SN Ia: Even Better Standard Candles in the Infrared

Robert P. Kirshner
Harvard University
I think it must be static!
Redshift proportional to distance: distances from Cepheid variables and from galaxy properties
Λ! Hau ab!
“Everything happens as though the energy in vacuo would be different from zero...we associate a pressure $p = -\rho c^2$ to the density of energy $\rho c^2$ of vacuum. This is essentially the meaning of the cosmical constant $\lambda$.”

PNAS 20, 12 (1934)
Supernovae can be detected at immense distances and, in principle, they are a criterion of distance about as reliable as that of total luminosities of the nebulae.

Actually, however, the maxima are so seldom observed and the [super]novae themselves are so rare that they contribute very little to the present problem.
Thermonuclear exploding stars
\(~4 \times 10^9\) Suns

10\(^6\) brighter than the stars Hubble used

\(~1\) SNIa /century in a galaxy
1/100 years $\sim$ 1/5000 weeks $\Rightarrow$ 5000 galaxies
Fritz Zwicky @ Palomar
The 18” Schmidt
The Beginning of Supernova Cosmology

Charlie Kowal (1940-2011)

Note the imaging technology of 1968!

Monthly searches in the dark of the moon at Palomar with 48” and 18”
Kowal (1968)

Had distances good to \(~30\%\) from SN I

Speculated that individual measurements might be good to 5-10%

"It may even be possible to measure the second-order term in the redshift-magnitude relation when light curves become available for very distant supernovae."

Fig. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.
Technology of the 1990s:

CCD: 0.24 Megapixels
Light Curves: Clues to Luminosity Related to $^{56}$Ni produced in the explosion

Pskovskii (1977, 1984)
Mark Phillips (1992)

Goal: better distances, determination of extinction by dust
Supernovae are imperfect standard candles— they vary by a factor of 2!

But we can tell which are bright and which are dim from the light curve shape and which are dimmed by dust from the color.

Today’s nearby Hubble diagram for Supernovae

CfA1,2,3
Today’s nearby Hubble diagram for Supernovae
$H_0 = \frac{a'}{a}$

$a''/a$ “the acceleration”
We expected Deceleration!

\[ \frac{a''}{a} \sim - (\rho + 3p) = - (1 + 3w) \rho \]

\( w \) gives the equation of state: \( p/\rho \)

\( w = -1 \) for the cosmological constant-

- negative pressure, positive acceleration!

---

THE HIGH-Z SUPERNOVA SEARCH: MEASURING COSMIC DECELERATION AND GLOBAL CURVATURE OF THE UNIVERSE USING TYPE Ia SUPERNOVAE

Brian P. Schmidt, Nicholas B. Suntzeff, M. M. Phillips, Robert A. Schommer, Alejandro Clocchiatti, Robert P. Kirshner, Peter Garnavich, Peter Challis, B. Leibundgut, J. Spyromilio, Adam G. Riess, Alexei V. Filippenko, Mario Hamuy, R. Chris Smith, Craig Hogan, Christopher Stubbs, Alan Diercks, David Reiss, Ron Gilliland, John Tonry, José Maza, A. Dressler, J. Walsh, and R. Ciardullo

ABSTRACT

The High-Z Supernova Search is an international collaboration to discover and monitor Type Ia supernovae (SNe Ia) at \( z > 0.2 \) with the aim of measuring cosmic deceleration and global curvature. Our collaboration has pursued a basic understanding of supernovae in the nearby universe, discovering and observing a large sample of objects and developing methods to measure accurate distances with SNe Ia.
1998 Data:

**HZT**: Riess et al.
Astronomical Journal
September 1998
50 SN Ia
Low z from
Calan/Tololo & CfA

**SCP**: Perlmutter et al.
Astrophysical Journal
June 1999
60 SN Ia
Low z from
Calan/Tololo
1990: Theoretical Consensus
\[ \Omega_{\text{total}} = \Omega_m = 1.0000 \ldots \]
(but observers knew \( \Omega_m \) was 0.3)

1995: some discussion of
\[ \Omega_\Lambda = \Omega_{\text{total}} - \Omega_m \]
Ostriker & Steinhardt
Turner & Krauss

Chief objection was SCP supernova result
widely reported
(Critical Dialogs June 1996) and published in 1997
“All truths are easy to understand once they are discovered; the point is to discover them.”
Today’s Sample $\sim$ 500 SN Ia

- CfA3: Hicken et al. (2009)
- Calán/Tololo: Hamuy et al. (1996)
- CfA1: Riess et al. (1999)
- CfA2: Jha et al. (2006)
- SDSS: Kessler et al. (2009)
- ESSENCE: Wood–Vasey et al. (2007)
- SNLS: Astier et al. (2006)
- HST: Riess et al. (2007)
Looks easy now!

