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学位論文題目	Correlation between Galaxies and IGM at z≈2 Mapped by Subaru/HSC
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(Form 3)

Summary of Doctoral Thesis

Name in full Yongming LIANG

Title Correlation between Galaxies and IGM at z≈2 Mapped by Subaru/HSC

The relation between galaxies and intergalactic medium (IGM) attracts great interest nowadays because it bridges galaxy formation and large-scale structure formation. Influenced by gravitational instability, the dense fluctuation began to collapse from the earliest homogeneous HI density field. Therefore, galaxies preferentially form in high-density regions where more pristine HI in IGM sinks in a potential well. As the large-scale filaments are the largest HI reservoir, the intersects of these filaments have provided an ideal platform to accrete the ingredient along the cold stream. Therefore, the overdense regions in our universe are the most vital laboratory to inspect the galaxies and IGM HI correlation. Nevertheless, to unveil the complete picture of the galaxy formation concerning this topic, one must overcome the cosmic variance to address the possible variation of the interplays between the galaxy and IGM.

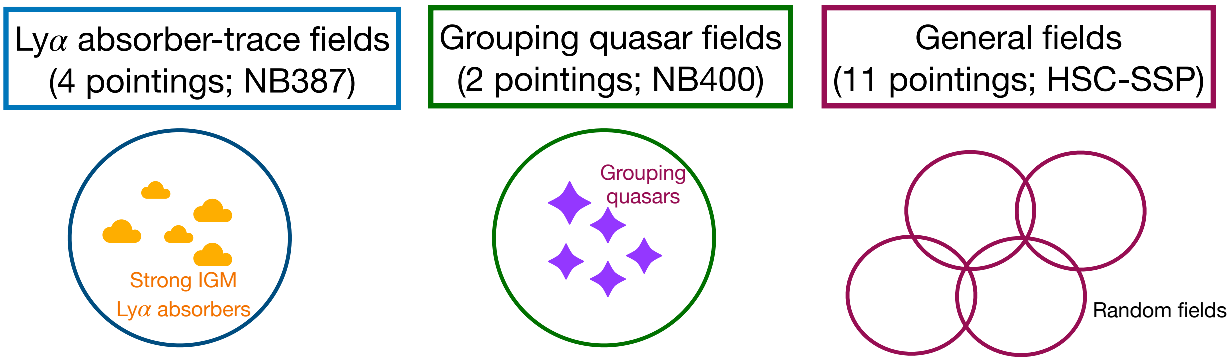

Figure 1. The largest LAE and LoS sample constructed in three distinct environments

In this thesis, we first search for the high-density region using a novel technique that utilizes the grouping of strong IGM Lya absorption systems imprinting in the SDSS/BOSS quasar spectra as the tracers. To expand the classes of different galaxy environments for discussing field variation, we have also collected the field candidates that enclose grouping quasars with ≥5 within 40x40 $cMpc^2$ sky area. Then we perform the narrowband imaging observations with the filters NB387 and NB400 on Subaru/Hyper Suprime-Cam to map the z=2.18 and z=2.29 Lya emitters (LAEs) in six fields, BOSS0210, BOSS0222, BOSS0924, BOSS1419, BOSS0240, and BOSS0755. Based on the narrowband images, we select the LAEs using the narrowband excess technique, and finally, we have built up a catalog consisting of 3,687 LAEs over a survey area of ~8 deg^2. Moreover, there is a recent opportunity from the Subaru HSC-SSP survey, and a new z=2.18 LAE catalog consisting of 3,720 LAEs is built based on the NB387 survey in the Deep/Ultra-Deep fields, i.e., DEEP2-3, E-COSMOS, and the XMM-SDSS, which covers the sky area of ~19 deg^2. We can combine both catalogs to discuss the field variation on the Lya emitters and the IGM HI correlation. This sample is the largest in terms of the LAEs and the covered sky area, giving us unprecedented power to address this topic.

