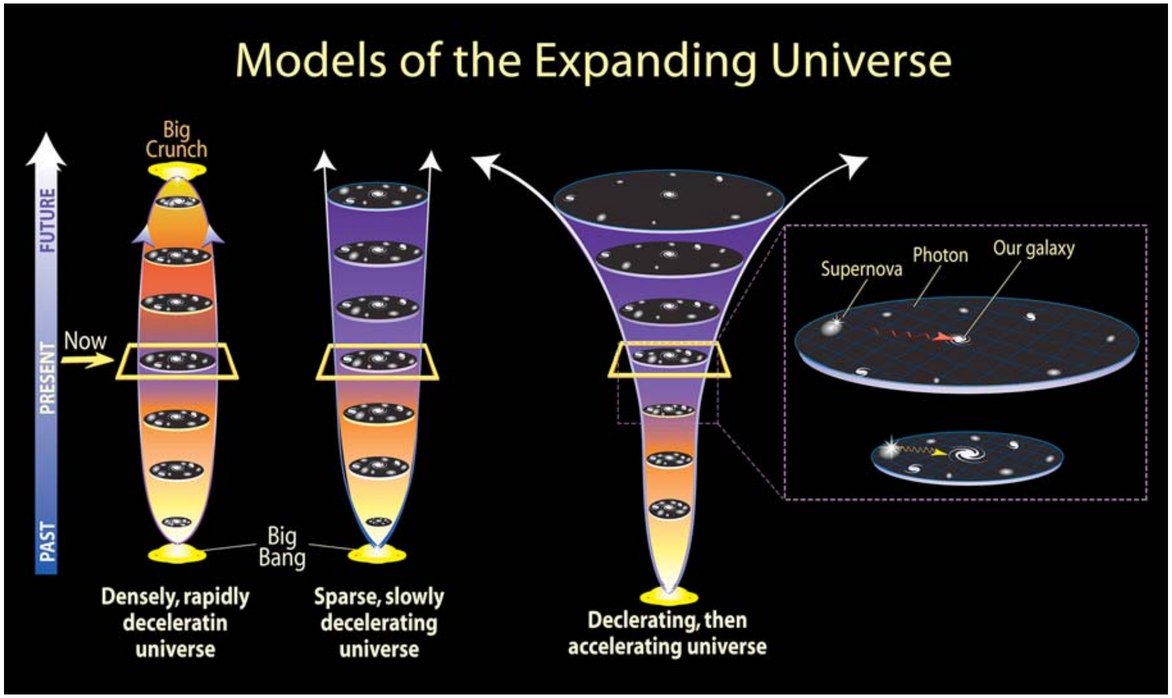
My Path to the Accelerating Universe
Adam G. Riess

Introduction

Supernovae and the Expansion History of the Universe. From antiquity to the time of Albert Einstein, scientists and philosophers believed that the Universe was static and immutable. The breakthrough in understanding came in 1929 when Edwin Hubble showed that the Universe is expanding, growing larger with time. Since that time, the goal of measuring the expansion rate of the Universe with time has consumed cosmologists (like me!)

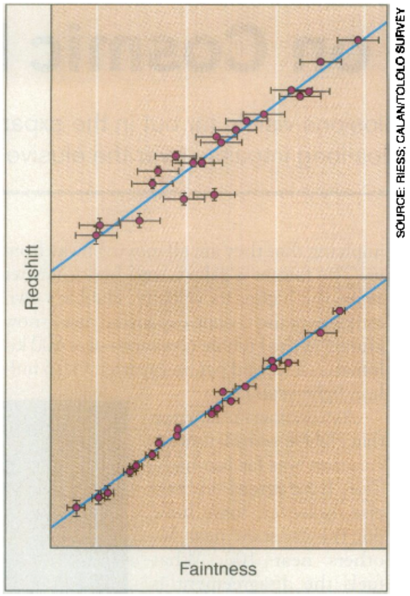
Mapping the kinematics of the expanding Universe requires sets of measurements of the relative size and age of the Universe at different epochs of its history. Unfortunately the evolution of the Universe is too slow to collect such measurements now and then wait for the Universe to change to record the changes. Our challenge is similar to the one facing geologists who seek to study the evolution of the surface of the Earth by drilling deep into the Earth's depths. Our solution is also very similar. We extract data from earlier periods in the Universe's history by collecting light from stars which exploded far into the Universe's past.



