Long-Term Evolution of Massive Black Hole Binaries

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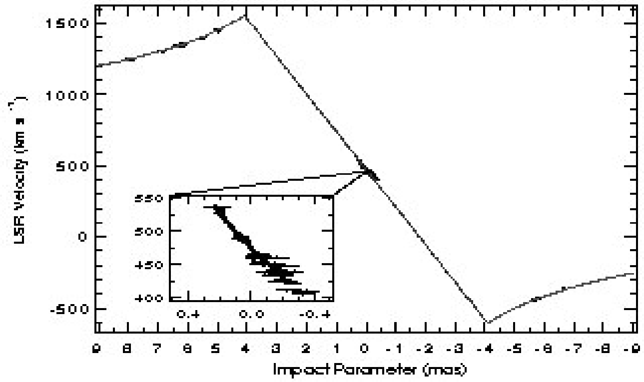
Evidence for Massive Black Holes

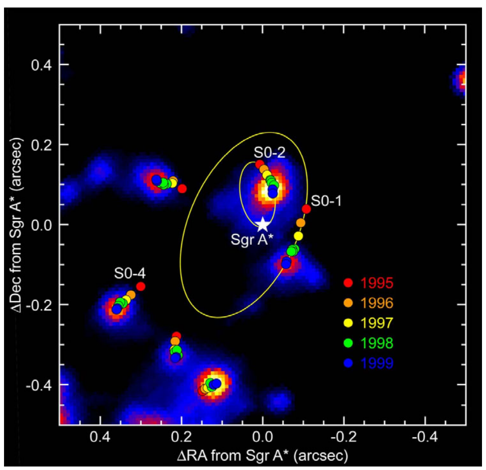
NGC 4258

Nakai, Inoue, Miyoshi 93



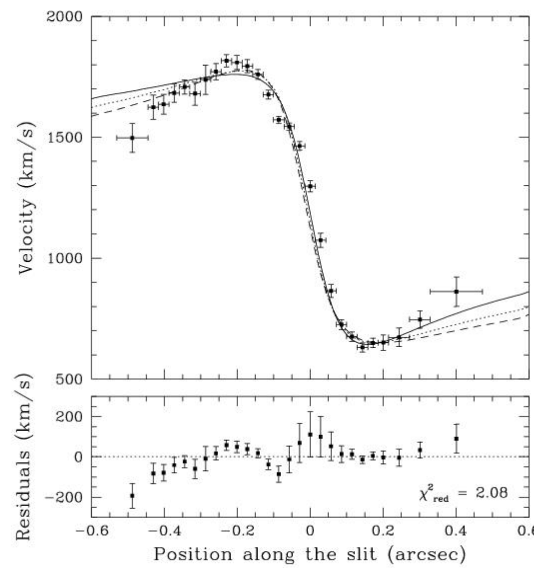
The Milky Way

Ghez 1998, Eckart et al 02

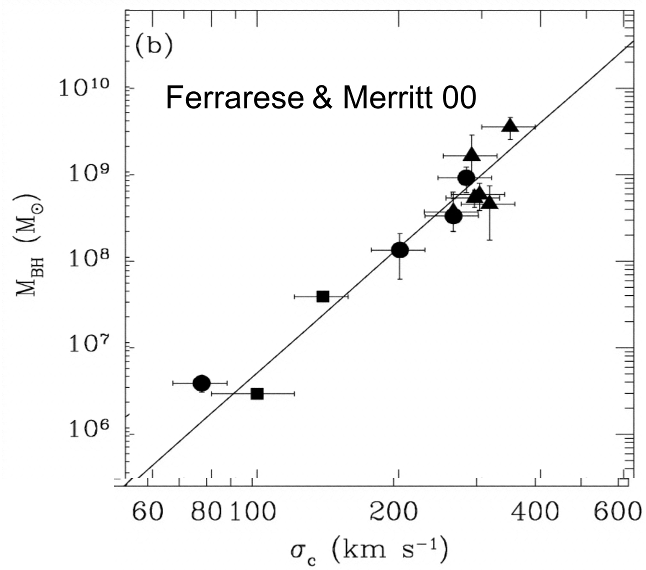


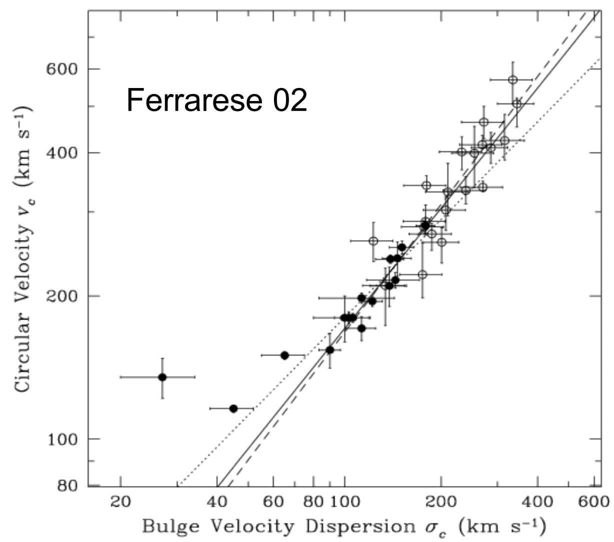
M87

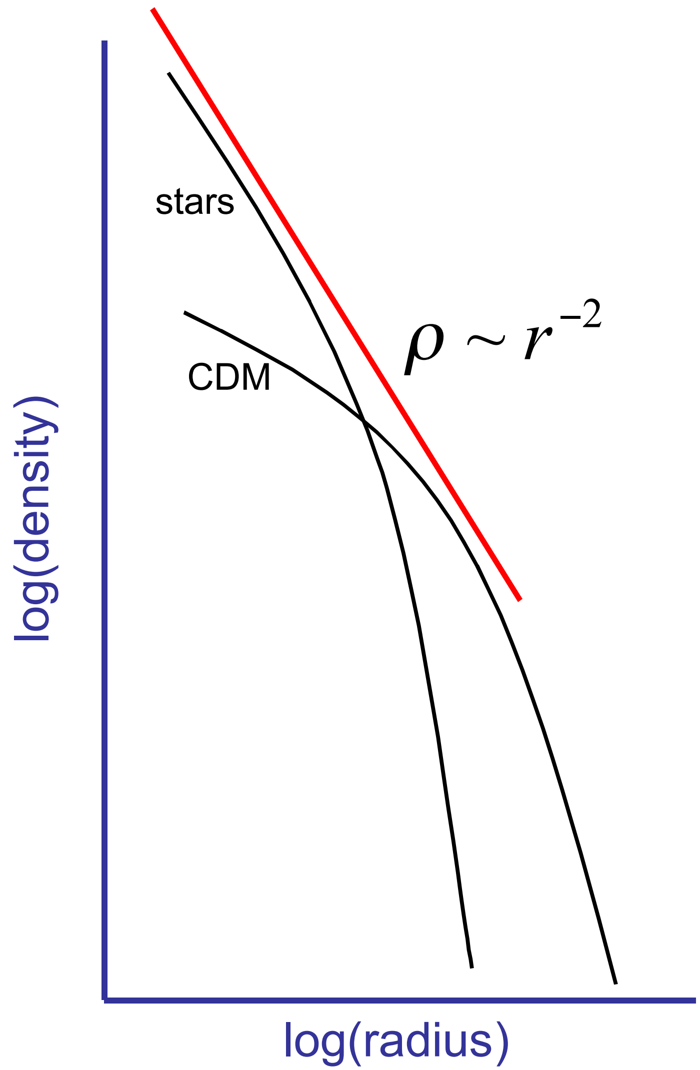
Macchetto et al 97



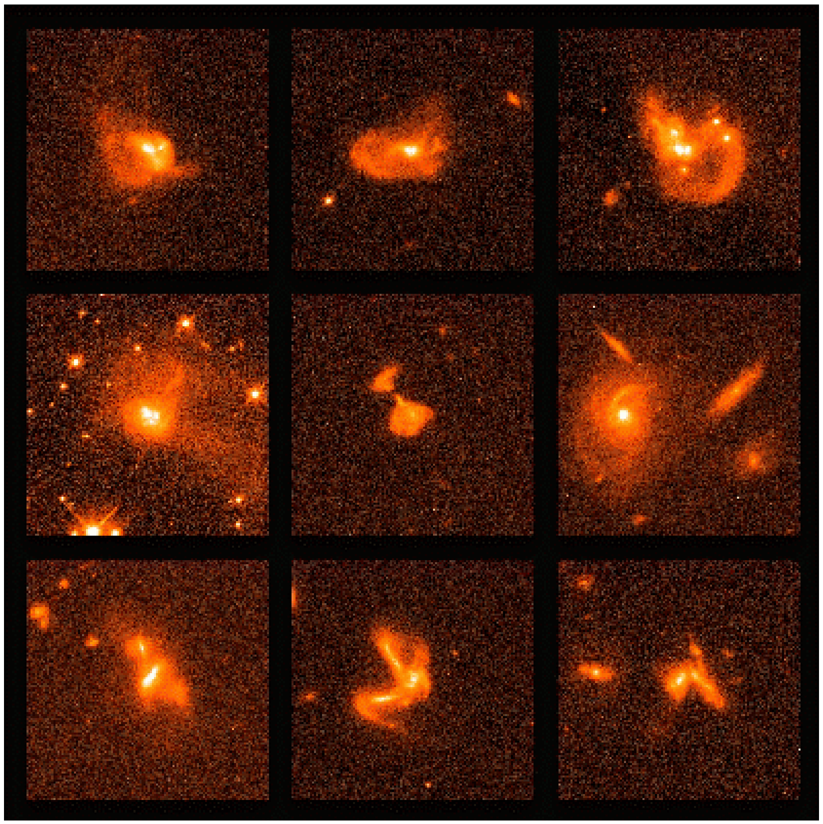
MBH are embedded in density cusps



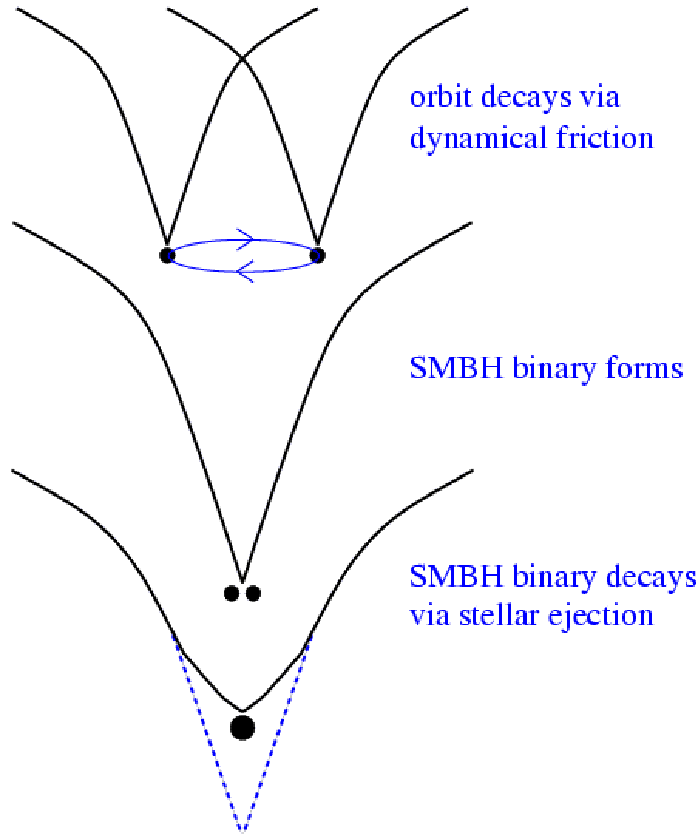




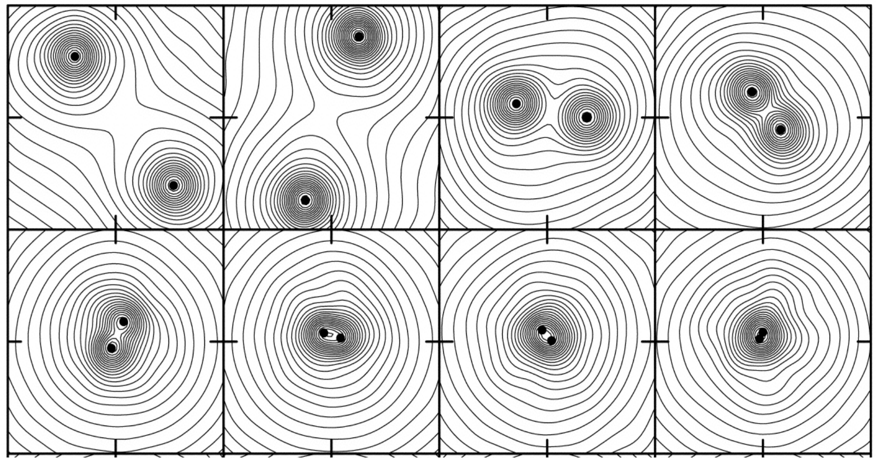
MBH Binaries Form in Galaxy Mergers



Borne et al 2000



In-spiral via dynamical friction



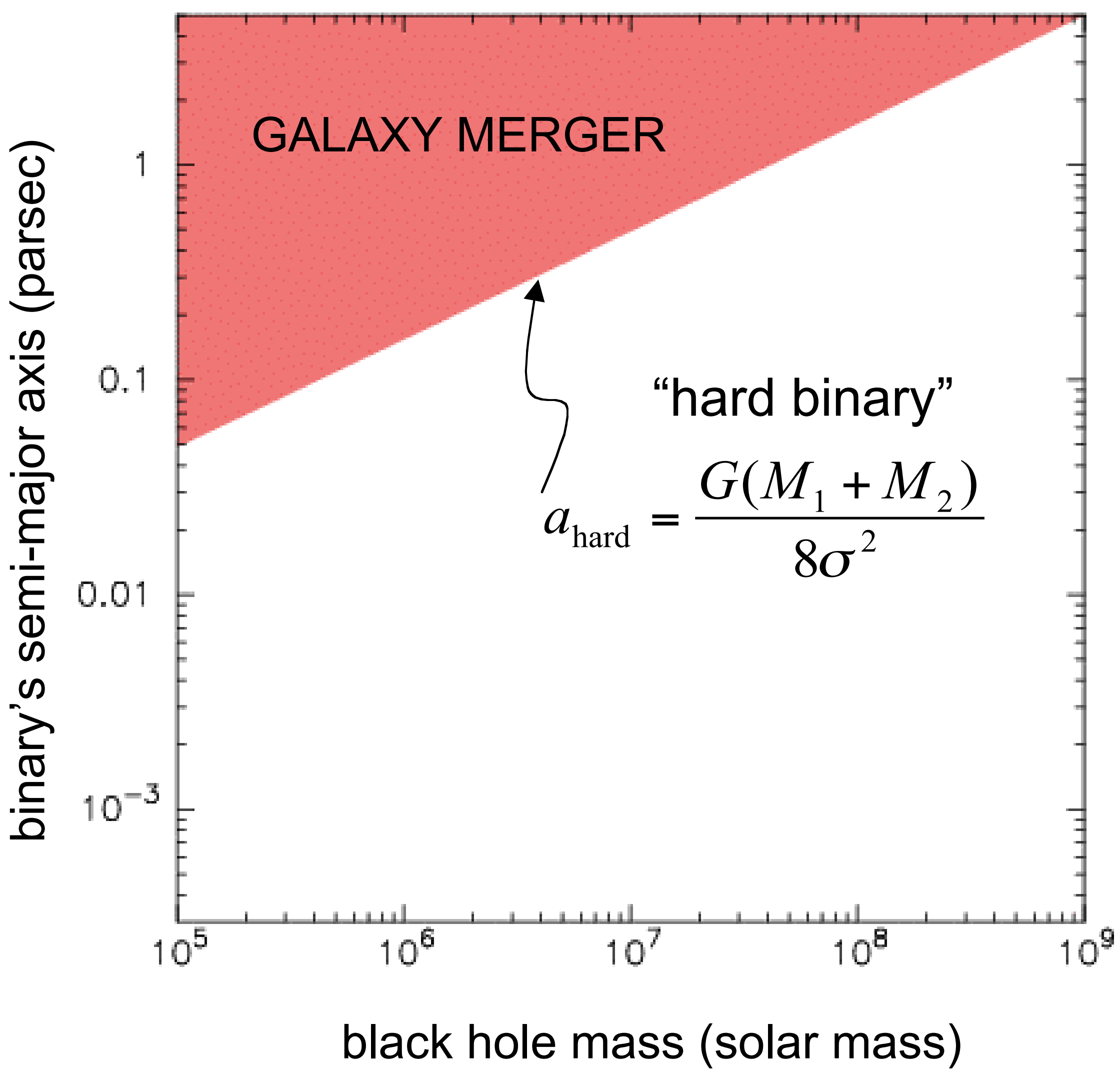
MM & Merritt 2001

Orbital decay rate is function of total mass: BH + bound stars

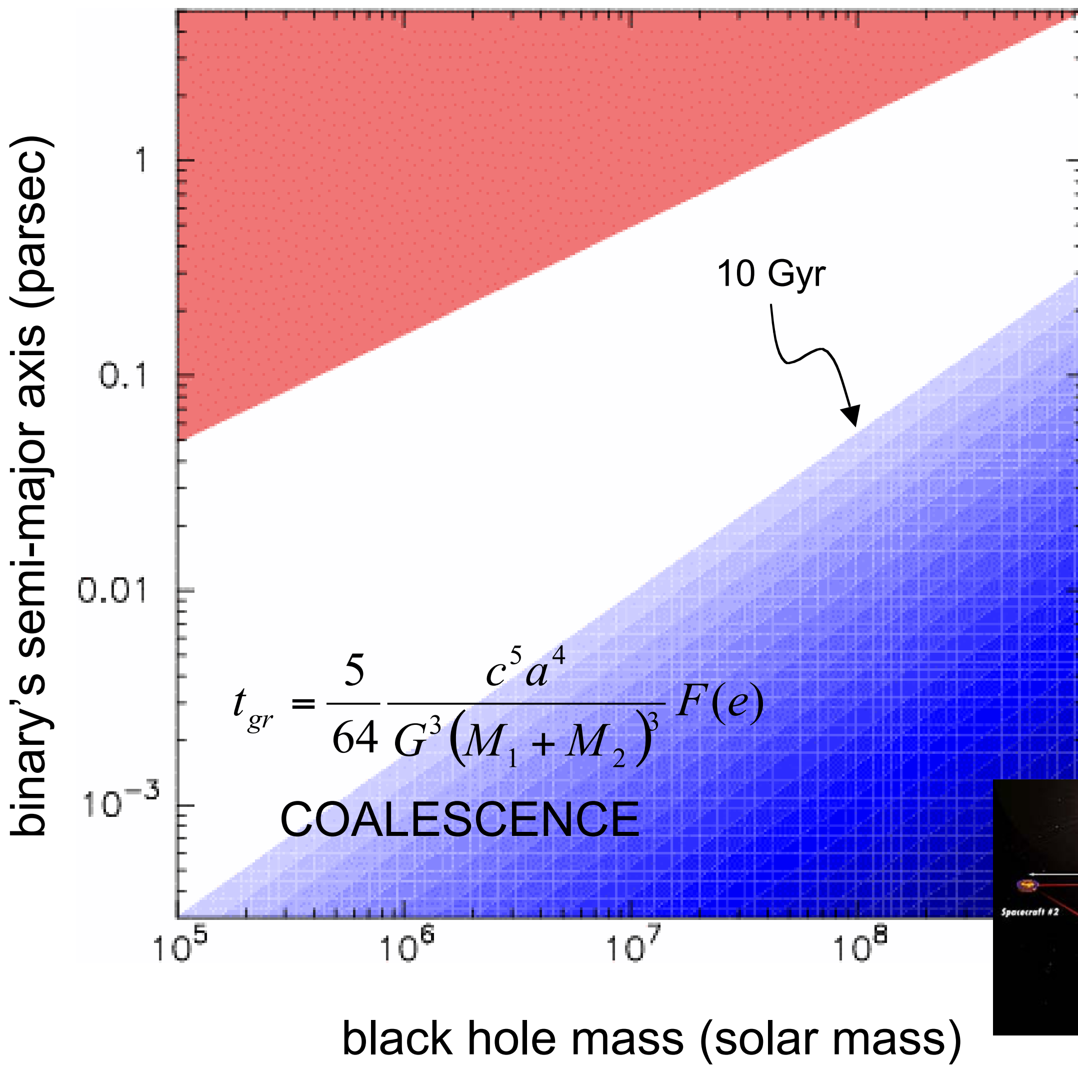
