ELT - MICADO

Phase B

MICADO Science Case

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Acronyms

This document employs several abbreviations and acronyms to refer concisely to an item, after it has been introduced. The following list is aimed to help the reader in recalling the extended meaning of each short expression:

AGN	Active galactic nuclei
CaT	Ca II triplet
CMD	Colour-magnitude diagram
ETG	Early type galaxy
FWHM	Full-width half maximum
HST	Hubble Space Telescope
IMBH	intermediate mass black hole
IMF	Initial Mass Function
JWST	James Web Space Telescope
LMC	Large Magellanic Cloud
MAORY	Multi-conjugate Adaptive Optics Relay
mas	milli-arcsecond
MBH	Massive black hole
MCAO	Multi-conjugate adaptive optics
MW	Milky Way
PSF	Point Spread Function
QSO	Quasi-stellar object
RGB	Red Giant Branch star
SCAO	Single-conjugate adaptive optics
SFR	Star formation rate
SFG	Star forming galaxy
SFH	Star formation history
Sgr	Sagittarius
SMC	Small Magellanic Cloud
S/N	Signal-to-noise
µas	micro-arcsecond

1 Scope

This document highlights the major science areas that will benefit from the MICADO imaging spectrograph on the ELT. MICADO will include both SCAO and MCAO imaging modes as well as spectroscopy. Many of the imaging examples are supported by SimCADO simulations. This is not a document to set out the GTO priorities. The aim is to cover a wide range of important science cases to demonstrate the capabilities of MICADO. In addition, this document aims to highlight that the capabilities of MICADO, MAORY and ELT must all remain sufficient to carry out these studies.

2 MICADO Science capabilities

MICADO is designed to work between 0.8-2.4microns, with the assistance of a single or multi-conjugate adaptive optics system (developed with & by MAORY respectively) at the diffraction limit of the ELT. The primary mode is imaging (see **Figure 2.1a**), with an emphasis on astrometry. In the MCAO mode there is a wide field option, where the field of view will be ~50" square with a pixel scale of 4mas. There is also a zoom mode with a finer 1.5mas pixel scale over ~20" field of view. MICADO images will provide comparable sensitivity to JWST (James Webb Space Telescope) at 6 times better spatial resolution, and enable proper motions as small as 5km/s to be measured at distances of up to 100kpc. The SCAO mode will provide good performance over a smaller region for a wide range of conditions; and in many cases the PSF is expected to keep a diffraction limited core over the full MICADO field of view. The primary use of SCAO is envisaged to be high contrast imaging. In addition, SCAO will enable sensitive detailed imaging of crowded fields and compact objects, albeit over small fields of view. MICADO also includes a long-slit spectroscopic mode (see **Figure 2.1b**) that is optimised for compact objects, with extended wavelength (0.83–2.45micron) coverage at moderately high spectral resolution (R~20k for point sources). These capabilities make a wide range of break-through science cases feasible (see **Figure 2.2**).

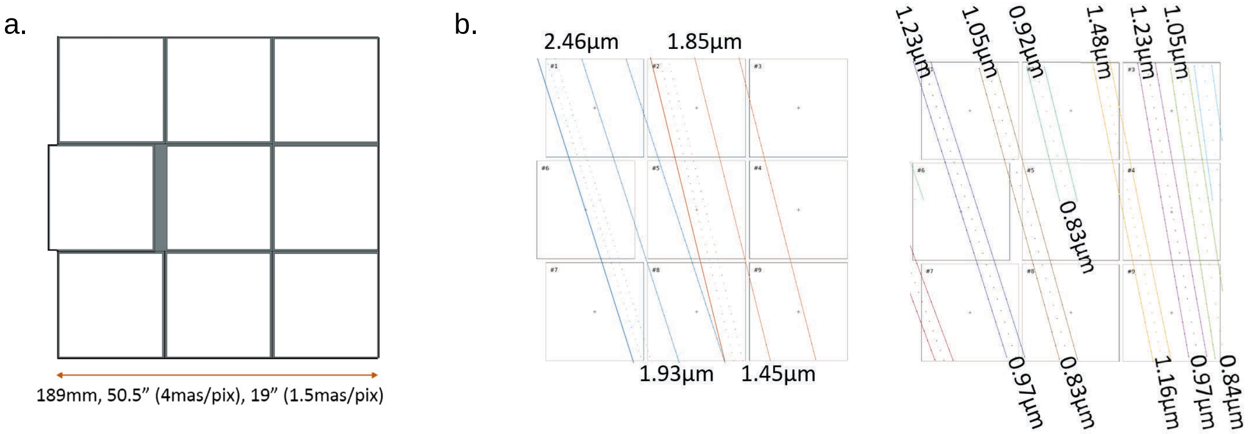

Figure 2.1 a) *The layout of the 9 MICADO detectors, with the gaps between them shown in grey. In the imaging layout, 50.5″ field of view is standard mode, and 19″ for the zoom mode;* ***b)*** *the HK-spectroscopic trace (left) and how it falls over the 9 detectors for a 15″ long slit and the IzJ trace (right) for a 3″ slit.*

The superior angular resolution of MICADO images makes crowded field photometry and astrometric applications especially attractive. Exciting opportunities include mapping individual stellar orbits in external stellar systems (see §3) and stellar orbits and flaring gas fainter and closer to the event horizon of the central black hole in the Galaxy than ever before with direct imaging (see §9). Astrometry will be feasible within the central regions of globular clusters over a range of distances (see §3) and can be extended to monitor black holes in other galaxies (see

§8). Proper motions of numerous individual stars in resolved stellar systems will allow a more active view of how stellar systems move and change (see §3). This will, amongst many other things, enable us to trace the presence (or absence) of black holes in a range of environments, as well as making accurate mass models by combining these results with radial velocity measurements to obtain a 3D view of stellar motions. We will be able to map the dark matter distribution in a variety of environments and for a range of spatial and temporal scales, and set constraints on the physical nature of dark matter particles.

Galaxy formation and evolution will always remain a central theme in observational astrophysics, and with the spatial resolution of MICADO it will be possible to make uniquely detailed studies of both local and very high redshift galaxies, and everything in between. In the nearby Universe, where individual stars can be resolved, star formation histories using colour-magnitude diagrams, will be possible well within the main body of dense stellar systems. These include the dense regions of nearby spiral galaxies, in nearby galaxy groups, and all the way out to the nearest of galaxy clusters such as Virgo and Fornax (see §4). This will be possible for a wide variety of galaxy masses, and types, including very small dwarf galaxies, a range of different mass Spiral and Elliptical galaxies, and a range of different environments. A critical question that this will allow us to answer is: how representative are the Milky Way and Andromeda of galaxy formation and evolution processes everywhere in the Universe? For much more distant, intermediate and high redshift galaxies multi-wavelength broad-band and narrow-band imaging will reveal the structure of galaxies at the peak of their star formation activity, mass assembly, and morphological transformations (see §5). MICADO will also be able to probe the star formation activity in the centres of dense active galaxies in extraordinary detail, to trace the evolution with redshift of the black hole mass and determine how this relates to the other galaxy properties, such as the bulge properties (see §8). This relates to the detailed effects of AGN feedback, and the role of environment in triggering and shutting down activity.

MICADO will make important contributions to the study of the solar system (see §7), especially the faint trans-Neptunian objects and the details of the surface of Moons for a variety of different environments. In addition, MICADO has an exciting potential for the study exo-planets, distant planetary systems, over a range of evolutionary stages to probe the initial conditions for planetary formation and the evolution of planetary systems over various time-frames (see §6). Until the arrival of the extreme-AO instrument on ELT, MICADO will provide the most detailed view of planetary systems that are not highly shrouded in dust.

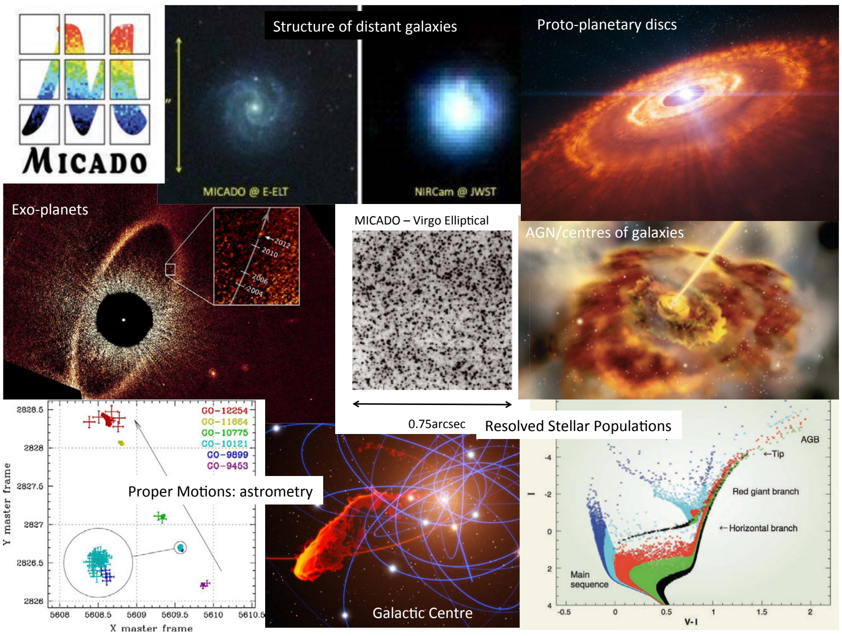

Figure 2.2 *An overview of the scientific areas covered by MICADO imaging capabilities.*

3 Dynamics of Dense Stellar Systems

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Outstanding Questions

Dark Matter remains a fundamental unknown substance and yet it is critical for a detailed understanding of galaxy formation and evolution. We detect its presence on galactic scales from the movement of stars and gas within galaxies. From these kinematic studies we understand that it needs to be there, however its nature remains uncertain. Direct and indirect detection from particle annihilation experiments towards nearby dark matter rich dwarf galaxies and the Galactic centre have so far failed to yield any clear and unambiguous detections. Our knowledge of dark matter is thus not improving. An approach that remains our best hope is to more precisely and on smaller scales determine how it must be distributed in both large and small nearby stellar systems. This is possible with kinematic studies of the motions of individual stars, from the inner most compact and crowded stellar component to the outer reaches of these systems. A major requirement is that there are sufficient numbers of stars that can have their motions accurately measured in 3D. Gaia will measure proper motions with dramatic accuracy down to a magnitude of V~20, but this magnitude limit will not allow us to look at stars sufficiently faint to measure the dynamics of a large samples of stars in most nearby ultra-faint dwarf galaxies, or in most stellar streams in the halo. GAIA will also not have the spatial resolution to look into the heart of dense systems like massive globular clusters and nucleated dwarf galaxies. It will also lack the sensitivity to measure the proper motions of sufficient numbers of stars in systems beyond the Local Group (e.g. in the Sculptor and Centaurus groups). For this we need an instrument like MICADO, able to take stable well calibrated images over time periods of 5—10yrs of stars with V>>20.

Nearby galaxies and globular clusters are important probes of dark matter and its distribution in the Milky Way environment and in the Local Group (e.g. Mateo 1998; Battaglia et al. 2005). These stellar systems have a variety of different masses and distances (Harris 1996; McConnachie 2012). Precise proper motion measurements can allow us to determine both the internal 3D velocities of stars, as well as the orbital motions of the entire galaxy. Nearby dwarf galaxies are the smallest systems where dark and visible (baryonic) matter co-exist, and thus they represent a benchmark to study how the presence of dark matter affects the evolution of visible matter (e.g. Tolstoy et al. 2004; Battaglia et al. 2008; Walker et al. 2009). Moreover, since 99% of their mass is dark, they are also ideal ground to set constraints on the physical nature of dark matter particles. To progress we need to break the degeneracy in the interpretation of the spectroscopic radial velocity measurements of the stellar populations by adding the transverse velocities, also called the proper motions. Galactic globular clusters are typically in reach of HST astrometric studies (e.g. Massari et al. 2013; Bellini et al. 2014; Watkins et al. 2015) see **Figure 3.1**, but dwarf galaxies are typically considerably further away and more challenging (e.g. Sohn et al. 2017; Massari et al. 2018). The current samples of measurable proper motions in nearby stellar systems remain quite small, even after Gaia, and so the interpretation of the results remains uncertain.

Proper motions of individual stars measured in an image can distinguish the variety, and the kinematic properties of stellar systems that overlap in the photometric properties of the stars in observed Colour-Magnitude Diagrams (CMDs) in the plane of the sky (see **Figure 3.1**). The stars within each independent component will move in the same way. The systemic velocity dispersion can be measured from the size of the internal motions about the mean motion of the system. This is a very powerful way of removing fore- and background contaminating sources that move differently (see **Figure 3.1**); it can unveil the presence of otherwise undetectable tidal distortions or streams. If there is a large difference in velocity between members and contaminants, this does not require exceptional precision. However, to go one step further and measure the motions of the individual stars within each distinct population (e.g. measuring the velocity dispersion) requires considerably more care and the precision has to be at least of the same order of magnitude as the systemic velocity dispersion. Also, to obtain absolute proper motions requires the local reference system to be anchored to an absolute reference (e.g. distant quasars or galaxies in the field, that do not move).

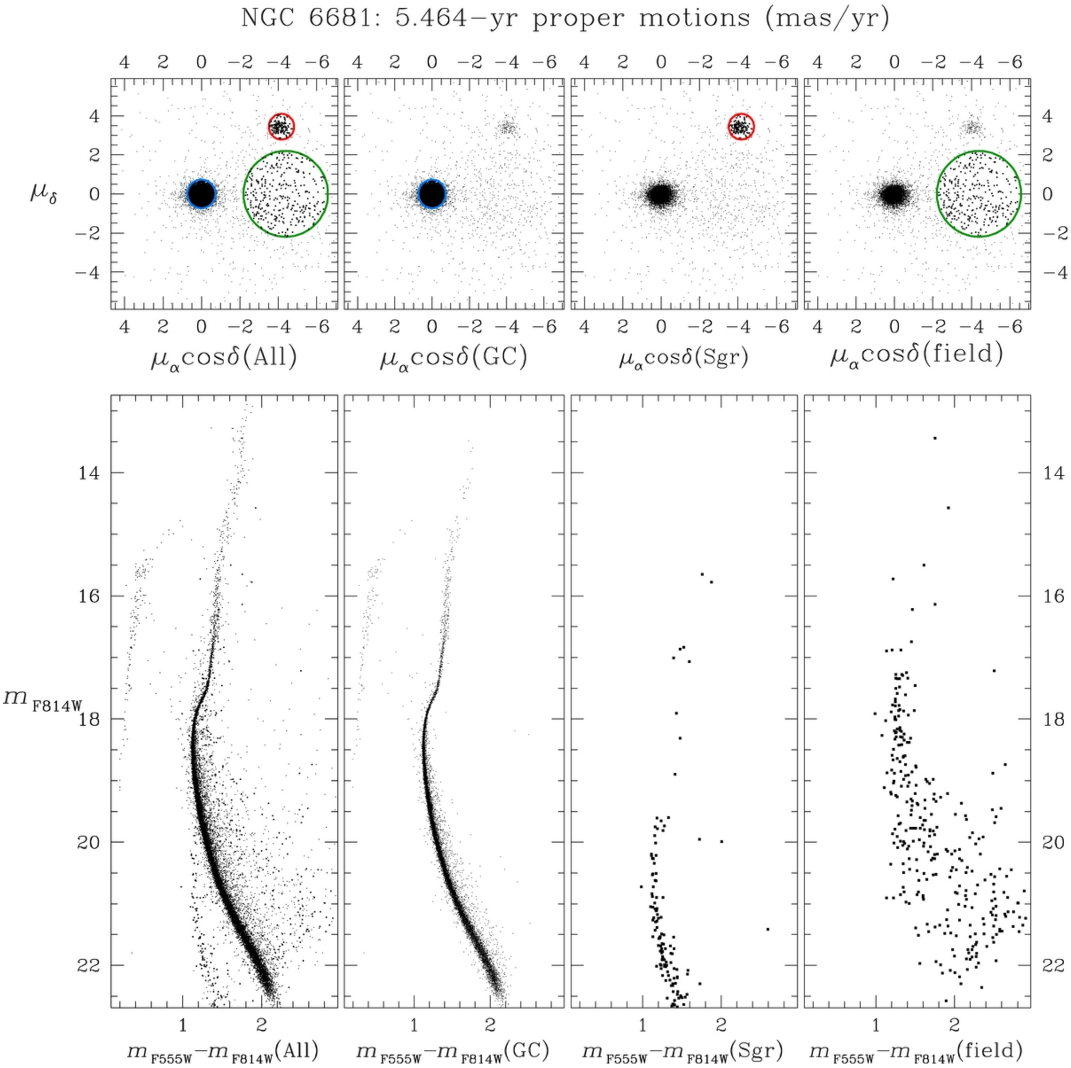

Figure 3.1 *The upper panels show the vector point diagrams of the relative proper motions of all the stars in the HST field of the globular cluster NGC6681. In the lower panels are the CMDs corresponding to the selections applied in the upper plots. First column: the full CMD of the field, no selection is applied. Second column: the cluster members are selected within the blue circle. Third column: Sgr dSph selection within the red circle. Fourth column: the selection of the bulk-motion of field stars. From Massari et al. (2013).*

Dwarf galaxies are also fundamental as dynamical probes of the extended gravitational potential of the Milky Way. Their orbits can be used to accurately determine the total mass and shape of the Milky Way (e.g. Vera-Ciro & Helmi 2013) and the Local Group. Gaia results have already made a huge leap forward by providing accurate proper motions for a sizeable fraction of the stars in the Milky Way and in many of the surrounding globular clusters, and also in several nearby dwarf galaxies (Gaia collaboration, Helmi et al. 2018). Gaia will however struggle with more distant (d>300kpc) galaxies, when too large a fraction of their stellar population is below the detection threshold. HST proper motion studies have been carried out in the Local Group by the HSTPROMO team (e.g. LMC at 50kpc, Kallivayalil et al. 2013; Sagittarius stream at ~20kpc, Sohn et al. 2015; M31, at ~750kpc, Sohn et al. 2012). However, these studies are typically not accurate enough to trace internal proper motions from individual stars (see **Figure 3.2**). Nonetheless, the LMC result revolutionised our understanding of the relation between the Milky Way and the Magellanic Clouds by explicitly measuring their relative motions, which were not what was expected. MICADO will extend astrometry beyond the limits of HST and Gaia, and build on the legacy of both, to determine the detailed dynamical properties of the outer halo of the Milky Way and galaxies in the Local Group and beyond.

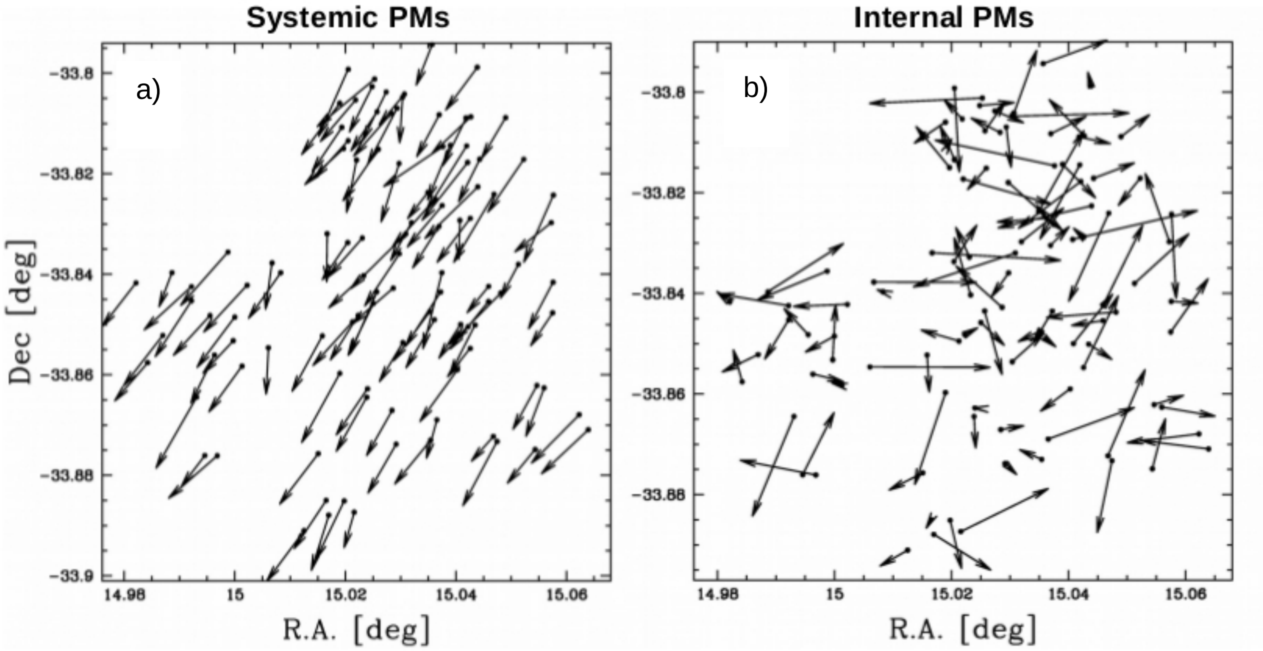

Figure 3.2 *The difference between absolute (systemic) and internal proper motions for the Sculptor dwarf spheroidal galaxy:* ***(a)*** *ordered arrows, all of them pointing on average towards the direction of the absolute system motion;* ***(b)*** *magnified by a factor of 40, the disordered internal motions in the same system, after the subtraction of the absolute motion. From Massari et al. (2018).*

MICADO will provide accurate astrometry of a large number of stars in different stellar systems making it possible to measure the internal variations in the velocities of individual stars, the velocity dispersion, in addition to their bulk motion across the sky. MICADO will be able to measure accurate density distributions and proper motions of faint stars near the centre of individual globular clusters and dwarf galaxies, much fainter than is currently possible with Gaia and at much higher stellar densities. This will reveal the mass distribution within the system, and also indicate whether low/intermediate mass black holes are present and to what level globular clusters are actually as dark matter free as is currently thought. This will accurately define the range of mass over which black holes exist in the centres of dense stellar systems. The internal proper motions of individual stars in dwarf spheroidal galaxies also reveals the mass and shape of the gravitational potential, which allows an accurate determination of the amount and distribution of dark matter in these objects, and even possibly to set constraints on the physical nature of dark matter particles. Measuring the overall dark matter content of dwarf spheroidal galaxies out to the faintest stars in the outer regions is then a powerful test of galaxy scale structure formation models. Internal proper motions can also directly measure the rotation of a stellar system (e.g. LMC, M31).

The Importance of MICADO

Proper motions of individual stars in relatively distant stellar systems are very challenging measurements for a ground-based telescope. They require exquisitely detailed measurements of the positions of individual stars, to be able to track how they move in the plane of the sky over the time-frame of several years. Obviously a 39m-telescope operating at its diffraction limit has intrinsically very high spatial resolution. However, it also needs to be able to provide accurate repeatable relative astrometry over a time frame of several years, which requires a very stable instrument and the ability to construct an accurate (local) astrometric reference frame using reference objects such as astrometric standard stars, or background QSOs and galaxies that do not move or change on these time scales. Gaia will do this for a substantial fraction of individual stars within the Milky Way, and in some cases up to 250kpc beyond. MICADO will have the power to push these kinds of detailed astrometric measurements to fainter stars and more crowded regions, and thus to the centres of dense nearby stellar systems and to more distant galaxies. With MICADO we can hope to obtain a detailed measurement of the dark matter mass and distribution beyond the Milky Way, including the entire Local Group, and even going beyond if MICADO proves sufficiently stable and suitable for exquisitely accurate astrometric measurements.

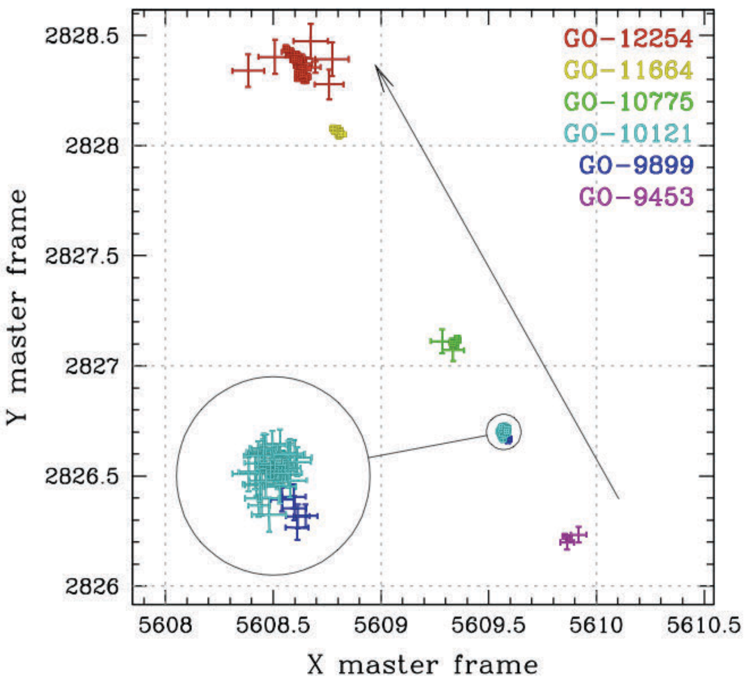

Figure 3.3 *The positions of a single star in globular cluster NGC6752, measured over 6 HST epochs as they appear in the reference frame. Star positions and error bars are colour coded according to the programme ID. The colours go from violet to green to red, moving from 2002 to 2006 to 2011 epochs. The black arrow shows the motion of the star over the 9 years of monitoring observations. The size of the error bars is related to the S/N of the measurements (some are short integrations). From Bellini et al. (2014). The precision reached with MICADO will supersede these HST measurements by a factor of at least ~10.*

HST accuracy and stability for astrometry is well documented, and assuming appropriate software and properly sampled images it has been shown that an astrometric precision <1% of the diffraction limit is possible (e.g., Bellini et al. 2014; Massari et al. 2013), see **Figure 3.3**. A similar level of accuracy has also been achieved on ground based images (<1% the seeing disc), which is 7mas, or 0.03pixels for the WFI on La Silla, corresponding to ~0.75% FWHM (Anderson et al. 2006). It has also been shown that the SCAO assisted VLT/NACO can reach an astrometric precision of 200µas, which is ~0.5% of the VLT diffraction limit at 1.2µm (Gillessen et al. 2009). The astrometric precision of the MCAO instrument GeMS on the Gemini-South telescope is <400µas (which is <1% of the diffraction limit, Massari et al. 2016). Assuming MICADO can achieve a similar level of accuracy this will enable unprecedented diffraction-limited position measurements of at least 40µas in a single image. **Figure 3.4** shows MICADO predicted astrometric precision as a function of magnitude. However, if it is possible to control the systematics, this precision should scale with 1/√N, where N is the total number of images over which the astrometric precision is reached. Optimistically it should then be possible to achieve a precision (with multiple images) down to <10μas (Cameron et al. 2009). Over a time-baseline of 10years, we may therefore hope to reach a proper motion accuracy of ~2μas/yr. Note that these numbers refer to relative motions of nearby objects on the same exposures; on larger scales these accuracies can only be attained provided an accurate, distortion-free astrometric reference frame can be established. A similar precision in relative parallax measurements should be attainable.

