Dynamics of Nuclear Star Clusters

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"Central Massive Objects"

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....

Image: NASA/JPL-Caltech/S. Stolovy (Spitzer Science Center /Caltech)

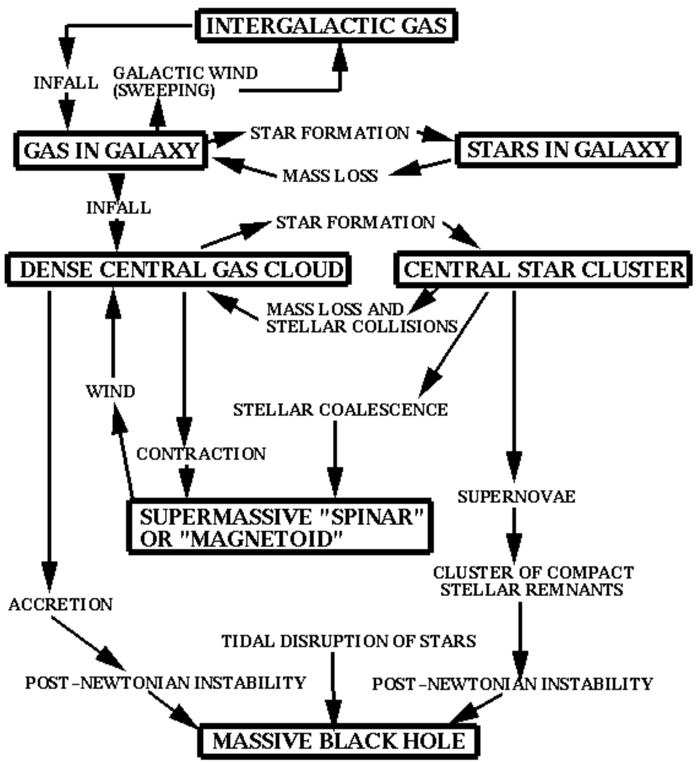
I. Formation via cluster infall

II. Evolution over relaxation time scales

III. Triaxiality and its consequences

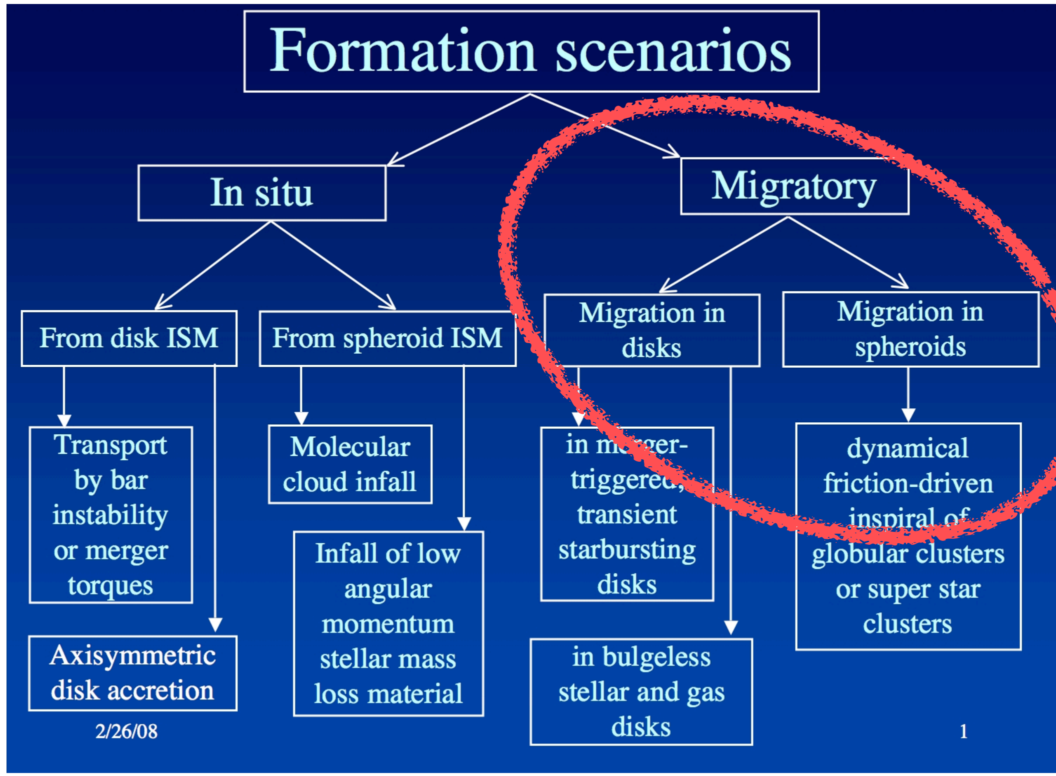
I. Formation

Black Holes



Rees 1988

Nuclear Star Clusters



Milosavljevic 2008

Why Migration of Star Clusters?

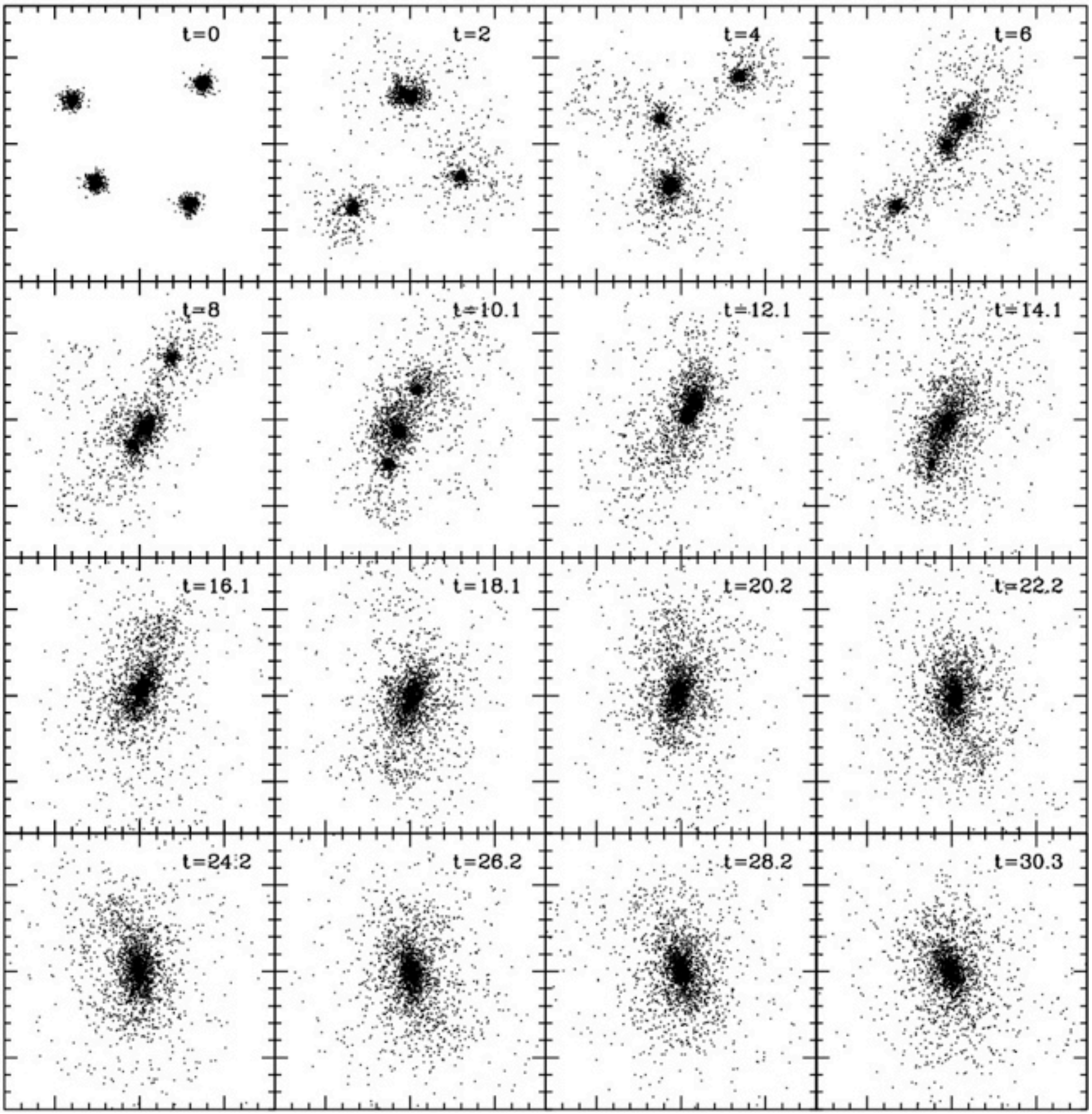
1. Infall time scales for globular clusters are roughly correct

2. While they often contain young stars, the dominant populations of NSCs are old

3. Migration of 10^4-10^6 $M_\odot$ objects to the center is common to both gas- and stellar-dynamical models

4. A massive “seed” is probably required for gas infall scenarios to work

5. Stars are easier than gas



Miocchi & Capuzzo-Dolcetta (2009)

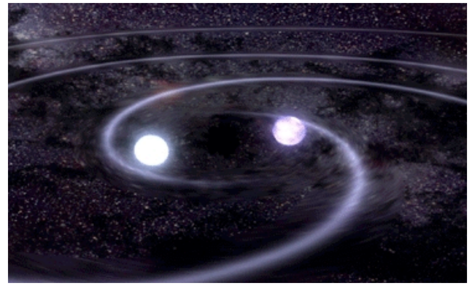
Also:

Fellhauer & Kroupa (2002)

Bekki et al. (2004)

Sequential Mergers of Clusters

Energy conservation implies



$$E_f = E_i + E_{\rm orb} + E_{\rm cl}$$

where

$$E_{i,f} = \text{initial, final energy of nucleus}$$

$$E_{\rm cl} = \text{cluster internal energy} = -Gm^2/2r$$

$$E_{\rm orb} = \text{cluster orbital energy} = -\alpha G m M_i/2R_i, \quad \alpha \approx 1$$

