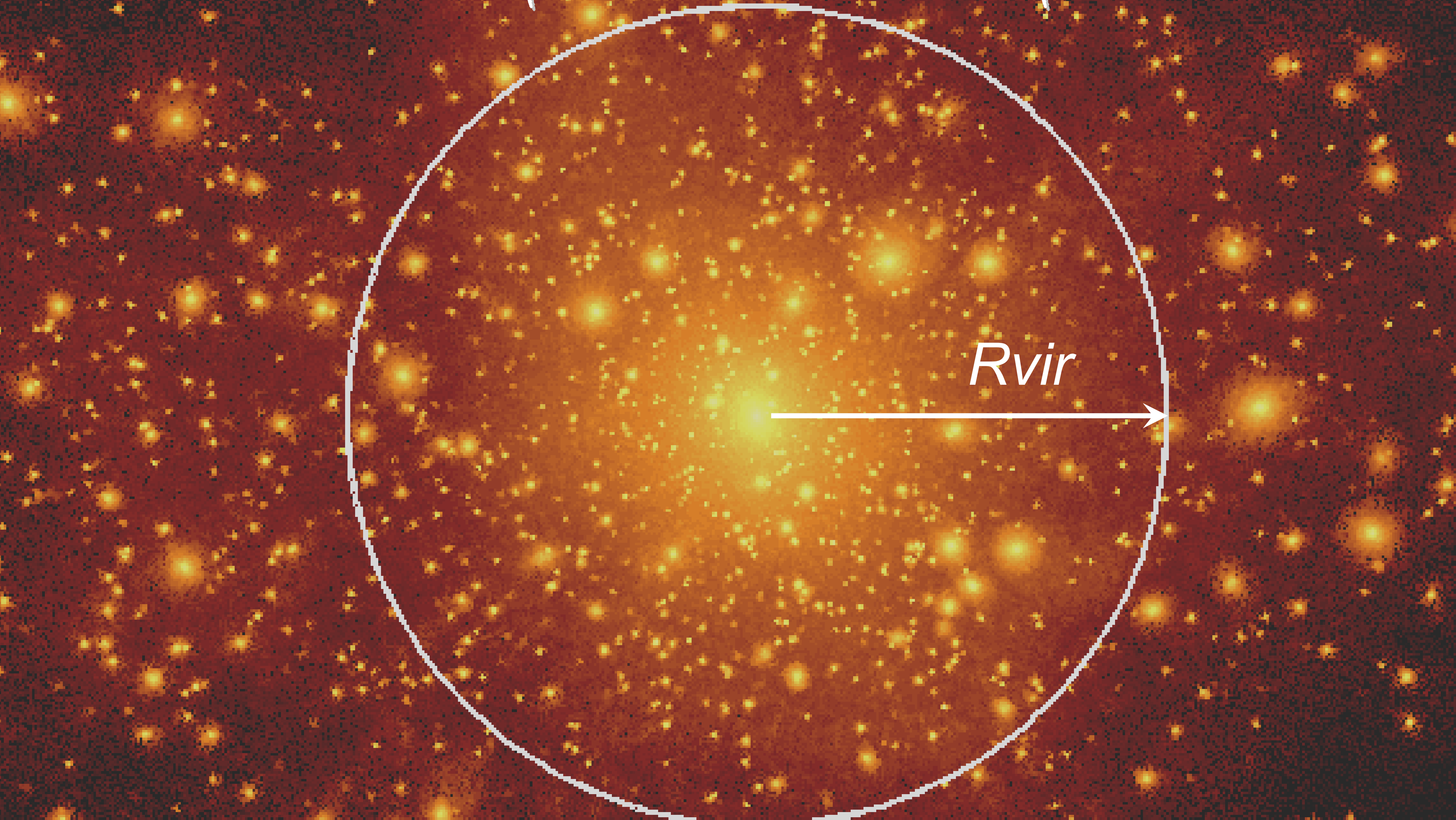
CDM substructure problem and star fomation in dwarf halos

