The First Type Ia Supernovae: An Empirical Approach to Taming Evolutionary Effects In Dark Energy Surveys from SNe Ia at $z > 2$

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ABSTRACT

Future measurements of the nature of dark energy using Type Ia supernovae will require a precise characterization of systematic sources of error. Evolutionary effects remain the most uncertain contributor to the overall systematic error budget. Present plans to probe evolution with cosmology-independent explosion parameters could yield absence of evidence for evolution without definitive evidence of its absence. Here we show that observations of Type Ia supernovae in the redshift interval $1.5 < z < 3.0$, where dark energy-dependent effects are relatively negligible, should provide direct evidence to discern evolutionary effects. As examples of our approach to constraining evolution, we examine the impact of changing progenitor metallicity and age on the degree of potential luminosity evolution. We show that the observations we propose can be carried out by existing space telescopes, or ones that are already under development.

Subject headings: galaxies: distances and redshifts — cosmology: observations — cosmology: distance scale — supernovae: general

1. Introduction

The discovery of the apparent acceleration of the Universe from observations of high-redshift type Ia supernovae (SNe Ia; Riess et al. 1998; Perlmutter et al. 1999) indicates the presence of a repulsive-like gravity on current horizon-size scales. Dubbed “Dark Energy,” but little understood, elucidating its nature provides perhaps the biggest challenge in physical cosmology. While many powerful observational tools have been focusing on this problem, including the cosmic microwave background, baryon acoustic oscillations,
gravitational lensing, the integrated Sachs-Wolfe Effect, and cluster counting, observations of SNe Ia remain one of the premier tools for characterizing the nature of dark energy. Measurement for measurement or source for source, SNe Ia provide the greatest precision for constraining dark energy within the epoch of its apparent dominance.

Substantial progress in measuring dark energy parameters with SNe Ia requires sample sizes of at least a few thousand, well-sampling the redshift range $0 < z < 2$. Indeed, some new SN Ia surveys are already underway with independent collections of $\sim 100$ objects (ESSENCE, CFHT, SDSS, Higher-$z$) and next-generation SN surveys are currently under design (Pan-starrs, LSST, JDEM). Yet, to achieve the precision available from the statistics of such sample sizes will require controlling the systematic sources of error to approximately $\sigma \sim 1$–$2\%$ in luminosity, for each subsample of a $\sim 100$ SNe Ia with uncorrelated errors.

Of all suspected sources of systematic uncertainty specific to SNe Ia, evolution is perhaps the most difficult to quantify. The perceived risk of SNe Ia evolving with redshift is driven by two factors: (i) observations of evolution among other astronomical objects pressed into service for measuring cosmic expansion (e.g., Sandage and Hardy 1973), and (ii) unpredictability resulting from the complexity of supernova explosions.

Yet SNe Ia have been shown to be far less susceptible to evolution than other astronomical objects, and the mechanism by which they are produced provides a sound reason for them to be “robust.” The Chandrasekhar limit can be understood from first principles and it homogenizes the explosion mass of SNe Ia to within a few percent. Observationally, no other known astronomical object visible at cosmological distances is nearly so uniform nor has it a theoretical reason to be.

Still, some differences do occur during the explosions altering their yields of radioactive $^{56}\text{Ni}$ and varying their apparent peak output by $\sigma \sim 20\%$ to $25\%$ (e.g., Branch and Tammann 1992; Filippenko 1997; Livio 2001; Leibundgut 2001). A single, visible parameter related to the speed of the light curve decline (Phillips 1993; Riess, Press, & Kirshner 1995, 1996; Tripp 1998) or spectral feature strengths (Nugent et al. 1995) is sufficient to reduce the remaining luminosity dispersion to $\sim 15\%$ ($7\%$ in distance). To date, the residual peak luminosity (in excess from the fiducial value) has no apparent dependence on properties of the supernova environment (including stellar population age, and global metallicity), indicating that samples of supernovae are still reliable when averaged to a fraction of their dispersion at moderate redshifts (e.g., $z < 2$; Riess et al. 1998, 1999, Sullivan et al. 2003). However, as the sample sizes surpass 100 SNe Ia at significant look-back time, the tolerance to a systematic error caused by evolution shrinks to $\sim \frac{15\%}{\sqrt{100}} \sim 1.5\%$ and must be questioned and demonstrated.
Empirically, the present task of constraining SN Ia evolution can be seen as a quest for a second (third, fourth, etc.) observable parameter with apparent dependence on luminosity. A purely empirical (i.e., uninformed) approach to taming SN Ia evolution is unlikely to be successful on simple statistical grounds. Given a set of >7 potential observables evenly (and crudely) quantified as having observed values which are "low", "medium" and "high", a set of a few thousand SNe Ia would be insufficient to even sample (or match similar SNe Ia across redshift) all possible combinations of these parameters (which would exceed a couple of thousands).

