Fine-structure transitions as a tool for studying variation of $\alpha$ at high redshifts

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ABSTRACT
Star-forming galaxies at high redshifts are the ideal targets to probe the hypothetical variation of the fine-structure constant $\alpha$ over cosmological time scales. We propose a modification of the alkali doublets method which allows us to search for variation in $\alpha$ combining far infrared and submillimeter spectroscopic observations. This variation manifests as velocity offsets between the observed positions of the fine-structure and gross-structure transitions when compared to laboratory wavelengths. Here we describe our method whose sensitivity limit to the fractional change in $\alpha$ is about $5 \times 10^{-7}$. We also demonstrate that current spectral observations of hydrogen and [C II] 158 $\mu$m lines provide an upper limit on $|\Delta \alpha/\alpha| < 6 \times 10^{-5}$ at redshifts $z = 3.1$ and $z = 4.7$.

Key words: methods: observational – techniques: spectroscopic – galaxies: high-redshift – cosmology: observations

1 INTRODUCTION
The Einstein equivalence principle (EEP) postulates that fundamental physical laws are invariant in space and time. However, some of new theories beyond the Standard Model (SM) of particle physics suggest a violation of the EEP (for a review, see, e.g., Liberati 2013). In particular, a changing dimensionless fine-structure constant, $\alpha = e^2/\hbar c$, accompanied by variation in other coupling constants can be associated with a break of local Lorentz invariance (Kostelecký et al. 2003). Thus, experimental validation of EEP is extremely important allowing us both to test limits of the standard theory, i.e. the quantum electrodynamics, and to probe the applicability of the new theories beyond the SM. Astronomical measurements seem to be the most suitable tool for this purpose thanks to their accuracy and the possibility to operate within and outside of our Galaxy and over time intervals comparable to the age of the Universe ($\sim 10^{10}$ yr).

In astrophysics, the validity of EEP was tested through the observed time delays between different energy bands from blazar flares, gamma-ray bursts, and fast radio bursts which constrain the numerical coefficients of the parameterized post-Newtonian formalism, such as the parameter $\gamma$ accounting for how much space-curvature is produced by unit rest mass (e.g., Wei et al. 2015; Petitjean et al. 2016). It was shown that general relativity, which predicts $\gamma \equiv 1$, is obeyed to the level of $\sim 10^{-8}$ (Gao et al. 2015; Wei et al. 2016).

More than two decades ago, Levshakov (1992) proposed a program of high resolution spectral observations of extragalactic sources – quasars – with a new generation of giant telescopes aimed at differential measurements of $\Delta \alpha/\alpha$ from alkali doublets. The alkali doublet method uses the ratio of the difference between fine-structure lines to their average wavelength (Savedoff 1956; Bahcall & Salpeter 1965; Bahcall & Schmidt 1967; Bahcall et al. 1967; Levshakov 1994; Bahcall et al. 2004). Later on, the alkali doublet method was supplemented with the so-called “many-multiplet” method which utilizes absolute laboratory wavelengths arising from many different multiplets in different ions (Dzuba, Flambaum, & Webb 1999a,b). The alkali doublet method was applied both to emission-line spectra of distant galaxies and to absorption-line spectra of the intervening quasar absorbers. The many-multiplet method dealt with quasar absorption-line spectra only. This may lead spectral lines sampling quite a different interstellar medium in the quasar absorption-line systems and distant galaxies seen in emission.

$\Delta \alpha/\alpha = (\alpha_z - \alpha)/\alpha$, with $\alpha_z$ being the fine-structure constant at redshift $z$, and $\alpha$ is the present-day value.
Since that time there appeared a number of controversial results suggesting a time dependence of \( \alpha \) and restricting \( \Delta \alpha/\alpha \) values to the same level of a few \( 10^{-6} \) (see, e.g., Molaro et al. 2013, and references cited therein). All measurements were tested on basis of optical observations performed at the VLT, Keck, and Subaru telescopes. Recently it became clear that the above mentioned inconsistencies were caused by systematic effects in the calibration of the wavelength scale of quasar spectra (Whitmore & Murphy 2015; Evans et al. 2014). The tightest present-day upper limit on the relative variation in \( \alpha \), obtained from optical spectra of quasars, is limited to a few \( 10^{-8} \) at \( z \sim 2 - 3 \) (e.g., Quast et al. 2004; Levshakov et al. 2006; Agafonova et al. 2011; Bonifacio et al. 2014). A further improvement – approximately by an order of magnitude – can be expected only with the new high-resolution-ultra-stable spectrograph ESPRESSO at the VLT, whose commissioning will start in 2017 (Leite et al. 2016).

