Community paper „Galaxy kinematics and evolution“

C.J. Walcher, T. Naab, N.M. Förster Schreiber, V. Springel, D. Bomans

Executive summary

This is the first draft of this white paper. To improve it further this now needs input from and discussion with the German community.

1. Introduction

This white paper summarizes perspectives and opportunities for the German community working on the topic of galaxy evolution and kinematics. Galaxies evolve from initial conditions through cosmic time to form the galaxy population we see today. Understanding galaxy evolution in general is fundamental to understanding the evolution of the Milky Way, our cosmic home. The field of galaxy evolution thus ultimately is one part of the answer to the questions “What is our place in the universe?”. Galaxy evolution is complex, involving many competing processes, none of which is fully understood. Additionally, it is likely that some processes are even completely unknown to this date. For the next decade, galaxy evolution studies will continue to concentrate on elucidating the processes that shape galaxy evolution and on trying to understand their relative importance. Besides directly studying those processes observationally and theoretically, the characterisation of the galaxy population will remain fundamental to quantify the actual state of galaxies’ evolution today.

Here we argue that big opportunities present themselves to improve our understanding of galaxy evolution in the next decade and that the German community is well placed to play a major role in these developments.

2. Key Questions for the Upcoming Decade

On the worldwide scene, the following areas of research will dominate galaxy evolution studies over the next decade. Note that we do not treat AGN and gas physics as these are covered by other white papers.

- Resolved, half-resolved and integrated galaxies: our ability to infer the properties of matter in galaxies from either spatially resolved or integrated spectral energy distributions and to draw conclusions about the assembly of galaxies.
- Chemodynamics of galaxies over cosmic time: the evolution of the kinematics and element abundances over cosmic time, how to measure them and how to use them to understand the processes involved in galaxy evolution.
- Angular momentum and large scale structure. The next decade will see a large increase of measured galaxy spins, allowing to tie back this fundamental parameter to the large scale structure surrounding galaxies and allowing to understand how it affects galaxy evolution.
- Interpretation and modeling through simulations: our improved understanding of galaxy evolution will be encoded in numerical simulations with varying treatments of

the physical processes involved in galaxy evolution, ultimately allowing to verify whether the large variety of relevant processes has been understood or not.

Resolved, half-resolved and integrated galaxies

Most of the light in galaxies is either directly emitted or reprocessed stellar light. Within the local group, these stars are visible one by one. However, single stars are not available for analysis in most galaxies, these being too far away. Over the last two decades, techniques have been developed to interpret the integrated light of stellar populations in galaxies, including the contributions of dust (absorption and emission) and the ionized interstellar medium. These techniques lie at the heart of our understanding of galaxy evolution, as only they allow to derive the galaxy properties from the observed light. The next decade will see very stringent tests of our capabilities to model integrated spectral energy distributions (SEDs) of galaxies by allowing spatially resolved studies with parsec resolution for a much greater volume than had hitherto been possible. For the first time, astronomers will have at the same time a full census of the stars in a region of a galaxy (from a colour-magnitude diagram), a full census of the ionized gas and dust (from emission line diagnostics) and an integrated spectrum showing the combined SED of all these components for tens of galaxies at a time. The new instrumentation making this possible consist of wide field integral field spectrographs (IFS) on the one hand. In the visible, the already commissioned MUSE@VLT is leading the field. The first wide field IFS in the near infrared will be commissioned soon (WIFIS@Kitt Peak), providing unprecedented access to red giant stars. Matching data for both HI and molecular gas can be obtained with increased survey speeds from both ALMA and NOEMA@IRAM. High angular resolution imaging of stars in galaxies is already available from the HST, with spatial resolution (and thus available volume) due to increase by a factor of ten (1000) with JWST and the ELT. In parallel, significant efforts will be invested in improving the interpretative modeling of stellar populations, ionized gas and other SED components to pin down the star formation and assembly histories of galaxies.

In the “era of Gaia”, the properties of single stars of the Milky Way and local group galaxies are measured in ever increasing detail and for larger and larger samples. This will allow to directly reconstruct the evolutionary history of the Milky Way, in particular its enrichment history. Together with the drastically improved diagnostic power of interpretative models, this revolution in our understanding of the processes involved in chemical evolution will directly influence our understanding of galaxy evolution, allowing to diagnose fundamental processes, such as gas accretion, matter redistribution within galaxies, galaxy merging and galaxy scale outflows.

