Binary Black Holes in Galactic Nuclei

- ❑ Bringing them together
- ❑ Binary at the Galactic center?
- ❑ Kicking them out

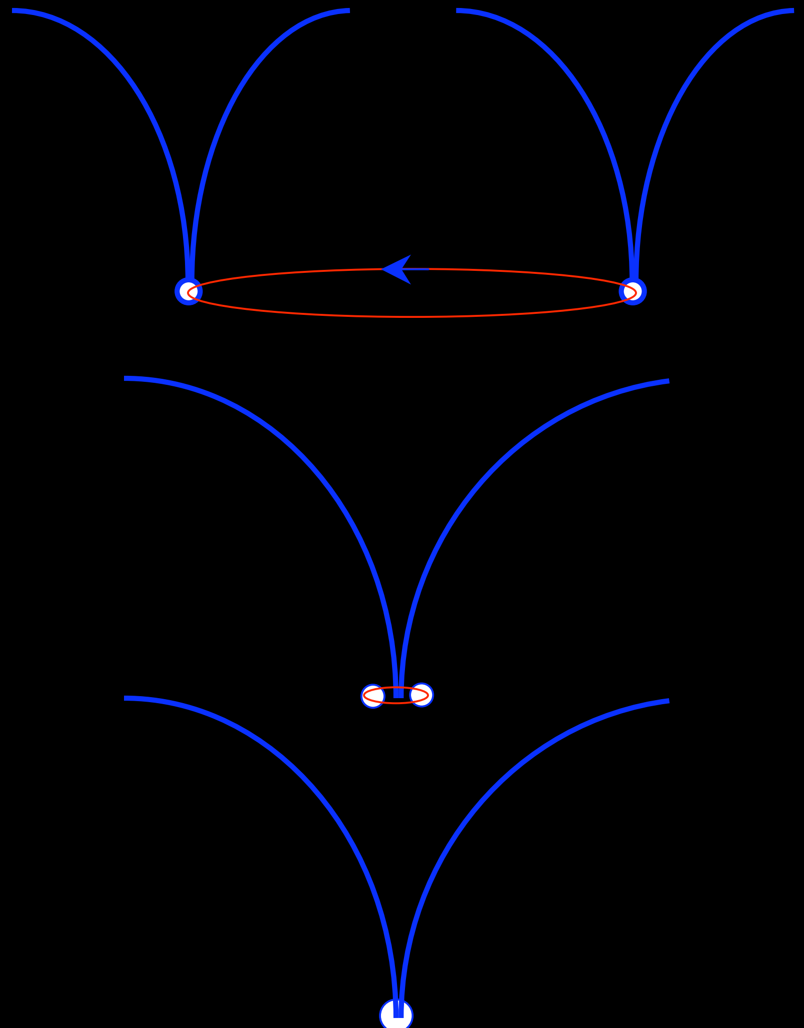
The Central Kiloparsec: Active Galactic Nuclei and Their Hosts
June 2008

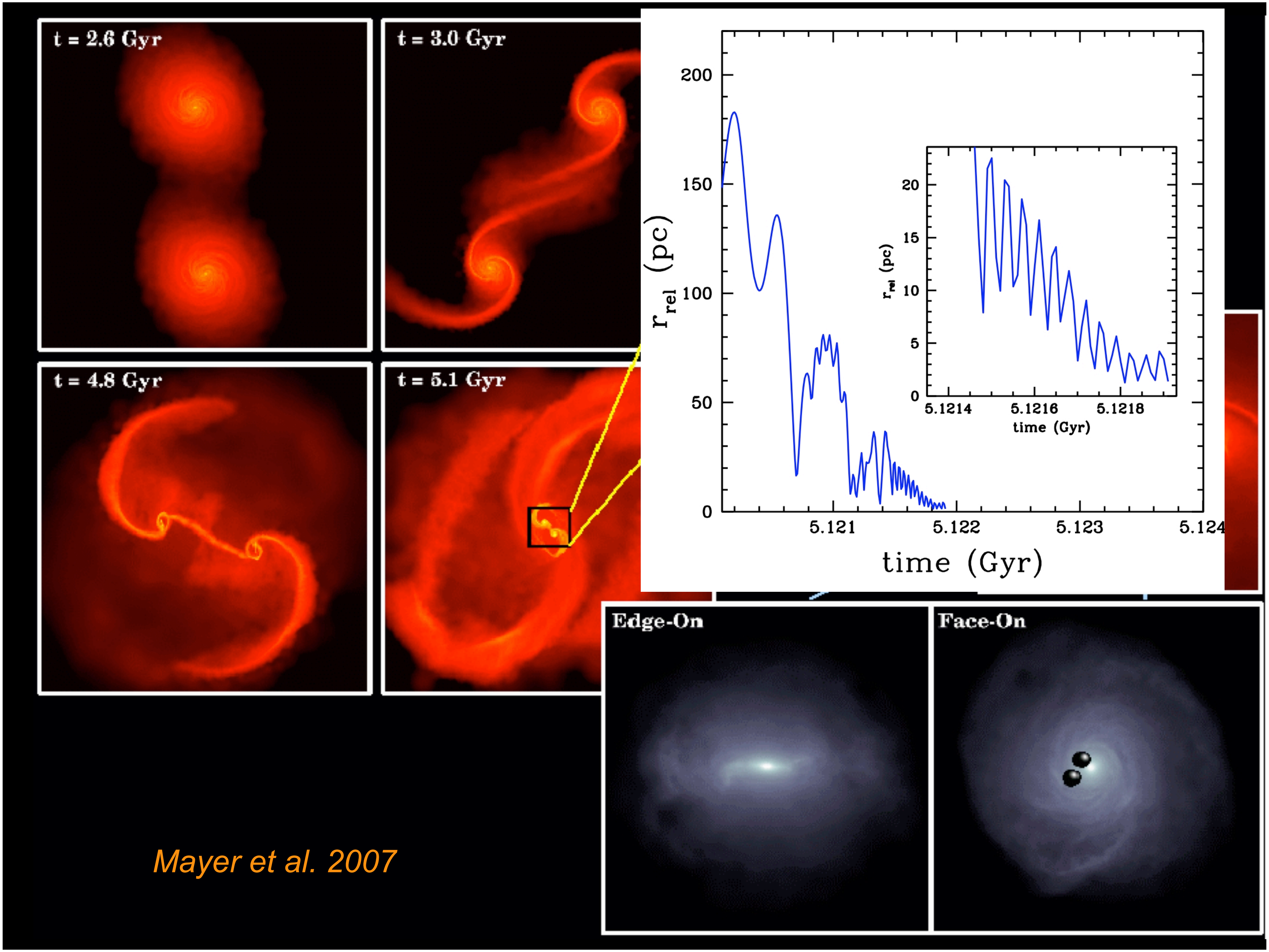
❑ Bringing Them Together

Galaxies merge

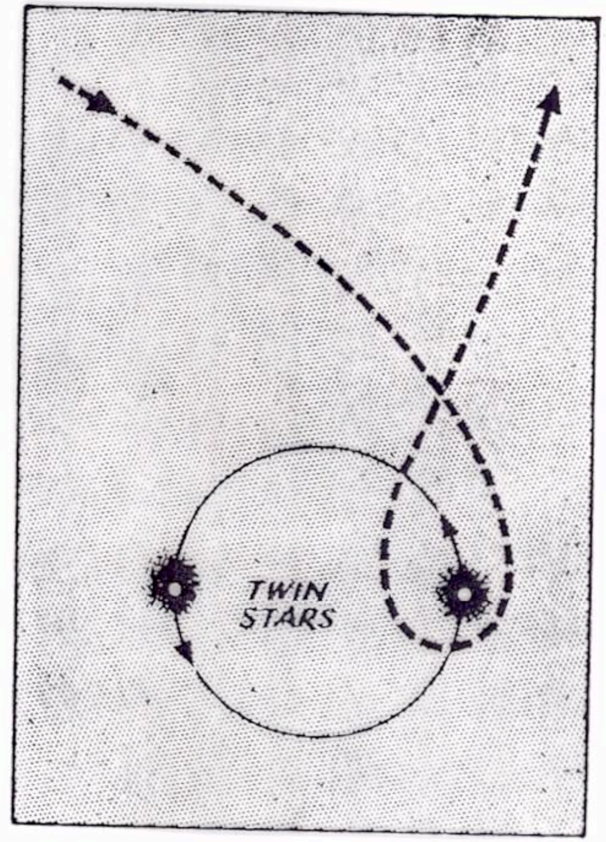
Binary forms

Binary decays (?), via:
-- ejection of stars
-- interaction with gas



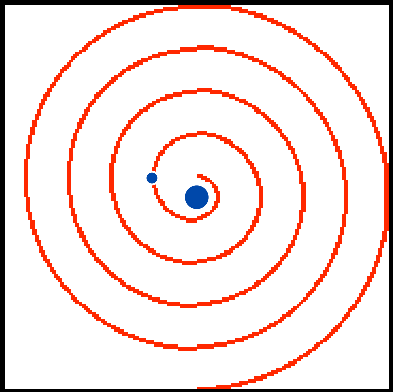


t = 2.6 Gyr
t = 3.0 Gyr
t = 4.8 Gyr
t = 5.1 Gyr
r_{rel} (pc)
time (Gyr)
Edge-On
Face-On
Mayer et al. 2007



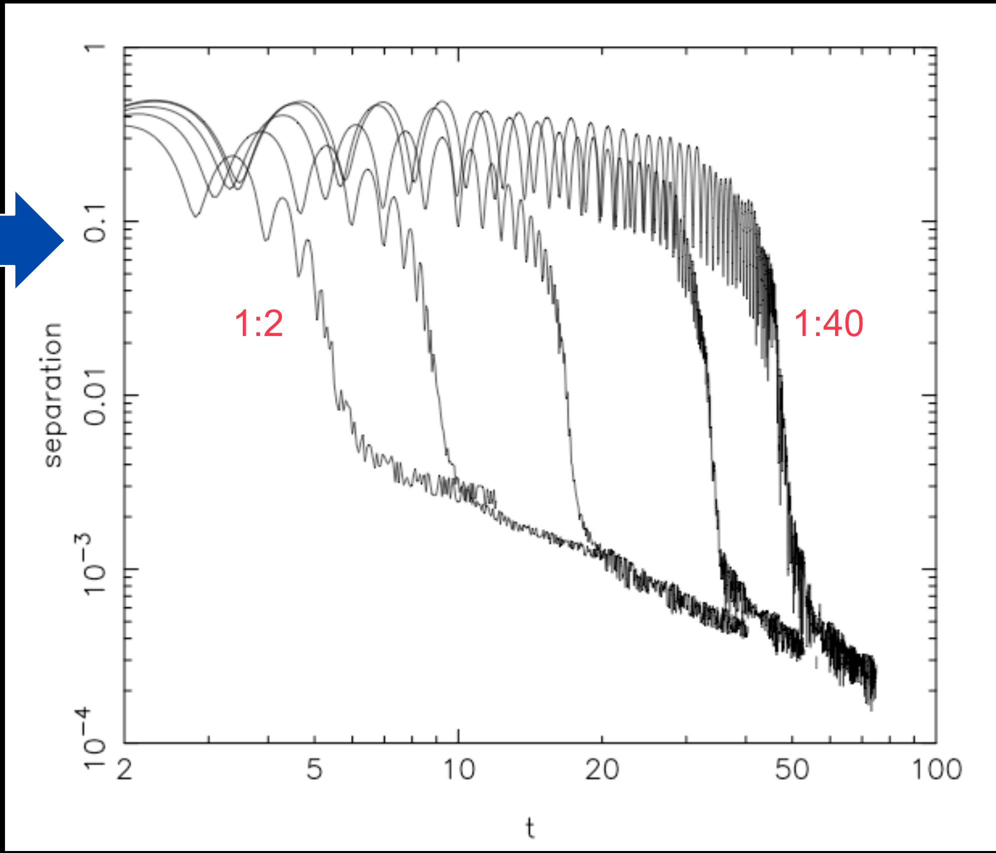
In Dyson's "gravity machine" an object is fired toward twin stars so that it circles the approaching star and is thrown back by that star's gravity, having gained much additional energy.

