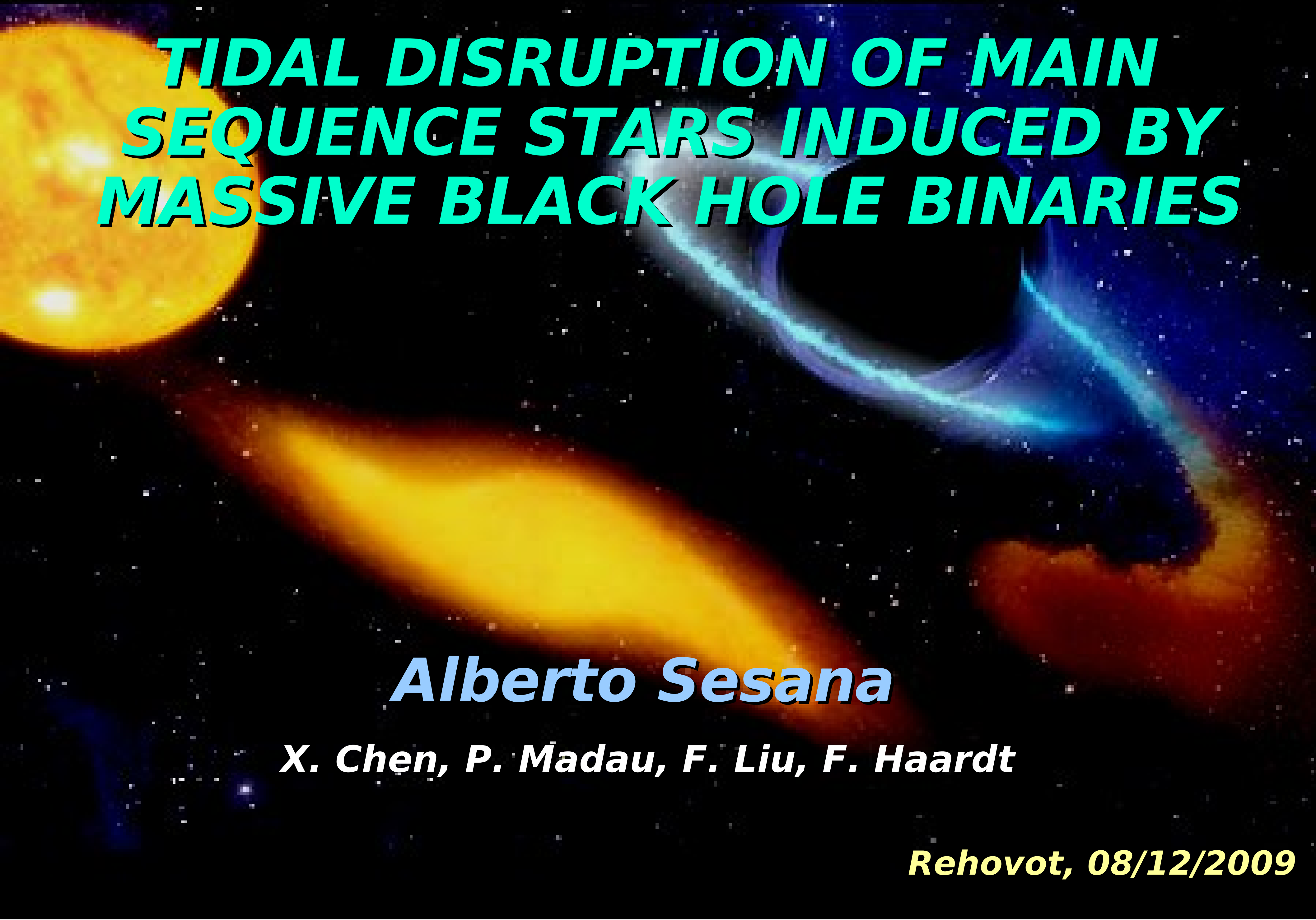
TIDAL DISRUPTION OF MAIN SEQUENCE STARS INDUCED BY MASSIVE BLACK HOLE BINARIES



Alberto Sesana

X. Chen, P. Madau, F. Liu, F. Haardt

Rehovot, 08/12/2009

OUTLINE

> The essential ingredients: MBHBs and dense stellar cusps

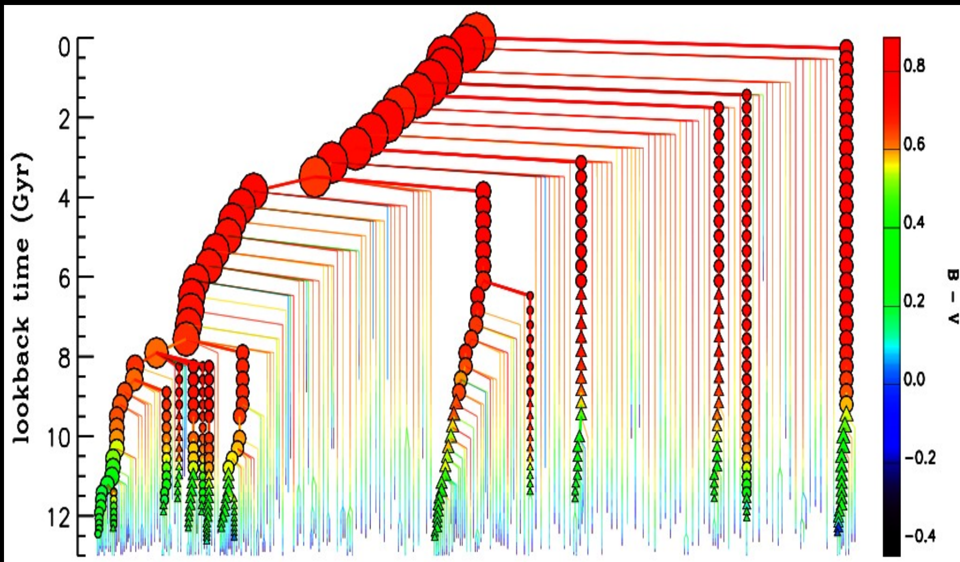
> Three body scattering experiments

> Hybrid model: enhanced tidal disruption rates of main sequence stars

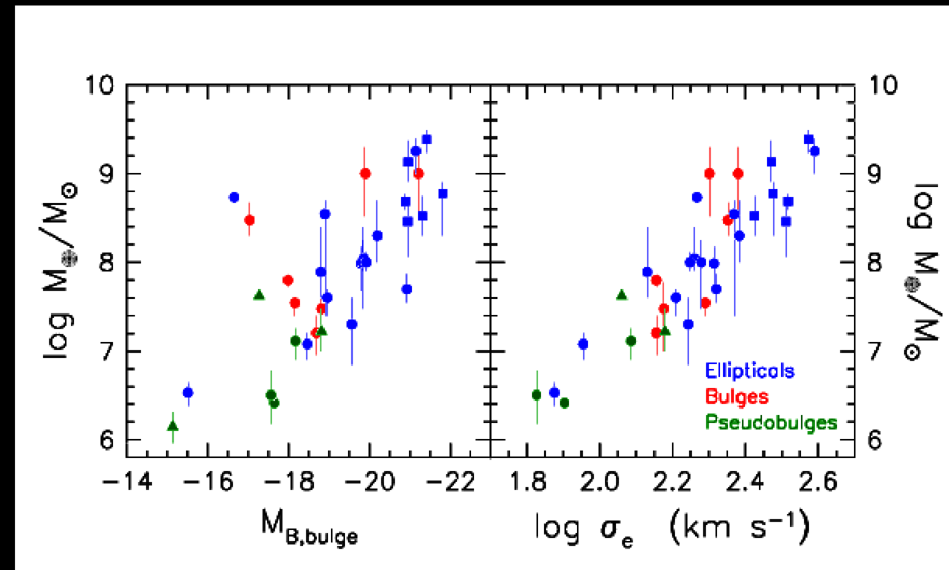
> Don't mess with GR: Kozai vs Einstein

> Numbers and observational relevance

Structure formation in a nutshell



From De Lucia et al 2006



Ferrarese & Merritt 2000, Gebhardt et al. 2000

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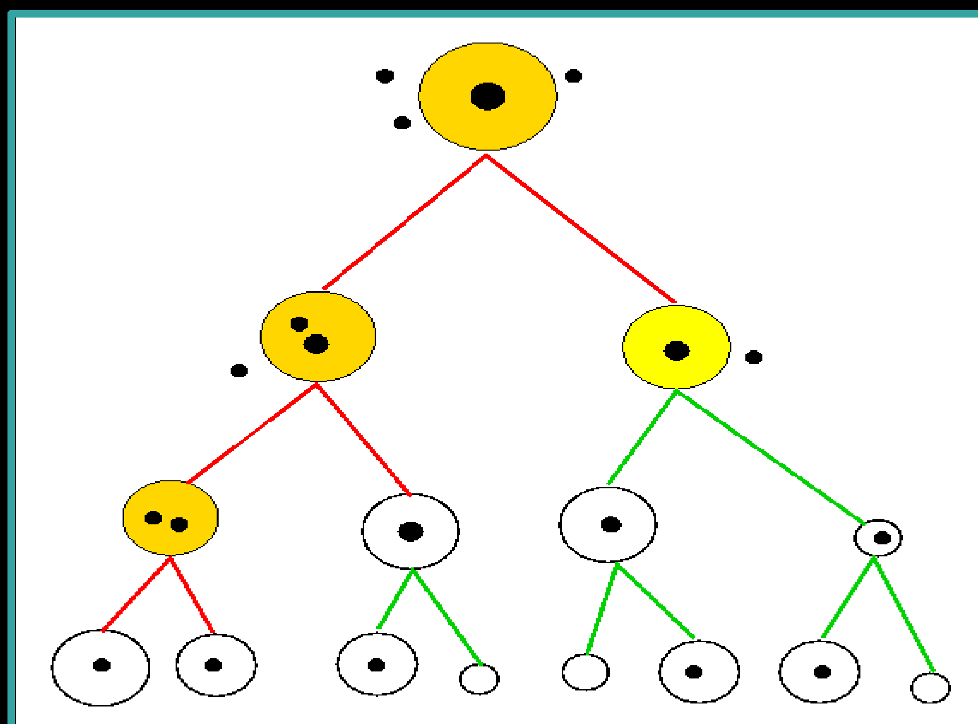
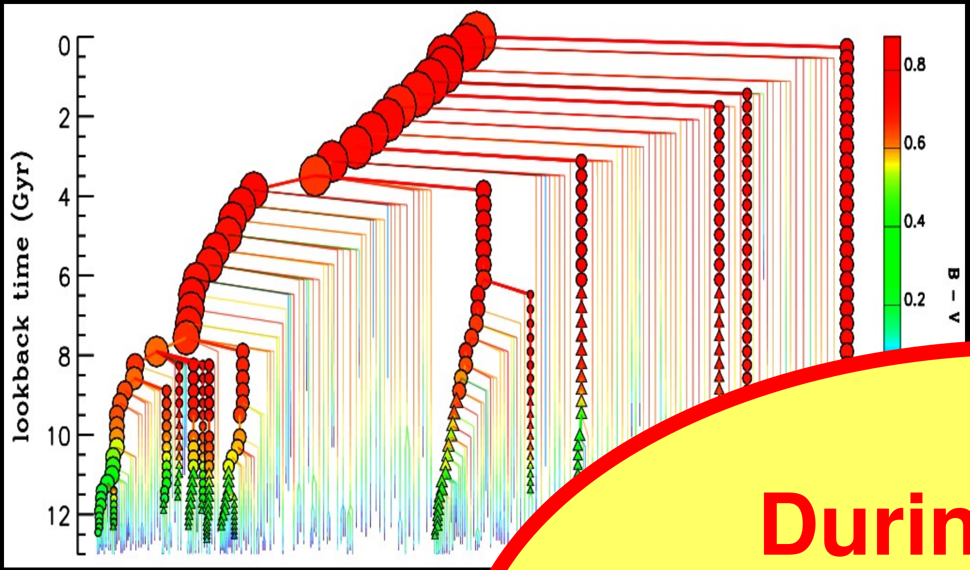
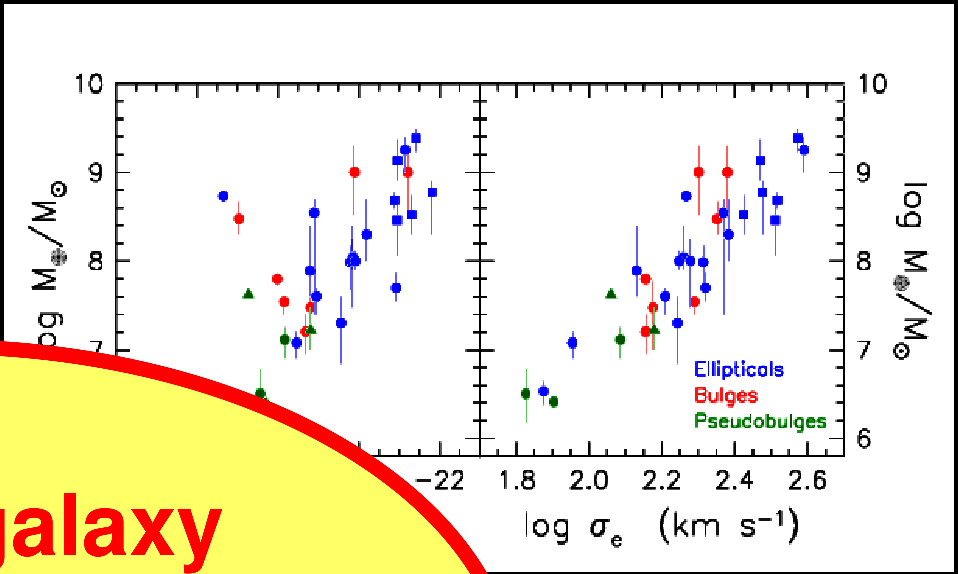


Volonteri Haardt & Madau 2003

Structure formation in a nutshell



From De Lucia et al 20



, Gebhardt et al. 2000

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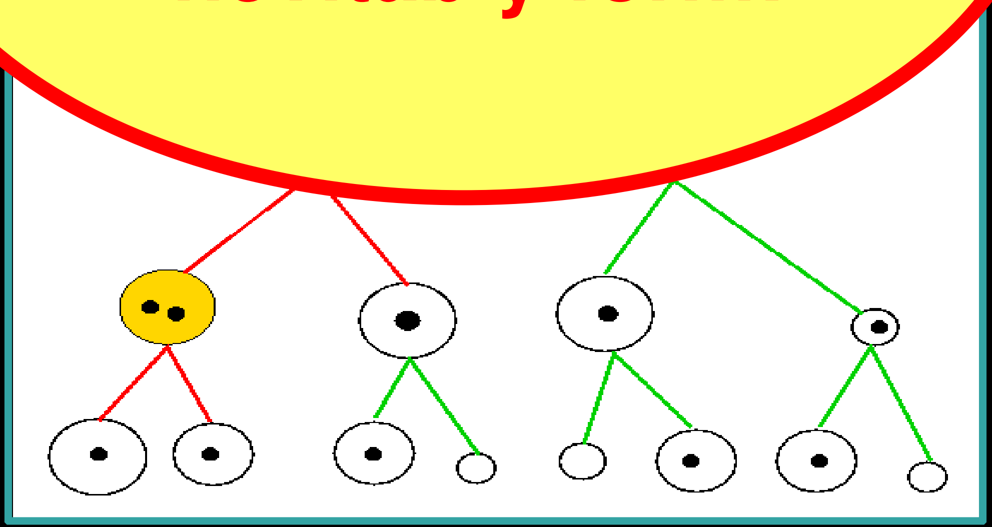
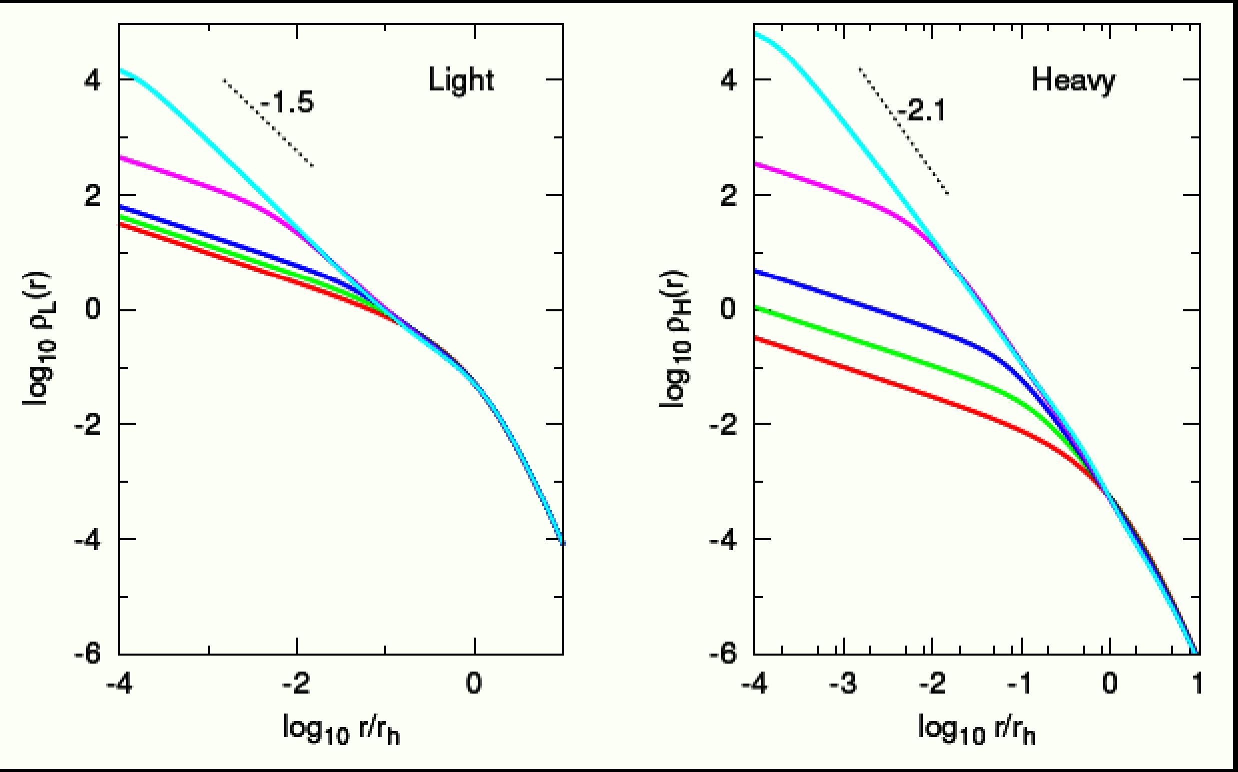
During galaxy mergers, MBHBs will Inevitably form!

