Dark Matter Exists

Sean at 11:52 am, August 21st, 2006

The great accomplishment of late-twentieth-century cosmology was putting together a complete inventory of the universe. We can tell a story that fits all the known data, in which ordinary matter (every particle ever detected in any experiment) constitutes only about 5% of the energy of the universe, with 25% being dark matter and 70% being dark energy. The challenge for early-twenty-first-century cosmology will actually be to *understand* the nature of these mysterious dark components. A beautiful new result illuminating (if you will) the dark matter in galaxy cluster 1E 0657-56 is an important step in this direction. (Here's the press release, and an article in the Chandra Chronicles.)

A prerequisite to understanding the dark sector is to make sure we are on the right track. Can we be sure that we haven't been fooled into believing in dark matter and dark energy? After all, we only infer their existence from detecting their gravitational fields; stronger-than-expected gravity in galaxies and clusters leads us to posit dark matter, while the acceleration of the universe (and the overall geometry of space) leads us to posit dark energy. Could it perhaps be that gravity is modified on the enormous distance scales characteristic of these phenomena? Einstein's general theory of relativity does a great job of accounting for the behavior of gravity in the Solar System and astrophysical systems like the binary pulsar, but might it be breaking down over larger distances?

A departure from general relativity on very large scales isn't what one would expect on general principles. In most physical theories that we know and love, modifications are expected to arise on *small* scales (higher energies), while larger scales should behave themselves. But, we have to keep an open mind — in principle, it's absolutely possible that gravity could be modified, and it's worth taking seriously.

Furthermore, it would be really cool. Personally, I would prefer to explain cosmological dynamics using modified gravity instead of dark matter and dark energy, just because it would tell us something qualitatively different about how physics works. (And Vera Rubin agrees.) We would all love to out-Einstein Einstein by coming up with a better theory of gravity. But our job isn't to express preferences, it's to suggest hypotheses and then go out and test them.

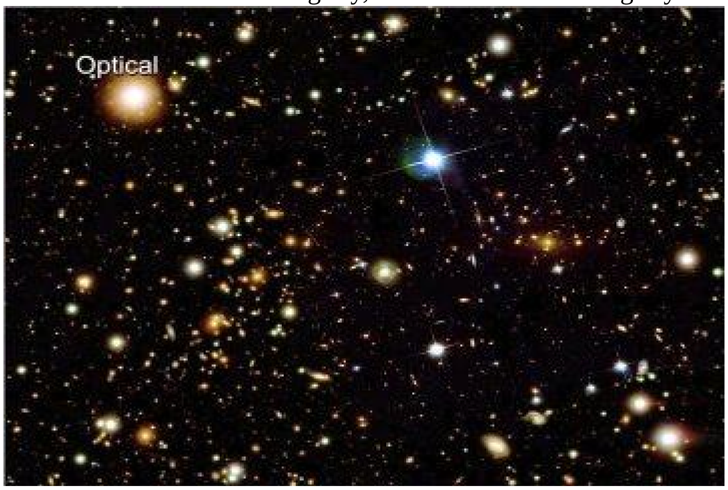
The problem is, how do you test an idea as vague as "modifying general relativity"? You can imagine testing specific proposals for how gravity should be modified, like Milgrom's MOND, but in more general terms we might worry that *any* observations could be explained by *some* modification of gravity.

But it's not quite so bad — there are reasonable features that any respectable modification of general relativity ought to have. Specifically, we expect that the gravitational force should point in the direction of its source, not off at some bizarrely skewed angle. So if we imagine doing away with dark matter, we can safely predict that gravity always be pointing in the direction of the *ordinary* matter. That's interesting but not immediately helpful, since it's natural to expect that the ordinary matter and dark matter cluster in the same locations; even if there is dark matter, it's no surprise to find the gravitational field pointing toward the visible matter as well. What we really want is to take a big cluster of galaxies and simply sweep away all of the ordinary matter. Dark matter, by hypothesis, doesn't interact directly with ordinary matter, so we can imagine moving the ordinary stuff while leaving the dark stuff behind. If we then check back and determine where the gravity is, it should be pointing either at the left-behind dark matter (if there is such a thing) or still at the ordinary matter (if not).