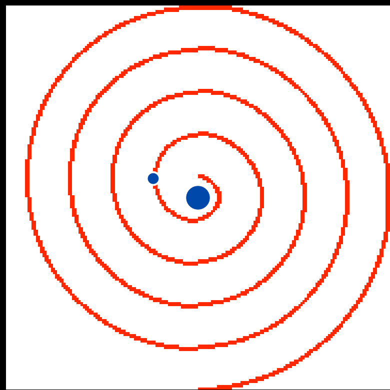
"Gravitational Slingshot"



In-Spiralling Black Holes

$$r_h \approx \frac{GM_{12}}{\sigma^2}$$
$$\approx 1.54\ \mathrm{pc}\left(\frac{M_{12}}{3.5\times10^6 M_{\mathrm{sun}}}\right)\left(\frac{\sigma}{100\ \mathrm{km\ s^{-1}}}\right)^{-2}$$



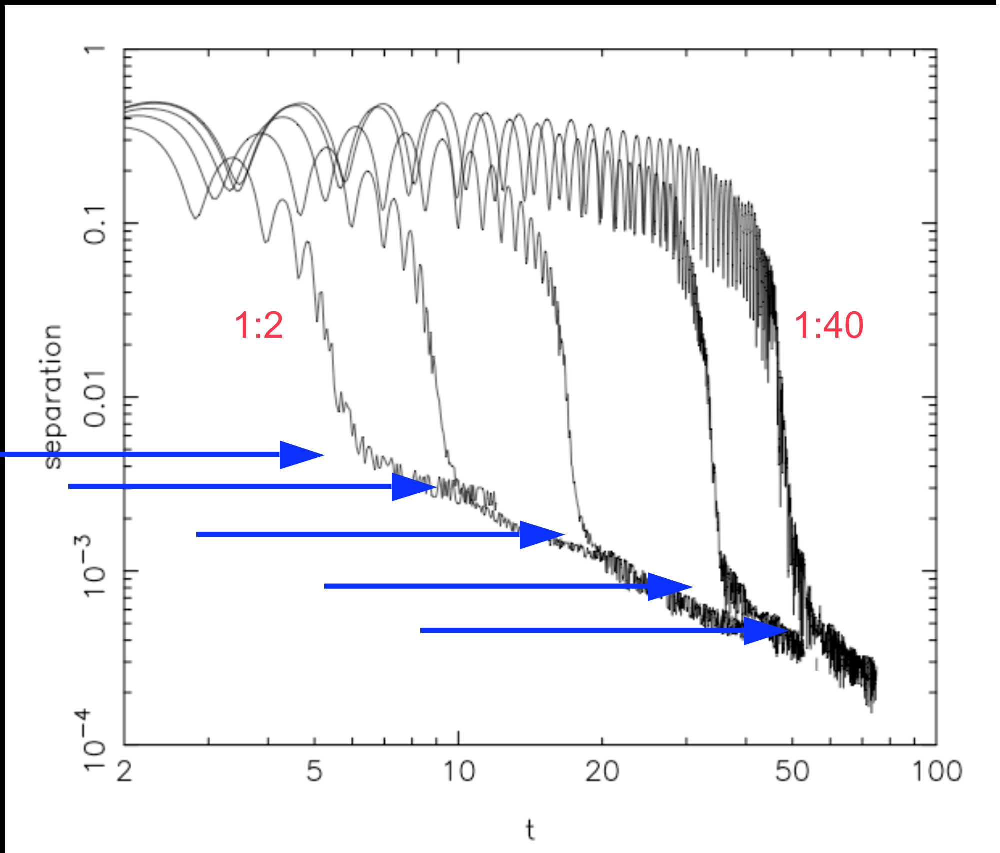


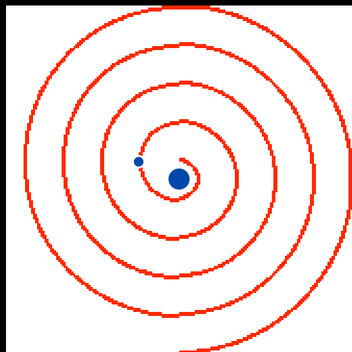
In-Spiralling Black Holes

$$a_h \approx \frac{GM_2}{4\sigma^2}$$

$$\approx 0.39 \text{ pc } q \left(\frac{M_{12}}{3.5\times 10^6 M_{sun}}\right)\left(\frac{\sigma}{100 \text{ km s}^{-1}}\right)^{-2}$$

$q \equiv M_2 / M_1$



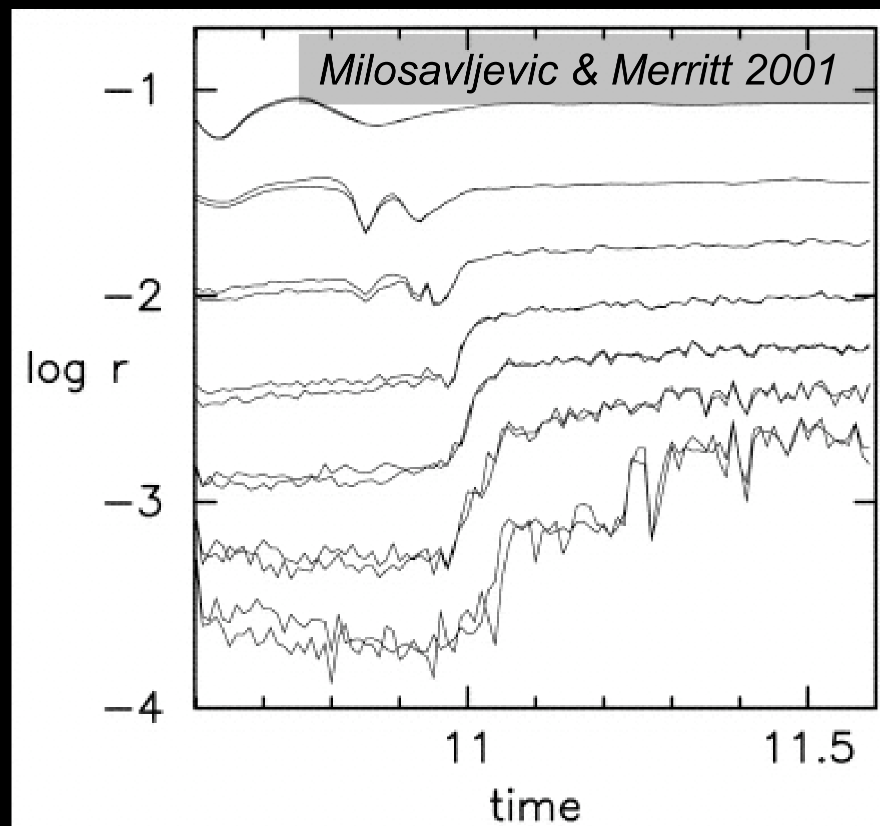


Binary SMBH forms by displacing stars.

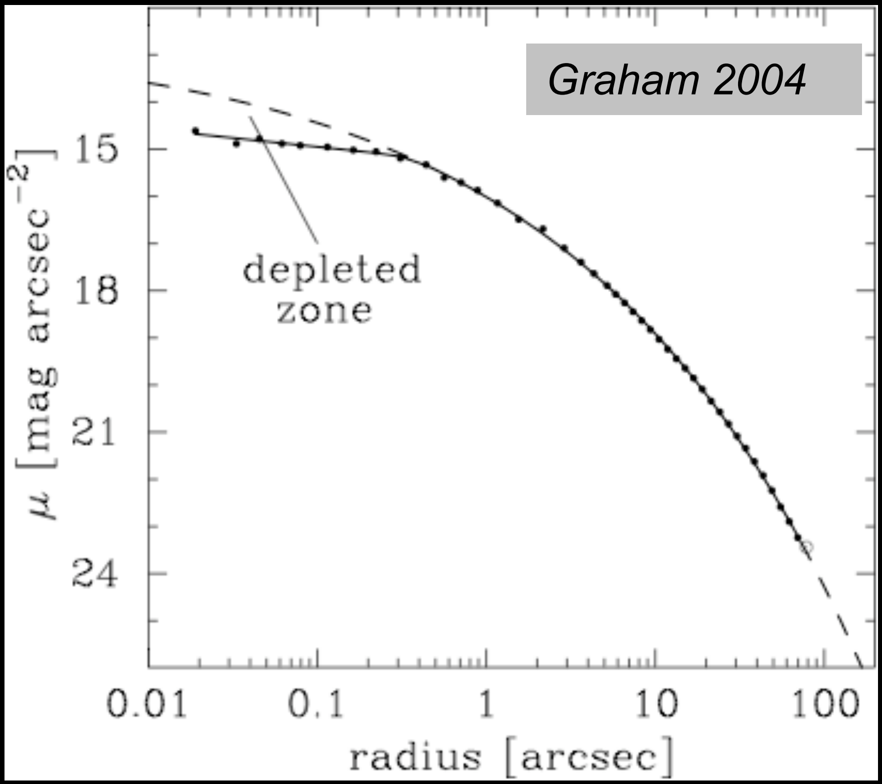
Energy released in reaching the "hard binary" separation, $a \approx a_h$, is:

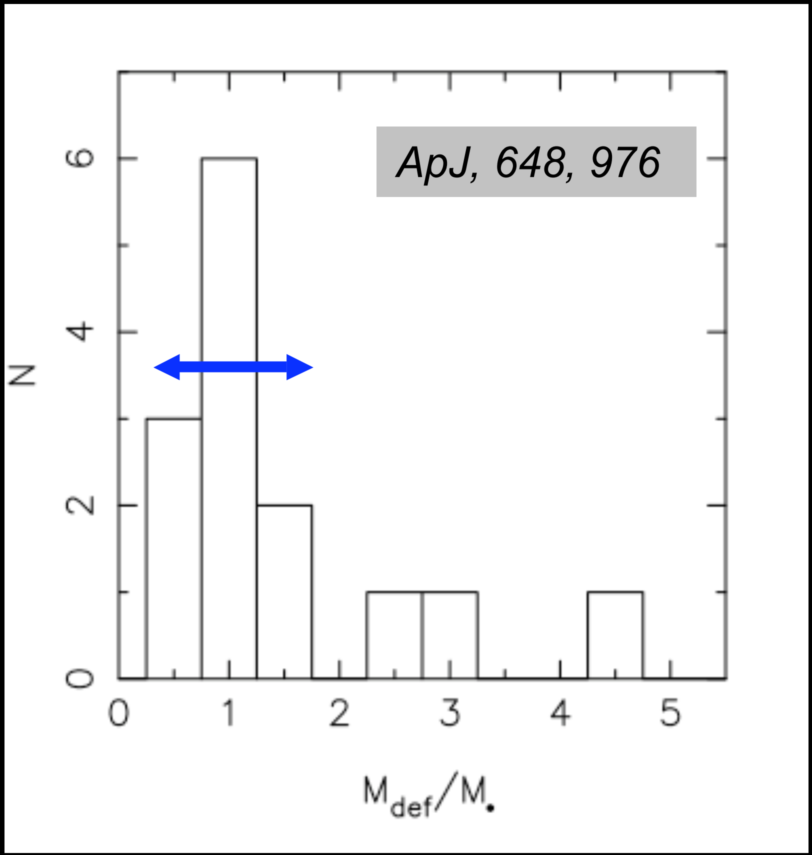
$$\Delta E \approx -\frac{GM_1M_2}{2r_h} + \frac{GM_1M_2}{2a_h}$$
$$\approx -\frac{1}{2}M_2\sigma^2 + 2M_{12}\sigma^2$$
$$\approx 2M_{12}\sigma^2$$

almost **independent** of the binary mass ratio M_1/M_2.



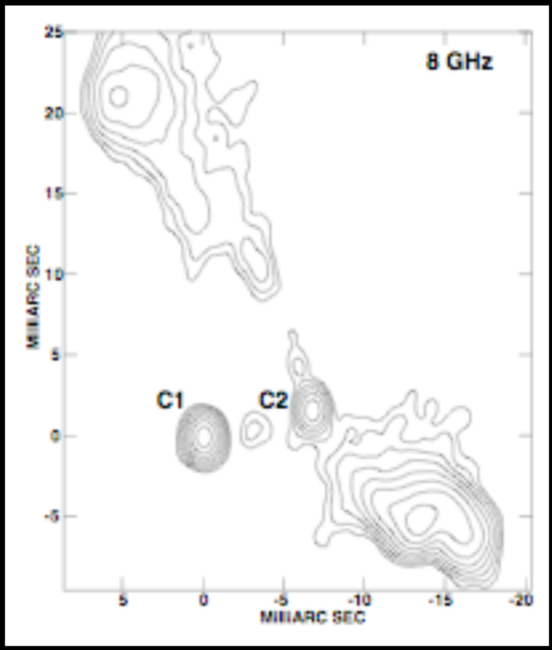
Mass Deficits





Milosavjlevic et al. 2002
Ravindranath et al. 2002

A Bona-Fide Binary Black Hole?

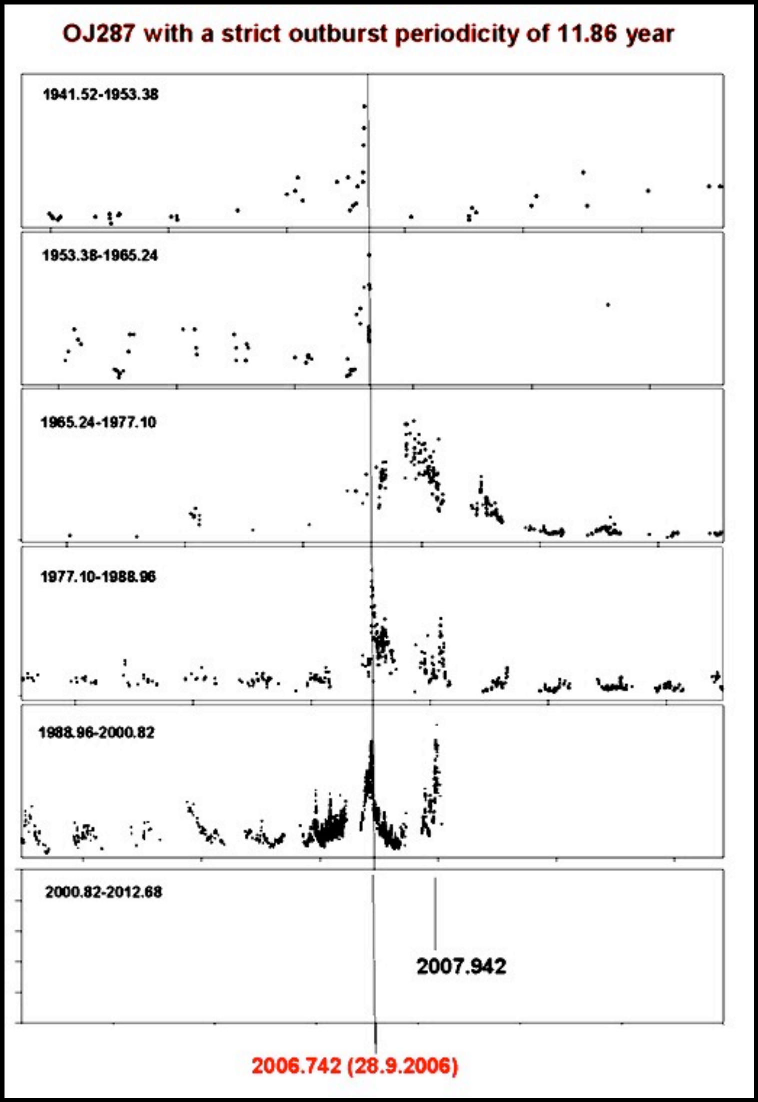


Rodriguez et al. 2006

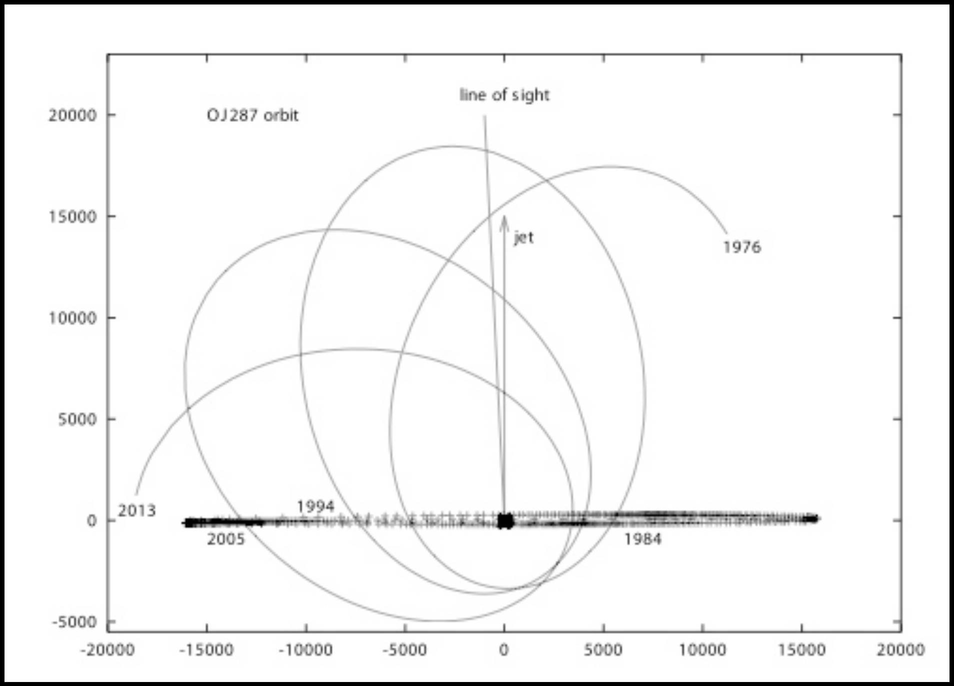
The observed (projected) separation of ~7 pc is the expected stalling radius for a ~10^9 M_{sun} binary SMBH.

