The Origin of Bulges and Discs.
The Stellar Mass Growth Unveiled using CALIFA Spectro-Photometric Decompositions

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ABSTRACT

Directly linked to the mass of the dark matter halo where baryons form, the galaxy stellar mass ($M_\star$) is the most important observable parameter to understand galaxy evolution. Still, we have not completely figured out how the growth of the stellar mass in galaxies happen. A fundamental problem stands at the fact that galaxies are complex systems with an intricate combination of different structural components such as bulges, discs, and bars. Each of these structures may have followed a different formation path, and therefore the separated mass growth of bulges, discs, and bars might hold the key to understand how galaxies evolved with time.

In a series of papers, we have applied a new spectro-photometric decomposition code (C2D; Méndez-Abreu et al. 2019) to a sample of photometrically classified bulge+disc galaxies observed within the CALIFA IFS survey (Sánchez et al. 2016). Our approach allows us to overcome the general problem of 'structure superposition' in galaxies by separating IFS datacubes, containing the spatial and spectral information, of the individual components shaping the galaxy. The analysis of the independent bulge and disc datacubes opens a new way to analyse their spectroscopic properties. We summarise here our main results on the stellar mass growth of bulges and discs in the nearby Universe.

SCIENTIFIC BACKGROUND: The mass growth in galaxies

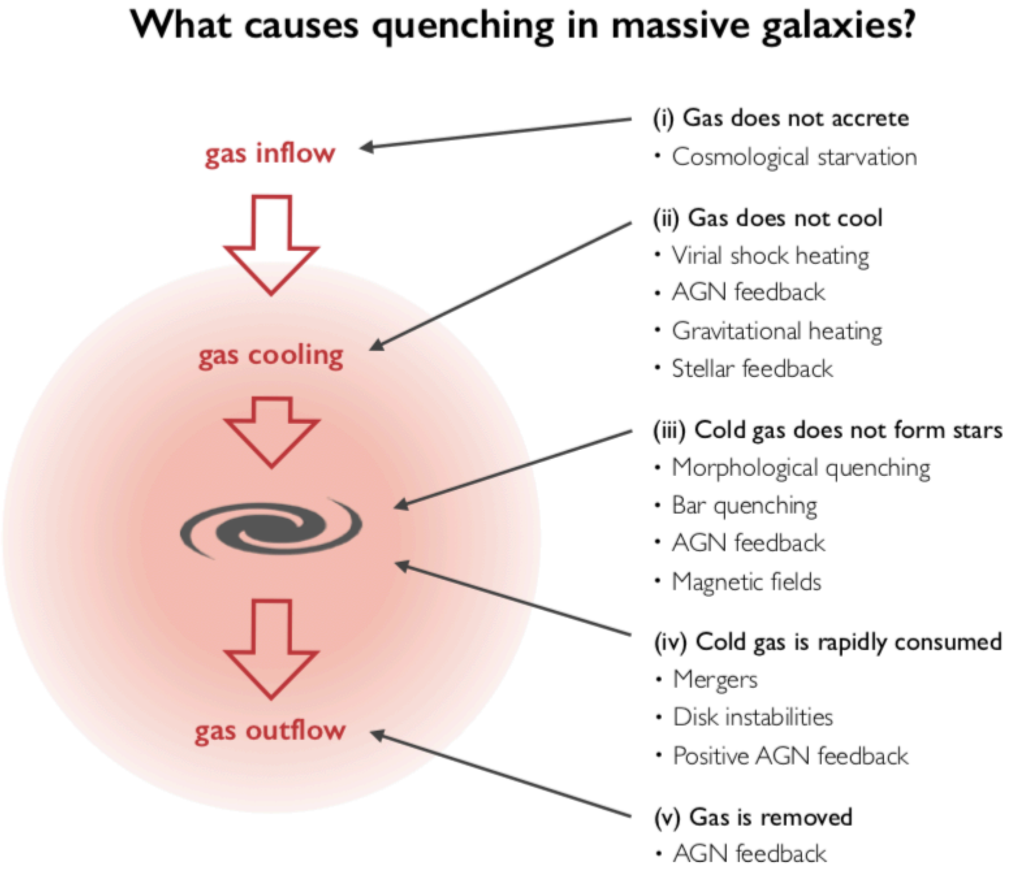


Fig. 1 Schematic diagram listing the plausible quenching mechanisms.

