Report on the ESO/MPA/MPE/Excellence Cluster/LMU and TUM Munich Joint Conference

Discs in Galaxies

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Richard Ellis[1]

[1] ESO

The annual Munich Joint Astronomy Conference brought together observers and theorists studying the full range of cosmic environments and epochs where discs play a role in shaping the structural assembly history of galaxies. Considerable progress is being made in interpreting the past history of the Milky Way and Andromeda through massive stellar imaging and spectroscopic campaigns. This is being augmented with interferometric studies of gaseous discs in nearby galaxies with exquisite angular resolution. Integral field spectrographs are providing resolved data for star-forming and quiescent galaxies to redshifts of three. This explosion of new data is being interpreted with high resolution numerical simulations in order to understand the physical processes which govern the stability, formation and disruption of early discs, and how star formation is regulated in the context of various feedback processes. Selected highlights of the progress reported at the conference are presented.

Stellar and gaseous discs represent a fundamental feature of the Hubble sequence of galaxies, acknowledged in 1994 by Allan Sandage when he remarked that the sequence represents "a true order among the galaxies, not one imposed by the classifier". The modern view now emphasises a continuity in the disc properties of host galaxies from gas-rich, rotationally-supported, thin spirals to dynamically hotter early-type galaxies. Decades ago many astronomers considered that galaxies evolved in isolation with their resulting stellar populations and kinematic properties established via their formation processes. Now we realise that galaxies interact both with one another and with their environment, so that key components, such as stellar discs, can be both assembled and destroyed as the systems evolve. Explaining the physical origin, time evolution and structural properties of discs clearly underpins our understanding of galaxies, which are the visible fabric of the Universe.

There is a veritable explosion of new observational data relating to the properties of discs from detailed chemical and kinematic studies of stellar components of the Milky Way, through a new generation of integral field spectrographs gathering resolved data on thousands of intermediate redshift galaxies, to impressive progress on the earliest star-forming systems. These observations extend beyond the familiar optical and near-infrared region to include gaseous structures probed by radio and sub-millimetre interferometers. This observational progress is mirrored by high resolution numerical simulations of evolving gas-rich galaxies as well as analytic studies of the stability of their discs.

This year's Munich Joint Conference held at ESO focused on addressing the role that discs play in the history of galaxy assembly. Over 130 registered participants from all over the globe participated in a lively four day programme addressing key topical issues. The programme (available online[1]) was assembled with input from an experienced Scientific Organising Committee aided by its local members Andi Burkert, Eric Emsellem, Guinevere Kauffmann, Linda Tacconi and myself.

Galactic discs: fundamentals

The conference was structured around four interlocking themes. In the first theme, concerned with the fundamental properties of disc galaxies, Bruce Elmegreen and Mark Krumholz tackled two long-standing fundamental questions. Since 1959 it has been known that the stellar distribution in disc galaxies is exponential along the major axis without any obvious "edge". What is the origin of this "exponential profile" which extends out to ten scale lengths? Deviations are seen at large radii which appear to correlate with Hubble type. Simulations of gaseous halos aligned in various ways with the dark matter can reproduce some of the trends, most likely through a combination of the redistribution of angular momentum, torques and the relationship between star formation and gas density. However, bars, spiral arms and interactions appear to affect the profiles in ways that are not yet understood. Higher order trends are seen when examining profiles in various colours, but these arise from age gradients rather than features in the mass distribution, consistent with old stars having migrated to the outer parts. Whereas various dynamical processes can move stars radially inwards and outwards, understanding why this continues to preserve the exponential profile is a puzzle.

