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# ALMA Lensing Cluster Survey: a strongly lensed multiply imaged dusty system at $z \geq 6$

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## ABSTRACT

We report the discovery of an intrinsically faint, quintuply-imaged, dusty galaxy MACS0600-z6 at a redshift  $z = 6.07$  viewed through the cluster MACSJ0600.1–2008 ( $z = 0.46$ ). A  $\simeq 4\sigma$  dust detection is seen at 1.2mm as part of the ALMA Lensing Cluster Survey (ALCS), an on-going ALMA Large programme, and the redshift is secured via [C II] 158  $\mu\text{m}$  emission described in a companion paper. In addition, spectroscopic follow-up with GMOS/Gemini-North shows a break in the galaxy's spectrum, consistent with the Lyman break at that redshift. We use a detailed mass model of the cluster and infer a magnification  $\mu \gtrsim 30$  for the most magnified image of this galaxy, which provides an unprecedented opportunity to probe the physical properties of a sub-luminous galaxy at the end of cosmic reionization. Based on the spectral energy distribution, we infer lensing-corrected stellar and dust masses of  $2.9_{-2.3}^{+11.5} \times 10^9$  and  $4.8_{-3.4}^{+4.5} \times 10^6 M_{\odot}$ , respectively, a star formation rate of  $9.7_{-6.6}^{+22.0} M_{\odot} \text{ yr}^{-1}$ , an intrinsic size of  $0.54_{-0.14}^{+0.26}$  kpc, and a luminosity-weighted age of  $200 \pm 100$  Myr. Strikingly, the dust production rate in this relatively young galaxy appears to be larger than that observed for equivalent, lower redshift sources. We discuss if this implies that early supernovae are more efficient dust producers and the consequences for using dust mass as a probe of earlier star formation.

**Key words:** gravitational lensing: strong – galaxies: evolution – galaxies: formation – galaxies: high-redshift .

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## 1 INTRODUCTION

Understanding the process of cosmic reionization, during which intergalactic hydrogen transforms from a neutral to an ionized state in less than a billion years, represents a major challenge in extragalactic astronomy and cosmology. Although star-forming galaxies are considered to be the primary ionizing sources, those which can be directly observed during the reionization era appear to be insufficient in number given their likely ionization output (e.g. Robertson et al. 2015). As a consequence, it is popular to appeal to contributions from a larger number of sub-luminous sources, which can only be partially probed via current deep surveys (e.g. Bouwens et al. 2015; Livermore, Finkelstein & Lotz 2017; Bhatawdekar et al. 2019; Kikuchihara et al. 2020). With current facilities, the only way to characterize the physical properties of this sub-luminous population is to use the magnification afforded by gravitational lensing (for a review see Kneib & Natarajan 2011). Although several surveys have harnessed the lensing power of foreground clusters, such as the Cluster Lensing And Supernova survey with Hubble (CLASH; Postman et al. 2012), the *Hubble* Frontier Fields (Lotz et al. 2017) and most recently REionization Lensing Cluster Survey (RELICS; Coe et al. 2019), the effective surface area explored for the most highly magnified background sources remains small. As a consequence, very few high-redshift sources ( $z \geq 6$ ) with magnifications  $\mu \geq 10$  have so far been found (e.g. Coe et al. 2013; Salmon et al. 2018).

Of particular interest in physical studies of galaxies in the reionization era is their dust content. Although dust can obscure the ionizing radiation and lead to underestimates of properties such as star formation rate and ionizing capability, dust masses have been proposed as a potential way forward in estimating the earlier star formation histories and hence ages of early galaxies (Laporte et al. 2017b; Katz et al. 2019). It is typically assumed that dust at early times is largely produced in core-collapse supernovae with a production rate similar to that observed in local events ( $< 0.2 M_{\odot}$  per event, e.g. Indebetouw et al. 2014). However, little is known about dust production rates at early times and thus correlating dust properties of early galaxies over the full range of stellar masses with stellar ages inferred independently from spectral energy distributions (SEDs) would be highly valuable. To date, there are very few convincing dust detections beyond  $z \simeq 6$  (e.g. Capak et al. 2015; Watson et al. 2015; Bradač et al. 2017; Laporte et al. 2017b; Marrone et al. 2018; Hashimoto et al. 2019; Tamura et al. 2019) and none for galaxies with UV magnitude  $M_{uv} > -18$ .

The ALMA Lensing Cluster Survey (ALCS; PI: K. Kohno) is motivated by multiple goals including probing the dust properties of strongly lensed galaxies near the end of the epoch of reionization. The programme has observed 33 clusters (5 from the Frontier Fields survey, 12 from CLASH and 16 from RELICS) in ALMA band-6 ( $\lambda \sim 1.2\text{mm}$ ) to reach a  $5\sigma$  lensing-corrected rms of  $\leq 0.1$  mJy over  $16 \text{ arcmin}^2$  (or  $0.01$  mJy over the  $0.5 \text{ arcmin}^2$  for the highest magnification regions). In this paper, we report the discovery of dust-emission from a multiply-imaged lensed system MACS0600-z6 at  $z = 6.07$  behind one of the ALCS clusters, MACSJ0600.1-2008 (Ebeling, Edge & Henry 2001). In Section 2, we describe the relevant observational data and the photometry of the lensed source. Based on three mass models described in Section 3, we identify five multiple images for this system, infer a total magnification of  $\mu \gtrsim 30$  for the most magnified arc. Section 4 presents spectroscopic follow-up with Gemini-North of several images, and we discuss the physical properties of this system in Section 5. Throughout this paper, we assume  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$ , and  $\Omega_{\Lambda} = 0.7$ . All magnitudes are in AB system (Oke & Gunn 1983).

**Table 1.** Properties of data used in this study. The  $2\sigma$  depth is measured in a  $0.4$  arcsec diameter aperture for *HST*,  $0.8$  arcsec radius aperture for Ks, and  $1.2$  arcsec radius aperture for *Spitzer*.

