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Scale Free Processes in Galaxy Formation

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Abstract. According to the ΛCDM paradigm of cosmology, galaxies form at the centers of dark matter (DM) halos. While galaxy formation involves complex baryonic physics, the formation of DM halos is governed solely by gravity and cosmology. As a result, many of their properties exhibit a near scale-free behaviour, self-similar in either halo mass, cosmic time or both. This is especially true in the Einstein-de Sitter (EdS) regime, valid at redshifts $z \gtrsim 1$, when cosmological scaling relations become particularly simple, and in the narrow mass range of normal galaxies, where the fluctuation power spectrum can be approximated by a power law. Since many galaxy properties are strongly correlated with halo mass, they tend to exhibit a self-similar behaviour as well. A partial list of self-similar properties include the mass function of DM halos, the structure of the cosmic web, the accretion/merger rate of matter onto halos, the density profiles of DM halos and their angular momentum, which eventually determines the galaxy structure. We briefly review these below, and comment on how they can be used in conjunction with simple toy models to gain insight into galaxy formation.

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EdS Cosmology: We consider standard, zero curvature ΛCDM cosmology in the EdS regime, where the cosmological constant is negligible. This is a useful approximation at $z \gtrsim 1$ and it becomes increasingly accurate at higher redshifts. In this regime, cosmological scaling relations become particularly simple, as do the virial relations of DM halos in the spherical collapse model (e.g. Dekel *et al.* 2013). The relation between the cosmological expansion factor a and the Hubble time t is $a = (1+z)^{-1} \simeq (t/17.5\mathrm{Gyr})^{2/3}$, the mean density in the Universe is $\rho_\mathrm{u} \simeq 2.5\times10^{-30}\,\mathrm{g\,cm^{-3}}a^{-3}$ and a DM halo is defined as a sphere about a density peak within which the average density is $\rho_\mathrm{v} \simeq 200\rho_\mathrm{u}$. Using virial equilibrium $V_\mathrm{v}^2 = GM_\mathrm{v}/R_\mathrm{v}$, one obtains the relations between the halo mass, radius and internal velocity: $M_{12} \simeq V_{200}^3 a_{1/3}^{3/2} \simeq R_{100}^3 a_{1/3}^{-3}$, where $M_{12} \equiv M_\mathrm{v}/10^{12}\,\mathrm{M_\odot}$, $V_{200} \equiv V_\mathrm{v}/200\,\mathrm{km\,s^{-1}}$, $R_{100} \equiv R_\mathrm{v}/100\,\mathrm{kpc}$ and $a_{1/3} \equiv 3a$. The virial crossing time is thus a constant fraction of the Hubble time, $t_\mathrm{v} = R_\mathrm{v}/V_\mathrm{v} \simeq 0.14t$, independent of halo mass or redshift.

Press-Schechter Halo Mass Function: Considering spherical halos, the "linear" density fluctuation at halo collapse, extrapolated from the initial fluctuation using the linear growth rate, is $\delta_\mathrm{c} \simeq 1.68$, independent of mass and time. The mass fraction within halos of mass $M > (4\pi/3)R^3\delta_\mathrm{c}\rho_\mathrm{u}(t)$ can be approximated by the probability for an overdensity $\delta(t)$, smoothed on a scale R, to be above δ_c (Press and Schechter 1974). This leads to the number density of DM halos $n(M) \propto (M/M_*)^{\alpha-2}\exp[-(M/M_*)^{2\alpha}]$, i.e. a power law at low masses with a steeper decline above a transition mass $M_*(z)$, representing the scale where 1σ fluctuations in the cosmic density field correspond to the critical overdensity δ_c. The parameter α depends on the power spectrum of linear fluctuations. If the power spectrum is a pure power-law, then α is constant and the halo mass function is exactly self-similar, having the same shape at all redshifts when the mass is properly scaled to

M_*. In practice, the large-scale structure (LSS) is nearly self-similar because the masses of normal galaxies are confined (by quenching processes) to a relatively narrow range, within which the ΛCDM power spectrum can be approximated by a power law, resulting in $\alpha \sim 0.14$. The galaxy mass function, scaled by its characteristic mass (Schechter 1976), has a shallower slope at the low-mass end and a steeper cutoff at the high-mass end, showing only small variations of shape with redshift (e.g. Song *et al.* 2015), despite the strong involvement of baryonic processes.