The second question relates to the origin of turbulence in gaseous discs. Typical discs have a dispersion of 6 km s^{-1} in warm H I gas, which is much larger than can be accounted for by thermal motions. Since turbulence decays on ~10 Myr timescales, its sustenance requires an energy source. Supernovae offer a potential continuous source of energy input, providing that the timescale of renewed star formation is about 3 Gyr, but simulations indicate many problems, particularly in regard to maintaining turbulence in outer discs. Gravity-driven turbulence is an alternative: turbulence transports angular momentum outward and mass inward; the decay of turbulence is balanced by inward accretion. In this picture, since mass inflow decreases with cosmic time, velocity dispersions should be higher in early galaxies, as observed.

The results of several new disc surveys were presented including BlueDisk (Guinevere Kauffmann), the EMIR Multi-line Probe of the ISM Regulating Galaxy Evolution (EMPIRE) by Frank Bigiel, the Hubble Legacy ExtraGalactic Ultra-violet Survey (LEGUS) by Dimitrios Gouliermis and the Westerbork Hydrogen Accretion in LOcal GAlaxieS (HALOGAS) by Guyla Józsa. Eva Schinnerer reviewed how millimetre interferometry is tracing molecular gas in nearby galaxies with exquisite (40 pc) resolution (Figure 1), enabling detailed studies of how star-formation is regulated and of environmental dependencies relating to the stellar surface density and the presence of spiral structure. Surprisingly, there is no simple spatial trend in activity as expected from star formation triggered by a spiral pattern. Kathryn Kreckel illustrated how the combination of the Atacama Millimeter/submillimeter Array (ALMA) and the Multi Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope will revolutionise such *in situ* studies. Extra-planar molecular gas is also seen in M51 and inferred from CO and H I line widths in

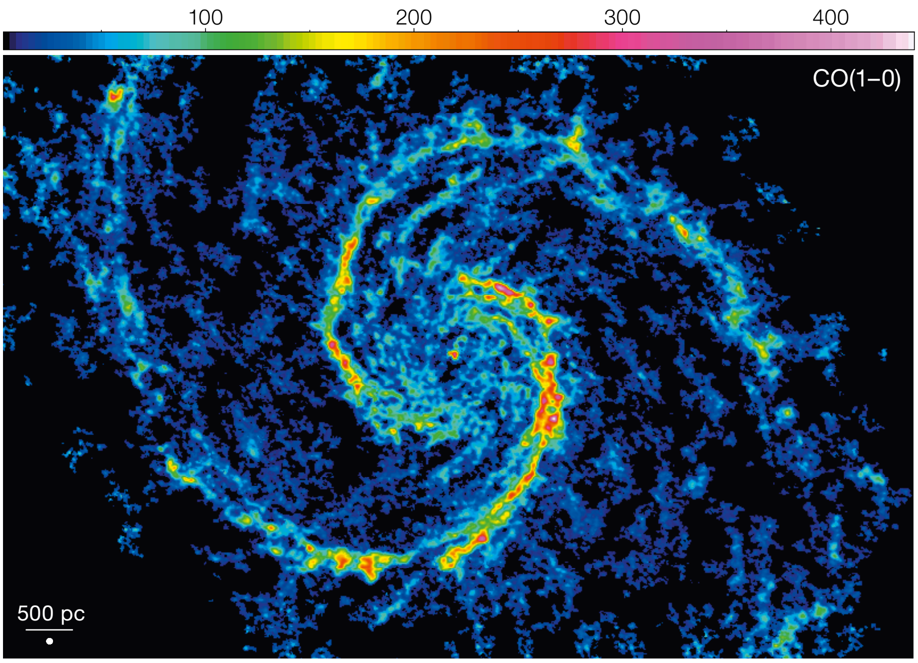

Figure 1. Plateau de Bure Interferometer (PdBI) image of CO molecular gas in M51 with a spatial resolution of 40 pc (from Schinnerer et al., 2013). Such data are probing the formation and timescales of giant molecular clouds in the presence of spiral arms in the disc. The colour bar shows CO integrated intensity.

other nearby galaxies, implying dense gas can be expelled from the thin disc via stellar feedback.

