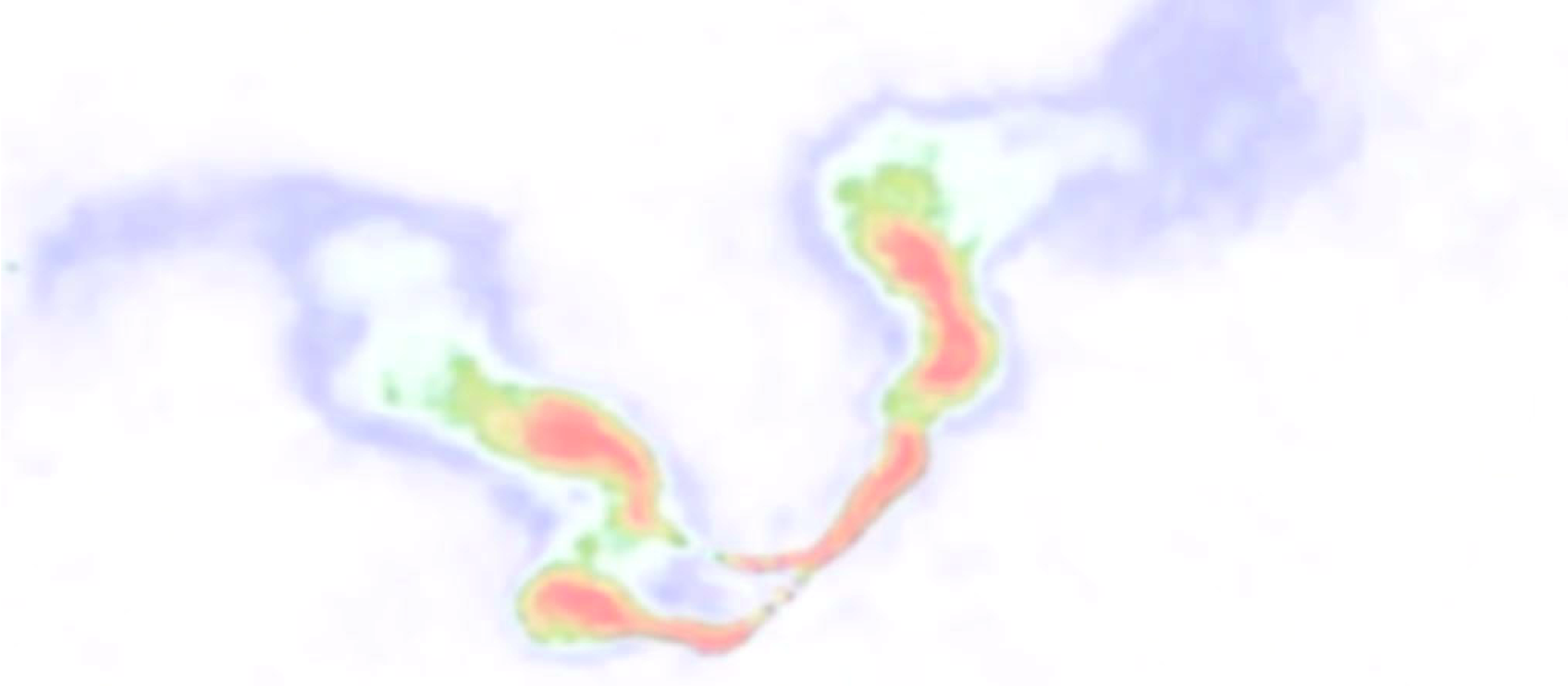
Life and adventures of binary supermassive black holes



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Plan of the talk

- Why binary black holes?
- Evolutionary stages:
  - galaxy merger and dynamical friction: the first contact
  - king of the hill: the binary hardens
  - the lean years: the final parsec problem
  - runaway speedup: gravitational waves kick in
  - anschluss
- Life after merger
- Perspectives of detection

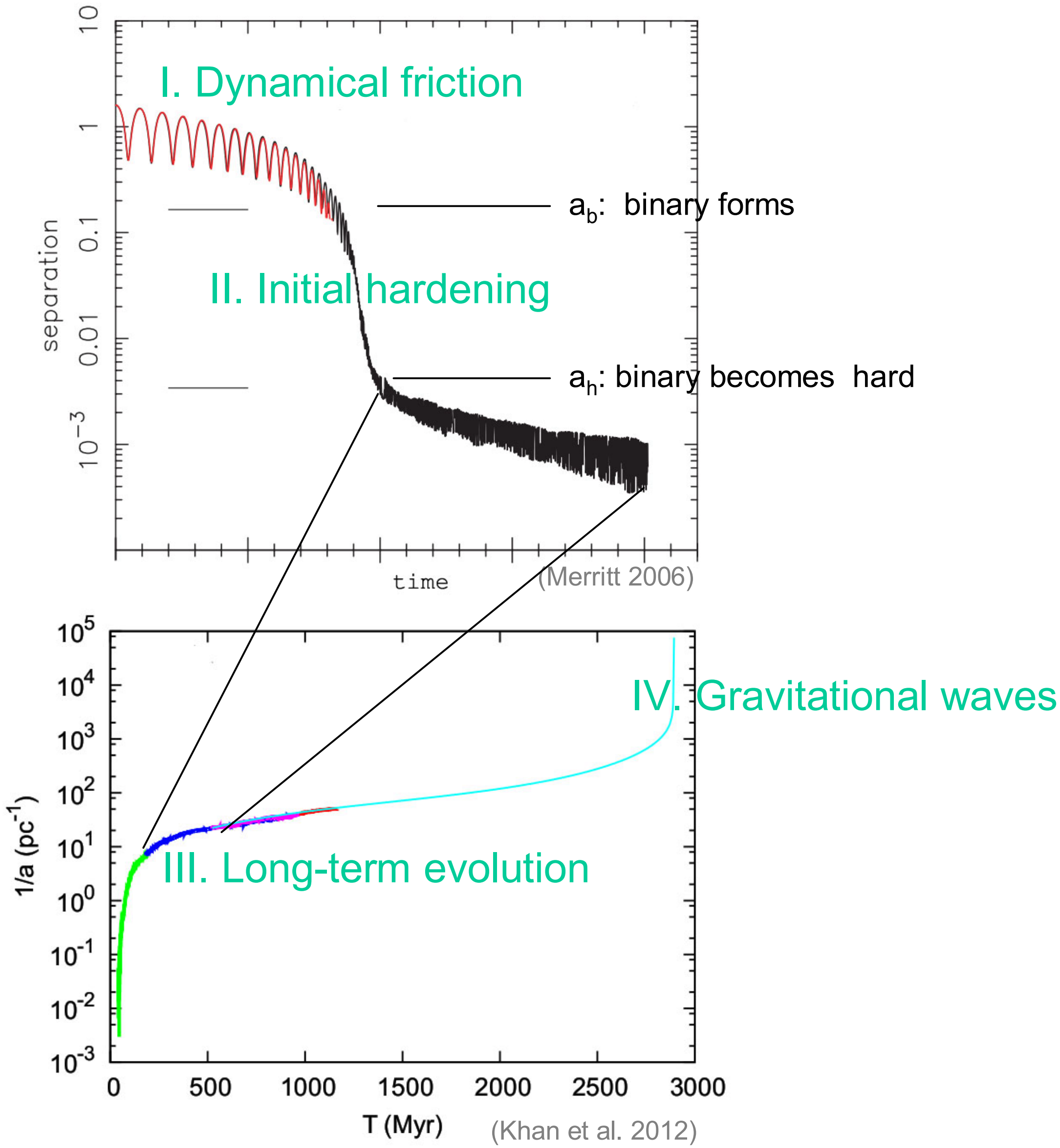
Origin of binary supermassive black holes

