Supernovae, Dark Energy, and the Accelerating Universe

Saul Perlmutter

*Supernova Cosmology Project*
Lawrence Berkeley National Laboratory
Center for Particle Astrophysics, U.C. Berkeley

*at LBNL:*

Gerson Goldhaber  Peter Nugent  Paris VI & VII:  Reynald Pain
Greg Aldering  Rob Knop  Sebastien Fabbro
Don Groom  Susana Deustua
Carl Pennypacker  Alex Kim
Brenda Frye  Alex Conley

*CalTech:*
Richard Ellis

*ESO:*
Chris Lidman

*Fermilab:*
Heidi Newberg

*Yale:*
Brad Schaefer

+ others

*Cambridge:*
Richard McMahon
Mike Irwin

*ROE:*
Isobel Hook

*ING:*
Nic Walton
Pilar Ruiz-LaPuente

*STScI*
Andrew Fruchter

*UCB:*
Alex Filippenko

http://supernova.lbl.gov
High-Z Supernova Search Team

Brian Schmidt
(MSSSO)

Adam Riess, Alex Filippenko
(UCB)

Nick Suntzeff, Mark Phillips,
Bob Schommer, Alejandro Clocchiatti
(CTIO)

Bob Kirshner, Peter Garnavich,
Pete Challis, Saurabh Jha
(CfA)

Craig Hogan, Chris Stubbs
David Reiss, Al Dierks
(UW)

Bruno Leibundgut, Jason Spyromilio (ESO)

Chris Smith
(UM)

John Tonry
(UH)

Ron Gilliland
(STScI)
A decade leading to an accelerating universe:

1988
1989 We knew or thought we knew…
1990
1991
1992 What we didn't know…
1993
1994
1995
1996 What we found…
1997
1998
1999
2000 Now what we don't know is…
2001 But we know how to find out…
We knew or thought we knew:
The universe is decelerating
Standard candles could measure deceleration
Supernovae could in principle be standard candles at great distances;
With HST, supernovae could be studied
at cosmologically relevant distances — if we knew where to look.

What we didn't know:
The mass density of the universe
  = how much is the universe decelerating
The current rate of expansion: the age of universe.

What we found

Now what we don't know is

But we know how to find out
FAINTER (Farther) (Further back in time)

At a given time...

- Less redshift = Slower expansion in past = Expansion is accelerating = Less mass
- More redshift = Faster expansion in past = Expansion is slowing = More mass

MORE REDSHIFT
(More total expansion of universe since light left the Standard Candle)
Supernova Light Curves

Composite light curve for 15 Type Ia SNe
We knew or thought we knew...

What we didn’t know:

about supernovae studies
that SNe could be found systematically
at cosmologically relevant distances \((z > 0.3)\)
that SNe could be identified spectroscopically at \(z > 0.3\)
that SNe K-corrections could be handled at \(z > 0.3\)
that extinction could be handled at \(z > 0.3\)
that SNe could be calibrated (accounts for progenitor variation)

What we found...

Now what we don’t know is...

But we know how to find out...
Search Strategy

RESULT: ~12 SNe Ia Discovered Before Maximum, at New Moon => Follow-up
Supernova 1998ba
Supernova Cosmology Project

(as seen from Hubble Space Telescope)

3 Weeks Before

(as seen from telescopes on Earth)

Supernova Discovery

Difference
SUPERNOVAE

The Supernova Cosmology Project [S. Perlmutter, S. Deustua, G. Goldhaber, D. Groom, I. Hook, A. Kim, M. Kim, J. Lee, J. Melbourne, C. Pennypacker, and I. Small, Lawrence Berkeley Lab. and the Center for Particle Astrophysics; A. Goobar, Univ. of Stockholm; R. Pain, CNRS, Paris; R. Ellis and R. McMahon, Inst. of Astronomy, Cambridge; and B. Boyle, P. BunctClark, D. Carter, and M. Irwin, Royal Greenwich Obs.; with A. V. Filippenko and A. Barth (Univ. of California, Berkeley) at the Keck telescope; W. Couch (Univ. of N.S.W.) and M. Dopita and J. Mould (Mt. Stromlo and Siding Spring Obs.) at the Siding Spring 2.3-m telescope; H. Newberg (Fermi National Accelerator Lab.) and D. York (Univ. of Chicago) at the ARC telescope] report eleven supernovae found with the Cerro Tololo (CTIO) 4-m telescope in their 1995 High Redshift Supernova Search:

