Shaw Lecture Essay

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Introduction

This is my attempt to explain supernovae, and how we use them to measure the Universe. I am an astronomer at the Australian National Universities' Research School of Astronomy and Astrophysics. The work described here is not just my work, but the collective effort of more than 20 people from around the globe with whom I worked on the High-Z SN search.

The Expanding Universe

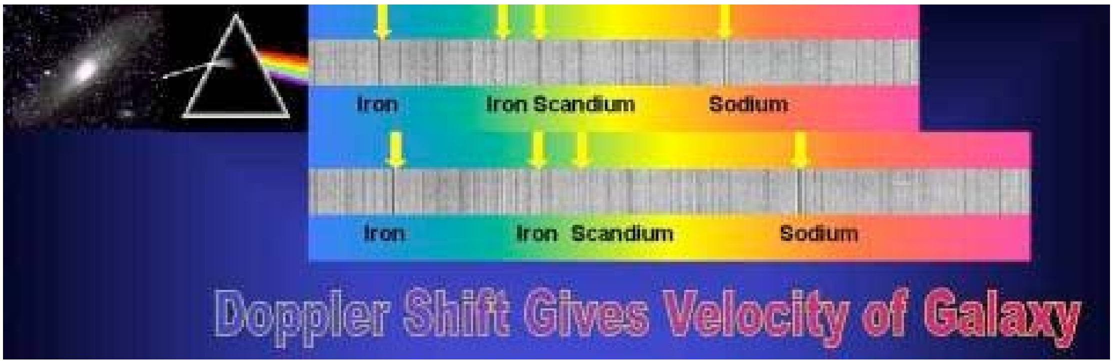

Figure 1: The Doppler shift is the effect of sound increasing or decreasing in pitch as an object moves towards or away from you. If an object moves away, the pitch is lowered, and if moving towards you, the pitch is raised. Light works the same way, except is shifted to redder colours when an object is moving away, and to blue colours when an object is travelling towards us. Here we show the spectrum of a galaxy as Slipher would have seen it. The light is stretched in the bottom spectrum, so that the dark lines (the colours where elements such as Sodium absorb light), are stretched to redder colours.

Observational Cosmology got its start in 1916 when Vesto Slipher (to whose family I am indebted for helping fund my undergraduate education through a scholarship set up at the University of Arizona in his honour) observed about 50 nearby galaxies, spreading their light out using a prism, and recording the results onto film. The results confounded him and the other astronomers of the day. Almost every object he observed had its light stretched to redder colours, indicating essentially everything in the Universe was moving away from us.

Slipher's represented a cosmic conundrum for astronomers of the day: Since the time of Copernicus, astronomy has presumed that we are not a special place in the Universe. But Slipher's results seemingly contradicted this belief - we were a special place, the most unpopular place in the Universe from which all other objects were trying to move away. Slipher's results remained a mystery until Edwin Hubble came along in the 1920s with the then world's most powerful telescope, the recently completed 100inch telescope on Mt. Wilson, near Los Angeles. He used the physical law that an object becomes fainter as its distance increases to gauge the distances to Slipher's galaxies.

In 1929 Hubble announced his results. He assumed that the brightest stars he could see in a galaxy were all the same brightness, and found that the faster an object was moving away, the fainter its brightest stars were, thereby showing that the more distant an object, the faster it was moving away from us. From this he inferred that the Universe was expanding.

This may not necessarily be obvious to everyone, but it is a natural description of Hubble's observations as is shown in figure 2.

