

Wide-Field Telescope Observations of Supernovae

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Abstract: The explosive universe of supernovae has been transformed from a slow target-by-target activity into a systematic census of the variable universe thanks to the advent of wide-field survey telescopes; this paper reviews this transition and its scientific consequences. Survey capability is not just a function of collecting area, as the five representative facilities examined here, ASAS-SN, ATLAS, Pan-STARRS, the Zwicky Transient Facility, and the Vera C. Rubin Observatory, demonstrate – they have an étendue of collecting area times field of view that varies by over two orders of magnitude among the facilities and is largest for Rubin. This increase in instrumental grasp, combined with an automated pipeline of difference imaging, the vetting of supernovae by means of machine-learning "real-bogus" classification, alert brokering, and photometric classification has led to a roughly tenfold increase in the annual number of classified supernovae and a growing discrepancy between supernova detection and spectroscopic confirmation. The samples produced are large and uniform enough to relate light-curve shape to progenitor channels, the core collapse of massive stars, and thermonuclear disruption of white dwarfs, and effectively use Type Ia supernovae as standardizable distance indicators, the key to the discovery of cosmic acceleration and current constraints on dark energy. Modern supernova astronomy is productive only through the integration of observing strategy with data analysis, not through either alone.

Keywords: Supernovae, Wide-field surveys, Time-domain astronomy, Difference imaging, Type Ia supernovae, Observational cosmology.

1. Introduction

Supernovae mark the violent deaths of stars, for a short period outshining its whole galaxy and dispersing heavy elements formed within stars into space. The events are all inherently transient; they reach their maximum brightness in days and then drop in subsequent weeks and months, and so their scientific value depends on their ability to be detected rapidly and tracked continuously over the following weeks and months. This was hard to achieve in most of the twentieth century. Galaxy after galaxy, observers looked through photographic plates, and even Fritz Zwicky, who established the name and started out with an energy to pursue these objects, found some one hundred and twenty.

This was a limitation of observational infrastructure rather than individual effort. One telescope pointing at one field at a time will only observe a small portion of the sky between revisits, limiting the number of explosions it can observe during their evolution. This was overcome using large-format charge-coupled devices (CCD) attached to telescopes that had intentional large fields of view. A wide-field survey of the sky looks at large areas of space again and identifies any objects that have moved or been discovered since the last scan. The modern time-domain astronomy is built on this synoptic strategy [1]. But the economic argument is equally potent – that a handful of automated survey telescopes can now do what once took the collective effort of the entire observing community.

The impact on discovery rates has been substantial. In the 1990s, a few tens of supernovae were classified each year, but current surveys report thousands of supernovae. ZTF alone has detected hundreds of thousands of transient candidates and has generated the largest flux-limited spectroscopic

sample of supernovae to date [2, 3]. This order-of-magnitude increase comes not from any single new technology but from the combined benefits of wide-field optics and automated data-analysis pipelines that discriminate true transients from artefacts in real time [4].

There are two reasons for developing such instruments. Supernovae are fundamental to stellar astrophysics because they leave a legacy of the state of the progenitor star, and of the heavy element synthesis in their interior [5]. They are also central to cosmology: Type Ia supernovae are used as standardizable distance indicators and it was through them that the accelerating expansion of the Universe, and by implication dark energy, was discovered [6, 7]. Large samples constitute two scientific programmes at the same time, therefore. The topic is also of increasing current relevance. The Vera C. Rubin Observatory and its ten-year Legacy Survey of Space and Time (LSST) have begun operations and will produce alerts for transient events, such as supernovae, every night, as well as providing images of an unprecedented number of astronomical objects. The techniques discussed here are not just an area of well-established research, but also the foundation upon which the next ten years of transient astronomy will be constructed. This paper is a review of the use of wide-field telescopes for supernova observation. It starts by providing an overview of previous research, then outlines the survey methodology used to detect and track stellar explosions, and finally discusses the resulting instrumental and scientific results, before concluding. Special focus is on the relative effectiveness of the top facilities; and on the analysis methods that make their data scientifically useful. The goal in all is to demonstrate that modern supernova science is dependent on, and grounded in, the combination of observational technology and data analysis rather than one or the other alone.

