Galaxies in 3D across the Universe
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IFUs surveys, a panoramic view of galaxy evolution

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Abstract. We present here a brief summary of the currenly on-going IFU surveys of galaxies in teh Local Universe, describing their main characteristics, including their sample selections, instrumental setups, wavelength ranges, and area of the galaxies covered. Finally, we make an emphasis on the main characteristics of the CALIFA survey and the more recent results that has been recently published.

Keywords. galaxies: evolution, techniques: integral field spectroscopy

1. Introduction

Much of our recently acquired understanding of the architecture of the Universe and its constituents derives from large surveys (e.g., 2dFGRS, Folkes *et al.* 1999;SDSS, York *et al.* 2000; GEMS, Rix *et al.* 2004; VVDS, Le Fèvre *et al.* 2004; COSMOS, Scoville *et al.* 2007 ; GAMMA, Driver *et al.* 2009, to name but a few). Such surveys have not only constrained the evolution of global quantities such as the cosmic star formation rate, but also enabled us to link this with the properties of individual galaxies – morphological types, stellar masses, metallicities, etc.. Compared to previous approaches, the major advantages of this recent generation of surveys are: (1) the large number of objects sampled, allowing for meaningful statistical analysis to be performed on an unprecedented scale; (2) the possibility to construct large comparison/control samples for each subset of galaxies; (3) a broad coverage of galaxy subtypes and environmental conditions, allowing for the derivation of universal conclusions; and (4) the homogeneity of the data acquisition, reduction and (in some cases) analysis.

On the other hand, the cost of these surveys, in terms of telescope time, manpower, and involved time scales, is also unprecedented in astronomy. The user of such data products has not necessarily been involved in any step of designing or conducting the survey, but nevertheless takes advantage of the data by exploiting them according to her/his scientific interests. This new approch to observational astronomy is also changing our perception of the scientific rationale behind a new survey: While it is clear that certain planned scientific applications are key determinants to the design of the observations and 'drive' the survey, the survey data should at the same time allow for a broad range of scientific exploitation. This aspect is now often called *Legacy* value.

Current technology generally leads to surveys either in the imaging or in the spectroscopic domain. While imaging surveys provide two-dimensional coverage, they carry very little spectral information. This is also true for multiband photometric surveys such as COMBO-17 (Wolf *et al.* 2003), ALHAMBRA (Moles *et al.*. 2008) or the planned PAU project (Benítez *et al.*. 2009), which will still be unable to accurately capture individual spectral lines and measure, e.g., emission line ratios or internal radial velocity differences. Spectroscopic surveys such as SDSS or zCOSMOS, on the other hand, do provide more detailed astrophysical information, but they are generally limited to one spectrum per

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Table 1. Comparison of IFU Surveys

Specification	MaNGA	SAMI	CALIFA	Atlas3D
Sample Size	10,000	3,400	600	260
Selection	$M > 10^9 M.$	$M > 10^{8.2} M.$	45" $< D_{25} <$ 80"	E/S0$M > 10^{9.8} M.$
Radial coverage	$1.5r_e$ (2/3), $2.5r_e$ (1/3)	1-$2r_e$	>$2.5r_e$	<$1r_e$
S/N at $1r_e$	15-30	10-30	∼30	15
Wavelength range(Å)	3600-10300	3700-7350	3700-7500	4800-5380
Instrumental resolution	50-80 km/s	75/28 km/s	85/150 km/s	105 km/s
Input Spaxel Size	2.0″	1.6’″	2.7″	1″
Input Spaxels per object	<3×127[1]	3×61	3×331	1,431
Spatial FWHM	2″	2″	2.5″	1.5″
Telescope size	2.5m	3.5m	3.5m	4.2m

[1] This corresponds to the largest MaNGA bundle. Each MaNGA plate provides with 17 bundles of different amount of fibers: 2x19; 4x37; 4x61; 2x91; 5x127.

galaxy, often with aperture losses that are difficult to control. For example, the 3″ diameter of the fiber used in the SDSS corresponds to vastly different linear scales at different redshifts, without the possibility to correct for these aperture effects.

