

# Exploding stars show us that time slows down in the distant Universe!

Ryan M. T. White<sup>1\*</sup>, Tamara M. Davis<sup>1</sup>, Geraint F. Lewis<sup>2</sup>, Christopher Lidman<sup>3,4</sup>, Paul Shore<sup>5</sup>, T. M. C. Abbott<sup>6</sup>, M. Agüena<sup>7</sup>, S. Allam<sup>8</sup>, F. Andrade-Oliveira<sup>9</sup>, J. Asorey<sup>10</sup>, D. Bacon<sup>11</sup>, S. Boccaletti<sup>12</sup>, D. Brooks<sup>5</sup>, D. Brout<sup>13</sup>, E. Buckley-Geer<sup>14,8</sup>, D. L. Burke<sup>15,16</sup>, A. Carnero Rosell<sup>17,7</sup>, D. Carollo<sup>18</sup>, J. Carretero<sup>19</sup>, L. N. da Costa<sup>7</sup>, M. E. S. Pereira<sup>20</sup>, J. De Vicente<sup>21</sup>, S. Desai<sup>22</sup>, H. T. Diehl<sup>8</sup>, S. Everett<sup>23</sup>, I. Ferrero<sup>24</sup>, B. Flaugher<sup>8</sup>, J. Frieman<sup>8,25</sup>, G. Galardi<sup>26</sup>, S. R. Hinton<sup>1</sup>, D. L. Hollowood<sup>32</sup>, K. Honscheid<sup>33,34</sup>, D. J. James<sup>35</sup>, K. Kessler<sup>14,25</sup>, K. Kuehn<sup>35,36</sup>, O. Lahav<sup>5</sup>, J. Lee<sup>37</sup>, S. Lee<sup>23</sup>, M. Lima<sup>38,7</sup>, J. L. Marshall<sup>39</sup>, J. M. Martínez<sup>40</sup>, R. Michel<sup>41,19</sup>, M. Myles<sup>42</sup>, A. Möller<sup>29</sup>, R. C. Nichol<sup>11</sup>, R. Ogando<sup>43</sup>, A. Palmese<sup>44</sup>, A. Pierini<sup>45</sup>, A. A. Ruiz Malagón<sup>15,16</sup>, A. K. Romer<sup>45</sup>, M. Sako<sup>37</sup>, E. Sanchez<sup>21</sup>, D. Sanchez Cid<sup>46</sup>, M. Schubert<sup>47</sup>, M. Smith<sup>46</sup>, E. Suchyta<sup>47</sup>, M. Sullivan<sup>46</sup>, B. O. Sánchez<sup>48,49</sup>, G. Tarle<sup>9</sup>, B. E. Tucker<sup>50</sup>, A. R. Walker<sup>6</sup>, N. Weaverdyck<sup>50,51</sup>, and P. Wiseman<sup>46</sup>,

This work is the combined effort of a \*lot\* of very smart people.



(DES Collaboration)

Affiliations are listed at the end of the paper.

← So many people from so many places that we had to put the places at the end of the paper!

Accepted XXX. Received YYY; in original form ZZZ.

Here's the tl;dr...

We present a precise measurement of cosmological time dilation using the light curves of 1504 type Ia supernovae from the Dark Energy Survey spanning a redshift range  $0.1 \lesssim z \lesssim 1.2$ . We find that the width of supernova light curves is proportional to (1+z)<sup>b</sup>, where b is the time dilation factor. Our models of an expanding Universe predict that a very far away clock will tick slower than one right next to us – something called cosmological time dilation. In this paper we treat exploding stars like clocks, using more of these and at higher distances than ever before to measure time dilation. Using the most data-driven approach so far, we find pretty much what we expected! With the quality of the data from our collaboration, the Dark Energy Survey, this is the most precise detection of cosmological time dilation yet.

Here's the background:

Time dilation is a fundamental implication of Einstein's theory of relativity. Cosmological time dilation is yet another prediction that can be traced back to Einstein!

$$\Delta t_{\text{obs}} = \Delta t_{\text{em}} (1 + z).$$

The idea of using time dilation to test the hypothesis that the Universe is expanding dates back as far as Wilson (1937) and revisited

by Rust (1974). One of the first observational hints of time dilation was the observation by Birkin (1982) and Peris et al. (1991) that the duration of gamma-ray bursts (GRBs) was inversely proportional to their redshift. It wasn't until the late 1980s that some GRBs must be cosmological. The first measurements of cosmological time-dilation using supernovae were made by Goldhaber et al. (1997) for seven supernovae at  $0.5 < z < 0.5$ . Most relevant to this work is the first measurement of cosmological time dilation in the art in identifying cosmological time dilation in SN Ia photometry. They used a model with a factor (1+z)<sup>b</sup> time dilation and found  $b = 1.07 \pm 0.06$ .

To avoid degeneracy between the natural variation of light-curve



\* E-mail: ryan.white@uq.edu.au

width and time dilation, Foley et al. (2005) and Blondin et al. (2008) observed time dilation in the evolution of spectral features of high- $z$  Type Ia supernovae (SNe Ia). The former found inconsistency with the expected time dilation of  $1+z$  (where  $z$  is redshift) for a sample of  $h = 0.97 \pm 0.10$ . Most recently, Lewis & Brewer (2023) inferred  $h = 0.79 \pm 0.29$  using the variability of 190 quasars out to  $z \sim 4$ . Despite these successes, there remains continued discussion of hybrid or static-universe models such as Tired Light (Zwicky 1929; Gupta 2023) that do not predict expansion-induced time dilation.

In this study, we measure cosmological time dilation using SNe Ia from the full 5-year sample released by the Dark Energy Survey (DES) (DES Collaboration et al. 2024), which contains  $\sim 1500$  SNe Ia spanning a redshift range of  $z = 0.1 - 1.2$ . We use a sample of larger and higher redshift than any sample of supernovae previously used for a time-dilation measurement. Such a large sample of SNe Ia is important in identifying statistical outliers and ensuring that the sample is the ideal regime to robustly identify time dilation. Over half the time away a supernova is, the stronger the time dilation signal! This lets us find the signal amongst the noise.

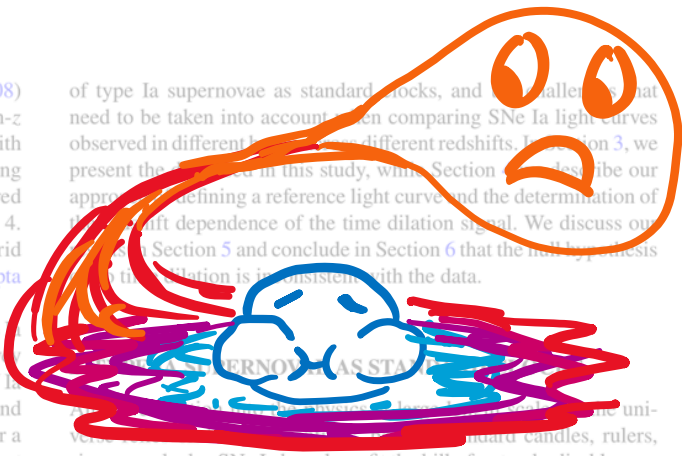
We test the model that time dilation occurs according to,  $\Delta t_{\text{obs}} = \Delta t_{\text{em}}(1+z)^b$ . (2)

If Type Ia supernovae are the result of white dwarf stars exploding, then time dilation occurs we should find  $b = 0$ . These white dwarf stars are the super-compact remnant cores of stars that have shed their outer layers, kind of like the skeleton left over after we die. Some of these stars steal extra material from nearby stars while in their white dwarf phase. When they steal so much matter that they reach a critical mass they explode! Since all these similar stars explode at this same critical mass, Type Ia supernovae all look pretty much the same no matter where they are!

The first method is entirely data-driven and has no time-dilation assumption. To use this method, we create the stacked reference by dividing the time axis of the light curves by  $(1+z)$ . This method therefore includes an assumption of time-dilation in the reference light curves, though this assumption is justified by the result of the first method, the second method should still be able to detect time dilation. It is possible to remove any circularity in keeping the reference light curves in their rest frame and fitting to  $w = \frac{(1+z_{\text{target}})}{(1+z_{\text{reference}})}$ , where  $w$  is the ratio of the rest-frame wavelength of the target supernova; mathematically this is very similar to our approach but requires even more data. To further check that this method rules out no time dilation we re-test method two *without* de-redshifting the reference light curves; it dramatically fails the consistency check, see Appendix C.

This paper is arranged as follows. In Section 2 we discuss the use

of type Ia supernovae as standard candles, and we discuss what need to be taken into account when comparing SNe Ia light curves observed in different bands at different redshifts. In Section 3, we present the data used in this study, while Section 4 describes our approach to defining a reference light curve and the determination of the redshift dependence of the time dilation signal. We discuss our results in Section 5 and conclude in Section 6 that the null hypothesis of no time dilation is inconsistent with the data.



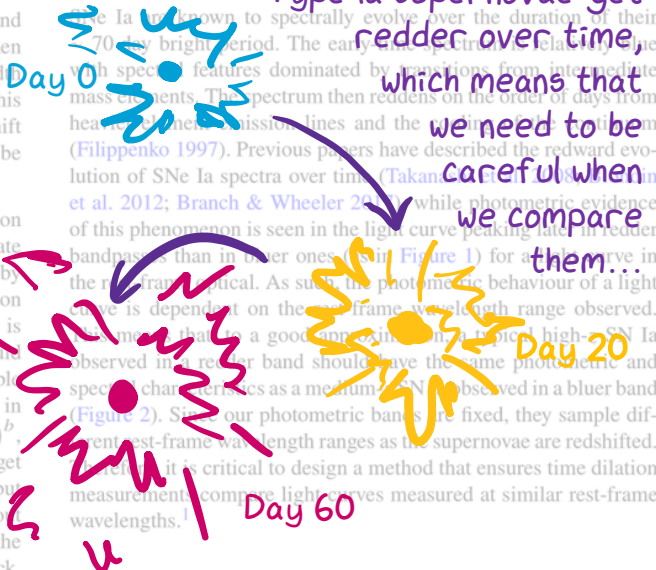
of type Ia supernovae as standard candles, rulers, sirens, or clocks. SNe Ia have long fit the bill of a standardisable candle on the basis of their extreme brightness and consistency (Tripp 1998; Müller-Bravo et al. 2022; Scolnic et al. 2023), allowing their observation over cosmic distances with only little uncertainty in their absolute magnitude. SNe Ia are also the only population of objects approaching the Chandrasekhar limit (Hoyle & Fowler 1960; Ruitter et al. 1999), their properties are remarkably uniform across the population, and they are easy to observe, not only in the optical but also in brightness, but also in time (Phillips 1993; Leibundgut et al. 1996). The observed duration of SN Ia explosions are well suited to investigating time dilation as a result of an expanding universe (Wilson 1939; Rust 1974).

