Formation of structure in the Universe

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In 1965 Arno Penzias and Robert Wilson detected the cosmic microwave background radiation. More than 13 billion years ago this radiation was imprinted on the sky, only a few 100,000 years after the Big Bang. In 1992 the COBE satellite detected anisotropies in the temperature of the CMB radiation. Meanwhile these temperature fluctuations are measured with very high precision by satellites (WMAP, Planck) as well as many ground based observations. The measured temperature fluctuations tells us that shortly after the Big Bang the Universe was almost homogeneous with tiny density fluctuations of the order of 10^{-5}. Comparing the power spectrum of measured density fluctuations with models the cosmologists concluded that the Universe is spatially flat and consists at present of about 68 % of some unknown Dark Energy, 27 % of also unknown Dark Matter and 5% of baryons.

In the evolved universe one can directly observe the distribution of baryons and indirectly (gravitational lensing, velocity measurements) the distribution of Dark Matter. We see huge clusters of galaxies with masses up to a few 10^{15} solar masses in the knots of the cosmic web which is build by galaxies in a wide range of masses from tiny dwarfs (10^9 solar masses) to massive ellipticals (10^{13} solar masses). All these structures have been formed out of the tiny fluctuations generated during the early inflationary phase and measured in the CMB background.

During the last two decades our understanding of the evolution of structure in the universe grew substantially. Due to the non-linear nature of the gravitational dynamics and the complicated gas-astrophysical processes numerical simulations on modern supercomputers have been the driving force behind much of this theoretical progress. Dark matter only simulations of the evolution of large cosmological volumes use thousands of cores of the largest supercomputers in parallel. In the analysis of these simulations assumptions must be made about the observable objects (galaxies) which are hosted by the dark matter halos. Gas-dynamical simulations allow to include the formation of stars but such simulations are much more demanding both in computational resources as well as in the number of physical processes which must be considered in addition to the gravitational clustering. This includes radiative cooling of the gas, star formation and the feedback of the stars. But also magnetic fields, supermassive black holes, and many other processes might be important.

Cosmological simulations must cover a large dynamical and mass range. A representative volume of the universe should be large, but this comes at the expense of the resolution. To overcome this problem a new, and almost orthogonal but yet complementary, approach to cosmological simulations has been introduced over the last few years. This consists of using observations of the nearby universe as constraints imposed on the initial conditions of the simulations. The resulting constrained simulations serve as a numerical laboratory of the nearby universe where small scale structures can be studied in detail.