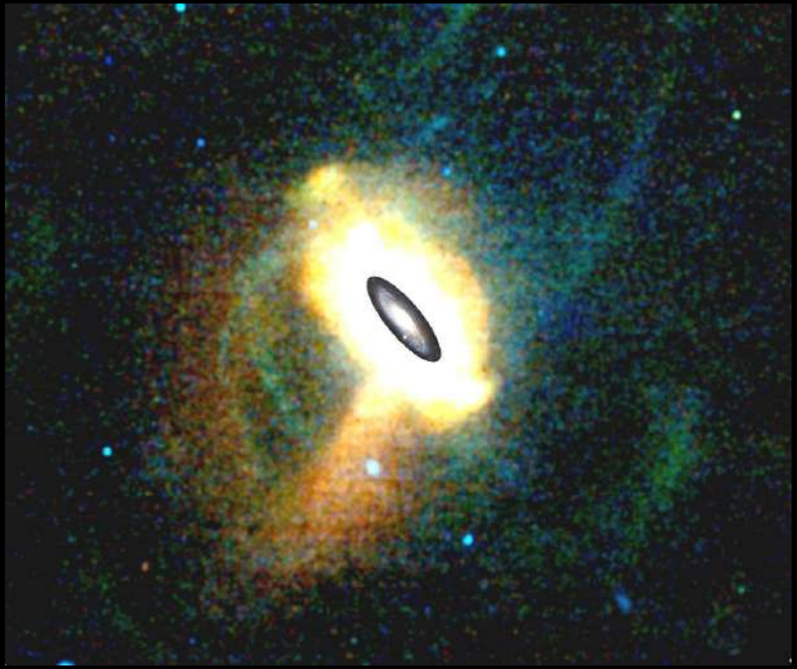
Stellar halo and stellar streams



Bullock & Johnston 2005



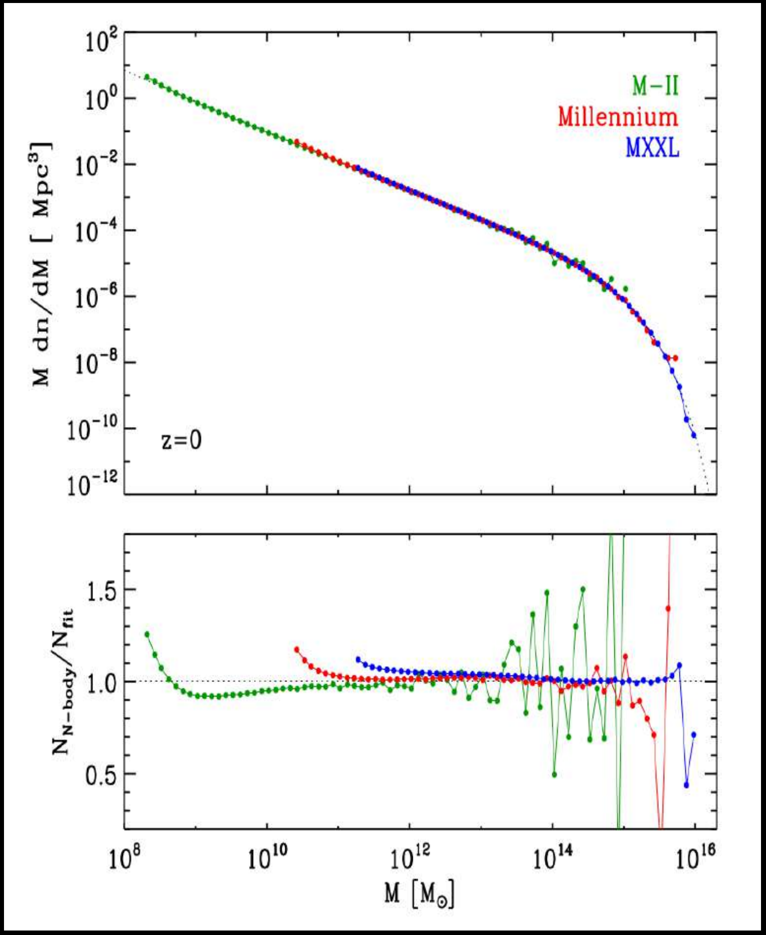
MW stellar halo streams (Credit: A. Bonaca)