Chemodynamics of galaxies over cosmic time

Over the last two decades, unique instrumentation and techniques have opened up the $z > 1$ Universe to direct “in-situ” observational studies. We now have a fairly robust outline of the evolution of the global galaxy properties over much of the Universe’s history, thanks to the statistical census of ever deeper lookback surveys of the integrated light and spectra of distant galaxy populations. To understand not only *when*, but also *how* galaxies assembled and transformed into the present-day Hubble Sequence, detailed spatially- and spectrally-resolved data of individual galaxies are critical, and the only means to achieve a comprehensive understanding of the physical processes at play. First glimpses of these processes have been obtained by mapping directly the motions, distribution of stars and star formation, cold molecular gas and dust reservoirs, large-scale galactic winds, and gas-phase chemical abundances within galaxies, down to physical scales of ~ 1 kpc and out to the peak epochs of cosmic star formation activity around 8 - 11 billion years ago. The next 10-20 years promise to revolutionize this area with: (1) further exploitation of newly commissioned and upcoming instruments at ESO VLT (e.g., KMOS, MUSE, ERIS+AO), at IRAM (NOEMA), and with ALMA, (2) JWST that will push such studies beyond z ~ 3 and into the epochs of reionization to z ~ 10, and (3) the next generation of 30-40m-class ground-based telescopes, including the E-ELT which, with the first-light instruments MICADO and HARMONI, will enable 10 times sharper views of distant galaxies than currently possible with any existing instrumentation.

Angular momentum and large scale structure

Galaxies acquire or loose angular momentum due to several processes. In the early universe, torques induced by the large scale structure on individual haloes should give an initial spin. This can subsequently be changed either gradually by accretion from the cosmic web or dramatically by merging of similar mass galaxies. Which of these processes dominate is unknown, with conflicting results on the observed and expected alignment between average galaxy spins and the density distribution of galaxies in the large scale structure. On the other hand, angular momentum should be a determining part of the properties of a galaxy. Low angular momentum material will concentrate in the center, making a bulge. High angular momentum material will form an extended disk. The connection between the Hubble sequence and the angular momentum history of a galaxy remains to be explored in detail. In the next decade, angular momentum will be added to the classical galaxy determinants mass and environment as a third parameter. Observational progress dominates this evolution, with the advent of large integral field surveys of local galaxies such as SAMI and MANGA, which are underway, and the planned Australian project HECTOR.

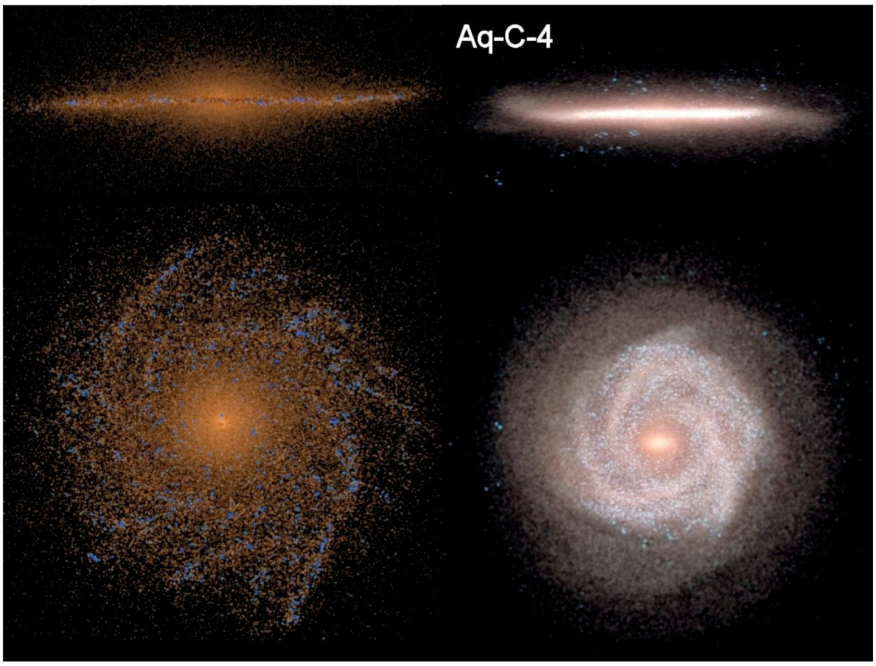
Interpretation and modeling through simulations

