Clumpy galaxies at $z \sim 0.6$: kinematics, stability, and comparison with analogs at other redshifts

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ABSTRACT
Distant clumpy galaxies are thought to be Jeans-unstable disks, and an important channel for the formation of local galaxies, as suggested by recent spatially-resolved kinematic observations of $z \sim 2$ galaxies. I study the kinematics of clumpy galaxies at $z \sim 0.6$, and compare their properties with those of counterparts at higher and lower redshifts. I selected a sample of 11 clumpy galaxies at $z \sim 0.6$ from the representative sample of emission line, intermediate-mass galaxies IMAGES. Selection was based on rest-frame UV morphology from HST/ACS images, mimicking the selection criteria commonly used at higher redshifts. Their spatially-resolved kinematics were derived in the frame of the IMAGES survey, using the VLT/FLAMES-GIRAFFE multi-integral field spectrograph. For those showing large-scale rotation, I derived the Toomre $Q$ parameter, which characterizes the stability of their gaseous and stellar phases. I find that the fraction of UV-selected clumpy galaxies at $z \sim 0.6$ is 20 ± 12%. Roughly half of them (45 ± 30%) have complex kinematics inconsistent with Jeans-unstable disks, while those in the remaining half (55 ± 30%) show large-scale rotations. The latter reveal a stable gaseous phase, but the contribution of their stellar phase makes them globally unstable to clump formation. Clumpy galaxies appear to be less unstable at $z \sim 0.6$ than at $z \sim 2$, which could explain why the UV clumps tend to vanish in rest-frame optical images of $z \sim 0.6$ clumpy galaxies, conversely to $z \sim 2$ clumpy galaxies, in which the stellar phase can substantially fragment. This suggests that the former correspond to patchy star-formation regions superimposed on a smoother mass distribution. A possible and widespread scenario for driving clump formation relies on instabilities by cold streams penetrating the dark matter halos where clumpy galaxies inhabit. While such a gas accretion process is predicted to be significant in massive, $z \sim 2$ haloes, it is also predicted to be strongly suppressed in similar, $z \sim 0.6$ haloes, which could explain why lowest-$z$ clumpy galaxies appear to be driven by a different mechanism. Instead, I found that interactions are probably the dominant driver leading to the formation of clumpy galaxies at $z < 1$. I argue that the nature of $z > 1$ clumpy galaxies remains more uncertain. While cold flows could be an important driver at $z \sim 2$, I also argue that the observed and cumulative merger fraction between $z = 2$ and $z = 3$ is large enough so that every $z \sim 2$ galaxy might be the result of a merger that occurred within their past 1 Gyr. I conclude that it is premature to rule out mergers as a universal driver for galaxy evolution from $z \sim 2$ down to $z = 0$.

Key words: Galaxies: evolution; Galaxies: kinematics and dynamics; Galaxies: high-redshifts; galaxies: general; galaxies: interactions; galaxies: spiral.

1 INTRODUCTION
How galaxies formed, evolved, and built-up the local Hubble sequence is still an open and highly debated issue. For instance, there is now evidence for a significant evolution of the stellar mass density at $z \sim 1$. Even between redshifts as low as $z \sim 0.6$ and $z = 0$, the stellar mass density appears to be evolving by 0.2 dex (i.e., ∼40%), see, e.g., Pérez-González et al. (2008). Such an evolution in stellar mass can also be seen in the evolution of the Tully-Fisher relation, which appears to be evolving by a factor two in stellar mass over the same redshift range (Puech et al. 2008, 2010a). Such an increase in stellar mass needs to be fed by fresh gas. The absence of evolution in zero point of the baryonic Tully-Fisher relation between $z \sim 0.6$ and $z = 0$ (Puech et al. 2010a) suggests that most of this gas was already gravitationally bound to galaxies at $z \sim 0.6$. What is the mechanism driving the conversion of this gas into stars? In spite of the impressive progress accomplished over the past years, mainly through spatially-resolved kinematics of distant galaxies, this issue still remains without a clear answer.

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sentative sample of 63 galaxies with $M_{\text{stellar}} \geq 1.5 \times 10^9 M_\odot$ and spatially-resolved kinematics derived from FLAMES/GIRAFFE observations at the VLT. They found that 40% of $z\approx 0.6$ intermediate-mass galaxies (i.e., the progenitors of local spirals), have chaotic velocity fields inconsistent with expectations from pure rotating disks. Subsequent analyzes suggest that most of them are likely associated with major mergers (Hammer et al. 2009b). Mergers are also found to be a good driver for the large scatter seen in the distant Tully-Fisher relation (Puech et al. 2010; Covington et al. 2010). Actually, the remarkable co-evolution of the morphology, kinematics, star formation density, metal density, and stellar mass density, all could find a common and natural explanation in the frame of the spiral rebuilding scenario, according to which 50 to 75% of present-day spiral disks were rebuilt after a major merger since $z\approx 1$, as proposed by Hammer et al. (2005). To this respect, the Milky Way appears to be exceptional, with a remarkable quite past history compared to other local spiral galaxies (Hammer et al. 2007).

There is now a growing body of evidence suggesting that disk rebuilding indeed took place at $z\approx 1$, which makes it as a viable driver for galaxy evolution at these epochs. On the theoretical side, numerical simulations showed how gas can be expelled in tidal tails during such mergers, and how it can be subsequently re-accreted (Barnes 2002). This re-accreted gas is expected to cool down and form new stars, re-building a new disk around a spheroidal remnant (Springel & Hernquist 2000; Robertson et al. 2006), which might correspond to morphologies as late as Sb galaxies (Lotz et al. 2008; Hopkins et al. 2009c). Recent theoretical developments have shed light on the underlying process, which appears to be purely gravitational (Governato et al. 2009). The requirement for a major merger to rebuild a new disk depends mainly on the gas fraction during the final coalescence, which needs to be at least 50% (Robertson et al. 2006). Cosmological simulations are now also producing such re-processed disks at $z<1$, although the role of cosmological gas accretion is not totally understood, but taking this process into account could result in a lower gas fraction threshold for rebuilding a new disk (Governato et al. 2009). On the observational side, first examples of rebuilt disks were recently detected at $z\approx 0.6$ (Puech et al. 2009; Hammer et al. 2009a), and the auto-consistency of the disk rebuilding process starts being investigated, both theoretically (Hopkins et al. 2009b; Stewart et al. 2009; Hopkins et al. 2009c), and observationally (Hammer et al. 2009b; Kannappan et al. 2009; Bundy et al. 2009; Huertas-Company et al. 2010).

If the spiral rebuilding scenario appears to achieve encouraging successes in describing galaxy evolution at $z\approx 1$, some points still need to be investigated. In particular, the impact of the expected numerous minor mergers on the survival of thin disks is still debated (Toth & Ostriker 1992; Hopkins et al. 2008; Purcell et al. 2009; Moster et al. 2009b). Furthermore, Luminous InfraRed Galaxies (LIRGs) account for about 80% of the star formation density reported at $z\approx 1$ (Hammer et al. 2005), but their morphologies reveal that only half of $z>0.5$ LIRGs are compatible with mergers, while those in the other half appear to be spiral (Melbourne et al. 2005). Marcillac et al. (2006) showed that the large number density of LIRGs at these epochs suggests that they could experience between two and four star formation bursts until $z\approx 0$, with typical timescales of $\sim 0.1$ Gyr, which is not consistent with a simply continuous star formation history. They concluded that minor mergers, tidal interactions, or gas accretion remain plausible triggering mechanisms in distant LIRGs harboring a spiral morphology. Interestingly, 75% of local LIRGs are barred, which could play a role in regulating star formation in such objects (Wang et al. 2006).

