Unveiling obscured star formation and AGN activity in the most IR-luminous massive galaxies at $z \sim 2$

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Scientific rationale: A fundamental goal of extragalactic astronomy is to understand the evolution of massive galaxies at $z \sim 2-3$, the critical epoch when the cosmic star formation (SF) and black hole activity peaked (e.g., Madau et al. 1996; Richards et al. 2006). Mounting evidence indicates that massive galaxies at these early cosmic times differ radically from their present-day counterparts. The star formation rate (SFR) at given stellar mass in some populations reaches much higher levels at $z \sim 2-3$ than today, often exceeding several hundreds $M_\odot$ yr^{-1}. Important insights on the assembly of the Hubble sequence can also be gleaned from structural differences: while most present-day massive ($M_\star \geq 1 \times 10^{11}$ $M_\odot$) galaxies are highly extended systems (e.g., S0, Sa, E) with significant bulges, correspondingly massive galaxies at $\sim 2-3$ show a large fraction of disky systems, which range from ultra-compact to extended in the rest-frame optical (e.g., Weinzirl et al. 2011, hereafter W11; van Dokkum et al. 2011; van der Wel et al. 2011). These disky extended systems tend to have the highest SFRs, while the compact ones tend to be more quiescent. Furthermore, in contrast to $z \sim 0$ most AGN hosts at $z \sim 2-3$ are disk-dominated galaxies (W11; Schawinski et al. 2011)

For massive galaxies at $z \sim 2-3$ constraints on the global unobscured SFR are typically obtained using the rest-frame UV light traced by *Hubble Space Telescope (HST)* Advanced Camera for Surveys (ACS) optical observations (e.g., Bauer et al. 2011; Daddi et al. 2007). Estimates of the obscured SF stem from *Spitzer* 24μm and Herschel far-infrared (FIR) data (250 to 500 μm), which are used to infer the IR (8-1000 μ m) luminosity $L_{\rm IR}$ (e.g. Papovich et al. 2007; Elbaz et al. 2010; Nordon et al. 2010; W11) The IR-based SFR ($SFR_{\rm IR}$) is derived from by assuming that dust is heated mainly by young massive stars, and can therefore be overestimated in AGN hosts (see W11; Fig. 1).

However, the time has now come to move beyond measurements of the global SFR and map *the spatial distribution* of rest-frame FIR emission at high resolution in $z \sim 2-3$ galaxies, in order to explore the drivers of SF and AGN activity, feedback effects, and the type of stellar components (e.g., bulge, disk) being built. While HST ACS optical images have adequate resolution ($0.''1$ or 800 pc at $z \sim 2$) to resolve the unobscured SF, they only show the tip of the iceberg as most of the SFR is typically obscured. The resolution of Spitzer ($6''$ or ~ 50 kpc at $z \sim 2$) and Herschel SPIRE ($> 18''$) are inadequate to resolve the obscured SF. In order to overcome these obstacles, *we request 1.1 hours of ALMA band 7 (345 GHz) continuum observations of the five most IR-luminous massive extended galaxies at $z \sim 2$ in the GOODS-NICMOS Survey-South in order to map their rest-frame FIR (~ 290 μm) continuum at high resolution ($0.''3$ or 2.4 kpc at $z \sim 2$).*

Sample Selection: Our ALMA sample is drawn from the complete sample of massive galaxies in the GOODS-NICMOS Survey (GNS; Conselice et al. 2011). GNS is a 180-orbit, deep ($5\sigma = 26.8$ AB in H) high resolution ($0.''3$) survey of massive galaxies with HST NIC3 in the F160W (H) filter. It provides one of the largest complete samples of massive galaxies (77 systems with $M_\star \geq 5 \times 10^{10}$ $M_\odot$) at $z \sim 2-3$. The sample is diverse, including Distant Red Galaxies (DRGs), Extremely Red Objects (EROs), and BzK-selected galaxies. An extensive study of the structure, SF, and AGN activity of these systems has been conducted by W11.

