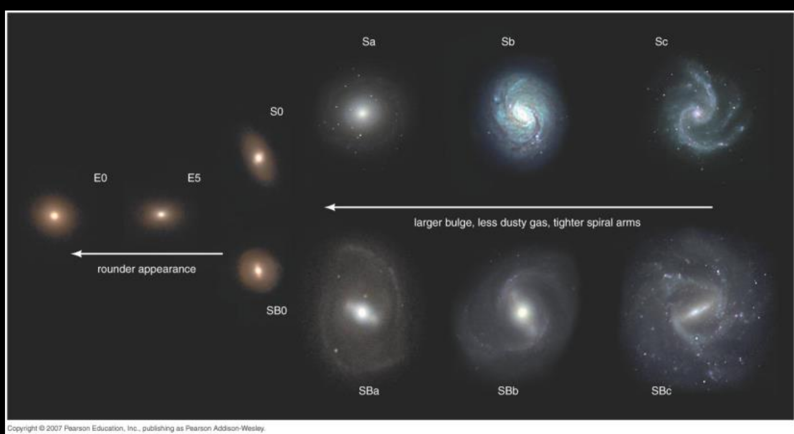
Upcoming Astronomy-themed Talks and Events

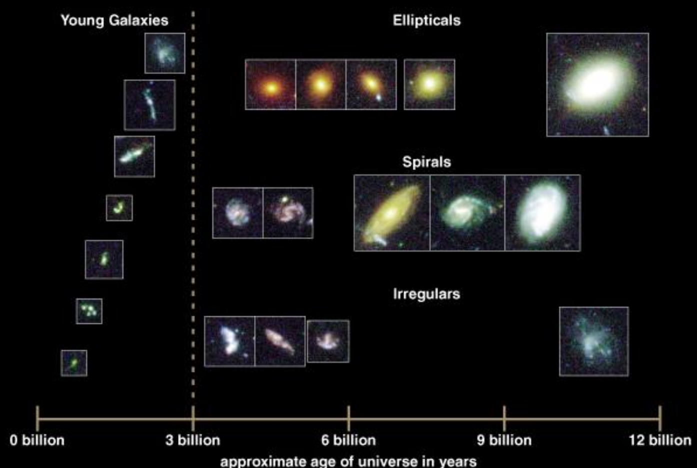
Thursday, 3/5, 3:30-5:00p Astronomy Colloquium – Phys-Astr A102 – Wen-fai Fong (Northwestern) – “Neutron Star Mergers, Near and Far”

Quick Recap: Galaxies



We focused last time on how we solved a great mystery in the last century – the true nature of galaxies as distant collections of stars like our own Milky Way.

These galaxies are distributed in small “Groups”, as well as much larger and denser “Clusters”.

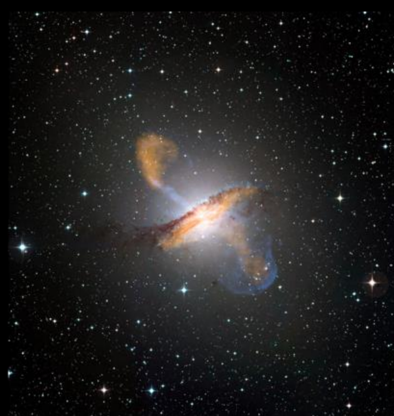


By studying galaxies of varying distances, we can compare galaxies of various ages. This allows us to develop an understanding of how galaxies form and change over time.

The future of our view of the Milky Way and Andromeda galaxies!

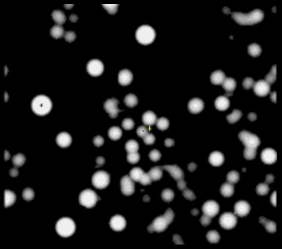
One way galaxies change over time is via ***collisions*** – relative to their sizes, galaxies are fairly closely packed together, so they “interact” with each other much more commonly that do individual stars inside of galaxies. Such a fate awaits us many billions of years from now!

Another way galaxies change is related to Active Galactic Nuclei (AGN), absurdly bright denizens of the distant universe powered by supermassive black holes, similar to the one in the center of our own galaxy.



A composite image of the Active Galaxy Centaurus A, as seen in X-ray, visible, infrared, and radio light

Early in their formation, galaxies seem to form these black holes – and the youth of these enormous objects appears to be quite violent indeed as nearby material falls into them.

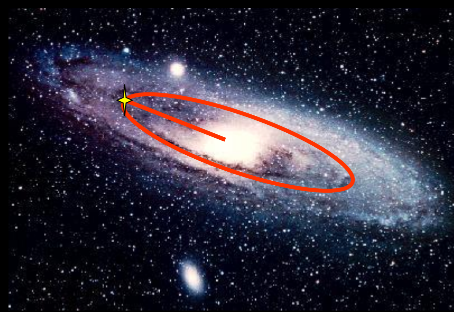


By the time a galaxy has been around for several billion years, its central black hole stops generating quite so much energy – though it’s still down there, as gravitationally potent as ever.

