The Virtual Observatory as a Tool to Study Star Cluster Populations in Starburst Galaxies

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Abstract

The cluster luminosity function (CLF) is one of the most important diagnostics in the study of old globular and young compact star cluster populations. The striking differences between the power-law distributions for young star clusters and the Gaussian distribution of the old Galactic globular clusters has led to predictions that any initial mass or luminosity distribution will shortly be transformed into peaked distributions due to the dynamical depletion of low-luminosity, low-mass star clusters over a Hubble time. However, these models apply only to Milky Way-type potentials, while it is expected that the dynamical evolution of the CLFs in interacting galaxies will be significantly different.

We are currently using ASTROVIRTEL to obtain CLFs in several optical and/or near-infrared passbands, and colour distributions. This will provide us with a powerful analytical tool for the determination of the violent star and cluster formation history of galaxies: we will address questions related to the universality of the globular CLF, the time-scale of low-mass, low-luminosity star cluster depletion and its observability, and environmental effects affecting the shape of the CLFs and the efficiency of the depletion process. This has required the development of complex data mining tools, which are currently being incorporated in ASTROVIRTEL's *querator*.

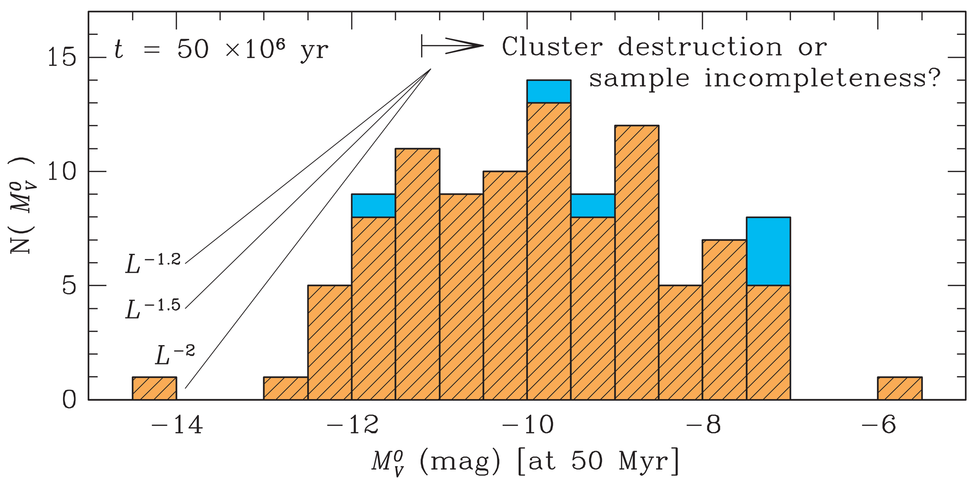

Fig. 2: CLF for the M82 B cluster sample corrected individually to a fiducial age of 50 Myr. The power-law slopes measured for other young cluster systems in interacting galaxies, are indicated. The CLF may be broadened due to dynamical destruction of lower mass clusters, although the degree to which our cluster sample is incomplete for these brightnesses is uncertain (this was beyond the scope of our paper; de Grijs et al. 2001).

