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Co-evolution of nuclear rings, bars and the central intensity ratio of their host galaxies

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Abstract Using a sample of 13 early-type spiral galaxies hosting nuclear rings, we report remarkable correlations between the properties of the nuclear rings and the central intensity ratio (CIR) of their host galaxies. The CIR, a function of intensity of light within the central 1.5 and 3 arcsec region, is found to be a vital parameter in galaxy evolution, as it shares strong correlations with many structural and dynamical properties of early-type galaxies, including mass of the central supermassive black hole (SMBH). We use archival *HST* images for aperture photometry at the centre of the galaxy image to compute the CIR. We observe that the relative sizes of nuclear rings and ring cluster surface densities strongly correlate with the CIR. These correlations suggest reduced star formation in the centres of galaxies hosting small and dense nuclear rings. This scenario appears to be a consequence of strong bars as advocated by the significant connection observed between the CIR and bar strengths. In addition, we observe that the CIR is closely related with the integrated properties of the stellar population in the nuclear rings, associating the rings hosting older and less massive star clusters with low values of CIR. Thus, the CIR can serve as a crucial parameter in unfolding the coupled evolution of bars and rings as it is intimately connected with both their properties.

Key words: galaxies: evolution — galaxies: formation — galaxies: photometry — galaxies: spiral — galaxies: starburst

1 INTRODUCTION

Nuclear rings, also known as circumnuclear starburst rings, preferentially reside in barred spirals that constitute nearly two-thirds of normal spirals in the local Universe (Knapen et al. 1999; Laurikainen et al. 2004). These rings, with their intense star formation activities and close association with their host galaxy's structural parameters, are believed to be ideal laboratories for understanding the secular evolution of their host galaxies (Martinet 1995; Buta & Combes 1996; Kormendy & Kennicutt 2004; Mazzuca et al. 2008; Knapen 2015).

The origin of nuclear rings is thought to be the gravitational torque formed as a result of non-axisymmetric perturbations emanating from the bars, spiral arms or ovals (Shlosman 1990; Athanassoula 1994; Combes 2001). The molecular gas, driven by shocks, flows inwards along the dust lanes on the leading edge of the bar and loses its angular momentum, thereby spiraling into the circumnuclear region (Kormendy & Kennicutt 2004; Knapen 2005). This inflow of matter can cause a burst of star formation activities and the matter gets trapped by the resonances in inner stellar orbits known as Inner Lindblad Resonances (ILRs, Combes & Gerin 1985; Shlosman et al. 1990; Athanassoula 1994; Knapen et al. 1995a,b; Buta & Combes 1996). There are various other theories about the origin of the rings, such as Shlosman et al. (1990) which predicts the influence of the axisymmetric bulge in ring formation. Yet another explanation suggests the nuclear rings are remnants of nuclear starbursts resulting from the high surface densities of gas in the central region (Kenney et al. 1993). Many simulations have been carried out based on various theories over the years (see e.g., Combes & Gerin 1985; Athanassoula 1992; Piner et al. 1995).

The nuclear rings are thus believed to be tracers of star formation in such galaxies. These rings are linked with the formation of massive clusters of stars near the centres of galaxies including Young Massive Clusters (YMCs) (Maoz et al. 2001; de Grijs et al. 2017). These clusters can also be used to constrain properties of their host galaxies (Weiner & Sellwood 1999; Li et al. 2015). Recent studies indicate that stronger bars have lower star formation at their central regions (Kim et al. 2017; Ma et al. 2018). In this light, we perform an optical study at the centres of nearby early-type spirals hosting a nuclear ring and its associated clusters using a sample of 13 galaxies. We utilise a newly introduced parameter known as the central intensity ratio (CIR, Aswathy & Ravikumar 2018) to probe the interplay between the bars and nuclear rings in the secular evolution process. The CIR is the ratio of intensity of light contained in a central circular aperture of radius *r* to that of an outer shell of width *r*.

The CIR for early-type galaxies is reported to be anti-correlated with the mass of the supermassive black holes (SMBHs, Aswathy & Ravikumar 2018). It is closely related to various structural and dynamical properties of host galaxies. The CIR is also found to contain information about star formation near the central region of these galaxies. Thus, the CIR can serve as an ideal tool for studying star forming nuclear rings. Since the majority of our sample galaxies is barred, we have also explored the relation between the CIR and evolution of the bars.

