The Acceleration of the Expansion of the Universe: A Brief Early History of the Supernova Cosmology Project (SCP)

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Abstract. It is now about 10 years since the evidence, based on Type Ia supernovae, for the acceleration of the expansion of the Universe was discovered. I will discuss some aspects of the work and events in the Supernova Cosmology Project (SCP), during the period 1988 to 1998, which led to this discovery.

PREAMBLE

In the past I have written papers that described new physics results. In this report, however, on this tenth anniversary of the discovery of dark energy, I present the history of our discovery *as I saw it*.

When the bubble chamber work in Luis Alvarez's group at LBNL came to an end in the early 1970s, there started an interest in astrophysics. Rich Muller became interested in the Cosmic Microwave Background (CMB). He was later joined by George Smoot. After convincing Luis Alvarez of the feasibility of a CMB measurement and obtaining his support , Rich Muller and George Smoot and their collaborators studied the CMB with detectors placed on U2 airplane flights. This led to their discovery of the CMB dipole asymmetry. Smoot then went on to work with the COBE satellite, and led the discovery of the CMB anisotropy.

Meanwhile, Rich Muller, joined by Carl Pennypacker (a staff member at the Space Science Laboratory) , set up an automated search for nearby Supernovae (SNe) This work was primarily under Pennypacker's responsibility and was helped by Richard Treffers of the Berkeley Astronomy department and others. They were later joined by Muller's student Saul Perlmutter who carried out his thesis, a search for "Nemesis", the suspected companion star to the sun, as well as working on the SNe search. During the period 1980-1988, they demonstrated that the method, originally suggested by Stirling Colgate et al. [1], worked, and they were able to discover about 25 nearby SNe. This work became the prototype of later automated SNe searches.

In 1988, a National Science Foundation (NSF) Center for Particle Astrophysics (CfPA) was being formed on the UC Berkeley campus. Pennypacker and Muller pro-

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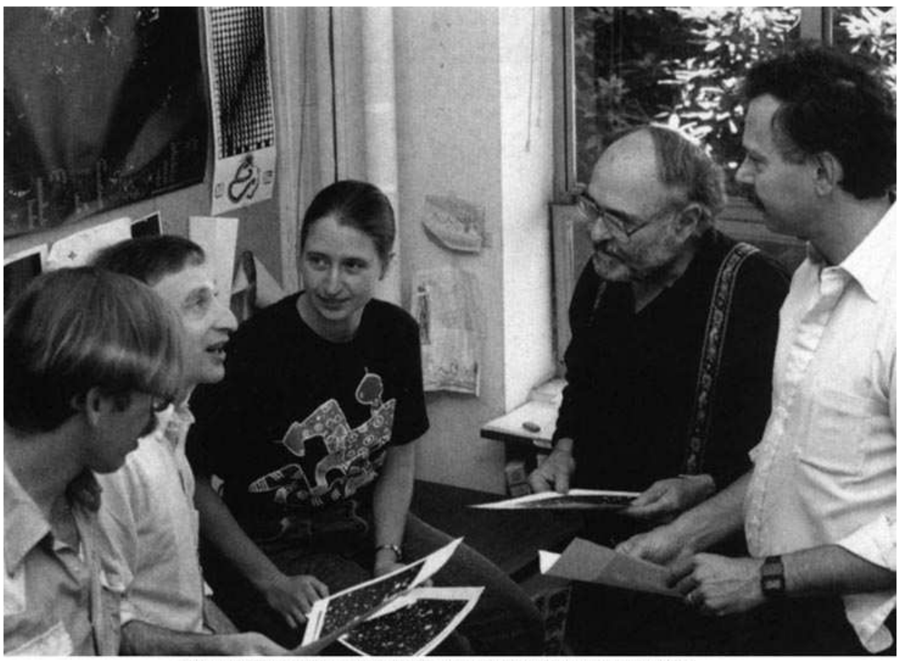
2 Talk presented on Feb. 20, 2008 at Dark Matter 2008 (DM08) Conference Marina del Rey California

posed an experiment to discover the “Fate of the Universe” through a study of distant Type Ia SNe, claimed to be “standard candles” [2].

THE SCP GROUP AND THE DISCOVERY OF DISTANT SNE

In 1989, as I was thinking about my next experiment,[3] I was invited by Carl Pennypacker, who was then leading the daily efforts of what was then called the "Deep Supernova Search", to join in the search for the discovery of the “Fate of the Universe”. The subject appealed to me, as did the proposed technique, since it involved evaluating images, something I have been doing throughout my career. [4]

In 1990-91 the entire group at Berkeley (now known as the Supernova Cosmology Project (SCP)), consisted of Carl Pennypacker, Saul Perlmutter, Heidi Marvin, myself, and Rich Muller (shown in Fig. 1, l. to r.) .



1991. Early days of the Supernova Search project, later to become the SCP.
L. to r., Carl Pennypacker, Saul Perlmutter, Heidi Marvin, Gerson, Rich Muller, at LBL.

FIGURE 1. The SCP group at Berkeley in 1990-91. Carl Pennypacker, Saul Perlmutter, Heidi Marvin, Gerson Goldhaber, and Rich Muller l. to r.

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[3] In 1989 my co-group leader George Trilling and I had come to an end of a nearly twenty-year collaboration with Burton Richter and Martin Perl and coworkers of SLAC and LBL where we had discovered the psion family, charmed mesons, and the tau lepton among many others.

[4] Evaluating images is something I have been doing throughout my physics career, beginning with photographic emulsions in the 1950s, to bubble chambers in the 1960s, to computer-reconstructed particle events in the 1970s, and 1980s. Thus, the supernova experiment with it’s computer-reconstructed optical images, seemed to be a nice fit with my experience and inclinations.

Soon after my joining the group, there were major changes in its makeup. In 1991 Rich Muller decided to spend his efforts in research on the ice ages and global weather patterns, and Carl Pennypacker founded the "Hands on Universe" Program for high school students and began to devote most of his time to educational activities. This left Saul and me to carry on with graduate student Heidi Marvin Newberg and later Alex Kim. Shortly thereafter, Bob Cahn, at the time the physics division director at LBNL, discussed with me the question of a group leader. With my strong support, he decided to appoint Saul to that position.

Perhaps because Rich, Saul, Carl, and I were not established as astronomers, it was at first difficult for us to get time on the large premier telescopes. Before I joined the group, on Carl's initiative , Carl, Rich and Saul, together with two colleagues in Australia, Brian Boyle and Warrick Couch, did manage to obtain scheduled time on the 3.9m Anglo Australian Telescope and built a focus reducing lens and CCD camera for it. During the three years we observed at this telescope, while the system worked well, there was no identified SN candidate. Unfortunately, many of our scheduled nights were lost due to bad weather. The lens and camera construction and installation and the techniques we developed, as well as an unidentified candidate found later at the 2.5m Isaac Newton Telescope, are discussed in great detail in Heidi Marvin Newberg's thesis [3].

While for the first three years of our efforts we did not find any identified supernovae, [5] this time was not wasted, as it allowed us to develop the techniques which led to the eventual success of the project.