Niv Drory presented the first results from the SDSS-IV MaNGA (Mapping Nearby Galaxies at Apache Point Observatory [APO]) survey — an integral field spectroscopic survey of 10 000 galaxies for which about 30 % of the data is now in hand; Figure 2 shows a few examples. Spatially resolved spectroscopy for such a large sample is a major advance and both interesting and puzzling results are emerging. The most intriguing result (presented by Jorge Barrera-Ballesteros) concerns a mass-metallicity relation derived from the localised mass density within a galaxy, that is just as tight as that determined from integrated measures. Does this indicate that some global scaling relations are governed by localised physics? Each conference theme was followed by a panel discussion, and this MaNGA result was the source of intense debate!

Emergence of early discs

The second theme concerned the emergence of early discs in high redshift galaxies. Reinhard Genzel reviewed the formation and evolution of massive star-forming galaxies, demonstrating the remarkable progress being made with integral field spectrographs such as the *K*-band Multi Object Spectrograph (KMOS), the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) and the OH-Suppressing Infra-Red Imaging Spectrograph (OSIRIS). Resolved kinematics is now available for several hundred galaxies in the range $1 < z < 3$ with ordered rotation evident in about 70 %. The gaseous velocity dispersion increases with redshift but is not correlated with the density of star formation, suggesting that it is gravitationally driven. ALMA will permit such studies to be extended beyond z ~ 3. By stacking the kinematic data, Philipp Lang demonstrated that outer rotation curves turn down at large radii, indicating a high baryon fraction and significant pressure support in the outer parts.

Higher spatial resolution spectroscopic data can be achieved using adaptive optics and by exploiting the magnification boost of gravitational lensing. Tucker Jones and Nicha Leethochawalit demonstrated how it is possible to probe Milky Way progenitors at z ~ 2 and systems with stellar masses less than $10^9 M_{\odot}$. Whereas strong metal gradients are seen in nearby spirals, these are largely absent at z ~ 2, suggestive of gas mixing from strong feedback processes. Perhaps the most surprising result from high redshift was the discovery (presented by Drew Newman) that several massive compact quiescent galaxies have rotating discs. If these are progenitors of today's non-rotating massive ellipticals, these discs must subsequently be destroyed, for example by minor mergers.

High redshift galaxies appear clumpy in form and although initially suggestive of widespread merging, the regular kinematics indicates that the clumps more likely represent instabilities. Avishai Dekel reviewed how adaptive mesh refinement simulations incorporating cold inflowing gas can address the build up of angular momentum. When interpreted in terms of a low Toomre parameter *Q* this naturally leads to violent instabilities. Frédéric Bournaud demonstrated that the largest clumps can survive for ~ 400 Myr and launch their own outflows. They may migrate to the nucleus, initially establishing metal gradients which are eventually disrupted by feedback. Ken-ichi Tadaki showed that dense cores can be found in z ~ 2 ALMA sources, perhaps indicative of bulge formation. Robert Feldmann offered a different perspective in his FIRE (Feedback In Realistic Environments) simulations. He argued that the Toomre instability criterion may not apply in asymmetric thick discs which are not isothermal. In the efficient feedback used in these simulations, such clumps would be transient and not contribute to bulge formation.

In the subsequent panel discussion there was a lively debate about the utility of pursuing various challenging observations (e.g., metal gradients in z ~ 2 galaxies) given the apparent ability of theorists to reproduce such observations in a wide variety of very different physical situations! It was unclear whether the community has reached a consensus on when thin discs in Milky Way-like galaxies emerged. Susan Kassin presented an update on the mass-dependent fraction of galaxies with various emission line rotational velocities, *V*, and internal dis-

