Characteristic Scales in Galaxy Formation

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Abstract. Recent data, e.g. from SDSS and 2dF, reveal a robust *bi-modality* in the distribution of galaxy properties, with a characteristic transition scale at stellar mass $M_* \sim 3 \times 10^{10} M_\odot$ (near L_*), corresponding to virial velocity $V \sim 100\,\mathrm{km\,s^{-1}}$. Smaller galaxies tend to be blue disks of young populations. They define a "fundamental line" of decreasing surface brightness, metallicity and velocity with decreasing M_*, which extends to the smallest dwarf galaxies. Galaxies above the critical scale are dominated by red spheroids of old populations, with roughly constant high surface brightens and metallicity, and they tend to host AGNs. A minimum in the virial M/L is obtained at the same magic scale. This bi-modality can be the combined imprint of several different physical processes. On smaller scales, disks are built by *cold flows*, and *supernova feedback* is effective in regulating star formation. On larger scales, the infalling gas is *heated by a virial shock* and star formation can be suppressed by *AGN feedback*. Another feedback mechanism – gas evaporation due to photo-ionization – may explain the existence of totally dark halos below $V \sim 30\,\mathrm{km\,s^{-1}}$. The standard cooling barriers are responsible for the loose upper and lower bounds for galaxies: $10 < V < 300\,\mathrm{km\,s^{-1}}$.

1 Introduction

Observations indicate four characteristic scales in the global properties of galaxies, expressed either in terms of virial velocity V, or stellar mass M_*:

- An upper limit at $V \sim \mathbf{300}\,\mathrm{km\,s^{-1}}$, which is the lower bound for clusters.
- A robust bi-modality scale at $M_* \simeq 3 \times 10^{10} M_\odot$ [15], corresponding to $V \sim \mathbf{100}\,\mathrm{km\,s^{-1}}$. This is comparable to L_* of the Schechter luminosity function, marking the exponential upper bound for disk galaxies. Smaller galaxies tend to be blue, star-forming disks with the surface brightness and metallicity decreasing with decreasing M_* (LSB). More massive galaxies are dominated by red, old-population spheroids with high surface brightness and metallicity insensitive to M_* (HSB) [15]. AGNs typically reside in halos above the bi-modality scale [16]. The halo M/L shows a minimum at the same scale [35].
- Dark-dark halos (DDH) with no luminous components seem to dominate the halo distribution below $V \sim \mathbf{30}\,\mathrm{km\,s^{-1}}$. The relatively flat faint-end luminosity function and the steeper mass function predicted by the standard ΛCDM cosmology cannot be reconciled with the virial theorem and the Tully-Fisher relation obeyed by the luminous galaxies (§5). Also, most dwarf spheroidals in the Local Group lie in this range, while dwarf irregulars are typically $V > 30\,\mathrm{km\,s^{-1}}$ [22] [32] [13] [9] [34].
- A lower bound at $V \sim \mathbf{10}\,\mathrm{km\,s^{-1}}$ for dwarf galaxies (see [9]).

We summarize here how *theory* predicts the following characteristic scales:

- A loose upper bound for cooling (by bremsstrahlung) on a dynamical time at $M \sim 10^{12-13} M_\odot$, corresponding to $V \sim 300\,\mathrm{km\,s^{-1}}$.
- A virial shock-heating scale at $M_* \sim 3\times 10^{10} M_\odot$, or $V \sim 100\,\mathrm{km\,s^{-1}}$. In less massive halos virial shocks cannot form and the gas flows cold into the disk vicinity (§2).
- A supernova-feedback scale at $V \sim 100\,\mathrm{km\,s^{-1}}$, below which the potential wells are shallow enough for the energy fed to the ISM by supernova to significantly heat the halo gas, or even blow it out (§3).
- A photo-ionization scale at $V \sim 30\,\mathrm{km\,s^{-1}}$. Once the gas is continuously ionized by the background UV flux, IGM gas cannot accrete into smaller halos and gas already in such halos evaporates via a steady thermal wind (§5).
- A lower bound for cooling (by atomic hydrogen) at $V \sim 10\,\mathrm{km\,s^{-1}}$.