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<td>Nov. 19</td>
<td>0 29 04.26</td>
<td>+ 7 51 20.0</td>
<td>22.4</td>
<td>0&quot;.6 W, 1&quot;.4 S</td>
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<td>1 04 50.94</td>
<td>+ 4 33 53.0</td>
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<td>Oct. 29</td>
<td>1 18 32.60</td>
<td>+ 7 54 03.5</td>
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<td>1&quot;.4 E, 3&quot;.3 N</td>
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<td>2 01 36.75</td>
<td>+ 3 38 55.2</td>
<td>20.1</td>
<td>0&quot;.2 W, 0&quot;.0 N</td>
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<tr>
<td>1995aw</td>
<td>Nov. 19</td>
<td>2 24 55.54</td>
<td>+ 0 53 07.5</td>
<td>22.5</td>
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<tr>
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<td>+ 0 48 44.2</td>
<td>22.6</td>
<td>0&quot;.3 W, 0&quot;.2 S</td>
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<td>Nov. 20</td>
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<td>+ 0 21 19.4</td>
<td>22.7</td>
<td>0&quot;.9 W, 1&quot;.4 S</td>
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<td>1995az</td>
<td>Nov. 20</td>
<td>4 40 33.59</td>
<td>- 5 30 03.6</td>
<td>24.0</td>
<td>1&quot;.6 W, 1&quot;.7 N</td>
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<tr>
<td>1995ba</td>
<td>Nov. 20</td>
<td>8 19 06.46</td>
<td>+ 7 43 21.2</td>
<td>22.6</td>
<td>0&quot;.1 E, 0&quot;.2 N</td>
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The spectra (Keck, Nov. 26-28) are consistent with type-I supernovae (except SN 1995av, a probable type II) at the redshift of the host galaxy: \( z = 0.45, 0.46, 0.49 \) (preliminary type-I identification), 0.65, 0.16, 0.30, 0.4 (supernova redshift only), 0.61, 0.48, 0.45, 0.39. Photometry obtained on Nov. 21-23 at CTIO (A. Walker) and Nov. 23-27 at WIYN (D. Harmer, D. Willmarth) indicates that SNe 1995ar, 1995at, 1995av, 1995aw, 1995ay, and 1995az are now before or at maximum, while the others are slightly past maximum. The previous observations not showing the supernovae (to limiting mag about 24) were on Oct. 29-30 at the CTIO 4-m (except SN 1995au, on 1994 Sept. 29 at the Kitt Peak 4-m telescope). Continuing R, I, and B photometry is important. Contact saul@LBL.gov for finding charts.
81 Type Ia Supernovae
Redshift Distribution

Supernova Cosmology Project

Redshift

$N_{SN}$

HST = Hubble Space Telescope

Oct. 1998 SNe

Mar. 1998 SNe

Dec. 1997 SNe

Mar. 1997 SNe

Jan. 1997 SNe

Mar. 1996 SNe

Dec. 1995 SNe

First 7 SNe
Composite light curve for Type Ia SNe
Lightcurve Width-Luminosity Relation

CHARACTERIZED BY:

Decline Rate

Phillips: 
(1993—)

Δm_{15}

+15 days

Riess, Press, & Kirshner: 
(1995—)

Light Curve Shape (LCS)

Perlmutter et al.: 
(1996—)

Timescale "stretch factor"

$S > 1$: Broader / Slower lightcurves are Brighter

$S < 1$: Narrower / Faster light curves are Fainter
B Band

Calan/Tololo SNe Ia

$M_B - 5 \log(h/65)$

light-curve timescale “stretch-factor” corrected

Kim, et al. (1997)
“Cross-Filter”
K corrections

Supernova rest frame


Supernova at $z = 0.45$

Goldhaber et al. (1998)
Supernova Cosmology Project

As Observed
(1 day averages)

Restframe, "Un-stretched":
timescale divided by
s (1+z)
stretch-factor
time-dilation

Days from peak
Normalized B-band Flux
Normalized B-band Flux

- 18 Low Redshift SNe: Calan/Tololo Supernova Survey
- 35 High Redshift SNe: Supernova Cosmology Project
We knew or thought we knew...