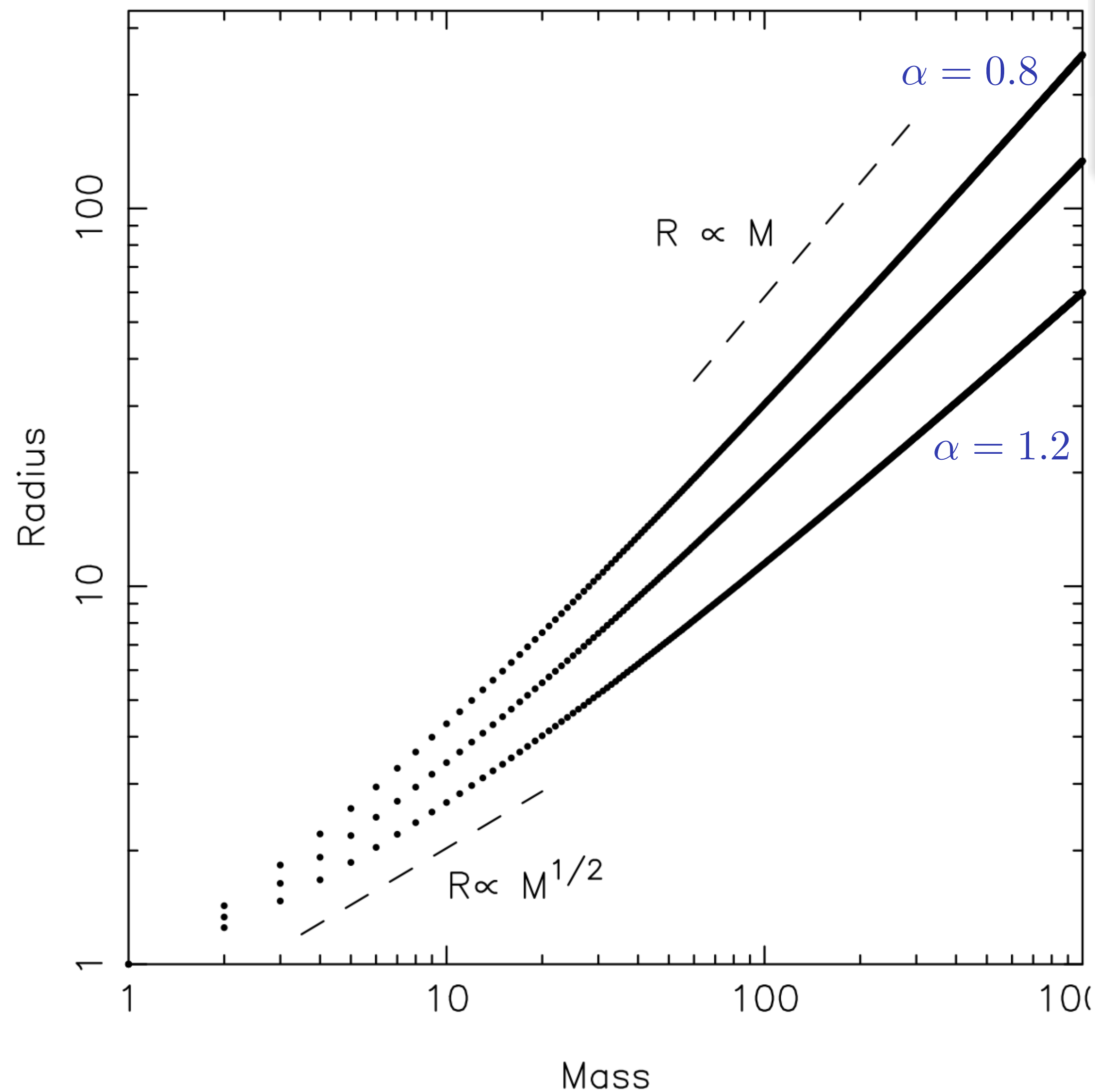
Then

$$M_{j+1} = (j+1)M_1 \qquad (M_1 = m)$$

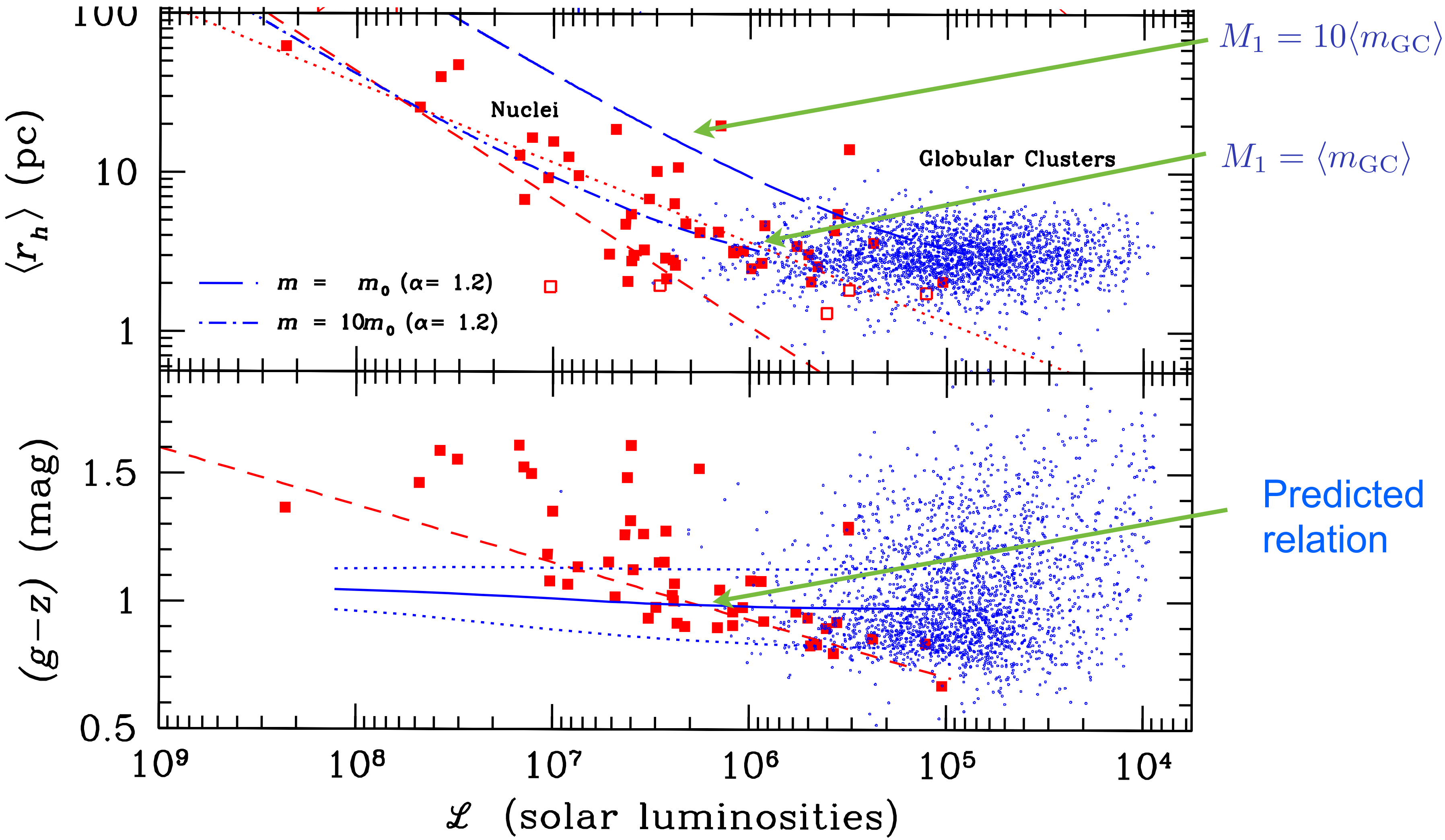
$$jE_{j+1} = (j+\alpha)E_j + jE_1$$

$$(j+1)^2 R_{j+1}^{-1} = j(j+\alpha)R_j^{-1} + R_1^{-1}$$

Sequential Mergers of Clusters



Radius-mass relation



Piatek et al. (unpublished)

Now Add a Supermassive Black Hole...

Complete disruption occurs when

$$r \approx \left(\frac{M_\bullet}{M_{\rm GC}}\right)^{1/3} R_{\rm GC}$$

i.e.

$$\frac{r}{r_{\rm infl}} \approx 2 \left(\frac{M_\bullet}{10^7 M_\odot}\right)^{-1/6} \left(\frac{M_{\rm GC}}{10^6 M_\odot}\right)^{-1/3} \left(\frac{R_{\rm GC}}{3 \rm pc}\right)$$

∴ The smallest NSCs should have sizes ~ a few x $r_{\rm infl}$ in galaxies with SMBHs

E. g. $M_\bullet = 10^6\ M_\odot$, $r_{\rm min} \sim 3$ pc ?

$M_\bullet = 10^7\ M_\odot$, $r_{\rm min} \sim 10$ pc ✓

Cluster:

$M_{GC} = 4x10^6 M_\odot$

(untruncated)

$= 1.1x10^6 M_\odot$

(truncated)

$\sigma(0) = 35$ km s^{-1}

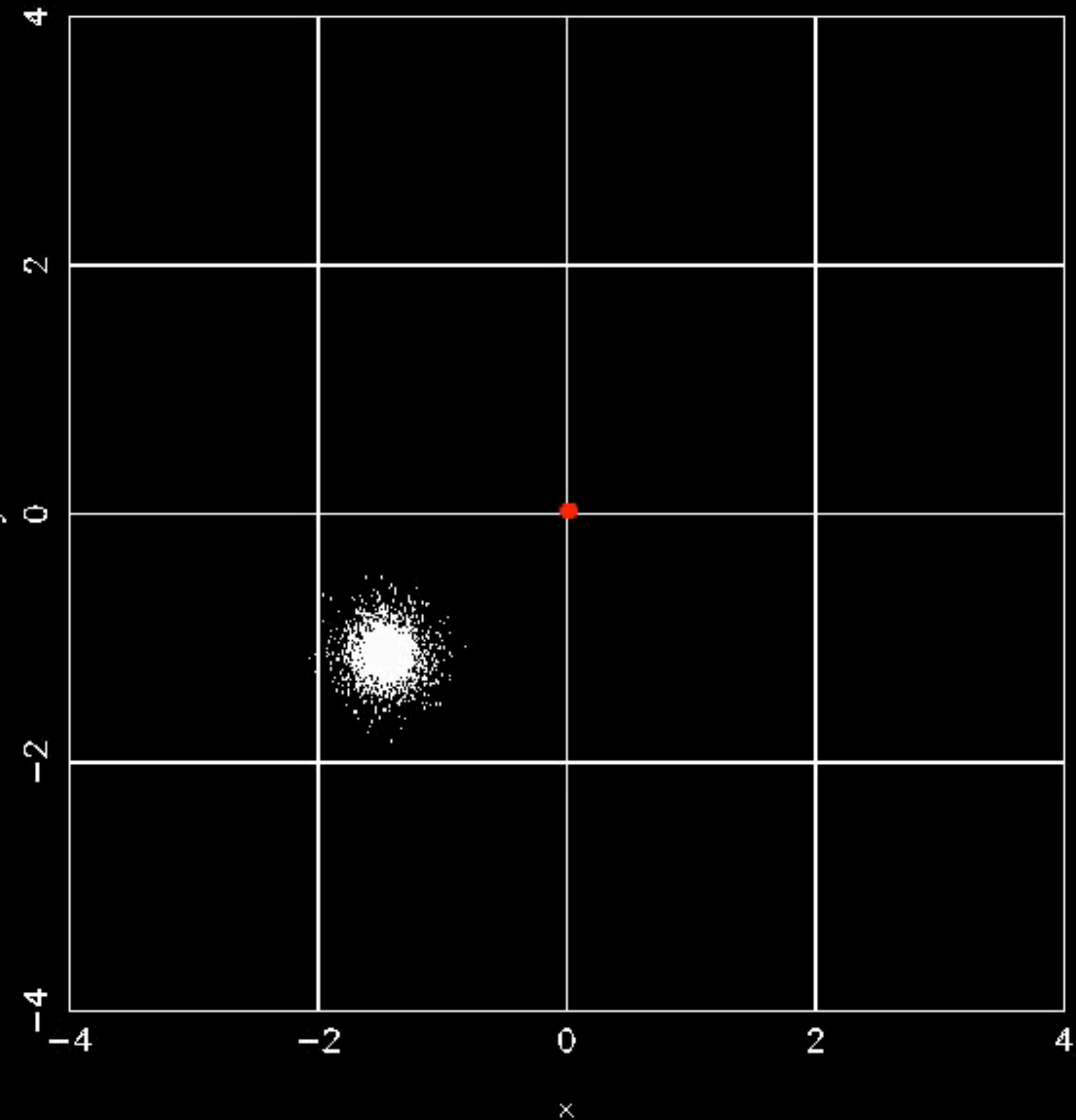
Galaxy:

$\rho(1\ pc) =$

$400\ M_{sun}\ pc^{-3}$

$\rho \sim r^{-0.5}$

A. Battisti et al.



Cluster:

$M_{GC} = 4 \times 10^6 M_\odot$ (untruncated)

$= 1.1 \times 10^6 M_\odot$ (truncated)

$\sigma(0) = 35$ km s^{-1}

Galaxy:

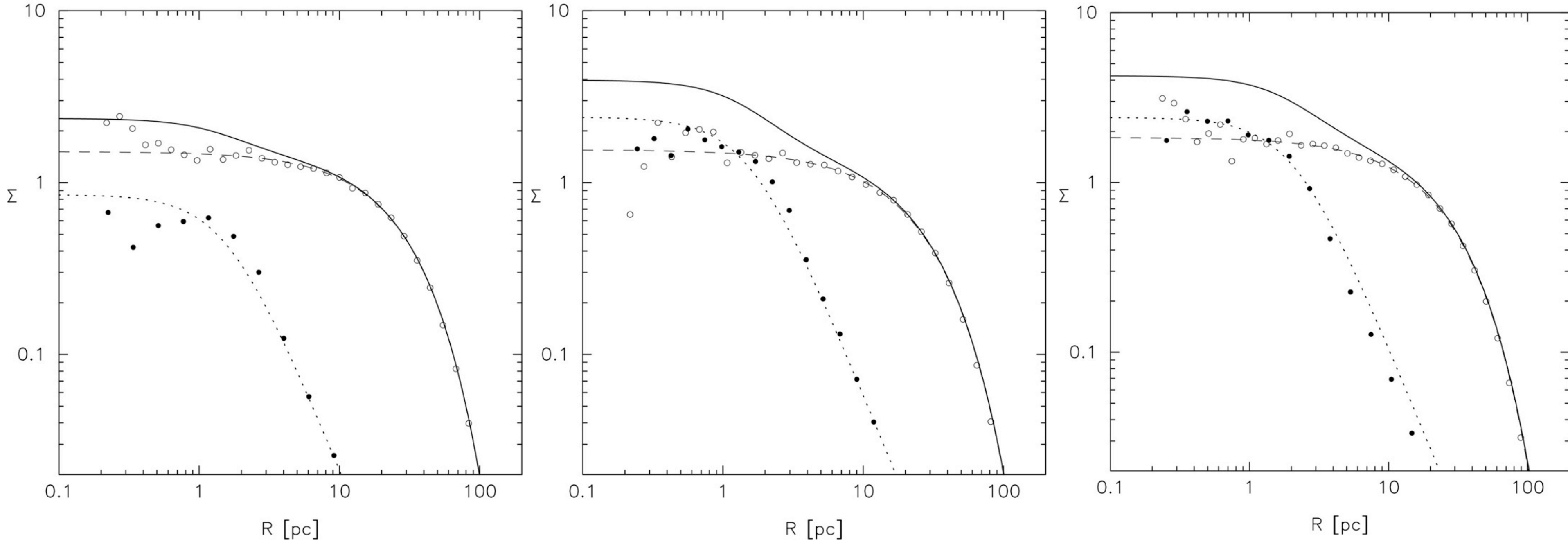
$\rho(1\ pc) = 400\ M_{sun}\ pc^{-3}$

$\rho \sim r^{-0.5}$

A. Battisti et al.

Surface Density Profiles

First Infall | Second Infall | Third Infall

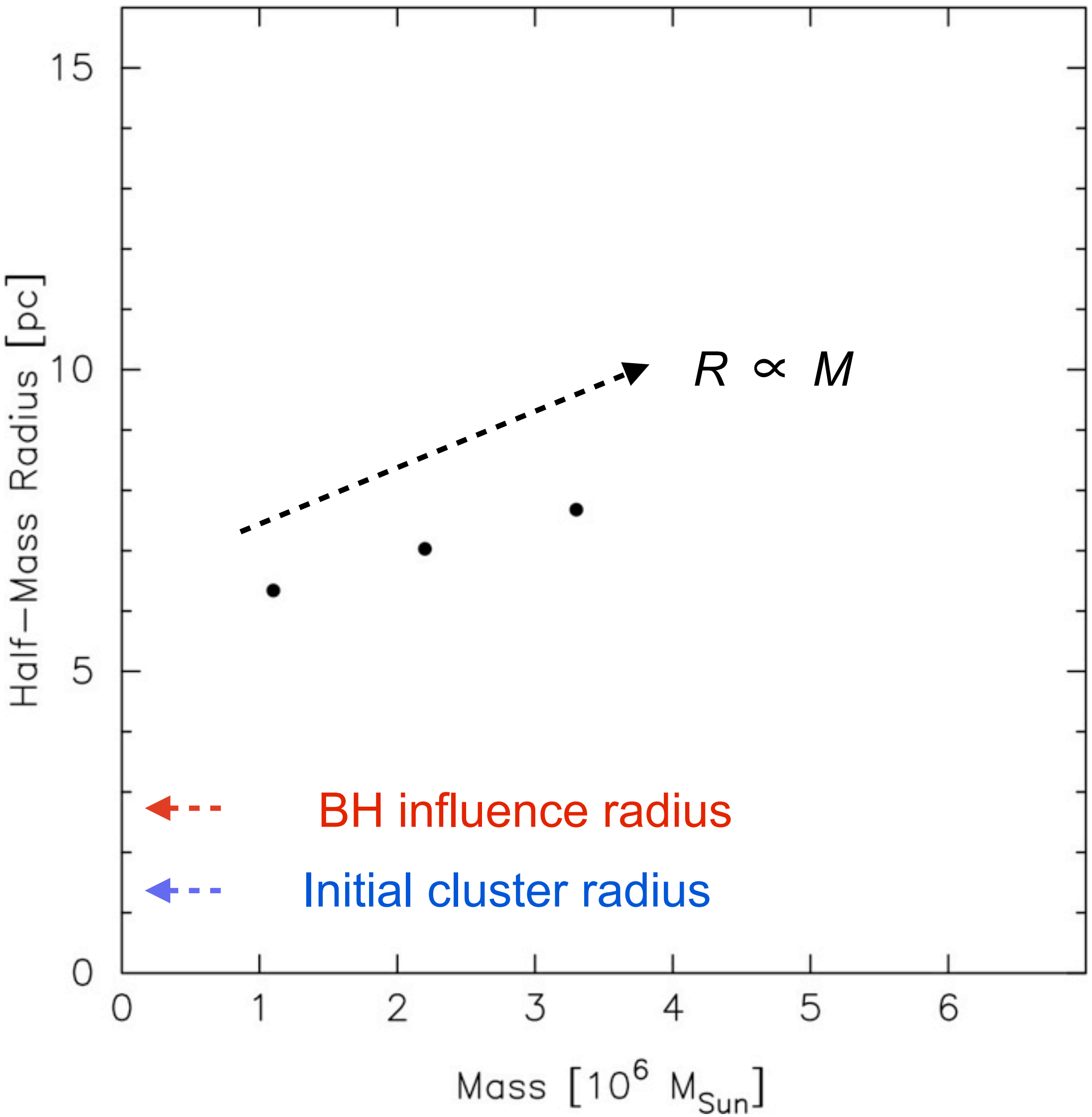


Galaxy : $\ln \Sigma = \ln \Sigma_e - b(R/r_e)^{1/n} + 1$

Cluster : $\Sigma = \Sigma_0 \left(1 + R^2/r_0^2\right)^{-1}$

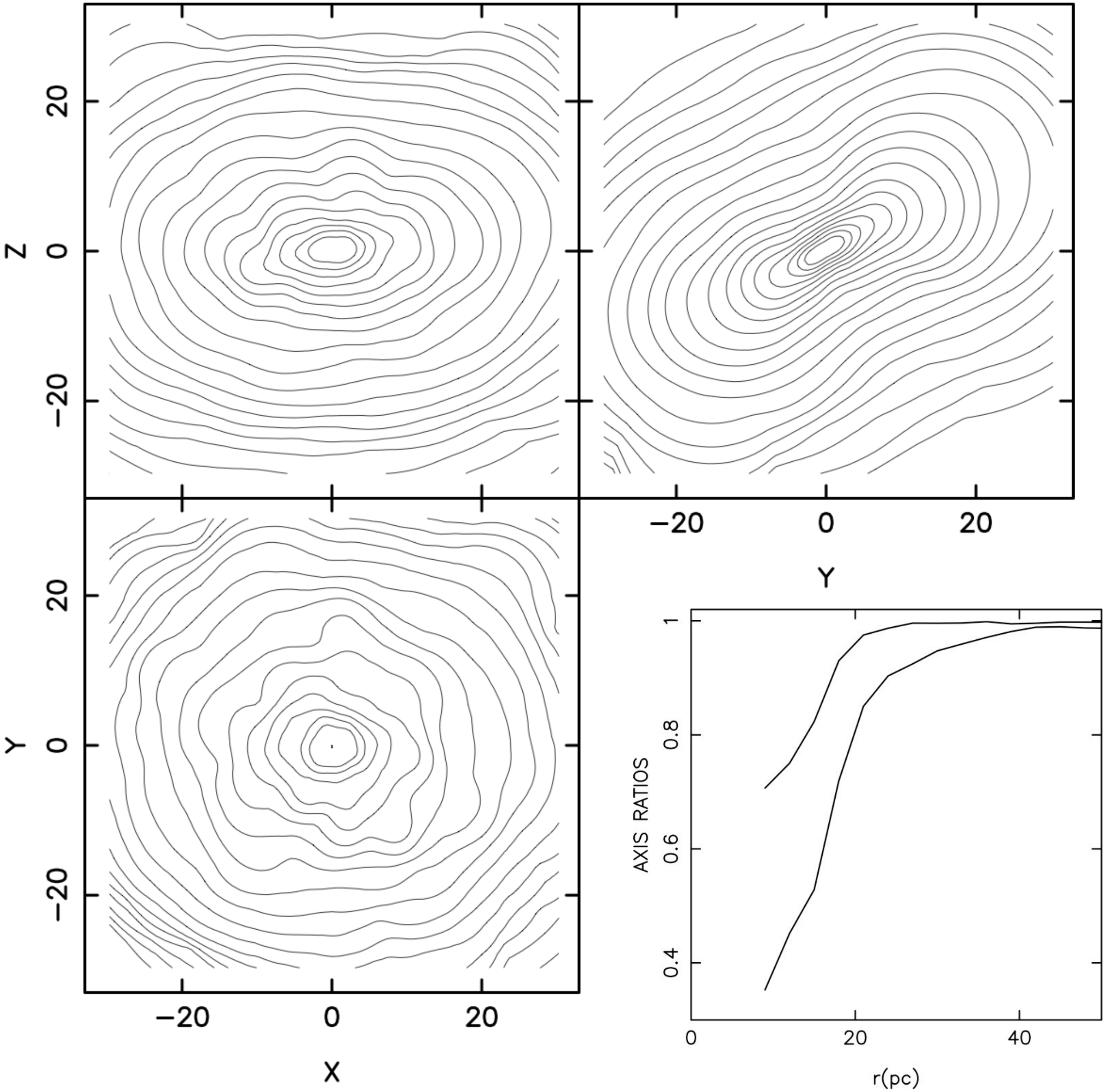
Battisti et al. (2010)