In particular, Saul Perlmutter developed the technique for finding "SNe on demand" or "batch mode". This involved taking a "reference" image just after a new moon, and coming back to take "discovery" images before the next new moon (See Fig. 2.) The data were sent back to Berkeley the same night they were taken at the telescope. On the next morning we ran a program that subtracted the reference image from the discovery image and flagged possible candidates. In a few hours of hand scanning we were able to select the promising SN candidates. Thus as soon as SN candidates were discovered one could send observer(s) to the Keck 10m telescope to measure spectra and, after that, start to take data points for the light curve at ground based telescopes. (See Fig. 2 for list of followup telescopes.)

After we found the first few SNe, Saul was able to convince the various telescope scheduling committees to give us time at the matching epochs to carry out this approach. By 1996-7 we were alloted time at the Hubble Space Telescope, where we measured lightcurve data points for some of the most reliably identified SNe.

To eliminate cosmic rays and hot pixels, we took two images, usually five minutes apart, both for reference images and discovery images. Early in 1990, while scanning for SNe candidates (but not finding any!) I did discover a group of about 20 asteroids. The asteroids are distinguished by the fact that they are seen to move between the two discovery images. However, some of them do not move significantly, and can be confused with SNe. We therefore introduced a change in our procedures, interspersing

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[5] However, our general approach received important validation with the discovery by Norgaard-Nielsen et al. [4] of a single high z supernova (red shift of 0.31) after a two year effort. This SN was however discovered well after maximum light.

Supernova Discovery and Measurement Sequence.

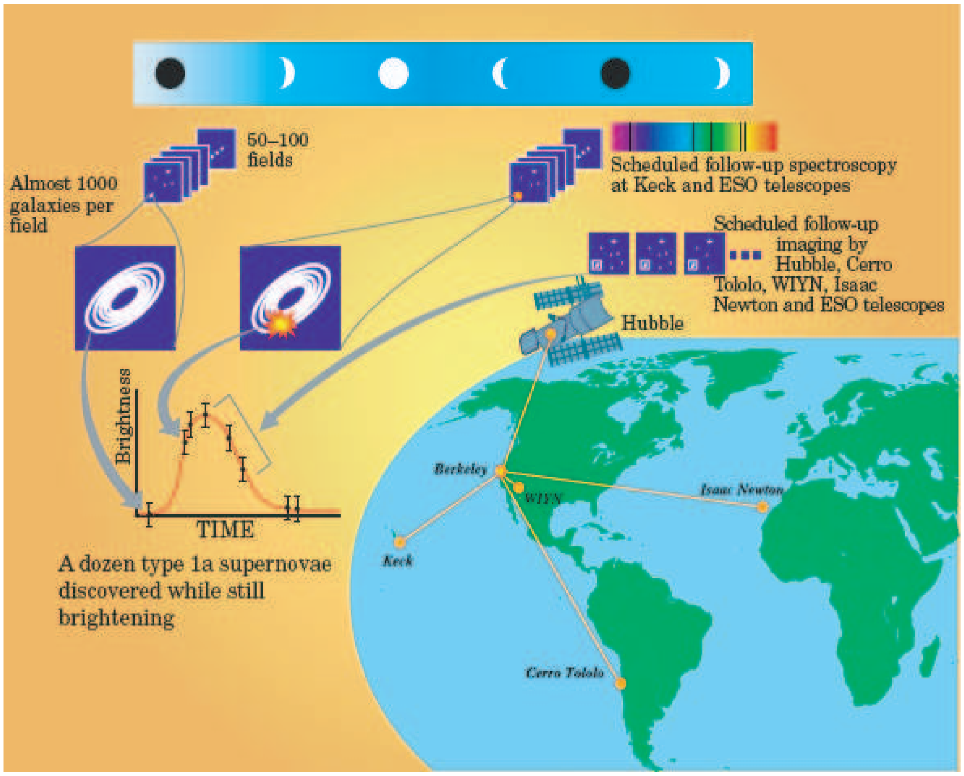

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FIGURE 2. The strategy developed by Saul Perlmutter for finding SNe on demand.

a different field between the two discovery images, so as to allow an additional interval of 5 to 10 minutes between them. This allowed easy identification of the asteroids. Asteroids were later used by Carl Pennypacker in his Hands on Universe program to allow students to discover and measure real astronomical objects.

In 1991 we were joined by visiting scholars Ariel Goobar and Silvia Gabi from Sweden and CERN and later on by Reynald Pain from France and Isobel Hook, an astronomer with expertise in spectroscopy, from England.

In 1993 we decided to collaborate with Alexei Filippenko, of the UC Berkeley Astronomy Department for measurements of spectra at the Keck Telescope in Hawaii.

In 1994 Don Groom, from the Particle Data Group at LBL, joined our group, as well as Susana Deustua. Don Groom adapted the CERN program MINUIT to fit our SNe to the light curve and to determine the stretch parameter.

Graduate students Alex Kim, Mathew Kim and programmer Ivan Small were also essential in this early work.

By 1995, as we became successful in finding distant supernovae, we were able to hire two postdocs, Rob Knop and Peter Nugent, and later a staff member, Greg Aldering. These new people, as well as Susana, all had a background in astronomy.

By 1998 our group had grown to an international collaboration with 32 members[6] that signed the Dark Energy discovery paper [5]. In 2007 Saul and the other 31 were co-recipients of the Gruber prize in cosmology for the discovery of Dark Energy, together with Brian Schmidt and the Hi-Z Team [6].

MILESTONES LEADING TO THE DISCOVERY OF DARK ENERGY

Here is a list of some of the important comments and papers which allowed us to make our discovery.

- Suggestions to use Type Ia SNe as standard candles: From 1930s on Zwicky, Baade, Sandage, Kowal, Tammann etc.
- 1984 Pskovskii [7], 1993 Phillips [8], 1995,1997 Perlmutter et al. [9, 10, 11], 1995,2001 Goldhaber et al. [9, 10, 12] : light curve shape related to brightness and introduction of “stretch".
- 1988 Leibundgut [13]: Type Ia Lightcurve Template.
- 1989 Norgaard-Nielsen et al. [4]: First distant SN, z = 0.31 however discovered well past maximum light (maximum brightness).
- 1992 After three years of searching we observed our first distant SN (z = 0.458) before maximum light [14].
- 1993 Hamuy et al. [15]: Single filter K-corrections. To convert a filter region of the redshifted spectrum to the same filter at zero redshift.
- 1993-6 Hamuy, Phillips, Suntzeff, Maza et al. [16, 17]: CALAN/TOLOLO $z < 0.1$ reference sample of 29 Type Ia SNe. Of these we used 18 they discovered before 10 days past maximum light.
- 1995 Kim, Goobar and Perlmutter [18], 2002 Nugent et al. [19] : Cross filter K-corrections.
- 1995 Goobar and Perlmutter [20]: Measurement of Ω_m and Ω_Λ from a best fit confidence level distribution on the Ω_m, Ω_Λ plane for a variety of z values. This paper also gives the formulae for the Hubble plot calculations.