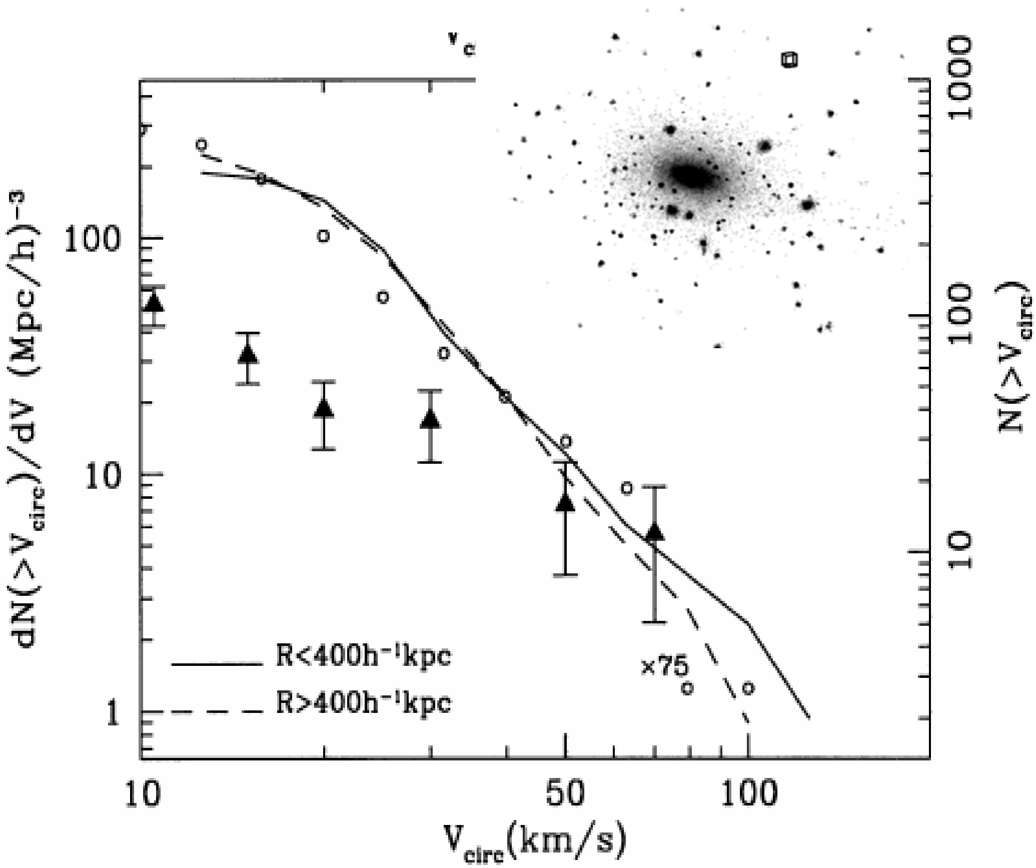


Andrey Kravtsov

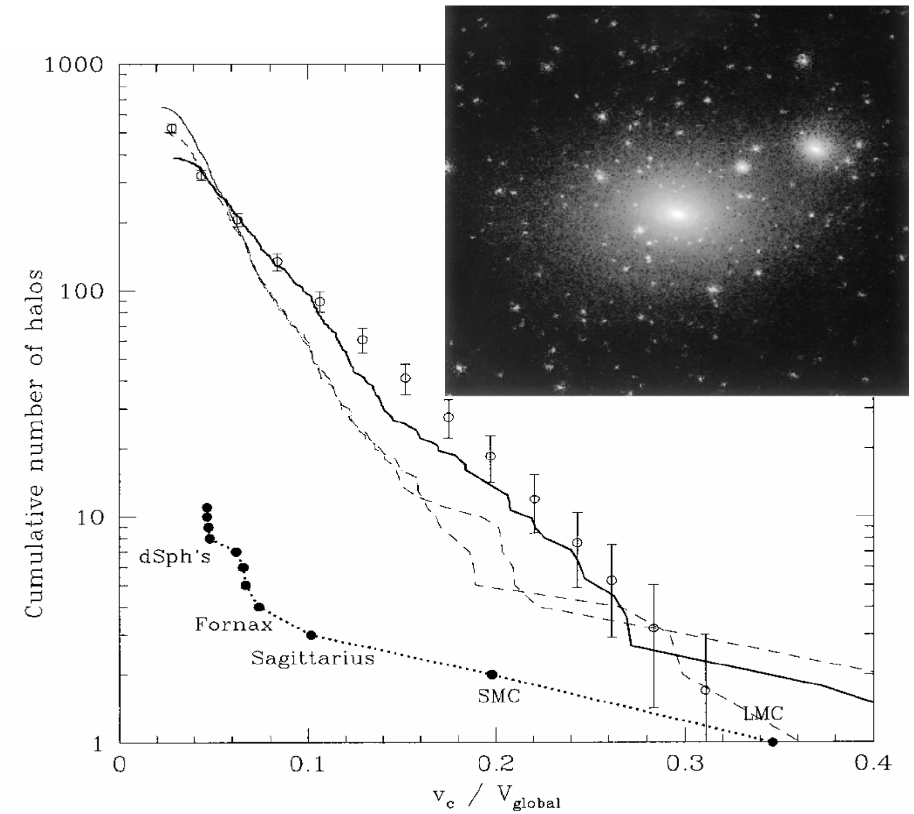
The University of Chicago

The missing satellite problem
quantified via velocity function

Klypin, Kravtsov, Valenzuela & Prada 1999



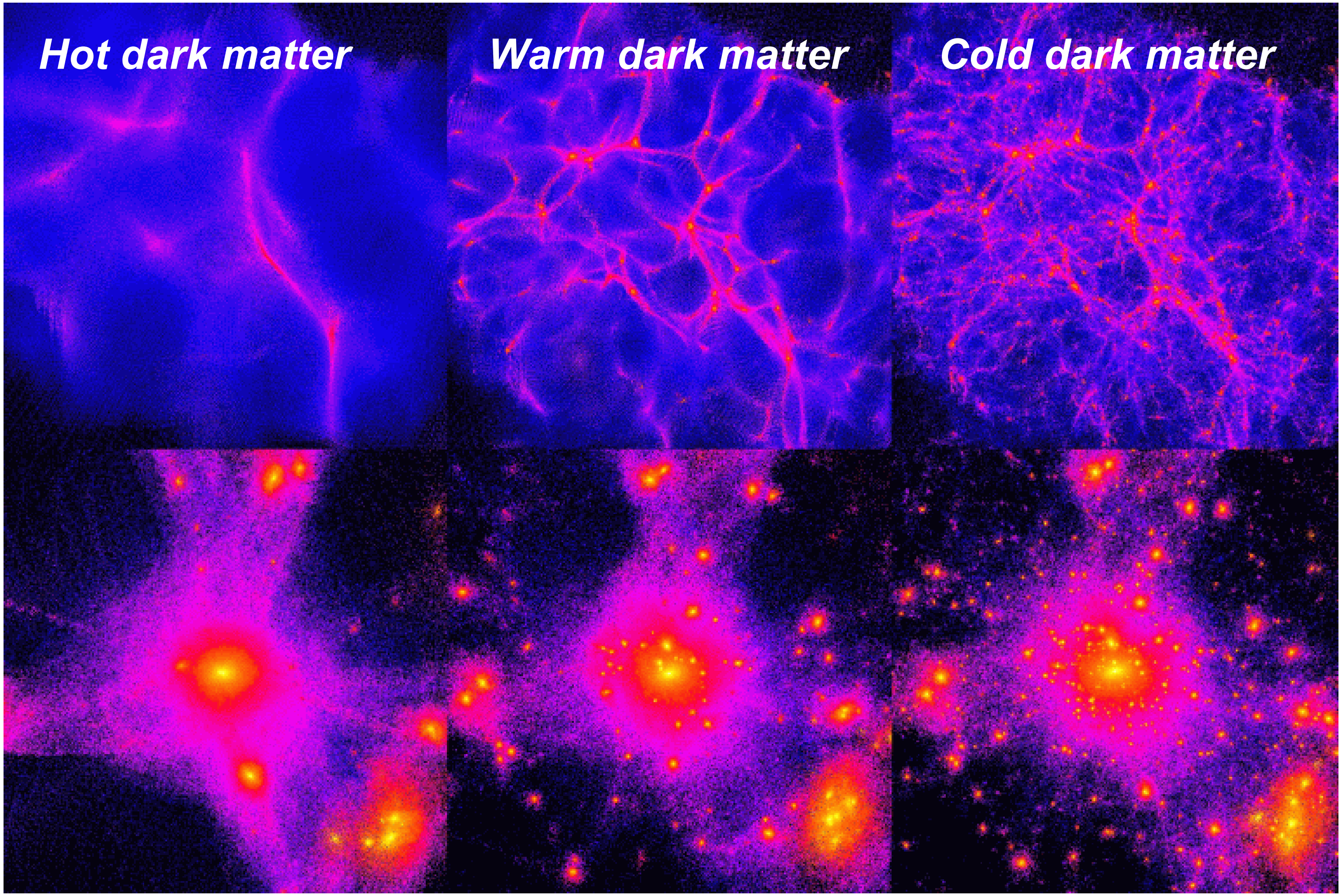
Moore et al. 1999



circular velocity = max of $(GM(<r)/r)^{1/2}$

One can break the hierarchy

by changing properties of dark matter and erasing small-scale fluctuations

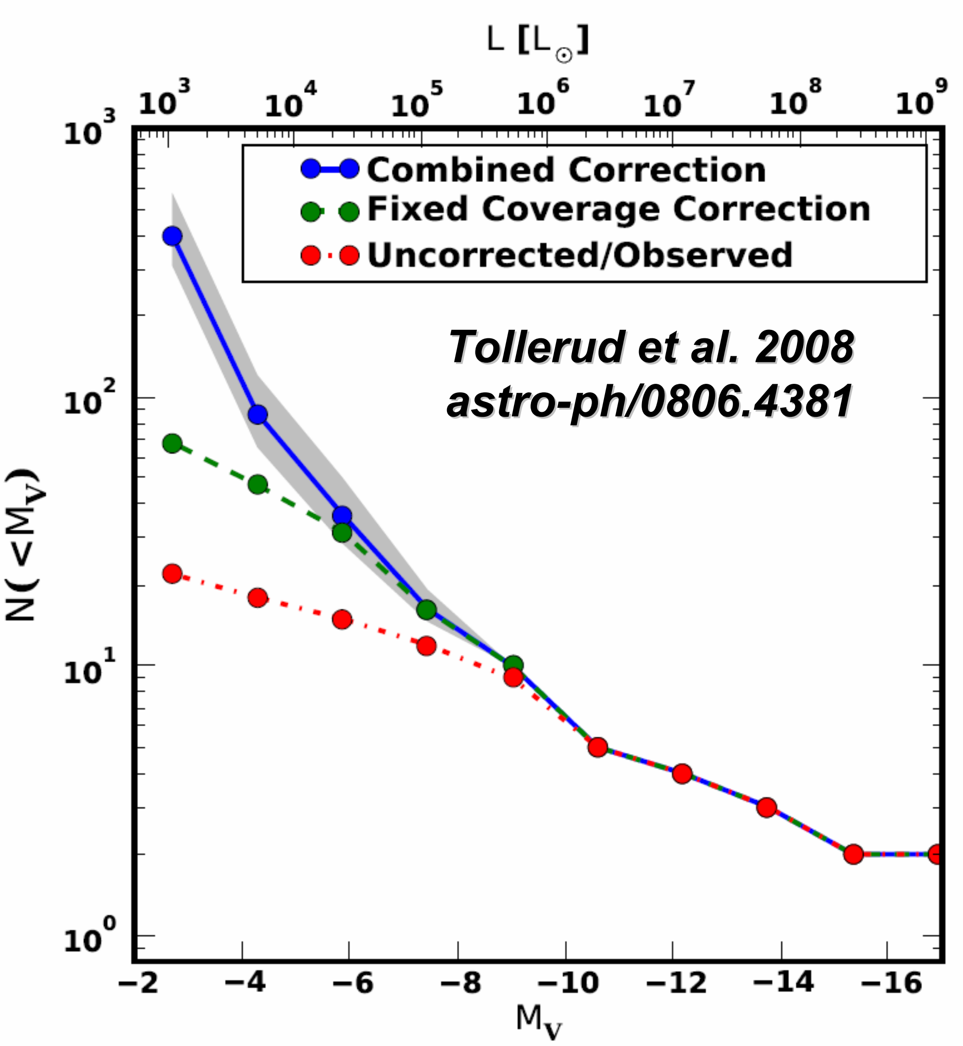


Credit: Ben Moore http://www.nbody.net

Still missing after all these years…

observations got better…

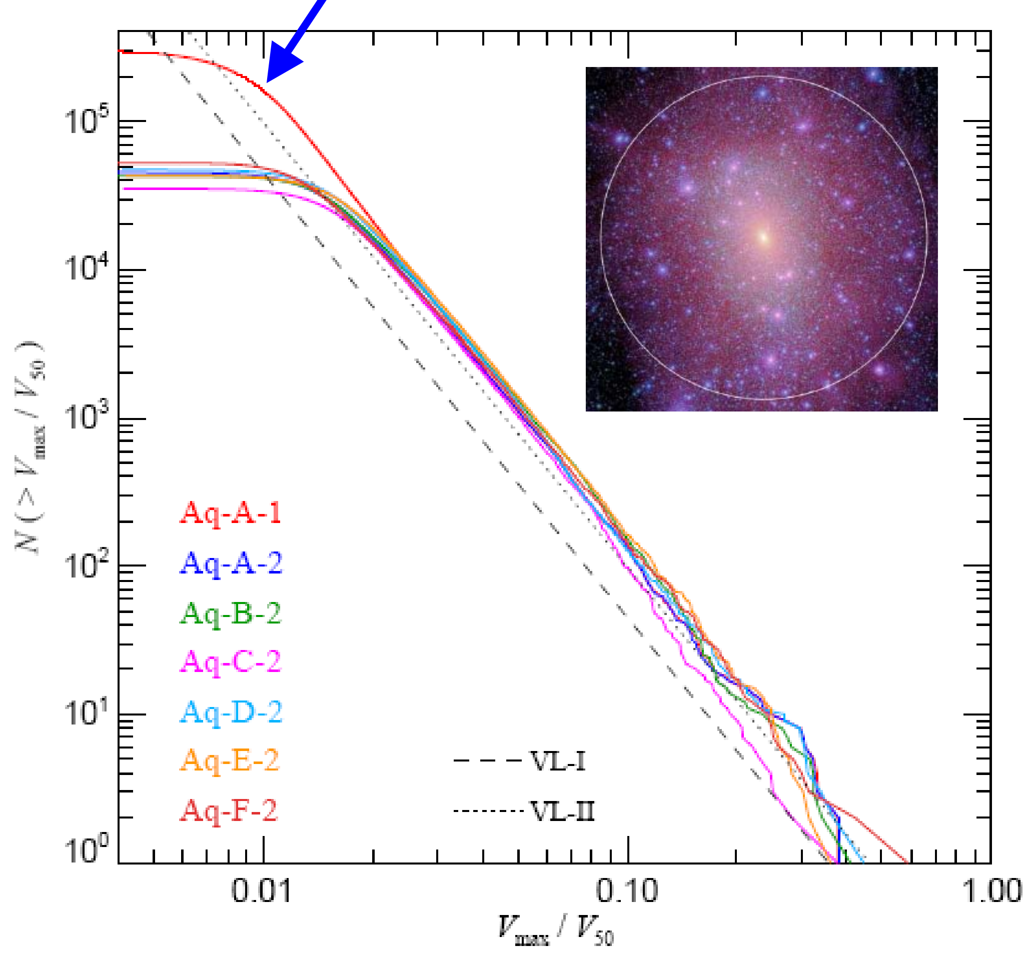
(e.g. discovery of increasing number of the ultra-faint dwarfs)



but so did simulations…

(>billion particles per halo simulations circa 2008 Diemand et al. 2008; Stadel et al. 2008; Springel et al. 2008)

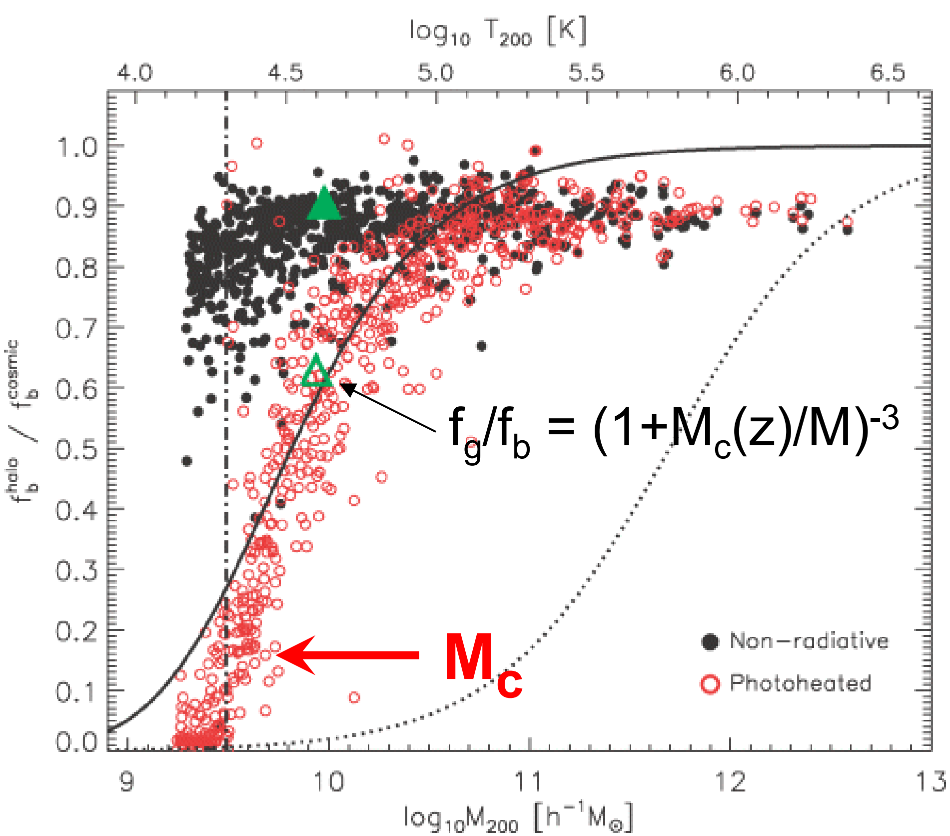
➢ ***100000 subhalos within MW-sized halo***



