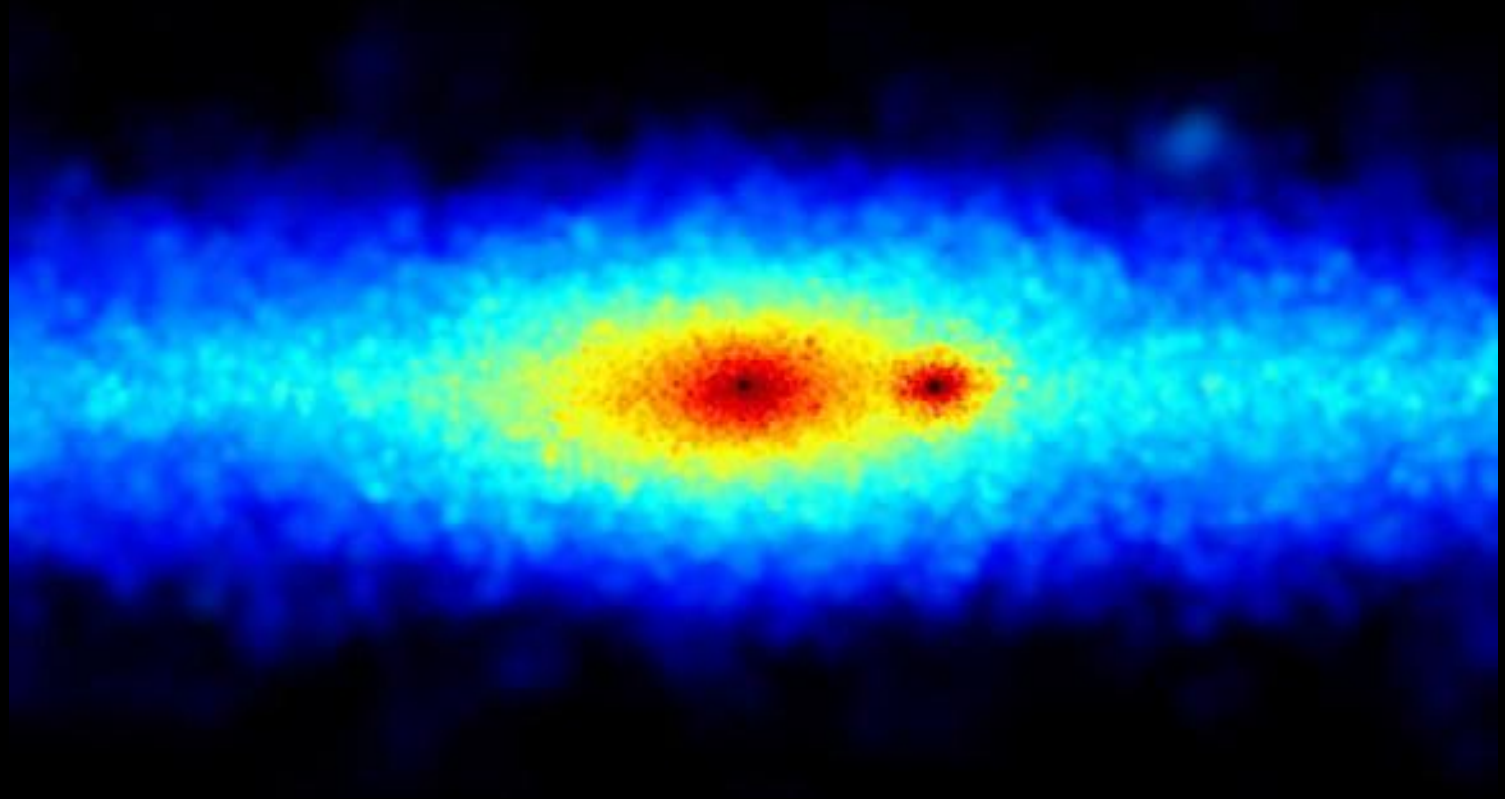
Supermassive Black Hole Binary Evolution in Axi-Symmetric Galaxies



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Massive Black Holes, KITP, August 5-9, 2013

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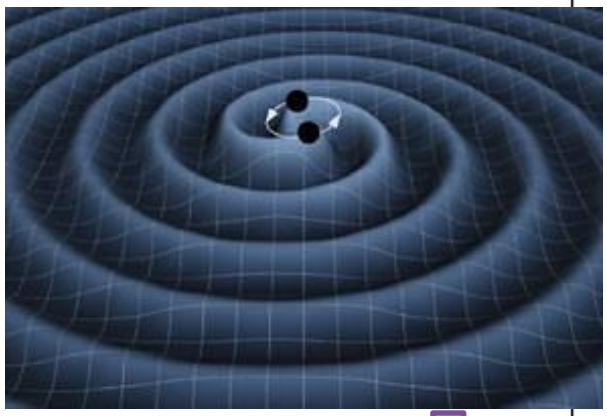
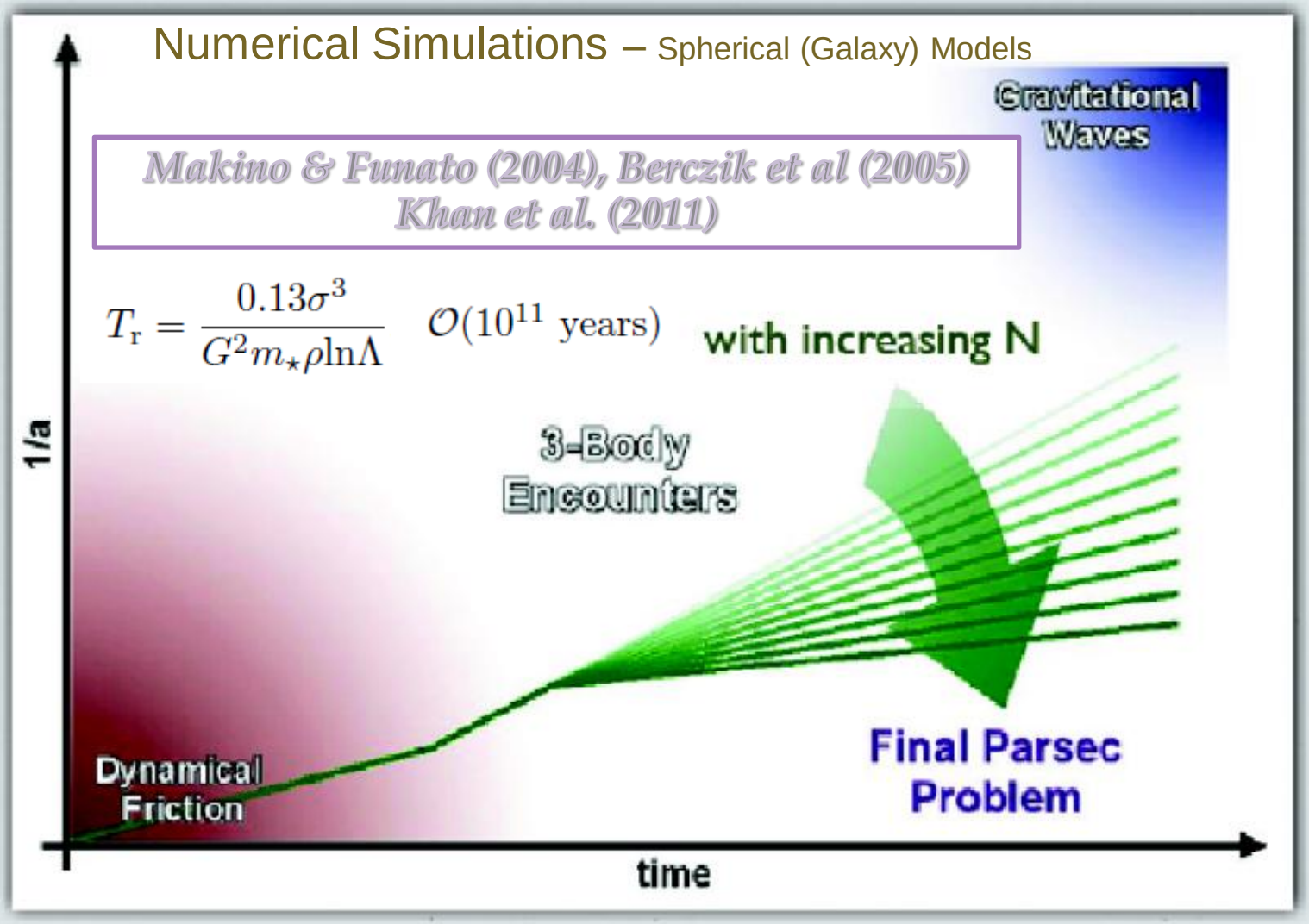
SMBH BINARY EVOLUTION IN GALAXY MERGERS