A particular class of supernovae known as Type Ia, are well suited to the task. They are bright enough (~10 billion solar luminosities at peak) to be seen halfway across the visible Universe from the ground and even farther back using the Hubble Space Telescope. Their intrinsic brightness has been well calibrated over the last decade so the distance to one of these events can be measured using the apparent brightness of the supernova and geometry. Because this distance is traversed by photons from the supernova traveling at a known speed (the speed of light), a distance measurement provides a measurement of the relative age of the Universe at the time of the supernova explosion, much as a geologist can measure the age of a layer of the Earth by radio carbon dating an artifact contained within it. The other measurement we need to obtain is the growth factor of the Universe at the time a supernova exploded. This is accomplished using the doppler effect, realized as the redshifting of the supernova (and its host galaxy's) light. For example, a doubling of the Universe's size between the time the photon leaves the supernova and reaches the Hubble Space Telescope results in a doubling of the wavelength of light. With this technique all that is needed is a large number of supernovae dispersed at different depths to provide a record of its growth history (see Figure 1)

My Path to the Accelerating Universe

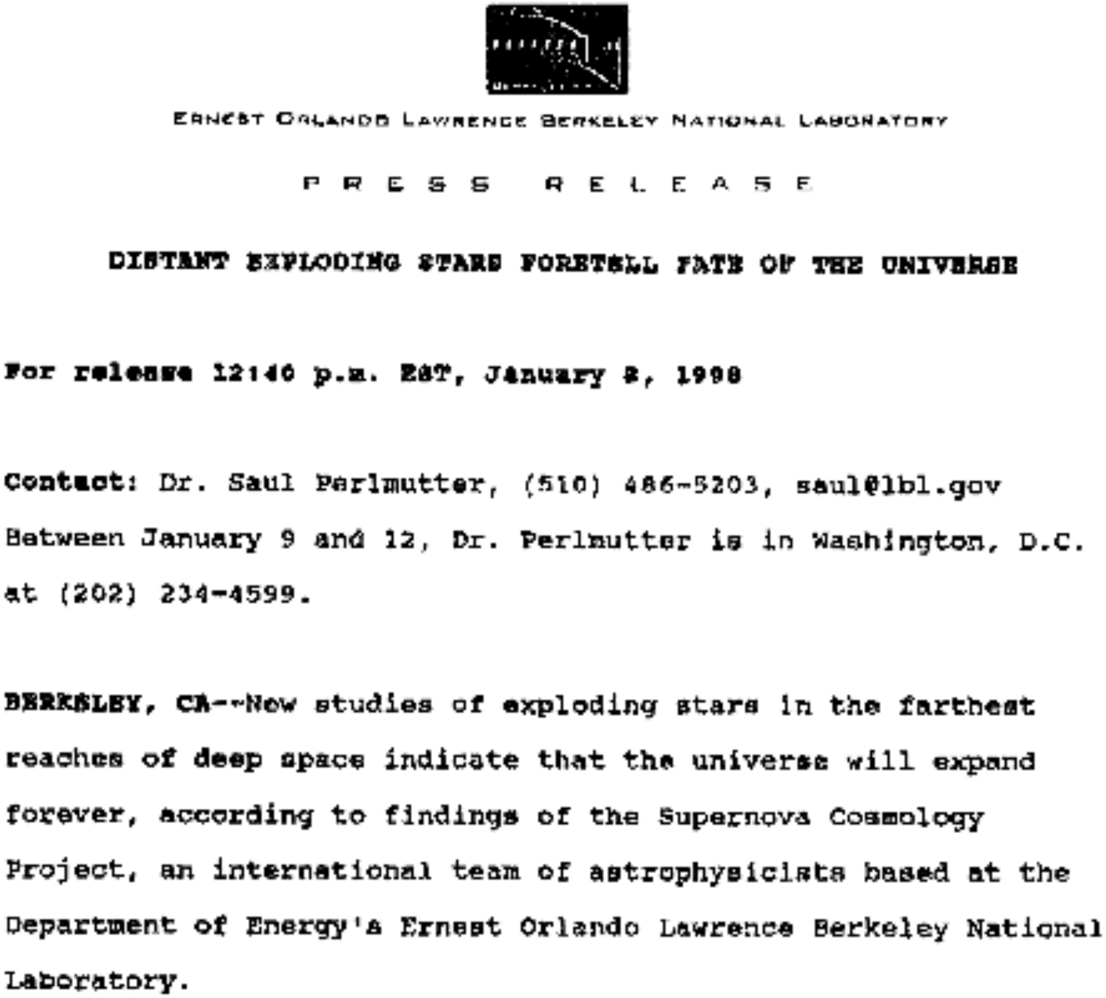
In 1992 I went to Harvard University's Center for Astrophysics to earn a doctorate in astrophysics. After a first course I knew I wanted to work on measurements of cosmological distances to calibrate the expansion rate of the Universe. Professor Robert Kirshner was already finishing with a student, Brian Schmidt (the other co-winner of the Shaw Prize), on methods to measure distances to core-collapse supernovae. He suggested I work on the other type of supernova (type Ia) in collaboration with Professor William Press. I was extremely fortunate to get to work with Bob who had great common sense, a nose for what was important, and the ability to marshal the resources his students needed to succeed. Bill had incredible talents and wisdom in the area of data analysis. And Bob's senior graduate student, Brian, patiently taught me a great deal about the techniques of making precise measurements with telescopes about which he was an expert. This work culminated in the development of my thesis, the Multicolor Light Curve Shape Method, a technique which could distinguish between the effects of distance, dust and dimness in type Ia supernovae to measure the expansion rate of the Universe to unprecedented precision (as seen in Figure 2). I had also collected one of the largest datasets, 22 new type Ia supernovae, for measuring the recent expansion rate of the Universe. My thesis later received the 1999 PASP Trumpler Award for the doctoral thesis with the greatest impact in astrophysics.