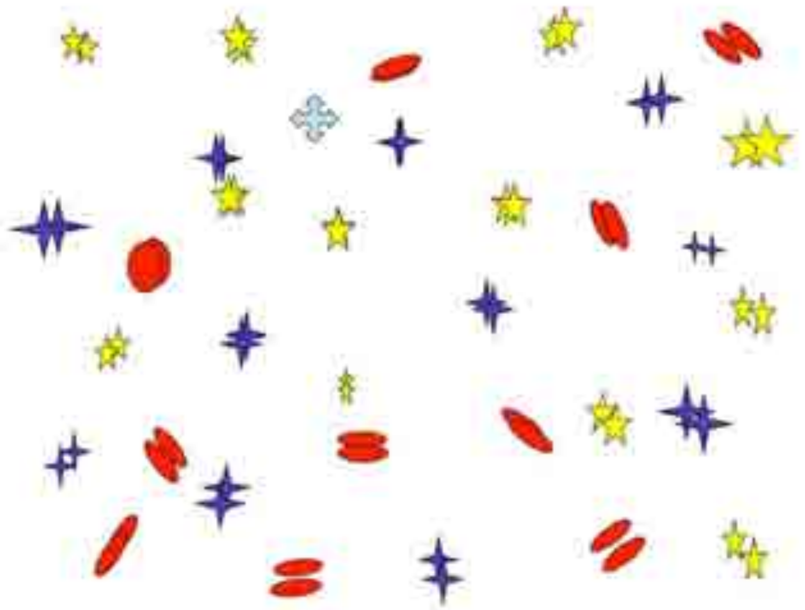

Figure 2: Here is a toy model of the Universe. Imagine if we expand it by 5%, and over overlay the two images, centered on a star near the center of the two pictures. As you can see, every object appears to have moved away from the object that we have centered the images on. Furthermore, the farther an object is away from the center object, the farther it has moved in the expansion. This is exactly what Hubble saw. Another good part of this explanation is that every one in the Universe sees the same thing. Here we have centered the two pictures on a different star. From this stars' perspective everything is moving away from it - it sees exactly the same thing as the previous star. This is what all good astronomical theories should have. There is no place in the Universe which is special, and everyone sees exactly the same thing, leaving astronomy's belief that we are not a special place, intact.

We name the rate that the Universe is expanding after Hubble - The Hubble Constant. The Hubble constant tells us how fast an object is moving away from us, given its distance. If you think about it, the Hubble constant therefore tells us given an object's distance, how far apart those two objects will be at any time. If we extrapolate to the time when these two objects were on top of each other, we reach the big bang. So the Hubble constant tells us how old the Universe is (Figure 3), but only if you assume the Universe isn't speeding up or slowing down in its expansion.

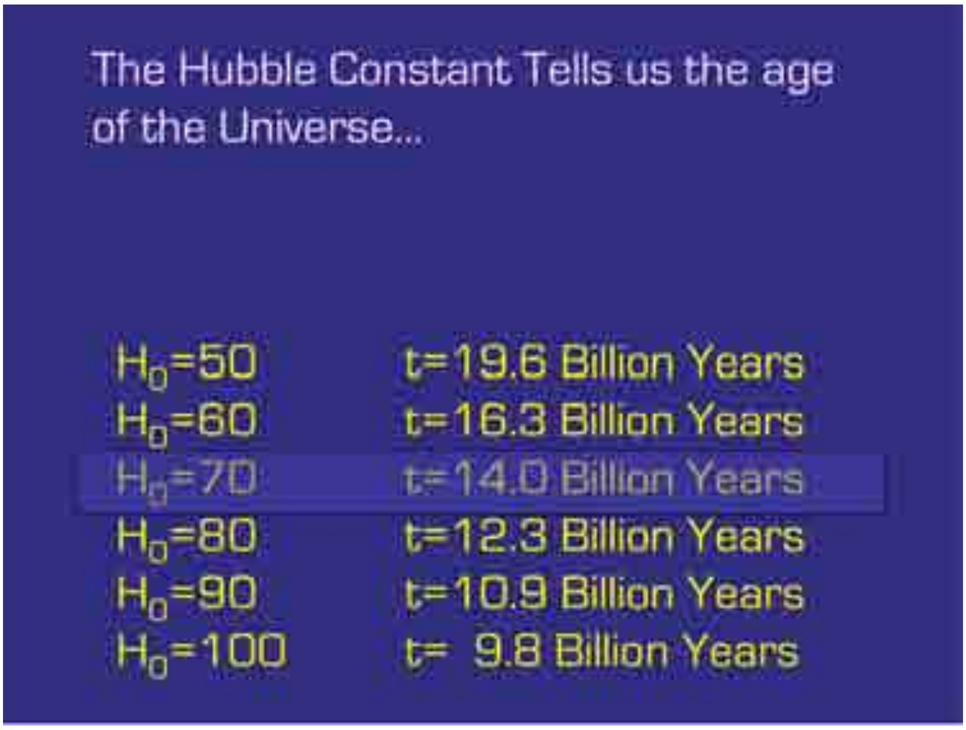

Figure 3: The Hubble Constant tells us about age of the Universe. The accepted value for the Hubble Constant is approximately 70 km/s/Mpc – a result I contributed to in the course of my thesis at Harvard University under the supervision of Bob Kirshner. That is, if we see a galaxy 1 Megaparsec in distance (about 3.2 million light years), on average, it should be receding from the observer at a rate of 70 km/s.