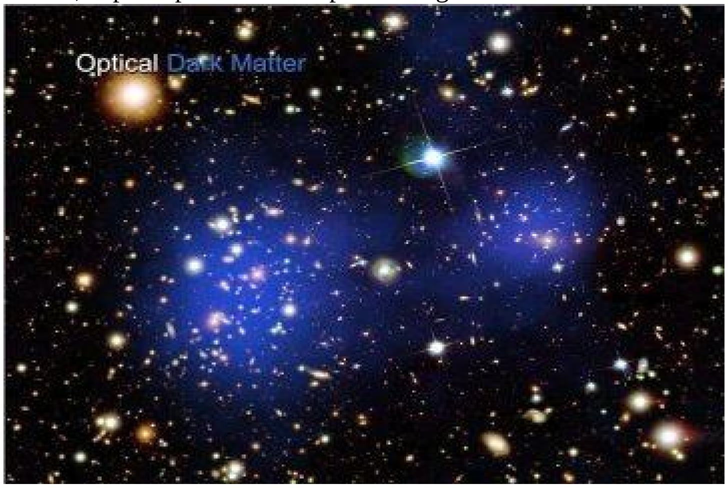
Happily, the universe has done exactly this for us. In the Bullet Cluster, more formally known as 1E 0657-56, we actually find two clusters of galaxies that have (relatively) recently passed right through each other. It turns out that the large majority (about 90%) of ordinary matter in a cluster is not in the galaxies themselves, but in hot X-ray emitting intergalactic gas. As the two clusters passed through each other, the hot gas in each smacked into the gas in the other, while the individual galaxies and the dark matter (presumed to be collisionless) passed right through. Here's an mpeg animation of what we think happened. As hinted at in last week's NASA media advisory, astrophysicists led by Doug Clowe (Arizona) and Maxim Markevitch (CfA) have now compared images of the gas obtained by the Chandra X-ray telescope to "maps" of the gravitational field deduced from weak lensing observations. Their short paper is astro-ph/0608407, and a longer one on lensing is astro-ph/0608408. And the answer is: there's definitely dark matter there!

Despite the super-secret embargoed nature of this result, enough hints were given in the media advisory and elsewhere on the web that certain scientific sleuths were basically able to figure out what was going on. But they didn't have access to the best part: pictures!

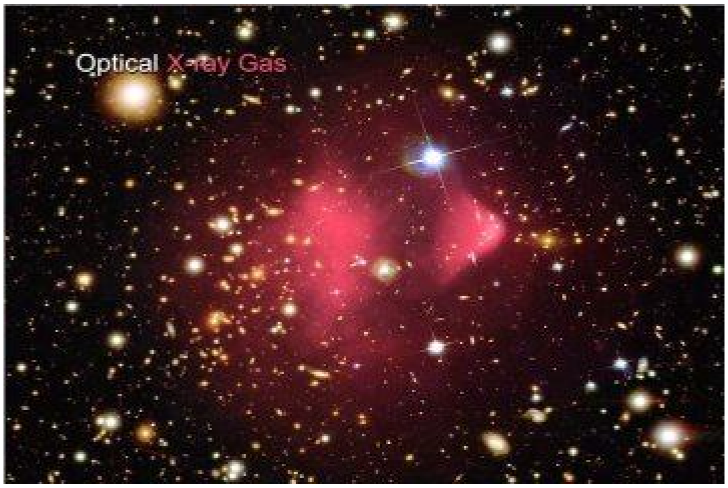
Here is 1E 0657-56 in all its glory, or at least some of it's glory — this is the optical image, in which you can see the actual galaxies.



