Time variance of recession velocities: A potential resolution to the 'Crisis in Cosmology' and a possible explanation for the Accelerating Universe along with a possible direct evidence for Inflation and Reheating

Abstract

The larger than expected discrepancy between values of the Hubble-Lemaitre constant, among those measured by various seemingly independent methods, has been called as a 'crisis' in Cosmology. By incorporating the time variance of recession velocities, we present an alternative model for the velocity-distance data of Type Ia supernovae, which can potentially explain the discrepancy between the various independent measurements of the Hubble-Lemaitre constant as well as possibly throw some light on the classically counter-intuitive accelerating expansion of the Universe. This model also gives a possible direct observational evidence for Inflation and Reheating.

The idea at its fundamental level is this: The velocity-distance data for Type Ia Supernovae have been traditionally plotted to pass through origin. This models an accelerating Universe as conventionally concluded. However, when we allow for an intercept in the velocity-distance plot, in other words when we allow for an extra-Hubble-Lemaitre (eHL) velocity, we, interestingly, potentially resolve the following four long-persisting intrigues:

1. 'Crisis in Cosmology': Allowing for an eHL velocity also allows us to model the rate of expansion as measured by the Planck collaboration thus removing the existing 'tension' between values of the Hubble-Lemaitre constant.

2. Counter-intuitive accelerating expansion of the Universe: It turns out, interestingly, that allowing for eHL velocities in the model turns the observational data for accelerating expansion into one for decelerating expansion. How this happens is explained in detail in the section titled: 'Decelerating Universe?'

3. Accounting for time dependence of observed recession velocities: The classical equation for the observed recession velocity, $v(D) = v_H(D) = HD$, neglects its dependence on time. Allowing for an eHL velocity also allows us to include the potential effects of time, which is expected to cause the recession velocities to reduce in a classical Universe dominated by gravity over Dark Energy. Interestingly, this prediction is confirmed by observations as illustrated in the section titled 'Nature of the eHL velocity' and Figure 4.

4. Direct observational evidence for reheating and inflation: Allowing for eHL velocities also permits it to be a potential direct remnant of explosive particle creation during reheating and inflation. Such a direct observational evidence was long sought by the Astronomy community.

Introduction

The larger than expected discrepancy between values of the Hubble-Lemaitre constant, among those measured by various seemingly independent methods, has been called as a 'crisis' or 'tension' in Cosmology (Keck Observatory 2019; Valentino 2020; Crane 2019; Chen 2018; Gonzalez 2019; Chen 2019; Riess et al. 2019). On the other hand, it has also been persuasively argued that, the fact that these measurements, using many independent methods and observations, give such close values for the Hubble-Lemaitre constant, is a testimony to the prevailing cosmological models being predominantly correct (Chen 2018; Gonzalez 2019). This dichotomy between strong evidence for rough correctness of prevalent cosmological models combined with ever stronger evidence for finer incorrectness is cause for much intrigue recently in the academia, literature and science news (Rameez & Sarkar 2019; Gohd 2020; Yonsei University 2020).

By incorporating the time variance of recession velocities, we present an alternative model for the Velocity-distance data for Type Ia supernovae from the Union 2.1 compilation provided by The Supernova Cosmology Project (Suzuki et al. 2012), which can potentially explain the discrepancy between the various independent measurements of the Hubble-Lemaitre constant as well as possibly throw some light on the classically counter-intuitive accelerating expansion of the Universe. As we shall see, this model also gives a possible direct observational evidence for Inflation and Reheating.

Choosing the dataset

Modelling the distance-velocity relationship for Type Ia supernovae is a challenging problem. Closer supernovae have slower Hubble-Lemaitre velocities and therefore their peculiar velocities create larger distortions in the Hubble-Lemaitre flow, thus making it difficult to accurately estimate the Hubble-Lemaitre constant. On the other hand, luminosity and thus distance measurement of farther supernovae is prone to errors due to their dimness as well as due to lesser angular resolution at larger distances making it more difficult to separate the light of the supernova from the light of its parent galaxy. Furthermore, distant supernovae have higher redshifts: calculating velocities for high redshifts is non-trivial and greatly depends on choice of the cosmological parameters as well as the cosmological model.

Therefore, it is important to be careful while modelling the Velocity-distance data for Type Ia supernovae so as to assume as less as possible, while still gleaning out meaningful probable conclusions from the model.

As noted earlier, in the cosmological paradigm, converting the redshift z to a recession velocity v accurately requires assumption of a suitable cosmological model as well as expansion history of the Universe. However, for $z \ll 1$, the approximation $v \approx cz$ holds, where c is the speed of light in vacuum.

To deal with the uncertainty of the cosmological model and expansion history, we choose to model data for supernovae with $0.01 < z < 0.08$, where the approximation $v \approx cz$ holds reasonably well. How well? Table 1 gives the answer. It may be noted here that the more widely accepted cosmological models currently predict the assumed component of Λ in the total energy density, $\Omega_\Lambda \sim 70\%$ (NASA Science 2020; National Geographic 2020; Woo 2007; Wolchover 2019; Dark Energy Survey 2020; Goudarzi 2006;

Institute of Cosmology and Gravitation 2020; European Space Agency 2020), giving an error of 1.86%, if the approximation $v \approx cz$ is assumed.

Table 1: Percentage error in assuming $v \approx cz$ for $z = 0.08$ depending on the cosmological model. The percent error will be lesser for lower redshift z. More widely accepted cosmological models currently predict the assumed component of Λ in the total energy density, $\Omega_\Lambda \sim 70\%$ (NASA Science 2020; National Geographic 2020; Woo 2007; Wolchover 2019; Dark Energy Survey 2020; Goudarzi 2006; Institute of Cosmology and Gravitation 2020; European Space Agency 2020).

Assumed component of Λ in the total energy density	% Error in v for $z = 0.08$ when assuming $v \approx cz$
$\Omega_\Lambda = 0\%$	5.96
$\Omega_\Lambda = 60\%$	2.47
$\mathbf{\Omega_\Lambda = 70\%}$	**1.86**
$\Omega_\Lambda = 75\%$	1.56
$\Omega_\Lambda = 80\%$	1.25
$\Omega_\Lambda = 100\%$	0

It is also noteworthy that a redshift of $z = 0.08$ corresponds to a recession velocity of about 24000 km/s, which corresponds to a distance of about 340 MPc or one billion light years. Thus, the supernovae data with redshift $z < 0.08$, which we choose to model, represents relatively local Universe and relatively recent expansion history. This should help us to isolate the evidence for accelerating Universe more clearly, since the effects of the hypothesized Dark Energy have been predicted to have grown in influence with the age of the Universe (Risaliti & Lusso 2019; Siegel 2019; Goudarzi 2006). Furthermore, this data from the local Universe is expected to adhere to a significantly higher value for the Hubble-Lemaitre constant than that obtained by the Planck Collaboration (Keck Observatory 2019; Valentino 2020; Crane 2019; Chen 2018; Gonzalez 2019; Chen 2019). However, as it turns out, we show that even the data from this most recent and nearest part of the Universe can be modeled to show a rate of expansion as measured by the Planck Collaboration, as well as a possibly decelerating Universe instead of an accelerating one.

