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The INvestigate Stellar Population In RElics (INSPIRE) Project — Scientific Goals and Survey Design

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Relics are the ancient fossils of the early Universe. They are ultra-compact and massive galaxies that formed only a few (1–2) billion years after the Big Bang, in a short and intense burst of star formation, and then evolved passively and undisturbed until the present day, completely missing the accretion phase predicted for the assembly of local giant early-type galaxies. As such, they represent a unique opportunity to put precise constraints on the first phase of structure formation in the Universe. Since the number of relics predicted at each redshift depends heavily on the mechanisms responsible for the accretion and growth of massive galaxies, obtaining number counts at $0 < z < 0.5$ is a very powerful way to validate and disentangle different possible physical scenarios driving their formation and size-evolution. INvestigating Stellar Population In RElics (INSPIRE) is an ongoing project based on an approved ESO Large Programme, targeting 52 relic candidates with the X-shooter spectrograph at ESO's Very Large Telescope with the aim of building the first statistically large catalogue of relics at $0.1 < z < 0.5$.

Relic galaxies: fossils of the ancient Universe

Massive early-type galaxies (ETGs) play a crucial role in the context of cosmic structure formation and mass assembly. Firstly, they contain the oldest stars at any epoch of the Universe's history, thus

retaining the memory of the star formation activity that occurred in the earlier phases of galaxy formation. Secondly, they account for more than half of the total stellar mass in the current Universe and are responsible for most of its chemical enrichment. Understanding the history of the assembly of the most massive galaxies throughout cosmic time is therefore crucial to constraining models of galaxy formation and evolution.

The first generation of massive ETGs is already in place at $z \sim 3$, i.e., only two billion years after the Big Bang. However, at this redshift, most of the massive red objects are found to be 3–5 times smaller in size than their counterparts in the local Universe, and thus they are 30–100 times denser (van Dokkum et al., 2008). To reconcile these observations, a two-phase formation scenario (Oser et al., 2010) has been proposed to explain the mass assembly and evolution across cosmic time of very massive galaxies (Figure 1).

Initially, a series of intense, fast, dissipative processes forms their central "bulk" mass (at $z > 2$) generating, after star formation quenches, a massive, passive and very compact galaxy with a size a factor of ~ 4 smaller than local massive galaxies (the so-called "red nuggets"). Then a second, prolonged phase, dominated by mergers and gas inflows, is responsible for the structural evolution and size growth from $z \sim 1$ to today. The ultra-compact objects formed at high redshift likely end up forming the cores of giant local galaxies, whilst subsequently accreted or newly formed stars remain preferentially in the external regions. Unfortunately, this "accreted" material overlaps, along the line of sight, with the spatial and orbital distributions of the *in-situ* pristine light that encodes the information about high-z baryonic processes, irreversibly limiting our resolving power and hampering our ability to study the early phases of galaxy formation. Luckily, since merging is a stochastic phenomenon, a small fraction of red nuggets survives intact until the present day, without experiencing any merger or interaction and thus remaining as massive and ultra-compact as they formed: relic galaxies (Trujillo et al., 2009). Since a detailed study of the stellar populations of high-z red nuggets would require prohibitive integration times with the currently available facilities, relics are the only systems that allow us to study the physical processes that shaped the mass assembly of massive galaxies in the high-z Universe in the amount of detail currently reachable only for the nearby Universe.

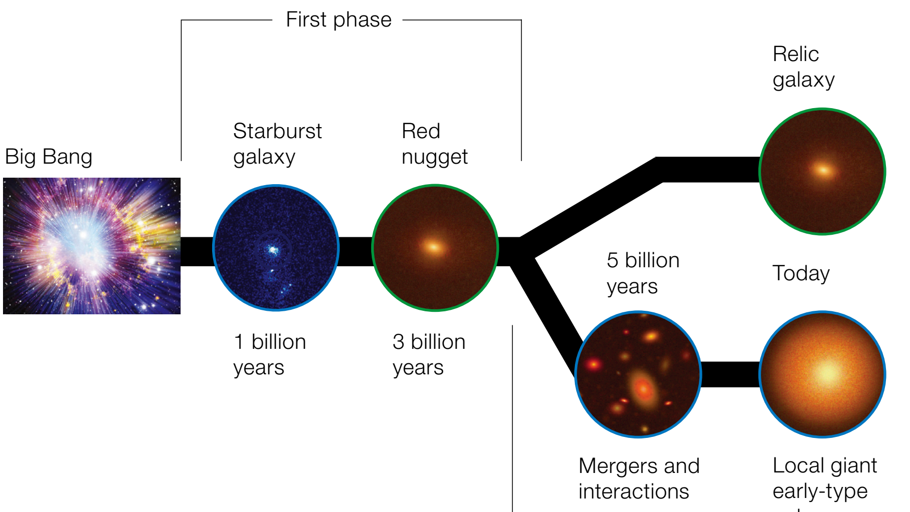

Figure 1. A sketch of the two-phase formation scenario for the mass assembly and cosmic evolution of massive early-type galaxies.

