Expansion and Exploration: A Deeper Look into Hubble Tension, Supernovae, and Other Stellar Mysteries

An Interview with Professor Alex Filippenko

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Dr. Alex Filippenko is an astrophysicist and professor of astronomy at the University of California, Berkeley. After earning his Bachelor of Arts in physics from the University of California, Santa Barbara in 1979 and a PhD in astronomy from the California Institute of Technology in 1984 as a Hertz Foundation Fellow, Dr. Filippenko came to the University of California, Berkeley as a postdoctoral Miller Fellow and soon after joined as a faculty member. Since then, Dr. Filippenko has conducted research ranging from supernovae and active galaxies at optical, ultraviolet, and near-infrared wavelengths, to black holes, gamma-ray bursts, and the expansion of the Universe. These endeavors have resulted in the impressive discoveries of dark energy, hundreds of supernovae, and the development of the Katzman Automatic Imaging Telescope, a fully robotic telescope which conducts the Lick Observatory Supernova Search.

Dr. Alexei Vladimir "Alex" Filippenko

BSJ: The Berkeley Scientific Journal has interviewed you every 5 years since 2013. How has your research evolved over this past decade? Are there any new and exciting developments in your work?

AF: One thing that has been really interesting recently is the James Webb Space Telescope. It was launched on December 25th, 2021, but observations only started in July of 2022. In the first year, I was involved in a couple of projects studying the formation of dust, little fine grains of material, graphite, and silicates in the ejected material from supernovae (exploding stars). The origin of this dust has been a bit of a mystery: we are made out of stardust, our solar system and other planetary systems were made out of it, but where does it come from? Certain types of red giant stars can produce dust at a number of places, but it has been long hypothesized that dust is formed in the ejected gasses of supernovae. We used the Webb's infrared wavelength capabilities to see the emission from relatively warm dust that was newly formed in the ejected material. In some cases, we see dust that has been illuminated by the explosion itself, but was created before the explosion in material that was expelled from the outer atmosphere of the dying star. There are these relatively gentle ejections that produce what is called circumstellar material, which can also form dust. This circumstellar material got illuminated and heated by the supernova explosion, and that caused it to glow at infrared wavelengths. So, we have seen dust formation both in the ejected material from a supernova explosion and in material that was gently expelled prior to the supernova explosion which formed this circumstellar envelope.

> *"We are made out of stardust, our solar system and other planetary systems were made out of it, but where does it come from?"*

The other thing with the Webb that I have been involved with is looking for some of the earliest galaxies to have formed. Some galaxies that have been found look bright and mature, despite being relatively young, forming five or six hundred million years after the Big Bang. But we do not know the distances of these galaxies until we measure their redshifts (how much the universe has expanded during the time that the light has been traveling from them to us). One of the projects I was involved with spectroscopically showed that the redshift of a galaxy was 9.51, which puts it at just six or seven hundred million years after the Big Bang. This showed that there really are galaxies that appeared shortly after the Big Bang, and galaxy evolution theories are going to have to account for how galaxies formed and evolved more quickly than standard galaxy formation and evolution theory would have suggested.

Something I've been doing with the Keck telescopes with Stanford Professor Roger Romani has been looking at these objects called Black Widow pulsars. Pulsars are rapidly spinning neutron stars that form after the collapse of a massive star at the end of its life. But in some cases, these neutron stars are in a binary system where they can steal material from another star which causes the neutron star to spin a few hundred times per second compared to the typical once per second. These are called millisecond pulsars, because their spin periods are on the order of a few milliseconds. The pulsar, spinning so quickly, then emits a very energetic wind of particles which blows away the outer atmosphere of the star that was donating material to begin with. This gradually whittles down the mass of the donor star, and can eventually destroy that star completely. This would be the origin of millisecond pulsars—hence the name Black Widow pulsars, because the female eats its mate after mating. The neat thing about the Black Widow pulsars that still have a companion star is that by measuring the orbital speed and the period of the companion star, you can use Newton's laws of motion and gravitation to calculate the mass of the neutron star. These are neutron stars that are likely to be more massive than typical neutron stars (around 1.4 solar masses). But if the neutron star then accretes material from a companion and builds up mass, at some point, it might