Man & Belli, 2018

INSIDE-OUT FORMATION

The preferred paradigm for the mass growth in galaxies can be summarized in the inside-out view of galaxy assembly (Aumer & White 2013). In this scenario, the central parts of the galaxies formed first, at high redshift, and then a surrounding disc or envelope is gathered around these central parts leading to nowadays spirals and elliptical galaxies (Oser et al. 2010).

However, galaxy growth is a complex process where the physics of baryons maintain a delicate balance between triggering and shut-down of the star formation (SF), and the radial growth of stellar mass seems to be dependent on both the galaxy mass (van Dokkum et al. 2014) and the presence of secular processes (de Lorenzo-Cáceres et al. 2013; Catalán-Torrecilla et al. 2017).

QUENCHING MECHANISMS

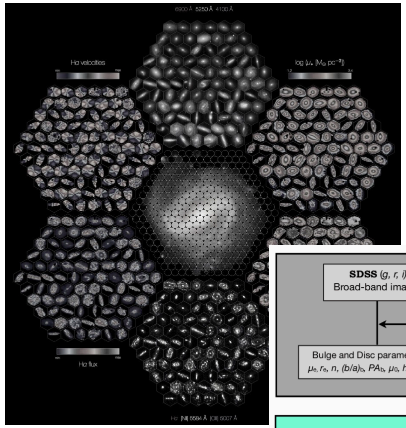
In the Figure, we show some of the proposed mechanisms for quenching the star formation in galaxies. Some of these mechanisms are directly related to the formation of galaxy bulges (e.g., galaxy mergers), others are the direct consequence of the presence of a bulge (e.g., morphological quenching), and others can be indirectly linked to their properties (bulge mass is related to that of the central black hole and consequently to either AGN or radio-mode feedback). Therefore, it is clear that looking for the imprints of these mechanisms on galactic bulges, as well as understanding the mass growth of galaxy structures, is key to understand the evolution of disc galaxies.

OUR APPROACH

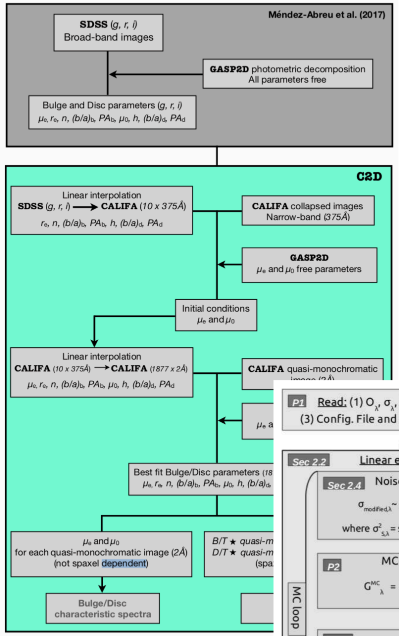
Observationally it is clear that a general scenario for the mass growth of disc galaxies must include a description on how this happens for their different structures: bulges and discs. However, the difficulties inherent to identify, and separate, these structures have hindered most of our advance in this.

Here we present the results of a new spectro-photometric decomposition code (C2D) able to separate galaxy structures in IFS datacubes. The application of this new technique, combined with the PIPE3D pipeline to derive stellar population properties, to a statistically representative sample of disc galaxies in the nearby Universe is providing new clues on the mass growth of galaxies.

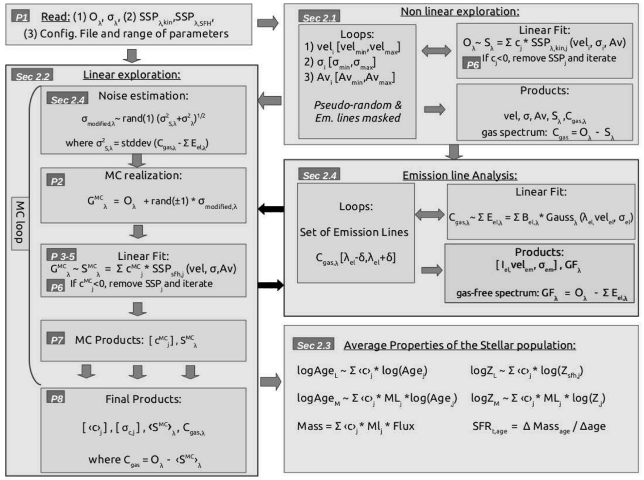
Methodology: CALIFA+C2D+PIPE3D the perfect cocktail to understand galaxy evolution



CALIFA: Sánchez et al. 2016



C2D: Méndez-Abreu et al. 2019



PIPE3D: Sánchez et al. 2016

CALIFA

The sample of galaxies analysed in this work is drawn from the CALIFA data release 3 (DR3; Sánchez et al. 2016). This data release comprises 667 galaxies covering a wide range of stellar masses and Hubble types. Méndez-Abreu et al. (2017) carried out a multicomponent multiband photometric decomposition of 404 galaxies present in the CALIFA DR3 using SDSS imaging. The final sample used in this work comprises 129 unbarred disc galaxies with a photometric bulge: 58 bulge-to-disc, 40 bulge-to-disc with a break, and 31 early-type galaxies.

