A massive disk galaxy at \( z > 3 \) along the sightline of QSO 1508+5714*†

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Abstract

We have obtained deep images in the \( BVRIJHKs \) bands of the field centered on QSO 1508+5714 (\( z_{\text{em}} = 4.28 \)) with the Suprime camera, FOCAS and MOIRCS cameras on Subaru telescope. We report here the detection of a B-dropout galaxy, which is 3''5 north-west of the QSO sightline. A photometric redshift analysis is presented to complement the color selection. Given the photometric properties of this object (\( M = -22.2 \), making \( L \approx 3L^* \), if placed at its photometric redshift \( z \sim 3.5 \)), as well as the Sérsic index (\( n \sim 1 \)) derived from a 2-D imaging decomposition of the HST WFPC2 image taken in the \( I_{F814} \) filter, the identified system is consistent with a massive disk galaxy at \( z > 3 \). If confirmed, it would be one of the most distant massive disk galaxies known so far.

Key words: galaxies: formation–intergalactic medium–galaxies: high redshift–quasars: individual: 87GB 1508+5714

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1. Introduction

Based on the cold dark matter theory, the models of “hierarchical formation” give a step-wise process in which small objects merge, inducing bursts of star formation that create different types of massive and bright galaxies which we see today (Searle et al. 1978). In contrast, the monolithic models suggest a top-down formation scenario assuming that stars form through a direct collapse of a large gas cloud, and flatten over time as the gas cools (Eggen et al. 1962).

According to hierarchical galaxy formation models, galactic sizes should grow with time, and massive disk galaxies were formed at $z \lesssim 1$ (Fall & Efstathiou 1980; Mo, Mao & White 1998). To place tight constraints on the galaxy formation scenario, observational studies of high redshift galaxies on the size, morphology, stellar mass and age et al. have been carried out over the past decade (Vogt et al. 1996; Lilly et al. 1998; Simard et al. 1999). Studies of the galaxy size evolution at high redshift ($z \sim 2 - 6$) from the Great Observatories Origins Deep Survey (GOODS), as well as Ultra Deep Field (UDF) and UDF-parallel Advanced Camera for Surveys fields showed a clear decrease in size from $z \sim 1$ to 4 and a possible extension to $z \sim 6$, indicating that high redshift galaxies are compact in size ($\sim 0''1 - 0''3$) and that large ($\gtrsim 0''4, \gtrsim 3\,\text{kpc}$) low surface brightness galaxies are rare (Bouwens et al. 2004; Ferguson et al. 2004). On the other hand, observational evidences of massive disk galaxies at redshift much beyond one has become considerably abundant in literatures recently (Liu et al. 2000; Cimatti et al. 2004; Yan et al. 2004; Daddi et al. 2005; Fu et al. 2005; Kriek et al. 2006; Papovich et al. 2006). The most direct evidences for the existence of large disks at high redshift are usually from the deep near-infrared imaging of high redshift QSO field, clusters and Hubble Deep Field-South (Iye et al. 2000; van Dokkum & Stanford 2001; Iye et al. 2003; Labbé et al. 2003; Stockton et al. 2008; McGrath et al. 2008). This is probably because previous U-dropout technique revealed only the unobscured star forming regions rather than the more evolved underlying population that forms the disk, and multiwavelength surveys with high quality photometry are suggested for an unbiased census of massive galaxies in the early universe (Giavalisco et al. 1996; Lowenthal et al. 1997; van Dokkum et al. 2006).

In this paper, we present the results from $BVRIJHKs$ broad-band deep images of the QSO 1508+5714 field ($z_{\text{em}} = 4.28$), as well as the analysis of the rest frame UV/optical morphology and the SED of a B-dropout galaxy nearby QSO. In addition, the low dispersion spectrum of the QSO, showing clearly the strong and sharp Lyman $\alpha$ and CIV emission lines, as well as a Lyman Limit System at $z = 3.88$ ($\tau_{\text{LLS}} > 4.6$, corresponding to a neutral hydrogen column density of $> 7 \times 10^{17}\,\text{cm}^{-2}$) (Storrie-Lombardi et al. 1994; Storrie-Lombardi et al. 1996). A possible connection between the Lyman Limit absorption and the galaxy would be discussed in the next paper. The cosmological parameters $\Omega = 0.27$, $\Lambda = 0.73$ and $H = 71\,\text{km/s/Mpc}$ are adopted throughout.
2. Observation and data reduction