At higher redshifts (i.e., $z>1$), the co-moving density of galaxy appears to be dominated by clumpy irregular galaxies (Elmegreen et al. 2007). Interest for such objects dates back to Cowie et al. (1995), who first noticed the unusual aspects of some high-$z$ galaxies, dubbed as "chain galaxies" and described as "linearly organized giant star-forming regions". The large occurrence of blue star-forming knots in less edge-on objects was also later recognized as a general and intriguing feature of distant galaxies, probably linked to an early phase in the formation of local spiral galaxies (Cowie et al. 1995; van den Bergh et al. 1996), and were latter referred to as "clump clusters" by Elmegreen et al. (2004). The improved spatial resolution provided by the HST/ACS re-invigorated the interest for these objects, which were all suggested to be different incarnations of the same underlying population viewed along different inclination angles (O’Neil et al. 2000; Elmegreen et al. 2004b). Both kind of objects are therefore often referred to as "clumpy galaxies". They are found to be typically made of 5-10 kpc-sized clumps with stellar masses $\sim 10^{-9} M_\odot$ (i.e., $\sim 100$ times more massive than the largest star complexes in present-day spiral galaxies), and they typically account for one third of the total galaxy emission (Elmegreen & Elmegreen 2005). Such clumps are thought to be linked to the formation of disks, as suggested by the increase of the inter-clump surface density, and the decrease of the mass surface density contrast between the clumps and the inter-clump regions, when going from clumpy galaxies with no evident inter-clump emission to clumpy galaxies with faint red disks, and spiral galaxies (Elmegreen et al. 2009).

What is driving the formation of these clumps has been the subject of many attentions during the past decade. Numerical simulations suggest that clumps might originate from the local gravitational instability of very gas-rich disks of young galaxies (Noguchi 1998; Immeli et al. 2004). Due to their large masses, the clumps would experience strong dynamical friction and spiral towards the galaxy center within a few Gyr, which might lead to the formation of a bulge (Noguchi 1999; Elmegreen et al. 2008, 2009), as well as a thick stellar disk through strong stellar scattering (Bournaud et al. 2009b). Simulated clumps are found to show properties similar to observations (Immeli et al. 2004b; Bournaud et al. 2007). The lifetime of these clumps is so short and the fraction of clumpy galaxies at $z>1$ so high, that making the clumpy phase a long-term phenomenon requires a continuous and rapid fresh supply of cold gas in order to feed the disk and regenerate new clumps (Dekel et al. 2009b). Theoretical developments indeed suggested that early galaxy formation is fed by cold streams penetrating through dark matter halos (Dekel et al. 2009). These cold streams are expected to maintain a dense disk that can undergo gravitational fragmentation into several giant clumps (Dekel et al. 2009b). This possible link between high-$z$ clumpy galaxies and the cosmological context was strengthened both by recent cosmological numerical simulations (Agertz et al. 2008; Ceverino et al. 2009), and semi-analytic models (Khochfar & Silk 2009).

Alternatively, it was proposed that clumps could also result from on-going mergers or interactions (Taniguchi & Shioya 2001; Overzier et al. 2008; di Matteo et al. 2008). Discriminating between the merger and fragmentation scenario is not straightforward because it requires high-resolution integral field spectroscopy in high-$z$ galaxies. Indeed, as stated by Noguchi (1999), the most straightforward and powerful test for discriminating between the two hypothesis is to examine the kinematics of the clumps: in the merger scenario, a random orientation of clump
spins is expected, while in the fragmentation scenario, clumps are expected to be coplanar. In particular, one interesting predictions of these simulations is that the large-scale rotation in the underlying disk should be preserved during the fragmentation phase (Immel et al. 2004; Bournaud et al. 2007). The achievement of integral field spectrograph working in the near infrared (e.g., SINFONI at the VLT, or OSIRIS at Keck), allowed several teams to gather spatially-resolved kinematic observations of z∼1 distant galaxies (see, e.g., Forster Schreiber et al. 2009; Law et al. 2009 and references therein, as well as Wright et al. 2009; Bournaud et al. 2009; van Starkenburg et al. 2009; Epinat et al. 2009). Detection of an underlying rotation was claimed in several z∼2 distant galaxies, which has been used as a support to the fragmentation scenario (Genzel et al. 2008).

Surprisingly, analysis of integral field spectroscopy observations suggest that two different scenarii might take place at z<1, and at z>1. It therefore becomes necessary to start investigating whether both scenarii are consistent, and whether or not a transition between the two different galaxy evolution drivers is occurring between these two epochs. To this aim, I take advantage of the IMAGES survey to study clumpy galaxies at z=0.6. The goal is to investigate which of the merger or fragmentation scenario is the most consistent with z<0.6 clumpy galaxies, and investigate whether clumpy galaxies at z<1 and at z>1 are driven by a common physical process. This paper is organized as follows: In Sect. 2, I describe how the clumpy galaxies at z∼0.6 were selected; In Sect. 3, I present their kinematic and dynamical properties; Sect. 4 discusses the origin of the clumpiness in distant galaxies; Sect. 5 discusses the results, while conclusions are drawn in Sect. 6. Throughout the paper, I adopt H0 = 70 km/s/Mpc, ΩM = 0.3, and ΩΛ = 0.7, and the AB magnitude system.

2 SAMPLE SELECTION & FRACTION OF CLUMPY GALAXIES AT Z∼0.6

In this paper, I made use of the representative IMAGES sample of 63 emission line galaxies at z∼0.6. The sample is fully described in Yang et al. (2008), and I refer the reader to this paper for details. This sample was observed by FLAMES/GIRAFFE at the VLT, which allowed us to derive spatially-resolved kinematics for all these galaxies. The dynamical state of these galaxies was studied, according to which they were classified into three classes: Rotating Disks (RDs) are galaxies showing regular rotation well-aligned along the morphological axis, Perturbed Rotators (PRs) show a large-scale rotation with a local perturbation in the velocity dispersion map that cannot be accounted for by rotation, while galaxies with Complex Kinematics (CKs) do not show any large-scale rotation, or a strong misalignment between the dynamical and morphological axes (Yang et al. 2008). This classification takes into account the residuals between the observed VΦ and σ-map and those predicted by a rotating-disk model (see Yang et al. 2008), which makes this classification objective and reproducible. For reasons of homogeneity, and to benefit from the most exquisite images from the ACS camera on-board the HST, I limited myself to galaxies lying in the CDFS-GOODS field. This study is therefore based on a sample of 32 galaxies. Note that this sample is still representative of z∼0.6, intermediate-mass galaxies, as shown by Yang et al. (2008).

