Galaxies don’t always exist in splendid isolation. Many live alongside other galaxies, tethered to them by their mutual gravity to form groups and clusters of galaxies. My talk today will concentrate on the properties of such clusters of galaxies, such as their contents and their masses – including what they can tell us about dark matter – how they are spread across the Universe to form superclusters that surround giant voids of empty space, and what this distribution might tell us about their formation and evolution.

When we look at maps of the distribution of the nearest galaxies, such as that given by the ‘2MASS’ all-Sky survey showing the very brightest extended sources in the near-infrared, the thing that immediately strikes the eye is that galaxies are not distributed randomly. Instead they form an amazing tapestry that traces the way that galaxies are bound together to form larger structures.

The Local Group
The three brightest galaxies are visible with the unaided eye. From the Northern Hemisphere we may be familiar with our sister galaxy, Andromeda, which is a similar shape, size and mass to the Milky Way, and 2.5 million light-years away. Andromeda is accompanied by a couple of obvious small galaxies in orbit around it. The same is true of our own Galaxy; if you’re lucky enough to ever view the Sky from the Southern Hemisphere, you can clearly see the Magellanic Clouds. These are two dwarf galaxies that orbit the Milky Way at distances of 170,000 and 200,000 light-years. There are plenty more such satellites around both us and Andromeda, although not quite so readily observable by eye. Along with another slightly smaller spiral galaxy, Triangulum, around 3 million light-years away – and its satellite dwarfs – we form the ‘Local Group’ of about fifty galaxies. Such groups are not unusual, and there are many examples observed in the local Universe. They all have a similar density, comprised of tens of galaxies spread over a volume about a few million light-years across. Such groups, however, pale into comparison to the clusters of galaxies.

Clusters of Galaxies
Much of today’s talk is concerned with far more complex systems than groups. Clusters contain hundreds, to thousands of galaxies, all confined to a volume of space that is not really that much bigger than that occupied by a galaxy group; the difference lies in the high density of galaxies. For example, one of the richest known clusters lying comparatively close to us is the Coma cluster, with over three thousand galaxies contained within a diameter of around twenty million light-years. The galaxies form a relaxed, fairly symmetric distribution that is dominated by two giant elliptical galaxies: named NGC4874 and NGC4889, each would dwarf our Milky Way galaxy. Our nearest rich cluster is the Perseus cluster of galaxies, some 250 million light-years distant from us, lying close to the plane of our Galaxy. Perseus contains over one thousand cluster galaxies, again in a volume of space some fifteen million light-years across.

Clusters are the largest organised structures in the Universe that appear gravitationally bound. They all tend to be around the same size; what differs is how many galaxies are packed into within this space. We describe the density of galaxies in a cluster by ‘richness’, where sparsely-populated groupings are ‘poor’, and ones teeming with galaxies are ‘rich’. The distribution of the galaxies with the cluster can also settle to a range of morphologies. Many are smooth and symmetric, but a considerable fraction are much more clumpy or bimodal. Many clusters of galaxies are themselves clumped into even larger structures called superclusters that can extend for tens of millions of light-years, and which are probably still forming. Although clusters contain many galaxies it is important to appreciate that not all galaxies reside in clusters. Indeed, the majority of galaxies exist outside of clusters, and a galaxy that is not part of a cluster is called a ‘field’ galaxy.

Finding Clusters
Clusters of galaxies were known about long before observers recognised what they were observing; simply lumped in with the rest of the obscure fuzzy ‘nebulae’. The first cluster to be noticed was catalogued by the French astronomer Charles Messier in the late 18th century, who listed a record total of eleven nebulae all contained within the constellation of Virgo. This concentration of objects was also remarked upon by William Herschel in 1811, and is now identified as the local rich Virgo cluster. The Local Group just sits at the edge of this structure. The Coma and Perseus clusters were also noticed and studied in the early years of the 20th century by the German astronomer Max Wolf, even though it was only realised that such nebulae were really external galaxies later on, in the mid-1920’s. At that point many other clusters of galaxies began to be mapped, in particular by the American astronomer Harlow Shapley, who discovered the largest nearby supercluster that bears his name.