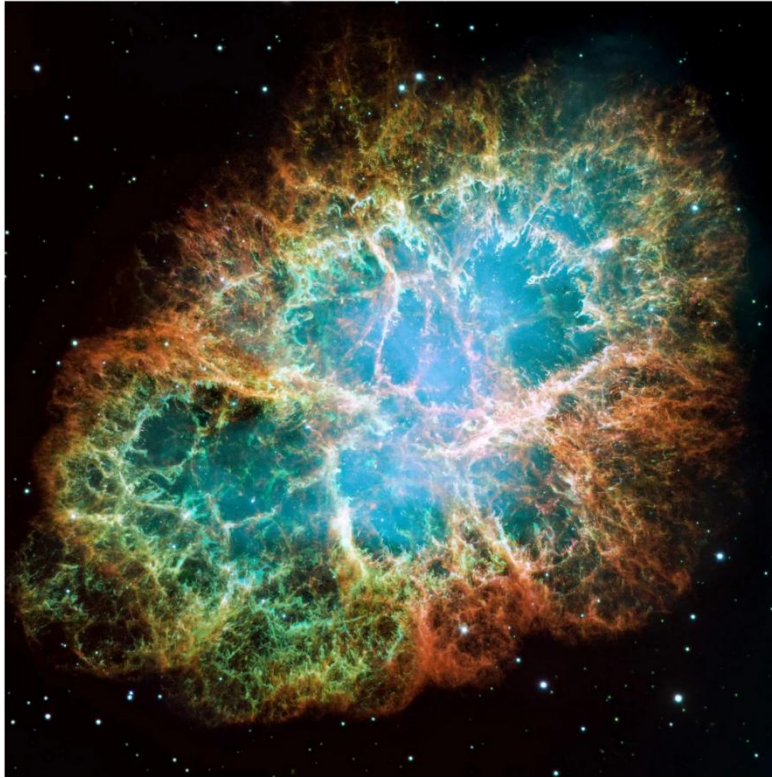


Figure 1. Hubble Space Telescope image of Messier 1 (the Crab Nebula), the remnant of a historical supernova.
(Source: <https://science.nasa.gov/mission/hubble/science/explore-the-night-sky/hubble-messier-catalog/messier-1/>)

2. Literature Review

There are three strands of the literature related to wide-field supernova surveys: instrument and survey descriptions, methods for transient detection and classification, and scientific applications. The first strand records details of the facilities. The All-Sky Automated Survey for Supernovae (ASAS-SN) was described by Kochanek et al. (2017) [8] as a small-telescope survey working toward monitoring the visible sky for bright, nearby transients. ATLAS is a high cadence system, mostly designed for asteroid detection, but also serving as a transient survey, described by Tonry et al. (2018) [9]. Chambers et al. (2016) [10] described the Pan-STARRS1 surveys, which sacrificed field of view for depth; Bellm et al. (2019) [1] and Graham et al. (2019) [4] outlined the system design and science goals of ZTF, which is the most successful optical transient survey of its time. The Catalina Real-Time Transient Survey and the Palomar Transient Factory, among others, were examples of programmes that were instrumental in scaling up techniques noted in the previous ones. The second strand concerns the analysis pipeline. Significant methodological literature covers difference imaging, subtraction artefacts and ‘real–bogus’ classifiers using machine learning to reduce the numbers of candidates in candidate streams by orders of magnitude [1]. As the volume of alerts increased, they needed to be better understood, so community brokers were developed; Förster et al. (2021) [11] present ALerCE, and Möller et al. (2021) [12] present Fink for pre-Rubin era alert ingestion, enrichment, and classification. The number of expected discoveries was quantified using simulation studies like Feindt et al. (2019) [13] and this helped guide survey design. The third is the association of data with physical interpretation. The canonical review on supernovae spectral classification was given by Filippenko (1997) [5] who connected the observed types with different progenitor channels. Phillips (1993) [14] found the

