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Investigating the Formation and Evolution of Massive Disc Galaxies with the MUSE TIMER Project

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The Time Inference with MUSE in Extragalactic Rings (TIMER) project is a survey using the integral-field spectrograph Multi Unit Spectroscopic Explorer (MUSE) on the VLT to study 24 nearby barred galaxies with prominent central structures, such as nuclear rings or inner discs. One of our main goals is to estimate the cosmic epoch when galaxy discs settle, leading to the formation of bars. This is also the onset of a phase in the history of the Universe during which secular evolution processes in galaxies become important. We illustrate the quality of the data with some first results and describe the legacy potential of the survey.

Timing a phase transition in galaxy evolution

In the nearby Universe, discs of massive spiral and lenticular galaxies show orderly dynamics, dominated by differential rotation and a relatively smooth rotation curve. However, this has not always been the case. At earlier cosmic epochs, at redshifts $z \sim 1$–2, discs were characterised by turbulent dynamics and a clumpy, irregular structure (for example, Förster Schreiber et al., 2006; Law et al., 2009). When and how did this transition happen? When and how do galaxy discs settle dynamically? The main goal of the TIMER project is to answer these questions.

We look for answers by investigating the archaeological evidence in nearby barred galaxies. Theoretical work suggests that bars can only form after the dynamical settling of the disc, or at least part of it. In addition, the formation of the bar will often happen a few hundred million years after the disc settles. Furthermore, on a similar timescale after the formation of the bar, the non-axisymmetric potential introduced by the bar produces tangential forces across the disc, which cause the cold gas in the interstellar medium (ISM) to shock, lose angular momentum and funnel down into the central region. The final fate of the gas is to form central stellar structures, such as nuclear rings, nuclear spiral arms, inner discs and inner bars. This is corroborated by both theoretical and observational work (for example, Buta & Combes, 1996).

The oldest stars in such bar-built stellar structures hold fossil evidence of the time at which the bar first brought gas to the centre; the ages of these oldest stars tell us directly how long ago the first bar-driven gas accretion event took place. This, in turn, gives us an estimate of the time of both bar formation (i.e., the age of the bar) and disc settling.

MUSE is perfectly suited to addressing these questions; its relatively large field of view, combined with the fine spatial sampling and large spectral coverage, allows a detailed derivation of the stellar population properties and kinematics across all stellar structures in the central region.

A proof of concept

We provided a proof of concept for the methodology outlined above during the first MUSE Science Verification campaign in 2014, when we collected data on the central region of NGC 4371, a nearby barred galaxy with a bar-built nuclear ring and inner disc (see Gadotti et al., 2015). We showed that these structures are dominated by stars that are older than 10 Gyr, with an uncertainty of about 0.8 Gyr based on Monte Carlo realisations. This sets a lower limit to the redshift at which the disc in NGC 4371 settled dynamically and developed a bar, in the range $1.4 \leq z \leq 2.3$.

At first sight, this is a surprisingly old bar, given the earlier difficulties with finding barred galaxies in the distant universe. However, while the fraction of disc galaxies with bars drops from about 70% at $z \sim 0$ to about 20% at $z \sim 1$, Simmons et al. (2014) present evidence suggesting that at least 10% of disc galaxies at $z \sim 2$ are strongly barred.

In addition, in the downsizing framework of galaxy evolution, more massive discs are expected to settle first and form bars first (Sheth et al., 2012), and the fact that NGC 4371 is a massive disc galaxy — at $6.3 \times 10^{10}\ M_{\odot}$ it is more massive than the Milky Way — is consistent with this picture. Incidentally, our results show that bars can be long lived (also see Seidel et al., 2015 for further evidence of long-standing bars).

The TIMER project

The Time Inference with MUSE in Extragalactic Rings (TIMER) project[1] is the fully-fledged version of our Science Verification programme, targeting 24 nearby galaxies (d < 40 Mpc) with a range of physical properties (Gadotti et al., 2018). Most importantly, the TIMER sample spans one order of magnitude in stellar mass, which allows us to test the downsizing picture in which more massive discs settle first. All 24 galaxies are barred, with different degrees of bar strength, and all host prominent bar-built central stellar structures, such as nuclear rings, nuclear spiral arms, inner discs and inner bars. Table 1 presents the full TIMER galaxy sample with some of their fundamental properties.

