Structural and Kinematic Constraints on the Formation of Nuclear Clusters

Markus Hartmann
Victor P. Debattista, Michelle Cappellari, Anil Seth

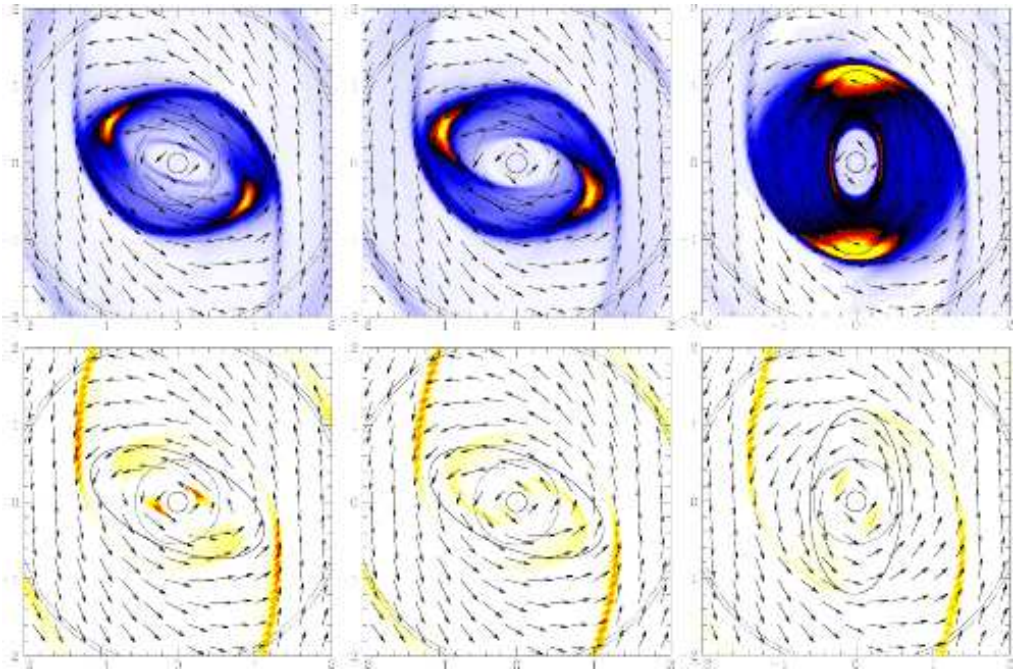
Jeremiah Horrocks Institute
University of Central Lancashire

24 June 2010

1. Introduction
   - Formation Scenarios
2. Simulations
   - Initial Conditions
   - Structural Properties
   - Kinematics
3. Conclusions

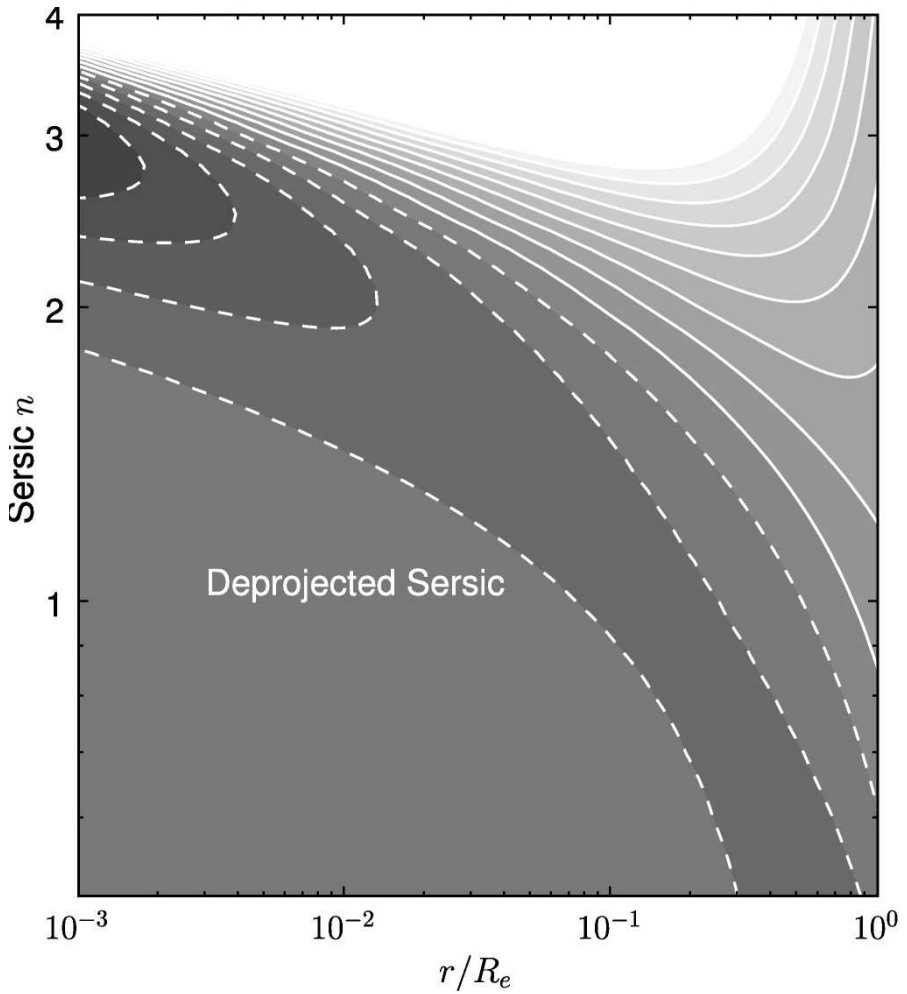
NCs forming in situ out of gas falling into the center

- Magnetorotational instability (Milosavljević, 2004)
- The action of instabilities (Shlosman and Begelman, 1989; Maciejewski et al., 2002; Schinnerer et al., 2008)
- Gas cloud mergers (Bekki, 2007)



Merger of Star Clusters

Tidal forces become compressive in host galaxies with profiles having a Sersic Index < 2 (Emsellem and van de Ven, 2008) within $1/10 R_{\rm eff}$



Merger of Star Clusters

Dynamical friction

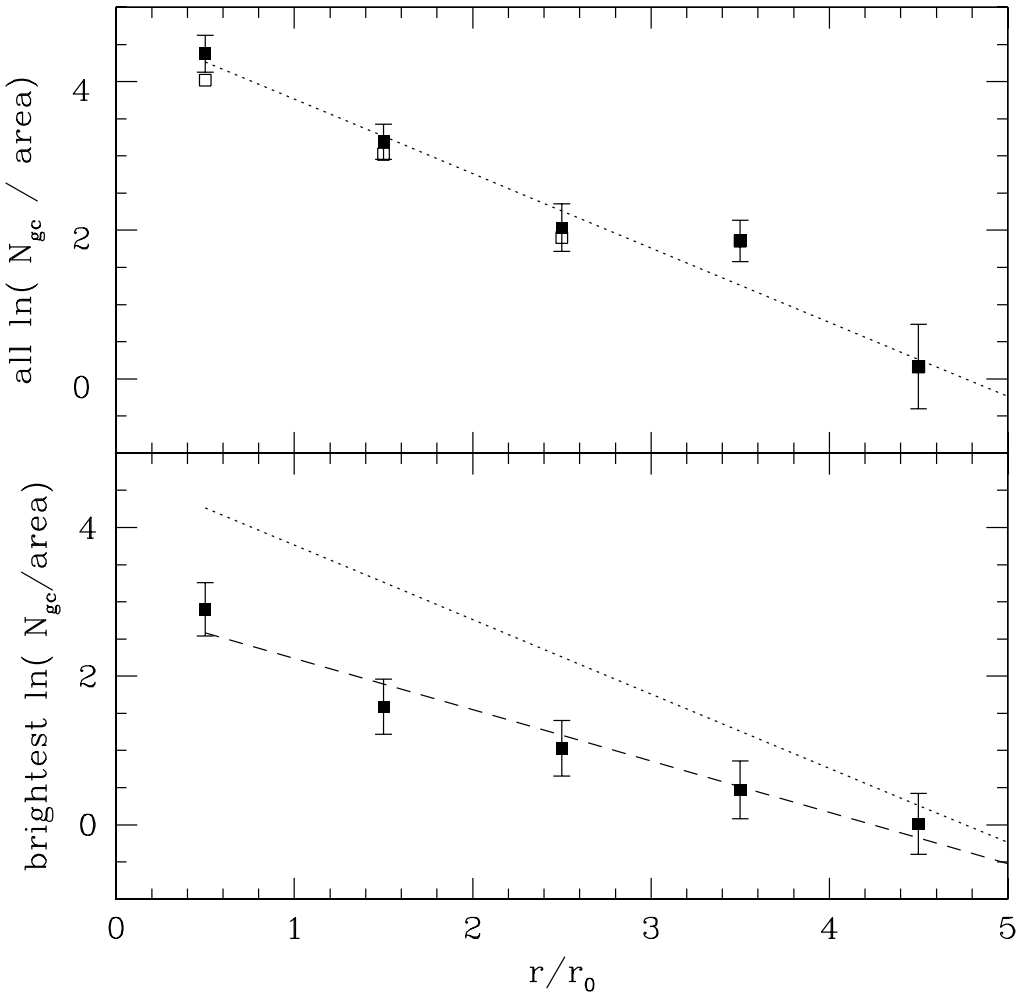
Beyond ~ 1 kpc, however, star clusters may not have enough time to in-spiral in late-type galaxies (Milosavljević, 2004),

$$t \geq 3 \times 10^9 yr \frac{v_{circ}}{50 kms^{-1}} \left(\frac{r}{1 kpc} \right)^2 \left(\frac{M_{GC}}{10^6 \mathrm{M}_\odot} \right)^{-1} \quad (1)$$

which assumes that the dark matter halo is spherical and concentric with the galactic disk. Then the dynamical friction can be calculated by $t \sim v_{circ}^3 / 4\pi G^2 M \rho$ (Chandrasekhar 1943) and the density is given by $\rho \sim v_{circ}^2 / 4\pi G r^2$.