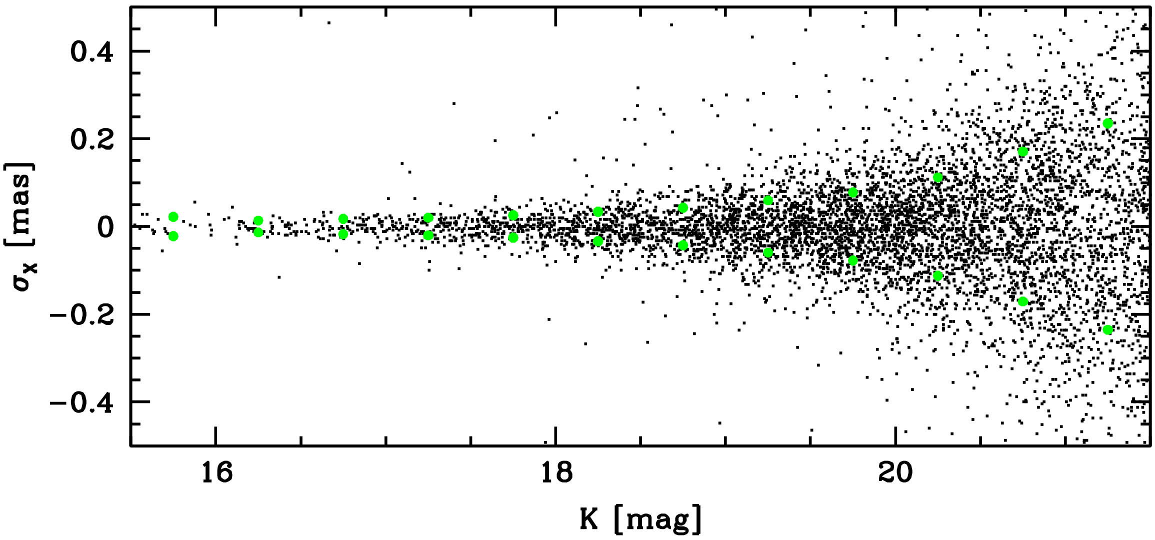

Figure 3.4 *Best achievable relative astrometric precision as a function of K-band magnitude for a 60sec exposure, from MICADO astrometric simulations. On the y-axis is the difference between the stellar positions measured in two images with a perfect geometric distortion correction. The green points mark the ±1σ dispersion of the distribution as a function of magnitude. For the brightest stars, the precision on single measurement is ~20μas.*

For comparison, Gaia is predicted to deliver proper motion accuracies as low as 4μas/yr, over a five-year mission lifetime. However, this precision will only be reached for very bright stars (V<10). At V=15, the error is expected to be 5–15μas/yr, and at V=20, this will be 100–300μas/yr.

MICADO will be able to measure proper motions with an accuracy of more than an order of magnitude higher than HST, and at much fainter magnitudes. In fact, after only five years it will be possible to reach 10μas/yr, which is equivalent to a motion of 5km/s at 100kpc (Trippe et al. 2010). At this level, many novel science cases become feasible, including proper motions of stars in the centre of our Galaxy and also other nearby galaxies; mass determinations of intermediate mass black holes; proper motions of globular clusters and their multiple populations, and testing cold dark matter structure formation from the internal kinematics of dwarf spheroidal galaxies.

Some Specific Science Cases

Looking for intermediate black holes: An intriguing science case is The hunt for intermediate mass black holes in the centre of stellar clusters and also nearby low mass dwarf galaxies. These are black holes with masses intermediate between stellar ($M<20M_\odot$) and super-massive ($M>10^6M_\odot$) as found in the centres of large galaxies. By simply following the M_{host}—M_{BH} Magorrian relation, one of the most promising places to find them should be the centres of star clusters, where theory predicts several mechanisms by which they may have formed. However, to date no conclusive evidence has been found of their existence. A major obstacle to overcome in this search is the extreme stellar crowding in the inner regions (<1-2″, see **Figure 3.5**) of dense clusters, which makes it very difficult to properly perform kinematic studies. The tell-tale signature of an intermediate mass black hole is a cusp in the velocity dispersion profile. The superior resolution of MICADO will make it possible to solve this problem, at least for Galactic star clusters and close by satellites.

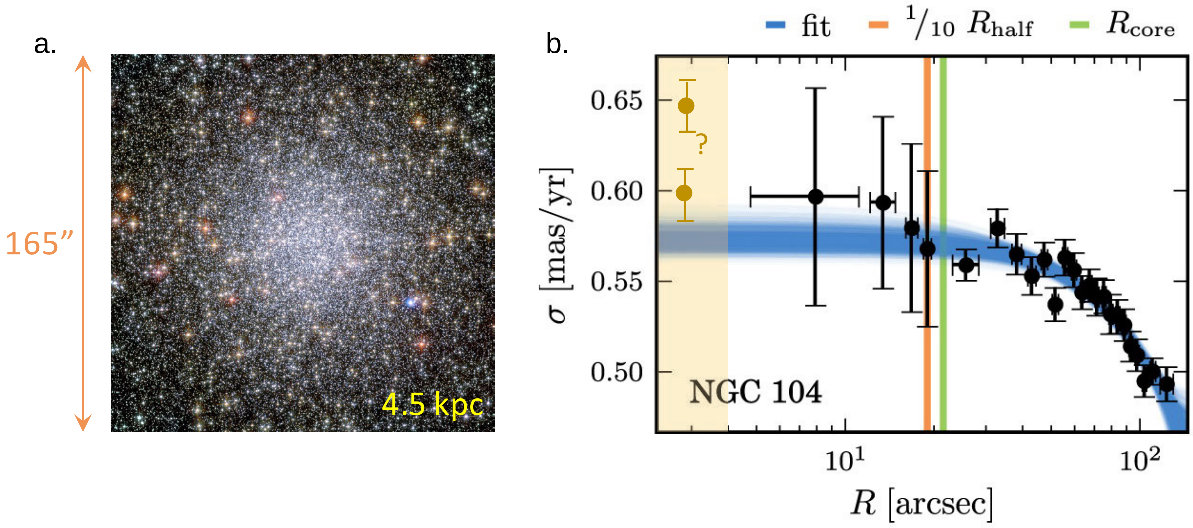

Figure 3.5 (a) *A multi-colour 165" square HST image of the well-studied globular cluster NGC 104 (47Tuc), which is at a distance of 4.5kpc;* ***(b)*** *a state of the art proper motion dispersion profile in globular cluster NGC104 with HST (from Watkins et al. 2015), where the inner regions (yellow shaded area) cannot be currently sampled because of crowding, with over-plotted potential MICADO measurements, with realistic error bars, overcoming the extreme crowding within the central arc-second of this stellar system.*

Dark matter in dwarf galaxies: Measuring the dark matter content of dwarf galaxies around the Milky Way and beyond is a fundamental test of structure formation models. Cold dark matter simulations of gravitational collapse show that extended halos like that of the Milky Way and the Local Group should be highly structured, with numerous clumps, as a consequence of hierarchical merging. On the assumption that these clumps (sub-halos) host distinct stellar populations, the visible mass function of the satellites should be similar to what is seen in the (dark matter) simulations. It is important to robustly establish if this relation is consistent with observations. If it is not observed, then this would require a significant modification in the cold dark matter structure formation mechanism, or the way that baryons evolve within dark matter halos, where they may be disrupted by early star formation and mass loss (feedback) processes.

There has been significant observational effort in this area with large spectroscopic surveys measuring line-of-sight radial velocities of individual stars in nearby resolved galaxies, to measure their dynamical masses using velocity dispersion profiles. Typically, the measured velocity dispersions stay flat out to large radii, suggesting that the dwarf spheroidal satellites are surrounded by massive halos. However, these radial-velocity measurements are subject to orbit anisotropy degeneracy, meaning that a deeper potential can mimic a tangentially biased orbit distribution. Proper motions are the only way to break this degeneracy, as they make it possible to directly measure the shape of the velocity ellipsoid (ratio of the radial and tangential velocity dispersions) of the stars. It has been shown that adding proper motion information for samples as small as 160 stars, it is possible to obtain accurate estimates of both the velocity anisotropy and the mass slope, and thereby unambiguously break model degeneracies (Wilkinson et al., 2002). This is also confirmed by Strigari et al. (2007), who show that for general dark matter density and anisotropy profiles, the log slope of the dark matter profile at about 2 core radii can be measured to within ±0.2 if the proper motions of 200 stars (with tangential velocity errors of ~5km/s) are added to the line of sight velocity measurements. This would allow tighter constraints on the type of dark matter halos hosting dwarf galaxies, and hence possibly also on the nature of dark matter everywhere.

Currently, the only case where proper motions have been measured in a dwarf spheroidal satellite of the Milky Way is the Sculptor dwarf (Massari et al. 2018). This has revealed 3D stellar orbits significantly more radially biased than expected, demonstrating how important the full knowledge of the velocity ellipsoid is. However, these proper motions were measured for stars offset with respect to the galaxy centre, where the difference between the prediction from different dark matter models should be clearer. Given the internal velocity dispersion of ~10km/s for these objects, MICADO will be able to measure these internal motions securely from a five-year baseline in the central regions of objects out to at least 200kpc (10km/s at 100kpc corresponds to 21µas/yr), see **Figure 3.6**. This accuracy is more than sufficient to measure the shape of the velocity ellipsoid of stars in these galaxies after the combination of the proper motions with radial velocity measurements of the same stars. From **Figure 3.6** it can be seen that internal proper motions depend not only on distance but also on the number of stars in a system at a given magnitude and in almost every case MICADO will significantly improve upon the Gaia measurements.

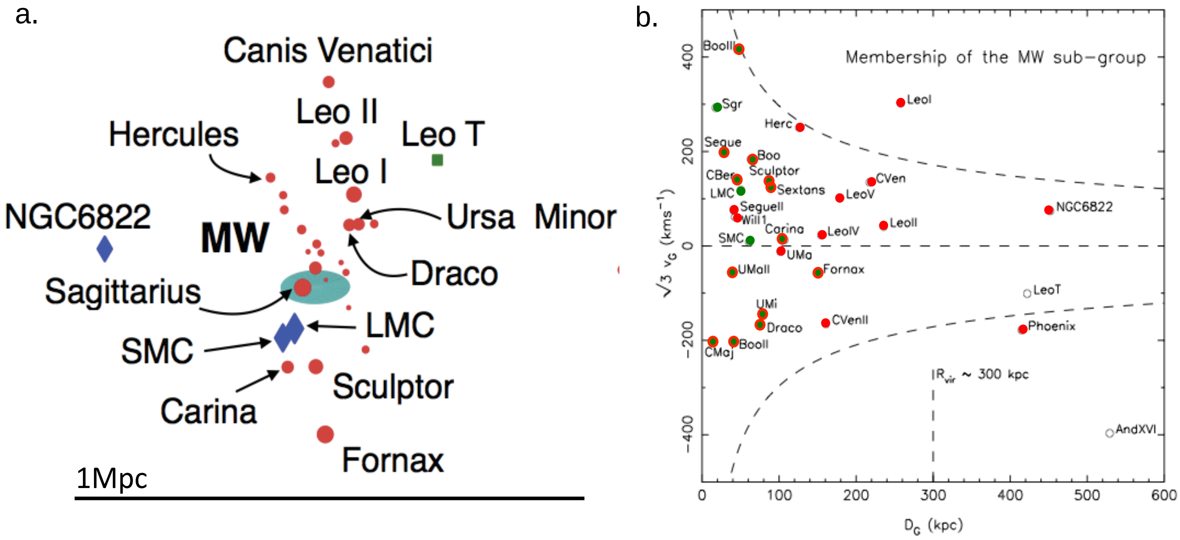

Figure 3.6 (a) *An overview of the distribution of dwarf galaxies around the Milky Way (MW), which is shown as a light green disc. The red dots are dwarf spheroidal and ultra-faint dwarf galaxies, and the blue diamonds are dwarf irregular galaxies. The physical scale is shown below. Credit: G. Iorio;* ***(b)*** *galacto-centric velocity vs. distance for all galaxies around the MW. The dashed lines show the escape velocity from a $10^{12} M_\odot$ point mass. The vertical dashed line indicates the location of the cosmological virial radius of the MW (R_{vir}~300kpc). From McConnachie (2012). The red-green points will first have their internal velocities measured by Gaia, but these will be substantially improved by MICADO. The red points will only be possible with MICADO. The three green points are large and nearby systems that will be done in great detail by Gaia, and MICADO will only be needed for the internal velocities of their globular cluster populations.*

Synergies with radial velocity campaigns: Ideally, the (proper) motion in the plane of the sky is complemented by spectroscopic radial velocity measurements to obtain the 3D velocity vector. Integral field instruments like VLT/MUSE have demonstrated that the dynamics in globular clusters can be investigated for a large number of individual stars with a rather modest investment of observing time (Kamann et al. 2018). Complementing IFU observations using ELT/Harmoni would match proper motions from MICADO at the appropriate high spatial and spectral resolution, allowing similar dynamical investigations in a range of dwarf galaxies. This will deliver full 6D phase space information for individual stars in nearby dwarf galaxies and Galactic globular clusters, which will enable the characterization of the distribution function of stars of different populations in these systems.

Absolute Motions of Local Group galaxies: The proper motion precision on a single high S/N point source in 5yrs is expected to be 10µas/yr. At 2Mpc, 100km/s (which is half the typical space velocity of Local Group galaxies) corresponds to 10µas/yr (see **Figure 3.7**). This means that over a 5yrs temporal baseline we will be able to directly measure the relative motion of the larger galaxies in the Sculptor group, such as NGC300, assuming that at least one background galaxy or quasar will fall in the targeted field of view (Kalirai et al. 2007). This means that MICADO will be a powerful complement Gaia and measure the absolute proper motions for stellar systems beyond Gaia's reach. Thus, obtaining the full 3D motion of virtually all the galaxies within the Local volume will be feasible with MICADO. This will provide the most accurate chance ever to estimate the total mass of the Local Group itself. Also globular clusters hosted by these distant galaxies are targets of such an investigation. The measurement of their motion would provide invaluable constraints on the dynamical mass of their hosts, which currently is the subjects of a hot debate within the community (e.g. van Dokkum et al. 2018).

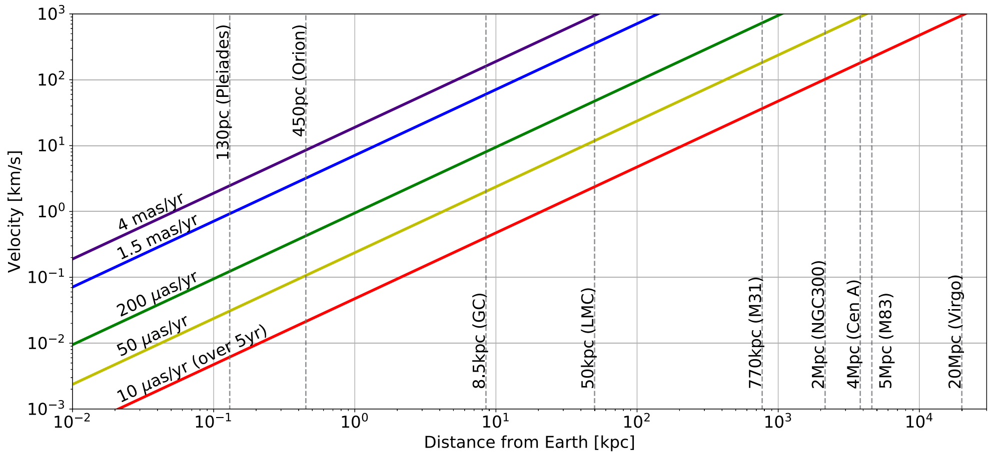

Figure 3.7 *An estimate of how the proper motion traces the transverse velocity of a system with increasing distance given a range of astrometric accuracies.*

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4 Resolved Stellar Populations

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Outstanding Questions

*A key issue in modern astrophysics is the star formation history of the Universe; where and when have most stars formed. This is of critical importance to understand the link between cosmological dark matter and the visible baryonic matter that we can directly observe. The development of large structures in the Universe can be successfully explained in terms of hierarchical growth in the framework of a Lambda Cold Dark Matter (ΛCDM) model, however it is still not completely clear how to successfully couple the baryonic component to the dark matter and explain the wide range of galaxy properties in the present day Universe. Direct observations of large samples of galaxies over a range of redshift can be used to map the star formation rate and how it changes with look-back time (see **Figure 4.1b**), but since integrated galaxy light is dominated by the most recent stellar generations, the information on the underlying older stellar population is limited. A similar problem affects the analysis of the spectral energy distribution of galaxies, from which only luminosity averaged ages and metallicities can be derived. It is only by resolving individual stars and accurately putting them in a Colour-Magnitude Diagram (CMD) that the star formation rate versus time can be accurately measured to trace the fossil record of the star formation history back to the early Universe for individual nearby galaxies (see **Figure 4.1a**).*

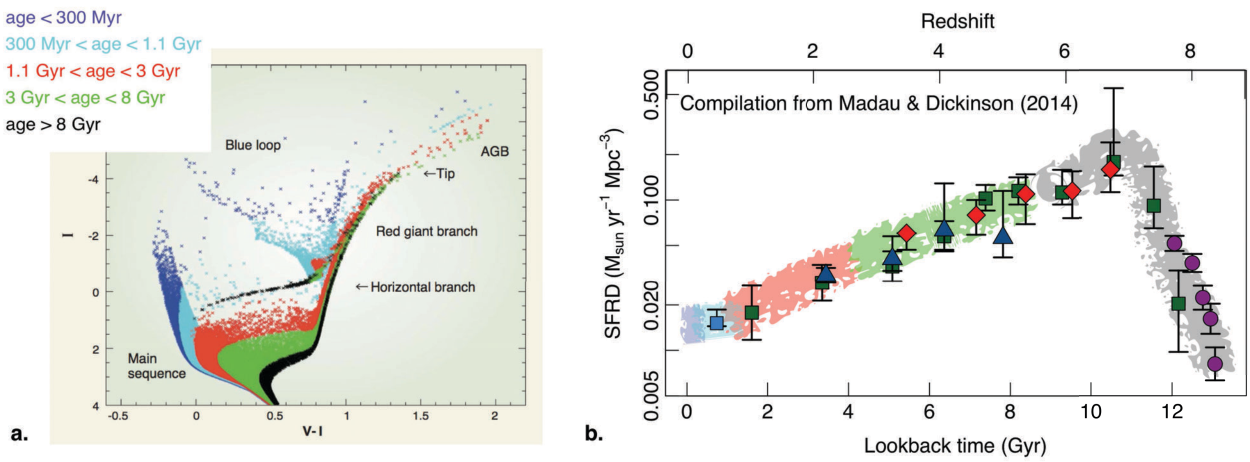

***Figure 4.1 (a)** A simulation of a Colour-Magnitude Diagram for a galaxy that has constantly formed stars over the last 13Gyr. The stars are colour-coded according to age, see inset. Key stellar evolution phases that mark the presence of stellar populations of different ages are labelled. From Tolstoy (2011); (**b)** The star formation rate density of the Universe as a function of redshift and thus also look back time. From a compilation by Madau & Dickinson (2014), with superposed the colours of the ages of the stars shown in (a), corresponding to the redshift range of formation.*

The detailed analysis of the properties of ancient stars is possible because low-mass stars have very long lives, and in many cases their photospheres remain unchanged samples of the gas out of which the star formed. When ancient low mass stars can be individually identified they provide uniquely accurate probes of the detailed chemical and physical conditions in the early Universe when galaxies were assembling. Stars of different ages thus can be used to follow galactic scale evolution, as the rate at which stars form in a galaxy with time is a direct measure of how the global properties (e.g. luminosity, colour, mass) change. This can only be uniquely determined by careful

CMD analysis (e.g. see **Figure 4.1a**). Stellar age dating is most effective in the Main Sequence Turn-off region, and old stellar populations can be uniformly sampled on the Red Giant Branch (RGB), as can be seen in **Figure 4.1a**. This approach has been successfully developed and verified for nearby dwarf galaxies (e.g. Tosi et al. 1991; Dolphin 2002; Tolstoy, Hill & Tosi 2009; Monelli et al. 2010; Weisz et al. 2014). **Figure 4.1a** also shows that old main sequence stars in galaxies can quickly become prohibitively faint even for MICADO, while accurate photometry of bright RGB stars will be feasible out to the Fornax Cluster and beyond (Deep et al. 2011; Greggio et al. 2012). Additional information can also be gained on ancient stellar populations from the Horizontal Branch stars (Salaris et al. 2013; Savino et al. 2018), and also from the intrinsically brightest regions of the CMD for the most recent star formation (e.g. Dohm-Palmer et al. 1997). The accurate analysis of CMDs is currently only possible for younger populations in larger galaxies, which are typically much more distant, because of a mixture of crowding and sensitivity limits (Olsen et 2006; Radburn-Smith et al. 2011; Bernard et al. 2015). It is in these larger systems that the majority of ancient stars in the Universe are to be found, and thus the most detailed information about the largest contributors to the star formation rate density of the Universe.

a. b.

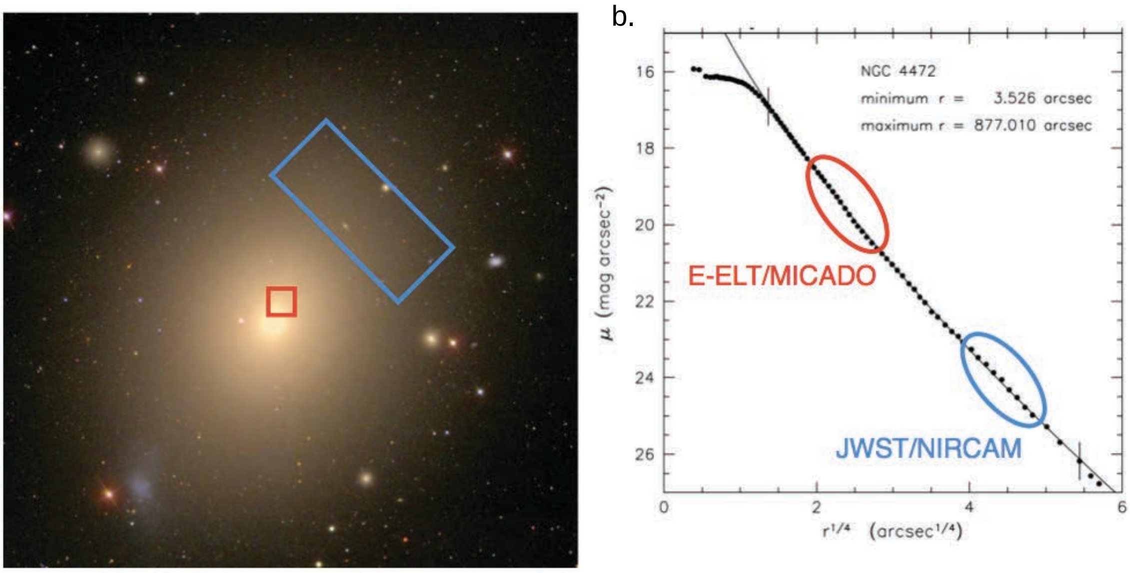

***Figure 4.2 (a)** An image of NGC4472 (M49), an Elliptical galaxy in the Virgo cluster, with representative areas that could be surveyed by JWST (blue rectangle) and MICADO (red square); **(b)** The surface brightness profile of NGC4472 showing where individual RGB stars can be resolved with MICADO and JWST. At higher surface brightness the crowding is too high for accurate photometry of individual stars, and at lower surface brightness the stellar density becomes very sparse and the CMD will not be very detailed.*

In short, in ΛCDM we have a compelling theory of galaxy formation and evolution, but observational verification on the scale of individual galaxies is challenging to interpret for a variety of reasons, and the results of these comparisons often appear contradictory (e.g., Moore et al. 1999; McGaugh et al. 2000; Venn et al. 2004; Helmi et al. 2006; Tolstoy et al. 2009; Tolstoy 2011; Boylan-Kolchin et al. 2012; Salvadori et al. 2015). We have very little direct proof of the major merger history of large galaxies. The Milky Way is the only galaxy that we can study in great detail and there is currently not very direct evidence for this, but it may have led a quiet life. Gaia will undoubtedly give us a more accurate picture of this in the coming years, and early results suggest that the Milky Way contains extensive sub-structure. However, the origin of this sub-structure still needs to be verified, and it currently seems most likely that most streams and structures found come from dwarf galaxy like objects.

