

# **Early Stages of Galaxy Cluster Formation:**

Mergers, Protoclusters, and Star Formation in Overdense  
Environments

ESO Garching, July 17 - 21, 2017



ESO Conference on

# Early Stages of Galaxy Cluster Formation

17–21 July 2017  
Garching, Germany

Mergers,  
Protoclusters,  
and Star Formation  
in Overdense  
Environments

#### Main topics

Merging clusters | High-z clusters |  
Protoclusters | Detection, classifica-  
tion & comparison | ICM physics |  
AGN feedback | Star formation |  
Galaxy evolution | Future facilities

#### Invited speakers

Monique Arnaud (Saclay)  
Nicholas Battaglia (Princeton)  
Caitlin Casey (Texas)  
Megan Donahue (MSU)  
Dominique Eckert (Geneva)  
Marcus Brüggen (Hamburg)  
Gabiella de Lucia (Trieste)  
Adam Muzzin (York)

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Tony Mroczkowski (co-chair, ESO)  
Paola Andreani (ESO)  
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Emanuele Daddi (Saclay)  
Carlos De Breuck (ESO)  
Simona Giacintucci (NRL)  
Nina Hatch (Nottingham)  
Yusei Koyama (NAOJ)  
Sophie Maurogordato (Nice)  
Gregory Rudnick (Kansas)  
David Sobral (Lancaster)  
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Registration/abstract submission from 9 January 2017 | Abstract submission deadline: 31 March 2017 |  
Early registration closes 28 April 2017 | Payment deadline: 31 May 2017



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The shape shown on this poster is the floor plan of the ESO headquarters extension building in which the conference will take place. The image inside the floor plan is an artist's impression of a protocluster forming in the early Universe. Credit: ESO/M. Kornmesser



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# Monday Afternoon

## Invited talk Monique Arnaud (CEA Saclay)

### The Hydrangea simulations: clusters with resolved galaxies Yannick Bahe (MPE)

I introduce the Hydrangea simulations, a suite of cosmological hydrodynamic zoom-in simulations of massive galaxy clusters. Their resolution and subgrid physics, developed for the EAGLE project, enables the simulations to follow the formation of individual cluster galaxies from high redshift to the present day. I present tests of the simulations on cluster and galaxy scales that demonstrate good agreement with observations. The simulations predict a significant impact of the cluster environment on the stellar masses of galaxies both in the cluster core and the far outskirts. I discuss how these differences are related to differences in the high-redshift properties of cluster and field galaxies, when the bulk of their present-day stellar mass was formed.

### XMM-OWLS insights into cluster assembly at redshift 1 to 2 Marguerite Pierre (IRFU CEA)

The presence of massive clusters in the redshift 1-2 range potentially provides a critical handle on the determination of the cosmological parameters. The practical difficulty however, resides in the inventory and characterisation of these objects, namely of their virialisation stage and of their mass. We have developed a procedure to address these issues in the X-ray band in the context of the XXL project (<http://irfu.cea.fr/xxl>). It is based on the modelling of real-like XMM images from the OWLS hydrodynamical simulations obtained for a range of hypotheses on AGN feedback and various XMM exposure times. Along with a semi-analytical modelling of halo formation, this allows us to characterise the detected sources as clusters or proto-clusters. Further information from S-Z observations, weak-shear analyses and velocity mapping provides a self-consistent description of the properties of the high-z (proto)cluster population. From this, we developed a formalism for the cosmological analysis. We will present the first results of this study.

# What distant clusters can reveal about galaxy evolution

**Nina Hatch (Nottingham)**

I will describe the cosmic star formation history of cluster galaxies using observations of clusters and protoclusters from  $z = 0$  to 4. I will show that the star formation history of clusters differs from the global cosmic star formation history: cluster galaxies typically form their stars earlier and over a shorter period of time. I will use semi-analytic models of galaxy formation to explain why their star formation histories differ. I will show that the star formation density in protoclusters is extremely high due their high matter densities, but the simulations suggest there is no reversal in the star formation - density relation at high redshift. The differences in the star formation histories of field and cluster galaxies are caused by the gradual suppression of star formation, starting at  $z = 3$ , and getting stronger with time. The main mechanisms responsible for this suppression are tidal stripping and AGN feedback. Looking ahead, I will describe several testable predictions of the different evolutionary paths of cluster and field galaxies. Comparing these predictions with JWST observations of distant clusters and protoclusters can test our understanding of galaxy evolution.



# The build-up of galaxy clusters in a hierarchical Universe

**Gabriella de Lucia (Triste)**

I will review how clusters and proto-clusters assemble in the framework of state-of-the-art semi-analytic models of galaxy formation and hydrodynamical simulations. I will use these theoretical tools to make connections between such an assembly process and the physical properties of galaxies we observe in galaxy clusters today.

## Semi-Analytic Model Predictions of the Galaxy Population in Proto-Clusters

**Emanuele Contini (Yonsei University)**

We investigate the galaxy population in simulated proto-clusters using a semi-analytic model of galaxy formation, coupled to merger trees extracted from N-body simulations. We select the most massive clusters at redshift  $z = 0$  from our set of simulations, and follow their main progenitors back in time. The analysis shows that proto-clusters are dominated by central galaxies and their number decreases with time as many become satellites, clustering around the central object. Proto-clusters are very extended regions,  $> 20$  Mpc at  $z > 1$ . The fraction of galaxies in proto-clusters that are not progenitor of cluster galaxies varies with redshift, stellar mass and area considered. It is about 20 – 30 per cent for galaxies with stellar mass  $10^9 M_{\odot}$ , while negligible for the most massive galaxies considered. Nevertheless, these objects have properties similar to those of progenitors. We investigate the building-up of the passive-sequence in clusters, and find that the main mechanism which quenches star formation is the removal of the hot gas reservoir at the time of accretion. The later galaxies are accreted, and the more the cold gas available, the longer the time spent as active.

## Simulating Galaxy Clusters with Dust Formation and Evolution

**Eda Gjergo (Trieste)**

In order to investigate basic properties of galaxies, such as the star formation rate and the masses of baryonic components, it is important to account for dust reprocessing. Dust particles absorb and scatter the stars' optical/UV emission, and they reradiate thermally in the infrared. A combination of simulations and post-processing radiative transfer computations can produce mock data, which can be compared directly to observations. Until now, however, dust properties have only been included by means of post-processing assumptions, leaving room for uncertainties, particularly significant at wavelengths shorter than 100 microns. To reduce these uncertainties, we implemented a state-of-the-art treatment of the production and evolution of dust grains within our simulation code, P-GADGET3. This model traces the creation, evolution, and destruction of dust through various processes. It accounts for the diameter of dust particles with a two-grain-size approximation proposed by H. Hirashita. We will present a first result of our new code applied to zoom-in simulations of massive ( $3 \times 10^{14} M_{\odot}$ ) galaxy clusters, focusing in particular to the early stages of assembly of the cluster at high redshift, around  $z = 2$ , where the SF activity is at its maximum and the proto-cluster regions are rich of cold, dust-polluted gas.



# Tuesday Morning

## Invited talk – Protocluster assembly: observations and theory **Nina Hatch (Nottingham)**

In this talk I will give an overview of the theory of protocluster formation and assembly in terms of Lambda-CDM cosmology. I will describe the implications of hierarchical and stochastic cluster assembly. I will report on recent observations that illuminate the assembly of clusters, focussing on the distribution and velocity structure of protocluster galaxies, and the distribution of proto-intracluster medium.

## A large-scale super-structure at $z \sim 0.65$ in the UKIDSS ultra-Deep survey field **Audrey Galametz (MPE)**

In hierarchical structure formation scenarios, galaxies accrete along high density filaments. Superclusters represent the largest density enhancements in the cosmic web with scales of 100 to 200 Mpc. As they represent the largest components of LSS, they are very powerful tools to constrain cosmological models. Since they also offer a wide range of density, from infalling group to high density cluster core, they are also the perfect laboratory to study the influence of environment on galaxy evolution. I will present a newly discovered large scale structure at  $z=0.65$  in the UKIDSS UDS field. Although statistically predicted, the presence of such structure in UKIDSS, one of the most extensively covered and studied extragalactic field, remains a serendipity. Our follow-up confirmed more than 15 group members including at least three galaxy clusters with  $M_{200} \sim 10^{14} M_{\odot}$ . Deep spectroscopy of the quiescent core galaxies reveals that the most massive structure knots are at very different formation stage with a range of red sequence properties. Statistics allow us to map formation age across the structure denser knots and identify where quenching is most probably occurring across the LSS. Spectral diagnostics analysis also reveals an interesting population of transition galaxies we suspect are transforming from star-forming to quiescent galaxies.

## A spectroscopically confirmed rich proto-cluster at $z \sim 6.5$ **Rafael Guzman (University of Florida)**

We have performed a search for Ly $\alpha$  sources around two spectroscopically confirmed star forming sources in the Subaru Deep Field. Deep imaging of this field has resulted in a large number of Ly $\alpha$  sources potentially related to the two strong star forming sources. Deep GTC/OSIRIS multi-object spectroscopy of a selected sample of these sources has resulted in the spectroscopic detection of at least 4 sources as well as one of the two fiducial sources used as sign post for the observations. At magnitude  $m = 26$  AB, these are some of the deepest spectroscopically confirmed Ly $\alpha$  sources. We have built the Luminosity function of this field, and have used the parameters found to determine the time evolution of such over-density. We find that by  $z = 0$ , this over-density would become a full fledged cluster similar or larger than the Coma cluster.

# Multi-wavelength investigation of Planck high-redshift proto-clusters **Mari Polletta (IRAP)**

High redshift proto-clusters might contain clumps of intensively star forming galaxies and thus appear as bright and red sub-millimeter sources. In order to find such proto-structures, the multi-frequency Planck all sky maps have been inspected yielding about 2100 proto-cluster candidates, the Planck high-redshift (PHz) sources. Multi-wavelength observations of these sources reveal over-densities of bright and red sub-millimeter sources associated with red IRAC sources. Spectroscopic near-infrared and millimeter observations confirm the presence of dusty star-forming galaxies at redshift  $\sim 2$  in several candidates, and photometric redshifts identify candidates up to redshift 3. Here, we review our current understanding of the PHz sources and of their galaxy members and compare their properties with those of known proto-clusters from the literature.