Simulations are powerful tools to compute the implications of cosmological assumptions and to test theoretical hypotheses about the physical processes occurring in galaxies. Future work will play a critical role in studying the energetic feedback processes that regulate star formation in galaxies, which are presently understood at best at a phenomenological level. It has yet to be established securely which physics is responsible for the apparent low efficiency of star formation in small galaxies, be it radiation pressure, cosmic rays, supernova driven turbulence, or any of the other numerous suggestions made in the literature. Likewise, it has yet to be shown how supermassive black holes quench star formation in massive galaxies, or whether it is completely different physics after all, say thermal conduction, just to name one of the potential alternatives that are still viable at some level. Understanding the feedback processes in galaxy formation and evolution is the principal challenge in this field. Solving it is unthinkable without further development of simulation methods. This is due to the multi-scale and multi-physics nature of the problem, which tends to limit analytic approaches for studying the problem to highly schematic and correspondingly uncertain models.

3. Key Results of the Previous Decade

Simulations of galaxy evolution

Over the previous decade simulations of galaxy formation have been particularly successful in two areas - understanding the relevant formation processes for individual galaxies (with high numerical resolution) with realistic morphological and kinematic properties and



simulating the formation and evolution of realistic galaxy populations, covering a wide range of masses, in large cosmological volumes. Key to the success was access to high-performance supercomputers and the development of advanced simulation software to make

Figure 1 Simulated disc galaxies from Aumer et al. (2014, left panel) and Marinacci et al. (2014, right panel). The figure shows that independent groups within Germany have reached the ability to simulate realistic disc galaxies in the last decade.

optimal use of these systems. In addition, in particular German groups have developed the necessary physical models for energetic feedback from newly formed massive stars and supermassive black holes which helped explaining the observed low formation efficiency of galaxies in the Universe. Although these models are still in their infancy (and need further development in the future) they have been used to solve a number of long standing and fundamental problems in galaxy evolution. Only recently it has become possible to simulate realistic spiral galaxies, like our own Milky Way, with correct masses, sizes, stellar population properties and gas distributions (Figure 1). The same is true for formation models of massive early-type galaxies whose evolution is significantly influenced by the formation, accretion and feedback from supermassive black holes. The resolution of the simulations has become high enough to make e.g. solid theoretical predictions for the internal gas and stellar kinematics, or the enrichment of the interstellar and circumgalactic medium with metals. These predictions have been used to interpret observations form e.g. integral field kinematic data or metal absorption lines in galactic halos.

Another breakthrough was the successful completion of cosmological galaxy formation simulations of large cosmological volumes with realistic properties of the simulated galaxy populations at various cosmological epochs. Not only do the simulated galaxies have masses and sizes in good agreement with observations but also the statistical mix of their gas content, formation histories, and stellar population properties are in good agreement with results from major observational surveys. These simulations have revealed unprecedented insight into the internal and environmental physical processes regulating galaxy formation and evolution. German groups are at the forefront of this research. It has to be pointed out that due to the highly complex and nonlinear physical processes involved in galaxy formation numerical simulations have become the major tool for theoretical progress in this field.

The physical properties of local galaxies

One of the most important scaling relations of galaxies links the central supermassive black hole masses to the properties of their host galaxies. German scientists have played key roles in studying this correlation. The specific relation between black hole mass and galaxy spheroid mass was established for the first time. Germany has been at the forefront in black hole mass determinations from stellar dynamics and in the determination of the morphological, dynamical and orbital structure of early type galaxies, highlighting the importance of mergers and black holes.

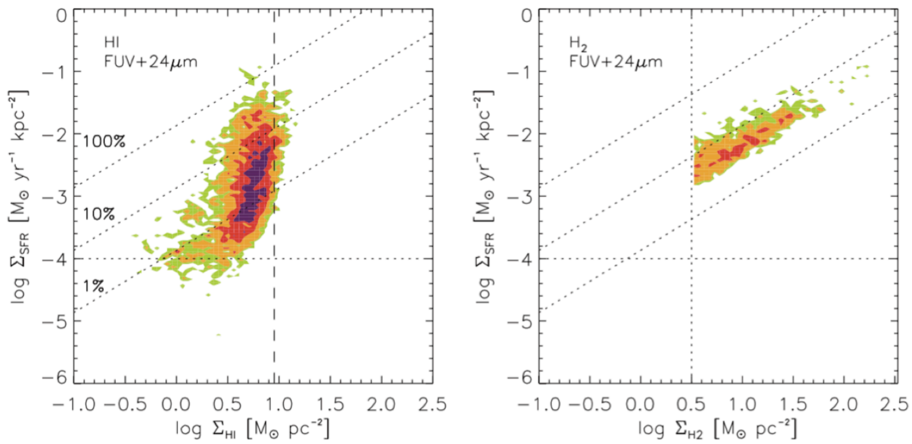


Figure 2 The correlation of star formatio rate with atomic Hydrogen gas (left panel) and molecular Hydrogren gas (right panel). Clearly, star formation correlates with the latter (Bigiel et al., 2008).

