following aspects: a) the multi-phase nature of a gas outflow; b) its connection to the inflow; c) its effect on the galaxy cold gas content and thus star formation activity; and d) its effect as preventive feedback in massive halos. As a first step, several speakers presented both observations and simulations, trying to clarify the occurrence of outflows and galactic winds in AGN and star forming galaxies. David Rupke reviewed the demographics of AGN outflows in the local Universe, and showed that most nearby quasars host galactic scale outflows in ionised gas, most likely powered by the quasar itself.

Ongoing surveys such as KASHz (KMOS AGN Survey at High redshift) and SUPER (SINFONI Survey for Unveiling the Physics and the Effect of Radiative feedback) will extend studies to much higher redshifts and link the properties of large-scale outflows with those of the galaxies' central black holes (for example, through measurements of the Eddington ratio, luminosity, black hole mass).

Thorsten Naab gave a review, from a theoretical perspective, of the galactic winds due to stellar outflows in several gas phases (molecular, neutral and ionised). While the simulations suggest that in most cases the gas should escape the galaxy, the observed outflow velocities for both AGN and stellar feedback outflows are well below the galaxy escape velocity. This could point to the circulation of gas that falls back into the system after outflowing from the disc to a small distance away, leading to accretion of recycled material.

The potential impact of outflows on the gas content of a galaxy and therefore its star formation activity was the subject of much discussion. Roberto Maiolino showed observational evidence for outflows to remove gas locally within the galaxy without affecting the global galaxy properties. As also pointed out by Romeel Dave during his review, AGN-driven outflows may provide preventive feedback by dumping energy into the galaxy halo and therefore preventing further gas accretion. However, the uncertainties in the current estimates of the mass-loading factor and wind geometry are still large, and the observational evidence for clear gas inflow into galaxies is elusive. Integral field spectroscopy with MUSE and ALMA will reveal much more about the nature of galaxies as "gas factories" in the near future.

Links

[1] MIAPP workshop: http://www.munich-iapp.de/programmes-topical-workshops/2017/galaxy-baryon-cycle
[2] ESO Excellence Cluster workshop: http://galaxyecosystem.wixsite.com/ecog

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Report on the ESO Workshop

Early Stages of Galaxy Cluster Formation 2017 (GCF2017)

held at ESO Headquarters, Garching, Germany, 17–21 July 2017

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The formation of the largest gravitationally bound structures in the Universe, clusters of galaxies, and how these environments affect the galaxies within them are major themes in cosmology and galaxy evolution. The high-redshift progenitors of clusters, called "protoclusters", are still in the process of hierarchical assembly. The transition from protocluster to cluster is gradual, driven by accretion and spectacular mergers that are expected to last roughly one billion years. This workshop aimed to address open questions in protocluster and cluster formation, to define the similarities and distinctions between the two, and to evaluate the best tools and methods for their detection and study.

Protoclusters, high-redshift galaxy clusters and merging clusters represent the first stages in the formation of the most massive known bound objects in the local Universe. The accepted view in hierarchical structure formation is that protoclusters and galaxy clusters form via mergers, the most energetic events since the Big Bang, and via the accretion of material along intercluster filaments. Merging cluster environments represent the only astrophysical laboratories where we can study a relatively short (< 1 Gyr) but decisive period in the evolution of clusters: a period that impacts the formation and evolution of both the intracluster plasma and the member galaxies of the cluster.

This workshop brought together experts who study the evolution of protoclusters and clusters across the entire electromagnetic spectrum. This workshop was unique due to the equal mix of scientists studying galaxy clusters and protoclusters (the precursors to galaxy clusters typically located at redshifts $z > 2$, i.e., the first 3 Gyr since the formation of the Universe), and also due to the goal of precisely defining what links and distinguishes protoclusters and clusters. Surprisingly, this workshop may have been the first of its kind, as protocluster experts tend to meet separately from their lower-redshift counterparts.

The workshop sought to place the evolution of protoclusters and clusters within a larger context, and to explore how they impact their constituent galaxies. The specific questions addressed during this workshop include:

- How do we define a protocluster, and how do we distinguish it from a cluster that is not yet virialised? How do we detect disturbed (proto)clusters in upcoming surveys? How can we optimise our observing strategies?
- How far back in time can protoclusters be found, and how reliably can they be identified? Are the high-z overdensities and galaxy associations really the progenitors of galaxy clusters in the local Universe? How do we differentiate between, for example, filaments, chance superpositions and true protoclusters? How do merging clusters in the local Universe ($z < 1$) compare to their high-z counterparts?
- At what stage does the intracluster medium (ICM) form? Do protoclusters have hot (> 1 keV) X-ray emitting atmospheres? How important are the non-thermal components (such as shocks, turbulence and cold fronts) to the properties of the intracluster medium of merging or forming clusters?
- How is the formation of protoclusters related to the peak of star formation and black hole activity? What is the nature of the galaxies within protoclusters and merging clusters? Do cluster member galaxies form and evolve in the (proto)cluster environment, or are the intermediate environments much more important than previously thought? What physical processes dominate the quenching of infalling satellite and member galaxies? How do shocks, turbulence and cold fronts affect star formation and active galactic nuclei (AGN) activity?
- When and how do the central AGN engines begin to interact with the ICM?
- What facilities will be required to address these questions in the future?