$$\langle \Delta v \rangle_{\text{parallel}} \sim -(\sigma_{\text{sat}})^2 \frac{r_{\text{trunc}}}{r^2} \ln \ddot{E}, \qquad \ln \ddot{E} \sim \frac{1}{2}, \qquad r_{\text{trunc}} \sim \left(\frac{\sigma}{\sigma_{\text{sat}}}\right)^2$$

Sensitive to tidal truncation: $\frac{dr}{dt} \sim \sigma \left(\frac{\sigma_{\text{sat}}}{\sigma} \right)^4$

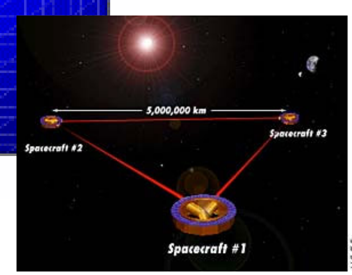
orbital
decay
rate



GALAXY MERGER
"hard binary"
$a_{\mathrm{hard}} = \frac{G(M_1 + M_2)}{8\sigma^2}$
binary's semi-major axis (parsec)
1
0.1
0.01
10^{-3}
10^5
10^6
10^7
10^8
10^9
black hole mass (solar mass)



$$t_{gr} = \frac{5}{64}\frac{c^5 a^4}{G^3 (M_1 + M_2)^3} F(e)$$



“The Last Parsec Problem”

Does the decay stall?

Gould & Rix, ApJL 532, 2000

- Misunderstood dynamics near MBHB
- Assumed calescence in < 1 Gyr is long

Milosavljevic & Merritt, ApJ 563, 2001

- Ignored collisional relaxation
- Simulations lacked the resolution to study long-term evolution

Yu, MNRAS 331, 2002

- Assumed unrealistic initial conditions for the post-merger galaxy
