The Dark Universe

Catherine Heymans presents the cosmological toolkit of observations to uncover the nature of dark matter and dark energy.

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For Triple Trouble; Magic Molly, Lanky Luke and Chocolate Jake.

Contents

Abstract

Just over 95% of our Universe comes in the shrouded form of dark energy and dark matter that we can neither explain nor directly detect. Together, these two dark entities play out a cosmic battle of epic proportions, with the gravity of dark matter slowly pulling structures in the Universe together, and dark energy fuelling the Universe's accelerated expansion, making it ever harder for those structures to grow. In this book we will explore this dark enigma and introduce the cosmologist's toolkit of observations and techniques that allow us to confront different theories on the dark Universe. I'll explain why I believe that, to truly understand the dark Universe, we will need some new physics that will forever change our cosmic view.

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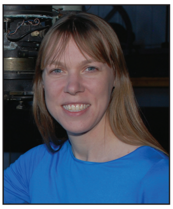
Author biography

Catherine Heymans



Catherine Heymans is professor of observational cosmology at the Institute for Astronomy in the University of Edinburgh, UK, and a European Research Council fellow. She specialises in observing the dark side of our Universe and co-leads the European Southern Observatory KiDS analysis team, using deep sky observations to test whether we need to go beyond Einstein with our current theory of gravity. Catherine has co-authored over 100 technical articles in peer-reviewed journals and a number of articles for *Physics World* magazine. She is devoted to promoting the public's understanding of her research, both virtually through a Massive Open Online Course 'AstroTech', which has attracted over 30 000 students worldwide, and in person through a wide range of events including art and science festivals. In recognition of this work, she was awarded the 2017 Darwin Lectureship from the Royal Astronomical Society. When Catherine is not busy unveiling the mysteries of the Universe or enthusiastically lecturing undergraduates, she can usually be found building sandcastles and paddling in the sea with her three small children.

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The Dark Universe

Catherine Heymans

Introduction

I'm told that at the tender age of six, I asked my class teacher 'What is the most challenging job in the world?', to which she replied 'Brain surgeon or astrophysicist'. It took a full decade before deciding which of these two career paths I would follow, but by the time I had acquired a degree in astrophysics, I found myself asking my course professor a very similar question: 'What is the most challenging PhD topic in the world?', to which he replied 'Finding out why the expansion of our Universe is accelerating'. My very first thought was—'accelerating???'

Now I knew at this point in my career that our Universe was a strange place, filled with a mysterious substance called dark matter that neither emitted nor absorbed light and whose gravity determined where and when the galaxies, that we can see, would form. I also knew that everywhere astronomers looked, those galaxies were moving away from us in an ever-expanding Universe whose motion had been kick-started by the Big Bang. Up until this point, I had, however, felt quite grounded in the thought that one day, gravity would conquer all. The Universe would collapse back in on itself, restarting an eternal cycle of explosive death and fiery re-birth that seemed to gel with my philosophy at that time. In this brief, career-defining moment, my professor had changed my entire world view. Accelerated expansion meant a Universe that carried on growing forever. Accelerated expansion meant that the stars would slowly burn their last reservoirs of fuel and one-by-one the galaxies would switch off their lights leaving a very cold, sad and empty Universe. Accelerated expansion simply made no sense! What possible source of energy could there be to fuel this ever increasing expansion of the Universe? Clearly no-one actually knew, as they had called it the very non-specific and completely general name 'dark energy'. The challenge had been set and I accepted it.

Two decades on, and we now have a vast wealth of independent and complementary data sets supporting the theory of a dark Universe. One shining example is the exquisite observations of the cosmic microwave background (CMB) by the Planck satellite, which provided an image of the early Universe as it was just 380 000 years after the Big Bang (see figure 1). By adopting a model of our Universe comprised of dark matter, dark energy and baryons—the ordinary visible particles that are described by the Standard Model of particle physics—we can predict the patterns

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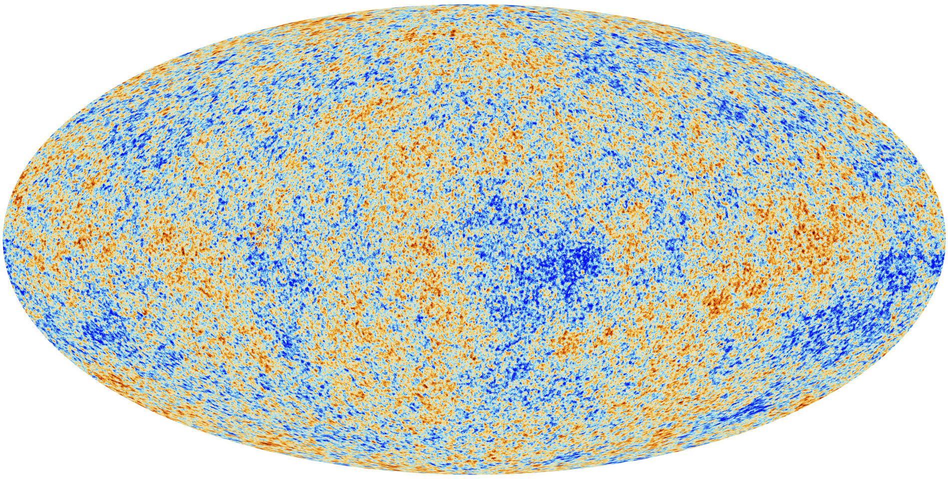

Figure 1. Temperature fluctuations in the cosmic microwave background (CMB) as imaged by the Planck satellite. Adopting a model of the dark Universe, theorists can predict the number and scale of the 'hot' spots (red) and 'cold' spots (blue) that are observed. Confronting theoretical predictions with Planck's observations has provided the most precise measurements to date of the different components in our Universe finding 26.6% dark matter, 68.5% dark energy and 4.9% baryons. Image credit: ESA/NASA.

that we should see in the small temperature fluctuations of the CMB across the sky. The resulting match between theory and Planck's data is impressive, providing the strongest evidence yet that the Universe we live in is very dark indeed with 26.6% dark matter, 68.5% dark energy and 4.9% baryons. This level of precision is a great testament to the ground-breaking developments in science and technology over the past 30 years, but unfortunately they get us no closer to finding out the answer to a much bigger and further-reaching question: what is the exact nature of this dark Universe?

It's widely believed that to truly understand the dark Universe, we will need to invoke some new physics that will forever change our cosmic view. As the conclusion of this dark quest could be so far reaching, astronomers are approaching the task with care using a series of independent and meticulous observations. This book introduces the new techniques that will be the foundations for modern observational cosmology over the coming decade. A decade where we will see three major international projects image the sky to greater depths and resolution than ever before. The Euclid satellite will image the full dark sky from above the Earth, the Large Synoptic Survey telescope (LSST) will image the full Southern sky from a mountain top in Chile and the Dark Energy Spectroscopic Instrument (DESI) will take spectra of over 30 million galaxies. These projects will chart the distant Universe, mapping the evolution of the dark-matter structures and documenting the accelerating expansion and curvature of space and time from 10 billion years ago to the present day. On completion, our goal will be to understand the fundamental physics that govern the dark side of the Universe.

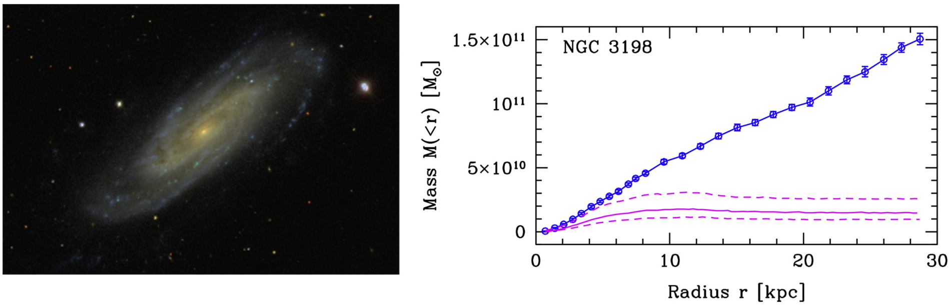

Figure 2. (Left) Spiral Galaxy NGC 3198, imaged by the Sloan Digital Sky Survey. The distance from the centre to the edge of the visible disk of stars is roughly 8 kpc = 2.5×10^{19} m. (Right) The mass $M_*(<r)$ enclosed within a radius r as inferred from the distribution of visible stars, i.e. the stellar mass (shown in pink with the uncertainty on this measurement indicated by the upper and lower dashed pink curves). This can be compared with the total mass, $M(<r)$ inferred from the rotational velocities of stars (blue data points). As the radius increases, the total enclosed mass continues to grow. The stellar mass, in contrast, stops increasing at roughly 8 kpc, where the visible stellar disk ends. This discrepancy provides strong evidence to support the theory of dark matter. Data Source: Matthew Bershady and collaborators.

