Life and adventures of binary supermassive black holes

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[image credit: Paolo Bonfini]

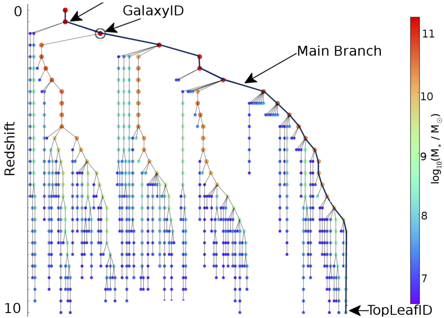
WFPC2 captures a SMBH binary kicking stars out of the bulge

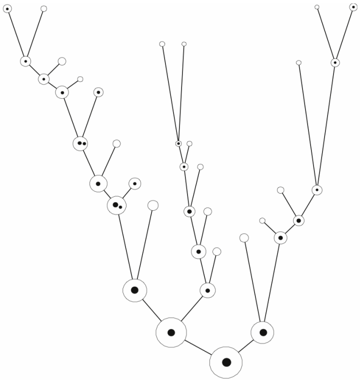
Plan of the talk

- Evolutionary stages of binary black holes
- The final-parsec problem
- Observational signatures and evidence
- Conclusions

Binary SBH in a cosmological context

- Most galaxies are believed to host central SBHs.
- Most galaxies experience many mergers during their lifetime.
- Each merger eventually creates a binary SBH.

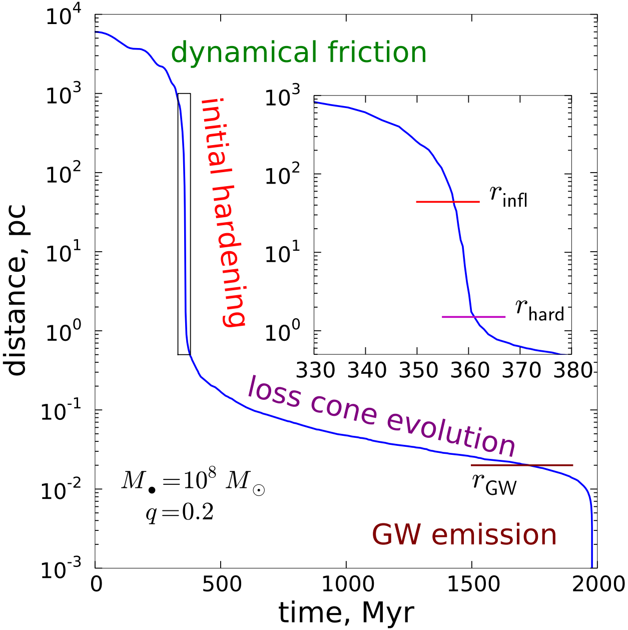




Evolutionary track of binary SBH

- Merger of two galaxies creates a common nucleus;
  dynamical friction rapidly brings two black holes together to form a binary (distance: $r \sim 10$ 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" ($r \sim 1$ 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 (GW) emission becomes the dominant mechanism that carries away the energy
- Reaching a few Schwarzschild radii ($\sim 10^{-5}$ pc), the binary finally merges

Evolutionary stages and timescales



Gravitational slingshot and binary hardening

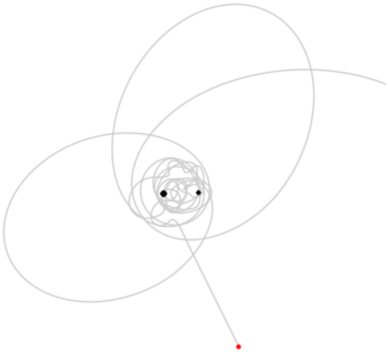
A star passing at a distance $\lesssim 2a$ from the binary experiences a complex three-body interaction resulting in an ejection with

$$v_{\rm ej} \sim \sqrt{\frac{m_1 m_2}{(m_1+m_2)^2}}\, v_{\rm bin} \;\gg\; \sigma .$$

In a fixed background, the binary hardens at a constant rate:

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

[Quinlan 1996]



