will need coronographic capabilities built into the instruments. Astrometric observations to constrain the orbits of larger, sub-stellar sized companions, and by extension the formation history of these systems, were presented by Christian Ginski.

Bernhard Brandl and Niranjan Thatte presented the capabilities of the E-ELT instruments METIS and HARMONI, respectively, and Markus Kasper showed the path that we will need to follow to reach the Planetary Camera Spectrograph instrument. Together with the presentations on MICADO (see above) and the discussions on the usage of multi-object instrumentation and high resolution spectroscopy, the totality of the instrument roadmap was extensively discussed at the workshop.

The last session at the workshop with presentations focused on the search for habitable planets. David Charbonneau gave the invited review and reminded the audience of the advances the field had made in the last year alone. A sobering thought when planning for instrumentation to go to sky in a decade from now! Ignas Snellen gave a taste of where the combination of high-resolution spectroscopy techniques with high-contrast imaging would lead us. Jay Farihi reminded us that what is left behind after planet formation will eventually fall back onto the star and can be detected by spectroscopy. Thus the meeting moved from the birth of the planets to the death of the material that made them.

Acknowledgements

The Scientific Organising Committee consisted of Bernhard Brandl, Gaël Chauvin, Ric Davies, Anne-Marie Lagrange, Michael Meyer, Jorge Melnick, Claudio Melo, Didier Queloz, Ignas Snellen, Jason Spyromilio and Niranjan Thatte. The meeting would not have been so successful without the efforts of the Local Organising Committee: Jochen Liske, Samantha Milligan, Neale Gibson and Katia Montironi.

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Links

[1] ExoELT2014 workshop website: http://www.eso.org/sci/meetings/2014/exoelt2014.html
[2] ExoELT2014 workshop programme: http://www.eso.org/sci/meetings/2014/exoelt2014/program.html

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Report on the ESO/RadioNet Workshop

3D2014: Gas and Stars in Galaxies: A Multi-wavelength 3D Perspective

held at ESO Headquarters, Garching, Germany, 10–14 March 2014

Matt Lehnert[1]
Carlos De Breuck[2]
Harald Kuntschner[2]
Martin A. Zwaan[2]

[1] Institut d'Astrophysique de Paris, France
[2] ESO

This is the second ESO workshop devoted to the topic of 3D spectroscopy of galaxies; the last one took place in 2008. An overview of the workshop themes is presented and a discussion of the progress and open questions that have been resolved by new facilities and theoretical modelling since the last workshop.

With our current knowledge of both the standard model of particle physics and cosmology, combined with the successes of Lambda Cold Dark Matter (ΛCDM) cosmology, we now have a scientifically robust model of galaxy formation and evolution that can be tested with observations. The goal of this workshop was to gauge our progress in understanding the baryonic physics involved in galaxy formation and evolution, as it is the foundation for our ability to test the growth of galaxies and structures in the ΛCDM model. The workshop builds on the previous ESO 3D workshop, held in 2008 with the same title (see Lehnert et al. [2008] for a report). In our summary we have tried to be comprehensive, but not all contributions could be mentioned. There will be no published proceedings, but most of the presentations can be consulted via the workshop website[1].

Our ability to quantitatively test the ΛCDM model relies on our ability to exploit technology — using fast computers for large high-dynamic-range simulations, with advanced data visualisation techniques (contributions by Fluke, Ott, van der Hulst and Koribalski), robust and efficient algorithms, sensitive detectors and efficient instruments, and building large aperture space and ground-based telescopes (summarised in talks by Bershady, Braun and Emsellem). The meeting six years ago took place during, what was in many ways, the infancy of 3D technology, especially in the optical and near-infrared and in visualisation techniques. Also in the radio, the world is now a richer place with the advent of focal plane arrays for single-dish telescopes and phased array feeds on interferometers coming online soon. The capabilities of the Atacama Large Millimeter/submillimeter Array (ALMA) with its wide frequency coverage, both overall and in single observations, the increasing bandwidth of instruments like the Plateau de Bure interferometer and the broad wavelength coverage of current optical/near-infrared instruments, such as the *K*-band Multi-Object Spectrograph (KMOS) and the Multi-Unit Spectroscopic Explorer (MUSE) recently commissioned