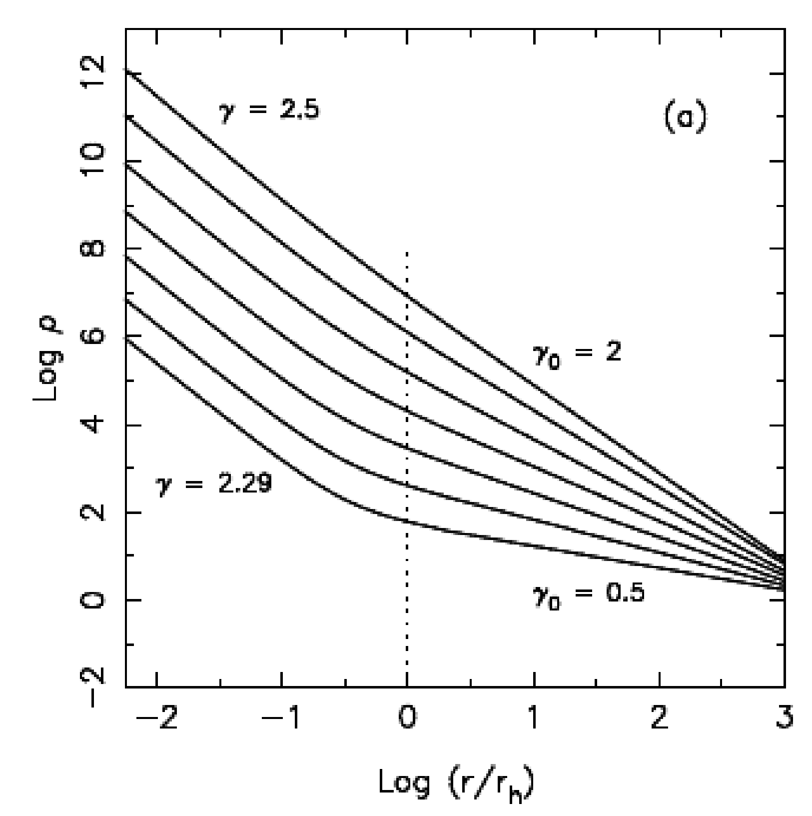


Volonteri Haardt & Madau 2003

Stellar cusps: theory



The growth of a massive object in a stellar core produces a steep power-law cusp $\rho \propto r^{-\gamma}$ with $1.5 < \gamma < 2.5$
(Young 1980)



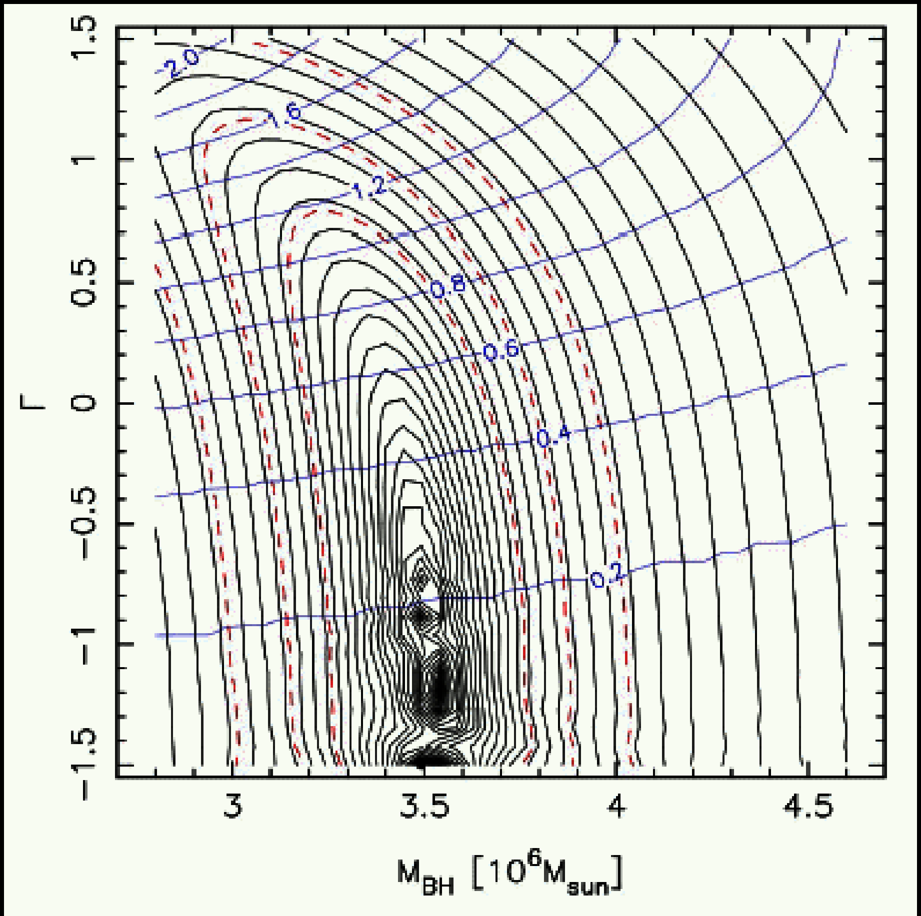
A collisional system around a massive object has a power-law steady state solution $\rho \propto r^{-7/4}$
(Bahcall & Wolf 1977)

Strong mass segregation cause the more massive objects to form even steeper cusps (Alexander & Hopman 2009)

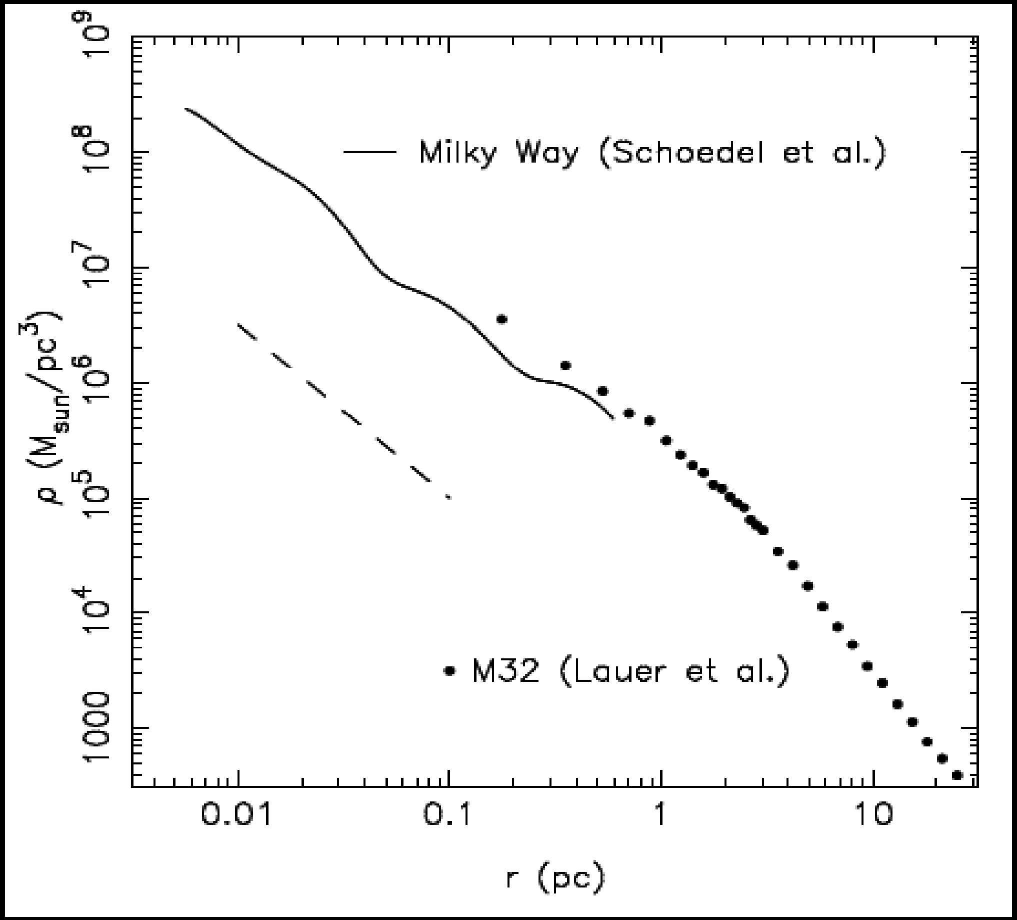
Stellar cusps: observations

Collisional nuclei ($T_{rel} < T_{Hubble}$) are expected to host steep cusps in their centres. *Should be common in spirals and in systems with M_{BH}<$10^7 M_\odot$*

Difficult to detect. Lack of resolution. MBH sphere of influence resolved for a handful of galaxies out to the Virgo cluster. But *cores seem to be common*.



MW: presence of a cusp now into question (Schoedel et al. 2009)



M32 shows a power law profile down to the resolution limit (Lauer et al. 1995)

MBHB formation in a nutshell

1. **dynamical friction** (Lacey & Cole 1993, Colpi et al. 2000)

- from the interaction between the DM halos to the formation of the BH binary
- determined by the global distribution of matter
- efficient only for ***major mergers*** against mass stripping

2. **binary hardening** (Quinlan 1996, Miloslavljevic & Merritt 2001)

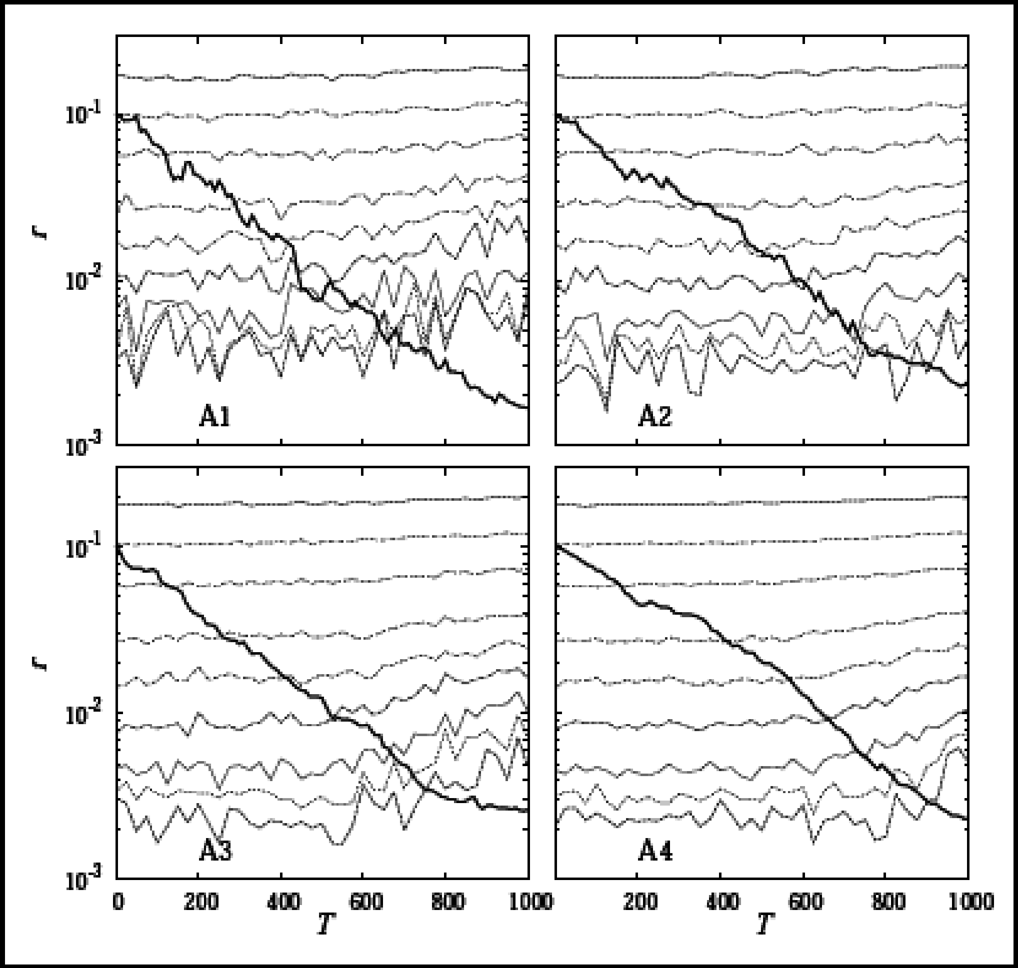
- ***3 bodies interactions*** between the binary and the surrounding stars
- the binding energy of the BHs is larger than the thermal energy of the stars
- the SMBHs create a ***stellar density core ejecting the background stars***

3. **emission of gravitational waves** (Peters 1964)

- takes over at subparsec scales
- leads the binary to coalescence

Length scales

Dynamical friction quickly drive the secondary hole down to a separation where the mass in stars enclosed in its orbit is of the order of its own mass



Matsubayashi et al. 2007

The cusp is modelled as a double power-law normalized to the isothermal sphere outside the radius of influence of M_1. *This defines the lengthscale of the system*

$$\rho_*(r) = \frac{\sigma_*^2}{2\pi G r^2}$$

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma}$$

$$r_0 = (3-\gamma)\frac{GM_1}{\sigma^2}$$

The presence of a tidal disruption radius breaks the scale-freedom of the 3-body integration

For a BH of mass M_1 embedded in a cusp with slope normalized to a standard isothermal sphere outside its radius of influence we have

$$\begin{aligned} r_{\rm inf} &= (3-\gamma)\frac{GM_1}{\sigma_*^2} \simeq 4.6 \text{ pc } (3-\gamma) M_7 \sigma_{100}^{-2}, \\ a_0 &= q^{1/(3-\gamma)} r_{\rm inf}, \end{aligned}$$

The tidal disruption radius is defined as

$$\begin{aligned} r_t &= r_* \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} \\ &\simeq 4.7 \times 10^{-6} \text{ pc } \left(\frac{r_*}{\rm R_\odot}\right) \left(\frac{M_*}{\rm M_\odot}\right)^{-1/3} \left(\frac{M_{\rm BH}}{10^7\,\rm M_\odot}\right)^{1/3} \end{aligned}$$

The ratio of the two relevant length scales is

$$\begin{aligned} \frac{r_{t1}}{a_0} &= \frac{\sigma_*^2 r_*}{G m_*} \frac{q^{-1/(3-\gamma)}}{(3-\gamma)} \left(\frac{M_1}{m_*}\right)^{-2/3} \\ &\simeq 1.0 \times 10^{-6} (3-\gamma)^{-1} M_7^{-2/3} q^{-1/(3-\gamma)} \sigma_{100}^2 \left(\frac{r_*}{\rm R_\odot}\right) \left(\frac{m_*}{\rm M_\odot}\right)^{-1/3} \end{aligned}$$

We normalize our experiment to the case $a=a_0$, $M_1=10^7 M_\odot$, $q=1/81$, $\gamma=2$

