A measure of cosmological distance using the C iv Baldwin effect in quasars

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ABSTRACT

We use the anticorrelation between the equivalent width (EW) of the C iv 1549 Å emission line and the continuum luminosity in the quasars rest frame (Baldwin effect) to measure their luminosity distance as well as estimate cosmological parameters. We obtain a sample of 471 Type I quasars with the UV-optical spectra and EW (C iv) measurements in the redshift range of 2.3 < z < 7.1 including 25 objects at 5 < z < 7.1, which can be used to investigate the C iv Baldwin effect and determine cosmological luminosity distance. The relation EW(C iv) ∝ (L c)γ can be applied to check the inverse correlation between the C iv EW and L c of quasars and give their distance, and the data suggest that the EW of C iv is inversely correlated with continuum monochromatic luminosities. On the other hand, we also consider dividing the Type I quasar sample into various redshift bins, which can be used to check if the C iv EW–luminosity relation depends on the redshift. Finally, we apply a combination of Type I quasars and Type Ia supernovae (SNIa) of the Pantheon sample to test the property of dark energy concerning whether or not its density deviates from the constant, and give the statistical results.

Key words. dark energy – quasars: emission lines – quasars: general – distance scale

1. Introduction

A wide variety of emission line strengths and velocity widths are the important spectral features of active galactic nuclei (AGNs) and quasars, which can be used to classify these objects and investigate the correlation between the equivalent widths (EWs) of emission lines and continuum luminosities in the UV-optical band. The full width at half maximum (FWHM) of the emission lines often involves the orientation relative to the line of sight (Shen & Ho 2014). Broad lines are defined as having FWHM ≈ 1000–15 000 km s⁻¹ and narrow lines as FWHM ≈ 200–2000 km s⁻¹ (Sulentic et al. 2000). On this basis, AGNs and quasars can be categorized by whether they have broad emission lines (Type I), only narrow lines (Type II), or no lines except when a variable continuum is in a low phase (Blazars; Urry & Padovani 1995; Sulentic et al. 2000). In addition, other classification methods of quasars can be based on the ratio of monochromatic luminosities. Radio-loud quasars satisfy log R > 1 and radio-quiet quasars with log R ≤ 1, where R is the ratio of monochromatic luminosities (with units of erg s⁻¹ Hz⁻¹) measured at (rest-frame) 5 GHz and 2500 Å (Strittmatter et al. 1980; Kellermann et al. 1989, 1994; Stocke et al. 1992).

On the other hand, the correlation between the equivalent width (EW) of the C iv 1549 Å emission line and the continuum luminosity in the quasars rest frame was investigated by Baldwin (1977). The data suggested that the C iv EW anticorrelates with continuum monochromatic luminosities based on a sample of 20 quasars in the redshift range 1.24 < z < 3.53. This has become known as the Baldwin effect (hereafter BEff). Subsequently, more spectroscopic data of AGNs and quasars are used to verify the BEff, and it exists not only for C iv but also for many other UV-optical emission lines such as Lyα λ1215.7, C iii] λ1908.7, Mg ii] λ2800.3 (Kinney et al. 1990; Netzer et al. 1992; Croen et al. 2002). Although the physical reason for the BEff remains unknown, there are several explanations that try to account for the UV-optical BEff.

One promising explanation is the softening of the spectral energy distribution (SED) that the soft X-ray continuum between 0.1 and 1 keV in high-luminosity quasars is weaker than that in low-luminosity AGNs, which determines the heating rate and the excitation of various collisionally excited lines (Netzer et al. 1992; Zheng et al. 1995; Dietrich et al. 2002). It is an important clue for the physical cause of the UV-optical BEff. Other underlying physical causes of the BEff involve the black hole mass (Xu et al. 2008; Chang et al. 2021), the Eddington ratio L/L Edd (Baskin & Laor 2004; Xu et al. 2008; Dong et al. 2009; Nikolajuk & Walter 2012; Shemmer & Lieber 2015), and the luminosity dependence of metallicity (Dietrich et al. 2002; Sulentic et al. 2007).