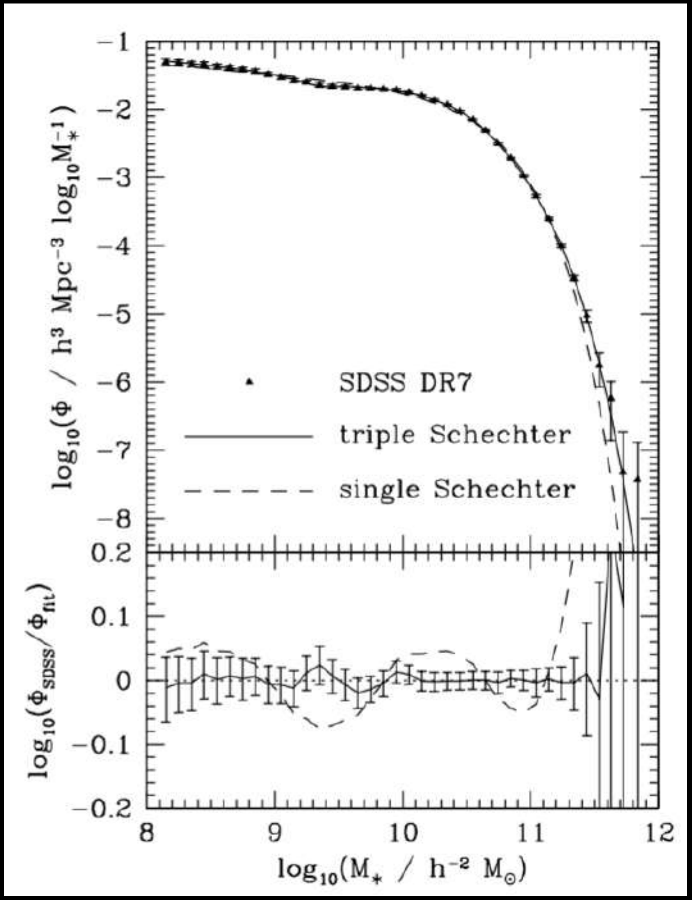
Andromeda stellar halo; PAndAS (McConnachie+2008)

How do galaxies poplulate DM halos?
The relation between stellar mass and halo mass