Galaxy	Type	Inclination degrees	Mass $10^{10}\,M_\odot$	Distance Mpc	Galaxy	Type	Inclination degree	Mass $10^{10}\,M_\odot$	Distance Mpc
IC 1438	(R$_1$)SAB$_a$(r'l,nl)0/a	24	3.1	33.8	NGC 4394*	(RL)SB(rs,bl,nl)0/a	30	2.8	16.8
NGC 613	SB(rs,bl,nr)b	39	12.2	25.1	NGC 4643	(L)SB(rs,bl,nl)$0^{0/+}$	44	10.7	25.7
NGC 1097	(R')SB(rs,bl,nr)ab pec	51	17.4	20.0	NGC 4981	SAB(s,nl)bc	54	2.8	24.7
NGC 1291	(R)SAB(l,bl,nb)0^+	11	5.8	8.6	NGC 4984	(R'R)SAB$_a$(l,bl,nl)0/a	53	4.9	21.3
NGC 1300	(R')SB(s,bl,nrl)b	26	3.8	18.0	NGC 5236	SAB(s,nr)c	21	10.9	7.0
NGC 1365	(R')SB(rs,nr)bc	52	9.5	17.9	NGC 5248	(R')SAB(s,nr)bc	41	4.7	16.9
NGC 1433	(R'$_1$)SB(r,p,nrl,nb)a	34	2.0	10.0	NGC 5728	(R$_1$)SB(r'l,bl,nr,nb)0/a	44	7.1	30.6
NGC 1512*	(RL)SB(r,bl,nr)a	43	2.2	12.3	NGC 5850	(R')SB(r,bl,nr,nb)ab	39	6.0	23.1
NGC 2903*	(R')SB(rs,nr)b	61	4.6	9.1	NGC 6902	(R')SAB(rs,nl)ab	37	6.4	38.5
NGC 3351	(R')SB(r,bl,nr)a	42	3.1	10.1	NGC 7140	(R')SAB$_x$(rs,nrl)ab	51	5.1	37.4
NGC 4303	SAB(rs,nl)bc	34	7.2	16.5	NGC 7552	(R'$_1$)SB(rs,bl,nr)a	14	3.3	17.1
NGC 4371	(L)SB$_a$(r,bl,nr)$0^{0/+}$	59	3.2	16.8	NGC 7755	(R')SAB(rs,nrl)bc	52	4.0	31.5

Table 1. Some fundamental properties of the full TIMER sample: morphological classification, inclination with respect to the plane of the sky, stellar mass, and redshift-independent distance. See Gadotti et al. (2018) for details. Galaxies marked with * are still to be observed.