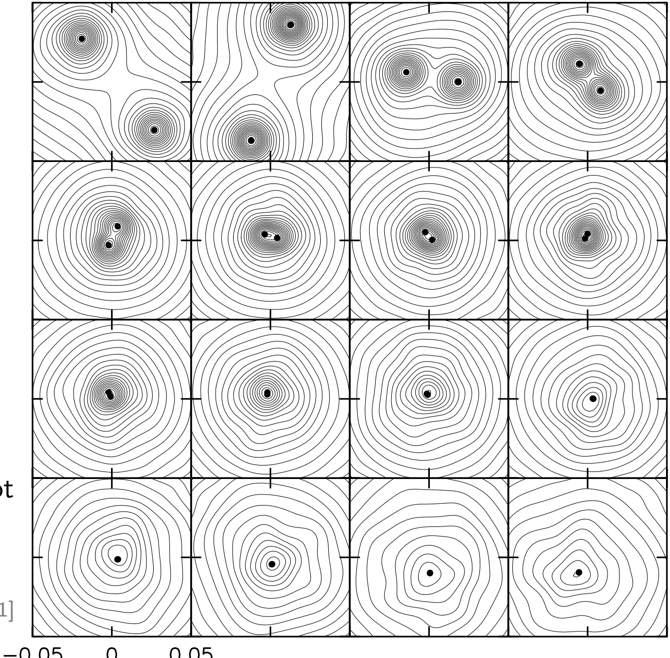
But: The reservoir of stars with low angular momentum may be depleted quickly $\Rightarrow$ the binary stalls at a radius $a_{\rm stall} \sim 0.1\, a_{\rm hard}$.

Formation of galactic cores

Dynamical friction

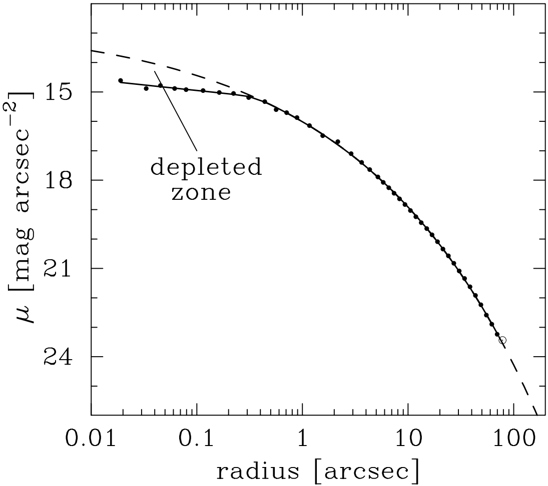
Bound pair

Ejection of stars via gravitational slingshot



[Milosavljević&Merritt 2001]

Formation of galactic cores



Surface brightness profile of NGC 3348. The solid line is the best-fitting core-Sérsic model, while the dashed line is the best-fitting Sérsic model to the large-radius data. The mass deficit is illustrated by the area designated as the 'depleted zone', corresponding to a mass deficit of $\sim 3 \times 10^8\ M_{\odot}$. [Graham 2004]

Loss cone theory

The region of phase space with angular momentum $L^2 < L_{\rm LC}^2 \equiv 2G(m_1 + m_2)\, a$ is called the loss cone.
Gravitational slingshot eliminates stars from the loss cone in one orbital period $T_{\rm orb}$. 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

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

Typically $T_{\rm rep} \gg T_{\rm orb}$ (the loss cone is nearly empty), and the hardening rate $S \equiv \frac{d}{dt}(a^{-1}) \simeq \frac{T_{\rm orb}}{T_{\rm rep}} S_{\rm full}$.
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.

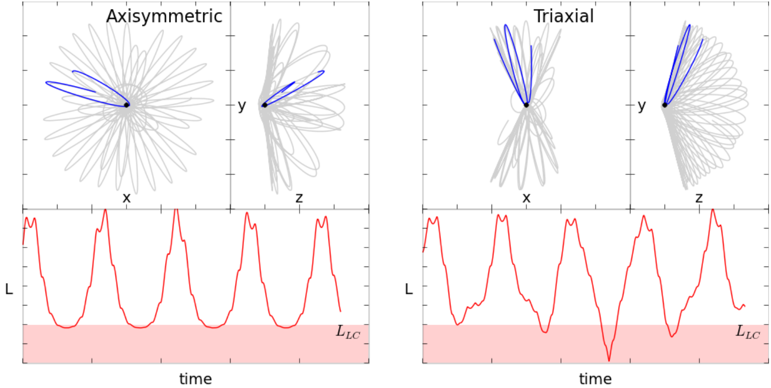
This is the "final-parsec problem" [Milosavljević&Merritt 2003]

Loss cone in non-spherical stellar systems

But: Merger remnants are never exactly spherical! ⇒

Angular momentum L of any star is not conserved, but experiences oscillations due to torques from non-spherical distribution of stars.