The presence of a time dilation signal in SNe Ia data tests the general relativistic prediction of an expanding universe having a factor of  $1+z$  time dilation (Sandage & Tammann 1957; Sandage 1963; Sandage & Tammann 1968; Sandage 1976; Sandage & Tammann 1977; Sandage & Tammann 1978; Sandage & Tammann 1979; Sandage & Tammann 1980; Sandage & Tammann 1981; Sandage & Tammann 1982; Sandage & Tammann 1983; Sandage & Tammann 1984; Sandage & Tammann 1985; Sandage & Tammann 1986; Sandage & Tammann 1987; Sandage & Tammann 1988; Sandage & Tammann 1989; Sandage & Tammann 1990; Sandage & Tammann 1991; Sandage & Tammann 1992; Sandage & Tammann 1993; Sandage & Tammann 1994; Sandage & Tammann 1995; Sandage & Tammann 1996; Sandage & Tammann 1997; Sandage & Tammann 1998; Sandage & Tammann 1999; Sandage & Tammann 2000; Sandage & Tammann 2001; Sandage & Tammann 2002; Sandage & Tammann 2003; Sandage & Tammann 2004; Sandage & Tammann 2005; Sandage & Tammann 2006; Sandage & Tammann 2007; Sandage & Tammann 2008; Sandage & Tammann 2009; Sandage & Tammann 2010; Sandage & Tammann 2011; Sandage & Tammann 2012; Sandage & Tammann 2013; Sandage & Tammann 2014; Sandage & Tammann 2015; Sandage & Tammann 2016; Sandage & Tammann 2017; Sandage & Tammann 2018; Sandage & Tammann 2019; Sandage & Tammann 2020; Sandage & Tammann 2021; Sandage & Tammann 2022; Sandage & Tammann 2023; Sandage & Tammann 2024). This signal needs to be corrected for in supernova cosmology analyses (Phillips 1993; Leibundgut et al. 1996; Phillips 1997; Phillips 1998; Phillips 1999; Phillips 2000; Phillips 2001; Phillips 2002; Phillips 2003; Phillips 2004; Phillips 2005; Phillips 2006; Phillips 2007; Phillips 2008; Phillips 2009; Phillips 2010; Phillips 2011; Phillips 2012; Phillips 2013; Phillips 2014; Phillips 2015; Phillips 2016; Phillips 2017; Phillips 2018; Phillips 2019; Phillips 2020; Phillips 2021; Phillips 2022; Phillips 2023; Phillips 2024). Quantifying the effect of time dilation is foundational to our cosmological model, especially considering the continued discussion of hybrid or static-universe models such as Tired Light (Zwicky 1929; Gupta 2023) that do not predict expansion-induced time dilation.

### 2.1 The importance of colour

Type Ia supernovae get redder over time, which means that we need to be careful when we compare them... Type Ia supernovae are known to spectrally evolve over the duration of their 70-day bright period. The early-time spectrum is relatively blue with spectral features dominated by transitions from intermediate mass elements. The spectrum then reddens on the order of days from heated metal emission lines and the appearance of titanium (Filippenko 1997). Previous papers have described the redward evolution of SNe Ia spectra over time (Takanashi et al. 2009; Branch et al. 2012; Branch & Wheeler 2000) while photometric evidence of this phenomenon is seen in the light curve peaking later in redder bands than in bluer ones (see Figure 1) for a given supernova in the rest frame. As such, the photometric behaviour of a light curve is dependent on the rest-frame wavelength range observed. To ensure that this is a good approximation, we pick high- $z$  SNe Ia observed in a rest band should have the same photometric and spectral characteristics as a medium- $z$  SNe Ia observed in a bluer band (Figure 2). Since our photometric bands are fixed, they sample different rest-frame wavelength ranges as the supernovae are redshifted. Therefore, it is critical to design a method that ensures time dilation measurements compare light curves measured at similar rest-frame wavelengths.<sup>1</sup>

We want to be really sure about how much time dilation there is as we correct for this in cosmological analyses.



<sup>1</sup> A note on language: The phrase 'rest-frame' wavelengths arises from the usual assumption that redshifts are due to recession velocities. The fact red-

Type Ia supernovae aren't actually as consistent as I've been letting on, but they do average out nicely! Some light curves are all similar. One dissimilarity between SNe Ia is the amount of up to  $\sim 20\%$  that is separate from time dilation and strongly correlated with the peak brightness (Möller et al. 2020). This does not affect the overall trend of light curve width against time-dilation for a longer duration. On the plot to the left, one of these special supernovae would be a bit taller and a bit wider!

This has the same effect as time dilation and this makes our analysis a bit trickier. Luckily, the Dark Energy Survey found so many supernovae of all types that we don't need to correct for this; it all averages out. Even if it didn't average out, this affect is not as strong as the time dilation.

### What data do we have?



The 4m Blanco Telescope at the Cerro Tololo Inter-American Observatory observed thousands of supernovae for the Dark Energy Survey. 1504 of them made the cut for this paper!

<sup>2</sup> FLUXCALERR is the Poisson error on FLUXCAL, which is the variable used for flux in SNANA corresponding to  $\text{mag} = 27.5 - 2.5 \log_{10}(\text{FLUXCAL})$ .

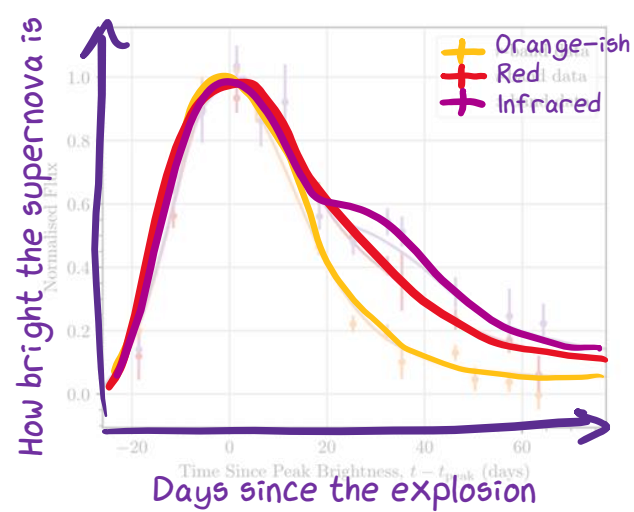


Figure 1. The normalised (to flux) light curve of a SN Ia at  $z = 0.4754$  shows intrinsically broader light curves at redder wavelengths that tend to peak later (at least in the optical regime; observed across our dataset). The x-axis represents time in the observer frame and SALT3 model fits (solid lines) are overlaid on the data for each band.

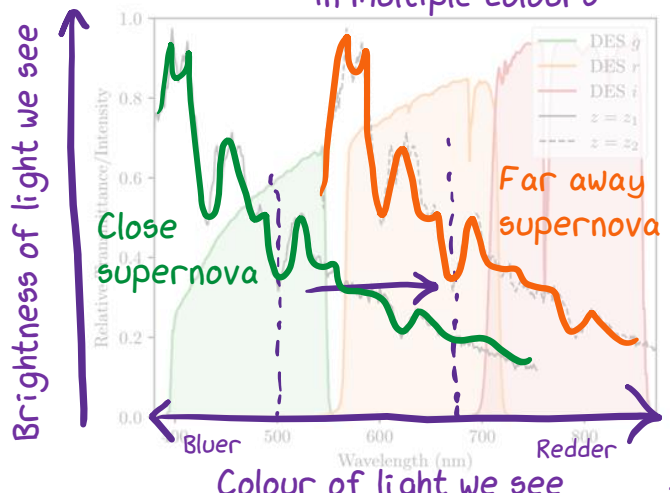
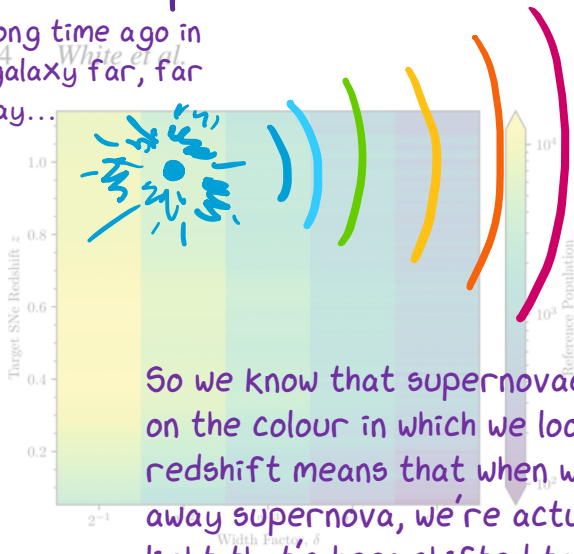


Figure 2. For a supernova at redshift  $z_1$  observed in a given filter, there exists a higher redshift  $z_2 > z_1$  such that another supernova at  $z_2$  observed in a different filter would appear to have the same flux as the nearer supernova. We show here the spectrum of SN2001V (Matheson et al. 2008) to clearly see the Si II absorption line (151nm) redshifted from the r band to the z band. This plot shows the transmission curves of the DES filters from Abbott et al. (2018) Fig. 1.

Our fitting methods are independent of individual supernova light curve models and are based only on the assumption that supernova shifts occur is not in question here (so it is fine to use  $(1+z)$  to calculate matching rest-frame wavelengths, and this contains no time-dilation assumption). The question is whether that redshift arises due to a recession velocity, which would also cause time-dilation.

The expanding Universe makes distant blue light appear red to us — we call this 'redshift'. This plot shows that the colour spectrum of a supernova that's far away is redshifted compared to one that's close by

A long time ago in a galaxy far, far away...