This paper is organized as follows. Section 2 describes the properties of the sample galaxies followed by the data reduction techniques employed in this study. Section 3 deals with various correlations while discussion and conclusion are provided in Section 4.

2 THE DATA AND DATA REDUCTION

The sample consists of 13 early-type spiral galaxies adopted from Ma et al. (2018) hosting nuclear rings. Their sample is taken from Comerón et al. (2010) based on the primary criterion that the galaxies are observed by both *Hubble Space Telescope* (*HST*) and *Spitzer*. These galaxies have observations in at least four *HST* bands. Also, the sample is devoid of galaxies possessing inclination $i > 70°$ and with central regions exhibiting dusty features (Ma et al. 2018). Most of the sample galaxies possess bars, except for NGC 7217, NGC 7742 and UGC 3789 which also helped us study the properties of the bars. Though nuclear rings are preferentially found in barred spirals, a number of unbarred galaxies with other non-axisymmetric features such as strong spiral arms were also reported to host nuclear rings as seen in NGC 7742 (de Zeeuw et al. 2002). We used archival *HST* images observed with WFPC2/ACS instruments with the *F814W* filter for our analysis. Though we employed the standard pipeline for calibrated images, the task *L.A.Cosmic* (van Dokkum 2001) and *IRAF* task *cosmicrays* were further applied to improve the removal of cosmic rays. Out of the 17 galaxies considered by Ma et al. (2018), we excluded galaxies with images that contained bad pixels in their central 3 arcsec region. We have excluded the galaxy NGC 7469 as the radius of the nuclear ring, as estimated by Comerón et al. (2010), is found to be within the 3 arcsec aperture.

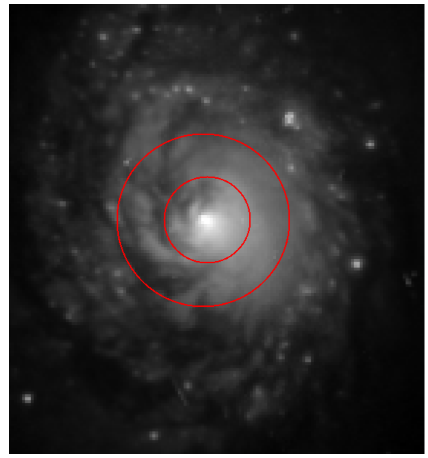

Fig. 1 WFPC2 image of the galaxy NGC 1672 with the apertures used to calculate the CIR, signified in *red* circle (*Color version is online*).

The CIR for the sample galaxies is determined using simple aperture photometry (MAG_APER) provided in source extractor (*SExtractor*, Bertin & Arnouts 1996). Aswathy & Ravikumar (2018) defined the CIR as,

$$\mathrm{CIR} = \frac{I_1}{I_2 - I_1} = \frac{10^{0.4(m_2-m_1)}}{1 - 10^{0.4(m_2-m_1)}} , \qquad (1)$$

where I_1 (of magnitude m_1) and I_2 (of magnitude m_2) are the intensities of light within the inner and outer apertures of radii r_1 and r_2 (which is $2\,r_1$), respectively. The simple definition of CIR helps avoid any dependence on a form following central intensity, $I(0)$ (i.e., surface brightness at a radial distance r, $I(r) = I(0)f(r)$ where $f(r)$ is a function of r). On the other hand, the definition boosts any addition to (or subtraction from) the central intensity $I(0)$. Further, simple Monte Carlo simulations of ellipsoidal systems exhibit remarkable stability over a range of radii (with $r_2 = 2\,r_1$). However, in the present study, the inner radius is selected to contain the effects of the point spread function (PSF) in *HST* images while the outer radius is chosen to be far smaller than the half light radii of the sample galaxies. Thus, we have selected the inner and outer radii as 1.5 and 3 arcsec, respectively, at a distance of 31.8 Mpc, which is roughly the mean distance of the sample galaxies. The physical distances corresponding to these radii are 0.23 and 0.46 kpc, respectively. One of the typical images of our sample galaxies is displayed in Figure 1, overlaid with the apertures used to calculate the CIR. The properties of the sample galaxies are provided in Table 1. The relative sizes of nuclear rings (see Sect. 3.1) are adopted from Comerón et al. (2010) while other parameters are taken from Ma et al. (2018). We have also listed the values of CIR along with their uncertainties in Table 1.