Based on the LAE catalog, we have constructed the LAE overdensity maps for nine HSC fields, including the HSC-SSP Deep/Ultra-deep fields and those traced by IGM HI absorbers or grouping quasars at the redshifts z=2.18 and z=2.29. These maps have identified structures like large filaments, clumpy overdensities, and voids. We perform the effective optical depth of the line-of-sight/LoS - the LAE overdensity (τ_{LoS} - δ_{LAE}) correlation analysis with the overdensity estimate. τ_{LoS} is measured on 15 h^{-1}Mpc scales in the background SDSS/BOSS quasars. This correlation is further transformed into the Lya forest transmission fluctuation - LAE overdensity ($\delta_{<F>}$ - δ_{LAE}) relation, whose slope can be compared among fields to inspect how the Lya absorption is dependent on the local galaxy overdensity. As a result, we find a moderate and positive correlation between LAE overdensity and IGM HI absorption based on the Lya absorber-trace fields, but the $\delta_{<F>}$ - δ_{LAE} slope is much flatter in general fields from HSC-SSP and in the grouping quasar fields. This result implies the variation in the galaxy-IGM HI correlation and has revealed that the IGM HI absorption is stronger at the given δ_{LAE} in the HI-rich regions compared to general fields. Meanwhile, grouping quasars may also play a role via the feedback to suppress the IGM HI, as the BOSS0210 that contains a significant quasar overdensity can essentially flatten the slope of the sample in the Lya absorber-trace fields and make the slope more consistent with model predictions. However, this effect is weaker in the general fields because of the initially thin IGM HI in the mean regions at z≈2, and therefore, grouping quasar fields can have a similar $\delta_{<F>}$ - δ_{LAE} slope to that of general fields.

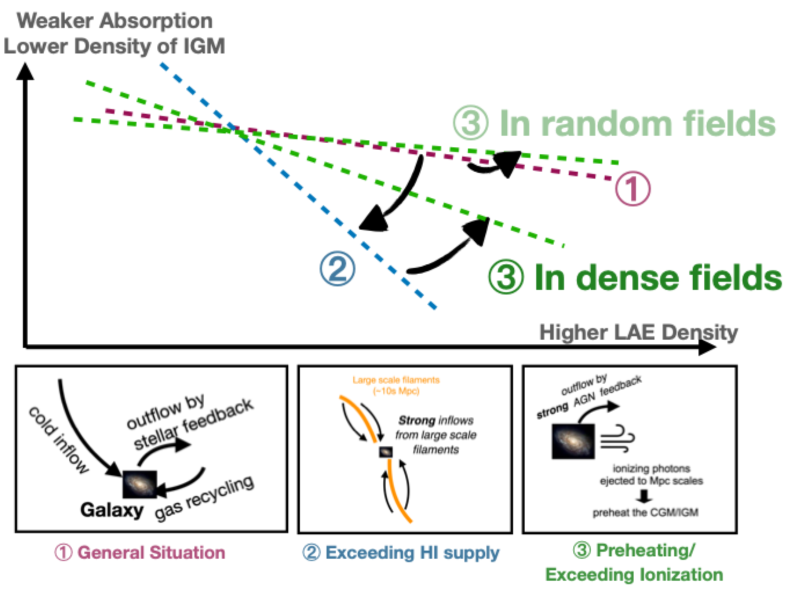

Figure 2. Schematic diagram to show interpretations of different slops in different environments.

We also perform correlation analysis using the two-point cross-correlation functions (CCFs) between the high-/low-τ_{LoS} LoSs and LAEs. From the CCFs, we find the positive correlation signal between the high-τ_{LoS} LoSs and LAEs up to a scale of 4±1 pMpc in the Lya absorber-trace fields, and the measured values can be well modeled by a power law. This suggests that the LAEs reside in the HI-rich regions up to a scale of 4 pMpc. By comparing the original CCFs among different fields, we find that the data points of CCFs in all samples broadly span around a power law and the optimized power-law fitting gives consistent clustering lengths r_0 among different samples, which suggests that the galaxy-IGM HI correlation is dominated by underlying halos regardless of the various environments. However, the only negative signal of the CCF between high-τ_{LoS} LoSs and LAEs at d≈200 kpc showing out in the grouping quasar still emphasizes the effects of quasar feedback, at least on the circumgalactic scales, collaborating with the suggestion from an analysis of the fluctuation of average τ_{LoS} profile $\delta_{<\tau LoS>}$(d) results.

Throughout this thesis, we confirm the correlation between galaxies and IGM in Hi-rich environments at z≈2, the epoch of the Cosmic Noon, with the largest sample size and the widest survey area. These unprecedented samples enable us, for the first time, to witness the possible existence of the field variation of the galaxy-IGM HI interplays. The steeper slope of $\delta_{<F>}$ - δ_{LAE} relation that we find in the Lya absorber-trace fields, and that is flattened with the emergence of grouping quasars can be explained as a result of the exceeding HI supply from the large-scale filaments, which causes the stronger IGM Lya absorption in high-density regions than in the field regions. Alternatively, the slope can also hint at the deficient LAE detection due to HI suppression, stressing the importance of studying different galaxy populations in surveys. However, the similarity of CCFs and their power-law fitting among different samples suggest the dominance of the gravitational potential of underlying halos in the galaxy-IGM correlation. Combining the two analyses, we conclude that despite the environments, dark matter halos still dominate the galaxy-IGM correlation at z≈2, although exceeding HI supply and AGN/quasar feedback can play secondary roles. The results from this thesis provide us with a unique key to open the door to understanding galaxy formation in the context of large-scale structure formation.