Catalogues of Clusters
Clusters weren’t systematically catalogued, however, until the 1950’s. The two pioneers in this respect were Fritz Zwicky and George Abell. Abell’s catalogue is still widely used today, and all rich clusters are regularly referred to by their ‘Abell number’ (for example, the Perseus cluster is A426, and the Coma cluster is A1656). The clusters were defined by the optical properties of their constituent galaxies, and identified from overdensities of galaxies on photographic plates of the Sky. This work was done before the advent of astronomical computers and ccd detectors, so all the assessment of clusters was done by eye; identifying and counting the number of galaxies.
within a certain radius around the brightest to determine an overdensity, and estimating the distance (and thus the likely size of the cluster) from the brightness of the dominant galaxies in the cluster.

Clusters appear obvious from the photographic plates if they are rich (ie with plenty of galaxies) and nearby (so these galaxies are spread across much of the photograph). Identifying clusters by eye is very subjective, and counts would have to be repeated at different times to be sure of consistent results. There are other problems: close to the plane of the galaxies, the situation is muddied by the presence of foreground stars and the need to distinguish between stars galaxies by their spatial extent. Decisions about which galaxies are cluster members can also be confused by chance projections of field galaxies along the line-of-sight to the clusters, which could be mistakenly included as part of a cluster. The Abell catalogue gets progressively less reliable for more distant cluster structures. Not only is it more difficult to ascertain if an object shows an extended image in more distant systems, but the contamination by unassociated galaxies intervening along the line of sight is greater. Furthermore, as there are a greater number of faint galaxies than bright in any cluster, it is harder to detect all possible cluster members the more distant the cluster.

In more recent decades we determine the presence of a cluster using spectra or even just the colour of individual galaxies to be sure they are physically associated. Automated galaxy detection, star/galaxy separation and counting all allow much more objective decisions about what does or does not constitute a cluster. At higher redshift, clusters are discovered and/or confirmed not from individual galaxy counts, but using properties of clusters in other wavebands. Today we have greatly extended both the number of clusters and how far away we can detect them, but the Abell catalogue is still the starting point for many studies. Containing over 2700 clusters, there are sufficiently many to allow meaningful comparisons of their optical characteristics, such as the cluster richness, types of galaxies contained therein, and the morphology of their distribution. The shape and content of a cluster was thought to be the logical first step to understanding how these structures formed.

Constituent Galaxies
One thing that is obvious from images of rich clusters is that most of the galaxies they contain are elliptical in shape. There are very few blue spiral galaxies; those that are present sit at the outskirts of the cluster, and are never found in the cluster core, which is dominated by large, yellow ellipticals. The richer and more massive the cluster, the more obvious is this contrast.

Galaxy Transformation
One special kind of galaxy is only found in a cluster environment, where more disc-shaped elliptical galaxies resemble ‘anemic’, or gas-poor spiral galaxies; showing a large central bulge of stars, the disc is far less obvious, and the lack of blue colour indicates a very low star formation rate compared to that normally associated with spirals. What disc-shaped galaxies can be found in a cluster show little in the way of cold atomic hydrogen or other molecular gas, and progressively less of either at more central locations. As it is this gas that stars condense from, the lack of current star formation in such galaxies is consistent with their depletion of neutral gas. It seems that the harsh, dense environment of the cluster affects the galaxies, changing their nature in an accelerated form of evolution. The cluster produces mechanisms that can remove the cold atomic and molecular gas from the vulnerable outer edges of a galaxy, transforming a gas-rich spiral-shaped galaxy into a gas-poor disc-shaped elliptical over a period of billions of years. There are two main ways that this is thought to happen, both of which can act on a spiral falling into the cluster from the outskirts.

Tidal Harassment
Tidal gravitational forces are rife throughout the cluster. The combined gravity of the whole cluster acts on any individual galaxy, to tug at the edges of a spiral galaxy. The effect is cumulative, acting on the galaxy all during its passage from the edge of the cluster into the core, gradually pulling the disc apart to leave behind a smaller, more spheroidal system. The less massive galaxies are the most vulnerable to this destruction of their disc.