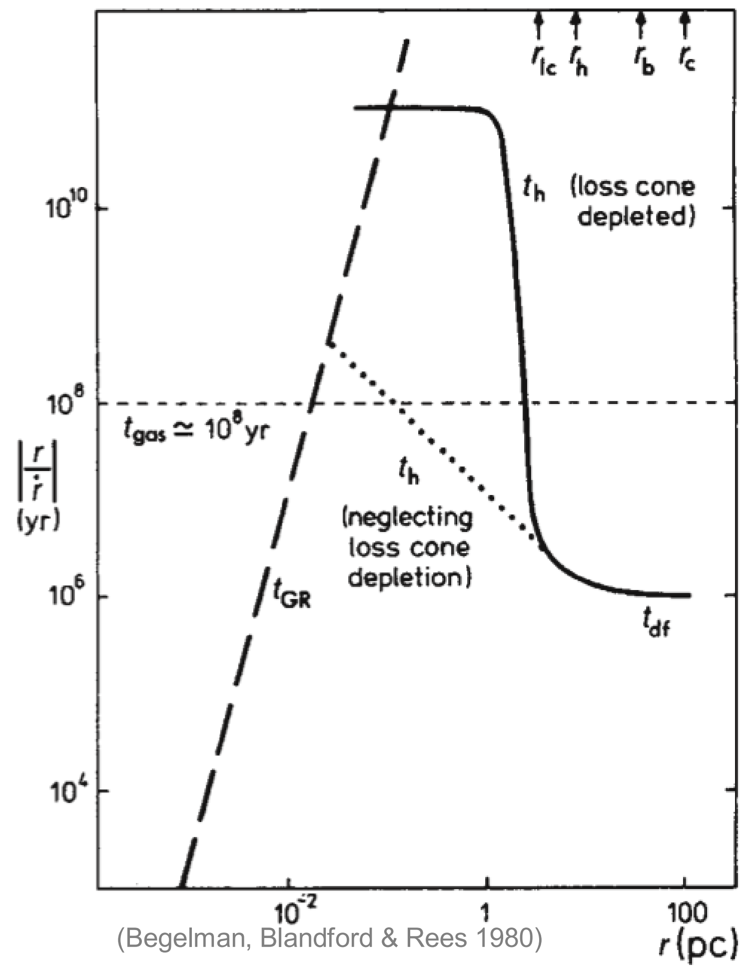
- Most galaxies are believed to host central massive black holes
- In the hierarchical merger paradigm, galaxies in the Universe have typically 1-3 major and multiple minor mergers in their lifetime
- Every such merger brings two central black holes from parent galaxies together to form a binary system
- We don't see much evidence for widespread binary SMBH (to say the least) – therefore they need to merge rather efficiently
- Merger is a natural way of producing huge black holes from smaller seeds

Evolutionary track of binary SMBH

- Merger of two galaxies creates a common nucleus; dynamical friction rapidly brings two black holes together to form a binary *(a~10 pc)*
- Three-body interaction of binary with stars of galactic nucleus ejects most stars from the vicinity of the binary by the slingshot effect; a “mass deficit” is created and the binary becomes “hard” *(a~1 pc)*
- The binary further shrinks by scattering off stars that continue to flow into the “loss cone”, due to two-body relaxation or other factors
- As the separation reaches $\sim 10^{-2}$ *pc*, gravitational wave emission becomes the dominant mechanism that carries away the energy
- Reaching a few Schwarzschild radii *($\sim 10^{-5}$ pc)*, the binary finally merges

Evolution timescales





(Begelman, Blandford & Rees 1980)

Evolution timescales

- Dynamical friction timescale:

$$t_{\rm DF} \sim 10^6 \text{ yr} \left(\frac{r}{100 \text{ pc}}\right)^2 \left(\frac{\sigma}{200 \text{ km/s}}\right) \left(\frac{m_2}{10^8 \, M_\odot}\right)^{-1} \left(\frac{\ln \Lambda}{15}\right)^{-1}$$

- A binary is called hard if its orbital velocity exceeds that of the field stars, or the separation is less than a_h:

$$a_h = \frac{G\mu}{\sigma^2} \approx 2.7 \text{pc} (1+q)^{-1} \left(\frac{m_2}{10^8 \, M_\odot}\right) \left(\frac{\sigma}{200 \text{km/s}}\right)^{-2}, \qquad \mu \equiv \frac{m_1 m_2}{m_1 + m_2}, \; q \equiv \frac{m_2}{m_1}$$

- The timescale for coalescence due to GW emission is (Peters 1964)

$$t_{\rm GW} = \frac{5}{256\, F(e)} \frac{c^5}{G^3} \frac{a^4}{\mu (m_1 + m_2)^2} \approx 7 \times 10^8 \text{yr} \frac{q^3}{(1+q)^6} \left(\frac{m_1 + m_2}{10^8 \, M_\odot}\right)^{-0.6} \left(\frac{a}{10^{-2} a_h}\right)^4$$

$$F(e) \equiv (1 - e^2)^{7/2} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right)$$

Gravitational slingshot and binary hardening

A star passing at a distance $\lesssim 3a$ from the binary will experience a complex 3-body interaction which results in ejection of the star with velocity $v_{\rm ej} \sim \sqrt{\frac{m_1 m_2}{(m_1+m_2)^2}}\, v_{\rm bin}$.

These stars carry away energy and angular momentum from the binary, so that its separation decreases:

$$\frac{d}{dt}\left(\frac{1}{a}\right) \approx 16 \frac{G\,\rho}{\sigma}$$

Thus, if density of field stars ρ remains constant, the binary hardens with a constant rate.