An observational technique combining the advantages of imaging and spectroscopy (albeit with usually quite small field of view) is Integral Field Spectroscopy (IFS). However, so far this technique has rarely been used in a ‘survey mode’ to investigate large samples. Among the few exceptions there is, most notably, the SAURON survey (de Zeeuw *et al.* 2002), focused on the study of the central regions of 72 nearby early-type galaxies and bulges of spirals. Others are (i) the PINGS project at the CAHA 3.5m of a dozen very nearby galaxies (Rosales-Ortega *et al.* 2010), (ii) the Disk Mass Survey (Bershady *et al.* 2010) that provided super high spectral resolution using PPAK and SparsePak of 46 face-on spirals; (iii) the VENGA project (Blanc *et al.* 2013), that is observing a sample of 32 face-on spirals with VIRUS-P; and (iv) and the SIRIUS project, currently studying 70 (U)LIRGS at $z < 0.26$ using different IFUs (Arribas *et al.* 2008), among others. However, despite the dramatic improvement over previous data provided by these ‘surveys’, they are all affected by non-trivial sample selection criteria and, most importantly, incomplete coverage of the full extent of the galaxies.

In the last few years this situation has changed dramatically, and it will change even more in the upcomming years, with the development of IFS surveys of galaxies, in particular Atlas3D (Cappellari *et al.* 2011), CALIFA (Sánchez *et al.* 2012), MaNGA (Law *et al.* 2014) and SAMI (Croom *et al.* 2012). We review here the current on-going or recently started surveys, making an emphasis on the result obtained by the CALIFA survey (Sánchez *et al.* 2012), the first of those surveys providing wih a panoramic view of galaxy properties.

2. Major recent and on-going surveys

Most of the listed on-going IFU surveys in the Local Universe have as a major goal to understand the nature of galaxies as a consequence of the evolution through cosmologocial times. Therefore, most of their differences are on the technical details of the selected IFU, the adopted setup and the sample selection. In general, all the surveys tries to select a

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sample representative of the population of galaxies at low redshifts. Therefore, most of them cover mostly all galaxy types, covering as much as possible the color-magnitude diagram. However the adopt different selection criteria. In the case of MaNGA and SAMI the main criteria was to cover a wide range of galaxy masses. In MaNGA it was forced that the distribution along masses was as flat as possible. SAMI adopted a different procedure, selecting a set of volume-limited sub-samples, together with a set of sub-samples centred in galaxy clusters. In the previous case the sample was derived from the SDSS catalogs, while in the former one it was extracted from the GAMMA survey. The CALIFA sample selection is based on their optical size, i.e., it is a diameter selection that guaranteed that all galaxies are observed in most of their optical extension, as we explain below. Atlas3D adopted a different scheme, their main science goal (to understand the building up of bulges and early-type galaxies). The selected early-type/red galaxies from a volume-limited sample up to ∼42 Mpc (being the sample at lower redshiffs of the different surveys).

Figure 1 and Table 1 presents an schematic comparison between the different surveys. The differences between different surveys are clearly highlighted in there. While Atlas3D provides the highest spatial resolution and better spatial sampling for the individual galaxies, if offers a limited wavelength range and FoV compared to the size of the galaxies. In other cases, like MaNGA, the total number of objects is the main statistical advantage, since it would provide with the average characteristics properties of the main population of galaxies for many different galaxy types with better statistical significance than any of the other surveys. The penalty is that not all the galaxies will be sampled by the same number of fibers (ranging between 3x19 to 3x127), and therefore the physical sampling is different for different galaxies. In the case of SAMI the main adventage is the wider range of galaxy masses sampled and the higher spectral resolution in the red wavelength range. However the large redshift range implies a different physical sampling of the different galaxies. Finally, in the case of CALIFA, it provides the widest spatial coverage compared to the spatial size of the galaxies, and one of the best spatial physical resolutions. However, the sample is more limited than the one studiest by MaNGA or SAMI. In summary we consider that each of the IFUs surveys is very complementary.

