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

The Dark Energy Survey Supernova Program: Slow supernovae show cosmological time dilation out to z ~ 1

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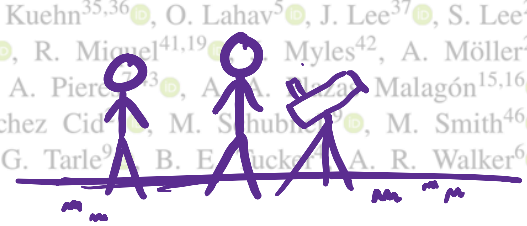
(DES Collaboration)

Affiliations are listed at the end of the paper.

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



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

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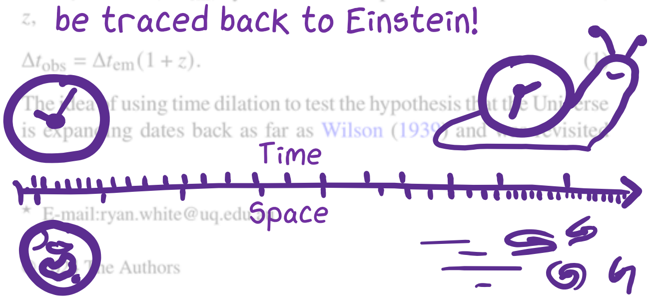
Here's the tl;dr...

For almost 100 years we've known that the Universe is expanding. 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:

Cosmological time dilation is yet *another* prediction that can be traced back to Einstein!

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



What we're looking for in the paper isn't a new idea; using exploding stars, supernovae, as clocks was proposed 85 years ago! Lots of people have used these and other transient light sources to quantify time dilation before...

To avoid degeneracy between the natural variation of light-curve

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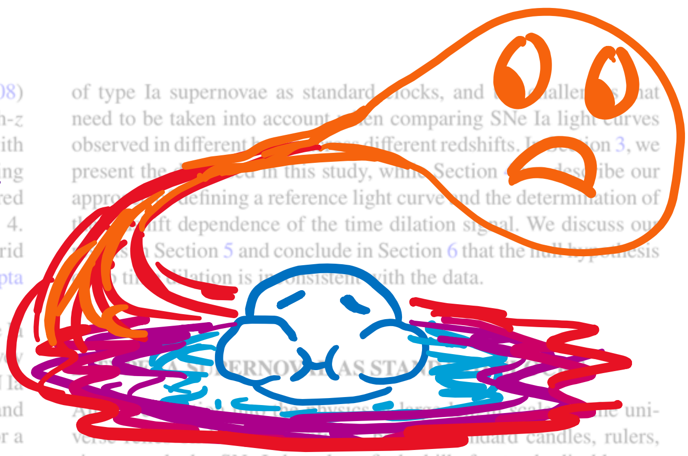
... seriously, this is something that lots of smart people have looked at before!



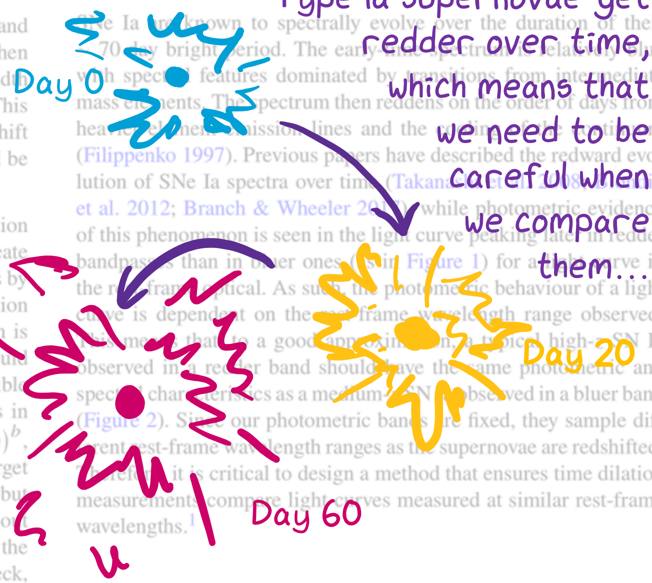
It's important to use the most distant supernovae possible for these types of studies. The further away a supernova is, the stronger the time dilation signal! This lets us find the signal amongst the noise.

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

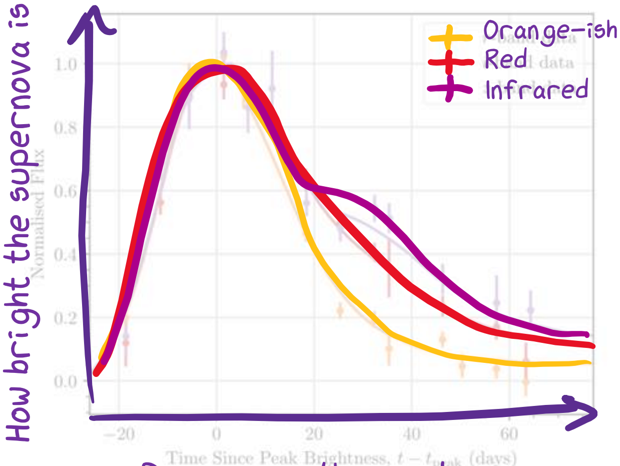
Type Ia supernovae are the result of 'white dwarf' stars exploding. These white dwarf stars are the super-compact remnant cores of stars that have shed their outer layers – kind of like the skeleton left over after we die. Some of these stars steal extra material from nearby stars while in their white 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!