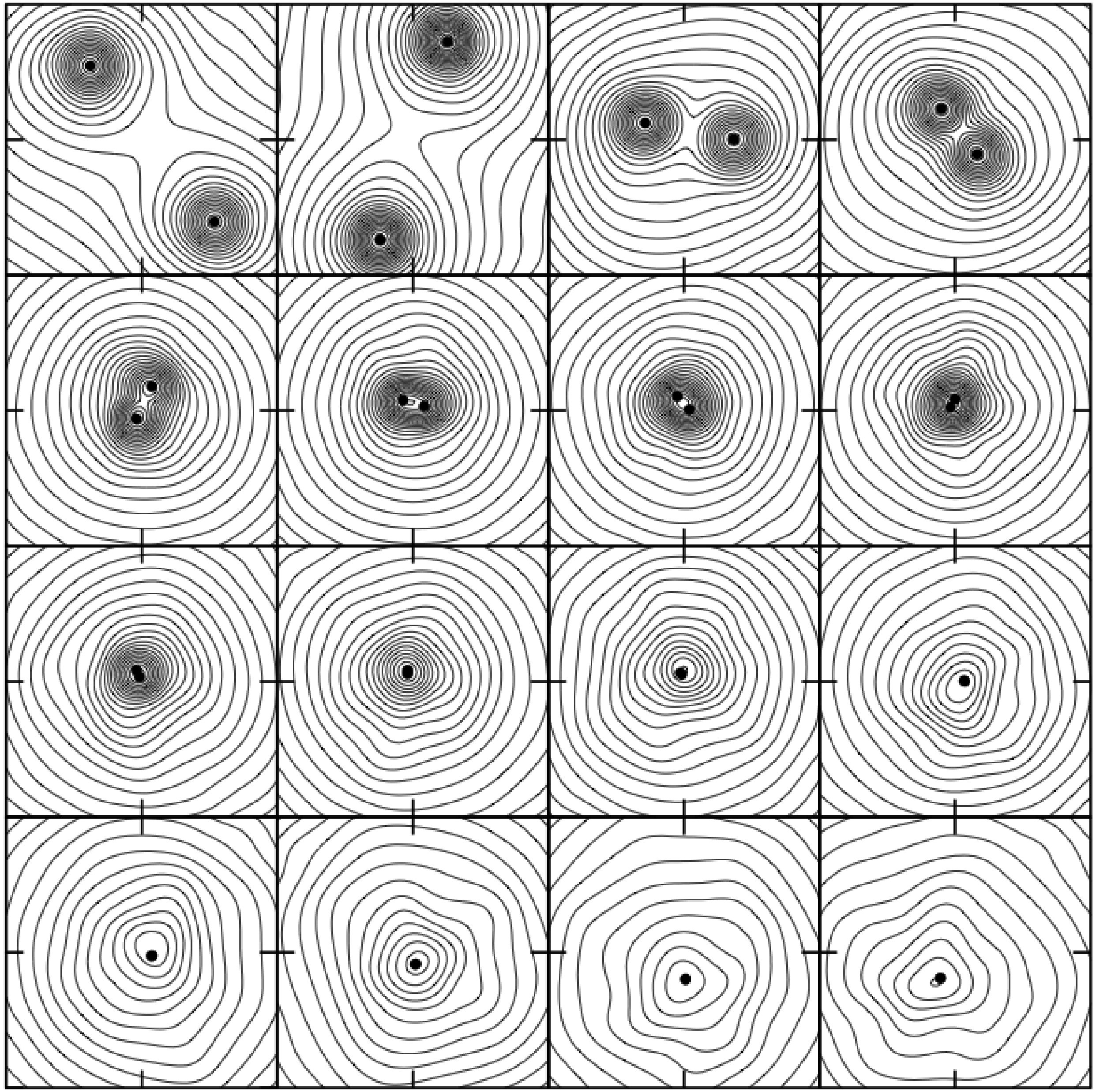
However, the reservoir of low angular momentum stars which can be ejected is finite and may be depleted quickly, so that the binary stalls at a radius $a_{\rm stall} \sim (0.1 - 0.4) a_h$.

Evolution of density profile in the merger

Dynamical friction

Bound pair

Ejection of stars via
gravitational slingshot



(Milosavljevic & Merritt 2001)