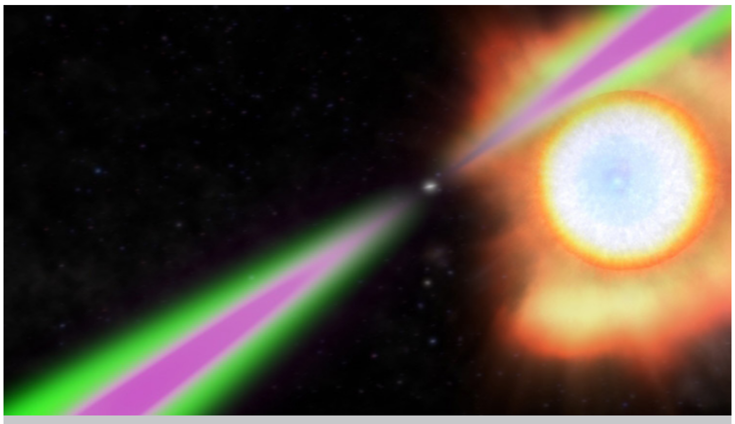

Figure 1: GMS: PSR J1311-3430 "Black Widow" Pulsar Animations. This model illustrates a rotating neutron star swinging its radio (green) and gamma (purple) ray beams past Earth and destroying its stellar partner (on the right).

become so large that the object becomes a black hole, and collapses. So it is of interest to find the most massive neutron star possible, because we still do not yet know the upper limit for the mass of a neutron star.

Last year, Romani and I published a paper where the most massive neutron star found so far was 2.35 ± 0.17 solar masses. On the other hand, the uncertainty is big enough that if we happen to be unlucky, and the true mass is closer to two solar masses, then that would not be the highest known answer. One thing we want to do next semester with the Keck telescopes is to measure the orbital parameters of the visible star and decrease the uncertainties in our derived mass for the neutron star. We are exploring the boundary between neutron stars and black holes, which will tell us something about how matter behaves at ultra high densities. We already somewhat know how matter behaves in the nucleus of the uranium atom. But if you have two solar masses worth of nuclear density material, that is a completely different matter.

Another project that I have been doing with a couple of my graduate students involves spectra polarimetry of supernovae. When you look through Polaroid sunglasses, the glare of the sunlight reflecting off water or pavement decreases. This is because when sunlight hits water or pavement, the electric field has two components, one that goes perpendicular to the surface off of which the light is bouncing and one that is parallel to the surface. When light bounces off a surface, the component that is perpendicular to the surface of reflection does not reflect very much, whereas the component that is parallel to the surface reflects a lot. Polarizing sunglasses allow that vertical perpendicular component through, even though most of the reflected light is this parallel component. Thus, light can be polarized if you have a geometry that is not spherically symmetric. In a similar way, if an exploding star is exploding as a sphere, then the electric field points every direction, and so there is no net polarization. But if the exploding star is oblong, or has various asymmetries, then the electric fields do not cancel out, and reflection of one direction of polarization is more likely than reflection of another direction. And so you get a net nonzero polarization. By doing polarimetry of supernovae, we can find out about asymmetries in the explosion. Spectra polarimetry is when you take a spectrum of the light and measure the brightness as a function of wavelength or color. You can see that not only does continuous light have some polarization properties, but the various features produced by elements in the atmosphere of the exploding star (ex. calcium, silicone or hydrogen) may have different polarization signatures, and that would suggest that there may be blobs of this material that get preferentially injected in certain directions and not in other directions. So, spectra polarimetry is a very powerful technique in finding interesting asymmetries in how stars explode.