empirical relationship between peak luminosity and decline rate for Type Ia supernovae that makes them “standardizable candles,” and Riess et al. [6] and Perlmutter et al. [7] applied these candles to establish cosmic acceleration. In the future, Ivezić et al. (2019) [15] outlined the reference design and expected data products of LSST, stating that they expect to define the expectation of having million-object samples of SNe, which will help to overcome the systematic uncertainties that currently constrain dark-energy constraints. Together, this collection of writing inspires the focus of the present review on instrumentation and analysis coupling. When read together the three strands provide a coherent progression: as more data have been collected, sky coverage has expanded, the limiting magnitude has been pushed to greater depth, and the cadence has been increased; at the same time, the analytical literature has been able to maintain the same level of reliability in classification. The present review brings these together and does not treat any one strand in isolation.

3. Methodology & Data Sources

There are two components to the methodology in which wide-field telescopes discover and track supernovae: an observing strategy to decide what is observed, and a data-processing pipeline to decide what is recovered. Both are described here and the comparative framework used in the analysis that follows is outlined.

3.1. Survey Design and Observing Strategy

Survey design is based on three parameters that jointly determine performance. Aperture establishes the limiting magnitude, the faintest object that can be seen, and thus the cosmic volume in which supernovae of a given luminosity can be seen, increasing in volume rapidly with depth, so that the detectable sample size increases substantially even with modest improvements in limiting magnitude. The other key

factor is the field of view: cameras with a field of view of tens of square degrees can map an entire hemisphere in a few nights. The repeat times, or cadence, determine the sampling resolution of rising and falling sections of the light curve and the rapidity at which a transient is identified. These parameters are coupled: increasing the depth decreases the sky coverage and increasing the cadence decreases both the depth and the sky coverage with a given amount of observing time. In this review, the collecting area, A , and the solid angle of the field of view, Ω , are combined into a single figure of merit for survey speed, namely the étendue, $A \cdot \Omega$ [15].

Another design consideration is multi-band imaging – taking a series of broad-band images sequentially gives the color information necessary to constrain the temperature of a transient, to separate the different types of supernovae photometrically, and to calibrate observations for cosmological applications. In practice, surveys also build a fixed map of the sky into a grid of fields and point slightly between visits to account for gaps between detectors as well as to get the deep reference frames needed for the later detection.

