Type Ia Supernova Science 2010-2020

A White Paper submitted to the *Astro2010*
Decadal Survey of Astronomy and Astrophysics

Primary Panel *Stars and Stellar Evolution (SSE)*
Secondary Panel *Cosmology and Fundamental Physics (CFP)*

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Draft version February 15, 2009

ABSTRACT

In the next decade Type Ia supernovae (SNe Ia) will be used to test theories predicting changes in the Dark Energy equation of state with time. Ultimately this requires a dedicated space mission like JDEM. SNe Ia are mature cosmological probes — their limitations are well characterized, and a path to improvement is clear. Dominant systematic errors include photometric calibration, selection effects, reddening, and population-dependent differences. Building on past lessons, well-controlled new surveys are poised to make strides in these areas: the Palomar Transient Factory, Skymapper, Pan-STARRS, the Dark Energy Survey, LSST, and JDEM. They will obviate historical calibrations and selection biases, and allow comparisons via large subsamples. Some systematics follow from our ignorance of SN Ia progenitors, which there is hope of determining with SN Ia rate studies from $0 < z < 4$.

Aside from cosmology, SNe Ia regulate galactic and cluster chemical evolution, inform stellar evolution, and are laboratories for extreme physics. Essential probes of SNe Ia in these contexts include spectroscopy from the UV to the IR, X-ray cluster and SN remnant observations, spectropolarimetry, and advanced theoretical studies. While there are an abundance of discovery facilities planned, there is a deficit of follow-up resources. Living in the systematics era demands deep understanding rather than larger statistics. NOAO ReSTAR initiative to build 2-4m telescopes would provide necessary follow-up capability. Finally, to fully exploit LSST, well-matched wide-field spectroscopic capabilities are desirable.

1. INTRODUCTION

A decade ago, Type Ia supernovae (SNe Ia) were used as standardized candles to reveal the presence of a previously unknown energy component of the universe which dominates its evolution (Riess et al. 1998; Perlmutter et al. 1999). We now know the Dark Energy, averaged over cosmic time, behaves similarly to a cosmological constant, $\langle w = P/\rho c^2 \rangle \simeq -1 \pm 6\%$ (stat, 1σ), with systematic errors of the same order or larger than statistical errors (Kowalski et al. 2008; Hicken et al. 2009, Fig. 1). The challenge for the next decade is to measure the variation of w with redshift. Excellent progress has been made in identifying errors that do not scale with $\sqrt{N}$ statistics, i.e. systematic errors (Table 1), and we now envision experiments that will address decades-old uncertainties enabling breakthroughs in the use of SNe Ia as standard candles. In the next ten years there is a high probability we will be able to answer the questions: "What are the progenitors of SNe Ia? Why does their brightness change with lightcurve shape, color, stellar population age, or metallicity? Do they evolve with redshift? What fraction are aspherical, and why? What role do SNe Ia play in galactic chemical enrichment?," and "How does extragalactic dust compare to Milky Way dust?"

The path to answering most of these questions and improving SNe as standard candles is the same, construct large subsamples of SNe Ia split by various properties, and study correlations between them. This is a paradigm shift that will be enabled by huge new SN discovery projects. First we discuss the planned new projects (§2), then we discuss the above scientific questions §3-6. In §7 we discuss the systematic errors temporarily affecting SN cosmology and prospects for their eradication, and we conclude with recommendations in §8.

2. OUTLOOK

All current SN studies are sample-size limited. But in the next 10 years, that will no longer be the case. With thousands of SNe Ia discovered per year (we will need a new naming convention), we are leaving the serendipity-driven era, where we learn what nature wants to tell us, and entering the hypothesis-driven era, where large large-N subsamples can be constructed to test ideas. We can compare SNe in ellipticals to those in spirals, split them by color, redshift bin, ejecta velocity, or host metallicity. We will be able to correlate IR or polarimetric properties against spectral features, optical properties,

