Are we closing in on dark matter?

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This composite image shows the galaxy cluster 1E 0657-56, also known as the "bullet cluster", formed after the collision of two large clusters of galaxies -- the most energetic event known in the universe since the Big Bang. The blue clumps show where most of the mass in the clusters is found, using a technique known as gravitational lensing. Most of the matter in the clusters (blue) is clearly separate from the normal matter (pink), giving direct evidence that nearly all of the matter in the clusters is dark. This result cannot be explained by modifying the laws of gravity. (Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

As the search for dark matter intensifies, the Kavli Institute for Cosmological Physics at the University of Chicago and the National Academy of Sciences organized a colloquium that brings together cosmologists, particle physicists and observational astrophysicists – three fields now united in the hunt to determine what is dark matter.

We believe it makes up about 23 percent of the mass-energy content of the universe, even though we don't know what it is or have yet to directly see it (which is why it's called "dark"). So how can we detect it and when we do, what will it reveal about the universe?

In mid-October, more than 100 cosmologists, particle physicists and astrophysicists gathered for a meeting called Dark Matter Universe: On the Threshold of Discovery at the National Academy of Sciences' Beckman Center in Irvine, CA. Their goal: to take stock of the latest theories and findings about dark matter, assess just how close we are to detecting it and spark cross-disciplinary discussions and collaborations aimed at resolving the dark matter puzzle. Following the meeting, The Kavli Foundation met with three leading participants and organizers of the meeting:

- Michael S. Turner – Rauner Distinguished Service Professor and Director of the Kavli Institute for Cosmological Physics at the University of Chicago.
- Edward "Rocky" Kolb – Professor in the Department of Astronomy and Astrophysics at the University of Chicago, where he is also a member of the Enrico Fermi Institute and the Kavli Institute for Cosmological Physics.
- Maria Spiropulu – Professor of Physics at California Institute of Technology who also works on experiments at the Large Hadron Collider, and a former fellow at the Enrico Fermi Institute.

The following is an edited transcription of the discussion.

THE KAVLI FOUNDATION: This meeting brought together theoretical cosmologists, observational astrophysicists and experimental particle physicists. Why this mix of researchers and why now?

MICHAEL TURNER: Figuring out what is dark matter has become a problem that astrophysicists, cosmologists and particle physicists all want to solve, because dark matter is central to our understanding of the universe. We now have a compelling hypothesis, namely that dark matter is comprised of WIMPs (Weakly Interacting Massive Particle), particles that don't radiate light and interact rarely with ordinary matter. After decades of trying to figure out how to test the idea that dark matter is made up of WIMPs, we have three ways to test this hypothesis. Best of all, all three methods are closing in on being able to either confirm or falsify the WIMP. So the stars have truly aligned.

ROCKY KOLB: The title to this meeting is a great answer to your question. It's "On the Threshold of Discovery," and it could happen within the next one or two years. It's so important to get the different communities here – experimentalists working at colliders, people analyzing gamma ray data from space, and those involved in direct detection.

TKF: So dark matter is a mystery that everyone wants to solve.

TURNER: Ten years ago, I don't think you would've found astronomers, cosmologists, and particle physicists all agreeing that dark matter was really important. And now, they do. And all of them believe we can solve the problem soon. It's wonderful listening to particle physicists explain the evidence for dark matter, and vice versa –astronomers explaining WIMPs as dark matter. At this meeting nobody said, "Oh, I don't really believe in the evidence. Nor did anyone say, "Yikes – a new form of matter. That's crazy."

MARIA SPIROPULU: One important thing we've seen at this meeting is a crossing of professional boundaries that have separated researchers in many different fields in the past. These boundaries have been strict. Cosmologists, astrophysicists and particle physicists, however, have now really started talking to one another about dark matter. We're only beginning and our language – the way speak to each other – is not yet settled so that we completely understand each other; but we are on the threshold of discovering something very important for all of us. This is critical because cosmologists and particle physicists have talked for a long time about how the very big and very small might be linked. And while the particle physicists study the very small with colliders, cosmologists study the galaxies and billions and billions of stars that make up the large-scale structure we see in the universe.

