The galaxy population in cold and warm dark matter cosmologies

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Outline

- Why warm dark matter
- Simulations: COLOR & COLOR-WARM
- Semi-analytic models
- Galaxy properties
- Conclusions

CDM: problems

- Much more substructures simulated than the observed number of satellites around Milky Way and M31 *(Moore et al. 1999; Stadel et al. 2009)*
- Inner density profiles of simulated haloes are cuspy vs. observed ‘core’ density profile of galaxies (*Springel et al. 2008)*
- The most popular CDM candidate- WIMP has not been detected yet *(Akerib et al. 2014, Ackermann et al. 2015)*

WDM?

- Alternative dark matter candidates, for example, the kev-scale gravitino or sterile neutrino — WDM
- WDM: lighter & intrinsic thermal velocities
    - thermal motion would quench the growth of structure below the free-streaming scale
      - less low mass haloes *(e.g. Bode et al. 2001)*
    - 'cores' - much smaller than observed *(Shao et al. 2013)*
- WDM mass constraint: high-z Ly-alpha forest data *vs.* hydrodynamical simulation — m_x>3.3kev
  (Viel et al. 2013; Garzilli et al. 2015)

Galaxy formation in WDM

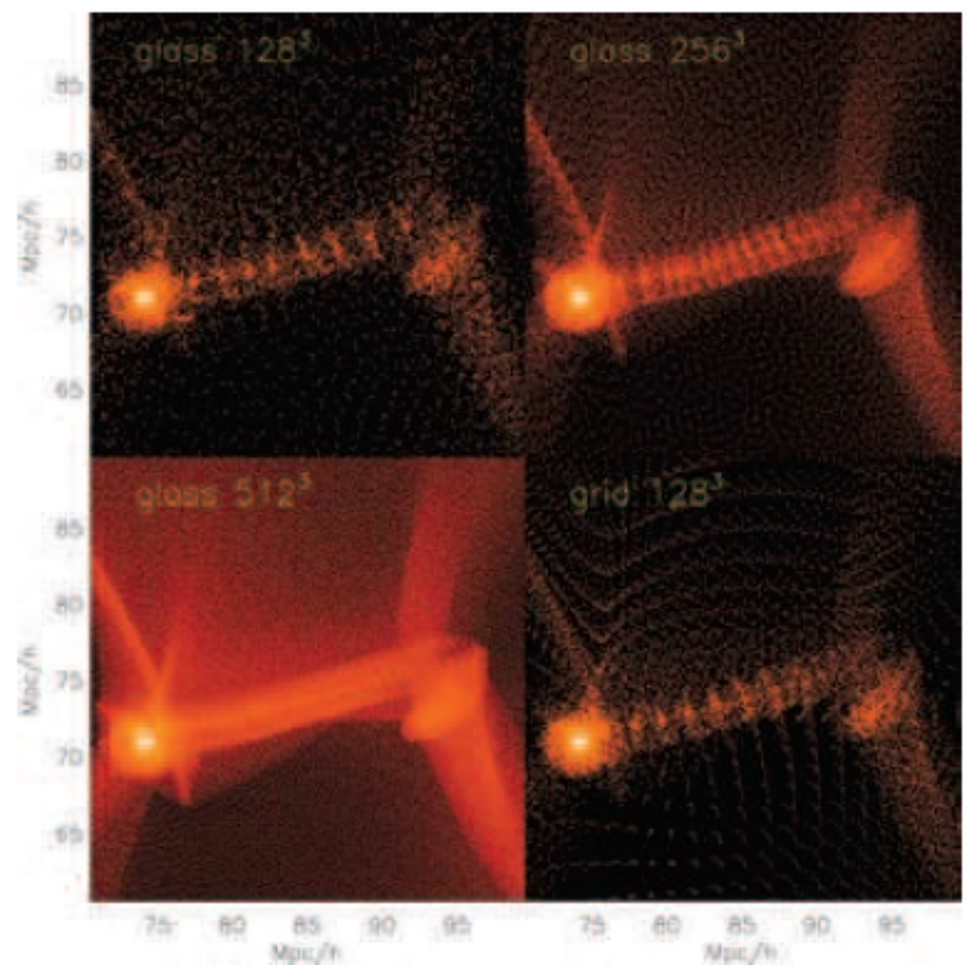
- LF, SMF, Tully-Fisher relation, AGN LF, properties of satellites, SFH and galaxy structure (e.g., *Menci et al. 2012; Kang et al. 2013; Lovell et al. 2016; Herpich et al. 2014; Gonzalez-Samaniego et al. 2016)*

- Numerical effect: spurious self-bound DM clumps arising from numerical discreetness effects, spaced regularly along filaments (*Wang & White 2007)*:

$$M_{\rm lim} = 10.1 \times \bar{\rho} d k_{\rm peak}^{-2}$$

$$d = N^{-1/3} L$$

$$k_{\rm peak} = 0.1 \times (m_\nu / 30\,{\rm eV})\,{\rm Mpc}^{-1}$$



COLOR simulations

- WMAP-7 cosmology

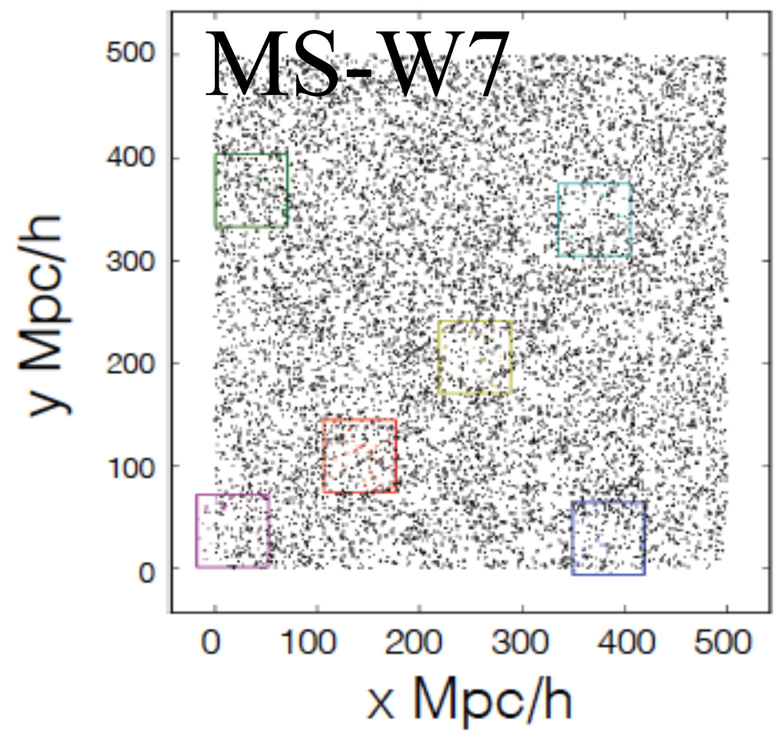
  $N = 1620^3, m_p = 6.20 \times 10^6 h^{-1} M_\odot$

