論文の内容の要旨

Demographics of the Cold Universe with ALMA:
From Inter-Stellar and Circum-Galactic Media to Cosmic Structures
(ALMA で探る冷たい宇宙: 星間及び銀河周辺物質から宇宙の構造までの統計研究)

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The cosmic infrared background light (CIB) is known to have energy comparable to the optical one (COB), suggesting that the half of the cosmic star-formation history is obscured by the cold dust. It is thus inevitably important to investigate the origin of the CIB and unveil the obscured side of the universe (i.e. Cold Universe) to fully understand the galaxy evolution and formation. In the frameworks of Λ cold dark matter structure formation, the cold gas and dust are widely distributed among the scales of the inter-stellar medium (ISM), the circum-galactic medium (CGM), and the cosmic structure, where the CIB is expected to be produced. To understand the origin of the CIB potentially produced from these three layers, a variety of submillimeter (submm) and millimeter (mm) observations have been performed with the single-dish and interferometric telescopes including Atacama Large Millimeter/submillimeter Array (ALMA). Although the previous observations show that about half of the CIB is explained by individual submm/mm emission identified in the ISM scale, the physical origin of these individual submm/mm emission is still unclear even with the recent ALMA observations. Moreover, no one knows where and how the rest half of the CIB is produced. One reason is that the ALMA field-of-view in submm/mm bands ($\simeq 30''$) is much smaller than the optical-near infrared (NIR) telescopes that often perform surveys over degrees. Another reason is the sensitivity. To detect the diffuse emission extended beyond the ISM scale, extremely deep data is required even with ALMA. Therefore, the lack of the ALMA statistical and deep studies prevents us from giving conclusions for where and how the CIB originates.

To approach these open questions, we have studied the submm/mm emission from high-z galaxies in the scales of ISM, CGM, and the cosmic structure based on the intensive ALMA data analyses. In our study, we have constructed 1254 ALMA submm/mm source sample from 1677 ALMA maps, that are the largest ALMA sample and dataset so far obtained, by making full use of the archive as well as our original data.

In the ISM scale, we focus on galaxy size (i.e. effective radius $R_{\rm e}$) and morphology

(i.e. Sérsic index n) that are key quantities to understand the galaxy evolution. First, with a large ALMA sample consisted of 1,034 ALMA mm sources, we homogeneously derive rest-frame far-infrared (FIR) size, $R_{\rm e,FIR}$, and luminosity, $L_{\rm IR}$, of the ALMA sources, carefully evaluating the uncertainties by realistic Monte-Carlo simulation in the uv-visibility plane. We find a positive correlation between $R_{\rm e,FIR}$ and $L_{\rm IR}$ at the $> 99\%$ significance level. We also find that $R_{\rm e,FIR}$ of our ALMA sources is comparable to the rest-frame optical one, $R_{\rm e,opt}$, of the quiescent galaxies at $z \sim 1-3$, supporting the evolutional connection from the dusty star-forming to the quiescent galaxies. Second, we have performed uv-visibility based stacking for 33 ALMA sources at $z =$ 1–3 identified in the high resolution (beam = $0.''2$) ALMA 1-mm map. Owing to the stacked, deep high-resolution ALMA map, we find that our sample has an average $R_{\rm e,FIR}$ and rest-frame FIR n, $n_{\rm FIR}$, values of $1.0 - 1.3$ kpc and 1.2 ± 0.2, respectively. Interestingly, we obtain the rest-frame optical n and $R_{\rm e}$ of $n_{\rm opt} = 0.9 \pm 0.3$ ($\simeq n_{\rm FIR}$) and $R_{\rm e,opt} = 3.2 \pm 0.6$ kpc ($> R_{\rm e,FIR}$), suggesting that the dusty disk-like structure is embedded in the larger stellar disk.

In the CGM scale, we study the dust continuum and the singly ionized carbon [C II] 158-μm line emission from $z \sim 6$ normal star-forming galaxies that are good probes for the metal-enrichment in the primordial CGM gas. We carry out the visibility-based [CII] 158-μm line stacking as well as the rest-frame FIR continuum for deep ALMA data of 18 normal star-forming galaxies at z = 5.15–7.14. Also performing the HST stacking for the same sample, we find that the stellar continuum of both the rest-frame UV and FIR emission shows a compact morphology, while the [C II] line is extended out to a radius of $\sim$10 kpc (9.2 σ), referred to as [CII] halo. This indicates that the extended [C II] emission is not powered by the stellar continuum such as faint satellite galaxies. Interestingly, the radial profile of the [CII] halo is well consistent with that of the Lyman-alpha (Lyα) halo that is universally identified around $z \sim 6$ normal star-forming galaxies in the recent deep MUSE observations, indicative of the association between the [CII] and Lyα halos.

In the cosmic structure scale, we evaluate the number density and the clustering of the faint submm/mm sources newly identified with ALMA. We have constructed a large ALMA sample composed of 133 faint submm/mm sources that are serendipitously detected in our original and the archival multi-field deep Band 6/7 data. With the assistance of the gravitational lensing, we explore the faint-end of the 1-mm number counts down to 0.02 mJy, and find that the total integrated flux reaches 104^{+31}_{-25} %

of the CIB. This clearly shows that the CIB is explained by the individual galaxies, and the contribution of the diffuse emission beyond the ISM scale is negligible to the CIB. The galaxy bias $b_{\rm g}$ value for the ALMA sources is evaluated by the counts-in-cells technique and placed a stringent upper limit of $b_{\rm g} < 3.5$ that is not similar to $b_{\rm g}$ values of massive distant red galaxies and submm galaxies but comparable to those of UV-bright, star-forming BzK galaxies and Lyman-break galaxies. However, we also find that a part of the ALMA sources is not detected even in the deep optical-NIR images taken with Subaru and Hubble Space Telescope. These results indicate that the ALMA faint submm/mm sources are overlapped with the well-known optical-NIR selected galaxies, while some of them have been missed in the previous optical-NIR surveys.