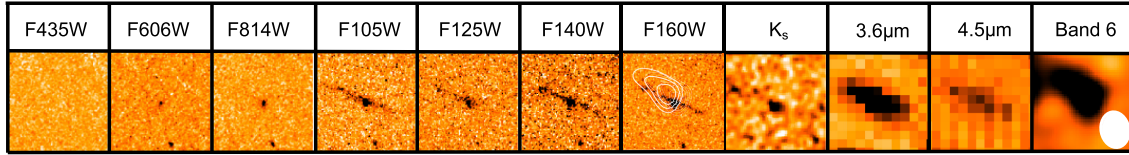
Image	$\lambda_c$ (Å)	$t_{\text{exp}}$ (ks)	ZP (AB)	$2\sigma$ -depth (AB)
F435W	4317.5	1.95	25.66	27.4
F606W	5924.7	2.18	26.50	28.3
F814W	8210.3	3.56	25.94	28.0
F105W	10530.9	1.41	26.27	27.1
F125W	12495.7	0.7	26.23	26.5
F140W	13976.1	0.74	26.45	26.5
F160W	15433.1	1.96	25.95	27.4
Ks	21440.4	2.16	30.05	24.4
IRAC1	35465.6	15.2	23.9	26.0
IRAC2	45024.3	15.2	23.9	25.6

## 2 OBSERVATION AND DATA ANALYSIS

The cluster MACSJ0600.1-2008 ( $z = 0.46$ ) was observed as part of the ALMA Lensing Cluster Survey (ID: 2018.1.00035.L; P.I. Kohno, K.) in band 6 frequency in January 2019 with a total exposure time of 3.3 h. The data was reduced using the ALMA pipeline (v. 5.6.1-8) with a natural weighting. A  $2$  arcsec  $uv$ -taper was used to maximize the detection of faint sources. The final beam size is  $2.21 \text{ arcsec} \times 1.99 \text{ arcsec}$  and the rms on the reduced mosaic is  $80 \mu\text{Jy beam}^{-1}$ . 13 sources with a signal-to-noise ratio (SNR)  $\geq 4$  were identified including one at RA = 06:00:09.143 and Dec. =  $-20:08:26.579$  with an elongated half-light radius of  $1.3$  arcsec. By extracting the flux on a line-free image at  $1.2 \text{ mm}$  using the CASA *imfit* task, the peak flux is  $S_{1.2\text{mm}}^{\text{peak}} = 366 \pm 62 \mu\text{Jy beam}^{-1}$  and the integrated flux is  $S_{1.2\text{mm}}^{\text{int}} = 484 \pm 135 \mu\text{Jy}$  on an emission line subtracted image.

A search for an ultraviolet (UV) rest-frame counterpart for this source was undertaken on deep *HST* images from the RELICS survey with a search radius of  $2$  arcsec. The data reduction of this data set is described in Coe et al. (2019). Photometric catalogues were built using version 2.19.5 of *SEXTRACTOR* Bertin & Arnouts (1996) in dual image mode on psf matched images. The extraction parameters were defined to maximize the detection of faint objects (DETECT\_THRESH =  $2\sigma$ ; ANALYSIS\_THRESH =  $2\sigma$ ; DETECT\_MINAREA =  $5 \text{ px}$ ) on a detection picture composed by the sum of all WFC3 images. The final catalogue contains 25200 detections. To estimate the depth of each image, we masked the bright sources and measured the rms in hundreds non-overlapping  $0.4$  arcsec radius aperture. Table 1 summarizes the data properties. Two overlapping sources were detected  $0'.4$  South of the ALMA detection (Fig. 1): a point source (referred to hereafter as ‘foreground’) and a background arc-like source (referred to as MACS0600-z6, whose discovery multiple image is denoted MACS0600-arc, see below for more details). The foreground source was identified in the public RELICS catalogue (Salmon et al. 2020) and assigned a photometric redshift of  $z_{\text{phot}} = 0.82_{-0.40}^{+0.28}$ . The multiple image MACS0600-arc is absent from that pipeline-generated catalogue, most likely because of its faintness and elongated shape.

Noting the overlapping foreground object, in order to extract the photometry of MACS0600-arc we model each source with a Sersic profile using GALFIT (Peng et al. 2002) on the WFC3-NIR and IRAC images, which accounts for PSF difference between *HST*, VLT, and *Spitzer*. Error bars are measured on the residual image in a  $0.4$  arcsec radius circle. We tested our method on



**Figure 1.** Thumbnail images of MACS0600-arc comprising images from ACS/*HST* (F435W, F606W, F814W), WFC3-IR/*HST* (F105W, F125W, F140W and F160W), HAWK-I/VLT ( $K_s$ ), IRAC/*Spitzer* (3.6 and 4.5  $\mu\text{m}$ ), and ALMA (Band 6). Each image is 7 arcsec  $\times$  7 arcsec. Note the overlap between the foreground object (detected at F606W and F814W) and the lensed galaxy. The ALMA contours are drawn on the F160W images in  $1\sigma$  from  $3\sigma$ . The ALMA beam size is at the bottom right corner of the last column.

the ACS data where only the foreground source is detected and compared the GALFIT photometry with that derived using the standard MAG\_AUTO photometry in single image mode with SExtractor (Bertin & Arnouts 1996). In F606W, our extracted photometry ( $m_{\text{F606W}}^{\text{GALFIT}} = 26.55 \pm 0.35$ ) is in excellent agreement with the SExtractor photometry ( $m_{\text{F606W}}^{\text{SETRACTOR}} = 26.72 \pm 0.08$ ). A similar conclusion is seen for the F814W image.

To increase the wavelength coverage, we searched for deep public data at longer wavelength. Using the ESO archive, we found a deep  $K_s$  exposure carried out with HAWKI/VLT (ID: 0100.A-785; P.I.: A. Edge) reaching a  $2\sigma$  depth in 1.2 arcsec radius aperture of 24.4. We also searched in the *Spitzer* archive for deep IRAC 3.6 and 4.5  $\mu\text{m}$  exposures. This cluster was part of two observing programs (ID: 90218; P.I.: E. Egami and ID: 12005, P.I.: M. Bradač), we combined all exposures and measured the depth in a 1.2 arcsec radius aperture distributed over the field of view. We present the final photometry in Table 2.

We determine the photometric redshift of the foreground source from a template-based SED-fitting method with HYPERZ (Bolzonella, Miralles & Pelló 2000). We used the standard list of templates including evolutionary SEDs with Chabrier IMF (Chabrier 2003) and solar metallicity from Bruzual & Charlot (2003), empirical SEDs built by Coleman, Wu & Weedman (1980) and two starburst galaxies from Kinney et al. (1996). We then searched for a solution between  $0 < z < 8$ , with an extinction range  $0.0 < A_v < 3.0$  mag assuming a Calzetti reddening law (Calzetti et al. 2000). The colour of the foreground source is similar to the colour of cluster members, we therefore allow a redshift range of  $z \in [0.0:3.0]$ . The best SED-fit for the foreground source is obtained at  $z_{\text{phot}} = 0.57_{-0.17}^{+0.14}$  and modest reddening ( $A_v = 1.5$  mag). Allowing a larger redshift range, the MACS0600-arc data provide a solution at  $z_{\text{photo}} = 6.68_{-0.67}^{+0.24}$  with an extinction  $A_v = 0.5$  mag, broadly consistent with the spectroscopic value (Fig. 2).

