# ERC Starting Grant 2015
# Research proposal [Part B2)] [1]
# *(not evaluated in Step 1)*

**Part B2: *The scientific proposal* (max. 15 pages)**

**Section a. State-of-the-art and objectives**

## 1. Introduction

***The Co-evolution of Galaxies and Dark Matter from Small to Large Scales***

A fundamental goal in observational cosmology is to understand the link between the luminous properties of galaxies and the dark matter halos in which they reside. A precise understanding of the primary mechanisms that determine the growth, evolution, and global properties of galaxies has eluded astronomers for more than half a century. Galaxies are thought to grow and evolve via two main channels: either directly via the conversion of gas into stars, or by accreting other neighboring galaxies via a process known as "merging". Both of these processes are intimately linked to the local dark matter environment in which galaxies are embedded. Because galaxies are trapped deep within the potential wells of massive dark matter halos, accretion processes (fresh supplies of gas as well as accretion by other galaxies) are primarily dark matter driven. For these reasons, dark matter is thought to play a key role in setting the conditions that determine galaxy properties. However, the exact details of how dark matter influences galaxy formation, and in turn, how galaxy formation modifies dark matter distributions, is a topic of active investigation and debate.

All galaxy formation models, from semi-analytic approaches to full hydrodynamic simulations, are built on top of a relatively well-understood dark matter framework which defines how dark matter halos form and grow, how they cluster and contain sub-halos, even how they spin. However, determining the set of physical processes that govern galaxy formation and evolution ("baryonic" processes) is a much more complex task that cannot be solved from first principles. Instead, galaxy formation models are informed, and tested iteratively, by comparing with new observations. Most of our galaxy observables are baryonic in nature (e.g., stellar mass function, mass-metallicity relation), but if we can probe the dark matter itself (as is the goal of GALDARK), we open up new possibilities that are more directly tied to the well-understood dark matter framework.

The goal of GALDARK is to understand the interplay between the dark and bright universe and to shed light on questions such as: 1) what is the co-evolution between dark matter and galaxy formation? How does dark matter influence galaxy formation processes and in turn, do baryonic physics affect the dark matter distribution? 2) What is the distribution of dark matter on both small scales and large scales? How do these distributions compare with predictions from the λCDM cosmological model?

We will tackle these questions by investigating the galaxy-dark matter connection over a broad range of physical scales ranging from galaxy scales (a few tens of kpc to 100 kpc) to scales comparable to the sizes of dark matter halos (hundreds of kpc to a Mpc). *By tackling both small and large scales, GALDARK will address a set of different, but inter-related questions with the aim of providing a complete and holistic view of the link between galaxies and dark matter.*

***The Large Scale (R>200 kpc) Connection between Galaxies and Dark Matter***

The large-scale connection between galaxies and dark matter provides us with insight about how galaxies grow (or do not grow) in relation to their global reservoirs of fuel. This connection is typically investigated by mapping out the average relationship between a given galaxy property and host halo mass. For example, in the last five years, there has been a tremendous interest in pinning down the relationship between halo mass, $M_{halo}$, and galaxy mass, $M_*$, as demonstrated by a flurry of recent publications (Shankar et al. 2014, Velander et al. 2014, Han et al. 2015, Hudson et al. 2015, to cite the most recent work). I pioneered early work in this field with a study that has now become a leading reference in this domain (Leauthaud et al. 2011, 2012).

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[1] Instructions for completing Part B2 can be found in the '*Information for Applicants to the Starting and Consolidator Grant 2015 Calls'*.

[2] An additional cost category 'Direct Costing for Large Research Infrastructures' applicable to H2020 can be added to this table (below 'Other goods and services') for PIs who are hosted by institutions with Large Research Infrastructures of a value of at least EUR 20 million and **only** after having received a positive ex-ante assessment from the

Mapping out the global connection between galaxies and dark matter is a statistical enterprise that has been spurred on by the relatively recent availability of large representative galaxy samples from surveys such as SDSS at low redshifts, and COSMOS, VVDS, and PRIMUS at higher redshifts. The large-scale component of GALDARK will primarily be statistical in nature and will take advantage of new large data sets from the Subaru telescope as well as from the SDSS-III and SDSS-VI programs (these will be discussed shortly).
GALDARK will employ two complementary techniques to probe the large-scale galaxy-dark matter connection. The first is *galaxy-galaxy lensing* which uses weak gravitational lensing to probe the gravitational potential around foreground ("lens") galaxies. The second is technique will be via measurement of *galaxy clustering*. We now describe each of these techniques in greater detail.

- **WEAK GRAVITATIONAL LENSING.** Gravitational lensing is a powerful technique, which measures distortions in the shapes of distant galaxies to infer how the gravitational field of massive objects bends the paths of approaching light rays. Weak lensing is recognized as a fundamental tool for observational cosmology, on par with studies of Supernovae and Baryon Acoustic Oscillations (BAO). The strength of this method is that it probes the total intervening mass distribution, including the dark matter component. In addition to being a powerful cosmological tool, weak lensing can also be used to elucidate the connection between galaxy formation processes and the underlying dark matter distribution via galaxy-galaxy lensing. This technique measures the average weak lensing signal from background "source" galaxies around a sample of foreground "lens" galaxies (typically several hundred to thousands of lens galaxies). Galaxy-galaxy lensing has emerged as the most effective technique to measure the full dark matter profile of an ensemble of galaxies, out to scales of several Mpc.
  The state of the art of current lensing surveys are efforts like the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) and the CFHT Stripe 82 survey (CS82) covering ~ 150 deg$^2$. <u>With greatly expanded capabilities, the field of weak lensing is about to undergo a mini revolution</u> thanks to next generation lensing surveys such as the Hyper-Suprime Cam survey (HSC) and the Dark Energy Survey (DES) which will cover <u>several thousands of square degrees</u>. Space-based lensing missions such as Euclid and the Wide-Field Infrared Survey Telescope (WFIRST) will follow these efforts in less than a decade. These surveys will produce a wealth of data and scientific opportunities. The HSC survey (of which I am a member) will provide one of the main data sets for GALDARK. At the same time, with a longer time-scale in perspective, the methods and techniques developed via this ERC grant will be of tremendous value for the preparation and analysis of the Euclid survey, which begins in 2020.
  The HSC survey is a truly ambitious multi-wavelength (g,r,i,z,y) weak-lensing program to map out 1400 square degrees of the sky with the 8.2m Subaru Telescope to i~26 mag. The HSC survey began collecting data in the spring of 2014 and will continue to do so for 5-6 years. Because weak lensing is inherently a minute and difficult signal to detect, significant challenges face its application. My deep involvement in previous lensing surveys (e.g., COSMOS, CS82) has enabled me to prepare the technical and theoretical machinery required to fully exploit new, more ambitious efforts.
  My core expertise is measurements and theoretical interpretation of weak lensing. I am one of the four core members of the COSMOS weak lensing team, which has produced more than 20 weak lensing publications. I am co-PI on the CS82 weak lensing survey which mapped out 150 deg$^2$ of the "Stripe 82" equatorial region for weak lensing studies. Finally, I have also played a leading role in realizing the HSC survey, including participating in writing the proposal that was awarded 300 nights on Subaru.