We briefly address the origin of these scales, and try to associate them with the observed scales.

2 Shock-Heating Scale

The standard picture of disk formation is that after the dark halo virializes, the infalling gas is shock heated near the virial radius. It then cools radiatively and, if the cooling time is shorter than the dynamical time, the gas accretes onto a central disk and forms stars with the associated feedback. The upper-limit halo mass for efficient cooling is $M_{\rm cool} \sim 10^{12-13} M_\odot$ [27] [33]. The common wisdom used to be that this explains the upper bound for disk galaxies, but it has been realized that the predicted scale is somewhat higher than the observed scale.

Fig. 1 shows the time evolution of the radii of Lagrangian gas shells in a spherical system consisting of gas (with primordial composition) and dark matter, as simulated by Birnboim & Dekel [5] using a 1D hydro code. Not shown are the dark-matter shells, which collapse, oscillate and tend to increase the gravitational attraction exerted on the gas shells. The left panel focuses on massive halos of $\sim 10^{12} M_\odot$. Indeed, a shock exists near the virial radius at all times; it gradually propagates outward, encompassing more mass in time. The hot post-shock gas is in a quasi-static equilibrium, pressure supported against gravity. The right panel focuses on halo masses smaller by an order of magnitude. An interesting new phenomenon is seen here, where a stable shock forms and propagates from the disk toward the virial radius only after a mass of $\sim 10^{11} M_\odot$ has virialized. In less massive systems, the cooling rate is faster than the infall time, making the "post-shock" gas unstable against gravitational infall and thus not being able to support an extended shock.

This behavior can be understood via the following instability analysis of the gas just behind the shock [5]. The standard equation of state is written as $P = (\gamma-1)\rho\, e$ where ρ and e are the gas density and internal energy, and $\gamma = 5/3$ for a mono-atomic gas. In the no-cooling case, the adiabatic index is defined as

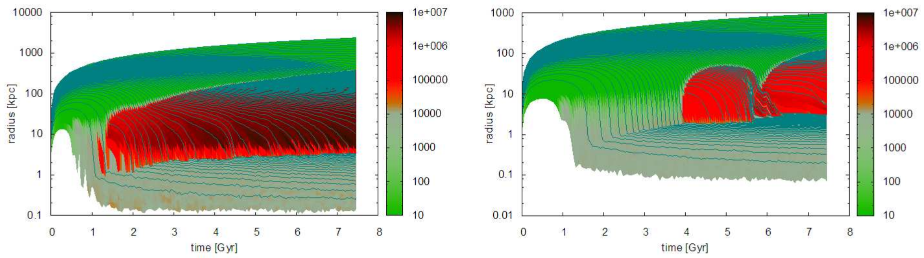

Fig. 1. Time evolution of the radii of Lagrangian gas shells (lines) in a spherical simulation of a protogalaxy consisting of primordial gas and dark matter. Temperature is marked by color. A shock shows up as a sharp break in the flow lines and as an abrupt change in temperature. The lower discontinuity marks the "disk" radius, formed due to an artificial centrifugal force. (**a**) A massive system, where the virialized masses are in the range $10^{11}-10^{13}M_{\odot}$. (**a**) A less massive system, $10^{10}-10^{12}M_{\odot}$. A virial shock exists only in systems more massive than $>10^{11}M_{\odot}$.