Together with astronomical studies the fundamental physical laws were tested for the passed decade in numerous laboratory experiments with atomic clocks. For this purpose, frequencies of two or more lines with different dependence on the fundamental constants are compared to each other in time to monitor a relative frequency shift, \( \Delta \omega \). Laboratory experiments provide extremely high sensitivity with fractional uncertainties of \( \Delta \omega/\omega \sim 10^{-16} - 10^{-17} \) (Tyumenev et al. 2016; Nemitz et al. 2016; Huang et al. 2016) and even at the \( 10^{-18} \) level (Nisbet-Jones et al. 2016; Huntemann et al. 2016; Nicholson et al. 2015). For the time scale of the order of one year the fractional change in \( \alpha \) was restricted at the \( \dot{\alpha}/\alpha \sim 10^{-17} \) yr\(^{-1} \) level (Godun et al. 2014; Rosenband et al. 2008).

To the same category of terrestrial experiments belongs the Oklo phenomenon – the uranium mine at age 2\(\times\)10\(^9\) yr in Gabon which provides the tightest terrestrial bound on \( \alpha \) variation: \( |\Delta \alpha/\alpha| < 1.1 \times 10^{-8}, \) or \( \dot{\alpha}/\alpha < 5 \times 10^{-18} \) yr\(^{-1} \) (Davis & Hamdan 2015).

An independent and important complement to laboratory experiments with atomic clocks and optical observations of quasars provide far infrared (FIR) and sub-mm observations of distant galaxies. Advantages of micro-wave observations are the absence of systematic errors in calibrating the wavelength scale and in a higher sensitivity of atomic transitions to changes in \( \alpha \) in this spectral range (Kozlov et al. 2008). For instance, in the case of the \( ^2P_j \) multiplet of C II there is a \( J = 3/2 \to 1/2 \) fine-structure (FS) transition (158 \(\mu\)m) which is about 30 times more sensitive to changes in \( \alpha \) than UV lines of atoms and ions employed in optical spectroscopy.

The C II ion is one of the main cooling agents of the interstellar medium (ISM) and its above mentioned transition forms the brightest line detected up to very high cosmological redshifts \( z \sim 3 - 8 \) (e.g., Carniani et al. 2017; Umehata et al. 2017; Knudsen et al. 2017; Aravena et al. 2016; Pavesi et al. 2016; Knudsen et al. 2016; Maiolino et al. 2015; Capak et al. 2015; Willott et al. 2015; Riechers et al. 2014; Carilli et al. 2013; Venemans et al. 2012; Maiolino et al. 2005).

With the ALMA (Atacama Large Millimeter/submillimeter Array) facility one might expect that observations of C II will become possible even for galaxies at extreme redshifts \( z \sim 20 \) (de Blok et al. 2016). Thus, FS transitions advance to an important tool in probing the fundamental physics at high redshifts.

The FS lines of [C II] 158 \(\mu\)m and [C I] 370 \(\mu\)m were used in conjunction with the pure rotational CO transitions to put constraints on the ratio \( F = \alpha^2/\mu \) (where \( \mu \) is the electron-to-proton mass ratio) at \( z = 6.42 \) and 4.69 (Levshakov et al. 2008), \( z = 5.2 \) (Levshakov et al. 2012), and \( z = 2.79 \) (Weiß et al. 2012). In these measurements, the most stringent upper limit on \( F \) was obtained by Weiß et al.: \( |\Delta F/F| < 10^{-5} \).

In the present letter, we discuss another possibility of using the atomic FS transitions – to probe the fractional changes not in a combination of constants, but directly in \( \alpha \). The proposed “FST method” (Fine Structure Transition) is based on the measurements of the radial velocity offset, \( \Delta V = V_{\text{opt}} - V_{\text{fs}} \), between optical and FIR fine-structure lines within ground multiplets.

The rest of this letter is arranged as follows. In Section 2, we briefly describe the FST method and show its applicability to recently published spectral observations of a dusty star-forming galaxy observed at \( z = 3.1 \), and a group of galaxies at \( z = 4.7 \). In Section 3, we summarize our results.