- **GALAXY CLUSTERING.** Galaxies are not randomly distributed in the Universe but instead follow a network of sheets, filaments, and nodes that together form the cosmic web. The most wildly used technique to characterize the spatial distribution of galaxies is via measurements of auto-correlation or cross-correlation functions. For example, the projected two point correlation function $w_p(r_p)$ specifies the probability that two galaxies are separated by a given distance $r_p$ where $r_p$ represents the separation vector projected perpendicular to the line-of-light. Spectroscopic redshifts are required to measure $w_p(r_p)$. If spectroscopic redshifts are not available, galaxy distributions may still be characterized via the angular two point correlation function $w(\theta)$, this is the analogue of $w_p(r_p)$ but where $r_p$ is replaced with an angular separation $\theta$.
  Low redshift clustering measurements from the Sloan Digital Sky Survey I/II (SDSS) revolutionized our understanding of the galaxy-halo connection (e.g., Zheng et al. 2007, Zehavi et al. 2011). <u>But the picture is far from complete and there is still much to be learned</u>. For example, Kauffmann et al. 2013 recently revealed that star-formation indicators in central galaxies are correlated with the properties of neighbouring galaxies out to scales of 4 Mpc (a phenomenon dubbed "2-halo conformity"). This result requires quenching processes to be coordinated in galaxies occupying wildly separated dark matter halos, and presents a seriouschallenge for galaxy formation models. Understanding how the properties of central

galaxies correlated with those of neighbouring galaxies ("conformity") is currently a hot topic of investigation (e.g., Hearin et al. 2014). There is also much progress yet to be made especially for massive galaxies (where larger volumes than SDSS are required) and at higher redshifts where a spectroscopic analogue of SDSS (targeting representative samples with similar constraining power) does not yet exist. Beyond SDSS I/II, the largest spectroscopic surveys (in excess of one million galaxies) are primarily driven by dark energy requirements with the primary goal of detecting the BAO feature in the correlation function at 100 Mpc. These samples have tremendous constraining power but only target particular sub-sets of galaxies instead of representative samples. This does not mean that they are not useful from a galaxy-halo perspective, but the samples need to be well characterized. We will make extensive use of these samples in GALDARK with the goal of harnessing the tremendous statistical power of BAO surveys to extract a maximum amount of information about the galaxy-halo connection. In particular, we will make use of two key data sets: Luminous Red Galaxies (LRGs) and Emission Lines Galaxies (ELGs) from the Baryon Oscillations Spectroscopic (BOSS) and the Extended Baryon Oscillations Spectroscopic (eBOSS) surveys.

***Combining Dark Matter Probes***

While both weak lensing and clustering are powerful techniques in their own right, significant gains can be made by using a joint analysis of both measurements. I pioneered research in this direction and performed the first joint analysis of galaxy clustering and galaxy-galaxy lensing in order to constrain the global $M_{halo}$-$M_*$ relation to z=1 (Figure 1, Leauthaud et al. 2012). In Tinker et al. (2013), we extended this work to include star-formation in addition to stellar mass. While convincing evidence at z=0 suggests that at fixed stellar mass, star-forming galaxies live in lower mass halos than quenched galaxies (e.g., Mandelbaum et al. 2006), our results revealed the unexpected and highly intriguing result that this trends is inverted at higher redshifts. Our results suggest that at z=0.5, star forming galaxies live in massive galaxies than quenched galaxies! These types of observations have strong consequences for models of galaxy formation (see discussion in Tinker et al 2013).

With upcoming data sets such as the HSC survey, we will be able to bin the data into much finer bins and to reveal this connection in exquisite detail. GALDARK will represent the next major leap forward in this field that will be enabled by combining new high-signal-to noise weak lensing measurements (with vastly expanded capabilities compared to COSMOS) and clustering measurements from large galaxy samples collected by BAO surveys. I have a strong experience with this topic with leading observational as well as theoretical papers in this field (Leauthaud et al. 2011, 2012, 2014).

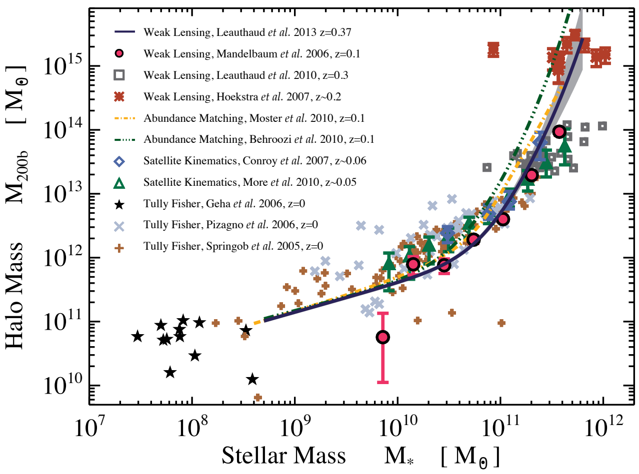


***Figure 1:*** The relationship between halo mass $M_{halo}$ and stellar mass $M_*$ at z~0.3 as measured by combining galaxy-galaxy lensing, galaxy clustering, and the galaxy stellar mass function in the COSMOS survey (blue solid line). The unique depth of the COSMOS data allowed us to probe the evolution of this relationship out to z~1 (Leauthaud et al. 2012). In this work, for the first time, we robustly measured the redshift evolution of the halo mass scale at which galaxy growth is maximally efficient.

***The Small Scale (R~20 kpc) Connection between Galaxies and Dark Matter***

The previous section described how galaxy clustering and galaxy lensing can be used to probe the dark-matter connection on large scales (on radial scales above a few hundred kpc). The small-scale component of GALDARK is a novel and potentially groundbreaking direction of research that aims to revolutionize our understanding of the galaxy dark-matter connection on much smaller scales (a few tens of kpc to a few hundred kpc). The goal of this component is to study the very inner mass profiles of galaxies in the regime where the lensing profile transitions from a dark matter dominated profile to a stellar dominated profile. For galaxy-galaxy lensing measurements this scale occurs at a few times the galaxy effective radius. This transition scale will be referred to hereafter as the "equality radius".

On small scales, the comparison between the stellar profiles of galaxies and their total profiles contains key clues about the processes by which galaxies acquire mass in respect to dark matter. The interplay between baryons and dark matter on these scales is sensitive to a variety of processes, including but not limited to, adiabatic contraction, dynamical friction from in-falling satellites, and feed-back from Active Galactic Nuclei (AGN). For example, in recent work, Newman et al. (2013) combined strong gravitational lensing measurements with spatially resolved stellar kinematics for a sample of 7 Brightest Cluster Galaxies (BCGs). They find tentative evidence for an anti-correlation between the inner dark matter density slope and the distribution of stars in the BCG. A correlation of this nature could be set in place as BCGs acquire mass via in-falling satellites, which contribute to the growth of the BCG but which may also cause a reduction in the central dark matter density due to dynamical friction (e.g., Nipoti et al. 2004).

A powerful approach to constrain the total density profile of galaxies on scales of about 3-9 kpc is to combine stellar kinematics with measurements of strong gravitational lensing (e.g., Newman et al. 2013; Sonnenfeld et al. 2014). However, strong lensing systems are rare (at most a handful per square degree) and are primarily limited to massive early type galaxies at intermediate redshifts. I propose to explore the possibility of using weak lensing measurements on small scales to potentially overcome these limitations and to probe the total density profiles of galaxies over a wide range in redshift and stellar mass. On very small scales, in addition to dark matter, the weak lensing signal is sensitive to the baryonic mass of the host galaxy. Figure 2 shows an example of the predicted galaxy-galaxy lensing signal around galaxies with log(M*)=11.2 and at z=0.68. For this set of galaxies, the weak lensing signal transitions from a stellar dominated regime to a dark matter dominated regime on scales of order $R_{eq}$ ~ 25 kpc. Future weak lensing measurements at these scales would offer the exciting possibility of directly measuring the inner dark matter slope but also mass-to-light ratios, thus providing independent constraints on the Initial Mass Function (IMF) and on the interplay between baryons and dark matter.

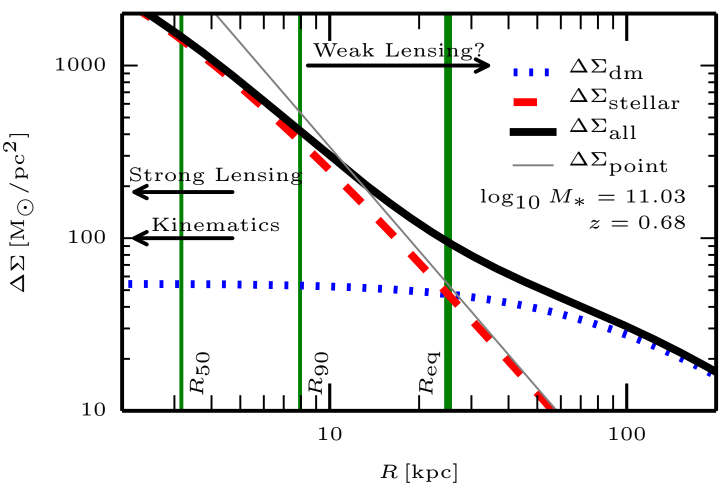


***Figure 2:*** model of the galaxy-galaxy lensing signal around galaxies with log(M*)=11.2 and at z=0.68. The black line shows the total mass profile. The dotted blue line represents the dark matter profile. The dashed red line represents the contribution to the total profile from stars. The solid green line is the "equality radius" ($R_{eq}$) where the dark matter and stellar components contribute equally to the lensing profile. Our goal is to push weak lensing measurements down to small enough scales to measure this transition regime (figure from Kobayashi et al. 2015).