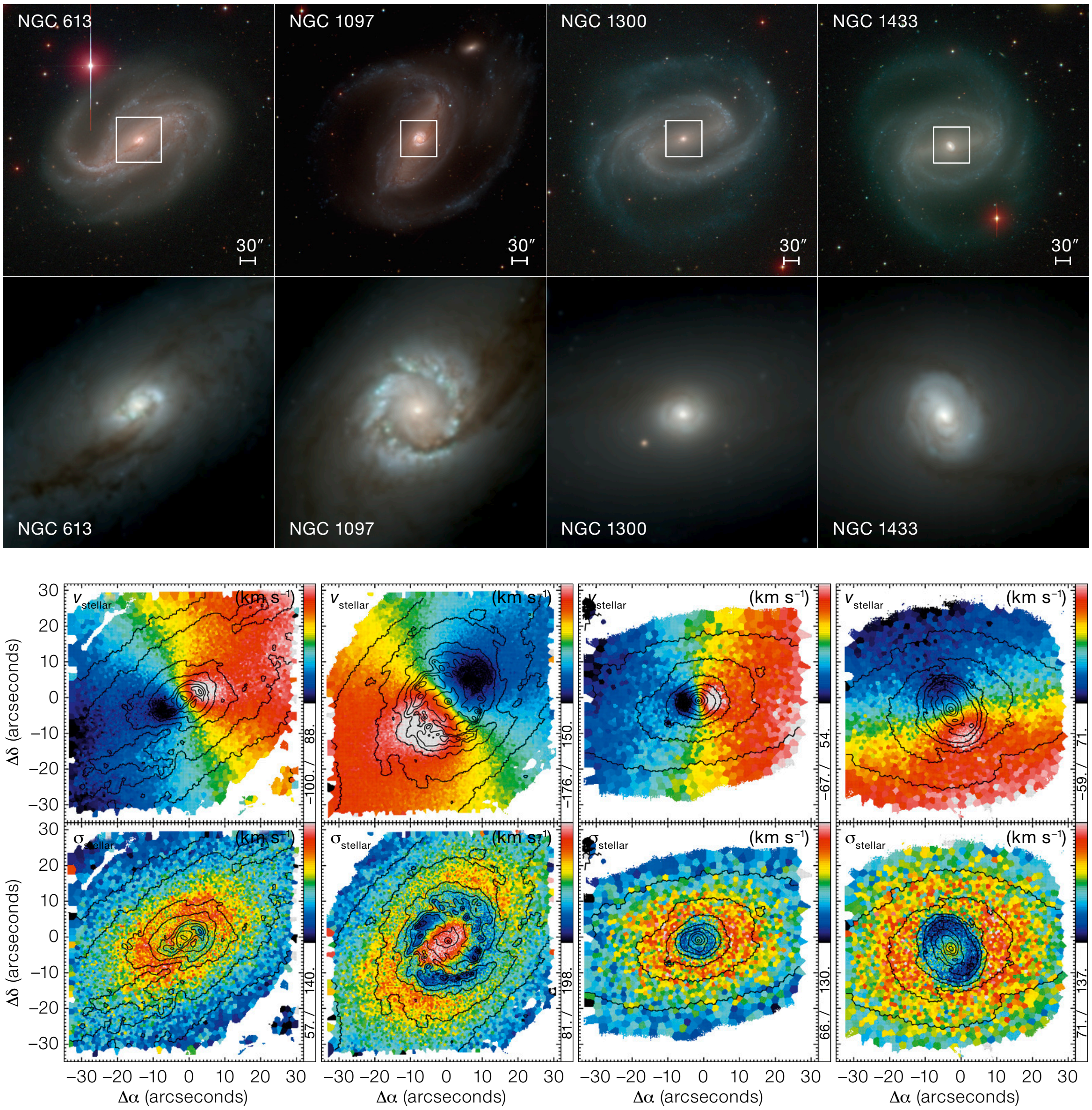

Figure 1. Various properties of four galaxies in the TIMER sample are shown here. Upper row: large-scale colour-composites from the Carnegie-Irvine Galaxy Survey[2] (Ho et al., 2011) — the white squares indicate our MUSE fields. Second row from top: colour composites derived from our MUSE data cubes of the inner one square arcminute. Third row from top: maps of the stellar radial velocity. Lower row: maps of the stellar velocity dispersion (units are km s^{-1}). The isophotes shown are derived from the MUSE data cube reconstructed intensities and are equally spaced in steps of about 0.5 magnitudes.

The top row of Figure 1 shows four examples of galaxies in the TIMER sample. We targeted the central 1 × 1 square arcminute of each galaxy (typically 6 × 6 kpc), with dedicated background exposures and a total integration time of typically one hour on source. The typical image quality of the data is between 0.8 and 0.9 arcseconds, and most of the data were taken during ESO Period 97. After employing the ESO data reduction pipeline to remove instrumental and background features, and to calibrate the raw data, we used a method based on principal component analysis to further remove residual background emission. Colour composites built directly from the MUSE data cubes are shown in Figure 1 (second row from top). These composites attest to the superb imaging quality of the instrument.

