Formation, evolution, and survival of massive star clusters
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Nuclear Star Clusters

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Abstract. The centers of galaxies host two distinct, compact components: massive black holes and nuclear star clusters. Nuclear star clusters are the densest stellar systems in the universe, with masses of $\sim 10^7 \mathrm{M}_\odot$ and sizes of ~5pc. They are almost ubiquitous at the centres of nearby galaxies with masses similar to, or lower than the Milky Way. Their occurrence both in spirals and dwarf elliptical galaxies appears to be a strong function of total galaxy light or mass. Nucleation fractions are up to 100% for total galaxy magnitudes of $\mathrm{M}_B = -19$mag or total galaxy luminosities of about $\mathrm{L}_B = 10^{10} L_\odot$ and falling nucleation fractions for both smaller and higher galaxy masses. Although nuclear star clusters are so common, their formation mechanisms are still under debate. The two main formation scenarios proposed are the infall and subsequent merging of star clusters and the in-situ formation of stars at the center of a galaxy. Here, I review the state-of-the-art of nuclear star cluster observations concerning their structure, stellar populations and kinematics. These observations are used to constrain the proposed formation scenarios for nuclear star clusters. Constraints from observations show, that likely both cluster infall and in-situ star formation are at work. The relative importance of these two mechanisms is still subject of investigation.

Keywords. galaxies: nuclei, star clusters, black holes

1. Frequency

Nuclear star clusters (NSCs) are almost ubiquitous at the centres of nearby low mass galaxies (similar to or lower mass than the Milky Way). For very late type, spiral galaxies the fraction of galaxies with a NSC (nucleation fraction) is above 75% (Böker et al. 2002, Georgiev & Böker 2014, see right panel of Fig. 1). For spirals with bulges the central regions are complex due to the presence dust and ongoing star formation. Of these galaxies only 55% are found to host a nuclear star cluster (Carollo et al. 1998). However, due to dust and star formation the detection of the nucleus is often difficult and the true nucleation fraction may be higher. For dwarf ellipticals and S0s at least 66% host a NSC with an increase in nucleation fraction to almost 100% for galaxies with $\mathrm{M}_B = -19$ (Côté et al. 2006, den Brok *et al.* 2014, see left panel of Fig. 1). On the other hand, it appears that the most massive ellipticals do not host nuclear star clusters, in fact, their central surface brightness shows a cored distribution. This transition to not having a nuclear cluster appears at about $\mathrm{M}_B = -20.5$ (Côté et al. 2006) and is probably linked to the presence of black holes. The most massive ellipticals are built by mergers of galaxies. During the process of merging the black holes drive out the stars from the centre due to three body encounters. This scenario has recently been proposed by Antonini *et al.* 2015.

2. Formation Scenarios

Although nuclear star clusters are so common in lower mass galaxies, their formation scenarios are still under debate. Two main scenarios were proposed to explain the formation and evolution of nuclear star clusters: 1) The infall and subsequent merging of star clusters and 2) the in-situ formation of stars at the center of a galaxy.