Background

Dark matter

Our own Milky Way Galaxy contains over 300 billion stars lying in a spiralling rotating disk similar to the galaxy NGC 3198 that is pictured in figure 2. As the stars orbit around the centre of our Galaxy, it is the gravity of the system that ensures that they don't fly off into the Universe! The faster the stars rotate about the galactic centre, the more gravity, or mass, there must be to keep the stars bound, which can be seen by equating the centripetal force experienced by an orbiting star of mass m with the gravitational force;

$$\frac{mv^2}{r} = \frac{GM(<r)m}{r^2} \Rightarrow M(<r) = \frac{v^2 r}{G}. \qquad (1)$$

Here G is the gravitational constant, m is the mass of a test star moving at speed v in an orbit with radius r, and $M(<r)$ is the mass of the galaxy that is enclosed within the test star's circular orbit.

Scientists who study the evolution of stars can provide an excellent estimate for the masses of different types of stars such that we can calculate how much stellar mass there is enclosed at different radii, $M_*(<r)$, stepping outwards with increasing r from the centre of the galaxy. Eventually we'll reach the edge of the visible galaxy, at which point the enclosed stellar mass $M_*(<r)$ becomes a constant, the total stellar mass of the galaxy.

The disk of stars imaged in figure 2 is rotating anti-clockwise, with the stars at the bottom of the image moving towards us, and the stars at the top of the image moving away from us. The light that we collect from these rotating stars will experience a Doppler shift with the stars that are moving towards (away) from us appearing very slightly bluer (redder) than a typical star. These precise Doppler measurements of the rotation speed at different radii can be used to calculate the galaxy mass $M(<r)$ using equation (1).

The right panel of figure 2 shows data collected from the spiral galaxy NGC 3198, comparing the galaxy mass that is required to keep the stars bound (blue) with the stellar mass that can be seen (pink). As we head towards the edge of the visible galaxy, we find that instead of the enclosed mass becoming a constant, as we would have predicted based on the stellar mass that we can see, the actual enclosed mass in the galaxy needs to continue to grow in order to keep the rotating stars bound.

This startling result can lead you to one of two conclusions. The first option is that equation (1) is wrong. But while it is a noble pursuit to question the core foundations of physics, we will work under the assumption, for now, that we do understand gravity such that the favoured conclusion is option two; there is a massive clump of invisible dark matter surrounding this galaxy.

Vera Rubin was the first to measure galaxy rotation curves in the mid-1970s, and initially her work was met with fierce scepticism. Measurements made by Fritz Zwicky in the 1930s of the faster-than-expected rotation of hundreds of galaxies within the massive Coma Cluster of galaxies, was also similarly disbelieved. But with the accumulation of more and more data all reaching the same conclusions as Rubin, Zwicky's original theory on the existence of dark matter has become a steadfast cornerstone of modern day cosmology.

What is dark matter?

The current leading theory for the nature of dark matter is that it is made up of cold non-baryonic massive particles that only weakly interact with the baryons through gravity and the weak nuclear force. This is a compelling model as it neatly solves the puzzle for how structure formed in the Universe. If there was no dark matter then the galaxies that we can see in the Universe wouldn't be distributed in the clumps and filaments that we observe today. It's the underlying cosmic web of dark matter that provides the scaffolding upon which the visible Universe is built.

Dark energy

In the 1990s, two teams of astronomers pioneered a method to find and use distant supernovae as standard candles to probe the Universe. What they found was so startling it resulted in them winning the Nobel Prize, and in me becoming a cosmologist.

A supernova SN1a explosion is the final episode in the turbulent life of a binary pair of unequal mass stars. The more massive star in the pair will evolve faster than its companion, such that by the time it has evolved to become an extremely dense white dwarf star, its partner is in the bulging red giant phase. The gravity of the white dwarf will strip the red giant of its loosely bound outer layers, resulting in the increase of its own mass. This cannibalism will only cease when the mass of the white dwarf approaches the ‘Chandrasekhar mass limit’, which is $1.44M_{\odot}$, where $M_{\odot}$ is the mass of our own Sun. Above this mass limit, Subrahmanyan Chandrasekhar showed that the electron degeneracy particle pressure[1], which has been supporting the white dwarf until this point, will no longer be sufficient to prevent the complete gravitational collapse of the dwarf’s core into a black hole. As this cataclysmic event always occurs at the same limiting mass, the light emitted by this explosion has roughly the same total energy, or luminosity L. This is known as a ‘standard candle’.

Finding supernovae requires constant monitoring of the same patch of sky, looking for objects that rapidly increase in brightness, by almost two orders magnitude over the course of two weeks, and then slowly decline by four orders of magnitude over the course of a month. If you can find an SN1a, you can measure its light curve, which is the variation of its flux f over time. Given a calibrated standard SN1a luminosity light curve L you can then immediately calculate distances D_L to all the supernovae that you’ve detected;

$$f = \frac{L}{4\pi D_L^2}. \tag{2}$$

An alternative method to determine distances to any object in the Universe is through the measurement of their redshift, which is defined as

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e}, \tag{3}$$

where λ_e is the wavelength of the light emitted by the distant galaxy and λ_o is the wavelength of the galaxy’s light that we observe from Earth. Spectra are observed from a distant supernova, and by identifying key chemical features, such as calcium, oxygen and silicon, both the observed, λ_o, and the emitted, λ_e, wavelengths can be determined and a redshift of the SN1a calculated.

The relationship between redshift and distance depends on the speed of the expansion of the Universe. There is a popular misconception, however, about why this relationship exists. Often you will hear that as photons of light from distant galaxies travel through the expanding Universe, their wavelengths are ‘stretched’ by the expanding space. Termed ‘cosmological redshift’, the more distant the Galaxy, the more the photons are stretched and hence the higher the redshift that is measured. This description is incorrect, however, because it suggests that there is some extra new force in the Universe that can physically stretch things, even massless photons. In an expanding Universe, the space between objects grows, but

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[1] Degeneracy pressure arises from a fascinating quantum phenomenon that kicks in when matter is squeezed to incredibly high densities. The Heisenberg uncertainty principle of quantum physics states that it is impossible to define the position x and momentum p of a particle to an accuracy which is better than $\Delta x \Delta p \geqslant \hbar/2$, where $\hbar/2\pi$ is Planck’s constant. For extreme density environments, the separation between particles (i.e. the uncertainty in the position of each particle) Δx is, by definition, very small. To satisfy the Heisenberg uncertainty principle, the average particle momentum p or the velocity must therefore be very high. This quantum random motion provides a source of pressure, known as degeneracy pressure, that supports some of the coolest densest objects in the Universe such as white dwarfs and neutron stars.

just because the space between the objects is expanding that does not mean that the contents of the Universe are expanding as well! Imagine standing on an expanding sheet of frictionless ice, just because the ice is expanding, it doesn't mean your legs will move apart. The correct interpretation of redshift is to consider a string of observers lining the light path from a distant galaxy to our telescopes on Earth. All these observers are moving away from each other with what is known as the 'Hubble flow', the motion initially seeded by the Big Bang. Each time the light is passed from one observer to the next, the observer will record a small Doppler shift. The further away the galaxy is, the more little Doppler shifts the emitted galaxy light will experience, and the further the light is shifted towards the redder wavelengths.

The Hubble parameter H_0, quantifies the rate of the expansion of the Universe, defined to be the constant of proportionality between galaxy recession speed and distance in the expanding Universe today. The relationship between redshift and distance will also depend on the rate of change of that expansion—that is to say, whether the expansion is accelerating or decelerating, quantified through the now quite ironically named 'deceleration parameter', q. For a decelerating Universe, which was the belief before the supernova results, $q > 0$. The equation for the full distance–redshift relation is quite extensive, but for redshifts with $z < 1$, a good approximation is given by

$$D_L \simeq \frac{c\left(z - \frac{1+q}{2}z^2\right)}{H_0(1+z)}. \tag{4}$$

In equation (2) we have a method to obtain direct measurements of distances in the Universe. In equation (4) we have a method to obtain an indirect measurement of distance that depends on the rate of expansion of our Universe. Figure 3 shows the results from four different supernova experiments where each line represents a different supernova explosion. On the x-axis is the redshift z measured from the spectrum of each supernova. The y-axis of the upper panel shows the direct measurements of the distances to the supernovae D_L. The lines show the distance–redshift relation (equation (4)) for different values of the deceleration parameter q and the lower panel shows the data with a $q = 0$ model subtracted to highlight the deviations of the data from this empty universe model.

The supernova data shows that the high redshift Universe is significantly further away than the decelerating or empty universe model would predict. The conclusion drawn is that the expansion of the Universe is therefore accelerating, and this finding was called dark energy.

What is dark energy?

