Redshift Evolution and Non-Universal Dispersion of Quasar Luminosity Correlation

Zhuoyang Li, Lu Huang*, Junchao Wang

School of Physics and Astronomy, Sun Yat-Sen University, 2 Daxue Road, Tangjia, Zhuhai, 519082, P.R.China

ABSTRACT

The standard ΛCDM model is recently reported to deviate from the high-redshift Hubble diagram of type Ia supernovae (SNe) and quasars (QSOs) at ~ 4σ confidence level. In this work, we combine the PAge approximation (a nearly model-independent parameterization) and a high-quality QSO sample to search for the origins of the deviation. By visualizing the ΛCDM model and the marginalized 3σ constraints of SNe+QSOs into PAge space, we confirm that the SNe+QSOs constraints in both flat and non-flat PAge cases are in remarkable tension with the standard ΛCDM cosmology. Next, we investigate the tension from the perspective of redshift-evolution effects. We find that the QSO correlation coefficient γ calibrated by SNe+low-z QSOs and SNe+high-z QSOs shows ~ 2.7σ and ~ 4σ tensions in flat and non-flat universes, respectively. The tensions for intrinsic dispersion δ between different data sets are found to be > 4σ in both flat and non-flat cases. These results indicate that the QSO luminosity correlation suffers from significant redshift evolution and non-universal intrinsic dispersion. Using a redshift-dependence correlation to build QSO Hubble diagram could lead to biases. Thus, the ~ 4σ deviation from the standard ΛCDM probably originates from the redshift-evolution effects and non-universal dispersion of the QSO luminosity correlation rather than new physics.

Key words: quasars: general – cosmological parameters – dark energy – observations

1 INTRODUCTION

The phenomenon of cosmic accelerating expansion is firstly indicated by observing the extra dimming of the high-redshift Type Ia supernovae (SNe) (Perlmutter et al. 1997; Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999). A widely accepted explanation of this mysterious phenomenon is that a hypothetical dark energy component with negative pressure drives the homogeneous and isotropic universe to accelerate. Interpreting dark energy as a cosmological constant Λ and assuming the validity of general relativity at all scales and epochs, the standard Λ cold dark matter (ΛCDM) model has achieved remarkable success in agreeing with a great majority of cosmological observational measurements (Scocline et al. 2018; Alam et al. 2021; Jimenez & Loeb 2002; Abbott et al. 2022; Aghanim et al. 2020). However, these modern cosmological measurements are restricted to either the low redshift range (0 ≤ z ≤ 2.33) or the high redshift range (z ~ 1100). The cosmic expansion history is still poorly explored in the redshift interval (2.33 < z < 1100) which is very essential for studying the dark energy models beyond the typical ΛCDM physics.

As the most luminous and persistent energy sources in our Universe, quasars (QSOs) serve as a potential candidate for high-redshift cosmological tests which can be detected up to redshift ~ 7.64 (Yang et al. 2021; Wang et al. 2021). Several empirical correlations between spectral features and luminosity have been proposed to enable QSOs as competitive cosmological tools (Baldwin 1977; Watson et al. 2011; La Franca et al. 2014; Wang et al. 2014). Particularly, the most investigated and best constructed QSO luminosity correlation is the observed non-linear correlation between ultraviolet (LUV at 2500Å) and X-ray (ŁX at 2 keV) luminosity which is firstly proposed in Tananbaum et al. (1979); Griffiths et al. (1981); Tananbaum et al. (1986) and subsequently developed in (Risaliti & Lusso 2015; Lusso & Risaliti 2016, 2017; Risaliti & Lusso 2019; Lusso 2019; Salvatrinì et al. 2019; Lusso et al. 2020; Bisogni et al. 2021). Although the detailed physical mechanism of the LUV – ŁX correlation still remains unknown (Haardt & Maraschi 1991, 1993; Ghisellini & Haardt 1994; Nicastro 2000; Merloni 2003; Arcodia et al. 2019), the authors in Lusso et al. (2020) have minimized all of the possible systematic effects and proven the stability of this QSO luminosity correlation. Based on the LUV – ŁX correlation, Risaliti & Lusso (2019) utilized a new technique to model-independently build the QSO Hubble diagram and extend it to z ~ 5.5. A good agreement is found between the constructed QSO Hubble diagram and the ΛCDM model at z < 1.4 while a ~ 4σ deviation emerges at higher redshift range. Two follow-up works further confirm this significant deviation with more precise approaches and cleaner QSO samples (Lusso et al. 2019, 2020). Since then, the deviation between the high-redshift QSOs Hubble diagram and the ΛCDM model arises heated debates (Melia 2019; Yang et al. 2020; Velten & Gomes 2020; Mehrabi & Basilakos 2020; Zheng et al. 2021; Lian et al. 2021; Colgáin et al. 2022; Li et al. 2021; Khadka & Ratra 2021, 2022).