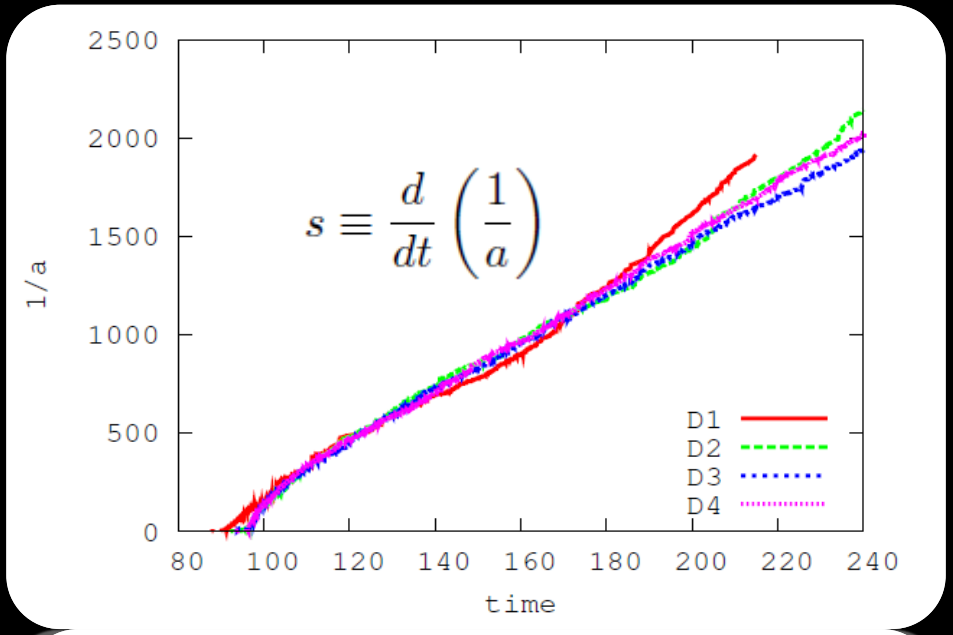
Begelman, Blandford & Rees (1980, Nature)

