

A NEW COSMOLOGICAL DISTANCE MEASURE USING AGN

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ABSTRACT

Accurate distances to celestial objects are key to establishing the age and energy density of the Universe and the nature of dark energy. A distance measure using active galactic nuclei (AGN) has been sought for more than forty years, as they are extremely luminous and can be observed at very large distances. We report here the discovery of an accurate luminosity distance measure using AGN. We use the tight relationship between the luminosity of an AGN and the radius of its broad line region established via reverberation mapping to determine the luminosity distances to a sample of 38 AGN. All reliable distance measures up to now have been limited to moderate redshift—AGN will, for the first time, allow distances to be estimated to $z \sim 4$, where variations of dark energy and alternate gravity theories can be probed.

Subject headings: distance scale — cosmological parameters — cosmology: observations — quasars: general — galaxies: Seyfert

1. INTRODUCTION

One of the simplest and, perversely, most intractable problems in astronomy has been to discover how far away something is. New distance measures have led to fundamental changes in our understanding of the Universe; for example Tycho Brahe’s supernova and Edwin Hubble’s Cepheids radically reshaped our understanding of the cosmos. It is almost two decades since type Ia supernovae (SNe) were shown to be accurate standard candles (Phillips 1993). That distance measure led directly to the discovery of the acceleration of the Universe and dark energy (Riess et al. 1998; Perlmutter et al. 1999). Finding reliable methods to determine distances, especially large distances in the Hubble flow, is an ongoing task. In particular, reliable distances beyond redshift $z \sim 1.7$ are beyond the scope of current tools. Investigating the evolution of the dark energy equation of state has therefore been very limited up to now. Since their discovery over four decades ago it has been hoped that quasars, or the more general class of active galactic nuclei (AGN) of which quasars are a subset, could be used as standard candles for cosmology. Many attempts were made (Baldwin 1977; Collier et al. 1999; Elvis & Karovska 2002; Marziani et al. 2003), none very successful. However, recent advances in our understanding of AGN, which are extremely luminous, common, and readily observable over a range of distances from ~ 10 Mpc to $z > 7$, prompted us to investigate their use as standard candles for cosmology.

Here we examine the possibility of using the relationship between the luminosities of type 1 AGN and the sizes of their broad-line regions established via reverberation mapping as a luminosity distance indicator. In section 2 we describe our methods, in section 3 we detail the data used. In section 4 we provide the results of our analysis and the sources of scatter in the relation. Section 5 contains a discussion on the prospects for this new distance measure, its competitiveness and unique features. Uncertainties quoted are at the 68% con-

fidence level. A cosmology where $H_0 = 70.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.725$ and $\Omega_m = 0.275$ is assumed throughout.

2. METHOD

2.1. Broad-line region reverberation mapping

The supermassive black hole that lies at the heart of every AGN and is its ultimate power source, is surrounded at a distance by high velocity gas clouds that produce the broad emission lines characteristic of the spectra of near-face-on AGN, i.e. quasars and Seyfert 1 galaxies. It has been known for some time that there is a relationship between the size of this broad-line emitting region (BLR) and the AGN’s central continuum luminosity (Kaspi et al. 2000, 2005; Bentz et al. 2009a). The size of the BLR is determined by the depth to which the surrounding gas can be photo-ionised by the central source. Since the ionising flux drops with distance according to the inverse square law, the radius of the BLR, r , is expected to be proportional to the square root of the luminosity, \sqrt{L} (McKee & Tarter 1975). Establishing r and the flux would clearly lead to a measure of the luminosity distance to the source.

The photons emitted by BLR gas are reprocessed continuum photons. Therefore, the flux in the broad lines varies in response to variations in the luminosity of the central source with a time-delay, τ , governed simply by the light travel time, $\tau = r/c$. Measuring the time delay thus allows a determination of the BLR radius, a technique known as ‘reverberation mapping’ (Blandford & McKee 1982; Peterson 1993). The radius is effectively determined by measuring the time lag between changes in the continuum luminosity of the AGN and the luminosity of a bright emission line (typically H β or C IV). The time lag should therefore be proportional to the square root of the luminosity of the central source: $\tau \propto \sqrt{L}$. The observable quantity, τ/\sqrt{F} , where τ is the emission line lag and F is the measured AGN continuum flux, is then a measure of the luminosity distance to the source.