With some imagination it shouldn't be too hard to make out the two separate concentrations of galaxies, a larger one on the left and a smaller one on the right. These are pretty clearly clusters, but you can take redshifts to verify that they're all really at the same location in the universe, not just a random superposition of galaxies at very different distances. Even better, you can map out the gravitational fields of the clusters, using weak gravitational lensing. That is, you take very precise pictures of galaxies that are in the *background* of these clusters. The images of the background galaxies are gently distorted by the gravitational field of the clusters. The distortion is so gentle that you could never tell it was there if you only looked at one galaxy; but with more than a hundred galaxies, you begin to notice that the images are systematically aligned, characteristic of passing through a coherent gravitational lens. From these distortions it's possible to work backwards and ask "what kind of mass concentration could have created such a gravitational lens?" Here's the answer, superimposed on the optical image.

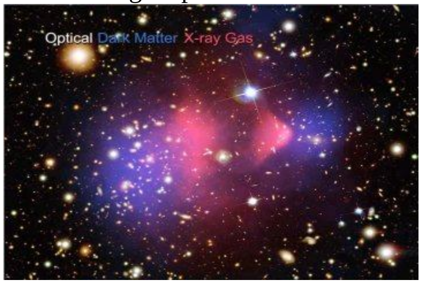


It's about what you would expect: the dark matter is concentrated in the same regions as the galaxies themselves. But we can separately make X-ray observations to map out the hot gas, which constitutes most of the ordinary (baryonic) matter in the cluster. Here's what we see.



This is why it's the "Bullet" cluster — the bullet-shaped region on the right is a shock front. These two clusters have passed right through each other, creating an incredibly energetic collision between the gas in each of them. The fact that the "bullet" is so sharply defined indicates that the clusters are moving essentially perpendicular to our line of sight.

This collision has done exactly what we want — it's swept out the ordinary matter from the clusters, displacing it with respect to the dark matter (and the galaxies, which act as collisionless particles for these purposes). You can see it directly by superimposing the weak-lensing map and the Chandra X-ray image.



Clicking on each of these images leads to a higher-resolution version. If you have a tabbed browser, the real fun is opening each of the images in a separate tab and clicking back and forth. The gravitational field, as reconstructed from lensing observations, is not pointing toward the ordinary matter. That's exactly what you'd expect if you believed in dark matter, but makes no sense from the perspective of modified gravity. If these pictures don't convince you that dark matter exists, I don't know what will.

So is this the long-anticipated (in certain circles) end of MOND? What need do we have for modified gravity if there clearly is dark matter? Truth is, it was already very difficult to explain the dynamics of clusters (as opposed to individual galaxies) in terms of MOND without invoking anything but ordinary matter. Even MOND partisans generally agree that some form of dark matter is necessary to account for cluster dynamics and cosmology. It's certainly conceivable that we are faced with *both* modified gravity and dark matter. If the dark matter is sufficiently "warm," it might fail to accumulate in galaxies, but still be important for clusters. Needless to say, the picture begins to become somewhat baroque and unattractive. But the point is not whether or not MOND remains interesting; after all, someone else might come up with a different theory of modified gravity tomorrow that can fit both galaxies and clusters. The point is that, independently of any specific model of modified gravity, we now know that there definitely is dark matter out there. It will *always* be possible that some sort of modification of gravity lurks just below our threshold of detection; but now we have established beyond reasonable doubt that we need a substantial amount of dark matter to explain cosmological dynamics.

That's huge news for physicists. Theorists now know what to think about (particle-physics models of dark matter) and experimentalists know what to look for (direct and indirect detection of dark matter particles, production of dark matter candidates at accelerators). The dark matter isn't just ordinary matter that's not shining; limits from primordial nucleosynthesis and the cosmic microwave background imply a strict upper bound on the amount of ordinary matter, and it's not nearly enough to account for all the matter we need. This new result doesn't tell us which particle the new dark matter is, but it confirms that there is such a particle. We're definitely making progress on the crucial project of understanding the inventory of the universe.

What about dark energy? The characteristic features of dark energy are that it is smooth (spread evenly throughout space) and persistent (evolving slowly, if at all, with time). In particular, dark energy doesn't accumulate in dense regions such as galaxies or clusters — it's the same everywhere. So these observations don't tell us anything directly about the nature of the 70% of the universe that is purportedly in this ultra-exotic component. In fact we know rather less about dark energy than we do about dark matter, so we have more freedom to speculate. It's still quite possible that the acceleration of the universe can be explained by modifying gravity rather than invoking a mysterious new dark component. One of our next tasks, then, is obviously to come up with experiments that might distinguish between dark energy and modified gravity — and some of us are doing our best. Stay tuned, as darkness gradually encroaches upon our universe, and Einstein continues to have the last laugh.