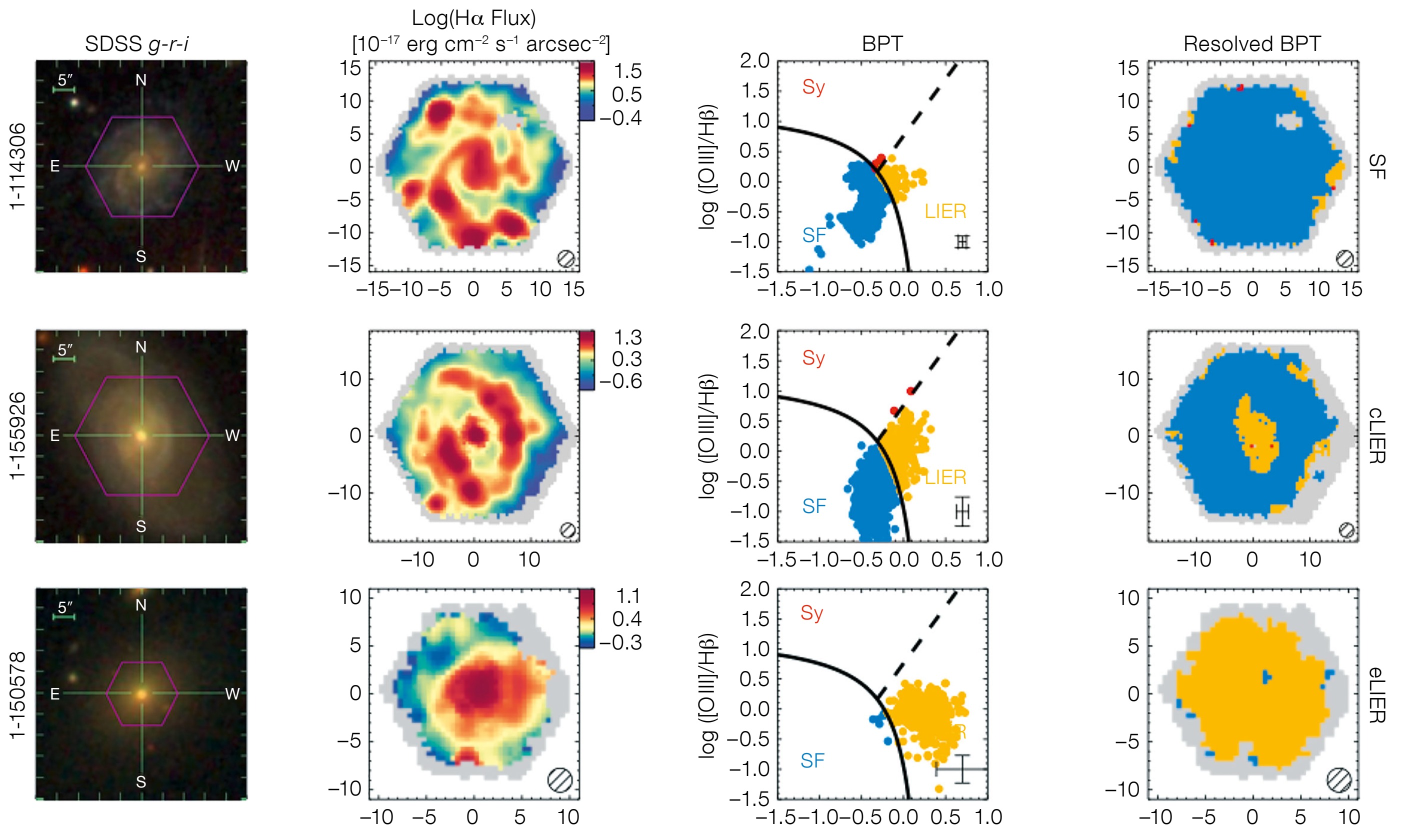

Figure 2. Spatially resolved excitation maps for a few *i*-band selected galaxies from the MaNGA survey. From Belfiore et al. (2016).

persions, σ. By z ~ 1, about 70 % of disc galaxies with masses greater than 10^{10} $M_{\odot}$ have $V/\sigma > 3$.