“Mass deficit” in observations of galactic nuclei

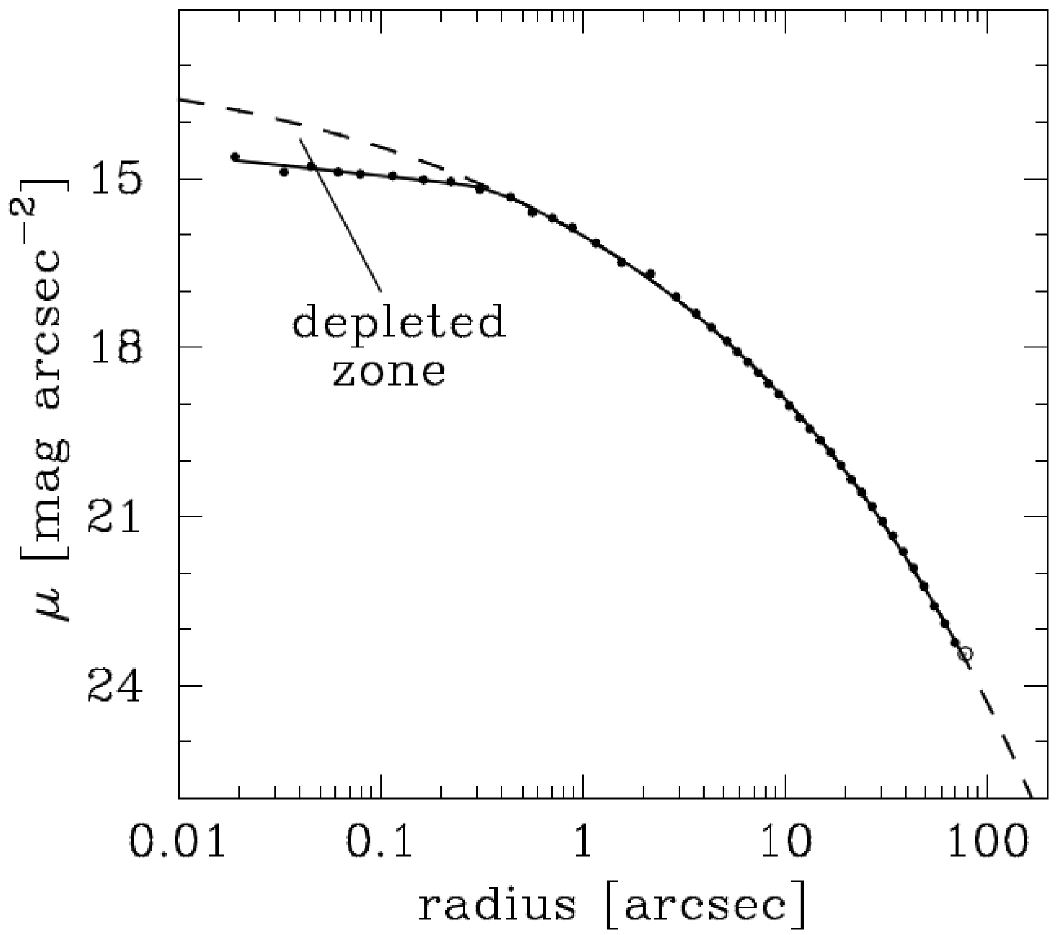


Figure 11: *Observed surface brightness profile of NGC 3348. The dashed line is the best-fitting Sersic model to the large-radius data. Solid line is the fit of an alternative model, the "core-Sersic" model, which fits both the inner and outer data well. The mass deficit is illustrated by the area designated "depleted zone" and the corresponding mass is roughly* $3 \times 10^8 M_\odot$ [Graham 2004]

Loss cone dynamics

The region of phase space with $L^2 < L_{\rm LC}^2 \equiv 2G(m_1+m_2)\,a$ is called the loss cone.
Gravitational slingshot eliminates stars from the loss cone in one orbital period.
The crucial parameter for the evolution is the timescale for repopulation of the loss cone.
In the absence of other processes, the repopulation time is

$$T_{\rm rep} \sim T_{\rm rel}\,\frac{L_{\rm LC}^2}{L_{\rm circ}^2}\ , \text{ where } T_{\rm rel} = \frac{0.34\,\sigma 3}{G^2\,m_\star\,\rho_\star\,\ln\Lambda} \text{ is the relaxation time.}$$

If $T_{\rm rep} \lesssim T_{\rm orb}$, the loss cone is full (refilled faster than orbital period).
In real galaxies, however, the opposite regime applies – the empty loss cone.
In this case the hardening rate $H \equiv \dfrac{d}{dt}(a^{-1}) \simeq \dfrac{T_{\rm orb}}{T_{\rm rep}} H_{\rm full}$.

Relaxation is too slow for an efficient repopulation of the loss cone:
in the absense of other processes the binary would not merge in a Hubble time.

This is the "final parsec problem" [Milosavljević&Merritt 2003]

Possible ways to enhance the loss cone repopulation

- Brownian motion of the binary (enables interaction with larger number of stars) [Milosavljevic&Merritt 2001; Chatterjee+ 2003]
- Non-stationary solution for the loss cone repopulation rate [Milosavljevic&Merritt 2003]
- Secondary slingshot (stars may interact with binary several times) [MM'03]
- Gas physics – under special circumstances [Lodato+ 2009]
- Perturbations to the stellar distribution arising from transient events (such as infall of large molecular clouds, additional minor mergers, …)
- Effects of non-sphericity on the orbits of stars in the nucleus [Berczik+ 2006; Khan+ 2011; Preto+ 2011; Vasiliev+ 2014]

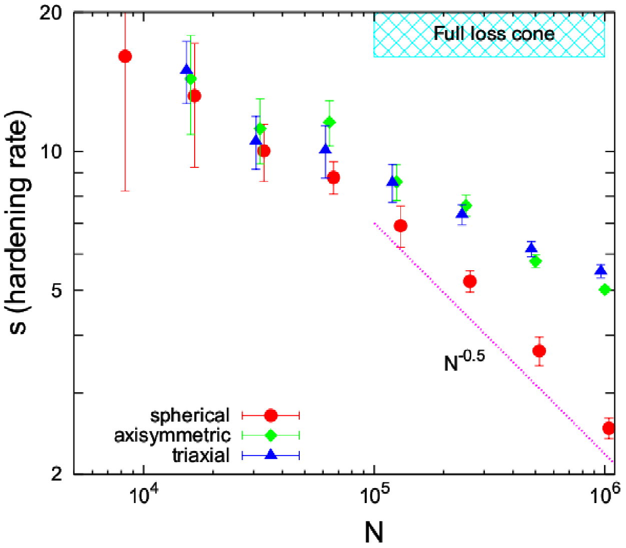
Is the final-parsec problem solved?

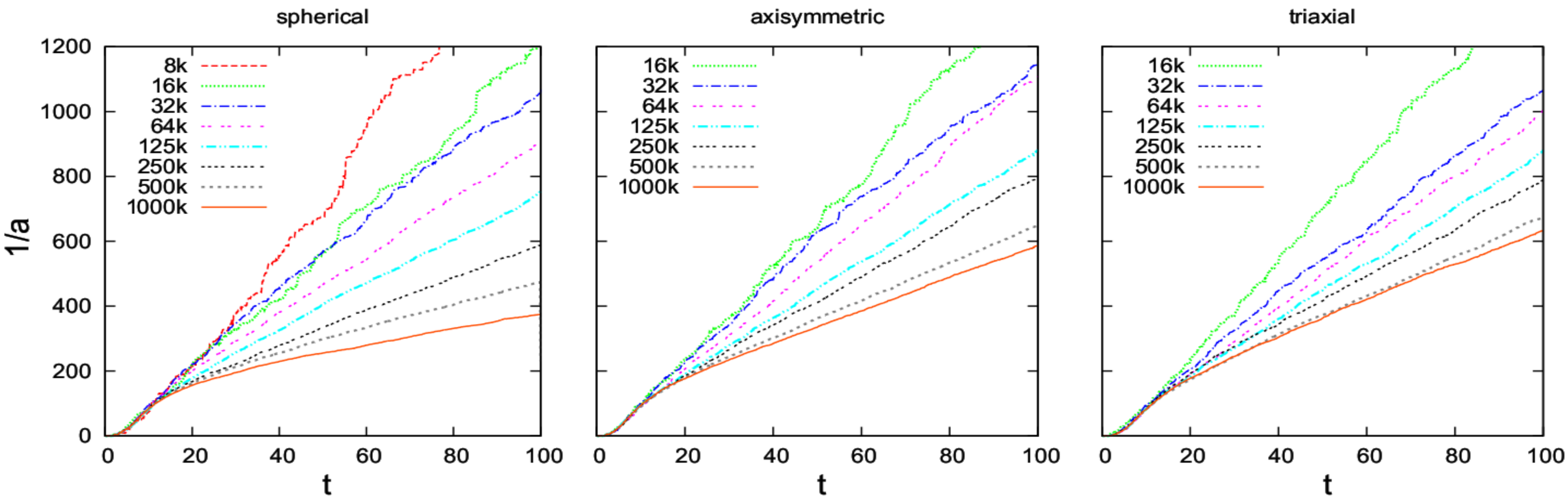
(by assuming non-spherical shape of galactic nucleus)

We have performed simulations of binary black hole evolution in three sets of models: spherical, axisymmetric and triaxial.