The Cosmic Web: The growth of non-spherical perturbations can be followed into the quasi-linear regime via the displacements of Lagrangian mass elements from their initial positions under the assumption of a potential flow, where velocities and accelerations are along the initial displacements (Zel'dovich 1970). Gravitational collapse occurs initially in one dimension, creating flattened "pancake" structures. Subsequent collapse along an orthogonal direction gives rise to "filaments", while the final collapse along the third dimension results in "knots". The axes along which collapse occurs are determined locally by the eigenvectors of the deformation tensor. This generic structure of knots within filaments within pancakes, themselves at the edges of "voids" that have been evacuated of matter, is known as the cosmic web (Bond *et al.* 1996). It has a fractal structure that appears the same at all scales and is nearly self similar in time. Galaxies that form within sub-M_* halos, located within individual filaments, have different properties than those that form within massive halos, situated at the nodes of several filaments (e.g. Dekel and Birnboim 2006).

The Accretion Rate Onto Halos: The variable $\omega \equiv \delta_c/a(t)$ is a self invariant time variable for structure formation (Press and Schechter 1974, Bond *et al.* 1991), such that the accretion rate $dM/d\omega$ must be a constant. With $a \propto t^{2/3}$ in the EdS regime, this translates to $\dot{M} \propto (1+z)^{5/2}$ for the total accretion rate onto DM halos, including mergers and smooth flows. The power spectrum of linear fluctuations introduces an additional weak mass dependence, resulting in a specific accretion rate (sAR) that is very well approximated by $\dot{M}/M \propto M^{0.14}(1+z)^{2.5}$ (Neistein and Dekel 2008). For most practical purposes, the mass dependence can be ignored, resulting in a scale-free mass evolution $M \propto \exp(-z)$ (Dekel *et al.* 2013). Assuming that the net baryonic accretion, corrected for outflows, is a fixed fraction of the total accretion, the sAR of baryons onto galaxies should obey the same expression. This prediction is confirmed in cosmological simulations of galaxy formation (e.g. Dekel *et al.* 2013). By assuming as well that the star-formation rate (SFR) in galaxies is proportional to the gas mass and that the outflow rate is proportional to the SFR, a "bathtub" toy model for galaxy formation naturally leads to a quasi-steady-state solution where the SFR follows the gas accretion rate and the gas mass is roughly constant in time (Dekel and Mandelker 2014 and references therein). Such models are very successful at reproducing key observed properties of galaxies.

Universal Density Profile of DM Halos: Observations of nearly flat rotation curves in galaxies together with Newtonian gravity lead to the conclusion that DM halos can be crudely approximated as singular isothermal spheres, with scale invariant density profiles $\rho(r) \propto r^{-2}$. Cosmological simulations indeed reveal that halos on all scales exhibit a universal density profile (NFW; Navarro, Frenk and White 1996). It is characterized by two parameters, e.g. the halo mass M_v and the concentration C, defined as the ratio of R_v to the scale radius where the power-law slope is -2. Halos that assembled earlier tend to have higher concentrations, making C a measure of the assembly time of the halo. At smaller radii the slope of the density profile approaches -1, and in the outer halo it increases toward -3. While there are several ideas concerning the origin of the exact shape of the NFW profile, there is no consensus yet. Furthermore, the effect of baryons on the profile when properly accounting for gas contraction and outflows, is also a non-trivial problem under investigation.