While the astronomical community is now fairly united in postulating the existence of an invisible dark matter particle, even though we don't know what that particle actually is, the same cannot be said about its support for the simplest explanation for dark energy. Observations that the expansion of our Universe is accelerating are most easily explained by considering the extra energy associated with the vacuum

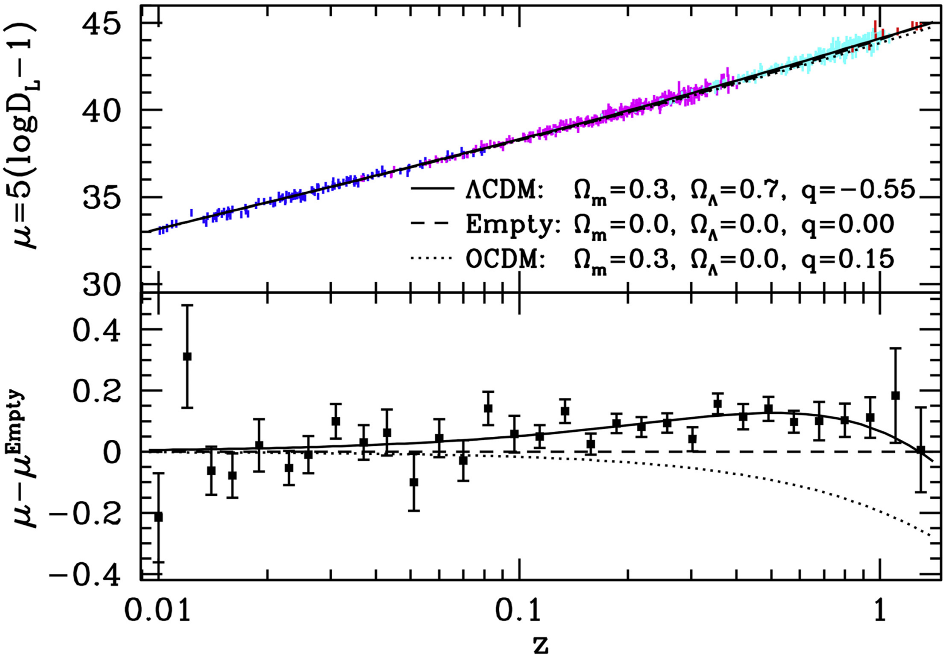

Figure 3. The distance–redshift relation: the upper panel shows a compilation of 740 supernova measurements of distance D_L (y-axis) and redshift z (x-axis) from four different supernova surveys (shown in blue, magenta, cyan and red). Astronomers have long measured the brightness of objects in units of magnitudes and so I've kept to this convention for this figure, where the length of each line indicates the error on each measurement of the 'absolute magnitude' of the supernova μ, which is related to the distance D_L through $\mu = 5(\log D_L - 1)$. The black solid, dashed and dotted lines show the distance–redshift relation (equation (4)) for three different cosmological models, one accelerating with $q < 0$ (solid), one decelerating with $q > 0$ (dotted) and finally an empty Universe that expands at constant speed with $q = 0$ (dashed). With so many supernova measurements, the data points overlap. In the lower panel I therefore show the data binned by redshift, where I have subtracted a distance–redshift relation that assumes an empty model of the Universe, with no dark energy and no dark matter. From this panel we can see that the high redshift supernovae are a lot further away from where they are expected to be in a Universe without dark matter and dark energy. The conclusion is that the expansion of our Universe cannot be decelerating, or expanding at constant speed. The expansion is in fact accelerating, fuelled by a mysterious source of dark energy. Data Source: Marc Betoule and collaborators.

that permeates the Universe. According to quantum theory, empty space is filled with swarm of virtual particles with a wide range of masses that can briefly pop in and out of existence. As mass and energy are equivalent, the growing vacuum within an expanding Universe acts like a bank of unlimited energy, inflating the whole Universe at an accelerated speed.

Unfortunately, there is a problem with this simple and elegant vacuum solution to the nature of dark energy. Particle and quantum physicists can make a theoretical estimate for the energy of a vacuum and they find that it is roughly 60 orders of magnitude larger than the dark energy that the supernova results show. This wild discrepancy has opened up a wide range of exciting new dark energy theories, including exotic models such as a multiverse containing many realisations of different bubble universes. Perhaps our Universe is just one of those bubbles where the value of the vacuum energy is unusually low. Or it could be that the Universe is experiencing a new period of inflation, akin to the rapid period of inflation 10^{-30} s after the Big Bang, when it is thought that an almost instantaneous expansion created the cosmological scales in the Universe that we see today. Maybe a new fundamental force field has recently kicked into action, causing this new phase of accelerated expansion.

Some cosmologists believe that the dark energy phenomenon indicates that we need to look beyond Einstein's theory of general relativity. By observing how dark matter structures change over cosmic time, we can investigate how dark energy evolves and test gravity for the first time on cosmological scales. Just as Einstein revolutionised our understanding of Newtonian gravity, confirmed through observations of the solar system, so new observations of gravity on cosmological scales may bring about another revolution in our understanding of gravity.

Flat ΛCDM and the cosmological parameters of the Universe

The current favoured dark Universe model is called flat ΛCDM. 'Flat' implies that the global geometry of space-time is flat and hence infinite. 'Λ' implies that dark energy exists in the form of a 'cosmological constant'—an arbitrary constant that can be included in Einstein's gravitational field equations to counteract the pull of gravity. 'CDM' implies that the dark matter that exists is 'cold' or non-relativistic. Only five numbers, known as the cosmological parameters, are required to describe the Universe when adopting the flat ΛCDM model. These are:

- The total matter density parameter (dark matter and baryons): $\Omega_m = 0.308 \pm 0.012$
- The baryon density parameter: $\Omega_b = 0.0491 \pm 0.0005$
- The amplitude of the density fluctuations, i.e. the variance in the distribution of matter, measured on 8 Mpc scales[2]: $\sigma_8 = 0.830 \pm 0.015$
- The scalar spectral index[3]: $n_s = 0.968 \pm 0.006$
- The Hubble parameter: $H_0 = 67.8 \pm 0.9$ km s^{-1} Mpc^{-1}

You may be wondering why dark energy is not mentioned in this list! In a flat universe the total density of matter and energy is equal to the density that gives zero global curvature of space-time. Known as the 'critical density', ρ_{crit}, is equivalent to just six protons per cubic metre today. The total matter density parameter, Ω_m, is defined as the ratio between the matter density ρ_m, and the critical density, $\Omega_m = \rho_m/\rho_{crit}$, and hence—for a flat universe—the dark energy density parameter $\Omega_\Lambda = 1 - \Omega_m$.

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[2] A megaparsec, 1 Mpc = 3.086×10^{22} m.

[3] A scalar spectral index $n_s = 1$ means that the density fluctuations that you can measure are independent of the distance scales that you measure them on. Models of Inflation predict that n_s should be slightly less than 1.

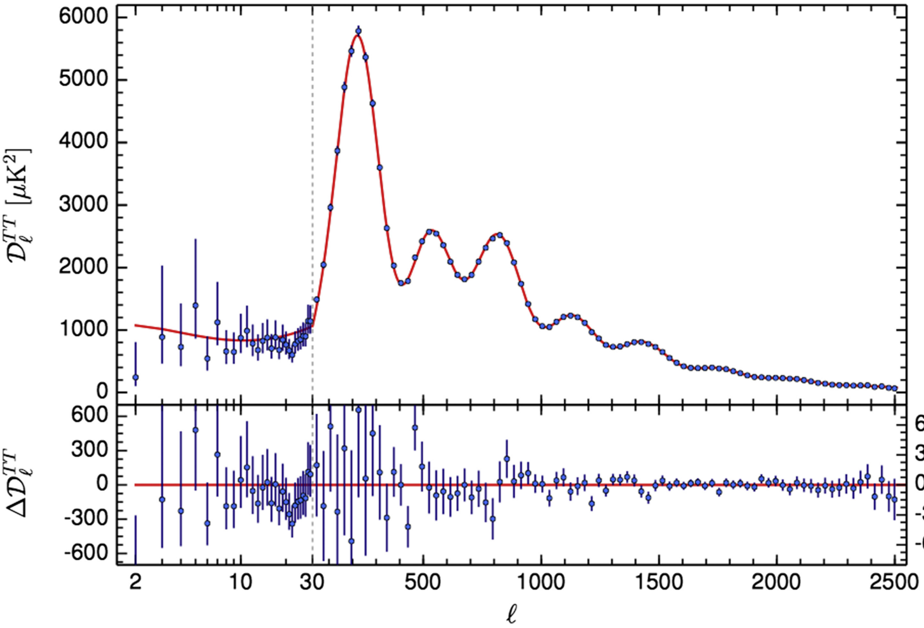

Figure 4. The Planck 2015 cosmic microwave background (CMB) temperature power spectrum showing the absolute amplitude of the CMB temperature fluctuations D_ℓ^{TT} as a function of scale ℓ (blue dots). This complex function is predicted from a theoretical model assuming the ΛCDM cosmological parameters listed in the text (red curve). As the agreement between the data and the prediction is so exquisite, the lower panel shows the 'residual' between the data and the ΛCDM model, highlighting that there are hardly any differences between the theory and the CMB observations. Image credit: Planck Collaboration.

Cosmological constraints from the cosmic microwave background

The numbers in our list of cosmological parameters are the most precise measurements to date, determined from measurements of the CMB by the Planck Collaboration. Figure 4 shows the absolutely exquisite agreement between the Planck CMB data (blue dots) and the flat ΛCDM model determined with these numbers (red curve). Most of my students are aware of this truly iconic result, named the CMB power spectrum. It is rare, however, that they can explain what is shown, only parroting the jargon that it is the 'Fourier transform of the CMB temperature fluctuations'. But what does that actually mean?

