Moving Beyond Gravity: Feedback and Gas Hydrodynamics in ΛCDM Disk Galaxy Simulations.

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Abstract

Cosmological galaxy simulations have made great advances in the last decade, and hold promise in the next to greatly influence theoretical and observational studies of galaxy formation. Convergence of collisionless systems has shifted focus to gas hydrodynamics and implementing physical mechanisms beyond gravitational interaction. We discuss here the models for energetic feedback from stars, metal enrichment, as well as diffusion and cooling processes. Basic analysis on two cosmological runs, one with metal cooling and diffusion, and one without either, shows improvement in the distribution of metals, cold gas, and star formation. However, overcooling still plagues most simulations of this type and incorporation of additional physics is needed to further match observational constraints.

Introduction

Baryonic matter, which is able to interact with radiation was unable to form structure in the early universe do to very strong photon coupling. This coupling maintained a high enough velocity dispersion to prevent primordial density fluctuations from evolving structure. Meanwhile, dark matter was able to begin forming a cosmic web of overdense regions in the form of filaments and nodes (where the filaments intersected). As the universe cooled, it was these nodes that collected the baryons. Gas was able to rapidly fall into deeper potential wells since it could radiate away energy. As the densities grew higher, the first quasars and primordial stars formed and reionized the gas. Once again coupling the baryons to radiation and delayed the formation of structure. This is the so-called epoch of reionization.

Because dark matter dominates the matter fraction in the universe, and because highly overdense regions formed before baryons were able to coalesce, it was the dominant force in early structure formation. Thus, particles which interact purely gravitationally were a primary focus of early cosmological simulations. Gravitational dynamics for a non-interacting system is a well defined problem involving the collisionless Boltzmann equation coupled with the gravitational Poisson equation and a set of initial conditions.

$$\nabla^2\phi = 4\pi G\rho$$

$$\frac{df}{dt} + \vec{v}\cdot\vec{\nabla}_r f = \nabla\phi\frac{df}{dv}$$

where f is the distribution function (this describes the particle density in a unit of phase space). With many particles and a finite mass contrast, the system is generally chaotic and highly non-linear so it is not possible to calculate a complete set of analytic solutions. Simulations provide a laboratory in which numerical experiments can be performed to study gravitational collapse in an expanding universe. Integrating these equations accurately *and* efficiently is a non-trivial task. A variety of methods exist, each with their own pros and cons. Of late, tree codes incorporating fast multipole expansion methods have been popular. These approximate regions of long range particles as one pseudo-particle and compute a truncated multipole expansion for the force calculation. This algorithm is able to reduce the compute time scaling from $O(N^2)$, with direct summation of forces, to $O(N)$. Combined with advances in computing resources, the largest simulations run have reached particle counts of 10^{10}.

In 1999, the Santa Barbara Cluster Comparison Project (Frenk et al 1999) compared twelve codes of differing implementations. The result shows good agreement between all methods ($\lesssim 5\%$ residual from mean for the dark matter density profile). The conclusion of this paper is that the gravitational methods are effectively convergent.

After incorporating gas dynamics, the methods do not agree as well. The same cluster comparison project compared thermodynamic quantities and found that differing implementations yielded different results at smaller scales that are approaching the order of the resolution limits. This difference arises primarily from differing algorithms. Eulerian codes, mostly mesh codes, discretize space, while Lagrangian codes, such as smoothed particle hydrodynamics (SPH), discretize mass. The formulation used in these simulations was SPH and the particular implementation explicitly conserves entropy, one of the quantities in disagreement. At small scales, mesh codes naturally introduce artificial entropy so the results differ from SPH. Work has been done to introduce artificial viscosity in SPH codes which bring the two into closer alignment and attempt to inject entropy that occurs from mixing below the scale that the simulations can resolve. As a result, better convergence has been achieved between methods.