Cosmology via the theoretical Path.

Einstein first published his final version of General Relativity in 1916, and within the first year, de Sitter had already investigated the Cosmological implications of this new theory. In 1917 Einstein published his Cosmological Constant model, where he attemped to balance Gravity with a negative pressure inherent to space, to create a static model seemingly needed to explain the Universe around him. In 1920 de Sitter published the first models that predicted spectral redshift of objects in the Universe, dependent on distance, and in 1922, Friedmann, published his family of models for an isotropic and homogenous Universe.

The contact between theory and observations at this time, appears to have been mysteriously poor. Hubble had started to count galaxies to see the effects of non-Euclidian geometry, possible with General Relativity, but failed to find the effect as late as 1926 (in retrospect, he wasn't looking far enough a field). In 1927, Lemaitre, a Belgian monk with a newly received PhD from MIT, independently derived Freidmann universes, predicted the Hubble Law, noted that the age of the Universe was approximately the inverse of the Hubble Constant, and suggested that Hubble's/Slipher's data supported this conclusion – his work was not well known at the time. In 1928, Robertson, at CalTech (just down the road from Hubble), in a very theoretical paper predicted the Hubble law and claimed to see it (but not substantiated) if he compared Sliper's redshift versus Hubble's Galaxy Brightness measurements. Finally, in 1929, Hubble presented data in support of an expanding universe, with a clear plot of galaxy distance versus redshift - it is for this paper that Hubble is given credit for discovering the Expanding Universe.

Understanding the past, present, and future of the Universe

As the Universe expands, gravity pulls on the Universe, and slows the expansion down over time. As we look to great distances, we are looking back in time. If we can measure how fast the Universe is expanding in the past, and compare it to how fast it is expanding now, we can see the total gravitational effect of all matter in the Universe.

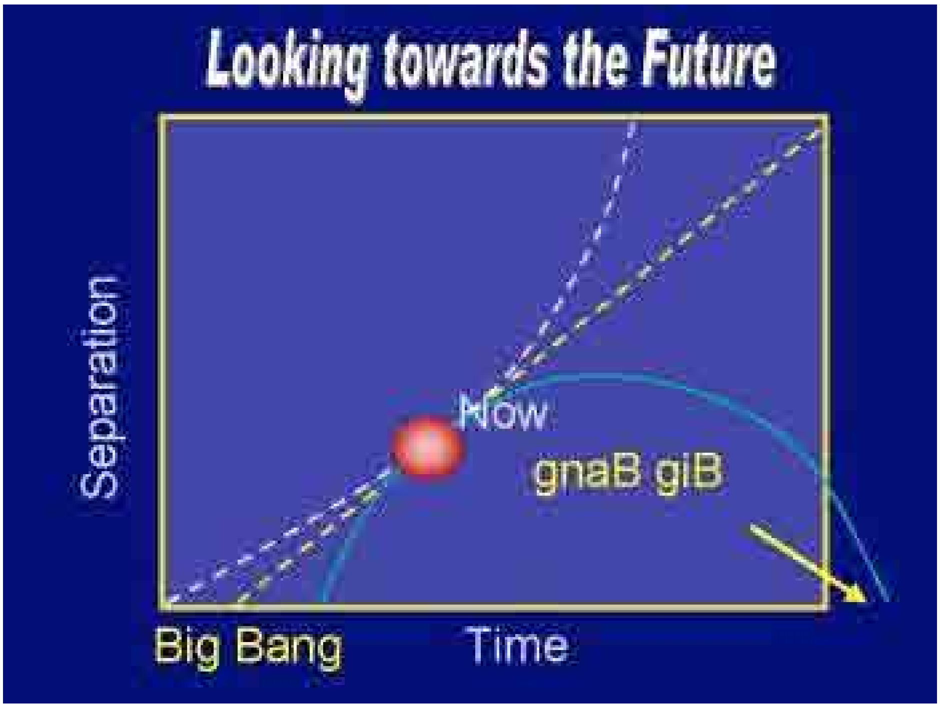

Figure 4: Here we plot the distance between two galaxies as a function of time for a model that is coasting, a model where the Universe is slowing down, and a Universe which is speeding up over time.

Figure 4. shows the distance between galaxies as a function of time. Looking back into the past we see that the galaxies get closer together until they are on top of each other – this is the time of the Big Bang.
If there is lots of material, the Universe will be expanding much faster in the past --- it will have slowed down a lot --- so much so that the Universe will eventually halt in its expansion, start to contract, and eventually end in the gnaB giB (that is the Big Bang backwards). In most models of the universe, this type of Universe curves onto itself (like a sphere), and is finite.