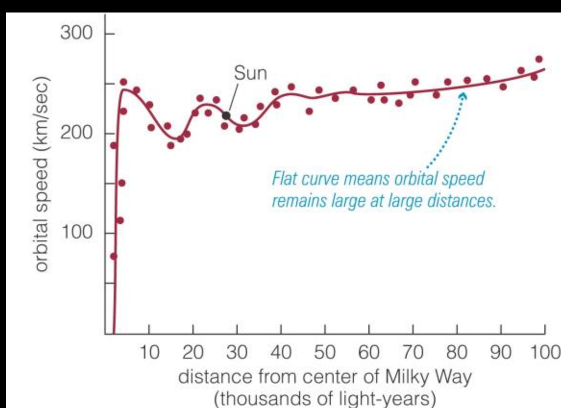
How do supermassive black holes form at all? What role do they play in their host galaxy’s formation? Answering those questions requires a deeper understanding of the gravitational forces that shape young galaxies – which introduces yet *another* question: How do we ‘weigh’ an entire galaxy?

One way to estimate the Milky Way's mass is via Kepler's Third Law – for example, using the Sun's orbital motion:

- Sun's distance from center: 28,000 l.y. = 1.75×10^9 AU
- Sun's orbital period: 230 million years
- $P^2 = 4\pi^2/GM\ a^3 \Rightarrow$ mass within Sun's orbit is over $10^{11}\ M_\odot$



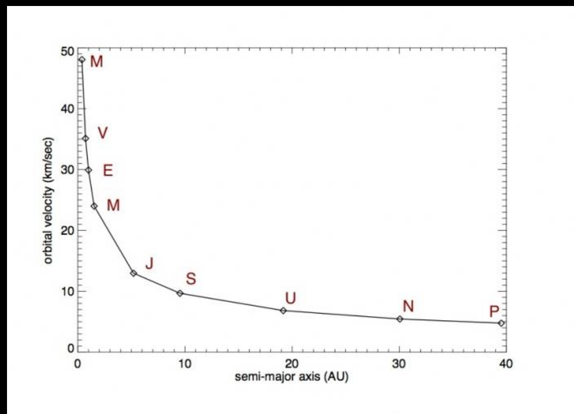
But this only tells us how much mass is between us and the center of the galaxy – to weigh the whole galaxy, we would need to make similar measurements for stars farther out.



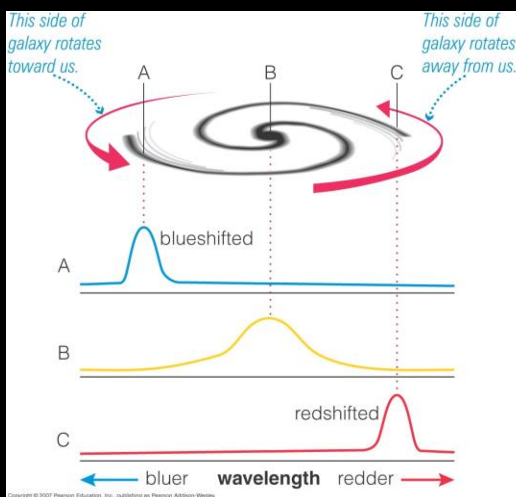
c The rotation curve for the Milky Way Galaxy. Dots represent stars or gas clouds whose orbital speeds have been measured.

Doing this at many locations produces a "rotation curve" of the Milky Way – a graph that shows the orbital speed of stars (and gas clouds) as a function of distance from the center. A key point to notice is that the orbital velocities remain very high far out into the halo.

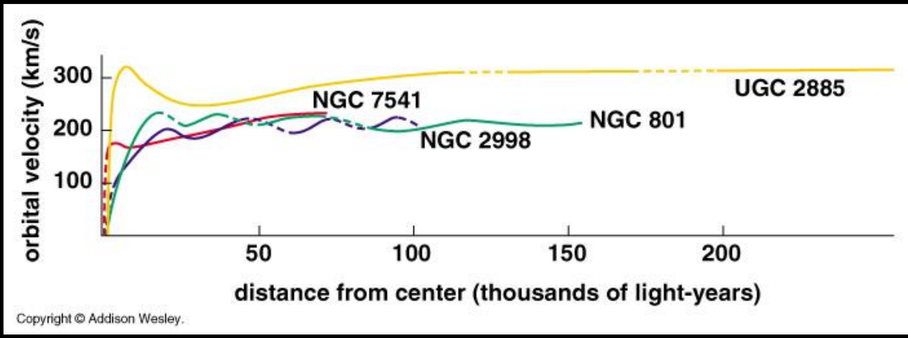
That's ***very*** different from what we see in the rotation curve of the planets of our Solar System. This sort of curve is what one sees when most of the mass – and therefore most of the gravitating material – is located at the center of a system.



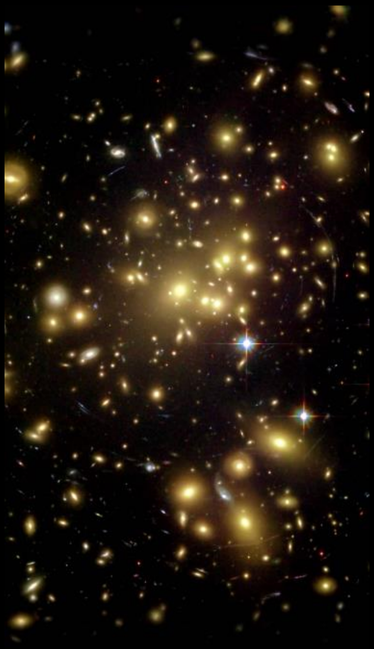
Rotation curve for the Solar System's major planets – lower velocities at larger distances.