SOURCE: RIESS; CALAN/TOLOLO SURVEY

Supernovas all in a row. Scatter in a plot of apparent brightness against redshift—relative distance—shows that Ia supernovas are not perfect standard candles *(top)*. Correcting for differences in their rate of dimming, however, refines the brightness-distance relationship.

After nearly accepting a generous offer to work with Saul Perlmutter as a post doctoral fellow in the Supernova Cosmology Project (SCP) on his efforts to measure changes in the expansion rate with supernovae I instead went to UC Berkeley in 1996 as a Miller Fellow, having recently become a founding member of the competing High-z Supernova Team. At Berkeley I was again fortunate to work with the best, Professor Alex Filippenko, an expert in supernova spectroscopy and enthusiastic figure. By 1997 the High-z Team had managed to find and observe a significant sample of very distant supernovae. The SCP published a first effort at measuring the expansion history which indicated that the Universe was heavy and strongly decelerating (Perlmutter et al. 1997) but this picture changed quickly. Preliminary results from our team and an update from the SCP were reported at the January 1998 AAS to be only good enough to show that the Universe was decelerating only modestly (at most) (see press release texts from each team below; Garnavich et al. 1998, Perlmutter et al. 1998). However, both teams were already beginning to see something more exciting.



ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

PRESS RELEASE

DISTANT EXPLODING STARS FORETELL FATE OF THE UNIVERSE

For release 12:40 p.m. EST, January 8, 1998

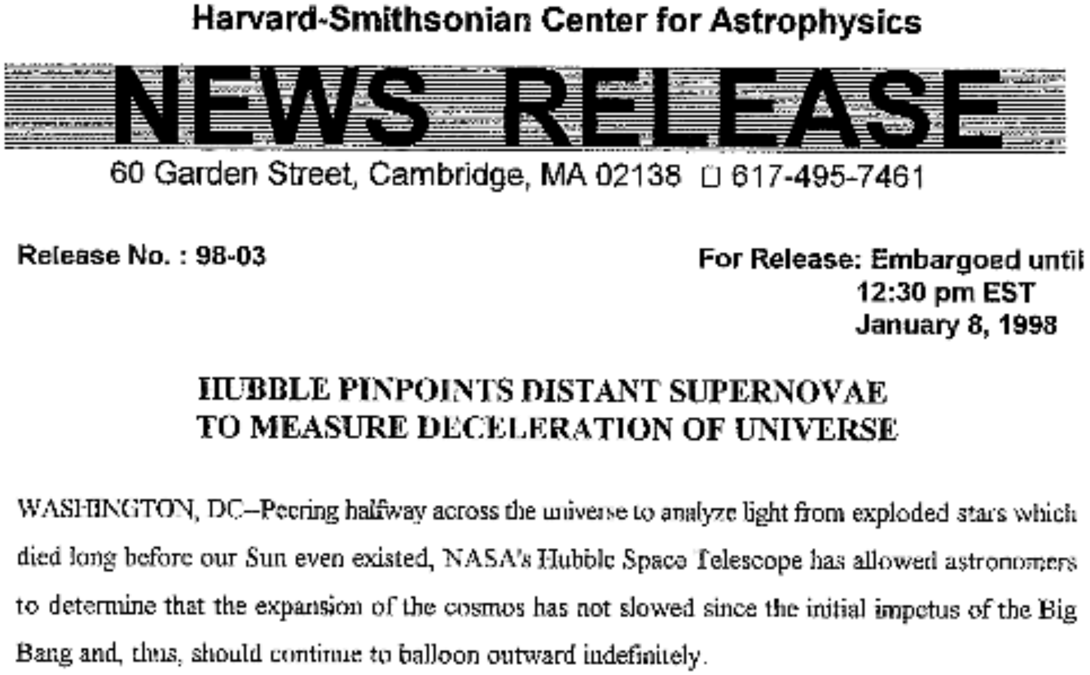
Contact: Dr. Saul Perlmutter, (510) 486-5203, saul@lbl.gov
Between January 9 and 12, Dr. Perlmutter is in Washington, D.C. at (202) 234-4599.

