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Mapping the Kinematically Decoupled Core in NGC 1407 with MUSE

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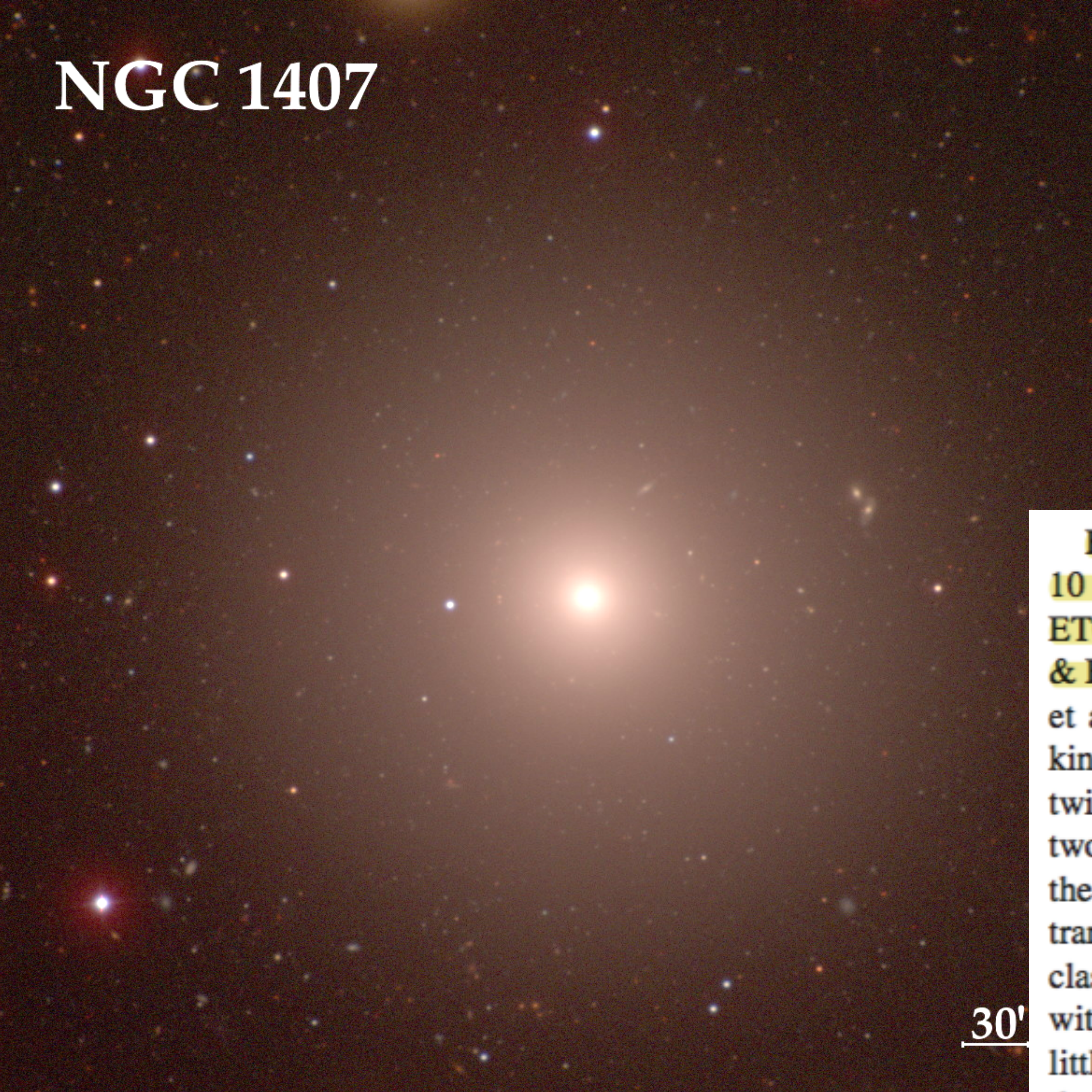
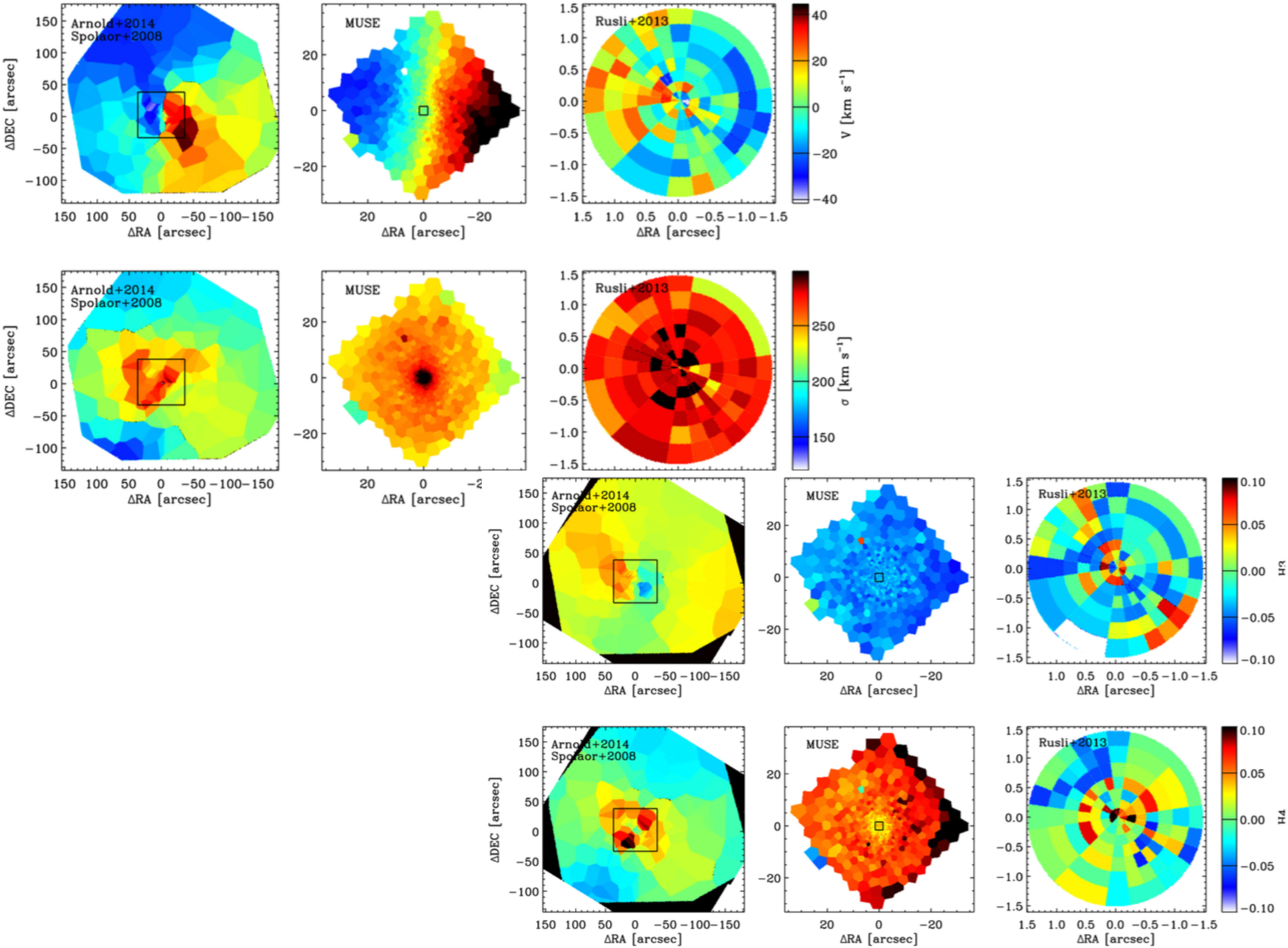
ABSTRACT