The Milky Way and Local Group

The third major theme of the conference addressed the progress being made in understanding discs in the context of the Milky Way and nearby galaxies, through detailed measures of stellar velocities, ages and abundances. Jo Bovy summarised the key parameters of the Milky Way Disc as well as the mass budget in the Solar Neighbourhood. The Gaia satellite is providing 6D phase space data which will be augmented with abundance data from many associated spectroscopic surveys. The APO Galactic Evolution Experiment (APOGEE) has been particularly effective in extending radius-dependent studies of the high α-element/Fe sequence as a probe of early disc evolution. The star formation rate and gas in/outflow rate have been similar across the entire Disc in its first 4 Gyr (Figure 3). Disc evolution appears to have been very quiescent over the past 10 Gyr with no large fraction of stars accreted by mergers. The migration of stars is a critical factor in understanding the metal-rich tail in the Disc.

There appears to be a smooth transition in composition (but not in angular momentum) between the thin, and so-called "thick", Disc, whereas the flaring of the low α/Fe population is consistent with radial migration. Although no flaring is seen in the high-α/Fe population, the Disc formed inside-out and was likely turbulent in its early phase. Stellar ages give an additional perspective to those based on chemical abundances, but reliable ages have always been a challenge. Gerry Gilmore introduced a potentially powerful method exploiting the [C/N] abundance ratio applicable for red giants, demonstrating that the thick Disc is likely old.

Julianne Dalcanton presented results from the Hubble Space Telescope (HST) M31 Treasury Survey; the data comprise an impressive 12 834 images taken at 414 positions, with photometric measures from six filters of the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3) infrared channel for 117 million stars (Figure 4). Detailed colour-magnitude diagrams to AB ~ 26 mag. enable reconstruction of the star formation history with a spatial resolution of 20 pc. These data demonstrate that features such as the 10 kiloparsec star-forming ring existed several dynamical times ago. The resolved stellar populations can also be used to predict the lower resolution ultra-violet GALaxy evolution EXplorer (GALEX) satellite map of M31; in fact the GALEX signal is stronger than predicted, enabling a detailed map of the dust distribution derived from its extinction (rather than emission). Although morphologically similar, the dust masses/emissivities derived from the Spitzer Space Telescope are too high by a factor of ~ 2.5.

Whether the Milky Way (and M31) are "typical" is an important question that was addressed by both Risa Wechsler and Jeff Newman. The Milky Way appears to be a fairly representative "green valley"