Stellar kinematics and dynamics

In order to study the stellar kinematics and dynamics, the fully reduced cubes were Voronoi binned[a] to ensure a minimum signal-to-noise ratio per spatial bin of forty. However, the TIMER cubes contain so much signal that many spaxels remain unbinned, and each of the cubes still contains tens of thousands of spatial bins. In Figure 1 we show maps of velocity and velocity dispersion, illustrating the fine spatial sampling of the data and the richness of detail and information that can be derived.

The velocity maps show that the central stellar structures identified photometrically as bar-built components are indeed dominated by stars in near-circular orbits, as expected, with line of sight velocities higher than those of stars in the underlying disc. This is also reflected in the low values of velocity dispersion shown in these structures (bottom row in Figure 1), and implies that the photometric and kinematic pictures are consistent.

We made an unexpected discovery when examining in detail the line of sight velocity distributions (LOSVDs) in the inner bar of the face-on double-barred galaxy NGC 1291. In Méndez-Abreu et al. (2018) we show that the changes in the kurtosis of the LOSVDs along the major axis of the inner bar are such that they can only be explained if the inner bar has buckled. Bar buckling is a process commonly seen in large-scale bars but this is the first time it is seen in an inner bar. This is remarkable, as it shows that inner bars are essentially governed by the same dynamical processes as large-scale bars, despite being substantially shorter.

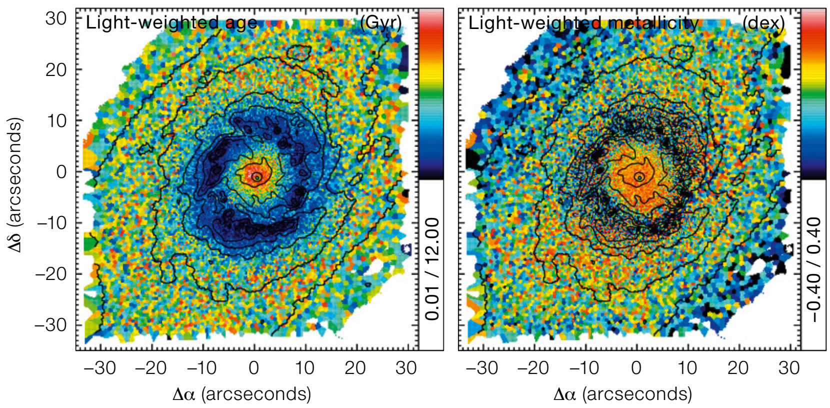

Figure 2. Maps of light-weighted mean stellar age and (left) metallicity (right) for the central square arcminute of NGC 1097.

Stellar ages and metallicities

Full spectral fitting allows us to derive spatially resolved star formation histories of all stellar structures seen in our MUSE fields. As described above, the star formation histories of the bar-built structures give an indication of the cosmic epoch in which discs settle dynamically and bars form. While this is a challenging enterprise, the first step — deriving mean stellar ages and metallicities — is more robust.

In Figure 2 we show the light-weighted maps of mean stellar age and metallicity for NGC 1097. They show an old, metal-rich nuclear component within a few arcseconds of the centre, and the much younger, metal-poor nuclear ring. The fact that the metallicity inside the ring radius is substantially higher than that in the ring itself, shows that nuclear rings can very efficiently halt the inflow of gas from the bar. In Gadotti et al. (2015, 2018) we show that bar-built central structures can display a wide range of stellar ages and metallicities. This is an important result since it means that not necessarily all stellar structures built via bar-driven secular evolution processes are young, as initially thought. The case of NGC 4371 is clear; the bar formed at $z \sim 1.8$ and then swiftly formed the nuclear ring and inner disc that only passively evolved afterwards, since the gaseous content within the bar radius was depleted by the bar and not replenished further. The absence of further gas infall to the galaxy is likely to be a result of environmental effects in the core of the Virgo cluster, where the galaxy is.

