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Mining the unrevealed population of red-nugget relics in disk galaxies.

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Abstract

Do galaxies that quenched at early epochs remain passive since then or do they rejuvenate, experiencing further episodes of star formation? We apply a structure spectro-photometric decomposition method to obtain the spectral energy distributions for bulges and disks in a representative sample of massive galaxies at redshift $0.14 < z \leq 1$. This opens the possibility to study the star formation history of each morphological component, a novelty in the characterization of galaxy evolution at this redshift. We find that bulges display a bimodal distribution of mass-weighted ages, i.e., they form in two waves. The first wave of bulges could start to form as early as $z = 10$ and evolve passively for as long as 6 Gyr before re-entering the star-forming main sequence at later times, after acquiring a stellar disk. Being very massive and compact systems, which formed through a very intense episode of star formation, we identify first-wave bulges to be the result of a compaction event that occurred at a very high redshift. These results allow extending to late-type galaxies the two-phase formation scenario currently accepted to shape early-type galaxies: first-wave bulges represent a complementary channel for the evolution of the blue and red-nugget systems observed at cosmic noon, which could enter the main sequence and acquire a stellar disk while evolving in massive disk galaxies as we observe them at $z < 1$.

1 Introduction

The formation of the first galaxies is supposed to take place in the largest dark matter halos at $z \sim 10$ when highly-perturbed systems form through accretion-driven violent instabilities and very efficient starbursts ([1], [2]). They are supposed to undergo a fast dissipative process characterized by an impressive star formation rate ($\sim 1000 M_\odot$ yr^{-1}) resulting at $z \sim 4$ into blue and centrally-concentrated galaxies, called blue nuggets ([3], [4], [5]). Then, they probably suffer violent compaction, exhaust their gas, stop forming stars, and passively evolve by $z \sim 2$ into red, spheroidal, and dense stellar systems named red nuggets ([6], [7]). At this stage, they are quite small (effective radii $r_e < 2$ kpc) but very massive stellar systems ($M_\star > 3 \times 10^{10} M_\odot$; [8], [9]).

Despite the major effort produced, the hunt for the relics of red nuggets still has not provided reasonable answers. Only a few of these systems survived intact until today and were spectroscopically observed at $z \sim 0$ in the form of ultra-compact massive ellipticals ([10], [11], [12]), but their number density is much less than predicted ([13], [14]). While some of them could possibly hide in the cores of ellipticals (e.g., [15]), their characterization is very complicated because of the mix of the different stellar populations that result from the multiple mergers and the chaotic star formation history that early-type galaxies experienced ([16], [17], [18]).

In [19] and [20] we proposed a novel approach based on the two-dimensional bulge/disk photometric decoupling of the galaxy light across wavelength (spectrophotometric decomposition) to derive the spectral energy distribution (SED) for individual morphological components in galaxies. This technique allowed us to study the interplay between the bulge and disk properties through cosmic time, identifying a fraction ($\sim 20\%$) of bulges in massive disk galaxies as candidate red-nugget relics.

2 Data

We studied the assembly history of bulges and disks in a sample of 91 massive ($M_\star > 10^{10} M_\odot$) galaxies at redshift $z \leq 1$ in the North field of the Great Observatory Origins Deep Survey (GOODS-N). For this study, we combine data from the Survey for High-z Absorption Red and Dead Sources (SHARDS; [21]) and the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; [22]; [23]). In particular, we used 25 filters for SHARDS data in the optical wavelength range $500 - 941$ nm and seven filters for HST images ($\sim 500 - 1600$ nm). This data set was complemented with the K-band information at ~2100 nm (Canada-France-Hawaii Telescope WIRCam data; [24]).

The combined dataset allowed us to take advantage of SHARDS spectral resolution and HST spatial resolution and perform a spectro-photometric decomposition of the morphological structures of our galaxies (Fig. 1). This technique, extensively described in [19], consists of a two-dimensional photometric decomposition across wavelength using the `GASP2D` algorithm ([25], [26]), where high spatial resolution broadband images (i.e., HST) are used to robustly constrain "spectroscopic data" (i.e., SHARDS) with a lower spatial resolution (see also [27, 28]).

