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CFHT [2013A - 2016B] Large Programs

First Call - Deadline: 28 Feb 2012 - 23:59 UTC

Information on the call available here

Title

MATLAS - Mass Assembly of early-Type GaLAxies with their fine Structures.

Abstract

MATLAS investigates the mass assembly of Early-Type Galaxies (ETGs) and the build-up of their scaling relations, with extremely deep optical images. The stellar populations in the outermost regions of ETGs, the fine structures (tidal tails, stellar stream, and shells) around them, and the Globular Cluster (GCs) populations, preserve a record of past merger events and more generally of the evolution and transformation of galaxies. The project capitalizes on several timely developments 1) The unique capabilities of MegaCam. Dedicated imaging procedures and a new pipeline now allow the detection of surface brightness structures, as faint as 29 mag/arcsec2 in the g band. We will thus apply a technique of galaxy archeology, that was first tested on local spirals, to lenticulars/ellipticals which are expected to exhibit many more relics of their mass assembly. The feasibility of the method was validated with pilot surveys 2) An already available stunning ancillary dataset provided by the ATLAS3D project giving complementary information on their dynamics, gas and stellar content. 3) State of the art numerical simulations developed by our team. They predict various types of fine-structures and stellar halos depending on the mechanism driving the mass assembly: major or minor, wet or dry mergers; secular evolution. The database collected as part of this Large Programme and earlier observations, consisting of multi-color images for a volume limited sample of 260 nearby ETGs - the ATLAS3D sample - will have a tremendous legacy value. It will also allow detailed studies of individual well-known objects, rejuvenated with the unprecedented deep images, and to address broader science topics, such as the origin of the

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Total number of **hours** requested 300

Hours per agency:	Canada 90	France 210	Hawaii	Brazil	China	Taiwan

Hours per semester:	13A 80	13B 31	14A 79	14B 31	15A 79	15B 0	16A 0	16B 0

Proprietary period for participating community access is zero by *default* (free immediate access).
If you want this proprietary period to be set to a specific time, provide below the time period and justify it in the proposal.

Free immediate access to the MATLAS images will be given to members of the French and Canadian communities.

Proprietary period for World Access is by *default* one year after the end of each semester for the duration of the survey.
If you want this proprietary period to be changed, provide below a data release schedule and justify it in your proposal.

1 Building massive galaxies

ETGs as cosmological objects

Early-Type Galaxies (ETGs, i.e. the traditional lenticulars and ellipticals) play a key role in modern cosmology, despite being less numerous than spirals and dwarfs. First, most (> 40 %) of the stars in the local ($z < 0.5$) Universe belong to early-type systems and the most massive galaxies are found among ETGs, giving them special status in cosmological models. According to the standard hierarchical cosmological model, galaxies build up from successive mergers, associated with a series of morphological transformations. The massive ETGs we see today are the end-product of this process.

Second, contrary to late-type galaxies, the structural properties of ETGs are apparently very homogeneous, as illustrated by the colour-magnitude relation. Whereas spirals populate a blue 'cloud', ETGs lie on a tight red 'sequence'. The physical processes that shape the transformation of galaxies from the blue cloud to the red sequence (through the 'green valley') have been explored by a striking number of observational and theoretical works. However, the naive, but widely supported, standard scenario involving small, star-forming and thus blue galaxies, that encounter dense environments, stop forming stars – the 'quenching phase' – redden and merge to make the massive, gas–poor, fully relaxed, 'red and dead' galaxies that we see today has been challenged by a number of discoveries.

The disputed build-up scenarios

At high redshifts, ETGs are rare, but surprisingly some are still present (Daddi et al., 2004), raising questions on how they formed so quickly in the traditional merging scenario. This has given support to alternative ideas, such as the now popular 'clumpy' scenario. Massive clumps, formed within unstable gaseous disks (fed by gigantic intergalactic streams), interact with each other and migrate to the inner regions, forming a prominent bulge. The gravitational forces in such a clumpy disk further cause inwards transfer of the diffuse gas and trigger an inner starburst, thus accelerating the development of the bulge. This gradual process leads to the formation of galaxies with light profiles typical of ETGs (Elmegreen et al., 2008). An issue hampering the identification of distant ETGs in optical images and the characterization of their structural parameters is the lack of sensitivity at moderate galactocentric radii, making the detection of stellar disks or halos particularly difficult. The current controversy on the real compactness of distant ETGs (Mancini et al., 2010) illustrates this problem.

At low redshift, ETGs display far more complex structural and kinematic properties than once believed. They contain cold and star-forming gas, show a variety of stellar and gas kinematics, and seem to be involved in active transformation processes. These results are the highlight of the ATLAS^{3D} Project, and form the motivation for this Large Program (LP) proposal.

Constraints from the outskirts of galaxies

The structure of galaxies, and how it relates to other local and global properties, can tell us how galaxies formed. In particular, *the outer-most parts of galaxies keep the long-term memory of past accretion events.* It is this property that we exploit fully with this LP.

Simulations indicate that while major mergers may be able to reproduce the global light profile of ETGs, characterized by a high Sersic index, multiple minor mergers may be necessary to explain their total mass and large radial size (e.g., Oser et al. 2010; Khochfar et al. 2011). Such repeated merger events *impact the properties of the stellar populations mostly at large galactocentric radii beyond two to five effective radii.* In particular, minor mergers bring low metallicity stars from the infalling dwarf satellites, contributing blue stars to the halos of ETGs, and creating radial color gradients. On the other hand, a major merger induces large radial mixing, washing out metallicity/age gradients.

Furthermore, the mass assembly of galaxies leaves structural imprints on their surroundings, such as shells, streams, tidal tails, extended halos, etc. *The frequency and properties of these fine structures depend on the mechanism driving the mass assembly* (see the review by Duc & Renaud, 2011). Depending on whether massive galaxies were formed through the clumpy secular scenario, minor mergers, or major dry / wet mergers, the ubiquity of fine structures will go from none to significant (see Fig. 2). The shape of fine structures gives information on the nature of the merger: gas-rich, wet major mergers produce tidal tails, while gas-poor, dry mergers do not; long, wide, tidal tails pinpoint major (i.e. equal mass) mergers; narrow pairs of stellar streams are suggestive of minor mergers, causing the total disruption of satellite galaxies, while shells reveal head-on collisions. Analysis of fine structures must take into account that galaxies may have formed by multiple events and processes, and that any resulting stellar debris will have a very low surface brightness, which will fade with age, or may be dispersed by the local environment. Current detailed numerical simulations done in cosmological context precisely address these issues and are now capable, for the first time, to relate the merging/accretion history of the simulated galaxy with the number, shape, brightness and ages of the fine structures present at the end of its evolution. Such techniques have so far been applied mostly to spiral galaxies, where the discovery of numerous faint substructures (e.g. McConnachie et al., 2009) have fundamentally changed our view of those systems. Early-Type Galaxies (ETGs), the most powerful probes at low redshift of the hierarchical mass assembly of galaxies, should exhibit even more fine structures than late-type galaxies.

