FEATURE

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Research Area: Astrophysics and Cosmology

# Using Galaxies to Shed Light on the Dark Universe

## 1. The Dark Universe

The grandeur of the night sky has bedazzled mankind from time immemorial. Human curiosity has lead us on a quest to understand fundamental questions about the nature of the Universe, its origin and its fate. Astrophysical observations remain at the front and center in this quest. They have continued to unravel a number of dark mysteries that the Universe holds in store for us.

The most puzzling of the many astrophysical discoveries so far, has been the existence of dark matter and dark energy. Dark energy is an omnipresent, nonclumpy form of energy (traditionally attributed to the vacuum), while dark matter is composed of slow-moving matter particles, which do not interact electromagnetically. These two components dominate (accounting for nearly 95%) the energy density budget of the cosmos over that of ordinary matter which we have explored and mastered very successfully so far with laboratory experiments (such as those carried out with particle accelerators like the Large Hadron Collider, LHC).

What is the nature of dark matter and dark energy, what are their properties, and how do they relate to ordinary matter? Do these components truly exist, or are they a result of an incomplete theory of gravity on cosmological scales? These questions lie at the interface between particle physics and cosmology and are at the prime focus of ongoing research. The Kavli IPMU is undertaking a multi-pronged approach to attack these problems by astrophysical observations and laboratory experiments, which can be used to build a theoretical understanding of these mysterious components of nature.

## 2. The Early Universe and the Birth of Galaxies

In the simplest concordance cosmological model, the early Universe started very hot and dense. It underwent a rapid phase of inflation where the tiny fluctuations of a quantum field were stretched to cosmologically large scales. These fluctuations were imprinted onto the density field of dark matter particles. The fluctuations in dark matter grew by the action of gravity and led to the formation of structure in the Universe.

The growth of these fluctuations can be studied with the help of computer simulations. This topic has been previously covered in the *Kavli IPMU News* (see feature article by Naoki Yoshida in the September 2014 edition). The statistics of the dark matter distribution on the largest scales is governed by a number of important cosmological parameters, such as the amount of matter in the Universe, the amplitude of initial density fluctuations. Mapping