BERKELEY, CA--New studies of exploding stars in the farthest reaches of deep space indicate that the universe will expand forever, according to findings of the Supernova Cosmology Project, an international team of astrophysicists based at the Department of Energy's Ernest Orlando Lawrence Berkeley National Laboratory.

The research, utilizing data obtained with the world's most powerful optical telescopes, including NASA's Hubble Space Telescope, is being presented today at the meeting of the American Astronomical Society in Washington, D.C.

"Distant supernovae provide natural mile-markers which can be used to measure trends in the cosmic expansion," says Berkeley Lab's Saul Perlmutter, leader of the Supernova Cosmology Project. "All the indications from our observations of supernovae spanning a large range of distances are that we live in a universe that will expand forever. Apparently there isn't enough mass in the universe for its gravity to slow the expansion, which started with the Big Bang, to a halt."

This result rests on analysis of 40 of the roughly 65 supernovae so far discovered by the Supernova Cosmology Project.



Harvard-Smithsonian Center for Astrophysics

NEWS RELEASE

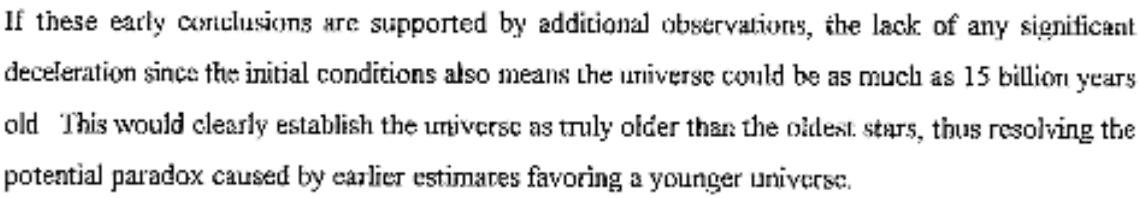
60 Garden Street, Cambridge, MA 02138 ☐ 617-495-7461

Release No. : 98-03

For Release: Embargoed until
12:30 pm EST
January 8, 1998

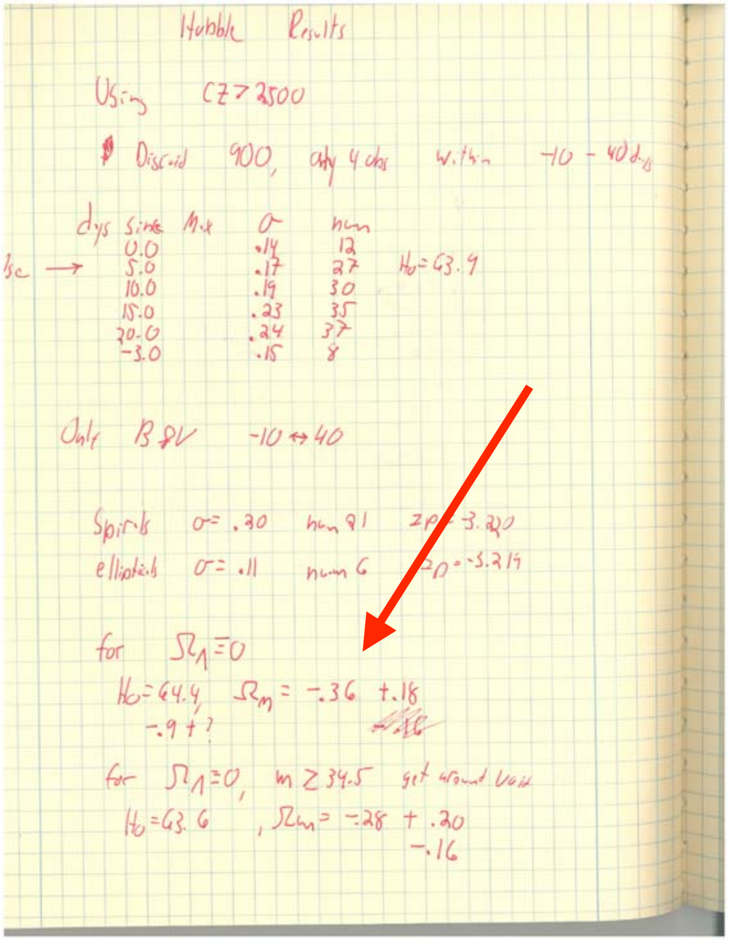
HUBBLE PINPOINTS DISTANT SUPERNOVAE
TO MEASURE DECELERATION OF UNIVERSE

WASHINGTON, DC–Peering halfway across the universe to analyze light from exploded stars which died long before our Sun even existed, NASA's Hubble Space Telescope has allowed astronomers to determine that the expansion of the cosmos has not slowed since the initial impetus of the Big Bang and, thus, should continue to balloon outward indefinitely.



If these early conclusions are supported by additional observations, the lack of any significant deceleration since the initial conditions also means the universe could be as much as 15 billion years old. This would clearly establish the universe as truly older than the oldest stars, thus resolving the potential paradox caused by earlier estimates favoring a younger universe.