I have also been working on tidal disruption events. When you have a supermassive black hole in the middle of a galaxy, and a star goes wandering close to it, the gravitational force on the near side of the star can be sufficiently greater than the gravitational force on the far side. The star gets stretched and disrupted because the tidal force is bigger than the gravitational force holding the star together. Because of this, material flies away from it and other material then forms an accretion disk of gas that settles into the black hole. In the rotating disk of gas, particles are hitting other particles, which causes a frictional drag and a loss of energy. This accretion disk also radiates light, which is why we see it. Then, this gas feeds into the black hole. In other words, these tidal disruption events are a way for black holes to grow. Through studying the process of the disruption of a star, we can figure out how much gas goes flying away from the black hole and how much gets created. This is a way of finding and studying supermassive black holes in the centers of galaxies that are not providing any other obvious clues to their existence. We think there is a supermassive black hole in the middle of nearly every galaxy. However, some of them are hard to find because they are acquiescent; they are not some bright active galaxy with a more or less constant accretion disk; they are not quasars; they might be too far away for you to measure the motions of stars in the center to see that they are going around so quickly. All in all, there are not other ways to discern the existence of the black hole. But if it suddenly tears apart a star and brightens, that is a way it can reveal its existence.

Finally, I have also been working on gamma ray bursts, which are also associated with a great increase in the amount of light emitted at other wavelengths of the electromagnetic spectrum. We found evidence that some gamma ray bursts occur when a very massive star collapses to form a black hole. That black hole then energizes a bunch of particles near it, which then form a jet of very rapidly moving particles along the axis of rotation, where there is a lower density of material than in the equatorial plane of the star. These high speed jets can go flying out more easily. Some gamma ray bursts are also produced by two neutron stars orbiting each other and having orbital decay through the initial gravitational waves. After they hit each other, they produce a burst of gamma rays and other forms of electromagnetic radiation. When that occurs, the electromagnetic outburst is called a kilonova, which is not as powerful as a supernova, but more powerful than a typical nova. On August 17th, 2017, we had the first compelling case that was suggestive of two neutron stars coming together. We saw both the electromagnetic signal and the gravitational wave signal, which showed that it could only have been two neutron stars coming together, forming short gamma ray bursts and producing a kilonova.

BSJ: It is really cool that you have been able to do so much research regarding a wide range of celestial objects and phenomenons, despite technical challenges. When we proposed this interview, the first topic you suggested we could talk about was Hubble tension. Could you explain what Hubble tension is and why it is currently the biggest news in cosmology?

AF: In 1998, I was part of two teams that figured out that, through observations of very distant supernovae, the expansion of the Universe has been accelerating for the past four or five billion years, which led to this concept of dark energy. Dark energy constitutes about 70% of the universe's contents. Dark matter of an exotic nature that is not made out of protons and neutrons, but some different particles, makes up 25% of the mass and energy content of the universe. But we still do not know what dark energy is. Normal matter makes up only 5%— we only understand 5% of the universe. One important clue to what it could be would be a measurement of how its density changes with time. If the density, the amount per unit volume, of dark energy does not change with time, then it is probably just a property of space, or a vacuum energy of space. But if it does change with time, then it is some sort of new energy, filling space but having a repulsive nature. One way to determine whether the energy density is changing is to map the expansion history of the universe more accurately. Another way is to measure the current expansion rate right now, using what is called the Hubble constant (this value changes with time). We can take observations of the early universe done by radio astronomers who study the cosmic microwave background radiation (the afterglow of the Big Bang) and look at the pattern of little hot spots and cold spots caused by small density variations in the early universe. Then we can propagate these observations forward 13.8 billion years to now and predict what the current value of the Hubble parameter should be. With the latest satellite (the Planck satellite), researchers came up with a Hubble constant with the value of 67.4 ± 0.5 km/s/Mpc. I have been on a team for nearly the past two decades, to try to measure the Hubble parameter. Over the years, our results have been getting progressively more precise, but a problem seems to be emerging. First, we measure the distances of nearby galaxies by looking at these types of stars called Cepheid variable stars. These are galaxies in which Type 1a supernovae have occurred, the kind of supernova that comes from a white dwarf exploding. By knowing the distance of a galaxy through measuring its Cepheid variables and the peak brightness of a Type 1a supernova, we can calibrate how powerful Type 1a supernovae really are. Then we look at more distant Type 1a supernovae and we use them to judge the distances of galaxies, and we measure the galaxies' redshift, and we get the Hubble law ($v = H_0 d$), and solve for H_0. Our latest and greatest value is 73.29 ± 0.9 km/s/Mpc. This differs by more than five standard deviations from the initial predicted measurement. And so, there is a discrepancy between the actual measured Hubble value of the Hubble constant and what is predicted. This is the tension: the prediction based on measurements of the early universe versus our actual measurement.

