THE MOST MASSIVE GALAXIES AT 3<z<4 FROM THE NEWFIRM MEDIUM-BAND SURVEY: IDEAL CANDIDATES FOR Early-Science ALMA

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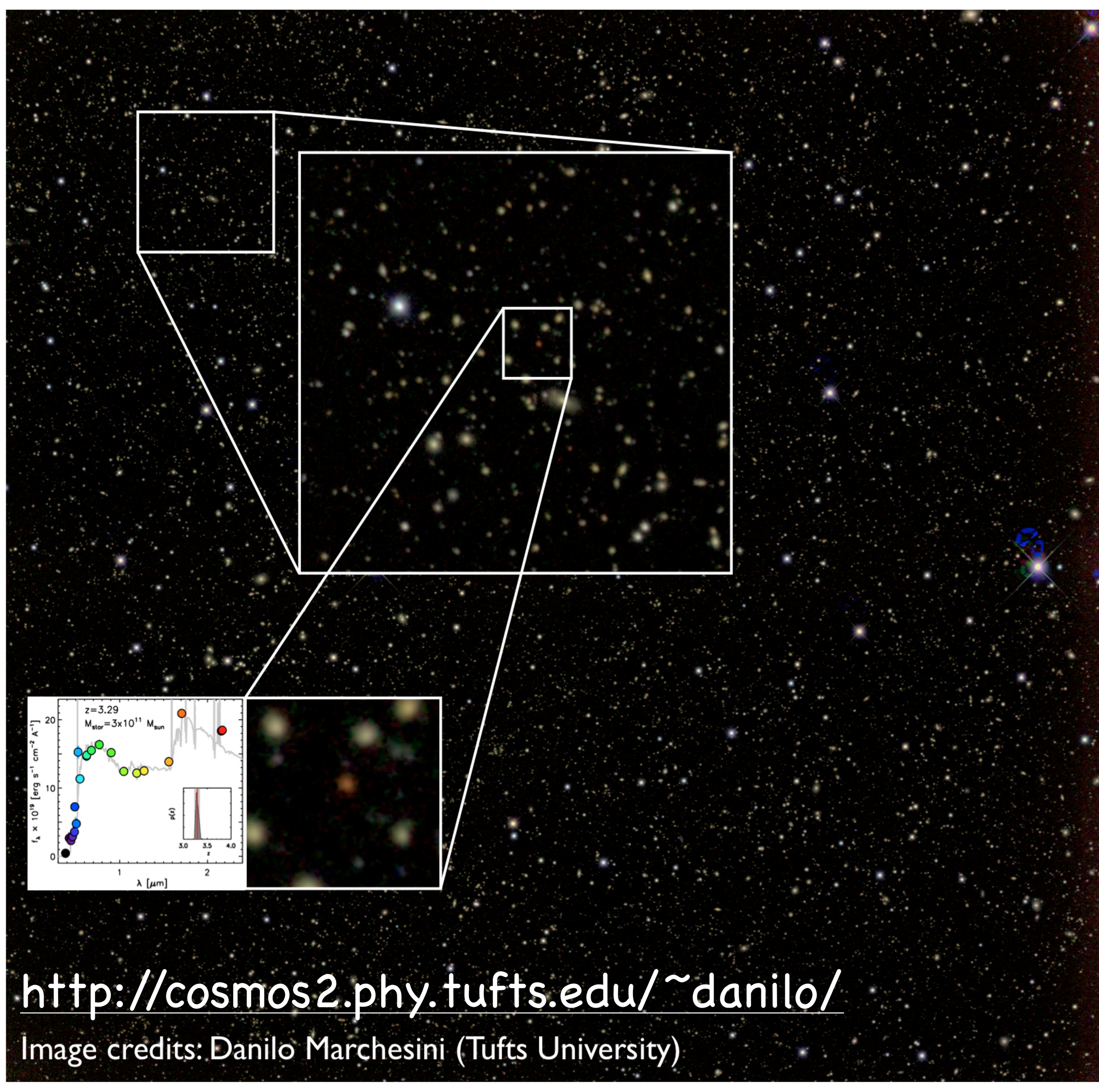
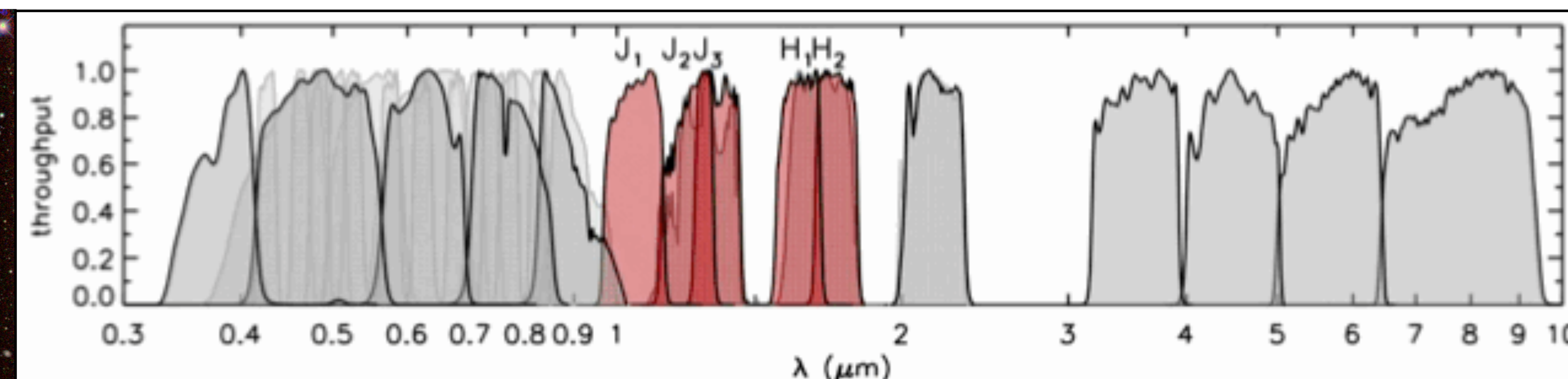
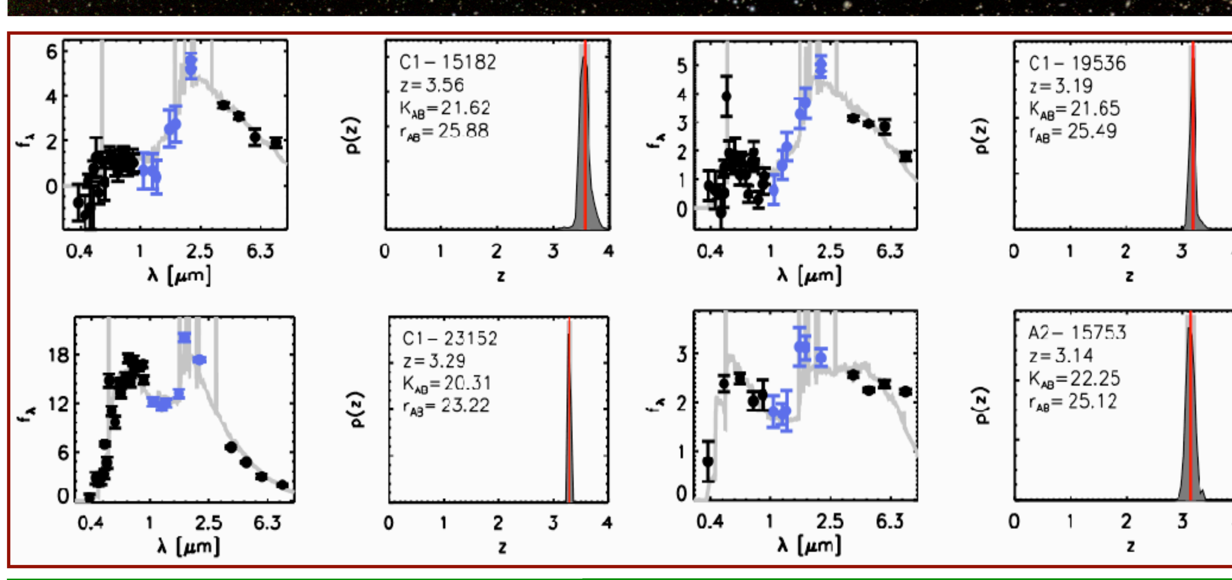