Germany has been leading several large surveys using IRAM and the VLA to understand the gas content in nearby galaxies and study its kinematics and influence on star formation. These surveys have allowed key results on the star formation law to emerge, in particular the fact that star formation correlates best with the molecular gas content, not the atomic gas. Major advances have also been made in assessing the importance of magnetic fields in galaxies. Observationally, the field strengths have been measured and specific geometries associated with galaxy structure have been found (e.g. following spiral arms). Improvements of dynamo models have produced clear predictions that could be tested in the future.

The last decade has seen a fundamental shift in the kind of optical / NIR data used to study the physical properties of local galaxies. Before, data were either „imaging“ or „spectroscopy“, severly limited in either spatial or spectral resolution. The field has

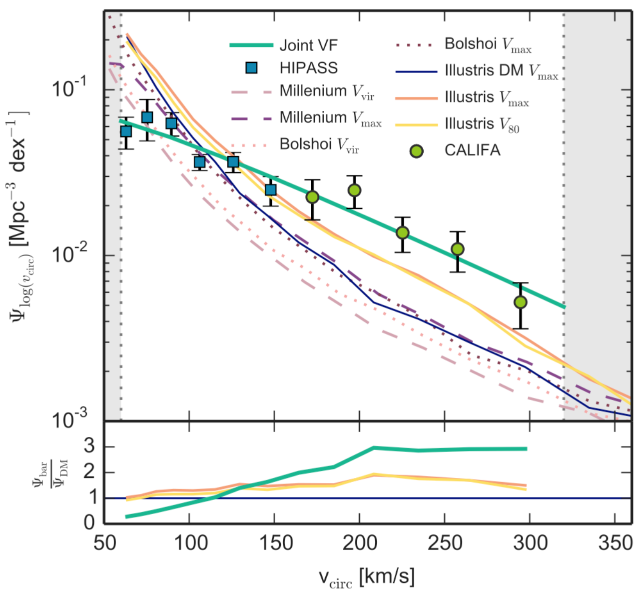


Figure 3 The first measurement of the velocity function valid in the range 60 to 320 km/s (Bekeraite et al., in prep.). The data points (squares, circles and green line) were derived from gas (HIPASS) and stellar (CALIFA) kinematics. Clearly simulations (colored lines) do not yet match observations in this important galaxy statistic.

now shifted to imaging spectroscopic data, i.e. using images with good spatial resolution and simultaneously very good spectral resolution. Germany has played a world leading role in this development, with leadership roles in the instrumentation development for PMAS, SINFONI, VIRUS-W, KMOS, and MUSE. These instruments have been used in pioneering projects that study the spatially resolved stellar and ionized gas properties for truly large samples of nearby galaxies. German-led fundamental results from these studies include a quantification on the possible link between the kinematic structures of early-type galaxies and their formation history. More results are appearing as this white paper is being written, such as the first measurement of the galaxy velocity function (Figure 2) or the first successful orbit decompositions of spiral galaxies from Schwarzschild modeling.

The evolution of the kinematics, structure, and gas properties properties of galaxies

Multi-wavelenth imaging surveys with German lead or key participation have allowed to study for the first time the evolution of the luminosities, colors and sizes of galaxies for large samples of galaxies over significant redshift ranges. These studies have shown the existence of passive, red galaxies at redshifts above 1, with a strong evolution towards smaller sizes at lager redshifts. The size evolution for late type galaxies is much less pronounced, with stable disks likely forming between redshifts 2 and 1.