Current constraints on dark matter density profiles from weak lensing are typically limited to radial scales greater than R>50 kpc. On smaller scales, there is a paucity of source ("background") galaxies due to poor image quality ("seeing") and complicating effects such as isophotal blending that inhibits shape measurements. With my graduate student Masato Kobayashi (U. Nagoya), we have investigated exactly how many background galaxies are lost due to proximity effects. Using high resolution HST data from the COSMOS survey, we show that the background source density drops by 60-90% at 20 kpc separations due to proximity effects (blends and masking by foreground galaxies). This sharp decrease in the source density prohibits weak lensing measurements on small scales with current surveys. However, the next generation of weak lensing surveys will have enough statistics that even after rejecting 90% of the source galaxies, the remaining 10% will be sufficient to perform high-signal-to-noise measurements. For example, our calculations for Euclid show that even after a conservative selection (e.g., rejecting all blends as well as sources galaxies with a very close by neighbor that may bias shape measurements), there are still enough "clean" background galaxies left over to measure the total mass profile at three times the half-light radius $R_{hl}$. Figure 3 shows the predicted signal for galaxies with masses of log(M*)=11.03 calculated by extrapolating the source counts from COSMOS (using conservative choices for the background source population). Figure 4 shows the predicted signal-to-noise as a function of stellar mass and redshift for Euclid and WFIRST. This figure assumes that lens galaxies are stacked in bins of stellar mass with a bin width of a mere 0.07 dex! The signal-to-noise on this type of measurement is predicted to be greater than S/N=20 on small scales for galaxies with log(M*)>10 and at z<1. This technique will enable studies of the galaxy-halo connection in regimes that are not accessible via strong lensing.

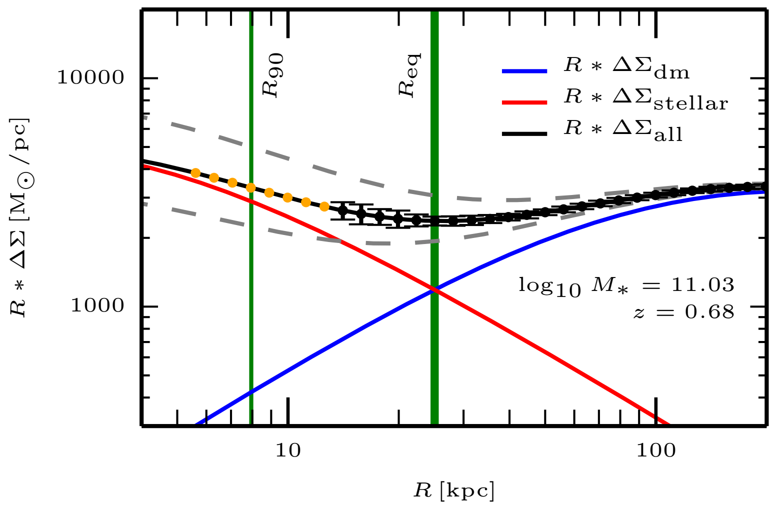


***Figure 3:*** our prediction for the lensing signal measured to small scales for galaxies with log(M*)=11.03 and in a stellar mass bin of a mere 0.07 dex. Note that the vertical scale is multiplied by R to highlight the error bars. Grey dashed lines show the lensing profile when M* is varies by 0.2 dex (roughly corresponding to the current uncertainty on the IMF). These measurements will place tight constraints on the IMF and on the inner dark matter slope (figure from Kobayashi et al. 2015).

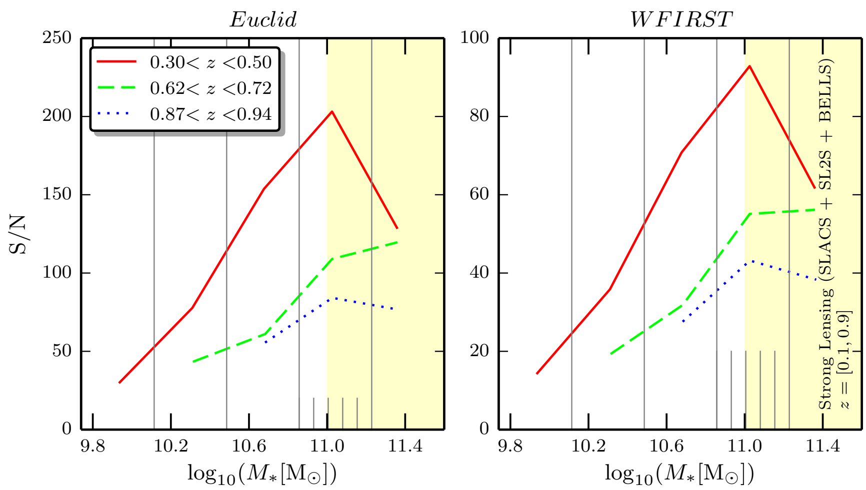


***Figure 4:*** predicted S/N of weak lensing measurements of the total density profile at r~20 kpc and for lens galaxies in stellar mass bins of 0.07 dex. The yellow shaded region corresponds to the mass range accessible via strong lensing measurements. Weak lensing will enable studies of the galaxy-halo connection for low mass galaxies that are not accessible using strong lensing techniques (figure adapted from Kobayashi et al. 2015).

Figures 3 and 4 clearly show that the tremendous power of upcoming weak lensing survey will open up a new window for the exploration of the small-scale galaxy-halo connection. These measurements will place strong constraints on both the inner shapes of dark matter halos as well as on the IMF, which is currently uncertain at the factor of 2 level. However, there are several technical challenges that need to be addressed to push weak lensing down to such small scales. The primary challenge will be to perform detailed simulations to understand how well galaxy shapes and photometric redshifts can be extracted in such close configurations. This type of measurement will also be more challenging for ground-based surveys compared to space based surveys (due to a larger smearing of galaxy isophotes by the point spread function). We will require simulations tailored for both ground and spaced-based observations.
The small-scale component of GALDARK will aim to address these challenges and to develop the techniques necessary to perform un-biased small-scale weak lensing measurements. At the same time, in parallel, GALDARK will also gain valuable experience in this new arena by tackling the "low-hanging fruit", namely, massive BCGs at very low redshifts (z<0.1). Indeed, there are multiple non-negligible advantages to beginning this work with massive galaxies at low redshifts. First, at low redshifts, the weak lensing signal is less sensitive to systematic errors from photoz's (most faint galaxies are far behind the lens). Second, the signal-to-noise for these types of studies is maximized for massive galaxies at very low redshifts owing to two facts: a) at lower redshifts there are more background galaxies to perform lensing measurements and b) a fixed physical radial separation corresponds to a larger angular separation at low redshifts (which again leads to a larger number of background galaxies). Finally, at low redshift we will be able to obtain high-quality resolved kinematics for BCGs out to large radii (>1.5 $R_e$) with reasonable amounts of telescope time.

## 2. Objectives

This work, funded by an ERC grant, will enable GALDARK team members to push the current boundaries in this field with the ambitious goal of completing the galaxy-halo picture at redshifts below z=1. We will use the latest data sets to explore the galaxy-halo connection from small to large-scales. These new data will require the development of new observational techniques as well as improved theoretical models. We will tackle both of these aspects and develop the tools for the future that will be required for even more ambitious surveys such as Euclid and WFIRST. The specific goals of GALDARK are to address the following set of key questions:

***Key Questions for Large Scale (LS) Galaxy-Halo Connection:***

★ ***LS-A – What is the Mapping between Galaxy Stellar Mass, Star-Formation Rate, and Halo Mass?***
Observational constraints on the mapping between galaxy mass, halo mass, and galaxy properties such as colour, and star-formation rate, place strong constraints on viable models of galaxy formation (see Vogelsberger et al. 2014 for a comparisons with the hydrodynamic simulations of the Illustris project). In Tinker et al. (2013), we used a combination of weak lensing and galaxy clustering to measure the global relation between halo mass, galaxy stellar mass, and star formation to z=1. Despite the small area covered by the COSMOS survey (2 $deg^2$), we were able to place strong constraints on the stellar-to-halo mass relation for passive and active galaxies up to z=1. With new upcoming data-sets such as the HSC survey that will vastly exceed COSMOS in coverage and signal-to-noise, we will be able to bin the data into much finer bins and to reveal this connection in exquisite detail.