In all three cases the hardening rate appears to drop with **N**, although it is factor of 2-3 larger for non-spherical models for the largest N in our runs.

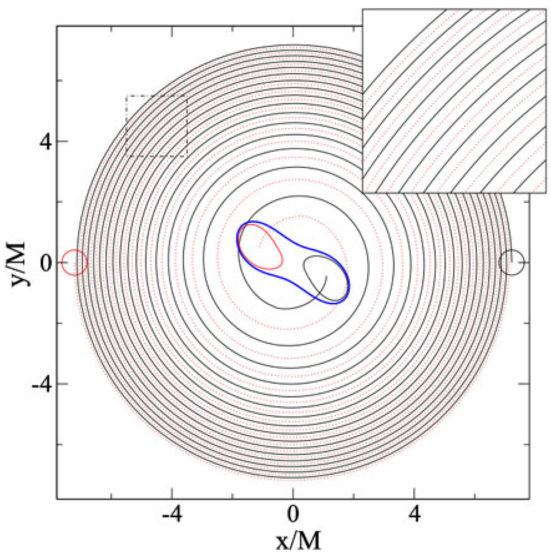
Moreover, this rate is several times **lower** than the rate that would be expected in the full loss cone regime.





Gravitational waves and the way towards merger

- As the separation drops below *~10^{-2} pc*, emission of gravitational waves becomes the dominant mechanism that brings the black holes together
- The binary eccentricity decreases to a fairly small value (<0.1)
- Spin-orbit interaction changes the orientation of binary plane and directions of black hole spins
- Reaching a few Schwarzschild radii *(~10^{-5} pc)*, the binary finally merges, producing a burst of gravitational radiation (anisotropically) and possibly an electromagnetic counterpart



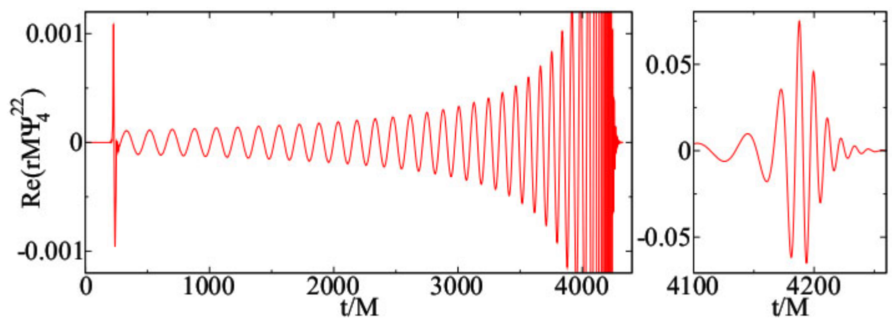
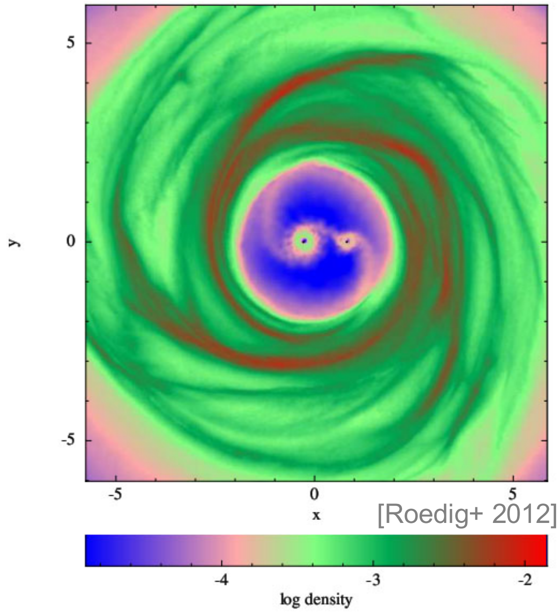


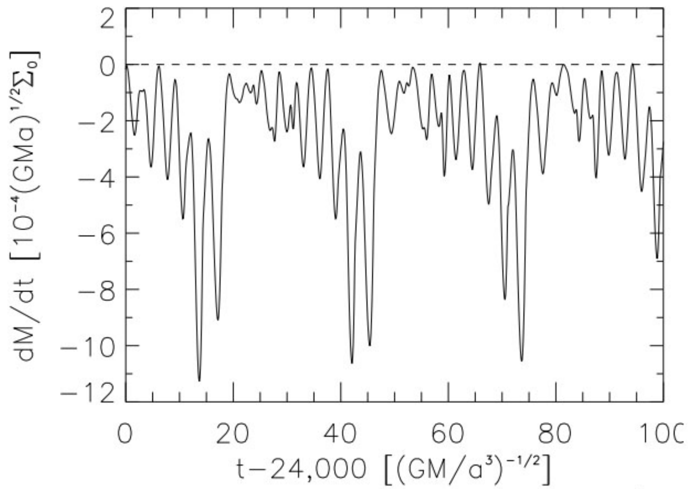
FIG. 14 Gravitational waveforms from the Caltech/Cornell merger simulation seen in Fig. 13 showing the $\ell = 2$, $m = 2$ component of $\mathrm{Re}(r\Psi_4)$ (Scheel *et al.*, 2009). The left panel shows a zoom of the inspiral waveform, and the right panel a zoom of the merger and ringdown.

Electromagnetic counterpart of a merger



[Roedig+ 2012]