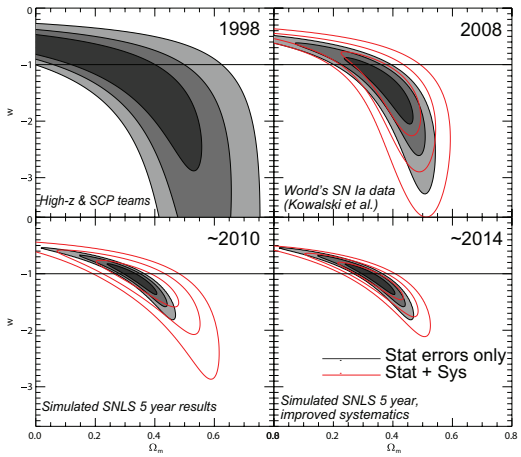

FIG. 1.— The top two panels show the remarkable improvements in w made using SNe Ia over the past decade (assuming a flat universe), the bottom two show the importance of improving systematics in the early years of the next decade. *Upper left:* $\Omega_M - w$ statistical-only constraints circa 1998 (see Garnavich et al. 1998). *Upper right:* By 2008, Kowalski et al., combining many data sets, showed that systematic errors are significant. *Bottom left:* Expected constraints for the year 5 results of SNLS, assuming additional low-z SNe, and double the number of $z > 1$ SNe from HST, assuming there is no improvement in systematic errors from the 3rd year result. *Bottom right:* Assumes the low-z data are on the SDSS photometric system, and a factor of two improvement in measurements of fundamental flux standards. Judged by the DETF figure of merit (the area of the inner 68.3% contour), the improvement from the 1998 results is a factor of 3, 5, and 10, including systematics

or host galaxy features. We can create data "cubes" in dozens of dimensions. It is hard to imagine where the most exciting discoveries will come from.

The most obvious progress will be at the high redshift frontier. At $z > 1$, less than two dozen SNe Ia are known (Riess et al. 2007). A refurbished HST should use ACS to continue to build the $1.0 < z < 1.5$ sample necessary to study the time evolution of w. However, to build a truly large, uniform sample will require JDEM/EUCLID. HST WFC3 will provide the first glimpse of SNe Ia at $1.5 < z < 3$ in the matter-dominated era (Riess & Livio 2006). The next generation of large telescopes, JWST, TMT, E-ELT and GMT will allow spectroscopy of $z > 3$ SNe, and extend studies to even higher redshifts. These studies may at last elucidate the progenitors of SNe Ia, and enable studies of SN Ia evolution over vast stretches of cosmic time.

Currently, intermediate redshift ranges are the best studied – ESSENCE (Wood-Vasey et al. 2008) and the Supernova Legacy Survey (SNLS; Astier et al. 2006) have obtained (but only published a fraction of) about 600 well measured, spectroscopically confirmed SNe Ia at $0.1 < z < 1.0$. The SDSS (Holtzman et al. 2008) has ~ 500 spectroscopically confirmed supernovae at $0.05 < z < 0.3$. Over the next few years the Pan-STARRS Medium Deep Survey (MDS) and the Dark Energy Survey will discover thousands of supernovae at $0.1 < z < 1.0$, though they will only be able to spectroscopically confirm a fraction of them. Ultimately LSST will produce tens of thousands of well measured SNe Ia per year in this redshift range, but will be limited by the number of follow-up facilities available. Many SN studies are done most efficiently at intermediate redshifts where large numbers of SNe can be studied over a few square degrees using a rolling search.

At low redshift SNe Ia have until this point been studied in more of a piecemeal fashion, necessitated by the lack of a multiplex advantage. Thus they suffer from, and cause, some of the largest systematic errors affecting SNe Ia (§7). However, in this regime there may be the greatest room for optimism in the coming decade. Within a few years, programs already underway, KAIT (Li et al. 2001), the Carnegie SN Program (CSP; Hamuy et al. 2006), the CfA program Hicken et al. (2009), and the Nearby SN Factory (Aldering et al. 2006) will produce a total of $\gtrsim 300$ cosmologically useful $z < 0.1$ SNe Ia. By 2010 a new wave of dedicated multi-square-degree detectors on small telescopes will be available, each of which will discover hundreds of SNe per year: Skymapper (5.7 sq. deg. FOV; Keller et al. 2007), the Palomar Transient Factory (7.5 sq. deg. FOV; Rahmer et al. 2008), the La Silla SN search (the QUEST camera on the La Silla Schmidt telescope), and the Pan-STARRS 3π search (7 sq. deg. FOV).

Low redshifts are where the fundamental work for understanding SNe Ia is done — time series spectroscopy, space-based UV follow-up, ground-based IR photometry and spectra, and spectropolarimetry. Because many of the systematic errors limiting SN Ia cosmology are a result of astrophysical ignorance, strides in this regime have an impact across SN cosmology at all redshifts, as seen in the bottom panels of Fig. 1.