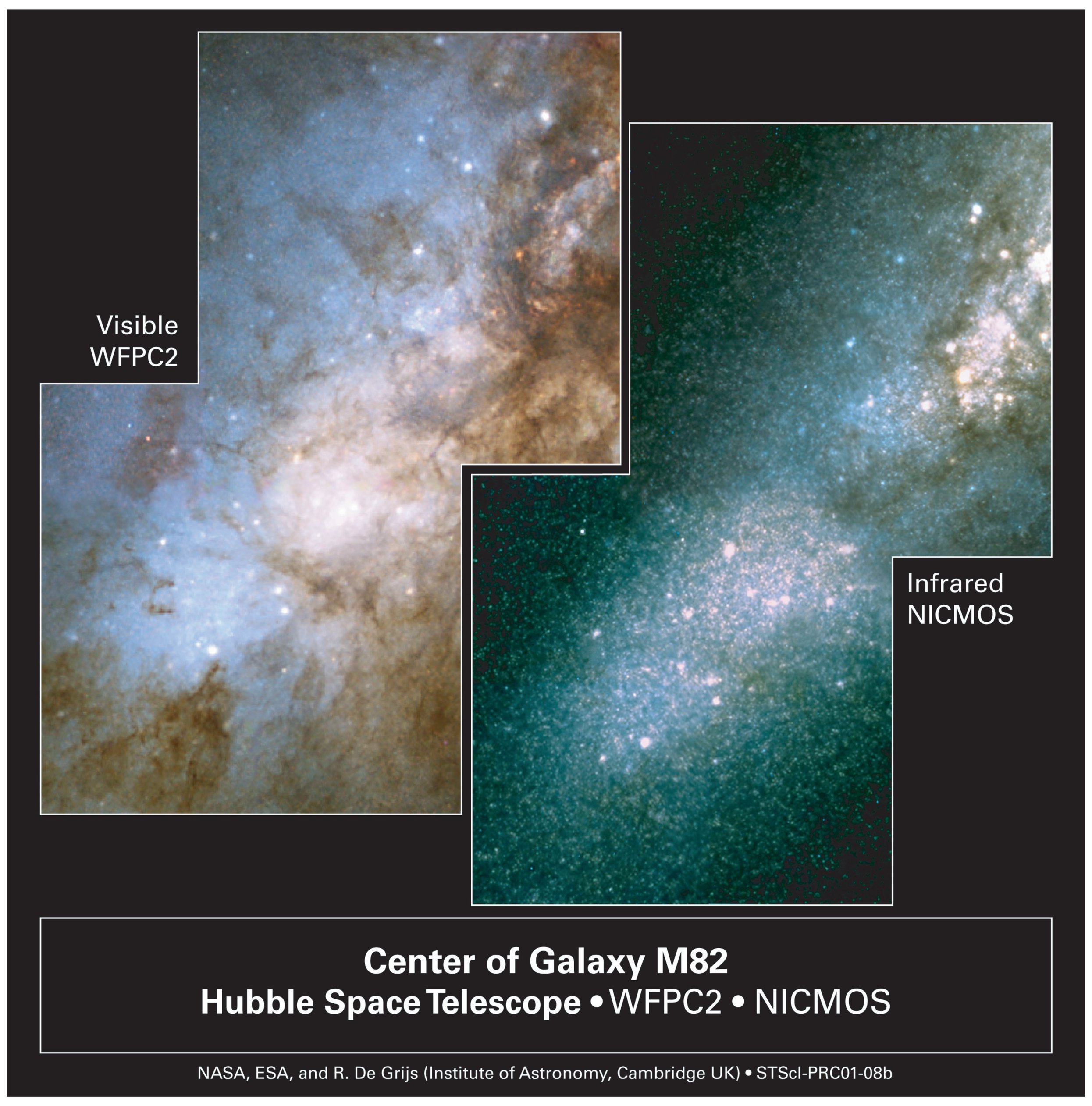

Fig. 1: Our *HST* observations of M82 (de Grijs et al. 2001) revealed these two views of the heart of the galaxy, referred to as ``M82 B''. The image at left was taken in the optical with the *WFPC2* camera; the picture at right, in the near-infrared. In the infrared view, the telescope's Near Infrared Camera and Multi-Object Spectrometer (NICMOS, camera 2) peered through thick dust lanes to find some of the galaxy's more than 100 super star clusters. The clusters are the larger pink and yellow dots scattered throughout the picture. They were formed during a violent collision with the galaxy M81 about 600-1000 Myr ago.

Background

The cluster luminosity function (CLF) is one of the most important diagnostics in the study of old globular and young compact star cluster populations.

For the old globular cluster systems in, e.g., the Galaxy, M31, M87, and old elliptical galaxies, the CLF shape is well-established: it is roughly Gaussian, with the peak at $M_V^0 \sim -7.4$ and a FWHM of ~3 mag (Harris 1991, Whitmore et al. 1993, Harris et al. 1998). The well-studied young star cluster population in the LMC, on the other hand, displays a power-law CLF (Elson & Fall 1985, Elmegreen & Efremov 1997).

Hubble Space Telescope (HST) observations have provided CLFs for young compact star cluster systems in more distant galaxies. Their CLF shapes are consistent with power laws down to the completeness threshold *(see de Grijs et al. 2001, and references therein)*.

Globular cluster formation models suggest that the distribution of the initial cluster masses is closely approximated by a power law (e.g., Harris & Pudritz 1994, McLaughlin & Pudritz 1996, Elmegreen & Efremov 1997).