The VRI deep imaging of the QSO1508+5714 field was made on May 28, 2001 (UT) during a test run, using the FOCAS camera on Subaru 8.2m telescope at Mauna Kea. The camera is made of two 2048 x 4096 CCDs and a pixel scale of 0.′104, providing a field size of 6′ × 6′ (Kashikawa et al. 2002). We adopted in the observation a binned mode to improve the signal-to-noise ratio, resulting in a pixel scale of 0.′208. The total exposure times were 2800, 1500 and 1700 seconds for $V$(5500˚A), $R$(6600˚A) and $I$(8050˚A) respectively.

The data reduction was performed using the IRAF package. After bias subtraction, each frame was subsequently flat-fielded using a combination of dome flats or twilight sky flats to remove pixel-to-pixel variations across the CCD chips. We perform sky background subtraction by removing a 2nd-order polynomial fitted to the sky components. Finally, the dithered frames within each bandpass were averaged using an outlier rejection algorithm. The weather was clear and the observational condition was good. The final combined image has a stellar PSF with full width at half maximum (FWHM) ∼ 0.′7 in the $R$ band.

In order to constrain the redshift range of the detected galaxies, we obtained a one hour deep-B exposure by service observing mode on July 14, 2007 (UT) with the Subaru Suprime camera, which is a mosaic of ten 2K × 4K CCDs and covers a 34′ × 27′ field of view with a pixel scale of 0.′20 (Miyazaki et al. 2002). The final combined image has a stellar PSF with full width at half maximum (FWHM) ∼ 0.′7. We also obtained 450, 1260 and 750 seconds exposure in the $J$(1.26μm), $H$(1.64μm) and $Ks$(2.14μm) bands on June 8 and June 25, 2007 (UT) using the Subaru MOIRCS camera, which is a wide-field imaging camera and spectrograph, with a field view of 4′ × 7′ and a spatial resolution of 0.′117/pixel (Ichikawa et al. 2006; Suzuki et al. 2008). We use data reduction packages “SDFRED” for the Suprime-Cam image (Yagi et al. 2002; Ouchi et al. 2004), as well as the package ”MCSRED” developed by Ichitanaka (2008) for the MOIRCS data, to reduce the raw data and produce the scientific images for further photometry. The weather was clear and we have gotten a stellar PSF with full width at half maximum (FWHM) ∼ 0.′3 in the $Ks$ band for the final combined image.

We retrieved from the HST data archive a 4800 seconds exposure taken by the Hubble Space Telescope (HST) WFPC2 in the F814W-band (approximately $I$ band, and a pixel scale of 0.′0996). Considering the high resolution of the HST image, we will rely on it for the morphological analysis of the galaxy candidates.

For the current study, we have performed: i) careful PSF subtraction on the combined images of all bandpasses, to reduce the effects of QSO light. The modeled PSF was determined using a set of bright stars in the same image with DAOPHOT; ii) Because our image is more sensitive in the $R$ than in the $I$ band, the object detection was done by running the SExtractor package on the combined and PSF subtracted image in the $R$-band, and a detection threshold of $\mu = 3\sigma$ of the skylevel was adopted (Bertin & Arnouts 1996). Colors were determined by
re-running SExtractor in the double-image mode, in which the faint objects detected on the “detection image” (in the $R$-band) were measured with the same aperture in the registered other bands. The photometric results are shown in Tab.1 and Tab.2, where the data with footnote $a$ for galaxy ”G1” and ”G2” are measured with a small diameter aperture ($1''25$) using SExtractor and those with footnote $b$ are measured with a large diameter aperture ($2''5$) using SExtractor.

Also observed were several standard stars selected from Landolt (1992) for $BVRI$ bands on the same night and at similar airmasses. The standard star FS27 was observed as the photometric calibrator for $JHKs$ bands, which was selected from Hunt et al. (1998) and the 2MASS All-Sky catalogue of Point Sources. We have adopted the equation $B(AB)=B-0.11$, $V(AB)=V+0.02$, $R(AB)=R+0.20$, $I(AB)=I+0.45$, $J(AB)=J+0.9$, $H(AB)=H+1.38$, $Ks(AB)=Ks+1.86$, to put the magnitude onto the AB system (Fukugita et al. 1995 ; Bessell & Brett 1988 ). All magnitudes subsequently quoted in this paper are on the AB system.