★ ***LS-B – Is there a Connection between the Properties of Central Galaxies and Halo Accretion Rates?***
Recent theoretical work by Diemer et al. 2014 demonstrates that the instantaneous accretion rate of dark matter halos leaves a characteristic features in the shapes of dark matter profiles on scales around the halo boundary, $R_{200m}$. Specifically, halos which have experienced recent large-scale mass accretion show "dips" in their profiles on scales of $r{\sim}R_{200m}$. This feature is sensitive to the overall amount of accretion over the past few billion years (not just to major mergers) and opens up a new possible method for assessing the dynamical state of halos. Because halos with high accretion rates should bring in fresh supplies of gas and lead to an enhancement of star-formation in the central galaxy, it would be of tremendous interest to study how this feature correlates with the properties of central galaxies. In GALDARK we will search for this signature in stacked weak lensing measurements of groups and cluster of galaxies using high signal-to-noise HSC data. By stacking groups and clusters according to the properties of the central galaxy (color, age, star-formation), we will search for correlations between these properties and the slope of the halo profile at the halo boundary. This new approach is out of reach of current lensing surveys and will only be possible thanks for the unprecedented statistical power of the HSC survey that will be able to pin down the mass profiles of groups and clusters to a few percent.

★ ***LS-C – Is Halo Mass the Primary Variable for Understanding the Galaxy-Halo Connection?***
A large body of theoretical work (e.g., Halo Occupation Models, various prescriptions in semi-analytic models) commonly assume that dark matter halo mass is the primary variable that governs galaxy properties. However, other halo properties may be more fundamental to galaxy evolution than halo mass, for example halo peak velocity, halo age, or halo assembly history. A recent exciting development in this field has been the semi-empirical "age matching" model by Hearin et al. 2013 and Watson et al. 2015 in which star-formation strongly correlates with halo age. This model is simple and yet astonishingly successful at describing clustering and galaxy-galaxy lensing measurements from the SDSS. Following this work, there has been a spike of recent interest in trying to understand how to discriminate between models that depend on just halos mass (such as traditional Halo Occupation Models) and models that depend on other halo parameters. The key to discriminating between such models will be the fact that halos selected via different properties (e.g, $M_{halo}$ versus $V_{peak}$) have different clustering properties (a manifestation of the effect know as "assembly bias", see Zentner et al. 2014). With my post-doc, Shun Saito, we are currently studying how to discriminate between various models by using via high signal-to-noise lensing and clustering measurements. In GALDARK, we will tackle this question by taking advantage of the availability of large spectroscopic galaxy samples from BAO surveys (specifically, BOSS and eBOSS) combined with gravitational lensing with HSC.

***Key Questions for Small Scale (SS) Galaxy-Halo Connection:***

***★ SS-A – Can we use Weak Lensing to Probe the very Inner Regions of Dark Matter Halos?***

Pushing weak lensing measurements down to small radial scales would open up the exciting possibility of probing the very inner regions of galaxy/halo density profiles. With my graduate student Masato Kobayashi we recently showed that upcoming lensing surveys will have enough statistics to measure the inner regions of halos (a few tens of kpc) for galaxies with log(M*)>10 and at z<1. The main challenge, however, will be to make sure that both shear and photoz measurements are unbiased on such small scales. We will develop detailed image simulations to understand how well galaxy shapes and redshifts can be extracted in such close configurations (see work-package WP5).

***★ SS-B – Can we Disentangle the Inner Dark Matter Slope from the Normalization of the Stellar IMF by Combining Stellar Kinematics with Stacked Weak Lensing?***

The total mass profiles of galaxies on scales of about one effective radius is sensitive to both the inner dark matter slope as well as to the normalization of the stellar IMF. There has been a tremendous amount of recent interest in measuring both of these quantities (Cappellari et al. 2012, Barnabe et al. 2013, Shetty et al. 2014, Smith et al. 2014, Sonnenfeld et al. 2015). Among these recent studies, Sonnenfeld et al. 2015 used stellar kinematics combined with strong lensing to place joint constraints on the IMF and the inner dark matter slope. However, the narrow radial range covered by the Einstein radii of these strong lensing systems limits the constraints on the inner dark matter slope. Weak lensing on larger scales (a few times the Einstein radii and above) could provide constraints over a larger dynamic range in radius. In GALDARK we will study the advantages (larger dynamic range in radius) and disadvantages (stacking over many systems, does not go to very small radii) of using weak lensing instead of strong lensing for this type of work. Our goal is to extend these studies to galaxy samples for which strong lensing data does not exist (low redshift galaxies and galaxies with stellar masses below $10^{11}$ $M_{\odot}$, see Figure 4).

***★ SS-C – Is there a Connection between the Inner Slope of the Dark Matter Distribution and the Assembly of Stars in Galaxies?***

Our ultimate goal will be tackle to tackle this question for galaxies covering a broad range in redshifts and stellar mass (for this, we first need to achieve goals SS-A and SS-B). Our first two goals are theoretical in nature and will rely heavily on analyzing simulations. In parallel though, we will also investigate this question in real data by analyzing BCGs in massive clusters at very low redshifts. The goal of this component of GALDARK will be to extend the work of Newman et al. (2013) (which was based on 7 BCGs) to a sample of 200 BCGs. These BCGs will have resolved kinematics measured from the MaNGA survey as well as from a dedicated MUSE follow-up program (see following section for a description of these surveys). Whereas Newman et al. (2013) were only able to detect a tentative anti-correlation between the stellar and dark matter profiles of BCGs, we will be able to place firm conclusions on this question.

**Section b. Methodology**

## 1. Methodology Overview

Both the small-scale and the large-scale goals described in the previous section will be addressed by harnessing the power of new state-of-the art surveys. A large fraction of our analysis will be based on the HSC multi-wavelength weak lensing survey, the MaNGA Integral Field Unit (IFU) survey of local galaxies, and the BOSS and eBOSS BAO surveys. More specifically, our key data sets will be:

- The Luminous Red Galaxy (LRG) sample from the Baryon Spectroscopic Survey (BOSS, 1.5 million galaxies, final data release in 2015) to study massive galaxies between z=0.4 and z=0.7.
- The eBOSS survey will provide an additional set of 300,000 Luminous Red Galaxies at higher redshifts (0.6<z<0.8). To complement this set of red galaxies, eBOSS will also provide a set of 180,000 emission line galaxies at 0.6<z<1.0.

- We will use the HSC 1400 deg$^2$ survey for weak lensing measurements. HSC fully overlaps with the BOSS survey and there is 700 deg$^2$ of overlap between the HSC survey eBOSS survey. There is a 300 deg$^2$ overlap between the HSC survey and the MaNGA survey (note however that a joint study of MaNGA kinematics with HSC lensing does not necessarily require overlapping data sets because BCGs are selected homogenously across both surveys using the Yang et al. 2008 cluster catalog).
- A sample of several hundred BCGs with IFU data to R>1.5Re from the MaNGA survey.
- To complement the MaNGA BCG data-set, we will also apply for time to observed BCGs with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST) and the Multi Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT).