SEPT. 24, 1997: A PEAK IN THE Ω_m HISTOGRAM

What has become the conventional way to determine Ω_m and Ω_Λ is the Goobar-Perlmutter [20] best fit confidence level distribution on the Ω_m, Ω_Λ plane. This approach,

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[6] Gregory Aldering, Brian Boyle, Patricia Castro, Warrick Couch, Susana Deustua, Richard Ellis, Sebastien Fabbro, Alexei Filippenko, Andrew Fruchter, Gerson Goldhaber, Ariel Goobar, Donald Groom, Isobel Hook, Mike Irwin, Alex Kim, Matthew Kim, Robert Knop, Julia Lee, Chris Lidman, Thomas Matheson, Richard McMahon, Heidi Newberg, Peter Nugent, Nelson Nunes, Reynald Pain, Nino Panagia, Carl Pennypacker, Saul Perlmutter, Robert Quimby, Pilar Ruiz-Lapuente, Brad Schaefer, Nicholas Walton. (Alexei Filippenko moved to the Hi-Z Team when it was formed in 1995.)

favored by astronomers, requires accurate determinations of the errors and correlated errors. When the SNe light curves are first fitted to a template this information is not yet available.

The alternative approach, similar to the technique used to find resonances in particle physics, is to look for peaks in the distributions (on histograms) of the variable being studied, namely mass in particle physics and Ω_m in our case here. In this approach the measurement errors are reflected in the width of the resulting peak.

In September 1997 we had completed a first pass of the light curve data point analysis on 38 SNe, but the detailed error analyses were not yet available. It took several months from the time a SN was discovered until the light curve points could be evaluated. We also took some final reference points a year after discovery. Rob Knop, who was working on this, was able typically to complete one to two SNe per month.

On the basis of these 38 Type Ia SNe we obtained an indication that the universe is accelerating, rather than decelerating as we had originally expected. This was the culmination of nine years of work learning how to find high redshift SNe, how to measure them, how to fit them, how to K-correct them, how to stretch correct them and then finally fit them to a lightcurve template. This was all achieved by a collaborative effort of the entire group. I studied the SNe after the data points on the lightcurve had been measured, fitted them to the lightcurve template which gave us the stretch value, and made a table with some 20 attributes for each SN. The effective B-magnitudes (after K-corrections and stretch corrections) were then displayed on a Hubble plot.

The question was next how to obtain the Ω_m distribution from this plot. What I tried was to plot Hubble curves, for a flat universe, with Ω_m in fine intervals at 0.0, 0.2, 0.4, 0.6, 0.8, 1.0. See Fig. 3. A distribution in Ω_m is then obtained by counting (by hand!) all the SNe that fell into each $\Delta\Omega_m$ interval giving the histogram shown in Fig. 4. A few days later Saul wrote a program, SNLOOK, to have the computer count the number of SNe in each $\Delta\Omega_m$ interval.

Here it should be noted that a flat universe was not completely established at that point in time (1997). Our assumption was based in part on inflation theory [21, 22, 23] and in part on very early rumors from CMB fluctuation data [24]. The detailed measurements of the fluctuations in the CMB, demonstrating a flat universe, came later [25, 26, 27].

In Fig. 4 the peak in $\Omega_m = 0.2$ to 03 for a flat universe indicates that Ω_Λ is 0.8 to 0.7. This gives a deceleration parameter $q_0 = -0.7$ to -0.55. A negative value for q_0 implies acceleration. This result was obtained without corrections for intrinsic color or extinction due to dust in the host galaxy in both the Cerro/Tololo reference sample and the 38 distant SNe. The narrowness of the observed peak demonstrates that this omission was not important for this preliminary result.

Excerpts from the SCP meeting notes, taken by Rob Knop, for our SCP group meetings of Sept, 24 1997 and October, 8 1997 are reproduced in Figs. 11 and 12.

This startling result was naturally treated with some skepticism. This result differed from our first seven SNe [9, 10, 11] which had indicated a high value for Ω_m.[7] These

[7] In retrospect, it is instructive to revisit the question of what happened with those first seven supernovae. As shown shaded in Fig. 4 they are all at high Ω_m values. Two turned out to be outliers with one probably not a Type Ia. The other 5 moved slightly towards lower mass densities with remeasurement, but for the

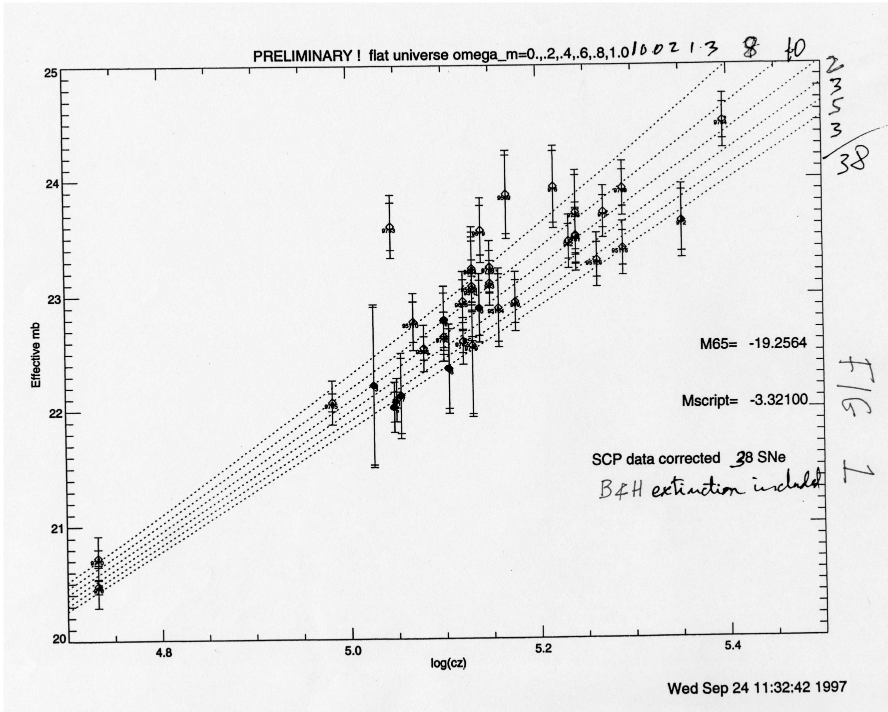

FIGURE 3. Our preliminary data of 38 SNe, as of Sep., 24, 1997. The effective B-magnitude vs. log(cz). Here the effective B-magnitude is the K-corrected and stretch-corrected magnitude and z is the redshift. The curves for a series of Ω_m values, in a flat universe, are shown. The sum of the data points in each $\Delta\Omega_m$ interval, as counted by hand, is also shown at the right hand upper edge of the figure.

seven SNe are shown as cross hatched in Fig. 4. and indeed occur at the upper end of the distribution.

Again the fact that the deceleration coefficient was negative, indicating acceleration, was hard to swallow at first. I had been “bump hunting " for the past 30 years, and found the observed peak completely convincing. I believe that Saul convinced himself after he wrote the program, SNLOOK and by independently studying our data. He later in December presented such a histogram in colloquia giving Ω_m and Ω_Λ. See Fig. 8. Some other colleagues, Rob Knop and Carl Pennypacker, appeared convinced, while Greg Aldering was not fully convinced, he stated however that this histogram “helped to galvanize the effort within our group". Indeed, as the result of a major effort, the SCP group was able to calculate the best fit confidence levels in time for the Jan. 8, 1998 AAS meeting.