3. CALIFA: A brief introduction

The Calar Alto Legacy Integral Field Area (CALIFA) survey (Snchez *et al.* 2012a) is an ongoing large project of the Centro Astronmico Hispano-Alemn at the Calar Alto observatory to obtain spatially resolved spectra for 600 local (0.005< z <0.03) galaxies by means of integral field spectroscopy (IFS). CALIFA observations started in June 2010 with the Potsdam Multi Aperture Spectrograph (PMAS, Roth *et al.* 2005), mounted to the 3.5m telescope, utilizing the large (74"×64") hexagonal field-of-view (FoV) offered by the PPak fiber bundle (Verheijen *et al.* 2004; Kelz *et al.* 2006). PPak was created for the Disk Mass Survey (Bershady *et al.* 2010). Each galaxy is observed using two different setups, an intermediate spectral resolution one (V1200, $R \sim 1650$), that cover the blue range of the optical wavelength range (3700-4700Å), and a low-resolution one (V500,$R \sim 850$, that covers the first octave of the optical wavelength range (3750-7500Å). A diameter-selected sample of 939 galaxies were drawn from the 7th data release of the Sloan Digital Sky Survey (SDSS, Abazajian *et al.* 2009) which is described in Walcher *et al.* (2014). From this mother sample the 600 target galaxies are randomly selected.

Combining the techniques of imaging and spectroscopy through optical IFS provides a more comprehensive view of individual galaxy properties than any traditional survey. CALIFA-like observations were collected during the feasibility studies (Mrmol-Queralt

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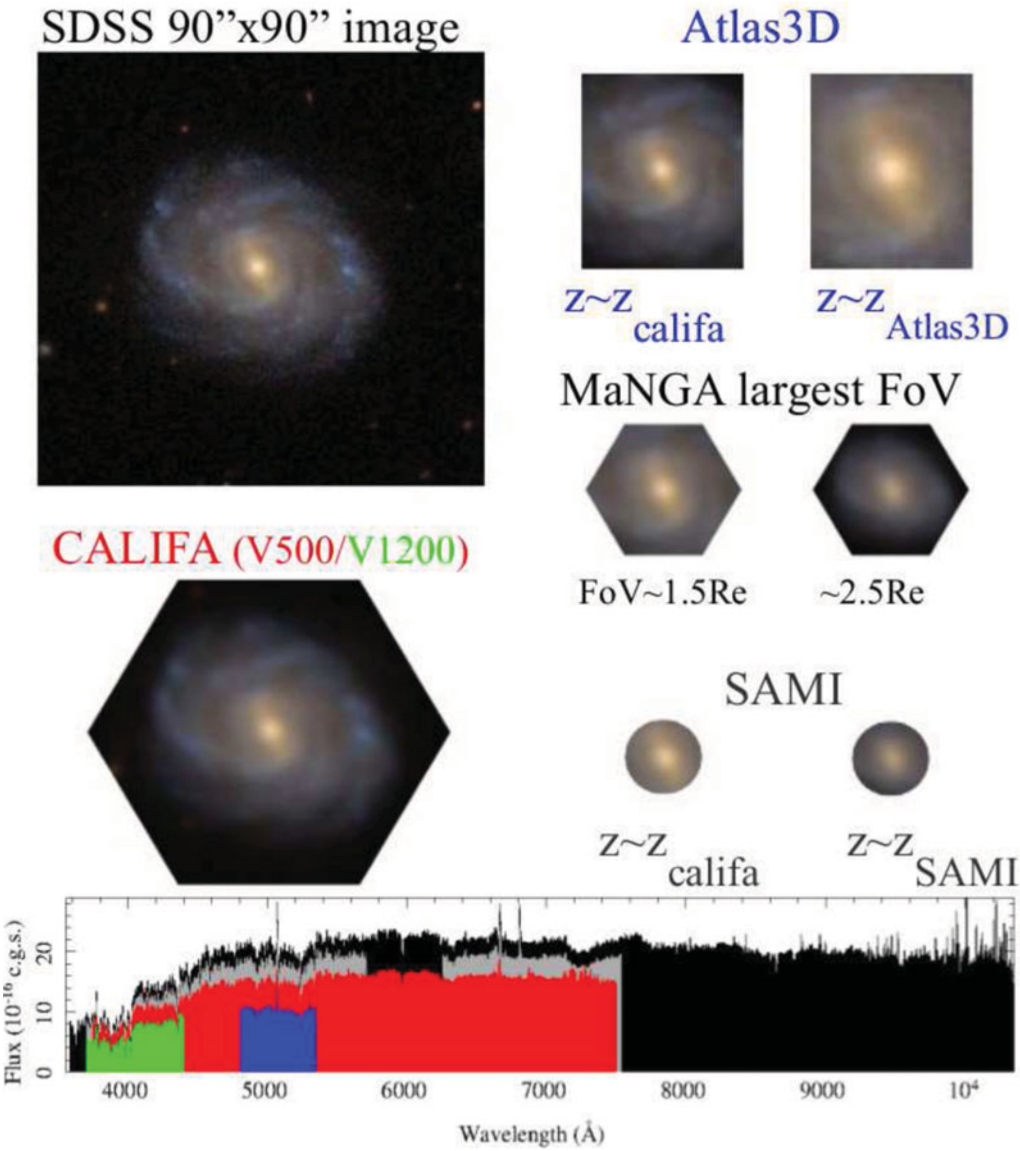