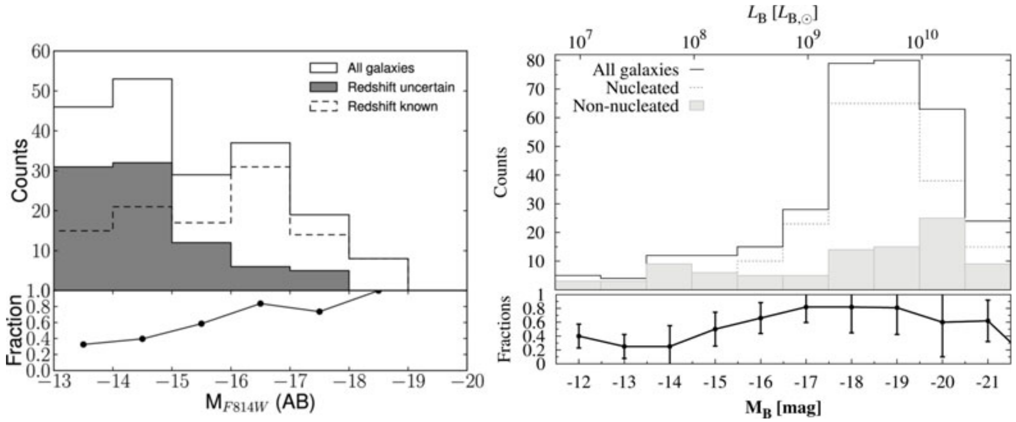

Figure 1. The fraction of galaxies that host a nuclear star cluster is presented as a function of galaxy total magnitude. On the left side for elliptical galaxies (from den Brok *et al.* 2014), and on the right side for spiral galaxies (from Georgiev & Böker 2014).

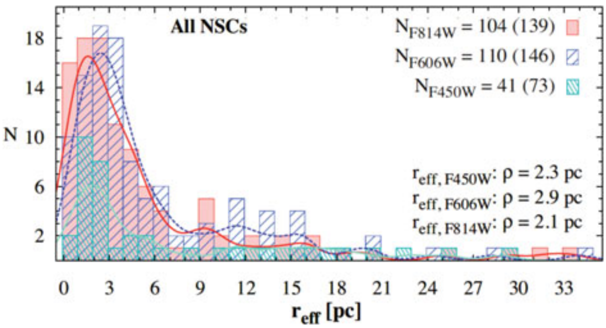

Figure 2. Distribution of effective radii for nuclear star clusters in spiral galaxies (taken from Georgiev & Böker 2014). The typical size of a NSC is between $3-5$pc.

Theoretical studies for the cluster merging scenario use mainly N-body or semi-analytical approaches (Tremaine *et al.* 1975, Capuzzo-Dolcetta 1993, Lotz *et al.* 2004, Agarwal & Milosavljević 2011, Gnedin *et al.* 2014, Antonini 2013, Arca-Sedda & Capuzzo-Dolcetta 2014). The main support for the in-situ formation is the on-going star formation at the center of galaxies as well as inefficient dynamical friction in bringing the globular clusters to the center of a galaxy (Milosavljević 2004, Schinnerer *et al.* 2008, Pflamm-Altenburg & Kroupa 2009, Seth *et al.* 2008).

Many authors have advocated that the formation is likely a combination of both processes (Hartmann et al. 2011, Neumayer et al. 2011, Turner *et al.* 2012, De Lorenzi et al. 2013, Feldmeier *et al.* 2014, den Brok *et al.* 2014). To test the relative importance of these processes requires observations that spatially resolve the structure, stellar populations, and kinematics of nuclear star clusters.

3. Structural Properties

Observational studies with the Hubble Space Telescope find that the half-light radii of NSCs are typically $3-5$pc (Böker et al. 2002, Georgiev & Böker 2014, see Fig. 2). Due to these small sizes, their detection requires very high spatial resolution observations, making the HST crucial for systematic searches. The sizes of NSCs appear to vary with the wavelength at which the observations are taken. NSCs seem to be more compact in bluer bands and more extended in redder filters (Georgiev & Böker 2014, Carson *et al.* 2015;

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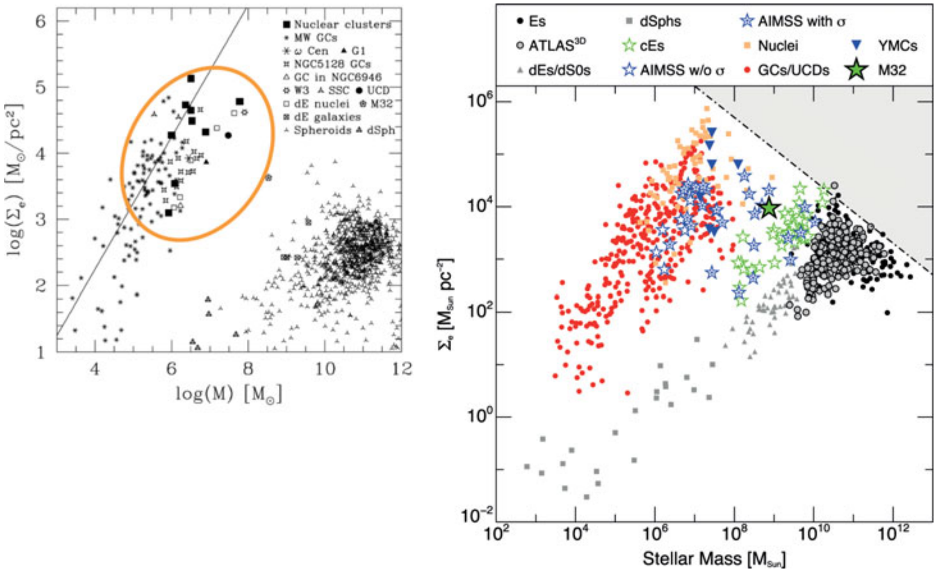