### 3 LENS MODELS AND MULTIPLE IMAGES

The elongated shape of the prominent  $z \sim 6$  arc supports the suggestion of a strongly lensed source. To determine the lensing configuration and hence the intrinsic properties of this source and the associated uncertainties, we have utilized several different lens models from within the ALCS team. These models exploit spectroscopic observations of MACS0600 using the MUSE integral field unit spectrograph (ID 0100.A-0792; PI: Edge) and the photometric redshift catalogue from RELICS. More details on the lens modelling of MACS0600 will be given in a separate paper, and here we provide only a brief summary. For convenience in this section, we drop the prefix MACS0600 in describing the multiple images.

The three models used here are produced using GLAFIC (Oguri 2010), LENSTOOL (Jullo et al. 2007), and Light-Traces-Mass (LTM; Zitrin et al. 2015). The first two models can be regarded as parametric

in the sense that both the galaxies and their dark matter haloes are described using independent analytic forms (e.g. combinations of pseudo-isothermal elliptical mass distributions) and adopt empirical scaling relations for cluster members. The LTM method is similar, but here the dark matter is assumed to follow the light distribution and thus is modelled as a smoothed version of the luminosity-weighted galaxy distribution. The parametric modelling of MACS0600 typically included three to four dark matter haloes and, whereas for the LTM models, the masses of several bright cluster members were modeled independently. All models are minimized using available multiple image constraints to find the best-fitting solution and its associated errors. Four modellers (MO, JR, GC, AZ) voted on the choice of multiply imaged systems which, besides the  $z \sim 6$  system, included nine other systems considered as secure. Five of these have a spectroscopic redshift from MUSE (spanning the redshift range  $z \sim 1.5$  to  $z \sim 5.5$ ). All three models indicate that the source MACS0600-z6 is quintuply imaged with the discovery arc (images z6.1 and z6.2) being a pair of multiple images that merge across the critical curve; an additional counter image inside the tangential critical curves (z6.3); a radial image (z6.4); and a fifth image on the other side of the cluster to the west (z6.5). The stamps of the five images are shown in Fig. 3, and the configuration derived from the LTM model for example, including all five multiple images, is shown on a *HST* image of the cluster in Fig. 4. To confirm the reliability of this system, we first check that the colours are similar for the four images within the error bars. We only include one of the fifth image candidates in this analysis (z6.5c) because *HST* coverage is missing for the other two. Colours measured on WFC3 images are similar with averaged values of  $F125W-F160W = 0.32 \pm 0.15$ . Another relevant feature that should be conserved by lensing is the surface brightness. We estimated the surface brightness of the four images using the extracted magnitude from GALFIT for the arc and z6.3a,b and from our SExtractor catalogues for the remaining objects using the MAG\_AUTO and the isophotal area. All images have consistent surface brightness in the WFC3 images (e.g. the averaged value on F160W is  $21.9 \pm 0.3$ ) reinforcing the multiple images system hypothesis.

In addition to the detected arc, two out of the three other predicted images, z6.3 and radial image z6.4, were easily identified in both the *HST* and ALMA data. These images lie within  $< 0''.4$  of their predicted locations and have photometric redshifts similar to that estimated for MACS0600-arc. In the *HST* data, image z6.3 consists of a bright ‘bulge’ referred to here as z6.3a and an additional faint component z6.3b which, according to the three lens models, is likely the multiply imaged counterpart of the arc, and on which the ALMA signal is centred. It is unclear whether image z6.3a is truly part of the lensed source despite not being quintuply imaged as well, and – while we acknowledge the possibility that z6.3a may be related – we consider only z6.3b a genuine multiple image of this system. In the ALMA data, z6.3b also shows a faint dust detection with an  $S/N \sim 3.5$

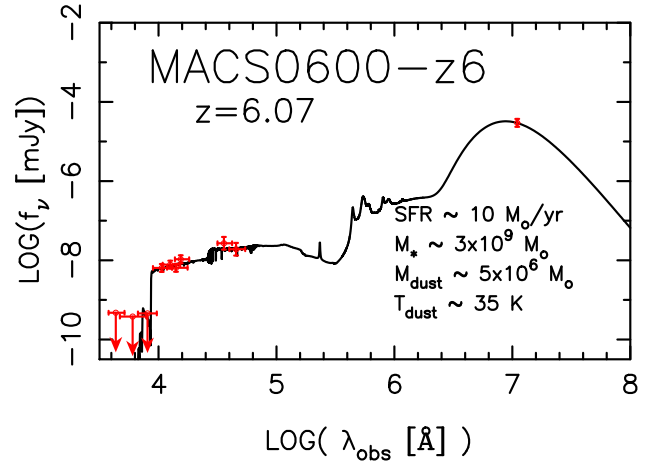


**Table 2.** Photometry of the multiple images of this  $z \geq 6$  system. Upper photometric limits on the ACS and WFC3 data were estimated in a 0.4 arcsec radius aperture, on HAWK-I data in a 0.8 arcsec radius aperture (taking into account the seeing of the data), and in a 1.2 arcsec radius aperture for IRAC images. For the photometric extraction of z6.3a and z6.3b, we used GALFIT on ACS and WFC3 images assuming a Sersic profile for both. On the IRAC data, where the separation is not clearly resolved, we used the flux ratio observed at 1.6  $\mu\text{m}$  to separate the contribution of each source.