3. Analysis

3.1. Galaxies near the QSO sightline and their colors

We show in Fig.1 the combined images of $\sim 15''$ square region surrounding the QSO in the $BVRIJHKs$ bands. Two objects standout in the images of $BVRI$ bands, within a distance of $3''5$ northwest and southeast of the QSO line of sight, which are designated as “G1” and “G2” in this work. Galaxy “G1” is marked by blue circles in the images, and “G2” is marked by green circles in the images of $BVRI$ bands. Galaxy “G2” is not detected in the NIR images.

Firstly, we adopt the V-dropout selection criteria designed by Fukugita et al.(2004) to select galaxies at $z \sim 4$, who use the same set of filters as ours to select galaxies at $z \sim 4$.

$$0.95 < V - R < 2.0,$$

$$0.59(R - I) + 0.54 < V - R < 3.6(R - I) + 0.4,$$

$$23.5 < I, \quad R - I < 1.0.$$ (1)

The colors of galaxies ”G1” and ”G2”, with small diameter aperture ($1''25$) and large diameter aperture ($2''5$), are shown in Tab.2. Considering the peculiar colors of galaxy “G1” with $V - R > 1.0, R - I < 0.7$, we tentatively suggest that it is most likely a candidate galaxy at redshift $z \sim 4$, and might be responsible for the Lyman Limit absorption at $z = 3.88$ seen in the QSO spectrum.

However, we understand that the $VRI$ filter set is not ideal for two-color photometric selection of galaxies at $z \sim 4$, according to various model calculations (Stevens & Lacy 2001 ). This is because an evolved galaxy at $z \sim 0.5$ is likely to have similar colors to the high redshift object owing to the presence of the 4000Å break. We therefore made deep B-imaging of the field centered on QSO1508+5714 with the Suprime camera on Subaru telescope to constrain the redshift range of galaxies “G1” and “G2”.

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Table 1. Photometric results 1. The footnotes a and b for “G1” and “G2” indicate the measurements with small and large apertures described in detail in Sec. 2.

| Obj  | $B_{AB}$  | $V_{AB}$  | $R_{AB}$  | $I_{AB}$  |
|------|-----------|-----------|-----------|-----------|
| $G1_a$ | 27.92 ± 0.08 | 27.06 ± 0.15 | 25.68 ± 0.06 | 25.01 ± 0.10 |
| $G2_a$ | 27.25 ± 0.05 | 26.34 ± 0.08 | 25.53 ± 0.06 | 25.50 ± 0.16 |
| $G1_b$ | 27.53 ± 0.10 | 26.09 ± 0.12 | 24.92 ± 0.06 | 24.39 ± 0.11 |
| $G2_b$ | 26.51 ± 0.04 | 25.62 ± 0.08 | 24.78 ± 0.06 | 24.31 ± 0.11 |

Table 2. Photometric results 2. Galaxy “G2” is not detected by the JHKs deep imaging.

| Obj  | $(B - R)_{AB}$ | $(V - R)_{AB}$ | $(R - I)_{AB}$ | $J_{AB}$ | $H_{AB}$ | $K_{SAB}$ |
|------|----------------|----------------|----------------|--------|--------|--------|
| $G1_a$ | 2.24 ± 0.1 | 1.38 ± 0.16 | 0.67 ± 0.12 | 22.98 ± 0.18 | 22.60 ± 0.10 | 21.87 ± 0.08 |
| $G2_a$ | 1.72 ± 0.08 | 0.81 ± 0.1 | 0.03 ± 0.17 | – | – | – |
| $G1_b$ | 2.61 ± 0.12 | 1.17 ± 0.13 | 0.53 ± 0.12 | 23.00 ± 0.27 | 22.37 ± 0.10 | 21.71 ± 0.09 |
| $G2_b$ | 1.73 ± 0.07 | 0.84 ± 0.1 | 0.47 ± 0.12 | – | – | – |