## Resolving with ALMA the nature of an early star-forming large-scale structure from PLANCK **Ryley Hill (UBC)**

A large sample of over-dense structures has been defined using Planck's all-sky submm maps and follow-up with Herschel-SPIRE. These sources are candidates for the progenitors of present-day, massive galaxy clusters. We targeted the eight brightest SPIRE peaks in the centre of one Planck source with ALMA, and complemented these observations with data from Spitzer-IRAC, CFHT-WIRCam (J,K) and SCUBA-2. We detected a total of 18 millimetre galaxies brighter than 0.3 mJy in 2.4 arcmin<sup>2</sup>, and we are able to match these to their NIR counterparts, deriving photometric redshifts, star-formation rates, IR luminosities, stellar masses, dust temperatures, and dust masses, indicating that three galaxies are starbursts. Serendipitous CO line detections of ALMA galaxies can be plausibly matched with photometric redshifts, and are concentrated in two groups. NIR colours show a red sequence, indicative of a galaxy cluster progenitor.

## The Densest Structures at $z = 1.4 - 2.8$ from the CARLA Survey **Gaël Noirot (LERMA, Paris Observatory)**

Radio-loud AGN (RLAGN) tend to reside in the most massive dark matter halos, and have a long history of being used to efficiently identify rich high- $z$  structures (i.e., clusters and protoclusters). Our team contributed to this effort with a targeted 400hr Spitzer program surveying 420 RLAGN (radio-loud quasars and high- $z$  radio galaxies) at  $z = 1.3 - 3.2$  across the full sky: Clusters Around RLAGN (CARLA). The CARLA Survey identified 200 cluster candidates at  $z = 1.3 - 3.2$  as  $2 - 8\sigma$  overdensities of red color-selected Spitzer/IRAC galaxies around the targeted powerful RLAGN. I will present results from our follow-up 40-orbit HST program on the 20 densest CARLA cluster candidates at  $z = 1.4 - 2.8$ . We spectroscopically confirm 16/20 distant structures associated with the RLAGN, up to  $z = 2.8$ . For the first time at these redshifts, we statistically investigate the star-formation content and line-ratios of a large sample of galaxies in dense structures. We also explore evolution in the morphological parameters of red sequence galaxies and how morphology depends on SFR in order to investigate the interplay between quenching and morphology in these high- $z$  structures.

# Starbursting Protoclusters from Herschel & Planck

## David Clements (Imperial College London)

Comparison of Herschel and Planck sources in large area surveys has revealed a population of objects that appear to be galaxy clusters or protoclusters, many of whose members are undergoing massive starbursts. Followup studies confirm the likely cluster/protocluster nature of these sources. Similar starbursting sources have also been found through pointed Herschel observations of specific Planck colour-selected sources, and known  $z > 2$  protoclusters. We compare our protocluster candidates to those selected in other ways, and to predictions from theoretical models, finding that current cluster formation models do not easily reproduce the protocluster population we see. We also extend our study of dust obscured star formation in dense environments to higher redshifts through studies of known  $z > 4$  protoclusters in Herschel fields.

# The High- $z$ Clusters Occupied by Bent Radio AGN (COBRA)

## Survey

### Emmet Golden-Marx (Boston University)

To probe the earliest eras of cluster formation, we need to find clusters with a variety of morphological states and masses across redshift space. Here, we present results from the Clusters Occupied by Bent Radio AGN (COBRA) Survey. The COBRA survey includes 646 bent, double-lobed radio sources selected from the VLA FIRST Survey, infrared observations from Spitzer, and optical observations from the Discovery Channel Telescope. The COBRA survey spans the redshift range  $0.5 < z < 3.0$  and includes objects with a wide range of masses and dynamical states. The bent radio morphology results from interactions between the AGN host galaxy and the surrounding intracluster medium; the relative motion results in ram pressure acting on the lobes, bending them. Using our IR and optical data, we measure galaxy excesses, locate red sequence galaxies, and determine photometric redshifts. We find that at least 40% of our high- $z$  the bent radio sources are found in clusters or protoclusters. Additionally, we measure galaxy surface densities to trace out the large-scale cluster morphologies and estimate dynamical states.



# Tuesday Afternoon

## Invited talk – Merging Clusters as Fundamental Physics Laboratories Marcus Brüggen (Hamburg Observatory)

Mergers between massive clusters show a number of interesting phenomena that probe fundamental physics. In this talk I will highlight three examples: particle acceleration, self-interacting Dark Matter and the effect of the environment on star formation. Observed in the radio part of the spectrum, merging clusters often display vast, extended synchrotron sources that are produced by relativistic electrons (these sources are known as radio halos and radio relics). Little is known about the mechanism for the acceleration of these electrons and new radio observations are beginning to constrain the physics of these processes. Merging clusters, most famously the Bullet cluster, show shifts between the locations of the peaks of baryonic and total matter, and possibly also the peak of the galaxy distribution. Thus, these objects have advanced to the most sensitive probes for the self-interaction cross-section of Dark Matter. Finally, galaxies in the wake of merger shock waves show properties that differ from the normal cluster population. These differences have been attributed to environmental effects caused by the conditions downstream of the shock wave. Ongoing research in this area is reviewed.

## Looking for merging clusters in SZ surveys Mariachiara Rossetti (IASF-Milano INAF)

While merging clusters have received a lot of attention in the era of Chandra and XMM-Newton, their number in X-ray surveys is relatively small, with the majority of X-ray detected clusters being relaxed cool-core systems. On the contrary, since the first catalogue of Planck SZ-selected clusters, it was noticed that most newly SZ-detected objects are dynamically disturbed. I will present our recent analysis of complete and representative subsamples of the Planck cluster catalogue, showing that the majority of them are merging non-cool core systems. I will also show for the first time the Chandra images of a sample including the most massive ( $M_{500} > 8 \times 10^{14} M_{\odot}$ ) high-redshift ( $z > 0.5$ ) clusters in the Planck catalogue, most of which are disturbed merging systems. Finally, I will present the properties of a population of X-ray underluminous objects in the Planck SZ catalogue, which is also composed mainly by disturbed systems.

# Shocks and cool cores: An ALMA view of cluster formation from outside and inside

**Kaustuv Basu (University of Bonn)**

I present some recent results on the Sunyaev-Zel'dovich (SZ) effect imaging of galaxy cluster substructures. The advantage of using SZ effect at high redshifts and low density cluster outskirts is well-known, and now with ALMA superior angular resolution is available as well. One example is the first ALMA measurement of a merger shock at  $z=0.9$ , in the famous El Gordo cluster. Here comparison between the SZ, X-ray and radio data constrains the magnetic field strength and inverse Compton emission behind this high- $z$  shock. The second example is ALMA imaging of the core region of the  $z=1.4$  galaxy cluster XMMU J2235.2-2557. Here ALMA SZ data provide an accurate measurement of the thermal pressure, and with a joint SZ/X-ray analysis we obtain a clear evidence of core temperature drop. The results indicate that a cool core establishes itself early enough in the cluster formation history while the gas accumulation is still continuing. Together with the El Gordo shock measurement these two ALMA results are some early precursors of the current generation SZ capabilities to elucidate the formation process of massive clusters at high redshifts.

## Probing the formation of distant clusters using NIKA SZ observations

**Rémi Adam (Laboratoire Lagrange, OCA)**

The clusters of galaxies grow from the accretion of surrounding structures and from the mergers of subclusters in the most energetic events since the Big Bang. One way to study their formation is to measure their hot gas pressure and momentum using the Sunyaev-Zel'dovich (SZ) effect. Thanks to recent SZ surveys, SZ observations have been proved very competitive both for cluster cosmology and astrophysics. Nevertheless, in order to push the exploration of cluster formation at higher redshift, dedicated follow-ups with much higher angular resolution are now necessary. NIKA2 is currently being commissioned at the IRAM 30m telescope. As it observes the sky at 150 and 260 GHz with an angular resolution of 18 and 12 arcsec and a field-of-view of 6.5 arcmin, it is an excellent instrument to do so. NIKA2 was precessed by its prototype, NIKA, which has already shown state-of-the-art capabilities for such follow-ups, to study distant cluster formation. I will discuss recent results obtained with NIKA in the context of the pilot project dedicated to the preparation of the NIKA2 SZ large program.



# Non-thermal phenomena in El Gordo at $z = 0.87$

**Andrea Botteon (IRA-INAF Bologna)**

El Gordo is one of the most extreme objects in the Universe. It is a massive merging galaxy cluster at  $z = 0.87$  which hosts the most distant complex of diffuse cluster-scale radio emission observed in the intra-cluster medium: two relics and a giant radio halo. The presence of powerful cluster-scale radio emission at this redshift challenges current theoretical models since most of the energy of relativistic electrons is radiated away efficiently via inverse Compton scattering of the cosmic microwave background. I will report the discovery in this system of a strong shock that is spatially coincident with the NW radio relic. This shock may be powerful enough to accelerate relativistic particles directly from the thermal pool, contrary to the majority of relics for which the presence of a pre-existing population of relativistic electrons is generally invoked. I will discuss how the presence of strong merger shocks in El Gordo combined with the extreme dynamics of the cluster may allow to reconcile observations with theoretical models.

## Deep in the (un)known: the Sausage Cluster

**Gabriella Di Gennaro (Harvard-Smithsonian Center for Astrophysics)**

Relics and halos are diffuse, extended radio sources found in cluster mergers only. Despite recent progresses in our understanding of these sources, there are still many open questions regarding the underlying particle acceleration mechanisms and magnetic field properties. New low-frequency radio telescopes in combination with deep imaging at GHz frequencies can provide important constraints on models for their formation. Here we present the ongoing study of one of the best examples of double radio relics, CIZA J2242.8+5301 (known as the Sausage Cluster), observed with LOFAR and JVLA. These JVLA observations are among the deepest ever obtained for a galaxy cluster. We use the LOFAR and ultra-deep JVLA images to construct high-resolution spectral index and curvature maps of the diffuse cluster emission and numerous head-tail radio galaxies. Our continuum and spectral studies hint that shock and turbulent re-acceleration play an important role in formation of halos and relics. In addition, we will present the first detailed high-resolution polarization study of the cluster to constrain the cluster magnetic field properties.

# The Cold Front Cluster Project: Probing the Impact of Hierarchical Growth on Cluster Galaxies

**Matt Owers (Macquarie University, AAO)**

The closest approach phase of major cluster mergers produce a hostile environment for the member galaxies. The impact that this hostile environment has on the star forming properties of the resident galaxies is currently an open question. I will present results from a survey which has used the AAT/AAOmega and MMT/Hectospec multi-object spectrographs to collect  $\sim 3000$  spectra for member galaxies in six clusters. These clusters exhibit signatures of recent merger activity as indicated by the existence of ‘cold fronts’ in Chandra observations. The spectroscopic redshifts were used to detect kinematical substructure in the clusters and to characterise the merger scale. The spectra offer a wealth of information on the recent star forming histories of the galaxies, providing an ideal sample to understand the impact of mergers on galaxies. As a benchmark for comparison to the merging clusters, we have collected 1500 member spectra in three relaxed clusters. We investigate the differences in the global fractions of spectral types between the merging and relaxed clusters, finding evidence for a higher fraction of star-forming galaxies in the merging clusters relative to the relaxed clusters.