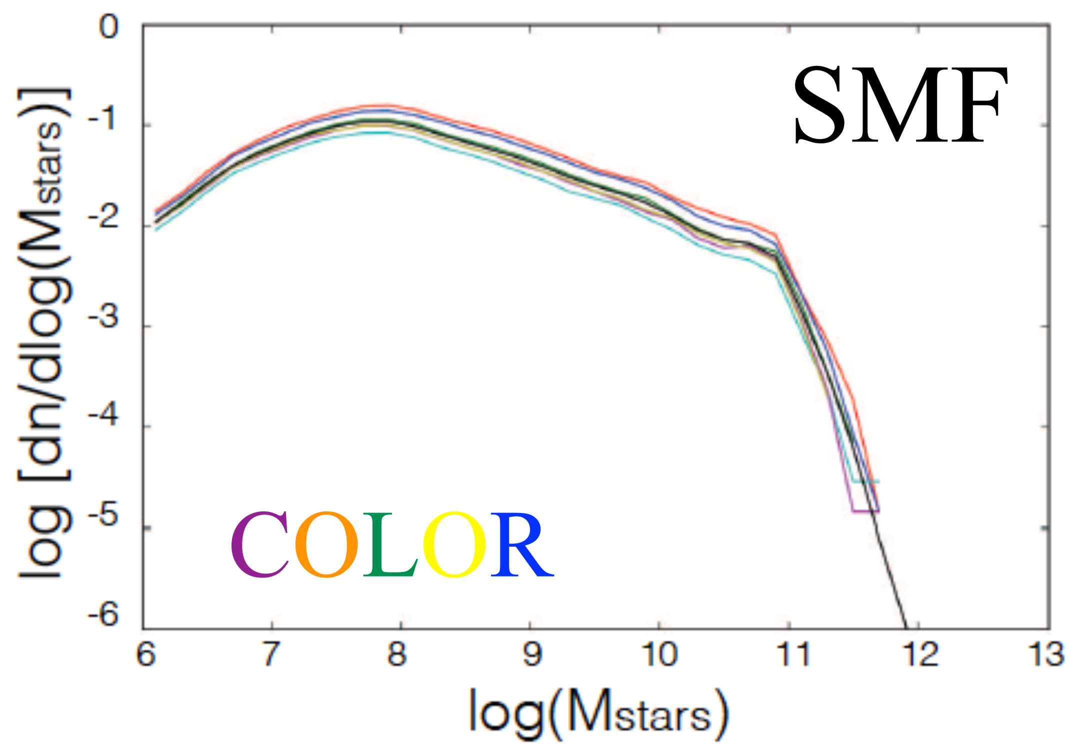
  $L = 70.4 h^{-1} Mpc, softening = 1 h^{-1} kpc$

- GADGET-3; from z=127 to today
- warm dark matter particle: 1.5kev
- $M_{\lim} = 2.42 \times 10^9 h^{-1} M_\odot$ *(Wang & White 2007)*
- COLOR-WARM: spurious halos removed following *Lovell et al. 2014*

Semi-analytic model

- *Gonzalez-Perez et al. 2014 (GP14)*
  - GALFORM & Millennium Simulation-WMAP7
  - constrained by LFs in the local Universe

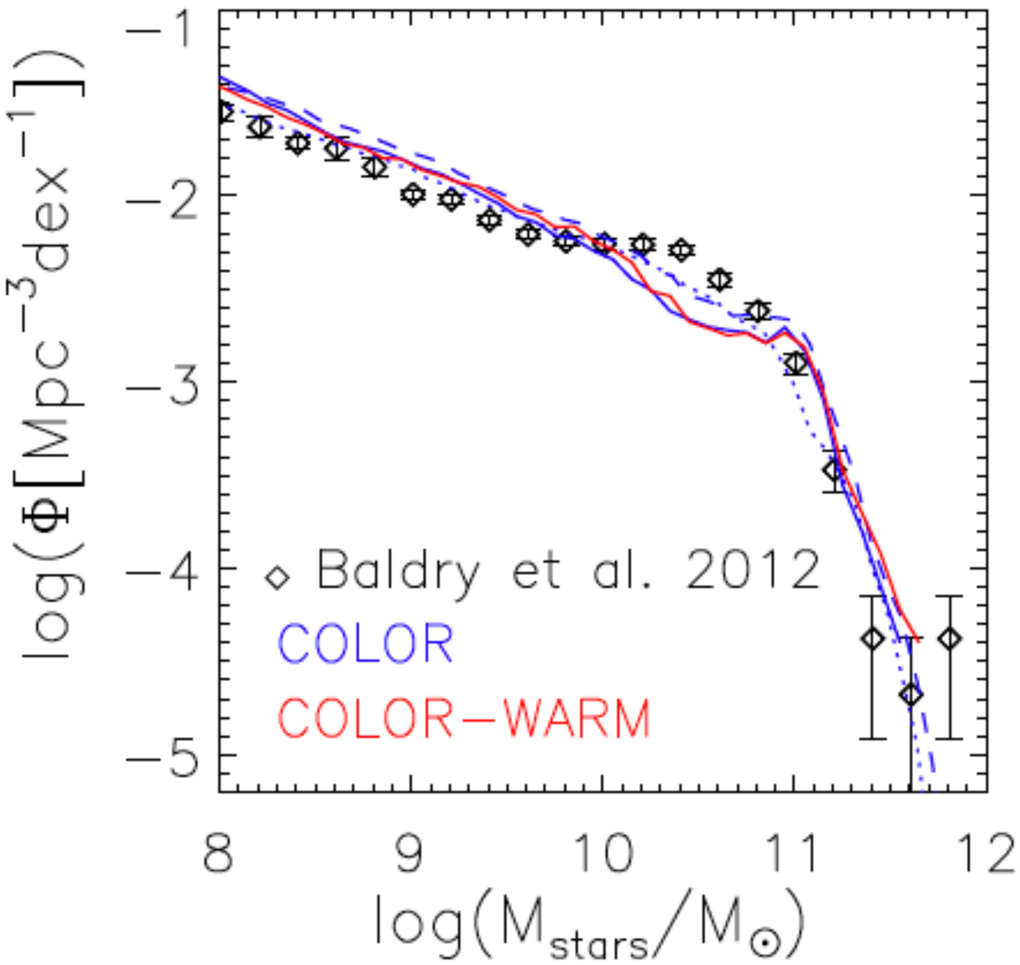




- cosmic variance can move the amplitude of SMF by about 0.2-0.3 dex; different mass resolution ~0.1 dex.