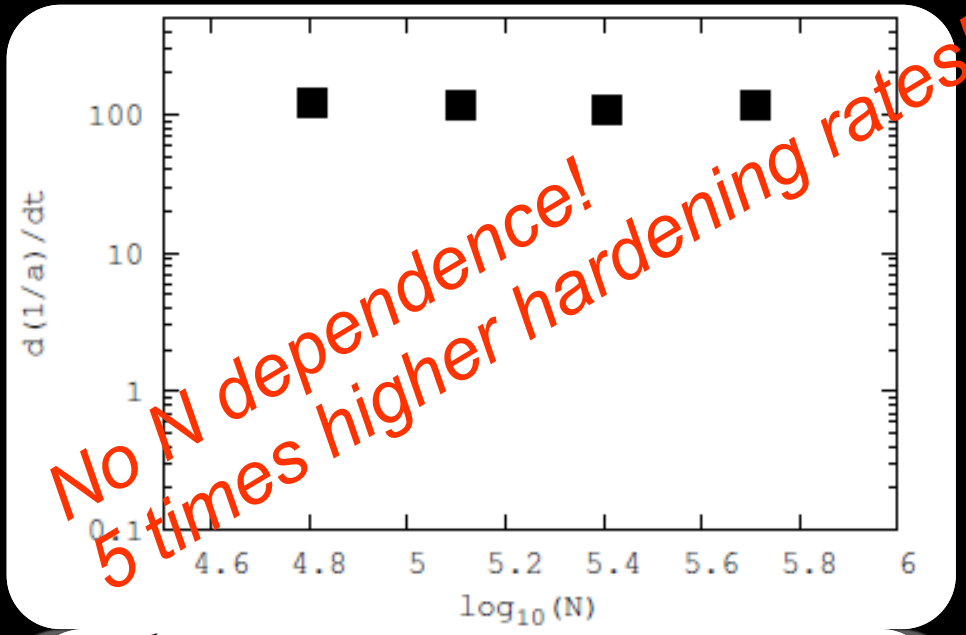
3-body Encounters

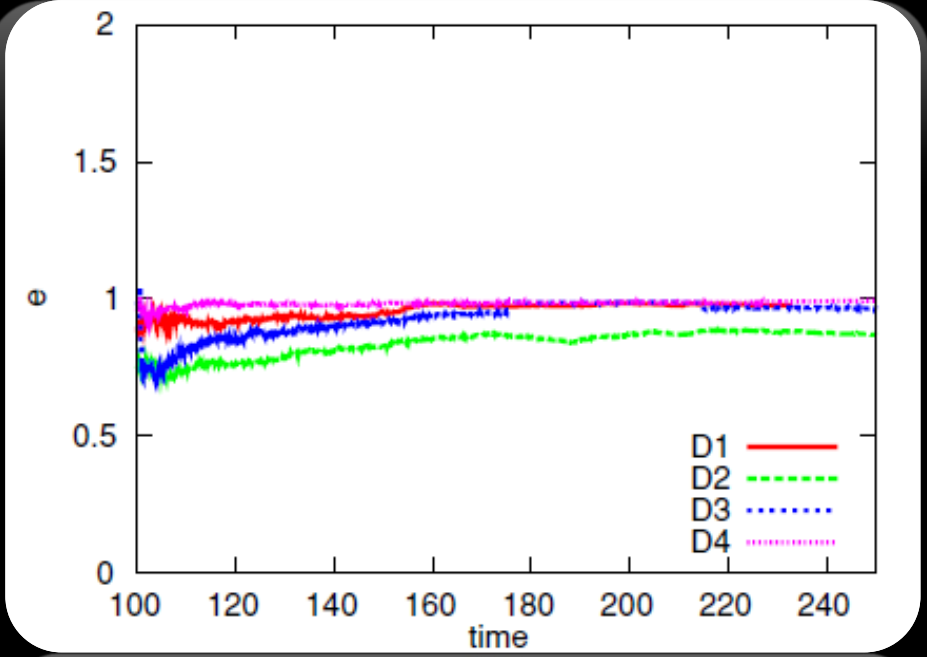


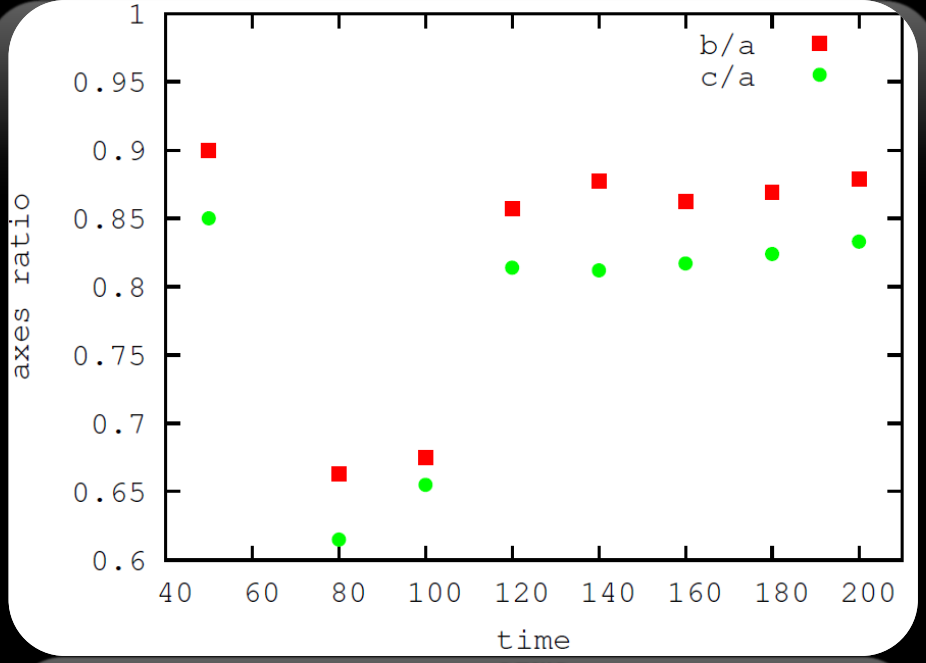
courtsey: I.Berentzen

Galaxy Mergers (Khan et al. 2011)