Figure 1. Schematic figure comparing the different on-going major IFU surveys. The top-left figure shows a 90"×90" post-stamp image of NGC5947 extracted from the SDSS imaging survey. The same image as it would be observed by the four different IFU surveys discussed in this article are presented in the different post-stamp figures. For MaNGA we have selected the bundle with the largest FoV, although we should remind the reader that only 1/5th of the survey will be observed using this bundle. Finally, the wavelength range covered by each survey is presented in the bottom panel. We should remind that the spectral resolution is different for each survey. For SAMI the largest resolution is achieved in the redder wavelength range covered by this survey.

et al. 2011; Viironen *et al.* 2012) and the PPak IFS Nearby Galaxy Survey (PINGS, Rosales-Ortega *et al.* 2010), a predecessor of this survey. First results based on those datasets already explored their information content (e.g. Snchez *et al.* 2011; Rosales-Ortega *et al.* 2011; Alonso-Herrero *et al.* 2012; Snchez *et al.* 2012b; Rosales-Ortega *et al.* 2012). CALIFA can therefore be expected to make a substantial contribution to our

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understanding of galaxy evolution in various aspects including, (i) the relative importance and consequences of merging and secular processes; (ii) the evolution of galaxies across the colormagnitude diagram; (iii) the effects of the environment on galaxies; (iv) the AGN-host galaxy connection; (v) the internal dynamical processes in galaxies; and (vi) the global and spatially resolved star formation history of various galaxy types.

Compared with other IFS surveys, CALIFA offers an unique combination of (i) a sample covering a wide range of morphological types in a wide range of masses, sampling the Color-Magnitude diagram for $M_g > -18$ mag; (ii) a large FoV, that guarantees to cover the entire optical extension of the galaxies up to $2.5r_e$ for an 80% of the sample; and (iii) an accurate spatial sampling, with a typical spatial resolution of ∼1 kpc for the entire sample, which allows to optical spatial resolved spectroscopic properties of most relevant structures in galaxies (spiral arms, bars, buges, Hii regions...). The penalty for a better spatial sampling of the galaxies is the somehow limited number of galaxies in the survey (e.g., MaNGA and SAMI). In terms of the spectral resolution, only the blue wavelength range is sampled with a similar spectral resolution than these two other surveys.

As a legacy survey, one of the main goals of the CALIFA collaboration is to grant public access of the fully reduced datacubes. In November 2012 we deliver our 1st Data Release (Husemann *et al.* 2013), comprising 200 datacubes corresponding to 100 objects †. After almost two years, and a major improvement in the data reduction, we present our 2nd Data Release (Garcia Benito *et al.*, in prep.), comprising 400 datacubes corresponding to 200 objects ‡, the 1st of October 2014.

4. CALIFA: Main Science Results

Figure 2 illustrate the dataproducts that can be derived from the IFU datasets obtained by the CALIFA survey, comprising a panoramic view of the spatial resolved spectroscopic prorperties of these galaxies, including information of the stellar populations, ionized gas, mass distribution and stellar and gas kinematics. Similar dataproducts are derived for any of the indicated projects: Atlas3D, MaNGA or SAMI.