Table 1 The Properties of Sample Galaxies

Galaxy	Hubble type [a]	Distance modulus[a] (mag)	$Q_g^{[a]}$	$\Sigma^{[a]}$ (kpc^{-2})	log $M_{cl}/M_\odot^{[a]}$	log (t_{cl} yr^{-1})[a]	$D_r/D_0^{[b]}$	CIR	Δ_{CIR}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ESO 565–11	(R)SB(r)0/a	34.23	0.316	8	5.56	7.59	0.212	1.06	0.08
NGC 1097	SB(s)b	31.4	0.241	213	6.11	8.83	0.041	0.58	0.01
NGC 1326	(R)SB0+(r)	30.86	0.163	484	5.58	8.11	0.048	0.77	0.03
NGC 1512	SB(r)a	30.48	0.366	363	5.15	8.18	0.052	0.72	0.06
NGC 1672	SB(s)b	30.81	0.349	3020	6.25	8.69	0.031	0.56	0.02
NGC 2997	SAB(rs)c	30.2	0.306	179	4.41	7.72	0.016	0.60	0.04
NGC 3081	(R)SAB(r)0/a	32.09	0.194	18	6.39	7.87	0.094	0.88	0.04
NGC 4314	SB(rs)a	29.93	0.432	565	4.6	7.96	0.061	0.74	0.04
NGC 6782	(R)SAB(r)a	33.61	0.205	7	5.92	8.59	0.06	1.41	0.06
NGC 6951	SAB(rs)bc	31.77	0.275	108	6.08	8.24	0.034	0.61	0.01
NGC 7217	(R)SA(r)ab	31.41	0.026	49	5.32	8.64	0.082	0.76	0.04
NGC 7742	SA(r)b	32.91	0.055	22	5.49	7.44	0.163	0.96	0.05
UGC 3789	(R)SA(r)ab	33.49	-	39	5.93	7.52	-	1.15	0.03

Column (1): Name of the galaxy; Col. (2): Hubble type; Col. (3): Distance modulus; Col. (4): non-axisymmetric torque parameter Q_g; Col. (5): surface density of ring clusters; Col. (6): average mass of the ring cluster population; Col. (7): average age of the ring cluster population; Col. (8): relative size of the ring; Col. (9): the CIR computed in *F814W* band; Col. (10): the uncertainty in the estimation of the CIR.
Refs: [a]: Ma et al. (2018); [b]: Comerón et al. (2010).

Table 2 The Table Lists the Best-fitting Parameters for the Relation $x = \alpha$ CIR + β

x	α	β	r	p	N
Q_g	-0.54 ± 0.17	0.63 ± 0.12	–0.85	99.66	9
Σ	-2.40 ± 0.58	3.97 ± 0.51	–0.78	99.82	12
D_r/D_0	0.35 ± 0.04	-0.18 ± 0.03	0.94	> 99.99	11
$M_{cl}/M_\odot$	1.66 ± 0.45	3.82 ± 0.43	0.81	98.55	8
t_{cl}	-2.13 ± 0.40	9.80 ± 0.33	–0.87	99.95	11

N signifies the number of galaxies included in the fit. Pearson's linear correlation coefficient (r) is listed along with the significance (p).

3 RESULTS

We find that the CIR is closely associated with various properties of nuclear rings. We also explore connections between the CIR and bar strengths of these galaxies. The linear correlation coefficients for all major correlations are given in Table 2 along with the values of the best-fitting parameters.

3.1 Correlations between the CIR and the Properties of Nuclear Rings

Nuclear rings are believed to be closely associated with activities in the central regions of host galaxies and their stellar population (Sarzi et al. 2007; Mazzuca et al. 2008; Ma et al. 2018). Evolution of a ring is also found to depend on the dynamics of the (associated) bar (Buta et al. 1999; Comerón et al. 2010). Yet, the photometric studies carried out so far seldom observed a direct connection between the properties of the ring and its host galaxy.

