The Milky Way in the cosmological context

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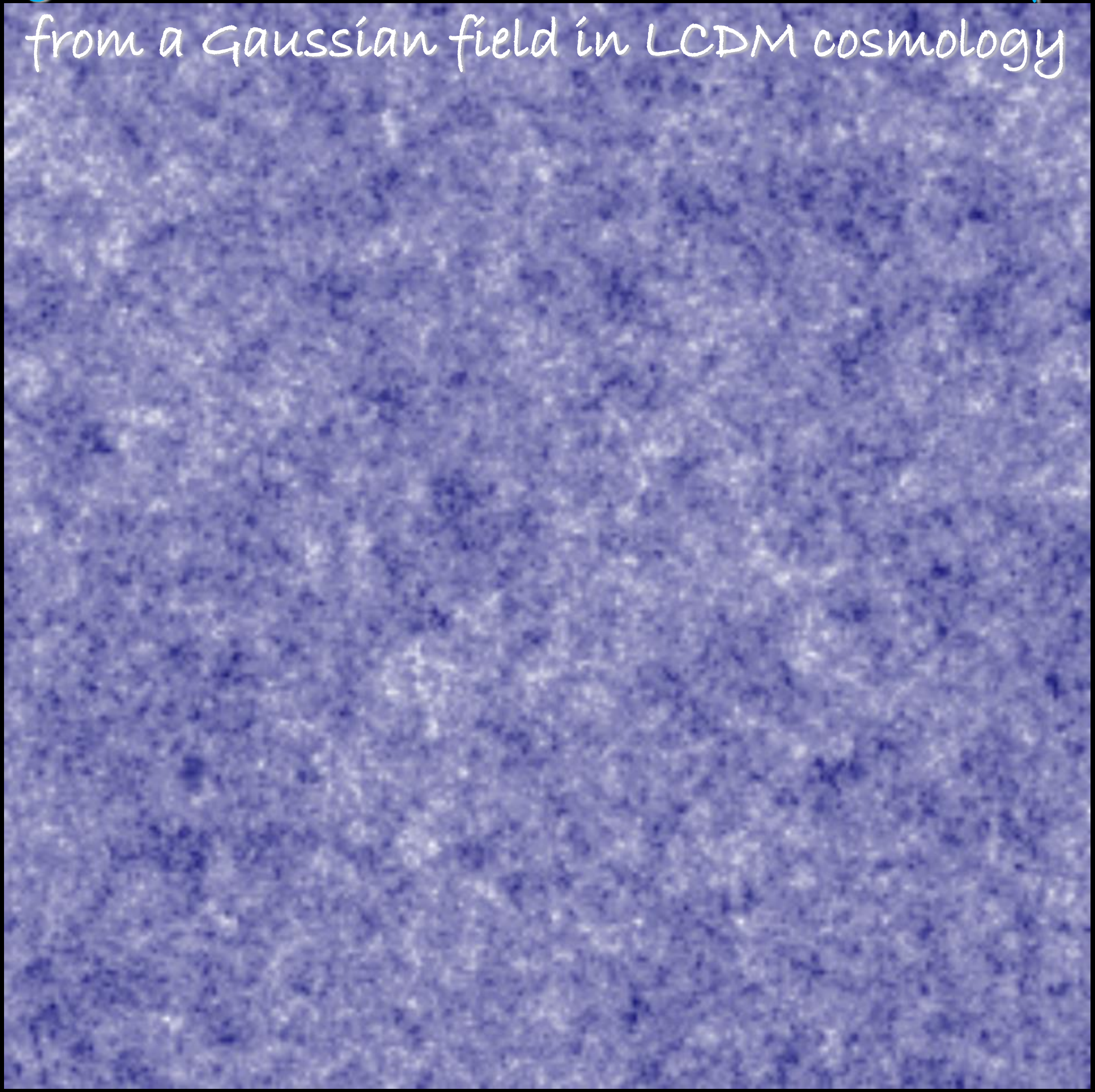
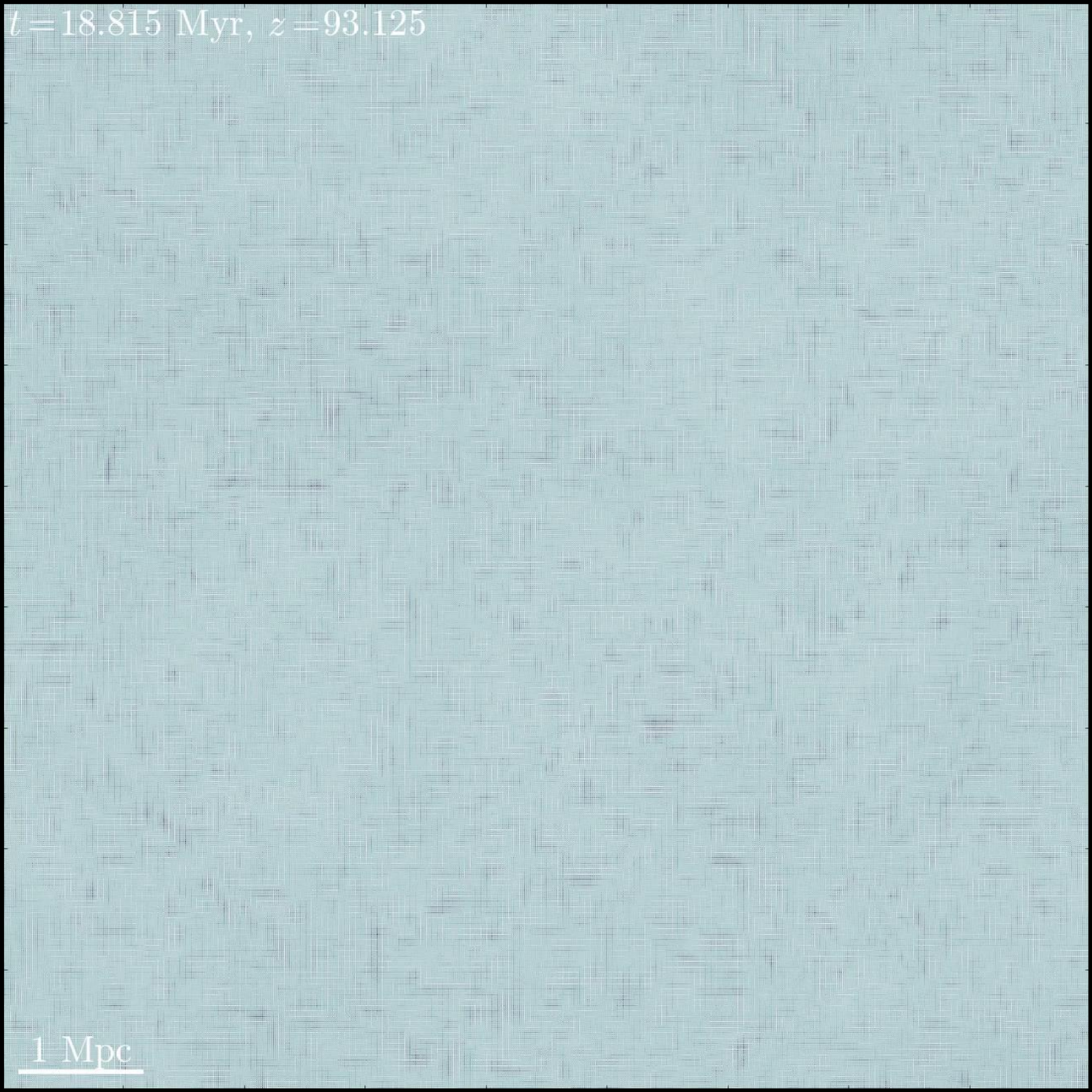
Milky Way and Its Stars, KITP, 2 February 2015

Cosmological context: hierarchical structure formation



Formation of a Local Group like pair in LCDM



Garrison-Kimmel et al. 2014, MN 438, 2578; http://localgroup.ps.uci.edu/elvis/
see also Yepes et al. 2014; the CLUES project http://www.clues-project.org/

Total halo mass definition

$$M_\Delta = \frac{4\pi}{3}\Delta\rho_{\rm ref}(z)R_\Delta^3$$

$$\rho_{\rm ref}(z) = \rho_{\rm crit}(z) \equiv \frac{3H^2(z)}{8\pi G} \quad \rightarrow R_{\Delta c}, M_{\Delta c}$$

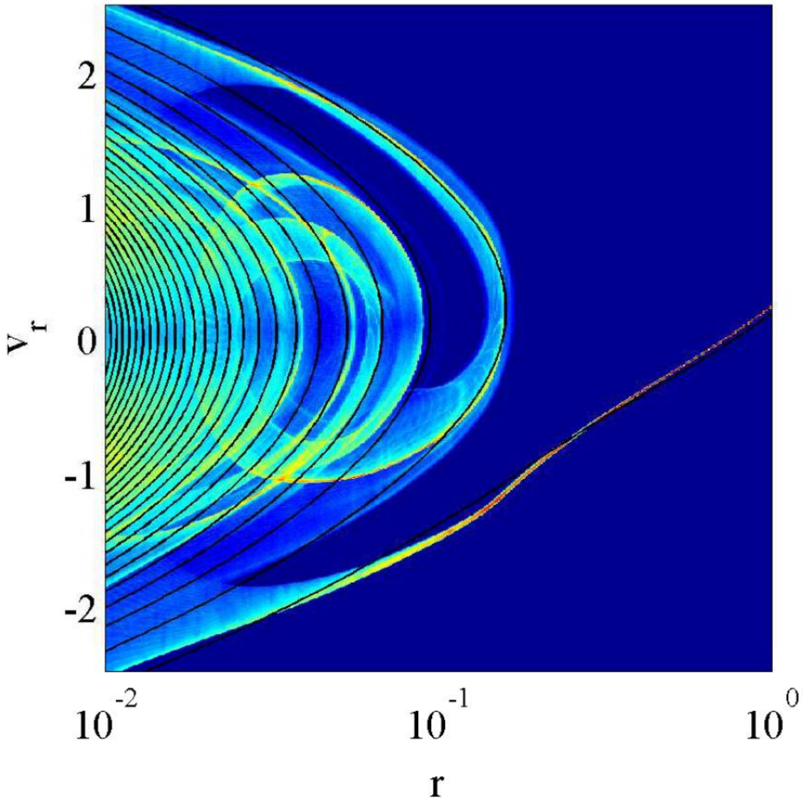
$$\rho_{\rm ref}(z) = \rho_{\rm mean}(z) \equiv \Omega_{\rm m0}\rho_{\rm crit0}(1+z)^3 \quad \rightarrow R_{\Delta m}, M_{\Delta m}$$