By 1997 we had collected significantly more data than we had reported on and these offered the potential for far greater precision and I took the lead in analyzing our first large dataset. Working down the hill from Saul's talented team, I collected the raw data and led the process of analyzing it, transforming large pixelated images into a record of the light history of a dozen distant supernovae. Armed with a similar product I had collected for local supernovae from my thesis (as well as the Calan-Tololo Survey) I measured the expansion rate of the Universe recently, in the past, and the apparent subsequent changes to it. I then transformed these measurements into an expectation of the forces at work in the Universe causing these changes. What I initially measured in the Fall of 1997 shocked me! The initial results indicated the dominating presence of negative mass accelerating the Universe (Figure 3, left panel, AGR lab notebook)! Of course I hadn't initially considered any force besides the gravity of matter and my computer programs were telling me that only the inverse of attractive gravity caused by a hypothetical negative mass would fit the bill.



Hubble Results

Using $CZ > 2500$

Discard 900, only 4 obs within $-10 - 40$ days

days since Max	σ	num
0.0	.14	12
5.0	.17	27
10.0	.19	30
15.0	.23	35
20.0	.24	37
-3.0	.15	8

Isc → 5.0 $H_0 = 63.9$

Only B & V $-10 \leftrightarrow 40$

Spirals $\sigma = .30$ num 21 $zp = -3.220$

ellipticals $\sigma = .11$ num 6 $zp = -3.219$

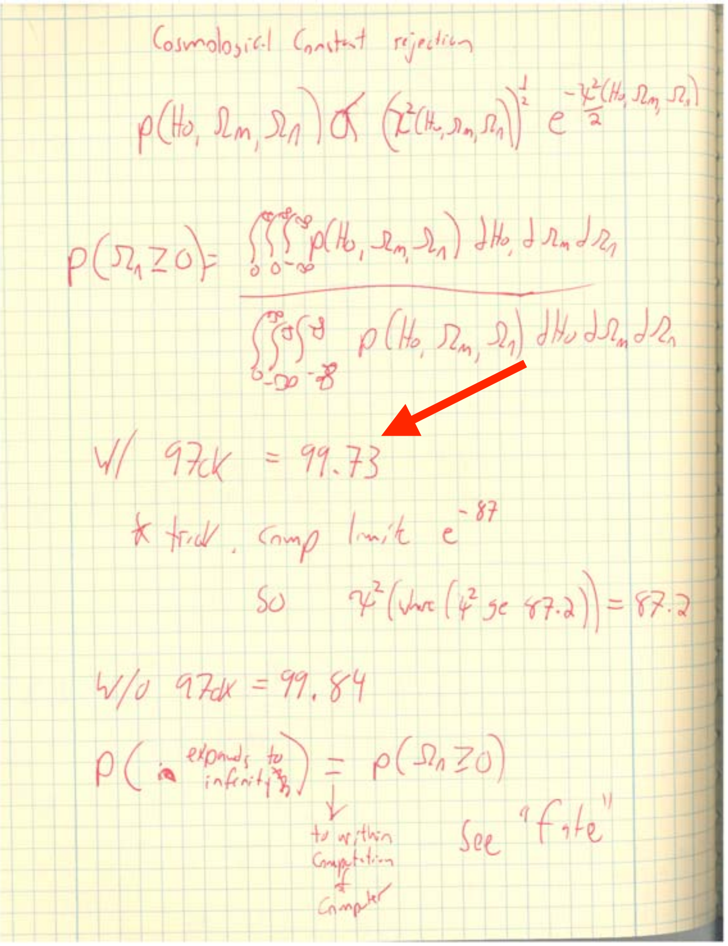
for $\Omega_\Lambda = 0$

$H_0 = 64.4$, $\Omega_m = -.36 \begin{smallmatrix} +.18 \\ \cancel{-.16} \end{smallmatrix}$

$-.9 + ?$

for $\Omega_\Lambda = 0$, $m \geq 34.5$ get around void

$H_0 = 63.6$, $\Omega_m = -.28 \begin{smallmatrix} +.20 \\ -.16 \end{smallmatrix}$



Cosmological Constant rejection

$$p(H_0, \Omega_m, \Omega_\Lambda) \propto \left(\chi^2(H_0, \Omega_m, \Omega_\Lambda)\right)^{\frac{1}{2}} e^{-\frac{\chi^2(H_0, \Omega_m, \Omega_\Lambda)}{2}}$$

$$p(\Omega_\Lambda \geq 0) = \frac{\int_0^\infty \int_0^\infty \int_{-\infty}^\infty p(H_0, \Omega_m, \Omega_\Lambda)\, dH_0\, d\Omega_m\, d\Omega_\Lambda}{\int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty p(H_0, \Omega_m, \Omega_\Lambda)\, dH_0\, d\Omega_m\, d\Omega_\Lambda}$$