Retuning of GP14 model

- GP14 model is retuned to make galaxy stellarmass function at z=0 to be the same in COLOR-WARM and COLOR in the range of log*Mstars*=[9, 11]
- Then we look at other properties of galaxies



Parameter	GP14	Re-GP14
α_{hot}	3.2	2.5
$V_{hot,disk}$	425	575
α_{cool}	0.6	0.55

supernovae feedback

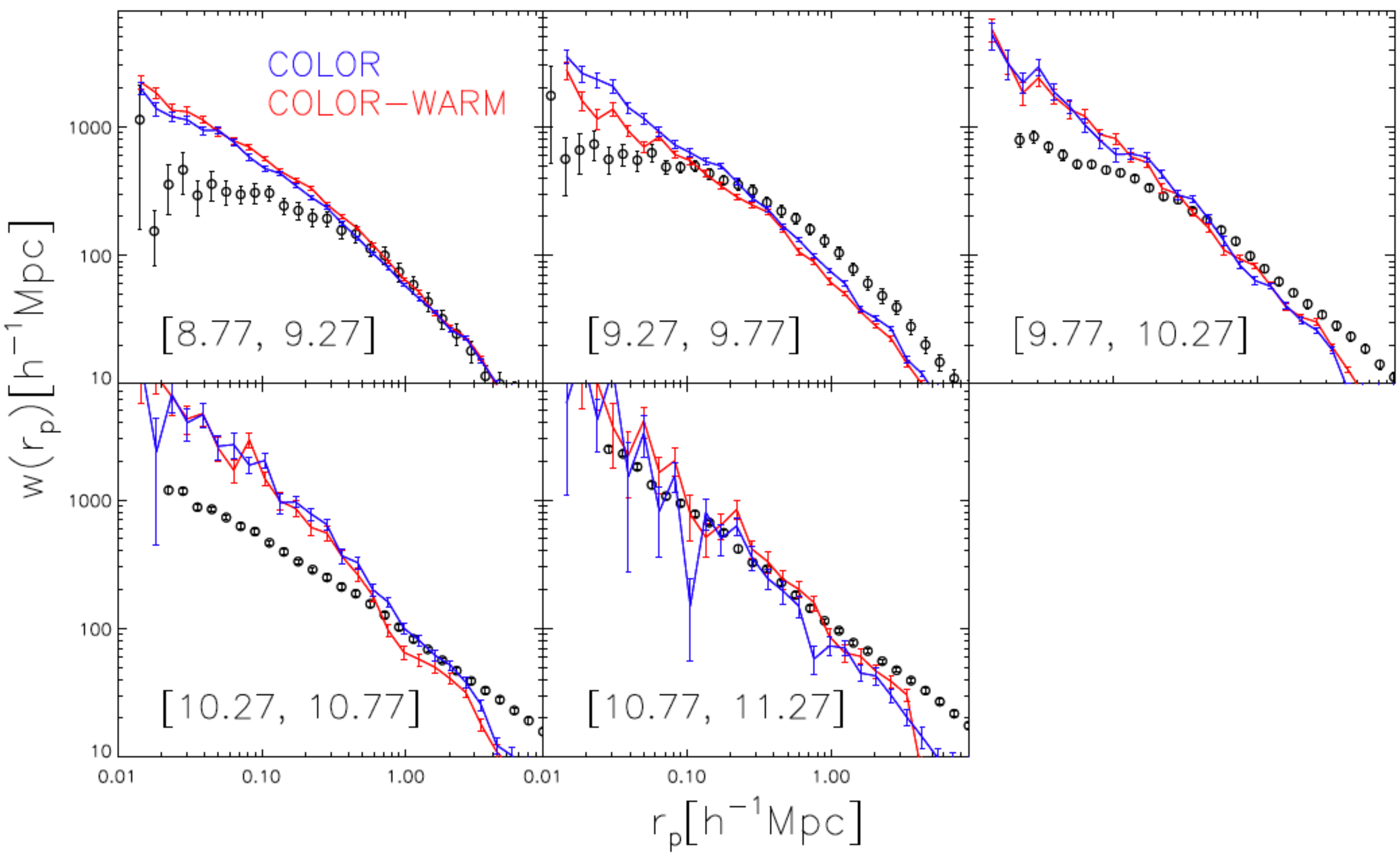
$$\dot{M}_{reheated} \propto (v_{circ}/v_{hot,disk})^{-\alpha_{hot}}$$

AGN feedback

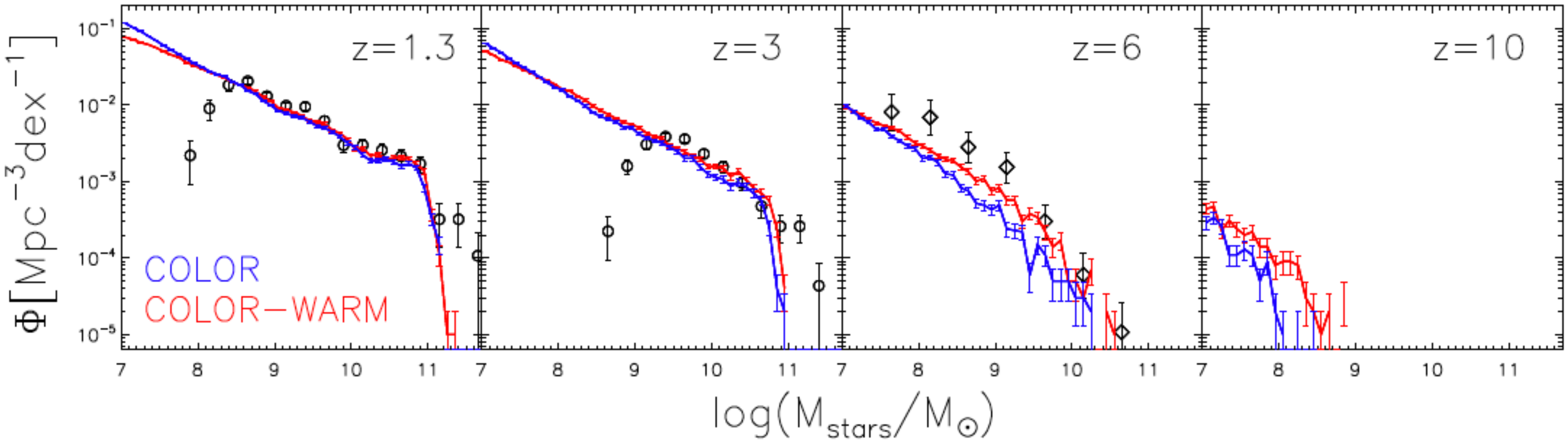
$$\tau_{\mathrm{cool}}(r_{\mathrm{cool}})/\tau_{\mathrm{ff}}(r_{\mathrm{cool}}) > 1/\alpha_{\mathrm{cool}}$$