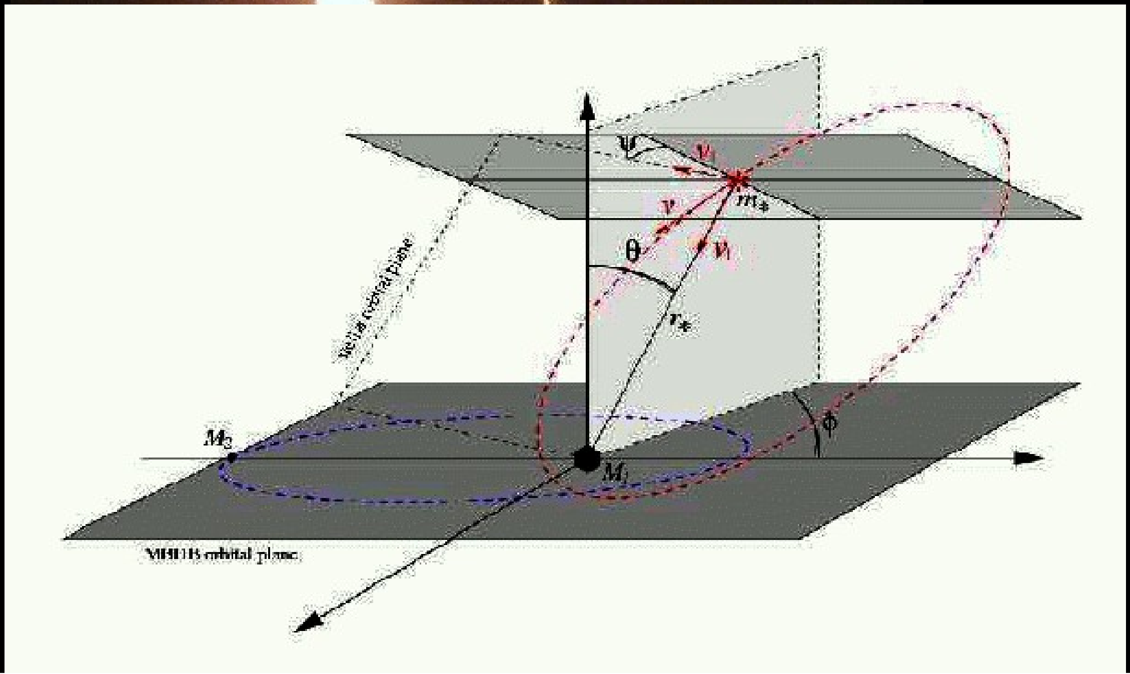
We record the first passage of each star in 20 equally log spaced points in the range (0.01-100) r_{t1}/a_0

Three body scattering experiments

We integrate the nine coupled second order, differential equations

$$\ddot{\mathbf{r}}_i = -G \sum_{i \neq j} \frac{m_j (\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^3}$$

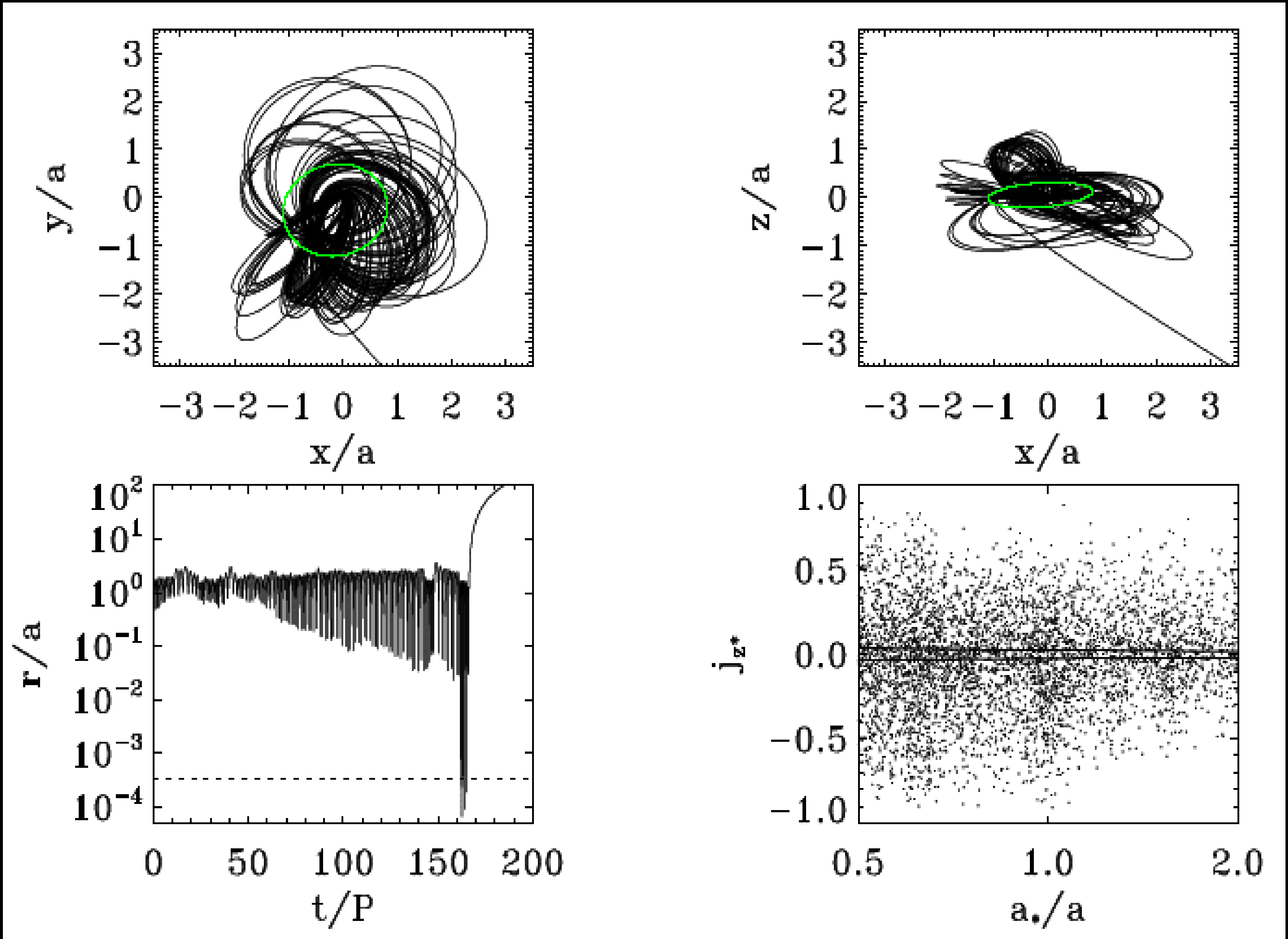
using the explicit **Runge-Kutta integrator DOPRI8** (Hairer & Wanner 2002)



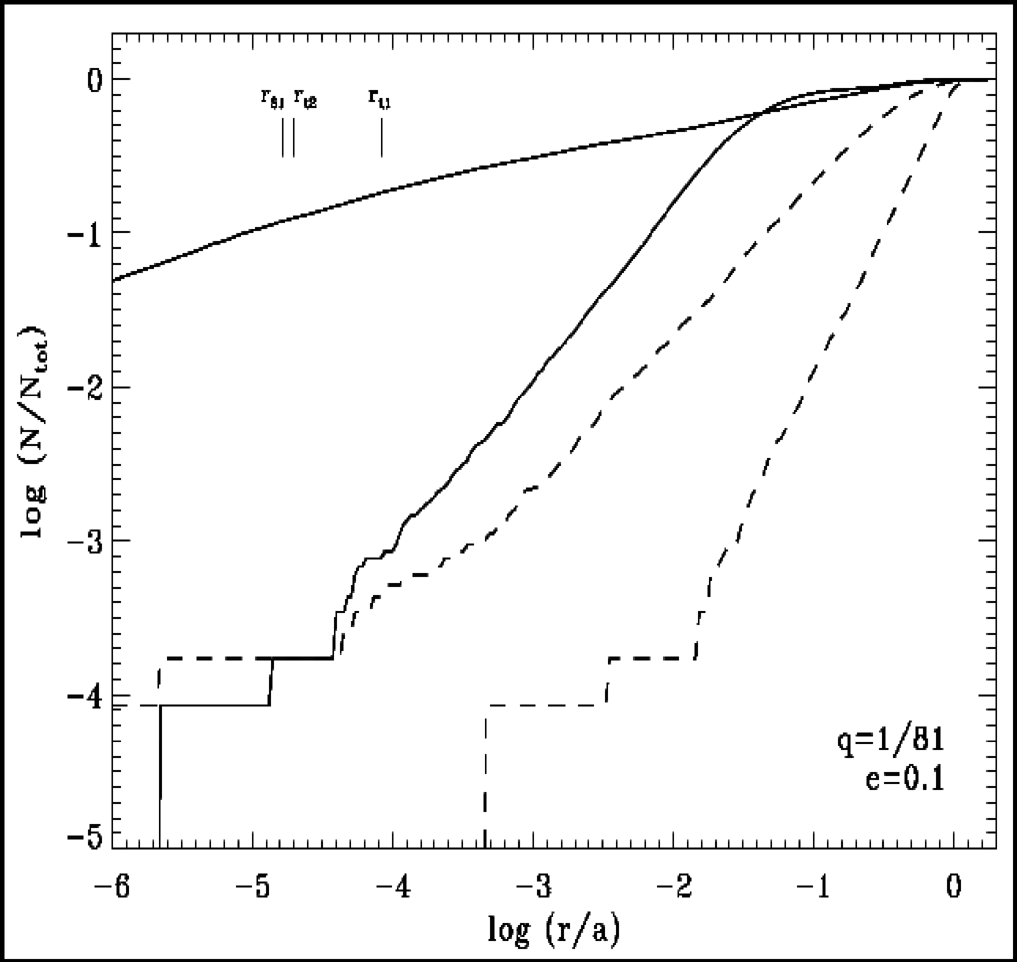
10 INITIAL CONDITIONS NEED TO BE SPECIFIED

1) binary mass ratio
2) binary eccentricity
3) star/BH mass ratio
4) initial distance of the star
5-6) energy and angular momentum of the stellar orbit
7-8-9) angles defining the star orbit
10) initial binary phase

Examples of orbit integration



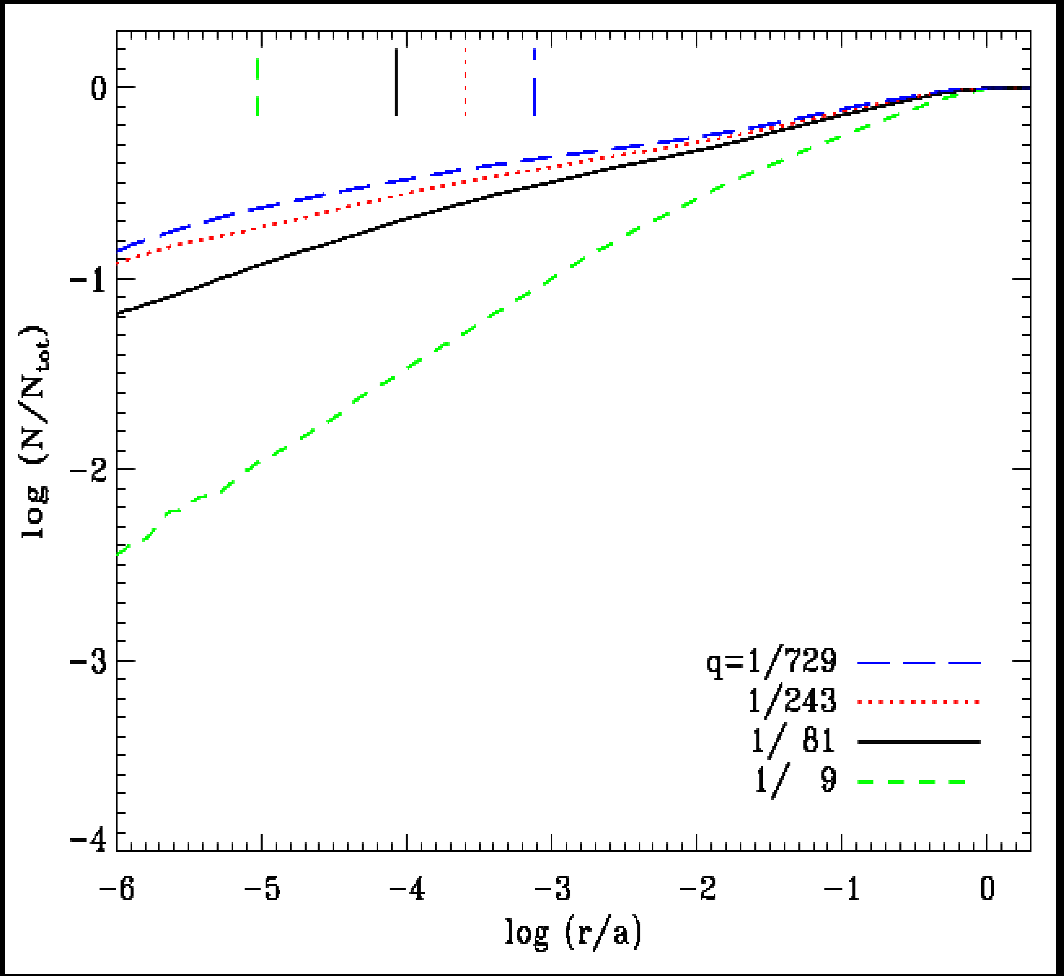
Tidal disruption 'cross sections'



Binary vs single MBH cross sections:

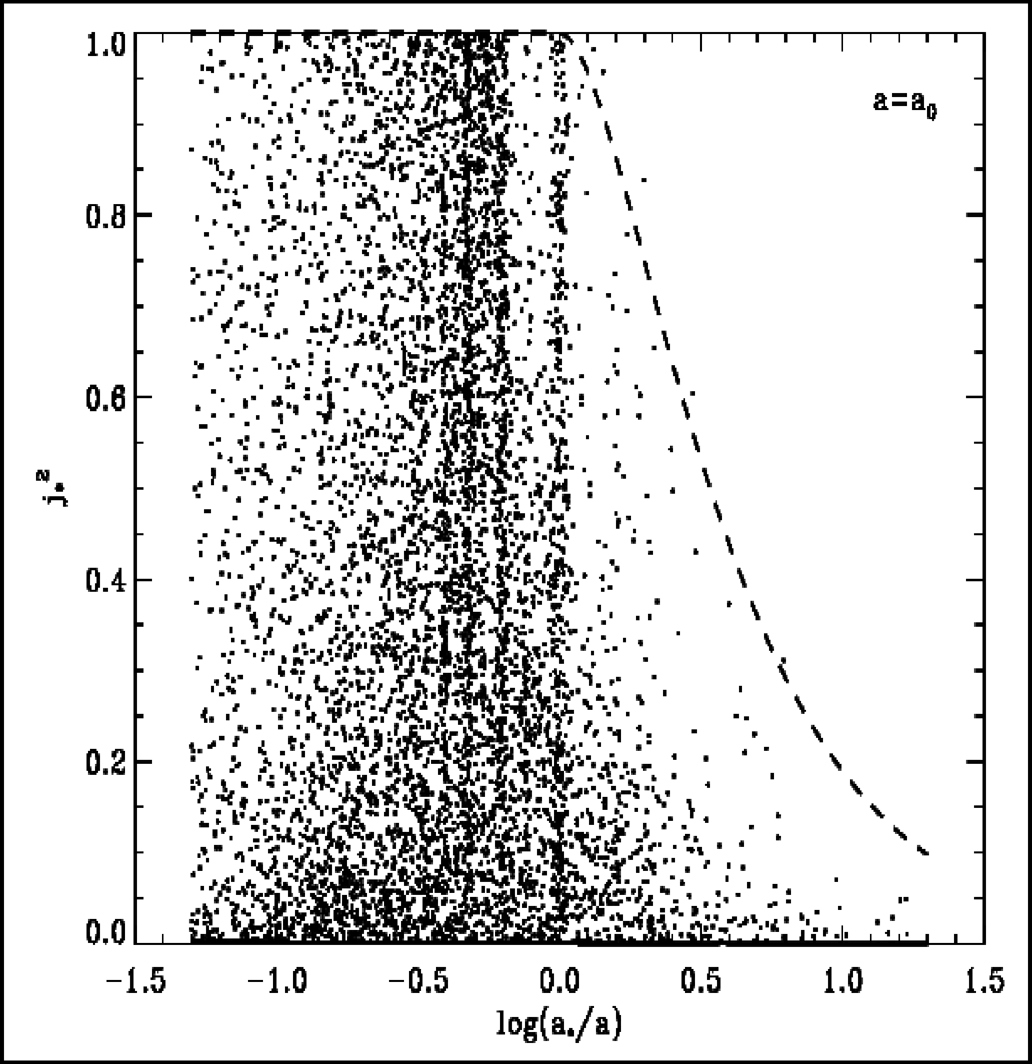
Tidal disruption cross section increases by 3 orders of magnitude

