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

Tao Wang (王涛) (University of Tokyo/NAOJ)

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



Madau & Dickinson, 2014

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

Hubble Sequence at z<3 (Why do galaxies exhibit different shapes?)



Wang, T., et al. 2012, ApJ, 752, 134

van der Wel+2014

Galaxy formation at high-z:

Knowns:

- Establishment of the Hubblesequence at z<3
- Stellar mass function and star formation rates density for galaxies at z<3
- UV luminosity function at z>3~8(10)

Unknowns:

- The origin of the Hubblesequence, 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 UVfaint (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 opticallyinvisible massive galaxies at z>3 revealed at sumbillimeter



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

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

Spectroscopic confirmation



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.



Wang, T., et al, 2019a,c(in preparation)

High-z Cluster Formation

z~0

z~2.5









The Hubble Space Telescope Treasury Survey of the Coma Cluster of Galaxies J1001: the most distant known X-ray cluster at z=2.51, Wang, T., et al. 2016, ApJ, 828,56

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



Wang, T., et al. 2018, ApJL, 867, 29

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.