Ram Pressure Stripping
A cluster doesn’t just comprise the galaxies we can readily observe in the optical. There is much more mass lying inbetween the galaxies of a cluster, in the form of a hot gaseous atmosphere. The gas is at temperatures of millions of degrees, thus only apparent in X-rays, where it appears as a large intergalactic puddle, and completely invisible in optical images. Prevalent in rich clusters, this intracluster medium can have a damaging effect on any galaxy passing through it. As a spiral galaxy falls in towards the centre of a cluster, pulled in under the combined gravitational attraction of the total cluster mass, it reaches huge speeds of a few million km an hour, and rams into the hot gas atmosphere. The charged particles in the X-ray plasma push on the extremities of the spiral galaxy, stripping them away to leave the bulge component. Over 500 million years, this ‘ram pressure stripping’ transmutes the gas-rich spiral into a gas-poor galaxy comprised of old red stars.

Both tidal harassment and ram pressure stripping result in millions of stars being pulled off their host galaxy, only to become scattered through the intracluster space. Over time these can slowly settle through gravity down into the core of the cluster, perhaps contributing to another type of galaxy particular to the cluster environment is often found.

Brightest Cluster Ellipticals
At the very heart of a cluster lie the most massive galaxies to be found anywhere in the Universe. These are unique to the cluster environment, and the dominant galaxy is always an elliptical occupying a privileged position at the centre of the cluster’s gravitational potential.
Detecting Distant Galaxy Clusters

The X-ray hot gas makes identification of distant galaxy clusters a lot more straightforward. In this waveband it is no longer necessary to determine the distances or colours of individual galaxies to see whether or not they form a physical association. The observation of an intracluster medium is sufficient, and a much better way to assemble catalogues of clusters. Not only is the distribution of gas in a cluster more easily assessed than distribution of galaxies, but the effects of any substructure are easily seen, and longer observations only give better statistical accuracy. There is no longer any problem of confusion between the identification of stars or galaxies, or concern about mistakenly including fore- or background galaxies in the count. The furthest cluster thus currently identified is JKCS041, estimated to be around ten billion light-years away from us, and seen today as it appeared at only one quarter of the present age of the universe. This is about the earliest that we think galaxy clusters can exist in the early Universe.

The Mass of a Cluster from Galaxy Motions

The Universe is expanding, pushing galaxies further and further apart from each other. This expansion happens on much larger scales than we are considering within a cluster of galaxies. The galaxies contained in a cluster or a group are sufficiently close together that the gravitational force they feel between them dominates over the force that is pushing the Universe apart. Clusters act as pockets of gravity that produce local motions in clusters that exist alongside the expansion of the Universe: while the cluster as a whole is moving away from us, individual galaxies within the cluster are moving around each other.

Each of the collection of galaxies in a cluster is not stationary, but continually swarming around each other like a cloud of bees - just like individual stars within an elliptical galaxy, but at speeds of up to 1000 km/s. The motion and orbit of each individual galaxy with a cluster is dictated by the overall gravitational field produced by the rest of the cluster.

The velocities of galaxies are observable quantities; once one removes the systemic velocity of the whole cluster away from us due to the expansion of the universe, then the residual local motions of the galaxies can be modelled as an ensemble of particles. By summing over all these separate motions, it is possible to calculate the strength of the total gravitational field the galaxies are responding to, and thus deduce how much gravitating mass there is in the cluster.

There is a problem, however, in that most of the galaxies are travelling too fast to remain bound to the observed mass of galaxies. A cluster should not remain bound together as a viable entity, as the galaxies are travelling so fast that they would disperse rapidly. The common occurrence of clusters, however, demonstrates that they are dynamically stable structures. To hold together, there needs to be much more gravitating mass present than we can infer just by summing up that visible in the stars and galaxies. For example, even a relatively poor system such as the Virgo cluster requires a total mass of over 100 trillion (100 million million, or \(10^{14}\)) Solar masses, and a rich cluster such as Coma requires even more mass. The total mass must be over a hundred times more than we can see just by adding up the observable mass. The implication is that most of the mass in the cluster is made up from something that is typically at least 100 times dimmer than our Sun. This is analogous to the way that spiral galaxies also rotate too fast for the stars to stay attached unless there is more mass there than we observe in all the stars and gas clouds. The discrepancy in the motions of galaxies in a cluster was the first line of evidence for the presence of dark matter, or as it was originally termed, ‘missing matter’ (though in practice it’s not the matter that’s missing, just the light from it). The requirement for such missing matter was first noticed in 1933 by Fritz Zwicky following his observations of the motions of galaxies in the Coma cluster. The inference was not well accepted at the time. Indeed, it is an important conclusion, particularly as we can’t observe mass directly, but can only infer it from measurements of observable quantities. There are always assumptions and physics that go into the interpretation. The idea that there are vast amounts of dark matter in clusters of galaxies has had to be confirmed from other methods.