The back story starts in the very early hot dense Universe, when the Universe is opaque with photons repeatedly scattering off the hot charged particles. During the rapid period of inflation 10^{-30} s after the Big Bang, tiny random quantum fluctuations are inflated leaving large-scale fluctuations in the distribution of matter. Gravity will always try to clump these matter particles together, but in this early radiation dominated Universe, the photons are so dense that the radiation pressure can push the collapsing clumps of baryons apart again. Local battles break out across the Universe, called 'acoustic oscillations'. It's a tale of gravity versus photon pressure.

As time marches on, the expanding Universe grows and cools and the charged particles combine to form neutral atoms. This point in the history of the Universe is known as ‘recombination’, some 380 000 years after the Big Bang. The photons can now freely travel as the Universe becomes transparent and the on-going battles immediately end. The battle scars are, however, forever imprinted in the energy distribution or temperatures of those photons, and in the spatial distribution of the baryons. In regions of space where gravity was winning the battle right before recombination, the photons will be slightly hotter than average (the red hot spots in figure 1). Where the photon pressure was winning and the clumps of baryons were expanding again, the photons will be slightly cooler than average (the blue cool spots in figure 1).

There is a fixed time between the end of inflation and recombination that will depend on the rate of expansion (quantified through the Hubble parameter H_0), the total amount of matter Ω_m, and the baryon density Ω_b. In that time, small-scale clumps will experience many victories and defeats for both sides in the battle. As the size of the clump and the corresponding collapse time increases, there will be fewer oscillations between the compressed and expanded states. As the CMB provides a snapshot at the precise moment of recombination, the locations of the maxima and minima in the temperature of the photons are associated with a preferred distinct set of distance scales, the set of baryonic clumps that experienced an integer number of oscillations.

The CMB power spectrum in figure 4 shows the absolute amplitude of the CMB temperature fluctuations (D_ℓ on the y-axis) as a function of scale (ℓ on the x-axis). It is indeed constructed from the Fourier transform of the CMB temperature fluctuation map in figure 1. All this transform does, however, is to re-formulate the information in the CMB map. The power spectrum isolates features at different angular scales on the sky, reporting the average absolute variation from the mean global CMB temperature of 2.73 K, at each scale. Just to confuse those of us who live in the real-world, in Fourier space the small-scale fluctuations on the sky have a large ℓ and the large-scale fluctuations on the sky have a small ℓ.

The peaks seen in the power spectrum reveal preferred scales with the first peak at $\ell \sim 200$, roughly 1 degree on the sky, corresponding to the largest scale fluctuation to have reached maximum compression at recombination. The second peak corresponds to the fluctuation that experienced one cycle of compression and expansion and so on. The position and relative heights of these peaks contains a wealth of information that is used to constrain the flat ΛCDM cosmological parameters, and further extensions to them. In modern-day cosmology, this CMB data is the foundation upon which we now seek to build our understanding of the dark Universe.

Current directions

The default position on the dark Universe for many astronomers is flat ΛCDM, with a heavy reliance placed on the particle physicists to resolve the quandary of why dark matter is believed to be the theoretically postulated cold supersymmetric partner to the particles that we are already familiar with. Dark energy is believed to be a cosmological constant with its low value, in comparison to the theoretical expectation of the vacuum energy, put down to an unlikely fluke when our Universe was made. The challenge for observational cosmologists is to directly confront this position, looking for any observations that deviate from the expectations of this default model. The CMB observations that favour this model tell us about the Universe right after the Big Bang, when dark energy played little role. If we want to understand dark energy and dark matter, we need to probe these two dark entities in the recent Universe during the era of structure formation when they are playing out a cosmic battle of epic proportions. While the gravity of dark matter slowly pulls structures in the Universe together over time, dark energy fuels the Universe's accelerated expansion, making it ever harder for those dark-matter structures to grow.

To rigorously test the flat ΛCDM model and Einstein's theory of gravity that underpins it, we need both geometrical probes to monitor the rate of the accelerated expansion and probes of the growth of structures in the Universe over time. In addition to the observations of supernovae and the CMB, we have four powerful techniques in our cosmologists' toolkit: weak gravitational lensing, baryon acoustic oscillations, galaxy clusters and redshift space distortions, I'll describe these in turn, providing a recent example where these measurements have been carried out using survey data. I do not wish to mislead you into thinking that the experiments I mention are unique, though, and refer you to the resources section for a list of review articles and papers that will give you a more complete overview of the extensive field of observational cosmology.

Weak gravitational lensing

If you are unfamiliar with gravitational lensing (and even if you're not, you may like this analogy) take a look out of your nearest window and ask yourself: how do I know the glass is there? Perhaps there are some little imperfections, or some raindrops that distort your view? If you see raindrops, the reason they are apparent is that these transparent globules bend the light travelling from an object beyond the window, from a tree, say, to your eye. And because you know how the scene outside should look in the absence of distortions, you infer the existence of the raindrops.

To apply the same thinking to gravitational lensing, you need to swap the trees for galaxies billions of light-years away. And for the raindrops, replace these tiny transparent objects with huge transparent clumps of dark matter, sitting between the distant galaxies and you. Finally, the physical reason for why the light is being bent is different: while raindrops simply refract light, clumps of dark matter bend the very fabric of space-time, and the path that the light is travelling along, gets bent with it.

Galaxy clusters like Abell 1689 in figure 5, provide the most striking images of this gravitational physics in action. The giant arcs that encircle these clusters show the highly distorted light emitted by distant galaxies situated almost directly behind the cluster. From Einstein's theory of general relativity you can calculate how the angle by which that light has been deflected is directly related to the mass of

Figure 5. Cluster Abell 1689 as imaged by the Hubble Space Telescope. The large yellow galaxies are members of this massive cluster, all hosted within a dense clump of dark matter that gravitationally distorts the local space and time around the cluster. The small blue objects are distant galaxies that are behind the cluster. As their light travels towards Earth, it becomes distorted as it passes by the cluster. This gravitational lensing effect bends the images of the background galaxies into the giant curved blue arcs that you can see surrounding Abell 1689. And what about those five blue dots with rainbow crosses around them? These are just stars in our own Milky Way Galaxy. The crosses are not a real cosmic feature though. They simply arise from light diffraction around the four struts that hold the secondary mirror in place within the Hubble Space Telescope. Image credit: NASA/ESA/STScI.

the lens, providing a unique way to measure the mass in the Universe. Strong lensing events where you can see the arc-like distortion by eye, are really quite rare. It's therefore a good job that actually every galaxy in the Universe tells us something about the structures of dark matter between it and us, even if its light has only been very mildly distorted, or weakly lensed, in a way that is imperceptible to the eye.

With weakly lensed galaxies you quickly come across a dilemma: how do you know if an elliptical galaxy, for example, looks that shape because it actually is that shape, or because its light has been gravitationally lensed? Help to answer this question comes from the other galaxies in the neighbourhood.

Imagine light travelling towards us from two nearby galaxies. As the light travels across the Universe, it will pass by the same structures of dark matter, and hence experience the same gravitational distortion (see illustration in figure 6). When we look at those two galaxies in the sky, they will appear to be very weakly aligned, and the more dark matter they have passed, the stronger the alignment will be. By assuming that galaxies are randomly oriented in the Universe, we could average their shapes in different patches across the sky. If there were no dark matter, the average galaxy shape in the patch would just be a circle. With dark matter however, we'll find the average galaxy shape to be an ellipse. The stronger the average galaxy ellipticity is in the patch, the more dark matter there is in that region of the Universe. This induced ellipticity is a faint signature that dark matter writes across the cosmos

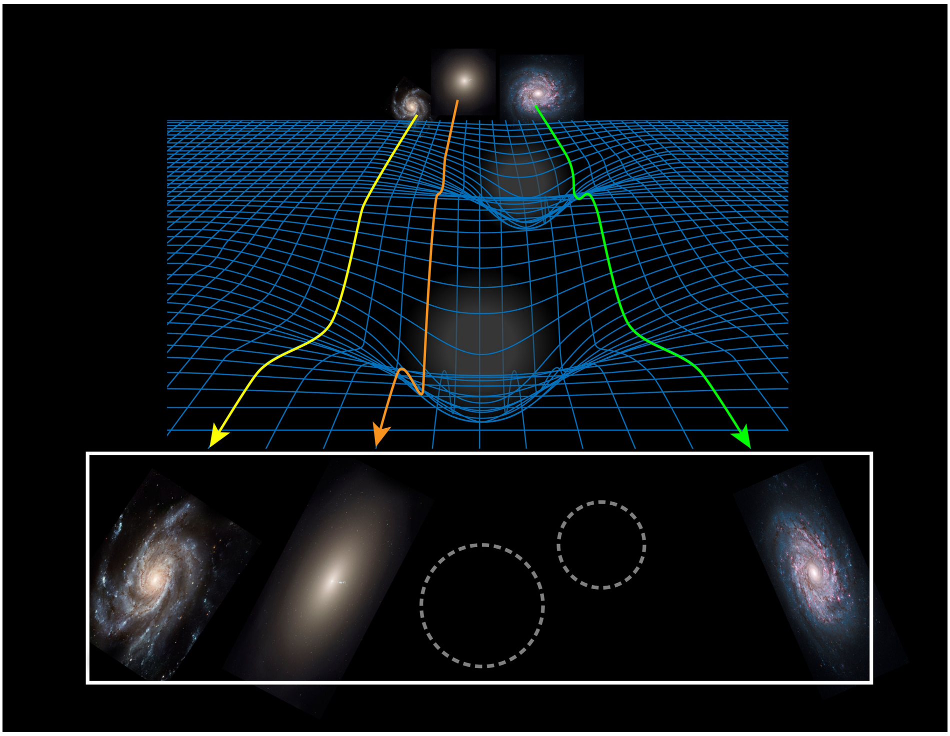

Figure 6. An illustration of weak gravitational lensing. As light from distant galaxies travels towards us, it passes by massive structures of dark matter (shown here as grey spheres). The gravity from this dark matter curves the local space-time and hence also the path that the light follows. This curvature distorts the images of the background galaxies that we then observe, with the amount of distortion depending on the distribution of dark matter along the light path. Galaxies that are near to each other in the sky (as shown on the left side) are distorted equally, making them appear to be aligned. By measuring this alignment, we can infer the size and location of invisible massive structures (dotted circles), and thereby construct a map of the dark matter, where an example is shown in figure 7. Image credit; APS/Alan Stonebraker; galaxy images from STScI/AURA, NASA, ESA, and the Hubble Heritage Team.