In the present study, we find a strong correlation between the CIR and the relative size of the ring (D_r/D_o), the size of the ring normalised with the diameter of the host galaxy, adopted from Comerón et al. (2010), as shwon in Figure 2(a). Here, D_o is the extinction-corrected D_{25} radius of the galaxy as defined by Bottinelli et al. (1995). Pearson's linear correlation coefficient, r, is 0.94 with the significance, P, greater than 99.99 percent. We have applied the recipe given in Press et al. (1992) to calculate the significance of the correlations reported in this paper. This parameter is reported to be connected with the non-axisymmetric perturbation strength (Comerón et al. 2010) and is further discussed in Section 3.2. The notable outlier which shows a large offset from the fitted relation in Figure 2(a) is NGC 6782. This galaxy is seen to be an outlier in almost all correlations reported in this study. Further, we see that the ring cluster surface densities are anti-correlated with the values of CIR, hinting at a close association of the CIR with the formation and evolution of the rings (see Fig. 2(b)).

Ma et al. (2018) performed a detailed population synthesis of nuclear rings in the sample galaxies using Flexible Stellar Population Synthesis models (Conroy et al. 2009). They fitted the observed spectral energy densities of the rings assuming a Kroupa (2001) initial mass function (IMF) and solar metallicity to derive average cluster ages and total stellar masses of the rings. The CIR exhibits a strong anti-correlation with the average cluster ages ($r = -0.87$, $P = 99.95\%$) while the correlation observed with the total stellar masses of the clusters is positive ($r = 0.81$, $P = 98.55\%$). The correlation between the CIR and average age of the ring sample is depicted in Figure 2(c). The galaxies NGC 6782 and NGC 2997 are seen to be deviating from the fitted relation whereas in Figure 2(d), we observe that all galaxies with masses above $10^6\ M_\odot$ deviate from the fitted relation.