Therefore, much larger number of stars can attain low values of L and enter the loss cone at some point in their (collisionless) evolution, regardless of two-body relaxation.



Numerical simulations

N-body simulations confirmed the depletion of the loss cone in isolated spherical galaxies, but not in merger remnants [Preto+ 2011, Khan+ 2011].

But:

- In a typical collisional N-body simulation, the number of particles $N \lesssim 10^6$ – much smaller than the number of stars in a galaxy ($N_\star \sim 10^{10-12}$).
- The collisional repopulation time scales as $T_{\rm rel} \propto N$, but the collisionless effects (non-spherical torques) are independent of N.

A novel simulation method

- **Dynamics:**
  particles move in a self-consistent smooth potential.
- **Gravitational potential:**
  spherical-harmonic expansion for $\forall$ geometry.
- **Suppression of relaxation:**
  use spatial and temporal smoothing and oversampling.
- **Star-binary interactions:**
  explicit tracking of energy and angular momentum exchanges in three-body scattering events.
- **Addition of relaxation:**
  local diffusion coefficients for velocity perturbations.

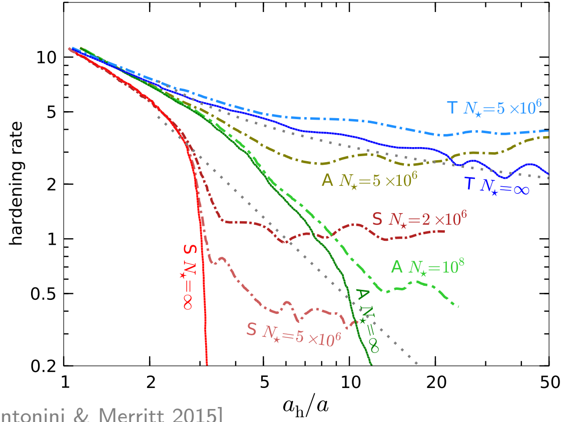
Assumptions:

- quasi-stationary evolution, well defined center;
- hard SBH binary already formed.

[Vasiliev 2015]

Long-term binary evolution

- To shrink the binary by a factor of two, one needs to eject stars with total mass $\sim M_\bullet$; thus one needs to supply a few$\times M_\bullet$ worth of stars into the loss cone over the entire evolution.
- The volume of the extended loss region is large enough only in a non-axisymmetric (triaxial) geometry.
- Non-spherical torques repopulate the loss cone at a sufficient rate for the binary to merge in $\lesssim 1$ Gyr.
- The final-parsec problem is solved.



[Vasiliev, Antonini & Merritt 2015]

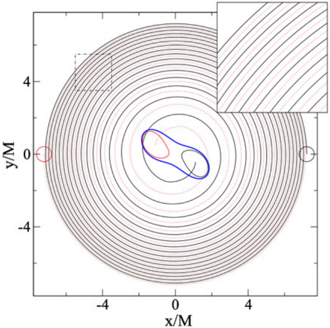
Gravitational waves and SBH mergers

Timescale for coalescence due to gravitational-wave emission alone:

$$T_{\rm GW} = \frac{5}{256\,F(e)}\,\frac{c^5}{G^3}\,\frac{a^4}{\mu(m_1+m_2)^2}$$

$$= 7\times10^8 {\rm yr}\,\frac{q^3}{(1+q)^6}\left(\frac{m_1+m_2}{10^8\,M_\odot}\right)^{-0.6}\left(\frac{a}{10^{-2}a_h}\right)^4,$$

$$F(e) \equiv (1-e^2)^{7/2}\left(1+\tfrac{73}{24}e^2+\tfrac{37}{96}e^4\right)$$ [Peters 1964].