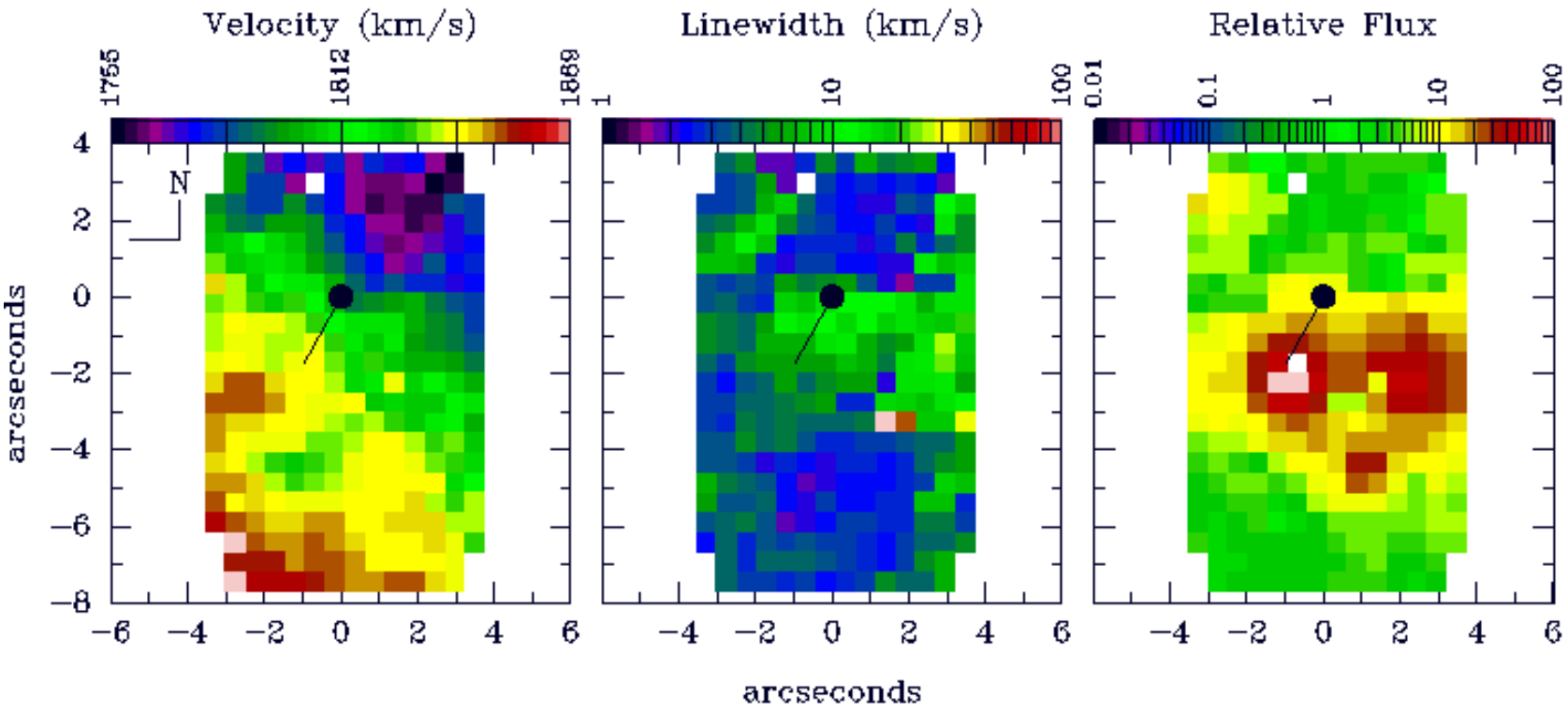
Merger of Star Clusters

Under the action of dynamical friction star clusters sink into the centre (Tremaine et al., 1975; Lotz et al., 2001, 2004; Bekki, 2010)



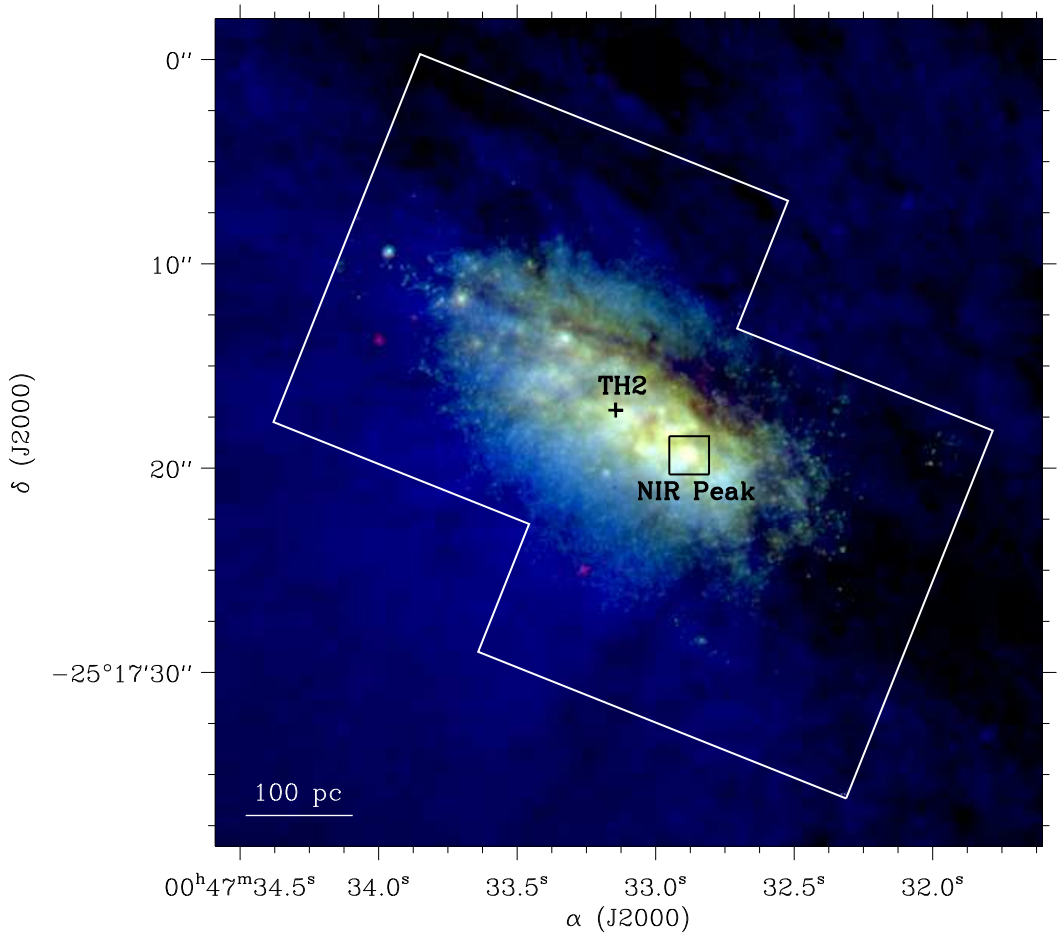
Merger of Star Clusters

Star Clusters in the inner region of NGC 2139 (Andersen et al., 2008)



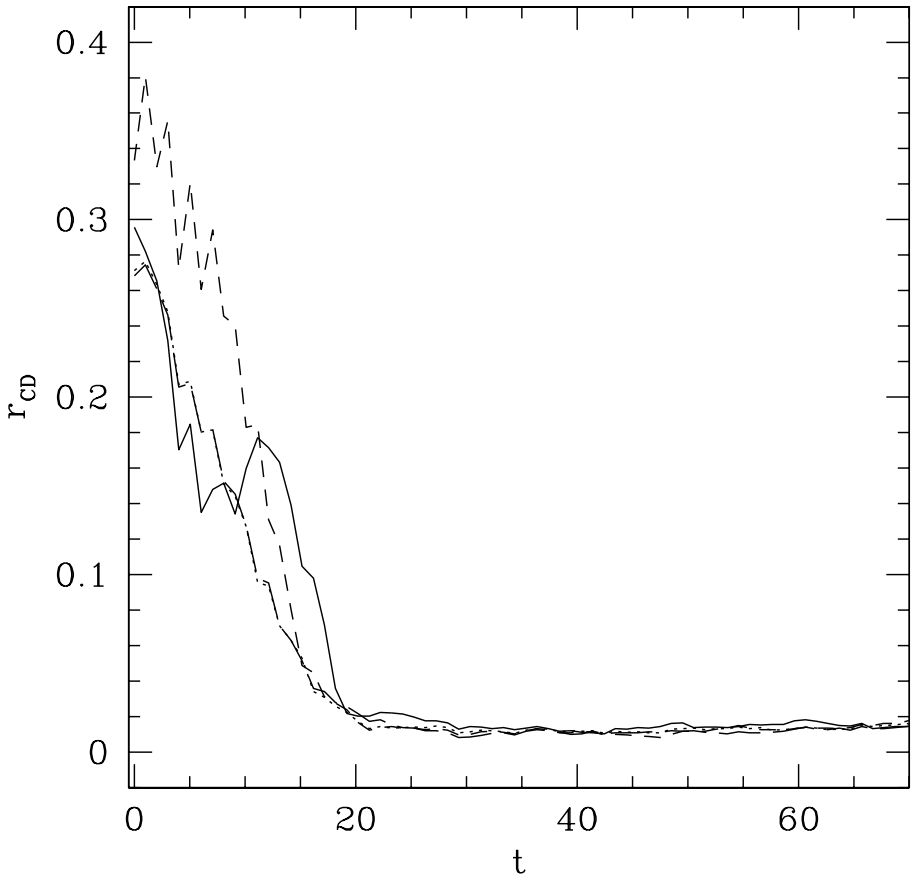
Merger of Star Clusters

Super Star Cluster in nuclear region of NGC 253 Kornei and McCrady (2009)

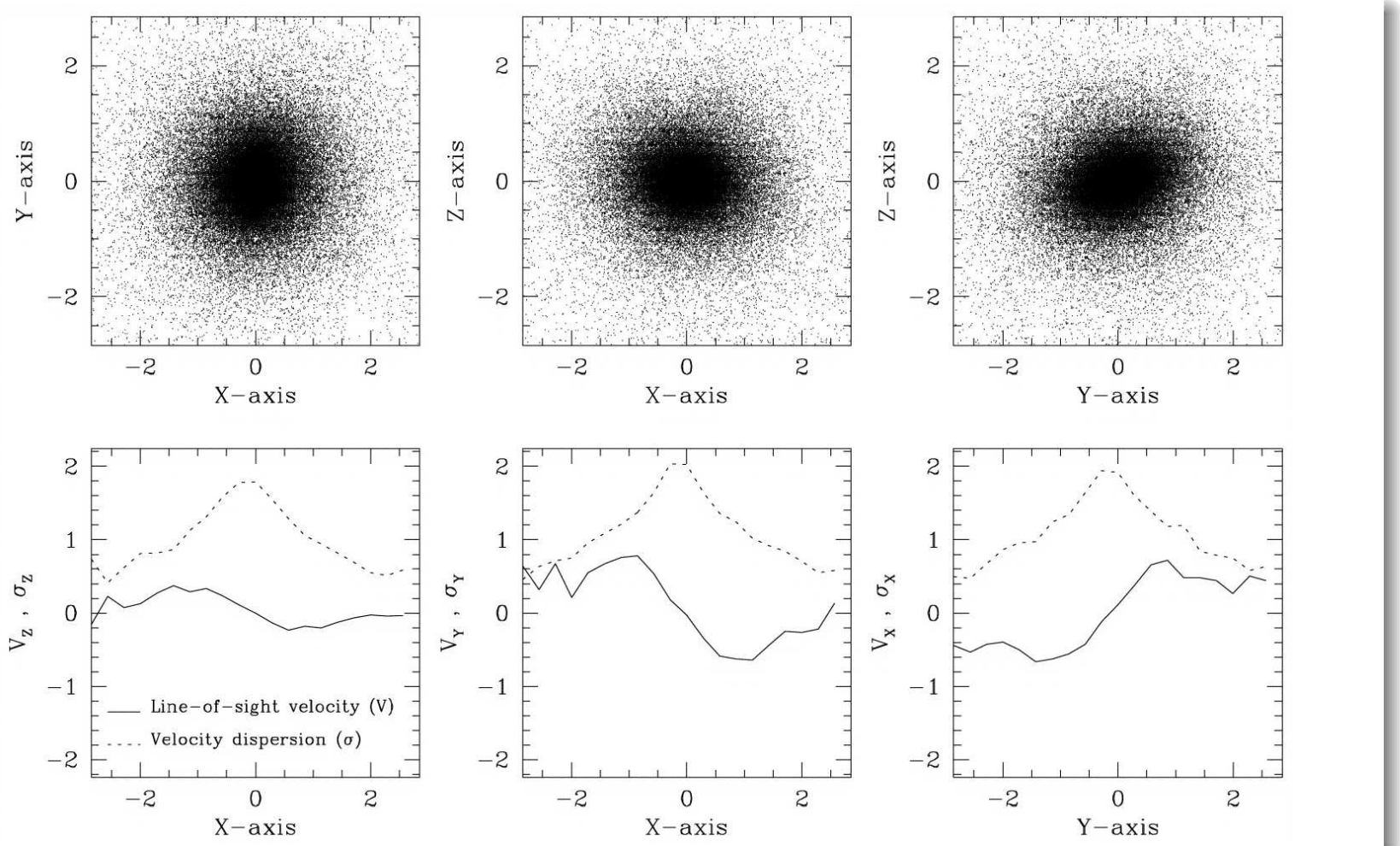


Merger of Star Clusters

Self-consistent simulations have found that mergers do occur (Capuzzo-Dolcetta and Miocchi, 2008) and the resulting NC has structural parameters that are consistent with those observed (Bekki et al., 2004; Capuzzo-Dolcetta and Miocchi, 2008).