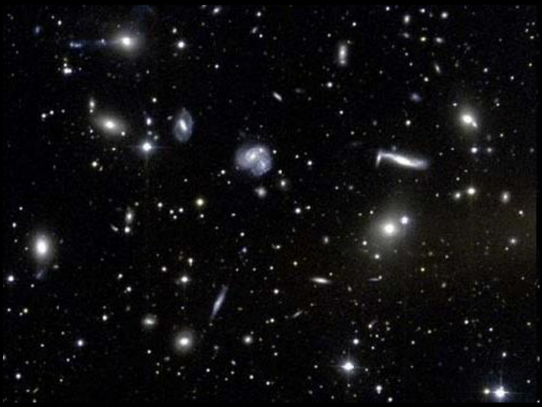
In other spiral galaxies, we can do similar things by measuring the Doppler shift of hydrogen gas at various radial distances and constructing a rotation curve of that gas (which extends beyond the visible disk of stars). We can then similarly calculate the gravitational force of the enclosed mass.



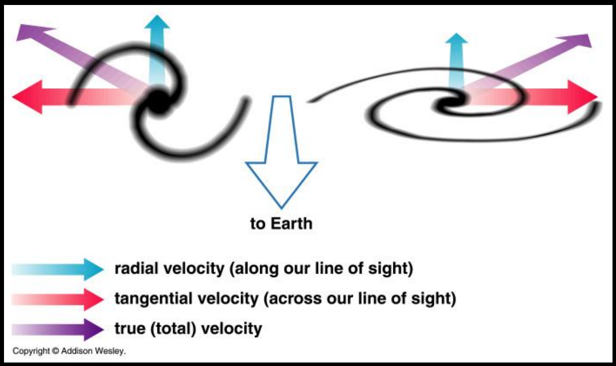
When we do, we find the rotation curves of other spirals – just as seen in the Milky Way – are flat at large distances from their centers. This indicates that most of their matter is not located at their centers (where most of the stars and gas are!), but is distributed far beyond the visible "stellar" components of these galaxies.



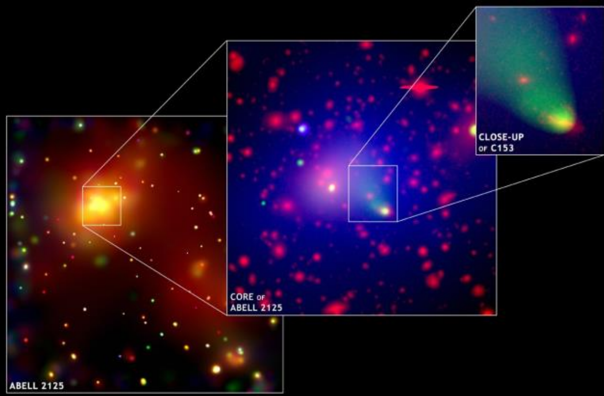
Mysterious indeed – and quite controversial when first revealed in the late 20th century. But soon further signs of some kind of "dark matter" were also found in measurements of the masses of entire clusters of galaxies – arguably the heaviest things in the universe!



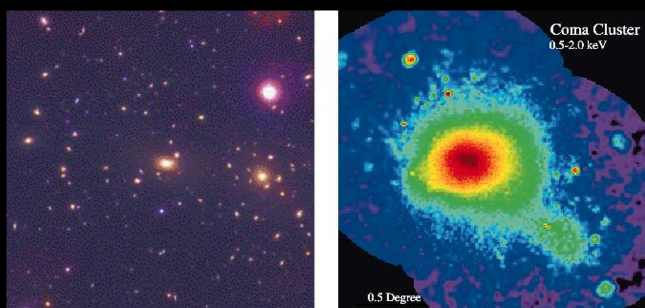
There are three independent ways that we can measure the mass of a galaxy cluster – the most seemly straightforward is to make something like a rotation curve: measure the motions of the galaxies within a cluster, and determine the mass needed to generate those velocities.



But this is tricky, since we can only truly measure radial velocity – a galaxy’s motion towards or away from the Earth. Fortunately, clusters contain many hundreds of galaxies – so that the distribution of their radial velocities still provides enough information to let you estimate the cluster’s total mass.



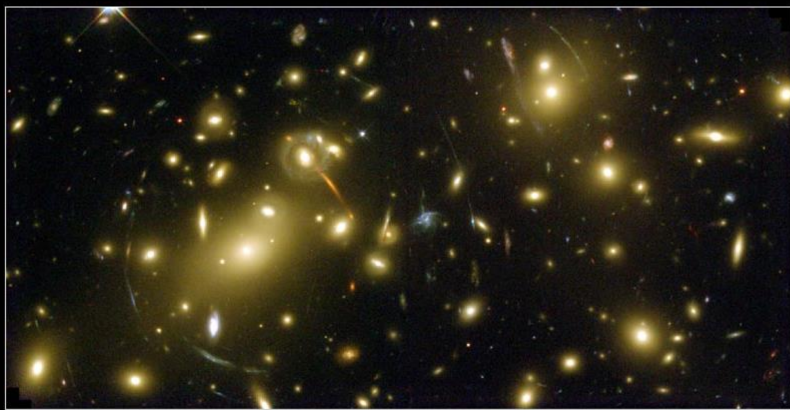
Another way to estimate the mass of a galaxy cluster is to measure the temperature and distribution of the hot gas *between* the galaxies. Because hot gases easily leave a cluster unless contained by gravity, the temperature of the gas between galaxies in a cluster gives information on the total mass of the cluster.