**Figure 3.** For each of the SNe Ia in our sample, we constructed a reference light curve with a  $\delta$  parameter according to Equation 3, with  $\Delta\lambda_f$  band FWHM. We counted how many data points populated the reference curves (i.e. the number of points in Fig. 4 for example) changing  $\delta$  in integer steps of powers of 2. This plot shows the reference population for a SN measured in the observer frame  $z$  band, and is largely similar to the different bands. The reference population for a SN measured in an analogous plot in a bluer band would see the colour distribution shifted downwards in target redshift.

high redshift (whose observations had comparatively low FLUXCAL). In the analysis, we did not attempt to fit SNe light curve widths their light curve widths  $\delta$  (Section 5) and if their reference curve had fewer than 100 data points (discussed in Section 4). This was done on a per-band basis; we estimated the width of each SN light curve in each band where it satisfied these criteria. Individual light curves were also omitted from the analysis if the  $\chi^2$  width fitting did not converge. All together, after these quality cuts we were left with width measurements of 1504 unique SN Ia across the dataset.

What do \*we\* do in the paper?

#### 4 FITTING SUPERNOVA PHOTOMETRY TO A REFERENCE LIGHT CURVE

If time dilation is real, we should see that supernovae take longer at higher redshift (from our perspective). That means that if we stack light curves from our own redshifts that should have the same shape, the higher redshift ones will appear wider!

Our method is unique in that we use

\*only\* the data from the Dark Energy Survey, no other supernovae were hurt in the making of this paper.

Space and time

to arrive at one target SN. The target is the SN whose width we are to measure.

Since the shape of a SN light curve is dependent on the rest-frame effective wavelength at which it is observed (Fig. 1; see also Takahashi et al. 2008; Blinnikov et al. 2012), the reference photometry must be composed only of light curves that have the same (or very similar) intrinsic shapes to the target SN. Hence, we must choose reference photometry that has the same rest-frame effective wavelength as the target light curve. This effect is shown in Fig. 2, where, for example, we might compare a low- $z$  supernova in some band against the same photometry measured with the same (or similar) rest frame effective wavelength. We can compare the photometry between bands where we know that their rest-frame effective wavelengths (and hence their light curve shape/evolution) is alike.

When we compare supernova light curves across different redshifts, we need to account for these effects. We proposed using a mathematical selection function\* to carefully choose light curves at certain redshifts and in certain colours so that we get a sample that should all have the same shape.

To avoid this bias, we use the aforementioned method of only using target light curve. To pick all light curves out of a calculated redshift range. To fit a single (target) SN light curve at redshift  $z$  imaged in a band of central wavelength  $\lambda_f$ , we can populate the reference curve with SNe within the redshift range

$$\frac{\lambda_r(1+z)}{\lambda_f} - \delta \frac{\Delta\lambda_f}{\lambda_f} \leq 1+z_r \leq \frac{\lambda_r(1+z)}{\lambda_f} + \delta \frac{\Delta\lambda_f}{\lambda_f} \quad (3)$$

These photometry is measured in a band of central wavelength  $\lambda_r$ . Here  $\delta$  is a free parameter which, together with the band full width at half maximum (FWHM)  $\Delta\lambda_f$ , depends on the relative band overlap. A derivation of this formula is given in Appendix A. To collect light in a redder filter, we need to

collect light in a redder filter so that we're seeing the same type of stuff!

Since we have a finite amount of data, we can't choose light curves that'll have exactly the same shape, but the sheer number of supernovae with DES means that we can pick lots of light curves that are pretty close!

After populating the reference curve with data points, we then normalise the photometry in flux as the curve is populated with light curves that are pretty close! The reference curve must be homogeneous in flux. To do this, we utilised the peak flux in the SALT3 model light curves provided for each SNe. The data in each constituent curve is normalised by this value before being added to the reference. For convenience we also use the time of peak brightness given by SALT3 as the reference point about which to stretch the light

\*For astrophysics, we're kind of light on the math in this paper!

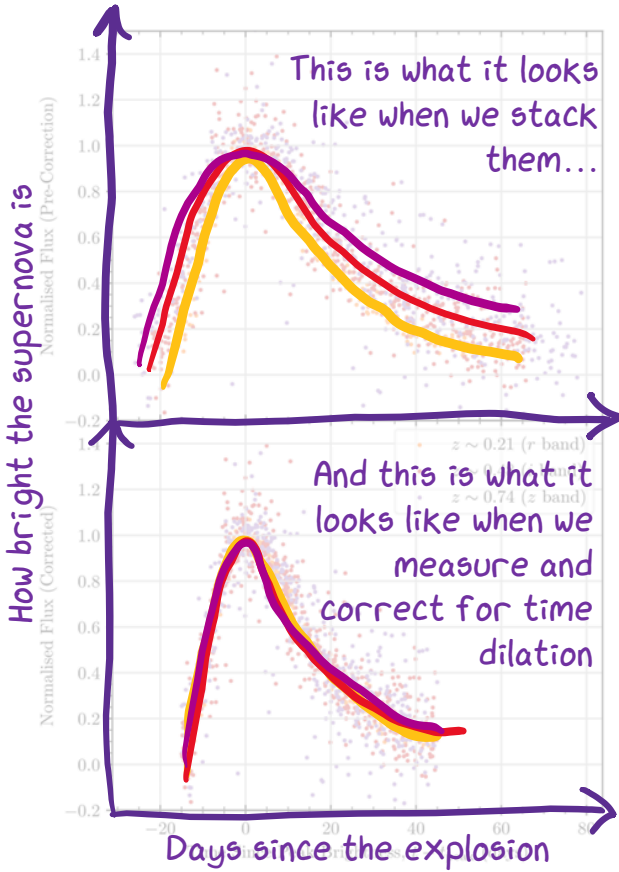


Figure 4. For a target SN Ia at  $z \approx 0.48$ , the  $i$ -band reference curve consists of data from the  $r$ ,  $i$ , and  $z$  bands. These data are taken at redshifts according to our redshift distribution shown in the left plot of Fig. 4. The data in different bands are not in phase (in the observer frame). If we visually observe the light curves at different redshifts ( $z$ ), then after a  $(1+z)$  correction to the SN Ia light curves, we see a consistent trend across all the different bands. This is the signal of time-dilation.

When we take orange light from redshift 0.2 supernovae, red light from redshift 0.5 supernovae, and infrared light from redshift 0.75 supernovae, the light curves should look the same! But the top plot shows that the redder light curves (from higher redshifts!) are

**4.2 First measure of time dilation: signal scatter in the reference curve**

After the flux of the reference curve is normalised, we see that the different bandpass data in the curve are temporally stretched (see the colour gradient of the top plot in Fig. 4). As the redder bandpasses are stretched more, this indicates that there is a signal of time dilation. Without assuming our expected cosmological time dilation of  $(1+z)$ , we can scale the data in *all* of the reference curves by a factor of  $(1+bz)$ , where  $b$  is a free parameter. We posit that minimising the scatter in the reference curve is the optimal temporal scaling, simultaneously minimising the dispersion in the fluxes, finding the value of  $b$  that minimises the flux scatter gives us our best estimate for  $b$ . To investigate this, we generated reference curves for each of the different colours line up, we've got our time dilation measurement!

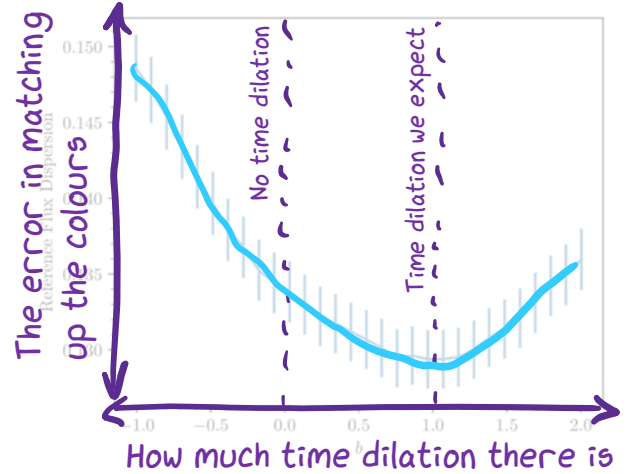


Figure 5. By scaling the reference photometry in time according to  $(1+z)^b$  for some free parameter  $b$ , we find  $b \approx 1$  minimises the reference flux dispersion across all the reference curves. The reference flux dispersion is the median dispersion of flux across the entire sample of normalised reference light curves in each band (here averaged for the  $riz$  bands), where the errorbars indicate one standard deviation in these values. We note that this figure yields a signal of  $(1+z)$  time dilation in the DES dataset, independent of the rest of the data.

What we did on the left column was just for one individual 'center' target SN in one observing band, and scaled the data in time according to the aforementioned relation in terms of  $b$  (Fig. 4 shows the scaling factor  $(1+bz)$  in purple). We then binned the time series data into 30 equal-width time bins and found the standard deviation of the flux in each bin, relative to the reference curve, and the standard deviations as a representative estimate of the total flux scatter for that reference curve with that tested  $b$  value. We then took the median of these values across all the SN Ia reference curves for each value of the dispersion for that  $b$ , which is shown in Fig. 5. That is, our reference flux dispersion is  $\sigma_{ij}(b) = \text{median}(|\sigma_{ij}(b)| \forall j \in (1, \dots, 30)) \forall i \in (1, \dots, N_{\text{SN}}))$  (4)

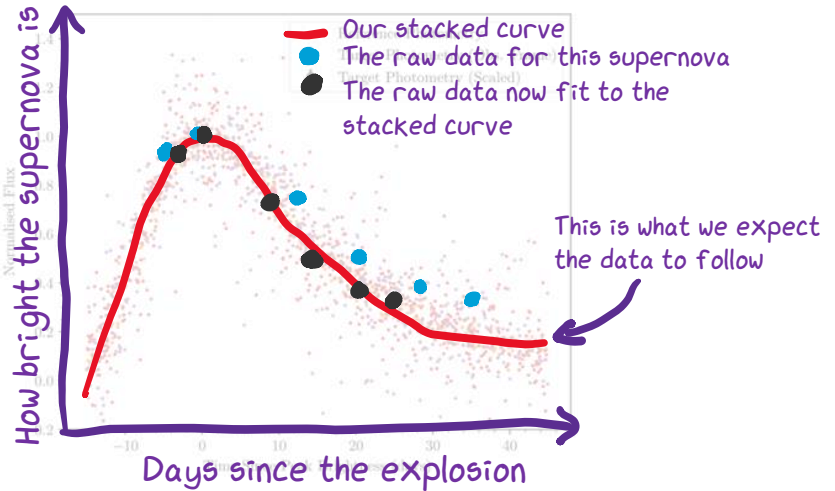
We fit a factor of time dilation of  $(1+z)^b$ , where  $z$  is the redshift value and  $b$  is just some number;  $b=0$  means no time dilation and  $b=1$  is the time dilation we expect in our expanding universe. The plot at the top of this column shows that when we fit for all of the light curves, we find  $b=1$  matches up best.