Figure 3. The surface mass density of stellar systems (star clusters and galaxies) plotted against their total mass. NSCs lie at the top of the star cluster sequence and are very different from bulges. Figures are taken from Walcher et al. 2005 and Norris *et al.* 2014.

this can be explained by the presence of young stars that are centrally concentrated, see below in Section 4).

Comparing the properties of nuclear star clusters with Milky Way globular clusters, one finds that they are similar in size, but are on average 4mag brighter (Böker et al. 2004) and hence more massive. Since they have similar half light radii as globular clusters but are more massive, they are also considerably denser than globular clusters. Nuclear star clusters are in fact the densest stellar systems in the universe (Walcher et al. 2005, Misgeld & Hilker 2011, Norris *et al.* 2014). Figure 3 shows the surface mass density of stellar systems as a function of the system's stellar mass. Nuclear star clusters clearly lie at the top of the star cluster sequence (top left of Fig. 3) and are structurally very different from bulges that lie towards the right of the diagrams.

4. Stellar Populations

Nuclear star clusters truly occupy the centers of galaxies, both photometrically but also kinematically (Böker et al. 2002, Neumayer et al. 2011, respectively), and it may be this special location at the bottom of the potential well of the galaxies, that causes the star formation history of NSCs to be rather complex. Several studies have shown that NSCs have multiple stellar populations both in late type (Walcher et al. 2006, Seth et al. 2006, Rossa et al. 2006) and also early type galaxies (Seth et al. 2010, Lyubenova *et al.* 2013). These spectroscopic studies analysed the integrated stellar population properties of nuclear star clusters. Looking at the resolved distribution of stars inside NSCs one finds the following: in the most nearby example of a NSC, at the center of the Milky Way, Feldmeier-Krause *et al.* 2015 showed that the population of young stars (of a few Myrs) is very centrally concentrated (confirming and extending the work of e.g Bartko *et al.* 2010, Do *et al.* 2013, Støstad *et al.* 2015). The young stars are confined to a radius of about 0.5pc around the central black hole, while the distribution of the older stellar population has an effective radius of 4.2pc (Schödel *et al.* 2014).

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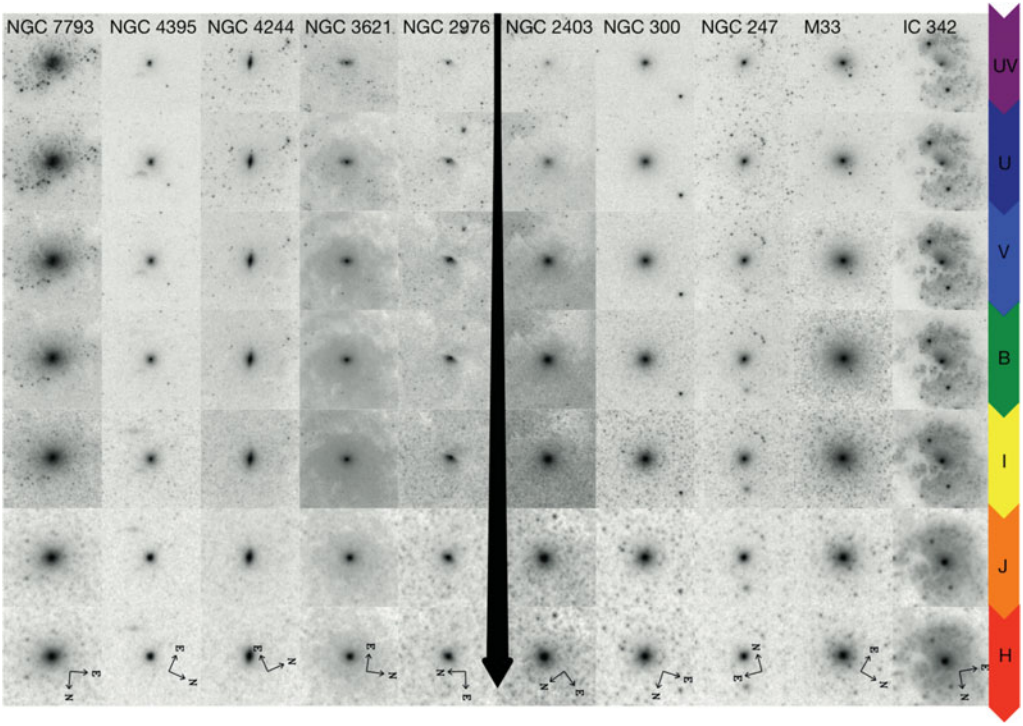