* E-mail: huanglu37@mail2.sysu.edu.cn

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test the robustness of the QSO Hubble diagram. Their result suggests that the QSO data cannot be used as a reliable cosmological tool because it even fails to state the cosmic accelerating expansion phase. Yang et al. (2020) claimed that the model-independent approach proposed in Risaliti & Lusso (2019) failed to recover the high-z cosmic expansion history of the flat ΛCDM model, which underlined the ~ 4σ deviation. Using the Gaussian process and a combination of SNIa, Quasars and gamma-ray burst data, Mehrabi & Basilakos (2020) found a less significant tension. They argued that the amount of the deviation might be affected by the choice of the kernel function. All these works challenge the claimed ~ 4σ deviation. However, the main cause of the deviation is still not found.

Our aim in this present work is to search for the possible origins of the significant deviation between the ΛCDM model and the high-z Hubble diagram of SNe+QSOs. The key is to adopt model-independent approaches and independent samples. To avoid model dependence, we perform our analyses in PAge approximation (Parameterization based on cosmic Age) which is a general approximation of many late-time cosmological models and a nearly model-independent framework (Huang 2020; Luo et al. 2020; Huang et al. 2021b,a, 2022; Cai et al. 2022a,b; Huang 2022). In addition, we take the most up-to-date QSO samples compiled by Lusso et al. (2020) as our data set.

Our work is organized as follows. We present the advantages of the PAge approximation in the next Section 2. The data and methodology are briefly introduced in Section 3. The detailed results are shown in Section 4. In the last Section 5, we conclude and discuss.

2 COSMOLOGICAL SCENE

The logarithm polynomial parameterization was firstly proposed to quantify the deviation between the concordance ΛCDM cosmology and the high-z QSO Hubble diagram in Risaliti & Lusso (2019). It defines the luminosity distance with a polynomial function of log10(1 + z)

\[ d_L(z) = \frac{c \ln(10)}{H_0} \sum_{i=1}^{n} a_i \log^{i}(1 + z), \]

where \( a_i \) are free parameters, except \( a_1 = 1 \). \( c \) is the speed of light. \( H_0 \) is the Hubble constant.

Based on the Taylor expansion in log10(1 + z), this parameterization provides a model-independent exploration of the late-time cosmological expansion history and approximately matches many cosmological models accurately at low redshift (\( z \lesssim 1 \)). However, its approximation precision worsens considerably when \( z \) exceeds 1, as shown in Table 1 (here we take its 4th-order expansion as an example). For the redshift range \([0,8]\), the maximum relative errors in luminosity distance are more than 2% for different ΛCDM models, which may cause biases in data fitting. Introducing higher orders in log10(1 + z) could certainly improve the fitting precision but also weaken the constraint power of data and complicate the procedure of comparing with the standard ΛCDM model.

Compared to the logarithm polynomial approximation, the recently proposed PAge approximation displays many prominent advantages in blindly modelling the late cosmological expansion history (Huang 2020; Luo et al. 2020; Huang et al. 2021b,a, 2022; Cai et al. 2022a,b; Huang 2022). Faithfully obeying the asymptotic matter-dominated assumption \( \frac{1}{t^2} \ll t^2 \) at high redshift \( z \gg 1 \) (the radiation component is not taken into consideration), PAge models the Hubble expansion rate as a function of cosmological time \( t \),

\[ \frac{H}{H_0} = 1 + \frac{2}{3} (1 - \frac{\Omega_{m0}}{\Omega_{age}}) \left( \frac{1}{H_0} - \frac{1}{\frac{\Omega_{m0}}{\Omega_{age}}} \right), \]

where the dimensionless parameter \( \Omega_{age} = \frac{\Omega_m}{\Omega_{age}} \) measures the cosmic age \( t_0 \) (both \( t \) and \( t_0 \) are in unit of \( H_0^{-1} \)), and the dimensionless parameter \( \eta \) characterizes the deviation from Einstein de-Sitter universe (flat CDM model). We set a bound condition \( \eta < 1 \) to guarantee the fundamental physical features, e.g. \( \frac{dt_0}{d\eta} > 0 \) and \( \frac{dt}{d\eta} > 0 \) (Huang 2020).