<u>The goals of our large-scale component will be achieved via two approaches:</u>

1) The first approach is to combine lensing measurements with clustering measurements using spectroscopic galaxy samples from the BOSS and eBOSS. The advantage here is that the availability of spectroscopic redshifts leads to high signal-to-noise clustering measurements ($w_p(r_p)$ as opposed to $w(\theta)$) and also reduces systematic errors in galaxy-galaxy lensing measurements. From a galaxy-halo perspective, the downside to these samples is that the selection functions are optimized for BAO survey and need to be characterized in detail. In sum, these measurements will be highly reliable but the theoretical modelling will be more challenging (see work-package WP3). This is as issue goal LS-A, however, this is not an important issue for goals LS-B and LS-C.
2) The second approach, which is more challenging, will be to analyse clustering ($w(\theta)$ in this case) and lensing measurements for stellar mass selected samples from the HSC survey using photometric redshifts. The main difficulty with this approach will be to understand and characterize the systematic effects introduced by using photometric redshifts instead of spectroscopic redshifts. Instead of just relying on SED fitting techniques, we will actively explore how to improve redshift estimators via cross-correlations with spectroscopic samples. This is a new promising approach that can be used to infer the redshift probability distribution for a single galaxy (Menard et al. 2013, Rahman et al. 2014). Because HSC fully overlaps with SDSS, BOSS, and partially overlaps with eBOSS, there are a tremendous amount of spectroscopic redshifts that can be used to apply this technique.

<u>The goals of our small-scale component will be achieved via two data-sets:</u>

1) The first approach will be to combine stacked gravitational lensing measurements with stellar dynamics from the MaNGA survey. In collaboration with Jenny Greene (Princeton), we have recently been awarded time to observe 200 BCGs with IFU spectroscopy as part of a MaNGA ancillary program. This ancillary program will provide resolved spectroscopy for 200 BCGs out to r>1.5Re. Weak lensing from the HSC survey will pin down the outer dark matter profile.
2) The MaNGA program will be extended by a follow-up survey of 50 BCGs in the most massive clusters at z=[0.1,0.2] with MUSE on the VLT and with the ACS camera on the HST. MUSE and ACS have matched field-of-views of one arc-minute, which corresponds to a physical transverse distance of 100-200 kpc at z=0.15. This is well suited for the small scales studies proposed in this research program. This survey will improve on our current MaNGA program in several key aspects. First, MUSE will provide deeper and higher resolution spatially resolved kinematics than MaNGA. Deeper observations will enable dynamical measurements out to larger radii (r>2Re). Second, the HST imaging will provide a higher number of source (background) galaxies that can be used for weak lensing (we expect a factor of 2 increase in the S/N of the weak lensing measurements). Finally, one of the main systematics for the weak lensing will be determining the redshifts of background galaxies. Because of the matched field-of-views, MUSE will provide redshifts for a large fraction of the background galaxies.

## 2. Core Team and Project Management

As the P.I of GALDARK I will participate in all components of this project and will coordinate the activities of team members. My skill set encompasses most aspects of this proposal with particular strengths in analysing weak lensing data and in interpreting these data via models build from N-body simulations. However, I only have limited expertise in building dynamical models from IFU observations. For this reason, I selected CRAL (Centre de Recherche d'Astrophysique de Lyon, a joint Research Unit between

CNRS, Université Claude Bernard Lyon 1 and Ecole Normale supérieure de Lyon) as the host institution for this project. CRAL is one of the most recognized institutions worldwide for IFU observations and built the highly successful SAURON and MUSE (P.I Roland Bacon from CRAL) instruments. Colleagues at my host institution will provide a firm knowledge base with which to develop the necessary expertise for this component of GALDARK. Also, to bolster expertise in this area, I will hire one post-doc with experience in analysing IFU data. As P.I, I will ensure that the data is analysed in a timely fashion and will be responsible for high-quality publication standards. I will also be responsible for the supervision and training of the PhD students. In particular, I will train the PhD students in the fields of weak lensing and galaxy clustering. Finally, as P.I I will also take responsibility for leading the initial HST and MUSE proposals.
In addition to the P.I, the GALDARK team will consist of two post-doctoral scholars and three PhD students. The duration of each PhD and postdoctoral appointment will be three years (a total of 18 FTE over 5 years). These other members of GALDARK will have the following complementary skill sets:

- **Postdoc 1 (PD1):** will have expertise in dynamical modelling from IFU data.
- **PhD student 1 (PhD1):** will develop a joint expertise in performing weak lensing measurements with HST as well as in dynamical modelling from IFU data. PD1 and PhD1 will work in close collaboration. Also, PD1 and PhD1 will benefit from strong existing expertise at the host institute in analysing IFU data and will interact with Roland Bacon (P.I of MUSE) and Johan Richard (MUSE GTO team) on a regular basis. PD1 and PhD1 will also be part of SDSS VI and will benefit from direct access to the expertise of the MaNGA team (e.g., Eric Emsellem, Michele Cappellari) and will attend MaNGA meetings and telecons.
- **Postdoc 2 (PD2):** will have expertise in analysing N-body simulations. PD2 will benefit from strong existing expertise at the host institute in working with N-body simulations and will interact with Jeremy Blaizot's group (N-body group at CRAL) on a regular basis.
- **PhD student 2 (PhD2):** will develop an expertise in measurements of galaxy clustering and will take the lead on all clustering measurement using BOSS and eBOSS. This student will also apply clustering techniques to build "clustering redshifts" for the HSC survey (for goal LS-A). This student will benefit from the expertise of the eBOSS team (e.g., Jeremy Tinker, Martin White) and will attend eBOSS meetings and telecons.
- **PhD student 3 (PhD3):** will develop expertise in measuring weak lensing from the HSC survey. This student will span the bridge between the two components of GALDARK and will perform the HSC weak lensing measurements for both the small and the large-scale programs. PhD3 will be a participating member of the HSC collaboration and will benefit from access to weak lensing expertise within the HSC team (e.g., Rachel Mandelbaum, Masahiro Takada, Takashi Hamana). PhD3 will attend HSC meetings and telecons.

Each PhD student and post-doc will be a participating member in a large international collaboration and will benefit from direct access to the expertise of these collaborations. Finally, beyond the core team of members, I will also draw on the expertise of a number of colleagues with whom I collaborate on a regular basis. These are not members funded by GALDARK but are colleagues with overlapping research interests and who are willing to provide advice and to host GALDARK members for extended collaborative visits. These collaborators include Jenny Greene (Princeton, spectroscopy of BCGs), Risa Wechsler (Stanford, galaxy formation and N-body simulations), Jeremy Tinker (galaxy clustering), Jean-Paul Kneib (EPFL, weak lensing, P.I of eBOSS).

## 3. Work Plan

GALDARK is organized in the form of 8 work packages addressing each of the main scientific questions in the proposal. The work packages and task assignments are outlined below.

**WP1: Weak Lensing of Luminous Red Galaxies from BOSS and Emission Line Galaxies from eBOSS**
The goal of this work package is to measure the lensing of spectroscopic galaxy samples from BOSS and from eBOSS using the HSC survey. These measurements will be divided into a series of different samples (redshift, stellar mass) and will be used as input for all three of our large-scale goals. This work package also includes lensing measurements for cluster samples for goal LS-B (halo accretion rates of clusters). For goal LS-B, we will study of clusters at low redshifts where the catalogs are most reliable ($z<0.5$). Our cluster catalog will be based on a state-of-the art red-sequence type cluster catalog based on algorithms such as the

redMaPPer algorithm (Rykoff et al. 2014). Although these methods are red-sequence based, they still have the ability to identify central galaxies with small amounts of residual star-formation, which will enable us to divide clusters according to central properties.
★ *This work package is linked with goal LS-A, LS-B, LS-C, and will be assigned to PhD3.*

**WP2: Clustering of Luminous Red Galaxies from BOSS, Emission Line Galaxies from eBOSS, and photometric samples**
The work-package is similar to WP1 but concerns the clustering measurements of spectroscopic galaxy samples from BOSS/eBOSS using the HSC survey. Again, the measurements will be divided into a series of different samples (redshift, stellar mass) and will be used as input for all three of our large-scale goals. This work-package will also involve the measurement of the clustering signals for photometric samples.
★ *This work package is linked with goal LS-A, LS-B, LS-C, and will be assigned to PhD2.*