An approach that is tractable, in principle, is to use a quasi-empirical or educated-empirical approach, by employing astronomical knowledge and theoretical input to investigate the “likely suspects” to constrain SN Ia evolution. Unfortunately, complete and highly predictive simulations of SNe Ia have proved elusive and are currently insufficient to identify all the important parameters (many of which are not even varied in the simulations, e.g., magnetic fields and rotation; see Discussion). Current modeling suffers from known gaps in our ability to characterize the physics of flame propagation and explosion conditions, insufficient resolution in position and velocity space, and an incomplete itemization of energy levels in the calculation of supernova photospheres. These deficiencies are unlikely to be fully remedied in the near future (e.g., Niemeyer, Reinecke, Hillebrandt, 2002).

The major problem with the empirical approach of regressing observed SN parameters with luminosity is that the absence of evidence for evolution does not provide evidence of absence.

Here we present an alternative, empirical approach, which requires much less guidance from theoretical modeling of supernovae. Our suggested approach is to increase possible evolutionary effects while simultaneously decreasing the dependence of the apparent brightness on uncertain parameters of cosmology. At $z > 2$, the Universe is observed and expected to be dark matter dominated and thus the measured SN Ia distances are relatively insensitive to the nature of dark energy (relative to lower redshifts). However, the increased look-back time and the concomitant changes to the global (mean) chemical abundances and stellar ages are substantial (as we will show), amplifying any potential SN Ia evolutionary effect above what may be readily detected at lower redshifts. Thus, even without a detailed initial knowledge of the cause of evolution, measuring a significant sample of SNe Ia at $z > 2$ should reveal the potential effects of evolution (e.g., by direct evidence of its absence), independent of the behavior of dark energy. In §2 we describe the basic measurement. In §3 we describe the feasibility of this measurement with existing or planned observatories, a discussion follows in §4, and our summary and conclusion are presented in §5.
2. SNe Ia at $z > 2$, a Route to Amplifying the Evolutionary Effects

The change in the luminosity distance with redshift is sensitive to the properties of the dark energy within the interval $0 < z < 1.5$ but decreasingly so (with increasing redshift), because the ratio of the dark matter to dark energy density increases rapidly as $(1 + z)^{-3w(z)}$. Thus, whatever the value of the equation of state ($w = P/\rho c^2$) of the dark energy, the high-redshift Universe must be dark matter dominated. As a result, increases in the luminosity distance with redshift become simpler to predict at higher redshifts.

To illustrate this phenomenon, we show in Figure 1 differences in the increase of luminosity distance with redshift for different dark energy parameters between $0 < z < 1.5$ and again between $1.5 < z < 3.0$. The predicted distances for a cosmological constant-type dark energy ($w_0, w' = (-1.0, 0.0)$ and models with dark energy parameters in close proximity ($-1.0, -0.3), (-1.0, +0.3), (-1.2, 0.0), (-0.8, 0.0)$ differ by $\pm 10\%$ in flux in the range $0 < z < 1.5$ [here $w_0$ is $w(z = 0)$ and $w' \equiv \frac{dw}{dz}|_{z=0}$]. However, in the next redshift range, $1.5 < z < 3.0$, the additional distance for these same dark energy models differs by only $\pm 1\%$ in flux. Thus, while the increase in the luminosity distance in the range $0 < z < 1.5$ depends on both (possible) evolution and the unknown dark energy model, the luminosity distance increase in the range $1.5 < z < 3.0$ is sensitive only to (possible) evolution. This relative insensitivity to dark energy at higher redshifts provides a powerful way to identify possible SN Ia evolution.