What makes small halos faint or completely dark?

suppression of gas accretion due to cosmic UV heating

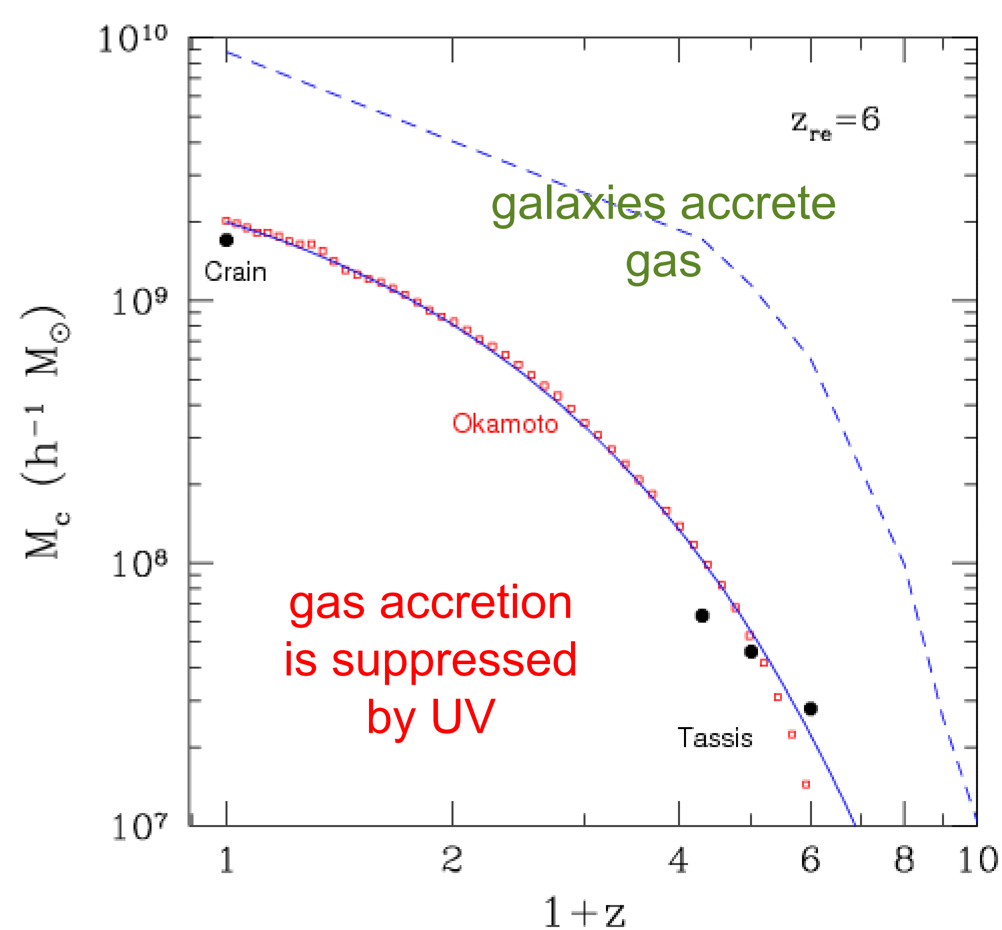
(parameterized by filtering mass of N. Gnedin 2000;
accurately quantified by
Hoeft et al. ’06; Crain et al. ’07;
Tassis et al ’08; Okamoto et al. ‘08)



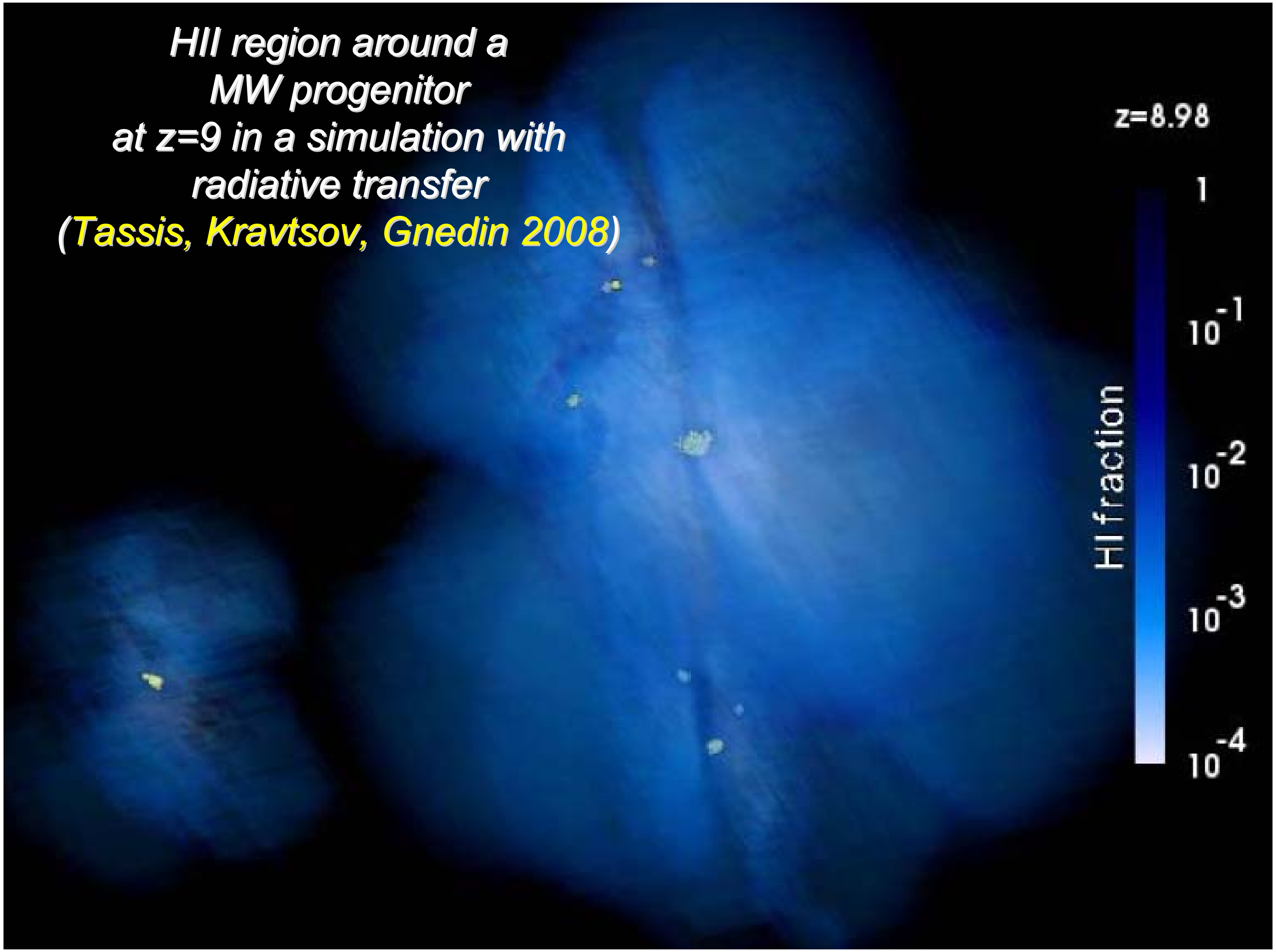
cutoff mass depends on z

(O. Gnedin’s fit)

$$M_c \approx 2x10^9 \, e^{-5.4 \, z/zre} \; h^{-1} \, M_\odot$$



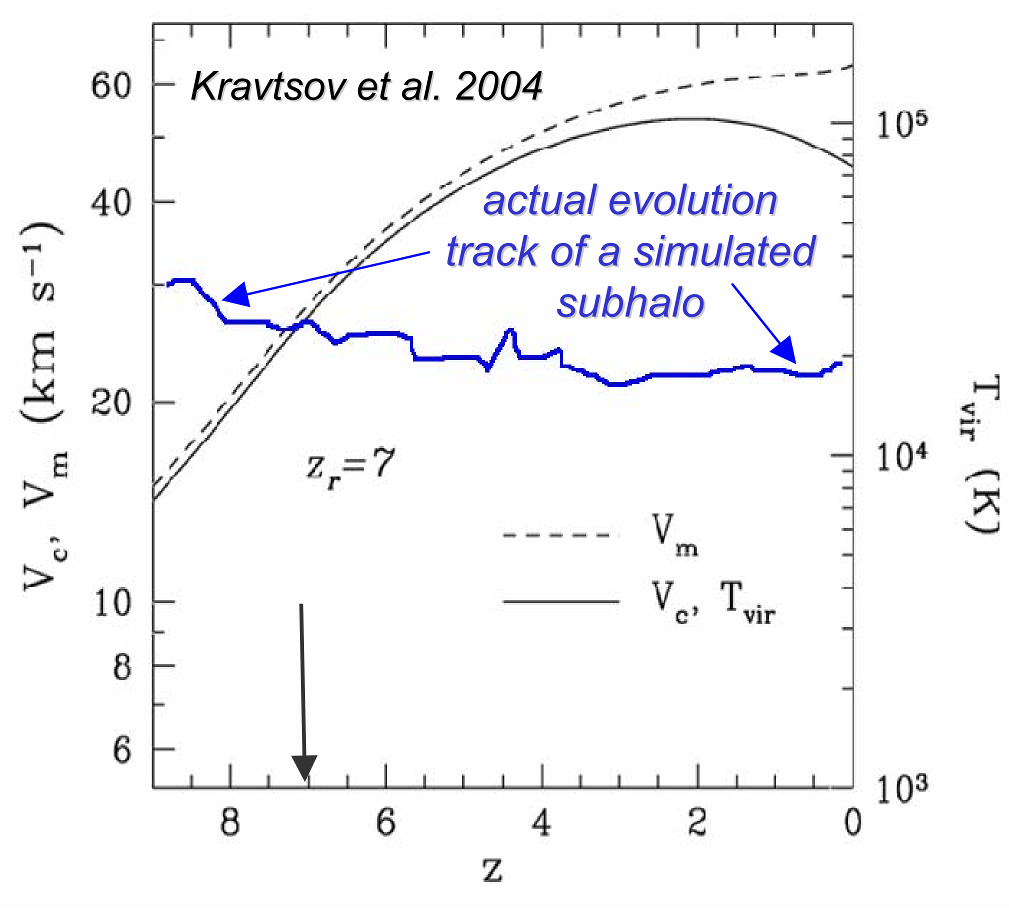
A large region around the Milky Way progenitor is expected to be reionized early by the progenitor itself or by the progenitors of other massive nearby halos (e.g., Virgo cluster)