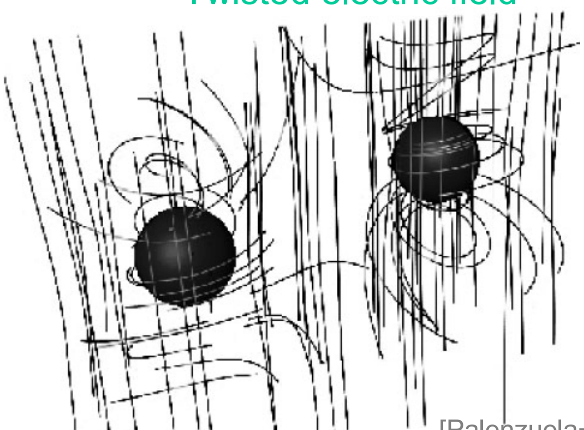
Gaps and spiral waves in accretion disc



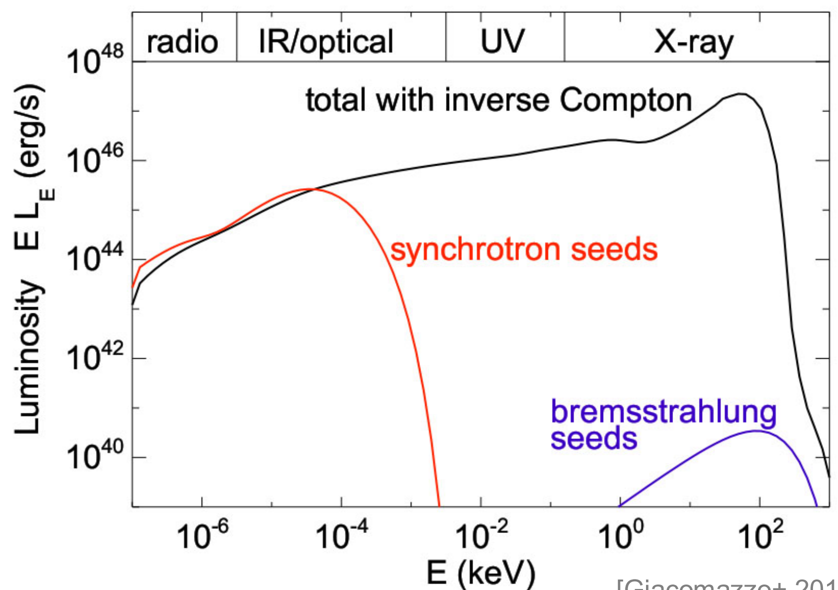
[MacFadyen&Milosavljević 2008]

intermittent accretion

Twisted electric field



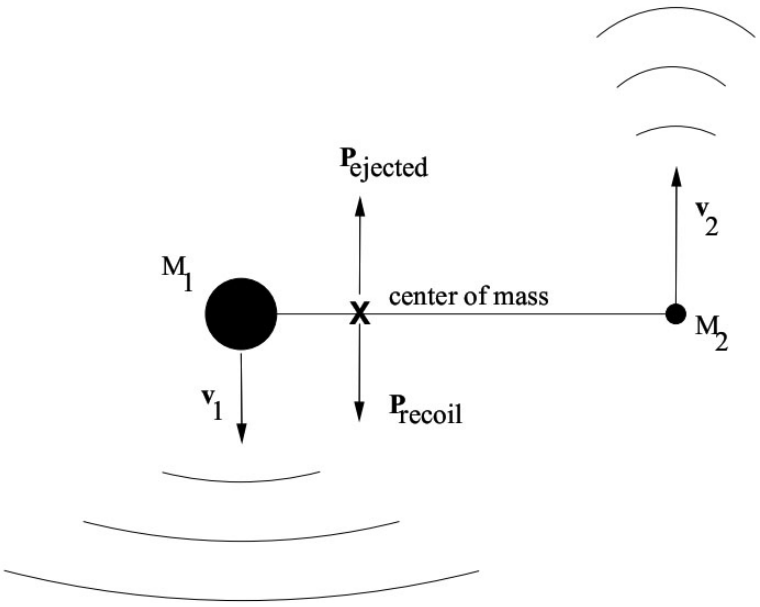
[Palenzuela+ 2009]



[Giacomazzo+ 2012]

Gravitational recoil

- Gravitational waves are emitted anisotropically and carry away linear momentum, thus the merged black hole receives a “kick” velocity of several hundred (in case of non-spinning BHs) or even up to several thousand (for specially aligned spin/orbit configurations) km/s
- The kick velocity may exceed the escape velocity from smaller galaxies, or at least push the merged black hole out of galactic nucleus
- The black hole may carry away a “hypercompact stellar cluster” [Merritt+ 2009]



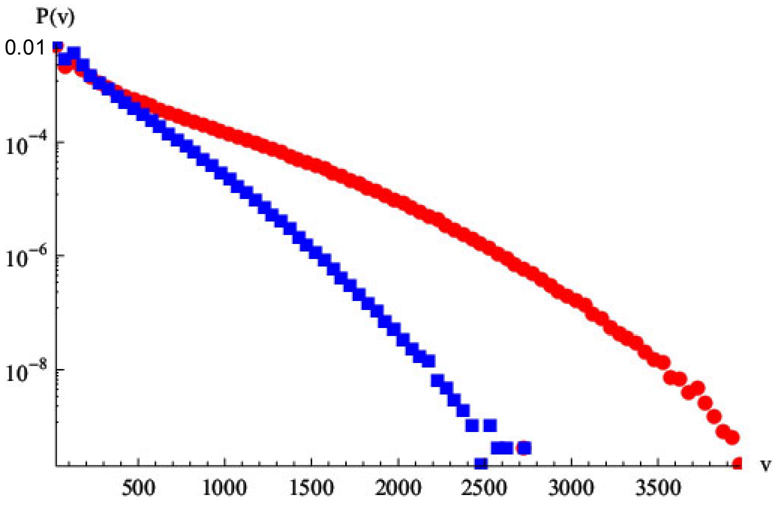
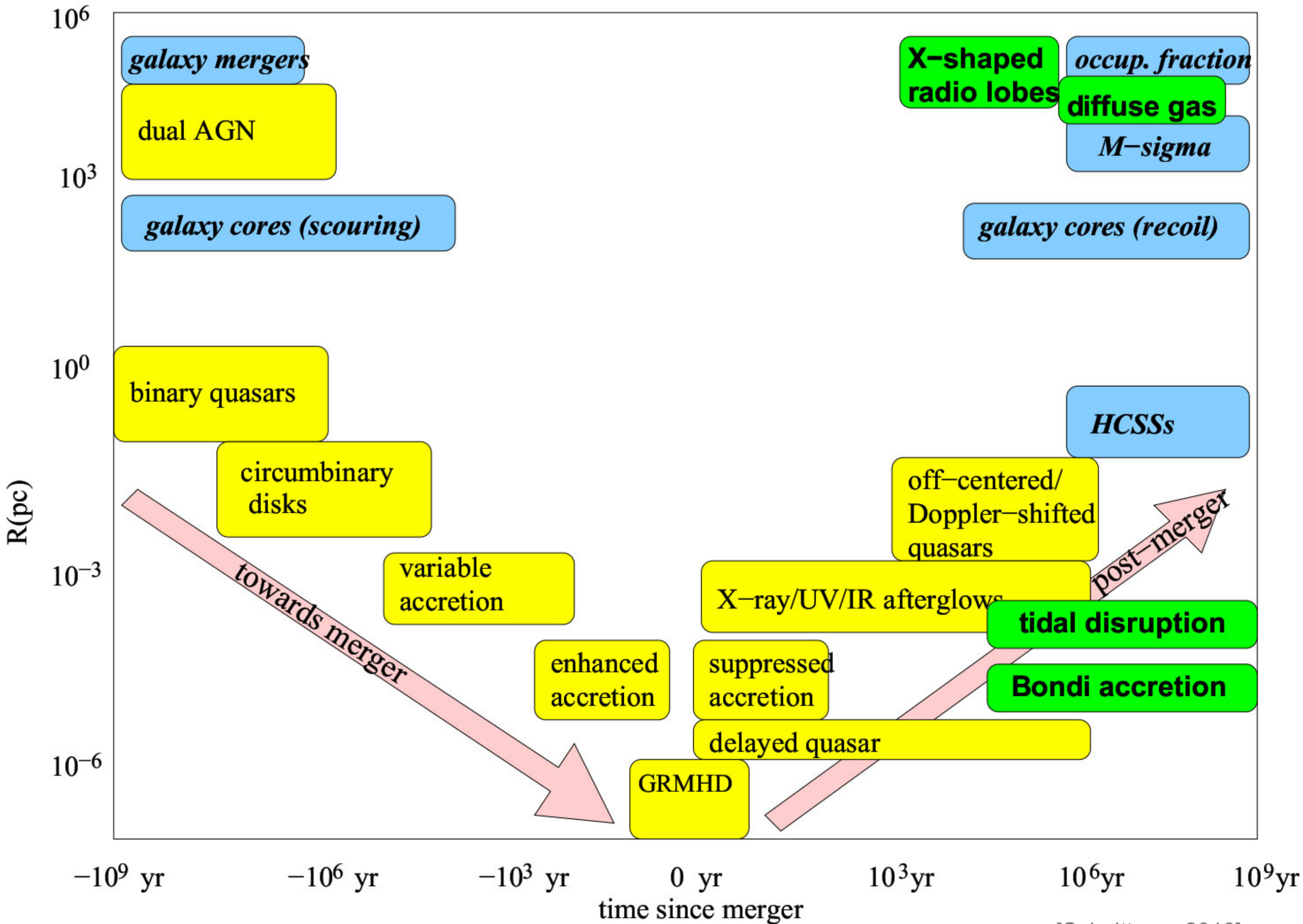


