Evolution of massive black hole binaries
and
Stars and gravitational waves in AGN disks

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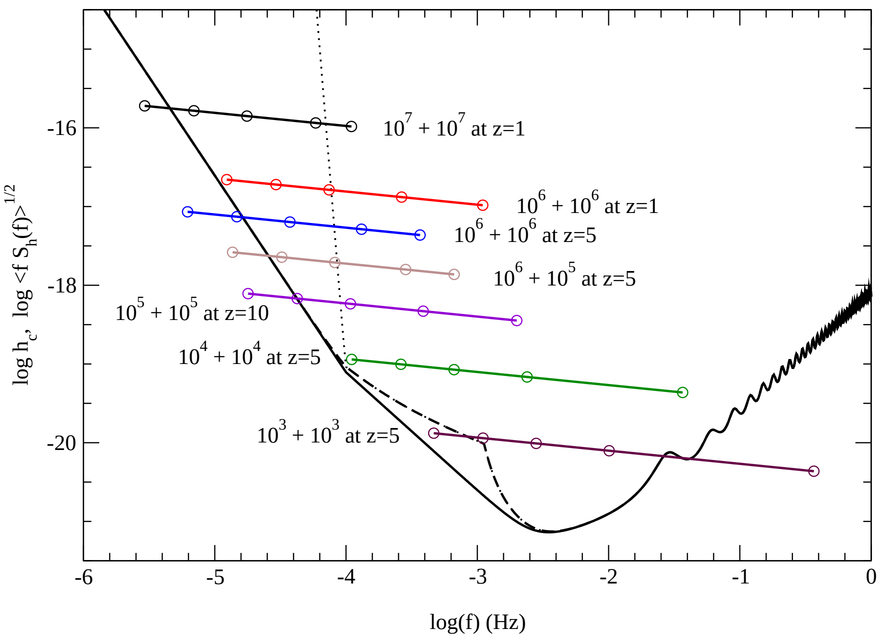
I. Evolution of massive black hole binaries

Coalescence and merger of massive black hole binaries

– strong source of low frequency gravitational waves ;
– same waveforms *a priori* as for stellar-mass black hole binaries ;
– in the frequency range for chirp mass $\lesssim 10^8 M_\odot$.



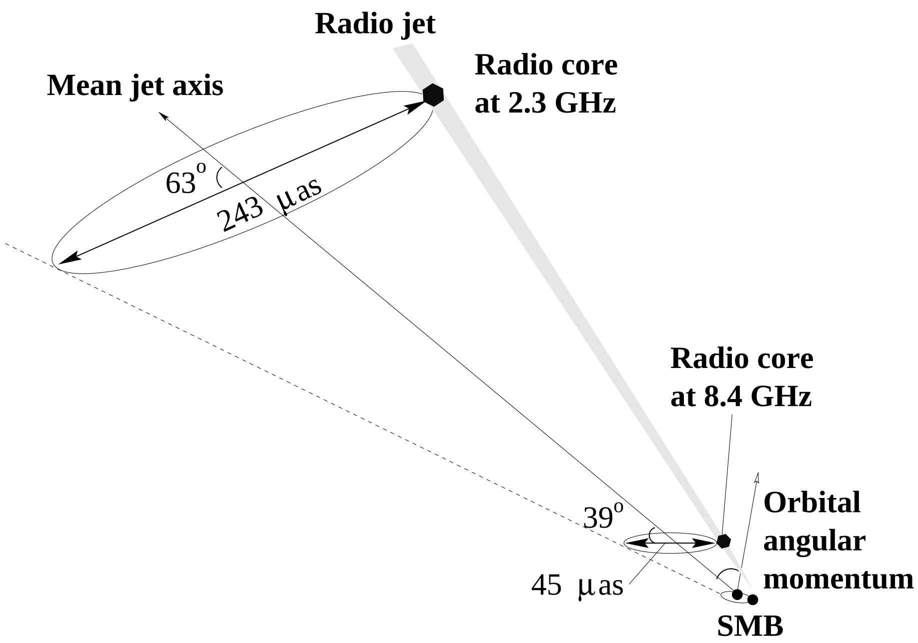
⇒observation of events at cosmological distances