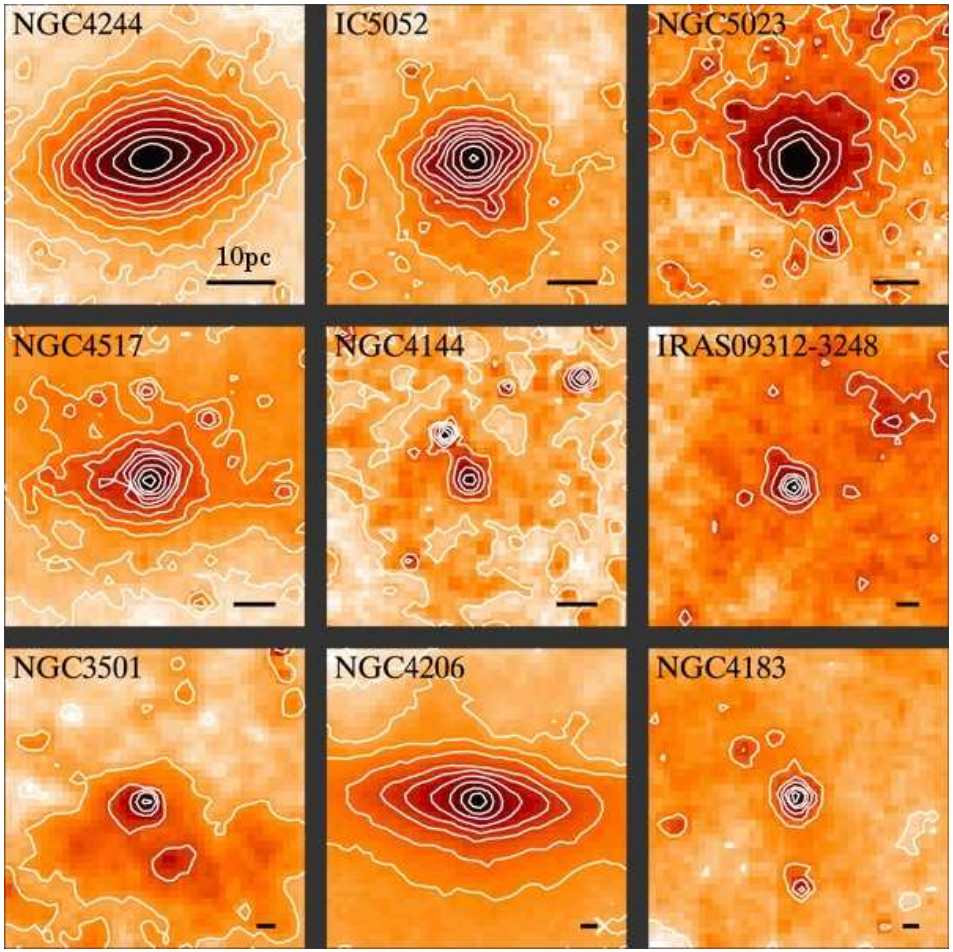
Merger of Star Clusters



The Nuclear Cluster in NGC4244

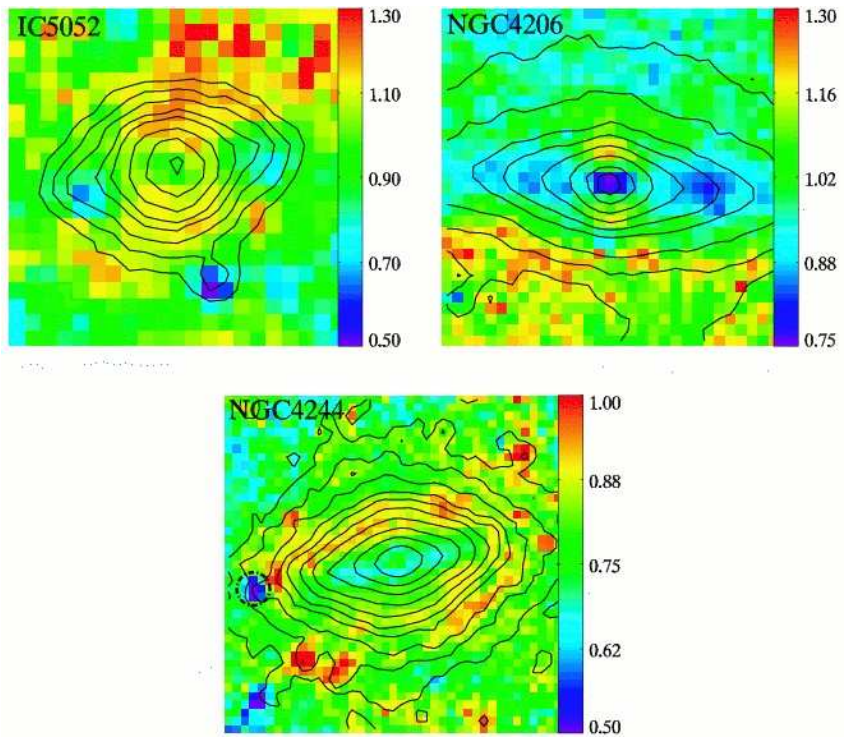
NCs in late-type spiral galaxies

- Multiple stellar populations, typically a young population < 100 Myr and a dominant population older than 1 Gyr.
- Most importantly, NCs are often flattened, compound structures, with a thin disk (NCD) and a spheroid (NCS) (Seth et al., 2006).



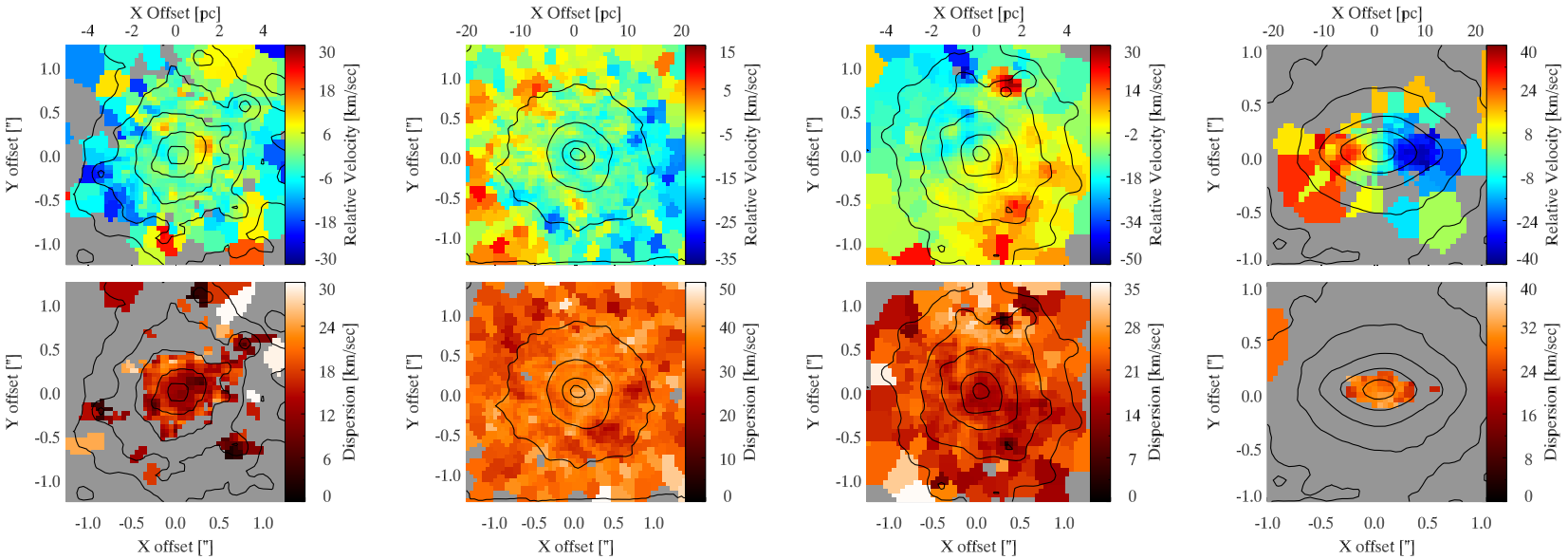
Nuclear Cluster Disks

- In a study of nine spiral galaxies, colourmaps of the NC in IC 5052, NGC 4206 and NGC 4244 show a nuclear cluster disk contain younger stars (Seth et al., 2006).
- In the case of the NC in NGC 4244, spectral and photometric data show that the younger population is in the disk component and comprises $\sim 5\%$ of the total NC mass.



Kinematics of NCs

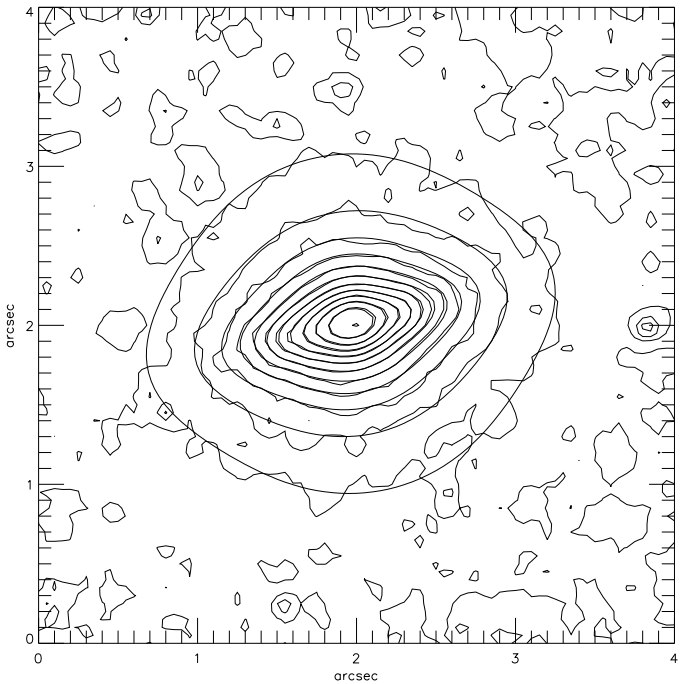
New integral-field data of NCs show rotation in both the disk and spheroidal component (Seth et al., 2008, 2010).

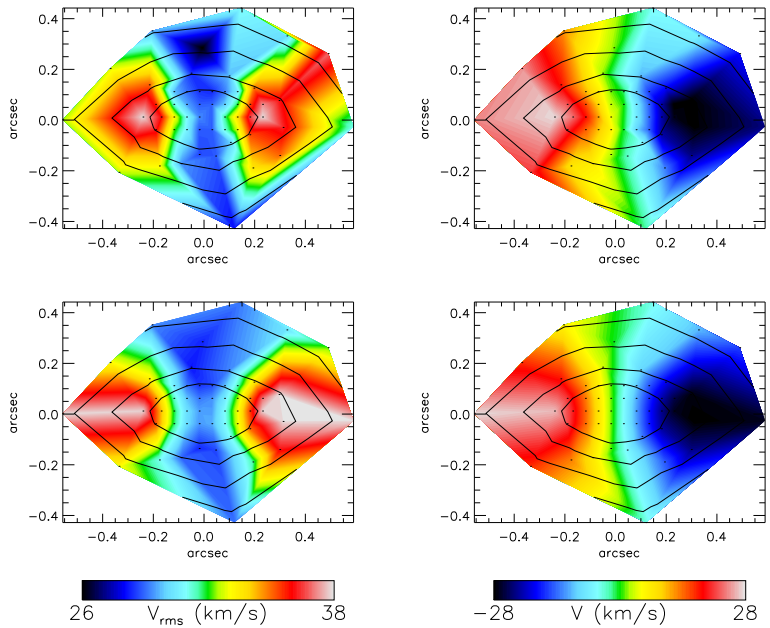


Kinematics of NCs

Jeans Anisotropic MGE Models

We are using the JAM models (Cappellari, 2002; Cappellari et al., 2007) for both the observations and for the simulations.