Motivating the data model

To motivate our data model, we plot the recession velocity versus distance for supernovae with $0.01 < z < 0.08$ in the Union 2.1 Type Ia Supernova compilation (Suzuki et al. 2012). The slope of the trendline then gives an estimate of the Hubble-Lemaitre constant.

We want to understand the change in Hubble-Lemaitre constant with distance. Therefore, we need to observe the change in slope of the trendline with distance. To this end, we divide our dataset into two parts: first from with $0.01 < z < 0.05$ with 140 supernovae, and second from $0.04 < z < 0.08$ with 61 supernovae.

The trendlines are plotted for both parts of the dataset in Figure 1. The trendline for $0.01 < z < 0.05$ with 140 supernovae has a slope of about 68 $km\, s^{-1}\, Mpc^{-1}$, whereas the the trendline for $0.04 < z < 0.08$ with 61 supernovae has a slope of about 67 $km\, s^{-1}\, Mpc^{-1}$.

As shown in Table 1, the maximum error introduced on account of assuming $\mathrm{v} \approx \mathrm{cz}$ would be 1.86% (at $z = 0.08$) assuming the prevalent cosmological models. Error bars representing this maximum error are plotted for all points in the graph. We can conclude that the error introduced due to assumption of $v \approx cz$ is statistically insignificant.

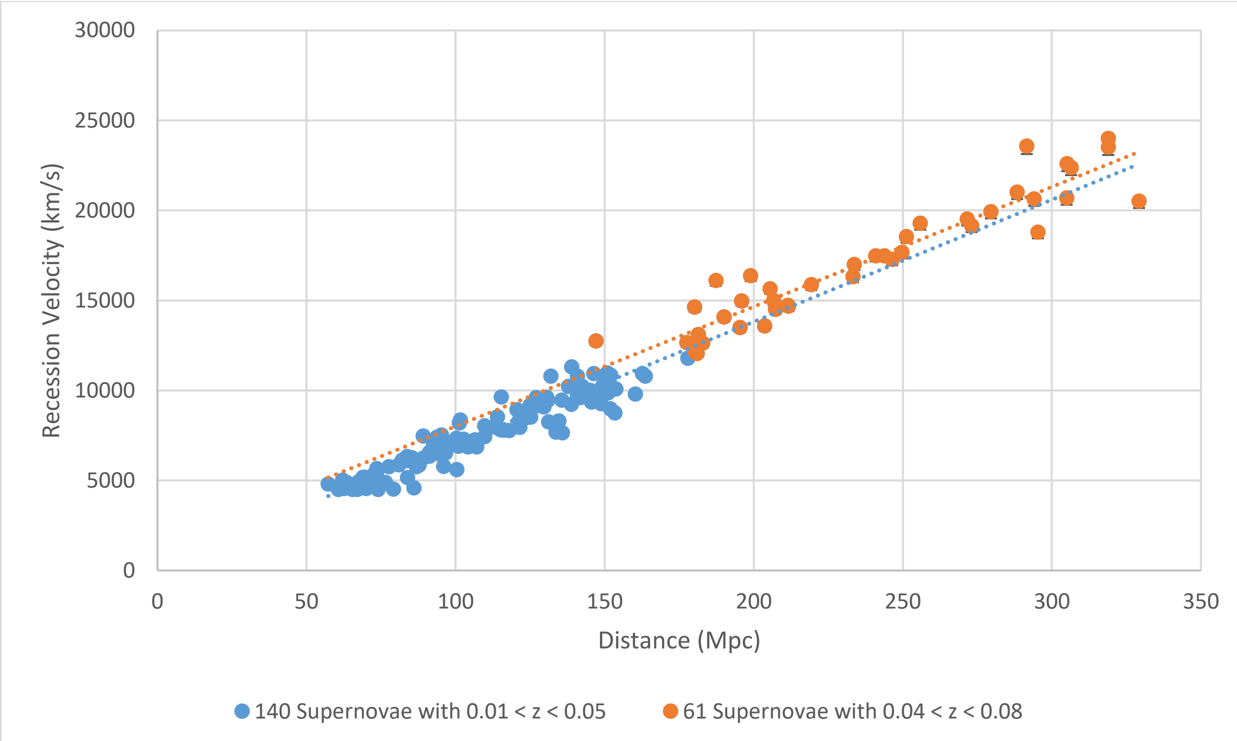

Figure 1: Data for 166 Type Ia supernovae with redshift $0.01 < z < 0.08$ from the Union 2.1 compilation courtesy the Supernova Cosmology Project (Suzuki et al. 2012). The slope of the trendline gives an estimate of the Hubble-Lemaitre constant. The trendline for $0.01 < z < 0.05$ with 140 supernovae has a slope of about 68 $km\ s^{-1}\ Mpc^{-1}$, whereas the the trendline for $0.04 < z < 0.08$ with 61 supernovae has a slope of about 67 $km\ s^{-1}\ Mpc^{-1}$. As shown in Table 1, the maximum error introduced on account of assuming v≈cz would be 1.86% (at $z = 0.08$) assuming the prevalent cosmological models. Error bars representing this maximum error are plotted for all points in the graph. We can conclude that the error introduced due to assumption of v≈cz is statistically insignificant. Complete data for this graph is given in Appendix 1 in the interest of reproducibility.

It is interesting to note the closeness of the slopes of the trendlines to the Hubble-Lemaitre constant determined by the Planck Collaboration (2018), namely $H = 67.4 \pm 0.5\ km\ s^{-1}\ Mpc^{-1}$. However, the similarity should be treated as statistically inconclusive because a different set of supernovae data can be selected to give a different value for the slope of the trendline.

However, given that the slopes of the two data sets are virtually the same, doesn't this contradict the observation that the Universe is accelerating (Kirshner 1999)? No, because even though the slopes of the trendlines are nearly the same, their intercepts are markedly different. And interestingly, it points to a decelerating Universe, rather than an accelerating one.

The trendline for $0.01 < z < 0.05$ with 140 supernovae has an intercept of about $+250\ km\ s^{-1}$, whereas the trendline for $0.04 < z < 0.08$ with 61 supernovae has an intercept of about $+1350\ km\ s^{-1}$.

This intercept can be interpreted as an extra-Hubble-Lemaitre (eHL) velocity, that is, a recession velocity over and above the Hubble-Lemaitre flow. One possible explanation can be that, while the fundamental nature of spacetime itself creates the constant Hubble-Lemaitre flow as per the Friedmann–Lemaître–Robertson–Walker equations (Piattella 2018; Dullemond, Hennawi & Maccio 2012), other physical processes impart the eHL velocity. Needless to say, this eHL velocity will also include the peculiar velocities of the distant supernovae (Leget et al. 2018; Neill, Hudson & Conley 2007) as well as the relative velocity due to the motion of our Local Group of galaxies towards the Great Attractor and the Shapely Supercluster (Colin et al. 2011), in addition to other proposed motion vectors (Colin et al. 2017).