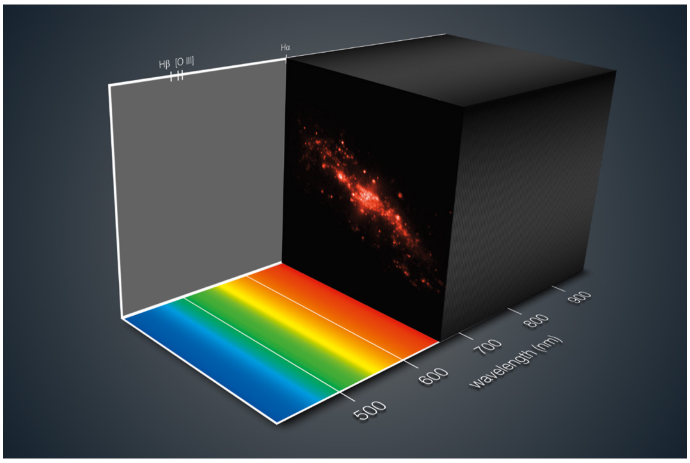

Figure 1. Visualisation of a MUSE datacube of the polar ring galaxy NGC 4650A. The galaxy image is a slice of the cube on the Hα emission line. More details available in release eso1407.

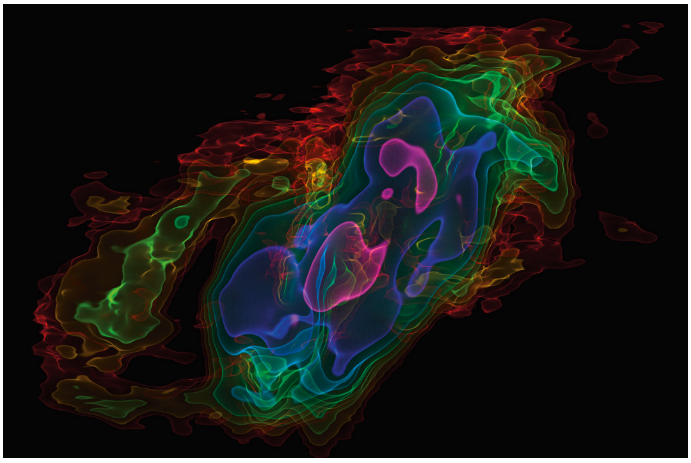

Figure 2. 3D visualisation of ALMA observation of cold CO gas in the nearby starburst galaxy NGC 253. The vertical axis shows velocity, the horizontal axis the position across the central region of NGC 253 and colours the intensity of the CO emission (pink strongest and red weakest). See release eso1334 for more details.

on the Very Large Telescope (VLT), means that the term 3D spectroscopy will soon become an anachronism — no longer a distinction, but the norm.

Moreover, these new instruments, as well as giving new life to older facilities, are leading to a convergence of multi-wavelength studies, especially blind spectroscopic surveys and studies of nearby galaxies and galaxy clusters. The instantaneous field of view of ALMA and MUSE, or the region sampled by KMOS in its mapping mode, are all approximately the same: multi-wavelength 3D observations are becoming well-matched.

In this meeting, the focus was on the *science exploitation* of telescopes and instruments, studying problems at the dawn of the era of ALMA, and on the science from H I absorption and emission line surveys and the potential of the Square Kilometre Array (SKA) and its precursors (talk by Braun). In particular, we hosted mini-workshops on the characteristics of and data analysis for ALMA, KMOS and MUSE, led by experts for each of these instruments (respectively Laing, Sharples and Bacon). While the future is now for ALMA, we had glimpses of the potential of both KMOS and MUSE to lead to real breakthroughs in our understanding of ΛCDM and galaxy formation and evolution. This conference gave the community a chance to learn about these phenomenal new instruments and facilities. Figures 1 and 2 show visualisations of MUSE and ALMA 3D data.

But, of course, we are not limited to those facilities only, as there is a huge variety of available and future facilities on the ground and in space in the ultraviolet, optical, and near-infrared using old and new technology (Bershady). These facilities allow us to study old problems in new ways and, because of their significantly increased efficiency or opening of new domains in wavelength, to dream of solving long-standing astrophysical questions that will undoubtedly lead us to propose new, but better framed and more significant, questions about the Universe in which we live.