We propose here to build on recent advances of wide-field optical imaging and data processing by conducting a CFHT Large Program of deep imaging aimed at characterizing the outer regions of a complete sample of 260 nearby ETGs.

2 The ATLAS^{3D} survey

The sample and ancillary data

ATLAS^{3D} (Cappellari et al., 2011a) is a large project targeting a volume-limited sample of 260 morphologically-selected ETGs located within 42 Mpc. The ATLAS^{3D} project collected a wealth of ancillary multi-wavelength data: integral-field optical spectroscopy with SAURON (WHT), deep HI interferometry (WSRT), single dish and interferometric CO imaging with the IRAM, BIMA and CARMA facilities. These data have provided comprehensive information on the dynamical status, gas content, stellar populations and chemical enrichment of the nearby ETGs.

Among the recent achievements of this survey:
- a revised classification of galaxies that relies on their internal kinematics, and defines a sequence going from the 'fast rotators' (galaxies with stellar velocity maps consistent with rotation) to 'slow' rotators (which encompass the massive ellipticals with M$> 10^{11}$M$_\odot$) (Emsellem et al., 2011; Krajnović et al., 2011)
- the discovery of a *kinematic* morphology-density relation (Cappellari et al., 2011b)
- the evidence that a large fraction of ETGs (50%) contain HI gas (Serra et al., 2012) and a significant fraction of them also molecular gas (22%) (Young et al., 2011)
- the evidence for a systematic variation of the stellar initial mass function in ETGs (Cappellari et al, 2012, Nature in press)

While some of these characteristics were previously known for biased samples of objects, it is only due to the completeness of the volume-limited sample of ATLAS^{3D} that these properties could be quantified on a firm statistical basis, and systematic trends fully explored.

The missing piece for a comprehensive view of ETGs is a scenario able to explain both the variety of the observed properties (kinematical features, gas content, etc), in particular the frequency of fast/slow rotators, and their global scaling relations (global color, mass, size). Simulations and semi-analytic models (SAM) made in the context of ATLAS^{3D} provide scenarios emphasizing the roles of gas accretion and late stellar assembly which roughly account for the properties of statistically defined samples (Khochfar et al. 2011); however, these scenarios are not fully consistent with the multi-component nature of ETGs, missing important observational constraints, such as the time scales involved. *The proposed deep-imaging observations may remedy this situation and allow to test predictions of the models, as detailed below.*

The pilot surveys

One quarter of the ATLAS^{3D} ETGs belong to Virgo. They already benefit from the extensive deep imaging survey with MegaCam made as part of the Next Generation Virgo Cluster Survey (NGVS), which is about to be completed (Ferrarese et al. 2012). Thanks to its unprecedented sensitivity for low surface brightness structures, coupled with excellent image quality, the NGVS addressed a broad range of science topics in the cluster environment, including the mapping of the intergalactic diffuse stellar light, mostly debris resulting from the interactions between the cluster members.

In parallel, we have conducted a series of PI pilot programs with MegaCam to observe sub-samples of ATLAS^{3D} ETGs outside Virgo (with a total of 104 targets) at sensitivities comparable to that of the NGVS, i.e. reaching surface brightness magnitudes of 28.5–29 mag/arcsec^2 in the g-band.
- Two runs targeted 38 gas-rich ETGs, exhibiting HI gas in their outskirts or molecular gas (CO) in their inner regions. The detection of tidal stellar counterparts to the HI clouds rather suggests a collisional origin. Galaxies for which molecular gas and the old stars share the same kinematics – an argument in favor of the internal hypothesis for the CO – are consistently less tidally perturbed than the others with decoupled stellar and gas kinematics, for which the CO might have been accreted during a merger. One highlight of this program has been the first detection of an optical counterpart to the famous huge intergalactic HI structure in the Leo group which we modeled as a collisional ring (Michel-Dansac et al., 2010).
- Subsequent MegaCam runs investigated the dynamical status of the most massive ETGs, targeting massive, slow rotators and ETGs with kinematically decoupled cores. It led to the discovery of gigantic stellar filaments (400–kpc long) around a slow rotator that so far was believed to be a fully relaxed, old object. We interpreted these structures as imprints from a moderately young – 1–3 Gyr – major merger (Duc et al., 2011; see Fig. 5, 2). We found a weak trend (unfortunately based on an incomplete sample) for slow rotators to be more tidally perturbed than the fast rotators.

The NGVS and above pilot programs ensure the feasibility and discovery potential of the proposed LP by emphatically demonstrating the capability of MegaCam to detect previously undiscovered low surface brightness, extended stellar halos and tidal debris (see Fig. 5 presenting the variety of fine structures so far detected). These data allow us to address particular (and important) scientific questions for specific sub-samples of objects. However, the *current data set is fundamentally limited by sample incompleteness and the strong selection biases* that were necessarily applied. This makes statistical comparisons to model predictions *impossible* with the current data, and exploration of empirical trends highly dependent on selection effects.

By capitalizing on the major investments already made with by the NGVS and ATLAS^{3D} pilot campaigns, *we propose here to realize the full potential of these MegaCam surveys, by obtaining deep (g,r,i) imaging for the complete ATLAS^{3D} sample.* This would give an unprecedented sample of 260 ETGs with homogeneous imaging of extraordinary depth and fidelity, casting new light on the dimmest regions of these galaxies.

3 MATLAS: Driving the mass assembly and scaling relations of ETGs

The main objective of MATLAS is the comprehensive understanding of the build-up of ETGs and their scaling relations. We will do this by focussing specifically on the faint outer regions of galaxies, which preserve the long-term memory of past accretion events. Most importantly, we aim at completing a volume-limited sample of 260 ETGs, spanning a large range of mass/environment. This sample is essential to allow rigorous comparisons with model predictions, and to provide robust demographics of observed phenomena - paramount to connect with results from massive surveys of more distant galaxies. Our immediate scientific aims are listed here:

Measuring the fine structure index of galaxies

Stellar tidal tails, streams, shells and ripples are unambiguous relics of past interactions - there are no other scenarios to form these. Contrast this with the formation of HI streams, which can have several origins, including ram pressure stripping. The mass assembly history of galaxies is punctuated by multiple merger events, each associated with the formation of tidal debris. Simply counting the number of such structures allows us to characterize the level of tidal perturbation and how rich the mass accretion of a galaxy was in the last few Gyrs.

