From *AKARI* to *SPICA*: a New Window to Understand Links between Cosmology and Galaxy Evolution

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ABSTRACT

Understanding the complex relation between the evolution of large scale structure of the Universe and of galaxies themselves is one of the key problems of modern cosmology. It is well known that galaxy clustering depends on galaxy types and properties, and that this relation evolved with cosmic time in a way which is not yet well understood. In the same time, optical surveys cannot be sufficient to solve the emerging questions: one of the key problems is the evolving dust extinction in galaxies. Hence the necessity of deep multiwavelength infrared observations to understand the link between galaxies and the underlying large scale structure woven from dark matter. However, the present-day infrared observations usually suffer from relatively low resolution which makes it impossible for example to trace the relation between the evolution of galaxies and the history of intergalactic interactions. Also, the spectroscopic data in the infrared are limited. In this paper, we summarize some of the results of our measurements of clustering of dusty galaxies from on the *AKARI* data, both deep surveys and all-sky survey. We mention the key problems which could not be successfully solved yet: the relation between galaxy clustering and interactions inside one dark matter halo; the evolution of the position in the large scale structure of the extreme types of infrared galaxies, like (U)LIRGs. We discuss the perspectives to answer these questions thanks to *SPICA* unique sensitivity, resolution, and spectroscopic capabilities.

1. INTRODUCTION

According to the widely accepted paradigm in modern cosmology, the formation and evolution of the large scale structure of the Universe, was driven by gravitational instability. So-called hierarchical scenario of the structure formation assumes that galaxies formed and evolved inside (cold) dark matter halos, growing under the effect of gravity. It implies that the density field of dark matter at all cosmic epochs can be, in general, traced by the distribution of galaxies. However, galaxies are *biased* tracers of the dark matter field; moreover, the corresponding bias depends both on cosmic time and on galaxy properties: morphological types, colors, masses, luminosities. Since galaxies evolve with time, in the evolving large scale net of dark matter, the interplay between evolution of their properties and position in the dark matter large scale structures, is not-trivial and not yet well understood.

It is well known that in the present cosmic epoch different types of galaxies cluster differently. Large, luminous, red, non-star forming elliptical galaxies are typically strongly clustered; they are usually found in highly overdense environments, e.g. in the central parts of galaxy clusters. Inversely, small, spiral or irregular, blue star-forming galaxies are usually characterized by low clustering amplitude, since they are located in low-density areas (e.g. Zehavi et al. 2011). However, it is clear that at some moment in the past the situation must have been different: today's' passive red galaxies in the clusters' centers must have once produced their star populations; thus, once upon a time they much have been blue and active. This shift of star formation activity to smaller galaxies and towards low density areas with cosmic time is (in many varieties of the precise definition) known as downsizing.

However, it is still unclear when this process of moving star formation outside of dense environments took place, what was its timescale and what were the key mechanism behind it. In the largest existing deep galaxy surveys (e.g. VIPERS: Guzzo et al. 2013) we find structure very similar to today's one at least up to $z \sim 1.2$: already then massive red galaxies were strongly clustered while blue star forming galaxies were located in the less dense environments. Only much more detailed studies show some possible hints for reversal of this tendency, but strongly dependent on galaxy properties (Cucciati et al. 2006). Also, the mechanism of formation of different morphological types of galaxies are still debatable: both initial conditions in the place where galaxy has been formed and interactions between galaxies might have played the role. The question about the level of importance of both these factors is nicknamed sometimes as cosmological "nurture or nature" problem.

To make a census of all possible types of galaxies at different cosmic epochs, deep surveys at all possible wavelength ranges, with spectroscopic information available, are crucial. In particular, information gathered at infrared (IR) wave-