KOLB: Ten years ago, it was "Call me maybe" and now it's …

TURNER: "Let's do lunch."

SPIROPULU: Yes, it's, "Let's do lunch and talk physics."

TURNER: I do want to make one point: the convergence of inner space and outer space really started in the 1980s. Back then it began with the origin of the baryon asymmetry, the monopole problem and dark matter to a lesser extent. Particle physicists agreed that dark matter was a real problem but said, "The solution could be astrophysics – faint stars, 'Jupiters', black holes and the like." It's been a long road to get to where we are now, namely where we all agree that the most compelling solution is particle dark matter. And even today, the different fields are still, in a sense, getting to know one another.

TKF: Let's cover a few basics. Why is the question of dark matter important?

KOLB: As cosmologists, one of our jobs is to understand what the universe is made of. To a good approximation, the galaxies and other structures we see in the universe are made predominantly of dark matter. We have concluded this from a tremendous body of evidence, and now we need to discover what exactly is dark matter. The excitement now is that we are closing in on an answer, and only once in the history of humans will someone discover it. There will be some student or postdoc or experimentalist someplace who is going to look in the next 10 years at their data, and of the seven or so billion people in the world that person will discover what galaxies are mostly made of. It's only going to happen once.

TURNER: The dark matter story started with fragmentary evidence discovered by Fritz Zwicky, a Swiss American. He found that there were not enough stars in the galaxy clusters he observed to hold them together. Slowly, more was understood and finally dark matter became a centerpiece of cosmology. And now, we have established that dark matter is about 23 percent of the universe; ordinary matter is only 4½ percent; and dark energy is that other 73 percent – which is an even bigger puzzle.

Nothing in cosmology makes sense without dark matter. We needed it to form galaxies, stars and other structures in the Universe. And so it's absolutely central to cosmology. We also know that none of the particles known to exist can be the dark matter particle. So it has to be a new particle of nature. Remarkably, our most conservative hypothesis right now is that the dark matter is a new form of matter – out there to be discovered and to teach us about particle physics.

SPIROPULU: I just want to say one thing. The phenomenon of dark matter was discovered from astronomical observations. We know that galaxies hang together and they don't fly apart, and it's the same with clusters of galaxies. So we know that we have structure in the universe. Whatever it is that keeps it there, in whatever form it is, we call that dark matter. This is the way I teach it to undergraduates. It's a fantastical story. It's still a mystery and so it's "dark," but the universe and its structures – galaxies and everything else we observe in the macroscopic world – are being held together because of it.

TKF: Dark matter is often described in the media as something that is inferred because of its gravitational effects on ordinary matter. But the case for dark matter is much more expansive than that, as astrophysicist Jeremiah [Jerry] Ostriker from Princeton University said at this meeting.

TURNER: Absolutely. Dark matter is absolutely central to cosmology and the evidence for it comes from many different measurements: the amount of deuterium produced in the big bang, the cosmic microwave background, the formation of structure in the Universe, galaxy rotation curves, gravitational lensing, and on and on. Jerry said that as far as he is concerned, the dark matter problem has been solved. And that's because this idea that dark matter is just a swarm of particles that are very shy, that rarely interact with ordinary matter and then only weakly, works perfectly. And at the end of his talk, he said, as a kind of footnote: "By the way, I would be interested in knowing what the dark matter is." This is a testimony to how central dark matter is to cosmology and culturally to how particle physicists and astrophysicists look at dark matter differently. Dr. Gross, the particle physicist, wanted to know what dark matter is made of.

TKF: So for Dr. Ostriker, knowing exactly what dark matter is is less important than the work done already – measuring its gravitational influence on ordinary matter, estimating how much of the universe is made from it, and affirming that what we do know about it fits with the standard model of cosmology.