The mysteries of local galaxies

While the idea that early-type galaxies always means a pressure-supported system with no recent star formation, and no significant gas content, was outmoded even before the last meeting, the full analysis of the ATLAS^{3D}, Calar Alto Legacy Integral Field Area survey (CALIFA) and other datasets, continues to offer a surprisingly rich variety of observed phenomenology. Our modern view of early-type galaxies, that they are composed of two classes — slow rotators and fast rotators — was developed in talks by Cappellari and Lyubenova. Early-type galaxies can also contain gas, both H_2 and H I, with about a quarter displaying detectable CO emission. The morphology of the CO emission shows a disc in about half the cases with the rest spread approximately equally between rings and bars and mildly or strongly distorted morphologies (Bureau). Almost half of the early-type galaxies have detectable H I with masses of 5–5000 × 10^6 $M_\odot$ (Serra). The H I morphologies are often extended discs and rings, which can reach beyond the high surface brightness inner regions, and outer rings often appear to be related to ongoing star formation. Two suggestions for the source of the gas in early-type galaxies are mass return from the stellar population and of external origin.

Beyond the structural characteristics of early-type galaxies, there are a number of theoretical evolution and relational puzzles. Kormendy & Bender (2012) advocated a parallel sequence between early-type galaxies and spiral galaxies with the origin of this sequence as evolutionary, or, put simply, some early-type galaxies are faded spirals. The evidence to support this origin appears to be complicated (Lyubenova).

By comparing dynamical and photometric masses, there appears to be a systematic change in the initial mass function (IMF) as a function of total stellar mass, whereby the lower-mass galaxies require a bottom-heavy IMF (Cappellari). Obviously, this has profound implications for our understanding of the conditions under which early-type galaxies formed. Additionally, these IMF variations must have been in place early, as the abundance pattern of early-type galaxies at roughly half the age of the Universe is consistent with passive evolution (Conroy). It will be very interesting indeed to determine the evolutionary state of the progenitors of early-type galaxies, especially their abundance ratios, at even greater lookback times.

Our understanding of the theoretical side of early-type galaxy formation and evolution is certainly richer, but perhaps not clearer than it was six years ago. It appears that there may be no unique evolutionary path to the end point of an early-type galaxy, but rather many (Naab). Historically, much attention has been paid to merger mass fractions leading to the range of properties in early-type galaxies. However, with larger samples of well-observed and characterised galaxies, it is clear that other factors play a role, perhaps even a major role, such as dissipation and orbital characteristics. One difficulty in modelling is to explain the existence of early-type galaxies with thin discs. Another may well be the passive nature of early-type galaxies out to half the age of the Universe. It is interesting that as samples of well-studied local and distant early-type galaxies grow in size, the theoretical challenges become greater.

Nearby disc galaxies appear to follow the textbook relationships between scale length and scale height for exponential discs (Verheijen, Martinsson). From studies of the kinematics and stellar populations of disc galaxies, it is becoming clear that there is a tight relation between the central velocity dispersion of the disc and the maximum in the rotation speed, implying that discs are sub-maximal. The dark matter appears to be distributed in a manner consistent with N-body simulations for concentrations of about 10–20 (Martinsson).

In addition to time-consuming techniques that take direct advantage of the dynamics of discs, it is also possible to use photometry coupled with molecular and H I observations (for gas content and velocity fields) to estimate the mass distributions of disc galaxies. A consistent problem with all techniques that rely on 1D rotation curves is how to deal with distortions in the velocity field induced by peculiar motions. Fitting all the 2D data simultaneously is possible, but a technique is required that allows for the transformation of observations into a density field. With such a technique, distortions are not a problem, but part of the solution in understanding the full matter distribution. Such inversion techniques look promising and may be a way to tackle large samples of galaxies over a wide range of masses with data already available (Chemin).

"Inside-out" evolution of galaxies, whereby the earliest stars to form are in the central regions with the outer disc growing at later times, is widely accepted. However, it is not clear whether this is a unique model and that inside-out could not be mimicked in some other way, such as by the superposition of two discs with differing ages and scale lengths (Haywood et al., 2013). The CALIFA survey may provide some insight into this problem as it appears that the metallicity of the gas follows that of the underlying stellar population and the gradients are negative, but relatively small. In addition, the mass-weighted age gradients are approximately flat, while the luminosity-weighted age gradients are relatively shallow but significant (Sanchez-Blazquez). It is not clear what the implications of inside-out galaxy formation are, but a careful study of the metallicity gradients and stellar populations of nearby galaxies may help to constrain how galaxies grow.