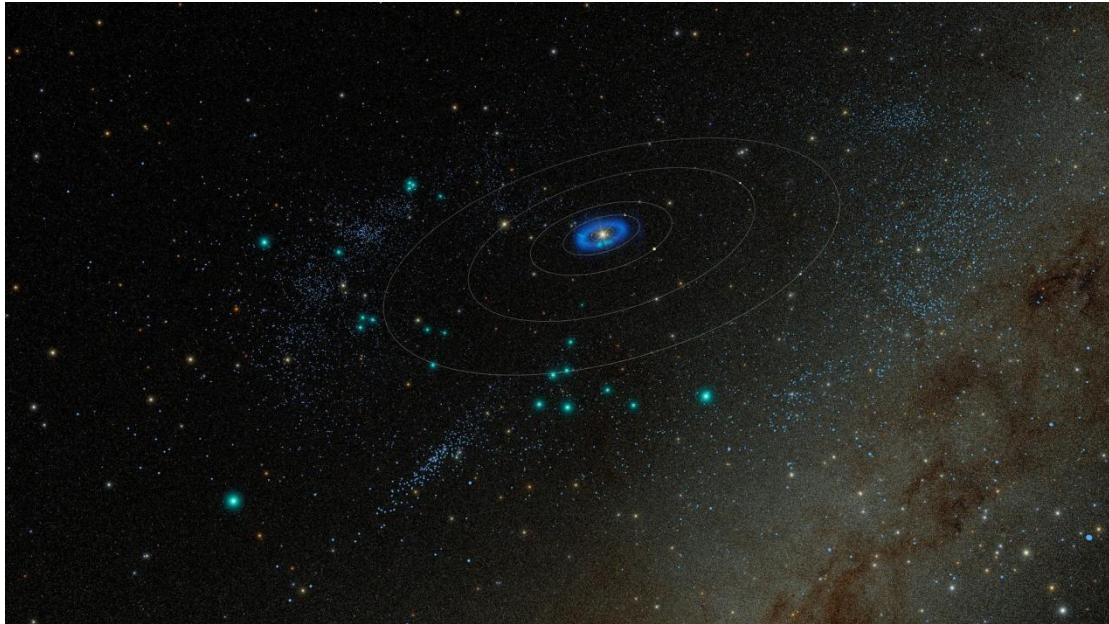


Figure 2. 3D rendering of trans-Neptunian objects discovered by NSF-DOE Rubin

(Source: <https://rubinobservatory.org/gallery/collections/main-gallery/6du3g42bol48nb2dolkk5pe77m>)

3.2. Difference Imaging and Candidate Vetting

The first step in the processing pipeline is difference imaging or, as it is sometimes called, template subtraction. Many exposures are used to make a deep reference image of each field, which is then geometrically matched to each new science frame, and convolved with the point-spread function of the science frame to match it before subtraction. If there is no change in the sky, the subtraction should remove all the static and leave only sources with changes, and in an ideal case, a supernova that has not been detected in the template should show up as a bright, clean point source, possibly overprinted by the sky background of the host galaxy. The convolution step is the most time-consuming step and is the main source of spurious residuals around bright or saturated stars due to variations in seeing and atmospheric transparency from epoch to epoch. The resulting detections are many and false, and each is given a ‘real-bogus’ score by a machine-learning classifier, traditionally a random forest, but more recently a convolutional neural network, based on the pixel information in the difference stamp. This stage eliminates by orders of magnitude the candidate stream but retains most of the true sources [1]. After the identification of a source, forced photometry at a fixed position is applied to reconstruct the full light curve even for the positions where the object was below the limit of detection in a single image.

3.3. Alert Distribution, Classification, And Follow-Up

Surviving candidates are packaged up in alert packets and broadcast in near real time. To manage the very high volume of alerts per day (up to millions per night), a “community of brokers” filters the stream, cross-matches candidates with external catalogues, adds contextual metadata, and applies additional photometric classifiers to identify good SN candidates [11, 12]. The classification is also aided by a second stage, based on the ‘light curve’ built up as the object brightens, which is used to determine the type of supernova from the shape and color evolution of the light curve. This is important, as the definitive classification is done from the spectrum of the light, and only a fraction of discoveries can be processed in the same way. Spectroscopically confirmed or reliably photometrically classified events are entered into the Transient Name Server, which is at the heart of the naming process and coordinates claims to prevent multiple claims. Importantly, the pipeline is not a linear sequence but is a feedback process: samples are used to train the classifiers, and the frequency of surveys can be adjusted based on the transients that were not captured. The approach can therefore be best seen as a single closed system in which the optimization of the optics, software, and follow-up resources are coupled. The same infrastructure enables fast public warning, in which case, when an alarm is received by a group around the world, they can send out follow-up within minutes of the detection and thus observe the initial and most informative stages of an explosion.

4. Results & Analysis

The above methodology results in two areas: relative effectiveness of the surveys as tools, and the relative scientific value of the samples they produce. These aspects are examined in turn, with supporting data presented in the tables and figures below.

4.1. Comparative Survey Capability

Table 1 is a summary of the defining parameters of the five representative facilities used in this study ranging from small-lens systems to an 8-meter-class telescope. These are approximate figures to indicate scale only and do not constitute a specification. These values show clear differences in survey design philosophy.

Table 1. Representative wide-field survey facilities and their principal observing parameters

Survey	Aperture (m)	Field of view (deg ²)	Single-visit depth (mag)	Typical cadence	First light
ASAS-SN	~0.14	all-sky / night	$g \approx 18.5$	~1 night	2013
ATLAS	0.5	~29	~19.5	1–2 nights	2015
Pan-STARRS1	1.8	7	~21	days	2010
ZTF	1.2	47	$r \approx 20.5$	2–3 nights	2017
Rubin / LSST	8.4	9.6	~24.5	3–4 nights	2025–26

ASAS-SN observes the entire sky at a shallow depth of ~18.5 mag, well suited to bright and close objects; Pan-STARRS1 has greater depth, but a narrower field of view; and ZTF is a medium-sized (1.2 m) telescope with a wide camera that observes the northern sky every two or three nights. These trade-offs are summarized in the étendue, shown in Figure 3. The surveys' grasp spans more than two orders of

magnitude when plotted on a log axis, ending with the Rubin Observatory with its 9.6-square-degree field of view, which exceeds the survey capability of previous facilities [15]. The result shows that survey performance is not driven by a single parameter, such as aperture or field of view, but by their combination and by the continued development of larger detectors.