OJ 287

Valtonen et al. 2006, 2008



Light Curve



Precessing Orbit Model

Overcoming the “Final-Parsec Problem”

I.e. how to bring binary separations from ~ 1 pc down to ~0.001 pc

1. Allow the BHs to interact with gas
2. Prolong BH-star interactions, by…
   - -- Collisionless loss-cone refilling
   - -- Collisional loss-cone refilling

3. Add additional BHs

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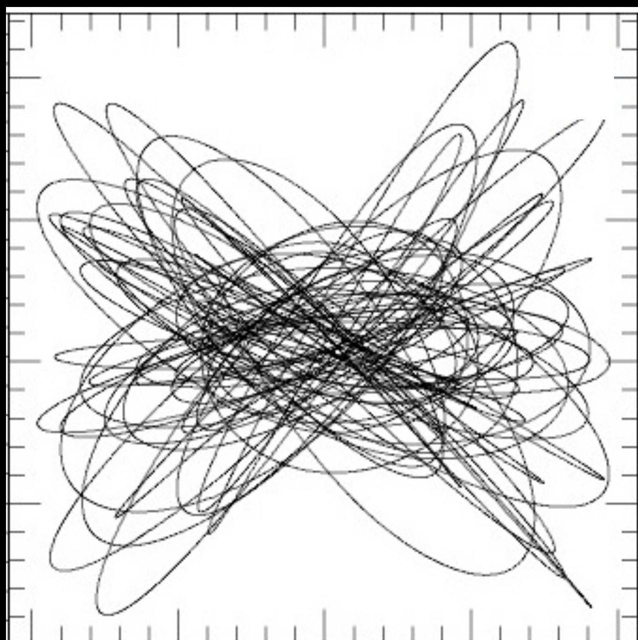
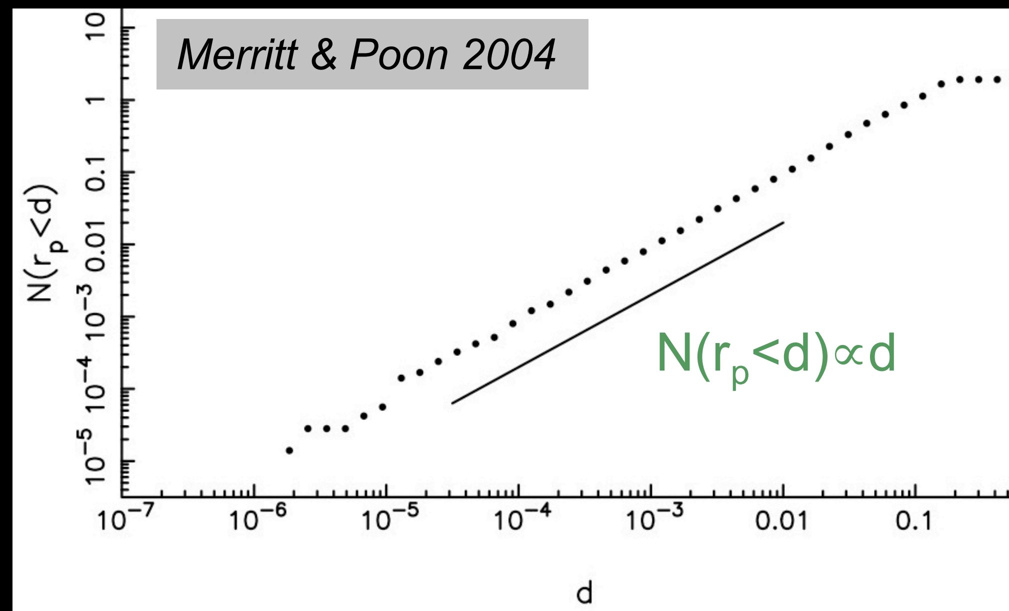
"Chaotic" Loss Cones

Box (chaotic) orbit



Distribution of pericenters

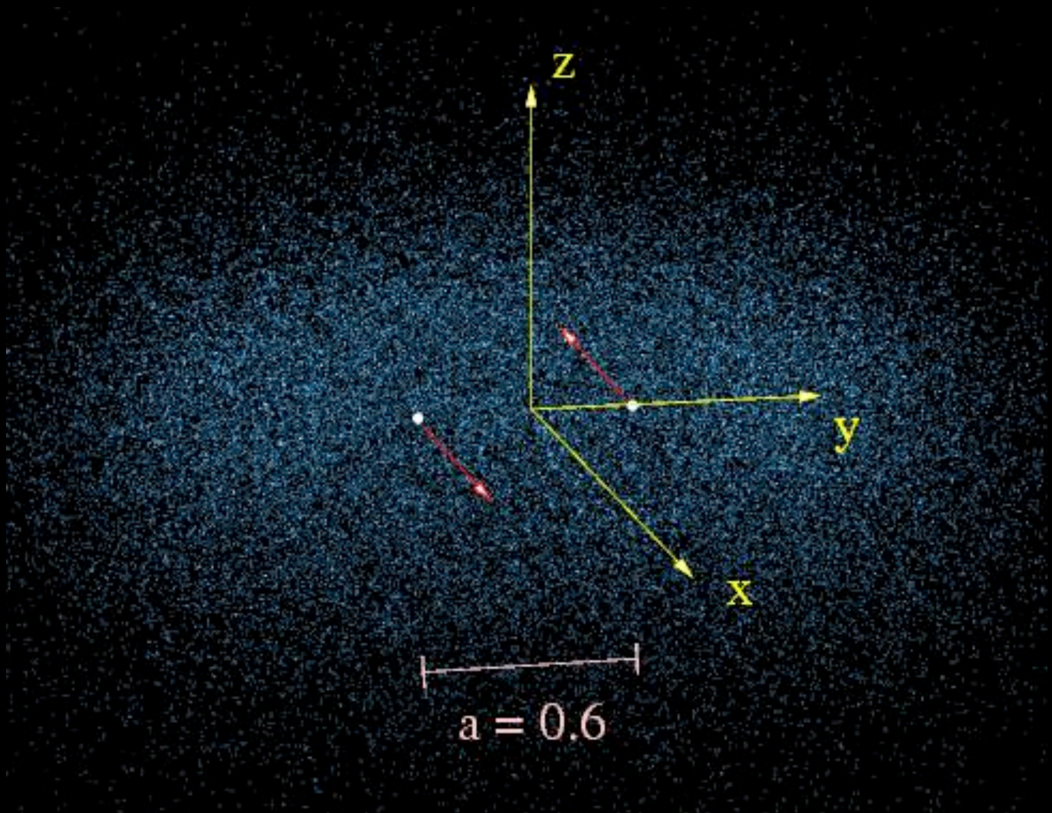


Holley-Bockelmann & Sigurdsson 2006
Merritt & Valluri 1999
…
Gerhard & Binney 1985
Norman & Silk 1983

Implies feeding rate of

$$dM/dt \approx f_{box}\sigma^3/G$$

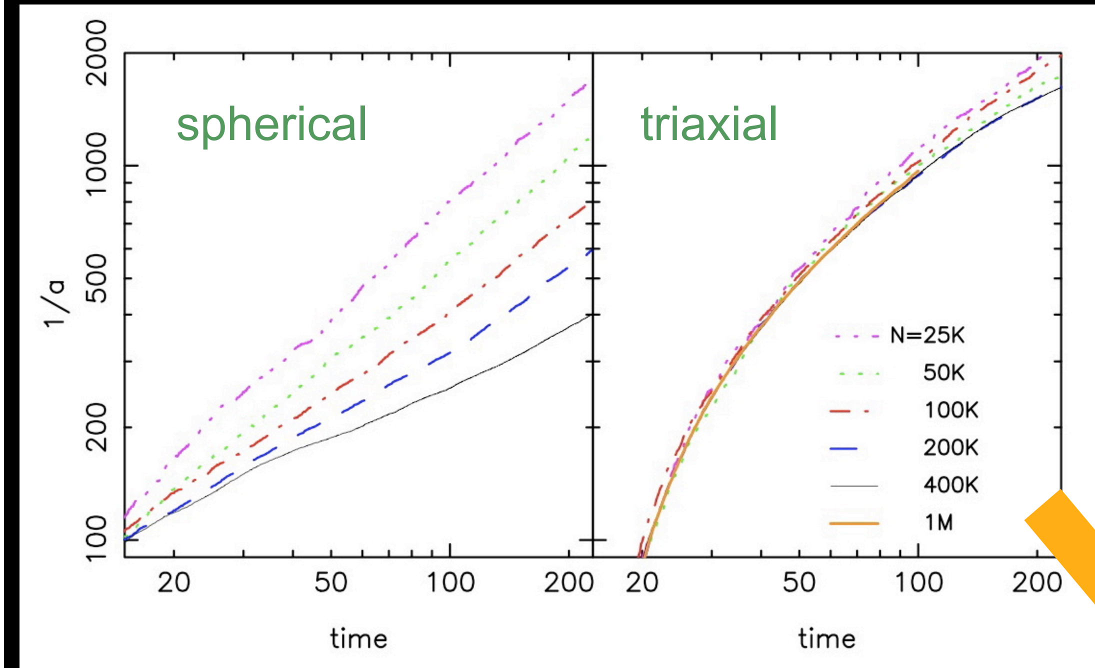
into a binary SMBH.



Initial conditions:

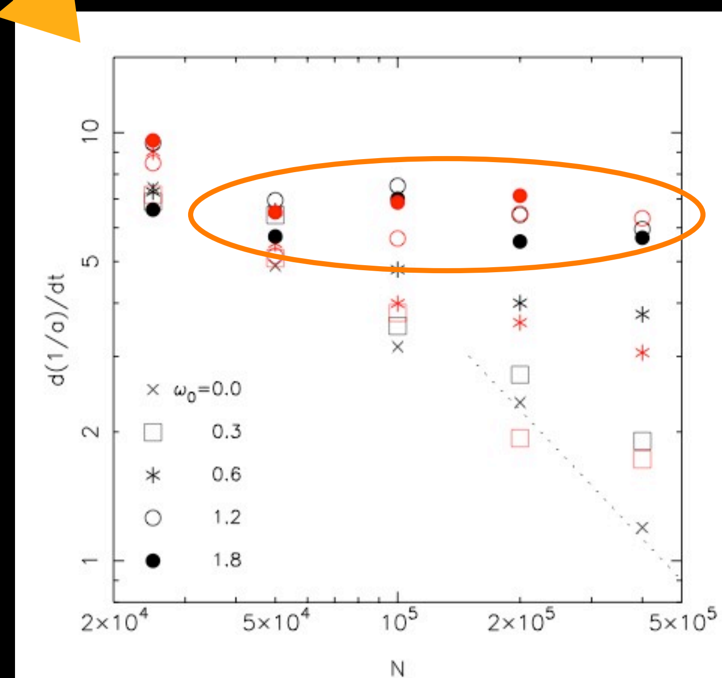
Rotating King model

Berczik et al. 2006



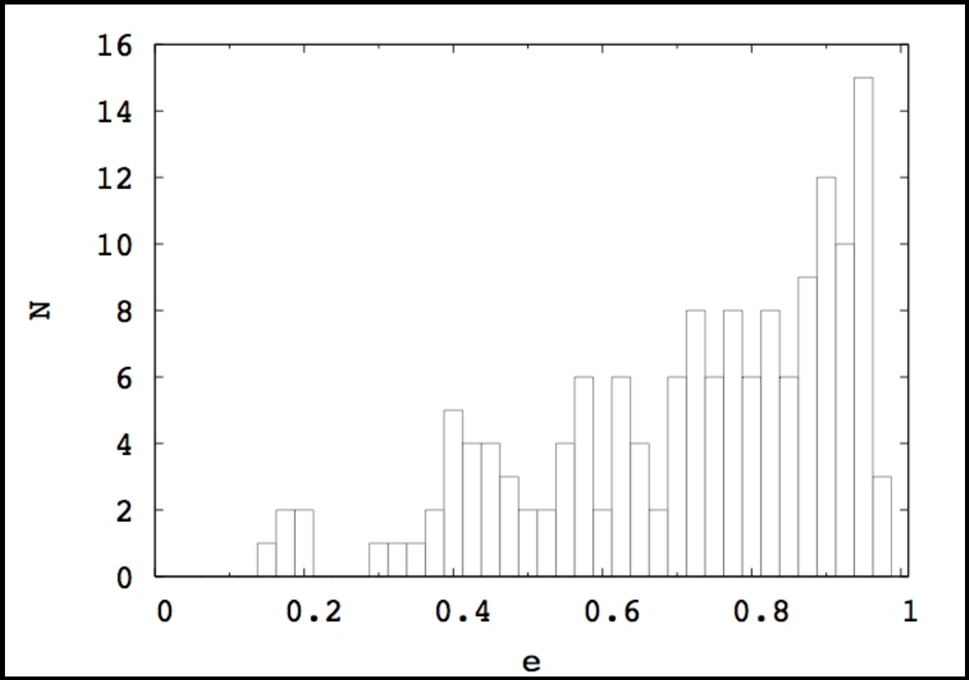
Berczik et al. 2006

Evolution of semi-major axis

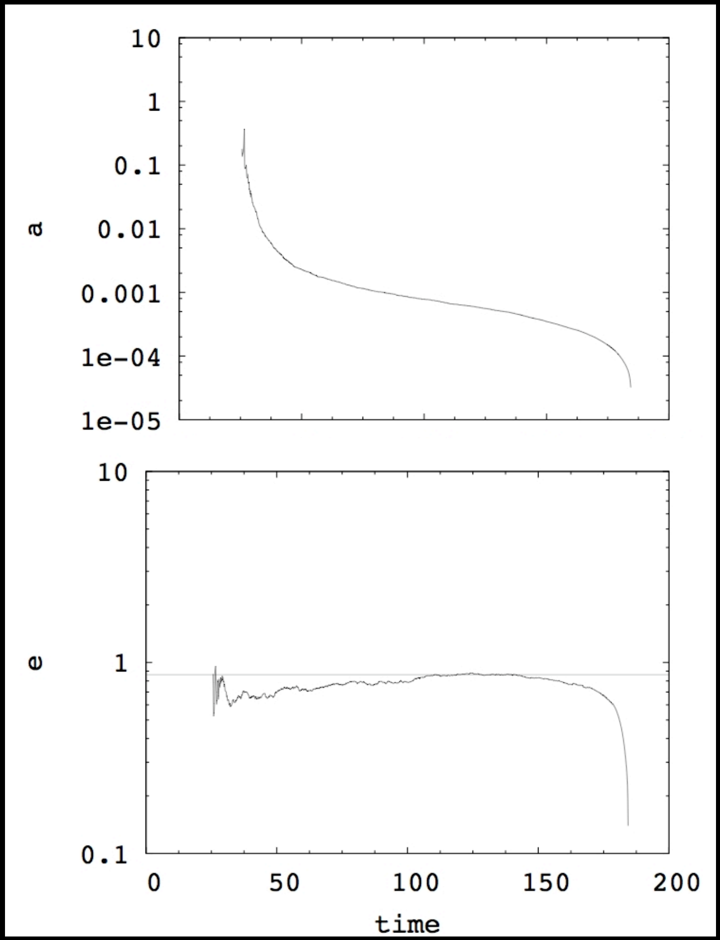


Hardening rates *vs. N.*

No N-dependence for triaxial models.



Eccentricity distribution at time of binary formation



Berentzen et al. 2008

Binary evolution
(including terms up to PN2.5)

❑ Bringing Them Together: Summary

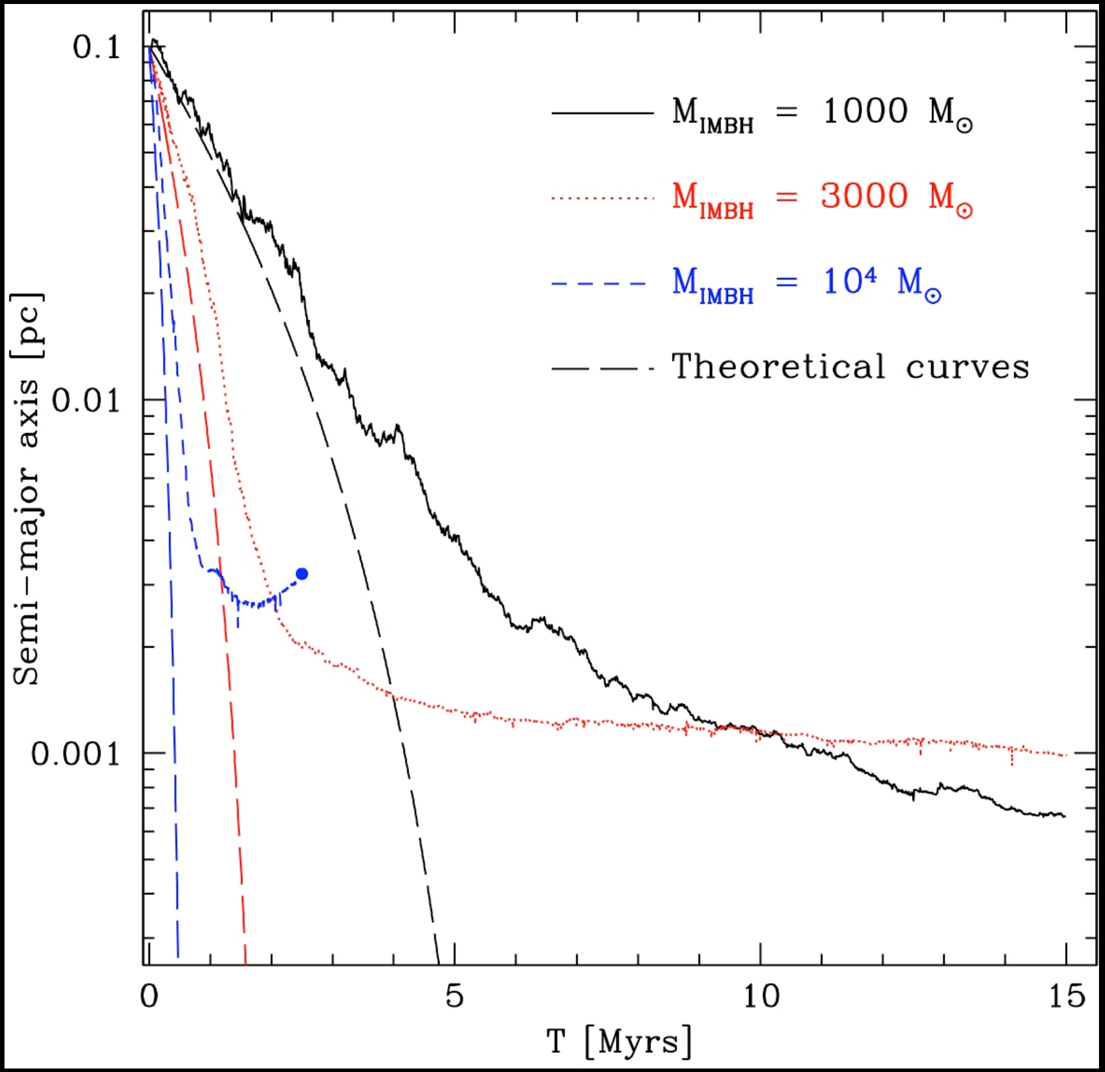
- Binary (bound) SMBHs **form quickly**
- However, subsequent evolution can be **slow**
  (e.g. spherical, gas-free galaxies)

  or **rapid**
  (e.g. triaxial / barred galaxies)

  or something in between.

Probably all occur in nature

❑ Binary at the Galactic Center?

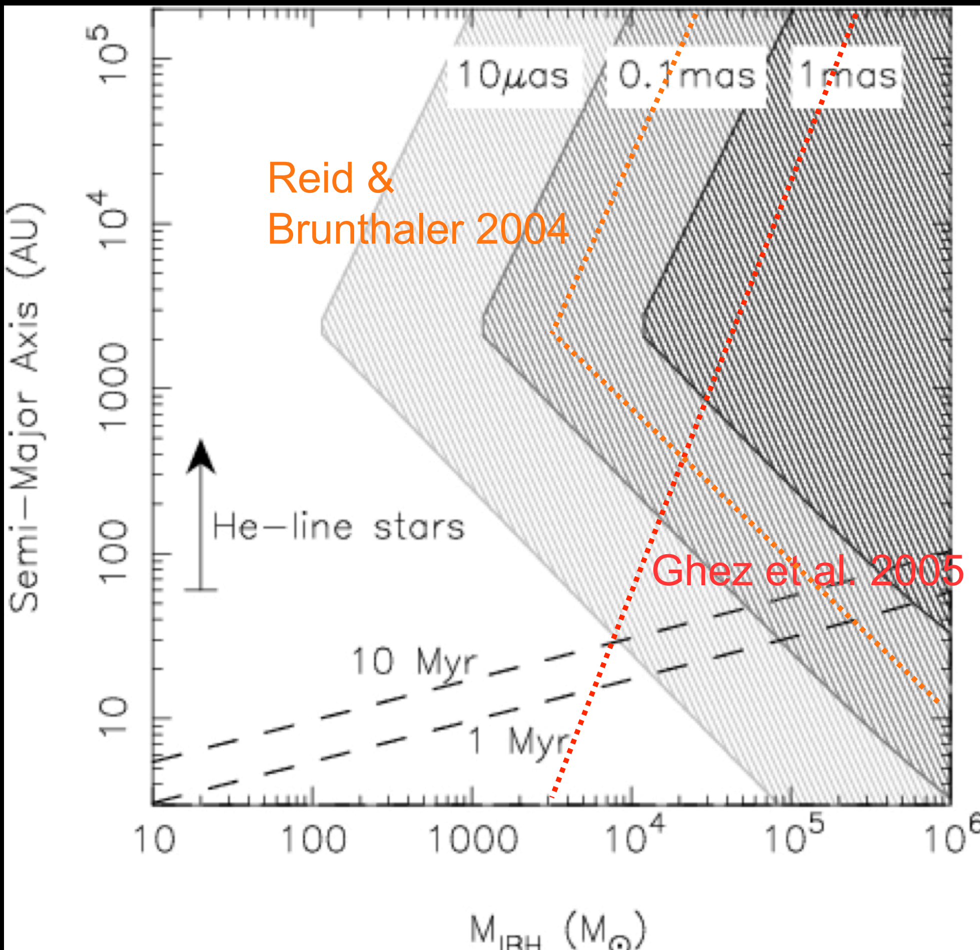


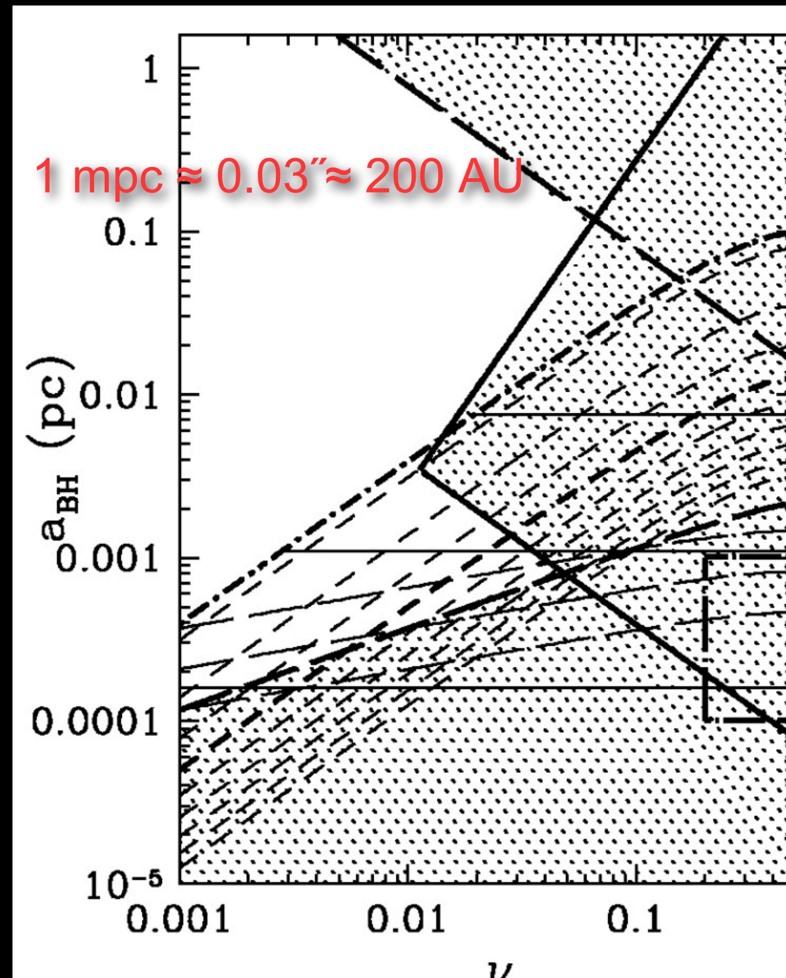
Evolution of the separation, for three values of M_{IMBH}.

Stalling radii are ~10^{-3} pc.