One should be cautious, however, to generalize these results, since this has only been applied to non-interacting galaxies. So far, it has not been possible to observationally study the progenitor molecular cloud mass spectrum in a merger, for which we expect significant differences w.r.t. the mass spectrum in non-interacting galaxies due to external pressure, shocks, etc.

Which processes will affect the CLFs such that they transform from a power-law shape to a Gaussian distribution?

The processes responsible for the depletion of, preferentially, low-luminosity, low-mass star clusters over time scales of a Hubble time are tidal interactions with the background gravitational field of the parent galaxy and evaporation of stars through two-body relaxation within clusters. From the models of Gnedin & Ostriker (1997) and Elmegreen & Efremov (1997) it follows that *any* initial mass (or luminosity) distribution will shortly be transformed into peaked distributions.

However, all of these models are valid *only* for Milky Way-type gravitational potentials; galaxy-galaxy interactions will obviously have a major effect on the resulting gravitational potential, in which the dynamical star cluster evolution is likely significantly different.

In fact, Vesperini (2000, 2001) has included the internal gravitational interactions between cluster stars in his models and concludes that these need considerable fine tuning to transform a power law cluster initial mass function (IMF) into a Gaussian distribution, whereas a Gaussian IMF conserves its shape rather independently of the choice of parameters: destruction of low-mass clusters by evaporation and the tidal field is balanced by the destruction of high-mass clusters through dynamical friction.

The Questions

- Is the *intrinsic* CLF (or, alternatively, the cluster initial mass function) a power law in all cases?

  Meurer (1995) pointed out that age spread effects in cluster systems still forming clusters (such as in the Antennae galaxies) affect the CLF, which might in fact make an intrinsically Gaussian CLF (or IMF) appear as a power-law CLF (cf. Fritze-v. Alvensleben 1999). It is obviously very important to age date the individual clusters and to correct the observational CLF to a common age before interpreting their CLF (see *Fig. 2*; Fritze-v. Alvensleben 1999, de Grijs et al. 2001).

- What are the time-scales for the evolution from the power-law young compact CLFs into old globular CLFs?

- Can we observe this process in action? In an ongoing nearby starburst like in the Antennae we see the entire continuum from OB associations to open and globular clusters forming. This might also affect the shape of the resulting CLF! Comparison with slightly older systems may show which objects survive.

- Is there a clear difference between OB associations/open clusters and compact globular clusters at formation or do they all form a continuum mass spectrum?

- Are cluster destruction effects selectively destroying the most weakly bound objects from that continuum the main cause of the power-law to Gaussian transformation of the luminosity distribution?

- Can we ``observe'' dynamical cluster destruction effects by comparison of young star cluster systems in ongoing mergers and merger remnants of various ages?

  These dynamical destruction effects – of low mass clusters by evaporation and tidal interaction with the parent galaxy's potential and of high mass clusters by dynamical friction – have theoretically been investigated only in the time-independent Milky Way potential. The tidal field of a merging galaxy pair is surely different, changing with time, dependent on the dark matter potential, and very difficult to model theoretically. Instead, dynamical cluster destruction processes may be assessed "observationally" by analysing cluster populations of various ages, either with evolutionary synthesis tools, or using the full-scale cluster destruction theory currently under development by us (de Grijs, Lamers & Bastian, 2002, submitted).

- Is there an environmental dependence on the efficiency and therefore the time-scale of low-mass star cluster depletion?

- Does this process proceed differently in spiral, elliptical or interacting/merging galaxies? Does a galaxy's membership of a rich cluster, sparse(r) group, or the field affect the properties of its CLF?

- Is the globular CLF *universal*?

  It is often used as a distance indicator, under the assumption that the turnover in the CLF occurs at the same luminosity for any galaxy type, for galaxies in any environment, but is there a basis for this assumption? If we adopt the notion that globular clusters are being formed today (cf. de Grijs et al. 2001 and references therein), and have been forming for a Hubble time, how can the globular CLF be universal? Surprisingly, Harris (1996) has shown that the turnover magnitude for old globular cluster systems depends only weakly on galaxy luminosity and type. On the other hand, Ashman et al. (1995) showed that the CLF is metallicity dependent, which has recently gained support from the theoretical models of Fritze-v. Alvensleben (2001 and submitted). We therefore need to obtain a significant number of CLFs to well (e.g., > 1.5 mag) below the "universal" turnover magnitude at $M_V^0 \sim -7.4$.