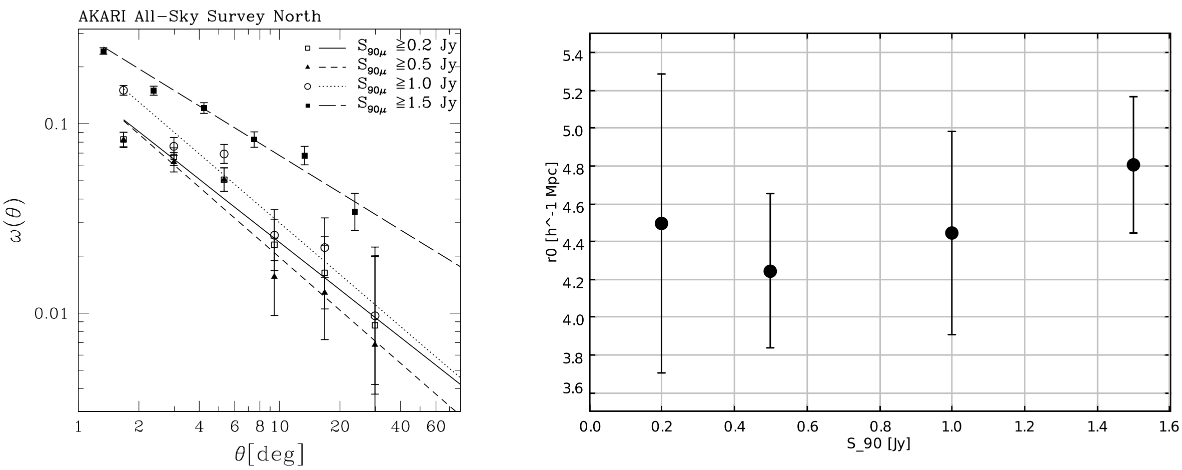

Figure 1. *Left:* Angular correlation function $\omega(\theta)$ of galaxies in the northern Galactic hemisphere in the *AKARI* All-Sky Survey for four flux-limited samples. *Right:* Spatial clustering lengths r_0 of the same four flux limited galaxy samples as in the left panel, reconstructed from the angular correlation function using the Limber inversion.

lengths plays an important role. First of all, observations in the IR significantly increase the sample of detected galaxies. One reason is that at near IR (NIR) dust is nearly transparent; it allows for galaxy surveys at NIR to cover much larger part of the sky than for optical surveys, which are limited by dust extinction from the disk in our own galaxy. At longer IR wavelengths emission from dust reveals the presence of dust obscured galaxies, often barely visible or undetectable by optical observations. Additionally, IR observations are crucial for proper estimation of key galaxy properties, in particular of their star formation rates (e.g., Takeuchi et al. 2010).

The large-scale structure of dusty galaxies can be then seen as the star-formation density field in galaxies. It may thus allow us to trace the relation between the dark matter density and star formation activity at different epochs (e.g., Małek et al. 2010; Solarz et al. 2013).

The breakthrough in the studies of dusty galaxies came with the launch of the *IRAS* satellite in 1983 (Neugebauer et al. 1984). More than 20 years later a Japanese satellite *AKARI* opened new possibilities to explore the whole sky in the mid- and far-infrared (Murakami et al. 2007). The primary purpose of the *AKARI* mission was to provide second-generation infrared (IR) catalogs characterized by a better spatial resolution and a wider spectral coverage than the *IRAS* catalogs. In addition to the all-sky surveys, some pointed deep observations were made by *AKARI*, in particular deep extragalactic surveys at the northern and southern ecliptic poles. These two deep surveys are now referred to as *AKARI* North Ecliptic Pole (NEP) and *AKARI* Deep Field-South (ADF-S) fields.

2. CLUSTERING OF *AKARI* GALAXIES

There was a number of attempts so far to investigate clustering of galaxies bright in IR both in *AKARI* All-Sky Survey and in the deep fields at NEP and ADF-S. Among others, Małek et al. (2010) have performed an attempt to identify the FIR-bright extragalactic sources in the ADF-S and then used their correlation function to estimate the limitations of the completeness of the sample due to source confusion. Matsuura et al. (2011) measured the power spectrum of the cosmic infrared background (CIB) in the ADF-S, providing a new upper limit for the clustering properties of distant infrared galaxies and any diffuse emission from the early universe which might have contributed to the CIB.

2.1. Local galaxies in the *AKARI* All-Sky Survey

Two all sky surveys, performed at FIR (90 μm) and mid-IR (MIR) can be counted among the main achievements of *AKARI*. Its Far-Infrared Surveyer (FIS; Kawada et al. 2007) scanned 96% of the entire sky, and the resulting *AKARI*/FIS Bright Source Catalogue v.1.0 (Yamamura et al. 2010) contains 427,071 point sources measured at 65, 90, 140 and 160 μm. Among them, 18,087 were identified as extragalactic sources located at low extinction ares of the sky, which are not affected by the dust neither from Milky Way nor Magellanic Clouds (Pollo et al. 2010, 2013a). After the cross-identification with the public catalogs it was found that a majority (over 60%) of these sources are very nearby galaxies at $z < 0.1$, and the remaining galaxies are mostly also local, at not much higher redshifts.