For confirmation, I asked my colleagues to check these results, in case there could have been a mistake. However, all the 20 entries in the so called “Gerson-table" for each of the 38 SNe were confirmed as correct. Later Greg Aldering added more columns to this table, giving the correlated errors, and Richard Ellis added a column with the best

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most part they simply happened to lie on the tail of the distribution. The lesson is: beware of statistics of small numbers!

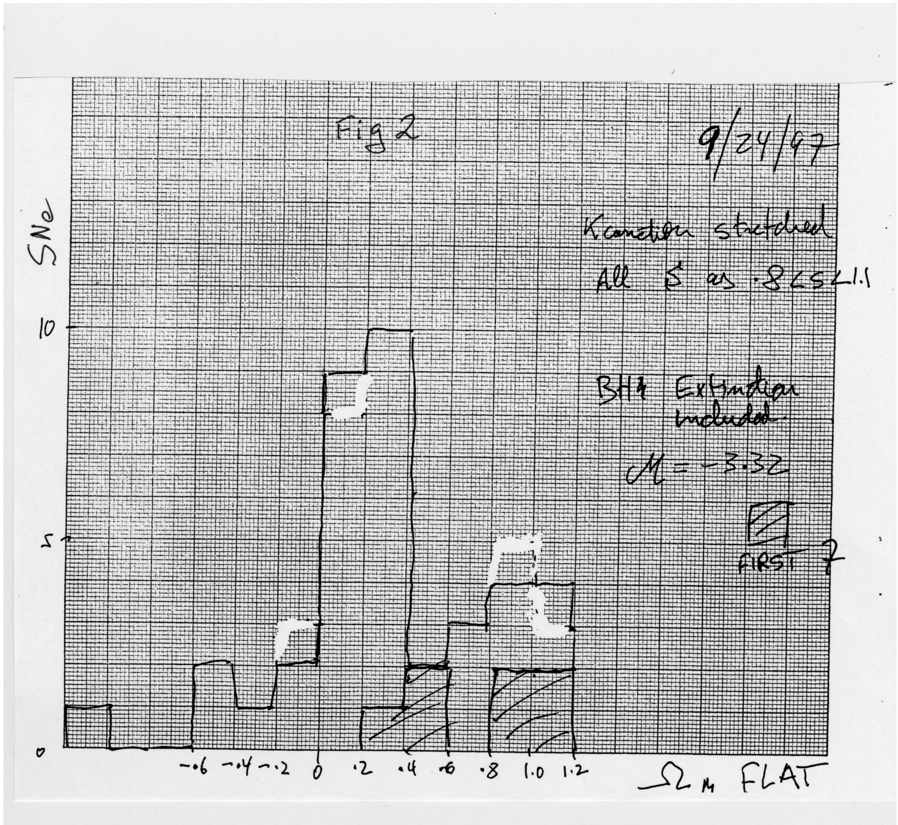

FIGURE 4. The Ω_m distribution for the data points in Fig. 3, as presented at our SCP group meeting on Sep. 24, 1997 , is shown. The values for the first 7 SNe, which gave a considerably larger value for Ω_m, are shown cross-hatched. Here Ω_Λ is given by $1-\Omega_m$.

estimate of the nature of each host galaxy.

We also obtained strong corroborating evidence that we needed a non-zero Ω_Λ value. In Fig. 5. the Hubble curves for both a flat universe and an $\Omega_\Lambda = 0$ universe are shown superimposed. For an $\Omega_\Lambda = 0$ universe we obtain a corresponding peak on the Ω_m histogram. However now it occurs for negative Ω_m values. In Fig. 6. is shown the Ω_m histogram, this time calculated with Saul's SNLOOK program, for this case. As can be noted, 25 out of the 38 SNe give a negative and hence un-physical value for Ω_m. This clearly demonstrates, independently of the flat universe condition, that Ω_Λ cannot be zero but must be greater than zero.

One can turn this argument around and calculate the location of the peak in an Ω_m histogram for a series of different Ω_Λ values and find for which Ω_Λ value the peak begins to lie at positive (hence physical) values. This approaches, and goes beyond, Ω_m, Ω_Λ values consistent with the above values for a flat universe. This method is equivalent to traveling along the central line for the confidence level "ellipses", starting at negative Ω_m values, shown in Fig. 9.

In Table 1 is shown the SN discoveries over the years 1989 to 1997. Saul's SNe on demand method really came into its own when we obtained time on the Cerro/Tololo

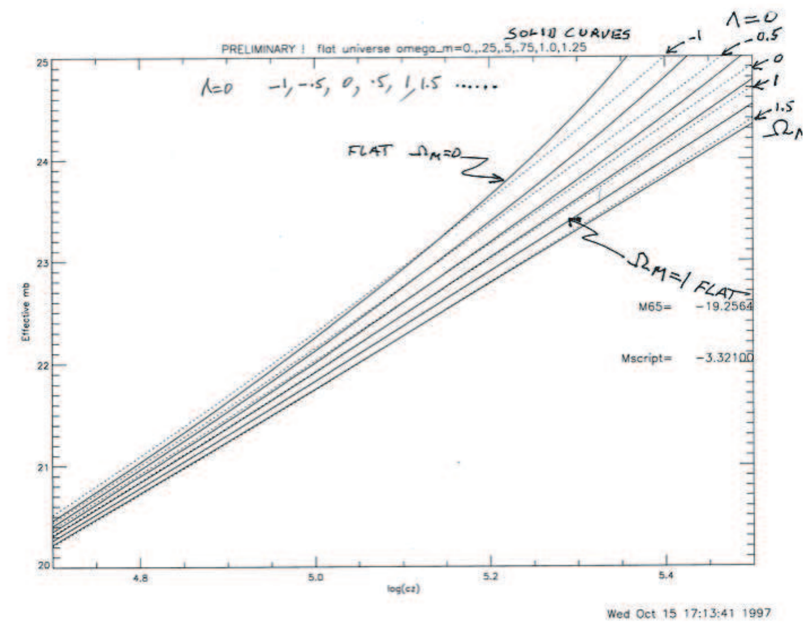

FIGURE 5. The Hubble curves for both a flat universe (solid curves) and an $\Omega_\Lambda = 0$ universe (dotted).

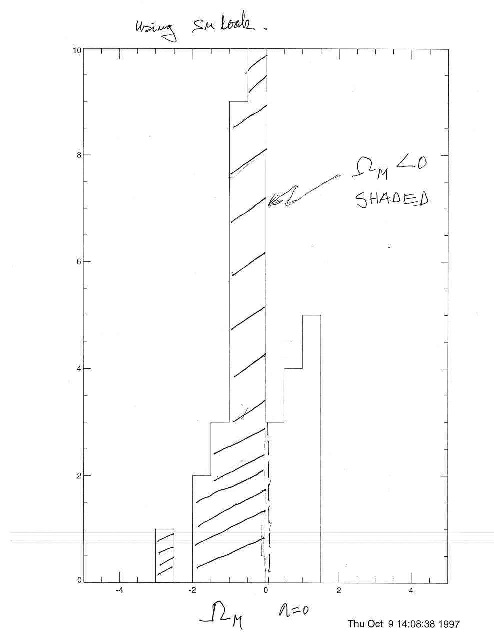

FIGURE 6. The Ω_m distribution for a $\Omega_\Lambda = 0$ universe. Note that 25 of the SNe have a negative Ω_m and hence an un-physical value. This shows clearly and independently of the flat universe condition that Ω_Λ must be greater than zero.

