# 1 Observations, or the birth of Cosmology

The study of the Universe, and the subject of Cosmology with it, started with some incredible observations, that we wish to summarize in this first chapter. Unfortunately, it is not as simple as "observations drive the theory", but rather it has been, historically, a constant feedback relationship. For instance, we will see how some preliminary observations drove the community to devise a theory that, however, was later shown to be missing some components.
In any case, in this chapter we will list the observations that allowed cosmologists to create a framework that describes of our Universe with very good precision.

## 1.1 Scales in the Universe

The length scales in our Universe can get incredibly big, so big in fact that there is no obvious way to get used to them unfortunately. Humbly, to get a sense of the distances in cosmology (if one can), we start out with the smaller scales, and then slowly build up the larger scales, up to the biggest ones we know.
Firstly, everyone knows that Earth is part of the *Solar System*, where it is the third planet from the Sun in terms of distance. In fact, we are 150 million kilometers away from it (about 11780 Earths stacked up side by side), such that light itself takes about 8 minutes to travel that distance.
Some time ago (not too far back) we also found out that our Solar System is not the end of the story, but much more can be found outside it. Peering out at the sky reveals the existence of a multitude of objects, of which the closest ones are stars, the little specks of light one sees at night (if you're lucky). The star nearest to us, *Proxima Centauri*, lies "just" 4.2 light years away. Since distances tend to get incredibly large outside of our Solar System, Cosmology, as any other framework in physics, decides to use its own length (energy) units, based on the scales at which it operates. (Think about particle or atomic physics. There the scales are much smaller, i.e. the energies at play are much bigger, so that it's convenient to use *electronvolts* eVs as a unit.) In particular, in Cosmology the *parsec* is the unit of choice:

$$1 \text{ pc} \approx 3.26 \text{ light years}$$

At the next level of scale we find galaxies. As it appears, the Universe contains roughly 100 billion galaxies, each of which hosts 100 billion stars; in fact, all the stars that we can see with our naked eye reside in our own galaxy, the *Milky Way*, a spiral galaxy around 30 kpc in length, with the Sun located at the edge of a spiral arm, 8 kpc away from its center. The Sun moves very slowly though, taking about 250 million years to complete a full orbit around the Milky Way.

Figure 1: A representation of our galaxy, the Milky Way

The nearest galaxy to ours is the famous *Andromeda Galaxy* or *M31*, a spiral galaxy about 2 million light years away. It is actually one of about 50 other galaxies that are gravitationally bound together: this arrangement (including our own) is what's called the *Local Group*.
At even bigger scales, galaxies organize themselves in *galaxy clusters* and *superclusters*, with filamentary structures and gigantic voids in between them. The scales of such clusters, like our own *Local Supercluster*, are in the order of about

500 million light years. These last objects can be very difficult to imagine, so here below we show images taken from the *Millennium Simulation*[1], which aimed to simulate the larges scales known in the Universe:

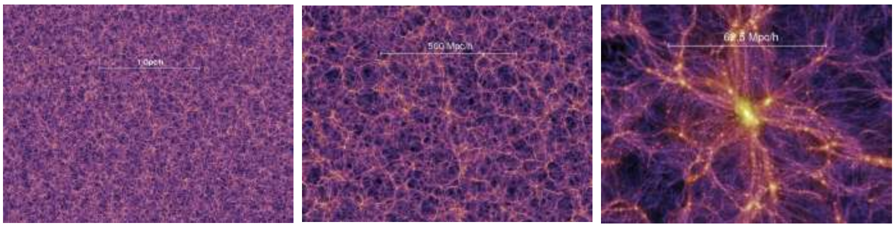

Figure 2: The largest scales in the Universe, from the Millennium Simulation. The figures show the dark matter distribution at present time, zooming in on a galaxy supercluster.

Finally, since light has only a finite speed, the largest scale we can probe is the *observable Universe*, i.e. the distance light could have travelled since the beginning of time, which has a radius of:

$$46.5 \text{ billion years} \approx 14 \text{ Gpc} \approx 4.4 \times 10^{26} \text{ m}$$

We have here discussed the observations regarding the scales of the Universe, to get a sense of how big these actually are. Now we turn to the observations regarding the content of the Universe. What is it made of?