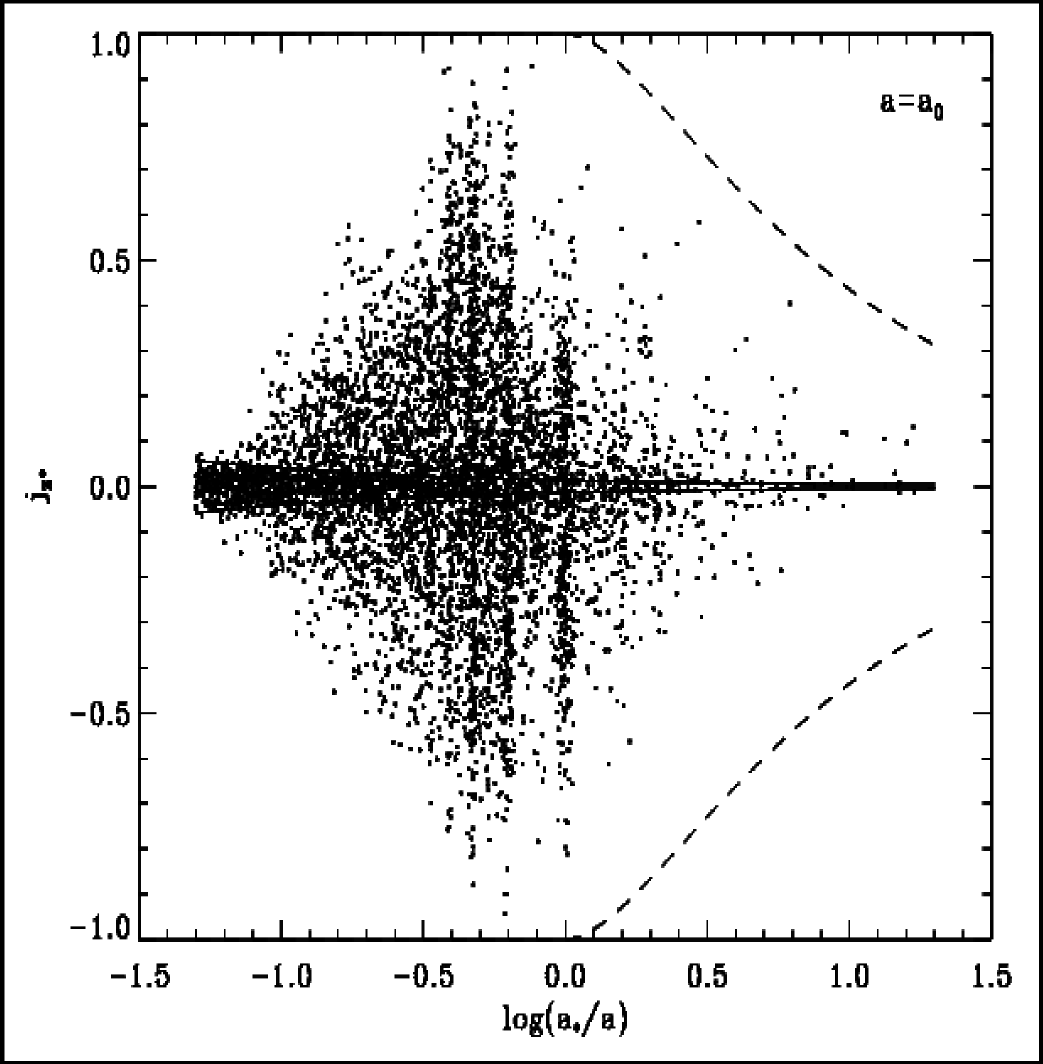
Dependence on the binary mass ratio



Phase space structure of the disrupted stars

No clear structure in the j^2-$\mathscr{E}$ space

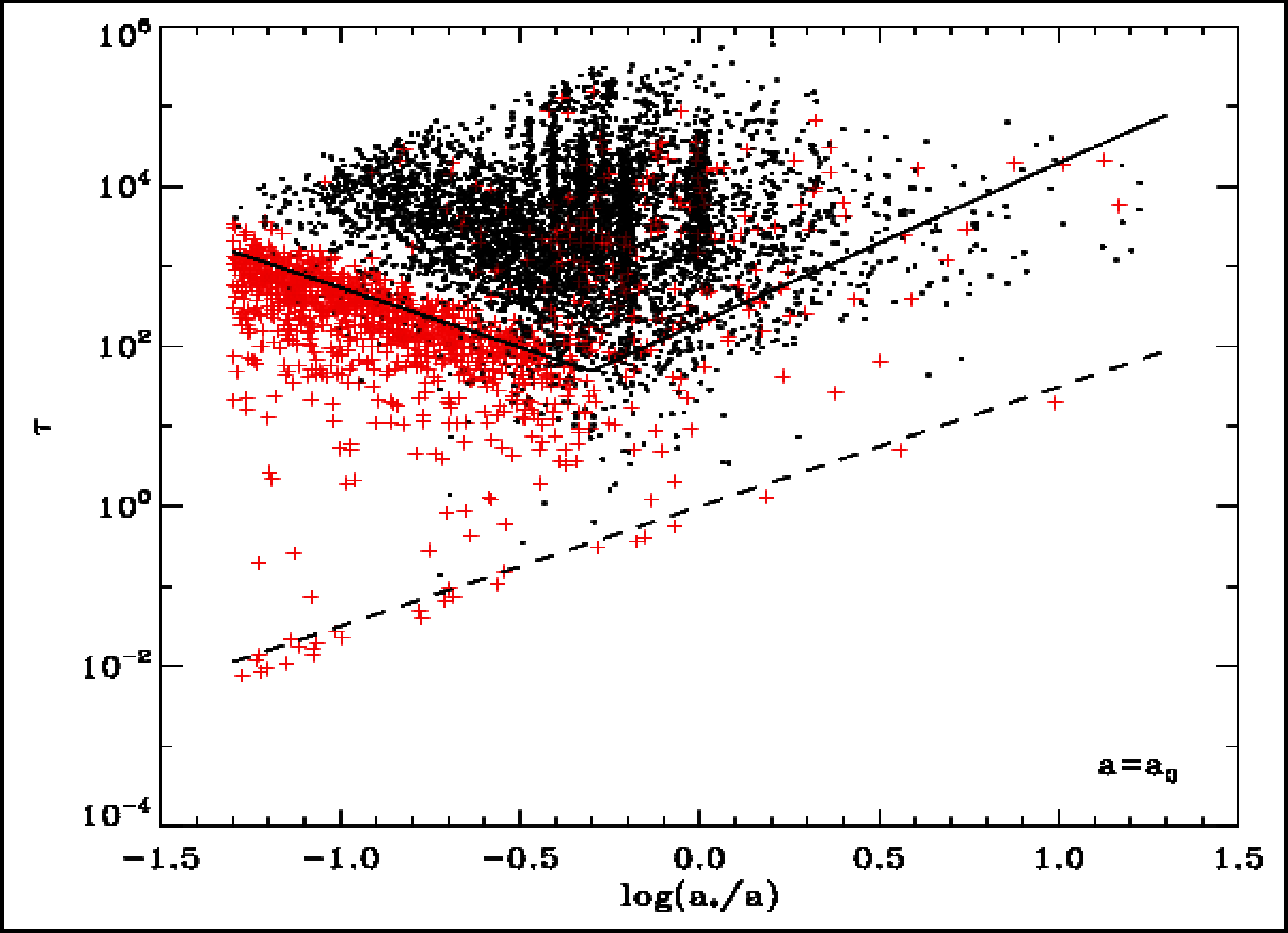




Structure emerging in the j_z-$\mathscr{E}$ space: ***Kozai resonances +chaotic interactions***

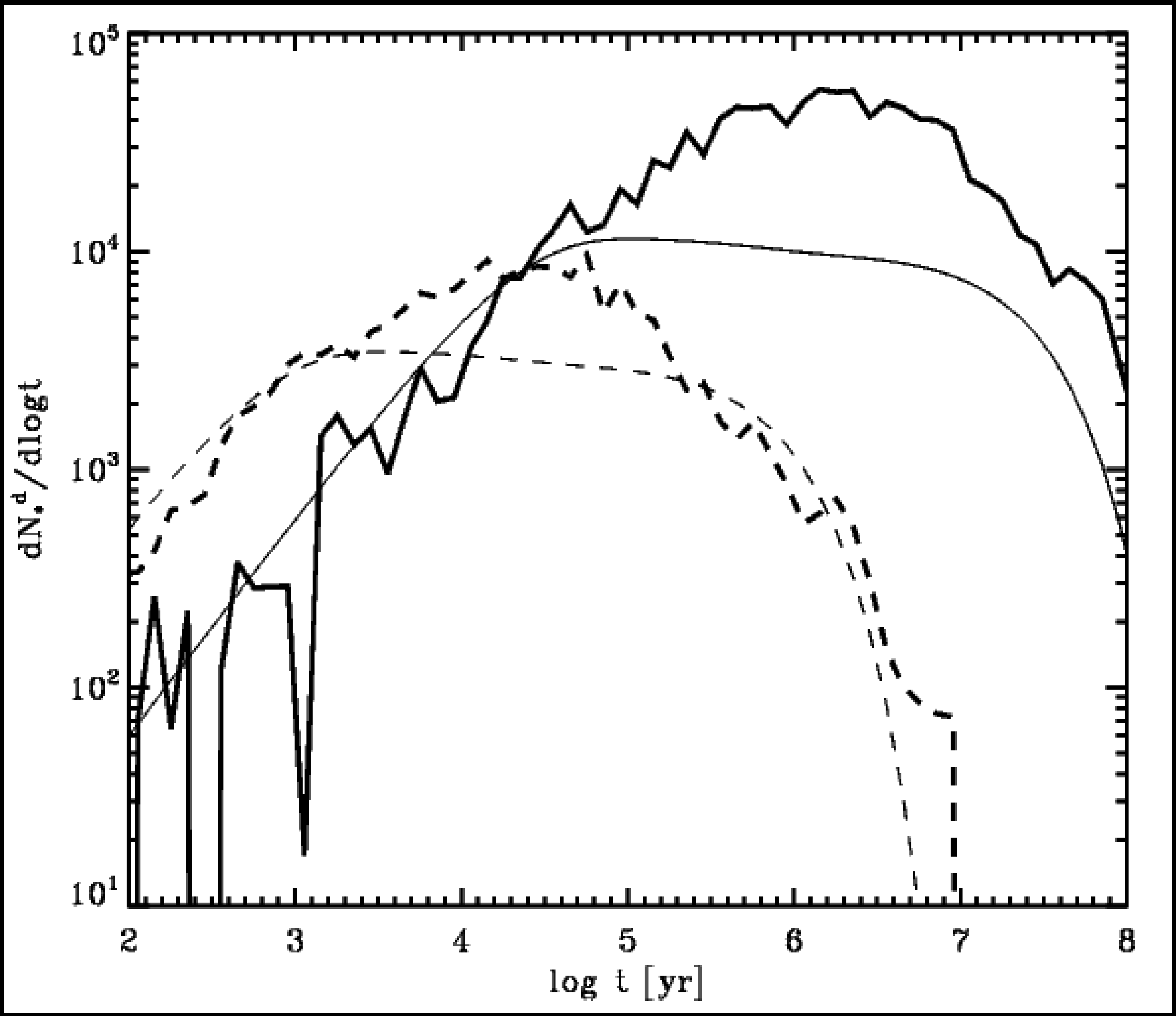
Tidal disruption timescales

$$T_{\rm K} = \begin{cases} \frac{2}{3\pi q}\left(\frac{a_*}{a}\right)^{-3/2} P & (a_* \leq a/2) \\ \frac{16\sqrt{2}}{3\pi q}\left(\frac{a_*}{a}\right)^{2} P & (a_* > a/2) \end{cases}$$



Static binary: tidal disruption rates

Weighting properly the tidal disruption events over an initial distribution function for the interacting stars in the cusp, the results can be translated into a *tidal disruption rate*



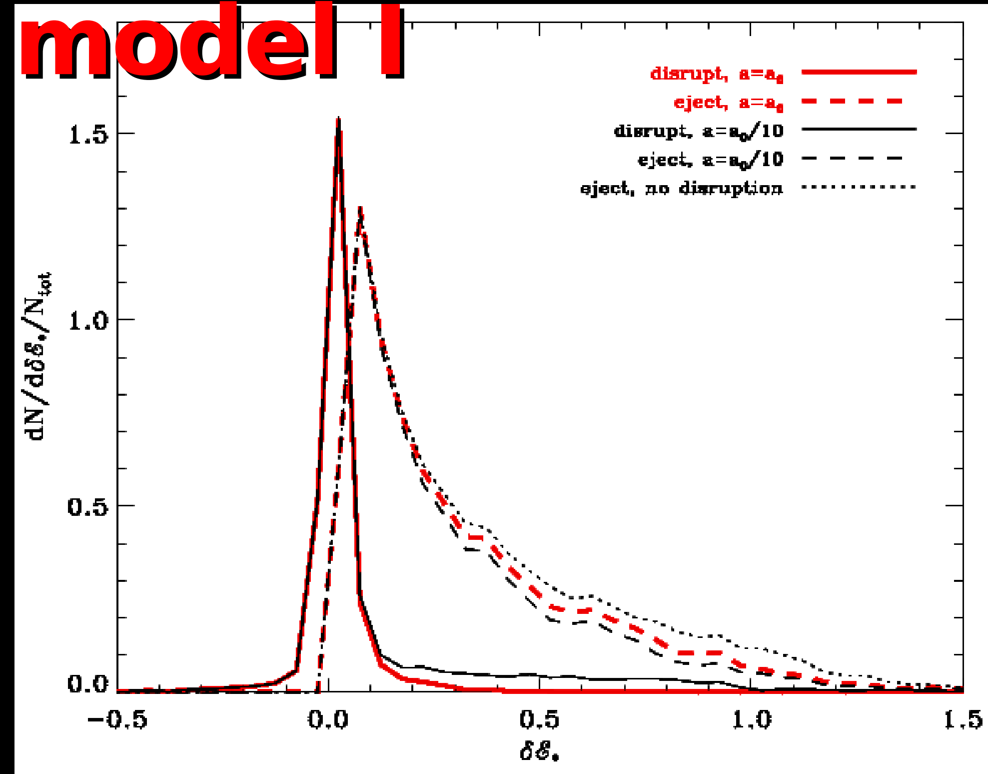
(M_1=10^7M$_\odot$, q=1/81, γ=2)

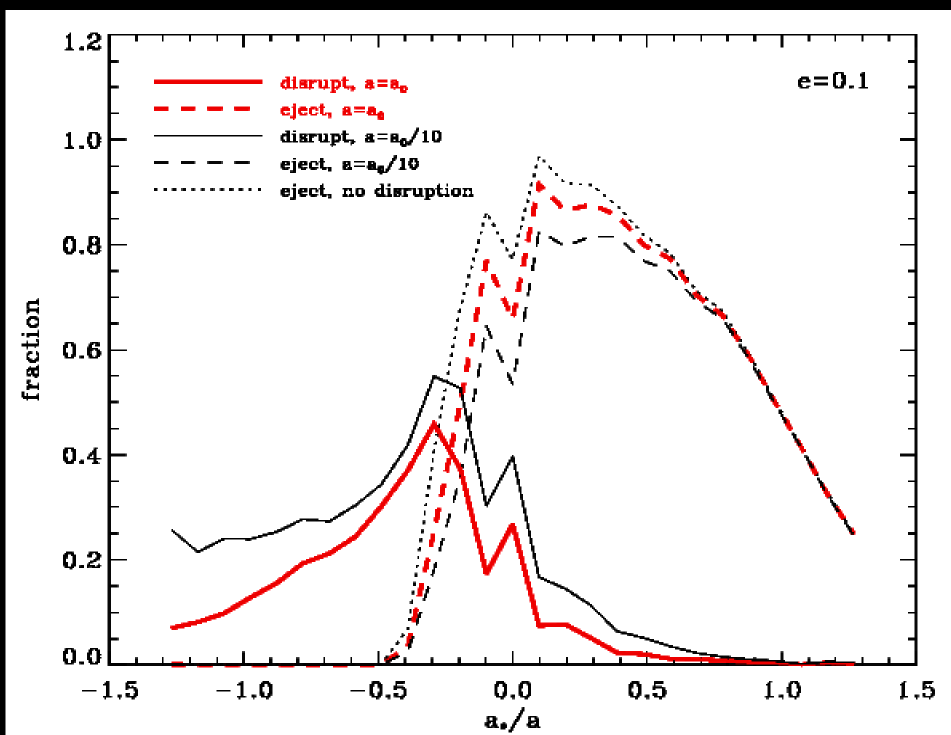
TD rates for a stationary MBHB in a SIS profile.