## Observing Ram Pressure Stripping and Morphological Transformation in the Coma Cluster

**Michael Gregg (University of California, Davis)**

The two largest spirals in the Coma cluster, NGC4911 and NGC4921, are being vigorously ram-pressure stripped by the hot intracluster medium. Our HST ACS and WFC3 images have revealed galactic scale shock fronts, giant ”Pillars of Creation”, rivulets of dust, and spatially coherent star formation in these grand design spirals. We have now obtained HST WFC3 imaging of five additional large Coma spirals to search for and investigate the effects of ram pressure stripping across the wider cluster environment. The results are equally spectacular as the first two examples. The geometry of the interactions in some cases allows us to estimate the various time scales involved, including gas flows out of the disk leading to creation of the ICM, and the attendant triggered star formation in the galaxy disks. The global star formation patterns yield insights into the spatial and temporal ISM-ICM interactions driving cluster galaxy evolution and ultimately transforming morphologies from spiral to S0. These processes, much more common in the early Universe when the intergalactic and intracluster components were initially created from stripping and destruction of member galaxies.

# Survival of the fittest under the influence of ram pressure stripping!

**Anshu Gupta (Australian National University)**

The debate between nature versus nurture is still not over regarding the chemical evolution. Recent observations presents the cluster-scale gradient in the metallicity of star-forming galaxies as a complementary method to discern the impact of environment on chemical evolution. Our observations for MACS J1115+0129 show that cluster galaxies near the cluster center are more metal rich compared to galaxies in the cluster outskirts. Ram pressure stripping in the cluster environment leads to truncated galactic disks, which can introduce an observational bias in the integrated metallicity measurement. In this talk, I will present our simulation of disk truncation in cluster galaxies using a semi-analytic model of ram pressure stripping and integral field spectroscopic data from the CALIFA survey. Under the influence of ram pressure only massive galaxies continues to form star in the cluster core resulting in a higher average stellar mass in the cluster center than the cluster outskirts for star-forming galaxies. The stellar mass bias induced by the ram pressure stripping is responsible for the negative gradient in the integrated metallicity predicted in our disk truncation simulation.

# SEEDisCS: how clusters form and galaxies transform in the cosmic web

**Pascale Jablonka (EPFL)**

I shall present a new survey, the Spatial Extended EDisCS Survey (SEEDisCS). This survey aims at understanding how galaxy clusters assemble and the level at which galaxies are preprocessed before falling on the cluster cores. Therefore SEEDisCS focusses on the changes in galaxy properties along the filamentary structures around a set of medium mass clusters at  $z \sim 0.5$ . The masses of the clusters make them analogous to the progenitors of those in the Local Universe, unlike the ultra massive ones which were looked at up to now. I shall discuss how galaxy properties already change at the density of the filaments: i) present how the fraction of red passive galaxies increases as compared to low density field-like regions; ii) describe how spiral disc stellar populations are affected by the environment, and how this provides constraints on the timescale of star formation quenching. Finally, I shall present new ALMA CO observations that trace the fate of the galaxy cold gas content along these infalling paths towards the cluster cores.



# Wednesday Morning

## Invited talk – The formation, evolution and chemical enrichment of the intracluster medium

**Dominique Eckert (ISDC, Geneva)**

The intracluster medium (ICM) contains the majority of the baryons (80-90%) of galaxy clusters and groups. It has been progressively heated up by gravitational and non-gravitational processes since the cluster formation epoch ( $z \sim 2 - 3$ ) until it reaches the very high temperatures we see today, i.e. between 10 and 100 million degrees. The global properties of the ICM follow tight scaling laws with halo mass which are shaped both by gravitational and non-gravitational effects (in particular gas cooling and AGN feedback). Finally, we also know that the ICM is enriched in metals which have been ejected from cluster galaxies throughout the cluster formation history. In will give a review of what is currently known about the formation and evolution of the ICM, focusing on the heating processes (shocks, turbulence), the evolution of the scaling laws, and the metal enrichment history of the gas.

## Simulation of AGN jet feedback in galaxy clusters **Martin Bourne (IoA/KICC, University of Cambridge)**

Accretion onto supermassive black holes releases vast amounts of energy, for example as radio jets, which inflate the X-ray cavities often observed in galaxy clusters. Jets heat and stir the ICM, and influence galaxy and cluster evolution. Detailed observations of galaxy clusters have shed light on the properties of the ICM and can be used to place constraints on jet-driven feedback in galaxy clusters. From a theoretical standpoint, hydrodynamic simulations provide a key opportunity to test models of jet feedback in galaxy clusters and explore parameter space. I will present results from a new jet feedback scheme, recently implemented into the moving mesh code AREPO, in order to further improve our understanding of jet feedback. We have compared jet injection techniques in order to understand how numerics impact jet evolution. Further, the simulations allow us to investigate the interplay between the jet and ICM in both idealised and more realistic conditions. We study mechanisms that heat the ICM, with particular emphasis placed upon the roles of jet-driven turbulence and pre-existing substructure-driven bulk turbulence within the ICM, comparing to the recent Hitomi observations.

## Enhancement of AGN activity in a protocluster at $z = 1.6$ **Charutha Krishnan (Nottingham)**

I will present our recent study of the prevalence of X-ray AGN in the high-redshift protocluster Cl 0218.3-0510 at  $z = 1.62$ , and review the implications for our understanding of galaxy evolution. There has long been a consensus that X-ray AGN avoid clusters in the local universe, particularly their cores. The high-redshift universe appears to not follow these trends, as there is a reversal in the local anti-correlation between galaxy density and AGN activity. In this  $z = 1.62$  protocluster, we find a large overdensity of AGN by a factor of  $\sim 23$ , and an enhancement in the AGN fraction among massive galaxies relative to the field by a factor of  $\sim 2$ . I will discuss the comparison of the properties of AGN in the protocluster to the field, and explain how our results point towards similar triggering mechanisms in the two environments. I will also describe how our study of the morphologies of these galaxies provide tentative evidence towards galaxy mergers and interactions being responsible for triggering AGN, and explain the reversal of the local anti-correlation between galaxy density and AGN activity.

## AGN activity in massive cluster at $z > 1$ **Rebecca Canning (KIPAC/Stanford University)**

A critical prerequisite for both AGN activity, and the formation of new stars in host galaxies, is the availability of gas. The cluster environment affects gas reservoirs in galaxies through processes such as ram-pressure stripping, evaporation, starvation, and tidal effects of the cluster potential. The density of cluster members and their relative velocities also depend on the cluster mass. As such, the rates of violent processes will differ in clusters and the field. The relative importance of these processes depends on both the position within, the mass of, and the redshift of the host galaxy cluster. I will share new results of the AGN distribution in the highest- $z$  SPT clusters and detail our survey which will identify  $\sim 40,000$  X-ray AGN and aims to trace the evolution of AGN in dense environments from early-times, through the peaks of AGN and SF activity, to the present day.

# Characterizing the First Galaxy Clusters at the Epoch of their Formation with STAR-X **Daniel Wik (NASA GSFC)**

The next generation survey with the South Pole Telescope (SPT-3G) will discover all galaxy clusters with masses above  $10^{14} M_{\odot}$ . Due to the comparable angular resolution of these SZ observations and the size of these high redshift clusters, we require higher resolution observations across the electromagnetic spectrum to reveal their morphology and other detailed properties. At present, such information on the ICM is most accessible at X-ray energies. We have proposed a new MidEx-class X-ray observatory, the Survey and Time-domain Astrophysical Research eXplorer (STAR-X), capable of surveying 300  $z > 1.5$  clusters and a thousand more at lower redshifts in its prime 2-year mission. With  $5''$  angular resolution, over  $2500 \text{ cm}^2$  of effective area, and soft X-ray sensitivity, STAR-X will be able to resolve the  $\sim 8''$  spatial structures that XMM-Newton cannot quite disentangle and gather photons  $> 4\times$  faster than Chandra. Its large  $1 \text{ deg}^2$  FOV and low background will also allow the outskirts of many nearby clusters to be mapped out to the virial radius. I will discuss how this new mission will expand our current understanding of how galaxy clusters form and evolve over all of cosmic time.

## Surprising existence of massive and large molecular gas reservoirs in a distant protocluster **Helmut Dannerbauer (Instituto de Astrofísica de Canarias)**

We know that environment has a critical impact on galaxy growth and evolution. What we do not know is when it starts to have an impact and how it does it. I present results of our on-going survey of low surface brightness emission of cold molecular gas in protoclusters galaxies and their halos with the Australian Telescope Compact Array (ATCA). These findings alter our view of the important topics of the development and gas phase distribution of the "proto-intracluster medium: how ram pressure stripping may operate in protoclusters, how the galaxies may contribute to the proto-intracluster medium and how their star formation may be limited by dynamics. Finally, I present our new ATCA Large Program, COALAS (CO ATCA Legacy Archive of Star-Forming Galaxies), which will extend significantly our study of environmental effects on cluster and field galaxies.

# Anatomy of a Merger: A Deep Chandra Observation of Abell 115

**William Forman (CfA)**

A deep Chandra observation of Abell 115 provides a unique probe of the anatomy of cluster mergers. The X-ray image shows two prominent subclusters, A115N (north) and A115S (south) with a projected separation of almost 1 Mpc. The X-ray subclusters each have ram-pressure stripped tails that unambiguously indicate the directions of motion. The central BCG of A115N hosts the radio source 3C28 which shows a pair of jets, almost perpendicular to the direction of the subcluster's motion. The jets terminate in lobes each of which has a "tail" pointing IN the direction of motion of the subcluster. The Chandra analysis provides details of the merger including the velocities of the subclusters both through analysis of the cold front and a weak shock. The motion of A115N through the cluster generates counter-rotating vortices in the subcluster gas that form the two radio tails. Hydrodynamic modeling yields circulation velocities within the A115N sub cluster. Thus, the radio emitting plasma acts as a dye tracing the motions of the X-ray emitting plasma. A115S shows two "cores", one coincident with the BCG and a second appears as a ram pressure stripped tail.



# Wednesday Afternoon

## Invited talk – Cluster and Protocluster Mass Estimation and Determination of their Dynamical States

**Nick Battaglia (Princeton University)**

The identification of high-redshift clusters and proto-clusters is a rapidly growing field. For the purposes of cosmology and galaxy formation characterizing the masses of these halos is critical. I will review methods for measuring proto-cluster masses and some of the systematic uncertainties associated with these estimates. I will present the exciting new opportunities to find and measure proto-cluster masses that future millimeter-wave surveys will provide.