In practice, we will use the empirical approach of Schweizer et al. (1990) and compute the fine structure index Σ which combines in a single parameter the number and strength of shells and tails. Σ is determined independently by several persons. Average values are then computed[1]. As a first step, *we will correlate the fine structure index to the structural parameters of all ATLAS*^{3D} *galaxies (mass, radius, angular momentum,* λ_R*), splitting the analysis between the various environments probed by the survey: cluster, group and field.*

Reconstructing the mass assembly of galaxies

To reach the ultimate goal of the project (reconstructing the mass assembly history), one needs to take into account not only the number of tidal structures but also their individual properties, and introduce time scales in the analysis: fine structures are transitory structures that fade within a few Gyr when isolated, and roughly ten times faster in dense environments. This property allows us to date, with a $\sim 20\%$ precision, past merging events through calibrations from the numerical simulations developed by the ATLAS^{3D} collaboration. We will compute the production efficiency and survival time of tails, streams and shells created during successive mergers. The frequency of the galaxy collisions and accretion events in the models is realistic, i.e. relying on cosmological initial conditions. Like for the observations, a fine structure index is determined at each snapshot, previously cut at the same surface brightness limit as for the MegaCam images (see Fig 2, right).

By averaging over sub-samples, for instance galaxies within the same bin of mass, effective radius and angular momentum, statistical constraints may be obtained on the recent merger rate history, and compared with predictions from semi-analytic or cosmological simulations. *This objective can only be met with observations of a sufficiently large and diverse sample, as provided by ATLAS*^{3D}*, in order to populate the parameter bins.*

The type of mergers in the buid-up of ETGs is actively debated. Hopkins et al. (2008) claimed that above 2×10^{11} M$_\odot$, the stellar mass growth is mainly due to major dry mergers, whereas Lopez-Sanjuan et al. (2010) argued that only 20% of ETGs more massive than 10^{10} M$_\odot$ have experienced a major merger since $z = 1$. On the other hand, Naab et al. (2009) argued that below $z < 1$, mass and size growth are primary due to minor mergers, a result consistent with the semi-analytical model of Khochfar et al. (2011, see Fig 3). All these models have specific predictions on the relative number/type of mergers an ETG has experienced since the last few Gyr, which translates into specific values of the fine structure index. *Comparing observations statistically with such models, to distinguish between these scenarios, can only be done with a complete sample.*

Investigating the build-up of the scaling relations of ETGs and galaxies in general

Scaling relations (e.g., the tight relationships between mass, size, and velocity dispersion) are a critical test of galaxy formation models. Fig. 4 plots the effective radius and the dynamical mass for all ATLAS^{3D} galaxies. The global shape of the envelope enclosing all the galaxies, and its associated cusps, can be interpreted as follows: galaxies of similar velocity dispersion, implying comparable bulge size, form nearly parallel sequences of homogeneous stellar populations (as traced by their mass to light ratio). A galaxy goes from one sequence to the other when its bulge grows and its star formation is quenched: from a spiral, it becomes an ETG, initially as a fast rotator. A galaxy moves along the sequence through a series of preferentially dry mergers (including accretion of gas–poor satellites) which increase galaxy masses and sizes while keeping the velocity dispersion and stellar properties nearly unchanged. At high masses, such mergers are the only path for galaxy evolution (Naab et al., 2009, Cappellari et al., in prep).

There are two facets to this picture: *bulge growth*, either through quenching of the disk (e.g. stripping of

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[1] Such 'by-eye' classification may seem antiquated and subjective, but it was nonetheless recently resurrected by e.g. the SDSS Galaxy Zoo or HST CANDELS projects. This technique proved to be the most efficient one for our own pilot study. Computerized indicators of tidal perturbations were tested, such as the CAS parameter which computes the degree of asymmetry (Conselice et al., 2009). They turned out to be poorly sensitive to the presence of collisional debris because their integrated light do not contribute much to the total luminosity of the galaxy, typically less than one percent, i.e. below the errors of the measure.

gas), or direct accretion of material, or both (morphological quenching); and *dry mergers*, either through major or minor mergers. *Our deep imaging data will allow us to differentiate these evolutionary paths by accurately constraining the accretion history of the past few Gyrs.* Again, for this science goal, having data for the entire sample is fundamental to determining which processes dominate and in which mass/environment regime. In particular, the fast rotators that make up the vast majority of ETGs (86%) play a key role in the journey of galaxies from the blue cloud to the red sequence, but are poorly sampled by the existing MegaCam data.

Obtaining accurate distances of the ETGs

The distance of many of the ETGs in the ATLAS^{3D} sample suffers from large uncertainties, up to 40%, which directly impacts the uncertainties in all our scaling relations. Outside Virgo, only a limited number of galaxies have benefited from measures obtained with the precise Surface Brightness Fluctuation (SBF) technique. Our requested image quality will allow us to measure SBF distances with a precision of about 8-10% for the closest galaxies to around 15% even at distances of 40 Mpc with a corresponding reduction in the uncertainties for half the ATLAS^{3D} sample.

Revisiting the effective radius and stellar masses of ETGs

The discovery of very faint and extremely extended stellar halos around some ETGs (see Fig. 5, p.2) requires a revision of their derived effective radii and inferred stellar masses[2]. Mass and effective radius are fundamental parameters of the galactic manifold used to test galaxy formation models. Increasing the effective radius of a galaxy has further consequences on the mass assembly scenario and related time scale. *A systematic and uniform measure of the masses and radii for the whole sample will thus be carried out.*

Tracing the large-scale structures of ETGs with Globular Clusters

In the very outskirts of galaxies, where the stellar density becomes too low to get meaningful information from unresolved observations, globular clusters (GCs) are often used as dynamical tracers. Furthermore their number, distribution and color provides additional information on the past assembly. The color distribution of GCs around massive galaxies is known to be bimodal, and sometimes even more complex (e.g., Blom et al. 2012). The red clusters are often interpreted as being metal-rich, and could thus have formed during gas-rich merger episodes. Their specific frequency (number of GCs divided by the total galaxy luminosity) is an indicator of the past collisionally induced starburst episodes in the host galaxy. The blue clusters are usually older and their radial distribution is often tracing the overall large-scale stellar profile of the galaxy.