Baumgardt, Gualandris & Portegies Zwart (2005)

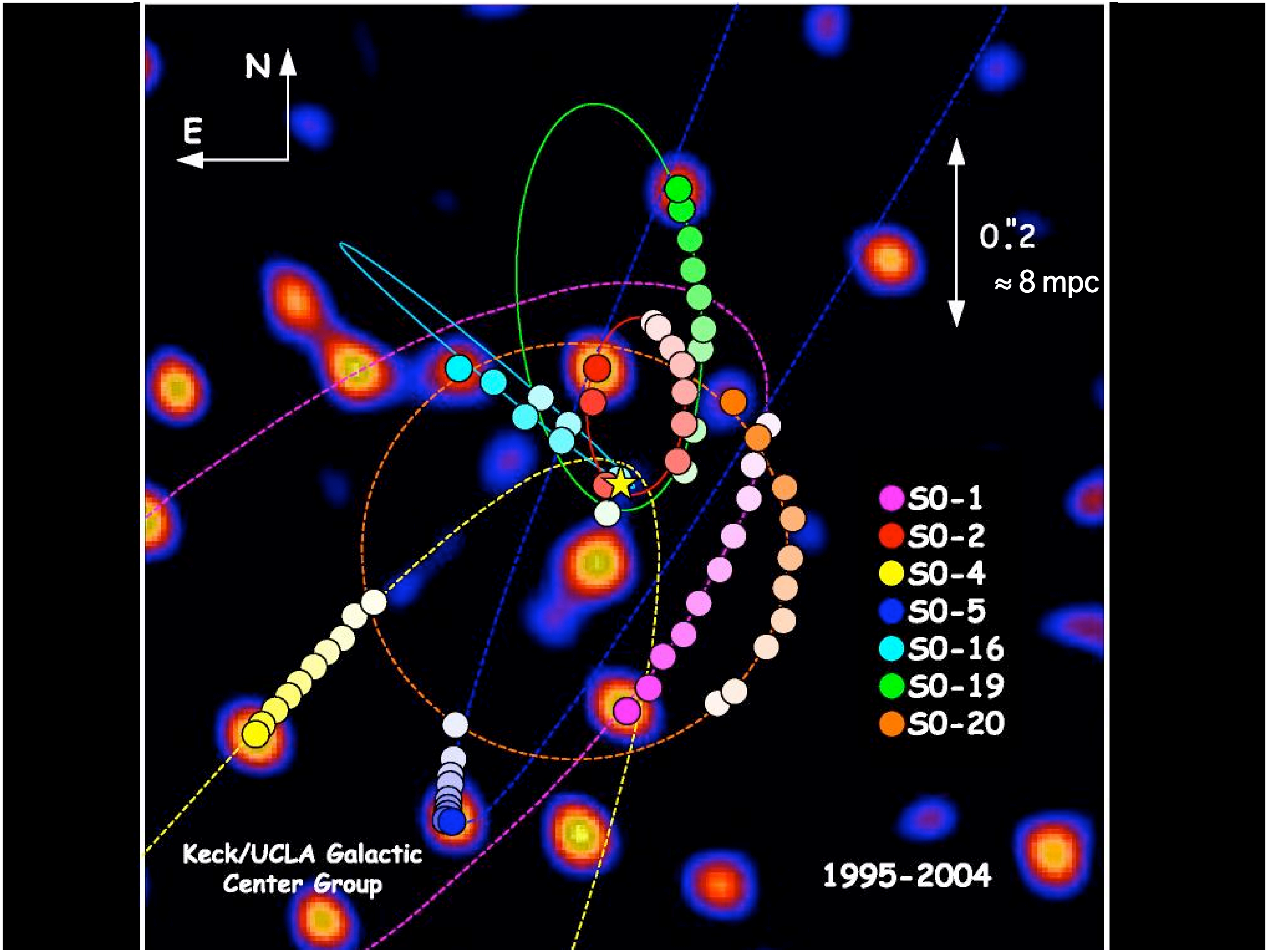
Constraints on IMBH at Galactic Center





Hansen & Milosavljevic 2003

Yu & Tremaine 2003

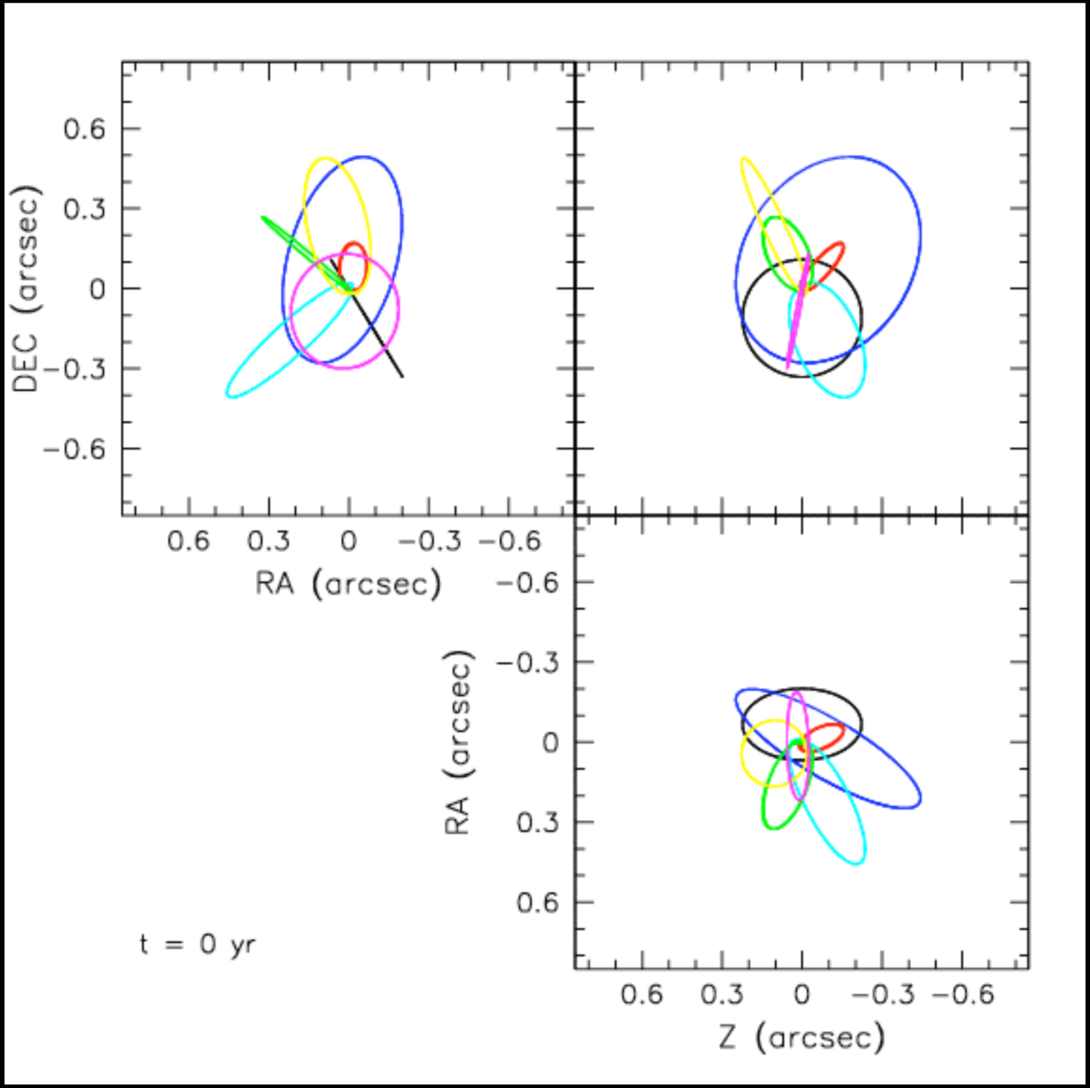

N
E
0."2
≈ 8 mpc
S0-1
S0-2
S0-4
S0-5
S0-16
S0-19
S0-20
Keck/UCLA Galactic
Center Group
1995-2004