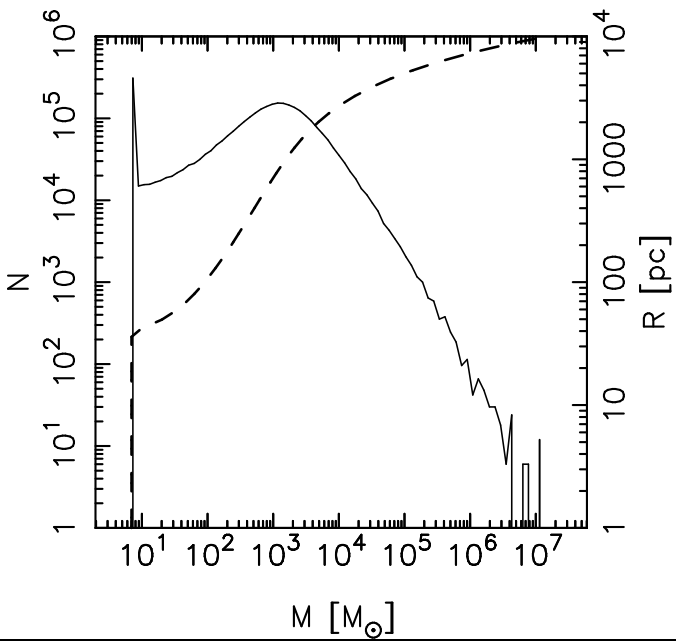
Main Questions

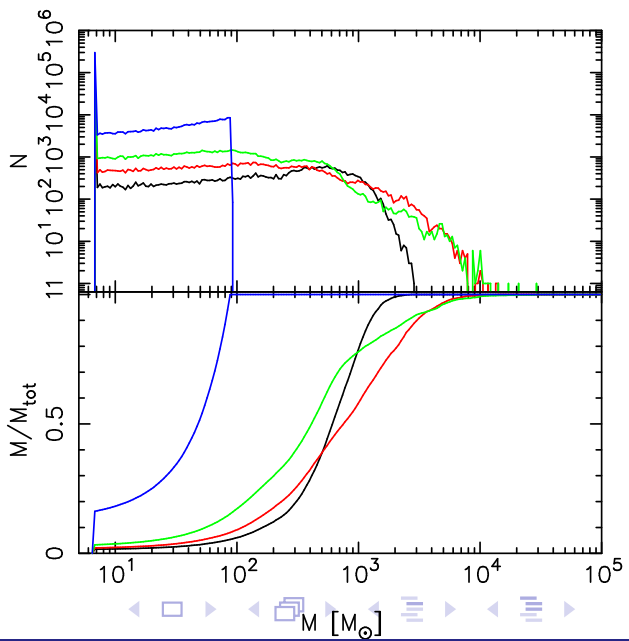
Merger Scenario

- Can the merger of star clusters produce NCs with observed structural and kinematical properties?
- Does the accretion of a star cluster destroy a nuclear cluster disk?
- Do we find any parameters to distinguish between the formation scenarios?

The Main Disk

- NGC 4244 is a late-type, bulgeless galaxy. We adopted an exponential disk.
- We use multi-mass disk particles, with masses ranging from 7 $M_\odot$ within the inner 20 pc increasing to 1.2×10^7 $M_\odot$ in the disk's outskirts.





Merger of Star Clusters

We chose SCs which are sufficiently massive and concentrated to not evaporate too rapidly (McLaughlin and Fall, 2008) and to have orbit decay times due to dynamical friction within the main disk < 3 Gyr (Milosavljević, 2004).

Single Accretion of Star Cluster

We run simulations in which a pre-existing NC accretes a SC. The NC contains a NCD embedded in a NCS. We also run simulations containing only a NCS or NCD component.

Structural properties

Merger Scenario

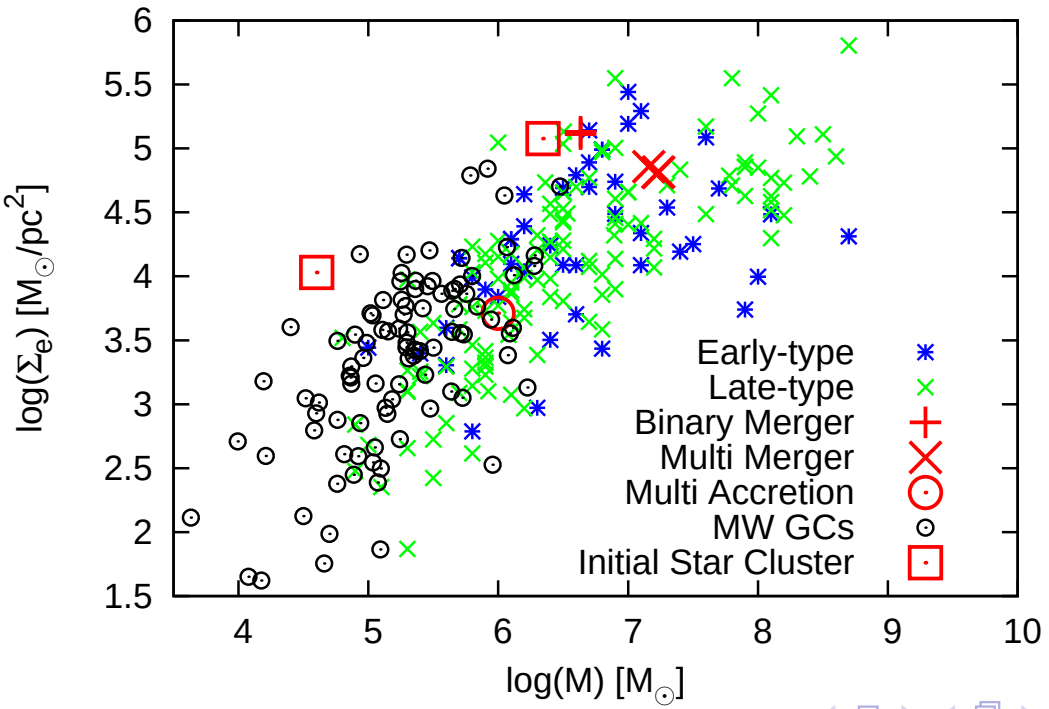
- The mergers are completed in < 40 Myr.
- The NCs have $R_{\rm eff}$ up to 6.1 pc with masses $\sim 10^7$ $\mathrm{M}_\odot$, *i.e.* 97% of the mass of the merged SCs.

Accretion of SCs

- In all simulations the NCs remain flattened, oblate systems. The merging process is rapid within times ranging from 7 to 150Myr.
- The remaining NC $R_{\rm eff}$ evolve by up to 15% due to the smaller mass of the SC.
- The NCs therefore remain with observed structural properties.

Structural Properties

These values are consistent with those of observed NCs in a samples in early-type galaxies (Côté et al., 2006), in late-type spiral galaxies (Carollo et al., 1997, 1998, 2002; Böker et al., 2002; Seth et al., 2006) and Milky Way GCs (Walcher et al., 2005).



Face-on Shape of NCs

Another key structural property of NCs is their shape. As was shown already by Bekki et al. (2004), the merger remnants are triaxial. Very little data exist for the face-on axial symmetry of NCs.

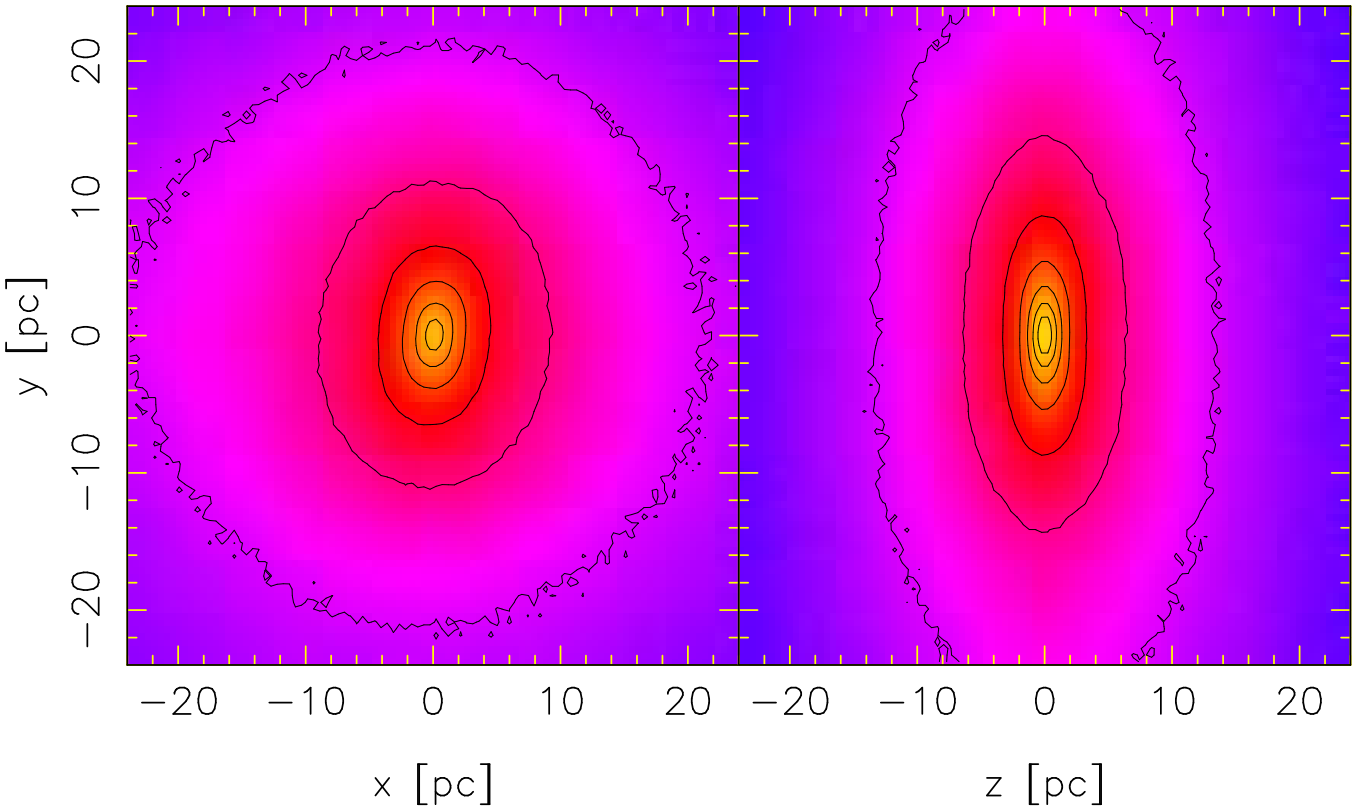
- M33 has an inclination $i = 49^\circ$ (Corbelli and Schneider, 1997) and the NC is aligned with the main disk.
- The intrinsic axis-ratio q_0 is given by

$$q_0 = \sqrt{\frac{(b/a)^2 - \cos^2 i}{\sin^2 i}} \tag{2}$$

- We found $q_0 \simeq 0.7$ that is fully consistent with the range of values of q_0 found in edge-on galaxies by Seth et al. (2006), suggesting that M33 has an nearly axisymmetric NC.