### How well do submillimeter galaxies trace protoclusters?

**Chris Hayward (Flatiron Institute)**

It has been suggested that associations of (or even individual) high-redshift submillimeter galaxies (SMGs) may serve as beacons of protoclusters because SMGs are high-mass galaxies undergoing rapid assembly. Moreover, it has been claimed that the protocluster environment may lead to ‘synchronized’ starbursts and thus multiple SMGs within the protocluster region. We investigate this possibility using the Bolshoi cosmological N-body simulation and a model for populating the simulation with SMGs. We find that although SMG associations correspond to some of the highest overdensities at  $z > 2.5$ , they are highly incomplete tracers because of stochastic sampling effects. At lower redshift, because of ‘downsizing’ (i.e. the most massive galaxies have already ceased forming stars and are thus not SMGs), the highest dark matter overdensities are not well traced by SMG associations. I will close by discussing the implications of this work for observational studies of protoclusters and how the highest-redshift SMGs can be used to maximize the potential of JWST for studying very high redshift galaxies.

## Protoclusters traced by high-redshift massive galaxies Cristina Garcia Vergara (Leiden Observatory)

A commonly adopted approach to detect protoclusters is to search for overdensities of galaxies around massive galaxies at high-redshift such as quasars (QSOs) and submillimeter galaxies (SMGs). However, the detection of overdensities in those environments has been elusive, against of theoretical predictions. Here, I present the first measurement of the QSO-LBG and QSO-LAE cross-correlation function at  $z \sim 4$ , based in the study of 23 QSO fields. My results indicate that LBG are strongly clustered around QSOs but LAE show similar clustering properties and number density as that observed in blank fields. One possible explanation for the lack of overdensities is that galaxies are highly obscured by dust and thus invisible at optical wavelengths. Additionally, I will present the clustering of SMGs based on spectroscopic redshift information of 52 SMGs recently identified by ALMA. This is critical to test if SMGs trace particularly massive structures. Finally, I will discuss the implications and interpretation of my results, in particular, I give the reasons of why I strongly suggest that the study of high-redshift protoclusters should be done from a combined optical+radio perspective.

## High-z protocluster survey by Subaru/HSC Nobunari Kashikawa (NAOJ)

We are now conducting a systematic survey for high-redshift ( $z > 3$ ) protoclusters using the extremely wide imaging data produced by the Subaru/Hyper Suprime Cam. The goal of the HSC protocluster survey is to trace redshift evolution of cluster galaxies up to  $z \sim 6$  with very high number statistics (10 – 20 protoclusters per redshift bins at  $z > 2$ ) as well as to see a possible variety of protoclusters ( $\sim 1000$  protoclusters at  $z \sim 4$ ) at the same redshift. We applied an effective method to find significant overdense regions of g-dropout galaxies at  $z \sim 4$  based on a high surface number density. We have found 179 protocluster candidates with more than  $4\sigma$  overdensity significance over  $107 \text{ deg}^2$  of the initial HSC data release for the wide layer. I will report the current status of the survey and initial results.

## Luminous Quasars Do Not Live in the Most Overdense Regions of Galaxies at $z \sim 4$ Hisakazu Uchiyama (Sokendai/NAOJ)

We present the cross-correlation between 151 luminous QSOs and 179 protocluster candidates at  $z \sim 4$  using Hyper Suprime Cam data. We find that only 2 QSOs reside in regions that are more overdense compared to the average field at  $> 4\sigma$ . The distributions of the distance between QSOs and the nearest protoclusters and the significance of the overdensity at the position of QSOs are statistically identical to those found for LBGs, suggesting that QSOs tend to reside in almost the same environment as LBGs at this redshift. Using stacking analysis, we find that the average density of LBGs around QSOs is slightly higher than that around LBGs on  $1.0 - 2.5 \text{ pMpc}$  scales, while at  $0 < .5 \text{ pMpc}$  that around QSOs tends to be lower. We also find that QSOs with higher UV-luminosity or with more massive black holes tend to avoid the most overdense regions, and that the QSO near zone sizes are anti-correlated with overdensity. These findings are consistent with a scenario in which the average QSO at  $z \sim 4$  resides in structures that are less massive than those expected for the progenitors of today's rich clusters, and possibly that luminous QSOs may be suppressing star formation in their close vicinity.

# High-redshift star-forming galaxies and proto-clusters: an insight from clustering studies

**Manuela Magliocchetti (IAPS-INAF Rome)**

One of the best ways to shed light on the possible links between high redshift proto-clusters and galaxy populations is to investigate the clustering properties of these latter ones as they provide a powerful method to constrain halo masses. In this talk I will present clustering results for galaxies with highly enhanced star-formation activity ( $\text{SFR} > 10 M_{\odot}/\text{yr}$ ) and will show that, at redshifts  $z > 1.5$ , irrespective of the selection technique and only very mildly depending on their SFR, they all reside in structures of masses  $> 10^{13.5} M_{\odot}$ , i.e. they are ubiquitously located in over-dense structures such as proto-clusters. A striking example of the above result is provided by the distribution of high-redshift star-forming galaxies in the GOODS-South as more than half of these sources is found to reside in an unvirialised, filamentary structure, centered at  $z \sim 2.2$ , which extends all along the field. Our data indicate an enhanced star-forming activity for the galaxies belonging to the proto-cluster with respect to those in the field. Finally, we will show how such structures are a rather common event in the epoch which coincides with the peak of star formation activity.

## Large $\text{H}\alpha$ surveys of field, filaments and (proto-)clusters at $z \sim 0.2 - 2.2$ : does the environment matter?

**David Sobral (Lancaster University)**

I will present results from the largest narrow-band surveys for  $\text{H}\alpha$  emitters in and around the richest clusters at  $z \sim 0.2 - 0.4$  and over the general large scale structure, including proto-clusters, up to  $z \sim 2.2$ . Our follow-up spectroscopy allows us to further investigate the nature and physical properties of star-forming galaxies and AGN within some of the most massive relaxed and merging clusters, and to directly contrast them to equally selected galaxies in the field and in filaments and to clusters and proto-clusters at higher redshift. We find interesting similarities between filament and merging cluster galaxies, but also point out how some  $\text{H}\alpha$  over-densities at higher redshift are likely group/filament structures instead of proto-clusters. I will finish by exploring the nature of a unique proto-cluster ( $9\sigma$  overdensity) surrounded by a potential filamentary structure in the COSMOS field, revealed by our very wide field  $\text{H}\alpha$  survey.

# The nature of H $\alpha$ selected galaxies along the huge cosmic web across cosmic time with Subaru **Yusei Koyama (Subaru Telescope)**

We present our recent results from our systematic, wide-field, narrow-band H $\alpha$  imaging survey of distant (proto-)clusters at  $z = 0.4 - 2.5$  using Suprime-Cam, MOIRCS, and Hyper Suprime-Cam on the Subaru Telescope. Using the large H $\alpha$  galaxies selected from a variety of environment across cosmic time, we find that the environmental dependence of specific SFR amongst H $\alpha$  galaxies is small ( $\sim 0.2-0.3$  dex at maximum); i.e. the location of the star-forming Main Sequence is always independent of environment over the last  $\sim 10$ -Gyrs. On the other hand, we also find an interesting hint that star-forming galaxies in higher-density environments tend to show (1) redder colours, (2) higher stellar mass, and (3) higher dust extinction, than field counterparts. We infer that such red/massive/dusty star-forming galaxies seen in high-density environments are the key for understanding the physics of environmental effects. In my presentation, I will put a special focus on our most recent results using the data from a newly released, extensive NB imaging survey with Hyper-Suprime-Cam, to provide a more detailed look on the environmental impacts on colour, mass, specific SFR of galaxies.

## A Large Sample of Proto-clusters and Proto-Groups from the VIMOS Ultra-Deep Survey **Brian Lemaux (University of California, Davis)**

Using observations from the VIMOS Ultra-Deep Survey (VUDS), a massive spectroscopic campaign targeting 10,000 typical star-forming galaxies at  $2 < z < 6$ , in conjunction with other surveys we have uncovered a large number of proto-structures that appear to resemble clusters and groups forming in the early universe. Though ostensibly a field survey, a number of factors relating to the survey itself and intrinsic to proto-structures have allowed VUDS to sample a large range of local and global densities at these redshifts. In this talk, I will discuss the development of the methods for finding, confirming, and characterizing proto-clusters and proto-groups in the context of VUDS including new techniques and tools developed specifically for these purposes. Several case studies of spectroscopically confirmed massive proto-clusters will be presented, focused both on the diversity of their global properties and that of their member populations. I will also discuss preliminary work on the full ensemble of VUDS proto-structures as well as measurements of the star formation rate-density and color-density relations at these redshifts.

# Epoch of Merger-Driven Star Formation and AGN in Galaxy Clusters

**Mark Brodwin (University of Missouri-Kansas City)**

Over the last few years, studies of distant galaxy clusters have found compelling evidence for a major epoch of merger-driven star formation and AGN fueling in  $z > 1$  galaxy clusters. I will briefly review the observations from the IRAC Shallow and Distant Cluster Surveys (ISCS/IDCS) that contributed to this new paradigm, and discuss new observations that extend it in both redshift (to  $z = 1.75$ ) and mass (to  $M > 10^{15} M_{\odot}$ ) in the IDCS, SPT and other surveys. As a case study I'll highlight the  $z = 1.75$  IR-selected cluster IDCS J1426.5+3508 that, with a mass of  $4 \times 10^{14} M_{\odot}$ , is the most massive cluster known at  $z > 1.5$ . This extremely distant cluster has high levels of both star formation and AGN activity, yet is a relaxed, self-similar, cool-core cluster apparently in hydrostatic equilibrium.



# Thursday Morning

## Invited talk – The Evolution of Proto-Cluster Galaxies

**Adam Muzzin (York University Toronto)**

I will present an overview of recent work on the formation and evolution of galaxies in proto-clusters. In particular, I will focus on the star-formation properties of these galaxies, and the role of quenching in their evolution. I will also discuss recent work on at what epoch the proto-cluster environment becomes important in the quenching process.

### Excess of rapidly-quenched galaxies in distant galaxy clusters **Miguel Socolovsky (Nottingham)**

I will present a study on the impact of environment on galaxy evolution in distant galaxy clusters between redshifts 0.5 and 1.0. We find candidate galaxy clusters by applying a friends-of-friends algorithm to the photometric data of the UKIDSS Ultra-Deep Survey. Through studying the stellar mass functions, we reveal a strong excess of low-mass rapidly-quenched galaxies in cluster environments compared to the field. This indicates that low-mass objects are preferentially quenched in dense environments. I will also show the radial distribution of different galaxy populations as a function of cluster-centric distance, which provides insight about where this environmental quenching is taking place and its timescale. Finally, I will explain how these results, taken together, point to the existence of two environmental quenching pathways (fast and slow), operating on different timescales. Fast quenching acts on galaxies with high sSFR, switching them off on timescales shorter than the cluster dynamical time, and is more efficient for quenching low-mass galaxies. In contrast, slow quenching affects galaxies with moderate sSFR regardless of their stellar mass, acting on longer timescales.

