Red Nuggets – Hunting for Untouched Survivors from the Early Universe

Krzysztof Lisiecki[1,2], Katarzyna Małek[2,3], Małgorzata Siudek[4,2], Agnieszka Pollo[2,5], Agata Karska[1] and Janusz Krywult[6]

1. Institute of Astronomy, Nicolaus Copernicus University in Torun, Grudziaadzka 5, 87-100 Torun, Poland
2. National Centre for Nuclear Research, ul. Pasteura 7, 02-693 Warszawa, Poland
3. Aix Marseille Univ., CNRS, CNES, LAM Marseille, France
4. Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, 08193 Bellaterra (Barcelona),Spain
5. Astronomical Observatory of the Jagiellonian University, Orla 171, 30-001 Krakow, Poland
6. Institute of Physics, Jan Kochanowski University, ul. Uniwersytecka 7, 25-406 Kielce, Poland

In order to understand the history of our Universe we attempt to trace different stages of evolution of different types of galaxies as a function of time. While we can easily detect and analyze sources at low redshift, at high redshift we face strong barriers due to the resolution and detection limits. Now, we finally have an opportunity to see those objects due to the technical progress of astronomical instruments. Recently, astronomers found a new population of compact and massive galaxies – "red nuggets". These specific objects are believed to evolve undisturbed from early cosmic epochs and represent a unique laboratory to study how the first massive galaxies formed and evolved. Here, we present the process of searching for the red nuggets in the sample of $\sim$90 k galaxies in VIPERS, a spectroscopic survey at redshift $0.5 < z < 1.2$. We present currently the largest sample of 77 red nugget candidates at redshift $z \sim 0.7$.

1 Introduction

Observations of distant objects allow us to re-evaluate models of the history of the Universe. For example, the discovery of massive galaxies at high redshifts has recently disrupted the model of hierarchical galaxy mergers. Some of such galaxies are remarkably small and passive, and might have been the progenitors of the most massive giant elliptical galaxies in the local Universe (Scognamiglio et al., 2020). Because of the stochastic nature of galaxy mergers, some of those objects survived untouched through billions of years and have been recently identified also at low and intermediate redshifts (e.g. Damjanov et al., 2014; Scognamiglio et al., 2020, Lisiecki et al., in prep.). They are referred to as "red nuggets" or "relic galaxies". Here, we present a first look at the new catalogue of 77 new red nugget candidates at redshifts $0.5 \leq z \leq 1$ found in the VIMOS Public Extragalactic Redshift Survey (VIPERS).

2 Data

To build a sample of red nugget candidates, we use a catalogue of $\sim$90 k galaxies from the VIPERS spectroscopic survey including both photometric and spectroscopic information, among them the spectroscopic redshift, line measurements (for a detailed description, see Scodeggio et al., 2018) and morphological parameters (Krywult et al., 2017), as well as derived galaxy physical properties, e.g. stellar masses ($M_\star$), published by the VIPERS team together with the database.

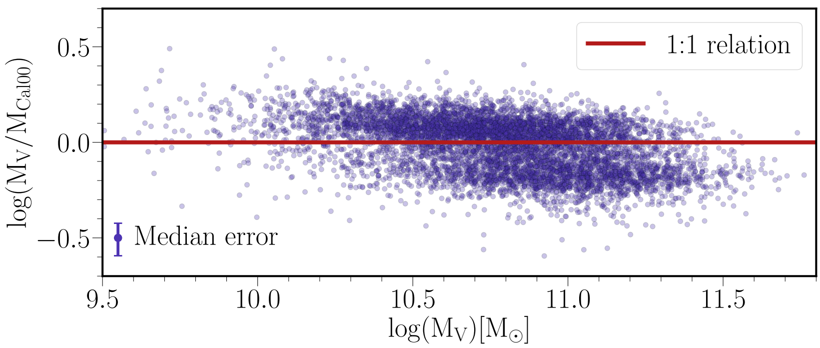

Fig. 1: Stellar masses obtained with the CIGALE code adopting the Calzetti et al. (2000) attenuation law ($M_{\rm Cal00}$) and those from the VIPERS database ($M_{\rm V}$) as a function of the VIPERS stellar mass for 6 961 galaxies.

The analysis involves sources with the 99% confidence level of redshift measurements (Scodeggio et al., 2018). Since we focus on compact and massive objects, we ensure compactness by the following cut, which is a modified criterion presented in Damjanov et al. (2014):

$$(\log(R_{\rm e}[{\rm kpc}]) + 5.64)/\log(M_\star[{\rm M}_\odot]) < 0.568, \tag{1}$$

where $R_{\rm e}$ is an effective radius of a galaxy. Moreover, we restrict the VIPERS sample to the redshift range of $0.5 - 1$ where the VIPERS survey is complete with respect to high stellar mass galaxies. The final sample consists of 6 961 candidates for ultracompact massive galaxies (UCMG).