FIG. 9: Probability distribution $P(v)$ of the recoil magnitude for BHBs alignment configurations in hot (top curve, red circles) and cold discs BHBs (lower curve, blue squares). The velocity is in units of km s^{-1}. [Lousto+ 2012]

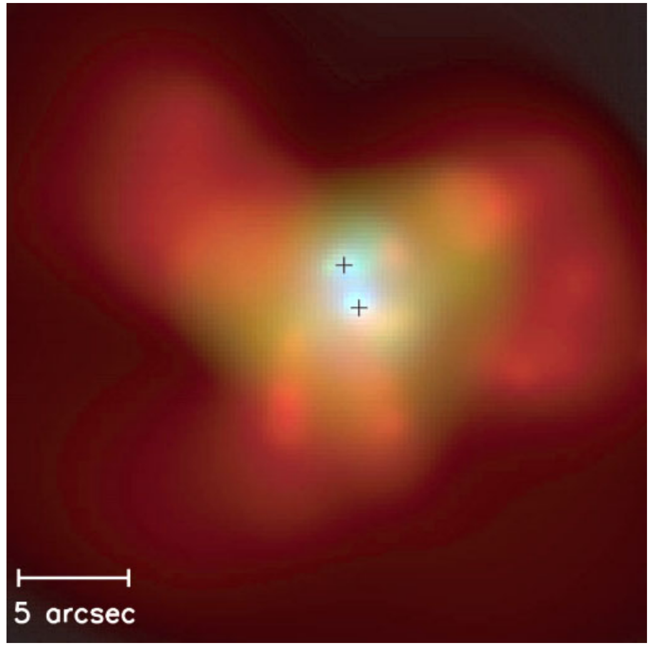
Observational signatures of binary SMBH and mergers



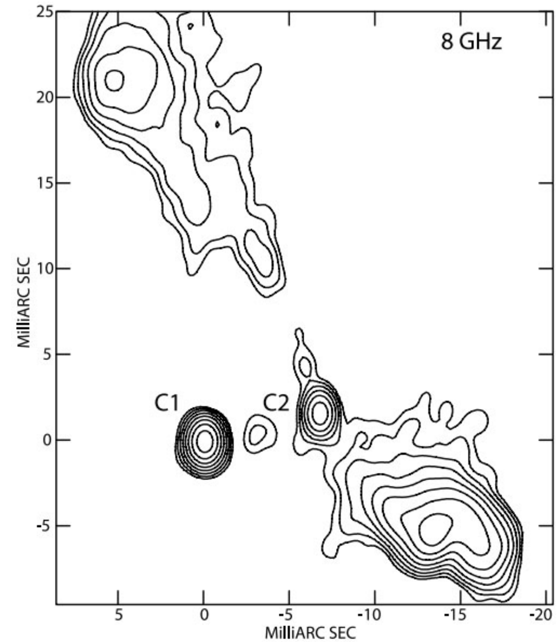
[Schnittman 2013]

Observational evidence for multiple SMBH

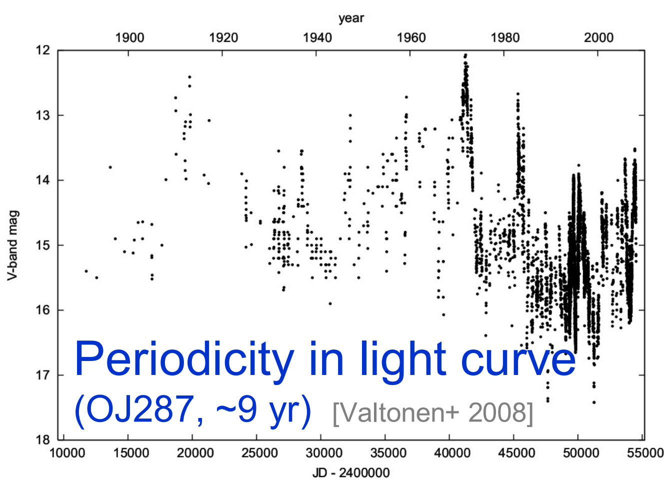
Dual jets (3C 75, a~7kpc)
[Owen+ 1985]



Dual X-ray sources
(NGC 6240, a ~ 1.5 kpc) [Komossa+ 2003]