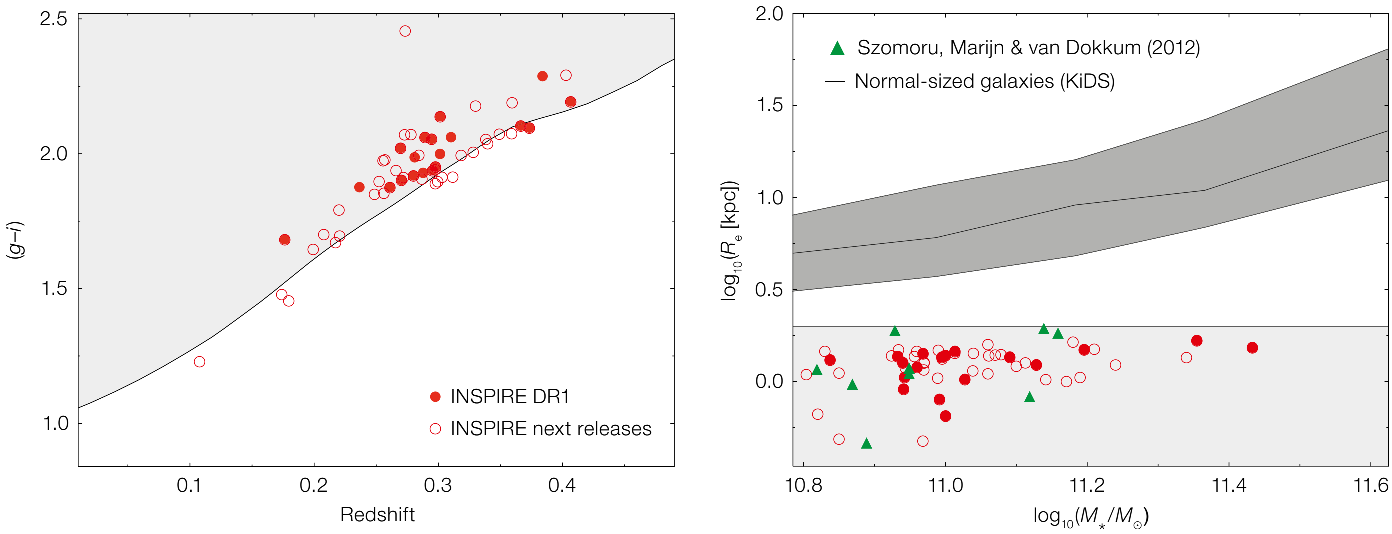

Figure 2. Left: Observer-frame (g–i) colour versus redshift for the 52 INSPIRE objects (red circles). Filled symbols indicate the 19 galaxies included in DR1, while empty ones are those that will be released in the future. The grey region shows the predicted values for single stellar population models with ages of 8 Gyr (black) or older. Right: Stellar mass–size relation of relic candidates (same colour code as above) compared to the relation for normal-sized passive galaxies from the KiDS survey, shown as a dark-grey shaded region and to high-redshift red nuggets from the collection of Szomoru, Marijn & van Dokkum (2012).

But how many relics exist in the Universe at each redshift, and how many survive until the present day? How can they passively evolve through cosmic time without experiencing any interaction? What can we learn about the merging history and the evolution of the most massive ETGs? Is there a physical scenario, predicted by hydrodynamical cosmological simulations, that is able to explain all the current observational results at all redshifts? These and other questions remain to be answered and constitute the main topics of the INvestigate Stellar Populations In RElics (INSPIRE) Project.