3 SED modeling

To obtain the main physical properties of selected candidates, we model their spectral energy distributions (SEDs) using the Code Investigating GALaxy Emission (CIGALE; Boquien et al., 2019). Figure 1 shows the comparison of the resulting stellar masses with those previously calculated by the VIPERS team, which did not account for the uncertainties. We find an overall good agreement between both estimates with the median $|\Delta M_\star|$ of 0.1 dex. We decide to use the CIGALE determination of physical properties, e.g. M_* and star formation rate (SFR), because the Bayesian analysis gives us the uncertainties and the information about the quality of the SED fit, which are not published by the VIPERS team.

4 Selection

In search for the compact and massive galaxies, we adopt the limit for stellar mass of $M_* > 8 \times 10^{10}{\rm M}_\odot$ and for the effective radius $R_{\rm e} < 1.5$ kpc, following Scognamiglio et al. (2020). The sample size is then limited to 86 UCMG.

To specify which of our UCMG are passive, we checked multiple indicators of active star formation including the object positions at the NUVrK diagram (Arnouts et al., 2013) and their optical spectra. We determined the distances of the objects from the main sequence of galaxies based on Schreiber et al. (2015), and defined

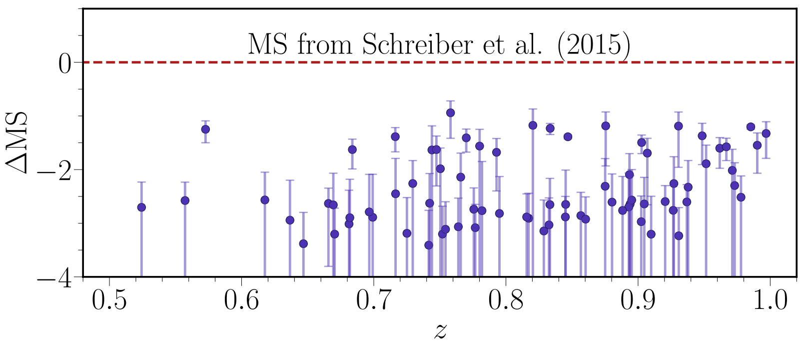

Fig. 2: The distance from the main sequence ΔMS versus the redshifts of the red nugget candidates from VIPERS.

as $\Delta\mathrm{MS} = \log(\mathrm{SFR_{Cal00}}) - \log(\mathrm{SFR_{MS}})$, where the $\mathrm{SFR_{Cal00}}$ is the SFR estimated using CIGALE and the Calzetti et al. (2000) dust attenuation law, and $\mathrm{SFR_{MS}}$ is the SFR calculated from the Schreiber et al. (2015) equation at a given redshift and $M_\star$. Figure 2 shows that the SFR of all of our red nuggets candidates is representative for quiescent, passive galaxies. Finally, we establish a catalogue of 77 previously not known red nuggets candidates.

5 Conclusions

Large surveys such as VIPERS offer a unique opportunity to test the models of galaxy formation and evolution by providing statistically significant samples of objects beyond the local Universe, representing variety of galaxy types. Here, we presented the selection process of a rare type of massive, compact and passive galaxies, forming the largest available catalogue of "red nuggets" outside of the local Universe. In the nearest future we will publish the catalogue and the study of the physical properties of those puzzling objects (Lisiecki et al., 2022).

Acknowledgements. KL, KM and AP acknowledge support from the Polish National Science Centre (UMO-2018/30/E/ST9/00082 and UMO-2018/30/M/ST9/00757).

References

Arnouts, S., et al., *A&A* **558**, A67 (2013)

Boquien, M., et al., *A&A* **622**, A103 (2019)

Calzetti, D., et al., *ApJ* **533**, 2, 682 (2000)

Damjanov, I., Hwang, H. S., Geller, M. J., Chilingarian, I., *ApJ* **793**, 1, 39 (2014)

Krywult, J., et al., *A&A* **598**, A120 (2017)

Lisiecki, K., et al., *arXiv e-prints* arXiv:2208.04601 (2022)

Schreiber, C., et al., *A&A* **575**, A74 (2015)

Scodeggio, M., et al., *A&A* **609**, A84 (2018)

Scognamiglio, D., et al., *ApJ* **893**, 1, 4 (2020)