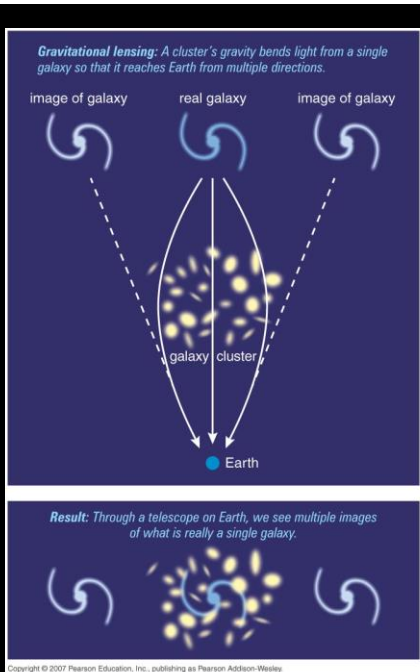
Coma cluster of galaxies in optical (l), and x-ray (r).

The ‘Intracluster Medium’ is so hot (10^7–10^8 K) that it emits X-rays, and we can use details of these X-rays to estimate the temperature – and therefore the average velocity – of the gas. From this velocity, we can calculate the minimum amount of mass needed to keep the gas contained within the cluster.

Finally, we can measure the mass of a galaxy cluster by noting the gravitational effects the cluster has on the light of *background* objects – that is, the strength of the cluster's gravitational lensing.

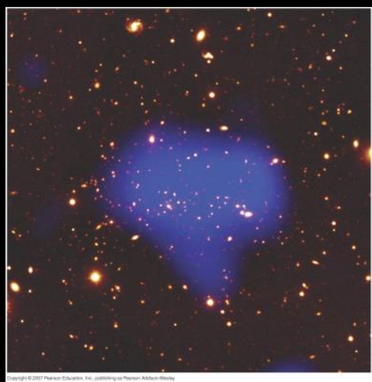


Galaxy Cluster Abell 2218 **HST** • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

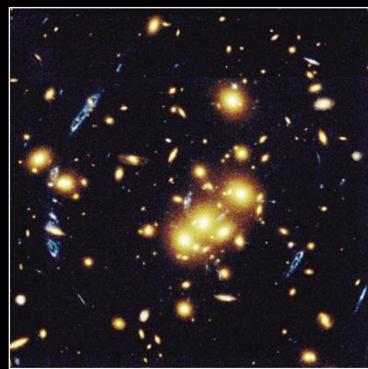


Recall that Einstein's Theory of Relativity states that massive objects distort spacetime. As a result, a massive cluster will bend the path of light which approaches it (like a lens). The degree to which the light is bent depends on the mass of the cluster, so that by analyzing lensed images, we can calculate the cluster's mass.

Evidence from all of these methods – rotation curves, rapid galactic orbits, hot intracluster gas, and gravitational lensing – all imply the existence of large amounts of dark matter – something like 90% of the gravitating matter in the universe!

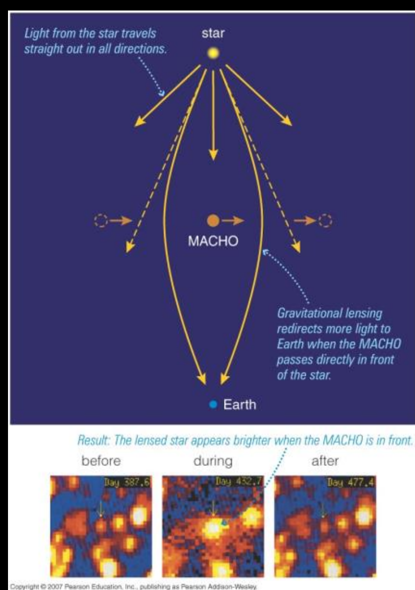


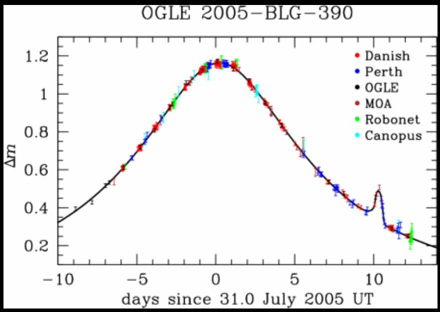
X-Ray emission from hot gas in a cluster of galaxies



Distant galaxies being lensed by a galaxy cluster.

This dark matter could be made out of protons, neutrons, & electrons – so-called "ordinary" matter. If this is so, then the only thing unusual about dark matter is that it is dim, so it could be in the form of small, dim stars, such as brown dwarfs, or even black holes – so-called MACHOs. Because these are dense concentrations of matter, a good way to detect them is through their local gravitational effects on light – so-called ***microlensing events***.