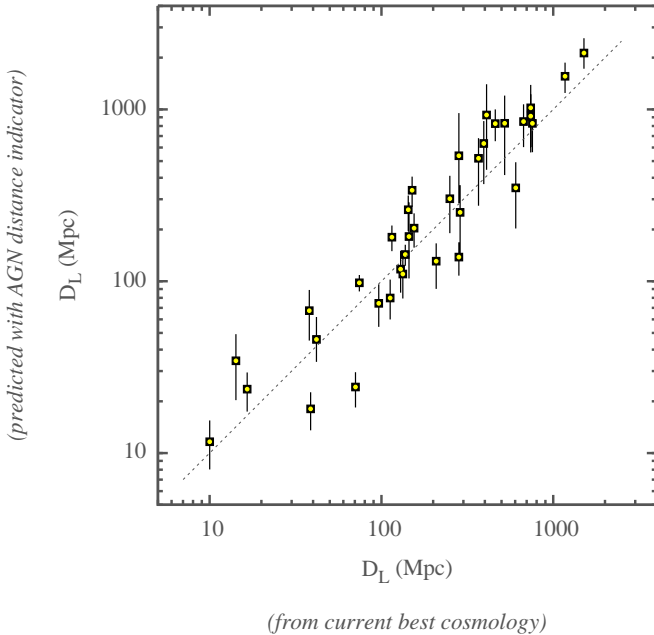


FIG. 1.— Comparison of AGN-derived distances to Hubble distances based on the best current cosmology (Komatsu et al. 2011). The dotted line is the equality of both distances. The AGN distance estimates follow the best current cosmology Hubble distances to good accuracy

Recent improvements in lag and luminosity measurements, notably, improving the luminosities by removing the contaminating effects of the host galaxy (Bentz et al. 2009a), improving lag measurements by reobserving AGN that previously had poorly-sampled lightcurves (Denney et al. 2010), and populating the low luminosity regime of the existing sample (Bentz et al. 2009b), have shown that the radius-luminosity relationship follows the expected $r \propto \sqrt{L}$ relation to good accuracy across four orders of magnitude in luminosity (Bentz et al. 2009a; Zu et al. 2011). We have used this relationship to turn a sample of AGN with well-determined lags into standard candles for cosmology.

3. OBSERVATIONAL DATA

To construct our sample of τ/\sqrt{F} values, we use all available lags for the $H\beta$ line and restframe 5100 Å continuum fluxes (Bentz et al. 2009a; Denney et al. 2010), where these measurements have the constant host galaxy component removed from the measured flux to obtain the AGN continuum flux. This host galaxy removal has been shown to be very important (Bentz et al. 2009a) and is done primarily using images from the *Hubble Space Telescope* (*HST*) to model the underlying galaxy contribution. We correct the fluxes for Galactic extinction (Schlegel et al. 1998; Schlafly et al. 2010). We do not apply a correction for internal extinction because extinction estimates have been made for only a fraction of the objects in our sample and typically the discrepancy between estimates in a single object are as large as the extinction correction itself (see below for a more detailed discussion of intrinsic extinction correction). We then calibrate τ/\sqrt{F} to the absolute distance for the source NGC 3227 (Tonry et al. 2001; Krisciunas et al. 2004). Fig. 1 shows that the luminosity distances we determine for our sample closely follow the predicted distances for the current best-estimated *WMAP*- Λ CDM cosmology (Komatsu et al. 2011).

3.1. The absolute distance calibration

TABLE 1
SCATTER IN THE AGN HUBBLE DIAGRAM

Source of scatter ^a	Current	Can be reduced to
Observational	0.14 (0.36)	0.05 (0.13)
Extinction	0.08 (0.20)	0.04 (0.10)
Bad lags	0.11 (0.28)	0.00 (0.00)
Other	0.05 (0.13)	0.05 (0.13)
Total	0.20 (0.50)	0.08 (0.20)

^aRoot mean square scatter in dex (mag)