## 1.2 The Content of the Universe

The Universe appears to strikingly simple. Observations suggest that the mass-energy content is divided into just four main components. The first, and one of the least relevant, is the "ordinary" *baryonic matter*, the protons, neutrons and electrons, the stuff we can actually see but makes up only a small percentage of the Universe; another component is the *radiation*, which is mostly made of photons and neutrinos; this, although important, takes up only a very small fraction of the budget.
However, things are still very mysterious when it comes to the most common types of mass-energy. In fact, we now are pretty certain that the majority of matter is in the form of an elusive *dark matter*, taking up roughly 27% of the energy pie. The final component, and the most incomprehensible, consists of what is usually called *dark energy*, which strikingly makes up the remaining 70% of the pie. Here we will summarize how observations managed to show what the Universe is made of.

### 1.2.1 Matter

While we will clarify what we mean by "matter" only later on, we can say here that cosmologists distinguish between:

- Baryonic matter: ordinary matter, such as nuclei and electrons. Clearly, this isn't strictly correct, as electrons are leptons, but their mass so small compared to the nuclei, that most of the mass is in the actual baryons anyway. This type of matter composes stars, planets and every living organism, and makes up only 5% of the energy content;

[1]More information can be found at the website https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/

- Dark matter: a type of matter of which the nature still remains a mystery. There are many candidates for dark matter (such as right handed neutrinos, axions, primordial black holes etc...), but we don't even know if it is just one thing or multiple. Luckily, the large scale description of our Universe doesn't really depend on the small scale nature of dark matter, so that in the end we are able to create theories which then make predictions. This type of matter makes up 27% of the matter content of the Universe.

Altogether, as we can tell, the matter content only makes up roughly 31% of the Universe.
It is interesting now to review all the evidence there is for dark matter, since one might ask how we could know of the existence of such a component, given that we don't even know what it is. The key to the answer lies in the large scale properties of dark matter, as we alluded to before.

The first evidence for dark matter was found by Zwicky around 1933 while studying the properties of the galaxies in the Coma cluster (a galaxy cluster), of which a picture is presented here below:

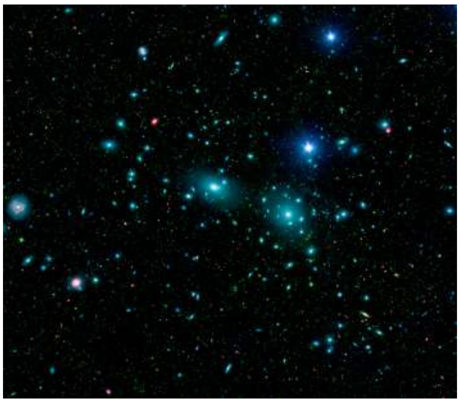

Figure 3: The Coma cluster

It turns out that there are multiple ways of estimating the mass of a galaxy cluster. One way is obvious. When looking with the telescope, we see a certain amount of light, which comes from galaxies, that are themselves made out of baryonic matter (stars are made of mostly hydrogen and helium, while bigger ones contain a small percentage of heavier nuclei. Altogether, however, we are still talking about "normal" matter). We then simply translate this total luminosity (energy of the photons per unit time) into the total baryonic mass of the cluster. There is also a way of calculating the mass that has to do with something called the *virial theorem* (the gravitational one). Let's suppose we have a system of $N$ particles, with masses $m_i$ and positions $\mathbf{x}_i$, that interact via a gravitational potential:

$$V = \sum_{i<j} V_{ij} = \sum_{i<j} -G\frac{m_i m_j}{|\mathbf{x}_i - \mathbf{x}_j|} \tag{1.1}$$

We also assume that the system is "bounded", i.e. all positions and velocities $\dot{\mathbf{x}}_i$ are bounded. The theorem then states that the average kinetic energy of the system $T$ is proportional to the average potential energy $V$:

$$\langle T\rangle = -\frac{1}{2}\langle V\rangle \tag{1.2}$$

Let's apply all this to the Coma cluster. To make things simpler, we assume that all the galaxies all have the same mass $m$, so:

$$\langle T \rangle = \frac{1}{2N} \sum_i m v_i^2 \tag{1.3}$$

the virial theorem then states:

$$m\langle v^2 \rangle = \frac{1}{2} G m^2 N \left\langle \frac{1}{r} \right\rangle \tag{1.4}$$

where $\langle 1/r \rangle$ is the mean inverse distance of the galaxies, so that we have a rough estimate of the mass in the cluster:

$$Nm = \frac{2\langle v^2 \rangle}{G\langle 1/r \rangle} \tag{1.5}$$

since all the quantities on the right are things we can measure. When comparing these two methods, the virial theorem and the luminosity conversion, we find that baryonic matter is not even close to the total amount of matter in the cluster.