Doing cosmological tests with PAge approximation has some distinct advantages, as follows:

1) The cosmic age \( t_0 \) absorbed in \( \eta \) parameter is easily applied to do astronomical tests (Luo et al. 2020). More specifically, Valcin et al. (2020) presented an independent inference of \( t_0 = 13.5_{-0.14}^{+0.16} \) (stat.) \( \pm 0.5 \) (sys.) from the full colour-magnitude diagram of the globular cluster. If a cosmological model predicts a significantly different \( t_0 \) compared to the above estimation, it can be ruled out safely. For instance, the flat CDM model corresponding to \( \eta = 0 \) in PAge approximation fails to accommodate this cosmic age inference, which is clearly shown in Figure 1.

2) The cosmic deceleration and acceleration are easy to distinguish in PAge. According to \( \eta = 1 - \frac{2}{3} \frac{\Omega_{age}}{\Omega_{m0}} (1 + q_0) \) (Luo et al. 2020), the PAge universe is divided into decelerating and accelerating regions in Figure 1.

3) As an almost model-independent framework, PAge is able to precisely approximate a broad class of physical models by matching the deceleration parameter \( q_0 \) or by doing a least-square fitting of cosmological observables (see Huang 2020; Luo et al. 2020; Huang et al. 2021b,a). The maximum relative errors of luminosity distance
(\(d_L\)) are controlled below 0.3%, and it is well held for both low redshift and high redshift, as indicated in Table 1.

4) Utilizing PAge approximation to do Bayesian analysis is economical, effective, and concise. Generally, many typical physical models can be approximately mapped into the \((p_{\text{age}}, \eta)\) plane, and some of them are superimposed onto one point (we visualize this unique feature in Figure 1). Performing data analysis with PAge provides the Bayesian evidence for all the models which are included in the marginalized contour of \(p_{\text{age}}\) and \(\eta\) parameters. This practice avoids the cumbersome and complex process of computing Bayesian evidence for all the models.

Almost having the same advantages as the logarithm polynomial approximation (Yang et al. 2020), PAge merely has two nuisance parameters \((p_{\text{age}}, \eta)\) and simultaneously has reliable fitting precision at both low-z and high-z. Since PAge displays many superiorities and can accurately describe the expansion history of the high-z universe, we utilize it to do an independent analysis of QSO cosmology.

### 3 DATA AND METHODOLOGY

A high-quality QSO sample is recently compiled in Lusso et al. (2020). This new sample includes 2421 optically selected QSOs with spectroscopic redshift (span the redshift interval 0.009 \(\leq z \leq 7.5413\)) and X-ray observations. Systematic effects and low-quality measurements are largely removed by applying a couple of preliminary filters. For example, 30% X-ray measurements are excluded by the conditions: \(\Delta F_{\text{X}} / F_{\text{X}} < 1\) and \(\Delta F_{\text{H}} / F_{\text{H}} < 1\). More detailed filter procedures are discussed in Lusso et al. (2020). After an optimal selection of clean sources, this high-quality QSO sample is suitable for investigating the non-linear relation between the ultraviolet (at 2500 Å, \(L_{\text{UV}}\)) and X-ray (at 2 keV, \(L_X\)) luminosity of QSO:

\[
\log_{10} L_X = \gamma \log_{10} L_{\text{UV}} + \beta, \tag{3}
\]

where \(\gamma, \beta\) are free parameters. \(L_X\) and \(L_{\text{UV}}\) are the rest-frame monochromatic luminosities which follow the standard luminosity-flux relation \(L = 4\pi d_L^2 F\). Further expressing Eq. 3 with flux, one obtains

\[
\log_{10} F_X = \gamma \log_{10} F_{\text{UV}} + (\gamma - 1) \log_{10} (4\pi d_L^2) + \beta, \tag{4}
\]

