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Type Ia Supernova Cosmology

C. M. Pfeffer[1]

[1]*Department of Physics, Virginia Tech, 850 West Campus Drive, Blacksburg, VA 24061, USA*

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ABSTRACT

Even in the days when all of the Type Ia Supernovae discovered in a year could be counted on two hands, astronomers recognized their strikingly uniform luminosity. An appealing distance indicator, cosmologists turned these cataclysmic explosions to their whims and began mapping the universe and its accelerating expansion. Now, the largest sample of Type Ia Supernovae ever assembled has been harnessed to put the best cosmological models to the test. These Supernovae occur all over the universe, from its most barren voids to the dense knots connecting the cosmic web. However, a new study hints they may not exactly follow the universe's matter distribution. Before tackling this tantalizing new science, it is important to take a step back and ask: just how standard are these standard candles, and what physics drives their predictable luminosity?

1. INTRODUCTION

Type Ia Supernovae (SNe Ia) are the explosive deaths of White Dwarfs (WDs). Of all the astronomical transients, these thermonuclear cataclysms are the most important to astrophysics, and particularly the field of cosmology. Their scientific value is owed to their use as standard candles. By the late 1980s, enough SNe Ia had been observed at different distances that astronomers could confidently say that all explosions of this type have remarkably similar luminosity (Norgaard-Nielsen et al. 1989). SNe Ia were concluded to be extremely regular events, and astronomers began using them as distance indicators. This paradigm was thrown into disarray with the discovery of SN1991bg. This supernova displayed all the hallmarks of a SN Ia, and was classified as such based on its spectra, but there was a problem. SN1991bg occured in the same galaxy as SN1957B, another SN Ia. However, SN1957B was $10\times$ brighter than SN1991bg (Leibundgut et al. 1993; Garnavich 2017)! It seemed that SNe Ia were not standard candles after all, and cosmology performed with this assumption was moot. Luckily, Mark Phillips had a solution. Though not all SNe Ia have the same luminosity, there is a relationship between their luminosity and the decline rate of their light curve (Phillips 1993). Thus, by carefully measuring how the brightness of a SN Ia changes over time, its intrinsic luminosity can be retrieved, and SN Ia cosmology was saved (Phillips 1993; Phillips & Burns 2017). This is known as the Phillips relation.

SN Ia Cosmology is built on a foundation of the Phillips relation. By carefully sampling as many SNe Ia as possible, the distances to their host galaxies can be retrieved and a map of the universe can be constructed. By 1998, Adam Riess and collaborators had assembled a sample of 50 SNe Ia. Using the Phillips relation, they determined the distance to these SNe and discovered a surprising fact: the redshifts of more distant supernovae were much larger than was expected. At the time, it was thought that the universe was expanding, but gravity was slowing the expansion. These findings suggested the opposite. Gravity is losing. The expansion of the universe is accelerating (Riess et al. 1998).

In the era of wide field surveys, the field of SN Ia cosmology has exploded. 27 years have passed since Riess and collaborators' discovery, and the largest samples of SNe Ia has grown from dozens to thousands. SNe Ia are now used as tools to map the large scale structure of the universe. Measurements of the universe's accelerating expansion have been greatly refined, and the matter density parameter (Ω_{m}) constrained. Evidently, the Phillips Relation is a powerful tool. But just how sure are we that SNe Ia can be standardized in this way? The empirical evidence for the Phillips Relation is very strong, but what physical processes link the decline rate of a SN Ia's light curve to its luminosity? Section 2 will address these questions about SN Ia cosmology's critical equation. Section 3 will pertain to the recent cosmological findings of the Dark Energy Survey; an analysis of over 1500 SNe Ia. Section 4 will examine the distribution of SNe Ia in the large scale structures of the universe. Section 5 will conclude this term paper.