Figure 4. Images of nearby nuclear star clusters in spiral galaxies taken with HST/WFC3 in 7 filters (from Carson *et al.* 2015). The effective radius of the NSCs is more compact in the blue filter while in the redder filters the clusters appear more extended. It appears that the young, blue stars are more centrally concentrated than the old, red stars.

For a sample of 10 nearby NSCs observed with WFC3/HST in seven filters (see Fig. 4) Carson *et al.* 2015 show that the effective radius of the light distribution in the blue filters is more compact while in the redder filters the clusters appear more extended. This hints towards the same finding of young stars being more centrally concentrated, and being formed in-situ at the very center. Moreover, the nucleus of a galaxy appears to be more metal-rich and younger than the surrounding galaxy (Koleva et al. 2011), and the abundance ratios [α/Fe] show that NSCs are more metal enriched than globular clusters (GCs) (Evstigneeva et al. 2007). This finding suggests that NSCs cannot solely be the merger product of GCs, but need some gas for recurrent star formation and enrichment. This finding is also supported by recent kinematical studies (Hartmann et al. 2011, De Lorenzi et al. 2013), where cluster infall alone cannot explain the dynamical state of the NSC.

5. Kinematics

Recent studies of the kinematics of NSCs with integral-field spectroscopy show that the cluster as a whole rotates (Seth *et al.* 2008, Seth et al. 2010, Lyubenova *et al.* 2013, Feldmeier *et al.* 2014, see Figure 5). Combined with the superb spatial resolution of adaptive-optics, the 2D velocity maps resolve stellar and gas kinematics down to a few parsecs on physical scales. In addition, due to the extremely high central stellar density in NSCs, it becomes possible to pick-up kinematic signatures for massive black holes inside NSCs (Seth et al. 2010, Lyubenova *et al.* 2013, den Brok *et al.* 2015, Neumayer *et al.* in prep).

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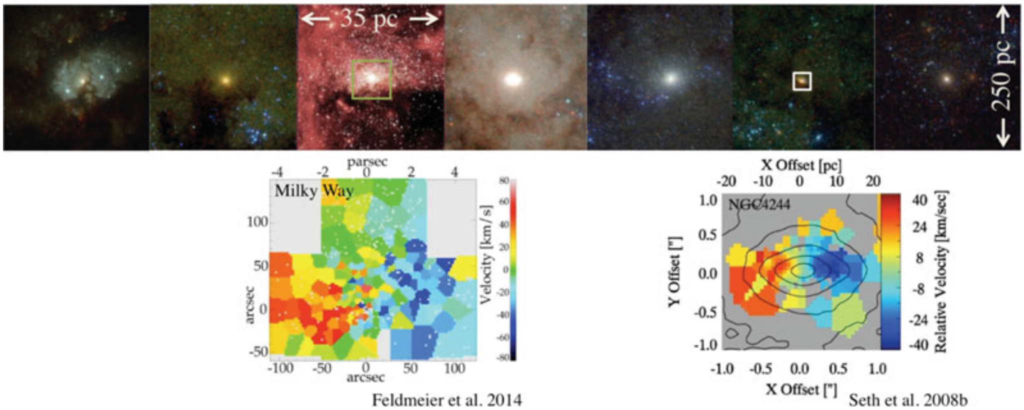