- Ignored repeated/multiple interactions of stars with MBHB

Why is This Problem Difficult?

- *N*-body simulations required
- Discreteness produces wrong trends for *N*<10^6
- Numerical algorithms partially developed and implemented (Aarseth, Hemsendorf, Kokubo, Makino, Merritt, Mikkola, MM, Spurzem)
- Parameter space:

  MBH masses

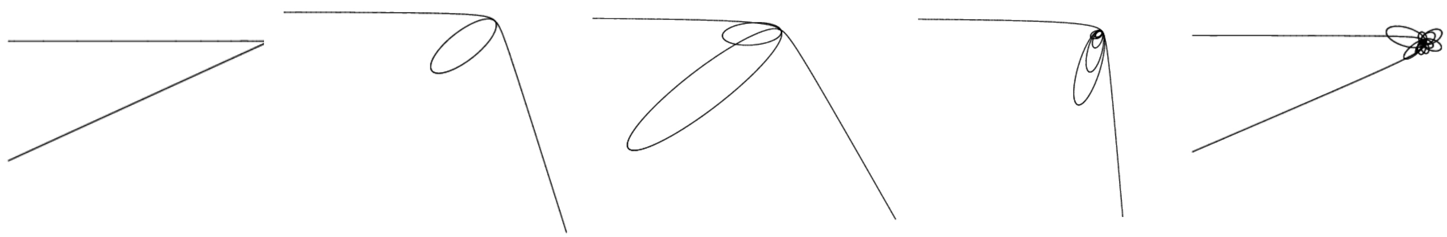
  Density profiles of the galaxies

  Flattening/triaxiality

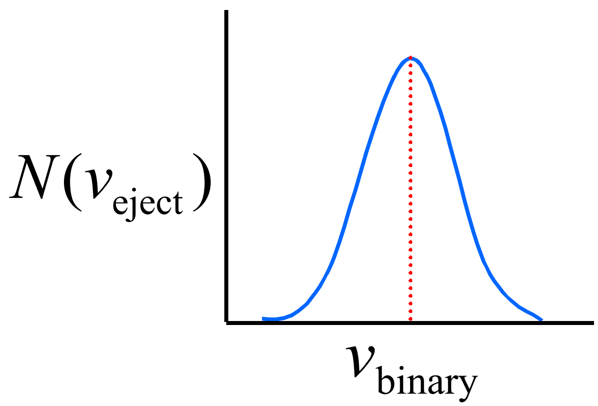
  Orbit of the galaxy merger: eccentricity?

  More than 2 black holes: Hierarchical triples,
  MBH-MBH slingshot interaction

Gravitational Slingshot Interaction



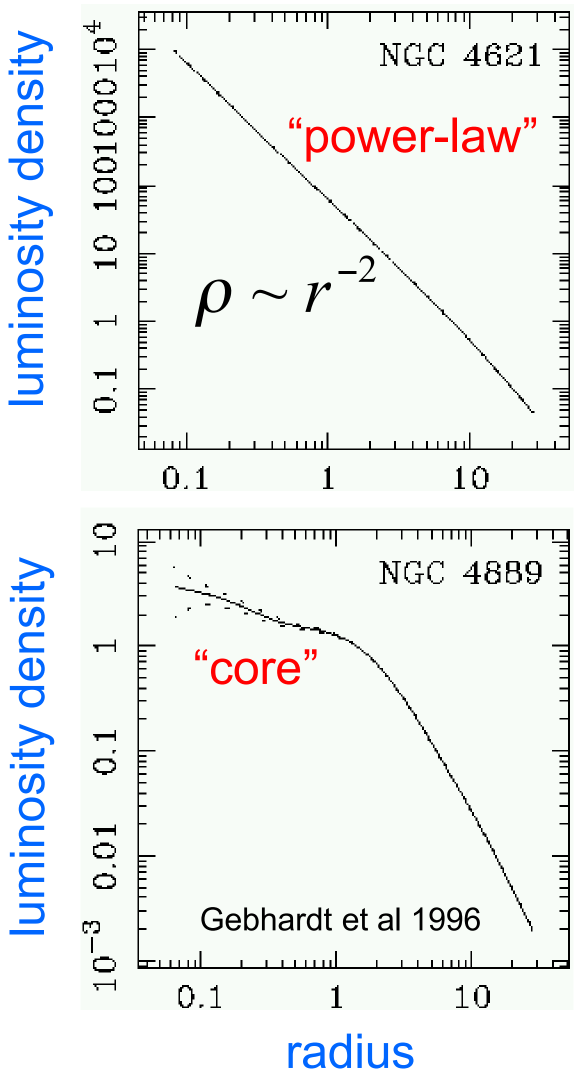
Velocity of a star can increase or decrease at each encounter

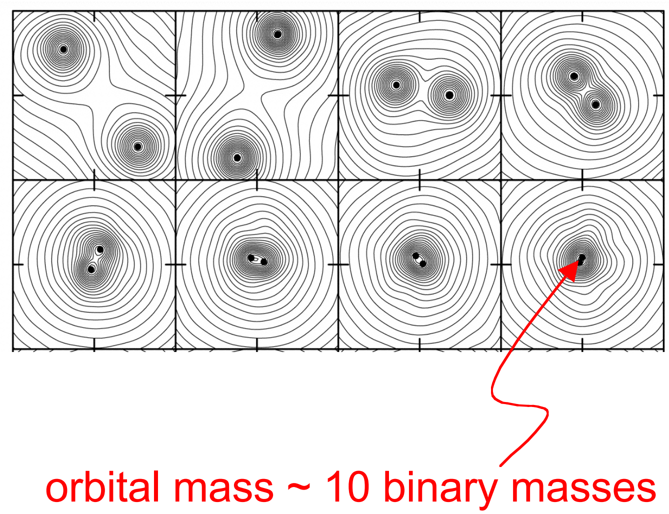


$$v_{\rm binary} \sim \sqrt{\frac{G(M_1+M_2)}{2a}}$$

For stars interacting with the binary, the binary is a thermostat with an internal degree of freedom positively coupled to the heat flow