Correlation functions

- Galaxy clustering is similar at all stellar masses

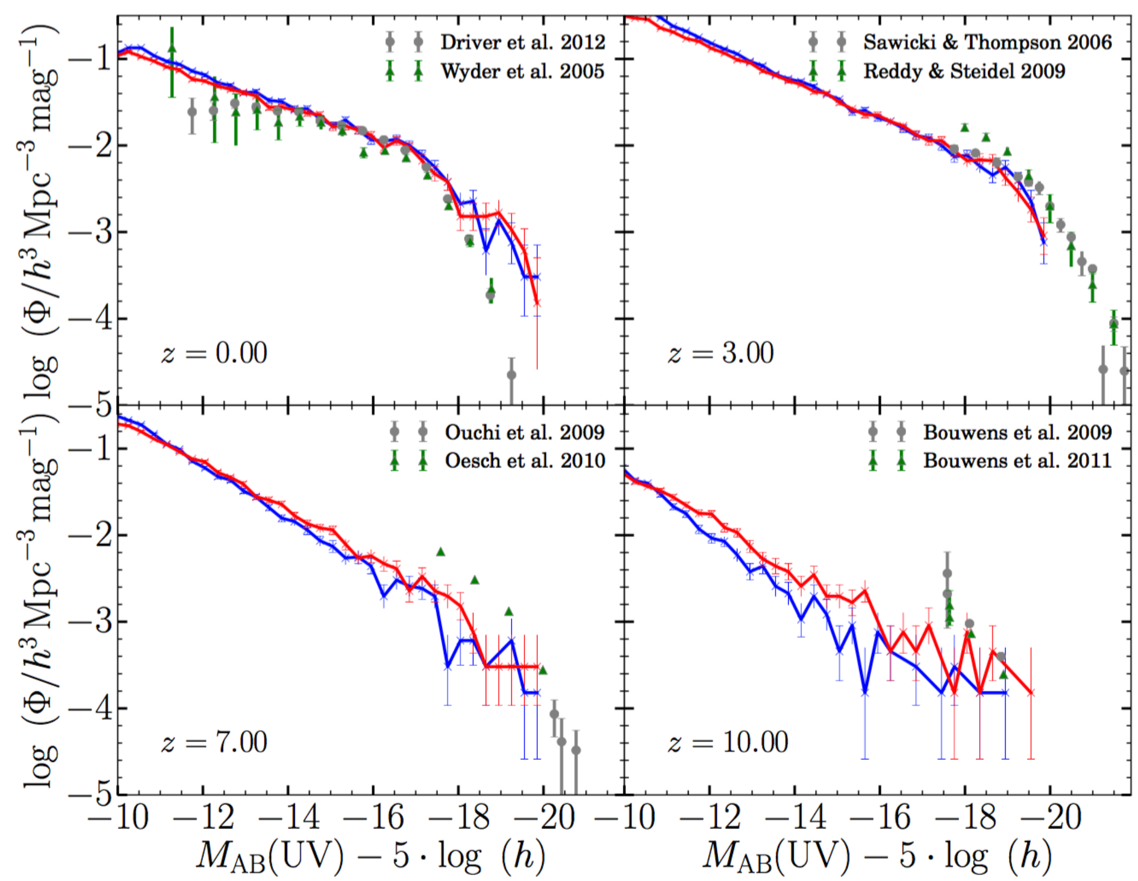


SMFs at high z



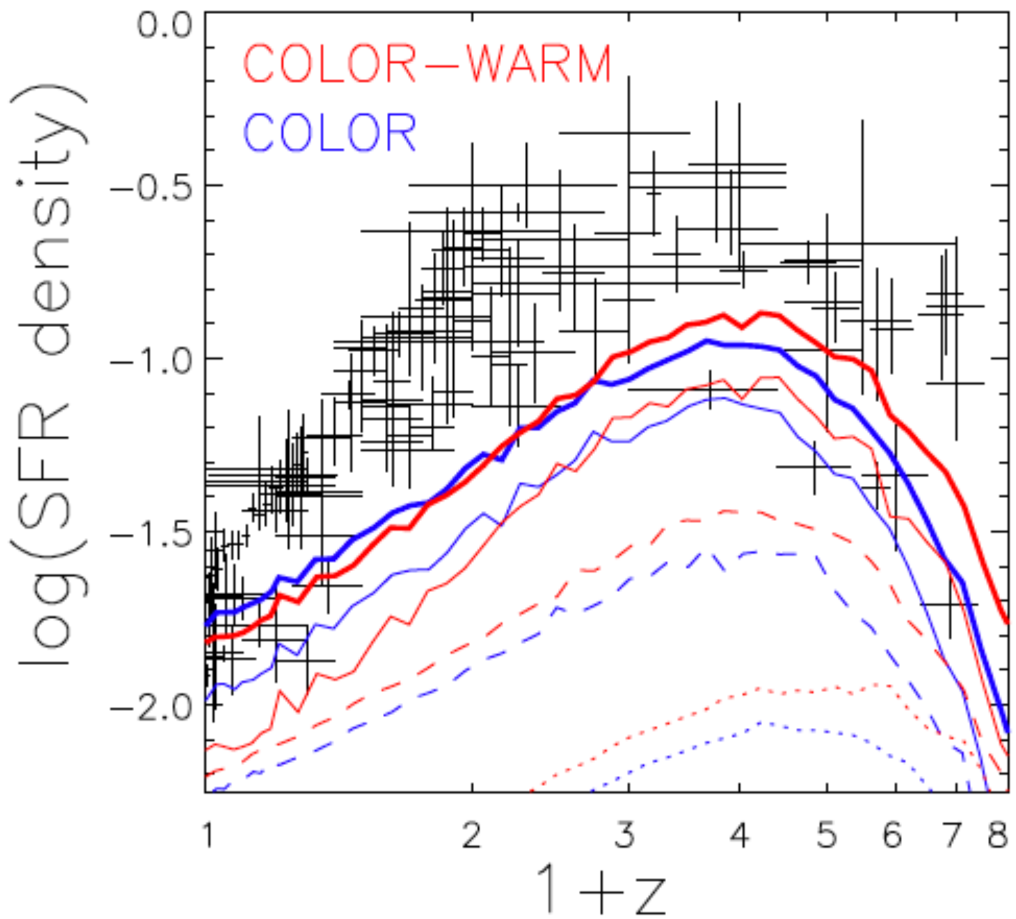
- At z>3, massive galaxies are more abundant in COLOR-WARM

Bose et al. 2016
(m_{WDM}=3.3kev)