In this paper we introduce the source of data used in Sect. 2, including the EW of the C iv 1549 Å emission line, and the continuum luminosity at 2500 Å of 471 Type I quasars. In Sect. 3 we employ the nonlinear relation EW(C iv) ∝ (L c2500Å)γ to check the correlation between the C iv EW and continuum luminosity of Type I quasars, and give their cosmological luminosity...
distance. In Sect. 4 we consider dividing the Type I quasar sample into various redshift bins, which can be used to check if the C iv EW–luminosity relation depends on the redshift. In Sect. 5, we apply a combination of Type I quasars and SNIa Pantheon to reconstruct the dark energy equation of state \( w(z) \), which can be used to test the nature of dark energy concerning whether or not its density deviates from the constant. In Sect. 6, we summarize the paper.

2. Data used

Modern optical instruments and surveys including the Sloan Digital Sky Survey (SDSS; Lyke et al. 2020; Ahumada et al. 2020), the Hubble Space Telescope (HST; Tacconi et al. 2018), and the International Ultraviolet Explorer (IUE) provide the UV-optical spectra for a large amount of quasars (Kondo et al. 1989), which can be used to investigate the C iv BEff. Alam et al. (2015) presented the Data Release 12 Quasar catalog (DR12) data gathered by SDSS-III from 2008 August to 2014 June, which includes the spectra of 294,512 quasars (Alam et al. 2015). Their emission line fluxes or EWs and widths can be measured by different techniques, and sometimes different results are obtained for the same set of data (Berk et al. 2001; Shen et al. 2008, 2011; Shen & Ménard 2012, Pâris et al. 2011, 2012).

We introduce two main calculation methods for the flux and width of emission lines. The first is to use two Gaussian functions to fit the emission-line spectrum given after subtracting the rest frame, and the weak emission line He ii lines with the fitting window 1450–1700 Å and 1800–2000 Å in the PCA method to study C iv BEff. Pâris et al. (2017) provided different results are obtained by sky subtraction.

We use two Gaussian functions to fit C iv and C iii emission lines with the fitting window 1450–1700 Å and 1800–2000 Å in the rest frame, and the weak emission line He ii is not taken into account. The width and amplitude are independent parameters, but the two Gaussians are bound to have the same emission redshift. Figure 2 shows the corresponding C iv emission line fit from a two-Gaussian fit. Meanwhile, the PCA method is also applied to fit the spectra. Examples of fitting results for the power-law and Gaussian method and the PCA method are presented in Fig. 1. The C iv EW from the two-Gaussian fit is larger than the measurement from the PCA method, and the power-law and Gaussian method gives simpler results to the PCA method, so we consider using the EW of emission lines obtained by the PCA method to study C iv BEff. Pâris et al. (2017) provided the various measured quantities of 297,301 quasars from DR12 based on the result of a PCA of the spectra. Therefore, we filter samples from their released data to check the correlation between the C iv EW and the continuum luminosity for quasars and measure their cosmological luminosity distance.

3. Parameter constraints from Type I quasars

3.1. Insights from scatter plots

The linear formula is usually used to investigate the correlation between the C iv EW and \( AL_{\lambda} \) for quasars, which can be written as

\[
\log \text{EW}(\text{C iv}) = \beta + \gamma \log(AL_{\lambda}(2500 \text{ Å})).
\]  

(1)

This equation is equivalent to the relation \( \text{EW}(\text{C iv}) \propto (AL_{2500 \lambda})^{\gamma} \). We fitted Eq. (1) to 8630 Type I quasars and obtained the residual \( \Delta \log(\text{EW}(\text{C iv})) \) from the statistical values of \( \beta \) and \( \gamma \); the luminosities \( L_{\lambda}(2500 \text{ Å}) \) were obtained from the measured fluxes assuming Lambda cold dark matter (ΛCDM) cosmology \((\Omega_{m} = 0.3, H_{0} = 70 \text{ km s}^{-1} \text{ Mpc}^{-1})\). The log EW(C iv)–\( L_{\lambda}(2500 \text{ Å}) \) plot of Type I quasars are shown in the upper panel of Fig. 3; the lower panel of Fig. 3 illustrates \( \Delta \log(\text{EW}(\text{C iv})) - \Gamma_{UV} \) relation and investigate the correlation between the luminosity \( L_{UV} \) and the UV-optical power-law index \( \Gamma_{UV} \), \( \Gamma_{UV} \) can be obtained from a fit of \( f_{\text{iv}} \propto \nu^{-\Gamma_{UV} - 1} \) to \( u, g, r, i \) and \( z \) band. The index \( \Gamma_{UV} \) of Type I quasars with \( z > 3 \) seem to be inapplicable to study a corresponding correlation and needs to be excluded. The residual \( \Delta \log(\text{EW}(\text{C iv})) \) against \( \Gamma_{UV} \) for Type I quasars with \( z \leq 3 \) is shown in the upper panel of Fig. 4; it implies that \( \Delta \log(\text{EW}(\text{C iv})) \) has no dependence on \( \Gamma_{UV} \). The luminosity \( L_{UV} \) against \( \Gamma_{UV} \) is provided in the lower panel of Fig. 4; their correlation coefficient is \( r = 0.131 \), which indicates that the luminosity \( L_{UV} \) might be weakly correlated with the UV-optical power-law index \( \Gamma_{UV} \).