In 1967, Vera Rubin observed that stars within the Andromeda galaxy had higher-than-expected orbital speeds.

Physicists have also observed the same phenomenon in the nearby Triangulum galaxy.

By measuring the orbital speeds of stars within Triangulum and using the formula

$$M_{gal} = \frac{v^2 r}{G}$$

physicists have calculated that the mass of this galaxy within a radius of r = 4.0 Ã 10^{20} m is equivalent to 46 billion Suns.

- However, by measuring the brightness of Triangulum, they have also calculated that its mass within a radius of r = 4.0 Ã 10^{20} m is equivalent to 7 billion Suns.
- The discrepancy between these two results implies that there is 39 billion Suns' of unseen mass within Triangulum.
- This unseen mass is called "dark matter".
- Physicists have observed many other galaxies and most are now convinced that, on average, dark matter accounts for 90% of the mass of every single galaxy in the universe.
- Physicists also have independent evidence for the existence of dark matter from observations of distorted images of distant galaxies (gravitational lensing).
- Although no one knows what dark matter is made of, physicists currently have a number of theories.
- One of the earliest theories of dark matter was that it consists entirely of compact celestial objects such as planets, dwarf stars, and blackholes. Careful observations have ruled out this theory.
- Most physicists today think that dark matter is made of a type of subatomic particle that, to date, has never been detected in the laboratory. The two leading candidates are weakly interacting massive particles (WIMPs) and axions.
- Numerous experiments that are trying to detect one of these particles are currently underway worldwide.
- As physicists do not yet know what dark matter is made of, they do not know the composition of a large fraction of the universe.

Team finds 'proof' of dark matter
By Paul Rincon
Science reporter, BBC News

US astronomers say they have found the first direct evidence for the mysterious stuff called dark matter.

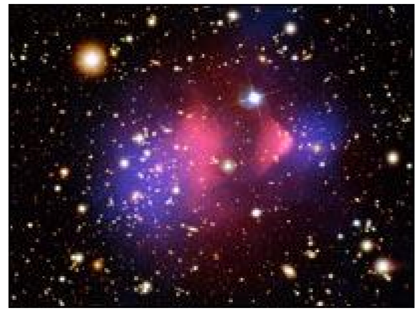
Dark matter - which does not emit or reflect enough light to be "seen" - is thought to make up 25% of the Universe.

By contrast, the ordinary matter we can see is believed to make up no more than about 5% of our Universe.

Until now, astronomers have only been able to infer the existence of this dark material through the gravitational effects it has on ordinary matter.

What the researchers have done is, in effect, to identify the gravitational "signature" of dark matter.

This signature was created by dark matter and ordinary matter being wrenched apart by the immense collision of two large galaxy clusters.



The claims are based on observations of the Bullet Cluster

"The kinetic energy of this collision is... enough to completely evaporate and pulverise planet Earth ten trillion, trillion times over," said team member Maxim Markevitch, of the Harvard-Smithsonian Center for Astrophysics in Cambridge, US.

Study leader Doug Clowe, from the University of Arizona, said: "This provides the first direct proof that dark matter must exist and that it must make up the majority of the matter in the Universe."

Gravity puzzle

Astronomers have known since the 1930s that these galaxy clusters have far too much gravity to be explained by the amount of visible matter in them alone.

This extra gravity has two possible explanations. One is that most matter in the clusters is in a form we cannot see, because it does not absorb or emit light.

A second explanation is that gravity does not behave the same way in galaxy clusters light-years in size as it does on Earth.