The INSPIRE ESO Large Programme: observational strategy and current status

The INSPIRE[1] ESO Large Programme (ID: 1104.B-0370, PI: Chiara Spiniello) was approved two years ago to spectroscopically follow up with the X-shooter spectrograph 52 ultra-compact, red, massive galaxies with redshifts $0.1 < z < 0.5$. They are the final products of a dedicated project within the Kilo Degree Survey[2] (KiDS) collaboration, one of the three ESO VST Imaging Public Surveys[3]. This project started in 2015 with the goal of building the largest catalogue of photometrically selected passive (non-star-forming) galaxies with incredibly small sizes but stellar masses comparable to those of massive local ETGs (Tortora et al., 2016), and with secure structural parameters inferred from *gri*-band KiDS images (Roy et al., 2018). Subsequently, spectroscopic follow-ups at many different ESO and non-ESO telescopes have been obtained to validate these objects, inferring their redshifts and masses and thus confirming them as ultra-compact massive galaxies (Tortora et al., 2018; Scognamiglio et al., 2020). These objects are the perfect relic candidates, as they all have large stellar masses ($M_* > 6 \times 10^{10}\ M_\odot$), small sizes ($R_e < 2$ kpc) and very red colours indicative of an evolved, old stellar population (see Figure 2).

The INSPIRE observing strategy has been optimised to capitalise on relatively sub-standard observing conditions (seeing up to 1.2 arcseconds, clear nights, grey lunar phase with a lunar illumination fraction up to 0.5), allowing the objects to be easily scheduled into the observing queue. Moreover, the selected targets span a very wide range in right ascension and declination, with an optimum observing time spread over the full year. We also note that we have many systems with declination below −30 degrees, perfect as "fillers" on nights with strong wind coming from the north. The integration time on target, which varies from target to target according to their r-band luminosity and surface brightness, has been set to reach a signal-to-noise ratio sufficient to infer the age, metallicity and α-abundance of the stellar populations.

At the time of writing, data on 38 out of 52 galaxies have been collected, and 36 objects have already been completely observed. In Spiniello et al. (2021a, hereafter S21a), we presented a pilot programme demonstrating the feasibility of the project and showing the kinematical and stellar population analysis for three objects representative of the whole sample. Results for the first 19 galaxies, completely observed before the end of 2020, are presented in Spiniello et al. (2021b, hereafter S21b), and released as part of the first INSPIRE data release (DR1). DR1 was made publicly available through the ESO Archive Science Portal[4] in March 2021. It comprises one-dimensional (1D) spectra in the UVB and VIS arms of X-shooter for 19 ultra-compact massive galaxies that were observed between 22 October 2019 and 31 December 2020 and were classified as relics or not in S21b. Near-infrared spectra, which are not necessary for the confirmation of the relic nature of the systems but which are crucial to correctly inferring the stellar initial mass function (IMF), will be analysed and released in a separate forthcoming data release, accompanied by a dedicated scientific publication (see next section for more details).