I selected clumpy galaxies following selection criteria depicted by Elmegreen & Elmegreen (2005) and Elmegreen et al. (2007). Specifically, I required for a galaxy to be clumpy to fulfill the following requirements:

(i) showing at least three clumps in the rest-frame UV image. To check this, I used B133-band HST/ACS images, which corresponds to ∼270 nm rest-frame. Note that Elmegreen & Elmegreen (2005) used the observed i575 band but at higher redshift (see also Elmegreen et al. 2007), which also roughly matches the rest-frame UV for most of their clumpy galaxies;

(ii) absence of spatial features associated with spiral galaxies (e.g., central bulge);

(iii) the underlying light profile must be inconsistent with an exponential disk (Elmegreen et al. 2005). Therefore, I discarded all galaxies where a Sersic profile resulted in a good fit (see Neichel et al. 2008).

Obviously, such a selection method is rather subjective. In order to stick to former studies of such galaxies at higher redshift, I nevertheless chose to keep these selection criteria and ignored further color and kinematic information from the IMAGES database. Instead, this information was used a posteriori to investigate whether the candidates selected this way were truly rotating and/or corresponded to Jeans fragmentation processes. The selection was done independently by three member of the IMAGES consortium (including the author), and results compared until a consensus was reached for each object. I ended up with a sample of 11 candidates, which are shown in Fig. 1. A visual comparison with Fig. 1 of Elmegreen & Elmegreen (2005) confirms that all z∼0.6 candidates indeed look similar to higher-z clumpy galaxies.

Since the IMAGES-CDFS sample is representative of z∼0.6 emission line galaxies, I can estimate the fraction of emission line clumpy galaxies at z∼0.6, which is found to be 34±18%, with error-bars due to Poisson fluctuation in the parent sample. This is in very good agreement with results from the UDF at z=1, and a factor ~2 less than at z∼2.3 (Elmegreen et al. 2007). If one accounts for the fact that emission line galaxies represent 60% of intermediate mass galaxies at z∼0.6 (Hammer et al. 1997; see also Mignoli et al. 2005), one finds that clumpy galaxies represent 20±12% of intermediate-mass galaxies at this redshift.

3 KINEMATICS & STABILITY OF Z∼0.6 CLUMPY GALAXIES

3.1 Clumpy galaxies with complex kinematics: mergers?

Spatially-resolved kinematics was obtained, amongst others, for all of the 11 clumpy galaxies by Yang et al. (2008). Amongst them, five were found to be CKs, four corresponded to PR, and two were classified as RDs (see Appendix). Rotation requires a significant inclination angle to be detected, (i.e., a face-on disk would not show any rotation due to projection effects). I checked that such projection effects do not affect the relative fraction of CK galaxies: considering the full sample of 63 IMAGES galaxies from Yang et al. (2008), the fraction of face-on galaxies (i.e., having an inclination angle smaller than 30 degrees), is found to be 10, 17, and 13%±8% amongst RD, PR, and CK galaxies, respectively. This rules out any significant bias due to such projection effects, even if it cannot be excluded that a particular object might be affected.

According to predictions from numerical models, Jeans-fragmentation should preserve the rotation of the underlying disk (see, e.g., Immeli et al. 2004; Bournaud et al. 2007). Therefore, it is expected that distant clumpy galaxies should in principle appear as RD or PR (see, e.g., Genzel et al. 2008). Indeed, clumps have diameters ~kpc, while the GIRAFFE IFU pixel size is 0.52 arcsec, which corresponds to 3.5 kpc at z=0.6. Therefore, the spatial
scale of clumps remains well below the spatial resolution of GIRAFFE observations. This means that all kpc-sized substructures are strongly smoothed by the GIRAFFE IFU, and it is therefore expected that most Jeans unstable disks show a clear large-scale rotation, possibly affected by perturbations. It cannot be excluded that due to a given particular orientation or a particularly large number of clumps, and due to the relatively coarse spatial resolution of the GIRAFFE IFU, a given Jeans-unstable disk could not be classified as a galaxy with a complex kinematics. However, this would require very strong perturbations in the morpho-kinematics at a level which does not appear to be representative of most clumpy disks observed at high redshifts. Moreover, we find that 9% of intermediate-mass galaxies at z<0.6 are CK clumpy galaxies. If clumps were strong enough to break a pre-existing disk, this would mean that such galaxies would result in elliptical galaxies. Indeed, given the low level of cold gas accretion at z<1 (see Sect. 4.2), there would be simply not enough fresh material available to reform a disk after its destruction. However, the fraction of elliptical galaxies does not evolve significantly over this redshift range. This implies that, if such strong clumps exist, they cannot destroy completely the disk. Hence, a rotation should be detected in such objects, particularly on large spatial scales, such as those probed by the GIRAFFE IFU. To this respect, there is a sub-class of CK galaxies which deserves more attention. Those are the galaxies which show a velocity gradient that might be associated with rotation, but which were classified as CK because of a significant misalignment between their kinematic and morphological main axes. In the sample of CK clumpy galaxies, only J033224.60-274428.1 belongs to this sub-class (see Fig. A1). Such a particular case cannot affect significantly the conclusions of this paper.

The above suggests that a very large majority of z<0.6 CK clumpy galaxies are not the result of Jeans instability. Actually, such a kinematics was rather associated with the result of major mergers, as suggested by Peirani et al. (2009), Puech et al. (2009), Hammer et al. (2009b), Yang et al. (2009), and Fuentes-Carrera et al. (2010). During such processes, the gaseous phase can be compressed to column densities high enough to make the gas unstable, which can result in the formation of clump

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1 Simulations confirm this effect, as illustrated in the frame of the E-ELT by Puech et al. (2010b), see their Fig. 13. After this work, Puech et al. (2009) and their Fig. 8: the smoothing applied to match observations is seven times smaller in length than the GIRAFFE IFU spatial resolution (~7 kpc), while all kinematic disturbances are already strongly attenuated at the kpc scale. Such a galaxy would clearly be classified as RD or PR, but not as CK because of the clear velocity gradient and the velocity dispersion peak located at the dynamical center.

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Figure 1. Rest-frame UV (~2700 Å) morphology of the 11 clumpy galaxies selected in the IMAGES survey, at z~0.6. From left to right, and top to bottom: J033231.58-274121.6, J033210.25-274819.5, J033219.61-274831.0, J033233.90-274237.9, J033234.04-275009.7, J033239.04-274132.4, J033224.60-274428.1, J033227.07-274404.7, J033230.57-274518.2, J033234.12-273953.5, J033239.72-275154.7.
complexes, as shown by Elmegreen et al. (1993). Interestingly, Elmegreen et al. (1993) mentioned that stronger perturbations are expected to lead to a larger velocity dispersion and larger cloud complexes by gravitational instability. If clumpy galaxies classified as CKs at \( z \approx 0.6 \) are the result of galaxy mergers, then one expects that their mass ratios, orbits, and merger phases correspond to the strongest perturbations, in terms of gas compression.

