Star formation efficiency in giant molecular clouds at z = 1 as probed by JWST

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Abstract

Deep HST images of strongly lensed clumpy galaxies at redshift z~1-3 shows UV-bright clumps, on average, 100x more massive than local star cluster complexes. Their physical properties supports an in-situ clump formation under fragmentation of turbulent, marginally stable high-redshift gas disks. Among these galaxies, the Cosmic Snake, a strongly lensed clumpy galaxy, resolved down to physical scale of 30-70 pc at z=1.036 sets a record of hosting 21 stellar clumps (HST rest-frame UV/optical) and 17 giant molecular clouds (GMCs) in ALMA CO observations at comparable spatial resolution. These GMCs have gas masses high enough to allow for the formation of the massive stellar clumps. The comparison of GMCs and stellar clump masses suggests a gas cloud star formation efficiency (~30%) much higher than observed in contemporary galaxies (~5%). If confirmed, it would suggest an evolution in the efficiency of gas consumption with redshift. Our accepted Cycle 1 JWST / NIRSpec-IFU program probing Halpha in this galaxy aims at using an independent approach to derive the star formation efficiency of these GMCs based on a statistical framework recently applied to nearby galaxies, which translates cloud-scale variations of the flux ratio between tracers of molecular gas and star formation to the molecular cloud evolutionary timeline, necessary to reliably determine the cloud scale star formation efficiency.

Objectives

ALMA CO(4{3) observations, obtained at matched HST resolution, reveal 171 giant molecular gas clouds (GMCs) shown in the upper-right figure (Dessauges-Zavadsky et al. 2019). With molecular gas masses of $8\text{x}10^{6-9}$ M and radii of 30-210 pc, these high-redshift GMCs are dense and very turbulent, with 10 times higher gas mass surface densities and Mach numbers than in local GMCs (Bolatto et al. 2013). In spite of these extreme properties, they appear as `in situ' gravitationally bound clouds.

- Inferring the GMC star formation efficiency at z = 1 is an outstanding measurement, since it is the key parameter which regulates the star formation process and the resulting stellar mass build-up in galaxies. It is thus essential in the implementation of star formation in numerical simulations (Krumholz et al. 2019). Most importantly, an enhanced fraction of gas that high-redshift GMCs convert into stars (see also Grudic et al. 2018) could explain the enhanced SFR observed in distant galaxies at a given M_{stars}. The current star formation efficiency measurement, however, critically relies on two assumptions: (1) one molecular cloud evolves into one stellar clump; and (2) GMCs and stellar clumps have equal lifetimes, while none of these lifetimes has been measured. Therefore, to ascertain the GMC star formation e ciency, we need to constrain the lifecycle of GMCs and stellar clumps, which at z = 1 is only enabled by JWST.

- We propose to measure the GMC evolutionary timeline and the associated star formation efficiency per star formation event in the Cosmic Snake galaxy at z = 1. None of these measurements have ever been made beyond galaxies in the nearby Universe, and are yet essential to obtain a complete view of the star formation process. Obtaining deep NIRSpec/IFU Halpha mapping at GMC scale in synergy with ALMA CO observations is the last missing piece of the puzzle to achieve this major objective:

(i) H observations trace the emission of newly born massive stars and thus provide a measurement of the very recent star formation (< 10 Myr), so that a comparison to the observed GMC population becomes meaningful;
(ii) they set an absolute reference timescale (Haydon et al. 2020);
(iii) together with CO observations, they enable to overcome the above critical assumptions and determine the lifetime, star formation efficiency, and feedback of individual GMCs within the statistical framework of Kruijssen & Longmore (2014) and Kruijssen et al. (2018), which translates cloud-scale variations of the flux ratio between tracers of molecular gas and star formation (CO-to-Halpha flux ratio) to the GMC evolutionary timeline (see applications in Kruijssen et al. 2019; Chevance et al. 2020).