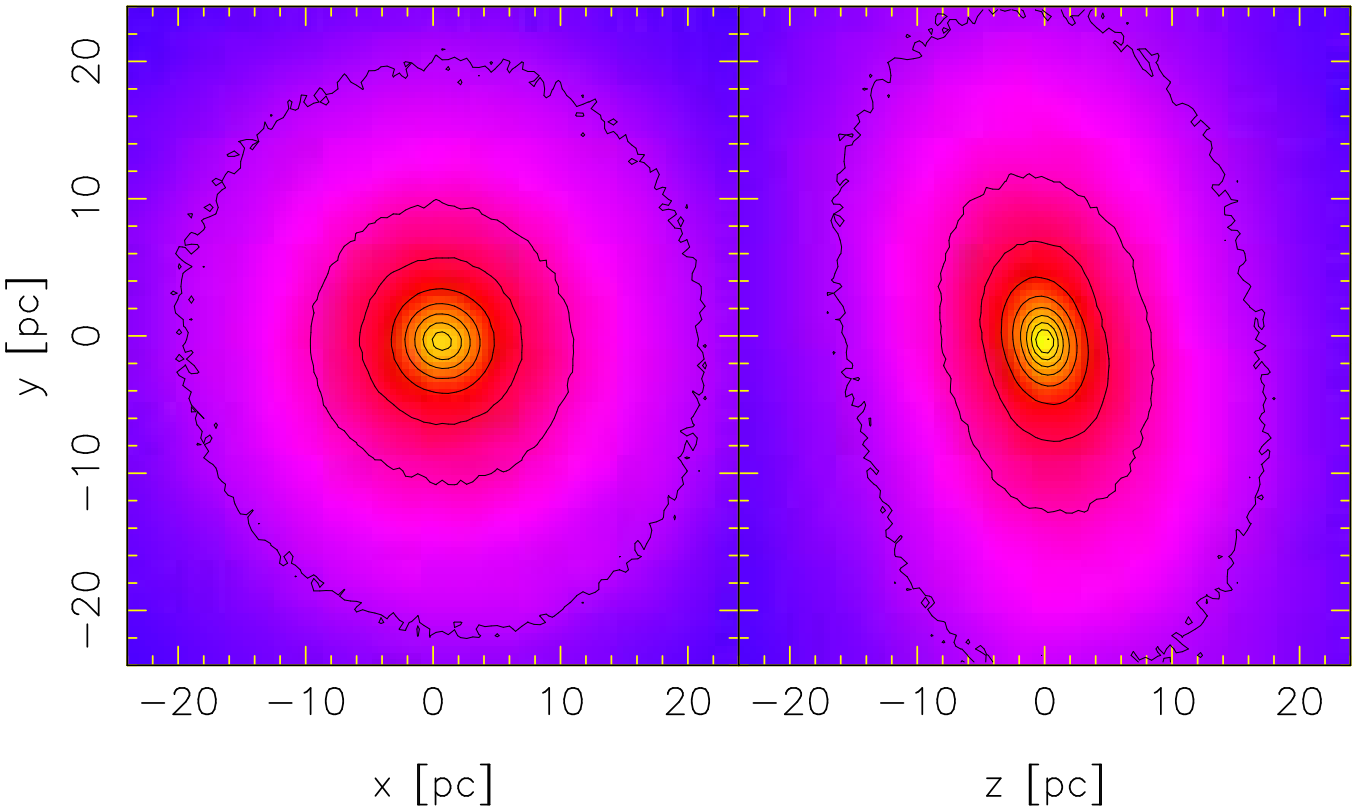
Shape of NCs

The merger of SCs produce a triaxial NC.



Shape cannot distinguish between the formation scenarios

However, if the SCs have initial vertical motions or intermediate mass black holes reside at the centre of the SCs, we find axisymmetric NC.

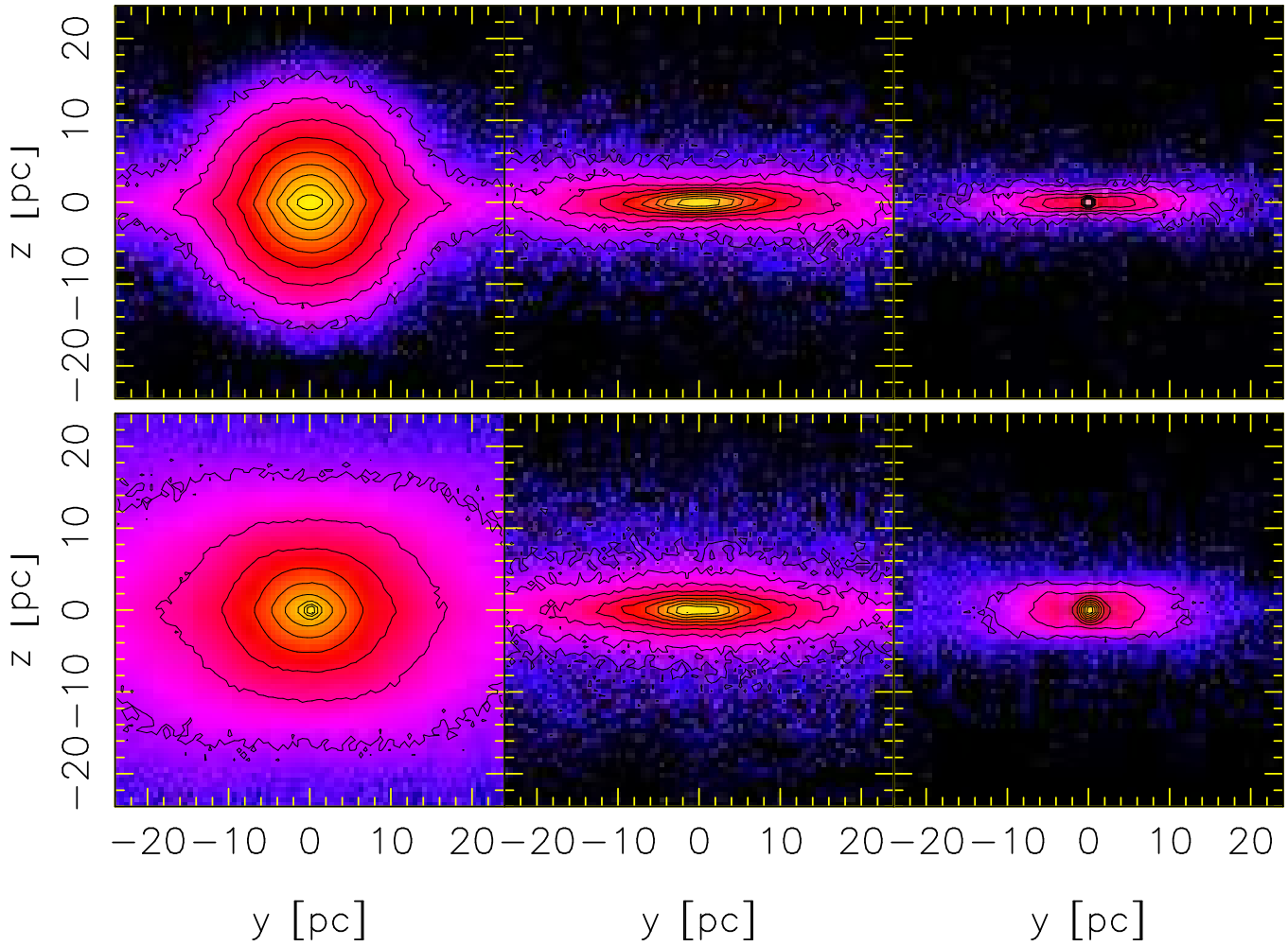


Structural Properties

Accreted spheroidal and disk particles

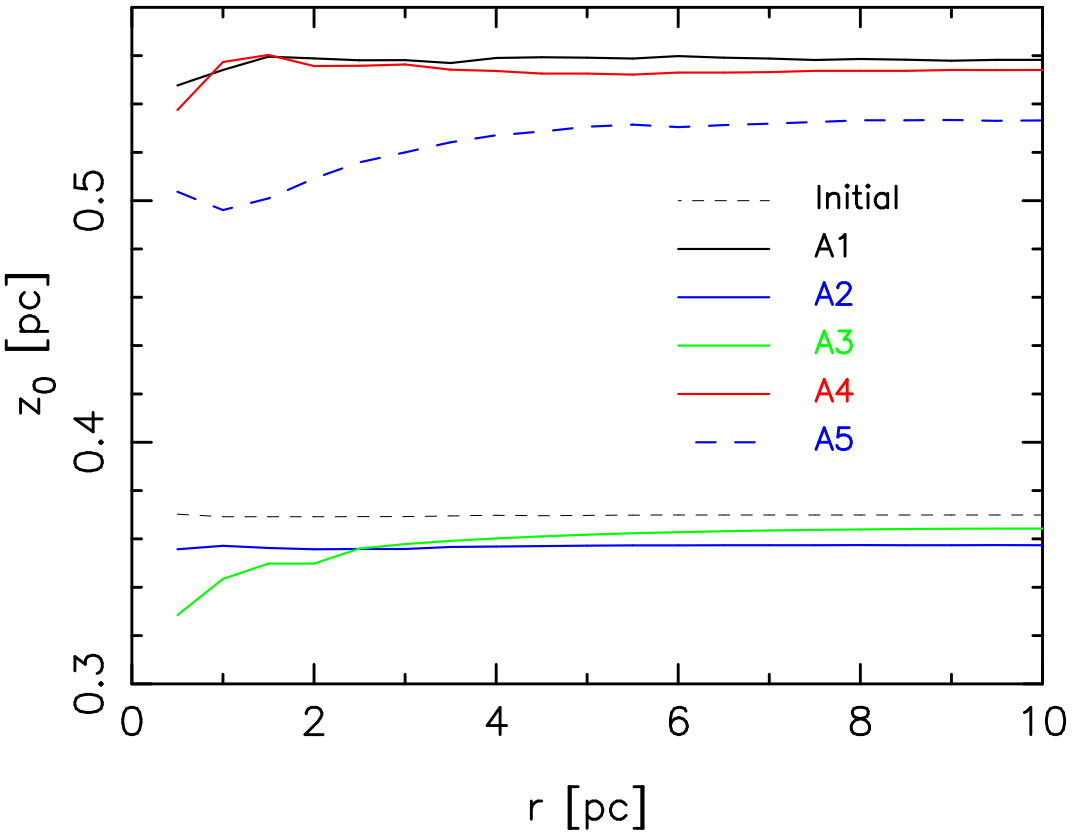
- The simulations show that most of the particles $> 90\%$ sink into the very centre of the pre-existing NC.
- In one simulation the SC disrupted at a radius of ~ 8 pc before merging.
- The rate of accretion and the disruption depends on the density of the merging SC.

Single Accretion of SC onto pre-existing NC



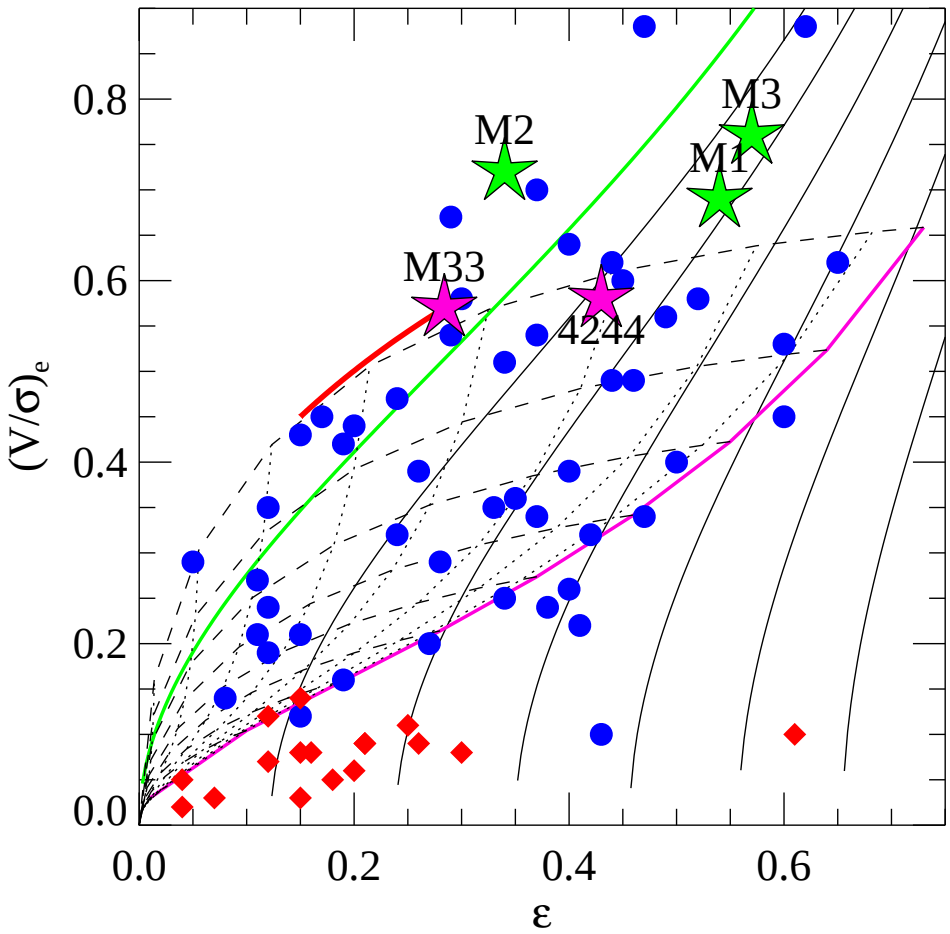
Nuclear Cluster Disk

- Initially $z_0 \simeq 0.37$ pc.
- Accretion heats the NCD within $R_{\rm eff} \approx 4$ pc.
- The NCD in NGC4244 has $z_0 \simeq 1.4$ pc.