A positive clustering signal of galaxies from this sample in both Galactic hemispheres extends up to 40°(Pollo et al. 2013a). As shown in the left panel of Figure 1, angular correlation function $\omega(\theta)$ for flux-limited subsamples displays a clear tendency: bright galaxies have a higher angular clustering amplitude. However, as presented in the right panel of Figure 1, a spatial clustering amplitude r_0 of these galaxies, reconstructed from their $\omega(\theta)$ using the Limber inversion, depends only weakly on the limiting FIR flux S_{90}; the observed differences in the angular clustering are rather related to different redshift distributions of different flux limited samples - brighter galaxies are typically more nearby.

FROM *AKARI* TO *SPICA*: CLUSTERING OF INFRARED GALAXIES

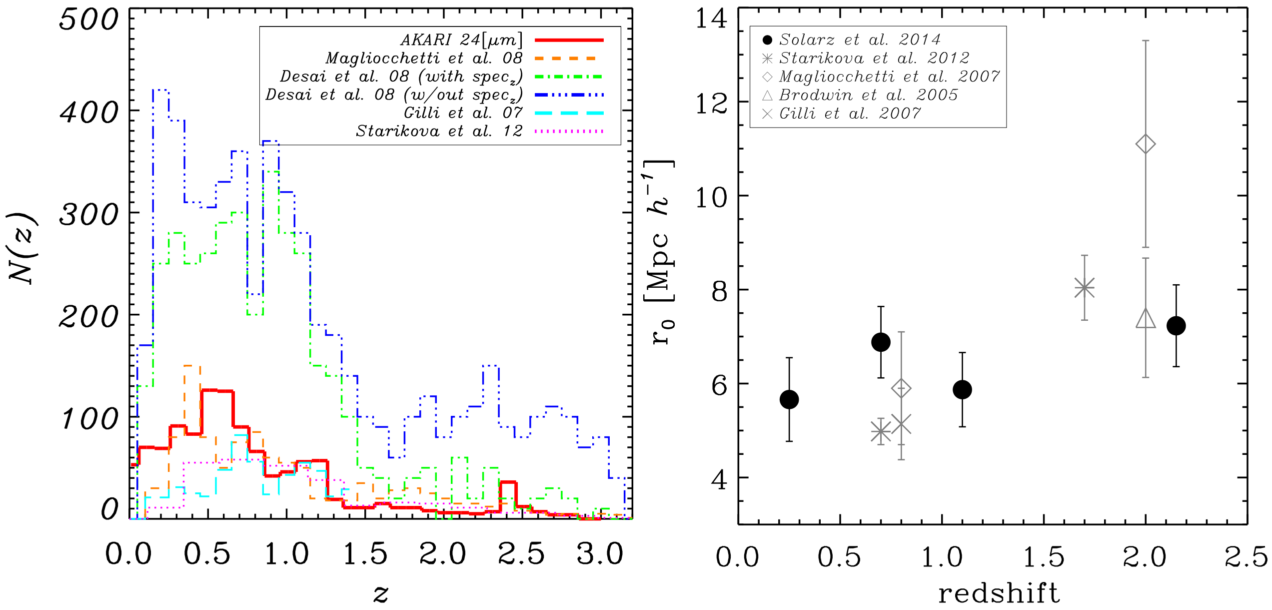

Figure 2. *Left:* Distribution of photometric redshifts of 24 μm-selected galaxies in the *AKARI* NEP-Deep field. *Right:* Dependence of the spatial correlation length. r_0 on redshift z of 24 μm-selected galaxies in the *AKARI* NEP-Deep field, compared to the measurements of r_0 of 24 μm-selected galaxies found in other surveys.

The spatial correlation length for local *AKARI* FIR-bright galaxies is $r_0 \sim 4.5\,\mathrm{h}^{-1}$ Mpc. This value is – with respect to the measurement uncertainties – consistent with $r_0 \sim 5h^{-1}$ Mpc typical for local optically bright galaxies. A weak dependence of r_0 of the limiting FIR flux may suggest that the luminosity of a galaxy in FIR is not related simply to the mass of the host dark halo of a galaxy but is affected also by other factors, like star formation rate in the galaxy. In the same time, the measured r_0 of this local population of FIR-selected star forming galaxies is significantly higher than the correlation lengths measured for local star forming galaxies selected w.g. according to their UV observed flux. It might imply that different tracers of star formation favor different populations of star-forming galaxies (Pollo et al. 2013b).