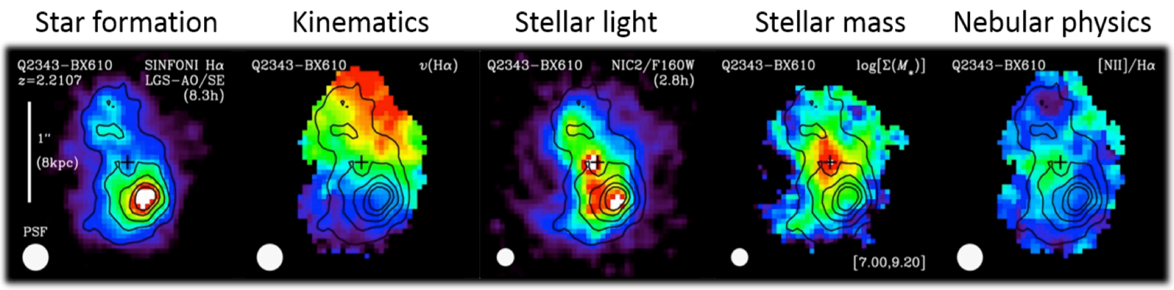


Figure 4 Different views of a massive star-forming galaxy at z = 2.21, Q2343-BX610, revealed by VLT/SINFONI+AO observations in the K band (~ 2.2μm), complemented with HST J and H band imaging. With a FWHM of ≈ 0.2″, the data resolve detailed structures on ~1.5 kpc scales. They reveal that this object is a regularly rotating disk galaxy, as well as the presence of an outflow driven by a low-luminosity AGN. Based on data presented by Genzel et al. (2014a) and Tacchella et al. (2015a).

Ground-breaking advances in this area over the past decade have come from two major European facilities with substantial German involvement: the ESO Very LargeTelescope (VLT) and the IRAM (sub-) millimeter Plateau de Bure Interferometer (PdBI), now NOEMA. Integral field spectrometers at the VLT, first SINFONI and now also KMOS and MUSE, have enabled mapping of the detailed distribution, motions, and physical properties of warm ionized gas within galaxies -- tracing star formation, shocks, and AGN -- for increasingly large and representative samples to z ~ 3.5 (Figure 4). Pioneering observations with PdBI/NOEMA, recently also with the ALMA interferometer, have started to bring resolved studies of the cold molecular gas and dust of distant star-forming galaxies on par with those of their ionized gas. In parallel, high-resolution imaging surveys with optical/near-infrared cameras on-board the Hubble Space Telescope (HST) have revealed the detailed stellar structure of distant galaxies, an important complement to the gaseous components. Among key highlights, these in-situ studies have (1) established prevalence of disks - rather than (major) mergers - among the bulk of star-forming galaxies out to at least z ~ 3, their increasing gas content and turbulence as a function of lookback time, and the importance of internal galaxy dynamics in growing early disks and bulges, (2) revealed the central role of the cold gas reservoirs in driving the star formation activity and gas turbulence of galaxies,

(3) enabled the first empirical connections between baryons in galaxies and their host dark matter halos, including through their angular momenta, (4) unveiled the nature, ubiquity, and energetics of powerful gas outflows driven by star formation and accretion onto supermassive black holes, (5) shown first evidence for the importance of this strong feedback in redistributing metals across disk galaxies, and (6) brought unique new insights into the mechanisms responsible for the rapid quenching of star formation at high galaxy masses, via powerful galactic-scale winds efficiently expelling gas out of galaxies and gravitational stabilization of the gas disks by young massive bulges preventing fragmentation into star-forming complexes. These results provided some of the essential observational foundations for the recently emerging "equilibrium growth" picture, wherein the balance between fairly smooth and continuous accretion of gas, star formation, and gas outflows tightly regulates the evolution of galaxies.

4. Particular Role/Strengths of Research Groups in Germany

The German galaxy evolution community is dominated by research institutes, with very few large groups residing at universities. The strong observational groups present at MPE, USM, MPIA, MPIfR and AIP lead vigorous instrumentation programmes. This provides them with large allocations of Guaranteed Time Observations and/or privileged facility access, which is one key to success by allowing comprehensive and coherent scientific programs to be carried out, while at the same time building unique technical and scientific expertise within Germany. These groups are then also able to leverage this strong standing into large time allocations at other observatories, such as e.g. HST. The larger theoretically oriented groups are centered at MPA, USM, and ZAH/HITS, fueled again by long-term development of strong, coherent research groups and significant investments into computational facilities and code bases.

To further improve the standing of galaxy evolution studies within Germany, a stronger role of university institutes in galaxy evolution would be desirable. German universities on average have a more prominent role in other, closely related topics such as Milky Way studies or the Interstellar Medium. Also, as described in Section 2, interpretative modeling of observational data is the key to our understanding of galaxies. While Germany has very strong groups in dynamical modeling of galaxies, the same cannot be said for stellar population models. Investment in this areas could even further improve the already impressive record in harvesting instrumentation investments.