Figure 5. Family portrait of nuclear star clusters in nearby galaxies. Almost all color images taken from Carson *et al.* 2015, except the third from the left: zoom into the Milky Way NSC, taken with Spitzer/IRAC; Stolovy *et al.* 2006). The images are all about 250 pc on the side (taken with HST/WFC3; Carson *et al.* 2015). The bottom shows the radial velocity maps for the nuclear star cluster of the Milky Way and the nearby edge-on galaxy NGC 4244 (taken from Feldmeier *et al.* 2014 and Seth *et al.* 2008). Both edge-on systems clearly show strong rotation in the nuclear cluster.

Recently, Feldmeier *et al.* (2014) observed the NSC of the Milky Way in a long-slit drift scan and constructed the first velocity map of the Milky Way NSC (see Fig. 5, and the chapter of Feldmeier-Krause *et al.* in this edition). This shows that the Milky Way NSC rotates at a maximum velocity of about $\pm 60 km/s$ (comparable to the rotation velocities observed in other NSCs), and its major axis is misaligned with the Galactic Plane by about 9 deg. Moreover, it shows complex kinematic substructures that could be left over coherent structures of infalling star clusters. The comparison of numerical simulations (e.g. Perets & Mastrobuono-Battisti 2014) to the observed maps will help to understand the possible origin of these substructures.

6. Summary - Constraints on Formation Scenarios

The centers of galaxies host two distinct, compact components: massive black holes and nuclear star clusters. Unlike black holes, nuclear star clusters provide a visible record of the accretion of stars and gas into the center of a galaxy. Studying their stellar populations, structure and kinematics allow us to disentangle their formation history and more generally that of galactic nuclei. The two formation scenarios proposed for nuclear star clusters are 1) star cluster infall to the center of a galaxy and subsequent merging; 2) in-situ star formation at the center of a galaxy and build-up of a massive and dense NSC. The observations summarised here can help to set constraints on these formation scenarios in the following way:

NSCs are very common: This observational fact suggests that both formation scenarios are at work to form and grow NSCs.

NSCs have the highest stellar densities in the universe: This observation clearly supports the in-situ formation scenario, since a merger of two globular clusters will not result in a NSC that is denser than the GCs were before. To make the NSC denser requires gas and star formation to dissipate away energy and angular momentum.

NSCs have complex star formation histories: This finding support both formation scenarios.

NSCs rotate: They are thus either built-up from gas and newly formed young stars that fall in from the galactic disk, or from star clusters that come preferentially from within the galactic disk and retain part of their angular momentum. Thus this observable supports both scenarios.

Young stars sit at the center: This observation clearly speaks for in-situ star formation. Especially for the case of the Milky Way nuclear star cluster it became obvious that the infall of young stars from outside the cluster cannot explain the population of very young stars at the very center. These stars must form there.

This list summarises that there are observations supporting both formation scenarios. It is likely that the formation and growth of nuclear star clusters is governed by both star cluster infall and in-situ star formation. Their relative importance is still subject of investigation.