$\gamma \equiv (\partial \ln P/\partial \ln \rho)_{\rm ad}$, and the system is known to be gravitationally stable once $\gamma > 4/3$. When there is radiative cooling at a rate q, we define a new quantity:

$$\gamma_{\rm eff} \equiv \left(\frac{d\ln P}{d\ln \rho}\right) = \gamma - \frac{\rho}{\dot\rho}\frac{q}{e} = \gamma - \frac{t_{\rm dyn}}{t_{\rm cool}} \ . \tag{1}$$

The second equality follows from energy conservation, $\dot e = -P\dot V - q$, plugged into the equation of state. Note that $\gamma_{\rm eff} = \gamma$ when $q=0$, and that the difference between the two is nothing but the ratio of characteristic times $t_{\rm dyn}/t_{\rm cool}$, where $t_{\rm dyn} \equiv \rho/\dot\rho \simeq r_{\rm s}/u$, with $r_{\rm s}$ the shock radius and u the infall velocity into it. Using the jump conditions across the shock, one can express $\gamma_{\rm eff}$ in terms of the pre-shock gas quantities:

$$\gamma_{\rm eff} = \gamma - \frac{(\gamma+1)^4}{6(\gamma-1)^2}\frac{\rho r_{\rm s}\Lambda(T)}{|u^3|}, \quad T = \frac{\mu}{k_{\rm B}N_{\rm A}}\frac{2\gamma-1}{(\gamma+1)^2}u^2 \ , \tag{2}$$

where ρ is the pre-shock density.

In order to test for stability, we perturb a shell by $r \to r+\delta r$ and compute the sign of the restoring force: $\ddot{\delta r}/\delta r$. We assume a homologous infall $\delta r = u\delta t$ (supported by the finding in the simulations above), and balancing forces $\ddot r = -\rho^{-1}\nabla P - GM/r^3 = 0$. This leads to

$$\ddot{\delta r}/\delta r \propto \gamma - 4/3 - 2\gamma_{\rm eff}^{-1}(\gamma-\gamma_{\rm eff}) \ . \tag{3}$$

The system is stable when this expression is positive, namely for

$$\gamma_{\rm eff} > \gamma_{\rm crit} = \frac{2\gamma}{\gamma+2/3}, \quad \text{or} \quad \frac{t_{\rm cool}}{t_{\rm dyn}} > \frac{\gamma+2/3}{\gamma^2-4\gamma/3} \ . \tag{4}$$

For $\gamma = 5/3$, we get $\gamma_{\rm crit} = 10/7$ replacing the $\gamma_{\rm crit} = 4/3$ of the adiabatic case. The critical scale is then characterized by $t_{\rm cool}/t_{\rm dyn} = 21/5$ at the disk vicinity, which translates to $t_{\rm cool}/t_{\rm dyn} \simeq 1$ at the virial radius. Note that in our notation $t_{\rm dyn} \simeq R/V$ at the virial radius, while the dynamical time used in the order-of-magnitude arguments of [27] and [33] is several times larger.

When $\gamma_{\rm eff}$ is computed using eq. (2) just above the disk radius at every time of the spherical simulation, we find that the criterion of eq. (4) indeed works very well. Before the shock forms, it is well below $\gamma_{\rm crit}$ and gradually rising, reaching $\gamma_{\rm crit}$ almost exactly when the shock starts propagating outward. It then oscillates about $\gamma_{\rm crit}$ with a decreasing amplitude, following the oscillations in the shock radius seen in Fig. 1.

When put in a cosmological setting, we find that the critical halo mass for virial-shock heating is

$$M_{\rm shock} \simeq (1-6) \times 10^{11} M_{\odot} \, . \tag{5}$$

The higher estimate is obtained for near solar metallicity. This scale is comparable to the observed bi-modality scale, and is quite insensitive to redshift. To see this, we use the spherical-collapse virial relations at z: $M \propto (1+z)^{-3/2} V^3 \propto (1+z)^3 R^3$, and the general trend in the relevant range $\Lambda \propto T^{-1/2}$, to obtain $t_{\rm cool}/t_{\rm dyn} \propto M$ independent of z. Since at $z > 2$ most halos are of $M < M_{\rm shock}$, we conclude that in most forming disks the gas never heats to the virial temperature – it flows cold all the way to the disk vicinity.