TABLE 1. SCP SNe Ia Discoveries

Epoch	Number	Total	Telescope
1989-91	0	0	Anglo Australian 3.9m
1992	1	1	La Palma 2.5m
1993	6	7	Kit Peak 4m
1995	9	16	Cerro Tololo 4m
1996	7	23	Cerro Tololo 4m
1997	19	42	Cerro Tololo 4m

4m telescope combined with the "large thruput" CTIO camera of Bernstein and Tyson. Table 1 shows that over a nine-year period we discovered 42 SNe.

Oct. 1997. Two papers by the SCP and Hi-Z Team as well as a joint paper submitted with hints, from very small samples of SNe, for a non-zero Ω_Λ

While our first 7 SNe gave a high Ω_m value [9, 10, 11], $\Omega_m = 0.94^{+0.34}_{-0.28}$ for a flat universe, we later obtained some hints of lower Ω_m values: One of the type Ia supernovae that we found, SN 1997ap, was at that time again the most distant that had ever been observed, $z = 0.83$. We were also able to obtain Hubble Space Telescope (HST) images for this supernova. The addition of this single SN allowed us to recalculate Ω_m for 5+1 supernovae, giving $\Omega_m = 0.6 \pm 0.2$ for a flat universe . See Fig. 7. Here two outliers were eliminated. We submitted this paper to *Nature* on Oct. 6, 1997 [28].

Garnavich et al. [29] submitted a paper by the Hi-Z Team on Oct. 13, 1997, based on three confirmed high red shift SNe measured with the HST, and one measured from the ground. They concluded that, for a flat universe, Ω_m was less than 1 with $> 95\%$ confidence and that an estimate for Ω_m is -0.1 ± 0.5 for an $\Omega_\Lambda = 0$ universe.

A joint paper by some members of the two groups Riess et al. [30] submitted Nov. 21, 1997 and accepted Apr. 17, 1998, showed that the "snapshot" method works. That involves taking a single photometry point and a single spectrum on the same night and deducing the magnitude at maximum light from this limited information. On the basis of four SNe handled in this fashion, as well as three SNe from the above two papers, they deduced that for a flat universe $\Omega_m = 0.19^{+0.32}_{-0.19}$ and $\Omega_m = -0.31^{+0.62}_{-0.36}$ for an $\Omega_\Lambda = 0$ universe.

While these SCP and Hi-Z papers, published in 1998, gave hints of a non-zero Ω_Λ they relied on a very small number of SNe, namely 1 and 4 respectively. The hints from the snapshot paper relied on four SNe using this less precise method.

All this work was going on more or less contemporaneously with my study of the 38 SNe. My colleague Peter Nugent, who did some of the fits of these confidence level distributions, felt that these 3 "hints" were a more convincing and possibly earlier evidence for a non-zero Ω_Λ than the peak in the Ω_m histogram. My feeling is that we needed the larger statistics since we had amply demonstrated that with a very small number of SNe (7 SNe) one can be way off!

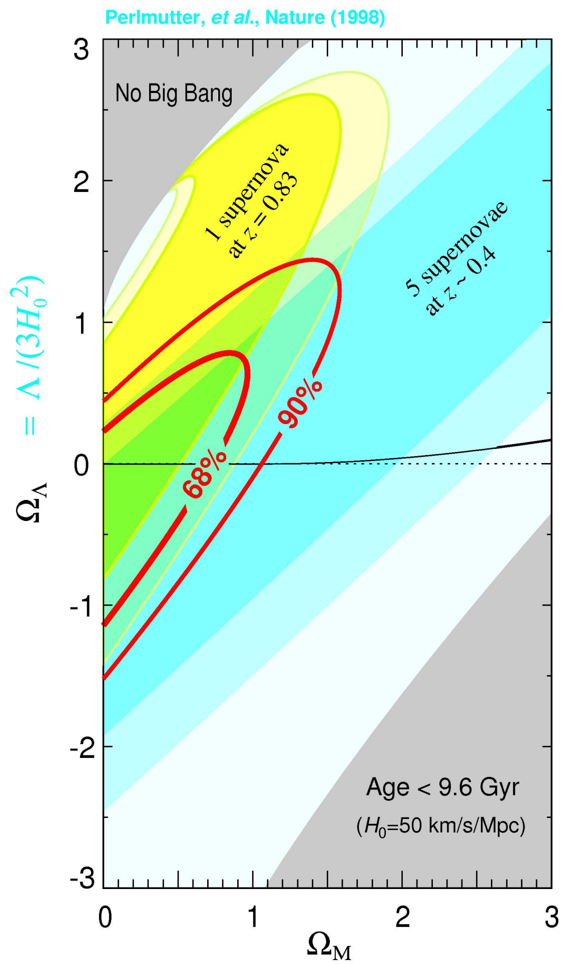

FIGURE 7. The Ω_Λ vs Ω_m best fit confidence level distribution for 5 of the 7 SNe as well as for the 5+1 SNe. The addition of the one SN 1997ap gives a non-zero value for Ω_Λ for a flat universe.

DEC 1 TO 14, 1997: TWO COLLOQUIA AND A SEMINAR

The first three public presentations of the SCP evidence for $\Omega_\Lambda > 0$ and acceleration, based on the peak in the Ω_m histogram for 40 SNe.

From October to November, we re-measured and re-fitted all of the 38 SNe and added two more, giving 40 (while three were identified as outliers). We also changed from the Burstein and Hiles [31] version of dust extinction in our galaxy to the more recent Schlegel, Finkbeiner and Davis [32] version. I then revised the tables to reflect all these changes. Both Saul and I plotted the Hubble plots, based on the revised tables, and used SNLOOK to obtain the latest version of the histogram.

The first public presentation of our results was a colloquium by Saul on Dec. 1, 1997 at the Physics Department UC Berkeley (See Fig. 8.) This was followed by Saul's colloquium at the Physics Department UC Santa Cruz on Dec. 11, 1997.