## 2 FST METHOD AND RESULTS

We consider FS transitions in the ground state multiplet of atoms and/or ions and illustrate results for the \( ^2P_j \) multiplet of the C II ion. In this case there is only one FS line \( ^2P_{3/2} \to ^2P_{1/2} \) at wavelength \( \lambda = 157.7409(1) \) \(\mu\)m (the corresponding frequency 1900.5369(13) GHz is given in Cooksy et al. 1986).

For reference we use the atomic hydrogen \( \text{H}_2 \) transition \((n = 4 \to n = 2)\) at vacuum wavelength \( \lambda = 4862.721(1) \) \(\AA \), which is recommended in the Sloan Digital Sky Survey [2]

[C II] emission arises predominantly from the warm neutral regions between the dense molecular clouds and \( \text{H}_2 \) regions and, thus, its distribution is confined to the optical disks of galaxies. Observations with high spatial resolution of \( \text{H}_2 \) regions in the nearby galaxy M33 show that the radial velocities of the [C II] and \( \text{H}_2 \) emitting clouds appear to match each other with an offset of a few \( \text{km s}^{-1} \) (e.g., Braine et al. 2012; Mookerjea et al. 2016). From this, we might expect that global velocity profiles of hydrogen Balmer and [C II] lines integrated over whole disks of high-redshift galaxies tend to match each other as well. However, any other atomic transitions, which trace the spatial distribution of C II, can be utilized as well. We note that numbers in parentheses in the wavelength values correspond to an error at the last digit. Converted into velocity scale these errors are equal to \( \sigma_v \) (C II) = 0.19 km s\(^{-1}\) and \( \sigma_v \) (H\(_β\)) = 0.06 km s\(^{-1}\).

The non-relativistic atomic energy differences (the gross structure) and the relativistic corrections due to the spin-orbit interaction (the fine-structure) are proportional to \( \alpha^2 \) and \( \alpha^4 \), respectively (e.g., Sobelman 1979). This means that the ratio of the frequencies of the fine-structure splitting to the optical transition is proportional to the fine-structure constant squared.

If \( \omega_{\nu_{\lambda_{\mathrm{ss}}}} \) is the frequency of the fine-structure splitting,
and \( \omega_{\beta}, \omega_{\alpha} \) is the frequency of the hydrogen H\(_{\beta} \) line, and \( \alpha_{\pm} \) is the value of the fine-structure constant at redshift \( z \), then

\[
\frac{\omega_{\beta} \omega_{\alpha}}{\omega_{\underline{\beta}} \omega_{\underline{\alpha}}} = \left( \frac{\alpha_{+}}{\alpha_{-}} \right)^2 \approx 1 + 2 \frac{\Delta \alpha}{\alpha},
\]

where \( \omega_{\beta}, \omega_{\alpha}, \) and \( \alpha \) are the present-day values, and \( \Delta \alpha = \alpha_{+} - \alpha_{-} \). Here we assume that \( |\Delta \alpha/\alpha| < 1 \).

If \( \Delta \alpha \neq 0 \) and \( \omega_{\underline{\beta}}, \omega_{\underline{\alpha}} \) are the observed frequencies from a distant object, then the apparent redshifts of the FS and H\(_{\beta} \) lines are given by

\[
1 + z_1 = \frac{\omega_{\beta}}{\omega_{\underline{\beta}}},
\]

and

\[
1 + z_2 = \frac{\omega_{\alpha}}{\omega_{\underline{\alpha}}}. \tag{2}
\]

Substituting equations 2 and 3 into equation 1 and carrying out the straightforward algebra, we find

\[
\frac{\Delta \alpha}{\alpha} = \frac{\Delta z}{2(1 + z)} = \frac{\Delta V}{2c}, \tag{4}
\]

where \( z \) is the mean redshift, \( \Delta z = z_2 - z_1 \), \( c \) is the speed of light, and \( \Delta V = V_\beta - V_\alpha \) is the velocity offset. Here we assume that \( |\Delta z| < 1 \).

