Colorful Investigations of WFIRST

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Standard Candles And Distances
Obs: \[ D = \left(\frac{L}{4\pi F}\right)^{1/2} \]
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Theory: $D = f(z, \Omega, w(z), \text{etc})$
SNe Ia are NOT Standard Candles!
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Luminous supernovae have slower light curves. First noticed in 1993 by Mark Phillips.
### Table 1: Uncertainties for $w$

<table>
<thead>
<tr>
<th>Source</th>
<th>$dw$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Uncertainty</strong></td>
<td>0.072</td>
</tr>
<tr>
<td><strong>Statistical Uncertainty</strong></td>
<td>0.050</td>
</tr>
<tr>
<td><strong>Systematic Uncertainty</strong></td>
<td>0.052</td>
</tr>
<tr>
<td>Photometric calibration</td>
<td>0.045</td>
</tr>
<tr>
<td>SN color model</td>
<td>0.023</td>
</tr>
<tr>
<td>Host galaxy dependence</td>
<td>0.015</td>
</tr>
<tr>
<td>MW extinction</td>
<td>0.013</td>
</tr>
<tr>
<td>Selection Bias</td>
<td>0.012</td>
</tr>
<tr>
<td>Coherent Flows</td>
<td>0.007</td>
</tr>
</tbody>
</table>

*AN e wF o u n d a t i o n f o r S N C o s m o l o g y*

Cosmological constraints from SNe Ia are derived by comparing the distances of low- to high-$z$ SNe, with the low-$z$ sample providing an ‘anchor’ to the high-$z$ sample. Our constraints are only as good as either sample. Because of significant effort (and telescope time) put into performing precise, systematic high-$z$ SN surveys, the high-$z$ samples are now both larger (about 800 compared to 200) and better calibrated than their low-$z$ counterparts. Currently, the low-$z$ SN Ia sample is a larger source of uncertainty than the high-$z$ samples. Any work on high-$z$ samples will have a marginal affect on $w$ until we improve the low-$z$ sample.

PI Foley is leading a team that includes Armin Rest (STScI) and Dan Scolnic (KICP fellow, U Chicago) that will replace the old, poorly calibrated low-$z$ sample with a modern sample with the same telescope used to measure high-$z$ SNe Ia. Through the PS1 collaboration, we have observed roughly 400 spectroscopically confirmed SNe Ia and roughly 3000 photometrically classified SNe Ia. We can use this same system (site/telescope/filters/detectors) to measure a large, homogeneous sample of low-$z$ SNe. We call this the “Foundation” sample. Foley is purchasing PS1 telescope time to observe 400 low-$z$ SNe Ia over two years starting around March 2015, with the exact start date depending on when current PS1 programs end. The money for the PS1 time is already secured and this project is guaranteed a set amount of open-shutter time — there is no weather loss for this project. SNe will be discovered by other sources such as the Catalina Sky Survey (Drake et al., 2009), SkyMapper (Keller et al., 2007), Palomar Transient Factory (Law et al., 2009), ASAS-SN, the La Silla-Quest Survey (Baltay et al., 2013), amateur astronomers, and many other sources. Our requirements are simply that the SNe are spectroscopically confirmed, pre-maximum brightness, low to moderately reddened SNe Ia either in a potential Cepheid galaxy or in the Hubble flow.
Dust Makes Things Fainter/Redder
Dust Makes Things Fainter/Redder

Av
Dust Makes Things Fainter/Redder

\[ A_v \quad E(B-V) \]
Dust Makes Things Fainter/Redder

\[ R_V = \frac{A_V}{E(B-V)} \]
Dust Makes Things Fainter/Redder

\[ R_V = \frac{A_V}{E(B-V)} \]

\[ \mu = m - M - A_V \]
Dust Makes Things Fainter/Redder
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Dust Makes Things Fainter/Redder
Dust Makes Things Fainter/Redder

\[ R_V = \frac{A_V}{E(B-V)} \]

\[ \mu = m - M - A_V \]
\[ = m - M - E(B-V) R_V \]
Samples of SNe Ia have Low $R_V$

$R_V = \frac{A_V}{E(B-V)}$

Foley & Kasen 2011
R_v Is A Significant Systematic
Dust Makes Things Fainter/Redder
Dust Makes Things Fainter/Redder

Dust

Different Intrinsic Colors
Different Intrinsic Colors

Dust Makes Things Fainter/Redder
Evidence for Two Color Components

By implementing new tools through this program, we believe that we can reduce the impact of this systematic on the DE-FoM by a factor of 2, making it subdominant.