For example, one of the primary global parameters whose cosmic evolution might affect SN Ia luminosities is metallicity (see §4). To illustrate the utility of the approach we advocate, we can reconstruct a representative history for the evolution of metallicity based on quasar absorption by damped Lyman-alpha systems. The relevant value of the cosmic metallicity is its value at the time of the SN Ia progenitor formation, not the value at explosion. In Figure 2 we show the mean cosmic metallicity derived from measurements by Kulkarni et al. 2005 and an assumed delay time for SNe Ia of 2–3 Gyr (Strolger et al. 2005; Dahlen et al. 2005). As shown, the mean global metallicity at the time of a SN Ia progenitor formation is expected to decrease by 2 decades in the redshift range of $0 < z < 1.5$ resulting in uncertain, and hard to predict, evolution in SN Ia luminosity. This is the redshift range where the observed fluxes of SNe Ia are increasingly being used to characterize dark energy (Riess et al. 2004, Aldering et al. 2004). In the redshift interval, $1.5 < z < 3.0$, the mean formation metallicity inferred from quasars decreases by an additional 2 decades (or more for delay times of $\geq 3$ Gyr). However, the change in flux due to increased distance is easily predicted from the value of $\Omega_M$ and depends negligibly on the dark energy model, providing a measurement of the change due to (possible) luminosity evolution resulting from decreased metallicity. (An uncertainty in $\Omega_M$ of $\sim 0.01$, forecast by Frieman et al.
2003 by the era of the Planck Surveyor, propagates only a 2% uncertainty in flux at the middle of this redshift range, thus retaining the required sensitivity to evolution.)

Another example of the utility of our approach derives from the necessary evolution (i.e., decrease) in the maximum age of stars and potential SN Ia progenitors with increasing redshift. White dwarfs at higher redshifts necessarily originate from shorter-lived and therefore more massive stars. These stars produce CO white dwarfs with a higher initial mass and a smaller ratio of carbon-to-oxygen. (e.g., Becker & Iben 1980, Dominguez, Höflich & Straneiro 2001). Some theoretical models (e.g., by Dominguez and Höflich 2001) predict a change in the peak luminosity of roughly 3% per 1 solar mass change in the progenitor star mass due to the decreased energy yield from the decreased $^{56}$Ni mass synthesized in the explosion [generally, a higher CO mass is accompanied by a lower C/O ratio (although not monotonically at the low-mass end), and consequently, a lower energy per gram; see also §4]. As shown in Figure 3, in the dark energy-sensitive redshift range ($0 < z < 1.5$), stars with masses as small as 1 to 1.5 solar masses have sufficient time to evolve to white dwarfs and may produce the SNe Ia we see. In the dark matter-dominated range ($1.5 < z < 3.0$), the minimum mass rises to 2 to 6 solar masses depending on the assumed delay (3 to 0.01 Gyr). According to the models of Dominguez et al. (2001), the evolution in the luminosity across the range $1.5 < z < 3.0$ is as large (or larger for delay times of $\geq 2$ Gyr) as for the range $0.0 < z < 1.5$, for SNe Ia resulting from the white dwarfs with the smallest initial mass which can explode. Thus, SNe Ia measurements at dark energy insensitive redshifts should provide a valuable, empirical constraint on the degree of such evolution.

The empirical approach that we propose has the additional advantage that, in principle, it is not even necessary to know the source of possible evolution in order to diagnose its influence at $z > 1.5$. While the look-back time over $1.5 < z < 3.0$ is modest (∼2 Gyr) compared to the interval over $0 < z < 1.5$ (∼9 Gyr), the known change in the cosmic environmental parameters (likely to effect the formation of SN Ia progenitors) is as large or larger. Consequently, for simple, monotonic evolution, the potential changes in luminosity distances that are due to evolution in the range $1.5 < z < 3.0$ provide an upper limit to the changes due to evolution that are likely to have occurred across the dark energy-sensitive redshift region.

