Improving Type Ia Supernova Standardisation

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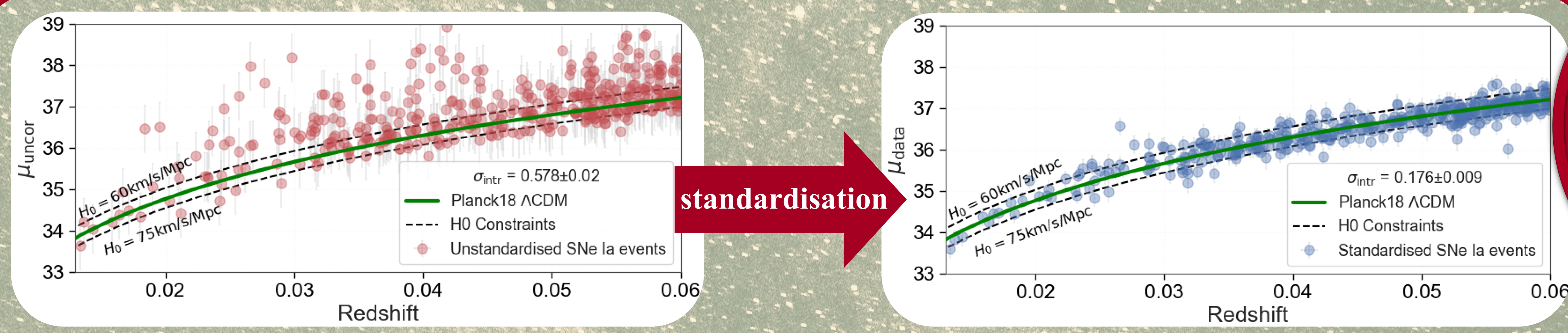


Figure 1 - Hubble diagrams of the Sne Ia sample used by this investigation before and after photometric standardisation to visually demonstrate how standardisation lowers the dispersion in the sample and can be used to constrain cosmological parameters such as H0.

Figure 2 - 48 inch Samuel Oschin Telescope at Mt. Palomar [1]

1 - Introduction

Type Ia Supernovae (SNe Ia) are powerful cosmological tools used to calibrate distance measurements. Due to an intrinsic brightness dispersion observed in their population, SNe Ia must undergo standardisation to be treated as standard candles. Current standardisation techniques make use of photometric data to employ empirical brightness corrections in order to reduce the average intrinsic dispersion in a sample. It is crucial to find ways to refine the standardisation process so that the accuracy of distance measurements is improved. This is essential for constraining cosmological parameters. This project evaluated the current widely used photometric correction parameters α, β and γ (see below) and explored spectroscopic data (see right) to find evidence for new corrections that could improve SNe Ia standardisation. The results of this project highlight that spectroscopic data has a great potential to enhance the SNe Ia standardisation process.

2 - SNe Ia Data

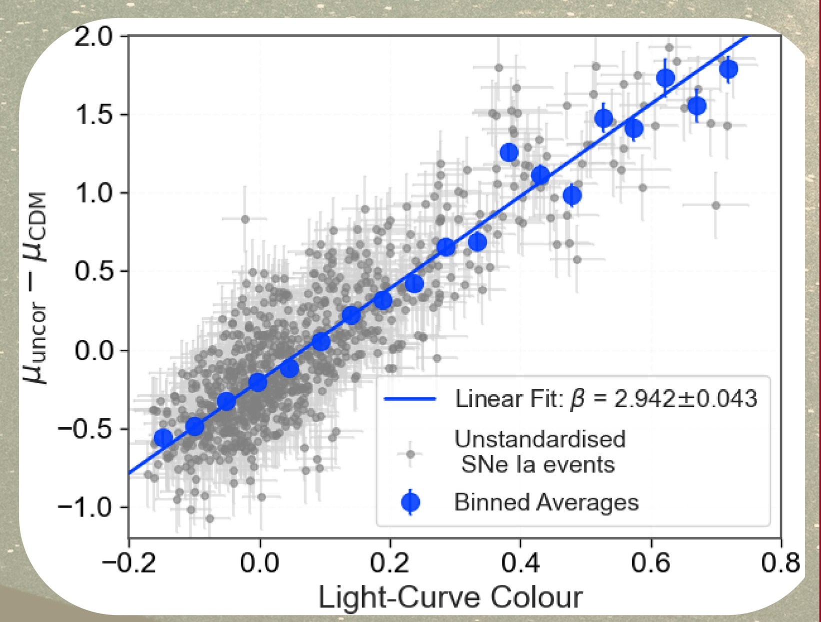
This investigation used data from the ZTF SN Ia DR2 sample presented in Rigault et al. (2025) [2]. The initial dataset contains 2663 spectroscopically confirmed SNe Ia after basic data cuts. These SNe Ia were detected by the Zwicky Transient Facility (ZTF) at Mount Palomar Observatory (see photo top right). This is still the largest collection of well-sampled SNe Ia across any redshift range to date. This provides an incredible opportunity to investigate deeper into SNe Ia standardisation than ever before. The data set contains photometric data such as light-curve width, light-curve colour, and host galaxy colour to derive the correction parameters α,β and γ (see left below). To hunt for potential improvements to this standardisation regime, spectroscopic data from Burgaz et al (2025) [3] was used to create a smaller sub-set of 416 SNe Ia. This smaller sample contains all objects for which spectroscopic and photometric data is available (SDA sample). The spectroscopic data used in this investigation was the pseudo-equivalent width (pEW) of the silicon (Si II) feature at λ6355 Å in the spectra of SNe Ia. See below for how this data was used to hunt for new spectroscopic standardisation corrections that could potentially improve upon current photometric methods.