WHAT THE UNIVERSE IS MADE OF
70% - dark energy
25% - dark matter
5% - ordinary matter

Usually, the gas and the galaxies in the clusters are held close together in space by gravity. But in the cosmic smash-up (the colliding feature is known to astronomers as the Bullet Cluster), these components have been pulled apart. The astronomers were lucky enough to catch the collision just 100 million years after it occurred - the blink of an eye in cosmic time.

The researchers could see that the hot gas in the collision had been slowed down by a drag force, similar to air resistance. Meanwhile, the galaxies themselves continued speeding through space, leaving the gas behind.

Dark matter particles should not slow down in the same way as the gas; they do not interact directly with themselves or the gas except through gravity. Instead, dark matter should behave in a similar way to the galaxies.

More mass in gas

If dark matter did exist, the astronomers expected to find the majority of mass in clusters residing around the galaxies.

But if dark matter did not exist, most of the galaxy clusters' mass would be in its diffuse hot gas. This is because galaxy clusters typically contain 10 times as much ordinary mass in gas as in stars.

The researchers found most of the mass was located near the galaxies - ahead of the gas clouds - showing the dark matter really was there.

The majority of the Universe - some 70% - is composed of dark energy, an equally mysterious quantity which exerts negative pressure.

"Dark matter and dark energy are not what anyone would have expected starting from the perspective of what the Universe should be like," said Sean Carroll, a cosmologist at the University of Chicago, who was not involved with the study, "but we're trying to understand why it's like that and this result puts us on that path."

Marusa Bradac, at the Stanford Linear Accelerator Center (Slac) in California, added: "We had predicted the existence of dark matter for decades, but now we've seen it in action. This is groundbreaking."

In order to locate the mass in the clusters, researchers used the Chandra and Hubble space telescopes, along with the Very Large Telescope and Magellan optical telescopes in Chile.

This was done by measuring the effect of gravitational lensing, where gravity from the clusters distorts light from background galaxies, as predicted by Einstein's theory of general relativity.

A big find in the hunt for elusive dark matter

Astronomers cite new evidence that the unseen 'glue' holding galaxies together really exists.

***By Peter N. Spotts** | Staff writer of The Christian Science Monitor* from the May 16, 2007 edition

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Ring of dark matter: The galaxy cluster at the center of this image is believed to have collided with another such cluster at least 1 billion years ago. That collision forced dark matter to separate from the luminous, or visible, matter in the clusters, rippling outward to form the ring (band in lighter blue) above.

NASA/ESA

Building cosmic maps of matter no one can see may seem like a strange way to make a living. But for astronomer Myungkook James Jee, the work may have netted evidence that seals the case for the existence of dark matter – unseen, "missing mass" first invoked in 1933 to explain why spinning galaxies and galaxy clusters don't tear themselves apart as they twirl.

Dr. Jee and his colleagues announced Tuesday that they have discovered a wispy ring of dark matter around a huge cluster of galaxies 5 billion light-years from Earth. The researchers didn't spot the dark matter directly; it doesn't emit light. Instead, they analyzed the way its gravity bends light from galaxies behind it – an effect called gravitational lensing. If confirmed, the result would rule out other, more exotic notions that have emerged to explain how galaxies and galaxy clusters are held together.

Typically, dark matter's gravity is thought to act as a scaffold for building galaxies and structures that astronomers can detect. That was their only initial explanation for how these structures held up – otherwise the mass in luminous matter wouldn't yield enough gravity to hold galaxies or galaxy clusters together as they rotate. So, astronomers surmised, bright and dark matter generally should go hand in glove.

Some scientists, however, are uncomfortable relying on the unseeable to act as this cosmic glue. For nearly 25 years, they have sought other ways to explain the structures they see. For example, some suggest that you don't need to invoke dark matter if gravity behaves differently at huge spatial scales than it does at small scales. Such alternative explanations couldn't be ruled out – unless someone could find dark matter out there on its own, with a structure unlike that of the nearest clusters.

Jee's discovery gets closer than ever to doing just that. It suggests that the ring of dark matter, 2.6 million light-years wide, is clearly separated from the hot gas and other luminous matter in the cluster. If the result holds up, this stand-alone dark matter would close the door to these other theories, some astronomers say.