Star formation is the bridge that links the gas flows from the intergalactic medium to the build-up of the stellar populations in galaxies. It is no hyperbole to say that without understanding the details of star formation we cannot understand galaxy evolution (but see Hopkins). Critical to this understanding is to probe the detailed properties of molecular clouds and star formation in different environments. With the advent of ALMA and the increased capabilities of other facilities, it is now possible to study the molecular gas on small scales and high sensitivity in nearby disc galaxies, starbursts and mergers. The external surface pressure on molecular clouds appears to be important, as the internal and external thermal pressures are in equilibrium for nearby spiral galaxies — galaxies with roughly constant global gas depletion timescales (Meidt). The importance of streaming motions implies that, at least for quiescent nearby spiral galaxies, large-scale shear and turbulence, as well as stellar feedback, play a less important role in regulating the local star formation surface density.

The processes occurring in the centres of galaxies may differ, since other types of phenomena may play a role in regulating the properties of molecular clouds and star formation. Detailed studies of nearby galaxy nuclei find that the CO-to-H_2 conversion factor may be different to other environments (generally lower); this change suggests that barred and unbarred galaxies have similar nuclear gas contents and that star formation efficiency is higher in galaxies with bars or oval shaped bulges (Sandstrom). It appears likely that these trends are related to the higher excitation of the molecular gas in galaxy centres, both in its temperature and turbulence.

Galactic centres/supermassive black holes

Gillessen opened this session with an update on the observations of the gas cloud G2 passing by the Milky Way Galactic Centre (GC). Already, these observations rule out several models for the evolution of the gas as it orbits the GC. The rich variety of phenomenology exhibited by the GC can help us understand black holes in nearby galaxies: more specifically, the similarity of the GC nuclear stellar cluster to the clusters observed in other galaxies. Nuclear star clusters are detected in about half to three-quarters of all galaxies and have multiple generations of stars, masses typically $10^{6-7}\ M_\odot$, the highest stellar densities of any objects in the Universe and some harbour supermassive black holes (SMBHs; Neumayer). The difficulty in knowing how similar these distant nuclear star clusters are to the one in the Galaxy is the large area that must be mapped in near-infrared imaging spectroscopy to understand our nuclear star cluster in its totality. Feldmaier presented innovative long-slit spectroscopy with ISAAC and early data from KMOS to map out a large enough area to encompass the star cluster. This rich 3D dataset supports the idea that much of the nuclear cluster was accreted into the GC.

The accurate determination of black hole masses is important in understanding the relationship between black holes and galaxy centres. With the advent of regular observations with ALMA, and the high spatial resolution offered by other facilities such as the Combined Array for Research in Millimeter-wave Astronomy (CARMA), it is possible to make extremely high resolution molecular maps of nearby, and increasingly more distant, galactic nuclei. Since CO is dynamically cold, it makes an excellent dynamical tracer even in dispersion-dominated systems such as early-type galaxies and galactic bulges. With ALMA, this technique can be potentially extended to thousands of galaxies out to 100 Mpc (Davis).

Active galactic nuclei/starburst galaxies

While studies of relatively quiet SMBHs enable us to understand the relation between black holes and stellar populations, they only hint at how black holes themselves might grow and evolve. Direct observations of accreting black holes are necessary to understand how they are fuelled and grow and what the impact on their surroundings is. Central to understanding these phenomena is high-resolution 3D spectroscopy of the gas on circum-nuclear scales and, since the inflow and outflow of gas is a multi-phase phenomenon, a variety of wavelength regimes and diagnostic lines are required.

New facilities and observations of larger samples of active galaxies are now painting a comprehensive picture of how active galactic nuclei (AGN) are fuelled and how they regulate the growth of the SMBH. Tracing the gas down to 1–10 pc scales suggests that: inflow rates are sufficient to fuel the AGN and these inflows may be driven by the bar (Fathi); compared to similar inactive galaxies, Seyfert galaxies have a significant gas reservoir which requires inflows/accretion and near nuclear gas that has also led to additional star formation (Hicks); large statistical studies in the near-infrared and millimetre suggest that Seyfert galaxies exhibit both inflows (molecular) and outflows (molecular and ionised), which are in rough balance, with the ionised gas requiring ~ 0.5% of the bolometric luminosity to be energised (Mueller-Sanchez). New observations show cavities in the molecular gas through which the AGN is emptying the nuclear region of gas; these cavities are then replenished by infalling material driven by instabilities (Mueller-Sanchez). Outflows are observed in H I as well as in the molecular and ionised gas. While we have reasonably good ideas of the outflow rates in H I in some nearby radio galaxies (a few to 50 $M_\odot$ yr^{-1}), the details of how they are driven remain poorly understood. High-resolution radio observations of H I in absorption against bright radio emission suggest that specific interactions, on scales of about 0.5 kpc, with the head of the jet account for the H I absorption and kinematics (Mahoney).