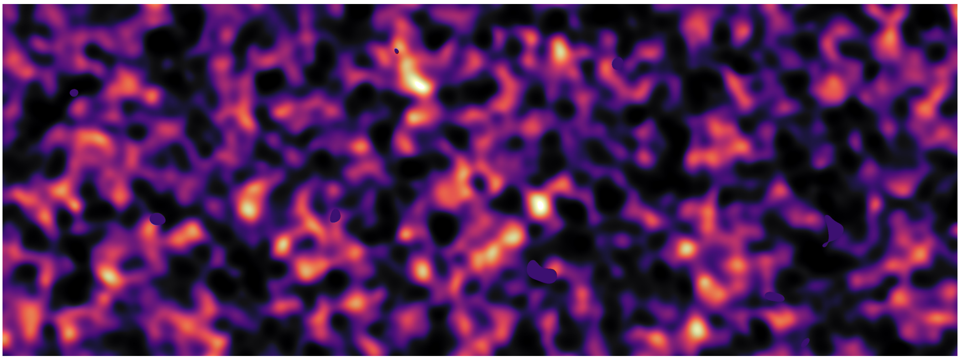

Figure 7. This map of dark matter in the Universe was obtained from data from the Kilo-Degree Survey (KiDS), using the Very Large Telescope Survey Telescope in Chile. It reveals an expansive web of dense (light) and empty (dark) regions. Here the invisible dark matter is seen rendered in pink, covering an area of sky around 420 times the size of the full moon. This image reconstruction was made by analysing the light collected from over three million distant galaxies more than six billion light-years away. The observed galaxy images were warped by the gravitational pull of dark matter as the light travelled through the Universe. Image Credit: Kilo-Degree Survey Collaboration/H Hildebrandt, B Giblin/European Southern Observatory.

to tell us exactly where it is and how much of it there is, as seen in the map of dark matter in figure 7.

The Kilo-Degree Survey (KiDS) measured the positions, shapes and photometric redshifts of over 15 million galaxies. Figure 8 shows the measurement of the alignment between pairs of galaxies as a function of their separation on the sky, known as the two-point shear correlation function. At small separations, you see a strong alignment signal, as the light from the two galaxies has travelled past the same structures of dark matter and hence has been lensed and distorted in the same way. At larger scales, the galaxies' light has travelled through different parts of the Universe and so the alignment signal tends to zero. The more dark matter there is Ω_m, or the more clumpy the dark matter is σ_8, the stronger the lensing effect and hence alignment signal.

Looking further away in our Universe is the same as looking back in time, with gravitational lensing surveys like KiDS so far having mapped objects as far as 10 billion light-years away when the Universe was only about four billion years old. This technique has therefore let us map dark matter in different epochs in the history of the Universe. Looking at the evolution of the cosmic web has allowed us to measure how dark energy has affected the growth of those structures. What the KiDS team has found doesn't quite fit with the flat LCDM model favoured by Planck. The Planck data suggest a much clumpier Universe than the lensing surveys are currently seeing. This lack of agreement could mean a flaw in one or both of the methods. If this discrepancy persists as the methods and data quality improve, it would be evidence for a complex source of dark energy that evolves with time, challenging the default cosmological constant theory.

Gravitational lensing has been heralded as the most powerful technique for studying the dark Universe. All methods face some challenges, however. For weak

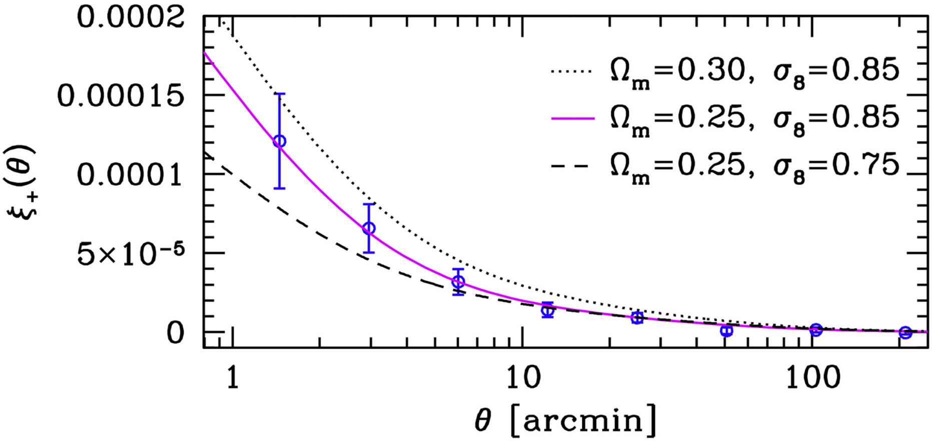

Figure 8. The weak lensing measurement of the alignment between pairs of galaxies as a function of their separation on the sky, known as the two-point shear correlation function ξ_+. The blue measurements from the Kilo-Degree Survey (KiDS) can be compared to the theoretical predictions for a flat ΛCDM cosmology, varying two dark matter parameters that set the amount of dark matter, Ω_m, and how clustered, or clumpy, the dark matter distribution is σ_8 (solid, dotted and dashed curves). Reducing the amount of dark matter, or making the matter distribution smoother, reduces the level of galaxy alignment that we expect to observe. Image credit APS/Alan Stonebraker. Data source: KiDS Collaboration.

lensing, the issue is that out of all of the four probes in our toolkit, weak lensing is by far the most technologically challenging. The typical distortion induced by dark matter, as a galaxy's light travels through the Universe, changes the ellipticity of that galaxy by less than 1%. In the last few moments before that light is captured on Earth, however, the atmosphere, telescope and detector can together change the ellipticity of the galaxy by 10% or more. So to isolate the alignment signature that dark matter imprints, we need to model all the distortions introduced by technology and the atmosphere to very high precision and then invert these terrestrial effects to accurately recover the cosmological signal. Just to up the ante, the terrestrial effects change every second as the wind and ground temperature alter the density of the air in different layers of the atmosphere, and the telescope slowly moves to track the rotation of the Earth. Furthermore, this lensing effect is so weak, that to detect it we need to analyse the images of hundreds of millions of galaxies, which involves rapidly processing peta-bytes of data.

Unlike the bright galaxy spectroscopic surveys designed for the studies of baryon acoustic oscillations and redshift space distortions, faint imaging lensing surveys estimate redshifts for their galaxies using broad-band photometry. In this technique, images are taken of the same galaxy in typically five different colours using broad filters. Comparing the measured colours to typical galaxy spectra, called templates, a rough redshift estimate can be made, known as a 'photometric redshift'. The use of this photometric technique is necessary as there are just too many faint galaxies in a lensing survey to contemplate the expensive task of obtaining spectroscopy for all of them. Accurate calibration of the photometric redshifts using a smaller sample of galaxies from deep and faint spectroscopic surveys is, however, an important challenge that has to be met if weak lensing is going to realise its full potential. Advances will certainly be made with upcoming narrow-band surveys that will image galaxies in up to 56 colours using narrow filters to produce the equivalent of very low resolution spectroscopy over large areas of sky.

One final astrophysical challenge persists, which the astute reader will have already recognised. What if our assumption that galaxies are randomly oriented throughout the Universe is wrong? We know that the way galaxies form and evolve depends on their local environment, and hence two galaxies in the same district of the Universe may well have a natural born alignment with each other. We have measured this effect by looking at the alignment of galaxies in tight-knit communities, in contrast to the alignment of galaxies widely dispersed through the Universe. What we found was that the average natural alignment between galaxies is roughly 100 times smaller than the observed alignment that dark matter induces. This is small, but not small enough to ignore and so it must be accounted for in every analysis.

Baryon acoustic oscillations

The acoustic oscillation battle in the early Universe, which causes the hot and cold spots in the cosmic microwave background, also imprints a preferred distance scale in the distribution of baryonic matter. We can use this scale as a 'standard ruler', using measurements of the distribution of galaxies at different epochs in time to track the accelerated expansion of the Universe.