The relationship between the recession velocity v, the Hubble-Lemaitre velocity v_H, the distance D, the Hubble-Lemaitre constant H, and the eHL velocity v_e then becomes:

$$v(D,t) = v_H(D) + v_e(D,t) = HD + v_e(D,t) \tag{1}$$

The intercepts in the trendline models of Figure 1 imply that the more distant, older supernovae have greater eHL velocities as compared to the nearer, more recent ones, thus indicating a Universe decelerating with the passage of time, rather than an accelerating one.

The results from the trendline models are collated in Table 2.

Table 2: Slope and intercept of the two trendlines in Figure 1. The slope gives an estimate for the Hubble-Lemaitre constant while the intercept gives a measure for the extra Hubble-Lemaitre (eHL) velocities.

Range of z	Number of supernovae datapoints	Slope of the trendline (km s^{-1} Mpc^{-1})	Intercept of the trendline (km/s)
$0.01 < z < 0.05$	140	68	250
$0.04 < z < 0.08$	61	67	1350

Nature of the eHL velocity

The classical equation for the observed recession velocity, $v(D) = v_H(D) = HD$, is expected to be not completely accurate, for it ignores the potential time variance of the recession velocity v, making it only a function of the distance D.

Indeed, studying this effect of time on the recession velocity was the original goal of the Supernova Cosmology Project as well as the High-Z Supernova Search Project, and they had expected to find a decelerating expansion (Kirshner 1999).

In other words a more accurate expression for the observed recession velocity v is:

$$v(D,t) = v_H(D) + E(D,t) + \int_{t=-T}^{-D} a(D,t)\,dt = HD + E(D,t) + \int_{t=-T}^{-D} a(D,t)\,dt \tag{2}$$

where $a(D,t)$ is the acceleration function and T is the age of the Universe with $T > D$. $E(D,t)$ represents velocity vector components from other possible physical processes.

The acceleration $a(D,t)$ was classically expected to be negative primarily due to gravity, thus making the integral in Equation (2), $\int_{t=-T}^{-D} a(D,t)\,dt$, negative, while decreasing in magnitude with increasing D.

The eHL velocity $v_e(D,t)$ includes the velocity vector components from all physical processes other than the Hubble-Lemaitre expansion. Thus,

$$v_e(D,t) = E(D,t) + \int_{t=-T}^{-D} a(D,t)\ dt \tag{3}$$

Ignoring the nature of $E(D,t)$, we would expect $v_e(D,t)$ to be increasing in D (decreasing with $-D$), if $a(D,t)$ is negative on account of gravity in absence of Dark Energy. Interestingly, this is exactly what we find as would be verified while plotting Figure 4 in the section titled 'Modeling eHL velocities for all 166 supernovae with $0.01 < z < 0.08$'.

In practice, we do not know $E(D,t)$ or $a(D,t)$. So, Equation (3) does not help us find the eHL velocity $v_e(D,t)$. Instead, we rearrange Equation (1) to get,

$$v_e(D,t) = v(D,t) - HD \tag{4}$$

We find the recession velocity $v(D,t)$ from the observed redshift z, distance D from the observed brightness, while we are free to assume a suitable value for the Hubble-Lemaitre constant H. In this article, we assume H from the most precise measurements of the Hubble-Lemaitre constant, done independently of the Type Ia Supernovae data. These measurements are listed in the section titled 'High confidence measurements of the Hubble-Lemaitre constant'.

In doing this, we are driven by the philosophy of placing greatest trust on the finest experimental results. We are guided in this direction by the revolutionary decision of Einstein to place absolute trust in the null result of the Michelson Morley experiment (Verma 2020).

Decelerating Universe?

How and why does the same data, which points to an accelerating Universe when modelled without the eHL velocity (Kirshner 1999), peculiarly starts pointing to a decelerating Universe when modelled with the eHL velocity?

To qualitatively understand this phenomenon, let us consider the supernova 2005bo (Puckett & Langoussis 2005) with redshift $z = 0.015$ at a distance $D = 60.75\ Mpc$, and the supernova 2006on (Sloan Digital Sky Survey II 2006) with redshift $z = 0.069$ at a distance $D = 294.06\ Mpc$, from the Union 2.1 supernova compilation (Suzuki et al. 2012).

Assuming the approximation $v \approx cz$ to hold, supernova 2005bo has a recession velocity $v = 0.015c = 4500\ km\ s^{-1}$, and supernova 2006on has a recession velocity $v = 0.069c = 20700\ km\ s^{-1}$. Assuming the peculiar velocities to be negligible for simplicity, 2006on gives a Hubble-Lemaitre constant $H = v/D = 74\ km\ s^{-1}\ Mpc^{-1}$, whereas 2006on gives a Hubble-Lemaitre constant $H = v/D = 70\ km\ s^{-1}\ Mpc^{-1}$. These results are collated in Table 3.

Table 3: Estimated Hubble-Lemaitre constant for the supernovae 2005bo (Puckett & Langoussis 2005) and 2006on (Sloan Digital Sky Survey II 2006) from the Union 2.1 supernova compilation (Suzuki et al. 2012), discounting peculiar velocities. The data shows that the supernova 2005bo at a distance of 200 million light-years is receding with a greater Hubble-Lemaitre constant than the supernova 2006on at a distance of 960 million light-years, implying that the rate of expansion of the Universe is increasing with time, as has been conventionally concluded.

Supernova	z	D (Mpc)	$v \approx cz$ (km/s)	$H = v/D$ (km s^{-1} Mpc^{-1})
2005bo	0.015	60.75	4500	74
2006on	0.069	294.06	20700	70

Table 3 shows that the supernova 2005bo at a distance of 200 million light-years is receding with a greater Hubble-Lemaitre constant than the supernova 2006on at a distance of 960 million light-years, implying that the rate of expansion of the Universe is increasing with time, as has been conventionally concluded.

However, let us now see what happens when eHL velocities, that is velocities arising out of other physical phenomena apart from the Hubble-Lemaitre expansion, are included in the calculations.

The Planck Collaboration (2018) has reported the highest confidence in its measurement of the Hubble-Lemaitre constant. So we assume $H = 67.4\, km\, s^{-1}\, Mpc^{-1}$, as measured on average by the Planck Collaboration (2018), for our model. This gives a Hubble-Lemaitre velocity $v_H = HD = 67.4 \times 60.75 = 4100\, km\, s^{-1}$ and thus an eHL velocity of $v_e = v - v_H = 400\, km\, s^{-1}$ for the supernova 2005bo. Similarly, we get a Hubble-Lemaitre velocity $v_H = HD = 67.4 \times 294.06 = 19800\, km\, s^{-1}$ and thus an eHL velocity of $v_e = v - v_H = 900\, km\, s^{-1}$ for the supernova 2006on. These results are collated in Table 4.