SPH is a natural choice when modeling systems with very high dynamic ranges. Density contrasts can be $\sim 10^{10}$ between dense galactic gas clouds and diffuse intergalactic medium. It works by smoothing the properties of a point particle over its neighboring space. By summing over all the contributing particles, you get the value of a quantity at that point. For a quantity q,

$$q_i = \sum_{j=1}^{N} q_j W(|\vec{r}_i - \vec{r}_j|, h_i, h_j)$$

where W is the weighting kernel, in this case a cubic spline interpolation, and h is the smoothing length of each particle. SPH inherently adapts to the resolution of the system at hand and thus is capable of handling a very large variation in system size. It also more realistically simulates gas as a continuous system that is modeled by point particles. The technique does have a caveat when modeling shocks or other highly discontinuous systems since it smooths out large velocity gradients. This is one of the reasons that artificial viscosity is added to the simulation. With reasonable agreement in gravitational dynamics and the methods to model gas dynamics, the challenge becomes incorporation of additional physical mechanisms to simulate real processes in galactic evolution.

A typical cosmological simulation might be a cube of ~100Mpc per side. A spiral galaxy has a visible diameter on the order of 50kpc. Thus the ratio of volumes of the simulation to the galactic scales is 10^{10}. To directly model galactic dynamics, a distance resolution of $\lesssim 0.1$pc would be required; an unreasonable goal for the current algorithms and computing resources. These simulations have a smoothing length of about 1kpc. Therefore, a star particle represents an entire distribution of hundreds of thousands of stars with a total mass on the order of $10^6 M_\odot$ and gas and dark matter particles represent substantial volumes of gas. If one particle represents an entire dynamical system, then methods of sub-grid physics must be developed which do not deal with individual events, but instead reproduce average behavior statistically. The specific subgrid models discussed in the follwing sections are those used in GASOLINE, the current simulation software developed at the University of Washington's N-Body shop (Wadsely et al 2004).

Star Formation

A stochastic model of star formation was introduced by Katz (1992). The first step is determining whether a gas particle is eligible for formation. This is based on three conditions. The first is that the region of interest must be overdense by a certain threshold, here $\rho/\bar{\rho} = 55$ where $\bar{\rho}$ is the mean density in the simulation. This ensures that the stars are not forming at early times when the mean density is high, but star formation should only be occurring in virialized structures. Second is a minimum density requirement such that the number density of gas particles is higher than 0.1 cm^{-3}. A region must have a critical local density above which it is assumed that regions inside the particle would initiate gravitational collapse and begin nuclear fusion. The third condition is a maximum temperature, T_{max}=30,000K. Gas above this temperature is unlikely to form stars, and the cooling rate below this temperature drops off quickly, thus the cooling timescale increases substantially. The dynamical timescale of the system, $\tau_{dyn} \sim \rho^{-1/2}$ then dictates the rate at which cloud collapse occurs.

Once these criteria are met, we need to stochastically choose which particles will actually form. Theoretical predictions propose that star formation density scales with gas density as a power law, $\rho_{sfr} \sim \rho_{gas}^{3/2}$ (Katz 1992). Based on this and the dynamical time $\tau_{dyn} = 1/\sqrt{4\pi G\rho}$, the rate at which stars form can be simply stated as,

$$\frac{d\rho_\star}{dt} = c^\star \frac{\rho_{gas}}{\tau_{form}}$$

where $\tau_{form} = \tau_{dyn}$ since the cooling timescale will be much larger and we have already required a maximum temperature. $c^\star$ is a formation efficiency parameter.

Temporal steps can be quite long, and this parameter allows for some adjustment of the formation rate since it may be decreased by interim feedback between timesteps. One can now assign a probability of formation to each star that meets the eligibility criteria.

$$P(\Delta t) = \frac{m_{gas}}{m_{star}}(1 - e^{-c^{\star}\Delta t/t_{form}})$$

The formulation used in these simulations chooses to have a constant fraction of the gas particle converted into stars. There is low sensitivity of the mean star formation rate, SFR, to the value of this parameter in the limit where $\Delta t/\tau_{form} \ll 1$. For more information see Stinson et al (2006).

The free parameter is then the star formation efficiency $c^{\star}$. The slope of the observed Kennicutt-Schmidt law, relating gas surface density to star formation rate, is naturally reproduced by this formulation. The normalization of the rate is dictated by the choice of $c^{\star}$ and therefore all of the free parameters of star formation are constrained by observations.

Feedback Mechanisms

Star formation without feedback is not only non-physical, but also results in star formation bursts that form stars at an unregulated rate until the gas supply is exhausted. This does not match observed star formation histories (SFH). As a result, it is necessary to also model negative feedback from stars back into the neighboring gas particles. This delays star formation after it begins by heating and expanding gas. This feedback also becomes important for enriching the surrounding gas with metals, and eventually forming new stars with higher metallicity. Since stars create almost all of the elements heavier than helium, it is clear from observations that this is a crucial mechanism.