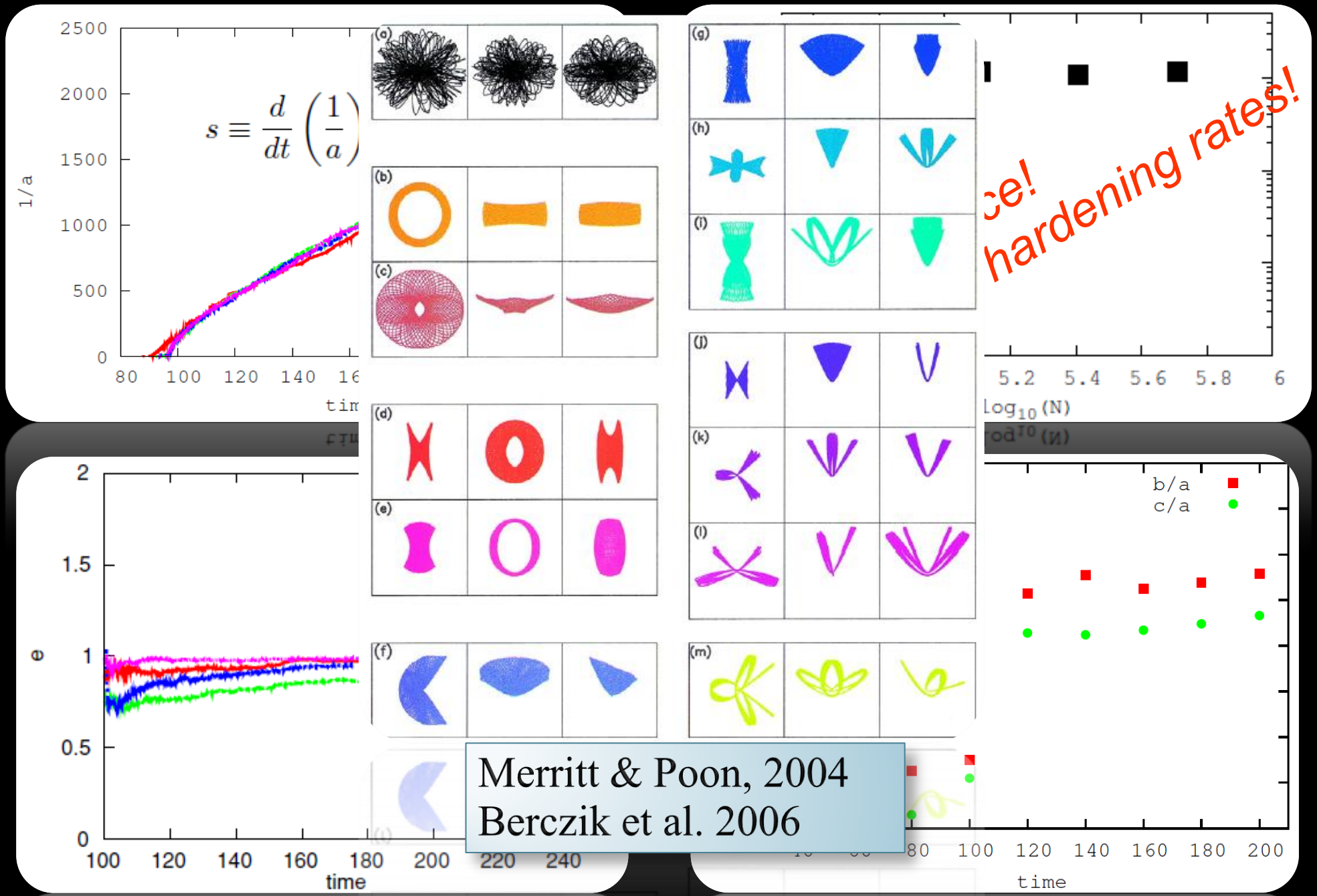




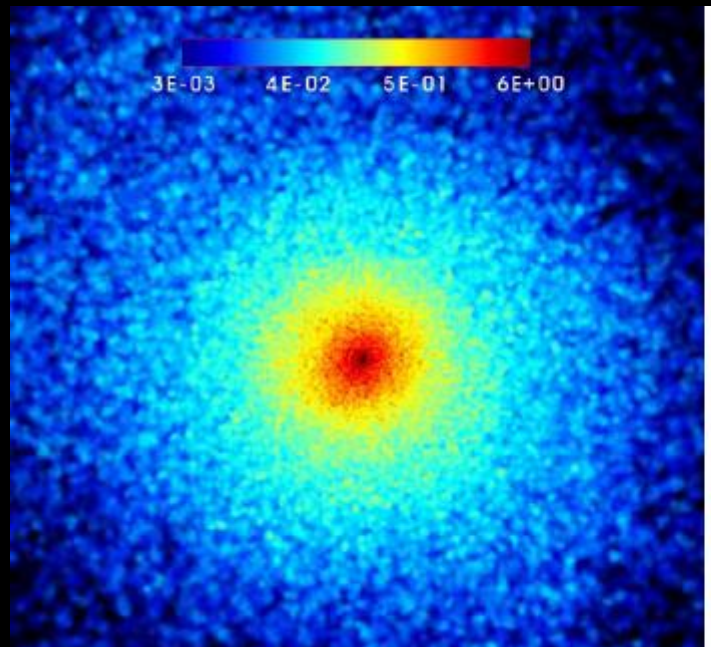


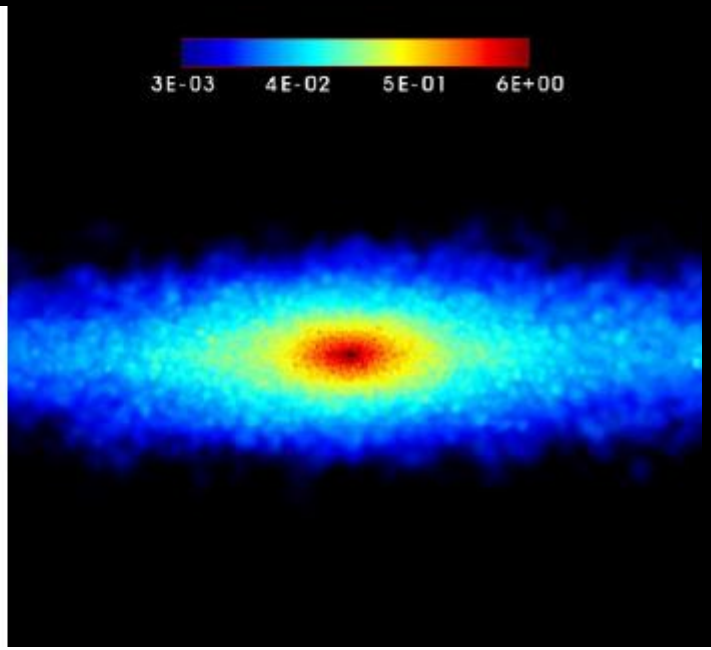
Preto, et al, 2011, Gualandris & Merritt, 2012

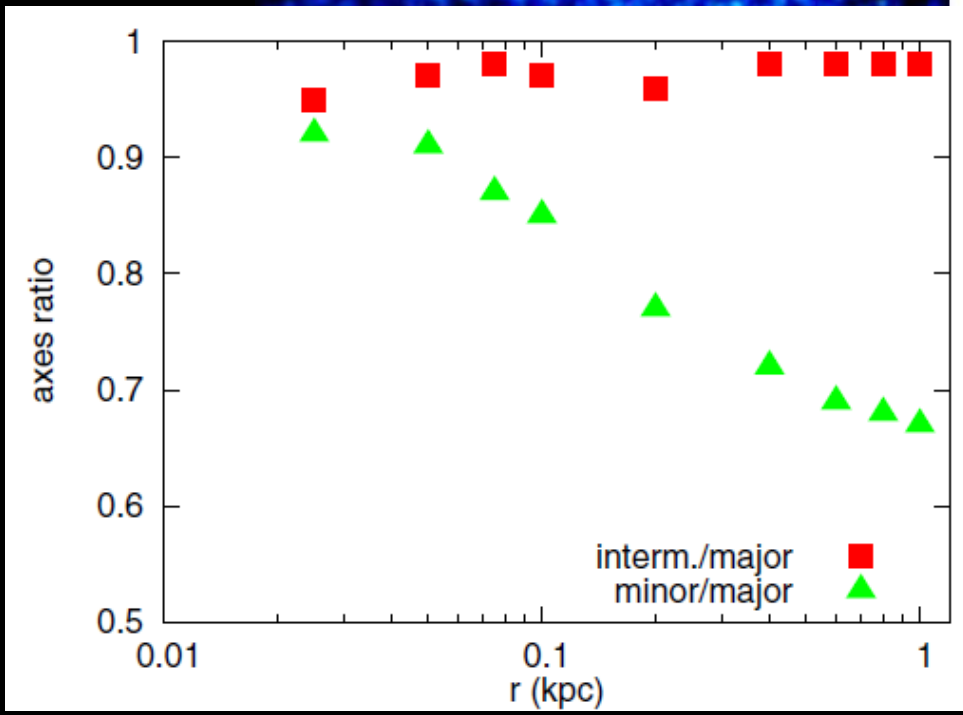
Galaxy Mergers (Khan et al. 2011)

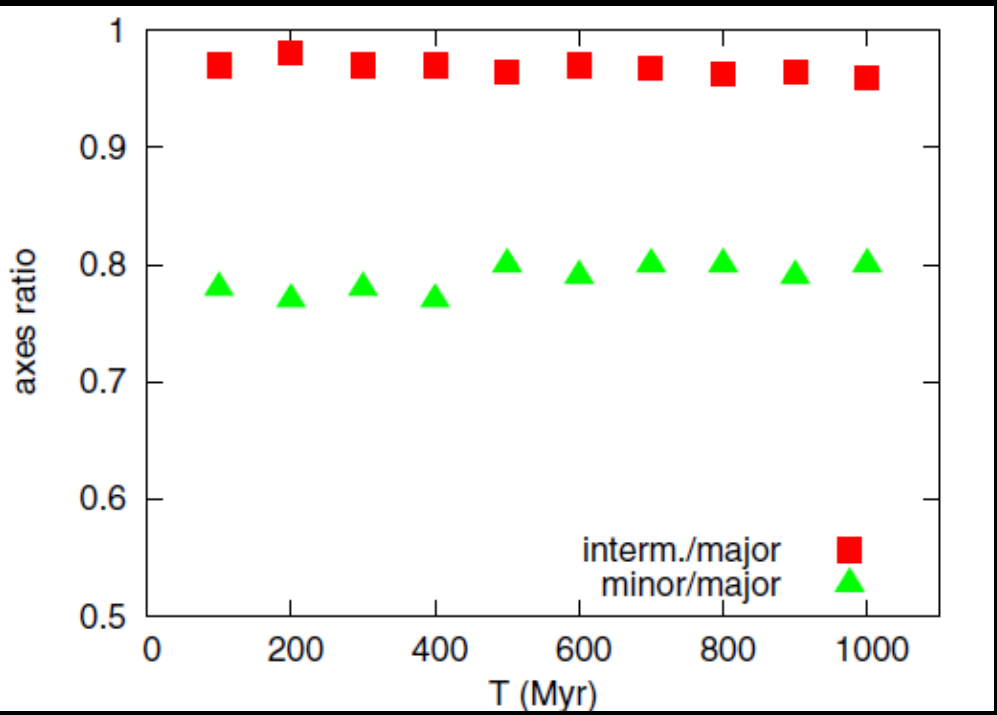


Merger of Gas Rich Disk Galaxies (Khan et al. 2012, Callegari et al. 2011)