Formation scenario

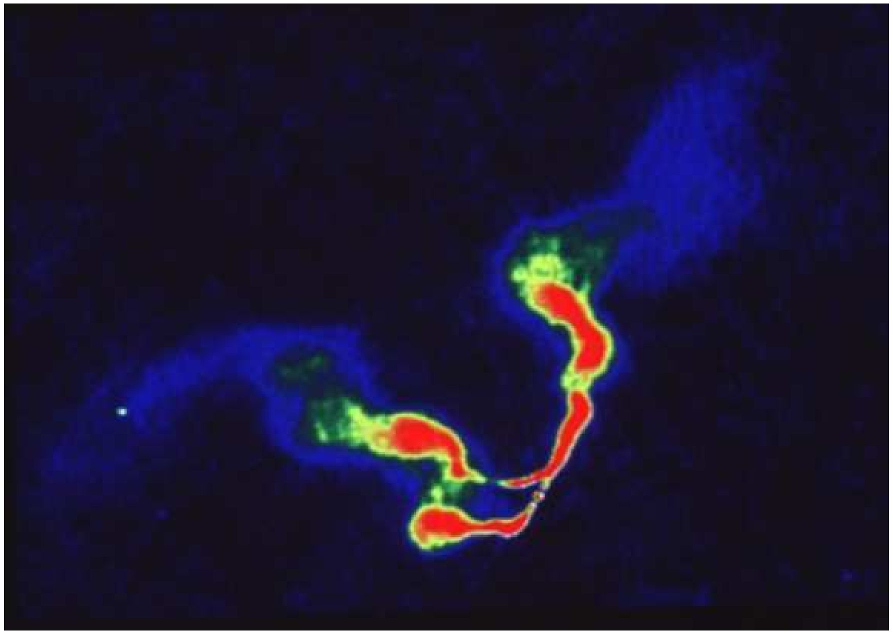
- evidences for massive black holes at (active) galaxy centers ;
- observation of merging galaxies ⇒formation of a binary system of massive black holes ;
- the binary hardens as stars from the galactic nucleus carry away angular momentum ⇒depletion of the loss-cone ;
- ... how does the binary enter the gravitational wave regime (coalescing time due to GW emission lower than the Hubble time) ?

⇒several scenarios but nothing certain for the "final parsec problem"

Observations of binary massive black holes



Pair of twin radio lobes at a separation of 7 kpc in 3C75 in two merging galaxies .



Radio core of 3C 66B shows well-defined elliptical motions with a period ∼ 1 year.

... and many evidences of periodic variability of active galaxies, consistent with the orbital periods of binary massive BH (e.g. OJ 287).

The final parsec problem : Interaction with stars

Standard picture :

– gravitational slingshot interaction : stars which orbits intersect the binary are ejected and take away angular momentum from the binary ;

– the nucleus loses stars able to interact $\Rightarrow$ "loss-cone depletion" ; the replenishment is too slow and the binary may stall before the GW regime !

Several reasons for the binary to merge (still) :

– interactions with stars increase binary eccentricity $\Rightarrow$faster evolution through GW emission ;

– nuclei undergoing mergers or accretion may refill the loss-cone much more efficiently (unrelaxed state and steep density gradient) ;

– models of spherical nuclei are limited : no star in *centrophilic* orbit (much more efficient to take away momentum) ;

– stars can interact several times and a third less-massive BH might come !