3 - SNe Ia Standardisation

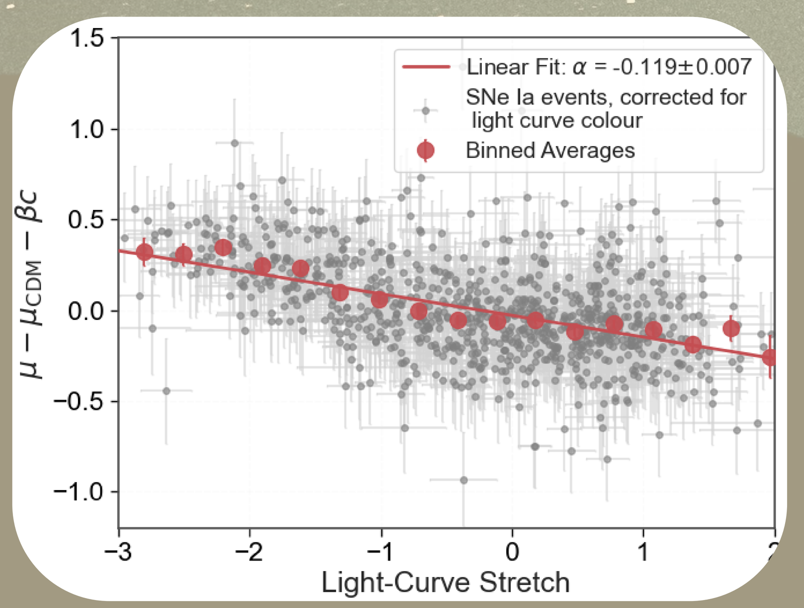
SNe Ia standardisation is the process by which the brightness dispersion of a sample of SNe Ia is reduced to an acceptable level. This is achieved by applying corrections derived from relationships identified in photometric data of SNe Ia. These corrections are then included as additional terms in the distance modulus equation (see below) to 'standardise' brightnesses and lower the dispersion in the sample:

$$\boxed{\mu_{data} = m_b - M + \alpha x_1 - \beta c + \gamma p}$$

Where μ is the distance modulus, m is the apparent magnitude (brightness), M is the absolute magnitude, α, β and γ are empirical correction coefficients that correct for the observed relationships between SNe Ia brightness and light curve-width (x1), light-curve colour (c) and host galaxy environment. This means a more reliable absolute brightness can be calculated when using SNe Ia as standard candles, which means distance measurements are more accurate. Improved distance measurements are essential for constraining cosmological parameters further. Figure 1 shows a Hubble diagram of the SNe Ia sample used in this investigation before and after standardisation to demonstrate the process clearly. The relationships that α, β and γ correct for are shown in the figures below and their values can be estimated from the plots.



Figures 3 and 4 - Relationships between SNe Ia Hubble residuals and light-curve colour (right) and residuals against light-curve width/stretch (below). These relationships were first identified by Tripp, R. (1998) [4] and were recreated for the SDA sample used in this investigation. The linear fits are used to approximate the values of α and β to use in the correction equation above.