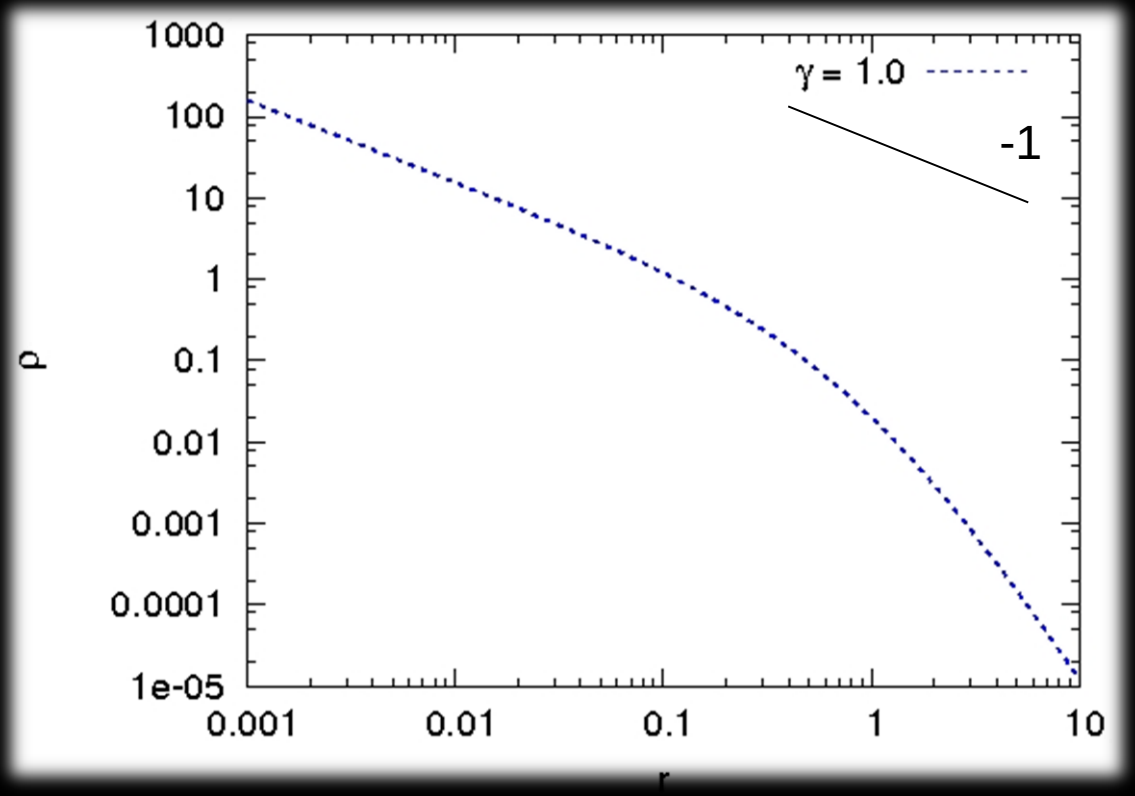


Galaxy Models

Tremaine et al (1994) model :

$$\rho(r) = \frac{(3-\gamma)M_{\rm gal}}{4\pi}\frac{r_0}{r^\gamma (r+r_0)^{4-\gamma}}$$

$$M(r) = M_{\rm gal}\left(\frac{r}{r+r_0}\right)^{3-\gamma}$$



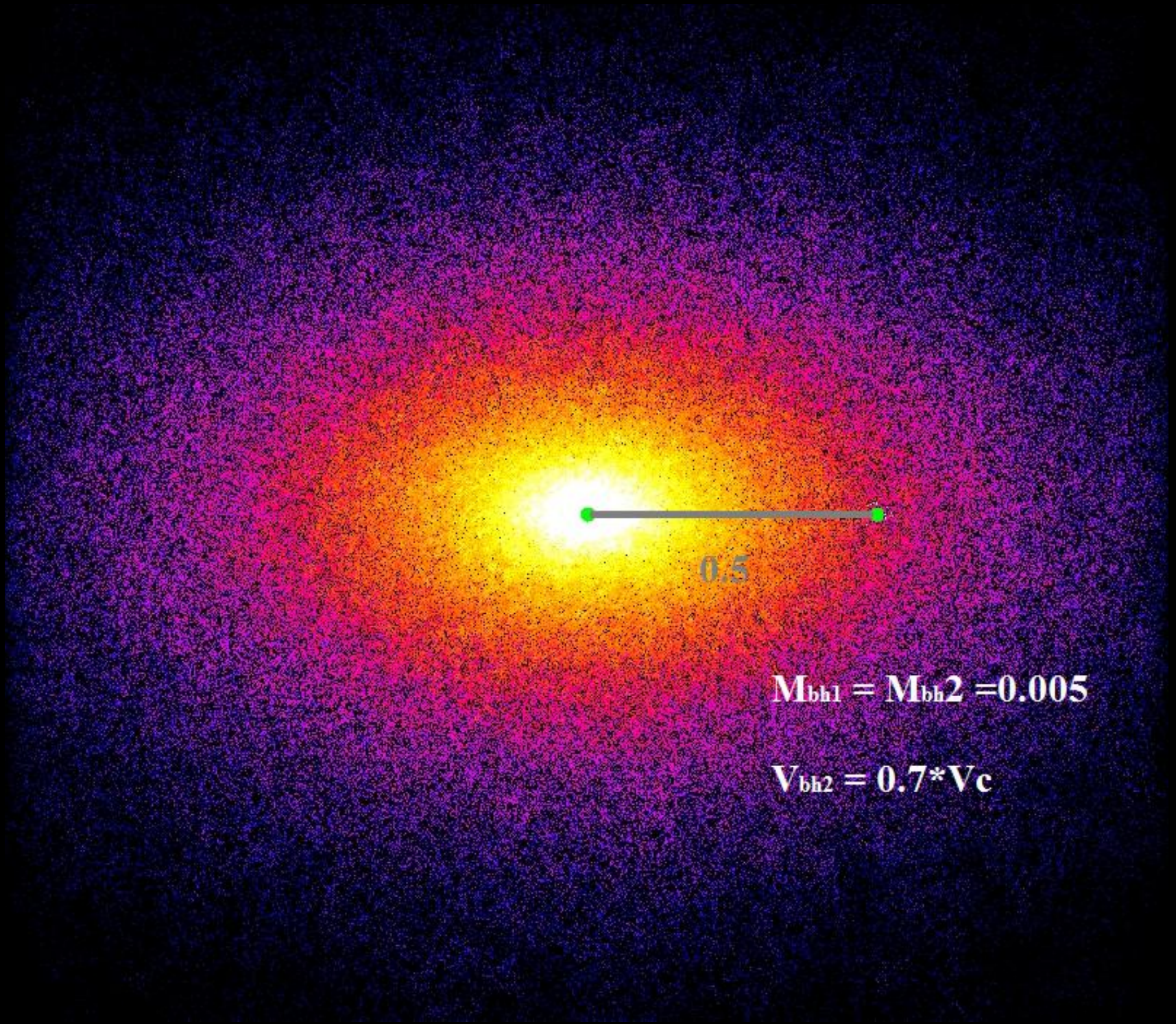
Adiabatic squeezing, Holley-Bockelmann et al. 2001

$M_{gal} = G = r_0 = 1.$

Khan et al. 2013, ApJ, 773,100

Parameters of the SMBH Binary Study

Run	N	γ	c/a	q
Spha	1000k	1.0	1.0	1.0
Flat9a	1000k	1.0	0.9	1.0
Flat9b	800k	1.0	0.9	1.0
Flat9c	500k	1.0	0.9	1.0
Flat9d	250k	1.0	0.9	1.0
Flat9e	125k	1.0	0.9	1.0
Flat8a	1000k	1.0	0.8	1.0
Flat8b	800k	1.0	0.8	1.0
Flat8c	500k	1.0	0.8	1.0
Flat8d	250k	1.0	0.8	1.0
Flat8e	125k	1.0	0.8	1.0
Flat75a	1000k	1.0	0.75	1.0
Flat75b	800k	1.0	0.75	1.0
Flat75c	500k	1.0	0.75	1.0
Flat75d	250k	1.0	0.75	1.0
Flat75e	125k	1.0	0.75	1.0