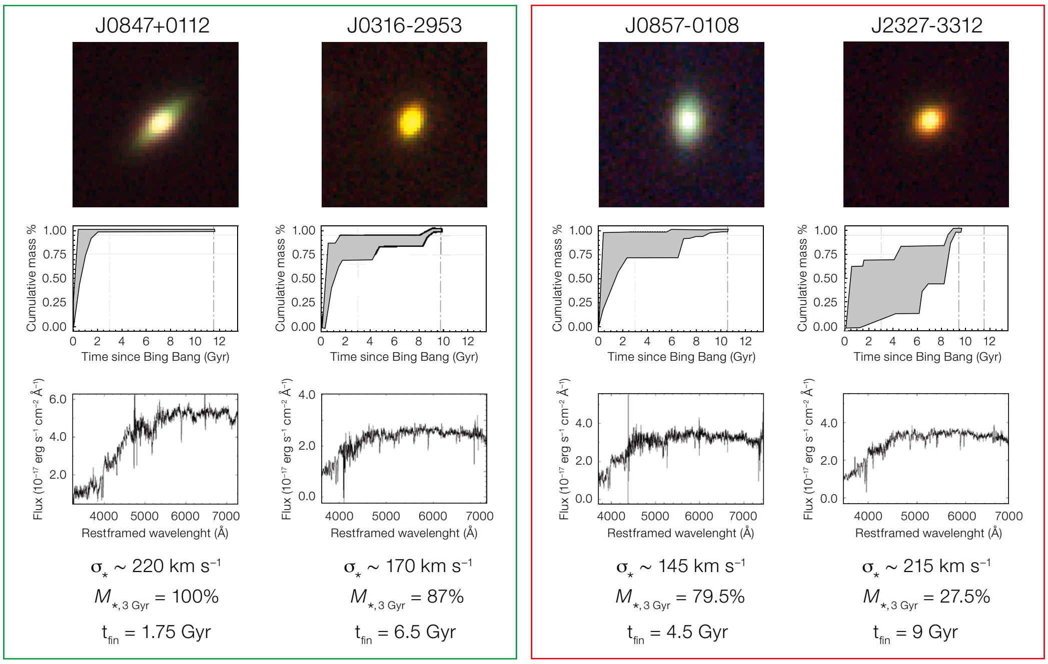

Figure 3. Four objects from INSPIRE DR1, each with a different "degree of relicness''. In the green box, we show the most extreme and the least extreme relics, whilst in the red box we show the non-relics with the least and most extended star formation history. For each galaxy, the top panel shows a 10 × 10 arcsecond colour-combined (*gri*) KiDS image, the middle panel shows the fraction of stellar mass assembled in cosmic time since the Big Bang, varying the [Mg/Fe] by ±0.1 (grey area), and the bottom panel shows a zoom-in to region of the spectrum used to compute the velocity dispersion, and the stellar age and metallicity. The values for the stellar velocity dispersion, the mass assembled at the end of the first formation phase ($z \sim 2$, 3 billion years after the Big Bang) and the time of final assembly (when more than 95% of the stellar mass was in place) are also provided.

INSPIRE DR1: kinematics, stellar population analysis and relic confirmation for the first 19 systems

Here we focus on three main scientific results, obtained from the 19 systems with complete observations until the end of 2020, presented in S21b (also including the three pilot galaxies presented in S21a): i) the integrated velocity dispersion values inferred from the 1D spectra encapsulating 50% of the light (30% in S21a) of the galaxies and those inferred from optimally extracted 1D spectra; ii) a precise estimate of the stellar age, metallicity and [α/Fe] abundance of the stellar populations, from line indices and full spectral fitting; and iii) star formation histories and "relic confirmation" based on the fraction of stellar mass assembled during the first phase of the two-phase formation scenario and on the cosmic time of "final assembly".

The velocity dispersion values are always relatively high ($\sigma_\star > 150$ km s^{-1}), confirming the massive nature of the systems. Although with limited statistics, we observe that the galaxies confirmed as relics have a systematically larger velocity dispersion compared to non-relics, for the same stellar mass. Since $\sigma_\star$ is approximately proportional to the dynamical mass of the galaxy within the half-light radius, the overall larger $\sigma_\star$ in relics would indicate a higher dynamical mass compared to non-relic galaxies of similar stellar mass. This can have two possible physical explanations. On the one hand, relics could have a larger number of stars with very low masses — i.e., a dwarf rich IMF — which contribute very little to the light but substantially to the dynamical mass. On the other hand, relics could have a larger fraction of dark matter in the central regions or, possibly, dark matter halos with a higher central mass density.

Spectroscopic ages are very old for 13 out of 19 galaxies, in agreement with the photometric ones, and metallicities are almost always (18 out of 19) super-solar, confirming the mass-metallicity relation. The [Mg/Fe] ratio, that sets the clock of the star formation (i.e., larger values indicate a faster star formation episode) is also larger than solar for the great majority of the galaxies, as expected.

We find that 10 objects have formed more than 75% of their stellar mass within 3 Gyr of the Big Bang, when the first phase is believed to end, and therefore we classify them as relics. Amongst these, we identify 4 galaxies which had already fully assembled by that time. They are therefore "extreme relics" of the ancient Universe.

The INSPIRE DR1 catalogue of 10 relics known to date augments by a factor of 3.3 the total number of confirmed relics, also enlarging the redshift window outside the local Universe (up to $z \sim 0.4$). It is therefore the largest publicly available collection at the moment. Thanks to the larger number of systems, we can confirm the existence of a "degree of relicness" (Figure 3), already hinted at in the literature, quantifying how fast the star formation histories are. This degree of relicness might correlate with the structural parameters of the galaxies (for example, size or ellipticity), dynamical properties (i.e., the extreme relics are the systems with the largest velocity dispersions) and/or with the environments in which they live. We will investigate this matter further once the full INSPIRE sample has been analysed, as described in the next section.