**4.3 Second measure of time dilation: Finding each light curve Cosmology can rest easy! For now...**

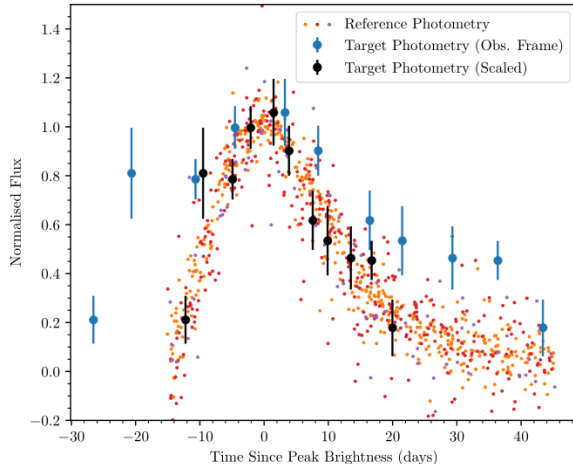
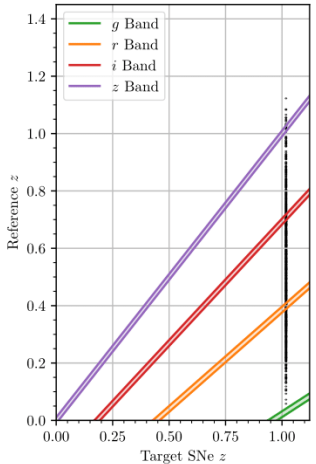
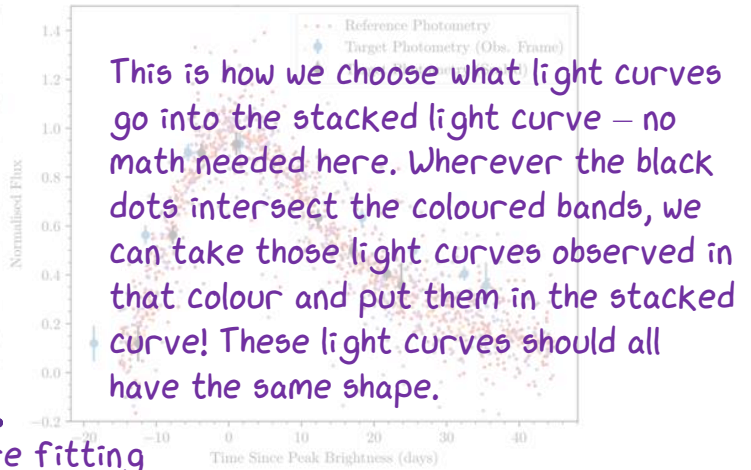
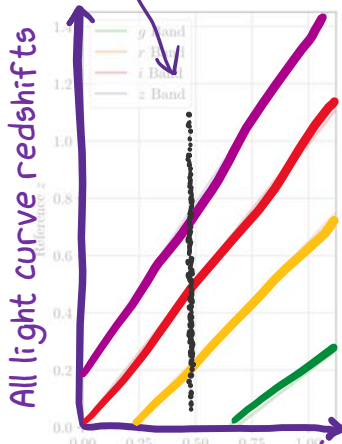
After constructing the reference curves for a target SN, we are ready to fit for the width,  $w$ , of each individual target light curve and look for a trend with redshift. This method enables a more precise measure of  $b$ .

Another way that we can find time dilation is to find the 'width' of each individual supernova light curve.

We can make the 'stacked' light curve (corrected for time dilation using the result from before) and fit an individual light curve to it to find how wide it is.

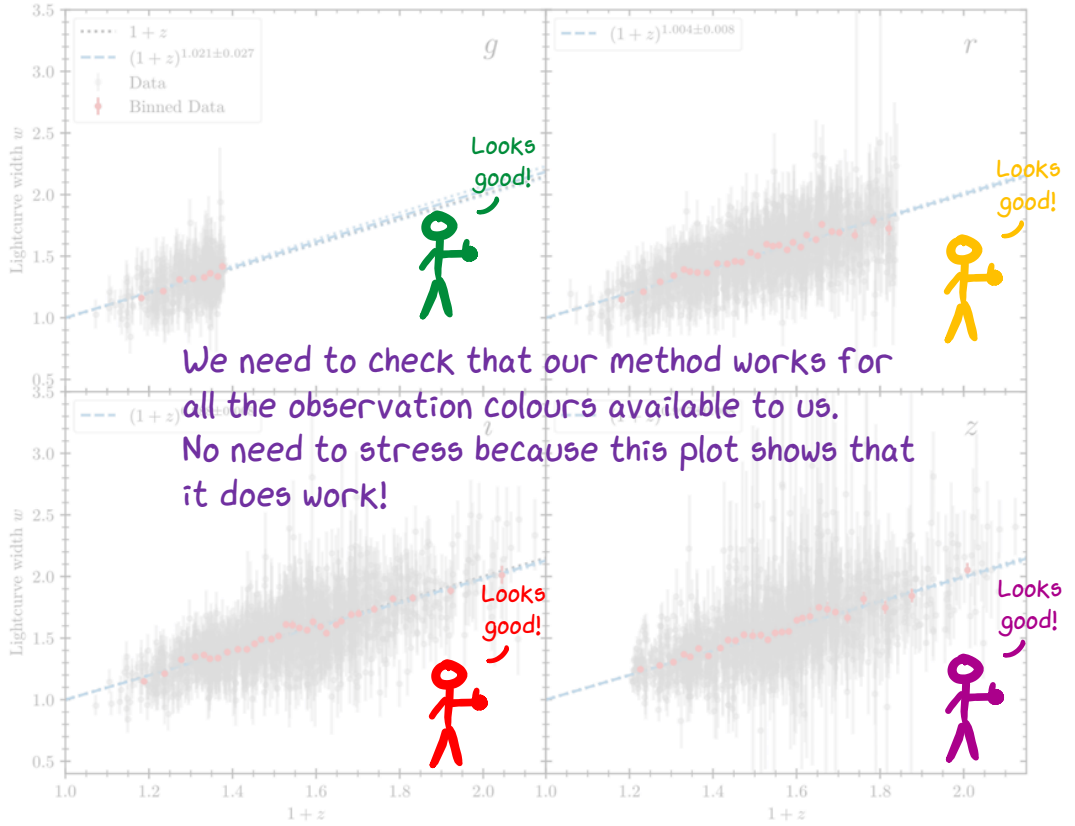


Each black dot is an individual supernova that we have light curves for



Here's one of the unedited plots from the paper now that we what's going on!

Figure 6. We show the reference curve construction and subsequent target SN fit for 3 SNe at redshifts  $z = 0.22$ ,  $z = 0.45$ , and  $z = 1.02$  and in fitting bands  $r$ ,  $i$ , and  $z$  respectively (in descending order). The left plots show the allowed ranges for reference curve SN sampling given the target redshift (and  $\delta = 2^{-4}$ ). The vertical line of dots is plotted at the target SN redshift, with each dot representing the redshift of a DES supernova (vertical axis). The dots that fall in the narrow coloured bands are the SNe that make up the reference population, as those data all share approximately the same rest-frame wavelength in their respective bands. The right plots show the constructed  $(1+z)$  time-scaled reference curve (small coloured points) with respect to the target SN photometry (blue points) and subsequent target photometry scaled on the time axis to fit the reference (best-fit widths of 1.42, 1.49, and 2.17 respectively). Due to the statistics associated with such large reference curve populations, the contribution of any individual reference point uncertainty to the overall reference curve uncertainty is negligible and not plotted; the uncertainty in the target data has a much higher contribution to the uncertainty in the fitting.



**Figure 7.** Using the reference-scaling method described in Section 4.3, we plot the fitted SNe widths of light curves observed in the  $g$ ,  $r$ ,  $i$ , and  $z$  bands (left to right, top down respectively). The lines of best fit (blue dashed) are in excellent agreement with the expected  $(1+z)$  time dilation (black dotted). The binned data are purely to visualise rough trends in 50 data point bins. 361 SNe in the  $g$  band passed the quality cuts described in Section 3, while the  $r$  band has 1380 SNe, the  $i$  band 1465, and the  $z$  band 1381. The reduced chi-square values,  $\chi^2_\nu$ , of each fit (left to right, top down) are 0.537, 0.729, 0.788 and 0.896 respectively.

We first normalise the target data to the peak flux using the SALT3 fit (as with the reference curves). The free parameter in the fit is the scaling parameter  $1/w$ , whereby changing this value would stretch and squash the data relative to peak (the time since peak). We find that the  $\chi^2$  is minimised. That is, we assume the SN light curve of the  $i$ th supernova is of a mathematical form similar to that described in Goldhaber et al. (2001),

$$F_i(t) \approx f_i \left( \frac{t - t_{\text{peak}}}{w} \right)$$

and change  $w$  until the data most closely matches the reference. Here,  $f_i(t)$  corresponds to the  $i$ th target light curve;  $F_i(t)$  corresponds to the  $i$ th reference curve where each point is now scaled in time by  $(1+z)$  relative to  $t_{\text{peak}}$  as per the results of Section 4.2.