Hammer et al. (2009b) conducted a systematic first-order modelling of \( z \approx 0.6 \) galaxies in the IMAGES-CTDFS sample. They used hydrodynamical simulations from Barnes (2002) to infer for each galaxy a possible mass ratio, merger phase (i.e., before the first pass, between the first and second pass, nuclei fusion, etc.), and orbit. They used a limited base of reference simulations, but this is enough to infer first-order conditions for the progenitors. Note that in two cases, a full modelling was carried out by Peirani et al. (2009) and Puentes-Carrera et al. (2010), which confirms the first-order model inferred by Hammer et al. (2009b). For the five clumpy galaxies classified as CKs, Hammer et al. (2009b) indeed found mass ratios between 1:4 and 1:1, merging phases between the first passage and the nuclei fusion, and direct or inclined orbits, i.e., the initial conditions that are expected to result in the strongest gas compression during the collision, as expected from numerical simulations of binary mergers (e.g., di Matteo et al. 2007; Cox et al. 2008). One might however object that clumpy galaxies with complex kinematics (and more generally \( z \approx 0.6 \) CK galaxies in the parent sample) do not necessarily show morphological features like tails, bridges, double nuclei, nearby companions, etc., which are generally considered as clear evidences for mergers. However, it is important to realize that available images, and even those from the HST/ACS, are not deep enough to guarantee a systematic detection of such features. For instance, with HST/ACS images in the GOODS field, one would detect the optical radius of the MW only up to \( z \approx 0.5 \) (as inferred by redshifting \( R_{\text{rot}} \)) and Puech et al. (2007). Thus, \( z \approx 0.6 \) galaxies are likely to be the result of mergers, and the contribution of these mergers to the global gas mass is expected to be significant.

3.2 Clumpy galaxies with rotation: Jeans-unstable disks?

In this section, I investigate the stability of the six remaining clumpy galaxies that were classified as RDs or PRs, i.e., those showing large-scale rotation. The instability of gravitational disks can be quantified using the Toomre parameter \( Q \) (Safronov 1963; Toomre 1964; Goldreich & Lynden-Bell 1965). For a gravitational disk to fragment into clumps, it is required that \( Q < 1 \), which means that the system is unstable to both radial and axisymmetric perturbations (e.g., Polvachenko et al. 1997; Griv 2006).

For a pure gaseous disk, and at large galacto-centric radius (i.e., on the flat part of the rotation curve), \( Q_{\text{gas}} \) can be directly estimated from observables in the following way (Elmegreen et al. 1993):

\[
Q_{\text{gas}} = 1.4 \left( \frac{V_{\text{rot}}}{20 \text{km s}^{-1}} \right) \left( \frac{\sigma_{\text{gas}}}{200 \text{km s}^{-1}} \right),
\]

where \( \sigma_{\text{gas}} \) is the gas velocity dispersion, \( \Sigma_{\text{gas}} \) is the gas surface density, \( V_{\text{rot}} \) is the gas rotation velocity, and \( R_{\text{gas}} \) is the gas extension. \( V_{\text{rot}} \) and \( \sigma_{\text{gas}} \) were taken from Puech et al. (2008), and \( R_{\text{gas}} \) from Puech et al. (2010a). \( \Sigma_{\text{gas}} \) was estimated following Puech et al. (2010a), i.e., by inverting the Schmidt-Kennicutt law that relates the star formation rate and gas surface densities. We refer the reader to Puech et al. (2010a) for a complete description of the method.

Finally, \( \sigma_{\text{gas}} \) were estimated following Puech et al. (2007), i.e., as a sigma-clipped mean over the velocity dispersion map, after having excluded the central pixel which, at the spatial resolution of the GIRAFFE IFU, is strongly contaminated by the contribution of larger-scale motions (see Puech et al. 2007 for details).

However, the use of the parameter \( Q \) is complicated by the fact that real galaxies are (at least at first order) a two-phase medium, and cannot be considered as pure stellar or gaseous systems (Jog & Solomon 1984). Indeed, the median gas fraction in the IMAGES sample is 31% (Puech et al. 2010a; Hammer et al. 2009b). In such mixed systems, the gravitational interaction between the stellar and the gaseous phase makes the global system more unstable than the two phases considered individually (Jog 1996). In this case, the stability of such systems cannot be derived from \( Q_{\text{gas}} \) alone, and one has to define an effective \( Q_{\text{eff}} \) that takes into account the effect of both stars and gas (e.g., Jog & Solomon 1984; Elmegreen 1995; Jog 1996). I used the first-order approximation derived by Wang & Silk (1994):

\[
Q_{\text{eff}} = Q_{\text{gas}} + Q_{\text{stars}}^{-1},
\]

with

\[
Q_{\text{stars}} = 1.3 \left( \frac{V_{\text{rot}}}{20 \text{km s}^{-1}} \right) \left( \frac{\sigma_{\text{stars}}}{50 \text{km s}^{-1}} \right),
\]

where the factor 1.3 in front of \( Q_{\text{stars}} \) comes from the factor 1.4 in \( Q_{\text{gas}} \), rescaled by \( \pi/3.36 \) (see, e.g., Elmegreen 1995). I converted half-light radii \( R_{\text{half}} \) derived by Neichel et al. (2008) from \( z \)-band HST/ACS images into total stellar radii \( R_{\text{stars}} \) using \( R_{\text{stars}} = 1.9 \times R_{\text{half}} \), which corresponds to the optical radius in thin exponential disks (see Puech et al. 2010a and references therein). \( \Sigma_{\text{stars}} \) was then derived using \( \Sigma_{\text{stars}} = M_{\text{stellar}}/\pi R_{\text{stars}}^2 \), where \( M_{\text{stellar}} \) are stellar masses derived by Ravikumar et al. (2007) in the IMAGES sample (see also Puech et al. 2008; Hammer et al. 2009a). I excluded contributions to stellar masses from bulges by rescaling the stellar mass using the bulge-to-total \( z \)-band light ratio \( B/T \) derived by Neichel et al. (2008). When no \( B/T \) could be measured, I assumed that all stars lie into a disk. I assumed that \( V_{\text{gas}} \sim V_{\text{stars}} \) as generally observed in local spiral galaxies (Veiga Beltrán et al. 2001; Pizzella et al. 2004). Finally, in distant star-forming galaxies, it is very likely that \( \sigma_{\text{gas}} \sim \sigma_{\text{stars}} \), because a significant fraction of stars were probably formed during the on-going starburst.

The resulting \( Q_{\text{gas}} \), \( Q_{\text{stars}} \), and \( Q_{\text{eff}} \) are shown in Fig. 3. While the gaseous phase appears to be stable for the six clumpy galaxies, the contribution of \( Q_{\text{stars}} \) makes them globally unstable to radial and azimuthal perturbations, i.e., to clump formation. However, a global instability does not necessarily imply that both the stellar and gaseous phases will fragment. If the instability is not strong enough, only the gaseous phase (eventually along with young hot O/B stars) can fragment, while the stellar distribution (i.e., later type stars) remains much smoother. To check this possibility, I examine \( z \)-band images, which corresponds to rest-frame optical wavelengths (i.e., 5451 Å), for all the \( z \approx 0.6 \) clumpy galaxies, as shown in Fig. 3. There is a strong trend in PR/RD clumpy galaxies to have their clumps vanishing in \( z \) band. This is in contrast with higher-\( z \) clumpy galaxies, for which it has been claimed that their morphologies do not change significantly at longer wavelengths (Elmegreen et al. 2007; Lehner et al. 2009). Note that clumpy
galaxies with complex kinematics tend to have persisting clumps in the red. This is consistent with the fact that clumps in these galaxies might result from merger-induced fragmentation, since, under this hypothesis, they were found to correspond to the strongest conditions in terms of gas compression (see above).