The image quality of our images will allow us to identify the GC populations for all ATLAS^{3D} galaxies located at distances below 20 Mpc (about 100 objects). *We will determine the variations of the specific frequency and radial profile of the GC populations as a function of environment and galaxy type.*

Probing the stellar populations in the very outskirts of galaxies

ETGs are considered 'red' but their colors are not necessarily uniform: radial color gradients are observed. These are usually interpreted as variations in either the metallicity and/or the age of the stellar populations. *Our deep images allow us to extend the measure of the large-scale color gradients to large radii, typically up to 5–10 effective radii (Re), whereas spectroscopic studies are limited to at most 2–3 Re* (e.g. Tortora et al., 2010). A variety of color profiles has been observed in the galaxies of our pilot survey, with instances of a strong decrease of the color index beyond 2 *Re* observed in some galaxies[3], consistent with an external, merger, origin for the outer stellar populations. The depth of our survey, and the choice of (g, r, i) filters, will allow us to sensitively test model predictions of how the large–scale color gradients vary systematically with the size, mass and environments of the ETGs. The colour information also gives added contrast for mergers involving different stellar populations (see Fig. 6) - an important indicator of the accreted galaxy's previous morphology.

4 The legacy value

MATLAS will provide a unique imaging data set with an exceptional and long standing legacy value. Indeed, the way in which our observations will be carried out will allow us to reach surface brightness with levels (29 mag/arcsec^2) that will not be reached in even future ground-based or space-based facilities. For instance, stacked images from the LSST observing strategy will not permit the background subtraction required to reach such sensitivities. Telescopes used for present or future space missions (HST, JWST, EUCLID) will have an inadequate focal ratio (and for the two former, a too small field of view) and will not be able to detect the low surface brightness structures probed by MATLAS. Resolved stellar populations in nearby galaxies is an alternative method to investigate the diffuse structures around galaxies. It was successfully applied to the galaxies in our Local Group, including the Milky Way and Andromeda. The ELTs will extend the distance up to which the method may be used to several Mpc, which is unfortunately not far enough to reach the bulk of the ETGs in the local universe.

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[2] Discrepancies by a factor up to 2 between the measures of *Re* given by the literature and made on the MegaCam images of our pilot program have been found.

[3] up to $\Delta(g-i) = -0.5$ mag (Duc et al., 2011)

Besides the works listed in the science rationale, a large number of additional scientific projects and public outreach initiatives may be achieved with the proposed imaging data-base. We list below a number of them.

Individual studies of ETGs

The ATLAS^{3D} sample includes many well known nearby ellipticals which are regularly devoted individual studies. The deep g, r, i and for a sub-sample, u bands provided by MATLAS may prove key to investigate for instance the environmental factors that might affect some observed properties[4].

Among the additional studies that will be conducted within the ATLAS^{3D} / MATLAS collaboration is the investigation of the gravitational potential of ETGs at large radii, where dark matter is thought to dominate. We are already accumulating stellar velocity dispersion measurements for our sample using integral field spectroscopic observations (about 20 so far). Determination of the stellar mass model requires the deep images that this proposal provides.

Globular Cluster follow-up studies

MATLAS will provide the most comprehensive and robust catalogue available of ETG GCs accessible for spectroscopic observations. In addition to probing accurate stellar population information, spectral follow-up of the GCs gives access to the kinematics of the GCs, which are invaluable tracers of the large-scale gravitational potential (for dark matter studies) and angular momentum. This has already been successfully tested on a few ATLAS^{3D} galaxies with works done as part of the NGVS collaboration as well as by competing teams (SAGES project; PI: J. Brodie). The deep MATLAS GC catalogue would be of substantial value to the community for planning similar campaigns, some of which would originate from within our collaboration.

Companion galaxies: dwarfs and spirals

Depending on distance, a MATLAS pointing covers a region of 200 to 700 kpc (the spatial scale of groups) around the ETG, enabling environmental studies. Many new, uncatalogued, companion galaxies are expected to be discovered in this field. The redshift of the star-forming, gas-rich, galaxies will be determined thanks to the HI line datacubes already available for all objects. For the faintest galaxies, photometric redshifts will provide rough probabilities for group membership.

The deep images provided by MegaCam have the sensitivity to detect *dwarf galaxies* – a class of objects with M_B below -8, the equivalent of the faintest regular Local Group dwarfs – up to at least the distance of the Virgo cluster (Ferrarese et al., 2012). This is a unique database to study how the distribution of faint dwarfs may vary with the environment and structural properties of the host galaxies. Besides, the close environment of ETGs that suffered major mergers might reveal the presence of Tidal Dwarf Galaxies (TDGs), objects born in bound collisional debris, and presumably evolve into dwarf spheroidal galaxies. In fact, TDG candidates have already been identified in the images of our pilot program (see Fig. 5, p.2; Duc et al., 2011). Spectroscopic time was awarded at Gemini to confirm their nature. A systematic survey of old TDGs aiming at determining their cosmological importance is planned.

The ATLAS^{3D} Early-Types Galaxies have been extracted from a larger sample of 871 massive galaxies (See Fig. 1). About 100 late-type spiral galaxies that lie close enough to the ETGs to be within the MATLAS field of view ($\sim$ 350 kpc$\times$350 kpc at 20 Mpc) will benefit of deep images for free, providing like for the ETGs, insightful information on their recent mass accretion events. While by definition, spirals should not have yet suffered major mergers, some may be involved in on-going interactions (possibly with the companion ETG) or have experienced minor mergers. Martinez-Delgado et al (2010) have revealed spectacular examples of destroyed dwarfs wrapping around galactic disks. Perturbed spirals are also found in our imaging database, as shown on Fig 6. *This database of spirals will be a useful complement for our study of the build-up of the scaling relations.*

Public outreach

The public outreach potential of the imaging database collected by ATLAS^{3D} is very strong. The true color-images obtained combining the multi-band data are gorgeous, and simply change the vision we might have of our massive neighbors. Elliptical galaxies that, compared to spirals, appear dull on regular images and are thus not often represented in public image galleries, acquire a new look with our deep images, exhibiting aesthetics colorful streams, rings and other features. In fact, results of our pilot program were already announced in two separate press releases of CNRS/CEA/CFHT (in 2010 and 2011)[5]. One of the MATLAS images showing a massive ETG with prominent shells and filaments attracted the attention of many amateur and professional astronomers world-wide after its selection as an Astronomical Picture of the Day. It is currently presented in an art exhibition gallery in California [6]. Several other images have had the honor of being shown in the 2012 CFHT/Coelum calendar (see Fig 6).

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[4] A recent paper illustrates the high legacy value of our LP: Bonfini et al. (2012) have analyzed the globular cluster population around NGC 4261 (using the standard Elixir pipeline, which is ok for point-like sources), one of the ATLAS^{3D} galaxy for which we already have MegaCam images. They noted a significant asymmetry in the azimuthal distribution of the GC population, and wondered whether it could be the result of a past merger, despite the fact that the galaxy looks regular lacking "any obvious feature" in its morphology. In fact our deep image of the galaxy shows prominent low surface–brightness tidal tails precisely in the direction of the asymmetry probed by the GCs!