Some time later, in the 1960s and 70s, Vera Rubin and her collaborator Kent Ford found further evidence for dark matter while studying the rotation curves of galaxies. What is a rotation curve? When talking about galaxies, a rotation curve describes how the velocity of objects, such as stars, changes as a function of their distance from the center of the galaxy. In order to get a feeling of what the problem seems to be, let's assume a spherically symmetric galaxy (although a bad approximation, this gets the idea across pretty well). If we consider a star, for instance, moving in a circular fashion inside the galaxy, we know that the centrifugal force is given by the gravitational attraction:

$$\frac{v^2}{R} = G\frac{M(R)}{R^2} \tag{1.6}$$

where $M(R) = \int_0^R dr 4\pi r^2 \rho(r)$ is the mass enclosed in a sphere of radius $R$. Clearly, this equation implies a certain expected function $v(R)$:

$$v(R) = \sqrt{\frac{GM(R)}{R}} \tag{1.7}$$

Now, in general $\rho(R)$ will be peaked near the center of the galaxy, so that when we get into the periphery, $M(R)$ will have stopped growing, i.e. it is a constant. This means that far from the center we have $v(R) \sim \sqrt{1/R}$. This theoretical prediction turns out to be basically always wrong for any given galaxy, for which the rotation curves can be determined by looking at the 21 cm line of hydrogen (converting from a blue/red-shift of the spectrum to the velocity of the gas). As we can see below, the velocity seems to saturate:

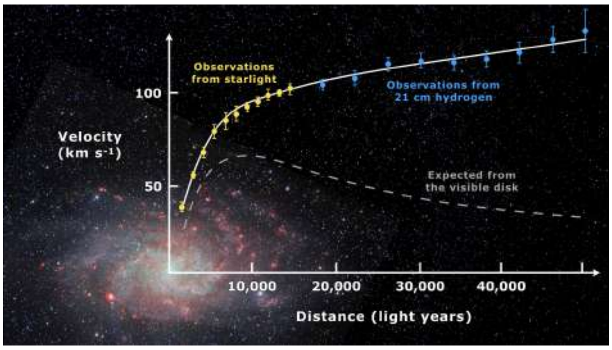


Figure 4: The rotation curve of the galaxy M33

What does this imply? Looking at (1.7), we see that a constant $v(R)$ far from the center is obtained if $M(R) \sim R$, that is the mass keeps growing. All in all we are starting to see a pattern: there is a certain mass that we can't seem to see. Since "seeing" implies some sort of interaction with matter or photons, this matter is labeled as non-interacting, or, better, "dark".

There is other stunning evidence for dark matter. This is seen through a phenomenon called gravitational lensing. It turns out that, in General Relativity, the trajectory of light (the geodesic) gets bent in the presence of massive objects, like cluster of galaxies; this allows us to see objects that are behind such clusters, and they will be more or less distorted, depending on how massive the lens is. Examples of gravitational lensing are shown below:

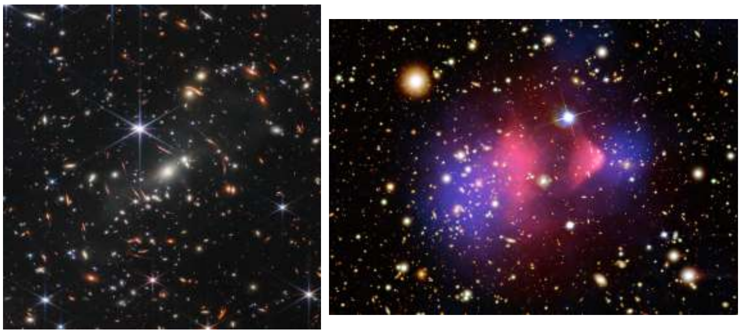

Figure 5: *Left*: the James Webb Space Telescope deep field. *Right*: the Bullet cluster

On the left we can see the first deep field of the James Webb Space Telescope, capturing thousands of galaxies, some of which are clearly distorted by the massive cluster in the middle of the picture. It should be intuitive that, given a lensed image of an object, like a galaxy or a group of galaxies, we can infer the mass of the lens. This is done for the Bullet cluster as we see on the right-hand side, formed by two clusters that are thought to have previously collided. Three types of matter are shown: the stars, the hot baryonic gas (baryonic matter not in the form of stars), shown in pink, which interacts rather strongly as the collision is taking place, and finally the dark matter, shown in purple, which clearly doesn't seem to have interacted with anything during the collision, since each cluster's halo looks basically unaffected. Again, this suggests that this type of matter is non-interacting.