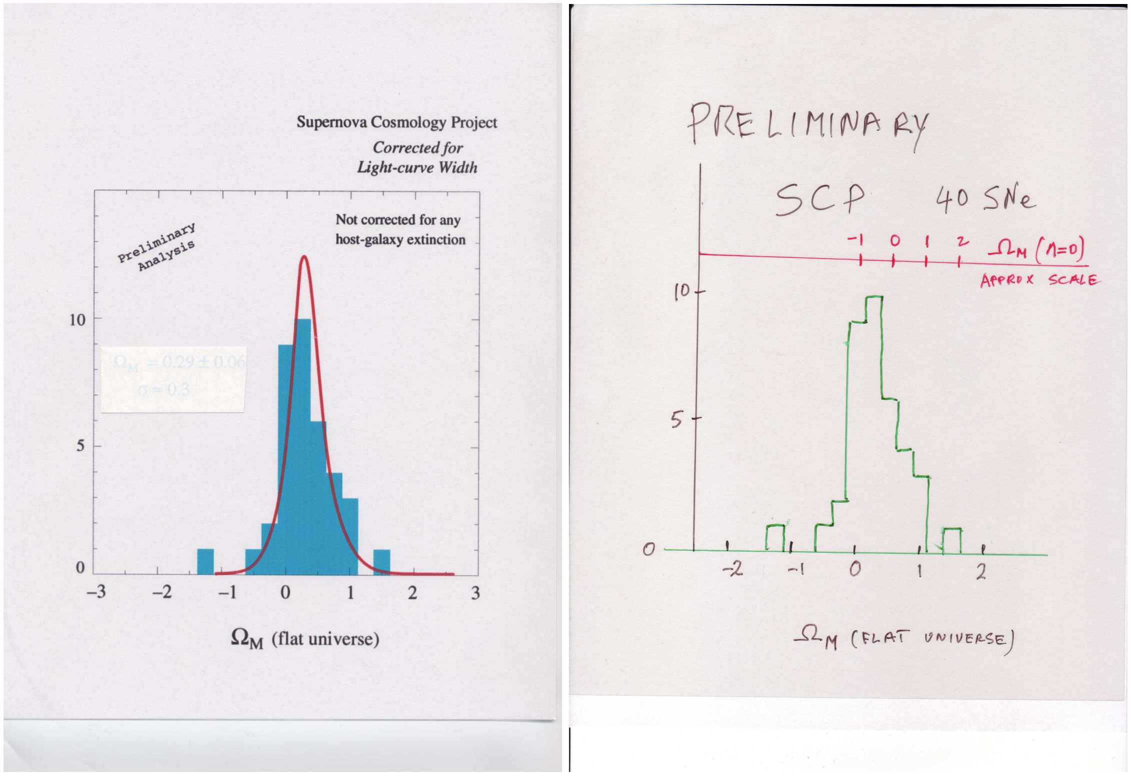

FIGURE 8. (*left*) The figure of the Ω_m distribution shown at Colloquia at UC Berkeley and Santa Cruz in early December 1997 by Saul Perlmutter. The x-axis gives Ω_m for a flat universe. All the SNe given in Fig. 4. have been re-fitted. The Gaussian fit to this preliminary data gave $\Omega_m = 0.29 \pm 0.06$ with a $\sigma = 0.3$ (*right*) A reproduction of the actual figure of the Ω_m distribution shown at the ITP Santa Barbara on Dec. 14, 1997 by Gerson Goldhaber. The lower scale gives Ω_m for a flat universe. The upper scale gives Ω_m for an $\Omega_\Lambda = 0$ universe. Note that this assumption gives negative (and thus unphysical) values for Ω_m. This demonstrates that Ω_Λ must be greater than zero.

Next, I gave a seminar at the Institute for Theoretical Physics (ITP) at UC Santa Barbara on Dec. 14, 1997 (See Fig. 8.) In all three of these talks, as stated above, the conventional description of the confidence level distribution on the Ω_m , Ω_Λ plane was not yet available for the 40 SNe. So in all three talks the Ω_m histogram, re-evaluated with more careful re-measurements, was shown. We considered our result as preliminary as we had not yet completely explored all the effects of systematic errors.

It was not easy to convince the astrophysics community of this result, as it was contrary to all ingrained beliefs.[8] Acceleration rather then deceleration as expected!

The question has been posed: who remembers the details of these talks? I know that Joel Primack and Michael Riordan remember Saul's talk at Santa Cruz. As former and

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[8] Examples of exceptions to the $\Omega_\Lambda = 0$ assumption are: Steve Weinberg [33] made an argument, on the basis of the anthropic principle, that Ω_Λ could be comperable to the currently observed value. Krauss and Turner [34] argued primarily on the basis of the age of the universe and other then available cosmological measurements that Ω_Λ should lie between 0.6 and 0.7. Ostriker and Steinhardt [35] derived a concordance model based on all the then available cosmological data and concluded $\Omega_\Lambda = 0.65 \pm 0.1$.

current particle physicists they understood the significance of a peak on a histogram. Joel Primack was particularly enthusiastic and stressed the importance of this discovery after Saul's colloquium. Dave Branch remembers my talk and subsequent discussions and understood its significance. David Gross asked me after my talk how I could come to such a momentous conclusion on the basis of just 40 SNe.

As is usual, Saul's Colloquium at UC Berkeley was video taped (DVD available). Saul first talked about the “hint" from our 5+1 SNe fit I mentioned above. Then based on a gaussian fit to the observed peak on the histogram, Saul quoted $\Omega_m = 0.29 \pm 0.06$ for a flat universe and thus $\Omega_\Lambda = 0.71$. In my presentation at the ITP I did not try for an accurate value of Ω_m, but rather showed Fig. 8. and indicated that $\Omega_m = 0.3$ agrees with our data. In addition I demonstrated what happens when we assume $\Omega_\Lambda = 0$. As seen from the upper scale in Fig. 8. this assumption gives negative and hence unphysical values for Ω_m. As stated earlier this demonstrates that Ω_Λ must be greater then zero.

In his talk Saul went on to point out that while on the one hand 0.7 for Ω_Λ corresponded to a large fraction of the universe but on the other hand it was a very small value, by a factor 10^{122}, compared to the value expected from virtual particle vacuum fluctuations.

It is remakable that in Saul's talk on Dec. 1, 1997 we had already presented, in public, evidence for the whole story of what was later called Dark Energy by Michael Turner. At DM08 I presented a four-minute video excerpt of Saul's talk, showing him making these points based on the histogram. (This video is given in the conference proceedings [36].)

Not much has changed qualitatively in the 10 years since then. With many more SNe studies [37] as well as concordance with CMB and evidence from cluster studies [38] and later Baryon Acoustic Oscillation (BAO) [39] studies, we now know Ω_m to more significant figures, but qualitatively there is no change from the value we quoted in 1997. We have learned that the equation of state w is very close to -1 and have some limits on the variation of w with z. But after all that, just as 10 years ago, we still do not understand the nature of Dark Energy [40].

JAN. 8, 1998: FIRST PUBLIC PRESENTATION OF THE SCP RESULTS AT AN AMERICAN ASTRONOMICAL SOCIETY MEETING

The fourth public presentations of the SCP evidence for $\Omega_\Lambda > 0$ *and acceleration, based on the fit to the confidence level distribution on the* Ω_m *,* Ω_Λ *plane for 40 SNe.*

From October to late in December 1997, the SCP group at Berkeley re-measured and re-checked and completed all error and correlated error calculations on what had by then become 40 SNe. This effort was primarily due to Saul, Greg Aldering and Peter Nugent. Each group member as well as the group members in Baltimore, Stockholm, Paris, England, Australia and Chile convinced himself/herself by direct study of the data that indeed $\Omega_\Lambda > 0$ and that contrary to all preconceived notions we were dealing with acceleration of the universe, namely a negative deceleration coefficient.