Separation is a function of the orbital mass intersecting the binary





MBH Separation After the Merger

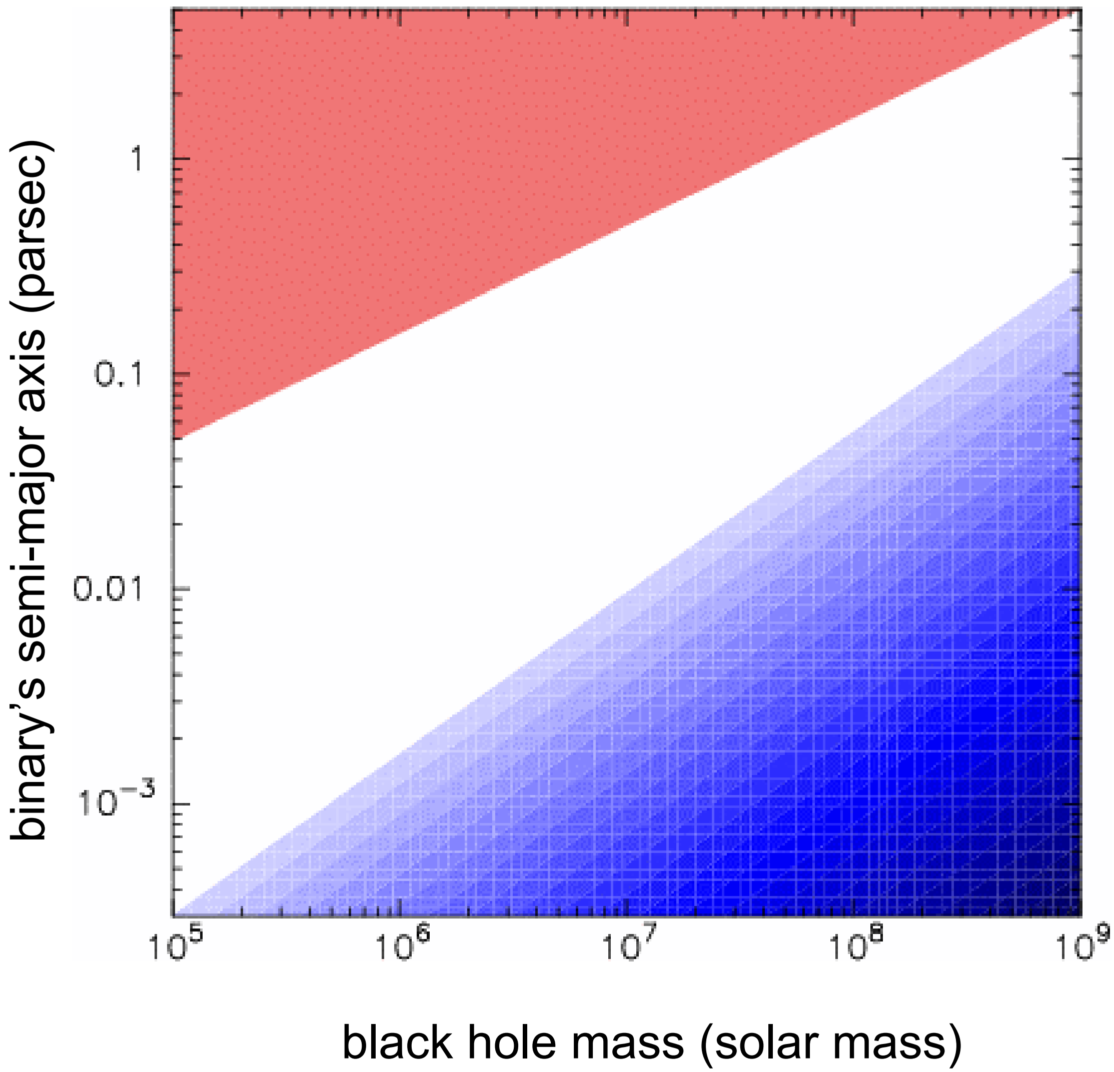
Steep cusp:

Separation ~ 10% hard binary

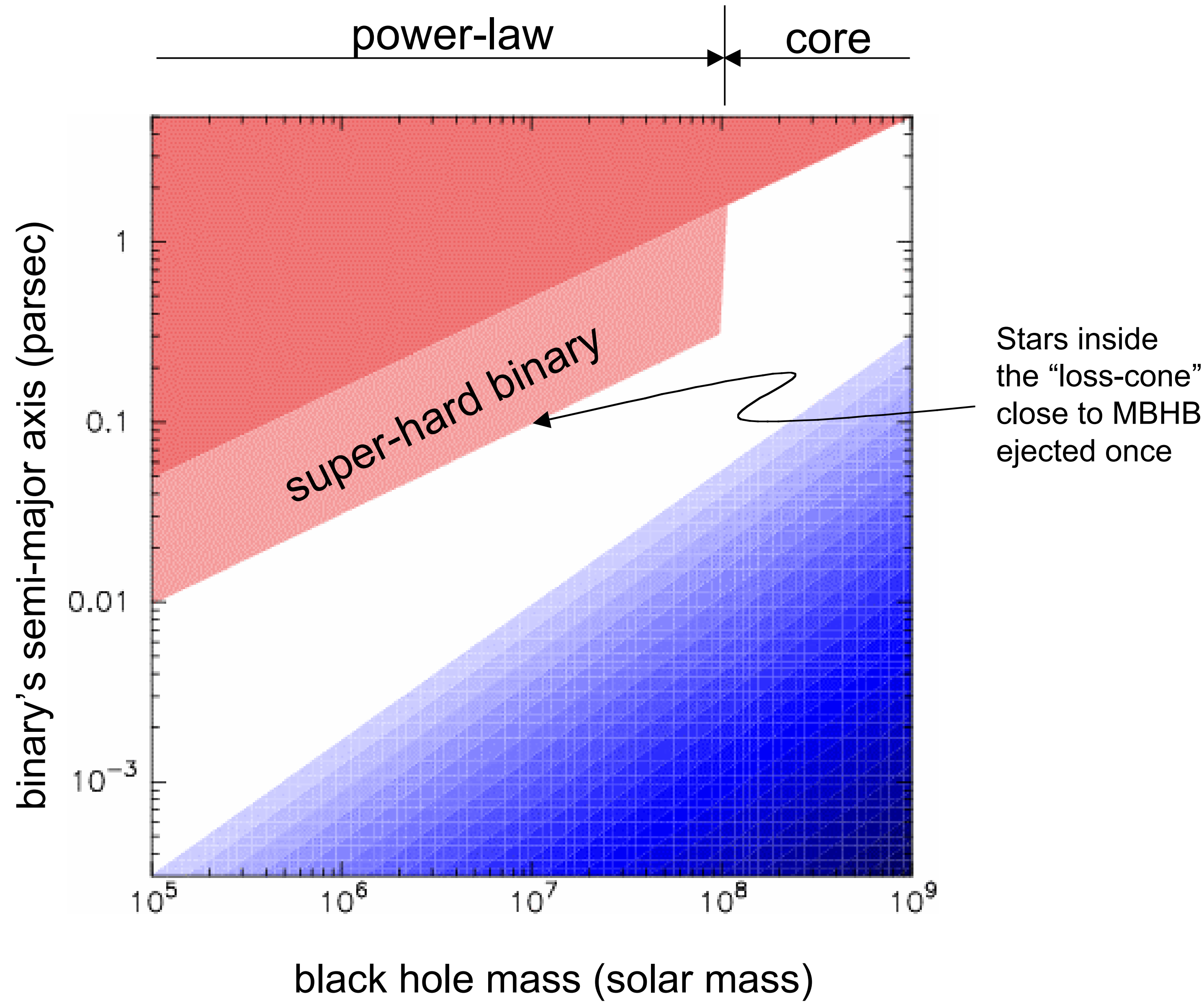
(MM & Merritt 2001)

Shallow cusp:

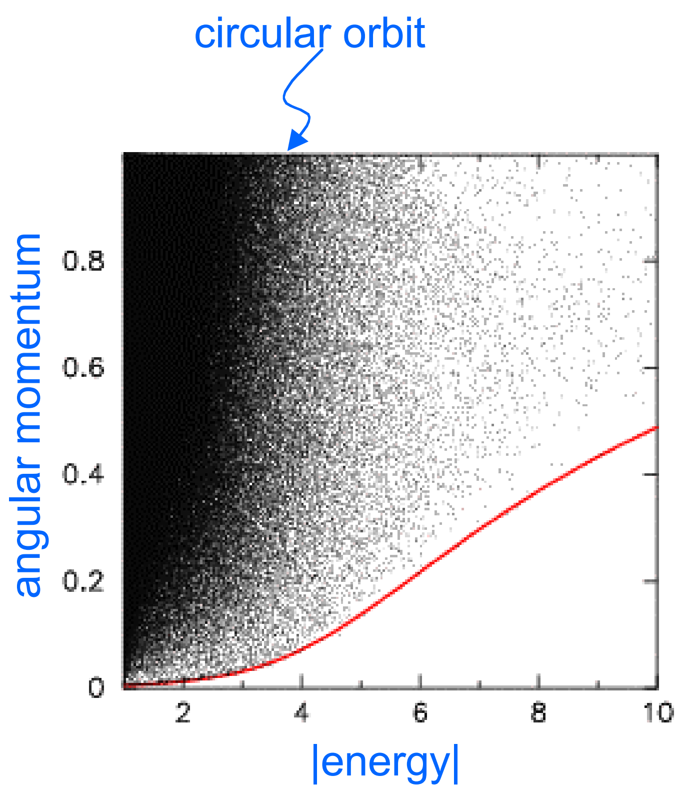
Separation ~ 100% hard binary



binary's semi-major axis (parsec)
1
0.1
0.01
10^{-3}
10^5
10^6
10^7
10^8
10^9
black hole mass (solar mass)


power-law
core
binary's semi-major axis (parsec)
1
0.1
0.01
10^{-3}
super-hard binary
Stars inside the "loss-cone" close to MBHB ejected once
10^5
10^6
10^7
10^8
10^9
black hole mass (solar mass)

The Loss Cone



Definition: Phase space domain consisting of orbits strongly perturbed by individual BHs

Around isolated MBHs:

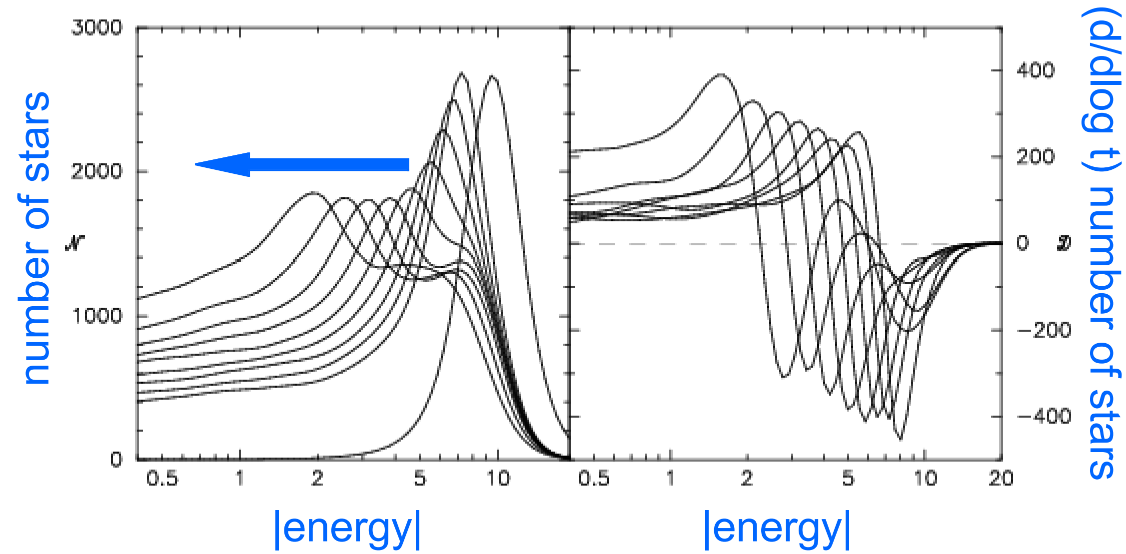
- Stars can wander in/out in 1 period
- Stars tidally disrupted near BH

Around MBH binaries:

- Diffusion into LC is slow
- Stars survive encounters with BHs
- Galactic nuclei are not collisionally relaxed

Encounters with MBHB move stars from one point in the phase space to another; repeated encounters are possible.

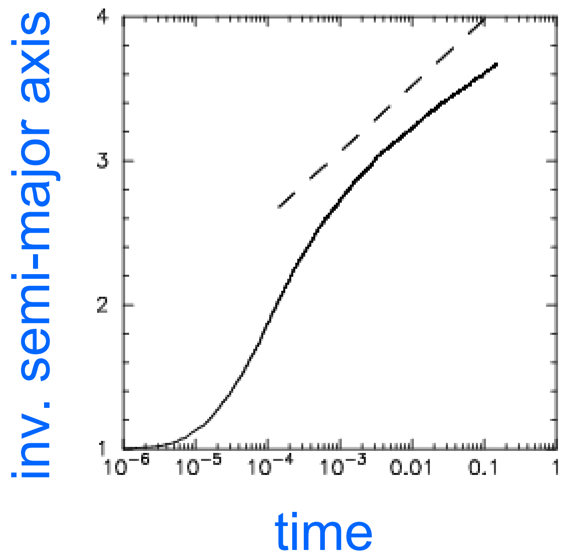
Re-Ejection



Stars ejected on radial orbits return to the nucleus and are re-ejected.