3. From Principle to Practice

While the proposed empirical approach to taming possible SN Ia evolution is powerful in principle, here we consider its practicality.
The most conservative approach to evolution would be to assume SNe Ia are evolving with redshift and to utilize the measurements at $1.5 < z < 3.0$ to correct for luminosity evolution. In that case the precision of the measurement of the evolution would need to match the precision of the dark energy measurement sought at $z \sim 1.5$.

The leverage on evolution at high-redshift will depend on the assembly time of SN Ia progenitors. Longer developing progenitor systems originate from a younger Universe and thus would provide greater leverage on evolution. From Figures 1 and 2 we surmise that assembly times of $> 2$ Gyr (favored by Strolger et al. 2005 and Dahlen et al. 2005) will provide more evolution per SN Ia per unit redshift at $1.5 < z < 3.0$ than $z \sim 1.5$, reducing the number of SNe Ia required to constrain evolution by a significant factor. However, a prompt population of SNe Ia (see Manucci et al. 2004) would likely require an equivalent sample size of SNe Ia in the two redshift intervals. Ongoing surveys of SNe Ia are likely to resolve the assembly time of SN Ia progenitors in the next few years.

Thus, we may assume the number of SNe Ia measured at $1.5 < z < 3.0$ would need to be between a few hundred and a thousand\(^3\)

An alternative, less demanding approach, would be to utilize the SNe Ia at $z > 1.5$ as a coarse check on evolution ("sanity check"). This approach would be sufficient to discriminate between the possibilities that SNe Ia are not evolving or if evolving, are doing so well beyond the unrelated precision of dark energy measurements. For this approach a few dozen SNe Ia would suffice, but would be unable to rule out an unfortunate coincidence, such that the degree of evolution of SNe Ia happens to match the desired precision of dark energy measurements (and that the Universe, in Einsteins words, maybe is malicious).

Thus, let us assume that the observational challenge is to measure $\sim 100$ SNe Ia (more or less depending on the aforementioned approaches) at 1.5 to 2.5 microns where they will peak at $24.0 < K < 24.6$ and $24.0 < H < 25.5$ and decline by $\sim 1$ mag at later phases. The

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\(^3\)In principle the number can be as small as the sample size of each redshift bin, defined so that between each pair, systematic errors are uncorrelated. Current descriptions of future, large number SN surveys (e.g., Aldering et al. 2004) generally consider errors due to systematics to be uncorrelated between SNe separated by $\Delta z = 0.1$ (e.g., the SNAP proposal, Aldering et al. 2004). The reasoning for such de-correlation is rather approximate but originates from the change in bandpasses and instrumentation used with changing redshift (Linder and Huterer 2003, Aldering 2004). Within one of these bins, the number of SNe Ia which can be averaged before reaching an assumed systematic error floor of $\sim 1\%$ in flux is 100. However, the exact number depends critically on the assumed size of the zeropoint error and its correlation with redshift, neither of which has been well-established. Errors due to evolution may be correlated across the entire redshift space of the survey thus raising the number of SNe Ia required to constrain evolution at $z > 1.5$ to our conservative description.
lower end of this redshift range is within the reach of *HST* with the IR channel of WFC3, for which the limiting factor is thermal background (which limits observations to $< 1.72$ micron and thus useful SN Ia measurements to $z < 2.2$). The entire range (and higher) is easily within the reach of *JWST*, as well as a possible $\sim 6$-m class *TPF-C* mission equipped with a general, near-IR astrophysics camera.

The survey area required to achieve such a sample of SNe Ia can be determined for an assumed star-formation history (SFH) and SN Ia progenitor formation time function. If we use the SFH from Giavalisco et al. (2005) and a formation delay time of 0 to 3 Gyr, we obtain results for WFC3 and *JWST* that are given in Table 1.