At present ancient resolved stellar populations can only be uniquely identified in the Milky Way and in the closest neighbouring galaxies, which are predominantly small dwarf galaxies (e.g. Tolstoy et al. 2009; Weisz et al. 2014) or extremely tiny outer regions in M31 (e.g. Brown et al. 2006). To make a breakthrough in our understanding of galaxy formation and evolution at the earliest times we need to study ancient stars and make accurate star formation histories in different environments and most importantly in massive galaxies, which contain the bulk of the stellar mass in the Universe. This means in the bulges and discs of Spiral galaxies (e.g. in the Sculptor group at 2-3Mpc); S0 galaxies (e.g. Centaurus A at ~4Mpc); and Elliptical and Spiral galaxies in a cluster environment, such as Virgo (16–18Mpc), see **Figure 4.2**. These are all key objects to study the star formation history of the Universe and they are also in the mass range covered by redshift surveys (Madau & Dickinson 2014). The current limitations in extending these studies to greater distances are both sensitivity and spatial resolution. The oldest Main Sequence Turnoff stars in a CMD are the most reliable age indicators (see **Figure 4.1**), but this requires accurate photometry at m_I~28 at 1Mpc distance (see **Figure 4.3**).

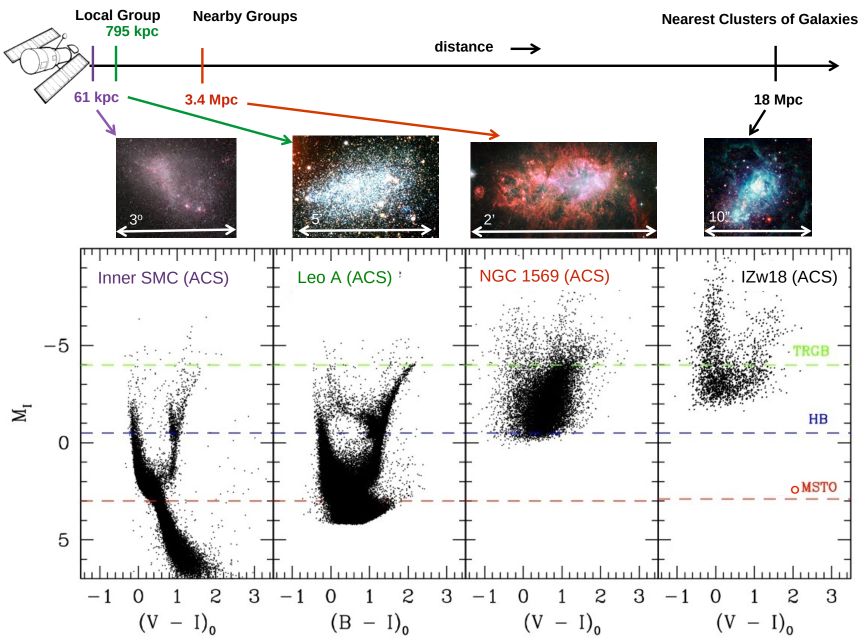

Figure 4.3 *A collection of HST/ACS CMDs for 4 dwarf galaxies at increasing distance. The dashed lines show the position of the oldest Main Sequence Turnoff (oMSTO), the Horizontal Branch (HB) and the Tip of the Red Giant Branch (TRGB). Photometry taken from Cignoni et al. 2012 (SMC); Cole et al. (Leo A); Grocholski et al. 2012 (NGC 1569) and Aloisi et al. 2007 (I Zw 18).*

The importance of MICADO

Resolved stellar population studies always benefit from increased spatial resolution and sensitivity, as HST showed extremely well. However, these studies also require a high degree of photometric fidelity, so magnitudes need to be measured with an accuracy in the range of ±0.03mag over the entire field of view, and the larger the field of view the better (see **Figures 4.2** and **4.3**). This accurate photometry typically requires a well-defined PSF, which to date is typically determined from relatively isolated stars within the observed field of view. It has also been shown that resolved stellar population studies of older systems require I-filter imaging combined with H or K, to ensure that there is significant (accurately measureable) spread in the CMD due to age (e.g. Deep et al. 2011). This is especially true when only the RGB is detected.

MICADO will make it possible to resolve individual ancient stellar populations in the heart of dense stellar systems outside the Local Group. This will dramatically improve the detail and accuracy of comparisons between observations of galaxy evolution going back to the oldest stars that formed in the early Universe and simulations that start in the early Universe and predict present day galaxy properties. Only by resolving individual stars in a galaxy and carrying out accurate photometry in at least two filters is it possible to uniquely determine the star formation history and thus the evolutionary pathway of a galaxy (e.g. Cole et al. 2007). The major observational challenge is that low mass ancient stars are faint, and they are often severely crowded together. This means that their study requires the demanding combination of high spatial resolution, flux sensitivity and also a high dynamic range (of order 10 magnitudes), see **Figures 4.1a** and **4.3.**

HST, with its high spatial resolution, flux sensitivity and uniquely stable PSF, led to a breakthrough in the study of resolved stellar populations in nearby galaxies. However, the 2.4m diameter primary mirror struggles with both sensitivity and spatial resolution for galaxies beyond ~1Mpc, see **Figure 4.4**, and thus we need to expand these capabilities to push our vision beyond the Local Group and into different environments. JWST should improve on HST performance for both sensitivity and spatial resolution, but MICADO will provide the necessary leap to push this kind of analysis well beyond the Local Group and deep into the heart of giant galaxies.

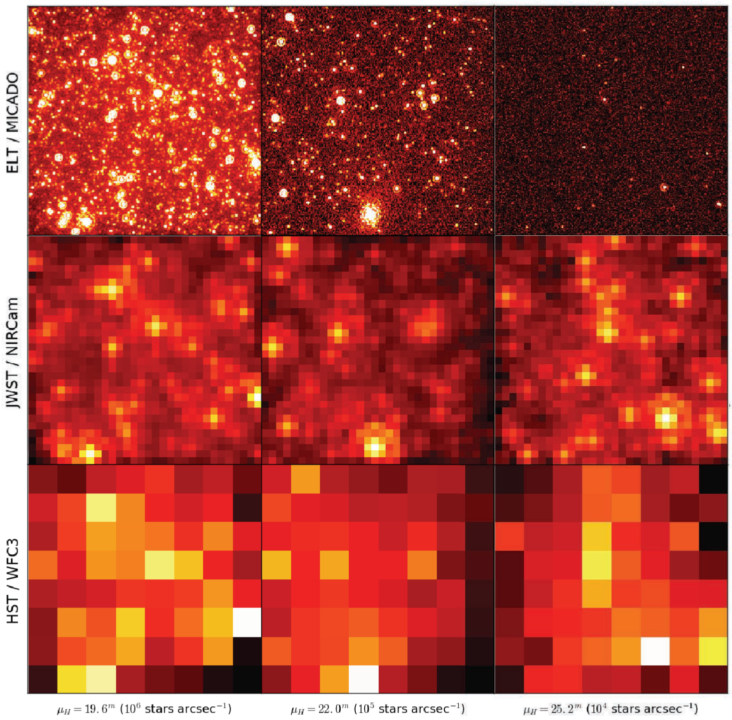

Figure 4.4 *SimCADO H-band simulations of three resolved stellar fields in an M49-like Elliptical galaxy at the distance of Virgo at different surface brightness levels (labelled at the bottom of the image) for HST, JWST and MICADO. Each individual image is 1" square, and the exposures times are all 10hrs.*

Resolved stellar population studies also include a range of related science cases, looking deep into star formation regions in a range of environments, searching for particular types of stars that indicate specific age populations, like Cepheid and RR Lyr variable stars and infrared luminous AGB stars, and looking in detail at the resolved properties of star clusters in galaxies beyond the Local Group. In addition, detailed CMDs also allow the careful selection of stellar targets for follow up spectroscopy to determine the detailed properties of young massive stars in distant galaxies, and older (fainter) stars in less distant systems. It is also possible to carefully determine the Initial Mass Function (IMF) in a range of different stellar systems by resolving and carefully measuring the magnitudes and colours of all the stars in a system. All these cases depend fundamentally on spatial resolution and flux sensitivity to accurately find and measure the properties of individual stars over a range of magnitudes in a range of different environments.

Some Specific Science Cases

Star formation histories beyond the Local Group: Potential targets include Spiral galaxies at the edge of the Local Group, such as NGC3109 (at 1.4Mpc) and NGC55 (at 1.9Mpc), which are small spiral galaxies. In addition, there are 3 medium-sized spiral galaxies in the Sculptor group (NGC253, NGC300 and NGC247), one of which is a starburst. The Sculptor group also contains a number of large and small irregular galaxies, and observing these will give us a detailed comparison to the similar galaxies in the Local Group. MICADO will also be able to look deep into the high surface brightness centres of Spiral galaxy bulges and Elliptical galaxies (see **Figure 4.2**). The nearest Ellipticals, after the peculiar S0 system Centaurus A, are in clusters such as Virgo (16–18Mpc distance) and Fornax (~19Mpc). This will provide extremely detailed information to compare with predictions from simulations and observations of the distant Universe.

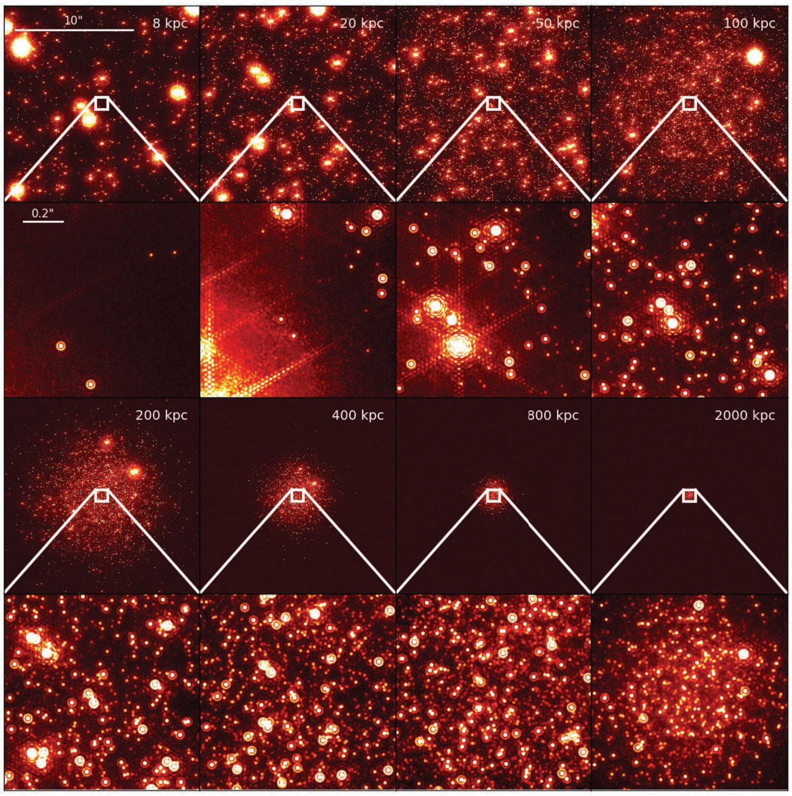

***Figure 4.5** SimCADO K-band simulations of an M4-like globular cluster at various distances between 8kpc and 2Mpc, assuming a 1hr exposure time. The top and third row are the central (16"x16") chip of MICADO, and the second and fourth rows are a 1" square zoom in.*

MICADO will also be able to resolve individual stars in (young) star clusters well beyond the Local Group (see **Figure 4.5**); indeed, this has already been done in a few (favourable) cases with HST at distances up to ~5Mpc (e.g. Larsen et al. 2011). Reproducing the CMDs of star clusters is a classical challenge for stellar evolutionary theory; yet constraints on the post-main sequence phases are difficult to obtain at young ages since even a ~$10^4 M_\odot$ cluster typically contains only a few post-main-sequence stars. The Magellanic Clouds host a well-studied system of young clusters, some of which have ~$10^5 M_\odot$, but even here there are limitations in terms of the age and metallicity ranges. By pushing such work to massive star clusters beyond the Local Group, we will have access to a far greater variety of environments, and this will provide empirical constraints on the properties of evolved stars (e.g. temperatures, luminosities, ratio of red/blue super-giants, etc.) as a function of age and metallicity. Such information, in turn, is crucial when modelling stellar populations, whether resolved or in integrated light, so that there is a great deal of synergy between this science case and many of the ELT spectroscopy cases.

Stellar clusters have traditionally been viewed as classical examples of "simple stellar populations" characterised by a single age and chemical composition, but observations of old globular clusters have made it clear that the situation is more complex, with most globular clusters showing complex colour-magnitude diagrams indicative of complex formation/enrichment histories (e.g. Bastian & Lardo 2018). For young clusters, we are once again limited by the small number of suitable targets in the Local Universe, although observations of clusters in the Magellanic Clouds have revealed intriguing complexity here, too (e.g. Martocchia et al. 2018). Observations of extragalactic young massive clusters with MICADO will provide information on age and metallicity spreads, with a significant potential for surprises.

Observing Star Formation in different environments: Star formation and how its properties vary with environment remains a challenging study. Measuring the properties of low mass star formation, and thus the form of the IMF is a critical element in this study. It requires accurate photometry in crowded regions down to faint magnitudes and thus MICADO can make a major contribution in pushing these detailed studies into a wide range of environments beyond the Milky Way (see **Figure 4.6**), to determine, for example, if the IMF is universal.

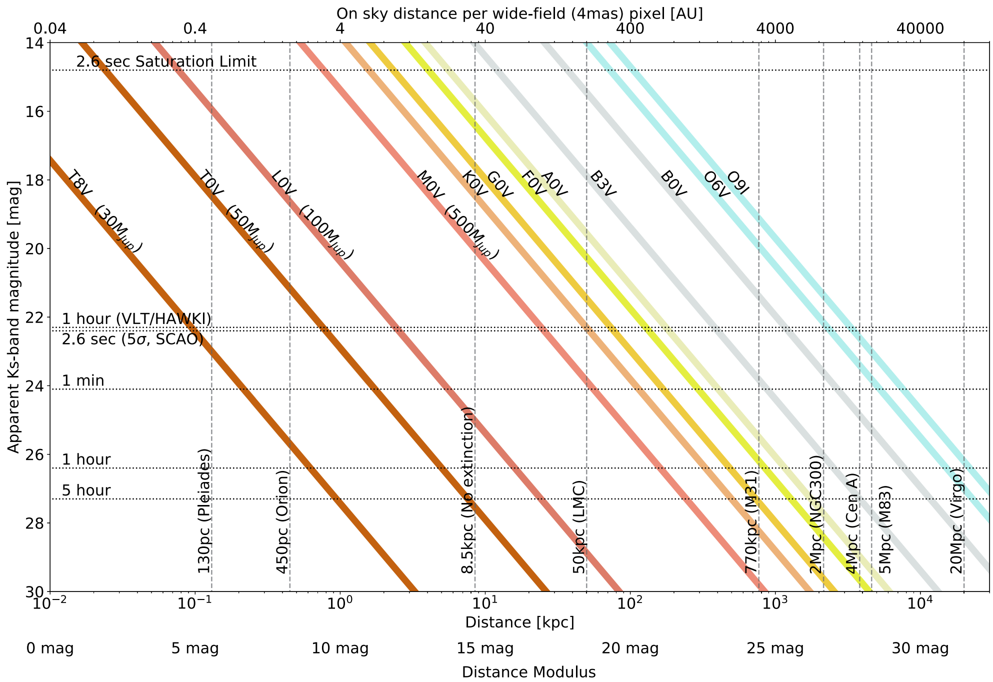

Figure 4.6 *Sensitivity-distance parameter space for resolved stars with MICADO. The diagonal lines show the apparent magnitude of a given stellar type. The dotted horizontal lines show the sensitivity limit for a given K-band exposure time using MICADO in SCAO mode. Where the diagonal and horizontal lines cross is the predicted detection limit for each stellar type.*

An important aspect is to connect the gas properties with the star formation rate. There have been numerous recent efforts to develop and refine the theories behind star formation, and yet we still do not have a predictive theory of star formation and realistic star formation models are critically needed for understanding almost every process in the universe, from the evolution of galaxies to the formation of planetary systems. Galaxy evolution models rely on an accurate IMF and star formation rate to describe their feedback mechanisms, and determining the star formation history of a galaxy is impossible without them (Kennicutt 1998). At the other end of the scale, the dynamics of the interstellar medium and planet formation require knowledge of the chemistry of the universe, for which we need information on where, when, which, and how stars are formed.

Currently, resolved observations of star formation regions, down to low mass limits are restricted to the Milky Way and nearby dwarf galaxies. Only the large increase in both sensitivity and angular resolution that MICADO can provide, will finally allow us to peer deeper into the realms of resolved star formation well beyond the Local Group. **Figure 4.6** highlights the effect of distance on our ability to detect individual stars of different types (and thus luminosities). This shows that MICADO will be able to detect almost all stars in the Milky Way within 20kpc of the Sun. This will allow detailed studies of the brown dwarf population ($M<0.5M_{\odot}$) in a large fraction of star clusters in and around the Milky Way, including the Galactic bulge and the Galactic Centre (see also §9). The exceptional resolving power and sensitivity of MICADO will also allow these studies to be extended to the satellite dwarf galaxies of the Milky Way down to much fainter (lower mass) limits than are currently possible. These observations of extremely low mass stars with MICADO in a range of different environments will dramatically improve our understanding of the very low mass component of the IMF, and the ancient star formation properties of the Local Group and how this may differ with similar studies in the Sculptor and Centaurus groups.

Cepheid period-luminosity relation out to 100Mpc: The Hubble constant (H0) determinations from the Planck Satellite and from local Cepheids and Supernovae are both formally precise but also in disagreement with each other. The results from Gaia DR2 reanalysis of Galactic Cepheids seems to have increased this inconsistency. This could indicate deviations from the cosmological standard model. For a definitive conclusion it is necessary to further decrease the error of the local H0 measurement and to better understand the systematics. A more precise measurement is also of general interest since it decreases the errors on the time derivative of the dark energy equation of state measurements in cosmological surveys. Decreasing the error on the determination of H0 requires that many more Cepheids in the Milky Way have parallax distances. It also needs a larger number of supernova-host galaxies (~80) where the Cepheid period-luminosity relation can also be measured. Because of the increased stellar crowding this is beyond HST and it requires an instrument with much higher spatial resolution. MICADO will outperform HST and JWST in spatial resolution and is the ideal instrument to push Cepheid period-luminosity determinations out to 100Mpc (Coma cluster) or even beyond, and thus to galaxies definitively within the Hubble flow. The spatial and temporal stability of a well understood PSF is required to carry out accurate and well calibrated photometry of Cepheids as they vary. The errors should not exceed the 1% level.

Stellar spectroscopy beyond the Local Group: The detailed spectroscopy of individual stars in nearby galaxies allows the determination of accurate metallicity distributions and kinematic properties for stars of a range of age in a range of different galaxies.

One common method that has been well calibrated for RGB stars, uses intermediate resolution spectroscopy of the Ca II triplet (CaT) metallicity indicator. With an R~8000+, it can provide accurate line-of-sight velocities (±1–2km/s) and metallicities [Fe/H] (±0.1–0.2dex) from the equivalent widths of CaT lines (e.g. Starkenburg et al. 2010). RGB have ages >1Gyr, and are thus tracers of all but the most recent star formation in a galaxy. At the present time to even get useful spectra of individual stars much beyond the outer halo of the Milky Way is challenging, and requires long exposures with sensitive spectrographs on the largest telescopes. The extra-galactic spectroscopy of RGB stars to date has been restricted to the nearest *dwarf* galaxies. Large numbers of careful measurements have led to a deeper understanding of the chemical evolution and the dynamical state of nearby dwarf galaxies. CaT spectra allows us to probe the total mass of these galaxies and also the chemical evolution history of all components (i.e., disc, bulge and halo), including a kinematic deconvolution of these components and a comparison of their detailed properties over a range of galaxy type and environment (Battaglia et al. 2013; Tolstoy et al. 2009).

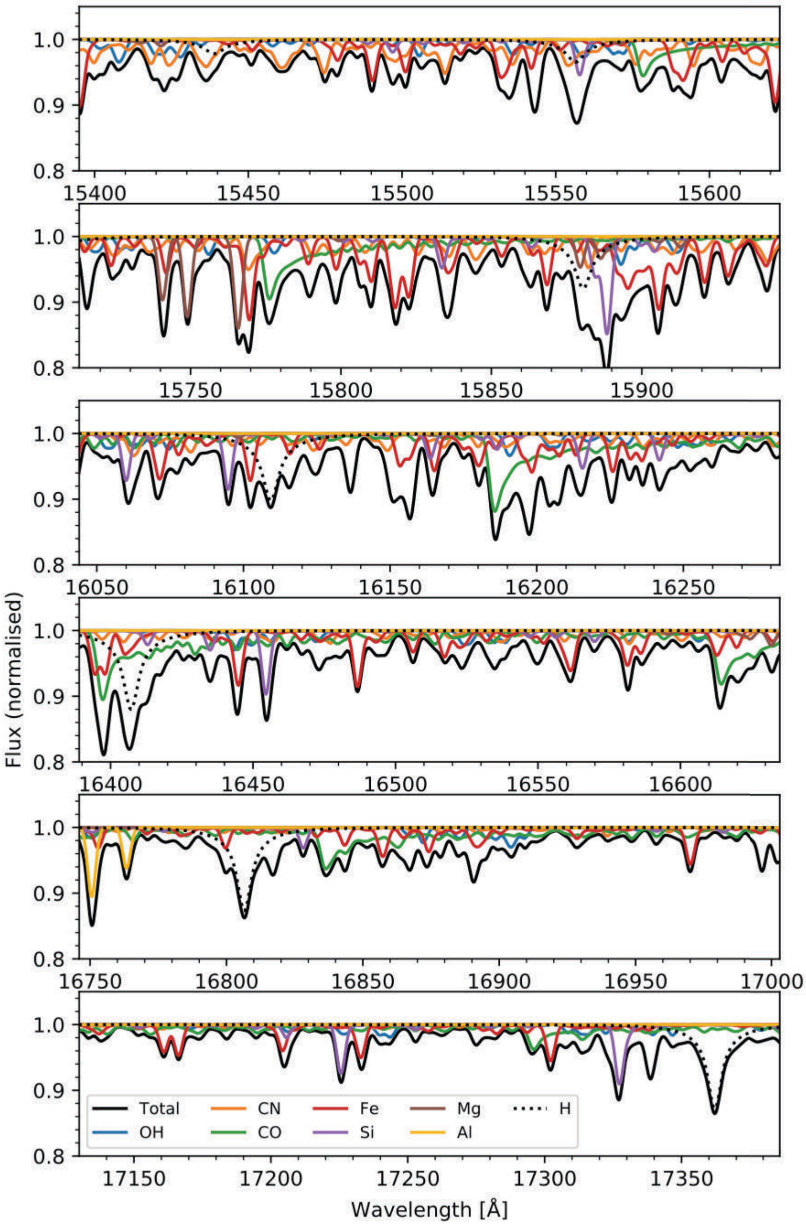

Figure 4.7 *Simulation of an H-band spectrum of an Arcturus-like star, highlighting a number of the stronger features, which are identified in the bottom panel. From Larsen et al. 2018.*

Naturally the next step in this field is to extend these studies, using the same well established and calibrated methods, to a broader range of galaxy types. This requires us to look beyond the Milky Way halo and even the Local Group. With MICADO we can look at the Sculptor group, for example, which contains a range of different galaxy types (from large spiral galaxies to small gas rich and poor dwarf galaxies) and allows us to study a different group environment in detail. Finally, the ultimate goal is to be able to make a study of the resolved stellar populations in giant Elliptical galaxies, of which there is no example in the Local Group, and we have to look at Cen A (at 4Mpc) to find the closest example, of a giant, if peculiar, Elliptical galaxy. We will thus obtain a more accurate picture of the dark matter properties of a range of different galaxy types, the effects of tidal perturbation and the ubiquity of metallicity distribution functions.

While the CaT is a well-established metallicity indicator, the wavelength coverage of MICADO will also cover the near-infrared where the AO correction will be better. The J-band region of the spectrum contains a significant number of metallic lines (e.g. Fe I, Mg I, Si I, Ti I) which are relatively uncontaminated by molecular bands and therefore very suitable for abundance measurements (e.g. Davies et al. 2010). In the H- and K- spectral regions, molecular bands are more prominent, but abundance measurements are still feasible with use of spectral synthesis (see **Figure 4.7**). Red super-giants in particular are extremely bright in the near-IR, and abundance measurements are already feasible for individual super-giants throughout the Local Group with current 8-10 m class telescopes (Patrick et al. 2015). Moreover, the near-infrared spectra of young "super star clusters" are strongly dominated by red super-giants, and detailed abundance measurements have been obtained from near-IR spectra of super star clusters well beyond the Local Group, in dwarf galaxies such as NGC 1569 (Larsen et al. 2008) and even as far away as the *Antennae* interacting galaxies (Lardo et al. 2015). With MICADO, it will be possible to push such measurements to distances of 100Mpc or beyond, where the 16mas MICADO slit will be well matched to typical cluster sizes of ~5pc.

Resolved versus unresolved stellar populations: For more distant galaxies the brighter stars are resolved and the fainter stars are hidden in the crowded background. This requires the consideration of semi-resolved or unresolved stellar populations. This approach maybe refined by using the bright stars to predict the corresponding underlying stellar component and see what may be missing. This could allow relatively detailed star formation histories of more distant galaxies than is currently possible. However, this does require that the method is calibrated on more fully resolved stellar systems to ensure the accuracy and efficacy of the method is properly understood.