On larger scales, the AGN can illuminate the large (10–100 kpc) scale haloes surrounding powerful AGN, which show a striking similarity with Lyα blobs (Overzier). Detailed studies of nearby starburst galaxies and AGN suggest that the gas is rapidly depleted by outflows (timescale ~ 10 Myr); there is a good correlation between star formation rate and outflow rate, with any contribution from AGN boosting the flow rates. These outflows only require ~ 1–10% of the bolometric luminosity and have a typical momentum output of about 10–20 times that of the bolometric momentum generated by the starburst and AGN (Cicone). Outflow velocities increase with both increasing star formation rate (SFR) and specific star formation rate (sSFR) with the highest outflow velocities being associated with galaxies with the largest deviations from the ridge line in the SFR-stellar mass plane (Maiolino). [O III] optical emission does not trace mass particularly well, so other tracers of outflows are obviously important to investigate.

There are a number of possible mechanisms through which star formation and the growth of SMBHs might be regulated. Massive stars inject energy and momentum into the interstellar medium and thus regulate the conditions in the ISM and hence star formation and accretion onto the SMBH. Recent modelling suggests that galaxy and black hole growth can be understood as a symbiosis of the many processes that compete with and enhance each other in regulating gas heating and cooling, and hence star formation and the accretion rate onto black holes (Hopkins). Black hole accretion in such a complex environment then becomes one of stochastically digesting gas at rapidly fluctuating rates (Bournaud). The interaction between various physical mechanisms through which stars and black holes influence their environments may imply that the exact details of how stars form is not determinant in galaxy evolution (Hopkins). If true, this is a radical conclusion to draw. Clearly, we have much more work to do to understand the complex gas physics exhibited by galaxies and how much material is blown out by outflows driven by young massive stars (e.g., Lilly, Bouché).

Distant galaxies and AGN

New facilities have allowed us to observe galaxies as they grow and evolve in much more detail (see Figure 3 for an example derived from KMOS 3D data). High-redshift galaxies are dominated by rotating discs that are highly turbulent (Förster-Schreiber) and the most massive ones appear particularly well-settled (Buitrago). These findings have a number of consequences, including explaining why discs are so clumpy and how star formation might be self-regulating (Bournaud, Förster-Schreiber). In addition, it appears that outflows in the warm ionised gas are quite common in these discs, with the outflow rates typically being one to a few times the star formation rate.

Well-selected samples observed with high-multiplex 3D spectrographs are important in understanding the properties of distant galaxies in a robust way. Narrowband surveys targeting Hα constitute one approach, as they are relatively insensitive to mass, but efficiently select star-forming galaxies over a wide range of redshifts. Following up such narrowband surveys with integral field spectroscopy suggests that the SFR-mass and Tully–Fisher relation does not change with environment: metallicity gradients are mostly negative or flat (also when including absorption lines in the haloes; Péroux). The gradients increase with sSFR, suggesting that funnelling of gas into galaxy centres plays an important role in enhancing relative galaxy growth rates (Sobral). The future is very bright for these types of studies with KMOS, allowing us to observe larger