To fit the target light curve width using its reference curve, we minimised the  $\chi^2$  value of the differences in the target flux compared to the median reference flux in a narrow bin around time values of the target photometry. That is, for each target light curve we minimised

$$\chi^2_i = \sum_j \frac{(f_{ij} - \text{Med}\{F_i(t) \mid \forall t \in [t_{ij}/w - \tau, t_{ij}/w + \tau]\})^2}{\sigma_{ij}^2} \quad (6)$$

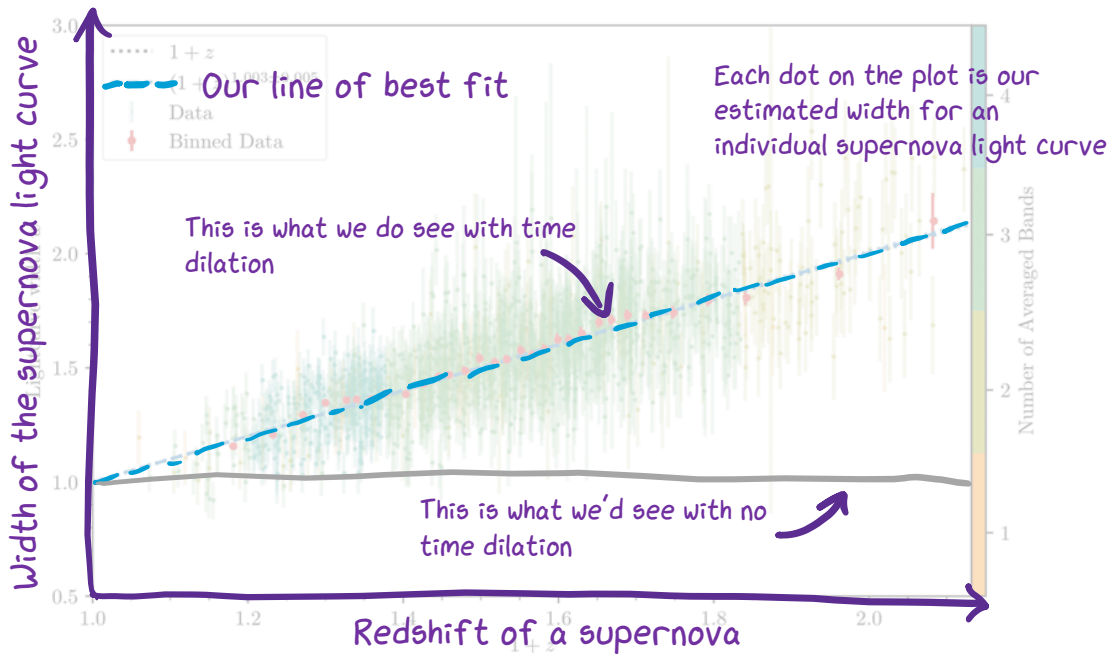
for  $N_p$  number of points in the  $i$ th target SN light curve ( $f_i$ ). The points in the reference curve ( $F_i$ ) bin that are averaged and compared

This is us describing the math and code that we used to find the widths of the light curves. We don't use a particularly difficult or advanced method, but it's accurate for our purposes and runs quickly on a personal computer.

to each target SN flux value ( $f_{ij}$  – with error  $\sigma_{ij}$ ) are selected within the time range  $[t_{ij}/w - \tau, t_{ij}/w + \tau]$ ; here  $t_{ij}$  is the time since peak brightness of each target data point scaled by the fitted width  $w$ , and  $t_{ij}$  is the time since peak brightness of the reference curve at its central time value  $t_{ij}$ .

During the fitting process, the bounds of this narrow bin around each time value changes as the target data is scaled in time but remains constant in the reference curve. We chose a bin width of  $2\tau$ , of 4 rest-frame days (i.e.  $\pm\tau = \pm 2$  of a central value); ideally this would be as low as practical to minimise any bias in the width measurements due to the target data point position and the reference curve slice, but needs to be large enough to provide a sufficiently populated sample of the reference to compare to. We find that a width of 4 days (just under the width of a minor tick span in Fig. 4) is low enough that the reference curve does not significantly change in flux but still contains enough points even for high/low redshift target SNe with small reference populations. With this  $\tau = 2$  value we find  $\geq 50$  data points per time slice at the highest and lowest redshifts, where a  $\tau = 1$  yields a prohibitively small  $\leq 20$  data points per slice even in the most well sampled photometric band ( $i$ -band).

In fitting the data, we did not include any target SN data points that extended past the maximum time value in the reference curve; the late-time light curves of SNe dwindle slowly and are less constraining for width-measurements than those near the peak. We also omitted any points that had observation times prior to the first reference curve point from the fitting procedure.



**Figure 8.** We show here the width value for each SNe averaged across all available bands. Since cosmological time dilation is independent of the observed band of any SN, we can fit the data with a model of the form  $(1+z)^b$  where  $b = 0$  means no time dilation and  $b = 1$  is the time dilation we expect. Remember that we're trying to find time dilation of the form  $(1+z)^b$  where  $b = 0$  means no time dilation and  $b = 1$  is the time dilation we expect. The reduced chi-square  $\chi^2_{\nu} = 1.441$  is comprised of the 104 unique SNe across the 4 bandpasses, where the error bars here are the Gaussian propagation of the fit. The best fit model recovers  $w = (0.988 \pm 0.016)(1+z) + (0.020 \pm 0.024)$  (with the same  $\chi^2_{\nu}$  to 4 significant figures), consistent with our power model fit above.

With our method we find **\*drumroll\***  $b = 1.003 \pm 0.015$ .

This means that our data is consistent with what we expect from theory.

The uncertainty in each estimated width was found via Monte Carlo simulation. We repeated the fitting process 200 times according to its Gaussian error, for each iteration we fit the width and the final error is the standard deviation in these widths. This provides some measure of the uncertainty in our model fits; this is where that plus or minus 0.015, or  $\pm 0.015$ , came from in our result. This means that we would normally expect the true result (that we're trying to find) to be somewhere in that range of our found result.

We note that while the width fitting for the whole dataset was calculated in all four DECam bands, only the  $i$  band encompasses the entire redshift range of the DES-SN sample. Due to the spectral shifting inherent in redshifted data, the  $g$  and  $r$  filters are unable to detect SNe at sufficiently high redshifts ( $z \geq 0.4$  and  $z \geq 0.65$  respectively) the observed wavelength shifts to lower emitted wavelengths (see Fig. 2 of DES Collaboration et al. 2024) and become fainter as a result. **0.988** Probably not over here. **1.003** Is the true value here? Or here? **1.018**

Figure 8 shows that fitting  $(1+z)^b$  to the  $z$ -band would require a positive redshift in the other bands to compute the reference; hence there is an inherent redshift floor for  $z$ -band fits leaving the  $i$ -band as the only suitable bandpass for the entire redshift range.

The widths obtained in all four bands separately are shown in Fig. 7. We see the truncated  $g$ ,  $r$  and  $z$  band data, and fit widths we mentioned before that we already corrected for time dilation in our stacked light curves.

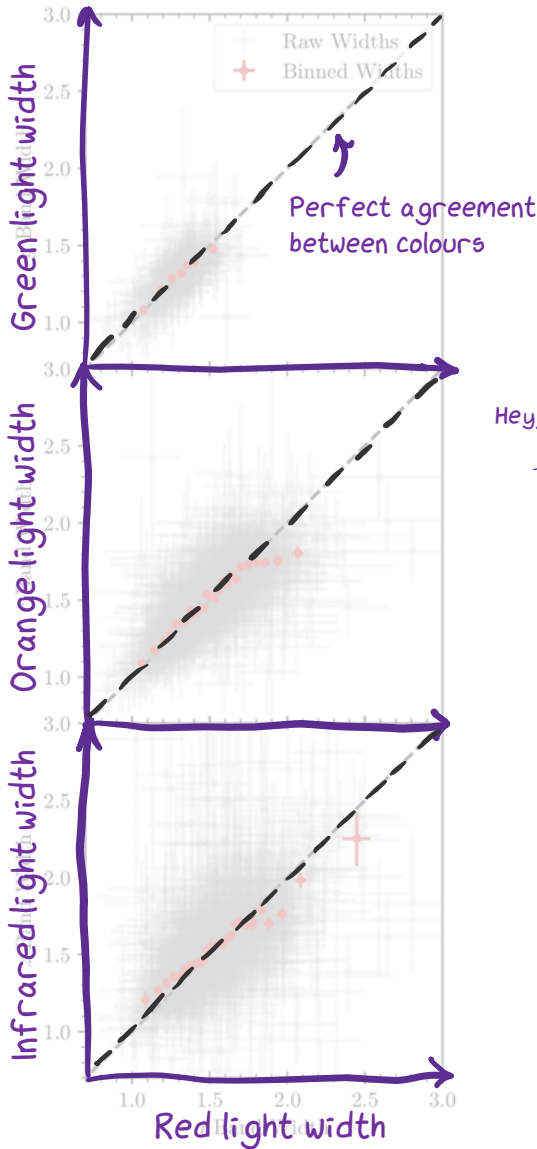
As mentioned in the introduction, the method has an element of circularity because we de-time-dilate the observed light curves to compare them against the reference. As a result, we are not just getting the answer we put in we repeated the analysis reference light curves more noisy and wider (like the top plot of Fig. 4). If the method is broken, we would get a consistent  $b = 0$  fit in this case. Spoiler: it's only possible to get a real signal when we correct for it in our stacked light curve!

Now let's talk about what we found

As we see in Fig. 7, there is a clear and significant non-zero time dilation signature in the DES SN Ia dataset, conclusively ruling out any static model. Our method described in Section 4 detects a time dilation signature in all of the  $g$ ,  $r$ , and  $z$  DECam bandpasses (on the next page)







You might expect that we see preferentially brighter objects when looking very far away — imagine your friend shining a flashlight at you as they walk away. Eventually, when they make a good distance, you won't be able to see them anymore unless they get a brighter flashlight!

As a test of the robustness of our method, we reran all the widths with a requirement of pre-peak observations in each light curve. This changed the power law fit by  $\Delta b = -0.004$  for the  $g$  band. The calculated  $b$  values in the other bands were increased by one or two thousandths (including the averaged fit of Fig. 8), or not at all. Interestingly, including this pre-peak restriction reduced our  $b$  values by only 24 in total. This reduction does not say if this method is robust at fitting light curves without pre-peak data, and future analyses may look at purposefully degrading the dataset (e.g. by manually removing pre-peak data).

Interestingly, the Dark Energy Survey Type Ia supernova sample avoids this bias quite a lot! Even if this bias were present in our data, it would only contribute  $<15\%$  to the light curve widths which is very small compared to the  $>100\%$  effect of time dilation at high redshift. At worst this would skew our fit, but we would still clearly see some non-zero time dilation signal.

We also looked at another, more advanced method that would mean that we **\*wouldn't\* need to correct for time dilation in the stacked light curve before fitting for light curve widths.** We found that this wasn't practical as we'd need even more data than we have; remember that DES has given us the largest sample of data at this high a distance, so we'd need a truly huge dataset to do this.