2. THE PHILLIPS RELATION: EVIDENCE AND PHYSICS

The Phillips relation allows for the determination of the peak absolute magnitude of a SN Ia, given its observed decline rate, $\Delta m_{15}(B)$ (Phillips 1993). To measure $\Delta m_{15}(B)$, a well sampled light curve of the SN must be constructed from photometric observations of the SN. $\Delta m_{15}(B)$ is the change in apparent magnitude of the SN over the 15 days following peak brightness in the B band (Phillips 1993). From a sample of 9 SNe Ia, Phillips first defined this empirical relationship to be

$$M_{Max}(B) = 2.698\Delta m_{15}(B) - 21.726 \qquad \text{Phillips (1993)}$$

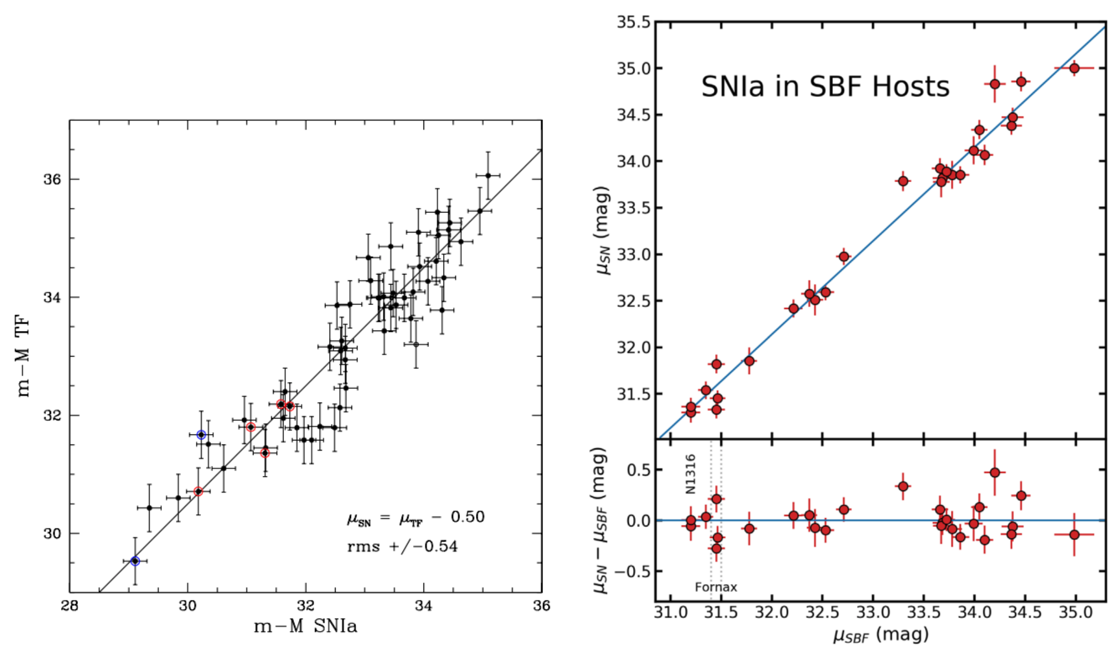
Since 1993, this relation has been refined by numerous new observations of SNe Ia. Other empirical relations have also been derived to depend on a "stretch" parameter rather than $\Delta m_{15}(B)$, but the crux of the relation is the same: the peak luminosity of a SN Ia can be retrieved by measuring the decline rate of its light curve.

2.1. *Imperial Evidence*

Before investigating what physics enable the Phillips relation, it is germane to consider whether the relation is valid in the first place. To validate the Phillips relation, the distances derived from this method must be consistent with those derived from other methods. There are numerous other distance indicators that can be used for this, but in this paper I will consider the following: Tully-Fisher (TF) and Surface Brightness Fluctuations (SBF). Their agreement with the distances derived from the Phillips relation is paramount to ensure that the Phillips relation is valid.

In a 2012 paper, Helene Courtois and R. Brent Tully compared distances to SNe Ia derived from the Phillips relation to those derived from the TF relation. The TF relation is also an empirical law; it relates the luminosity of a spiral galaxy to its rotation velocity. Courtois and Tully used the Phillips relation to determine the distance to 56 SNe Ia, and then used the TF relation to independently determine the distance to the host galaxies of this sample of SNe Ia (Courtois & Tully 2012). A comparison of the distance moduli derived from both methods is shown in Figure 1 (a). Here it can be seen that there is good agreement between these two distance indicators. On average, the distance modulus derived from the Phillips relation are half of a magnitude smaller than those from the TF relation, but this is within the scatter of the data (Courtois & Tully 2012).

Figure 1.



(a) Shown here are the Phillips relation derived distance moduli for 56 SNe Ia compared with TF derived distance moduli For their host galaxies. Adapted from Courtois & Tully (2012).