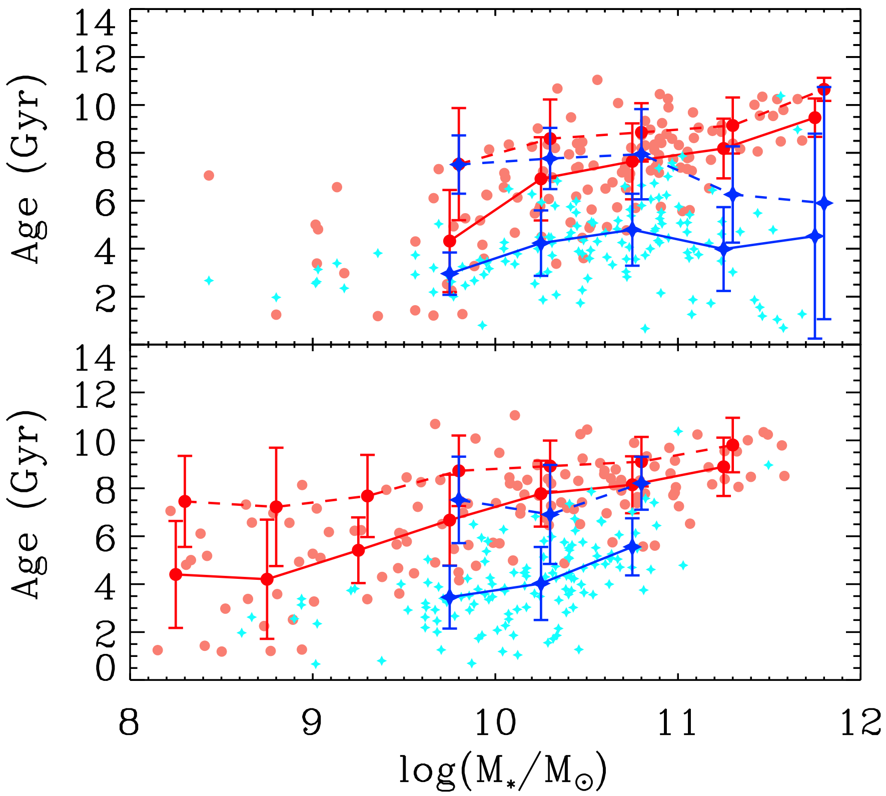
C2D. The next natural step of photometric decompositions.

Briefly, C2D is based on the idea that IFS datacubes can be worked out as a sequence of quasi-monochromatic 2D images at different wavelengths. Thus, standard 2D photometric decomposition techniques will be able to isolate the photometric contribution of both the bulge and disc. In C2D, the photometric decomposition engine is provided by GASP2D (Méndez-Abreu et al. 2008, 2014)

PIPE3D

PIPE3D is a well-tested code specifically designed to extract the stellar population and ionised gas properties from IFS data. The main data products obtained from PIPE3D include luminosity/mass weighted ages and metallicities, star formation histories, and intensity maps of strong emission lines for both components.