Although we are back to a condition involving $t_{\rm cool}/t_{\rm dyn}$, which seems to remind us of the original criterion by Rees & Ostriker, it is now based on analyzing the actual physical process that could be responsible for the heating to the virial temperature, namely the existance of a virial shock. Because the dynamical time involved in the current analysis is smaller than the one used in the original estimate by a factor of a few, our derived upper bound for halo masses in which cold flows prevail is smaller by a similar factor.

Preliminary results from cosmological hydro simulations indicate that the phenomenon is not restricted to spherical systems, and that our stability criterion may in fact be approximately valid in the general case where the inflow is along filaments. Fig. 2 shows snapshots from Eulerian simulations by A. Kravtsov [19] [20], showing the gas temperature and flow fields in two protogalaxies: one of $M \simeq 3 \times 10^{11} M_{\odot}$ at $z \simeq 4$, and the other of $M \simeq 2 \times 10^{10} M_{\odot}$ at $z \simeq 9$. While the more massive galaxy shows a hot gas component at the virial temperature behind a virial shock, the smaller galaxy has mostly cold gas inside the virial radius. Also seen in the massive galaxy are cold streams penetrating the hot medium toward the central disk. Similar results have been obtained by Fradal et al. [11], who emphasis the feeding of galaxies by cold flows preferentially at early epochs, corresponding to less massive galaxies. We are in a process of testing our shock-stability criterion using cosmological simulations, and generalizing it to the realistic case of elongated streams.

Beyond introducing a new scale in galaxy formation, the cold streaming toward the disk, as opposed to the commonly assumed shock heating and slow accretion, may have several interesting implications. For example:

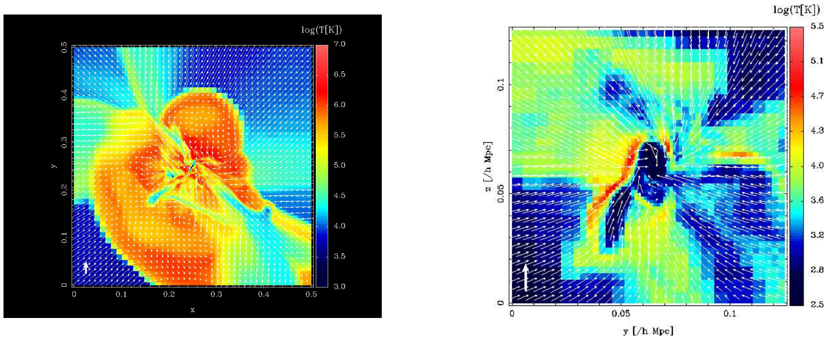

Fig. 2. Snapshots from cosmological hydro simulations (courtesy of Andrey Kravtsov), showing the gas temperature and flow fields in two protogalaxies. (**a**) A halo of $M \simeq 3 \times 10^{11} M_{\odot}$ at $z \simeq 4$, showing a virial shock and heated gas penetrated by cold streams. (**b**) A halo of $M \simeq 2 \times 10^{10} M_{\odot}$ at $z \simeq 9$, showing cold infall with little shock heating inside the virial radius of $\sim 7\,h^{-1}$kpc.

- It may modify the star formation rate and the associated supernova feedback. If the result of the cold stream hitting the disk is a burst of stars at high z, this may help the semi-analytic models (SAMs) explain better the presence of luminous red galaxies at $z \sim 1$. This process should be properly incorporated in the SAMs.
- It may reduce the soft X-ray flux from halos. This is consistent with observed individual galaxies [6], and may explain why the observed X-ray background is lower than the predictions based on shock heating in all halos [26].
- The cold gas may emit a significant fraction of its infall energy in Ly-α, either if the streams cool and merge into the rotating disk gradually without shocking [17], or after shocking at the disk vicinity. In the latter, the X-rays produced are likely to be captured inside a dense Strongrem sphere of a few kpc and the energy may eventually be released by Ly-α. This may explain the observed Ly-α emitters [21].