Interestingly, all RDs and PRs in the IMAGES-CDFS sample lie downward the $Q_{\text{eff}} = 1$ stability limit, while all do not harbor clumps, since this includes those that were not selected as clumpy galaxies based on their UV morphology (see Sect. 2). This could be linked with the temporal evolution of instabilities in gas-rich disks. Indeed, Immeli et al. (2004) studied the behavior of $Q_{\text{gas}}, Q_{\text{stars}},$ and $Q_{\text{eff}}$ in gas-pure unstable disks. Their simulations show that Jeans-unstable disks are produced by early instabilities lasting a few 100 Myr, and driven by the gaseous phase (see their Fig. 3). Conversely, instabilities first driven by the stellar phase tend to result in stellar bars or spiral arms, depending on the radius where the instability occurs. Therefore, at least some of the $z \sim 0.6$ regular (i.e., not clumpy) RD or PR galaxies could be associated with such initially star-driven instabilities, which will not result in clumps but will rather develop bars or spiral arms. This could also be due to a non-negligible contribution from the stellar mass by their stellar halo, which can easily contribute to stabilize a disk (Bournaud & Elmegreen 2009).

Figure 3. Stability parameter $Q$ for the rotating disks (blue dots) and perturbed rotators (green squares) in the IMAGES-CDFS sample. The biggest symbols correspond to the six clumpy galaxies showing rotation; their median values are indicated by the black squares, with error-bars corresponding to 1-$\sigma$ bootstrap re-sampling. From left to right: $Q_{\text{gas}}, Q_{\text{stars}},$ and $Q_{\text{eff}}$ as a function of $f_{\text{gas}}$. The marginal stability limit $Q=1$ is indicated as a solid black line.

Table 1. Median properties of clumpy galaxies at $z \sim 0.6$ (i.e., those classified as PRs or RDs) and at $z \sim 2$. From top to bottom: rotation velocity, stellar mass (a diet Salpeter IMF was used by puech et al. (2008) at $z \sim 0.6$, while a Chabrier IMF was used by Genzel et al. (2008)); stellar masses derived by Genzel et al. (2008) were converted into a diet Salpeter IMF using $M_{\text{stellar}}(\text{IMF}_{\text{dietSalpeter}}) = 0.93 \times M_{\text{stellar}}(\text{IMF}_{\text{Chabrier}})$, following Gallazzi et al. (2008), gas fraction (using the Schmidt-Kennicutt law of Kennicutt et al. (1989), optical half-light radius (in $z$ band for $z \sim 0.6$ galaxies, and $1.68 \times R_e$ for $z \sim 2$ galaxies), gas radius (from Puech et al. 2009 at $z \sim 0.6$ and Erster-Schreiber et al. 2006 at $z \sim 2$), gas velocity dispersion (following Puech et al. 2007), and Toomre stability factor of the gas.

| $z \sim 0.6$ | $z \sim 2$ |
|-------------|------------|
| $N_{\text{galaxies}}$ | 6 | 6 |
| $V_{\text{rot}}$ [km/s] | 155 | 233 |
| $\log (M_{\text{stellar}})$ [M$_\odot$] | 10.2 | 10.9 |
| $f_{\text{gas}}$ [%] | 34 | 65 |
| $R_{\text{half}}$ [kpc] | 3.8 | 7.5 |
| $R_{\text{gas}}$ [kpc] | 10.5 | 11.2 |
| $\sigma_{\text{gas}}$ [km/s] | 39 | 69 |
| $Q_{\text{gas}}$ | 2.6 | 0.5 |
| $Q_{\text{stars}}$ | 0.8 | 1.0 |
| $Q_{\text{eff}}$ | 0.6 | 0.3 |

4 COMPARING CLUMPY GALAXIES AT DIFFERENT REDSHIFTS

4.1 General properties of clumpy galaxies as a function of redshift

In Table 1 I compare the main (median) properties of $z \sim 0.6$ and $z \sim 2$ clumpy galaxies showing rotation. For comparison at $z \sim 2$, I adopted the sample of clumpy galaxies studied by Genzel et al. (2008), removing BzK6004-3482 and ZC782941 for which no gas radius measurement were available. On overall, clumpy galaxies at $z \sim 2$ have a more massive and larger stellar phase than rotating clumpy galaxies at $z \sim 0.6$, which is reflected in their larger $V_{\text{rot}}, M_{\text{stellar}},$ and $R_{\text{half}}$. They are also more gas-rich, even relative to galaxies of similar stellar mass at $z \sim 2$ (Erb et al. 2006). This larger gas content make their gaseous phase Toomre-unstable ($Q_{\text{gas}} < 1$), conversely to rotating $z \sim 0.6$ clumpy galaxies (see Sect. 3.2), while their stellar phase is only marginally stable on average. This suggests that $z \sim 2$ clumpy galaxies got unstable in their gaseous phase first, and then developed clumps as described by Immeli et al. (2004). Because their $Q_{\text{eff}}$ is on average a factor two lower than in $z \sim 0.6$ clumpy galaxies, the fragmentation process is expected to be stronger in $z \sim 2$ clumpy galaxies. This could explain why $z \sim 2$ clumpy galaxies appear to be more clumpy at optical wavelengths, compared to their $z \sim 0.6$ counterparts (see Fig. 2 and above).

Another difference between $z \sim 2$ and $z \sim 0.6$ clumpy galaxies is that the former have a gas velocity dispersion twice as

\[ \sigma_{\text{gas}} \]
Clumpy galaxies at z ∼0.6

In comparison to z ∼2 galaxies, the pressure in the ISM of z ∼0.6 clumpy galaxies appear to be much lower: the mean velocity dispersion is twice lower, while the star formation density, with a mean value of ∼0.02 M⊙/yr/kpc^2, is one order of magnitude lower than at z ∼2 (Lehnert et al. 2009). Following Lehnert et al. (2009), one can roughly estimate that feedback from star formation could account for 36-85% of the median gas turbulence. For five out of the eleven z ∼0.6 clumpy galaxies, it was possible to compare the positions of emission and absorption lines using FORS2 spectra from Rodrigues et al. (2008). Only J033224.60-274428.1 shows a significant shift (∼100 km/s, Puech et al. 2010a), which suggests substantial winds in this galaxy. Therefore, feedback from star formation is probably not the main driver for the high velocity dispersion observed in z ∼0.6 clumpy galaxies. Inter-clump gravity could account for an additional 21-69% contribution in z ∼0.6 clumpy galaxies (Lehnert et al. 2009), which is not sufficient to account for the observed level of turbulence. Another source of turbulence could be associated with cold gas accretion. In their semi-analytic model, Khochfar & Silk (2009) calibrated a relation between the cold gas accretion rate and the associated generated gas velocity dispersion using z ∼2 galaxies. Using the same calibration, I estimate that to generate the observed level of gas turbulence in z ∼0.6 clumpy galaxies, an accretion rate of ∼34 M⊙/yr would be required.
This is one order of magnitude above what is expected from full numerical simulations (see Kereš et al. 2009 and discussion below in Sect. 4.2). Finally, the turbulence in \( z \approx 0.6 \) clumpy galaxies could be merger-driven. Simulated gas-rich remnants from major mergers (e.g., Robertson & Bullock 2008) indeed show similar \( V_{\text{rot}}/\sigma \) ratios in the rebuilt disks compared to observed values (Puech et al. 2007).