With one hour exposure, we clearly detected galaxy “G2”, with a detection threshold of $> 3\sigma$ over the sky level. However, galaxy “G1” is much fainter, and gives a $2\sigma$ detection of $B = 27.92$. This means that the spectrum properties of galaxy “G1” do show the Lyman break, and indicates that galaxy “G1” might be a high redshift galaxy at $z \sim 4$. Comparing with the BRI color selection for $z \sim 4$ LBGs given by Prochaska et al. (2002), we found that the colors of galaxy “G1” satisfy their criteria, but not for galaxy “G2”.

$$B - R > 2.0,$$
$$B - R > 1.2(R - I) + 1.6,$$
$$R - I < 1.0.$$ (2)

Although we cannot completely exclude the possibility that galaxy “G2” is also at high-z with $B - R = 1.73 ± 0.07$, we suspect that it is most likely a foreground contaminator. The reasons are as following: 1) considering the surface density of Lyman Break Galaxies at $z \sim 4$, down to magnitude $R = 25.5$ ($\sim 1$ per square arcmin), the probability of finding two objects at such high redshift and within such a small area ($\sim 15''$ square) is very low; 2) meanwhile, inferred from the presence of only one absorption line system in the QSO spectrum (Steidel et al. 1999), we suspect that most likely only galaxy “G1” is a high-z object.

3.2. Photometric redshifts

We used the public code (Hyperz) to obtain the photometric redshift for the galaxy candidate, $z_{\text{phot}}$. This code uses SED fitting through a standard $\chi^2$ minimization procedure. The photometric uncertainties in the $BVRIJHKs$ fluxes of the object are accounted for and the fluxes are compared with a set of template spectra. For a complete description of the code and
the accuracy of its results, we refer the readers to Bolzonella et al. (2000).

We adopted a full range of solar metallicity stellar population models, including models matching the sequence of colors from E-S0 to Sd, as well as a single starburst model, which was built by the Bruzual & Charlot evolutionary code (BC03, Bruzual & Charlot 2003). The template SEDs were reddened by applying the Calzetti reddening law with a wide range of reddening values from \( E_{B-V} = 0.0 \) to \( E_{B-V} = 2 \), with steps of 0.2 (Calzetti et al. 2000). The fitting procedure allowed redshifts in the range of \( 0 \leq z \leq 6 \).

Fig. 2 shows the best fit SED for galaxy "G1" from our multi-band photometry, which is a \( \sim 2 \) Myr old young starburst at \( z \sim 3.5 \) with \( A_V \sim 2 \text{mag} \), giving a fitting result of \( \chi^2 \sim 0.9 \) and the corresponding probability of 49%. The estimated error on the redshift is 0.05(0.11) at 90%(99%) confidence level. The NIR color of galaxy "G1" \( (J-Ks = 1.29 \pm 0.28 \text{ and } H-Ks = 0.66 \pm 0.13) \) indicates that galaxy "G1" is slightly bluer than the distant red galaxies (DRGs) at \( 2 < z < 4.5 \), which would have a strong Balmer/4000Å break. The stellar mass of galaxy "G1" is estimated from the multi-band photometry SED fitting. We get a value of \( \sim 8.9 \times 10^{10} M_\odot \), which is consistent with the relation between stellar mass and observed total \( Ks \) magnitude for galaxies at \( 2 < z < 3 \) in the FIRES, GOODS and MUSYC fields, given by van Dokkum et al. (2006).

Galaxy "G2" is not detected in the \( JHKs \) bands. We will not include its fitting result here, due to the poor accuracy of the photometric redshift calculation. Even for galaxy "G1", we understand that the low detection limits in \( BVJ \) bands \( (S/N < 3) \) would affect the precision of the photometric redshift estimation. This is because it would cause relatively "flat" probability function due to a lack of sufficient photometric information. For detailed scientific research, further spectroscopy to confirm the redshift of the candidates is strongly required.

3.3. Size and morphology

To study the morphologies and sizes of both detected objects, we estimated their structural parameters by running a 2-D fitting algorithm GALFIT (Peng et al. 2002) on the HST WFPC2 archive image in the F814W filter. We also show a montage figures of galaxy “G1” in Fig.3, to confirm the disk morphology in other bands.