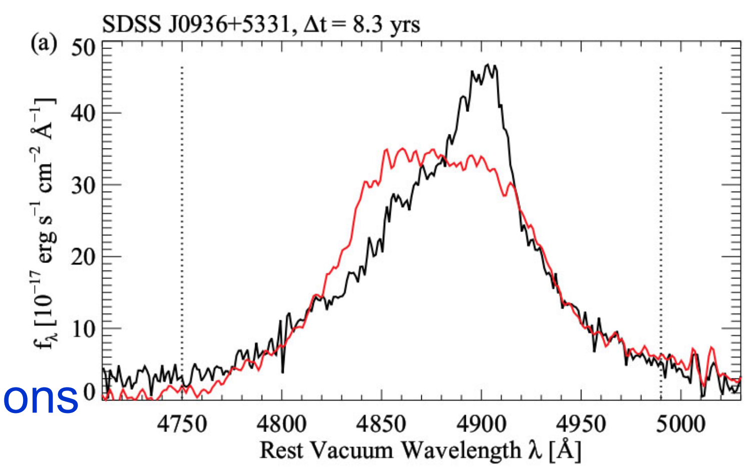


Binary radio sources
(0402+379, a ~ 7pc) [Owen+ 1985]



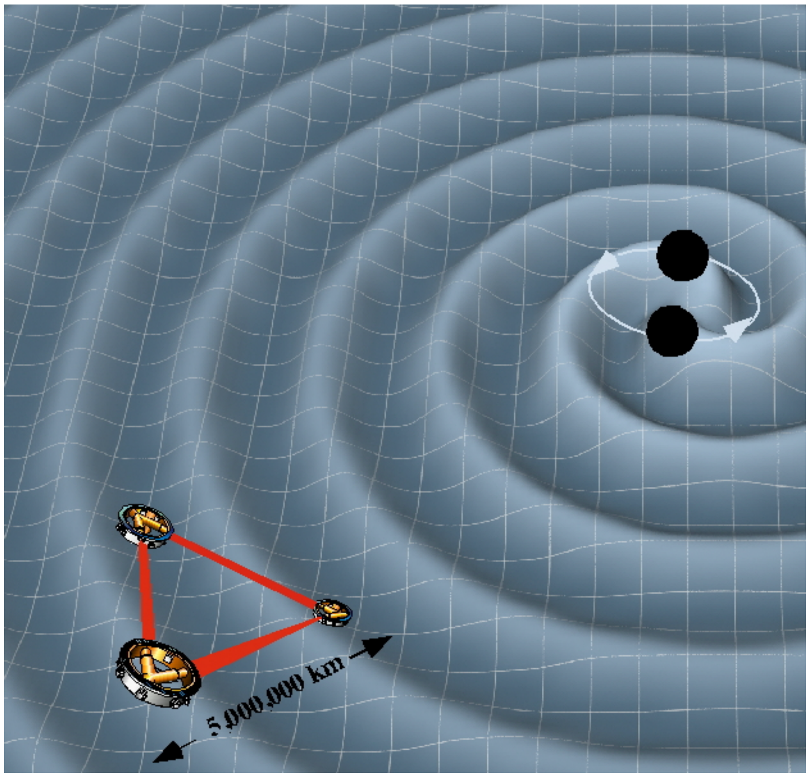
Periodicity in light curve
(OJ287, ~9 yr) [Valtonen+ 2008]

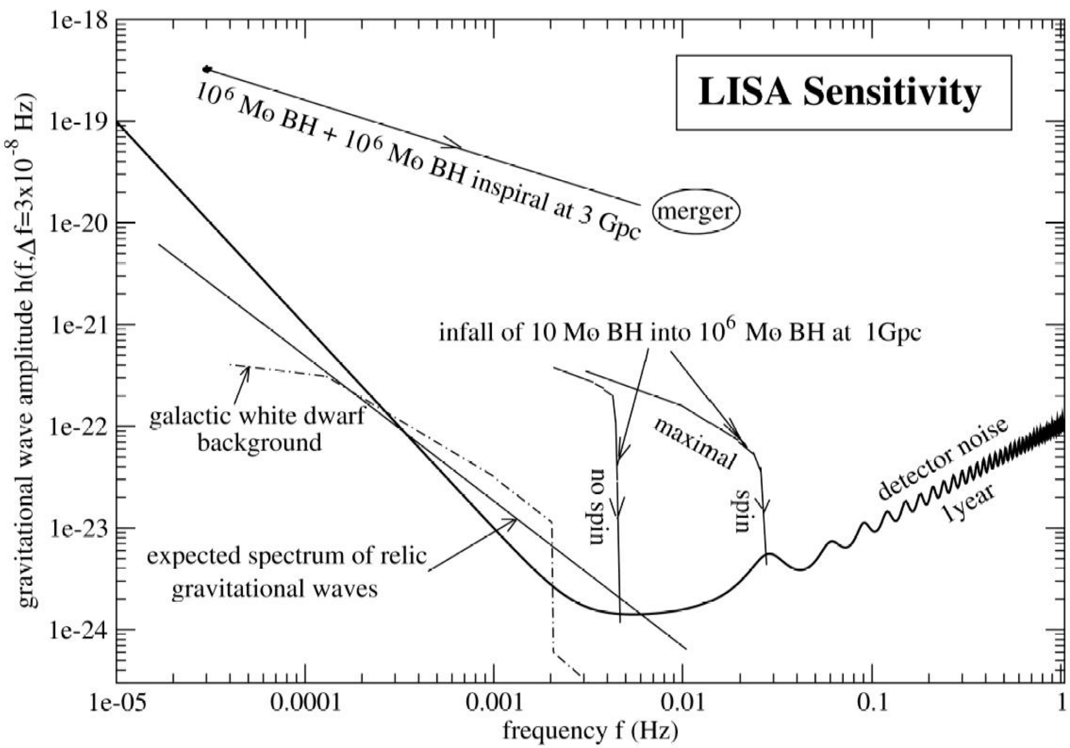
Kinematic shift in
multi-epoch observations
[Liu+ 2013]



Gravitational waves from binary mergers

- With a space-based gravitational wave interferometer of size $\sim 10^6$ km, we may expect to detect mergers of binary supermassive black holes at the low-mass end (10^5-10^6 solar masses) in almost entire Universe





Conclusions

- Binary supermassive black holes are expected to be ubiquitous in the Universe.
- At early stages of evolution, the binary shrinks due to interaction with stars of galactic nucleus; if the supply of stars into the "loss cone" is efficient enough, this process should decrease the separation from ~1pc to ~0.01pc in ~10^9 yr.
- Gravitational waves kick in at smaller separations and rapidly lead to circularization and coalescence.
- Observational evidence for <u>binary</u> black holes is rare; only in a couple of cases a bound pair has been identified (as opposed to <u>dual</u> black hole).
- The merger event should produce detectable electromagnetic counterpart (in addition to GW signal); the merged black hole may receive substantial recoil velocity to be ejected from galactic nucleus or even from entire galaxy.