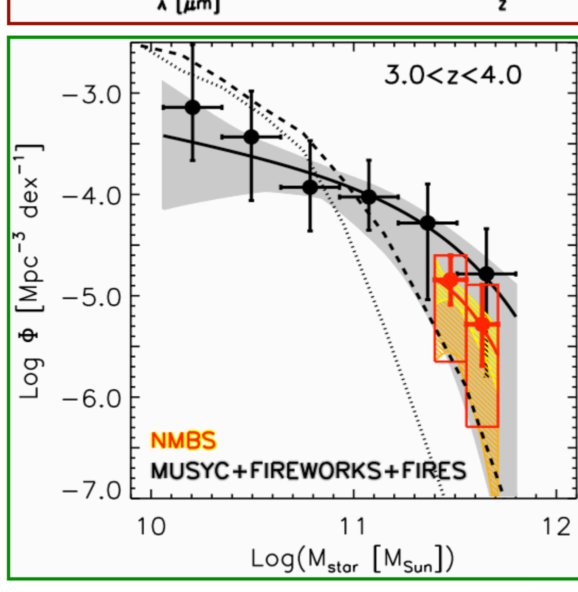


TOP: Throughput of the filters used in the NEWFIRM Medium-Band Survey (NMBS; van Dokkum et al. 2009): CFHTLS/ugriz + $J_{123}H_{12}$ + K + Spitzer/IRAC. The NMBS employs a new technique of using medium-bandwidth NIR filters to sample the Balmer/4000A breaks at 1.5<z<3.5 at a higher resolution than the standard broadband NIR filters, dramatically improving the accuracy of the photometric redshifts. The canonical J-band is split into 3 filters J_1, J_2, and J_3, and the H-band is split into 2 filters H_1 and H_2. The NMBS targeted two fields within the COSMOS (Scoville 2007) and AEGIS (Davis et al. 2007) surveys, chosen to take advantage of the wealth of publically-available ancillary data over a broad wavelength range. The observations were carried out on the Mayall 4m telescope on Kitt Peak using the NOAO Extremely Wide-Field Infrared Imager (NEWFIRM) 27.6x27.6 arcmin^2 camera with the $J_1J_2J_3H_1H_2$ medium bandwidth and the K broadband filters (for details, see Whitaker et al. 2011). The 90% point-source completeness of the K-band detected NMBS catalogs is K_{AB}=23.2. The NMBS catalogs contain about 13,000 galaxies at z_{phot}>1.5 with accurate photometric redshifts and rest-frame colors.

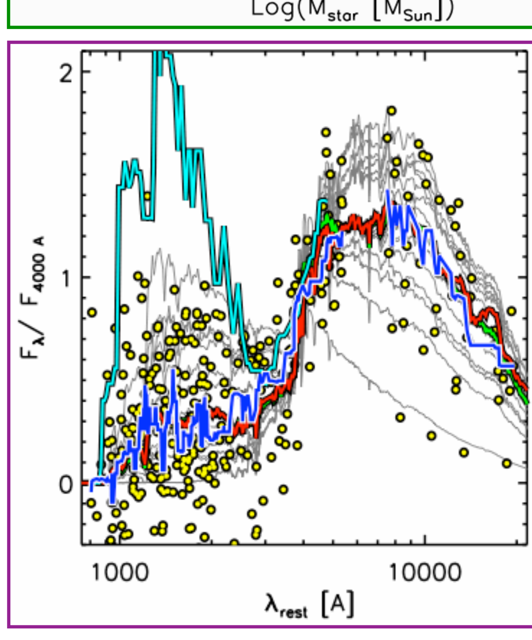
LEFT: $J_3H_1H_2$ color image of the 30x30 arcmin^2 NMBS COSMOS field. The highlighted red object represents the brightest object in a sample of 14 mass-selected galaxies at 3<z<4 (see below SAMPLE SELECTION). The observed spectral energy distribution and the redshift probability function are also plotted.