Color scatter: After making all corrections, a sample of SNe Ia will have an intrinsic Hubble residual scatter. Historically, this has been assumed to be due to luminosity variation (SNe with the same light-curve shape have a scatter in their luminosities), but can also be attributed to color variation (Scolnic et al., 2014). Of course both effects can contribute to the overall scatter, and the exact contribution from each source has significant implications on the measured distances.

As noted above, we correct SN distances with a single color law, described by $\beta$. But as also noted above, this relation corrects for two completely separate physical effects: dust reddening/extinction and intrinsic color-luminosity relations. It is quite a coincidence that the two effects are so similar (or one is so subdominant) that a single relation can describe both effects. We should be able to separate the two effects at some level. A large wavelength range should aid in this task.

This is especially true for WFIRST-AFTA, where we will have extensive rest-frame NIR data. If these two relations are slightly different, then one might expect a different $\beta$ for blue SNe (those with minimal dust reddening and are intrinsically blue) and red SNe (those that are primarily red because of dust). Scolnic et al. (2014) showed that there exists a different relation for blue and red SNe for the combined SDSS and SNLS sample. Using the photometrically classified SN Ia sample from SDSS, we have also found different relations for blue and red SNe. This needs to be investigated with even larger samples, but such an effect would directly affect WFIRST-AFTA.

Figure 6: Left: Hubble residuals as a function of SN color, $c$, for the photometrically selected SDSS SN Ia sample, consisting of 1201 SNe. The full sample is consistent with zero trend between the two values. However, splitting the data into blue ($c<0$) and red ($c>0$) SNe, we see a significant trend for the blue SNe. Outlier-resistant linear fits for the blue and red data are represented by the red lines. A non-zero trend is significant at 4.0 $\sigma$ for the blue SNe.

Figure 7: Right: Evolution of $\beta$ with redshift for the SNLS sample. The solid line is the best-fit values assuming no evolution, including systematic effects, while the point in each redshift bin is evaluated with the same fixed cosmology. The dashed line is the best linear fit to the points. From Conley et al. (2011).
Optical Spectrum to Measure Velocity

![Optical Spectrum](image)
Optical Spectrum to Measure Velocity

- **High Velocity**
- **Low Velocity**
Optical Spectrum to Measure Velocity

- High Velocity
- Low Velocity

Silicon
Measure Silicon Velocity

High Velocity: 
~ -13,000 km s\(^{-1}\)

Low Velocity: 
~ -10,000 km s\(^{-1}\)

Wider Lines With Higher Velocity
Measure Silicon Velocity

High Velocity: 
~ \(-13,000\) km s\(^{-1}\)

Low Velocity: 
~ \(-10,000\) km s\(^{-1}\)

Wider Lines With Higher Velocity
Samples of SNe Ia have Low $R_V$

$R_V = \frac{A_V}{E(B-V)}$

Foley & Kasen 2011
Intrinsic Color Depends on SN Velocity

Foley & Kasen 2011
also Foley 2012; Foley, Sanders, & Kirshner 2011; Mandel, Foley, & Kirshner 2014

\[ R_V = \frac{A_V}{E(B-V)} \]
Intrinsic Color Depends on SN Velocity

![Graph showing the relationship between Si II velocity and modal A_V estimate change]

Mandel, Foley, & Kirshner 2014
Ejecta Velocity is the “Next Parameter”
Ejecta Velocity is the “Next Parameter”

Velocity Improves Precision by 2.4x and Reduces Bias
Evidence for Two Color Components

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Populations from Simulations

Scolnic & Kessler 2016
Simulations Predict (Remove) Biases

![Graph showing comparisons between simulated and observed Hubble residuals and their best-fit predictions.](image)

- **Data**: Observation points.
- **Sim G10**: Simulation predictions for the G10 intrinsic scatter model.
- **Sim C11**: Simulation predictions for the C11 intrinsic scatter model.

**Legend**:
- Blue line: Sim G10 predictions.
- Red line: Sim C11 predictions.
- Black line: Best-fit predictions.
- **Points**: Observed data points with error bars.

**Discussion**:
- The graph illustrates the improvement in Hubble residual predictions with the use of simulations (Sim) compared to best-fit predictions.
- The blue line (Sim G10) and red line (Sim C11) show the predictions for each model.
- The black line represents the best-fit predictions derived from the observations.
- The data points (black circles) with error bars indicate the observed Hubble residuals.

**Key Points**:
- The simulation predictions (Sim G10 and Sim C11) generally follow the best-fit predictions but with some deviation.
- The C11 model shows a better fit to the data compared to the G10 model.
- The improvement in predictions is evident, particularly at the extreme color and stretch values.

**References**:
- Scolnic & Kessler 2016

**Fig. 3** — Graph showing the comparison between simulated and observed Hubble residuals.