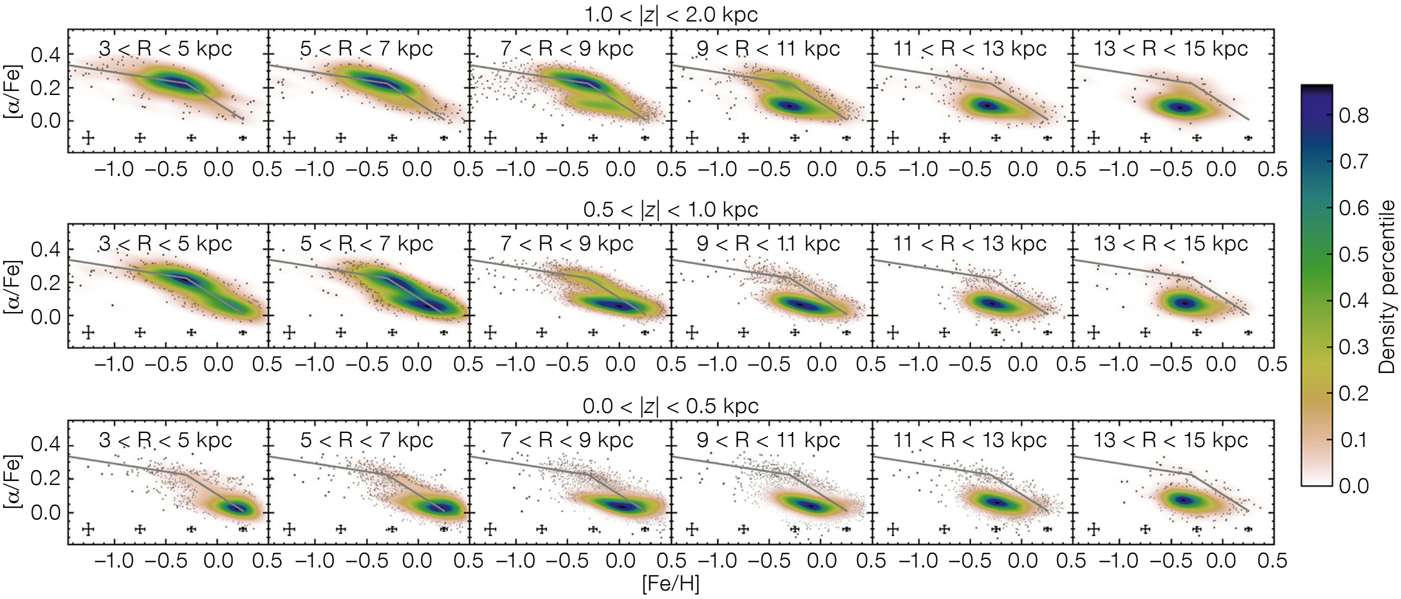

Figure 3. Chemical abundance patterns [α/Fe] *vs.* [Fe/H] across the entire Milky Way Disc from APOGEE (from Hayden et al., 2015). The high [α/Fe] sequence probes the early history of the Disc; the uniformity in the radial direction suggests a quiescent history since z ~ 2 with no major mergers.

galaxy on the Tully-Fisher relation, but is in the lowest 10 % by physical size despite its other physical properties. Wechsler described an ambitious SAGA (Strömgren survey for Asteroseismology and Galactic Archaeology) survey aimed at addressing this discrepancy in the context of securing detailed structural properties for 74 nearby isolated galaxies.

As expected, the panel discussion session was dominated by debate over the physical reality of a thick Disc component and its connection with dispersion-dominated rotating systems seen at z ~ 2. Several erudite participants commented that the nomenclature is unfortunate. Not everything in the Milky Way that is “thick” is lying in the so-called thick Disc, since part of the thin Disc is flaring. The debate continues...

Interfacing theory with observations

The final conference theme related to the interface between theory and observations. Numerical simulations traditionally