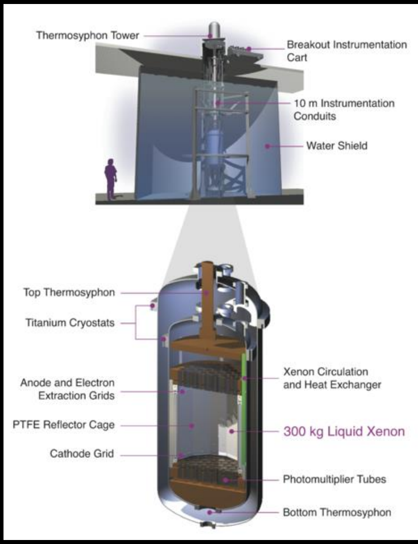


The magnification of a background star by a "microlens" – the secondary peak on the right indicates the presence of a planet around the star!

These sorts of brief, gravitationally induced magnifications are the very sorts of observations I cut my astronomical research teeth on as a student here at UW – research that has since led to discoveries of black holes and extrasolar planets! And kangaroos!

Right outside my kitchen window!

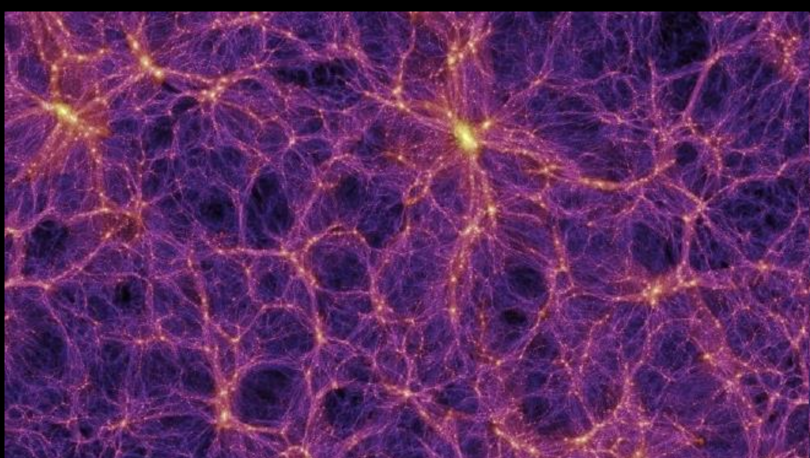
After extensive searches, however, the evidence at this point suggests that dark matter is most likely composed of new subatomic particles that we have yet to discover. These particles must interact only very weakly with "normal" matter and with radiation, but must have a nonzero mass, and therefore a measurable gravitational influence – *Weakly Interacting Massive Particles* – or WIMPs.



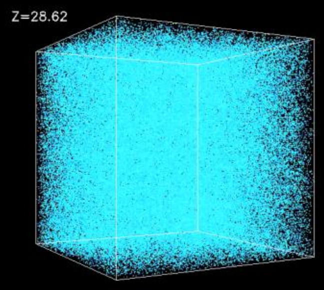
Schematic of the LUX detector, which uses Xenon atoms to search for WIMPs.

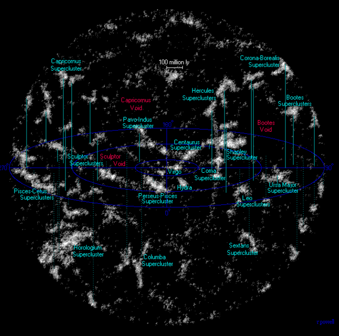
The 2 billion dollar Alpha Magnetic Spectrometer, installed in 2011 on the International Space Station, and designed to look for evidence of Dark Matter.

The search for such particles is at the forefront of modern experimental physics – a Nobel Prize is certainly on the line!



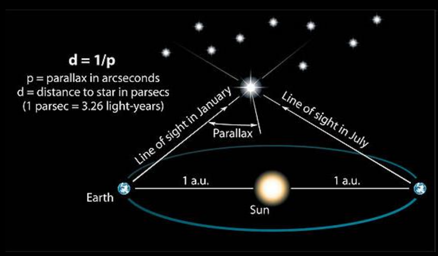
Additional limits on the properties of Dark Matter come from computer simulations ("N-body" models) of the formations of clusters and superclusters of galaxies – all driven by the interactions of dark and ordinary matter.

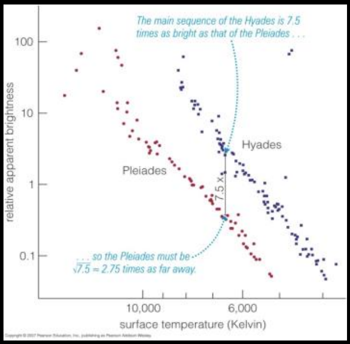


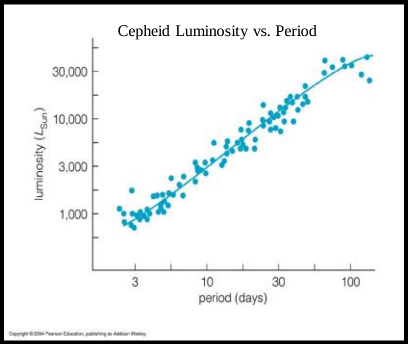


These limits emerge because our models of galaxy formation must match observed reality! But how do we definitively ‘map’ such remarkably distant regions of the universe in order to make this comparison? A key component is being able to measure distances reliably and accurately on such large scales.