All this evidence, for now, points towards a new type of non-interacting matter at macroscopic scales. There is, however, some last bit of evidence even at way smaller scales.
It turns out, in fact, that the abundances of light elements, like hydrogen and helium, that make up the baryonic matter in the Universe (combined, hydrogen and helium make up roughly 100%), can be estimated via an accurate theory called *Big Bang Nucleosynthesis*. The baryon energy density that we get with this theory is, unsurprisingly, in contrast with mainly two observations. Unfortunately, the math being quite involved, we cannot dwell too much on these discrepancies, but rather we will give just a rough idea. For starters, it can be shown that, if dark matter did not exists, the amount of baryons would not be sufficient to form the galaxies we see today in the Universe. Basically, baryons need to be "gravitationally assisted" by dark matter. Finally, the total amount of matter (baryons and dark matter) influences the *cosmic microwave background* (CMB), a background radiation whose properties are known to incredible levels of precision. Again, if the baryons were all that existed, the CMB predictions would look rather wrong.

### 1.2.2 Radiation

Cosmologists usually label as radiation every particle whose momentum is much larger than its mass, an example clearly being photons, since they are massless. All the photons in the Universe are in the form of a background radiation, which we mentioned before.
Finally, in general, very light particles are considered radiation as well, like neutrinos, which turn out to have a non-negligible impact on the evolution of galaxies. In total, the radiation makes up roughly 0.01% of our Universe, a rather small percentage.

### 1.2.3 Dark Energy

To understand this last piece, we need to briefly explain the historical situation in cosmology at that time. Famously, Edwin Hubble in 1929 observed that galaxies moved away from our own at speeds proportional to their distance, i.e. the farther they were, the faster they moved. This is usually regarded as the first evidence of the fact that our Universe is *expanding* (actually, the expansion of the Universe was already predicted by Friedmann some years prior). Hubble presented his findings in a "Hubble diagram", as we see below (together with more recent measurements):

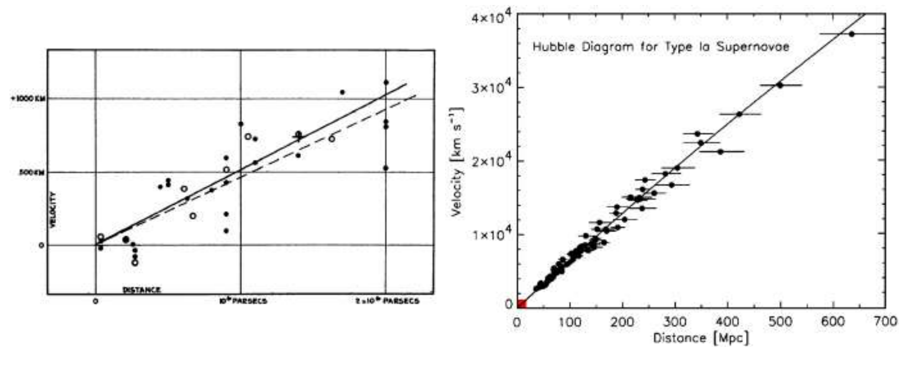


Figure 6: *Left*: Hubble's original results from his article in 1929. *Right*: the same diagram, but with more data points

In general, it is clear that such a diagram implies:

$$v_{\rm gal} = H_0 D \tag{1.8}$$

where $D$ is the distance of the galaxy, and $H_0$ is a constant, dubbed the *Hubble constant*, that we will encounter and explain in more details later on. What does this have to do with the rest of the energy content of the Universe? It turns out that this diagram was reasonably well fitted by a Universe with only matter and some radiation. However, at that time this "matter-only" model was in serious trouble, mainly for two reasons. First, it predicted the age of the Universe to be smaller than the age of some of the oldest stars within it; secondly, some other observations suggested that matter was only roughly 30% of the total content of the Universe. Incredibly, in the 1980s, very precise measurements of distant supernovae explosions, showed that they appeared fainter than a matter-only Universe predicted:

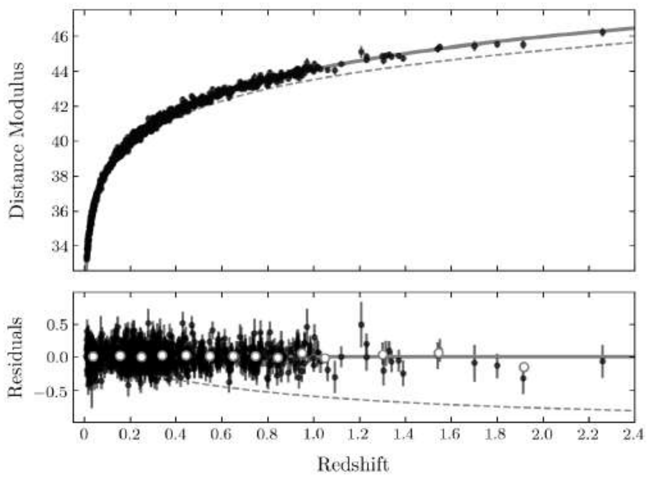


Figure 7: Distance of supernovae as a function of their redshift. The dashed line is the "matter-only" Universe, whereas the solid line introduces a dark energy component

The data could only be consistent if the Universe started *accelerating* sometime recently, and this is possible in General Relativity if one admits the existence of some sort of energy that doesn't dilute with the expansion of the Universe, some sort of *dark matter*. Fitting these new results, then, cosmologists deduced that this new component makes up a good 70% of our Universe. Its nature is still a mystery.