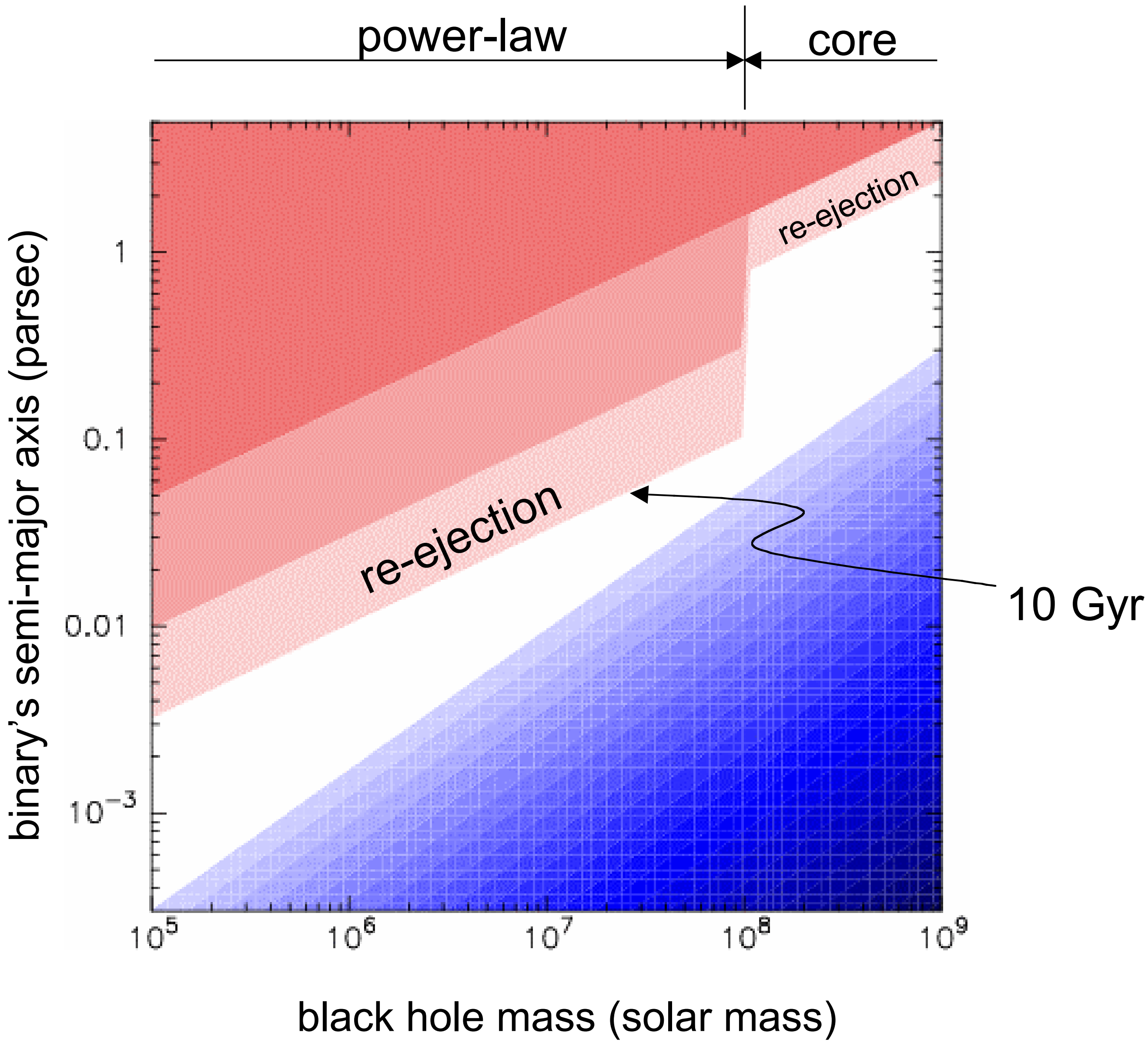
Re-Ejection in S. Isothermal Sphere

Radial orbit return time at energy $E \sim \dfrac{1}{P(E)} \sim e^{E/2\sigma^2}$

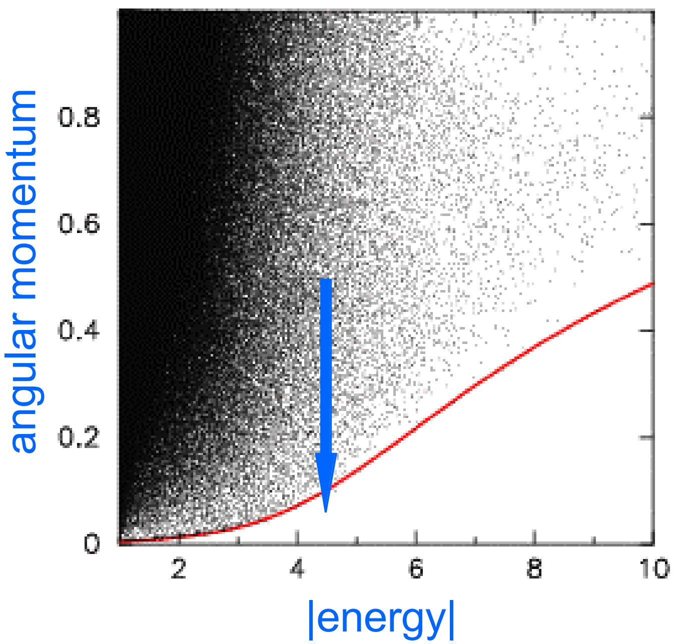


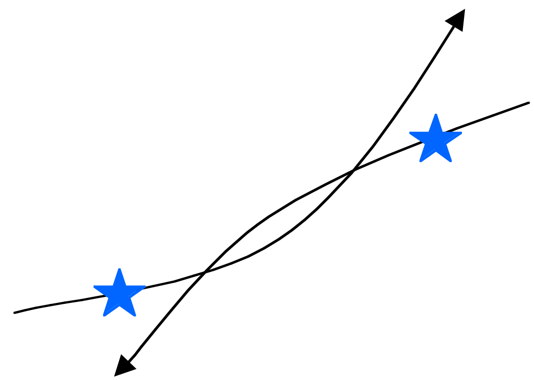
Decay due to re-ejection:
x2-5 in Hubble time

$$\frac{1}{a(t)} = \frac{1}{a(0)} + \frac{4\sigma^2}{G(M_1 + M_2)} \ln\left[1 + \frac{m_* N\langle \Delta E\rangle}{2\mu\sigma^2}\frac{t}{P(E_0)}\right]$$


power-law
core
re-ejection
re-ejection
10 Gyr
1
0.1
0.01
10^{-3}
10^5
10^6
10^7
10^8
10^9
binary's semi-major axis (parsec)
black hole mass (solar mass)

Diffusion into the Loss Cone





Equilibrium diffusion:

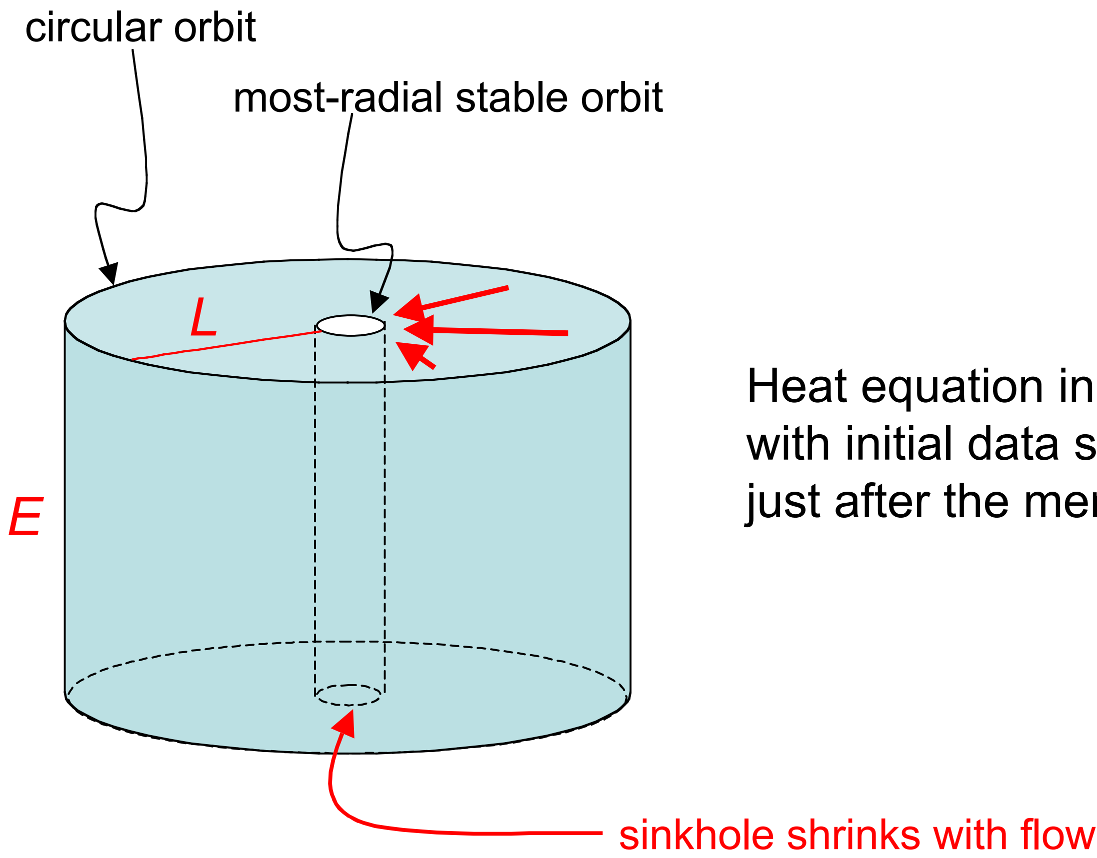
- Lightman & Shapiro 1977
- Cohn & Kulsrud 1978, etc.
  } GC
- Magorrian & Tremaine 1999
- Yu 2002
  } Galaxies

WARNING: Assume equilibrium w.r.t. collisional relaxation.

Following mergers, galaxies are not in a state of collisional equilibrium (the loss cone is too wide).

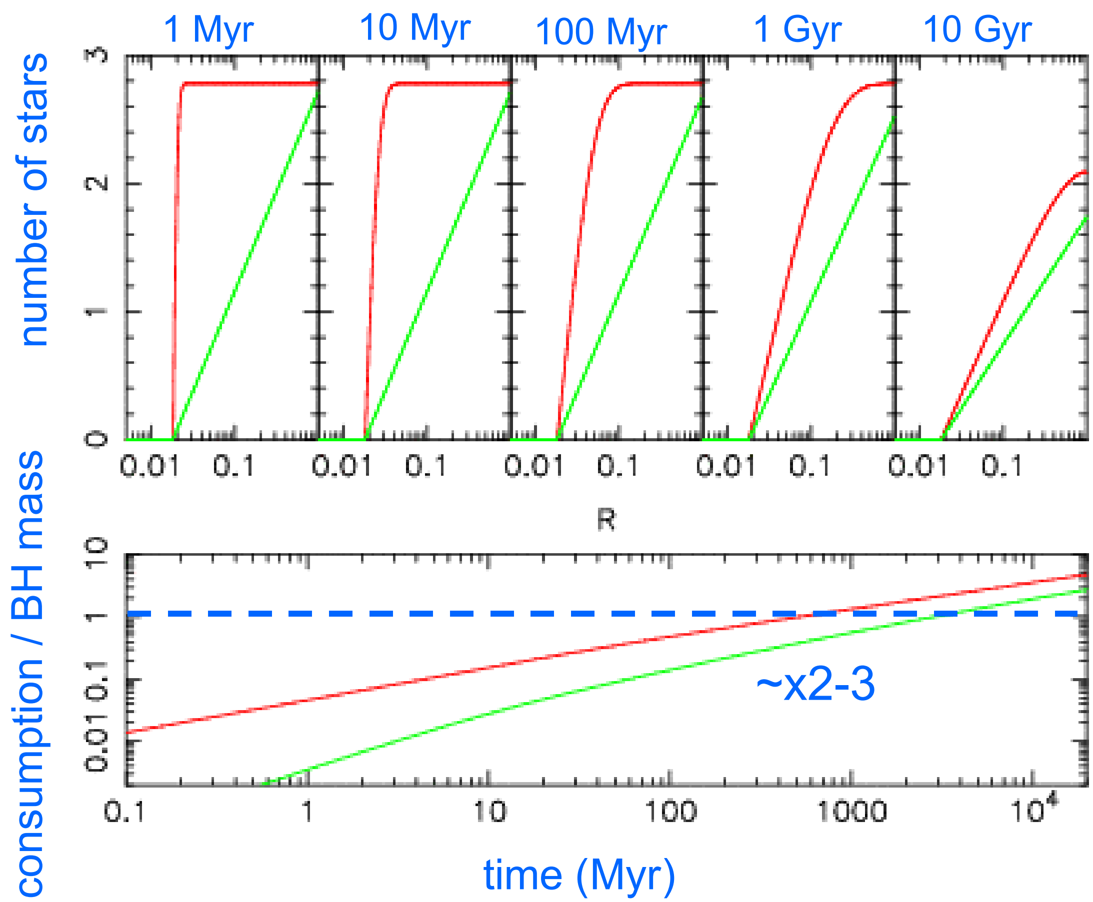
The equilibrium is never reached!