**WP3: Developing State-of-the-Art Semi-Empirical Models via N-body Simulations**
Goals LS-A and LS-C will require theoretical modeling derived directly from N-body simulations for three reasons. First, the signal-to-noise of the clustering and lensing signals will be such that analytic approximations to describe the scale-dependent bias will be insufficient to model this data. Second, simulations will allow us more flexibility for modeling complex galaxy populations. Third, the use of N-body simulations will allow us to easily explore models in which halo mass is not the primary variable (goal LS-C). For this reason, we will populate N-body simulations with galaxy models and compute the model predictions directly from the mocks. This approach will require a significant computational resource (for dealing with large simulations and running MCMC chains). In collaboration with my post-doc Shun Saito, we have already put the first elements of this methodology into place. We are currently working on a sophisticated model for the BOSS "CMASS" sample that accounts for the fact that the incompleteness of this sample varies with redshift. Our current efforts include: a) measuring the stellar mass completeness of this sample and b) building a realistic model based on abundance matching techniques that accounts for selection effects. Our constraints on the galaxy-halo connection will be the first to account for the BOSS selection function. Understanding how to account for these effects will be critical for the types of studies that I am proposing for GALDARK, even more so for the Hα detected samples expected from Euclid further down the line. Our work represents the first step towards understanding how to model complex galaxy selections and we will continue to develop this direction in GALDARK.
★ *This work package is linked with goal LS-A, LS-C, and will be assigned to the P.I and PD2*

**WP4: Redshift Estimators via Clustering Techniques**
In order to fully achieve goal LS-A, we will need to develop well-understood redshift estimators for the HSC survey. The most promising avenue forward is the "spectroscopic redshift" technique outlined in Menard et al. 2013 and further developed in Rahman et al. 2014. The HSC overlaps with a large numbers of spectroscopic redshift surveys that can be used to apply this technique. The goal of this work-package is to continue the development of these new methods and to apply these methods to the HSC survey. This work-package will form the bulk of the PhD project for PhD2.
★ *This work package is linked with goal LS-A and will be assigned to PhD2.*

**WP5: Assessing Systematics in the Weak Lensing Analysis of Galaxies in Close Pair Configurations**
With my graduate student Masato Kobayashi, we recently showed that next generation lensing surveys will have the statistical power to constrain the total mass profiles of galaxies on radial scales of a few effective radii. However, undertaking this novel approach will require developing methods to measure galaxy shapes in close pair configurations. Figure 5 shows an example of two lens galaxies from the COSMOS survey. Our goal is to measure the shapes of background galaxies in the region encompassed by the blue circle (corresponding to the equality radius). We will develop a suite of simulations to test shear and photoz recovery on these small scales. For this, we will use the recently developed lensing image simulations from the GalSim simulation package (Great3, Mandelbaum et al. 2014). This tool provides a set of postage-stamps from the COSMOS survey as well as a suite of tools to modify and manipulate the images (modify noise, convolve with PSF, etc.). We will insert fake galaxies into these postage stamps at varying distances from lens galaxies and test shear and photometric redshift recovery as a function of radius. It is likely that small-scale weak lensing will require a shape measurement method that performs a simultaneous fit to the lens profile together with the background galaxy. While simultaneous fitting methods are computationally too expensive for shear surveys in general, they would not be an issue for this particular application which does not require fitting a large number of galaxies (only a sub-set of close-pairs).
★ *This work package is linked with goal SS-A and will be assigned to PhD3.*

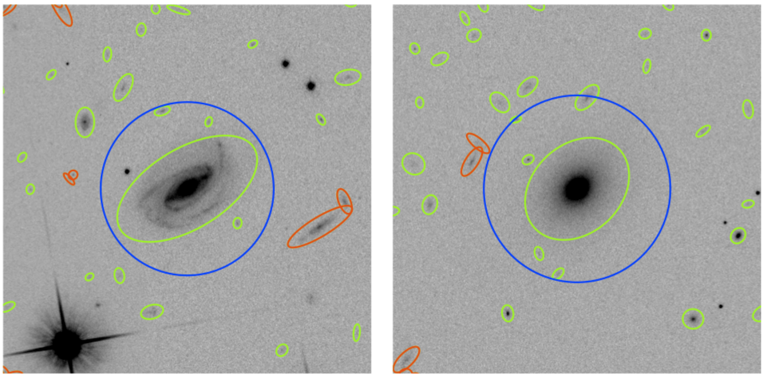

***Figure 5:*** two lens galaxies from the COSMOS survey at z=0.25 and with log(M*)~11. Green circles are KRON ellipses that show the location and spatial extend of galaxies. Red ellipses show galaxies with overlapping KRON ellipses. The blue circle shows the equality radius $R_{eq}$. Our small scale lensing aims to measure weak lensing within the region enclosed by the blue circle (Figure from Kobayashi et al. 2015).

**WP6: Testing Methods on Full Idealized Mock Observations of MaNGA Galaxies**
The goal of this work package will be to use a suite of simulations to test methods for combining resolved kinematics with stacked weak lensing measurements. For this we will use a suite of fully idealized mock observations of MaNGA that are currently being developed within the MaNGA team (lead: Eric Emsellem). The current timeline is that these mock observations should be completed by the summer of 2015, well before we intend to use them in GALDARK. We will compute the expected S/N for the lensing component directly from the mock given the total mass profile and assuming a background source density and a level of shape noise.
★ *This work package is linked with goal SS-B and will be assigned to PD1.*

**WP7: Analysis of Kinematics from MaNGA BCGs and HSC weak lensing**
The goal of this work package is to perform a joint analysis of the kinematics and lensing of our MaNGA BCG sample. BCGs are particularly interesting for our purposes because they are expected to grow in part due to merging – radial stellar population gradients in BCGs may be a signature of this process. Merging also affects the inner dark matter profiles, and thus the stellar kinematics, of BCGs. Minor, dry mergers tend to flatten the dark matter profiles in the center of BCGs, leading to decreased dark matter fractions. Indeed, Newman et al. (2013) claim that the distribution of stars in BCGs may be anti-correlated the inner dark matter profile. Using HSC together with MaNGA, we will reveal this connection in much finer detail. MaNGA will observe signatures of merger driven BCG assembly, such as stellar population gradients, and will also provide resolved kinematics at 1-2 effective radii. Weak lensing from HSC will provide the shape of the density profile at larger radii (see Figure 6). By using a joint analysis of kinematics and weak lensing, we will be able to robustly determine dark matter fractions for BGCs. Putting these ingredients together will provide valuable insights about how massive galaxies assemble mass in relation to their dark matter halos.
★ *This work package is linked with goal SS-B and will be assigned to PD1, PhD1, PhD3*

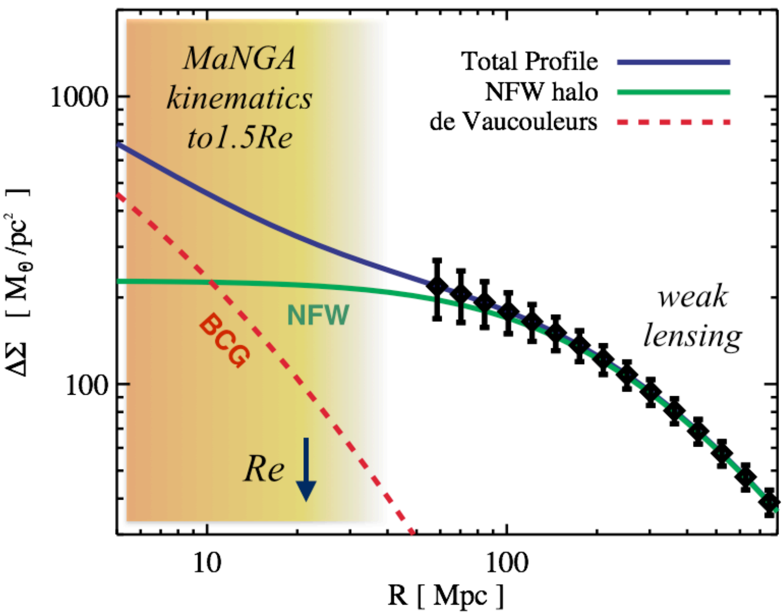


***Figure 6.*** Predicted weak lensing signal for BCGs in our MaNGA sample with halo masses between $M_h=10^{14}$ $M_\odot$ and $M_h=10^{14.25}$ $M_\odot$ in the HSC survey. The blue curve shows the total mass profile, while the red and green curves show the stellar and dark matter profiles, respectively. Weak lensing measurements will enable us to accurately study the shapes of density profiles on large scales while our MaNGA ancillary program will constrain the mass profile at 1.5Re using resolved kinematics. Direct lensing measurements (not stacked) will be possible for BCGs in halos with $M_h>10^{14.5}$ $M_\odot$.