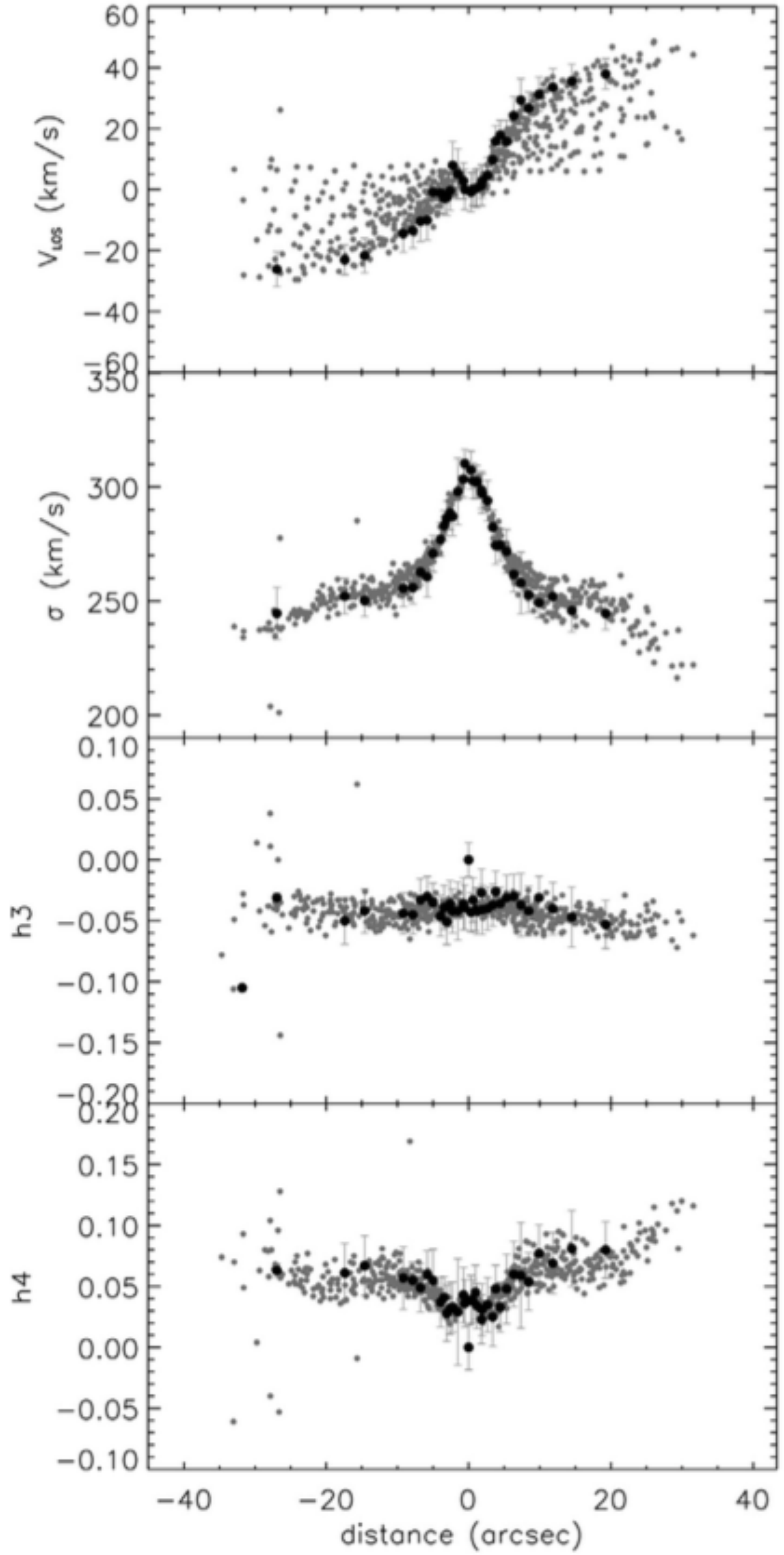
Studies of the kinematics of NGC 1407 have revealed complex kinematical structure, consisting of the outer galaxy, an embedded disc within a radius of ∼60 arcsec, and a kinematically decoupled core (KDC) with a radius of less than 30 arcsec. However, the size of the KDC and the amplitude of the kinematic misalignment it induces have not yet been determined. In this paper, we explore the properties of the KDC using observations from the Multi-Unit Spectroscopic Explorer (MUSE) Integral Field Spectrograph to map out the kinematics in the central arcminute of NGC 1407. Velocity and kinemetry maps of the galaxy reveal a twist of ∼148° in the central 10 arcsec of the galaxy, and the higher order moments of the kinematics reveal that within the same region, this slowly rotating galaxy displays no net rotation. Analysis of the stellar populations across the galaxy found no evidence of younger stellar populations in the region of the KDC, instead finding uniform age and super-solar α-enhancement across the galaxy, and a smoothly decreasing metallicity gradient with radius. We therefore conclude that NGC 1407 contains a triaxial, kiloparsec-scale KDC with distinct kinematics relative to the rest of the galaxy, and that is likely to have formed through either a major merger or a series of minor mergers early in the lifetime of the galaxy. With a radius of ∼5 arcsec or ∼0.6 kpc, NGC 1407 contains the smallest KDC mapped by MUSE to date in terms of both its physical and angular size.