We used the public software Tiny-Tim to create a PSF for the convolution of the HST WFPC2 image, and made a model fitting to the QSO field where the QSO (PSF) and the two galaxies “G1” and “G2” (Sérsic profiles) are fitted simultaneously to deblend everything together, and to reduce the contaminating flux from the wings in the PSF of the QSO. Haussler et al. (2007) shows that this kind of simultaneous fitting gives the most reliable results against the neighboring contamination, especially in the analysis of deeper cosmological images or of more crowded fields. This is because the simultaneous fit of the profiles of multiple companions thereby deblends their effect on the fit to the galaxy of interest. The output images from GALFIT are presented in Fig. 4, which shows from left to right, the original image specified
by the convolution box size, the final model of the objects in the selected field and the residual image by subtracting the second from the first image. The surface brightness radial profiles of galaxy “G1” is shown in Fig.5, which is measured by fitting ellipses to the WFPC2 images with the STSDAS task ELLIPSE.

For galaxy ”G1”, the best fit structural parameters are $\chi^2 = 1.58$, the Sérsic index $n = 0.7 \pm 0.2$, and an effective radius $r_e = 0''.57 \pm 0''.23$. In addition, we have done several checks of the systematics, such as, by masking out the central region of the QSO which cannot be fitted well, and running again the simultaneous model fitting to the QSO field. We found that there is no significant systematic errors for the current results, especially for the Sérsic index.

However, the WFPC2/F814 image maps the unobscured star-forming regions at rest frame UV wavelengths, it would not be appropriate for discussing the radial profile or morphology of the galaxy. On the other hand, MOIRCS Ks-band imaging is looking at the rest-optical wavelength which has a stellar PSF with full width at half maximum (FWHM) $\sim 0''.3$ for the combined image. We understand that the parameters of the Sérsic profiles would be affected by seeing. In case of a $\sim 0''.3$ (FWHM) resolution, we hope to see at least the radial profile in the outer region. So, the seeing-limited ground-based Ks imaging would be a good complement to the WFPC2/F814 results for the morphological studies.

Similar as we have done for the WFPC2 F814 image, we made a GALFIT fitting to the Ks image by convolving a PSF to the models. The PSF image for convolution is created by fitting a nearby bright star with a number of Sérsic profiles. The surface brightness radial profile of galaxy “G1” is shown in Fig.6, which is measured by fitting ellipses to the WFPC2 images with the STSDAS task ELLIPSE. The overplotted lines are the best-fit exponential and $r^{1/4}$ laws from GALFIT fitting.

The measured angular size corresponds to a physical radii of $r_e \sim 3$ kpc at $z \sim 3.5$. According to the relationship between the Sérsic index ($n$) and the morphological type, we propose that galaxy “G1” is most probably a large disk galaxy at high-z (de Jong 1996 ; Ravindranath et al. 2004 ).

The studies of the size and morphology of distant objects have been carried out by several authors, and the detections of large disk galaxies at high redshift have been accumulating (Iye et al. 2003 ; Labbé et al. 2003 ; Bouwens et al. 2004 ; Ferguson et al. 2004 ; Overzier et al. 2008 ). Recently, a few large disk systems at $z \sim 2.5 - 3$, with $r_e \sim 3.5 - 7$ kpc are reported by Stockton et al. (2008) and Akiyama et al. (2008). If the redshift of galaxy ”G1” could be confirmed, it would give evidence for the existence of such large disks at even higher redshift, which might be the progenitors of the similar systems detected by Stockton et al. (2008) and Akiyama et al. (2008). Considering that most of the large disks detected by other groups are old galaxies, galaxy “G1” has a bluer color, and a young “dusty” starburst spectrum. This provides strong evidence for a large disk formation in the early universe with on-going star formation. Meanwhile, the presence of such a population at high redshift would require the
current galaxy formation models to allow for the presence of early-forming massive disks.

4. Summary

We have presented an analysis of deep images in the $BVRIJHKs$ bands centered on QSO 1508+5714 at $z_{em}=4.28$, which is known to contain a Lyman Limit System at $z_{abs}=3.88$ seen in the QSO spectrum.

