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SUPERNOVAE, DARK ENERGY, AND THE ACCELERATING UNIVERSE

Members of the Academy, Ladies and Gentlemen,

It is a great honor to be invited here today, and to receive this prize. It is hard to imagine a more appropriate place to discuss cosmology than at this Academy that descends from the one that Galileo was a member of. And the distinguished list of previous awardees is humbling.

I will be speaking today about research that has to do with the most fundamental questions that human beings can ask. One can imagine the very first humans walking out of their caves at night and looking up at the stars, and wondering whether the universe goes on forever in space and whether it will last for ever in time. In fact it almost defines what it means to be human to be able to ask such questions. Throughout almost all of human history there has only been one way to address such questions, and that was to ask philosophers.

And philosophers had answers. Aristotle, thousands of years ago could tell you that we lived in a universe that was finite. He had a very interesting argument: If the universe is infinite there is no center; every place is equivalent to any other place. But you can do a very simple experiment and walk out of your house at night and look up at the sky, and you'll see that we are right in the center of a beautiful bowl of stars. Clearly the universe has a center, and we are there. So the universe must be finite. Today, we laugh at this logic, but if you think about it, it is actually a fairly sophisticated argument.

In fact, we did not make much progress beyond this point for several thousands of years, until at the beginning of the 20th century Einstein set down his theory of General Relativity. This theory gave us the conceptual tools to ask the question again in a more rigorous manner. In the summer of 1916, Einstein was working on the implications of his equations of General Relativity for the universe that we live in. I imagine that he was excited to see the outcome. But he was disappointed to find that when he applied his equations to the universe, he found that he could explain a universe that was contracting or a universe that was expanding, but he could not get a universe that would stand still. In the end he was forced to do something that many of us have felt tempted to do in a high school physics class when we couldn't get the answer to quite work out. He put in an extra variable, which he called the cosmological constant.

When Einstein does this it looks good: he used the Greek variable lambda, and with that extra term in his equations he could just make the universe balance – not contract and not expand.

It was only a dozen or so years later that Edwin Hubble discovered that the universe was expanding. Einstein was annoyed at himself for having added the extra term, the cosmological constant, and he reputedly called it his "greatest blunder." He had missed an opportunity to predict that the universe was expanding or contracting.

What was it that Hubble measured that indicated the universe was expanding? He was studying distant faint smudges of light, which we now know are distant galaxies (at the time they weren't sure). He found that the further and fainter they were, the faster they appear to be moving away from us as judged by the reddening of their spectral lines. He was interpreting these "redshifted" spectral lines as the Doppler shifts that make things sound lower pitched (that is, longer wavelength) as they move away from us. Apparently every galaxy in the universe is moving away from us, and the further you look the faster they are moving. This is the indication of an expanding universe.

Now, when I talk about an expanding universe, it's important for me to be clear what this means. When people hear the expression "big bang" they often imagine an explosion at the beginning of time, sending material out into space. But of course this can't be right, since there is no space for material to explode into at the creation of the universe. Let me show you a simplified cartoon of the universe to explain what it is that we are really talking about. As you can see, this is a rather simplified picture of our universe. Each of these dots is supposed to represent a galaxy, and we live in one of those galaxies. And although I can't draw it, you're supposed to imagine that the dots extend off infinitely in space above the screen, below the screen, side to side, and in fact into the screen and out toward you. So there are endless galaxies as far as you can possibly imagine and beyond.

When I talk about an expanding universe, what I really mean is that the average distance between each of these galaxies gets just a little bit bigger. It's still infinite, just all the distances are slightly bigger. Now, if you go backwards in time, all distances are smaller and smaller, until presumably at the very beginning of time there was essentially no distance between all the galaxies. The universe could still be infinite in all directions, but everything in the universe is right on top of each other with no distances between. This dense, hot state is really what we mean by the Big Bang.

This model of an expanding universe makes it possible to ask our original question about the fate of the universe in a somewhat more concrete way. If you picture a universe expanding, with all the distances getting larger with time, you can now ask the simple question: are these distances getting bigger by the same amount every year? Or perhaps, this expansion is slowing down. In fact, we might assume that it is slowing down because we know that gravity attracts everything in the universe to everything else in the universe. In 1987, we realized that we had the opportunity to actually *measure* the history of the expansion of the universe and to find out how much it was slowing.

It is fitting that the tool we could use for this measurement was also something studied by ancient civilizations. For thousands of years, humans have noticed occasional new stars which suddenly appeared in the sky and then faded away in a few months. These are supernovae, which we now know to be very distant exploding stars. The ancient court astronomers in China recorded them thousands of years ago, and often the same objects were noted by the Anasazi Indians in the Americas. These supernovae are very dramatic events: when a supernova explodes, that one dying star can outshine the entire galaxy of 100 billion stars in which it was found. So they can be seen at vast distances across the universe.

One of the pleasures of the work that I've been doing is that we can ask such a fundamental, philosophical question about the universe by making a measurement that you can explain to almost everybody. So let me try telling you just the few ideas that you need to know to see how this measurement works. Perhaps when you go home this evening, you can try to explain the measurement of the fate of the universe to your friends and families and see if it makes sense to them.