**WP8: HST and MUSE follow-up of most massive clusters**
The MaNGA program will be extended by proposing a follow-up survey of 50 BCGs in the most massive clusters at z=[0.1,0.2] with MUSE on the VLT and with the ACS camera on the Hubble Space Telescope. This work-package involves writing the proposals to secure this data set as well as the analysis of the joint analysis of the data set. This work-package will require a close collaborative effort between the P.I, PhD1, and PD1 together with colleagues from the host institute.
★ *This work package is linked with goal SS-C and will be assigned to the P.I, PhD1, PD1*

## 4. Timeline and Milestones

The following table provides an outline of the timeline for this project. When GALDARK begins, the HSC survey, MaNGA, and eBOSS will already be actively collecting data and will continue to do so until 2019. At the onset of GALDARK, HSC and eBOSS will of collected enough data so that measurements of galaxy clustering and weak lensing (PhD2 and PhD3) can begin immediately (2016/2017). Data from the full BOSS survey are already in hand (DR12, 2015). The two initial goals of GALDARK will be to immediately begin to put the N-body framework into place and to submit the HST and MUSE proposals. I have allocated a three-year window (2016-2018) within which to collect the HST and MUSE data. The bulk of the work related to the small-scale component will occur in the second half of the project, following the success of these proposals. We will host a small workshop on the galaxy-halo connection in 2018. The completion of GALDARK is marked by the launch of the Euclid weak lensing mission in 2020.

| | 2016 | 2017 | 2018 | 2019 | 2020 | Assignment |
|---|---|---|---|---|---|---|
| **SMALL SCALES** | | | | | | |
| P.I (50%) | | | | | | |
| PD1 (100%) | | | | | | |
| PhD1 (100%) | | | | | | |
| PhD3 (50%) | | | | | | |
| WP5 | | | | | | PhD3 |
| WP6 | | | | | | PD1 |
| WP7 | | | | | | PD1, PhD3, |
| WP8 | | | | | | P.I, PhD1, PD1 |
| **LARGE SCALES** | | | | | | |
| P.I (50%) | | | | | | |
| PD2 (100%) | | | | | | |
| PhD2 (100%) | | | | | | |
| PhD3 (50%) | | | | | | |
| WP1 | | | | | | PhD3 |
| WP2 | | | | | | PhD2 |
| WP3 | | | | | | P.I, PD2 |
| WP4 | | | | | | PhD2 |
| **OTHER MILESTONES** | | | | | | |
| SDSS IV | eBOSS and MaNGA surveys | | | | | |
| HSC survey | | | | | | |
| Euclid Launch | | | | | | |
| HST & MUSE proposals | | | | | | P.I |
| Workshop | | | | | | |

## 5. Risk Assessment

GALDARK is an ambitious and novel program that is not without risk. Our main challenge will be to ensure that the systematic errors associated with weak lensing measurements are kept under control. However, it is important to note that the challenge of systematic errors will be the responsibility of the entire HSC weak lensing team, not just GALDARK team members. Our proposed analysis will also be computationally challenging which is why I have allocated a significant portion of the budget towards computational resources. The existing N-body group at CRAL will also be an important asset in this regard. The small-scale component of GALDARK is a particularly novel approach that may be subject to unforeseen systematic errors. For this reason, a significant amount of resource is dedicated to these aspects (WP5 and WP6). Finally, another risk is that we do not obtain the desired HST and MUSE data. However, I have scheduled an ample 3-year window to obtain this data. If we do not obtain these data, significant progress can already be made with the MaNGA BCG program.

## 6. Impact of GALDARK and Future Prospects

This work, funded by an ERC grant, will enable GALDARK team members to push the current boundaries in this field with the ambitious goal of completing the galaxy-halo picture at redshifts below z=1. The impact of our work will be driven by a) exploiting synergies between new state-of-the art surveys, b) developing new observational techniques (particularly our small scale component), and b) the use of sophisticated modelling approaches. ***Our work will provide the most complete and holistic view of the link between galaxies and dark matter before the era of Euclid and WFIRST***. The methods and techniques developed via this ERC grant will be of tremendous value for the preparation and analysis of the Euclid survey in 2020. ***There are also very close connections between our work and the cosmological analysis of BAO surveys such as BOSS and eBOSS. Indeed, a better understanding of the galaxy-halo picture can be used to greatly improve cosmological constraints from BAO surveys.*** Our work in Reid et al. (2014) showed that the growth of structure can be constrained to 2.4% for the BOSS CMASS sample by using small-scale information in the redshift space clustering of galaxies.

Finally, the techniques developed in GALDARK will naturally extend to next generation surveys such as Euclid and 4MOST (4-Meter Multi-Object Spectroscopic Telescope, de Jong et al. 2012). 4MOST is a project currently under development to provide a wide-field (>3 deg$^2$), high-multiplex (> 1500 fibers) spectrograph for the ESO 4m VISTA telescope. This instrument would provide spectroscopic follow-up for key European missions, including Euclid. The baseline 4MOST survey covers 15,000-20,000 deg$^2$ and will yield 20 million spectra at resolution R~5000 ($\lambda$=390-1000 nm). Also, in addition the visible wavelength imaging necessary for weak lensing, Euclid will also benefit from a near-infrared slitless spectrometer (NISP-S) covering the wavelength range 1.1-2 micron. By measuring the H$\alpha$ line at z=0.7 to z=2, Euclid will yield a sample of 52 million galaxies over 15,000 deg$^2$. Measuring galaxy-galaxy lensing for galaxies at z>1 will be challenging (because there will be too few background galaxies), but Euclid will provide a large sample of star forming galaxies at z=[0.7,1.0]. ***A joint analysis of galaxy-galaxy lensing from Euclid with clustering from 4MOST and from NISP-S samples will provide an unparalleled view of the galaxy-dark matter connection.***

REFERENCES


Barnabè M., Spiniello C., Koopmans L. V. E., Trager S. C., Czoske O., Treu T., 2013, MNRAS, 436, 253
Cappellari M. et al., 2012, Nature, 484, 485
de Jong R. S. et al., 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 8446, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 0
Diemer B., Kravtsov A. V., 2014, ApJ, 789, 1
Han J. et al., 2015, MNRAS, 446, 1356
Hearin A. P., Watson D. F., Becker M. R., Reyes R., Berlind A. A., Zentner A. R., 2013, ArXiv e-prints
Hearin A. P., Watson D. F., van den Bosch F. C., 2014, ArXiv e-prints
Hudson M. J. et al., 2015, MNRAS, 447, 298
Kauffmann G., Li C., Zhang W., Weinmann S., 2013, MNRAS, 430, 1447
Kobayashi M., Leauthaud A., More S., Okabe N., Aigle C., Rhodes J., 2015, Monthly Notices of the Royal Astronomical Society, submitted
Leauthaud A. et al., 2015, MNRAS, 446, 1874
Leauthaud A., Tinker J., Behroozi P. S., Busha M. T., Wechsler R. H., 2011, ApJ, 738, 45
Leauthaud A. et al., 2012, ApJ, 744, 159
Leauthaud A., et al., 2007, ApJS, 172, 219
Mandelbaum R., Seljak U., Cool R. J., Blanton M., Hirata C. M., Brinkmann J., 2006, MNRAS, 372, 758
Ménard B., Scranton R., Schmidt S., Morrison C., Jeong D., Budavari T., Rahman M., 2013, ArXiv e-prints
Newman A. B., Treu T., Ellis R. S., Sand D. J., 2013, ApJ, 765, 25
Nipoti C., Treu T., Ciotti L., Stiavelli M., 2004, MNRAS, 355, 1119
Rahman M., Ménard B., Scranton R., Schmidt S. J., Morrison C. B., 2014, ArXiv e-prints
Reid B. A., Seo H.-J., Leauthaud A., Tinker J. L., White M., 2014, MNRAS, 444, 476
Rykoff E. S. et al., 2014, ApJ, 785, 104
Shankar F. et al., 2014, ApJ, 797, L27
Shetty S., Cappellari M., 2014, ApJ, 786, L10
Smith R. J., 2014, MNRAS, 443, L69
Sonnenfeld A., Treu T., Marshall P. J., Suyu S. H., Gavazzi R., Auger M. W., Nipoti C., 2014, ArXiv e-prints
Tinker J. L., Leauthaud A., Bundy K., George M. R., Behroozi P., Massey R., Rhodes J., Wechsler R. H., 2013, ApJ, 778, 93
Velander M. et al., 2014, MNRAS, 437, 2111
Vogelsberger M. et al., 2014, MNRAS, 444, 1518
Watson D. F. et al., 2015, MNRAS, 446, 651
Yang X., Mo H. J., van den Bosch F. C., 2008, ApJ, 676, 248
Zehavi I., et al., 2011, ApJ, 736, 59
Zentner A. R., Hearin A. P., van den Bosch F. C., 2014, MNRAS, 443, 3044
Zheng Z., Coil A. L., Zehavi I., 2007, ApJ, 667, 760

**Section c. Resources (including project costs)**

Here we summarize and justify the GALDARK budget.