Currently only NGC 3227 and NGC 4051 have direct distance estimates. The Tully-Fisher distance to NGC 4051 is the less accurate of the two. We therefore calibrated τ/\sqrt{F} to the luminosity distance to the galaxy NGC 3227 based on a distance modulus of $m-M = 31.86 \pm 0.24$ determined using the surface brightness fluctuations (SBF) method to its companion galaxy NGC 3226 (Tonry et al. 2001). Due to the occurrence of a supernova, 2002bo, in another member of the Leo III group to which NGC 3227 belongs, the SBF distance quoted above has been examined in detail and seems likely to be correct within the quoted uncertainty (Krisciunas et al. 2004). However, the uncertainty in this calibration is relatively large, and we use it here only to determine an initial estimate of the luminosity distances. NGC 4051, NGC 4151, and NGC 3227 are certainly close enough that it should be possible to obtain more reliable Cepheid-derived distances with *HST* to these galaxies for a better absolute calibration. In practice, we expect that Cepheid distances can in fact be determined to multiple nearby AGN, allowing at least a dozen AGN to be distance-calibrated in this way.

4. RESULTS

4.1. How tight is the relation?

In order to be a successful distance indicator, τ/\sqrt{F} must follow the luminosity distance with little inherent scatter. We estimate below the different sources of scatter in the relation with the current data and determine how far this scatter can be reduced in the immediately foreseeable future. This is summarised in Table 1.

We have estimated the root mean square scatter in our AGN Hubble diagram (Fig. 2) to be 0.2 dex, equivalent to 0.5 mag in distance modulus. Based on the expectation of a reduced χ^2 value of unity, we have determined the observational uncertainty to account for $\sim 50\%$ of the total scatter in the relation, or 0.14 dex (0.36 mag).

4.1.1. Scatter due to observational uncertainty

The scatter due to observational uncertainty can be reduced significantly. A major advantage held by AGN is that they can be observed repeatedly and the distance to any given object substantially refined. For example, the observational uncertainty for NGC 5548 is 0.05 dex (0.13 mag) after roughly a dozen reverberation measurements, while it is typically ~ 0.14 dex (0.35 mag) for sources with single measurements. In Fig. 3 we show τ/\sqrt{F} from all observing campaigns of NGC 5548. The reduced χ^2 is very close to unity for a constant value fit to the data, indicating that the scatter is almost entirely accounted for by the uncertainty related to the observations. There is thus very little intrinsic variation in τ/\sqrt{F} for a given object. This means that repeated observations of