Of these 77 massive galaxies at $z \sim 2-3$, 36 lie in the GNS-South (the GOODS-South field) and are observable by ALMA. Of these, only 17 have bright enough mid-IR emission to have a detection with $S/N > 5$ ($f_{24\mu m} > 30$ μJy) at 24μ from the *Spitzer* GOODS Legacy Program (Dickinson et al. 2003). This subset of 17 galaxies is shown in Fig. 1. From this subset, we selected the five most IR-luminous[1] galaxies (with $L_{\rm IR}$ ranging from 6.3×10^{12} to 4.7×10^{13} $L_\odot$), which also have extended

[1]The IR-luminous galaxies in our sample include ULIRGs with $L_{\rm IR} > 10^{12} L_\odot$ and Hyper-LIRGS with $L_{\rm IR} > 10^{13} L_\odot$

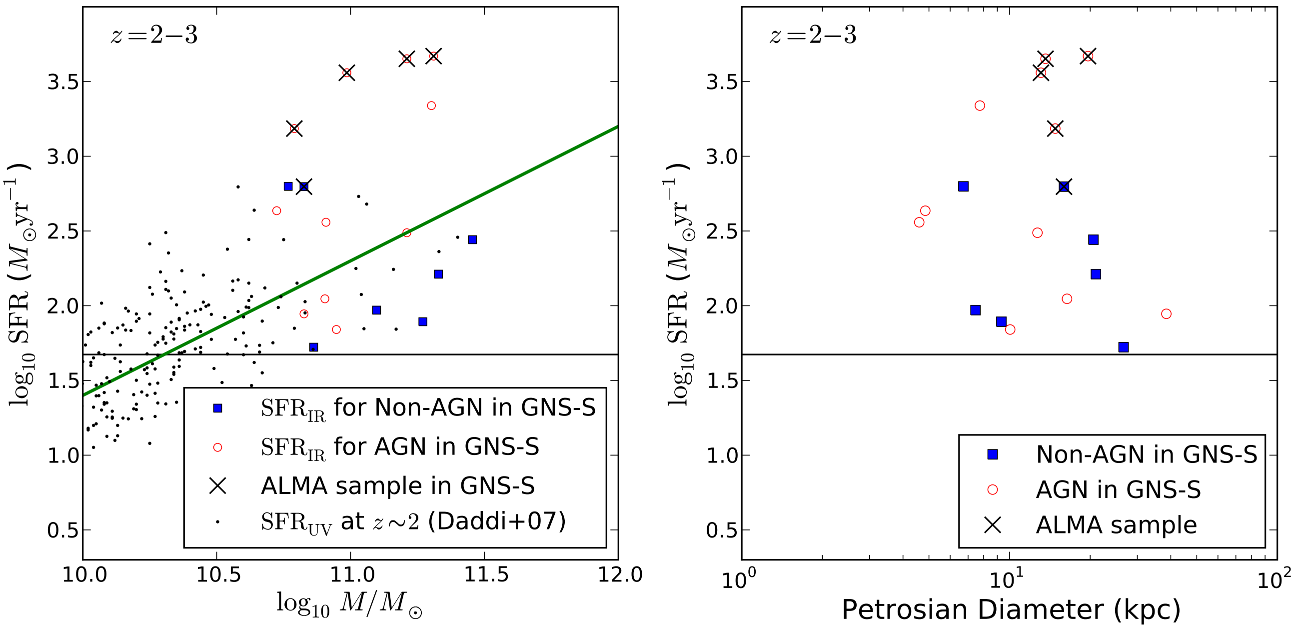

Figure 1: **Left**: For the GNS-South sample of massive ($M_\star \geq 5 \times 10^{10}\ M_\odot$) galaxies at $z \sim 2-3$, the IR-based SFR ($SFR_{\rm IR}$) is plotted versus stellar mass. $SFR_{\rm IR}$ is derived from the IR (8-1000 μm) luminosity $L_{\rm IR}$ by assuming that dust is heated by massive stars and is therefore likely overestimated in AGN hosts (see Weinzirl et al. 2011). The five galaxies in the ALMA sample include both AGN and non-AGN hosts with the largest $L_{\rm IR}$. For comparison, we also show the extinction-corrected UV-based SFRs and mean mass-SFR relation (diagonal line) at lower masses from Daddi et al. (2007). **Right**: For the same GNS-South sample shown in the left panel, $SFR_{\rm IR}$ is plotted versus the Petrosian diameter of the NIC3 H-band (rest-frame optical) image. The five ALMA sample galaxies have large Petrosian diameters (12.5 to 20.6 kpc) and are easily resolved by the ALMA synthesized beam of $0\farcs3$ (2.5 kpc at $z \sim 2$) resolution. [Adapted from Weinzirl et al. 2011]