Table 4: Extra-Hubble-Lemaitre (eHL) velocities for the supernovae 2005bo and 2006on derived by assuming the Hubble-Lemaitre constant $H = 67.4\, km\, s^{-1}\, Mpc^{-1}$, as measured on average by the Planck Collaboration (2018). Subtracting the Hubble-Lemaitre velocity $v_H = HD$ (derived from the assumed value of the Hubble-Lemaitre constant H and the measured distance to the supernova D) from the recession velocity $v \approx cz$ measured via redshift z gives the eHL velocity $v_e = v - v_H$.

Supernova	z	D (Mpc)	H (km s^{-1} Mpc^{-1})	$v \approx cz$ (km/s)	$v_H = HD$ (km/s)	$v_e = v - v_H$ (km/s)
2005bo	0.015	60.75	67.4	4500	4100	400
2006on	0.069	294.06	67.4	20700	19800	900

The results show that the nearer, younger (198 million years ago) supernova 2005bo is receding at a slower eHL velocity $v_e = 400\, km\, s^{-1}$, than the older (959 million years ago), more distant supernova 2006cn with an eHL velocity $v_e = 900\, km\, s^{-1}$, thus implying, remarkably, that the rate of expansion of the Universe could be decelerating. Such a decelerating expansion is expected due to gravity, and if established with a high degree of confidence, can potentially affect the hypothesization of dark energy. It may be noted here that there is some recent evidence pointing towards a need for relooking at the data showing that the Universe is accelerating (Colin et al. 2019; Wolchover 2019; Nielsen, Guffanti & Sarkar 2016; Kang et al. 2020; Hossenffelder & Sarkar 2020; Yonsei University 2020). Further discussion in this direction is beyond the scope of this article.

It is also interesting and instructive to look at this behavior graphically. Without postulation of eHL velocities, the trendlines in a recession velocity versus distance graph need to pass through the origin. This is because the Hubble-Lemaitre velocity at a distance of 0 would be 0. Therefore, the Universe appears to be accelerating, because the nearer, recent supernovae appear to be receding with a greater Hubble-Lemaitre constant (greater slope of the trendline), than the distant, older supernovae. This is illustrated for the supernovae 2005bo and 2006on in Figure 2.

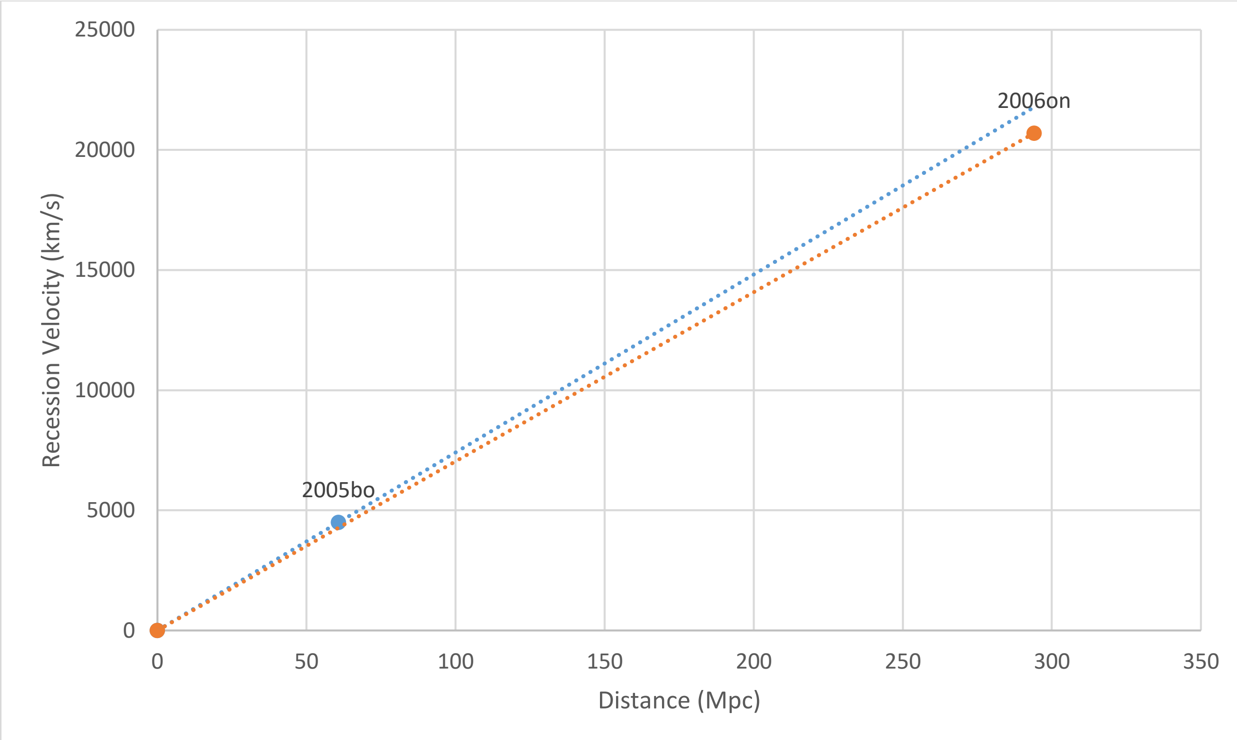

Figure 2: Trendlines for the supernovae 2005bo and 2006on without the postulation of eHL velocities. The trendlines need to pass through the origin because the Hubble-Lemaitre velocity at a distance of 0 would be 0. Due to this requirement, the Universe appears to be accelerating, because the nearer, recent supernova 2005bo appears to be receding with a greater Hubble-Lemaitre constant (greater slope of the trendline), than the distant, older supernova 2006on.

However, when we include eHL velocities in our model, while assuming the rate of Hubble-Lemaitre expansion from the results of the Planck Collaboration (2018), it allows for an intercept in the trendline. This also allows the intercept (eHL velocity) of the farther, older supernovae to be greater than that of the nearer, more recent supernovae, thus showing the expected decelerating effects of gravity and as a result, a decelerating Universe. This is illustrated for the supernovae 2005bo and 2006on in Figure 3.