The following month, on Jan. 8, 1998 [41, 42], Saul Perlmutter presented our data at the AAS meeting in Washington DC. By this time we had the much more elaborate analysis, based on detailed error calculations, by the entire SCP group. We had 40 fully analyzed SNe and the confidence level calculation was already available on the Ω_m , Ω_Λ plane (Fig. 9). Here it should be noted that the confidence level distribution does

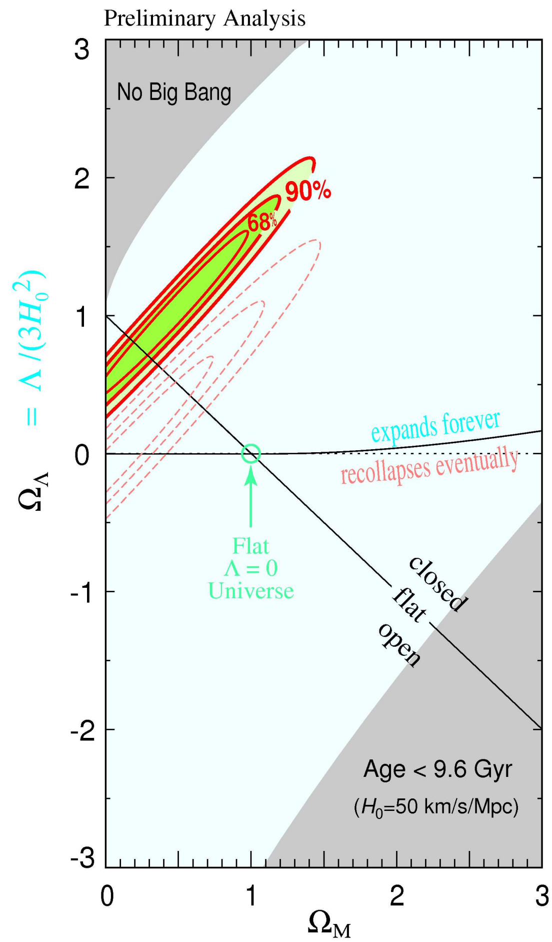

FIGURE 9. The Ω_Λ vs Ω_m best fit confidence level distribution shown at the Washington meeting of the AAS on Jan, 8 1998 by Saul Perlmutter. The dashed curves represent a very generous estimate of what possible systematic errors could do.

not require the flat universe condition to give Ω_Λ greater than zero. This was the first presentation at an official conference of any evidence for $\Omega_\Lambda > 0$, and hence acceleration of the expansion of the universe. To take possible systematic uncertainties into account, we allowed for a very generous systematic error. This is shown by the dotted confidence level curves in Fig. 9. This figure was reproduced by James Glanz in his report on our presentation in Science [43]. Furthermore, using the same Ω_m histogram for a flat universe as in Fig. 8. Saul also showed that we had already started to study the effects of systematics: Malmquist bias, stretch dependence and color dependence.

FEB. 18, 1998: PUBLIC PRESENTATIONS AT THE DARK MATTER 1998 (DM98) CONFERENCE.

The fifth and sixth public presentations of the SCP evidence for $\Omega_\Lambda > 0$ and acceleration based on 42 SNe was presented. The first public presentation by the Hi-Z Team of evidence for $\Omega_\Lambda > 0$ and acceleration based on 16 SNe was also presented. Both teams quoted results based on fits to the confidence level distribution on the Ω_m , Ω_Λ plane.

The following month, on Feb. 18, 1998, both I and Saul Perlmutter gave talks, in that order [44], showing our results at the meeting organized by Dave Cline just 10 years ago (Dark Matter 1998) at Marina del Rey. By this time our number of fully analyzed SNe had grown to 42. (See Table 1.)

I spent part of my talk on some work I had done on time dilation in SNe explosions, proving that the redshift is due to the expansion of the universe, rather then to the "tired light" hypothesis [9, 10, 12]. I then showed the best fit confidence level distribution on the Ω_m, Ω_Λ plane, which for a flat universe implied $\Omega_m = 0.28^{+0.09}_{-0.08}$ (statistical) $^{+0.05}_{-0.04}$ (systematic) and hence acceleration of the universe at the present epoch.

In his talk Saul Perlmutter gave more details on our results and on the error calculations, and stressed that we were still investigating how systematic errors might affect these results.

Following our talks, Alexei Filippenko presented the results [45] of the Hi-Z Team, who claimed they had established the acceleration of the universe on the basis of a confidence level analysis of 16 SNe. These consisted of 10 well measured SNe, plus 4 from the "snapshot" method [30] plus 2 which came from our set of 42 [5].

Later the refereed publications of the two groups capped these momentous results. The Hi-Z Team paper was submitted on Mar. 13, 1998 [6] and the SCP paper was submitted on Sept. 8, 1998 [5].

HOW DOES AN Ω_m HISTOGRAM LOOK TODAY?

To see how the method, patterned on particle physics and used to indicate acceleration on Sept. 24, 1997, works with larger statistics I have analyzed (this time with a computer program) a sample of 257 SNe with $z > 0.2$ [28] in the same fashion as in Figs. 3 and 4. Fig. 10 shows the resulting distribution in Ω_m. The enormous peak is clearly observed, which completely confirms the validity of the peak for the 38 SNe in Fig. 4.

FEB. 20, 2008: SO WHAT IS THE "FATE OF THE UNIVERSE" ?

By now, 10 years later, there are many experiments which have confirmed Dark Energy. We can however still ask: what is the "Fate of the Universe" ?

The question is now in the form: is Ω_Λ constant or does it vary with z? Or alternatively: is $w = -1$, namely are we dealing with Einstein's cosmological constant ? Or can one measure deviations from -1 where w is the equation of state?

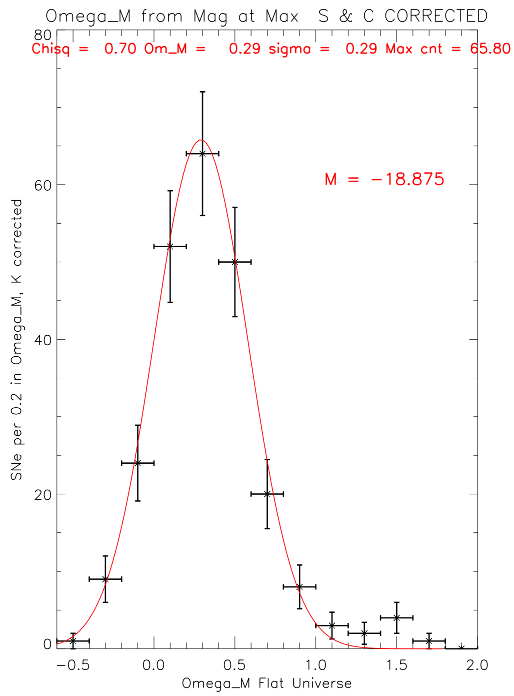

FIGURE 10. The Ω_m distribution for a sample of 257 SNe with $z > 0.2$ out of a total of 307 which were collected and re-analyzed by Marek Kowalski, David Rubin et al. [29] in connection with a current (2008) paper giving a Union of all published SNe. The SN magnitudes at maximum light were K-corrected as well as stretch and color corrected. Here as above Ω_Λ is given by $1 - \Omega_m$.