To detect time dilation we can compare how different supernovae change over time.

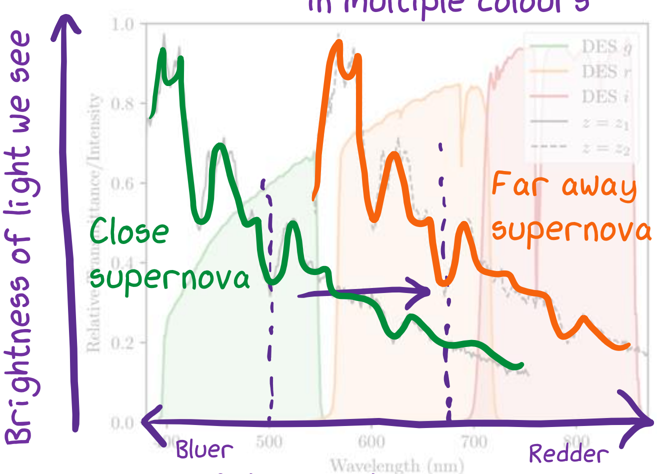
Type Ia supernovae get redder over time, which means that we need to be careful when we compare them...



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



This is what our data looks like! We have 'light curves' of 1504 unique supernovae, in multiple colours



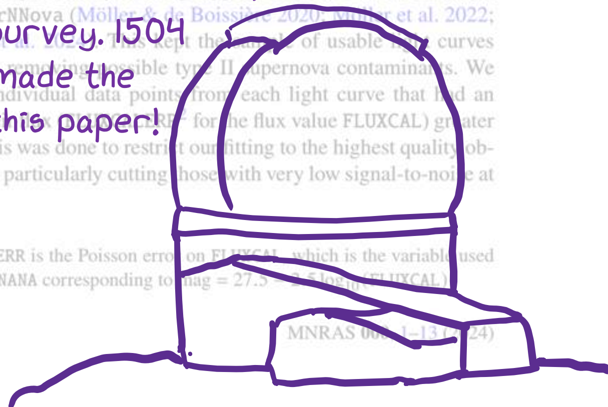
The expanding Universe makes distant blue light appear red to us – we call this 'redshift'. This plot shows that the colour spectrum of a supernova that's far away is redshifted compared to one that's close by

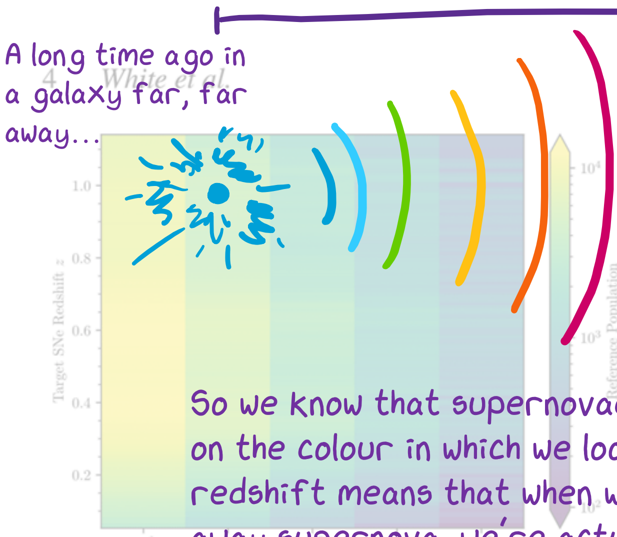
Type Ia supernovae aren't actually as consistent as I've been letting on, but they do average out nicely! Some supernovae are intrinsically brighter than others and so they have 'wider' light curves, meaning they effectively explode for a longer duration. On the plot to the left, one of these special supernovae would be a bit taller and a bit wider!

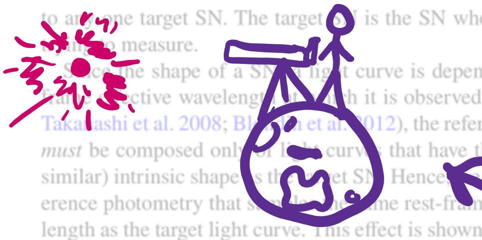
This has the same effect as time dilation and this makes our analysis a bit trickier. Luckily, the Dark Energy Survey found so many supernovae of all types that we don't need to correct for this; it all averages out. Even if it didn't average out, this affect is not as strong as the time dilation.

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!







So we know that supernovae appear differently depending on the colour in which we look at them. We also know that redshift means that when we look at red light from a far away supernova, we're actually looking at intrinsically blue light that's been shifted to the red as the light has travelled to us.

If we want to 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.

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

This equation essentially says that if we want to compare with a supernova at a very high redshift, we need to collect light in a redder filter so that we're seeing the same type of stuff!