ID	RA	Dec.	F435W	F606W	F814W	F105W	F125W	F140W	F160W	K <sub>s</sub>	3.6 $\mu\text{m}$	4.5 $\mu\text{m}$	$z_{\text{phot}}$
Foreground	06:00:09.13	-20:08:26.67	>27.34	26.55 $\pm$ 0.35	24.89 $\pm$ 0.11	25.01 $\pm$ 0.02	25.27 $\pm$ 0.15	24.71 $\pm$ 0.03	24.67 $\pm$ 0.01	23.64 $\pm$ 0.14	23.90 $\pm$ 0.27	24.70 $\pm$ 0.62	4.4 <sup>+0.4</sup> <sub>-0.4</sub>
MACS0600-arc <sup>a</sup>	06:00:09.13	-20:08:26.59	>27.34	>26.74	>26.35	23.83 $\pm$ 0.14	24.08 $\pm$ 0.16	23.89 $\pm$ 0.15	23.39 $\pm$ 0.15	>23.5	22.30 $\pm$ 0.08	22.75 $\pm$ 0.13	6.7 <sup>+0.2</sup> <sub>-0.7</sub>
MACS0600-z6.3a <sup>d</sup>	06:00:09.56	-20:08:10.80	>27.9	>29.2	26.46 $\pm$ 0.31	24.12 $\pm$ 0.12	24.10 $\pm$ 0.13	24.10 $\pm$ 0.13	23.86 $\pm$ 0.11	>23.5	22.66 $\pm$ 0.11	23.16 $\pm$ 0.12	6.7 <sup>+0.2</sup> <sub>-0.6</sub>
MACS0600-z6.3b	06:00:09.53	-20:08:10.84	>26.8	>27.8	>27.5	25.24 $\pm$ 0.13	24.92 $\pm$ 0.13	25.01 $\pm$ 0.14	24.88 $\pm$ 0.12	>23.5	23.66 $\pm$ 0.29	24.16 $\pm$ 0.29	6.8 <sup>+0.5</sup> <sub>-1.2</sub>
MACS0600-z6.4 <sup>a</sup>	06:00:08.57	-20:08:12.30	>28.1	>29.4	27.11 $\pm$ 0.25	25.51 $\pm$ 0.26	26.25 $\pm$ 0.31	25.96 $\pm$ 0.24	25.75 $\pm$ 0.23	>24.6	>24.2	>23.6	5.7 <sup>+0.6</sup> <sub>-0.6</sub>
MACS0600-z6.5a <sup>b</sup>	06:00:05.16	-20:07:13.87	>27.3	>28.4	>28.0	-	-	-	-	25.47 $\pm$ 0.31	>24.8	>24.0	-
MACS0600-z6.5b <sup>b</sup>	06:00:04.49	-20:07:14.93	>27.5	>27.8	>28.1	-	-	-	-	25.17 $\pm$ 0.24	>25.5	>24.2	-
MACS0600-z6.5c	06:00:05.57	-20:07:20.84	>27.5	>27.8	25.86 $\pm$ 0.05	24.87 $\pm$ 0.02	24.73 $\pm$ 0.02	24.66 $\pm$ 0.02	24.65 $\pm$ 0.02	24.37 $\pm$ 0.20	>25.5	>24.2	5.7 <sup>+0.2</sup> <sub>-0.2</sub>

<sup>a</sup>Spectroscopically confirmed at  $z = 6.07$  (see Fujimoto et al. 2021).

<sup>b</sup>Candidates for the fifth image of this system. The absence of WFC3 data at the expected position makes difficult the clear identification of the image.

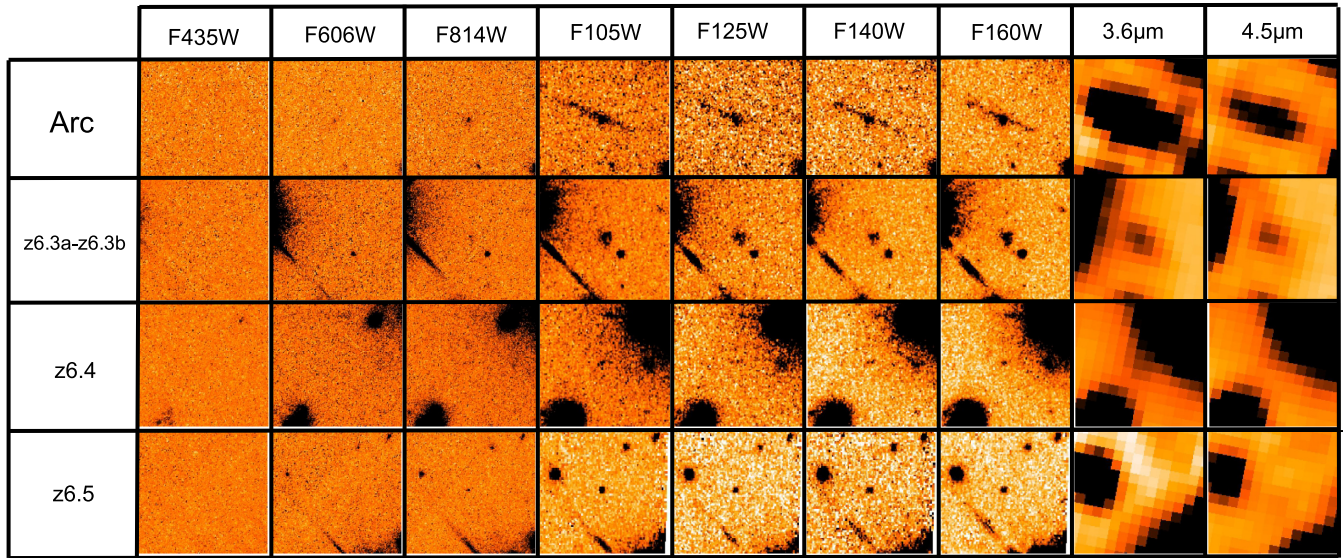


**Figure 2.** SED of MACS0600-z6 showing the best fit from MAGPHYS and the best physical properties corrected for magnification.