Different science goals have been already addressed using this information: (i) New techniques has been developed to understand the spatially resolved star formation histories (SFH) of galaxies (Cid Fernandes *et al.*, 2013, 2014). We found the solid evidence that mass-assembly in the typical galaxies happens from inside-out (Pérez *et al.*, 2013). The SFH of bulges and early-type galaxies are fundamentally related to the total stellar mass, while for disk galaxies it is more related to the local stellar mass density (González Delgado *et al.*, 2013 & 2014); (ii) We developed new tools to detect and extract the spectroscopic information of HII regions (Sánchez *et al.*, 2012b), building the largest catalog currently available (∼6,000 HII regions and aggregations). This catalog has been used to define a new oxygen abundance calibrator anchored with electron temperature measurements (Marino *et al.*, 2013). From these, we explored the proposed dependence of the Mass-Metallicity relation with SFR (Sánchez *et al.*, 2013), and the local Mass-Metallicity relation (Rosales-Ortega *et al.* 2012). We found that all galaxies in our sample present a common abundance radial gradient with a similar slope when normalized to the effective radius (Sánchez *et al.*, 2014), which agrees with the proposed inside-out scenario for galaxy growth. This characteristic slope is independent of the properties of the galaxies, and in particular of the presence or absence of a bar, contrary to previous results. More

† http://califa.caha.es/DR1/
‡ http://califa.caha.es/DR2/

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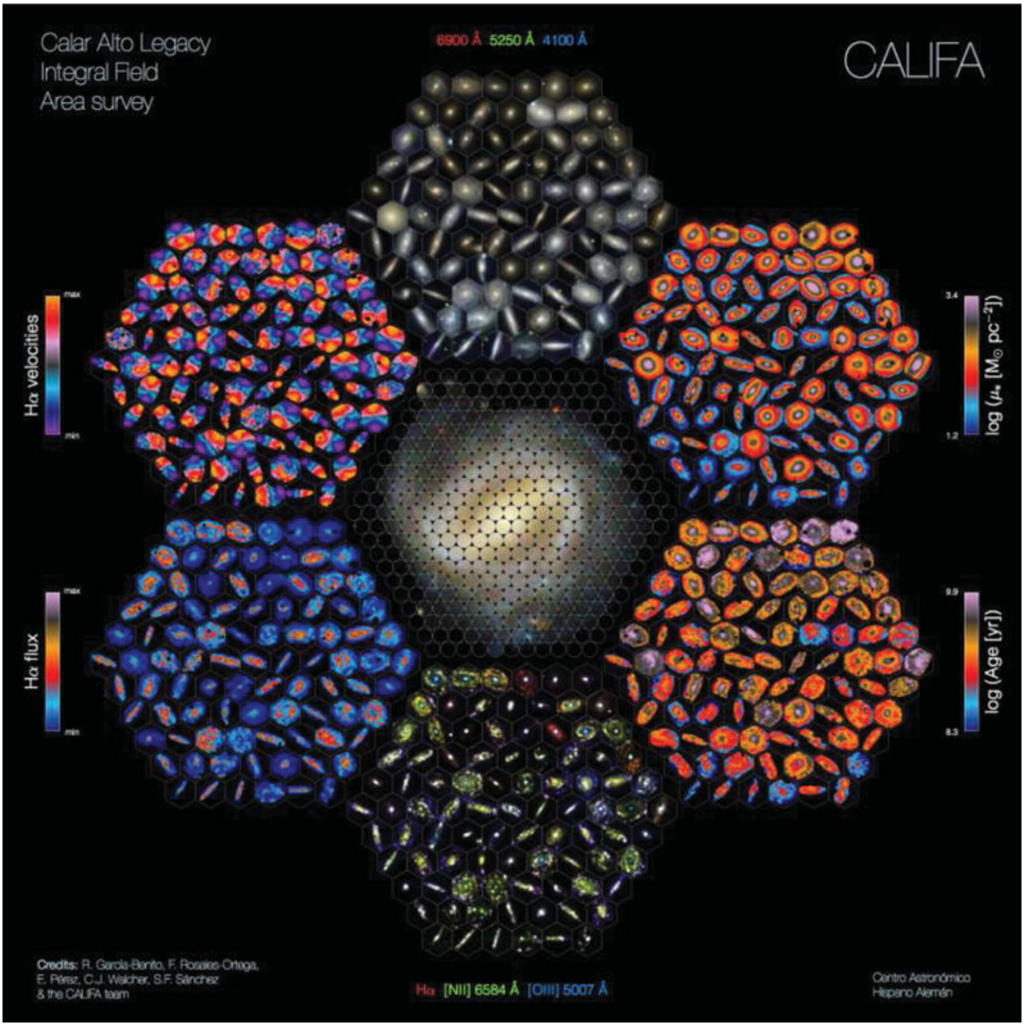