Mass-Radius Relation



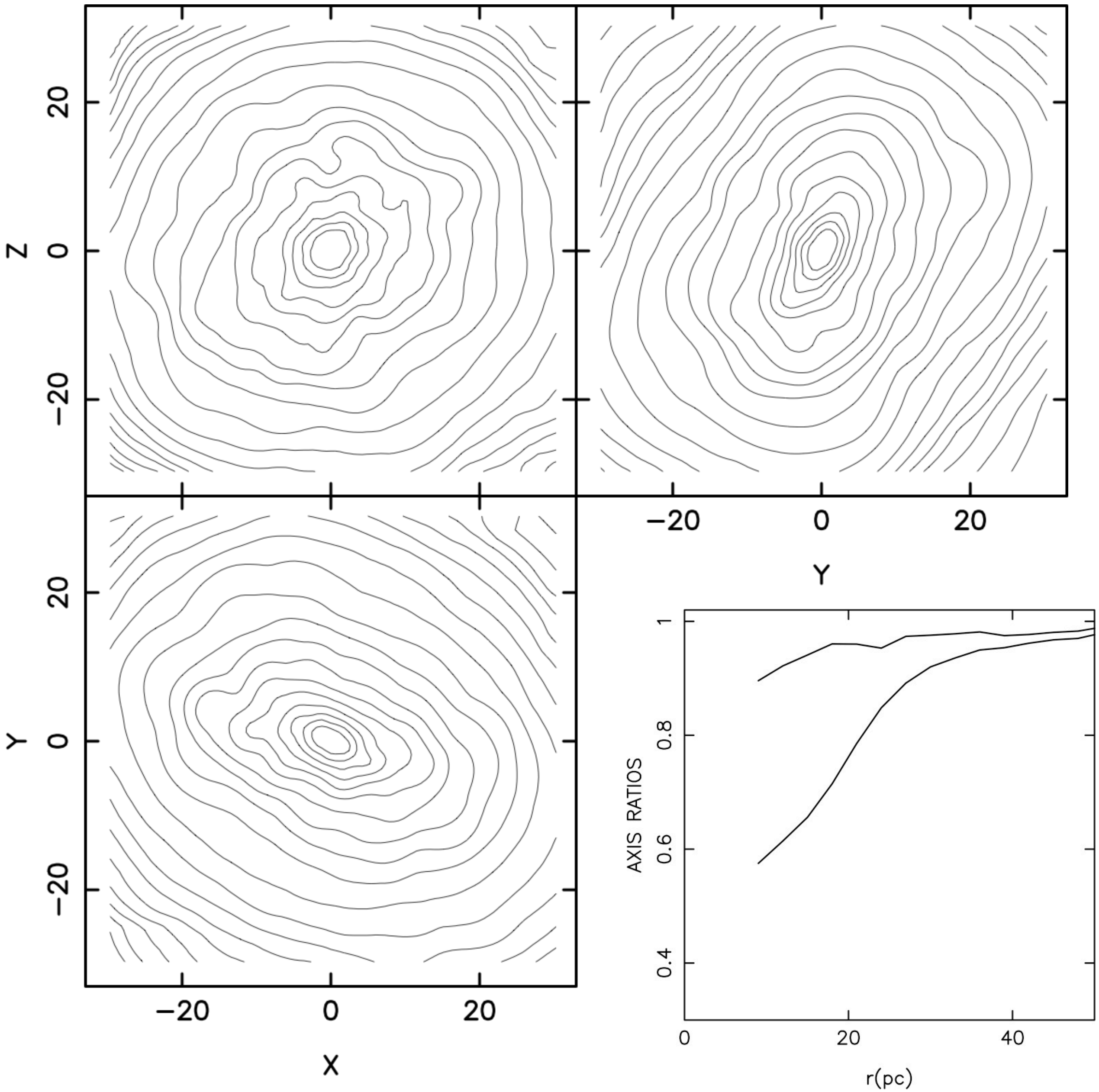
Battisti et al. (2010)

First Infall



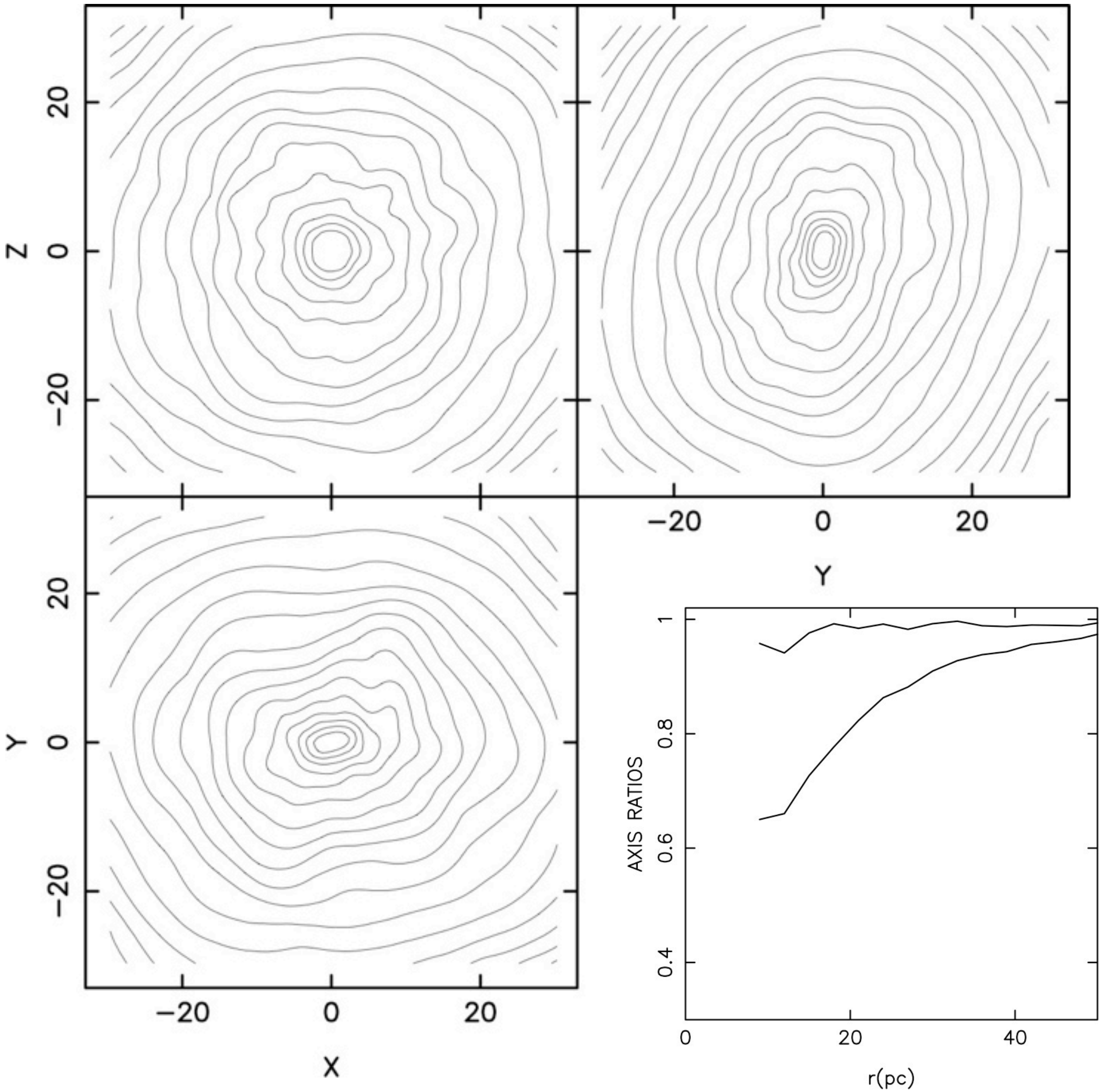
Battisti et al. (2010)

Second Infall



Battisti et al. (2010)