Figure from Ariel Goobar
The diagram is full!
What do the supernovae measure?

Cosmic Age!
\( (H_0 t_0) \)

\( \Omega_\Lambda - \Omega_m : \)

the **difference**
between the acceleration due to the dark energy and the braking due to gravitation

Perpendicular to CMB
which measures
\( \Omega_\Lambda + \Omega_m \)
Is the Dark Energy the Cosmological Constant?

Not good quantitative agreement!

Anthropic selection from a landscape? Ugh!

Other possibilities:
Something that is not constant
Quintessence or other scalar
Modifications to gravity? f(R)

Cannot tell from expansion history alone- growth of structure
From Sullivan et al. 2011
(SNLS results)

\[ 1 + w = -0.06 \pm 0.07 \]
(statistical + systematic)

Importance of photometric calibration
$w$ is More difficult!

$w = \frac{p}{\rho}$

$w = -1$ for Cosmo constant

$(1 + w = 0)$

Thanks again to Ariel Goobar
The Future
Finding SN with Pan-STARRS

Medium-Deep Fields

Good light curves at z~0.4
Every 4 days griz
7 square degrees 0.26 “/pixel
Dozens of supernova candidates every month!
PanSTARRS SN Ia Sample
Rest, A. et al. ArXiV:1310.3828
146 Spectroscopically Confirmed SN Ia with $griz$ light curves from PanSTARRS (MMT, Gemini, Magellan)
PanSTARRS measures both low-z and high-z scatter at low-z same as high-z— not just measurement error— more to be learned about SN Ia!
First Cosmology Results

Systematic Errors discussed at length by Dan Scolnic et al. ArXiv:1310.3824
Dust both dims and reddens -- but less so in the infrared


Folatelli et al. AJ 139, 120 (2010)
J, H, Ks image from PAIRITEL

Seeing through the dirt
Seeing through the dirt

0.55 µm
Seeing through the dirt

Z

0.90μm
Seeing through the dirt
Seeing through the dirt
Seeing through the dirt

K

2.16μm
Kaisey Mandel
Won Savage Award from ISBA!
Hire him!
Most important slide of this talk!

At H-band (1.6m) SN Ia really are standard candles (and there’s much less trouble with dust!)

The payoff for nearby supernovae
Could we get this advantage for the high-z supernovae?

RAISIN
Use the infrared camera on HST to get rest frame IR of cosmological SN Ia!

SN IA in the IR = RAISIN 100 orbits in Cycle 20
Prof. Robert P. Kirshner: RAISIN: Tracers of cosmic expansion with SN IA in the IR

**Investigators:**

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Institution</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>Prof. Robert P. Kirshner</td>
<td>Harvard University</td>
</tr>
<tr>
<td>CoI</td>
<td>Mr. Peter Challis</td>
<td>Harvard University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Ryan Chornock</td>
<td>Harvard University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Wendy L. Freedman</td>
<td>Carnegie Institution of Washington</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Peter Garnavich</td>
<td>University of Notre Dame</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Ryan Foley</td>
<td>Smithsonian Institution Astrophysical Observatory</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Joshua Frieman</td>
<td>University of Chicago</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Andrew Friedman</td>
<td>Harvard University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Eric Hsiao</td>
<td>Carnegie Institution of Washington</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Mark E. Huber</td>
<td>University of Hawaii</td>
</tr>
<tr>
<td>CoI</td>
<td>Mr. David Oscar Jones</td>
<td>The Johns Hopkins University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. G. H. Marion</td>
<td>Harvard University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Kaisey Mandel</td>
<td>Imperial College London</td>
</tr>
<tr>
<td>CoI</td>
<td>Mr. Gautham Narayan</td>
<td>Harvard University</td>
</tr>
<tr>
<td>CoI*</td>
<td>Prof. Bob Nichol</td>
<td>University of Portsmouth</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Mark M. Phillips</td>
<td>Carnegie Institution of Washington</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Adam Riess</td>
<td>The Johns Hopkins University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Steven A. Rodney</td>
<td>The Johns Hopkins University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. Armin Rest</td>
<td>Space Telescope Science Institute</td>
</tr>
<tr>
<td>CoI</td>
<td>Prof. Masao Sako</td>
<td>University of Pennsylvania</td>
</tr>
<tr>
<td>CoI</td>
<td>Prof. Christopher W. Stubbs</td>
<td>Harvard University</td>
</tr>
<tr>
<td>CoI</td>
<td>Dr. John L. Tonry</td>
<td>University of Hawaii</td>
</tr>
<tr>
<td>CoI</td>
<td>Prof. Michael Wood-Vasey</td>
<td>University of Pittsburgh</td>
</tr>
</tbody>
</table>

Number of investigators: 23
Find SN with Pan-STARRS
Get spectrum with MMT

Input: j440162.txt
No. 1: sn02er (ln–norm; -4); z = 0.431±0.008
HST/WFC3–IR  F125W 0.4 orbits F160W 0.6 orbits PS1C490037 z=0.422
One or more observations from the following HST proposal have been scheduled for execution on SMS 133297A5. The SMS begins 25-NOV-2013 00:00:00(UT) and ends 02-DEC-2013 00:00:00(UT). No action is required on your part unless you have a Real Time Contact. Please contact your Program Coordinator (PC) if you have any questions.