References:

Aloisi et al. 2007 ApJL, 667, 151; Bastian & Lardo 2018 ARA&A, in press; Battaglia et al. 2013 NewAR, 57, 52; Bernard et al. 2015 MNRAS, 453, L113; Boylan-Kolchin 2012 MNRAS, 422, 1203; Brown et al. 2006 ApJ, 652, 323; Cignoni et al. 2012 ApJ, 754, 130; Cole A.A. et al. 2007 ApJL, 659, L17; Davies B. et al. 2010 MNRAS 407, 1203; Deep, A. et al. 2011 A&A, 531, A151; Dohm-Palmer R.C. et al. 1997 AJ, 114, 527; Dolphin A. 2002 MNRAS, 332, 91; Greggio L. et al. 2012 PASP, 124, 653; Grocholski A.J. et al. 2012 AJ, 143, 117; Kennicutt R.C. 1998 ApJ, 498, 541; Lardo, C. et al. 2015 ApJ 812, 160; Larsen et al. 2008: MNRAS 383, 263; Larsen et al. 2011 A&A 532, A147; Larsen et al. 2018, A&A, 613, A56; Madau P. & Dickinson 2014 ARAA, 52, 415; Martocchia S. et al. 2018 MNRAS, 473, 2688; McGaugh S. et al. 2000 ApJL, 533, L99; Monelli M. et al. 2010 ApJ, 720, 1225; Moore B. et al. 1999 ApJL, 524, 19; Olsen K. et al. 2006 AJ, 132, 271; Patrick L.R. et al. 2015 ApJ 803, 14; Radburn-Smith et al. 2011 ApJS, 195, 18; Salaris et al. 2013 A&A 559, A57; Savino et al. 2018 MNRAS, in press; Starkenburg E. et al. 2010 A&A, 513, A34; Tolstoy et al. 2009 ARAA, 47, 371; Tolstoy 2011 Science, 333, 176; Tosi M. et al. 1991 AJ, 102, 951; Venn K.A. et al. 2004 AJ, 128, 1177; Weisz D. et al. 2014 ApJ, 789, 147.

5 Galaxy Evolution: detailed properties of distant galaxies

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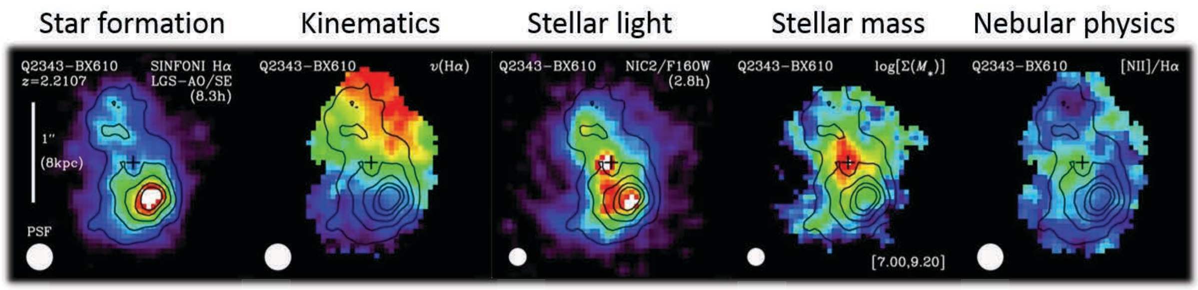
Outstanding Questions

The field of galaxy evolution has undergone major developments in the past decades, with the confluence of unique new instrumentation and techniques that have opened up the z>1 Universe to detailed observational studies. In addition, computational power has enabled ever more sophisticated numerical simulations. We now have a robust outline of the evolution of the global galaxy properties of high mass systems over much of the history of the Universe, and thus the first tantalizing pieces of evidence as to how galaxies assembled and transformed into the present-day Hubble sequence. The next obvious step is to move further down the mass scale and resolve faint distant galaxies on sufficiently small physical scales to accurately characterize these sub-galactic components, and also look at big galaxies closer to the scale on which star-formation is occurring.

The mechanisms driving galaxy formation and evolution involve a complex interplay between hierarchical merging of dark matter halos, the accretion and cooling of gas, gravitational fragmentation and the formation of molecular clouds, the resulting star formation, nucleosynthesis, and metal-enriched outflows (feedback) that are driven by stellar winds, supernova explosions and energetic output from accretion onto supermassive black holes (AGN activity). Recent developments have shown that ≥90% of star-forming galaxies out to a look-back time of 11Gyrs (redshift z~3) exhibit a tight relation between their star formation rate and their assembled stellar mass (e.g., Daddi et al. 2007; Whitaker et al. 2014) and consist mainly of discs that are increasingly star-forming, gas-rich, clumpy, and turbulent as a function of look back time (e.g., Wuyts et al. 2011; Tacconi et al. 2013; Wisnioski et al. 2015). In the “equilibrium growth” picture suggested by these results (e.g., Lilly et al. 2013), the elevated star formation rates of early galaxies are sustained by a continuous supply of fresh gas from the cosmic web that maintains large gas reservoirs. While the statistical census of deep surveys, that look back to the distant past, plays an important role in establishing the broad scope of scenarios such as the “equilibrium growth model”, more detailed spatially and spectrally resolved studies of individual galaxies are critical to improve our understanding of the critical physical processes. It is clear that as accurate as our studies are today, they are not able to trace the small spatial scales required to comprehensively follow the growth of galaxies. We also need to get closer to the scale on which star formation occurs, which is the scale of giant molecular clouds.

Resolving galaxy morphologies and colours out z~3 advanced dramatically with HST/WFC3. This extended our view of evolving galaxies from the optical to the near-IR window probing the rest-frame optical emission from the bulk of stars at z~3. In parallel, integral field spectrometers such as SINFONI, KMOS, and MUSE at the VLT routinely map the ionized gas kinematics and physical conditions of galaxies out to z~3, see **Figure 5.1**. With HST and ground-based AO-assisted observations, one can achieve an angular resolution of 0.1″–0.15″, corresponding to a physical scale of ~1kpc at z>1. The deepest observations probe galaxies during the first 2Gyr after the Big Bang, with the detection of many hundreds of galaxies well into the epoch of reionization (z>7), and even the spectroscopic confirmation of a handful at z>8 (e.g. Oesch et al. 2015). At sub-mm to radio wavelengths ALMA, NOEMA, and E-VLA are bringing resolved studies of the cold gas and dust reservoirs of galaxies in line with their stellar and ionized gas components.



a b c d e

Figure 5.1 *A z=2.21 massive star forming galaxy (the cross marks the kinematic centre):* ***(a)*** *SINFONI+AO observations in the K-band;* ***(b)*** *the SINFONI+AO Hα velocity field, which shows this to be a regularly rotating disc;* ***(c)*** *HST/NICMOS H-band imaging, rest-optical continuum light, with a PSF FWHM~0.2″, detailed structures are resolved on ~1.5kpc scales, notably bright off-centre star-forming clumps;* ***(d)*** *the distribution of stellar mass inferred from the J-H colour map reveals the presence of a massive stellar bulge;* ***(e)*** *spatial variations in [NII]/Hα nebular line ratios imply enhanced excitation around the centre due to the presence of an outflow driven by a low-luminosity AGN, and a shallow gas-phase oxygen abundance gradient towards the outer disc. From Genzel et al. (2014) and Tacchella et al. (2015).*

Importance of MICADO

Due to our present limits in spatial resolution the current picture remains incomplete because: (i) the best resolved physical scales are ~1kpc at z>1 (with the rare exceptions of strongly-lensed objects); (ii) the well-populated low-mass galaxy population [$\log(M_*/M_\odot)<10$] is largely missing and (iii) the detailed properties for galaxies at z>3 are poorly explored, which is when galaxies were first building up their stellar populations and gas reservoirs. We need to overcome these limits to build a more detailed physical characterization of galaxies over a wider range of mass, star formation activity, and environment. This requires the giant leap in spatial resolution, which is uniquely afforded by the ELT, with its 39m aperture and a 2µm diffraction limit of 13mas (which is ~100pc at z>1). It is important to stress that JWST's diffraction limit at 2µm is only 80mas (which is ~650pc at z>1). Moreover, the best spectral resolution offered by JWST spectrographs in the optical/near-IR will be modest (R≤2700, which is a velocity dispersion, $\sigma\geq$50km/s). By exploiting the angular resolution and sensitivity of the ELT, *MICADO will take resolved studies of distant galaxies to the next level*, opening unprecedented opportunities to address outstanding questions in galaxy evolution.

It is now fairly well established that the Hubble sequence, which is a correlation between global galactic structure and stellar population properties, was already in place at z~2.5 among massive galaxies (e.g., Wuyts et al. 2011). It is however not understood how this came about so rapidly, and what happens during the subsequent 11Gyr of cosmic time until the present day. Do galaxies form (and quench) inside-out? What is the rate of size growth of discs and spheroids? What is the role of mergers, internal dynamical processes, and feedback in galaxy growth? When and how do the thick discs, bulges, and globular clusters of today's galaxies form? How were the densest galaxies in the local Universe and out to z~3 assembled? What did the progenitors of Milky Way-like galaxies look like in their first few billion years?

MICADO will enable deep views of galaxies across cosmic times that are ~10 times sharper than is currently possible with HST, and ~5 times better than with JWST (see **Figure 5.2**). MICADO will be able to detect a wealth of detailed structure even at z=2 (see **Figure 5.2c** and **Figure 5.2d**), including compact star clusters to K_{AB}~28.5 mag; this limit corresponds to an absolute magnitude in the rest-optical at z=2 of R_{AB}~–16, which is comparable to the most luminous "super star clusters" in nearby starburst galaxies such as M82 and the Antennae. The smallest and faintest galaxies, as well as substructure within galaxies, will become accessible for study on scales of ~100pc. Key science drivers for MICADO encompass a broad range of themes addressing fundamental aspects of the lifecycle of galaxies from the earliest times, and also the connection with the circum-/intergalactic medium and the dark matter.

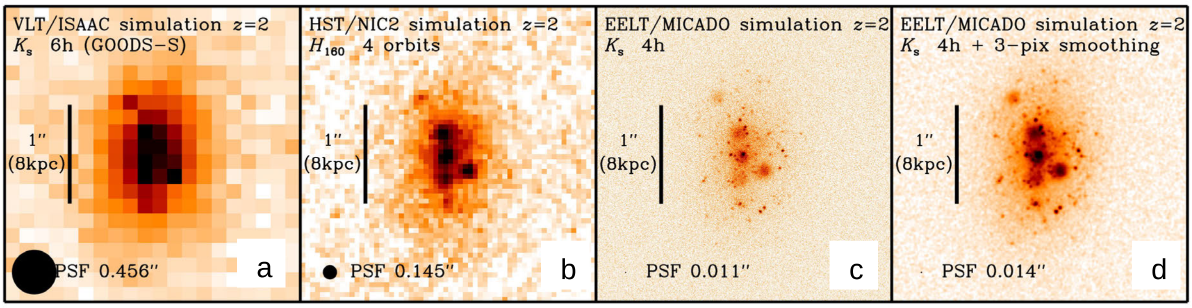


Figure 5.2 *Illustration of the gain in resolution with MICADO. The panels show the same simulated bright and large galaxy (K_{AB} ~21.3mag, half-light radius ~5kpc) at z=2. In addition, a few hundred compact (unresolved) clusters were added with a range of magnitudes. The clumps and clusters contribute roughly 40% of the total light of this simulated galaxy. Simulations are:* ***(a)*** *deep, seeing-limited ground-based image (6 hours with VLT/ISAAC in K);* ***(b)*** *deep diffraction-limited HST/NICMOS image (4 orbits with NIC2 camera in H);* ***(c)*** *a similar integration time of 4 hours with MICADO in K, at a resolution of about 10mas or 80pc;* ***(d)*** *smoothing MICADO image, with a Gaussian of FWHM equal to the PSF, to enhance the rich structure.*

Some Specific Science Cases

Resolving discs at high redshift: The detailed workings of the physical processes at the origin of the early Hubble sequence remain elusive. The main limitation is spatial resolution (see **Figure 5.2**). Current observations of faint high-redshift galaxies achieve at best 0.1″–0.15″ spatial resolution (which corresponds to ~1kpc at z>1). This resolution corresponds to the typical radii of $\log(M_*/M_\odot)$~9 star-forming galaxies and $\log(M_*/M_\odot)$~10.5 quiescent galaxies, and to the inferred vertical height of star-forming discs at z~2. High resolution imaging with HST generally gives very few resolution elements, of order 10, within an effective radius. This is equivalent to imaging Virgo galaxies with 10″ seeing. Morphological features such as star-forming clumps and putative bulges can be viewed only on ~1kpc scales and so the detailed profiles cannot be determined.

One of the most striking feature in the morphologies of z>1 galaxies is the common presence of giant kpc-scale, luminous "clumps", see **Figure 5.1**. It is now well established that these clumps represent star-forming complexes within otherwise fairly regularly rotating discs, scaled up by a factor of ~10 in size, mass, and luminosity compared to those in present-day star-forming galaxies. High-redshift galaxy discs also differ from z~0 discs in that they have 10–20 times higher global star formation rates, are several times more gas rich, and are characterized by a more turbulent ISM with up to ~10 times higher intrinsic velocity dispersions, σ_0. The ratio of rotation velocity, v_{rot}, to dispersion, σ, are ~1–10, which implies that high-z discs are also geometrically thicker than local spirals, which have v_{rot}/σ_0~10–20. These results raise many questions about the nature and timescales of internal dynamical processes at the epochs when thick discs, bulges, and metal-rich globular clusters were forming. To address these questions, in the necessary detail, images are needed with the high spatial resolution that only MICADO can provide.

With its much larger collecting area and higher spatial resolution MICADO will provide multi-colour images of high-redshift galaxies with a richness of detail approaching what is currently only possible for relatively nearby galaxies. This leap in resolution and sensitivity will make it possible to map the distribution of stellar light on scales of ~100pc or better. This will make it possible to distinguish bulge and disc components of distant galaxies and measure their sizes and detailed structural profiles. It will also allow the search for luminous star clusters, and for unambiguous signatures of AGN activity. This will make it possible to pinpoint the physical processes that are shaping galaxies at the epoch when mass build up and morphological differentiation are at their peak. Diffraction-limited imaging with MICADO will typically provide >100 resolution elements across galaxies, and this will make it possible to isolate and even resolve regions with sizes comparable to individual star-forming complexes such as 30Dor in the LMC and N66 in the SMC. In addition, slit spectroscopy with MICADO on these spatial scales, with R~10k spectral resolution, will allow measurements of the kinematics of clumps down to 100pc size, providing their dynamical masses. For example a $10^8 M_\odot$ clump of 500pc radius would have an emission line width of σ~15 km/s. High-resolution slit spectroscopy will further help to determine if there is evidence for rotational-support as some simulations suggest (e.g., Ceverino et al. 2012). The rest-frame optical emission line spectra of clumps will enable measurements of their metallicities and gas mass outflow rates driven by star formation, further constraining their origin (in-situ vs. external) and their long-term fate.

Looking for signs of bulge formation: The presence of genuine “bulges” in massive high redshift discs remains uncertain. The central excess in stellar light/mass detected in HST imaging, that is most pronounced for higher mass galaxies, is barely or not resolved in current observations, such that it is unclear whether the associated structure is a classical bulge (with a $R^{1/4}$ de Vaucouleurs profile), or a pseudo-bulge or inner disc (and a shallower profile). The detailed profiles of galactic components carry the imprint of the formation mechanism (e.g., Kormendy 2016; Bland-Hawthorn & Gerhard 2016). MICADO high-resolution imaging will for the first time resolve the inner regions (R<1kpc) of massive galaxies and shed crucial light on the mechanism(s) and timescale for the formation of bulges (see also §8). High-resolution spectroscopy will constrain the dynamical state (dominant rotation vs pressure support) and total enclosed mass as a function of radius on unprecedented scales in and around the nuclear regions. Spectroscopy will enable to determine the origin of powerful “nuclear outflows” recently discovered in the majority of galaxies at or above the Schechter mass, which are thought to play a role in quenching of high-mass galaxies. These could be caused by AGN or compact nuclear starbursts, and high spatial resolution spectroscopy is needed to be able to make this distinction.

Looking for Globular cluster formation: Metal-rich globular clusters in nearby galaxies are known to be dynamically associated with their bulges and thick discs. The ages and abundance patterns of these globular clusters suggest an early formation a few billion years after the Big Bang (e.g., Searle & Zinn 1978). These properties, together with the typical distribution and kinematics of globular cluster populations, have led to the suggestion that the giant clumps seen in z~2 star forming galaxies may be emerging globular cluster populations (e.g., Shapiro et al. 2010). MICADO will directly test this scenario, by resolving the structure of clumps and determining their kinematics. This experiment has demanding requirements for MICADO, in terms of image stability, resolution and sensitivity, see **Figure 5.2**. To be able to characterize clump substructure above the host galaxy luminosity requires a very well determined high strehl PSF. MICADO imaging simulations with a PSF FWHM of 100pc and Strehl of 50% suggest that compact putative globular cluster progenitors could be detected (S/N~3) up to K_{AB}=28.5 mag, see **Figure 5.3**. At z~2, this sensitivity corresponds to a rest-frame absolute R-band M_{AB}=–16mag, which is about that of the most luminous "super star clusters" in local starburst galaxies such as M82 and the Antennae. Sensitive high spatial and spectral resolution spectroscopy with MICADO, would allow an estimate of the dynamical masses of such young luminous stellar clusters. For example, a $10^7 M_\odot$ cluster with a 50pc radius would have an emission line width, σ~15 km/s. Their chemical abundances can be measured from strong emission lines. For instance, if such a compact young cluster at z~2.3 is forming stars at ~$30 M_\odot yr^{-1}$ (scaling from the masses and SFRs of nearby examples; e.g. Weidner et al. 2010), has a visual extinction of 1mag, and a nebular metallicity of 1/3 the solar value, a 1hr integration with MICADO in slit spectroscopic mode would detect its Hα emission line at >100σ and measure its metallicity from the [NII]/Hα line ratio at ~8σ.

The simulations shown in **Figure 5.3** illustrate the potential of MICADO to resolve detailed substructure in low-mass $\log(M_*/M_\odot)$~9 galaxies at z>1. In the z=1.85 galaxy of the left panel, the three brightest clumps (H_{AB}~26-26.5) are retrieved as are the brightest ~1/3 of the clusters (at H_{AB}~26-30) are detected at $\gtrsim 5\sigma$. In the two z~3 galaxies, the brightest 5 clusters (H_{AB}~29-30) are well detected at $\gtrsim 5\sigma$. At z~5, clumps and clusters would be more difficult to detect if they follow the scaling in properties assumed in these simulations; nonetheless, the 2D galactic profiles will be resolved and deviations from axisymmetry caused by clumps/clusters should be measurable, as in the example in the right-most panel of **Figure 5.3**, where a H_{AB}~30.5 cluster causes the off-centre peak in the light distribution.

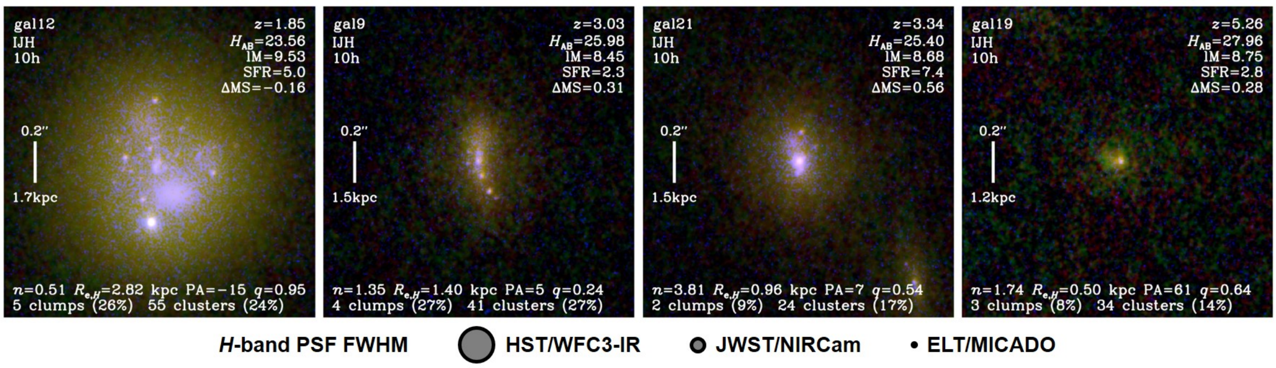


***Figure 5.3** Simulations of composite IJH colour maps of distant galaxies in deep MICADO/SCAO images made with SimCADO, assuming 10hrs integration in each band, with 4mas pixels. The global galaxy parameters and redshifts were taken from the HUDF source catalogue and these properties are given in the labels of each panel (redshift z, total H-band magnitude H_{AB}, $\log(M_*)$ as lM, star formation rate, SFR etc.). Several Gaussian "clumps" with half-light radii in the range ~100–500pc, and bluer colours than the galaxy were added at random positions within the central 1-2$R_{e,H}$ (effective radii) based on expected clump properties. The total number and light contribution in the H-band of the clumps and clusters is indicated in the images and the magnitude and colours of all components are adjusted such that the integrated properties correspond to the input HUDF catalogue measurements.*

Resolving compact galaxies at z>2: Recent results have shown a population of compact galaxies at z>2 (Daddi et al. 2005; Cimatti et al. 2008; van Dokkum et al. 2008; Huertas-Company et al. 2015; van der Wel et al. 2014, and references therein), consistent with some of the galaxies increasing their size by minor mergers (Naab et al. 2009; van Dokkum et al. 2010; Shankar et al. 2014) and others quenching at later time (Carollo et al. 2013; Stringer et al. 2013). We still do not understand how these galaxies formed. They are four times more compact at z~4 than compact galaxies in the local Universe, and they show both quiescent and star-forming stellar populations (Barro et al. 2017; Mei et al. 2015), see **Figure 5.4**. Most objects show asymmetries, faint substructures and tails, which may signal merger events. The star-forming compact galaxies number density drops at z>3 (with only 15% of compact galaxies being passive at these redshifts; Marchesini et al. 2014; Williams et al. 2014), indicating that they are quenched between z~2 and z~3. These galaxies will likely only be marginally resolved with the JWST. On the contrary, MICADO will certainly resolve them, identify signatures of mergers, and obtaining precise radial profiles to determine where and how quenching happens.

Figure 5.4 *Examples of galaxies in clusters at z~2: combined colour images of the spectroscopically determined members of the proto-cluster HUDFJ0332.4-2746.6 at z~1.84, from HST/ACS and WFC3 images. From Mei et al. (2015).*

Progenitors of massive Early Type Galaxies in the densest environments: The galaxies found in clusters out to z~1.5 are very different from the field (e.g. Mei et al. 2009). In galaxy clusters, ~80% of the galaxies have early-type morphology. This means Elliptical and Lenticular galaxies with large bulges and small or no discs, and typically with old stellar populations. This is in contrast to the field, where ~80% of the galaxies have late-type morphology. This means spiral galaxies with small bulges and large discs, and irregular galaxies, that are typically still forming stars. These fractions change dramatically at z>1.5, where star-forming galaxies significantly populate cluster cores (e.g. Brodwin et al. 2013; Mei et al. 2015; Alberts et al. 2016), indicating both stellar population and morphological transformations at this epoch. The high resolution imaging from MICADO will permit us to study in detail the structure of the galaxies found in young clusters and proto-clusters at z>1.5 and discriminate between the physical mechanisms behind their transformations (e.g. mergers, disc instabilities, etc.). These objects cannot be resolved with HST imaging in which they appear as blurred irregular features (see **Figure 5.4**). To study detailed morphology and identify mergers, we require a resolution of at least 10mas to distinguish low mass merger partners and low surface brightness features. This is also beyond HST and JWST capabilities. A depth of M_{AB}~28 is necessary to identify galaxies brighter than L* at the higher redshifts. Thus, only MICADO will be able to detect such low surface brightness features, identify potential mergers, and disturbed morphologies at the needed scale of ~100pc. Spectroscopy will be able to separate multiple companions and determine if the structures originate from mergers.

QSO host galaxy properties: More than 50 years after the discovery of quasars, the origin and role of powerful nuclear activity in the centres of massive galaxies is still poorly understood. Yet, the evidence that virtually all massive galaxies host a super-massive black hole at their centre indicates that there is an important link between the processes that govern the formation of galaxies and super-massive black holes. To explain this link it is necessary to measure both the mass of the black hole and the properties of the host galaxy over a wide range in cosmic time (e.g., Decarli et al. 2010). The black hole mass can be estimated from the width of the broad emission lines and the continuum luminosity of the nucleus (e.g., Peterson 2014), while the properties of the host galaxy can be derived from deep, high-resolution images in the near-IR dominated by starlight (e.g., Falomo et al. 2005). The faintness of host galaxies and their small size (at z>1, the light from massive galaxies is concentrated at radii <0.2–0.4″), means that it is notoriously difficult to separate them from the bright QSO with the angular resolution afforded by current instrumentation. Both high sensitivity and superb resolution are mandatory. A high Strehl ratio is essential to concentrate the light from the active nucleus, and to boost the contrast between the emission of the QSO and the host galaxy. In addition, the detection and characterization of potential features very close to the nucleus, such as companion galaxies, jets, and tails as are observed in low-z QSO galaxies by HST, puts similar requirements on sensitivity and resolution for high-redshift objects. These requirements will be met by MICADO, as illustrated with an example of the simulated high-redshift QSO image in **Figure 5.5**. No other currently planned instrument will reach the same combination of sensitivity and angular resolution. The high sensitivity and high spatial resolution of MICADO will make it possible to de-blend the light of both components and thus characterize the QSO host galaxy properties. MICADO will thus uniquely enable the characterization of z>1 QSO host galaxies, crucial to understand the physics underlying the galaxy–black-hole co-evolution.