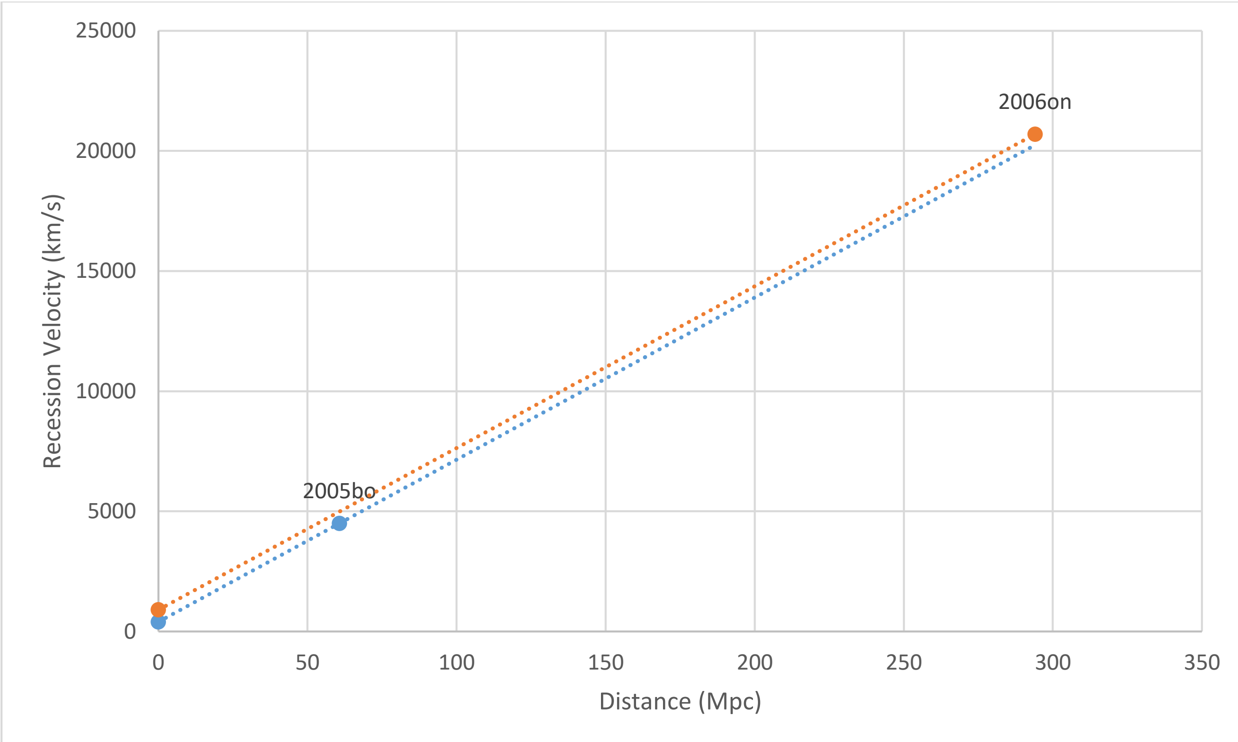

Figure 3: Trendlines for the supernovae 2005bo and 2006on when eHL velocities are included in the model. The average Hubble-Lemaitre constant measured by the Planck Collaboration (2018) $H = 67.4\ km\ s^{-1}\ Mpc^{-1}$ gives the Hubble-Lemaitre velocity $v_H = HD$. The remaining contribution to the measured recession velocity $v \approx cz$ comes from the eHL velocity $v_e = v - v_H$. The eHL velocity appears as intercept of the trendline. This allows the eHL velocity (intercept) of the farther, older supernovae to be greater than that of the nearer, more recent supernovae, thus showing the expected decelerating effects of gravity and as a result, a decelerating Universe.

High confidence measurements of the Hubble-Lemaitre constant

The Planck Collaboration (2018), using data from the Planck space observatory, have measured the value of the Hubble-Lemaitre constant to be $H = 67.4 \pm 0.5\ km\ s^{-1}\ Mpc^{-1}$, with an amazingly high degree of confidence. Grieb et al. (2017), using data from the Baryon Oscillation Spectroscopic Survey, a part of the Sloan Digital Sky Survey, have determined the value of the constant to be $H = 67.6^{+0.7}_{-0.6}\ km\ s^{-1}\ Mpc^{-1}$. Ryan, Chen & Ratra (2019), by modelling all available Baryon Acoustic Oscillation (BAO) data, have determined the value to be $H = 67.99^{+0.91}_{-0.88}\ km\ s^{-1}\ Mpc^{-1}$. Macaulay et al. (2019) using data from the Dark Energy Survey have determined the value to be $H = 67.8 \pm 1.3\ km\ s^{-1}\ Mpc^{-1}$, based on data from 329 Type Ia Supernovae different from the Union 2.1 database, and an inverse distance ladder derived from BAO observations.

Among the recent measurements of the Hubble-Lemaitre constant, these aforementioned four have reported the highest degree of confidence. They are summarized in Table 5. Incidentally, these measurements are also interestingly close to the slopes of the trendline models shown in Figure 1, namely $68\ km\ s^{-1}\ Mpc^{-1}$ and $67\ km\ s^{-1}\ Mpc^{-1}$. However, as mentioned earlier, this similarity is statistically insignificant since a different supernova dataset can be chosen to give a different value for the slope of the trendline.

Table 5: Four of the measurements of the Hubble-Lemaitre constant with the highest degree of confidence. Based on this review, we assume the Hubble-Lemaitre constant $H = 67.4\ km/s$ for our models. The trendline models of Figure 1 have also been added

for an interesting comparison. However, the error in the trendline models is large and therefore, no conclusion should be drawn out of the closeness of the models with the measurements.

Observation	Average value of the Hubble-Lemaitre constant (km s^{-1} Mpc^{-1})	Error (km s^{-1} Mpc^{-1})
Planck Collaboration	67.4	±0.5
Baryon Oscillation Spectroscopic Survey	67.6	+0.7, -0.6
Joseph Ryan, et al.	67.99	+0.91, -0.88
Dark Energy Survey	67.8	±1.3
Trendline for Type Ia supernovae with $0.1 < z < 0.5$	68	Large
Trendline for Type Ia supernovae with $0.4 < z < 0.8$	67	Large

Since all of the high confidence measurements of the Hubble-Lemaitre constant lie in the range of 67 to 68 km s^{-1} Mpc^{-1}, choosing the value to be $H = 67.4\ km\ s^{-1}\ Mpc^{-1}$ for our models is not expected to be greatly erroneous.

Modeling eHL velocities for all 166 supernovae with $0.01 < z < 0.08$

Assuming $H = 67.4\ km\ s^{-1}\ Mpc^{-1}$, we now plot eHL velocity $v_e = v - v_H \approx cz - HD$ versus redshift z for all 166 supernovae with $0.01 < z < 0.08$ from the Union 2.1 Type Ia Supernova compilation (Suzuki et al. 2012). The results are given in Figure 4. Redshift was chosen as abscissa instead of distance because it is a directly observed quantity and not a derived one, which reduces the potential for uncertainty and errors. The trendline in Figure 2 was drawn after discounting the two outlier supernovae 2006cj and 1992bs.