Halo mass function



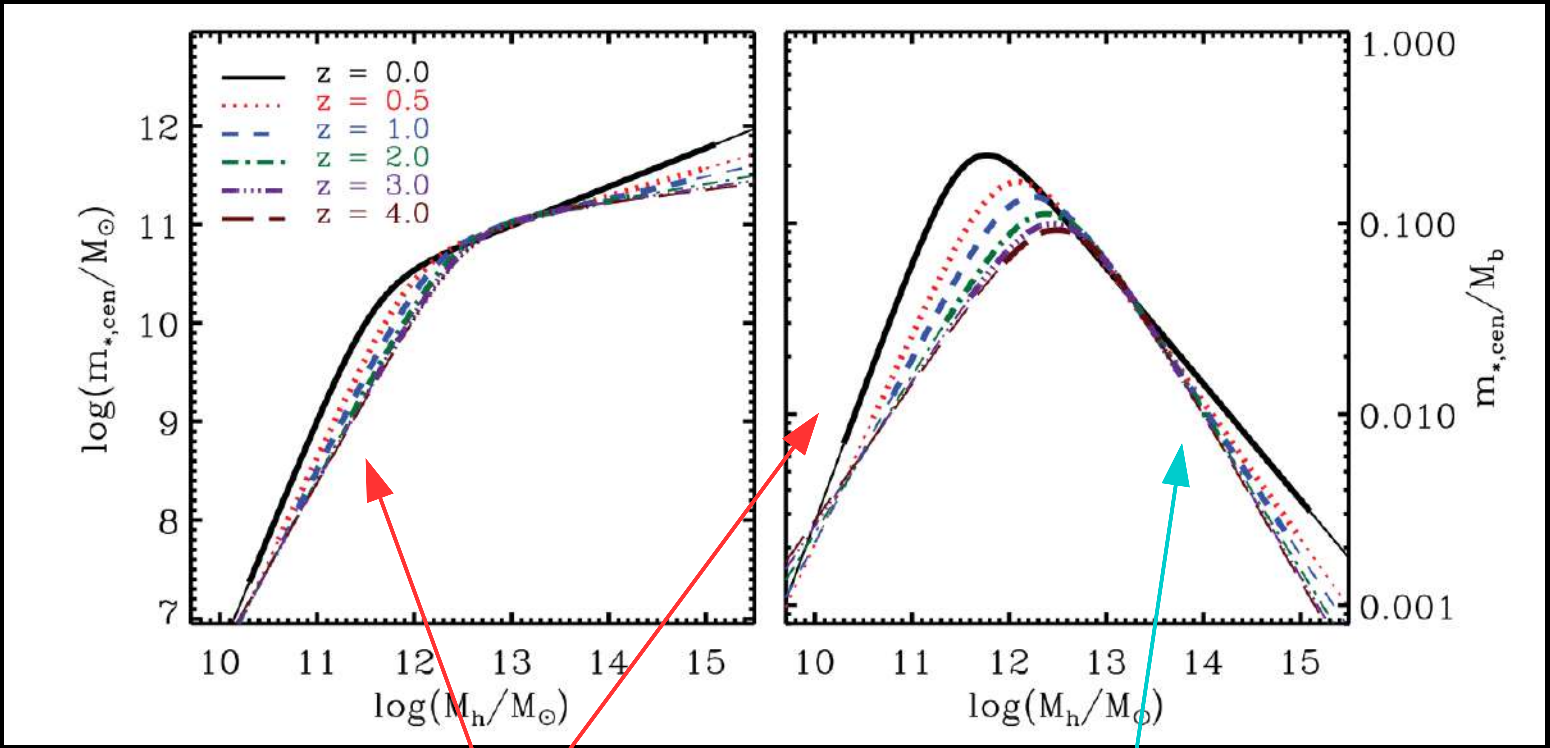
Stellar mass function



Li & White 2009

Note the difference in the slopes of HMF and SMF at both ends: Galaxy formation effeciency is different at different scales; different mechanisms play role in galaxy formation

How do galaxies poplulate DM halos?
The relation between stellar mass and halo mass



Supernovae feedback

AGN feedback

Side note: Cosmic reionization important at smaller scales: $M_{halo} \sim 10^{10}\ M_{sol}$

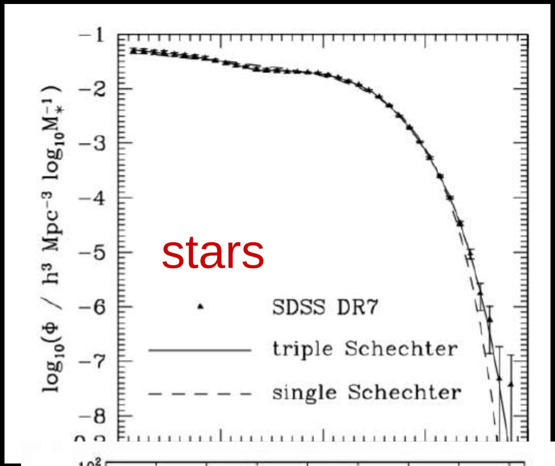
How do galaxies poplulate DM halos?