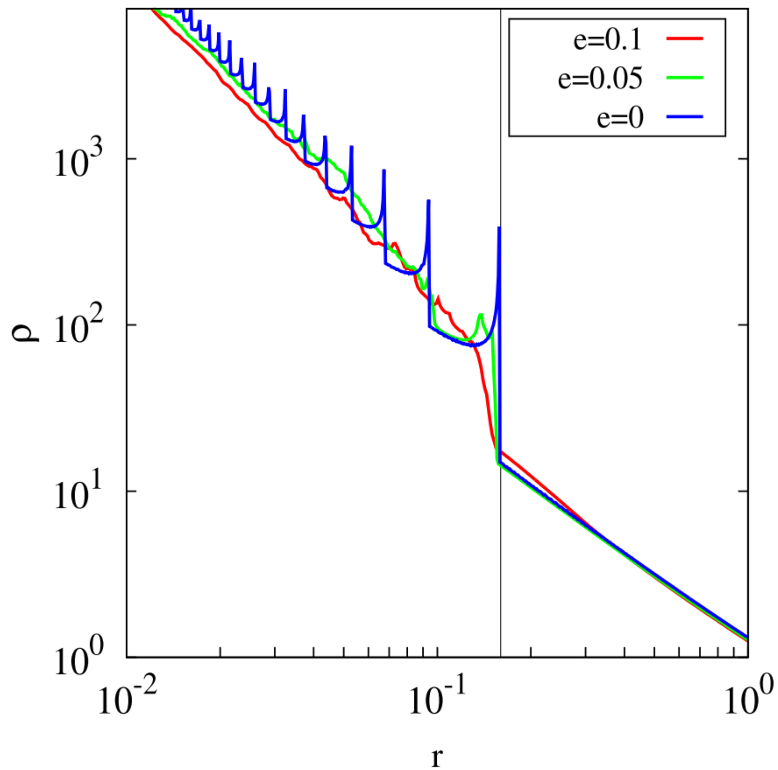
$$\approx 0.6 : 0.8 : 1.0 = R_{\rm 200c} : R_{\rm vir} : R_{\rm 200m}$$

Milky Way virial halo mass: $\approx 0.8 - 2\times 10^{12}\, M_\odot$
Smith+ '07; Xu+ `10; Gnedin+ `10; Busha+`11; Boylan-Kolchin+ `11; Bovy+ `12;

Milky Way + M31 sum of masses: $\sim 1.5 - 6.5 \times 10^{12}\, M_\odot$
Li & White '08; van der Marel+ '12; Gonzalez, Kravtsov & Gnedin '14

Density profile formed in secondary infall model of spherical collapse





Fillmore & Goldreich 1984
(cf also Gunn & Gott 1972; Bertschinger 1985; Lithwick & Dalal 2011; Vogelsberger et al. 2011; Adhikari et al. 2014)

Is Milky Way still expected to accrete mass at z~0?

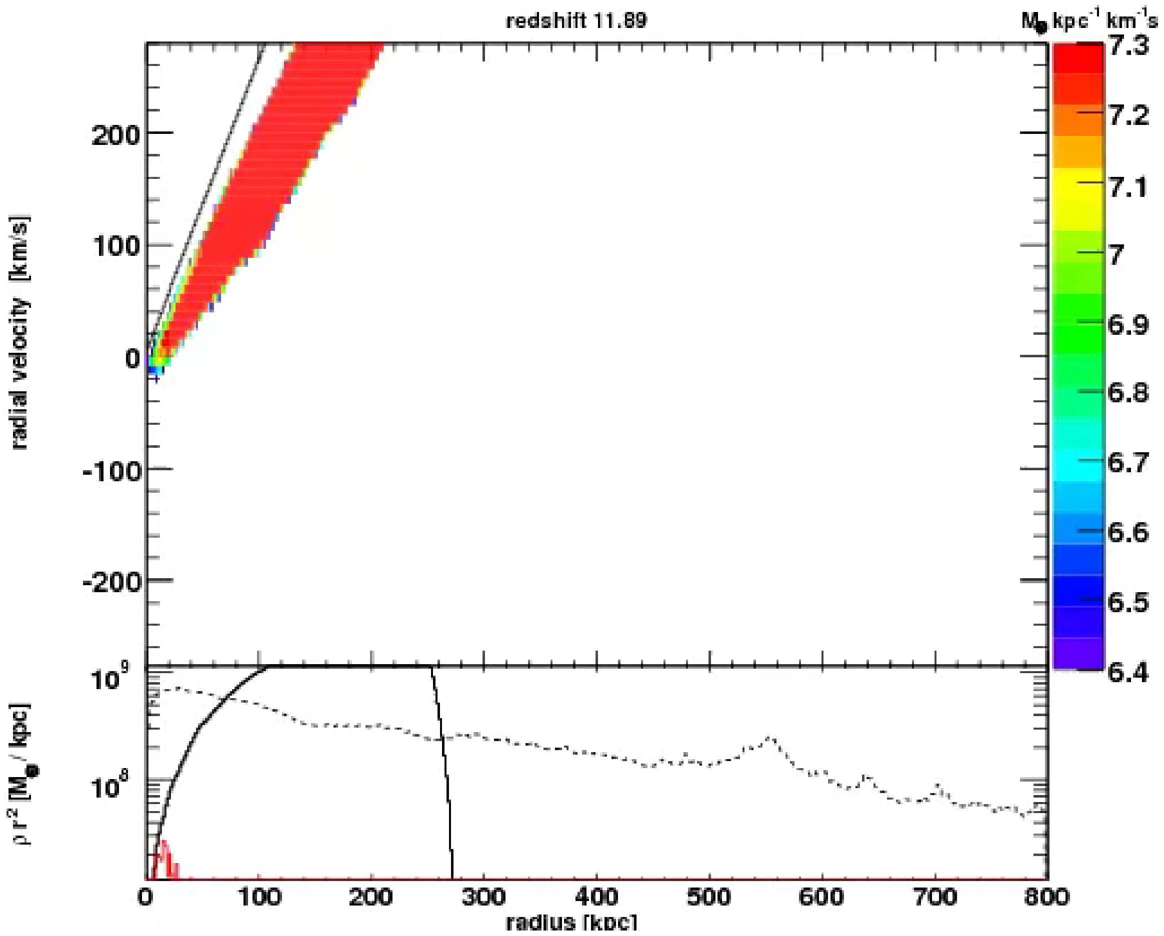
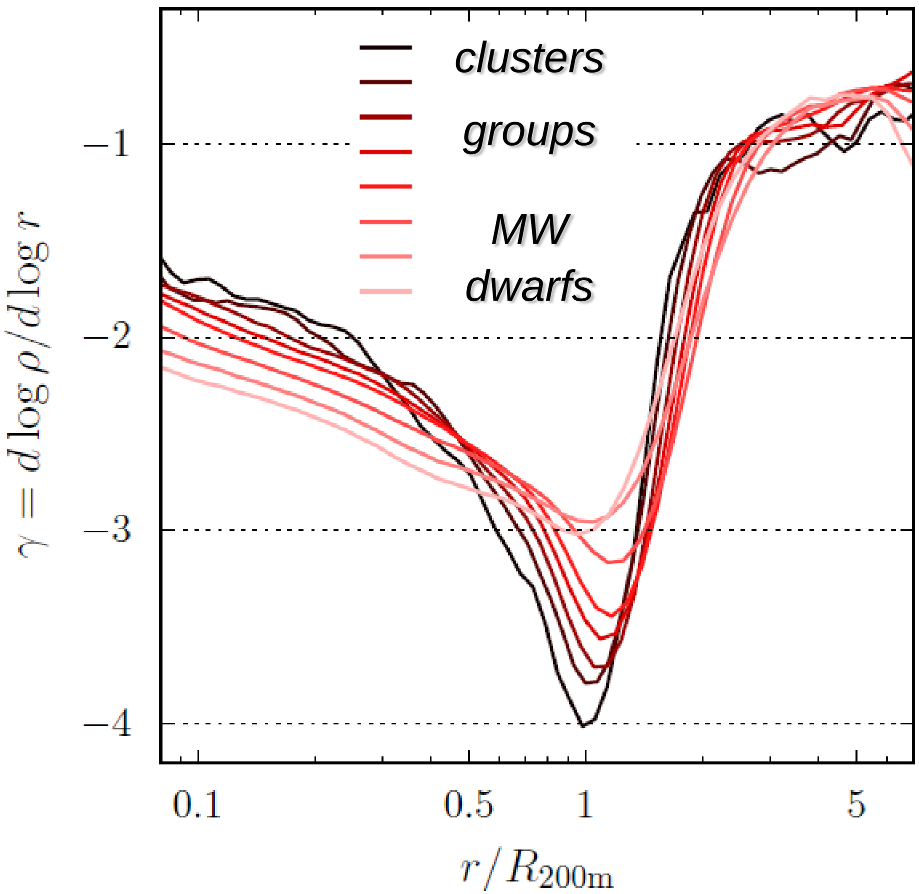