Some of the dwarf spheroidals could be "fossils" of the reionization epoch

Bullock, Kravtsov & Weinberg 2000;
Ricotti & Gnedin 2005; Gnedin & Kravtsov 2006
Moore et al. 2006; Madau et al. 2008; Busha et al. 2008

cuttoff
circular velocity
(corresponding to Mc)

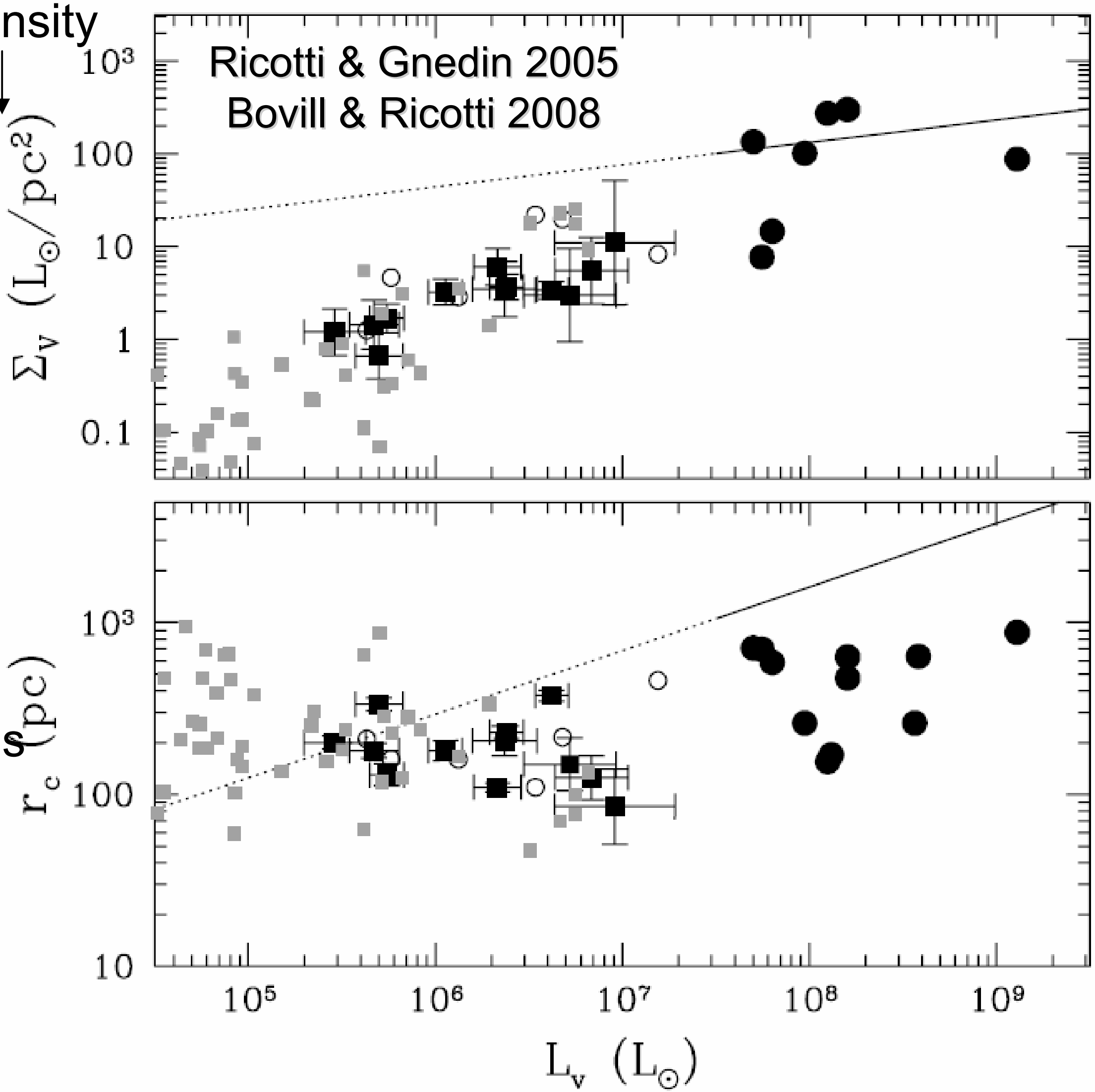


cutoff
virial temperature

redshift

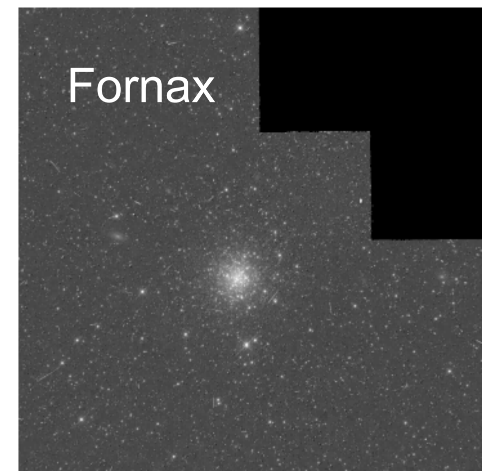
"Fossils" have dSph morphology and structural properties