Emily Wisniosky (MPE) and KMOS3D team

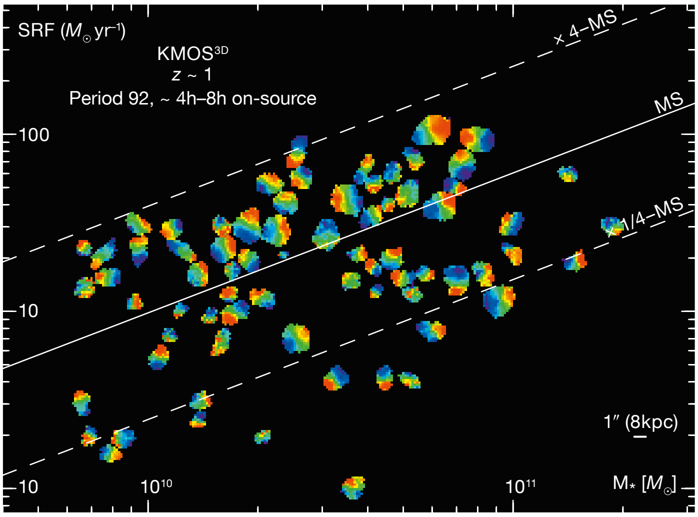

Figure 3. Hα velocity fields for the first 72 spatially-resolved sources at z ~ 1 observed as part of the KMOS^{3D} survey of > 600 mass-selected galaxies at $0.7 < z < 2.7$ (from Wisnioski et al., 2014, in prep.). Blue to red colours correspond to velocities that are blueshifted to redshifted relative to the systemic velocity of each galaxy. The galaxies are located according to their stellar mass (M_*) and star formation rate (SFR). The solid line indicates the locus, or main sequence (MS), of star-forming galaxies at z = 1, and the dashed lines show offsets by factors of 4 in SFR.

samples with a wider range of redshift and intrinsic properties.

Integral field observations of moderate-redshift galaxies suggest that many of the morphologies and kinematics are consistent with being produced by remnants of major mergers. For example, the tightness of the SFR–stellar-mass relation and the distribution of bulge-to-disc ratios are not in tension with such a picture. Major mergers could be a viable, or perhaps even the best, explanation for many of the properties of disc galaxies (Puech). By its very nature direct observations of gas accretion are challenging. However evidence is accumulating that perhaps some quasi-stellar object (QSO) absorption lines have properties consistent with those expected for cosmological accretion. There are possible signs of inflow in some sources, or at least there is material in the halo that has gravitational motion, and is likely a source of accreting gas (Bouché). But outflows are also probably very common and a source of the absorption line material (Péroux).

The combination of deep HST imaging data, especially in the near-infrared, and 3D spectroscopy in the near-infrared and millimetre enables a detailed look at the spatially resolved properties of distant galaxies, especially their clumpy structure and the relative growth of galaxy centres. Clumps have bluer colours, higher Hα equivalent widths, and higher specific star formation rates than the underlying discs, but do not seem to be a significant contributor to the global mass budget. It is particularly surprising that the clumps do not appear to be regions of mass enhancement as compared to the underlying disc (Wuyts). High resolution (~ 0.2 arcsecond) mapping with the Jansky Very Large Array (JVLA) of a distant, z ~ 4, submillimetre galaxy (SMG) shows a large massive rotating disc galaxy with a flat rotation curve. The molecular gas in this galaxy is clumpy and the properties suggest that the large 1 kpc scale clumps are self-gravitating and constitute about 50 % of the total molecular mass (Hodge). This differs markedly from the picture of the clumps detected in the restframe optical. At even higher redshift, z = 4.76, another SMG also exhibits a large extended disc (see De Breuck et al., p. 38).

The capabilities of ALMA and of other interferometers allow us to conduct surveys and types of observations that could only be imagined previously. Blind redshift surveys of individual sources, and even in wide (somewhat) blank fields, in both lines and continuum are now possible (Aravena, Ouchi, da Cunha, Decarli). These types of surveys break the stranglehold on both having to identify the source and determine its redshift from optical or near-infrared imaging and spectroscopy. We can now find sources that are not identified in any other way and their properties are surprising: they are at very high redshift, have particularly narrow emission lines and compact structures that suggest they are extremely gas-rich and dense (Ouchi). We are undoubtedly on the verge of a revolution in our understanding of distant galaxies by finally being able to select targets based on their dust emission and molecular gas content, instead of on the surface brightness of their stellar populations, and therefore robustly determining the evolution of the gas content of galaxies (Decarli).

While outflows driven by AGN are firmly established locally, at high redshift our observational census of the role in early galaxy evolution is still quite limited. ALMA allows for routine observations of distant z ~ 7 QSOs in [C II]. QSOs turn out to have a [C II] to infrared luminosity budget deficit similar to local powerful starbursts, but they also show diversity with hints for outflows in their kinematics and morphology (Venemans). In particular, J1148+5251 is driving an incredible outflow in the very early Universe, a mass-loss rate of thousands of $M_{\odot}$ yr^{-1} (Miaolino), and this outflow may be very extended (30 kpc; Cicone). Hopefully and eventually, it may be possible to observe both the infall onto the circum-nuclear region of distant AGN as well as their outflows. This would finally allow us to complete the feedback cycle in distant galaxies. As it stands now, we observe mostly one side of the gas ledger, the outflow.

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