fig. 2 from Diemand et al. 2008. ApJL 680, L25
Diemer & Kravtsov 2014

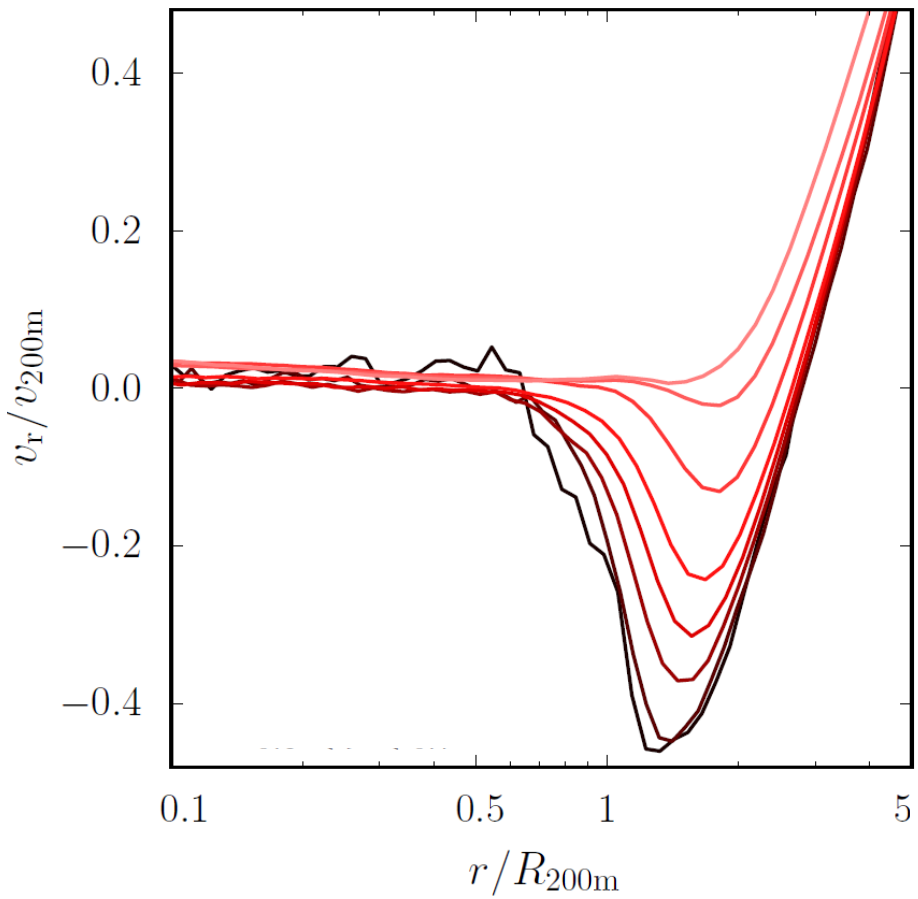
The edge of halos

The steepening of the density profile corresponds to caustics forming as accreted matter accumulates at the first apocenter after infall. For MW approximately the outer caustic is predicted to be at ~1.4 R_{200m}~400-500 kpc

log. slope profile as a function of halo mass



mean radial velocity profile



radius in units of the radius enclosing overdensity 200 wrt the mean density

Diemer & Kravtsov 2014a, ApJ 789, 1; More, Diemer, Kravtsov 2015, in prep.; Adhikari et al. 2014

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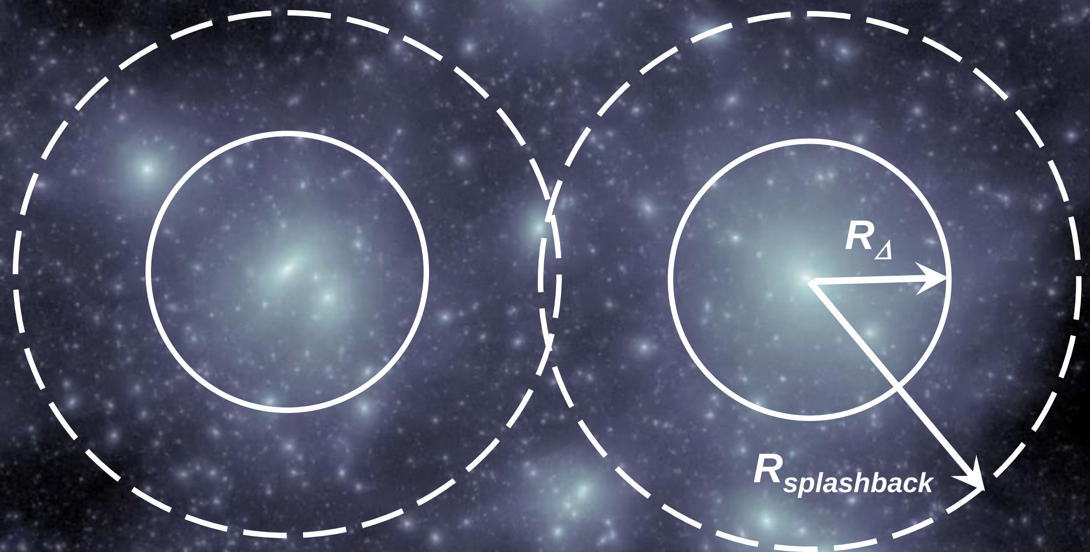
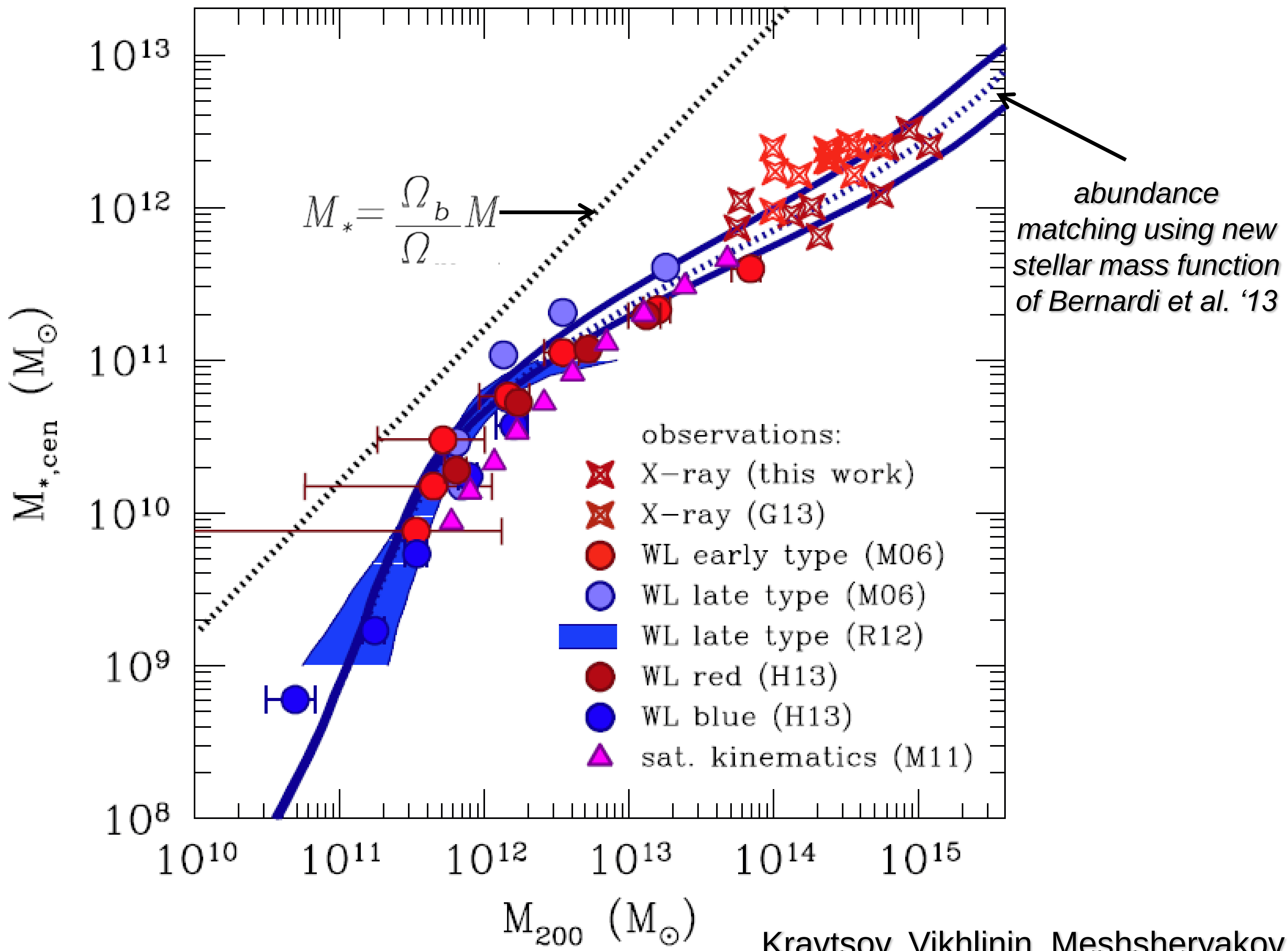


$$\approx 0.6 : 0.8 : 1.0 : 1.4 = R_{\rm 200c} : R_{\rm vir} : R_{\rm 200m} : R_{\rm splashback}$$

for the Milky Way and Andromeda splashback radius is expected to be: $R_{\rm splashback} \sim 400 - 600\,{\rm kpc}$

Diemer & Kravtsov ‘14; More, Diemer, Kravtsov ‘15, in prep.