We hope the Joint Dark Energy Mission (JDEM) - possibly SNAP - will answer this question before the next decade is up at DM2018.

SUMMARY OF THE STEPS IN THE SCP DISCOVERY OF EVIDENCE FOR DARK ENERGY

- 1988 proposal to NSF center at UCB for “Fate of Universe" study.
- 1992 discovery of SN1992bi, z = 0.486.
- 1995 first 7 SNe yielded large Ω_m value.
- Sept. 24, 1997 Ω_m = 0.2 to 0.3 for flat universe from peak in histogram, SCP group meeting based on 38 SNe.
- Oct. 1997 hints for non zero Ω_Λ from SCP and Hi-Z Team.
- Dec. 1 to 14, 1997 public talks by Saul Perlmutter and Gerson Goldhaber showing evidence that for a flat Universe Ω_m = 0.3 and hence Ω_Λ = 0.7 based on the peak in the Ω_m histogram, Figs. 8, and by than on 40 SNe.
- Jan. 8, 1998 SCP presentation by Saul Perlmutter at the AAS meeting in Washington DC showing the Ω_m , Ω_Λ plane with best fit confidence level distributions yielding flat universe values of $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

- Feb. 18, 1998 Both groups talk at Marina del Rey DM98. Gerson and Saul show evidence for a non-zero Ω_Λ and acceleration based on 42 SNe. Followed by Filippenko who showed evidence for a non-zero Ω_Λ and acceleration based on 10 + 4 + 2 SNe for the Hi-Z Team.

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SCP Meeting Notes, 1997 September 24

Preliminary Omega from 38 SNe

Gerson has a value of Omega for 38 SNe. He went through the Hamuy, and did the fits allowing the K correction to stretch. He got constants for color corrected and not color corrected (by which he means correcting for the extinction in the host galaxy; B&H was already included, and will henceforth be ignored). He says that the difference is small, of about a tenth of a magnitude.

⋮

Gerson goes to our data and looks at 38 SCP SNe, throwing out some really bad ones (in terms of really poor measurements). (Perhaps others should be argued to be thrown out.) If s<0.8 or s>1.4, he limited the stretch to those extreme values. This is the first time that B&H extinction is included. He has a hubble diagram, and made a histogram of Omega_M in the flat universe. It comes out peaking somewhere near 0.2, with more or less symmetric tails on either side (so much for the host eextinction tail). (Well, OK, the shoulder to the higher values of Omega_M is bigger than the other one.) (None of this is host extinction corrected.) All 7 of our first 7 SNe have Omega_M values greater than the peak.

Saul thinks that we are probably more affected by extinction; the assertion is that we have more dynamic range, and that the nearby guys are more affected by Malmquist than we are, meaning we are probably sampling a greater range of extinction.

Re: the first 7 being higher, Saul denys that Malmquist bias of the first seven could explain this, since the efficiency curves were investigated, and that we were well away from the edge and not suffereing from Malmquist bias.

Our recent SNe: we can make cuts for their redshift for how close they are to the limit. (I.e. at a given magintude SN, cut out those SN whose redshifts would put them towards low efficiency.) (This requires thought.) Malmquist bias is a potential explanation for the higher shoulder towards higher Omega_M.

In any event, there seems to be a real peak at Omega_M=0.2 for the flat universe.

Peter says that there seems to be a correlation between extinction and stretch, i.e. wider SNe tend to higher extinction. Rob says he thinks this means that the color-stretch relationship could be misunderstood. Greg points out that this could be Malmquist bias, because you'd preferentially find the wider (brighter) extinction ones. This could affect things if the nearby SNe are more effected by extinction than ours.

Peter argues that the only fair way to do it is to somehow correct for extinction independently for both sets. For instance, you could just do cuts on both; only keep the SNe which have colors close to the Branch normal set, with B-V=0.0+-0.2. (The actual distribution has far more on the red side than the blue side, probably because of extinction.) Peter says that $20 says you get rid of 3+-1 of the ones in the high shoulder and 2+-1 of those in the low shoulder. Gerson says that he will attempt this.

OK, we're puzzled again. Why is Gerson's distribution so different from the same distribution we did earlier? (Basically, it seems that Saul and Gerson produce a different histogram.) We hemed and hawed, and didn't really decide much. We still need to worry some more.

Gerson says he will keep working on this. He would also like somebody else to check it.

I've been known to make mistakes.

-G. Goldhaber

FIGURE 11. Excerpts from the minutes by Rob Knop of the SCP group meeting on Sep. 24, 1997.

SCP Meeting Notes, 1997 October 08

Gerson's Preliminary Omega

Gerson has been running SNe events through the fitting program, and has been busy plotting them. He starts by showing what Saul presented in a meeting earlier. Gerson doesn't agree with what Saul has now that we have more data. He plots a histogram of Omega_M in the flat universe for all SNe. Before, he showed us the plot with a peak at Omega of 0.3 or so, and with all of the old SNe to one side of that peak.

Based on the idea that the amount of light underneath the SNe may be correlated with how much extinction there could be, Gerson made a cut on SNe which have at least a 100% increase over the light that was under the SN before. (How well this is defined is a good question, since in the lightcurve software every image subtracts a different amount of host galaxy based on the relative seeing of data image and reference image.)

Gerson also tried using the Finkbeiner extinction (in the galaxy) rather than the B&H extinction. He did it to both Hamuy and our data. For the Hamuy data, it changed script-M by about 0.1 (the Finkbiner value is higher). The distribution is more or less the same... in other words, changing to Finkbiner extinction doesn't do anything since it changes both our calibration and our data. He is testing several other things which aren't quite ready, so he won't go into it.

Gerson also ran a Chisqr distribution in Omega for each of the SNe. (This should give you an idea of the uncertainty.) (Well, not really a chisqr, but something like a normalized uncertainty... Don suggests calling it Chisqr - Chisqr_min.) Gerson then showed us the sum of all those... which probably really is a Chisqr, which is a kind of a fit (weighted average?) to Omega_M in the flat universe. Result: Omega_M=0.41+-0.25, with no cuts, no host reddening correction, but with stretch correction. For stretches less than 0.8 or greater than 1.1, Gerson arbitrarily assigned stretch to the limit. Out of 38 SNe, he did this to 7 SNe. The asserion is that this didn't change the answer much.

Perhaps the most disturbing thing is that the first 7 were consistent within themselves, but the next 31 SNe give what seems to be a consistent answer that is lower.

There is some discussion of trying to figure out if our SNe and the Hamuy data have the same absolute magnitude distribution as our SNe. THere are issues of measuring absolute magnitudes and cosmology... but it would be interesting to see if there are non Gaussian tails (particularly on the "correct" side) in the distribution of Hamuy absolute magnitudes after stretch correction.

Reddening correction is also a problem; when Gerson tries to apply it based on our colors, the scatter goes way up. It could be just bad color measurements, which we probably have. However, I anyway have worries about how well we really know SNe colors, and the colors of stretches and such.

FIGURE 12. Excerpts from the minutes by Rob Knop of the SCP group meeting on Oct. 8, 1997.

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