Spatially resolved star formation histories

One of the most powerful aspects of integral-field spectroscopy is the combination of photometric and spectroscopic information. We are currently performing sophisticated structural decompositions using deep ancillary imaging data from the Spitzer Space Telescope, including a number of structural components beyond bulge, disc and bar (for example, inner discs, inner bars, lenses, and disc breaks) and carefully masking structures that are not modelled, such as rings. This allows us to determine which spaxels in our MUSE data are dominated by each stellar structure, which in turn helps to more accurately determine the stellar population content and the star formation history of each stellar structure separately. This is undoubtedly a powerful tool for shedding light on the assembly history of massive disc galaxies.

Following this approach, in de Lorenzo-Cáceres et al. (2018) we study the formation of the inner bars, inner discs and other central structures in the double-barred galaxies NGC 1291 and NGC 5850. We find evidence suggesting that these inner bars are long-lived and formed at least ~ 6 and ~ 4 Gyr ago, respectively. The TIMER data also indicate that the inner bars are formed from a dynamical instability in the inner disc, just like their outer bars but at a smaller spatial scale.

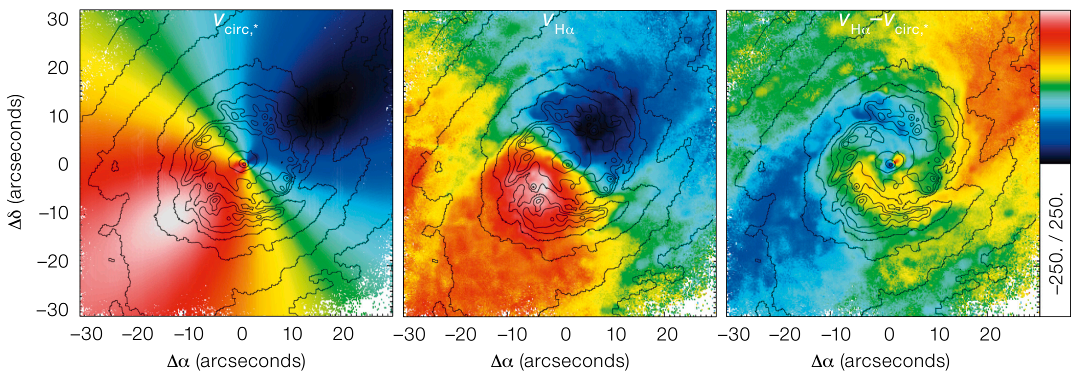

Figure 3. Jeans stellar dynamical model circular velocity field (left), unbinned Hα velocity field (centre), and the difference between both (right) for NGC 1097. The colour scale units are km s^{-1}.

Ionised gas properties, kinematics and dynamics

In all TIMER galaxies we detect a number of optical emission lines from ionised gas, which can be used to assess which processes are causing the ionisation of the interstellar medium (ISM), as well as a number of other physical properties, such as electron density and temperature, and gas metal content. Only one galaxy has ionised gas produced exclusively by star formation; most galaxies have their centres dominated by ionisation similar to that seen in low-ionisation nuclear emission-line regions (LINERs), and two are broad-line, type 1 active galactic nuclei (AGN).

We can also use the emission lines to study the kinematics of the warm, ionised gas, and physical processes other than gravity affecting its dynamics. Figure 3 illustrates how we detect and measure the inflow of gas along the leading edges of bars, where the gas shocks and loses angular momentum. The left panel shows the circular velocity field derived from modelling the stellar dynamics in NGC 1097 (after correcting for asymmetric drift), while the middle panel shows the observed velocity field of the gas. The right panel is produced by subtracting the dynamical model from the gas velocity field, and thus shows deviations from circular speed in the motions of the gas. Such deviations are associated with non-gravitational motion, and, in this case, clearly show the inflow of gas via the bar, feeding star formation in the nuclear ring.

AGN and stellar feedback

The central region of a disc galaxy is home to a number of physical processes that are fundamental to galaxy evolution. It is there that supermassive black holes reside and trigger AGN, which in turn may cause AGN feedback, having a strong effect on the physical properties of the ISM in the galaxy and the circumgalactic medium in its immediate surroundings. AGN feedback may alter star formation histories, the building of central stellar structures and patterns of chemical abundance in and outside galaxies.