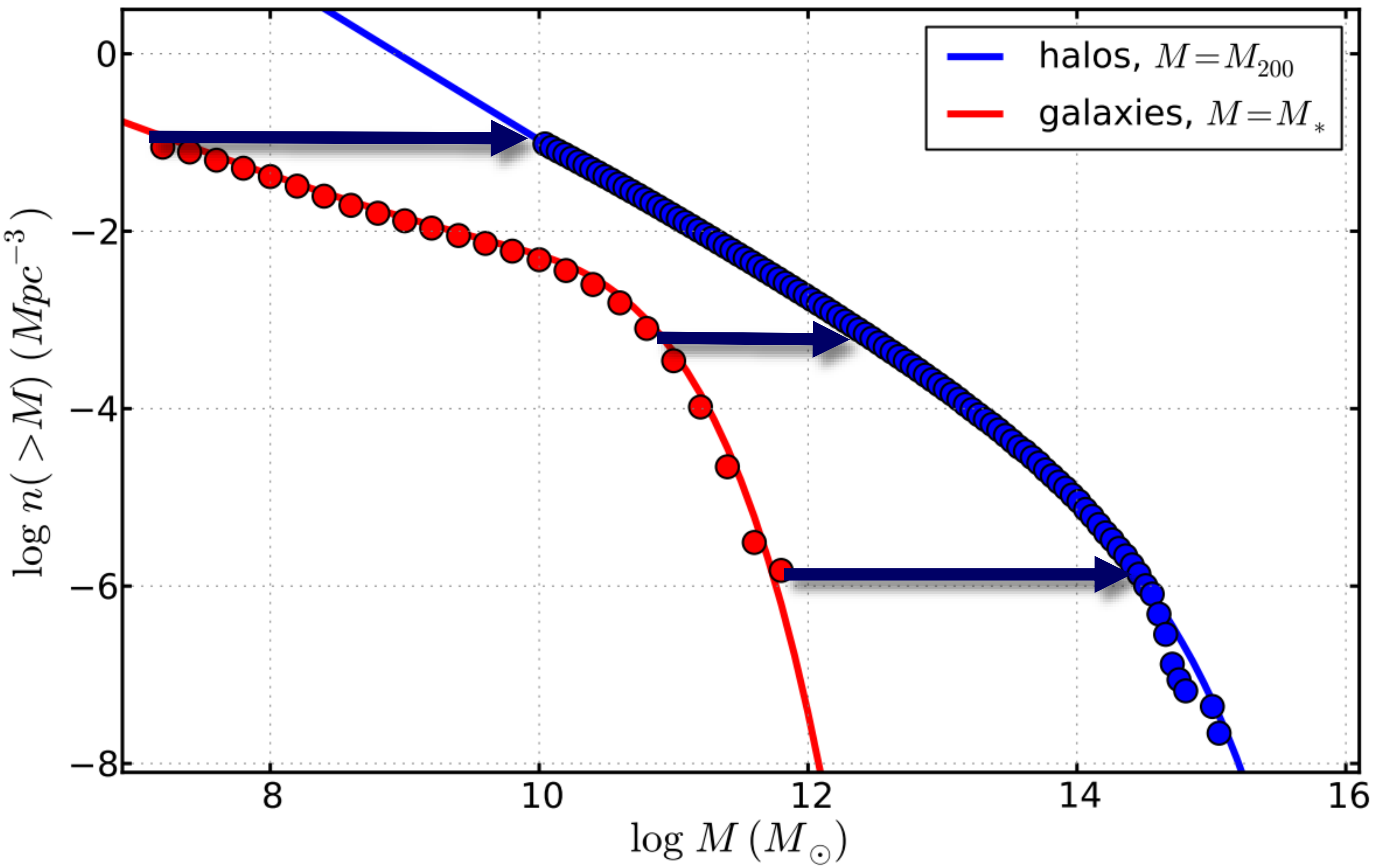
The stellar mass-halo mass relation



Kravtsov, Vikhlinin, Meshsheryakov
arxiv/1401.7329

Stellar and halo mass functions

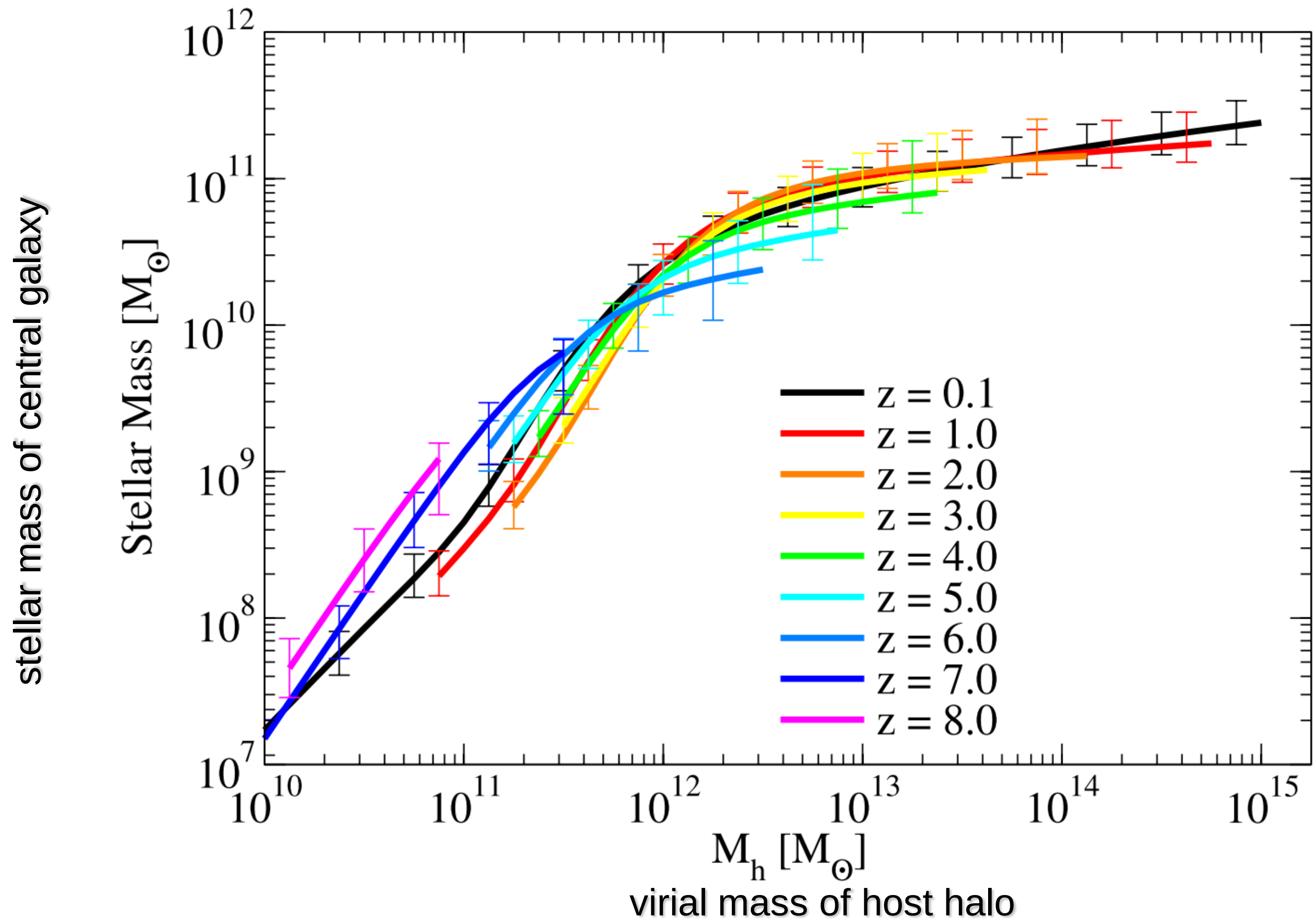
stellar and halo mass functions have qualitatively similar shapes, but are very different in detail.