If there isn't much material, the Universe will be expanding about the same speed in the past as now, and will continue to expand forever. This type of universe curves away from itself (like a saddle), and therefore is without end, now, in the future, and even at the time of the Big Bang.

A final possibility is that the Universe has something other than normal matter in it which accelerates the Universe over time. Einstein's Cosmological Constant is one such material which has this property.

A favourite model amongst theorists is for the Universe to be precariously balanced between being finite and infinite. This balanced Universe is known as a critical universe. Space neither curves away nor onto itself, it is flat, and is, for most theorists infinite. So the amount of material affects how old we think the Universe is, it forms the future and past behaviour of the Universe, and it also tells us the Shape of the Universe – as shown in figure 5.

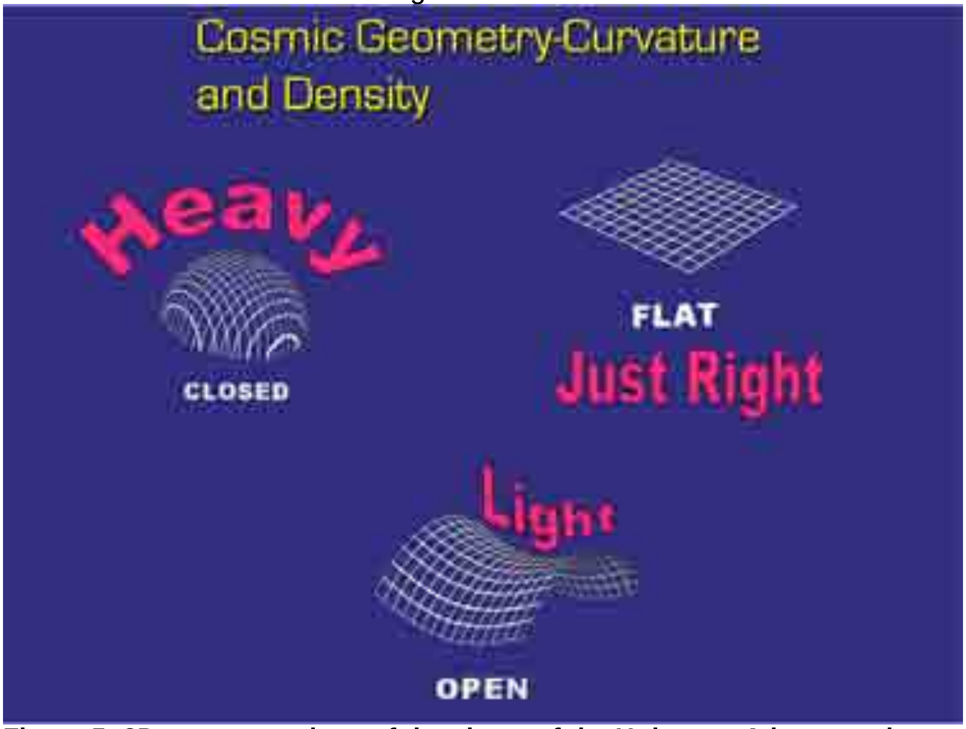

Figure 5: 2D representations of the shape of the Universe. A heavy universe – one that has more than a critical density of material (of any sort) – has a closed finite geometry. Universe's which are light, have less than the critical density, have a hyperbolic geometry, and finally Universes which are just right – have the critical density, are geometrically flat.

We use Einstein's equations of General Relativity to understand what we see in the Universe. In addition to assuming his theory is right (it sure seems to be everywhere we have be able to measure so far), we do have to make a few assumptions. The most important of these are that the universe is homogenous (that is, the material in the Universe is, on average, evenly spread through out the Universe) and isotropic (matter, the expansion, and everything else is the same in all directions that we look). With these assumptions we can predict how bright an object will be given its rate of recession (the simple relation found by Hubble breaks down at large distances).

If we can measure distances, we can see how these compare to the predictions of General Relativity, and in this way we can see what is in the Universe, and gauge how this material affects the Universe. It turns out this also allows us to predict what the future holds for the Universe.

But to do this we need a way of measuring distances halfway across the visible Universe. Measuring distances in astronomy is not trivial and this process has lead to some of the greatest controversies in astronomy over the past two hundred years. Galaxies, which are bright enough to be seen to the great distances required, unfortunately, seem to evolve over time, so comparing the size or brightness of galaxies we see today to those in the distant Universe is fraught with danger. However, Type Ia supernovae, which are individual stars, can also be seen to these great distances, and these are what we have used to measure the Universe.