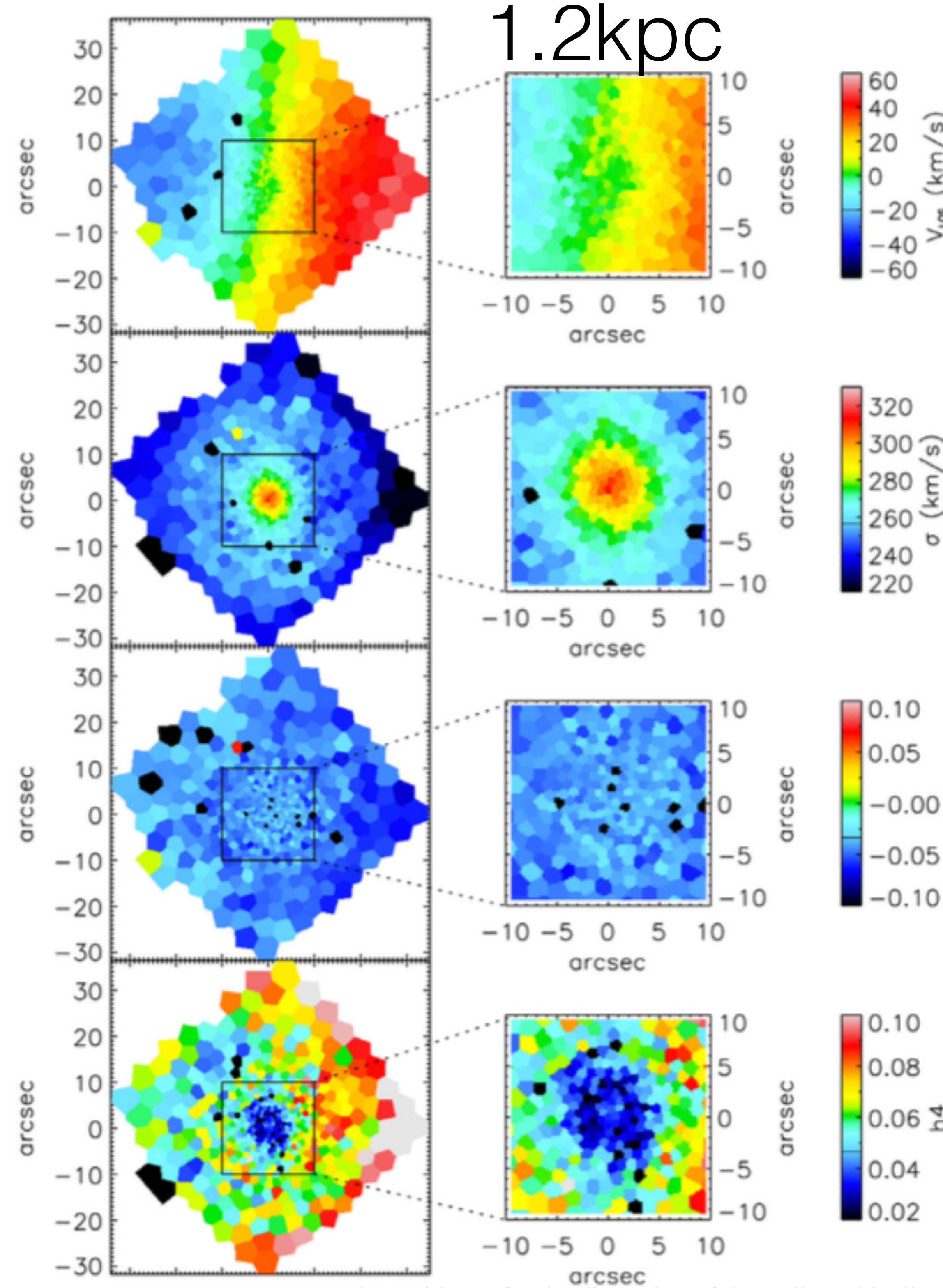
Key words: galaxies: elliptical and lenticular, cD – galaxies: individual: NGC 1407 – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: structure.



