A Submillimeter Perspective on Galaxy and Cluster Formation in the Early Universe

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Cosmic Star Formation History
(When and how do stars form?)

Star formation rate density (both UV and IR) of stellar-mass limited samples at $z<3$

Star formation rate density (UV only) of UV-selected galaxy samples at $z>3$

Madau & Dickinson, 2014
Hubble Sequence at $z<3$
(Why do galaxies exhibit different shapes?)

van der Wel+2014
Galaxy formation at high-z:

**Knowns:**

- Establishment of the Hubble-sequence at $z<3$
- Stellar mass function and star formation rates density for galaxies at $z<3$
- UV luminosity function at $z>3\sim8(10)$

**Unknowns:**

- The origin of the Hubble-sequence, in particular, what are the roles of internal and external process (environment) in shaping galaxies?
- **Stellar mass function and star formation rates density at $z>3$**
- UV luminosity function at $z>8$
Towards a Complete Census of Massive Galaxies at z>3


The majority of massive galaxies at z>3 are UV-faint (H - [4.5] > 2.5), hence are missed from Lyman-break Galaxy (LBG) selection.

Wang, T., et al. 2019a, in press
A dominant population of optically-invisible massive galaxies at $z>3$ revealed at submillimeter

870um(ALMA)/450um(SCUBA-2) colors as redshift indicators

Wang, T., et al. 2019a, in press
Spectroscopic confirmation

(a) Spectroscopic confirmation from NIR spectroscopy

ID=25363
$z_{\text{spec}}=5.113$

IB738

ID=32932
$z_{\text{spec}}=3.097$

IB505

Wang, T., et al. 2019a, b (in preparation)
Towards a Complete Census of Massive Galaxies at $z>3$: What is needed?

We require deep surveys at both 450um (rms~1mJy) and 870um (rms~0.5 mJy) towards deep HST fields (CANDELS, Frontier fields…), which would enable systematic identifications of normal, high-$z$ massive and dusty galaxies.

Five H-dropouts behind a low-$z$ cluster detected at 1.2mm (ALMA Lensing Cluster survey (PI: K. Kohno)) confusion is not a major concern once rich ancillary data is available. Wang, T., et al, 2019a,c( in preparation)
High-z Cluster Formation

The Hubble Space Telescope Treasury Survey of the Coma Cluster of Galaxies


SSA22: Progenitor of a coma like cluster at z=3.1, Umehata+2015
Evidence for the environmental dependence of gas content in high-z clusters

Systematic search/studies of high-z clusters at z>2: What is needed?

- Wide-field blind search of over-densities of SMGs
- Targeted observations of over-densities of UV-selected galaxies (e.g., from HSC survey)
Summary

- ALMA/JCMT(SCUBA-2) reveals a dominant population of optically-invisible (HST-dark) massive galaxies at $z>3$. Future deep surveys at both 450 and 850um are required to obtain large samples, and eventually answer the fundamental question as to how many massive galaxies are formed during the first Gyr of the universe.

- Progenitors of today’s most massive clusters contain significant over-densities of SMGs at $z>2$, and systematic search and studies of these structures in the submillimeter are likely the most efficient way in unveiling the evolution of clusters and their effects on galaxy evolution.