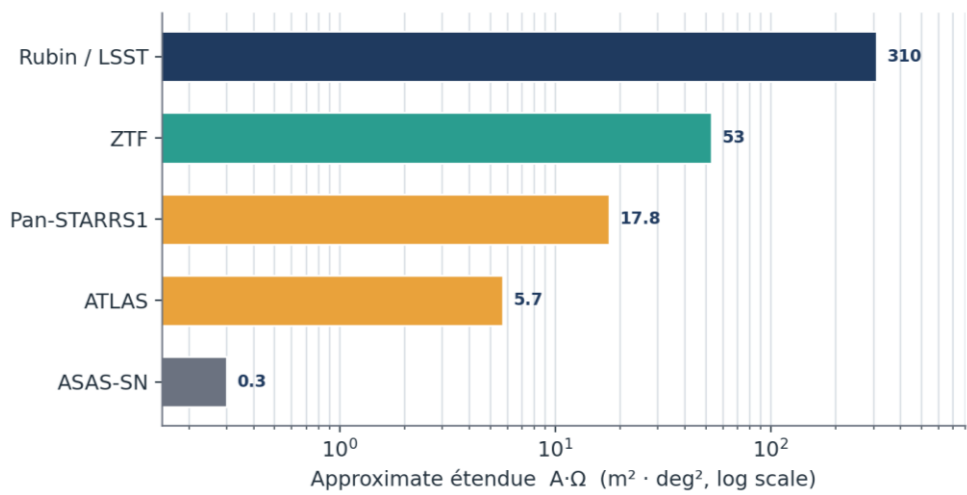


Figure 3. Approximate étendue ($A \cdot \Omega$) of the surveys in Table 1, on a logarithmic axis

4.2. Detection Pipeline and Discovery Yield

The recovery of transients from raw imaging is done according to the pipeline as described in figure 4. This reflects the scale of the system, since a single ZTF exposure contains

on the order of a quarter-billion pixels, and the Rubin Observatory is expected to produce of order twenty terabytes of nightly imaging data, and of order tens of billions of difference-image detections during its lifetime, far more than can be inspected by any human eye [15].

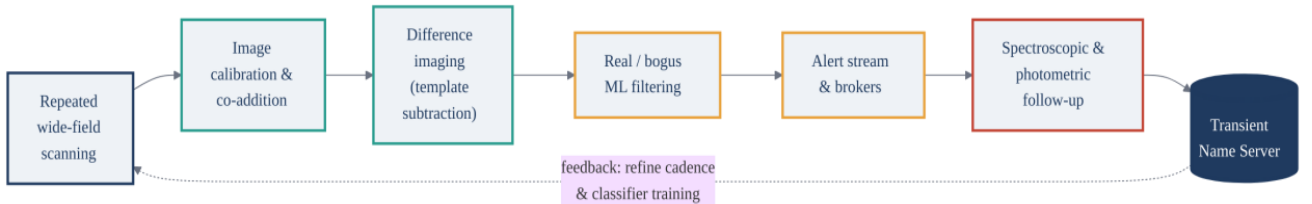


Figure 4. The standard wide-field transient discovery pipeline, from repeated scanning through difference imaging, machine-learning vetting, and alert distribution to spectroscopic follow-up, with feedback to cadence and classifier training

The result of this automated method is displayed in Figure 5, which plots the annual number of classified supernovae. This is an order-of-magnitude increase from the few tens of supernovae per year found in the photographic era, to several thousand in the high cadence digital era, as exemplified by the

supernova discoveries of ZTF, which includes the largest flux-limited supernova survey to date [2–4]. The figure also reveals a growing bottleneck – detection now far outpaces spectroscopic classification, and that is driving the selection of which events are studied in detail.