Kinematic misalignments have been detected in around 10 per cent of ETGs (Krajnović et al. 2011), although in isolated ETGs the fraction has been seen to increase to 40 per cent (Hau & Forbes 2006). Using data from the ATLAS^{3D} survey (Cappellari et al. 2011), Krajnović et al. (2011) proposed a classification of kinematic misalignments, in which KDCs are defined as having a twist of $>30^{\circ}$ in the kinematic position angle (PA_{kin}) between the two components, and where the k_1 coefficient, which represents the amplitude of the bulk rotation in the velocity, drops to 0 in the transition region, reflecting little or no net rotation there. Using this classification, they detected KDCs in around 7 per cent of ETGs, with the majority residing within slow rotators – galaxies that show little or no net rotation (Emsellem et al. 2007). KDCs do not share the same properties, and McDermid et al. (2006) have proposed that they fall into two categories. The first are kiloparsec-scale KDCs, which are typically older than 8 Gyr and generally reside within slow rotators, and the second type are compact KDCs, which are generally younger ($\sim$1 Gyr), exclusively found within fast rotators, and rotate around the same axis as the host galaxy. The differences in the stellar populations of these KDCs and of the kinematics of their hosts suggest that these two types of KDCs are formed through different mechanisms. The younger stellar populations of the compact