For the field size of WFC3 (2.3 by 2.1 arcminutes), 745 pointings are required to cover an area of one square degree and the maximum useful SN Ia redshift is 2.2. *JWST*’s NIRcam is planned to have twice the field of view, and we can see from Table 1 that it is about three times faster at finding these SNe; it will therefore yield about six times as many objects in a typical exposure with a maximal redshift surpassing six. Thus, 260 pointings will be required for *JWST* for a long delay or 50 pointings for prompt SNe Ia. This (and more) is readily achievable over the lifetime of this observatory. At these redshifts, a field will “refresh” and provide new SNe Ia with a timescale of $\sim 2$ months (risetime * (1 + z)).

We conclude that a powerful empirical approach to constraining SN Ia evolution, sufficient for the next generation of SN Ia-based dark energy surveys, will be provided by space telescopes and instrumentation already under development.

### 4. Discussion

Characterizing evolutionary effects in SNe Ia by theoretical modeling is not easy, and quantifying them is even harder. There are several reasons for these difficulties: (i) The progenitor systems of SNe Ia have not been identified unambiguously, (ii) The physics of flame propagation is not fully understood, (iii) Many uncertainties still plague the calculations of the evolution towards explosion, (iv) Multi-dimensional simulations of all the processes involved are only beginning to emerge. Let us discuss briefly, in turn, the resulting ambiguities.

#### 4.1. Progenitors

In spite of considerable progress in the understanding of the progenitor systems, and fairly strong theoretical arguments suggesting that SNe Ia originate from single-degenerate
systems (in which a white dwarf accretes from a normal companion; see Livio 2001 for a review), there is no observational evidence to show that double-degenerate systems do not produce SNe Ia. Since double-degenerate scenarios differ from single-degenerate ones both in the delay time (typically less than 1 Gyr in the double-degenerate scenario, compared to $\sim 1.5$–3 Gyr in the single-degenerate case), and in the environment leading to the explosion, the uncertainty in the identification of the progenitor system translates into an uncertain evolutionary effect (especially if both single-degenerate and double-degenerate systems can lead to SNe Ia).

4.2. Physics of the Flame

Delayed detonation models, in which the burning starts as a subsonic deflagration that later turns into a supersonic detonation, have been found to be reasonably successful in reproducing both the light curves and spectra of SNe Ia (e.g., Höflich, Khokhlov, & Wheeler 1995; Lentz et al. 2000). The problem is that these models still involve two free parameters: the speed of the deflagration, and the density $\rho_v$ at the point of transition from deflagration to detonation. Since the amount of $^{56}$Ni produced (and consequently the brightness) depends sensitively on $\rho_v$, the lack of a detailed understanding of what determines $\rho_v$ (and of whether a transition occurs at all!) is a serious deficiency of the models (see also §4.5).

4.3. The Evolution towards Explosion

Of the many known uncertainties in the theory of binary star evolution, some are particularly crucial for SNe Ia. For example, the observed rates of SNe Ia in the low-redshift Universe can be reproduced in the single-degenerate scenario, if one assumes an important role for a white dwarf wind during the accretion process (this avoids the formation of a common envelope and allows for a steady increase in the white dwarf mass; e.g., Hachisu, Kato, & Nomoto 1999). Since optically thick winds are driven by a peak in the opacity, which is due to iron lines, the model that invokes an important role for the winds necessarily predicts a strong dependence of SNe Ia rates on metallicity (e.g., Kobayashi et al. 1998). Still, the role of these winds remains, at present, in the realm of theoretical conjecture.
4.4. Multi-Dimensional Effects

While multi-dimensional SNe Ia simulations have made remarkable progress in the past few years (e.g., Röpke 2005), treating all the relevant physics in three dimensions remains a challenge. In some cases, the newly emerging results are in conflict with results from spherically symmetric models (see also §4.5).