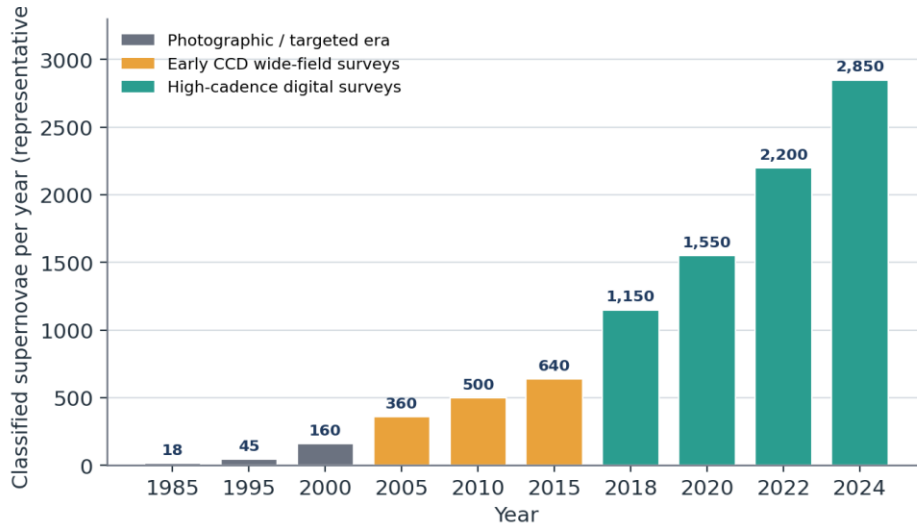


Figure 5. Representative growth in the annual number of classified supernovae, illustrating the order-of-magnitude rise that accompanied high-cadence digital surveys.

4.3. Classification, Light Curves, And Progenitors

All samples are classified before scientific analysis. The main types of spectra and their physical causes are listed in Table 2. SNe with hydrogen are Type II; SNe without hydrogen are Type I, further classified as Si (Ia), or He (Ib, Ic).

This taxonomy reflects two separate explosion channels: collapse of the iron core of a massive star, and thermonuclear disruption of an accreting white dwarf [5], as illustrated in Figure 6. A key survey product is the light curve, which contains complementary information, and schematic light

curves of the major classes are displayed in Figure 7. Type Ia supernovae brighten rapidly to a peak and then decline more slowly, fueled by the radioactive decay of nickel and cobalt; Type II-P supernovae have a long plateau phase over the course of months, as a recombination front travels back through a hydrogen envelope; and stripped-envelope Types Ib and Ic are similar to Type Ia but tend to be lower in peak brightness and broader in profile. These are densely and uniformly sampled in surveys, so that population studies, rates, luminosity functions, and host-galaxy correlations can only be made using them, and rather than from single-object campaigns alone.

Table 2. The principal supernova spectral classes, their progenitors, and explosion mechanisms. GRB denotes gamma-ray burst

Class	Spectral signature	Progenitor	Mechanism	Notable use
Type Ia	No H; strong Si II	C/O white dwarf in a binary	Thermonuclear runaway	Standard candle
Type II	Hydrogen lines	Massive star with H envelope	Iron-core collapse	Plateau (II-P) studies
Type Ib	He, no H	Stripped massive star	Core collapse	Mass-loss / binaries
Type Ic	No H, no He	Heavily stripped massive star	Core collapse	Links to GRBs