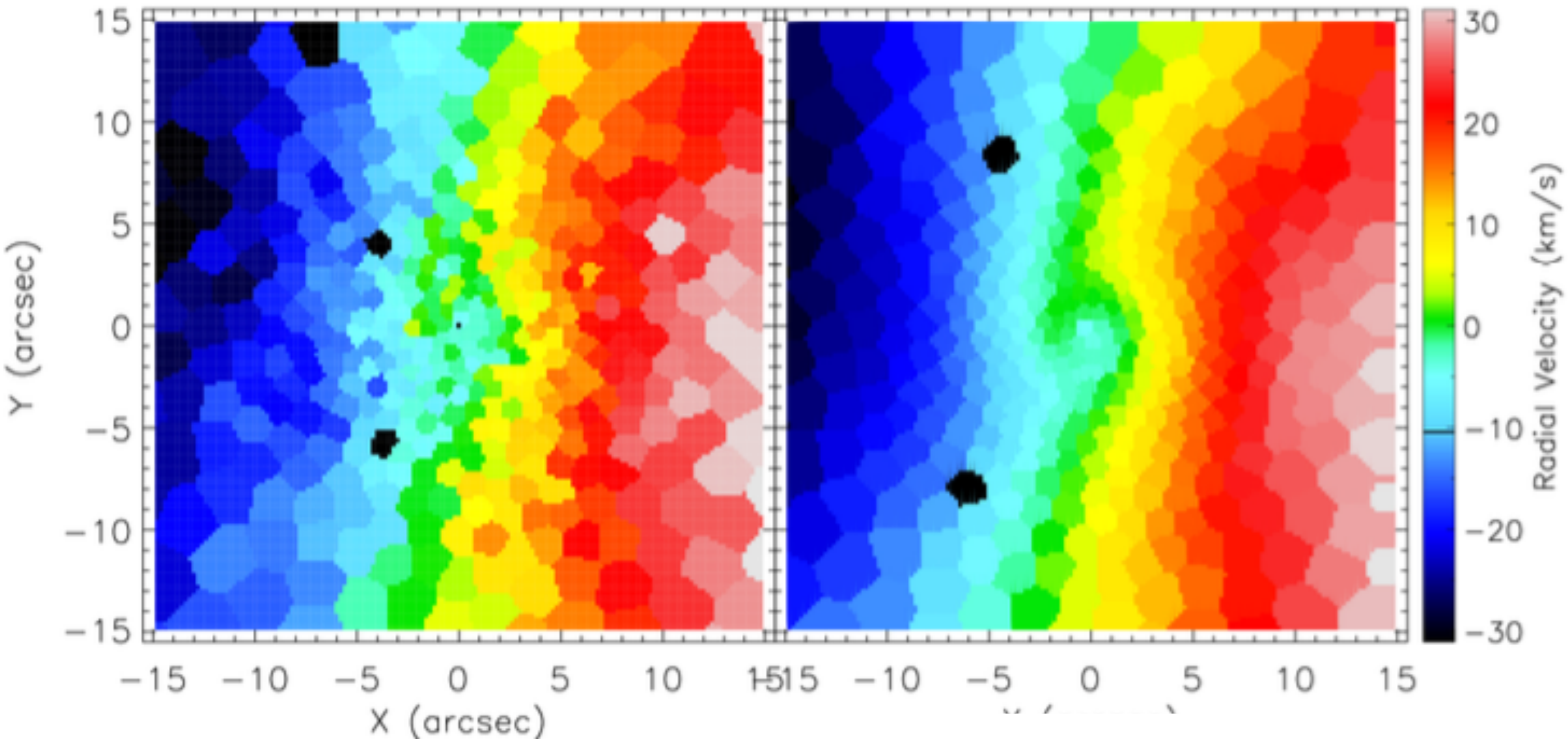

Arnold+2014
Spolaor+2008
MUSE
Rusli+2013
ΔRA [arcsec]
ΔDEC [arcsec]
V [km s⁻¹]
σ [km s⁻¹]
H3
H4