5. Key Infrastructures needed/relevant for Researchers in Germany

Observational infrastructure

Continued access to world-class instrumentation is key to continue playing a leading role in observational studies of galaxy evolution. The scientific opportunities described in Section 2 are driven by access to the major projects of the next decade. JWST and the ELT will improve the spatial resolution of imaging by up to one order of magnitude. This is both necessary to study the stellar populations of galaxies in sufficient detail to compare them directly to integrated spectroscopy as well as crucial in the study of the structural evolution of galaxies over cosmic time. The latter will also significantly profit from the HST-like spatial resolution offered by Euclid for truly large samples of galaxies. The next generation of NIR imaging spectrographs (NIRSPEC@JWST, HARMONI@ELT) will push measurement of the motions of gas and stars as well as the distribution of star formation to redshifts above 3. High multiplex imaging spectroscopy with MOSAIC@ELT will be the next step, obtaining these measurements for large samples. Simultaneous access to ALMA and NOEMA@IRAM will provide data at matching spatial resolution to determine the gas reservoirs fueling the star formation both at high and low redshifts. Much of the instrumentation required to carry out these programs is built and operated by ESO. Continued support for IRAM is clearly essential as well.

In particular at radio frequencies, the ngVLA will provide very high spatial resolution, while the sensitivity gains of the SKA will revolutionize our HI maps of the universe.

Currently Germany has no share in a high multiplex integral field spectroscopic survey machine beyond the on-going MANGA and SAMI surveys. Such projects are being pursued elsewhere though (WEAVE, HECTOR). A German participation in this development would capitalize on the past successes and the expertise built, and provide crucial science return for the understanding of galaxy evolution.

Computing infrastructure

Computing infrastructure both at the tier-0 level (leadership class facilities that are competitive with the largest supercomputers in the US and elsewhere) and at smaller regional and university centers (tier-1, tier-2) is needed to provide access to sufficient CPU cycles to carry out state-of-the-art simulations of galaxy formation and evolution. The physical nature of the problem is characterized by long-range coupling through gravity, defeating embarrassingly parallel approaches. Instead, high-performance parallel computers that excel in communication latency and bandwidth between the different compute elements are critically needed. Also, the requirement to model a huge number of degrees of freedom demands large memory and massive disk systems to store complex simulation models for scientific analysis. These requirements are currently best met by general purpose machines with a high single-core performance, large memory per core, fast parallel I/O subsystems, and specialized high performance communication networks. The technological difficulties associated with developing next generation “exaflop” supercomputers may well lead to much more specialized machines that support only narrower classes of scientific fields. It will therefore be important to ensure that sufficiently versatile, leading-edge computing platforms suitable for galaxy formation and evolution continue to be deployed in Germany.

It has become evident in recent years that the traditional approach to software development in the field has become a severe bottleneck for fully exploiting the potential of simulation methods in galaxy formation and evolution. In the past, simulations codes in astrophysics have typically been developed by graduate students “on the side”, either alone or in small teams. Development projects have been driven by the needs of the immediate scientific projects of the involved scientists, typically with little strategic planning and even less considerations of principles of modern software design. This mode of operation has been ingrained in the field also by a lack of systematic funding of simulation code development and a reluctance to give scientific credit to such work. Nowadays, current simulation codes in galaxy formation approach millions of lines. They rapidly become impossible to maintain and advance further without a professionalisation of simulation code development and, importantly, the creation of new funding lines to support teams of computational astrophysicists that systematically advance the increasingly complex simulation packages.

Even a modest investment in this area (still small compared to the cost of the hardware) may well lead to a strategic advantage of the German community relative to competitors abroad.

Strong research groups

With major German investments into JWST and Euclid, continued competitive funding for science exploitation of these observatories is a necessity.

As stated in Section 4, the German galaxy evolution community is distributed over several larger (mainly) non-university institutes, as well as several smaller university groups. There is huge scientific potential in intensifying the connections between observations and simulations, as well as in the study of galaxy chemodynamics at different redshifts. Connections to other areas such as X-ray studies of galaxy clusters are equally improtant. A modest investment fostering collaborations between the relevant groups would allow to exploit this potential.

6. Summary and Conclusion

The German galaxy evolution community has a world leading role in several areas of galaxy evolution. This strong standing is the result of privileged access to instrumentation and computing facilities, as well as of strong groups with specific core expertise. The participation of the German community in future large infrastructure projects, such as e.g. the ESO ELT, is pivotal for continuing these trends into the future. New investments in particular in the area of computational infrastructures will further capitalize on the current excellent standing. It would be desirable the increase the role of universities in the field to levels more comparable to other areas of astronomical research.