### Tracing the evolution of passive galaxies at $1.4 \leq z \leq 1.8$ with KMOS **Alessandra Beifiori (USM/MPE)**

The galaxy population undergoes rapid changes in the redshift range  $1 \leq z \leq 2$ , when the Universe transitions from the peak star formation at  $z > 2$  to an era where quenching shapes galaxies as we see them today. In this talk I will discuss recent progress studying the rest-frame optical properties of quiescent galaxies at this critical epoch using KMOS, the K-band Multi-Object Spectrograph on the ESO/VLT. I will highlight recent results from the KMOS Cluster Survey (KCS), whose aim is to provide a census of quiescent galaxy kinematics at  $1.4 \leq z \leq 1.8$  in known overdensities. The combination of kinematic measurements from KMOS and structural parameters measured from deep HST imaging allowed us to place constraints on the formation ages of passive galaxies and on the evolution of galaxy properties and scaling relations at high redshift.

# Galaxy Transformations in the Most Massive high-redshift Clusters

**Pierluigi Cerulo (Universidad de Concepcion)**

Clusters of galaxies are the most massive virialised cosmic structures. Understanding the interplay between galaxy evolution and cluster halo assembly is a crucial problem and challenge in modern astrophysics. I present the results from the study of 9 clusters at  $0.8 < z < 1.5$  from the HAWK-I Cluster Survey (HCS), which provide a sample of the most massive high- $z$  large-scale structures. We find that the build-up of the red sequence is accelerated in clusters with respect to the field, suggesting that the mass of the host dark matter halo is a crucial parameter in setting the timescales for star formation quenching. Further, from the comparison of different cluster samples at  $0.0 < z < 1.0$  (HCS, WINGS, EDisCS), we find indication of morphological transformation from red, quenched spiral to S0 galaxies. I discuss the implications of these results in the general framework of galaxy and cluster evolution and give an overview of my current and ongoing work with the HCS and other cluster surveys.

## Quiescent and star-forming galaxy populations in the core of ClJ1449+0856 at $z = 2$ **Veronica Strazzullo (LMU)**

ClJ1449+0856 is a  $z = 2$  structure in the mass range of likely progenitors of today's clusters, allowing a study of galaxy populations in the first cluster environments 10 billion years ago, at a crucial epoch bridging proto-clusters and the first established clusters. We present recent results from HST and ALMA observations, showing that the core of this system hosts at the same time a first red-sequence seedling with a characteristic population of quiescent galaxies, and a 10x overdensity of 870 $\mu$ m continuum sources with respect to blank fields. These data highlight a picture of both activity and quiescence in dense environments at  $z \sim 2$ , with the combination of HST imaging and spectroscopy and ALMA continuum and CO line observations critically improving our understanding of the remarkably diverse galaxy populations in this structure.



Witnessing the onset of environmental quenching at  $z \sim 2$ .  
Results and implications from 3D-HST  
**Matteo Fossati (MPE)**

During the last decade observations of galaxies across cosmic times coupled with cosmological simulations have provided an increasingly clear description of galaxy evolution. In particular we have a fairly detailed phenomenological picture of how galaxies transition from star forming to passive (or quenched) as a function of their internal properties (e.g. stellar mass) and the external environment (e.g. local density). By exploiting the highly complete coverage of grism and spectroscopic redshifts from the 3D-HST survey, we derive the local environment for a deep and complete sample of galaxies in the five 3D-HST deep fields at  $0.5 < z < 2.5$ . A robust definition of environment also requires accurate calibrations obtained using the most up to date semi-analytic model derived from the Millennium simulation. By combining observational data and models we have devised a robust statistical framework within which we link observables to physical quantities (e.g. halo mass and central/satellite status). In this talk I will present our latest results on the environmental quenching of satellites up to  $z \sim 2.5$  in the range of haloes commonly included in our sample  $M_{\text{halo}} < 10^{14}$ .

The Spectroscopic Ages of Passive Galaxies in a  $z = 1.62$   
Protocluster  
**Donald Lee-Brown (University of Kansas)**

IRC 0218 is a protocluster at  $z = 1.62$  with a wealth of observations that make it an ideal target for resolving the interplay between galaxy properties and environment at high redshift. We have used extremely deep HST spectroscopic data to derive unambiguous membership and stellar ages via the 4000 angstrom break for 14 members with stellar masses  $\log(M) > 10.2$ . We find that at high stellar masses,  $\log(M) > 10.85$ , the fraction of quiescent galaxies in the cluster is  $2\times$  higher than the field value. At lower stellar masses, the protocluster and field have consistent quiescent fractions. Despite this mass trend, we see no comparable relation between galaxy stellar age and mass for the quiescent members. Taken together, these results may reflect the impact of dry mergers on the protocluster galaxies. Alternately, the results may imply that the mass trend we observe in the IRC 0218 quiescent fraction was imprinted over a short timescale. This talk will place our results in the context of studies of other high redshift clusters and likely descendent environments at  $z = 1$ .

The buildup and structural evolution of the cluster red sequence  
between redshift 1 to 1.5  
**Jeffrey Chan (University of California, Riverside)**

The red sequence galaxies in clusters are a unique population that can provide valuable constraints on the role of environment in quenching and mass assembly. I will present results from two ongoing surveys, the KMOS-Cluster Survey (KCS) and the Gemini Observations of Galaxies in Rich Early Environments (GOGREEN), which focus on  $1 < z < 1.5$ , the period during which the galaxy population transitions from star-forming to passive. The KCS aims at studying the kinematics of red sequence galaxies with KMOS in 4 clusters. Combined with HST imaging, we also derive structural parameters and construct individual stellar mass surface density maps. I will focus on their structural properties and how they compare with field galaxies, in order to trace their structural evolution and mass growth. The GOGREEN survey is obtaining deep imaging and spectroscopy with GMOS in 21 overdensities, selected to span a broad range in halo masses as progenitors of massive groups and clusters we see today. I will discuss recent progress on using the large number of confirmed members and the deep imaging to construct the red sequence luminosity function as a probe of the buildup of the faint passive population.

# Thursday Afternoon

Evolutionary phase of gas-rich galaxies in a galaxy cluster at

$$z = 1.46$$

**Masao Hayashi (NAOJ)**

We present evolutionary phase of gas-rich galaxies associated with XMMXCS J2215.9-1738 galaxy cluster at  $z = 1.46$ . We have detected emission lines from 17 galaxies in ALMA Band 3 data within a radius of R200 from the cluster center, all of which are identified to be a CO(2-1) emission line from cluster members by their redshifts and the colors of optical/NIR counterparts. The line luminosities reach down to  $L'_{CO(2-1)} = 4.2 \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$ , which correspond to  $M_{H_2} = (1.8 - 9.4) \times 10^{10} M_{\odot}$ . The galaxies are gas-rich with a gas fraction of  $> 0.5$  and they disappear from the very center of the cluster. A phase space diagram showing relative velocity versus cluster-centric distance indicates that the gas-rich galaxies enter into the cluster more recently than the gas-poor star-forming galaxies and passive galaxies located in the virialized region of this cluster. The results imply that the galaxies have experienced ram-pressure stripping and/or strangulation during the course of infall towards the cluster center and then the molecular gas in the galaxies at the cluster center is depleted by star-formation.

## An ALMA Study of Gas-Rich Galaxies in $z \sim 1.6$ Galaxy Clusters

**Allison Noble (MIT)**

Galaxy cluster formation and evolution is intertwined with that of its constituent galaxies. Therefore in order to understand the former, we must also explore the baryonic processes the shape the latter. In particular, this requires a solid understanding of the evolution of the molecular gas content in cluster galaxies, since the gas provides the necessary raw material to feed star formation. I will present ALMA CO 2-1 detections in nine cluster galaxies at  $z \sim 1.6$ , the largest study of molecular gas in high-redshift clusters to date. These cluster galaxies have main-sequence star formation rates, but gas fractions up to  $\sim 60 - 80\%$ . In the local universe, high-density clusters are devoid of star-forming gas-rich galaxies; with this ALMA data, we are witnessing the first direct evidence that gas-rich galaxies are located indistinguishably in the field and clusters.

## The molecular gas properties of $z = 1.62$ proto-cluster galaxies Gregory Rudnick (University of Kansas)

I will present JVLA CO imaging in the 1-0 transition of a  $z = 1.62$  galaxy proto-cluster located in the UKIDSS/UDS. These are the deepest existing data in CO(1-0), corresponding to nearly 100 hours of on-target JVLA observations, and are giving us the powerful ability to study the molecular gas contents of massive cluster galaxies when they were in the last throes of their star formation. We securely detect two spectroscopically confirmed proto-cluster members in CO(1-0), nearly doubling the number of published CO(1-0) detections of normal star-forming galaxies at high redshift. These two proto-cluster members are massive, with  $\log(M_\star \sim 11)$ , and with significant gas reservoirs. We derive star formation rates using Spitzer and Herschel data and find that one galaxy is on the main sequence while the other is a factor of 10 below it. Despite being in a proto-cluster dominated by passive galaxies, our CO sources are broadly consistent with the expected gas fractions from field galaxy scaling relations. I will discuss the implications that these detections on the implied effect of the proto-cluster environment on galaxy gas fractions.

## The molecular gas content of star-forming galaxies in a $z \sim 2$ cluster as seen by JVLA and ALMA Rosemary Coogan (University of Sussex)

This work focuses on understanding the formation of the first massive, passive galaxies in clusters, as a first step to the development of environmental trends seen in the low-redshift galaxy population. CL J1449+0856 is an especially good case to study this - a galaxy cluster at redshift  $z \sim 2$  that already shows evidence of a virialised atmosphere. Unlike unrelaxed proto-clusters, CL J1449+0856 already contains a large fraction of passive galaxies at its core, as well as numerous, highly star-forming galaxies. We have obtained observations of CL J1449+0856 with JVLA and ALMA to study how dust-obscured star-formation, ISM content and AGN activity are linked to environment and galaxy interactions during this crucial phase of high- $z$  cluster assembly. I will present the results of our analysis of multiple transitions of CO and of the dust continuum emission from cluster member galaxies. With this data we are able to measure their gas fractions, gas excitation and gas consumption time scales. I will then compare these results with literature measurements for field galaxies in order to assess the environmental effect on gas reservoirs and the enhancement/suppression of star-formation.