A B-dropout galaxy “G1” which is about 3$''$5 northwest of the QSO sightline is clearly detected. To complement the color selection, a photometric redshift analysis is presented and gives a value of $z_{phot} \sim 3.5$. We estimate its projected distance of 24 kpc at $z \sim 3.5$, and further derive the absolute magnitude $M = -22.2$, making it about $\sim 3 L^*$ for a star-forming galaxy spectrum. The stellar mass of galaxy “G1” is estimated from the multi-band photometry SED fitting method. We get a value of $\sim 8.9 \times 10^{10} M_\odot$, consistent with the relation between stellar mass and observed total $Ks$ magnitude for galaxies at $2 < z < 3$ in the FIRES, GOODS and MUSYC fields, given by van Dokkum et al. (2006).

We have run a 2-D imaging decomposition on the HST WFPC2 archive image of the QSO nearby field by GALFIT, which gives a Sérsic index ($n \sim 1$) for galaxy “G1”, indicating a possible late-type morphology according to the Sérsic index–morphological type relation. The radial profile of the seeing-limited ground-based $Ks$ image is shown as a complement to the WFPC2/F814 results (rest frame UV wavelengths) for the morphological studies, since it is looking at the rest-optical wavelength. We can see in Fig.6 the radial profile can be well described by exponential curve at least at the larger radii ($>0''5$). If galaxy “G1” is placed at $z \sim 3.5$, we derive its effective radius ($r_e \sim 3$ kpc), with the WMAP cosmology adopted by this study.

Given the small impact parameter, the peculiar colors, the estimation of the photometric redshift, as well as various lines of evidence discussed in the previous sections, we suspect that galaxy “G1” is most likely to be a massive disk at high redshift, and might give rise to the known LLS ($z_{abs}=3.88$) seen in the QSO spectrum.

Such a large disk galaxy at high redshift would have a strong impact on the galaxy formation theory, if the redshift of galaxy ”G1” could be confirmed. Thus, a spectroscopic redshift is needed to test these conclusions.

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Fig. 1. The combined images of a region of $\sim 15 \times 15$ arcsec$^2$ nearby the QSO in the $BVRIJHK_s$ bands (top figures: B,V,R,I bands from left to right, and bottom figures: J, H, Ks bands from left to right). Galaxy “G1” is indicated by blue circles, which is located in the northwest of the QSO sightline in the image, and ”G2” is marked by green circles in the southeast of the QSO. The diameters of circles match roughly the aperture diameters for the photometry, i.e. $\sim 2''5$. North is up and East to the left.

Fig. 2. Broad-band photometry of galaxy ”G1” in the $BVRIJHK_s$ bands. The best-fit evolutionary synthesis model is a young starburst of age of $\sim 2$ Myr at $z \sim 3.5$ with extinction of $A_V \sim 2$.

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Fig. 3. B, V, R, I, J, H, Ks, and WFPC2/F814 images of galaxy “G1” (top figures: B, V, R, I bands from left to right, and bottom figures: J, H, Ks, and WFPC2/F814 bands from left to right). The image size is $\sim 4.2 \times 4.2$ arcsec$^2$. For the orientation of images in $BVR$ bands, north is up and east to the left. North is 20$^\circ$.77 left of upper and east is left of it for the WFPC2/F814 filter. For the MOIRCS images in JHKs bands, the orientation is different, with north is 40$^\circ$.0 right of up and east is left of it. We show images here in its original orientation to avoid distortion.

Fig. 4. 2-D image decomposition on the HST WFPC2+F814W data of the QSO field ($\sim 10'' \times 10''$), centered on QSO 1508+5714. From left to right, they are the original image, the final model of the objects and the residuals from GALFIT. North is 20$^\circ$.77 left of upper and east is left of it.

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**Fig. 5.** Radial surface brightness profile of the WFPC2 F814W image of the galaxy “G1”, with best-fit Sérsic, exponential, $r^{1/4}$ profiles shown. The profiles are shown at the top panel and the deviations of the observed profile and two other models from the best-fit Sérsic profile are given at the bottom.

**Fig. 6.** Radial surface brightness profile of the MOIRCS Ks-band image of the galaxy “G1”. The over-plotted lines are the best-fit exponential and $r^{1/4}$ laws.

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