(b) Shown here is a comparison of Phillips relation derived distance moduli for 25 SNe Ia and the independently derived SBF distance moduli for the host galaxies of these SNe. Adapted from Garnavich et al. (2023)

Another distance indicator is the SBF method. This method relies on the fact that galaxies are luminous because they contain individual stars. For nearby galaxies, these individual stars or close-knit stellar populations can be resolved by a telescope. However, for distant galaxies, telescopes can no longer resolve these point-like sources, and they are smeared into a more uniform surface brightness. Thus, by measuring the amplitude of fluctuations in surface brightness, the distance to a galaxy can be inferred. In a 2023 paper, Garnavich and collaborators compared the Phillips relation distances to 25 SNe Ia to the SBF distances to the host galaxies of these SNe (Garnavich et al. 2023). This comparison is shown in 1 (b). The Phillips relation distances are in fair agreement with the SBF distances. Notably, the largest error in this sample comes from 2 SNe that occurred in the same host, SN2007on and SN2011iv in NGC1404. These two SNe give Phillips relation distance moduli that differ by a half a magnitude, though they are at the same luminosity distance in reality (Garnavich et al. 2023). This is certainly a peculiarity and warrants further investigation, but it does not invalidate the Phillips relation. On the whole, the SBH distances do match the Phillips relation distances, and at least the SBF distance to NGC1414 splits difference between the Phillips relation distances to SNe 2011iv and 2007on.

2.2. *Physical Origin*

The Phillips relation is well verified and widely used. In spite of this, the physical mechanism that leads to the correlation between the decline rate of a SN Ia and its peak luminosity is far from agreed upon. In fact, the progenitor scenario and explosion mechanism of SNe Ia is a contentious and highly debated topic. Seemingly, the only accepted aspect of the systems that lead to a SN Ia is that they must involve the runaway thermonuclear explosion of a WD in a binary system. From there, the literature is deeply divided over the nature of the binary partner, and the mechanism by which the explosion ignites and proceeds. What is agreed upon is that such an explosion would produce copious ^{56}Ni, and it is this radioactive isotope that powers the optical luminosity of the SN Ia. ^{56}Ni decays by electron capture into ^{56}Co with a half life of 6.077 days. ^{56}Co is also radioactive, and decays by β^+ into stable ^{56}Fe with a half life of 77.23 days. The decay chain is thus:

$$^{56}\mathrm{Ni} \longrightarrow \, ^{56}\mathrm{Co} + \gamma \longrightarrow \, ^{56}\mathrm{Fe} + e^+$$

γ-rays from ^{56}Ni are quickly absorbed in the dense SN ejecta and are thermalized, eventually leaving the SN as optical photons. In the times before several ^{56}Ni half lives have passed, this is the process that powers the light curve of a SN Ia (Bersten & Mazzali 2017). Once most of the ^{56}Ni has been converted to ^{56}Co, the e^+ from ^{56}Co decay annihilating in the ejecta becomes the dominant mechanism powering the lightcurve, though the much longer half life of ^{56}Co makes this process slower and less luminous (Bersten & Mazzali 2017).

During the 15 days following peak luminosity, it is ^{56}Ni decay that powers the light curve. About 2.5 half lives of ^{56}Ni pass in this time, reducing ^{56}Ni abundance in the ejecta to ∼18% of the quantity present at max light. One might naively expect that the $\Delta m_{15}(B)$ of all SNe Ia would be the same, as the luminosity should decrease to ∼18% of its maximum value over this time, but there is more at play. This is where theories diverge, and experts disagree.

Some say that the Phillips relation is an opacity effect. It is widely accepted that SNe Ia produce varying quantities of ^{56}Ni, leading to a range of possible luminosities. The thinking goes that SNe Ia that synthesize lots of ^{56}Ni also synthesize a higher abundance of other Fe-group elements (Mazzali 2001). The main source of opacity in SNe Ia is line opacity, that is to say atomic absorption lines are the main mechanism impeding the escape of photons from the ejecta (Mazzali 2001). Fe-group elements are rich with atomic absorption lines, readily blocking photons of numerous wavelengths. Because of this, photons in an Fe-group rich ejecta must spend more time randomly walking between atoms, being absorbed and re-emitted countless times before eventually escaping as optical photons. In short, the photon diffusion time for Fe-group rich ejecta is longer. The higher ^{56}Ni abundance thus yields a higher luminosity, and the higher Fe-group abundance is responsible for the slower evolution of the light curve (Mazzali 2001; Phillips & Burns 2017; Bersten & Mazzali 2017).