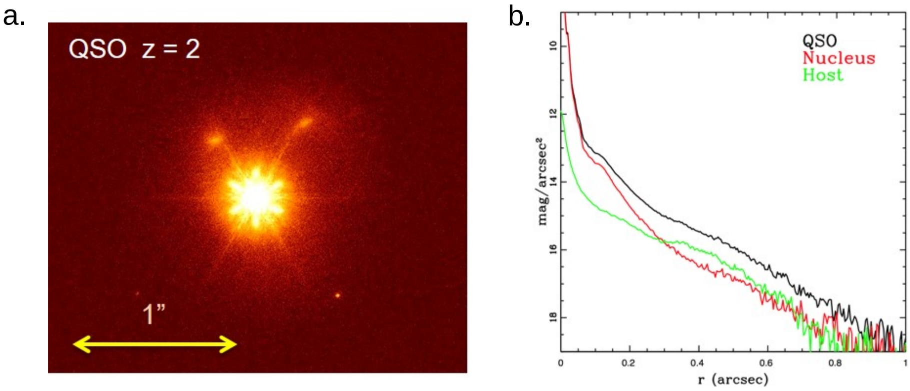


Figure 5.5 ***(a)*** *MICADO simulation of the image of a QSO at z=2 in K_s for a 2hr exposure;* ***(b)*** *The average total radial brightness profile of the QSO (black) compared separately with that of the active nucleus (red) and of the host galaxy (green). Simulations provided by AETC.*

Structure of strongly lensed galaxies and dark matter halo substructure: One of the most significant challenges of modern cosmology and particle physics is to explain the nature of dark matter. Although several hypotheses have been proposed, no final theory has yet been obtained. All dark matter models predict that structures form via gravitational instability from primordial density fluctuations in the early Universe and grow hierarchically in time through the merging and accretion of smaller objects (e.g., White & Rees 1978). As a result, it is expected that the dark matter distribution should be clumpy and that there should be many smaller dark matter haloes within other more massive structures and along their line-of-sight. The specific scale at which the Universe is expected to be clumpy depends strongly on the assumed physics of the dark matter particles (e.g., Lovell et al. 2014). However, most of these low-mass dark matter haloes are expected to be completely dark and not directly observable. At present, strong gravitational lensing is one of the most promising tools to resolve this issue. Being sensitive only to gravity, lensing is the ideal method to robustly detect these small dark-matter haloes via their gravitational effect on the surface brightness distribution of Einstein rings and highly-magnified arcs (Vegetti et al. 2014; Despali et al. 2018). This approach requires deep imaging observations at high angular resolution. Currently available datasets collected with HST and Keck AO-assisted observations only allow observations of the higher-mass end of the dark matter mass function. In this regime, predictions from different dark matter models do not differ significantly, and substantial degeneracies between galaxy formation and dark matter models are expected (Despali & Vegetti 2017). Even JWST will not be enough to reach the required sensitivity and resolution. MICADO, thanks to its exquisite angular resolution, will lower the detectable mass limit by 1–2 orders of magnitude down to ~$10^7 M_\odot$ for substructure within the lensing galaxy, and down to ~$10^6 M_\odot$ for line-of-sight haloes located at lower redshift (Despali et al. 2018), see **Figure 5.6**. At these masses, predictions from different dark matter models are expected to differ >2 orders of magnitude. Coupled with EUCLID, which is expected to discover $>10^5$ new lens systems, MICADO will therefore be an essential instrument for detecting the smallest and farthest dark matter haloes, and setting constraints on the nature of dark matter, with high statistical precision.

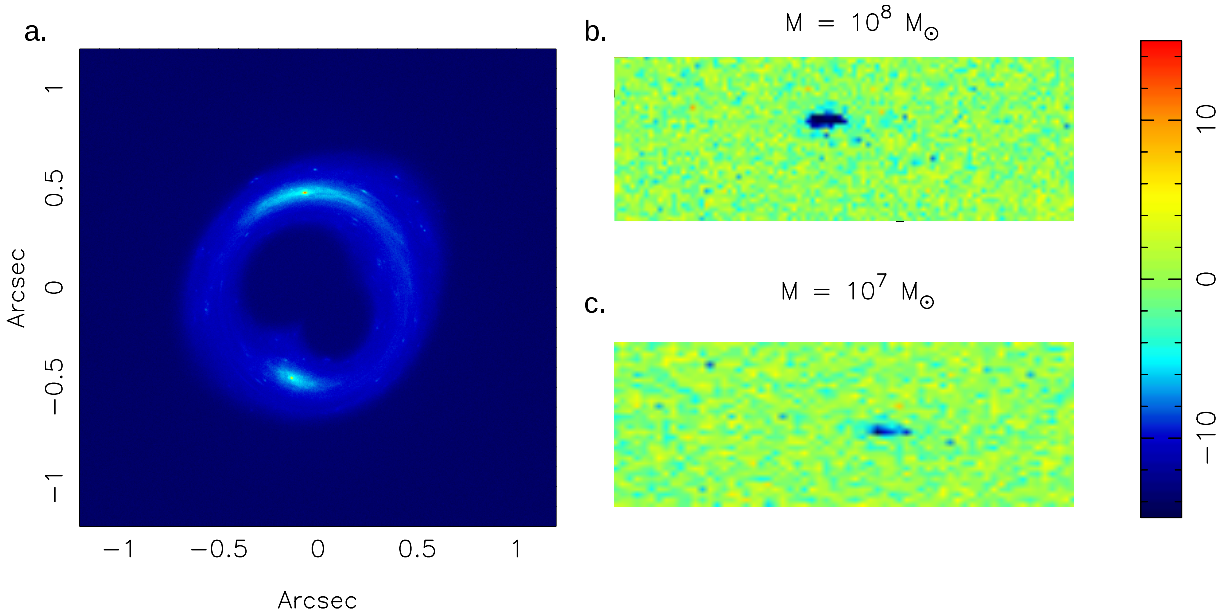


Figure 5.6 (a) *H-band simulation of a gravitationally lensed galaxy at z=2, from SimCADO, assuming 4mas/pixel, and the SCAO PSF, for a 2hr exposure time. The compact foreground lens galaxy (at z=0.88) is not included as its light distribution does not affect the analysis of the source structure. Sub-halos of various masses were placed in the upper part of the Einstein ring to assess their effect on the source structure. The zoomed in normalised residuals between a mock data without substructure and a substructure are shown for substructure masses of (b)* $10^8 M_\odot$ *and (c)* $10^7 M_\odot$*. Both sub-halo masses are responsible for localised changes of the surface brightness distribution above the 10-sigma level.*

References:

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6 Planets and planet formation

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Outstanding Questions

The observation and characterization of exoplanets and planetary architectures is crucial to expand and complete our view of planetary formation and evolution, as well as of the physics of exoplanets. During the two decades of exoplanet studies observations have regularly obtained key successes. For example, the discovery of the Hot-Jupiter family; the detection and confirmation of ~2000 exoplanets (see http://exoplanet.eu); the first glimpse of planetary atmospheres and internal structures; the first direct images of exoplanets; the discovery of Super-Earths in the Habitable Zone (where water is expected to be liquid); and most recently Earth- and even Mars-mass planets. These discoveries need to be followed up with detailed characterisation of the different types of exoplanets, for example through monitoring their orbits, looking for other planets in the same system, and spectroscopic follow up to determine their surface and atmospheric compositions, determining if they are rocky of gaseous, and if there are molecules present. All these approaches require very sensitive instrumentation that is capable of working on the smallest spatial scales possible. Thus moving to a large telescope with a smaller diffraction limit immediately expands the range of planets that can be discovered and studied around nearby stars.

The main techniques currently used to find and study exoplanets are radial velocites; transits; micro-lensing; direct imaging; astrometry; polorimetry and spectroscopy, either direct, or mostly using sophisticated techniques to disentangle the star and planet signatures. The techniques are all complementary and can be combined to constrain planet properties like density (using radial velocities and transit information) or internal entropy (radial velocities and direct imaging), chemical properties (high contrast imaging plus spectroscopy). Radial velocity and transit surveys have been particularly successful with the discovery of thousands of planetary candidates. Combining these discovery surveys with micro-lensing and astrometry, it is possible to study the inner regions of exoplanetary systems, at <5–10AU (see **Figure 6.1**). Direct Imaging is uniquely able to explore the outer regions >5-10AU to complete our view of exoplanetary systems. The exoplanet light can also be resolved and dispersed spectroscopically to probe the atmospheric properties of the imaged exoplanets. Young exoplanets are the most commonly discovered, as they are hotter and brighter. The study of their atmospheres shows low-gravity features, as well as the presence of clouds, and non-equilibrium chemistry processes. Moreover, direct imaging enables an overview of the presence of planets in their birth environment (within discs). Their physical properties can then be directly connected to the observed spatial structures in young proto-planetary or debris discs to study the young planets, namely disc interactions and the overall stability of the system.

In the coming decade, there are numerous facilities planned for exo-plantary studies. There will be space missions and ground-based instrumentation dedicated to exoplanet detection and characterization. ALMA in its complete form will pursue the characterization of the cold dusty and gaseous component of young protoplanetary and debris discs with an exquisite spatial resolution (down to 0.1"). NIRPS being built for the ESO3.6m will extend the current HARPS horizon to the population of light telluric planets around solar and low-mass stars. In space, Gaia will discover thousands of new planetary systems, providing a complete census of the giant planet population between 2–4AU for stars closer than 200pc. The new transiting exoplanet survey satellite (TESS, Transiting Exoplanet Survey Satellite) will go beyond the Corot and Kepler missions. It is designed for a full-sky survey to reveal thousands of transiting exoplanet candidates the size of Earth or larger and orbital periods of up to two months. This will be complemented in the near future by the ESA CHEOPS (CHaracterising ExOPlanet Satellite) mission aimed at characterizing the structure of exoplanets with typical sizes ranging from Neptune down to Earth diameters orbiting bright stars. PLATO (Planetary Transits and Oscillations of Stars) will further extend our knowledge on the content of telluric planets at longer periods, up to several years, around relatively bright, nearby stars. Within 10–15yrs, the era of large-scale systematic surveys will end thanks to a complete census of exoplanetary systems within 100–200pc from the Sun. All these missions are designed to find and characterise the size and orbits of these new planetary systems, focusing on telluric planet, but it is only with the extremely high spatial resolution of an ELT that selected individual systems can be directly imaged in detail, or spectra taken of individual exoplanets.

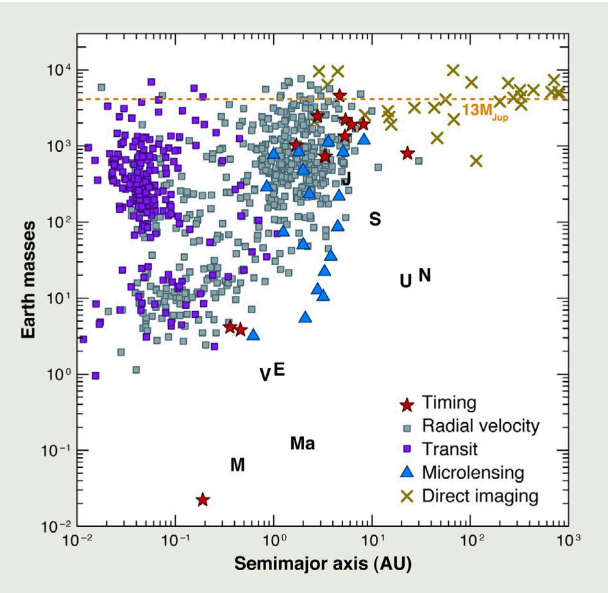

***Figure 6.1** Overview of exoplanet discoveries for different planet hunting techniques. The exoplanet masses are shown as a function of their semi-major axes. Many different techniques are successful at discovering exoplanets, as indicated by the different symbols. The solar system planets are denoted by the first one or two letters of their name. The horizontal line is the conventional upper limit to a planet mass (13 Jupiter masses). The sloped, lower boundary to the collection of grey squares is due to a selection effects. Small planets are beneath the threshold for the current state of almost all exoplanet detection techniques. From Seager (2013).*

Importance of MICADO

Thus, a new era is about to begin, fully dedicated to the characterization of known systems. Hubble, Spitzer and the first generation of planet imagers and spectrographs on 8m ground-based telescopes (SPHERE and GPI) have already initiated these studies (see **Figure 6.2**). The characterization of the physics of giant planets will intensify with the operation of the JWST, which will address several key questions for the study of young circumstellar discs and exoplanetary atmospheres using direct imaging and transit and secondary eclipse spectroscopy. MICADO will offer uniquely high spatial resolution imaging combined with high resolution spectroscopy, and will arrive at a propitious time to exploit discoveries of the upcoming years. MICADO offers the possibility to image and characterize planets and young planetary systems at the ELT diffraction limit in the near-infrared (10mas at K-band), see **Figure 6.2**.

VLT/NACO first opened up a window in exoplanet imaging science, making it possible to detect and study young giant exoplanets as well as circumstellar discs, but also forming planets buried in protoplanetary discs. This has been achieved thanks to the use of pupil tracking to stabilize the telescope/instruments aberrations with respect to the detector while the field rotates and also dedicated filters to reduce the star/planet contrast. The same kind of general purpose instrument on ELT will improve the current angular resolution limits by a factor of 4–5. MICADO is a general purpose instrument and thus will be able to tackle some particular aspects of the studies of young exoplanets (see **Figure 6.2**). The high contrast imaging capability will take advantage of the obvious gain in angular resolution with respect to any other current or planned facilities. In addition, the photon collecting power of the spectrograph will enable the detection of chemical species in the atmospheres of smaller and cooler planets. MICADO will be the most powerful facility for direct imaging of exoplanets pending the installation of a dedicated facility on the ELT (EPICS) where the objective will be the complementary case to address more mature and colder exoplanets.

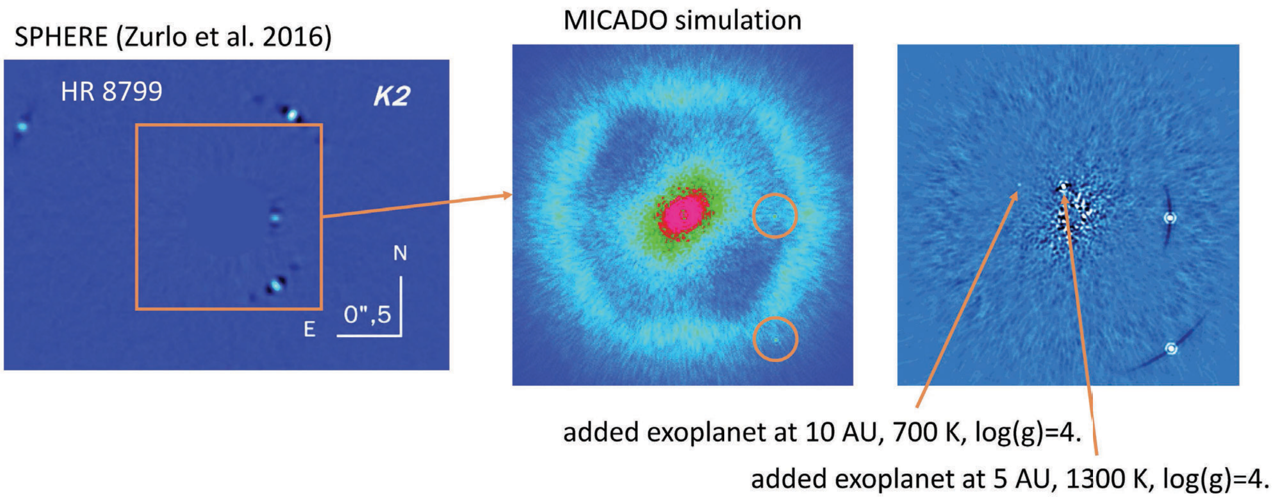

***Figure 6.2** Compares SPHERE observations of the planetary system around HR8799 to simulations for MICADO. Left: SPHERE image of HR8799 showing the 4 known planets (from Zurlo et al. 2016). Centre: Coronographic simulation of 30s integration with MICADO reveals the two inner planets. The structure in the image arises from the optical configuration of the telescope and AO system, and its wave-front correction. Right: with basic processing of a series of exposures, one is in principle able to detect other fainter and cooler planets at smaller radii.*

The high-contrast imaging mode of MICADO plus the high resolution spectrograph will use the combination of SCAO-correction, coronography and angular differential imaging to address several still unanswered questions, which are likely to remain unanswered until an imager and high resolution spectrograph with the spatial resolution of MICADO becomes available:

1. *How do giant planets form?* Understanding how the giant exoplanets form, how they evolve and interact, is critical. They completely shape their planetary system architecture and appear to offer the possibility to form Earth or Super-Earth-like planets, which means rocky planets on a stable orbits, capable of retaining liquid water and sustaining life. There are still fundamental questions for which we do not know the answer. For example, is there a single formation mechanism or several to form giant planets and these may possibly operate over different timescales, locations and physical conditions. We do not understand the influence of the initial conditions, such as the importance of the stellar mass, the stellar metallicity or the stellar multiplicity, the effect of the close stellar environment on planetary formation. The synergy between the MICADO high-contrast imaging mode and additional techniques like astrometry (GAIA) and radial velocity (VLT/ESPRESSO) will offer a unique view of the planetary system architecture at all orbital distances for the giant planet populations. This will include the characterization of their frequency, multiplicity, distribution of mass and orbital parameters for a broad range of stellar properties (mass, metallicity and age). Observables will be directly compared to predictions from population synthesis

models for various types of formation mechanisms (core accretion, gravitational instability and gravo-turbulent fragmentation). Furthermore, MICADO's spectrograph will enable metallicity measurements of exoplanets. This will reveal the gas properties in the primordial birth environment and break degeneracies distinguishing those with large rocky cores and those with extended H/He envelopes.

2 *What are the initial conditions of planet formation?* The high-contrast mode of MICADO combined with the large field of view of the near-infrared camera will offer the unique possibility to explore the properties and morphology of young protoplanetary and debris discs at an unprecedented spatial resolution. It will be possible to connect asymmetries (e.g. cavities, gaps, holes, clumps, vortexes) to the various physical processes at play including planetary formation. This will allow the identification of the key mechanisms of dynamical evolution (planet-disc and planet-planet interactions) in a range of systems.

3 *What are the physical properties of young Jupiters and Saturns?* There are still large uncertainties crossing two orders of magnitude to predict basic properties such as the luminosity of young Jupiters and Saturns. We do not understand how the gaseous component is transferred and accreted from the protoplanetary disc onto the planetary atmosphere. The masses of young imaged exoplanets are currently predicted by non-calibrated evolutionary models. MICADO high-contrast imaging mode will offer the unique possibility to simultaneously derive the dynamical mass together with the orbital properties and the luminosity of the young Jupiters and Saturns. This will set stringent constraints on the phase of planetary atmosphere formation and will offer unprecedented tests for theoretical predictions of giant planet formation and evolution.

Some Specific Science Cases

Given the current estimations of performance, four particular areas were identified as niches for MICADO in breakthrough studies of exoplanetary systems.

Study of nearby known planetary systems: Assuming MICADO is able to achieve the same level of contrasts as NACO, a βPicb-like object becomes easily detectable at ~2AU, instead of the current limit of 8-10AU, with the capability to extend this distance even closer in (down to 1AU for a star at 10-20pc). MICADO will have the capability to reach closer physical separations than NACO and even SPHERE on nearby targets (<50pc), see **Figure 6.2**. Since planetary systems are found to be compact in RV surveys, this means that the discovery of planets at long periods favours the existence of other planets at shorter periods. This means that it is crucial to reach down to smaller separations to confirm this. In addition, this range of physical distances overlaps with those probed by RV studies, which now starts to be applicable to young early type stars. The GAIA satellite will also bring new detections in the same range of physical distances probed with MICADO. Therefore, it will become possible to connect these techniques for the same systems and derive constraints on the true masses of a range of different planets. This will allow a more precise calibration of evolutionary models, which ultimately makes it possible to carry out better spectral characterization (from photometric or even spectroscopic data). These type of observations will provide substantial new information about the range of physical properties of exoplanets.

For observing young and nearby stars, MICADO must be capable of pointing at bright stars (V>2-3). The most interesting targets will be known beforehand from SPHERE or from future RV and astrometric surveys.

Planetary systems in young distant associations: A complete new range of targets will be attainable with MICADO given the larger collecting area and the gain in resolution. Observations will preferentially be made in the K band, combined with narrow bands to derive near IR colours and to put constraints on some atmospheric properties like temperature and surface gravity. MICADO will be able to search for young planets in distant (>50-100pc) young stellar associations, such as the ScoCen associations that have been fruitful for the search of exoplanets and discs. Typical performances will allow the detection of massive planets (>5M_J) on wide orbits (>10AU) complementing the current performance of SPHERE in these young associations. These MICADO observations will allow us to understand how these planets form.

Planet-disc interactions: Circumstellar disc studies are strongly connected to those of exoplanets, as exoplanets form in circumstellar discs. Here again there are several interesting gains to be made in the imaging of protoplanetary and debris discs with MICADO thanks to the enhanced angular resolution. There are hundreds of stars with infrared excesses detected in unresolved photometry. The modelling of their spectral energy distribution informs us about the likely dust properties, but the detailed knowledge of the dust spatial distribution is critical to remove important degeneracies. SPHERE and GPI have boosted disc science by improving contrast. In the first two years of operation, these instruments have provided several exciting discoveries of new discs or structures in known discs, both in the protoplanetary regime (where the gas dominates the dynamics) or in the debris disc regime (where the gas is mostly evacuated). MICADO will be able to resolve a whole class of discs observed recently by Spitzer that are too small or too faint for SPHERE or even JWST to make follow-up imaging of their inner regions. Measuring the size of the discs as well as their surface brightness is the key to determine the location of the planetesimal belts, which are the seeds for planets. In addition, near-infrared colours are important to measure the scattering efficiency which will bring additional constraints on the dust properties.

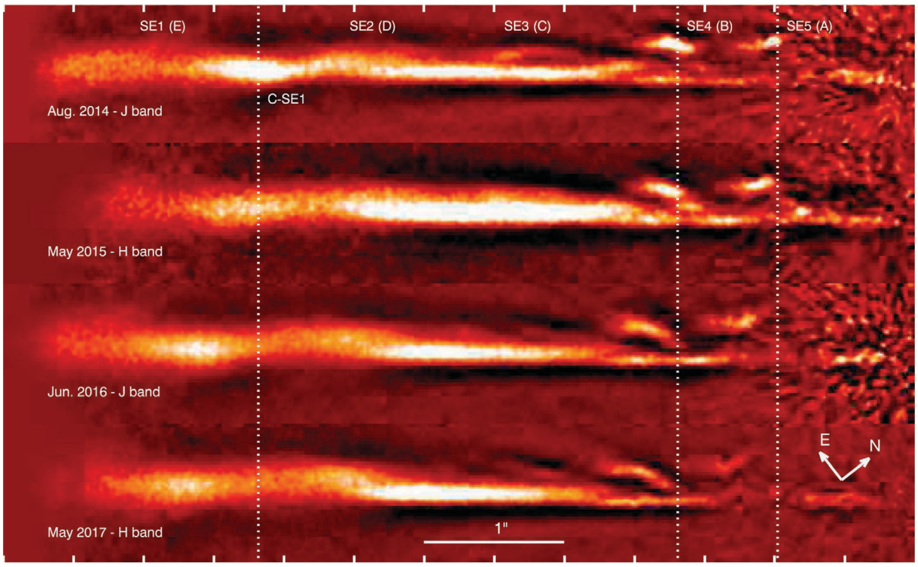

Figure 6.3 *SPHERE/IRDIS total intensity images of the AU Mic debris disc taken over a period of nearly 4 years. The star is at the right of the image. The field of view is 6.5"×1.0" for each image. The intensity scale is adapted for each epoch. Recurrent features can be seen moving outwards from the centre of the system at high speeds. From Boccaletti et al. (2018).*

For previously known discs the improvement in angular resolution of MICADO imaging will be invaluable to carry out detailed dynamical studies of the small scale structures. Any structures (warps, clumps, offsets, spirals) deviating from the simple assumption of an axi-symmetrical system is of interest in the context of planetary formation. Either some of these structures can be indirectly generated by planets or they may lead to planet formation. Here the advantage of MICADO is to be able to resolve these structures down to extremely small scales, but also to see how the structures change over different time periods to determine their dynamics. This work has been started with SPHERE (Boccaletti et al. 2018), see **Figure 6.3**. This approach will be much more powerful for a larger number of systems with MICADO. This category of observations will provide information to address questions related to the initial conditions of planet formation.