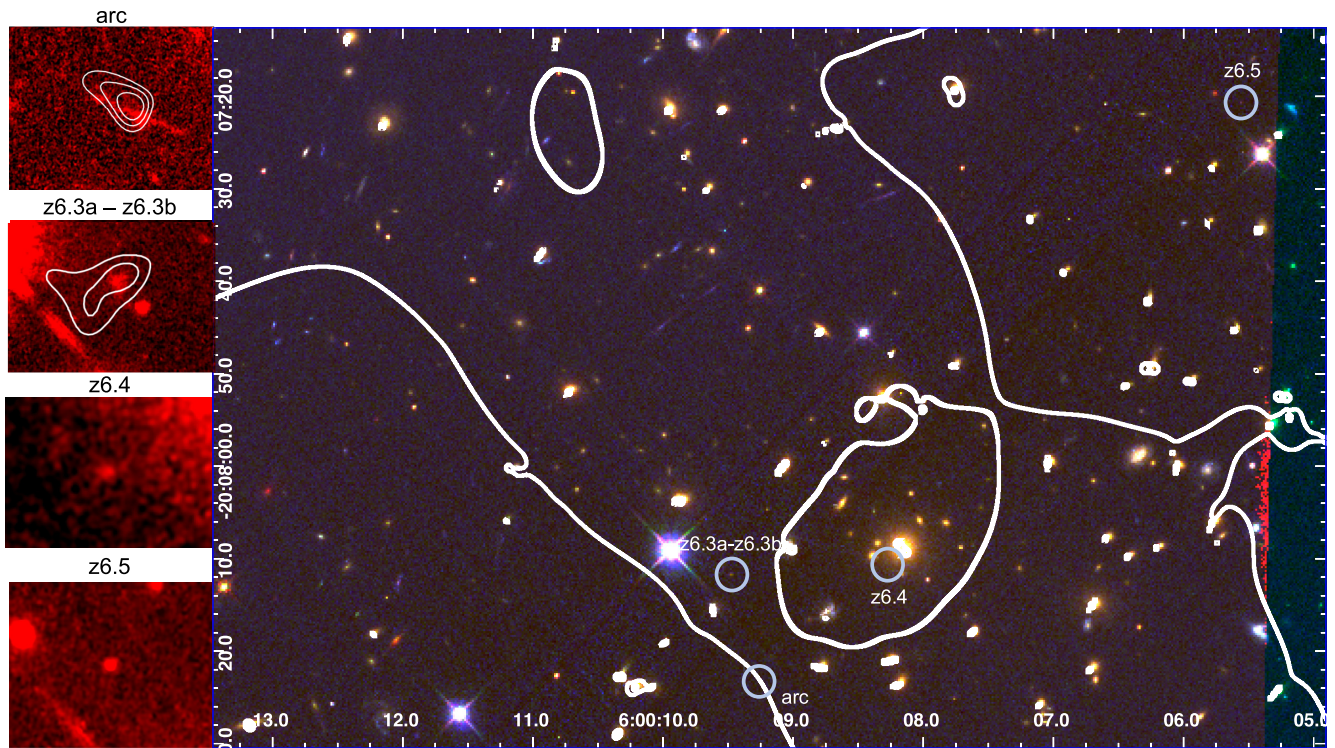
( $f_{\text{peak}} = 226 \pm 63 \mu\text{Jy beam}^{-1}$  as measured with imfit). The 1.2 mm flux ratio between 1.3b and the arc is  $0.62^{+0.33}_{-0.24}$  in excellent agreement with ratios observed in the near-infrared and with the predicted lens-model magnifications (see below). [C II]158  $\mu\text{m}$  emission lines at  $z = 6.07$  are detected in all images of this system that are covered by ALMA's FOV: the arc, z6.3b, and z6.4, strengthening further the adopted lensing configuration, again with line ratios that commensurate with the expectations from the lens models. More extensive details on these detections are given in a companion paper (Fujimoto et al. 2021).

While all models reassuringly agree on the positions of the five multiple images, there is larger scatter ( $\sim 12$  arcsec) in the predicted location of the fifth image, z6.5. The GLAFIC and LTM models predict image z6.5 lies outside the region covered by WFC3 data, making its identification more challenging, and two objects undetected on the ACS images but seen on the HAWK-I data are considered as potential candidates (z6.5a and z6.5b). The LENSTOOL model predicts the fifth image within the WFC3 field, and one clear dropout is identified as a potential candidate using the ACS, WFC3, and HAWK-I data (MACS0600-z6.5c).

Magnification factors  $\mu$  for the five images were estimated as follows. The two parametric models (LENSTOOL and GLAFIC) extracted values by first planting a compact source in the expected position, and adjusting its exact position with respect to the critical curves to match the observed [C II] 158  $\mu\text{m}$  line flux ratio. The LTM magnification values were derived in a slightly different manner: here the source was not planted in the source plane but formed there by directly delensing the arc, and the magnification of the arc was then extracted by comparing the model's prediction for the three other multiple image sizes with their absolute magnification values. The magnification for the five images from the GLAFIC model is  $\mu \sim 33$  for the arc,  $\mu \sim 35$  for z6.3,  $\mu \sim 5.7$  for z6.4, and  $\mu \sim 14$  for z6.5. The LENSTOOL model yields  $\mu \sim 22.1$  for the arc,  $\mu \sim 14$  for z6.3,  $\mu \sim 2.1$  for z6.4, and  $\mu \sim 2.9$  for z6.5. The LTM model magnifications are  $\mu \sim 31.2$  for the arc,  $\mu \sim 13.5$  for z6.3,  $\mu \sim 2.1$  for z6.4, and  $\mu \sim 3.8$  for z6.5. We note that the magnifications for the arc are likely lower limits. If the magnification for the arc is instead estimated by directly averaging the magnification next to the critical curves, or alternatively by comparing the area of the arc to its delensed size, values around  $\mu \sim 150$ – $200$  are obtained, although such estimates are typically more uncertain.



**Figure 3.** Thumbnail images of all images of the quintuply lensed galaxy presented in this paper. Each stamp is  $7''.5 \times 7''.5$  where the image is located at the centre, except for MACS0600-z6.3a (left) and MACS0600-z6.3b (right) where the two images are very close. For the fifth image, we only show the candidate detected on all WFC3/HST images (see the text for details).

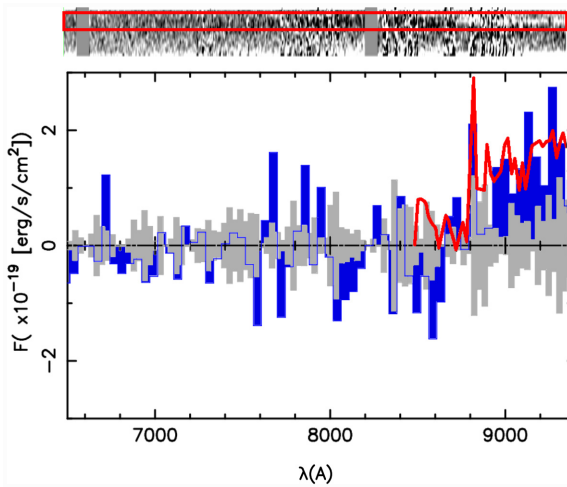


**Figure 4.** *Right:* Position of the five images of MACS0600-z6 superimposed on a colour *HST* image (F435W – blue; F814W – green; F160W – red). The white contours from the LTM model are overlotted. *Left:* Labelled F160W stamps of four multiple images. MACS0600-z6.1 and MACS0600-z6.2 (top left) are a merging pair crossing the critical line, and seen on *HST* images as an elongated arc and referred in the text as MACS0600-arc. MACS0600-z6.3 comprises a bright object (z6.3a) and a fainter, fuzzy part (z6.3b), which is the quintuply imaged part as indicated by the lens models, and on which the line emission seems to be concentrated. ALMA contours are overlotted on the arc stamp from  $3\sigma$  and from  $2\sigma$  for z6.3b.