In order to relax towards local galaxies, the stellar phase of \( z \sim 0.6 \) clumpy galaxies needs to get stabilized by increasing \( Q_{\text{int}} \) by at least \( \sim 25\% \) on average. This could be achieved by increasing \( V_{\text{rot}} \) through gas accretion within the optical radius. Alternatively, this can also be achieved through the stabilizing influence of a growing bulge as described by Bournaud & Elmegreen (2009). Finally, if self-gravity drives disk turbulence (Burkert et al. 2009), then one expects that \( z \sim 0.6 \) clumpy galaxies get stabilized by increasing their velocity dispersion to \( \sim 49 \) km/s in order to reach \( Q_{\text{eff}} = 1 \). This is relatively close to the median value observed in \( z \sim 0.6 \) RD galaxies, with \( 47 \pm 3 \) km/s.

### 4.2 Cold streams as a driver for clump formation

Cold streams are thought to be an important process triggering instability, as \( z \approx 2 \) disks are expected to be fuelled by such cold streams, which could maintain a dense gaseous disk that can undergo gravitational fragmentation into clumps (Dekel et al. 2009). Indeed, \( z \approx 2 \) clumpy galaxies are thought to live in \( \sim 10^{12} M_\odot \) dark matter haloes (e.g., Dekel et al. 2009), in which such cold flows are expected to take place (Dekel et al. 2009). To estimate the halo mass of the \( z \sim 0.6 \) clumpy galaxies, we assumed that rotation velocity is a good tracer of the circular velocity of their halos, from which the halo mass can be estimated, following the formalism of Mo et al. (1998). Similar results were obtained from halo abundance matching models (Conroy & Wechsler 2009; Moster et al. 2009): we indeed found that \( z \sim 0.6 \) clumpy galaxies also reside in \( \sim 10^{12} M_\odot \) haloes. Therefore, clumpy galaxies at \( z \approx 2 \) and \( z \sim 0.6 \) inhabit halos of similar [mass]. However, according to numerical simulations (Kereš et al. 2005), and theoretical expectations (Dekel et al. 2009), while cold flows are expected to penetrate such halos at \( z \approx 2 \), they are expected to be strongly attenuated in halos of similar mass at \( z \approx 1 \). The dominant mode of accretion in such \( z \sim 0.6 \), \( \sim 10^{12} M_\odot \) haloes is rather expected to be hot gas accretion, since these haloes are too massive to allow spherical cold gas accretion to be significant. The cosmological simulations of Kereš et al. (2009) indeed suggest that the average total accretion rate of gas onto the central galaxies inhabiting \( \sim 10^{12} M_\odot \) halos dropped down by a factor \( \sim 3 \) between \( z \approx 2 \) and \( z \sim 0.6 \) (see their Fig. 7), while the fraction of gas accreted cold versus hot decreased by a factor \( \sim 1.5 \) over this redshift range (their Fig. 8). As a consequence, according to these simulations, the cold gas accretion rate typically dropped down from \( \sim 7.5 M_\odot /yr \) to \( \sim 1.5 M_\odot /yr \) (see also Brooks et al. 2009).

Moreover, the simulations of Kereš et al. (2009) suggest that mergers dominate the mass growth of galaxies at \( z < 1 \), which is in line with spatially-resolved kinematics of \( z \sim 0.6 \) galaxies (see Introduction). Finally, the average velocity dispersion is found to be roughly the same between rotating disks, perturbed rotators, and galaxies showing a complex kinematics at \( z \sim 0.6 \) (Puech et al. 2007; Epinat et al. 2010), as well as in the clumpy galaxies (see Tab. 1), if cold flows were feeding \( z \sim 0.6 \) clumpy galaxies, then one would expect to detect an increase of the velocity dispersion in these systems, which is not observed. In summary, theoretical expectations are found to be drastically different, when comparing \( z \approx 2 \) and \( z \sim 0.6 \) massive haloes. While cold streams are expected to feed \( z \sim 2 \) clumpy galaxies in fresh gas and trigger the formation of clumps, this is unlikely to be the dominant mechanism at \( z \sim 0.6 \).

### 4.3 Interactions as a driver for clump formation

Numerical simulations have suggested that interactions could be also an efficient trigger for instabilities in gaseous disks, resulting in the formation of clumps (di Matteo et al. 2008). Simulations revealed that such a trigger is efficient only if the fragmenting disk in the progenitor is already marginally stable before the interaction. The interaction does not necessary result in a merger, but even in this case, it is the distant interaction that triggers the instability, and not the eventual subsequent merger (di Matteo et al. 2008). Another possibility is that distant clumpy galaxies with complex kinematics could also be compact groups observed while they are merging (Amram et al. 2004, 2007). Finally, disk rebuilding, i.e., the latest phase of a gas-rich merger where the gas expelled during the process falls back to reform a disk, could also be a good driver for clump formation, especially in galaxies that do not show any obvious of morphological or kinematic peculiarities (although the depth of images might not be large enough, see Sect. 3.1). Note that in principle, disk rebuilding does not necessarily require merging. Indeed, the disk rebuilding phase involves mainly infalling gas, which can comes from gas accretion from the intergalactic medium (e.g., through cold streams, see below), or from the gas expelled during the merger itself. However, given the low accretion rate at \( z < 1 \), disk rebuilding is probably systematically associated with merging at these redshifts.

It is interesting to look for local counterparts of clumpy galaxies, because of the much higher spatial resolution and sensitivity of observations. As part of a morphological study of Markarian galaxies (Markarian 1977, Casini & Heidmann 1976) identified “a new class of object, with UV emission, irregular clumpy structure, large dimension, high luminosities and large internal motions” compared to normal irregular galaxies, which they called “clumpy irregular” (see also Casini & Heidmann 1976). They suggested that these galaxies might be “in a turbulent or fragmented state, with large cells where the rate of star formation is high”. Their description matches astonishing well the definition of clumpy galaxies at high redshift (e.g., Elmegreen et al. 2007). A few other clumpirregular (cI) were later identified by Maehara et al. (1988). It is likely that other unidentified cI exist, but they are clearly very rare locally, even among interacting and peculiar galaxies (Casini & Heidmann 1976); the number of known cI so far is 11, among which only 7 are not known members of clusters (Mrk 325, 7, 8, 432, 297, VV 523, and NGC 6120). Here we consider only these latter 7 cI for comparison with higher-z galaxies in the field. Interestingly, two of them (i.e., Mrk8 and 325) were recently shown to be structurally similar to high-redshift clumpy galaxies (Pettini et al. 2009).