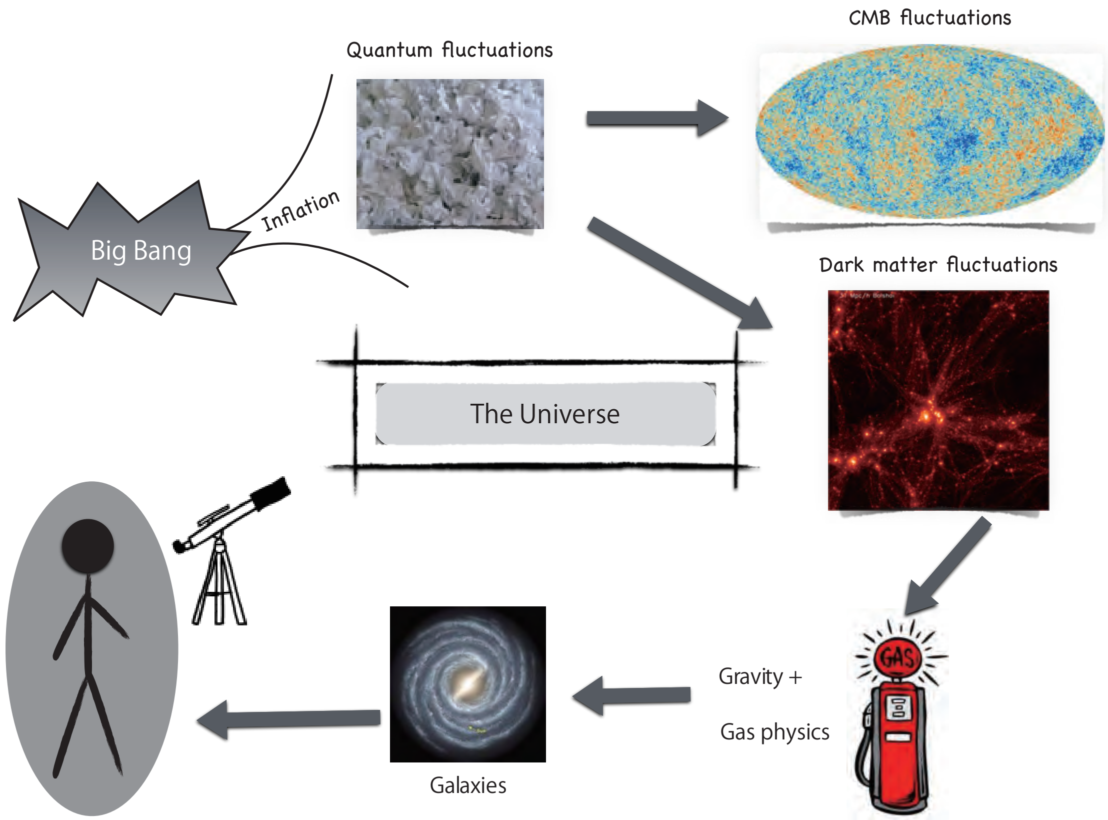



Figure 1. Cosmic inflation results in a nearly homogeneous Universe, seeded with tiny primordial fluctuations. These tiny fluctuations are imprinted onto the matter distribution. A snapshot of these fluctuations about 380000 years after the big bang can be observed by looking at the cosmic microwave background radiation (see feature article by David Spergel in *IPMU News* No. 10, June 2010). The dark matter fluctuations grow to form a cosmic web structure which forms the backbone of structure in the Universe. Complex astrophysical processes then result in the formation and evolution of galaxies. Intelligent life can arise in such galaxies which can then observe the Universe and unravel its history.

out the growth of these fluctuations with time is important to understand the temporal behavior of dark matter and dark energy. But since dark matter does not emit light, it is hard to detect. Fortunately, we have galaxies which emit lots of light and can be detected out to large distances. How are these galaxies then related to the dark matter?

Dark matter particles clump together to form gravitationally bound objects (we will call them dark matter halos). These clumps come in a variety of shapes and sizes, there are numerous small ones, but the big ones are relatively rare. Baryons (primarily primordial gas clouds) are attracted towards the center of the gravitational potential of these dark matter halos. Places which are rich in dark matter attract more baryons towards them. The baryons undergo a series of complex astrophysical processes (such as radiative cooling, star formation and feedback) and eventually form galaxies such as our own galaxy, the Milky Way.

On the largest scales, the galaxy distribution is expected to trace the dark matter distribution just due to gravity: wherever there is a lot of dark matter, we expect more and brighter galaxies to form. Galaxies can therefore be used to probe the structure of the dark matter distribution, and its growth in time, thereby improving our understanding of the nature of dark matter and dark energy.