log space density

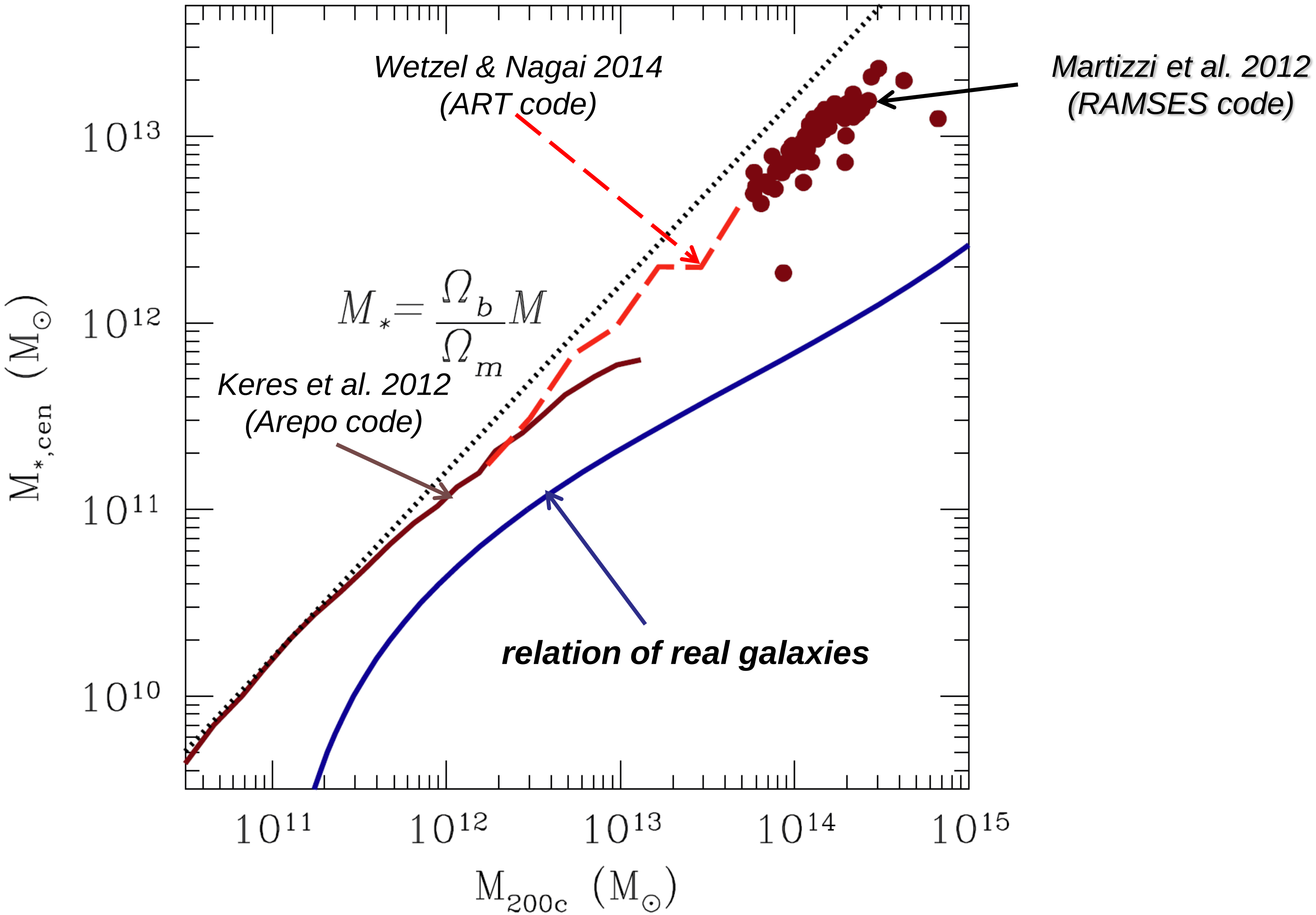
log mass in solar masses

Evolution of stellar mass-halo mass relation



Behroozi, Wechsler, Conroy 2013
cf. also Moster et al. 2013

Cosmological simulations including cooling and inefficient stellar/AGN feedback do not produce a pronounced characteristic mass



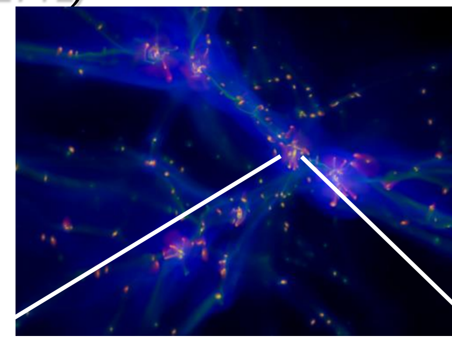
Galaxy formation simulation with inefficient feedback

Temperature distribution of baryonic matter in a region around forming galaxy

Agertz & Kravtsov arxiv/1404.2613

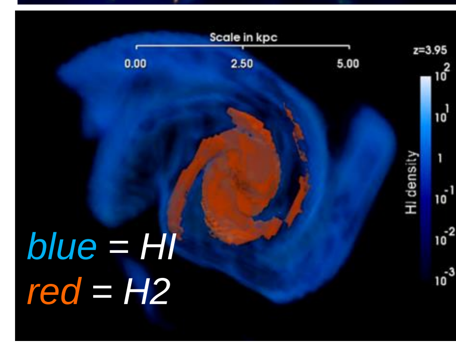
Recent generation of galaxy formation simulations with improved recipes for star formation and feedback

Guedes+ 11; Governato+ 10,11,12; Stinson+ 2013; Hummels & Bryan '12; Hopkins+ 2014; Ceverino+'14; Trujillo-Gomez+ 14; Agertz & Kravtsov '14; Salem+ 14
See recent review by Somerville & Dave 2015, ARAA (arxiv/1412.2712)



→ *Resolution of ~50-70 pc in the ISM of forming galaxy progenitors*

→ *Improved star formation modeling based on local density of molecular gas tracked in simulation*
(Krumholz et al. '09; Gnedin et al. '09; Gnedin & Kravtsov '10, '11)

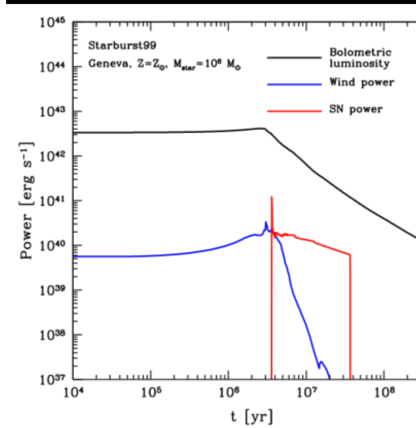


$$\dot{\rho}_* = f_{H_2}\frac{\rho_g}{t_{SF}}$$

$$t_{SF} = t_{ff}/\epsilon_{ff}$$

$$t_{ff} = \sqrt{3\pi/32G\rho_g}$$

→ *New subgrid models for stellar feedback that takes into account momentum injection due to "early feedback" (radiation pressure, winds, HII regions) designed to work at ~50-100 pc scale, + subgrid models of "turbulent" energy due to SN feedback, cosmic ray feedback*
(cf. Springel '03; Teyssier et al. '13; Salem & Bryan '13; Booth+'13)



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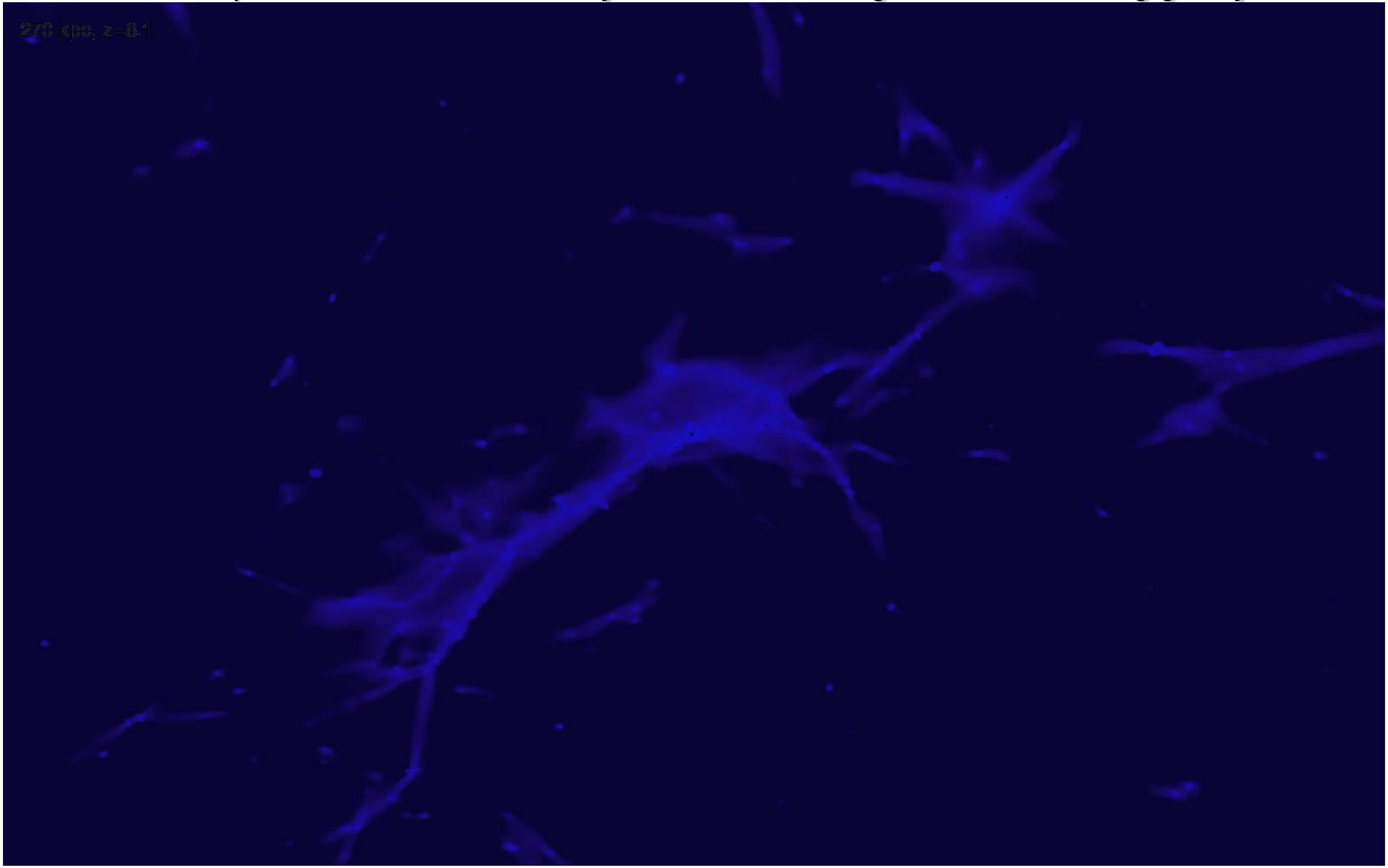