We also take benefit from the detection of the dust continuum in two of the multiple images (z6.3 and the arc) to estimate the physical offset between the FIR continuum and the UV continuum. The position of the UV continuum was estimated on the F160W

image using the centroid of the counterpart. In the image plan, we measured an observed offset of 0.24 and 0.35 arcsec, respectively, for z6.3b and the arc. Accounting for the magnification, we estimate a physical offset of  $<0.4$  kpc.





**Figure 5.** *Top:* 2D GMOS/Gemini spectrum of MACS0600-z6.3a smoothed with a boxcar of 5 pixels. The red rectangle shows the position of our object in the slit. The continuum is clearly visible at the larger wavelength. (*Bottom:*) The blue histogram shows the extracted spectrum of MACS0600-z6.3a within a  $1.5\times$  seeing diameter aperture. The grey histogram displays the  $\pm 1\sigma$  noise level extracted in a similar size diameter aperture. The red line is the best fit of the Jones et al. (2012) spectra to our data which is found at  $z_{\text{spec}} = 6.19^{+0.06}_{-0.16}$ , consistent with the redshift measured from [C II]158  $\mu\text{m}$  Fujimoto et al. (2021).

#### 4 SPECTROSCOPIC FOLLOW-UP

The detection of an emission line within the ALMA band 6 datacube suggests a redshift  $z_{\text{spec}} = 6.07$ , assuming the line is [C II]158  $\mu\text{m}$  (Fujimoto et al. 2021). However, with only one line detected, a low/intermediate redshift interloper cannot be excluded. The relatively shallow MUSE data used to constrain the mass models did not show any features for the multiple-images of this system. Therefore, we conducted a spectroscopic follow-up campaign with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) installed on Gemini-North on three images of the system, namely MACS0600-arc, MACS0600-z6.3a, and MACS0600-z6.4. Observations were done in service mode on the 18th and 19th October 2020 (ID : GN-2020B-Q-903; P.I.: A. Zitrin). We secured 4.5 h reaching a  $1\sigma$  sensitivity of  $8.9 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2}$  over the wavelength range of 505 to 980 nm. We reduced the data using the Gemini IRAF package, as recommended by the instrument team. We follow the standard reduction procedure including bias subtraction, flat fielding, wavelength calibration from the illumination of our mask by the CuAr lamp and flux calibration from the white dwarf Wolf 1346.

Interestingly, the continuum of the more compact and brightest image (MACS0600-z6.3a) is visible on the Gemini spectra. We extracted the spectrum in a  $1.5\times$  seeing diameter aperture and a break is clearly identified between 850 and 900 nm. To improve the signal, we binned the spectra in the spectral direction with a binning factor of 30 (see Fig. 5). We determined the spectroscopic redshift by fitting our observed spectra with a stacked spectra coming from 81 LBGs (Jones, Stark & Ellis 2012). We searched for the best-fit using a  $\chi^2$  minimization technique over a redshift range between  $z = 0$  and  $z = 8$ . The best fit is found at  $z_{\text{spec}} = 6.19^{+0.06}_{-0.16}$ , consistent with both the photometric redshift and the [C II]158  $\mu\text{m}$  emission line detected in the ALMA data. One can also argue that if the break seen in the Gemini data is the Balmer Break at  $z \sim 1.1$  instead of the Lyman Break at  $z \sim 6$ , we would have detected the [O II]3727,3729 doublet, which makes the high-redshift identification for this system robust.

However, in the case of an extremely dusty  $z \sim 1$  galaxy, with  $A_v > 4.5$  mag (assuming  $\text{SFR} = 10 M_{\odot} \text{ yr}^{-1}$ ), the [O II]3727,3729 doublet might be attenuated so as to render its flux below our detection limit. Moreover, after a careful visual inspection of the 2D spectra, no emission line is detected in any of the three images allowing us to place a firm upper limit on the Ly  $\alpha$  luminosity in this  $z \sim 6$  system at  $L(\text{Ly } \alpha, 2\sigma) < 2.4 \times 10^{42} \text{ erg s}^{-1}$ , corresponding to a rest-frame EW of  $\text{EW} < 3.6 \text{ \AA}$  assuming a magnification factor of  $\mu = 31$ . We note that the level of the continuum is consistent with the photometry we measured on *HST* images (F814W and F105W). While it would be valuable to compare the UV slope inferred from our GMOS spectrum with that indicated photometrically, the limited wavelength range of the form is insufficient for a precise measurement.

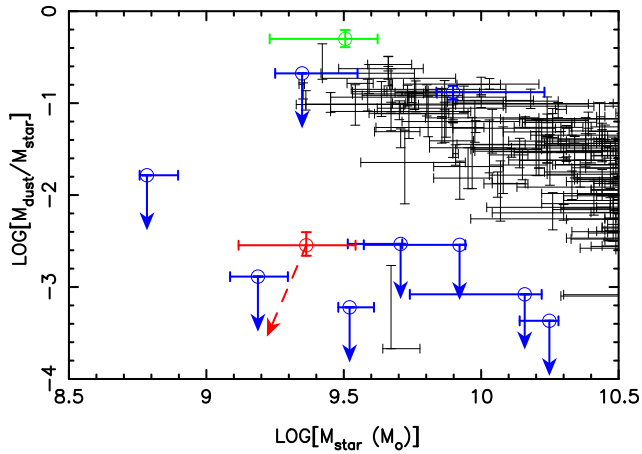
#### 5 PHYSICAL PROPERTIES

We determine the intrinsic (lensing-corrected) physical properties for those two images with a clear dust detection (MACS0600-arc and MACS0600-z6.3b) using MAGPHYS (da Cunha, Charlot & Elbaz 2008a), which includes FIR models to fit the dust properties, while we use BAGPIPES (Carnall et al. 2018) to provide constraints for the remaining images. For the BAGPIPES runs, we assume a constant star formation history (SFH) with a stellar mass ranging from  $10^6$  to  $10^{12} M_{\odot}$ , and an age ranging from 0.0 Gyr to the age of the Universe at  $z = 6.07$ . For each image, we adopt the magnification from the LTM model, based upon the spectroscopic redshift, although as seen in the previous section the magnifications from the three models seem to agree fairly well. Reassuringly, we determine that all images have similar properties. Excluding image MACS0600-z6.3a, which does not seem to contribute significantly to the flux compared to MACS0600-z6.3b, the mean stellar mass is  $2.9^{+11.5}_{-2.3} \times 10^9 M_{\odot}$ , the mean SFR is  $9.7^{+23.0}_{-6.6} M_{\odot} \text{ yr}^{-1}$  and the mean dust mass (computed only from images MACS0600-arc and MACS0600-z6.3b) is  $4.8^{+4.5}_{-3.4} \times 10^6 M_{\odot}$ , where error bars take into account uncertainties on the magnification factor. The latter is obtained assuming a dust temperature of 30 K, a dust emissivity of  $\beta = 2.0$  and the mean magnification. Including *Herschel*/SPIRE  $3\sigma$  upper limit (13.9 mJy/ $\mu$  at 250  $\mu\text{m}$ ), we can rule out  $T_{\text{dust}} \geq 85 \text{ K}$  (Sun et al. in preparation). We measure the UV slopes of all images from the best SED fit and find an average  $\beta = -1.66 \pm 0.08$ . We follow the method described in Oesch et al. (2010) to determine the size of this galaxy, taking into account the SExtractor half-light radius and the *Hubble* PSF. We apply this method on z6.4, since this image is not blended with other sources. After correcting for magnification, we find an intrinsic size of 0.10 arcsec corresponding to  $0.54^{+0.26}_{-0.14} \text{ kpc}$  at  $z \sim 6.07$ , in good agreement with previous size estimates at these redshifts (Bouwens et al. 2017; Kawamata et al. 2018). The individual properties of each image are summarized in Table 3.