3.2. Filter data for measuring luminosity distance

As can be seen in the lower panel of Fig. 3, the luminosity dependence of the BEff slope is indicated for a large number of

\[
\log \text{EW}(\text{C iv}) = \beta + \gamma \log(AL_{\lambda}(2500 \text{ Å})).
\]  

(1)
samples, so we fitted our data points with 45.8 ≤ log(\(\lambda L_\lambda(2500 \text{ Å})\)) ≤ 46.5 to avoid the luminosity dependence for \(\gamma\). Meanwhile, in order to reduce the dispersion, we select the sample at \(z \leq 3\) by \(\sigma(\text{EW})/\text{EW(C IV)} < 0.02\), \(\sigma(\text{EW})/\text{EW(C IV)} < 0.023\) for \(3 < z \leq 5\), \(\sigma(\text{EW})/\text{EW(C IV)} < 0.06\), which ensures that the numbers of objects are close in different redshift bins. We then obtain a sample of 471 Type I quasars \((2.3 < z < 7.1)\). We also match the sample to the latest FIRST catalog and The NRAO VLA sky survey (NVSS) data using a 2′′ matching radius (Helfand et al. 2015; Condon et al. 1998), only about 20 objects have FIRST and NVSS counterparts, but all of them satisfy log \(R > 1\), these radio-loud sources and other quasars compose a total sample of 471 Type I quasars. We can use this sample to investigate BEff and calculate the luminosity distance.

3.3. Parametric formula for C IV EW and the continuum flux

Using relation \(L = 4\pi D_L^2 f\) in Eq. (1), we get

\[
\log \text{EW(C IV)} = \Phi(\lambda f_\lambda(2500 \text{ Å}), D_L) = \beta + \gamma \log(\lambda f_\lambda(2500 \text{ Å})) + \gamma \log(4\pi D_L^2),
\]

where \(f_\lambda(2500 \text{ Å})\) is the flux measured at (rest-frame) 2500 Å; \(\text{EW(C IV)}\) is the equivalent width of the C IV 1549 Å emission line; and \(D_L\) is the luminosity distance, which depends on the redshift \(z\). Thus, Eq. (2) can be used to check the C IV EW–luminosity correlation for Type I quasars and determine their cosmological luminosity distance.

We fit the C IV EW–luminosity relation to Type I quasars by minimizing a likelihood function consisting of a modified \(\chi^2\) function based on a Markov chain Monte Carlo (MCMC) function, allowing for an intrinsic dispersion \(\delta\).

\[
-2 \ln L = \sum_{i=1}^{N} \left\{ \frac{[\log \text{EW(C IV)}_i - \Phi(\lambda f_\lambda(2500 \text{ Å}), D_L)_i]^2}{s_i^2} \right\} + \sum_{i=1}^{N} \ln(2\pi s_i^2),
\]