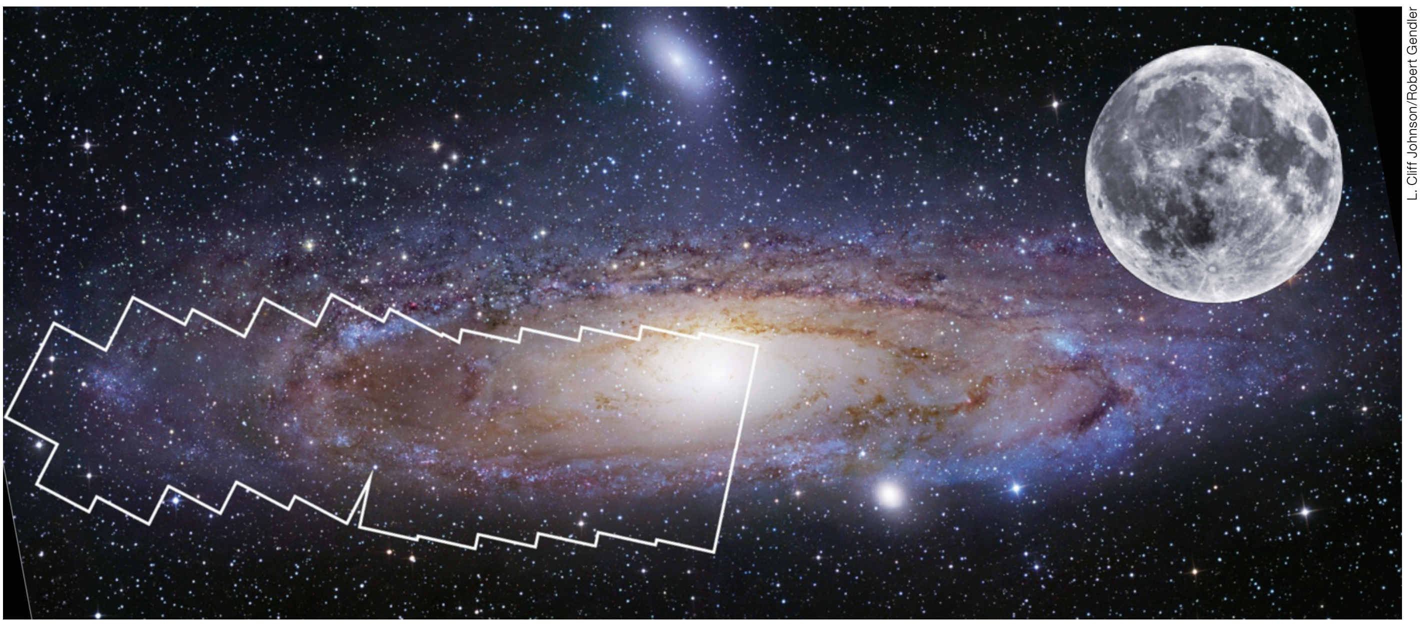

Figure 4. Survey strategy for the Panchromatic Hubble Andromeda Treasury (PHAT) survey comprising 23 “bricks” each an array of 3 × 6 HST pointings. Six-filter photometry provides colour-magnitude diagrams, star formation histories and measures of dust extinction with 20 pc resolution across the entire disc.

had great difficulty reproducing even the most basic observational scaling relations, but recent progress has been impressive. Richard Bower summarised the results from the EAGLE project, and Shy Genel those from Illustris simulations (Figure 5). Strong feedback that declines with increasing halo mass is a key ingredient in enabling us to reproduce, for example, the relationship between the stellar specific angular momentum and galaxy mass, as well as both galaxy sizes and their angular momentum distributions. The onset of black holes is necessary for the termination of widespread star formation.

Rob Grand presented moving mesh, magneto-hydrodynamic simulations of Milky Way sized galaxies (the Auriga project). These simulations are claimed to have sufficient resolution to address important observables, such as the time-dependent velocity dispersion and the effect of spiral arms and bars on chemodynamics of galaxies. Discs grow thinner with time and outward radial migration, driven by spiral arms, decreases their velocity dispersion and leads to azimuthal metallicity enhancement signatures that can readily be tested, e.g., with MUSE observations. In a complementary approach, James Binney modelled the controlled growth of a thin disc in an isolated galaxy. Heating by giant molecular clouds seems a critical factor in establishing the vertical structure, with radial migration essential for reproducing chemical gradients. Karl Glazebrook presented a new picture of disc stability and bulge formation, illustrating how the atomic gas fraction is intimately connected to the angular momentum.

The last panel discussion focused on where the subject is moving observationally. Integral Field Unit (IFU) data is clearly a major advance in intermediate redshift studies and we can expect close synergies between observations by MUSE with adaptive optics and studies of the gaseous component with the ALMA and the Square Kilometre Array (SKA) precursors. With the first Gaia data release imminent and enabling multi-element tagging, it is questionable whether we ready for this explosion of data. Which of these numerous observational directions best test the physical processes? Many worry that