SFR density evolution

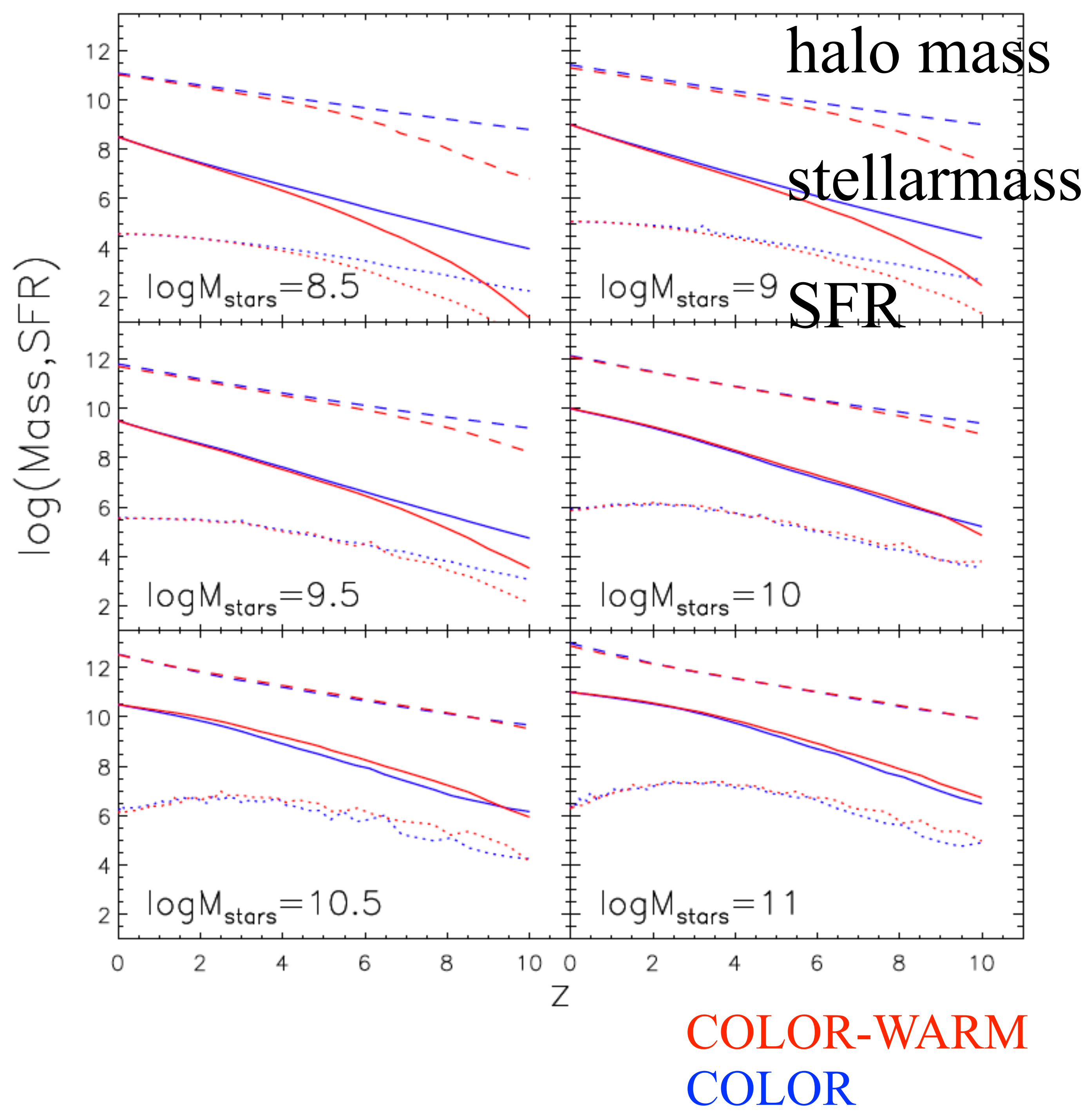
- Massive galaxies in WDM form more efficiently at high redshifts.
- *Bose et al. 2016:* at high z, the brightest galaxies form through starbursts triggered by mergers. In WDM, the first galaxies that collapse are more massive and more gas rich than in CDM, producing brighter starbursts when they merge.



- COLOR-WARM: more starburst galaxies at z>3.

Mass assembly & SFR histories

- For low mass galaxies, galaxies of given stellar mass in WDM model assemble both their halo mass and stellar mass later, with lower SFR at high z.
- For massive galaxies, stellar mass assembles earlier, and SFR higher at high z in the WDM model.



Galaxies in low dense regions

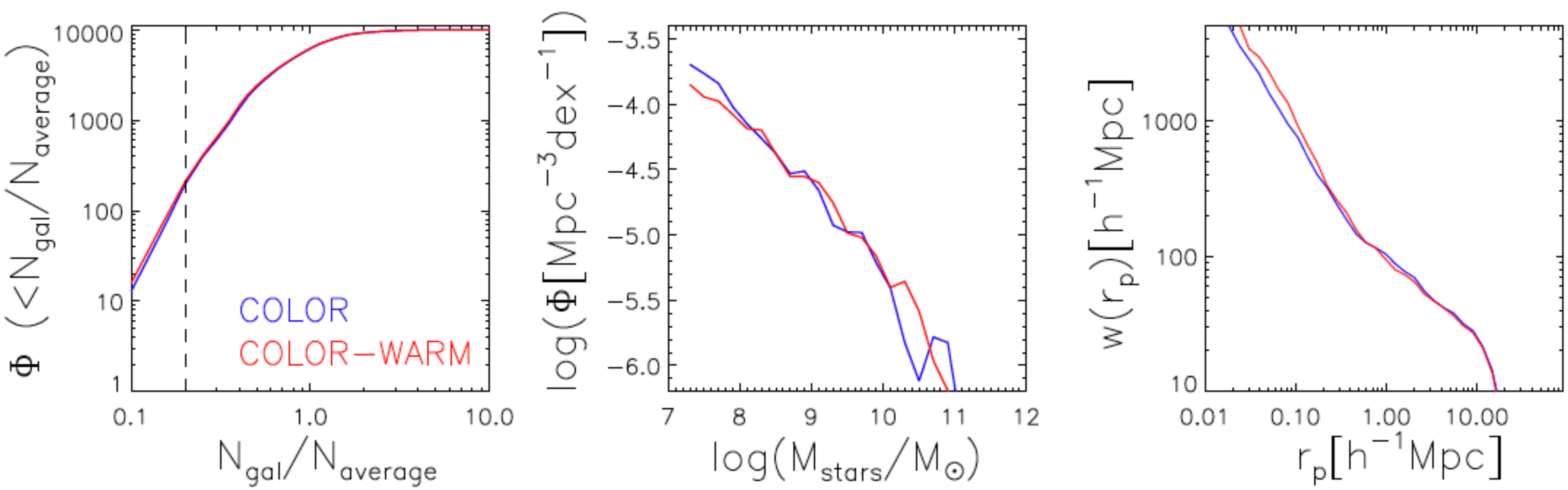
Numerical simulation studies of structure formation indicate that the differences between WDM and CDM models are most pronounced on small scales and in under-dense regions *(e.g., Bode et al. 2001; Knebe et al. 2002, 2003)*.

- Galaxies in voids
- Local Volume and Local Void

Galaxies in voids

Voids are large, under-dense regions in the Universe, usually defined as under-dense spheres *(e.g. Kauffmann & Fairall 1991; Colberg et al. 2005)*.