Outcomes

The programme and presentations from GCF2017 are available as an online archive[1]. Here, we highlight the invited review talks that introduced the topic of each section. Monique Arnaud gave the opening address, summarising the field and placing structure formation in context. Gabriella de Lucia summarised the state-of-the-art hierarchical structure simulations. Nina Hatch provided the observers' perspective on protocluster assembly and placed it in theoretical context. Marcus Brueggen shifted the discussion to more local cluster studies, where clusters are used as laboratories for fundamental plasma interactions. Dominique Eckert then discussed the chemical enrichment histories of the ICM. Nick Battaglia opened the discussion of how and why we could measure the masses of forming protoclusters, focusing on their relevance as cosmological probes, while Adam Muzzin moved the discussion back to the difficult but crucial work necessary to understand protocluster environments and their evolution into clusters. Finally, Megan Donahue outlined what we have learned about nearby ($z < 0.2$) clusters in the last two decades and how this knowledge can be applied in future work.

Overall, the evolution of a protocluster into a cluster is a continuous process, marked by dramatic merger events along the way. As such, the definitions of each will always include a few ambiguous cases, but the workshop facilitated useful discussions between theorists, observers, and instrumentation experts. Rather than simply hearing the latest results from one's own field, many — including the organisers — felt the workshop had taught them something beyond their area of expertise.

With an increasing number of cluster-like objects being found beyond $z > 1$ and with protoclusters now found at lower redshifts (as low as $z \sim 1.6$, rather than $z > 3$), it is clear that the distinction between protoclusters and clusters is mainly a matter of the median density reached by the object. Large objects that exceed galaxy scales at overdensities greater than 200 times the critical density of the Universe, typically within a Mpc radius, qualify as bona fide clusters or groups of galaxies. Protoclusters, on the other hand, are looser associations that are on their way to becoming clusters, and often span ~ 10 Mpc. A third grouping

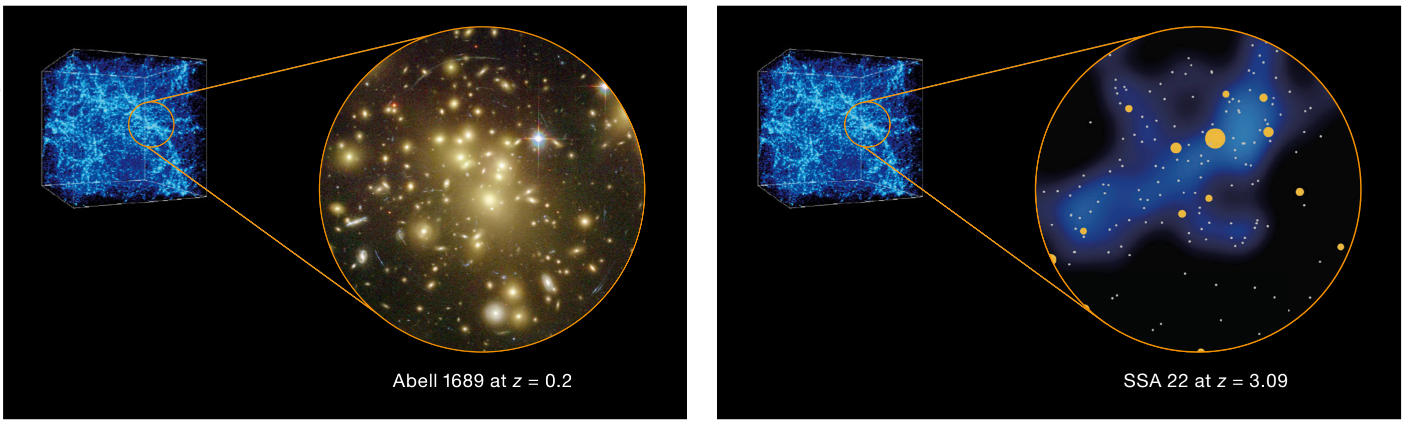

Figure 1. The left panel shows a cosmological volume simulation at $z = 3$, and the massive protocluster SSA22 at $z = 3.09$. The right panel shows the simulation at local redshifts, when the density contrast of the largest objects has dramatically grown, alongside a Hubble Space Telescope (HST) observation of the massive cluster Abell 1689 at the local redshift of $z = 0.23$.