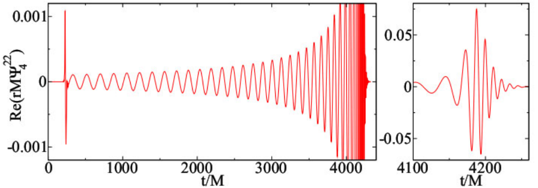
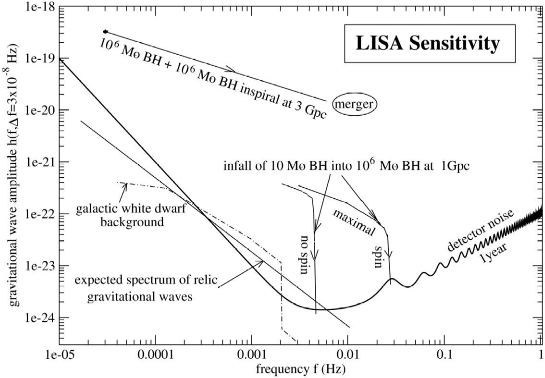
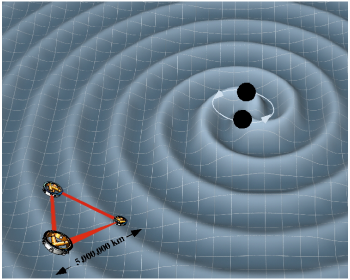


FIG. 14 Gravitational waveforms from the Caltech/Cornell merger simulation seen in Fig. 13 showing the $\ell = 2$, $m = 2$ component of $\mathrm{Re}(r\Psi_4)$ (Scheel *et al.*, 2009). The left panel shows a zoom of the inspiral waveform, and the right panel a zoom of the merger and ringdown.

Gravitational waves and SBH mergers

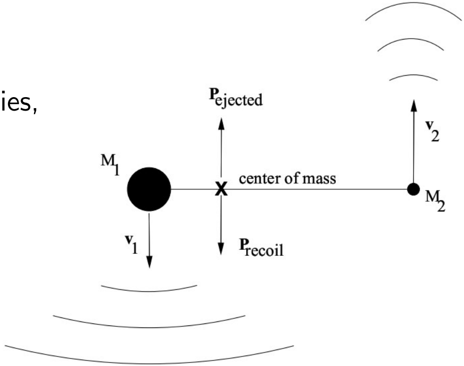
Having a space-based gravitational wave interferometer with arm length $\sim 10^6$ km, we may expect to detect mergers of binary SBHs at the low-mass end ($10^5 - 10^6\, M_\odot$) across almost the entire Universe.



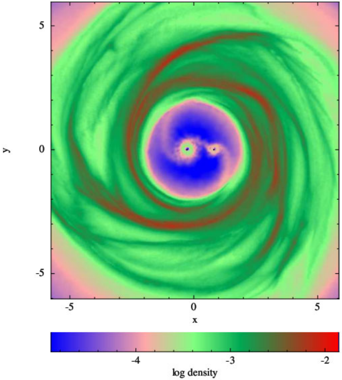


Gravitational recoil and ejection of SBHs

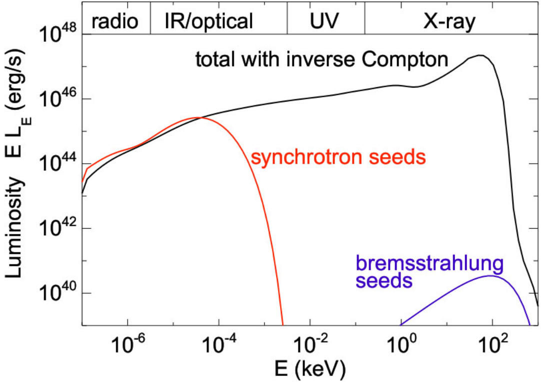
- Gravitational waves are emitted anisotropically and carry away linear momentum, thus the merged black hole receives a "kick" velocity of several hundred (in case of non-spinning SBHs) or even up to several thousand (for specially aligned spin/orbit configurations) km/s.
- The kick velocity may exceed the escape velocity from smaller galaxies, or at least push the merged SBH out of galactic nucleus.
- The SBH may carry away a "hypercompact stellar cluster" [Merritt+ 2009].
- The recoiled SBH sinks back to the galaxy center in $\sim 10^8$ yr.