It could be possible that we have made an error, although highly unlikely, but I think that it is more likely that the universe is trying to tell us something interesting. Could it be that the dark energy is getting stronger, in which case someday, everything, including us and the atoms we are made out of will get ripped apart? Maybe instead, general relativity is wrong. Could it be that dark matter is interacting with light in some way that is changing the world and is responsible for the peculiar observations that we are making? Or maybe there was an early boost by a different form of dark energy early on in the universe's existence that could have made the universe expand faster at early times than is assumed by the cosmic microwave background. The analogy I like to give is, suppose you are watching a kid's soccer game and you are kind of myopic. You are looking in one direction, and you see the soccer ball zipping along more quickly than could have been kicked by any one kid. Well, maybe another kid kicked it first in the same direction. So, the Hubble tension is one of the biggest, if not the biggest, new conundrum.

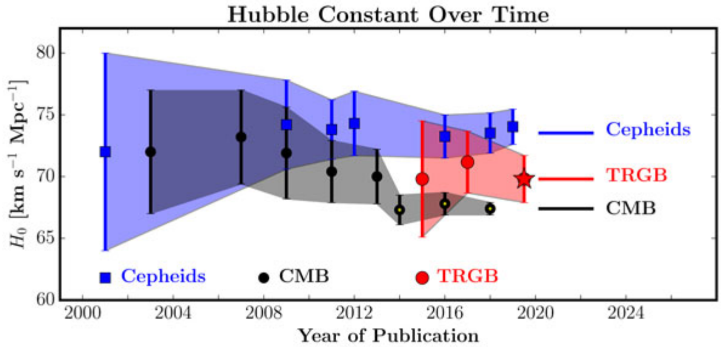

Figure 2: Hubble Constant Over Time. This model compares the various values of the Hubble Constant that were determined through three

"Normal matter makes up only 5%— we only understand 5% of the universe."

BSJ: How is your research team currently investigating Hubble tension? Could you describe your research process, some interesting conclusions that your team has reached, and how your work supports or refutes current theories?

AF: It is important in science, especially when you have really puzzling or interesting results, to verify it in completely different ways. Our measurement of the current value of the Hubble constant is based on Type Ia supernovae. Another technique I have been doing with a former postdoc is measuring the distances of galaxies using Type II supernovae. These supernovae come from massive stars whose iron core collapses, bounces, and explodes the outer parts, leaving behind the neutron star. Since Type II supernovae have a big hydrogen envelope, they are easy to distinguish from a Type Ia, which does not have hydrogen. We are getting distances using type IIs, but they are not nearly as standardizable or calibratable as Type Ias in terms of finding their true luminosity. Our answer right now has big error bars, but nevertheless, it is consistent with what we are getting with the Ias.

Although I am involved in the supernova techniques for Hubble tension, there are other techniques that researchers are using. One technique is surface brightness fluctuations, where they look at elliptical galaxies, the smoothness of their star distribution, and little variations in the apparent number of stars between locations in order to determine the distance of the galaxy. Another technique is using the time delay. If there is a quasar, which is a very bright center of a galaxy that has a supermassive black hole acting as a gravitational lens, then that lens can give you some number of quasar images. If the quasar varies in brightness, we see a variation in brightness in one of the images and the same variation in brightness in the other images, but with a time delay. That time delay is because the light is following paths of different lengths around the gravitational lens and going through different valleys of the gravitational field. This leads to different amounts of time dilation, and therefore, delays. By knowing the physics of the gravitational lens, and by measuring the time delays, you get the scale of the whole configuration and can determine distances. This, along with measuring the redshift, gives us the Hubble constant. But a more powerful technique, in my opinion, is to do it with supernovae.

BSJ: Many of the discussions around Hubble tension debate whether or not dark energy might be a potential solution. In your research paper, "Constraints on the Hubble constant from supernova Refsdal's reappearance,"[4] we noticed that you utilized models constructed from assigning dark-matter halos to cluster and individual galaxies. How effective did these models prove to be in your research?