W/ 97ck = 99.73

* trick, comp limit e^{-87}

so $\chi^2(\text{where}(\chi^2 \text{ ge } 87.2)) = 87.2$

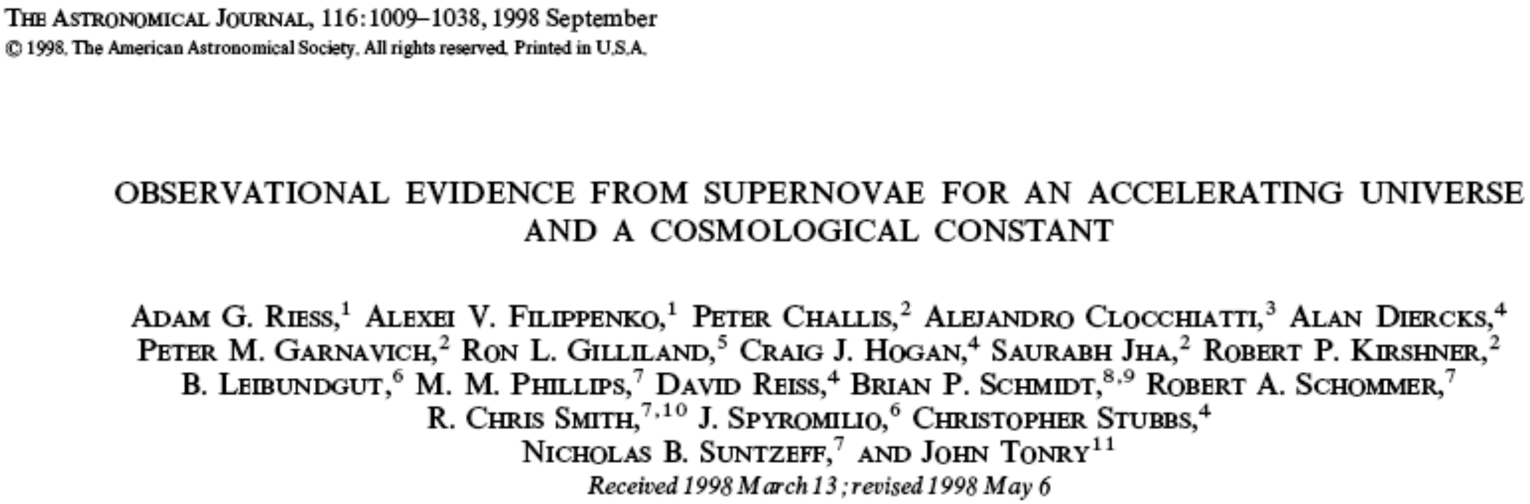
W/o 97ck = 99.84

$p(\text{expands to infinity}) = p(\Omega_\Lambda \geq 0)$

↓ to within computation of computer

See "fate"

Since there is no such thing as negative mass I introduced the next best thing, the famous cosmological constant to the fit in desperation (in the same spirit Einstein had introduced it long ago) and immediately found that its dominating presence (i.e., a non-zero vacuum energy with negative pressure causing repulsive gravity) could explain the apparent acceleration I was seeing (Figure 3, right hand side. This was remarkable and experience told me that such "discoveries" are usually the result of simple errors. Being young and relatively unsure, I spent a long time double checking my results but could find no errors. I thought hard about unexpected astrophysical sources of contamination to the experiment but could not identify any sufficient to explain what I was seeing. Here my thesis which had focused on recognizing and correcting for the effects of cosmic dust was very helpful. With growing confidence in the results, the first person I told was Brian who spot-checked the final calculations and came to the same conclusions. His famous quote in the media was, "My own reaction is somewhere between amazement and horror." Coincidentally, another, even more exciting event was occurring in my life as Nancy Joy Schondorf and I were married on January 10th in 1998, the best day of my life. We planned a honeymoon to Hawaii, after the next supernova observing run on the Big Island. Meanwhile, the rest of the team did their own spot-checking of the results and more thinking and they too could not find any errors. It is very amusing for me to look back at some of the (emailed) conversations from that point in time. My graduate school advisor and teammate Bob Kirshner wrote (on January 12, 1998), "I am worried that the first cut looks like you might need [the cosmological constant]. In your heart you know this is wrong, though your head tells you that you don't care and you're just reporting the observations…It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year." I responded later that day in email (over understandably icy stares from my wife as I was still working on the eve of our honeymoon!) with, "The results are very surprising, shocking even. I have avoided telling anyone about them for a few reasons. I wanted to do some cross checks (I have) and I wanted to get further into writing the results up before [the other team] got wind of it…The data require a nonzero cosmological constant! Approach these results not with your heart or head but with your eyes. We are observers after all!" My sponsor at UC Berkeley and team mate Professor Alex Filippenko was for publishing too. Brian was more conflicted, "It is true that the new SNe say that [the cosmological constant] is greater than zero … but how confident are we in this result? I find it very perplexing…Let's put out a paper we can be proud of---quickly." And senior team member and supernova expert Nick Suntzeff wrote to me, "I really encourage you to work your butt off on this. Everyone is right. We need to be careful and publish good stuff with enough discussion to make it believable to ourselves…If you are really sure that the [cosmological constant] is not zero—my god, get it out! I mean this seriously—you probably never will have another scientific result that is more exciting come your way in your lifetime." In the end the High-z Team published our paper entitled, "Observational Evidence From Supernovae for an Accelerating Universe and a Cosmological Constant" 60 days later (Riess et al. 1998). Saul's competing team reached the same conclusion during this same period of time (Perlmutter et al. 1999). Together the two team's conclusion became the "Breakthrough of the Year" in 1998 of Science Magazine (see Figure 4, top and bottom) . Nick was right!