Petrosian diameter ($D_{\rm Pet} \sim 12.5 - 20.6$ kpc; Fig. 1) and half-light diameter ($D_e \sim 6 - 9$ kpc) so that they are easily resolved by the ALMA beam ($0\farcs3$ or 2.5 kpc at $z \sim 2$; see Fig. 2). These five ALMA sample galaxies all turn out to have a low Sérsic index ($n \leq 1$) and high projected ellipticity suggestive of a disky system (W11). They include both non-AGN and AGN hosts, based on their X-ray and mid-IR properties (W11). They have a wide range of ancillary data, including *HST* ACS $BViz$, NIC3, *Spitzer*, and Herschel images.

Technical Justification: For our sample of five IR-luminous extended galaxies at $z \sim 2$, we request continuum observations at a sky frequency of ~ 345 GHz in order to map their rest-frame FIR (~ 290 μm) continuum at a high spatial resolution of $0\farcs3$ (2.4 kpc at $z \sim 2$). This resolution is well matched to the effective PSF of our NIC3 H ($0\farcs3$) and ACS ($0\farcs1$) data (Fig. 2). The maximum recoverable scale of $\sim 2\farcs6$ is adequate as the Petrosian diameter of our sample galaxies ranges from $1\farcs5$ to $2\farcs4$ (12.5 to 20.6 kpc at $z \sim 2$; Fig. 1). Our 5 targets have high IR-luminosities, ranging from 6.3×10^{12} to $4.7 \times 10^{13}\ L_\odot$. Extrapolations from their Spitzer 24 μm or/and Herschel observations at 250-500 μm yield a continuum flux density ranging from 6 to 39 mJy at 345 GHz (e.g., Hilton et al. 2012). If we assume a conservative fraction ($\sim 20\%$) of this number as the peak continuum flux density per beam, then our requested rms of 0.01 mJy per beam gives a peak SNR ranging from 12 to 78 across the five targets. The OT gives a total on-source time of ~ 21 minutes for all five targets, and a total time of 1.06 hr, including all calibrators and overheads. More technical details are provided in the

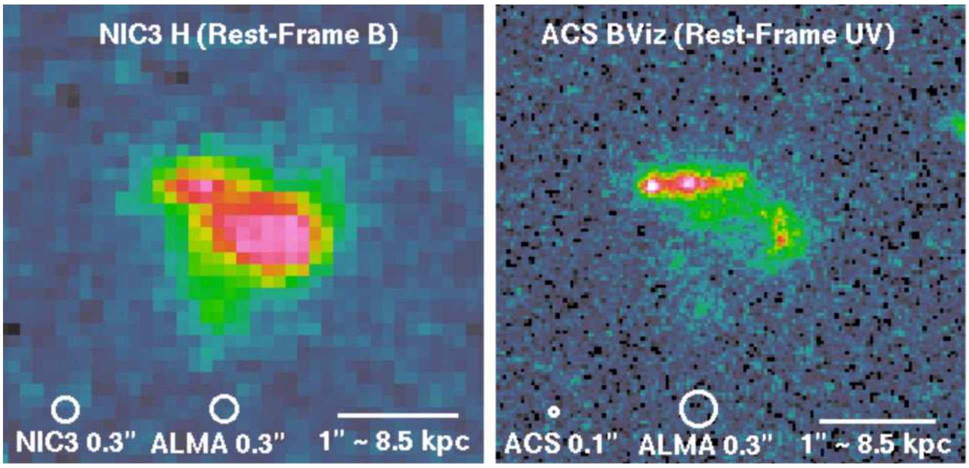

Figure 2: *HST* NIC3 *H*-band (rest-frame *B*) image (left) and *ACS BViz* (rest-frame UV) image (right) of a representative galaxy at $z \sim 2$ in our ALMA sample. The synthesized beam (0.″3) for our ALMA 345 GHz continuum observations is well matched to the resolution of the NIC3 (0.″3) and ACS (0.″1) data. This will allow us to make spatially resolved comparisons of the obscured SF (ACS), unobscured SF and AGN activity (ALMA), and intermediate age stellar population (NIC3).