Angular Momentum of DM Halos: DM halos acquire their angular momentum (AM) through tidal interactions with the LSS (Peebles 1969, White 1984)). Most of this AM is acquired when the proto-halo is at its maximum expansion and its size is roughly $R_{\rm max} \simeq 2R_{\rm v}$, over a timescale of roughly $t_{\rm max} \sim t_{\rm v} = R_{\rm v}/V_{\rm v}$ (Porciani, Dekel and Hoffman 2002). The tidal forces induced by the LSS on the proto-halo scale as $F_{\rm tidal} \sim GM_{\rm v}(M_{\rm LSS}/R_{\rm LSS}^3)R_{\rm max}$. In the EdS regime, $M_{\rm LSS}/R_{\rm LSS}^3 \propto \rho_{\rm u} \propto \rho_{\rm v} \propto M_{\rm v}/R_{\rm v}^3$. The resulting AM acquired by the proto-halo is $J \sim t_{\rm max}F_{\rm tidal}R_{\rm max} \sim M_{\rm v}R_{\rm v}V_{\rm v}$. The spin parameter of DM halos, $\lambda \equiv J/(\sqrt{2}MVR)$, used to characterize their AM (Bullock *et al.* 2001), is thus predicted to be constant in the EdS regime, independent of both halo mass and redshift. Cosmological simulations confirm this prediction, and reveal a log-normal distribution for λ, centered at $\lambda \simeq 0.035 - 0.040$ (Bullock *et al.* 2001, Dekel *et al.* 2013). Assuming that the baryons conserve their AM as they cool and form disk galaxies, and approximating the halos as isothermal spheres where $M(r) \propto r$ and $V_{\rm circ} \propto M(r)/r \sim const$, the disk size is predicted to be a constant fraction of the virial radius, $R_{\rm d} \simeq \lambda R_{\rm v}$. As a result, the disk dynamical time is a constant fraction of the Hubble time, $t_{\rm d} \equiv R_{\rm d}/V_{\rm d} \simeq \lambda R_{\rm v}/V_{\rm v} = \lambda t_{\rm vir} \simeq 0.007t$. While the actual build up of AM in disk galaxies is more complicated and intimately linked to the cosmic web and to AM exchange by torques in the inner halo (e.g., Danovich *et al.* 2015), the end result is actually very similar to this simple picture, and maintains its scale-free nature.

Summary: Since the formation of DM halos depends only on gravity and cosmology, elegant self-similar and scale-free properties emerge in the EdS regime. While baryonic processes complicate matters, the strong correlations between galaxy properties and halo mass result in scale-free features in galaxy properties as well. Further insights into galaxy formation can be achieved via simple toy models combined with our understanding of the dark matter sector.

References

Bond, J. R., Cole, S., Efstathiou, G., & Kaiser, N. 1991, *ApJ*, 379, 440-460
Bond, J. R., Kofman, L., & Pogosyan, D. 1996, *Nature*, 380, 603-606
Bullock, J. S., Dekel, A., Kolatt, T. S., *et al.* 2001, *ApJ*, 555, 240-257
Danovich, M., Dekel, A., Hahn, O., *et al.* 2015, *MNRAS*, 449, 2087-2111
Dekel, A. & Birnboim, Y. 2006, *MNRAS*, 368, 2-20
Dekel, A., Zolotov, A., Tweed, D., *et al.* 2013, *MNRAS*, 435, 999-1019
Dekel, A. & Mandelker, N. 2014, *MNRAS*, 444, 2071-2084
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, *ApJ*, 462, 563-575
Neistein, E. & Dekel, A. 2008, *MNRAS*, 383, 615-626
Peebles, P. J. E. 1969 *ApJ*, 155, 393-401
Porciani, C., Dekel, A., & Hoffman, Y. 2002, *MNRAS*, 332, 325-338
Press, W. H. & Schechter, P. 1974, *ApJ*, 187, 425-438
Schechter, P. 1976 *ApJ*, 203, 297-306
Song, M., Finkelstein, S. L., Ashby, M. L. N., *et al.* 2015 ArXiv e-prints, 1507.05636
White, S. D. M. 1984 *ApJ*, 286, 38-41
Zel'dovich, Y. B. 1970 *AAp*, 5, 84-89