Equation (4) shows that the key point in probing \( \Delta \alpha/\alpha \) is the accurate determination of the radial velocity offset between emission lines of two elements which should trace closely each other. If both line centers are measured with the same uncertainty \( \sigma_\alpha \), then the error of the offset \( \Delta V \) is

\[
\sigma_{\Delta V} = \sqrt{\frac{2}{\Delta z}} \sigma_\alpha,
\]

which gives the error \( \sigma_{\Delta \alpha/\alpha} \) of the fractional change in \( \alpha \):

\[
\sigma_{\Delta \alpha/\alpha} = \sigma_\alpha / (\sqrt{2} \Delta z). \tag{5}
\]

If the quoted above accuracy level for these lines (\( \sigma_\alpha < 0.2 \text{ km s}^{-1} \)) is the only source of uncertainties in the line centers, then the limiting sensitivity of the FST method for the combination of the [C\text{ii}] 158 \mu m and H\(_{\beta} \) lines is

\[
\sigma_{\Delta \alpha/\alpha} \lesssim 5 \times 10^{-7}. \tag{6}
\]

Of course, in real observations, the measurement error is larger.

To illustrate the FST method, we consider a limit on \( \Delta \alpha/\alpha \) towards a dusty star-forming galaxy embedded in a giant Ly-\( \alpha \) blob (LAB) at \( z = 3.1 \) where strong [C\text{ii}] 158 \mu m and H\(_{\beta} \) emission lines were recently detected by Umehata et al. (2017), and Kubo et al. (2015), respectively. This galaxy, called LAB1-ALMA3, was discovered in the ALMA dust continuum survey at 850 \mu m (Geach et al. 2016).

According to Umehata et al. (2017), the velocity offset between the [C\text{ii}] 158 \mu m and H\(_{\beta} \) lines is within \( \sim 50 \text{ km s}^{-1} \) and the two measurements are consistent within errors (the corresponding channel widths were \( \sim 80 \text{ km s}^{-1} \) for both observations). The lines are reported at redshifts \( z(\text{C}\text{ii}) = 3.0993(4) \), and \( z(\text{H}_{\beta}) = 3.1000(3) \), and thus their position errors are \( 30 \text{ km s}^{-1} \) and \( 23 \text{ km s}^{-1} \), respectively. If we consider the velocity offset of 50 km s\(^{-1}\) as caused by the Doppler noise (see Sect. 3), then the limit on \( \Delta \alpha/\alpha \) is defined by the line position errors which give \( |\Delta \alpha/\alpha| < 6 \times 10^{-5} \).

Other high-redshift objects, where both hydrogen and [C\text{ii}] emission lines were detected, are the galaxies Ly-\( \alpha \) and Ly-\( \beta \), and a sub-millimeter galaxy – companions of the quasar BR 1202-0725 at \( z = 4.7 \) (Wagg et al. 2012; Carilli et al. 2013; Williams et al. 2014). The narrowest [C\text{ii}] 158 \mu m profile with an FWHM \( \sim 56 \text{ km s}^{-1} \) was observed towards the Ly-\( \alpha \) object, yielding a redshift \( z = 4.6950(3) \). The comparison of the hydrogen Ly-\( \alpha \) profile with that of [C\text{ii}] 158\mu m shows that their peak positions are slightly shifted with respect to each other by \( \Delta V = 49 \text{ km s}^{-1} \). Again, assuming that this shift is due to the Doppler noise and that the uncertainty of \( \Delta V \) is of the same order as in the previous case, one obtains \( |\Delta \alpha/\alpha| \lesssim 6 \times 10^{-5} \).

3 DISCUSSION AND CONCLUSION

The application of the FST method based on different species may yield a biased estimate of \( \Delta \alpha/\alpha \) if the velocity distribution of these species in the same galaxy is different. Random Doppler shifts of global velocity profiles (integrated spectra) caused by non-identical spatial distributions of tracers can mimic non-zero signals in \( \Delta \alpha/\alpha \). This so-called Doppler noise (e.g., Levshakov et al. 2008) may become a problem when the accuracy of the line position measurements is increased.