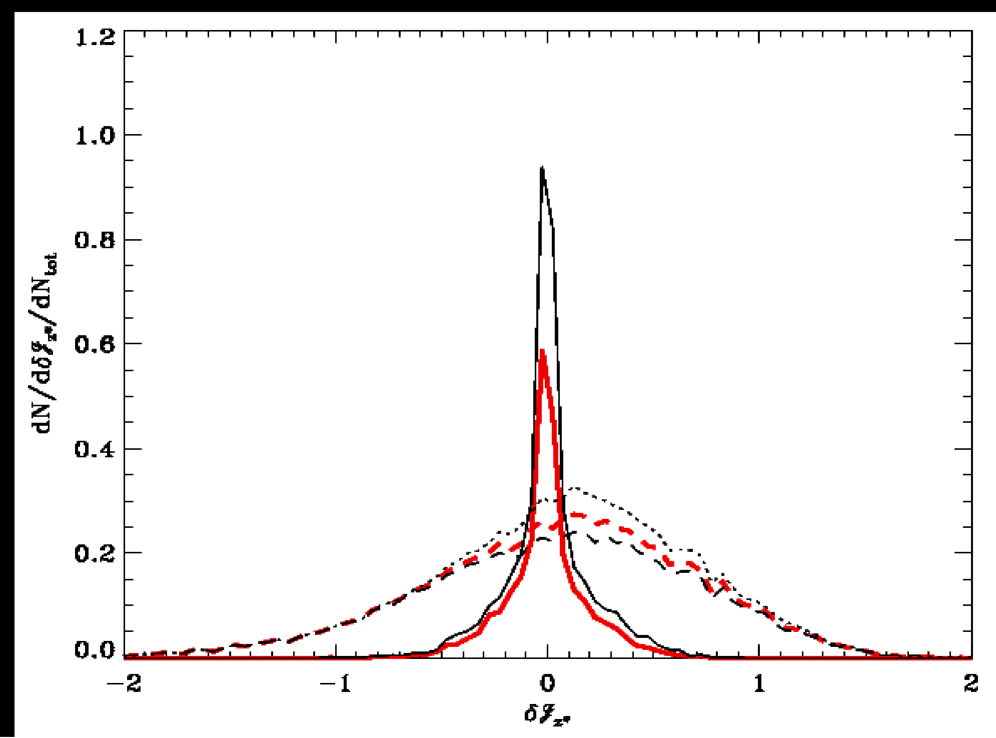
The two set of curves are for $a=a_0$ and $a=0.1a_0$

The hybrid model I

We construct distributions of ejected and disrupted stars as a function of time on a grid of *a/a_0* and *e*







The hybrid model II

Stars are drown from an initial distribution function representing a cusp centred onto M_1 with a given slope. M_2 is initially at a_0 so that $M_*(r<a_0)=2M_2$

$$f_0(a_*, j_*, j_{z*}) = n_0(a_*) = \frac{2(3-\gamma)}{a_0}\frac{M_2}{\mathrm{M}_\odot}\left(\frac{a_*}{a_0}\right)^{2-\gamma}$$

We divide the a_* axis into logarithmic bins and we compute the initial mass in each bin

We evolve the binary according to:

$$\Delta m_i^{\mathrm{eff}}(\Delta t) = \Delta m_i(\tau_i + \Delta t/P) - \Delta m_i(\tau_i),$$

$$\Delta \mathcal{E}_b(\Delta t) = \sum_{i=1}^{100}[\Delta \mathcal{E}_i(\tau_i + \Delta t/P) - \Delta \mathcal{E}_i(\tau_i)],$$

$$\Delta \mathcal{J}_b(\Delta t) = \sum_{i=1}^{100}[\Delta \mathcal{J}_i(\tau_i + \Delta t/P) - \Delta \mathcal{J}_i(\tau_i)].$$

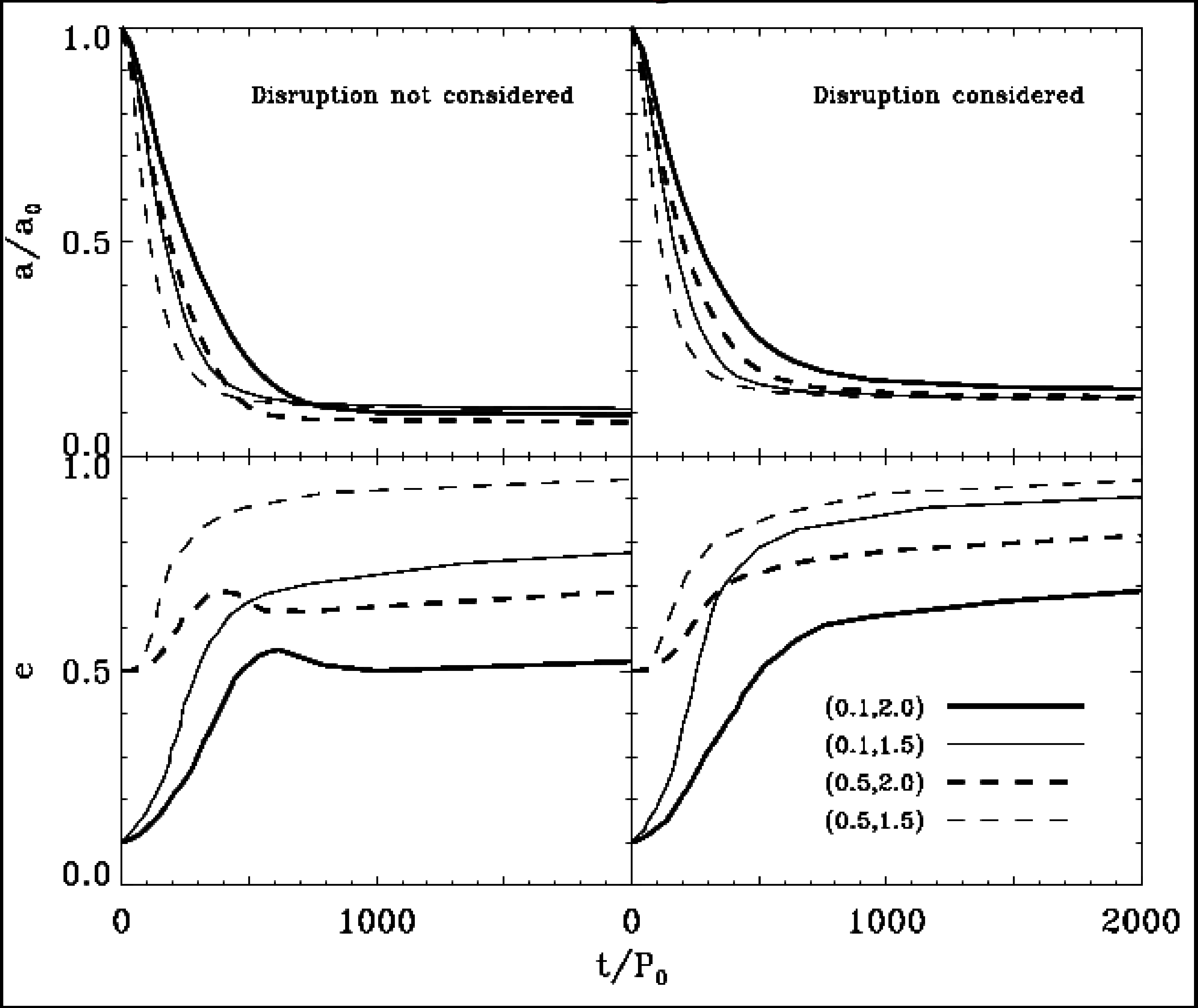
$$m_i' = m_i - \Delta m_i^{\mathrm{eff}}(\Delta t),$$

$$a' = a - \frac{\Delta \mathcal{E}_b(\Delta t)}{\mathcal{E}_b} a,$$

$$e' = e - \frac{1-e^2}{2e}\left[\frac{\Delta \mathcal{E}_b(\Delta t)}{\mathcal{E}_b} + \frac{2\Delta \mathcal{J}_b(\Delta t)}{\mathcal{J}_b}\right]$$

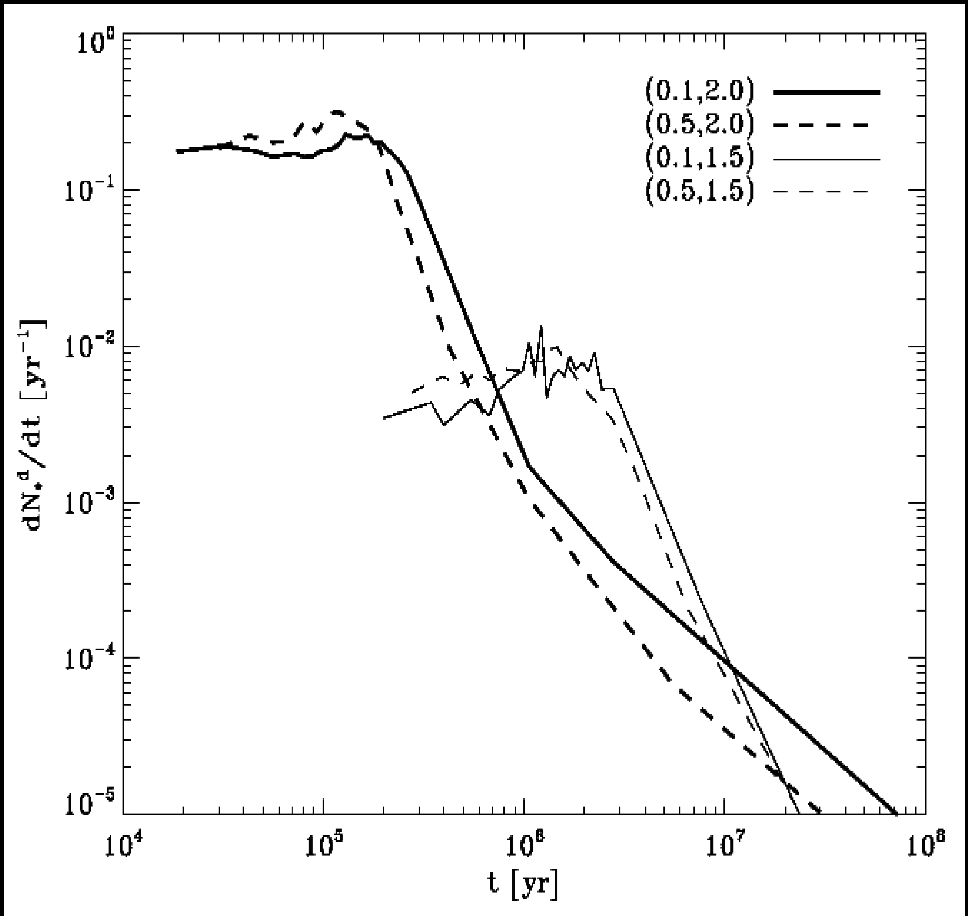
At each timestep the number of ejected and disrupted stars computed interpolating among the grids and the stellar profile is accordingly updated

Results: binary evolution



(M_1=10^7M$_\odot$, q=1/81, γ=2)

Results: tidal disruption rates



Tidal disruption rate for an evolving MBHB

(M_1=10^7M$_\odot$, q=1/81)

The *peak tidal disruption rate* is

***R*~0.3/yr**

scaling as

$$\dot{N}_*^d \propto (3-\gamma)^{-2} q^{(4-2\gamma)/(3-\gamma)} \left(\frac{a}{a_0}\right)^{1-\gamma} M_1^{-1/3}\sigma_*^4$$
$$\propto (3-\gamma)^{-2} q^{(4-2\gamma)/(3-\gamma)} \left(\frac{a}{a_0}\right)^{1-\gamma} M_1^{2/3},$$

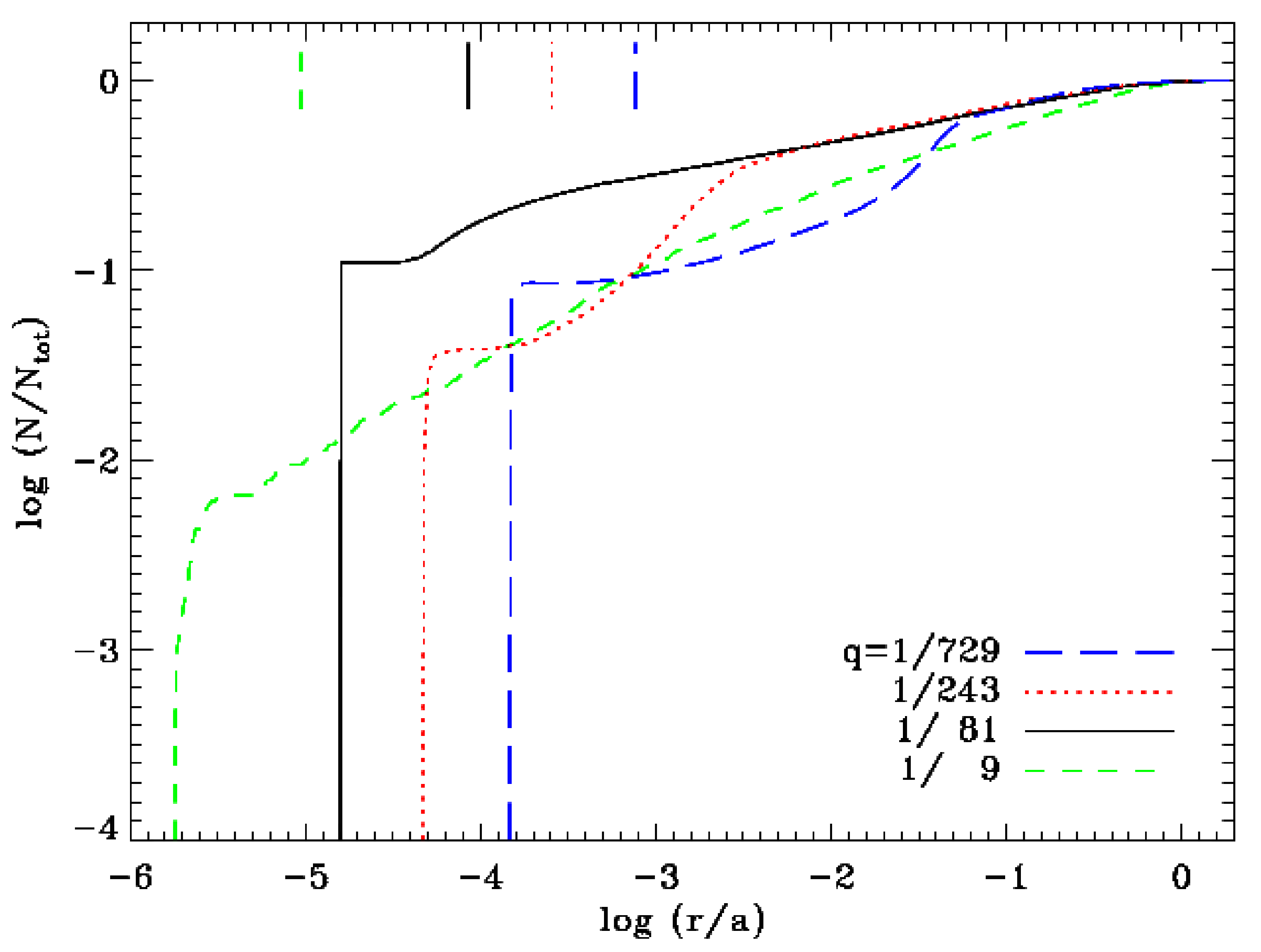
The *number of disrupted stars* is

***N*~5x10^4**

scaling as

$$N_{\rm tot}^d \propto t_{\rm evo}\dot{N}_*^d \propto (3-\gamma)^{-1/2} q^{(2-\gamma)/(6-2\gamma)} M^{2/3}\sigma$$
$$\propto (3-\gamma)^{-1/2} q^{(2-\gamma)/(6-2\gamma)} M^{11/12}$$

The effect of GR



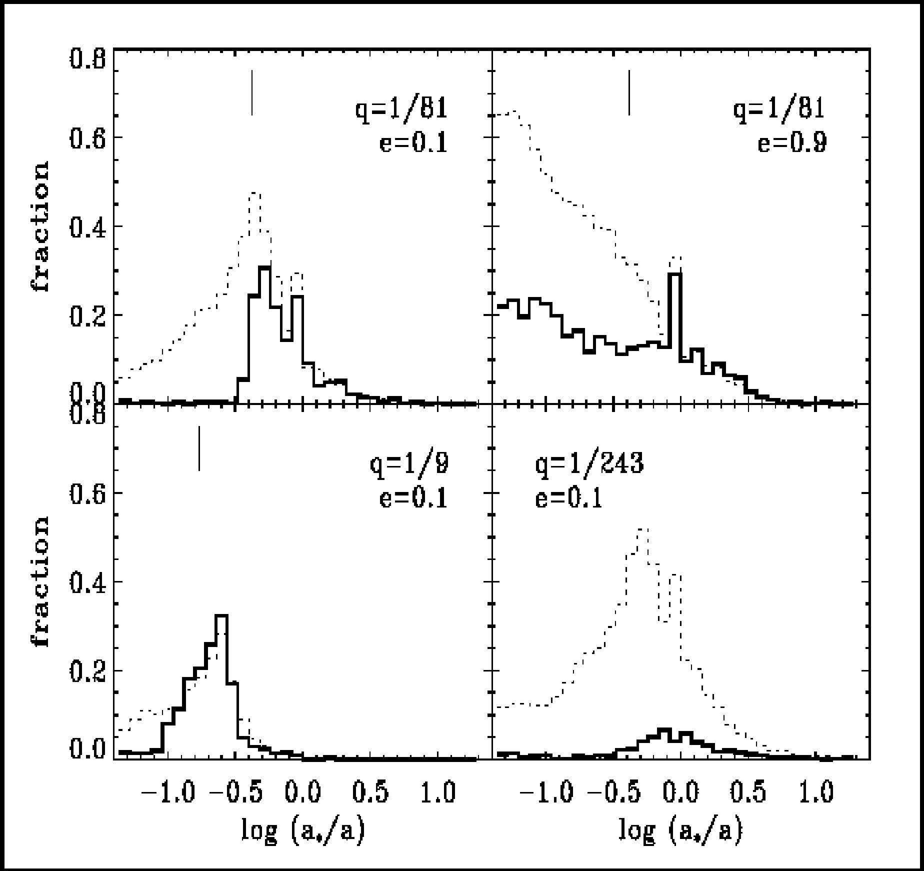
Paczynski-Witta pseudo-Newtonian potential