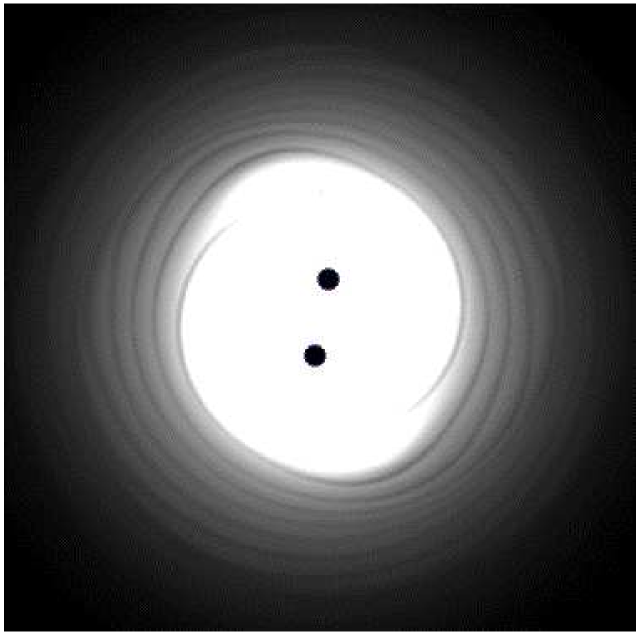
Numerical simulations have resolution problems : relaxation times are shorter by factor $\sim N/10^{11}$ $\Rightarrow$spurious loss-cone refilling !

The final parsec problem : Interaction with gas

Very few studies...

– hot (virialized) gas : gravitational drag from the gas might induce decay in the binary orbit.

– cold gas (in accretion disk) : tidal coupling and density waves can extract angular momentum from the binary and increase its eccentricity.



In the final stage, the disk decouples from the binary which may change the electro-magnetic emission of the AGN.

Summary – Merging rate

– pessimistic view : binary massive black holes evolution usually stalls before they enter the GW regime due to the loss-cone depletion ;

– optimistic view : several physical processes can increase the angular momentum loss : interaction with gas, non-relaxed nucleus, centrophilic orbits, intermediate-mass BH ...

– *a posteriori* view : if the binary would not merge, we should see either more binary-like structures (radio lobes, jets, galactic central structure...) or no massive BH at all (ejection of the binary when a third massive BH comes through additional merger).

With this last, the event rate should be about 0.1 - 1/ year if massive BH form only by direct collapse in deep galactic potential wells (for $0 \leq z \leq 5$), or 10-100/ year if massive BH can appear in pre-galactic structures ($z \gtrsim 5$).

References :

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II. Stars and gravitational waves in AGN disks

Gravitational waves and massive stars in AGNs

Massive stars are forming in accretion disks of bright galactic nuclei...

Y.Levin, astro-ph/0307084

J.Goodman & J.C. Tan, astro-ph/0307361

- What is the fate of these objects ? (Do they collapse to black holes ?)
- How good are they as gravitational wave emitters when coalescing into the supermassive black hole ?
- What would be the event rate seen by LISA ?
- What can we learn from those waves ?
- What is the influence of the accretion disk on the waveforms ?

Very massive stars up to $5 \times 10^5\, M_\odot$

J.Goodman & J.C. Tan predict the formation of such very massive stars that reach the main sequence and **assume** they remain there until they migrate to the supermassive black hole. The main sequence lifetime is :

$$t_{\rm ms} \simeq 10^6 \text{ years},$$

and the star is supposed to open a gap in the disk $\Rightarrow$ Type II migration toward the center on the viscous timescale :

$$t_{\rm visc} \simeq 10^5 \text{ years}.$$

The gravitational wave signal is supposed to come from the orbits closest to the supermassive black hole **eventually after a tidal disruption !**
The radius of these stars is :