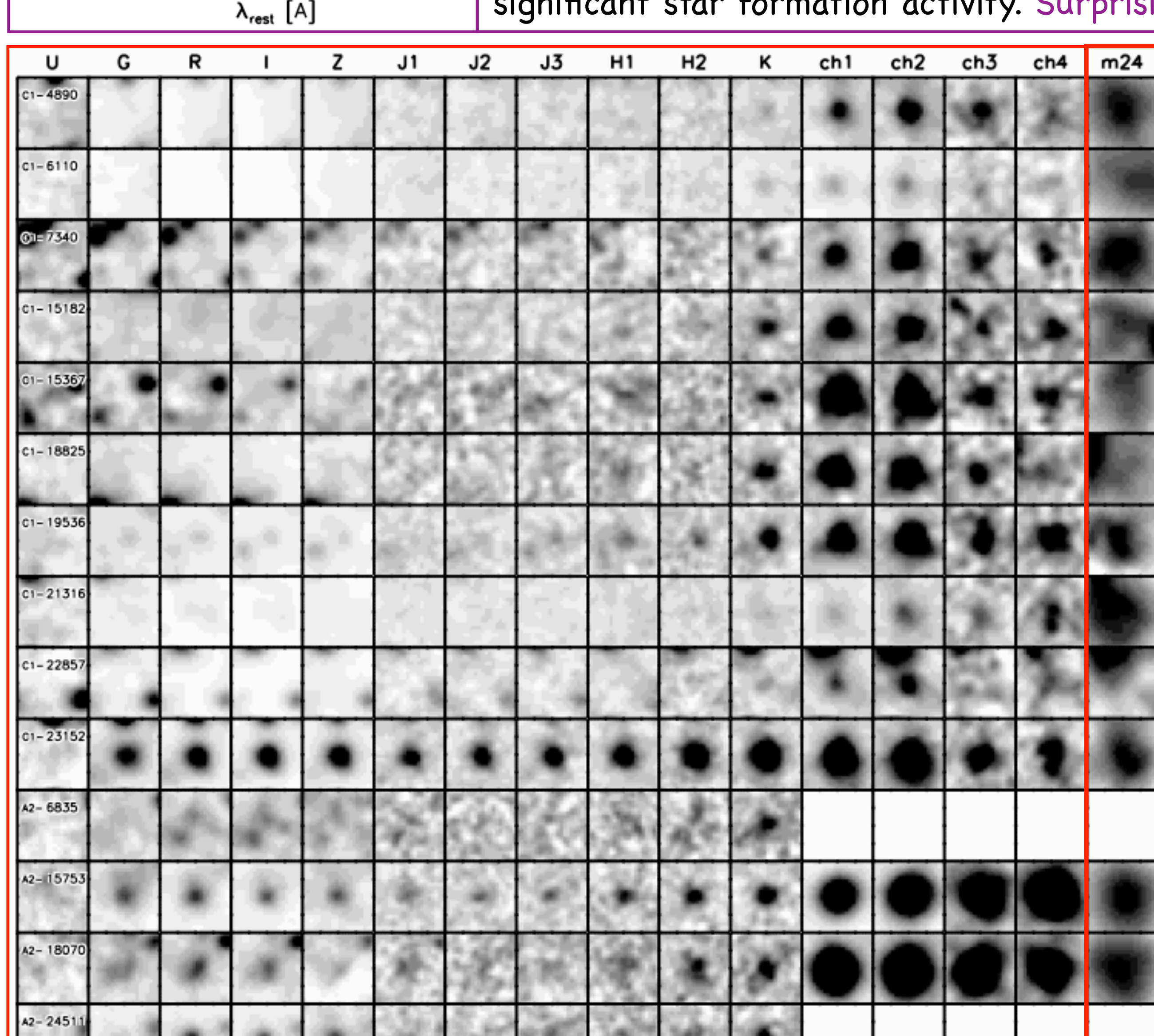
We use the optical to mid-infrared coverage of the NEWFIRM Medium-Band Survey to characterize, for the first time, the properties of a mass-complete sample of 14 galaxies at 3<z<4 with M_{star}>2.5x10^{11} M_{Sun}, and to derive significantly more accurate measurements of the high-mass end of the stellar mass function (SMF) of galaxies at 3<z<4. SAMPLE SELECTION: From the NMBS, sources were selected to be at redshift 3<z<4 and with stellar masses larger than 2.5x10^{11} M_{Sun}, which is the stellar mass completeness limit of the NMBS at z=3.5. The resulting mass-selected sample at 3<z<4 contains 14 galaxies with well-sampled SEDs from the ultra-violet to the mid-infrared. The figure on the left shows the SEDs and the redshift probability distributions of four of the 14 massive galaxies at 3<z<4. The main strength of this sample is that it is carefully selected on high-accuracy photometric redshifts, with no observed-frame color selection (e.g., Lyman break galaxies, LBGs, or sub-millimeter galaxies).