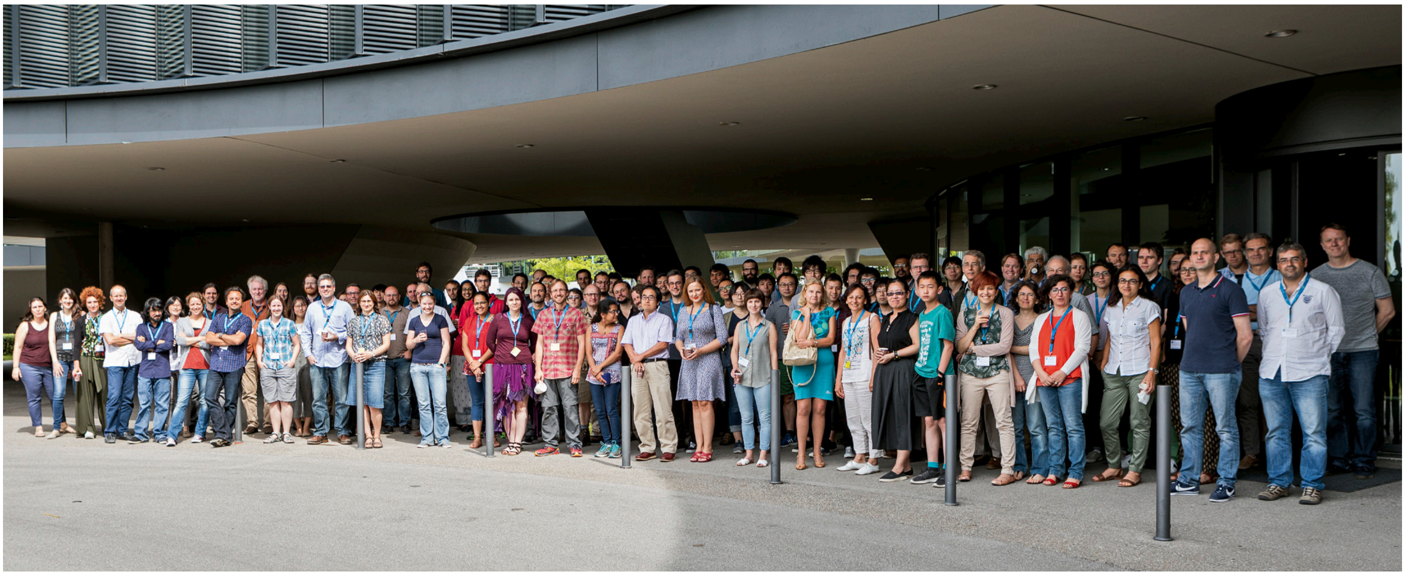

Figure 2. Workshop participants.

includes unbound structures — often superpositions thought to be protoclusters — that have not and will not exceed the overdensity threshold critical to collapse gravitationally.

Many of the questions we set out to address remain unanswered. However, it is clear the field is making substantial progress with the tools available, and will benefit greatly from the next generation of tools. More detailed gas physics, including star formation and AGN feedback at all epochs, is necessary for progress to be made with the simulations. From an observational perspective, it is clear the community is looking forward to the Extremely Large Telescope for improved imaging and spectroscopy at visible wavelengths. However, there is an equally high demand to improve the mapping speeds at millimetre and submillimetre wavelengths through projects such as the Atacama Large Aperture Submillimeter/millimeter Telescope (AtLAST[2]), particularly for high-redshift clusters and protoclusters, and through X-ray surveyors for their lower redshift counterparts ($z < 1.3$).

Workshop demographics

Like many workshops, the Science Organising Committee sought fair representation from the community. To this end, we voted on eight invited speakers, using the sole criterion of who would give the best review of each topic. The end result was a 50:50 ratio of male to female speakers.

Attendees came from five continents (all but Africa and Antarctica), with the following percentages:
- 54 % Europe (Germany, Italy, France, UK, Switzerland, Turkey, Spain, The Netherlands);
- 23 % North America (US, Canada);
- 15 % Asia (Japan, South Korea, India, China);
- 5 % South America (Chile, Brazil);
- 3 % Australia.

We find that 35 % of the abstract submissions were from women, which matched the 35 % of talk allocations to women. The talk selection was made blindly (one member of the Science Organising Committee removed names and identifying information about the authors and then abstained from voting), so we conclude that the method likely worked to address gender biases. We also had a decent level of participation from young researchers, with the following breakdown according to seniority: ~ 25 % students, ~ 30 % postdoctoral researchers, and 45 % tenure-track or tenured faculty. Each of these groups was well-represented in the talks.

The workshop had a high level of participation, with approximately 100 participants. We attribute this to both the compelling nature of the subject matter, which draws researchers at all career stages, and to the generous support that kept the cost of attendance relatively low (see acknowledgements).

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References

Tamura, Y. et al. 2009, Nature, 459, 61

Links

[1] GCF2017 Programme: https://www.eso.org/sci/meetings/2017/GCF2017/program.html
[2] The upcoming AtLAST workshop: https://www.eso.org/sci/meetings/2018/AtLAST2018.html
[3] HST image of Abell 1689: http://hubblesite.org/image/1276/news_release/2003-01