Type Ia Supernovae

Type Ia Supernova are the explosions of white dwarfs. This is a pinnacle that only a few stars like our sun are able to achieve. Unfortunately we are not sure exactly how these events occur. We think they are related to white dwarf stars which are near another star in a binary system. Chandrasekhar, as part of his Nobel Prize in Physics demonstrated that white dwarf stars, if they become more massive than 1.4 times our sun can explode. They do this because at this point, the forces (electrons repelling electrons – electron degeneracy pressure) which keep the star from collapsing against the force of gravity, lose their battle, and the white dwarf begins to collapse. White dwarf stars are composed of Carbon and Oxygen and there is still substantial amounts of nuclear energy left in their atoms. As the white dwarf begins to collapse against the weight of gravity, this material is ignited, and rather than collapsing further, this nuclear blast wave consumes the star in a second, creating an explosion 5 billion times brighter than our sun.

Figure 6: SN 1994D as viewed with HST. This type Ia supernova was as bright as the rest of the galaxy of stars, combined. Credit: Pete Challis and the High-Z Team.

Type Ia supernovae in the nearby universe are observed to all have a similar brightness, and this makes them very powerful objects for measuring distances. In addition, because they are so bright, they can be seen at great distances, and these two things make them currently unique objects for measuring the vast distances of the Universe. Unfortunately, they are very rare. The last one seen in our galaxy was in 1006, and it must have been incredibly bright - easily visible in the daytime.

To measure the fate of the Universe, we need both distant and nearby objects, as it is only through the comparison of nearby and distant objects that the Universe's behaviour uncovered. Amazingly enough, the first good nearby sample was only completed in 1996 by a group at Cerro Tololo Inter-American Observatory (CTIO), and these objects are what enable us to use supernovae to measure the ultimate fate of the Universe.

Type Ia Supernovae are not all exactly the same brightness. They vary by as much as a factor of two. But Mark Phillips, Mario Hamuy and collaborators at Cerro Tololo Inter- American Observatory in Chile showed that faint supernovae rise and fall very quickly, whereas bright supernova brighten and fade much more slowly, By looking at how much the objects faded in the first 15 days following maximum light, their work showed that type Ia supernovae can give distances which are good to about 7% - equal to the best of astronomical distance indicators.

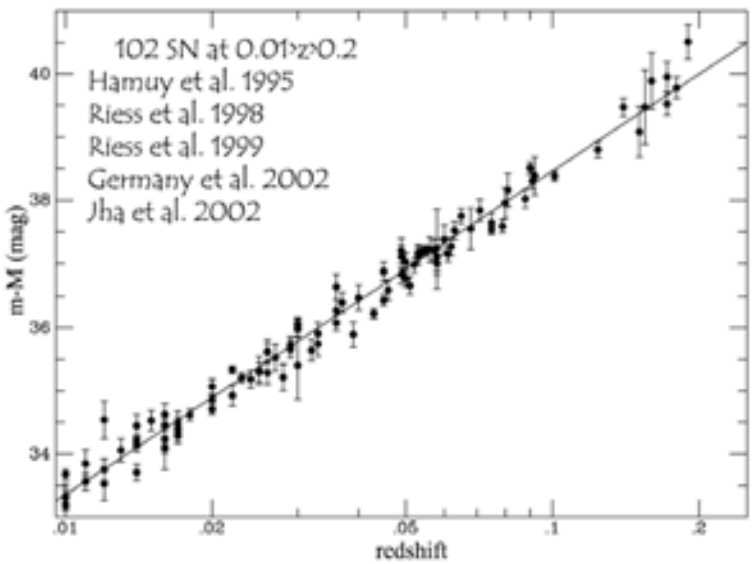

Figure 7: The Type Ia Hubble Diagram. These 102 objects represent the cumulative individual effort of members of the High-Z team. This figure demonstrates that SN Ia track the expansion of the Universe with a precision of better than 10% per object.

Another key addition was by Adam Riess, who as part of his thesis, used the Chilean dataset to create a statistically powerful tool (MLCS) which could fit distances to less than ideal data, and simultaneously, take out the effects of dust. Dust dims supernova light, and makes them redder – and if left unaccounted, can lead to erroneous cosmological conclusions.