- Do the numbers, luminosities, metallicities, masses, and spatial distributions of young star clusters formed in a starburst depend either on the types and masses of the galaxies involved in the interaction or on the geometry of the encounter?

- Are there age spreads in the star cluster populations formed in merger-induced starbursts (these typically last for a few 100 Myr)? If so, is there evidence for the propagation of the starburst activity, or is the age spread randomly distributed across the merging system? Does cluster formation occur during the entire time of the interaction, or only at peak starburst activity? Are there spatial variations in the metalicities or masses of the young star clusters?

- Do stronger starbursts allow for more massive clusters?

- Is the formation of the more massive clusters only due to statistical effects (a very massive cluster being more likely in a richer cluster system) or by star cluster formation systematically biased towards higher cluster masses in stronger bursts?

- Does the ratio between field star formation and star formation in clusters depend on the galaxy or interaction properties?

- Can we determine the violent star and cluster formation of galaxies based on star cluster colour distributions and deep luminosity functions?

- What happened to the older starburst galaxies? Do star clusters form in merging/interacting galaxies and evolve into the old globular cluster systems we see today? Can we see anomalies in the star cluster populations and relate these to the merger stage or the time since the last external disturbance? There is now clear evidence that many elliptical and interacting galaxies contain two (or more) populations of star clusters (cf. Kundu & Whitmore 2001 and references therein). Fritze-v. Alvensleben (2001) has shown, on theoretical grounds, that for two hypothetic populations of globular clusters, there are combinations of age and metallicity for which one can have:

  - unimodal optical colour distributions (e.g., B-V, V-I), corresponding to unimodal luminosity functions
  - unimodal color distributions, combined with bimodal optical luminosity functions
  - bimodal colour distributions, but unimodal luminosity functions (as observed in, e.g., NGC 4472; Puzia et al. 1999)
  - bimodal colour distributions corresponding to bimodal luminosity functions

  The reason for having an apparently unimodal luminosity function, but a bimodal colour distribution is that the width of the colour distribution is primarily due to observational uncertainties, while the width of the luminosity function is primarily due to the underlying cluster mass function. Moreover, there are evolutionary phases where the colour evolution is particularly strong and others where the luminosity evolution is strong. In several cases, a unimodal colour distribution in (V-I) translates into two well separated peaks when going to (V-K).

Thus, if we can obtain luminosity functions in several optical and/or near-infrared passbands, and therefore colour distributions, this provides us with a powerful analytical tool for the determination of the violent star and cluster formation history of a galaxy.