3 Supernova Feedback Scale

Supernova feedback, which is a very different physical process, gives rise to a characteristic scale in the same ballpark. The energy fed to the ISM by supernovae can be written as

$$E_{\rm SN} \simeq \nu\epsilon\dot{M}_* t_{\rm rad} \propto M_*(t_{\rm cool}/t_{\rm dyn}) \ , \qquad (6)$$

where ν is the number of supernovae per unit mass of forming stars, ϵ is the typical supernova energy, and $t_{\rm cool}$ is the time available for the supernova remnant to share its energy with the medium during its adiabatic phase, before a significant fraction of it is radiated away. The second proportionality follows from the crude assumption $\dot{M}_* \sim M_*/t_{\rm dyn}$. Dekel & Silk [8] pointed out that for halos in the relevant range, where the virial temperature is $T \sim 10^5$K, the cooling rate behaves roughly like $\Lambda \propto T^{-1}$, and then $t_{\rm cool}/t_{\rm dyn} \simeq 0.01$ for all galaxies. This means that, despite the significant radiative losses, the energy fed to the ISM is $E_{\rm SN} \propto M_*$. When this energy input is compared to the energy required for significantly heating the gas or blowing it out, $E_{\rm binding} \simeq M_{\rm gas} V^2$, one ends up with the critical scale for effective feedback,

$$V_{\rm SN} \simeq 100\,{\rm km\,s^{-1}}\,. \tag{7}$$

In shallower potential wells, the feedback from a burst of stars can significantly suppress further star formation, and produce low-surface-brightness (LSB) and dwarf galaxies. We note that $V_{\rm SN}$ corresponds to $M_* \simeq 3\times 10^{10} M_\odot$, comparable to the observed bi-modality scale.

Tight correlations between the properties of galaxies below $3\times 10^{10} M_\odot$ define a "*fundamental line*" (FL) which stretches across five decades in luminosity down to the smallest dwarfs. The mean scaling relations, involving M_*, V, the metallicity Z and the surface brightness μ, are approximately [15] [9] [34] [31]

$$V \propto M_*^{0.2}, \quad Z \propto M_*^{0.4}, \quad \mu \propto M_*^{0.6}\ . \tag{8}$$

Note that the familiar Tully-Fisher relation at the bright end, $V \propto M_*^{0.3}$ [7], seems to flatten in the dwarf regime. Supernova feedback can explain the origin of the FL in simple terms [9]. The above energy criterion, $E_{\rm SN} \propto M_* \propto M_{\rm gas} V^2$, with the assumption that the relevant gas mass is a constant fraction of the halo mass, $M_{\rm gas} \propto M$, immediately implies the relation driving the FL:

$$M_*/M \propto V^2\ . \tag{9}$$

Assuming spherical collapse to virial equilibrium, the halo virial quantities are related via, $M \propto V^3 \propto R^3$. In the instantaneous recycling approximation, we approximate $Z \propto M_*/M_{\rm gas}$. For the stellar radius we adopt the standard assumption of angular-momentum conservation [10] [24], $R_* \propto \lambda R$, with λ a constant spin parameter, and use it in $\mu \propto M_*/R_*^2$. Combining the relations from eq. (9) and on, we recover the scaling relations, eq. (8). This success of this simplest possible toy model indicates that supernova feedback could indeed be the primary driver of the FL below the bi-modality scale, and it strengths the association of this process with the origin of the transition scale itself.

4 The Origin of Bi-Modality

In Fig. 3, we schematically put together the physical scales discussed so far in the classic density-temperature diagram. Galaxies are loosely confined to the region where $t_{\rm cool} < t_{\rm ff}$. The line $M_{*,\rm shock} \sim 3\times 10^{10} M_\odot$ distinguishes between massive galaxies which suffer virial shock heating and lower mass galaxies where the gas flows cold toward the disk. The line $V \sim 100\,{\rm km\,s^{-1}}$ marks the transition from deep potential wells where HSBs form to shallow potential wells where supernova feedback is effective and leads to LSBs and dwarfs along the FL.