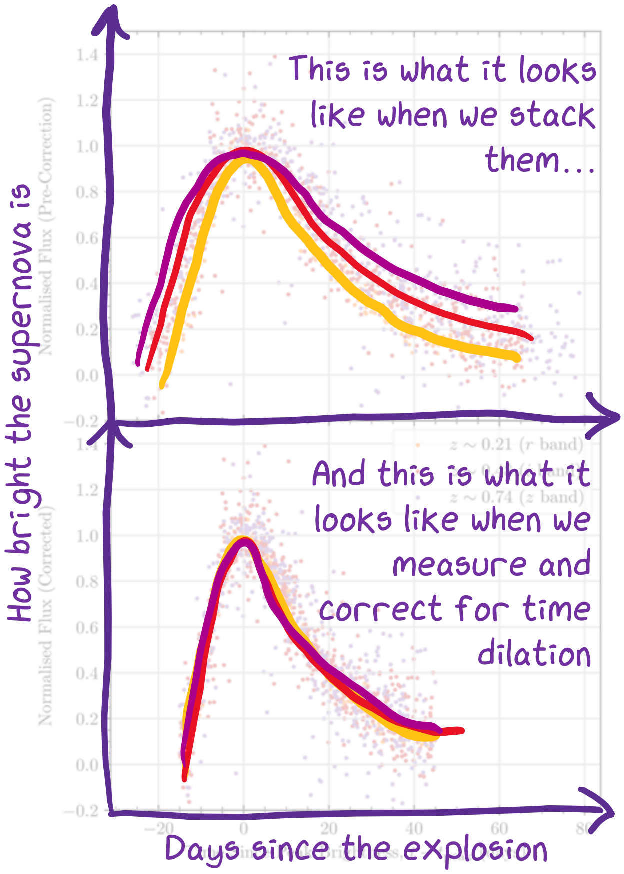
Since we have a finite amount of data, we can't choose light curves that'll have *exactly* the same shape, but the sheer number of supernovae with DES means that we can pick lots of light curves that are pretty close!

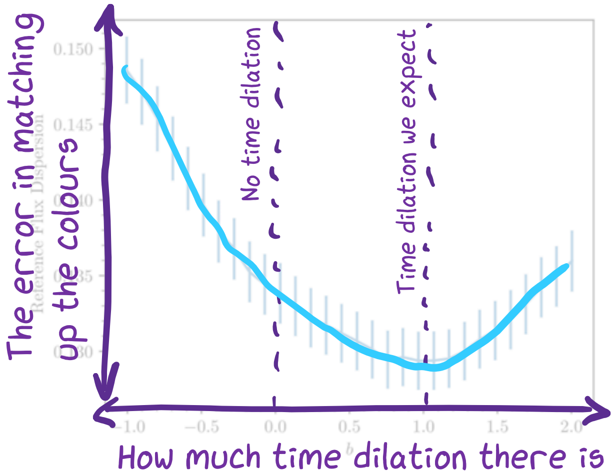
What do *we* do in the paper?

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 various 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.

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





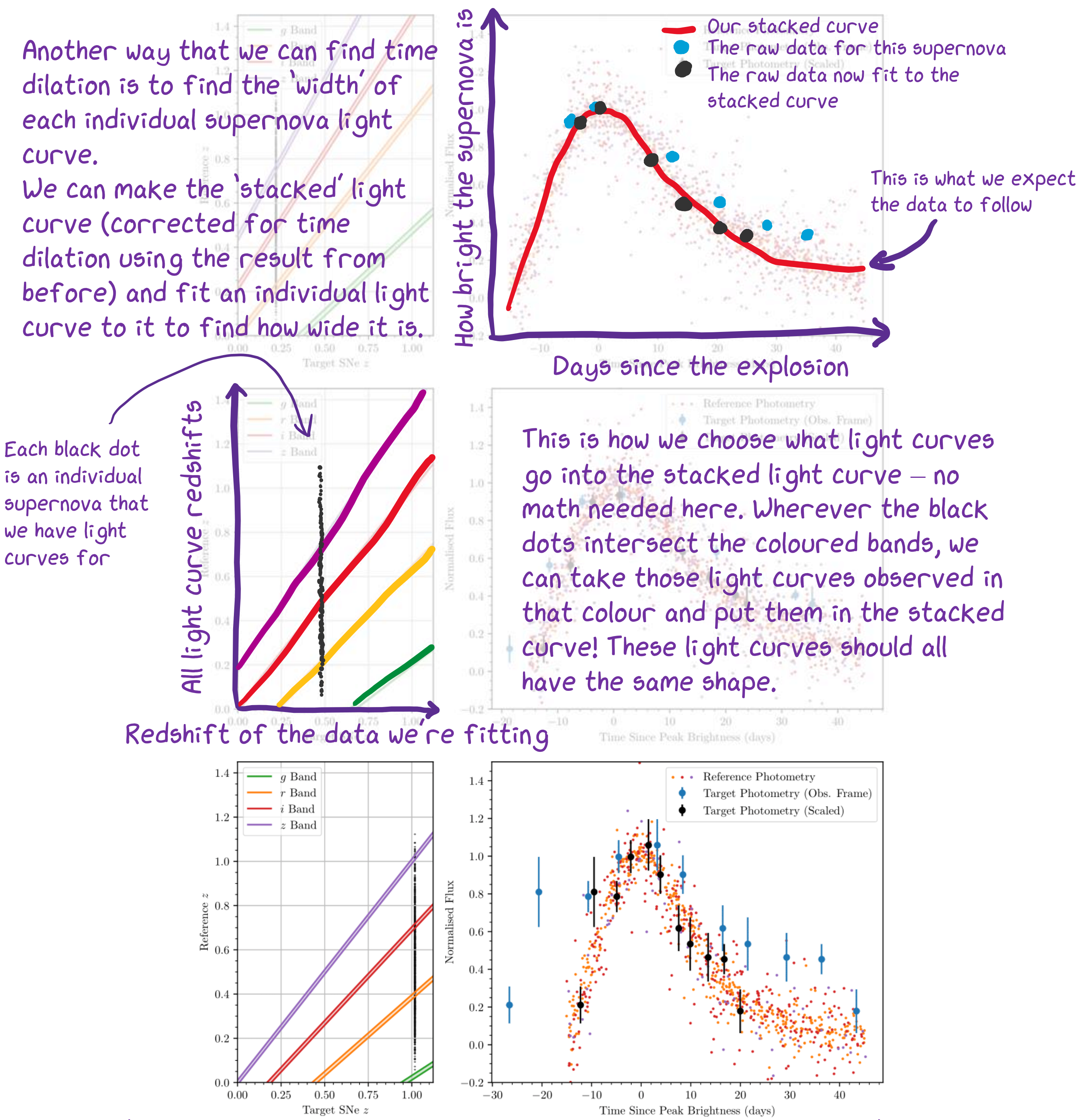
(lower values of error is better!)