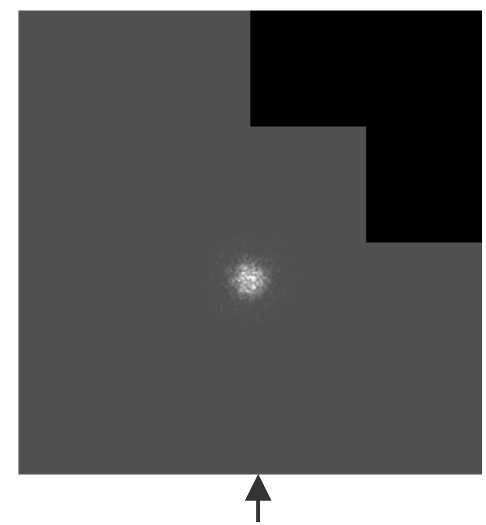
light surface density



core radius

V-band luminosity

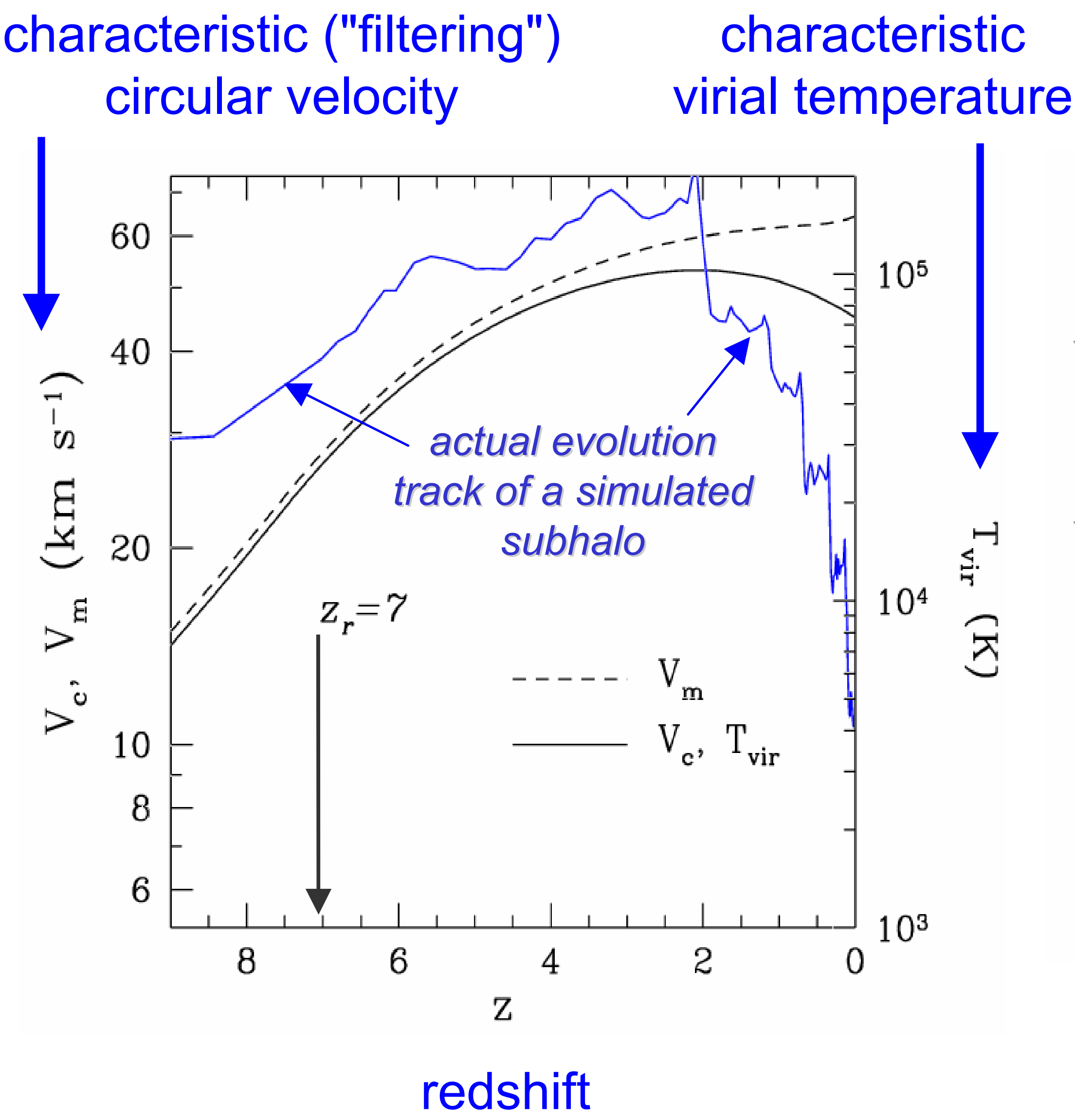


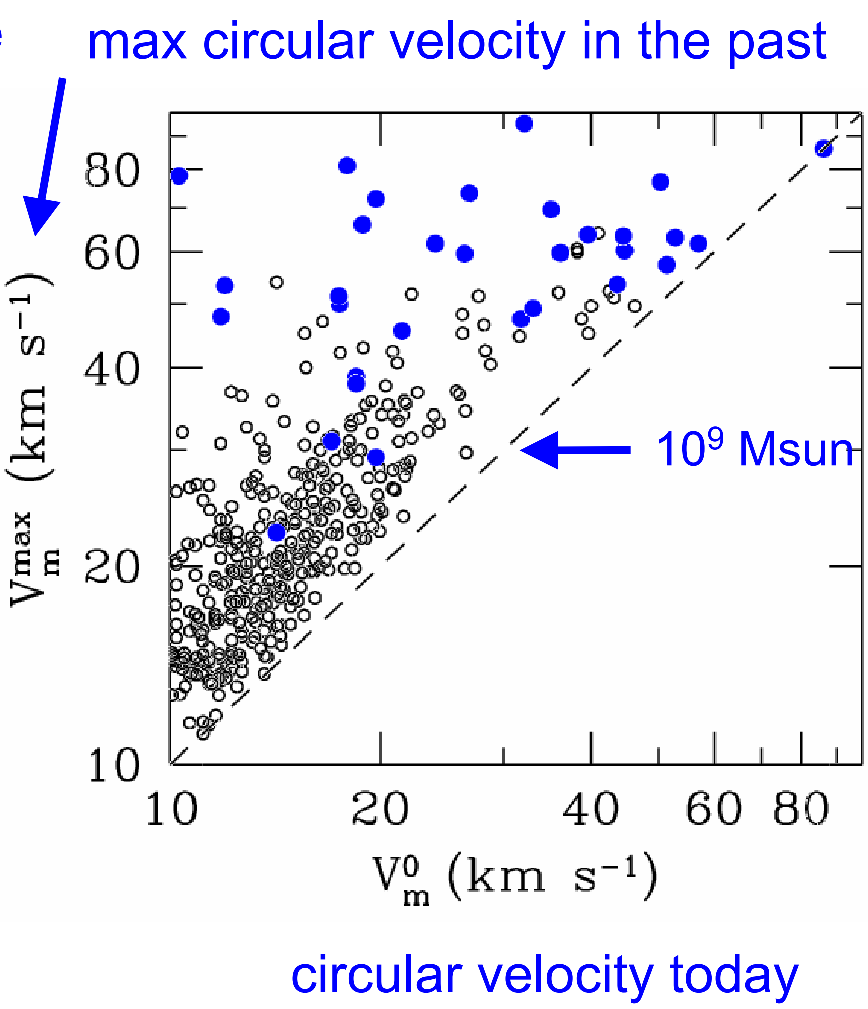


high-z dwarf galaxy from hydro simulation with RT (Ricotti & Gnedin 2006)

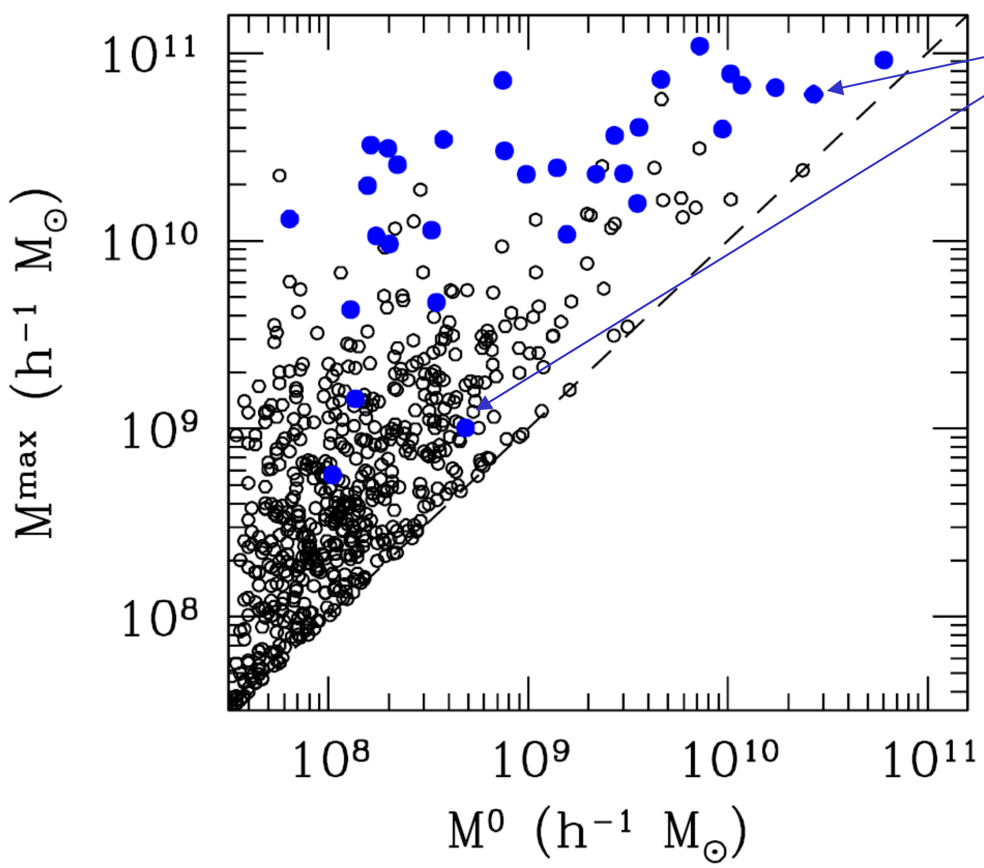
Many of the dwarf satellite halos were able to grow the mass after reionization

Kravtsov, Gnedin & Klypin 2004





We thus expect progenitors of the luminous dwarfs to have a wide variety of masses



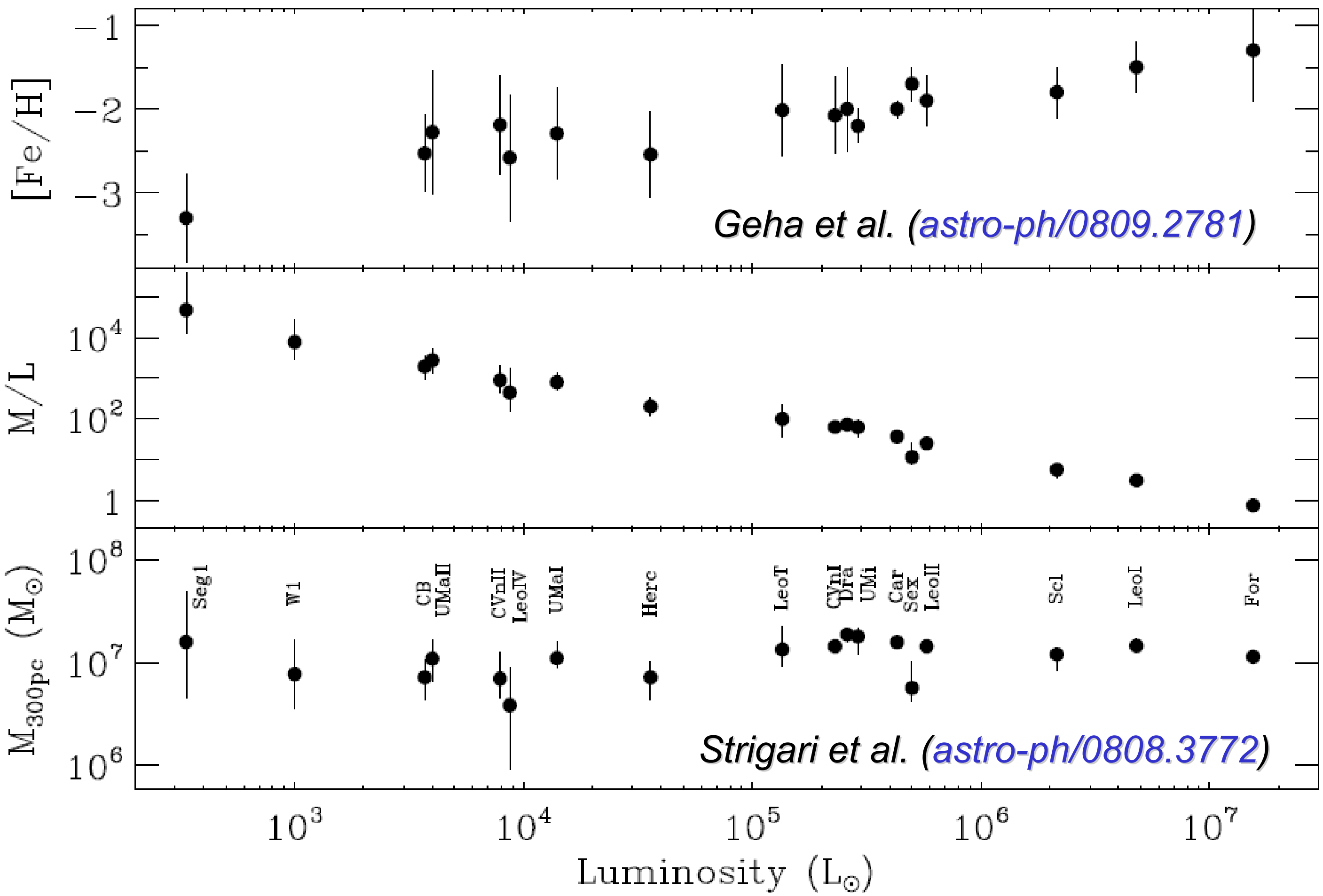
Luminous dwarfs are shown by the blue circles and were identified using semi-analytic galaxy formation model of Kravtsov, Gnedin & Klypin 2004, which contains two key ingredients:

- suppression of gas accretion into progenitor satellite halos due to the UV heating of intergalactic medium.

- inefficient star formation at low gas surface densities

Is this consistent with observations?

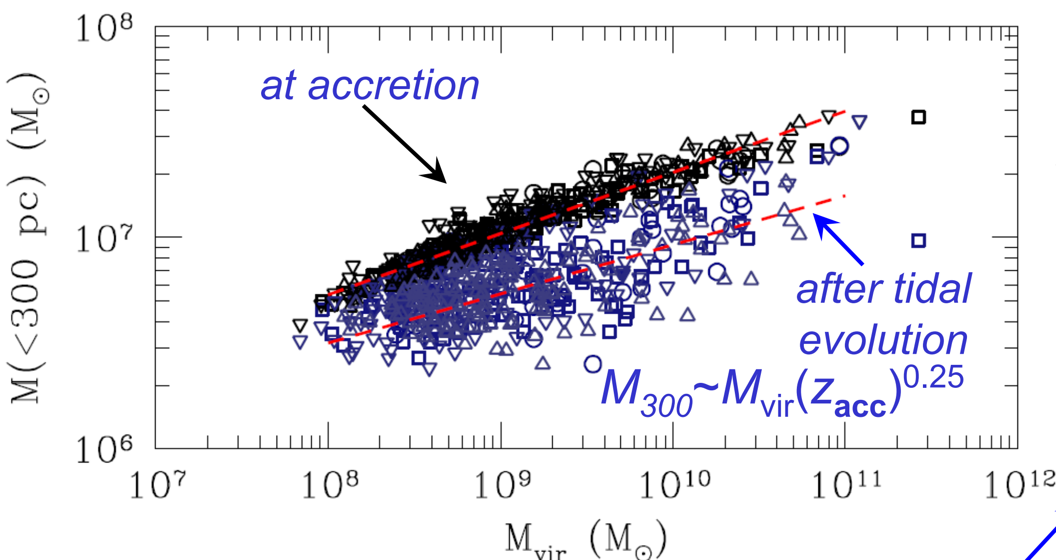
Observed Milky Way dwarf satellites exhibit variation of ~2 orders of mag in [Fe/H], >4 orders of mag in L but almost constant M(<300 pc)

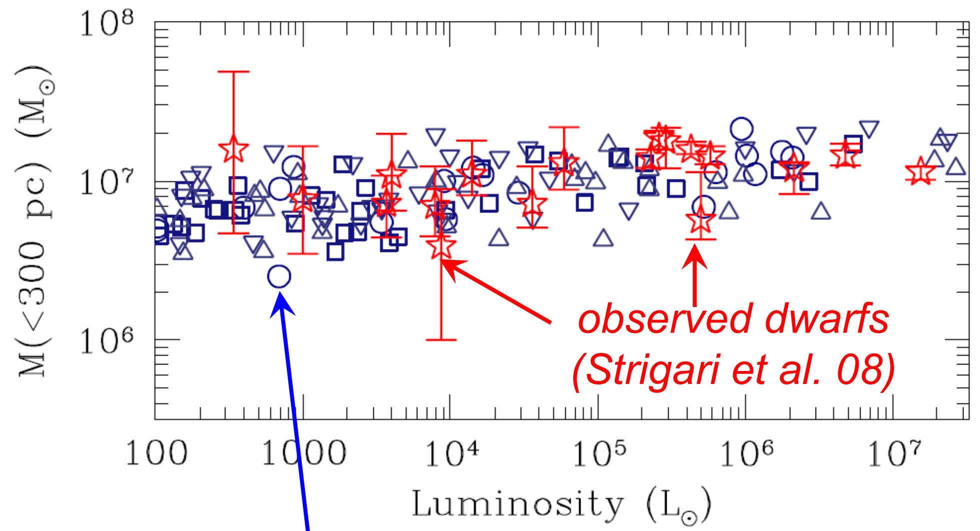


Does constant M(<300pc) imply similar halo masses for the dwarfs?