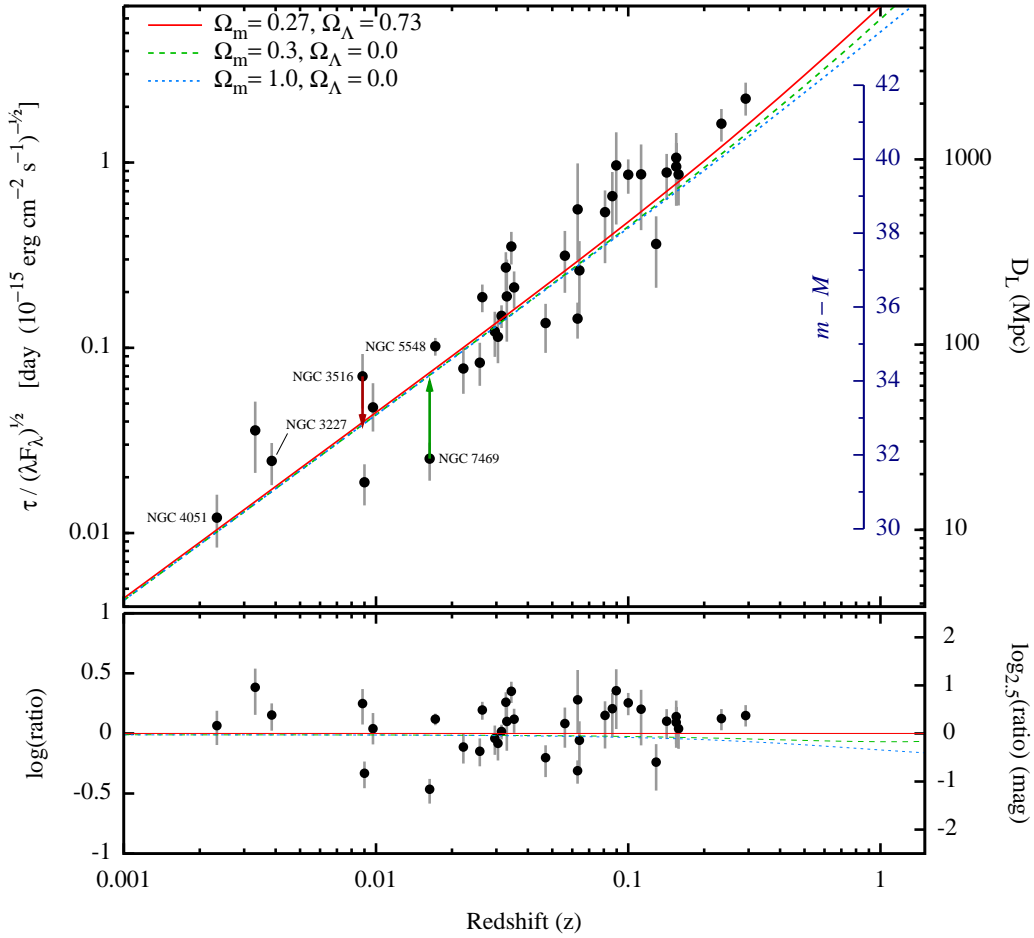


FIG. 2.— The AGN Hubble diagram. The luminosity distance indicator τ/\sqrt{F} is plotted as a function of redshift for 38 AGN with $H\beta$ lag measurements. On the right axis the luminosity distance and distance modulus ($m-M$) are shown using the surface brightness fluctuations distance to NGC 3227 as a calibrator. The current best cosmology (Komatsu et al. 2011) is plotted as a solid line. The line is not fit to the data but clearly follows the data well. Cosmologies with no dark energy components are plotted as dashed and dotted lines. The lower panel shows the logarithm of the ratio of the data compared to the current cosmology on the left axis, with the same values but in magnitudes on the right. The red arrow indicates the correction for internal extinction for NGC 3516. The green arrow shows where NGC 7469 would lie using the revised lag estimate from Zu et al. (2011). NGC 7469 is our largest outlier and is believed to be an example of an object with a misidentified lag (Peterson 2010).

given sources will reduce the scatter related to observational uncertainty to a level similar to that observed in NGC 5548.

4.1.2. Extinction

Another likely source of scatter is due to extinction associated with the AGN and its host galaxy. As an example, in Fig. 2 we plot the shift in τ/\sqrt{F} resulting from the extinction correction for NGC 3516 (Denney et al. 2010). This shift moves NGC 3516 very close to the best-fit line. Currently, few reliable extinction measurements exist for these AGN. We show the extinction correction for NGC 3516, in Fig. 2, however, because it may be reliable as it is based on two different extinction estimations with different methods that give consistent results (Denney et al. 2010). An accurate correction for internal extinction should reduce the scatter in the Hubble diagram. A mean scatter of ~ 0.16 dex (0.4 mag) as suggested by Cackett et al. (2007), induced in the luminosities of these AGN by internal extinction, would contribute 0.08 dex (0.2 mag) scatter to the relationship. Using the Balmer decrement method, Na I D or K I line equivalent widths, or a calibration based on several methods, we would then expect to be able to reduce the scatter induced by extinction from 0.08 dex (0.2 mag) to the level at which these correlations are calibrated, 0.04 dex (0.1 mag) (Munari & Zwitter 1997).

Adding an extinction correction will of course systematically make the distances smaller, but since the objects are currently calibrated to the distance to NGC 3227, it is the extinction relative to this object that matters. Currently we assume that the extinction of NGC 3227 is reasonably close to the mean extinction of the sample. The fact that the distances are not noticeably offset from the distances based on current best estimates of H_0 (Fig. 1) suggests that this is a reasonable assumption.