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 *wider*. This is time dilation in action!

This part of the paper describes one way that we can numerically measure time dilation. If we squish the light curves along the time axis by a certain amount so that all of the different colours line up, we've got our time dilation measurement!

What we did on the left column was just for one individual 'center' redshift value (in that case, trying to match the shape of a red light curve at redshift 0.5). We can do this for all of the 1504 DES center redshifts and find the time dilation value that best matches up all of the colours.

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. Cosmology can rest easy! For now...



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 $z \approx 0.22$, $z \approx 0.43$, and $z \approx 1.02$ 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.

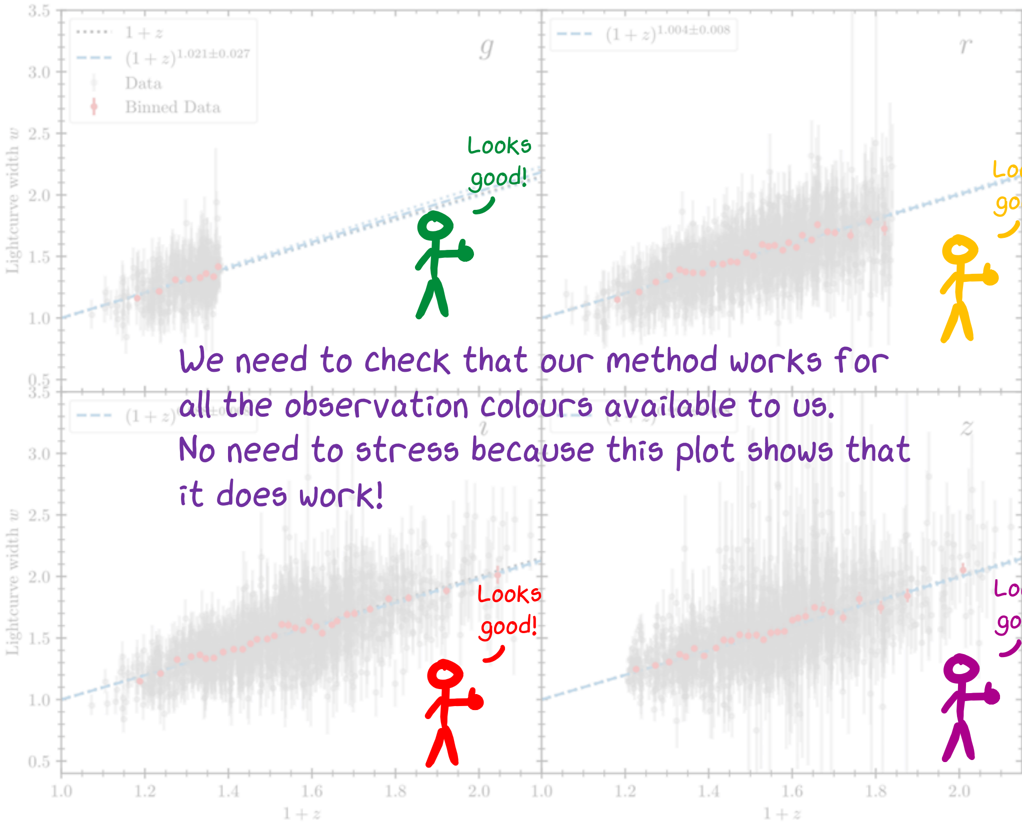


Figure 7. Using the reference-scaling method described in Section 4.3, we plot the fitted SNe widths of light curves observed in the g, r, i, and z bands (*left to right, top down* respectively). The lines of best fit (blue dashed) are in excellent agreement with the expected $(1+z)$ time dilation (black 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, χ^2_ν, of each fit (left to right, top down) are 0.537, 0.729, 0.788 and 0.896 respectively.

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.

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 $t_{\rm peak}$ (the time since peak flux) until the χ^2 is minimised. That is, we assume the SN Ia light curve of the ith supernova is of a mathematical form similar to that described in Goldhaber et al. (2001),

$$F_i(t) \simeq f_i\left(\frac{t - t_{\rm peak}}{w}\right) \quad (5)$$

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

To fit the target light curve width using its reference curve, we minimised the χ^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

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

for N_p number of points in the ith target SN light curve (f_i). The points in the reference curve (F_i) bin that are averaged and compared to each target SN flux value (f_{ij} – with error σ_{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 τ is the half-width of the bin around the 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 the same size. We chose a bin width, 2τ, of 4 rest-frame days (i.e. $\pm\tau = \pm2$ of a central value); ideally this would be as low as practical to maximise the time similarity between 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 $\gtrsim 50$ data points per time slice at the highest and lowest redshifts, where a $\tau = 1$ yields a prohibitively small $\lesssim 20$ 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.