both \(F_X\) and \(F_{\text{UV}}\) are the flux densities in the unit of erg/s/cm². We quantify the uncertainties of \(\gamma, \beta\) and the variability of cosmologies with the joint likelihood function (D’Agostini 2005):

\[
\ln \mathcal{L} \propto -\frac{1}{2} \sum_{i=1}^{N} \left[ \frac{(\log_{10} F_{\text{obs}}^{\text{X,i}} - \log_{10} F_{\text{obs}}^{\text{mod}})}{\sigma_{\text{total}}^2} \right]^2 + \ln (2\pi \sigma_{\text{total}}^2), \tag{5}
\]

the total uncertainties \(\sigma_{\text{total}}^2 = \sigma_{\text{obs}}^2 + \gamma^2 \sigma_{\text{obs}}^2 + \delta^2\), where \(\delta\) is a scatter parameter representing uncounted extra variability.

It is worth noting that the QSOs cannot be used to do cosmological tests directly because they do not provide absolute distance values (Bargiacchi et al. 2022). A cross-calibration procedure is needed to match the distance values between QSOs and SNe in the common redshift range. The detailed calibration procedure is to multiply the luminosity distance by a calibration parameter \(k\), i.e. \(d_L^{\text{calibration}} = kd_L^{\text{model}}\) (\(z\)), and the \(k\) parameter requires a simultaneous fitting of QSOs and SNe. In the cross-calibration procedure, \(k\) degenerates with \(H_0\). To avoid parameter degeneracy, we fix \(H_0 = 70\) km/s/Mpc in the following analyses. We calibrate the QSO distances with the Pantheon SNe sample (Scolnic et al. 2018) and use the combination data set of SNe+QSOs to build the QSO Hubble diagram.

As indicated in Table 2 of Bargiacchi et al. (2022), the spatial curvature has a great impact on the cosmological constraints when using QSO data. The joint analysis of SNe+QSO in non-flat \(\Lambda\)CDM background prefers a closed universe with spatial curvature \(\Omega_k \approx -0.6\), which is inconsistent with the Planck+CMB result \(\Omega_k = -0.044^{+0.013}_{-0.015}\) (Aghanim et al. 2020). To not miss some important information, we consider both flat and non-flat cosmological cases in the following analyses.

### 4 RESULTS

In Table 2, we list the marginalized 1\(\sigma\) constraints on parameters with SNe+QSOs data in PAge backgrounds. Both the flat and non-
flat cases are taken into consideration. For better comparison with the standard \( \Lambda \)CDM model, we visualize the marginalized 1\( \sigma \), 2\( \sigma \) and 3\( \sigma \) constraints on PAge parameters in Figure 2. We find both the marginalized contours on \( p_{\text{age}} \) and \( \eta \) in flat and non-flat PAge cases significantly deviate from the standard \( \Lambda \)CDM model ( red point in Figure 2 ) at > 3\( \sigma \) confidence level. The marginalized contours of the flat and non-flat PAge cases also show a > 3\( \sigma \) discrepancy, which indicates the inferences of PAge parameters are much affected by the addition of spatial curvature \( \Omega_k \) freedom. Indeed, the spatial curvature \( \Omega_k \) is found to be $-0.946^{+0.017}_{-0.051}$, which strongly supports a closed universe. And the exotic \( \Omega_k \) inference is actually inconsistent with other measurements (Scolnic et al. 2018; Alam et al. 2021; Jimenez & Loeb 2002; Abbott et al. 2022; Aghanim et al. 2020).

The SNe+QSOs constraints on PAge parameters in both flat and non-flat universes seem to suggest new physics beyond the \( \Lambda \)CDM. However, whether the QSOs can serve as a reliable cosmological tool still requires cautious research. As mentioned in Lusso et al. (2020), using the non-linear QSO luminosity correlation to build the QSO Hubble diagram may still have shortcomings. For example, the systematics in the QSO samples selection, the process used to fit the QSO Hubble diagram and the redshift evolution effect of QSO luminosity correlation may cause biases and lead to an unreliable QSO Hubble diagram. Possible systematics have been carefully checked in Lusso et al. (2020) and we focus on the redshift evolution effect of the QSO luminosity correlation in this present work.