Figure 2. Schematic representation of the different dataproducts that can be obtained for sample of galaxies with the state-of-the art IFU surveys. In this case it shows for a set of 100 galaxies extracted from the CALIFA survey six hexagons showing (following the clock arrows): (i) The true-color maps showing the light distribution; (ii) The stellar mass density distribution; (iii) The distribution of the luminosity weighted ages across the galaxies; (iv) a three-color image showing the ionized gas distribution for Hα, [NII]λ6584 and [OIII]λ5007; (v) the Hα intensity distribution and (vi) the ionized gas kinematics. Similar dataproducts are derived for Altas3D, MaNGA and SAMI datasets.

recently, this result has been confirmed by the analysis of the stellar abundance gradient in the same sample (Sánchez-Blázquez *et al.*, 2014). We also explore the progenitors of SuperNovae based on the gas phase metallicity and loca SFR at the location of the explosion (Gabany *et al.* 2014); (iii) We explore the origin of the low intensity, LINER-like, ionized gas in galaxies. These regions regions are clearly not related to star-formation activity, or to AGN activity. They are most probably relatd to post-AGB ionization in many cases (Kehrig *et al.*, 2012; Singh *et al.*, 2013; Papaderos *et al.* 2013); (iv) We explore the aperture and resolution effects on the data. CALIFA provides a unique tool to understand the aperture and resolution effects in larger single-fiber (like SDSS) and

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IFS surveys (like MaNGA, SAMI). We explored the effects of the dilution of the signal in different gas and stellar population properties (Mast *et al.*, 2014), and proposed an new empirical aperture correction for the SDSS data (Iglesias-Páramo *et al.*, 2013); (v) CALIFA is the first IFU survey that allows gas and stellar kinematic studies for all morphologies with enough spectroscopic resolution to study (a) the kinematics of the ionized gas (García-Lorenzo *et al.*, 2014), (b) the effects of bars in the kinematics of galaxies (Barrera-Ballesteros *et al.* 2014a); (c) the effects of the intraction stage on the kinematic signatures (Barrera-Ballesteros *et al.*, submitted), (d) measure the Bar Pattern Speeds in late-type galaxies (Aguerri *et al.*, submitted), (iv) extend the measurements of the angular momentum of galaxies to previously unexplored ranges of morphology and ellipticity (Falcón-Barroso *et al.*, in prep.); and (v) finally we explore in detail the effects of galaxy interaction in the enhancement of star-formatio rate and the ignition of galactic outflows (Wild *et al.* 2014).

5. Conclusions

Along this review we have presented the main characteristics of IFU surveys in the Local Universe, describing their main advantage with respect to precedent techniques (like single fiber spectroscopic surveys or imaging surveys). We made a summary of some of the first attempts of performing a major IFU survey, and we describe the current on-going or recently finished ones. Finally, we present the main data-products that can be derived using these surveys and made a brief summary of the science goals achieved recently by the CALIFA survey, one of the most advanced on-going surveys that sample the full range of morphological types of galaxies.

Recent results already presented based on the pilot and even the main samples of the recently started MaNGA and SAMI surveys in this conference, and the quality shown by MUSE data (Bacon *et al.*,), illustrate how IFU surveys would fundamental tools in our understanding of the evolution of galaxies.

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