Not necessarily (and most likely not)…

M(<300pc) for subhalos at z=0 in simulations is a weak function of the virial mass Mvir of their progenitor halo





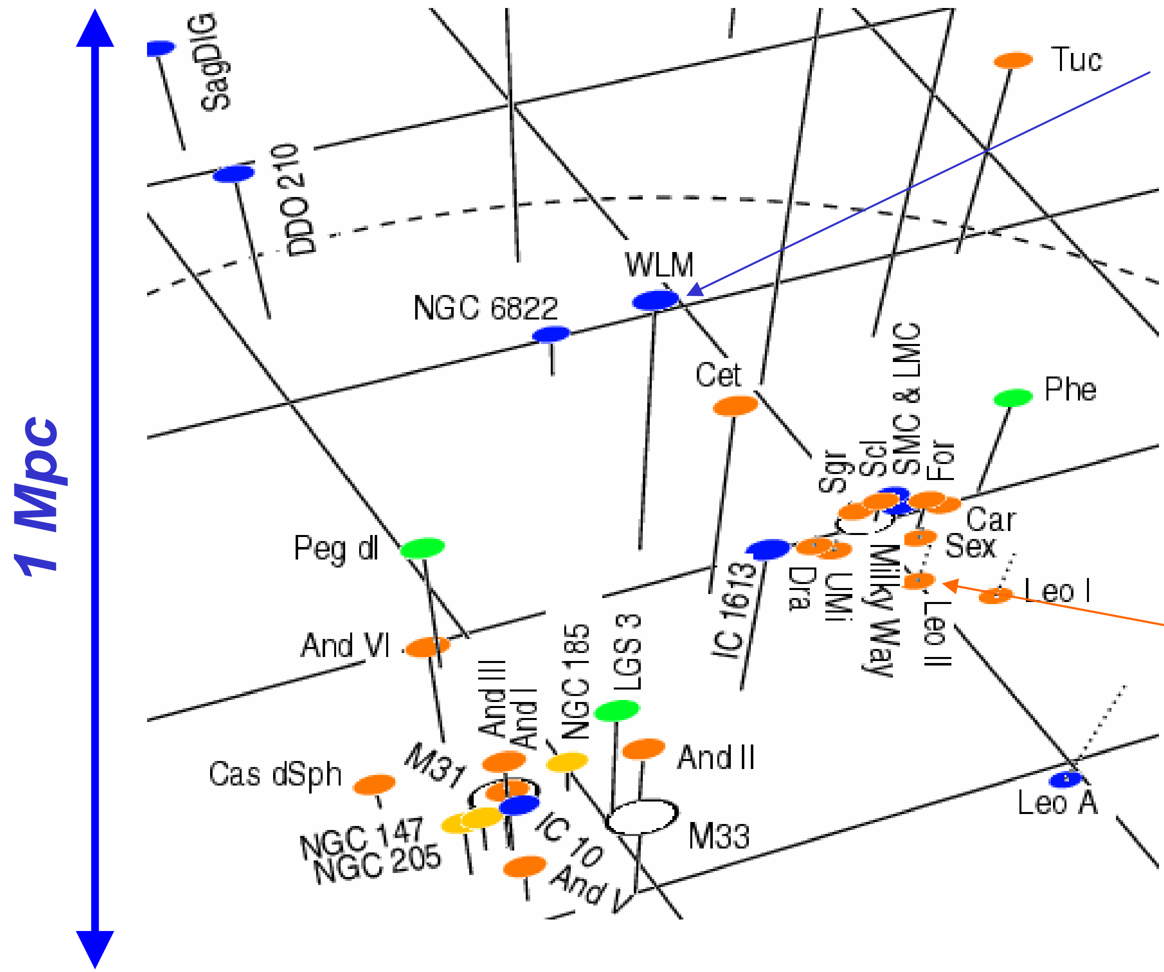
If dependence of luminosity on virial mass is $L \sim M_{vir}(z_{acc})^{3\text{-}4}$ (it can be shallower if the relation evolves with z), the observed flatness of the M(<300pc)-L relation is consistent with progenitor masses varying by a factor of ~20-50 or more

such dependence is what is approximately what is needed to explain difference in slope between faint end field LF and predicted halo mass function and comes out of simulations of dwarfs (e.g. Ricotti & Gnedin '05), so there is nothing crazy about it…

similar arguments along these lines: Helmi et al. 09; Maccio et al. 09

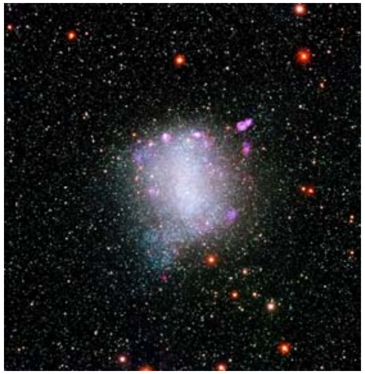
Environment of dwarf galaxies does seem to determine their morphology and gas content

(morphology segregation in the Local Group: dwarf spheroidals tend to be near MW and Andromeda, dIrrs – tend to be found far from them)

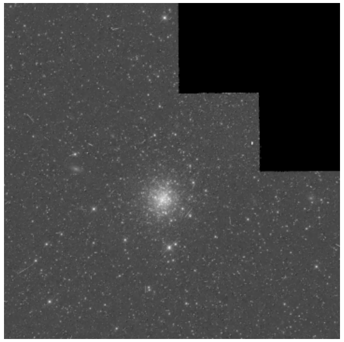


The Local Group

blue = dwarf irregular galaxies (dIrrs)