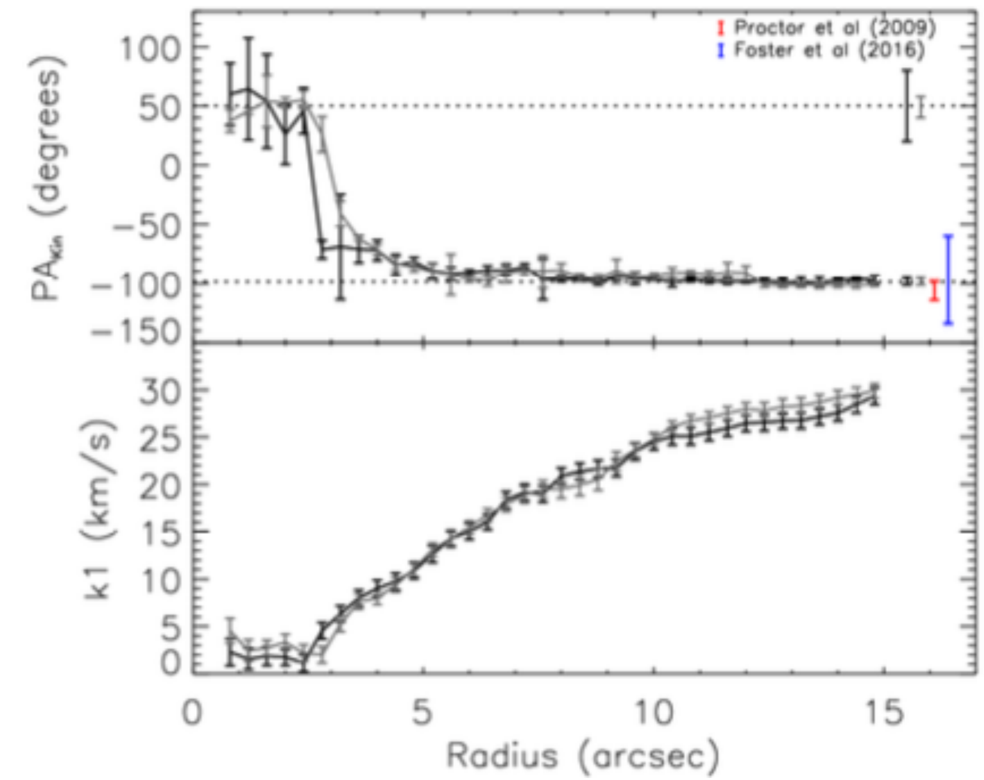


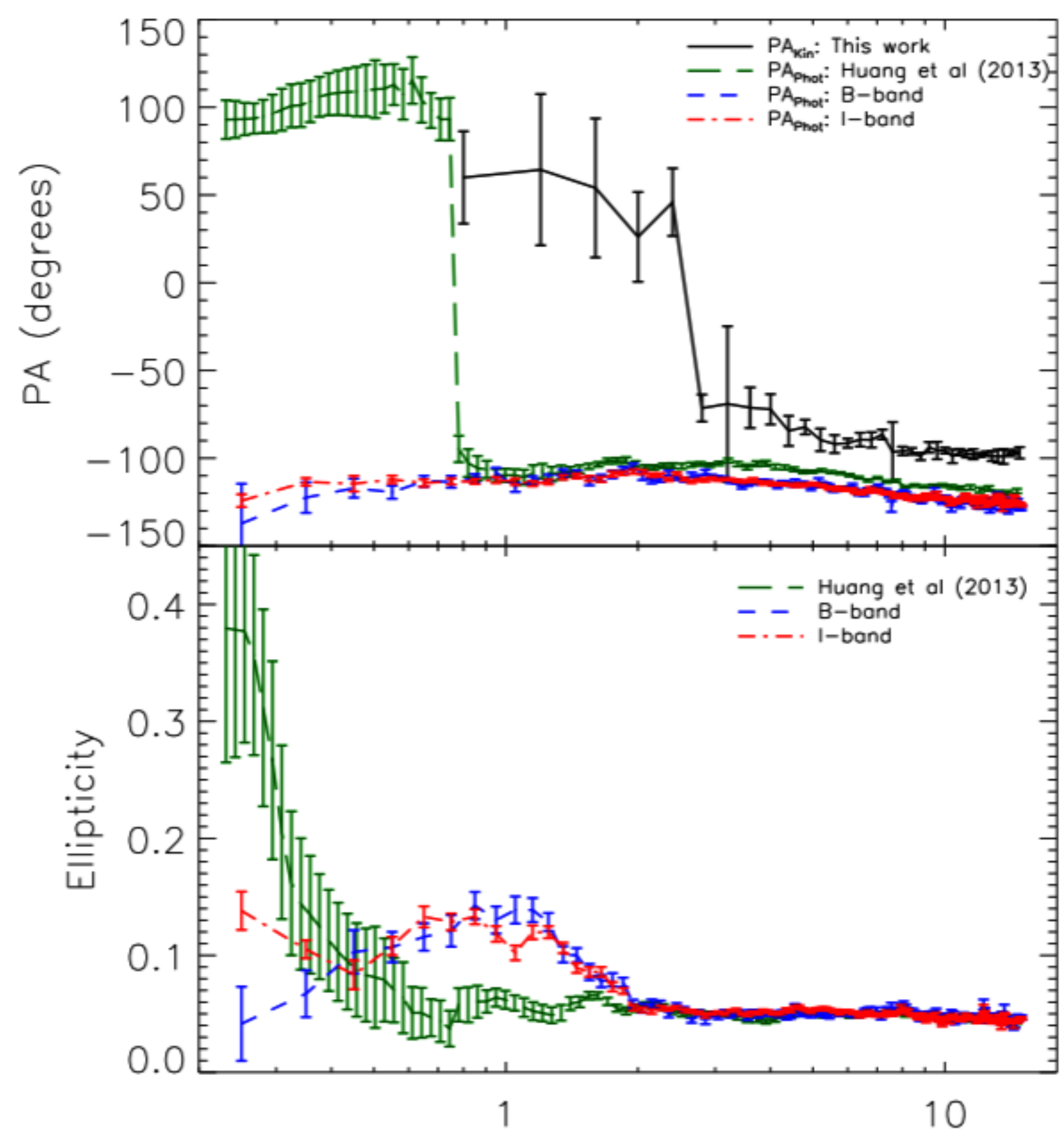


Further evidence for the disruption of the stellar orbits lies in the h_4 maps for the MUSE data presented here and from Arnold et al. (2014), which display a drop within the region of the KDC. This trend indicates a transition from tangential orbits in the region of the KDC to radial orbits within the embedded disc. A similar h_4 profile was detected in the region of the KDC in NGC 5813 by Krajnović et al. (2015). Together, the kinematics maps presented here are reminiscent of those of NGC 4365 by van den Bosch et al. (2008), whose models for those maps represent the KDC as a triaxial structure at the centre of the galaxy. Therefore, it is likely that the KDC in NGC 1407 has a similar structure.