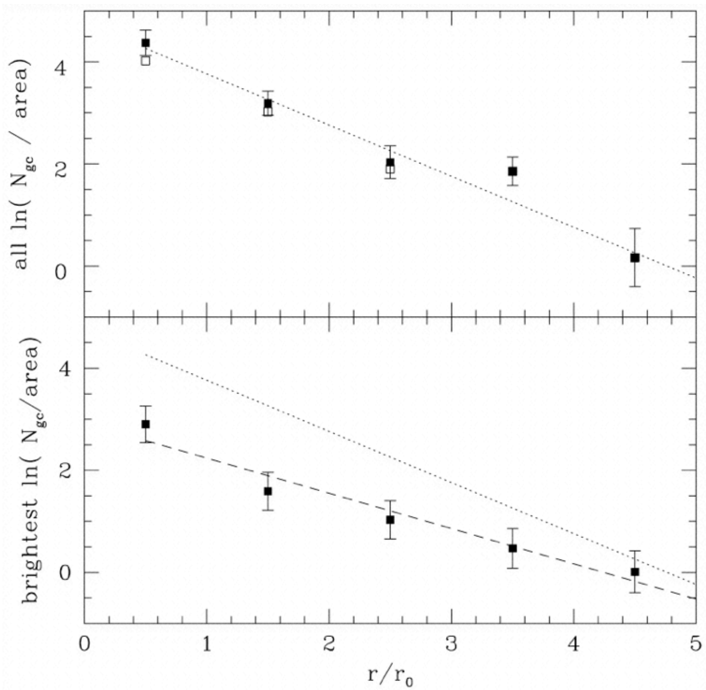
Third Infall



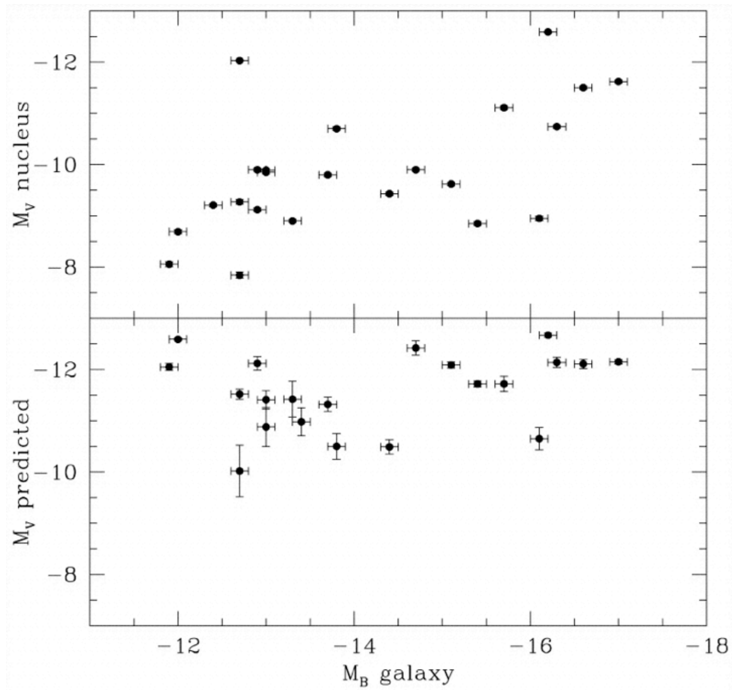
Battisti et al. (2010)

Growth Timescales - dE Galaxies

Lotz et al. (2001):
Examined globular cluster systems in 51 Virgo, Fornax dE galaxies.



Summed radial distributions



Observed/predicted NSC magnitudes

Growth Timescales - gE Galaxies

Assume that the mass density of the galaxy follows

$$\rho(r) = \rho_a (r/r_a)^{-\gamma}$$

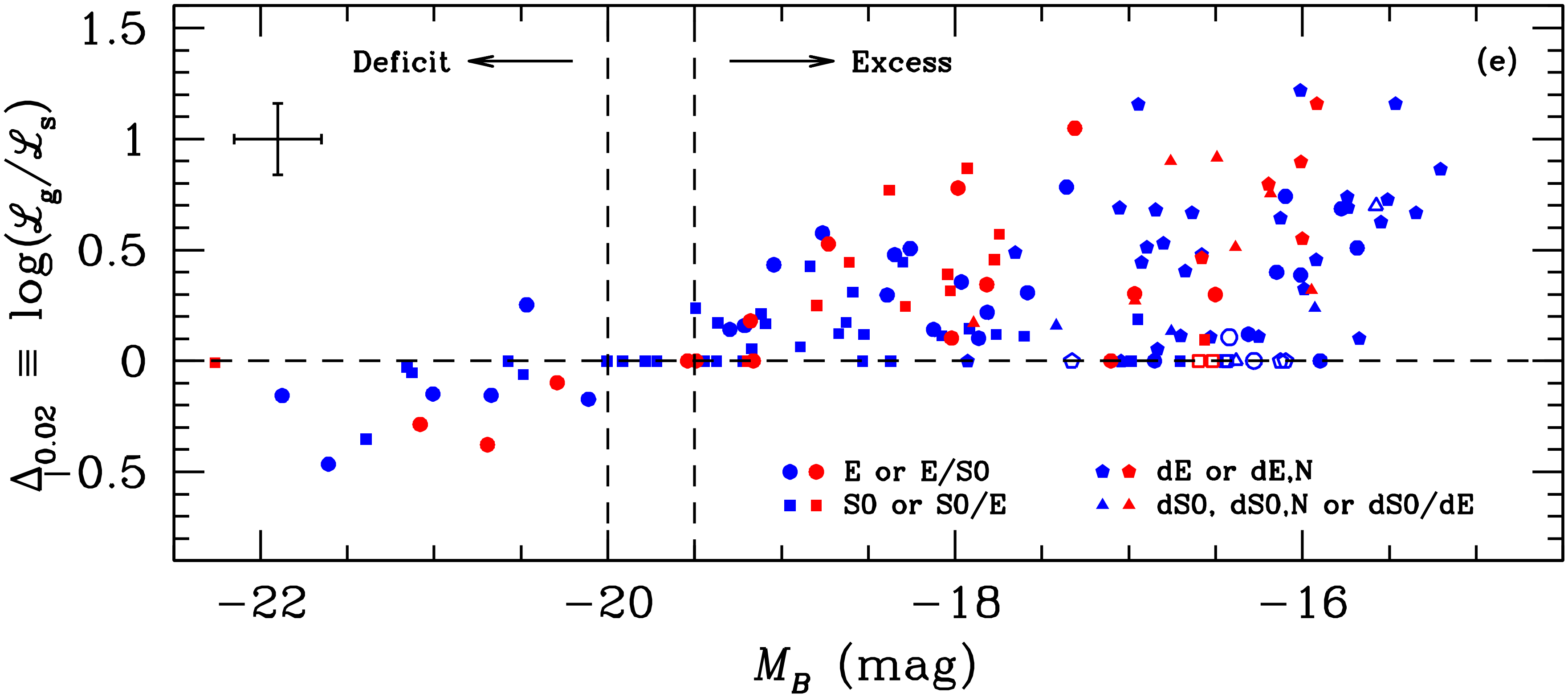
The time for a GC at initial radius r_0 to spiral in to the center is

$$\Delta t = \frac{C(\gamma)}{\ln\Lambda} \frac{r_a^3}{M_{\rm GC}} \left(\frac{\rho_a}{G}\right)^{1/2} \left(\frac{r_0}{r_a}\right)^{(6-\gamma)/2}$$

$$\approx 9 \times 10^{10} {\rm yr} \left(\frac{r_a}{1{\rm kpc}}\right)^3 \left(\frac{M_{\rm GC}}{10^5 M_\odot}\right)^{-1} \left(\frac{\rho_a}{1 M_\odot {\rm pc}^{-3}}\right)^{1/2} \left(\frac{r_0}{r_a}\right)^{(6-\gamma)/2}$$

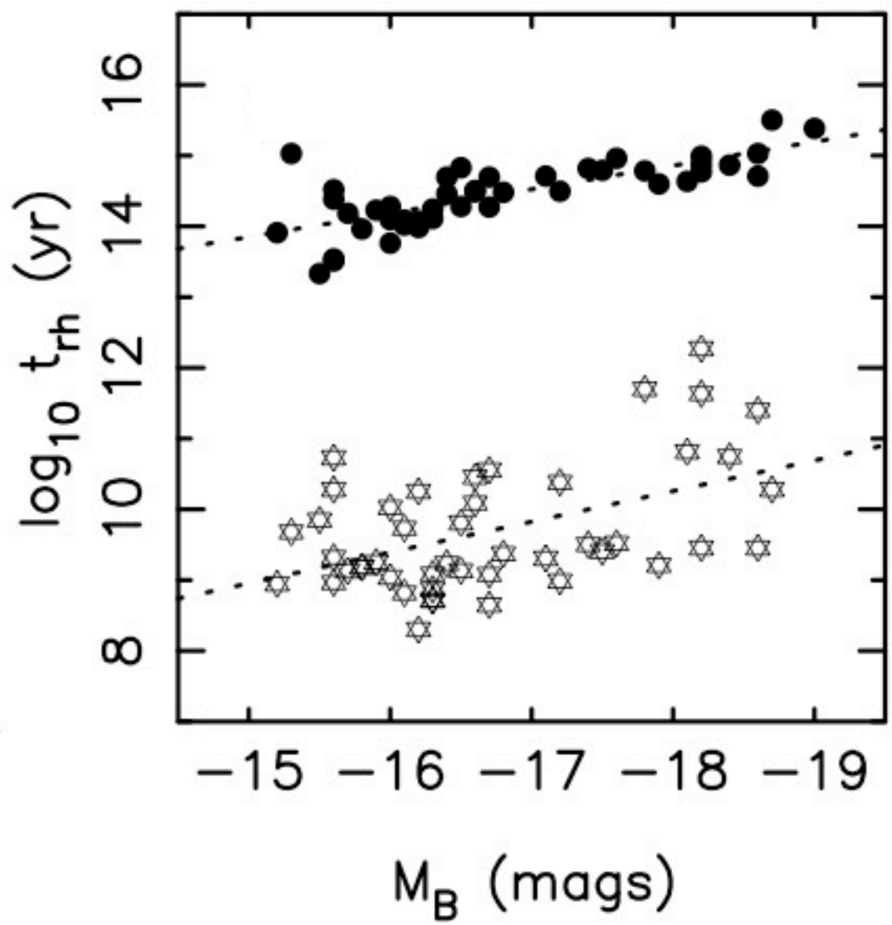
The time for GCs initially within R_e to spiral to the center is

$$\Delta t_{1/2} \approx 3 \times 10^{11} {\rm yr} \left(\frac{R_e}{1{\rm kpc}}\right)^{1.8} \left(\frac{M_{\rm GC}}{10^5 M_\odot}\right)^{-1}$$



Cote et al. (2007)