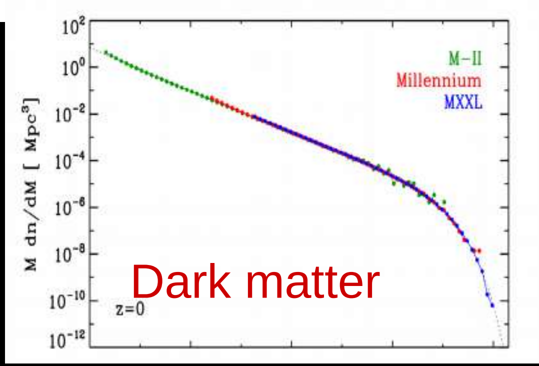
The relation between stellar mass and halo mass

"Abundance Matching" as a powerfull tool:

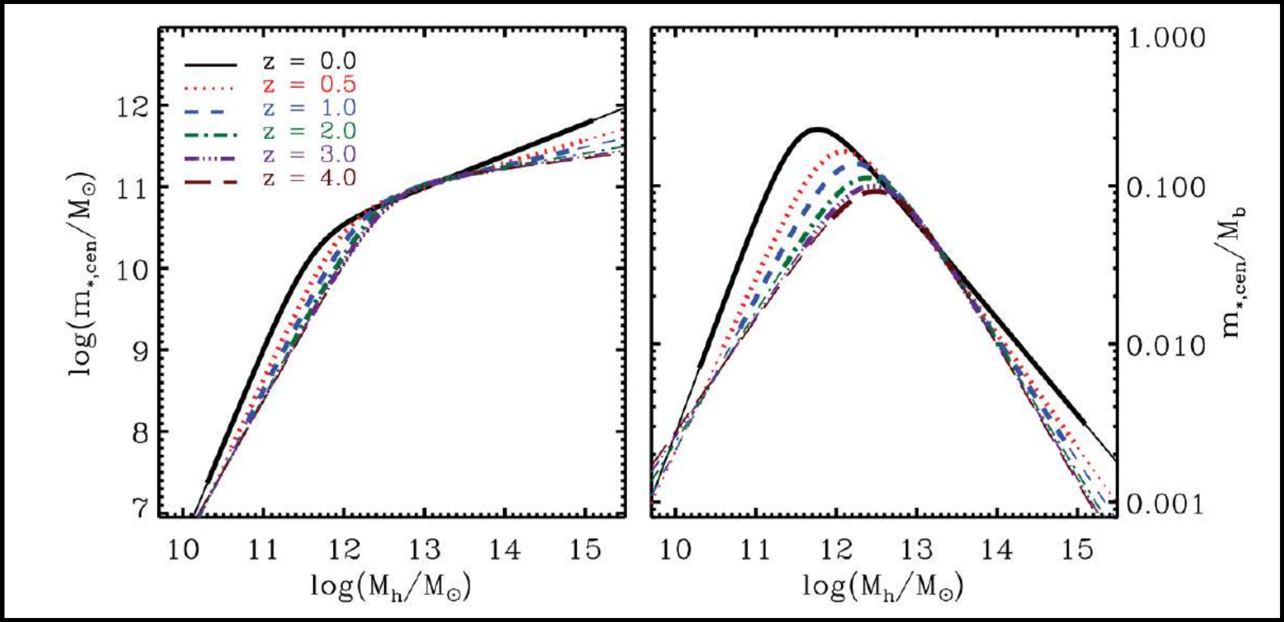
Assuming there is a one-to-one and monotonic relation between stellar mass and halo mass