[5] Leo Ring PR: http://www.cfht.hawaii.edu/en/news/LeoRing/ NGC 5557 PR: http://www.cfht.hawaii.edu/en/news/EllGal/

[6] http://www.pasadena.edu/artgallery/exhibition.cfm?ID=15314

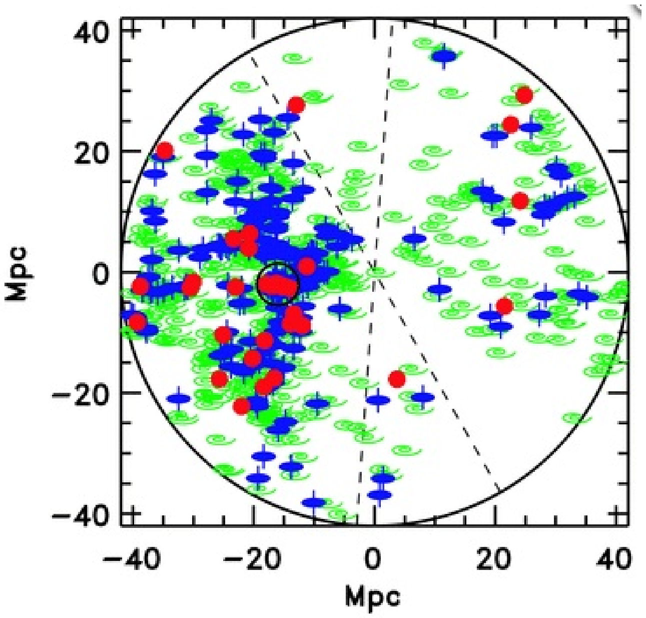

Figure 1: Distribution of all ATLAS^{3D} galaxies in the local volume. Green spirals are the late-type galaxies from the parent sample. Blue ellipses are the fast rotators. Red dots are the slow rotators. The large variety of environments and galaxy density provided by the ATLAS^{3D} survey is clearly visible on this diagram (Cappellari et al., 2011)

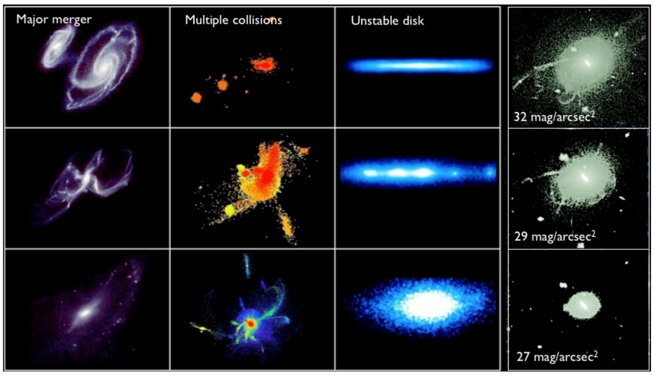

Figure 2: *left:* Numerical simulation predictions of the frequency, colors and shapes of fine structures for three mass-assembly scenarios. Time sequences are shown for a single major merger (left col), multiple collisions (middle col., from Martig et al., 2009) and evolution of an unstable disk ('clumpy' scenario, right col., Bournaud et al., 2007). *Right:* Surface brightness maps predicted for the numerical model with multiple collisions. The images are cut at surface brightness of 32 mag.arcsec^{-2} (top), 29 mag.arcsec^{-2} (middle; our goal) and 27 mag.arcsec^{-2} (bottom; similar to SDSS and typical published images of nearby ETGs: the collisional debris is no longer visible).

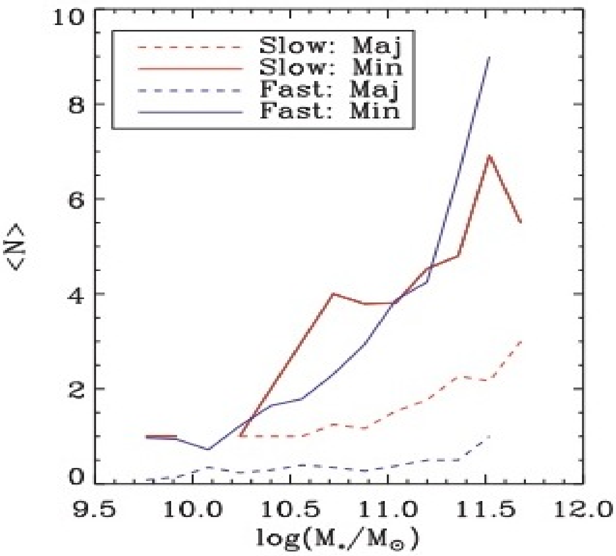

Figure 3: Predictions from our SAM model constrained to reproduce the observed mass function of fast and slow rotators (Khochfar et al. 2011): average number of minor/major (solid/dashed) mergers that the most massive progenitors of present-day ETGs experience during their evolution. The number of mergers rises with the present-day stellar mass of ETGs, a result that MATLAS will be able to directly check.

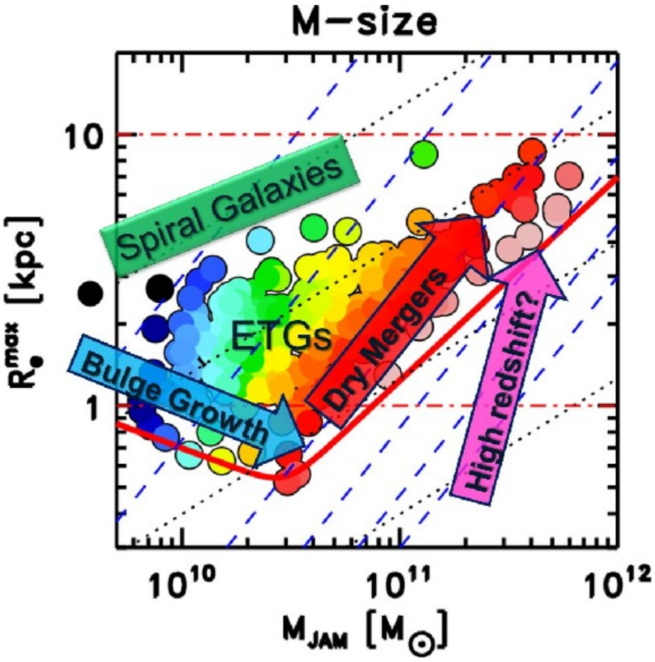

Figure 4: *left:* Effective radius vs dynamical mass for the ATLAS^{3D} sample of ETGs. The stellar mass to light ratio is coded with the colors (Cappellari M., 2011, paper presented at the conference "Galaxy Formation", ed. Ryan Hickox in Durham, http://astro.dur.ac.uk/Gal2011/uploads/gal2011_durham_talk_Cappellari.pdf). Note the parallel sequences in this scaling relation, along which and perpendicular to which galaxies evolve, with processes involving star-formation quenching and mergers. MATLAS will probe these proposed scenarios.