4.1.3. Incorrect Lags

The scatter due to an apparent diversity between objects can also be rapidly reduced. While we use all available $H\beta$ lag detections with published host-corrected AGN fluxes here to avoid biasing our results, it has been shown (Peterson 2010) that with selection of only good quality lag measurements, the scatter in the observed radius-luminosity relation can be reduced to a level almost consistent with the observational uncertainty. This suggests that some of the lag measurements currently in use are incorrect at a level much larger than their quoted uncertainties. This may in part be due to developing observational expertise, where later lag measurements benefitted from improved observing practices, e.g. better-sampled lightcurves. NGC 7469 alone contributes 0.09 dex (0.22 mag)

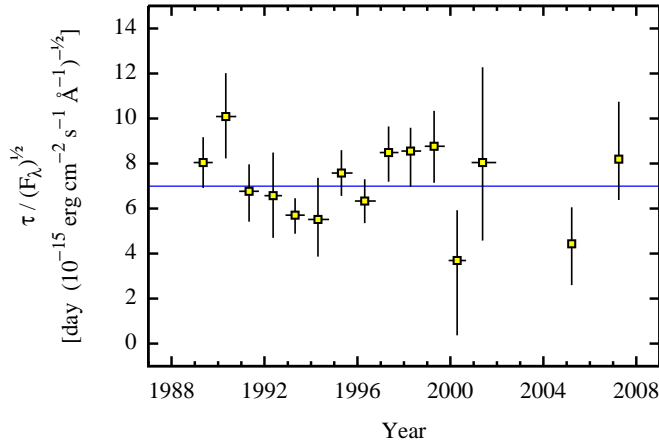


FIG. 3.— The distance indicator for NGC 5548, the best observed AGN in our sample, showing that the indicator is constant over time. The scatter in the data is consistent with the statistical uncertainty, showing that the scatter in excess of the observational uncertainty in the AGN Hubble diagram is largely due to object-to-object variations

to the total scatter. The lags of most of our objects were recalculated by Zu et al. (2011) using the stochastic process estimation for AGN reverberations (SPEAR) method. The only object with a significantly discrepant lag they found was NGC 7469. A more recent observation of this source (C. Grier, private communication) has also given a value of τ/\sqrt{F} consistent with the SPEAR value (Zu et al. 2011). Using the SPEAR value for its lag (see Fig. 2) the scatter in the diagram is reduced to 0.18 dex (0.45 mag), and the reduced χ^2 drops from 4.0 to 2.9. A small number of misidentified lags can contribute a very large fraction of the scatter in excess of the observational uncertainty and should easily be spotted and removed with multiple observations of the same source.

We have noted above how an observational error contribution to the total scatter of ~ 0.05 dex (0.12 mag) or less is achievable with multiple observations of each source. In addition, correcting NGC 7469 alone is enough to reduce the component of the scatter unrelated to observational uncertainty from 0.14 dex (0.36 mag) to 0.11 dex (0.28 mag). Choosing only good lags improves the scatter in excess of the observational uncertainty to a level consistent with the extinction-related scatter estimated above (Peterson 2010). With many more good quality observations it therefore seems likely that the scatter unrelated to observational uncertainty will be reduced to a level dominated by the uncertainty in the extinction correction, ~ 0.04 dex (0.1 mag, see above). With these improvements, the total known scatter in the relationship could therefore be reduced to 0.06 dex (0.16 mag), dominated by the extinction correction and observational uncertainties (see Table 1).

Given these straightforward improvements in the statistical quality of the measurements via an increased number of observations per source, more reliable lags, and better extinction estimates, the scatter in the AGN Hubble diagram can be decreased very substantially with medium-sized programmes on existing facilities in only a few years. Based on the arguments made above we estimate that the total scatter in the relationship could, in a few years observing, be reduced to 0.08 dex (0.20 mag, see Table 1), not far in excess of the current SNIa samples (Kessler et al. 2009; Conley et al. 2011).

5. DISCUSSION

5.1. Prospects for extension to high redshift

The unique aspect of the AGN Hubble diagram is that while SN distances are currently observationally restricted to less than $z \sim 1.7$ (Riess et al. 2001), and are unlikely to exceed $z = 2$, there is no such impediment to extending the AGN diagram to the redshift range $z = 0.3-4$, where the power to discriminate dark energy models lies. Effects related to changes with time in the equation of state of dark energy or to alternate gravity theories should be more apparent with higher redshift data and can only be constrained very poorly with current methods. We already know that the radius-luminosity relationship holds in an unaltered form over four decades in luminosity (Kaspi et al. 2000; Bentz et al. 2009a; Zu et al. 2011). We have no reason to believe that it should change with redshift either, as its form is based strictly on the simplest photo-ionization physics.