Frenk+1983, Guo+2010, Behroozi+2013, Moster+2013



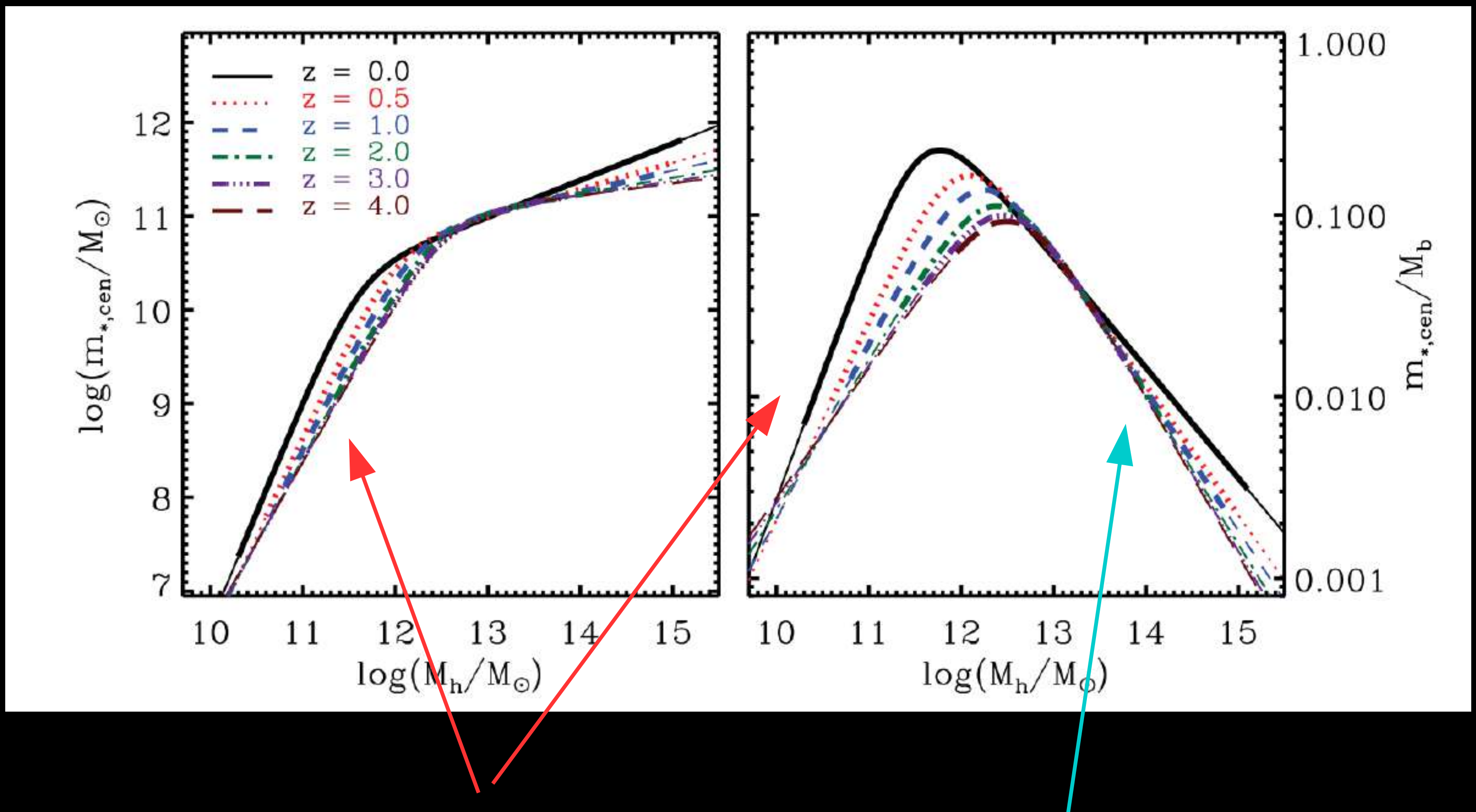


Mass



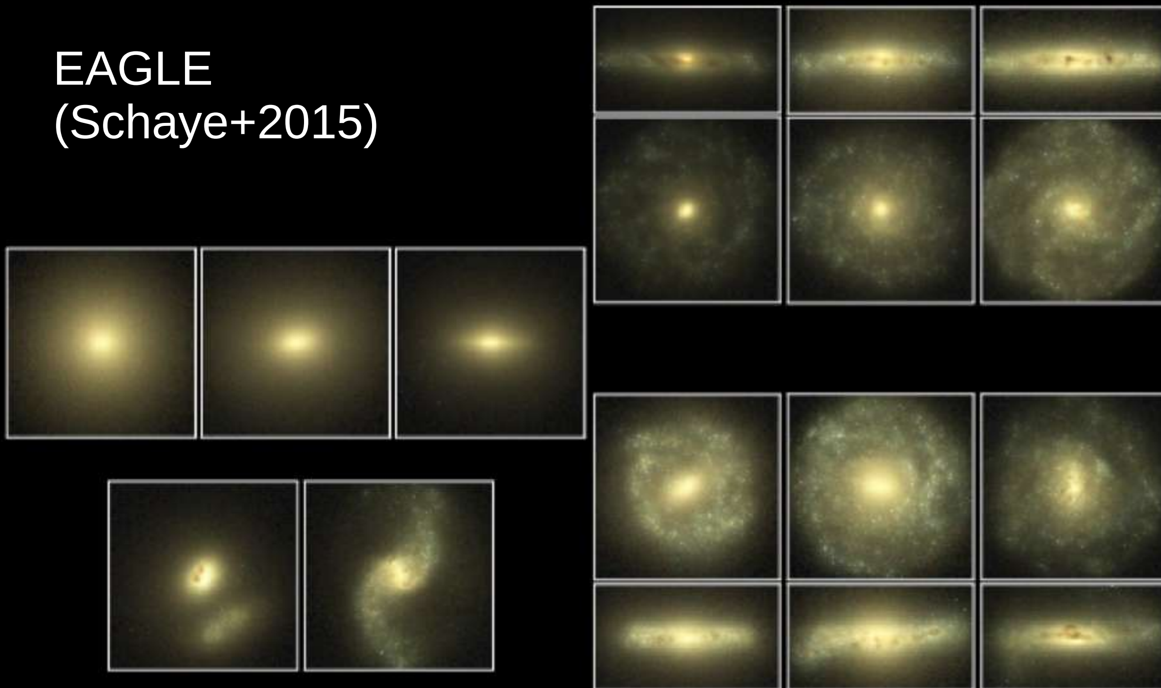
L^* galaxies (10^{12} M_{sol} halos) are most