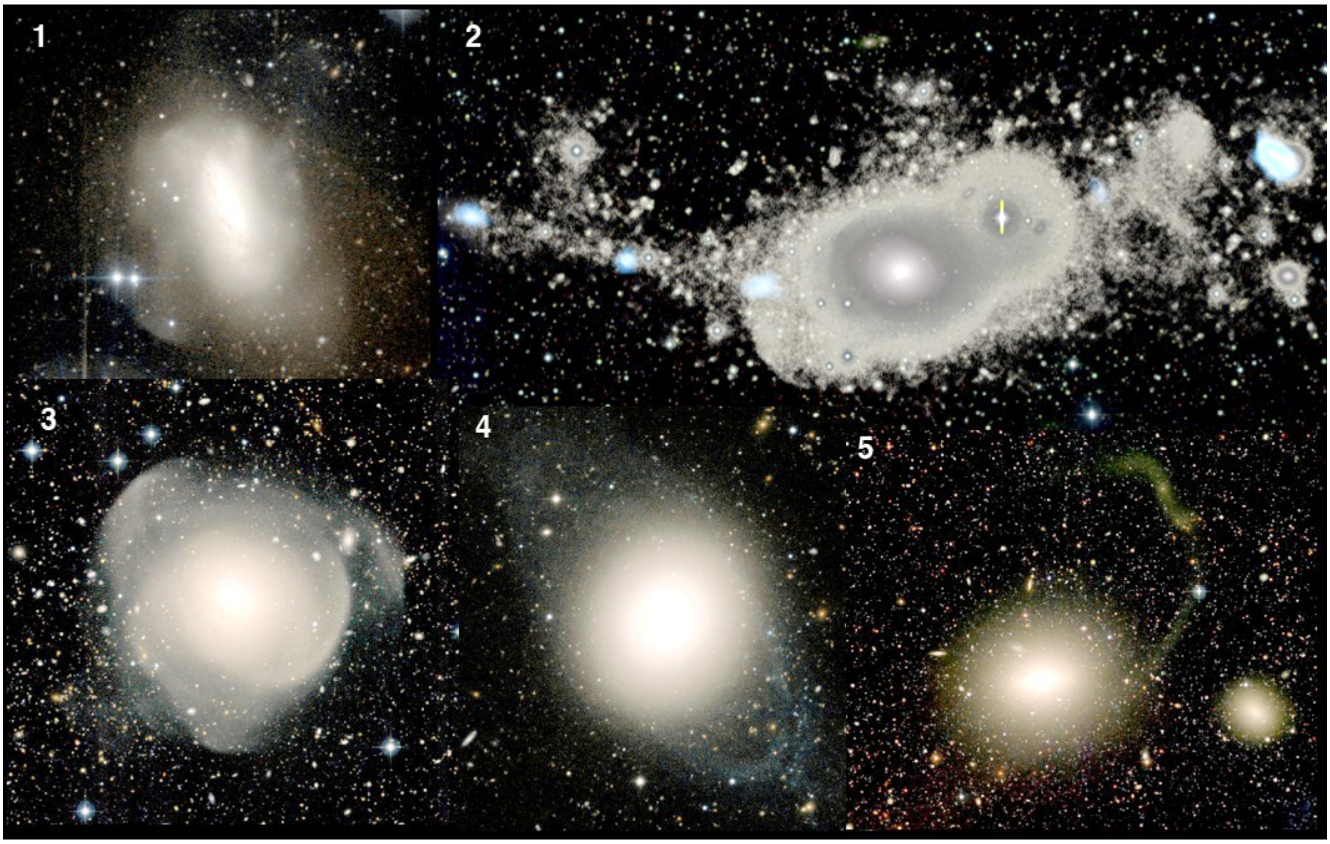

Figure 5: The variety of low-surface brightness fine structures around ETGs disclosed by our pilot surveys; prominent tidal tails (2, with HI overlaid in blue pinpointing TDG candidates), shells (1,3), ring (4) and streams due to minor mergers (5). For the ETG shown in panel 2, the SDSS image of the galaxy is superimposed on the MegaCam image. This illustrates how our view of elipticals may be changed with the deep imaging proposed by MATLAS.

Figure 6: Two images obtained as part of our pilot surveys and shown in the 2012 CFHT/Coelum calendar.

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5 Technical justification

We provide here the technical details of interest for our proposed Large Program. In particular we justify:

The strategy for completing the ATLAS^{3D} sample

ATLAS^{3D} galaxies were selected according to the following criteria: they were extracted from a complete parent sample of 871 galaxies brighter than $M_K < -21.5$ mag (corresponding to a stellar mass above 6×10^9 M$_\odot$), located at distances below 42 Mpc and observable from northern facilities ($|\delta - 29| < 35$, $|b| > 15$). The ETGs were then selected, eliminating galaxies with spiral arms and prominent dust lanes.

Some MegaCam images to be used for the MATLAS project have already been acquired. We report here on the available observations and justify the need to complete them.

Among the 260 ATLAS^{3D} galaxies, 58 were observed as part of the NGVS and will have u, g, i and z images by the end of 2012 when the LP is completed. Our PI pilot program has produced g–band images (and for some ETGs r or i bands) for 104 additional galaxies outside Virgo. Thus 38% of the ATLAS^{3D} galaxies do not have yet **any** deep optical image. The fraction of galaxies having at least the 3 bands (g, r, i) required to constrain their stellar populations **drops to 12%**. Fig. 7 summarizes the available data.

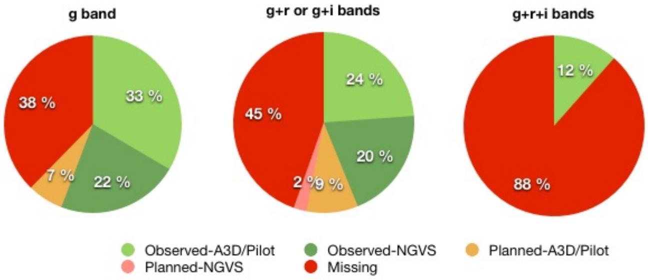

Figure 7: Fraction of ATLAS^{3D} ETGs with available MegaCam images as a function of band. The planned observations correspond to the 2012A runs of NGVS and PI pilot program.