IMBH + S-stars

$M_{IMBH} = 1000\ M_{sun}$

$a_{IMBH} = 10$ mpc

$e_{imbh} = 0.5$



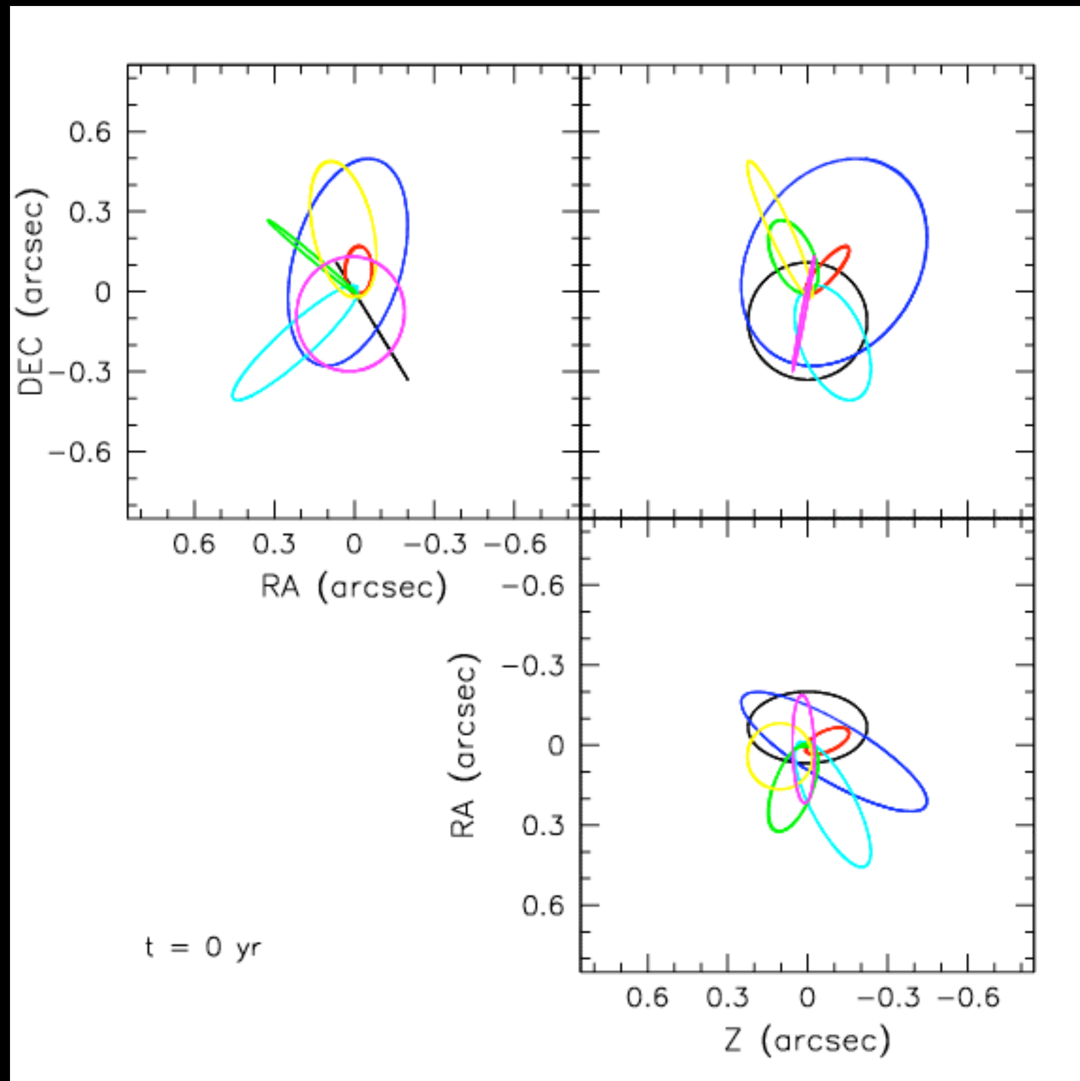
Gualandris & DM 2008

IMBH + S-stars

M_{IMBH} = 3000 M_{sun}

a_{IMBH} = 10 mpc

e_{imbh} = 0.5



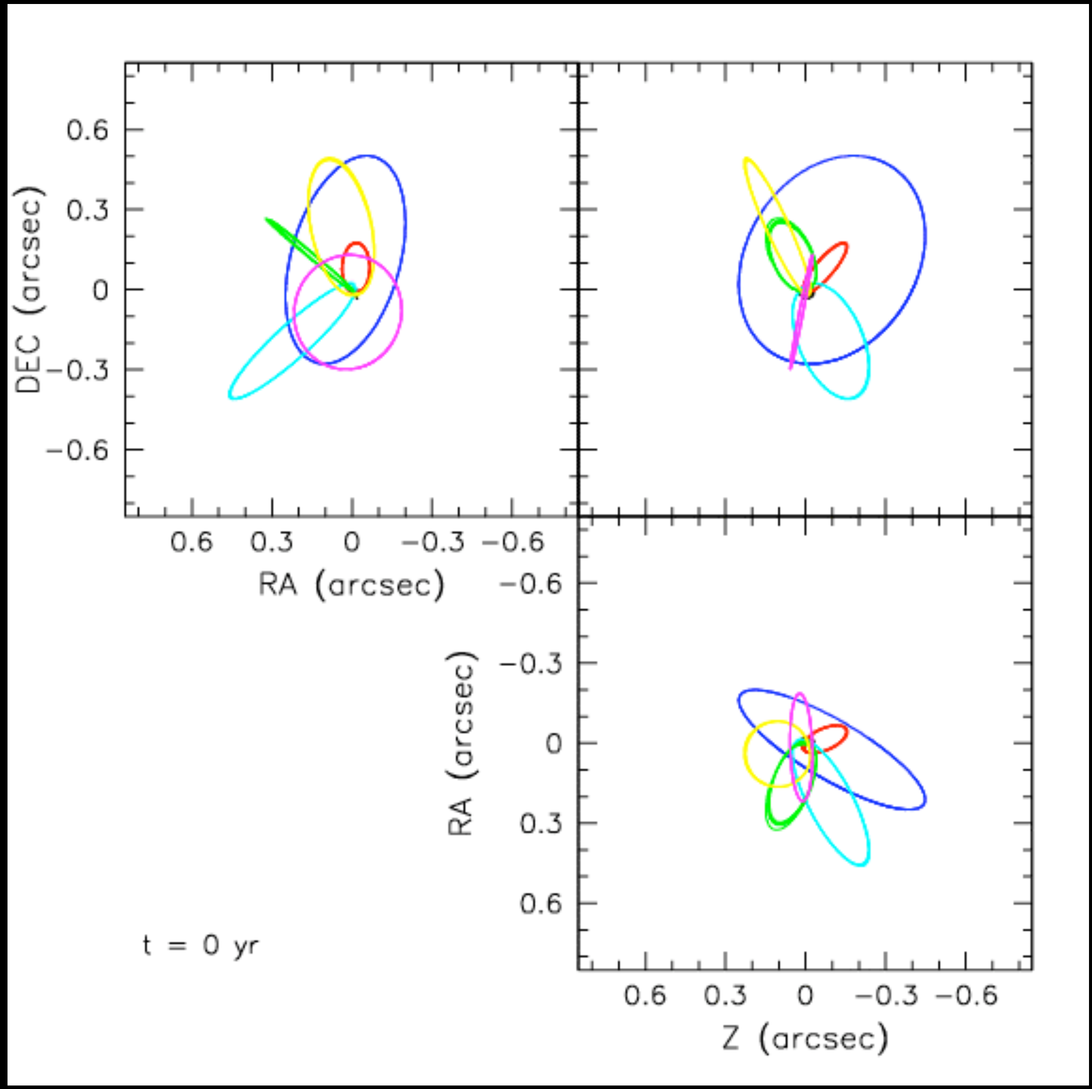
Gualandris & DM 2008

IMBH + S-stars

M_{IMBH} = 3000 M_{sun}

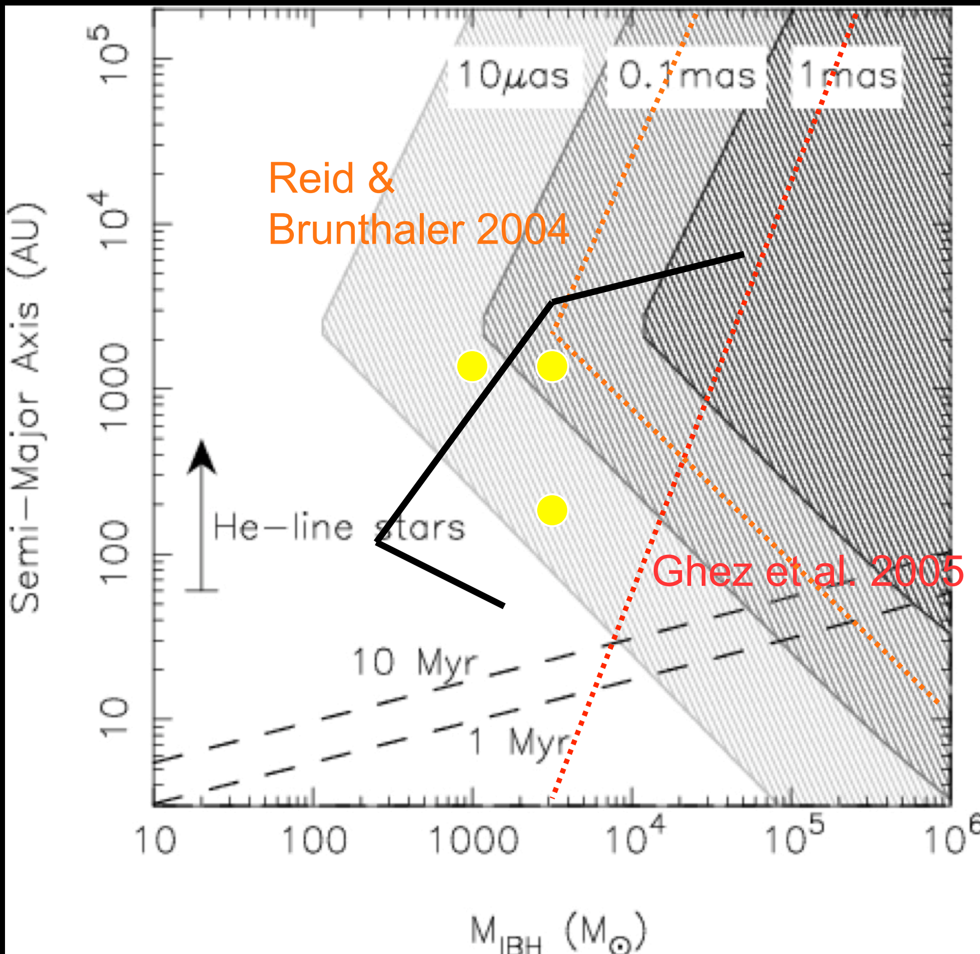
a_{IMBH} = 1.0 mpc

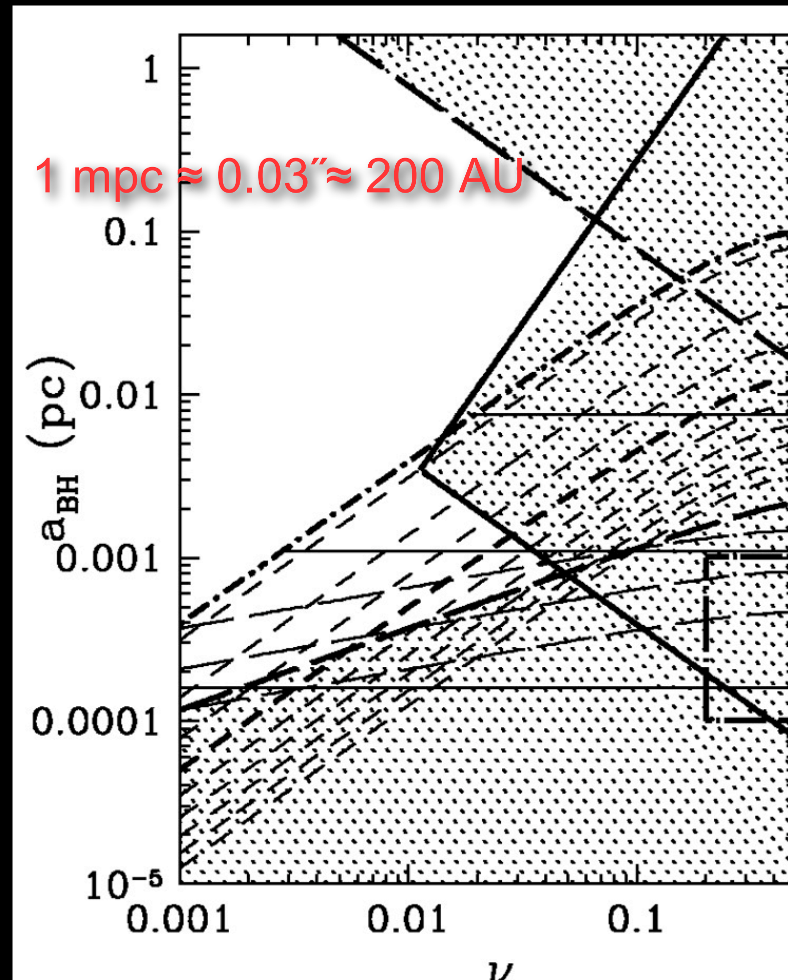
e_{imbh} = 0.5



Gualandris & DM 2008

Constraints on IMBH at Galactic Center

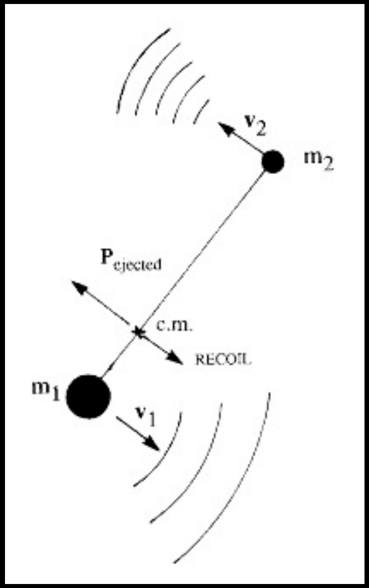




Hansen & Milosavljevic 2003

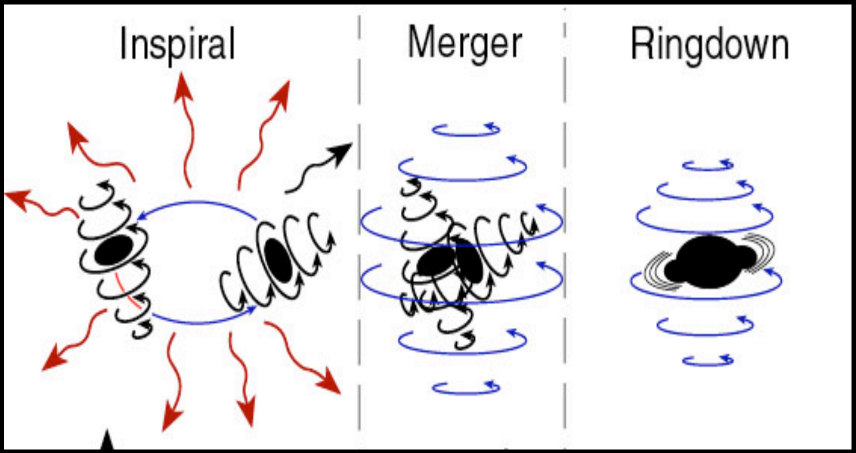
Yu & Tremaine 2003

❑ Kicking Them Out



Redmount & Rees (1989):

"…recoil speeds hundreds of times larger [than in the non-spinning case], hence larger than galactic escape velocities, might be obtained from the coalescence of rapidly rotating holes…This effect…might be largest for two holes of equal mass"



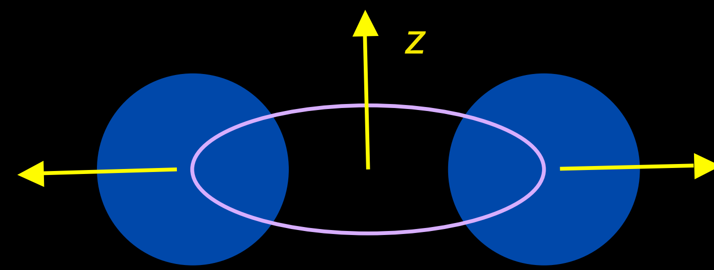
Rocket Effect

max. recoil when:

$M_1 = M_2$,

$a_1 = -a_2 = 1$,

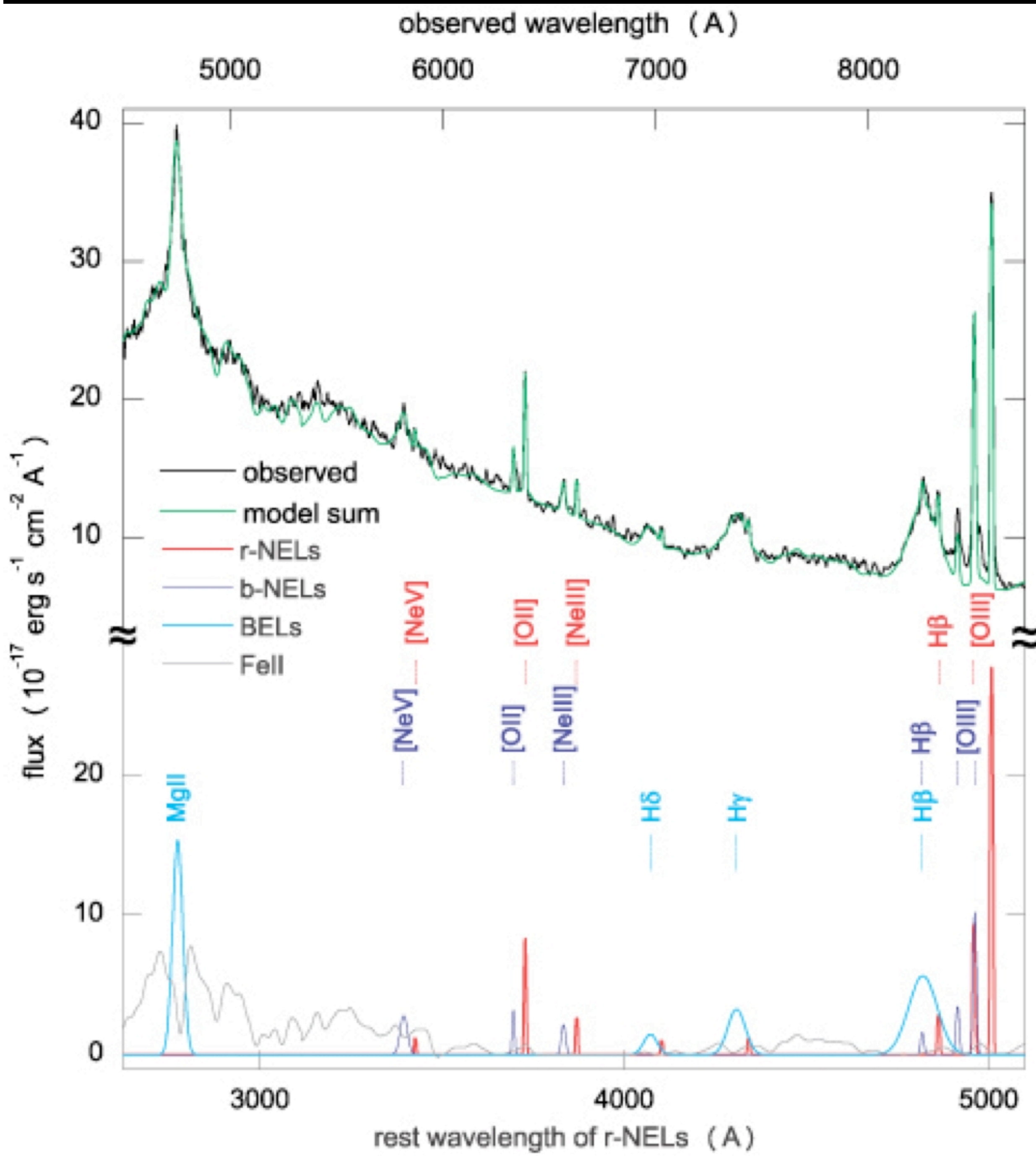
a parallel to orbital plane



$$V_z \approx 6 \times 10^4 \,\mathrm{km\ s^{-1}} \frac{q^2}{(1+q)^4}$$

$$(\, q \equiv M_2 / M_1)$$

Mass ratios as extreme as 5:1 can result in $V_{kick} > 1000$ km s^{-1}.