where \(\Phi(\lambda f_\lambda(2500 \text{ Å}), D_L)_i\) is given by Eq. (2) and \(s_i^2 = \sigma^2(\log \text{EW(C IV)}) + \gamma^2 \cdot \sigma^2(\log(\lambda f_\lambda(2500 \text{ Å}))) + \delta^2\); \(\sigma(\log \text{EW})\) and \(\sigma(\log(\lambda f_\lambda(2500 \text{ Å})))\) indicate the statistical errors for \(\log \text{EW(C IV)}\) and \(\log(\lambda f_\lambda(2500 \text{ Å}))\); and \(\delta\) is the intrinsic dispersion (Kim 2011; Risaliti & Lusso 2015), which can be fitted as a free parameter.
A prior cosmological constant (Dultzin et al. 2020). Equation (2) gives the distance modulus as
\[
\Delta m = 5 \frac{\log(\text{EW}([\text{C}\,\text{IV}])) - \log(\text{EW}([\text{C}\,\text{IV}]))_{\text{min}}}{2\beta} + 25,
\]
where \(\beta = \gamma + \gamma \log(4\pi)\). The error is
\[
\sigma_{\Delta m} = \Delta m \sqrt{\frac{\sigma_\gamma^2}{r^2} + \frac{\sigma_{\text{EW}}^2}{\gamma^2}},
\]
where \(r = \log(\text{EW}([\text{C}\,\text{IV}])) - \gamma \log(\text{EW}([\text{C}\,\text{IV}])) - \gamma \log(\text{EW}([\text{C}\,\text{IV}]))_{\text{min}}\) is the intrinsic dispersion of \(\beta\), and \(\sigma_{\text{EW}}^2 = \sigma^2(\log(\text{EW}([\text{C}\,\text{IV}])) + \gamma^2 \cdot \sigma^2(\log(\text{EW}([\text{C}\,\text{IV}])) + \sigma_\gamma^2\). From Eq. (5), the uncertainty of the slope of the BEF \(\gamma\) obviously influences the error of distance modulus for Type I quasars.

### 3.4. Fitting result for the relation of \(C_{\text{IV}}\) EW to the continuum flux

We adopt the maximum likelihood function (Eq. (3)) based on MCMC to constrain the parameters; the fitting results are shown in Table 2, and the slope of the BEF is \(\gamma = -0.164 \pm 0.006\), which suggests that the EW of \([\text{C}\,\text{IV}]\) is inversely correlated with continuum monochromatic luminosities. It is consistent with the result by Bian et al. (2012).

We obtain the distance modulus of Type I quasars by substituting the statistical average values of \(\beta\) and \(\gamma\) into Eq. (4), which are shown in the upper panel of Fig. 5, including their averages in small redshift bins. Meanwhile the distance modulus and properties of the 471 Type I quasars are listed in Table 1. The lower panel of Fig. 5 shows the plot of the residuals of the distance modulus against redshift; the residuals are from measuring the distance modulus for Type I quasars and \(\Lambda\)CDM cosmology (\(\Omega_m = 0.3\)). There could be several reasons for the large scatter in the luminosity distance, including observational error, and intrinsic variation of the BEF (Shields 2006; Dietrich et al. 2002). Figure 6 illustrates the diagram of the residuals against the luminosity \(L_{\text{UV}}\) or the UV-optical power-law index \(\Gamma_{\text{UV}}\). The correlation coefficient for the residuals \((\Delta(\log(\text{EW}([\text{C}\,\text{IV}]))))\) and \(L_{\text{UV}}\) is \(r = -0.097\), which represents that \((\Delta(\log(\text{EW}([\text{C}\,\text{IV}]))))\) is not correlated with the luminosity \(L_{\text{UV}}\). The residuals \((\Delta(\log(\text{EW}([\text{C}\,\text{IV}]))))\) is also not relevant with \(\Gamma_{\text{UV}}\); their correlation coefficient is \(r = 0.046\), which implies that the BEF slope has no dependence on \(L_{\text{UV}}\) or \(\Gamma_{\text{UV}}\) in the final sample.