Discovering Distant Explosions and the formation of the High-Z Team

The idea to measure the Universe with Supernovae is not new, it has long been contemplated, but it is only in the past decade that it has become feasible.
The first distant SN search was started by a Danish team. With significant effort and large amounts of telescope time spread over more than two years, they discovered a single SN Ia in a z = 0.3 cluster of galaxies (and one SN II at z = 0.2) The SN Ia was discovered well after maximum light, and was only marginally useful for cosmology itself.

Just before this first discovery in 1988, a search for high-redshift Type Ia supernovae was begun at the Lawrence Berkeley National Laboratory (LBNL) and the Center for Particle Astrophysics, at Berkeley. This search, now known as the Supernova Cosmological Pro ject (SCP), targeted SN at z > 0.3. In 1994, the SCP brought on the high-Z SN Ia era, developing the techniques which enabled them to discover 7 SN at z > 0.3 in just a few months.

The High-Z SN Search was conceived in mid 1994, when I visited Cerro-Tololo, and discussed with Nick Suntzeff, the possibility of doing the search in Chile with the 4m. Here, at CTIO, we had the best instrument in the world for doing this search, we could almost guarantee clear weather during the summer, and we could use the expertise of the group there to our advantage. My colleagues and I had finally become convinced that it was both possible to discover SN Ia in large numbers at z > 0.3 by the efforts of Perlmutter, and also use them as precision distance indicators as demonstrated by the Calan/Tololo group.

Figure 8: The High-Z Team as seen in a team meeting in Aspen. From Left to Right. Alejandro Clocchiatti, Peter Garnavich, Armin Rest, Weidong Li, Adam Riess, Nick Suntzeff, Bob Kirshner, Chris Stubbs, Saurabh Jha, Alex Filippenko, Jason Spyromilio, Pete Challis, John Tonry, Bruno Leibundgut, Brian Schmidt, Stephen Holland, Tom Matheson, Chris Smith, Gajus Miknaitis, Brian Barris. Not shown: Mark Phillips, Mario Hamuy, Bob Schommer, Jose Maza, Ron Gilliland, Al Diercks, and David Reiss.

To find supernovae, we need to scan large areas of sky – and the latest instruments enable us to do just that. Our program concentrated initially using Cerro Tololo's Blanco 4m telescope, and later the Canada-France-Hawaii 3.5 metre telescope. With these telescopes we were able to scan a piece of sky larger than the size of the moon every 5 minutes to a faintness level which allows us to find Type Ia supernovae halfway across the Universe. Although Type Ia supernovae are very rare - each image we take contains 50000 galaxies. With these telescopes we were able to survey more than a million galaxies in a night, and find tens of supernovae. This was, in 1995, not easy. Dodgy software, computers which were hundreds of times slower than we have today, and internet connections which were measured in bits per second, all contributed to the team working weeks at a time 20hours per night.

The Discovery of Acceleration

But the effort did pay off. By 1997 we had collected 14 usable objects. The High-Z team, with our late start, was attempting to catch up to Perlmutter's group, and we made the decision to have our young hungry postdocs write the first papers. I (one of the young postdocs), got to write paper 1, Peter Garnavich paper 2, and Adam Riess paper 3. Our first handfulof objects were submitted for publication in mid-1997 by Peter Garnavich. These 5 objects demonstrated that the Universe was not slowing down fast – it was not going to end in the “gnaB giB”. However, this answer seemed at odds to what our competition, Saul Perlmutter’s team showed also in a 1997 paper. Their data suggested that the Universe was slowing down considerably. But both teams only had a handful of objects, and uncertainties still prevailed. Adam Riess, in charge of the 3rd paper, worked feverishly in the second half of 1997 to finish the analysis of our next 10 objects. At the end of November, he sent me a figure of the objects with a simple subject line…”What do you think of this?” What I saw was that the objects were almost all fainter than what any Universe composed of normal matter could have. I could only think of what he might have done wrong. It is one thing to get a different answer than the competition, it is quite another to get a different answer, and have your answer be crazy.

I remember very little of the rest of November and December. Just long days checking everything over and over again. I was constantly iterating with Adam over email, occaisionally the phone, trying to sort out what could be wrong. But by the end of December, it was clear that the answer was not going away. Little did we know that Saul Perlmutter’s group was getting the same answer with their data set.