STELLAR MASS FUNCTION (SMF): The large surveyed area (effective area 0.44 deg^2) and the accurate photometric redshift estimates allow for the determination of the number density of the most massive galaxies at 3<z<4 with unprecedented accuracy, as shown on the left. Total random 1σ errors (red error bar and hatched yellow area) include photometric redshift errors and field-to-field variations. The number density of the most massive galaxies appears to have evolved by a factor of 2 from z=3.5 to z=2.5, and by a factor of about 3 from z=3.5 to z=1.6. Due to the steepness of the high-mass end, the implied evolution of the number density translates to small growth in stellar mass of the most massive galaxies, by 30-40% from z=3.5 to z=1.6, and by 40% from z=1.6 to z=0.1. The comparison between the NMBS-derived and the model-predicted SMFs (dotted and dashed curves; Somerville et al. 2008) provides further supporting evidence for the deficit of very massive galaxies at 3<z<4 in the theoretical models of galaxy formation previously highlighted by Marchesini et al. (2009). Without systematic uncertainties, the disagreement is significant at the 3σ level. The significance is reduced to only 1σ if we include systematic uncertainties due to different SED-modeling assumptions (i.e., adopting the Maraston 2005 instead of the Bruzual & Charlot 2003 models, and different star-formation histories; red boxes and hatched orange area).



PROPERTIES OF VERY MASSIVE GALAXIES AT 3<z<4: The typical very massive galaxy at 3<z<4 is red and faint in the observer's optical, with median r_{AB}=26.1. The median H-K color is 1.2 (AB). The median rest-frame U-V color is $U-V_{AB}$=1.6, similar to local Sb spirals, although the U-V colors range from the typical color of nearby irregular galaxies to those of local ellipticals. By constructing a mass-limited sample, we were able to FIND A POPULATION OF GALAXIES MOSTLY COMPLEMENTARY TO the typical population of DROPOUT GALAXIES AT z=3-4. Specifically, 57% of the mass-selected sample have observed optical colors satisfying either the U- or B-dropout color criteria, although 50% of these galaxies are too faint to be included in typical spectroscopic samples of LBGs. The figure on the left shows the rest-frame SEDs of the mass-selected sample at 3<z<4 (yellow circles), normalized at 4000 A; the solid blue curve represents the median of the observed SEDs, whereas the cyan curve is the median SED of H-K selected galaxies at z=3.7 (Brammer & van Dokkum), highlighting the differences between our sample (mass-selected) and color-selected samples. About 40-60% of the sample is characterized by ages consistent with the age of the universe at the targeted redshifts. Dust seems to be quite ubiquitous, with median A_V=1 mag. About 30% of the sample have SFR estimates from SED modeling consistent with no star formation activity, while the rest of the sample is characterized by significant star formation activity. Surprisingly, most (>80%) of the massive galaxies at 3<z<4 are detected in the Spitzer-MIPS 24 micron data.