II. Relaxation

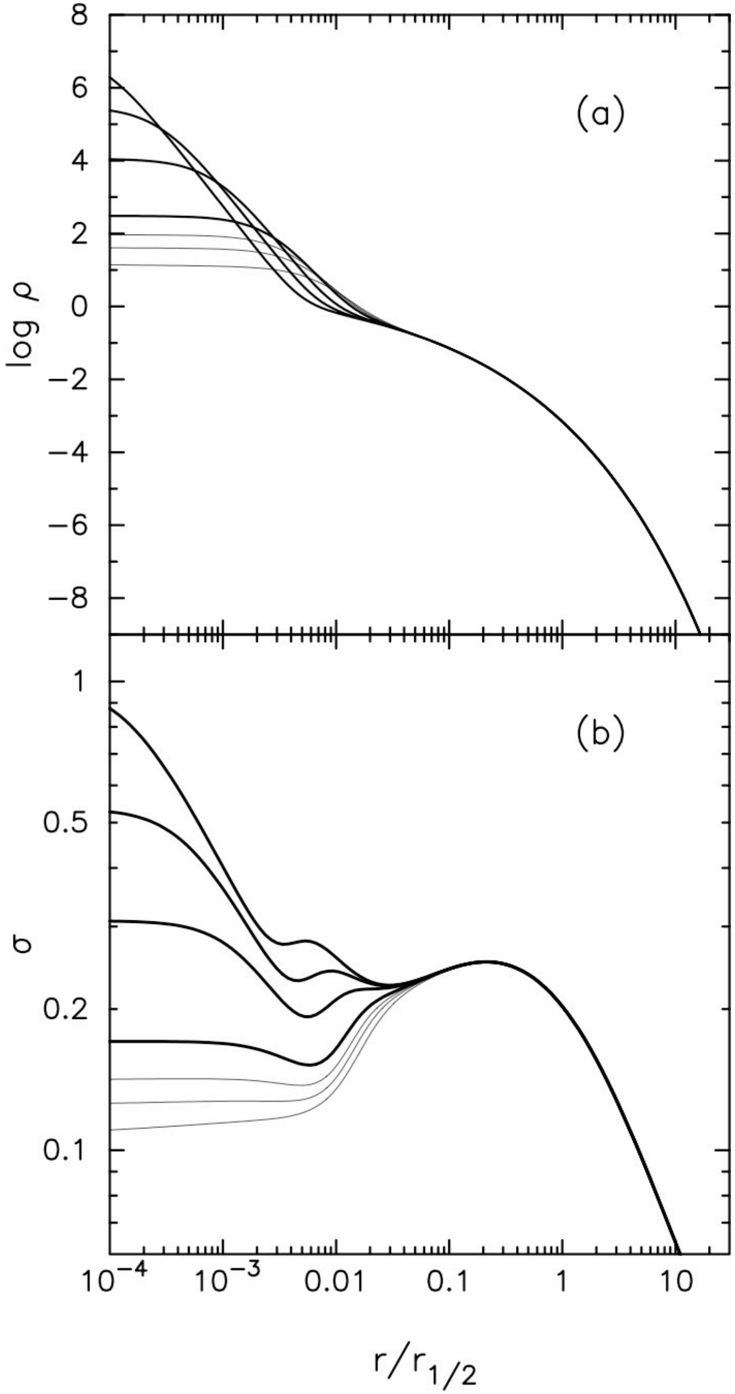


Half-mass relaxation times*

• galaxy

✡ NSC

*assuming no SMBHs



Net effect of two-body relaxation depends on whether the galaxy is “hotter” or “colder” than the NSC.

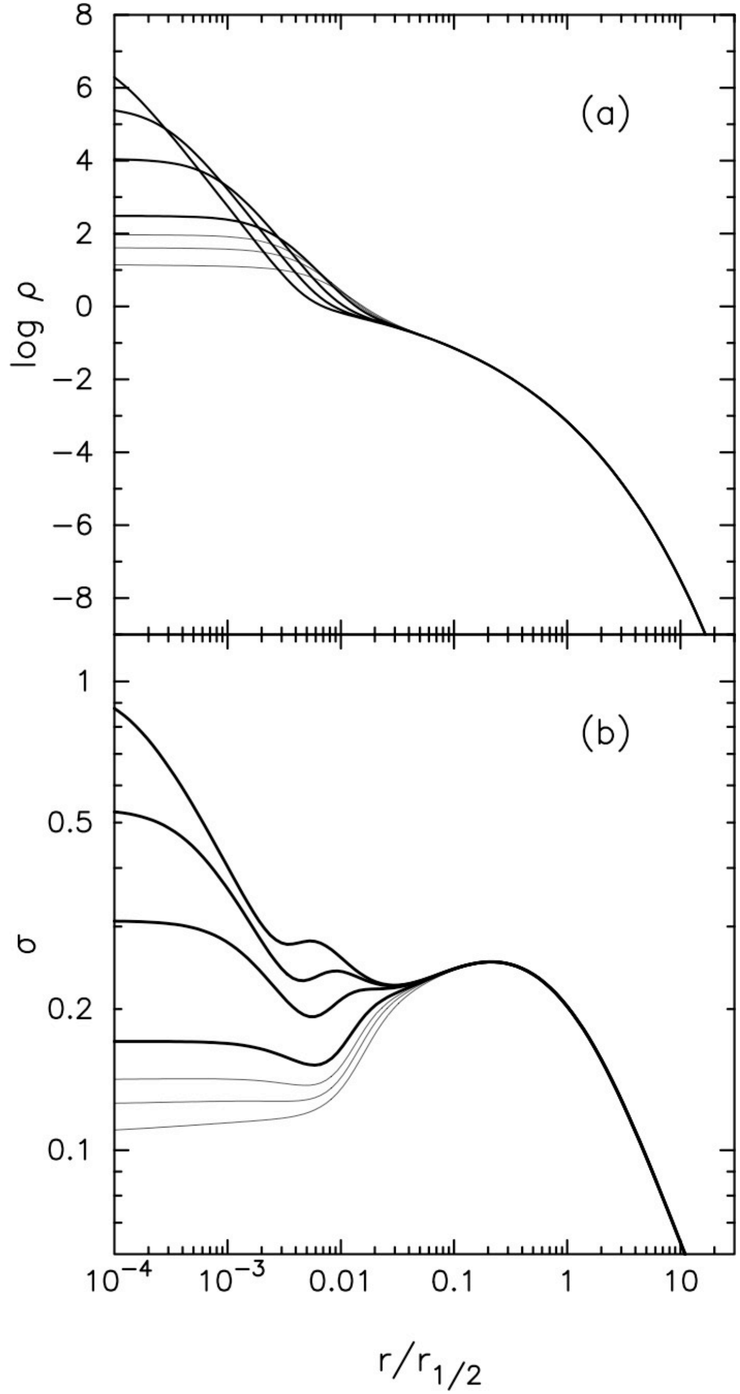
If the galaxy is hotter, it transfers heat to the NSC on a timescale:

$$\tau_{\rm heat} \approx \left(\frac{\rho_{\rm nuc}}{\rho_{\rm gal}}\right)^{1/2} \left(\frac{V_{\rm nuc}}{V_{\rm gal}}\right)^{1/2} (t_{\rm nuc} t_{\rm gal})^{1/2}$$

$$\lesssim (t_{\rm nuc} t_{\rm gal})^{1/2}$$

roughly the geometric mean of the galaxy and NSC relaxation times.

Dokuchaev & Ozernoi (1985)
Kandrup (1990)
Quinlan (1996)



This heat transfer will **reverse core collapse** if

$$\tau_{\rm heat} \lesssim \tau_{\rm cc} \equiv \xi^{-1} t_{\rm nuc} \qquad 10 \lesssim \xi^{-1} \lesssim 300$$

i.e.

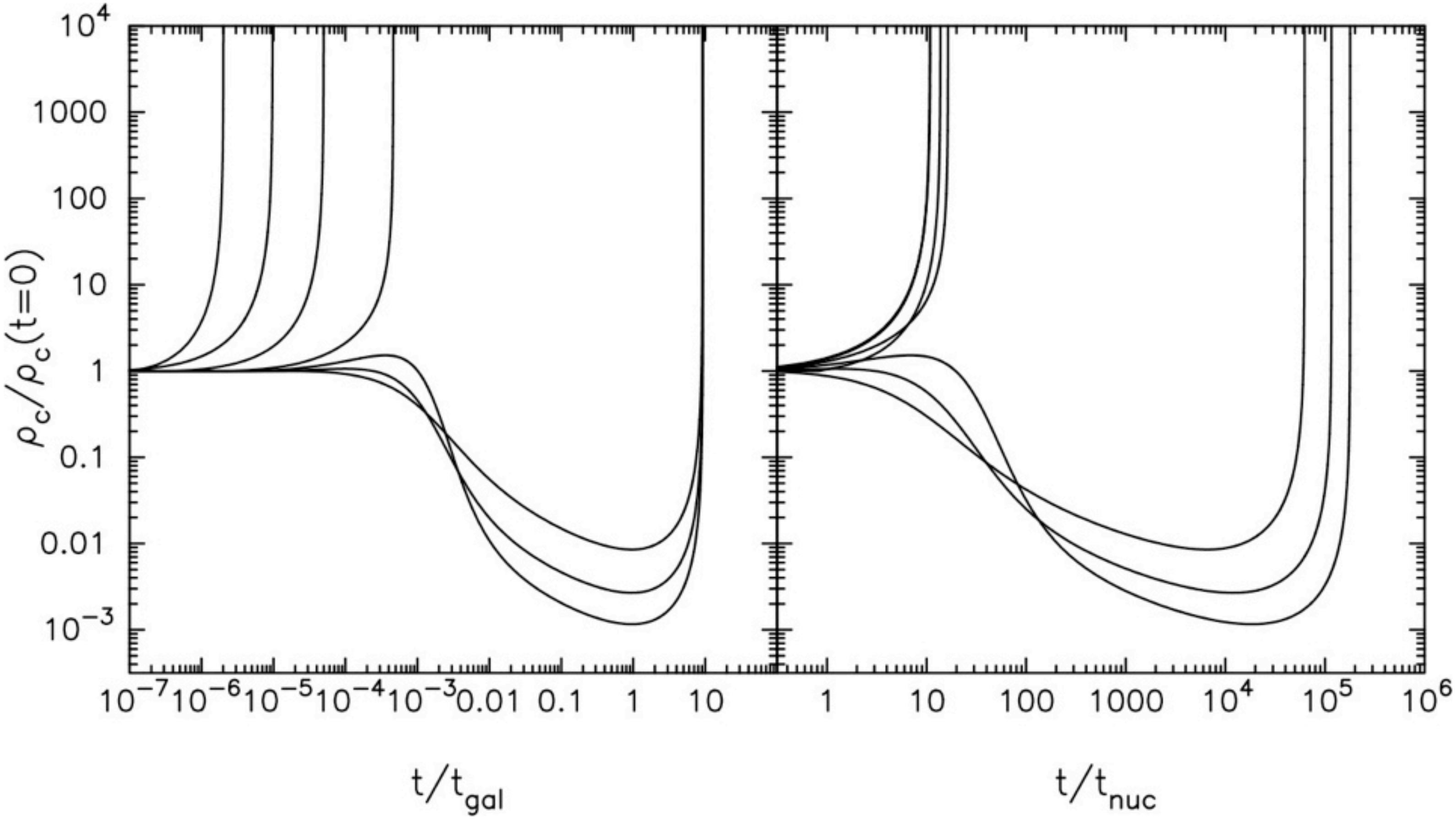
$$\frac{M_{\rm nuc}}{M_{\rm gal}} \lesssim 10^4 \left(\frac{\xi^{-1}}{100}\right)^2 \left(\frac{r_{\rm nuc}}{r_{\rm gal}}\right)^5$$

More generally, one finds a critical size:

$$\frac{M_{\rm nuc}}{M_{\rm gal}} = A \left(\frac{r_{\rm nuc}}{r_{\rm gal}}\right)^B$$