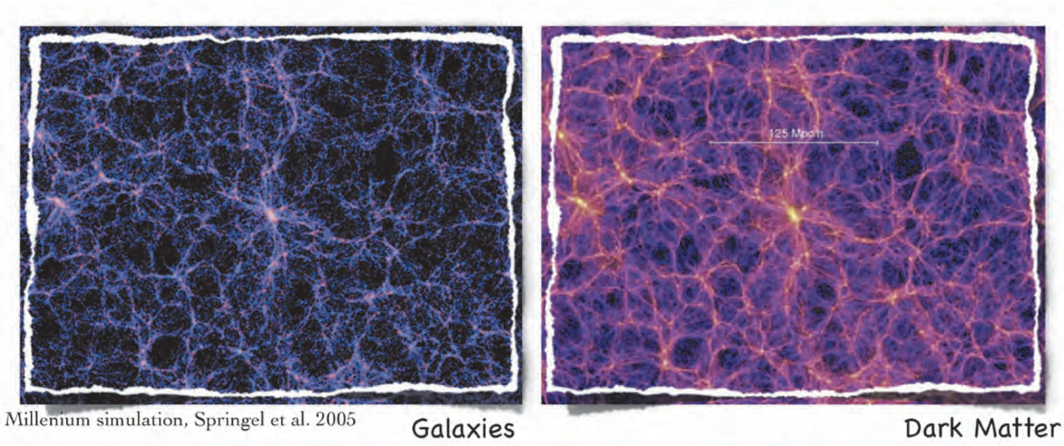



Figure 2. The expected distribution of galaxies (left) and the corresponding distribution of dark matter (right) today in the concordance cosmological model. The dark matter distribution was obtained by running large computer simulations. Semi-analytical recipes for the physics of the galaxy formation and evolution were implemented to predict the distribution of galaxies in the dark matter structure. The galaxy distribution traces the dark matter distribution on large scales. Observations of galaxies at different cosmic epochs can be used to study the growth rate of structure in dark matter. Measurements of the growth of structure can help us understand the nature of dark matter and dark energy.

## 3. The Clustering of Dark Matter Halos

Since galaxies live in dark matter halos, it is important to understand how halos are related to the dark matter distribution. Dark matter halos form at the peaks of the density distribution. Most massive halos form at the rare, large scale peaks of the density field. The distribution of such massive halos is highly clustered compared to the low mass halos. This behavior is qualitatively similar to that of the highest mountain peaks that we find on earth. The chance of finding a mountain peak at close proximity to another one is very high (all mountain peaks with height greater than 7200m are located in the region of the Himalayas). Therefore one gets a biased view of the dark matter distribution by just studying the peaks of the density field. Fortunately, one can also predict the distribution of dark matter halos and quantify its dependence on the mass of halos. This exact dependence of the clustering amplitude on halo mass is also a sensitive probe of cosmology (see Figure 3). In observations, one can substitute galaxies for halos, and measure their clustering amplitude. Additional measurements of the mass of the halos of these galaxies can then yield cosmological constraints.

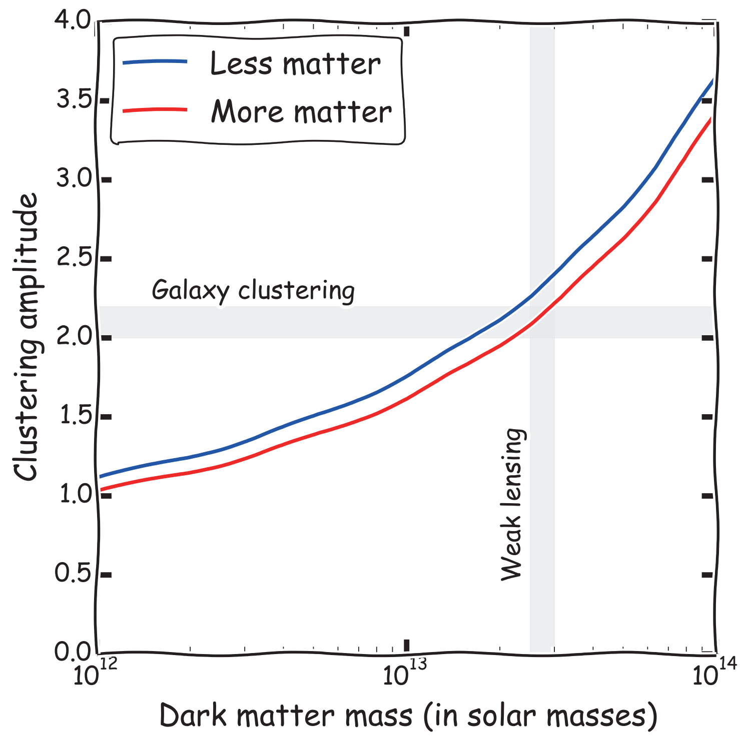
## 4. Galaxy Observables

### 4.1 Galaxy Clustering

Astronomers all over the world are carrying out large galaxy surveys to map the distribution of galaxies on large scales. One of the prime examples is the Sloan digital sky survey (SDSS), which has recently concluded its third incarnation (SDSS-III). They obtain accurate positions of galaxies in the plane of the sky via imaging data, as well as along the radial line-of-sight using the shift of galaxy spectral lines towards the red side of the spectrum (redshift). This results in a three dimensional map of galaxies in space.

