Paper IV: Dark Matter Substructure Within Galactic Halos

Background:

For this paper, we must start our "background" section many years ago -- about 13 billion years to be exact, when the Universe was a nearly homogeneous soup of protons, electrons, and photons (oh, and *dark matter* too!). The picture we have of this time comes to us in the form of the Cosmic Microwave Background (CMB). This is very high wavelength light that has traveled through time and space from when the Universe was only ~380,000 years old. This light permeates all of the space around us. In fact, it is what makes the vacuum of space ~2 degrees Kelvin in temperature. If you ever used an old TV, a small part of the static comes from the TV picking up these photons!

We learn a lot from looking at this picture of the Universe. We see that during this time, the Universe was nearly homogeneous, but only *nearly*. There existed small over-dense regions that we see as temperature fluctuations in this CMB radiation. These fluctuations only differ from the average by about 1 part in 100000 (or 0.001%). It is these regions that become the structures we observe today. Everything exists because of these over-densities! Because these regions are slightly more dense than the average Universe, they are more gravitationally attractive. More stuff will flow in, growing the over-density and making it more gravitationally attractive, and so on. "The rich get richer" in the gravitational Universe.

Today, we also realize that the mass that is dominating these gravitational interactions comes in the form of Dark Matter, so this is what we (and the paper) will focus on, leaving out the "normal" matter (or "baryons") since it is relatively unimportant (...or is it?!). As these over-dense regions collapse, they form what we call dark matter halos, gravitationally bound, stable structures of dark matter. It is within these halos that galaxies form -- the bigger the halo, the bigger the galaxy. To learn more about the formation of these structures, we run simulations of dark matter. We start with the initial density perturbations derived from the CMB and just let things play out gravitationally. This way, we can watch as structures form naturally.

What we find is that structures form *hierarchically*, meaning that small things form first and merge together to form bigger things and so on. This is very important because it explains a lot of what we see, including the different types of galaxies -- spirals and ellipticals -- and the existence of galaxy clusters. However, there is a major discrepancy between simulations and observations in the amount of substructure that exists in halos corresponding to Milky Way sized galaxies. "Substructure" is a term used to describe the halos within halos. These halos orbit around the main halo and are aptly called *satellite* halos.

We assume that our galaxy is not special. In fact, no galaxy is special. So, if I look at a galaxy of a given size, it should match relatively well to galaxies of similar size picked out of a simulation. What we find is that in these dark matter simulations Milky Way sized halos have a lot of satellite halos (100-1000). However, when we look around us, we don't see nearly that many satellites. Where did these galaxies go? Is there something about the Cold Dark Matter physics that we do not understand? Or is there something going on with the "normal" matter that makes these halos invisible to us? This is the issue that this paper is discussing.

After reading this paper, answer the following questions:

1) Explain the purpose of figures 1 and 2. What are they plotting and why is it important in the context of this paper? In figure 2, the authors use the circular velocity as a proxy for mass. Explain how this works and why it is nice to use in place of mass when comparing to observations (**Hint**: Tully-Fisher Relation).

2) The "missing satellites problem" is possibly explained by the existence of some mechanisms that inhibit the formation of stars, making these smaller halos "dark" and unobservable to us (like feedback!). Explain how the fact that we know of the existence of old disks in galaxies cause further complications in explaining these "missing satellites" (**hint**: these disks need to be relatively *old* and dynamically *cool*!... look in section 3!)

3) Based on this paper, put forth an argument as to why simulations with both dark matter and gas/stars are important for understanding galaxy evolution. (I expect a well thought out answer to this question! Don't be afraid to be wrong, but take some time to think about it!)

Glossary:

Mpc: Mega Parsec, or 10^6 parsecs, where one parsec is 3.26 light years.

Dark Matter: This is the term used to describe the majority of gravitationally interacting material in the Universe that we can't see. We don't know what it is, but we know it only seems to interact gravitationally.

Accretion: In this paper, this term refers to the accumulation of mass by objects through gravitational interactions. For example, gas or other dark matter halos falling into a larger dark matter halo.

Baryons: This is a broad term for the "normal" matter, i.e. stuff that we can see -- protons, electrons, atoms, molecules, etc. Stars and gas are made of baryons.

Tides: This refers to the tidal forces that two objects have on one another. An object feels a tidal force because the force of gravity is different across the object. For example, the side of the earth closest to the moon feels a stronger gravitational force than the side farthest from the moon. This differential force cases the object to stretch along the direction of the gravitational field.

Satellites: smaller halos that exist within bigger halos.

Hierarchical Formation: "bottom-up" building of structures. Start small and merge to grow bigger.