Additionally, nuclear rings are often sites of elevated star formation rates and this is seen also in some of the galaxies in the TIMER sample. These sites host young massive stars and are the locations of supernova explosions, both at the root of the stellar version of feedback processes into the ISM.

It is no surprise then that the TIMER data can help shed light on AGN and stellar feedback, as well as other astrophysical problems beyond the main scope of the project. In fact, the top panels of Figure 4 show the powerful bi-conic outflow seen in [O III] produced by the AGN in NGC 5728. MUSE provides a view of this system in unprecedented detail.

The bottom panels of Figure 4 illustrate our serendipitous discovery of stellar feedback from the star-bursting nuclear ring in NGC 3351. Our data show expanding bubbles of warm gas (emitting in Hα) emerging from the nuclear ring, which in some places has a star formation rate surface density reaching 20 $M_{\odot}$ yr^{-1} kpc^{-2}. With ancillary ALMA data (from Principal Investigator Karin Sandstrom, see Figure 5), we see that the Hα is confined within a dense molecular gas shell perpendicular to the bar major axis, which is also a region with elevated dust content. The neighbouring warm gas shows high velocity dispersion (up to 150 km s^{-1}), and with dynamical models we show that it is expanding radially away from the ring at speeds of up to 70 km s^{-1} just inside the molecular gas feature (Figure 5).

Such a strong gas and dust shell perpendicular to the bar major axis is not reproduced by hydrodynamical simulations of barred galaxies without feedback. Given the observed properties described above, we propose in Leaman et al. (2018) the idea that the molecular band was pushed outwards from the region of the nuclear ring by stellar feedback processes. Consistent with this picture, the ALMA data show that the molecular shell has peculiar dynamics and a relatively high velocity dispersion.

A strong legacy

TIMER's rich dataset is allowing us to explore a number of other astrophysical problems, including:
1. star formation and stellar populations in primary bars;
2. the star formation desert in barred galaxies;
3. the connection between box/peanuts and barlenses;
4. stellar migration in disc galaxies;
5. the location of nuclear rings with respect to the inner Lindblad resonance;
6. gas shear and shocks along bars;
7. the excitation states of the ionised gas in the ISM;
8. the initial mass function across disc galaxies.

Furthermore, forthcoming observations of TIMER galaxies with the MUSE Narrow-Field Mode will help us understand how

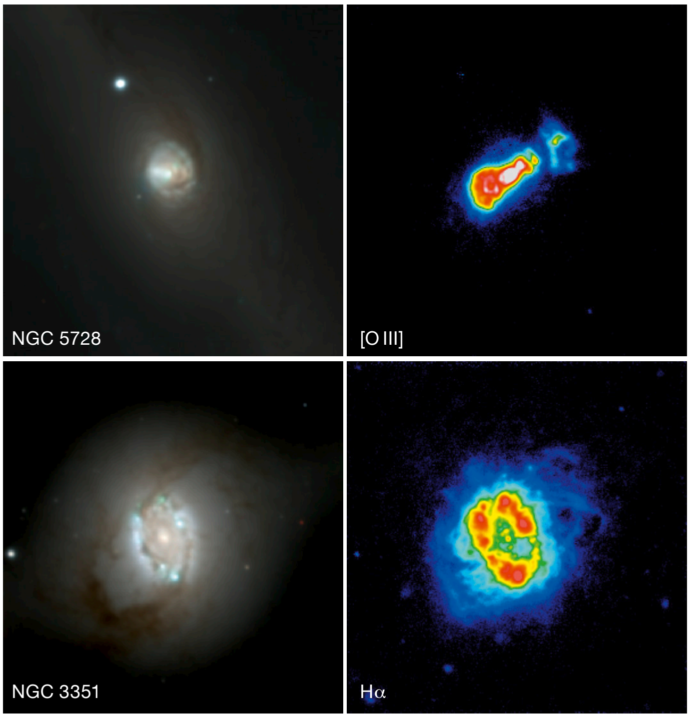

Figure 4. (Left) Colour-composites images from the TIMER MUSE data cubes for NGC 5728 and NGC 3351, as indicated. (Right) Continuum-subtracted images of [OIII] emission (upper: NGC 5728) and Hα emission (lower: NGC 3351).