What we didn’t know:

**about supernovae studies**
that SNe could be found systematically
   at cosmologically relevant distances \((z > 0.3)\)
that SNe could be identified spectroscopically at \(z > 0.3\)
that SNe K-corrections could be handled at \(z > 0.3\)
that extinction could be handled at \(z > 0.3\)
that SNe could be calibrated (accounts for progenitor variation)

**about the universe**
That the measurement of \(\Omega_M\) could be separated
   from the measurement of \(\Omega_\Lambda\)

What we found...

Now what we don’t know is...

But we know how to find out...
At a given time...

FAINTER (Farther) (Further back in time)

Less redshift
= Slower expansion in past
= Expansion is accelerating
= Less mass

More redshift
= Faster expansion in past
= Expansion is slowing
= More mass

OR = More vacuum energy

OR = Less vacuum energy

"Nearby" Standard Candles

MORE REDSHIFT
(More total expansion of universe since light left the Standard Candle)
If the universe were flat, with no vacuum energy...

Hypothetical SN Ia at $z = 0.5$

mass density

vacuum energy density (cosmological constant)

Goobar & Perlmutter  
If the universe were flat, with no vacuum energy...

Hypothetical SN Ia at $z = 0.5$

Hypothetical SN Ia at $z = 1$

mass density

vacuum energy density (cosmological constant)

Goobar & Perlmutter

$\Omega_M = \frac{\Lambda}{(3H_0^2)}$

$\Omega_\Lambda$

No Big Bang

1 supernova at $z = 0.83$

5 supernovae at $z \sim 0.4$

Age < 9.6 Gyr

($H_0 = 50$ km/s/Mpc)
We knew or thought we knew...

What we didn’t know...

What we found:
The universe is not decelerating, but accelerating.
Some unidentified negative-pressure energy density exists.
This “dark energy” density dominates over mass density today.

Now what we don’t know is:
the values of the “dark” and mass energy densities
the curvature of space
the identity of the “dark energy”

But we know how to find out...
Type Ia Supernovae

- Calan/Tololo Supernova Survey
- Supernova Cosmology Project


cosmological constant
no cosmo. constant
Einstein-de Sitter

fainter

Accelerating Universe
Decelerating Universe

magnitude vs. redshift

Λ -- cosmological constant
Open -- no cosmological constant
Standard -- Einstein-de Sitter


Two groups results agree:
c.f. Riess et al. (1998)
14 Supernovae from High-z Supernova Search Team
+2 Supernovae from Supernova Cosmology Project

Reiss et al. (1998)
No Big Bang

Flat Universe: $\Lambda = 0$

Expands forever

Recollapses eventually

Supernova Cosmology Project Perlmutter et al. (1999)

Ap.J.

astro-ph/9812133
No Big Bang

Supernovae

Clusters

CMB

vacuum energy density (cosmological constant)

mass density

Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall and Fan (1998)
Systematic Error Checks

• Malmquist bias

• Extinction in SN-host galaxy or our Galaxy.  
  Evolution of dust?

• Evolution of SNe Ia  
  Shift in metallicity/progenitors?  Calibratable?

• Local Hubble bubble  
  Kim et al. (1996)  
  Riess et al. (1997)

• Gravitational Lensing  
  Frieman (1996)  
  Wambsganss et al. (1996)  
  Kantowski et al. (1994)  
  Holz & Wald (1998)
Measurements by SCUBA at 850 µm are already close to ruling out gray dust.

Aguirre & Haiman (1999)
Spectra
An Example: SN1994an

SN1994an at $z = 0.378$
+9 days past max observer frame
= +6 days rest frame

“Nearby” Type Ia
SN1992A

Keck 10-m Telescope
The time series of spectra is a “CAT Scan” of the Supernova
Time Series of **Low-Redshift** and **High-Redshift** Spectra

**SN 1997ex** at $z = 0.36$

Supernova Cosmology Project

Riess (1998)

-6 days

-14 days

-17 days

SN Cosmology Project

High-Z SN Team

High-Z SN Team

rest wavelength
Supernova 1997ap at $z = 0.83$

Supernova Cosmology Project

Flux (in arbitrary units)

Wavelength Redshifted to $z = 0.83$ (Angstroms)

Note: –4 days (before) max observer frame = –2 days rest frame
Score Card of Current Uncertainties

on \((\Omega^\text{flat}_M, \Omega^\text{flat}_\Lambda) = (0.28, 0.72)\)

**Statistical**

- ✔ high-redshift SNe 0.05
- ✔ low-redshift SNe 0.065
  
  **Total** 0.085

**Systematic**

- ✔ dust that reddens < 0.03
  
  \(R_B(z=0.5) < 2 R_B(\text{today})\)

- ❓ evolving grey dust
  
  clumpy

- ❓ same for each SN

- ✔ Malmquist bias difference < 0.04

- ❓ SN Ia evolution
  
  shifting distribution of prog mass/metallicity/C-O/..