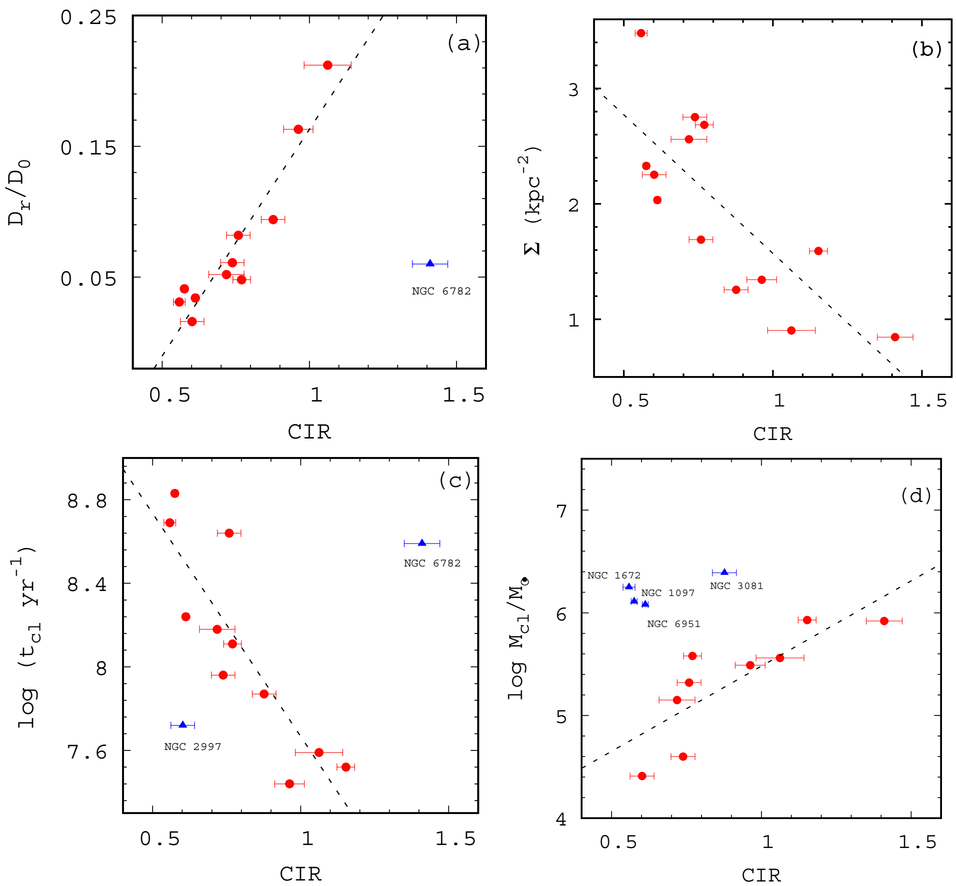

Fig. 2 Correlations between the CIR and (a) relative size of the ring, D_r/D_o, the ratio of the size of the ring to the diameter of its host galaxy adopted from Comerón et al. (2010), (b) ring cluster surface density, Σ, (c) the average age of the ring cluster population, t_{cl} and (d) the average mass of the ring cluster population, $M_{cl}/M_\odot$ taken from Ma et al. (2018). The *red circles* represent the galaxies following the fitted relations and outliers are marked by *blue triangles* (*Color version is onlie*).

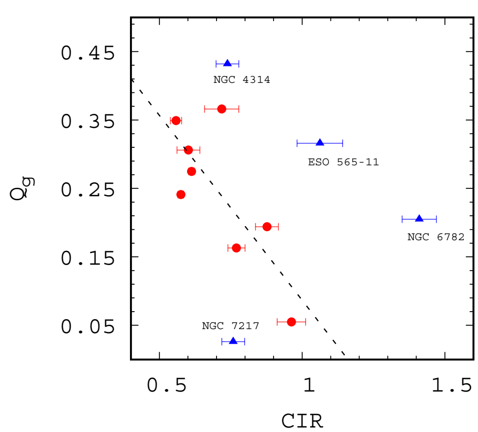

Fig. 3 Correlation between the CIR and non-axisymmetric torque parameter (Q_g) adopted from Ma et al. (2018). The symbols are similar to those used in Fig. 2.

3.2 Correlation between CIR and Strength of the Bar

The non-axisymmetric torque parameter (Q_g) was first defined by Combes & Sanders (1981) as the ratio of the maximum tangential force to the mean radial force and it quantifies the strength of the bar. Higher values of Q_g indicate stronger bars while lower values might be attributed to arm perturbations and oval distortions (Comerón et al. 2010). In the case of galaxies without bars, this parameter may statistically be related to the strength of the spiral arms (Ma et al. 2018). We find a striking anti-correlation ($r = -0.85$ with $p = 99.66$ percent) between the CIR and Q_g as shown in Figure 3. Four galaxies (NGC 4314, NGC 7217, ESO 565–11 and NGC 6782) manifest significant offsets with respect to the fitted relation between CIR and Q_g. The galaxy NGC 7217 is an unbarred galaxy. This galaxy is known to contain a counter rotating stellar disc unlike the other galaxies in the sample (Comerón et al. 2010). Mazzuca et al. (2008) proposed that this galaxy might have undergone a minor merger in the past with a gas-rich dwarf galaxy. The galaxy ESO 565–11 hosts a highly elliptical ring which is currently being formed (Buta et al. 1999). This galaxy is also found to be an outlier in many of the correlations exhibited by galaxies hosting nuclear rings (Comerón et al. 2010). Also, NGC 4314 has the youngest ring in the sample which is reported to be behaving differently (Ma et al. 2018). The strong correlation between the bar strength and the CIR probably reflects the bar-driven star formation in the sample galaxies.

4 DISCUSSION AND CONCLUSIONS

We perform photometric studies of the centres of 13 early-type spirals (majority with bars) in the nearby Universe hosting nuclear rings. We use the CIR, a recently introduced measure of the concentration of light at the very centre of the galaxy image, to study the formation and evolution of the nuclear rings and their host galaxies. The CIR is found to be a significant parameter in galaxy evolution studies as it is correlated with many structural and dynamical properties of early-type galaxies including the mass of the SMBH at the centre (Aswathy & Ravikumar 2018). However, estimation of CIR is not straightforward for spiral galaxies due to orientation effects posed by the disc component. But in the present study of spiral galaxies with nuclear rings, the orientations of most of the galaxies are face-on ($i < 70°$), enabling us to neglect the orientation effects induced by dust present in disc. Also, early-type spirals are known to be less heavily obscured by dust compared to late-type spirals (Comerón et al. 2010). These features of our sample helped us unveil, for the first time, striking photometric correlations between the properties of nuclear rings and the CIR of their host galaxies. Also, we find that the bar strength of the sample galaxies is strongly correlated with the CIR, restating the importance of the latter in galaxy evolution studies.