The stars are born with an initial mass function, or IMF, based on a three power-law model of Kroupa 1993. This yields three scaling relations over the range $0.1M - 0.5M_{\odot}, 0.5 - 1M_{\odot}, and > 1M_{\odot}$. With these IMFs, it is possible to calculate stellar lifetimes as a function of metallicity. The number of stars at a given mass that will explode can be calculated by integrating the IMF over the range of stellar masses that are expected to die in a time $t - (t + \Delta t)$. Stars from 8-40$M_{\odot}$ explode as type II supernovae (SN). These feedback both energy and metals to the system.

Each type II SN radiates $\sim 10^{51}$ erg of containable energy (about 100 times less than is output in neutrinos), though the fraction of this that is actually captured by the host galaxy is not well known. A SN energy efficiency parameter, E_{SN}, is left as a free parameter that is observationally constrained most strongly by cold gas velocity dispersion measurements. The cooling rates in the simulation are large enough that if the energy were simply deposited into the neighbor particles, the energy would be radiated away before the gas had a chance to thermodynamically react (due to the temporal resolution of the simulation). Instead, cooling is temporarily shut-off for a certain number of neighboring gas particles, and then energy is deposited. The gas will then adiabatically expand providing naturally providing galactic winds without explicitly modeling them. This becomes particularly important when coupled with metal cooling and diffusion. The energy and metals are deposited based on the SPH smoothing formula, and the number of particles which have their cooling shut off is based on a mass-loading scheme. First the mass of stars going SN is multiplied by a parameter, β. A sphere is made around the exploding star particle which contains this mass in gas. All particles within this sphere have their cooling shutoff for a time determined by McKee & Ostriker 1977.

$$\beta M_{SNII} > \frac{4\pi(|r_i - r_s|)^3}{3}\bar{\rho}$$

where M_{SNII} is the mass of stars which exploded as SN II and $\bar{\rho}$ is the mean density determined by the SPH summation.

SN type Ia and stellar winds do not contribute to energy feedback, but instead only to metal enrichment. Type Ia SN explode at $1.4M_{\odot}$ after accreting from a binary companion. Based on the number of observed binary systems at various masses, it is estimated that these make up 10-20% of the total SN explosions, matching observations. All of the $1.4M_{\odot}$ ($0.63M_{\odot}$ iron, and $0.13M_{\odot}$ oxygen) is fed back to the neighbor particles based on the SPH smoothing.

Stellar winds contribute substantial fractions of the initial stellar mass back to the gas particles mostly from planetary nebulae. Only stars from 1-8$M_{\odot}$ are evolved in this way, below which the lifetimes are longer than the age of the universe, and above which explode as SNII. This mass feedback can lengthen star formation in regions without fresh cold gas inflow.

Metal enrichment from all three of these feedback mechanisms is crucial to stellar lifetimes, cooling rates, spectral signatures, and a host of other properties. Energetic feedback and the subsequent adiabatic expansion is important to not only heat and expand the gas, thus quenching star formation and clumpy cold gas clouds, but also to drive galactic winds that can enrich the surrounding otherwise primordial intergalactic medium.

Cooling and Metal Diffusion

Cooling provides a way for gas to quickly fall into deeper potential wells, both of the galaxy, and of compact regions such as cold gas clouds which then can begin forming stars. Accurately modeling these mechanisms is a challenge, but incorporating different cooling models can drastically change the nominal rates which have strong consequences for galactic evolution.

Primordial cooling is calculated based on the ionization fraction of hydrogen and helium and the temperature of the gas. Cooling without metals or molecular hydrogen is found to become very inefficient at temperatures below 10^4K. It also significantly underestimates the rate at almost all temperatures when metal line cooling is included and the medium is enriched. Additionally, UV background radiation ionizes the many of the metals which shifts the cooling peaks downward for temperatures below 10^5 and upward for temperatures above 10^5. This background radiation is approximated as uniform and isotropic, but evolving with time. It comes from the active galactic nuclei, AGN, and quasars. Since this evolves with time, the cooling rate does as well. The net cooling rate can be broken down as,