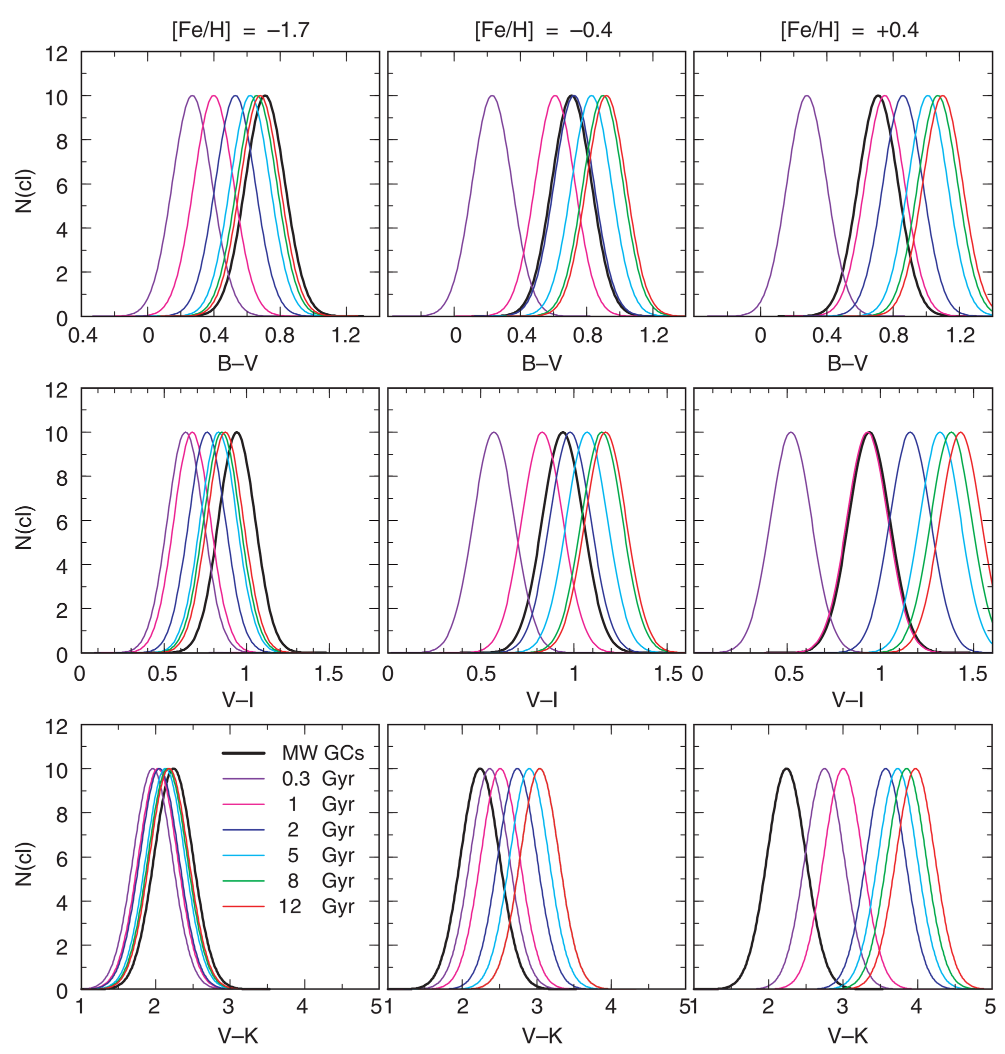

Fig. 3: Colour evolution of fiducial star cluster populations formed in a secondary burst of cluster formation (e.g., triggered by a tidal interaction). The thick solid distribution represents the old Milky Way globular cluster population, which appears to be a universal feature in all galaxies. The coloured distributions show the effects in (B-V), (V-I) and (V-K) of young secondary cluster populations of varying metallicities. It is clear that with the right choice of passbands, we will be able to distinguish the old and young populations, and get a better handle on their metallicities. This is the strength of the ASTROVIRTEL initiative, and that of an International Virtual Observatory as such, which could provide us with the multi-passband observations needed.