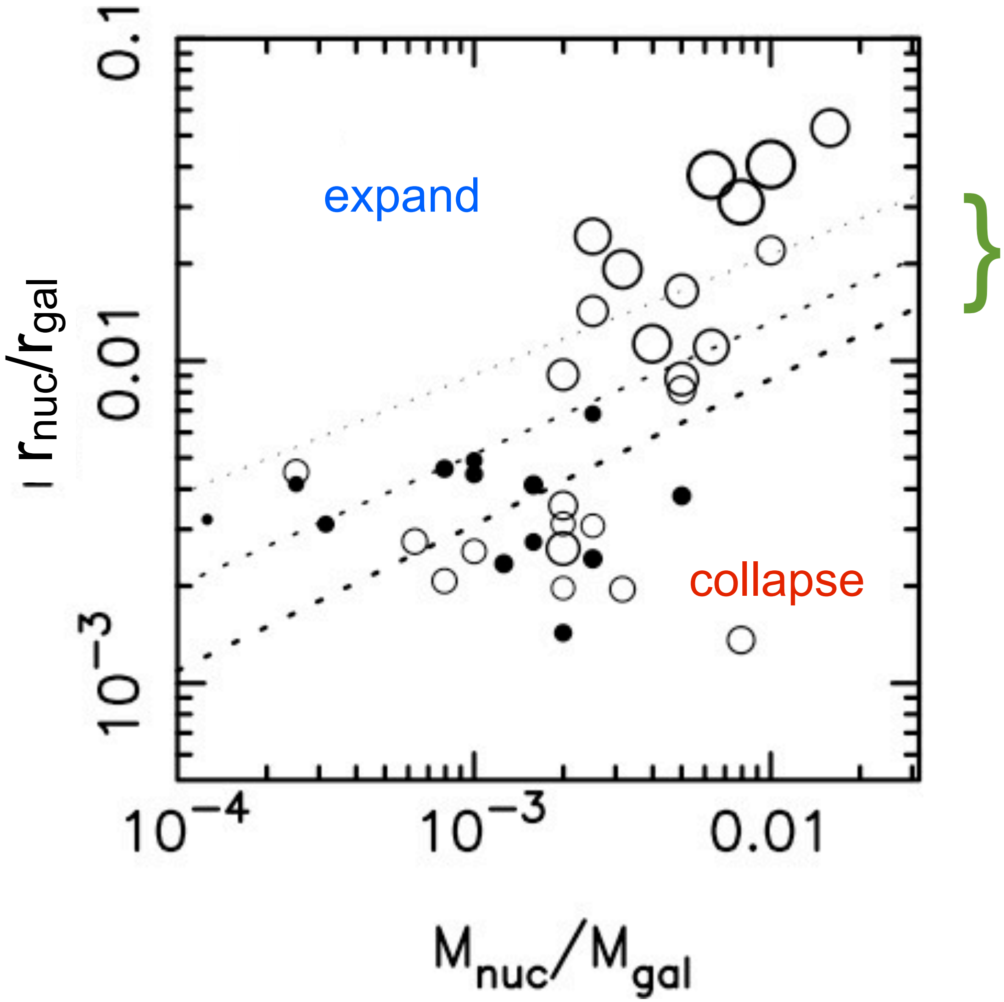
above which a NSC expands rather than contracts; A and B depend (weakly) on the galaxy density profile

Core Collapse vs. Core Expansion



Merritt (2009)

Evidence of NSC Evaporation?

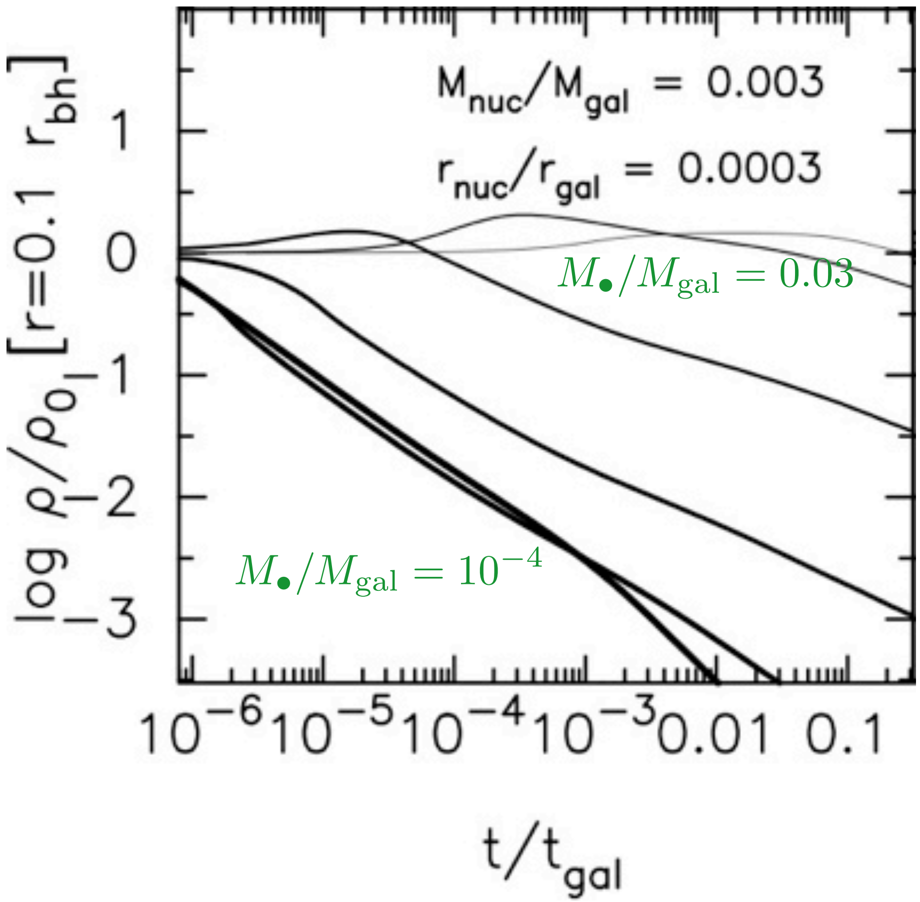


$$\frac{M_{\rm nuc}}{M_{\rm gal}} = A\left(\frac{r_{\rm nuc}}{r_{\rm gal}}\right)^B$$

- ○ $t_{evol} \gtrapprox 10$ Gyr
- ● $t_{evol} \lessapprox 10$ Gyr

Merritt (2009)

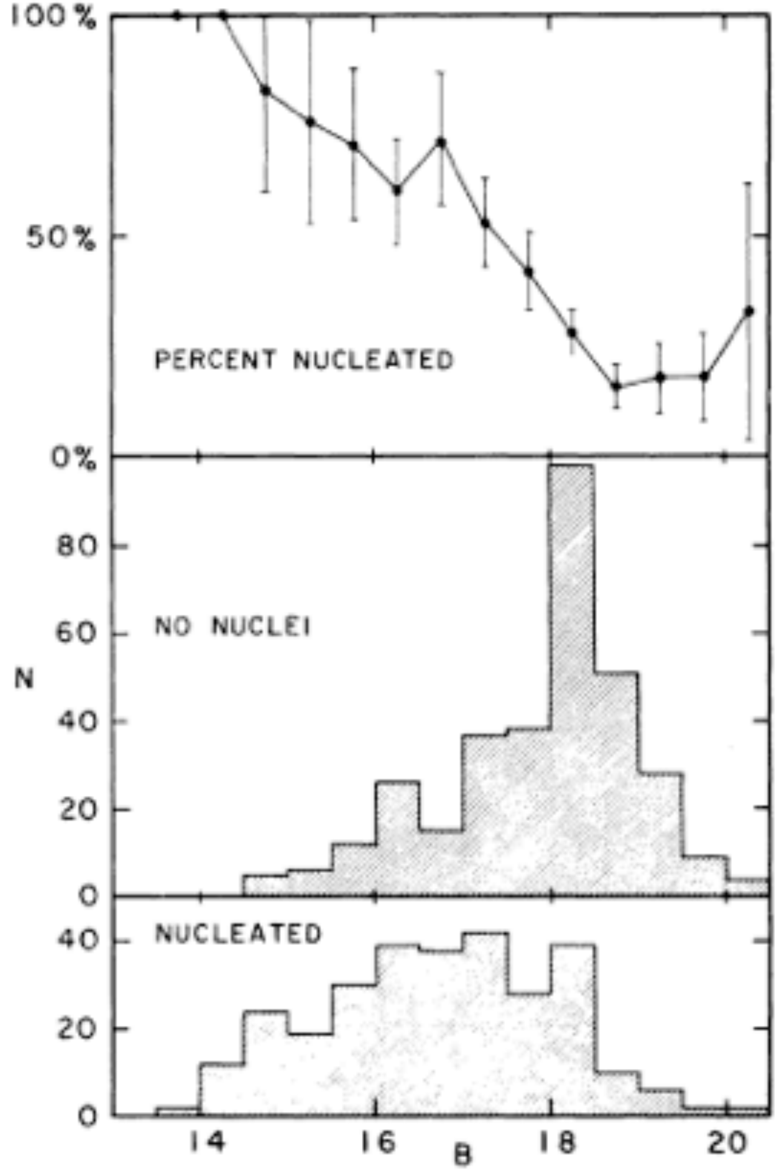
Adding a Black Hole



A large BH reverses the temperature gradient, slowing the transfer of heat from galaxy to NSC

A small BH inhibits core collapse, causing the NSC to expand more quickly

Merritt (2009)



M_B = -16 -14 -12 -10

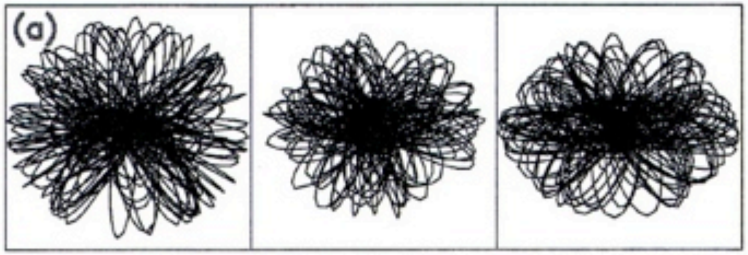
van den Bergh (1986):

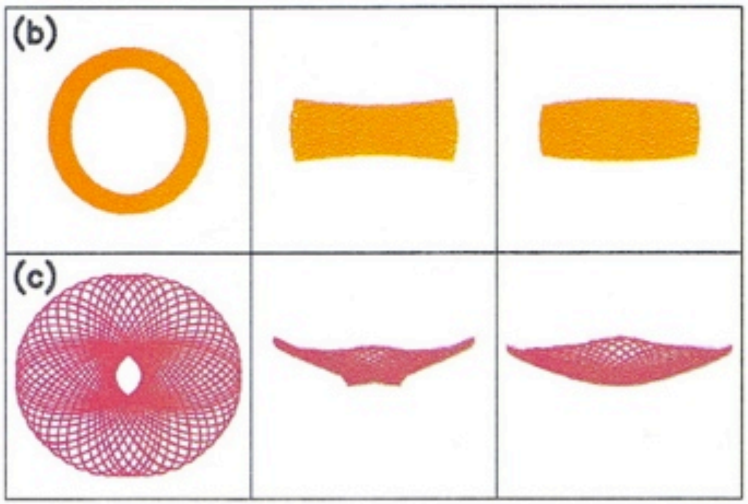
Nucleation fraction vs. galaxy magnitude