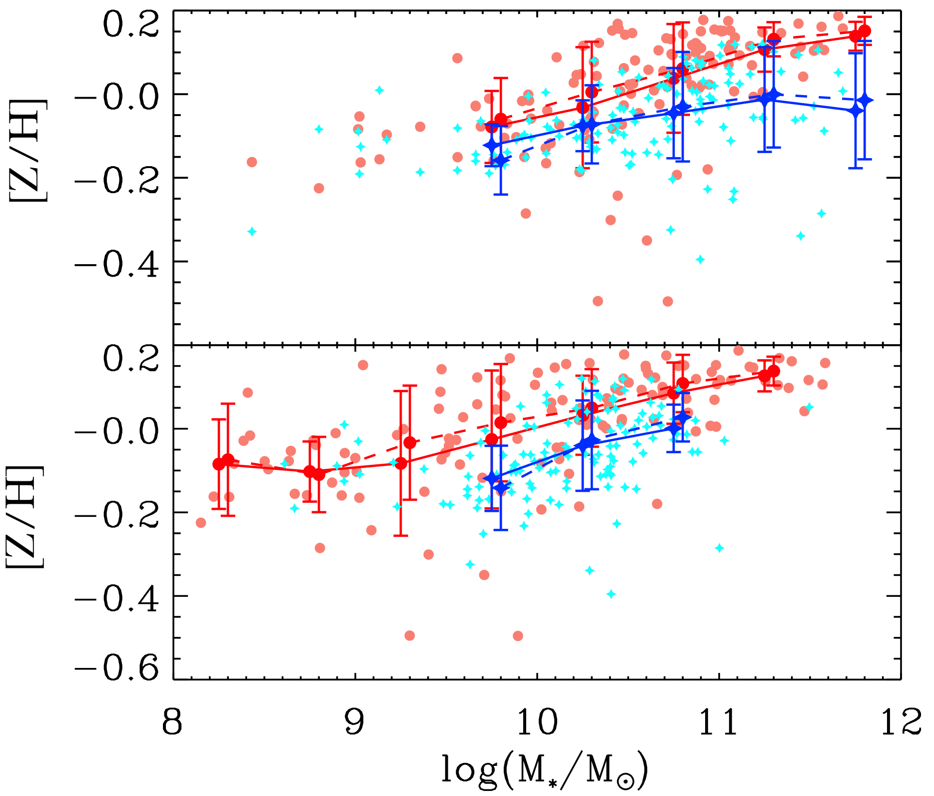
The stellar population properties of bulges and discs in the nearby Universe



Distribution of ages as a function of the galaxy stellar mass (upper panels) and bulge or disc stellar mass (lower panels). Solid and dashed lines represent luminosity and mass weighted quantities, respectively. Red and blue lines show the mean values for bulges and discs. Salmon circles and cyan stars show luminosity weighted values for individual bulges and discs, respectively.

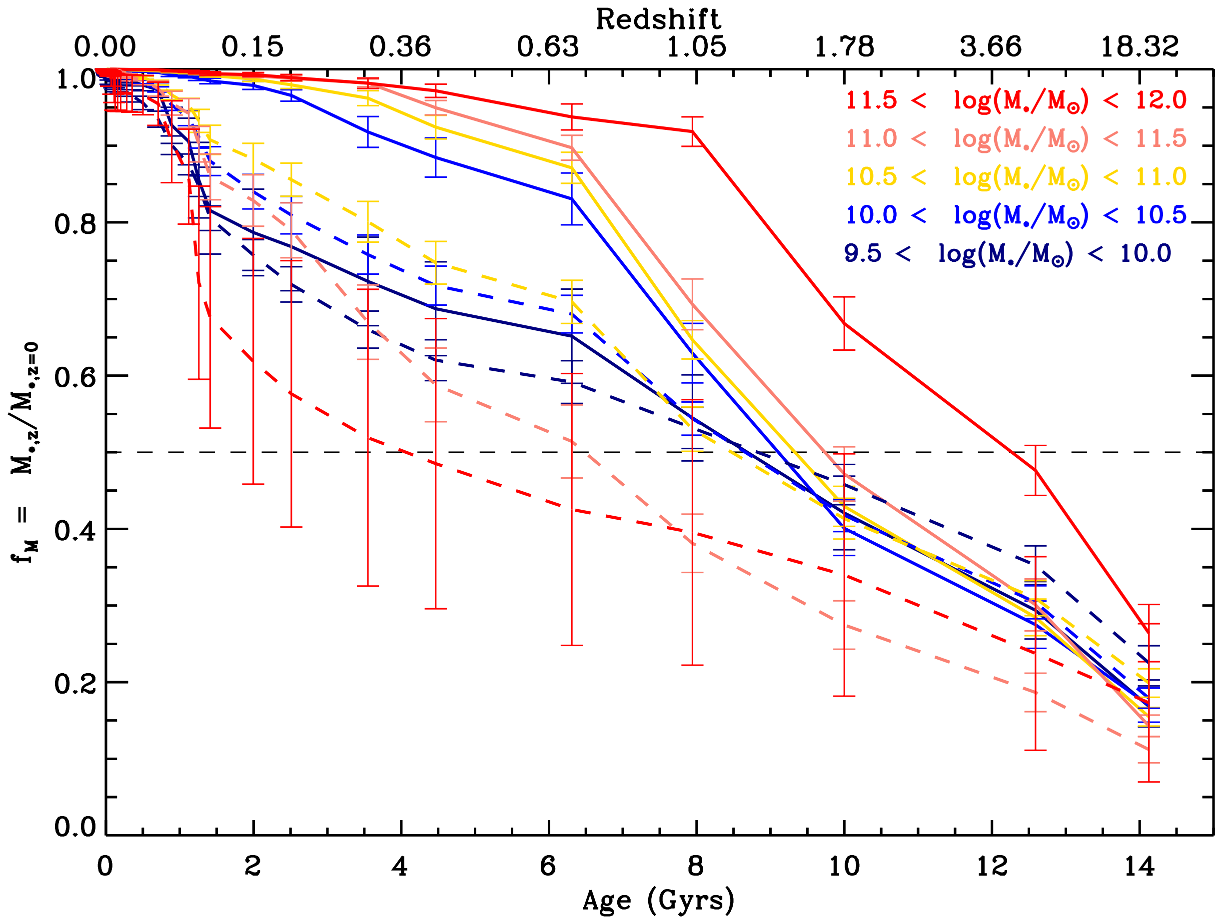
Bulges are, on average, always older and more metal-rich than discs. This trend is independent of using the stellar mass of the galaxy or the mass of the individual components, and it is also independent of using either luminosity o mass weighted quantities in the analysis.