Using this data, the clustering of galaxies can be quantified with one of the simplest spatial statistics, the two-point correlation function. The correlation function quantifies the excess probability to find two galaxies separated by a given distance over that if they were distributed randomly. If galaxies cluster strongly, then one should be able to find a

Figure 3. The clustering amplitude of dark matter halos of different mass depends upon cosmological parameters such as the amount of matter density in the Universe. More matter in the Universe results in a smaller amplitude of clustering for the same mass of dark matter halos. Galaxies live in dark matter halos. By measuring the clustering of galaxies, we can measure the clustering of their dark matter halos. The weak gravitational lensing effect around these galaxies can be used to measure their halo masses. Together such observations can constrain cosmological parameters (see Figure 4). (Image adapted from S. More et al., "The Weak Lensing Signal and the Clustering of BOSS Galaxies II: Astrophysical and Cosmological Constraints," arXiv:1407.1856; to be published in *Astrophysical Journal*.)




large number of pairs of galaxies at relatively short distances from each other. We have measured the clustering signal of galaxies from the SDSS-III survey with very high fidelity. This gives us the amplitude of the clustering of halos in which these galaxies reside. But how to determine the mass of the halos of these galaxies?

## 4.2 Gravitational Lensing

In ordinary life, we experience that light always travels in straight lines. It was Einstein's great insight that the path of light rays could be significantly distorted if it passed near a very massive object. This phenomenon called gravitational lensing has turned out to be an extremely useful tool in astrophysics. It can be used to detect and measure dark matter simply by quantifying the bending of light. Gravitational lensing in its strongest form results in beautiful mirages in the Universe, such as galaxies morphed into thin elongated arcs, or sometimes even resulting in multiple images of single galaxies (or even objects like supernovae).

In its weak form, lensing due to intervening mass causes spherical objects to look elliptical. The minor axis of this ellipse is oriented in the direction joining the object and the intervening mass. By measuring this coherent ellipticity signal, we can measure the dark matter distribution around galaxies, and thus the masses of their dark matter halos.

For carrying out such measurements around the galaxies, we need to find surrounding background galaxies and measure their shapes. This is a very difficult task as the background galaxies are faint. A large amount of telescope time is needed to image these galaxies with a quality which is good enough to measure their shapes.

We have carried out such measurements using the deep imaging data around SDSS-III galaxies obtained by the Canada France Hawaii Telescope Legacy Survey*. This data can then be used to understand the dark matter distribution surrounding these galaxies, in particular the mass of