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Results of the doctoral thesis defense

博士論文審査結果

Name in Full
氏　名　　Yongming LIANG

Title
論文題目　　Correlation between Galaxies and IGM at z≈2 Mapped by Subaru/HSC

The relationship between galaxies and the intergalactic medium (IGM) is one of the key subjects in modern astronomy since it bridges galaxy and large-scale structure formation. Overdense regions of galaxies in the universe at high-z are important in studying the galaxy and IGM correlation, given that galaxies preferentially form in high density regions from pristine neutral Hydrogen (HI) gas in IGM. In the last decade, the existence of a relationship between galaxy overdensity and the IGM opacity has been reported by studies based on observations. One of the major caveats of the efforts is, however, that those efforts just study the relationship within only a limited area in the sky and the field-to-field (cosmic) variation of the interplay between galaxies and IGM may affect the outcome which has not been fully explored.

The applicant attempted to overcome the field variance issue and explored the relationship between galaxies and IGM by making use of a large database of quasar spectra and wide-field imaging data taken with Subaru/Hyper Suprime-Cam (HSC). Regarding the IGM, the applicant constructed a sample of IGM HI absorption system at a specific redshift ($z \approx 2$) imprinted on the Sloan Digital Sky Survey/Baryon Oscillation Spectroscopic Survey quasar spectra. Regarding galaxies, he performed narrow-band imaging observations with Subaru/HSC toward fields containing IGM HI absorbers. From the HSC images, he picked up galaxies emitting strong Lyα emission (Lyα emitters, hereafter LAEs) at the corresponding redshift. The above efforts were done in two types of fields (environments): fields with high surface density of IGM HI absorption system implying HI-rich environment (Lyα absorber-trace fields) and fields enclosing groups of quasars (grouping quasar fields). The applicant also made use of a new LAE catalog in general fields from a recent literature. Then, he constructed a surface density (overdensity) map of LAEs for each field. By combining the above, he constructed a set of LAE overdensity maps accompanied with an IGM HI absorption systems which are within the overdensity maps in three types of fields (environments).

In order to see the relationship between the IGM HI absorption system and LAE over-density map, the applicant performed correlation analysis between the effective Lyα optical depth of the IGM HI absorption system and the LAE overdensity. He found a moderate and positive correlation between IGM HI absorption optical depth and LAE overdensity on the Lyα absorber-trace fields, while the correlation was weak or marginal in the other two fields. The slope of correlation, which differs among the fields, is steeper in the Lyα absorber-trace fields than those in the grouping quasar fields and the general fields. These results reveal that the IGM HI absorption is stronger at the given LAE surface density in the HI-rich regions compared to the general fields, and this can be explained as a result of HI supply from the large-scale structure. Meanwhile, groups of quasars may also play a role in flattening the slope of correlation via ionizing of the IGM HI.

The applicant performed correlation analysis by using the two-point cross-correlation functions (CCFs) between the IGM HI absorption system and LAEs. He found a positive correlation signal up to a scale of four physical Mpc between the IGM HI absorption systems having high Lyα optical depth and LAEs in the Lyα absorber-trace fields. This suggests that the LAEs reside in the HI-rich regions up to a scale of four physical Mpc. He compared the CCFs among the three fields and found that the data points of CCFs in all the fields broadly span around a power law and the clustering lengths are consistent among the fields. The results imply that the IGM HI–galaxy correlation is dominated by underlying halos regardless of the environments.

Combining the two analyses above, correlation analysis between the effective Lyα optical depth of IGM HI absorption system and the LAE overdensity and CCFs, the applicant concluded that the gravitational potential of dark matter halos still dominates the IGM–galaxy correlation at $z \approx 2$ despite their environments, although exceeding HI supply and quasar feedback can play secondary roles.

The applicant made effective use of the data-sets with the largest sample size and the widest survey area ever used in similar means to other published efforts. He analyzed the quasar spectra data by using a novel approach and successfully constructed a large and robust sample of the IGM HI absorption system. He also constructed a solid sample of LAEs by performing careful data processing and analysis of Subaru/HSC data as much as possible. All the efforts led to the unique findings of a relationship between IGM and galaxies.

The applicant's study is recognized such that it provides new findings on the relationship between IGM and galaxies. These results will push research on galaxy and large-scale structure formation forward. The review panel members all agree to judge that the applicant passes the examination.