Using individual galaxies, we found that only 9% (30%) of our bulges are younger than their surrounding discs when using luminosity (mass) weighted ages.



Distribution of metallicities as a function of the galaxy stellar mass (upper panels) and bulge or disc stellar mass (lower panels). Solid and dashed lines represent luminosity and mass weighted quantities, respectively. Red and blue lines show the mean values for bulges and discs. Salmon circles and cyan stars show luminosity weighted values for individual bulges and discs, respectively.

The mass growth of bulges and discs in the nearby Universe



Cumulative fraction of stellar mass with respect to z = 0 as a function of cosmic time for bulges (solid lines) and discs (dashed lines). Top axis shows the redshift and bottom axis the age of the stellar populations. The colors represent bins of global galaxy mass. Error bars show the Poissonian uncertanties.

BULGES

- Bulges in the most massive galaxies (it also holds for the most massive bulges) form their stars at earlier times than bulges in lower mass galaxies (low-mass bulges).
- At all galaxy (and bulge) masses, at least half of the bulge stellar mass was already formed at z~1.
- The shape of the cumulative mass fraction is similar for high mass bulges, i.e., a step rise until ~6 Gyrs look-back time followed by a minimal contribution of new stars (< 20%) after this time. However, the situation changes at a galaxy mass of $\log(M_\star/M_\odot)$ ~ 9.5-10 (or bulge mass of $\log(M_\star/M_\odot)$ ~ 9-9.5). Lower mass bulges show a step rise of their cumulative mass fraction in the last 1.5 Gyrs, which can contribute up to 20% of their z = 0 stellar mass.

DISCS

The picture of the mass growth for galactic discs is more complex.

- Discs in more massive galaxies (or also more massive discs) tend to form their stars earlier than their lower mass counterparts.
- For a given galaxy mass, the stars in their discs were generally formed after those of the bulge, and the delay between the mass grow of the disc and the bulge is strongly dependent on the galaxy mass.
- We find that for the most massive galaxies, their discs have formed at much later times (Δage ~8 Gyrs at 50% of the mass) whereas for less massive bulges this delay on the mass growth become negligible for the lowest mass galaxies in our sample.

Conclusions and further prospects

- Bulges in non-barred galaxies are generally older and more metal-rich than their host discs.
- Only 9% (30%) of our sample bulges are younger than their surrounding discs when using luminosity (mass) weighted ages.
- Bulges in massive galaxies (or massive bulges) formed >50% of their stellar mass before z~1.
- Discs show a delay in their mass growth with respect to bulges. This delay is mass dependent, with a longer delay for more massive galaxies.

Our results show that the inside-out scenario represents well the formation of non-barred disc galaxies in the mass range $9.5 < \log(M_\star/M_\odot) < 12$. Bulges formed first, and quickly, in the early Universe. The latter evolution of the disc (and the galaxy) is mainly dominated by the properties (mass) of the early bulge, which properties does not change much through cosmic time. The influence of secular processes on building new central structures in non-barred galaxies is negligible, possibly only affecting galaxies with $\log(M_\star/M_\odot) < 10$

Our new approach combining C2D+PIPE3D is producing a new wealth of data to study the evolution of bulges and discs. Its application to new galaxy samples from state-of-the-art IFS instruments like MUSE, and the inclusion of further structures such as bars, will shed new light on the physical processes driving galaxy evolution.