2.2. Star forming galaxies in the *AKARI* NEP-Deep field

The NEP-Deep survey covers an area of 0.4 square degree, and it was observed by nine NIR and MIR filters of the *AKARI* Infra-Red Camera (IRC, Onaka et al. 2007). Solarz et al. (2013) measured clustering of 1339 24 μm-selected sources, classified as galaxies using the Support Vector Machines (SVM, Solarz et al. 2012). Photometric redshifts of these galaxies, estimated with the aid of the CIGALE code (Noll et al. 2009; Małek et al. 2013), and callibrated using the spectroscopic follow-up data, cover a wide redshift range from $z \sim 0$ to 3.

As shown in the left panel of Figure 2, the redshift distribution of 24 μm-selected NEP galaxies displays three clear peaks. The broad peak centered at $z \sim 0.6$ most probably consists of star forming galaxies, including (Ultra)Luminous IR Galaxies (ULIRGs). A second peak at $z \sim 1.2$ might be due to 12.7 μm polycyclic aromatic hydrocarbons (PAH) feature and 12.8 μm Ne II emission line entering the selection wavelength. Finally, the most tentative peak at $z \sim 2.4$ might consist of Active Galactic Nuclei (AGNs) and/or sources with a strong 8 μm PAH line. As shown in the plot, similar two or three different populations of galaxies at comparable redshifts were also detected by other surveys of 24 μm-selected galaxies.

All these populations seem to be strongly clustered. In the right panel of Figure 2 the spatial clustering length r_0 of these galaxies is presented as a function of redshift z. Its high values are consistent with other measurements of similar populations found in the literature and suggest that all these three populations, although not directly related, represent strongly clustered galaxies residing in the massive dark matter haloes. In the same time, their IR features imply ongoing active star formation in them. The precise link between these galaxy populations, their star formation histories, and properties of underlying dark matter field, remains to be revealed by future studies.

3. *SPICA*: WHAT WE WANT AND WHAT WE EXPECT

The planned *SPICA* mission (Nakagawa et al. 2011) should become a next major milestone in the investigations of all types of IR-bright galaxies and their relations to the underlying dark matter field. Thanks to the resolution and sensitivity much superior to any of the previous missions it should allow to go down to the very small scales and solve the question of small scale environment of IR-bright galaxies. As shown e.g. by Małek et al. (2010), among galaxies very bright at FIR we find a much higher percentage of interacting galaxies, or galaxies with disturbed morphologies, bearing traces of interactions, than in the optical catalogs. Małek et al. (2010) have also shown that the reconstruction of a shape of correlation function at small scales allows to expect a significant amount of "invisible" galactic companions, not detected by optical observations and in IR hidden by the source confusion. Careful analysis of small scale environment of dusty star forming galaxies should allow to solve the question about the role of environmental effects in triggering star formation at different cosmic epochs and in different galaxy types and environments.

Another, and probably most important feature of *SPICA* will be the presence of spectroscopic instruments. All the IR space missions until now have had only limited spectroscopic capabilities. In the same time, spectroscopy is the key to the galaxy studies: on one hand, it allows for much wider and more precise estimation of galaxy properties than any estimators based only on photometric data. On the other hand, IR spectroscopy allows for precise redshift measurement independently on the optical spectroscopy. This becomes particularly important for galaxies for which optical redshift measurement is not possible or very difficult. Among such galaxies we have very dusty galaxies like Dust Obscured Galaxies (DOGs) or (U)LIRGs.

A well known limitation of optical redshift surveys is related to the existence of so-called redshift desert: at $1.4 \leq z \leq 2.5$ typical galaxies do not have strong emission lines falling into optical regime; this property makes the measurement of their redshifts very difficult. Redshift histograms $N(z)$ of deep optical surveys usually show a depletion in this redshift range, which results only from this technical limitation (see, e.g., Le Fèvre et al. 2005, 2013). The succesful redshift measurements require spectroscopic observations at wavelengths other than optical. On the other hand, redshift desert may be the cosmic epoch when and where we can find clues to the origin of well developed large scale structure formed by different types of galaxies which we observe at lower redshifts.

IR spectroscopic measurements by *SPICA* should lead to new cosmological surveys which create a new view of different epochs, and link the star formation history of galaxies to the local properties of dark matter field in which they formed and evolved.

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