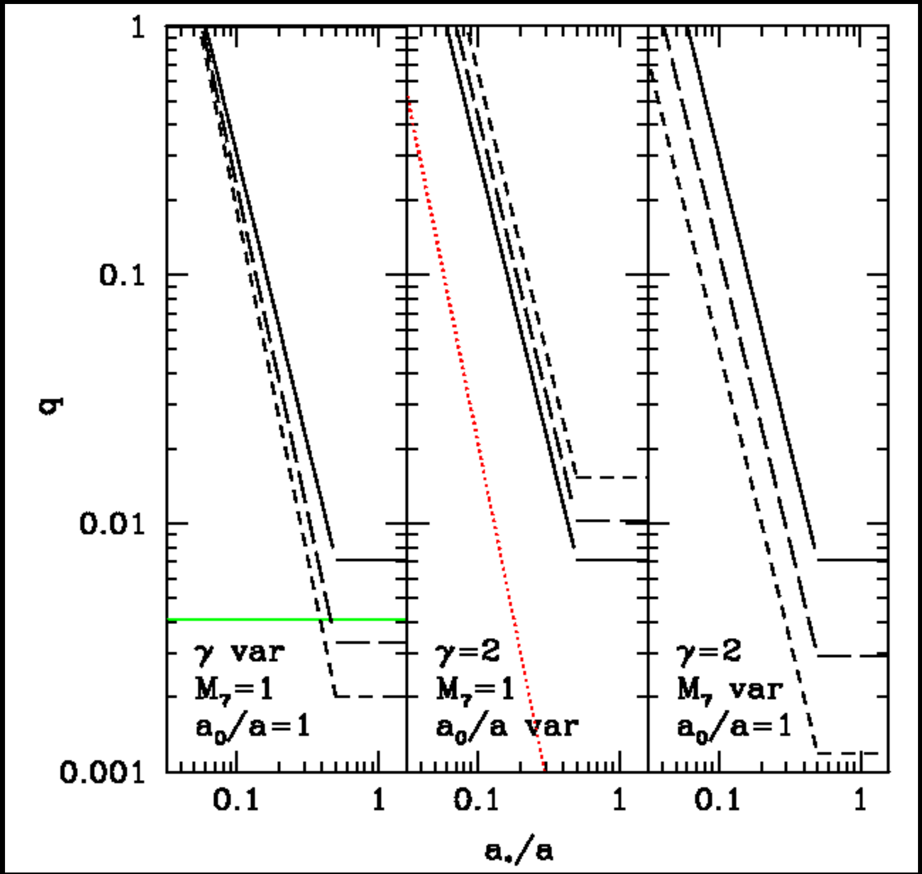
The disruption cross section drops significantly for *q*<0.01

GR vs. Kozai precession

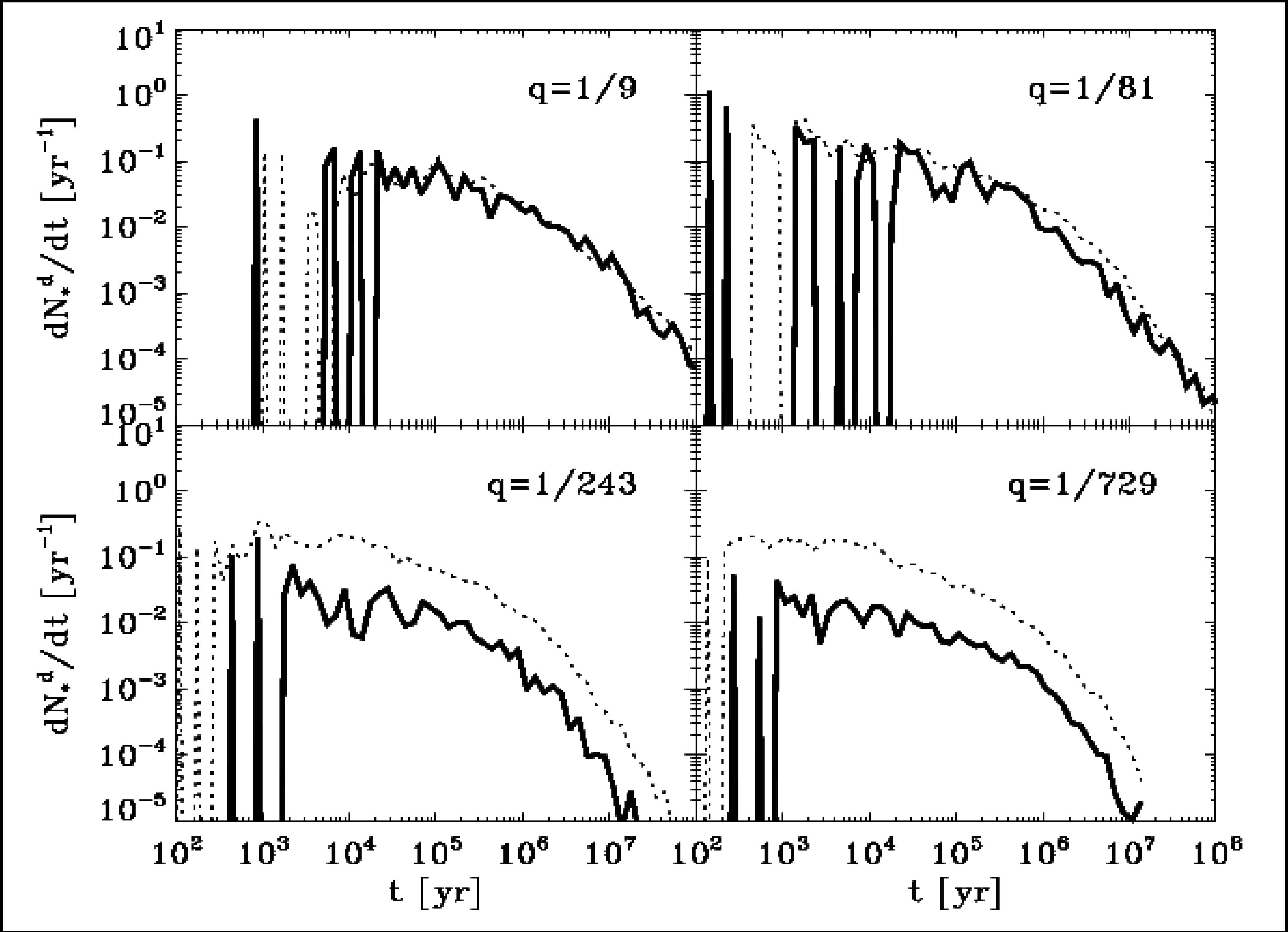
$$\dot{\omega}_K \simeq \begin{cases} \frac{15\pi q}{2\sqrt{2}P(a)} \left(\frac{r_{t1}}{a}\right)^{-1/2} \left(\frac{a_*}{a}\right)^{2} & (a_* < a/2) \\ \frac{15\pi q}{32P(a)} \left(\frac{r_{t1}}{a}\right)^{-1/2} \left(\frac{a_*}{a}\right)^{-3/2} & (a_* \geq a/2) \end{cases}$$

$$\dot{\omega}_{\rm GR} \simeq \frac{6\pi G M_1}{(1-e_*^2)c^2 a_*} P(a_*)^{-1} = \frac{3\pi}{2P(a)} \left(\frac{r_{g1}}{r_{t1}}\right) \left(\frac{a_*}{a}\right)^{-3/2}$$





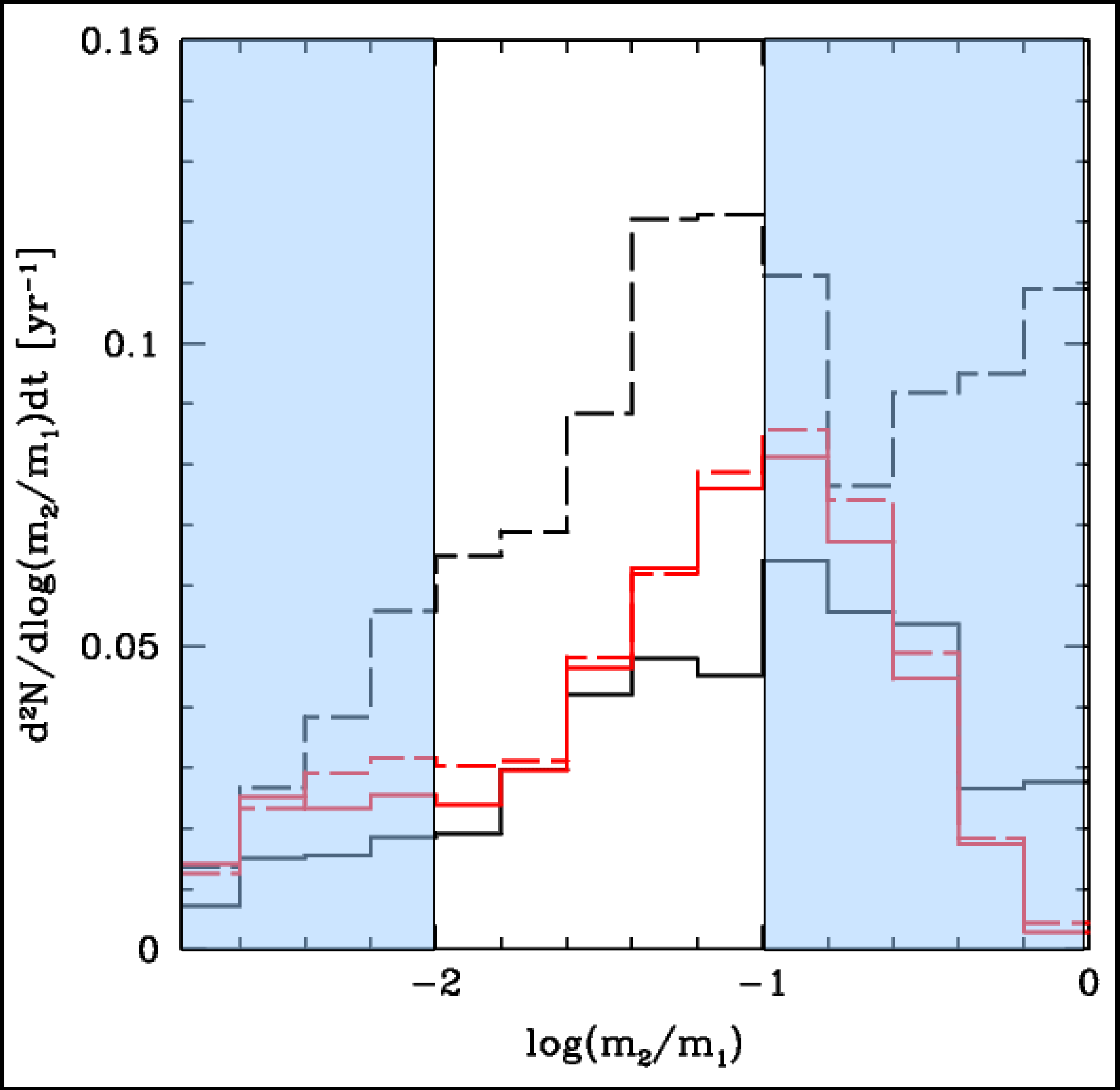
Disruption rate suppression



Number of events

~5x10^4 *M/M$_7$ disrupted stars, if* 0.01*<q<*0.1*,*

numbers are weakly dependent on the cusp slope



Cosmological models for MBHB formation and evolution predict a coalescence rate of ~0.1/yr in the relevant *M* and *q* range, at *z*<1

We thus may expect ~10^3 *flaring events to be associated with MBHBs at z<1*

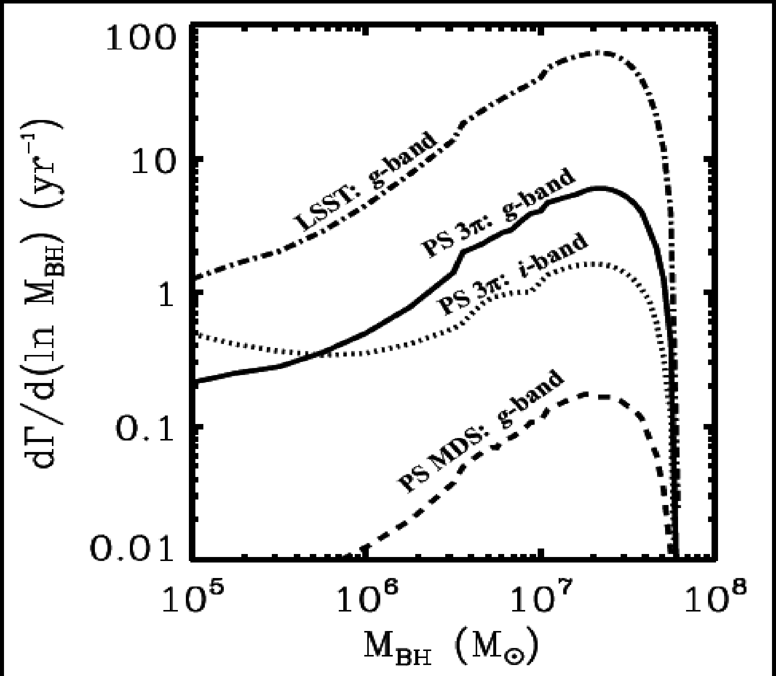
Observational probe of MBHBs?

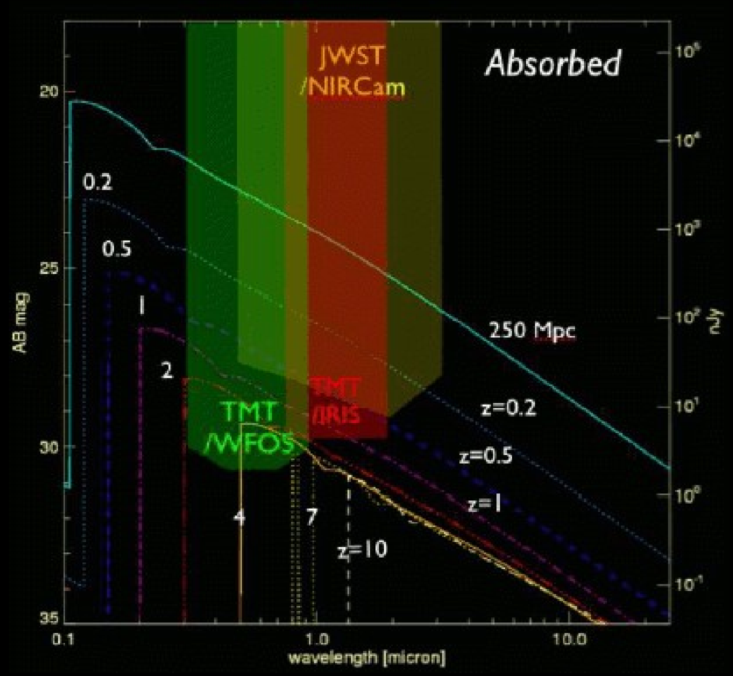
TD flares may provide an efficient way to discover MBHBs:

1-TD rates for individual MBHs implies ~fewx10^5 disruption events per galaxy per Hubble time. If all the galaxies experienced 1 minor merger in their lifetime, *as many as 10% of identified flares may be associated to MBHBs.*

2-In dense cusps, rates may be higher than 0.1/yr: the detection of a *recursive flare activity* in the same galaxy may provide evidence of a MBHB

3-If rates are >0.1/yr, the accretion episodes related to subsequent events may overlap, giving origin of a *short living* (10^5yr) *AGN-type activity*





Gezari et al 2009

Summary

- unequal MBHBs in dense stellar cusp produce a boost in the tidal disruption rate of main sequence stars

- A tidal disruption rate as high as 0.1/yr can be sustained for fewx10^5 yrs

- GR mitigates the tidal disruption boost for $q<0.01$

- For $0.01<q<0.1$, 10^3-10^5 stars may be disrupted in 10^5-10^7 yrs depending on M and γ.