We can compare the above results for MACS0600-z6 to similar spectroscopically confirmed galaxies at  $z \sim 6-7$  (either a detection or upper limit) in the literature (Kanekar et al. 2013; Ouchi et al. 2013; Schaerer et al. 2015; Knudsen et al. 2016; Bradač et al. 2017; Marrone et al. 2018; Smit et al. 2018). Most of these galaxies have upper limits on their dust content, emphasizing the importance of MACS0600-z6. Despite its modest stellar mass, its dust to stellar mass ratio is somewhat larger than that observed in other  $z \sim 6$  galaxies (Fig. 6). This implies either that MACS0600-z6 is already a relatively mature system or that its dust production was unusually efficient. We can provide an independent estimate of the stellar age via the amplitude of the Balmer Break (see e.g. Scoville et al. 2016). This requires comparing the fluxes in the F160W and 4.5  $\mu\text{m}$

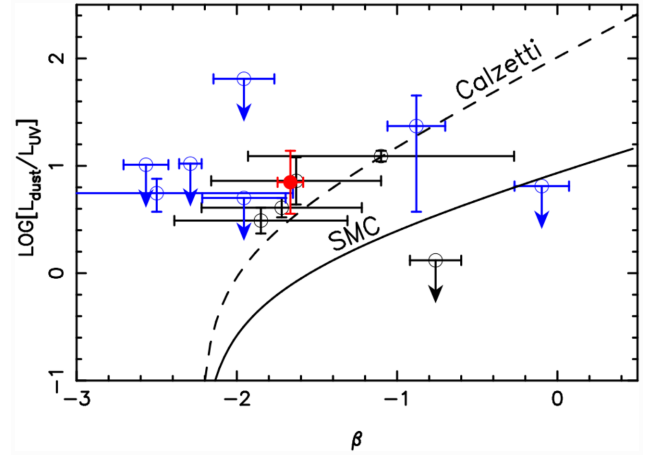
**Table 3.** Physical properties of all multiple images of MACS0600-z6 computed with MAGPHYS (da Cunha et al. 2008a) for sources with dust detection (arc and z6.3b) and BAGPIPES (Carnall et al. 2018) for the remaining. Uncertainties for the LTM model magnification represent the range of values predicted by four other trial LTM models. The central value is obtained by averaging the parameter value of the best-fitting model obtained assuming the mean, min and max magnification value and the error bars included uncertainties on the magnification factor.

Source	$M_*$ [ $\times 10^9 M_\odot$ ]	$M_{\text{dust}}$ [ $\times 10^6 M_\odot$ ]	SFR [ $M_\odot \text{ yr}^{-1}$ ]	$\beta$	$\mu$
arc	$2.2^{+1.3}_{-0.9}$	$4.5^{+3.4}_{-3.1}$	$6.1^{+7.6}_{-1.9}$	$-1.6 \pm 0.1$	$31^{+10}_{-9}$
z6.3a	$2.7^{+1.9}_{-1.0}$	–	$15.3^{+4.6}_{-6.3}$	$-1.6 \pm 0.2$	$(13^{+3}_{-2})$
z6.3b	$1.1^{+0.6}_{-0.5}$	$5.1^{+4.2}_{-3.2}$	$5.9^{+3.5}_{-2.8}$	$-1.7 \pm 0.3$	$13^{+3}_{-2}$
z6.4	$3.7^{+2.3}_{-2.1}$	–	$10.3^{+12.0}_{-6.0}$	$-1.7 \pm 0.1$	$2.1^{+0.6}_{-0.7}$
z6.5	$4.7^{+9.7}_{-3.4}$	–	$10.7^{+22.0}_{-5.8}$	$-1.6 \pm 0.3$	$3.8^{+0.3}_{-0.4}$



**Figure 6.** Dust to stellar mass ratio as a function of the stellar mass. The red dot shows the properties of MACS0600-z6, blue dots represent previously observed galaxies with dust constraints (detections or upper limits) with a spectroscopic redshift between  $z \sim 6$  and 7 (Kanekar et al. 2013; Ouchi et al. 2013; Schaerer et al. 2015; Knudsen et al. 2016; Bradač et al. 2017; Laporte et al. 2017a; Marrone et al. 2018; Smit et al. 2018). Black dots show lower redshift galaxies at  $z \sim 1.5$ –3.5 (Sklia et al. 2014; Dudzevičiūtė et al. 2020). The ratio for MACS0600-z6 is fairly high for its redshift, indicating either that it is relatively old or that its dust production was unusually efficient. The green circle shows the position of MAMBO-9, a sub-mm galaxy with an extreme dust to stellar mass ratio at  $z = 5.9$  (Casey et al. 2019); the distinct natures of these two galaxies (sub-mm versus LBG) makes a comparison of their dust production efficiency difficult. The red dashed arrow shows the direction in parameter space that the LBG would move when taking into account high dust temperature ( $T = 85$  K) and uncertainties on the magnification..

bands, since the  $3.6 \mu\text{m}$  band could be contaminated by strong [O III] emission (Labbé et al. 2013). Following the methodology discussed in Roberts-Borsani, Ellis & Laporte (2020), we estimate an age of  $200 \pm 100$  Myr, indicative of a formation redshift of  $z_{\text{form}} = 7.2^{+0.8}_{-0.6}$ , comparable to values estimated for the other  $z \sim 6$  galaxies cited above. This relatively young age would suggest that most of the dust detected by ALMA maybe produced by early core-collapse supernovae (SNe) (Gall, Andersen & Hjorth 2011). Assuming a Chabrier (Chabrier 2003) IMF for the production rate of SNe, for the measured dust mass and stellar age, each SN would have produced  $0.3^{+0.5}_{-0.2} M_\odot$  of dust. Although this estimate is highly uncertain given the uncertain production rate of SNe in early metal-poor galaxies and possible dust destruction and ejection processes in low-mass