## The topology of the Spider's web Mehdi Walji (Nottingham)

We investigate the topology of the Spiderweb protocluster (MRC1138-262) at  $z = 2.16$  and explore how galaxy properties vary throughout this structure. I will show that the Spiderweb has lots of substructure and consists of several groups surrounding a dense core. We compare the properties of galaxies within the different regions of the protocluster and find that the densest regions are rich in massive, red galaxies, which are sparse in the rest of the structure. I will show that this excess is due to an enhancement of both passively evolving galaxies and dusty star forming galaxies. These passive and dusty star forming galaxies are not exclusive to the protocluster core, but populate the dense subgroups throughout the Spiderweb.

A mature galaxy cluster at  $z = 1.58$  around the radio galaxy  
7C1753+6311  
**Elizabeth Cooke (Durham University)**

In the last few years the number of high redshift protoclusters has rapidly increased by utilizing radio-loud AGN (RLAGN) as beacons for overdense regions at  $z > 1.3$ . However, there has been some debate over whether these structures are representative of protoclusters as a whole or whether they preferentially select young structures. I will present our recent discovery of a  $z = 1.58$  mature cluster from the Clusters Around Radio-Loud AGN survey. Over half of the cluster galaxies lie on a red sequence with a colour that suggests an average formation redshift of  $z = 3$ . I will show that 82% of the red galaxies in the core are passive and demonstrate that the cluster has an enhanced passive galaxy fraction that is three times that of the control field. Interestingly, this enhancement is mass dependent: the higher passive fraction is only observable for high mass galaxies, whereas the fraction of passive galaxies at lower masses is similar in the cluster and field. The presence of a dense core and a passive red sequence suggest that radio galaxies do not solely reside in young, uncollapsed protoclusters, rather they can be used as beacons for clusters in a wide range of evolutionary states.

Insights of environmental effect in high- $z$  galaxy evolution from  
radio and (sub)mm perspectives  
**MinJu Lee (The University of Tokyo)**

An intensive star formation in high- $z$  (proto)clusters is predicted by galaxy archaeology and simulations, and there are increasing number of candidate protoclusters at high redshift. The detailed picture, nevertheless, has been hampered by the coarse resolution of (sub)mm regime (mostly probed by a single dish) that is an ideal tool to address obscured star formation within a galaxy. This talk, I present our recent results from ALMA and JVLA observations both at sub-arcsec resolution, targeting star-forming galaxies associated to a protocluster which is placed at the peak epoch of galaxy formation. We pin-down radio and dust continuum emission at 10 cm and 1.1 mm, respectively, and investigate their star forming activity, relation to AGN activity (if any), and kinematics with the help of molecular (CO) and atomic ([CI]) line detections from ALMA. The massive ( $> 4 \times 10^{10} M_{\odot}$ ) star forming populations associated to a protocluster  $z = 2.49$  are generally detected from the observations. The rich data sets allow in-depth studies of the protocluster, addressing the importance of deep and high resolution imaging in multi-band data.

# Bimodal morphologies of massive galaxies at the core of a protocluster at $z = 3.09$ **Mariko Kubo (NAOJ)**

We present the morphologies of galaxies in the extremely dense group at the core of the protocluster at  $z = 3.09$  in the SSA22 field by using the K-band image taken with AO. We investigate seven members with  $z_{\text{sp}} = 3.09$ . Their wide morphological variety suggests the on-going dramatic evolutions; The most massive one is a compact elliptical, supporting the two-phase formation scenario that a massive compact elliptical is formed at once and evolves in the size and mass by many mergers. Very rare overdensity of the group implies that this object is a plausible progenitor of a brightest cluster galaxy of one of the most massive clusters today, requiring strong size ( $\sim 10$ ) and stellar mass ( $\sim$ four times by  $z = 0$ ) growths. Another member shows spatially extended [OIII] $\lambda$ 5007 emission line which is a plausible evidence of outflows. Other members are two to three times larger than the field SFGs at similar redshift. Another key results was no detection of candidate new members though we obtained the image deeper than the previous one. This implies a physical deficiency of low mass galaxies and/or poor detection completeness of them owing to their diffuse morphologies.

# The role of galaxy mergers and molecular gas in the early phase of galaxy cluster assembly **Chao-Ling Hung (University of Texas, Austin)**

High-redshift protoclusters are ideal places to study the formation of the largest structures in the Universe and the early environmental influences on galaxy evolution. Recent discoveries of  $z > 2$  protoclusters with extremely rich populations of dusty star-forming galaxies (DSFGs;  $SFR > 100 M_{\odot}/\text{yr}$ ) represent the most active assembly phases of massive galaxy clusters. Understanding the triggering mechanisms of these unusual concentrations of extreme star-forming galaxies can provide critical insights into the formation of most massive galaxies in these clusters and the assembly of massive clusters themselves. For example, an increased probability of galaxy interactions and/or enhanced gas supply may trigger an excess of DSFGs. Using the extensive ancillary data in the COSMOS field, we study the role of galaxy mergers through measuring the frequency of galaxy pairs in two such DSFG-rich protoclusters at  $z = 2.10$  and  $2.47$ , respectively. We also investigate the mean molecular gas content of protocluster galaxies by stacking SCUBA-2 850 micron images. These independent investigations provide complementary views into the physical nature of these DSFG-rich protoclusters.

# Dust and gas in distant cluster galaxies with ALMA

**Eelco van Kampen (ESO)**

After a brief overview of what we have learned so far from ALMA observations of dust and gas in distant cluster galaxies, a few ideas are discussed on the way forward to better understand these objects and their environment, and on how to deal with the challenges in going deeper and/or wider with ALMA. For example, as ALMA is not an efficient survey instrument, going wider means relying on target selection from other instruments, often at different wavelengths. Going deeper is one of the strengths of ALMA, but there are natural limits to this, like heating of the targeted cold gas by the cosmic microwave background. A proper understanding and modelling of these issues is therefore an essential step towards understanding and modelling the physical processes in and around young galaxy clusters.





# Friday Morning

## Invited talk – Lessons Learned from Multiwavelength Studies of Low Redshift Clusters of Galaxies **Megan Donahue (Michigan State University)**

I will review multi-wavelength studies of clusters and brightest cluster galaxies at relatively low redshifts, with the aim of informing approaches to collecting and interpreting data from high redshift clusters and proto-clusters. In particular I will examine the interpretation of signatures of feedback and star formation at low redshift. High resolution views of X-ray-emitting gas surrounding central X-ray cavities in the intracluster gas at low-redshift, filled by radio-emitting plasma, have allowed us for the first time to estimate the amount of kinetic energy injected by the central radio AGN. Future X-ray missions may allow us to make similar measurements of higher-redshift cluster AGN, to see whether and when the mode of AGN feedback changes in massive galaxies. At low redshift, Brightest Cluster Galaxies (BCGs) with star formation, multiphase gas, and/or powerful radio AGN appear exclusively in clusters of galaxies with low central entropies, a pattern which strongly connects the thermodynamic state of the circumgalactic medium (CGM) with the activity of the central galaxy. The fueling of AGN and star formation from the CGM is unlikely to be a steady relationship; evidence for the lack of lock-step correlation is seen comparing rest-frame UV observations of OVI in BCGs to their SFRs: the rate of gas cooling at a million K exceeds the SFR in some systems with  $(\text{cooling rate}/\text{SFR}) \gg 1$ , but at least one system has a strong OVI upper limit where the  $(\text{cooling rate}/\text{SFR}) < 1$ . Also, at high redshift this dichotomy between low-entropy and high entropy clusters may not be so clear cut. Multi wavelength observations have also revealed surprising (perhaps) similarities and differences between BCGs and normal galaxies. For example, star formation rates (SFRs) in low-redshift BCGs are similar to SFRs in star-forming and starburst galaxies with similar cold gas masses, even though the star formation in BCGs are not happening in disks. I will attempt to anticipate some of the opportunities and the interpretation issues (our lessons learned) for rest-frame optical and near-UV observations of higher redshift clusters.

## Enhanced Ly $\alpha$ depletion in the proto-cluster cores at $z = 2.5$ **Tadayuki Kodama (Astronomical Institute, Tohoku University)**

Galaxy proto-clusters at high redshifts are ideal laboratories where we can test the early environmental effects on galaxy formation and evolution. In particular, gaseous inflow/outflow are naturally expected to be depending on environments, as these processes are exchanging materials between galaxies and their surrounding regions. Based on our unique sample of H $\alpha$  emitting star-forming galaxies in a proto-cluster at  $z \sim 2.5$  (Mahalo-Subaru narrow-band imaging survey), we investigate the environmental dependence of the Ly $\alpha$  photon escape fractions for the first time by the combined analyses of our dual narrow-band imaging data (Ly $\alpha$  and H $\alpha$ ). We will discuss the implications of this intriguing result in the context of environmental variations of inflow/outflow processes together with chemical abundance analyses.

# MApping the Most Massive Overdensity Through Hydrogen (MAMMOTH) Zheng Cai (UCO/Lick Observatory)

In this talk, I will present our survey of the most massive overdensities of galaxies in the peak of cosmic star formation and QSO activities ( $z = 2 - 4$ ). These structures are traced by the strongest intergalactic HI ( $\text{Ly}\alpha$ ) absorption on large scales of 10-30 Mpc. Our cosmological simulations show a strong correlation between the optical depth of  $\text{Ly}\alpha$  absorption and mass overdensities. I will present the survey of the strong HI absorption due to intergalactic medium (IGM) overdensities, and further present our discovery of a sample of extremely massive overdensities at  $z \sim 2.3$  by utilizing LBT, Keck, KPNO-4m, and CFHT. These large-scale structures all have overdensities greater than six which represent the most overdense high- $z$  structures. I will further discuss the discovery of largest  $\text{Ly}\alpha$  nebulae in these extremely massive fields, which are unique laboratories to study the IGM-galaxy interactions. In the end, I will talk about how our unique sample will constrain the fundamental questions of galaxy/structure formation.

## Mapping of HI absorption structure in the SSA22 protocluster at $z = 3.1$ Ken Mawatari (Osaka Sangyo University)

We developed a new scheme to evaluate  $z = 3.1$  HI  $\text{Ly}\alpha$  absorption strength relative to the cosmic mean from photometric data of star-forming galaxies at  $z = 3.3 - 3.5$ . With the new measure, dNB497, we have made two dimensional HI absorption maps in the  $z = 3.1$  SSA22 proto-cluster region and two control fields with a spatial resolution of 5 comoving Mpc. The HI absorption strength in the SSA22 field are systematically larger than those in the control fields, and this HI absorption enhancement extends more than 50 comoving Mpc. The field-averaged (i.e., 50 comoving Mpc scale) HI absorption strength and the overdensity of  $\text{Ly}\alpha$  emitters (LAEs) seem to be correlated, while there is no clear dependency of the HI absorption strength on the local LAE overdensity in a few comoving Mpc scale. These results suggest that diffuse HI gas spreads out in/around the SSA22 proto-cluster. We have also found an enhancement of HI absorption at a projected distance less than 100 physical kpc from the nearest  $z = 3.1$  galaxies at least in the SSA22 field, which is probably due to HI gas associated with the CGM of individual galaxies.