Others claim that the higher photon diffusion time of more luminous SNe Ia is a secondary effect to evolution of the ionization states in the ejecta (Kasen & Woosley 2007). Shortly after the SN Ia, most of the Fe-group elements are doubly ionized (Fe III, Co III, etc) as a result of the high temperatures in the ejecta. These lines are primarily at ultraviolet wavelengths, and photons absorbed by these lines are re-emitted at optical or near ultraviolet wavelengths. As the SN ejecta cools, the Fe-group elements undergo recombination to their first ionization state. This causes a stark change in the spectrum, as Fe II / Co II absorb in the blue part of the optical electromagnetic spectrum, and reprocess this flux to the red (Kasen & Woosley 2007). Hence, once the ejecta drops below a critical temperature (∼7000 K), the SN quickly becomes less luminous in the B band as photons are absorbed by Fe II and Co II lines, and re-emitted to the red, outside the B band. The link to luminosity comes again from increased ^{56}Ni abundance. A higher ^{56}Ni abundance leads to more γ-rays deposited in the ejecta, heating it to higher temperatures and increasing the luminosity. The result is that Fe-group elements spend a longer time in their doubly ionized states, before recombining and absorbing in the B band (Kasen & Woosley 2007). In this model, the Phillips relation is mostly a temperature effect, and is highly specific to the photometric band used used to observe the SN (B).

The mechanism behind the Phillips relation is still a controversial topic. With more observations, higher resolution spectra, and more spectra at infrared and ultraviolet wavelengths, perhaps there will be a more definitive model of the Phillips relation in the future. For now, we must be content with the fact that it is empirically true and therefore immensely useful for cosmology.

3. THE DARK ENERGY SURVEY SUPERNOVA PROGRAM

The Dark Energy Survey Supernova Program (DES-SN) is a modern effort to extract cosmological parameters from a large sample of SNe Ia. The novelty of this program comes from its enormous sample of ∼1500 SNe Ia out to z = 1.13 (DES Collaboration et al. 2024; Vincenzi et al. 2024). This unprecedented sample size is owed to the classification method used by DES-SN. Most SNe Ia are classified by optical spectra, which is particularly difficult for SNe beyond z = 0.1. To illustrate this, I performed a search on the transient name server. I found that of the 153 SNe Ia classified in the month of April 2025, not a single SN was further than z = 0.1. It's not that SNe at $z > 0.1$ go undetected, rather it is simply too costly and time consuming to get spectra of such dim transients. To obtain a spectrum of such a distant SN, hours of telescope time on some of the worlds largest telescopes such as Keck or the Gran Telescopio Canarias must be used. The result is that most classified SNe Ia are closer than z = 0.1.

The DES-SN program sidesteps this issue by classifying SNe Ia using only their light curves. As the Phillips relation shows, SNe Ia have very uniform and distinct light curves that differentiate these explosions from SNe II or other more exotic transients. DES-SN employs the wide field Dark Energy Camera mounted on a 4-m Victor M. Blanco Telescope in the Atacama Desert (Flaugher et al. 2015). Over 5 years, this telescope surveyed the sky and searched for SNe by the technique of difference imaging (DES Collaboration et al. 2024). By continually revisiting the same fields, this telescope constructs light curves in multiple photometric bands for the SNe it detects. After the 5 years of data was collected, these light curves were fed into a machine learning algorithm trained to differentiate between SNe Ia and non Ia SNe (Möller & de Boissière 2020; DES Collaboration et al. 2024; Vincenzi et al. 2024). This technique is extremely powerful and achieved an accuracy of 96.9% without any redshift information (Möller & de Boissière 2020). If redshift was provided, accuracy increased to 99.6% (Möller & de Boissière 2020). By utilizing this light curve based classification algorithm, they amassed a SNe Ia sample of unprecedented size.

With this enormous sample of SNe Ia secured, they fed the light curves into the Spectral Adaptive Light-curve Template V3 (SALT3) model (DES Collaboration et al. 2024; Vincenzi et al. 2024). This model uses a modified version of the Phillips relation to determine the luminosity of, and therefore the distance to, a SN Ia based on its light curve. The "Spectral Adaptive" part of this model refers to the fact that it analyzes light curves in multiple photometric bands. By accounting for the differing evolution of SN Ia flux in different band passes, it improves on the basic Phillips relation and achieves a more accurate result (Kenworthy et al. 2021).