AF: Quasars are not the greatest technique to use because their light variations are erratic and sometimes slow, so it is hard to measure a robust time delay from one image to another. But if you have an exploding star, where there are no stars visible beforehand and suddenly there is something bright visible, there is a rapid onset in brightness. Since it decays away and doesn't happen again, measuring this star in images of a strongly lensed supernova can provide a much more accurate measure for the time delay, and as a result, the Hubble constant.

One of my former postdocs, Pat Kelly, discovered the first example of a strong lens multiply-imaged supernova called supernova Refsdal consisting of four images. There was a fifth image, whose appearance we predicted based on the amount of visible and dark matter in this cluster of galaxies as well as an individual galaxy causing a lot of lensing. We found that some assumed distributions of matter gave results for the predicted reappearance of yet another image of supernova Refsdal more accurately than other models for the distribution of dark matter. In particular, if you have dark matter halos to galaxies (see Figure 3), which was found for both clusters and individual galaxies, then you get better agreement with the Hubble constant.

These models have proven to be effective because we now have a derived value of the Hubble constant from supernova Refsdal time delays. It is on the low side, but still within two standard deviations of the current Hubble constant. Our result of 64 km/s/Mpc, does not entirely disagree with the result we are getting much more precisely with the Type Ia supernovae.

The uncertainties, however, are so big for two reasons. First, this is the only object of this type that we have measured so far, so we do not have a sample of them. The error bars will go down as there are more of them. Second, despite our modeling of the dark matter in the cluster, our models are not unique. We have a few models that yield nearly as good results, and there might be models not considered that agree with the results, but it is not fully verified yet. There could also be systematic effects that we have not taken into account. But this is a technique that will grow in importance in the future.

Figure 3: Simulated Dark Matter Depiction. A simulated image of the Milky Way halo with dark matter displayed in blue.

BSJ: What technologies in your research have made it possible in recent years to find a value for the Hubble constant?

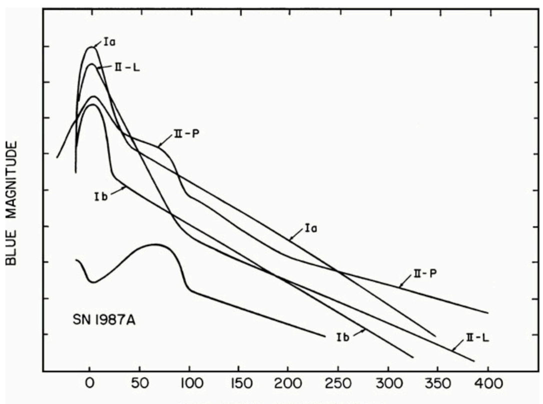

Figure 4: Spectra and Light Curve. This model displays the relationship between brightness and time of various supernovae of Types Ia, Ib, II-L, II-P, and SN 1987A. They can help determine rotational period and shape/size of supernovae.

AF: Our result with Type Ia supernovae and Cepheid variables has improved so much in the recent past as we have gotten distances to Cepheid variables using Hubble Space Telescope images. The Webb telescope, used on projects that I am not a member of, has shown that Cepheids do not suffer from crowding in the Hubble images, because one concern in the Hubble images was if the Cepheids alone were being measured or if there were nearby stars contributing to the light. With the Webb, there is finer angular resolution and clarity

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which has shown that there are not nearby stars next to them and that the scatter in the Hubble Diagram, which is the distances of galaxies based on Cepheids, went way down using the Webb.

I have personally contributed to spectra and light curves, which are brightness versus time graphs of the Type Ia supernovae, and that has allowed us to perfect their use as calibratable or standardizable candidates.

BSJ: What aspects of your findings on supernova SN 2017egm are transferable to other SLSNe-I superluminous supernovae? Are any findings unique to SN 2017egm?