- LSST will detect hundreds of tidal flares, as many as 10% of which may be associated to MBHBs

The "final parsec problem"

We want MBHBs to coalesce after a major merger

Dynamical friction is efficient in driving the two BHs to a separation of the order

$$a_h \simeq 0.31\,\mathrm{pc}\; M_{2,6}^{1/2} \sqrt{\frac{q}{1+q}}$$

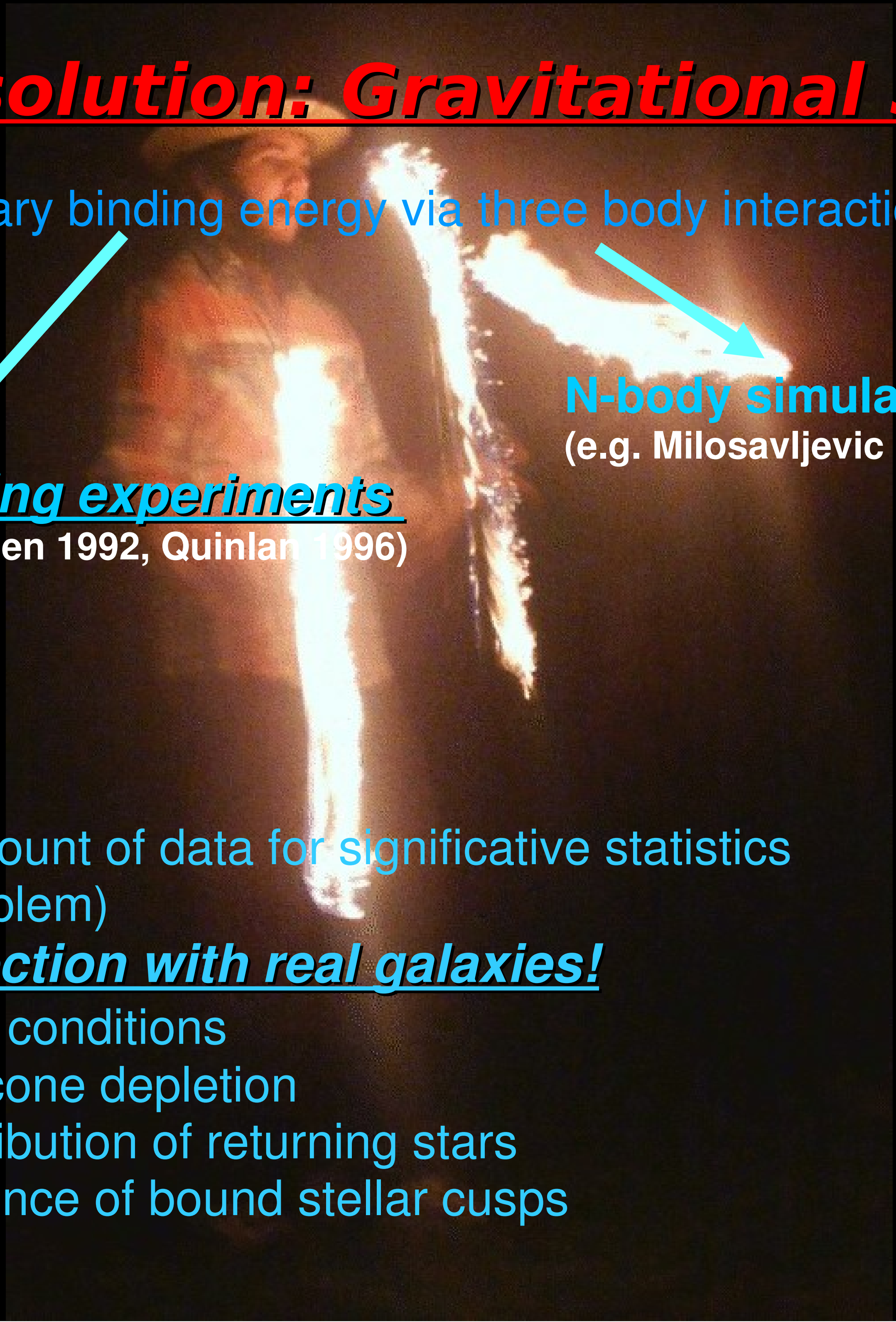
GW emission takes over at separation of the order

$$a_{GW} \approx 0.0014\,\mathrm{pc}\; \left(\frac{M M_1 M_2}{10^{18.3}\ \mathrm{M}_{\odot}{}^3}\right)^{1/4} F(e)^{1/4}\, t_9^{1/4}$$

The ratio can be written as

$$\frac{a_h}{a_{GW}} \approx 2.5 \times 10^2 \left(\frac{q}{1+q}\right)^{3/4} F(e)^{-1/4}\, M_6^{-1/4}\, t_9^{-1/4}$$

A possible solution: Gravitational Slingshot



Extraction of binary binding energy via three body interaction with stars

N-body simulation
(e.g. Milosavljevic & Merritt 2001)

3-body Scattering experiments
(e.g. Mikkola & Valtonen 1992, Quinlan 1996)

> More feasibles
> need a large amount of data for significative statistics (eccentricity problem)
> warning: ***connection with real galaxies!***
  > initial conditions
  > loss cone depletion
  > contribution of returning stars
  > presence of bound stellar cusps

Hardening in a fixed background

Quinlan 1996

$$H = \frac{\sigma}{G\rho_0}\frac{d}{dt}\left(\frac{1}{a}\right)$$

HARDENING RATE

$$K = \frac{de}{d\ln(1/a)}$$

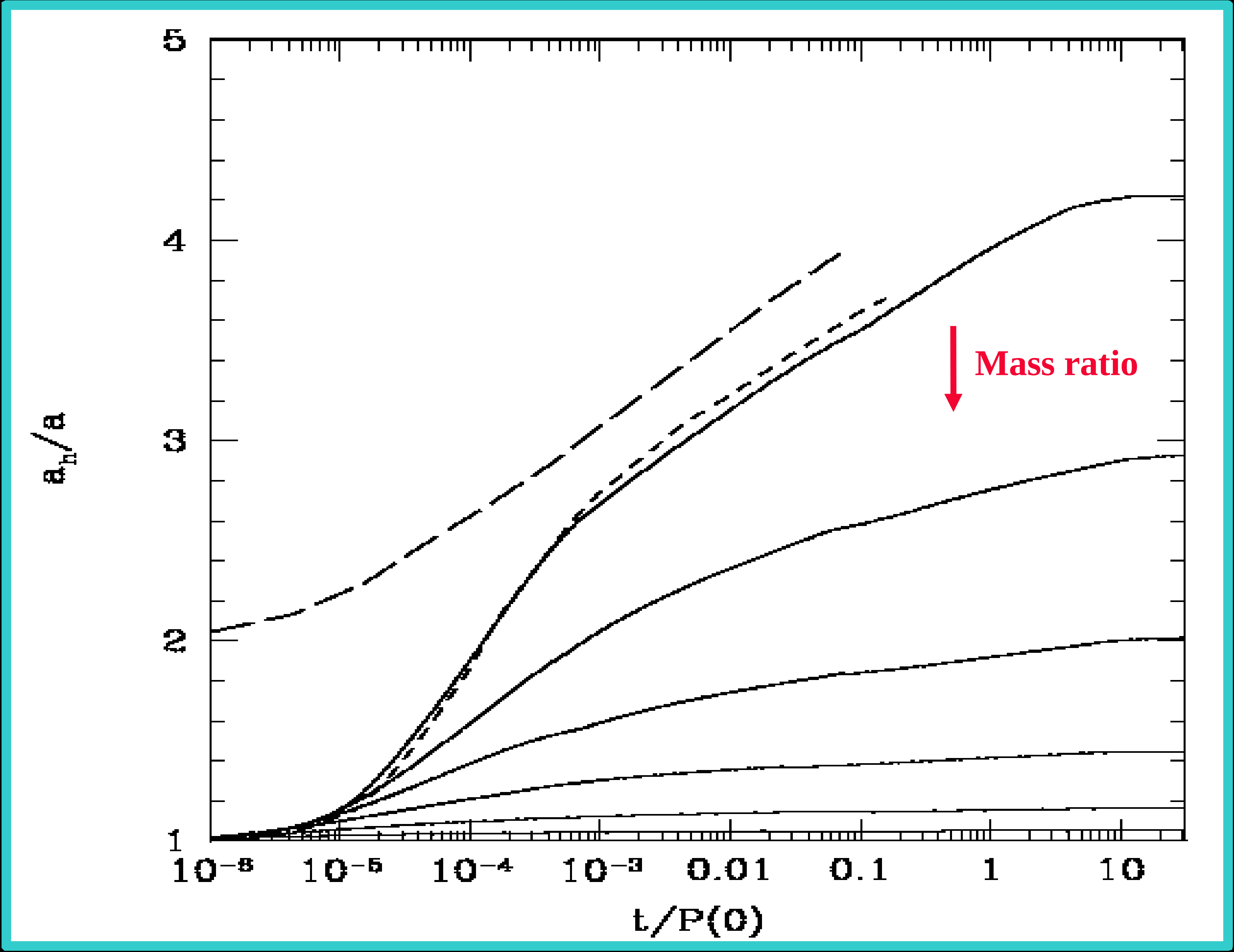
ECCENTRICITY GROWTH RATE

$$J = \frac{1}{M}\frac{dM_{\rm ej}}{d\ln(1/a)}$$

MASS EJECTION RATE

$$v_{\rm esc} \equiv \sqrt{-2\phi} - 2\sigma\sqrt{[\ln(M_B/M)+1]} - 5.5\sigma$$

a-Orbital decay



1) orbital decay is at most a factor of ~5
2) loss cone depletion is fast

The MBHB fate depends on the supply of stars

> Loss cone amplification

> Axisymmetric and triaxial potentials

(e.g. Yu 2002, Merritt & Poon 2004, Berzcik et al. 2006)

> MBHB random walk

(e.g. Quinlan & Hernquist 1997, Chatterjee et al. 2003)

> Relaxation processes

> Standard two body relaxation **(Milosavljevic & Merritt 2001)**

> Massive perturbers driven relaxation **(Perets & Alexander 2007)**

> Resonant relaxation **(Hopman & Alexander 2006)**

Additional sources of energy!

> Extraction of potential energy from a Bound Stellar Cusp

(See next slide…)

> Torques exerted on the MBHB by a gaseous disk

(Armitage & Natarajan 2002, Escala et al. 2005, Dotti et al. 2006)

Why consider bound environments

For equal MBHBs, $a_h \sim a_i$ → The mean stellar binding energy to the binary is negligible

But: $\boldsymbol{a_h \propto M_2,\ a_i \propto M_1}$

For unequal MBHBs, $a_h << a_i$ → The mean stellar binding energy to the binary cannot be neglected

binding energy contribution *important if* $q<0.1$
and the stellar distribution is cuspy

↓

> Cosmological unequal MBHBs
> non-cosmological IMBH-MBH inspirals
(e.g. from SC inspirals)

The hybrid model

We consider a MBHB with mass ratio q with initial eccentricity e_i in a power law stellar cusp $\propto r^{\gamma}$

The integration start at a_i, so that $M_*(a<a_i)=2M_2$ (Matsubayashi et al. 2005)

We solve the evolution equations

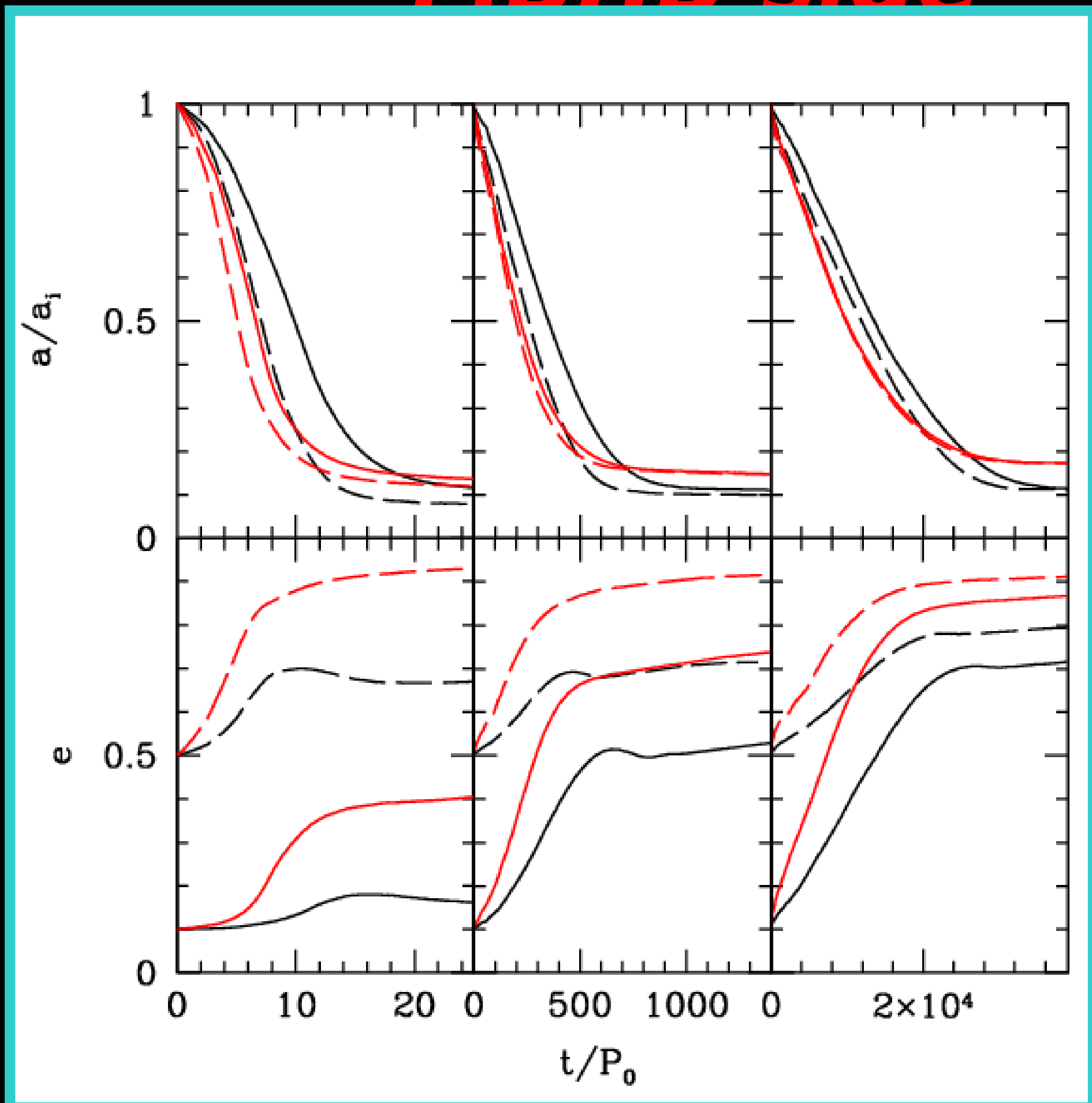
$$\frac{da}{dt} = -\frac{2a^2}{GM_1M_2}\int_0^\infty \Delta\mathcal{E}\,\frac{d^2N_{\rm ej}}{da_\star dt}da_\star$$

$$\frac{de}{dt} = \int_0^\infty \Delta e\,\frac{d^2N_{\rm ej}}{da_\star dt}da_\star$$

Δe, $\Delta\varepsilon$ and d^2N_{ej}/da_*dt are provided by 3-body experiments

Results I: the MBHB side

(All the results are shown in units of a_i, P_0, $V_c(a_i)$)