Future INSPIRE data releases and final scientific goals

At least two further data releases will be issued for INSPIRE. In the second data release, foreseen in roughly six months, we will add the near-infrared (NIR) spectra of the 19 systems released in DR1. Extending the wavelength range towards the red, we will be able to constrain, at least for the stacked spectrum of all the 10 relics, the slope of the IMF at the low-mass end. The stellar IMF is the distribution of stellar masses that form in one star-formation event in a given volume of space. Hence, all the observable properties of stellar systems are heavily influenced by their IMFs, since the mass of a star determines its subsequent evolutionary path. Furthermore, almost every observable property of a galaxy depends on its mass-to-light ratio (M/L) and the low-mass end of the stellar IMF is crucial in determining that. In fact low-mass stars account for more than half of the mass budget but they contribute very little to the integrated luminosity of a galaxy with an old stellar population. This makes the characterisation of the low-mass IMF slope from integrated light a very difficult task but also a crucial ingredient for partitioning galaxy mass into stellar and dark matter, and for understanding how they interact in the internal region of galaxies. This, in turn, allows one to predict the luminosity evolution of passively evolving stellar systems and thus to correctly interpret the cosmic evolution of the most massive galaxies in the Universe.

The third data release, which will be made available upon completion of all the spectroscopic observations, will comprise 1D spectra for all the 52 objects, of which half will likely be confirmed as relics, based on the current results (10 out of 19). With more objects at our disposal, we will further investigate possible correlations between the degree of relicness and other galaxy properties (size, mass, colours) and/or with the environments in which they sit.

The final INSPIRE catalogue of confirmed relics, all with precise structural, kinematic and stellar population parameters measured, multi-band wide-field optical and NIR photometry and high signal-to-noise spectroscopic data, will represent an important benchmark for cosmological simulations that should reproduce the number density and the morphological, dynamical and stellar characteristics of both relics and younger ultra-compact galaxies.

Since different models predict a different redshift evolution of the number density of relics, a statistically significant catalogue of relics at different redshifts is a *conditio-sine-qua-non* to disentangle possible physical scenarios driving the formation and size-evolution of galaxies. At the same time, the characterisation of the structural, dynamical, environmental, and stellar properties of the non-relics, ultra-compact systems that have just stopped forming stars, will provide a key test for models of galaxy formation. In fact, according to hydrodynamical simulations very compact and very massive galaxies should only form in gas-rich environments, and thus early on in time, and then undergo a series of mergers and interactions which should cause a growth in size. We will compare the INSPIRE galaxies (both relics and non-relics) with ultra-compact simulated galaxies from different hydrodynamical simulations to shed light on the formation scenario and mass assembly of these extremely compact, passive and massive objects, and to understand the conditions that allowed these objects to survive intact to the present day without undergoing any accretion event.

Likewise, we will compare the final INSPIRE sample with normal-sized ETGs at similar redshifts and with similar structural and photometric (magnitudes and colours) distribution, of comparable stellar masses and with optical spectra available. In particular, for the normal-sized ETGs we will derive mass-weighted ages and metallicities, and thus star formation histories, using the same code and under similar assumptions and setups to those used in S21b. This will allow us to assess whether relics are simply the ultra-compact tail of the distribution of red and dead ETGs or if they are special and very rare systems with a completely different evolutionary path.

Thanks to the high quality of the spectra, we will measure very precise (< 5% uncertainties) integrated velocity dispersion values (σ_*) for each system. This is one of the most fundamental tracers of the stellar populations and halo masses of galaxies, and hence can act as a valuable identifier of a consistent population over cosmic time. Measuring σ_* from spectroscopic data and performing dynamical models, we will infer dynamical masses. Then, estimating precise stellar masses via stellar population analysis, we will be able to compute the ratio between stellar and dynamical mass (M_*/M_{dyn}) which is a valuable tracer of the likely mechanism by which galaxies grow. In fact, under merger-driven growth, the M_*/M_{dyn} ratio, measured within the effective radius, should decrease with time; this decrease would be stronger in the case of minor mergers. Thus, under the hypothesis that relics experienced very few mergers, or none at all, they should all show a very high M_*/M_{dyn}, compared to normal-sized galaxies of similar stellar masses, and thus a smaller amount of dark matter.

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Links

[1] The INSPIRE project webpage: https://sites.google.com/inaf.it/chiara-spiniello/inspire/
[2] The Kilo Degree Survey: http://kids.strw.leidenuniv.nl
[3] The ESO VST Public Surveys: https://www.eso.org/sci/observing/PublicSurveys/sciencePublicSurveys.html#VST
[4] The INSPIRE DR1 ESO Phase 3 collection on the Science Archive Portal: http://archive.eso.org/scienceportal/home?data_collection=INSPIRE