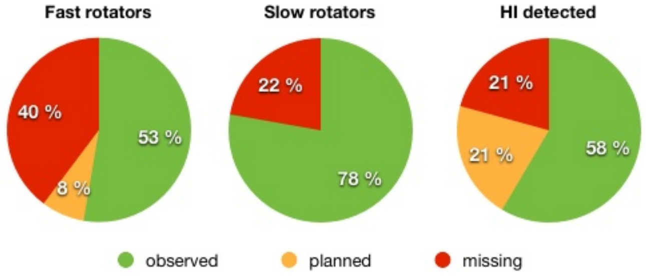

Figure 8: Fraction of ATLAS^{3D} ETGs with available MegaCam images as a function of galaxy class.

The fraction of ETGs having deep images in at least one band varies very much depending on the sub-classes of ATLAS^{3D} galaxies (see Fig. 8). This bias reflects the strategy of the pilot program: each observing run has targeted specific families of galaxies, selected to probe specific questions, such as the origin of their HI or CO gas. Those sub-classes have a MegaCam sampling up to 80%. The much poorer sampling of the fast rotators – a critical family that contains objects on the path between the spiral and elliptical sequences, as argued in the science rationale – hampers the proposed studies of the mass assembly and build-up of the scaling relations.

Furthermore the high legacy value of MATLAS will only be ensured if all the nearby ETGs from the ATLAS^{3D} sample are observed in the g, r and i bands.

The necessity and feasibility of reaching very low–surface brightness limits

Collisional debris is of faint surface brightness, usually not exceeding 26 mag.arcsec^{-2} at the moment it is formed. When getting older, it disperses and becomes much fainter. Fig. 2 (right) shows predictions from numerical simulations on the detectability of fine structures in an ETG. It demonstrates that reaching a level of ~ 29 mag.arcsec^{-2} in the g band is required to determine a useful tidal index for most systems. As shown by the NGVS Large Programme and our Pilot Surveys, this is now feasible with the right observing strategy applied to MegaCam: images processed at CFHT by Elixir-LSB reveal faint features only a fraction of the sky background level (0.2% peak-to-peak, or seven magnitudes fainter than the sky background). Fitting the surface brightness profiles of large galaxies in the NGVS field, one could estimate the limiting magnitudes to 29 mag.arcsec^{-2} in the g band and reveal fine structures invisible on the previously existing images.

The choice of filters

The filter selection was motivated by our aim to detect low–surface brightness features and extend the study of the stellar populations of ETGs to large radii (up to 10 *Re*). We have selected the three filters that maximize the contrast between the sky background and the debris while keeping the exposure time reasonable: g', r' and i' [7]. Having two colors is a minimum to estimate the age/metallicity of the stellar populations. These colors will further be used to distinguish major tidal tails formed in major mergers, composed of mixed, metal–rich, stellar populations expelled from their parent spiral galaxies, to stellar streams that result from the disruption of low–mass satellites primary composed of low–metallicity stars. Foreground galactic cirrus become a significant contaminant at that super low surface brightness level for some of the low galactic latitude ETGs.

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[7] A further motivation for having these three bands is the homogenization of the data set already available. Because of the adverse weather conditions that affected some of our past observing runs, some images in the r', i' or both bands that were planned are missing. This is not the case for the g' band images which were obtained with highest priority.

The color information from the g'r'i' data set **is crucial to differenciate cirrus from the tidal material.** Note that the multi-color images will be used to produce the true color images used in public image releases (and the CFHT calendar).

In addition, u* band images will be acquired for the sub-sample of ETGs with distances compatible with the study of the Globular Cluster populations, i.e. below 20 Mpc. There are 37 ETGs outside Virgo (those in Virgo will benefit from the u* band observations of the NGVS), observable with 35 fields. The u* band is mostly required for the robust identification of GCs among foreground stars and background distant galaxies. With just the g', r' and i' filters, the contamination would increase by a factor of at least 4, thus strongly limiting the usefulness of this catalogue for expensive spectroscopic follow-up. Having a baseline as wide as possible is needed to investigate the nature of the bi-modality of the GC population. Finally, the u* band helps to identify star–forming regions within gas–rich tidal debris (that result from wet mergers) and even provides a rough estimate of their star–formation rate. Note that adding the u* band to the survey corresponds to only a modest increase of 15% to the total amount of time requested to complete the g', r', i' observations.

The need for a large-field of view camera

Our sample consists of nearby early-type galaxies that have a typical angular size of 10 arcmin. Their fine structures might extend by a further 10-20 arcmin. In addition, the detection of faint low–surface brightness structures requires a dedicated observing strategy for which a large-field of view camera is a clear asset. On typical Elixir processed MegaCam images, in particular those obtained as part of the CFHTLS, the presence of scattered light masks extended features below a surface brightness of 27 mag.arcsec^{-2}. Investigations motivated by the NGVS have shown that this problem can be overcome carrying out a sequence of observations with large offsets between the images, as it is usually done with infrared observations. A background map is then computed and subtracted from the individual images, before they are stacked. The target source can be be kept within the one square degree field of view of MegaCam, thus minimizing the observation overheads. In some favorable cases, several close-by ATLAS^{3D} ETGs will be simultaneously observed.

The choice of observing conditions

Dark time for the u*g'r' filters is absolutely required to detect the low–surface brightness structures at the heart of this proposal. For the same reason, twilight periods should be avoided. Thin ($<$ 0.1 mag. absorption) cirrus are acceptable in the u*g'r' bands as long as the Moon is not up : this adds great flexibility to the queue scheduling. The low surface brightness science does not require exceptional Image Quality. Many other science aims, in particular the identification of the GCs and the SBF distance measurement, will benefit from the high IQ of MegaCam under good seeing conditions. Whereas our pilot programs (aimed at detecting fine structures) only requested seeing better than 1.2 arcsec, its high ranking by the TAC resulted in most of the acquired images having much better conditions. Thus the vast majority of our MegaCam images (including those coming from the NGVS) are compatible with GC studies. Our IQ constraints will therefore be the same as for the NGVS, namely 1 arcsec for u, g, r and 0.6 arcsec for i.

Due to the complete volume limited nature of our sample, our targets are distributed over a wide range of RA (see attached table). Data for the most clustered ones (in Virgo) were already obtained as part of the NGVS (except in the r band).

The required observing time

The total observing time per target is constrained by the surface brightness limit we wish to reach, but also by the observing strategy. At least 7 individual exposures (as done for our pilot program) are required to get an accurate background image and eliminate as much as possible faint residuals. The offsets are chosen to be much larger than the galaxy size, typically 15 arcmin.