We need to check to make sure that in each band for each SNe should be intrinsically correlated as they arise from the same event. We find that there is a good agreement between bands. We plot their agreement relative to the  $i$  band width. The  $i$  band width is used as a reference width. This corresponds to a width in Fig. 7 of bands  $g$ ,  $r$  or  $z$  against the  $i$  band widths. The 1:1 dashed line shows perfect agreement and binned points are plotted to represent the trends in the agreement.

as expected. The power-law fits to the data in each bandpass are all consistent with the expected  $(1+z)$  law to within  $2\sigma$ .

Since there is a well documented stretch-luminosity relationship in Ia light curves (Phillips 1993; Phillips et al. 1999; Kasen & Woosley 2007), it is possible that Malmquist bias could skew the data to larger widths at high redshift where we may not see the less-luminous SNe. Regardless, this does not greatly influence the quality of our fits since the DES SN data extend to such high redshifts that the

which will be the topic of future work). We instead performed the analysis with flux-scatter minimisation and width-fitting methods as signal from our data can be precisely constrained, but there are other (physical) effects happening that make it a bit harder to nail down. Therefore we need to make our errorbars a little bit bigger with something called 'systematic' uncertainty.  $\sigma_b^{sys} + \sigma_b^{stat} \approx 0.015$  this remains the most precise constraint on cosmological time dilation.

**The take home message:**

Using two distinct methods, we have conclusively identified (1+z) time dilation in the data. We've done all of this work and effectively shown what we already knew and expected. We did this mainly for three reasons:  
 1. we're in an era of cosmology where it's more important than ever to have a solid grasp of the fundamental building blocks  
 2. it's a good idea to periodically check up on old results with new and shiny data  
 3. it's really just super cool that we can see time dilation from exploding stars!  
 We discuss factors and choices that affect our fits and see no indication that Malmquist bias or light-curve stretch significantly impacts our results. Our results infer a cosmological time dilation that is consistent with the standard model and past findings (Leibundgut et al. 1996; Giordano et al. 2001; Blondin et al. 2004; Kasliwal & Brice 2023) with more size and at a higher redshift range.

**ACKNOWLEDGEMENTS**

RMTW, TMD, RCa, SH, acknowledge the support of an Australian Research Council Australian Laureate Fellowship (FL180100168) funded by the Australian Government. AM is supported by the ARC Discovery Early Career Researcher Award (DECRA) project number DE23010001.

Funding for the DES Projects has been provided by the U.S. Department of Energy, the U.S. National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at

the Ohio State University, the Mitchell Institute for Fundamental Physics of Brazil, the European Union (ERC Grant No. 101019723), the FAPESP (2014/07696-2, 2013/07399-6, 2011/04749-0, 2014/11446-5, 2015/05507-0, 2016/03030-7, 2016/03831-2, 2016/03832-2, 2016/03833-2, 2016/03834-2, 2016/03835-2, 2016/03836-2, 2016/03837-2, 2016/03838-2, 2016/03839-2, 2016/03840-2, 2016/03841-2, 2016/03842-2, 2016/03843-2, 2016/03844-2, 2016/03845-2, 2016/03846-2, 2016/03847-2, 2016/03848-2, 2016/03849-2, 2016/03850-2, 2016/03851-2, 2016/03852-2, 2016/03853-2, 2016/03854-2, 2016/03855-2, 2016/03856-2, 2016/03857-2, 2016/03858-2, 2016/03859-2, 2016/03860-2, 2016/03861-2, 2016/03862-2, 2016/03863-2, 2016/03864-2, 2016/03865-2, 2016/03866-2, 2016/03867-2, 2016/03868-2, 2016/03869-2, 2016/03870-2, 2016/03871-2, 2016/03872-2, 2016/03873-2, 2016/03874-2, 2016/03875-2, 2016/03876-2, 2016/03877-2, 2016/03878-2, 2016/03879-2, 2016/03880-2, 2016/03881-2, 2016/03882-2, 2016/03883-2, 2016/03884-2, 2016/03885-2, 2016/03886-2, 2016/03887-2, 2016/03888-2, 2016/03889-2, 2016/03890-2, 2016/03891-2, 2016/03892-2, 2016/03893-2, 2016/03894-2, 2016/03895-2, 2016/03896-2, 2016/03897-2, 2016/03898-2, 2016/03899-2, 2016/03900-2, 2016/03901-2, 2016/03902-2, 2016/03903-2, 2016/03904-2, 2016/03905-2, 2016/03906-2, 2016/03907-2, 2016/03908-2, 2016/03909-2, 2016/03910-2, 2016/03911-2, 2016/03912-2, 2016/03913-2, 2016/03914-2, 2016/03915-2, 2016/03916-2, 2016/03917-2, 2016/03918-2, 2016/03919-2, 2016/03920-2, 2016/03921-2, 2016/03922-2, 2016/03923-2, 2016/03924-2, 2016/03925-2, 2016/03926-2, 2016/03927-2, 2016/03928-2, 2016/03929-2, 2016/03930-2, 2016/03931-2, 2016/03932-2, 2016/03933-2, 2016/03934-2, 2016/03935-2, 2016/03936-2, 2016/03937-2, 2016/03938-2, 2016/03939-2, 2016/03940-2, 2016/03941-2, 2016/03942-2, 2016/03943-2, 2016/03944-2, 2016/03945-2, 2016/03946-2, 2016/03947-2, 2016/03948-2, 2016/03949-2, 2016/03950-2, 2016/03951-2, 2016/03952-2, 2016/03953-2, 2016/03954-2, 2016/03955-2, 2016/03956-2, 2016/03957-2, 2016/03958-2, 2016/03959-2, 2016/03960-2, 2016/03961-2, 2016/03962-2, 2016/03963-2, 2016/03964-2, 2016/03965-2, 2016/03966-2, 2016/03967-2, 2016/03968-2, 2016/03969-2, 2016/03970-2, 2016/03971-2, 2016/03972-2, 2016/03973-2, 2016/03974-2, 2016/03975-2, 2016/03976-2, 2016/03977-2, 2016/03978-2, 2016/03979-2, 2016/03980-2, 2016/03981-2, 2016/03982-2, 2016/03983-2, 2016/03984-2, 2016/03985-2, 2016/03986-2, 2016/03987-2, 2016/03988-2, 2016/03989-2, 2016/03990-2, 2016/03991-2, 2016/03992-2, 2016/03993-2, 2016/03994-2, 2016/03995-2, 2016/03996-2, 2016/03997-2, 2016/03998-2, 2016/03999-2, 2016/04000-2).



Based in part on observations taken by the American Astronomical Society's NOIRLab (NOIRLab Prop. ID 2012B-0001; PI: J. F.roman), which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.  
 The DES data management system is supported by the National Science Foundation under Grant Numbers AST-1138766 and AST-1536171. The DES participants from Spanish institutions are partially supported by MICINN under grants ESP2017-89838, PGC2018-094773, PGC2018-102021, SEV-2016-0588, SEV-2016-0597, and SEV-2016-09949. Funding from the Ministry of Science and Innovation of the European Union, IFAE is partially funded by the CERCA program of the Generalitat de Catalunya. Research and development costs for these results have been funded from the European Research Council under the European Union's Seventh Framework Program (FP7/2007-2013) including ERC grant agreements 240672, 291329, and 306478. We acknowledge support from the Brazilian Instituto Nacional de Ciência e Tecnologia (INCT) do CNPq (grant number 301301/2014-2).

This manuscript has been authored by Argonne National Laboratory of the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

**Want to try it yourself?**

The data are available on Zenodo and GitHub as described in the All of the data is now publicly available so you can go and try to reproduce our (or other people's) results. The code we wrote uses popular and well tested packages NumPy (Harris et al. 2020), Matplotlib (Hunter 2007), and SciPy (Virtanen et al. 2020).

Dealing with this much data is only possible with programming! The code we wrote uses popular and well tested packages

The code we wrote is also publicly available, so you can take a look at my spaghetti code if you'd like! There's also some bonus plots on our [GitHub repository](#) that we didn't include in the paper.

Whose work did we build on?

Every new piece of science builds on the shoulders of giants. We're continuously improving, refining, finding new results based on the work that other smart people have published. For this paper we had to read a bunch of other papers to learn more about what's been done in the past, intricacies about supernovae, and the Dark Energy Survey data!

Guy J., et al., 2007, *A&A*, 466, 11  
 Harris C. R., et al., 2020, *Nature*, 585, 357  
 Howell D. A., Sullivan M., Conley A., Carlberg R., 2007, *ApJ*, 667, L37  
 Hoyle F., Fowler W. A., 1960, *ApJ*, 132, 565  
 Hunter J. D., 2007, *Computing in Science & Engineering*, 9, 90  
 Kasen D., Woosley S. E., 2007, *ApJ*, 656, 661  
 Kenworthy W. D., et al., 2021, *ApJ*, 923, 265  
 Kessler R., et al., 2015, *AJ*, 150, 172  
 Leibundgut B., Sullivan M., 2018, *Space Sci. Rev.*, 214, 57  
 Leibundgut B., et al., 1996, *ApJ*, 466, L21  
 Lewis G. F., Brewer B. J., 2023, *Nature Astronomy*,  
 Matheson T., et al., 2008, *AJ*, 135, 1598  
 Möller A., de Boissière T., 2020, *MNRAS*, 491, 4277  
 Möller A., et al., 2022, *MNRAS*, 514, 5159  
 Möller A., et al., 2024, arXiv e-prints, p. arXiv:2402.18690  
 Müller-Bravo T. E., et al., 2022, *A&A*, 665, A123  
 Nelder J. A., Mead R., 1965, *The Computer Journal*, 7, 308  
 Nicolas N., et al., 2021, *A&A*, 649, A74  
 Norris J. P., Nemiroff R. J., Scargle J. D., Kouveliotou C., Fishman G. J., Meegan C. A., Paciesas W. S., Bonnell J. T., 1994, *ApJ*, 424, 540  
 Phillips M. M., 1993, *ApJ*, 413, L105  
 Phillips M. M., Lira P., Suntzeff N. B., Schommer R. A., Hamuy M., Maza M., 1999, *ApJ*, 513, 1006  
 Piran T., 1992, *ApJ*, 389, L45  
 Rana D. W., 1997, Ph.D. thesis, Oak Ridge National Laboratory, Tennessee  
 Sanchez et al., 2024, in prep  
 Scolnic D., et al., 2023, *ApJ*, 954, L31  
 Smith M., et al., 2020, *AJ*, 160, 267  
 Takahashi N., Doi M., Yasuda N., 2008, *MNRAS*, 389, 1577  
 Tripp R., 1998, *A&A*, 331, 815  
 Vincenzi M., et al., 2024, arXiv e-prints, p. arXiv:2401.02945  
 Virtanen P., et al., 2020, *Nature Methods*, 17, 261  
 Wang L., Goldhaber G., Aldering G., Perlmutter S., 2003, *ApJ*, 590, 944  
 Wilson O. C., 1939, *ApJ*, 90, 634

Zwicky F., 1929, *Proceedings of the National Academy of Sciences*, 15, 773  
 pandas development team T., 2023, pandas-dev/pandas: Pandas, doi:10.5281/zenodo.8364959, <https://doi.org/10.5281/zenodo.8364959>

Now for some bonus content!