In practice, extending the diagram to high redshifts requires substantially longer temporal baselines: 1) redshift increases the observed-frame lags due to time dilation effects, 2) at higher redshift we observe more luminous AGN, which have larger BLRs and hence larger rest-frame lags. For example, for a redshift $z \sim 2$ AGN, we expect a $H\beta$ observed lag of ~ 2 years based on the AGN Hubble diagram and assuming an observed continuum flux of $1 \times 10^{17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ at a rest-frame wavelength of 5100 \AA . For $H\beta$ the likely minimum time required to obtain a lag reaches close to a decade at $z \sim 2.5$, making this the practical redshift limit for obtaining lags with $H\beta$. On the other hand, strong UV lines such as C IV 1549 \AA are readily observable even for the most distant known AGN. Since the BLR is ionization-stratified (Dietrich et al. 1993), higher excitation lines such as C IV have the advantage that they are emitted closer to the central source and hence have shorter lag times. And it is worth noting that a detection of a lag at $z \sim 2$ has already been made using C IV (Kaspi et al. 2007). For C IV, the lags are typically shorter than $H\beta$ by a factor of 2–3 (Clavel et al. 1991), meaning that C IV lags should be measurable for objects up to $z \sim 4$. It has been shown that the N V 1240 \AA line has an even shorter lag time than C IV, by another factor of 2–3 (Clavel et al. 1991), allowing lag measurements to be made in principle to $z \sim 6$. But disentangling the N V flux from $\text{Ly}\alpha$ may not be straightforward, and we do not believe that distance measurements are currently feasible with available facilities beyond $z \sim 4$. Using the C IV line as a lag estimator has the added advantage that no host galaxy subtraction needs to be made, thus reducing the flux uncertainty further, somewhat improving our accuracy at high redshift. It is worth noting as well that higher redshift sources require roughly the same total number of observations to obtain a lag measurement as lower redshift sources, but spread over a longer time. This means that, counter-intuitively, high-redshift campaigns are less resource intensive in a given observing semester.

5.2. Absolute distances

The AGN Hubble diagram, like SNe Ia, currently requires calibration to absolute distances. Our developing understanding of the radius-luminosity relation for the BLR means that direct determination of H_0 may be possible with AGN, though via a different avenue than previously imagined (e.g. Collier et al. 1999; Cackett et al. 2007). With direct observations of the densities and structures of BLRs, the $H\beta$ or C IV radius may be obtained from first principles, ultimately obviating the need for the distance ladder in determining cosmological distances. While currently we have no means to directly deter-

mine the densities in the BLR, we do have methods (Horne 1994) to begin to dissect the BLR structure using velocity-resolved time lags (Denney et al. 2009) and velocity delay maps (Bentz et al. 2010), and future work may reveal density diagnostics for the BLR.

5.3. Intrinsic diversity between objects

The ultimate limit of the accuracy of the method will rely on how the BLR responds to changes in the luminosity of the central source. The current tight radius-luminosity relationship indicates that the ionisation parameter and the gas density are both close to constant across our sample. Where the ionisation parameter is $U \propto L/(n_e r^2)$, with L being the luminosity of the source, n_e the electron density and r the distance between the source and the gas. That the ionisation parameter might be constant is not unexpected based on the locally optimally-emitting cloud model (Baldwin et al. 1995). However, the mechanism that keeps the density at close to the same value in a given region of the BLR, across sources, and for a wide range of luminosities, is unclear. Precisely how constant the density is, seems likely to be the factor ultimately limit-

ing the accuracy of the AGN Hubble diagram if the extinction correction can be perfected. Now and for the foreseeable future, however, observational uncertainty, misidentified lags, and extinction dominate the scatter in the diagram.

5.4. Accuracy and competitiveness

The AGN Hubble diagram seems likely to be competitive with the best current distance indicator at moderate redshifts within a decade. The facilities required up to $z \sim 1.5$ are only small ground-based telescopes with low-resolution spectrographs. At higher redshifts, where it is the only distance measure, moderate aperture telescopes and years of monitoring will be required to obtain lags for a significant number of sources. However, if experiments of the scale currently being employed for cosmography are applied to the AGN Hubble diagram, constraints competitive with the best current methods should be achievable in less than a decade at redshifts up to $z = 3$.

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