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OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7]
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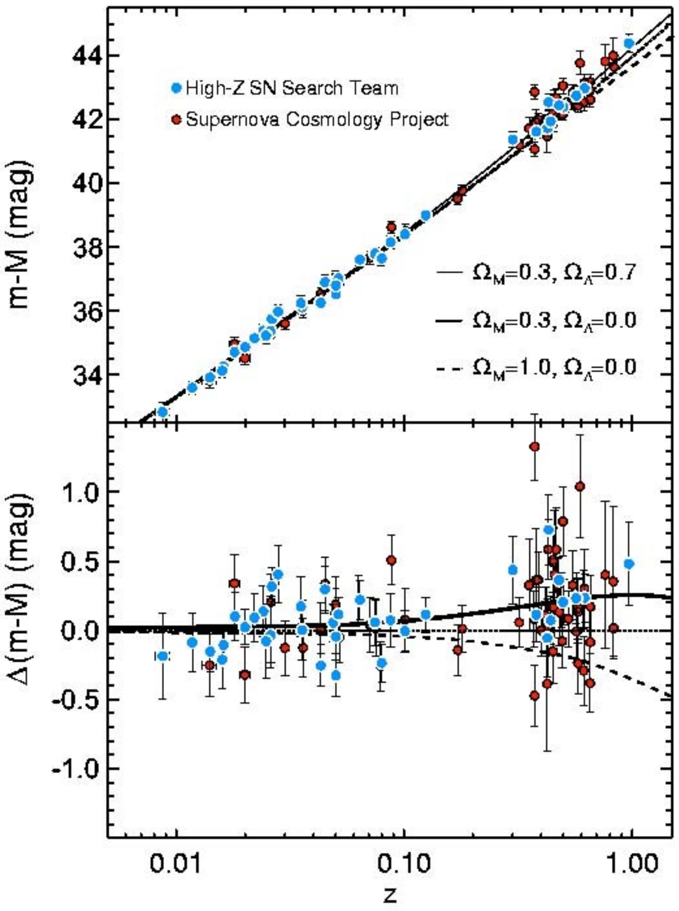
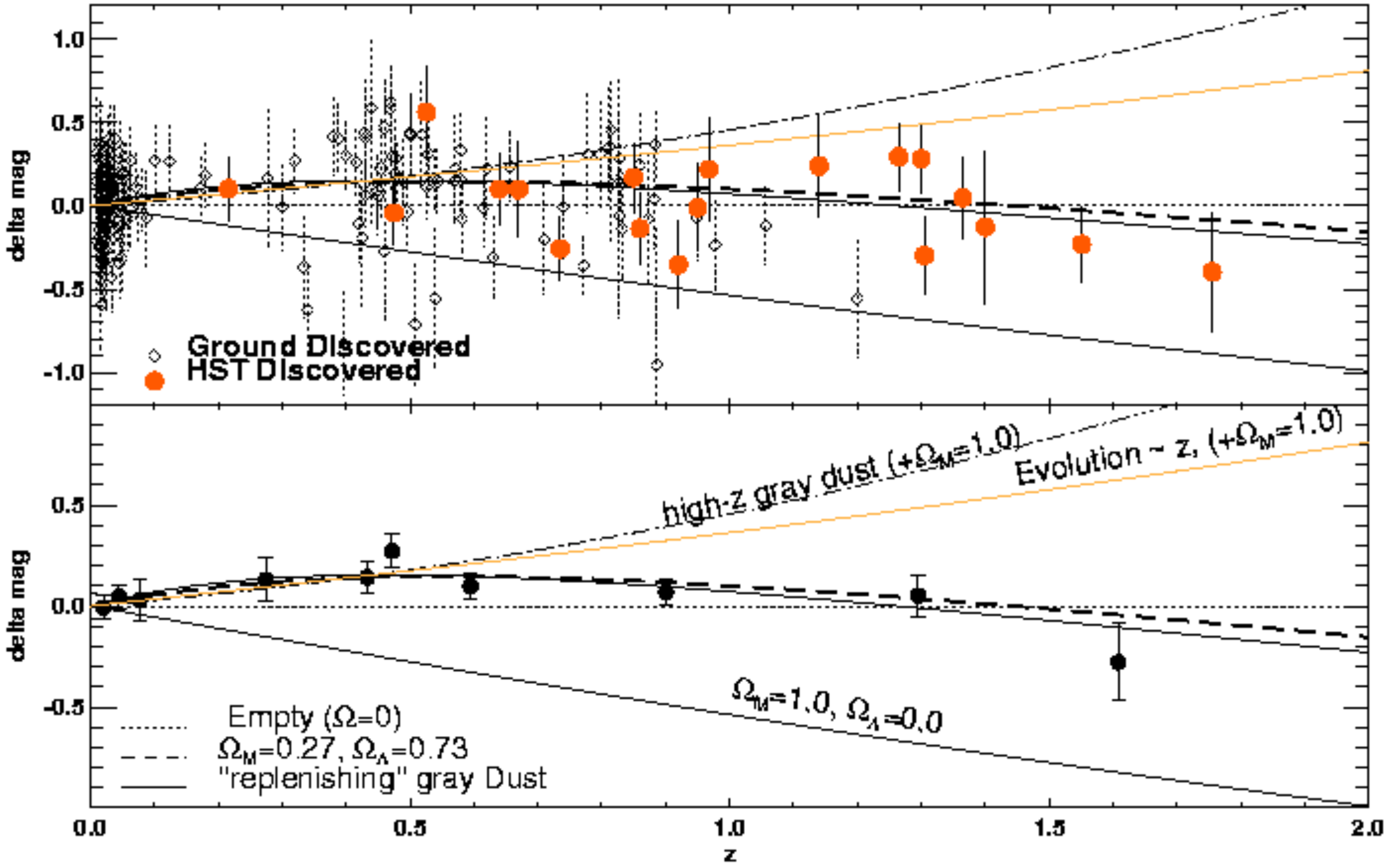
Received 1998 March 13; revised 1998 May 6