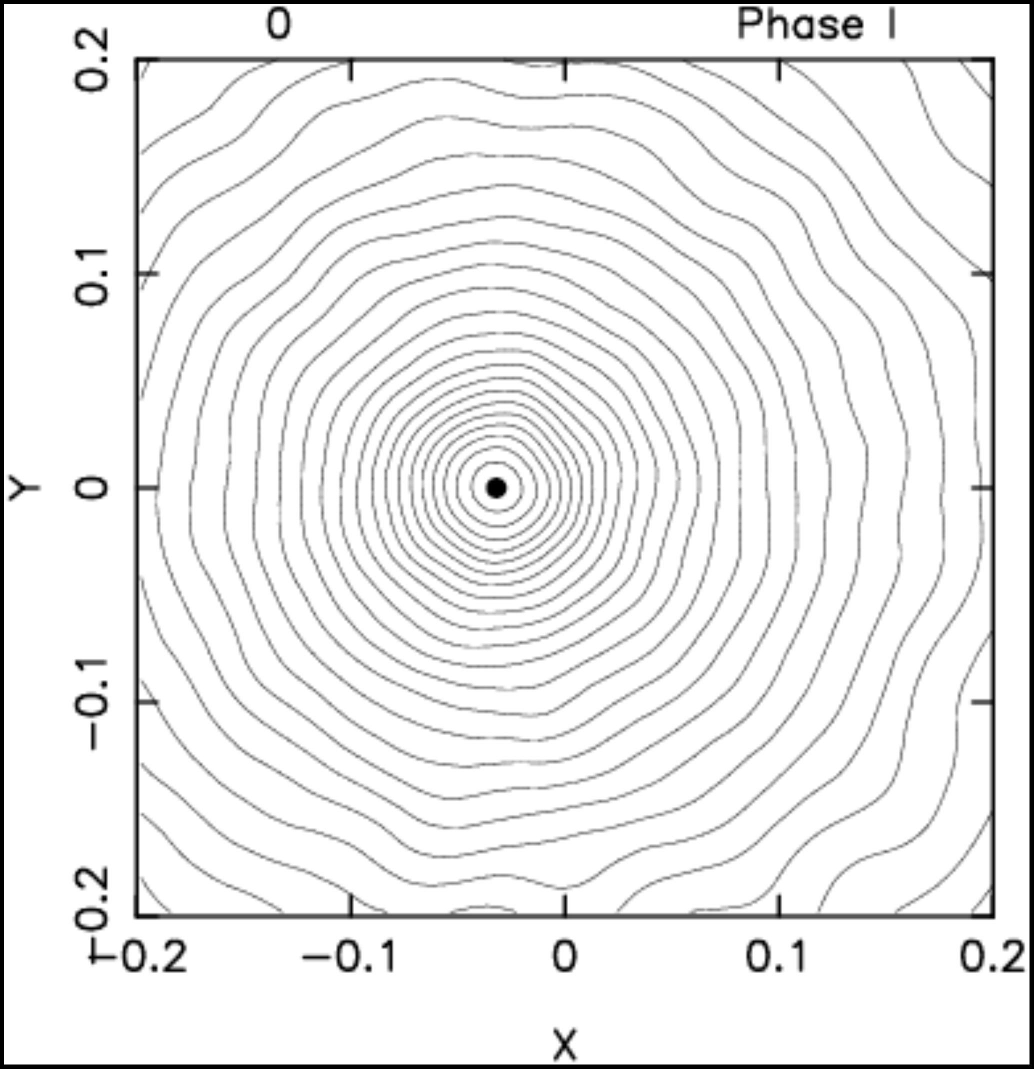
Komossa et al. (2008):

First compelling candidate for recoiling SMBH!

$\Delta V = 2650$ km s^{-1}

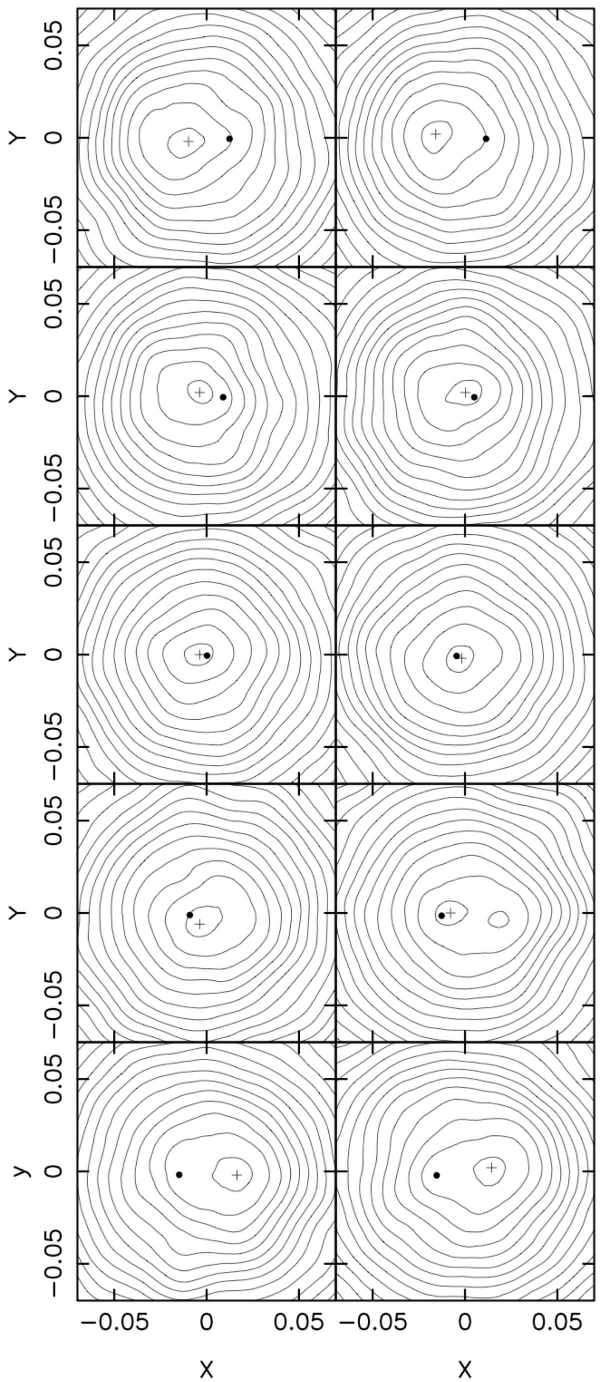
Kicked SMBH

$V_{kick} \approx (1/2)\ V_{escape}$

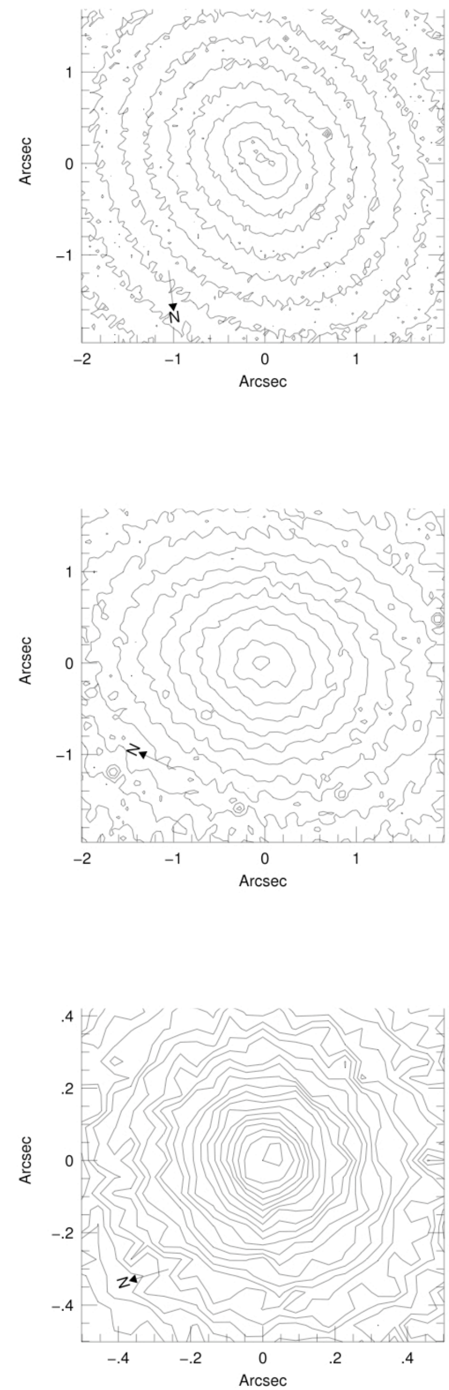


Gualandris & DM 2008

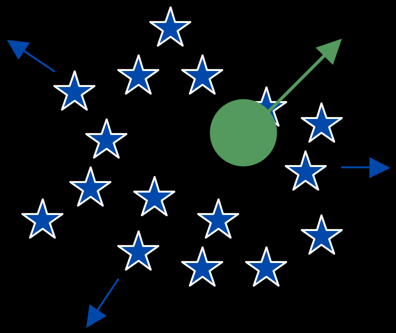
N-body oscillations



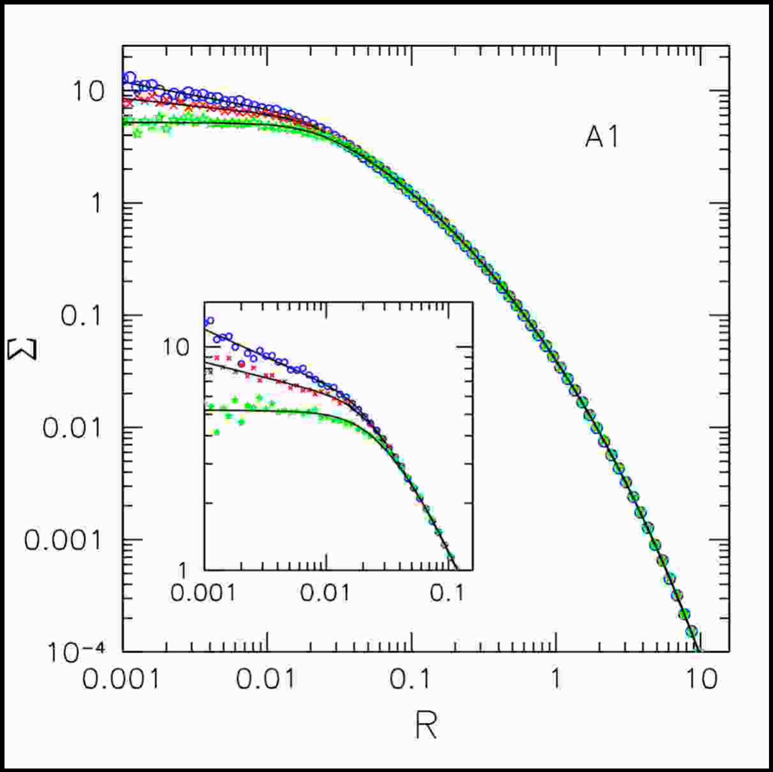
Offset/double nuclei

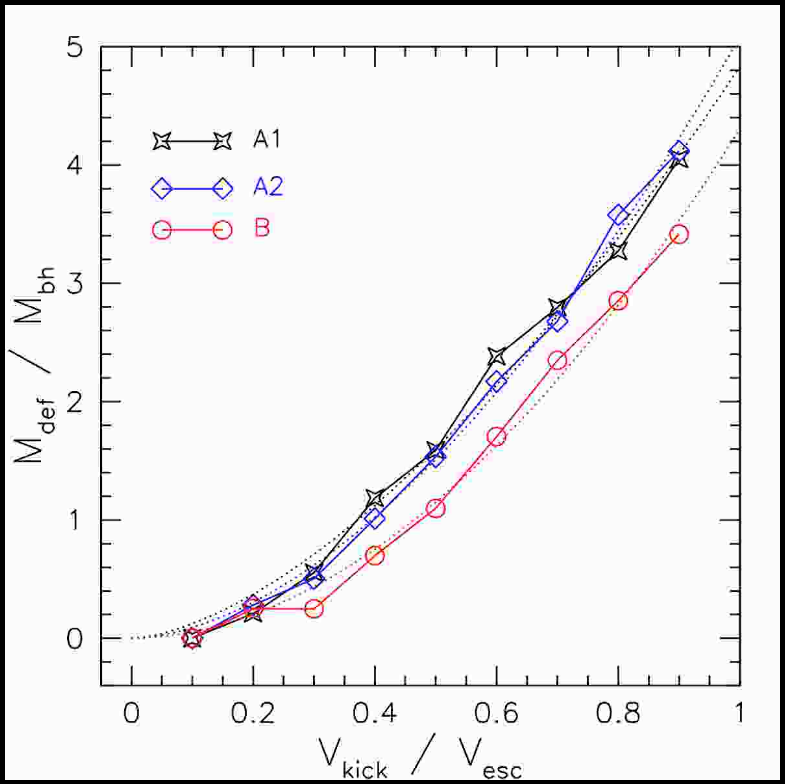


Lauer et al. 2005



Mass deficits produced by kicked SMBHs.