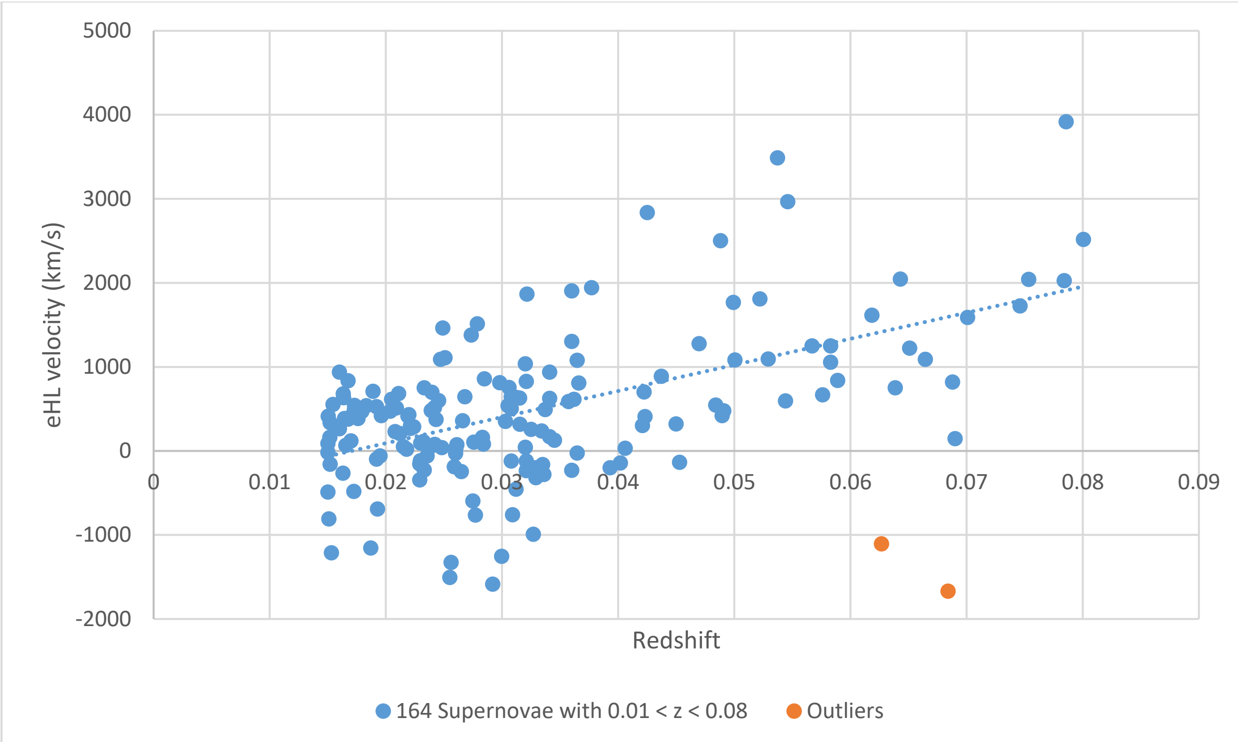

Figure 4: eHL velocity $v_e = v - v_H = cz - HD$ is plotted with redshift z. It is clear that eHL velocities tend to increase with increasing redshift and hence increasing distance to the supernovae. In other words, nearer, more recent supernovae tend to have smaller eHL velocities than older, farther ones. This gives further strength to the idea that the Universe may in fact be decelerating due to gravity (as would be classically expected), rather than accelerating. Since the eHL velocities incorporate effects from all the physical phenomena other than the Hubble-Lemaitre expansion (including peculiar velocity of the supernova and the apparent velocity due to the motion of the Earth through space), the broad velocity spread is expected.

It is clear from Figure 4 that eHL velocities tend to increase with increasing redshift and hence with increasing distance to the supernovae. In other words, nearer, more recent supernovae tend to have smaller eHL velocities than older, farther ones. This gives further strength to the idea that the Universe may in fact be decelerating due to gravity (as would be classically expected), rather than accelerating.

Significance of the eHL velocity: Potential remnant of Inflation?

Since the eHL velocities incorporate effects from all the physical phenomena other than the Hubble-Lemaitre expansion (including peculiar velocity of the supernova and the apparent velocity due to the motion of the Earth through space), the broad velocity spread as seen in Figure 4 is expected.

However, what physical phenomena comprise the backbone of the eHL velocities, steadily decreasing throughout the history of the Universe? In other words, what constitutes $E(D,t)$ in Equation (3)?

For a phenomenon to be observed throughout the Universe, as eHL velocities potentially are, it needs to have its origins close to the beginning of the Universe, when the Universe was small and Universe-scale events were physically possible. It is now quite evident that the early Universe was much hotter and denser, and involved extremely energetic processes (Weinberg 1972). It is not illogical to expect that some of the extreme energies involved in those processes got manifested as kinetic energy of matter in the Universe which then got partially converted into gravitational potential energy as the Universe expanded.

One such candidate physical process involving extreme energies is Inflation. Specifically, the process of Reheating during Inflation has been predicted to involve explosive creation of matter (Lozanov 2018; Kofman 1996, 1998; Kofman, Linde & Starobinsky 1994, 1997; Linde 1995, 1996, 1998). Such an explosive creation could also potentially impart kinetic energy to the created matter. If more theoretical and observational evidence could be found for tracing the eHL velocities to inflation, the eHL velocities have the potential to become the first direct observational evidence of inflation. Further discussion on this topic is beyond the scope of this article.

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Appendix 1: Dataset for Figure 1

Note that the below dataset just shows the exact values plotted in the interest of reproducibility. The number of decimal points should not form a basis to draw conclusions about confidence in the values.

Supernova Name	Redshift z	Distance (Mpc)	Recession Velocity (km/s)
1999aa	0.015	67.02467781	4500
2006td	0.015	74.04376925	4500
2007s	0.015	65.43591063	4500
2005bo	0.015027043	60.75201505	4508.112829
2007ca	0.0151	79.18925001	4530
1994s	0.015166	65.13227669	4549.8
2001bf	0.0152	62.63675506	4560
2002do	0.0152	70.00391837	4560
2006cm	0.0153	86.06820777	4590
2001cn	0.0154363	60.46958594	4630.89
2001da	0.016	67.28362332	4800
2001v	0.016	57.28330536	4800
2002hw	0.0163	76.49422639	4890
1996bo	0.016321	62.58255986	4896.3
2001cz	0.016345641	63.35255377	4903.6923
2000dk	0.01645	67.47971458	4935
1997y	0.016559	72.71670168	4967.7
1996bv	0.01673	68.87502915	5019
1998ef	0.016743	62.13472341	5022.9
1998co	0.016991	73.86475333	5097.3
1998v	0.017173	69.94222884	5151.9
1992bo	0.017227	83.84093463	5168.1
2001g	0.0173	69.58216145	5190
2006le	0.0173	68.95474622	5190
1999ek	0.017605	72.64068099	5281.5
2006ax	0.017931283	72.81913892	5379.385009
2005a	0.018315232	73.53070669	5494.569611
2002jy	0.0187	100.3722508	5610
2008l	0.0189	73.58829992	5670
2006ej	0.0192	86.91130585	5760
2007ci	0.0192	77.63419456	5760
1999gd	0.019264	95.9922256	5779.2
2002kf	0.0195	87.69909382	5850
1992bc	0.019599	81.02407569	5879.7
2005ki	0.020374725	83.6621608	6112.417359
2005ls	0.0205	82.15670346	6150
2006kf	0.0208	89.15600744	6240