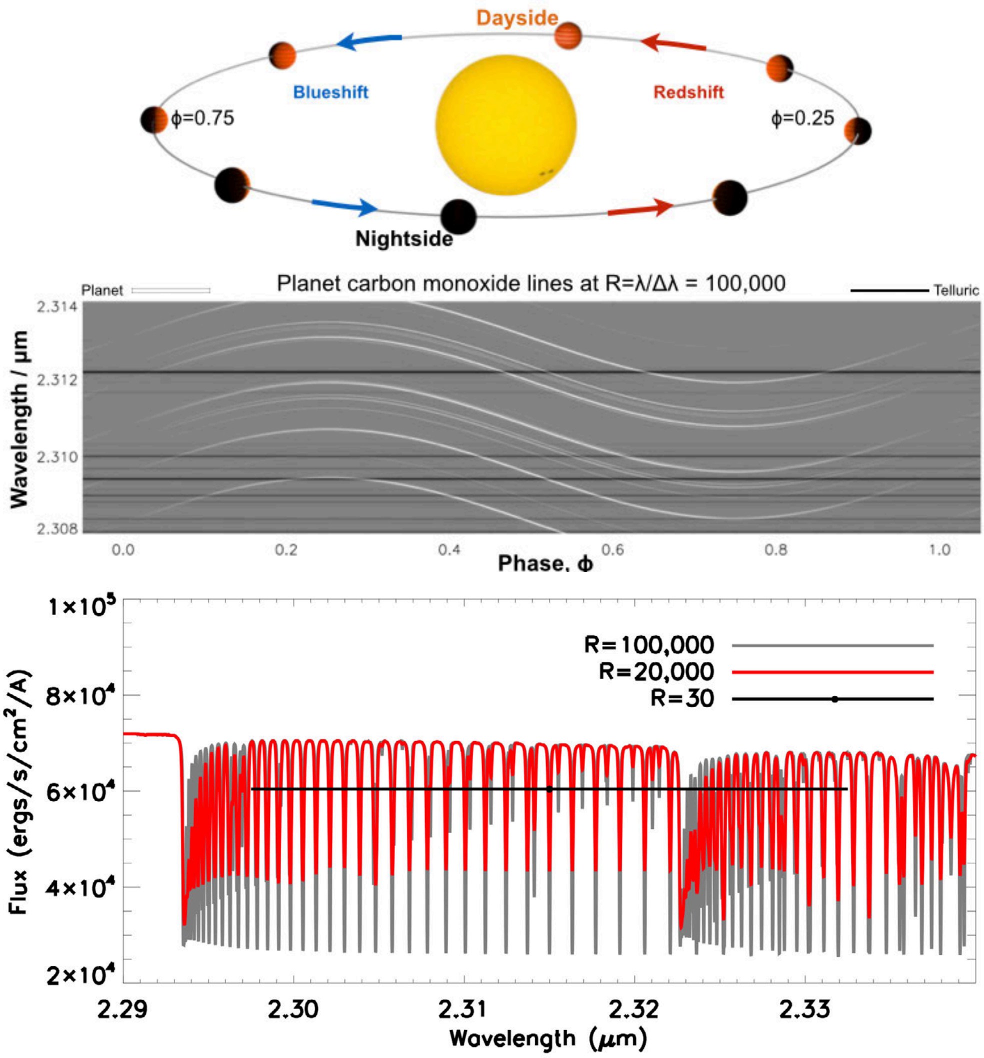

***Figure 6.4** Schematic of the high-resolution spectroscopy technique for characterizing exoplanet atmospheres. The planet changes its velocity significantly more than its host star and Earth's telluric features during its orbit, enabling it to be disentangled by removing all features that do not vary in wavelength over time. A cross-correlation of the remaining signal with a high-resolution theoretical template combines the signal from all of the planetary spectral lines to determine the molecules present in its atmosphere, and measure its orbit velocity and mass. The bottom panel highlights the information gained when moving to higher spectral resolution compared to current low-resolution space-based data (R=30). Figure adapted from Birkby (2018).*

Exoplanet atmospheres with high resolution spectroscopy: High-resolution spectroscopy (R>20,000) is a powerful tool for characterizing exoplanets and their atmospheres (Snellen et al. 2010; Brogi et al. 2012; Birkby et al. 2013, 2017, Lockwood et al. 2014; Birkby 2018). It uses the large velocity change (Δkm/s) of a planet during its orbit to disentangle it from the quasi-stationary spectral features of its host star (Δm/s) and Earth's telluric lines (see **Figure 6.4**). This is applicable not only when a planet transits its host star, but also at any point during the orbit when the planet is emitting flux, and thus can be used to study non-transiting systems as well. This opens up the entirety of the exoplanet zoo for characterization. The observations provide measurements of the relative abundance ratios of molecular species in the planet atmosphere, along with its atmospheric structure, as well as a true measurement of the planetary mass, even in non-transiting planets. Key to its success is the technique’s power in resolving molecular bands into dense forests of individual lines in patterns that are unique for any given chemical species. These patterns are difficult to mimic by chance with systematics, especially when combined with wide instantaneous wavelength coverage. The high-resolution single-slit spectrograph of MICADO at R=20,000 is ideally suited to leverage this technique. MICADO will enable precise measurements of C/O ratios (to the 10% level) for a statistically large sample of giant planet atmospheres. These primordial atmospheres are fossil records of the gas they accreted from their birth environments, connecting them to the planet’s formation pathway and location in its protoplanetary disc. Not only will MICADO provide constraints on formation mechanisms, but the large diameter of the ELT will enable MICADO to extend beyond the giant exoplanets and determine the composition of smaller, cooler planets such as warm mini-Neptunes. This class of exoplanet has no analogue in our solar system and is a key demographic to understand when assessing the physical mechanisms responsible for the incredible diversity of the exoplanet population (Fulton et al. 2017, Van Eylen et al. 2018).

References:

Birkby, J. et al. 2013 MNRAS Letters, 436, 35; Birkby, J. et al. 2017 AJ, 153, 138; Birkby, J. 2018 Springer Handbook of Exoplanets, 16-1; Boccaletti, A., 2018 A&A, 614, A52; Brogi, M. et al. 2012 Nature, 486, 503; Fulton et al. 2017 AJ, 154, 109; Lockwood et al. 2014 ApJL, 783, 29; Seager S. 2013 Science, 340, 577; Snellen, I. et al. 2010 Nature, 465, 1049; Van Eylen, V. et al. 2018 MNRAS in press, arXiv:1710.05398; Zurlo et al. 2016 A&A, 587, A57

7 The Solar System

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*The physical properties of Solar System objects can be usefully explored through high-resolution ground-based photometric and spectroscopic observations. Highly detailed information has of course been collected during spacecraft flybys of all the planets of the Solar System and this has provided a good general understanding of several aspects of these major bodies and their satellites. In contrast Earth-based observations allow for systematic surveys over much longer time periods, with higher spectral resolution, and these shed critical light on numerous important processes that determine the properties bodies of all shapes, sizes and composition within the Solar System. Ground-based monitoring can measure how these objects change over a variety of timescales, and is uniquely able to observe in a consistent way the numerous small Solar System bodies at a range of distance. Ground-based monitoring can discover and follow transient activity that is indicative of a range of physical processes. These investigations are currently limited, by the spatial resolution of existing ground-based telescopes. It is possible to resolve the large satellites of the giant planets, the largest asteroids and Trans-Neptunian-Objects (TNOs). MICADO will open a new era in our ability to study the properties of many more "small bodies", resolving many for the first time (see **Figure 7.1**) and monitor processes that change them over time. MICADO will also be able to monitor real time changes in larger bodies, such as in the atmospheres of gas Giant Planets and volcanism of various kinds in their moons.*

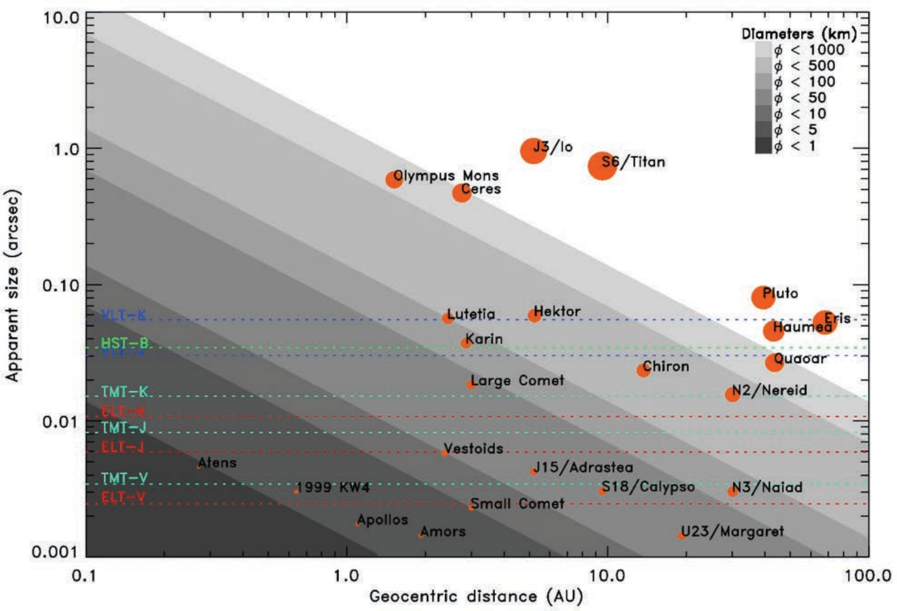

Figure 7.1 *The angular size of minor planets, asteroids and moons as function of their geocentric distance. The angular resolution limits for HST, VLT, TMT, and ELT are shown, for a range of filters. Courtesy of B. Carry.*

Outstanding Questions

The exploration of all the different bodies in the Solar System, from the Giant Planets to the tiny but numerous minor bodies provides key information about the origin and evolution of the Solar System, as they have best preserved chemical, dynamical and chronological information from the earliest times. It is necessary to determine the physical properties (spin, size, and shape) of all the minor bodies in the Solar System, such as asteroids, comets and TNOs. Disc-resolved imaging is the best method to provide these accurate measures (e.g. Carry et al. 2012). However, the small systems studied so far are limited to the main-belt asteroids, with the exception of a few near-Earth asteroids. The angular resolution provided by MICADO will open other more distant classes of small bodies to these studies. It is important to understand differences between inner and outer Solar System small bodies, as this will give critical information on the development of our entire Solar System from its proto-planetary disc.

Importance of MICADO

The powerful combination of space missions and high spatial and spectral resolution ground-based observations allow us to study the detailed properties of the Solar System and its formation and evolution from the earliest times. The limited spectral resolution of the space instruments, the short duration of these missions compared to the time-scale of the processes being monitored and the limited spatial resolution from current ground-based instruments still leave many unresolved questions. The high spatial resolution of MICADO will offer the unique possibility to carry out deeper investigations of a large fraction of the bodies in the solar system, including as yet unvisited small, cold and faint objects, such as TNOs, throughout the Solar System.

Observations of spectroscopic reflectance at visible and near-infrared wavelengths allows the characterisation of the surface of a resolved object. It is used to classify the population of asteroids into different spectral groups. In this way we get information on the radial gradients in the chemistry of the solar nebula. The distribution of types within the main belt shows that the asteroids have been moved around by Giant Planet migration, as shown by the presence of volatile-rich objects in the inner solar system that were formed in the outer solar system. These results need deeper and more detailed investigations and a more complete temporal monitoring. Detailed studies of the physical characteristics of minor bodies in the solar system require the angular resolution provided by MICADO to open several new classes of these targets (see **Figure 7.1**) to detailed investigation. As an example, only 11 of the 24 classes in the asteroid classification scheme have density estimates and only 12 have a mineralogical interpretation, which is the ultimate goal to understand the distribution of elements in the primordial nebulae out of which the terrestrial planets and other minor bodies formed.

The multiplicity of faint objects is a particular useful search as, from the companion orbit, the mass can be obtained. This can be combined with the volume estimate to yield the bulk density of the minor planet, which is a key parameter to infer its composition and internal structure (e.g. Carry 2012, Margot et al. 2015). The ability to detect binaries depends on their velocity on the sky. To avoid smearing, individual and total exposure times decrease as a function of the relative proximity of the objects. This favors binary detection for the more distant bodies (see **Figure 7.2**). With current technology, we have access to all the main-belt asteroids where the physical diameter is >100km. However, it is of even greater interest to have access to smaller bodies, such as the members of young dynamical families: e.g. Karin's family, or the Vestoids that are ejecta from Vesta. These small (few km diameter) targets are affected not only by gravitation but also by non-gravitational effects, such as the Yarkovsky and YORP effects (Slivan et al. 2003). The imaging capabilities of MICADO will allow the search for companions around bodies with smaller physical diameters than is currently possible. This survey will also allow a more robust global estimate of the global binarity properties of small bodies in the Solar System.

In addition, the near-infrared wavelength range gives access to spectral features associated with molecules H_3^+, H_2, H_2S, H_2O, CH_4, and hydrocarbons located in the atmosphere or in the rings of the Giant Planets and some of their moons. Narrow-band filter observations provide maps of the emission (e.g. Lellouch et al. 2006).

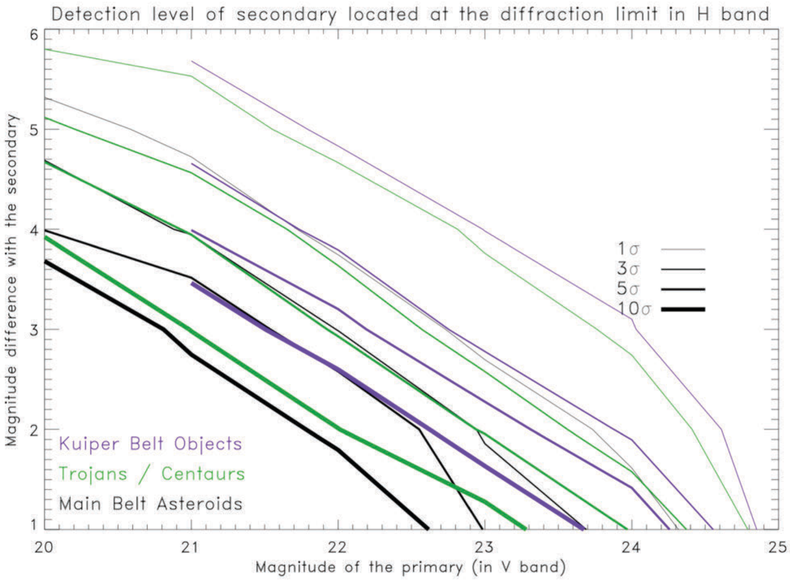

***Figure 7.2** The predicted detectability of binary objects in the H-band is shown at 1, 3, 5 & 10σ levels (as indicated by thinner to thicker lines). Simulations made with SimCADO.*

Some Specific Science Cases

Composition of the surface of the smallest bodies of the solar system: Asteroids and TNOs are coated with silicates, minerals or ices, which display many absorption bands in the near-infrared wavelength range (e.g. Barucci et al 2008).

<u>Looking for water ice</u>: A key question for our understanding of the Solar System is the distribution of water ice. It has so far only been detected on the largest bodies, but this is likely to be an observational bias. The faintness of the Centaurs, Trojans and TNOs typically does not allow sufficient S/N observations with present day instrumentation. MICADO will change this. A combination of narrow band filters and spectroscopy, will allow the identification of chemical compounds and their properties (dilution level, phase) on the surface of the smallest asteroids and the medium-sized class of TNOs and Centaurs. This will allow us to study the relative abundance of minor compounds, which could be primordial or formed by the space weathering processes.

The debate is still open as to whether water ice in the proto-solar nebula was *amorphous* or *crystalline*. All high S/N spectra of TNOs and Centaurs, and many objects show the presence of the crystalline water ice feature at 1.65 µm, which implies that early water ice was *crystalline*. However, when modelling the spectra, the best fit is usually also requires a small component of *amorphous* water ice (Merlin et al. 2007). If the original water ice was *amorphous*, then it could survive for the age of the Solar System on these objects due to their very low temperatures, and the presence of *crystalline* water ice could merely suggest a recent resurfacing event, that may be due to collisions, or internal activity. MICADO with high sensitivity and spectral resolution will be able to take extremely detailed spectra of even very faint objects, and this is expected to lead to a breakthrough in our understanding of the surface composition of a range of different small bodies, and clarify the importance of internal and external processes in changing the original water ice composition of the proto-solar nebula. With high resolution spectra it will also be possible to discover minor species and follow any temporal variations. The combination of the resulting knowledge of the physical and chemical properties of the surfaces with constraints on the bulk density of these objects will fully constrain their internal structure.

Retrieving chemical information from the surface of comet nuclei is a particularly difficult task as the surface of comets tend to be depleted of ices, which sublimate as the comet approaches the

Sun. The *Deep Impact* mission has revealed only a few small spots composed of water ice close to the dimly illuminated and cold pole of 9P/Tempel at a heliocentric distance of 1.5AU (Sunshine et al. 2006). MICADO will provide the possibility to observe the surface of many more of these objects and at greater distances from the Sun.

The outer Solar System: The Trans-neptunian region is still poorly known, and the more we learn about the extremely faint TNOs, the more complicated the picture appears. As more objects are discovered, the dynamical theories of the formation and evolution of the solar system are constantly being revised. Large surveys are required to obtain comprehensive information on the range of different object types. MICADO can be used to go well beyond the current limits. Satellites such as *Spitzer* and *Herschel* have been used to constrain the physical properties of some of these uncommon objects (Lellouch et al. 2013). However, results are still limited to the biggest relatively dark objects, which are the warmest. The study of well selected statistically significant samples of TNO, Centaurs, comets, irregular satellites of giant planets and Trojans with MICADO will lead to better models of our planetary system. There will also be synergy with the observations that can be made of these objects at mm-wavelengths with ALMA.

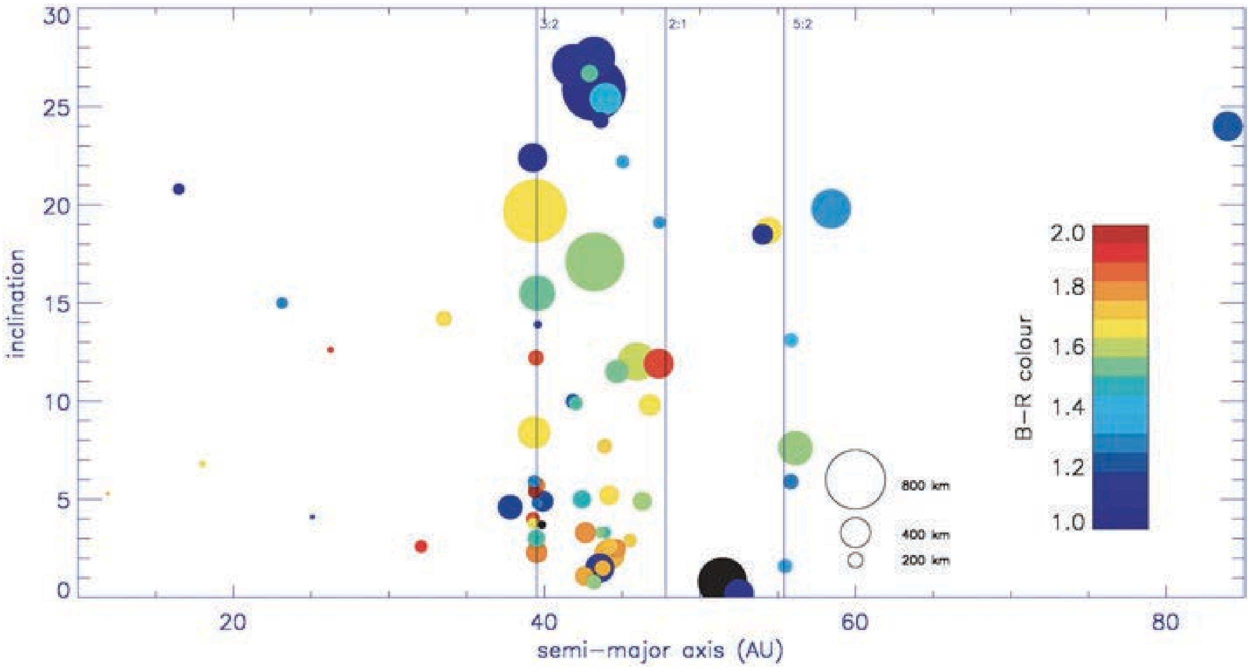

Figure 7.3 *The colours of Centaurs and TNOs (from Doressoundiram et al. 2005). Symbols sizes are proportional to the object sizes. The colour range has been adopted to scale the objects colour from red (in dark red with B-R=2.0) to blue (in dark blue with B-R=1.0). Three resonances with Neptune are also plotted as vertical lines.*

TNOs and Centaurs display a wide range of colours, as can be seen in **Figure 7.3**. Cold Kuiper Belt objects are rather red, while hot ones display the whole range of colours suggesting that these two populations have different origins. A taxonomy has been developed (Barucci et al. 2005; Fulchignoni et al. 2008) that suggests the different colours represent different evolutionary states of the surface. The reddest visible spectra also flatten toward the near-infrared, which is consistent with the idea that TNOs and Centaurs surfaces are an irradiated crust. The different colours are thus the result of the competition between composition, since different bodies will have formed in different locations; irradiation, laboratory experiments show that irradiated ices become redder with increasing irradiation; collisions, which expose the underlying non-irradiated material and internal processes, such as comet-like activity or cryo-volcanism that can bring up fresh “blue” material onto the surface. The activation of these physical processes depends on the distance from the Sun and the size of the object, but also on the thickness of the surface crust. MICADO will provide detailed photometry for a larger fraction of the population than is currently possible, especially for the smallest objects, and will thus be able to determine the importance and role of each of these processes in the different types of small bodies found in the solar system.

The satellites of the Giant Planets: These are barely resolved with current ground-based observations, however several have been visited by spacecraft (*Voyager, Galileo, Cassini*). The resolved images from these spacecraft are taken over a limited time period, and several satellites clearly exhibit important temporal evolution processes. The explanation for these physical and chemical processes observed require continuous monitoring (e.g. Hirtzig et al. 2007; Porco et al. 2006). Earth-based instruments, with lower spatial resolution than spacecraft, but with time coverage flexibility, are a necessary complement for the space missions. With the capabilities of MICADO (imaging and spectroscopy), it will be possible to investigate the activity of the "geologically modified" satellites (Johnson et al. 1998). This requires coupling good spatial resolution (a few kilometers/pixel for the satellites of Jupiter) and good spectral resolution (R>10k) to allow us to study the detailed physical and chemical processes acting on the most active satellites and the biggest dwarf planets, where recent observations suggest the presence of jets or transient atmosphere (e.g. Küppers et al. 2014). The capabilities of MICADO will allow us to map and accurately constrain the chemical compounds detected on several objects:

Io: Measuring the SO_2 distribution on the surface and in the atmosphere to determine the relative importance of these frost deposits in sustaining the local and global atmosphere and to investigate the mechanisms in action.

Europa: Measuring the ice and salt distributions on the surface. High spectral resolution (R>10k) is required to detect narrow lines in the wavelength range 1.45–2.45µm. In addition, this is an important exobiological target with its possible sub-surface briny ocean buried under a water-ice dominated crust several kilometres thick.

Titan: Measuring the abundance of CH_4, N_2 and hydrocarbons in the atmosphere. This is the only satellite with a dense atmosphere, primarily made of nitrogen and methane. It displays an intricate photochemistry, that populates the atmosphere with aerosols. The features that are found in Titan’s atmosphere can last for timescales varying from years to days. For instance, the reversal of the north–south asymmetry is linked to a 16-year seasonal cycle. Diurnal phenomena have also been observed, like a stratospheric haze enhancement or a possible tropospheric drizzle. All these observations need high spatial resolution imaging and spectroscopy and long term monitoring.

Triton: Measuring the H_2O, CO, CH_4 and N_2 distributions on the surface and in the atmosphere. Ground-based observations provided the first detection of CO in the atmosphere, and the first observation of CH_4 gas since *Voyager* (Lellouch et al. 2010). The results show a CO/N_2 atmospheric abundance consistent with its surface abundance (0.05%) and a CH_4 column density several times larger than that measured by *Voyager* in 1989. This increase could be explained if Triton's surface temperature increased from the 38K measured in 1989, but these measurements are lacking. Without spatially resolved observations, conclusions as to the origin of these changes remain uncertain and MICADO is needed to make progress. MICADO will provide enough spatial resolution to clearly identify the distribution of different ices at the scale of a few dozens of km (see **Figure 7.4**). MICADO will also make it possible to extend this kind of analysis to the other medium-size satellites and dwarf planets (such as Makemake, and Eris), and allow us to consider the role of other parameters on the evolution of these bodies, such as the heliocentric distance (i.e: the temperature, past and ambient conditions), the local environment (i.e: effect of the planets for the satellites), and the physical properties of the different objects (size, chemical composition).

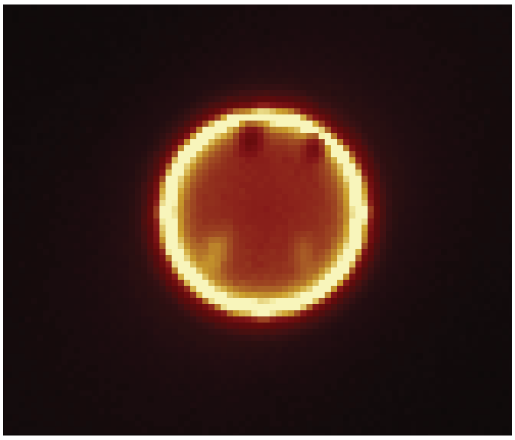

Figure 7.4 *A simulation of an $H_2O/CH4$ map of a Triton-like object (130mas in diameter), showing the detectability of ices. The picture was generated by combining two images taken in different filters (with transmission curves peaking at 2.04 and 2.27µm). The H_2O enriched areas appear dark and the CH_4 enriched areas appear bright orange (excluding the edges of the simulated object). Simulations from SimCADO. Including noise*

The composition and temporal variation of the atmospheres of Giant Planets: The MICADO pixel scale is 20, 40, 80, and 120 km for Jupiter, Saturn, Uranus, and Neptune, respectively. Reflectivity observations that make use of the variable opacity of methane and centre to limb variations will enable altitude determinations of the cloud features in storms and vortices.

Jupiter: Among the phenomena of interest are the varying South Equatorial Belt and North Temperate Belt Disturbances (Sanchez-Lavega et al. 2008), and the ongoing evolution of the Great Red Spot as it diminishes in size. These time varying phenomena need careful and detailed observations over many years.

Since its discovery in Jupiter's polar regions at 2µm in its $2v_2$ band (Drossart et al. 1989), the H_3^+ ion has been recognized as an important tracer of the Jovian upper atmosphere and the coupling with Jupiter's magnetosphere, and a general tracer of the upper atmosphere energetics and dynamics (e.g. Miller et al. 2006). High-spectral-resolution spectral-imaging observations of H_2 and H_3^+ in the 2µm region in both hemispheres provide information on the composition, temperature and potentially wind speeds, in the Jovian auroral upper atmosphere.