Different from the narrow redshift bins split in Risaliti & Lusso (2019); Lusso et al. (2020), we divide QSO samples into the low-z (\( z \leq 1.5 \)) bin and high-z bin (\( z > 1.5 \)) to test the redshift evolution, because the strong deviation from \( \Lambda \)CDM model roughly emerges at \( z > 1.5 \). We analyze the SNe+low-z QSOs and SNe+high-z QSOs data sets in flat and non-flat PAge backgrounds, respectively. The marginalized 1\( \sigma \) constraints on the PAge parameters, QSO correlation coefficients and intrinsic dispersion are presented in Table 3.

Either in flat or non-flat PAge cases, significant evolutionary trends emerge for the \( \gamma \), \( \delta \) parameters. For the \( \gamma \) parameter, we find $\sim 2.7\sigma$ and $\sim 4\sigma$ discrepancies between the two data sets in flat and non-flat PAge universes respectively. For the \( \delta \) parameter, the discrepancies are found to be $> 4\sigma$ in different PAge backgrounds. These results indicate that the QSO luminosity correlation evolves with redshift and suffers from non-universal dispersion. In addition, we find the PAge parameters inferred from the SNe+low-z QSOs and SNe+high-z QSOs data sets, as shown in Figure 3, coincide well. More importantly, the marginalized 3\( \sigma \) contour of SNe+high-z QSOs deviates from the \( \Lambda \)CDM significantly while the SNe+low-z QSOs case roughly accommodates it, which implies that the PAge parameter inferences are probably biased by the redshift evolution and non-universal dispersion.

In the Bayesian framework, performing a linear fit between two data sets with errors on both axes and with an extra variance is quite subtle. Different analysis methods may yield inconsistent results, as indicated in Guidorzi et al. (2006). In our above analyses, we use the likelihood function (5) derived by D’Agostini (2005) to estimate the parameters and find remarkable discrepancies for \( \gamma \), \( \delta \) parameters. To demonstrate the discrepancies are not dominated by the statistical analysis method, we further perform Bayesian analyses with the Reichart method (Reichart 2001; Reichart et al. 2001) and present the parameter inference results in Table 4.

According to Table 4, we find the \( \gamma \), \( \delta \) parameters derived from the Reichart method also show prominent discrepancies. The \( \gamma \) parameters calibrated by SNe+low-z QSOs samples are in $\sim 3.4\sigma$ and $\sim 4.1\sigma$ tension with that calibrated by SNe+high-z QSOs samples in flat and non-flat PAge respectively. The \( \delta \) parameters show $\sim 4.0\sigma$ and $\sim 4.4\sigma$ discrepancies between different data sets and backgrounds. This suggests that the redshift-evolution effect and non-universal dispersion of QSO luminosity correlation are independent of the statistical analysis method.

### 5 Conclusions and Discussion

In this research, we provide an independent search for the origins of the $\sim 4\sigma$ deviation between the standard \( \Lambda \)CDM model and the constructed Hubble diagram of SNe+QSOs (Risaliti & Lusso 2019; Lusso et al. 2019, 2020). We adopt a nearly model-independent parameterization (PAge approximation) to visualize the standard \( \Lambda \)CDM model and marginalized 3\( \sigma \) constraints of SNe+QSOs data. To a certain degree, we have avoided the model dependence and...
Table 3. Marginalized 1σ constraints on parameters with SNe+low-z QSOs sample and SNe+high-z QSOs sample respectively.

| Model          | Sample            | \( \Omega_k \) | \( \rho_{\text{age}} \) | \( \eta \) | \( \gamma \) | \( \beta \) | \( \delta \) |
|----------------|-------------------|----------------|----------------|----------|----------|----------|----------|
| Flat PAge      | SNe+low-z QSOs    | -              | 0.940\(^{+0.033}_{-0.062}\) | 0.480\(^{+0.21}_{-0.13}\) | 0.637 ± 0.013 | 7.18 ± 0.41 | 0.237 ± 0.0047 |
|                | SNe+high-z QSOs   | -              | 0.875\(^{+0.025}_{-0.032}\) | 0.727\(^{+0.12}_{-0.066}\) | 0.585 ± 0.014 | 8.80\(^{+0.52}_{-0.43}\) | 0.207 ± 0.0054 |
| Non-flat PAge  | SNe+low-z QSOs    | -0.512\(^{+0.066}_{-0.35}\) | 1.21\(^{+0.28}_{-0.10}\) | 0.05\(^{+0.48}_{-0.35}\) | 0.635 ± 0.013 | 7.21 ± 0.43 | 0.237 ± 0.0047 |
|                | SNe+high-z QSOs   | -0.795 ± 0.078 | 1.24\(^{+0.057}_{-0.071}\) | 0.220\(^{+0.26}_{-0.19}\) | 0.561\(^{+0.0088}_{-0.013}\) | 9.49\(^{+0.49}_{-0.15}\) | 0.203 ± 0.0053 |