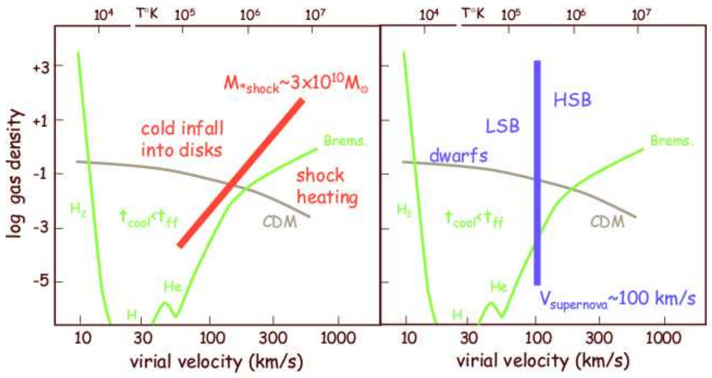

Fig. 3. the characteristic scales in the classic diagram of gas density versus virial velocity. The horizontal (gray) curve marks 2-σ halos in ΛCDM. The V-shaped (green) curve refers to $t_{\rm cool} = t_{\rm dyn}$; galaxies can form only above this line. (**a**) The shock-heating scale. (**b**) The supernova feedback scale. The two scales are comparable, at $V \sim 100\,{\rm km\,s^{-1}}$ or $M_* \sim 3\times10^{10}M_\odot$.

The two different physical processes happen to yield a similar characteristic scale, and they thus combine to produce the bi-modality. A possible scenario is as follows:

- Halos below $M_{\rm shock}$ had cold infall to disks, possibly associated with bursts of star formation. Galaxies above this threshold are built from progenitors that were below the threshold at high z and thus formed early disks, which later merged to spheroids of red, old stars. Any halo gas in such massive halos consists of a hot medium and possibly cold streams.
- In halos below $V_{\rm SN}$, the SN feedback regulates the star-formation rate, which leads to blue, young stars and the FL, $M_*/M \propto V^2$, with M/L rising toward smaller halos. The SN feedback may also suppress any AGN activity in these halos.
- In more massive halos, the gas, which has been heated by virial shocks, may be prevented from cooling by AGN feedback, causing M/L to rise toward larger halos in proportion to the total-to-cold gas ratio. There seems to be enough energy in AGNs, though the actual feedback mechanism is not properly understood yet.
- Protogalaxies below $M_{\rm shock}$ may be seen as Ly-α emitters rather then as X-ray sources, while the hot gas in more massive halos still produces X-rays.

5 Photo-evaporation Scale

Some of the halos below $V \sim 30\,{\rm km\,s^{-1}}$ must be *totally dark*, with no luminous component. Marginal evidence is starting to emerge from the statistics of image multiplicities in gravitational lenses [18], and independently from the following comparison between theory and the observed frequency of dwarf galaxies. While the faint-end galaxy luminosity function is roughly $\phi(L) \propto L^{-1}$ (or steeper), the halo mass function predicted in ΛCDM is roughly $\psi(M) \propto M^{-2}$ (or flatter). These cannot be reconciled with the virial relation $M \propto V^3$ and the Tully-Fisher relation in the dwarf regime, $L \propto V^5$ (or flatter). If, however, only a fraction $f_{\rm L}(V)$ of the small halos have a luminous component (with $L/M \propto V^2$ as discussed above), then the observations can be reconciled once $f_{\rm L} \propto V^2$. Thus, if the dark-dark halos appear at $V \sim 30\,{\rm km\,s^{-1}}$, we expect $\sim 90\%$ of the halos to be totally dark at the faint end, $V \sim 10\,{\rm km\,s^{-1}}$.