The Mass of a Cluster from the X-ray Emission

As already mentioned, the visible galaxies are, of course, not the only observable component of clusters. In the X-ray waveband, clusters appear bright, but one no longer sees the individual galaxies, just the hot gas that lies between them to form the intracluster medium, centred on the core of the cluster. This hot gas is diffuse, and fully occupies the volume of space between the galaxies. From its spatial extent and luminosity, we find that there is on average about seven times more mass in the hot gas than that in all the stars in the galaxies added together. Indeed, it is the dominant form of the observed light from the cluster, but it’s still nowhere near enough to account for all the missing matter!

Observations of the hot gas can, however, be used to confirm the need for a large gravitational mass in a cluster. The amount of X-ray emission emitted directly depends on the temperature and density of the hot gas. It is thus possible to directly calculate the pressure in the gas from the observations. This pressure depends on the total gravitational force in the cluster, as at any radius the gas is squeezed by, and is supporting the weight of, all the overlying layers of hot gas further out in the cluster. Mathematically we can use observations of this pressure gradient to deduce the gravitational force, and thus mass, that is producing the observed pressure at all different radii. The results are in whole-hearted agreement with estimates from the galaxy motions, in that there is far too much matter causing the gravitation than implied by the luminous mass: X-ray observations only confirm the need for a huge amount of dark gravitating matter to be present.
**The Mass of a Cluster from Gravitational Lensing**

One final method used to map out the distribution of this dark matter is a phenomenon known as gravitational lensing. Gravitational lensing is a direct consequence of Einstein’s interpretation of gravity, which replaced Newton’s interpretation of gravity as an invisible force acting over a distance, by the way that a mass can distort space and time around it. Thus light can be deflected if its path passes close enough to a massive object – the light is still travelling in a straight line, but now that straight path takes it through curved space. The more massive the object, the more warped the space and the more the light is bent, with the curvature greatest for light passing very close to a very massive body. The use of the term ‘lensing’ is a little misleading, as the optics don’t behave in the same way as a conventional idea of a lens bringing the light to a simple focus. As the cluster mass distribution is uneven and clumpy, complex bands of light and dark are produced instead as the focus of the light moves in and out. Known as caustics, these may be most familiar to us as the bright and dark patches seen when sunlight is refracted by the surface of water, or produced at the inside base of a cylindrical mug when illuminated by a strong overhead light. The background source of light is usually a galaxy, so is spatially extended, and is rarely aligned on an exact axis with a massive cluster and the observer. The light is smeared round into a mirage that resembles an arc shape. As clusters have such large concentrations of mass, they can produce a pronounced lensing distortion in the image of background objects, where the amount of distortion produced depends on the total gravitating mass (whether dark or light-emitting matter). Einstein himself only considered predictions of lensing that might result as light passed by massive point sources such as stars; it was again Zwicky who posited the idea of galaxies and clusters of galaxies also producing these mirages, in 1937. However it was not until the advent of ccd detectors and large telescopes that the way that clusters can produce gravitational distortions could begin to be routinely studied.

The lensed light is smeared into arcs – both radial and tangential – and the amount of shear observed depends on whether the light travels on paths that pass through the core of the cluster or through the outer edges of the cluster. Around the brightest cluster galaxy it is usual to see giant arcs in the region for ‘strong’ lensing; further out from the centre of the cluster many more smaller arclets are seen, and eventually only a sense of a slight shearing of very far out galaxies remains. The overall distortion is not dissimilar to the view through the bottom of a glass tumbler. The way the light is distorted traces the distribution of mass in a cluster. Thus with some knowledge of the distance of the background source, and distance to the lens, we can use the observed distribution of these mirages to infer the distribution of the total gravitating mass in a cluster.