On overall, cI have stellar masses ranging between \( 10^{10} M_\odot \) and \( 10^{11} M_\odot \), and their star formation rates is in the order of \( 10^2 M_\odot /yr \). Moreover, the number of clumpy galaxies have increased by more than \( 10\% \) in the last 10 Gyr, and are expected to continue at the same rate in the next 10 Gyr. This suggests that clumpy galaxies are a common phenomenon in the universe, and that they are forming in all types of environments, from low-mass dwarfs to massive ellipticals. Consequently, it is likely that clumpy galaxies are a fundamental building block of the universe, and that they play a key role in the formation and evolution of galaxies.
and $10^{11.4} \, M_\odot$ with a median of $10^{10.2} \, M_\odot$, according to their rotation velocities and the local stellar-mass Tully-Fisher relation (Puech et al. 2008). They are on overall gas-rich galaxies (e.g., Casini et al. 1998; Maehara et al. 1998; Garland et al. 2007), with HI gas fractions ranging between 4 and 77%, and a median of 40%, i.e., a fraction usually found in local dwarfs rather than in spiral galaxies (Schombert et al. 2001). Those for which kinematic data are available show a distorted rotation (Mrk 296, see Casini et al. 1998; Mrk 325, see Garland et al. 2007; Pérez-Gallego et al. 2005; Mrk 297, see Garland et al. 2007; García-Lorenzo et al. 2008; VV 523, see Rampazzo et al. 2005).

These cl galaxies are almost always found to be merging or interacting systems (Mrk 325, see Duflot-Augarde & Allon 1983; Homeier & Gallagher 1994; Conselice et al. 2000; Garland et al. 2007; Mrk 8, see Casini & Heidmann 1976; Conselice et al. 2000b; Mrk 423, see Rothberg & Joseph 2004; Mrk 297, see Taniguchi & Noguchi 1991; Rothberg & Joseph 2004; Garland et al. 2007; García-Lorenzo et al. 2008; VV 523, see Pustilnik et al. 2003; Rampazzo et al. 2005), or are part of a pair that could explain their morpho-kinematic peculiarities (Mrk 7 and NGC 6120).

A similar class of objects was recently pointed up as presenting similarities with distant clumpy galaxies. Those were selected as super-compact UV Luminous galaxies by Heckman et al. (2005) and Hoopes et al. (2007) in order to isolate Lyman Break Analogs (LBAs) of distant Lyman Break Galaxies (LBGs). LBAs appear to be very rare locally (Heckman et al. 2005), and indeed share many similarities with distant LBGs, such as their (stellar or dynamical) masses, UV luminosities, sizes, star-formation rates, dust attenuation, or gas metallicities (Heckman et al. 2005; Hoopes et al. 2007; Basu-Zych et al. 2007). High-resolution images from the HST revealed UV morphologies similar to those of LBGs, once degraded to similar depth and spatial resolution (Overzier et al. 2008b; 2009a). In the UV, they are also characterized by complexes of massive clumps of star formation, while in the optical, they appear to be dominated by features evidencing post-mergers of interactions (Overzier et al. 2008b). These low-surface brightness material characteristic of mergers or interactions such as faint companions or tidal features, are almost impossible to detect in the redshifted images, which led Overzier et al. (2008b) to suggest that LBGs could be gas-rich mergers or interactions of relatively low-mass galaxies. In a preliminary study of LBA kinematics, Basu-Zych et al. (2009) found quite disturbed gas dynamics suggestive of feedback, interaction, or merger events. They simulated how their kinematics would appear at higher redshifts, and found similarities with spatially-resolved kinematics of distant LBGs (e.g., Wright et al. 2007; Law et al. 2009).

LBAs have stellar masses ranging from $10^{9.2} \, M_\odot$ to $10^{10.8} \, M_\odot$, with an average of $10^{10} \, M_\odot$ (see Hoopes et al. 2007; Basu-Zych et al. 2009), i.e., similar to cl galaxies. Using the relationship between SFR/M$_\odot$ (see Hoopes et al. 2007 for typical values in LBAs) and the gas-to-stellar mass ratio found in local galaxies by Zhang et al. (2009), one can infer gas fractions in LBAs, which are found to be typically larger than 40-50% i.e., again in good agreement with cl galaxies. Jeans instabilities in gas-rich disks require relatively high gas densities to happen. As well as at z $\approx$ 0.6 (see Sect. 4.2), cold streams are also suppressed in z $\approx$ 0 haloes more massive that $\sim 10^{12} \, M_\odot$ (corresponding to stellar masses larger than $\sim 10^{10.5}$, as suggested by halo occupation models; see e.g., Conroy & Wechsler 2009), but cold gas accretion can still take place in a more spherical geometry in lower mass haloes, such as those where cl and LBAs inhabit in on average. This might be a mechanism by which dense gas disk might be maintained, and fragmentation could follow. However, numerical simulations showed that this mode of cold gas accretion is very low, which was confirmed by observations, with $\sim$0.3$M_\odot$/yr (Sancisi et al. 2008). One could therefore expect that local clumpy galaxies, just like their z $\approx$ 0.6 counterparts, would be rather driven by interactions. Interactions, and more generally collisions, are indeed the only way to pressure the gas at level high enough to allow fragmentation, except at very high redshifts, where cold streams can bring a lot of cold gas directly to the disk within a dynamical time (see also Elmegreen et al. 2009b).

### 5 DISCUSSION

Spatially-resolved kinematics of distant galaxies suggested two different mechanisms to account for galaxy evolution. While observations at z $\approx$ 2 suggested that the dominant mechanism taking place would be Jeans fragmentation leading to thick gas-rich, rotating clumpy galaxies, observations at z $\approx$ 0.6 led to a different conclusion, with interactions being the dominant driver, even in clumpy galaxies, as suggested by the present study. Both populations of clumpy galaxies are found to inhabit in halos with similar mass, but numerical simulations and theoretical studies suggested that the cosmological context evolved strongly during this redshift range: while massive cold flows are expected to penetrate z $\approx$ 2 halos and feeding the central disks in cold gas, such cold streams are also expected to be strongly suppressed in halos of same mass at z $\approx$ 1. This explains why z $\approx$ 2 could indeed being undergoing a Jeans instability phase, with cold flows maintaining a dense enough gaseous disk resulting in the formation of clumps in a pre-existing rotating disk. Such cold flows are almost suppressed at z $\approx$ 0.6 and therefore cannot drive anymore the formation of clumps. Instead, interactions, with or without a subsequent merger, can induce gas compression high enough to result in the formation of clumps. Detections of cold gas at high redshifts were claimed in a several cases (e.g., Nilsson et al. 2006; Noterdaeme et al. 2008; Jorgenson et al. 2009), and recent numerical simulations suggest that Ly-α blobs at high redshifts might be a direct signature of cold streams (Goerdt et al. 2009). If the theoretical frame and numerical simulations depicting cold flows turn out to be correct, there would be no contradiction between the interpretations of spatially-resolved kinematics of z $\approx$ 2 and z $\approx$ 0.6 galaxies.