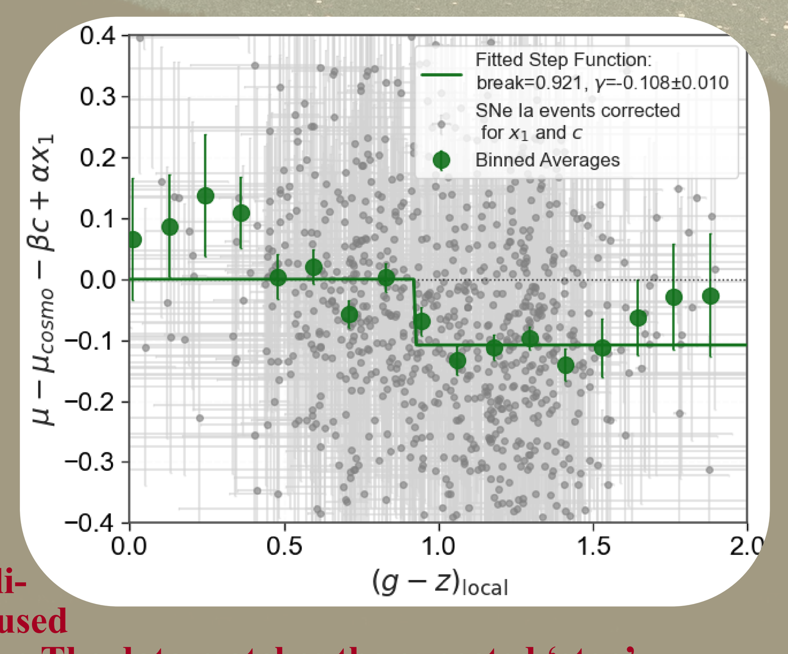


Figure 5 - (right) Relationship between SNe Ia Hubble residuals (after α and β corrections) and host galaxy environment, identified by Sullivan et al. (2010) [5]. The environmental tracer used by this investigation was local host galaxy colour. The data matches the expected 'step' functional form. The value of γ is approximated as the magnitude of the step.

4 - Using Spectroscopic Data to Improve Standardisation

Spectroscopic data was explored to search for similar relationships as seen in Figures 3,4 and 5 that could be used to derive new standardisation corrections. If a significant relationship was found, a python code (developed for this investigation) that ran Markov-Chain Monte-Carlo (MCMC) simulations was used to fit for all standardisation parameters simultaneously. This means any underlying relationships between parameters was taken into account. The uncertainty in the parameters was estimated as the standard deviation of the sampled posterior chain. The 'best-fit' values from the posterior chain were taken as the values of α, β and γ. The sampler also simultaneously fit for a parameter known as intrinsic dispersion. This is a way of quantifying the dispersion in a sample that takes the uncertainties of all parameters into account. If the addition of a new spectroscopic correction significantly lowers the intrinsic dispersion in a sample, this means the new correction is a good improvement to standardisation.

5 - Results & Discussion

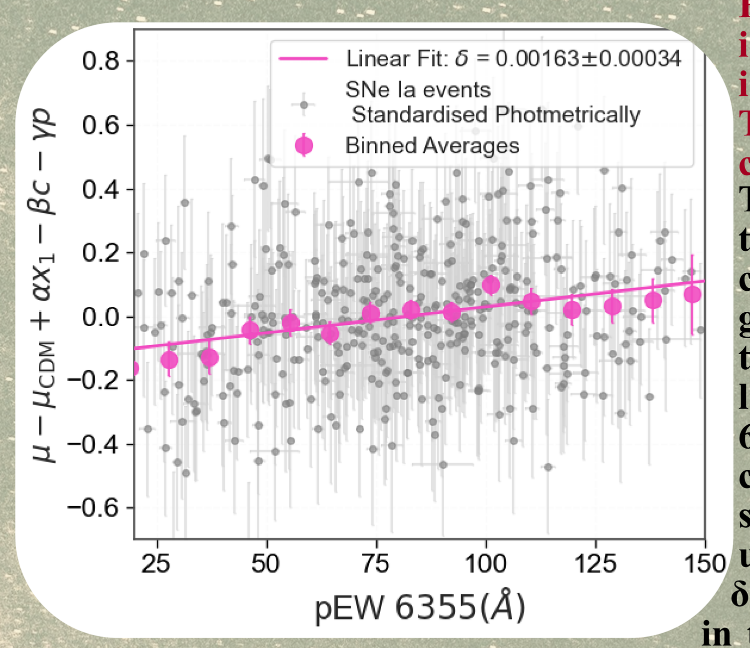


Figure 6 - A 4.66σ significant linear relationship was identified in the plot of photometrically standardised Hubble residuals against Si II λ6355 Å pEW. This could be evidence for a new standardisation correction.