$$R_* \sim 1.6 \left(\frac{M_*}{M_\odot}\right)^{0.47} R_\odot .$$

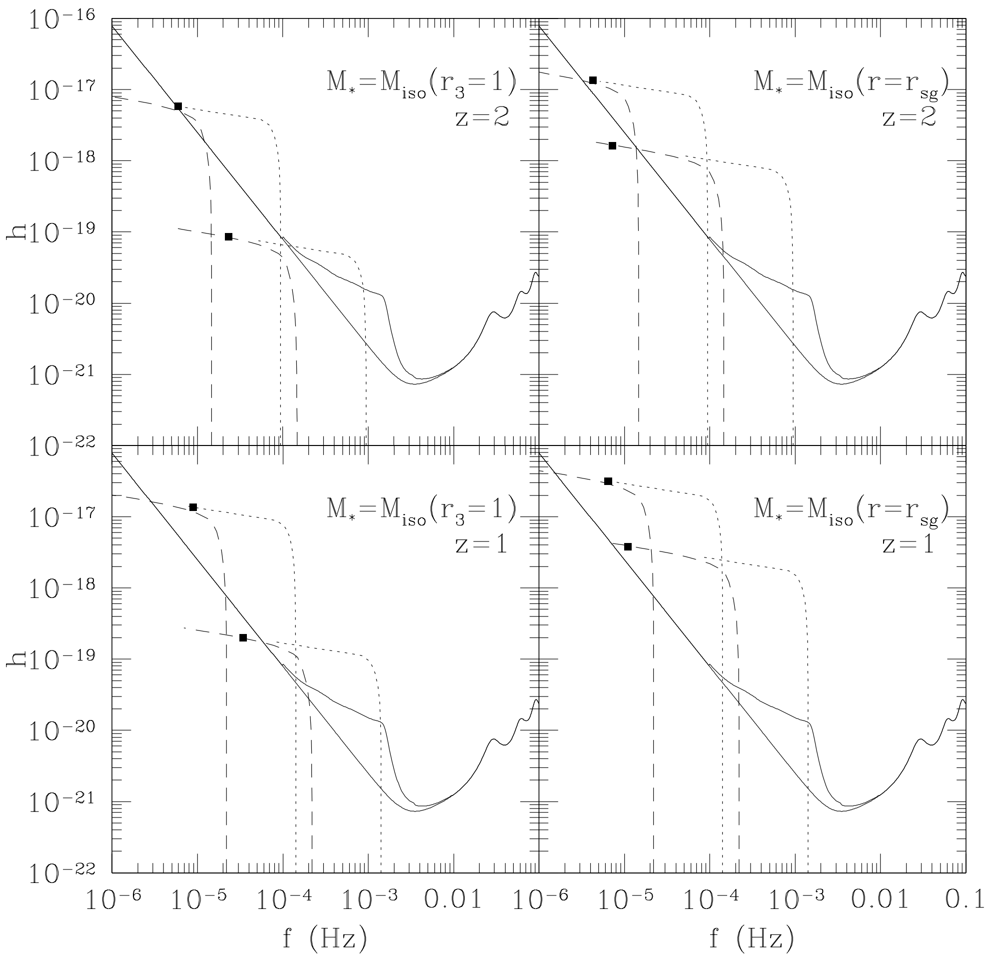
Stellar black hole in the accretion disk

$Y.Levin$ supposes that clumps accrete material from the disk and collapse to $\sim 10\,M_\odot$ black holes in less than 10^6 years.

These black holes do not have any significant velocity kick at their birth and remain embedded in the disk.

They merge with the central black hole on $10^6 - 10^7$ years timescale (type II or type I migrations), which can be shorter due to gravitational radiation.