4.5. Possible Evolutionary Effects

In spite of the uncertainties listed above, the risk of evolutionary effects appears to be high. For instance, since the high-redshift universe is characterized by a lower metallicity, we should consider potential metallicity-related effects. Similarly, progenitors in the early universe have necessarily to be shorter lived, and therefore of a higher mass. Interestingly, detailed calculations of the delayed detonation model by Dominguez et al. (2001) and Lentz et al. (2000) show that for a progenitor with a main sequence mass of $M_{MS} = 5 M_{\odot}$, a change in the metallicity from $Z = 0.02$ to $Z = 10^{-10}$ has little effect (and is not monotonic) on the energetics and on the light curve. Due to changes in the line blending by Fe, the decline in the metallicity is expected to be accompanied by a decline in $B - V$ by $\sim 0.05^m$.

Rather different results were found in the three-dimensional calculations of Röpke et al. (2005). Specifically, these authors found that changing just the $^{22}$Ne mass fraction from 0.5 to 3 times solar resulted in a 20% change in the mass of the $^{56}$Ni produced (and thereby in the SN brightness). At present, it is not entirely clear what these variations between the spherical and three-dimensional models are due to (see also Timmes et al. 2003). The metallicity may have a more dramatic effect on SNe Ia if indeed the white dwarf wind plays an important role in the evolution towards explosion. Specifically, the metallicity-dependent conditions for a strong wind (Nomoto et al. 2000) predict a lower bound on the core mass, $M_{CO}$ (e.g., $M_{CO} \gtrsim 0.95 M_{\odot}$ for $Z = 0.004$), which translates into an upper bound on the $^{56}$Ni mass. Consequently, this model predicts an absence of bright SNe Ia at high redshifts (lower metallicity environments). In addition, the strong-wind scenario predicts a strong decline in SNe Ia rates at $z > 2.5$.

Perhaps the largest expected evolutionary effect comes from changes in $M_{MS}$. At a fixed value of $Z = 10^{-3}$, changing the main sequence mass from 1.5 $M_{\odot}$ to 6.0 $M_{\odot}$ results in a change in the average C/O ratio in the WD (before explosion) from 0.76 to 0.60 and a concomitant reduction in the $^{56}$Ni mass (which is the main factor in determining the explosion strength), from 0.59 $M_{\odot}$ to 0.52 $M_{\odot}$ (Dominguez et al. 2001; Umeda et al. 1999). Consequently, in addition to the change in the peak luminosity, the expansion velocities are
altered as well, with different chemical layers differing in their speeds by up to 1500 km s$^{-1}$. At $Z = 0.02$, increasing $M_{MS}$ from 1.5 $M_\odot$ to 7.0 $M_\odot$ decreases (in the models) the peak luminosity (in both $B$ and $V$) by $\sim 0.15\text{m}$. Again we should note that three-dimensional calculations (Röpke et al. 2005) are at variance with the results of spherically-symmetric models when it comes to the effect of the progenitor’s C/O ratio. The three-dimensional simulations show only a small impact of the C/O ratio on the amount of $^{56}\text{Ni}$ produced. This may be due to the fact that the three-dimensional models achieved only partial burning of the white dwarf, and no layered chemical structure.

In the single-degenerate scenario, SNe Ia at $z \sim 3$ could also be expected to be brighter due to age effects. The reason is that in these models, the lifetime of the system is essentially the lifetime of the companion star, which is determined by its mass $M_2$. For a younger system (larger $M_2$), the total mass that can be transferred to the white dwarf is higher, requiring a smaller white dwarf mass, which translates into a higher $^{56}\text{Ni}$ mass.

Another potential metallicity-dependent evolutionary effect which has not yet been explored in detail is related to neutrino cooling. The density at which the ignition of carbon occurs depends sensitively on the cooling rate, which in turn depends on the local Urca $^{21}\text{Ne}$$-^{21}\text{F}$ process. At a lower metallicity environment, the abundance of $^{21}\text{Ne}$ is lower, resulting in less efficient cooling. Ignition therefore may occur at a lower central density (lower binding energy of the white dwarf). As a result, the light curve evolution may be faster in such an environment.

Even if luminosity evolution of SNe Ia does occur in the Universe, its effects may already be included in, if not already explain, the observed and utilized relation between light curve shape and luminosity. An indication that this may be true comes from evidence that the specific light curve shape and luminosity of a SN Ia does depend on the characteristics of its host (e.g., elliptical vs. spiral, e.g. Howell 2005).