These three methods of weighing clusters all depend on completely different assumptions in interpreting the physics -whether assuming something about the dynamical state of the cluster, the balance between gravity and pressure in the gas, or the way that the space is bent around the mass - and each employ very different observing techniques of imaging and spectroscopy in both the X-ray and optical wavebands. Yet they all come to the same conclusion, requiring total gravitating masses of clusters in the range of 100 to 1000 trillion (10^{14} - 10^{15}) times the mass of our Sun. Nearly all of the the ‘ordinary’ mass is in the form of the hot X-ray gas, but most of the overall, gravitating mass is in the form of the unknown dark matter.

**So What is The Dark Matter?**

If only we knew... Dark matter is mass that only reacts with other matter (whether light-emitting or dark) only through the force of gravity. In particular it does not interact with light in any way – neither emitting nor absorbing light at any wavelength. We don’t really have a good idea of what dark matter is. It’s unlikely to be made up of ‘ordinary’ baryonic matter, by which I mean matter we are familiar with, assembled from protons, neutrons and electrons. Not only is it difficult to see how one can create enough dark matter in this way (and in particular so enormously more than the visible baryonic matter) and how to separate it spatially so far away from the baryonic matter.

Current thinking is that dark matter is most likely to be exotic, i.e non-baryonic. Many such types of particles are known to exist, and others have been theorised to exist precisely to solve the dark matter problem. One example often invoked are neutrinos, which we do at least know to exist. Neutrinos take part in reactions that involve the weak force, and are thought to be massless. There are so many neutrinos in the universe, however, that if each even the tiniest mass associated with it, they could account for much of the dark matter. As they are relativistic particles (meaning that they travel at velocities very close to the speed of light), and resist clumping together, their properties would have the effect of smoothing out the distribution of matter. Cosmological predictions of the structure that would result in the Universe if massive neutrinos were the main constituent of dark matter are at odds with what we observe – the models predict too much structure on too large a scale.

Most other exotic matter candidates fall into the category of WIMPS, or Weakly Interacting Massive Particles. These are, as the name suggests, stable heavy particles that only interact weakly with other matter. As they are not relativistic like the neutrinos, they don’t smear out the structure of forming matter in the same way as predicted by the idea of massive neutrinos. The major drawback is, however, that there are no known candidate particles; plenty of theoretical possibilities exist, most in the context of supersymmetry theories that attempt to unify gravity with other forces. Such particles go under monikers such as neutralinos, axions, photinos. If such particles do constitute the dark matter, they will tell us something about the Universe at the earliest times. Having most likely played a very important role in the reactions right at the beginning of time, and having contributed to the blueprint of our cosmos, they have since decoupled from everything else in the Universe to become slow-moving and unreactive relics that litter space.
Even though the nature of dark matter remains uncertain, we are able to combine the lensing, X-rays and galaxy distribution properties of clusters of galaxies not just to demonstrate the requirement for dark matter, but to also find out a little bit more about it and how it reacts with other matter during one of the more extreme and energetic events that can happen in the Universe.

Colliding Clusters
If two clusters are sufficiently close, their mutual gravitational attraction will eventually cause them to crash into each other at speeds of millions of km an hour. During this collision, we can trace how the visible and invisible components interact with each other. Such an event happens comparatively rarely, but nonetheless, several have been observed. The most famous example is the ‘Bullet’ cluster. An optical image reveals the distribution of galaxies to be in two major concentrations, each representing one of the two merging clusters. As the galaxies are only a minor component of the total mass of a cluster, we use the presence of gravitational mirages to derive the distribution of the total gravitational mass present. This is dominated by the dark matter, which is concentrated in two clumps, each tracking one of the clusters. Although they seem quite separate in optical images, we get a very different impression from the distribution of the hot X-ray gas. This shows the distribution of the dominant form of the baryonic matter, and reveals that there’s a clear spatial separation between dark and ordinary matter.

In particular, the two clusters appear to have already passed through each other once. The distribution of the galaxies is largely unaffected, as the distance between them is far greater than the size of any one galaxy, and thus head-on collisions between galaxies are almost non-existent. The galaxies simply fly past each other. In contrast, the hot, X-ray atmosphere is pervasive throughout the cluster and the two intracluster media cannot avoid each other, but collide, squeeze and compress each other. The hot gas in the smaller cluster is slowed right down by the drag force (similar to air resistance) as it passes right through the other larger cluster during the collision. The dark matter in each cluster, however, remains largely unaffected by the impact; it does not interact directly with itself or the gas except through the pull of gravity. The Bullet cluster is the ‘textbook’ example of how colliding clusters seem to behave, and the other examples so far studied seem to follow this pattern.