3. THE PROGENITOR QUESTION

There is consensus that SNe Ia are the result of the explosion of a carbon-oxygen white dwarf that grows to near the Chandrasekhar limit in a binary system (Hoyle & Fowler 1960). But is debate over whether the companion is an

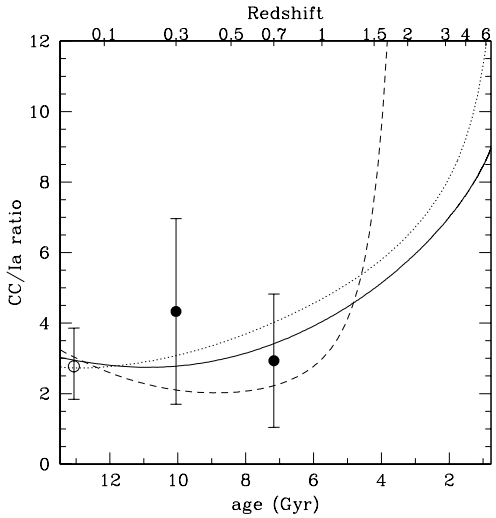

FIG. 2.— Ratio of the rates of the CC to Ia SNe as a function of redshift. The white and black dots are observed values (Dahlen et al. 2004; Mannucci et al. 2005). The lines show the predictions of the Gaussian "single-population" model (i.e. a model in which the DTD is a narrow Gaussian centered at 3-4 Gyr; dashed line), (Yungelson & Livio 2000) DD Chandrasekhar mass model (dotted line), and the "two-populations" shown in Figure 1 (solid line). The predictions use a Salpeter IMF and mass ranges of 3-8$M_\odot$ (SN Ia) and 8-40$M_\odot$ (CC SNe), and are scaled to match the observed values. Plot from Mannucci, Della Valle, & Panagia (2006).

evolved or main sequence star (single degenerate system; Whelan & Iben 1973), or whether it is another white dwarf, i.e. a double degenerate system (Iben & Tutukov 1984; Webbink 1984). The two scenarios produce different delay times from the birth of the binary system to explosion, so there is hope of deducing the progenitors of SNe Ia by studying their delay time distribution (DTD).

Empirically, the delay time distribution can be determined from the lag between the cosmic star formation rate and the SN Ia birthrate. However, without exquisite data, the shape can be ambiguous, with authors advocating a single Gaussian delay time (Gal-Yam & Maoz 2004; Strolger et al. 2004), bimodality, (Mannucci, Della Valle, & Panagia 2006; Scannapieco & Bildsten 2005; Sullivan et al. 2006) or a continuous, declining DTD from young to old stellar ages (Pritchet, Howell, & Sullivan 2008; Totani et al. 2008). These DTDs can then be compared to theoretical models to determine the progenitor (Belczynski, Bulik, & Ruiter 2005; Greggio 2005; Pritchet, Howell, & Sullivan 2008; Hachisu, Kato, & Nomoto 2008b,a)

Future outlook: There is a real possibility of determining the progenitors of SNe Ia in the next decade, after combining accurate $z < 1$ rates with measures at $1 < z < 4$. Different scenarios predict different Ia to core collapse ratios with redshift (Fig, 2).

Host galaxy photometry and spectroscopy can reveal the ages and metallicity of the gas and stars (Sullivan et al. 2006; Gallagher et al. 2008; Aubourg et al. 2008; Howell et al. 2009), and DTDs can be directly constructed from this information (Totani et al. 2008). Supernovae discovered at low redshift can provide the greatest amount of host information, though intermediate redshift surveys have a multiplex advantage when multislit spectroscopy is used to build large samples. These studies can benefit by choosing well studied fields (e.g. COSMOS, GOODS, VVDS).

4. SURVIVING OR PRECEDING MATERIAL

Occasionally SNe Ia leave hints about the explosion process or progenitors. This can take the form of SN ejecta interacting with previous phases of stellar mass loss (Hamuy et al. 2003), or absorption line evidence of mass loss episodes (Patat et al. 2007). It is possible for progenitors to be visible in pre-explosion X-ray images (Kahabka & van den Heuvel 1997). Finally, radio (Panagia et al. 2006) and optical (Leonard 2007) searches for companion star material reach contradictory conclusions unless the companion is also degenerate.