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References

Agarwal, M. & Milosavljević, M. 2011, *ApJ*, 729, 35
Antonini, F. 2013, *ApJ*, 763, 62
Antonini, F., Barausse, E., & Silk, J. 2015, *ApJLetters*, 806, L8
Arca-Sedda, M. & Capuzzo-Dolcetta, R. 2014, *MNRAS*, 444, 3738
Bartko, H., Martins, F., Trippe, S., *et al.* 2010, *ApJ*, 708, 834
Böker, T., Laine, S., van der Marel, R. P., *et al.* 2002, *AJ*, 123, 1389
Böker, T., Sarzi, M., McLaughlin, D. E., *et al.* 2004, *AJ*, 127, 105
Capuzzo-Dolcetta, R. 1993, *ApJ*, 415, 616
Carollo, C. M., Stiavelli, M., & Mack, J. 1998, *AJ*, 116, 68
Carson, D. J., Barth, A. J., Seth, A. C., *et al.* 2015, *AJ*, 149, 170
Côté, P., Piatek, S., Ferrarese, L., *et al.* 2006, *ApJS*, 165, 57
De Lorenzi, F., Hartmann, M., Debattista, V., *et al.* 2013, *MNRAS*, 429, 2974
Do, T., Lu, J. R., Ghez, A. M., *et al.* 2013, *ApJ*, 764, 154
den Brok, M., Peletier, R. F., Seth, A., *et al.* 2014, *MNRAS*, 445, 2385
den Brok, M., Seth, A. C., Barth, A. J., *et al.* 2015, *ApJ*, 809, 101
Evstigneeva, E. A., Gregg, M. D., Drinkwater, M. J., & Hilker, M. 2007, *AJ*, 133, 1722
Feldmeier, A., Neumayer, N., Seth, A., *et al.* 2014, *A&A*, 570, A2
Feldmeier-Krause, A., Neumayer, N., Schödel, R., *et al.* 2015, *A&A*, 584, A2
Georgiev, I. Y & Böker, T. 2014, *MNRAS*, 441, 3570
Gnedin, O. Y., Ostriker, J. P., & Tremaine, S. 2014, *ApJ*, 785, 71
Hartmann, M., Debattista, V. P., Seth, A., *et al.* 2011, *MNRAS*, 418, 2697
Koleva, M., Prugniel, P., de Rijcke, S., & Zeilinger, W. W. 2011, *MNRAS*, 417, 1643
Lotz, J. M., Miller, B. W., & Ferguson, H. C. 2004, *ApJ*, 613, 262
Lyubenova, M., van den Bosch, R. C. E., Côté, P., *et al.* 2013, *MNRAS*, 431, 3364
Milosavljević, M. 2004, *ApJL* 605, L13
Misgeld, I. & Hilker, M. 2011, *MNRAS*, 414, 3699
Neumayer, N., Walcher, C. J., Andersen, D., *et al.* 2011, *MNRAS*, 413, 1875
Neumayer, N. & Walcher, C. J. 2012, *Advances in Astronomy*, 2012,
Norris, M. A., Kannappan, S. J., Forbes, D. A., *et al.* 2014, *MNRAS*, 443, 1151
Perets, H. B. & Mastrobuono-Battisti, A. 2014, *ApJL*, 784, L44
Pflamm-Altenburg, J. & Kroupa, P. 2009, *MNRAS*, 397, 488
Rossa, J., van der Marel, R. P., Böker, T., *et al.* 2006, *AJ*, 132, 1074
Schinnerer, E., Böker, T., Meier, D. S., & Calzetti, D. 2008, *ApJL*, 684, L21

Schödel, R., Feldmeier, A., Kunneriath, D., *et al.* 2014, *A&A*, 566, A47
Seth, A. C., Dalcanton, J. J., Hodge, P. W., & Debattista, V. P. 2006, *AJ*, 132, 2539
Seth, A. C., Blum, R. D., Bastian, N., *et al.* 2008, *ApJ*, 687, 997
Seth, A. C., Cappellari, M., Neumayer, N., *et al.* 2010, *ApJ*, 714, 713
Seth, A. C., van den Bosch, R., Mieske, S., *et al.* 2014, *Nature*, 513, 398
Stolovy, S., Ramirez, S., Arendt, R. G., *et al.* 2006, Journal of Physics Conference Series, 54, 176
Støstad, M., Do, T., Murray, N., *et al.* 2015, *ApJ*, 808, 106
Tremaine, S. D., Ostriker, J. P., & Spitzer, L., Jr. 1975, *ApJ*, 196, 407
Turner, M. L., Côté, P., Ferrarese, L., *et al.* 2012, *ApJS*, 203, 5
Walcher, C. J., Böker, T., Charlot, S., *et al.* 2006, *ApJ*, 649, 692
Walcher, C. J., van der Marel, R. P., McLaughlin, D., *et al.* 2005, *ApJ*, 618, 237