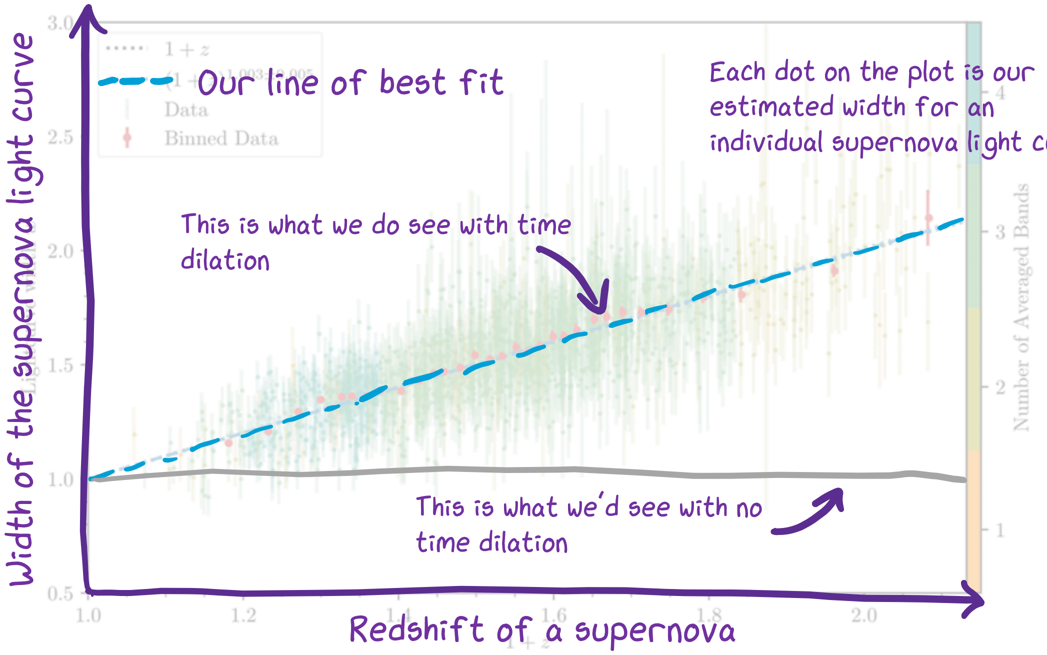


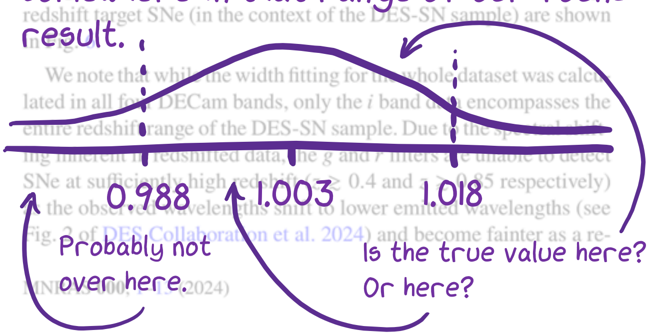
Figure 8. We show here the width value for each SNe averaged across all available bands. Since cosmological time dilation is independent of the observed band of any SN, we … time dilation (reduced chi-square $\chi^2_\nu \approx 1.441$) is comprised of the 1504 unique SNe across the 4 bandpasses, where the error bars here are the Gaussian propagation of … A linear model fit to the data recovers $w = (0.988 \pm 0.016)(1+z) + (0.020 \pm 0.024)$ (with the same χ^2_ν to 4 significant figures), consistent with our power model fit above.

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.

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.

In science we usually can never claim a perfectly precise result and need to discuss our uncertainty in our model fits; this is where that 'plus or minus' 0.015, or ±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 mentioned before that we already corrected for time dilation in our stacked light curves. To be sure that we're not just getting the result that we put in, we do it all again later without correcting beforehand.

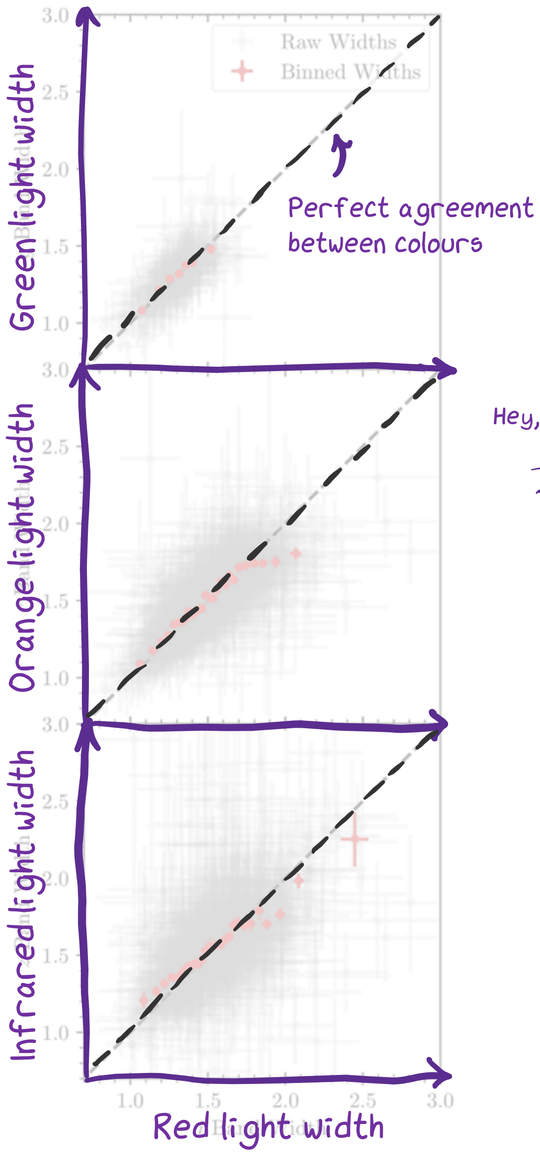
Spoiler: it's only possible to get a real signal when we correct for it in our stacked light curve!