- 10000 random spheres of radius 10Mpc
- voids: the number of galaxies included in the sphere is less than 20 per cent of the average



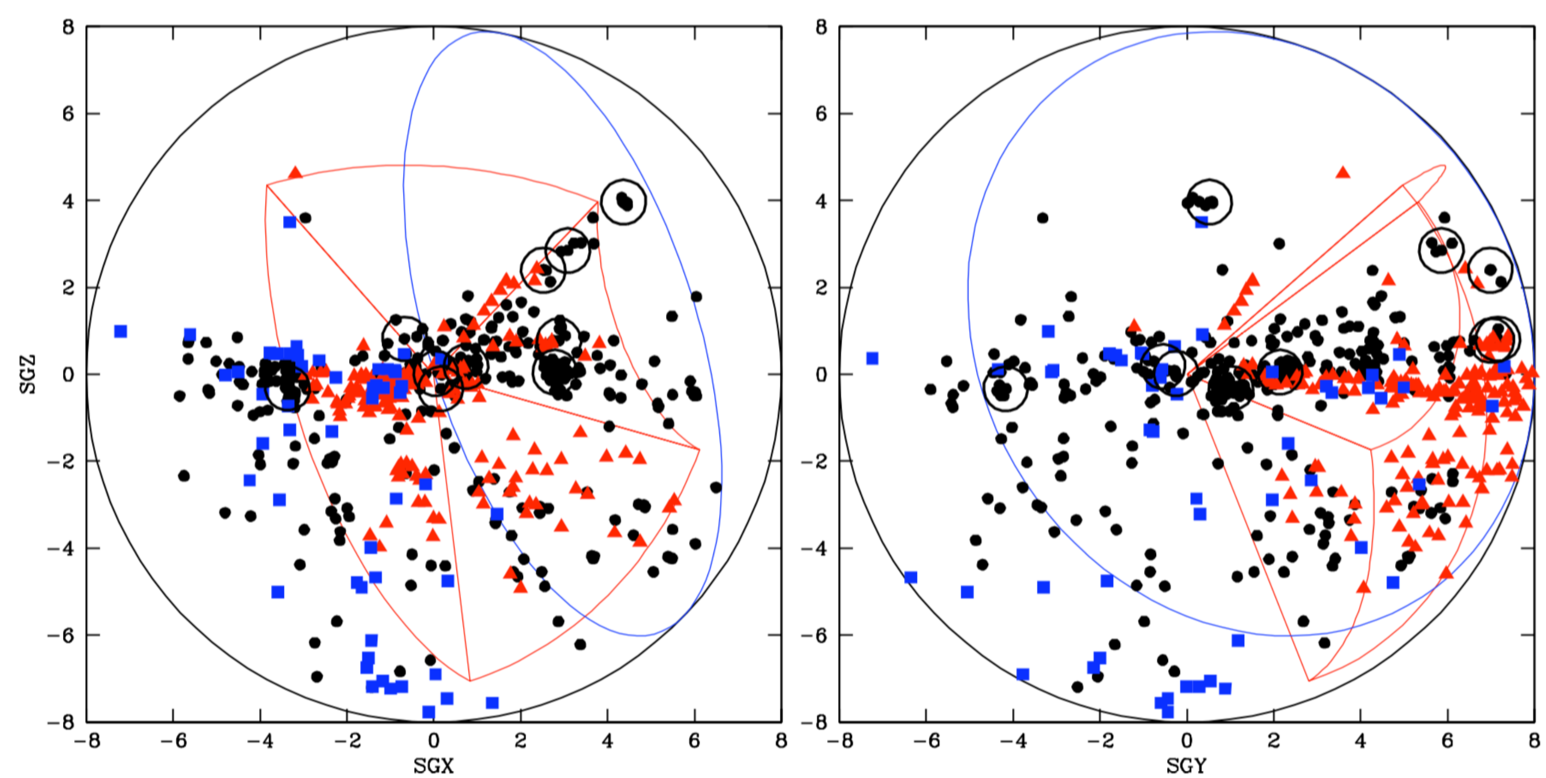
"Local Void" probability

Peebles & Nusser 2010

- Full sky galaxy surveys in the local Universe: about a third of the Local Volume area contains only 3 galaxies. The emptiness of Local Void is a potential challenge to the standard ΛCDM cosmology.