An exciting recent finding is the discovery of light echoes enabling spectroscopic observations of historical SNe (Rest et al. 2008; Krause et al. 2008). When combined with knowledge of the SN remnant, this may allow us to connect SN spectroscopic features with progenitor metallicity (Badenes, Bravo, & Hughes 2008a,b)

Future outlook: While finding traces of progenitors is rare, chances are directly proportional to the nearby SN discovery rate and the aperture of the telescopes used. X-ray facilities such as Chandra, and in the future, IXO, will help to find possible progenitors and study SN remnants in detail, and JWST and GSMTs may directly pre-image progenitors in the optical or IR. Rare signatures of pre-SN mass loss require time series spectroscopic observations of many supernovae to find the occasional goldmine.

5. GALACTIC FEEDBACK AND ENRICHMENT

SNe Ia are a significant source of iron-peak elements and energy input into the intergalactic medium. The realization that a significant frac-

tion of SNe Ia occur only a few hundred million years after star formation solved problems regarding cluster iron abundances (e.g. Matteucci et al. 2006; Scannapieco & Bildsten 2005). X-ray observations of clusters can also constrain SN Ia rates and models (de Plaa et al. 2007).

Future outlook: A refined understanding of SN Ia DTDs and theory of energetics and elemental yields will allow progress understanding galactic chemical enrichment. The synergy between SN rate studies and cluster studies, and between SNe Ia and X-ray studies is again apparent.

6. THEORY AND EXPLOSION

Theoretical explosion studies in 3d have only just begun (Gamezo, Khokhlov, & Oran 2005), though improvements in algorithms and computing power should make such studies routine. New observations can constrain open theoretical questions about the explosion:

- IR spectra constrain the transition to detonation: lines from CI, OI, and MgII probe explosion products in the outer layers (Marion et al. 2006).
- Unburned carbon probes incomplete burning: (Howell et al. 2006; Marion et al. 2006; Thomas et al. 2007; Hicken et al. 2007).
- Spectropolarimetry shows that some SNe Ia depart from spherical symmetry (see Wang & Wheeler 2008), forcing theoretical creativity (Wunsch & Woosley 2004; Röpke, Woosley, & Hillebrandt 2007; Hillebrandt, Sim, & Röpke 2007).
- Late time observations place limits on ^{56}Ni production, the source of SN Ia luminosity (Mazzali et al. 2007).
- Oddballs SNe Ia can require new classes of models (Hamuy et al. 2003; Li et al. 2003), even pushing classification boundaries (Benetti et al. 2006; Valenti et al. 2009). A few high luminosity discoveries suggest the existence of super-Chandra mass explosions (Howell et al. 2006).

Future outlook: Theoretical studies most readily benefit from the discovery of large numbers of low redshift SNe Ia, because this allows more high S/N observations, the discovery of outliers, spectropolarimetry, and challenging UV, IR, and late time observations.

TABLE 1
CURRENT ESTIMATES OF SYSTEMATIC ERRORS ON W

Systematic	SNLS	ESSENCE	SDSS
Flux reference	0.053	0.02	0.037
Experiment zero points	0.01	0.04	0.014
Low-z photometry	0.02	0.005	···
Landolt bandpasses	0.01	···	0.019
Local flows	0.014	···	0.04
Experiment bandpasses	0.01	···	0.014
Malmquist bias model	0.01	0.02	0.017
Dust/Color-luminosity (β)	0.02	0.08	0.017
SN Ia Evolution	···	0.02	···
Restframe U band	···	···	0.08

NOTE. — Systematic error estimates on $\langle w \rangle$ from Conley et al. (2009), Wood-Vasey et al. (2007), and Kessler et al. (2009). Hicken et al. (2009) CfA3 systematics are similar to those for Wood-Vasey et al., though they are not separately tabulated. The SDSS errors are for their MLCS2k2 fit. Errors for each survey use their largest sample. For the SNLS 3rd year results the total systematic error is ~ 0.06, comparable to the statistical error, and the total statistical + systematic error is ~ 0.09. The other studies find that systematic errors are dominant.

7. COSMOLOGY: SYSTEMATIC ERRORS

Arguably, the most important science done with SNe Ia is their use as standard candles. Systematic errors now dominate, but most are known problems solvable with next-generation data sets. Table 1 shows the dominant systematic errors for the measurement of w, and we discuss the important ones here.

7.1. *Flux reference and zero points*

The dominant systematic in many studies (up to a 6% systematic error on w; Table 1), is flux calibration of photometry across multiple passbands, an effect which introduces correlated errors when comparing SNe at different redshifts. Because of the need to use historical low-z data, today SNe Ia are usually calibrated onto the Landolt system, which is not sufficiently well understood and is no longer fully reproducible. A related problem is that at low redshift there is no single, uniform, well characterized low z data set, so we must cobble together inhomogeneous data with varying qualities of flux calibration and bandpass knowledge.