efficient in retaining their baryons and turning them into stars!

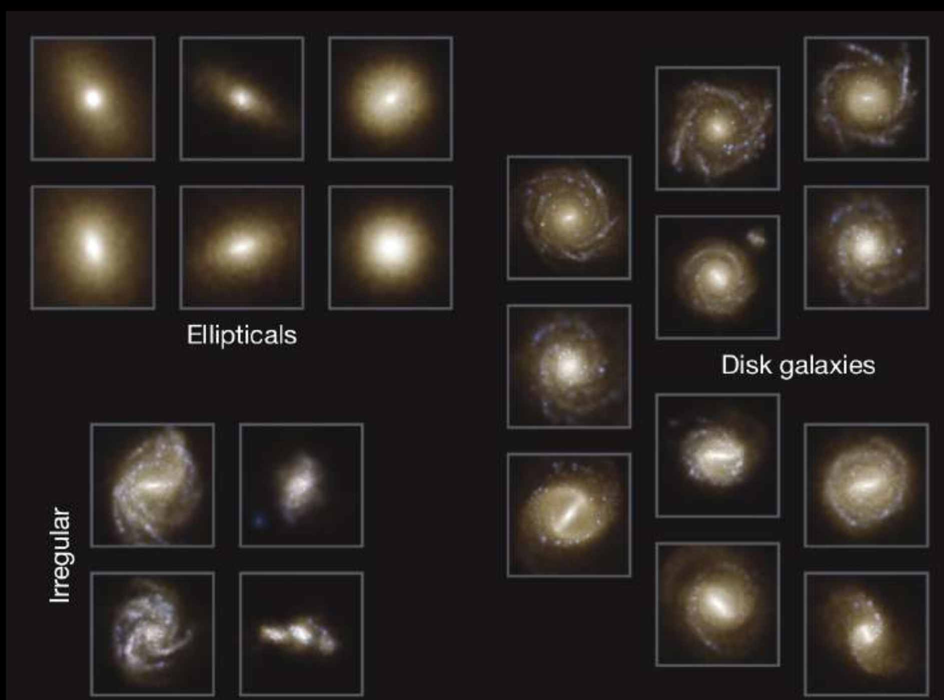
How do galaxies poplulate DM halos?
The relation between stellar mass and halo mass