We measure the distances to objects in many ways – geometric parallax, main-sequence fitting, and Cepheid “standard candles” are some we’ve discussed already.

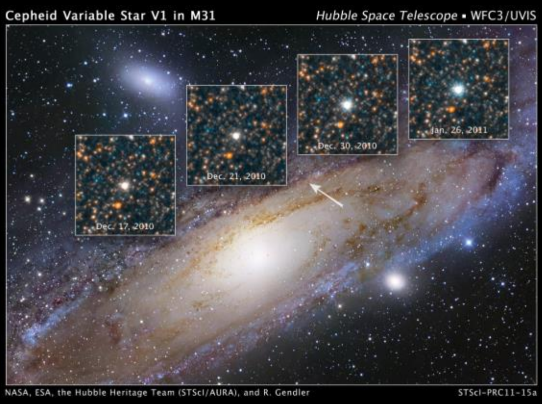




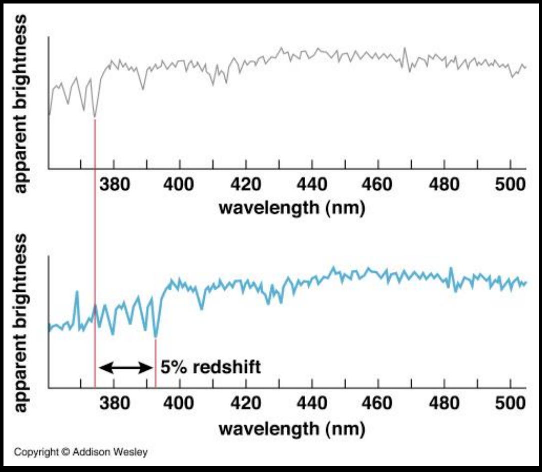


A New and Amazing Method of Distance Measurement

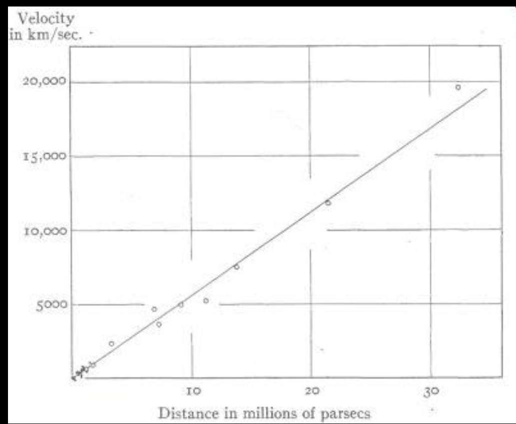
In the late 1920’s, excited about the discovery that “spiral nebulae” were in fact other galaxies like the Milky Way, Hubble (and others!) began measuring the distances to as many galaxies as possible, largely using Cepheid variables.



But he also took spectra of these galaxies and measured the Doppler shift of absorption lines for each of them. Hubble and others then used these data to calculate the galaxy’s velocity towards or away from the Earth.

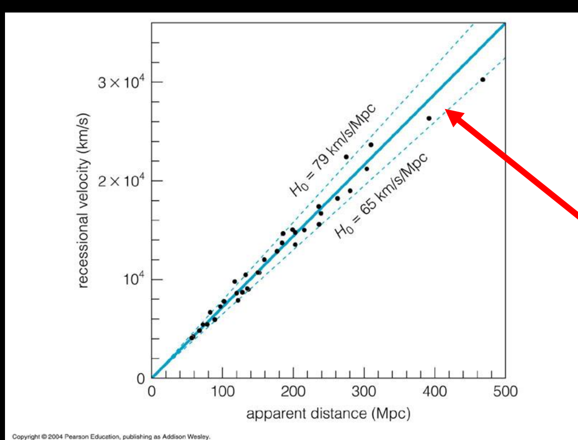


Plotting *velocity* vs. *distance* showed that there was a simple relationship between the two – the farther away a galaxy was, the higher its velocity was. Numerically, the line could be written in the form:



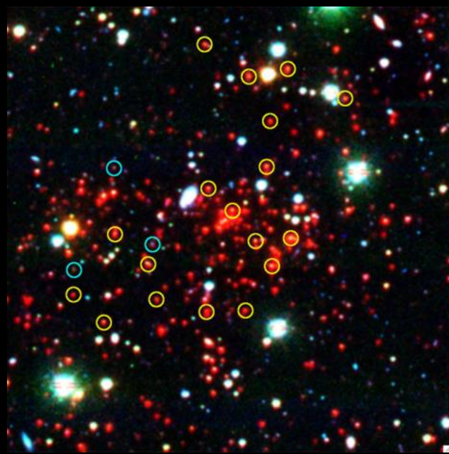
$$\mathbf{v = H_o\, d}$$

where H_o is the slope of the line, and is called “Hubble’s constant”. This value has units of speed/distance [km/s per Mpc], and the relationship is generally referred to as the “Hubble Law”.