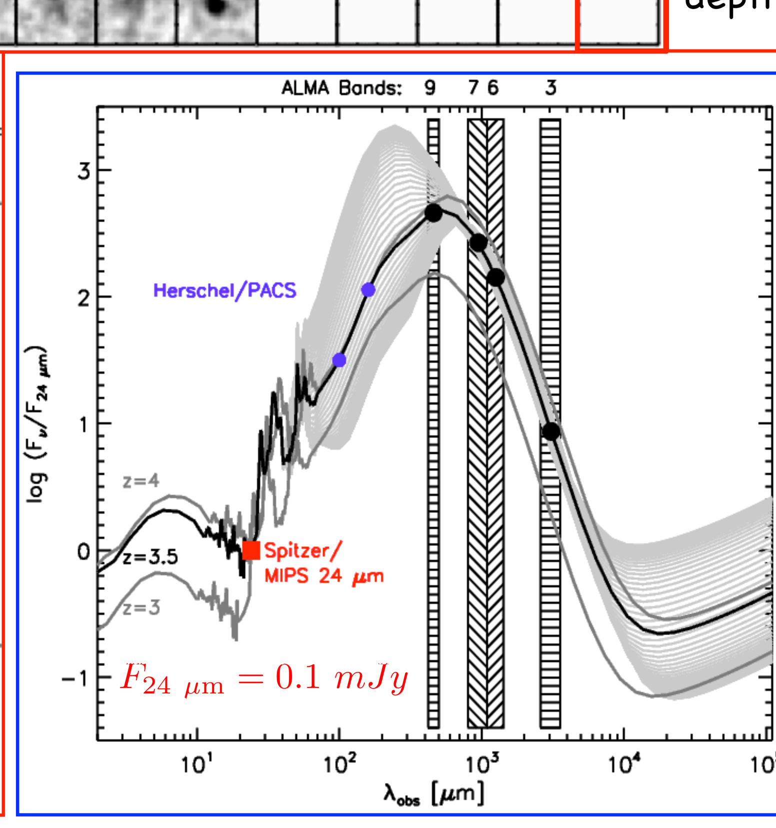
MASSIVE GALAXIES AT 3<z<4 HOST ULIRGs/HLIRGs: Most (>80%) of the massive galaxies at 3<z<4 are detected in the Spitzer-MIPS 24 micron data. The total infrared luminosities, L_{IR}, estimated from the observed 24 micron fluxes range from 5x10^{12} to 4x10^{13} L_{Sun}, with 80% of them having L_{IR}>10^{13} L_{Sun}, typical of hyper-luminous infrared galaxies (HLIRGs), and the remaining being ULIRGs. This implies extreme dust-enshrouded star-formation rates (600-4300 M_{Sun}/yr, tens to several hundreds of times larger than the SFRs estimated from SED modeling), or very common heavily-obscured active galactic nuclei (AGNs), or both, in the most massive galaxies at z=3.5. Whereas it is not possible to discriminate between the AGN or starburst as the dominant source responsible in heating the dust, we favor the AGN as a significant, if not a dominant, contributor. Specifically, the reasons for this are trifold. First, the extreme MIPS-derived SFRs cannot be sustained for more than 10^8 yr without over-prediction of the high-mass end of the SMFs of galaxies at z<3. This seems in contradiction with the very large fraction of MIPS detections, which implies a long duty cycle of the star formation. Second, 80% of the MIPS-detected sources are HLIRGs. In the local universe, the AGN is thought to be the dominant source of radiation responsible for the mid- and far-IR SEDs of HLIRGs. Third, for the targeted redshift range, the MIPS 24 micron band probes the rest-frame wavelengths from 4.8 to 7.1 microns, where hot dust dominates the MIR emission, and the contribution from an AGN as the source of the radiation field heating the dust becomes increasingly more likely. IF THE MIPS EMISSION IS DOMINATED BY AGN-HEATED DUST, THE LARGE FRACTION OF VERY MASSIVE GALAXIES AT 3<z<4 WITH MIPS DETECTION SUGGESTS THAT AGNs ARE VERY COMMON, PROVIDING FURTHER SUPPORTING EVIDENCE FOR THE CO-EVOLUTION OF MASSIVE GALAXIES AND AGNs.