#### APPENDIX A: SUPERNOVA STRETCH REDSHIFT

There is evidence that the stretch distribution of SNe evolves with redshift, as the fraction of older and younger progenitors evolves. Nicolas et al. (2021) give the following relation for the evolution of the SN stretch distribution,

$$P(s_1) = \delta(z)N(\mu_1, \sigma_1^2) + (1 - \delta(z)) \left( aN(\mu_1, \sigma_1^2) + (1 - a)N(\mu_2, \sigma_2^2) \right), \quad (\text{A1})$$

where  $N(\mu, \sigma^2)$  is a normal distribution with mean  $\mu$  and variance  $\sigma^2$  and the values of the parameters were  $(\mu, \mu_1, \mu_2, \sigma_1, \sigma_2, K) = (0.51, 0.27, 0.21, 0.04, 0.056, 0.87)$ , so the fractional of young supernovae in the population is given by,

$$\delta(z) = \left( K^{-1}(1+z)^{-2.8} + 1 \right)^{-1} \quad (\text{A2})$$

This distribution is shown by equation (A1) shown in the upper panel of Fig. A1 for several redshifts, where the vertical dashed lines show the resulting change in the mean  $x_1$ .

The stretch of the supernova is given by (Guy et al. 2007), We found that this effect isn't noticeable in the Dark Energy Survey dataset,

$$s = 0.98 + 0.091x_1 + 0.003x_1^2 - 0.00075x_1^3 \quad (\text{A3})$$

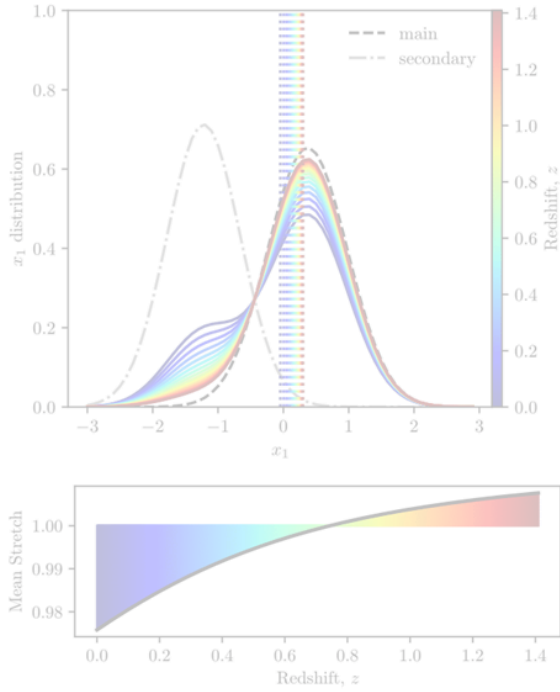
and this is shown in the lower panel of Fig. A1. Since light curve width is directly proportional to stretch, that means that the light curve width should be approximately 3% wider than those at  $z = 0$ . This is therefore substantially smaller than the effect of how we take our data.

Crunching the numbers shows that compensating this effect, supernovae with wider light curves tend to have a higher redshift effect, so you would expect a shift to wider light curves at higher redshifts.

Given the evidence that the mean stretch parameter  $x_1$  changes with redshift, see Fig. A2, our signal by  $\sim 3\%$  if we did see it!

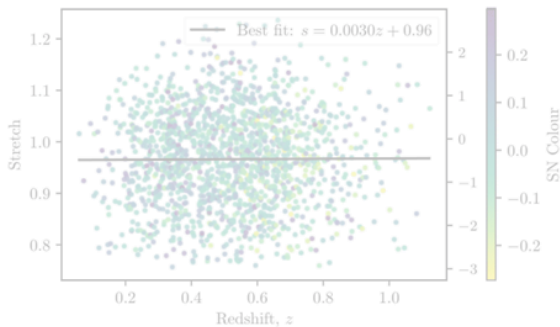
Despite the consistency of  $x_1$  in the DES sample we want to quantify how large the potential drift in the light curve widths could be if equation (A1) holds. Thankfully this over-estimation can be reduced if we were to incorporate the intrinsic widening included you find you would actually get a line of  $\Delta t \approx 1.005 + 0.005 \log(z)$ . Fig. 8 shows that the older widths would change the slope by  $\sim 3\%$ . This is in contrast to the recovered linear model fit in the Fig. 8 caption, hence indicating that this redshift-dependent stretch is not evident in the DES-SN5YR data.

The impact of high-redshift supernovae tending to have a few percent wider stretch than their low-redshift counterparts would cause us to slightly overestimate  $b$ . The magnitude of the impact on  $b$  depends on your redshift distribution, we estimate a shift of  $|\Delta b| \leq 0.01$  for the DES data, and we consider this a likely upper limit to the systematic uncertainty on our result. Since our aim in this paper is to fit the light curves with the minimal modelling assumptions (and since we do not see an  $x_1$  trend in our light curve fits) we have chosen *not* to correct for this trend. Instead we note that any potential effect would only be a small deviation around the slope of  $w/(1+z) \sim 1$  that we see.

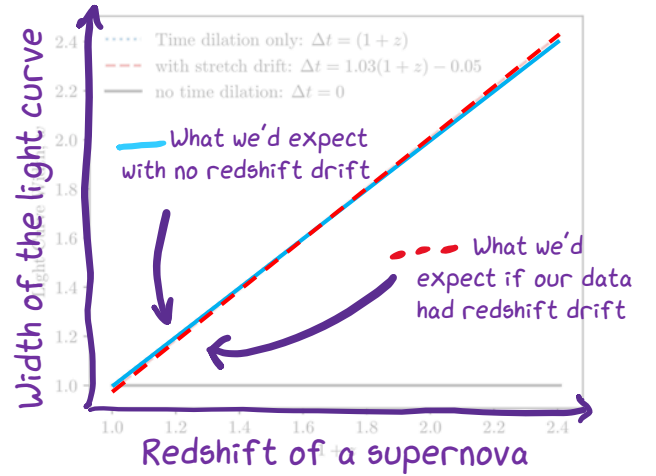


**Figure A1.** Upper panel: Distribution of  $x_1$  values predicted by Nicolas et al. (2021). The black line shows the evolution of the mean stretch ( $s$ ) of the supernova population with redshift. The colored lines show the total distribution for several different redshifts. The colored lines in the upper legend of the redshift distribution (in the same colours as the legend). One can see that the mean drifts back up over time and this is not what we expect. The black line shows the evolution of the mean stretch ( $s$ ) of the supernova population with redshift. The colored lines show the total distribution for several different redshifts. The colored lines in the upper legend of the redshift distribution (in the same colours as the legend). The intrinsic light curve width is proportional to  $s$ , and therefore light curves are expected to be about 5% wider at  $z = 1$  than at  $z = 0$ . This is much less than the factor of two widening due to time dilation.

These plots show what we'd expect to happen to our data with the redshift drift, and back up our claim that we don't really see it with the DES dataset.



**Figure A2.** The distribution of stretch in the DES-SN5YR data as a function of redshift (calculated from the SALT3 fitted  $x_1$  values using equation A2), with  $x_1$  shown on the right axis. Fitting a straight line to this distribution shows no significant trend in the stretch with redshift.



**Figure A3.** The effect of adding the predicted stretch evolution of SNe Ia vs redshift to the time dilation effect. The red dashed line is the result. If this result is present we therefore expect to slightly overestimate  $b$ , as we will attribute that widening to time dilation.

## Bonus content 2: electric boogaloo

### APPENDIX B: REFERENCE CURVE SELECTION DERIVATION

We begin with the definition of redshift,

$$1 + z = \frac{\lambda_o}{\lambda_e} \quad (\text{B1})$$

I was a little bit silly and repeatedly messed up this math in the early stages of the project. I wrote it out here so that everyone could see my attempt and correct me if I got it wrong! (thank god for peer reviewers and my supervisor). It's always good to remind ourselves that we're not infallible and talking to others helps us improve our work!

$$1 + z_r = \frac{\lambda_r / \lambda_e}{\lambda_r / \lambda_e} = \frac{\lambda_r}{\lambda_e} \quad (\text{B2})$$

Then, we can rearrange to find an expression for our target redshift

$$z_r = \frac{\lambda_r}{\lambda_e} - 1 \quad (\text{B3})$$

$$z_r = \frac{\lambda_r (1 + z)}{\lambda_f} - 1 \quad (\text{B4})$$

We can then append a term  $\pm \Delta z$  on equation (B4) to give us a range of applicable redshift values as in Section 4.1. Finally, it is useful in the broader context of the paper (and Fig. 3) to show this redshift range in terms of some fraction of the band FWHM of the band that the target SN was observed in,  $\delta \Delta \lambda_f$ . To do this we set  $\Delta z = \delta \Delta \lambda_f / \lambda_f$  and shift the term into the fraction within equation (B4),

$$z_r = \frac{\lambda_r (1 + z) \pm \delta \Delta \lambda_f}{\lambda_f} - 1 \quad (\text{B5})$$

which yields the redshift sampling range of equation (3) that we use in the analysis.

Bonus content 3: it's the last from me!