The first concept that you need to explain is actually a rather trivial point: light takes time to travel. Most people know that this is the case, but probably most people are not thinking of what this means in a very large universe. For example, light from the sun takes eight minutes to reach us. So if the sun were someday to suddenly go out we would not know about it for eight minutes – and then we'd really know about it! Light from the next nearest star takes several years to reach us, so we have orbited around the sun four times while the light traveled to us.

But things start to get really interesting when we look at the light from the nearest galaxy of stars. These stars are so far away that their light has been traveling to us for 150,000 years. So at the time that the light left these distant stars, there is the first evidence of human culture here on earth. The nearest cluster of galaxies of stars is even further away, and the light left those stars around the time 65 million years ago when here on earth the dinosaurs were going extinct. But the supernovae that we are studying are so bright that the most distant supernovae that we see are much further away still. The light from these supernovae travels for about 10 billion years to reach us. That means that we get to learn about an explosion that occurred some 10 billion years ago and only lasted for a few months back then. This is a bit of history from two thirds of the way back to the beginning of time!

Let me show you a film clip I like very much. This begins with an artist's impression of a supernova going off in a distant galaxy. But it turns into the actual data from the Hubble space telescope showing the galaxy in which that supernova exploded. And then we zoom out to see where this galaxy fits in with the rest of the galaxies that you can observe with the Hubble space telescope, and then those even closer to us seen with telescopes on the ground. As you can see, this supernova is very, very, very, very, very far away.

There is one kind of supernovae, the "type Ia," which always explodes at the same brightness. So we can tell exactly how far away the supernova is by how bright it appears to us. This is similar to telling how far away a candle is by seeing it get fainter and fainter as someone carries it across the room – so astronomers called this a "standard candle". Since we know the speed of light, we also know exactly how long ago each such supernova exploded.

The only other thing we need to know is how much the universe has expanded since each of those supernova explosions. Here we take advantage of the fact that these supernovae look blue when they explode. You may remember that blue light has a short wavelength while red light has a longer wavelength. While the light from the supernova travels to us in a universe that is expanding, the wavelength of the light gets stretched just as the universe stretches. So although the supernova looks blue when you see it up close, by the time the light reaches us its wavelengths have been stretched so that the supernova looks red. You may have heard the term "red shift" – this is what it really is.

We can take advantage of this amazing trick then: how red the supernova looks – how much it is redshifted – tells us exactly how much the universe has stretched since the time that the supernova exploded. And we know when it exploded, because we know how far away it appears to be, based on its brightness. In my cartoon picture of the universe, you can imagine a supernova exploding in a distant galaxy and then watch the wavelength get redder and redder, longer and longer, as the universe stretches until it looks red when we see it. Now we just need to find many supernovae with a range of different brightnesses, representing explosions at different times in the history of the universe, to get a detailed history of the universe's expansion over time.

In fact, this measurement is so simple that for a little while I considered giving this talk under the title, "How to measure the fate of the universe with tools you can find in your own house." It almost works: first, you can take the detector in the back of your video camera. It's called a CCD detector and it is very similar to ones that we use for astronomy. You attach this detector to your laptop computer. Nowadays, everybody's laptop computer is fast enough to analyze the pictures you get from the CCD cameras. (This wasn't the case when we began the project!) Finally, you take the CCD camera and computer out to your backyard and attach it to your telescope. This is where I ran into problems with this talk title, because most of us do not have a 4-meter telescope in our backyard.

In fact this was one of most difficult problems when we began the project. To use the largest telescopes in the world, it is necessary to write a proposal six months in advance, specifying what night you request telescope time and giving the scientific rationale. At that time it appeared impossible to propose to study supernovae this way. They appeared to be the worst research tool imaginable: they are rare – the type Ia supernovae explode only a couple of times per millennium in any given galaxy. They give no advanced warning when they're going to explode. And they brighten and fade away within weeks, so you have to be studying them within days after the explosion if you're going to measure their peak brightness. It makes a pretty terrible proposal to say that you request the night of March 3 to study a supernova that may or may not explode in the next 500 years.

So our first challenge was to develop a technique that would make it easier to work with these impossibly difficult supernovae. We designed and built a new wide-field camera that would allow us to study thousands and thousands of galaxies in a night, with hundreds of galaxies on each picture. (Each of the tiny little blue specks in this image is a distant galaxy, whose light has been traveling some 4 billion years to reach us.) With this many galaxies to search in you can guarantee not just one but a dozen new supernova discoveries every time you go to the telescope.

Now the problem is that you have to find a small new speck of supernova light amidst the hundreds of galaxies that you can see in each image. This is clearly not a job for even your most patient graduate student, so we spent several years developing the image analysis software that would allow the computer to home in on the galaxy with a new supernova in it. In this picture, you can see that the computer has found a supernova at this location on the image and then shows us, first, a large picture of the galaxy before the supernova explodes, second, the galaxy with a supernova in it, and, third, a subtraction of those two pictures, which leaves just the light of the supernova.