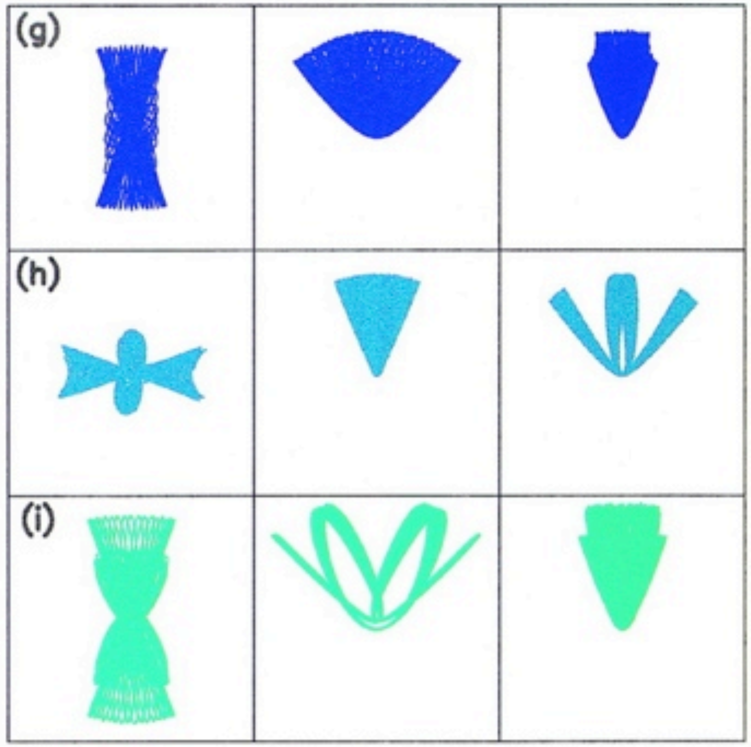
Perhaps NSCs in fainter spheroids were destroyed by heating from the galaxy.

III. Triaxiality

Poon & Merritt (2001)







(g-i) pyramids

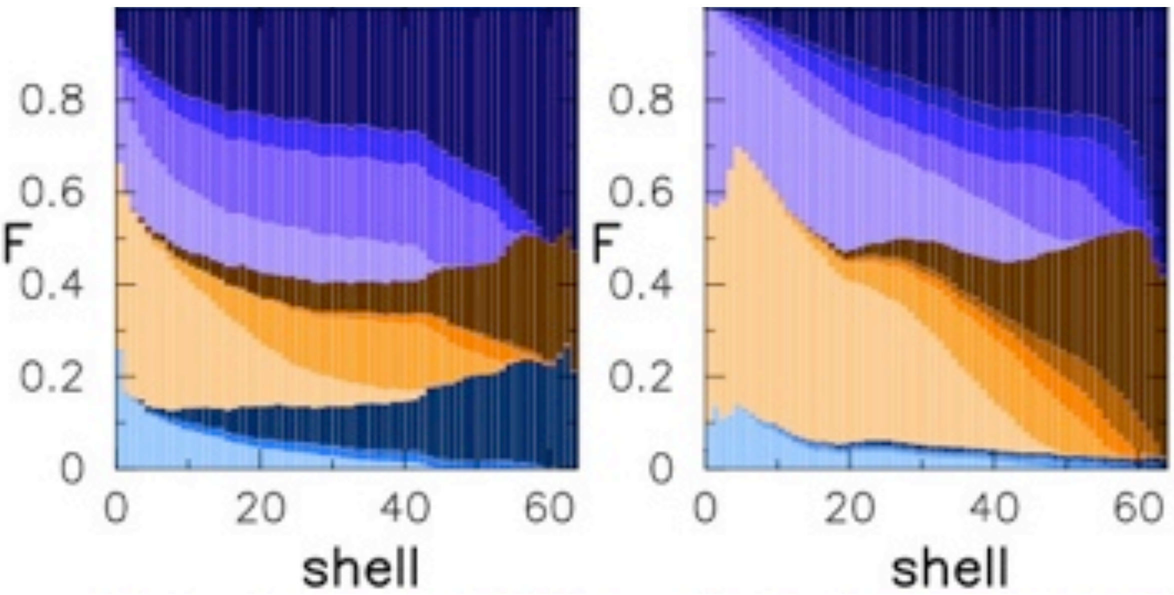
(a) chaotic

(b-c) tubes

Orbits in Triaxial BH Nuclei

Self-Consistent Triaxial NSCs

$\gamma = 1, \; T = 0.75$ $\quad$ $\gamma = 2, \; T = 0.75$



$\rho \propto r^{-\gamma}$

$$T \equiv \frac{a^2 - b^2}{a^2 - c^2}$$

F = orbital fraction

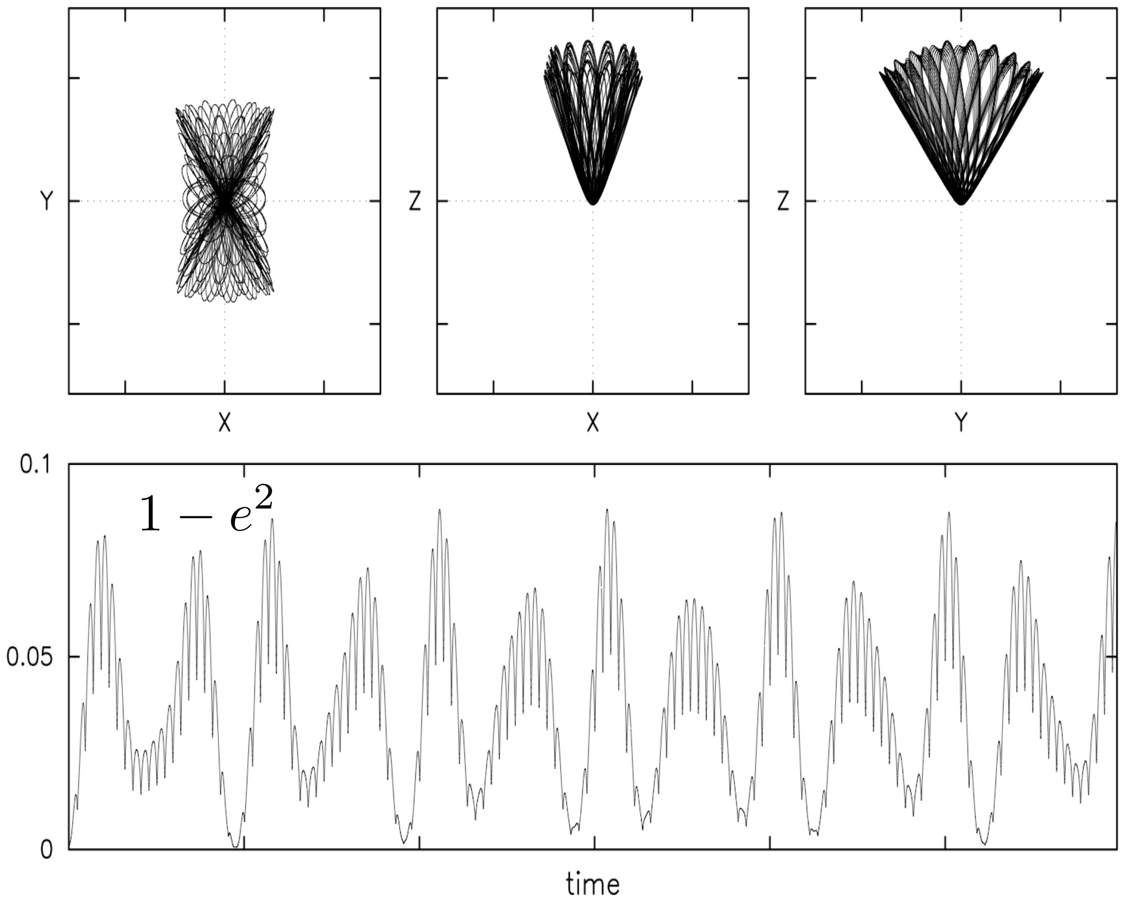
Pyramid

Tube

Chaotic

Poon & Merritt (2004)

Pyramid Orbits



- ~ Keplerian ellipses
- Librate about short axis
- Integrable (regular)*
- **e ⇒ 1** at the corners!

*for $r_{\rm GR} \lesssim r \lesssim r_{\rm infl}$

Merritt & Vasiliev (2010)

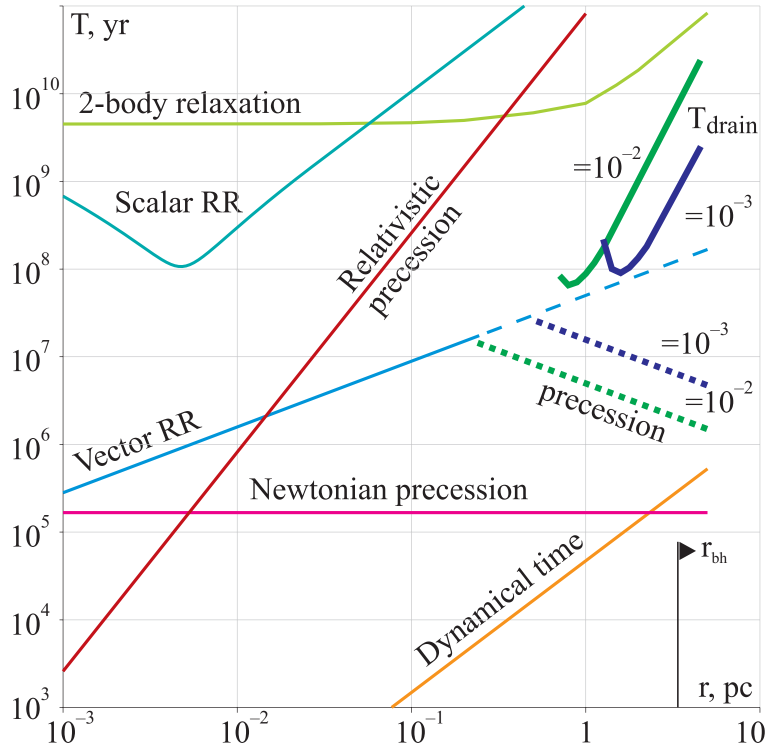
Pyramid Orbits

The time for pyramid orbits to "drain" is:

$$t_{\rm pyr} \approx 3 \times 10^8 {\rm yr} \left(\frac{T}{10^{-2}}\right) \left(\frac{M_\bullet}{10^6\, M_\odot}\right)^{2/3}$$

where T is the dimensionless coefficient of triaxiality.

The BH feeding rate can be much greater than that due to two-body relaxation.



Merritt & Vasiliev (2010)

Summary

• Accretion of globular clusters appears to be a viable model for NSC formation, at least in bulge-dominated systems

• Disappearance of NSCs in spheroids with $M_B > -16$ may be due to relaxation effects (heating from the galaxy)

• Stellar tidal disruption rates might be very high in triaxial NSCs (if SMBHs are present)