In this case, the positive h_4 in the outer parts of the field of view indicate a bias towards radial orbits, while the drop in the h_4 at the centre reflects a bias towards tangential orbits. The change in the h_4 value at the boundary of the KDC therefore indicates a change in the orbital bias, and thus provides further evidence for a KDC with triaxial orbits. The elongated shape of the region, where h_4


Y (arcsec)
X (arcsec)
Radial Velocity (km/s)

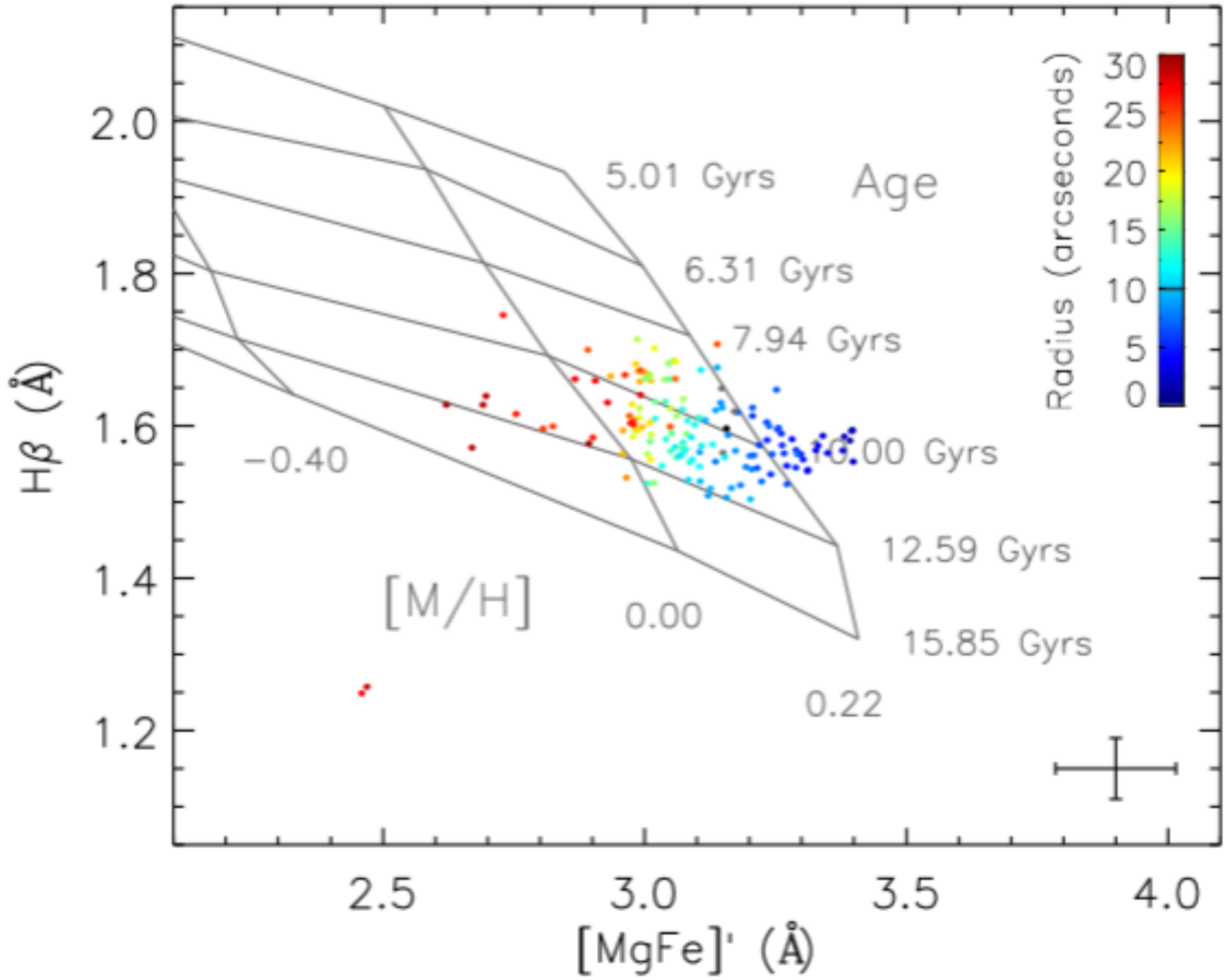

Proctor et al (2009)
Foster et al (2016)
PA_Kin (degrees)
k1 (km/s)
Radius (arcsec)