### 5. Summary and Conclusions

Future, high-precision measurements of dark energy utilizing thousands of SNe Ia will require a high degree of control of systematic errors. The most uncertain and hardest to quantify systematic source of uncertainty impacting SNe Ia is evolution. Despite the absence of present evidence of SN Ia evolution, some effects that depend on the metallicity and age of the progenitor systems appear likely. Without a complete theoretical description of SNe Ia, better agreement among present efforts to model the explosions, or a massive sample of SNe Ia spanning all combinations of all observable explosion characteristics across
redshift, absence of evidence of evolution is unlikely to provide evidence of its absence.

As an alternative approach to this thorny problem, we have shown that observations of SNe Ia at $1.5 < z < 3.0$, where the relative dependence on uncertain dark energy parameters is negligible and the change in progenitor environmental parameters is large, should provide a positive identification of evolution if it is significant. The observations we propose can be carried out by space telescopes that already exist, or are already under development.

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Table 1. Square degrees required to collect 100 SNe Ia at $1.5 < z < 3.0$ at typical (1 hour) exposure times

<table>
<thead>
<tr>
<th>Delay (Gyr)</th>
<th>WFC3* ($H = 25$ Vega)</th>
<th>JWST ($K = 27$ Vega $\sim 10$ nJy)</th>
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<tr>
<td>0</td>
<td>0.83</td>
<td>0.14</td>
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<tr>
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*1.5 < z < 2.2 is the useful redshift range

*Rates normalized to match observed from Strolger et al. 2005
Fig. 1.— Luminosity Distance and Cosmology

\[
\begin{align*}
\Delta \text{mag} &= w_0 = -0.8, w' = 0 \\
\Delta \text{mag} &= w_0 = -1.0, w' = 0.3 \\
\Delta \text{mag} &= w_0 = -1.0, w' = -0.3 \\
\Delta \text{mag} &= w_0 = -1.2, w' = 0
\end{align*}
\]
Figure Captions

Figure 1: Dark Energy and Evolution Sensitivity. At $0 < z < 1.5$, luminosity distances to SNe Ia are sensitive to differences in the dark energy model, with a ± 10% variation in flux for dark energy parameters currently favored (see upper panel). However, it is possible that SNe Ia in this range could be altered by a significant, unknown luminosity evolution. At $1.5 < z < 3.0$, variations in the dark energy model from a fiducial model (cosmological constant) become very small as the Universe becomes dark matter-dominated (see lower panel). However, the known cosmic evolution of parameters related to progenitor formation continues in this higher redshift interval providing the means to diagnose and calibrate the degree of SN Ia evolution affecting dark energy measurements.

Figure 2: The mean global metallicity of the formation of SN Ia progenitor systems as inferred from damped Lyman-alpha systems. The upper panel shows the relation between discovery redshift and progenitor formation redshift depending on the time interval between formation and explosion. The bottom panel uses the results from Kulkarni et al. (2005) to show the mean global metallicity for SNe Ia progenitors as a function of discovery redshift. As shown, the variation in global metallicity at $1.5 < z < 3.0$ where SNe Ia distances are relatively insensitive to knowledge of the correct dark energy model, is as larger or larger than at $0 < z < 1.5$, where SNe Ia are used to measure dark energy. These changing dependendies allows in principle for the breaking of possible degeneracies between SN Ia luminosity evolution and dark energy.

Figure 3: The minimum main-sequence mass of a progenitor star to evolve to a white dwarf as a function of the discovery redshift of a SN Ia. Depending on the interval between the Big Bang and the formation of the star as indicated, the minimum mass star from which the white dwarf originates is a strong function of redshift. For some SN Ia models (e.g., Dominguez et al. (2001), the initial mass determines the carbon to oxygen ratio of the white dwarf, a ratio which can alter the peak luminosity of the SN Ia by 5% to 15%. Thus expanding the range of redshift where SNe Ia are measured provides important leverage on this possible evolution scenario.
Fig. 2.— Metallicity
Fig. 3.— Star Age