Now let's talk about what we found

5 DISCUSSION

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 universe models. Our method described in Section 4 detects a time dilation signature in all of the g, r, i, and z DECam bandpasses

(on the next page)

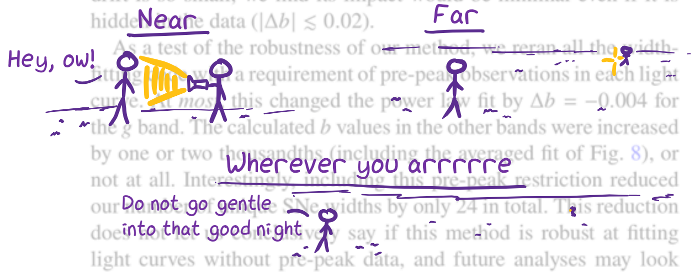


We need to check to make sure that we're finding roughly the same width in all of the different colours we look at each supernova in. On average, we do!

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

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

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 good distance, you won't be able to see them anymore unless they get a brighter flashlight!



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.

The uncertainty in our time dilation 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.

The take home message:

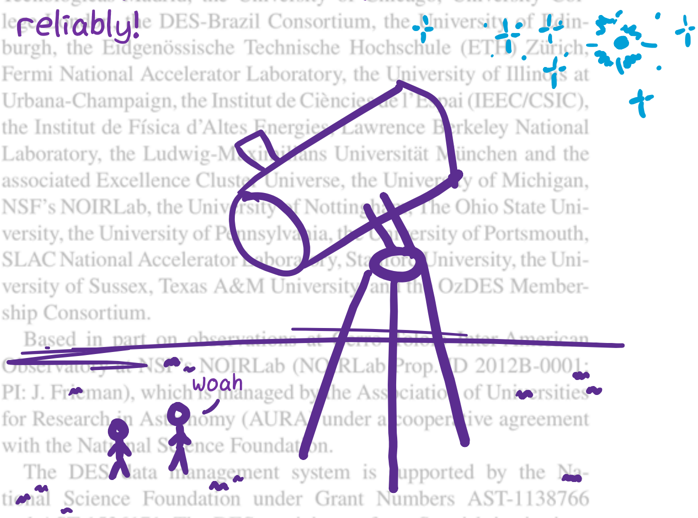
We've done all of this work and effectively shown what we already knew and expected. We did this mainly for three reasons:

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!

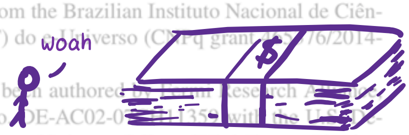
Time dilation is a real thing that we see in the Universe, and we've shown it with the most precise method and data so far

And now for thanks!

It takes a *lot* of funding for a lot of people to allow us to do these kind of studies. Even though the light from these supernovae is raining down everywhere on Earth, it takes a huge and expensive telescope to collect it all reliably!



...looooots of funding from a lot of different governments and institutions.



Want to try it yourself?

All of the data is now publicly available so you can go and try to reproduce our (or other people's) results!

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!

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It's great to live in a time when so many are given the opportunity to study the Universe and share what they find

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Now for some bonus content!

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,

While we were writing the paper we came across an interesting study that suggests that supernova light curves really are somewhat *intrinsically* wider at high redshift. We don't yet know why this is, but as with any good science we can model it!

We found that this effect isn't noticeable in the Dark Energy Survey dataset, not because it doesn't exist but probably just because of how we take our data. Crunching the numbers shows that this 'redshift drift' in the width of light curves would only change our signal by ~3% if we did see it! Like before, this isn't make-or-break for detecting time dilation, but it is important to consider with a result as precise as ours.

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 $|\Delta b| \lesssim 0.01$ 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.