AF: I have done work on superluminous supernovae, supernovae that are even more powerful at their peak than expected based on the usual mechanisms of production, a bunch of radioactive nickel in the explosion of a Type Ia supernova, or the energy released following core collapse in a more normal, massive star Type II supernova. We have studied several of them to investigate some of the possible causes of this super luminous phenomenon. One thing is that stars can gently eject material before they become a supernova. But then when they do become a supernova, the rapidly expanding exploded material can

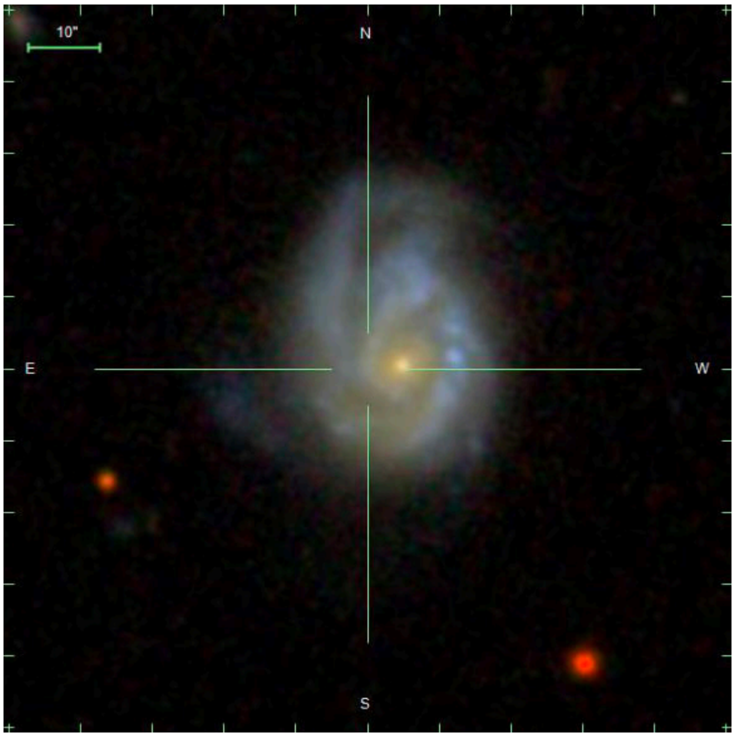

Figure 5: SN 2017egm, a 'Heavy Metal' Superluminous Supernova. SN 2017egm, whose position is marked by the cross-hairs, was found in a galaxy 420 million light-years away from Earth.

hit the gently ejected material and convert the kinetic energy of the ejected material into radiation. That is one of the mechanisms that can produce the super luminous phenomenon. In the case of SN 2017egm, the injection of the outer envelope came about as a result of what is called a pair-instability shell, when very massive stars form electron-positron pairs. This can then rob the star of internal pressure, causing its core to collapse and the whole thing to explode in a very energetic way. But prior to exploding, the star becomes unstable and pulsates, and that can eject some shells of atmosphere which the injected matter can then slam into. And the light curve, the brightness versus time of SN 2017egm, suggested that the ejected material from the supernova was hitting several shells of previously more gently expelled material. The pair-instability process is one way of temporarily reducing internal