0.5
$M_{bh1} = M_{bh2} = 0.005$
$V_{bh2} = 0.7 * Vc$

Numerical Code

Phi-GRAPE+GPU (Harfst et al. 2007):

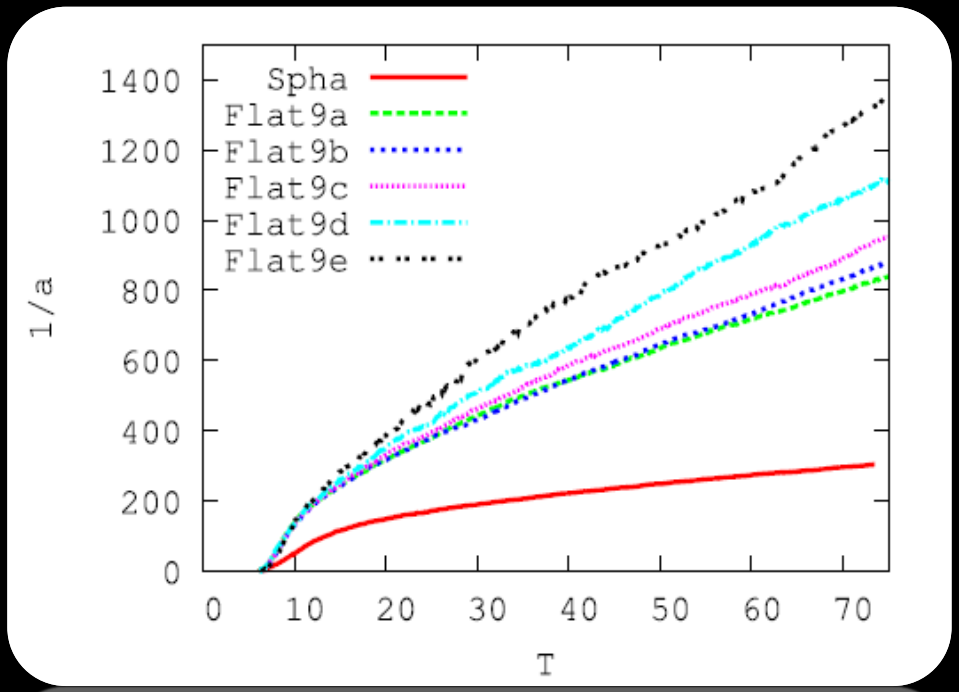
- parallel direct summation N-body code.

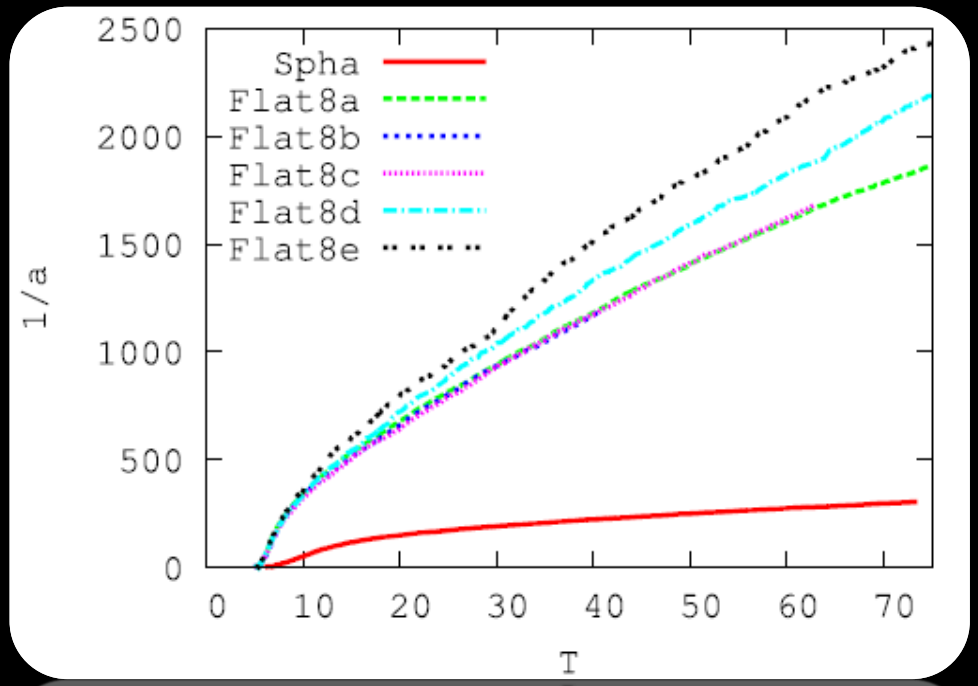
$$\mathbf{F}_i = -m_i \sum_{j=1, j\neq i}^{N} \frac{m_j(\mathbf{r}_i - \mathbf{r}_j)}{(|\mathbf{r}_i - \mathbf{r}_j|^2 + \epsilon^2)^{3/2}}$$

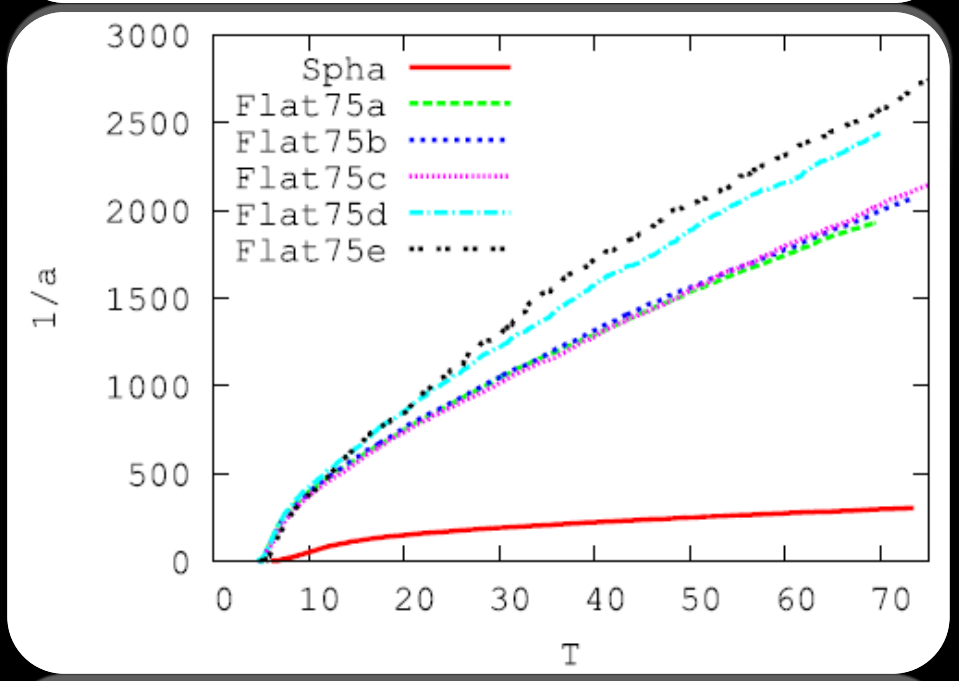
-Fourth-order Hermite integrator with individual block time steps and zero softening for black holes.