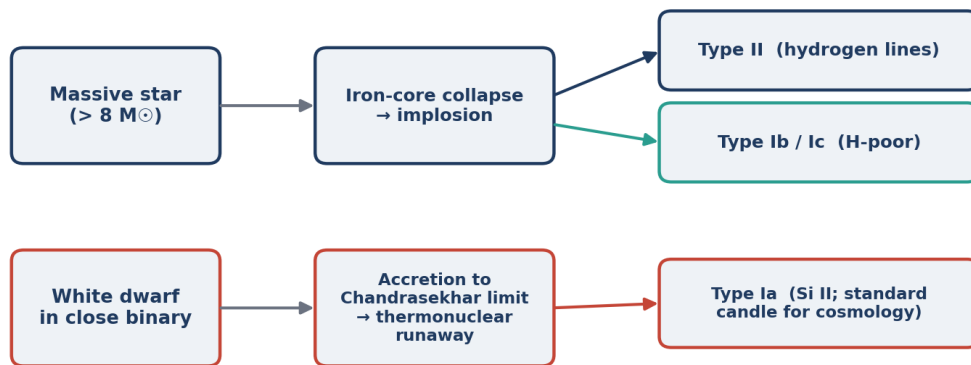


Figure 6. Stellar progenitor pathways mapped to observed supernova spectral types

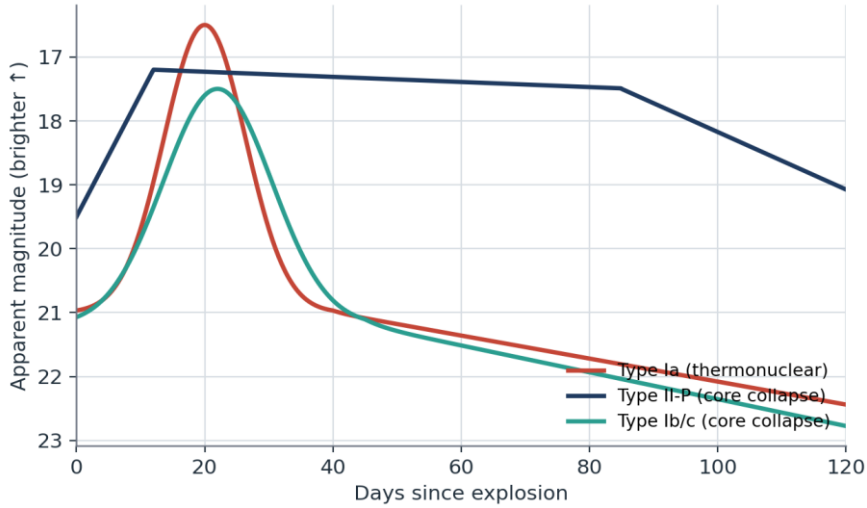


Figure 7. Schematic light curves of the principal supernova classes; the y-axis is inverted so brighter events lie higher.

4.4. Cosmological Results

The most significant impact has been cosmological. Type Ia supernovae tend to have a near-universal peak luminosity, as their white-dwarf progenitors are detonated near the Chandrasekhar mass, and the remaining variations are minimized by the Phillips (1993) [14] relation, which states that brighter events fade more slowly. Standardized in this way, their apparent brightness yields a distance and their host-galaxy redshift a recession velocity. When applied to these distant events, the method showed that the supernovae were fainter than would be expected from a universe that is slowing down with time [6][7], thus setting up cosmic acceleration based on a handful of dozen sources. Since then, this enterprise has been transformed by wide-field surveys, such as ZTF, which should provide light-curves for on the order of one thousand low-redshift Type Ia supernovae for cosmology, and the Rubin Observatory, which is designed to observe millions of supernovae over a broad redshift range within a single, internally-consistent photometric system, thereby removing systematic uncertainties that plague current constraints on dark energy.

5. Conclusion

In this review, the application of wide-field telescopes for discovery and monitoring of supernovae has been discussed and the productivity has been attributed to the combination of observing strategy with automated analysis. On the instrumental side, the key distinction is the difference in étendue, over two orders of magnitude, between the shallow all-sky survey of ASAS-SN and the deep, wide survey of the Rubin Observatory. Analytically, a pipeline for difference imaging, machine-learning vetting, alert brokering and photometric classification yields a manageable sample of true transients in the presence of hundreds of thousands of transient candidates per night.

The scientific implications are determined by the size and consistency of the samples that can be produced. Densely sampled light curves have resolved the connection between supernova classes and their progenitors, distinguishing the core collapse of massive stars from the thermonuclear disruption of white dwarfs. The same samples are also the basis of the use of Type Ia supernovae as standardizable candles, with which cosmic acceleration was discovered, and dark energy remains a topic of ongoing research.