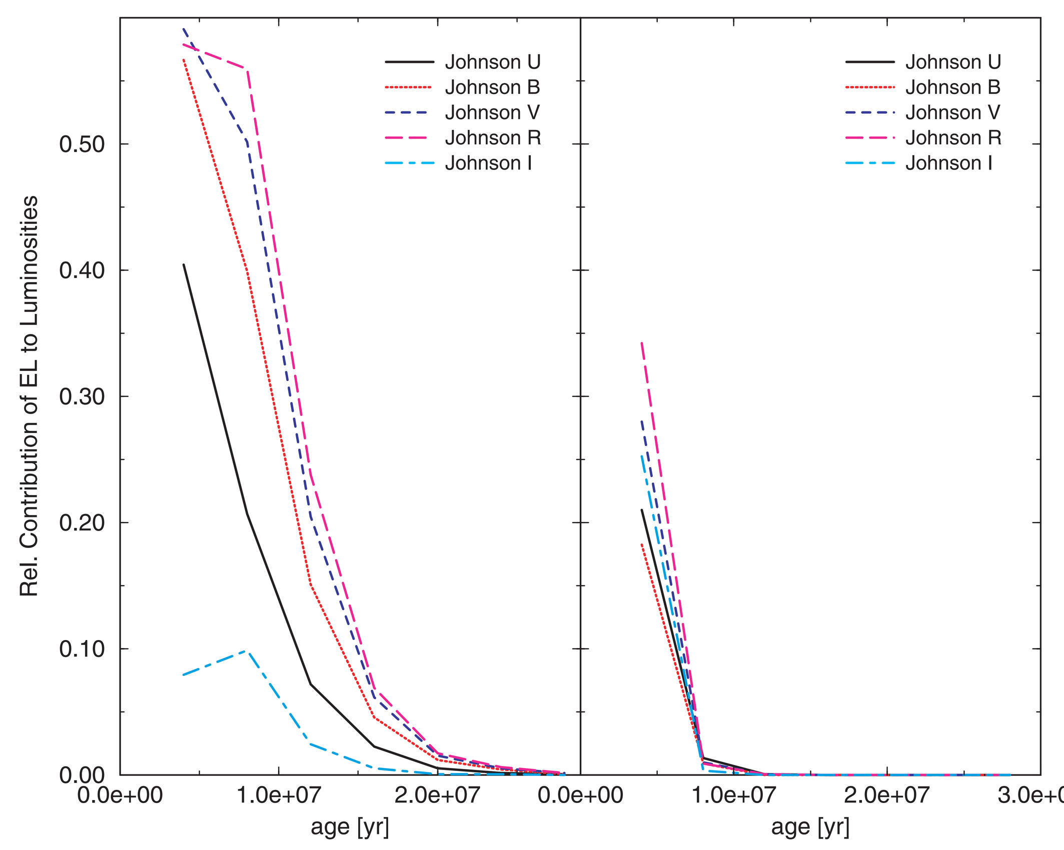

Fig. 4: The youngest stellar populations, such as star clusters recently formed through tidal interactions, will be severely affected by emission-line contributions, thus making their broad-band spectral energy distributions more difficult to interpret. We show the relative contributions of an exhaustive set of emission lines to the broad-band colours for the youngest-age star clusters for subsolar (Z = 0.004; left) and solar (Z = 0.02; right) metallicities.

The Way Forward

- The ASTROVIRTEL project has provided the tools required for this project:
  – Imaging observations: http://archive.eso.org/querator/
  – Spectroscopic observations: http://archive.eso.org/listator/
- We are currently finalising our stellar populations models, which now *also* include emission-line contributions, important for the youngest ages (Anders, Fritze-v. Alvensleben, de Grijs, in preparation; *Fig. 4*)
- We are currently focusing on multi-colour observations of a pilot sample, for which we observed the bluest passbands as part of our *HST* GO programme 8645 (Windhorst et al. 2002; *Fig. 5*)
- The pilot sample of galaxies consists of galaxies that all show signs of a past or current tidal interaction or accretion
- Our first results tie the star cluster formation history to this encounter, in some cases via propagation of cluster formation from the outskirts to the the inner regions of the galaxy.

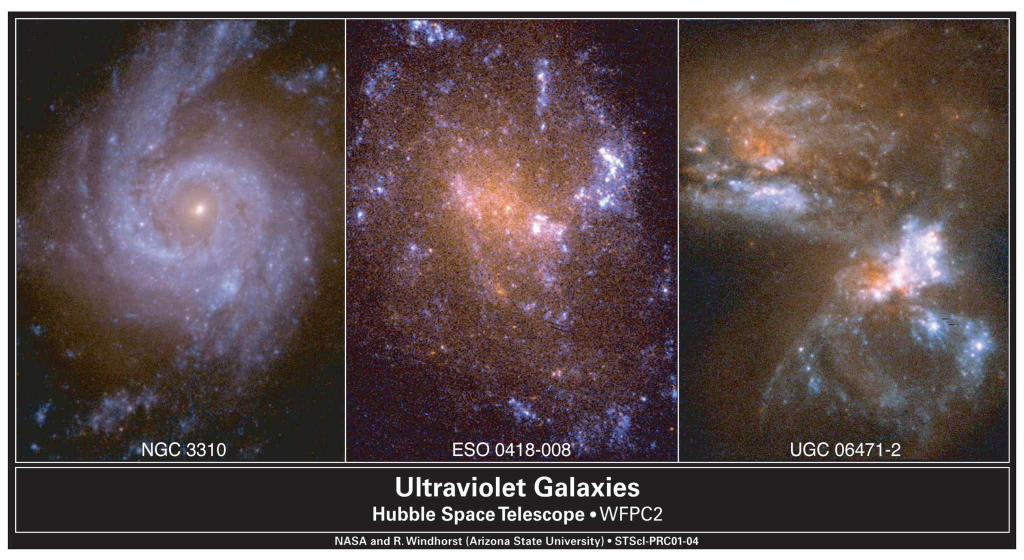

Fig. 5: Our pilot sample of galaxies for which we have observed the mid-ultraviolet images in our *HST* GO programme 8645. In each of these galaxies, we find large (> 100) young star cluster systems, for which the multicolour observations obtained through the ASTROVIRTEL portal provide important clues as to their formation histories.

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