We also consider the relevance of the \(C_{\text{IV}}\) EW dependence on Eddington ratio \(L/L_{\text{Edd}}\) and use the relation log(\(CE\)) = \(a + \beta \log(L/L_{\text{Edd}})\) to measure luminosity distance for quasars (Baskin & Laor 2004; Bian et al. 2012; Ge et al. 2016). The virial black hole (BH) Masses \(M_{\text{BH}}\) or Eddington ratio \(L/L_{\text{Edd}}\) can be estimated from \(C_{\text{IV}}\) emission lines (Sheen et al. 2008, 2011) by formula \(\log(M_{\text{BH}}/M_{\odot}) + \log(L/L_{\text{Edd}}) + 2\log(\text{FWHM}/(\text{km} \cdot \text{s}^{-1}))\), which is derived from the so-called virial black hole mass estimate \(M_{\text{BH}} = G^{-1}R_{\text{BLR}}V_{\text{BLR}}^2\) and \(R_{\text{BLR}}-\lambda_L\) relation, and \(a = 0.66, b = 0.53\) for \(C_{\text{IV}}\) estimators (Mclure & Dunlop 2004; Vestergaard & Peterson 2006). Then we can obtain Eddington ratios \(L/L_{\text{Edd}}\), where \(L_{\text{Edd}} = 1.3 \times 10^{38} (M_{\text{BH}}/M_{\odot})\) erg s\(^{-1}\) is the Eddington luminosity. We use the CIV EW–L/L_{\text{Edd}} relation to measure the luminosity distance for Type I quasars. Nonetheless, there are even greater errors in the luminosity distance than the results from the CIV EW–luminosity relation (Eq. (4)). Therefore, we only use the distance modulus for Type I quasars obtained from CIV BEF and SNIa Pantheon to test the property of dark energy in Sect. 5.

### 4. Analysis of the relation \(\log(\text{EW}([\text{C}\,\text{IV}]) \propto (\lambda L_{\text{f}})^{-1}\) as a function of \(z\)

We divide the Type I quasar data into several redshift bins, which can be used to check if relation \(\log(\text{EW}([\text{C}\,\text{IV}]) \propto (\lambda L_{\text{f}})^{-1}\) depends on redshift. The redshift bins satisfy \(\Delta(1/(1+z)) = 0.033\). We adopt the parametric model
\[
\log(\text{EW}([\text{C}\,\text{IV}]) = (\beta(z) + \gamma(z) \log(\lambda L_{\text{f}}(2500 \, \text{Å})))
\]
where \(\gamma(z)\) and the intrinsic dispersion \(\delta(z)\) are free parameters, and \(\beta(z)\) is obtained from Eq. (2) and can also be a free parameter. We apply segmented Type I quasars data to fit \(\gamma(z)\) as well as test whether there is a dependency upon redshift. The fit results of \(\gamma(z)\) and \(\delta(z)\) at different redshifts are illustrated in Fig. 7; it is easy to see that their values do not obviously deviate from the
average, which shows there is no obvious evidence for any significant redshift evolution. The average values of parameter is $\langle \gamma \rangle = -0.154 \pm 0.009$.

5. The reconstruction of dark energy equation of state $w(z)$

Although dark energy can be used to effectively explain the accelerating expansion of the universe and the cosmic microwave background (CMB) anisotropies (Riess et al. 1998; Amanullah et al. 2010; Betoule et al. 2014; Scolnic et al. 2018; Conley et al. 2010; Hu & Dodelson 2002; Ade et al. 2016), the origin and property of its density and pressure remain unclear.

Dark energy can be researched using two main methods. One is to constrain dark energy physical models from observational data and try to explain the physical origin of its density and pressure (Peebles & Ratra 2003; Ratra & Peebles 1988; Li 2004; Maziashvili 2007; Amendola 2000; Gao et al. 2017). Understanding the physical origin of dark energy is important
for our universe. It is necessary to determine whether the dark energy is composed of Boson pairs in a vacuum, Fermion pairs, or the Higgs field, and whether it has weak isospin, which may determine whether it can be detected directly in the laboratory. The other method is to study the properties of dark energy, focusing on whether or not its density evolves with time. This can be tested by reconstructing the dark energy equation of state \( w(z) \) (Linder 2003; Maor et al. 2002), which does not depend on physical models. High-redshift observational data such as quasars can better solve these issues.