* www.cfht.hawaii.edu/Science/CFHTLS/

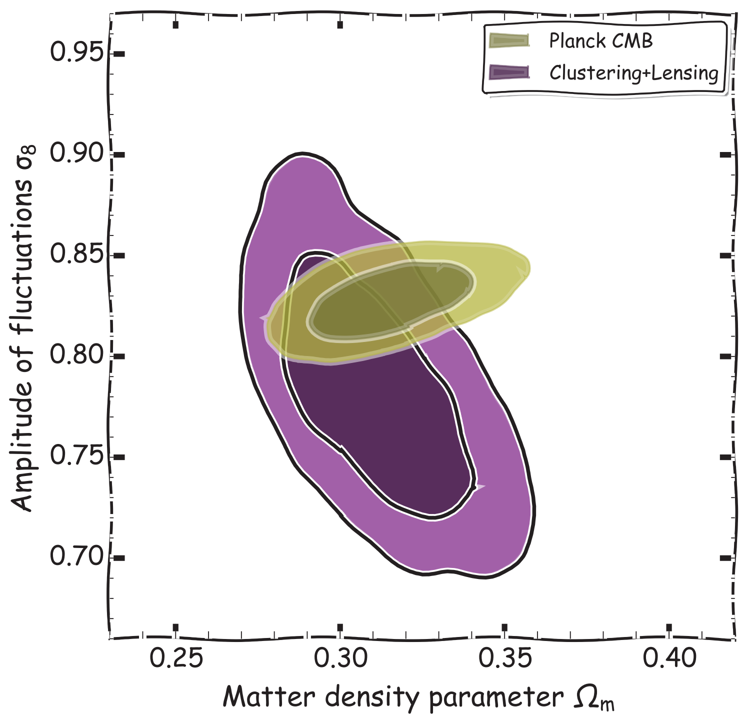



Figure 4. We have measured the clustering amplitude of galaxies from the SDSS-III Baryon oscillation spectroscopic survey (BOSS). (H. Miyatake et al., "The Weak Lensing and Clustering of BOSS Galaxies I: Measurements," arXiv:1311.1480; to be published in *Astrophysical Journal*.) The masses of the halos of these galaxies were measured by using the weak gravitational lensing effect. These measurements allowed us to obtain cosmological constraints on the matter density parameter and the amplitude of density fluctuations in the Universe today (magenta contours show the 68 and 95 percent confidence regions). We can compare our results with those obtained by the analysis of CMB observations in the very early Universe using the Planck satellite. The consistency and complementarity of the two results: the former based on non-linear gravitational physics in the late Universe, and the latter based on physics in the very young Universe, is remarkable. (Image adapted from S. More et al., "The Weak Lensing Signal and the Clustering of BOSS Galaxies II: Astrophysical and Cosmological Constraints," arXiv:1407.1856; to be published in *Astrophysical Journal*.)

their dark matter halos.

## 5. Cosmological Concordance

It is important to test the current cosmological model using a variety of observables. It not only establishes confidence in the model, but also implies that the current description is a very reasonable approximation of the reality, even though it may not completely represent the true underlying reality. Some of the main observations which support the current cosmological model are those of the cosmic microwave background (CMB) and the distance redshift relation obtained from observations of supernovae of Type Ia (SNeIa) and baryon acoustic oscillations (BAO).

Using the amplitude of the galaxy clustering and the dark matter halo mass, we can also infer constraints on the cosmological parameters such as the amount of matter density in the Universe and the amplitude of the initial density fluctuations. These constraints give a consistent picture of the Universe and are often of a complementary nature to the CMB, BAO, and SNeIa measurements.

## 6. The Future Is Here!

The Hyper Suprime-Cam instrument on the Subaru telescope in Mauna Kea, Hawaii is an engineering marvel. It consists of a wide field of view and has the world's biggest camera on any astronomical telescope. A large imaging survey was started last year in March 2014 with the help of this instrument. The aim of this survey is to provide high quality imaging at unprecedented depths over large area of the sky. The survey, once complete, will make it possible to construct a dark matter map from weak lensing observations. It will enable a lot of exciting research in areas of astrophysics and cosmology. I am looking forward in particular to revisiting the weak lensing of the SDSS-III galaxies in light of this new data. Joint analyses of clustering