The relationship identified in Figure 6 suggests that a new correction term that uses pEW values could be implemented into the standardisation regime. This was tested by using a new correction term δW in the distance modulus equation (see left) where δ is the slope of the linear fit in Figure 6 and W is pEW. Two new models were tested and compared to the widely used α, β and γ standardisation method. The models tested were: one that uses α, β, γ and δ and a model that replaces γ with δ (because the Host-step correction is controversial in the literature due to its physical origin being debated). The results from the MCMC simultaneous fits are outlined in the table below:

Model Used	Intrinsic Dis	STD
αβγ	0.187±0.009	0.228
αβδ	0.191±0.009	0.227
αβγδ	**0.176±0.009**	**0.221**

Table 1 - Results from the MCMC simultaneous fits for the 3 standardisation models tested on the SNe Ia sample.

Table 1 shows that the αβγδ model successfully lowers the standard deviation of the SNe Ia brightnesses in the sample compared to the αβγ model. However, due to the size of the uncertainties, the reduction in intrinsic dispersion is not statistically significant. This means there is not enough statistical evidence from this investigation alone to confirm if the αβγδ model significantly improves SNe Ia standardisation. However, it does highlight that the use of spectroscopic data such as Si II pEW has a great potential to do so. Future studies must be carried out using a larger sample size to determine if the δ correction has a significant impact.

6 - Conclusions

A 4.66σ significant linear relationship was identified in the plot of photometrically standardised Hubble residuals against Si II λ6355 Å pEW. This was tested as a potential new standardisation term δW to use in addition with the widely used αβγ corrections. The αβγδ model standardised the SNe Ia sample such that the standard deviation was 0.221 and intr dis =0.176±0.009. These are both an improvement upon the values obtained by the current widely used photometric standardisation model which uses only αβγ (STD=0.228, intr dis=0.187±0.009). However, due to the large uncertainties in the σint values obtained by the simultaneous fits for each model, the reduction in intr dis is only 0.86σ significant. This means there is not enough statistical evidence from this investigation to confirm if the αβγδ model significantly improves SNe Ia standardisation. This investigation highlighted the fact that spectroscopic data has a great potential to improve Sne Ia standardisation. If spectroscopic corrections, such as ones like δ suggested by this investigation, can be shown to significantly reduce the dispersion in an SNe Ia sample, this will enhance SNe Ia standardisation considerably. A significant correction parameter was discovered using spectroscopic data in this investigation. This report emphasises the need to explore this further to conclusively determine if SNe Ia standardisation can be improved. This work lays a foundation for future studies to expand and robustly test spectroscopic SNe Ia standardisation corrections so that the ultimate goal of improving distance measurements and advancing cosmological understanding is achieved.

Acknowledgements

Background Image: Free to use photo by Colin Lloyd from Pexels

[1] Telescope image: © Palomar/Caltech
[2] Rigault, M., Smith, M., Goobar, A., et al. (2025). Ztf sn ia dr2: Overview. Astronomy & Astrophysics, 694:A1.
[3] Burgaz, U., Maguire, K., Dimitriadis, G., Harvey, L., Senzel, R., Sollerman, J., Nordin, J., Galbany, L., Rigault, M., Smith, M., et al. (2025). Ztf sn ia dr2: The spectral diversity of type ia supernovae in a volume-limited sample. Astronomy & Astrophysics, 694:A9.
[4]Tripp, R. (1998). A two-parameter luminosity correction for type ia supernovae. Astronomy and Astro-
[5] Sullivan, M., Conley, A., Howell, et al. (2010). The dependence of type ia supernova luminosities on their host galaxies. Monthly Notices of the Royal Astronomical Society, 406(2):782–802. physics, v. 331, p. 815-820 (1998), 331:815–820.