Proposal Id: 13046  
Program Id: C1X  
Title: RAISIN: Tracers of cosmic expansion with SN IA in the IR

-------------------------------------------------------------------
<<< PLEASE DO NOT RESPOND TO THIS MESSAGE >>>>
-------------------------------------------------------------------

Start time: 29 Nov 2013 02:37:53  
End time: 29 Nov 2013 03:29:44

<table>
<thead>
<tr>
<th>SCIENCE</th>
<th>SPECTRAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROP</td>
<td>VISIT</td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>13046</td>
<td>N4</td>
</tr>
<tr>
<td>13046</td>
<td>N4</td>
</tr>
<tr>
<td>13046</td>
<td>N4</td>
</tr>
<tr>
<td>13046</td>
<td>N4</td>
</tr>
</tbody>
</table>
RAISIN Scorecard

23 PanSTARRS targets

3 epochs of IR with HST in two near-IR bands

Images without the supernovae will be complete by mid-2014
IR with WFC3
(a good test case for AFTA/WFIRST)
Predicted Distance Modulus $m$ (mag)

Extinction $A_V$ (mag)

$E_{m(z=0.43, LCDM, h=0.72)} = 0.183$

$S_m = 0.116$

PS1 Optical (68%, 95%)

PS1 Optical + HST NIR

(z=0.43, LCDM, h=0.72)
Dark Energy Survey

Have found a few SN Ia: many more to come: Vineyard for future RAISINS!
BIG RAISIN?
(5 year DES program @ 2/month)

$\sigma = +/\!\!/- 0.02$

80 SN Ia @ $z = 0.35$
45 SN Ia @ $z = 0.60$
Large Synoptic Survey Telescope
JWST— the infrared Space Telescope 2018
Giant Magellan Telescope includes Texas & Texas A&M
Better resolution helps distinguish a supernova from its host galaxy.
Site in Chile
1st Mirror Polished to Perfection
2\textsuperscript{nd} & 3\textsuperscript{rd} Mirrors Cast
The Ice Mirror!
D’ou venons nous
Ou sommes nous
Ou allons nous
Paul Gauguin 1897
High-Z Team at Nobel Prize Ceremony
Single degenerate
Double degenerate

Moaz et al. ARAA 2014
It is a good rule not to put overmuch confidence in a theory until it has been confirmed by observation.

I hope I shall not shock the experimental physicists too much if I add that it is also a good rule not to put overmuch confidence in the observational results that are put forward until they have been confirmed by theory.

Sir Arthur Stanley Eddington (1882-1944)
K-corrections needed!

Carnegie (Eric Hsiao) & CfA (Howie Marion) have a vigorous program to get the needed spectra—Magellan & Gemini
Giant Magellan Telescope
Putting $\Lambda$ on the Right Hand Side
An accelerating universe!

$q_o < 0$

$q_o > 0$
Hubble’s first-hand account of these discoveries:

*The Realm of the Nebulae*

1936 Silliman Lectures at Yale—new edition from Yale Press
Hubble in *The Realm of the Nebulae*

Why did it take from 1925 until 1929 for Hubble to get around to connecting Slipher’s redshifts with his own distances?

“a natural inertia in the face of revolutionary ideas couched in the unfamiliar language of general relativity, discouraged immediate investigation.”
Modeling SN Ia Light Curves:
Using the Optical + IR to learn about dust and distance

The IR is not strongly correlated with the Optical
Chart compiled by Mark Sullivan
Today’s Hubble diagram for SN Ia

• Intercept adds only ½% to uncertainty in $H_0 =>$ don’t need to use any ancient supernovae!

• Use only calibrators that are observed in the same way as the modern Hubble flow sample: CCD.

• Improvement not likely from $N^{1/2}$ must improve the systematic effects
Cosmic Flows from SN Ia
Inference from flows

Consistent with $\Lambda$CDM

$$\Omega_m^{0.55} \sigma_8 = 0.40 \pm 0.07$$

This subject will benefit from larger, and more isotropic samples of SN Ia

X-ray cluster data agree
Uncertainty in dust properties leads to uncertainty in dark energy!
Only in space!

Rest frame IR measurements of z~1 supernovae are not possible from the ground

Go as far into the IR as technically feasible!

Sky is very bright in NIR: >100x brighter than in space
Sky is not transparent in NIR: absorption due to water is very strong and extremely variable