Future outlook: The release of new low redshift data will allow cosmological studies to move off of the Landolt system, though selection effects, and the problems associated with combining data sets will persist. Further progress will require better calibration in physical units, including the laboratory or in-

situ measurements of bandpasses. The ACCESS experiment aims to establish a standard star network based on physical units by calibrating a number of nearby stars, e.g. Sirius, Vega, BD+174708 through direct comparison to NIST standards.

A comparison low-redshift sample must be built for JDEM, including 500 SNe Ia at $z < 0.1$ of sufficient flux calibration that they can be compared to space-based detections (Albrecht et al. 2009). This requires low redshift projects on the scale of this decade's intermediate redshift efforts.

7.2. *The Ultraviolet*

The restframe ultraviolet accounts for the largest systematic in the SDSS SN survey (Table 1). Jha et al. (2006) indicate that the restframe U-band is not as well behaved photometrically as other optical bands, with as much as 0.08 mag dispersion. Meanwhile, it remains poorly understood spectroscopically, (Ellis et al. 2008; Foley et al. 2008), possibly due to line blanketing effects sensitive to metallicity. Differences in treatment of the restframe U-band account for many of the differences in contemporary lightcurve fitters and directly impact their extinction calculations.

Future outlook: Because of the difficulty of scheduling and signal-to-noise requirements, space-based UV programs with HST and Swift require the discovery of hundreds of nearby supernovae at very early times over the course of a year. This is only now becoming possible with large low redshift surveys. Another possibility is studying SNe at $z \sim 0.2$ where the restframe UV is shifted into observed g-band. SDSS-II will soon provide hundreds, and ultimately LSST will provide thousands. It may also be desirable to avoid restframe U in future studies like JDEM.

7.3. *Dust extinction*

Corrections for reddening due to dust in SNe Ia are complicated by the fact that this correction is degenerate with an intrinsic color-luminosity relation — brighter SNe Ia are intrinsically bluer, dimmer ones are redder (Riess, Press, & Kirshner 1996; Tripp & Branch 1999). A further complication is that the dust along the line of sight to SNe Ia does not have the same average properties as Milky Way dust – R_B appears to range from 2-3, as compared to 4.1 for the average line of sight in the Milky Way. This is most apparent in low redshift studies of SNe Ia with optical to IR photometry (Krisciunas et al. 2007; Wang et al. 2008; Elias-Rosa et al. 2008), though it is also seen at high redshift (Astier et al. 2006; Conley et al. 2007; Hicken et al. 2009).

Lightcurve fitters treat reddening differently. SALT2 (Guy et al. 2007), and SiFTO (Conley et al. 2008) fit for a color-luminosity relation with a slope, β, but do not distinguish between the intrinsic SN dim-red relation and dust. MLCS2k2 (Jha, Riess, & Kirshner 2007) attempts to separate the two effects using assumptions and redshift-dependent priors. Because average corrections are made, either method is susceptible to the observed evolution in supernova properties and environments with redshift (Howell et al. 2007).

Estimates of the systematic impact on w range from 0.02 to 0.08 (Table 1), arguably the dominant systematic. At the core of this error is a trifecta of ignorance: our lack of understanding of dust in distant galaxies, our poor knowledge of the intrinsic colors of SNe Ia, and our uncertainty regarding the progenitor systems of SNe Ia and how the mix in SN Ia subtypes will evolve with redshift.

Future outlook: It may be overly conservative to consider the dust issue a 2% in distance "systematic floor" as characterized by the JDEM FoMSWG (Albrecht et al. 2009), because there is hope for solving it and possibly ways of circumventing it.

The reduced sensitivity to dust in the IR should allow the characterization and mitigation of the dust extinction problem. Long wavelength baseline observations from the optical to the UV for low redshift supernovae have allowed determinations of the extinction law along the line of sight to individual SNe (Elias-Rosa et al. 2008; Krisciunas et al. 2007). When huge SN samples are available in the next decade, indicators of intrinsic SN color (e.g. certain spectroscopic features) may allow the separation of intrinsic and dust reddening. Meanwhile, SNe Ia appear to be better standard candles in the near-IR, requiring little to no lightcurve shape or color correction (Krisciunas, Phillips, & Suntzeff 2004; Wood-Vasey et al. 2008). The sample size of NIR spectra (now > 50) is just beginning to make accurate

K-corrections feasible for the IR which will improve the calibration of IR photometry.