Table 1. Properties of the 471 Type I quasars.

| SDSS name                  | \( z \)   | \( m_r \) (mag) | EW(C IV) (Å) | \( \log f_r(2500 \, \text{Å}) \) | \( \Gamma_{\text{UV}} \) | DM | \( \sigma_{DM} \) |
|----------------------------|-----------|----------------|--------------|-------------------------------|---------------------|-----|-----------------|
| 143112.39+093915.4         | 7.011     | 21.094±0.047   | 26.56±0.97   | −24.536±0.019                 | 2.964               | 49.389 | 1.956           |
| 112310.06+134622.5         | 6.038     | 21.06±0.038    | 27.49±1.13   | −24.505±0.015                 | 4.383               | 49.077 | 1.949           |
| 115132.69+550317.3         | 5.338     | 21.166±0.054   | 28.96±1.68   | −24.534±0.022                 | 3.823               | 48.789 | 1.959           |
| 125718.02+374729.9         | 4.745     | 20.757±0.037   | 29.16±0.48   | −24.358±0.015                 | 5.042               | 48.302 | 1.904           |
| 131808.44+215437.0         | 4.258     | 20±0.032       | 28.06±0.58   | −24.043±0.013                 | 4.245               | 47.78  | 1.886           |

Notes. DM is the distance modulus from a fit of the relation \( \text{EW}(C IV) \propto (\lambda_{\text{L}})^{\gamma} \) with \( \Lambda \) CDM model; \( \sigma_{\text{DM}} \) is the error. Only five of the objects are listed. The full table is available at the CDS.

Table 2. Fit results on model parameters for a combination of Type I quasars and SNla.

| Parameter | \( \beta \) | \( \gamma \) | \( \delta \) | \( \Omega_m \) | \( \alpha \) | \( \omega \) | \( \chi^2_{\text{total}}/\chi_{\text{total}}^2 \) |
|-----------|-----------|------------|-----------|-------------|-------|-------|-----------------|
| ACDM      | Quasars (Type I) |          |          |             |       |       |                 |
| Sample    | Best fit  | 5.021     | 0.092    | 0.268       | –      | –      | –902.9(475.9)    |
| Mean      | 5.002     | 0.086     | 0.258    | 0.034       | –      | –      | 134.1(1512.9)    |
| ACDM      | SN+Quasars (Type I) |       |          |             |       |       |                 |
| Sample    | Best fit  | 5.021     | 0.092    | 0.268       | –      | –      | –902.9(475.9)    |
| Mean      | 5.002     | 0.086     | 0.258    | 0.034       | –      | –      | 134.1(1512.9)    |

Fig. 6. Residuals of distance modulus against luminosity \( L_{\text{UV}} \) or UV-optical power-law index \( \Gamma_{\text{UV}} \) for the selected sample. This is used to measure the luminosity distance, and \( r \) is the correlation coefficient.

Fig. 7. C IV EW–luminosity correlation in narrow redshift intervals. The blue points are the fit results of \( \gamma(z) \), \( \delta(z) \) at different redshifts. The horizontal lines show their average values.

The reconstruction of the equation of state of dark energy \( w(z) \) includes parametric and non-parametric methods (Huterer & Starkman 2003; Clarkson & Zunckel 2010; Holsclaw et al. 2010; Seikel et al. 2012; Crittenden et al. 2009; Zhao et al. 2012). We employ Type I quasars and Type Ia supernova (SNla) to reconstruct \( w(z) \) by the parametric method assuming C IV EW–luminosity relation Eq. (2), which can be used to test the nature of dark energy.

For SNla data, the Pantheon sample contains 1048 SNla from the Pan-STARRS1 (PS1), the Sloan Digital Sky Survey (SDSS), SNLS, and various low-z and Hubble Space Telescope samples. There are 279 SNIa provided by PS1 (Scolnic et al. 2018), and SDSS presented 335 SNla (Betoule et al. 2014; Gunn et al. 2006; Sako et al. 2018). The rest of the Pantheon sample are from the CfA1 – 4, CSP, and Hubble Space Telescope (HST) SN surveys (Amanullah et al. 2010; Conley et al. 2010). This combined sample of 1048 SNla is called the Pantheon sample.
The integral formula of the luminosity–redshift relation in flat space can be written as (Linder 2003; Sahni & Starobinsky 2006)

\[
D_L = \frac{1+z}{H_0} \int_0^\infty dz' \left[ \Omega_m (1+z')^3 + \Omega_m (1+z')^3 + \Omega_{\Lambda} \left( \frac{1}{1+z'} \right)^{3/2} \right]^{-1/2},
\]