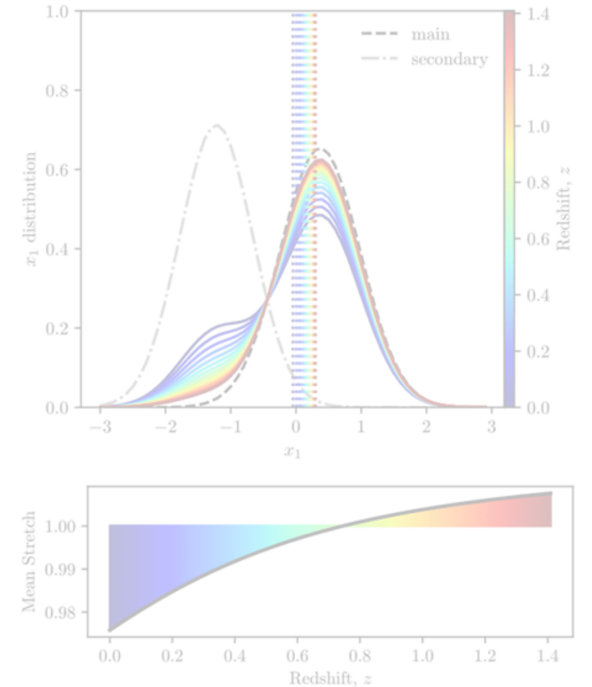

Figure A1. Upper panel: Distribution of x_1 values predicted by Nicolas et al. (2021). The [illegible] components of the supernova population. The coloured lines show the total distribution for several diff[illegible] of the redshift distribution (in the same colours as the legend). One can see that the mean drifts [illegible] black line shows the evolution of the mean stretch (s) of the supernova population with redshi[illegible] legend. The intrinsic lig[illegible] proportional to s, and therefore light curves are expected to [illegible] 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.

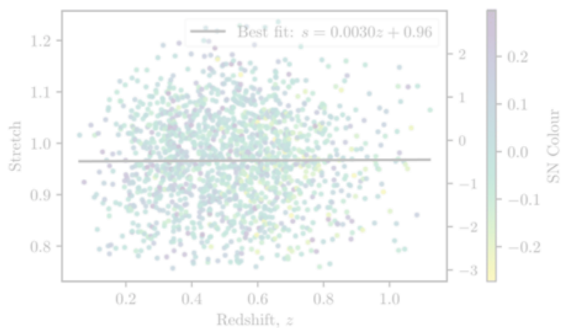

Figure A2. The distribution of stretch in the DES-SN5YR data as a function of redshift (calculated from the SALT3 fitted x_1 values using equation A2), with x_1 shown on the right axis. Fitting a straight line to this distribution shows no significant trend in the stretch with redshift.

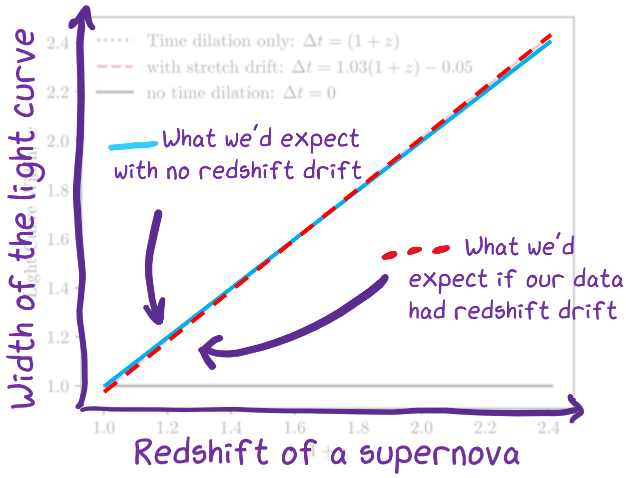

Figure A3. The effect of adding the predicted stretch evolution of SNe Ia vs redshift i[illegible] steeper. If this result is present we therefore expect to slightly overestimate b, as we will attribute that widening to time dilation.

Clearly a very small effect!

Bonus content 2: electric boogaloo

APPENDIX B: REFERENCE CURVE SELECTION DERIVATION

We begin with the definition of redshift,

$$1 + z = \frac{\lambda_o}{\lambda_e} \tag{B1}$$

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!

where z is the source redshift, λ_o is the observed wavelength of l[illegible] are sampling from a band with central wavelength λ_r during reference curve construction, we [illegible] to find a central redshift z_r for our reference SN selection [illegible] the target light curve in a band of central wavelength λ_f. The idea is to match t[illegible] by another instance of equation (B1).

$$\frac{1+z}{1+z_r} = \frac{\lambda_f/\lambda_e}{\lambda_r/\lambda_e} = \frac{\lambda_f}{\lambda_r} \tag{B2}$$

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

$$\lambda_r(1+z) = \lambda_f(1+z_r) \tag{B3}$$

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

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),

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

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 [illegible] ves. That means that the reference curves would look like the top panel of Fig. 4. If the data were not time dilated, then we should fit consistently $b = 0$ in this case. Fig. C1 clearly shows that this null test fails. Because time-dilation is present in the data, it means that the reference curves [illegible] light curve widths narrower. Despite this, the trend for higher-redshift light curves to be wider persists, in very strong contradiction to the no-time-dilation hypothesis.

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).