• **Team composition.** The GALDARK team will consist of the P.I, two post-doctoral scholars, and three PhD students. PhD and postdoctoral appointment will be three years each (a total of 18 FTE over 5 years). The ambitious nature of this project requires a large team of students and post-doctoral scholars to complete the proposed research.

• **Salaries.** The primary expenditure of GALDARK corresponds to salaries in order support the large team necessary for this project. The P.I will be fully involved in GALDARK (project management, student supervision, proposal writing, communication with external collaborations, scientific analysis and paper writing) and is covered at the 100% level over 5 years. Salaries are determined according to the CNRS salary scale: 89.7k€ per FTE for the P.I, 33k€ per FTE for PhD students and 50k€ per FTE for postdoctoral scholars. The total cost of salaries over 5 years is **1048k€.**

• **Travel.** The second major expense of GALDARK is in the form of travel. I expect all GALDARK members to disseminate our results in international conference but also to participate in external collaboration meeting (at least one per year). I have allocated 5k€/year for the P.I and 3k€/year for PhD students and post-doctoral scholars for travel. Since the P.I will be part of all the teams (HSC, MaNGA, eBOSS), the P.I will attend a larger number of collaboration meetings than other GALDARK team members. The total travel budget is **70k€**.

• **Publications.** Our work will be published in international journals such as Monthly Notices of the Royal Astronomical Society, the Astrophysical Journal, Nature, and Science. I have allocated 3k€/year for the cost of GALDARK publications. In addition, all papers will be on the arXiv preprint server free of charge.

• **Equipment & Consumables.** I have allocated 4k€/person for the initial purchase of computer equipment (desktop, depreciation over 5 years). GALDARK team members will not require powerful individual workstations because they will have access to a large computer cluster funded as part of my start-up costs (see below). Consumables are limited to 600€/year (for the purchase of back-up drives and other equipment). The total equipment budget is **24k€** excluding start-up costs and **124k€** including start-up costs (see below).

• **Visitors and Workshop.** I have also included a budget for inviting specialists to give seminars and to discuss our results. The budget for inviting visitors is 4k€ per year (corresponding to 2 to 4 visitors depending on if they travel locally or internationally). In 2018 when all the team members are present, I also plan to host a small invitation-only workshop (20 people total) on the topic of the galaxy-halo connection. This will enable us bring together specialists from the field to advertise our results but also to provide feedback on our work. For the workshop, I have included a budget a 5k€ for the workshop organization (rent for conference room, coffee breaks) and 10k€ to invite five invited speakers and to support travel costs for invited speakers (2k€/person). The total budget for the workshop and visitors is **35k€**.

• **Start-up costs.** Because I will move from a non-EU country, I am eligible for additional start-up costs (up to 500k€). I request 200k€ to buy-in to the SDSS IV project. I am currently a member of SDSS IV but will lose this access by moving to CRAL. This purchase will provide me with access to the eBOSS and MaNGA data-sets. PD1, PhD1, and PhD2 will also join these teams as part of this buy-in. In addition, I currently have access to a large cluster facility (30 nodes, 6 cores per node), which I use on a regular basis. GALDARK requires significant computational resources (WP1, WP2, WP3, WP4) and will handle large-data sets. For this reason, I request the purchase of a modern cluster facility to support these needs. My cost estimate is based on http://www.aslab.com/ and corresponds to a cluster with 8 nodes, 34 cores per node, 256GB memory, 12TB of disk space, for a total of 100k€ spend over 5 years (depreciation). The total start-up costs amount to **300k€** before overheads and to **325k€** after applying overheads to the purchase of the cluster. Overheads do not apply to buy-in to the SDSS IV project (access to a large facility not on the premises).

Total budget before start-up costs: **1,494,856€**
Total budget including start-up costs: **1,819,856€**

| **Cost Category** | | | **Total in Euro** |
|---|---|---|---|
| **Direct Costs**[2] | **Personnel** | PI[3] | 448,885 |
| | | Senior Staff | 0 |
| | | Postdocs | 300,000 |
| | | Students | 300,000 |
| | | Other | 0 |
| | *i. Total Direct Costs for Personnel (in Euro)* | | 1,048,885 |
| | **Travel** | | 70,000 |
| | **Equipment** | | 124,000 |
| | **Other goods and services** | Consumables | 3,000 |
| | | Publications (including Open Access fees), etc. | 15,000 |
| | | Other: workshop and visitors | 35,000 |
| | *ii. Total Other Direct Costs (in Euro)* | | 247,000 |
| **A – Total Direct Costs (i + ii)** (in Euro) | | | 1,295,885 |
| **B – Indirect Costs (overheads)** 25% of Direct Costs[4] (in Euro) | | | 323,971 |
| **C1 – Subcontracting Costs** (no overheads) (in Euro) | | | 0 |
| **C2 – Other Direct Costs with no overheads**[5] (in Euro) | | | 200,000 |
| **Total Estimated Eligible Costs (A + B + C)** (in Euro)[6] | | | 1,819,856 |
| **Total Requested EU Contribution** (in Euro)[6] | | | 1,819,856 |

The project cost estimation should be as accurate as possible. Significant mathematical mistakes may reflect poorly on the credibility of the budget table and the proposal overall. The evaluation panels assess the estimated costs carefully; unjustified budgets will be consequently reduced. The requested contribution should be in proportion to the actual needs to fulfil the objectives of the project.

| | |
|---|---|
| **For the above cost table, please indicate the duration of the project in months:**[7] | **60** |
| **For the above cost table, please indicate the % of working time the PI dedicates to the project over the period of the grant:** | **100%** |

Specify briefly your commitment to the project and how much time you are willing to devote to the proposed project in the resources section. Please note that you are expected to devote at least 50% of your total working time to the ERC-funded project and spend at least 50% of your total working time in an EU Member State or Associated Country.

[2] An additional cost category 'Direct Costing for Large Research Infrastructures' applicable to H2020 can be added to this table (below 'Other goods and services') for PIs who are hosted by institutions with Large Research Infrastructures of a value of at least EUR 20 million and **only** after having received a positive ex-ante assessment from the Commission's services (see '*Information for Applicants to the Starting and Consolidator Grant 2015 Calls'* for more details).

[3] When calculating the salary, please take into account the percentage of your dedicated working time to run the ERC-funded project (i.e. minimum 50% of your total working time).

[4] Please note that the overheads are fixed to a flat rate of exactly 25%.

[5] Such as the costs of resources made available by third parties which are not used on the premises of the beneficiary (see '*Information for Applicants to the Starting and Consolidator Grant 2015 Calls'* for details).

[6] These figures MUST match those presented in the online proposal submission form, section 3 – Budget.

[7] The maximum award is reduced pro rata temporis for projects of a shorter duration (e.g. for a project of 48 months duration the maximum requested EU contribution allowed is EUR 1.2 million). Additional funding to cover major one-off costs is not subject to pro-rata temporis reduction for projects of shorter duration (e.g. with additional funding it is possible to request a maximum EU contribution of EUR 1.7 million for a project).