The SED of each bulge and disk component was fitted with the Bruzual & Charlot (2003) stellar population library ([29]) by means of the `synthesizer` fitting code ([30], [31]). We assumed a Chabrier (2003) initial mass function ([32]) and parametrized the star formation history (SFH) of each morphological component with a declining delayed exponential law. Models were chosen to have subsolar, solar, or super-solar metallicity ($Z/Z_\odot = [0.4, 1, 2.5]$). The V-band attenuation was parametrized by the extinction law of Calzetti et al. (2000)

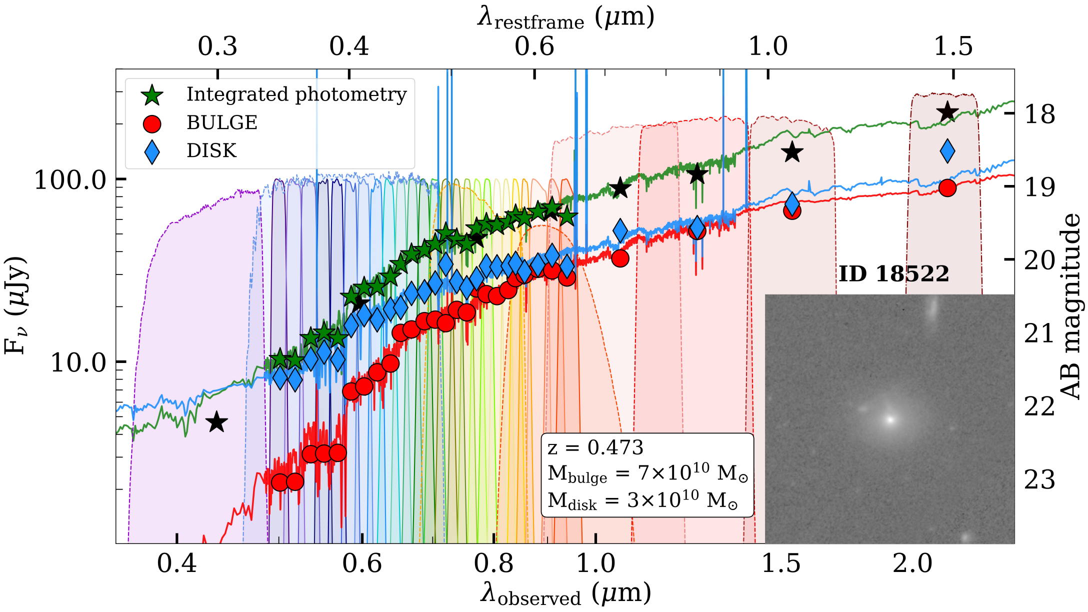

Figure 1: Example of SED for galaxy ID 18522. Green and black stars stand for SHARDS and HST integrated photometry, respectively (apart from the latest K-band WIRCam data point). Red dots and blue diamonds and red dots represent the individual photometric results of our decoupling analysis of the bulge and disk components, respectively. The best models for the bulge, disk, and galaxy are shown as red, blue, and green lines, respectively. HST, SHARDS, and WIRCam filters are shown as dashed, solid, and dashed-dotted profiles.

([33]) with values ranging from 0 to 3 mag.

As an example, in Fig. 1 we presented the best model for the bulge and disk SED for the galaxy ID 18522.

3 Results and Conclusions

The characterization of each bulge and disk SFH allows us to derive their stellar masses ($M_{\rm b}$ and $M_{\rm d}$), mass-weighted ages ($\bar{t}_{M,\rm b}$ and $\bar{t}_{M,\rm d}$), as well as their corresponding redshift (i.e., the mass-weighted formation redshift $\bar{z}_{M,\rm b}$ and $\bar{z}_{M,\rm d}$). In Fig. 2 we show the correlation between mass-weighted formation redshift and stellar mass of bulges and disks in our sample. We found that bulges form in two waves: first-wave bulges have median $\bar{z}_{M,\rm b} = 6.2^{+1.5}_{-1.7}$, while second-wave bulges have median $\bar{z}_{M,\rm b} = 1.3^{+0.6}_{-0.6}$ ([19]). On the other hand, the majority of