$$\Lambda = \Lambda_{H,He} + \Lambda_{metal} + \Lambda_{compton}$$

Where $\Lambda_{compton}$ are the Compton heating and cooling processes. Λ_{metal} is calculated by tabulating cooling rates at permutations of metallicity, redshift (for the UV), temperature, and density, and then interpolating as necessary during the simulation. Figure 1 shows the rates of the primordial case, and several other metallicities both with UV background radiation, and without. This increased cooling rate ultimately changes the dynamics of the forming galaxy. It also provides gas a mechanism to cool below 10^4K all the way down to 100K which was not possible with basic primordial cooling. It is clear that the inclusion of metals is important. Accurate distribution of the metals, and diffusion processes then must also play an important role.

The metal diffusion mechanism used in these simulations is based on a method developed for atmospheric models called the Smagorinsky subgrid turbulent diffusion model. This constructs a shear tensor based on the relative velocities of particles. This allows metals to diffuse in regions where turbulent mixing would be strong, namely outflows driven by galactic winds or merger situations. combined with supernova feedback, metals are able to distribute themselves much more homogeneously, in better agreement with observations. Figure 2 shows the effects of metal cooling and diffusion, hereafter MC&D. Plotted is a relative logarithmic colormap of mass weighted metal content of cold gas ($T < 20,000K$). The simulations have the same initial conditions, and the primary difference is that the right galaxy includes MC&D, while the left includes only primordial cooling. It is clear that the diffusion model dramatically redistributes metals to larger radii, in closer agreement with observation. The galactic cold gas fraction increased by 300% with MC&D. This seems to occur due to the higher cooling rates, and enrichment of the halo gasses with metals from supernova induced galactic winds. As the metals are injected into the hot gas, it then cools more rapidly and falls into the galactic disk, feeding primordial gasses to star forming regions. The resulting effect is not a substantial increase in total metal content, but instead a lower mean metallicity distributed over a larger volume and more gas.

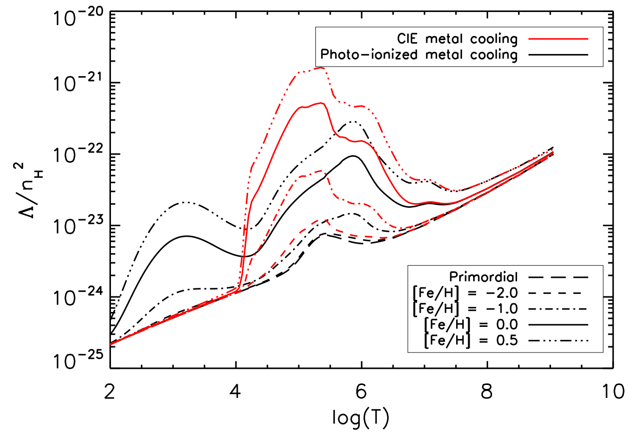

Figure 1: Cooling rates as presented in Shen et al (2010). The red lines indicate metal cooling with no UV background, the black lines are with an isotropic UV background. Lines at varying metallicities show the strong dependence of rates on the metal content of the gas. The lowest line is the primordial curve. Cooling rates can vary up to 3 or 4 orders of magnitude when metal lines cooling is compared to primordial.