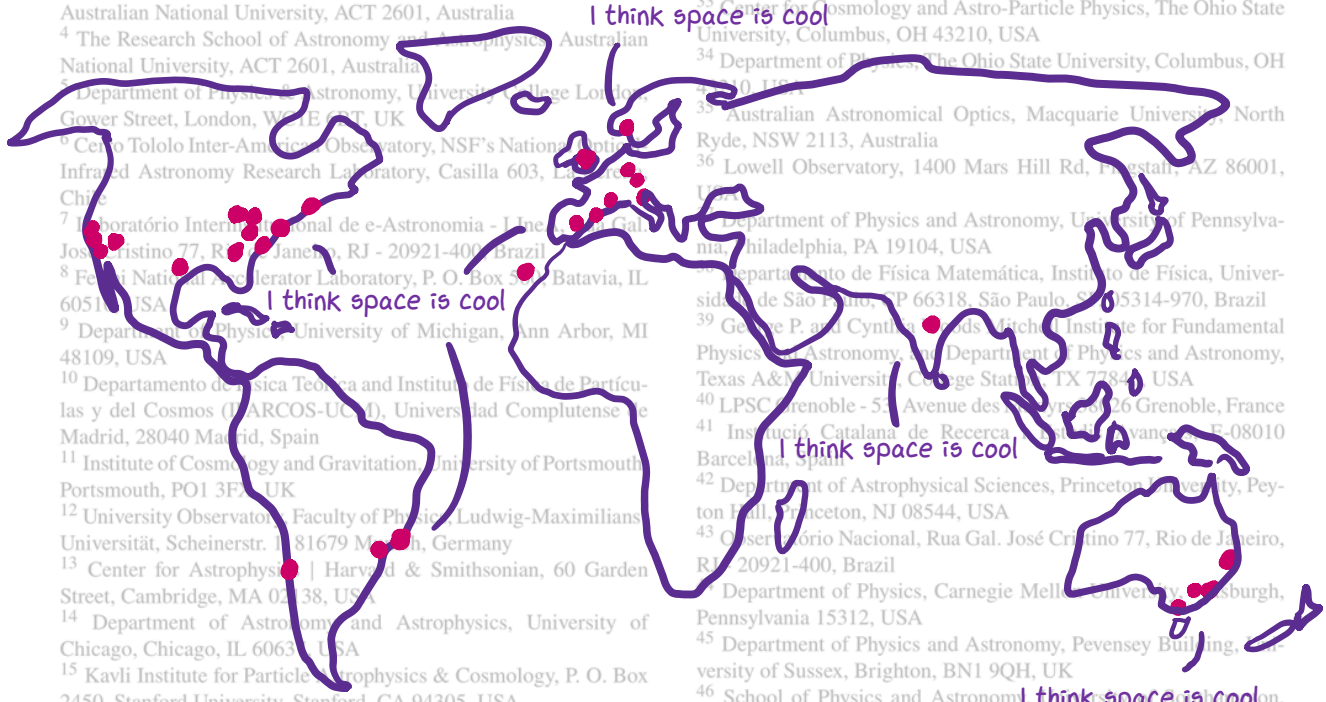
APPENDIX C: NULL TEST — NO DE-REDSHIFTING OF REFERENCE LIGHT CURVES

To confirm that our method is able to rule out no time dilation we  
 This is where we describe how badly  
 things mess up when we don't correct  
 for time dilation in the stacked light  
 curves. See the next page to see it in  
 action (it might help to compare with  
 the analogous plot a few pages back).

**AFFILIATIONS**

- 1 School of Mathematics and Physics, The University of Queensland, QLD 4072, Australia
- 2 Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW 2006, Australia
- 3 Centre for Gravitational Astrophysics, College of Science, The Australian National University, ACT 2601, Australia
- 4 The Research School of Astronomy and Astrophysics, Australian National University, ACT 2601, Australia
- 5 Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK
- 6 Cerro Tololo Inter-American Observatory, NSF's National Optical Infrared Astronomy Research Laboratory, Casilla 603, La Serena, Chile
- 7 Laboratório Interinstitucional de e-Astronomia - LIneA, Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil
- 8 Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510, USA
- 9 Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA
- 10 Departamento de Física Teórica and Instituto de Física de Partículas y del Cosmos (IFARCOS-UCM), Universidad Complutense de Madrid, 28040 Madrid, Spain
- 11 Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK
- 12 University Observatory, Faculty of Physics, Ludwig-Maximilians-Universität, Scheinerstr. 1, 81679 Munich, Germany
- 13 Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
- 14 Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
- 15 Kavli Institute for Particle Astrophysics & Cosmology, P. O. Box 2450, Stanford University, Stanford, CA 94305, USA
- 16 SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
- 17 Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
- 18 INAF-Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, I-34143 Trieste, Italy
- 19 Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UB, Marti i Franqués, Barcelona (Barcelona), Spain
- 20 Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany
- 21 Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

- 22 Department of Physics, IIT Hyderabad, Kandi, Telangana 502285, India
- 23 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA
- 24 Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, NO-0315 Oslo, Norway
- 25 Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
- 26 Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain
- 27 Institut d'Estudis Espacials de Catalunya (IEEC), 08034 Barcelona, Spain
- 28 Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, s/n, 08193 Barcelona, Spain
- 29 Centre for Astrophysics & Supercomputing, Swinburne University of Technology, Victoria 3122, Australia
- 30 Center for Astrophysical Surveys, National Center for Supercomputing Applications, 1205 West Clark St., Urbana, IL 61801, USA
- 31 Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, IL 61801, USA
- 32 Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA
- 33 Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA
- 34 Department of Physics, The Ohio State University, Columbus, OH 43210, USA
- 35 Australian Astronomical Optics, Macquarie University, North Ryde, NSW 2113, Australia
- 36 Lowell Observatory, 1400 Mars Hill Rd, Flagstaff, AZ 86001, USA
- 37 Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
- 38 Departamento de Física Matemática, Instituto de Física, Universidade de São Paulo, CP 66318, São Paulo, SP 05314-970, Brazil
- 39 George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
- 40 LPSC Grenoble - 53 Avenue des Bains, 38000 Grenoble, France
- 41 Institució Catalana de Recerca i Innovació Tecnològica, E-08010 Barcelona, Spain
- 42 Department of Astrophysical Sciences, Princeton University, Peyton Hall, Princeton, NJ 08544, USA
- 43 Observatório Nacional, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil
- 44 Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15312, USA
- 45 Department of Physics and Astronomy, Pevensey Building, University of Sussex, Brighton, BN1 9QH, UK
- 46 School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK
- 47 Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
- 48 Department of Physics, Duke University Durham, NC 27708, USA
- 49 Université Grenoble Alpes, CNRS, LPSC-IN2P3, 38000 Grenoble, France
- 50 Department of Astronomy, University of California, Berkeley, 501
- 51 Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA



You saw on the first page how many people contributed to this work and the Dark Energy Survey. This is (roughly) where every author's institution for this paper is!

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.

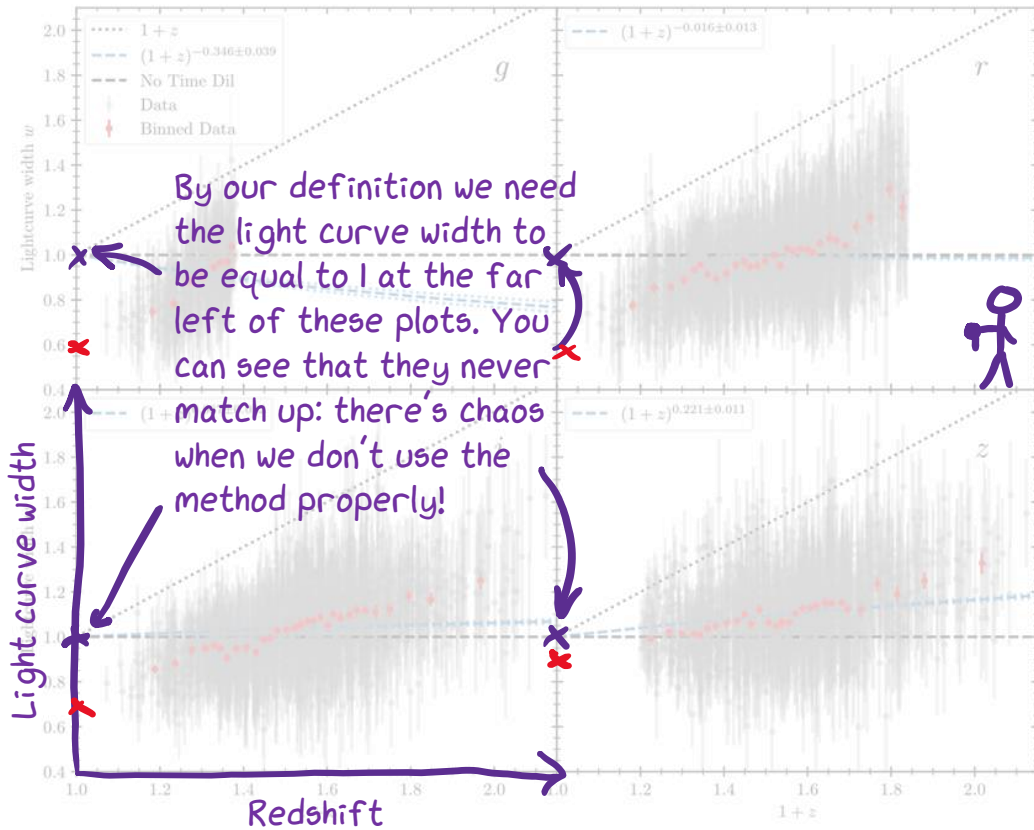


Figure C1. Light curve widths measured with respect to a reference curve that has *not* been de-time-dilated. We nevertheless still see a persistent trend of increasing light curve width with redshift. The vertical offset from the  $w=1$  line also arises because the non-time-dilated reference curves are wider than rest-frame light curves, i.e. this offset is yet another indication of time dilation. The black horizontal dashed line indicates no time dilation and the blue dashed lines are (poor)  $(1+z)^b$  model fits to the data. If there was no time dilation, these fits would be horizontal lines with  $b=0$ .

Congratulations on making it to the end! We've put a lot of effort into making the paper readable to astrophysicists, but I hope these notes were readable regardless of your background!

These scribbles were inspired by the wonderful work of [Claire Lamman](#) and [Sydney Vach](#) (who was also inspired by Claire!) Please go check out their annotated papers [here](#) and [here](#). I used PowerPoint to write over the paper text and plots by hand, using the XKCD font for the text (you don't want to see my handwriting!). You can download the font at [github.com/ipython/xkcd-font](https://github.com/ipython/xkcd-font)

Want to read more about the Dark Energy Survey? There's a lot of cool science happening! [darkenergysurvey.org](https://darkenergysurvey.org)

  
(Ryan White, me!)