OT science goal.

Immediate Objectives:

(1) Highest resolution maps to date of obscured SF in the most IR-luminous massive galaxies $z \sim 2$: The ALMA maps of the rest-frame FIR (~ 290 μm) continuum will reveal the distribution of warm dust. This reflects the distribution of obscured SF if one assumes that the dust is predominantly heated by young massive stars, rather than by an AGN. This assumption is expected to hold everywhere in the galaxy for the non-AGN host, and outside the central ALMA beam (inner 2.4 kpc) for the four AGN hosts in our sample. In the SF-dominated regions, we will compare the distributions of obscured SFR (from ALMA), unobscured SFR (from the rest-frame UV light traced by *HST* ACS *BViz* images), and intermediate age stellar population (from the the rest-frame *B*-band traced by *HST* NIC3 images). We will determine whether most of the ongoing SF activity is building extended disks or centrally concentrated bulges, and test different dust models used for deriving extinction-corrected UV-based SFRs.

(2) Assessing the impact of the AGN : In our four sample galaxies that host an AGN, dust in the central ALMA beam (inner 2.4 kpc) can be heated both by SF and an AGN. We will compare the ratio of rest-frame IR to UV luminosity between the central beam and the outer regions of the galaxy in order to assess the impact of the AGN. These investigations can yield important insights on why the *global* ratio of IR to UV luminosity is often much larger in AGN hosts than non-AGN hosts. In particular, they can help assess whether these large ratios are due to dust heating by the AGN, or/and are caused by large extended amounts of gas and dust across the whole galaxy.

(3) SF triggers and dynamical evolution of massive disks: We will explore whether the morphology of SF is more consistent with disturbed and centrally concentrated morphologies typical of merging systems, or with ordered, extended distributions typical of non-interacting disks, including those fed by cold mode accretion. (e.g., Khochfar & Silk 2009, Dekel et al. 09, Keres et al. 2005). We will also constrain theoretical models of how clumpy disky galaxies evolve by answering the following questions. Is the clumpy appearance of disks in the rest-frame UV mainly the result of patchy dust obscuration or is it indicative of organized structures? This can be assessed by comparing the rest-frame FIR continuum from ALMA to the rest-frame UV images from ACS. Where are most massive SF clumps located and how does this relate to the local SFR, stellar age, and environment