While there is much room for growth in IR observations in the next decade, they are expensive, particularly at high redshift. Another alternative is to construct dust-reduced samples of SNe Ia from those in elliptical hosts, or far from the centers of galaxies. This should become possible with the discovery of hundreds to thousands more SNe Ia in next-generation surveys.

7.4. *Evolution*

There is strong evidence that some SNe Ia come from a short-lived population of at most a few hundred million years (i.e. "prompt"), while "tardy" SNe Ia arise in an old population of at least several Gyr (Mannucci et al. 2005; Scannapieco & Bildsten 2005; Sullivan et al. 2006). Moreover, the prompt SNe Ia are have broader lightcurves and are on average brighter than their tardy counterparts (Hamuy et al. 1996; Howell 2001; Sullivan et al. 2006). Thus, as star formation increases by a factor of 10 from $z = 0$ to $z = 1.5$, the ratio of prompt to tardy SNe Ia rises, resulting in an increase in the average lightcurve width and intrinsic brightness of SNe Ia (Howell et al. 2007). Additionally, SNe Ia at higher redshift show weaker intermediate mass element features in their spectra, consistent with the idea that they instead have more iron-peak elements, including the ^{56}Ni that gives rise to their brighter lightcurves (Sullivan et al. 2009). Gallagher et al. (2008) and Howell et al. (2009) find that metallicity has some effect on SN Ia ^{56}Ni yield, and thus luminosity.

An evolving mix of SNe Ia need not inhibit cosmological studies, because supernovae are calibrated based on their lightcurve shape. Problems could arise if the correction is imperfect (Hicken et al. 2009), though Howell et al. (2009) find that the SiFTO lightcurve fitter, at least, produces no Hubble residuals with respect to the galaxy properties studied.

Future outlook: In the next decade it will be possible to separate SN Ia samples by features like host galaxy metallicity, or age of the stellar population. Hints of demographic shifts will also become well measured. While many future SN Ia programs are looking towards photometric identification of targets, rigorous testing of possible SN Ia evolution with redshift requires spectroscopy. The host galaxies of SNe Ia should also be well characterized with spectroscopy and UV to IR photometry to understand progenitor populations.

8. PRIORITIES

Many exciting science questions will be answered in the next decade by the study of SNe Ia, including the nature of Dark Energy, but it will require building large samples of supernovae from $0 < z < 4$, involving new resources.

The top priority for the immediate future is building new, well controlled low redshift SN Ia samples comparable to those that JDEM/EUCLID will ultimately produce. Systematic effects are most easily reduced by low redshift studies, and this is where most non-cosmology SN Ia science is done. New low redshift surveys to discover hundreds of SNe per year starting in 2009/10 include PTF, Skymapper, the La Silla SN search, and Pan-STARRS 3π. Skymapper will produce its own lightcurves, but the rest will be limited by follow-up resources. Therefore, massive follow-up programs targeting low-redshift SNe Ia are necessary. One such program is Las Cumbres Observatory Global Telescope Network (LCOGTN), a planned worldwide network of 12-15 1 meter optical imaging telescopes to supplement the existing 2 meter Faulkes North and South telescopes. A large fraction of the time on LCOGTN will be dedicated to low redshift SN follow-up. In addition, the continued operation or growth of small, especially robotic or queue scheduled telescopes is essential to the immediate future of SN Ia science. The NOAO ReSTAR initiative to grow the number of 2-4m telescopes is of particular importance.

Looking farther ahead, the next priority is measuring the Dark Energy equation of state with JDEM/EUCLID, though only if there is a significant SN component and a spectrograph that can resolve SN Ia features (thousands of km/s). In this case many of the selection effects are mitigated by the single space mission concept, and the follow-up resources are self-contained.

Of equal or greater importance to SN Ia studies is LSST. This will be the holy grail of transient studies, with tens of thousands of well sampled multiband lightcurves per year. However, many studies will be limited by the follow-

up resources available, e.g. spectroscopy, IR, UV, polarimetry.

Finally, JWST, E-ELT, TMT, and GMT will allow great strides in SN Ia science including the determination of SN Ia progenitors from high redshift SN Ia rates, studies of evolution pushing to an era when SNe Ia may be physically different, and allowing IR studies to become what optical studies are today.

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