# Discovery of a Protocluster Associated with a Ly $\alpha$ Blob Pair at $z = 2.3$

**Toma Badescu (Argelander Institut für Astronomie)**

Previous studies suggest that bright Ly $\alpha$  blobs extended nebulae with sizes of  $\sim 100$  kpc and Ly $\alpha$  luminosities of  $\sim 10^{44}$  erg/s preferentially reside in over-dense regions, and thus could be used as tracers of protoclusters. To investigate this hypothesis and look for new blobs, we present deep, wide-field Ly $\alpha$  narrowband imaging of a  $1 \times 0.5$  square degree region around a known Ly $\alpha$  blob pair at  $z = 2.3$ , which was originally discovered by a blind survey. We find 183 Ly $\alpha$  emitters, including the Ly $\alpha$  blob pair and 3 new intermediate Ly $\alpha$  blobs with Ly $\alpha$  luminosities of  $(0.9 - 1.3) \times 10^{43}$  ergs $^{-1}$  and isophotal areas of  $16 - 24$  arcsec $^2$ . Using these Ly $\alpha$  emitters as tracers, we discover a new proto-cluster (Bootes J1430+3522) associated with the Ly $\alpha$  blob pair, with a surface density contrast of  $\delta = 2.7$ , a de-projected volume density contrast of  $\delta \sim 10.4$ , and a projected diameter of  $\sim 20$  comoving Mpc.

## Mass-Richness relation for X-ray and SZE-selected clusters at $0.4 < z < 2$ as seen by Spitzer at 4.5um **Alessandro Rettura (Caltech/IPAC)**

We study the mass-richness relation of 116 spectroscopically-confirmed massive clusters at  $0.4 < z < 2$  by mining the Spitzer archive. We homogeneously measure the richness at 4.5um, making appropriate corrections for both background galaxies and foreground stars. We have two subsamples, those which have a) literature X-ray luminosities and b) literature Sunyaev-Zeldovich effect masses. For the X-ray subsample we re-derive masses adopting the most recent calibrations. We then calibrate an empirical mass-richness relation for the combined sample spanning more than one decade in cluster mass and find the associated uncertainties in mass at fixed richness to be  $\pm 0.25$  dex. We study the dependence of our richness estimates with galaxy concentration and depth of the 4.5um imaging data and find that reaching a depth of at least  $[4.5] = 21$  AB mag is sufficient to derive reasonable mass estimates. We discuss the possible extension of our method to the mid-infrared WISE all-sky survey data, and the application of our results to the Euclid mission. This technique makes richness-based cluster mass estimates available for large samples of clusters at very low observational cost.

# Understanding ‘galaxy groups’ as a unique structure in the universe

**Reju Sam John (Pondicherry University)**

‘Galaxy groups’ have never been realised as unique objects in the structural hierarchy. The presumption that the self-similarity of dark matter structures is a valid prescription for baryonic universe at all scales has rendered smaller structures undetectable by current observational facilities, leading to lesser dedicated studies on them. Some recent reports that indicate a deviation of Lx -T scaling in groups compared to clusters has motivated us to study their physical properties in depth. We have produced a mock sample of 362 objects with a mass ranging from  $5 \times 10^{12} M_{\odot}$  to  $2.5 \times 10^{15} M_{\odot}$ . Strikingly, we have found that objects with the mass below  $\sim 8 \times 10^{13} M_{\odot}$  do not follow any of the cluster self-similar laws. Two distinct scaling laws are observed to be followed with a break at  $\sim 8 \times 10^3 M_{\odot}$  for mass,  $\sim 1$  keV for temperature and  $\sim 1$  Mpc for radius. This places groups as a distinct entity in the hierarchical structures, well demarcated from clusters. This study reveals that groups are mostly far away from virialization, suggesting the need for formulating new models for deciphering their physical parameters.

## Ten Billion Years of Brightest Cluster Galaxy Alignments

**Michael West (Lowell Observatory)**

Astronomers long assumed that galaxies are randomly oriented in space. However, it’s now clear that some, perhaps most, have preferred orientations with respect to their surroundings. Chief among these are the giant ellipticals found at the centers of rich galaxy clusters, whose major axes are often aligned with those of their host clusters - a remarkable coherence of structures over millions of light years. A better understanding of these alignments can yield new insights into the processes that have shaped galaxies over the history of the universe. Using Hubble Space Telescope observations of high-redshift galaxy clusters, we show for the first time that such alignments are seen at epochs when the universe was only one-third its current age. These results suggest that the brightest galaxies in clusters are the product of a special formation history, one influenced by development of the cosmic web over billions of years.

# Monday Posters

## High-Redshift Protoclusters Traced by Submillimeter Galaxies **Karín Menéndez-Delmestre (Valongo Observatory, Federal University of Rio de Janeiro)**

Radio galaxies have been used quite successfully as protocluster tracers. However, because they are only visible for a short period in the evolution of a massive galaxy, a significant fraction of forming clusters remains unexplored. Clustering analysis indicate that submm-selected galaxies (SMGs) reside in very massive halos, suggesting that they trace high-density environments. Conversely, SMGs have been identified as tracers of structures with more modest masses caught in highly active periods. This suggests that SMGs may be tracers of a wider range of environments beyond the progenitors of today's rich clusters, opening a window for a more complete exploration of protoclusters. With narrow-band Ly $\alpha$  imaging and multi-object spectroscopy using Palomar/Keck/Magellan/Gemini telescopes we probe for galaxy overdensities in SMG environments at  $z \sim 1 - 5$ . With  $> 200$  spectroscopically-confirmed Ly $\alpha$  emitters, we quantify the overdensities in these regions. We are also studying galaxy properties according to the maturity of SMG-traced protoclusters to explore the way galaxy and local environment relate to each other within the broader picture of a cosmologically-evolving large scale structure

## Understanding Starbursting Protoclusters: Follow-up of Herschel-Planck Selected Sources **Tai-An Cheng (Imperial College London)**

Multi-wavelength follow-up observations of candidate protoclusters selected by cross-matching Planck and Herschel data have uncovered the nature of these starbursting galaxy clusters. Although these candidate protoclusters are overdense in far-IR-bright starbursts, they contain a broader galaxy population which can be probed by multi-wavelength follow-up observations. In this poster we present optical and near-infrared observations which are used to derive photometric redshifts for members of the candidate protoclusters. We also present radio and submm follow-up observations using ATCA, VLA and SCUBA-2, which probe radio and submm properties and allow clear identifications of a number of Herschel counterparts. This multi-wavelength data on candidate protoclusters not only enable us to crossmatch them with Herschel sources but also give more accurate SED fits. Future spectroscopic observations of these candidate protoclusters will confirm their protocluster memberships, find AGN within them, estimate unobscured SFRs, and study their gas and dynamical masses using emission line properties.

## Which comes first: the cluster or the early-type galaxy?

**Julie Nantais (Universidad Andres Bello)**

The association between galaxy clusters and early-type galaxies has existed for more than half the history of the Universe, and both stellar mass and environment are known to be correlated with color, morphology, and star formation rates of galaxies. But at which stages of cluster formation, in which epochs of the Universe, did galaxy clusters begin on average to have a substantial excess of early-type galaxies? Did early clusters simply form from massive precociously-quenched galaxies as a rule, or did they quench their galaxies later as they built up halo mass, or some mixture of both scenarios? With the SpARCS and GOGREEN surveys, we study galaxy clusters between redshifts 1 and 1.7 to understand better how they came to be dominated by early-type galaxies. Early results from SpARCS at  $z > 1.3$  show that the conversion fraction (environmental quenching efficiency) in clusters of ordinary richness increases between  $z \sim 1.3$  and  $z \sim 1.6$ , indicating these clusters are not born dominated by mass-quenched early types. Future results from GOGREEN should help constrain the onset of quenching in clusters.

## Galaxy Clusters around $z \sim 1 - 2$ Low Luminosity Radio Galaxies

**Gianluca Castignani (Observatory of Paris, LERMA)**

At variance with powerful radio galaxies Low Luminosity Radio Galaxies (LLRGs) are almost invariably found in clusters and often associated with the brightest cluster galaxies, at least at low-redshifts. In order to prove that this holds also at high- $z$  we exploit a sample of 32 LLRGs at  $z \sim 1 - 2$  drawn from the COSMOS survey and search for Mpc-scale overdensities using photometric redshifts and our recently developed Poisson Probability Method. We find that  $\sim 70\%$  of the LLRGs reside in rich groups or (proto-)clusters. This fraction is higher than that found for powerful radio galaxies at similar redshifts and is in excellent agreement with results obtained at low redshifts. Independent confirmation of some of our cluster candidates is found in catalogs of clusters selected in X-rays or spectroscopically. Our strategy is unbiased with respect to colors and star formation history of cluster galaxies and represents a valuable alternative to conventional methods that search for clusters. We observed with the 30 mt. IRAM telescope two of our  $z = 1$  LLRGs in clusters to search for molecular gas and set CO upper limits. Our clusters are optimal targets for mm observations with NOEMA and ALMA.

## High-redshift, High-SFR clusters unveiled by Planck, Herschel, Spitzer - prospects for JWST Euclid

**Herve Dole (IAS)**

From about 2000 high- $z$  ( $z > 2$ ) cluster candidates detected by Planck, we followed-up about 2000 with Herschel and 80 with Spitzer. They show high SFR and high surface densities, more than any other sample. We will also discuss the prospects for JWST and Euclid to search, find and study new classes of  $z > 2$  clusters.

## Discovery of protocluster by SPT

**Carlos De Breuck (ESO)**

# Bridging the gap: a database of 9.5 Gyr of evolution of galaxies in clusters

**Miguel Sánchez-Portal (ESO Santiago)**

Aiming at bridging the gap between the star formation properties of mature, low redshift clusters and young, high redshift ones, we have built a database of nine clusters in the range  $0.39 < z < 1.63$  observed by the Herschel Space Observatory. We have compiled multi-wavelength catalogues of cluster member candidates determining their photometric redshifts based on SED-fitting and Monte Carlo simulations and built a comprehensive database containing a number of physical properties (e.g. stellar mass, SFR, projected local density). In addition, whenever possible we have discriminated the AGN population by different diagnostics and performed a morphological classification for those clusters at  $z < 1$ . With this dataset, we are addressing a number of outstanding questions that include: how does the SF and AGN activity vary with the local density? Is there a reversal of the SFR-density relation in this sample? how the total SFR relates to the clusters' stellar mass? Our current progress tackling these questions will be reported in this talk.