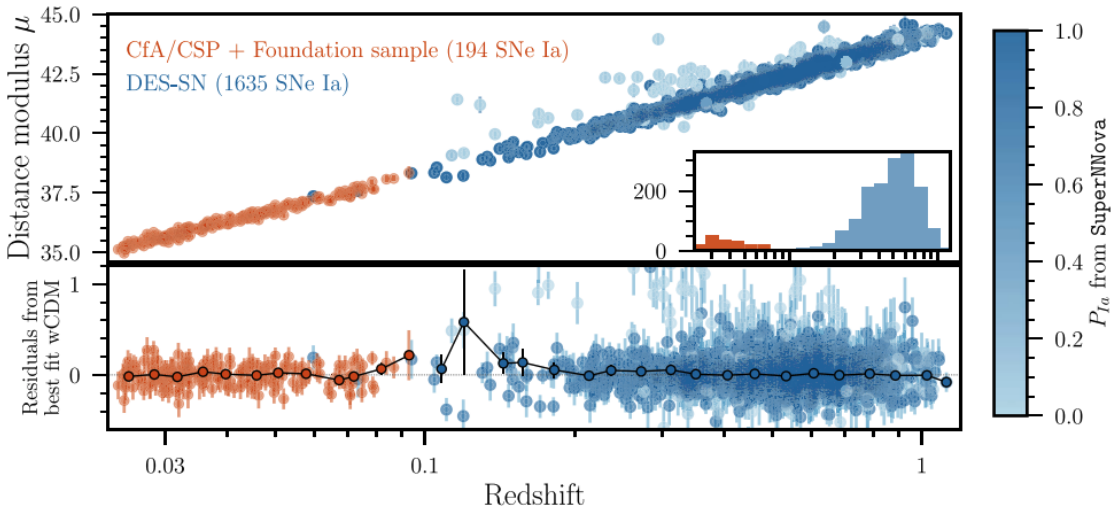


Figure 2. Shown here is the Hubble diagram constructed by the DES collaboration from a sample of 1635 SNe Ia at high redshift combined with a sample of 194 SNe Ia at lower redshift. Adapted from Vincenzi et al. (2024)

The researchers could now compare the distances to these SNe Ia with the redshifts of the host galaxies of these SNe to construct a Hubble Diagram. To supplement these higher redshift SNe, they combine this dataset with 194 well-calibrated and spectroscopically confirmed SNe Ia closer than z = 0.1 from other observing programs such as the Carnegie Supernova Project (DES Collaboration et al. 2024; Vincenzi et al. 2024). This provides an anchor to their sample to help constrain the equation of state for dark energy (Vincenzi et al. 2024). They cut the low-z sample at z=.025 to mitigate errors arising for the peculiar velocity of SNe that are outside of the Hubble flow (Vincenzi et al. 2024). The Hubble diagram arising from this analysis is found in Figure 2.

By assuming flat ΛCDM is the correct model of the universe, they found that $q_0 = -0.530^{+0.018}_{-0.017}$ (DES Collaboration et al. 2024). This confirms that the expansion of the universe is accelerating with 99.99998% certainty (DES Collaboration et al. 2024). While this is no surprise, what is more unexpected is that ΛCDM is not the best fit cosmological model for the SN data. Rather, the best fit cosmological model is $w_0 w_a$CDM. $w_0 w_a$CDM is much like ΛCDM, but rather than assuming that dark energy is constant, it instead depends on the scale factor (a), and therefore depends on time (DES Collaboration et al. 2024). The preference for this model is marginal, and ΛCDM is still a good fit to the data (DES Collaboration et al. 2024).