Our results in the ISM, CGM, and cosmic structure scales provide us with a consistent picture of the Cold Universe: the dusty obscured star-formation takes place in the compact region in the ISM scale, instead of widely placing in the CGM and cosmic structure scales. This directly reveals where and how much amount of the dusty obscured star-formation occurs in the universe, for the first time. The total (= dust-obscured + unobscured) cosmic star-formation rate density (SFRD) at $z \simeq$ 1–4 is estimated to be 140^{+20}_{-40} % of the previous results obtained with the optical-NIR galaxies. While our results newly identify the submm/mm sources that have been missed in the previous optical-NIR surveys, the total cosmic SFRD value suggests that the general understanding of the cosmic SFRD is unchanged by a factor of two even with these submm/mm sources.

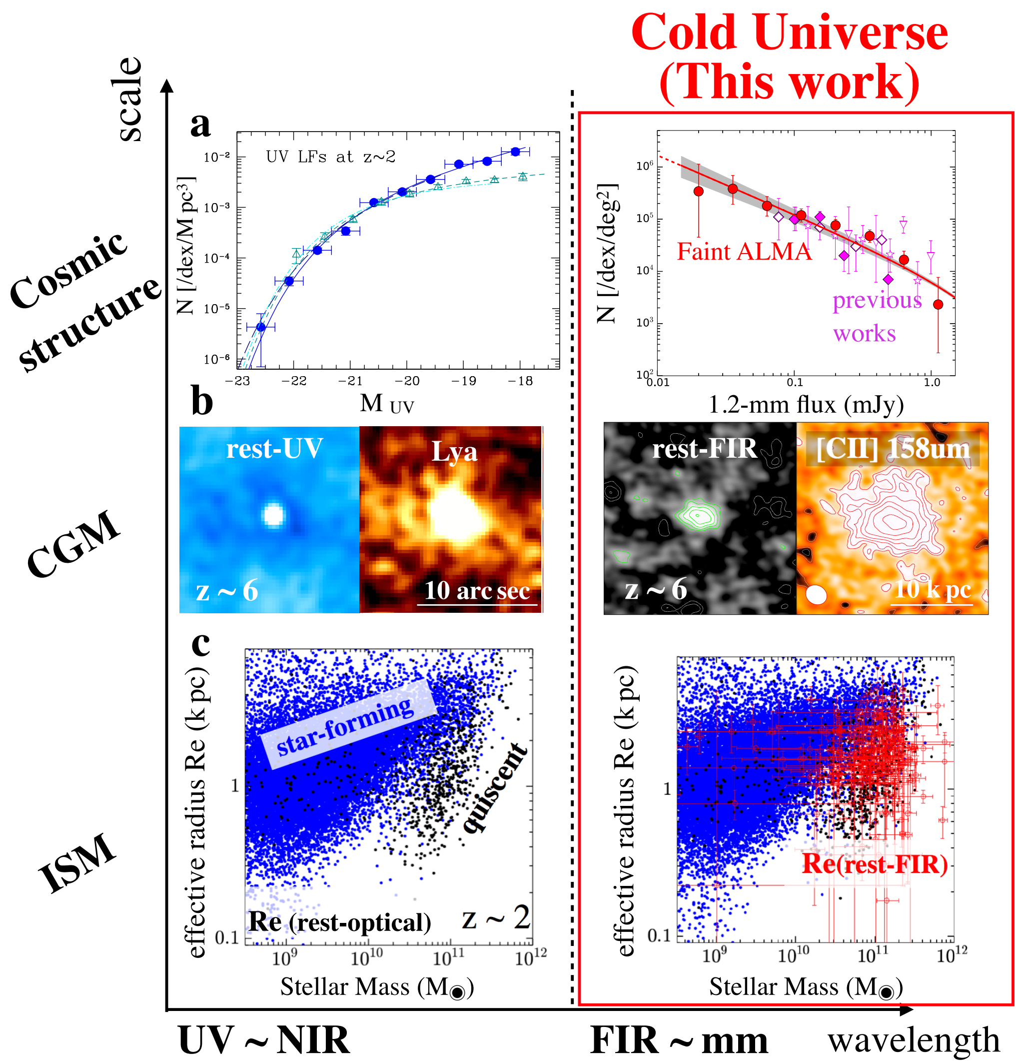

Figure 1 Schematic overview of the scope of this thesis in the scales from ISM and CGM to the cosmic structure. (a) Rest-frame ultra-violet (UV) luminosity function. (b) Lyα halo universally identified in the high-z star-forming galaxies. (c) Size and mass relation among star-forming and quiescent galaxies at $z \sim 2$. Figures of (a), (b), and (c) are referred from Figure 4, 2, and 5 of Reddy et al. (2009), Momose et al. (2014), and van der Wel et al. (2014), respectively.