At the beginning of January, Adam and I decided we were ready to tell the team about the result (Adam had already leaked it to Alex Filippenko). Peter Garnavich was going to the AAS meeting to present his result. We agreed that he would not discuss this result at his press conference. Imagine our surprise when Saul showed his 40 objects, and stated that they were fainter than expected in a matter-dominated universe. However, as indicated in their press release, the SCP was still struggling to deal with dust and were not yet ready to claim the Universe was accelerating. Dealing with dust was a problem that our team from the outset had included in our experiment. We observed each supernova in at least two wavelengths, and used Adam’s thesis work on using this information to remove the effects of dust in each of our distances. So at the AAS meeting, Peter kept quiet despite the temptation to do otherwise, and we worked hard to get our result ready for publication. Adam’s paper was ready at the end of February, and Alex Filippenko had the opportunity to present our results at a conference in California. The Universe appeared to be accelerating - even if one corrected for dust.

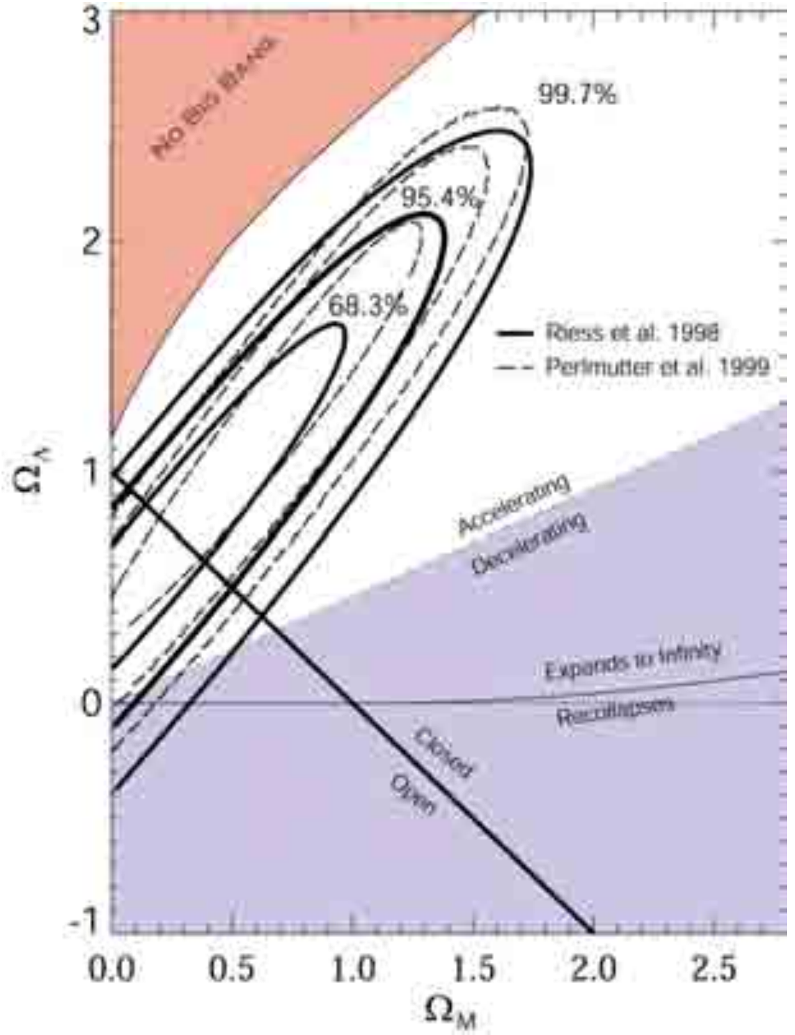

Figure 9: Comparison of The High-Z Team and Supernova Cosmology Project's values of the Cosmological Constant and Normal Matter. The two groups agreed almost perfectly. The values of Ω represent the fraction of the amount of matter necessary to make space flat. If Ω=1 – the Universe is geometrically flat.

Implications of an Accelerating Universe

The SCP soon followed suit in publishing their result of the accelerating Universe, and the results – shown in figure 9, were nearly identical. But just because the two teams independently got the same answer does not mean we are both right. We could both be fooled because we were using supernovae in more or less the same way. Or maybe our whole cosmological model is flawed.

So our observations really meant one of three things:

- The Exciting: the Universe is accelerating. The Universe is accelerated by some unknown type of Dark Energy that is spread throughout the Cosmos.
- The Heretical: General Relativity is as sacred as anything in Physics, but it may be wrong, and so may be our simplifying assumption – that the Universe is homogenous and isotropic. Since our work is comparing the predictions of General Relativity with observations under these assumptions, if General Relativity is wrong, or the Universe is not homogenous and isotropic, so are our conclusions.