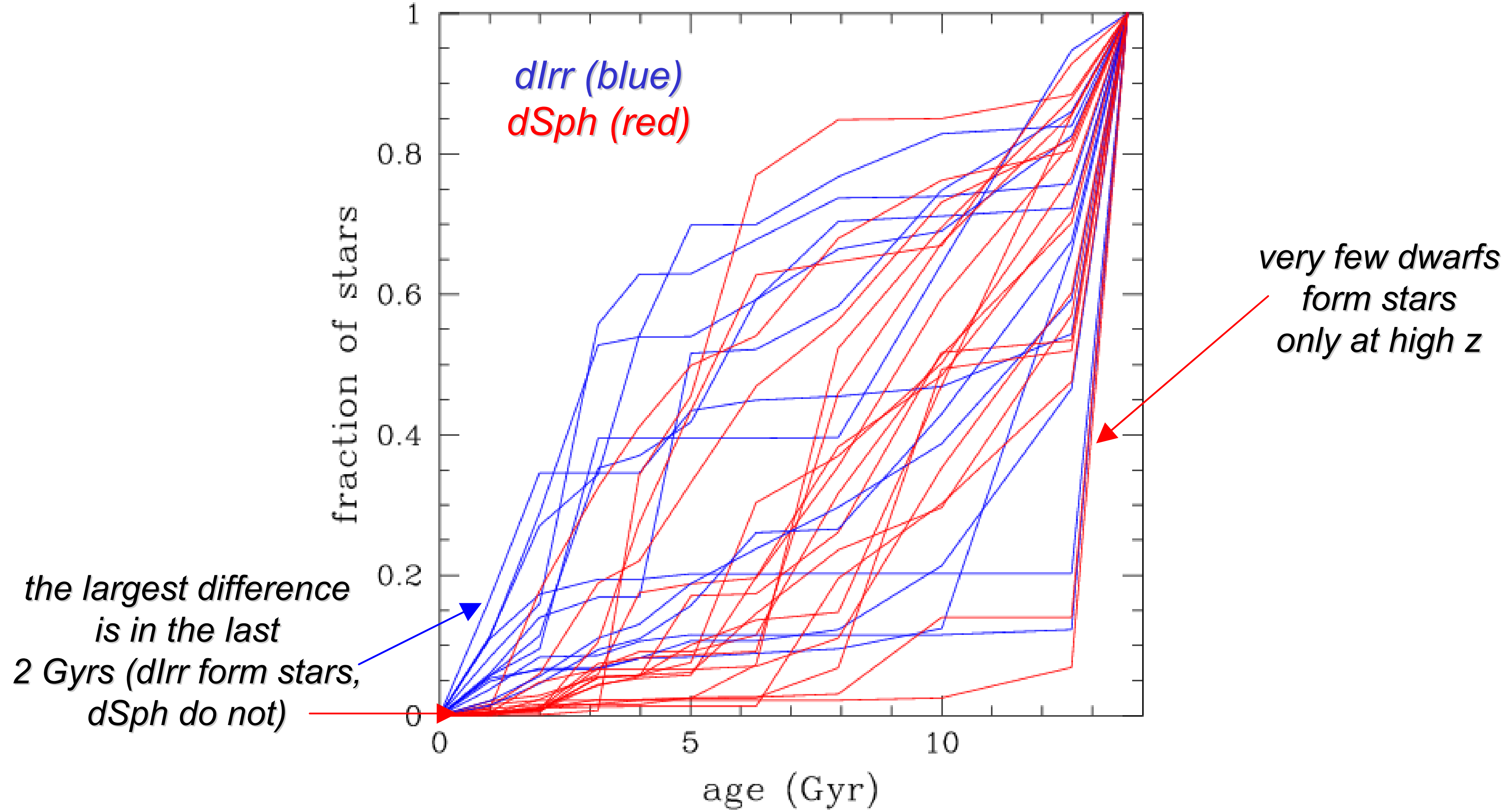


orange = dwarf spheroidal galaxies



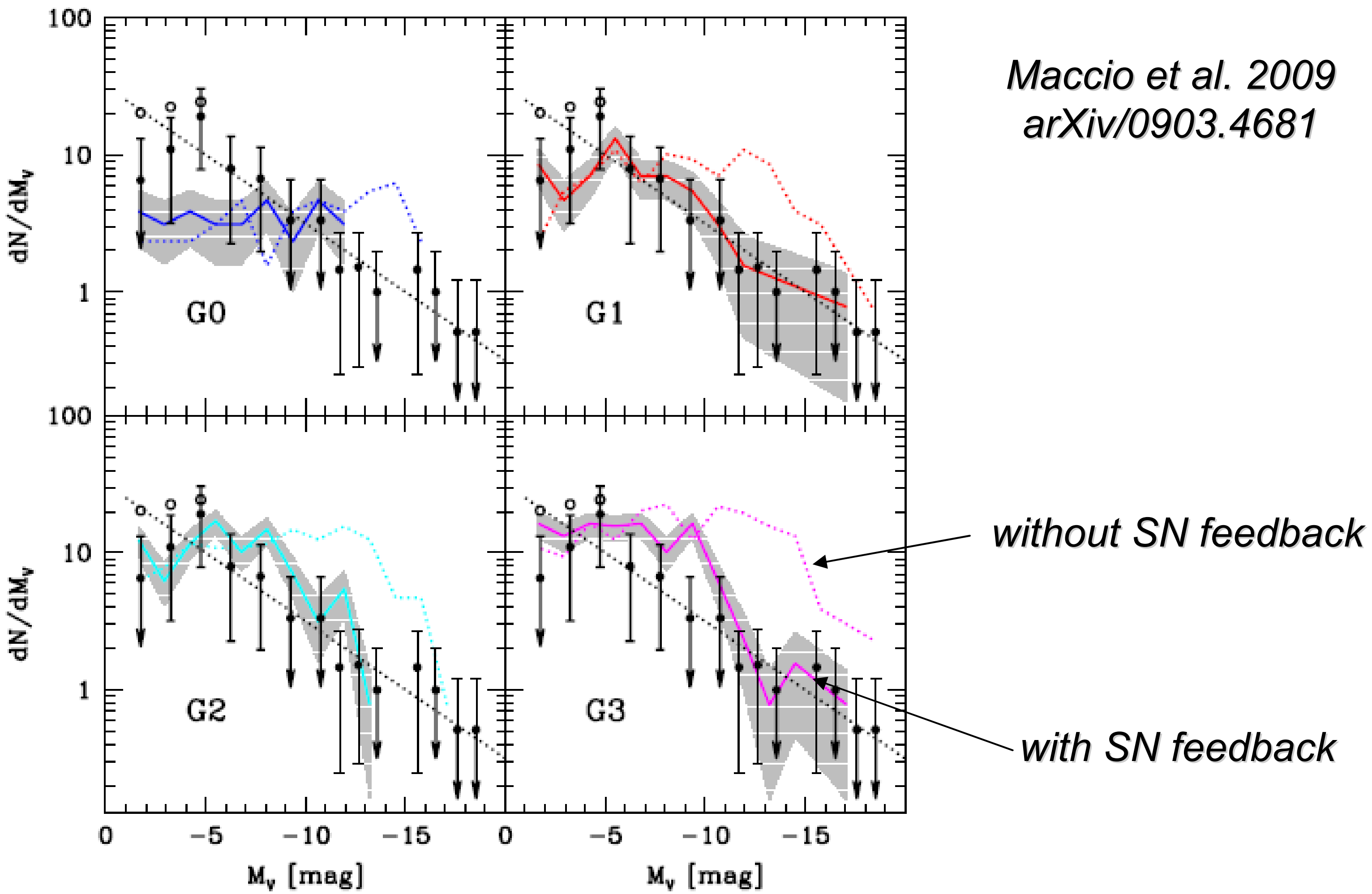
star formation history, however, is at best weakly dependent on environment

Orban et al. 2008 (astro-ph/0805.1058)
based on HST observations of Dolphin et al. 2005; Holtzman et al. 2006



The key to understand faintness of dwarf galaxies and their high M/L ratios is in their internal processes

[such as UV heating, star formation, supernova feedback…]

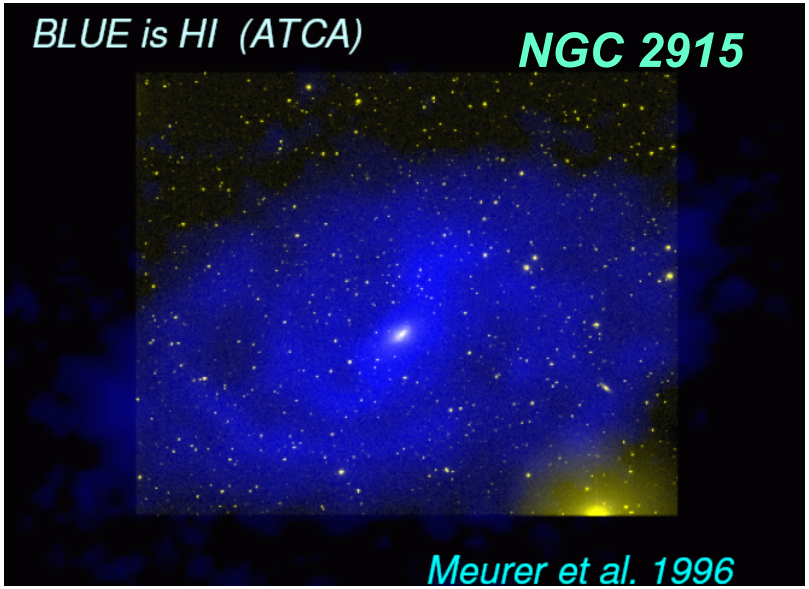


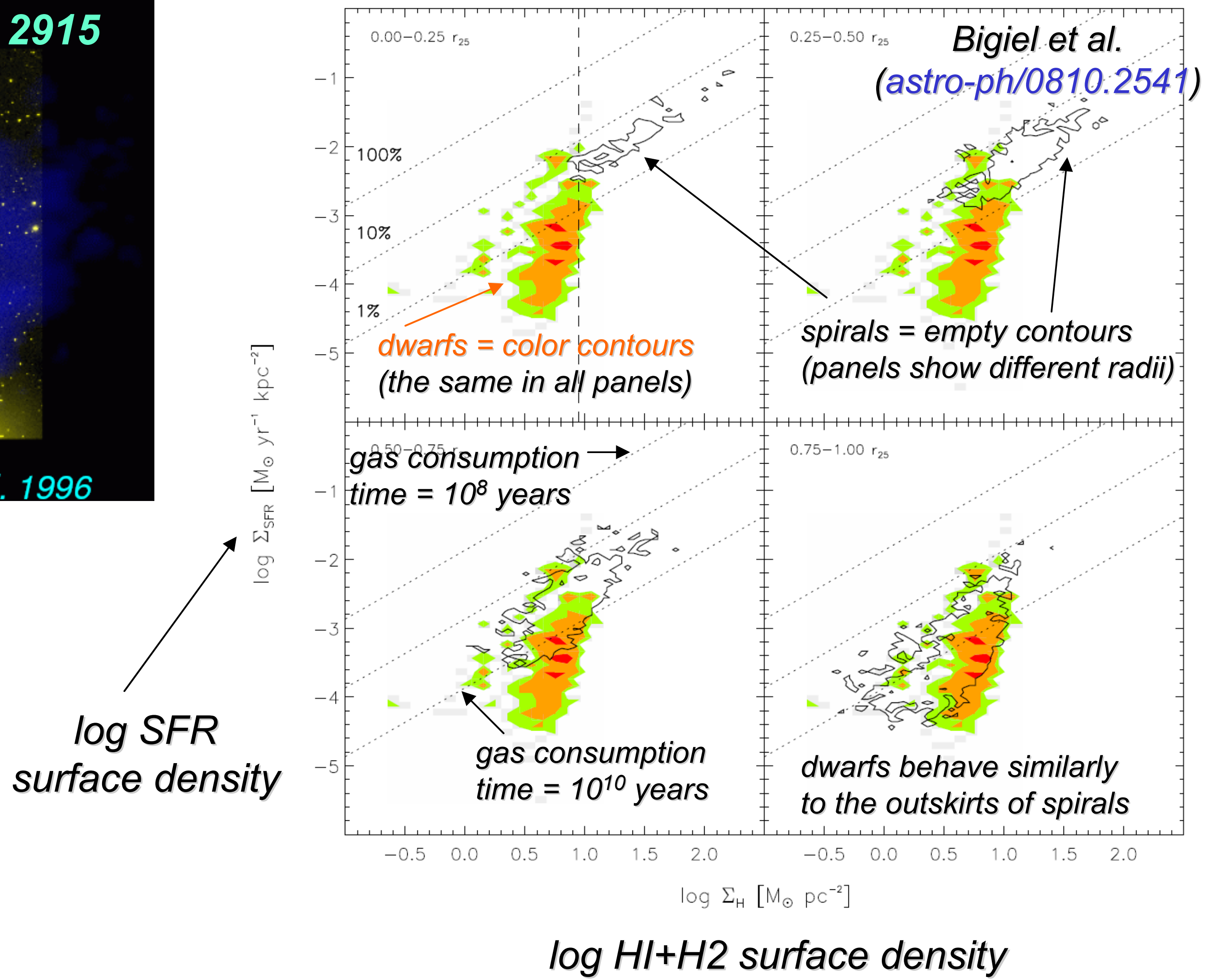
Maccio et al. 2009
arXiv/0903.4681

I will focus on

Inefficiency of star formation in dwarfs

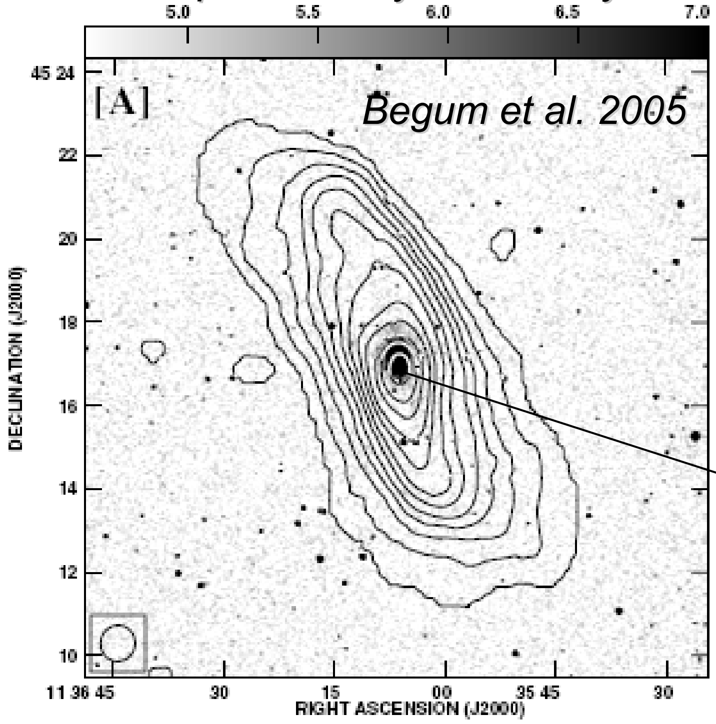
at low surface densities (dwarfs, LSBs, outskirts of large spirals) galaxies are inefficient in converting "cold" HI gas into stars