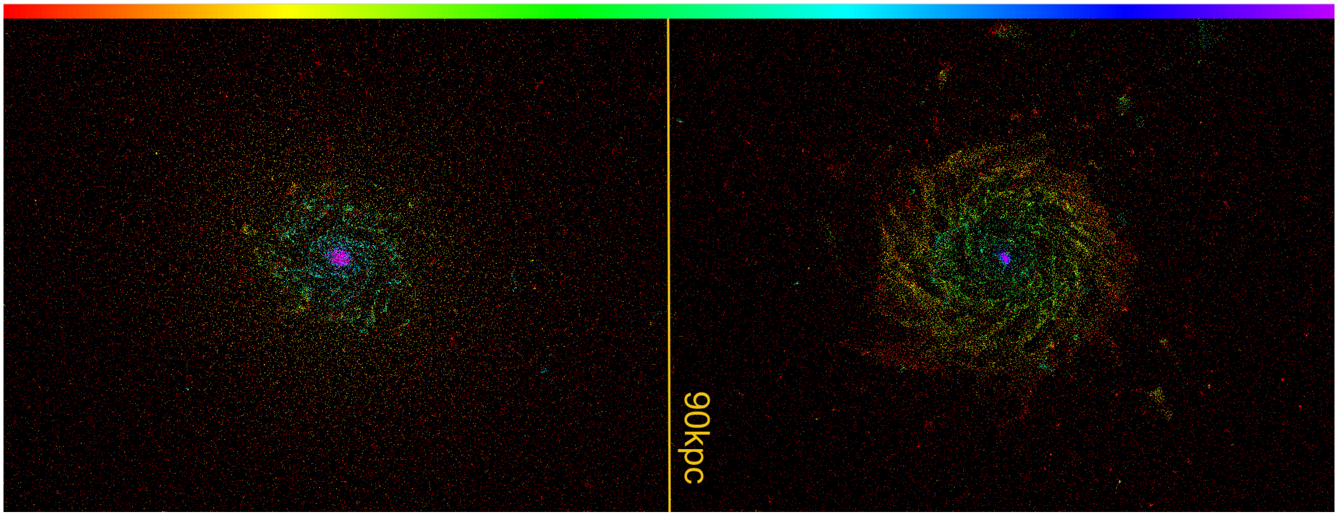

Figure 2: Relative log colormap of mass weighted metal content of gas with $T < 20,000K$ spanning two orders of magnitude. The left galaxy has only primordial cooling and no metal diffusion, while the right has MC&D with UV background enabled. Over-concentration of metals in central regions is somewhat thwarted, and they are distributed to much larger radii with MC&D, in better agreement with observations than the clumpy and centrally concentrated regions exhibited on the left.

Figure 3 shows the cold gas density as a function of radius to the outer edge of the galaxy. The run with MC&D shows substantially more cold gas (integrating the curve) as well as a strong redistribution to larger radii. This cool gas correlates very strongly with star formation rate which is also seen to strongly redistribute to larger radii. In typical spiral star formation occurs throughout the disk, in low temperature molecular clouds, HII regions. MC&D seems to be a substantial improvement in cold gas fraction and metal distribution.

Conclusion

Dark matter only simulations have enjoyed the luxury of simple physics to explain gravitational collapse in an expanding universe, though the solutions are nontrivial to come by. The modeling of baryonic particles adds considerable complexity to the simulations, both in the dynamical integrators, and in the complicated physics. Scales necessary for full cosmological simulations limit the resolution that can be achieved at a galactic scale. As a consequence, statistical, or simplified models must be developed to model physics below the scale of the simulations.

A stochastic star formation model yields natural agreement with the scaling of the observed Kennicutt-Schmidt law and the free parameters of the model are constrained by normalizing the star formation rate to that of the observations. SFR is relatively insensitive to pertubations parameter space of the eligibility criteria, such as the max temperature and density thresholds.

Stellar evolution is based on observationally determined initial mass functions and standard theoretical models of stellar lifetimes. When the stars are aged, feedback is modeled using a blast-wave model for type II supernovae, which deposit energy and metals, and using simple mass fractions for type Ia SN and stellar winds. Parameter space for the energetic feedback is reasonably constrained by measurements of radial velocity dispersion in cold gas. Other parameters such as cooling shutoff times, are based on observational, or theoretical models. The interplay between star formation and feedback from dying stars is crucial to evolutionary history of galaxies. Metal cooling and diffusion further complicates the story, but it appears to be a step in the right direction. These early results of MC&D inclusion indicate that it is working to increase the overall cold gas fraction substantially. Especially in the outer regions of the galaxy where star formation has also become more prominent.

Several problems still present themselves, predominantly the overcooling problem. Baryon concentrations in central regions of galaxies are far too high to match observations. Star formation rates are too high at recent epochs, and the intergalactic medium is too metal poor to match observations. The favored solution is to implement AGN feedback into the simulations which would produce outward pressure from the center that would likely relieve many of the is-