To understand the origin of this ruler, picture the early Universe and focus in on an over-dense region in the plasma of photons and charged particles. Under gravity, the matter will start to compress, increasing the density of the plasma and the rate at which the photons scatter off the particles. The resulting increasing outward radiation pressure will eventually halt and reverse the gravitational collapse. The process can repeat, over and over again, setting up a local oscillator.

To help understand what happens next, picture a ball compressing and expanding on the surface of your bath water. This oscillation will send out waves across the water, and the distance between two crests of each wave (i.e. the wavelength) is set by the time it takes the ball to compress and expand again, which will depend on the size of the ball, and the speed that the wave moves through the water, known as the 'sound speed'[4]. To apply the same thinking to baryon acoustic oscillations, you need to swap the ball for an over-density in the plasma, and the bath water for the sea of

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[4] The concept of sound speed is maybe a strange one, particularly as there is no human audible sound in this case. Sound waves move by vibrating particles in the liquid, gas or solid through which they travel. This is why 'in space, no one can hear you scream' (tagline for the awesome 1979 movie *Alien*), as in space there is a vacuum and hence no air through which your scream can travel! Sound waves are different from light waves, which travel by varying the local electromagnetic force field—so you'll need to send SOS light pulses if you want your space-cries to be heard. Any waves moving through a fluid, such as the plasma of the early Universe, are known as sound waves, and the speed with which they transport energy through the fluid is known as the sound speed.

plasma, which surrounds the over-density and behaves like a fluid in the early Universe.

As seen in the CMB data (figure 4) these oscillations occur on many different scales throughout the Universe sending waves out into the plasma. This adds new fluctuations on top of the initial distribution of baryons that was seeded by the quantum fluctuations before inflation. The more cycles each oscillator passes through, the more damped these waves become. The biggest amplitude wave will therefore arise from the largest scale over-density to have undergone a single compression, sending a single pulse out into the plasma before recombination.

In the expanding Universe, the plasma density decreases, photons travel further before scattering off other particles, and atoms form. Having travelled far from their origin, the crests of all the sound waves become frozen in time because the fluid, which they have been travelling through, ceases to exist. For our largest amplitude wave, and others whose source has also been caught in the same instant of maximum collapse, their origin hosts a massive over-density of particles.

Given a cosmological model, the sound speed in the plasma can be calculated and it is found to be very fast, close to $c/\sqrt{3}$, where c is the speed of light. As the collapse timescale is fixed by the age of the Universe at recombination, the position of the crest of our high-amplitude single pulse wave, relative to its origin, can then be determined. Using CMB data, this is found to be in a spherical shell of radius ~ 150 Mpc. This fixed scale-length from the early Universe provides the theoretical underpinning for our observational standard ruler in the present day.

Dark matter has taken a bit of a back seat in this discussion so far. Completely oblivious to the electromagnetic force battles going on around it, large-scale dark matter fluctuations will collapse under gravity. There is a subtlety here, however: the rapid, radiation-driven expansion, which occurs before recombination, prevents the growth in the density of dark matter structures that are smaller in size than the ‘horizon’, which is set by the furthest distance that light could have travelled at that moment in time.

Post-recombination, the Universe is transparent and the photons are free-streaming through the expanding Universe, some of which will eventually be caught by telescopes and used to map the CMB. A field of clumpy dark matter and baryonic particles remains. Forming deep potential wells, the growing dark matter clumps have been awaiting the epoch of recombination enabling the gravitational attraction of the baryonic particles. As the baryons account for 16% of the total mass, however, over-densities of baryons—both the clumps and the newly created spherical shells around them—will also attract dark matter. Over time, in regions of gravitational collapse, the temperature of the baryons rises and we see the birth of the first stars and galaxies roughly 500 million years later, lighting up the web of dark matter that underpins them. That web still retains its memory though of the acoustic oscillations from the first 380 000 years.

The Baryon Oscillation Spectroscopic Survey (BOSS) measured the redshift and sky position of 1.2 million galaxies in the northern skies. Figure 9 shows the clustering of those galaxies as a function of their separation in the Universe, known as the galaxy correlation function. Specifically, it shows the numbers of galaxy pairs

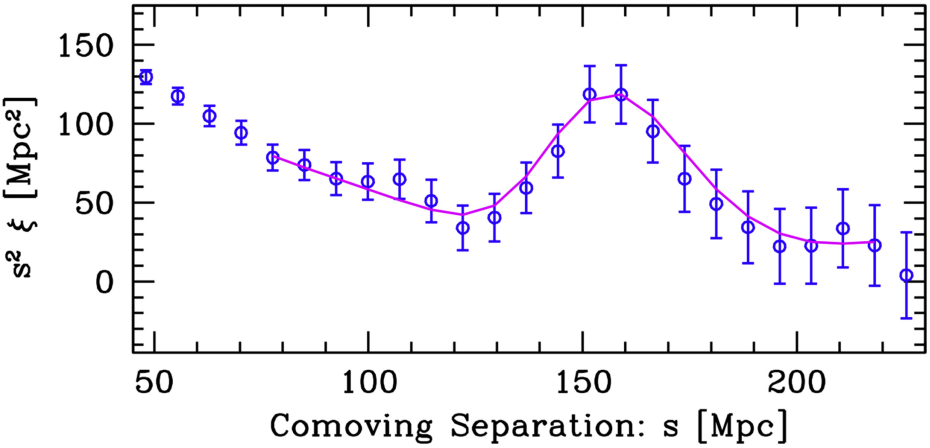

Figure 9. The baryon acoustic oscillation, as seen as a peak in the large-scale clustering of luminous red galaxies from BOSS. The clustering statistic ξ measures the number of galaxy pairs, separated by a comoving distance s, in excess of the number of pairs that you would measure from a purely random distribution of galaxies. To highlight the BAO peak at ~ 150 Mpc, I have multiplied ξ by s^2, which skews the appearance of the position of the peak to slightly higher s. The pink curve is the theoretical model assuming a flat ΛCDM model, which provides an excellent fit to the BOSS data (blue dots). Data source: Ashley Ross and collaborators.

as a function of separation, relative to the number of pairs you would measure if they were distributed completely randomly. We expect galaxies to cluster together on small scales, as they live in the same dark matter haloes (clumps). As the distance between galaxies grows, we expect to see the pair count tending towards the random pair count. Until, that is, we hit the distance scale of the spherical shell that was frozen into the baryon distribution at recombination and has been expanding along with the growing Universe ever since. The presence of these shells can be clearly seen as an increase in the number of galaxy pairs separated by a ‘comoving distance’ of about 150 Mpc.

A comoving distance is defined as the distance between two objects that remains constant with time, if the two objects are moving with the Hubble flow, i.e. the global expansion of the Universe. It’s therefore no surprise that BOSS finds the comoving distance to be the expected 150 Mpc, in fact, it is by design. In order to carry out this measurement of galaxy clustering, BOSS needs to assume a cosmological model, for example flat ΛCDM and a set of cosmological parameters in order to turn the observed galaxy redshifts and positions into distances. Theoretically, we know to expect a bump in the correlation function at the comoving distance 150 Mpc at all redshifts, and so the cosmological parameters are varied until that requirement is met. The best-fitting cosmological parameters from BOSS are in good agreement with those from the Planck CMB experiment.

This observational probe of cosmology has been called Baryon Acoustic Oscillations (BAO). It is a powerful probe of the expansion rate of the Universe, when used in combination with the CMB. All methods face some challenges, however, and for BAO it all depends on whether the galaxies trace the underlying matter distribution sufficiently accurately to carry out this measurement; it is the total matter distribution not the galaxy distribution that carries the cosmological information. Given the large scales of the BAO signal, however, this is a fairly safe assumption to make given the current accuracy of the measurements.

Galaxy clusters

The most dense regions of the Universe are lit-up by thousands of galaxies. These galaxy clusters shine brightly at both optical and X-ray wavelengths courtesy of the hot, X-ray emitting gas at their core. Seeded by the most over-dense dark matter fluctuations in the early Universe, clusters have grown in density over time by gravitationally attracting the matter around them. If you were able to decrease the fraction of dark matter in the Universe, the result would be fewer massive clusters today. If you were able to decrease the fraction of dark energy in the Universe, however, the result would be more massive clusters today. The accelerated expansion caused by the dark energy inhibits the ability of gravity to pull masses together to create galaxy clusters. Counting the number of clusters of a certain mass, at different redshifts, therefore gives you a sensitive probe of the total amount of dark matter, and also the evolution of dark energy.

All observational probes of cosmology face some challenges, and for clusters the main issue is how to determine an unbiased measurement of the total cluster mass. In the era of new, all-sky X-ray surveys such as eROSITA, one promising method is to use temperature measurements of the X-ray gas. The more massive the system, the faster are the velocities of the intra-cluster gas and the hotter the emitted X-rays. Using gravitational lensing, direct mass measurements can be made to calibrate a temperature–mass relation.