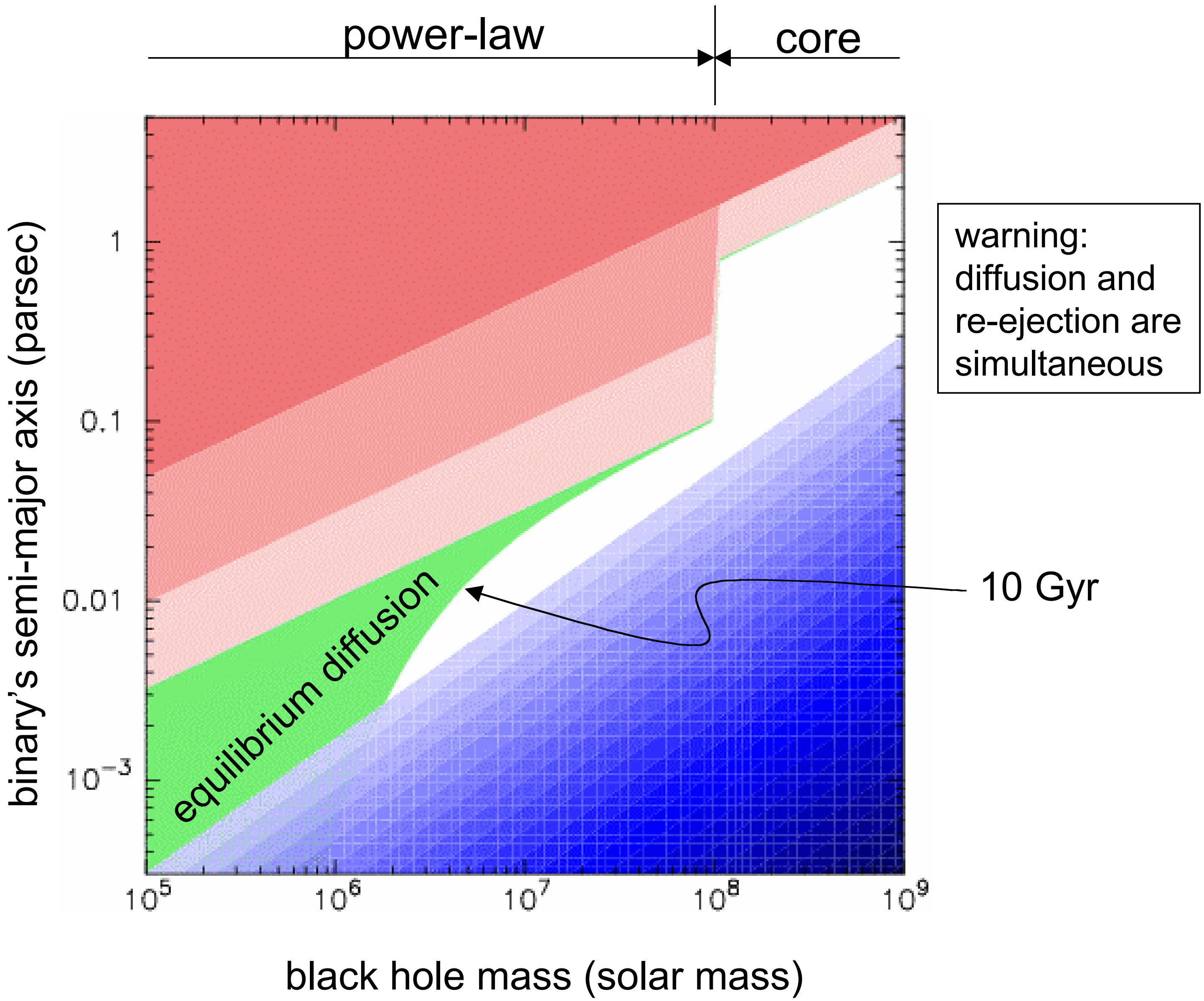
Non-Equilibrium Diffusion: Solution

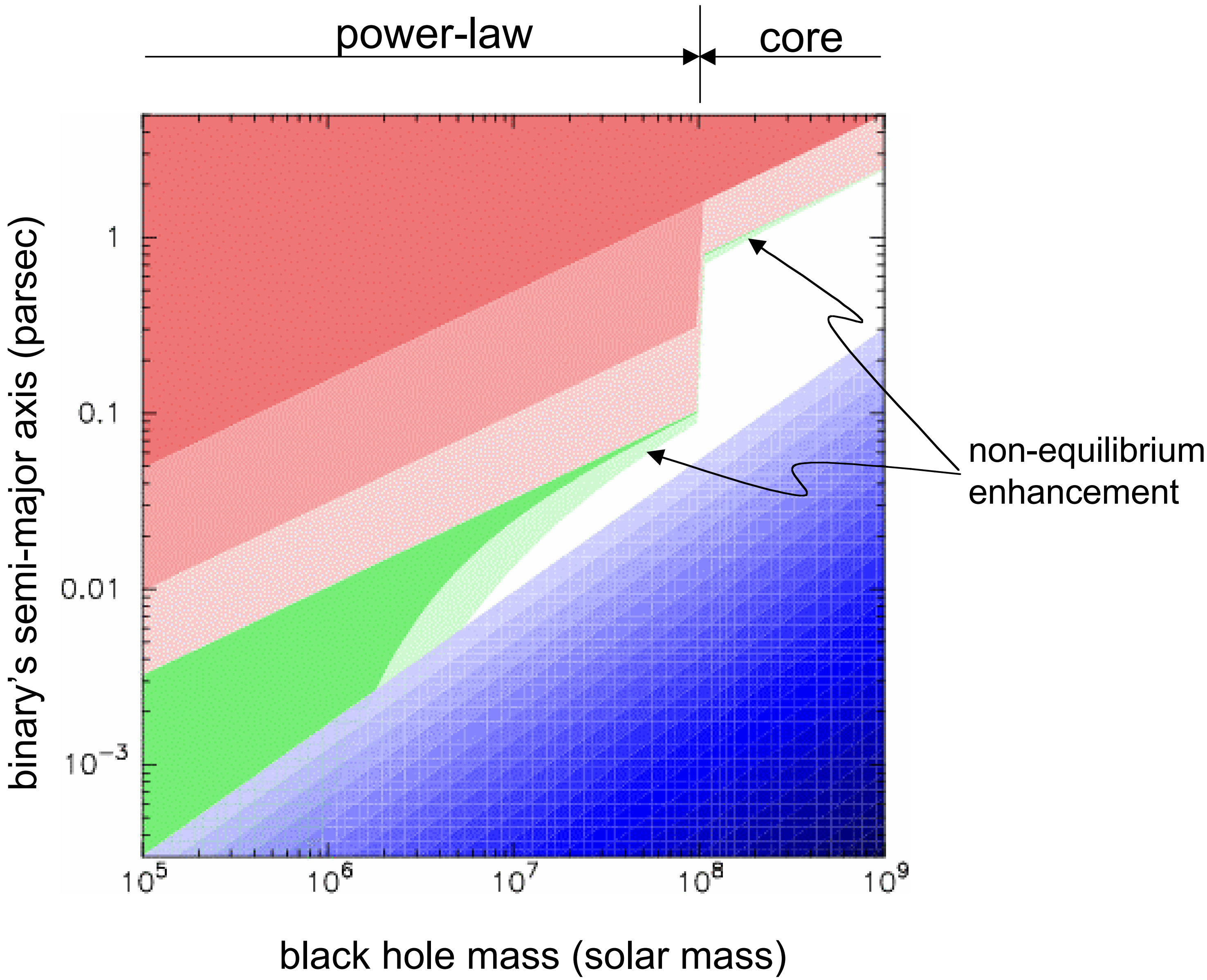


Heat equation in cylindrical coordinates with initial data specified by the galaxy just after the merger is complete

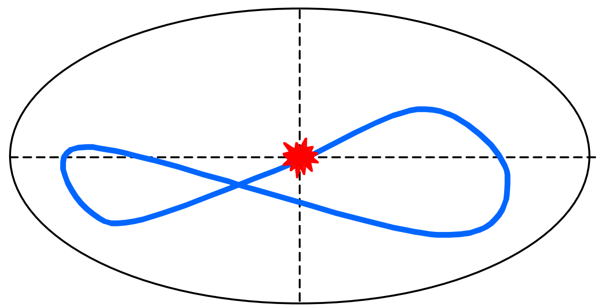
Non-Equilibrium Enhancement




power-law
core
warning:
diffusion and
re-ejection are
simultaneous
equilibrium diffusion
10 Gyr
1
0.1
0.01
10^{-3}
10^5
10^6
10^7
10^8
10^9
binary's semi-major axis (parsec)
black hole mass (solar mass)


power-law
core
1
0.1
0.01
10^-3
10^5
10^6
10^7
10^8
10^9
binary's semi-major axis (parsec)
black hole mass (solar mass)
non-equilibrium
enhancement

Flattening



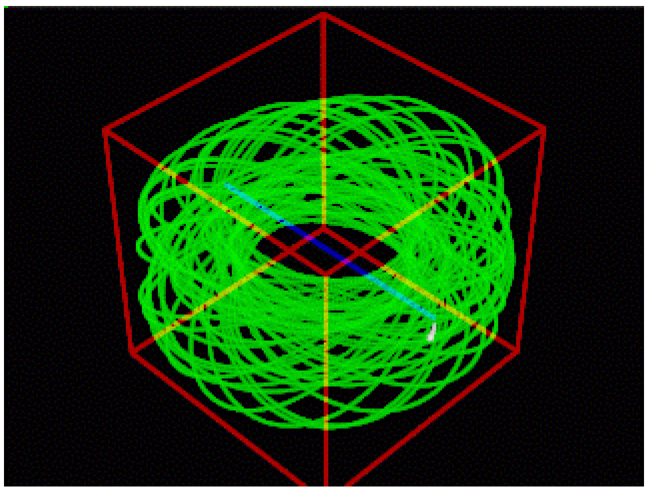
"The loss wedge"
(Magorrian & Tremaine 1999)

Enhancement of the loss cone flux due to flattening:
Not studied in *N*-body context!