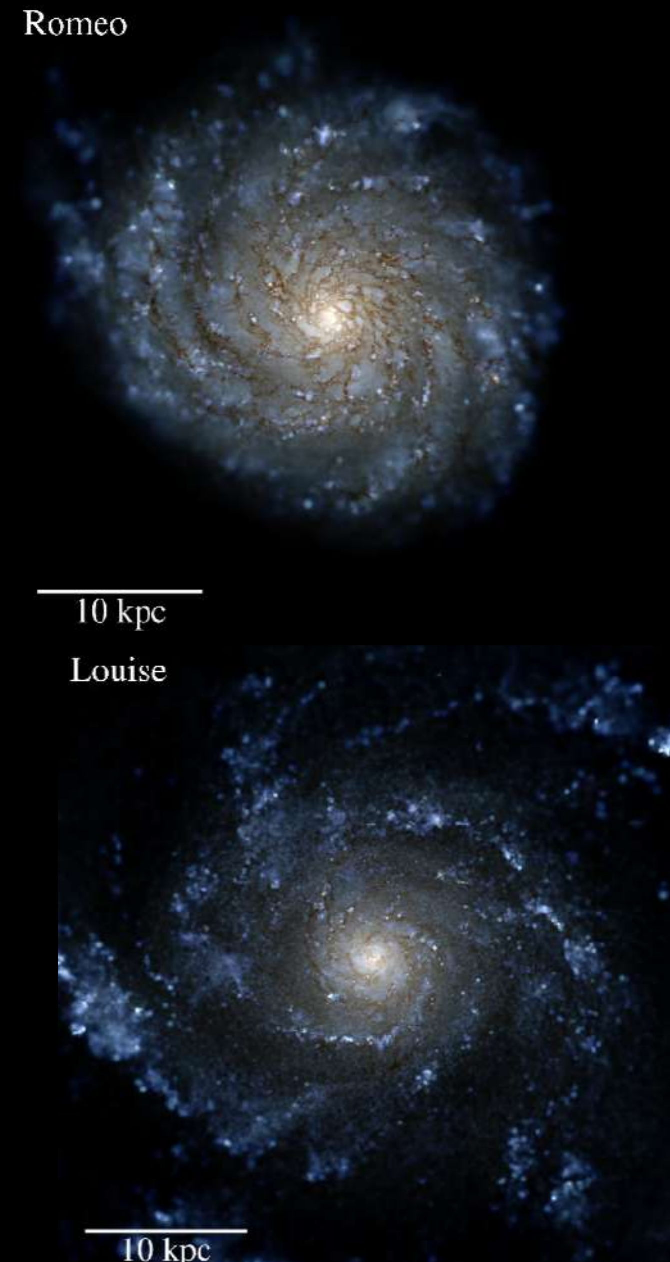
Side note: Cosmic reionization important at smaller scales: $M_{halo} \sim 10^{10}$ M_{sol}

EAGLE
(Schaye+2015)





Illustris (Vogelsberger+2014)



FIRE – (Garrison-Kimmel+2018)