The analysis shows three results. The comparison of

facilities indicates that no single parameter, such as aperture, field of view, or cadence, alone determines survey power. Survey speed is more appropriately summarized by the étendue, defined as collecting area times field of view ($A \cdot \Omega$), while cadence remains a separate constraint on temporal sampling. The étendue has increased by more than two orders of magnitude and strongly favors the Rubin Observatory. Second, the discovery record shows that the classification rate has increased by about an order of magnitude, with the gap between discovery rate and spectroscopic confirmation rate growing. Third, the mapping of light-curve morphology onto progenitor channels shows that uniform photometric samples can retrieve physical information previously only available via intensive single-object study.

Important challenges persist. Discovery has not been matched by spectroscopic follow-up, and transforming photometric classification into a reliable service must be tested on a limited number of labelled objects. Cross-instrument calibration will constrain cosmological precision and the data sets expected from the Rubin Observatory will stretch the scalability of existing brokers and archives. None of these barriers appears fundamental. The trajectory described here - larger samples, deeper limits, faster cadences, and more sophisticated analysis - is moving toward supernova samples that can be considered problems in precision statistics, both of stellar death and cosmic expansion. The wide-field survey is not just a quicker way to look for familiar objects but an instrument that can ask new statistical questions as well, a lasting shift in the type of questions that the data can answer.

References

- [1] Bellm, E. C., et al. (2019). The Zwicky Transient Facility: System overview, performance, and first results. *Publications of the Astronomical Society of the Pacific*, 131(995), 018002.
- [2] Fremling, C., et al. (2020). The Zwicky Transient Facility Bright Transient Survey. I. Spectroscopic classification and the redshift completeness of local galaxy catalogs. *The Astrophysical Journal*, 895(1), 32.
- [3] Perley, D. A., et al. (2020). The Zwicky Transient Facility Bright Transient Survey. II. A public statistical sample for exploring supernova demographics. *The Astrophysical Journal*, 904(1), 35.
- [4] Graham, M. J., et al. (2019). The Zwicky Transient Facility: Science objectives. *Publications of the Astronomical Society of the Pacific*, 131(1001), 078001.

- [5] Filippenko, A. V. (1997). Optical spectra of supernovae. *Annual Review of Astronomy and Astrophysics*, 35, 309–355.
- [6] Riess, A. G., et al. (1998). Observational evidence from supernovae for an accelerating universe and a cosmological constant. *The Astronomical Journal*, 116(3), 1009–1038.
- [7] Perlmutter, S., et al. (1999). Measurements of Ω and Λ from 42 high-redshift supernovae. *The Astrophysical Journal*, 517(2), 565–586.
- [8] Kochanek, C. S., et al. (2017). The All-Sky Automated Survey for Supernovae (ASAS-SN) Light Curve Server v1.0. *Publications of the Astronomical Society of the Pacific*, 129(980), 104502.
- [9] Tonry, J. L., et al. (2018). ATLAS: A high-cadence all-sky survey system. *Publications of the Astronomical Society of the Pacific*, 130(988), 064505.
- [10] Chambers, K. C., et al. (2016). The Pan-STARRS1 surveys. [arXiv:1612.05560](https://arxiv.org/abs/1612.05560).
- [11] Förster, F., et al. (2021). The Automatic Learning for the Rapid Classification of Events (ALeRCE) alert broker. *The Astronomical Journal*, 161(5), 242.
- [12] Möller, A., et al. (2021). Fink, a new generation of broker for the LSST community. *Monthly Notices of the Royal Astronomical Society*, 501(3), 3272–3288.
- [13] Feindt, U., et al. (2019). *simsurvey*: Estimating transient discovery rates for the Zwicky Transient Facility. *Journal of Cosmology and Astroparticle Physics*, 2019(10), 005.
- [14] Phillips, M. M. (1993). The absolute magnitudes of Type Ia supernovae. *The Astrophysical Journal Letters*, 413, L105–L108.
- [15] Ivezić, Ž., et al. (2019). LSST: From science drivers to reference design and anticipated data products. *The Astrophysical Journal*, 873(2), 111.