2007au	0.0209	85.42726376	6270
2003w	0.0211	83.7674649	6330
2006et	0.0212	91.26748857	6360
2006bq	0.0215	94.90932718	6450
2000fa	0.021793	96.69287003	6537.9
2007bc	0.0219	91.28295635	6570
1995ak	0.021980006	91.44338037	6594.001774
2001n	0.0221	93.93264755	6630
2004bg	0.0221	94.39140099	6630
2001cp	0.0224	95.45454231	6720
2006ar	0.0229	107.0385593	6870
2007qe	0.0229	104.2058344	6870
2005m	0.022971168	103.9712336	6891.350273
2006sr	0.023	100.9840693	6900
2000cn	0.023208	101.6587152	6962.4
2006cp	0.0233	92.55987528	6990
2006mp	0.0233	107.0701743	6990
1998eg	0.023536	105.6371548	7060.8
2006ac	0.0239	99.25154724	7170
2000bh	0.023953	96.26358973	7185.9
2003it	0.024	105.9100564	7200
2005bg	0.024185299	100.0198772	7255.589724
2007f	0.0242	106.5347632	7260
1994m	0.024314	102.675282	7294.2
2000ca	0.024525	100.2562769	7357.5
2007cq	0.0247	93.78682404	7410
2002he	0.0248	109.7984944	7440
2002bf	0.0249	89.13739178	7470
2008bf	0.0251	95.25522645	7530
2006br	0.0255	135.8623	7650
2003ch	0.0256	133.6491948	7680
2005ms	0.0259	118.056175	7770
2005mc	0.026	116.1746265	7800
1999gp	0.026038	115.4220991	7811.4
2003u	0.0261	115.0519198	7830
1992p	0.026489	121.5577744	7946.7
2007co	0.0266	113.0570002	7980
2005na	0.026809197	109.7843305	8042.759244
1992ag	0.027342	101.2600401	8202.6
1996c	0.0275	131.2681459	8250
2004gs	0.027568726	121.1388606	8270.617773
2006gj	0.0277	134.6276912	8310
1998ab	0.027865	101.5639511	8359.5

2002de	0.0283	123.5760061	8490
2005eq	0.028396027	125.1610805	8518.808043
1993ah	0.028488	114.0558196	8546.4
2002hu	0.0292	153.4664967	8760
2004ef	0.029802137	120.6231188	8940.64107
1997dg	0.029955	151.9264239	8986.5
2002ck	0.0303	129.6249404	9090
2001ba	0.030529	127.8759656	9158.7
1990o	0.030604	125.0131586	9181.2
2006bw	0.0308	129.6049986	9240
2006en	0.0308	138.8841992	9240
2006qo	0.0308	127.5047707	9240
2001ay	0.0309	148.8257351	9270
2001ie	0.0312	129.4252607	9360
2007r	0.0312	145.6226091	9360
2006az	0.0315	130.8452726	9450
1999cc	0.031528	135.604073	9458.4
2007ai	0.032	141.7942341	9600
2007bd	0.032	127.0631939	9600
2004as	0.0321	146.3784474	9630
2006os	0.0321	130.5850888	9630
2006te	0.0321	144.6607088	9630
2004gc	0.032134017	115.3159777	9640.205058
2006bt	0.0325	140.8407155	9750
2006cc	0.0327	160.2725939	9810
2006s	0.0329	149.3810236	9870
2005iq	0.032912371	151.1843804	9873.711326
2004l	0.0334	145.1174382	10020
2006gr	0.0335	151.5151384	10050
2003iv	0.0336	153.7185961	10080
2003cq	0.0337	142.6737732	10110
2003kc	0.0341	142.5011606	10230
2005eu	0.0341	149.2607536	10230
2008af	0.0341	137.8898867	10230
2002g	0.0345	151.6765361	10350
1994t	0.03572	150.2677437	10716
1996bl	0.036	140.8781577	10800
2002hd	0.036	131.9751551	10800
2006mo	0.036	163.6439737	10800
2001eh	0.0362	152.0304329	10860
2000cf	0.036457	162.6654564	10937.1
1992bg	0.03648	146.3873223	10944
2007o	0.0366	150.8852985	10980

2007cp	0.0377	138.9860044	11310
1999aw	0.0393	177.884487	11790
2005lz	0.0402	181.0463469	12060
2001az	0.0406	180.2366902	12180
2005hf	0.0421	182.8873258	12630
1992bl	0.042233	177.5526218	12669.9
2006cf	0.0423	182.2100979	12690
2006cz	0.0425	147.076843	12750
2005ku	0.043718911	181.4385851	13115.67345
2005hc	0.044976673	195.4215653	13493.00178
1992bh	0.045295	203.6177162	13588.5
2004gu	0.046967335	190.0857486	14090.20038
2006eq	0.048392195	207.3209056	14517.65862
1995ac	0.048818	180.1781083	14645.4
1993ac	0.048948	211.6242931	14684.4
2006cq	0.0491	211.4512659	14730
1990af	0.049922	195.9916902	14976.6
1993ag	0.050043	206.6647938	15012.9
2006ot	0.0522	205.4776662	15660
1993o	0.052926	219.3513951	15877.8
1998dx	0.05371	187.3124297	16113
1999ao	0.0544	233.2822443	16320
2003ic	0.0546	198.9866479	16380
2006py	0.056683367	233.7651368	17005.01012
2005hj	0.0576	246.4506054	17280
2001ah	0.0583	240.9446221	17490
2006ob	0.0583	243.8084951	17490
2006oa	0.0589	249.7322065	17670
2005ho	0.061835765	251.2705249	18550.72941
1992bs	0.062668	295.3141571	18800.4
2005kt	0.063864084	273.0877223	19159.22511
2007ae	0.0643	255.8800232	19290
2006an	0.0651	271.6112629	19530
2005if	0.066440312	279.5660675	19932.0937
2006cj	0.0684	329.2346361	20520
2006on	0.0688	294.0564326	20640
2006al	0.069	304.952284	20700
1993b	0.070086	288.3557569	21025.8
1992ae	0.074605	306.4603508	22381.5
2005ir	0.075350112	305.1181895	22605.03359
1999bp	0.0784	318.9100543	23520
1992bp	0.078577	291.595822	23573.1
2005ag	0.080048144	318.9324816	24014.4432

2006bu	0.0843	376.0250402	25290
2005ff	0.085689459	366.2495163	25706.83781
2005ed	0.085696117	365.6369331	25708.83512
2005gb	0.085854644	358.6882342	25756.39324
1992br	0.087589	406.7678345	26276.7
2005iu	0.089019429	337.7963539	26705.82879
2005ex	0.092936818	389.5569453	27881.04546
2005je	0.093149403	414.4796602	27944.82081
2005fn	0.093908632	394.0787832	28172.58957
1992aq	0.100915	446.267572	30274.5
2005lk	0.102715034	451.8441066	30814.51018
2005hn	0.10671234	482.2793066	32013.70203
2005jh	0.108638266	484.5182892	32591.47966
2005ml	0.113042645	461.0829058	33912.79339
2005kp	0.114712621	486.0221977	34413.78626
2005hr	0.116348503	502.8377088	34904.55078
2005fv	0.117277363	502.3723928	35183.20887
2005fh	0.117625329	465.1440457	35287.59863
2005hx	0.119671538	503.5203007	35901.4614
2005fz	0.1228289	512.4415757	36848.66999

Appendix 2: Dataset for Figure 2

Note that the below dataset just shows the exact values plotted in the interest of reproducibility. The number of decimal points should not form a basis to draw conclusions about confidence in the values.