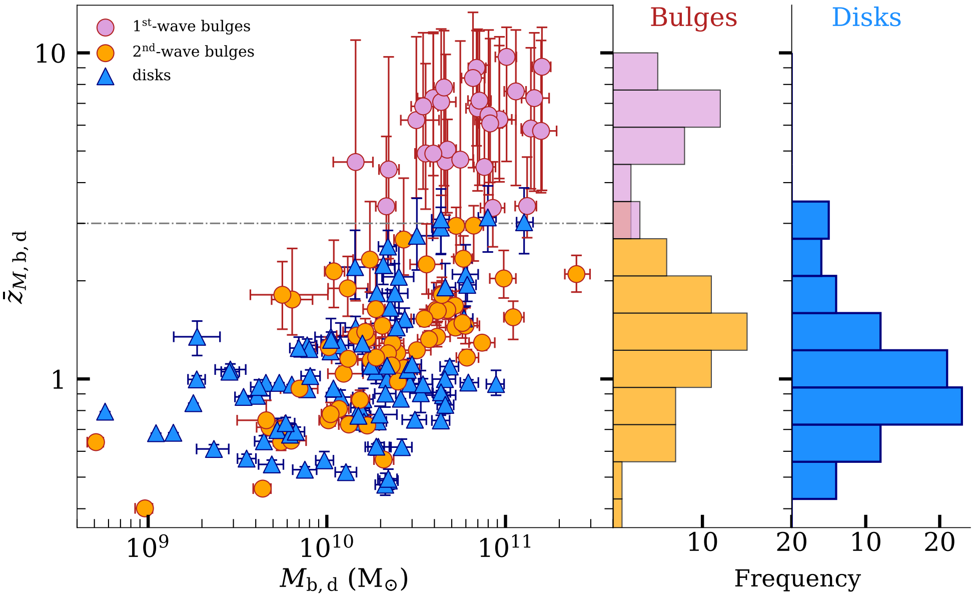

Figure 2: Mass-weighted formation redshift of bulges (dots) and disks (triangles) as a function of their stellar mass. Bulges are separated into first-wave (purple) and second-wave (orange) ones. Errors are reported as a 16th–84th percentile interval. The gray dashed-dotted horizontal line marks $\bar{z}_{M,\mathrm{b}} = 3$. The histograms represent the frequency of the mass-weighted formation redshifts of the bulge and disk populations. Purple and orange histograms stand for first- and second-wave bulges, while the blue histogram stands for the disk population.

our disks formed at similar cosmic times as second-wave bulges ($\bar{z}_{M,\mathrm{d}} = 1.0^{+0.6}_{-0.3}$), since only 10 out of 91 disks have $\bar{z}_{M,\mathrm{d}} > 2$ ([20]).

First-wave bulges are fast-track spheroids (i.e., short formation timescale) and have similar sizes but higher masses compared to second-wave bulges. Thus, we interpret the population of bulges formed at $\bar{z}_{M,\mathrm{b}} > 3$ as relics of the early Universe, formed by compaction events driven by violent disk instabilities and clump migration, in agreement with predictions from numerical simulations ([34], [35], [36]).

Finally, we quantified the differences in mass-weighted ages between each bulge and disk, finding a median $\Delta\bar{t}_{M,\mathrm{bd}} = \bar{t}_{M,\mathrm{b}} - \bar{t}_{M,\mathrm{d}} = 1.6^{+5.4}_{-0.7}$ ([20]). In particular, first-wave bulges and their disks have $\Delta\bar{t}_{M,\mathrm{bd}} = 5.2^{+1.1}_{-1.9}$, while the age difference for second-wave bulges is $\Delta\bar{t}_{M,\mathrm{bd}} = 0.7^{+1.5}_{-1.6}$ ([20]). In this context, we argue that a fraction of massive disk galaxies, hosting a compact core (first-wave bulge), went through a blue and red nugget phase and grew an extended stellar disk at later cosmic times. This could allow one to extend the two-phase paradigm to late-type galaxies, as already proposed by recent studies ([37], [38], [39], [40]).

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