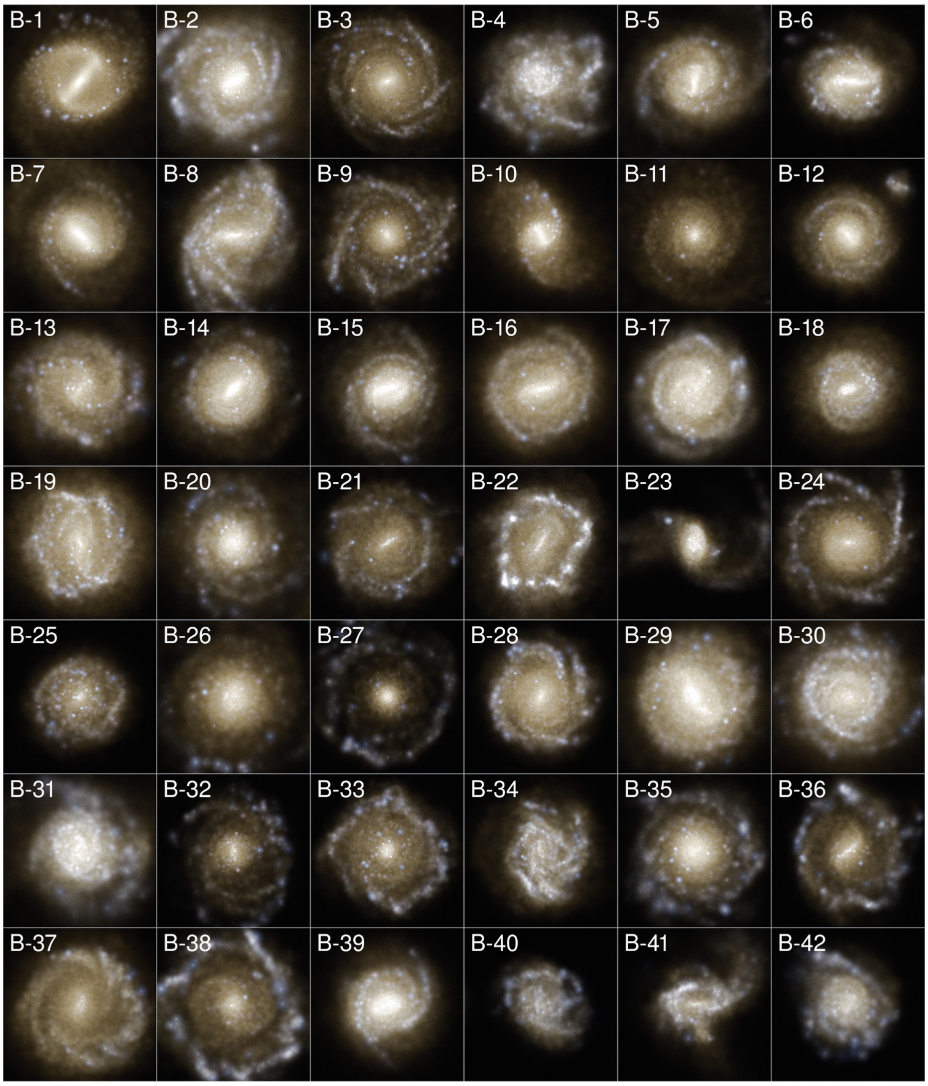

Figure 5. Simulated present-day disc galaxies in $10^{12-13} M_{\odot}$ halos from the Illustris simulation. From Vogelsberger et al. (2014).

feedback is still treated rather as a black box! Florent Renaud emphasised the importance of feedback, and how it is just as dependent on the topology of the interstellar medium as the choice of subgrid recipes; he warned of the critical need for high resolution.

As in all successful meetings, one is overwhelmed by the sheer enthusiasm of the participants, the intense level of activity and progress, as well as some outstanding puzzles. The participants were uniformly good-natured (despite the torrential downpour during the conference dinner held in a Schwabing biergarten!).

Acknowledgements

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Links

[1] Workshop programme: http://www.eso.org/sci/meetings/2016/Discs2016/program.html