## The Global Intergalactic Globular Cluster System of Virgo **Michael Gregg (UC Davis)**

We have identified a new sample of Virgo intergalactic globular clusters (IGCs) and ultra compact dwarfs (UCDs) which have been serendipitously observed to date in Sloan Survey spectroscopy. To this sample, we add another ten from our own observations using the WIYN Hydra multi-fiber spectrograph. There are more than 30 new objects in total, all relatively red point sources with reliable velocities placing them at Virgo distances. They are spread widely across Virgo, significantly extending the spatial distribution of Virgo IGCs and UCDs to regions outside the well-studied M87 core region. The new sample are generally fainter, bluer, and probably more metal poor on average than the more centrally located, previously known objects. This systematic change carries information about the formation and continued evolution by accretion of the Virgo cluster, indicating a transition to less massive and less luminous objects being tidally disrupted in the outskirts now and in the recent past, compared to conditions in the inner cluster at early epochs.

# Wednesday Posters

## Star Formation in Central Galaxies of Clusters at $0.1 < z < 1$ Sinan Alis & Suleyman Fisek (Istanbul University)

A search for star formation activity were carried out for the brightest cluster galaxies selected from CFHTLS-Deep clusters. Our BCG sample consisting 89 galaxies between redshift  $0.1 < z < 1.0$ . Star formation rates for 24 BCGs were computed using  $H\alpha$  line fluxes obtained from SDSS. BPT diagram were also used to demonstrate the star formation activity where corresponding emission line fluxes are available. For the rest of our sample, that is 65 BCGs, we perform template fitting for the spectral energy distribution to obtain star formation rates.

## X-ray Spectral Analysis of the Low Surface Brightness Cluster A1631 with Suzaku Babazaki Yasunori (Nagoya University)

The entropy distribution of the intracluster gas (ICM) and the X-ray surface brightness trace the history of the dynamical evolution of cluster of galaxies. It is expected that evolved clusters of galaxies show higher entropy and brighter X-ray surface brightness. On the other hand, several clusters of galaxies which show high entropy and faint X-ray surface brightness, were found in observations of ROSAT satellite. Actually, A76 shows the properties in Suzaku observations (Ota et al. 2013). It is called a low surface brightness cluster. In order to expand this study, We conducted an analysis of A1631 ( $z = 0.046$ ), which was the lowest surface brightness cluster in ROSAT sources, using Suzaku satellite data. As the result, We detected the diffuse X-ray emission (size  $\sim 500$  kpc). The surface brightness profile was an asymmetric. It was found that the X-ray properties of A1631 showed a similar trend as in A76. The temperature profile of ICM shows flat ( $\sim 2.3$  keV). In addition, the very low central density of  $\sim 6^{-4} \text{ cm}^{-3}$  was shown. It suggests that this system is in an early phase of the dynamical evolution.

## Major Cluster Mergers as Drivers of Galaxy Evolution and Transformation Tiffany Day (Macquarie University)

Clusters of galaxies are the largest and most massive virialized objects in the observable Universe, growing hierarchically over cosmic time by the accretion of surrounding gas, dust and matter, including the infall of individual field galaxies or groups of galaxies. More rarely, clusters of galaxies grow by means of a gravitational merger between two or more existing clusters of galaxies, providing the most extreme example of this hierarchical formation scenario. In order to understand the kinematic state and dynamical history of major cluster mergers, and use that advancement to understand galaxy properties and how they evolve over time, we will consider this most extreme example - a major cluster merger - as this will exemplify the physical processes governing infalling galaxies, and reveal clues as to their differing properties. This poster focuses on the galaxy cluster Abell 2744, a massive cluster at a redshift of  $z = 0.3$ , and one of the most complicated merging systems known. Using both radio continuum data and optical spectroscopy of Abell 2744, I will present my preliminary analysis of this major merger.



## Mergers and AGN feedback on galaxy groups scale Gerrit Schellenberger (Smithsonian Astrophysical Observatory)

Low mass galaxy cluster systems and groups play an essential role in upcoming cosmological studies like those to be carried out with new instruments such as eROSITA. A detailed understanding of the astrophysical processes taking place in these systems is crucial before using them as cosmological tools. The effects of AGNs and merging processes, although of special importance to quantify biases like selection effects or deviation from hydrostatic equilibrium, are poorly understood on the galaxy group scale. We present an analysis of recent deep Chandra and XMM-Newton integrations of NGC741, which provides an excellent example of a group with multiple concurrent phenomena: both an old central radio galaxy and a spectacular infalling head-tail source (only 17 kpc from the BCG), strongly-bent jets and a 130 kpc radio trail, intriguing narrow X-ray filaments, and gas sloshing features. Supported principally by X-ray and radio continuum data, we address the merging history of the group, the nature of the X-ray filaments, the extent of gas stripping from NGC742, the character of cavities in the group, and the roles of the central AGN and infalling galaxy in heating the intra-group medium.

## Discovery of an early-phase merging cluster system with XMM-Newton Ikuyuki Mitsuishi (Nagoya University)

To establish a formation scenario of clusters, extensive studies in X-ray have been performed mainly using on-going merging clusters around the most contracting epoch while early-phase merging clusters are observationally very rare. Thus, in order to find an early-phase sample, we looked for cluster pairs and found an excellent target in RASS and SDSS cluster catalogs. We discovered an interacting equal-mass system. One of the pair possess asymmetric morphology elongating toward another and show flat temperature distribution. The X-ray peak in another cluster corresponds to the position of the BCG but similarly the hot gas distribution indicates an extended feature toward the other after subtracting azimuthally-averaged surface brightness distribution, suggesting hot gas in both clusters is now interacting even though the cores are about  $1 R_{\text{vir}}$  away from each other. Interestingly, red-sequence galaxy distribution also shows an elongated feature in the same direction as that in X-ray and a significant discrepancy is also found between the peaks in the luminosity-weighted galaxy and X-ray distribution, which suggests that the dark matter are forming into a larger potential structure.

# X-ray Follow-up Survey in the Hyper Suprime-Cam Subaru Strategic Program Field **Ikuyuki Mitsuishi (Nagoya University)**

The HSC SSP Survey is an ambitious observing program designed to probe the matter distribution in the Universe (up to  $z$  1.2). The goal is to obtain five-band (grizy) imaging over 1400 deg<sup>2</sup> spending 300 nights. The survey has both much better imaging quality (0.7 arcsec seeing) and deeper observations (26 AB mag) than other surveys. By utilizing the highest quality data, we have constructed two unique cluster catalogs, an optically-selected (Oguri et al., submitted) and a shear-selected cluster catalogs (Miyazaki et al. in prep.). The optically-selected catalog contains 900 clusters ranging from 0.1 to 1.1 in  $z$  and 200 clusters exceeding a redshift of 0.8. The shear-selected catalog contains more than 50 clusters ranging up to 0.8 in  $z$  and  $7e14$  Msun in mass. We will report on our first results of X-ray follow-up survey with archival data for newly-discovered clusters in the catalogs. We cross-matched X-ray sources in RASS and 3XMM catalogs with the clusters and more than 500 X-ray sources are cross-matched. Our X-ray analysis shows asymmetric morphologies, centroid shifts relative to the BCG and underluminosity, suggesting the cluster candidates are in different evolutionary stages.

## Hitomi X-ray spectroscopy of the Perseus cluster core **Takayuki Tamura (ISAS, JAXA)**

To advance X-ray spectroscopy, we have developed a new X-ray observatory, Hitomi, and launched on 2016 February 17, under international collaboration lead by JAXA. This was equipped with an X-ray calorimeter, with a 4.9-eV FWHM energy resolution. We observed the core of the Perseus cluster and performed high spectral resolution analysis of the hot plasma. I will present new results on (1) gas dynamics from X-ray line profiles, (2) thermal structure based on line emission, and (3) elemental abundances. Discussion will be made on the dynamical and chemical history of the cluster core, where large scale interactions among the central AGN, stars in galaxies, and the hot ICM are expected.

## BCGs radio analysis from a EGMRT and CLASH sample of galaxy cluster **Beatrice Terni de Gregory (IRA-INAF Bologna)**

We analyze new GMRT (602 – 330 MHz, beam size  $\sim 10''$ ) and VLA (1.4 GHz, beam size  $1.5'' - 15''$ ) archival data of 10 galaxy clusters mainly from CLASH sample. In this poster we present preliminary results from the study of the BCGs radio emission.

## Do galaxies have a more rapid star formation process during the early evolution? **Fenghui Zhang (Yunnan)**

The determinations of galaxy parameters (such as photometric redshift, star formation rate [SFR], total stellar mass  $M^*$ , stellar metallicity  $Z^*$ , gaseous metallicity  $Z_{\text{gas}}$ , etc.) often need the results of evolutionary population synthesis (EPS) models and photoionization models of HII regions. Stars are not only the building block of EPS models, but

also, together with stellar populations (SPs), are the key ingredients of photoionization models of HII regions. In most EPS models and HII studies, only single stars or SPs comprising single stars were considered, while observations found that binaries are common in the Universe: 50% of the Galactic field stars and 70% of massive O-type stars are in binary systems. Moreover, Sana et al. (2012) found that  $\sim 70\%$  of binaries would merge, have their envelope stripped and spun-up and only  $\sim 29\%$  are effectively single in O-type SPs. Therefore, we considered various binary interactions in our Yunnan-II EPS models, combined SPs results with MAPPINGS photoionization models, and studied the effect of binary interactions on the determinations of galaxy total-stellar-mass  $M^*$ , SFR, stellar metallicity  $Z^*$ , and so on.

We found that the inclusion of binaries would (i) raise the derived accumulated quantities (such as total stellar mass  $M^*$ , stellar metallicity  $Z^*$  and age  $t$ ) of galaxies; (ii) make it possible for the radiation fields emitted by intermediate-age (107-8 yr) SPs as theoretical candidates for significant central ionizing sources of classic H II regions, previous studies thought only young SPs or OB-type stars can ionize the surrounding gas; (3) make the selection criterion lines between star-forming galaxies and AGNs in the diagnostic diagrams move into the region occupied originally by AGNs; (iv) the derived gaseous metallicity  $Z_{\text{gas}}$  and (v) SFR of galaxies decrease because the spectrum hardness increases. Because that SFR and  $Z_{\text{gas}}$  show the recent status of galaxies,  $M^*$  and  $t$  are the accumulated results, do the decrease of SFR and  $Z_{\text{gas}}$  and the increase of  $M^*$  and  $t$  mean that galaxy has a more rapid star formation process during the early evolution?