<u>Circular Velocity</u>: The velocity of a circular orbit at a given position assuming gravity is the only force. The more mass inside your imaginary circular orbit, the higher the circular velocity.

<u>Feedback</u>: This is a term used to describe energy outputted from astrophysical events such as star formation, supernovae, or supermassive black hole accretion. It is called "feedback" since the energy released usually hinders the process that caused the energy itself. For example, stars forming causes supernovae and strong UV radiation, which will heat up the gas and make it harder for stars to form.

<u>Redshift</u>: The Universe is expanding. This means that the farther away something is from us, the *faster* it is moving away from us. This outward motion causes light from these objects to be doppler shifted toward higher (or "redder") wavelengths, hence called redshift. The higher the "redshift", the farther away the galaxy is (and therefore the farther into the past you are looking). So, statements like, e.g. "this galaxy is at a redshift of...", generally are referring to the "**cosmological redshift**" described here.

<u>Virial Theorem</u>: This relates the kinetic energy and the potential energy of any bound orbit. For a two object system, it is simply that the KE = -1/2 PE (KE = kinetic energy, PE = potential energy). For dark matter halos, you get that $GM/R \approx \sigma^2$, where σ is the velocity dispersion just like in the black holes paper (paper II). This means that you can measure the mass within some radius R if you can measure the velocity dispersion (usually using doppler shifts of spectra)

<u>Virial Radius/Mass</u>: These are the M and R such that $GM_{vir}/R_{vir} \approx \sigma_{max}^2$, where σ_{max} is the maximum velocity dispersion of an object, like a dark matter halo.

<u>Virialized</u>: This is a term that describes a dark matter halo that has "settled down" into an equilibrium state where the virial theorem holds true. This would not be the case while the halo is in the process of collapsing, or right after mergers.

<u>Tully-Fisher Relation</u>: This is an empirical (i.e. observed) relationship between the Luminosity of a galaxy and the rotation speed far from the center. Due to the existence of dark matter, the average rotational velocity of disk galaxies levels off at large distances, rather than declining as one would expect if visible matter was the only thing providing mass (and therefore gravity) to the system.

<u>Dwarf Spheroidals (dSph's)</u>: these are really low mass, spherical galaxies. They are very diffuse, have very little gas, and have mostly old stars.

<u>Quasi-Stellar Objects (QSOs):</u> these are very distant, bright objects. They look a lot like stars, but are way too bright. Originally a mystery, we now know that they come from rapidly accreting supermassive black holes (quasars). These objects can provide a lot of UV and X-ray radiation to heat up and ionize gas in the Universe.

<u>Intergalactic Medium</u>: the stuff in between galaxies. Usually very hot and diffuse.

<u>Heat</u>: In the context of this paper, this refers to *dynamical* heating. Meaning that you are "mixing things up", increasing the velocity dispersion. Structures that have very regular motions (coplanar, similar direction, more circular) are dynamically "cold" while those that have more random orbits (variety of inclinations and eccentricities) are dynamically "hot".

<u>Apocenter</u>: the farthest point in an orbit

<u>Pericenter</u>: the closest point in an orbit

<u>Sum in quadrature</u>: take the square root of the sum of the square of values, $\sqrt{(x^2+y^2)}$

<u>Galaxy Clusters</u>: Large groups of galaxies. They exist in the largest dark matter halos and usually have a very bright elliptical galaxy at their center. They also tend to have a lot of hot gas, called the intracluster medium. These are the largest and densest regions of the Universe.

<u>Power Spectrum</u>: This is actually a very complicated subject and is related to the distribution of dark matter halo sizes. The following is a good way to think about it. You can have small scale overdense regions. These small scale regions exist in larger scale overdensities that will eventually collapse and cause the smaller guys to merge. The larger guys exist in even larger overdensities and so on. The cool thing about hierarchical formation is that things are self-similar; small scale things are just scaled down versions of larger scale things. The "power" of a scale is related to how many objects there are of that size. For example, there are more small halos that hold dwarf galaxies than there are big halos that hold clusters. So, those smaller scales have a higher "power" than the larger scales.

<u>Gravitational Lensing</u>: This comes from general relativity. Gravity comes from massive bodies warping the space-time around them, changing what a "straight" path through space and time means. This means that gravity also has an affect on light. A massive object will cause light to be bent around it. We can measure this affect by looking at light from sources (usually galaxies) that exist behind a massive body. The gravity of the massive body will warp the light from those background objects. The way the light is bent can tell us the mass of the object in the foreground.

<u>Draco</u>: an example of an observed dwarf spheroidal galaxy. These small galaxies are rather dim and hard to see so there are not very many examples that we can observe very closely.