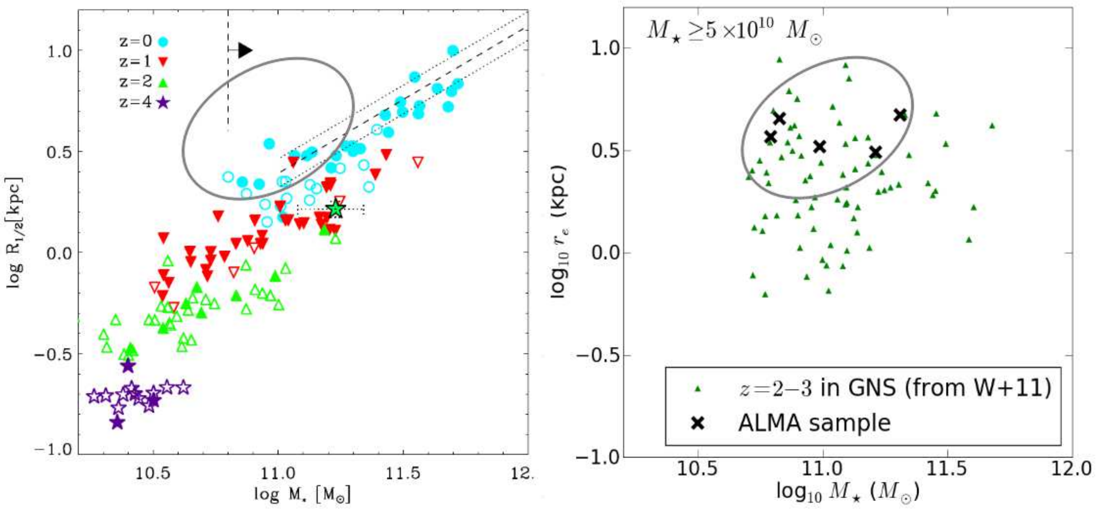

Figure 3: Distribution of half-light radius (r_e) as a function of stellar mass for galaxies at $z \sim 0-4$ in the cosmological simulations of Oser et al. (2012) (left panel) and for massive galaxies at $z \sim 2-3$ in the GNS survey (right panel). As highlighted by the overlaid oval, the simulations fail to produce the observed large population of massive disky extended ($r_e > 2.5$ kpc), actively star-forming galaxies. Our ALMA sample includes galaxies that both agree and strongly disagree with the model.

associated with the clump region or disky sub-structures? Is there evidence for large star-forming clumps migrating to the central regions and building bulges (e.g., Bournaud et al. 2007)?

Another important problem in galaxy evolution is that many cosmological simulations (e.g., Oser et al. 2012; Ceverino & Dekel in prep.) can form compact massive galaxies at $z \sim 2-3$, but fail to simultaneously reproduce the highly extended star-forming galaxies (Fig. 3). The ALMA data will help us compare the SF properties of galaxies agreeing and strongly disagreeing with the models (Fig. 3). It is believed that the discrepancy may be driven by poor models of SF and supernovae feedback (e.g., Governato et al. 2007), or by the lack of AGN feedback.

Potential for Publicity: The proposed ALMA observations will capture the public's imagination by providing the highest resolution maps to date of obscured SF and AGN activity in the most IR-luminous massive galaxies at an epoch when the Universe was less than 4 billion years old. As per her established track record, the PI plans to communicate the ALMA results through Stardate radio programs aired to a weekly audience of over ten million people; YouTube educational videos;[2] and McDonald observatory nationally-recognized workshops for secondary school teachers. The latter impact tens of thousands of secondary students yearly, of which over 49% are expected to be Hispanics, a demographic group greatly underrepresented in STEM fields.

References: [1] Bauer, A., et al. 2011, MNRAS, 417, 289; [2] Bournaud F., et al. 2007, ApJ, 670, 237; [3] Conselice, C. J., et al. 2011, MNRAS, 226; [4] Daddi, E., et al. 2007, ApJ, 670, 156; [5] Dekel, A., et al. 2009, Nature, 457, 451; [6] Dickinson, M., et al. 2003, ApJ, 587, 25; [8] Elbaz, D., et al. 2010 A&A, 518, L29; [9] Governato, F., et al. 2007, MNRAS, 374, 1479; [10] Hilton, M., et al. 2012, MNRAS, 425, 540; [11] Kereš, D., et al. 2005, MNRAS, 363, 2; [12] Khochfar, S. & Silk, J. 2009, ApJL, 700, L21; [13] Madau, P., et al. 1996, MNRAS, 283, 1388; [14] Nordon, R., et al. 2010, A&A, 518, L24; [15] Oser, L., et al. 2012, ApJ, 744, 63; [16] Papovich, C., et al. 2007. ApJ, 668, 45; [17] Richards G. T., et al. 2006, AJ, 131, 2766; [18] Schawinski, K., et l. 2011, ApJL, 727, L31; [19] van der Wel, A., et al. 2011; [20] van Dokkum, P. G., et al. 2011 ApJ, 743, 15; [21] Weinzirl, T., Jogee, S., Conselice, C., et al. 2011, ApJ, 743, 87 [W11]

[2]e.g. see http://www.youtube.com/stardatemagazine#p/u/8/hvSzVW1KACE