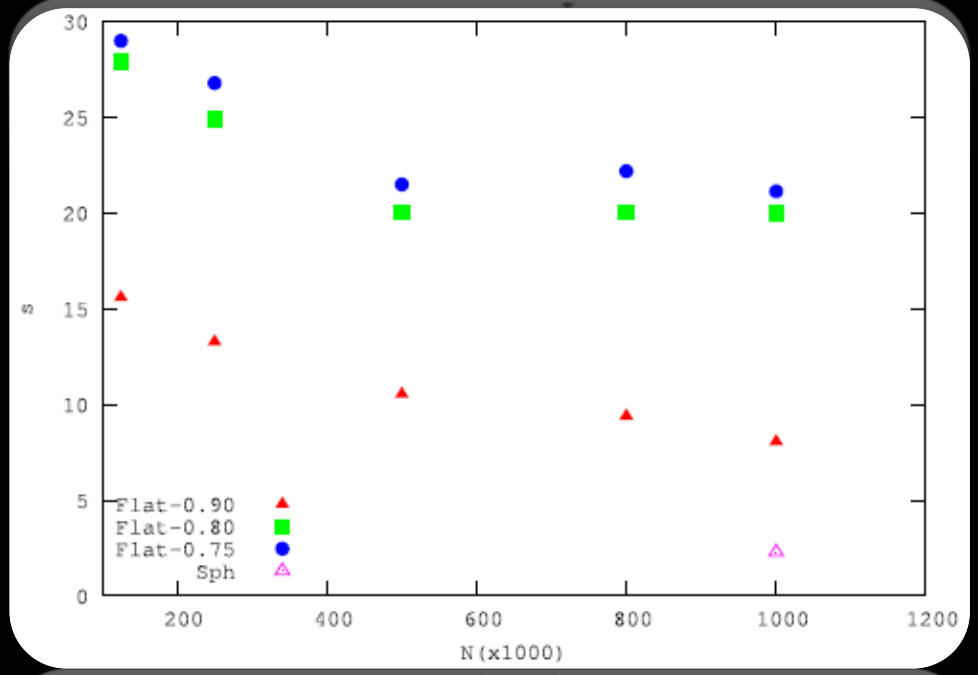
-The N-body integrations were carried on ***ACCRE*** employing 192 GPUs at Vanderbilt University, Nashville, TN.