Our now extensive experience with deep MegaCam imaging with the Elixir-LSB observing and data-reduction strategy allowed us to obtain reliable estimates of the required exposure time to get 29 mag.arcsec^{-2} in the g' band (and 28.5 mag.arcsec^{-2} in the r' band, collisional debris having a typical color of g-r=0.5 mag). We stress that it is not totally determined by the photon noise statistics. It is first and foremost defined by the elimination of the systematics in the sky background. Taking into account all our constraints, exposures of 7 × 345 sec will be needed in g and r, and 7 × 230 sec in the i band, matching the exposure times of our pilot programs. Adding 40 sec of overhead (readout time) per frame and band, the total time per target is 45 min for the g and r bands, and 32 min for the i band. For targets observed in the u band (31 of them), an additional observing time of 87 minutes per target (corresponding to individual exposure times of 7 × 700 sec) is requested.

Our total time estimate takes into account several additional factors: the data already available, either from our pilot programs or from the NGVS[8], but also the position of the targets. Outside Virgo, a fraction of the MegaCam pointings contains at least 2 ETGs with positions on the field compatible with our observing strategy. Table 1 summarizes the number of required pointings per band and corresponding total exposure time.

A total of 300 hours is requested to complete our observations (238+62), distributed over 5 semesters.

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[8] At time of writing, full depth r band / NGVS observations are still missing for the Virgo ETGs. They will not be obtained before the completion of the LP. However, shallow r–band observations of 2 × 687 sec are scheduled. Thus for the ATLAS^{3D} galaxies belonging to the NGVS, we request here additional integrations to complete the observations to the requisite depth

Time request and RA distribution of the observations

Table 1: Time request

Band	N(ETGs)	N(fields)	Exposure Time
u (field)	37	35	51 hours
g (field)	98	90	68 hours
r (field)	116	103	78 hours
r (Virgo)	58	54	23 hours
i (field)	173	149	80 hours

Below is a proposal for the time share between A and B semesters. Note that this is flexible. The share may be adjusted to optimize the pressure on PI and LP time. Time is requested for 5 semesters (3 A with 80+79+79h and 2 B of 31h each).

Semester A	
RA	Hours
00-04	0
04-08	0
08-12	69
12-16	161
16-20	8
20-24	0
Total	**238**

Semester B	
RA	Hours
00-04	16
04-08	2
08-12	38
12-16	0
16-20	0
20-24	6
Total	**62**

6 Management plan

The international team and its French & Canadian visibility

The MATLAS consortium consists of members of the ATLAS^{3D} international collaboration (PIs: Michele Cappellari, Eric Emsellem, Davor Krajnović, Richard McDermid [9]), joined by several researchers that were involved in the NGVS Large Program (PI: Laura Ferrarese), in which they developed expertise in deep imaging and globular cluster studies.

The CoIs are experts on galaxy evolution in general, and studies of early-type galaxies, and galaxy scaling relations, in particular. The list of CoIs includes observers as well as modellers (theorists and "simulators"). The team composition reflects the multi-wavelength, multi-technique approach of the ATLAS^{3D} survey. One should stress that the French (F) and Canadian (C) visibility in the MATLAS consortium is very high, with F+C CoIs playing key roles in the survey, as detailed below.

Data-analysis plan

- The PI (Pierre-Alain Duc, F) will manage the observations through a dedicated database already built (available on line to CoIs of the MegaCam pilot project: http://ccngvs.in2p3.fr:8080/A3Dmeg/).
- Adopting the working model of the NGVS, data reduction will be carried out by Jean-Charles Cuillandre (F) who developed the CFHT new arm of the detrending software Elixir optimized for the photometry and detection of faint and or extended sources (Elixir-LSB),
- and stacking will be performed by Stephen Gwyn (C) at CADC using MegaPipe who will also manage the access of these products to the team.
- The image analysis required to identify the fine structures – modeling of the host galaxy with GALFIT and ellipse fitting, modeled ETG subtraction, unsharp masking (see Fig. 9) will be carried out in Saclay (F) and Victoria (C).
- The eye classification of the observed fine structures and those simulated by our cosmological/galaxy models will be made by a sub-group supervised by Leo Michel-Dansac (F).
- The SBF distance measurements will be done by an expert in that field, Simona Mei (F).
- The globular cluster identification and follow-up observations will be carried in the joined Chilean/French laboratory (Thomas Puzia, Roberto Munoz)[10], with the help of Patrick Durrell (USA) and Eric Peng (China).

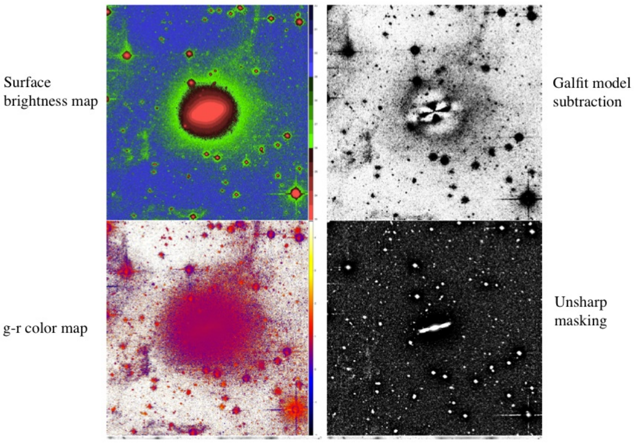

Figure 9: Typical image analysis done to disclose the fine structures around the ETGs: determination of surface brightness and color maps, revealing the most diffuse external tidal structures, unsharp masking revealing the sharp edged structures, including shells and finally GALFIT modeling and subtraction of the host galaxy, disclosing structures within the galaxy halo, and large-scale asymmetries in the galaxy profile.

- The study of the scaling relations will involve the whole collaboration, with as key experts: Michele Cappellari (UK), Eric Emsellem (F) and Patrick Coté (C)
- The dark matter modeling will be done by Anne-Marie Weijmans (C)
- The identification of dwarf companions will be done by James Taylor (C)

Data-access

Time will be shared between Canada and France according to the ratio between French and Canadian CoIs, i.e. 70% – 30%.

Free immediate access to the MATLAS images will be given to members of the French and Canadian communities. Note that the topics addressed by the LP are of interest to a community which is much larger than that represented by the official CoIs of MATLAS. Researchers working in the Paris, Marseille and Strasbourg observatories in France, Victoria and Queen's universities in Canada are particularly active in the field of galactic archeology, with past record studies on the external parts of galaxies. They will be interested in exploiting the MATLAS archives to which they will have an immediate access.

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[9] full list available at: http://www-astro.physics.ox.ac.uk/atlas3d/people.html

[10] The members of this laboratory located in Santiago have an official access to the French facilities, including CFHT, and to the Chilean time of the international telescopes based in Chile