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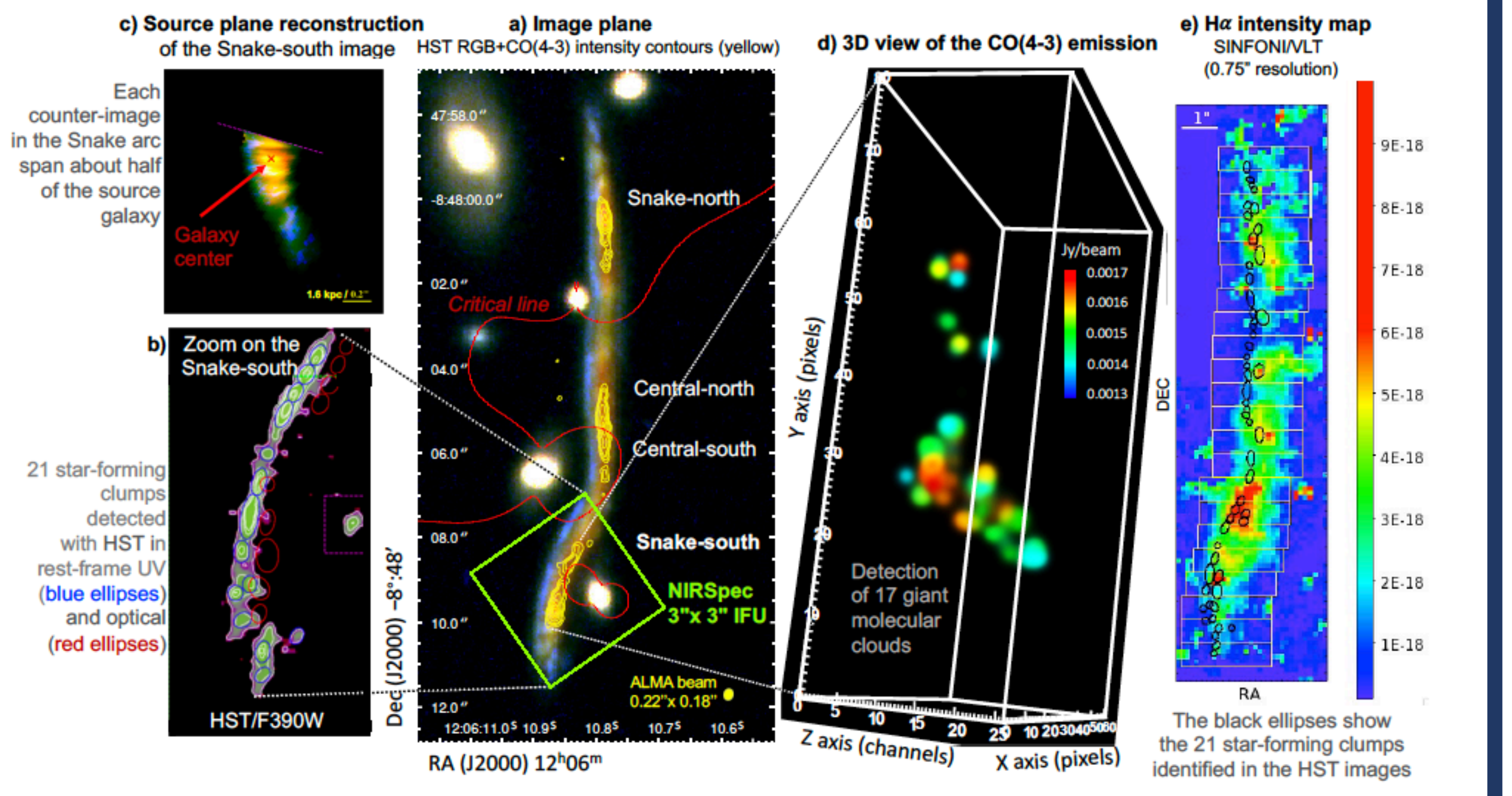
A unique z = 1 target to study the star-formation process at 30-70 pc scale

The Cosmic Snake galaxy, discovered in the MACSJ1206.2-0847 cluster field (Ebeling et al. 2009), is an exceptionally lensed and stretched galaxy at z = 1.036, which appears as a four-fold multiple image along a snake-like arc in HST images (Right). With a stellar mass of ~ 2.4 10^{10} Msun, a star formation rate of SFR = 18 M_{sun} yr^{-1}, and a molecular gas fraction of 30% (Patricio et al. 2018; Cava et al. 2018; Dessauges-Zavadsky et al. 2019), it is representative of main-sequence (MS) galaxies at z = 1 (e.g., Speagle et al. 2014).