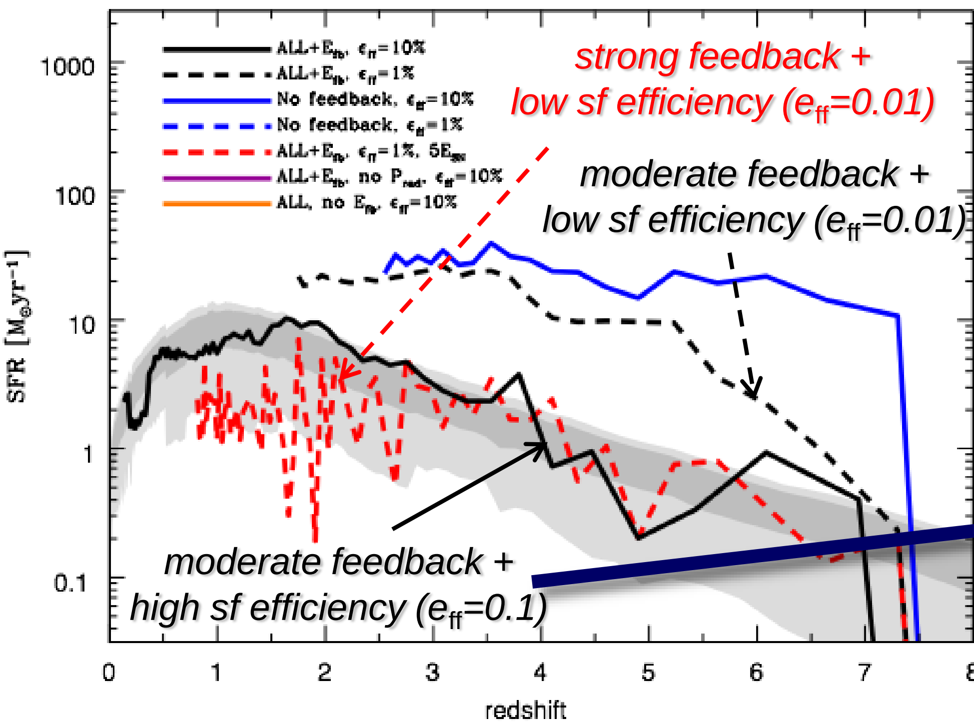
Agertz & Kravtsov arxiv/1404.2613

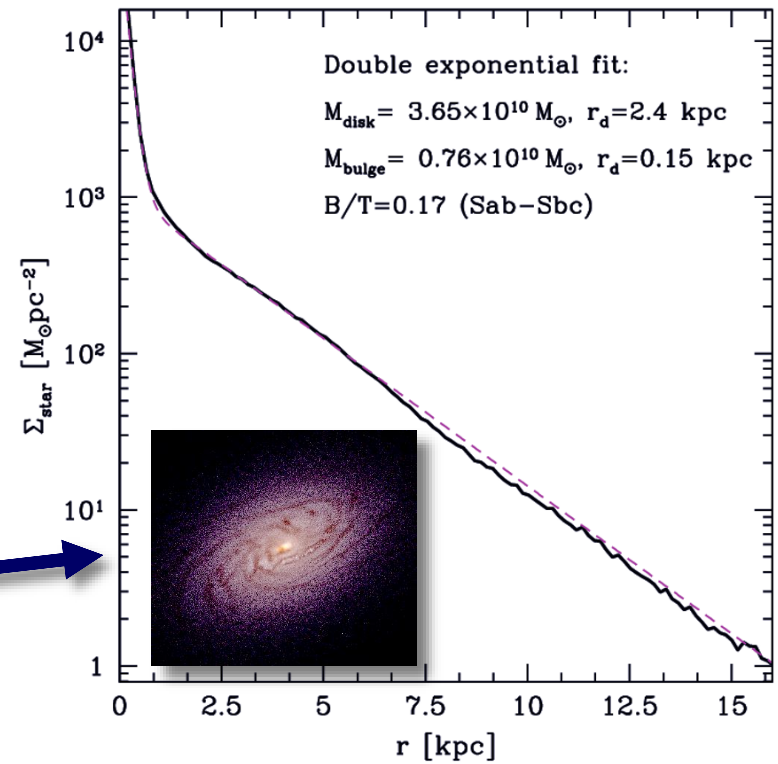
Modelling "early feedback" due to winds and radiation pressure helps in reproducing star formation histories and M*-M relation

Agertz & Kravtsov 2014, arxiv/1404. 2613

- Star formation history of MW-sized progenitor and corresponding evolution in M*-M plane

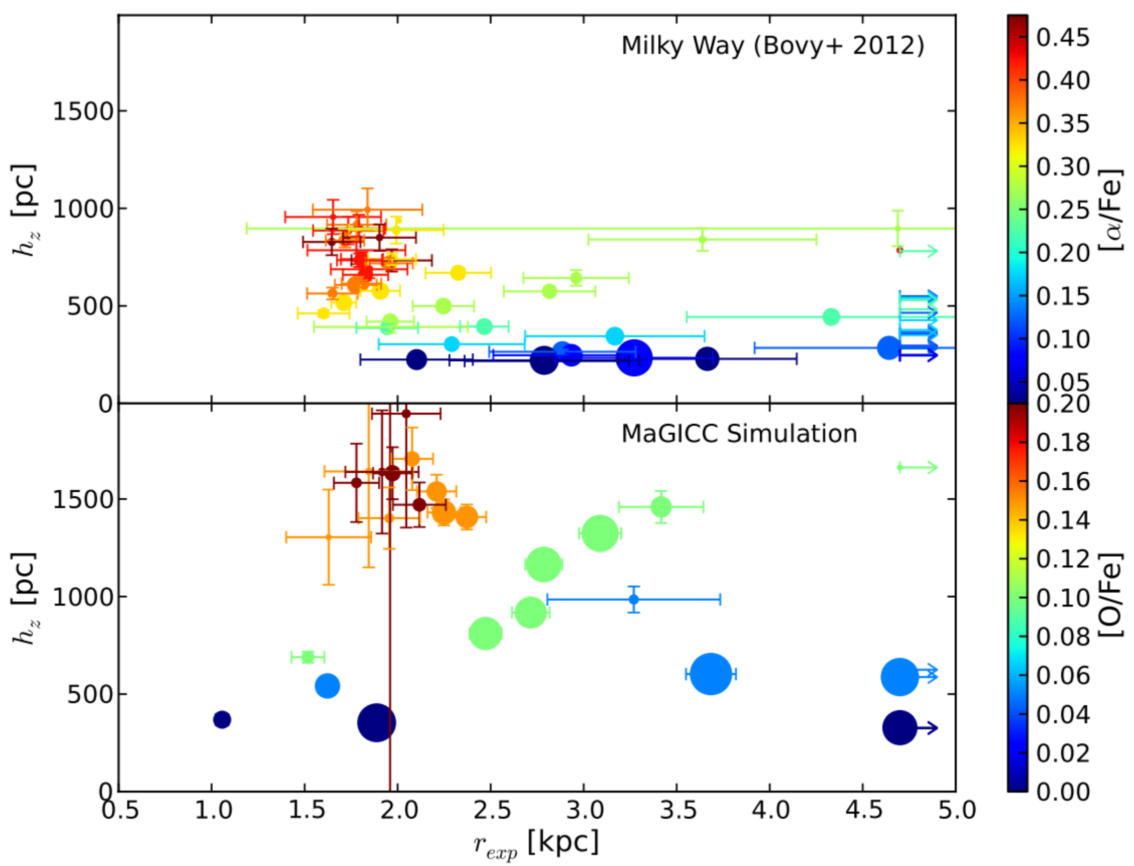
Semi-empirical star formation history for a 10^{12} Msun halo (Behroozi et al. '13)





HST mockup RGB using F450W, F606W, F814W filters

Detailed disk structure trends with metallicity of stellar populations is qualitatively reproduced in such simulations



Stinson et al. 2014, MN 436, 625

summary

- *A typical Milky Way sized halo still accretes at z=0, albeit at a slow rate. Matter that passed through the inner regions of the Milky way at least once can extend as far as ~500-600 kpc (i.e., 2/3 of the way to Andromeda galaxy). The spheres of influence of the Milky Way and Andromeda thus overlap.*

  The extent to which Andromeda and Milky Way influence each other is still debated. The answer to this question likely depends on the specific question.

- *Current generation of cosmological galaxy formation simulations with phenomenological models for star formation and stellar feedback can produce galaxies with realistic stellar masses, sizes, rotation curves and disk morphologies.*

  More detailed comparisons with data on the Milky Way structure and kinematics now makes sense!

discussion questions

- *Can we estimate the splashback radius of the Milky Way or Andromeda from observations?*
  distant streams? radial distribution of dwarf galaxies?

- ***Can stellar archaeology and better stellar age estimates significantly improve our knowledge of the star formation and chemical enrichment history of the Milky Way?***