- ✔ K-correction uncertainty < 0.025
  
  including zero-points

  **Total** 0.05

identified entities/processes

**Cross-Checks** of sensitivity to

- ✔ Width-Luminosity Relation < 0.03
- ✔ Non-SN Ia contamination < 0.05
- ✔ Galactic Extinction Model < 0.04

- ✔ Gravitational Lensing < 0.06
  
  by clumped mass

Perlmutter et al. (1998)
astro-ph/9812133
What's wrong with a non-zero vacuum energy / cosmological constant?

Two coincidences:

• Why so small?

Might expect \[ \frac{\Lambda}{8\pi G} \sim m_{\text{Planck}}^4 \]

This is off by ~120 orders of magnitude!

• "Why now?"

\[ \frac{\ddot{R}}{R} = -\frac{4\pi G}{3} (\rho + 3p) \]

MATTER: \[ p = 0 \quad \rightarrow \quad \rho \propto R^{-3} \]

VACUUM ENERGY: \[ p = -\rho \quad \rightarrow \quad \rho \propto \text{constant} \]
What's wrong with a non-zero vacuum energy / cosmological constant?

Two coincidences:

- **Why so small?**
  
  Might expect \( \frac{\Lambda}{8\pi G} \sim m_{\text{Planck}}^4 \)
  
  This is off by \( \sim 120 \) orders of magnitude!

- "Why now?"
  
  \[
  \frac{\ddot{R}}{R} = -\frac{4\pi G}{3} (\rho + 3p)
  \]
  
  **MATTER**: \( p = 0 \) \( \rightarrow \rho \propto R^{-3} \)
  
  **VACUUM ENERGY**: \( p = -\rho \) \( \rightarrow \rho \propto \text{constant} \)

What are the alternatives?

New Physics:

“Dark energy”: Dynamical scalar fields, “quintessence”,

- **COSMIC STRINGS**: \( p = -1/3 \) \( \rho \rightarrow \rho \propto R^{-2} \)

- General Equation of State: \( p = w\rho \rightarrow \rho \propto R^{-3(1+ w)} \)

  and \( w \) can vary with time
"Dark Energy"

Unknown Component, $\Omega_u$, of Energy Density

$\text{equation of state ratio } w = \frac{p_u}{\rho_u}$

Flat Universe Constant $w$

$c.f. \ Garnavich \ et \ al. \ (1998)$

$\Omega_M = 1 - \Omega_u$

c.f. Garnavich et al. (1998)
Constraints on Equation of State of "Dark Energy"

S.P., Turner, & White (1999)
We knew or thought we knew…

What we didn’t know…

What we found…

Now what we don’t know is...

But we know how to find out:

- We can systematically find low-redshift supernovae.
- We can find and study supernovae at $z \sim 1.2$
- We can dramatically improve statistics and systematics with a satellite.
Redshift Distribution from "Nearby" SN Campaign

Redshift Distribution of 20 Targeted SNe Ia

- 29 SNe Ia
- 11 non-Ia
- EROS
- NEO Searches
- CTIO/MOSAIC
- Other
Magnitude difference from best fit cosmology


"Albinoni" preliminary magnitude estimate

$\Omega_M, \Omega_\Lambda$

0.28, 0.00
0.73, 1.32
1.00, 0.00

Effective $m_B$
SN 1981B at max redshifted to z = 1.20

SN "Albinoni" Keck spectrum

Host Galaxy Ca H & K

z = 1.2

Observed Wavelength
Recognizing Intergalactic Grey Dust Using SNe at Redshifts > 1

see Aguirre (1999) astro-ph/9904319
Hubble Space Telescope Lightcurves: High Redshift Type Ia Supernovae