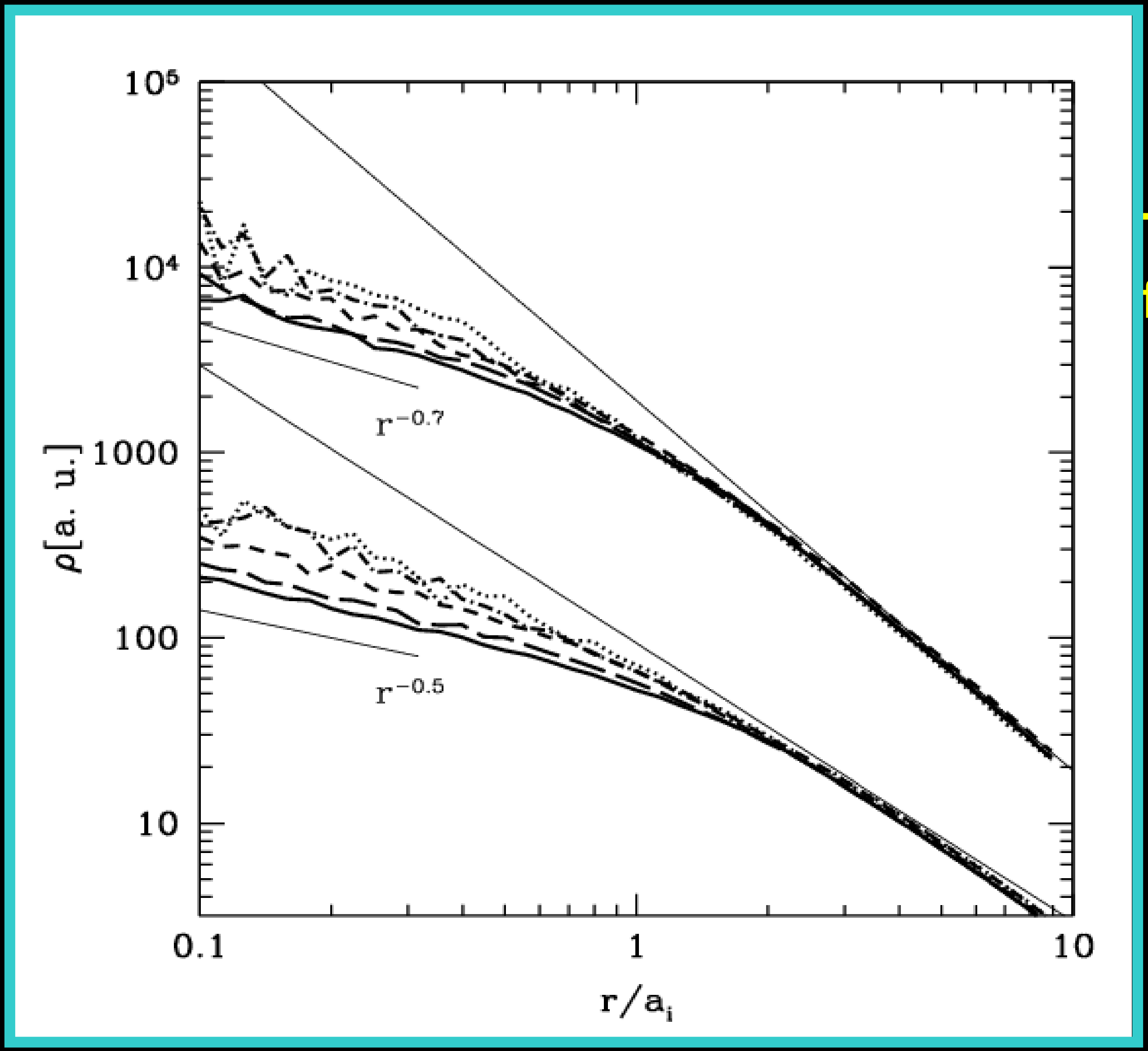
		$\gamma = 1.5$		$\gamma = 1.75$		$\gamma = 2$	
q	e_i	x	e_f	x	e_f	x	e_f
	0.1	9.63	0.608	9.89	0.350	11.38	0.179
1/9	0.5	9.99	0.972	11.55	0.907	15.77	0.753
	0.9	10.06	0.998	11.80	0.992	17.73	0.969
	0.1	8.06	0.691	8.35	0.532	10.19	0.408
1/27	0.5	8.26	0.959	9.35	0.862	12.35	0.710
	0.9	8.27	0.996	9.64	0.988	14.03	0.958
	0.1	6.99	0.755	7.75	0.650	9.39	0.542
1/81	0.5	6.90	0.922	7.81	0.828	10.14	0.717
	0.9	6.89	0.996	7.81	0.974	11.00	0.937
	0.1	6.49	0.906	7.28	0.805	9.30	0.688
1/243	0.5	6.39	0.971	7.25	0.914	9.92	0.818
	0.9	6.38	0.962	7.19	0.986	10.09	0.955
	0.1	6.12	0.881	6.91	0.814	8.94	0.724
1/729	0.5	5.95	0.919	6.91	0.869	9.09	0.797
	0.9	5.94	0.977	6.92	0.953	9.41	0.900

Shrinking factors $6 < x < 18$

MBHB eccentricity grows

Results II: the stellar side

a- density profile evolution

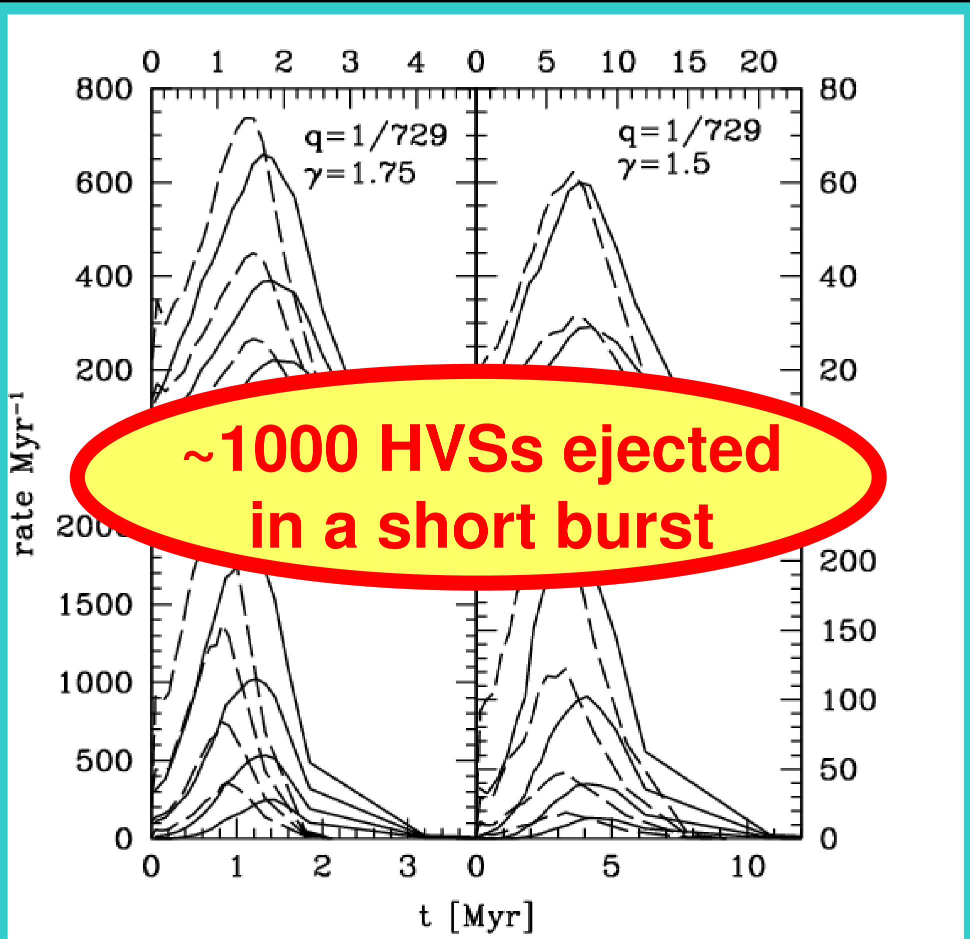


The density profile flattens significantly

The unbound mass is 2-4M_2 almost independently on e and γ

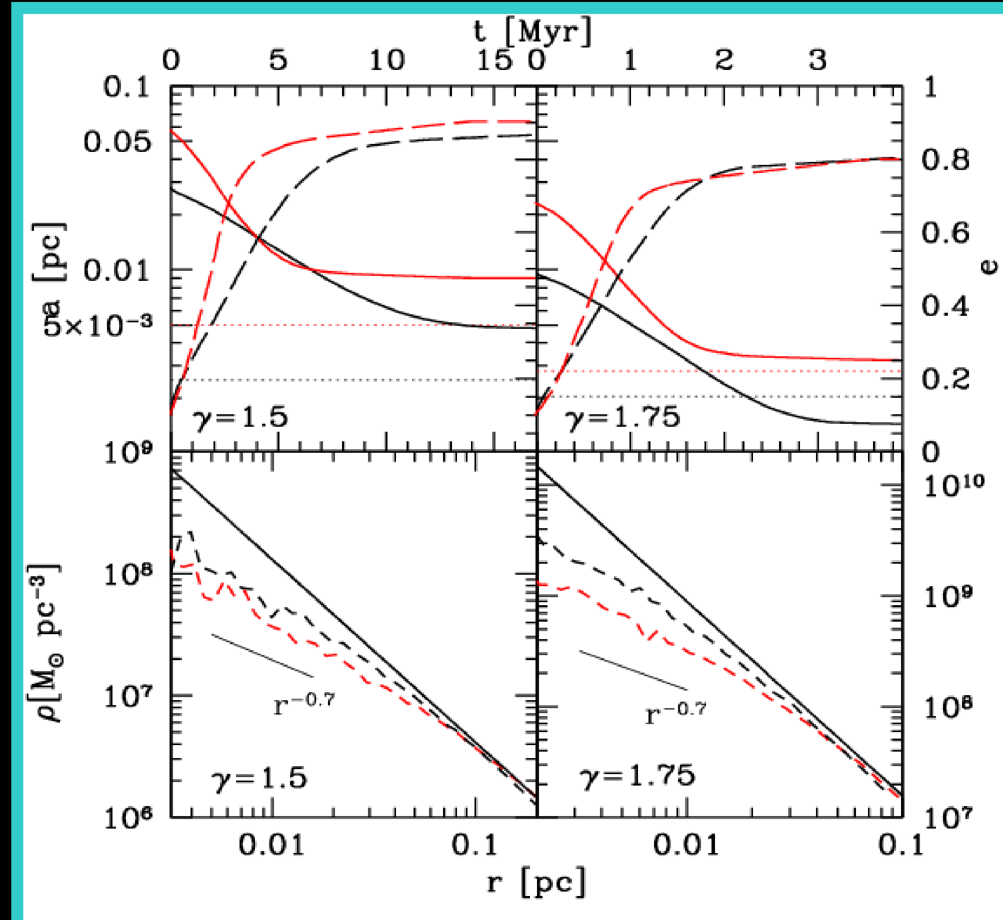
THE CASE STUDY OF THE MILKY WAY

γ^a	r_0^b [pc]	ρ_0^c [$M_\odot pc^{-3}$]	q^d	a_i^e [pc]	$P_0(a_i)^f$ [yr]	$V_c(a_i)^g$ [km/s]
1.5	2.25	7.1×10^4	1/243	5.8×10^{-2}	1344	510
			1/729	2.8×10^{-2}	448	735
1.75	1.88	10^5	1/243	2.3×10^{-2}	340	806
			1/729	9.6×10^{-3}	91	1250



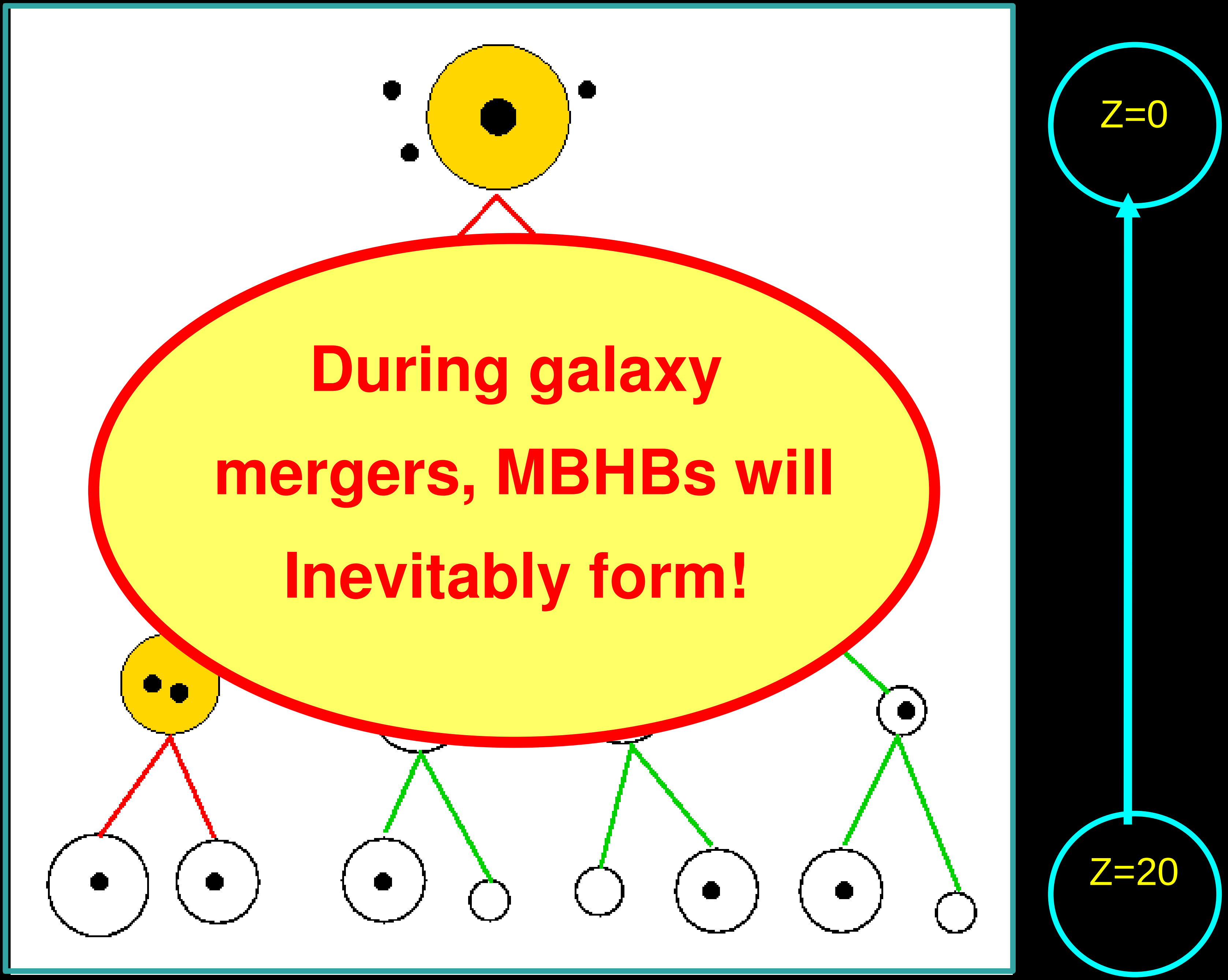
~1000 HVSs ejected in a short burst

Large eccentricity growth during the MBHB shrinking

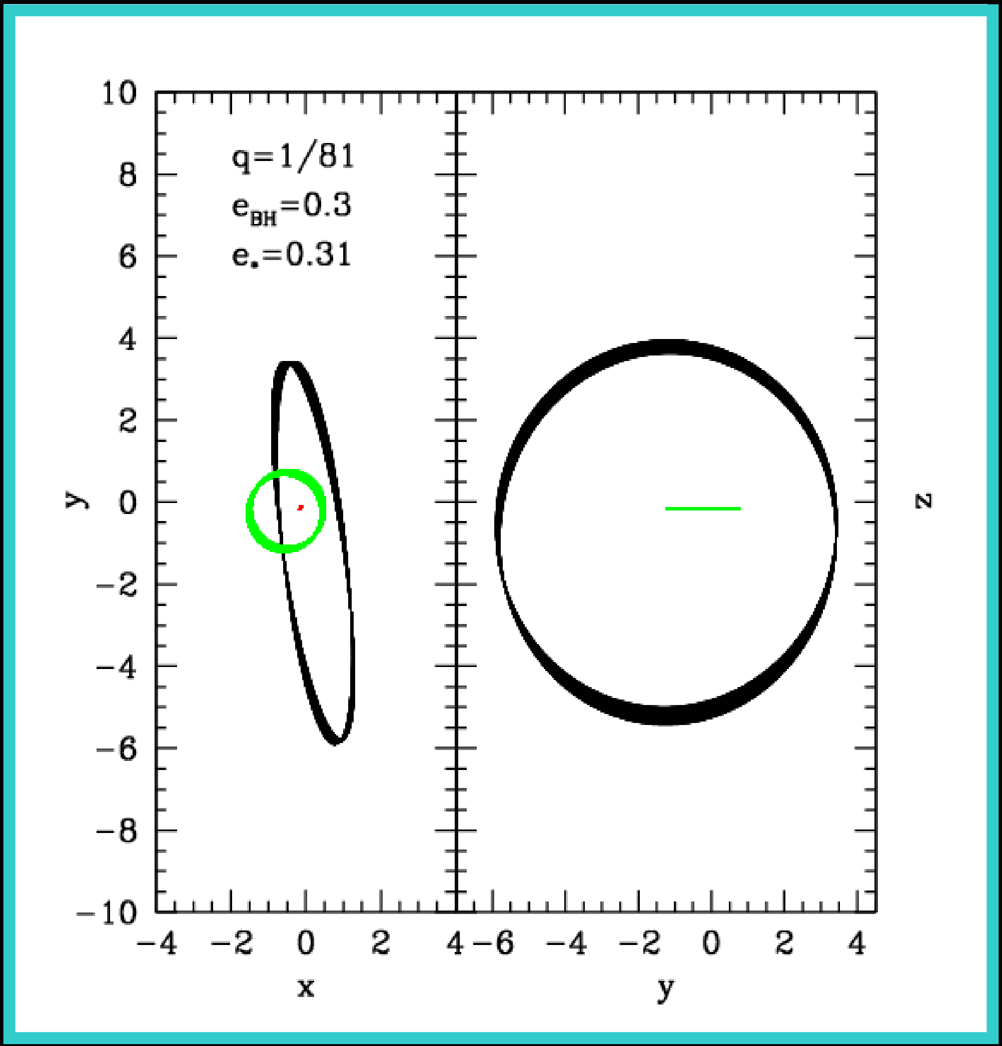


Significant flattening of the inner 10^{-2} pc

...HIERARCHICAL MBH FORMATION



Examples of orbit integrations



Weak interaction: the system behaves as a stable hierarchical triplet

Strong interaction resulting in a stellar ejection