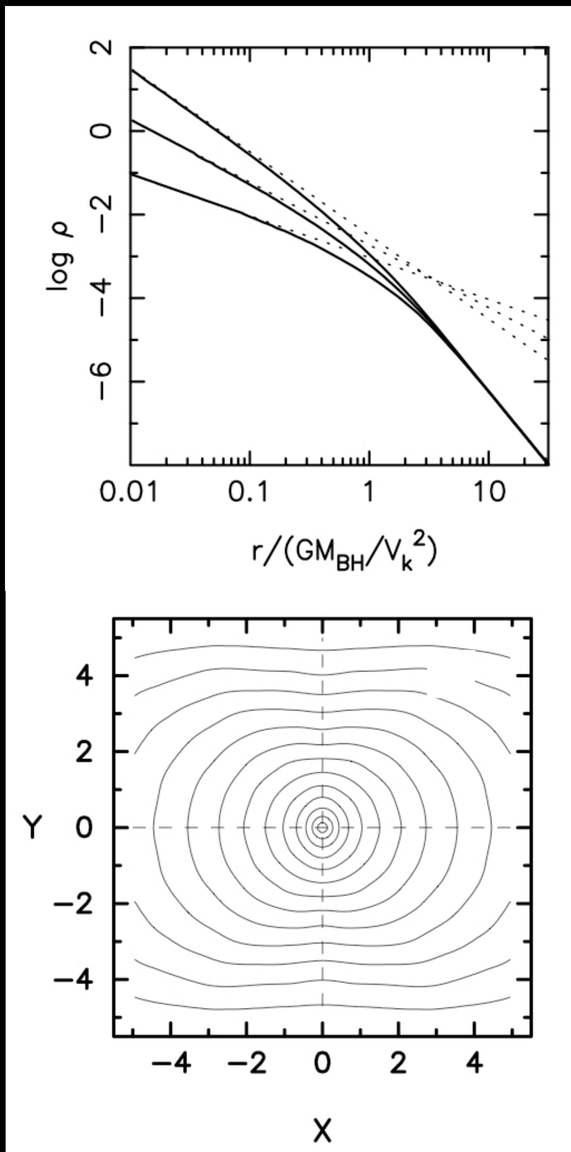
$$M_{def} \approx 5M_{\bullet}\left(V_{kick}/V_{esc}\right)^{1.75}$$

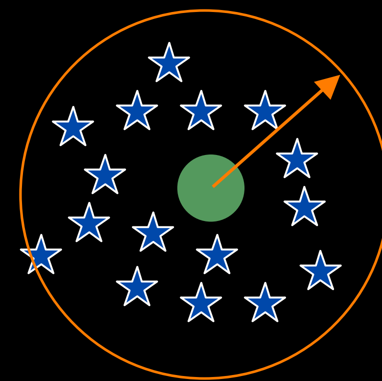
Observing Recoiling SMBHs

- Offset QSO
  (Kapoor 1976; Madau & Qataert 2004; Loeb 2007)
- Interrupted accretion
  (Liu et al. 2003; Milosavljevic & Phinney 2005)
- UV / IR / X-ray flares
  (Lippai et al. 2008; Shields & Bonning 2008; Schnittman & Krolik 2008)
- Features in the hot gas
  (Devecchi et al. 2008)

All of these require the presence of gas

Stars Bound to a Recoiling SMBH





Stars initially within a radius:

$$r_{kick} = GM_{\bullet} / V_{kick}^2$$

remain bound to the BH after the kick.

The total bound mass is:

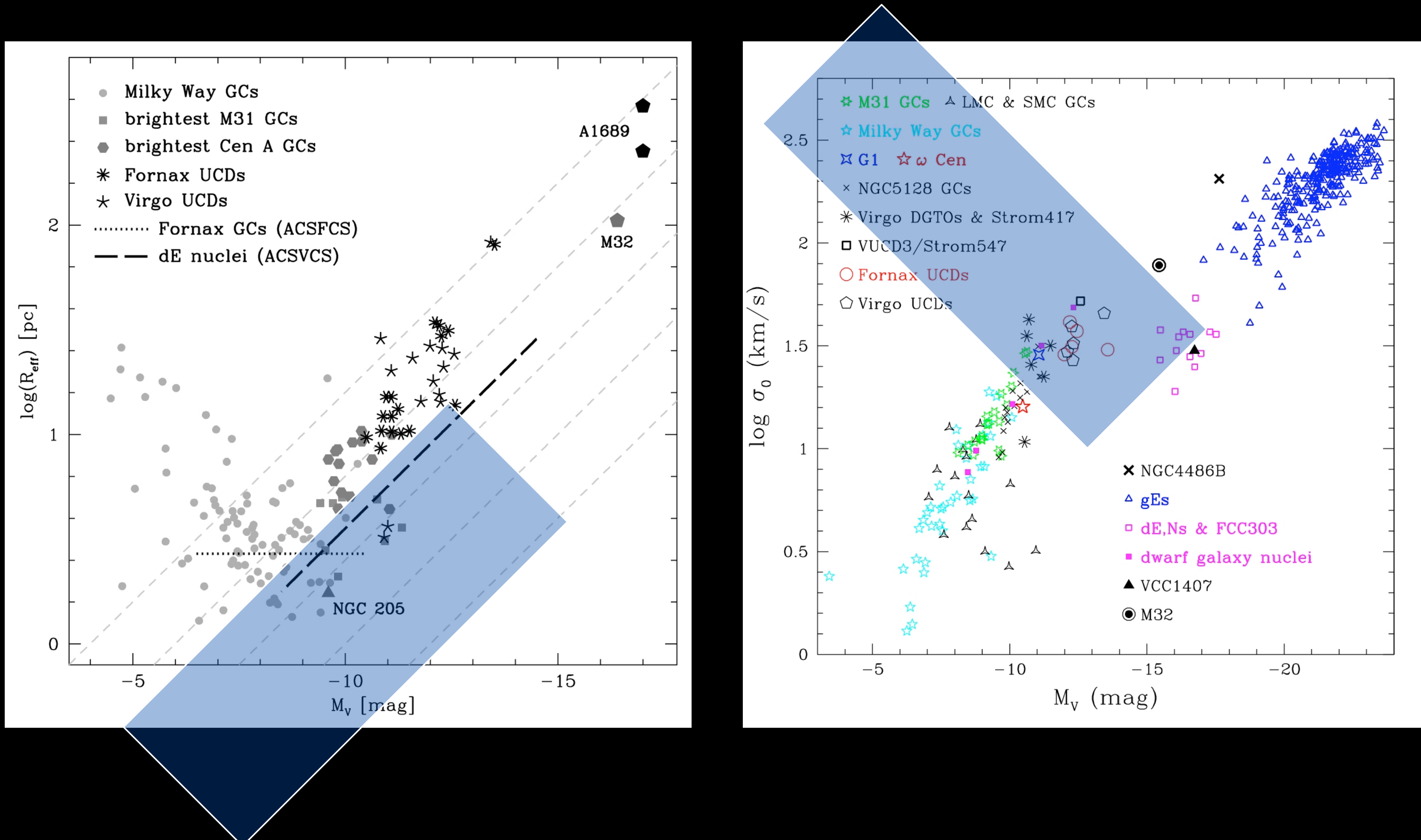
$$M_{bound} \approx \rho(r_{kick}) r_{kick}^3$$

$$\propto V_{kick}^{2(\gamma-3)} \qquad (\rho \propto r^{-\gamma})$$

and is of order 1% $M_{\bullet}$ for $V_{kick} = 10^3$ km s^{-1}.

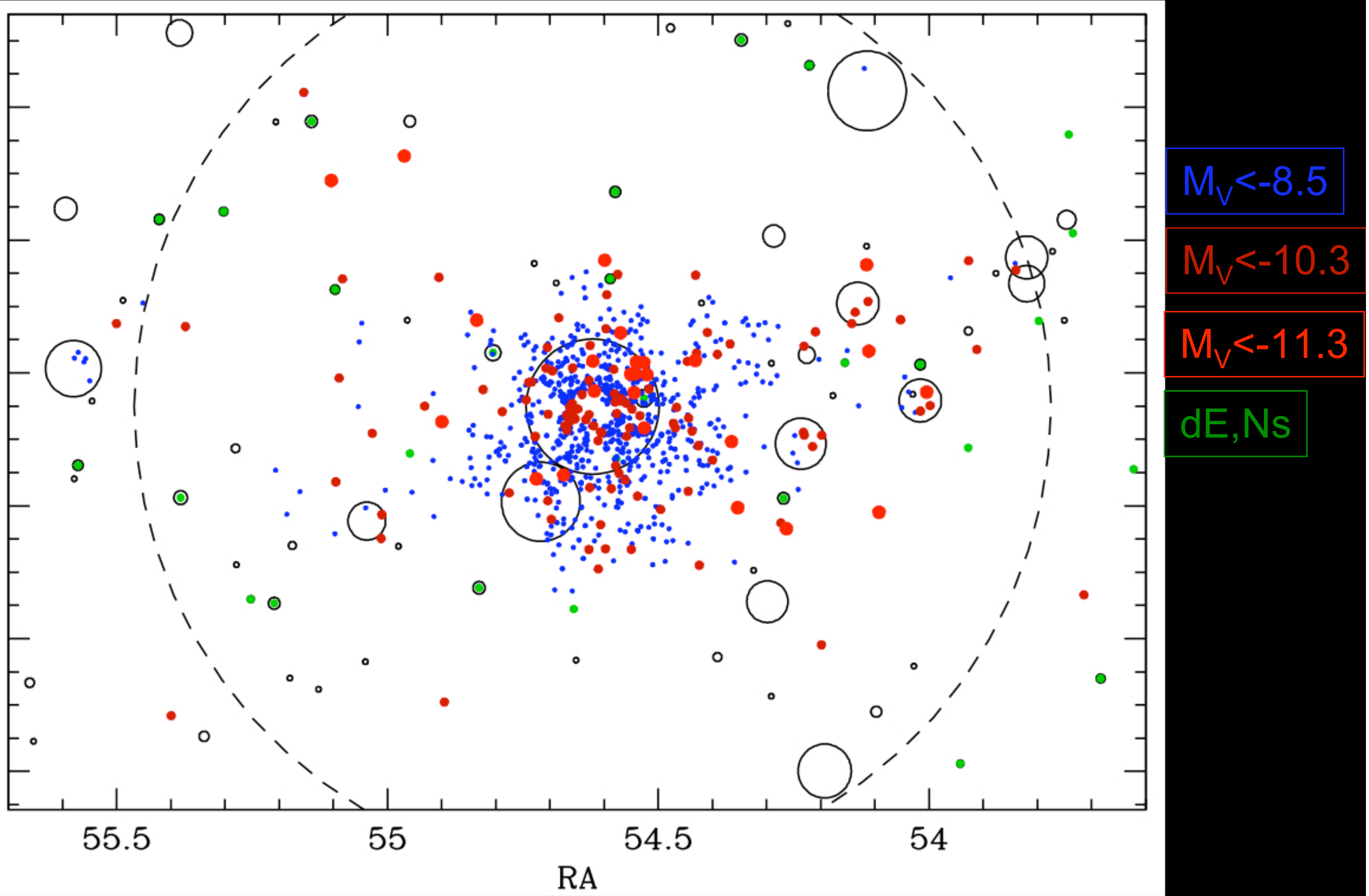
Komossa & DM 2008

“Hyper-Compact” Stellar Systems?



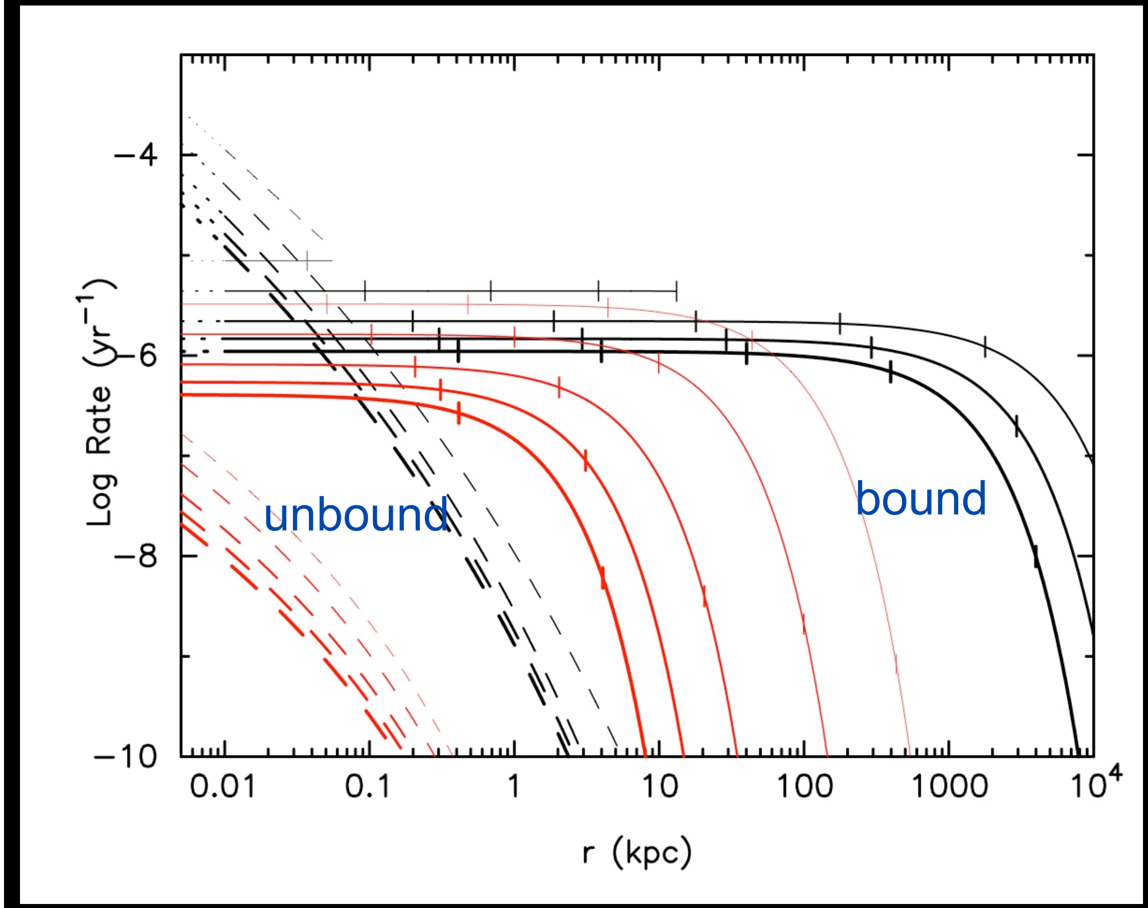
Komossa, DM & Schnittman 2008

Distribution of confirmed UCDs/GCs and NCs in Fornax



Hilker et al. 2008

Recoil Flares



A recoiling SMBH disrupts both bound, and unbound, stars.

Disruption rates are only moderately lower than those of nuclear SMBHs.

Komossa & DM 2008

Signatures Associated with Stars Bound to Recoiling SMBHs

Komossa & DM 2008

- Episodic X-ray emission from accretion due to stellar mass loss
- Intergalactic / Intracluster supernovae
- Feedback trails
  E.g. ISM cavities due to radio jets *(Wong et al. 2007);*
  excitation of local gas; etc.

Because SMBH / galaxy core oscillations are so long-lived, any signatures associated with AGN could appear off-center, even long after a kick.

END