Another important question is how to ensure that you haven’t missed any clusters in your count. Not all clusters emit in X-rays. Not all clusters contain the ‘red-and-dead’ old, red elliptical galaxies, which are characteristic of most galaxy clusters, and hence considered as a good alternative to X-ray detection. One potential solution is to use photons from the CMB to locate galaxy clusters. CMB photons receive an energy boost by scattering off any charged intra-cluster gas particles if they pass through a galaxy cluster, producing a characteristic deviation in the CMB spectrum at the location in the sky of the galaxy cluster. This is known as the Sunyaev–Zel’dovich (SZ) effect after the two scientists who predicted that this effect would be seen.

The Planck collaboration has used a catalogue of clusters, detected through the SZ effect, with a weak lensing mass calibration to set constraints on the cosmological parameters. Interestingly, assuming a flat ΛCDM cosmology, they find fewer clusters today than they would expect given the cosmological parameters favoured by the CMB power spectrum in figure 4. This could suggest that dark energy is evolving, slowing down the growth of these structures, or, perhaps more mundanely, that the cluster selection or mass calibration is still missing an important ingredient in the analysis.

The Bullet Cluster: strongest support yet for the existence of dark matter

The Bullet Cluster, shown in figure 10, is a rare beast in the Universe where a catastrophic collision between two galaxy clusters has occurred. What we can see from such a collision proves the existence of dark matter cannot be explained away as simply non-luminous gas.

To visualize what's going on, in the Bullet Cluster collision, imagine two rugby teams warming up by running across the pitch from opposite ends. With so few players, in such a wide space, it's highly unlikely that they will collide. Think of the players as the galaxies in each cluster: they are so sparse that most will fly past each other, unscathed.

Now imagine allowing all of the supporters onto the pitch, starting at opposite ends just like the players, and shouting 'Charge!' A huge scrum will occur in the middle of the pitch. Think of the supporters as the dense gas in the two colliding galaxy clusters: it will collide and get left behind, caught in a giant hot X-ray scrum.

A gravitational-lensing analysis to locate the total mass in the Bullet Cluster reveals two peaks in the matter distribution situated around the galaxies, (shown in blue), not on the gas in between (shown in pink). The total mass far exceeds the matter that can be seen in the galaxies alone and this rare cosmic event has therefore provided some of the most concrete evidence to support the existence of dark matter, and proof that dark matter is not simply non-luminous gas. Furthermore, it supports our default theory that the dark matter is a cold, weakly interacting matter particle (WIMP) that hardly interacts with itself or other types of matter. If we threw two giant balls of WIMPs and galaxies together, we would expect them to simply pass by one another, just as we see in the Bullet Cluster.

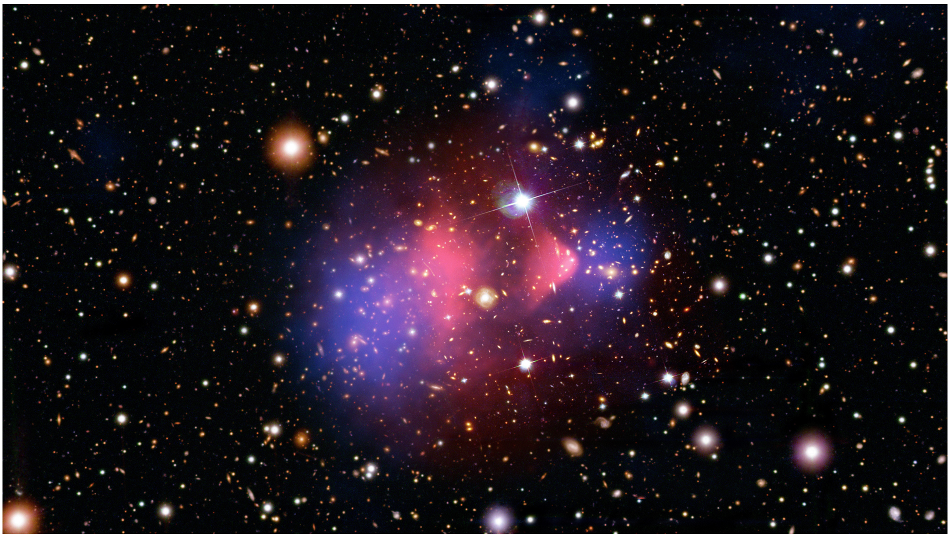

Figure 10. Galaxy cluster 1E 0657-56, better known as the Bullet Cluster. The visible-light image has been overlaid with X-ray observations of hot gas (pink) and the total mass distribution inferred by gravitational lensing (blue). Image credit: NASA/CXC/ESO/Clowe and Markevitch.

An extensive survey of clusters is expected to reveal hundreds of merging cluster candidates like the Bullet. With such observations, astronomers will be able to set constraints on just how weakly interacting the dark matter particle has to be.

Redshift space distortions

In our expanding Universe, every galaxy is moving away from every other galaxy, following what is known as the 'Hubble flow'. Measuring the resulting redshift in the emission and absorption lines of galaxy spectra then allows us to calculate distances to each galaxy, given a cosmological model. See the section on Flat Λ CDM and the cosmological parameters of the Universe, for more details. This description is not the complete picture, however, as it misses the impact of local gravitational distortions that add 'peculiar' velocities. Take our nearest neighbour Andromeda as an example. It has a redshift of $z = -0.001$, which is actually a blueshift. Andromeda and the Milky Way are moving towards each other under the gravitational forces of a large-scale dark matter structure in which our whole Local Group of galaxies is housed.

Figure 11 shows a computer simulation of a ΛCDM cosmology. You, the observer, are at the centre of the diagram looking out at a stripe across the sky. The quadrant on the left of the image shows the distribution of the galaxies that you have observed in terms of their true distance from you. Every red and blue dot represents a different red or blue galaxy. You can see that the galaxies are tracing out the cosmic-web-like structure of the underlying dark matter, where the densest regions host the largest number of galaxies. The quadrant on the right shows the mirror image, but now plotted using the distances that you would have inferred from measurements of galaxy redshifts, using equation (4). In this case, we see that the web pattern is now stretched out along the 'line-of-sight' (i.e. the direction that you, the observer, are looking in). We see this effect from the forwards (blue-shifted) and backwards (red-shifted) motion of galaxies hosted inside massive dark matter structures. The more massive the structure, i.e. the more dark matter there is, the faster the motion (see for example equation (1)) and the longer the so-called 'fingers of God' become.

On first sight, this might be considered to be a nuisance as redshift becomes an increasingly less accurate measurement of distance when the galaxy is in a dense environment. In fact, though, this effect gives us an exciting, new observational probe of the dark Universe as it allows us to monitor the growth of massive structures over time and potentially map out the gravitational force field in 3D.

This observational probe has been called 'redshift space distortion' or RSD. It uses a similar galaxy clustering statistic to the baryon acoustic oscillation probe looking for an enhanced number of galaxy pairs at fixed separation, relative to the number of pairs that you would expect from a random distribution. The twist with RSD is that you first make this clustering measurement for galaxy pairs that are relatively close to each other in the sky, but separated by a certain distance along the line of sight. You then also measure the clustering for galaxies pairs that are relatively close to each along the line of sight, but are now separated by a certain

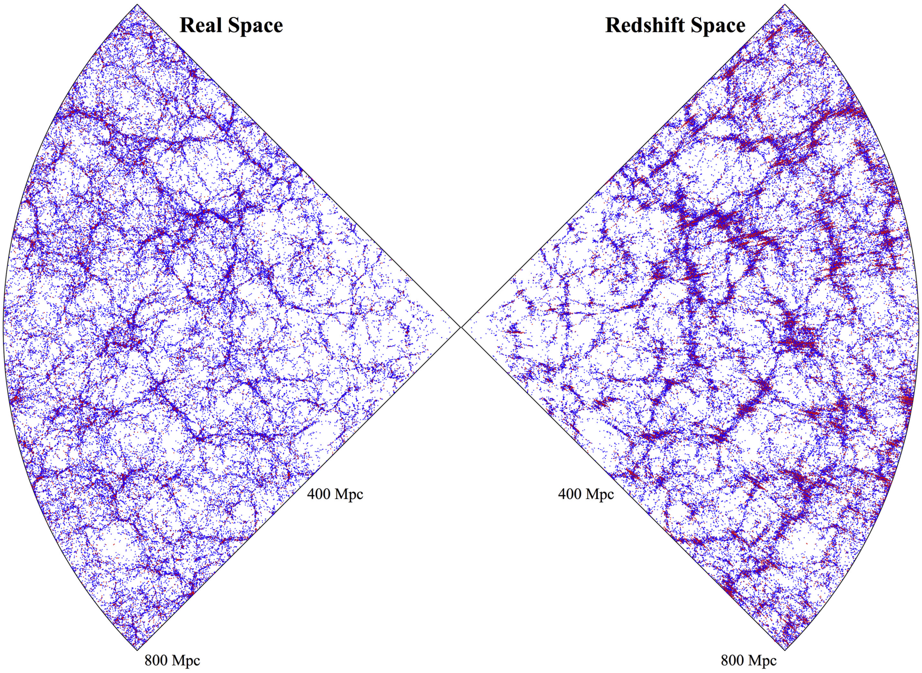

Figure 11. Illustrating redshift space distortions using a mock galaxy catalogue of a ΛCDM cosmology. On the left we see the 'real-space' distribution of the red and blue galaxies that we would see when observing a stripe across the sky, shown out to distances of 800 Mpc from Earth. If we measured the redshifts for all these galaxies and used the redshifts to estimate a distance to each galaxy, we would infer that the galaxies were distributed as shown in the 'redshift space' mirror image universe on the right. In dense regions of the cosmic web, the gravitational pull introduces additional peculiar velocities, distorting the true distribution of galaxies, hence the name 'redshift space distortions'. Data source: Institute for Computational Cosmology, Durham.

distance across the sky. If there were no peculiar velocities, you would expect to find the same clustering measurement in both cases. We're not in a special place in the Universe, so the direction we choose to look in should not impact our results. As seen in figure 11, the effect of the peculiar velocities is to extend the galaxy distribution along the line-of-sight and the RSD measurements detect these 'fingers of God' as a difference between the two clustering measurements out to scales of about 10 Mpc.