By 1994, we had this technique working smoothly, and we would find a new batch of supernovae every time we went to the telescope to search. Since we could now guarantee supernova discoveries when we wrote a telescope proposal, we could even use the Hubble Space Telescope to study the supernovae. For the Hubble Space Telescope proposals it is necessary to say not only what day you will discover the supernovae, but where in the sky the supernovae will be, but this is precisely what our "batch discovery technique" could do. From space, you can actually see the spot that is the supernova, separate from the smudge that is the distant galaxy in which it exploded. This makes it easier to study than from the ground were the two are blurred together by the atmosphere.

So we started to collect and study batch after batch of type Ia supernovae, every semester at the telescope. Finally, by 1997 we had 42 supernovae in our collection, and we were ready to use them to measure the expansion history of the universe – and discover the fate of the universe! We plotted them on the graph of the average distance between galaxies as a function of time. The question in our minds was how much the universe was slowing. It may not be slowing very much, so it may slow and slow, but continue expanding forever.

I've made a little animation to show what this would look like. Imagine that you are lying on your back, looking up at the sky with telescopes for eyes; this is what you would see. The galaxies get further and further from us and further or further from each other, but slower and slower and slower. This scenario looks a little boring at the end. The other possibility that we were considering is a little more exciting. Here, the universe slows down so much that it comes to a halt, turns around, and collapses into a "Big Crunch" – and the universe comes to an end.

But when we actually plotted our supernova data on the graph we found that the universe was not slowing enough to come to a halt. In fact, surprisingly, it was not slowing at all – the expansion was speeding up!

What would this look like in the animation? The galaxies begin spreading apart and then – whoosh! – they are gone. So we better do all of our astronomy studies now; in a few billion years, we will not be able to see any other galaxies.

What does this acceleration mean? Apparently, some previously unknown "Dark Energy" is making the universe expand faster and faster. Not only that, but most of the universe, almost 75%, is made of this mysterious Dark Energy. Galileo told us that we are not at the center of the universe: we orbit around the Sun. Now we find that we are not even made of the stuff which most of the universe is made of.

The scientists who were most shocked by this new result were the theoretical physicists. Over the past 50 years, particle physics has become amazingly good at explaining and predicting all the forces and particles that shape our world. But this Dark Energy does not fit into our physics theories. You get these great quotes from the leading theoretical physicists of our day: Frank Wilczek calls this "maybe the most fundamentally mysterious thing in basic science." Ed Witten, the father of modern-day string theory, says it "would be number one on my list of things to figure out." And for Mike Turner, "this is the biggest embarrassment in theoretical physics."

So not only was there great excitement in the popular press, but ever since 1998 when these results came out, there has been paper after paper after paper appearing on the physics Web servers, proposing new ideas for dark energy, new ideas to explain the acceleration of the universe's expansion. But when you ask the theorists who are writing these papers if they believe their own theory is correct, they will cheerfully say that they do not expect their own theory to be the final explanation. Rather, they are still trying to expand the range of physics ideas that we can consider. In fact, at times it seems that the best we can say is that the theorists are coming up with great names for their theories: "Quintessence," "Phantom Energy," "Big Rip Cosmology" – and I can barely pronounce "Ekpyrotic Universe."

Ultimately, the theorists have thrown the ball back into our court, and they are looking for us observers and experimentalists to come up with new data that will point them towards the correct theory. We need to go back and make a new measurement of the expansion history of the universe that is much more precise than the measurement that showed the acceleration. Now we need a measurement so precise that it can distinguish between the very small differences in the way the different Dark Energy theories predict that the universe went from a very early deceleration to today's acceleration. In the end, we had to design a new space telescope to accomplish this task.

The new satellite that we are proposing is similar to the Hubble Space Telescope in the size of the telescope mirror, but it has a much wider "field of view" so it can see hundreds of times more sky with every picture it takes. We call this proposed space telescope "SNAP," for SuperNova Acceleration Probe. It would be launched into an orbit well beyond the moon, where it would not go in and out of the Earth's shadow, as the Hubble Space Telescope does. From there, it would look out to the most distant galaxies and study thousands of supernovae. It would make measurements of each of the supernovae that are more detailed and more precise than the measurements of any previously studied supernova.

I am currently very optimistic that such a satellite will be built and launched within the next few years, and I hope in the not-too-distant future to return to Rome to discuss what we have learned about the mysterious dark energy and the acceleration of the universe.

Let me conclude with two surprisingly prescient quotes from Galileo Galilei: "Infinities and indivisibles transcend our finite understanding, the former on account of their magnitude, the latter because of their smallness; Imagine what they are when combined." In the puzzle of dark energy the infinite and the indivisible are indeed combined, and we are indeed baffled! But Galileo also said: "Measure what is measurable, and make measurable what is not so." It is wonderful to live at a time when we have created new tools with which we can go out and make measurements that might allow our understanding to transcend these infinite puzzles.

Thank you, again, for honoring me with the Feltrinelli Prize, and thank you for your kind hospitality.