This finding ran counter to what was expected, namely that the attractive gravity of dark matter would have been slowing the expansion of the Universe. However, a theoretical explanation for cosmic speedup was waiting in the wings; the Universe's dynamics was apparently dominated by Dark Energy whose negative pressure caused the less familiar but repulsive variety of gravity to dominate. Was this the correct interpretation of the supernova data or was some more mundane effect causing the supernovae to only appear fainter (and thus incorrectly inferred to be more distant) than expected? Past attempts to use distant objects (Brightest Cluster Galaxies) to measure the change in the expansion rate had been foiled before by evolution of the object's intrinsic luminosity, so a good test of cosmic speedup was needed. Fortunately a good test of competing hypothesis was available and was posited shortly after the findings in 1998.



. If distant supernovae appeared faint not because of a change in the expansion history but because of an astrophysical cause such as a pervasive screen of dust making supernovae appear dim or perhaps past supernovae were just born dimmer (due to chemical changes in the Universe), the putative dimming effect would most likely continue in the past. However, if the dimming were due to a recent cosmic speedup, following an earlier cosmic slowdown, supernovae from the period of the slowdown would appear relatively brighter and provide the evidence to distinguish between the competing possibilities. (We note that a poorly understand source of astrophysical dimming could be tuned to precisely match both the cosmic speedup and cosmic slowdown but such conspiracies are generally disfavored when they are artificially tuned and invoked to precisely match a more natural explanation).



Unfortunately, finding supernovae so far back and away is difficult because they are so faint (like a 60 watt light bulb held at a distance of 400,000 miles (twice the distance to the moon). Five years of trying demonstrates that this is too hard to do reliably from the ground, but is readily achievable with the Hubble Space Telescope. In 2001 we announced that HST had serendipitiously and repeatedly observed one such object 1997ff in the Hubble Deep Field, and this single event indicated that past cosmic slow-down had indeed happened! Outfitted in 2002 with the Advanced Camera for Surveys, HST was converted into a supernova hunting machine. In 2002 I led a team called the Higher-z Team to discover and collect a sample of supernovae from the young Universe. We found 6 of the 7 most distant, well beyond the anticipated "coasting" point. These supernovae confirmed past cosmic slowdown and provided the critical "reality-check" of recent cosmic speedup by disfavoring alternative astrophysical explanations as first posited in 1998. (See Figure 5; Riess et al. 2004). Further, supernovae from this far back can give new clues about dark energy such as how "springy" it is and how it has been changing in time. This will be the second important clue to help us solve the riddle of what is dark energy. Einstein's constant has no time evolution, mini-inflation would.