It would also sustain a long-cherished assumption underlying space science: Gravity works the same way everywhere in the universe as it does on Earth.

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The results "are suggestive," acknowledges Douglas Clowe, an Ohio University astronomer who is not part of Jee's team. They don't help identify the exotic subatomic particles dark matter is made of. But if confirmed, the results would "remove the last conspiracy theories against dark matter."

Jee, an astronomer at The Johns Hopkins University in Baltimore, notes that at first he didn't believe his results. His team was mapping the distribution of dark matter in the galaxy cluster, dubbed CL0024+17, using the Hubble Space Telescope's Advanced Camera for Surveys. When the team saw the ring in the data, members suspected it came from flaws in a computer program they'd used. "We spent nearly a year searching for the cause of the problem," Jee says. The more the group tried to remove the ring, the more distinctly it showed up. Then the group came across an earlier study of the cluster indicating that 1 billion to 2 billion years ago the collection of galaxies collided with another galaxy cluster. The team realized it was viewing the remnants of the collision end-on. The dark-matter ring was, in effect, a ripple expanding out from the collision.

Last year, Dr. Clowe and colleagues reported the first direct evidence for dark matter in another cluster that had endured a collision. But in terms of testing alternative ideas on missing mass, it provided only half a loaf, he explains. The collision had stripped the cluster of its hot gas, so the dark matter was decoupled from that batch of luminous matter – which accounts for most of a cluster's luminous mass. But the dark matter still appeared to be associated with the galaxies in the cluster. Jee's team apparently has found dark matter that has been fully pushed out of the nest.

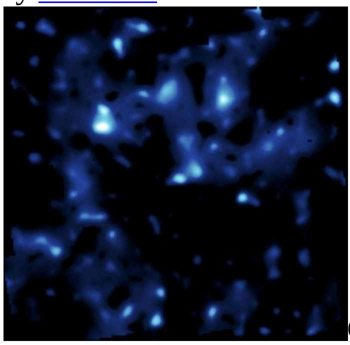
The findings are controversial, notes Cal Tech astronomer Richard Massey, who this year published a map of dark matter embracing some 500,000 galaxies. The latest measurements come from only one instrument; other studies combine optical images with data taken at other wavelengths. Moreover, "the signal is very weak. Some people are not yet convinced it's more than an artifact," he notes.

Follow-up studies may have to await the launch of the James Webb Space Telescope, slated for 2013. The Hubble camera Jee's team used blew a fuse and ceased operation in January, and it's not clear whether a space shuttle mission can repair it.

Found: Most of the Universe

An Astronomer Puts the COSMOS Survey In Perspective

by Phil Plait • Posted February 2, 2007 02:06 AM



Cosmic Evolution Survey - Dark Matter *Credit: NASA, ESA, and R. Massey (California Institute of Technology)*

After decades of attempts, astronomers have unveiled the dark side of the Universe.

Dark matter, the ubiquitous yet ethereal stuff filling the cosmos, has been mapped three-dimensionally for the first time by a team of astronomers using a fleet of orbiting and ground-based telescopes. Implementing techniques not even dreamed of when dark matter was first postulated, they have created a map two degrees on a side (roughly 15 times the area of the full Moon) and 6 *billion* light years deep. The Cosmic Evolution Survey, or COSMOS, reveals the spatial distribution of dark matter stretching back to a time when the Universe was half its present age.

The first hint of dark matter came in the 1930s, when astronomer Fritz Zwicky investigated clusters of galaxies. He found that the galaxies in the clusters were moving so rapidly that the clusters should fly apart, yet they were clearly holding themselves together just fine. Zwicky concluded that there must be a lot more mass to the cluster than what he could see with his telescope—in fact, 90 percent of the mass of the clusters was "missing."

As time went on, more and more data suggested that the bulk of the Universe is invisible. Astronomers weren't thrilled with this (who wants to be told you can't see the majority of what you're trying to study?), but the evidence kept mounting. Galaxies rotated too quickly, implying that they had extra matter surrounding them in halos that were totally invisible. X-ray images revealed galaxies that were submerged in vast pools of million-degree gas, which should quickly dissipate unless the gravity from some unseen matter held it in place. And so on.