Figure 3. Marginalized 1σ, 2σ and 3σ constraints on PAge parameters with SNe+low-z QSOs and SNe+high-z QSOs samples in flat and non-flat PAge universes, respectively. The red point represents the standard ΛCDM model.

Table 4. Marginalized 1σ constraints on parameters with Reichart method.

| Model          | Sample            | \( \Omega_k \) | \( \rho_{\text{age}} \) | \( \eta \) | \( \gamma \) | \( \beta \) | \( \delta \) |
|----------------|-------------------|----------------|----------------|----------|----------|----------|----------|
| Flat PAge      | SNe+low-z QSOs    | -              | 1.05\(^{+0.051}_{-0.10}\) | 0.140\(^{+0.36}_{-0.18}\) | 0.750\(^{+0.033}_{-0.011}\) | 3.72\(^{+0.32}_{-0.46}\) | 0.244 ± 0.0050 |
|                | SNe+high-z QSOs   | -              | 0.919\(^{+0.033}_{-0.044}\) | 0.570\(^{+0.16}_{-0.11}\) | 0.681 ± 0.016 | 5.84 ± 0.51 | 0.213 ± 0.0059 |
| Non-flat PAge  | SNe+low-z QSOs    | -0.240\(^{+0.12}_{-0.44}\) | 1.20\(^{+0.29}_{-0.10}\) | -0.096\(^{+0.52}_{-0.39}\) | 0.748\(^{+0.014}_{-0.012}\) | 3.76\(^{+0.35}_{-0.44}\) | 0.244 ± 0.0050 |
|                | SNe+high-z QSOs   | -0.638\(^{+0.081}_{-0.10}\) | 1.26 ± 0.11 | -0.01\(^{+0.38}_{-0.26}\) | 0.660 ± 0.017 | 6.45 ± 0.55 | 0.210 ± 0.0058 |

The fitting errors of the assumed background cosmology (Yang et al. 2020). According to the results shown in Figure 2, we confirm that the marginalized 3σ constraints of SNe+QSOs on PAge parameters are in remarkable tension with the standard ΛCDM model in both flat and non-flat universes. This result agrees with Risaliti & Lusso (2019); Lusso et al. (2019, 2020).

We proceed to investigate the tension from the perspective of redshift evolution. By splitting QSOs into low-z and high-z samples, we find that there indeed exist remarkable discrepancies for the slope \( \gamma \) parameter and intrinsic dispersion \( \delta \) between low-z and high-z QSOs calibrated by SNe. And the remarkable discrepancies for \( \gamma \) and \( \beta \) parameters persist in the parameter inferences derived from the Reichart method. These results reveal that the QSO luminosity correlation suffers from the redshift-evolution effect and non-universal intrinsic dispersion.

Building a QSO Hubble diagram with a non-robust QSO luminosity correlation may provide unreliable results. As indicated in Figure 3, with the evolutions of the \( \gamma \) and \( \delta \) parameters, the marginalized
contour of the SNe+low-z QSOs sample is consistent with the ΛCDM while significant deviation emerges for the SNe+high-z QSOs case. This indicates the PAge parameter constraints can be biased by the evolutions of γ and δ parameters. Therefore, the significant deviation found in (Risaliti & Lusso 2019; Lusso et al. 2019, 2020) may mainly originate from the redshift-evolution effect and the non-universal intrinsic dispersion of the QSO luminosity correlation instead of new physics beyond the ΛCDM cosmology.

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6 DATA AVAILABILITY

The quasar data underlying this article are available in Lusso et al. (2020) and in its online supplementary material. The supernova data underlying this article are publicly available in Scolnic et al. (2018).

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