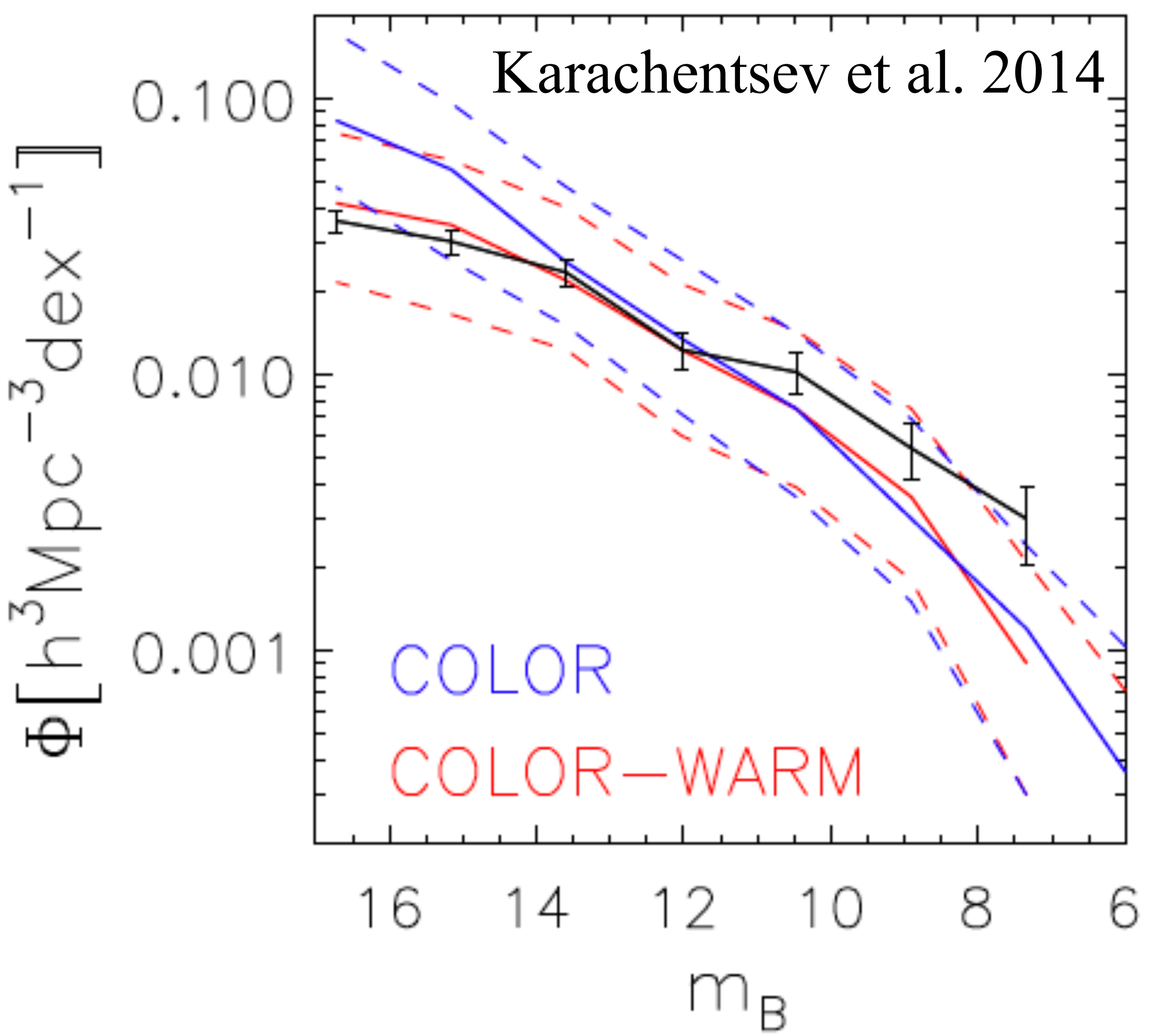
Xie et al. 2014

- a probability of 14 percent to find a Local Void in a simulated galaxy catalogue in ΛCDM cosmology



Simulated "local volume"

- "local volumes": regions within a radial range of [1, 8Mpc] around MWs, and have a companion giant galaxy with stellar mass similar as M31, within 1 Mpc from the MW.

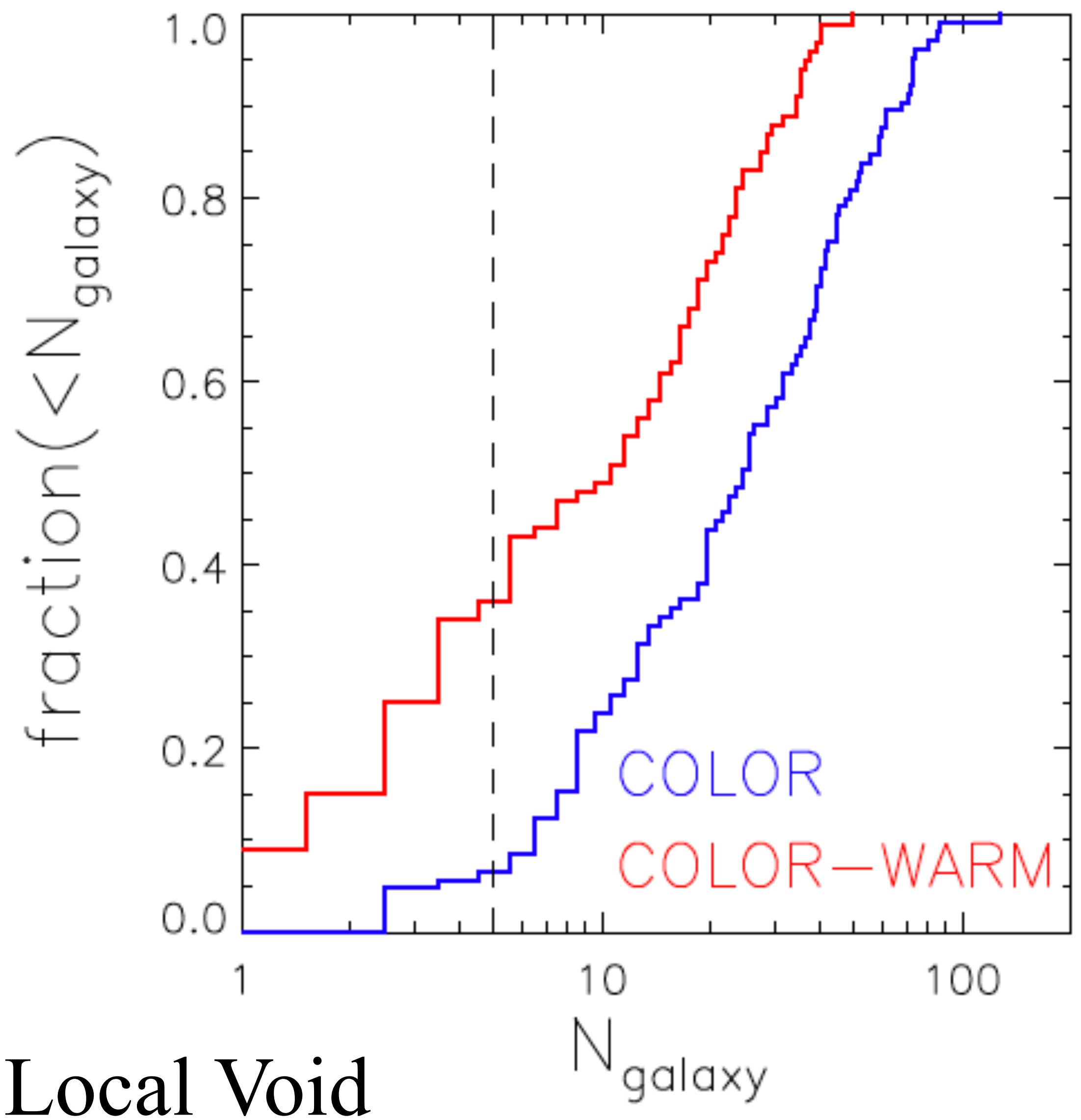


galaxy LF in Local Volumes

Simulated “local void”

- “local voids”: the most empty, truncated, cone-shaped region with solid angle π in each simulated Local Volumes.

- simulated “local voids” that are as empty as the observed one:
  - 5.7 percent in COLOR
  - 34 percent in COLOR-WARM



dashed line: the real observed Local Void

Conclusion

Galaxy populations in WDM and CDM cosmologies are quite similar

- both dark matter scenarios match current observational data equally well.