Astronomers knew dark matter was out there, but it was frustratingly, well, *dark*. What could it be? There was no lack of theories—maybe dark matter was made up of black holes, or planets, or faint old dead stars, or cold gas—but all these ideas fell short. Each of these objects would have betrayed its presence in one way or another. In fact, recent observations suggest that dark matter is some exotic form of matter that only interacts with normal matter through gravity.

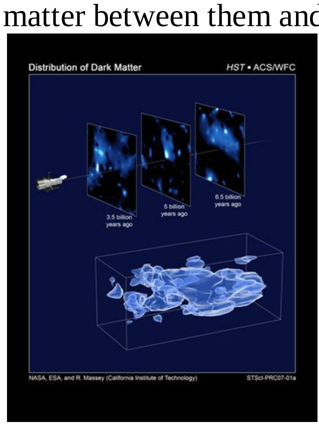
So how do you find what you can't see and see what you can't find?

Astronomers got clever. The COSMOS team made their map of dark matter by exploiting a peculiar characteristic of gravity: its ability to warp space. Einstein postulated that gravity bends space like a bowling ball placed in the middle of a bed distorts the mattress. Light moving through empty space travels in a straight line, but if it passes by a mass, the gravity will bend the light's path. How much the path bends depends on how much mass there is and how it's distributed.

That is how scientists can detect dark matter. Mass (both visible and invisible) twists, bends, and warps the light from distant galaxies on its way from there to here. The visible mass can be measured in several ways, and by subtracting the visible component from the total mass, researchers are able to find the location and quantity of dark matter.

Of course, actually doing this is a bit trickier. It takes the combined might of telescopes, such as the orbiting Hubble, Spitzer, and XMM-Newton observatories together with ground-based instruments including the Very Large Telescope and the Subaru Observatory, to be able to make these high-precision observations.

The COSMOS team—over 100 astronomers in a dozen countries—used this formidable array of telescopes to map the positions, distances, and shapes of over 2 million galaxies. The most distant objects they were able to measure were about 6 billion light years away, halfway to the observable edge of the Universe. The team carefully applied statistical methods to the shapes of the galaxies to deduce the amount and location of dark matter between them and us.



The dark matter detected by the COSMOS survey can be mapped in three dimensions, with distance running from left (near) to right (far). *Credit: NASA, ESA, and R. Massey (California Institute of Technology)*

The result is nothing less than profound: a three-dimensional map millions of light years across and billions deep, showing the location of trillions of solar masses of invisible ethereal stuff that only decades ago was a complete mystery.

Even glancing at the map reveals insights into the Universe. The left hand side represents matter that is close to us, and the right side is farther away. We see more distant matter as it was farther in the past, so in a sense we have a time machine that lets us understand the Universe as it was 6 billion years ago. In the past, dark matter formed huge structures spanning hundreds of millions of light years across. But in more recent history, these enormous blobs have broken into smaller, scattered clumps. This shows that over time, the gravity of the big structures made them collapse into an array of smaller ones—just as modern theories of cosmology have predicted.

COSMOS verifies theory's next prediction, too: Once dark matter condensed into smaller blobs, its gravity would increase, drawing in more dark matter and normal matter. Eventually, the normal matter would gather near clumps of dark matter, so wherever we see large amounts of dark matter today, we should also see normal matter. The survey confirms this; the visible matter detected lies roughly along the same positions as the dark matter.

As incredible as it is, COSMOS represents only the first tentative steps into understanding dark matter. While the map is a vast repository of data, it only covers about $1/10000^{th}$ of the sky. Larger scale surveys that will map more ambitious areas are already in the planning stages.

Nor does this survey answer the biggest mystery of all: Just what *is* dark matter? No one knows for sure. But scientists love a mystery, especially a big one. And they don't get any bigger than figuring out what the matter is with the Universe.

Phil Plait is an astronomer and writer. He runs the Bad Astronomy website and writes the Bad Astronomy Blog, where he reports on all manners of cosmic news, both good and bad.