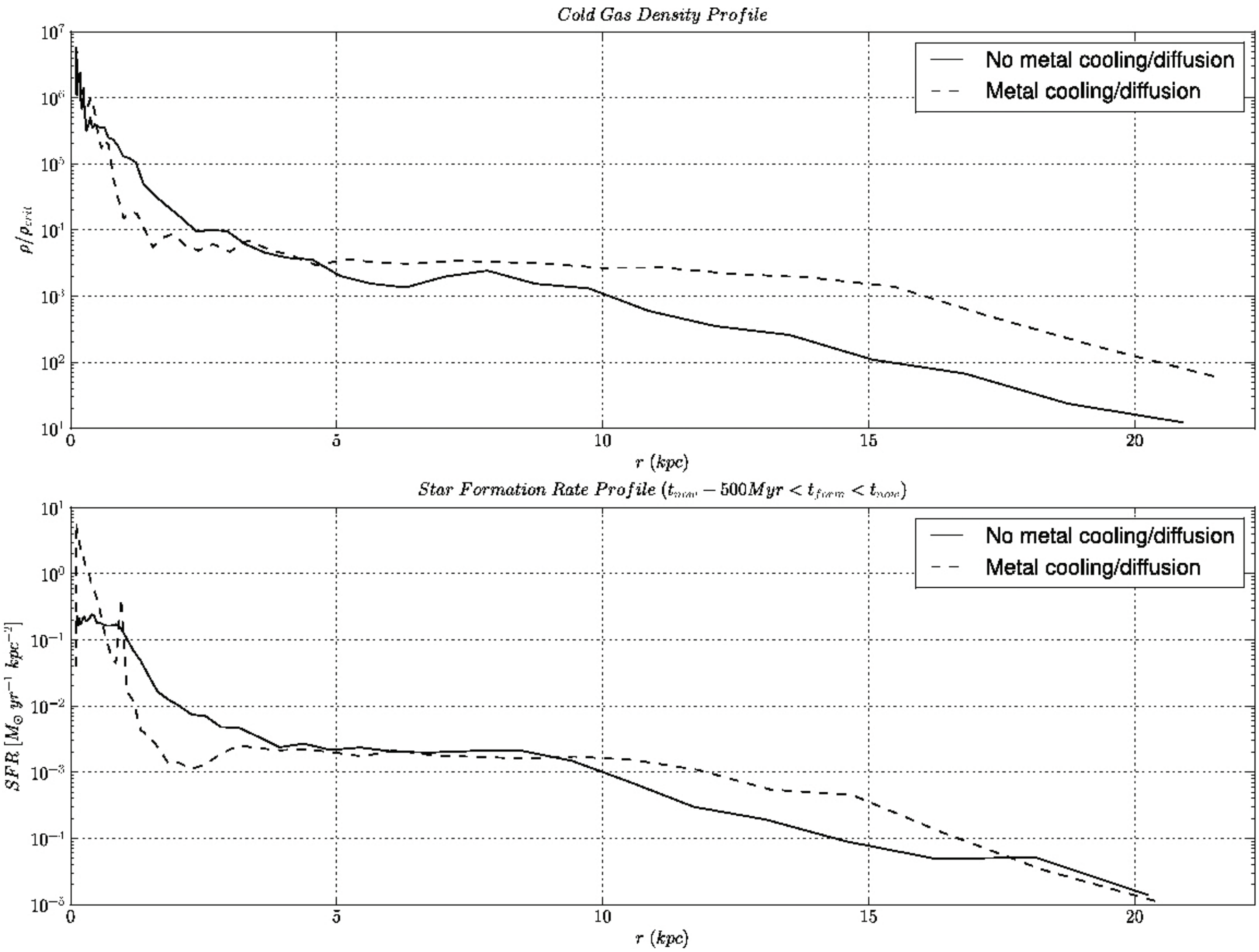

Figure 3: The top figure is a radial density profile of the cold gas, $T < 20,000K$. In the simulation with MC&D, there is a 300% increase in the amount of cold gas within the galactic sphere. There is a substantially lower gas fraction in the central regions which has been moved out radially. Metal diffusion in tandem with the cooling is able to much more effectively cool enriched gasses at larger radii, and consequently star formation shifts toward the mid and outer disk.

sues. Without basic physical understanding of these processes, however, it is impossible to formulate a realistic model and theoretical models of AGN are still in their early stages.

Theoretical and observational study of galaxy formation stands to gain a tremendous amount as simulations continue to improve. Direct comparisons with observations will provide a powerful probe of dark matter, determination of important evolutionary events, and of the key physical mechanisms that influence formation. Simulations are a powerful tool that have already enjoyed many successes in dark matter studies and have the chance to grow in utility in the coming decade.

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