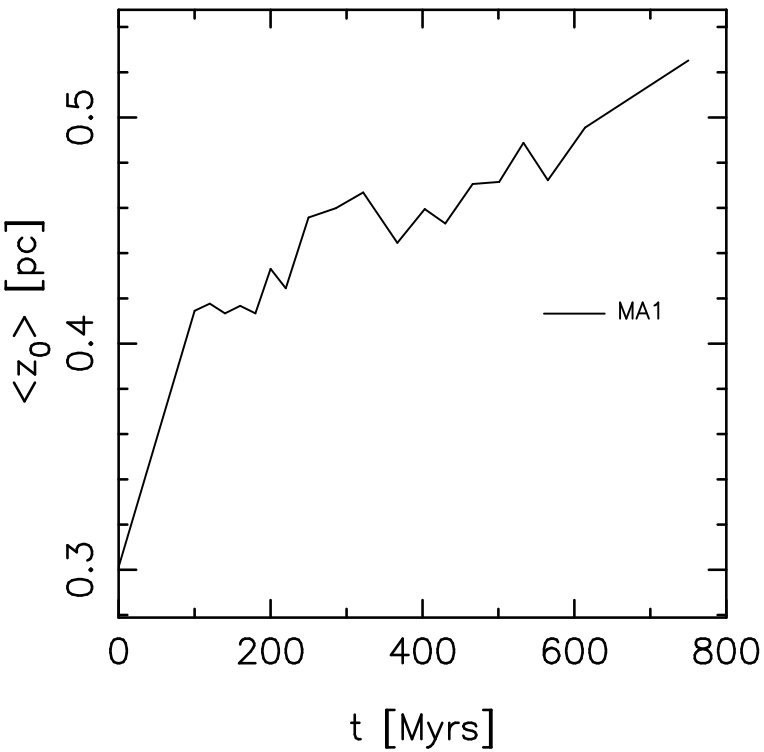
Kinematics

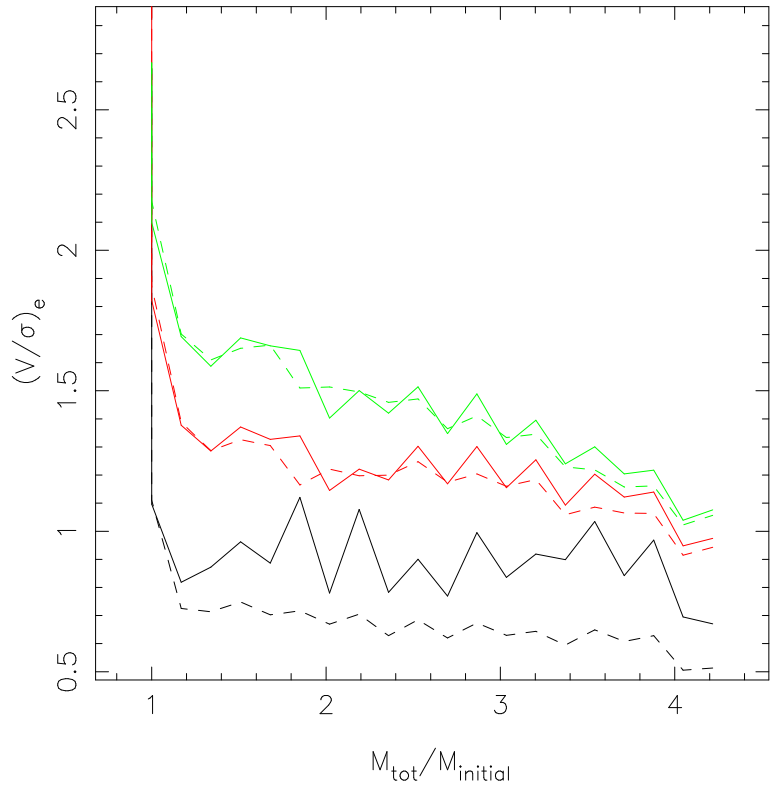
- In the $V_p/\sigma - \epsilon$ plot (Binney, 1978, 2005) we are able to diagnostic that the mergers produced rotating NCs considerably than observed in NGC 4244 and M33.
- NCs M1 and M3 are more anisotropic and flatter than M2
- The NC in NGC 4244 is also weakly anisotropic.



Multiple Accretion of SCs

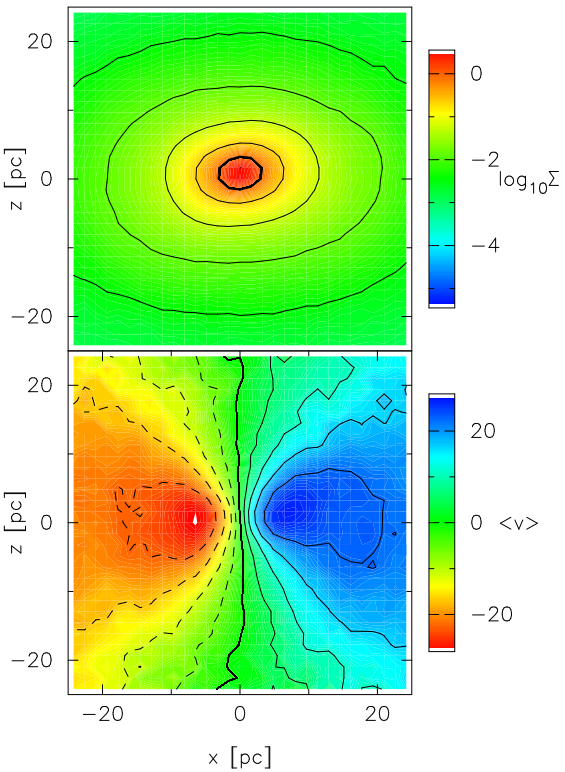
Nuclear Cluster formation is an on-going process. We study the multiple accretion of SCs onto a initial NCD; how the NCD evolves and how the accretion alters the kinematics.

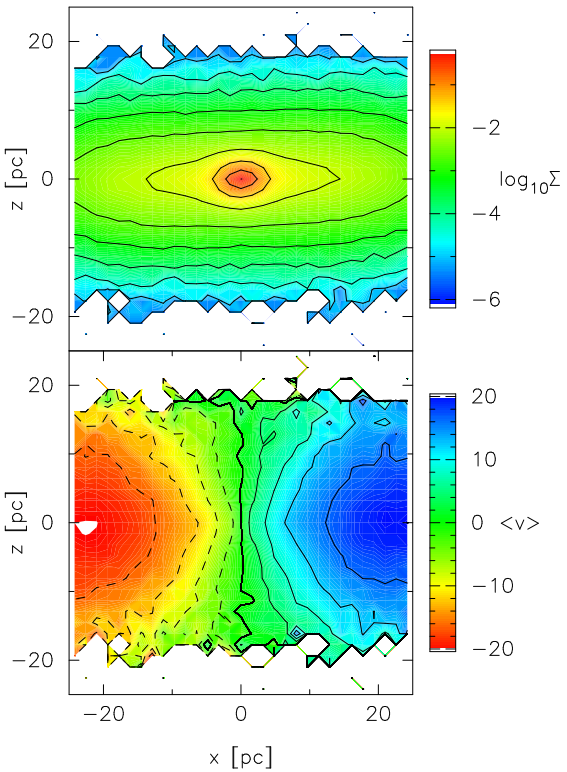


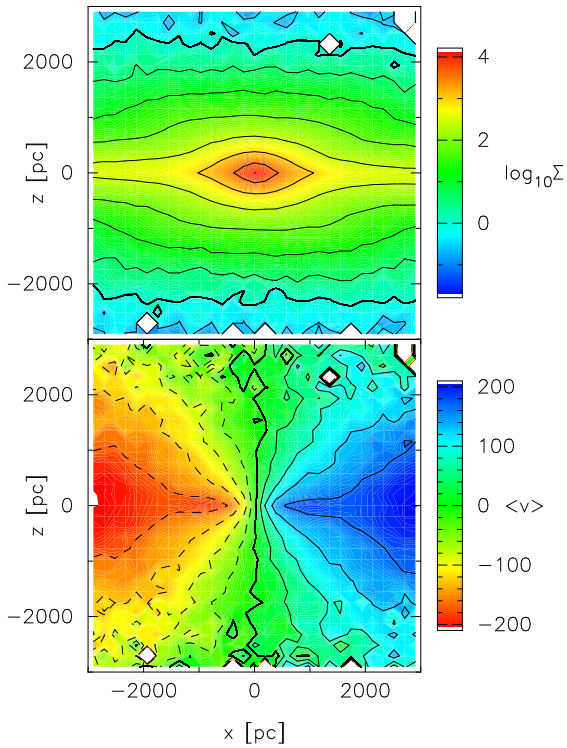


Kinematics

Comparison of the velocity fields with a simulation of a disk galaxy (Roškar et al., 2008a).





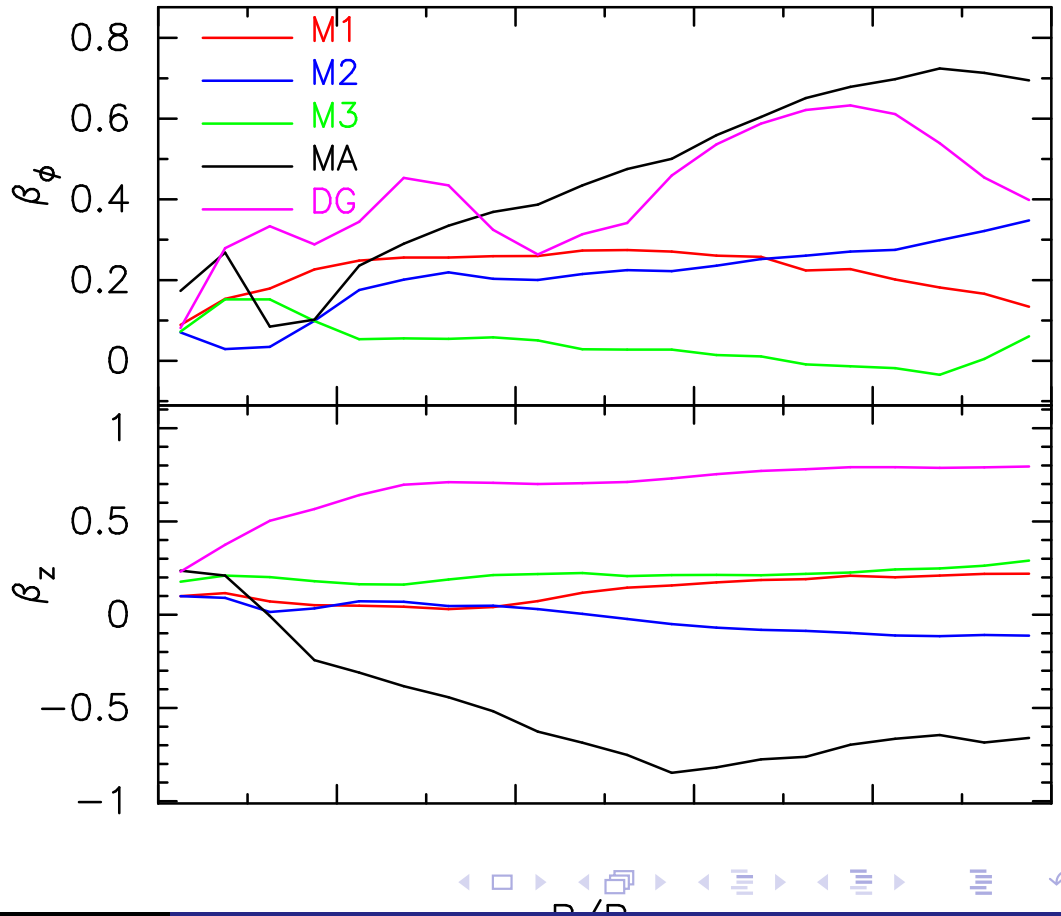


Kinematics

Anisotropy $\beta_\phi = 1 - \frac{\sigma_\phi^2}{\sigma_R^2}$ and $\beta_z = 1 - \frac{\sigma_z^2}{\sigma_R^2}$

- Initial vertical motions of the SCs in M2 leads to the smallest β_z.
- The anisotropy is consistent with the JAM models.

