Simulating the joint evolution of quasars, galaxies and their large-scale distribution: a Summary

Springel et al. begin by explaining the two chief difficulties in matching galaxy survey data to theoretical predictions – the need for a large volume to include rare objects and the immense complexity of incorporating sub-grid physics. They say that observational data supports the ΛCDM model, but that the hierarchical and non-linear growth of structure resulting from density perturbations necessitates the use of numerical simulation. They offer the Millennium Simulation (cube with 500h-1Mpc edges and about 1.0078 x 1010 gravitationally interacting dark matter particles from z=127 to z=0) combined with semi-analytical models as a partial solution to these problems.

They discuss the evolution of dark matter halos in the simulation, demonstrating graphically the increasing percentage of dark matter particles involved. The combination of high-resolution simulation and the tweaking of semi-analytic models to fit observational data, they explain, allows both for accurate current and historical data for individual galaxies.

In the next section, Springel et al. use the Millennium Simulation to contribute to the debate on the fate of the first quasars. They trace the idea that " the brightest quasars are located in the largest galaxies" by identifying the 10 largest objects in the simulation – with "large" related to dark matter halo mass, stellar mass, or star formation. By examining the local environment and merger history of several such objects, they find that these quasar candidates lie on a prominent dark matter filament and at the heart of a rich galaxy cluster.

They discuss the correlation between semi-analytic modeling and observational data, noting that on small scales the galaxies follow power laws, but that on larger scales the clustering pattern may show "baryon wiggles" – small scale (~one degree) fluctuations in the CMB that imprint early formation of structure. Having found such wiggles in the simulation, they suggest that future galaxy surveys attempt to measure these oscillations and use that data to "constrain the nature of the dark energy."

In their conclusion, they argue that the Millennium Simulation dataset should motivate the collection of new survey data against which to test predictions about quasars/supermassive black holes, deviations from power laws in correlation functions and baryonic oscillations.

At "Physical model for galaxy formation" in the supplemental paper, Springel et al. explain the use of semi-analytic modeling—including models of dark matter substructure—before introducing the differential equations governing the their semi-analytic treatment of galaxy evolution.

They list factors involved in modeling radiative cooling and star formation: the factor of baryonic matter in dark matter halos, the temperature differences of gases in halos, the size of rotating halo disks, the start of star formation, and mass loss from halos due to supernova explosion.

The factors involved in modeling morphological evolution fall under two galactic bulge-forming categories: disk instability-caused evolution or galaxy mergers. They use "stability arguments" – matching the mass of the bulge to make the stellar disk stable for the first, "secular evolution," and model galaxy mergers from the halo merger tree after dividing them into two categories based on size.

In order to translate simulation data into spectra and luminosity data, they model spectrophotometric data based on age and metallicity of the galaxies involved. Dust obscuration is apparently very difficult to model – this uncertainty is magnified at high redshift.

Lastly, Springel et al. discuss the formation of supermassive black holes and active galactic nuclei. They model black hole accretion as occurring primarily during a quasar phase in which cold gas falls into black holes during galaxy mergers. Into this model, they add a “radio mode” which includes relativistic jets and the effects they have on cluster cooling.