In local disk galaxies the H\(_1\) disk, traced by the hydrogen 21 cm emission, typically extends significantly beyond the main stellar disk. On the other hand, the ionized carbon [C\text{ii}] is observed throughout the ISM and the [C\text{ii}] emission is usually enhanced at the edges of molecular clouds in the photodissociation regions. C\text{ii} can be excited by collisions with electrons, neutral H\(_1\) atoms and molecular H\(_2\) and because of the low ionization potential of carbon (11.26 eV versus 13.60 eV for hydrogen), the [C\text{ii}] 158 \mu m line arises both from ionized and neutral gas, thus tracing most of the phases of the ionized and atomic ISM (e.g., Pineda et al. 2013; Kaufman et al. 1999). But these are the regions of enhanced hydrogen Balmer lines as well. A co-spatial distribution of the [C\text{ii}] emission with regions seen in H\(_\alpha\) emission are known to be observed in some dwarf galaxies (e.g., Cigan et al. 2016). This tendency might be expected since both the H\(_\alpha\) and [C\text{ii}] emission is generally confined to the optical disks of galaxies (e.g., de Blok et al. 2016). Thus, we may suppose a close correlation between the [C\text{ii}] 158 \mu m and H\(_{\beta}\) spatial distributions over the surface of distant galaxies as well. We can also expect that the value of the Doppler noise for the global velocity profiles of the [C\text{ii}] 158 \mu m and H\(_{\beta}\) emission lines does not exceed a few \( \text{km s}^{-1} \) which is less than the current error of the line position measurement, \( \sigma_\alpha \approx 20 - 30 \text{ km s}^{-1} \) (see Sec. 2).

As for the hydrogen Ly-\( \alpha \) line, it should be noted that at high redshifts its blue wing may suffer from some intergalactic medium attenuation which causes the Ly-\( \alpha \) centroid to be artificially redshifted. Besides, additional uncertainties in interpreting differences among profiles may appear if different components of distant sources had different values of internal dust extinction. Velocity offsets between emission lines relative to Ly-\( \alpha \) were found by several authors (e.g., Stark et al. 2017; Erb et al. 2014). From this point of view the mid-infrared and far-infrared atomic transitions are more preferable as reference lines in probing \( \Delta \alpha/\alpha \). In any case to quantify uncertainties induced by the Doppler noise a sample of \( \Delta \alpha/\alpha \) measurements is needed.

To conclude we note that the current spectral observations of the dusty star-forming galaxy LAB1-ALMA3 at \( z = 3.1 \), and the Ly-\( \alpha \) galaxy at \( z = 4.7 \) reveal no evidence or a variability of \( \alpha \) and constrain the value of \( \Delta \alpha/\alpha \) at the level of \( 6 \times 10^{-5} \).
ACKNOWLEDGEMENTS

We thank our referee Christian Henkel for valuable comments and suggestions that improved the paper.