where \( \Omega_R, \Omega_m, \) and \( \Omega_{\Lambda}^{(0)} \) are the present radiation density, matter density, and dark energy density and satisfies \( \Omega_{\Lambda}^{(0)} = 1 - \Omega_m \) when ignoring \( \Omega_R \). \( w(z) \) is the dark energy equation of state. We adopt the parametric form for \( w(z) \)

\[
w(z) = w_0 + w_a \frac{z}{1+z},
\]

and denote it \( w_0, w_a, C_{DM} \). Therefore dark energy density is

\[
\Omega_{DE}(z) = \Omega_{DE}^{(0)} (1+z)^{3(1+w_0+w_a)} \exp[-3w_a z/(1+z)].
\]

We constrain the \( w_0, w_a, C_{DM} \) model parameters for Type I quasars and SN Ia by minimizing a modified \( \chi^2_{\text{Total}} \) function. The \( \chi^2_{\text{Total}} \) is

\[
\chi^2_{\text{Total}} = -2 \ln L_{\text{Quasars}} + \chi^2_{\text{SN}},
\]

where \( -2 \ln L_{\text{Quasars}} \) is given by Eq. (3), and \( \chi^2_{\text{SN}} \) can be expressed as

\[
\chi^2_{\text{SN}} = \Delta t^T C_{\mu, \nu}^{-1} \Delta t,
\]

where \( \Delta t = \mu - \mu_0; C_{\mu} \) is the covariance matrix of the distance modulus \( \mu \); \( \chi^2_{\text{Total}} \) function also satisfies \( \chi^2_{\text{Total}} = \chi^2_{\text{Quasars}} + \chi^2_{\text{SN}} \); and

\[
\chi^2_{\text{Quasars}} = -2 \ln L_{\text{Quasars}} = \sum_{i=1}^{N} \ln(2\pi \sigma_i^2).
\]

We use Type I quasars and SN Ia to fit the Eq. (10) and obtain the statistical results for the cosmological parameters, and their mean and best fit values are listed in Table 2. When using a combination of Type I quasars and SN Ia which covers low- and high-redshift data, the results show \( w_0, w_a, C_{DM} \) has better goodness of fit than \( \Lambda \) CDM, and \( \chi^2_{\text{Total}} \) is improved by \(~3.9\), which indicates that the \( \Lambda \) CDM model is in tension with Type I quasars and SN Ia at \(~1.5\)σ. The results are consistent with the values from radio-loud quasars (Huang & Chang 2022). Meanwhile, Fig. 8 illustrates the 68% and 95% contours for \( w_0 \) and \( w_a \) from a combination of SN Ia and Type I quasars, assuming the C IV–luminosity relation EW(CIV) \( \propto (L_{\text{ff}})^{y/2} \). The fitting results show the slope \( y(z) \) approaches the constant, which shows that there is not an obvious redshift evolution for EW(CIV) \( \propto (L_{\text{ff}})^{y/2} \).

Finally, we used a combination of Type I quasars and SN Ia to test the property of dark energy by reconstructing the equation of state \( w(z) \). The 471 high-redshift Type I quasars included 25 objects at \( 5 < z < 7.1 \), which can be applied to check the cosmological model and test the nature of dark energy more efficiently. The results show the \( w_0, w_a, C_{DM} \) model is superior to the cosmological constant \( \Lambda \) CDM model at \(~1.5\)σ.

In the future, we will select more Type I quasars at high redshift \( (z > 5) \) with the C IV 1549 Å emission line and the continuum luminosity from the SDSS quasar catalogs, and hope to obtain \( z > 7 \) quasars from future optical observations, such as the James Webb Space Telescope (JWST; Naidu et al. 2022). The high-redshift observational data can be better used to reconstruct the equation of state and test the properties of dark energy, which involves whether or not the universe will keep expanding.

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Fig. 8. Contours at 68% and 95% (\( \Delta \mu^2 = 1.5, 6 \)) for \( w_0 \) and \( w_a \) from a fit of the relation EW(C IV) \( \propto (L_{\text{ff}})^{y/2} \) with \( w_0, w_a, C_{DM} \) model to a combination of SN Ia and Type I quasars. The plus sign (+) in the corresponding color represents the best fitting values for \( w_0, w_a \).