TURNER: That was Jerry's point, yes. There is five times more dark matter than ordinary matter, and its existence allows us to understand the history of the universe beginning from a formless particle soup until where we are today. If you said, "You no longer have dark matter," our current cosmological model would collapse. We would be back to square one.

TKF: Dr. Ostriker also argued that we should be open to dark matter being a variety of fundamental particles and not only WIMPs. Other possibilities could be neutrinos and axions.

TURNER: Because he doesn't care what it is. They all work equally well. The flip side is that cosmology tells us little about dark matter except it is cold.

TKF: Do they all work equally well for each of you?

KOLB: Well, for cold dark matter – which is made from particles that move slowly compared with the speed of light, and is the kind needed for forming galaxies and galaxy clusters – they all work equally well. The thing about the WIMP, as opposed to some of these other candidate particles, is that it's a very compelling possibility we can test right now. So we don't have to wait for the next 30 years or the next century, as we might if we were trying to detect another type of hypothesized particle. We don't have to build an accelerator larger than LHC.

This is one of the most detailed maps of dark matter in our universe ever created. The location of the dark matter (tinted blue) was inferred through observations of magnified and distorted distant galaxies seen in this picture. (Credit: NASA/JPL-Caltech/ESA/Institute of Astrophysics of Andalusia, University of Basque Country/JHU)

It's a magical moment when astronomers, astrophysicists, string theorists, particle experimentalists and cosmologists get together because they all have a common purpose. There is a common problem that excites them.

TKF: What makes you most optimistic that we're on the threshold of discovery?

KOLB: First of all, the hypothesis that dark matter is made up of WIMPs – and that it was produced by normal particles, say quarks, in the early universe – is an amazing achievement all by itself. Independent of a lot of the details of what goes on there and exactly how that happens, we expect that you should be able to reverse things and produce WIMPs in particle accelerators. We also expect they should be annihilating today in the galaxy, which we should be able to detect indirectly. Now, it's another issue who will be the first to find WIMPs. It's possible that it will be another 30 years before we do that, but we should be able to make a detection – whether it's direct or indirect.

SPIROPULU: With the Large Hadron Collider, and before that the Tevatron collider, we have been chasing and targeting the dark matter candidate. For us, the optimism is because the LHC is working and we're collecting a lot of data. In the standard model of particle physics, when we enlarge it to help explain how the universe began and evolved, we have a story that is a mathematical story. It's very good at describing how we can have dark matter. And if the mathematics accurately describes reality, then the LHC is now achieving the energies that are needed to produce dark matter particles.

Getting to these high energies is critical, and we are even going to higher energies. When we were building the standard model of particle physics, we kept saying that the next particle discovery that we predicted was "right around the corner." In other words, we were not, and we are not, flying in the dark. We are guided by a huge amount of data and knowledge, and while you might think there are infinite possibilities of what can happen, the data actually points you to something that is more probable. For example, we have found the Higgs-like particle, but that was predicted. So the next big step for this edifice of knowledge is to find something that will look like supersymmetry – a hypothesis that, if true, offers a perfect candidate for dark matter. We call it a miracle, because the mathematics works. But the way nature works, in the end, is what you see in the data. So if we find it, there is no miracle.

TURNER: These dark matter particles, or WIMPs, don't interact with ordinary matter often. It's taken 25 years to improve the sensitivity of our detectors by a factor of a million, and now they have a good shot at detecting the dark matter particles. Because of the technological developments, we think we are on the cusp of a direct detection.

Likewise for indirect detection. We now have instruments like the Fermi satellite (the Fermi Gamma-ray Space Telescope) and the IceCube detector (the IceCube Neutrino Observatory at the South Pole) that can detect the ordinary particles (positrons, gamma rays or neutrinos) that are produced when dark matter particles annihilate, indirectly allowing dark matter to be detected. IceCube is big enough to detect neutrinos that are produced by dark matter annihilations in the sun.

TKF: A few people over the past two days have said the dark matter particle might not be detectable.