Supernova Cosmology Project

SN1998ax

SN1998aw

SN1998ba

SN1998as

SN1997eq

SN1998bi

z = 0.740
SNAP SuperNova Acceleration Probe
SNAP
SuperNova Acceleration Probe

**Satellite Overview**

**Instruments:**

- **~2 m aperture telescope**  
  *Can reach very distant SNe.*

- **1 square degree mosaic camera, 1 billion pixels**  
  *Efficiently studies large numbers of SNe.*

- **3-channel spectroscopy, 0.3um -- 1.7um**  
  *Detailed analysis of each SN.*

**Satellite:**

- Dedicated instrument.
- Designed to repeatedly observe an area of sky.
- Essentially no moving parts.

- **4-year construction cycle.**
- **3-year operation for experiment**  
  *(lifetime open-ended).*
Search Strategy - Deep & Often

Co-added images: $m_{AB} = 32.0$!

Size of
Hubble Deep Field
Cosmological Params.

Dark Matter Properties

Dark Energy Properties
No Big Bang

Supernova Cosmology Project
Perlmutter et al. (1998)

- 42 Supernovae
- 99% confidence region
- 95% confidence region
- 90% confidence region
- 68% confidence region

mass density

vacuum energy density (cosmological constant)

- Flat Universe: $\Lambda = 0$
- Closed Universe
- Open Universe

Expands forever
Recollapses eventually
No Big Bang

Flat Universe $\Lambda = 0$

Expands forever

Recollapses eventually

Supernova Cosmology Project
Perlmutter et al. (1998)

42 Supernovae
Dark Energy
Unknown Component, $\Omega_u$, of Energy Density

\[ \text{equation of state} \quad w = \frac{p_u}{\rho_u} \]

\[ \Omega_M = 1 - \Omega_u \]

**Supernova Cosmology Project**
Perlmutter et al. (1998)

- **Flat Universe Constant** $w$
- **network of cosmic strings** $w = -1/3$
- **range of "Quintessence tracker" models**
- **cosmological constant** $w = -1$

**SNAP Satellite**
**Target Uncertainty**
Current ground-based data compared with binned simulated SNAP data.

Dark Energy Models:

- inverse tracker potential
- Albrecht & Skordis potential
- two D3–Brane potential
- double exponential potential
- periodic potential
- pure exponential (fine tuned)
- Pseudo–Nambu–Goldstone Boson
- SUGRA potential
- exponential tracker potential

- $\Omega_\Lambda = 0.6$
- $\Omega_\Lambda = 0.8$
- SCDM ($\Omega_m = 1.0$)

Each SNAP point represents ~50-supernova bin.
Binned simulated SNAP data compared with Dark Energy models currently in the literature.

Weller & Albrecht
$W = -0.600$

$2\text{EXP}$

$-1.00$

$-0.90$

$-0.825$

$-0.74$

$-0.675$

$W = -0.600$
\[ w_{\text{today}} = w_0 + w_1 \]
Key Instruments:

1) Wide Field Imager
   (one billion pixels)
2) IR Photometer
   (small field of view)
3) 3-channel spectrograph
   350-600 nm,
   550-1000 nm,
   900-1700 nm
4) Star Guider
   (image stabilization)
5) Telescope, Optics Bench,
   Filters, Shutters
LBNL CCD Technology

High quantum efficiency from near UV to near IR
No thinning, no fringing.
High yield.
Radiation hard.

4 side abuttable.
We knew or thought we knew:
The universe is decelerating
Standard candles could measure deceleration
Type Ia SNe could in principle be standard candles at great distances;
With HST ("ST" then) Type Ia supernovae could be studied
at cosmologically relevant distances — if we knew where to look.

What we didn’t know:

about the universe
The mass density of the universe
  = how much is the universe decelerating
The current rate of expansion: the age of universe.
That the measurement of mass density could be separated
  from the measurement of the cosmological constant energy density

about supernovae studies
that SNe could be found systematically
  at cosmologically relevant distances (z > 0.3)
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  the curvature of space
  the identity of the “dark” energy

But we know how to find out:
  We can find and study supernovae at z ~ 1.2
  We can systematically find low-redshift supernovae
  We can dramatically improve statistics and systematics with a satellite.
average distance between galaxies

- **Finite Universe**
- **Borderline Universe**
- **Infinite Universe**

*Universe with a Positive Cosmological Constant*