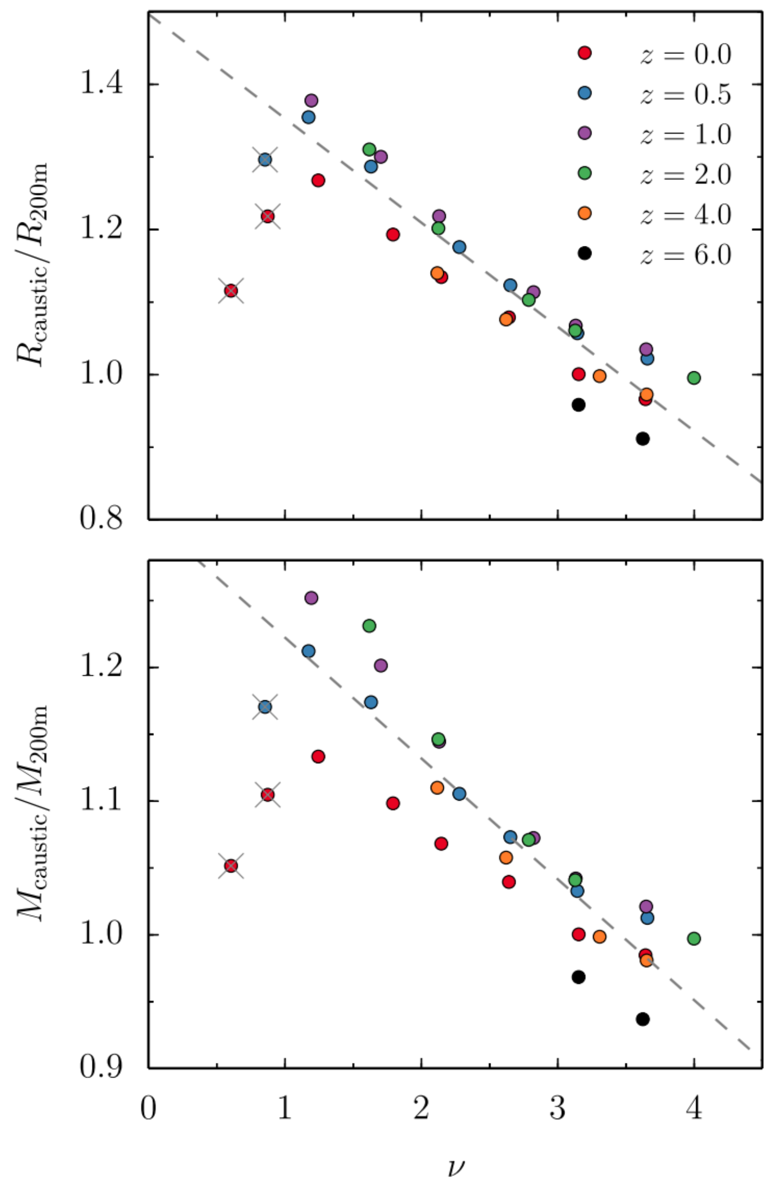
  This would help to constrain cosmological models of galaxy formation and understand how typical is our Galaxy among the galaxies of similar mass.

- ***What are the best statistics/properties to use for comparisons with models.***

  Currently, disk thickness as a function of age/metallicity seems to be a good statistics. Most current models do not reproduce it in detail.

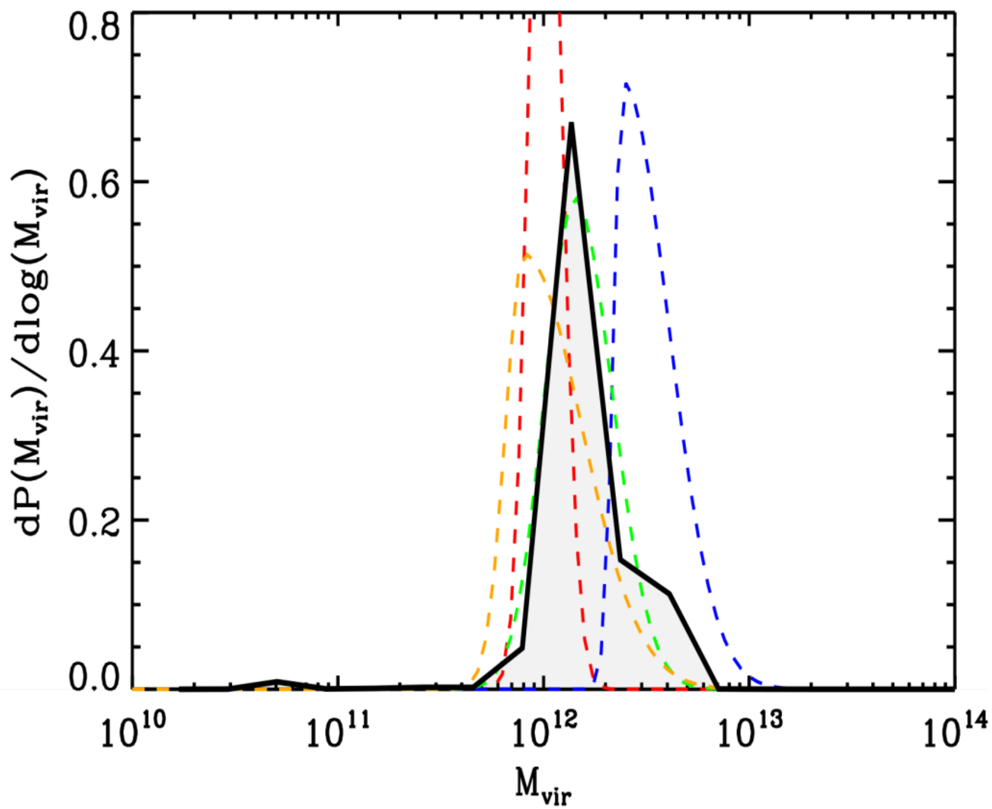
- ***Era of precision near field cosmology?***

  What are the prospects of improving estimates of total mass distribution around the Milky Way from expected advances in quantifying structure and kinematics of the stars in the Galaxy and its stellar halo?

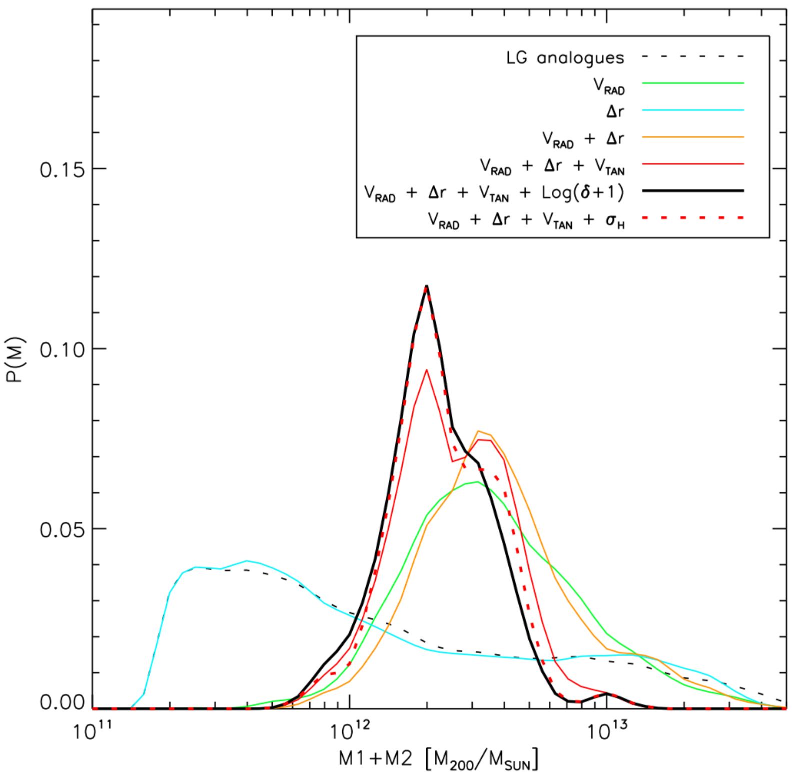


$R_{\rm caustic}/R_{\rm 200m}$
1.4
1.2
1.0
0.8
$z = 0.0$
$z = 0.5$
$z = 1.0$
$z = 2.0$
$z = 4.0$
$z = 6.0$
$M_{\rm caustic}/M_{\rm 200m}$
1.2
1.1
1.0
0.9
0
1
2
3
4
ν

mass estimates for the Milky Way and Local Group



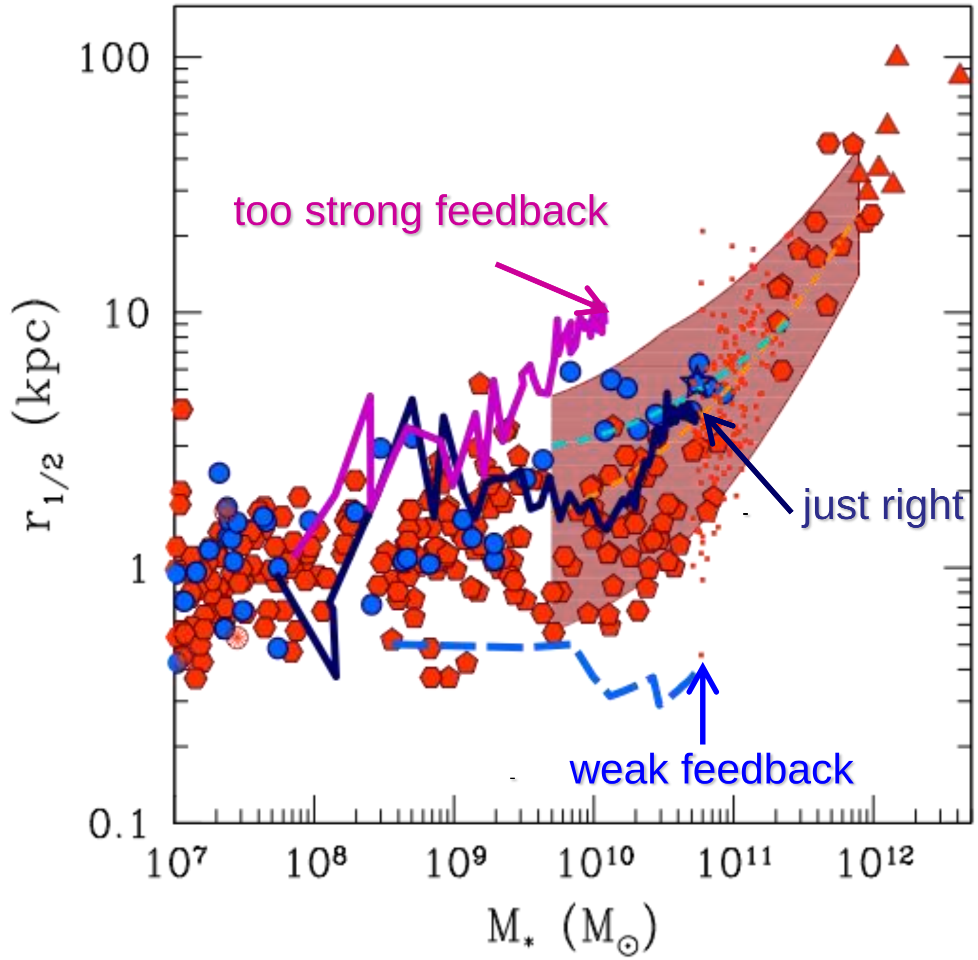
Busha et al. 2012, MNRAS COMPLETE REF!!!