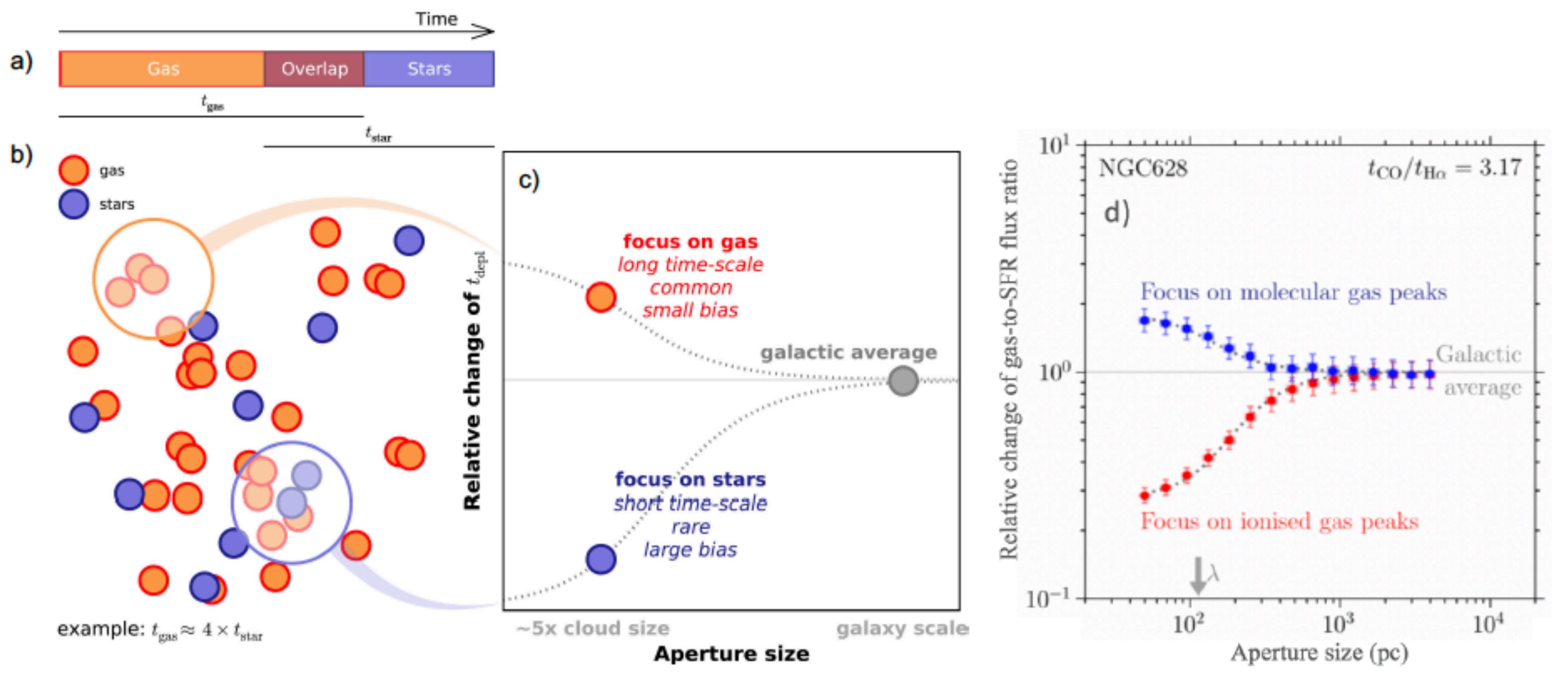
- 21 stellar clumps are identified in HST rest-frame UV and optical images with Mclumps ~ 10^6 - $3\text{x}10^8$ Msun and radii of 35-350 pc (Cava et al. 2018). These clumps are two orders of magnitude more massive than star clusters in nearby galaxies (Messa et al. 2018) and have stellar mass densities of $10^{2.5\text{-}4}$ Msun pc^{-2}, typical of globular clusters and super star clusters (Overzier et al. 2009). Such clumps are ubiquitously observed in galaxies at z~1-3 and beyond (e.g., Elmegreen et al. 2013; Livermore et al. 2012, 2015; Shibuya et al. 2016; Vanzella et al. 2017; Huertas-Company et al. 2020), with the fraction of clumpy galaxies reaching ~ 60% of MS galaxies at z ~ 2 (Guo et al. 2015).
- The Cosmic Snake galaxy thus is the natural and unique target to undertake, for the first time, the study at z = 1 of the star formation process down to the scale of individual local HII regions.



Statistical Framework

The GMC evolutionary timeline can be decomposed in three evolutionary phases: the cloud lifetime during which the molecular cloud is visible in CO emission; the feedback timescale during which the molecular cloud is still visible in CO and the young massive stars become visible in Halpha emission and are co-spatial with CO; and the star formation tracer timescale during which a young star cluster remains visible in Halpha after the birth molecular cloud is dispersed.

The framework allows the durations of these three phases to be accessed statistically from the spatial (de)-correlation between molecular clouds and star-forming regions determined by placing apertures on peaks of CO or Halpha emission and by measuring how the enclosed CO-to-Halpha flux ratios are elevated or suppressed relative to the galactic average as the aperture size is changed.



a) Timeline showing the transition from molecular gas (CO) to young stars (Halpha).
b) A galaxy consists of a random distribution of regions in the gas phase (red filled circles) and in the young stellar phase (blue filled circles) situated on the timeline in a).
c) In this tuning fork diagram, the relative change of the CO-to-Halpha flux ratio (tdepl) in small apertures (large open circles) with respect to the galactic average (solid line) respects the duration of the phases in a). By measuring this relative change, we obtain a non-degenerate constraint on the evolutionary timeline of molecular clouds. In this example from Kruijssen et al. (2018), the duration of the gas phase is 4 times that of the young stellar phase.
d) Example of the tuning fork diagram obtained for a nearby galaxy from Chevance et al. (2020).