Run	β_ϕ	β_z
M1	0.1	0.25
M2	0.1	0.10
M3	0.1	0.25
NGC 4244	0.0	-0.1



Structural Properties

- The structural properties of the merger remnants NCs are consistent with observed properties of NCs.
- The accretion of star clusters do not destroy the nuclear cluster disk.

Kinematics

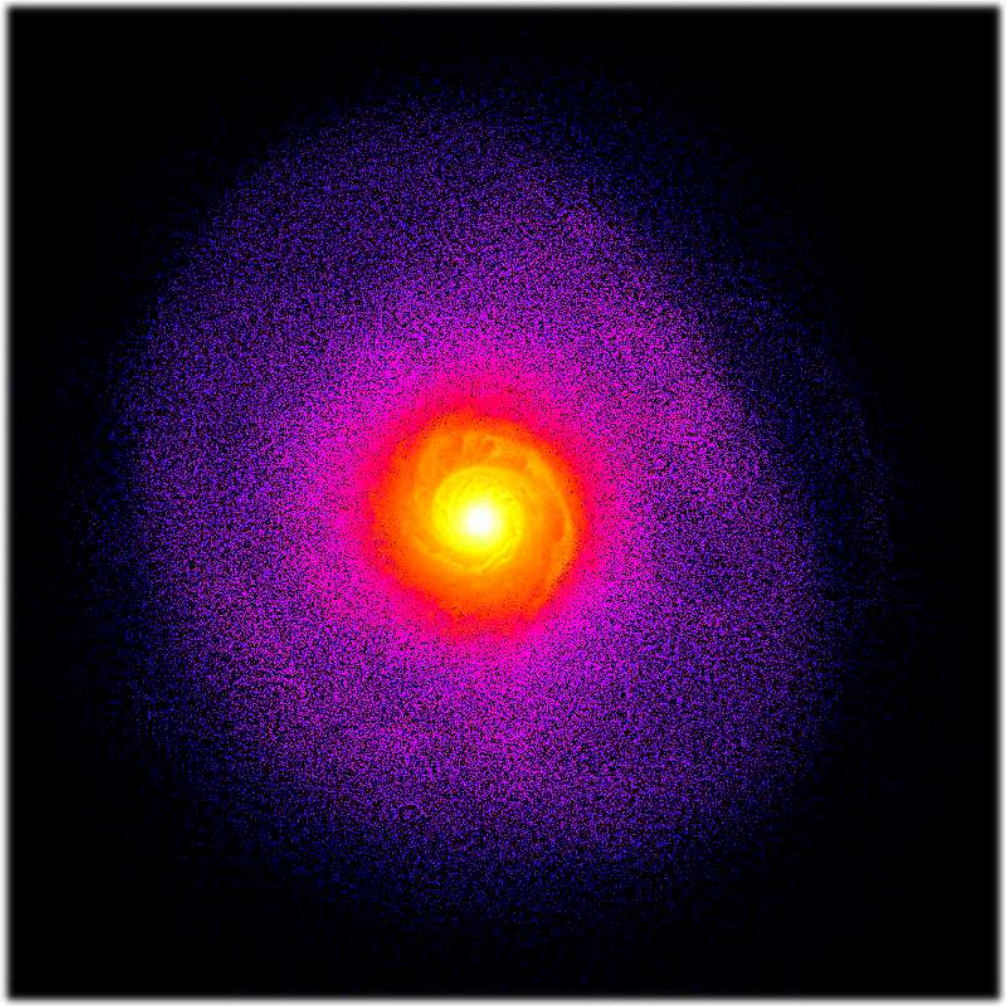
- The merger and the subsequent accretion of SCs produce NCs having rotation as observed in NGC4244 and M33.
- The merger scenario predicts radially biased NCs.
- The anisotropy and velocity fields are promising parameters to distinguish between the formation scenarios of SC mergers and the accretion of gas with in situ star formation (Hartmann et al. in progress)

Kinematics

- The merger scenario predicts radially biased NCs.
- The anisotropy and velocity fields are promising parameters to distinguish between the formation scenarios of SC mergers and the accretion of gas with in situ star formation.

Future Work

- In a merger of galaxies gas is funneled to centre and forms a massive and turbulent nuclear disk. A comparison of these nuclear disks with our simulations will bring deeper insights in the differentiation of the formation scenarios.



Future Work

Formation scenario

- We are planning to setup initial conditions to study the supply of gas into the central region.
- The formation of long-lived secondary bars without the presence of gas has been shown by Debattista & Shen (2007).

Literature

Andersen, D. R., Walcher, C. J., Böker, T., Ho, L. C., van der Marel, R. P., Rix, H.-W., and Shields, J. C. (2008). Caught in Formation: The Nuclear-Cluster-to-Be in NGC 2139. ApJ, 688:990–999.

Bekki, K. (2007). The Formation of Stellar Galactic Nuclei through Dissipative Gas Dynamics. *Publications of the Astronomical Society of Australia*, 24:77–94.

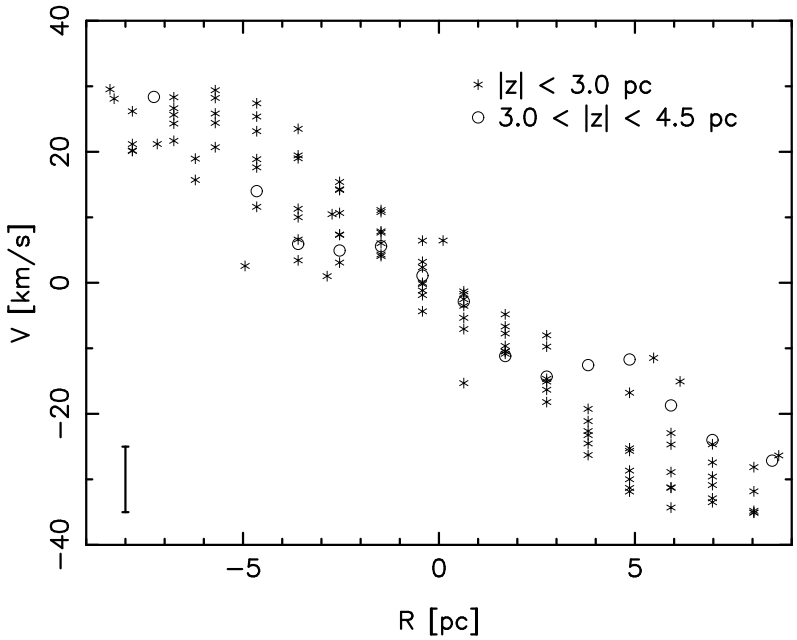
Bekki, K. (2010). Dynamical friction of star clusters against disc field stars in galaxies: implications on stellar nucleus formation and globular cluster luminosity functions. MNRAS, 401:2753–2762.

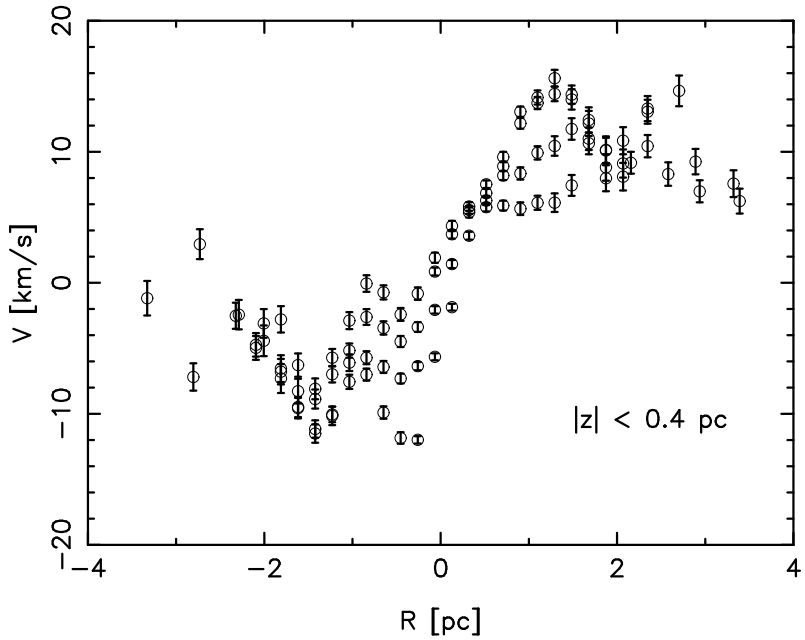
Bekki, K., Couch, W. J., Drinkwater, M. J., and Shioya, Y. (2004). Cluster Cannibalism and Scaling Relations of Galactic Stellar Nuclei. ApJ, 610:L13–L16.

Binney, J. (1978). On the rotation of elliptical galaxies. MNRAS,

Kinematics of NCs

Rotation along the major axis - NGC4244 shows rotation in NCD and NCS component and the NC in M33 is also in rotation.

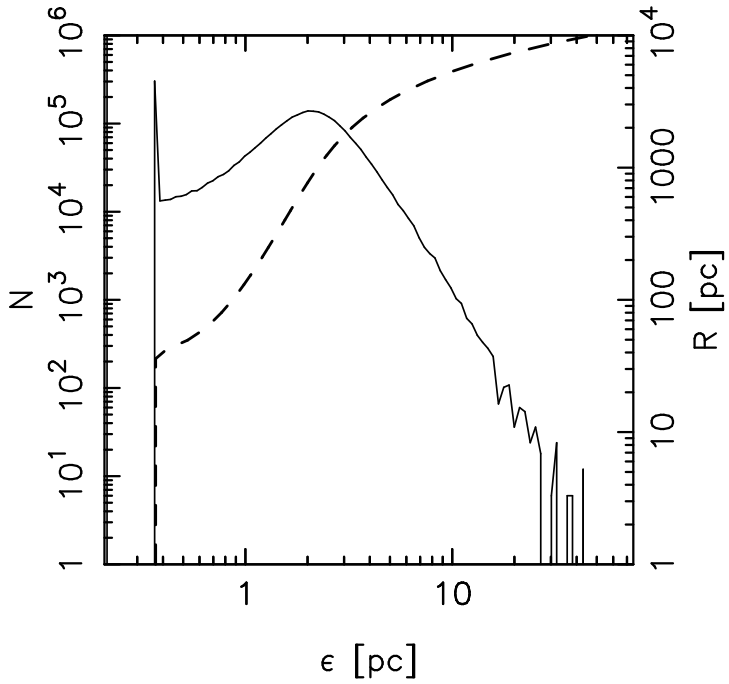




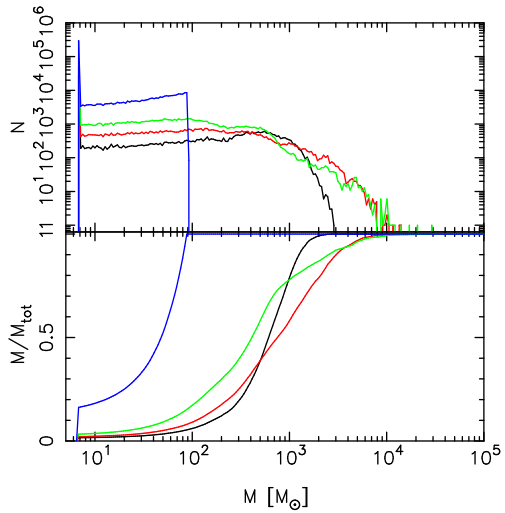
The Main Disk

Softening

The softening length is related to the mass via $\epsilon_p(m_p) \propto m_p^{1/3}$.