Uranus and Neptune: These systems are far from the Sun, and thus will have formed from a less dense component of the proto-planetary disc, and so the accretion processes of the rock and ices to the central cores probably took longer than for Jupiter and Saturn. Jupiter and Saturn probably took 1-3Myr, while Uranus and Neptune may have taken ten times longer (Taylor 1992). It is unclear why Uranus and Neptune are so different from each other. In spite of their similarities in global atmospheric composition and tropospheric temperature structure, they differ from each other in many ways. For example, Neptune has an internal source of energy, while none has been detected on Uranus; Neptune has a very efficient dynamical circulation, while Uranus has none. With MICADO one of the key studies will be investigation of the composition and vertical structure of the upper tropospheres of both planets to look for explanations for these different properties.

References:
Barucci et al. 2005 AJ 130, 1291; Barucci et al. 2008 in *Solar System Beyond Neptune*, p143; Carry et al. 2012 P&SS 66; Carry 2012 P&SS 73; Doressoundiram et al. 2005 *Icarus* 174, 90; Drossart et al. 1989 *Nature* 340, 539; Fulchignoni et al. 2008 in *The Solar System Beyond Neptune*, p181; Hirtzig et al. 2007 JGR 112, E02S91; Johnson et al. 1998 in *Solar System Ices*, 511; Küppers et al. 2014 *Nature* 505, 525; Lellouch 2006 PTRS, A364, 3139; Lellouch et al. 2010 A&A 512, L8; Lellouch et al. 2013 A&A 557, A60; Margot et al. 2015 in *Asteroids IV*, p355; Merlin et al. 2007 A&A 466, 1185; Miller et al. 2006 *PTRS, A* 364, 3121; Porco et al. 2006 *Science,* 311, 1393; Sanchez-Lavega et al. 2008 *Nature* 451, 1022; Slivan et al. 2003 Icarus, 162, 285; Sunshine et al. 2006 *Science* 311, 1453; Taylor, S. R. 1992 in *Solar System Evolution*.

8 Black-holes in Galaxies

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Contributors: Ximena Mazzalay/MPE, Nadine Neumayer/MPIA, Roberto Saglia/MPE

Outstanding Questions

All reasonably massive galaxies appear to host supermassive black holes in their centres ranging in mass from several million to several billion solar masses (Kormendy & Richstone 1995; Magorrian et al. 1998; Richstone et al. 1998; Kormendy & Ho 2013). Understanding why this is so and what is the link with galactic evolution processes, and how their properties depend on, or are affected by their environment are long standing and important issues. We still need to understand the formation of galaxy cores, central star clusters and supermassive black holes, and the mechanisms of mass transport into these central regions and the influence of and on the galaxy-scale and larger environment. A suite of different mechanisms is expected to be at work, spanning nine orders of magnitude in linear scales from galaxy environment down to the sphere of influence of a central black hole.

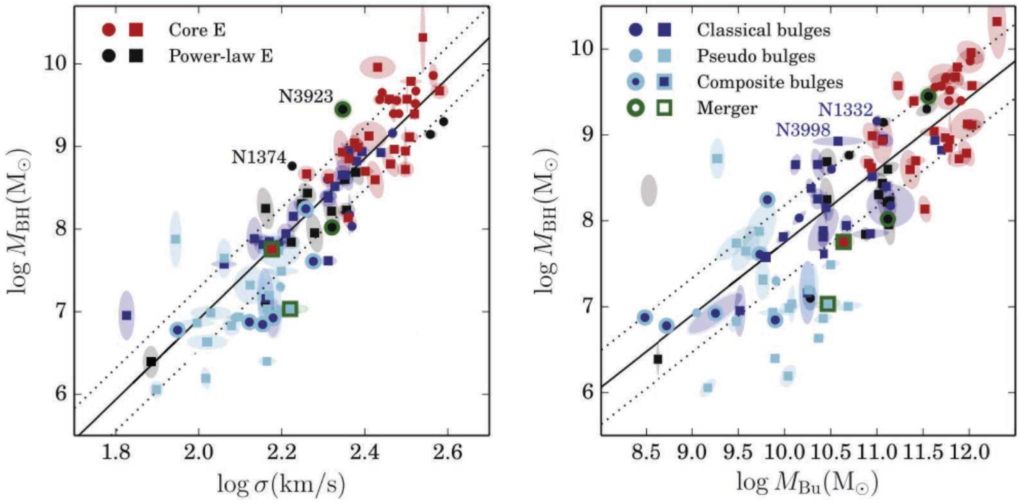

***Figure 8.1** The black hole to galaxy scaling relations. From a compilation by Saglia et al. 2016. The left panel shows the correlation of the black hole mass with central velocity dispersion while the panel on the right shows the correlation with bulge mass.*

Massive black holes, up to $10^5 M_\odot$, are thought to form either via the direct collapse of dense gas clouds or star clusters or in a runaway collision of remnants of Population III stars. Subsequent gas accretion and black hole merging means they are expected to grow over time into the present day supermassive black holes which typically have a mass ~0.1—1% of the stars in a galaxy (Häring & Rix 2004). This and other tight scaling relations, most notably with the host's stellar velocity dispersion, with only 0.3dex scatter (Gebhardt et al. 2000; see **Figure 8.1**), suggests that the evolution of galaxies and their central black holes are intimately linked by yet to be understood mechanisms. It is expected that the energy output from the accretion onto a black hole impacts the growth of stellar mass of the host through the heating and removal of gas in the galaxy by the active black hole, which is then not available anymore to form stars. We are still not sure if this QSO/AGN feedback is the physical process that ultimately quenches star formation as massive star forming galaxies evolve into passive spheroids. Nor do we know which are the exact physical processes that can trigger nuclear activity. The role of environment (via interactions and/or merging) also remains unsure. MICADO will be the only instrument to address these questions with its combination of superb spatial resolution and its high flux sensitivity and relatively wide field of view.

The central limit theorem states that the correlation of black hole mass to stellar mass could arise naturally from randomly distributed seed masses coming from a large number of consecutive mergers (Peng 2007). This implies that the scatter in the black hole scaling relations should decrease at the high-mass end. Currently, even black holes above a mass of $10^9 M_\odot$ can only be resolved using stellar kinematics out to a distance of ~100Mpc and so the scatter in the scaling relation even at the high-mass end remains uncertain. Likewise, due to the current limits in spatial resolution, we lack information on the distribution of seed masses (10^2—$10^6 M_\odot$). Currently the sphere of influence of a black hole with $10^6 M_\odot$ can only be resolved for the few galaxies <5Mpc away. Finally, it is unclear if black holes are also always present in the centres of globular clusters, nuclear star clusters, dwarf galaxies, and pure disc galaxies. For disc galaxies we do know, from the observation of AGNs, that massive black holes can exist in discs (Filippenko & Ho 2003), but we have very limited information on the frequency of their occurrence as currently they can only be detected when active or in the nearest galaxies (den Brok et al. 2015).

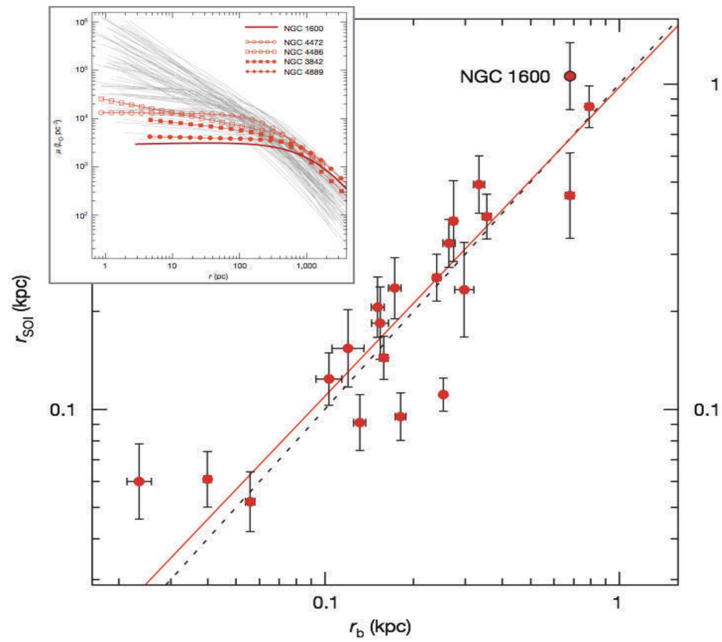

Figure 8.2 *The inner light profile of high mass Elliptical galaxies tend to be flattened compared to the more normal power law profiles of less massive Elliptical galaxies (top left inset). The main panel shows that the break radius (r_b) from the outer power law profile to the central region occurs at an almost constant surface brightness density that correlates 1:1 with the sphere of influence of the central black hole (r_{SOI}). From Thomas et al. 2016.*

Most high mass Elliptical galaxies exhibit flattened central light profiles as compared to the power law profiles of lower mass elliptical galaxies (Kormendy 1985; Lauer et al. 1995; Trujillo et al. 2004; Dullo & Graham 2014), see **Figure 8.2**. More recently it has become apparent that in these cored galaxies, black hole masses correlate strongly with the size of the core region (Thomas et al. 2016) while the amount of missing light — the difference in total light with respect to a power law density profile or mass, when multiplied by an appropriate M/L ratio — is related to the total number of merger events (Merritt 2006). In our current understanding, cores form in the late stages of major dry galaxy mergers. As the central black holes of the two progenitor galaxies spiral into the centre of the new system, stars on radial orbits that fall close to the merging supermassive black holes are preferentially ejected from the central region and a core is left behind with stars mainly on tangential orbits (Thomas et al. 2014). This process is referred to as “core-scouring” (Faber et al. 1997). The core sizes are found to be identical to the black hole sphere of influence (Thomas et al. 2016, see **Figure 8.2**). In the local Universe, essentially all galaxies with M_V<-21 exhibit these flattened central stellar light profiles and their core sizes scale linearly with the mass of the central black hole, thus being a potential proxy for the black hole mass in giant Elliptical galaxies. Core-scouring appears to be an essential process in the evolution of the largest galaxies. However, are there other processes, such as strong AGN feedback, that can result in low-density cores but do not require gasless mergers without star-formation. Understanding how this could work will fundamentally change our understanding of galaxy evolution. To resolve this it is crucial to determine at which mass and when in the evolutionary history of massive galaxies cores are formed. Our current ignorance comes largely from the lack of instrumentation that is capable of working at the required spatial resolution to study core properties and black hole masses in statistically meaningful numbers of galaxies and over a representative cosmological volume.

The Importance of MICADO

To further our understanding of the coevolution of central black holes, their host galaxies and cores, systematic surveys sampling a large range of black hole masses across cosmic time are required. So far, the fundamental limiting factor has been that of spatial resolution of current imaging and spectroscopic instrumentation. The highest fidelity measurements of supermassive black hole masses are obtained either through the observation of quasi-Keplerian orbits of stars around the black hole in our own Milky Way (Schödel et al. 2002, Eisenhauer et al. 2005, Gillessen et al. 2008) or from the measurements of the circular motions of water masers (Miyoshi et al. 1995, Greene et al. 2010, Kuo et al. 2011). But such measurements are only possible for a very few cases. While larger numbers and larger volumes can in principle be reached through secondary techniques such as the measurements of the widths of the broad line region in AGN (Reines & Volonteri 2015) or the reverberation mapping method (Blandford & McKee 1982; Netzer & Peterson 1997), they need to be calibrated against measurements that rely on first principles for their mass estimates, namely dynamical measurements. There is some hope that ALMA with its superior spatial resolution will add new mass determinations (Barth et al. 2016), but gaseous kinematics are notoriously more difficult to interpret and are of course limited to objects that contain gas. While challenging to obtain observationally, and to treat numerically, stellar kinematic data are the easiest to interpret physically and are regarded as the highest confidence mass determinations beyond maser measurements.

The size of the spatial region where black holes directly influence the motions of stars and gas through their gravity — the sphere of influence — ranges from 1pc (for M_{BH}~$10^6 M_\odot$) to 1kpc (for the most massive M_{BH}~$10^{10} M_\odot$ black holes), see **Figure 8.3**. To obtain accurate measurements this sphere of influence must be at least marginally resolved. Currently available instrumentation, with the highest available spatial resolution (~70mas) cannot probe the sphere of influence of typical supermassive black holes beyond ~100Mpc, and the most massive black holes are detectable only out to ~200Mpc. In the closest galaxies passive black holes can only be detected with masses above ~$10^6 M_\odot$. Currently, direct stellar dynamical measurements are only possible for ~100 objects. The regime of progenitor mass black holes (~$10^{4-6} M_\odot$) as well as the redshift evolution of black hole scaling relations as measured by dynamical means are entirely hidden to us (see **Figure 8.3**) and thus any study of a possible correlation with environment is impossible.

JWST will improve on the flux sensitivity of current black hole surveys but it will not significantly improve upon the spatial resolution. NIRSpec has a pixel scale of 100mas and the diffraction limit of JWST at 2µm is 80mas. In contrast MICADO will reach 10mas spatial resolution, and consequently the observable volume will increase by a factor of >300 over what is possible today. With this, MICADO will be the first instrument able to probe core properties and nuclear morphologies for a large number of objects over a range of distance. MICADO will be able to determine black hole masses down to ~$10^6 M_\odot$ and out to redshifts, z ~ 3. This will increase the number of direct stellar dynamical black hole mass measurements from the current few hundred to several tens of thousands. MICADO will also deliver superior sky subtraction compared to small IFUs, such as on HARMONI. This is crucial for the study of extended objects where the surface brightness typically lies below that of the night sky.

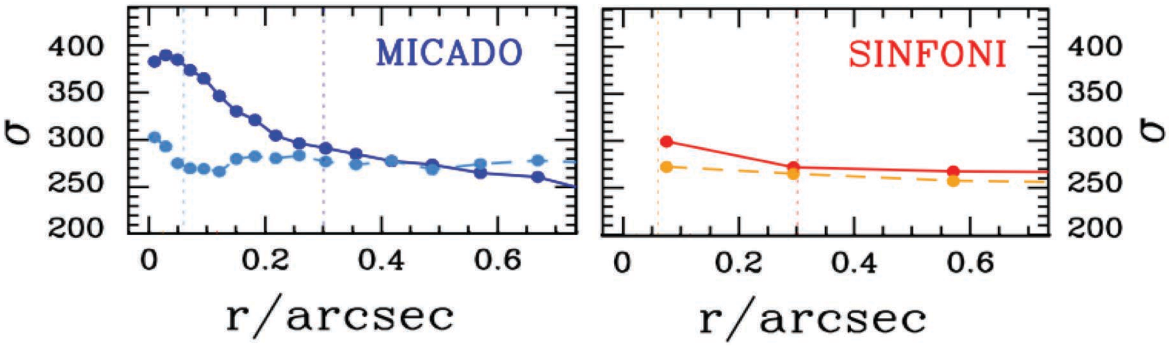

Figure 8.3 *Both plots show the simulated stellar velocity dispersion profile of a massive cored Elliptical galaxy. We use the gravitational potential of the galaxy NGC1600 (z=0.016, Thomas et al. 2016) as the basis of a simulation that moves this galaxy out to z=0.2. The left panel shows how the velocity dispersion profiles would look like for MICADO data, and the right panel shows the case for VLT/SINFONI, for two different assumed black hole masses in the centre of the simulated galaxy. The lighter coloured dispersion profiles come from a* $1.7x10^7 M_\odot$ *black hole while the dark blue curve a* $1.7x10^9 M_\odot$ *black hole. The vertical dashed lines indicate the spheres of influence of the two different mass central black holes, which must be resolved for an accurate dynamical measurement of the black hole mass.*

Census of the supermassive black hole mass function out to z = 0.2 and beyond: With its exquisite spatial resolution MICADO will be able to resolve the black hole sphere of influence out to 5 times larger distances than current ground based instrumentation and 2 times larger than JWST. Assuming the z=0 scaling relations hold MICADO will be able to detect and measure black holes in galaxies with velocity dispersions >270km/s out to a redshift of z=0.2 (see **Figure 8.4**) which is a co-moving distance of ~1Gpc. The corresponding 300-fold increase in available volume will result in tens of thousands of new observable targets. This is a comfortable number of objects to test for time evolution of the mass function and to probe for correlations with the environment. For the highest mass black holes, thanks to the flattening of the angular diameter to redshift relation, the corresponding 1kpc cores will be resolvable at virtually all redshifts and, ultimately, their observability will be limited only by surface brightness dimming. While the spectroscopic mode of MICADO will deliver the stellar kinematic information, high angular resolution imaging will allow us to relate black hole mass measurements to core radii across a range of redshift. We will be able to determine if there is an evolution of the local almost perfect one-to-one correlation (see **Figure 8.2**) both in offset and scatter.

One of the most exciting prospects is to detect black hole mergers through gravitational wave emissions. Black holes can only grow in mass through the accretion of gas and/or through mergers with other black holes. At the high masses we expect mergers to be the dominant growth mechanism. Coalescing supermassive black holes are the most luminous and longest frequency sources of gravitational waves in the Universe. Future gravitational wave observatories will be increasingly sensitive to these events and enable us to establish their number density in space and time. Combined with independent measurements of the evolution of the mass function through stellar dynamical measurements, we can develop a detailed understanding of the hierarchical buildup of black holes in their hosts across cosmic time.

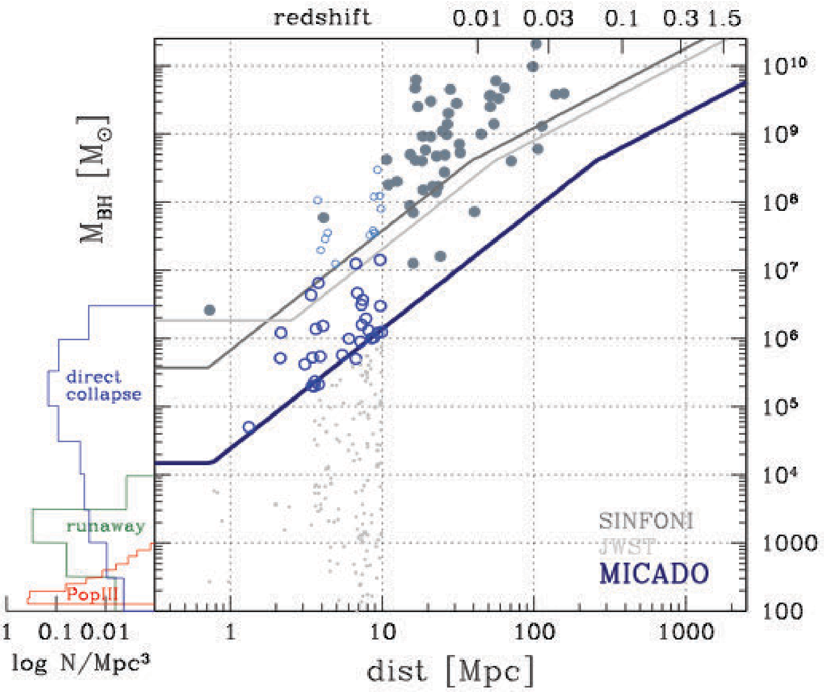

Figure 8.4 *The masses of the central supermassive black holes that can be measured using stellar dynamics as a function of redshift and co-moving distance. Grey filled circles indicate galaxies with mass determinations from the OPINAS VLT/SINFONI programme. Light blue open circles and dark blue open circles show galaxies that become observable with JWST and MICADO. The grey dots indicate mass predictions (from the central velocity dispersion) that will not be accessible even with MICADO. The solid lines indicate the resolution limits of the three different observatories as a function of redshift. The histograms on the left hand side show the expected mass distributions of low mass black holes based on different seed black hole populations.*

Unbiased measurement of the black hole scaling relations: About 100 stellar dynamical black hole mass measurements exist today, and these have been used to establish the relationship between black hole mass and central velocity dispersion, and black hole mass and stellar mass. The importance of these and other parameters on the black hole scaling relations have been rigorously established (Saglia et al. 2016). These relations are in turn used to calibrate secondary techniques such as reverberation mapping and the inference of masses from broad line region emission in AGN. Currently, only broad line emission region can be used to infer black hole masses across a cosmologically significant volume to follow the evolution of black hole mass functions with redshift. The current target selection is severely limited by the size of the sphere of influence that can be resolved. It has been argued that as a result the velocity dispersion based mass estimates may be too high by up to a factor of three (Shankar et al. 2016). As essentially all hosts that are either close enough or massive enough to have their sphere of influence resolved, have been observed, and this means that the number of mass determinations is not going to change significantly until MICADO is available. The high spatial resolution of MICADO will significantly increase the number of targets where the sphere of influence can be resolved. It will finally be possible to probe an unbiased sample of galaxies, including sampling central velocity dispersions significantly below the current limits. The primary challenge that needs to be overcome is the spatial resolution, and the required exposure times range from a few minutes (S/N=200 in 5minutes for a surface brightness of 10mag/arcsec^2 in K) for typical power law galaxies in the local Universe, to a few hours (S/N=35 for 3hours for a surface brightness of 15mag/arcsec^2 in K) for local cored galaxies or power law galaxies out to a redshift of z=0.2. A sample of several dozen mass measurements in early type galaxies will thus be feasible over the course of a few nights of observation with MICADO.

Study of black holes in disc galaxies: Currently, the tight correlation between stellar mass and central black hole mass appears to hold true for classical galactic bulges of Spiral galaxies. Conversely the stellar mass of disc-like central mass concentrations, or pseudo-bulges, do not seem to correlate with their central black hole mass. These pseudo-bulges are thought to be the result of a secular evolution of the host galaxy, where gas inflow, often assisted by angular momentum transport in a stellar bar, leads to a continuous mass buildup in the central region of the spiral galaxy (Kormendy & Kennicutt 2004). In contrast, classical bulges are thought to be the result of mergers. If mergers do drive the black hole scaling relations, then one might expect only classical bulges to follow those relations. Systematic studies of black hole masses in pseudo-bulges have so far been limited to about two dozen galaxies, this effort is once again restricted by limited spatial resolution and our inability to resolve the sphere of influence of small mass black holes.

Probing of the lower mass end of the black hole range is of significant diagnostic value as different models of the origins of supermassive black holes point to different progenitor mass distributions (Volonteri et al. 2008; see **Figure 8.4**). Currently there are three main contenders to explain the formation of supermassive black holes: 1) direct gravitational collapse; 2) supernovae from massive population III stars; 3) intermediate mass black hole formation in young compact star clusters through runaway merging of massive stars. These three channels are predicted to result in different forms of the black hole mass function at the low mass end (see **Figure 8.4**). MICADO will allow us to systematically sample the black hole mass range between 10^5—$10^7 M_\odot$ and to determine which of the formation scenarios is favoured. Typical exposure times range from minutes to hours in K-band such that the build-up of a sample of a few tens of objects is well feasible over the course of a few nights.

Measurement of the core radii distribution for massive Elliptical galaxies and its redshift evolution: The measurement of the evolution of galactic core radii yields exciting prospects to further our understanding of the coevolution of supermassive black holes and their host galaxies. Known galaxy core sizes — the radius where the inner light becomes essentially constant — range from 1kpc down to 50pc (see **Figure 8.2**). This lower limit is likely to be an observational limit that is set by the current spatial resolution limitations of available instrumentation and of the telescopes themselves rather than a physical limit. Our current understanding is that galactic cores form when two galaxies that are relatively devoid of any gas merge. Cores may also form in gas-rich mergers but are expected to be less prominent, as the supermassive black hole binary can lose energy not only to the stars but also via interaction with the gas. Moreover, even if a core can still form, it may be replenished by subsequent central star formation. The ability to probe core sizes all the way down to parsec scales will allow us to test where exactly the domain of gas rich mergers ends and that of core scouring begins and to relate this to the nature of the progenitor host galaxies in a statistically robust fashion. The few dozen objects where cores have so far been detected, yield insufficient statistics to tell us how the frequency of the occurrence of cores correlates with quantities like galaxy mass, gas mass, black hole mass and nuclear activity. MICADO's spatial resolution will allow us to measure for the first time the occurrence of cores across a wide range of galaxy masses and redshifts for large numbers of targets. JWST will not be able to determine core radii for z>0.3, which is in contrast to MICADO, that with exposure times as short as 5 minutes will be able to measure core sizes out to z~1. This will of course be aided further by MICADO's large 50" square field of view and the resulting ability to observe several objects at once, allowing for an efficient survey of ~100 objects in a few nights of MICADO observations (see **Figure 8.5**).