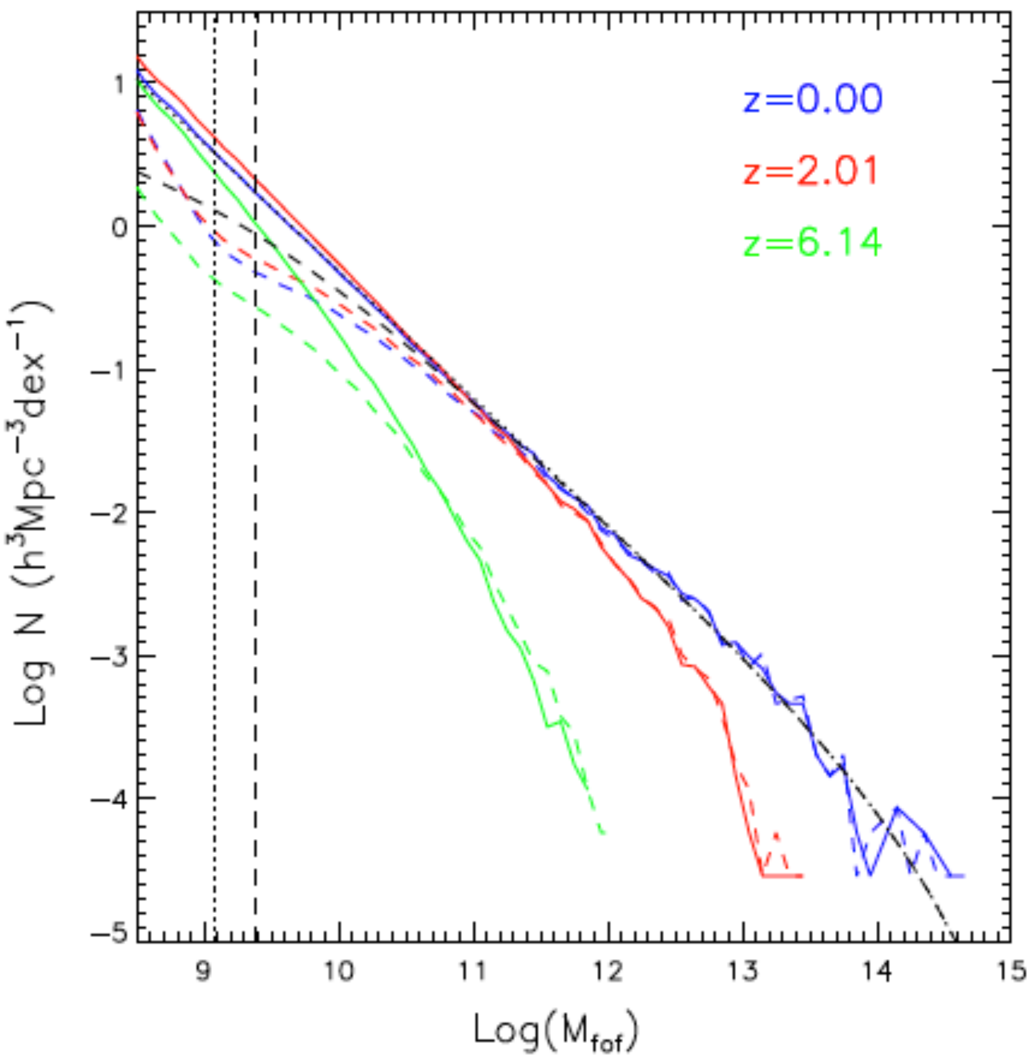
differences can be found in:

- high redshifts populations
- local volumes & local voids

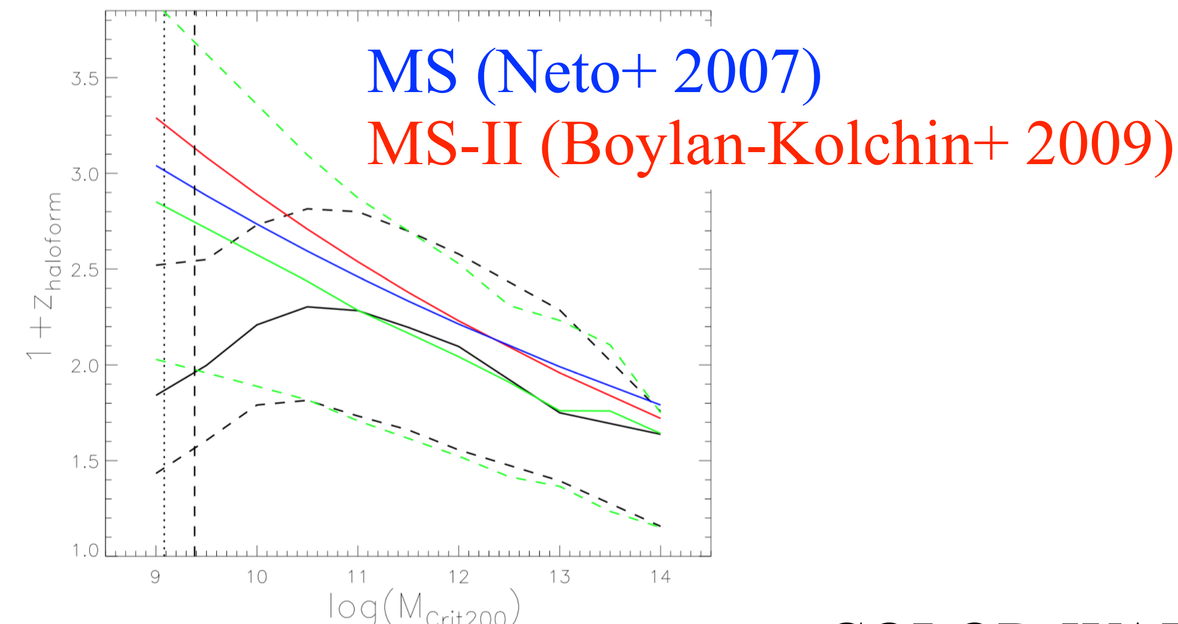
Thank you!

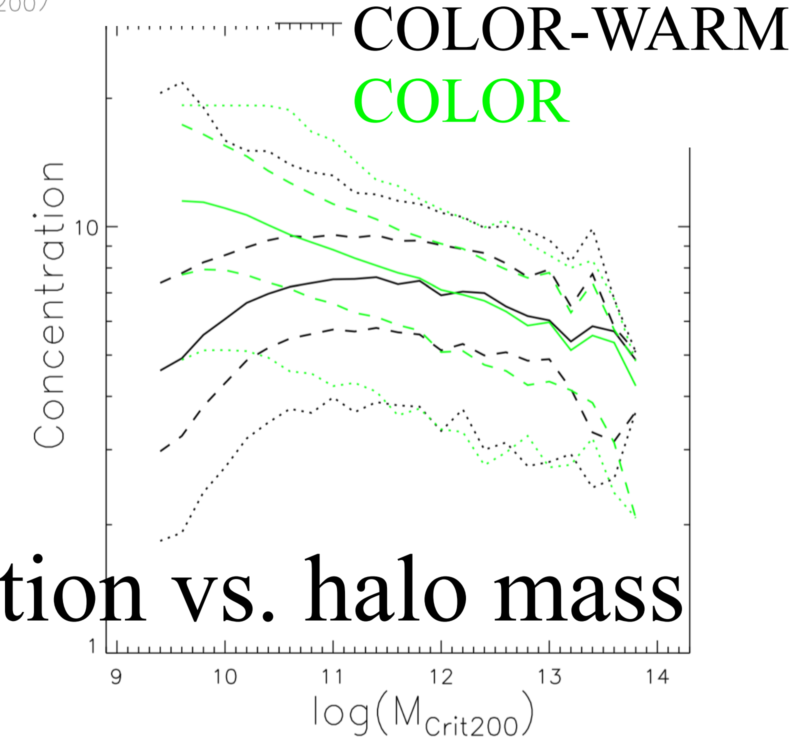
Halo properties

halo mass function



formation time vs. halo mass





concentration vs. halo mass