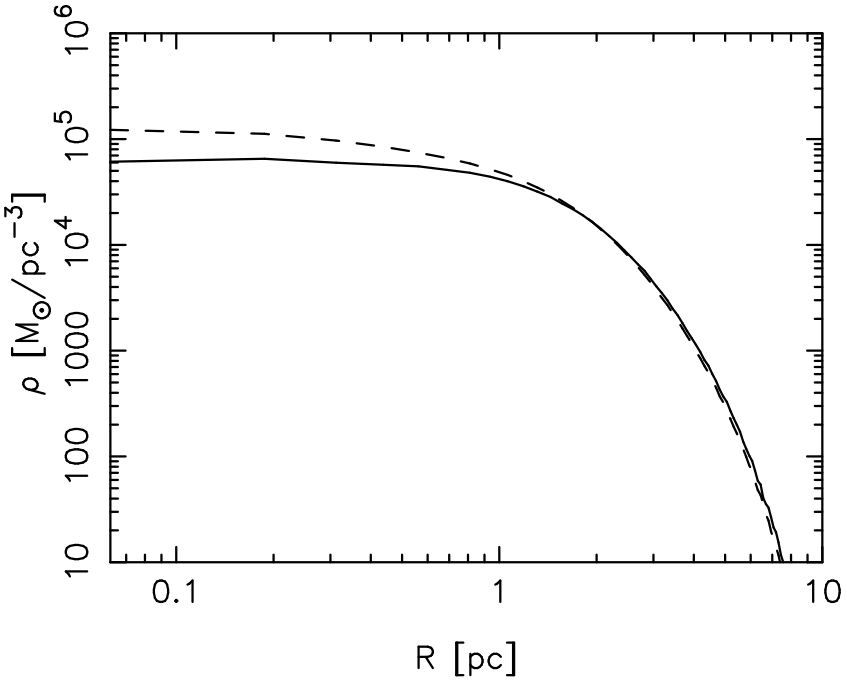
Radial oscillations can drag massive particles to the central regions (Debattista et al., 2006; Sellwood and Binney, 2002; Roškar et al., 2008b). We relaxed the system for 10 Myr, after which particles in the central 100 pc have masses ranging from $6.9\mathrm{M}_{\odot}$ to $2.9 \times 10^4 \mathrm{M}_{\odot}$.



PKDGRAV

PKDGRAV is an efficient, parallel treecode and a multi-stepping code, with timesteps refined such that $\delta t = \Delta t/2^n < \eta(\epsilon/a)^{1/2}$, where ϵ is the softening and a is the acceleration at a particle's current position. We use base timestep $\Delta t = 5 - 25 \times 10^4$ years and $\eta = 0.1$ in all cases.

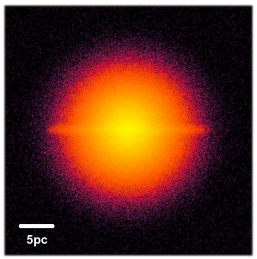
Star Cluster Merger Simulations

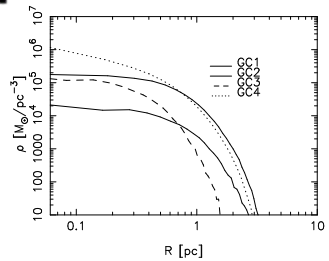


In one simulation, we include intermediate mass black holes (IMBHs) in the SCs, which have been suggested to lurk at the centers of some SCs (Gebhardt et al., 2000; Gerssen et al., 2002, 2003; Noyola et al., 2008). We adiabatically grew, over a period of 100 Myr, the IMBHs as a single particle with softening $\epsilon_p = 0.042$

Star Cluster Accretion

We also run simulations in which a pre-existing NC with a NCD accretes a SC. The NCD consists of an exponential disk of the type of the galactic disk. The NC consists of 3.76×10^6 and the NCD of 2.4×10^5 particles, so that the disk particles represent 6% of the total mass. The total mass of the NC is 4.03×10^6 $\mathrm{M}_\odot$. The accreted SCs had a variety of masses and concentrations.





Merger Scenario

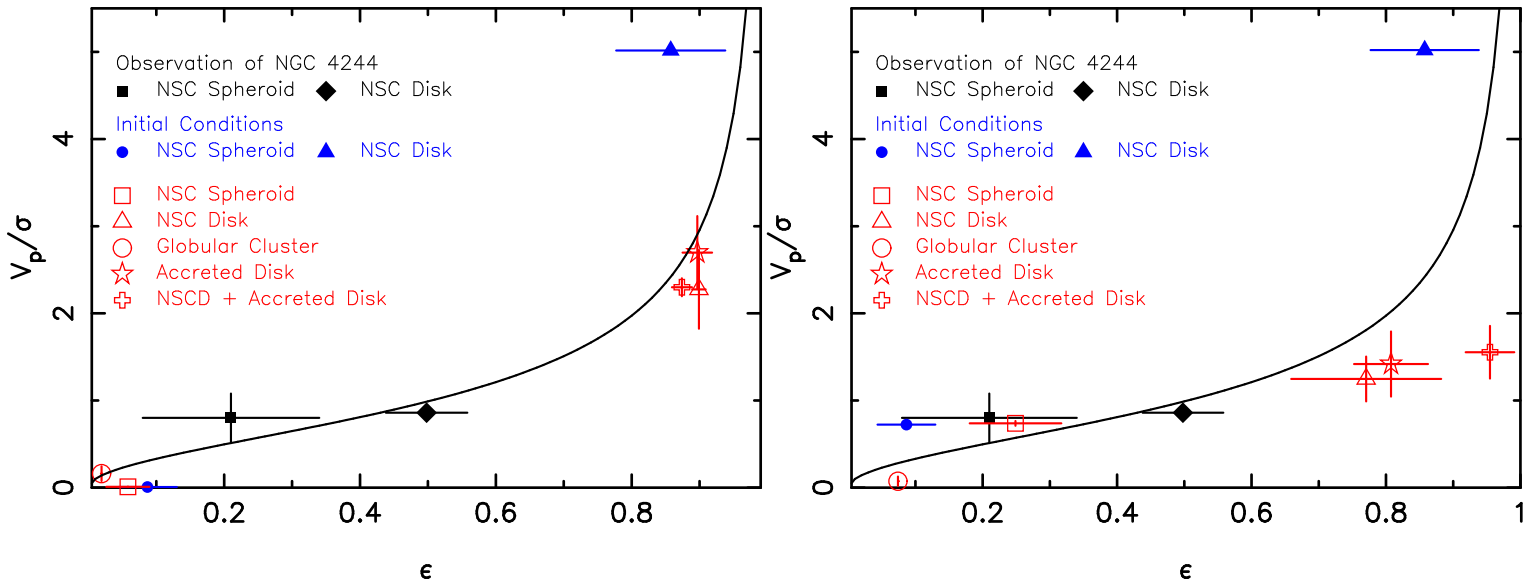
We ran two sets of simulations to investigate the formation of NCs in mergers of SCs within the centre of the galaxy.

- The first set consists of two massive SCs placed on opposite sides of the galaxy centre and separated by 66 pc. We gave them tangentially directed velocities $3.3\,\mathrm{km\,s^{-1}} \sim 0.4 V_c$ in B1 and $4.1\,\mathrm{km\,s^{-1}} \sim 0.5 V_c$ in B2. The mass ratio of the SCs mass within 33 pc of the main disk is 3.2.
- The second set of simulations uses the merger of eight SCs. In run M1 the SCs were placed at radii from 14 to 92 pc with velocities in the range 8 to 13 $\mathrm{km\,s^{-1}}$, which are $\sim 60\%$ of the local circular velocity.

Accretion Scenario

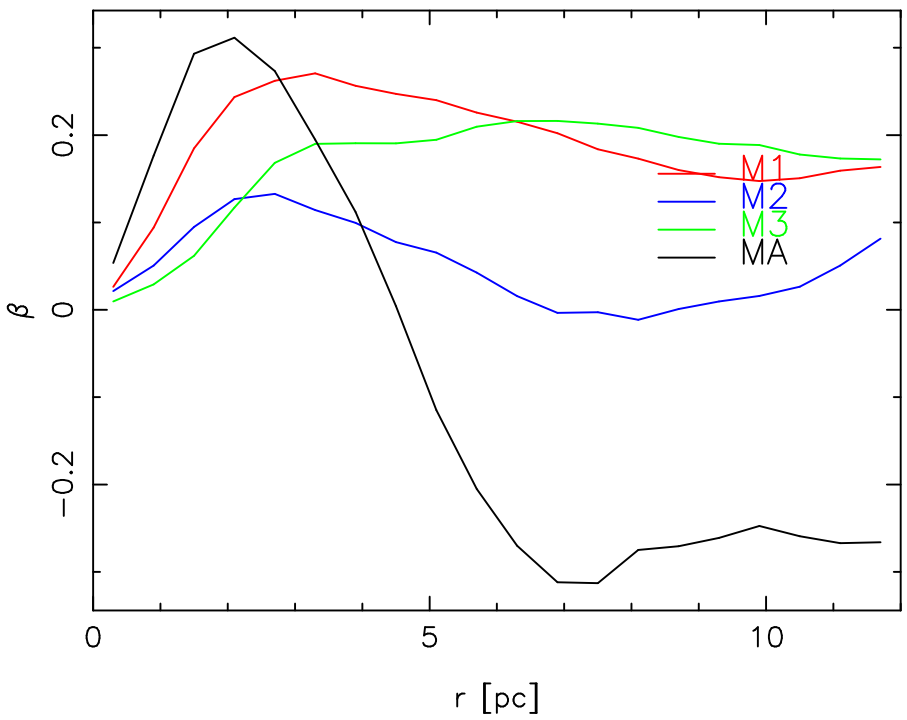
In all accretion simulations we placed the SC 50 pc from the centre of the NC in the plane of the NCD, which is also the plane of the main disk. We varied the orbits, masses and concentrations of the SCs. We used SC1 in runs A1, A2, A3, A7 and A8, SC2 in A4, SC3 in A5 and finally SC4 in A6 containing an IMBH.

The decomposition of the NCs show negligible rotation in the NCS, except the NCS is initially in rotation. The NCDs rotate comparable to NGC4244.



Kinematics

- The anisotropy $\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$ shows in all simulations radially biased systems.
- Despite the presence of a IMBH M3 is more radially than M2, however the radius of influence of the IMBH is smaller than 1 pc, which explains the absence of tangential bias within $R_{\rm eff}$.



If the super star cluster found by Kornei and McCrady (2009) in the nuclear region of NGC 253 were to form the basis of a NC, how would the accretion of SCs alter its kinematics?