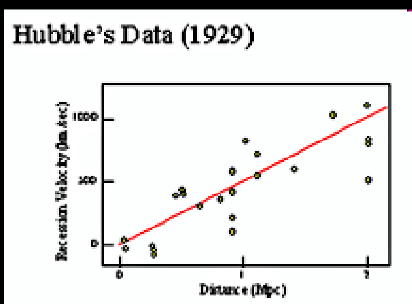


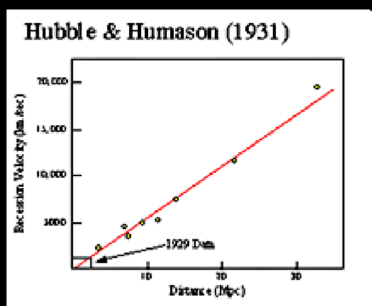
Notice that if this relationship holds for all galaxies – and for all but the very closest of galaxies, it does – you can use this line, along with a measurement of a galaxy’s Doppler velocity, to easily estimate the distance to that galaxy.

In fact, since it is so straightforward to measure Doppler velocities, this method of measuring distances to galaxies is by far the most common way it is done in modern astronomy – and the overwhelming majority of “galaxy distances” that have been measured have used the Hubble Law.



Perhaps the most distant and massive galaxy cluster known – distances courtesy of spectra and the Hubble Law!

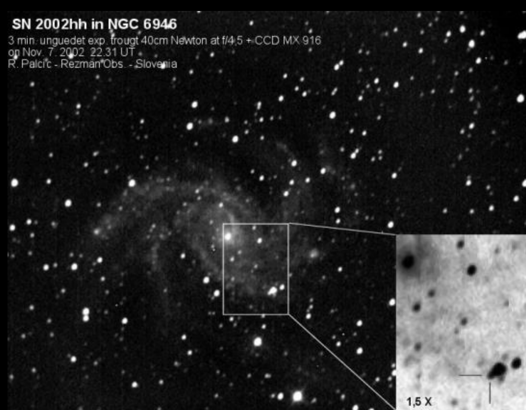




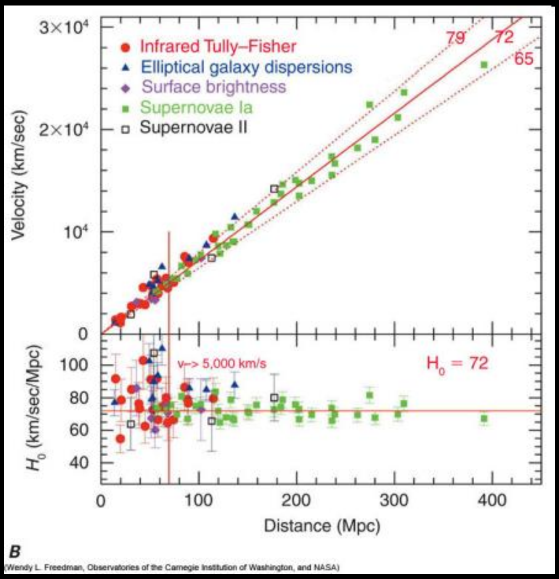
But the distances that we calculate using Hubble’s Law are obviously only as accurate as our understanding of that line and its true shape at large distances. Hubble calibrated his measurements using Cepheid variables to verify the distances – but Cepheids aren’t useful beyond distances of about 60 million light years.

To obtain a more accurate understanding of the Hubble Law at very large distances, we need standard candles brighter than Cepheid variables – objects that would let us check the truth of Hubble’s Law at even greater distances than Cepheids allow.

Fortunately we *do* have a brighter candle – in fact, a much, much brighter candle: White Dwarf Supernovae.

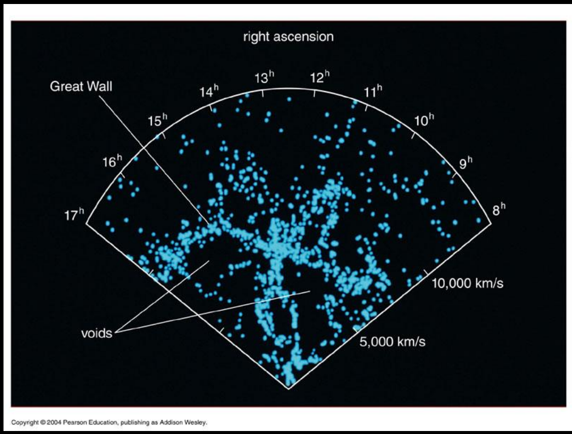


White Dwarf Supernovae are fantastic standard candles because they all have about the same peak luminosity – roughly 10 billion times the Sun’s luminosity – bright enough that WD Supernovae can be observed in galaxies billions of light years away!