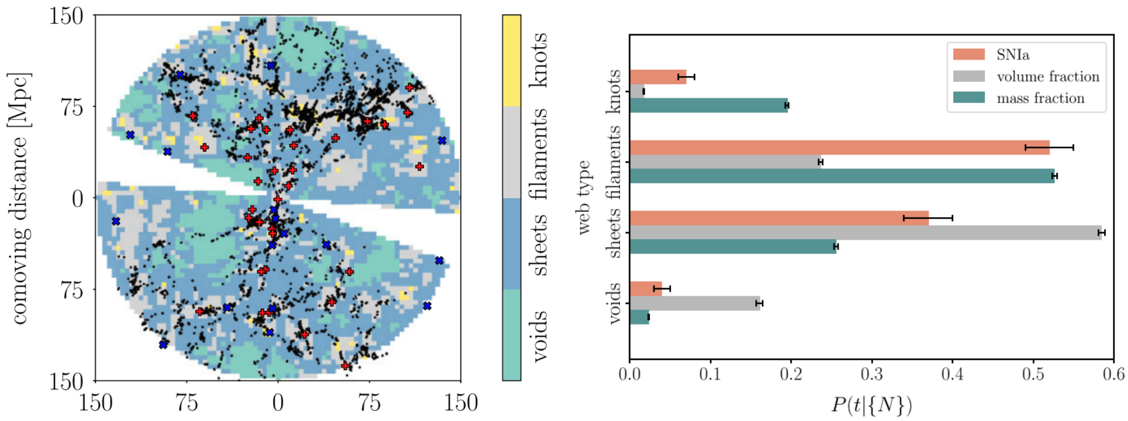
Within the context of flat ΛCDM, they find $\Omega_M = 0.352 \pm 0.017$. If $w_0 w_a$CDM is used instead, they find $\Omega_M = 0.495^{+0.033}_{-0.043}$, $w_0 = -0.80^{+0.14}_{-0.16}$, $w_a = -0.37^{+0.36}_{-0.30}$.

4. SNE IA IN THE LARGE SCALE STRUCTURE

SNe Ia can be used to trace the large scale structure of the local universe. But exactly how do SNe Ia cluster in these massive structures? Are they under or over represented with respect to galaxies or dark matter in the voids, sheets, filaments, and knots that comprise the cosmic web? In 2021, Eleni Tsaprazi and collaborators sought to answer that question.

First, they used the BORG algorithm, which traces the density and peculiar velocity in the large scale structure by utilizing numerous galaxy surveys (Tsaprazi et al. 2022). Then they classified sections of the density field using a tidal shear classifier (Tsaprazi et al. 2022). Regions of space were defined as either voids, sheets, filaments, or knots. Finally, they combined this with 498 SNe Ia and 782 SNe II from the Zwicky Transient Facility Data Release 5 (Tsaprazi et al. 2022). The furthest of these SNe was at z = .036. As much as I wish the SNe Ia distances were found using the Phillips relation, this study simply adopted ΛCDM and found the comoving distance of these SNe from their redshift. The SNe locations were then compared with the large scale structure components that were classified earlier. A map of the locations of SNe within a 2D slice of our local universe is shown in Figure 3 (a).

Figure 3.



(a) Shown here are the locations of SNe (black dots) in a 2D slice of the local universe. Different large scale structures are color coded. Adapted from Tsaprazi et al. (2022).

(b) Shown here are the web type posterior distributions for SNe Ia. This is compared to the volume and mass fraction contained within these different types of structures. Adapted from Tsaprazi et al. (2022).

Figure 3 (b) shows how the SNe Ia distribution compares to the overall volume these structures comprise, and mass fraction contained in each type of structure. Here, it can be seen that SNe are strongly clustered, but do not necessarily follow the mass fraction of each structure (Tsaprazi et al. 2022). For example, knots are the intersections of filaments in the large scale structure. They are regions of high density packed into a small volume. As such, they comprise a significant fraction of the mass in the local universe, despite their small volume.The plot shows that in these regions, there are less SNe Ia than one might expect given the mass fraction. This is because knots have a higher concentration of dark matter when compared to other regions (Tsaprazi et al. 2022), and dark matter cannot cause a SN Ia. This plot also shows that SNe Ia are under-represented in sheets, while roughly following the mass distribution in filaments. In voids there are few SNe Ia, but a higher ratio of SNe Ia to the mass contained in these voids (Tsaprazi et al. 2022). SNe Ia are thefore a biased tracer of the large scale structure. They should not be assumed to simply follow the mass density in the universe at large (Tsaprazi et al. 2022).

5. CONCLUSION

SNe Ia are extremely valuable cosmological tools. Though the theory of exactly which processes lead to the thermonuclear runaway of a WD, and how their luminosity is linked to the duration of the fading explosion is not fully settled, we can rest assured that they are reliable distance indicators. Distances derived from the Phillips relation agree with independently derived distances. Using thousands of these cosmic candles, researchers have confirmed the accelerating expansion of the universe, and exposed hints that the dark energy equation of state may be changing over time. SNe Ia are highly clustered in the universe, but do not follow the mass density as may be expected. Rather, they are biased towards voids and filaments, and away from knots and sheets. Perhaps insights into the progenitors of SNe Ia can be gleamed from their relative overabundance in both the tendrils connecting the cosmic web and the desolate voids between them.

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