The present study indicates that the CIR is lower in strongly barred galaxies compared to the weak ones as quantified by the non-axisymmetric torque parameter. We know that stellar bars in nearby spirals play a major role in the secular evolution of their host galaxies as they are capable of redistributing gaseous matter from the discs to inner regions of the galaxy (Sanders & Huntley 1976; Athanassoula 1992). Such an infall of materials might trigger starbursts at the galactic centres (Ho et al. 1997; Hunt & Malkan 1999). Several observational and theoretical studies dealing with bar-driven star formation in spirals suggest that this enhancement in star formation activity near the central region occurs at the onset of bar formation (e.g., Heckman 1980; Ellison et al. 2011; Fanali et al. 2015; Spinoso et al. 2017). Once the bar is formed, the star formation starts declining and by the time the bar grows stronger, the star formation gets suppressed (Spinoso et al. 2017; Abdurro'uf & Akiyama 2017).

The CIR contains information regarding the star formation activities near the central region of early-type galaxies (Aswathy & Ravikumar 2018). As seen in Figure 3, the CIR decreases with the increasing strength of bars. The lower values of the CIR suggest that the star formation at the centre is minimum compared to the outer regions. This might be the result of the bar sweeping out the gaseous matter as it gets stronger and this is consistent with previous studies (James & Percival 2018). Recently, Ma et al. (2018) investigated the star formation rates (SFRs) in nuclear rings of barred spirals and arrived at the conclusion that the SFR in rings is low in galaxies with strong bars. It is possible that the observed low values of CIR in such galaxies might be indicating low star formation in their very central region as well.

Also, we find that various properties of the nuclear rings correlate with the CIR. Smaller rings are found to possess lower values of CIR as seen in Figure 2(a). The ring cluster surface density is anti-correlated with the CIR, re-affirming that in the galaxies with small and dense rings, star formation activities at the centre are reduced. This might be a consequence of bar controlled evolution for nuclear rings (see, e.g., Knapen 2005). Many simulations also suggest that smaller rings occur in strongly barred galaxies (e.g., Kim et al. 2014). Knapen (2005) proposes that the nuclear rings can shrink as the bar gets stronger which seems to support our observation.

The average ring cluster masses and ages are also seen to be correlated with the CIR, suggesting that old clusters which are less massive cause low values of CIR in their host galaxies. Except for four galaxies with masses above $10^6\,M_\odot$, the age of the ring clusters seem to be increasing with the CIR. It is tempting to propose an evolutionary history as follows: the clusters when they are formed due to starbursts are not only younger but also massive as they are rich in gaseous materials driven inwards by the newly formed bar. As the clusters get older, the bar gets stronger but the gas at the centre is exhausted due to the series of starbursts happening around the nuclear region. This results in a reduction of the intensity of light at the very centre of the galaxy as suggested by lower values of the CIR. Initially, when the starbursts occur, light from the inner aperture is higher compared to the outer one, and therefore the CIR is higher.

The CIR is reported to be anti-correlated with mass of the central SMBH in early-type galaxies. So far, studies have not been successful in unveiling any direct observational correlation between the active galactic nucleus (AGN) activities and occurrence of bars or formation of nuclear rings. The absence of intense star formation in the central region and strong AGN activities may be due to the prompt removal of gas in the central region (Ho et al. 1997; Hunt & Malkan 1999; Knapen et al. 2000; Laine et al. 2002). Recently, a numerical simulation exploring the AGN feedback and star formation history in barred spiral galaxies proposed that after the initial starburst, as a result of the inflowing gas materials towards the central AGN, the gas is gradually pushed away from the galactic centres, shifting the star formation sites to larger radii (Robichaud et al. 2017). This scenario is also supported in the present study as we find low values of CIRs in strong bars. In the case of early-type systems, it was observed that low values of CIR suggest massive black holes in galactic centres (Aswathy & Ravikumar 2018). Thus, CIR seems to possess the potential to play a crucial role in understanding the linked evolution of rings, bars and central AGNs.

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