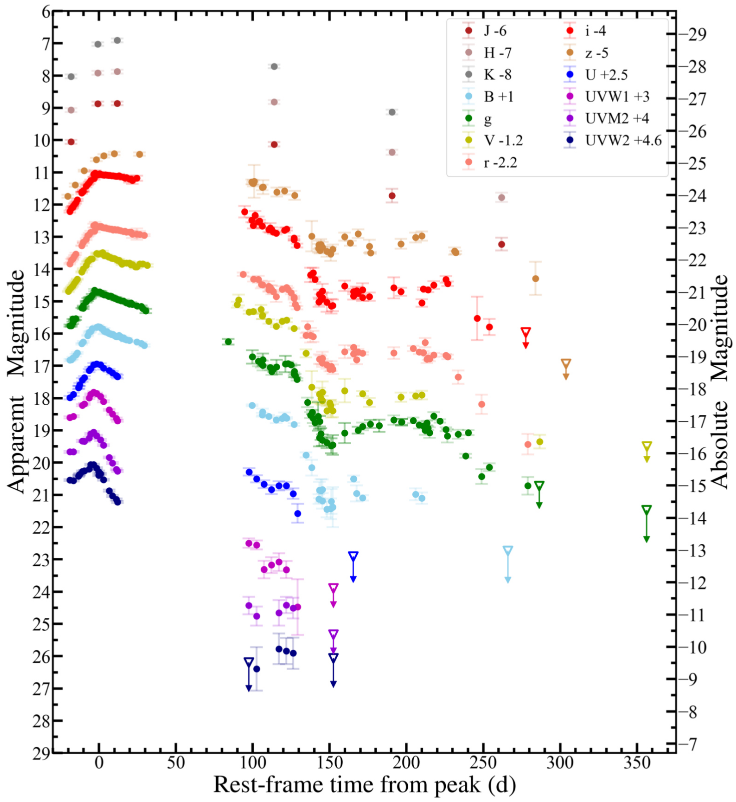

Figure 6: SN 2017egm, a 'Heavy Metal' Superluminous Supernova. SN 2017egm, whose position is marked by the cross-hairs, was found in a galaxy 420 million light-years away from Earth.

radiation pressure and causing a partial collapse which is why we preferred the pair-instability process in that particular paper for this supernova.

There are other ways of getting superluminous supernovae. Following a core collapse, you might get a neutron star. But if it is very rapidly spinning and highly magnetized, it is called a magnetar. That rapidly spinning magnetic field can energize lots of particles that then pummel their way through the ejected material, heating it up and causing it to glow more. Another possibility is what is called fall back accretion. In other words, the star basically explodes in the outer parts, but the inner parts are not given enough energy. After going outward for a while, they then fall inward, releasing gravitational potential energy that can be turned into light. Finally, you can have a gamma ray burst. Following a supernova, the jet from the gamma ray burst can pummel through this material and cause it to glow more as well. This area of research, called superluminous supernovae, is very active. We do not think our findings for any one supernova, like 2017 EGM, are necessarily unique to that supernova. Indeed, we have a few other objects now that seem to show some of the same observational characteristics.

BSJ: In the next decade, what direction do you see your research on Hubble tension and supernovae taking?

AF: One thing I am really excited about is an eight meter telescope that is nearing completion in Chile. It is called the Vera Rubin telescope, named after Vera Rubin, whose work on the rotation curve of spiral galaxies found that even far out from the center, spiral galaxies are rotating just as fast as closer in. And that implies a growing amount

Figure 7: The Vera C. Rubin Observatory and Telescope. This 8.4-meter telescope with its 3200 megapixel Camera and automated data processing system, will contribute to the legacy survey of space and time (LSST) survey and help identify rare supernovae which astronomers like Dr. Filippenko plan to study.

AF: Exoplanets are a giant growth field in astronomy because they are being found around nearly every star and they have a wide range of properties. With the Rubin telescope and the Roman telescope, there will be lots more supernovae to study. I am hoping that in the next few years, the gravitational wave observatories start localizing where the graph gravitational waves are coming from. If we know where the gravitational waves are coming from more precisely, then I and other optical and ground-based astronomers will be able to direct our telescopes into the right part of the sky to find the optical counterpart.

Merging black holes are also really interesting. When two neutron stars come together, or when a neutron star gets eaten by a black hole, it can cause a gamma ray burst and electromagnetic flashes. By studying the light curves and the spectra of those flashes, we can learn all kinds of things. For example, on August 17th, 2017, the crashing of binary neutron stars showed spectroscopic evidence of very heavy, neutron-rich elements—in particular gold, platinum, and silver—along with the series of elements called the lanthanides and actinides. We have only observed one object of this sort so far but we need to observe lots of them to know what is typical. This is an area of astrophysics that is just beginning to grow and I certainly hope to contribute to once gravitational wave observatories become more precise.

I also hope to continue perfecting other techniques for measuring the Hubble constant like the use of Type II supernovae that I mentioned before. I also want to continue working on more binary pulsars or more Black Widow pulsars to try to find the upper mass limit to a neutron star. If we are really lucky, in the next 10 years, we will figure out what dark energy is, but I am not holding my breath, because it is a really hard problem.

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