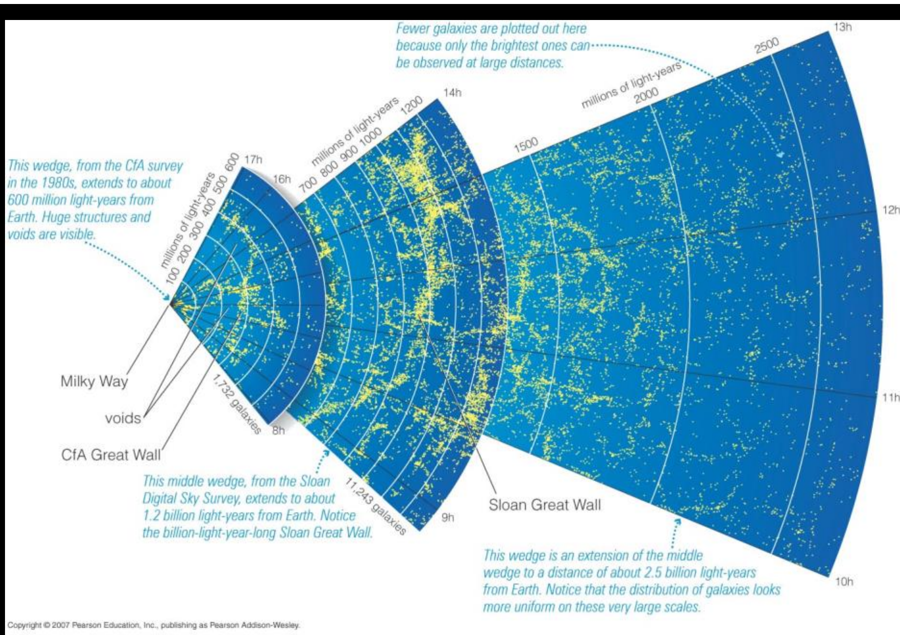
Thanks to these new standard candles, we now know with great confidence that the Hubble Law remains valid to very large distances in the universe – albeit with some subtle but ***extremely*** interesting modifications that we'll see next time!

Using Hubble Distances to Map Large-Scale Structure

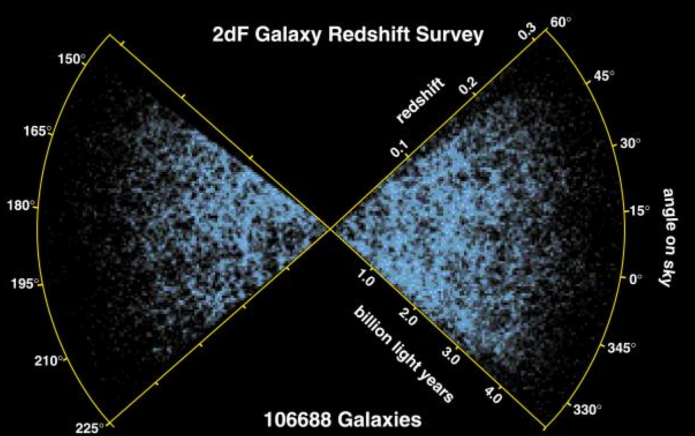


A slice of the Universe out to 7 x 10^8 ly

On scales of 10^8 l.y., galaxies are distributed in gigantic chains and sheets surrounding great voids. These chains come from regions of density enhancement in the early universe, while the voids come from the initial regions of density depletion.

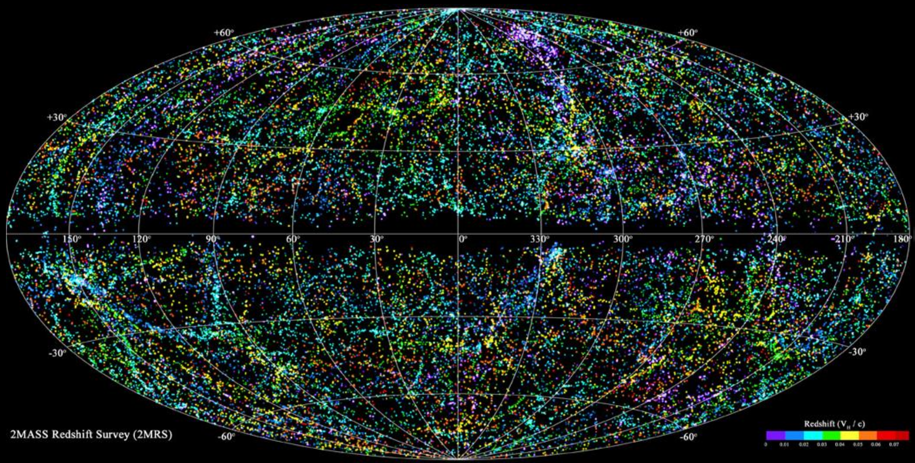


The view out to ~ 2.5 billion l.y. from Earth



A slice of the Universe, showing the locations of galaxies out to 4×10^9 l.y. from Earth.

However, on the very largest scales – out to several billion l.y. – galaxies begin to appear more evenly distributed, like a vast galactic foam. The distant, and therefore early, universe appears remarkably homogeneous and smooth.



A more recent version, showing a panoramic view of galaxy clusters as seen from the Earth! And check out the "Cosmography and Data Visualization" paper posted online!

Comparing the results of simulations of galaxy formation, like the "Illustris" model shown above – which includes a wide variety of theoretical physical effects and interactions between dark matter, ordinary matter, and light – allows us to better constrain what dark matter could possibly be made of.

But we still lack a definitive answer, and these observations at large distances introduce many new mysteries – such as why almost all galaxies are apparently moving away from us!?! Are we back at the center of the universe again?

We’ll pick up the story there next time with as we approach the very limits of the universe in space and time!