Supernova outflows alone are not likely to produce DDHs, both because they must leave a trace of stars behind, and because they tend not to be equally effective in all directions [23]. Ram pressure due to outflows from nearby galaxies may remove gas in some cases [28], but probably not enough for the purpose. On the other hand, the origin of DDHs could be explained by *radiative feedback*. The first stars and AGNs produce UV flux which ionizes most of the gas in the universe by $z_{\rm ion} \sim 10$, and keeps it at $T \sim (1-2) \times 10^4$K until $z_{\rm end} \sim 2$ or so [2]. Further infall of gas is suppressed in halos below the Jeans scale, which is crudely estimated to be about $V \sim 30\,{\rm km\,s^{-1}}$ [12], but this does not explain the complete removal of the gas already residing in those halos. A significant fraction of $T \simeq 10^4$K gas is expected to escape instantaneously from halos of a correspondingly shallower potential, $V < 10\,{\rm km\,s^{-1}}$ [1], but not from halos of $10 < V < 30\,{\rm km\,s^{-1}}$.

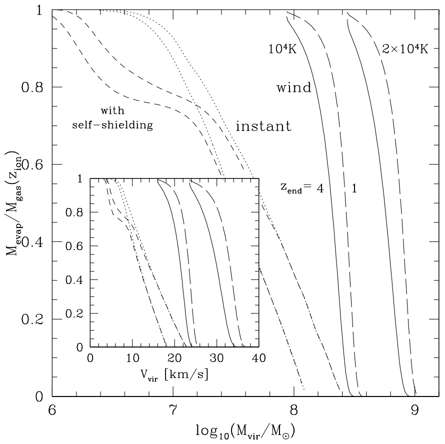

Fig. 4. The evaporated mass fraction as a function of virial mass and velocity (insert). The curves on the left correspond to instantaneous expulsion, and the curves on the right refer to steady evaporation, where the ionization is assumed to be efficient from $z = 8$ till either $z = 4$ (solid) or $z = 1$ (dashed). The gas temperature is either 10^4K (left) or 2×10^4K (right). While half the gas is lost instantaneously from $V \sim 10\,{\rm km\,s^{-1}}$ halos, a steady wind can remove a similar fraction of the gas from $V \sim 30\,{\rm km\,s^{-1}}$ halos.

However, if a continuous input of energy keeps the gas ionized for many dynamical times, it can evaporate via a *steady thermal wind* even from deeper potential wells. Once the gas is lost from the shallow edge of the potential well, it is continuously replenished by interior gas, and so on. In Shaviv & Dekel [29] we analyzed this process following the classic solar-wind analysis [25], and found that a significant fraction of the gas eventually evaporates from halos as large as $V \sim 30\,\mathrm{km\,s^{-1}}$. Fig. 4 summarizes the results of this analysis.

Thus, halos in the range $10 < V < 30\,\mathrm{km\,s^{-1}}$ lose most of their gas after the cosmological reionization. They may end up as gas-poor dwarf spheroidals with an old stellar population [9] [29], or as DDHs (see also [30]).

Halos of $V < 10\,\mathrm{km\,s^{-1}}$ are not expected to form stars at all because of the cooling barrier at $T \sim 10^4$K (Fig. 3). Atomic line cooling is very efficient just above this temperature, but the only cooling agent below 10^4K is molecular hydrogen, which cannot survive the UV background and is anyway very inefficient [14].

6 Conclusion

The following table summarizes the characteristic scales originating from the physical processes discussed above and their possible association with the observed scales. The classic argument of cooling on a vaguely-defined dynamical time provides relatively loose upper and lower bounds for luminous galaxies. The combination of (a) the newly discovered scale distinguishing between virial shock heating and cold flows and (b) the familiar supernova feedback scale seems to produce the robust bi-modality imprinted on the observed galaxy properties, and in particular the characteristic upper limit for disk galaxies near L_*. This is provided that AGN feedback, or another process such as thermal conductivity, indeed prevents the shock-heated gas in massive halos from ever forming stars. The details of the proposed scenario are yet to be worked out (see also [3] [4]). While supernova feedback can be the primary process responsible for the "fundamental line" of LSB and dwarf galaxies, the radiative feedback due to cosmological reionization may be responsible for totally evacuating small halos from gas and producing dwarf spheroidals and dark-dark halos. Once these physical