Name	Redshift z	eHL Velocity (km/s)
1999aa	0.015	-17.4632842
2006td	0.015	-490.550047
2007s	0.015	89.61962334
2005bo	0.015027043	413.4270144
2007ca	0.0151	-807.355451
1994s	0.015166	159.8845513
2001bf	0.0152	338.2827091
2002do	0.0152	-158.264098
2006cm	0.0153	-1210.9972
2001cn	0.0154363	555.2399075
2001da	0.016	265.0837881
2001v	0.016	939.1052189
2002hw	0.0163	-265.710859
1996bo	0.016321	678.2354656
2001cz	0.016345641	633.7301759
2000dk	0.01645	386.8672375
1997y	0.016559	66.59430667
1996bv	0.01673	376.8230355
1998ef	0.016743	835.0196422
1998co	0.016991	118.8156253
1998v	0.017173	437.7937764
1992bo	0.017227	-482.778994
2001g	0.0173	500.1623186
2006le	0.0173	542.4501049
1999ek	0.017605	385.5181015
2006ax	0.017931283	471.3750459
2005a	0.018315232	538.5999802
2002jy	0.0187	-1155.08971
2008l	0.0189	710.1485851
2006ej	0.0192	-97.8220143
2007ci	0.0192	527.4552866
1999gd	0.019264	-690.676006
2002kf	0.0195	-60.9189233
1992bc	0.019599	418.6772982
2005ki	0.020374725	473.5877212
2005ls	0.0205	612.638187
2006kf	0.0208	230.8850989

2007au	0.0209	512.2024229
2003w	0.0211	684.0728661
2006et	0.0212	208.5712701
2006bq	0.0215	53.11134788
2000fa	0.021793	20.80056015
2007bc	0.0219	417.5287417
1995ak	0.021980006	430.7179375
2001n	0.0221	298.9395554
2004bg	0.0221	268.0195735
2001cp	0.0224	286.363848
2006ar	0.0229	-344.398895
2007qe	0.0229	-153.473238
2005m	0.022971168	-116.310872
2006sr	0.023	93.67372906
2000cn	0.023208	110.6025984
2006cp	0.0233	751.4644058
2006mp	0.0233	-226.52975
1998eg	0.023536	-59.1442314
2006ac	0.0239	480.4457163
2000bh	0.023953	697.7340522
2003it	0.024	61.66219981
2005bg	0.024185299	514.2499974
2007f	0.0242	79.5569571
1994m	0.024314	373.885993
2000ca	0.024525	600.2269375
2007cq	0.0247	1088.76806
2002he	0.0248	39.58147736
2002bf	0.0249	1462.139794
2008bf	0.0251	1109.797737
2006br	0.0255	-1507.11902
2003ch	0.0256	-1327.95573
2005ms	0.0259	-186.986198
2005mc	0.026	-30.1698233
1999gp	0.026038	31.9505219
2003u	0.0261	75.5006058
1992p	0.026489	-246.293996
2007co	0.0266	359.9581848
2005na	0.026809197	643.2953684
1992ag	0.027342	1377.673295
1996c	0.0275	-597.473034
2004gs	0.027568726	105.8585665
2006gj	0.0277	-763.906388
1998ab	0.027865	1514.089698

2002de	0.0283	160.9771877
2005eq	0.028396027	82.95121596
1993ah	0.028488	859.037759
2002hu	0.0292	-1583.64188
2004ef	0.029802137	810.642861
1997dg	0.029955	-1253.34097
2002ck	0.0303	353.2790202
2001ba	0.030529	539.8599209
1990o	0.030604	755.3131123
2006bw	0.0308	504.6230933
2006en	0.0308	-120.795025
2006qo	0.0308	646.1784547
2001ay	0.0309	-760.854547
2001ie	0.0312	636.7374263
2007r	0.0312	-454.963856
2006az	0.0315	631.0286276
1999cc	0.031528	318.6854787
2007ai	0.032	43.06862232
2007bd	0.032	1035.940734
2004as	0.0321	-235.907355
2006os	0.0321	828.5650163
2006te	0.0321	-120.131775
2004gc	0.032134017	1867.908163
2006bt	0.0325	257.3357757
2006cc	0.0327	-992.372826
2006s	0.0329	-198.280993
2005iq	0.032912371	-316.115915
2004l	0.0334	239.0846646
2006gr	0.0335	-162.120329
2003iv	0.0336	-280.633378
2003cq	0.0337	493.7876861
2003kc	0.0341	625.421775
2005eu	0.0341	169.8252041
2008af	0.0341	936.2216381
2002g	0.0345	127.0014693
1994t	0.03572	587.9540736
1996bl	0.036	1304.812168
2002hd	0.036	1904.874548
2006mo	0.036	-229.603828
2001eh	0.0362	613.1488256
2000cf	0.036457	-26.5517628
1992bg	0.03648	1077.494479
2007o	0.0366	810.3308835

2007cp	0.0377	1942.343307
1999aw	0.0393	-199.414425
2005lz	0.0402	-142.523783
2001az	0.0406	32.04708012
2005hf	0.0421	303.3942425
1992bl	0.042233	702.8532901
2006cf	0.0423	409.0394025
2006cz	0.0425	2837.020783
2005ku	0.043718911	886.7128112
2005hc	0.044976673	321.5882848
1992bh	0.045295	-135.334074
2004gu	0.046967335	1278.420932
2006eq	0.048392195	544.2295806
1995ac	0.048818	2501.395497
1993ac	0.048948	420.9226425
2006cq	0.0491	478.1846816
1990af	0.049922	1766.760083
1993ag	0.050043	1083.692901
2006ot	0.0522	1810.805297
1993o	0.052926	1093.515967
1998dx	0.05371	3488.142237
1999ao	0.0544	596.7767325
2003ic	0.0546	2968.299934
2006py	0.056683367	1249.2399
2005hj	0.0576	669.2291979
2001ah	0.0583	1250.332469
2006ob	0.0583	1057.307432
2006oa	0.0589	838.0492844
2005ho	0.061835765	1615.09603
1992bs	0.062668	-1103.77419
2005kt	0.063864084	753.1126279
2007ae	0.0643	2043.686436
2006an	0.0651	1223.400882
2005if	0.066440312	1089.340751
2006cj	0.0684	-1670.41447
2006on	0.0688	820.5964435
2006al	0.069	146.2160607
1993b	0.070086	1590.621987
1992ae	0.074605	1726.072358
2005ir	0.075350112	2040.067623
1999bp	0.0784	2025.46234
1992bp	0.078577	3919.541595
2005ag	0.080048144	2518.39394