Gravitational waves from supermassive stars

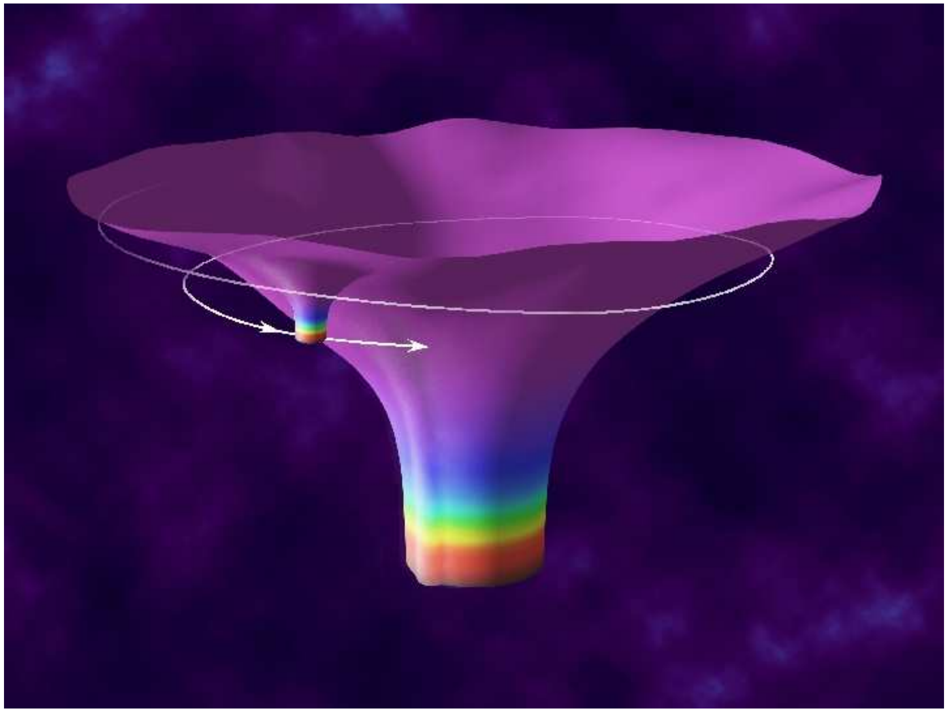


In *J.Goodman & J.C. Tan* the wave amplitudes are computed assuming a **compact object** coalescing with the supermassive black hole.

⇒ tidal disruption (black boxes) before the system enters the LISA band ?

Stellar black holes orbiting around a supermassive one

F. Ryan (1997) has shown that it is possible to get information about supermassive black hole's multipole moments from the gravitational waves emitted by a small compact object orbiting around it.



⇒ it is (technically ?) better if these orbits lie in the equatorial plane... the model by *Y.Levin* seems promising / stellar black hole capture by the supermassive black hole.

Event rates

$Y.Levin$ shows that for an accretion disk in bright AGN to be stable, a mass fraction of the material accreted by the central black hole must collapse to stellar-mass black holes embedded in the disk.

He then assumes that :

- a mass fraction η of the gas accreted by AGNs is converted to $100\,M_\odot$ black holes,
- the mass density of $10^5 - 10^7$ black holes is $\sim 10^5\,M_\odot/\mathrm{Mpc}^3$,
- about 10 percent of integrated radiation from AGNs comes from $z < 1$,
- supermassive black holes have acquired most of their mass through accretion

$\Rightarrow\sim 1000\eta$ mergers per year in this toy-model

Influence of the accretion disk on the orbital motion

Necessity of having very accurate templates on the orbital phase for $\sim 10^5$ cycles of evolution.

Hydrodynamic torques might spoil these...
$\Rightarrow$ *Y.Levin* applies the analysis by *R.Narayan (2000)* (ADAF models) to the case of radiative disk flows with high accretion rate (radiation-pressure dominated).

$$q = 10 n_m \frac{t_{\rm gw}}{t_{\rm drag}} \simeq 2 \times 10^{-7} \frac{\epsilon_{0.1}^3}{\dot{m}^3 \alpha_{0.1}} \frac{(M_{\rm bh}/10 M_\odot)^{13/8}}{M_6^{13/4}} t_{m,yr}^{21/8},$$

If $q \ll 1$, the disk drag does not influence the inspiral signal.

Note : assumption of a thin disk (maybe not valid close to the supermassive black hole).

Summary

- very poor knowledge of the evolution of very massive main-sequence stars ;
- formation of such stars in AGN disks should be a good source of gravitational waves if they evolve to stellar-mass black holes before they are tidally disrupted by the supermassive black hole ;
- these waves carry information about the metric near the central object ;
- event rate (and amplitudes) seem fair ;
- the disk influence on the waveforms may be weak...