However, it is not clear whether mergers and/or interactions could also account for the clumpy galaxies observed at z $\approx$ 2. Numerical simulations showed how very gas-rich major mergers can also result in similar star formation rates, gas surface density, and circular velocity-to-velocity dispersion ratios that match observations (Robertson & Bullock 2008). However, Bournaud & Elmegreen (2009) noticed that the Robertson & Bullock (2008) simulation failed to reproduce the observed clumps in these galaxies, which, they argue, can be attributed to the fact that the remnant has too low a disk density to fragment. The numerical simulation of Robertson & Bullock (2008) result in a bulge that indeed contains 46% of the stellar mass, which might explain why the rebuilt disk did not fragment. Bournaud & Elmegreen (2009) further argued that mergers systematically result in the build-up of a central stellar spheroid that stabilizes the disk against fragmentation, which would rule out merging
as the underlying cause of fragmentation in z∼2 clumpy galaxies. However, Bournaud & Elmegreen (2009) models of unstable disks allow a maximal fraction of 20% and possibly up to 30% of the stellar mass to be in the bulge (and/or halo) for the fragmentation to occur. Nevertheless, Hopkins et al. (2009b) showed that about 40-50% of the galaxies with stellar mass of 10^10 M_⊙ at z∼2 could have a stellar bulge-to-disk ratio lower that 0.3, as a result of mergers at higher redshift, which lets room for a significant fraction of z∼2 galaxies that could possibly result from major mergers (see below). In z∼2 galaxies, the median gas fraction is estimated to be ~50% (Erb et al. 2006; Daddi et al. 2008), therefore, even larger gas fraction in their progenitors can be expected, which will limit the effect of the violent relaxation in the remnant, hence the bulge-to-disk ratio (Hopkins et al. 2009b). Moreover, interactions between gas-rich, marginally unstable progenitors with similar masses were shown to possibly result in clump formation (di Matteo et al. 2008). Given the large gas fraction of z∼2 galaxies, it is not unreasonable to expect such a marginal stability in a large fraction of them. It appears therefore possible that the z∼2 clumpy galaxies might result from distant interactions of gas-rich galaxies, possibly followed by a merger.

In addition, while the fraction of clumpy galaxies at high redshift is unambiguously large, it is still not clear whether they are all truly rotating. Förster Schreiber et al. (2009) found that roughly one third of galaxies in their sample are dominated by rotation, another third is found to be clear interacting/merger systems, while the remaining third is found to correspond to corresponding velocity-dispersion dominated systems. The latter tend to show motions compatible with expectations from close mergers, at least in a significant fraction of them (Förster Schreiber et al. 2009). Strikingly, while their "observed kinematics [...] are similar to those of merger-driven starburst galaxies in the local universe", Law et al. (2009) claimed that these systems are probably resulting from other processes probably related to gas accretion. The main argument raised by Law et al. (2009) is that the major merger rate found in cosmological simulations is not large enough to account for the density of all star-forming galaxies at z∼2. However, this argument relies only on comparisons with semi-analytic simulations, which are well known to be unable to reproduce a number of properties of local galaxies (see, e.g., Dutton et al. 2008). Observations suggest that the cumulative fraction of merger that M_{stellar} >10^{10} M_⊙ galaxies undergo between z=2 and z=3 (i.e., over 1.2 Gyr) is ~2 (Conselice et al. 2006), meaning that all z∼2 galaxies with M_{stellar} >10^{10} M_⊙, i.e., as massive as clumpy galaxies, might potentially be the remnant of a recent gas-rich major merger occurring at higher redshift. The comparison between the spatially-resolved kinematics of local and distant galaxies reveals that it remains difficult to assess unambiguously the real nature of very distant systems (Epinat et al. 2010). The morphology and kinematics of local analogs of some of these distant objects (i.e., the LBAs) reveal features characteristic of mergers or interactions (see Sect. 4.3); once projected at higher redshifts, these objects show striking similarities with dispersion-dominated z∼2 galaxies (Overzier et al. 2008, 2009b; Basu-Zych et al. 2009). This suggests that galaxy interactions and/or mergers could also be driving the dynamics of dispersion-dominated z∼2 galaxies. This might potentially raise the fraction of merger-driven galaxies to the two-thirds of the z∼2 galaxy population.

The different possible drivers for clump formation as a function of redshift are summarized in Tab. 2.

| Interactions | Mergers | Cold gas accretion |
|-------------|---------|--------------------|
| z∼2         | +       | +                  |
| z=0.6       | ++      | ++                 |
| z=0         | ++      | -                  |

6 CONCLUSION

I selected and studied 11 clumpy galaxies at z=0.6, drawn from the representative IMAGES sample of emission line, intermediate mass galaxies. Clumpy galaxies were selected mimicking the morphological UV selection criteria used at lower redshifts, and their fraction at z=0.6 was found to be ~20%. Among the 11 clumpy galaxies, 5 were found to show complex kinematics compatible with major mergers, as suggested by Hammer et al. (2008). The remaining clumpy galaxies, i.e., which show large-scale rotation, are found to be Toomre-stable in their gaseous phase, but unstable in their stellar phase, contrary to higher-z clumpy galaxies, which are found to be unstable in both phases, with a stronger level of effective instability. This could originate both in the likely higher fraction of old stars in z∼0.6 clumpy galaxies, which would not participate into the fragmentation process. This would naturally explain why z∼0.6 UV clumps tend to vanish when looking at reddest-band images, unlike z∼2 clumpy galaxies, which appear to be more persistent at longer wavelengths.

While z>1 clumpy galaxies were largely associated with Jeans-unstable disks in the literature, I argue that current kinematic observations could actually support a fraction of only ~33% of such systems among z>2 star-forming galaxies. While this is not incompatible with the cumulative fraction of major mergers in such objects over their past ~1 Gyr, theoretical and numerical works suggested a different channel for disk fragmentation, which could result from cold flows from the inter-galactic medium penetrating through the surrounding dark matter halos. These cold flows could maintain the gaseous phase high enough to fragment and regenerate clumps at a rate high enough to be consistent with observations. The progressive shut down of these cold flows with redshift in massive haloes could also explain why the formation of z<1 clumpy galaxies are found to be preferentially driven by interactions, since the duty cycle of merger would dramatically evolve between these two epochs. Within this theoretical frame, there is therefore no contradiction between the interpretation of kinematic observations of z∼2 and of z∼0.6 galaxies. However, it remains unclear whether interactions could not account for all or at least most of the evolution seen in intermediate and massive galaxies all the way from z∼2-3 down to z=0.

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5 It must be mentioned here that their full sample is biased toward relatively massive star-forming galaxies. However, this fraction seems to hold when restricting their sample to stellar masses larger than 2×10^{10} M_⊙, for which the resulting sub-sample is truly representative of z∼2 galaxies, see Fig. 4 of Förster Schreiber et al. (2009).
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APPENDIX A: KINEMATICAL MAPS OF Z~0.6 CLUMPY GALAXIES

The kinematical maps of the 11 clumpy galaxies discussed in Sect. 3 were published in Yang et al. (2008) as part of the IMAGES sample of intermediate-mass, emission line galaxies at z~0.6. For the sake of completeness, they are reproduced below.
Figure A1. Kinematics of the 11 clumpy galaxies observed by FLAMES/GIRAFFE at \(z\sim0.6\) (reproduced from Yang et al. 2008). From left to right: HST/ACS I-band images with the GIRAFFE IFU superimposed (0.52 arcsec/pix), velocity field (with a 5x5 linear interpolation), and velocity dispersion map. The first column corresponds to the 5 clumpy galaxies showing rotation (RD/PR), while the second column corresponds to CK galaxies (see Sect. 3). J033239.72-275154.7, and J033227.07-274404.7 were studied and modelled in detail by Peirani et al. (2009) and Fuentes-Carrera et al. (2010), respectively.