On larger scales, another interesting effect can be detected with RSD. Over long distances, galaxies are being gravitationally attracted and drawn towards over-dense structures. For galaxies housed in different haloes, this effect will tend to pull them towards each other. For pairs separated along the line of sight, this additional peculiar velocity will add to the redshift of one member of the pair, whilst the other will experience some opposing blueshift. For galaxy pairs that are separated across the sky—in other words, perpendicular to the line of sight—these pairs will still be attracted towards each other. The additional peculiar velocity will, however, be in a direction that is perpendicular to us as observers, thus making no change to the galaxy redshifts that we measure. The more massive structures there are in the

Universe, the stronger the difference will be between the two large-scale RSD clustering measurements. Members of the BOSS survey have carried out this type of RSD analysis, using it to set constraints on the growth of structures. They find that their measurements are consistent with the expectation of the best fitting flat ΛCDM model from the Planck CMB experiment.

All methods face some challenges, and for RSD, just as with BAO, it all depends on whether the galaxies trace the underlying matter distribution sufficiently accurately to enable direct comparisons between data and theory; it is the total matter distribution—not the galaxy distribution—that carries the cosmological information. Given the distance scales over which the RSD signal is measured, we don’t yet know if it’s safe to assume a linear relationship between the galaxy distribution and dark-matter distribution. This matter is often referred to as galaxy bias and is a potential limitation for obtaining accurate cosmology from RSD measurements. When used in combination with weak lensing measurements to calibrate the galaxy bias mapping between galaxies and dark matter, this cosmological probe holds significant promise.

Outlook

Now is a very exciting time to be an observational cosmologist. In the short-term there are three lensing teams currently competing to be the first to reveal the next major leap in our understanding of the dark Universe. The Kilo-Degree Survey along with the Hyper-Suprime Camera survey are imaging 1500 square degrees of the cosmos, nearly 5% of the full sky. The Dark Energy Survey, will cover more than three times that area, and all three surveys will conclude their observations over the next few years.

Over the next decade, three new major international projects will work in tandem in the hopefully final stages of our quest to understand the dark side. The Euclid satellite will be launched above the atmosphere, providing images as good as those taken with the Hubble Space Telescope across the whole sky and near infra-red spectroscopy for millions of high redshift galaxies. Getting above the atmosphere gives us a much clearer view of the Universe, and the keen vision of Euclid will be extremely sensitive to the weak dark matter distortions and the baryon acoustic oscillations that we are trying to detect. The Dark Energy Spectroscopic Instrument will also measure the spectra, and hence redshift and distance information, of millions of galaxies with which to chart the expansion of the Universe and the growth of structures using both baryon acoustic oscillations and redshift space distortions. The Large Synoptic Survey Telescope will image the whole southern sky every three nights and provide deep, multi-colour imaging with which to measure distances to the galaxies without spectra and provide a second measurement of the weak lensing distortions. Not only will this survey thus allow us to chart the evolution of dark matter structures, but this telescope will also be able to detect killer rocks in our solar system that may one day obliterate planet Earth!

Looking slightly further into the future, the Wide Field Infra-Red Survey Telescope (WFIRST) will peer deep into the Universe over a 1000 square degree patch, using weak lensing to resolve dark matter structures out to a redshift $z \sim 2$. The Square Kilometre Array, being built in South Africa and Australia, will provide high-resolution imaging in the radio part of the electromagnetic spectrum, with precision redshift and polarisation observations that will allow us to untangle the lensing alignment signature of dark matter from naturally arising alignments. In combination, these surveys will be able to use gravitational lensing to map dark matter and dark energy over the last 10 billion years in the history of the Universe, testing gravity on the largest of scales in space and time.

What is my bet for what these amazing new facilities will conclude? My hope is that we find something truly ground-breaking and unexpected. Perhaps our model of gravity is incomplete and when we finish this puzzle we will have turned our understanding of the dark Universe on its head. My fear, however, is that we'll find no deviations from the default flat ΛCDM model that Planck has already clearly shown to fully explain the Universe right after the Big Bang. I fear this as, in my opinion, the most solid theoretical reasoning for why Λ should be as small as it is, is grounded in a theory that predicts an almost infinite number of multiple universes. Each one of these bubble universes features a different realisation of the constants that determine the amplitudes of the fundamental forces. We imagine that our Universe is the only reality, but perhaps the reason why we exist at all is because in our realisation the fundamental constants, including Λ, are well-tuned for life. As an observer, this is a hard concept to swallow as it cannot be directly tested. However, there is some glimmer of hope as it is a branch of the different inflation theories that infers this multiverse conclusion, and with the next generation of CMB experiments planned for the coming decades, these theories can and will be rigorously confronted.

Additional resources

- For an excellent and extensive up-to-date text book, I strongly recommend the second edition of *Extragalactic Astronomy and Cosmology* by Peter Schneider (Springer, 2015). This is a beautiful book to read, with excellent diagrams and images to illustrate the clear explanations of the theoretical physics behind modern-day astronomical observations.
- For the more theoretically inclined, you cannot do better than what I consider to be my essential manual of cosmology—*Cosmological Physics* by John Peacock (Cambridge University Press, 1999). With the fast-moving field of cosmology, some of the more recent observational cosmology aspects of this book are missing. For example baryon acoustic oscillations had only just been proposed as a cosmological tool when this first edition came out. Every new year John's resolution is to write a second edition though, so look out for that.
- One of my favourite review papers on observational probes of dark energy has been written by David Weinberg and colleagues in 2013 (*Physics Reports* **530** 87–256). A fully open-access version can be downloaded from https://arxiv.org/pdf/1201.2434v2.pdf.
- Given the iconic nature of the Planck results and the profound impact they have made in observational cosmology, I reference here their key cosmological

parameter paper published in 2016 (*Astronomy and Astrophysics* **594** 13–66). A fully open-access version can be downloaded from https://arxiv.org/pdf/1502.01589v3.pdf. In our desire to keep this book short, there hasn't been space to talk about the incredible history of cosmic-microwave-background science before Planck, most importantly the contributions of the WMAP satellite and the ground-based BOOMERanG, SPT and ACT experiments, which can be read about in a 2013 paper by Gary Hinshaw and collaborators, published in 2013 (*Astrophysical Journal Supplement Series* **208** 19–44). A fully open-access version can be downloaded from https://arxiv.org/pdf/1212.5226v3.pdf.

- The galaxy rotation-curve data for figure 2 came from the DiskMass Survey, by Matthew Bershady and collaborators, published in 2010 (*Astrophysical Journal* **716** 198). An open access version can be downloaded from https://arxiv.org/pdf/1004.4816v1.pdf.
- By far the best paper to get a more detailed understanding of the physics behind baryon acoustic oscillations was published by Daniel Eisenstein and collaborators in 2007 (*Astrophysical Journal* **664** 675–9). A fully open-access version can be downloaded from https://arxiv.org/pdf/astro-ph/0604361v1.pdf. The pedagogical review of the acoustic phenomenon in section 2 is extremely insightful.
- If you are interested in learning more about the history of weak gravitational lensing measurements, Martin Kilbinger wrote a really useful review article in 2015 (*Reports on Progress in Physics* **78** (8)). A fully open-access version can be downloaded from https://arxiv.org/pdf/1411.0115v2.pdf.
- The most recent compilation of supernova measurements can be found in a paper by Marc Betoule and collaborators published in 2014 (*Journal of Astronomy and Astrophysics* **568** 22). An open-access version can be downloaded from https://arxiv.org/pdf/1401.4064v2.pdf.
- The most recent baryon acoustic oscillation measurements can be found in papers by the BOSS collaboration that—at the time of writing—are pre-prints being peer reviewed. An open access version of the main BOSS overview paper by Shadab Alam and collaborators can be downloaded from https://arxiv.org/pdf/1607.03155v1.pdf.
- The most recent weak lensing measurements can be found in a paper by Hendrik Hildebrandt, Massimo Viola, me and the KiDS collaboration, published in 2017 (*Monthly Notices of the Royal Astronomical Society* **465** 1454). An open access version can be downloaded from https://arxiv.org/pdf/1606.05338v2.pdf.
- Finally, for the multiverse fans in the audience, you will enjoy reading Max Tegmark's popular-science book *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality* (Penguin 2013). I'd also recommend this book to those who argue that the multiverse is wild fantasy and evidence that mathematics is no guide to reality. Max has some very convincing arguments otherwise in this book.