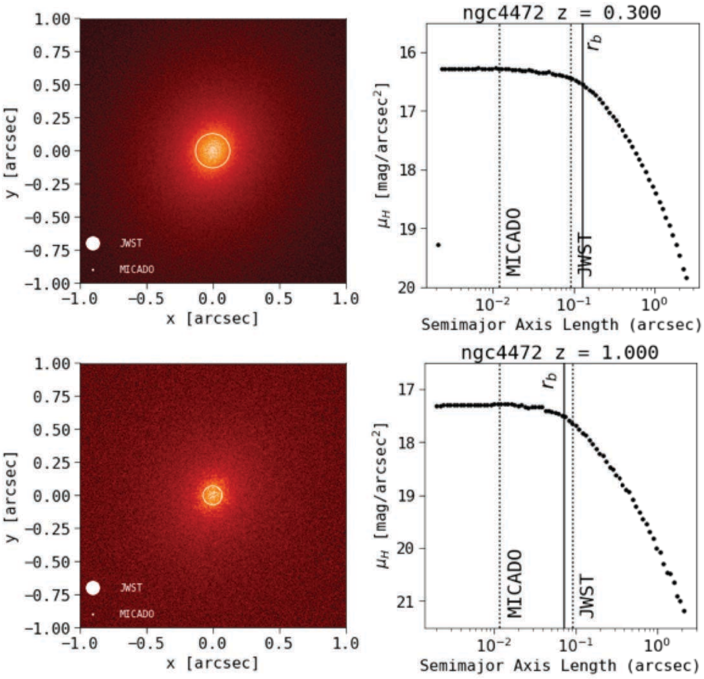

Figure 8.5 *The images on the left show SimCADO simulations of the same galaxy at z=0.3 and z=1 with exposure times of 5 minutes. The parameters of the simulated 2D light distribution were chosen to resemble the cored Elliptical galaxy NGC4472 that is actually at z=0.003. The circle in the centre indicates the break radius r_b and the circles in the lower left indicate the spatial resolution of JWST and MICADO. The plots on the right show the true (known) surface brightness profile. They highlight the importance of sampling the surface brightness well inside r_b to reliably measure r_b. The solid line and the dotted lines indicate r_b, and the two instrumental resolution limits.*

Study of nuclear morphology and a census of black hole binaries: Massive Elliptical galaxies are thought to form through multiple mergers of smaller galaxies (and their dark matter halos) throughout cosmic time. Observations and theoretical calculations suggest that massive early-type galaxies have undergone about one major merger since redshift z=2 (Lotz et al. 2011). Through dynamical friction, the central black holes of the merging galaxies sink to the common centre of the gravitational potential of the newly formed host where they form a black hole binary. While no consensus has yet been reached for the mechanisms that allow black hole binaries to overcome their final few parsec separations, the dynamical friction phase is better understood and simulations predict merging timescales of several Gyrs (Merrit 2006; Boylan-Kolchin et al. 2008). If a black hole is located in a central star cluster, as for instance in the Milky Way, this star cluster will be carried along and should be directly observable. While many galaxies are observed

to host nuclear star clusters, only a few cases of binary nuclear star clusters have been found. An example is the case of NGC5419 (Mazzalay et al. 2016), which hosts a binary cluster/black hole system with a projected separation of about 300mas (**Figure 8.6**). This is comfortably resolved in optical bands by HST and also by VLT/SINFONI, but in the near-infrared it is only marginally resolved by HST. This highlights that many binary systems may not yet have been detected.
MICADO will improve upon spatial resolution by a factor of 6 over JWST and current ground based instrumentation. A systematic mapping of core properties, will simultaneously yield a

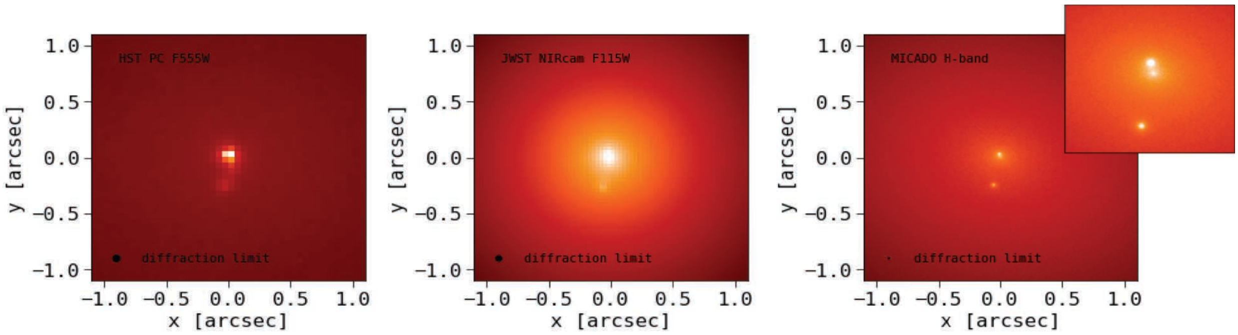

Figure 8.6 *The left is an HST/PC V-band image of the central region of the cored Elliptical galaxy NGC5419. The diffraction limit of 58mas is indicated by the black circle in the lower left corner. The brighter main nucleus is located at the geometric centre of the galaxy. A second nucleus can be seen about 250mas south and 50mas east (left) of the galaxy centre. The middle image is a simulation of how the central region of NGC5419 would appear with JWST/NIRCam at 1.15µm, which is only a marginal improvement upon HST. The image on the right shows a SimCADO simulation of the central region of NGC5419 for MICADO in the H-band. The secondary nucleus is now well resolved. Also, as shown in the inset, a simulated third nucleus added to the simulations visible. It is 5 times closer to the galaxy centre than the known companion. This could not be resolved by HST or JWST.*

census of nuclear morphologies also in only a few minutes of exposure time per object. For example, the exposure time for the MICADO simulation in **Figure 8.6** is only 30s, demonstrating how well suited MICADO is to efficiently survey the central morphologies of a large sample of core galaxies. We can thus build up samples of ~100 hosts during the course of a few nights which will constrain central merging time scales and reveal the underlying physical processes that dominate the late merging stages. Using the spectroscopic capabilities of MICADO we can follow these object up and test that their stellar dynamical properties match theoretical expectations, such as that cores should be dominated by tangential obits as stars on radial orbits are preferentially affect by scouring.

Low mass/low velocity dispersion galaxies, dwarfs, and globular clusters in the local universe: While the bulge mass to black hole mass relation is well established at 10^6—10^{10} $M_\odot$, little is known about the existence of the scaling below 10^6 $M_\odot$. This is the realm of intermediate mass black holes that potentially exist in the centres of globular clusters, nuclear star clusters, and dwarf galaxies (see also §3). Whether or not black holes have been detected in Globular Clusters is subject of an active debate. We know from Milky Way and AGN detections (Moran et. al 2014), that nuclear star clusters in galaxies can contain massive black holes and stellar dynamical detections are exceedingly difficult and only a handful of cases exist today with solid detections (e.g. Seth et al. 2010, den Brok et al. 2015, Nguyen et al. 2018). This is once again due to the limits in currently available spatial resolution. MICADO will be able to spatially resolve the dynamical influence of “seed black holes” in local inactive bulge-less or dwarf galaxies out to ~50Mpc.

By the time of the first light of MICADO current and future gravitational wave observatories will have measured several hundreds of stellar mass black hole mergers. MICADO will be the first instrument to close the evolutionary gap between these and the intermediate mass black hole population and to follow the black hole mass function throughout all rages up to most massive object in the universe.

References:

Barth et al. 2016 ApJ 822, L28; Blandford & McKee 1982 ApJ, 255, 419; Boylan-Kolchin et al. 2008 MNRAS, 383, 93; Dullo & Graham 2014 MNRAS, 444, 2700; den Brok et al. 2015 ApJ, 809, 101; Eisenhauer et al. 2005 ApJ, 628, 246; Faber et al. 1997 AJ, 114.1771; Filippenko & Ho 2003 ApJ, 588, 13; Gebhardt et al. 2000 ApJ, 539, 13; Gillessen et al. 2008 IAUS, 248, 466; Greene et al. 2010 ApJ,721, 26; Häring & Rix, 2004, ApJ, 604, 89; Lauer 1995 AJ, 110.2622; Lotz et al. 2011 ApJL, 742, 103; Kormendy & Richstone 1995 ARA&A, 33, 581; Kormendy 1985 ApJL, 292,9; Kormendy & Kennicut 2004 ARA&A, 42, 603; Kormendy & Ho 2013 ARA&A, 51, 511; Kuo et al., 2011 ApJ, 727, 20; Magorrian et al. 1998 AJ 115, 2285; Mazzalay et al. 2016 MNRAS, 462, 2847; Merritt 2006 AJ, 648, 976; Moran et al. 2014 AJ, 148, 136; Miyoshi et al. 1995 Nature, 373, 127; Netzer & Peterson 1997 ASSL, 218, 85; Nguyen et al. 2018 ApJ, 858, 118; Peng 2007 ApJ, 671, 1098; Reines & Volonteri 2015 ApJ, 813, 82; Richstone et al. 1998 Nature, 395, 14; Saglia et al. 2016 ApJ, 818, 47; Seth et al., 2010 ApJ, 714, 713; Schödel et al., 2002 Nature, 419, 694; Shankar et al. 2016 MNRAS, 460, 3119; Thomas et al. 2013 ApJ, 782, 39; Thomas et al. 2016 Nature, 532, 340; Trujillo et al. 2004 AJ, 127, 1917; Volonteri et al. 2008 MNRAS, 383, 1079

9 The Centre of the Milky Way

Coordinator: Stefan Gillessen/MPE
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Outstanding Questions

*The centre of the Milky Way is a unique laboratory for exploring strong gravity around the closest massive black hole, and for studying fundamental and broadly relevant processes happening in the very dense star cluster surrounding this massive black hole, at a level of detail and quality that will never be possible in external galaxies (see **Figure 9.1**). The Galactic Centre also serves as a crucial guide for theoretical studies of accretion onto massive black holes and the important issue of co-evolution of massive black hole activity and nuclear star formation*.

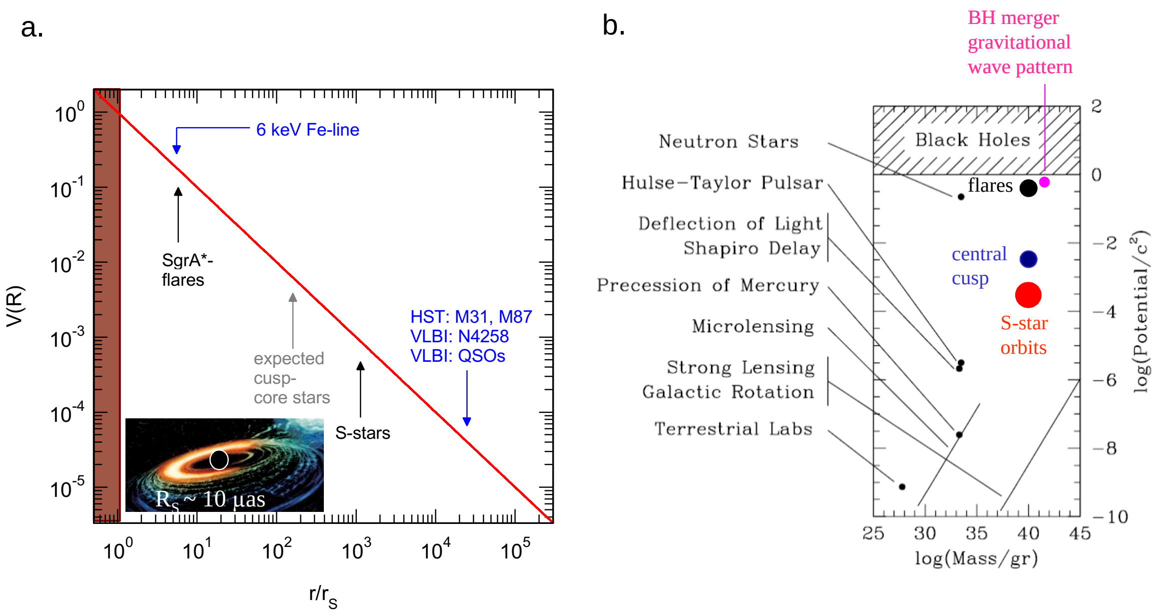

***Figure 9.1 a.** Gravitational potential around a (massive) black hole, as a function of radius in units of the radius of the event horizon. Current dynamical measurements in the Galactic Centre ('S-stars') probe to ~1000R_S, while external galaxies (blue) probe to ~3x10^4R_S. Measurements with MICADO will probe faint cusp stars ten times closer to the event horizon, where β^2-effects of Special and General Relativity, as well as the Schwarzschild precession term can be observed. GRAVITY-VLTI observations of infrared flares and potentially also spectrally resolved X-ray reverberation mapping of the 6.4keV Fe-line may be able to push dynamical measurements into the very strong curvature regime at a few times R_S. **b.** comparison of different probes of gravity, as a function of mass scale (horizontal) and field curvature (vertical). The Galactic Centre stellar orbits and flares probe a hitherto totally untested regime of mass and field curvature.*

Arguably the most fundamental goal of Galactic Centre research in the next decades will be dynamical measurements of the gravitational potential ever closer to the event horizon, with the ultimate goal of testing General Relativity in the strong field limit. In the past decades the VLT and Keck telescopes have observed the orbits of ~40 bright 'S-stars' in the stellar cusp around the massive black hole coincident with the compact radio source SgrA*. Until very recently these have been the cleanest dynamical measurements of the gravitational potential to a scale of ≥10^3 times the radius of the event horizon, R_s (**Figure 9.1a**). Since 2017, the VLTI instrument GRAVITY delivers a full order of magnitude improved resolution and astrometry, pushing the scales probed to $\geq 10^2 R_s$ for stellar orbits, and potentially to very few R_s for the astrometry of flares. For comparison, the best observations in external galaxies can sample $>3\times10^4 R_s$.

The single-telescope VLT/Keck observations are strongly limited by confusion, while the VLTI can only cover a limited field of view and has a smaller throughput. Fainter stars further in than presently observable are very likely present, as the observed K-band luminosity function (KLF) is very steep (see **Figure 9.2**). The volume density of the S-stars increases inward with $R^{-1.3\pm0.1}$, such that it is likely that higher resolution and sufficiently sensitive measurements will find a sample of faint stars at 10^2–$10^3 R_s$. At that radius, orbital velocities approach 0.1c and orbital periods may be as short as a few years, allowing the routine detection of the effects of Special and General Relativity (SR and GR) on these orbits. Such measurements will test SR and GR in an otherwise unexplored regime of field curvature and mass scale (**Figure 9.1b**). Still further in, at a radius of a few R_s, variable infrared emission from transiently accelerated electrons ('flares') probe the innermost accretion zone around the massive black hole. Detection of orbital motions of this hot gas requires an astrometric precision and stability of about 10mas for a few orbital revolutions, or around two hours.

Because of the effects of confusion, the current precision of astrometric measurements is significantly worse than the fundamental measurement limit. Higher resolution observations (with higher precision and lower confusion) are required to detect the Newtonian precession of these orbits due to any extended mass outside of the central massive black hole. Such a mass distribution consists of the observed stars themselves ($<10^2 M_\odot$ in the central 0.1") and in addition, stellar remnants (stellar black holes and neutron stars: estimated to be $\leq 10^4 M_\odot$) and perhaps dark matter. Detection of these components is obviously of great interest, also for determining the expected rates of extreme mass ratio in-spiral events leading to gravitational waves.

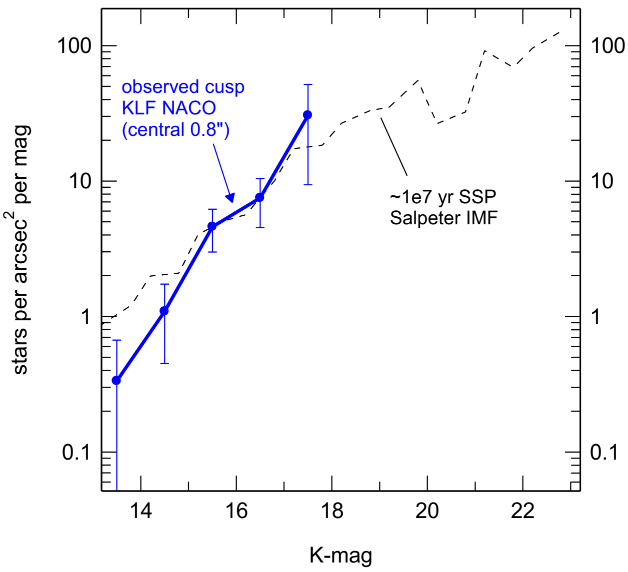

***Figure 9.2** Observed K-band luminosity function (KLF) of the central 0.8″ as observed with NACO on the VLT (solid blue line), compared to a t=10^7yr age population with a Salpeter IMF (dashed black line). Combined with the observed $R^{-1.3\pm0.1}$ power law stellar density distribution, there are likely to be ~5–10 K<20 stars in the central 0.1–0.2″.*

Another important issue is whether the gas that falls into the nuclear region forms stars near the massive black hole, or whether it is accreted directly into the massive black hole, and whether nuclear star formation and massive black hole activity are related. Observations of population of young stars in the Galactic Centre have yielded the remarkable result that episodic star formation deep in the sphere of influence of the massive black hole appears to be efficient, and has a top-heavy mass function. A better quantitative determination of the processes involved in stellar formation in this extreme environment, a precise determination of the resulting stellar mass function and density profile, and the exploration of the connection between the rates of star formation and black hole accretion are critical for understanding the cosmological co-evolution of galaxies and massive black holes.

Finally, the massive black hole in the Galactic Centre (SgrA*) is the prototype of the very common class of radiatively inefficient accretion sources (L/L_{edd}~10^{-8}–10^{-6}). Detailed multi-wavelength observations of SgrA* have shed light on the complex physics underlying this inefficient accretion process that appears to dominate at relatively low accretion rates and is guiding current theoretical work. The fact that the emission from SgrA* is sporadic and faint and at a very confused location makes further substantial observational progress difficult without instrumental advances. Future work could emphasize high time resolution, spectrally resolved observations, polarization studies and eventually astrometry. Astrometry of the ‘infrared’ flares would be extremely exciting, but probably requires unconfused astrometry at the ~10µas level.

a. b.

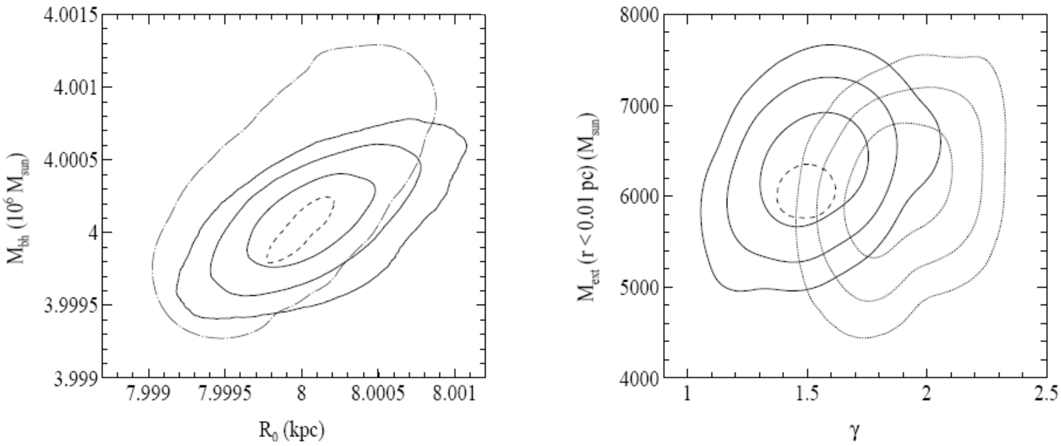

***Figure 9.3** Examples of the precision of parameter estimations in the Galactic Centre, obtained from simulations of stellar orbital astrometric and radial velocity data with an ELT (from the TMT study by Weinberg, Milosavljevic & Ghez 2005): **a.** 1, 2 and 3σ uncertainty contours (solid) of mass and distance to the Galactic Centre massive black hole obtained from an astrometric study of 20 stars with a modest precision of 500µas and 10 km/s. The dotted contour gives the 3σ contour for a 5 times higher precision, which will be achievable with MICADO; **b.** Same for the estimate of the extended mass around the massive black hole for two different choices of the power law slope γ of the cusp’s density distribution.*

The Importance of MICADO

MICADO is uniquely suited for the exploration of the Galactic Centre. The central stellar cusp around SgrA* is strongly confusion limited for current AO observations on 8m class telescopes, limiting the reliable detection and measurement of positions of stars to K~16–17.5, which corresponds to main sequence B-stars. The combination of MICADO and the ELT will push the effective stellar detection sensitivity by ≥5mag in modest integration times, making studies of even sub-solar mass stars possible and allowing mass function studies across the entire range of stellar masses. It should be possible to carry out astrometry with a long term precision of 50–100µas with MICADO, this is 3–6 times better than currently with NACO at the VLT. At this level of precision a number of key issues of the physics of massive black holes and their surroundings can be tackled.

Compared to VLTI/GRAVITY, MICADO will excel with its much higher sensitivity and the larger field of view: Imaging with GRAVITY is limited by principle to a 50milli-arscec field of view (the single-telescope beam size); and astrometry is limited to object separations of 2" (UT) or 6" (AT). GRAVITY offers the higher resolution (by roughly a factor 3), though.

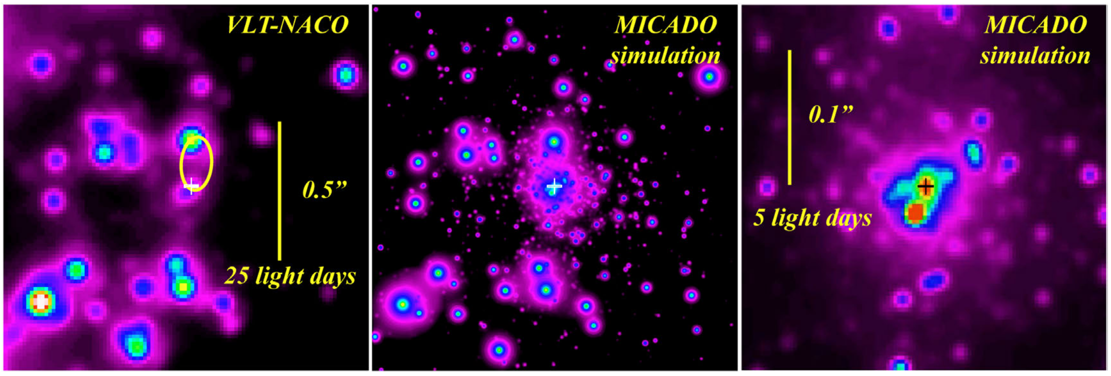

Figure 9.4 *A simulation of a MICADO image of the central cusp around the MBH in the Galactic centre, compared to a current high-quality VLT/NACO K-image at 60mas resolution (left). The KLF- and surface density information and extrapolating NCAO results to fainter magnitudes with a Salpeter IMF yields the simulated MICADO image in the central panel (on the same scale as the NACO image). The rightmost panel shows a zoom into the central region of the MICADO image. A number of stars in this image are close enough to the central massive black hole (cross) that the Schwarzschild precession of their orbits should be observable for sufficiently high ellipticity, as depicted in the simulation in the lower right corner.*

Some Specific Science Cases

MICADO research on the Galactic Centre can explore the following issues.

Detection and characterization of β^2 (β=v/c) post-Newtonian effects of SR and GR, as well as possibly the Schwarzschild pro-grade precession term, for some of the orbits of the already known S-stars to K~17.5, in particular the stars S2 and S14, which have the smallest peri-bothroi (15–20 light hours). Because of the confusion with fainter stars these effects will almost certainly not be measurable in proper motion data with current 8m-class telescopes, even with great patience. The combination of MICADO and GRAVITY will be most fruitful here: GRAVITY is suited best to follow close peri-centre passages; while MICADO can track the orbits more easily out to the apo-centre. Given the degeneracies between Keplerian and relativistic orbits, both a good determination of the orbital elements as well as following in detail the moment of closest approach is needed.

Determination of the orbits of fainter (K ≤ 20-21) main sequence stars inside the central, inner cusp with semi-major axes significantly smaller than the current S-stars, using both astrometric data and Doppler spectroscopy. Extrapolations from the surface density distribution and KLF indicate ~5–10 stars with K≤20 ($m \geq 1.4 M_{\odot}$) in the innermost 0.1–0.2", of which a few stars may have peri-bothroi $<10^3 R_S$, several times smaller than that of S2. Such stars would have orbital time scales of a few years. In this case the Schwarzschild precession term and other GR terms will be detectable in a decade of observations (see **Figure 9.4**). Depending on the brightness of the stars, GRAVITY data might be helpful here, too.

Detection of the theoretically predicted cusp of stellar remnants (stellar black holes and neutron stars) by the Newtonian retro-grade precession of the apo-bothroi of the known S-stars.

Of special interest is the possible detection of more massive intermediate mass black holes that have been hypothesized to form in dense star clusters outside the Galactic Centre and then secularly sink into the central cusp by dynamical friction. The determination of this dark cusp is of great general importance for predicting event rates for LISA large mass ratio in-spiral events. Simulations show that MICADO will be able to determine the mass of this extended dark halo around the massive black hole with an accuracy of less than a few per cent.

Determine orbits of ~10^3 individual stars over a decade of observation: With the outstanding astrometric precision of the ELT (50–100µas) it will be possible to determine orbits of ~10^3 individual stars over a decade of observation. Such a data set would be extremely rich. With a large sample of stellar orbits of fainter (K≤20–21) stars throughout the regime of the central cusp (r<1") and the stellar discs (1"<r<10") it will be possible to robustly draw conclusion on the dynamical state of the Galactic Centre system based on statistics of the orbital elements. It will also be possible to determine the distance to the Galactic Centre to 0.1–0.3%, thus enabling a number of powerful constraints on the dynamics of the Galaxy.

It will also be possible to explore stellar phase space clumping directly (such as the one or two discs of young massive stars already known), and binary fractions and to search for possible intermediate mass black holes in the central cluster. The disc membership of individual stars can be determined, and a complete census of the dynamical state and the mass function of the discs will be possible.

Count stars to <1 $M_\odot$ and establish the present day mass function: With the high angular resolution and enormous sensitivity of MICADO it will be possible, in combination with colours and spectra to determine a robust initial mass function in the Galactic Centre and test the emerging evidence that the IMF in the Galactic Centre region is much flatter than that in the Galactic disc.

Study of the central accretion zone surrounding SgrA*: the spatial resolution of MICADO (5–10mas) it will possible to study in detail the spectral and temporal properties of accretion events and search for evidence of outflows/jets predicted for radiatively inefficient accretion flows as in the Galactic Centre. Short term astrometry within an accretion event, as well as the search for positional shifts between accretion events at different times are of great interest for finding evidence for orbital motion and outflow of the hot gas and the predicted Brownian motion of the central massive black hole. For this science case, both MICADO and GRAVITY will deliver extremely valuable data set.

Dynamical measurements of the prominent young star clusters in the central 50pc: outside of the central parsec MICADO astrometry will allow dynamical measurements of the other prominent young star clusters in the central 50pc (Arches, Quintuplet etc.). Perhaps the most intriguing issue is the search for possible intermediate mass black holes there (as in globular clusters). The unambiguous detection of an intermediate mass black hole in such a cluster has far-reaching consequences for seed black hole formation during the epoch of reionisation.

References:

Weinberg, Milosavljevic & Ghez 2005 ApJ, 622, 878

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