## 1.3 Large Scale Structure

We now Understand what the Universe is made of. To complete our observational tour-de-force we need to explain what the geometry of our Universe looks like and how the components are arranged in this geometry.
We start with the second topic. There is very good reason to believe that our Universe is *spatially homogeneous* and *isotropic* at very large scales (say, scales greater that 100 Mpc, since clearly it is not so locally). These are arguably the two most important attributes of the Universe, because they ensure that observations made from any vantage point (like where we are), are representative

of the whole Universe. This is clearly very powerful when it comes to testing our theories, made from our standpoint, against the properties of the distant Universe. The most incredible evidence for the isotropy of the Universe is the background radiation we mentioned before, the CMB:

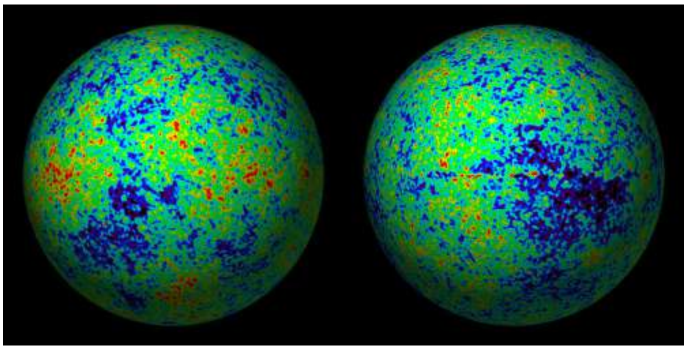

Figure 8: The cosmic microwave background as seen in the sky. The colormap distinguishes hot spots (red) from cold spots (blue). Note that the difference in temperature is of the order of $10^{-5}$ K.

Notwithstanding the origin of this background radiation, we only note that it is the most perfect black body we have in nature, at a temperature of $\bar{T}_0 = 2.73$ K. More importantly, this temperature is exactly the same (except minor fluctuations of the order of $10^{-5}$ K) in every direction we look.
In addition to the CMB, lately large galaxy surveys like the 2dF (2 degree field) survey, computed the position and distance of a huge number of galaxies. Strikingly, at scales $\gtrsim 100$ Mpc, they are distributed homogeneously and isotropically:

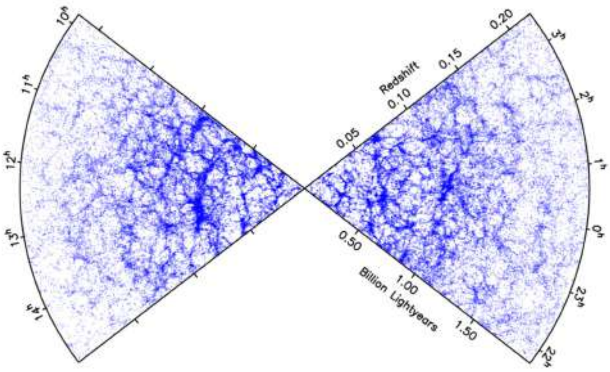


Figure 9: The 2dF galaxy survey

Finally, the last piece of observation regards the spatial geometry. It turns out that, by measuring the properties of the CMB (we are starting to see that this radiation is a rich source of information), we can distinguish between different geometries; this is roughly because the photons travel in very specific ways (they follow geodesics) in the respective geometries, leaving an imprint on the CMB. Very insipidly, our Universe looks very much *flat*, with no hint of any spatial curvature.

## 1.4 Where do we go from here?

Let's summarise what we know so far. Our Universe is mostly made of dark energy, a mysterious entity, dark matter, baryons and some radiation. Moreover, these components, if we zoom out enough, are distributed in an isotropic and homogeneous fashion throughout a space that looks flat. Finally, not only is the Universe expanding, but it is doing so while also accelerating.
What do we do now with these facts? Miraculously, cosmologists have devised a model, called the $\Lambda$*CDM model*, which explains to a high degree of precision every observation that we have listed. This model is the center of focus of the remaining lectures.