**Figure 7.** The IR/UV luminosity ratio IRX as a function of the UV slope  $\beta$ . Black points represent galaxies at  $z \geq 7$ , blue points are  $z \sim 6$  galaxies and the red circle shows MACS0600-z6. All values are computed assuming a dust temperature of 35 K. The expected trend assuming the Calzetti et al. (2000) and SMC laws are shown.

galaxies at high redshift, it is perhaps somewhat larger than that derived locally ( $<0.2 M_\odot$ , see e.g. Cherchneff & Dwek 2010; Gall et al. 2011; Gomez et al. 2012; Indebetouw et al. 2014). Recent chemical evolution models predict dust-to-mass ratios similar to that observed for MACS0600-z6 could be achieved in  $\leq 200$  Myr (Calura et al. 2017). Even higher values have also been observed recently in MAMBO-9 (Casey et al. 2019), an intensely star-forming submm galaxy whose properties are otherwise quite distinct from those of MACS0600-z6. Applying the same method, MAMBO-9 may be even more efficient to produce dust, but the different nature of these two objects makes the comparison of their dust production efficiency difficult.

The ratio between the IR and UV luminosity, often referred to as  $\text{IRX} = \log(L_{\text{IR}}/L_{\text{UV}})$ , can be compared to the UV continuum slope  $\beta$  to offer insight into the dust extinction law at early cosmic epochs. Bouwens et al. (2016) found that  $z > 4$  galaxies with  $\log[M_*, <9.75]$  (comparable to MACS0600-z6) may have extinction laws that deviate from both the Calzetti et al. (2000) and SMC relations, in the sense of having lower IRX values. They argued that a higher dust temperature may explain this difference. Although there is some evidence for higher dust temperatures at  $z \geq 8$  (Behrens et al. 2018; Laporte et al. 2019; Bakx et al. 2020), there is currently no strong evidence for evolution at  $z \sim 6$  (e.g. Schreiber et al. 2018; Faisst et al. 2020). Assuming a dust temperature of 35K to estimate the IR luminosity of MACS0600-z6 and the other  $z \sim 6$  galaxies, Fig. 7 shows that most  $z \sim 6$  galaxies follow the Calzetti law.

## 6 DISCUSSION AND CONCLUSION

Recent studies have suggested that the dust temperature may be higher at high-redshift than what is measured at lower redshift. Obtaining an accurate measurement of the dust temperature in high-redshift galaxies requires to constrain the red slope and the peak of the FIR emission (see fig. 1 of da Cunha, Charlot & Elbaz 2008b). The evolution of the dust temperature with redshift can be studied at intermediate redshift combining data from *Herschel* and ALMA. Schreiber et al. (2018) demonstrate that the dust temperature goes from 25K at  $z \leq 1$  up to 40 K at  $z \sim 5$ . At  $z \geq 7$ , few sources have been observed at multiple sub-mm wavelengths (Watson et al. 2015;



Knudsen et al. 2017; Laporte et al. 2017b; Laporte et al. 2019; Tamura et al. 2019; Bakx et al. 2020). They all estimate a dust temperature at  $z \geq 7$  above the ‘standard’ value of 30 K observed at low-redshift, but deeper data at  $\lambda \geq 1$  mm are needed. Recent theoretical models suggest that the dust temperature in  $z \geq 5$  galaxies is  $T_{\text{dust}} = 45$  K for  $0.1 \mu\text{m}$  grain, and could reach as high temperature as  $T_{\text{dust}} \geq 60$  K for smaller grains (Ferrara et al. 2017). In view of this, we explore whether a higher dust temperature would change our conclusions. For a temperature of 85 K, the estimated dust mass would decrease to  $M_{\text{dust}} = 6.3_{3.6}^{+1.6} \times 10^6 M_{\odot}$ , and its dust-to-stellar mass ratio will be comparable to previous findings at high redshift. Further ALMA observations at longer wavelength (e.g. in band 5) are needed to constrain the dust temperature and to refine our dust mass estimates. Moreover, adopting a higher dust temperature to study the IRX– $\beta_{\text{UV}}$  relation confirms our conclusion on the dust law preferred by our object, since an increase in dust temperature will increase the dust luminosity without changing the UV luminosity, and will therefore tend to higher IRX, consistent with the Calzetti law.

Such intrinsically faint sources ( $M_{\text{UV}} = -19.9 \pm 0.15$ ) emitting light during the Epoch of Reionization are considered to be dominant contributors to the cosmic reionisation of hydrogen (e.g. Atek et al. 2015; Bouwens et al. 2017). This strongly lensed system has therefore the capabilities of testing this hypothesis. Recent studies of the Ly  $\alpha$  emission line (either from LBG or LAE) using MUSE/VLT (e.g. de La Vieuville et al. 2019; de La Vieuville et al. 2020) or the Hyper Suprime-Cam/Subaru (e.g. Konno et al. 2018) show that the luminosity of Ly  $\alpha$  at  $z \geq 5.5$  ranges from  $10^{40}$  to  $10^{43.8} \text{ erg s}^{-1}$ . The Ly  $\alpha$  properties in MACS0600-z6 ( $L(2\sigma) < 2.4 \times 10^{42} \text{ erg s}^{-1}$  and  $\text{EW}_{\text{RF}} < 3.6 \text{ \AA}$ ) are therefore not particularly exceptional and comparable in luminosity and Ly  $\alpha$  EW to the bulk of the galaxy population at  $z \sim 6$ .

We report the discovery of a  $z = 6.07$  dusty galaxy strongly lensed by the cluster MACS0600.1-2007 comprising five multiple images. We used three different mass models for the cluster, showing good agreement between predicted magnification factors and observed flux ratio between the five images of this galaxy. The physical properties we deduced from a detailed SED analysis show that this galaxy has a stellar mass of  $\sim 10^9 M_{\odot}$ , a dust mass of  $\sim 10^6 M_{\odot}$ , respectively, a small star formation rate ( $< 10 M_{\odot} \text{ yr}^{-1}$ ) and a size ( $\sim 0.5$  kpc) consistent with previous observations. We estimate the dust production rate in this galaxy and conclude that it seems higher than what has been observed in  $z \leq 5$  galaxies. Further sub-mm observations, as provided by ALMA, are crucial to improve the estimate of the dust content of this galaxy.

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## DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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