TURNER: For many of us, for 20 to 30 years, this idea that dark matter is part of a unified theory has been our Holy Grail and has led to the WIMP hypothesis and the belief that the dark matter particle is detectable. But there's a new generation of physicists that is saying, "Well, there's an alternative view. Dark matter is actually just the tip of an iceberg of another world that is unrelated to our world. And I cannot even tell you about that world. There are no rules for that other world, at least that we know of yet." Sadly, this point of view could be correct and might mean the solution to the dark matter problem is still very far away. That is what led Jerry to say that discovering what dark matter actually is could be 100 years away.

TKF: Michael Witherell, Professor of Physics at the University of California, Santa Barbara, also said that nature doesn't guarantee an observation.

TURNER: Also true. But we have the WIMP hypothesis and it is falsifiable. And there's a good chance it's true. A "good chance" in this business means 10 percent or 20 percent. But when you're trying to solve a problem of this magnitude, if you have a 10-20 percent chance, I say let's double down on that.

TKF: When do you predict we'll detect WIMPs?

KOLB: It's easy to say, "A decade." LHC is turning on now. It'll be another year or so before they are at full energy, and they may run a couple of years to accumulate data. Meanwhile, the Fermi satellite is in space making observations. And then we have experiments underground: a detection may come with Xenon100, one dark matter experiment now underway in central Italy, or some successor to Xenon100.

TKF: And programs like LUX, the Large Underground Xenon dark matter experiment in South Dakota, are just coming online.

KOLB: In ten years, if there is no indication of supersymmetry or a WIMP – either from direct detection or indirect detection searches – then there is going to be a sea change. Now, there is not going to be one experiment announcement that says, "OK, let's look at something else." But if ten years from now there is no evidence, then we are going to other possibilities. You could not have said that ten years ago, or even five years ago. Today, I think you can say that.

TKF: Because we have so much work behind us and have already eliminated numerous possibilities.

KOLB: As in Ghostbusters, we have the tools. We have the talent.

SPIROPULU: I think it's fair to say the discovery is "around the corner." If we continue with exclusions, then we have to come up with better ideas. We are doing all this because we want to characterize dark matter. We are not just saying, "It is dark matter." We don't want to just say, "The universe is." We want to know exactly what it is made of. We want to know the dynamics and what it involves. A lot of work is ahead of us. Somebody said that it's not going to be as easy as finding the Higgs. Well, finding the Higgs was extremely nontrivial. Of course, once we find it, it goes in the pool of knowledge and then you say, "Well, it was easy."

TKF: Painting a picture for the general public about how incredible it would be to discover a WIMP is challenging. How do you convey just how sensitive this measurement would be?

TURNER: I keep saying these particles are very shy. Here's one way to think about this: if you had 100 kilograms of material, one of these shy particles – one of these WIMPS – would interact with that 100 kg once in a year or even less often. So you really have to build very sensitive detectors. Because of the cosmic rays and other particles that light up your detector and obscure the WIMP signal you're looking for, you have to put WIMP detectors underground. And even underground you still get natural radioactivity clouding your signal, so you have to discriminate against that as well.

Now, we also expect there's a seasonal modulation in the dark matter signal as the Earth orbits the sun through the sea of dark matter particles that permeate space. The modulation signal is expected to be only a few percent of the rare, dark-matter signal I talked about a minute ago. We do have the equipment in place to make these detections, but we just need Nature to cooperate.

KOLB: It's a fantastical story. One hundred years ago, if I told you that we are surrounded by these invisible particles and they're passing through us – you don't feel them yet they form the entire structure of the universe – you would have locked me up.

TKF: Do any of you expect that learning about dark matter will help us also learn about the other big mystery in cosmology – dark energy?

KOLB: Possibly nothing. It depends on what the answer will be. It is possible it won't shed any light on the nature of dark energy.

TURNER: There are two views. One is a conservative view, which is that dark matter is just made up of particles that don't give off light. It's just particles that happened to be more important than the stuff that we are made out of, which we only discovered in the past 70 years. And dark energy is a new problem that is unrelated.