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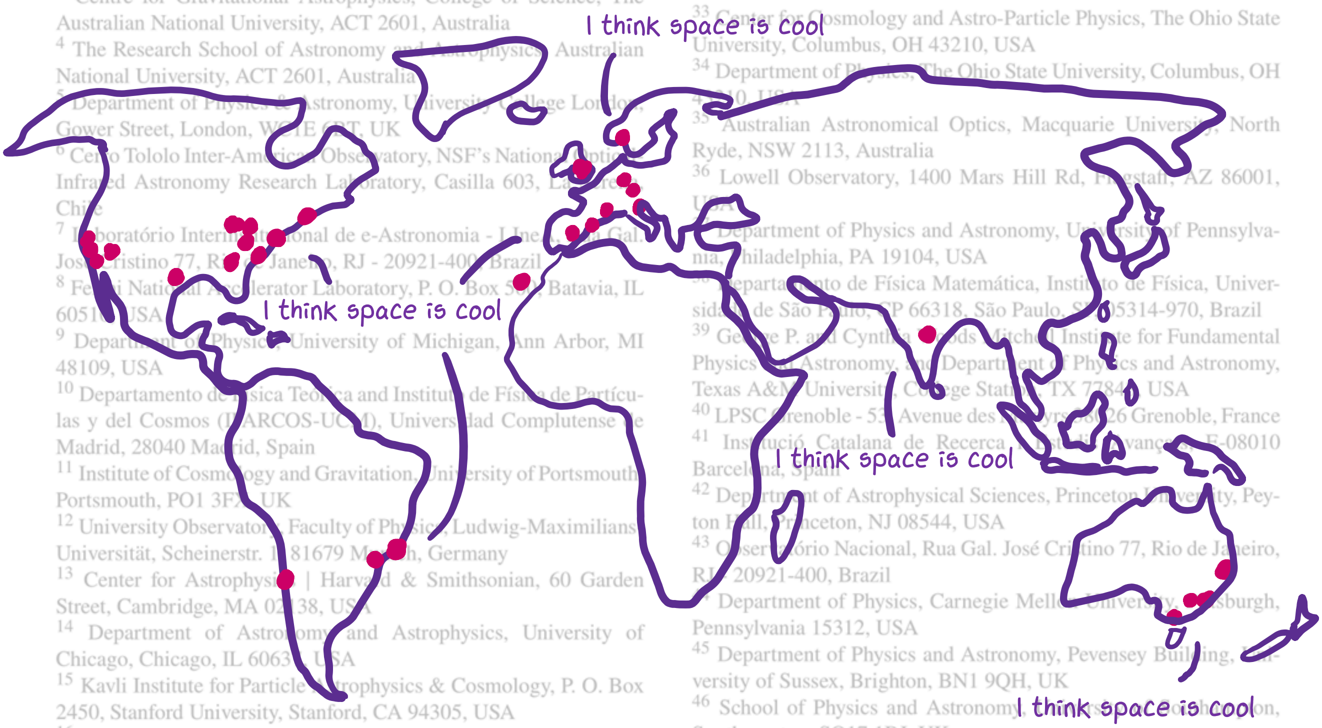

You saw on the first page how many people contributed to this work and the Dark Energy Survey. This is (roughly) where every author's institution for this paper is!

This paper has been typeset from a TEX/LATEX file prepared by the author.

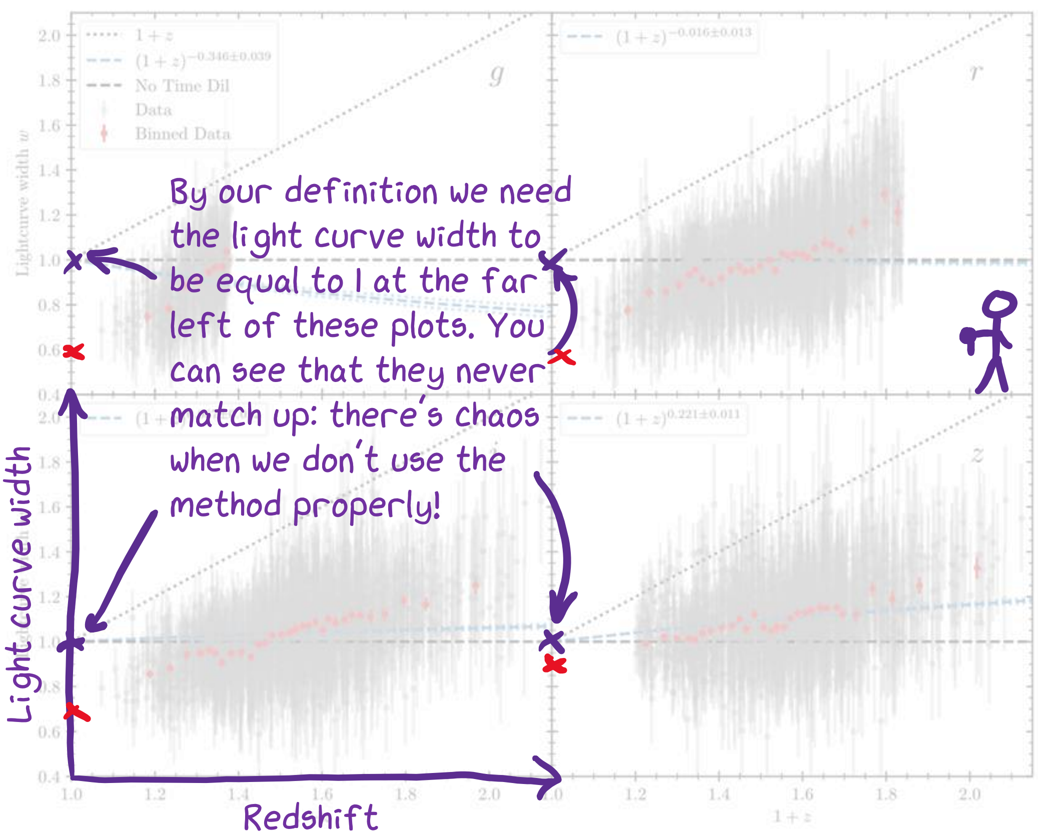

Figure C1. Light curve widths measured with respect to a reference curve that has *not* been de-time-dilated. We nevertheless still see a persistent trend of increasing light curve width with redshift. The vertical offset from the [illegible] arise because the non-de-time-dilated reference curves are 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 the (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

Want to read more about the Dark Energy Survey? There's a lot of cool science happening! darkenergysurvey.org

(Ryan White, me!)