Three galaxies are detected in the Chandra X-ray data, with 2-7 keV luminosities and hardness ratios typical of obscured, high-luminosity AGNs ($L_{2-7\,keV}$=3.8-10x10^{44} erg/s; N_H=1-6x10^{23} cm^{-2}). We note that, given the depth of the X-ray data, only AGNs with $L_{2-7\,keV}$>10^{44} erg/s at z>3 could have been detected.

Spitzer-MIPS 24 μM FLUXES AND DERIVED PROPERTIES OF THE $3.0 \le z < 4.0$ MASS-SELECTED SAMPLE

ID	S_{24} [μJy]	L_{IR} [10^{13} $L_\odot$]	SFR [$M_\odot$ yr^{-1}]
C1-4890	206.2±32.8	$3.3\pm0.5(^{+2.1}_{-2.3})$	$3611\pm574(^{+2280}_{-2500})$
C1-6110	116.4±28.0	$2.3\pm0.5(^{+1.1}_{-0.9})$	$2458\pm591(^{+1142}_{-1030})$
C1-7340	133.0±28.9	$1.9\pm0.4(^{+1.5}_{-0.9})$	$2078\pm451(^{+1682}_{-1025})$
C1-15182	78.6±25.7	$1.5\pm0.5(^{+0.6}_{-0.6})$	$1614\pm528(^{+694}_{-663})$
C1-15367	167.3±30.8	$3.9\pm0.7(^{+1.2}_{-0.8})$	$4275\pm787(^{+1226}_{-909})$
C1-18825[a]	blended	···	···
C1-19536	61.6±24.6	$0.5\pm0.2(^{+0.3}_{-0.2})$	$584\pm233(^{+300}_{-282})$
C1-21316	177.1±31.3	$4.0\pm0.7(^{+1.0}_{-1.0})$	$4330\pm765(^{+1064}_{-1095})$
C1-22857	<19.9	<0.4	<395
C1-23152	110.5±27.6	$1.2\pm0.3(^{+0.4}_{-0.4})$	$1331\pm333(^{+424}_{-408})$
A2-6835[b]	···	···	···
A2-15753	165.7±22.8	$1.3\pm0.3(^{+0.5}_{-0.5})$	$1371\pm378(^{+557}_{-476})$
A2-18070	127.0±21.3	$0.9\pm0.3(^{+0.5}_{-0.4})$	$918\pm308(^{+582}_{-420})$
A2-24511[b]	···	···	···

NOTE. — [a]no reliable MIPS 24μm flux could be obtained for C1-18825 due to blending issues; [b]no MIPS 24μm data available for A2-6835 and A2-23152. The errors listed for L_{IR} and SFR are computed using just the 24 μm photometric errors (values not in parenthesis) and the combination of the 24 μm photometric errors and the photometric redshift errors (values in parenthesis).



IDEAL CANDIDATES OF EARLY SCIENCE ALMA: The figure on the left shows the infrared SEDs of star-forming galaxies from Dale & Helou (2002), F_ν, redshifted at z=3.5 and normalized to the average observed flux at 24 micron of the mass-selected sample at 3<z<4 (gray curves). The black solid curve is the average of all the Dale & Helou (2002) templates for z=3.5, whereas the dark gray curves represent the average of the templates at z=3 and z=4. The red filled squared represents the MIPS 24 micron band. The large filled black circles represent the expected fluxes in the Early Science ALMA bands. For z=3.5, the fluxes in the ALMA bands are expected to range from 1 mJy (in band 3) up to 100 mJy (in band 9). Early Science ALMA will provide detection of the far-infrared continuum emission at a S/N=10 for exposure times from a few minutes to an hour, depending on the band. CO, ^{13}C, and OH molecular emission lines are expected to be detected in the Early Science ALMA bands. ALMA will be therefore crucial to spectroscopically confirm the redshifts of the mass-selected galaxies, and to constrain the amount of dust and gas in these systems, as well as discriminating between dust-enshrouded star-formation and obscured AGN activity. Ultimately, ALMA will allow for measurements of the kinematics in these systems, providing estimates of dynamical masses at 3<z<4.