Characteristic Scales

	V (km/s)	$M_*(M_\odot)$	$M(M_\odot)$	
Cooling (Brems.)	300	10^{12}	10^{13}	clusters
Shock heating	100	3×10^{10}	3×10^{11}	L_*, discs
Supernovae	100	3×10^{10}	3×10^{11}	LSB
Photoionization	30	10^8	3×10^9	dSph dark
Cooling (H)	10	5×10^5	5×10^7	

process are properly incorporated in semi-analytic models of galaxy formation, they may help solving the apparent conflicts between theory and observation.

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References

1. Barkana R., Loeb A., 1999, ApJ, 523, 54
2. Barkana R., Loeb A., 2001, PhR, 3
3. Benson A.J., Bower R.G., Frenk C.S., Lacey C.G., Baugh C.M., Cole S., ApJ, 599, 38
4. Binney J., 2004, MNRAS, astro-ph/0308172
5. Birnboim, Y., Dekel, A., 2003, MNRAS, 345, 349
6. Ciotti L., Pellegrini S., Renzini A., D'Ercole A., 1991 ApJ, 376, 380
7. Courteau, S., MacArthur, L.A., Dekel, A. et al., 2004, astro-ph/0310440
8. Dekel, A., Silk, J., 1986, ApJ, 303, 39.
9. Dekel, A., Woo, J., 2003, MNRAS, 344, 1131
10. Fall M., Efstathiou G., 1980, MNRAS, xxx
11. Fardal, M.A., Katz, N., Gardner, J.P., Hernquist, L., Weinberg, D.H., Dave, R., 2001, ApJ, 562, 605
12. Gnedin N.Y., 2000, ApJ, 542, 535
13. Grebel E.K., Gallagher J.S., Harbeck D., 2003, AJ, 125, 1926
14. Haiman Z., Rees M.J., Loeb A., 1996, ApJ, 467, 522
15. Kauffmann et al. 2003, MNRAS, 341, 54
16. Kauffmann et al. 2004, in preparation
17. Keres D., Dave R., Katz, N., Weinberg, D.H. et al., 2004, in preparation
18. Cohn J.D., Kochanek C.S., 2004, astro-ph/0306171
19. Kravtsov A.V., 2003, ApJL, 590, L1
20. Kravtsov A.V., Gnedin, O.Y., 2003, ApJ submitted (astro-ph/0305199)
21. Manning C., Stern D., Spinrad H., Bunker A.J., 2000, ApJ 537, 65
22. Mateo M., 1998, ARA&A, 36, 435
23. Mac low M.M., Ferrara A., 1999, ApJ, 513, 142
24. Mo H.J., Mao S., White S.D.M., 1998, MNRAS, 295, 319
25. Parker E.N. 1960, ApJ, 132, 821
26. Pen U. L., 1999, ApJL 510, L1
27. Rees M.J., Ostriker J.P., 1977, MNRAS, 179, 541
28. Scannapieco E. Ferrara A., Broadhurst T., 2000, ApJL, 536, L11
29. Shaviv, N., Dekel, A., 2004, astro-ph/0305527
30. Somerville, R.S. 2002, ApJL, 572, L23
31. Tremonti et al. (SDSS), 2004, in preparation
32. van den Bergh S., 2000, The Galaxies of the Local Group (Cambridge University Press)
33. White, S.D.M., Rees, M.J., 1978, MNRAS, 183, 341.
34. Woo, J., Dekel, A., Courteau, S., 2004, in preparation
35. Yang X., Mo H.J., van den Bosch F.C., 2003, MNRAS, 339, 1057