SMBH Binary Evolution | Axi-Symmetric Models

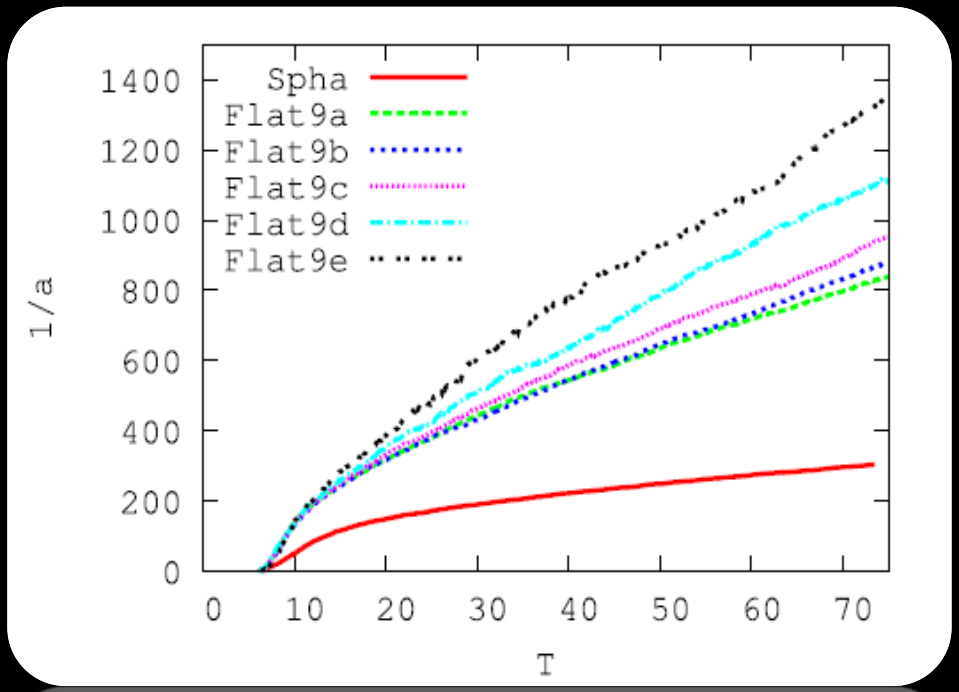


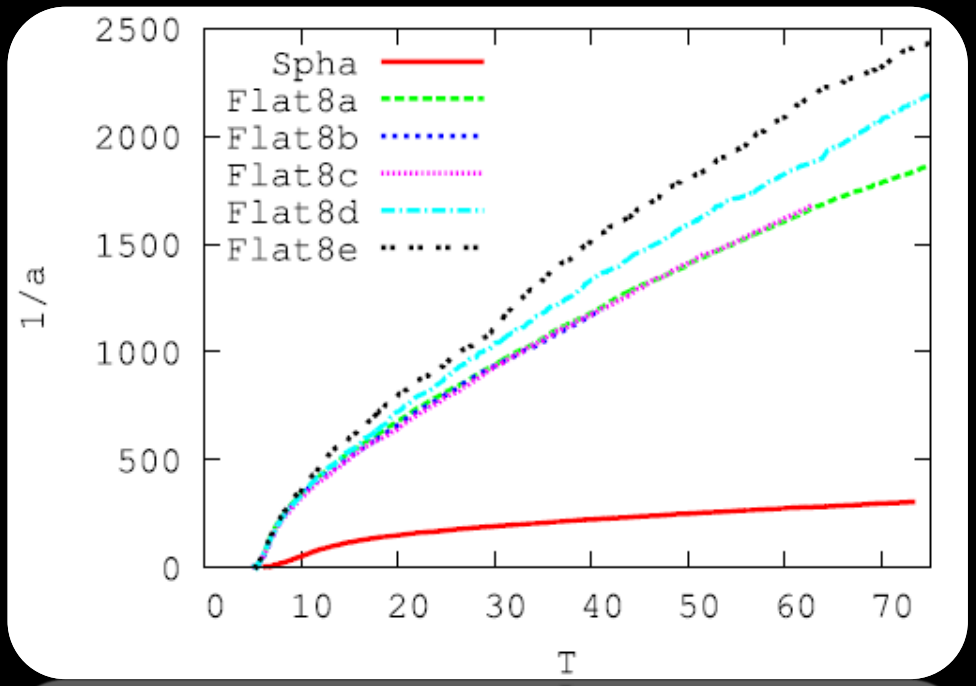


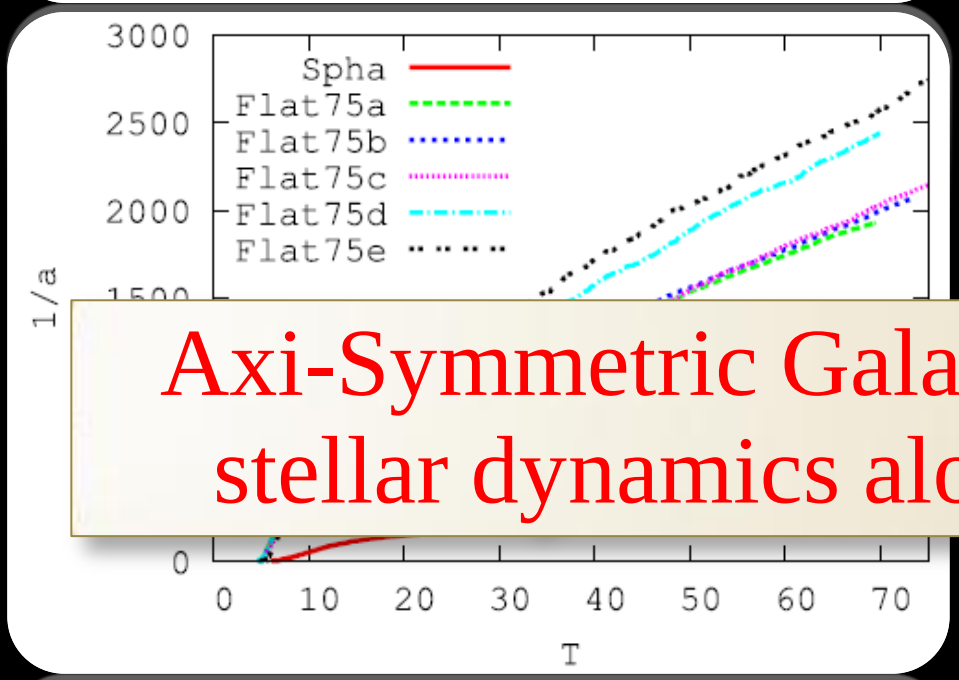


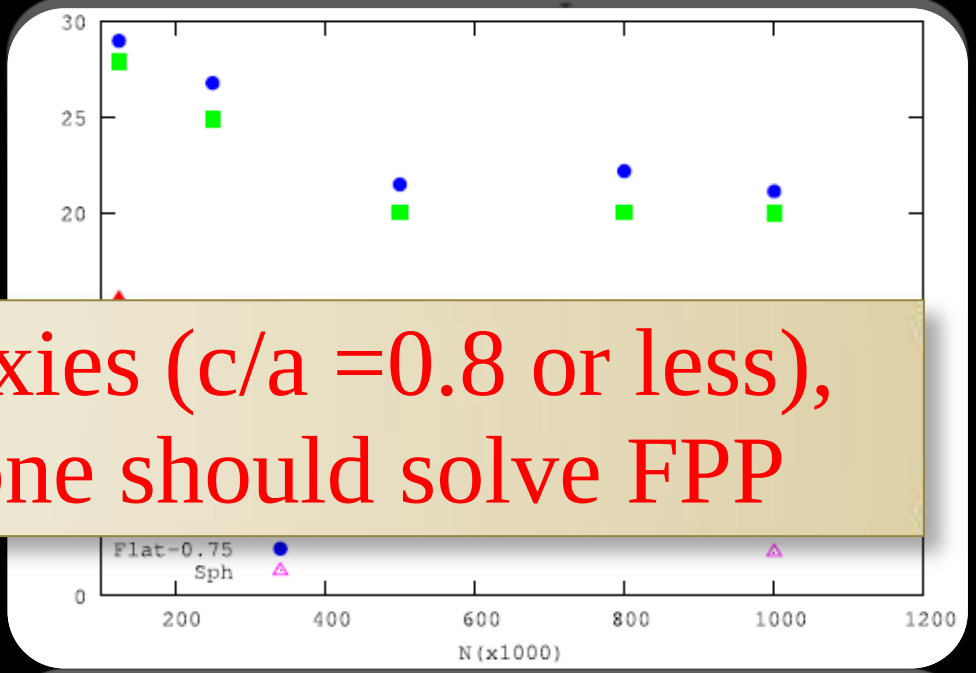


SMBH Binary Evolution | Axi-Symmetric Models









Axi-Symmetric Galaxies (c/a =0.8 or less), stellar dynamics alone should solve FPP

Coalescence Time Estimates

SMBH Binary Evolves (st. dynamics) at a constant rate.

Eccentricity remains approximately constant during Stellar dynamical phase.

$$\frac{da}{dt} = \left(\frac{da}{dt}\right)_{\rm NB} + \left\langle \frac{da}{dt} \right\rangle_{\rm GW} = -sa^2(t) + \left\langle \frac{da}{dt} \right\rangle_{\rm GW}$$

$$\left\langle \frac{da}{dt} \right\rangle_{\rm GW} = -\frac{64}{5} \frac{G^3 M_{\bullet 1} M_{\bullet 2} (M_{\bullet 1} + M_{\bullet 2})}{a^3 c^5 (1-e^2)^{7/2}} \times \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right),$$

$$\left\langle \frac{de}{dt} \right\rangle_{\rm GW} = -\frac{304}{15} e \frac{G^3 M_{\bullet 1} M_{\bullet 2} (M_{\bullet 1} + M_{\bullet 2})}{a^4 c^5 (1-e^2)^{5/2}} \times \left(1 + \frac{121}{304} e^2\right).$$

Peters 1964

Coalescence Time Estimates

Reference Galaxy --------> NGC4486A

SMBH mass (0.005) --------> Observed (13 million x sun)

Influence radius (0.1) -----> Observed (31 pc)

Time unit ------> 1.4 Myr

Speed of light (c) -------> 1550

Coalescence Time ----------> 2.4 billion years

Coalescence Time Estimates

$10^9 M_\odot$

$10^8 M_\odot$

$10^6 M_\odot$

Table 8.5: Time to Gravitational Wave Coalescence

Run	$a_{\rm final}$	$s_{\rm final}$	e_0	a_0 (pc)	t_0 (Gyr)	$t_0/t_{\rm GW}$	$t_{\rm coal}$ (Gyr)
A1	6.4×10^{-4}	9.10	0.50	3.5×10^{-1}	1.30	2.1	1.89
A2	5.5×10^{-4}	10.8	0.98	3.9×10^{0}	0.12	1.1	0.23
A3	5.9×10^{-4}	10.3	0.70	6.9×10^{-1}	0.63	1.2	1.15
A4	9.7×10^{-4}	9.60	0.88	1.6×10^{0}	0.30	1.1	0.57
B1	2.9×10^{-4}	23.3	0.62	7.4×10^{-3}	2.10	1.3	3.70
B2	3.0×10^{-4}	21.9	0.98	7.1×10^{-2}	0.24	0.5	0.77
B3	4.0×10^{-4}	20.4	0.95	4.5×10^{-2}	0.39	1.4	0.66
B4	3.9×10^{-4}	22.2	0.96	6.3×10^{-2}	0.27	0.7	0.64
D1	9.2×10^{-5}	75.7	0.69	2.1×10^{-3}	0.48	1.0	0.98
D2	7.1×10^{-5}	69.8	0.66	2.4×10^{-3}	0.43	1.0	0.82
D3	7.6×10^{-5}	69.5	0.61	2.6×10^{-3}	0.41	1.4	0.70
D4	7.5×10^{-5}	59.9	0.60	3.3×10^{-3}	0.38	1.3	0.67

Coalescence Time ----------> 2.4 billion years

Conclusions

- We studied the dynamics of SMBHs in axi-symmetric galaxies having different amount of flattening (c/a = 0.9 – 0.75).
- The SMBH binaries in axi-symmetric models evolve at a higher rate when compared to the evolution in spherical models.
- For models having flattening (c/a = 0.8, 0.75) the evolution is independent of particle number N (N > 500K) suggesting ***Final Parsec Problem should not be a problem for SMBH binaries evolving in these nuclei.***
- The SMBH binaries have very low eccentricities (~ 0.1).
- Estimated Coalescence time for the SMBH binaries is ~ 2.5 Gyrs.