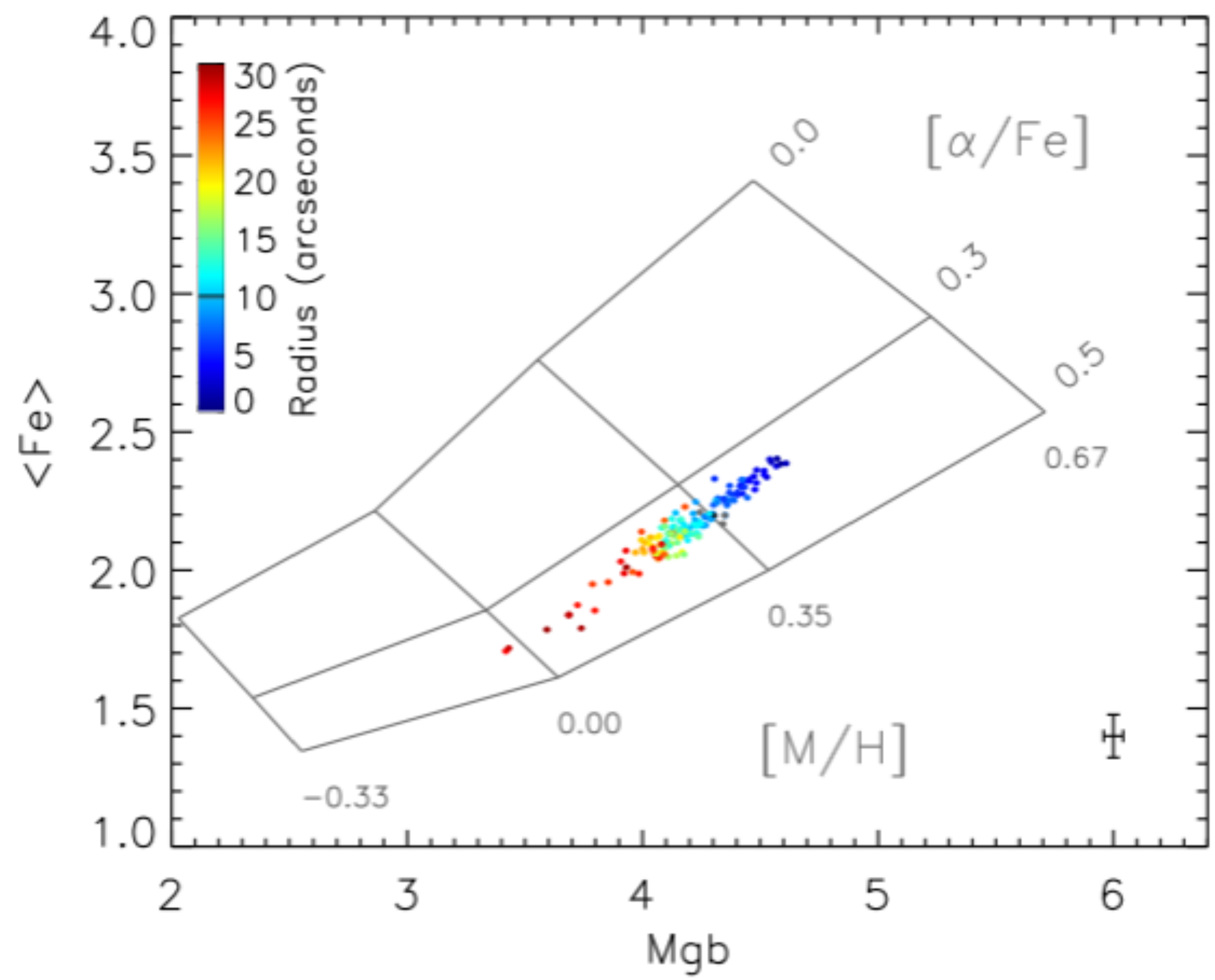

PA_Kin: This work
PA_Phot: Huang et al (2013)
PA_Phot: B-band
PA_Phot: I-band
PA (degrees)
Huang et al (2013)
B-band
I-band
Ellipticity

4 STELLAR POPULATIONS ACROSS NGC 1407

The next question to consider is the formation of the KDC, which can be determined through analysis of the stellar populations within the KDC and the surrounding embedded disc. Events such as major mergers would lead to little difference in the stellar populations between the two kinematical structures since the stellar populations would be thoroughly mixed by the disruption in the stellar orbits (Carollo et al. 1997; Balcells & González 1998; Jesseit et al. 2007; Bois et al. 2010, 2011). On the other hand, a minor merger would produce a KDC that either retains the stellar populations of the progenitor accreted galaxy (Kormendy 1984; Hernquist & Barnes 1991; McDermid et al. 2006), or that shows enhanced metallicity, α-enhancement, and younger ages due to the induced star formation following gas accretion (Balcells & González 1998; Hau, Carter & Balcells 1999). An alternative process would be the creation of a rapidly rotating KDC at the centre of an elliptical galaxy through *in situ* star formation triggered by a flyby interaction with another galaxy (Hau & Thomson 1994).

ence of a black hole. According to Rusli et al. (2013), the black hole has a mass of 4.5×10^9 $M_\odot$ and the diameter of its sphere of influence is 4.38 arcsec, putting it inside the KDC. This black hole may have had a role in the formation of the KDC. For example, simulations by Bekki (2000) have shown that the accretion of gas by the black hole could lead to the formation of a disc around it, and Holley-Bockelmann & Richstone (2000) found that the accretion of a dense stellar structure, such as an infalling galaxy, could lead to the formation of a counter-rotating core when a black hole is present.





age of ∼2.5 Gyr. The uniformly old stellar populations reflect that the KDC formed a long time ago, around the same time as the host galaxy since there is no distinct signature in the age or metallicity at the boundary of the KDC, and the α-enhancement indicates that the material in both the KDC and the embedded disc was formed over similarly short time-scales early in the lifetime of the galaxy. While these results allow us to rule out the possibility of the KDC being formed through a recent accretion event or interaction with a passing galaxy, the difficulties in distinguishing between stellar populations older than ∼10 billion yr mean that we cannot determine if the KDC formed through a major merger or multiple minor mergers at high redshift.