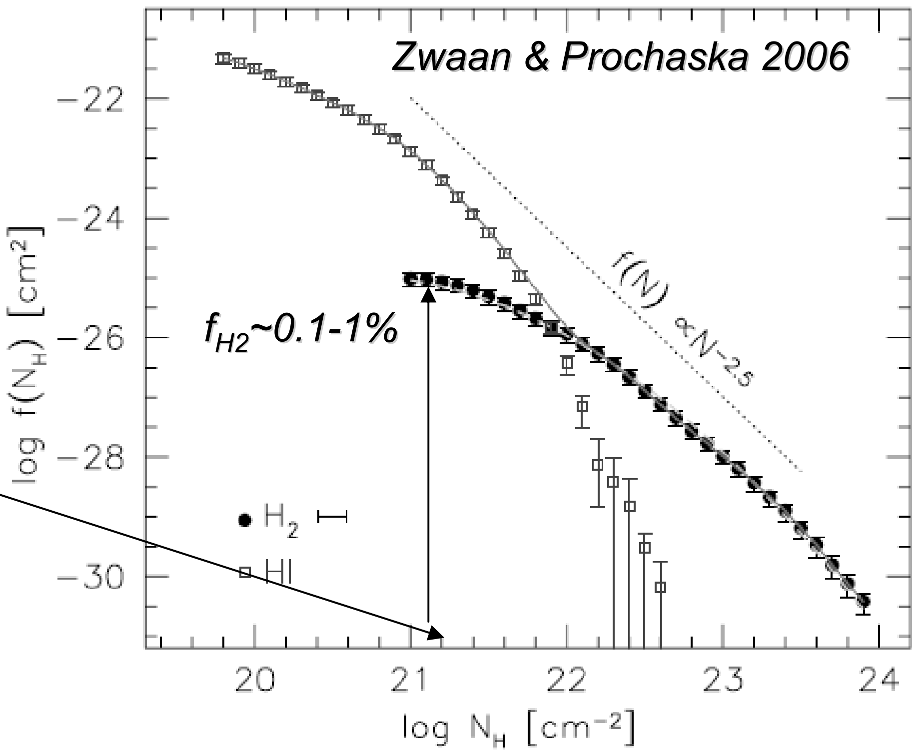


Observed dwarfs have low surface gas densities, low molecular fractions, and correspondingly low rate, centrally-concentrated star formation

a dwarf galaxy NGC 3741 (Vmax=45 km/s)
with HI disk extending to ~40 optical
disk scale lengths
but H2 is expected only in the very center



distribution of HI and H2 column densities
in nearby galaxies



possible cause of inefficiency is inability of galaxies to form molecular gas efficiently at low gas surface densities

Robertson & Kravtsov, 2008 ApJ (*astro-ph/0710.2102*)
Tassis, Gnedin & Kravtsov 2009, ApJ (*astro-ph/0810.4148*)

$$f_{H2} = f_{H2}\left(\rho_g, T, Z_g, U_{isrf}\right)$$

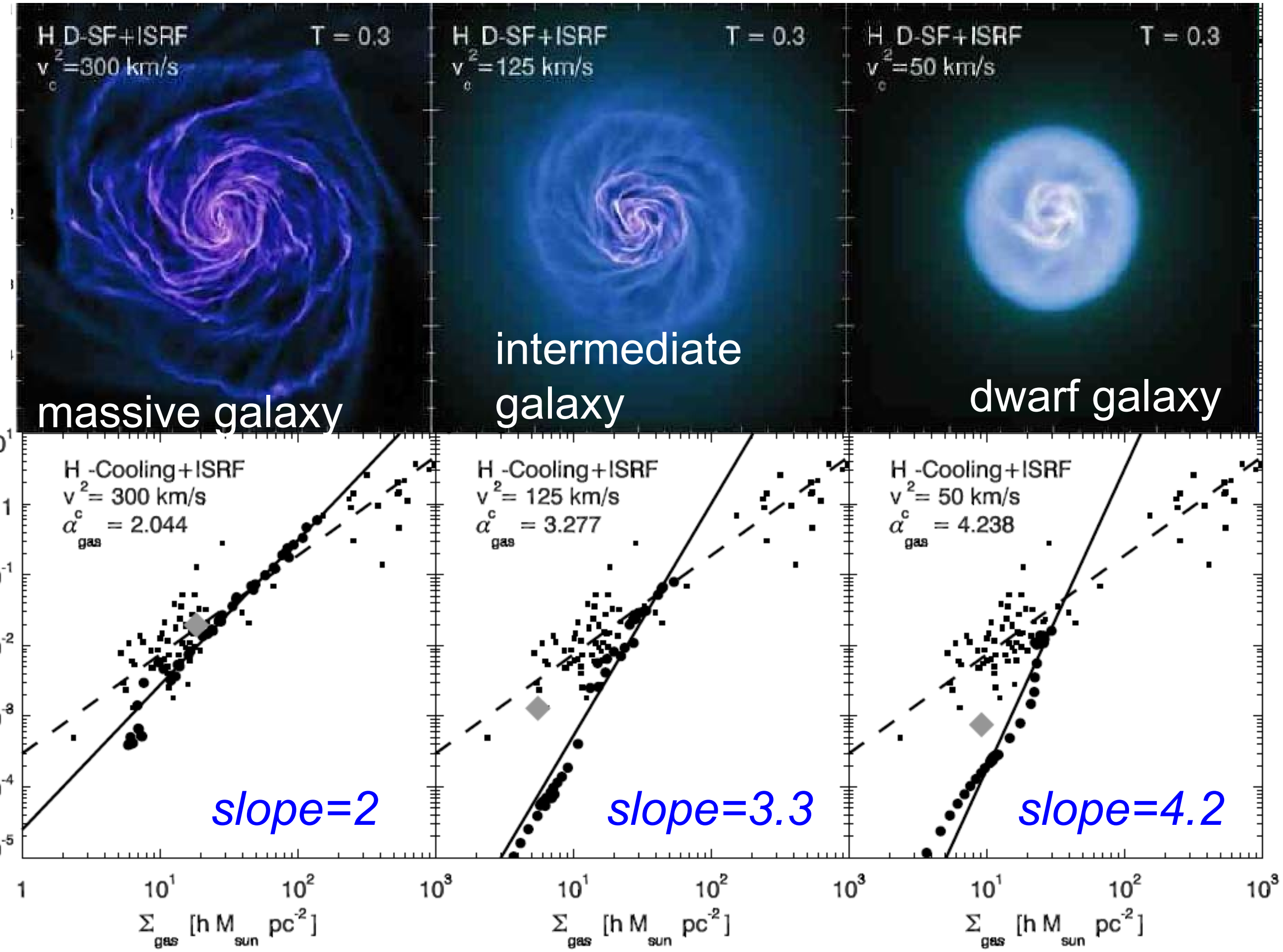
tabulated using Cloudy code

$$\dot{\rho}_\star = f_{H2}\frac{\rho_g^{1.5}}{t_\star}$$

$$\Sigma_{SFR} \propto \langle f_{\mathbf{H2}} \rangle \frac{h_{SFR}}{h_g^{1.5}}\Sigma_g^{1.5}$$

low f_{H2} can make SF inefficient at small Σ_g and metallicities

gas surface density (colored by T)

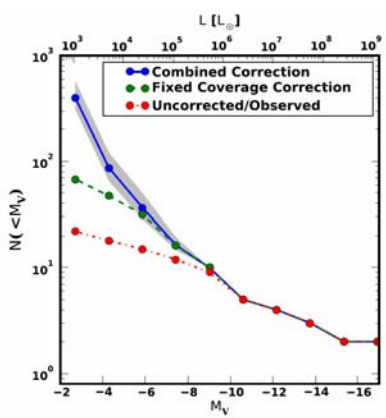


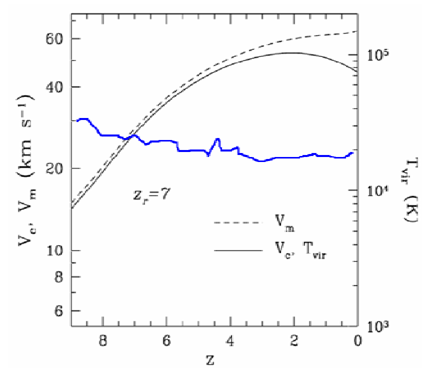
SFR surface density

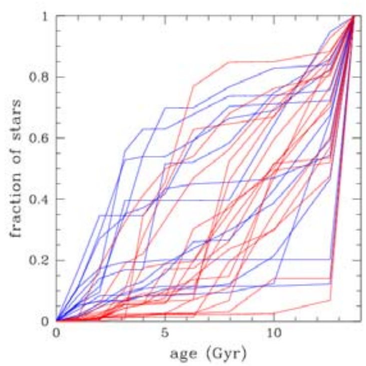
total gas surface density

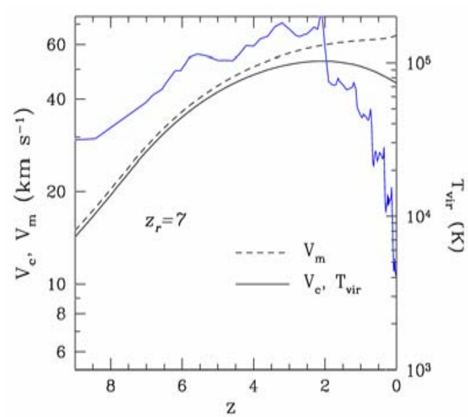
Summary

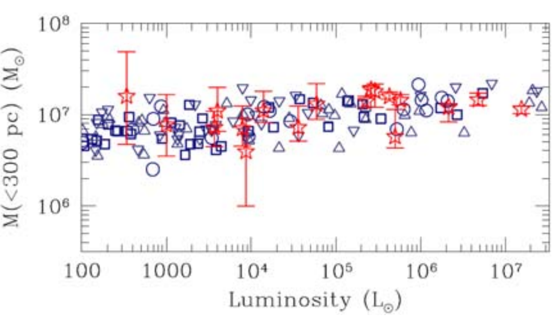
The substructure problem is likely explained by inefficiency of star formation in small-mass halos (no indications yet that CDM has a problem here)











Luminous satellite dwarfs form in small-mass DM halos if

- Halos form before reionization and do not evolve significantly afterwards (*"fossils"*)

- Halos become sufficiently massive and stay above cutoff mass after reionization (most satellite halos do)

These halos can subsequently lose most of their DM halo (but may be not stars) due to tidal stripping, so that the current dynamical mass of their host halo can be small.

- Low efficiency of SF, related to difficulty in forming molecular H2 in low density, low metallicity gas, can help explain extended and varied SF history of nearby dwarfs and their high M/L values