TKF: And the only thing they share at this point is being unknown?

TURNER: That's right. The conservative point of view is that dark energy is unrelated to dark matter. Recall, dark energy is the stuff that is causing the universe to speed up. This is the simple view where we are solving problems one at a time.

A more radical view which we heard about at this meeting from Erik Verlinde (from the University of Amsterdam) is, "You know, guess what? Don't you guys get it? The two of them are related. It has nothing to do with particles. It's something much, much bigger. The two are related and are pointing to a much richer explanation. You are trying to explain things in a simple-minded way: dark matter particles and dark energy. Just like Ptolemy's epicycles (the epicycles of Claudius Ptolemy, a Greek astronomer who lived in Alexandria, Egypt under Roman rule, is a false construction of an Earth-centered universe, specifically describing the observed retrograde motion of planets), a desperate attempt to make a wrong hypothesis work.

And so those are the two extremes. One is that we are just about to solve dark matter and then we will go on to dark energy and they're probably not related; the other is that together, they make this big flashing sign: You guys really need to sit down and reconsider the whole framework.

SPIROPULU: I think it's worth noting that the dark sector (i.e. dark matter and dark energy) has to do with gravity. They are linked via gravity. Gravity is a force that in particle physics we have not been able to put together with the rest of the forces. Somehow, if you could stand outside the universe – that's an absurd statement, of course – but stand outside it and see how everything relates, you could say something about the dark sector and gravity.

TURNER: You're right that gravity could be the connector, because in cosmology and astrophysics gravity is the most important force. In particle physics, it's the least important force. Consequently particle physicists are just getting around to worrying about it, and in cosmology we mostly worry about gravity. And so now, we have come together because of a common interest in gravity – gravity revealed to us through dark matter and dark energy.

SPIROPULU: Here we are, with dark matter between us. It's a beautiful story of how we are trying to solve the problems, the challenges of characterizing our physical world.

KOLB: Dark matter holds together the galaxies. It holds together cosmologists and particle physicists.

TURNER: We know that Einstein didn't get the last word on gravity, because his theory doesn't have quantum mechanics in it. And so any problem that involves gravity, you are thinking, nervously and excitedly, that this could be the clue to the grander theory of gravity.

KOLB: I don't think the general public appreciates that we would love to find something wrong with what we think about the universe, about the laws of nature. And that's because it points the way toward new discoveries. I don't think most people work that way, thinking that, "Boy, I would love to be shown that I'm wrong about something that I really thought was true for 30 years or 100 years."

TURNER: We want new puzzles.

SPIROPULU: Always. And I have to say that in particle physics, there is a list of experiments and projects that have been built in the past 30 years that did not find what they were built for. None. They found other things, other important things. It's incredible. One example of this is the Hubble Space Telescope, which has revealed more about the universe than we ever could have imagined when it was conceived. The series of deep field images of the very distant universe, which has given us glimpses of the earliest galaxies, is just one example of this. So, when you write a proposal for something and you say what you are building it for, and you get the money and you go and build it and you find something completely unexpected – Wow. Our physical world is surprising. And it's very surprising that we can get it, even at the level we do. Or that we can do the experiments that we do.

TURNER: I think the universe is vast. It's often beyond the reach of our instruments and our minds, but we are at a point in time here where we really think we understand it and that we can identify what dark matter is. We have an accounting of the universe and a compelling hypothesis for dark matter. It is not unexpected that the younger generation of scientists wants a more radical solution to dark matter. The older generation developed the WIMP hypothesis, and this is our solution and we want to see it come true. The younger generation wants the excitement of solving a problem.

TKF: Would any of you trade this point in time with another in the history of physics?

KOLB: No, no. For dark matter, I think this is the time. I can't see everything converging at another time like it is now.

TURNER: This is the time to be a dark cosmologist.

Provided by The Kavli Foundation