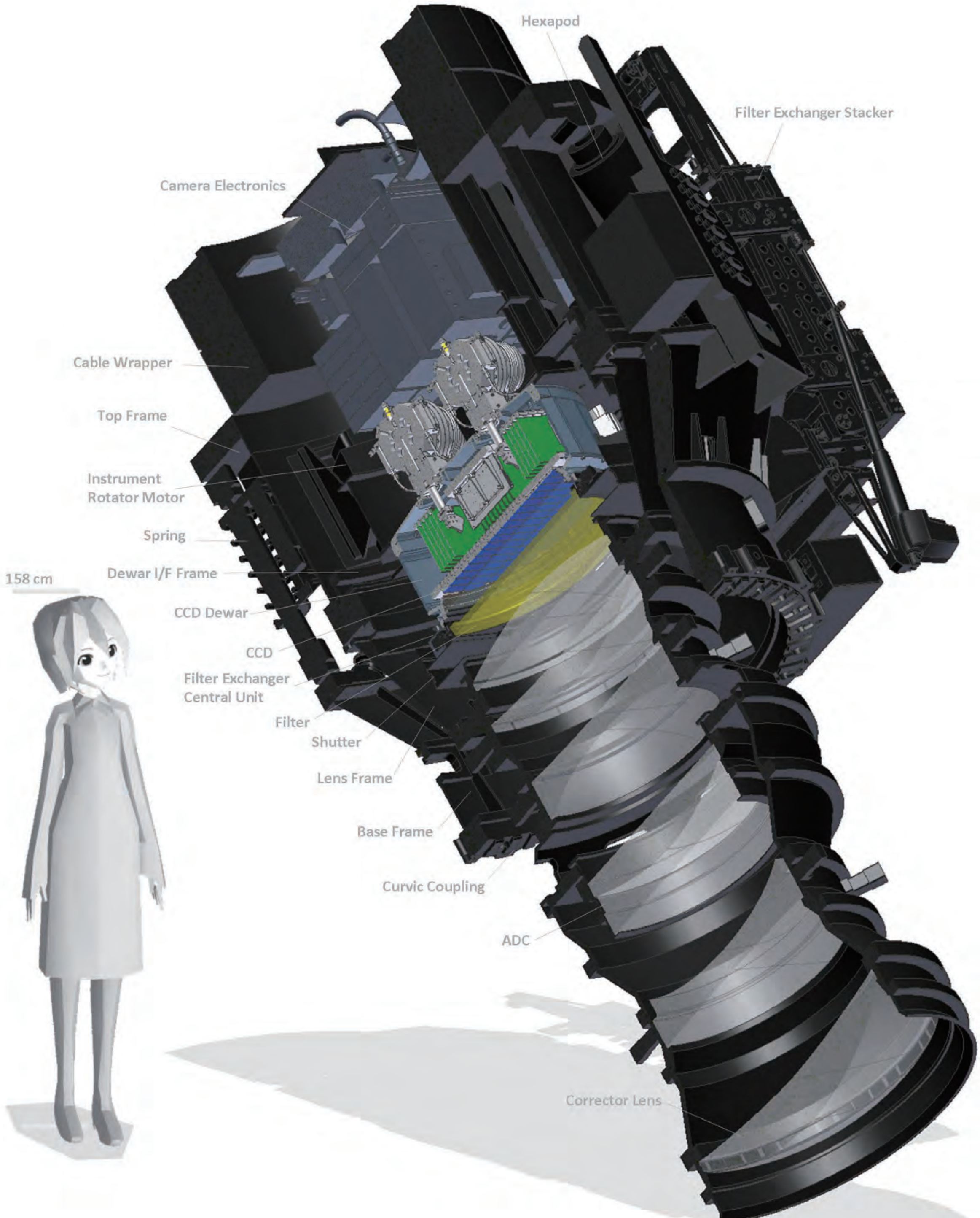





Figure 5. The Hyper Suprime-Cam (HSC) instrument is a large digital camera built by the National Astronomical Observatory of Japan in collaboration with international academic and industrial partners including the Kavli IPMU (see *Kavli IPMU News* No. 23, pp.10-13. The camera is installed on the 8.2 m Subaru telescope at Mauna Kea, Hawaii. It is currently carrying out a large galaxy imaging survey as part of a Subaru Strategic Program. The HSC survey, once complete, will cover 1400 sq deg of sky at unprecedented depths. (Image credit: NAOJ)

and weak lensing of galaxies like the one presented in this article can be performed at different epochs, tracing the growth of structure in the Universe. This is extremely important to shed light on the nature of dark energy, one of the principal goals of the survey. Exciting times surely lie ahead!