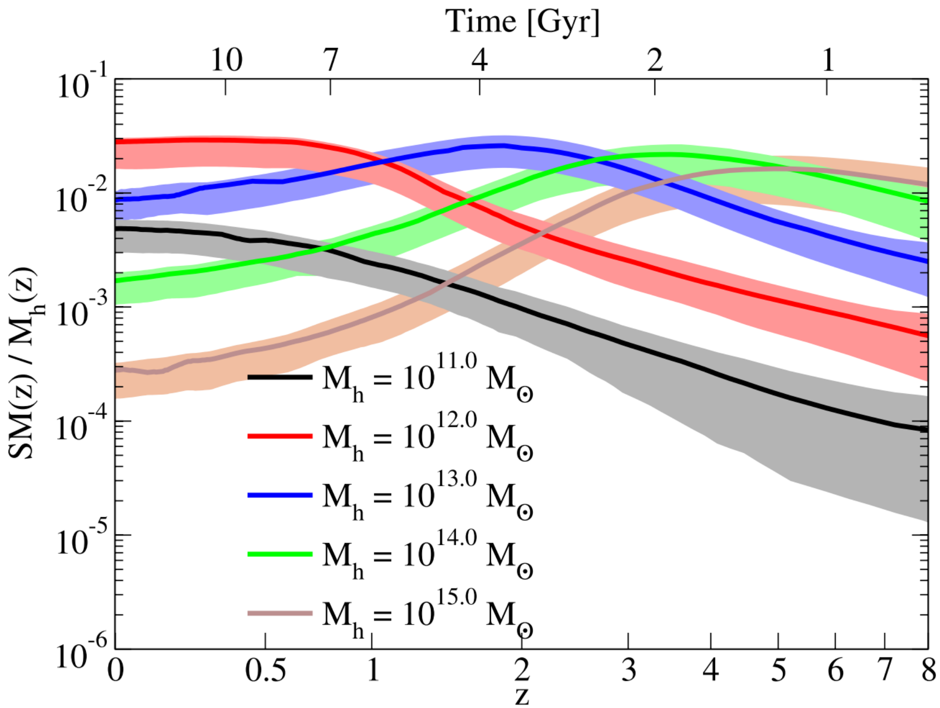


Gonzalez, Kravtsov & Gnedin 2009, ApJ 793, 91

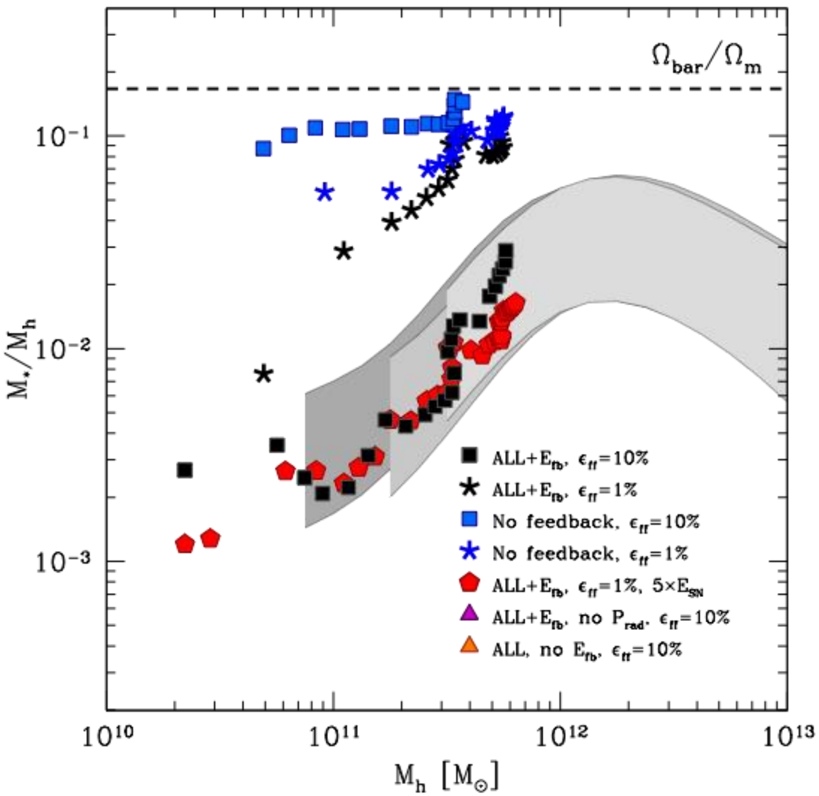
Sizes and morphologies

Jagged lines = tracks of galaxy progenitor from z~7 to 0
Points = observed galaxies from Misgeld & Hilker '11, Leroy et al. '08, Zhang et al. '12, Bernardi et al. '12. Szomoru et al. '13; Kravtsov et al. '14

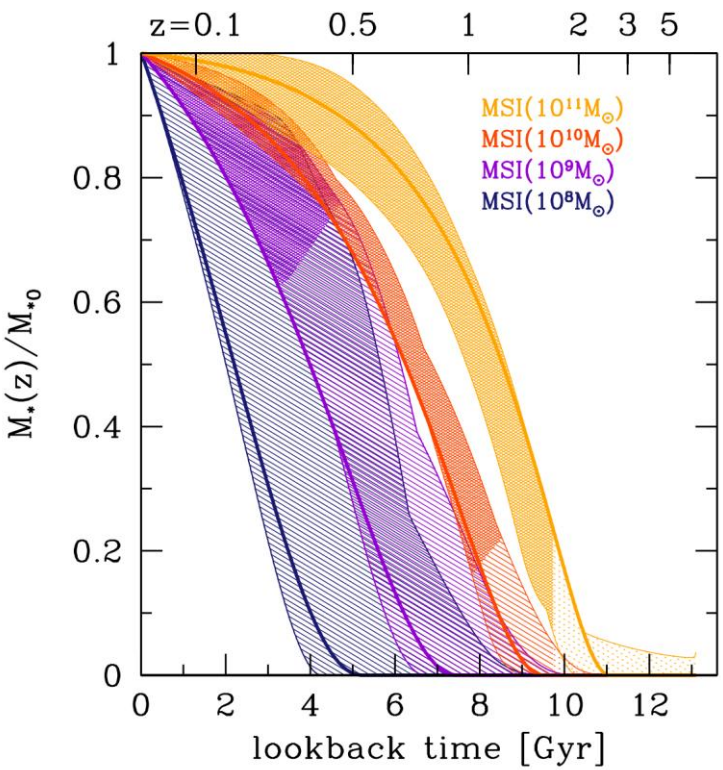




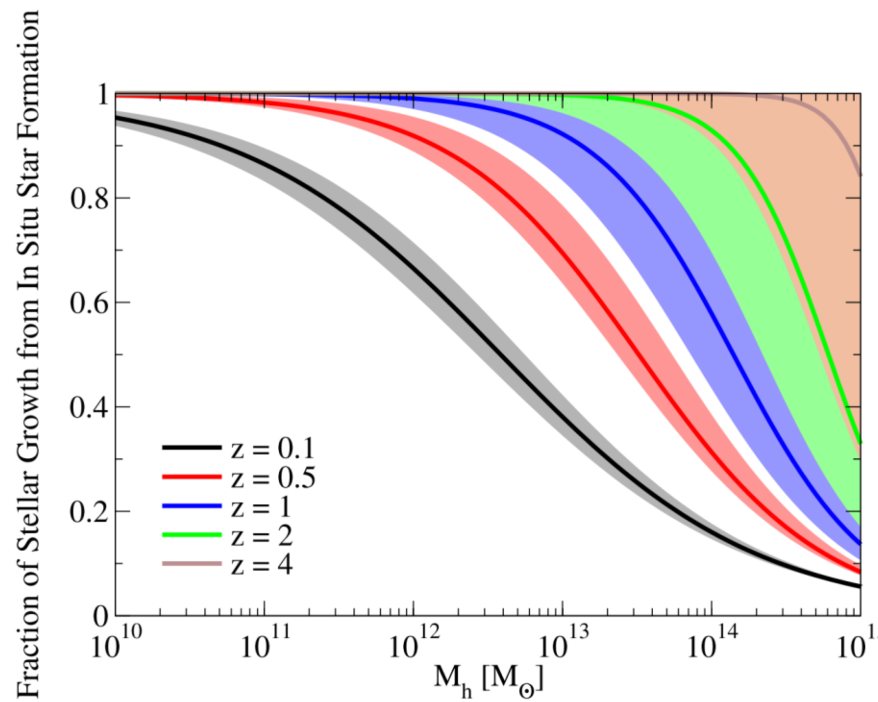
Time [Gyr]
10
7
4
2
1
SM(z) / M_h(z)
z
M_h = 10^11.0 M_⊙
M_h = 10^12.0 M_⊙
M_h = 10^13.0 M_⊙
M_h = 10^14.0 M_⊙
M_h = 10^15.0 M_⊙



Ω_bar/Ω_m
M_*/M_h
M_h [M_⊙]
ALL+E_fb, ε_ff=10%
ALL+E_fb, ε_ff=1%
No feedback, ε_ff=10%
No feedback, ε_ff=1%
ALL+E_fb, ε_ff=1%, 5×E_SN
ALL+E_fb, no P_rad, ε_ff=10%
ALL, no E_fb, ε_ff=10%



Leitner 2012, ApJ 745, 149



Behroozi, Wechsler, Conroy
2013, ApJ 770, 57