- The Mundane (at least from our point of view): We are simply wrong and have been fooled by Supernovae into believing the Universe is accelerating. Maybe supernovae are intrinsically fainter in the past, and therefore look further away than they really are.

So for the past 8 years, hundreds of researchers have attempted to make progress on the three possibilities. Countless new theories have been proposed which might lead to the acceleration. Several papers have suggested possible ways the supernova might fool us, but none of these seems to be anywhere near a large enough effect to make the acceleration go away. And finally, and most importantly, other methods have been used to check the supernova results.

There are two principal methods that have been used to make measurements of what is in the Universe. These are using the large scale structure of galaxies in the Universe to trace how much gravity (and hence measure the amount of normal matter) there is in the local Universe. The other is to look at the Universe when it was very young, and glowed like the sun. This radiation is the furthest thing we can see in the Universe, and is known as the Cosmic Microwave Background. Because the theory of the Cosmic Microwave Background is very well understood, astronomers can calculate accurately how big the lumps in the Universe which eventually became the galaxies we see today were at this early stage of the Cosmos. By observing how big the lumps in this background appear today, it is possible to measure the geometry of space.

The results of these two experiments are shown in figure 10. The measurement of gravity (2dF and more recently SDSS) shows that the Universe has roughly 25% of the amount of gravitating matter necessary to make the Universe flat. At the same time, the Cosmic Microwave Background measurements (by MAXIMA, Boomerang, and more recently WMAP) show that the Universe is geometrically flat! The only way to reconcile these two experiments is to have a missing type of matter/energy – the same dark energy that the supernovae see accelerating the Universe. In order to make the Dark Energy disappear, at least two of these three experiments must be terribly flawed.

Despite 8 years of work, Astronomy is still unsure of what is accelerating the Universe. Additional supernovae by the High-Z team, the SCP, and the new experiments Essence and CFHTLS, all are finding answers consistent with the Dark Energy being tied to space itself. In this case, space has associated with it, an energy, and as space doubles in volume, the amount of dark energy per volume remains fixed (where as the density of gravitating matter drops as the volume increases). This form of Dark Energy is known as the Cosmological Constant and was originally proposed by Einstein to keep the Universe from expanding (or collapsing) under his equations of General Relativity. But other types of dark energy, which dynamically evolve as the Universe expands, are also possible using the same framework (quantum field theory) that is used to understand how the forces of nature are joined together. These types of dark energy will not have their density remain exactly fixed as the Universe expands – but the difference from a Cosmological Constant can be very small, and therefore hard to measure.

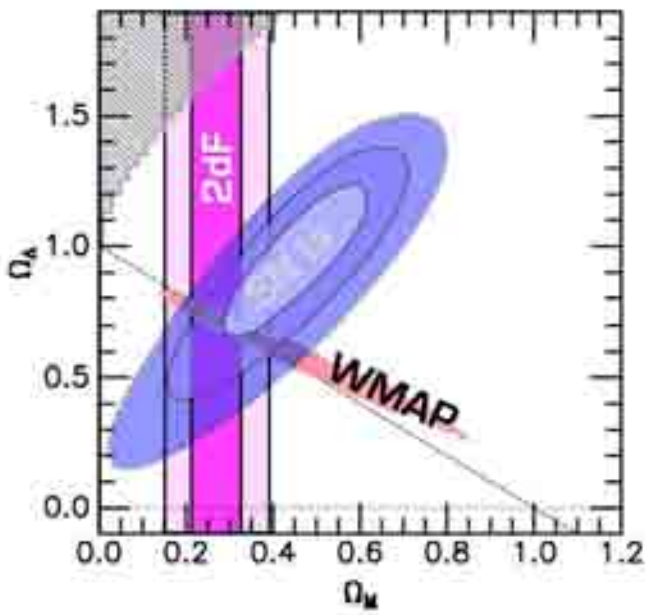

Figure 10: The measurement of the Cosmological Constant by Type Ia supernovae, the Cosmic Microwave Background (WMAP), and Large Scale Structure (2dF). The 3 methods are consistent that the Universe is made up of 25% normal matter and 75% Dark Energy.

Over the coming decades, a whole raft of new experiments – some in space – many from the ground - will come on line, searching for clues which distinguish the dark energy from Einstein's Cosmological Constant. These experiments – backed up with a greater theoretical basis for understanding Dark Energy will hopefully illuminate this, a most perplexing problem currently facing modern Physics. I am unwilling to speculate what we will find – I never expected to see a Universe dominated by Dark Energy – and I hope I will continue to be surprised.