REFERENCES

Agafonova I. I., Molaro P., Levshakov S. A., Hou J. L., 2011, A&A, 529, 28
Aravena M., Decarli R., Walter F., et al., 2016, ApJ, 833, 153
Bahcall J. N., Steinhardt C. L., Schlegel D., 2004, ApJ, 600, 520
Bahcall J. N., Sargent W. L. W., Schmidt M., 1967, ApJ, 149, L11
Bahcall J. N., Schmidt M., 1967, PhRvL, 19, 1294
Bahcall J. N., Salpeter E. E., 1965, ApJ, 142, 1677
Bonifacio P., Rahmani H., Whitmore J. B., et al., 2014, Astron. Nachrichten, 335, 83
Braine J., Gratier P., Kramer C., et al., 2012, A&A, 544, A55
Capak P. L., Carilli C., Jones G., et al., 2015, Nature, 522, 455
Carilli C. L., Riechers D., Walter F., et al., 2013, ApJ, 763, 120
Carniani S., Maiolino R., Pallottini A., et al., 2017, arXiv:1701.03468
Cigan P., Young L., Cormier D., et al., 2016, AJ, 151, 14
Cooksy A. L., Blake G. A., Saykally R. J., 1986, ApJL, 305, L89
Davis E. D., Hamdan L., 2015, PhRvC, 92, 014319
de Blok W. J. G., Walter F., Smith J.-D. T., et al., 2016, AJ, 152, 51
Dzuba V. A., Flambaum V. V., Webb, J. K., 1999a, PhRvA, 59, 230
Dzuba V. A., Flambaum V. V., Webb, J. K., 1999b, PhRvL, 82, 888
Erb D. K., Steidel C. C., Trainor R. F., et al., 2014, ApJ, 795, 33
Evans T. M., Murphy M. T., Whitmore J. B., et al., 2014, MNRAS, 445, 128
Gao H., Wu X. F., Mészárös P., 2015, ApJ, 810, 121
Geach J. E., Narayanan D., Matsuda Y., et al., 2016, ApJ, 832, 37
Godun R. M., Nisbet-Jones P. B. R., Jones J. M., et al., 2014, PhRvL, 113, 210801
Huang Y., Guan H., Liu P., et al., 2016, PhRvL, 116, 013001
Huntemann N., Sanner C., Lipphardt B., Tamm C., Peik E., 2016, PhRvL, 116, 063001
Iono D., Yun M. S., Elvis M., et al., 2006, ApJ, 645, L97
Kaufman M. J., Wolfire M. G., Hollenbach D. J., Luhman, M. C., 1999, ApJ, 527, 795
Knuelsen K. K., Watson D., Frayer D., et al., 2017, MNRAS, 466, 138
Knuelsen K. K., Richard J., Kneib J.-P., et al., 2016, MNRAS, 462, L6
Kostelecky V. A., Lehnert R., Perry M. J., 2003, PhRvD, 68, 123511
Kozlov M. G., Porsey S. G., Levshakov S. A., et al., 2008, PhRvA, 77, 032119
Kubo M., Yamada T., Ichikawa T., et al., 2015, ApJ, 799, 38
Leite A. C. O., Martins C. J. A. P., Molaro P., Corre D., Cristiani S., 2016, arXiv:1612.03281
Levshakov S. A., Combes F., Boone F. et al., 2012, A&A, 540, L9
Levshakov S. A., Reimers D., Kozlov M. G., et al., 2008, A&A, 479, 719
Levshakov S. A., Centurión M., Molaro P., et al., 2006, A&A, 449, 879
Levshakov S. A. 1994, MNRAS, 269, 339
Levshakov, S. A., 1992, in High Resolution Spectroscopy with the VLT, ed. M.-H. Ulrich, ESO: Garching/Munchen, p. 139
Liberati S., 2013, Class. Quant. Grav., 30, 133001
Maiolino R., Carniani S., Fontana A., et al., 2015, MNRAS, 452, 54
Maiolino R., Cox P., Caselli P., et al., 2005, A&A, 440, L51
Molaro P., Centurión M., Whitmore J. B., et al., 2013, A&A, 555, A68
Moookerjea B., Israel F., Kramer C., et al., 2016, A&A, 586, A37
Nemitz N., Ohkubo T., Takamoto M., et al., 2016, Nat. Photonics, 10, 258
Nicholson T. L., Campbell S. L., Hutson R. B., et al., 2015, Nat. Comm., 6, 6896
Nisbet-Jones P. B. R., King S. A., Jones J. M., et al., 2016, Applied Phys. B, 122, 57
Pavesi R., Riechers D. A., Capak P. L., et al., 2016, ApJ, 832, 151
Petitjean P., Wang F. Y., Wu X. F., Wei J. J., 2016, Sp-ScRv, 202, 195
Pineda J. L., Langer W. D., Velusamy T., Goldsmith P. F., 2013, A&A, 554, A103
Quast R., Reimers D., Levshakov S. A., 2004, A&A, 415, L7
Riechers D. A., Carilli C. L., Capak P. L., et al., 2014, ApJ, 796, 84
Rosenband T., Hume D. B., Schmidt P. O., et al., 2008, Science, 319, 1808
Savdoff M. P., 1956, Nature, 176, 688
Sobelman I. I., 1979, Atomic spectra and radiative transitions, Springer-Verlag, Berlin
Stark D. P., Ellis R. S., Charlot S., et al., 2017, MNRAS, 464, 469
Tyumenev R., Favier M., Bliciki S., et al., 2016, NJPh, 18, 113002
Umehata H., Matsuda Y., Tamura Y., et al., 2017, ApJ, 834, L16
Venemans B. P., McMahon R. G., Walter F., et al., 2012, ApJL, 751, L25
Wagg J, Wiklind T., Carilli C. L., et al., 2012, ApJ, 752, L30
Wei J. J., Wang J. S., Gao H., Wu X. F., 2016, ApJ, 818, L2
Wei J. J., Gao H., Wu X. F., Mészárös P., 2015, PhRvL, 115, 261101
Weiß A., Walter F., Downes D., et al., 2012, ApJ, 753, 102
Whitmore J. B., Murphy, M. T., 2015, MNRAS, 447, 446
Williams R. J., Wagg J., Maiolino R., et al., 2014, MNRAS, 439, 2096
Willoct C. J., Carilli C. L., Wagg J., Wang R., 2015, ApJ,
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807, 180