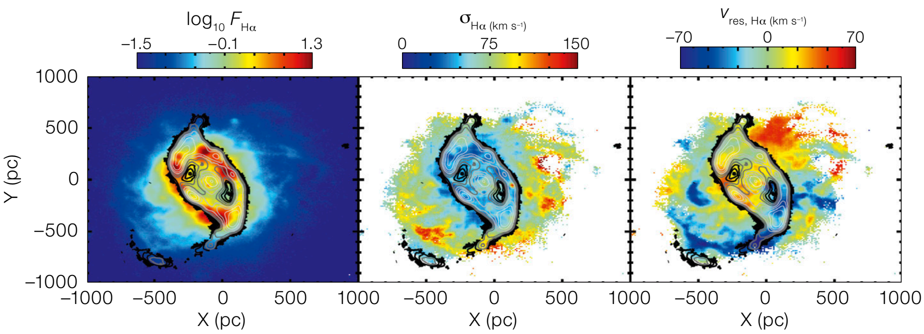

Figure 5. Hα flux (left), velocity dispersion (middle) and residual velocity (right) fields of NGC 3351 are shown in the colour scale. The velocity fields are built by subtracting a dynamical model of the circular speeds from the Hα velocity field. The ALMA CO(1–0) intensity map is overlaid as contours, and clearly encloses the ionised outflows to the south-west of the nuclear ring.

the inflow of gas via primary and inner bars proceeds from kiloparsec scales down to parsec scales, approaching the supermassive black hole.

Another exciting window that opens up with TIMER is the possibility to work in tandem with other revolutionary facilities such as ALMA, as has already been demonstrated above. By combining MUSE and ALMA observations of nearby galaxies, it is now possible to connect, at high angular resolution, the cause and effect of star formation (including molecular gas and young stellar populations), as well as monitoring their interplay in the form of stellar feedback. Moreover, we can probe that connection spatially and kinematically at the same time, which can help to understand the cycling of ISM phases and their associated timescales. AGN feedback can also be explored simultaneously at these different phases of the ISM, bridging the gap between ionised and molecular outflows. These observables are crucial to inform galaxy-scale hydrodynamical simulations, which often assume simple analytic prescriptions for the conversion of gas into stars and for the various forms of feedback.

The policies governing the project are such that collaborations with experts outside the team are encouraged, and interested parties should contact the Principal Investigator, Dimitri Gadotti.

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References

Buta, R. & Combes, F. 1996, Fundamental Cosmic Physics, 17, 95
Förster Schreiber, N. et al. 2006, ApJ, 645, 1062
Gadotti, D. A. et al. 2015, A&A, 584, A90
Gadotti, D. A. et al. 2018, MNRAS, in press
Ho, L. et al. 2001, ApJS, 197, 21
Law, D. R. et al. 2009, ApJ, 697, 2057
Leaman, R. et al. 2018, submitted to MNRAS
de Lorenzo-Cáceres, A. et al. 2018, submitted to MNRAS
Méndez-Abreu, J. et al. 2018, submitted to MNRAS
Seidel, M. S. et al. 2015, MNRAS, 446, 2837
Sheth, K. et al. 2012, ApJ, 758, 136
Simmons, B. et al. 2014, MNRAS, 445, 3466

Links

[1] TIMER Project: https://www.muse-timer.org/
[2] The Carnegie-Irvine Galaxy Survey (CGS): https://cgs.obs.carnegiescience.edu/CGS/Home.html

Notes

[a] Voronoi binning is an an algorithm that bins two-dimensional data in such a way as to ensure a constant signal-to-noise ratio per bin, optimally preserving the spatial resolution of the data.