Electromagnetic counterpart of SBH mergers

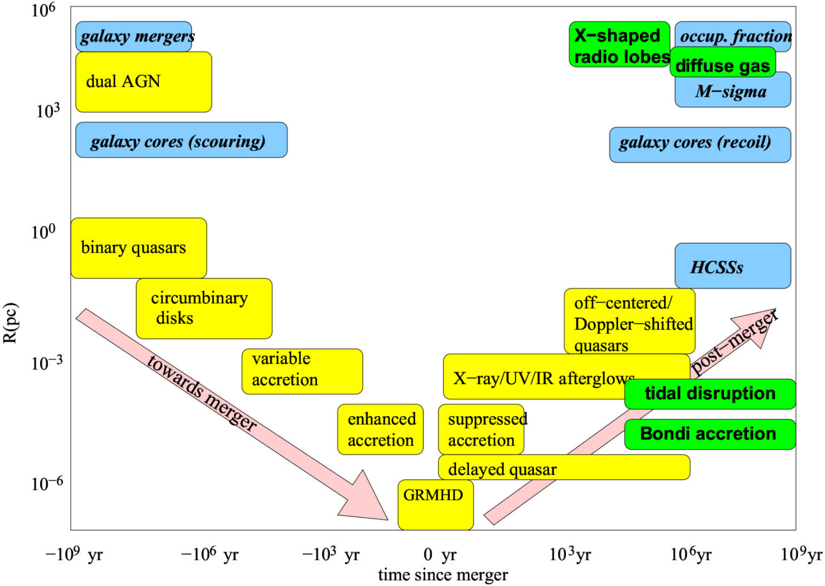


[Roedig+ 2012]



[Giacomazzo+ 2012]

Observational signatures of binary SBHs

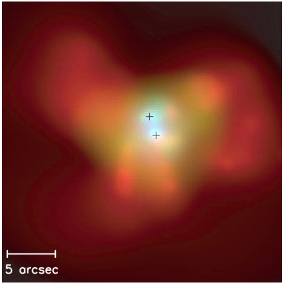


[Schnittman 2013]

Observational evidence for multiple SBH

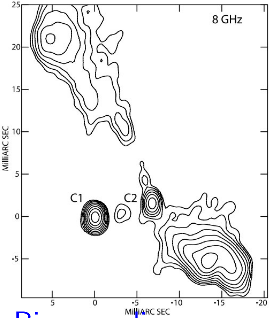
Dual jets

3C 75, $a \sim 7$ kpc [Owen+ 1985]



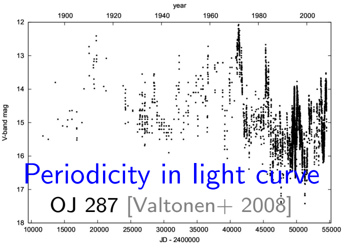
Dual X-ray sources

NGC 6240, $a \sim 1.5$ kpc
[Komossa+ 2003]



Binary radio sources

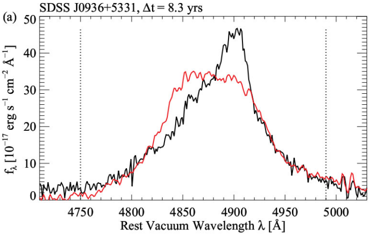
0402+379, $a \sim 7$ pc
[Rodriguez+ 2006]



Periodicity in light curve

OJ 287 [Valtonen+ 2008]

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



Summary

- Binary supermassive black holes naturally form in galaxy mergers and are expected to be ubiquitous in the Universe;
- The binary shrinks due to three-body scattering of stars in the galactic nucleus;
- The early phase leads to core formation, and the entire evolution can take $\sim 10^9$ yr;
- Non-axisymmetric shape of the merger remnant is crucial for the merger timescale;
- So far, observational evidence for *binary* (as opposed to *dual*) MBH is rather scarce;
- MBH coalescence could be easily detected with GW observatories and can also produce electromagnetic counterpart and lead to ejection of MBH from galactic centre.