Or they did... just last week observations of an much more anomalous example have been announced. A520 is a merging cluster some 2.4 billion light-years away, where the dark matter doesn’t seem to be behaving as we might expect from the Bullet cluster. The lensing analysis reveals the dark matter to have congregated more into a core that lags the galaxies (which have moved on past the collision site). In other cluster collisions the dark matter and galaxies have remained anchored together, but here we are left with a core rich in both dark matter and hot gas, but containing few luminous galaxies. We don’t know yet whether this cluster presents a major problem for our understanding of dark matter and how it behaves, or whether this collision is just an oddball, maybe representing a much more complicated collision between three systems.

The idea that clusters can merge and collide then begs the question, are there even larger structures than clusters of galaxies?

Large Scale Structure
The all-sky distribution of the nearest galaxies across the Sky shows that they are not just knotted into clusters, but that these knots join up to form walls or bands of structures. Clusters of galaxies also do not exist in isolation, but are themselves clustered to form even larger structures that we term superclusters. Our Local Group lies at the very outskirts of the local (and relatively small) supercluster dominated by the Virgo cluster, which is linked by a smattering of further clusters up to our nearest major superstructure.

The Shapley Supercluster
The Shapley supercluster is 650 million light-years away. It occupies a volume of space comparable to that of the Virgo supercluster, but contains a huge number of major clusters. It’s the richest concentration of mass in the local Universe, comprising over thirty rich Abell clusters of galaxies within a volume 180х300х600 million light-years; six of these clusters are amongst the brightest 46 known. X-ray observations suggest that the total mass in the supercluster is of the order of over twenty thousand trillion (~2 10^{16} ) Solar masses. The Shapley supercluster is linked to the Virgo supercluster by a wall of galaxies that in itself joins the Coma and Hercules clusters.

Superclusters and Voids
Superclusters such as Shapley are the largest known systems in the Universe. They typically contain up to 20 clusters, and can span tens of millions of light years usually flattened into slab-like concentrations known as walls. As we view the structures in the Universe with increasing distance from us, a particular pattern becomes evident. The three-dimensional distribution of luminous matter takes on a distinctive cobwebby, or ‘soap bubble’ structure. While half of all clusters are contained in superclusters, the superclusters themselves only occupy about 3% of the volume of space. They surround under-dense regions of comparable size, known as voids, with almost zero luminous density. Galaxy redshift surveys show that this pattern only repeats itself as we move further out, leading to a cellular appearance for the Universe on the largest scales.

Cluster Orientations and Formation
Superclusters are still evolving, so they are not yet dynamically stable, gravitationally bound structures. Within
any cluster, the brightest dominant galaxy is elongated, and its orientation is usually very similar to that of the whole of the surrounding cluster, as delineated by their X-ray emission and galaxy distribution. Furthermore, this orientation clearly corresponds to the orientation of the supercluster chain in which the cluster is situated, in that the cluster tends to point to its nearest neighbour if that is within about 100 million light-years. There is thus a correlation of properties, and a shared knowledge of orientation over distances from the size of the brightest galaxy right up to the scale of the surrounding supercluster structure. This alignment of galaxies/clusters/superclusters provides an echo of how these objects formed, suggesting that matter comes together in a very anisotropic manner, and accumulates along preferential axes. This filamentary structure has to be matched in simulations of cluster formation /universe evolution, and so the large scale distribution of structure can thus provide a constraint for theories seeking to account for the way that structure in the Universe forms and grows. Simulations such as the famous Millenium Simulation aim to mimic the creation of a void-filled Universe surrounded by filamentary structure and walls, with clusters of galaxies forming at the intersections of the filaments via anisotropic infall of material flowing into the cluster along one or more axes. The clusters have been built by a series of subcluster mergers that occur along preferred directions, and naturally develop major axis orientations that reflect orientation of the dominant filament feeding them.

And For the Future...
There are other ways that understanding the contents of clusters, and how these change (or not) with the history of the Universe can constrain our ideas about cosmology. In particular they provide strong evidence for another invisible component of our Universe, dark energy. But that’s a subject for another lecture next year, when I’ll discuss the Age of the Universe.

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