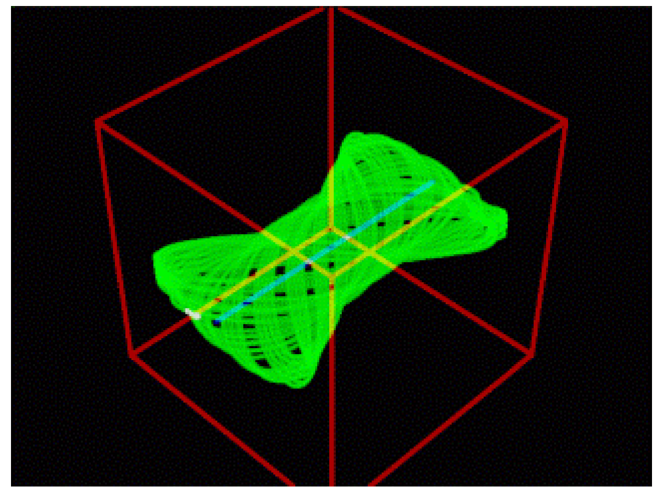
Triaxiality?

Poon & Merritt 2002
Holley-Bockelmann et al 2002

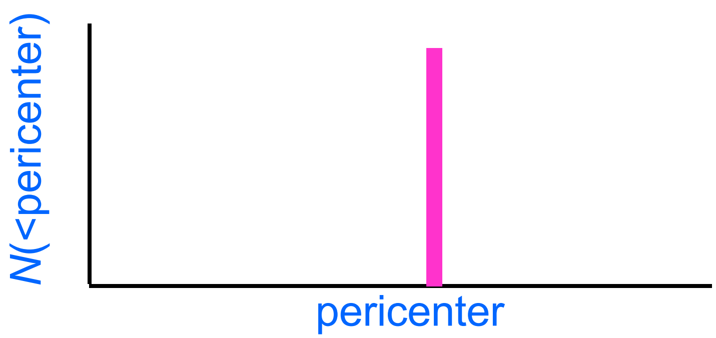
“tube”

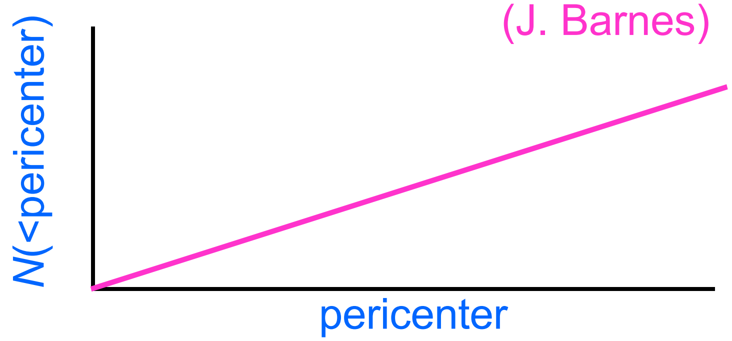


“box”



(J. Barnes)





Gerhard & Binney 1985, Merritt & Poon 2002

Other Processes

Stellar-dynamical:

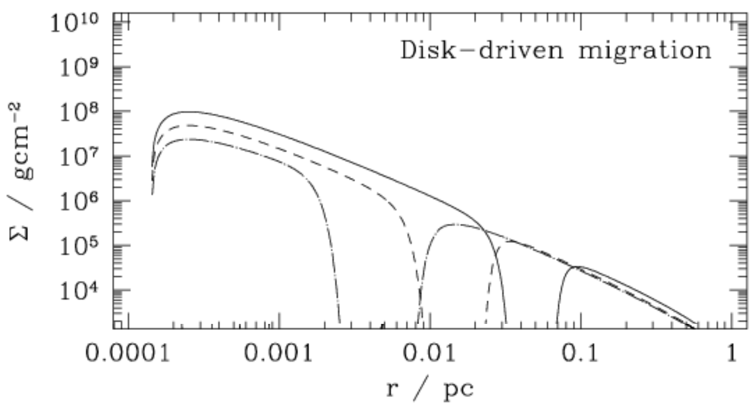
Non-sphericities in the galactic potential (bars, stellar disks, etc.)

Gas-dynamical:

Accretion during the binary phase

Torques by a viscous massive disk:

e.g. Armitage & Natarajan 2002:



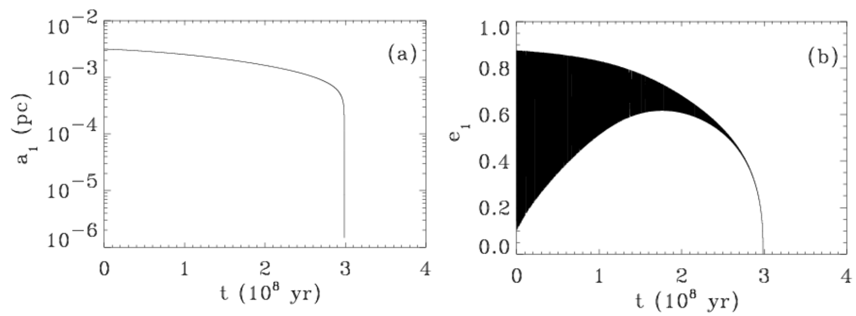
Multiple black hole:

3+ BH encounters lead to ejection of BHs, formation of high-eccentricity systems, replenishment of the loss cone (Valtonen et al 1994).

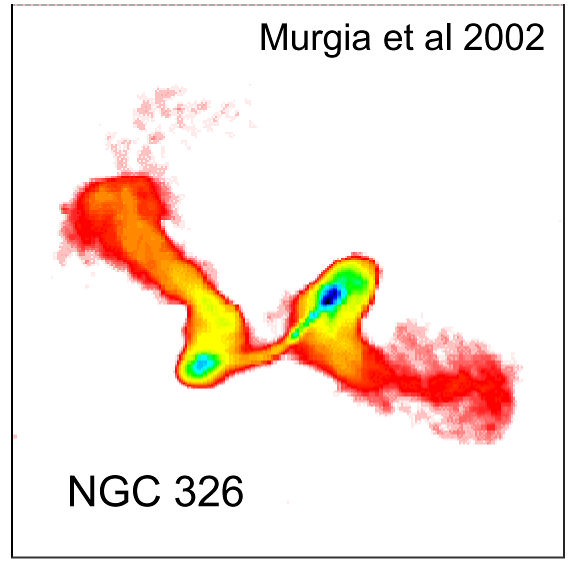
Hierarchical 3 BH configurations:

The Kozai mechanism

e.g. Blaes, Lee & Socrates 2002:



Do most MBHB coalesce?

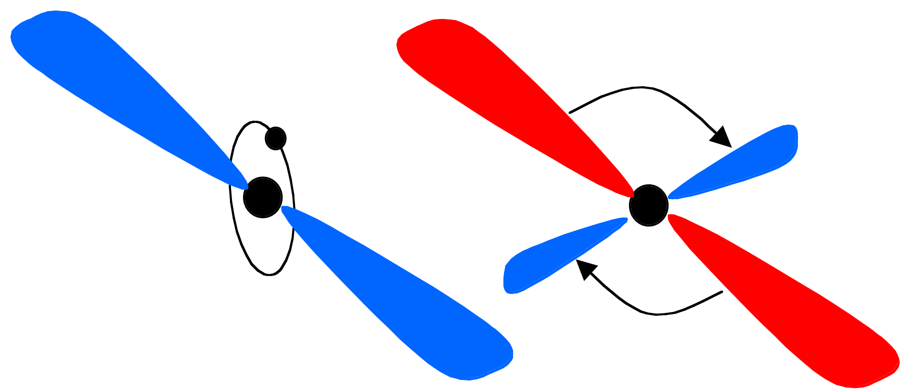


Circumstantial evidence: They do!

- No smoking gun for long-lived MBHB
- Scarcity of wiggly jets
- Some galaxies exhibit no cusp-destruction in spite of mergers
- Cosmological arguments: BH mass conservation

Anecdotal evidence: Some survive:

- OJ 287 (e.g. Sillanpaa et al 1992)
- 3C 273 (e.g. Kaastra & Roos 1992)
- Mkn 501 (e.g. Conway & Wrobel 1995)
- PKS 0420-014 (e.g. Britzen et al 2001)



Merritt & Ekers 2002: New jet points in the direction of BH spin following coalescence

Hughes & Blandford 2002: MBH are spun –down by mergers with undermassive secondaries

Conclusions

Idealized dynamical models suggest that long-lived massive black hole binaries are generically produced in mergers of intermediate and large mass galaxies.

Circumstantial evidence suggests that massive black hole binaries are not ubiquitous. All established physical mechanisms aid an efficient coalescence of the black holes.

Time-dependent, non-equilibrium dynamics of binary black hole nuclei is not fully understood. Quantitative work will shed light on the aspects important for LISA.